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ATLAS 实验含 τ 末态超对称粒子的寻找

(English Version Translated by Google Translate)

作者姓名: 蔡雨辰

指导教师: 庄胥爱 研究员 中国科学院高能物理研究所

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CAI Yuchen

Supervisor: Professor Zhuang Xuai

Institute of High Energy Physics, Chinese Academy of Sciences

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摘 要

标准模型是目前成功描述微观粒子及其相互作用的理论，但它仍有很多不足，比如标准模型的中微子没有质量、无法提供暗物质粒子、不能在高能标时统一相互作用耦合常数等等，所以当前的物理学需要构建超出标准模型理论来解释这些问题。超对称理论是超出标准模型理论中的热门候选者，它可以解释粒子物理中存在的绝大多数问题，实验中可以通过寻找其理论预言的超对称粒子来寻找新物理。

目前世界上能量最高的大型强子对撞机 (LHC) 实验没有观测到超出标准模型存在的迹象，LHC 实验对强相互作用产生的超对称粒子 ($\tilde{g}$ 、 $\tilde{q}$) 的质量排除限已经很强，但对电弱相互作用产生的超对称粒子 (带电的 Chargino 粒子 $\tilde{\chi}^\pm$ 和中性的 Neutralino 粒子 $\tilde{\chi}^0$) 的质量排除限较弱，所以电弱相互作用产生的超对称粒子还有很大的探索空间。本文利用 ATLAS 实验在 2015 至 2018 年第二轮取数期间获得的质心能量为 13 TeV 下总积分亮度为 139 fb^{-1} 的质子-质子对撞数据，开展了四个分析。前两个分析是对关于电弱相互作用产生最轻的 Chargino 粒子和次轻的 Neutralino 粒子对 ($\tilde{\chi}_1^\pm \tilde{\chi}_2^0$ 、 $\tilde{\chi}_1^\pm \tilde{\chi}_1^\mp$) 通过不同衰变过程的研究，第三个分析是利用 ATLAS 已发表分析的信号区对 R 宇称破坏的信号模型进行了诠释，最后一个分析对包含 19 个自由参数的唯象最小超对称标准模型 (pMSSM-19) 进行限制。

第一个分析是 $\tilde{\chi}_1^\pm \tilde{\chi}_2^0$ 通过 W 、 h 玻色子衰变至单轻子和双陶子末态过程的寻找，这是 ATLAS 首次对此过程进行寻找。此过程中 W 玻色子衰变的轻子可以有效压低强相互作用过程产生的本底， h 玻色子衰变至双陶子末态的分支比相对较高。本研究使用数据驱动的 Fake Factor 方法估计不可约本底，使得相关本底估计的误差降低约 3 倍，从而有效提高了信号灵敏度。由于本研究在信号区中没有发现明显超出标准模型的现象，因此在 95% 置信度下给出了 $\tilde{\chi}_1^\pm/\tilde{\chi}_2^0$ 的质量排除限。当 $\tilde{\chi}_1^0$ 质量为 0 时， $\tilde{\chi}_1^\pm/\tilde{\chi}_2^0$ 质量低于 330 GeV 的区域在 95% 置信度下被排除。

第二个分析是 $\tilde{\chi}_1^\pm \tilde{\chi}_2^0$ 、 $\tilde{\chi}_1^\pm \tilde{\chi}_1^\mp$ 通过 $\tilde{\tau}$ 或 $\tilde{\nu}$ 衰变至含有两个陶子末态过程的寻找。该过程可以合理解释宇宙学实验观测到的暗物质遗留密度以及实验观测到的缪子反常磁矩超出。本研究首次通过加入末态陶子电荷同号的信号区大幅提高了质量压缩区域的显著性，同时通过横动量最高和次高陶子携带的电荷同号、异号末态的联合拟合大幅提高了整个质量区域的显著性。由于信号区中没有发现明显超出标准模型的现象，本研究在 95% 置信度下给出了相关粒子的质量排除限，当 $\tilde{\chi}_1^0$ 质量为 0 时， $\tilde{\chi}_1^\pm$ 质量低于 970 GeV 的区域被排除；对于质量简并的 $\tilde{\chi}_1^\pm/\tilde{\chi}_2^0$ 的产生过程， $\tilde{\chi}_1^\pm/\tilde{\chi}_2^0$ 质量低于 1160 GeV 的区域被排除，这是 ATLAS 实验目前最强的 $\tilde{\chi}_1^\pm/\tilde{\chi}_2^0$ 排除限。

第三个分析利用 ATLAS 实验 Run2 期间针对双陶子末态和多轻子末态的分

析对 R 宇称破坏下 Higgsino 成对产生的模型进行了诠释。超对称寻找实验通常针对超对称粒子迅速衰变的模型，但理论上超对称粒子的寿命可以较长，目前对相关模型的限制较弱，所以研究超对称寻找实验对不同寿命的模型的显著性变化并对这些模型进行限制是十分重要的。本文详细研究了 R 宇称破坏项耦合系数 λ_{i33} 对 Higgsino 寿命和分支比的影响，这是 ATLAS 首次研究此模型，同时本文给出了目前最新的 λ_{i33} 耦合系数的理论上限。在系统误差方面，本文详细研究了移位陶子的重建、鉴别和相关触发器的系统误差，这是 ATLAS 首次对相关误差进行研究，得到了 ATLAS Tau 工作组的认可。本研究在 95% 置信度下给出了质量简并的 Higgsino 在不同寿命下的质量排除限，当耦合系数较大，Higgsino 衰变至标准模型粒子的分支比较高时，Higgsino 质量低于 800 GeV 的区域被排除。

第四个分析是对 pMSSM-19 模型进行限制。此分析利用了 ATLAS 实验在 Run2 期间的超对称寻找实验、希格斯粒子衰变宽度的测量、超出标准模型希格斯粒子的寻找实验和非 ATLAS 实验进行约束。基于简化模型的质量排除限在更真实地超对称模型上的限制较弱，可能仍存在超对称粒子质量较低的模型未被排除，所以检验目前超对称实验对较真实的模型的限制十分重要。本分析不仅是对 ATLAS 实验 Run2 期间实验结果的系统性总结，更为未来超对称寻找实验提供了重要参考。本分析发现 ATLAS 实验对 pMSSM-19 模型中超对称粒子质量参数的限制普遍低于基于简化模型的排除限，尤其是对 $\tilde{\chi}_1^\pm$ 、 $\tilde{\chi}_2^0$ 粒子质量的限制，质量谱处于质量压缩区域的超对称模型仍有较大的可能未被排除。对于暗物质粒子候选者来说，基于 Z/h -funnel 湮灭机制的 Bino 型 LSP (Lightest SUSY Particle, 最轻超对称粒子) 作为暗物质粒子的可能性较低，但质量较高的基于 A/H -funnel 和 $\tilde{q}$ 、 $\tilde{\chi}_1^\pm$ 、 $\tilde{\chi}_2^0$ 联合湮灭机制的 Bino 暗物质仍可能存在。

总而言之，本文的研究内容涵盖了 Wino 型 $\tilde{\chi}_1^\pm/\tilde{\chi}_2^0$ 对产生过程并通过标准模型玻色子和超对称轻子衰变这两种衰变模式的研究，同时涵盖 R 宇称守恒和破坏的 SUSY 模型的研究、简化 SUSY 模型和非简化模型的 pMSSM-19 模型的研究，几乎涵盖了 SUSY 的大部分研究方向。本文研究的 $\tilde{\chi}_1^\pm\tilde{\chi}_2^0$ 、 $\tilde{\chi}_1^\pm\tilde{\chi}_1^\mp$ 模型可以自然解释缪子反常磁矩的超出和暗物质遗留密度，其中通过 W 、 h 玻色子衰变的过程是 ATLAS 上首次寻找，通过 $\tilde{\tau}$ 或 $\tilde{\nu}$ 衰变过程首次研究了同号双陶子过程从而大幅度提升了质量压缩区域的信号灵敏度，研究中研发并使用了 Fake Factor 和 ABCD 等多种数据驱动的本底估计方法有效降低了本底估计误差从而大幅提升了信号灵敏度。本文考虑的 R 宇称破坏的 Higgsino 模型也是 ATLAS 上首次研究，同时本文对 pMSSM-19 模型的研究是 Run2 首次限制此模型的全部自由参数。

关键词：超对称物理, R 宇称, 最小超对称标准模型, 大型强子对撞机, ATLAS 探测器

Abstract

The Standard Model (SM) is a successful theory describing the fundamental particles and their interactions. However, it is still imperfect due to some limitations: the neutrinos are considered massless, dark matter particles are absent, and the interaction coupling constants do not unify at high energy scales. Clearly, new theories beyond the Standard Model (BSM) are needed to resolve these issues. Supersymmetry (SUSY) is one of the most popular BSM theories aiming to solve most of the big questions in particle physics. SUSY models predict supersymmetric particles, which can be searched for by experiments at the Large Hadron Collider (LHC).

While the current exclusion limits on the strong production of SUSY particles ($\tilde{g}, \tilde{q}$) are stringent, the limits on the electroweak production of SUSY particles (electroweakinos, Chargino $\tilde{\chi}^\pm$ and Neutralino $\tilde{\chi}^0$) are relatively weak. Therefore, chargino and neutralino production could play a significant role at the LHC. In light of this, four analyses are performed in this thesis utilizing a dataset of pp collisions corresponding to an integrated luminosity of 139 fb^{-1} , recorded with the ATLAS detector at a centre-of-mass energy of 13 TeV during the Run 2 period from 2015 to 2018. Searches for chargino and neutralino productions via intermediate W/h boson or $\tilde{\tau}$ or $\tilde{\nu}$ decay are considered in the first two analyses. The third analysis reinterprets a selection of ATLAS SUSY searches, optimized for R-parity conserving (RPC) and R-parity-violating (RPV) models, in SUSY models with variable RPV-coupling strength. The last analysis provides constraints on the 19-parameter phenomenological Minimal Supersymmetric Standard Model (pMSSM-19).

The $\tilde{\chi}_1^\pm \tilde{\chi}_2^0$ production via W/h boson decay to a final state of at least one light lepton and two tau-leptons has been studied in the first analysis. The multi-jet background can be strongly suppressed by requiring one light lepton from the W decay, and the analysis also benefits from the higher branching ratio of higgs decay to two tau-leptons. The analysis is expected to be sensitive to light electroweakinos, which are strong candidates to explain the excess from the Fermilab Muon $g-2$ Experiment and can also provide an excellent dark matter candidate. To estimate the reducible background, a data-driven Fake Factor method is developed and implemented. This method has reduced the uncertainty of the reducible background estimation by a factor of three, consequently increasing the signal significance. Since no significant deviation from the expected SM background is observed, SUSY particle mass limits at 95% confidence level are obtained in simplified models. For a massless $\tilde{\chi}_1^0$, $\tilde{\chi}_1^\pm/\tilde{\chi}_2^0$ masses up to 330 GeV are excluded.

The $\tilde{\chi}_1^\pm \tilde{\chi}_2^0$ and $\tilde{\chi}_1^\pm \tilde{\chi}_1^\mp$ production via $\tilde{\tau}$ or $\tilde{\nu}$ decay with a final state of at least

two tau-leptons has been studied in the second analysis. This model not only satisfies the requirements of relic density measurements but also offers an explanation for the observed excess in the Muon g-2 experiments. The same sign (SS) two tau-lepton events are studied to improve the sensitivity, especially at a very compressed mass spectrum, which is the first study in such analyses. No significant deviation from the expected SM background is observed and SUSY particle mass limits at 95% confidence level are obtained in simplified models. In the scenario of direct production of $\tilde{\chi}_1^\pm$ pairs, $\tilde{\chi}_1^\pm$ masses up to 970 GeV for a massless $\tilde{\chi}_1^0$ are excluded. In the case of associated production of pairs of $\tilde{\chi}_1^\pm$ and pairs of degenerate $\tilde{\chi}_1^\pm$ and $\tilde{\chi}_2^0$, masses up to 1160 GeV are excluded for a massless $\tilde{\chi}_1^0$. These limits improve upon previous results by around 340 to 400 GeV.

The third analysis reinterprets ATLAS SUSY searches from di-tau and multi-lepton analyses in RPV higgsino pair production models. The SUSY models considered in ATLAS SUSY searches mostly assume prompt decay of SUSY particles, while they could be long-lived. The current constraints on the models with long-lived SUSY particles remain relatively weak. Therefore, it is crucial to reinterpret the public SUSY searches targeting prompt decay models in SUSY models with varying lifetimes or decay branching ratios. The study explores the impact of λ_{i33} coupling strengths on the lifetimes and branching ratios of the higgsino and provides the latest theoretical upper limits for these strengths, which is the first result of its kind for ATLAS. Specifically, the systematics of displaced tau reconstruction, identification, and triggers have been studied for this analysis, which is the first such study in the ATLAS experiment and has been approved by the ATLAS Tau Performance group. The exclusion limits on higgsino masses reach up to 800 GeV in scenarios with lifetimes below 10^{-3} ns.

The final analysis provides a summary of the constraints from SUSY and BSM Higgs searches performed by the ATLAS Collaboration in the context of the pMSSM-19 model. External constraints from previous electroweak, flavour and dark matter related measurements are also considered. Whilst exclusion limits using simplified models provide an easily interpretable picture of the sensitivity of analyses to specific areas of parameter space, they are far from an exhaustive exploration of the MSSM. Thus, it is important to recast or validate existing exclusion limits derived from the simplified models against more intricate SUSY models. This study not only serves as a systematic summary of ATLAS Run 2 searches but also stands as an important reference for future SUSY searches. In general, the bounds on SUSY particle masses from the ATLAS searches are weaker in the pMSSM when assumptions entering the simplified models are relaxed, especially in the compressed regime. The Higgs boson and Z boson funnel regions, where a low-mass neutralino would not oversaturate the dark matter relic abundance, are almost completely excluded by the considered constraints. However, models

with A/H -funnel or $\tilde{q}/\tilde{\chi}_1^\pm/\tilde{\chi}_2^0$ co-annihilation as the dominant mode are still viable.

In summary, the studies in this thesis have comprehensively covered nearly most of the aspects of SUSY searches, they include studies on R -parity conserving and R -parity violating models, on simplified models and the pMSSM-19 models, and on the boson decay mode and slepton decay modes of the wino-like gaugino pair production. The models involving light electroweakino $\tilde{\chi}_1^\pm\tilde{\chi}_2^0$ and $\tilde{\chi}_1^\pm\tilde{\chi}_1^\mp$ productions can explain the observed excess in the Muon $g-2$ experiment and the observed dark matter relic density. Notably, it is the first time that the channel decay via W/h boson with two tau-leptons has been explored within the ATLAS experiment. The combination of same-sign and opposite-sign two tau finals states has significantly improved signal sensitivity, particularly in the mass compressed regime. The data-driven methods employed in the analyses, such as the Fake Factor method and the ABCD method, have effectively mitigated uncertainties in background estimations. Furthermore, the exploration of higgsino R -parity violation models is the first of its kind for the ATLAS experiment. This thesis also provides a summary of the constraints from searches performed by the ATLAS experiments on the 19-parameter pMSSM, which is an important reference for future SUSY searches.

Key Words: Supersymmetry, R -parity, MSSM, LHC, ATLAS detector

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符号列表

字符

tau 陶子

缩写

LHC 大型强子对撞机 (Large Hadron Collider)
HL-LHC 高亮度大型强子对撞机 (High Luminosity LHC)
ATLAS 超环面仪器 (A Toroidal LHC ApparatuS)
SM 标准模型 (Standard Model)
SUSY 超对称 (Supersymmetry)
EWKino 超电弱规范子 (Electroweakino)

第 1 章 Introduction

Currently, the Standard Model is the most successful theory in particle physics for describing fundamental particles and their interactions. After the discovery of the Higgs boson at CERN in 2012 [1, 2], all fundamental particles predicted by the Standard Model have been identified. However, many phenomena observed in particle physics and cosmological experiments cannot be explained by the Standard Model, such as the problem of neutrino mass [3, 4], the existence of dark matter and dark energy [5–7]. In addition, the mass of the Higgs boson has led to naturalness issues [8]. The existence of these issues has led physicists to believe that the Standard Model is a low-energy approximation of a theory beyond the Standard Model at a higher energy scale.

Among the many theories beyond the Standard Model, supersymmetry is one of the most elegant. Supersymmetry theory [9] is a general term for a class of theories incorporating supersymmetry, which posits that bosons and fermions are in the same supermultiplet, with equal degrees of freedom for fermions and bosons within a supermultiplet, and that the Lagrangian of a supermultiplet system remains invariant under supersymmetry transformations. Supersymmetry theory requires supersymmetry breaking at low energies, leading to differences in the fundamental physical quantities of Standard Model particles and supersymmetric particles.

Particle physics is a discipline where experiment and theory are closely intertwined, and while supersymmetry theory is highly elegant, without experimental support, it remains “just a theory.” The Large Hadron Collider (LHC) at CERN is currently the highest-energy circular proton-proton collider in the world [10]. The ATLAS [11] and CMS experiments [12] conducted there are significant experiments in exploring the high-energy frontier, and one of their physics goals is to search for new physics beyond the Standard Model, especially for supersymmetric particles. During the first data-taking period, ATLAS collected experimental data with a center-of-mass energy of 7 TeV and an integrated luminosity of 4.5 fb^{-1} and data with a center-of-mass energy of 8 TeV and an integrated luminosity of 20.3 fb^{-1} . During the second data-taking period from 2015 to 2018, ATLAS collected experimental data with a center-of-mass energy of 13 TeV and an integrated luminosity of 139 fb^{-1} . However, the analysis of this data showed no signs of supersymmetric particles in the ATLAS experiment. Consequently, based on a simplified model, the ATLAS experiment set exclusion limits on the mass of supersymmetric particles at the 95% confidence level. If the mass of the lightest supersymmetric particle is close to 0 GeV, the mass exclusion limits for supersymmetric particles ($\tilde{g}$ and $\tilde{q}$) produced via the strong interaction are generally around 2 TeV, which is near the detection limit of the LHC. For supersymmetric particles ($\tilde{\chi}^\pm$,

$\tilde{\chi}^0$, and $\tilde{\ell}$) produced via electroweak interaction, the mass exclusion limits are relatively lower, ranging from a few hundred GeV to about 1 TeV, leaving significant space for further exploration [13], with CMS arriving at similar conclusions [14, 15]. Additionally, other direct or indirect experiments probing supersymmetric particles have also found no evidence of supersymmetric particles.

Given that no experiment has directly observed evidence of supersymmetric particles, this paper investigates three research directions:

(1) The cross-section for producing supersymmetric particles $\tilde{g}$ and $\tilde{q}$ through the strong interaction is high. Given the lack of observation of $\tilde{g}$ and $\tilde{q}$, there are stringent experimental constraints on them. However, constraints on supersymmetric gauginos ($\tilde{\chi}_1^\pm$ and $\tilde{\chi}_2^0$) produced by the electroweak interaction, with a lower cross-section, are relatively weaker, leaving substantial room for exploration at the current LHC center-of-mass energy. Therefore, searching for gauginos is essential.

(2) In most supersymmetric models used in experiments, the lightest supersymmetric particle is stable or quickly decays by selecting a higher R -parity violating coupling parameter. However, in supersymmetric models, the lightest supersymmetric particle can also have a relatively long lifetime and decay after traveling some distance. Such models are subject to weaker experimental constraints. Given the large number of such models, studies on searching for long-lived particles often cannot rule out models one by one, so it is essential to examine the exclusion capability of general analysis signal regions as a function of lifetime and branching ratio.

(3) Most exclusion limits obtained by experiments are for simplified supersymmetric models, typically with only two or three free parameters, so experiments impose very stringent constraints on these simplified models. However, the MSSM has many parameters, and supersymmetric models with relatively low masses for supersymmetric particles might still exist and be unexplored.

This paper focuses on the above three directions based on ATLAS data from the second data-taking period at a center-of-mass energy of 13 TeV and an integrated luminosity of 139 fb^{-1} . The main structure of this paper is as follows:

Chapter 2 introduces the Standard Model and its deficiencies, briefly discusses supersymmetry theory and the MSSM, and touches on their physical motivations and significance.

Chapter 3 provides an introduction to the LHC and the ATLAS detector, covering basic concepts in collider physics, proton-proton collision simulation, and ATLAS detector simulation.

Chapter 4 presents ATLAS data acquisition and processing, the reconstruction and calibration of physical objects, and in-situ tau energy correction. This tau energy correction study will provide a more accurate tau simulation for future tau-involved research.

Chapter 5 focuses on the search for gaugino pairs produced by the electroweak interaction and decaying to a single lepton and ditau final state through W and h bosons. Signal region optimization in this study adopts the “cut and count” method, with main irreducible backgrounds estimated using the “Fake factor” method.

Chapter 6 discusses the search for gaugino pairs produced via the electroweak interaction and decaying to ditau final states through stau or sneutrino intermediates. Signal region optimization uses the “cut and count” method, the main irreducible background is estimated using the “ABCD” method, and a combined fit of multiple decay channels is used for statistical interpretation.

Chapter 7 explores the study of R -parity violating models by utilizing published ATLAS results on searches for electroweak supersymmetric particles decaying to multi-lepton and ditau final states. Supersymmetric particles in this model have a relatively long lifetime.

Chapter 8 examines current experimental constraints on the phenomenological MSSM. This study imposes limits on the Bino-like LSP model by generating signal models with uniform sampling of model parameter space and using ATLAS and other non-ATLAS searches from the second data-taking period.

Chapter 9 contains a summary of the research and an outlook on future searches for supersymmetric particles.

Moreover, the research and development of future colliders are also important in searching for new physics beyond the Standard Model. Appendix ?? introduces a study of beam tests and muon response for dual-readout calorimeters.

第 2 章 The Standard Model of Particle Physics and the Supersymmetric Model

This chapter will briefly introduce the theoretical background of this article, mainly including the standard model, supersymmetric theory and the minimum supersymmetric standard model, and briefly introduce the current status of supersymmetric physics search in the ATLAS experiment in the last part of this chapter.

2.1 The Standard Model

The Standard Model of Particle Physics (SM) is the most successful theory to describe elementary particles and their interactions. The Standard Model mainly consists of two parts: the electroweak unification theory that describes the electroweak interaction and quantum chromodynamics (QCD) that describes the strong interaction. Physicists generally believe that there are four fundamental interactions in the universe, namely strong, weak, electromagnetic and gravitational interactions. Our understanding of gravitational interactions is not comprehensive, and we cannot obtain a theory that is complete at high energy scales (Ultraviolet completion) and approximates general relativity at low energy scales. But for the other three interactions, the Standard Model can accurately describe these three interactions and the elementary particle fields involved in them.

In 1961, Glashow proposed one of the core theories of the Standard Model: the electroweak unification theory. Glashow introduced the gauge group structure of $SU(2) \otimes U(1)$ and predicted the existence of neutral particles Z_0 that transmit weak interactions by directly introducing the mass term [16]. After that, Ward and Salam used similar structures to predict that the charged particle W that transmits weak interactions has the same charge as electrons and muons, and successfully estimated the mass of this particle [17]. In terms of strong interactions, Gell-Mann and Zweig each proposed the quark model [18, 19] in 1964, and humans began to explore the internal structure of hadrons in depth. Based on the contributions of predecessors, physicists gradually established the standard model based on gauge field theory, unified the three interactions, and explained the source of the mass of elementary particles through the Brout–Englert–Higgs mechanism (Higgs mechanism). In terms of experiments, physicists discovered the existence of c quarks, b quarks, gluons, and τ leptons in the late 1970s, W and Z bosons in 1983, t quarks and τ neutrinos in the 1990s, and finally the existence of the Higgs particle h in 2012. So far, the Standard Model has been fully verified by experiments.

2.1.1 Elementary particles

In the Standard Model, elementary particles and their interactions can be roughly described as spin-1/2 fermions interacting through bosons with spin-1.

The Standard Model uses a Lagrangian with $SU(3)_c \otimes SU(2)_L \otimes U(1)_Y$ gauge invariance to describe the real world. The generators of the gauge symmetry correspond to the bosons that transmit the interaction. $SU(3)_c$ is used to describe the strong interaction, and the subscript c stands for "color". Its eight-dimensional representation G^a ($a \in [1, 8]$) is used to describe the gluon field with eight color states. Gluons are massless particles in the Standard Model. The generator W^α ($\alpha \in [1, 3]$) of $SU(2)_L$ and the generator B of $U(1)_Y$ are mixed after spontaneous symmetry breaking to become $W^\pm$, Z bosons and photon fields (γ) that describe the transmission of electroweak interactions, where the subscript L represents the weak isospin quantum number, and Y represents the weak supercharge quantum number. Similar to the case of the gluon field, W^α and B in the gauge field theory cannot have mass terms, so the standard model introduces the Higgs mechanism to make $W^\pm$ and Z bosons gain mass through mixing. The introduction of the Higgs mechanism predicts the existence of the Higgs boson, which has a spin of 0 and a scalar field ϕ to represent its particle field. Their properties are shown in the table 2-1 [20]. The standard model has 12 intermediate bosons and 1 Higgs boson.

表 2-1 标准模型玻色子的性质 [20]。

Table 2-1 The properties of bosons in the SM [20].

Boson	Mass	Charge [e]	Spin	Interaction	Relative Strength
Gluon (g)	0 $\leq 1 \text{ MeV}$ [21]	0	1	Strong	1
Photon (γ)	0 $< 10^{-18} \text{ eV}$ [20]	0 $< 10^{-46}$ [20]	1	Electronic	10^{-2}
W boson	$80.377 \pm 0.012 \text{ GeV}$ [20]	± 1	1	Weak	10^{-6}
Z boson	$91.1876 \pm 0.0021 \text{ GeV}$ [20]	0	1	Weak	10^{-6}
Higgs boson (h)	$125.25 \pm 0.17 \text{ GeV}$ [20]	0	0	-	-

Fermions are the basic particles that make up the material world. They are classified into quarks that participate in strong interactions and leptons that do not participate in strong interactions. There are three generations of quarks and leptons observed in experiments so far. Their names and basic properties are shown in the table 2-2 [20]. Considering that each fermion has a corresponding antiparticle and quarks carry three colors, the standard model contains a total of 12 leptons and 36 quarks. In the standard model, the right-handed singlet charged lepton field is represented by E , and the left-handed part and the neutrino field form the $SU(2)_L$ doublet state represented by

L [22]:

$$E = \ell_R, \quad L = \begin{pmatrix} \nu \\ \ell_L \end{pmatrix} \quad (2-1)$$

where ℓ and ν represent the spinor fields of charged leptons and neutrinos, respectively. Similarly, the right-handed singlets of the quark field are represented by U and D , and the left-handed part of the $SU(2)_L$ doublet is represented by Q [22]:

$$U = u_R, \quad D = d_R, \quad Q = \begin{pmatrix} u_L \\ d_L \end{pmatrix} \quad (2-2)$$

where u and d represent the spinor fields of (u, c, t) and (d, s, b) quarks respectively.

表 2-2 标准模型费米子的性质 [20]。

Table 2-2 The properties of fermions in the SM [20].

Type	Generation	Mass	Spin	Charge [e]	Lifetime
e^-	1st	0.5101 ± 10^{-10} MeV	1/2	-1	$> 6.6 \times 10^{28}$ 年
ν_e	1st	< 0.8 eV	1/2	0	lifetime/mass > 300 s/eV
μ^-	2nd	105.6 ± 10^{-6} MeV	1/2	-1	$(2.196 \pm 10^{-6}) \times 10^{-6}$ s
ν_μ	2nd	< 0.19 MeV	1/2	0	lifetime/mass > 15.4 s/eV
τ^-	3rd	1776.86 ± 0.12 MeV	1/2	-1	$(2.903 \pm 0.005) \times 10^{-13}$ s
ν_τ	3rd	< 18.2 MeV	1/2	0	-
u	1st	$2.16^{+0.49}_{-0.26}$ MeV	1/2	2/3	-
d	1st	$4.67^{+0.48}_{-0.17}$ MeV	1/2	-1/3	-
c	2nd	1.27 ± 0.02 GeV	1/2	2/3	-
s	2nd	$93.4^{+8.6}_{-3.4}$ MeV	1/2	-1/3	-
t	3rd	172.69 ± 0.30 GeV	1/2	2/3	$\sim 10^{-24}$ s
b	3rd	$4.18^{+0.03}_{-0.02}$ GeV	1/2	-1/3	-

2.1.2 Fundamental Interactions

The Lagrangian of the Standard Model consists of the gauge field part ($\mathcal{L}_{\text{EW, Strong}}$) describing the electroweak and strong interactions and the Yukawa coupling term and Higgs term part ($\mathcal{L}_{\text{Higgs}}$) containing the Higgs field:

$$\mathcal{L} = \mathcal{L}_{\text{EW, Strong}} + \mathcal{L}_{\text{Higgs}} \quad (2-3)$$

2.1.2.1 Lagrangian of the gauge field part

The electroweak and strong interaction terms in the gauge field part describe the kinetic energy and self-interaction terms of gauge bosons, as well as the kinetic energy

and gauge interaction terms of fermions [22]:

$$\begin{aligned} \mathcal{L}_{\text{EW, Strong}} = & -\frac{1}{4}G_{\mu\nu}^a G^{\mu\nu a} - \frac{1}{4}W_{\mu\nu}^\alpha W^{\mu\nu \alpha} - \frac{1}{4}B_{\mu\nu} B^{\mu\nu} \\ & + \sum_{\text{generation}} (i\bar{L}\mathbb{D}_L L + i\bar{E}\mathbb{D}_E E + i\bar{Q}\mathbb{D}_Q Q + i\bar{U}\mathbb{D}_U U + i\bar{D}\mathbb{D}_D D) \end{aligned} \quad (2-4)$$

The Feynman slash notation covariant differentials ($\mathbb{D} = \gamma^\mu D_\mu$) of the second row are respectively [22]:

$$\begin{aligned} \mathbb{D}_{L\mu} &= \partial_\mu + \frac{i}{2}g\tau_\alpha W_\mu^\alpha - \frac{i}{2}g'Y B_\mu \\ \mathbb{D}_{E\mu} &= \partial_\mu - \frac{i}{2}g'Y B_\mu \\ \mathbb{D}_{Q\mu} &= \partial_\mu + \frac{i}{2}g_s\lambda_\alpha G_\mu^\alpha + \frac{i}{2}g\tau_\alpha W_\mu^\alpha - \frac{i}{6}g'Y B_\mu \\ \mathbb{D}_{U\mu} &= \partial_\mu + \frac{i}{2}g_s\lambda_\alpha G_\mu^\alpha - \frac{2i}{3}g'Y B_\mu \\ \mathbb{D}_{D\mu} &= \partial_\mu + \frac{i}{2}g_s\lambda_\alpha G_\mu^\alpha + \frac{i}{3}g'Y B_\mu \end{aligned} \quad (2-5)$$

where g , g' , g_s are the coupling constants of the $SU(2)_L$, $U(1)_Y$ and $SU(3)_c$ gauge fields, τ_α is the Pauli matrix, and λ_α is the Gell-Mann matrix.

Electroweak interaction:

In the Lagrangian 2-4, the electroweak gauge boson kinetic energy terms $W_{\mu\nu}$ and $B_{\mu\nu}$ are written as [22]:

$$W_{\mu\nu}^\alpha = \partial_\mu W_\nu^\alpha - \partial_\nu W_\mu^\alpha + g\epsilon_{\alpha\beta\gamma} W_\mu^\beta W_\nu^\gamma \quad (2-6)$$

$$B_{\mu\nu} = \partial_\mu B_\nu - \partial_\nu B_\mu$$

Where $\epsilon_{\alpha\beta\gamma}$ represents the Levi-Civita symbol. The part of the standard model that describes the electroweak interaction consists of the kinetic energy term of the electroweak gauge boson, the kinetic energy term of the fermion in the covariant differential of the formula 2-5, and the coupling term of the fermion-gauge field in the covariant differential.

Quantum Chromodynamics (QCD) Theory:

In the Lagrangian 2-4, the kinetic energy term and the self-interaction term $G_{\mu\nu}^a$ of the gluon gauge field are written as [22]:

$$G_{\mu\nu}^a = \partial_\mu G_\nu^a - \partial_\nu G_\mu^a + g_s f_{\beta\gamma}^a G_\mu^\beta G_\nu^\gamma \quad (2-7)$$

among them, g_s is the strong coupling constant, and $f_{\beta\gamma}^a$ is the structure constant of the commutation relation of the Gell-Mann matrix of $SU(3)_c$. This term describes the

kinetic energy and self-interaction of the gluon field. The fermion kinetic energy term and the fermion-gluon gauge field coupling term of the covariant differential term 2-5 constitute the QCD model of the standard model. The QCD model accurately describes two characteristics of strong interactions. One is that the interaction vertices of three gluons and four gluons appear in the self-interaction term; The second is that the results of the deep inelastic scattering experiment of nucleons require the theoretical description to have the property of asymptotic freedom: at high energy scales, the interaction strength between quarks will weaken. The non-Abelian gauge field used in the QCD theory of the standard model is the only theory that meets the asymptotic freedom requirement[23], and this property is reflected in the decrease of the coupling constant with the increase of the energy scale.

No single quark or gluon was observed in the experiment. This phenomenon is explained as "color confinement". The phenomenological explanation for this is that when a single quark is separated, a pair of quark pairs with opposite color charges will be produced in the vacuum, and finally the final state of color charge is zero. The hadrons observed in the experiment so far include mesons and baryons. Mesons contain a pair of positive and negative valence quarks with the same color charge, and baryons contain three valence quarks with different color charges, both of which are in a "colorless" state. In the low-energy scale region where the perturbation method is applicable, the strong interaction coupling constant of QCD theory increases with decreasing energy, so QCD theory can also partially explain the asymptotic freedom and color confinement phenomena, but how to explain color confinement from the first principles in the energy region where the perturbation method is not applicable is still a difficult problem. In addition, in collider experiments, high-energy quarks or gluons can form a group of emitted particles dominated by colorless hadrons. This phenomenon is called a jet.

2.1.2.2 Higgs term and Lagrangian of Yukawa coupling

Gauge symmetry requires that the Lagrangian does not contain the mass term of the gauge field. For massless gluons, there is no need to introduce the gluon field mass term. However, for W and Z bosons, they are experimentally observed to be massive particles. In order to solve the problem of how to add mass terms to the Lagrangian that satisfies gauge symmetry, theorists proposed the Higgs mechanism (BEH mechanism). The Higgs mechanism can be described as: the spontaneous symmetry breaking of the vacuum of the Higgs field produces the mass terms of the W and Z bosons in the standard model, and the Yukawa coupling term containing the Higgs field explains the source of the mass of fermions. The expression of the Yukawa coupling term and the Higgs term containing the Higgs field is [22]:

$$\mathcal{L}_{\text{Higgs}} = (D_\mu \phi)^2 - \lambda \phi^4 + 2\mu^2 \phi^2 \quad (2-8)$$

$$- \sum_{\text{generation}} (\lambda_e \bar{L} \phi E + \lambda_d \bar{Q} \phi D + \lambda_u \bar{Q} \phi U + \text{h.c.})$$

among them, the covariant differential of ϕ is: $D_\mu = \partial_\mu + \frac{i}{2} g \tau_\alpha W_\mu^\alpha - \frac{i}{2} g' B_\mu$ to satisfy gauge invariance.

Braut-Engeler-Higgs mechanism and electroweak unification theory:

If $\mu^2 < 0$, the minimum value of the Higgs potential term in the formula 2-8 is not at the origin, but on a circle with radius $\phi^2 = \frac{\mu^2}{\lambda}$ in the complex plane, so the vacuum expectation value $v^2 = \frac{\mu^2}{\lambda}$. Considering that the vacuum of this world is at a certain point on the circle, and the gauge transformation can transform any point selected on the circle into another point, for convenience, we can choose:

$$\phi = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v + \Phi(x) \end{pmatrix} \quad (2-9)$$

substituting this term into the Lagrangian, the kinetic energy term can be expanded as:

$$(D_\mu \phi)^2 = \frac{1}{2} (\partial \Phi)^2 + \frac{1}{8} (v + \Phi)^2 g |W_1 - iW_2|^2 + \frac{1}{8} (v + \Phi)^2 (gW_3 + g'B)^2 \quad (2-10)$$

it can be found that the last two terms of the formula 2-10 contain mass terms, and the Weinberg angle $\tan \theta_W = \frac{g'}{g}$ is defined. By comparing the form of the mass terms, we can finally get:

$$\begin{aligned} W^\pm &= \frac{1}{\sqrt{2}} (W_1 \mp iW_2) \\ Z &= \cos \theta_W \cdot W_3 - \sin \theta_W \cdot B \\ A &= \sin \theta_W \cdot W_3 + \cos \theta_W \cdot B \end{aligned} \quad (2-11)$$

That is, the Z boson and γ are the result of the mixing of the neutral W gauge field and the B gauge field through the Weinberg angle. At the same time, the Higgs mechanism naturally introduces the mass term of the boson without destroying the gauge symmetry, thus obtaining:

$$\begin{aligned} M_W &= \frac{gv}{2} \\ M_Z &= \frac{\sqrt{g^2 + g'^2} v}{2} \\ M_A &= 0 \end{aligned} \quad (2-12)$$

In the experiment, since the measurement accuracy of the W and Z boson masses is high, the ratio of their masses is used to determine the Weinberg angle.

After obtaining the expression of the boson and γ field expressed by the gauge field, the fermion kinetic energy term of the gauge field part is rearranged 2-4, the form of flow coupling can be obtained [22]:

$$\mathcal{L}_{\text{Fermion}} = -e[J_{\text{EW}}^\mu A_\mu + \frac{1}{\sqrt{2} \sin \theta_W} (\bar{\ell}_L \gamma^\mu \nu_L W_\mu^- + \bar{\nu}_L \gamma^\mu \ell_L W_\mu^+) + \frac{1}{\sin \theta_W \cos \theta_W} J_{\text{NC}}^\mu Z_\mu] \quad (2-13)$$

Among them, $J_{\text{EW}}^\mu = \bar{f} \gamma^\mu (T_3 + Y) f$ describes the electromagnetic flow, f represents an arbitrary fermion field, and it can be seen that the electromagnetic flow coupling is exactly the same as the description of quantum electrodynamics. The second term describes the interaction between the weak band current and the $W^\pm$ boson. Only the weak band current composed of the left-handed lepton or quark fermion field can couple with the $W^\pm$ field. The last term of the expression describes the interaction between the weak neutral current and the Z boson, where $J_{\text{NC}}^\mu = \bar{f} \gamma^\mu T_3 f - Q_f \sin^2 \theta_W \bar{f} \gamma^\mu f$. By rearranging the gauge field kinetic energy term and the self-interaction expression in the gauge field part 2-4, we can obtain the interaction vertices of a pair of W bosons and a single or two Z bosons or photons, which describes the interaction between bosons.

The potential energy part of the Lagrangian expression 2-8 can be expanded to obtain:

$$V = \frac{\lambda}{4} \Phi^4 + \lambda \nu \Phi^3 + \lambda \nu^2 \Phi^2 \quad (2-14)$$

The last term is the mass term, and the mass of the Higgs boson is $M_{\text{Higgs}} = \sqrt{2\lambda\nu^2}$. The other two terms are Higgs self-coupling terms. The standard model predicts the existence of three Higgs interaction vertices and four Higgs interaction vertices.

Yukawa coupling and Cabibbo-Kobayashi-Maskawa matrix:

The second line of the Lagrangian expression 2-8 describes the Yukawa coupling term between the Higgs field and the fermion field. By considering the conjugate part and expanding it into the Dirac spinor representation, we can get the form of: $\mathcal{L} = \frac{-1}{\sqrt{2}} \nu (\lambda_e \bar{e} e + \lambda_u \bar{u} u + \lambda_d \bar{d} d)$, Therefore, the Yukawa coupling after the vacuum symmetry is broken can describe the mass of the fermion, which is $\frac{1}{\sqrt{2}} \lambda \nu$, and the mass of the fermion is linearly related to the coupling strength of the fermion-Higgs boson. The Yukawa coupling term can also be expressed in a more compact form:

$$\mathcal{L} = - \left(\bar{e}_R, \bar{\mu}_R, \bar{\tau}_R \right) Y_\ell \begin{pmatrix} \phi \begin{pmatrix} \nu_{eL} \\ e_L \end{pmatrix} \\ \phi \begin{pmatrix} \nu_{\mu L} \\ \mu_L \end{pmatrix} \\ \phi \begin{pmatrix} \nu_{\tau L} \\ \tau_L \end{pmatrix} \end{pmatrix} - \left(\bar{d}'_R, \bar{s}'_R, \bar{b}'_R \right) Y_q \begin{pmatrix} \phi \begin{pmatrix} u_L \\ d'_L \end{pmatrix} \\ \phi \begin{pmatrix} c_L \\ s'_L \end{pmatrix} \\ \phi \begin{pmatrix} t_{\tau L} \\ ' _L \end{pmatrix} \end{pmatrix} \quad (2-15)$$

$$+ \left(\bar{u}_R, \bar{c}_R, \bar{t}_R \right) Y'_q \begin{pmatrix} \phi^T i \sigma_2 \begin{pmatrix} u_L \\ d'_L \end{pmatrix} \\ \phi^T i \sigma_2 \begin{pmatrix} c_L \\ s'_L \end{pmatrix} \\ \phi^T i \sigma_2 \begin{pmatrix} t_{\tau L} \\ ' \\ L \end{pmatrix} \end{pmatrix}$$

Among them, Y_ℓ , Y_q and Y'_q are Yukawa matrices. By selecting a suitable diagonalization of the Yukawa matrix, we can introduce the matrix V , which satisfies the following conditions:

$$Y_q = V \begin{pmatrix} y_u & 0 & 0 \\ 0 & y_c & 0 \\ 0 & 0 & y_t \end{pmatrix} V^\dagger$$

And it can describe the mixture of quark mass eigenstates and weak interaction eigenstates, so the Cabibbo-Kobayashi-Maskawa (CKM) matrix is also incorporated into the standard model and represented by the matrix V :

$$\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} = V_{\text{CKM}} \begin{pmatrix} d \\ s \\ b \end{pmatrix}$$

2.1.3 Flaws in the Standard Model

The Standard Model is the most successful low-energy effective theory to describe microscopic physics to date, and it can still accurately describe experimental results at higher TeV energy scales. Although the Standard Model does not incorporate gravity into the theoretical framework, it describes the electroweak and strong interactions, explains the source of the mass of elementary particles, and naturally introduces the CKM matrix. However, the Standard Model also has the following problems or defects:

First, the Standard Model does not describe the mass and flavor mixing matrix (Pontecorvo–Maki–Nakagawa–Sakata matrix) of neutrinos. At present, the solar neutrino experiment [24], the reactor neutrino experiment [3], the atmospheric neutrino experiment [25] and the neutrino beam experiment [26] have all proved the existence of neutrino oscillation and measured the absolute value of the mass difference of three generations of neutrinos [3, 4]. The experimental results show that neutrinos have a tiny mass, which is inconsistent with the description of the standard model.

Secondly, the standard model does not explain the existence of dark matter and dark energy. Physicists have found that the observable baryonic matter density of galaxies Combined with the inverse square relationship of Newton's classical gravity theory, it cannot explain the excessive rotation speed of galaxy clusters [27], This shows that there

is extra matter in the galaxy clusters that binds the galaxies through gravity, Thus revealing the existence of dark matter. At the same time, if the description of the "standard model" Λ CDM model [28] of cosmology is correct, Then there must be some kind of dark energy in the universe to satisfy the experimentally observed accelerated expansion of the universe [29]. At present, experiments such as cosmic microwave background radiation (CMB) [5], cosmological large-scale structure [6] and cosmological baryon acoustic oscillation [7] have all shown the existence of dark matter and dark energy, and found that about 27% of the energy in the universe comes from dark matter, about 68% of the energy comes from dark energy, and the matter described by the standard model theory accounts for only 5%.

Finally, the standard model is not a grand unified theory (Grand Unified Theory, GUT). A grand unified theory refers to a theory that satisfies the following conditions: at high energy scales, the electroweak interaction and the strong interaction are unified into the same interaction, at low energy scales, these three interactions are broken into three distinguishable interactions. The success of gauge field theory has prompted physicists to believe in the existence of this theory, and they have tried to put the $SU(3)_c \otimes SU(2)_L \otimes U(1)_Y$ symmetry of the standard model into a larger symmetry. The grand unified theory contains many models, among which the more famous ones are $SU(5)$ theory [30, 31] and $SO(10)$ theory [32, 33]. These theories predict the existence of proton decay and electric dipole moments of elementary particles, but such phenomena have not been observed experimentally, and the proton lifetime is obtained to be greater than 0.96×10^{30} years with a 90% confidence level [34]. The electric dipole moment (nEDM) measurement experiment of the electron also did not find the existence of the electric dipole moment, and ruled out the range of $|d_e| > 4.1 \times 10^{-30} e \text{ cm}$ with a 90% confidence level [35]. In addition, $SU(5)$ and $SO(10)$ theories, like the Standard Model, cannot unify the coupling constants of the three gauge fields, G_μ^a , B_μ , and W_μ^α , at high energy scales.

In addition, the hierarchy problem of the Standard Model is also an imperfection of the Standard Model. The Standard Model has some hierarchy problems, such as why the mass of the t quark is four orders of magnitude heavier than the mass of the u quark, and other flavor physics-related problems. These flavor physics-related problems have little relevance to the selection of energy scales and do not belong to naturalness problems. The biggest naturalness problem in the Standard Model is the mass of the Higgs boson. Due to the Yukawa coupling between the Higgs scalar field and fermions, the physical mass of the Higgs particle will receive a circular correction with a square relationship with the energy scale [8]:

$$\delta m_{h,f}^2 = \frac{\lambda_H - \lambda_f^2}{8\pi^2} \Lambda^2 + (\log. \text{ div.}) + \text{finite terms.} \quad (2-16)$$

Where f represents fermions, λ_H is the Higgs self-coupling coefficient, λ_f is the Yukawa coupling coefficient, and Λ is the cutoff energy scale. It can be seen that the mass of the Higgs boson is very dependent on the choice of the energy scale, which is the naturalness problem. The experimentally observed Higgs mass is about 125 GeV. If Λ is selected near the TeV energy scale, the loop diagram correction can satisfy the experimental observation, but this means that the standard model will be replaced by a theory with a higher energy scale above the TeV energy scale, and the current experiments have not found new particles beyond the standard model at the TeV energy level. On the other hand, the mass of the W boson produced by the electroweak symmetry breaking is about 80 GeV, and the Planck energy scale of the gravitational interaction is $m_{\text{Pl}} \sim 10^{19}$ GeV. Considering that the standard model is a renormalizable theory, it is reasonable to select an energy scale close to the Planck energy scale, and the mass of the Higgs boson will also be close to the Planck energy scale. At present, without introducing new physics, the observed mass of the Higgs boson can be obtained by fine tuning the parameters of the theory, but this introduces a philosophical or aesthetic question: Why are the parameters of the universe in which humans live at such appropriate values? This is the fine tuning problem. In addition, a more common approach is to admit that the standard model is not applicable to the TeV energy scale. Above the TeV energy scale, the standard model will be replaced by a new theory, such as supersymmetric theory or Technicolor-like theory [36]. In addition, the naturalness problem can be solved by lowering the Planck energy scale, such as introducing extra dimensions, and its effective Planck scale can be as low as the TeV level [8].

2.2 Supersymmetric model

The proposal, development and maturity of supersymmetry [37–40] occurred in the 1970s. When supersymmetry theory was first proposed, it referred to the symmetry of mesons and baryons, which had nothing to do with space and time [37]. In the subsequent development, supersymmetry theory based on space-time coordinate system and quantum field theory was built, and supersymmetry became a theory describing the symmetry of fermion field and bosonic field. Thereafter, supersymmetry was combined with gauge field theory to become a renormalizable theory [41]. In 1977, Fayet combined supersymmetry theory with the standard model and proposed the minimum supersymmetric standard model [42], which was the first supersymmetric extension of the relativistic properties of the standard model. At present, supersymmetry is still a popular theory among theorists. It has the following main advantages [43]:

- Supersymmetry theory can be perfectly combined with quantum field theory to satisfy Lorentz invariance and local gauge invariance.
- Since the secondary divergence in supersymmetry theory that depends on the

cutoff energy scale can be offset, supersymmetry theory is more natural at high energy scales.

- Supersymmetry theory can make the interaction coupling constants of the three gauge fields more consistent at the grand unified energy scale.
- Supersymmetry theory is a low-energy approximation of superstrings theory and M theory (M -theory).

2.2.1 Brief Introduction to Supersymmetry Theory

Supersymmetry refers to a symmetry that connects fermions and bosons. Supersymmetry theory regards fermions and bosons as a supermultiplet in a certain hyperspace. Supersymmetric transformation of supermultiplet can keep the Lagrangian of the system unchanged. Supersymmetric transformation Q satisfies [9]:

$$\hat{Q} |\text{boson}\rangle = |\text{fermion}\rangle, \quad \hat{Q} |\text{fermion}\rangle = |\text{boson}\rangle \quad (2-17)$$

where the spinor $|\text{boson/fermion}\rangle$ represents the pure boson/fermion state. Theorists have found that if a symmetry can link the Poincare group of spacetime symmetry with the intrinsic symmetry of particles, and consider that the spin of bosons and fermions differ by $1/2$, then the generators of this symmetry must also carry a spin of $1/2$. In this case, the algebraic form of the symmetry is uniquely determined [44, 45]:

$$\{Q_\alpha^N, Q_\beta^{\dagger M}\} = 2\gamma_{\alpha\beta}^\mu P_\mu \delta^{NM} \quad (2-18)$$

Where α is the spinor index, N is the free index, γ is the Dirac matrix, δ is the Kronecker δ function, and P_μ is the four-dimensional vector that can produce space-time translation. At the same time, we can get:

$$\{Q^\dagger, Q^\dagger\} = \{Q, Q\} = 0, \quad (2-19)$$

$$[P^\mu, Q^\dagger] = [P^\mu, Q] = 0,$$

After obtaining the commutation relation between p^μ and Q , the mass square operator $-P^2$ also commutes with Q , so the masses of particles in the same supermultiplet are the same. At the same time, Q also commutes with the generators of the standard model, so the weak isospin, weak hypercharge and color charge of particles in the same supermultiplet are also consistent. Considering the spin operator $(-1)^{2s}$, where s represents spin, the eigenvalue of the operator acting on the bosonic state is 1 and the fermionic state is -1. Combined with the formula 2-18, the following inference is obtained [9]:

$$Q(-1)^{2s} |\text{boson}\rangle = |\text{fermion}\rangle = -(-1)^{2s} Q |\text{boson}\rangle \quad (2-20)$$

$$\begin{aligned}
\sum_i i \langle i | (-1)^{2s} P^\mu | i \rangle &= \sum_i \langle i | (-1)^{2s} Q Q^\dagger | i \rangle + \sum_i \langle i | (-1)^{2s} Q^\dagger Q | i \rangle \\
&= \sum_i \langle i | (-1)^{2s} Q Q^\dagger | i \rangle + \sum_{ij} \langle i | (-1)^{2s} Q^\dagger | j \rangle \langle j | Q | i \rangle \\
&= \sum_i \langle i | (-1)^{2s} Q Q^\dagger | i \rangle + \sum_j \langle i | Q (-1)^{2s} Q^\dagger | i \rangle \\
\sum_i i \langle i | (-1)^{2s} P^\mu | i \rangle &= 0 \\
p^\mu \sum_i \langle i | (-1)^{2s} | i \rangle &= 0
\end{aligned}$$

Therefore, the degrees of freedom of fermions and bosons in a supersymmetric multiplet are equal.

In summary, if supersymmetry exists, then each standard model particle will have a corresponding superpartner. But we have neither found a pair of particles that satisfy this symmetry in the standard model, nor detected new particles whose mass and quantum numbers are consistent with the standard model. So if supersymmetry exists, then supersymmetry must be broken at a certain energy scale. Since the specific mass and properties of the superpartner are currently unknown, it is impossible to know how supersymmetry is broken. The current simple approach is to introduce a "soft breaking" term, that is, [9]:

$$\mathcal{L} = \mathcal{L}_{\text{SUSY}} + \mathcal{L}_{\text{soft}} \quad (2-21)$$

Among them, $\mathcal{L}_{\text{SUSY}}$ contains all supersymmetry invariant gauge field coupling terms and Yukawa coupling terms, $\mathcal{L}_{\text{soft}}$ contains the supersymmetric partner mass term after supersymmetry breaking. Phenomenologically analyzing the supersymmetry breaking term, its form should be close to the Lagrangian after electroweak breaking at low energy, that is, [9]:

$$\mathcal{L} \simeq M_a \lambda^a \lambda^a + a^{ijk} \phi_i \phi_j \phi_k + b^{ij} \phi_i \phi_j + c^{ijk} \phi^{*i} \phi_j \phi_k - (m^2) \phi^{*i} \phi_j \quad (2-22)$$

This expression will be very helpful in constructing the minimum supersymmetric standard model.

The supersymmetric model can explain many imperfections of the standard model theory by introducing supersymmetry and soft breaking. On the one hand, there is the problem of the level of the Higgs boson mass. In the soft breaking term, the contribution of the supersymmetric partner Yukawa coupling term to the Higgs mass can be written as [9]:

$$\delta m_h^2 = m_{\text{soft}}^2 \left[\frac{\lambda}{16\pi^2} \ln(\Lambda_{\text{UV}}/m_{\text{soft}}) + \dots \right] \quad (2-23)$$

Where m_{soft} is the mass of the supersymmetric partner, representing the energy scale of supersymmetry breaking. It can be seen that if the breaking energy scale is close to the mass of the standard model particle, the divergence of the standard model fermion

on the Higgs boson mass can be offset. However, in the experiment, we did not observe the supersymmetric partner at the TeV energy scale, so even if supersymmetry exists, then only part of the hierarchy problem can be solved, and fine adjustment still exists, and this part of the hierarchy problem is called the Little Hierarchy Problem. On the other hand, at the grand unified energy scale, supersymmetric theory can also unify the coupling constants of the three gauge fields in the standard model. Figure 2-1 [9] shows the movement of the coupling constant under the correction of the two-circle diagram, where the solid line represents the coupling constant after the introduction of supersymmetry, and the dotted line represents the coupling constant of the standard model. Therefore, supersymmetric theory is a very popular theory.

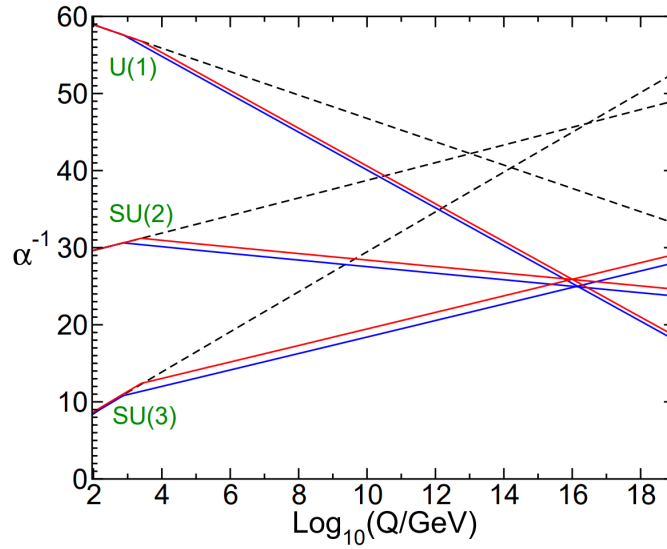


图 2-1 引入超对称性的耦合常数 (实线) 与标准模型的耦合常数 (虚线) 随能标的跑动, 不同颜色代表不同规范场, 计算精度为两圈 [9]。

Figure 2-1 The coupling constants after introducing SUSY (solid line) and those only considering SM (dashed line) vary with the energy scale. Different colours represent different gauge fields. The calculations are conducted with a precision of up to two loops [9].

2.2.2 Minimal Supersymmetric Standard Model

The Minimal Supersymmetric Standard Model (MSSM) combines supersymmetric theories with the Standard Model theory with a supersymmetric partner of one. In addition to requiring each Standard Model particle to have a supersymmetric partner, it also extends the Higgs scalar field of the Standard Model with two complex doublet Higgs fields ($H_u = (H_u^+, H_u^0)$, $H_d = (H_d^+, H_d^0)$), thereby eliminating the gauge anomaly [46] and giving particles mass. In the CP (charge conjugated parity) eigenstate, MSSM introduces two bosons with charge of one and opposite signs ($H^\pm$), two neutral bosons with CP transformation to even (H^0, h^0) and one neutral boson with CP transformation to odd (A^0). It is generally believed that the Higgs boson with a mass

of 125 GeV found in the experiment is h^0 . In addition, the supersymmetric partners of quarks and leptons with spin 1/2 in the standard model have spin 0, and the supersymmetric partners of vector bosons in the standard model have spin 1/2, and they each form a super multiplet. In addition, if supersymmetry is a global symmetry, Goldstone fermions (Goldstino, $\tilde{G}_{1/2}$) will be generated when the spontaneous symmetry is broken. On the contrary, if supersymmetry is localized, it must be combined with the theory of gravity to form supergravity theory (Supergravity) and produce supergravitons (Gravitino, $\tilde{G}_{3/2}$) [20]. Table 2-3 [20] summarizes the symbols and properties of the above supersymmetric particle fields in this article.

表 2-3 最小超对称标准模型的表示，表中并未列出超引力子 [20]。

Table 2-3 The fields of MSSM and representations of the gauge groups, graviton is not listed [20].

Supermultiplet	Superfield	Boson Field	Fermion Field	SU(3)Representation	SU(2)Representation	U(1)Representation
gluon/gluino	$\hat{V}_8$	g	$\tilde{g}$	8	1	0
gaugino boson	$\hat{V}$	$W^\pm, W^0$	$\tilde{W}^\pm, \tilde{W}^0$	1	3	0
gaugino	$\hat{V}'$	B	$\tilde{B}$	1	1	0
slepton/	$\hat{L}$	$(\tilde{\nu}_L, \tilde{e}_L^-)$	$(\nu, e^-)_L$	1	2	-1
lepton	$\hat{E}^c$	$\tilde{e}_R^+$	$\tilde{e}_L^c$	1	1	2
squark/	$\hat{Q}$	$(\tilde{u}_L, \tilde{d}_L)$	$(u, d)_L$	3	2	1/3
quark	$\hat{U}^c$	$\tilde{u}_R^*$	u_L^c	$\bar{3}$	1	-4/3
	$\hat{D}^c$	$\tilde{d}_R^*$	d_L^c	$\bar{3}$	1	2/3
Higgs boson/	$\hat{H}_d$	(H_d^0, H_d^-)	$(\tilde{H}_d^0, \tilde{H}_d^-)$	1	2	-1
higgsino	$\hat{H}_u$	(H_u^+, H_u^0)	$(\tilde{H}_u^+, \tilde{H}_u^0)$	1	2	1

In MSSM theory, the Higgs potential can be expanded as [20]:

$$\begin{aligned}
 V = & (|\mu|^2 + m_{H_u}^2)(|H_u^0|^2 + |H_u^+|^2) + (|\mu|^2 + m_{H_d}^2)(|H_d^0|^2 + |H_d^-|^2) \\
 & + [b(H_u^+ H_d^- - H_u^0 H_d^0) + \text{c.c.}] \\
 & + \frac{1}{8}(g^2 + g'^2)(|H_u^0|^2 + |H_u^+|^2 - |H_d^0|^2 - |H_d^-|^2)^2 \\
 & + \frac{1}{2}g^2|H_u^+ H_d^{0*} + H_u^0 H_d^{-*}|^2
 \end{aligned} \quad (2-24)$$

Among them, m_{H_u} , m_{H_d} and b are mass term coefficients. Define v_u and v_d to represent the vacuum expectation values of H_u^0 and H_d^0 , respectively. Define $\tan \beta$ to represent the ratio of v_u to v_d . After the electroweak symmetry is broken, in addition to the production of W and Z bosons, this Higgs potential also produces the five Higgs bosons mentioned above, whose masses are [9]:

$$\begin{aligned}
 m_A^2 &= m_{H_d}^2 + m_{H_u}^2 + 2|\mu|^2 \\
 m_{H^\pm}^2 &= m_A^2 + m_W^2 \\
 m_{H,h}^2 &= \frac{1}{2}(m_A^2 + m_Z^2 \pm \sqrt{(m_A^2 + m_Z^2)^2 - 4m_Z^2 m_A^2 \cos^2 2\beta})
 \end{aligned} \quad (2-25)$$

In the mass eigenstate, particles of Table 2-3 in the interaction eigenstate will mix. A 2×2 matrix M_C will describe the mixing of charged super-gauge bosons $\tilde{W}^\pm$ and charged Higgs bosons $\tilde{H}^\pm$, forming $\tilde{\chi}_1^\pm$ and $\tilde{\chi}_2^\pm$ (Chargino) in the mass eigenstate, $\tilde{\chi}_1^\pm$ being lighter than $\tilde{\chi}_2^\pm$. The expression of M_C in tree graph precision is as follows [9]:

$$M_C = \begin{pmatrix} M_2 & \frac{1}{\sqrt{2}}g v_u \\ \frac{1}{\sqrt{2}}g v_d & \mu \end{pmatrix} \quad (2-26)$$

Where M_2 is the mass parameter of the super gauge boson $\tilde{W}$ of the SU(2) gauge field. The mass and mixing of Chargino can be obtained by diagonalizing M_C , that is:

$$U^* M_C V^{-1} = \begin{pmatrix} M_{\tilde{\chi}_1^\pm} & 0 \\ 0 & M_{\tilde{\chi}_2^\pm} \end{pmatrix} \quad (2-27)$$

The mixture of neutral super-gauge bosons $\tilde{B}$, $\tilde{W}^0$ and Higgs bosons $\tilde{H}_d^0$, $\tilde{H}_u^0$ is described by M_N , The expression under tree diagram accuracy is as follows [9]:

$$M_N = \begin{pmatrix} M_1 & 0 & -\frac{1}{2}g' v_d & \frac{1}{2}g' v_u \\ 0 & M_2 & \frac{1}{2}g v_d & -\frac{1}{2}g v_u \\ -\frac{1}{2}g' v_d & \frac{1}{2}g v_d & 0 & -\mu \\ \frac{1}{2}g' v_u & -\frac{1}{2}g v_u & -\mu & 0 \end{pmatrix} \quad (2-28)$$

Where M_1 is the mass parameter of the super gauge boson $\tilde{B}$ of the U(1) gauge field. The particles of the four mass eigenstates after mixing are $\tilde{\chi}_i^0$ (Neutralino), i ranges from 1 to 4, sorted from light to heavy in terms of mass. Their masses can be obtained by diagonalizing M_N , that is:

$$N^T M_N N = \begin{pmatrix} M_{\tilde{\chi}_1^0} & 0 & 0 & 0 \\ 0 & M_{\tilde{\chi}_2^0} & 0 & 0 \\ 0 & 0 & M_{\tilde{\chi}_3^0} & 0 \\ 0 & 0 & 0 & M_{\tilde{\chi}_4^0} \end{pmatrix} \quad (2-29)$$

According to the mixing ratio of $\tilde{W}$, $\tilde{B}$, and $\tilde{H}$, a Chargino or Neutralino can be defined as Wino type ($\tilde{W}$ accounts for the vast majority), Bino type ($\tilde{B}$ accounts for the vast majority), or Higgsino type ($\tilde{H}$ accounts for the vast majority). In MSSM theory, supersymmetric leptons and supersymmetric quarks can also be mixed. Generally, the mixing of third-generation supersymmetric leptons ($\tilde{\tau}$) and third-generation supersymmetric quarks ($\tilde{t}$, $\tilde{b}$) is greater.

The MSSM Lagrangian allows the existence of superpotential terms that violate the conservation of lepton number or baryon number, and these terms meet the requirements

of gauge invariance and renormalizability. In order to limit these violation terms, a new symmetry: R parity can be artificially introduced, which is defined as follows:

$$R = (-1)^{3(B-L)+2S} \quad (2-30)$$

Where B and L are the number of leptons and baryons respectively, and S is the spin. If R parity conservation is observed, then the lightest supersymmetric particle (LSP) will be stable and can be used as a candidate for dark matter particles. At the same time, R parity conservation also requires that supersymmetric particles must be produced or annihilated in pairs, and a supersymmetric particle can only produce an odd number of supersymmetric particles after decay.

The complete MSSM theory has 124 free parameters [20]. The high degree of freedom has prompted theorists to propose some theories to simplify the MSSM parameters. The following is a brief introduction to the two theories involved in this article:

Phenomenological Minimal Supersymmetric Standard Model (pMSSM)

The pMSSM theory is described by 19 parameters [47, 48] (due to the excess of the anomalous magnetic moment of the muon, there is also a version with 20 parameters). It merges the descriptions of the first and second generation leptons and quarks for simplification, does not introduce new CP phase angles, does not introduce flavor-changing neutral currents, does not introduce lepton generation band destruction, and is ultimately simplified to 19 parameters: M_1, M_2, M_3 are the super-gauge boson mass parameters of the U(1), SU(2), and SU(3) gauge fields, respectively, m_A, μ are the Higgs field mass parameters, $\tan \beta$ is the vacuum expectation value v_u and The ratio of v_d, A_t, A_b, A_τ respectively describe the A parameters of the third generation quarks and leptons and the Higgs field Yukawa coupling, and the mass parameters of the supersymmetric partners of the standard model fermions are $M_{\tilde{Q}}^2, M_{\tilde{U}}^2, M_{\tilde{D}}^2, M_{\tilde{L}}^2$, and $M_{\tilde{E}}^2$.

Simplified models

The simplified model [49–54] is one of the most widely used models in experiments. In the simplified model, generally only two or three supersymmetric particles can be produced in the experiment, and the remaining supersymmetric particles do not participate in the reaction. And the mass and decay branch ratio of supersymmetric particles are greatly simplified. The simplified model is very helpful in experiments. Its final state characteristics are obvious, which is helpful for experimental search, but the mass exclusion limit of supersymmetric particles obtained by this simplification may be quite different from the theoretical exclusion limit of MSSM.

2.2.3 Supersymmetry theory related to theories beyond the Standard Model

Supersymmetry theory not only develops the MSSM theory based on the standard model, but is also often related to some other theories beyond the standard model (Beyond the Standard Model, BSM). Among them, the two-Higgs-doublet model (2HDM) [55]

is currently a popular model, which predicts the existence of two $SU(2)$ doublet Higgs fields. 2HDM is the simplest SM extension. It can be used as part of the SUSY model prediction or can be separated from SUSY, such as as a key theory supporting the axion model [56]. In addition, it can also explain the asymmetry of matter and antimatter [55]. The most universal 2HDM contains 14 free parameters, which can be a model of CP parity conservation, a model of CP parity violation, or even a model of charge non-conservation [55]. At present, the most common model is the CP parity conservation model, which predicts the difference between the scalar Higgs boson and the pseudoscalar Higgs boson. In addition, according to the different coupling forms of the Higgs field and the fermion field, the 2HDM model can be further divided. Each type of 2HDM model has rich theoretical predictions. For example, the type-3 model can include flavor-changing neutral current (FCNC) at the tree graph level [55].

Supersymmetric grand unified theory (SUSY GUT) is also an extension of supersymmetry. Due to the introduction of supersymmetry, SUSY GUT can solve the hierarchy problem and unify the three interaction constants at the grand unified energy scale [20]. It also has the potential to explain the source of the Yukawa coupling strength between the fermion field and the Higgs field and the source of the neutrino mass [57]. Depending on the different symmetries introduced by GUT, the phenomena predicted by GUT theory are also different, and the common ones include the existence of new gauge bosons.

If the extra dimensions theory (ED) is related to string theory, then the extra dimensions theory will also be related to supersymmetric theory, [8]. The ADD model [58] proposed by Arkani-Hamed, Dimopoulos and Dvali is a popular theory in ED. It predicts gravitons of TeV magnitude and the possibility of the generation of extremely short-lived micro black holes in colliders [8].

In addition, the MSSM model can be described by the Standard Model Effective Field Theory (SMEFT) [59], and some supersymmetric theories predict the existence of long-lived particles. The study of SMEFT and the search for long-lived particles are gradually becoming hot topics in collider experiments.

2.2.4 ATLAS experiment searches for supersymmetric physics

Searching for supersymmetric particles has always been one of the important physical goals of the ATLAS experiment. In the ATLAS detector, the production of supersymmetric particles can generally be divided into two production processes. The first is the strong interaction that produces a pair of supersymmetric gluons ($\tilde{g}$) or supersymmetric quarks ($\tilde{q}$), or a supersymmetric gluon and a supersymmetric quark. The second is the electroweak interaction that produces a pair of supersymmetric leptons ($\tilde{\ell}$) or Chargino and Neutralino. Under the pp collision at 13 TeV center-of-mass en-

ergy, the cross section of the strong interaction is much higher than the cross section of the electroweak interaction. The cross sections of these two processes vary with the mass of the SUSY particle as shown in Figure 2-2 [60, 61]. In addition, the ATLAS experiment has searched for models of whether R parity is conserved. For the case of R parity conservation, a pair of supersymmetric particles produced by the pp collision will eventually decay into at least two LSPs. If the LSP is an electrically neutral particle and does not interact strongly, it cannot leave a response in the detector, which eventually manifests as a higher transverse energy loss (E_T^{miss}). This type of analysis is more common. For the case of R parity violation, the LSP will eventually decay into multiple leptons or quarks, forming a multi-lepton or jet final state, and E_T^{miss} is low. For example, the four-lepton analysis is aimed at this type of model [62]. ATLAS also searches for long-lived particles. Depending on the lifetime and charge of long-lived particles in the model, these experiments will also restrict supersymmetric models. For example, when the R parity violation coupling coefficient is low, the LSP will fly a distance in the detector before decaying, resulting in a displaced vertex, lepton or jet final state, and there are many related analyses [63].

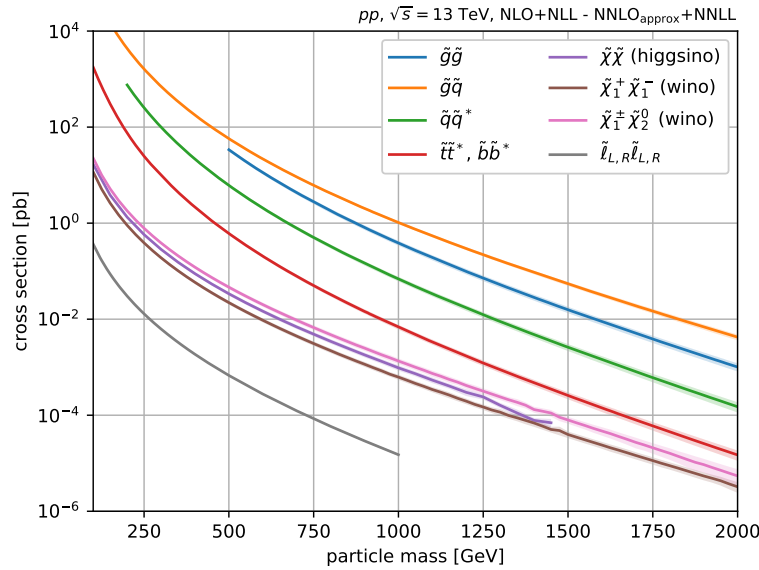


图 2-2 质心能量 13 TeV 下 pp 对撞产生超对称粒子的截面 [60, 61]。

Figure 2-2 The cross-section of sparticles production for 13 TeV pp collision [60, 61].

At present, no obvious signs of the existence of supersymmetric particles have been found in the experiment. Therefore, the ATLAS experiment excludes the mass of supersymmetric particles at a confidence level of 95%. Figure 2-3 [13] shows the mass exclusion range of each supersymmetric particle at present. First is the case of R parity conservation. For $\tilde{g}$ particles, the parameter space with a mass less than about 2.45 TeV has been excluded. For the first two generations of $\tilde{q}$, considering the left-

handed, right-handed and first- and second-generation mass degeneracy, the parameter space with a mass less than 1 TeV has been excluded. For the third generation $\tilde{q}$, that is, $\tilde{t}$ and $\tilde{b}$, the range with a mass less than about 1.25 $\sim$ 1.35 TeV has been excluded. In the electroweak production process, $\tilde{\chi}_1^\pm$ and $\tilde{\chi}_2^0$ with masses below 1 TeV have been excluded, and the first and second generation $\tilde{\ell}$ with masses below 0.7 TeV and $\tilde{\tau}$ with masses below 0.4 TeV have been excluded. In addition, for the case of R parity violation, because there is more than one violation term in the Lagrangian and each violation term has multiple parameters to describe, it is difficult to give a unified exclusion limit. It can be seen that although the models considered in each experiment are different, in most studies using part of the Run2 experimental data, the exclusion limit of $\tilde{t}$ reaches 0.5 TeV, and the exclusion limit of $\tilde{t}$ in some studies has also reached 1 TeV. At the same time, the exclusion limits of $\tilde{\chi}_1^\pm$ and $\tilde{\chi}_2^0$ in some models are also close to 1 TeV.

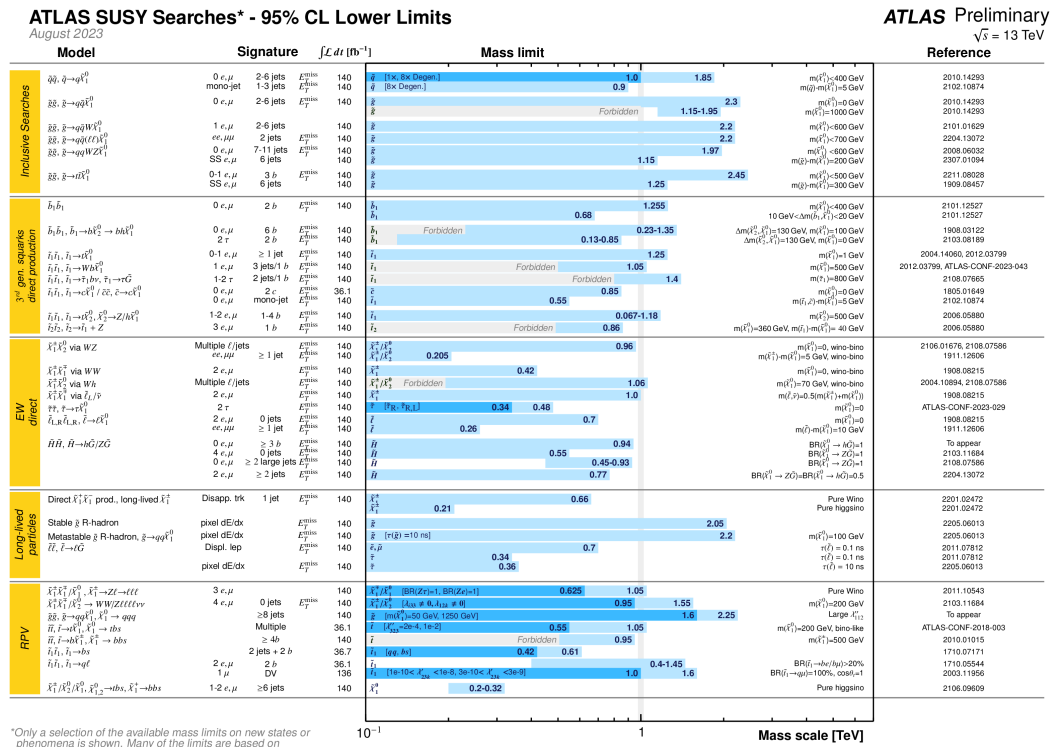


图 2-3 ATLAS 上超对称粒子寻找实验的排除质量区间 [13]。

Figure 2-3 The mass exclusion limits of sparticles from ATLAS SUSY searches [13].

第 3 章 Large Hadron Collider and the ATLAS experiment

The development of particle physics is inseparable from the close combination of theory and experiment. The previous chapter introduced the most successful standard model theory in the current field of particle physics and the beautiful supersymmetry theory. This chapter will introduce the source of experimental data used in this article - the ATLAS experiment. This chapter first introduces the Large Hadron Collider and related collider physics foundations, and then introduces the ATLAS experiment on the Large Hadron Collider. The introduction of the ATLAS experiment includes the structure, performance and acquisition of experimental data of the ATLAS detector.

3.1 Large Hadron Collider

The Large Hadron Collider (LHC) [10] is the world's largest particle accelerator. It is located at the European Organization for Nuclear Research (CERN) on the border between Switzerland and France. It has a circumference of 26.7 kilometers and a depth of 50 to 175 meters underground. The LHC has a total of 1,232 superconducting dipole electromagnet tubes to constrain or deflect the movement of proton or heavy ion bunches in the tubes, and 392 superconducting quadrupole electromagnet tubes to focus the bunches. All tubes are in a vacuum environment to prevent the bunches from interacting with air molecules. In order to constrain high-energy bunches, the tubes use superconducting magnets that can provide a magnetic field of up to 8.33 T. The operating temperature of the superconducting magnets is about 1.9K and they are cooled by liquid nitrogen. The superconducting magnet pipes form two parallel beam rings with a spacing of 192 mm. The beams in the two beam rings move in opposite directions, and the energy of the bunches in the beams is 6.5 TeV. Each beam ring contains eight straight areas and eight arc areas. Each straight area is about 528 meters long and is used to place detectors and equipment, as shown in the figure 3-1 [10].

Among the eight linear areas, the beam rings in four areas intersect to facilitate bunch collisions, and four large detectors are installed on them for physical experiments. The ATLAS (A Toroidal LHC Apparatus) experiment [11] and the CMS (Compact Muon Solenoid) [12] experiment are located in areas 1 and 5, respectively. They are multi-purpose detectors. The main experimental goals are to accurately measure the standard model, search for and measure the Higgs boson and its properties in the standard model, and search for new physical phenomena beyond the standard model. In area 2 is the ALICE (A Large Ion Collider) experiment [64], which is the only experiment on the LHC that studies the properties of high-energy-density strongly interacting mat-

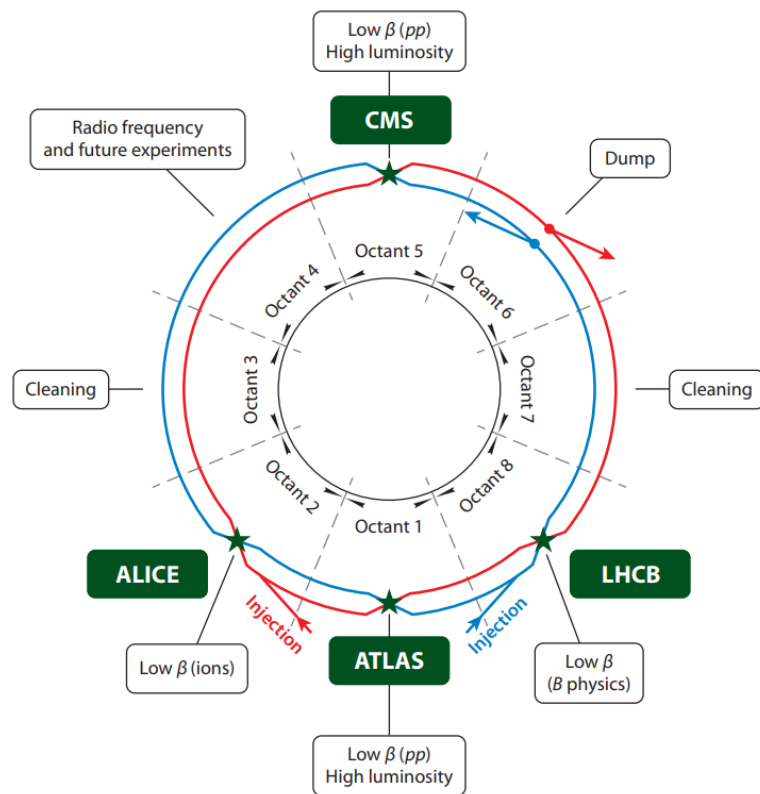


图 3-1 LHC 束流环布局，按顺时针排序八个直线区域 [10]。

Figure 3-1 The layout of the LHC beam rings, with eight straight sections sorted clockwise [10].

ter through quark-gluon plasma produced by heavy ion collisions. Area 8 is the LHCb (Large Hadron Collider beauty) experiment [65], whose main scientific goal is to accurately measure the decay properties of heavy flavor hadrons and strange hadron states. At the same time, areas 2 and 8 also contain multiple beam injection systems. The other four straight areas do not contain intersections. There are two sets of 400 MHz superconducting radio frequency cavity acceleration systems, two sets of beam alignment systems and one set of beam cleaning systems. The radio frequency cavity acceleration system contains a total of 16 sets of radio frequency cavities (Radiofrequency Cavity). The radio frequency cavity uses microwaves to generate periodic resonant electromagnetic fields along the beam direction in each radio frequency cavity. The peak electric field of a single radio frequency cavity is 2 MV. Under ideal conditions, a set of radio frequency cavity acceleration systems can generate a peak electric field of 16 MV. When the electromagnetic field frequency matches the bunch velocity and arrival time, the direction of the electromagnetic field is the same as the direction of the bunch movement, thereby accelerating the bunch. In addition, the periodic electromagnetic field in the RF cavity will further compress the beam along the beam direction.

Before entering the LHC beam ring, protons are accelerated step by step in other facilities, as shown in the figure 3-2 [10]. The protons in the bunch come from the ionization of hydrogen atoms. After being accelerated by the LINAC 2 linear accelerator, they enter the Booster (Proton Synchrotron Booster, PSB) system. The protons are accelerated to 1.4 GeV in the Booster and then enter the CPS (Circle Proton Synchrotron, PS) system and are accelerated to 26 GeV. At the same time, the protons in the CPS will be compressed into bunches. The bunches then enter the SPS (Super Proton Synchrotron) system and are accelerated to 450 GeV. The bunches pass through a three-kilometer-long straight channel from the SPS into the LHC, and are gradually accelerated to 6.5 TeV by the LHC's superconducting radio frequency system. This process takes at least 20 minutes and requires more than 10 million accelerations in the ring. Finally, they collide at the intersection of the beams, which are recorded by the detector for physical experiments.

In the LHC, each beam ring contains about 2000 bunches, and the protons inside the bunches are approximately Gaussian distributed. A single bunch contains up to 10^{11} protons [66], with a longitudinal energy distribution length of about 10 cm and an initial transverse energy distribution width of about 3.5 microns. After upgrading to the BCMS (Batch Compression Merging and Splitting) [67] mode in 2016, it was about 2 microns. Thereafter, it fluctuated slightly due to the working mode of reducing the heat load. The front and rear spacing of the bunch is 25 ns. Table 3-1 [66] records the beam parameters over the years.

In the experiment, the frequency of bunch collisions is called luminosity, which is

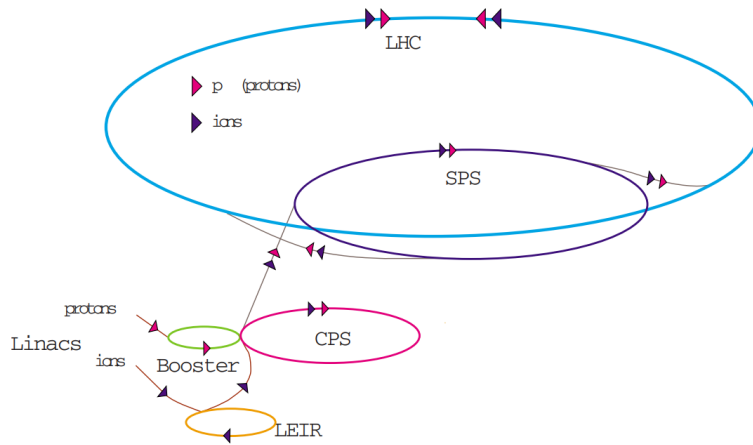


图 3-2 LHC 束流注入与加速系统示意图 [10]。

Figure 3-2 The schematic diagram of the LHC beam injection and acceleration system [10].

表 3-1 历年的束流参数 [66]。

Table 3-1 The LHC beam parameters of each year [66].

beam parameters	anticipation	2015	2016		2017		2018
Percentage of stable beam time	-	33%	49%		49%		49%
Operating mode	Standard	Standard	Standard/BCMS	BCMS	Reduced heat load mode 1	Reduced heat load mode 2	BCMS
Beam energy [TeV]	Standard	6.5	6.5	6.5	6.5	6.5	6.5
Number of bunches	2808	2244	2040/2076	2556	1916	1868	2556
Bunch spacing [ns]	25	25	25	25	25	25	25
Number of protons in a bunch [10^{11}]	1.15	1.15	1.2	1.2	1.2	1.25	1.1
Transverse energy distribution [mm-mrad]	3.75	3.5	3.5/2.1	2.1	2.3	1.8	2
Instantaneous peak brightness [$10^{34}\text{cm}^2/\text{s}$]	1	0.55	0.83/1.4	1.74	1.9	2.06	2.1

a key indicator of collider performance. In order to increase the luminosity, the bunches will be further compressed at the collision point. The luminosity L can be expressed as:

$$L = f_{\text{coll}} \frac{N_1 N_2}{4\pi\sigma_x^* \sigma_y^*} F \quad (3-1)$$

Where N_1 and N_2 represent the number of particles in the bunch, σ_x^* and σ_y^* represent the root mean square of the horizontal and vertical distribution of the bunch at the collision point, The frequency factor f_{coll} can be expanded to $f_{\text{coll}} = n_b f_0$, where n_b is the number of bunches in the beam, f_0 is the revolution frequency of the beam in the LHC. The brightness attenuation factor F describes the efficiency attenuation caused by the angle between the two beams, the longitudinal length of the bunch and the beam focusing performance, and can be expressed as:

$$F = \sqrt{1 + \frac{(\theta_c \sigma_z^*)^2}{4\sigma_x^* \sigma_y^*}} \quad (3-2)$$

Where θ_c is the beam angle, σ_z^* is the root mean square of the longitudinal length distribution of the bunch, It can be found that compressing the bunch or increasing the bunch density and collision frequency can increase the instantaneous brightness. In the experiment, the total number of bunch collisions obtained by the collider after running for a period of time is called the integrated luminosity:

$$L_{\text{int}} = \int L(t) dt \quad (3-3)$$

When bunches collide, the protons in the bunches interact with each other, and the total scattering cross section can be obtained by the differential scattering cross section $d\sigma/d\Omega$. In collider experiments, the size of the total cross section depends almost only on the scattering amplitude $|M|$:

$$\sigma_{\text{tot}} = \int \frac{d\sigma}{d\Omega} d\Omega \propto |M|^2 \quad (3-4)$$

The total number of interactions between bunches over a period of time is:

$$N_{\text{exp}} = \sigma_{\text{tot}} \cdot L_{\text{int}} \quad (3-5)$$

Therefore, in LHC experiments, the total integrated brightness can be expressed by the inverse of the cross section. The commonly used units are fb^{-1} (inverse femtobarn), and the conversion relationship is $1 \text{ fb}^{-1} = 10^{39} \text{ cm}^2$. 1 fb^{-1} represents the total integrated brightness required to produce an event with a cross section of 1 fb, so the instantaneous brightness unit can be written as cm^2/s .

When designing the LHC experiment, the expected center-of-mass energy of proton collisions was 14 TeV. During the first round of data collection (Run 1) from 2010

to 2012, the LHC produced a total of experimental data with a center-of-mass energy of 7 TeV to 8 TeV and a total integrated brightness of 28.3 fb^{-1} . During the second round of data collection (Run2) from 2015 to 2018, the actual center-of-mass energy of the LHC was 13 TeV. A total of about 156 fb^{-1} of data were obtained, of which the ATLAS experiment collected 139 fb^{-1} of data that can be used for physical analysis. Figure 3-3 [66] summarizes the integrated brightness collection and the highest instantaneous integrated brightness of Run1 and Run2 over the years. This article uses all 139 fb^{-1} of experimental data from the ATLAS experiment. The LHC experiment will continue to run for a long time. The third round of data collection (Run3) is currently underway, with the center-of-mass energy increased to 13.6 TeV. The operation period is planned to be from 2023 to 2025, with an expected total integrated brightness of 260 fb^{-1} . After the third round of data collection, the LHC will be upgraded to the High-Luminosity Large Hadron Collider (HL-LHC), which is planned to start operation and data collection in 2029, with an expected center-of-mass energy of 14 TeV. Figure 3-4 shows the plan for the start time of the third round of LHC data collection and HL-LHC data collection (the plan was revised in February 2022).

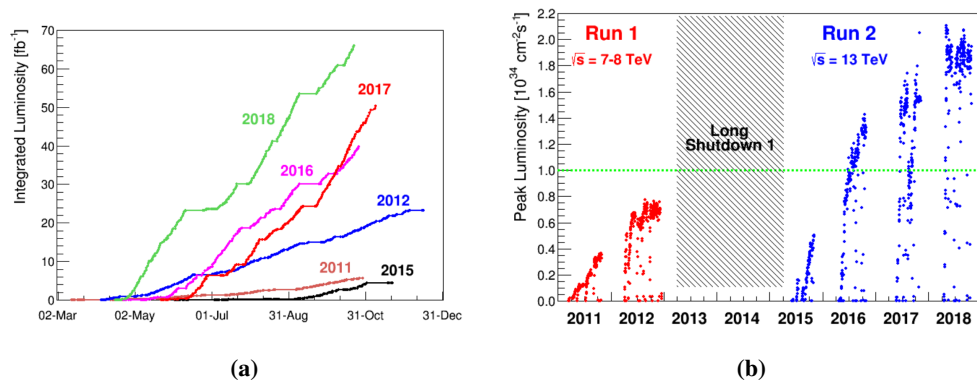


图 3-3 (a) LHC 历年积分亮度收集情况与 (b) 瞬时亮度峰值情况 [66]。

Figure 3-3 The situations of (a) integrated luminosity and (b) peak of instantaneous luminosity over the years [66].

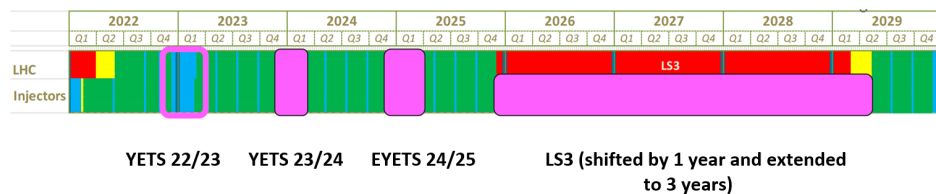


图 3-4 LHC 第三轮取数与 HL-LHC 取数的时间规划 (规划修订于 2022 年 2 月)。

Figure 3-4 The schedule of LHC Run3 and HL-LHC Run (revised in February 2022).

3.2 ATLAS Experiment

The ATLAS detector used in the ATLAS experiment is the largest multi-purpose detector on the LHC, located 100 meters underground. The ATLAS detector is a cylindrical detector with front and back symmetry, about 46 meters long, and the beam pipeline runs through the front and back ends. ATLAS has a diameter of 25 meters and weighs about 7,000 tons. There are six different sub-detection systems from the inside to the outside, achieving a solid angle coverage of almost 4π . At the same time, there is a huge magnet system to deflect charged particles for energy-momentum measurement. Figure 3-5 [11] shows the various sub-detection systems of the ATLAS detector. At the innermost part of the detector is the Inner Detector (ID), which is mainly used to measure the track of charged particles and is in a 2 T magnetic field as a whole. Outside is the calorimeter system, which mainly consists of two layers. The inner layer is a liquid argon calorimeter, which can detect the energy of electromagnetic showers and hadron showers at the same time. The outer layer is a hadron calorimeter, which is composed of a tile-shaped scintillator layer and a steel layer. The outermost layer of ATLAS is the Muon Spectrometer (MS), which is mainly composed of a gas drift chamber. At the same time, there is a complex and huge superconducting magnet system inside ATLAS, with an operating temperature of 4.5 K, which provides a magnetic field for the internal track detector, end-cap and muon spectrometer.

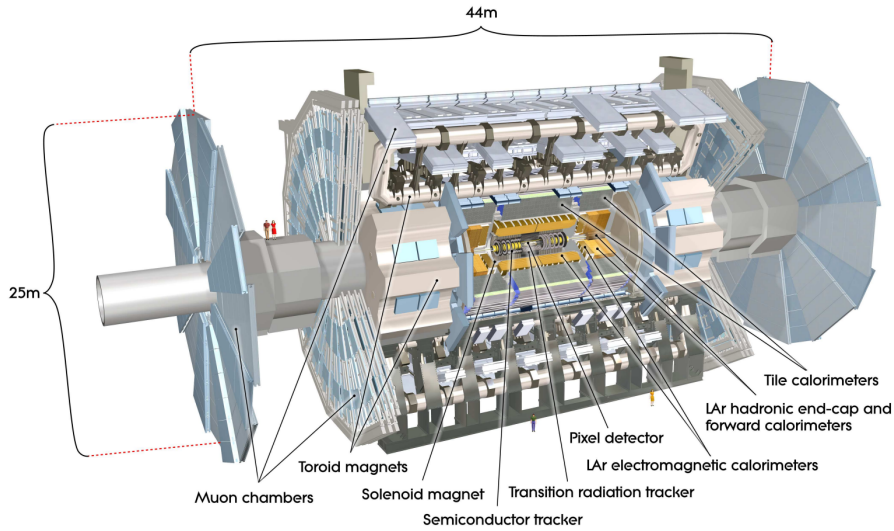


图 3-5 ATLAS 探测器的各级子系统 [11]。

Figure 3-5 Sub-detectors of the ATLAS detector [11].

3.2.1 ATLAS and Detector Coordinate System

ATLAS uses a right-hand system to construct a coordinate system, with the origin being the collision point, the z-axis parallel to the beam direction, the x-y plane perpendicular to the beam direction, the x-axis pointing to the center of the beam ring, and the

y-axis pointing to the surface. The z-axis direction is then determined by the right-hand system. The detector in the positive half of the z-axis is called the A end, and the other half is called the C end. Considering that the ATLAS detector is symmetrical about the z-axis, a cylindrical coordinate system can also be used. The $r - \phi$ plane is used to represent the x-y plane, ϕ is defined as the angle with the x-axis, and θ is defined as the angle with the z-axis.

The commonly used definition of rapidity in particle physics experiments is: $y = \frac{1}{2} \ln \frac{E+p_z}{E-p_z}$, y greatly simplifies the Lorentz transformation along the particle beam direction (z axis), simplifies the matrix transformation to simple addition and subtraction, for example: $y' = y - \tanh^{-1} \beta$, and it is not difficult to find that Δy is Lorentz invariant. In ATLAS experiments, pseudo-rapidity η is more commonly used instead of θ angle, and the relationship is: $\eta = -\ln \tan(\theta/2)$. For particles moving close to the speed of light, pseudo-rapidity is approximately equal to rapidity, and for massless particles, pseudo-rapidity is equal to rapidity. So pseudo-rapidity simplifies the calculation of rapidity and approximately retains the advantages of rapidity. After replacing η , a new method for calculating angular distance needs to be introduced: $\Delta R = \sqrt{\Delta\eta^2 + \Delta\phi^2}$.

Considering the conservation of momentum of all initial and final state particles projected on the $r - \phi$ plane in the ATLAS experiment, the transverse momentum $p_T = \sqrt{p_x^2 + p_y^2}$ and transverse energy $E_T = E/\cosh \eta$ are important dynamic variables in the ATLAS experiment. For particles with a small cross-section of interaction with the detector material, such as neutrinos, it is difficult for them to leave signals in the detector, which eventually manifests as missing transverse momentum (E_T^{miss}). Theoretically, E_T^{miss} is consistent with the vector sum of the transverse momentum of all detectable particles, but in the opposite direction, that is: $E_T^{\text{miss}} = -\sum \vec{p}_T$.

3.2.2 Inner Detector

The Inner Detector (ID) is the innermost sub-detector system of the ATLAS detector, responsible for measuring the tracks of charged particles and the primary and secondary vertices of pp collisions. The inner track detector has a magnet system that provides a 2 T magnetic field, which can measure charged particles with p_T greater than 500 MeV. The ID is about 6.2 meters long and 2.1 meters in diameter, covering the area of $|\eta| < 2.5$. It mainly includes three different but complementary subsystems: Pixel Detector (Pixel), Semiconductor Tracker (SCT) and Transition Radiation Tracker (TRT). These subsystems cover the barrel and the end cap. Figure 3-6 [11] shows the radial and axial cross-sections of the ID respectively.

Pixel Detector

Pixel is the detection system with the highest granularity. It is about 1.4 meters long and 0.4 meters in diameter. It contains three layers of N-type silicon pixel detectors

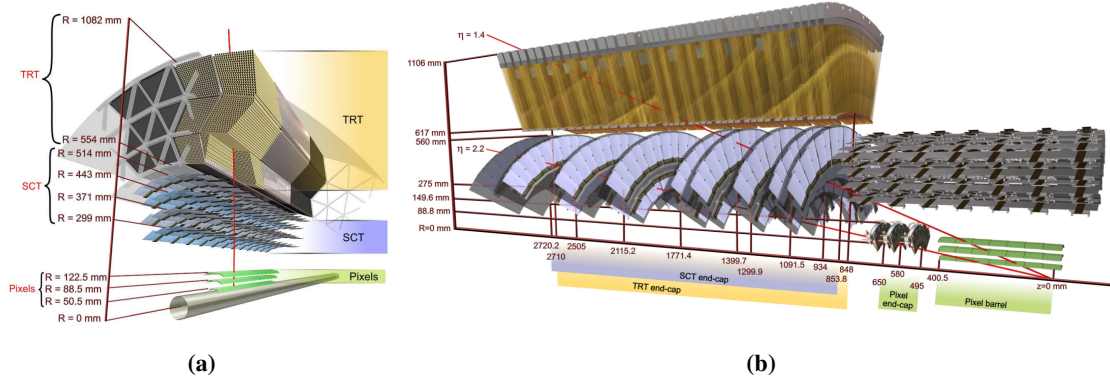


图 3-6 内部径迹探测器的内部结构，图上并未标出 IBL [11]。

(a) 展示内部径迹探测器径向结构，(b) 为内部径迹探测器轴向结构。

Figure 3-6 The structures of the Inner Tracker, IBL is not shown on the figure [11].

Figure (a) shows the radial structure and (b) shows the axial structure.

and the innermost IBL (Insertable B-Layer)[68]. There are 2024 detection modules in total, containing about 92 million pixels in total, which can provide at least three sets of position information and threshold crossing time.

IBL is the first detection system to apply 3D detection technology [69] on a large scale. It consists of 14 64 cm long strip IBL units, located about 33 mm from the beam tube. Each unit contains 20 IBL modules, including 12 planar silicon pixel detectors with a thickness of 200 microns in the middle and 4 3D silicon pixel detectors with a thickness of 230 microns at both ends. Each IBL module has a total of 12 million pixels with a resolution of 250×50 microns, providing a position resolution of 10-45 microns in the lateral ($r - \phi$ plane) and 60-180 microns in the longitudinal (z axis). IBL was added to the ATLAS detector before the second round of data acquisition to compensate for the efficiency loss of other detector layers due to irradiation damage. IBL improves the identification and reconstruction efficiency of short-lived particles and vertices.

The three-layer silicon pixel detector is named Layer-0, Layer-1 and Layer-2 from the inside to the outside. The three-layer detector located in the barrel is located in the range of about 50.5 mm to 122.5 mm, and the three layers of the end cap are located in the range of $|z|$ from 495 mm to 650 mm. The three-layer silicon pixel detector has a total of 1744 detection modules with an area of $10 \times 10 \text{ cm}^2$. Each module is 250 microns thick and contains 47232 pixels. Due to space limitations, the effective pixels are reduced to 46080. The pixels in each detection module are 50 microns wide and 400 microns long. The pixel length of the chip module unit covering the front end is increased to 600 microns, providing a resolution of 10 microns in the circumferential direction and 110 microns in the axial direction.

Semiconductor Track Detector (SCT)

SCT is a silicon microstrip detector. The barrel has 4 layers, ranging from 299

mm to 514 mm, and the end caps have 9 layers, ranging from 934 mm to 2720 mm. SCT surrounds the pixel and can provide four to nine sets of position information. The four-layer barrel SCT has a total of 2112 detection modules, and the nine-layer SCT of each end cap has a total of 988 detection modules. Each detection module is about 285 microns thick and contains 4 rectangular silicon microstrip sensors. There are multiple silicon microstrips connected end to end between each two sensors to form a detection unit about 6 cm long and 80 microns wide. Two detection units are connected together to form a detection module about 12 cm long. A single detection module contains 768 silicon microstrips. Each two detection modules form a group back to back, with an angle of about 40 mrad, which can provide three-dimensional information of charged particles in an ideal state. Each group of detector modules can provide a position resolution of 17 microns in the horizontal direction and 580 microns in the vertical direction.

Traversing Radiation Tracker (TRT)

TRT is a sub-detection system located at the outermost part of ID, with a total length of about 6.8 meters, an outer diameter of about 1.1 meters, and an inner diameter of about 0.55 meters. It covers the area of $|\eta| < 2$ and consists of a straw-shaped drift tube counter with a diameter of 4 mm and filled with gas. The counter at the barrel is 144 cm long, and the counter at the end cap is 37 cm long. TRT contains a total of about 350,000 counters. The center of the straw-shaped drift tube counter is a gold-plated tungsten wire with a diameter of about 31 microns as the anode. The tube wall is a multi-layer structure film with two sides hot-melt pasted back to back, each side is 35 microns thick, and contains an aluminum-plated layer as the cathode. The gas pressure in the counter is 5-10 mPa, and the composition is 70% argon, 27% carbon dioxide and 3% oxygen. The TRT in the barrel is divided into three layers, each layer contains 32 detection modules, and a total of 73 layers of counters. The TRT of the end cap contains 20 disk-shaped structures, each of which contains 8 layers of detection units, and each layer of detection units has 768 radially arranged counters. TRT can detect the minimum ionization energy loss of low-momentum charged particles, as well as the through-radiation of high-momentum particles, and can record the threshold time. In addition, since the drift tube counters in the barrel are placed along the beam direction, they can only provide lateral position information, and the drift tube counters at the end cap are arranged radially, so they can only provide $z - \phi$ position information. The resolution of the detectors in the barrel and the end cap is about 130 microns, which can generally provide 36 sets of position information.

3.2.3 Calorimeter

The calorimeter system of ATLAS is a sampling calorimeter that can measure the energy of hadrons, electrons and photons, covering the region of $|\eta| < 4.9$. Figure 3-7 [11] shows the structure of the calorimeter system, which has two subsystems. The

inner subsystem is a liquid argon electromagnetic calorimeter, which consists of the innermost liquid argon electromagnetic calorimeter of the barrel part and the innermost liquid argon electromagnetic calorimeter (EMEC) of each end cap. Another subsystem surrounding the electromagnetic calorimeter is the hadron calorimeter, which consists of a liquid argon hadronic calorimeter (HEC) located behind the end cap EMEC, a liquid argon forward calorimeter (FCal) at the center, and a sampling hadronic calorimeter located outside the barrel liquid argon electromagnetic calorimeter. The sampling hadronic calorimeter is composed of scintillator and steel, including a barrel section and an extended barrel section at the A end and the C end.

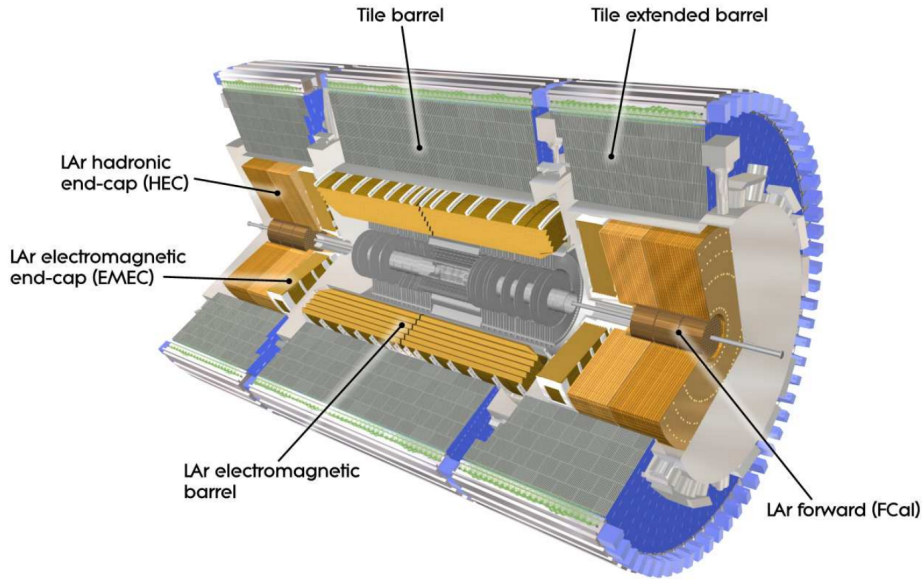


图 3-7 ATLAS 量能器系统示意图 [11]。

Figure 3-7 Structure of the ATLAS calorimeter system [11].

Liquid Argon Electromagnetic Calorimeter

The module of the liquid argon electromagnetic calorimeter uses lead as the absorber and liquid argon as the sampler. The module has an accordion-shaped geometric structure, which can measure electromagnetic showers and hadron showers. The energy resolution design value of the liquid argon electromagnetic calorimeter is $\sigma_E/E = 9\%\sqrt{E} \oplus 0.3\%$. The liquid argon electromagnetic calorimeter in the barrel is divided into two parts by the plane of $\eta = 0$. Each part is 3.2 meters long, 1.35 meters in inner diameter, 2 meters in outer diameter, and the distance between the two parts is 4 mm, covering the area of $|\eta| < 1.475$. Each part is divided into 16 detection modules according to the ϕ angle, with a total of 1024 layers of lead absorbers. Copper electrodes are placed between the absorbers to read the signal. The distance between the electrode and the absorber is about 2 mm. Liquid argon is filled in between to absorb the shower energy. The electrical signal generated by the liquid argon is transmitted to the electrode for reading. Their position arrangement is shown in Figure 3-8 [70].

The electrode distribution of the barrel is shown in the upper part of Figure 3-9 [11]. The electrode distribution can be divided into three layers with different granularity. The innermost layer has the highest granularity, providing the most accurate energy and position information. The outermost layer has the lowest granularity and is mainly responsible for absorbing the energy of the remaining electromagnetic shower. It can be seen from the figure that the calorimeter lengths in different $|\eta|$ directions are different, providing absorption lengths ranging from 22 radiation lengths (X_0) to 33.

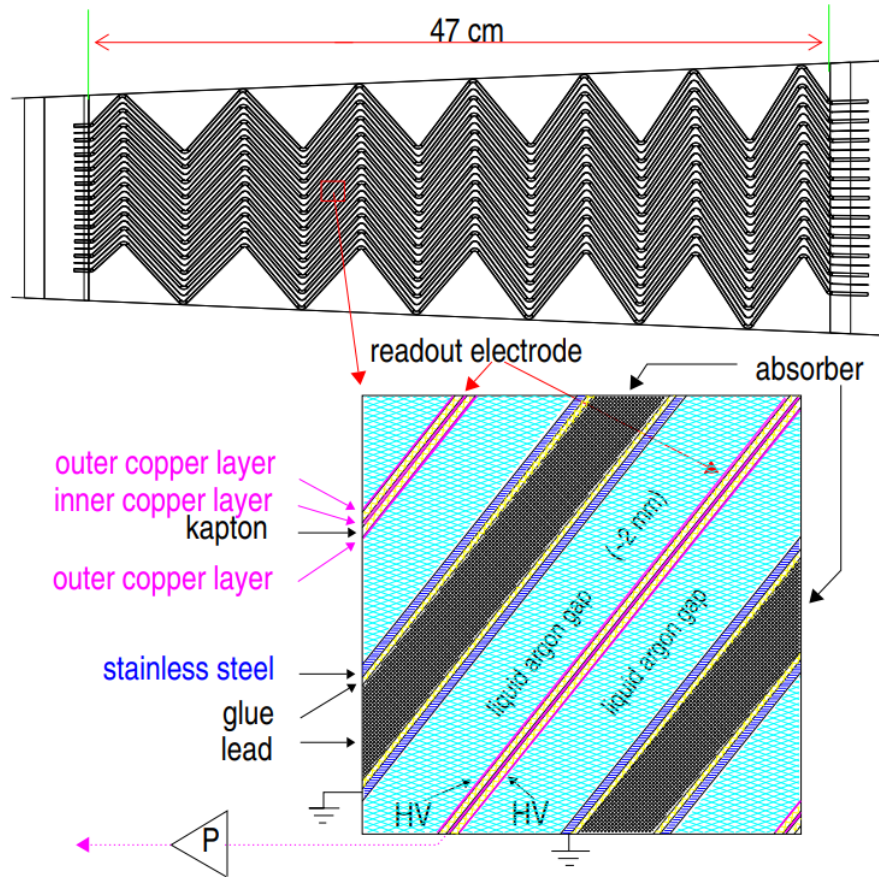


图 3-8 桶部液氩电磁量能器的结构 [70]。

上图展示了横截面的手风琴结构，下图展示了吸收体、采样体和电极的结构。

Figure 3-8 Structure of the barrel liquid argon electromagnetic calorimeter [70].

The upper figure shows the accordion structure and the lower figure shows the structure of the absorber, sampling element and electrode.

The EMEC at the end cap has a "wheel" at each end. The wheel is 63 cm thick, with an inner diameter of about 0.3 meters and an outer diameter of about 2.1 meters. It covers the area where $|\eta|$ is between 1.375 and 3.2, and is divided into 8 modules according to the ϕ angle. Each wheel contains an "outer wheel" and an "inner wheel". The inner and outer gaps are located at $|\eta| = 2.5$, with a spacing of three millimeters. Each inner wheel has a total of 256 absorbers, divided into two layers with different particle sizes, and the outer wheel has a total of 768 absorbers, which are divided into

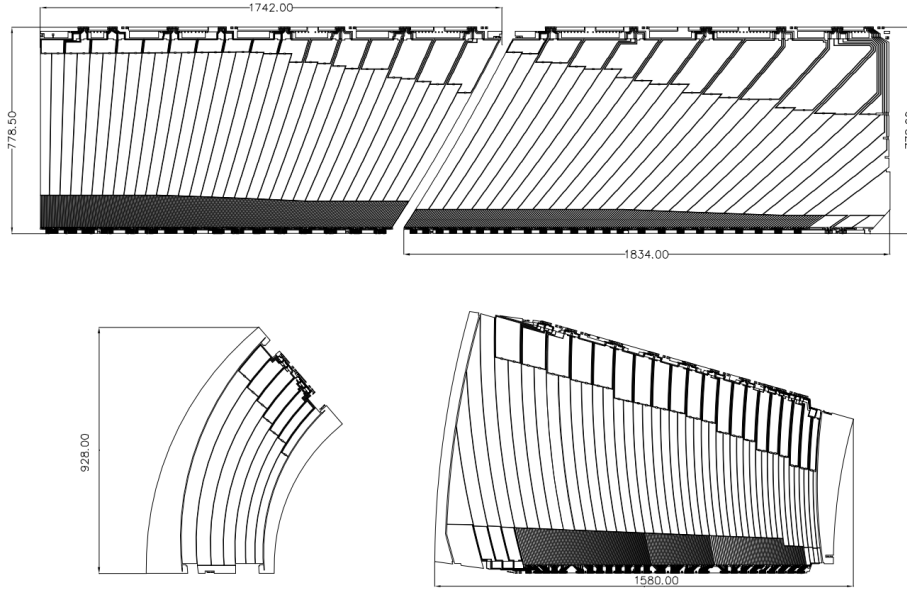


图 3-9 液氩电磁量能器的电极分布 [11]。

上图展示了桶部部分的结构，左下图展示了端盖“内轮”的结构，右下展示了“外轮”的结构。

Figure 3-9 The electrode distributions of the liquid argon electromagnetic calorimeter [11].

The upper figure shows the structure of the barrel part, the lower left figure shows the structure of the endcap ‘inner wheel’, and the lower right shows the structure of the ‘outer wheel’.

three layers with different particle sizes like the barrel. The end cap provides absorption lengths ranging from $24 X_0$ to $38 X_0$.

Hadron Calorimeter

The hadron calorimeter is composed of tile-shaped sampling calorimeters (The Tile Calorimeter, Tile), covering the range of $|\eta|$ less than 1.7. The barrel of the hadron calorimeter is 5.8 meters long, and the extensions of the A and C ends are 2.6 meters long each. The hadron calorimeter has an inner diameter of 2.28 meters and an outer diameter of 4.25 meters, and each has 64 detection modules. The detection module is composed of a periodic structure of tile-shaped steel and scintillator layers, with a thickness ratio of about 4.7:1. The shower energy generated by the steel as an absorber will be absorbed by the scintillator. The light signal generated by the scintillator absorption is transmitted by optical fiber to the photomultiplier tube at the top for reading. Its structure is shown in Figure 3-10 [11]. Tile is divided into three layers from the inside to the outside, as shown in the figure 3-11 [11], providing at least 7.4 interaction lengths (λ).

The liquid argon hadron calorimeter (HEC) uses copper as an absorber and liquid argon as a sampler, covering the region where $|\eta|$ is between 1.5 and 3.2. Similar to the EMEC, the HEC on each end cap also contains a “near wheel” (HEC1) and a “far wheel” (HEC2), with a spacing of about 8 mm. Their readout granularity is the same, with a radius of 2 meters and each containing 32 modules. Its structure is shown in

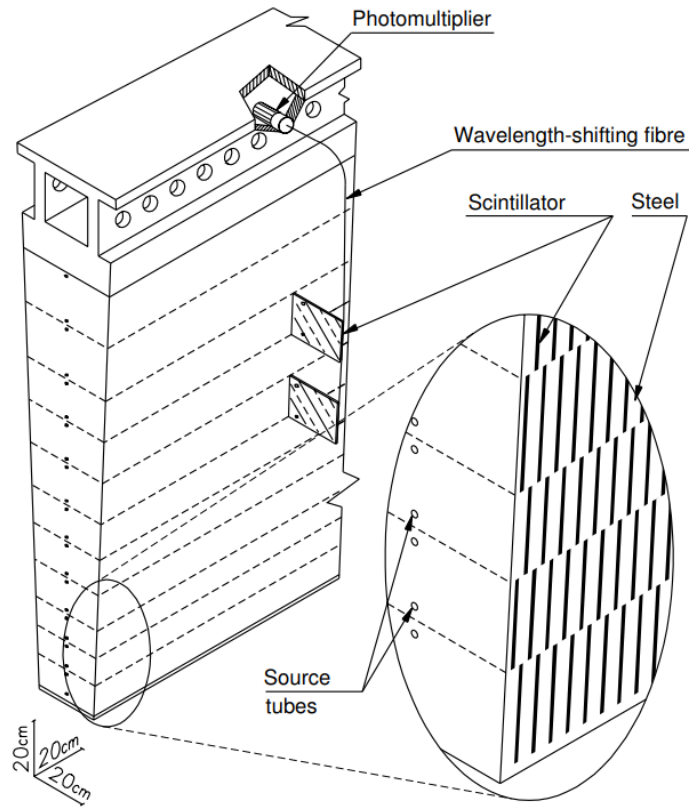


图 3-10 瓦片状采样量能器的结构示意图 [11]。

Figure 3-10 Structure of the Tile Calorimeter [11].

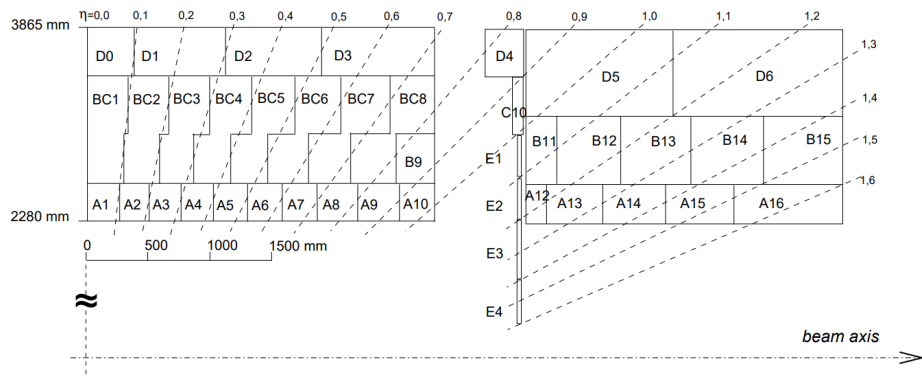


图 3-11 Tile 桶部与延长部分的三层结构示意图 [11]。

Figure 3-11 Structure of the three-layer structure of the ATLAS Tile calorimeter in the barrel region and the extended region [11].

Figure 3-12 [11].

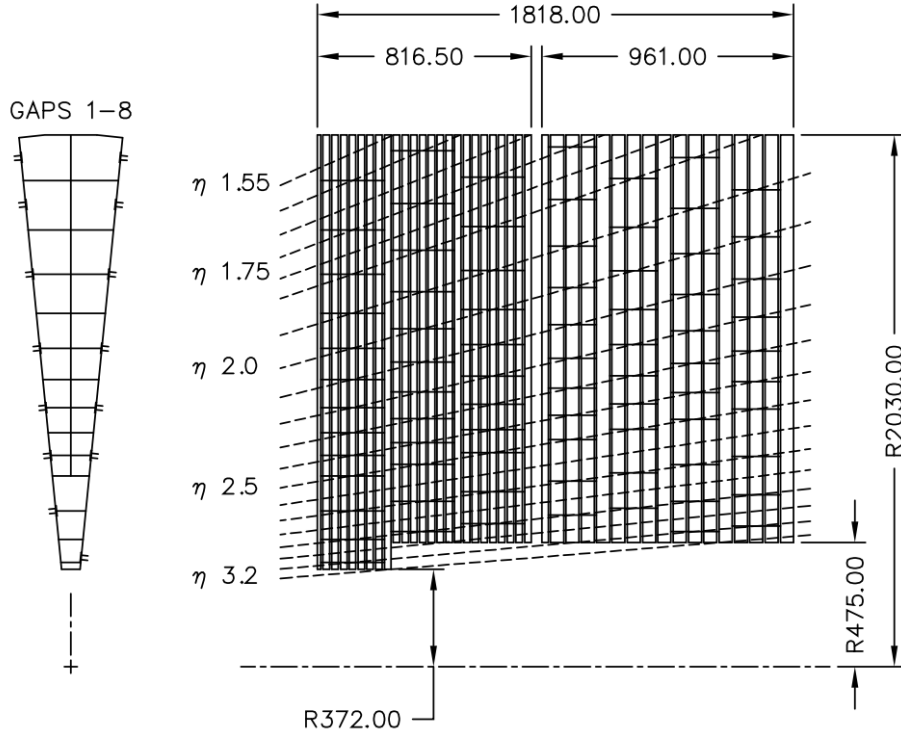


图 3-12 液氩强子量能器 (HEC) 结构示意图 [11]。

Figure 3-12 Structure of the liquid argon hadronic calorimeter (HEC) [11].

Liquid argon forward calorimeter (FCal), covering the region of $|\eta|$ from 3.1 to 4.9. The particles emitted in the forward direction usually have high energy and the number density of particles is also high, so FCal requires special design. FCal is divided into three layers of modules, and its structure is shown in Figure 3-13 [11]. Each layer is 45 cm thick. The innermost absorber uses copper, which has good performance for electromagnetic showers, and the outer two layers use tungsten with higher density. Each layer of FCal module has a copper plate with uniform holes to support the absorber and the sampler. There are columnar absorbers and copper shells in the holes, which are filled with liquid argon, and the signal is derived from the optical fiber placed in it. In addition, the copper shells of the outer two layers of modules are also about 1 cm thick tungsten to increase the mass.

The hadron calorimeter system in the barrel can provide a total absorption distance of 9.7λ , and the energy resolution is $\sigma_E/E = 50\%\sqrt{E} \oplus 3\%$. The forward calorimeter can provide a total absorption distance of 10λ , and the energy resolution is $\sigma_E/E = 100\%\sqrt{E} \oplus 10\%$.

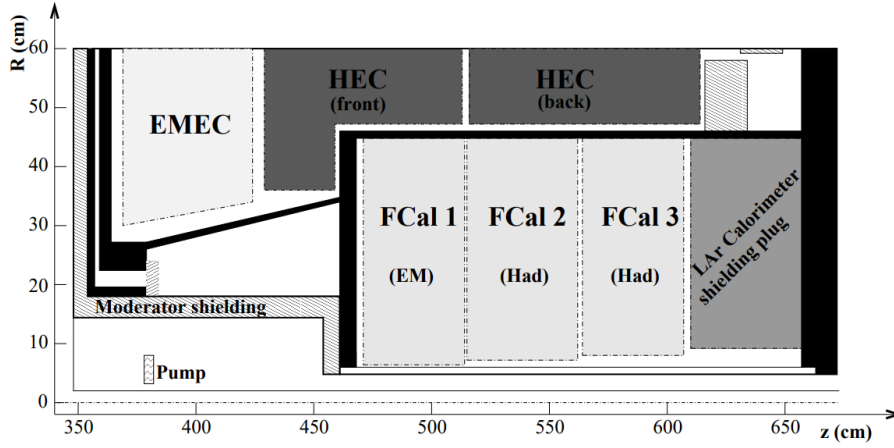


图 3-13 液氩前向量能器 (FCal) 结构示意图 [11]。

Figure 3-13 Structure of the Liquid argon forward calorimeter (FCal) [11].

3.2.4 Muon Spectrometer

The Muon Spectrometer (MS) is located at the outermost layer of the ATLAS detector. It can measure the momentum information of muons within $|\eta| < 2.7$, and can also provide a muon trigger system within the range of $|\eta| < 2.4$. The MS contains four gas detector subsystems, namely: Monitored Drift Tubes Chambers (MDT), Cathode Strip Chambers (CSC), Resistive Plate Chambers (RPC) and Thin-gap Chambers (TGC). Their principle is to measure the position information of particles through the gas ionization and avalanche amplification generated by charged particles passing through the gas. At the same time, the magnetic field provided by the magnet system in the MS measures the momentum by bending the particle track. The magnetic field within the range of $|\eta| < 1.4$ is provided by the large barrel ring magnet, the magnetic field within the range of $1.6 < |\eta| < 2.7$ is provided by the end cap magnet, and the magnetic field in the area between 1.4 and 1.6 is provided by both the barrel and the end cap. The four subsystems together form the three-layer detector in the barrel and the three-layer disk detector in each end cap. The structure is shown in Fig. 3-14 [11]. Among them, MDT and CSC can provide high-precision momentum measurement, and RPC and TGC are responsible for providing the trigger system for muons.

MDT covers the area of $|\eta| < 2.7$, covering the barrel and the end cap. Each MDT contains three to eight layers of drift tubes. The diameter of the drift tube is about 3 cm, the internal gas pressure is 3 Pa, and the gas composition is 93% argon and 7% carbon dioxide. The position resolution of the drift tube is 80 microns, and the resolution of the MDT composed of multiple layers of drift tubes is reduced to 35 microns. CSC covers the area of $2 < |\eta| < 2.7$, located in the innermost layer of the end cap, and consists of a multi-wire positive proportional chamber. The anode wire spacing and the spacing between the anode wire and the cathode strip of the multi-wire positive

proportional chamber are both 2.5 mm, and the internal gas is also argon and carbon dioxide. The dead time and time resolution of CSC are better than MDT, with a lateral spatial resolution of about 5 microns and a radial resolution of about 40 microns.

RPC covers the barrel area of $|\eta| < 1.05$, and TGC covers the end cap area of $1.05 < |\eta| < 2.4$. Their response time is 15 to 25 nanoseconds, which is suitable for fast screening of cases under high brightness. RPC has 3 layers, and some areas have 4 layers because of the overlap of the end cap and the barrel. Each layer of RPC contains two independent detection units. Each detection unit consists of two resistive plates with a spacing of 2 mm, and is filled with 94.7% $C_2H_2F_4$, 5% Iso – C_4H_{10} and 0.3% SF_6 . The two inner layers of RPC can effectively exclude false tracks with low momentum, and combined with the outer layer of RPC, it can exclude false tracks with high momentum, which improves the selection efficiency of the trigger system. The structure of TGC is similar to that of CSC, which is also a multi-wire proportional chamber, but the wire spacing and the wire-readout spacing are smaller, so it can not only provide a trigger system, but also provide better spatial resolution.

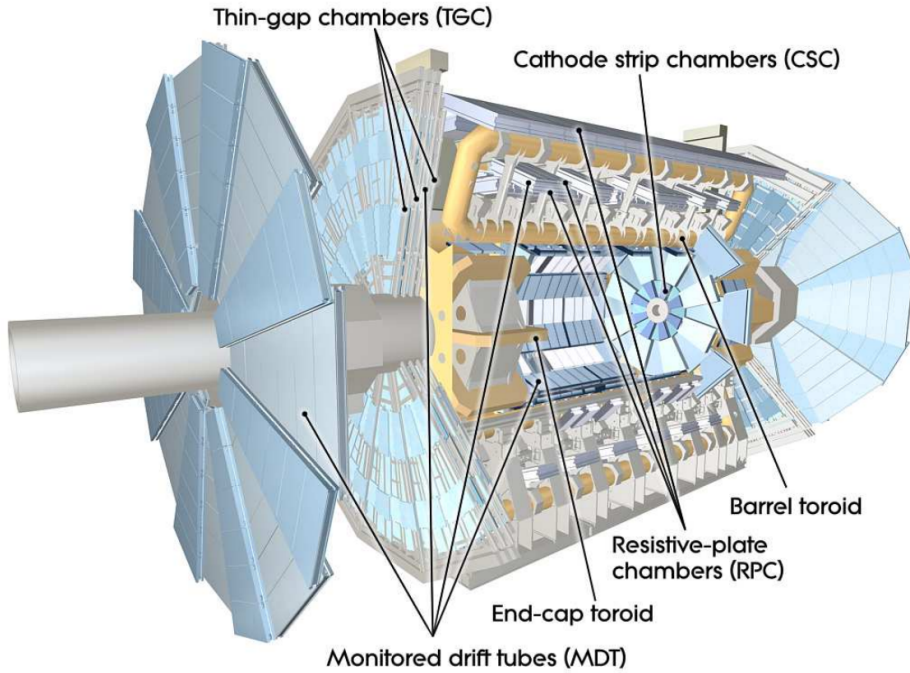


图 3-14 缪子谱仪 (MS) 结构示意图 [11]。

Figure 3-14 Structure of the Muon spectrometer (MS) [11].

3.2.5 Magnet System

The magnet system of ATLAS is mainly divided into two parts. The first part is the central solenoid magnet surrounding the ID, which is about 5.8 meters long and 2.56 meters in diameter. In order to reduce the mass, it is only 4.5 cm thick and has an absorption length of only $0.66X_0$, but provides a magnetic field of up to 2 T parallel

to the beam direction. The second part is the toroid magnet, which includes eight large magnets in the barrel and one end cap magnet in each end cap part, providing a magnetic field around the beam direction. The eight large magnets are 25.3 meters long, 4.7 meters in inner diameter, and about 10 meters in outer diameter, providing a 0.5 T magnetic field; the end cap magnet is 5 meters thick, 10.7 meters in diameter, and provides a 1 T magnetic field. In general, the magnet system is responsible for deflecting the trajectory of charged particles, so that the central track chamber and the muon spectrometer can measure the momentum of charged particles and perform particle identification.

3.2.6 Trigger and Data Acquisition System

Figure 3-3 [66] shows the peak instantaneous brightness of the LHC over the years. In order to match such a high instantaneous brightness, the ATLAS detector is designed to be able to process 1.7 billion pp collisions per second. In addition, the ATLAS sub-detector has more than 100 million electronic readouts. Such a high collision frequency and so many electronic readout channels can generate 60 billion MB of electronic data per second. It is impossible to record all 60 billion MB/S of experimental data, so the ATLAS trigger and data acquisition system (TDAQ) is used to screen, preliminarily process and save the parts of interest in the massive data. The TDAQ system processes experimental data in two steps. The first step is the hardware-based L1 trigger, and the second step is the software-based HLT trigger (High Level Trigger). The processing result of the L1 trigger will be used as the input data of the HLT trigger. HLT can be further divided into L2 triggers and EF (Event Filter) systems. Figure 3-15 [71] shows the triggers and strategies at each level of TDAQ.

A subsystem of the L1 trigger is the L1 Calorimeter Trigger (L1Calo), which is responsible for processing the information of all calorimeter systems, and ultimately screening out events with high p_T electrons, photons, jets, and hadronic decaying τ_{had} , and their isolation can also be required as needed. L1Calo can also screen out events with high E_T^{miss} , high total transverse momentum, or multiple jets. Another subsystem of L1 is the Muon Trigger, which is responsible for screening out muons with high p_T detected in RPC and TGC. These two parts of the trigger only screen for quantity, without considering spatial position information. The collision information of these two triggers will be passed to the Central Trigger Processor (CTP) for L1-level screening. At the same time, the detector information will continue to be processed to provide accurate spatial position information. After the case passes L1 screening, its spatial location information is passed to the L2 trigger as a Regions-of-Interest (RoI). The L1 trigger completes the decision in 2.5 microseconds, and the frequency of the case is reduced to 100 kHz.

The L2 trigger is mainly based on software algorithms. It consists of more than 40,000 CPU cores. After receiving the RoI information, it will further screen according

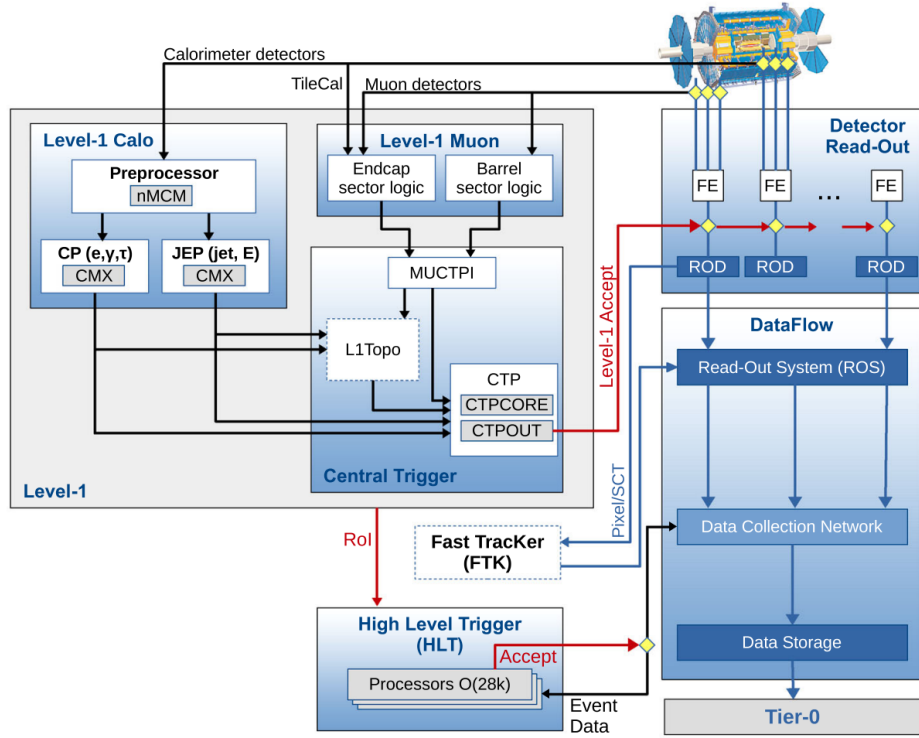


图 3-15 ATLAS 触发与数据获取系统示意图 [71]。

Figure 3-15 Schematic diagram of the ATLAS trigger and data acquisition system [71].

to the spatial location information, energy information and candidate type provided by the RoI. L2 will use the full-precision detector information and make decisions within 40 milliseconds. The frequency of the case will be reduced to 3 kHz. The DAQ system will temporarily store the sub-detector information of all cases that pass through L1. If the case passes the L2 trigger, the DAQ system will reconstruct the stored information for the complete case and then pass the reconstructed case information to EF. EF will screen out the cases that will be used for offline physical analysis, and the case frequency will be further reduced to 200 HZ. Before the second round of data acquisition, ATLAS installed a fast track reconstruction system (Fast TracKer, FTK), which is based on a programmable logic chip (FPGA) and uses a table lookup method to perform pattern recognition on the track. The expected processing frequency is the screening frequency of the L1 trigger (100 kHz). The track information obtained after processing will be provided to HLT for use.

If the efficiency of a trigger strategy is too low in the L1 or HLT stage, exceeding the processing limit of the TDAQ system, TDAQ will use a pre-compression (Prescale) strategy: only one out of a fixed number of cases is stored. After the case passes all the above trigger strategies, all information will be stored in the Tier-0 data center of CERN for subsequent physical analysis. In addition, some metadata will also be stored, generally the information of the data generated by the ATLAS detector, that is, "data of data". Metadata has many types and sources [72], such as the integrated brightness

(Luminosity Blocks) within a certain period of acquisition time and the GRL (Good Run List) that records the high-quality acquisition time, They are very important for physical analysis.

3.2.7 ATLAS Detector Performance

Between April 2015 and October 2018, the ATLAS experiment conducted its second round of data collection. The beam used in Run2 was a proton beam, with a bunch spacing of 25 ns and a center-of-mass energy of 13 TeV. The LHC acquired 156 fb^{-1} experimental data, of which 0.6% was used for brightness scale, 0.4% was not recorded due to performance problems with the L1 trigger, 147 fb^{-1} experimental data were recorded by the ATLAS experiment, and 139 fb^{-1} experimental data were used for physical analysis. It can be found that the data utilization rate of the ATLAS experiment is extremely high. The experimental data used for the physical analysis involved in this article are all 139 fb^{-1} experimental data of Run2. Figure 3-16a shows the temporal distribution of the accumulated brightness of ATLAS during Run 2.

The ATLAS experiment recorded high-brightness data, but high brightness also means high pile-up. The pile-up effect is an unavoidable shortcoming of high-brightness collider experiments. It has two main sources: (1) In-time pile-up: multiple pp interactions occur when a single bunch collides; (2) Out-of-time pile-up: multiple pp interactions occur continuously. Although there is a time difference between the two, they still cause interference. This situation often occurs in multi-bunch collisions. It is caused by the performance of the detector. The pile-up effect will generate a large amount of background, which will cause trouble for physical analysis. In experiments, the pile-up effect is usually reduced by software algorithms, and the Out-of-time pile-up is reduced by adjusting the time windows of different sub-detection systems [73]. In experiments, $\langle\mu\rangle$ is generally used to represent the average number of interactions between bunches in a certain period of time. Figure 3-16b [74] shows the distribution of $\langle\mu\rangle$ values over the years of the ATLAS experiment and during the entire Run-2 period. Overall, $\langle\mu\rangle$ is between 10 and 70. The Monte Carlo simulation samples used in the analysis will make the simulation consistent with the impact of $\langle\mu\rangle$ in the real experimental data by changing the case weights.

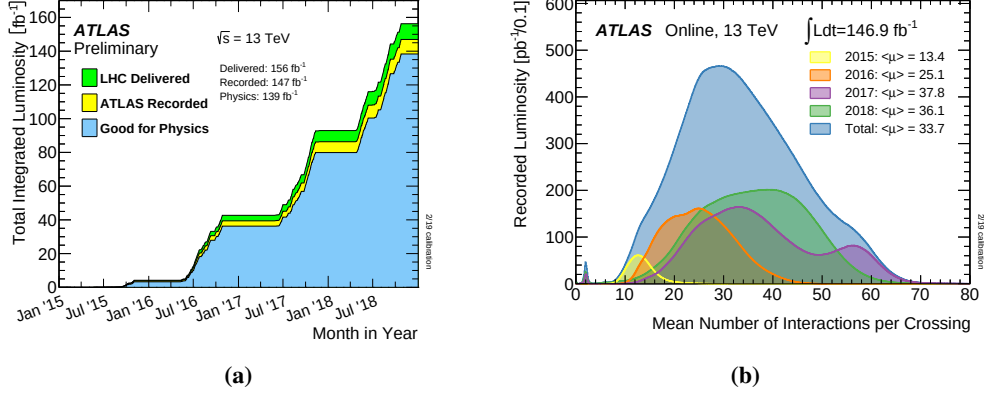


图 3-16 ATLAS 在 Run-2 阶段取数积分亮度示意图 (a) 与束团间平均相互作用次数的分布 (b) [74]。

Figure 3-16 The integrated luminosity (a) and mean number of interactions per bunch crossing (b) of the ATLAS detector in Run2 [74].

3.3 Monte Carlo simulation of the ATLAS experiment

3.3.1 Parton Model

The electron-proton deep inelastic experiment [75] revealed the existence of charged free particles inside the nucleon, Therefore, the Parton Model was proposed to explain this phenomenon[76, 77]. The Parton Model believes that the pp collision process is essentially the interaction of partons inside each proton. Partons carry a part of the momentum of the proton, which can be expressed as: $p_{T, \text{parton}} = xp$, where x is the proportion of momentum carried, between 0 and 1, and p is the momentum of the proton. The density distribution function $f(x)$ of x is called the Parton Distribution Function (PDF), and the integral value of the sum of the nucleon's partons is one: $\sum_i \int x f_i(x) dx = 1$. The deep inelastic experiment of neutrino-proton shows that the isospin and charge of partons are the same as those of quarks. It is also found that there are neutral partons inside the nucleon, so gluons also carry the momentum of the nucleon. The interaction cross section of pp collision can be written as:

$$\sigma = \sum_{a,b} \int dx_1 dx_2 f_a(x_1) f_b(x_2) \sigma_{ab \rightarrow X(x_1, x_2)} \quad (3-6)$$

The a, b on the right side of the equation is the sum of different parton components, $\sigma_{ab \rightarrow X(x_1, x_2)}$ is the cross section of the interaction between partons a and b to produce X , which can be calculated by perturbation theory, and the left side of the equation is the experimentally measured cross section, which is then inversely solved by global fitting to obtain the parton distribution function. It is a very complex topic to continuously adjust the PDF based on experimental data and theoretical expectations. In the experiment, the results of some international research groups specializing in the PDF distribution of the LHC are used to simulate the collision process. The more commonly used ones

are: MSTW [78], CT [79] and NNPDF [80], which provide the sub-leading order and higher order PDF distributions used by ATLAS.

3.3.2 Monte Carlo simulation of proton-proton collisions

Searching for physical processes beyond the Standard Model requires accurate simulation of Standard Model processes and processes beyond the Standard Model. The ATLAS experiment uses the Monte Carlo algorithm software framework (Monte Carlo generator) for simulation. The formula 3-6 describes the hard scattering process. After determining the partial distribution function, the $\sigma_{ab \rightarrow X(x_1, x_2)}$ on the right side of the equal sign will be calculated by the Matrix Elements (ME), which is the only calculation based on first principles in the proton collision simulation. The calculation of ME depends on the selection of μ_f (Factorisation scale) and μ_r (Renormalisation scale). The distribution changes caused by different selections are considered as systematic errors. The ME method can finally obtain the dynamic distribution of the emitted partons. The calculation of this process requires the determination of the order of calculation, so it is impossible to calculate the processes containing variable initial state radiation (ISR) and final state radiation (FSR), and the simulation performance for low momentum partons is not good, therefore, the Parton Showers (PS) method is proposed to simulate the partons generated by radiation. The accuracy of the PS method in simulating low momentum partons is better than that of the ME method. Combining the ME and PS methods can simulate hard scattering and radiated partons at the same time, and improve the calculation accuracy of low momentum and high momentum partons. Considering that the two methods have some overlap, the Matching and Merging Schema is proposed to solve the transition and overlap problems between ME and PS, such as the CKKW mode [81] and the MLM mode [82], the errors caused by different modes will be regarded as part of the system error.

The parton showers produced by the ME and PS methods are color-charged. In order to obtain the color-singlet emitted hadrons, the parton showers need to be hadronized. Since there is currently no theory based on the first principles to describe the hadronization process, the description of hadronization is phenomenological. The PS generators used in the current experiments all adopt the Lund String Model [83] or the Cluster Model [84]. Finally, the PS generator can simulate the final state particles entering the detector.

In addition, in the proton collision process, in addition to the interaction between a pair of partons, there are also potential events (Underlying Event, UE) that cannot be ignored. UE is mainly produced by the remaining partons of the proton. The remaining partons can continue to interact with each other or directly hadronize. The former is called Multiple Parton Interactions (MPI), and the latter is called beam remnants. The remaining partons are the main reason why the background of the hadron collider is

more complex than that of the lepton collider. There is also no complete theoretical description, which is simulated by PS generation sub-.

In the pp collision simulation, except for the hard scattering from the calculation based on the first principles, the rest of the process depends on the parameters provided by the experimental results, so additional adjustments (Tune) are needed to make the simulation results closer to the real experimental data. Commonly used adjustments in ATLAS include A2 adjustment for UE [85], A14 adjustment for MPI and PS [86], and sub-leading order adjustment for $t\bar{t}$ process [87, 88], etc.

Table 3-2 shows the PDF, ME and PS generators and Tune of the simulation samples used in this article. Except for the parts listed in the table, all samples use A3 adjustment [89] for UE.

表 3-2 本文所使用的 PDF、ME 与 PS 产生子和 Tune。

Table 3-2 The PDF, ME and PS generators, and the Tunes used in this thesis.

Process	PDF	ME Generator	PS Generator	Tune
SUSY Signals	NNPDF2.3LO [90]	MADGRAPH5_aMC@NLO 2.2.3 [91]	PYTHIA 8.186 [92]	A14 [86]
$t\bar{t}$	NNPDF2.3LO	POWHEG-BOX v2 [93–96]	PYTHIA 8.186	A14
Single top Wt , s/t channel	NNPDF2.3LO	POWHEG-BOX v2	PYTHIA 8.186	A14
$t\bar{t}W/Z$	NNPDF2.3LO	MADGRAPH5_aMC@NLO 2.2.2	PYTHIA 8.186	A14
Z+jets, W+jets	NNPDF3.0NNLO [80]	SHERPA 2.2.1 [97, 98]	SHERPA 2.2.1	SHERPA
Multi-boson	NNPDF3.0NNLO	SHERPA 2.2.1/2.2.2	SHERPA 2.2.1/2.2.2	SHERPA
ggh , VBF- h	NNPDF3.0NNLO	POWHEG-BOX v2	PYTHIA 8.186	AZNLO/NNLOPS
$t\bar{t}h$, $h+W/Z$	NNPDF3.0NNLO	MADGRAPH5_aMC@NLO 2.2.2	PYTHIA 8.186	AZNLO

3.3.3 Simulation of ATLAS Detector

After simulating the collision process, the sample needs to go through the detector simulation, which mainly simulates the interaction between the emitted particles and the detector and the further decay of the emitted particles. The detector simulation will give the energy deposited by the particles in each sub-detector. Then, the sample will undergo an electronic simulation. The input information of this step is the simulated deposited energy of the detector, and the output is the simulated detector electronic readout. Finally, the reconstruction and identification simulation of the case is carried out. Like the data acquisition of the real experiment, the simulated electronic signal will be reconstructed through the reconstruction and triggering system.

There are two main methods for ATLAS detector simulation. The first is full simulation (FS) based on Geant4 [99–101], which has the highest accuracy, but consumes a lot of computing resources, so there is another fast simulation (AtlasFastII, AF2) [102], which uses simplified calorimeter simulation (FastCaloSim) and track simulation (Fastras), which reduces the simulation time by an order of magnitude [102]. The standard model samples used in this paper are all simulated by FS, and the signal samples are all simulated by AF2.

第 4 章 Reconstruction and Identification of Particle

This paper introduces the data screening of the ATLAS detector in Section 3.2.6. In addition to the processing of electronic signals, data screening also requires the use of information from event reconstruction. The reconstructed events include not only the reconstructed elementary particles, but also the tracks and interaction vertices of charged particles, and also the jets produced by hadron decay and the transverse energy loss produced by undetected particles. Among them, the reconstruction of tracks is the starting point of event reconstruction, and the reconstruction of almost all physical objects depends on the reconstruction of tracks. After obtaining the track information, the vertex of the proton collision can be reconstructed, and combined with the information of the calorimeter and the muon spectrometer, the remaining physical objects can be reconstructed, identified and calibrated. In addition, the last step of event reconstruction requires the de-coincidence of the reconstructed objects to prevent one particle from being reconstructed into two reconstructed objects. This chapter will introduce the reconstruction, identification and calibration methods of tracks/vertices, electrons/photons, muons, jets, tau and transverse energy loss commonly used during the ATLAS experiment Run2.

4.1 Track/Vertex

When the ATLAS experiment took data in 2018, the peak value of the number of pp collisions $\langle \mu \rangle$ of a single bunch was about 40. Each collision produced an average of 15 tracks, so each bunch collision will produce about 600 tracks. How to deal with such a large number of tracks and proton collision vertices depends on the sophisticated design of software and hardware. This section will briefly introduce the reconstruction strategy on the software. Since the research in this article does not involve the reconstruction of short tracks (short tracklet) and large radius tracks (Large Radius Tracking), this section only introduces the reconstruction of ordinary tracks and the reconstruction of proton collision vertices.

Charged particles are affected by the magnetic field in the internal track detector and deflected in the x-y plane, while the movement in the z-axis direction is not affected by the magnetic field. For this spiral-shaped track, the ATLAS experiment uses five parameters to describe it, where the origin of the coordinate parameters is the average position of the proton collision:

$$(d_0, z_0, \phi, \theta, \frac{Q}{p_T}) \quad (4-1)$$

d_0 is called the transverse impact parameter, which indicates the distance between the point on the track closest to the z-axis (beam) and the z-axis. The distance from this point to the x-y plane is z_0 , and z_0 is called the longitudinal impact parameter. It can be found that z_0 is not necessarily the distance between the point on the track closest to the x-y plane. ϕ is the angle between the transverse momentum component of the track at this point and the x-axis, that is, the azimuth angle of the track tangent. θ is the angle between the track tangent at this point and the z-axis, that is, the polar angle of the track tangent.

Track reconstruction can be divided into two categories. The first category is primary tracking, the main target is charged particles produced by hard scattering, the second category is secondary tracking, the main target is the charged decay products of long-lived particles and the secondary particle conversion tracks (Conversion) produced by the interaction between detector matter and particles. Although their physical processes are different, the reconstruction ideas are similar: find the "seed" of the track, expand the track from the seed, and refit the complete track.

The seeds of the primary track come from the eight-layer silicon detectors of Pixel and SCT. If there are three space-points in three consecutive layers whose positions resemble the motion trajectory of charged particles, they can be used as seeds. Then, the hitting range of the track in other layers is estimated by the information of the seeds as the search path. The composite Kalman filter (CKF) is used to extend the track inside and outside the detector within the search path. The layers where no hitting points are found in the search path are called holes. For seeds that cannot continue to extend the track, the algorithm checks whether it is in the RoI of the calorimeter signal. If so, its track extension will allow a turning point to exist and be used as a potential Bremsstrahlung radiation process for electron reconstruction. The complete track candidate also needs to go through the step of ambiguity solving. A neural network (NN) model will score the track candidates and remove low-scoring tracks with too many shared hits (SH). If multiple tracks share a small part of the hit point, they may be the products of multiple tracks close to each other from the decay of the high-energy jet. At this time, another set of NNs will be used to estimate the possible shower range of the jet. Finally, the least squares fitting is used to calculate the parameters of the track candidates. The parameters will be used to estimate the search path of the candidate track in the TRT. The CKF method will be used again to extend the track to the TRT. If there is no corresponding response in the TRT, the track will be marked as a silicon detector track (Si-only track). Otherwise, the track will be fitted with the least squares fitting method again to obtain the final track parameters. The seeds of the secondary track come from the TRT response in the RoI of the electromagnetic calorimeter, and the response of the TRT is required not to be within the TRT extension of the primary track. The response of the TRT will

extend inward to the hit points of the two outermost layers of SCT and gradually extend to the pixel. The subsequent reconstruction process is similar to the primary track.

In order to reduce the false tracks caused by the pile-up effect and the mis-combination of hit points, the reconstructed track requires at least 7 hits from silicon detectors, at most one shared hit and at most two misses, and the pixel cannot have more than one miss. This set of conditions is defined as the loose working point (Loose WP). The reconstruction efficiency of Loose WP is higher than 80%, and it is as high as 90% [103] when the particle $p_T > 5$ GeV. The false track content (Fake rate) is proportional to $\langle \mu \rangle$. When $\langle \mu \rangle = 30$, the Fake rate is close to 5% [103]. The resolution of the collision parameters d_0 and z_0 measured by the $Z \rightarrow \mu\mu$ process is less than 20% [103].

The vertex reconstruction of proton collision is achieved through an iterative algorithm. The first step of reconstruction is to find the "seed". Assuming that the collision parameters of the reconstructed track conform to the Gaussian distribution, the probability density of the reconstructed track along the beam direction can be calculated, and the place with high probability density will be used as the seed of the vertex. After the seed is determined, an algorithm based on adaptive Kalman filtering (Weighted adaptive Kalman filtering) will estimate whether the track near the seed belongs to the seed. The last step of each iteration will determine whether the seed is a reconstructed vertex or should be discarded through pre-designed conditions (such as the seed contains at least two tracks). After multiple rounds of iterations, a set of reconstructed collision vertices can be obtained.

The reconstruction efficiency of the collision vertices that produce at least three tracks is as high as 95%, and it is close to 100% for four tracks [104]. The resolution of the vertex position is $\mathcal{O}(10)$ micrometers, and decreases with the number of tracks [104], where the track transverse momentum scalar and the largest vertex are selected as primary vertices (PV), and the other vertices are marked as pile-up vertices (Pile-up vertices).

4.2 Electrons/Photons

Since both electrons (e) and photons (γ) can leave electromagnetic showers in the electromagnetic calorimeter, and photons can decay into positive and negative electron pairs by interacting with matter in the ID, such photons are called converted photons, so in the ATLAS experiment, the reconstruction algorithms of photons and electrons are highly correlated. This section will introduce the reconstruction of electrons and photons that reach the electromagnetic calorimeter and the reconstruction of converted photons that complete the conversion in the ID in the ATLAS reconstruction algorithm.

4.2.1 Reconstruction of Electrons/Photons

The reconstruction of electrons and photons depends on "superclusters". The 3.2.3 section of this article mentions that the granularity of the electromagnetic calorimeter is very high, so the shower energy of electrons and photons in ECal will be deposited in multiple detection units. This distribution of energy deposition is called a cluster. Superclusters refer to the reconstruction algorithm using clusters to construct superclusters of variable size. Compared with the traditional sliding window algorithm, the new method can consider wider electromagnetic showers. Overall, the supercluster method improves the reconstruction efficiency of wider distributed conversion photons by about 15%, and the energy resolution of electrons is improved by 15% to 25%.

Standard Cluster Reconstruction Standard clusters are the seeds of super clusters. In order to reduce the impact of background fluctuations, only the information of the second-layer ECal detection units is used for cluster reconstruction. Cluster reconstruction starts from the detection units with a deposition energy four times higher than the background noise, and then expands outward to all connected detection units with a deposition energy higher than two times the background noise. Finally, the cluster is expanded by an adjacent unit with a deposition energy higher than the background noise. If there are multiple clear and distinguishable peak energy depositions in a single cluster, the single cluster will be divided into multiple clusters [105].

Cluster-track matching of electrons The tracks used for reconstruction basically follow the standard track reconstruction algorithm, but more energy loss is allowed when using the least squares method to fit the calculation parameters. Next is the "rough" cluster-track pairing, extending the track to the second layer of ECal detection units. If the $\Delta R(q)$ of the extended track and the cluster is less than 0.05, the track momentum and cluster energy are matched. If multiple tracks point to the same cluster, the track with more pixel hits is preferred. If the number of pixel hits is the same, the track with the smallest ΔR is used.

Cluster-track matching of converted photons It can be imagined that the performance of the converted photons in the ID should be a pair of secondary tracks with opposite curvature radii. So the reconstruction algorithm selects a pair of tracks with opposite charges and a total system mass of almost 0, or a secondary track that does not leave any information in the pixel. The algorithm based on TRT information determines whether the source of the track is likely to be an electron [106]. If so, after a series of selection conditions, the vertices of these tracks are defined as conversion vertices. The tracks starting from the conversion vertices will undergo cluster-track matching similar to electronic reconstruction.

Reconstruction of Superclusters Previously, clusters that passed rough electron matching and clusters that did not pass electron or conversion photon matching

were used as candidates for super clusters of electrons and non-conversion photons, respectively. Afterwards, a fixed-size $\Delta\eta \times \Delta\phi$ window will search for satellite clusters around the candidates. Their sources are usually bremsstrahlung or shower splitting, and the window size is related to the physical process. Similarly, track information is also needed to match satellite clusters to prevent them from pile-up effects or other electromagnetic showers. Clusters and satellite clusters form super clusters, which will expand from the second layer of ECal to the inside and outside by one layer each. So the energy of the super cluster comes from the deposited energy of the innermost three layers of ECal detection units.

Reconstruct electron/photon After obtaining the supercluster, the reconstruction strategy will perform a rough energy scale and position correction [105], and then use the information after the preliminary scale to perform supercluster-track matching in a method consistent with the cluster-track matching method. If the supercluster of the electron matches the track, the reconstructed electron is obtained. If the conversion vertex matches the supercluster of the photon, the reconstructed conversion photon is obtained. If the supercluster cannot match the track information, the reconstructed non-converted photon is obtained. In addition, for the case where the matches overlap and cannot be distinguished, a single supercluster may be reconstructed as an electron and a photon at the same time. Finally, the reconstructed electron/photon is finally corrected by the energy scale [107] based on the track and supercluster information, and their kinetic variables are calculated for particle identification.

4.2.2 Identification and Isolation of Electron/photon

In order to distinguish whether the reconstructed electrons come from real electrons, photon conversion, or whether the energy deposition injected into ECal constructs a fake electron, a likelihood function based on track information, cluster shape, and track-cluster η - ϕ matching is used to judge the electron reconstruction performance [105]. The expression of the likelihood function of background and signal is as follows [105]:

$$L_{S(B)}(x) = \prod_i P_{S(B),i}(x_i) \quad (4-2)$$

Among them, x_i is the i th variable used to judge the reconstruction performance, $P_{S(B),i}$ represents the probability density function distribution (PDF) of the signal (background), The PDF of the signal is taken from the $Z \rightarrow ee$ or $J/\psi \rightarrow ee$ process, and the PDF of the background is mainly taken from the di-jet process. After obtaining the PDFs of the background and signal, the distribution of the likelihood function $d_{L,(S/B)} = \log L_S/L_B$ can be calculated. The identification of electrons is mainly determined by comparing the d_L of the case and the distribution of the likelihood function to determine whether the case is closer to a real electron or a fake electron. Finally, the three more commonly used standard working points of Loose, Medium, and Tight are defined with d_L

as the main variable. Figures 4-1a and 4-1b [105] show the selection efficiency at different working points respectively. As E_T and η change, it can be found that when $E_T > 40$ GeV, Tight's selection efficiency can be as high as 80%, and the selection efficiency of the barrel is much higher than that of the end cap. The Tight working point of photon identification uses electron-like input variables as the input of the TMVA algorithm [105], and TMVA optimization is performed for different E_T ranges. Figures 4-1c and 4-1d [105] respectively show the changes of the selection efficiency of the converted photon and non-converted photon Tight working points with E_T . The hollow points (solid points) represent the working points optimized for (not for) different E_T ranges. It can be found that when $E_T > 40$ GeV, the selection efficiency of Tight is as high as 85% or more. Since the trigger system of ATLAS does not distinguish between converted photons and non-converted photons, the definition of Medium and Loose only uses cluster information, so these two working points do not distinguish between the two types of reconstruction photons.

In order to further reduce the background, two variables, E_T^{cone20} based on ECal cluster isolation and $p_T^{(\text{var})\text{cone20}}$ based on track isolation, are used to measure the isolation of reconstructed particles. E_T^{cone20} represents the energy deposition outside the range of $\Delta R < 0.2$ from the cluster center, except for the energy deposition outside the range of $\Delta\eta \times \Delta\phi = 5 \times 7$ ECal detection units around the cluster center, while considering the effects of pile-up effect, UE and shower leakage, so the more concentrated the cluster energy is, the smaller E_T^{cone20} is. In the range of $\Delta R < 0.2$ ($\Delta R < \min(10/p_T[\text{GeV}], 0.2)$) from the matched track represented by $p_T^{(\text{var})\text{cone20}}$, the transverse momentum distribution of all unmatched reconstructed tracks shows that the more isolated the track is, the fewer other tracks there are within ΔR , and the lower $p_T^{(\text{var})\text{cone20}}$ will be. The operating point of the isolation of photons and electrons and the requirements for E_T^{cone20} and $p_T^{(\text{var})\text{cone20}}$ are shown in Table 4-1, where E_T^{cone40} indicates that the ΔR standard is relaxed to 0.4. The requirements for E_T^{cone20} and $p_T^{\text{varcone20}}$ of the electron Gradient working point will change with p_T . When $p_T = 25$ GeV, the selection efficiency ϵ of Gradient is 90%, and when $p_T = 60$ GeV, ϵ is as high as 99%. The requirements for isolation at the remaining working points are all fixed values, among which FCHighPtCaloOnly/FixedCutTightCaloOnly designed according to the requirements only requires ECal isolation of high p_T reconstructed electrons/photons. The overall selection efficiency of each Tight working point is above 90%, and the overall selection efficiency of the Loose working point is about 99% [105].

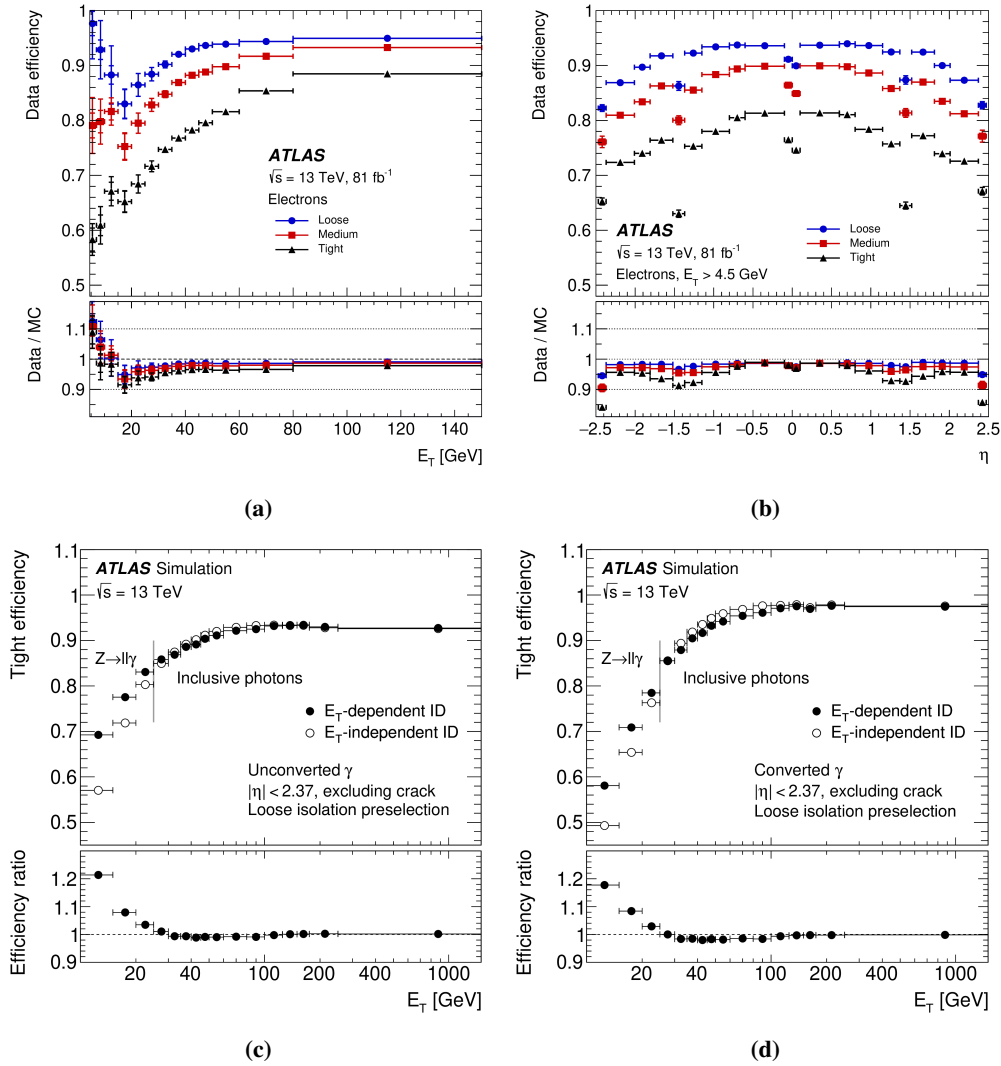


图 4-1 电子/光子的鉴别工作点的选择效率与动力学变量的关系 [105]。

(a) 展示了电子鉴别工作点的选择效率与 E_T 的关系，(b) 展示了电子鉴别工作点的选择效率与 η 的关系，(c) 展示了非转化光子鉴别 Tight 工作点的选择效率与 E_T 的关系，(d) 展示了转化光子鉴别 Tight 工作点的选择效率与 E_T 的关系。

Figure 4-1 The selection efficiency of

electron/photon identification working points as a function of kinematic variables [105].

(a) shows the relationship between the selection efficiency of electron identification working points and E_T , (b) shows the relationship between the selection efficiency of electron identification working points and η , (c) shows the relationship between the selection efficiency of non-converted photon identification Tight working points and E_T , and (d) shows the relationship between the selection efficiency of converted photon identification Tight working points and kinematic variables.

表 4-1 电子/光子不同孤立度工作点 [105], p_T 单位为 GeV。

Table 4-1 Isolation criteria of electron and photon [105], p_T is in the unit of GeV.

	Working point	Isolation of Cluster	Isolation of Track
Electron	Gradient	$\epsilon = 0.1143 \times p_T + 92.14\%$	$\epsilon = 0.1143 \times p_T + 92.14\%$
	FCHighPtCaloOnly	$E_T^{\text{cone20}} < \max(0.015 \times p_T, 3.5 \text{ GeV})$	-
	FCLoose	$E_T^{\text{cone20}}/p_T < 0.20$	$p_T^{\text{varcone20}}/p_T < 0.15$
	FCTight	$E_T^{\text{cone20}}/p_T < 0.06$	$p_T^{\text{varcone20}}/p_T < 0.06$
Photon	FixedCutLoose	$E_T^{\text{cone20}} < 0.065 \times E_T$	$p_T^{\text{cone20}}/E_T < 0.05$
	FixedCutTight	$E_T^{\text{varcone40}} < 0.022 \times E_T + 2.45 \text{ GeV}$	$p_T^{\text{cone20}}/E_T < 0.05$
	FixCutTightCaloOnly	$E_T^{\text{varcone40}} < 0.022 \times E_T + 2.45 \text{ GeV}$	-

4.3 Muon

After the muon (μ) in the ideal state is generated from the collision vertex, it passes through the ID and leaves track information, and passes through the calorimeter and leaves ionization energy loss. Finally, the track information is left again in the MS. Considering the small cross-section of muons, the long motion trajectories, and the geometric structure of ID, muons may not be able to leave significant features in all three sub-detection systems, so ATLAS has five common muon reconstruction strategies. to increase reconstruction efficiency.

4.3.1 Reconstruction of Muon

Reconstruction of the track in the muon spectrometer The 3.2.4 section of this article mentions that although there are only three layers of high-precision muon detectors (MDT and CSC) in the MS, each layer has multi-faceted detection units, so in theory each layer of detectors can detect the shorter tracks (segments) left by muons. The track reconstruction in the MS starts from these short tracks, and determines whether the hits of the multi-faceted detection units of each layer of detectors can constitute tracks through Hough transform, and excludes false hits caused by noise. Then, the muon trajectory is preliminarily established by fitting each group of three layers of short tracks with a quadratic function passing through the origin. The three-dimensional track information is then constructed in combination with the information of the detection units (RPC and TGC) used for triggers in the MS. Finally, the three-dimensional track information is fitted by the least squares method. The fitting will take into account the influencing factors such as the magnetic field configuration and the possible muon-detector material interaction, and finally the parameters describing the candidate track are obtained. After determining the candidate track, it is also necessary to traverse the hit points near the hit point of the candidate track to check whether changing the hit point can obtain a better reconstructed track. In addition, if two tracks share too many hit points, the track with lower quality will be removed from the candidate tracks [108].

Reconstruction of Muon

The five reconstruction strategies of muons correspond to five different results of the interaction between muons and detectors. The classification and reconstruction methods are as follows:

- **CB (Combined) muon:** This is the ideal muon reconstruction. In the region of $|\eta| < 2.5$, if the tracks of ID and MS can be described by the same set of track parameters, their hit information is used to fit a complete track from ID to MS. Since the muons will also pass through the detector at this time, the track fitting also takes into account the ionization energy loss information of the muons in the calorimeter. Since the track accuracy provided by ID is higher, the selection of the hit points in MS may be adjusted and refitted according to the fitting results. When $|\eta| > 2.5$, due to the geometric structure of ID, the corresponding ID track may not be found. At this time, the reconstruction will consider the hit points on the pixel and SCT instead of the track to repeat the above strategy. This kind of reconstructed muon is called SiF (Silicon-associated Forward) muon.

- **IO (Inside-out combined) muon:** For muons with low transverse momentum or tracks passing through the gap of MS, they may not leave tracks in MS. At this time, the IO strategy can improve its reconstruction efficiency. For ID tracks that cannot be matched to MS tracks, if at least three collision points that can form a "rough" track can be matched in MS and a good fitting result is obtained, they can also be candidates for IO muons. After obtaining the complete ID track, the collision point of MS and the information of the calorimeter ionization energy loss, the IO muon will be reconstructed by a method similar to the CB muon reconstruction.

- **ME (Muon-spectrometer extrapolated) muon:** Due to the structural limitations of the ID, the track reconstruction efficiency of the end cap part is low, so muons with a large $|\eta|$ have a probability of producing a complete MS track, but cannot produce a complete ID track. In this case, the ME strategy can improve its reconstruction efficiency. If the MS track cannot find a matching ID track, it will be extended to the beam to check the match with the vertex, thereby reconstructing a ME muon with a higher $|\eta|$.

- **ST (Segment-tagged) muon:** This reconstruction strategy is aimed at the case where there is a complete track in the ID and at least one complete short track in the MS. The reconstruction criterion is that the ID track is consistent with the short track of MS in terms of azimuth, and the track parameters of ID will be directly used to calculate the parameters of the reconstructed muon.

- **CT (Calorimeter-tagged) muons:** This situation is for muons that fail to leave tracks in MS. For example, MS has gaps in the region of $|\eta| < 0.1$, and muons in this range may not be detected. At this time, the complete ID track will be used to match the

signal of the minimum ionization energy loss in the calorimeter. If it can be matched, the track parameters of ID will be directly used to reconstruct the parameters of muons, but the candidate ID track needs to meet $p_T > 5$ GeV to reduce background contamination.

4.3.2 Identification and isolation of Muon

The main goal of muon identification is to mark out muons produced by hadron semilepton decay and heavy flavor hadron decay. This type of muon is called non-prompt muon. The background mentioned in this section refers to non-prompt muons. Since the track has a turn at the decay point during the hadron decay to muon, the track quality is poor and can be distinguished by the track quality. However, heavy flavor hadrons have a shorter lifetime and higher track quality, so they need to be distinguished by vertex reconstruction and isolation between ID and calorimeter. The input variables of muon identification can be generally divided into four categories. The first category is the requirements for the track, including the requirements for the ID hit point and the MS short track, where the MS short track requires at least three hit points in a layer of detectors. The second category is the matching of the ID track and the MS track. There are two variables used to describe the quality of the match. The first is the matching based on q/p measurement:

$$q/p \text{ compatibility} = \frac{|q/p_{ID} - q/p_{MS}|}{\sqrt{\sigma^2(q/p_{ID}) + \sigma^2(q/p_{MS})}} \quad (4-3)$$

The second is based on the measurement of p_T :

$$\rho' = \frac{|p_{T,ID} - p_{T,MS}|}{p_{T,CB}} \quad (4-4)$$

The third type of variables is the parameter performance of the trajectory after the overall fitting of the ID and MS hit points, which is generally calculated using the normalized χ^2 test and used to define the Tight working point. The fourth type is the requirements for the vertex of the reconstructed trajectory, which generally require $|d_0|/\sigma(d_0) < 3$ and $z_0 \sin \theta < 0.5\text{mm}$. The former is the accuracy requirement for vertex measurement, and the latter is the requirement that the vertex position should be close to the primary vertex.

Through the requirements of these four types of variables, five commonly used muon working points are finally defined, namely: Loose, Medium, Tight, High- p_T , and Low- p_T . Among them, Loose includes CT, ST, CB, and IO muons, so the reconstruction efficiency is the highest, but the background suppression performance is also the lowest, mainly for the analysis of multi-muon final states. Medium only includes ME, CB, and IO muons, so when it has a higher reconstruction efficiency, the background suppression performance is also better. Tight only includes CB and IO muons, and has

strict requirements for the χ^2 test of the track, so the reconstruction efficiency is low, mainly suitable for physical analysis where the background and signal are difficult to distinguish. The reconstruction efficiency of these three working points is shown in Figure 4-2 [108]. It can be found that even at the Tight working point, the efficiency can reach 90%. In addition, High- p_T only includes muons with $p_T > 100$ GeV of CB and IO identified by Medium. Since the higher the p_T of muons, the larger the curvature radius of the track and the lower the resolution, an independent working point is required to reconstruct high-momentum muons. When $p_T > 100$ GeV, the efficiency of the High- p_T working point can reach 80%, and the efficiency reaches the maximum at $p_T \sim 1$ TeV, about 99%, and then gradually decreases [108]. Low- p_T is designed for low-momentum muons. Low-momentum muons may not leave a complete track in MS, so this working point additionally requires that the track of ID cannot have a turn to suppress the muons from semi-lepton decay, and use selection conditions (cut-based) or multivariate analysis (MVA) to reduce the background and improve efficiency. For low transverse momentum muons with $p_T < 5$ GeV, the efficiency of this working point can reach above 86% [108].

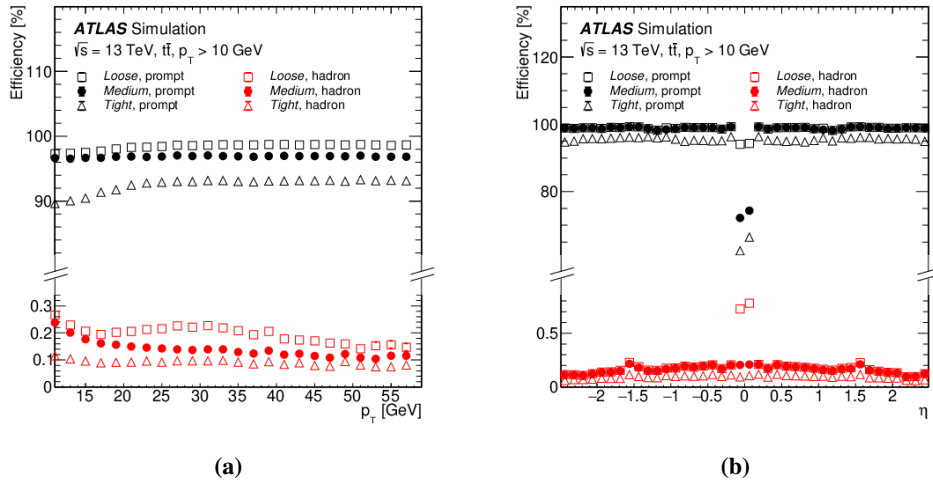


图 4-2 缪子 Loose、Medium、Tight 工作点的选择效率与 (a) p_T 和 (b) η 的关系 [108]。
Figure 4-2 The selection efficiencies of Loose, Medium, and Tight working point as a function of (a) p_T and (b) η [108].

The isolation standard of muons is similar to that of electrons/photons. It can be judged by the isolation of the track and the isolation of the response of the calorimeter, respectively. It can also be judged by combining the track and calorimeter information into a particle flow (PFlow) [109]. Table 4-2 [109] summarizes the selection conditions of commonly used isolation working points, where the rules of p_T and E_T are consistent with the definition of electrons/photons, indicating the energy sum of other tracks or calorimeters within the range of ΔR . The difference from the electron isolation is that

the definition of varcone30 is that when $p_T < 50$ GeV, $\Delta R = \min(10 \text{ GeV}/p_T, 0.3)$, otherwise $\Delta R = 0.2$. In general, when muon $p_T > 50$ GeV, the selection efficiency of each working point is close to 100%. When $p_T \sim 10$ GeV, the efficiency of the Tight working point is only about 65%, but the Loose working point is still maintained above 80%.

表 4-2 常用的缪子的孤立度工作点, p_T 表示重建缪子的横动量, 单位为 GeV [109]。

Table 4-2 Commonly used muon isolation working points, where p_T represents the transverse momentum of the reconstructed muon in the unit of GeV [109].

Working point	Isolation	Constrain on track's p_T
PflowLoose PflowTight	$(p_T^{\text{varcone30}} + 0.4 \cdot E_T^{\text{neflow20}}) < 0.16 \cdot p_T$ $(p_T^{\text{varcone30}} + 0.4 \cdot E_T^{\text{neflow20}}) < 0.045 \cdot p_T$	$p_T > 500 \text{ MeV}$
Loose Tight	$p_T^{\text{varcone30}} < 0.15 \cdot p_T, E_T^{\text{topocone20}} < 0.3 \cdot p_T$ $p_T^{\text{varcone30}} < 0.04 \cdot p_T, E_T^{\text{topocone20}} < 0.15 \cdot p_T$	$p_T > 1 \text{ GeV}$
HightPtTrackOnly TightTrackOnly	$p_T^{\text{cone20}} < 1.25 \text{ GeV}$ $p_T^{\text{varcone30}} < 0.06 \cdot p_T$	$p_T > 1 \text{ GeV}$

4.4 Jet

The jet is the most dominant end-state product of the ATLAS experiment. The source of the jet is not only the quarks and gluons produced from the primary vertex, but also the partons of the UE process. After the hadronisation process, these particles produce a large number of hadrons, and each hadron leaves clusters inside the quantum energy apparatus. So reconstructing an injection is reconstructing a collection of multiple clusters. In general, the hadrons produced by the injection are more concentrated in the angular distribution, and form multiple concentrated clusters in the quantum energiser. Charged hadrons also leave trajectory information within the ID, which is a commonly used feature for jet reconstruction. The ATLAS experiment uses a particle flow algorithm to reconstruct the clusters produced by the charged hadrons. The jet is then reconstructed using the anti- k_t algorithm [110] provided by the FAST JET software [111].

4.4.1 Reconstruction of Jet

This section will focus on the ParticleFlow-based anti- k_t algorithm. In this paper, the reconstruction of clusters is introduced in section 4.2.1. electrically neutral hadrons can only leave cluster information inside the quantum energiser. However, charged hadrons can leave trails within the ID. Considering that the ID is more energy-resolved, the particle flow algorithm that combines the trail information and the quantum energiser information is proposed. Figure 4-3 [112] summarises the steps of the particle

flow algorithm, starting with the selection of trails that pass through the Tight working point but are not reconstructed as electrons or muons. An additional requirement is that the transverse momentum of the trajectory be below 40 GeV to prevent the end-state hadrons from being boosted, resulting in too low an isolation of the deposition energy. Next, the trajectories and clusters are matched by η and ϕ angles, and cluster energies are required to be higher than 10% of the trajectory momentum. Prior to performing the reconstruction, the MC simulation-based study pre-obtained a correspondence between the trajectory momentum and the cluster deposition energy in the range of $\Delta R = 0.4$. This correspondence will be used to obtain the expected cluster deposition energy when performing the reconstruction. Considering that multiple clusters can be produced by the cluster shot of a single hadron, a comparison of the cluster energies with the expected deposition energies will determine whether other clusters in the range $\Delta R = 0.2$ need to be included in the reconstruction of the cluster shot. If the expected energy is higher than the energy of the cluster shot, the other clusters will be included in the cluster shot reconstruction, and conversely, energy removal will be required. The energy removal will expand from the probe unit with the highest deposited energy density as the centre centre outwards until the energy of the cluster to be removed is higher than the remaining expected energy, at which point only the energy deposited by the cluster equal to the remaining expected energy will be removed. The residual portion of the cluster after completing the removal step is compared to the error value of the expected energy, and if the residual portion is less than 1.5 times the error value of the expected energy, the then the removal of the residual portion is considered to belong to the reconstructed cluster shot, and vice versa, the residual portion is considered to be caused by another cluster shot, and the residual portion is put into the iteration again. This step is performed for several rounds of iterations to obtain multiple particle streams with matching cluster shots and trajectories.

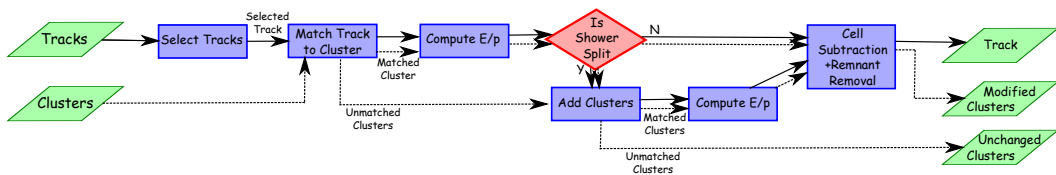


图 4-3 粒子流的重建流程 [112]。

Figure 4-3 Workflow of ParticleFlow reconstruction algorithm [112].

The anti- k_t algorithm uses particle flows and clusters to reconstruct the jet. The core of the algorithm is to determine whether the difference in transverse momentum (k_T) and spatial angle (ΔR) between the i th and j th particle flows/clusters can originate from the same jet. The specific definition is as follows [110]:

$$d_{i,j} = \min(k_{Ti}^{2p}, k_{Tj}^{2p}) \frac{\Delta R_{ij}^2}{R^2} \quad (4-5)$$

Among them, p and R need to be determined in advance. The jet reconstruction algorithm of the ATLAS experiment uses $p = -1$ and $R = 0.4$. $p = -1$ is the source of "anti" in the algorithm. The anti- k_t algorithm can better reconstruct the jet from the high background, but its poor ability to expand clusters makes it unsuitable for studying the structure of the jet [110]. When $p = 1$, this algorithm is called the k_t algorithm, and its performance is poor in the environment of high UE and pile-up effect [110]. When $p = 0$, the Cambridge/Aachen algorithm is regressed, which is suitable for studying the structure of the jet [110]. In addition, the Jet used in general analysis needs to be marked by Jet vertex (jet-vertex-tagger, JVT), which is a strategy based on multivariate analysis, the purpose of which is to suppress the background caused by the pile-up effect [113].

Since the jet is not a fundamental particle, but a phenomenon of quarks or gluons after hadronization, its reconstruction depends on the jet model and reconstruction strategy. Therefore, the reconstruction algorithm needs to perform multiple energy scales [112, 114]. The energy scale of the jet mainly includes the following four links [114]: energy scale that removes the influence of the pile-up effect with μ and the number of primary vertices as parameters; Correct the energy response of the reconstructed jet to the energy response of the Truth-level to obtain more accurate energy and direction reconstruction; Perform global order correction through the information of ID and MS to deal with the energy leakage caused by the insufficient thickness of the hadron calorimeter; After the above three corrections, in order to prevent the gap between Data and MC, the Data will be quickly corrected (in-situ calibration) to approach MC.

4.4.2 Labelling of b -jet

The lifetime $c\tau$ of hadrons containing b quarks can reach $450 \mu\text{m}$, which will produce a displaced vertex far away from the primary vertex. The characteristics of the displaced vertex can be used to mark the reconstructed jets originating from b hadrons, and this mark is called b -tag. The background of b -tag is the heavy hadron jet containing c quarks and the light hadron jet without c and b . ATLAS adopted low-level strategies and high-level multivariate analysis strategies during Run2 to achieve b jet labeling. The low-level strategy makes decisions based on the likelihood ratio. According to the reconstruction objectives, the low-level strategy can be divided into three types: (1) IP2D and IP3D [115]: the input variables are the collision parameters of the track; (2) SV1 [116]: the quality of the least squares fitting is used as the track matching standard to reconstruct the shifted vertices; (3) JETFITTER's topological multi-vertex algorithm [117]: the longitudinal development of the jet is reconstructed based on the Kalman filter method to obtain the structure of the cascade decay. The high-level strategies are mainly the MV2 strategy using the Boosted Decision Tree (BDT) model [115] and the DL1 strategy using NN [115], their input variables use the output variables of

the low-level strategies, and four working points are defined according to the marking efficiency of b injection, with efficiencies of 85%, 77%, 70% and 60% [118] respectively.

4.5 Tau

The tau (τ) is a special lepton. Its large mass can make the tau decay to the hadron final state (τ_{had}) dominated by π mesons, or decay to the lepton final state (τ_{lep}). At the same time, due to its short lifetime $c\tau \sim 80 \mu\text{m}$, it decays rapidly within the ID, so τ can only be reconstructed by the final state hadrons or leptons. This section will introduce the τ_{had} reconstruction strategy of the ATLAS experiment. Although τ_{had} has a short lifetime, it can still produce a small distance displacement vertex. At the same time, the τ_{had} jet structure contains one or three $\pi^\pm$ mesons, which is also one of its main characteristics.

4.5.1 Reconstruction of Tau

The basic process of τ_{had} reconstruction algorithm is to first determine the direction of τ_{had} , reconstruct the τ vertex (Tau vertex, TV) through the direction, find the track left by $\pi^\pm$ in the ID according to the vertex, and finally perform energy calibration [119]. Since τ_{had} mainly decays to a single-hadron final state (1-prong) or a three-hadron final state (3-prong), in which the hadrons are mainly $\pi^\pm$ and $K^\pm$ mesons, the reconstruction of τ_{had} depends on the jet. The "seed" used for τ_{had} reconstruction is $p_T > 10 \text{ GeV}$, $|\eta| < 2.5$, and anti- k_t jets in the "crack" region of the calorimeter ($1.37 < |\eta| < 1.52$) are not considered. The reconstruction algorithm first uses the cluster deposition energy of the injection as the weight, and the weighted average position from the injection vertex to the cluster deposition energy direction is defined as the rough τ_{had} direction. In the range of τ_{had} direction as the axis and $\Delta R < 0.2$ as the angle, there are usually multiple tracks with $p_T > 0.5 \text{ GeV}$. By using a method similar to reconstructing the primary vertex, these tracks can be reconstructed into multiple vertices. Among them, the vertex with the largest sum of the p_T scalar squares of the vertex-connected tracks is taken as the τ vertex. Figure 4-4 [120] shows the relationship between the selection efficiency and p_T of the $\gamma^* \rightarrow \tau\tau$ process 1-prong and 3-prong τ through τ vertex and primary vertex for track selection. It can be seen that compared with using primary vertex to reconstruct τ , the efficiency of using independent τ vertex reconstruction algorithm is higher, especially for low momentum τ . After constructing the TV and τ_{had} directions, a recurrent neural network (RNN) algorithm will classify all tracks with $\Delta R < 0.4$. The tracks are mainly divided into four categories. The first two categories are core tracks (Core Track) and isolated tracks (Isolation Track, IT). The main source of core tracks is the tracks of $\pi^\pm$ mesons related to TV, also known as τ tracks (Tau Track, TT), while the source of isolated tracks is hadrons unrelated to τ_{had} . The third type of track is called

conversion tracks (CT). Considering that photons can interact with detector materials to produce electrons, electrons are one of the main backgrounds of τ_{had} reconstruction, and the π^0 of τ_{had} decay mainly decays to the two-photon final state, it is particularly important to identify the tracks of electrons converted from photons. The tracks of such electrons are called conversion tracks. The last category is all background tracks that are not classified as IT and CT. These are called fake tracks (FT), and their main source is the pile-up effect. Figure 4-5 [120] shows the confusion matrix of the track classification algorithm, and it can be found that the track classification efficiency is very high. Since the τ particle not only produces $\pi^\pm$ when it decays, but also produces particles such as ν that cannot be measured by the detector, the deposited energy of the hadron cannot reflect the energy of the τ_{had} , so the energy scale is very important.

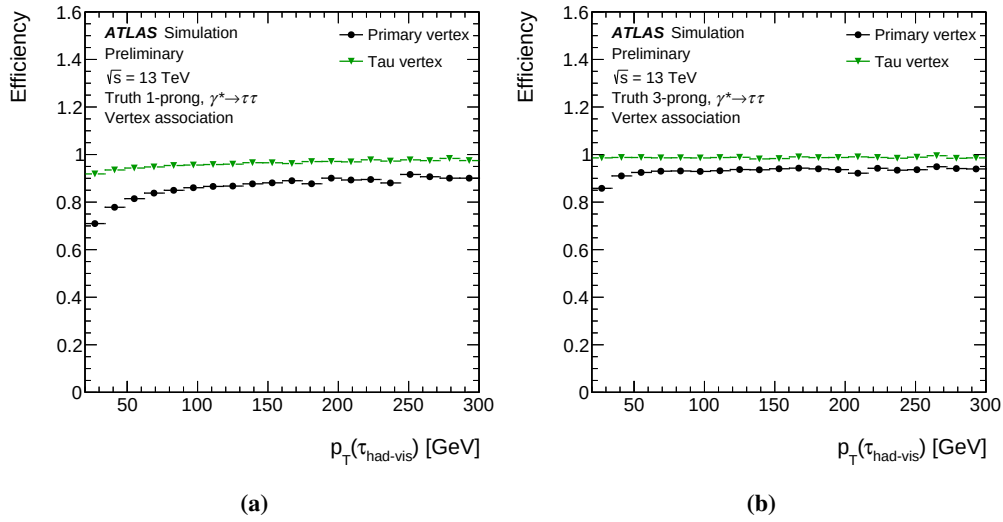


图 4-4 $\gamma^* \rightarrow \tau\tau$ 过程的末态 τ 通过 τ 顶点和初级顶点进行径迹选择的选择效率与 p_T 的关系 [120], (a) 为 1-prong τ , (b) 为 3-prong τ 。

Figure 4-4 The efficiency to select the correct τ production vertex using TJVA or the default primary vertex in $\gamma^* \rightarrow \tau\tau$ events as a function of p_T for truth 1-prong τ (left) and truth 3-prong τ (right) [120].

The ATLAS τ_{had} energy scale has two steps. The first step (baseline) is to correct for the pile-up effect and the response of the calorimeter [119], which can be expressed as

$$E_{\text{calib}} = \frac{E_{\text{LC}} - E_{\text{pileup}}}{R(E_{\text{LC}} - E_{\text{pileup}}, |\eta|, n_p)} \quad (4-6)$$

The numerator represents the effect of the pileup effect subtracted from the cluster deposited energy, and the denominator is the response of the calorimeter, which is a function of the corrected deposited energy, the η angle, and the number of prongs. After simulation, E_{pileup} can be expressed as a function of the number of primary vertices, the η angle, and the number of prongs:

$$E_{\text{pileup}} = A(|\eta|, n_p) \times (N_{\text{PV}} - \langle N_{\text{PV}} \rangle) \quad (4-7)$$

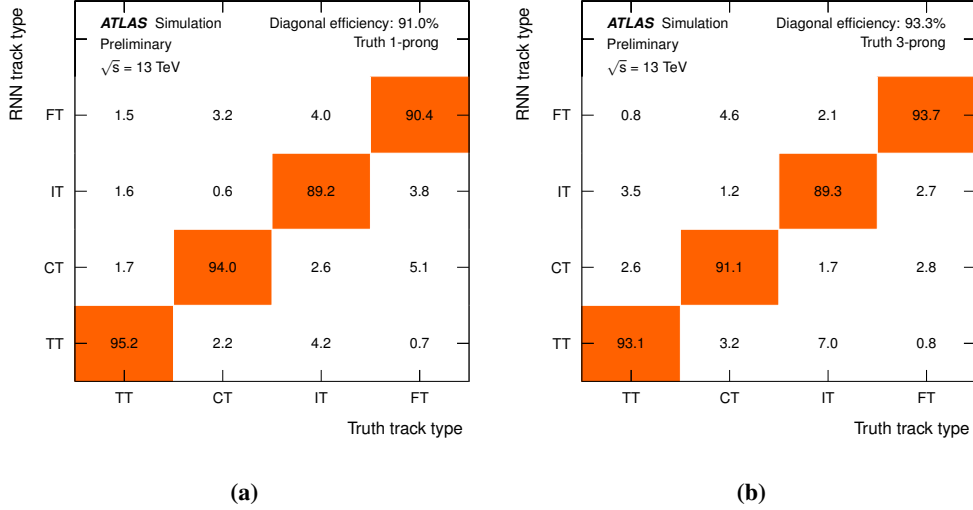


图 4-5 $\gamma^* \rightarrow \tau\tau$ 过程的混淆矩阵，横轴为径迹真实的类型，纵轴为基于 RNN 算法的分类结果 [120]，(a) 为 1-prong τ ，(b) 为 3-prong τ 。

Figure 4-5 The confusion matrices of the classification of a track by the RNN and its truth classification, measured with $\gamma^* \rightarrow \tau\tau$ events for truth 1-prong τ (left) and truth 3-prong τ (right) [120].

The A function is obtained through MC simulation. The response function of the calorimeter is obtained by calculating the average value of the Gaussian-like distribution of $(E_{LC} - E_{pileup})/E_{true}^{vis}$ in each bin, where E_{true}^{vis} is the τ_{had} deposition energy of the Truth-level, and the distribution in each bin is also from MC simulation. The second step of energy scaling uses the boosted regression tree (BRT) algorithm [121], the input variables are N_{PV} , μ , cluster structure related variables and track related variables, and the training samples are MC simulation samples of $\gamma^*/Z \rightarrow \tau\tau$. The reconstructed τ_{had} is corrected through the trained model to make its energy close to the real energy. Figure 4-6 [121] shows the relationship between energy resolution and p_T after baseline and baseline+BRT, respectively. It can be found that the BRT algorithm greatly improves energy resolution.

4.5.2 Identification of Tau

The identification of τ_{had} is divided into two parts. The first part is to distinguish it from electrons [121], because the charged tracks of electrons and the clusters deposited in the calorimeter are consistent with the characteristics of 1-prong τ ; the second part is to distinguish it from non- τ_{had} -generated jets. ATLAS uses the Recurrent Neural Network (RNN) algorithm [122].

The way to distinguish electrons from 1-prong τ is close to the requirement for isolation. All τ_{had} with a reconstructed electron in the range of $\Delta R < 0.4$ will be rejected. The section 4.2.1 of this chapter mentions that the reconstruction criterion of electrons depends on the likelihood function. In the algorithm for distinguishing

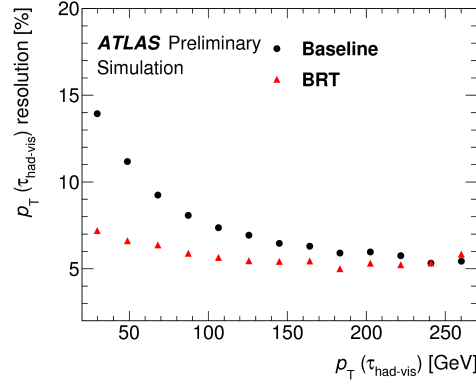


图 4-6 通过第一步能量刻度 (baseline) 和通过第一、二步能量刻度 (BRT) 的 τ_{had} 能量分辨 [121]。

Figure 4-6 The τ_{had} energy resolution of Baseline energy scale and Baseline+BRT energy scale [121].

electrons from 1-prong τ , the working point of the likelihood function for reconstructing electrons is adjusted to make the 1-prong τ pass efficiency reach 95% [121]. The specific parameters of this working point will fluctuate according to different p_T and η ranges.

τ_{had} The input parameters of the RNN algorithm used for identification take into account the basic information of the candidate's track and cluster, as well as the advanced variables calculated based on the basic information, such as the maximum spatial angle between the injection's transverse momentum and the track, etc. [122]. The training samples use the MC simulation samples of $\gamma^* \rightarrow \tau\tau$ as the background and the di-jet process as the background, and train the 1-prong and 3-prong τ separately, and finally determine four working points based on the selection efficiency, namely Very Loose, Loose, Medium and Tight. The passing efficiency of these four working points for 1-prong (3-prong) τ is 95% (95%), 85% (75%), 75% (60%) and 60% (45%) from high to low. Figure 4-7 [122] shows the distribution of 1-prong and 3-prong τ efficiencies with p_T and η , respectively. It can be found that the efficiency in most regions is weakly dependent on η of p_T , but the efficiency will also decrease when p_T is extremely low. Figure 4-8 [120] shows the distribution of 1-prong and 3-prong τ identification efficiency and reconstruction + identification efficiency with p_T of the $\gamma^* \rightarrow \tau\tau$ process, as well as the distribution of 1-prong and 3-prong τ rejection rate with p_T of the di-jet process, where the rejection rate is defined as the inverse of the efficiency. It can be found that the reconstruction + identification efficiency of the 3-prong τ_{had} decreases with the increase of p_T , while the rejection rate of the false reconstruction τ_{had} increases with the increase of p_T .

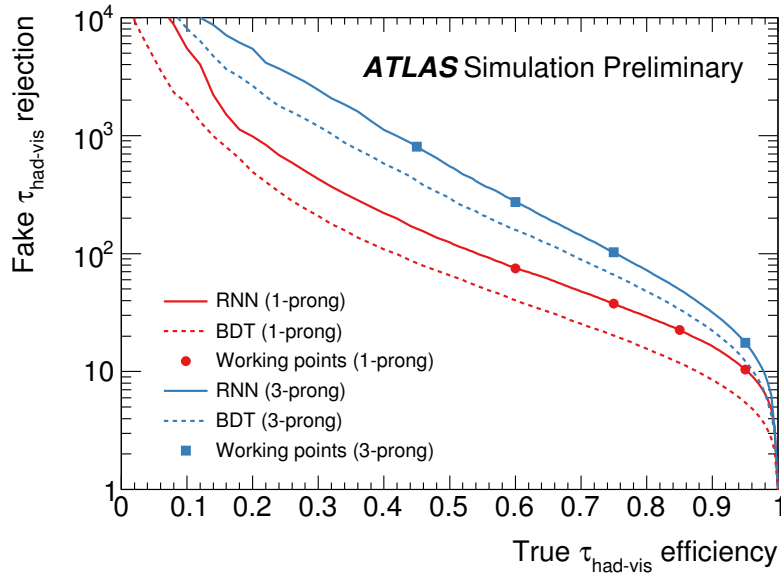


图 4-7 τ_{had} 鉴别工作点的选择效率和本底压制率 [122]。

虚线为此前基于 BDT 模型的分布，实线为目前基于 RNN 模型的分布，工作点从左至右分别为 tight、medium、loose 和 veryloose。

Figure 4-7 Rejection power for misidentified τ_{had} depending on the true τ_{had} efficiency [122].

Shown are the curves for τ_{had} candidates using the RNN-based (full line) and the BDT-based (dashed line) identification algorithms. The markers indicate the four defined working points tight, medium, loose and veryloose.

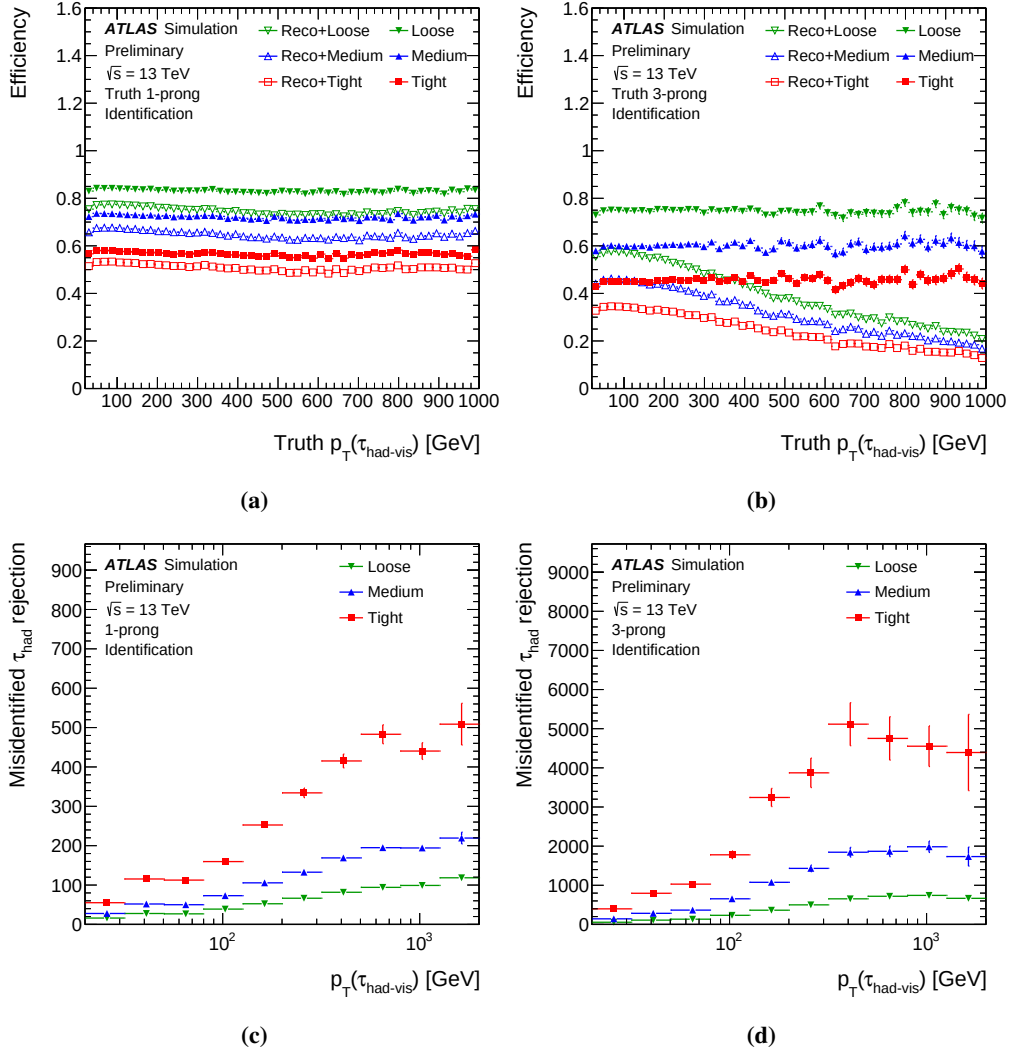


图 4-8 τ_{had} 鉴别效率、重建 + 鉴别效率和误重建 τ_{had} 拒绝率随 p_T 的分布 [120]。
(a) (b) 分别为 1-prong 和 3-prong 的鉴别效率和重建 + 鉴别效率，所用样本为 $\gamma^* \rightarrow \tau\tau$ 过程。
(c) (d) 分别为 1-prong 和 3-prong 的误重建 τ_{had} 拒绝率，定义为鉴别效率的倒数，所用样本为 di-jet 样本。

Figure 4-8 [Efficiency for τ_{had} identification, combined reconstruction + identification efficiency, and the inverse of the efficiency (rejection) as a function of the τ_{had} p_T [120].

Efficiency for τ_{had} identification, combined reconstruction + identification efficiency for 1-prong (a) and for 3-prong (b), and the inverse of the efficiency (rejection) for misidentified 1-prong and 3-prong τ_{had} candidates from di-jet events as a function of the τ_{had} p_T for 1-prong (c) and 3-prong (d).

4.6 In-situ Tau Energy Scale Correction

The τ_{had} energy scale at the reconstruction algorithm level uses MC simulation information to correct the deviation of the reconstruction algorithm. In addition, the complete reconstruction of τ_{had} requires another in-situ energy correction (in-situ TES) to correct the gap between the experimental data and the MC simulation sample. The purpose of In-situ TES is to correct the energy gap between the experimental data and the MC sample after the same reconstruction algorithm, and obtain a correction parameter for the MC simulation. In-situ TES uses a "tag and probe" method based on the $Z \rightarrow \tau_{\text{had}}\tau_{\mu}$ process: tag the μ from the τ leptonization decay through the single muon trigger to select the τ_{had} from the τ hadronization decay, and obtain the correction parameter by comparing the system invariant mass m_{vis} of the τ_{had} and μ of the experimental data and the MC sample. The variables for parameterizing τ_{had} in this study are the number of prongs (1-prong or 3-prong), whether $|\eta|$ is in the central region or the forward region, m_{vis} which is highly correlated with p_T , and the identification working point (loose, medium, tight).

Table 4-3 summarizes the definitions of the signal region, W+jetsprocess control region (W-CR) and multi-jet process control region (QCD-CR) in this study, where $\Sigma \cos \Delta\phi = \cos \Delta\phi(\mu, E_T^{\text{miss}}) + \cos \Delta\phi(\tau_{\text{had}}, E_T^{\text{miss}})$ is the angle between τ_{had} or μ and E_T^{miss} . The μ used for "tag" in this analysis needs to pass through a single muon trigger to reach the medium identification working point and be in the barrel region ($|\eta| < 2.5$). The isolation requirements are different in the signal region (SR) and the control region (CR). τ_{had} requires to carry unit charge, p_T is higher than 20 GeV, and pass through crack region veto. Since the final state does not require the participation of b jet, both SR and CR require b -jet veto. The target signal of SR is $Z \rightarrow \tau_{\text{had}}\tau_{\mu}$, so μ in SR is required to meet the isolation requirement and have the opposite charge to τ_{had} . In addition, considering that W boson decays into muons and neutrinos, and neutrinos constitute E_T^{miss} , the W+jetsprocess is suppressed by requiring the transverse mass of the μ and E_T^{miss} system to be lower than 60 GeV. Considering that the misreconstruction of W+jetsand multi-jet processes τ_{had} comes from the jets, the correlation between the jets and E_T^{miss} is low and the angle is large, so SR further improves the signal purity by requiring $\Sigma \cos \Delta\phi > -0.2$.

The main background in SR is the W+jetsprocess, the multi-jet final state produced by QCD, the top quark related process and the multi-bosonprocess. The τ_{had} of the first two processes is most likely to come from the jet misreconstruction, so the semi-data-driven method is used to estimate their background. The estimation of the W+jetsprocess adopts the method of obtaining correction parameters in the control region to correct the W+jetscontent in SR and QCD-CR. The correction parameter is $k_{\text{W+jets}}^{\text{SS/OS}} = (\text{Data} - \text{MC}_{\text{not W+jets}})^{\text{SS/OS}} / \text{MC}_{\text{W+jets}}^{\text{SS/OS}}$. The estimation of the multi-jet pro-

cess adopts the SS-OS method. Considering that the correlation between μ and the jet misreconstruction τ_{had} is low, the multi-jet process of SS is used to estimate the distribution of the OS process. Considering the residual charge correlation, the background of OS process is more than that of SS process, so it is necessary to obtain the ratio of μ and τ_{had} of the same sign and the opposite sign in QCD-CR, so as to use the same sign multi-jet process to estimate the contribution of the multi-jet process in the signal area of the opposite sign. The number of multi-jet process events is obtained by removing the contribution of other background processes in the experimental data. W-CR is similar to SR, requiring the final state μ to meet the isolation requirement, and requiring the transverse mass of the μ and $E_{\text{T}}^{\text{miss}}$ system to be higher than 60 GeV and $\Sigma \cos \Delta\phi < 0$ to improve the purity, and requiring $E_{\text{T}}^{\text{miss}} > 30$ GeV to further reduce the content of multi-jet processes with lower $E_{\text{T}}^{\text{miss}}$. The definition of QCD-CR selects the cases where μ does not meet the isolation condition, thereby selecting the cases with stronger jet activity, and the requirements for other variables are relatively simple to increase the statistics.

表 4-3 In-situ TES 的信号区 (SR)、W+jets 过程控制区 (W-CR) 和多喷注过程控制区 (QCD-CR) 的定义。

Table 4-3 Signal region (SR), W+jetscontrol region (W-CR), and multi-jet control region (QCD-CR) definitions of In-situ TES.

Selection	Signal Region	W+jetsControl Region	Multi-jet Control Region
μ Isolation (PflowTight_VarRad)	pass	pass	fail
μ - τ_{had} Charge	OS	OS SS	OS SS
b -jet Tag(DL1dv01, $\epsilon = 70\%$)		b -jet veto	
$m_{\text{T}}(\mu, E_{\text{T}}^{\text{miss}})$	< 60 GeV	> 60 GeV	-
$E_{\text{T}}^{\text{miss}}$	-	> 30 GeV	-
$\Sigma \cos \Delta\phi$	> -0.2	< 0	-
m_{vis}	1-prong central: $\in (46, 86)$ GeV 1-prong forward: $\in (50, 90)$ GeV 3-prong: $\in (50, 92)$ GeV	$\in (40, 90)$ GeV	

After the background estimation, the in-situ TES uses the least squares fitting method to calculate the degree of correction for the MC sample. This analysis introduces the TES correction parameter α acting on τ_{had} to correct the p_{T} distribution: $p_{\text{T}} \rightarrow (1 + \alpha)p_{\text{T}}$, and keeps the related variables of μ unchanged to prevent repeated corrections, so that the correction of m_{vis} is obtained as:

$$m_{\text{vis}} \rightarrow \sqrt{1 + \alpha} \cdot m_{\text{vis}} \quad (4-8)$$

The least squares fitting based on the m_{vis} distribution can be written as:

$$\chi^2(\alpha, f) = \sum_i \frac{(N_i^{\text{Data}} - f N_i^{\text{sig}}(\alpha) - N_i^{\text{bkg}})^2}{(\sqrt{N_i^{\text{Data}}})^2 + f^2(\Delta N_i^{\text{sig}}(\alpha))^2 + (\Delta N_i^{\text{bkg}})^2} \quad (4-9)$$

Where $N_i^{\text{Data/sig/bkg}}$ is the number of cases of experimental data, true τ_{had} (truth τ_{had}) and misreconstructed τ_{had} in the i th bin in the m_{vis} distribution. f is a floating parameter used to reduce the impact of the overall gap between experimental data and MC samples from other aspects on TES correction, such as the gap in identification efficiency between experimental data and MC samples. α is only applied to all truth τ_{had} , and most of the truth τ_{had} comes from the $Z \rightarrow \tau_{\text{had}}\tau_{\mu}$ process. $\Delta N_i^{\text{sig/bkg}}$ is the statistical error and background estimation error of the corresponding process. The fitting of in-situ TES is divided into two steps. The first step is to scan the working space where α is in the range of $[-2, 2]\%$, and the step length of scanning α is 0.1%. For each α_{fixed} , the optimization of $\chi^2(\alpha_{\text{fixed}}, f)$ adopts the gradient descent method and combines it with momentum optimization. Finally, the minimum $\chi^2(\alpha_{\text{fixed}}, f_{\text{min}})$ corresponding to α_{fixed} is obtained. The fitting input parameters of the second step are the data points with α_{fixed} as the horizontal coordinate and the corresponding minimum $\chi^2(\alpha_{\text{fixed}}, f_{\text{min}})$ as the vertical coordinate. A quadratic function can be obtained by fitting these data points by the least squares method. The horizontal coordinate of the minimum point of the quadratic function is the final correction parameter α_{nom} , and the corresponding minimum value is recorded as χ_{min}^2 . The horizontal coordinate value of the point on the quadratic function with the vertical coordinate equal to $\chi_{\text{min}}^2 + 1$ is taken as the fitting error of α .

This study performed fitting measurements for different inclusive identification working points, prong numbers, and $|\eta|$ regions. Since the number of prongs and $|\eta|$ have a great influence on the reconstruction of τ_{had} , this study also optimized the m_{vis} distribution range and bin width for different prongs and $|\eta|$ regions. By fitting different combinations of m_{vis} distribution ranges and bin widths, and selecting the combination with the lowest χ^2/NDF , the optimal fitting scheme is determined, where NDF is the degree of freedom of fitting, which is the number of bins plus two in this study. Finally, for the 1-prong central region, the m_{vis} distribution range is [46, 86] GeV, and the width is 8 GeV; the range of the 1-prong forward region is [50, 90] GeV, and the width is 8 GeV; the range of all 3-prong regions is [50, 92] GeV, and the width is 6 GeV. In previous studies, the fitting range and bin width were considered as part of the error. This study optimized this, so the change in the fitting scheme is not considered as a systematic error.

The systematic errors of In-situ TES mainly include the following parts: the error of W+jets correction parameters, the error of transfer parameters of SS-OS method,

the error of Run2 total brightness, the error of pile-up effect, the systematic error of jet reconstruction, the systematic error of b -jet labeling, the systematic error of muon reconstruction and the error of single muon trigger. Since it is difficult to add systematic errors to the fitting by least squares fitting, this study adopts the following method to calculate the impact of each systematic error on α : For each error, by modifying the case weight, m_{vis} becomes the distribution under $\pm 1\sigma$ systematic error, Repeat the least squares fitting for the distribution under $+1\sigma$ error and -1σ error to obtain the systematic error correction parameters $\alpha_{+\text{syst}}$ and $\alpha_{-\text{syst}}$, Finally, the error direction and error value with a larger difference in $|\alpha_{\pm\text{syst}} - \alpha_{\text{nom}}|$ are taken as the systematic error. The experiment found that the most important systematic error was the error of spraying reconstruction.

Figures 4-9 and 4-10 show the distribution of m_{vis} in the forward and central regions of 1-prong and 3-prong under medium respectively. It can be found that the SM process after fitting is in good agreement with the experimental data, and χ^2/N_{bins} is less than 1. The difference between the SM process and the experimental data is within the error range. Figure 4-11 shows the distribution of α under loose, medium and tight respectively. It can be found that the correction parameters under different IDs are relatively close, and the difference between the correction parameters under different IDs is regarded as part of the system error. The α of τ_{had} of 1-prong is close to 0%, while the α of 3-prong is larger, higher than 1%, which may be because the MC simulation of multiple $\pi^\pm$ mesons has a certain gap with the experimental data.

This study adopted the least squares fitting method and treated all systematic errors as independent distributions for independent fitting, so the research process was more complicated. This study later attempted to use the maximum likelihood fitting based on the Morphing method [123]. The Morphing method is an interpolation method that parameterizes the template of a discrete variable into a distribution function that depends on this variable. Through the Morphing method, α acting horizontally on the m_{vis} distribution and other systematic errors acting on the m_{vis} distribution are put into the same likelihood function with f , thereby associating α , systematic errors and f , and obtaining the fitting result by minimizing the likelihood function. The maximum likelihood fitting based on Morphing uses the TRExFitter software package [124]. The experimental results of the Morphing method are close to those based on the least squares fitting method:

The result of the 1-prong central area is $\alpha = -0.56^{+0.09}_{-0.13}\%$; The result of the

1-prong forward area is $\alpha = -0.22^{+0.06}_{-0.08}\%$; The result of the 3-prong central area is

$\alpha = 0.75^{+0.10}_{-0.18}\%$; The result of the 3-prong forward area is $\alpha = 0.59^{+0.28}_{-0.14}\%$ However,

the experiment did not use the Morphing method in the end. The main reasons are as

follows: due to the limited computational performance, the analysis did not use all the systematic errors, and the overall systematic error was low, which resulted in the gap between the SM process and the experimental data being unable to be covered by the error. This ultimately resulted in the large pulling of the SF error of Wjets, the TF error of the SS-OS method, and other experimental errors, which were highly correlated.

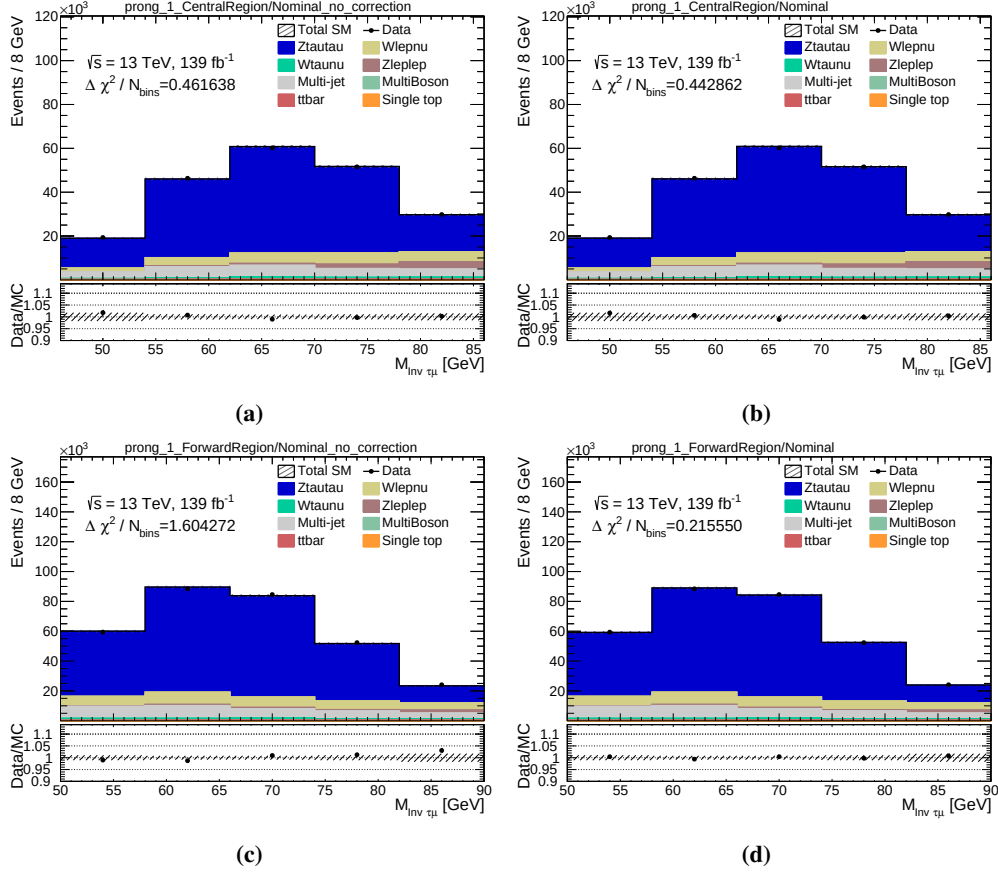


图 4-9 Medium 工作点下, 1-prong 的中心区域、前向区域 m_{vis} 的拟合前、后分布。左列 (a) 和 (c) 为拟合前分布, 右列 (b) 和 (d) 为拟合后分布, (a-b) 为 1-prong 中心区域, (c-d) 为 1-prong 前向区域。

Figure 4-9 Pre-fit and post-fit dis-

tributions of m_{vis} for the 1-prong central and forward regions of Medium working point.

The left column, (a) and (c), shows the pre-fit distributions, and the right column, (b) and (d), shows the post-fit distributions. (a-b) are for the 1-prong central region, and (c-d) are for the 1-prong forward region.

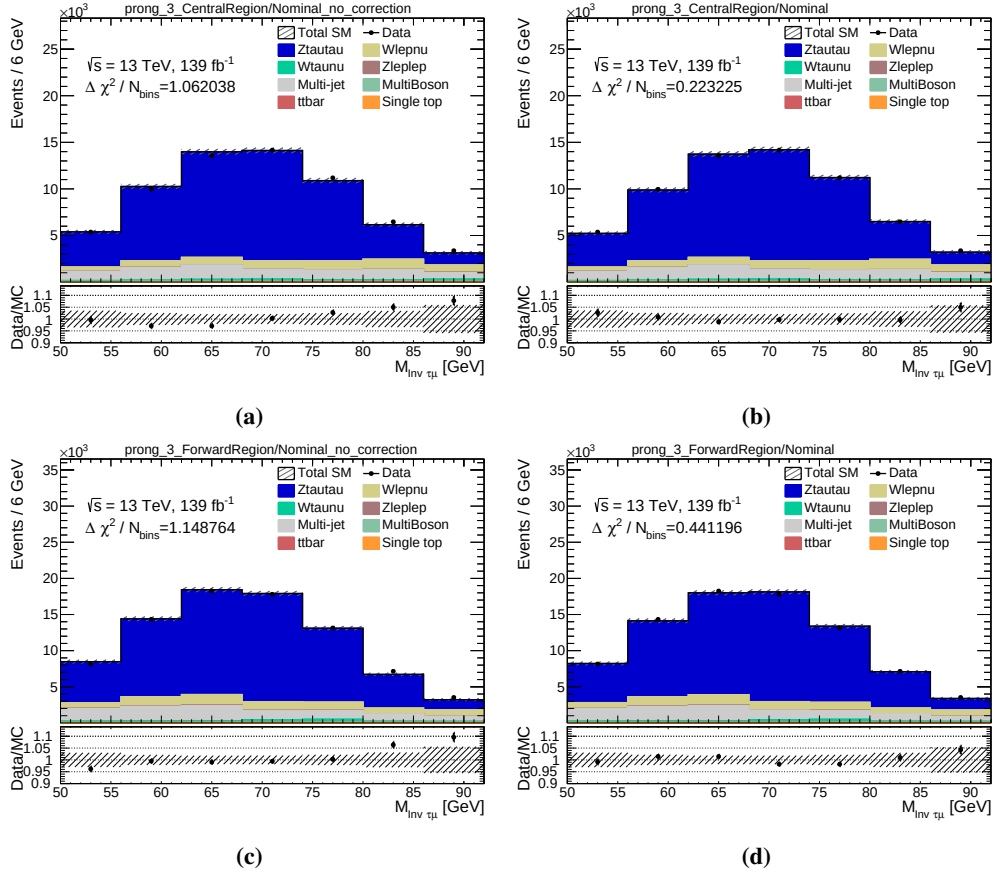


图 4-10 Medium 工作点下，3-prong 的中心区域、前向区域 m_{vis} 的拟合前、后分布。左列 (a) 和 (c) 为拟合前分布，右列 (b) 和 (d) 为拟合后分布，(a-b) 为 3-prong 中心区域，(c-d) 为 3-prong 前向区域。

Figure 4-10 Pre-fit and post-fit distributions of m_{vis} for the 3-prong central and forward regions of Medium working point.
The left column, (a) and (c), shows the pre-fit distributions, and the right column, (b) and (d), shows the post-fit distributions. (a-b) are for the 3-prong central region, and (c-d) are for the 3-prong forward region.

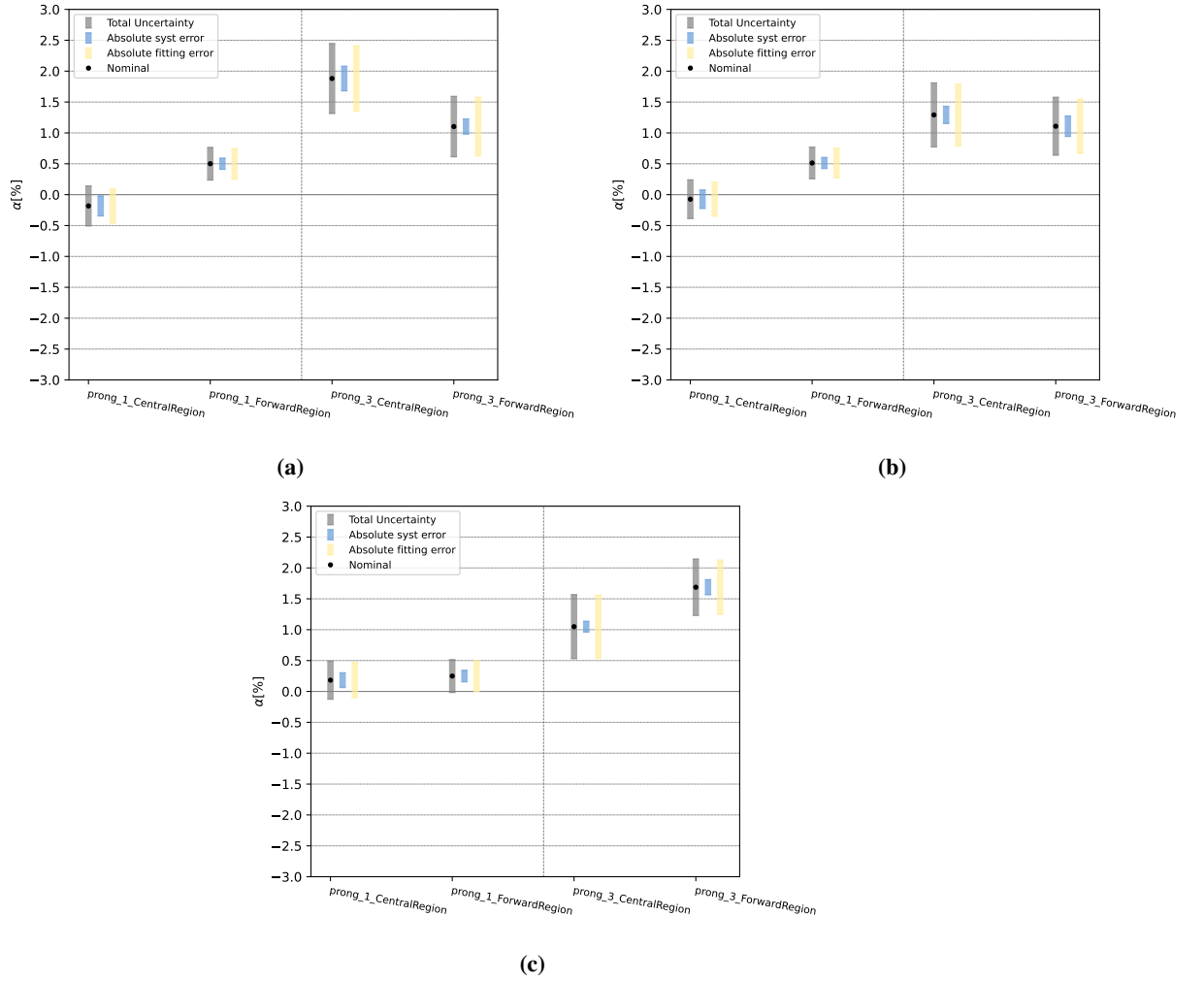


图 4-11 (a) Loose、(b) Medium 和 (c) Tight 鉴别工作点下的 in-situ TES 拟合结果总结。
 Figure 4-11 Summary of the in-situ TES scale factors for (a) Loose, (b) Medium, and (c) Tight working point.

4.7 Missing Transverse Energy

This thesis introduces the definition of E_T^{miss} under ideal conditions in section 3.2.1. In addition to neutrinos, some particles beyond the standard model, such as LSP, will also produce considerable E_T^{miss} , so the reconstruction of E_T^{miss} is crucial for the search for new physics.

The reconstruction of E_T^{miss} depends on the reconstruction of other physical final states and the tracks and clusters that are not involved in the reconstruction of other physical final states. In addition, since other reconstructions may reconstruct a set of detector signals into multiple particles, thereby reducing the accuracy of E_T^{miss} , the overlap removal process (OR) is also a key step in E_T^{miss} reconstruction. The reconstruction formula of E_T^{miss} in the x and y direction components is as follows:

$$E_{x(y)}^{\text{miss}} = E_{x(y)}^{\text{miss},\mu} + E_{x(y)}^{\text{miss},e} + E_{x(y)}^{\text{miss},\gamma} + E_{x(y)}^{\text{miss},\tau_{\text{had}}} + E_{x(y)}^{\text{miss},\text{jets}} + E_{x(y)}^{\text{miss},\text{soft}} \quad (4-10)$$

The first five terms on the right side of the equal sign are "hard final states", which refer to the reconstructed physical final states. The order of the terms in the equation is also the calculation order of the E_T^{miss} reconstruction. The hard final state reconstruction used in the analysis must be consistent with that used in the calculation of E_T^{miss} to ensure the consistency of the reconstruction of the case. The last term of the equation is called the soft term, which mainly comes from clusters and tracks that have not been reconstructed into hard final states, as well as the pile-up effect and UE as the background. There are two methods for reconstructing soft terms. The first is the CST [125] method based on cluster information. Since the CST method is greatly affected by the pile-up effect, the second is the track-based TST method, which is the main reconstruction algorithm of ATLAS [126]. The TST method considers all tracks that have not been reconstructed into hard final states, selects tracks that are closer to the primary vertex according to the collision parameters, and reconstructs the soft terms based on the p_T of these tracks.

In the ATLAS experiment, even if the TST method is used, the pile-up effect still has a great influence on the reconstruction of E_T^{miss} . Figure 4-12 [126] shows the relationship between E_T^{miss} resolution and $\langle \mu \rangle$ in the $Z \rightarrow \mu\mu$ process. Since the distribution of E_T^{miss} is non-Gaussian, the root mean square is used to calculate the resolution [126]. The physical process in this figure is mainly the $Z \rightarrow \mu\mu$ process. The truth-level E_T^{miss} is 0. It can be found that the higher the $\langle \mu \rangle$, the worse the resolution of E_T^{miss} . The overall $\langle \mu \rangle$ peak of Run2 is about 33.7, and the E_T^{miss} system error of the signal area defined in this analysis is 5% to 7%. For the study using part of Run2 data and the same E_T^{miss} trigger and E_T^{miss} selection conditions in the signal area [127], the $\langle \mu \rangle$ peak of the experimental data used is lower than 25.1. Although the reconstruction algorithm used in its soft term is CST with relatively poor performance, its E_T^{miss} system

error is only 2% to 6%. In addition, the forward jet in the figure refers to the jet with $|\eta| > 2.5$ in the case. The fJVT reconstruction algorithm [128] can effectively improve the reconstruction performance of the forward jet. It can be found that the improvement of the hard final state reconstruction performance will also improve the reconstruction performance of E_T^{miss} . This is because the reconstruction of E_T^{miss} is highly dependent on the reconstruction of the hard final state.

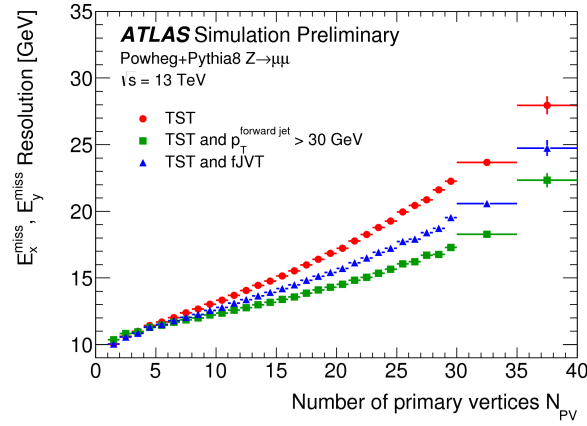


图 4-12 E_T^{miss} 分辨率与 $\langle \mu \rangle$ 的关系，其中 fJVT [128] 是重建前向喷注 (Forward jet) 的算法 [126]。

Figure 4-12 E_T^{miss} resolution as a function of $\langle \mu \rangle$, where fJVT [128] represents Forward jet reconstruction algorithm [126].

第 5 章 Search for Gauginos in the Final State of a Single Lepton and Two Taus

This chapter introduces the search for the pair production of $\tilde{\chi}_1^\pm \tilde{\chi}_2^0$ and decay to a lepton (ℓ) and two τ_{had} final states via Wh using the experimental data of 139 fb^{-1} during Run2 in the ATLAS experiment. In the simplified model used in this chapter, $\tilde{\chi}_1^\pm$ and $\tilde{\chi}_2^0$ are Wino-type, while $\tilde{\chi}_1^0$ is Bino-LSP. As supersymmetric partners of gauge bosons B and W , they are collectively called super-gauge bosons (gaugino).

5.1 Motivations and Signal Models

In the section 2.2.4, it is mentioned that $\tilde{q}$ and $\tilde{g}$ particles are mainly produced by strong interactions at the LHC, so the production cross section is large. The current mass exclusion limit has reached the TeV level, so even if $\tilde{q}$ and $\tilde{g}$ exist, their masses are very likely to exceed the current LHC detection range. As for the process of producing $\tilde{\chi}_1^\pm$ and $\tilde{\chi}_2^0$ by electroweak interaction, their cross sections are small, so at the current LHC center of mass energy, there is still a large space of mass parameters that have not been studied. At the same time, Bino-type $\tilde{\chi}_1^0$ is a major candidate for dark matter particles. If $\tilde{\tau}$ or $\tilde{\chi}_1^\pm/\tilde{\chi}_2^0$ is close to the mass of Bino-type LSP, LSP can reduce the dark matter remnant density to match cosmological observations through co-annihilation or self-annihilation with the next-lightest supersymmetric particle (NLSP) [20]. In addition, the lighter $\tilde{\tau}$ and $\tilde{\chi}_1^\pm/\tilde{\chi}_2^0$ can explain the observed anomalous magnetic moment of muons exceeding [129]. In summary, searching for electroweak processes involving $\tilde{\chi}_1^\pm$ and $\tilde{\chi}_2^0$ is one of the important research directions for searching for supersymmetric particles on ATLAS. Figure 5-1 shows the process of $\tilde{\chi}_1^\pm \tilde{\chi}_2^0$ decaying through Wh studied in this chapter. This model is a simplified model of R parity conservation. pp collision produces a pair of wino- $\tilde{\chi}_1^\pm \tilde{\chi}_2^0$, $\tilde{\chi}_1^\pm$ decays to LSP and W bosons in the shell, W lepton decays to produce e or μ (ℓ), $\tilde{\chi}_2^0$ decays to LSP and h bosons in the shell, h decays to two strong decay tausons (τ_{had}), and finally forms the final state of $1\ell 2\tau_{\text{had}}$, and the charges of the two τ_{had} are opposite. The process studied in this chapter is referred to as "Wh process" or "Wh analysis" (Intermediate Wh analysis) below.

In Run2, the ATLAS experiment searched for the decay of $\tilde{\chi}_2^0$ to two photons, $b\bar{b}$, and $\ell\bar{\ell}$ through h , and found no experimental phenomena that were obviously beyond the standard model. The mass was restricted at 95% confidence. When the LSP mass is close to 0, $\tilde{\chi}_1^\pm \tilde{\chi}_2^0$ with a mass lower than 740 GeV is excluded. This study is the first time that the ATLAS experiment considers the process of h decay to two tau, which completes the main decay process of Wino-type $\tilde{\chi}_1^\pm \tilde{\chi}_2^0$ decaying through Wh .

In this study, the branching fraction (B) of the $\tilde{\chi}_1^\pm$ and $\tilde{\chi}_2^0$ decay channels is set to 100% to reduce model parameters. $B(h \rightarrow \tau\tau)$ and $B(W \rightarrow \ell\nu)$ use the global fitting results of the relevant experimental measurements provided by PDG. The mass range of $\tilde{\chi}_1^0$ is 0 to 160 GeV, $\tilde{\chi}_1^\pm$ and $\tilde{\chi}_2^0$ are degenerate, ranging from 126 GeV to 500 GeV, of which the minimum value of 126 GeV can ensure the production of shell h , The masses of all other supersymmetric particles are set to $\mathcal{O}(10 \text{ TeV})$ so that they do not participate in the signal process (decoupling). Figure 5-2 summarizes the signal mass distribution used in the study. The masses of LSP and $\tilde{\chi}_1^\pm/\tilde{\chi}_2^0$ are far away from the diagonal to avoid the generation of off-shell h .

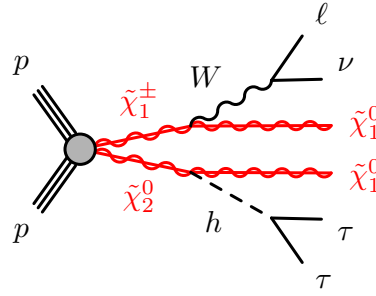


图 5-1 $\tilde{\chi}_1^\pm \tilde{\chi}_2^0$ 通过 Wh 衰变过程示意图。

Figure 5-1 Representative diagram of $\tilde{\chi}_1^\pm \tilde{\chi}_2^0$ via Wh decay process.

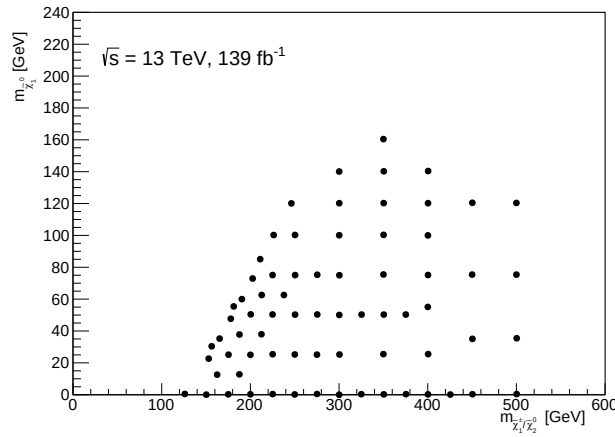


图 5-2 Wh 研究的信号质量参数分布。

Figure 5-2 Mass grid of the Wh signal points.

The interaction cross section calculation of the signal sample uses the RESUMMINO framework, using the PDF of CTEQ6.6 and MSTW2008nlo90cl, the calculation accuracy is next-to-leading order (NLO), and the NLL (Next-to-leading logarithmic) algorithm is used to correct the logarithmic divergence in the calculation (NLO+NLL) [61, 130–132].

5.2 Event Reconstruction

5.2.1 Reconstruction of Event and Physics Objects

Considering that the lifetime of $\tilde{\chi}_1^\pm/\tilde{\chi}_2^0$ particles is extremely short, they decay instantaneously near the collision vertex, and the final state of Wh has two τ , it is required that each reconstructed event has at least one primary vertex reconstructed using the standard algorithm, and the primary vertex contains at least two $p_T > 400$ MeV dotted tracks.

Since the signal in this article does not have significant jet characteristics, there is only one basic standard for the definition of jet and b -jet. Table 5-1 summarizes the jet reconstruction standards.

表 5-1 Wh 过程的喷注重建标准。

Table 5-1 Summary of the selections for jets in the Intermediate Wh analysis.

	Jets	b -jets
Baseline	Anti- k_t EMPFlow	anti- k_t EMPFlow
	$p_T > 20$ GeV	$p_T > 20$ GeV
	$ \eta < 2.8$	$ \eta < 2.5$
	JVT _{ID} = Tight	DL1r algorithm
	JVT _{$p_{T\max}$} = 60 GeV	77% WP

Even if the signal process does not include signal jets, the background jets caused by the pile-up effect and UE are still unavoidable, and the reconstruction of τ_{had} also requires the participation of the jet, so the choice of the jet is crucial. The jet reconstruction uses the standard anti- k_t particle flow algorithm, ΔR is set to 0.4, and the energy scale uses the standard of electromagnetic shower. The reconstructed jet candidates need to meet the basic conditions of $p_T > 20$ GeV and $|\eta| < 2.8$. Because the signal cannot produce a large proportion of forward jets, the upper limit of $|\eta|$ of 2.8 can meet the analysis requirements. When reconstructing the jet, the reconstruction cases containing false jets that may be caused by cosmic rays or detector noise are also removed. In addition, in order to further reduce the background jet, the JVT of the jet with p_T lower than 60 GeV is required to meet the most stringent Tight standard in the study.

The reconstruction of the heavy-flavor injection adopted the DL1 standard b -tag algorithm and used a working point with a labeling efficiency of 77%. Except that $|\eta|$ was further restricted to the barrel region less than 2.5, the rest of the reconstruction criteria were consistent with the injection criteria.

Since the final state of the Wh process contains multiple leptons, there are two standards for the reconstruction of e , μ , and τ . One is called the basic standard (baseline), which will be used for the reconstruction of the decoincidence and transverse energy loss of physical objects. Its loose selection conditions have a higher selection efficiency

for signal cases. The other is called the signal standard (signal), which is used to further require physical objects on the basis of the baseline and lower the background. Table 5-2 summarizes the reconstruction standards of leptons.

表 5-2 Wh 过程的 e 、 μ 、 τ 的重建标准

Table 5-2 Summary of the selections for e , μ , and τ in the Intermediate Wh analysis.

	τ_{had}	e	μ
Baseline	$p_T > 20 \text{ GeV}$ Crack region veto Tau Track = 1 OR 3 $\text{BDT}_{\text{Ele OR}} = \text{medium}$ RNN-ID = medium	$p_T > 4.5 \text{ GeV}$ $ \eta < 2.47$ LooseAndBLayerLLH $d_0 \text{ significance} < 5 \text{ mm}$ $z_0 \sin \theta < 0.5 \text{ mm}$	$p_T > 3 \text{ GeV}$ $ \eta < 2.7$ ID = medium $z_0 \sin \theta < 0.5 \text{ mm}$
Signal	RNN-ID = medium OR tight	$p_T > 25 \text{ GeV}$ FCLoose ($p_T < 200 \text{ GeV}$) FCHightPtCaloOnly ($p_T > 200 \text{ GeV}$) TightLLH	$p_T > 25 \text{ GeV}$ $d_0 \text{ significance} < 3 \text{ mm}$ FCLoose

The reconstruction of τ_{had} uses the standard RNN-based reconstruction method, with the seed being the reconstructed jet with p_T higher than 10 GeV. The reconstructed τ_{had} needs to satisfy p_T higher than 20 GeV and $|\eta|$ lower than 2.5, which is the loosest reconstruction standard and includes all reconstructed τ_{had} of the standard reconstruction algorithm. Since the calorimeter has a gap in the interval $1.37 < |\eta| < 1.52$, this interval is called the crack region, the reconstruction efficiency of τ_{had} in the crack interval is low, so the τ_{had} with $|\eta|$ in this part is lost (crack region veto). In addition, τ_{had} is required to be 1-prong or 3-prong, carry unit charge, and pass the electron-tauhad decoincidence algorithm based on BDT, with a working point of medium. For baseline τ_{had} , the discrimination working point based on the RNN algorithm is medium, and for signal τ_{had} , it may be increased to tight working point depending on the specific situation.

In order to improve the selection efficiency of Wh process, baseline e is reconstructed loosely. In addition to the two basic requirements $p_T > 4.5 \text{ GeV}$ and $|\eta| < 2.47$, Since the signals are all prompt processes, the d_0 significance (d_0/σ_{d_0}) and $z_0 \sin \theta$ of the track are also required to be small, and through the likelihood function-based Identify the loose working point of the strategy (LooseAndBLayerLLH). The requirements for Signal e are relatively strict. In addition to raising the p_T requirement to 25 GeV, based on different p_T ranges, there are also requirements for the isolation degree of e . The working point of the identification algorithm is also increased to tight including the participation of the MVA algorithm. Work point.

The strategy of μ is similar to e . For baseline μ , p_T requires only 3 GeV, $|\eta|$ is less than 2.7, and satisfies the medium identification working point and $z_0 \sin \theta$ request. But for signal μ , the requirements for isolation and p_T are similar to those for signal

e , and the significance of d_0 is required to be less than 3 mm, thereby improving the background suppression rate.

5.2.2 Overlap Removal

Since not all physical objects have isolation requirements relative to other reconstructed objects during event reconstruction, offline physical object overlap removal is required to eliminate overlap and "ambiguity" during event reconstruction. Table 5-3 summarizes the overlap removal process. The arrangement from top to bottom indicates the order of overlap removal steps. For example, the first step is to remove the jets that overlap with μ . It can be seen that most overlap removal criteria are based on the fixed ΔR criteria. In addition to the overlap removal of e and μ , the ID information is also used. The ΔR criteria for overlap removal of e , μ and jets will change with the lepton p_T , because the lower the p_T , the larger the spatial angle passed when passing through the detector, and the easier it is to cause overlap. In addition, when conducting background estimation for certain backgrounds, this study lowered the baseline τ_{had} standard to loose or very loose, resulting in a significant increase in the number of misreconstructed τ_{had} . If this table is still used, most of the jets will be removed, so only the τ_{had} with the highest and second highest p_T in the samples for background estimation will be de-overlapped with the jets.

5.2.3 Reconstruction of Missing Transverse Energy and Trigger

After obtaining the baseline physical objects after de-overlapping, the case-based algorithm will use these physical objects to calculate the offline E_T^{miss} of each case. This analysis uses the TST algorithm to reconstruct the contribution of soft-term.

In addition to the number of physical objects in the final state, the selection of triggers is also based on the distribution of their dynamic variables. The efficiency of trigger selection is not fixed. The efficiency of most triggers varies with p_T . When p_T is greater than a certain threshold, the efficiency will be fixed at a value. At this time, the reconstruction efficiency is higher, the background suppression ability is stronger, and the study of system uncertainties is more detailed. The corresponding p_T is called the offline threshold (Plateau).

For the Wh process, its final state contains a lepton, and the p_T threshold of the single lepton trigger is lower, so the efficiency of using a single electron/muon trigger is higher than that of using a τ_{had} -related trigger. The Wh process uses both electron and muon triggers, and the two are in an "or" relationship. The threshold value varies with different acquisition times. Table 5-4 summarizes the p_T selection conditions and p_T thresholds (Offline p_T cut) of HLT used in previous years. The three electronic triggers for different p_T are also in an "or" relationship.

表 5-3 Wh 过程的去重合过程，rad 表示随 p_T 变化的标准，ID track 表示利用 ID 的信息。
用于本底估计的样本中只有 p_T 最高和次高的 τ_{had} 参与对喷注的去重合。

Table 5-3 Consecutive steps of the overlap-removal procedure for the Intermediate Wh analysis, where ‘rad’ represents the standard that varies with p_T and ‘ID track’ represents the use of ID information. For the samples used in the background estimation, only τ_{had} of the highest and second highest p_T are involved in the overlap-removal with jets.

Procedure	Be Removed Object	Be kept Object	Conditon	Comment
1.	jet	muons	various criteria	Removes p-Flow jets based on various criteria including delta-R, jet track multiplicity , mu_ID_pt/jet_SumTrkPt ratio and muon calo isolation.
2.	tau	electron	$\Delta R < 0.2$	Variable “rad” is based on the electron pt: $\text{rad} = 0.04 + 10 \text{ GeV}/p_{Te}$. If rad is larger than 0.4, rad will be 0.4.
3.	tau	muon	$\Delta R < 0.2$	
4.	electron	muon	shared ID track	
5.	jet	electron	$\Delta R < 0.2$	
6.	electron	jet	$\Delta R < \text{rad}$	
7.	jet	muon	NumTrack < 3 and (ghost-associated or $\Delta R < 0.2$)	“rad” definition same as the “rad” in step 6 but use muon p_T
8.	muon	jet	$\Delta R < \text{rad}$	
9.	jet	tau	$\Delta R < 0.2$	
				Only leading and sub leading τ_{had} if τ_{had} ID is loose or veryloose

表 5-4 Wh 过程的触发器选择，Offline p_T cut 表示离线阈值。

Table 5-4 The triggers for the Intermediate Wh analysis, ‘Offline p_T cut’ represents the offline thresholds.

Trigger Type	Name	Year	p_T Online [GeV]	p_T Offline [GeV]
Single electron	HLT_e24_lhmedium_L1EM20VH	2015	24	25
	HLT_e60_lhmedium	2015	60	61
	HLT_e120_lhloose	2015	120	121
	HLT_e26_lhtight_nod0_ivarloose	2016-2018	26	27
	HLT_e60_lhmedium_nod0	2016-2018	60	61
	HLT_e140_lhloose_nod0	2016-2018	140	141
Single muon	HLT_mu20_iloose_L1MU15	2015	20	21
	HLT_mu26_ivarmedium	2016-2018	26	27.3
	HLT_mu50	2015-2018	50	52.5

5.3 Signal Region Definition

5.3.1 Preselection

After obtaining the reconstructed cases, case primary selection is required to retain all signal cases while removing most of the background cases. The preliminary selection of cases relies on MC simulation samples, mainly screening for the salient characteristics of the final state of the signal (Event Topology). The case primaries of the Wh procedure depend on the following variables:

m_T : The definition of transverse mass in SUSY analysis is slightly different from the common definition in collider physics. Considering that the decay of SUSY particles can produce LSPs that cannot be directly detected by detectors, the signal characteristic of LSPs is E_T^{miss} , so the transverse mass in SUSY analysis refers to the transverse mass of visible physical objects and E_T^{miss} systems: $m_T(p_T, q_T) = \sqrt{2(p_T^\mu q_{T,\mu})}$, it can be seen that the upper limit of m_T is the transverse mass of the SUSY parent particle.

m_{T2} (Stransverse mass) [133, 134]: m_{T2} refers to the process in which a pair of parent particles decays into a detectable particle and an undetectable particle, and then the undetectable particles constitute the vast majority of E_T^{miss} . For the final state containing two τ_{had} and E_T^{miss} , m_{T2} is defined as:

$$m_{T2} = \min_{q_T} \left[\max \left(m_{T,\tau 1}(p_T, q_T), m_{T,\tau 2}(p_T, E_T^{\text{miss}} - q_T) \right) \right] \quad (5-1)$$

Where q_T represents the transverse momentum of the undetectable particle from $\tau 1$. So m_{T2} constructs a transverse mass close to the parent particle by dividing E_T^{miss} into the contribution of p_T from two invisible particles, Therefore, the upper limit of m_{T2} is the parent particle mass.

m_{T2}^{max} : The largest m_{T2} selected after calculating the m_{T2} of all pairs of ℓ or τ_{had} and E_T^{miss} . For the Wh process, this variable is calculated using a single lepton and two τ_{had} in the final state.

$m(\tau_1, \tau_2)$: The invariant mass of the double τ_{had} in the final state.

Table 5-5 summarizes the preliminary selection of events for the Wh process. First, the event needs to pass the single lepton trigger and the p_T threshold, and requires a signal lepton. Since the signal does not involve t and b quarks, the event without b -jet is selected. In addition, considering that the signal final state has two tau leptons from h decay, the event is required to contain at least two signal τ_{had} , and the p_T highest and second highest τ_{had} have opposite charges, and the invariant mass is near $m(h)$. Considering that the invisible energy of neutrinos produced by tau lepton decay cannot be reconstructed, the window of $m(\tau_1, \tau_2)$ is selected to be wide, between 40 GeV and 160 GeV. This can retain most of the signal and remove part of the background from the t quark process and W +jets process. In addition, since the accuracy of W +jets in the

MC simulation sample is low when the two jets are in opposite directions and collinear, the angle between the two τ_{had} is limited to $|\Delta\phi(\tau_1\tau_2)| < 3$. Since the mass difference between NLSP and LSP in most signal points is large, the p_T of h decayed by NLSP is high, and the τ_{had} angle of h decayed after boost is small, so $|\Delta\phi(\tau_1\tau_2)| < 3$ has little effect on signal efficiency. Finally, considering that the theoretical upper limits of m_{T2}^{max} of Z+jetsprocess and W+jetsprocess are about 91 GeV and 80 GeV respectively, and the $\tilde{\chi}_1^\pm/\tilde{\chi}_2^0$ mass of the signal is higher than 126 GeV, $m_{T2}^{\text{max}} > 30$ GeV is required.

表 5-5 Wh 过程的事例初选。

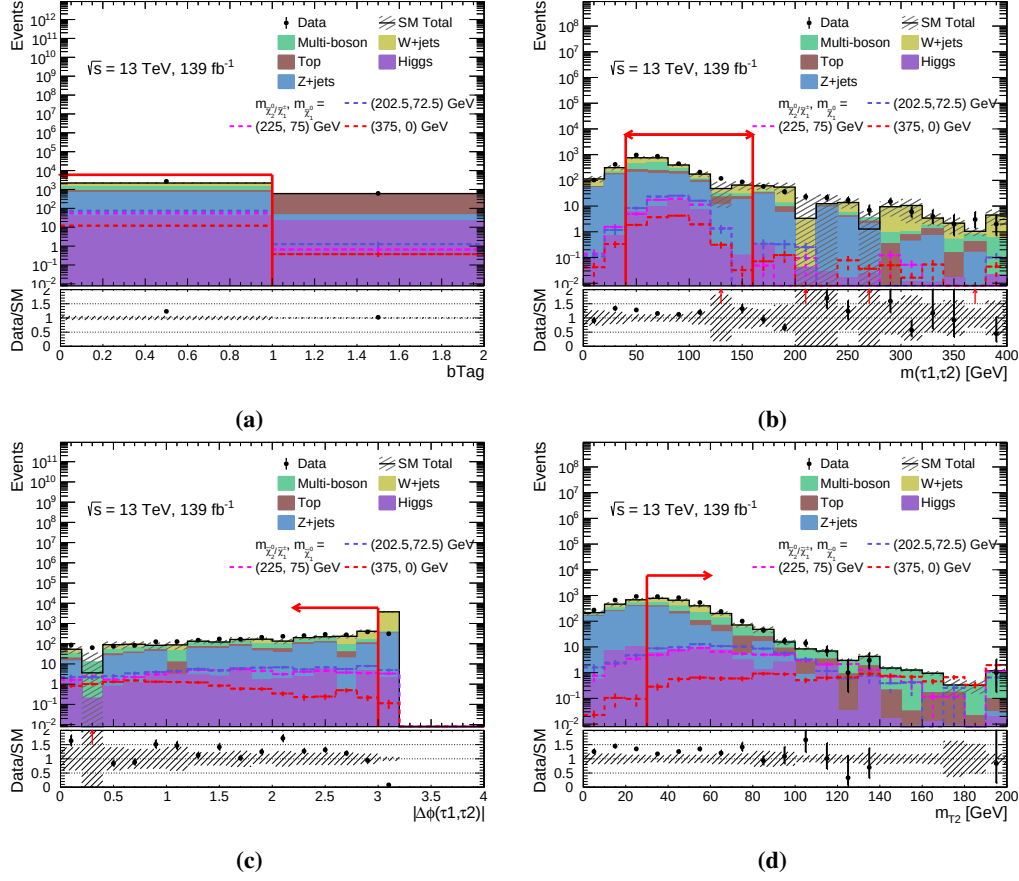
Table 5-5 Summary of preselection requirements for the Intermediate Wh analysis.

Single lepton trigger and offline p_T cut
== 1 signal lepton
≥ 2 medium τ_{had} (OS)
b -jet veto
Higgs requirement ($40 \text{ GeV} < m(\tau_1, \tau_2) < 160 \text{ GeV}$)
$ \Delta\phi(\tau_1, \tau_2) < 3$
$m_{T2}^{\text{max}} > 30 \text{ GeV}$

Figure 5-3 shows the "N-1" distribution of the case preselection. The N-1 distribution shows the distribution after applying other selection conditions except the variables involved in the figure. The distribution of three signal points in the figure is used to verify the rationality of the selection conditions. It can be found that the selection conditions have a high selection efficiency for the signal and effectively suppress the background. The lower part of each picture is a comparison of the experimental data and the MC simulated background sample. It can be found that the degree of agreement is very good, indicating that the MC simulation of the SM background process is reliable.

5.3.2 Signal Region Definition

After primary case selection, the ratio of the total number of cases and the background relative signal is reduced to an acceptable level. In order to further improve the signal background ratio, it is necessary to further define the signal region (Signal region, SR) where signal instances dominate. The definition of a signal region can be strongly model-dependent (Exclusion SR), or it can be less or even independent of the model (Discovery SR). The variable that measures the performance of the signal area is signal significance. In order to obtain the maximum significance of each signal simulation sample in the signal area as a whole, it is very important to select the reference signal sample. The model of Wh has only two variable parameters, so the selection of the signal reference point mainly considers the following two points: (1) Covers a wide range


 图 5-3 Wh 的事例初选动力学变量分布。

 (a) b -jet 数量、(b) $m(\tau_1, \tau_2)$ 、(c) $|\Delta\phi(\tau_1, \tau_2)|$ 、和 (d) m_{T2} 。

Figure 5-3 The distributions of relevant

 kinematic variables from the pre-selection requirements in the Intermediate Wh analysis.

 (a) shows the number of b -jet, (b) shows $m(\tau_1, \tau_2)$, (c) shows $|\Delta\phi(\tau_1, \tau_2)|$, and (d) shows m_{T2} .

of Gaugino quality, and also covers a wide range of quality differences between $\tilde{\chi}_1^\pm/\tilde{\chi}_2^0$ and LSP. (2) is near the expected exclusion limit. In order to meet this requirement, multiple rounds of iterations may be performed on the selection of reference points. Finally, three signal points were selected as references, and their quality parameters and cross-sections are shown in Table 5-6.

 表 5-6 Wh 过程的信号参考点。

 Table 5-6 The signal reference points for the Intermediate Wh analysis.

Reperence	Cross-section [pb]
$m(\tilde{\chi}_1^\pm/\tilde{\chi}_2^0, \tilde{\chi}_1^0)$ [GeV]	
(202.5, 72.5)	1.726134
(275.0, 75.0)	1.165122
(375.0, 0.0)	0.1580759

After determining the signal reference point, the ‘‘Cut and Count’’ method is used to

determine the final signal area. This method scans all combinations of different selection conditions for multiple kinetic variables, and finally selects the combination with higher signal significance and signal statistics as the SR definition. The variables used by the Wh procedure are summarized in table 5-7, In addition to further restrictions on related variables such as $m(\tau_1, \tau_2)$ and $m_{T2}^{\max}$ that have been used in the preliminary stage, Also utilized are the following new variables:

- (1) $m_{T\text{sum}}$: The m_T scalar sum of the final state signal object (e or μ and double τ_{had}). The upper limit of $m_{T\text{sum}}$ is related to the mass of the parent particle.
- (2) $m_T(\text{lep})$: p_T is the highest transverse mass of e or μ .

表 5-7 Wh 过程 “Cut and Count” 方法所用的扫描设置。

Table 5-7 Cut combinations of ‘Cut and Count method’ for the Intermediate Wh analysis.

Variable	Condition
$m(\tau_1, \tau_2)$	$\geq 40., 50., 60., 70., 80., 90., 100., 110. \text{ GeV}$
$m(\tau_1, \tau_2)$	$\leq 80., 90., 100., 110., 120., 130., 140., 150., 160. \text{ GeV}$
$m_{T2}^{\max}$	$\geq 30., 40., 50., 60., 70., 80., 90., 100., 110. \text{ GeV}$
$p_T(\tau_1)$	$\geq 20., 30., 40., 50., 60., 70., 80. \text{ GeV}$
$p_T(\tau_2)$	$\geq 20., 30., 40., 50. \text{ GeV}$
$m_T(\tau_1)$	$\geq 0., 20., 30., 40., 50. \text{ GeV}$
$m_T(\text{lep})$	$\geq 0., 20., 40., 60., 80., 100. \text{ GeV}$
$m_{T\text{sum}}$	$\geq 0., 300., 350., 400., 450., 500., 550. \text{ GeV}$
N_{TightTau}	$\geq 0, 1, 2$
$\Delta R(\tau_1, \tau_2)$	$\leq 2.0, 2.2, 2.3, 2.4, 2.5, 2.6., 3., 100.$

Finally, due to the limitation of background event statistics, the Wh process defines two non-orthogonal signal regions (SR-Wh-LM, SR-Wh-HM) as discovery and exclusion SRs at the same time. SR-Wh-LM is used to find signals in the $\tilde{\chi}_1^\pm/\tilde{\chi}_2^0$ low-mass region and the NLSP-LSP mass compression region, and SR-Wh-HM is used to find the $\tilde{\chi}_1^\pm/\tilde{\chi}_2^0$ high-mass region. Their definitions are shown in Table 5-8. SR-Wh-LM (SR-Wh-HM) further limits the selection window of $m(\tau_1, \tau_2)$ to 90 to 130 GeV (80 to 160 GeV), making it closer to the mass of h , thus suppressing the lower-mass W +jets, Z +jets and top processes. In SR-Wh-HM, the restriction of the final state double τ_{had} angle $\Delta R(\tau_1, \tau_2) < 2.2$ can reduce the contribution of the misreconstructed τ , because there is no dynamic correlation between the jets of the misreconstructed τ , and the angle distribution is more random and wider. At the same time, in order to further screen the signal process, $m_{T2}^{\max}$ is further restricted to no less than 100 (80) GeV in SR-Wh-LM (SR-Wh-HM). Considering that the $\tilde{\chi}_1^\pm/\tilde{\chi}_2^0$ mass of the signal process targeted by SR-Wh-HM is higher, the energy of the final state particle will also be higher, therefore, the selection conditions of $m_T(\text{lep}) > 80 \text{ GeV}$ and $m_{T\text{sum}} > 450 \text{ GeV}$ in SR-Wh-HM can further improve the signal significance.

表 5-8 Wh 过程的信号区定义。Table 5-8 SR definitions of the Intermediate Wh analysis.

	SR-Wh-LM	SR-Wh-HM
Trigger	Single e or μ trigger	
$N(\text{Medium } \tau)$	≥ 2	
$N(e/\mu)$	$= 1$	
τ_{had} Charge combination	OS	
$N(b\text{-jets})$	$= 0$	
$ \Delta\phi(\tau_1, \tau_2) $	< 3	
$\Delta R(\tau_1, \tau_2)$	–	< 2.2
$m(\tau_1, \tau_2)$ [GeV]	$\in [90, 130]$	$\in [80, 160]$
m_{T2} [GeV]	> 100	> 80
$m_{T,\ell}$ [GeV]	–	> 80
$m_{T\text{sum}}$ [GeV]	–	> 450

Figures 5-4 and 5-5 show the N-1 distribution of each variable in SR-Wh-LM and SR-Wh-HM respectively, The N-1 distribution shows the distribution of signal significance with the variables on the graph under different selection conditions after applying other signal area selection conditions other than the variables involved in the graph. It can be found that for SR-Wh-HM, The statistics of the background simulation samples are insufficient, which is one of the reasons why SR-Wh-LM and SR-Wh-HM are not orthogonal. The lower part of each distribution diagram shows the signal significance when the corresponding value of the abscissa coordinate of the dynamic variables in the diagram is selected as the selection condition. It can be found that the selection conditions of SR are almost always at the position with the highest significance. Table 5-9 summarizes the number of cases of MC samples in each signal area that have not undergone background-only fit.

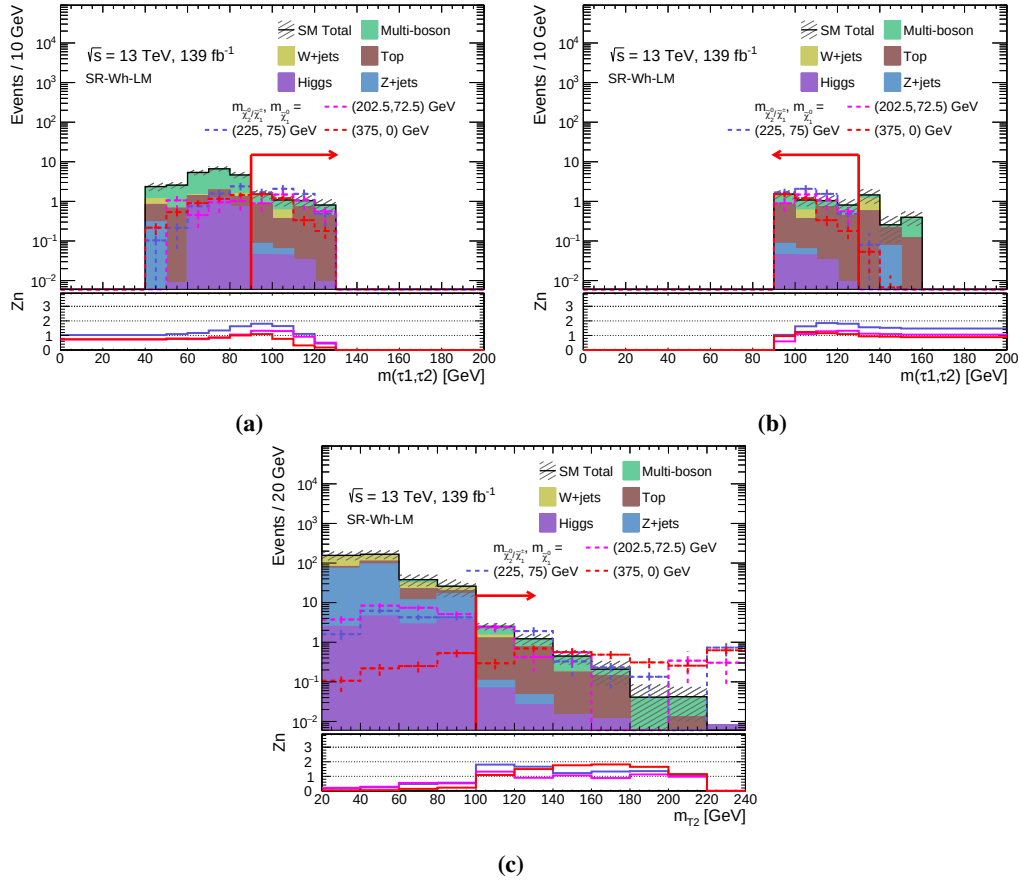


图 5-4 SR-Wh-LM 信号区定义的 N-1 分布。

除图上变量涉及的选择条件外，其他 SR-Wh-LM 的选择条件已全部考虑，图上变量的选择条件分别为：(a) $m(\tau_1, \tau_2)$ 下限的选择条件、(b) $m(\tau_1, \tau_2)$ 上限的选择条件和 (c) m_{T2} 下限的选择条件。

Figure 5-4 “N-1” distributions of relevant kinematic variables.

The distributions after SR-Wh-LM requirements, except the one on the shown variable, have been applied: (a) $m(\tau_1, \tau_2)$ lower cut, (b) $m(\tau_1, \tau_2)$ uppercut, and (c) m_{T2} lower cut.

表 5-9 Wh 过程信号区的未进行本底拟合的事例数。

Table 5-9 Event yields in the Wh SRs. All SM background yields are before the background-only fit.

	SR-Wh-LM	SR-Wh-HM
Top	2.16 ± 0.60	0.16 ± 0.12
Multi-boson	1.87 ± 0.28	1.07 ± 0.16
W+jets	0.23 ± 0.22	0.062 ± 0.062
Higgs	0.131 ± 0.013	0.059 ± 0.0082
Z+jets	0.061 ± 0.030	0.030 ± 0.022
SM Total	4.45 ± 0.70	1.38 ± 0.21
$m(\tilde{\chi}_1^\pm/\tilde{\chi}_2^0, \tilde{\chi}_1^0) = (202.5, 72.5) \text{ GeV}$	4.01 ± 0.80	-
$m(\tilde{\chi}_1^\pm/\tilde{\chi}_2^0, \tilde{\chi}_1^0) = (225.0, 75.0) \text{ GeV}$	5.79 ± 0.82	-
$m(\tilde{\chi}_1^\pm/\tilde{\chi}_2^0, \tilde{\chi}_1^0) = (375.0, 0) \text{ GeV}$	-	4.02 ± 0.33

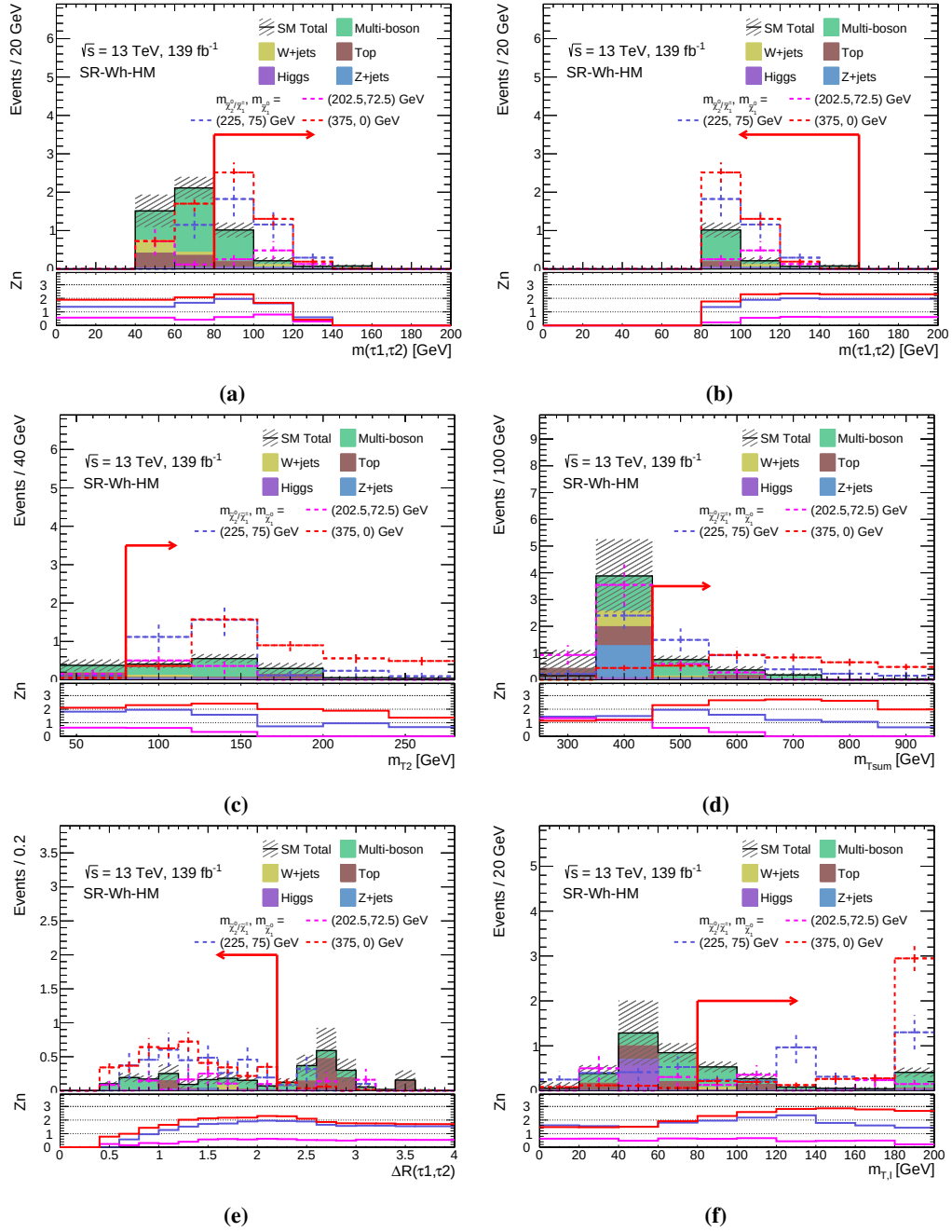


图 5-5 SR-Wh-HM 信号区定义的 N-1 分布。

除图上变量涉及的选择条件外，其他 SR-Wh-HM 的选择条件已全部考虑，图上变量的选择条件分别为：(a) $m(\tau_1, \tau_2)$ 下线的选择条件、(b) $m(\tau_1, \tau_2)$ 上线的选择条件、(c) m_{T2} 下线的选择条件、(d) $m_{T\text{sum}}$ 下线的选择条件、(e) $\Delta R(\tau_1, \tau_2)$ 上线的选择条件和 (f) $m_{T,\ell}$ 下线的选择条件。

Figure 5-5 “N-1” distributions of relevant kinematic variables.

The distributions after SR-Wh-HM requirements, except the one on the shown variable, have been applied: (a) $m(\tau_1, \tau_2)$ lower cut, (b) $m(\tau_1, \tau_2)$ upper cut, (c) m_{T2} lower cut, (d) $m_{T\text{sum}}$ lower cut, (e) $\Delta R(\tau_1, \tau_2)$ upper cut, and (f) $m_{T,\ell}$ lower cut.

5.4 Background Estimation

From Table 5-9, we can see that the main background in the Wh signal region is multi-boson, top quark-related processes and W +jets, and multi-jet misreconstruction τ_{had} processes, Z +jets and higgs-related background also contribute. In order to estimate the background with poor MC simulation performance and further improve the accuracy of other background estimates, Wh analysis uses three different methods to estimate the background for different background processes. The final state of the Wh process is a lepton and two τ_{had} . According to the sources of the leptons and τ_{had} , they can be divided into the following three categories: (1) The leptons and two τ_{had} come from the background (irreducible background) of the correctly reconstructed physical object (Truth), and the main source is the multi-boson process, especially the process of simultaneous production of WZ bosons. In addition, $t\bar{t}$, Wt and Z +jets processes also contribute a small part of the irreducible background. (2) The final state contains correctly reconstructed leptons and a misreconstructed τ_{had} (fake- τ_{had}). The source of the misreconstructed τ_{had} is mainly the jet. The main background process is the t quark (Top) related process, and a small part comes from Z +jets and multi-boson processes. (3) Both τ_{had} in the final state come from the jet misreconstruction, and the main background source is the W +jets process.

For the background of type (1), because the accuracy of the simulated correctly reconstructed physical object is high, this analysis directly uses MC simulation samples and defines a validation region (VR) to verify the accuracy of MC simulation. For the background of type (2), this analysis defines a control region (CR) with the top process as the main contribution for background estimation, obtains the correction parameters of the top process through the control region, and defines VR for verification. The background estimation of type (3) background adopts a data-driven fake factor method, and defines the corresponding CR and VR. The final contribution of the background in the signal region will be obtained by background fitting. The background fitting method used in this paper is detailed in Section 5.5.3 of this paper.

5.4.1 Estimation of Two-fake- τ_{had} Process

The goal of the fake factor method is to use the distribution information of fake- τ_{had} (anti-tau) that does not pass the medium identification working point to extrapolate to estimate the distribution of fake- τ_{had} (medium-tau) that passes the medium working point. The ratio used for extrapolation to SR is called transfer factor (TF), which is recorded as fake factor (FF) in the fake factor method. In order to estimate the process containing two medium fake- τ_{had} , it is necessary to define the following three regions in the CR with higher anti-tau content to calculate FF: (1) p_T The highest and second highest τ_{had} are both anti-tau (AA region); (2) p_T The highest τ_{had} is medium-tau and

the second highest is anti-tau (MA region); (3) p_T The highest and second highest τ_{had} are both medium-tau (MM region); Therefore, when calculating the number of cases of MM type background in SR (N_{fakes}), the distribution of p_T The highest τ_{had} in AA type background ($N_{\text{AA, fakes}}$) is extrapolated first, and then the second highest τ_{had} is extrapolated. The FF used for extrapolation is denoted as $\text{FF}_{\tau_1}^{\text{CR}}$ and $\text{FF}_{\tau_2}^{\text{CR}}$:

$$N_{\text{fakes}} = N_{\text{AA, fakes}} \times \text{FF}_{\tau_1}^{\text{CR}} \times \text{FF}_{\tau_2}^{\text{CR}} \quad (5-2)$$

The calculation method of FF is:

$$\text{FF}_{\tau_1}^{\text{CR}} = \frac{N_{\text{data,MA}} - N_{\text{MC,MA}}^{\geq 1 \text{ truth tau}}}{N_{\text{data,AA}} - N_{\text{MC,AA}}^{\geq 1 \text{ truth tau}}} \quad (5-3)$$

$$\text{FF}_{\tau_2}^{\text{CR}} = \frac{N_{\text{data,MM}} - N_{\text{MC,MM}}^{\geq 1 \text{ truth tau}}}{N_{\text{data,MA}} - N_{\text{MC,MA}}^{\geq 1 \text{ truth tau}}} \quad (5-4)$$

where N_{data} is the experimental data (Data), $N_{\text{MC}}^{\geq 1 \text{ truth tau}}$ represents the number of MC simulation background sample cases containing at least one truth τ_{had} , so the influence of the background containing the truth τ_{had} is completely removed when calculating FF.

The FF of the Wh process is calculated in the control region FFCR- Wh dominated by the W +jets process. In addition to the W +jets process, the number of cases of the top process in FFCR- Wh accounts for about 6% to 7%. In order to make the background estimation of SR more accurate, the definition of FFCR- Wh is similar to that of SR, but in order to improve the anti-tau content, the charge types of the two τ_{had} are required to be the same, and the requirements for some variables are reduced. In addition, in order to verify the accuracy of FF, the Wh analysis also defines the test region FFVR- Wh . The definition of FFVR- Wh is consistent with SR- Wh -LM, but the selection conditions of $m(\tau_1, \tau_2)$ and m_{T2}^{max} are relaxed to improve the statistics. The definitions of FFCR- Wh and FFVR- Wh are shown in Table 5-10.

表 5-10 Wh 过程的 fake factor 方法所用的控制区和检验区的定义。

Table 5-10 The definition of the fake factor control and validation regions.

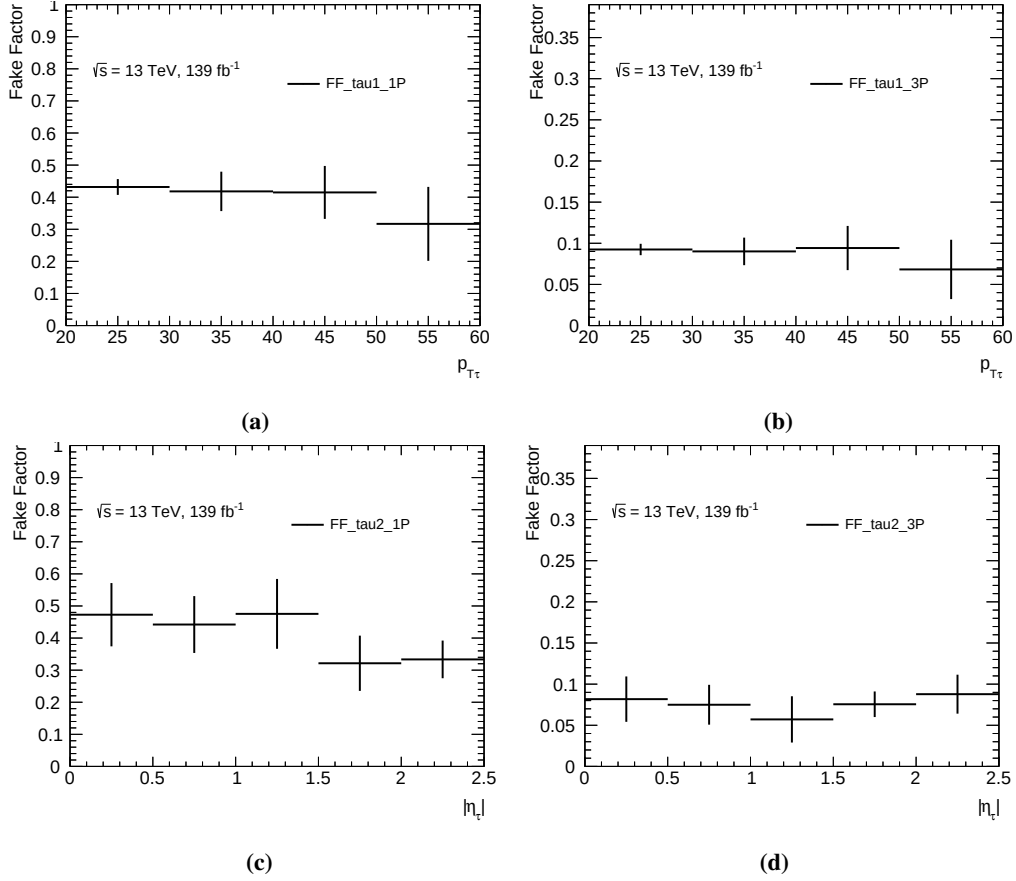
FFCR- Wh	FFVR- Wh
≥ 2 very loose τ (SS)	≥ 2 medium τ (OS)
$m(\tau_1, \tau_2) > 20 \text{ GeV}$	$40 < m(\tau_1, \tau_2) < 160 \text{ GeV}$
$m_{T2}^{\text{max}} > 20 \text{ GeV}$	$m_{T2}^{\text{max}} > 30 \text{ GeV}$
b -jet veto	
$ \Delta\phi(\tau_1, \tau_2) < 3$	
$= 1$ signal light lepton (e or μ)	

The parameterization of τ_{had} in this analysis mainly depends on three independent variables, namely p_T , η and the number of prongs. Considering that the selected variables need to make the FF of τ_1 and τ_2 highly dependent on the variables, τ_1 is binned by p_T , and τ_2 is binned by η . The bin width is also optimized due to the limitation of statistics. At the same time, considering that the sources of the jets mistakenly reconstructed as τ_{had} are different physical objects such as quarks (q) and gluons (g), the jet type can be used as a new independent parameter. Due to the limitation of statistics, the proportion of the number of cases (q/g) of the jet type of fake- τ_{had} in FFCR-Wh and SR is finally taken as the systematic uncertainty of FF. The results show that the difference in q/g of W+jets is within the statistical uncertainty range, and the difference in q/g of the top process is within 20%. By calculating FF in FFCR-Wh, it is finally found that the FF of 1-prong τ_{had} is about 0.4, and the FF of 3-prong is about 0.1. Their center values and uncertainties in each bin are shown in Figure 5-6, where the systematic uncertainty of FF includes statistical uncertainty and the systematic uncertainty of $N_{\text{MC}}^{\geq 1 \text{ truth tau}}$ in the MC sample. Due to the limitation of fitting strategy, the systematic uncertainty of $N_{\text{MC}}^{\geq 1 \text{ truth tau}}$ in the MC sample is conservatively estimated. Because the final systematic uncertainty of SR is about 30%, this study uses a relative uncertainty of 30% as the systematic uncertainty.

After obtaining the complete FF, this analysis also uses the validation area FFVR-Wh to test the accuracy of the FF. Figure 5-7 shows the distribution of p_T and m_{T2} of τ_{had} in FFVR-Wh. The gray histogram comes from the fake factor background estimation. It can be found that the experimental data and the background estimation results are consistent. Since the fake factor method estimates the contribution of the misreconstructed τ_{had} , the MC simulation samples of the remaining backgrounds are required to contain at least one Truth τ_{had} in the case to avoid overlapping with the background estimated by the fake factor.

5.4.2 Estimation of Top quark processes

The top quark process is the second highest background in SR-Wh-LM, mainly from the $t\bar{t}$ process, where a t quark decays to produce a W boson that decays to a lepton, another t quark decays to τ_{had} , and a jet is mistakenly reconstructed as τ_{had} . The top process is mainly obtained through MC simulation samples. In order to estimate the top process more accurately, this analysis obtains the correction parameter (Scale factor, SF) in the control region TCR-Wh with a high content of top process, and at the same time establishes the control region TVR-Wh to verify the rationality of SF. The definitions of TCR-Wh and TVR-Wh are close to those of SR. In order to improve the statistics of the top process, b -jet veto in SR is replaced by $1 \leq N_{b\text{-jets}} \leq 2$, the requirement of opposite charge signs of the two τ_{had} in the final state is removed, and the mass window requirement of $m(\tau_1, \tau_2)$ is also relaxed to 40 GeV to 160 GeV. In order


 图 5-6 Wh 过程 Fake factor 的参数和误差的分布。

其中 (a) 为 p_T 最高的 1-prong τ_{had} p_T , (b) 为 p_T 最高的 3-prong τ_{had} p_T , (c) 为 p_T 次高的 1-prong τ_{had} $|\eta|$, (d) 为 p_T 次高的 3-prong τ_{had} $|\eta|$ 。

Figure 5-6 The Fake Factors and uncertainties.

The Fake Factors and uncertainties as a function of (a) 1-prong leading τ_{had} p_T , (b) 3-prong leading τ_{had} p_T , (c) 1-prong sub-leading τ_{had} $|\eta|$, and (d) 3-prong sub-leading τ_{had} $|\eta|$ for the Intermediate Wh analysis.

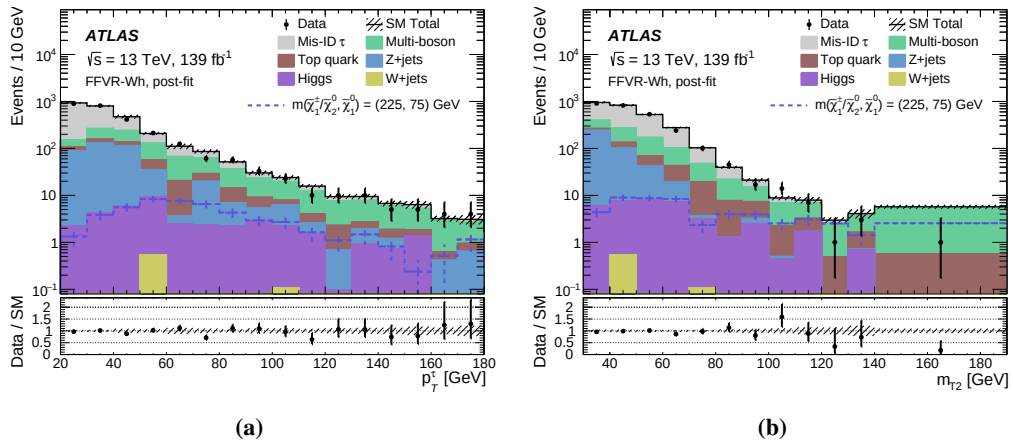

 图 5-7 FFVR-Wh 中 τ_{had} p_T (a) 与 m_{T2} (b) 经过纯本底拟合后的分布。

 Figure 5-7 The post-fit distributions of (a) τ_{had} p_T and (b) m_{T2} in FFVR-Wh region.

to reduce the content of other background processes and further improve the content of top processes, the requirement of $m_{T\text{sum}}$ is increased to 250 GeV. Table 5-11 shows the definitions of $TCR\text{-}Wh$ and $TVR\text{-}Wh$, and the contents of top processes are about 73% and 81%, respectively. Figure 5-8 shows the m_{T2} distribution of $TCR\text{-}Wh$ before fitting and the m_{T2} distribution of $TVR\text{-}Wh$ after applying SF. It can be found that the experimental data is in good agreement with the standard model process.

表 5-11 $TCR\text{-}Wh$ 与 $TVR\text{-}Wh$ 的定义。

Table 5-11 Definitions of $TCR\text{-}Wh$ and $TVR\text{-}Wh$.

$TCR\text{-}Wh$	$TVR\text{-}Wh$
= 1 light lepton (e or μ)	
≥ 2 medium τ	
$40 < m(\tau_1, \tau_2) < 160$ GeV	
$1 \leq N_{b\text{-jets}} \leq 2$	
$\Delta\phi(\tau_1, \tau_2) < 3$	
$m_{T\text{sum}} > 250$ GeV	
$20 \text{ GeV} < m_{T2}^{\text{max}} < 80 \text{ GeV}$	$m_{T2}^{\text{max}} > 80 \text{ GeV}$

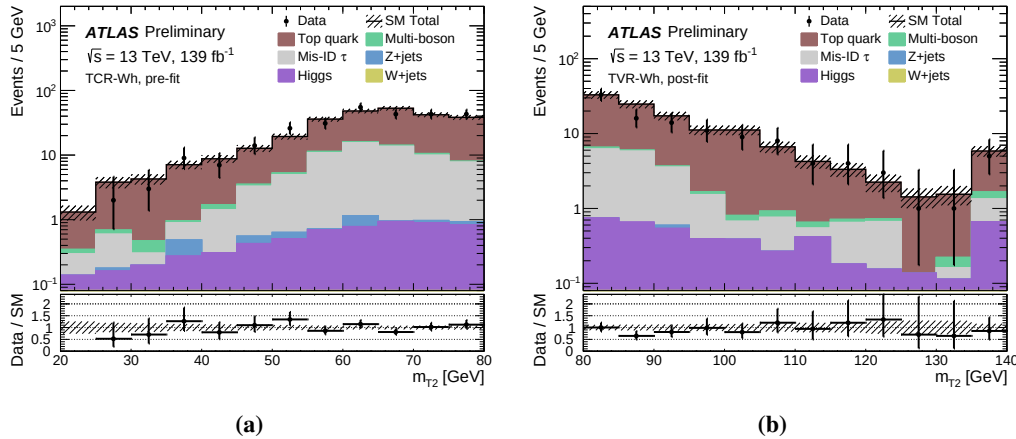


图 5-8 (a) $TCR\text{-}Wh$ 未经纯本底拟合的和 (b) $TVR\text{-}Wh$ 经过纯本底拟合后的 m_{T2} 分布。

Figure 5-8 The m_{T2} distributions of (a) pre-fit $TCR\text{-}Wh$ and (b) post-fit $TVR\text{-}Wh$.

5.4.3 Estimation of Multi-boson process

Multi-boson process is one of the main backgrounds of SR, and its main source is the decay of WZ boson to single lepton and two τ_{had} . In addition, a small part of multi-boson in SR-Wh-LM also comes from the production process of WW or ZZ bosons, which contains a misreconstructed τ_{had} . The background estimation of multi-boson mainly uses MC simulation samples, so this analysis defines the verification area $MBVR\text{-}Wh$ to verify it. In order to increase the content of multi-boson process and be orthogonal to SR statistics, considering that the mass of W and Z bosons is low and the

upper limit of m_{T2} is the mass of W and Z, the $m(\tau_1, \tau_2)$ window is selected between 40 GeV and 70 GeV, and m_{T2} is selected as $m_{T2} < 80$ GeV. In order to suppress the W+jets and Z+jets processes, MBVR-Wh also requires $p_{T\tau_2} > 30$ GeV for the second highest τ_{had} of p_T . This selection condition can reduce the process of τ_{had} including injection misreconstruction. In order to further reduce the impact of Z+jets process, the transverse mass of leptons needs to be higher than 70 GeV. Table 5-12 summarizes the definition of MBVR-Wh, in which the content of multi-boson process is about 61%. Figure 5-9 shows the distribution of m_{T2} and $m(\tau_1, \tau_2)$, and it can be found that the experimental data is in good agreement with the SM process.

表 5-12 MBVR-Wh 的定义。

Table 5-12 Definition of MBVR-Wh.

MBVR-Wh
= 1 light lepton (e or μ)
≥ 2 medium τ (OS)
$40 \text{ GeV} < m(\tau_1, \tau_2) < 70 \text{ GeV}$
$p_{T\tau_2} > 30 \text{ GeV}$
$m_{T,\ell} > 70 \text{ GeV}$
$m_{T2} < 80 \text{ GeV}$
b -jet veto
$ \Delta\phi(\tau_1, \tau_2) < 3$

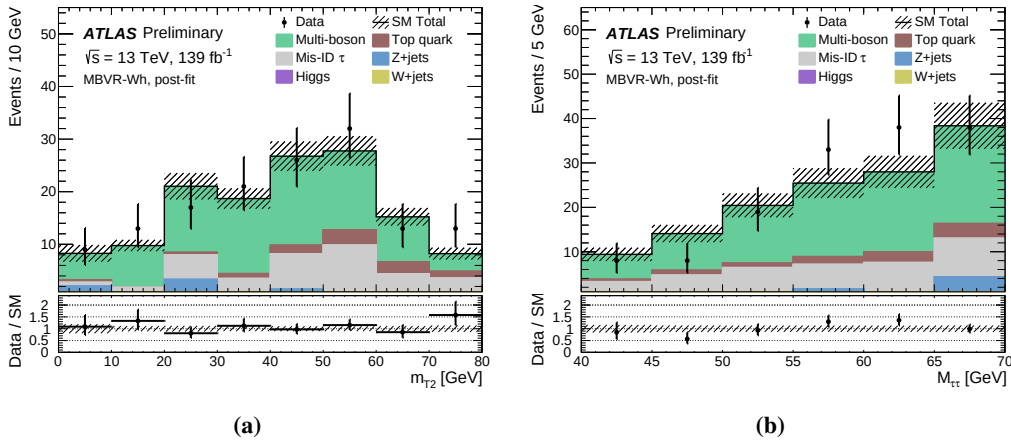

 图 5-9 MBVR-Wh 的 (a) m_{T2} 和 (b) $m(\tau_1, \tau_2)$ 经过纯本底拟合后的分布。

 Figure 5-9 The (a) m_{T2} and (b) $m(\tau_1, \tau_2)$ distributions of MBVR-Wh.

5.5 Systematic Uncertainties

There are multiple sources of systematic uncertainties in experiments, mainly experimental uncertainties from physical object reconstruction, uncertainties in integrated brightness, theoretical uncertainties in SM and signal simulation, and uncertainties caused

by background estimation methods. The uncertainties of the fake factor method have been introduced in 5.4.1 and will not be repeated in this chapter. This chapter mainly introduces the systematic uncertainties of the rest of the Wh process.

5.5.1 Experimental Uncertainties

The experimental uncertainties used in this analysis uses the experimental uncertainty estimation method officially recommended by the ATLAS experiment. The specific uncertainty sources vary depending on the physical object:

- e, μ 's uncertainties include the uncertainties in energy scale and energy resolution, the uncertainties caused by identification efficiency, reconstruction efficiency and isolation requirements, the uncertainties in trigger efficiency and correction.
- τ_{had} 's uncertainties include the uncertainties in jet seed energy scale and jet seed reconstruction and identification, the uncertainties caused by distinguishing electron algorithms, the uncertainties in reconstruction, identification and scale of τ_{had} .
- **jets, b -jets**'s uncertainties mainly come from the uncertainties in jet energy scale and energy resolution, and also include the uncertainties in JVT reconstruction.

In addition, the uncertainties of b -jets also include the uncertainties of the b -tagging algorithm.

- $E_{\text{T}}^{\text{miss}}$'s uncertainty consists of two parts. One part is the uncertainty of the physical object when reconstructing $E_{\text{T}}^{\text{miss}}$, which is passed to the reconstruction of $E_{\text{T}}^{\text{miss}}$.

The other part is the uncertainty of soft-term, which includes the uncertainty of energy scale and resolution.

- **integrated brightness**'s uncertainty is mainly provided by the front-end detector, and the relative uncertainty during ATLAS experiment Run-2 is $\pm 1.7\%$.

- **pile-up effect**'s uncertainty comes from passing the uncertainty of parameter $\langle \mu \rangle$ to the weight of the case.

5.5.2 Theoretical Uncertainties

The theoretical uncertainty includes two parts: the background uncertainty and the signal uncertainty. They are mainly determined by calculating the relative difference between the acceptance (Acc) of the MC sample (nominal sample, Nom) used in the analysis in each region and the MC sample (variation sample, Var) used as the uncertainty:

$$\sigma_{\text{Var}} = \frac{\text{Acc}_{\text{Nom}} - \text{Acc}_{\text{Var}}}{\text{Acc}_{\text{Nom}}} \quad (5-5)$$

For the process with a defined control area, when performing background fitting, the Scale factor (SF) obtained by fitting in the control area will be transferred to the signal area. Therefore, when calculating the theoretical uncertainty in the control area, the

theoretical uncertainty transferred to the scale factor will be calculated to improve the efficiency of fitting. The calculation formula is as follows:

$$\sigma_{\text{SF}} = \frac{\text{Acc}_{\text{SR,Var}}}{\text{Acc}_{\text{SR,Nom}}} \cdot \frac{\text{Acc}_{\text{CR,Nom}}}{\text{Acc}_{\text{CR,Var}}} - 1 \quad (5-6)$$

Different SM background generators and simulation methods bring different types of uncertainties. In addition to the theoretical uncertainties listed below, all SM background processes that directly use MC simulation samples for estimation take into account the uncertainty of the reaction cross section:

- **multi-boson**'s theoretical uncertainties include: (1) μ_R (Renormalisation scale), μ_F (Factorisation scale) and μ_{R+F} (changing μ_R and μ_F at the same time) on which ME calculations depend; (2) PDF uncertainty, by selecting the maximum deviation caused by 100 different PDF changes on the case as the uncertainty; (3) The influence of the initial state evolution constant α_S on the case weight; (4) CKKW uncertainty of Matching and Merging Schema, checking the changes of MC samples with different Matching and Merging energy parameters in the signal region; (5) QSF uncertainty: the uncertainty of the resummation used to calculate gluon radiation; (6) CSS_KIN: the uncertainty of the recoil scheme of the PS method.

- **W+jets/ Z+jets**'s theoretical uncertainties are similar to those of multi-boson, except that the calculation methods of CKKW and QSF use the parameterized estimation uncertainty method given by the physical model research group.

- **$t\bar{t}$ / single top / $t\bar{t}V$** : (1) ISR uncertainty and FSR uncertainty, obtained by comparing samples using different parameters; (3) PDF uncertainty, obtained by selecting the maximum deviation caused by 30 different PDF changes on the case as the uncertainty; (4) Interference of the Wt process, calculated by studying different MC samples of DR schemes and DS schemes; (5) Strong scattering and hadronization uncertainties, each calculated by comparing different MC samples.

- **$t\bar{t}h$** The theoretical uncertainty is similar to that of the $t\bar{t}$ process, the only difference is that the PDF uncertainty is not considered due to the sample restriction.

The theoretical uncertainty of the signal includes the uncertainty of the signal response cross section and the following four parts: (1) The uncertainty of PDF comes from 100 different PDF changes; (2) The uncertainty of μ_R and μ_F ; (3) The uncertainty of Matching and Merging Schema; (4) The uncertainty of initial/final state radiation.

5.5.3 Background Only Fit

In order to verify the rationality of background estimation and uncertainty estimation, physical analysis will first perform background-only fit before fitting with signal samples. The input data used for background-only fit is the real experimental data in the control area, only considering the SM background process, and ignoring the contribu-

tion of the signal in each area. The signal area is used as a verification area. According to the different stages of the analysis, the experimental data in the signal area may be the real experimental data after unblinding. The fitting method used is maximum likelihood fitting (Profile likelihood fit), The HistFitter software [135] is used. In the fitting, the Gaussian distribution G is used to model the systematic uncertainty. The width of the Gaussian distribution is the size of the systematic uncertainty before fitting. Finally, the expression of the likelihood function can be obtained:

$$L(n, \theta^0 | \mu, k, \theta) = \prod_{\text{bin-}i} P(n_i | \mu \cdot S_i(\theta) + k \cdot B_i(\theta) + B_i'(\theta)) \times \prod_{\text{syst-}j} G(\theta_j^0 | \theta_j, \Delta\theta) \quad (5-7)$$

Where P is the Poisson distribution, n_i is the number of cases observed in the i th bin, μ is used to measure the signal strength and is set to 0 in background-only fit, S_i is the number of signal cases, k represents SF, $B_i^{(')}$ is the number of background cases (not including SF correction), and G is the Gaussian distribution describing the systematic uncertainty, where θ^0 is the uncertainty center value of the systematic uncertainty, $\Delta\theta$ is the size of the systematic uncertainty (the width of the Gaussian distribution), and the statistical uncertainty is also treated as an independent Gaussian distribution. The result of background-only fit is obtained by maximizing the likelihood function.

The control region TCR-Wh was defined in the Wh study, and the SF obtained after background-only fit was 1.00 ± 0.14 . Figure 5-10 shows the distribution of SM background in various regions except the control region TCR-Wh. The blue dotted line in the figure is the signal point with a quality parameter of (225,75) GeV. It can be found that the background expected value and the experimental observation value are in good agreement in each verification region.

Table 5-13 shows the relative size of the main systematic uncertainties in the signal region after background-only fit. It can be found that in these two signal regions, statistical uncertainty is one of the main uncertainties. In addition, the theoretical uncertainty of the multi-bosonprocess is also one of the main uncertainties in these two signal regions. Part of the reason is that the multi-bosonprocess has a high content in the signal region, and the other part is that the MC sample statistics for calculating the multi-bosontheoretical uncertainty are limited and the statistical uncertainty is large, especially SR-Wh-HM. The second is the systematic uncertainty of the energy resolution of the jet and the energy scale and identification efficiency of τ_{had} . This is because the definition of the signal region is very dependent on the reconstruction of τ_{had} , and the reconstruction of τ_{had} is closely related to the reconstruction of the jet. In addition, the systematic uncertainty of E_T^{miss} cannot be ignored, and the definition of the signal region depends on the E_T^{miss} variable. The uncertainty of integrated brightness also contributes a lot in the two signal regions. Finally, it can be noticed that the top-related uncertainty and the associated b -tag uncertainty are higher in SR-Wh-LM due to the

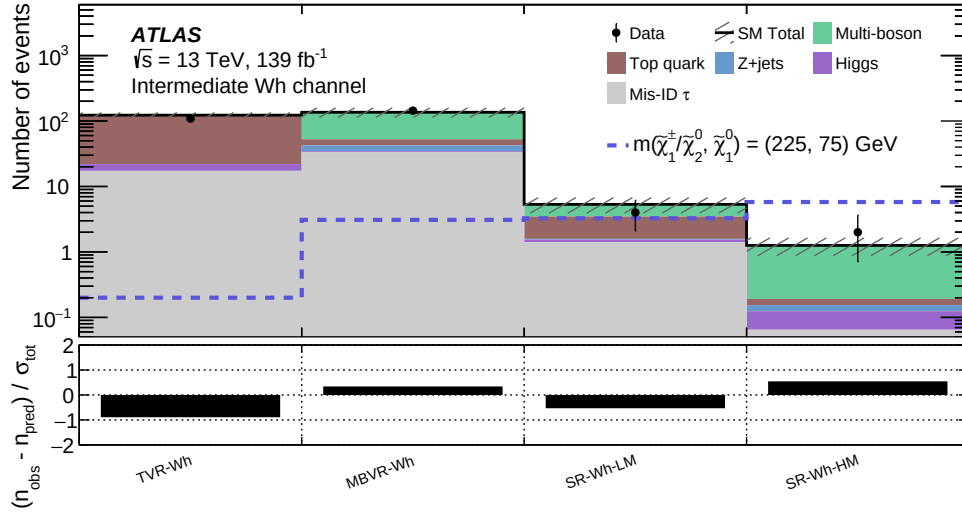


图 5-10 Wh 过程中，实验数据与 SM 本底估计在 $TVR-Wh$ 、 $MBVR-Wh$ 和 SR 中通过纯本底拟合后的分布和比较，其中误差部分包含了全部的系统误差。

Figure 5-10 Comparison of the observed and expected event yields in the $TVR-Wh$, $MBVR-Wh$, and two SRs after the background-only fit, where the hatched band represents the combined statistical and systematic uncertainties of the total SM background.

higher number of top process instances in SR-Wh-LM.

表 5-13 SR-Wh-LM 和 SR-Wh-HM 中的主要的系统误差。

Table 5-13 The dominant systematics in SR-Wh-LM and SR-Wh-HM.

Systematics	SR-Wh-LM	SR-Wh-HM
Total	26.6%	30.4%
STAT	14.1%	13.5%
Multi-boson jet modelling	7.1%	21.8%
Top Theoretical	4.6%	<1.0%
Factor factor	11.1%	2.5%
Top SF	5.0%	<1.0%
E_T^{miss}	2.5%	7.4%
b -jet Tag	7.6%	1.5%
Jet energy resolution	17.6%	9.7%
τ_{had} energy scale	1.7%	8.6%
τ_{had} identification efficiency	1.2%	2.9%
Integrated Lumi	1.1%	1.6%

5.6 Results

This section will introduce the experimental results of this study. In order to test whether there are processes beyond the standard model in the signal region, this study performed model-independent fitting and gave the upper limit of the cross section of the process beyond the standard model in the signal region. In order to test the compatibility of the SUSY process and experimental data, this paper performed model-dependent fitting and gave the relevant mass exclusion limit.

5.6.1 Model-independent Fit

The model-independent fit uses the expected value of the SM background in the SR obtained by background-only fit. By comparing the expected value of the SM background with the experimental data observed in the experiment, it is tested whether there are signal events in the signal area that exceed the standard model. In order to determine the probability of the existence of a process beyond the standard model, it is necessary to define the profile likelihood ratio (PLR):

$$\lambda(\mu) = \frac{L(\mu, \hat{\hat{\theta}}_\mu)}{L(\hat{\mu}, \hat{\theta})} \quad (5-8)$$

The denominator is the maximized likelihood function, and the signal strength μ in the numerator is a free parameter. The test statistic of PLR is defined as $t_\mu = -2 \ln \lambda(\mu)$. After determining the test statistic t_μ , the p-value can be expressed as:

$$p = \int_{t_\mu}^{\infty} f(t_\mu) dt_\mu \quad (5-9)$$

Among them, the distribution function $f(t_\mu)$ of t_μ can use the χ^2 test with one degree of freedom when the number of cases is large (≥ 10). When the number of cases is low, the Toy model should be used to generate false data points based on the probability density function of the distribution of the number of cases to calculate the distribution of the test statistic. From this, the significance Z is $Z = \Phi^{-1}(1 - p)$, where Φ is the quantile function of the normal distribution.

The hypothesis of model-independent fitting is that the contribution of the signal is 0, that is, $p(\mu = 0)$ (p_0), so the smaller p_0 is, the lower the probability of the absence of the signal is, and the higher the probability of the existence of a process beyond the standard model is. Table 5-14 summarizes the p_0 , observed experimental data and SM background expected values in the signal region. The number of cases of expected values is the result after background-only fit. It can be found that in each signal region, the observed data and SM expected values are in good agreement. The table also gives the upper limit of the cross section of the signal beyond the standard model at 95% confidence (σ_{vis}^{95}).

表 5-14 SR-Wh-LM 和 SR-Wh-HM 中的观测数据和预期值。

Table 5-14 Observed and expected numbers of events in SR-Wh-LM and SR-Wh-HM. The one-sided p_0 -values, and the observed and expected 95% CL upper limits on the visible non-SM cross-section (σ_{vis}^{95}) from the model-independent fit are given. Values of $p_0 > 0.5$ are truncated to $p_0 = 0.5$.

SM process	SR-Wh-LM	SR-Wh-HM
Multi-boson	1.85 ± 0.5	1.1 ± 0.4
Misidentified processes	1.4 ± 0.6	0.06 ± 0.03
Top quark	1.9 ± 0.6	$0.04^{+0.06}_{-0.04}$
Z+jets	0.05 ± 0.02	0.03 ± 0.01
Higgs	$0.13^{+0.99}_{-0.13}$	0.06 ± 0.02
SM total	5.3 ± 1.4	1.3 ± 0.4
Observed	4	2
$m(\tilde{\chi}_1^\pm/\tilde{\chi}_2^0, \tilde{\chi}_1^0) = (225, 75) \text{ GeV}$	5.8 ± 1.5	3.3 ± 0.9
p_0	0.5	0.3
Expected $\sigma_{\text{vis}}^{95} [\text{fb}]$	0.05	0.03
Observed $\sigma_{\text{vis}}^{95} [\text{fb}]$	0.04	0.03

5.6.2 Model-dependent Fit

The model-dependent fit assumes that the signal exists (p_{s+b}) and defines the confidence level $\text{CLs} = p_{s+b}/p_0$. Model-dependent fit takes into account the number of cases of each signal model in the SR, and combines the signal strength μ to perform hypothesis testing on the model, and the SF of the SM background is fitted simultaneously with μ . If the hypothesis that the signal strength $\mu \geq 1$ of a signal model is excluded at 95% confidence, the signal model is excluded [136].

Since there are no phenomena in SR that significantly exceed the standard model, This analysis calculates the mass exclusion limits for SR-Wh-LM and SR-Wh-HM at 95%. Since the definitions of SR-Wh-LM and SR-Wh-HM are not orthogonal, the final exclusion limits select each $\tilde{\chi}_1^\pm \tilde{\chi}_2^0 \rightarrow Wh$ model expected to be more significant in the two signal regions of, Figure 5-11 shows the quality exclusion limit, It can be found that SR-Wh-LM and SR-Wh-HM target different mass ranges. Finally, when the LSP mass is 0, this analysis excludes regions with $\tilde{\chi}_1^\pm/\tilde{\chi}_2^0$ masses below 330 GeV.

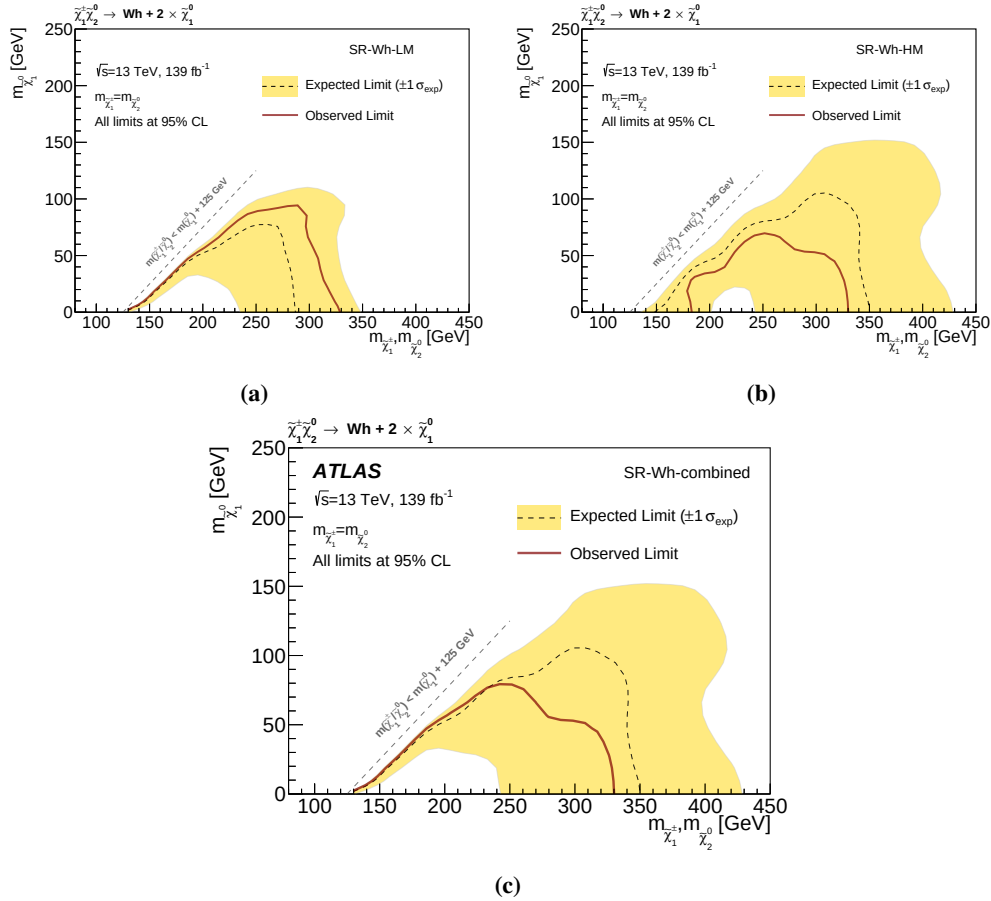


图 5-11 95% 置信度下 $\tilde{\chi}_1^\pm \tilde{\chi}_2^0$ 通过 Wh 衰变的质量排除限。

- (a) 只考虑 SR-Wh-LM; (b) 只考虑 SR-Wh-HM; (c) SR-Wh-LM 和 SR-Wh-HM 联合排除限, 联合排除限利用了预期显著性更大的信号区。

Figure 5-11 The 95% CL exclusion

contours for simplified models of $\tilde{\chi}_1^\pm \tilde{\chi}_2^0$ production decaying via an intermediate Wh .

- (a) SR-Wh-LM, (b) SR-Wh-HM, and (c) the combined contour where the best expected limits for SR-Wh-LM and SR-Wh-HM are used. The solid (dashed) lines show the observed (expected) exclusion contours. The band around the expected limit shows the $\pm 1\sigma$ variations, including all uncertainties except theoretical uncertainties in the signal cross-section.

5.7 Conclusion

This study uses the complete experimental data during the ATLAS experiment Run2 to study the process of Gaugino pair production and decay to the single-lepton double-tau state through W and h . The signal region defined in this analysis has a certain sensitivity to all similar new physical processes with a final state of $1\ell 2\tau_{\text{had}}$. Since no phenomena that obviously exceed the standard model are observed in the signal region, this analysis gives the upper limit of the signal reception degree $\times$ cross section beyond the standard model in each signal region at a 95% confidence level. The reception degree $\times$ cross section of the new physical process in SR-Wh-LM (SR-Wh-HM) should be lower than 0.04 fb (0.03 fb). At the same time, under the assumption of a simplified model, this analysis gives the exclusion limit of the $m(\tilde{\chi}_1^\pm/\tilde{\chi}_2^0) - m(\tilde{\chi}_1^0)$ mass parameter space. When the LSP mass is 0, this analysis excludes the region where $m(\tilde{\chi}_1^\pm/\tilde{\chi}_2^0)$ is below 330 GeV. This is the first time that the ATLAS experiment has given the exclusion limit for this process.

第 6 章 Searching for Gauginos in the Final State of Two Taus

This chapter introduces the search for the production of $\tilde{\chi}_1^\pm \tilde{\chi}_2^0$ and $\tilde{\chi}_1^\pm \tilde{\chi}_1^\mp$ by decaying to at least two τ_{had} final states via $\tilde{\tau}$ or $\tilde{\nu}_\tau$ using experimental data from 139 fb^{-1} during Run 2 on the ATLAS experiment.

6.1 Motivation and Signal Model

The signal model of this analysis is shown in Figure 6-1. Both processes are derived from the simplified model of R parity conservation. Figure 6-1(a) and 6-1(b) respectively show the two processes of gaugino decay through the $\tilde{\tau}/\tilde{\nu}_\tau$ intermediate state, which are collectively referred to as "Stau process" (Intermediate Stau analysis) below. The experimental motivation of this analysis is basically consistent with the research in Chapter 5.1. This study is about the production process of gaugino pairs, and the production cross section is relatively higher than that of slepton production process; In some models, the third generation slepton ($\tilde{\tau}$) is lighter than the first and second generation slepton ($\tilde{\ell}$) [137], so the relatively low mass gaugino particles can be studied through the $\tilde{\tau}$ intermediate state; In addition, the lower mass gaugino and $\tilde{\tau}$ can explain the excess of the anomalous magnetic moment of the muon observed in the experiment [129], and this study provides dark matter candidates that are consistent with the observed values of the universe. Therefore, this analysis process has strong physical motivation and significance.

The ATLAS experiment searched for the gaugino pair production process in the Run 1 phase and the early stage of Run 2, and found no experimental phenomena that were obviously beyond the standard model, and gave a mass exclusion limit at 95% confidence level [138–140]. If the mass of LSP is 0, in the $\tilde{\chi}_1^\pm \tilde{\chi}_1^\mp$ production process, the parameter space with a $\tilde{\chi}_1^\pm$ mass lower than 630 GeV is excluded, In the $\tilde{\chi}_1^\pm \tilde{\chi}_2^0$ pair production process, the region with a mass of $\tilde{\chi}_1^\pm$ and $\tilde{\chi}_2^0$ below 760 GeV is excluded [140]. At the same time, the CMS experiment used the complete Run2 experimental data to search for the process of $\tilde{\chi}_1^\pm \tilde{\chi}_2^0$ decaying through $\tilde{\tau}$, and the gaugino mass exclusion limit reached 980 GeV [141]. It can be found that the ATLAS experimental exclusion limit is still far from the TeV level, so it is very important to use the complete ATLAS Run2 experimental data for searching. In addition, compared with previous studies, this study considers the final state of the same-sign tau, which can effectively improve the signal sensitivity in the mass compression region. This study also uses the τ_{had} identification working point based on the RNN model, which greatly improves the reconstruction efficiency of τ_{had} and reduces the related background.

In this study, in order to simplify the parameters required by the model, for the intermediate states $\tilde{\tau}$ and $\tilde{\nu}_\tau$, their decay branch ratios are fixed to $B(\tilde{\tau} \rightarrow \tau \tilde{\chi}_1^0) = B(\tilde{\nu}_\tau \rightarrow \nu \tilde{\chi}_1^0) = 1$, ultimately, the final state of the $\tilde{\chi}_1^\pm \tilde{\chi}_1^\mp$ process contains two τ_{had} , two ν_τ and a pair of LSPs, and the final state of $\tilde{\chi}_1^\pm \tilde{\chi}_2^0$ contains three (one) τ_{had} , one (three) ν_τ and a pair of LSPs. This chapter mainly studies the process with at least two τ_{had} in the final state. In terms of mass parameters, $\tilde{\nu}_\tau$, $\tilde{\tau}_L$ and $\tilde{\tau}_R$ are mass degenerate and satisfy the mass condition: $m(\tilde{\tau}/\tilde{\nu}_\tau) = [m(\tilde{\chi}_1^\pm/\tilde{\chi}_2^0) + m(\tilde{\chi}_1^0)]/2$. The mass range of $\tilde{\chi}_1^0$ in the signal model selected for this analysis is 0 to 800 GeV, and the mass range of $\tilde{\chi}_1^\pm$ and $\tilde{\chi}_2^0$ is 100 to 1500 GeV. The settings of the remaining supersymmetric particles are consistent with the Wh process, all of which are in a decoupled state. Figure 6-2 shows the specific signal mass parameter distribution. Considering that $\tilde{\chi}_1^\pm \tilde{\chi}_2^0$ is wino type and the masses of $\tilde{\tau}$ and $\tilde{\nu}_\tau$ are consistent, the following simplification is made: $B(\tilde{\chi}_1^\pm \rightarrow \tilde{\tau}\nu) = B(\tilde{\chi}_1^\pm \rightarrow \tilde{\nu}_\tau\tau) = B(\tilde{\chi}_2^0 \rightarrow \tilde{\tau}\tau) = B(\tilde{\chi}_1^\pm \rightarrow \tilde{\nu}_\tau\nu) = 0.5$. The interaction cross section calculation of the signal sample also uses the RESUMMINO framework, using the PDF of CTEQ6.6 and MSTW2008nlo90cl, and obtains the accuracy of NLO+NNL.

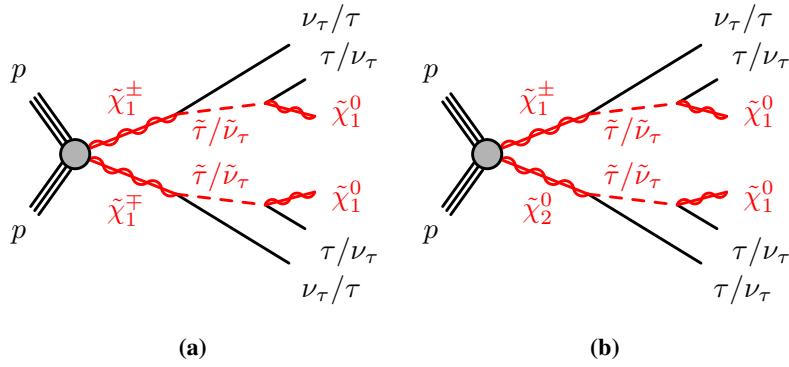


图 6-1 Gaugino 对产生并通过 $\tilde{\tau}/\tilde{\nu}_\tau$ 衰变的示意图。

(a) 展示了 $\tilde{\chi}_1^\pm \tilde{\chi}_1^\mp$ 通过 $\tilde{\tau}/\tilde{\nu}_\tau$ 衰变过程, (b) 展示了 $\tilde{\chi}_1^\pm \tilde{\chi}_2^0$ 通过 $\tilde{\tau}/\tilde{\nu}_\tau$ 衰变过程。

Figure 6-1 Representative diagrams of Gaugino pair productions via $\tilde{\tau}/\tilde{\nu}_\tau$ decay.

(a) shows $\tilde{\chi}_1^\pm \tilde{\chi}_1^\mp$ and (b) shows $\tilde{\chi}_1^\pm \tilde{\chi}_2^0$.

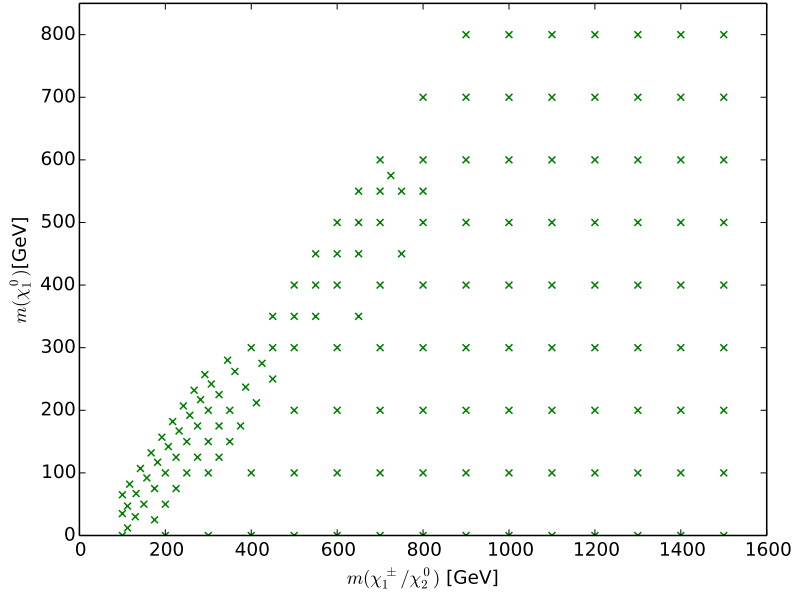


图 6-2 信号点质量参数分布。

Figure 6-2 The mass grid of the signal points.

6.2 Event Reconstruction and Selection

The physical object reconstruction, event reconstruction and de-coincidence process of the Stau process are consistent with the Wh process, which can be referred to Chapter 5.2.1, and will not be repeated in this chapter. However, the trigger selection of the Stau process is completely different from that of the Wh process.

For the Stau process, because the reconstruction of τ_{had} requires the participation of the jet, and the number of jets in the LHC events is relatively high, the threshold for the di- τ_{had} un-prescale trigger is usually high, thus reducing the efficiency of event selection. At the same time, considering that the mass range of the Stau signal point is large, the $E_{\text{T}}^{\text{miss}}$ distribution peaks of different signal points vary greatly, so the Stau process simultaneously uses the asymmetric di- τ trigger based on the two τ_{had} high transverse momentum requirements and the di- $\tau + E_{\text{T}}^{\text{miss}}$ trigger based on the high $E_{\text{T}}^{\text{miss}}$ requirements to improve the signal selection efficiency. Table 6-1 summarizes the trigger threshold requirements of these two triggers over the years. It can be found that these two triggers target different final state dynamic phase spaces, and the asymmetric di- τ trigger has higher requirements for p_{T} . The triggers in 2018 contain "tracktwoEF", while the triggers from 2015 to 2017 only contain "tracktwo", This is because an algorithm based on full track information replaces the fast track reconstruction system.

表 6-1 Stau 过程的触发器的 p_T 与 E_T^{miss} 的离线阈值。

Table 6-1 The triggers and the offline thresholds of p_T and E_T^{miss} for the Intermediate Stau analysis.

Trigger Type	Trigger Selections	Year	p_T Online [GeV]	p_T Offline [GeV]
Di- τ + E_T^{miss} trigger	leading tau p_T [GeV]	2015-2017	35	50
		2018	60	75
	2nd leading tau p_T [GeV]	2015-2018	25	40
	E_T^{miss} [GeV]	2015-2018	50	150
Asymmetric di- τ trigger	leading tau p_T [GeV]	2015-2018	80	95
	2nd leading tau p_T [GeV]	2015-2017	50	60
		2018	60	75

6.3 Signal Region Definition

6.3.1 Preselection

In this study, there are two mechanisms for the process of gaugino pair generation and $\tilde{\tau}/\tilde{\nu}_\tau$ decay: $\tilde{\chi}_1^\pm \tilde{\chi}_1^\mp$ (C1C1) and $\tilde{\chi}_1^\pm \tilde{\chi}_2^0$ (C1N2) generation process. The final state of the C1C1 process has at most two τ_{had} , and the charges are opposite. The final state of the C1N2 process has one or three τ_{had} . This paper only considers the final state that contains at least two τ_{had} , and the charges of the highest and second highest τ_{had} can be the same (C1N2SS) or opposite (C1N2OS). In the specific analysis, considering that the main backgrounds of OS and SS are not consistent, C1C1, C1N2OS and C1N2SS are studied separately as three different processes.

In the preliminary selection stage of the cases, considering that the signal quality parameter distribution range of C1C1 and C1N2 is large, and the phase space of the two triggers used in the final state is quite different, the low-quality (LM) and high-quality (HM) signal regions are defined respectively. The main purpose of the high-quality signal region is to expand the exploration range obtained by using part of the Run2 data, and the main purpose of the low-quality signal region is to study the area with low gaugino quality and small NSLP-LSP quality difference. Table 6-2 shows the preliminary selection conditions of the cases for OS and SS processes. Each process requires that the final state contains at least two τ_{had} , C1C1 and C1N2OS require that the two τ_{had} have different signs, and C1N2SS requires that the two τ_{had} have the same sign. Considering that there is no b -jet related physical object in the final state of the signal, the selection condition of b -jets veto is added to suppress the top related background. In order to reduce the contribution of the Z or h boson correlation background in the OS final state, this analysis requires the invariant mass $m(\tau_1, \tau_2)$ of the final state τ_{had} to be higher than 120 GeV in the OS process to suppress the correlation background (Z/ h -veto). In addition, in order to be orthogonal to the HM signal region, the LM signal

region requires $E_T^{\text{miss}} < 150 \text{ GeV}$.

表 6-2 Stau 过程的事例初选条件。

Table 6-2 Summary of preselection requirements for the Intermediate Stau analysis.

LowMass SR	HighMass SR
≥ 2 medium taus	
b -jet veto	
Z/h -veto ($m(\tau_1, \tau_2) > 120 \text{ GeV}$) (only for OS channel)	
Asymmetric di-tau trigger	di-tau+ E_T^{miss} trigger
$E_T^{\text{miss}} < 150 \text{ GeV}$	$E_T^{\text{miss}} > 150 \text{ GeV}$
Table 6-1 shows requirements on τ_1 and τ_2 p_T .	

6.3.2 Signal Region Definition

In order to define the signal area, the three processes C1C1, C1N2OS and C1N2SS adopt the "Cut and Count" method. Each process defines two orthogonal signal areas for LM and for HM, so that statistical interpretation can use these jointly. Two signal areas. The definition of the signal area also takes advantage of signal saliency. Due to the wide range of signal quality parameters, three signal reference points with different quality parameter settings are used:

- $m(\tilde{\chi}_1^\pm, \tilde{\chi}_1^0) = (700, 400) \text{ GeV}$: $\sigma = 4.4387 \text{ [fb]}$, for the transition region between LM and HM.
- $m(\tilde{\chi}_1^\pm/\tilde{\chi}_2^0, \tilde{\chi}_1^0) = (1100, 400) \text{ GeV}$: $\sigma = 0.740372 \text{ [fb]}$, for the HM region.
- $m(\tilde{\chi}_1^\pm/\tilde{\chi}_2^0, \tilde{\chi}_1^0) = (157, 92) \text{ GeV}$: $\sigma = 4389.25 \text{ [fb]}$, for the LM region.

The C1N2OS (C1N2SS) signal region obtained by the Cut and Count method requires that the final state contains at least two OS (SS) passing through the medium working point. C1C1 requires that the final state can only have two OS medium- τ_{had} .

In the LM signal region, both the LM signal region of C1C1 (SR-C1C1-LM) and the LM signal region of C1N2OS (SR-C1N2OS-LM) require that at least one of the final medium- τ_{had} passes the tight working point. This is because the E_T^{miss} requirement of the LM signal region is low and there are more injections, so the identification of τ_{had} is strictly required to reduce the misreconstructed τ_{had} caused by the injection. SR-C1C1-LM and SR-C1N2OS-LM also require $E_T^{\text{miss}} > 60 \text{ GeV}$ to further reduce the contribution of the misreconstructed τ_{had} of the injection. At the same time, SR-C1C1-LM (SR-C1N2SS-LM) requires $|\Delta\phi(\tau_1, \tau_2)| > 1.5 (> 1.6)$, and SR-C1N2OS-LM and SR-C1N2SS-LM require the number of injections to be less than three, all of which are used to suppress the background of the QCD process. In addition, SR-C1N2SS-LM uses $m_{T\text{sum}} > 200 \text{ GeV}$ to further suppress the background related to W and Z bosons.

All HM signal regions have a requirement of $m_{T\text{sum}}$ to suppress the background. All signal regions have a requirement of m_{T2} to further suppress $t\bar{t}$ and the WW process

background. The definition of the signal regions is summarized in Table 6-3, and the number of cases that have not been fitted with background is summarized in Table 6-4.

表 6-3 Stau 过程的信号区定义。

Table 6-3 SR definitions of the Intermediate Stau analysis.

SR-	C1C1-LM	C1N2OS-LM	C1N2SS-LM	C1C1-HM	C1N2OS-HM	C1N2SS-HM
Trigger	asymmetric di- τ			di- $\tau + E_T^{\text{miss}}$		
E_T^{miss} [GeV]	< 150			> 150		
N(Medium τ)	= 2	≥ 2	≥ 2	= 2	≥ 2	≥ 2
N(Tight τ)	≥ 1	≥ 1	–	–	–	–
τ_{had} charges	OS	OS	SS	OS	OS	SS
N(b -jets)	= 0	= 0	= 0	= 0	= 0	= 0
N(Jets)	–	< 3	< 3	–	–	–
$ \Delta\phi(\tau_1, \tau_2) $	> 1.6	–	> 1.5	–	–	–
$m(\tau_1, \tau_2)$ [GeV]	> 120	> 120	–	> 120	> 120	–
E_T^{miss} [GeV]	> 60	> 60	–	–	–	–
$m_{T\text{sum}}$ [GeV]	–	–	> 200	> 400	> 400	> 450
m_{T2} [GeV]	> 80	> 70	> 80	> 85	> 85	> 80

表 6-4 Stau 过程的未进行本底拟合前的事例含量。

Table 6-4 The event yields in the SRs, The yields are before the background-only fit.

	SR-C1C1-LM	SR-C1N2OS-LM	SR-C1C1-HM	SR-C1N2OS-HM
Top	0.95 ± 0.38	1.08 ± 0.40	0.36 ± 0.22	0.36 ± 0.22
W+jets	0.43 ± 0.50	0.62 ± 1.18	0.30 ± 0.17	0.30 ± 0.17
Z+jets	1.42 ± 0.51	2.46 ± 1.43	0.78 ± 0.56	0.86 ± 0.56
Multi-boson	1.65 ± 0.36	3.18 ± 0.47	2.19 ± 0.42	2.43 ± 0.44
Higgs	0.27 ± 0.26	0.39 ± 0.27	0.011 ± 0.003	0.73 ± 0.72
Multi-jet	1.86 ± 0.19	4.51 ± 0.29	0.77 ± 0.20	0.72 ± 0.19
SM total	6.58 ± 0.95	12.24 ± 2.00	4.41 ± 0.78	5.40 ± 1.07
	SR-C1N2SS-LM		SR-C1N2SS-HM	
Top	0.01 ± 0.01		0.84 ± 0.36	
W+jets	0.32 ± 0.32		0.10 ± 0.10	
Z+jets	0.20 ± 0.20		0.59 ± 0.56	
Multi-boson	0.47 ± 0.11		0.81 ± 0.21	
Higgs	0.00 ± 0.00		0.02 ± 0.00	
Multi-jet	0.94 ± 0.27		0.0 ± 0.0	
SM total	1.95 ± 0.48		2.35 ± 0.80	

6.4 Background Estimation

The main background of the Stau process can be classified as "real" or "false reconstruction" τ_{had} , the former is called irreducible background, and the latter is called reducible background. The fake τ_{had} in the reducible background mainly comes from the jets produced by the hadronization process of the first two generations of quarks or gluons, and the e or μ are misreconstructed as 1-prong τ_{had} . The main sources of the reducible background in the Stau process are multi-jet processes (multi-jets), W +jets and top quark related processes. Among them, although the jet false reconstruction rate of the multi-jet process is low, the total number of cases is still high due to the large cross section. The proportion of multi-jets in the LM signal area is 28% to 48%, and the proportion of multi-jets in the HM signal area is less than 17%. For the multi-jets process, the Stau analysis uses the data-driven ABCD method for estimation.

Most W +jets processes contain a truth τ_{had} of W boson decay and at least one fake τ_{had} caused by injection. Therefore, Stau analysis adopts a semi-data-driven method to define a control region (WCR) dominated by W +jets and correct the W +jets process to the real data. W +jets accounts for about 4% to 16% of the total background events. The fake- τ_{had} caused by the top process in the SS final state signal region is also the main source of background. Therefore, the relevant control region defined for the top process is also corrected for this final state.

In terms of irreducible background, For the multi-boson process, the main background process of the OS final state is the WW or ZZ generation process, while the main source of the SS final state is the truth τ_{had} generated by WZ . In addition, the Z +jets process is also dominated by truth τ_{had} . The truth τ_{had} content in the Z +jets and multi-boson processes is as high as 85% to 90%. The truth τ_{had} content of the top process in the OS final state is also as high as 80%. For the process dominated by truth τ_{had} , Stau analysis directly uses MC simulation samples for estimation and defines validation areas to test the model performance.

6.4.1 Background estimation and ABCD method for multi-jet process

Figure 6-3 is a schematic diagram of the ABCD method. The ABCD method first needs to define three mutually orthogonal control zones for the signal zone. These three control zones and the signal zone are conventionally named A, B, C (control zone) and D (signal zone). These four zones are generally defined by two or two groups of kinetic variables with almost no correlation. The core assumption of the ABCD method is that the proportion of the background of the multi-jet process in the control zone C (CR-C) and B (CR-B) is the same as that in the signal zone D (SR-D) and the control zone A (CR-A). Thus, the number of multi-jet process cases in SR-D is obtained as $N_D = N_A \times (N_C/N_B)$, where N_C/N_B is defined as the transfer factor (TF), and SR-D corresponds

to the six signal zones of Stau analysis. In addition to these four CRs (SRs), the ABCD method also defines validation regions VR-E and VR-F to verify the rationality of TF and estimate the systematic uncertainty caused by the correlation of dynamic variables. As shown in the figure, the validation region VR-F (VR-E) is close to SR-D (CR-C) and between SR-D and CR-C (CR-A and CR-B) to ensure the orthogonality of the two regions.

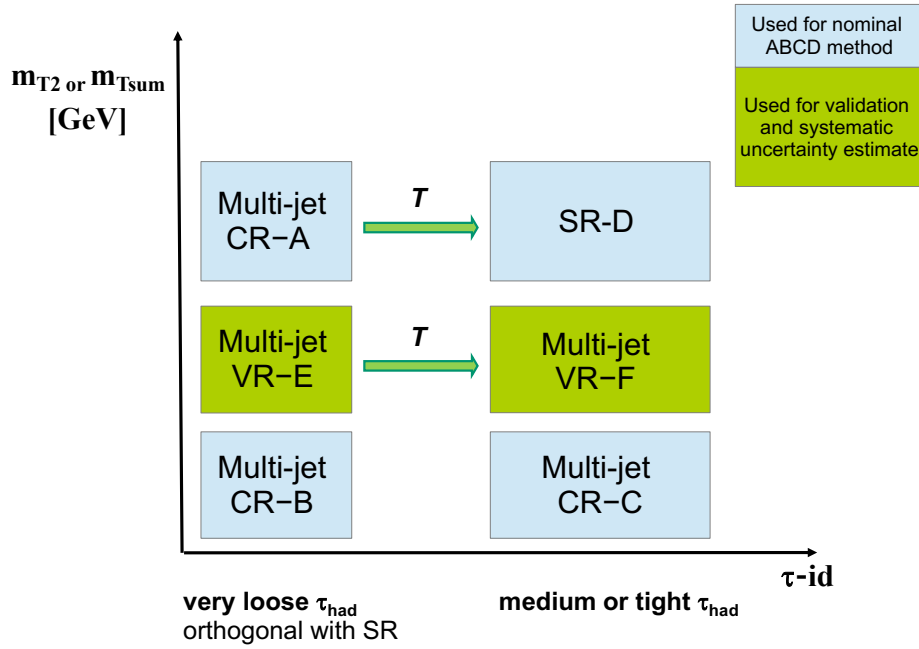


图 6-3 ABCD 方法示意图。

Figure 6-3 Illustration of the ABCD method.

In the analysis, two sets of variables with small correlation, τ_{had} identification working point and m_{T2} (or m_{Tsum}), are used to define the control area, verification area and signal area. The uncertainty caused by the correlation between the two sets of variables is also taken into account in the system uncertainty. Among them, CR-C, VR-F and SR-D use medium or tight identification working point, and the charge requirement of τ_{had} is consistent with the signal area, while CR-B, VR-E and CR-A use very loose working point and are orthogonal to SR-D. The selection conditions of other variables are shown in Table 6-5. In addition, because the multi-jet process is mainly generated by strong interactions and the final state E_T^{miss} is low, the effect of reducing the selection conditions of E_T^{miss} on TF is very small. In order to improve the purity and statistics of the multi-jet process in the control area and the verification area, all triggers of CR-B, C and VR-E, F use di-tau triggers, but the p_T threshold of di-tau+ E_T^{miss} trigger is still used, so the final state phase space of τ_{had} is not greatly changed, and the impact on TF is low.

Except for SR-D, the number of cases of multi-jet processes in each area of the

ABCD method is calculated by subtracting the MC simulation samples of other SM processes from the experimental data. Finally, it is found that the content of multi-jet processes in CR-B and VR-E corresponding to the signal area of the three processes is as high as 90%, the content of multi-jet processes in CR-A is 41% to 95%, and the content of multi-jet processes in CR-C is 26% to 54%.

表 6-5 Stau 过程的 ABCD 方法中, CR 和 VR 的定义。其中 CR-B、VR-E 和 CR-A 的定义使用了 very loose ID。

Table 6-5 The definition of the ABCD regions for all channels, where the definitions of CR-B, VR-E, and CR-A use very loose ID.

	Kinematics	CR-B / CR-C	VR-E / VR-F	CR-A / SR
C1C1-LM	m_{T2} [GeV]	$\in [15, 35]$	$\in [35, 80]$	> 80
	E_T^{miss} [GeV]	$\in [10, 150]$	$\in [10, 150]$	$\in [60, 150]$
C1C1-HM	m_{T2} [GeV]	$\in [35, 60]$	$\in [60, 85]$	> 85
	$m_{T\text{sum}}$ [GeV]	$\in [100, 300]$	$\in [200, 400]$	> 400
	E_T^{miss} [GeV]	> 50	> 50	> 150
C1N2OS-LM	m_{T2} [GeV]	$\in [15, 35]$	$\in [35, 70]$	> 70
	E_T^{miss} [GeV]	$\in [10, 150]$	$\in [10, 150]$	$\in [60, 150]$
C1N2OS-HM	m_{T2} [GeV]	$\in [35, 60]$	$\in [60, 85]$	> 85
	$m_{T\text{sum}}$ [GeV]	$\in [150, 300]$	$\in [200, 400]$	> 400
	E_T^{miss} [GeV]	> 50	> 50	> 150
C1N2SS-LM	$m_{T\text{sum}}$ [GeV]	< 100	$\in [100, 200]$	> 200
	$ \Delta\phi(\tau_1, \tau_2) $	< 1.5	< 1.5	> 1.5
C1N2SS-HM	$m_{T\text{sum}}$ [GeV]	$\in [100, 200]$	$\in [200, 450]$	> 450
	E_T^{miss} [GeV]	> 50	> 50	> 150

The systematic uncertainty of the ABCD method has multiple sources, mainly including:

- τ_{had} Identify the systematic uncertainty caused by the correlation between the working point and m_{T2} ($m_{T\text{sum}}$). The uncertainty is calculated by checking the difference between the TF of CR-B and C and the TF of VR-E and F.
- Systematic uncertainty caused by other SM processes in CR-A: Because the calculation method of the multi-jet process is to use the experimental data minus the MC simulation samples of other background processes, it is necessary to consider the influence of the systematic uncertainty of the MC simulation samples of other backgrounds that are subtracted. The specific calculation of this uncertainty is achieved through pure background fitting. In the fitting stage, an additional SF for the multi-jet process is defined, and CR-A is considered as its control area to calculate the influence of the sys-

tematic uncertainty on SF. Since CR-A and SR-D share the same SF in the fitting, the influence of the systematic uncertainty will be transmitted to the multi-jet process of SR in the form of the uncertainty of SF.

- Sample statistics of the control area: The influence of the statistical uncertainty of CR-B and CR-C on TF is also an independent systematic uncertainty.

6.4.2 Estimation of W+jetsprocess

In each signal region of the Stau process, most of the W+jetsbackground contains at least one fake τ_{had} . In order to correct the model performance of the misreconstructed τ_{had} and reduce the theoretical uncertainty of the W+jetsprocess, This study defines the WCR-OS (WCR-SS) control region for the C1C1 and C1N2OS (C1N2SS) processes to correct the number of W+jetsevents. The definition of WCR is to obtain the misreconstructed τ_{had} of the injection by marking the $W \rightarrow \mu\nu$ process. The trigger of WCR selects a single muon trigger, and WCR-OS (WCR-SS) considers the final state of the charge OS (SS) of μ and fake τ_{had} . In order to reduce the influence of other backgrounds, the p_T of muons is required to be higher than 40 GeV, and the p_T of τ_{had} is required to be higher than 50 GeV. In addition, because the decay of top quarks can produce W bosons and be accompanied by the production of multiple jets, the definition of WCR also utilizes the b -jet veto and m_{CT} (Cotransverse mass) [142] to suppress the top process. The idea of defining the variable m_{CT} is: Assume that the source of the final state E_T^{miss} is the neutrino produced by the $t\bar{t}$ pair and the decay of the W boson when $t \rightarrow b/s + W$ decays, At the same time, assume that μ and τ_{had} each come from a W boson decay, and finally assume that the final state jet comes from the b/s quark. Then, in theory, the combination of the invariant mass of the system composed of the jet + μ/τ_{had} + part of the E_T^{miss} can be determined by traversing all the combinations of the final state jets, and the combination closest to the top quark mass can be determined, so as to determine the possibility that the event comes from $t\bar{t}$ to minimize the $t\bar{t}$ process. In addition, in order to further reduce the single top and Z+jetsbackground, the definition of CR and VR of OS also requires $m_T < 140$ GeV of muons to suppress the Z+jetsprocess with higher transverse momentum. Because the contribution from the Z boson in the SS final state is low, the m_T defined by CR and VR is relaxed to 150 GeV, but $m_{T,\mu} + m_{T,\tau} > 80$ GeV is required to suppress the multi-jet background. Finally, considering that the neutrinos produced by W decay can produce a considerable contribution E_T^{miss} , OS (SS) uses the selection condition of $E_T^{\text{miss}} > 60$ GeV ($E_T^{\text{miss}} > 50$ GeV) to suppress other backgrounds without significantly affecting the W+jetsprocess. Since the fake τ_{had} and μ of the final state of the W+jetsprocess are not related, the m_{T2} calculated by fake τ_{had} and μ will not be truncated at the mass of the W boson, so there is basically no need to consider the impact of m_{T2} on the W+jetsprocess. In order to make the definitions of WCR and WVR close to SR, OS additionally requires $m_{T2} > 40$ GeV, and OS (SS) uses

$m_{T2} = 70 \text{ GeV}$ ($m_{T2} = 60 \text{ GeV}$) to divide CR and VR. The definitions of each WCR and WVR are shown in Table 6-6.

表 6-6 Stau 过程的 WCR 和 WVR 的定义。

Table 6-6 The definition of WCR and WVR.

WCR-OS	WVR-OS	WCR-SS	WVR-SS
Baseline electron veto			
b -jet veto			
$p_{T\tau} > 50 \text{ GeV}, p_{T\mu} > 40 \text{ GeV}$			
$= 1 \text{ medium } \tau, = 1 \text{ isolated } \mu \text{ (OS)}$		$= 1 \text{ medium } \tau, = 1 \text{ isolated } \mu \text{ (SS)}$	
$m_{CT} \text{ top-tagged events veto}$		-	
$m_{T,\mu} < 140 \text{ GeV}$		$50 < m_{T,\mu} < 150 \text{ GeV}$	
-		$m_{T,\mu} + m_{T,\tau} > 80 \text{ GeV}$	
$E_T^{\text{miss}} > 60 \text{ GeV}$		$E_T^{\text{miss}} > 50 \text{ GeV}$	
$40 < m_{T2}(\tau, \mu) < 70 \text{ GeV}$	$m_{T2}(\tau, \mu) > 70 \text{ GeV}$	$m_{T2}(\tau, \mu) < 60 \text{ GeV}$	$m_{T2}(\tau, \mu) > 60 \text{ GeV}$

The background estimation method for the multi-jet process in WCR and WVR is the OS-SS method, which uses the number of multi-jet process cases in the SS (OS) final state to estimate the number of multi-jet process cases in the OS (SS) final state. Taking WCR-OS as an example, the OS charge requirement in the definition of WCR-OS is changed to the SS charge requirement, and the distribution obtained by subtracting other background MC simulation samples from experimental data at the SS final state is directly used as the multi-jet process distribution at the OS final state. This method relies on the expected value of the SS and OS ratio of the multi-jet process to be 1. Considering that the ratio may change in the actual situation, for example, the charge measurement accuracy of particles with larger p_T in the track chamber is low, so a conservative systematic uncertainty of 100% is added to the multi-jet process. Since the content of multi-jet processes in WCR and WVR is very low, the uncertainty has little effect on the background estimation of W+jets. In each WCR and WVR, the purity of W+jets is as high as 73% to 85%.

6.4.3 Estimation of Top process of SR-C1N2SS-HM

The content of top-related processes in SR-C1N2SS-LM is less than 1%, but it is larger in SR-C1N2SS-HM. Considering that most of the top-related processes have at least one fake τ_{had} , Stau analysis defines the control region TCR-SS-HM and the verification region TVR-SS-HM to better estimate the top background, as shown in Table 6-7. In order to increase the fake τ_{had} content, the requirements for the identification working point of τ_{had} are reduced to veryloose and loose. The reduction of the working point will increase the background of the multi-jet process. Therefore, the definition of CR

and SR adopts the higher requirement of $E_T^{\text{miss}} > 150$ GeV to reduce the background. Finally, the content of top processes in CR and VR is as high as 83%.

表 6-7 Stau (SS) 过程的 TCR-SS-HM 和 TVR-SS-HM 的定义。

Table 6-7 The definition of TCR-SS-HM and TVR-SS-HM.

TCR-SS-HM	TVR-SS-HM
Di- τ + E_T^{miss} trigger	
≥ 2 very loose τ , ≥ 1 loose τ	
$N_{\text{medium-}\tau} < 2$	
≥ 1 b -jet	
$E_T^{\text{miss}} > 150$ GeV	
$m_{\text{Tsum}} \leq 400$ GeV	$m_{\text{Tsum}} \geq 400$ GeV

6.4.4 Background estimation of irreducible background

The irreducible background of Stau analysis includes the multi-boson process, as well as the top process in the OS signal region (for example, the decay of $t\bar{t}$ to produce two W bosons) and the Z+jets process. Table 6-8 summarizes the definitions of each verification region.

- The top process content in the OS final state is 7% to 14%. MC simulation is used for direct estimation in the analysis, and TVR-OS-LM and TVR-OS-HM verification areas are defined to verify the reliability of MC simulation estimation. The definition requires at least one b -jet to increase the top process content and be orthogonal to the signal area. The requirements of m_{Tsum} and m_{T2} are slightly changed compared with SR to suppress W+jets and Z+jets. In addition, considering that the angle between the two τ_{had} decayed by boost Z/h is small, the requirement of $|\Delta\phi(\tau_1, \tau_2)| > 1.0$ is added, and $m(\tau_1, \tau_2)$ is required to avoid the Z/h window, thereby suppressing Z+jets and h related processes.

- The content of Z+jets process in the OS final state is between 16% and 21%, and the multi-boson process accounts for 25% to 50%, so ZVR-OS-LM (MBVR-OS-LM) and ZVR-OS-HM (MBVR-OS-HM) are defined to verify the reliability of MC simulation estimation of Z+jets(multi-boson). The definition of VR uses $\Delta R(\tau_1, \tau_2) < 1$ ($\Delta R(\tau_1, \tau_2) < 1.2$ and $\Delta\phi(\tau_1, \tau_2) < 1.1$) to mark the product of boost Z (Z, W) bosons to increase the content of Z+jets(multi-boson). Considering that the τ_{had} of the multi-boson final state may come from multiple bosons, m_{Tsum} is large, so $m_{\text{Tsum}} > 150$ GeV is added to select the process from the simultaneous decay of multiple bosons. Since the m_{T2} distribution of the $Z \rightarrow \tau\tau$ process is truncated at the Z boson mass, $m_{\text{T2}} = 60$ GeV is used to divide the verification area of Z+jets and multi-boson.

- 73% of the events in the multi-boson process of the SS final state are truth τ_{had}

events. The definition of the verification area MBVR-SS uses a single muon trigger. The Z boson is marked by selecting μ of two OSs, and the τ_{had} and ν decayed by the W boson are selected by $|\Delta\phi(\tau_1, E_T^{\text{miss}})| < 1.75$, thereby increasing the content of the multi-boson process. In addition, $E_T^{\text{miss}} > 100$ GeV is used to suppress the multi-jet process.

Figure 6-4 shows the distribution of related variables of TVR-OS-LM, TVR-OS-HM, ZVR-OS-LM, ZVR-OS-HM, MBVR-OS-LM and MBVR-OS-HM respectively. It can be seen that the purity of the background process in each verification area is relatively high, and the data is in good agreement with the MC simulation background estimate, indicating that the MC simulation estimate of the relevant background is reliable.

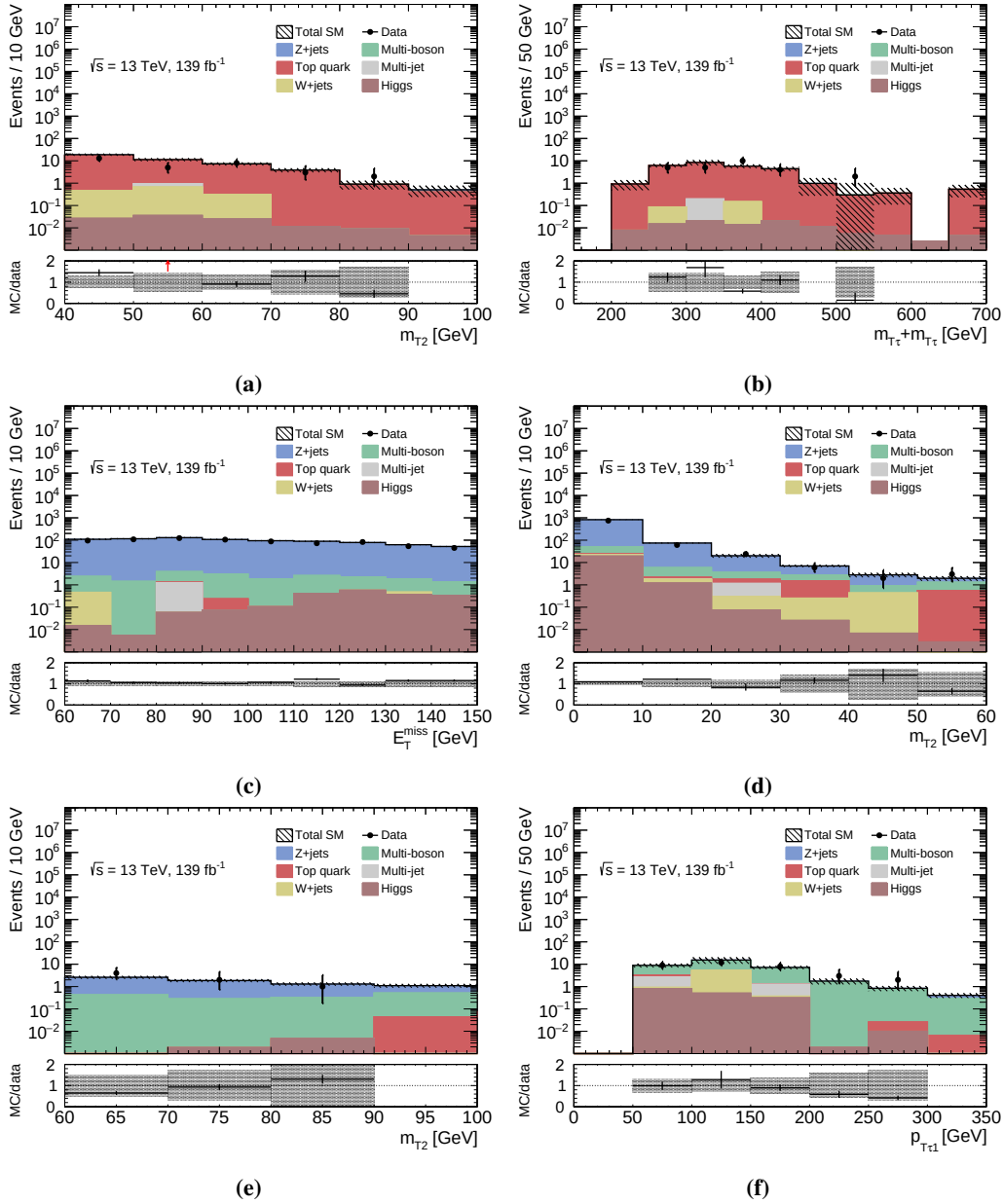


图 6-4 各验证区的动力学变量分布。

- (a) TVR-OS-LM 的 m_{T2} 分布, (b) TVR-OS-HM 的 m_{Tsum} 分布, (c) ZVR-OS-LM 的 E_T^{miss} 分布, (d) ZVR-OS-HM 的 m_{T2} 分布, (e) MBVR-OS-LM 的 m_{T2} 分布, (f) MBVR-OS-HM 的 $p_{T,\tau1}$ 分布。

Figure 6-4 Kinematic variable distributions of each validation region.

- (a) m_{T2} distribution for TVR-OS-LM, (b) m_{Tsum} distribution for TVR-OS-HM, (c) E_T^{miss} distribution for ZVR-OS-LM, (d) m_{T2} distribution for ZVR-OS-HM, (e) m_{T2} distribution for MBVR-OS-LM, and (f) $p_{T,\tau1}$ distribution for MBVR-OS-HM.

表 6-8 Stau 过程不可约本底的验证区定义。

Table 6-8 The definition of validation regions for irreducible background.

Process	Top		Z+jets		Multi-bosons		
Region	TVR-OS-LM	TVR-OS-HM	ZVR-OS-LM	ZVR-OS-HM	MBVR-OS-LM	MBVR-OS-HM	MBVR-SS
Charge combination	OS						SS
Trigger	asymm. di- τ	di- $\tau + E_{\text{T}}^{\text{miss}}$	asymm. di- τ	di- $\tau + E_{\text{T}}^{\text{miss}}$	asymm. di- τ	di- $\tau + E_{\text{T}}^{\text{miss}}$	single μ
N medium τ			≥ 2				$= 1$
N tight τ			≥ 1				-
N μ			-				$= 2$
N b -jets	≥ 1				$= 0$		$= 0$
$E_{\text{T}}^{\text{miss}}$ [GeV]	$\in (20, 150]$	> 150	$\in (40, 150]$	> 150	$\in (70, 150]$	> 150	> 100
$m(\tau_1, \tau_2)$ [GeV]	> 120	> 120	< 70	< 60	< 80	< 90	-
$m_{\text{T}2}$ [GeV]	> 40	> 30	< 60	< 60	> 60	> 60	-
m_{Tsum} [GeV]	> 150	> 150	-	-	> 180	> 180	-
$ \Delta\phi(\tau_1, \tau_2) $	> 1.0	> 1.0	-	-	< 1.0	< 1.0	-
$ \Delta\phi(\tau_1, E_{\text{T}}^{\text{miss}}) $	-	-	-	-	-	-	≤ 1.75
$\Delta R(\tau_1, \tau_2)$	-	-	< 1.0	< 1.0	< 1.2	< 1.2	-

6.5 Systematics Study

The sources of systematic uncertainties in this analysis are basically consistent with the Wh study introduced in Section 5.5, and can be generally divided into experimental uncertainties and theoretical uncertainties. Experimental uncertainties include event reconstruction uncertainties, uncertainties in background estimation methods, and statistical uncertainties. Since Stau's signal sample quality parameters cover a large range, the theoretical uncertainty calculation of signal samples is different from that of Wh study.

6.5.1 Signal Theoretical Uncertainties

Since the signal quality parameters cover a wide range, including the low-gaugino mass region, high-gaugino mass region and compressed region, and the signal acceptance of the OS signal region in the low-mass region and compressed region is low, and the signal cross section in the low-mass region is large, requiring a very high number of sample events, so this paper selects the theoretical uncertainties of the four signal points $(m_{\tilde{\chi}_1^\pm/\tilde{\chi}_2^0}, m_{\tilde{\chi}_1^0}) = (267.0, 232.0)$ GeV, $(232.0, 167.0)$ GeV, $(225.0, 125.0)$ GeV and $(200.0, 50.0)$ GeV as $m_{\tilde{\chi}_1^\pm/\tilde{\chi}_2^0} < 500$ GeV or $\Delta m(\tilde{\chi}_1^\pm - \tilde{\chi}_1^0) < 150$ GeV. The theoretical uncertainty of the GeV signal is estimated. Finally, the theoretical uncertainties of the signals in the low-quality region and the compressed region are about 10%, and the theoretical uncertainties of the other signal points are about 5%. For example, Figure 6-5 shows the Matching and Merging Schema uncertainty of the SR-C1C1-LM signal region.

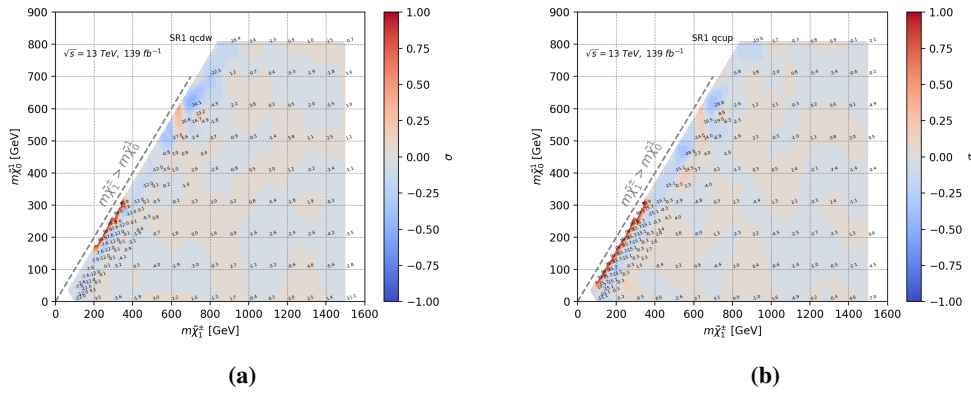


图 6-5 SR-C1C1-LM 信号区的 Matching and Merging Schema 的误差。

(a) 是误差的下限, (b) 是误差的上限。

Figure 6-5 The uncertainty of Matching and Merging Schema in SR-C1C1-LM.

(a) shows the down uncertainty and (b) shows the up uncertainty.

6.5.2 Uncertainties of QCD Estimation

In the ABCD method, other SM background processes in CR-A are subtracted from the data, so the systematic uncertainties of other SM background processes will also affect the ABCD estimation of the multi-jet process. In the pure background fitting, the multi-jet process introduces SF (μ_{QCD}), and the uncertainty of SF is transferred to the signal area by fitting with other areas at the same time. Table 6-9 shows the main systematic uncertainties of each CR-A in the OS decay channel after pure background fitting. In each control area, due to the high content of W +jets process and large statistical uncertainty, the total statistical uncertainty of the control area is large, and the theoretical uncertainty of W +jets is large. In addition, the energy resolution systematic uncertainty of the jet and the energy scale uncertainty of τ_{had} are also large. Finally, the uncertainty of SF of each process is between 20% and 30%.

6.5.3 Uncertainties of other process

Due to the large statistical uncertainty of the SM background in the signal area of OS, especially in the HM signal area, in order to reduce the systematic uncertainty caused by the statistical effect, some selection conditions are temporarily lowered when calculating the background theoretical uncertainty in the signal area. The $E_{\text{T}}^{\text{miss}}$ of SR-C1C1-LM and SR-C1N2OS-LM is reduced to 30 GeV, and the m_{Tsum} of SR-C1C1-HM and SR-C1N2OS-HM is reduced to 200 GeV. The figure 6-6 distribution shows the distribution of the number of cases of the samples used in the analysis and the theoretical uncertainty samples with the variable. The figure shows the uncertainty of CKKW of multi-boson. By comparing the bottom, it can be found that the difference of the samples is within the statistical uncertainty, indicating that the reduction of the above selection conditions is reasonable.

6.5.4 Background-only Fit

In the Stau analysis, the SF of W +jets obtained by WCR-OS is 0.98 ± 0.12 , the SF of W +jets obtained by WCR-SS is 1.04 ± 0.09 , and the SF of the top process obtained by TCR-SS-HM is 0.71 ± 0.11 . Figure 6-7 shows the distribution of SM expected values, experimental data and signal reference points in each verification area and signal area after pure background fitting. In all verification areas, the SM expected values and experimental data are in good agreement.

Figure 6-8 shows the size of the systematic uncertainty in each SR. It can be found that the main systematic uncertainties of C1C1, C1N2OS and C1N2SS are the statistical uncertainty of the MC sample, the uncertainty of the background estimation of the multi-jet process, the identification and energy scale uncertainty of τ_{had} , the uncertainty of the energy scale and resolution of the injection, and the theoretical uncertainty of the multi-

表 6-9 Stau 过程 OS 信号区对应的 CR-A 的主要系统误差。

Table 6-9 The dominant systematics of CR-A for the OS SRs.

Multijet-CR-A, C1C1-LM	
BKG Total	98.00
mu_QCD_OS	± 28.06 [28.6%]
alpha_FakeTauBGQCR1	± 21.21 [21.6%]
gamma_stat_MultiJetCR_C1C1_LM_cuts_bin_0	± 12.45 [12.7%]
alpha_W_PDF_Theo	± 8.91 [9.1%]
alpha_JET_JER_EffectiveNP_1	± 3.23 [3.3%]
mu_W_OS	± 2.61 [2.7%]
alpha_JET_JER_EffectiveNP_6	± 1.24 [1.3%]
alpha_JET_JER_EffectiveNP_7	± 1.08 [1.1%]
alpha_W_CKKW_Theo	± 1.06 [1.1%]
Multijet-CR-A, C1N2OS-LM	
BKG Total	245.01
mu_QCD_OS	± 58.95 [24.1%]
alpha_FakeTauBGQCR2	± 51.22 [20.9%]
gamma_stat_MultiJetCR_C1N2OS_LM_cuts_bin_0	± 17.95 [7.3%]
alpha_W_PDF_Theo	± 11.67 [4.8%]
alpha_TAUS_TRUEHADTAU_SME_TES_DETECTOR	± 4.71 [1.9%]
mu_W_OS	± 4.10 [1.7%]
alpha_JET_Flavor_Composition	± 3.12 [1.3%]
alpha_JET_Pileup_RhoTopology	± 2.69 [1.1%]
alpha_JET_JER_EffectiveNP_5	± 2.31 [0.94%]
Multijet-CR-A, C1C1-HM	
BKG Total	14.99
gamma_stat_MultiJetCR_C1C1_HM_cuts_bin_0	± 4.13 [27.6%]
alpha_FakeTauBGQCR3	± 3.09 [20.6%]
mu_QCD_OS	± 2.88 [19.2%]
alpha_W_QSF_Theo	± 1.61 [10.8%]
alpha_Z_PDF_Theo	± 0.90 [6.0%]
alpha_W_PDF_Theo	± 0.72 [4.8%]
alpha_TAUS_TRUEHADTAU_SME_TES_INSITUFIT	± 0.63 [4.2%]
alpha_Z_CKKW_Theo	± 0.54 [3.6%]
alpha_JET_JER_EffectiveNP_9	± 0.46 [3.1%]
Multijet-CR-A, C1C1-HM	
BKG Total	14.99
gamma_stat_MultiJetCR_C1C1_HM_cuts_bin_0	± 4.13 [27.6%]
alpha_FakeTauBGQCR3	± 3.09 [20.6%]
mu_QCD_OS	± 2.88 [19.2%]
alpha_W_QSF_Theo	± 1.61 [10.8%]
alpha_Z_PDF_Theo	± 0.90 [6.0%]
alpha_W_PDF_Theo	± 0.72 [4.8%]

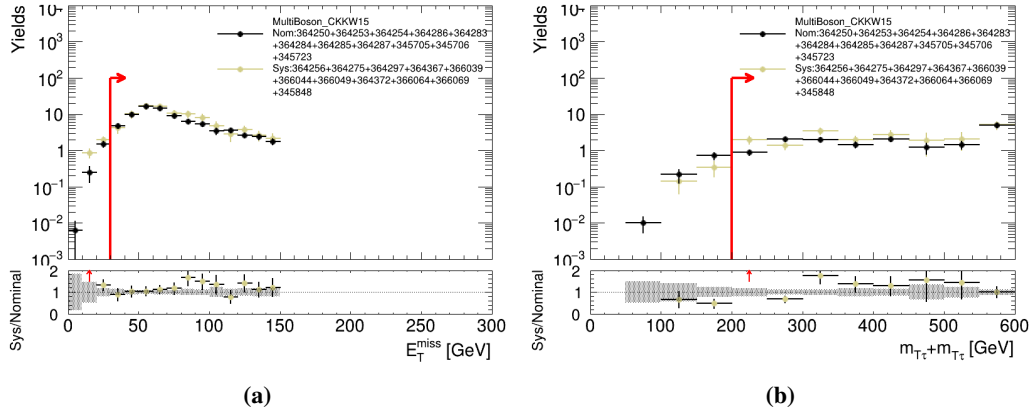


图 6-6 分析样本和理论误差样本

的事例分布，以 OS 末态 LM 信号区的 Matching and Merging Schema 模式误差为例。CKKW 误差随 (a) E_T^{miss} 和 (b) m_{Tsum} 的变化。

Figure 6-6 The kinematic variable distributions of the nominal sample and variation sample for the CKKW uncertainty of the OS-LM SRs.
(a) is E_T^{miss} and (b) is m_{Tsum} .

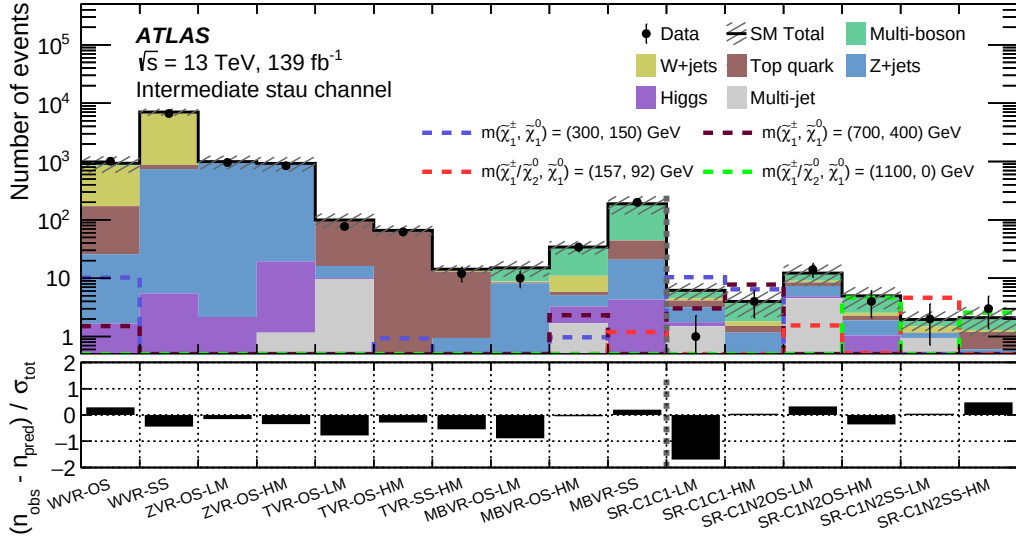


图 6-7 各个区间中实验数据、SM 过程和信号的事例分布。

Figure 6-7 Comparison of the observed and expected event yields in all VRs and SRs after the background-only fit.

bosonprocess. The reasons why the theoretical uncertainty of the multi-bosonprocess is large are: (1) The multi-bosonprocess is the main background in the signal area, but there is no corresponding control area to reduce the uncertainty; (2) The statistics of the multi-bosonprocess are low. Some uncertainties that are highly dependent on kinetic variables cannot be improved by reducing the selection conditions. The statistical value, so the theoretical uncertainty is greatly affected by the statistical value.

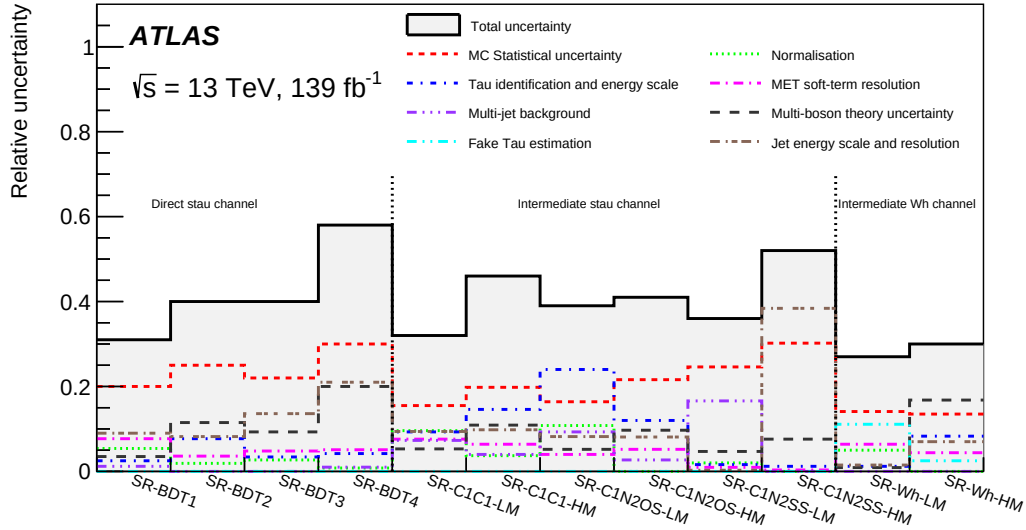


图 6-8 信号区中误差的分布，前四个信号区不在本文的讨论范围内。

Figure 6-8 Summary of the total uncertainty in the predictions of the background event yields of each SR. The first four SRs are not involved in this thesis.

6.6 Results

6.6.1 Model-independent Fit

Table 6-10 summarizes the experimental data observed in the signal region and the expected values of the SM background. The cases of the expected values pass the pure background fitting. It can be found that in each signal region, the observed experimental data and the expected values of SM are in good agreement. The table gives the upper limit of the cross section (σ_{vis}^{95}) beyond the standard model signal at 95% confidence level.

6.6.2 Model-dependent Fit of Multiple Channels

Since there are no phenomena in SR that significantly exceed the standard model, This analysis calculates exclusion limits for quality parameters at a 95% The $\tilde{\chi}_1^\pm \tilde{\chi}_1^\mp$ process and the $\tilde{\chi}_1^\pm \tilde{\chi}_2^0$ process are simplified Wino-Bino models, Therefore, the masses of $\tilde{\chi}_1^\pm$ and $\tilde{\chi}_2^0$ are degenerate, and the production processes are independent. Therefore, the

表 6-10 SR-C1C1 和 SR-C1N2 的观测数据和 SM 过程预期值。

Table 6-10 Observed and expected numbers of events for the background-only fit in the SR-C1C1 and SR-C1N2. The one-sided p_0 -values, and the observed and expected 95% CL upper limits on the visible non-SM cross-section (σ_{vis}^{95}) from the model-independent fit are given. Values of $p_0 > 0.5$ are truncated to $p_0 = 0.5$.

SM Process	SR-C1C1-LM	SR-C1C1-HM	SR-C1N2OS-LM	SR-C1N2OS-HM
Multi-boson	1.6 ± 0.6	2.2 ± 1.6	3.2 ± 1.2	2.4 ± 1.6
W +jets	0.4 ± 0.4	$0.29^{+0.35}_{-0.29}$	$0.6^{+2.2}_{-0.6}$	$0.29^{+0.35}_{-0.29}$
Top quark	1.0 ± 0.5	0.36 ± 0.13	$1.1^{+1.2}_{-1.1}$	0.36 ± 0.14
Z +jets	$1.4^{+1.5}_{-1.4}$	0.78 ± 0.34	2.5 ± 1.7	0.9 ± 0.4
Higgs	0.27 ± 0.06	$0.01^{+0.13}_{-0.01}$	0.40 ± 0.22	0.73 ± 0.23
Multi-jet	1.5 ± 0.5	0.37 ± 0.21	4.5 ± 1.0	0.31 ± 0.17
SM total	6.2 ± 2.0	4.0 ± 1.8	12.2 ± 4.8	5.0 ± 2.0
Observed	1	4	14	4
$m(\tilde{\chi}_1^\pm, \tilde{\chi}_1^0) = (700, 400)$ GeV	3.0 ± 0.6	7.8 ± 1.6	4.7 ± 1.0	14.1 ± 2.8
$m(\tilde{\chi}_1^\pm/\tilde{\chi}_2^0, \tilde{\chi}_1^0) = (1100, 0)$ GeV	0.20 ± 0.05	3.1 ± 0.6	0.39 ± 0.11	4.6 ± 1.0
p_0	0.5	0.5	0.4	0.5
Expected σ_{vis}^{95} [fb]	0.04	0.05	0.10	0.05
Observed σ_{vis}^{95} [fb]	0.02	0.05	0.10	0.05

SM Process	SR-C1N2SS-LM	SR-C1N2SS-HM
Multi-boson	0.47 ± 0.20	0.8 ± 0.4
W +jets	0.33 ± 0.25	0.10 ± 0.05
Top quark	$0.01^{+0.02}_{-0.01}$	0.59 ± 0.20
Z +jets	0.20 ± 0.15	$0.6^{+0.8}_{-0.6}$
Higgs	< 0.01	0.02 ± 0.01
Multi-jet	0.9 ± 0.5	0.00 ± 0.00
SM total	2.0 ± 0.7	2.1 ± 1.1
Observed	2	3
$m(\tilde{\chi}_1^\pm/\tilde{\chi}_2^0, \tilde{\chi}_1^0) = (157, 92)$ GeV	4.6 ± 1.3	0.00 ± 0.00
$m(\tilde{\chi}_1^\pm/\tilde{\chi}_2^0, \tilde{\chi}_1^0) = (900, 300)$ GeV	0.84 ± 0.07	6.23 ± 0.21
p_0	0.4	0.3
Expected σ_{vis}^{95} [fb]	0.03	0.04
Observed σ_{vis}^{95} [fb]	0.03	0.04

signal samples can be directly merged to obtain the generation process of $\tilde{\chi}_1^\pm \tilde{\chi}_1^\mp + \tilde{\chi}_1^\pm \tilde{\chi}_2^0$. SR-C1C1-LM and SR-C1C1-HM are orthogonal, so they can be jointly fitted to obtain the exclusion limit of the $\tilde{\chi}_1^\pm \tilde{\chi}_1^\mp$ process. SR-C1N2OS-LM, SR-C1N2OS-HM, SR-C1N2SS-LM and SR-C1N2SS-HM are orthogonal, so joint fitting can also be performed to obtain the exclusion limit of the $\tilde{\chi}_1^\pm \tilde{\chi}_2^0$ process. Since SR-C1C1-LM (SR-C1C1-HM) and SR-C1N2OS-LM (SR-C1N2OS-HM) are not orthogonal, the fitting of the $\tilde{\chi}_1^\pm \tilde{\chi}_1^\mp + \tilde{\chi}_1^\pm \tilde{\chi}_2^0$ process needs to be Select a signal area among SR-C1C1-LM (SR-C1C1-HM) and SR-C1N2OS-LM (SR-C1N2OS-HM), and finally select the one with the strongest elimination ability among all combinations. This study adopted the combined elimination $\tilde{\chi}_1^\pm \tilde{\chi}_1^\mp + \tilde{\chi}_1^\pm \tilde{\chi}_2^0$ process of SR-C1N2OS-LM and SR-C1N2OS-HM. The merging and fitting of the workspace analyzed by Stau uses the pyhf software package [143, 144].

Figure 6-9(a) shows the mass exclusion limit of the $\tilde{\chi}_1^\pm \tilde{\chi}_2^0$ process in the OS signal region. When the LSP mass is 0, the exclusion limit for the $\tilde{\chi}_1^\pm \tilde{\chi}_2^0$ mass reaches 1060 GeV. Figure 6-9(b) shows the mass exclusion limit of the $\tilde{\chi}_1^\pm \tilde{\chi}_1^\mp$ process. When the LSP mass is 0, the exclusion limit for the $\tilde{\chi}_1^\pm$ mass reaches 970 GeV. Figure 6-9(c) shows the mass exclusion limit of the $\tilde{\chi}_1^\pm \tilde{\chi}_1^\mp + \tilde{\chi}_1^\pm \tilde{\chi}_2^0$ process and the mass exclusion limit obtained in the SS signal region by the $\tilde{\chi}_1^\pm \tilde{\chi}_2^0$ process, as well as the results of the SS-OS joint fitting. Figure 6-9(d) is consistent with 6-9(c), but the vertical axis is changed to the mass difference between $\tilde{\chi}_1^\pm/\tilde{\chi}_2^0$ and LSP, showing the exclusion ability of this analysis for the compressed region. It can be found that the SS signal region has a strong exclusion ability for the compressed region. When the LSP mass is 0, the exclusion limit of the mass-degenerate $\tilde{\chi}_1^\pm$ and $\tilde{\chi}_2^0$ in this analysis reaches 1160 GeV. The exclusion limit obtained in this analysis is improved by 340 GeV to 400 GeV compared with previous studies. The main reason is the improvement in statistics brought by the use of complete Run2 data and the improvement in reconstruction and identification performance of the τ_{had} reconstruction algorithm using RNN.

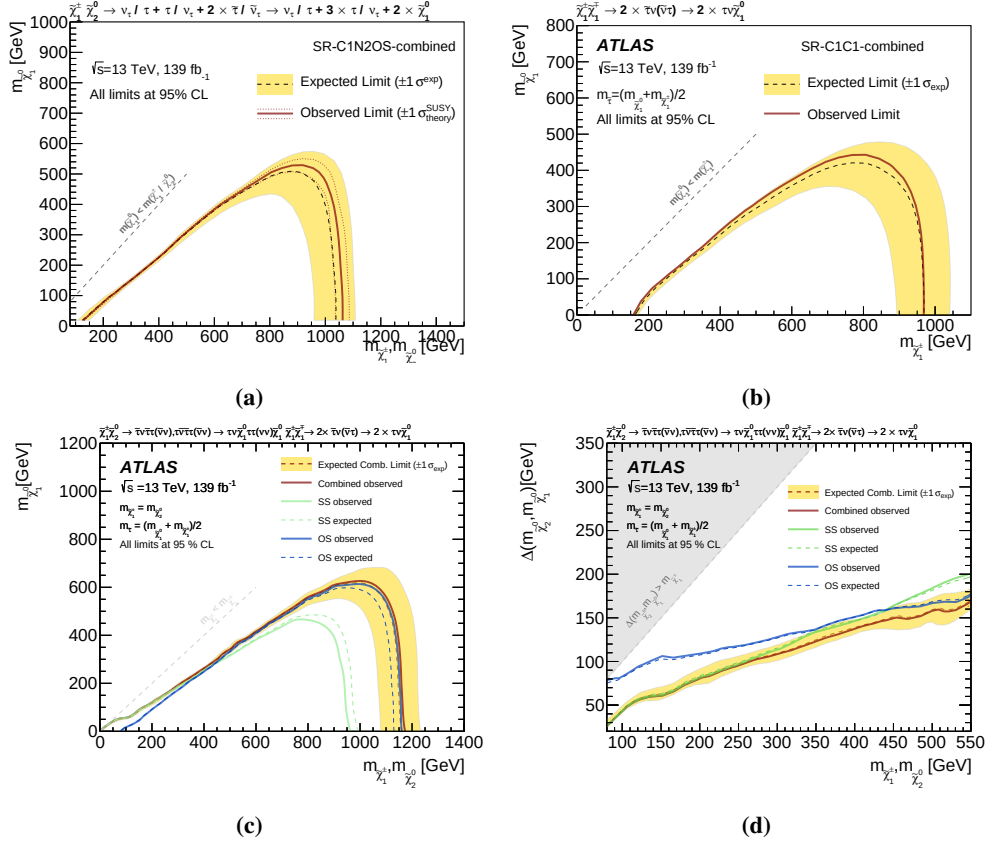


图 6-9 Stau 分析的质量排除限。

- (a) 只考虑了 $\tilde{\chi}_1^\pm \tilde{\chi}_2^0$ 过程在 C1N2OS 信号区的质量排除限, (b) 展示了 $\tilde{\chi}_1^\pm \tilde{\chi}_1^\mp$ 过程的质量排除限, (c) 展示了 $\tilde{\chi}_1^\pm \tilde{\chi}_1^\mp + \tilde{\chi}_1^\pm \tilde{\chi}_2^0$ 过程的质量排除限、 $\tilde{\chi}_1^\pm \tilde{\chi}_2^0$ 过程在 SS 信号区得到的质量排除限和 SS-OS 联合拟合的结果, (d) 展示了质量压缩区域的排除限。

Figure 6-9 The 95% CL exclusion contours for simplified models.

- (a) $\tilde{\chi}_1^\pm \tilde{\chi}_2^0$ production only considering C1N2OS-SRs, (b) $\tilde{\chi}_1^\pm \tilde{\chi}_1^\mp$ production, (c-d) $\tilde{\chi}_1^\pm \tilde{\chi}_1^\mp + \tilde{\chi}_1^\pm \tilde{\chi}_2^0$ production considering the combination of the channels, where (d) shows the details of the compressed region. The solid (dashed) lines show the observed (expected) exclusion contours. The band around the expected limit shows the $\pm 1\sigma$ variations, including all uncertainties except theoretical uncertainties in the signal cross-section.

6.7 Conclusion

This study uses the complete experimental data during the ATLAS experiment Run2 to study the process of Gaugino pair production and decay to at most τ_{had} final states through $\tilde{\tau}$ or $\tilde{\nu}_\tau$. The signal region defined in this analysis has a certain sensitivity to the new physical process of multiple τ_{had} final states. Since no phenomena that obviously exceed the standard model are observed in the signal region, this analysis gives the upper limit of the $\times$ cross section of the signal reception beyond the standard model in each signal region at 95% confidence. At the same time, under the assumption of a simplified model, this analysis gives the exclusion limit of the $m(\tilde{\chi}_1^\pm/\tilde{\chi}_2^0) - m(\tilde{\chi}_1^0)$ mass parameter space. When the LSP mass is 0, the exclusion limit of the mass degenerate $\tilde{\chi}_1^\pm$ and $\tilde{\chi}_2^0$ in this analysis reaches 1160 GeV, which is the strongest mass exclusion limit of $\tilde{\chi}_1^\pm/\tilde{\chi}_2^0$ decay through the third generation supersymmetric lepton in the ATLAS experiment. In addition, this analysis fully demonstrates the sensitivity of the same-sign final states in the mass compression region, providing a reference for optimization strategies for subsequent related analyses.

第 7 章 Interpretation of the R parity violation process of lepton number non-conservation

Chapters 5 and 6 of this article show two R parity-conserving SUSY particle search experiments, which did not observe any phenomena beyond the Standard Model. Other R parity-conserving SUSY particle search experiments of ATLAS have not observed any phenomena beyond the Standard Model. This makes people wonder, if SUSY physics exists, in what form it will exist. One of them may be a SUSY model with R parity violation. R parity violation will cause the decay of LSP. If the LSP decays in the detector far away from the collision vertex, it will produce displaced particles or long-lived particles. There are many studies on this type of model, such as the analysis of the minimum ionization energy loss for long-lived charged particles [145], the disappearing-track study in the extreme mass compression region [146], and the shift vertex analysis of the second-lightest SUSY particles [147]. However, changes in the coupling constant will lead to changes in the lifetime and branching ratio of SUSY particles, and it is impossible to exclude models with R parity violation one by one. Therefore, it is very important to check the analysis of the published particle transient decay signal process for the ability to exclude such R parity violation models with variable lifetime and branching ratio.

7.1 SUSY model of R parity violation and research motivation

In the superpotential of the SUSY model, there are the following expressions that can cause the lepton number or baryon number to be not conserved:

$$W_{\text{RPV}} = \frac{\lambda_{ijk}}{2} L_i L_j \bar{E}_k + \lambda'_{ijk} L_i Q_j \bar{D}_k + \frac{\lambda''_{ijk}}{2} \bar{U}_i \bar{D}_j \bar{D}_k + k_i L_i H_u \quad (7-1)$$

Where i, j and k represent the algebra of leptons or quarks, L_i and E_i represent the left-hand doublet and right-hand singlet of SU(2) of leptons, respectively, and Q_i , U_i and D_i represent the left-hand doublet, right-hand up-type quark singlet and right-hand down-type quark singlet of quarks, respectively. H_u is the Higgs superfield and couples only to up-type quarks. Since these terms violate the R parity, the model containing these terms is called the R parity violation (RPV) model. The constants of the trilinear coupling terms λ_{ijk} and λ''_{ijk} are antisymmetric tensors, for example, λ_{ijk} satisfies: $\lambda_{ijk} = -\lambda_{jik}$, so the original 27 free parameters are reduced to 9 independent parameters. The trilinear coupling constant λ'_{ijk} has 27 independent parameters. In addition, the bilinear coupling constant k_i has three independent parameters. The SUSY model (RPC) of R parity conservation has been studied more extensively, while the

RPV model has been studied relatively less, but the RPV model may still exist. In the RPC model, LSP is a stable particle, while in the RPV model, LSP can decay, and its lifetime (τ_{LSP}) is determined by the strength of the coupling constant and the mass of the supersymmetric fermions involved in the LSP decay.

The signal model of this study is that the Higgsino-type $\tilde{\chi}_1^\pm$, $\tilde{\chi}_2^0$ and $\tilde{\chi}_1^0$ are produced in pairs and decay through λ_{133} or λ_{233} , where the coupling constants λ_{133} or λ_{233} are variable. The λ_{133} and λ_{233} terms can lead to the production of neutrino mass, and this production mechanism does not require the introduction of a seesaw mechanism [148, 149]. At the same time, the λ_{133} and λ_{233} terms can simultaneously explain the excess of the anomalous magnetic moment of the muon [129, 150] and the excess of the branching ratio in heavy flavor physics [151, 152]. In addition, the existence of the RPV term causes LSP decay to reduce the $E_{\text{T}}^{\text{miss}}$ of the signal final state, thereby alleviating the mass limit of the SUSY particle in current research. In addition, the lighter higgsino or stop can meet the requirements of naturalness [153].

If τ_{LSP} is long enough, LSP can decay after flying out of the detector, thus producing a signal final state close to the RPC model. If τ_{LSP} is between $\mathcal{O}(10^{-3} - 1)$ ns, the decay of LSP will produce displaced vertices, and the research on finding displaced particles [154] aims at such models. If the coupling constant continues to increase, NLSP may decay immediately into standard model particles instead of decaying into LSP. The coupling constants of the signals in this study cover the range from $\tau_{\text{LSP}} \sim \mathcal{O}(1)$ ns to the immediate decay of NLSP.

The ATLAS cooperation group previously used the complete experimental data of 139 fb^{-1} during Run2 to study both the RPC model and the RPV model of higgsino. Among them, the coupling constants for the study of higgsino direct RPV decay are λ_{ijk}' and k_i [155]. The research on λ_{ijk} generated by $\tilde{\chi}_1^\pm \tilde{\chi}_2^0$ is only the wino-bino model [62]. Therefore, the current ATLAS research does not cover all RPV models. At the same time, although the ATLAS cooperation group has conducted research on the salient characteristics of τ_{LSP} in different ranges, However, it does not cover the situation where τ_{LSP} is low but does not decay immediately, so traditional SUSY research may still be significant. This study makes use of the di- τ analysis and four-lepton (4L) analysis in Chapter 6 [62] to study the exclusion of these two analyzes in higgsino's RPV model ability. Di- τ analysis only requires two τ_{had} and higher $E_{\text{T}}^{\text{miss}}$ for the final state, so theoretically the significance is greater when τ_{LSP} is higher, while the final state of 4L analysis The state requires at least four leptons, so the significance is higher when τ_{LSP} is lower and LSP decays directly. This study will use these analyzes to constrain the higgsino mass and coupling constants λ_{133} and λ_{233} .

7.2 Model Study

Table 7-1 summarizes the settings of the signal model for this analysis.

表 7-1 信号模型的设置。

Table 7-1 Summary of signal models.

Production	Higgsino pair production
Couplings	λ_{i33} , where $i \in \{1, 2\}$
λ_{i33} weak	$\tilde{\chi}_1^\pm/\tilde{\chi}_2^0 \rightarrow qq(\ell\nu/\ell\ell)\tilde{\chi}_1^0$
λ_{i33} mild	$\tilde{\chi}_1^\pm/\tilde{\chi}_2^0 \rightarrow qq(\ell\nu/\ell\ell)\tilde{\chi}_1^0$, $\tilde{\chi}_1^0 \rightarrow \ell\tau\nu/\tau\tau\nu$
λ_{i33} strong	$\tilde{\chi}_1^\pm \rightarrow \ell\tau\tau/\tau\nu\nu/\ell\nu\nu$ and $\tilde{\chi}_2^0 \rightarrow \ell\tau\nu/\tau\tau\nu$
Other Sparticles	$m(\tilde{\tau}) = 2 \text{ TeV}$ $m(\tilde{\ell}) = 5 \text{ TeV}$
LSP	higgsino-like $\tilde{\chi}_1^0$ $m(\tilde{\chi}_1^\pm) - m(\tilde{\chi}_1^0) = 0.25 \text{ GeV}$ $m(\tilde{\chi}_2^0) - m(\tilde{\chi}_1^0) = 0.5 \text{ GeV}$

This analysis studies the λ_{133} and λ_{233} models and considers the antisymmetric case, while all other trilinear and bilinear RPV couplings are set to 0. In the Higgsino process, the mass difference between $\tilde{\chi}_1^\pm$ ($\tilde{\chi}_2^0$) and $\tilde{\chi}_1^0$ is 0.25 GeV (0.5 GeV). The small mass difference can ensure that an off-shell boson is produced when $\tilde{\chi}_1^\pm$ or $\tilde{\chi}_2^0$ decays to $\tilde{\chi}_1^0$, and the existence of the mass difference is consistent with the prediction of the Higgsino model. Although the production of the Higgsino process does not involve $\tilde{\tau}$ particles, $\tilde{\tau}$ particles will participate in the decay of LSP as off-shell intermediate particles, thereby affecting the decay branching ratio and lifetime of LSP (see Figure 7-1). Considering that the upper limit of the mass of the higgsino in the model of this study is 1 TeV, the mass of $\tilde{\tau}$ is set to 2 TeV to ensure that it does not act as an intermediate particle in the decay of NLSP to LSP, but can participate in the decay of LSP. Other irrelevant particles are set to 5 TeV for decoupling. The coupling constant λ_{i33} ($i \in \{1, 2\}$) and the relationship between the decay branch ratio and lifetime of the higgsino are calculated by SPheno 4.0.2 [156, 157] combined with SARAH 4.12.0 [158]. Figure 7-1 shows the decay path of the Higgsino-type LSP. Since the Higgsino-type LSP has low coupling with $\tilde{\nu}$ and ν , the LSP only decays through the off-shell $\tilde{\tau}$.

7.2.1 Upper limits of λ_{133} and λ_{233} Coupling Strength

Since the existence of the RPV term not only causes the decay of LSP, but also affects other physical measurements, the coupling coefficient of the RPV term can be constrained through other non-SUSY direct search experiments.

The restriction on λ_{133} mainly utilizes the mass measurement of electron neutrinos.

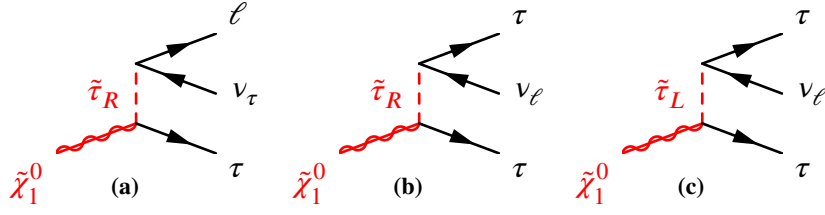


图 7-1 LSP 通过 RPV 项衰变的费曼图。

Figure 7-1 LSP possible decay channels.

If the λ term exists, the RPV superpotential can be expanded as: [159]:

$$W_\lambda = \lambda_{ijk}[\tilde{\nu}_{L,i}\bar{e}_{R,k}e_{L,j} + \tilde{e}_{L,j}\bar{e}_{R,k}\nu_{L,i} + \tilde{e}_{R,k}\bar{\nu}_{L,i}e_{L,j} - \text{antisymmetry terms}] \quad (7-2)$$

If the λ_{133} coupling strength is non-zero, the second term in the formula describes the coupling of ν_e , τ , and $\tilde{\tau}$. Therefore, ν_e can obtain the Majorana mass through a single-loop graph involving $\tau\tilde{\tau}$, and the specific expression is [160]:

$$\delta m_{\nu_e} \sim \frac{\lambda_{133}^2}{8\pi^2} \frac{1}{m_{\tilde{\tau}}^2} M_{\text{SUSY}} m_{\tilde{\tau}}^2 \quad (7-3)$$

Among them, M_{SUSY} is the supersymmetric energy scale, which can be understood as the energy at which supersymmetry is broken, and the masses of supersymmetric particles and standard model particles differ. In the Higgsino study, decoupled SUSY particles are not considered, and the heaviest SUSY particle is $\tilde{\tau}$, so the mass of $\tilde{\tau}$ is taken as M_{SUSY} . The upper limit of the mass of the electron neutrino used in this study is the measured value of the Karlsruhe Tritium Neutrino Experiment (KATRIN) in 2022: 0.8 eV [161], and the final upper limit of λ_{133} is:

$$\lambda_{133} < 0.0014 \sqrt{\frac{m_{\tilde{\tau}}}{100 \text{ GeV}}} \quad (7-4)$$

Since the upper limit of the mass of muon neutrinos is relatively high, about 0.2 MeV or more [162], the ν_μ measurement experiment cannot provide the most stringent restriction on λ_{233} . The strict restriction on λ_{233} comes from the measurement related to lepton universality. Consider the definition of the decay branch ratio R_τ of τ as follows:

$$R_\tau = \Gamma(\tau \rightarrow e\nu\bar{\nu})/\Gamma(\tau \rightarrow \mu\nu\bar{\nu}) \quad (7-5)$$

The theoretical prediction of the Standard Model is R_τ^{SM} is 1.0282 [163], and any coupling coefficients of λ_{13k} and λ_{23k} can lead to deviations between the measured value R_τ^{exp} and the theoretical value [163]:

$$R_\tau^{\text{exp}}/R_\tau^{\text{SM}} = \frac{|1 + r_{13k}|^2}{|1 + r_{23k}|^2} \quad (7-6)$$

Where r_{ijk} is defined as:

$$r_{ijk} = \frac{M_W^2}{g^2} \frac{|\lambda_{ijk}|^2}{m_{\tilde{f}}^2} \quad (7-7)$$

The measured values used in this study come from the fitting results of PDG [162], and take into account the σ uncertainty: $1/R_\tau = (97.62 \pm 0.28) \times 10^{-2}$. In addition, since $m(\nu_e)$ has a strong restriction on λ_{133} , λ_{133} can be ignored in the calculation. Finally, by comparing the measured values with the theoretical values, the upper limit of λ_{233} can be obtained as:

$$\lambda_{233} < 0.047 \frac{m_{\tilde{\tau}}}{100 \text{ GeV}}. \quad (7-8)$$

7.2.2 Parameter setting of Higgsino model

This study includes the following four mass-degenerate Higgsino pair production channels: $\tilde{\chi}_1^0 \tilde{\chi}_1^\pm$, $\tilde{\chi}_2^0 \tilde{\chi}_1^\pm$, $\tilde{\chi}_1^\pm \tilde{\chi}_1^\mp$ and $\tilde{\chi}_1^0 \tilde{\chi}_2^0$, and studies λ_{133} and λ_{233} respectively. The experiment found that the difference between the $\tilde{\chi}_1^0 \tilde{\chi}_1^\pm$ and $\tilde{\chi}_2^0 \tilde{\chi}_1^\pm$ processes can be ignored because their signal generation cross sections are the same, and the final state kinetic variable distributions of $\tilde{\chi}_2^0$ and $\tilde{\chi}_1^0$ after decay are similar, so the final exclusion limits are also consistent. Figure 7-2 shows the Feynman diagrams of the decay paths if all NLSP decay to LSP, and Figure 7-3 shows the Feynman diagrams if all higgsino decay directly through the RPV process. Since the particles decayed by the off-shell bosons have low momentum and cannot be correctly reconstructed, the final states of these processes all contain at least four leptons.

The mass range of Higgsino signal is 100 GeV to 950 GeV. Figure 7-4 shows the relationship between the decay branching ratio and coupling constant of $\tilde{\chi}_1^0$, $\tilde{\chi}_2^0$ and $\tilde{\chi}_1^\pm$ at different masses. Because $\tilde{\chi}_2^0$ and $\tilde{\chi}_1^0$ are mass degenerate and both are Higgsino type, their RPV decay branching ratios are consistent. The decay branching ratio $B(\tilde{\chi}_1^0 \rightarrow \ell \tau \nu)/B(\tilde{\chi}_1^0 \rightarrow \tau \tau \nu)$ of $\tilde{\chi}_1^0$ is close to 1/2, because the decay width of each decay channel in Figure 7-1 is similar. Figure 7-5 shows the Feynman diagram of $\tilde{\chi}_1^\pm$ decaying through the RPV term. Since the branching ratios of $\tilde{\chi}_1^\pm$ decaying to $\tilde{\tau}$ and $\tilde{\nu}_\tau$, $B(\tilde{\chi}_1^\pm \rightarrow \tilde{\tau} \nu)/B(\tilde{\chi}_1^\pm \rightarrow \tilde{\nu}_\tau \tau)$, are close to 1, and the branching ratios of $\tilde{\tau}$ decaying to $\ell \nu$ and $\tau \nu$ are also close to 1, so the final branching ratio of $\tilde{\chi}_1^\pm$ decaying through the RPV term is: $B(\tilde{\chi}_1^\pm \rightarrow \tau \nu \nu) : B(\tilde{\chi}_1^\pm \rightarrow \ell \nu \nu) : B(\tilde{\chi}_1^\pm \rightarrow \tau \tau \ell) = 1 : 1 : 2$.

7.2.3 Simulation Samples

The signal simulation samples and signal cross-section calculations in this study are consistent with Chapters 5 and 6. Figure 7-6 shows the effect of LSP lifetime on the final state products of the $\tilde{\chi}_1^0 \tilde{\chi}_2^0$ production process. The reconstruction of the final state particles in the figure is similar to the analysis in Chapter 6. The only difference is that the identification working point of baseline τ_{had} is changed to veryloose, so that

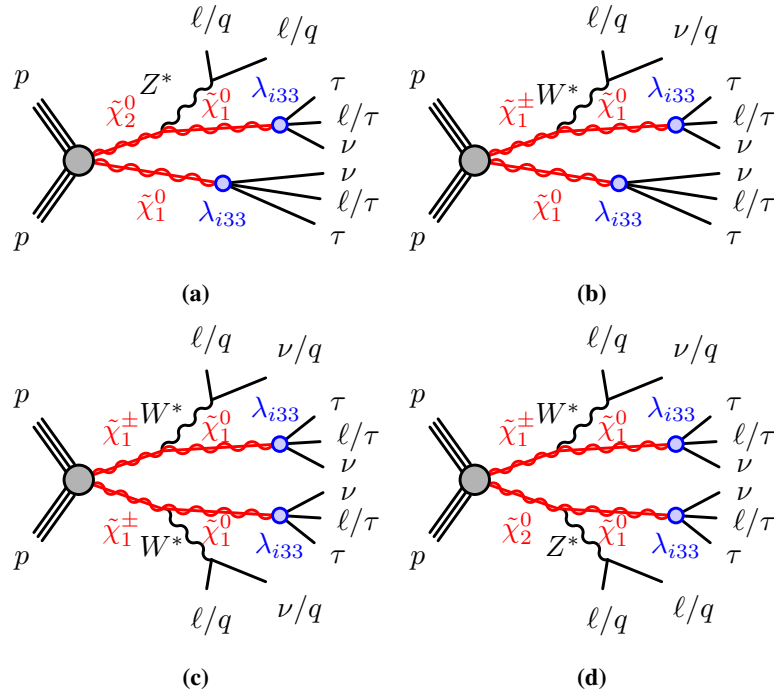


图 7-2 Higgsino 衰变道的费曼图，其中 $\tilde{\chi}_1^\pm \tilde{\chi}_2^0$ 会衰变到 $\tilde{\chi}_1^0$ ， $\tilde{\chi}_1^0$ 继续衰变至 SM 粒子。

Figure 7-2 Higgsino pair production channels, where NLSP decays to the LSP.

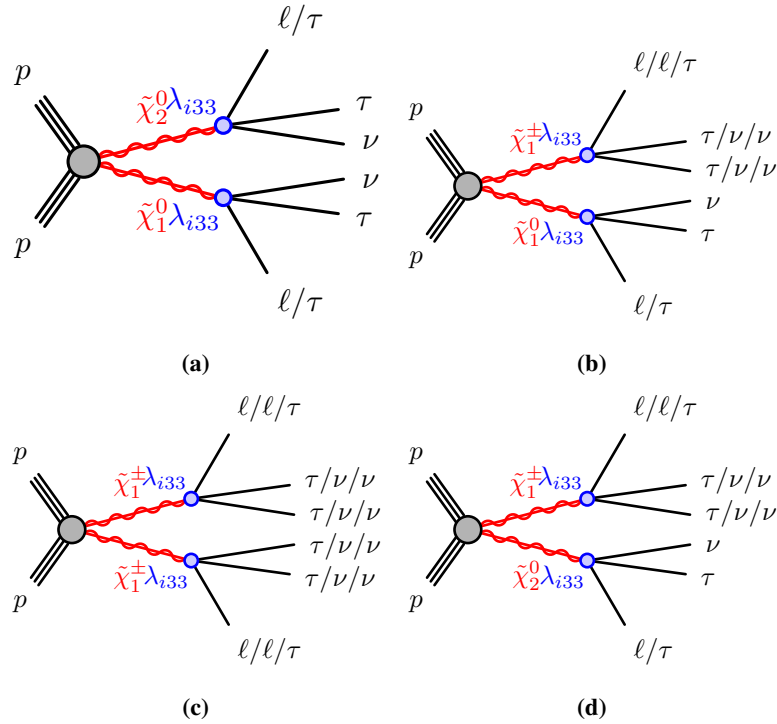
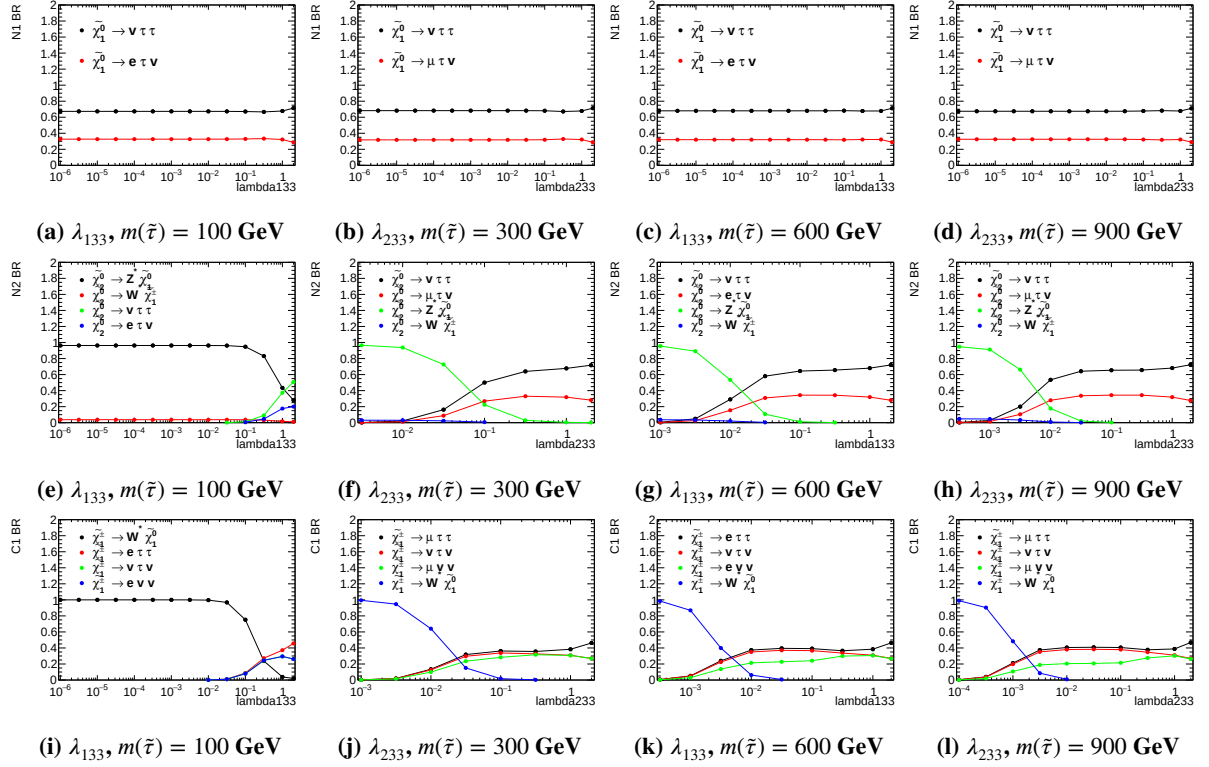


图 7-3 Higgsino 衰变道的费曼图，其中 higgsino 会直接衰变到标准模型粒子。

Figure 7-3 Higgsino pair production channels, the NLSP decays to SM particles.


 图 7-4 Higgsino 的衰变分支比随 λ_{i33} ($i \in \{1, 2\}$) 的变化分布。

 (a-d) 为 $\tilde{\chi}_1^0$, 图 (e-h) 为 $\tilde{\chi}_2^0$, 图 (e-h) 为 $\tilde{\chi}_1^\pm$ 。

 Figure 7-4 The branching fractions of Higgsino as a function of λ_{i33} ($i \in \{1, 2\}$).

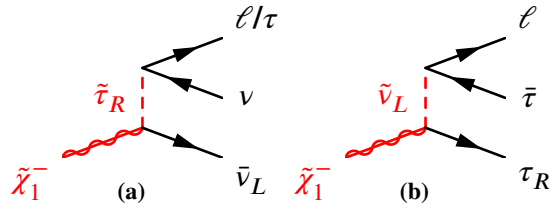
 (a-d) show $\tilde{\chi}_1^0$, (e-h) show $\tilde{\chi}_2^0$, and (e-h) show $\tilde{\chi}_1^\pm$.

 图 7-5 $\tilde{\chi}_1^-$ 通过 RPV 项衰变的过程, $\tilde{\chi}_1^+$ 为电荷共轭的过程。

 Figure 7-5 $\tilde{\chi}_1^-$ possible decay channels, $\tilde{\chi}_1^+$ is the conjugation.

more physical objects suspected of τ_{had} are considered in the reconstruction of $E_{\text{T}}^{\text{miss}}$. In addition, the signal samples are required to have at least one baseline τ_{had} . Considering that the higher p_{T} requirement of di- τ analysis for signal τ_{had} can remove leptons with lower momentum and reduce the impact of false reconstruction on the distribution, so the physical object reconstruction standard in the figure is consistent with the di- τ analysis. It can be found that for the distribution of the number of final states e and μ , the longer the LSP lifetime, the lower the number is relatively, because the efficiency of being reconstructed into signal particles decreases after they are far away from the vertex. For the number of τ_{had} , the situation is more complicated. The number of τ_{had} of samples with $\tau_{\text{LSP}} = 1$ ns is higher than that of samples with shorter lifetimes, and the number of τ_{had} of samples with $\tau_{\text{LSP}} = 0.01$ ns is also higher than that of samples with $\tau_{\text{LSP}} = 0.0001$ ns. This is caused by the relative relationship between the distribution of τ_{had} cases and the distribution of τ_{had} reconstruction efficiency of different samples. Taking the case of 1-prong τ_{had} as an example, if τ_{had} is parameterized using the collision parameter d_0 of the track with the highest p_{T} and the decay vertex L_{xy} of τ_{had} , then in the sample of $\tau_{\text{LSP}} = 0.0001$ ns, the τ_{had} decayed by LSP is mainly concentrated in the region of $\log d_0/[\text{mm}] \in (-2, -1)$ and $\log L_{xy}/[\text{mm}] \in (0, 1)$. For the sample with $\tau_{\text{LSP}} = 0.01$ ns, the peak value of τ_{had} decayed from LSP moves to the region of $\log d_0/[\text{mm}] \in (-1, 0)$ and $\log L_{xy}/[\text{mm}] \in (0, 2)$. If the lifetime is further increased to $\tau_{\text{LSP}} = 1$ ns, the peak value will move to the region of $\log d_0/[\text{mm}] \in (1, 2)$ and $\log L_{xy}/[\text{mm}] \in (1, 3)$. Meanwhile, the reconstruction peak of τ_{had} is in the region of $\log d_0/[\text{mm}] \in (-2, 0)$ and $\log L_{xy}/[\text{mm}] \in (0, 2)$, and the efficiency drops sharply when $\log d_0/[\text{mm}] > 0$ or $\log L_{xy}/[\text{mm}] > 2$. On the other hand, if τ_{had} satisfies $\log d_0/[\text{mm}] < -2$ or $\log L_{xy}/[\text{mm}] < 0$, although the efficiency still drops, the drop rate is slower. Therefore, for samples with $\tau_{\text{LSP}} = 0.0001$ ns, more of them contain at least one baseline τ_{had} . For samples with $\tau_{\text{LSP}} = 0.01$ ns or 1 ns, the proportion of cases containing at least one baseline τ_{had} is low, especially for the case of $\tau_{\text{LSP}} = 1$ ns, almost all cases cannot meet this condition. At the same time, after considering the selection condition of containing at least one baseline τ_{had} , since the τ_{had} of long-lived cases is closer to the efficiency peak, the τ_{had} reconstruction efficiency of the "surviving" cases is relatively higher, resulting in a relatively larger number of τ_{had} of the "surviving" cases of long-lived samples. $E_{\text{T}}^{\text{miss}}$ increases with the increase of the lifetime of LSP, because the leptons decayed by LSP cannot be reconstructed, and the unreconstructed momentum becomes part of the $E_{\text{T}}^{\text{miss}}$ reconstruction. m_{eff} is defined as the scalar sum of p_{T} and $E_{\text{T}}^{\text{miss}}$ of all final state leptons. It can be seen that this variable becomes lower as the lifetime increases. This is because when the LSP lifetime is shorter, more final state products can be reconstructed, and the p_{T} scalar sum of the final state products is greater than the vector sum they contribute to $E_{\text{T}}^{\text{miss}}$ when they are not reconstructed.

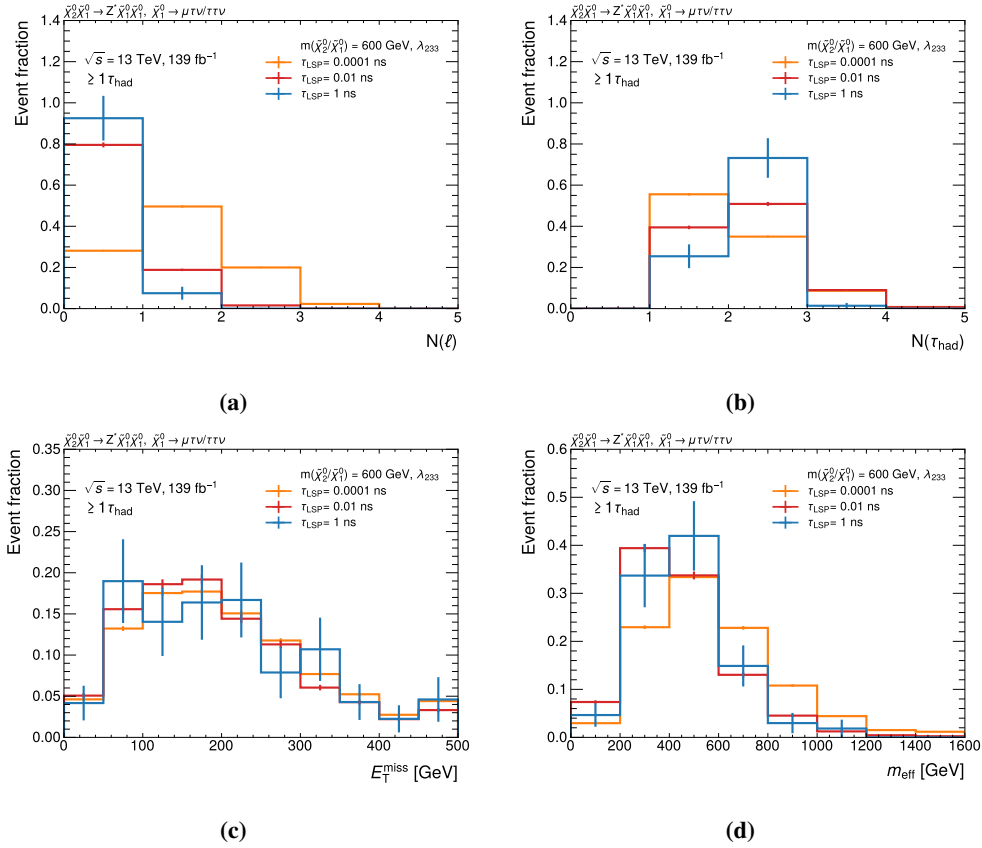


图 7-6 Higgsino 质量为 600 GeV 时, RPV 耦合项为 λ_{233} 时的变量分布。

(a) e 和 μ 的数量; (b) τ_{had} 的数量; (c) E_T^{miss} ; (d) m_{eff} 。

Figure 7-6 Distributions for the scenarios with the higgsino masses of 600 GeV and λ_{233} .

(a) lepton multiplicity, (b) τ_{had} multiplicity, (c) E_T^{miss} , and (d) m_{eff} .

7.3 Interpretation of the ATLAS analysis

This study uses two published analyses by the ATLAS collaboration, one of which is the study of OS final states in Chapter 6 (di- τ analysis) and the other is the four-lepton analysis (4L analysis) [62]. Neither of these two analyses found phenomena beyond the Standard Model. Considering that the di- τ analysis has been documented in detail in this paper, this section will briefly introduce the 4L analysis. The REANA software [164] was used to reproduce these two analyses. The statistical joint measurement strategy of the signal region of each of the two analyses was retained, but due to the overlapping definition of the signal region of the two analyses, a joint measurement could not be performed.

7.3.1 Four-lepton Analysis

The SUSY process studied in the four-lepton analysis consists of two parts: (1) the λ_{12k} and λ_{i33} models, in which LSP is an instantaneous decay; (2) the multi-lepton final state produced by the most general gauge mediation model (General Gauge Mediation, GGM) under RPC [165], where the GGM model is a universal theory that describes how supersymmetry breaking is transmitted to SUSY particles through gauge interactions to degenerate them from standard model particles. The signal region of the 4L analysis requires at least four e , μ or τ_{had} , and is divided into different signal regions according to the number of $e + \mu$, the number of b -jets and whether a pair of leptons can reconstruct the invariant mass of the Z boson. Table 7-2 summarizes the final 13 signal region definitions.

表 7-2 4L 分析的信号区定义和物理目标。

Table 7-2 SR definition and physical motivation of 4L analysis.

Type	$N(e, \mu)$	$N(\tau_{\text{had}})$	$N(b - \text{tagged jets})$	Z Boson Candidate	Condition	Target
4L0T	≥ 4	≥ 0	$= 0$	require 2 candidates	$E_{\text{T}}^{\text{miss}} > 100 \text{ GeV}$	higgsino GGM
			$= 0$	require 2 candidates	$E_{\text{T}}^{\text{miss}} > 200 \text{ GeV}$	higgsino GGM
			≥ 0	require 2 candidates	$E_{\text{T}}^{\text{miss}} > 50 \text{ GeV}$	Excess
			≥ 0	require 2 candidates	$E_{\text{T}}^{\text{miss}} > 100 \text{ GeV}$	Excess
			$= 0$	veto	$m_{\text{eff}} > 600 \text{ GeV}$	General
			$= 0$	veto	$m_{\text{eff}} > 1250 \text{ GeV}$	RPV $LL\tilde{E}i_{12k}$
			≥ 1	veto	$m_{\text{eff}} > 1300 \text{ GeV}$	RPV $LL\tilde{E}i_{12k}$
3L1T	$= 3$	≥ 1	$= 0$	veto	$m_{\text{eff}} > 600 \text{ GeV}$	General
			$= 0$	veto	$m_{\text{eff}} > 1000 \text{ GeV}$	RPV $LL\tilde{E}i_{33}$
			≥ 1	veto	$m_{\text{eff}} > 1300 \text{ GeV}$	RPV $LL\tilde{E}i_{33}$
2L2T	$= 2$	≥ 2	$= 0$	veto	$m_{\text{eff}} > 600 \text{ GeV}$	General
			$= 0$	veto	$m_{\text{eff}} > 1000 \text{ GeV}$	RPV $LL\tilde{E}i_{33}$
			≥ 1	veto	$m_{\text{eff}} > 1100 \text{ GeV}$	RPV $LL\tilde{E}i_{33}$

The first four signal regions target the higgsino pair production process of the GGM model, and require that the final state particles can reconstruct the shell Z boson, and divide the two orthogonal signal regions according to E_T^{miss} for different SUSY particle masses. Two additional signal regions are to verify the possible excess of [166] found in some Run-2 data. The remaining signal regions for the RPV model require that the shell Z boson cannot be reconstructed by the final state particles, and since the decay of LSP leads to a lower E_T^{miss} , m_{eff} is used to divide the orthogonal signal regions for different SUSY particle masses. Since this analysis considers the process of producing SUSY particles by both strong and electroweak interactions, b veto is used to mark the b -jets produced by $\tilde{g}$ decays. Finally, in the RPV model, when $m(\tilde{\chi}_1^0)$ is between 400 GeV and 700 GeV, the 4L analysis excludes the production of $\tilde{\chi}_1^\pm \tilde{\chi}_2^0$ particles with masses below 980 GeV. Considering that the mass difference between $\tilde{\chi}_1^\pm/\tilde{\chi}_2^0$ and $\tilde{\chi}_1^0$ in this study is very low, which will lead to a low number of final state particles and m_{eff} , the significance will be relatively reduced.

7.4 Systematic Uncertainties

The workflow used in this study includes the systematic uncertainties of the complete standard model background, so this study only examines the systematic uncertainties of the signal. Since the di- τ and 4L analysis are for transient decay τ_{had} , the conventional τ_{had} reconstruction and identification strategy is used, which is optimized for short-lived τ_{had} , while the LSP in the signal studied in this paper can fly a distance before decaying to produce a displaced τ_{had} . Since the reconstruction and identification of transient decay τ_{had} and displaced τ_{had} may be different, this paper compares the transient decay τ_{had} produced by the $Z \rightarrow \tau\tau$ process and the displaced τ_{had} produced by the RPV signal to obtain the systematic uncertainty for the displaced τ_{had} . Finally, the systematic uncertainty of the signal includes the experimental uncertainty recommended by the ATLAS collaboration, the systematic uncertainty caused by the displaced τ_{had} , and the theoretical uncertainty.

7.4.1 Reconstruction and identification uncertainties of displaced τ_{had}

The variables used to parameterize τ_{had} are the collision parameter d_0 of the track with the highest p_T of τ_{had} , the vertex L_{xy} of τ_{had} and the number of prongs. The impact of p_T and η on the reconstruction efficiency is much lower than that of d_0 , so d_0 , L_{xy} and the number of prongs are finally selected to divide the bins. Considering that the lifetime distribution of a single signal sample is relatively concentrated while the lifetime coverage of the overall signal sample is relatively large, then the system uncertainty is finally calculated only in the bins where the reconstruction efficiency of $Z \rightarrow \tau\tau$ samples is not 0% and the statistical uncertainty of at least two signal samples

is less than 50%. Finally, the reconstruction efficiency of $Z \rightarrow \tau\tau$ samples is compared with the average value of the signal sample efficiency, where the average value of the signal sample efficiency is fitted by the least squares method, and the corresponding efficiency difference is taken as the system uncertainty of the current bin. Figure 7-7 shows the signal average, the reconstruction efficiency of $Z \rightarrow \tau\tau$ and the final efficiency difference, respectively, and is divided into 1-prong and 3-prong τ_{had} . It can be found that the peak of the reconstruction efficiency of τ_{had} is in the region of $\log_{10}(d_0/[\text{mm}]) \in [-2, -1]$ and $\log_{10}(L_{xy}/[\text{mm}]) \in [0, 2]$. Most of the efficiency differences of 1-prong τ_{had} are within 5%, and those of 3-prong τ_{had} are 20%. If τ_{had} is in a bin with no efficiency difference, the efficiency difference of the nearest bin is taken as the uncertainty.

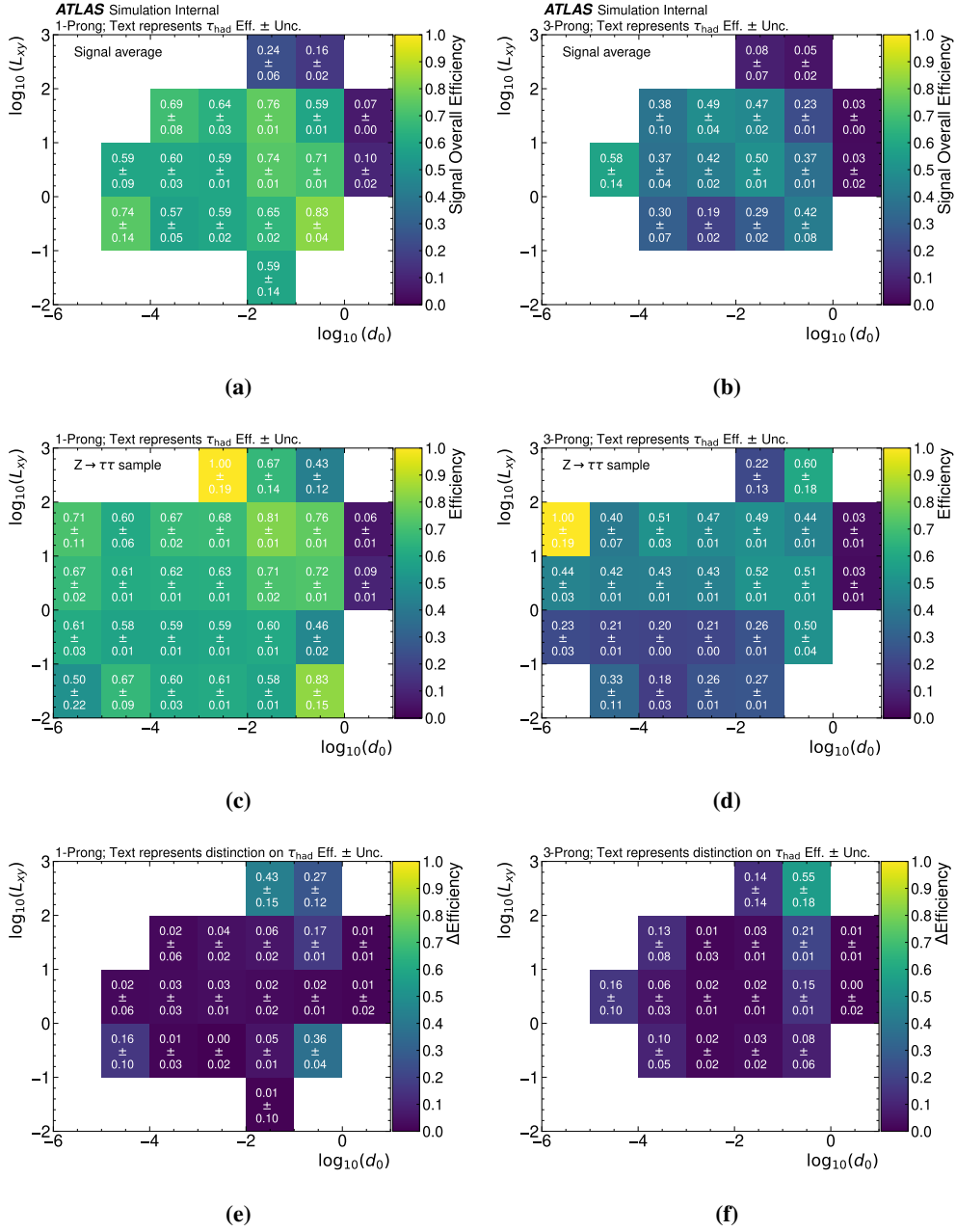
7.4.2 Systematic uncertainty of the trigger with displaced τ_{had}

Since the asymmetric di- τ and di- $\tau + E_{\text{T}}^{\text{miss}}$ triggers used in di- τ analysis are optimized for the τ_{had} of instantaneous decay, it is necessary to study the difference between the two di- τ triggers in the τ_{had} of instantaneous decay and the displacement τ_{had} as the system uncertainty. This study still uses the comparison of the $Z \rightarrow \tau\tau$ process and signal samples. In order to avoid repeated calculation uncertainties, the parameterization of this uncertainty uses the second highest p_{T} of all τ_{had} . For the di- $\tau + E_{\text{T}}^{\text{miss}}$ trigger, $E_{\text{T}}^{\text{miss}}$ is also considered as the second parameter. In the asymmetric di- τ trigger, the distribution of the efficiency of the $Z \rightarrow \tau\tau$ process and signal samples with the second highest p_{T} of τ_{had} as the variable is flat, and the overall efficiency difference is about 6%, which is used as the additional uncertainty of the asymmetric di- τ trigger. In the di- $\tau + E_{\text{T}}^{\text{miss}}$ trigger, when $E_{\text{T}}^{\text{miss}}$ is higher than 130 GeV, the distribution of the efficiency ratio with the second highest p_{T} or $E_{\text{T}}^{\text{miss}}$ is also flat, and the overall efficiency difference is about 12%, which is used as the additional uncertainty of the di- $\tau + E_{\text{T}}^{\text{miss}}$ trigger.

7.4.3 Theoretical uncertainty of the signal

Similar to the di- τ and 4L analysis, the signal theory uncertainties are mainly cross-section uncertainties, PDF uncertainties, μ_R, μ_F uncertainties, Matching and Merging Schema uncertainties, and uncertainties in initial/final state radiation. The cross-section uncertainty uses the value recommended by the ATLAS collaboration, and the calculation methods of other uncertainties are slightly different in the two re-interpretations:

- PDF uncertainty: For the PDF uncertainty of the re-interpretation of the di- τ analysis, this study uses the same method as the Wh analysis to select the LHE weights of 100 NNPDFs (PDF260000-PDF260100) with the largest difference in signal area reception as the uncertainty, and finally found that most signal points are within 10%. Due to the workflow limitations of 4L analysis, it is impossible to directly calculate the impact of PDF on acceptance, so a conservative estimate of 10% is used.


 图 7-7 τ_{had} 重建和鉴别效率。

(a)、(b) 分别为来自信号的 1-prong、3-prong τ_{had} 的加权平均效率，(c)、(d) 分别为来自 $Z \rightarrow \tau\tau$ 过程的 1-prong、3-prong τ_{had} 的效率，(e)、(f) 分别为 1-prong、3-prong τ_{had} 的信号与 $Z \rightarrow \tau\tau$ 的效率差别。

Figure 7-7 The Reco+Medium-ID efficiency.

(a) 1-prong τ_{had} in signal samples, (b) 3-prong τ_{had} in signal samples, (c) 1-prong τ_{had} in $Z \rightarrow \tau\tau$ samples, and (d) 3-prong τ_{had} in $Z \rightarrow \tau\tau$ samples, where the efficiency of the signal samples is the weighted mean. Figure (e) and (f) shows the efficiency difference between $Z \rightarrow \tau\tau$ and signal samples of 1-prong and 3-prong τ_{had} separately.

- μ_R, μ_F uncertainties, Matching and Merging Schema uncertainties, and initial/final radiation uncertainties: For the reinterpretation of di- τ analysis, this study used the difference between the samples used in the truth-level analysis and the uncertainty samples as the uncertainty, and finally found that most uncertainties were within 20%; 4L analysis has added uncertainties estimated based on the signal to the signal area, and this analysis directly adopts their conclusions. The uncertainties in most signal areas are within 20% [62].

7.5 Results

This study uses pyhf [143, 144] software for statistical interpretation. Using di- τ analysis and 4L analysis, this study finally ruled out the Higgsino pair production process at 95% confidence. Figure 7-8 shows the exclusion limits of $\tilde{\chi}_1^0 \tilde{\chi}_2^0$, $\tilde{\chi}_1^0 \tilde{\chi}_1^\pm$ and $\tilde{\chi}_1^\pm \tilde{\chi}_1^\mp$ processes with non-zero λ_{133} or λ_{233} coupling, respectively. The parameters of the exclusion limits are the Higgsino mass and coupling strength. The dotted lines on the figure show the contours of τ_{LSP} and the branching ratio $B(\tilde{\chi}_1^\pm / \tilde{\chi}_2^0 \rightarrow \tilde{\chi}_1^0)$, respectively. The upper limit of the coupling in the gray area on the far right comes from the measurement experiments of $m(\nu_e)$ and R_τ . When the coupling strength is low, the exclusion ability of di- τ analysis is higher than that of 4L analysis, and vice versa. The main reasons why the exclusion ability of 4L analysis is lower than expected are: (1) The reconstruction efficiency of leptons decreases rapidly with the increase of τ_{LSP} , thereby reducing the reception of the 4L signal area; (2) The smaller mass difference of the Higgsino model leads to a lower content of leptons with higher momentum, while the di- τ analysis only requires two τ_{had} , so the reception is higher when τ_{LSP} is larger; However, in the $\tilde{\chi}_1^\pm \tilde{\chi}_1^\mp$ process, when $B(\tilde{\chi}_1^\pm \rightarrow \tilde{\chi}_1^0)$ is higher, the 4L analysis is stronger than the di- τ analysis. This is mainly because $\tilde{\chi}_1^\pm$ has a high probability of producing three leptons when decaying through the RPV term, while the m_{Tsum} in the definition of the signal area of the di- τ analysis only considers the highest and second highest τ_{had} of p_T , and E_T^{miss} decreases as the reconstruction rate of the final state particles increases. When the final state of the $\tilde{\chi}_1^\pm \tilde{\chi}_1^\mp$ signal produces more leptons and the reconstruction efficiency is high, the significance of the di- τ analysis will decrease slightly.

When $\tau_{\text{LSP}} = 0.01$ ns, the Higgsino mass exclusion limit is between 200 GeV and 600 GeV. When $\tau_{\text{LSP}} = 0.001$ ns, the Higgsino mass region below 800 GeV is excluded. If the coupling strength is higher, the Higgsino mass exclusion limit will increase to 900 GeV. When λ_{i33} is lower than 10^{-4} or $\tau_{\text{LSP}} \geq 0.01$ ns, the di- τ and 4L analysis cannot obtain the exclusion limit.

Among the cases excluded by the di- τ analysis, the signal sensitivity of the SR-C1N2OS-HM signal region is the highest. This is because the boosted τ_{had} and neutrinos produced by the higgsino decay can constitute larger m_{Tsum} and E_T^{miss} to meet the

definition of the signal region.

The signal sensitivity of the cases excluded by the 4L analysis is more complicated. Different production processes have different most sensitive signal areas: (1) For the $\tilde{\chi}_1^0 \tilde{\chi}_2^0$ process, the signal area with $2L2T$ and $m_{\text{eff}} > 600$ GeV has the highest sensitivity. This is because the $\tilde{\chi}_1^0 \tilde{\chi}_2^0$ decay produces relatively less e and μ , so the sensitivity of the signal area with lower requirements for e and μ is higher. (2) For the $\tilde{\chi}_1^0 \tilde{\chi}_1^\pm$ process, the signal region with $2L2T$ and $m_{\text{eff}} > 600$ GeV or $m_{\text{eff}} > 1000$ GeV has the highest sensitivity. However, for the signal with Higgsino mass around 200 GeV, the signal region with $4L0T$ requiring $E_T^{\text{miss}} > 100$ GeV and reconstruction of two in-shell Z boson candidates has higher sensitivity. For the former case, since the branching ratio of $\tilde{\chi}_1^\pm$ decaying to the three-lepton final state is 50%, the decay product of $\tilde{\chi}_1^\pm$ has a higher m_{eff} than the decay product of $\tilde{\chi}_2^0$, so the signal region with stricter requirements on m_{eff} can also have the highest sensitivity to samples with higher Higgsino mass. For the latter case, when the Higgsino mass is lower, m_{eff} will also decrease, but the number of final state leptons has a 50% probability of reaching five. More leptons and lower p_T mean that the final state leptons have a higher probability of mistakenly reconstructing two pairs of leptons that meet the mass of the shell Z boson. (3) For the $\tilde{\chi}_1^\pm \tilde{\chi}_1^\mp$ process, the signal region with $3L1T$ and $m_{\text{eff}} > 600$ GeV has the strongest exclusion ability, mainly because the decay of $\tilde{\chi}_1^\pm$ can produce relatively more leptons and fewer τ_{had} . In addition, the probability that the final state produced by the decay of the $\tilde{\chi}_1^\pm \tilde{\chi}_1^\mp$ process contains more than four leptons is much lower than that of the $\tilde{\chi}_1^0 \tilde{\chi}_1^\pm$ process, so the signal sensitivity of the $4L0T$ signal region in the low Higgsino mass region is weaker.

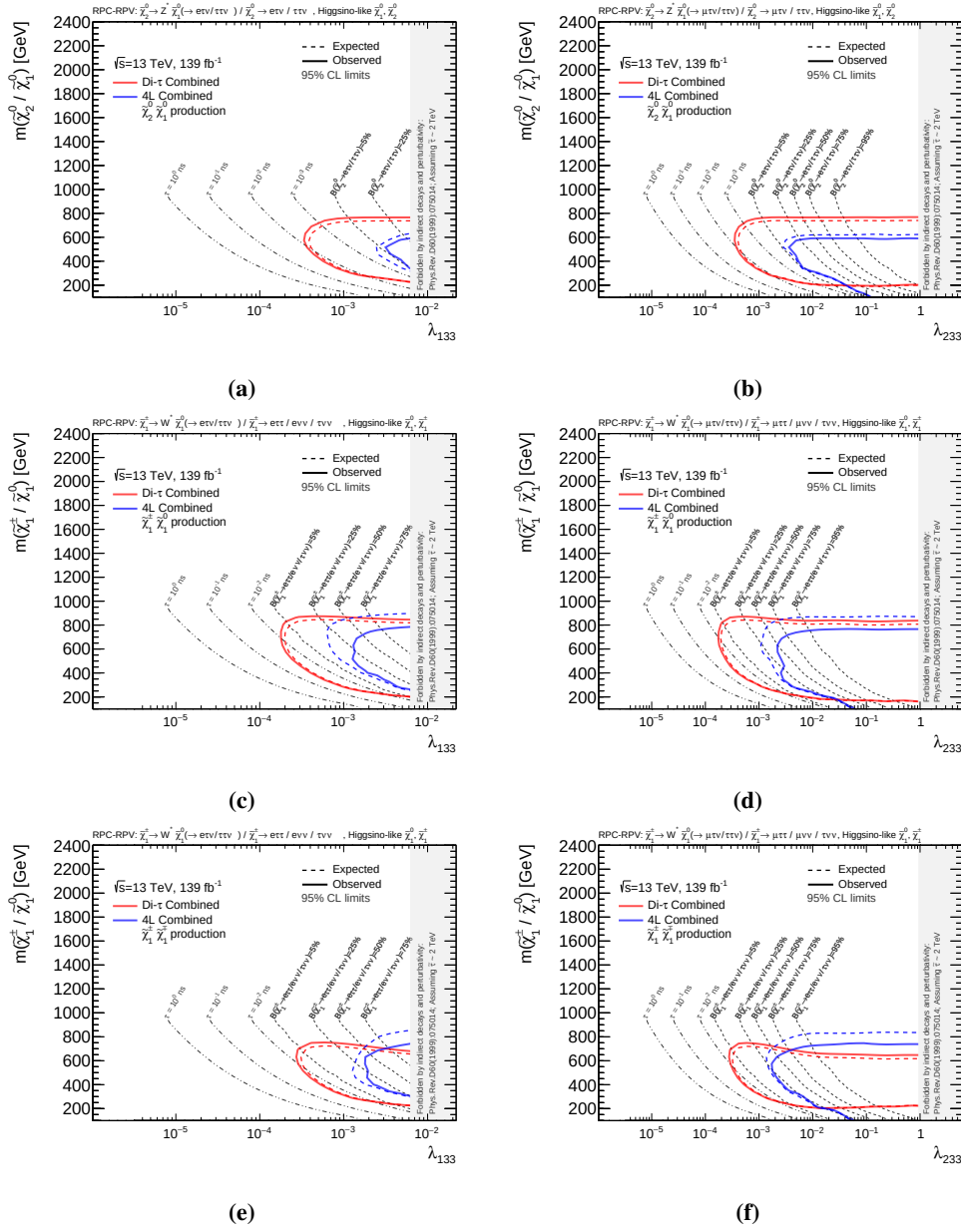


图 7-8 Higgsino 模型的排除限。

图 (a-b) 为 $\tilde{\chi}_1^0 \tilde{\chi}_2^0$ 产生过程、图 (c-d) 为 $\tilde{\chi}_1^0 \tilde{\chi}_1^\pm$ 产生过程、图 (e-f) 为 $\tilde{\chi}_1^\pm \tilde{\chi}_1^\mp$ 产生过程。其中，图 (a)、(c) 和 (e) 为 λ_{133} 耦合，图 (b)、(d) 和 (f) 为 λ_{233} 耦合。预期排除限为虚线，观测排除限为实线，灰色区域的限制 $m(\nu_e)$ 和 R_τ 的测量实验。

Figure 7-8 Exclusion limits for the higgsino model.

(a-b) $\tilde{\chi}_1^0 \tilde{\chi}_2^0$ production, (c-d) $\tilde{\chi}_1^0 \tilde{\chi}_1^\pm$ production, and (e-f) $\tilde{\chi}_1^\pm \tilde{\chi}_1^\mp$ production as a function of λ_{133} and higgsino mass. Among them, (a), (c), and (e) correspond to λ_{133} , while (b), (d), and (f) correspond to λ_{233} . Expected limits are shown with dashed lines, and observed as solid. The grey region is forbidden by constraints from $m(\nu_e)$ and R_τ measurement.

7.6 Conclusion

This paper studies in detail the impact of the coupling coefficients λ_{133} and λ_{233} of the R parity destruction term on the Higgsino lifetime and branch ratio. This is the first time that ATLAS has studied this model. At the same time, this paper gives The current theoretical upper limit of the latest λ_{133} and λ_{233} coupling coefficients. In terms of systematic uncertainties, this paper studies in detail the systematic uncertainties of the reconstruction, identification and related triggers of displaced Taozi. This is the first time that ATLAS has studied related uncertainties. This study gives the mass exclusion limit of the mass-degenerate Higgsino under different lifetimes at a 95% confidence level. When the coupling coefficient is large and the branch of Higgsino decaying into standard model particles is relatively high, the Higgsino mass is lower than 800 The GeV region is excluded, which also illustrates that the traditional signal region is still significant for models with particles with a certain lifetime.

第 8 章 Interpretation of Phenomenological Minimal Supersymmetric Standard Model

8.1 Motivation

During the Run1 and Run2 phases of the LHC, the ATLAS and CMS experiments respectively conducted a detailed search for the SUSY model. Since no phenomena were found that were obviously beyond the standard model, the parameters of the simplified model were strictly constrained. However, the free parameters of this type of simplified model are only in the single digits, and do not cover the complete MSSM parameter phase space, so the actual exclusion capability is still far behind that of more complex models. As introduced in Section 2.2.2, the MSSM parameter phase space has extremely high degrees of freedom, and it is impossible to directly exclude the MSSM model parameters. However, the pMSSM-19 model can reasonably simplify the MSSM to 19 free parameters, so it is possible to restrict the pMSSM-19 model. The constraints on the pMSSM-19 model can not only check the constraints and exclusions of the ATLAS experiment on more realistic SUSY models, but also have important reference significance for future SUSY searches.

In Run1, the ATLAS experiment reinterpreted the SUSY search experiment by taking 30,000 pMSSM models in the 19-dimensional phase space. The CMS experiment also used global Bayesian statistics to sample and reinterpret the phase space. The results showed that the masses of Squark and Gluino particles were strongly constrained. In Run2, the ATLAS experiment reinterpreted the electroweak supersymmetric particles that were weakly constrained in Run1 in the five-dimensional phase space. The results showed that the ability to exclude electroweak supersymmetric particles with lower mass was still limited. This paper uses the results of the ATLAS experiment during Run2 to search for SUSY particles produced by electroweak or strong processes to constrain the pMSSM model. Compared with the research of Run 1, the analysis of Run 2 used in this study has improved MC sample simulation, physical object reconstruction, and detector performance. In addition, Run 2 has higher center of mass energy and more integrated brightness. In addition, this study used new software developed by the ATLAS collaboration: SIMPLEANALYSIS framework [167], workspace storage [168], RECAST [169, 170] and REANA [164] reinterpretation framework.

This article mainly focuses on the model where LSP is a Bino type $\tilde{\chi}_1^0$. This type of model has a high relic density of dark matter. LSP as a dark matter particle can meet the experimental observation value: $\Omega h^2 = 0.12$ [5], so it is a relatively popular model.

8.2 Strategy

This section will introduce the analysis strategy of this study, including the software framework, simulation samples, scanning of pMSSM model parameters, and experimental constraints adopted.

8.2.1 Software Framework and Constraints of Indirect Probing Experiments

The sampling strategy of the pMSSM parameter space in this paper is to sample uniformly in the parameter space of interest. Figure 8-1 shows the workflow for determining whether the sampled pMSSM model is excluded.

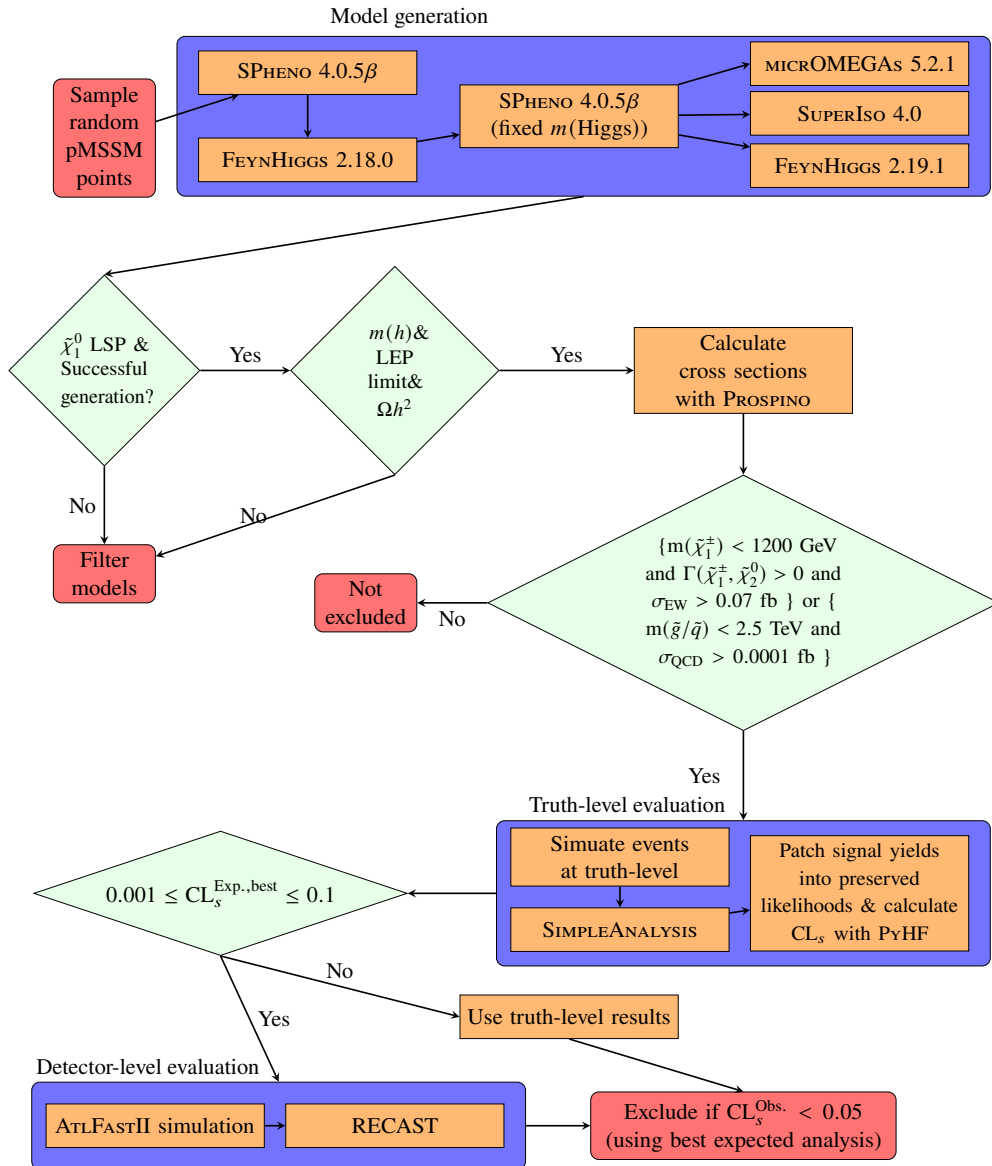


图 8-1 pMSSM 研究工作流程，从模型取样至判断模型是否被排除。

Figure 8-1 Workflow for the pMSSM scan, starting from sampling the pMSSM parameter space and ending at the determination of whether each model is excluded or not.

The pMSSM model first calculates the physical variables used in the analysis through several procedures:

- SPHENO 4.0.5 [171, 172] is used to calculate the mass spectrum and decay branching ratio of SUSY particles, recorded as SLHA files [173].
- FEYNHIGGS 2.18.0/2.19.1 [174–181]: Version 2.18.0 is used to calculate variables related to Higgs physics (Higgs sector) in the MSSM model, such as the mass and decay branching ratio of Higgs particles in SM and SUSY. The mass and branching ratio obtained by FEYNHIGGS will be used to modify the relevant information in the SLHA file. Considering that the change of the Higgs sector will also affect the mass and branching ratio of the SUSY particles, the modified SLHA file will be updated again through SPHENO. Version 2.19.1 is used to calculate the mass of the W boson in the MSSM.
- MICROMEGAS 5.2.1 [182, 183] is used to calculate Ωh^2 , LSP as a channel and cross section for dark matter particle annihilation and LSP as a spin-dependent (SD) and spin-independent (SI) scattering cross section of WIMP particles (Weakly interacting massive particles) with nucleons. The model used in the direct detection experiment of dark matter assumes that the WIMP's $\Omega h^2 = 0.12$. Considering that the Ωh^2 of LSP as a WIMP particle may be lower, the calculated result of the WIMP-nucleon scattering cross section will be reduced to $\Omega h^2 / 0.12$.
- SUPERISO 4.0 [184] is used to calculate the branching ratio involved in flavor physics in the MSSM model.

If a model reports an error when running any of the above programs, it will be removed from the model used for analysis. This error is most likely caused by the SUSY mass spectrum not meeting the theoretical requirements. After that, the analysis will screen out the Bino type (Bino mixing ratio is higher than 50%) $\tilde{\chi}_1^0$ as the model of LSP, and determine whether the lightest Higgs boson in the model meets the SM Higgs boson mass: $m(h) \in [120, 130]$ GeV. It can be found that this mass range is large, mainly because when the $\tilde{g}$ mass is large, the theoretical error of the loop diagram contributing to $m(h)$ by $\tilde{t}$ and $\tilde{b}$ may be higher than 3 GeV [185]. In addition, it is also important to remove models that have been excluded by other collider experiments. This paper uses the results of LEP experiments and D0 experiments for pre-exclusion. In EWKino (Electroweakino), if the mass difference $\Delta m(\tilde{\chi}_1^\pm, \tilde{\chi}_1^0) \geq 3$ GeV, the model satisfying $m(\tilde{\chi}_1^\pm) < 103$ GeV is removed. If the mass difference is less than 3 GeV, the model with $\tilde{\chi}_1^\pm$ mass lower than 91.9 GeV is removed. In $\tilde{g}$, the model used in the D0 experiment is cMSSM [186, 187]. The parameter phase space of the pMSSM-19 model includes the phase space of the cMSSM model. If the experimental results of D0 are used directly, it may cause erroneous exclusion. Finally, the conservative choice is to remove the model with $\tilde{g}$ mass lower than 100 GeV.

In addition to the constraints of the ATLAS experiment on the pMSSM model, this paper also considers the constraints of non-ATLAS experiments, including constraints of non-direct search experiments such as the W boson mass on the pMSSM model. Table 8-1 summarizes the range of each constraint. In terms of flavor physics, three branching ratios are considered as constraints: $B(b \rightarrow s\gamma)$, $B(B_s \rightarrow \mu\mu)$, and $B(B^+ \rightarrow \tau\nu)$. The experimental constraints come from the global fitting of PDG [162] and the latest LHCb experimental results [188], and the error range of 2σ is considered. In terms of electroweak precision observables (EWPO), the ρ parameter, the width of the Z boson decay to undetectable particles ($\Gamma_{\text{inv}}(Z)$), and the W boson mass ($m(W)$) are considered respectively. The ρ parameter is defined as $\rho = m_W^2/m_Z^2 \cos^2 \theta_W$. It can be seen that ρ of the SM model is 1 under the tree graph accuracy. The SUSY process can contribute to this variable through the loop graph. The constraint of ρ adopts the results of the GFITTER collaboration group [189]. $\Gamma_{\text{inv}}(Z)$ adopts the results of the SLC and LEP experiments [190]. $m(W)$ uses the global fitting of PDG, and the fitting does not take into account the results of the CDF experiment [191], because the results of the CDF experiment deviate greatly from the results of other experiments. In addition, since the theoretical error of $m(W)$ in the calculation of the MSSM model is large, the constraint range of $m(W)$ not only considers the 2σ error, but also expands the window range of 6 MeV. The constraints of the dark matter direct detection experiments SI and SD respectively use the results of the LZ collaboration [192] and PICO-60 experiments [193], which have the strongest constraints at present.

表 8-1 非 ATLAS 实验对 pMSSM 模型参数的约束，分别来自味物理分支比、电弱精确观测物理量和暗物质直接探测实验。

Table 8-1 Constraints from non-ATLAS experiments. They are electroweak precision measurements, flavour physics observables and direct-detection DM searches.

Type	Constraints	Lower	Upper	Comment
Flavour	$B(b \rightarrow s\gamma)$	3.11×10^{-4}	3.87×10^{-4}	2022 PDG average (2σ window) [162]
	$B(B_s \rightarrow \mu\mu)$	1.87×10^{-9}	4.31×10^{-9}	Most recent LHCb result (2σ window) [188]
	$B(B^+ \rightarrow \tau\nu)$	6.10×10^{-5}	1.57×10^{-4}	2022 PDG average (2σ window) [162]
EWPO	$\delta\rho$	-0.0004	0.0018	Updated global electroweak fit by GFITTER group [189] (not including CDF W -mass measurement [191])
	$\Gamma_{\text{inv}}(Z)$	--	2 MeV	Beyond-the-Standard Model contributions to precision electroweak measurements on the Z-resonance from experiments at the SLC and LEP colliders [190].
	$m(W)$ (extended)	80.347 GeV	80.407 GeV	2022 PDG result (excluding CDF W mass measurement [191]) [162] but with the 2σ window expanded by 6 MeV to allow for uncertainty due to the top-quark mass in the MSSM Higgs calculation [194]
DM	Relic density	--	0.12	Latest bound from Planck [5]
	Direct detection σ_{SI}			Exclusion contour on direct detection of DM from the LZ collaboration [192]
	Direct detection σ_{SD}			Exclusion contour on direct detection of DM from PICO-60 [193]

For the pMSSM models that pass the pre-screening, the analysis will use the PROSPINO

software to calculate the cross section of the model at the LHC with an accuracy of sub-leading order. Next, the pMSSM model will be pre-screened again based on experimental expectations, and a part of the models with higher SUSY particle masses will be marked as non-excluded models in advance. The specific criteria are: If $m(\tilde{\chi}_1^\pm) > 1.2$ TeV in the model, the process of producing SUSY particles by electroweak interaction is marked as not excluded, If $m(\tilde{g})$ and $m(\tilde{q})$ in the model are both higher than 2.5 TeV, the process of producing SUSY particles by strong interaction is marked as not excluded. In addition, if the model contains $\tilde{\chi}_1^\pm$, $\tilde{\chi}_2^0$, $\tilde{g}$ or $\tilde{q}$ with long or even stable lifetimes, the corresponding production process will also be marked as not excluded. Eliminating such long-lived models requires the use of long-lived particle search experiments that are not currently considered in this analysis, such as the ATLAS experiment, which searches for charged long-lived particles through minimal ionization energy loss [145].

The MC generator of the signal sample of the pMSSM model is MADGRAPH5_AMC@NLO2.9.5, and the PS generator is PYTHIA 8.306. Depending on the situation, a signal sample may correspond to two detector simulations. One is the conventional simulation based on Geant4 or AF-II. This simulation consumes high computing resources, so only a small number of signal samples use this simulation. The other simulation uses information at the particle level. By using the SIMPLEANALYSIS framework [167], the parameterized detector response function is applied to the final state particles to simulate the reconstruction efficiency and resolution (Smearing). In order to verify the rationality of SIMPLEANALYSIS, this analysis selects some signal points to generate both conventional detector simulation and Smear simulation, and compares the difference in the number of cases in the signal area used in this analysis. Finally, it is found that most of the errors are less than 20%.

After the two-step pre-screening model has completed the signal sample generation, this analysis uses the PyHF framework [143, 144] and the workspace stored in HepData [168] to exclude the pMSSM model. If a model has the lowest expected confidence CL_{exp} between 0.001 and 0.1 in all analyses, it is necessary to perform AF-II simulations and use RECAST [169, 170] and REANA [164] frameworks for complete analysis reproduction. Finally, models with CL_{obs} lower than 0.05 (at 95% confidence) will be excluded by the ATLAS experiment.

8.2.2 Signal Model and Sampling

Table 8-2 shows the pMSSM model parameter scanning range for Bino-type LSP, hereinafter referred to as Bino-DM scanning. In order to improve the sampling efficiency of Bino-type LSP, the Bino quality parameter M_1 is set between 0 and 2 TeV, and the scanning upper limit of Wino's quality parameter M_2 and Higgsino's quality parameter μ is 5 TeV. Considering that the ATLAS experiment has a strong ability to exclude $\tilde{g}$ and $\tilde{q}$, the upper limits of $\tilde{g}$ quality parameter M_3 and left-hand and right-

hand $\tilde{q}$ quality parameters $m_{\tilde{Q}_i}$ and $m_{\tilde{u}_i/\tilde{d}_i}$ are all set to 5 TeV. Considering that $\tilde{g}$ or $\tilde{q}$ can decay to produce $\tilde{\ell}$ through the intermediate state EWKino, the upper limit of the mass parameters $m_{\tilde{L}_i}$ and $m_{\tilde{e}_i}$ of the left and right $\tilde{\ell}$ is also as high as 5 TeV. In the Higgs sector, the scanning range of the trilinear coupling constant is set to a wider 8 TeV, the mass parameter of the pseudoscalar Higgs boson A is set to 5 TeV, and the vacuum expectation value ratio $\tan\beta$ is between 1 and 60, which is more common.

表 8-2 pMSSM 模型取样的参数范围。

Table 8-2 Parameter ranges that are randomly sampled for the pMSSM scan.

Parameter	Low Range	High Range	Comment
$m_{\tilde{L}_1} (=m_{\tilde{L}_2})$	0 TeV	5 TeV	左手第一、二代 slepton 质量
$m_{\tilde{e}_1} (=m_{\tilde{e}_2})$	0 TeV	5 TeV	右手第一、二代 slepton 质量
$m_{\tilde{L}_3}$	0 TeV	5 TeV	左手 stau 质量
$m_{\tilde{e}_3}$	0 TeV	5 TeV	右手 stau 质量
$m_{\tilde{Q}_1} (=m_{\tilde{Q}_2})$	0 TeV	5 TeV	左手第一、二代 squark 质量
$m_{\tilde{u}_1} (=m_{\tilde{u}_2})$	0 TeV	5 TeV	右手第一、二代 up 型 squark 质量
$m_{\tilde{d}_1} (=m_{\tilde{d}_2})$	0 TeV	5 TeV	右手第一、二代 down 型 squark 质量
$m_{\tilde{Q}_3}$	0 TeV	5 TeV	左手第三代 squark 质量
$m_{\tilde{u}_3}$	0 TeV	5 TeV	右手第三代 up 型 squark 质量
$m_{\tilde{d}_3}$	0 TeV	5 TeV	右手第三代 down 型 squark 质量
M_1	-2 TeV	2 TeV	Bino 质量参数
M_2	-5 TeV	5 TeV	Wino 质量参数
μ	-5 TeV	5 TeV	双线性 Higgs 质量参数
M_3	0 TeV	5 TeV	Gluino 质量参数
A_t	-8 TeV	8 TeV	Top 三线性耦合强度
A_b	-8 TeV	8 TeV	Bottom 三线性耦合强度
A_τ	-8 TeV	8 TeV	Tau 三线性耦合强度
M_A	0 TeV	5 TeV	赝标量 Higgs 质量参数
$\tan\beta$	1	60	Higgs 真空期望值比值

Table 8-3 shows the number of signal points after screening in each step of Bino-DM scanning. Bino-DM scanning uniformly sampled 8 million signal points in the initial stage. In the end, only about 10% of the models met the requirements of the MSSM model, LSP was $\tilde{\chi}_1^0$ and the Bino mixing ratio was higher than 50%. The lower efficiency was expected in the experiment, because although uniform sampling reduced the bias caused by other sampling methods, the efficiency was indeed low. Among the 820,000 models, only 32,000 of them finally met the Ωh^2 condition. This is because the cross section of the joint annihilation of Bino-type LSP and other SUSY particles is low. For LSPs with a high Bino mixing ratio, only when the LSP mass is close to half

of the mass of Z and h bosons, can a pair of LSPs decay to SM particles (Z/h -funnel) through the Z/h channel, thereby reducing Ωh^2 . If the mass of LSP is higher than the mass of Z and h bosons, only when the mass of LSP is close to half of the mass of A/H bosons or when the mixing of Bino is low and the mixing of Wino/Higgsino is high, LSP can meet the Ωh^2 condition. At this time, LSP can reduce Ωh^2 by decaying in pairs to A/H particles (A/H -funnel) or decaying with NLSP.

After passing the $m(h)$ requirement, only about 20,000 models survive, mainly because the uniform sampling used in this analysis results in a low mass contribution of $\tilde{t}$ to Higgs. Since the upper limit of the mass parameter of M_A is 5 TeV, in most models, $m(A)$ is much higher than $m(Z)$. At this time, the mass contribution of $\tilde{t}$ to Higgs under the accuracy of the single-loop graph can be expressed as [195]:

$$m(h)^2 = m(h)^{2,\text{tree}} + \Delta m(h)^{2,1\text{-loop}} \quad (8-1)$$

Where the single-loop graph contribution is [195]:

$$\Delta m(h)^{2,1\text{-loop}} = \frac{3}{4\pi^2} \frac{m(t)^2}{v^2} \left(\log \frac{M_S^2}{m(t)^2} + \frac{X_t^2}{M_S^2} \left(1 - \frac{X_t^2}{12M_S^2} \right) \right) \quad (8-2)$$

Where $X_t = A_t - \mu \cot \beta$ is the $\tilde{t}$ mixing parameter, and $M_S = \sqrt{m(\tilde{t}_1) \cdot m(\tilde{t}_2)}$ is the SUSY energy scale. It can be found that under the single-loop graph accuracy of $|X_t/M_S| \sim \sqrt{6}$, $\tilde{t}$ contributes the most to the $m(h)$ loop graph, but a large proportion of the pMSSM models analyzed in this analysis have a mixing parameter lower than 1, resulting in a low distribution of $m(h)$. Therefore, the constraint of $m(h)$ finally removes about 1/3 of the models. The models constrained by $m(h)$ are the models finally used in this analysis, about 20,000.

After being constrained by other non-dark matter, about nine thousand models survived, most of which were constrained by $B(b \rightarrow s\gamma)$. This is because the scanning upper limit of $\tan \beta$ is high, and $\tan \beta$ has a strong influence on $B(b \rightarrow s\gamma)$ [196]. In the end, about four thousand models can pass the constraints of the direct detection experiment of dark matter, among which the strongest constraint is σ_{SI} .

8.2.3 Interpretation of the ATLAS analysis

This analysis uses the results of the search for supersymmetric particles in the ATLAS experiment and the results of the search for Higgs physics beyond the standard model. Table 8-4 summarizes the constraints of the ATLAS experiment. The first part is to search for supersymmetric particles produced by electroweak processes, and the second part is to search for supersymmetric particles produced by strong processes. Their research is aimed at finding specific final states of the simplified model, and assumes that EWKino is a pure gaugino mixture, so changes in the decay branch ratio and

表 8-3 pMSSM 模型取样的参数范围和经过不同选择条件的事例数。

Table 8-3 Set-ups for the pMSSM scan performed and the number of models passing each step and constraint.

Scan	Bino-DM
$ M_1 $ range	0 – 2 TeV
LSP type	Bino-like $\tilde{\chi}_1^0$
Generation	
Sampled	8,000,000
Successful generation	1,354,670
Bino-like LSP type	824,891
Satisfy DM relic density constraint $\Omega h^2 \leq 0.12$	32,846
Selection	Strong Electroweak
Pass pre-filter	30,971 18,808
Successful particle-level evaluation	30,954 18,789
Selection	
Satisfy LEP and D0 constraint	31,908
$120 \text{ GeV} < m(h) < 130 \text{ GeV}$	19,249
Satisfy non-DM external constraints	8,937
Satisfy all external constraints	4,412

gaugino mixture of SUSY particles will greatly affect their significance. In addition, for the "Disappearing Track" analysis, since complete reproduction requires the use of the most accurate detector simulation, this analysis ultimately uses a method to determine whether the generation cross section, mass and life of the $\tilde{\chi}_1^\pm$ particles are within the exclusion limit. were excluded from this analysis. In terms of the Higgs experiment, the first constraint comes from the branch ratio of h bosons decaying into undetectable particles. This analysis directly determines $B(h \rightarrow \nu\nu) + B(h \rightarrow \tilde{\chi}_1^0 \tilde{\chi}_1^0)$ is less than 0.107 [197] to constrain. The second constraint is the mass measurement of the pseudoscalar Higgs boson, using the constraint of the lower mass limit of 480 GeV [198]. The final constraint comes from the cross section of the pseudoscalar Higgs boson decaying to the $\tau\tau$ final state. This analysis uses the SUSHi [199] framework to calculate the gluon aggregation (ggH) and The production cross section of the b quark-related (bbH) heavy neutral Higgs particle, and considering the branch ratio of its decay to the $\tau\tau$ final state, determine whether the product of the mass and cross section and the branch ratio is in Exclude constraints within [200].

表 8-4 pMSSM 分析采用的 ATLAS 实验分析。

Table 8-4 List of ATLAS analyses considered in this analysis.

Analysis	Target
FullHad [201]	Wino $\tilde{\chi}_1^\pm \tilde{\chi}_2^0$ via WZ, Wino $\tilde{\chi}_1^\pm \tilde{\chi}_2^0$ via Wh , Wino $\tilde{\chi}_1^+ \tilde{\chi}_1^-$ via WW, Higgsino GGM
1Lbb [202]	Wino $\tilde{\chi}_1^\pm \tilde{\chi}_2^0$ via Wh
2L0J [203]	Wino $\tilde{\chi}_1^+ \tilde{\chi}_1^-$ via WW, slepton pairs
2L2J [204]	Wino $\tilde{\chi}_1^\pm \tilde{\chi}_2^0$ via WZ, Higgsino GGM
3L [205]	Wino $\tilde{\chi}_1^\pm \tilde{\chi}_2^0$ via WZ, Wino $\tilde{\chi}_1^\pm \tilde{\chi}_2^0$ via Wh , Higgsino $\tilde{\chi}_1^\pm \tilde{\chi}_2^0 \tilde{\chi}_1^0$, Higgsino GGM
4L [206]	Higgsino GGM
Compressed [207]	Wino $\tilde{\chi}_1^\pm \tilde{\chi}_2^0$ via WZ, Higgsino $\tilde{\chi}_1^\pm \tilde{\chi}_2^0 \tilde{\chi}_1^0$
Disappearing Track [146]	Wino $\tilde{\chi}_1^+ \tilde{\chi}_1^-$ and $\tilde{\chi}_1^\pm \tilde{\chi}_2^0$
Strong 1L [208]	$\tilde{g}\tilde{g}/\tilde{q}\tilde{q}$ via $\tilde{\chi}_1^\pm$
Strong 2L2J [204]	$\tilde{g}\tilde{g}/\tilde{q}\tilde{q}$ via $\tilde{\chi}_2^0$, $\tilde{g}\tilde{g}$ via $\tilde{\chi}_2^0$ then $\tilde{\ell}$
Strong SS/3L [209]	$\tilde{g}\tilde{g}$ via $\tilde{\chi}_1^\pm$ then $\tilde{\chi}_2^0$, $\tilde{g}\tilde{g}$ via $\tilde{t}$ in λ_{313}'' , $\tilde{t}/\tilde{b}$ via $\tilde{\chi}_2^0/\tilde{\chi}_1^\pm$
Strong MultiJets [210]	$\tilde{g}\tilde{g}$ via $\tilde{\chi}_1^\pm$ then $\tilde{\chi}_2^0$, $\tilde{g}\tilde{g}$ to $\tilde{\chi}_1^0$ directly, $\tilde{g}\tilde{g}$ vis $\tilde{t}$ in λ_{323}''
Strong 0L [211]	BDT, Discovery, and Multibin analyses $\tilde{g}\tilde{g}/\tilde{q}\tilde{q}$ via $\tilde{\chi}_1^\pm$, $\tilde{g}\tilde{g}/\tilde{q}\tilde{q}/\tilde{g}\tilde{q}$ to $\tilde{\chi}_1^0$ directly
$B(h \rightarrow \text{inv})$ measurement [197]	-
$m(A)$ measurement [198]	-
$\sigma_{\phi \rightarrow \tau\tau}$ measurement [200]	-

8.3 Result

This section will summarize the analysis results. For convenience, the "ATLAS Run2 searches" that appear below and in the figure mean that the constraints from both SUSY and Higgs studies are included, and "ATLAS SUSY (Higgs) searches" means that only the constraints from the ATLAS SUSY (Higgs) research experiment are considered. "EWK (Strong) Prod." means that only the electroweak process (strong process) in the model is considered to produce SUSY particles, and "Strong+EWK Prod." means that the better CLs (smaller CLs) are selected from the CLs obtained from these two production processes. "all non-DM constraints" means that all non-ATLAS experimental constraints are considered except for the constraints of the dark matter direct detection experiment, and "all constraints" means that all non-ATLAS experimental constraints are considered. This section will show the constraints of ATLAS and non-ATLAS experiments on the mass and decay branching ratio of SUSY particles in the pMSSM model. Due to space limitations, the experimental constraints on pMSSM-19 parameters are shown in Appendix 二, the exclusion capability of the one-dimensional distribution of SUSY particle mass is shown in Appendix 三, and the distribution of experimental constraints on the pMSSM model other than ATLAS SUSY research is shown in Appendix 四.

8.3.1 Constraints on LSP

Figure 8-2 shows the LSP mass distribution and the excluded proportion of the model, respectively. Figure 8-2(a) shows the distribution of all models before and after adding ATLAS experimental constraints, where the blue dotted line indicates only the constraints related to ATLAS Higgs research; Figure 8-2(b) shows the distribution of all models after non-ATLAS experimental constraints, after non-ATLAS experimental constraints and ATLAS Higgs research constraints, and after non-ATLAS experimental constraints and ATLAS experimental constraints. It can be seen that the mass constraints of the ATLAS experiment on LSP are mainly concentrated in the low-mass region. The range of LSP mass below 100 GeV is almost excluded by the ATLAS experiment, and more than 90% of the models with LSP mass below 500 GeV are also excluded by the ATLAS experiment. If non-ATLAS experimental constraints are considered at the same time, LSP particles with a mass below 550 GeV are almost completely excluded, and 90% of the models with a mass below 1.1 TeV are excluded by ATLAS and non-ATLAS experimental constraints.

8.3.2 Constraints on Gluino and Squarks

Figure 8-3 shows the exclusion ratio of the Bino-DM model by the ATLAS SUSY study, where the first column is the distribution of $m(\tilde{g})-m(\tilde{\chi}_1^0)$, and the second col-

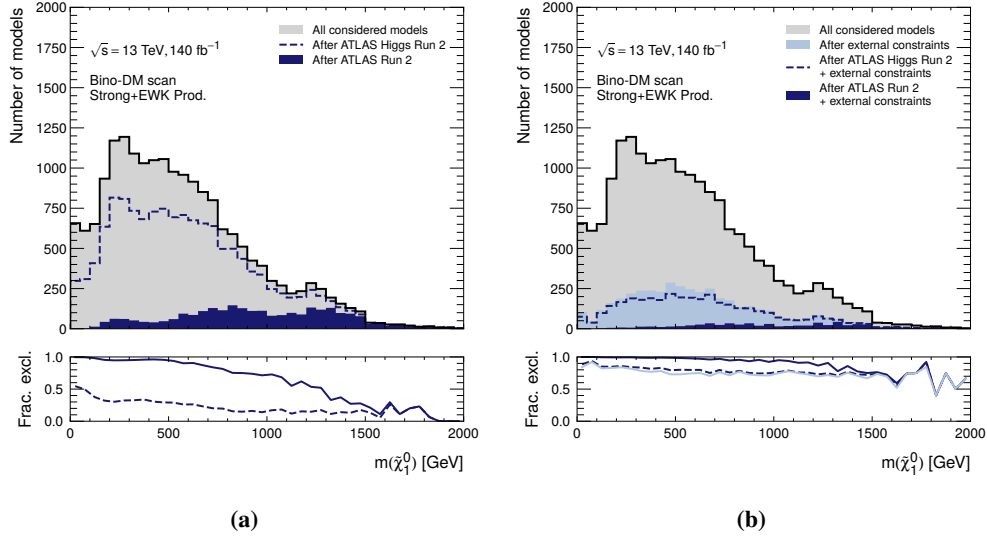


图 8-2 Bino-DM 模型的 LSP 质量分布与被排除的比例。

(a) 展示了所有的模型在加入 ATLAS 实验的约束前后的分布，其中蓝色虚线表示只有 ATLAS Higgs 研究相关的约束；(b) 展示了所有模型经过非 ATLAS 实验约束后的分布、经过非 ATLAS 实验约束后和 ATLAS Higgs 研究约束、经过非 ATLAS 实验约束和 ATLAS 实验约束后的分布。

Figure 8-2 Distributions of the LSP mass.

(a) The distribution of all considered Bino-DM scan models before and after the ATLAS Run 2 constraints are applied, and the blue dashed line shows the remaining models after the ATLAS Higgs constraints applied. (b) The distribution of all considered Bino-DM scan models, the remaining models after all the external constraints are applied, the remaining models after all external constraints and the ATLAS Higgs constraints, and the remaining models after all external constraints and the ATLAS Run 2 constraints are applied.

umn is the distribution of $m(\tilde{q})-m(\tilde{\chi}_1^0)$. $\tilde{q}$ represents the lightest supersymmetric quark in the first and second generation left-handed and right-handed supersymmetric quarks ($\min [\tilde{q}_L, \tilde{q}_R]$, $q \in u, d, c, s$). It also shows the exclusion of all models, models constrained by non-ATLAS constraints, and models constrained by non-ATLAS constraints and ATLAS Higgs studies. The ATLAS exclusion limit in the figure comes from the exclusion limit based on the simplified model used in the correlation analysis used in this analysis.

It can be found that the SUSY study of ATLAS has a very high exclusion ratio for the lighter $\tilde{g}$ under different constraints imposed on the model. At the same time, the range of the pMSSM model being excluded is close to the exclusion limit of the simplified model, which shows that the simplified model captures the characteristics of the $\tilde{g}$ of the pMSSM model very well, and the range of $m(\tilde{g}) \leq 1$ TeV is almost completely excluded. In addition, some pMSSM models within the exclusion limit of the simplified model have not been excluded. They are mainly concentrated in two areas. The first area is $m(\tilde{g})$ near ~ 200 GeV and the mass difference with LSP is $\Delta m(\tilde{g}, \tilde{\chi}_1^0) \leq 15$ GeV. The second area is $m(\tilde{g})$ heavier, but the mass difference with LSP is $\Delta m(\tilde{g}, \tilde{\chi}_1^0) \leq 1$ GeV. If the mass of $\tilde{g}$ is low, the peak momentum of the partial particles that produce $\tilde{g}$ will also be low, so even if $\Delta m(\tilde{g}, \tilde{\chi}_1^0)$ is large, the p_T of the decay products of $\tilde{g}$ may still be low. If the mass of $\tilde{g}$ is high but the mass difference is less than 1 GeV, in this extreme mass compression region, the p_T of the final state product will be very low, which also affects the signal acceptance. It is expected that the exclusion ability of these two regions will improve with the addition of Mono-jet analysis in the future. In addition, it can be found that when $m(\tilde{g}) \sim 2$ TeV and the LSP mass is relatively low, the exclusion range of the pMSSM model is also inferior to the simplified model range. This is because when the mass of $\tilde{g}$ is high and the mass difference between $\tilde{g}$ and $\tilde{\chi}_1^0$ is large, other SUSY particles can join the decay process of $\tilde{g}$ to form a cascade decay, resulting in a large number of final state products but low p_T , thereby reducing the signal acceptance. This study also found a model in which $\tilde{g}$ decays to $\tilde{\chi}_1^0$ through $\tilde{\chi}_2^0$ in the non-excluded models in the relevant region, but the decay branch ratio $B(\tilde{\chi}_2^0 \rightarrow \tilde{\chi}_1^0 + \gamma)$ is close to 1. It is expected that such models will be excluded after the introduction of the photon-related signal region. In addition, the SUYS analysis constraints of ATLAS still exclude nearly 50% of the models when the $\tilde{g}$ mass is close to 4 TeV. This is because the model used in this analysis does not decouple $\tilde{q}$. The lower-quality $\tilde{q}$ in the model is excluded by the SUSY analysis after pairing, resulting in the model being shown as an excluded state when projected onto the $m(\tilde{g})-m(\tilde{\chi}_1^0)$ plane.

On the $m(\tilde{q})-m(\tilde{\chi}_1^0)$ plane, the range of $m(\tilde{q}) \leq 400$ GeV is almost completely excluded. At the same time, most of the models are still excluded when the $\tilde{q}$ mass is

higher than 2 TeV. This is due to the $\tilde{g}\tilde{g}$ process or the $\tilde{g}\tilde{q}$ process. It can be seen that there are two parts of the pMSSM model that are within the simplified model exclusion limit but are not completely excluded. One of them is the part between the dotted line and the solid line. This is because the simplified model that the solid line exclusion limit depends on sets the masses of $\tilde{q}_L$ and $\tilde{q}_R$ to be consistent, resulting in the eightfold degeneracy of $\tilde{q}$ mass, while the dashed line exclusion limit decouples $\tilde{q}_R$ and only forms a fourfold degeneracy. For the pMSSM-19 model, since only the first and second generation $\tilde{q}_L$ share a mass parameter, the fourfold degeneracy is a more common state, and the eightfold degeneracy is a rare case, so the models within the dashed line exclusion limit are almost completely excluded, but the exclusion of the area between the dashed line and the solid line depends on $\tilde{g}$. The second area that is not completely excluded is close to the mass compression area. The lightest $\tilde{q}$ in this part of the model is $\tilde{q}_R$, and the mass parameters of the first and second generation $\tilde{q}_R$ are independent of each other, so there is a greater probability of forming a state of double mass degeneracy, and its scattering cross section is half of the fourfold degeneracy. The lower cross section causes it to not be excluded.

Figure 8-4 shows the projection of the exclusion ratio of the ATLAS SUSY experiment on the $m(\tilde{g})$ - $m(\tilde{q})$ plane. The exclusion limit of the simplified model is the model with eight-fold mass degeneracy, and the $\tilde{g}\tilde{q}$ generation process is considered. It can be seen that the range of $\tilde{g}$ mass below 1 TeV is completely excluded, and the exclusion ability is independent of the mass of $\tilde{q}$. At the same time, the lighter $\tilde{q}$ is also strongly constrained by the SUSY study of ATLAS. When the $\tilde{g}$ mass is low, the $\tilde{q}$ with a mass below 1 TeV is completely excluded. As the $\tilde{g}$ mass increases, the constraints on the $\tilde{q}$ mass are also reduced. This is because when $\tilde{g}$ is high, the cross section of $\tilde{q}\tilde{q}$ generated by the $\tilde{g}$ t-channel and the cross section generated by $\tilde{g}\tilde{q}$ will be suppressed, resulting in a decrease in the ability to be excluded. In general, the region where the $\tilde{q}$ mass is less than 400 GeV is completely excluded. By comparing the graphs 8-4(a) and 8-4(b), it can be found that the constraints of non-ATLAS experiments also have strong restrictions on this part. The main source of this part of the constraint is the upper limit of the cross section of the direct detection experiment of dark matter. The lighter $\tilde{q}$ can enhance the t-channel cross section of LSP and quarks. In addition, it can be found that some pMSSM models outside the simplified model exclusion limit are also excluded. These models are characterized by lighter LSP mass and closer masses of $\tilde{q}$, $\tilde{t}$ and $\tilde{b}$, which eventually form a mass degeneracy higher than eightfold, thereby improving the cross section produced by strong interactions. Finally, it can be found that the proportion of the pMSSM model excluded in the region where $m(\tilde{g})$ and $m(\tilde{q})$ are close is relatively high. This is because the scattering cross section generated by $\tilde{g}\tilde{q}$ is relatively high when $m(\tilde{g})$ and $m(\tilde{q})$ are close.

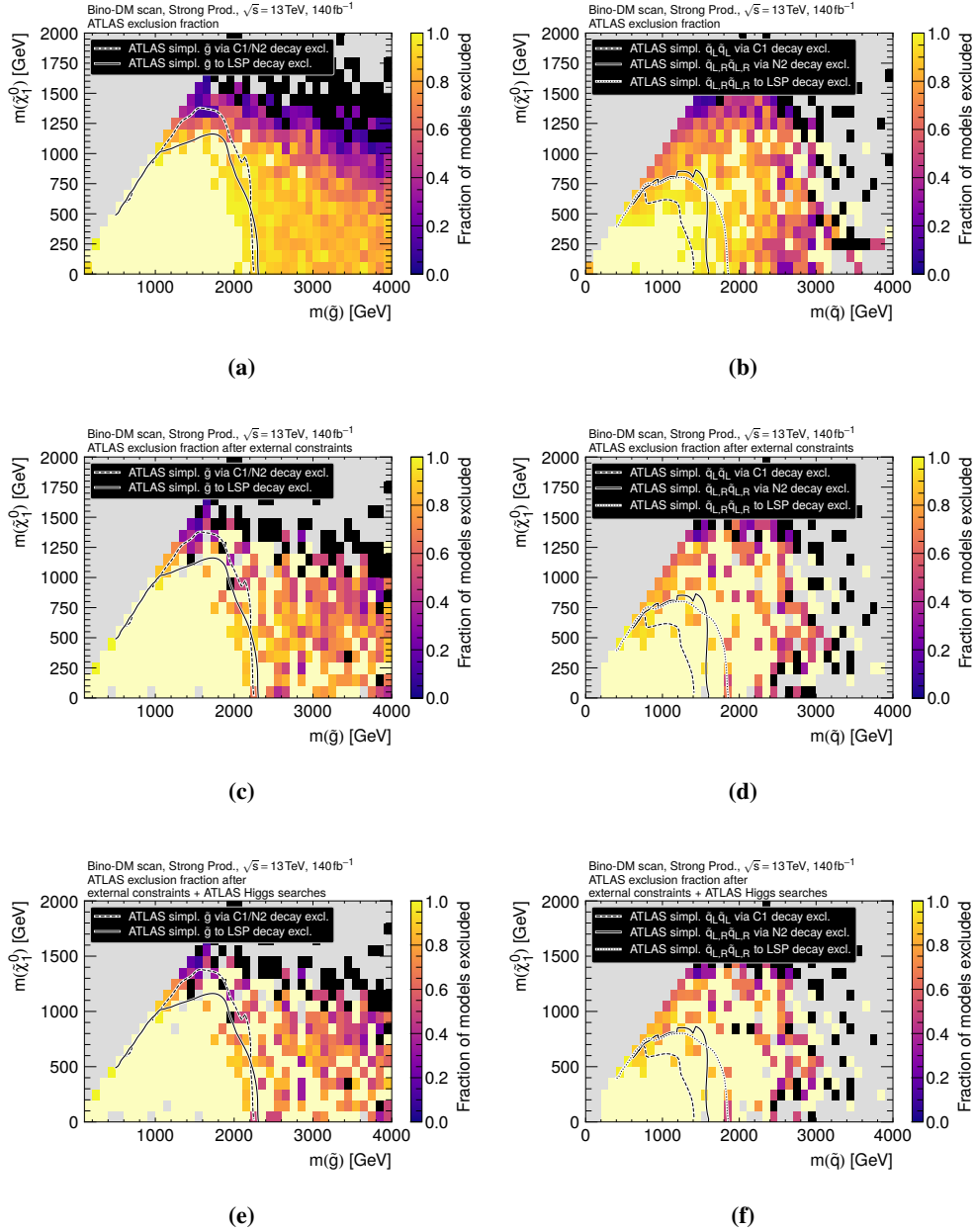


图 8-3 Bino-DM 被 ATLAS SUSY 研究约束排除的比例 ($m(\tilde{g})-m(\tilde{\chi}_1^0)$ 、 $m(\tilde{q})-m(\tilde{\chi}_1^0)$)。
(a,c,e) 展示了模型在 $m(\tilde{g})-m(\tilde{\chi}_1^0)$ 平面的投影；(b,d,f) 展示了模型在模型在 $m(\tilde{q})-m(\tilde{\chi}_1^0)$ 平面的
投影。(a-b) 考虑了全部的 Bino-DM 模型，(c-d) 考虑了通过非 ATLAS 约束的模型，(e-f)
考虑了通过非 ATLAS 约束和 ATLAS Higgs 研究的约束的模型。

**Figure 8-3 The fraction
of the Bino-DM scan models excluded by ATLAS SUSY results ($m(\tilde{g})-m(\tilde{\chi}_1^0)$, $m(\tilde{q})-m(\tilde{\chi}_1^0)$).**
The first column shows the $m(\tilde{g})-m(\tilde{\chi}_1^0)$ plane and the second column the $m(\tilde{q})-m(\tilde{\chi}_1^0)$ plane. The
first row includes all considered models, the second includes models that satisfy all external
constraints and the third row includes models that satisfy all external constraints and ATLAS
Higgs constraints.

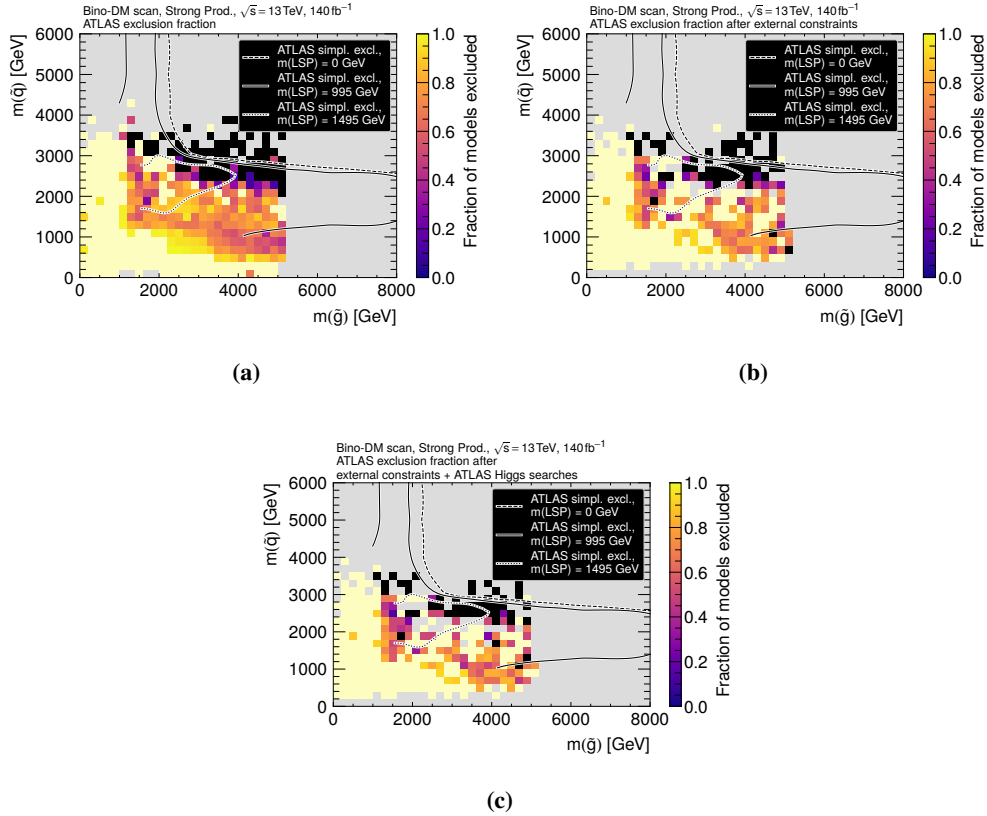


图 8-4 Bino-DM 被 ATLAS SUSY 研究约束排除的比例在 $m(\tilde{g})$ - $m(\tilde{q})$ 平面的投影。

(a) 考虑了全部的 Bino-DM 模型, (b) 考虑了通过非 ATLAS 约束的模型, (c) 考虑了通过非 ATLAS 约束和 ATLAS Higgs 研究的约束的模型。

Figure 8-4 The fraction of the

Bino-DM scan models excluded by ATLAS SUSY results shown on the $m(\tilde{g})$ - $m(\tilde{q})$ plane.

(a) includes all considered models, (b) includes models that satisfy all external constraints, and (c) includes models that satisfy all external constraints and ATLAS Higgs constraints.

Figure 8-5 shows the projection of the exclusion ratios of the ATLAS SUSY experiment onto the $m(\tilde{g})$ - ΔX and $m(\tilde{q})$ - ΔX planes, where ΔX is defined as $\Delta X = \Delta m(\tilde{\chi}_1^\pm - \tilde{\chi}_1^0)/\Delta m(\tilde{g} - \tilde{\chi}_1^0)$ or $\Delta m(\tilde{\chi}_1^\pm - \tilde{\chi}_1^0)/\Delta m(\tilde{q} - \tilde{\chi}_1^0)$. The exclusion limits for the simplified model are $\tilde{q}$ quadruple mass mergers, and $\tilde{q}$ or $\tilde{g}$ decays via $\tilde{\chi}_1^\pm$. It can be found that the exclusion range of the pMSSM model in the figure is quite different from that of the simplified model. The reasons are as follows: (1) For the pMSSM model, if the mass of $\tilde{g}$ or $\tilde{q}$ is large, even if its mass is within the exclusion limit of the simplified model, it can still decay in cascade or decay through $\tilde{\chi}_2^0$ instead of just one step of $\tilde{\chi}_1^\pm$; (2) In the pMSSM model, $\tilde{g}$ and $\tilde{q}$ are not decoupled.

Figure 8-6 shows the exclusion of $\tilde{q}_L$ and $\tilde{q}_R$ respectively, where the exclusion limit of $\tilde{q}_L$ ($\tilde{q}_R$) only uses the model with $\tilde{q}_L$ ($\tilde{q}_R$) as the lightest $\tilde{q}$. By comparing the left and right columns, we can clearly see the difference between the left and right hand $\tilde{q}$ in the pMSSM-19 model. The first and second generation $\tilde{q}_L$ come from the same mass parameter, so their mass is quadruple degenerate, but for $\tilde{q}_R$ it is only doubly degenerate, so SUSY analysis has a stronger exclusion ability for $\tilde{q}_L$. In addition, in the Bino-DM model, the proportion of Wino in $\tilde{\chi}_1^\pm$ is relatively high, while the coupling strength between Wino and $\tilde{q}_R$ is relatively weak, so if the branching ratio $B(\tilde{q} \rightarrow \tilde{\chi}_1^\pm) = 100\%$ in the simplified model used in SUSY analysis, the ability to exclude $\tilde{q}_R$ will be further reduced.

Simplified SUSY models often use simplified branching ratios, for example, fixing the branching ratio of a SUSY particle decay to 100%. However, the branching ratio in the pMSSM model varies with different model parameters. Figure 8-7 shows the branching ratios of $\tilde{g}$ decaying to EWKino ($\tilde{\chi}_1^0$, $\tilde{\chi}_2^0$ and $\tilde{\chi}_1^\pm$), $\tilde{q}_L$, $\tilde{q}_R$ and $\tilde{t}/\tilde{b}$. Due to the high proportion of wino mixing in $\tilde{\chi}_2^0$, $\tilde{\chi}_1^+$ and $\tilde{\chi}_1^-$, and the close branching ratios of $\tilde{g}$ decaying to these three particles, $B(\tilde{g} \rightarrow \tilde{\chi}_2^0)$ and $B(\tilde{g} \rightarrow \tilde{\chi}_1^\pm)$ are difficult to approach 100%. Although the exclusion ratio of the ATLAS experimental SUSY study is high in all branching ratio distributions, some exclusion ratios that vary with the branching ratio can still be found. When the branch ratio of $\tilde{g}$ decay to EWKino is high, the exclusion ratio of the ATLAS analysis is also high. This is because the SUSY analysis often chooses a simplified model of one-step decay of EWKino as the signal model, so the exclusion ability of the pMSSM model with high branching ratio is also strong. In addition, the exclusion ratio will increase with the decrease of $B(\tilde{g} \rightarrow \tilde{t}/\tilde{b})$ or the increase of $B(\tilde{g} \rightarrow \tilde{q}_L/\tilde{q}_R)$. This is mainly because this analysis does not consider the analysis of the third generation of supersymmetric quarks, and the exclusion ability of the process with high $B(\tilde{g} \rightarrow \tilde{t}/\tilde{b})$ is weaker, and the two branching ratios have a "competitive" relationship.

Figures 8-8 and 8-9 show the relationship between the exclusion ratio and the decay branching ratio of $\tilde{q}_L$ and $\tilde{q}_R$, respectively. The branching ratios of $B(\tilde{q}_L \rightarrow \tilde{\chi}_1^\pm)$

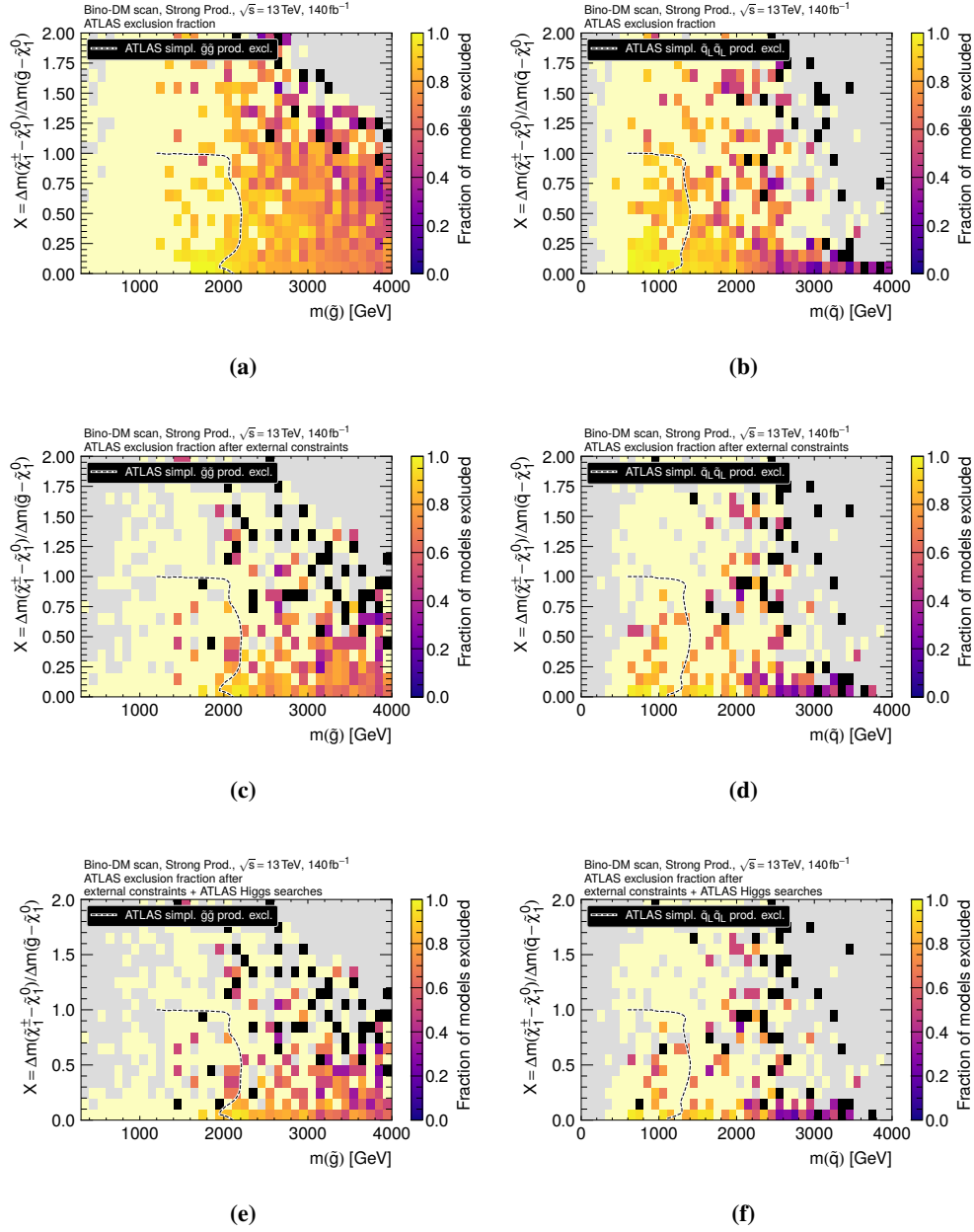


图 8-5 Bino-DM 被 ATLAS SUSY 研究约束排除的比例 ($m(\tilde{g})-\Delta X$ 、 $m(\tilde{q})-\Delta X$)。
 (a,c,e) 展示了模型在 $m(\tilde{g})-\Delta X$ 平面的投影；(b,d,f) 展示了模型在模型在 $m(\tilde{q})-\Delta X$ 平面的投影。
 (a-b) 考虑了全部的 Bino-DM 模型，(c-d) 考虑了通过非 ATLAS 约束的模型，(e-f) 考虑了通过非 ATLAS 约束和 ATLAS Higgs 研究的约束的模型。

Figure 8-5 The fraction of the Bino-DM scan models excluded by ATLAS SUSY results ($m(\tilde{g})-\Delta X$, $m(\tilde{q})-\Delta X$).
 The first column shows the $m(\tilde{g})-\Delta X$ plane and the second column the $m(\tilde{q})-\Delta X$ plane. The first row includes all considered models, the second includes models that satisfy all external constraints and the third row includes models that satisfy all external constraints and ATLAS Higgs constraints.

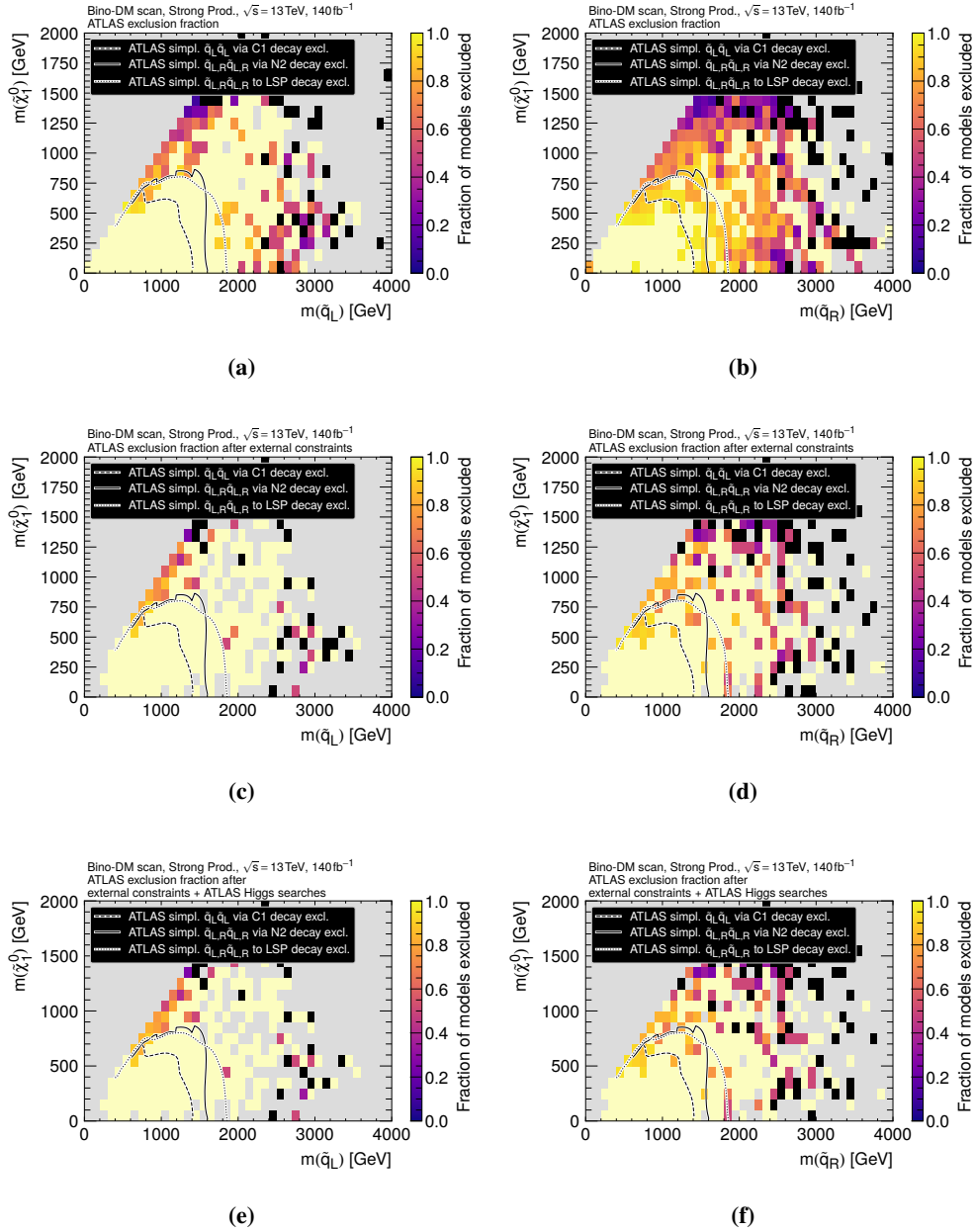


图 8-6 Bino-DM 被 ATLAS SUSY 研究约束排除的比例 ($m(\tilde{q}_L)$ - ΔX 、 $m(\tilde{q}_R)$ - ΔX)。
(a,c,e) 展示了模型在 $m(\tilde{q}_L)$ - ΔX 平面的投影；(b,d,f) 展示了模型在模型在 $m(\tilde{q}_R)$ - ΔX 平面的投影。
(a-b) 考虑了全部的 Bino-DM 模型，(c-d) 考虑了通过非 ATLAS 约束的模型，(e-f) 考虑了通过非 ATLAS 约束和 ATLAS Higgs 研究的约束的模型。

Figure 8-6 The fraction of the Bino-DM scan models excluded by ATLAS SUSY results ($m(\tilde{q}_L)$ - ΔX , $m(\tilde{q}_R)$ - ΔX).
The first column shows the $m(\tilde{q}_L)$ - ΔX plane and the second column the $m(\tilde{q}_R)$ - ΔX plane. The first row includes all considered models, the second includes models that satisfy all external constraints and the third row includes models that satisfy all external constraints and ATLAS Higgs constraints.

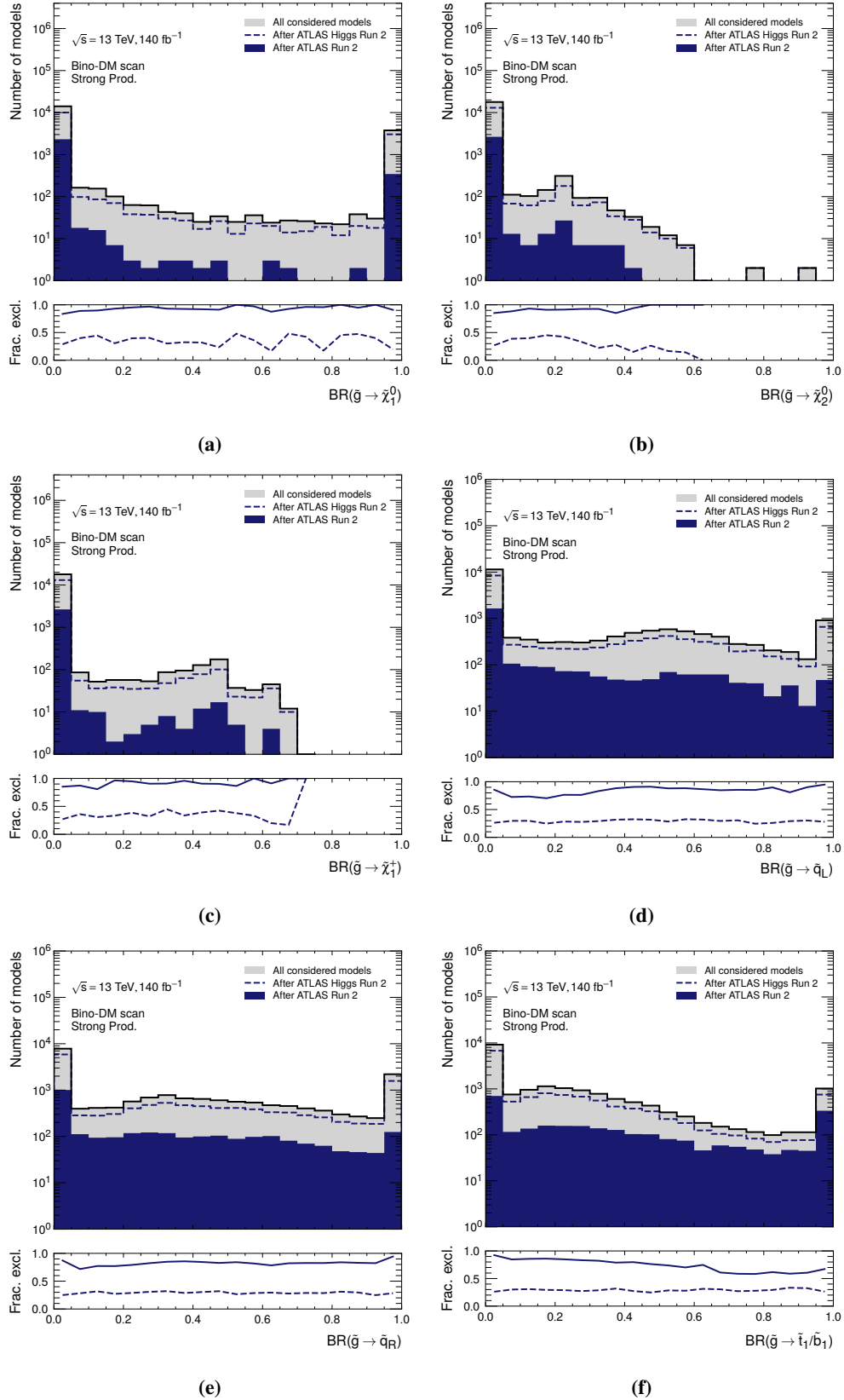


图 8-7 Bino-DM 模型中被 ATLAS SUSY 研究约束排除的比例和 $\tilde{g}$ 衰变分支比的关系。
 (a) $BR(\tilde{g} \rightarrow \tilde{\chi}_1^0)$; (b) $BR(\tilde{g} \rightarrow \tilde{\chi}_2^0)$; (c) $BR(\tilde{g} \rightarrow \tilde{\chi}_1^\pm)$; (d) $BR(\tilde{g} \rightarrow \tilde{q}_L)$; (e) $BR(\tilde{g} \rightarrow \tilde{q}_R)$; (f) $BR(\tilde{g} \rightarrow \tilde{t}/\tilde{b})$ 。

Figure 8-7 Distributions of

the $\tilde{g}$ branching ratios before and after the ATLAS Run 2 SUSY constraints are applied.

(a) $BR(\tilde{g} \rightarrow \tilde{\chi}_1^0)$, (b) $BR(\tilde{g} \rightarrow \tilde{\chi}_2^0)$, (c) $BR(\tilde{g} \rightarrow \tilde{\chi}_1^\pm)$, (d) $BR(\tilde{g} \rightarrow \tilde{q}_L)$, (e) $BR(\tilde{g} \rightarrow \tilde{q}_R)$, and (f) $BR(\tilde{g} \rightarrow \tilde{t}/\tilde{b})$.

and $B(\tilde{q}_L \rightarrow \tilde{\chi}_2^0)$ also have cutoff points, which is consistent with the reason for the cutoff point of the $\tilde{g}$ branching ratio. The coupling between $\tilde{q}_R$ and Wino-type $\tilde{\chi}_1^\pm$ is very weak, so the branching ratios are almost 0. The cutoff point of the branching ratio $B(\tilde{q}_R \rightarrow \tilde{\chi}_2^0)$ is because the Higgsino mixing ratio of $\tilde{\chi}_2^0$ in the pMSSM model and the Bino mixing ratio of $\tilde{\chi}_3^0$ are not negligible, so $B(\tilde{q}_R \rightarrow \tilde{\chi}_3^0)$ and $B(\tilde{q}_R \rightarrow \tilde{\chi}_2^0)$ show a "competitive" relationship. Finally, it can be found that the exclusion ratio of the pMSSM model is weakly correlated with the branching ratio of $\tilde{q}$.

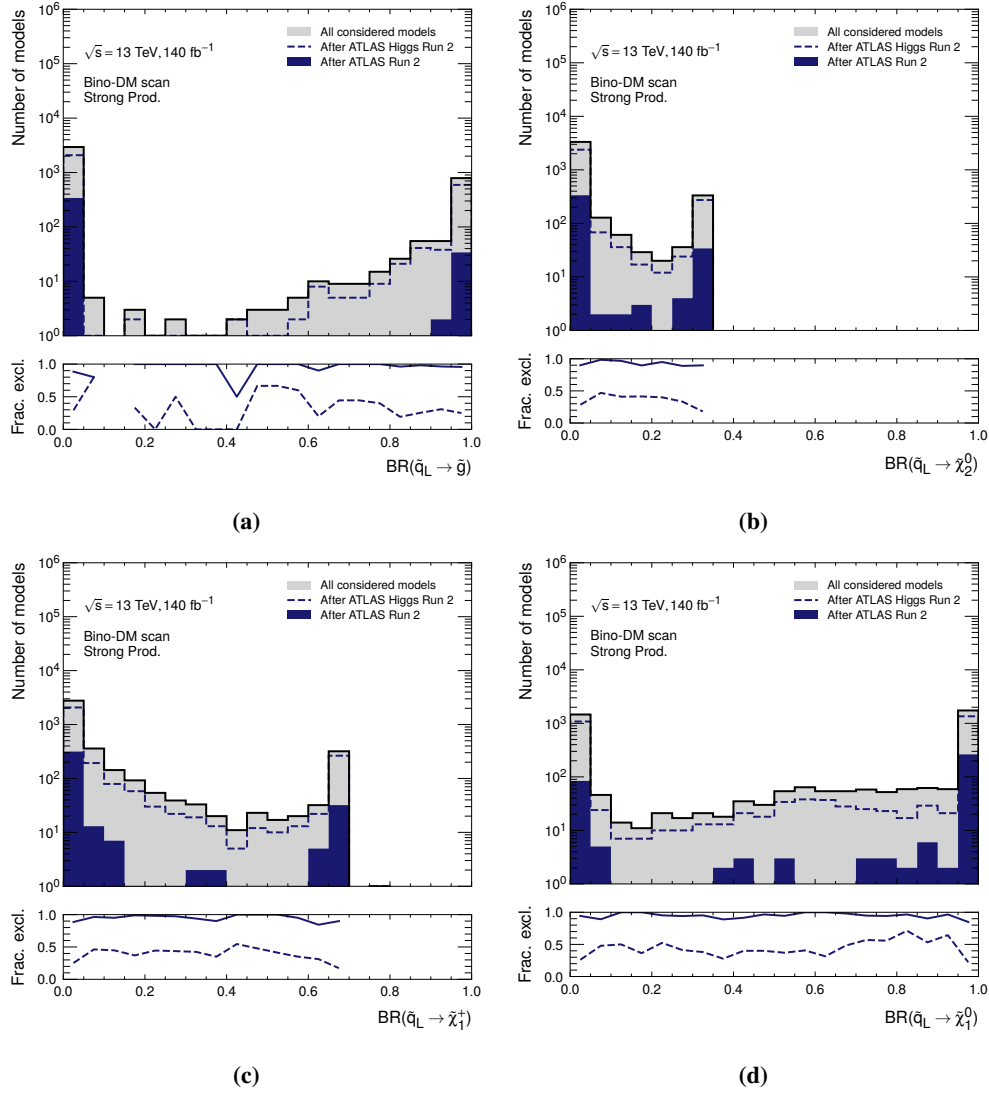


图 8-8 Bino-DM 模型中被 ATLAS SUSY 研究约束排除的比例和 $\tilde{q}_L$ 衰变分支比的关系。
(a) $BR(\tilde{q}_L \rightarrow \tilde{g})$; (b) $BR(\tilde{q}_L \rightarrow \tilde{\chi}_2^0)$; (c) $BR(\tilde{q}_L \rightarrow \tilde{\chi}_1^\pm)$; (d) $BR(\tilde{q}_L \rightarrow \tilde{\chi}_1^0)$ 。

Figure 8-8 Distributions of
the $\tilde{q}_L$ branching ratios before and after the ATLAS Run 2 SUSY constraints are applied.
(a) $BR(\tilde{q}_L \rightarrow \tilde{g})$, (b) $BR(\tilde{q}_L \rightarrow \tilde{\chi}_2^0)$, (c) $BR(\tilde{q}_L \rightarrow \tilde{\chi}_1^\pm)$, and (d) $BR(\tilde{q}_L \rightarrow \tilde{\chi}_1^0)$.

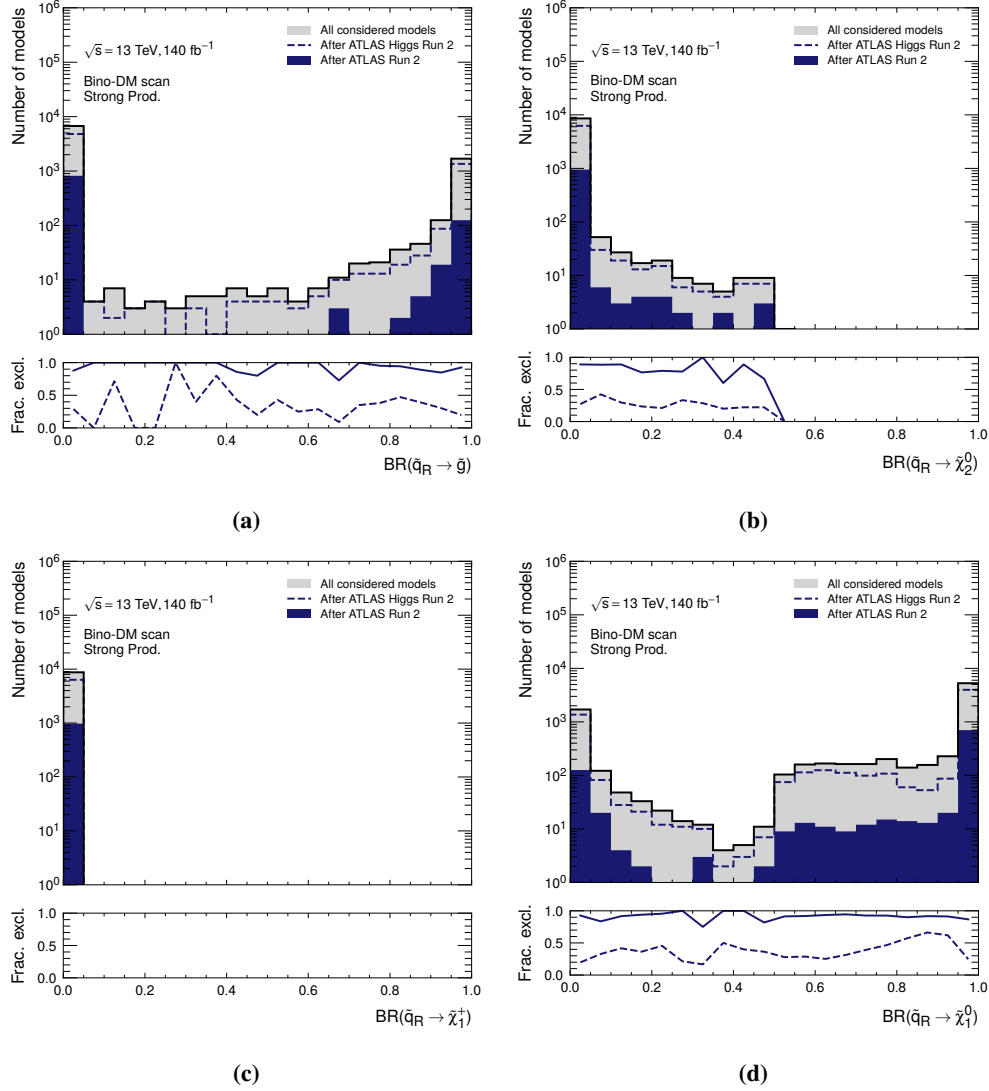


图 8-9 Bino-DM 模型中被 ATLAS SUSY 研究约束排除的比例和 $\tilde{q}_R$ 衰变分支比的关系。

(a) $BR(\tilde{q}_R \rightarrow \tilde{g})$; (b) $BR(\tilde{q}_R \rightarrow \tilde{\chi}_2^0)$; (c) $BR(\tilde{q}_R \rightarrow \tilde{\chi}_1^\pm)$; (d) $BR(\tilde{q}_R \rightarrow \tilde{\chi}_1^0)$ 。

Figure 8-9 Distributions of the

$\tilde{q}_R$ branching ratios before and after the ATLAS Run 2 SUSY constraints are applied.

(a) $BR(\tilde{q}_R \rightarrow \tilde{g})$, (b) $BR(\tilde{q}_R \rightarrow \tilde{\chi}_2^0)$, (c) $BR(\tilde{q}_R \rightarrow \tilde{\chi}_1^\pm)$, and (d) $BR(\tilde{q}_R \rightarrow \tilde{\chi}_1^0)$.

8.3.3 Constraints on the Third Generation Squarks

The third generation squarks ($\tilde{t}$, $\tilde{b}$) are more popular as the SUSY model of the lightest supersymmetric quarks, because the lighter $\tilde{t}$ can solve the naturalness problem. Figure 8-10 shows the mass exclusion ratio of $\tilde{t}$ and $\tilde{b}$. The exclusion ratio of $\tilde{t}$ ($\tilde{b}$) only uses the pMSSM model with the lightest supersymmetric quark as $\tilde{t}$ ($\tilde{b}$). The simplified model exclusion limit in the figure still comes from the ATLAS analysis aimed at finding the first and second generation $\tilde{q}$, while $\tilde{t}$ and $\tilde{b}$ do not have mass degeneracy in most cases, so the exclusion region of the pMSSM model is quite different from the simplified model exclusion limit. Since this analysis does not consider the analysis of the third generation of supersymmetric quarks, the exclusion ratio of pMSSM is lower. The constraint of $m(h)$ leads to a lower number of models for $\tilde{t}$. Even so, it can be found that $\tilde{t}$ or $\tilde{b}$ with masses below 600 GeV are almost completely excluded.

8.3.4 Constraints on electroweakinos and sleptons

Figure 8-11 shows the projection of the exclusion ratio of the pMSSM model from the ATLAS SUSY study on the $\tilde{\chi}_1^\pm$ and $\tilde{\chi}_2^0$ in EWKino and the LSP mass plane. Considering that EWKino can participate in the $\tilde{g}$ or $\tilde{q}$ decays produced by strong interactions, if EWKino participates in the decay, the better confidence of the exclusion confidence of the strong interaction process and the exclusion confidence of the electroweak interaction process will be used to determine whether the model is excluded. The exclusion limit of the simplified model in the figure comes from the relevant SUSY analysis for the electroweak process. The region with masses below 200 GeV for $\tilde{\chi}_1^\pm$ and $\tilde{\chi}_2^0$ is almost completely excluded. If the LSP mass is relatively low, the ATLAS experiment can constrain pMSSM to the order of TeV. The source of this exclusion capability is mainly caused by the decay of $\tilde{g}$ or $\tilde{q}$ through $\tilde{\chi}_1^\pm$ or $\tilde{\chi}_2^0$. In contrast, it can be found that the exclusion ratio of many bins in the simplified model exclusion limit is far less than 100%. The main reason is that the exclusion limit of the simplified model often sets a 100% decay branch ratio, but the number of $\tilde{\chi}_1^\pm$ or $\tilde{\chi}_2^0$ decay channels in the pMSSM model is relatively large. In addition, Figures 8-11(c) and 8-11(d) show that in the (close to) mass compression region, the pMSSM model in two mass regions has a high exclusion ratio and is outside the simplified model exclusion limit. In the extreme mass compression region, the exclusion ratio is close to 80%, and the sources of exclusion are mainly disappearing-track analysis and the generation of higher quality EWKino, such as $\tilde{\chi}_2^\pm$ or $\tilde{\chi}_4^0$. Among them, $\tilde{\chi}_1^\pm$ in the mass compression region has a longer life span and can decay after leaving a track. The decay product $\tilde{\chi}_1^0$ cannot generate track information, and the final state of the signal is a track that suddenly disappears, so the disappearing-track analysis is sensitive to the signal in the mass compression region. The other part is the area with mass difference $\Delta m(\tilde{\chi}_2^0/\tilde{\chi}_1^\pm, \tilde{\chi}_1^0) \sim 100$ GeV, where the

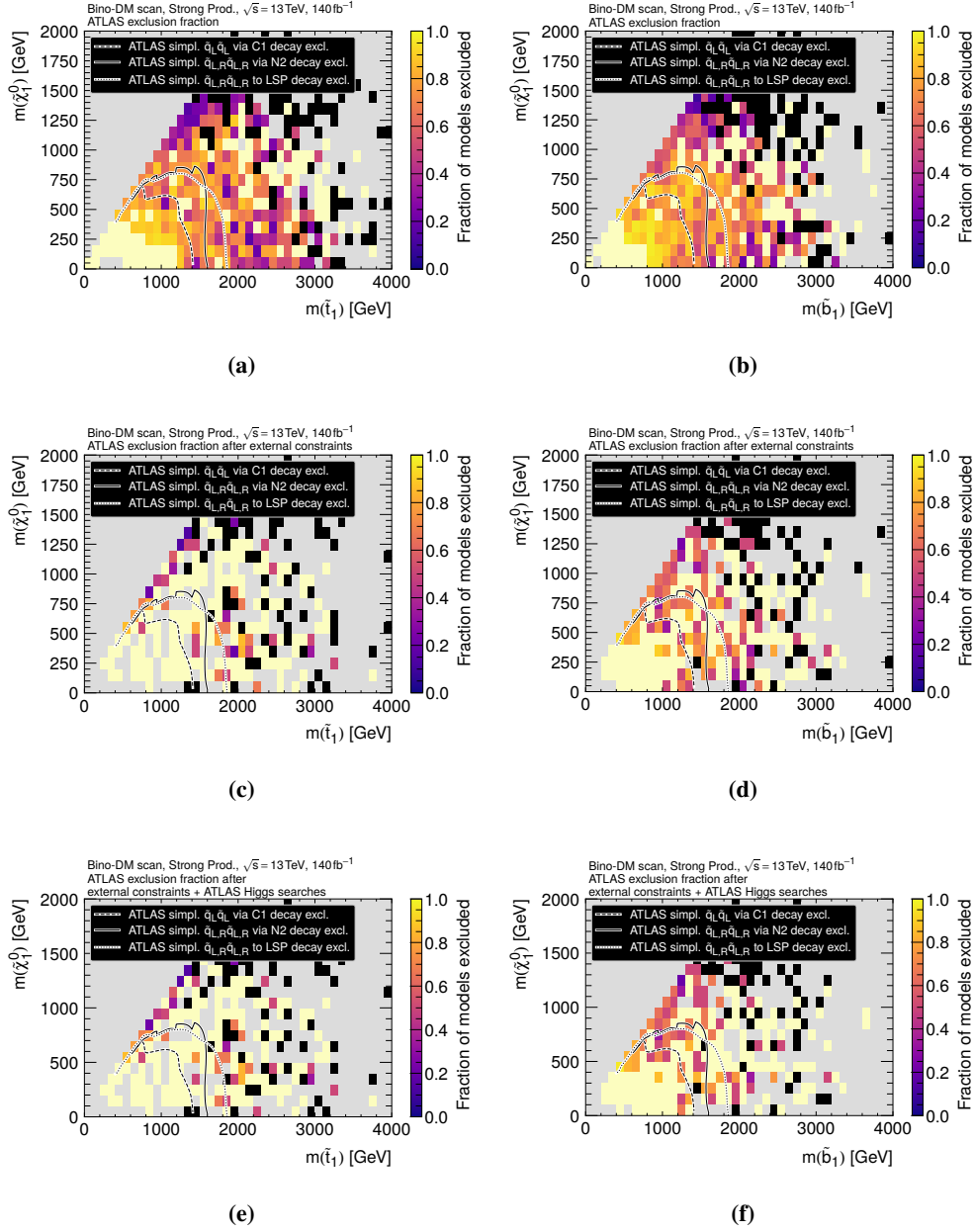


图 8-10 Bino-DM 被 ATLAS SUSY 研究约束排除的比例 ($m(\tilde{t})-m(\tilde{\chi}_1^0)$ 、 $m(\tilde{b})-m(\tilde{\chi}_1^0)$)。

(a,c,e) 展示了模型在 $m(\tilde{t})-m(\tilde{\chi}_1^0)$ 平面的投影；(b,d,f) 展示了模型在模型在 $m(\tilde{b})-m(\tilde{\chi}_1^0)$ 平面的投影。(a-b) 考虑了全部的 Bino-DM 模型，(c-d) 考虑了通过非 ATLAS 约束的模型，(e-f) 考虑了通过非 ATLAS 约束和 ATLAS Higgs 研究的约束的模型。

Figure 8-10 The fraction of the Bino-DM scan models excluded by ATLAS SUSY results ($m(\tilde{t})-m(\tilde{\chi}_1^0)$, $m(\tilde{b})-m(\tilde{\chi}_1^0)$). The first column shows the $m(\tilde{t})-m(\tilde{\chi}_1^0)$ plane and the second column the $m(\tilde{b})-m(\tilde{\chi}_1^0)$ plane. The first row includes all considered models, the second includes models that satisfy all external constraints and the third row includes models that satisfy all external constraints and ATLAS Higgs constraints.

exclusion ratio is close to 100%. The exclusion capacity of this part mainly comes from the strong interaction producing $\tilde{q}$ or $\tilde{g}$ and decaying through EWKino.

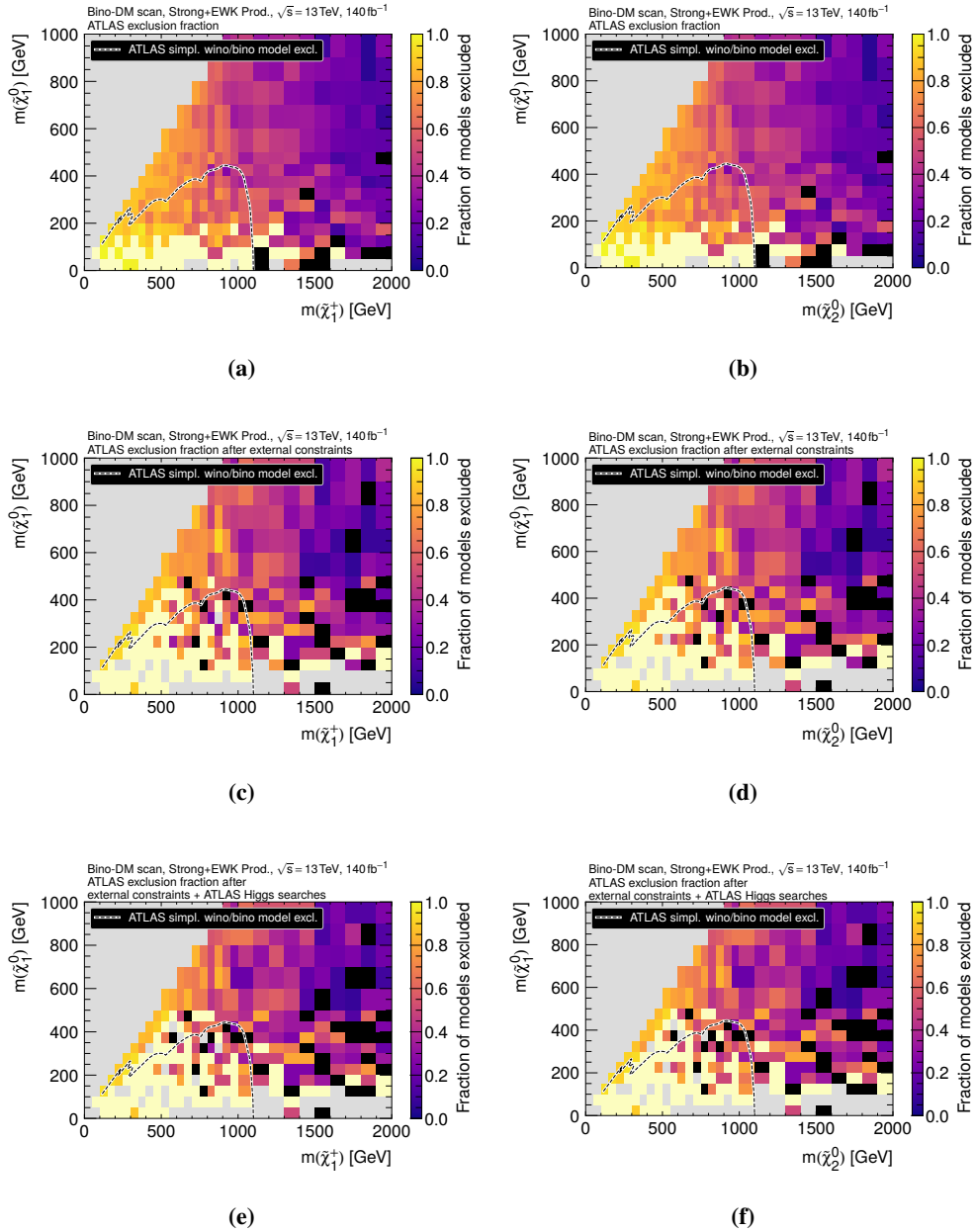


图 8-11 Bino-DM 被 ATLAS SUSY 研究约束排除的比例 ($m(\tilde{\chi}_1^\pm)-m(\tilde{\chi}_1^0)$ 、 $m(\tilde{\chi}_2^0)-m(\tilde{\chi}_1^0)$)。 (a,c,e) 展示了模型在 $m(\tilde{\chi}_1^\pm)-m(\tilde{\chi}_1^0)$ 平面的投影；(b,d,f) 展示了模型在模型在 $m(\tilde{\chi}_2^0)-m(\tilde{\chi}_1^0)$ 平面的投影。(a-b) 考虑了全部的 Bino-DM 模型，(c-d) 考虑了通过非 ATLAS 约束的模型，(e-f) 考虑了通过非 ATLAS 约束和 ATLAS Higgs 研究的约束的模型。

Figure 8-11 The fraction of

the Bino-DM scan models excluded by ATLAS SUSY results ($m(\tilde{\chi}_1^\pm)-m(\tilde{\chi}_1^0)$, $m(\tilde{\chi}_2^0)-m(\tilde{\chi}_1^0)$).

The first column shows the $m(\tilde{\chi}_1^\pm)-\Delta X$ plane and the second column the $m(\tilde{\chi}_2^0)-\Delta X$ plane. The first row includes all considered models, the second includes models that satisfy all external constraints and the third row includes models that satisfy all external constraints and ATLAS Higgs constraints.

Figure 8-12 shows the projection of the exclusion ratio on the distribution of the branching ratios of $\tilde{\chi}_1^\pm$ and $\tilde{\chi}_2^0$ decays. It can be found that the ATLAS SUSY experimental constraints are strongest when $B(\tilde{\chi}_2^0 \rightarrow \tilde{\chi}_1^0 Z)$ is high, which is mainly because the analysis used in this study has conducted an exhaustive search for this branching ratio. While $B(\tilde{\chi}_1^\pm \rightarrow \tilde{\chi}_1^0 W)$ and $B(\tilde{\chi}_2^0 \rightarrow \tilde{\chi}_1^0 h)$ have relatively low correlation with the exclusion ratio, among which $B(\tilde{\chi}_1^\pm \rightarrow \tilde{\chi}_1^0 W) = 1$ has the strongest exclusion ability, which is also because part of the analysis is optimized for a simplified model of this process.

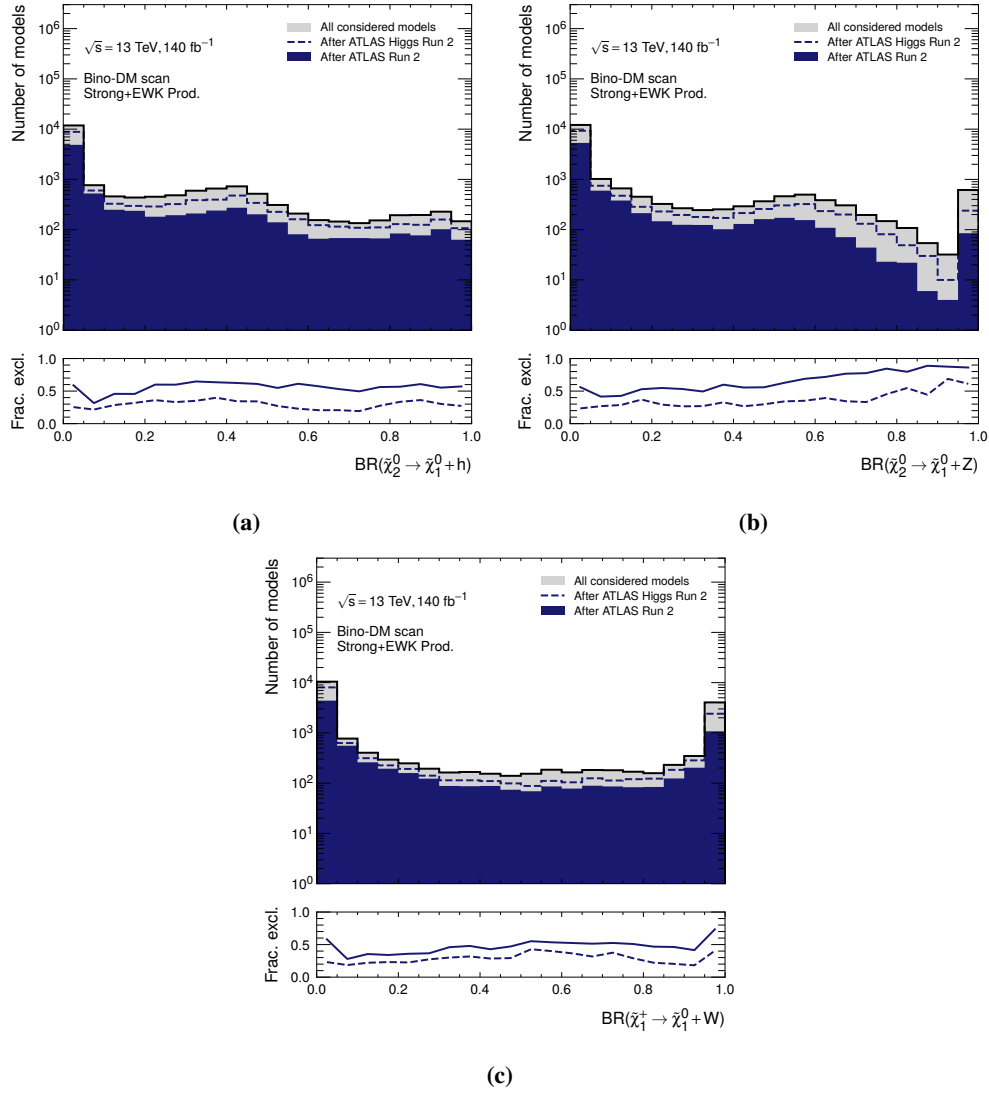


图 8-12

Bino-DM 模型中被 ATLAS SUSY 研究约束排除的比例和 $\tilde{\chi}_1^\pm$ 和 $\tilde{\chi}_2^0$ 衰变分支比的关系。(a) $BR(\tilde{\chi}_2^0 \rightarrow \tilde{\chi}_1^0 + h)$; (b) $BR(\tilde{\chi}_2^0 \rightarrow \tilde{\chi}_1^0 + Z)$; (c) $BR(\tilde{\chi}_1^\pm \rightarrow \tilde{\chi}_1^0 + W)$ 。

 Figure 8-12 Distributions of the $\tilde{\chi}_1^\pm$ and

$\tilde{\chi}_2^0$ branching ratios before and after the ATLAS Run 2 SUSY constraints are applied.

(a) $BR(\tilde{\chi}_2^0 \rightarrow \tilde{\chi}_1^0 + h)$, (b) $BR(\tilde{\chi}_2^0 \rightarrow \tilde{\chi}_1^0 + Z)$, and (c) $BR(\tilde{\chi}_1^\pm \rightarrow \tilde{\chi}_1^0 + W)$.

Figure 8-13 shows the projection of the exclusion ratio of the ATLAS SUSY analy-

sis on the mass and LSP plane of the first and second generation supersymmetric leptons $\tilde{\ell}$ and the third generation supersymmetric leptons $\tilde{\tau}$. The simplified model in the figure considers the first and second generation left and right-handed $\tilde{\ell}$. Since EWKino is not decoupled from $\tilde{\ell}$ or $\tilde{\tau}$ in the pMSSM model, the main source of the constraints on $\tilde{\ell}$ and $\tilde{\tau}$ is still the high-cross-section EWKino production process, and the constraint range on $\tilde{\ell}$ is much larger than the exclusion limit of the simplified model. At the same time, some pMSSM models within the simplified model exclusion limit are not excluded because the left and right-handed $\tilde{\ell}$ mass parameters of the pMSSM model are different, and the left-handed $\tilde{\ell}$ mass in the model is higher. In addition, the exclusion ratio of $\tilde{\ell}$ is slightly higher than that of $\tilde{\tau}$. The main reason is that this paper does not consider the analysis of $\tilde{\tau}$, and the proportion of leptons produced by $\tilde{\ell}$ decay is higher than that of $\tilde{\tau}$.

8.3.5 Dark matter phenomenology

Figure 8-14 shows the constraints of ATLAS SUSY research on the $m(\tilde{\chi}_1^0)$ - Ωh^2 plane. Comparing Figures 8-14(b) and 8-14(c), it can be found that the direct detection experiment has stronger constraints on the Z/h -funnel region. After considering the ATLAS experimental constraints at the same time, the models in the Z/h -funnel region are almost all excluded. In contrast, the ATLAS experiment and other experiments have low constraints on high-quality LSP particles. Bino-type LSP particles with a mass close to 2 TeV can pass all experimental constraints, but the possibility of bino-type LSP particles with a mass of 1 ~ 100 GeV being dark matter particles is low.

In order to further study the influence of experimental constraints on bino-type LSP, Figure 8-15 shows the exclusion ratio of SUSY constraints on all models, models that meet non-ATLAS experimental constraints except the direct detection experiment of dark matter, and models that pass all non-ATLAS experimental constraints and ATLAS Higgs research constraints. It can be found that the experimental constraints of ATLAS can exclude regions that cannot be excluded by the direct detection experiment of dark matter. For σ_{SI} , vice versa, σ_{SI} can exclude LSP particles with higher mass, while LSP particles with higher mass cannot be excluded by the ATLAS experimental constraints.

In addition, the figure 8-16 shows a scatter plot on the $m(\tilde{\chi}_1^0)$ - Ωh^2 plane. The color of each point represents a different LSP joint annihilation mechanism. There are more ways to reduce LSP density than LSP joint annihilation. If NLSP can annihilate into standard model particles in pairs instead of decaying into LSP particles, Ωh^2 can also be effectively reduced. The main mechanism for reducing Ωh^2 in about half of the models in the Bino-DM scan is NLSP annihilation into SM particles in pairs. The distribution of such particles is not considered in the figure. The number of such models accounts for about 1/3 of all models. By comparing Fig. 2d-

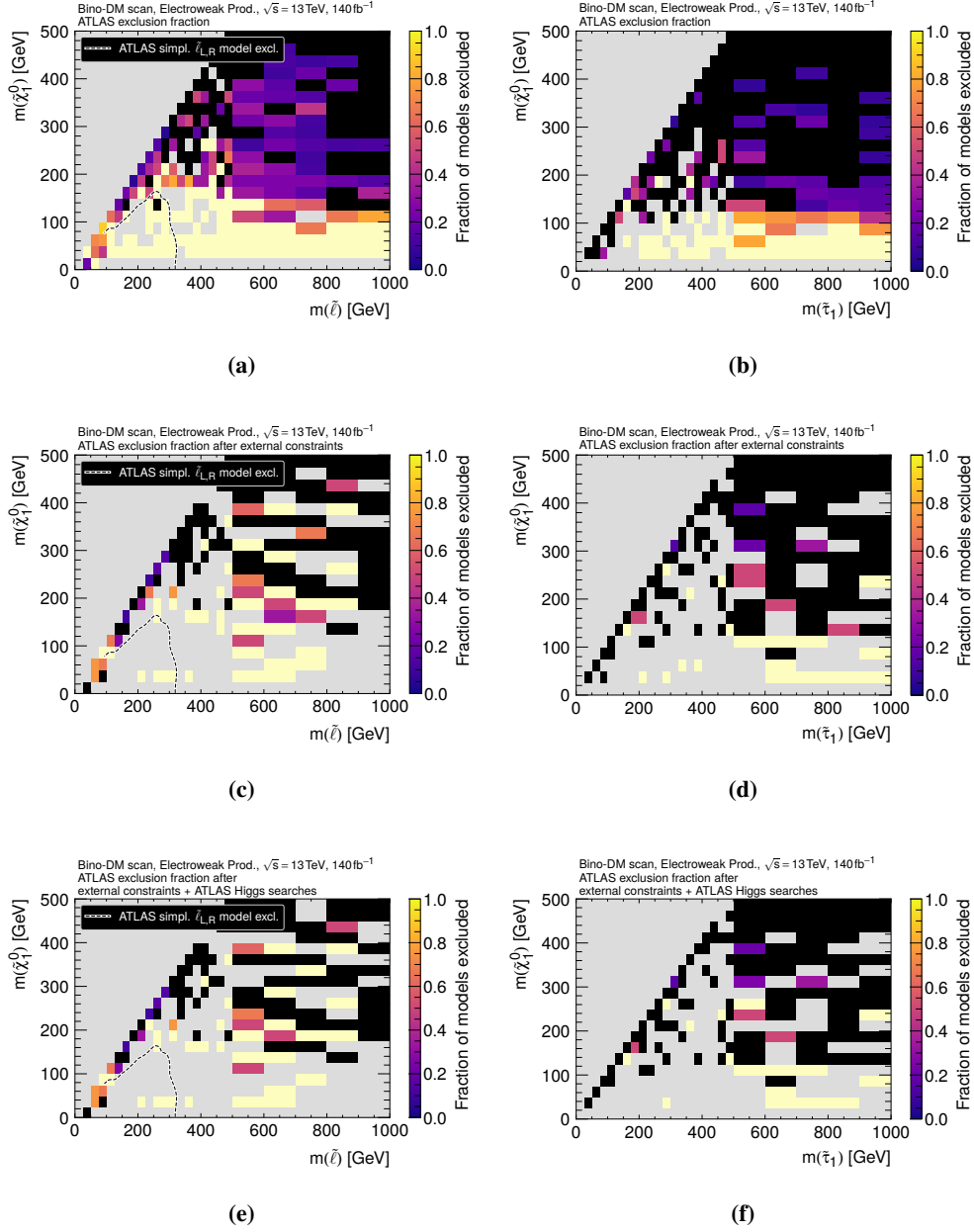


图 8-13 Bino-DM 被 ATLAS SUSY 研究约束排除的比例 ($m(\tilde{\ell})-m(\tilde{\chi}_1^0)$ 、 $m(\tilde{\tau})-m(\tilde{\chi}_1^0)$)。 (a,c,e) 展示了模型在 $m(\tilde{\ell})-m(\tilde{\chi}_1^0)$ 平面的投影；(b,d,f) 展示了模型在模型在 $m(\tilde{\tau})-m(\tilde{\chi}_1^0)$ 平面的投影。(a-b) 考虑了全部的 Bino-DM 模型，(c-d) 考虑了通过非 ATLAS 约束的模型，(e-f) 考虑了通过非 ATLAS 约束和 ATLAS Higgs 研究的约束的模型。

Figure 8-13 The fraction of the Bino-DM scan models excluded by ATLAS SUSY results ($m(\tilde{\ell})-m(\tilde{\chi}_1^0)$, $m(\tilde{\tau})-m(\tilde{\chi}_1^0)$). The first column shows the $m(\tilde{\ell})-m(\tilde{\chi}_1^0)$ plane and the second column the $m(\tilde{\tau})-m(\tilde{\chi}_1^0)$ plane. The first row includes all considered models, the second includes models that satisfy all external constraints and the third row includes models that satisfy all external constraints and ATLAS Higgs constraints.

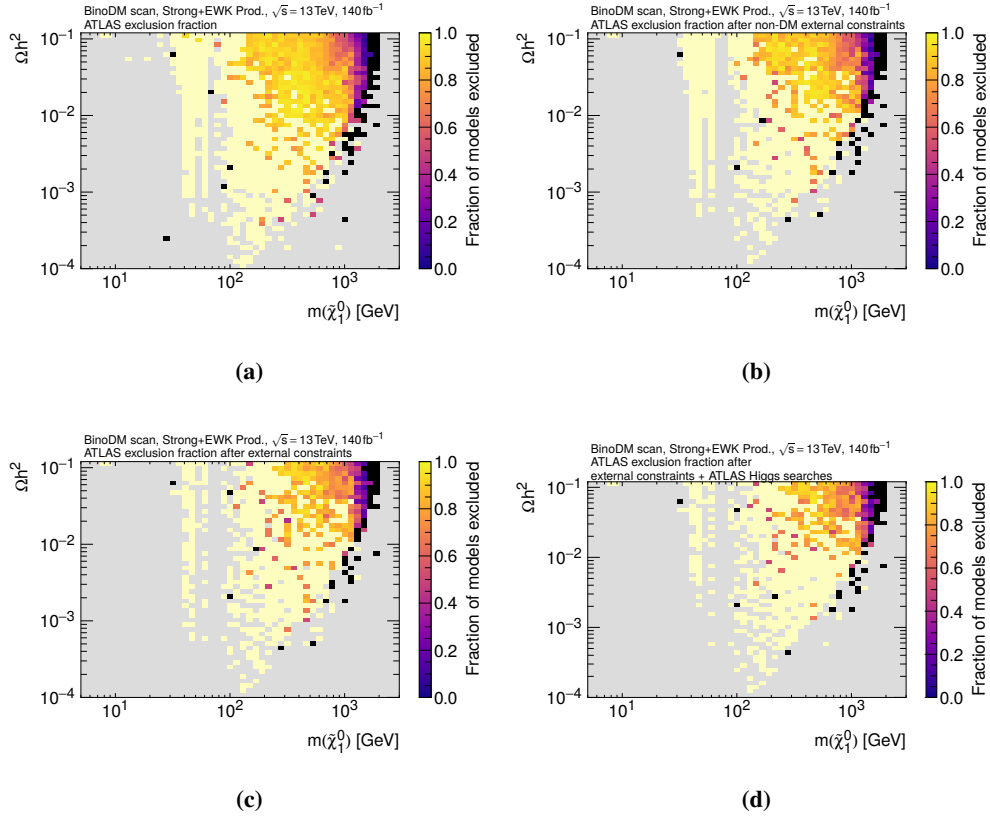


图 8-14 Bino-DM 被 ATLAS SUSY 研究约束排除的比例在 $m(\tilde{\chi}_1^0)$ - Ωh^2 平面的投影。

- (a) 全部模型, (b) 考虑了通过除暗物质探测实验约束外的非 ATLAS 实验约束的模型, (c) 考虑了通过非 ATLAS 约束的模型, (d) 考虑了通过非 ATLAS 约束和 ATLAS Higgs 研究的约束的模型。

Figure 8-14 Exclusion of models from the Bino-DM scan in the $m(\tilde{\chi}_1^0)$ - Ωh^2 plane.

- (a) all models, (b) models with all non-DM external constraints applied, (c) models with all external constraints applied, and (d) models with all external constraints and ATLAS Run 2 Higgs constraints applied.

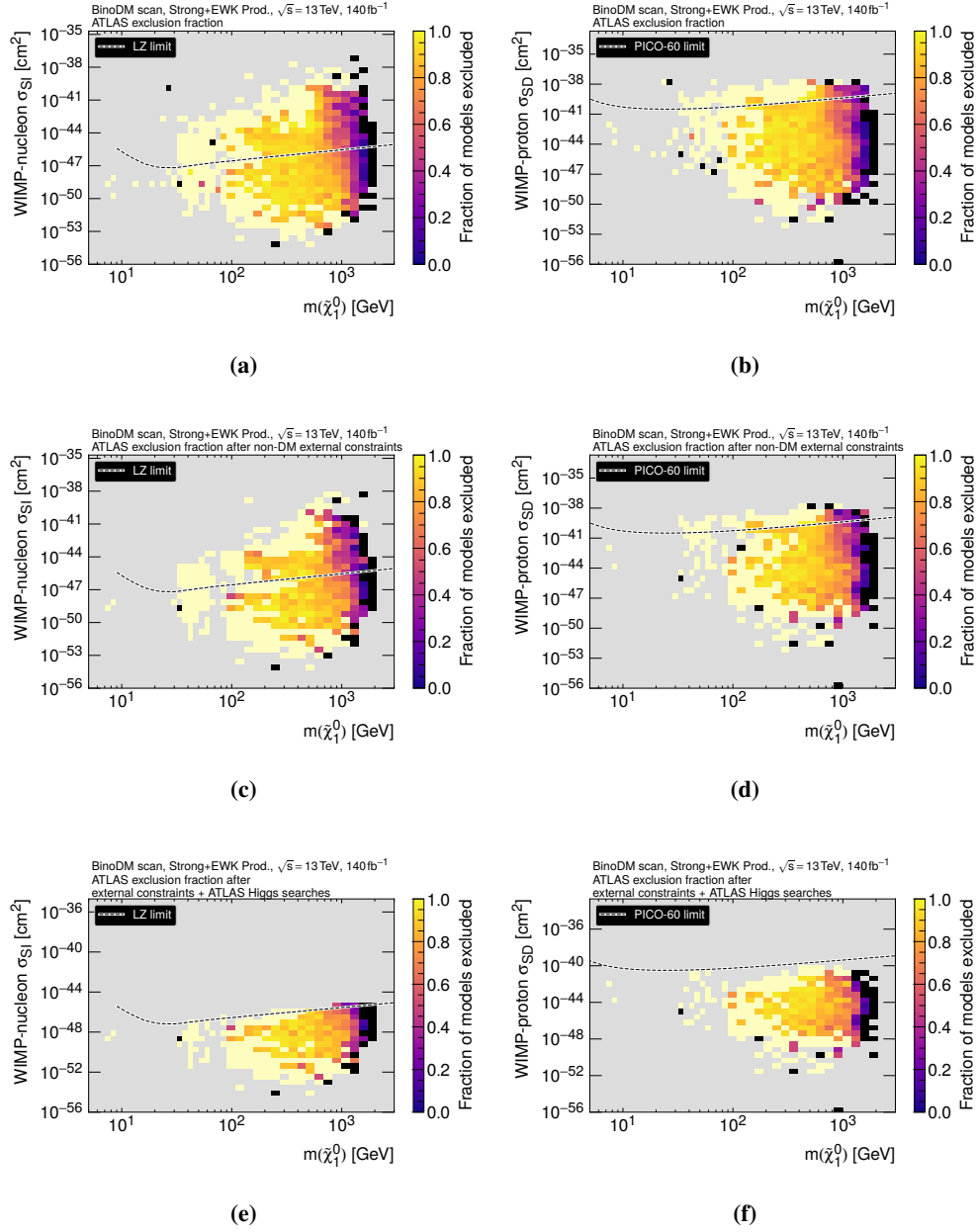


图 8-15 Bino-DM 被 ATLAS SUSY 研究约束排除的比例 ($m(\tilde{\chi}_1^0)$ - σ_{SI} 、 $m(\tilde{\chi}_1^0)$ - σ_{SD})。

(a,c,e) 展示了模型在 $m(\tilde{\chi}_1^0)$ - σ_{SI} 平面的投影；(b,d,f) 展示了模型在模型在 $m(\tilde{\chi}_1^0)$ - σ_{SD} 平面的投影。(a-b) 考虑了所有模型，(c-d) 考虑了通过除暗物质直接探测实验外非 ATLAS 约束的模型，(e-f) 考虑了通过非 ATLAS 约束和 ATLAS Higgs 研究的约束的模型。

Figure 8-15 The fraction

of the Bino-DM scan models excluded by ATLAS SUSY results ($m(\tilde{\chi}_1^0)$ - σ_{SI} , $m(\tilde{\chi}_1^0)$ - σ_{SD}).

The first column shows the $m(\tilde{\chi}_1^0)$ - σ_{SI} plane and the second column the $m(\tilde{\chi}_1^0)$ - σ_{SD} plane. The first row includes all considered models, the second includes models that satisfy all non-DM external constraints and the third row includes models that satisfy all external constraints and ATLAS Higgs constraints.

exclusion-relicdensitychannels(a), Fig. 2d-exclusion-relicdensitychannels(c) and Fig. 2d-exclusion-relicdensitychannels(d), which are all models, models constrained by non-ATLAS and models constrained by non-ATLAS and ATLAS SUSY, we can find that the experimental constraints almost exclude all models with LSP masses lower than 100 GeV. Among the remaining models with higher LSP masses, in addition to the NLSP pair annihilation mechanism, the reduction of LSP Ωh^2 is mainly achieved through A/H -funnel, joint annihilation with $\tilde{q}$ and joint annihilation with EWKino.

8.3.6 Constraints on the heavy neutral Higgs particle

Figure 8-17 shows the projection of the proportion of SUSY research constraints excluded on the $m(A)$ - $\tan \beta$ plane, where the dotted line comes from the ATLAS heavy neutral Higgs particle search experiment [200]. It can be found that the non-ATLAS experimental constraints are stronger in the region with higher $\tan \beta$, mainly due to the $B(b \rightarrow s\gamma)$ constraint. ATLAS's SUSY research has a strong exclusion ability in the region with lower $m(A)$, but most of the regions with higher exclusion ratios are also excluded by Higgs-related research. Due to the existence of the A/H -funnel mechanism, the correlation between $m(A)$ and $m(\tilde{\chi}_1^0)$ in some models is relatively large. Since the SUSY research has stronger constraints on the region with lower $m(\tilde{\chi}_1^0)$, the constraints are also stronger in the region with lower $m(A)$.

8.3.7 Complementarity and overlap between ATLAS experimental constraints and other experimental constraints

Figure 8-18 summarizes the overlap of various experimental constraints. The numbers on the diagonal represent the proportion of models excluded by the corresponding constraints, while the numbers on the off-diagonal represent the proportion of models excluded by the constraints corresponding to the ordinate that are also excluded by the constraints corresponding to the abscissa. Figure 8-18(a) shows that the models excluded by the analysis of SUSY particles produced by strong interactions overlap greatly with those excluded by 2L, 3L, and 4L analyses. This is mainly because the decay branches of SUSY particles in the pMSSM model are relatively complex, the branch ratios of decay to quarks and the branch ratios of decay to leptons can exist at the same time, and the final state phase space of Strong 2L and SS/3L analyses overlaps with that of 2L and 3L analyses. At the same time, since the model targeted by the Disappearing-track analysis is very different from all other analyses, the overlap with other constraints is the lowest. From Figure 8-18(b), we can see that Strong 0L analysis and other analyses have a large overlap. The reasons are two-fold. First, the more complex branching ratio in the pMSSM model causes the branching ratio of the hadronic final state and the branching ratio of the lepton final state to exist simultaneously during the decay of $\tilde{g}$ or $\tilde{q}$ through $\tilde{\chi}_1^0$ or $\tilde{\chi}_1^\pm$ to $\tilde{\chi}_1^0$. Second, the intermediate bosons produced by the decay

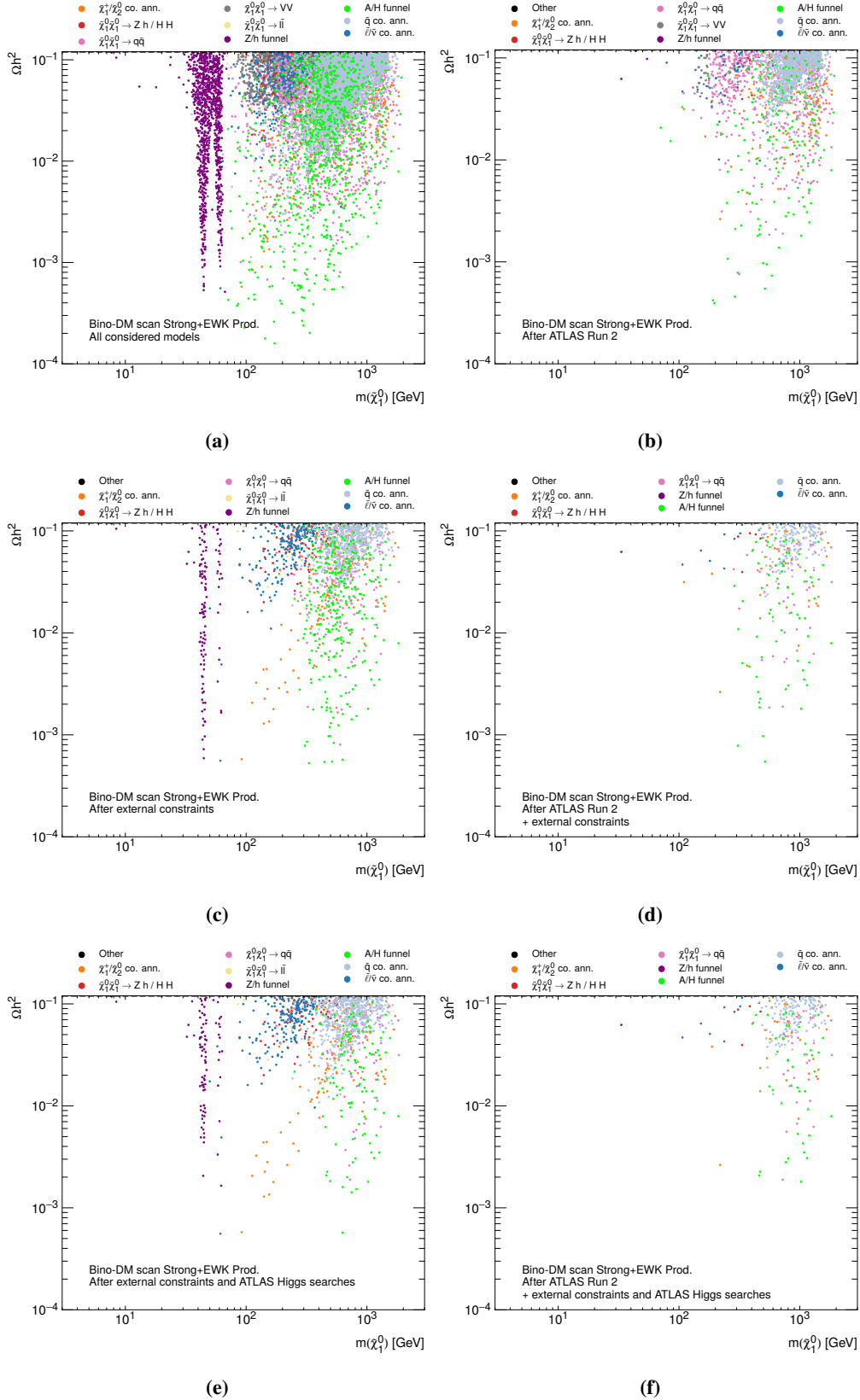


图 8-16 Bino-

DM 扫描在被 $m(\tilde{\chi}_1^0)$ - Ωh^2 平面上的散点图，每个点的颜色代表不同的联合湮灭机制。(a-b) 所有的模型在通过 ATLAS SUSY 研究约束前后的分布；(c-d) 通过非 ATLAS 约束的模型在通过 ATLAS SUSY 实验约束前后的分布；(e-f) 通过非 ATLAS 约束和 ATLAS Higgs 研究约束的模型在通过 ATLAS SUSY 研究约束前后的分布。

Figure 8-16 Scatter plots of models from the Bino-

DM scan in the $m(\tilde{\chi}_1^0)$ - Ωh^2 plane, coloured by the dominant annihilation mechanism.

Each row shows the considered models before and after ATLAS Run 2 SUSY constraints: (a-b) for all models. (c-d) for models that passed all external constraints, and (e-f) for models that passed

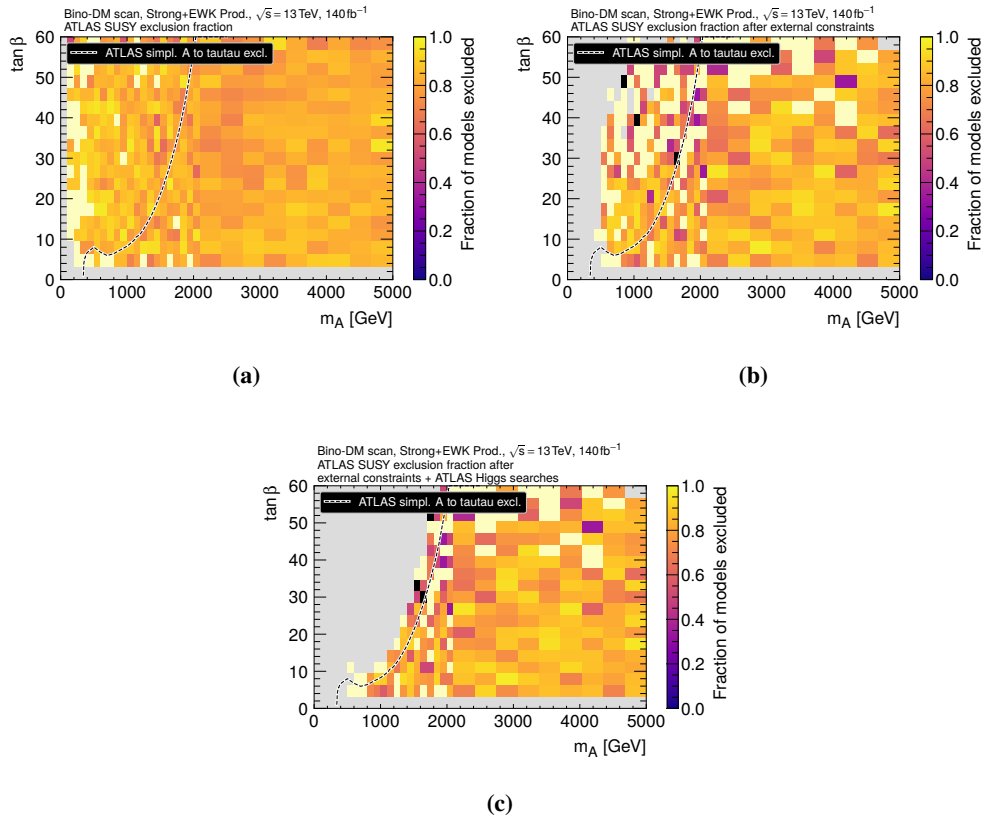


图 8-17 Bino-DM 被 ATLAS SUSY 研究约束排除的比例在 $m(A)$ - $\tan \beta$ 平面的投影。
(a) 考虑了全部的 Bino-DM 模型, (b) 考虑了通过非 ATLAS 约束的模型, (c) 考虑了通过非 ATLAS 约束和 ATLAS Higgs 研究的约束的模型。

Figure 8-17 The fraction of the Bino-DM scan models excluded by ATLAS SUSY results shown in the $m(A)$ - $\tan \beta$ plane.
(a) includes all considered models, (b) includes models that satisfy all external constraints, and (c) includes models that satisfy all external constraints and ATLAS Higgs constraints.

of $\tilde{g}$ or $\tilde{q}$ have the final state of hadronized decay, and Strong 0L analysis has a strong ability to exclude hadronic final states. In addition, there are many overlaps between Strong 1L, 2L2J, SS/3L and Multi-jet. In addition to the branching ratio, the overlap of the final state phase space is also part of the reason. Figure 8-18(c) shows the overlap between the ATLAS SUSY constraints, the Higgs constraints, and the non-ATLAS constraints. First, it can be noted that the overlap between the $B(h \rightarrow \text{inv})$ constraint, the SUSY constraints, and the direct dark matter detection experiments is high. This is mainly because $B(h \rightarrow \text{inv})$ is strongly restricted in the Z/h -funnel region, which is also where the SUSY and direct dark matter detection constraints are strong. The ATLAS constraints on the search for heavy neutral Higgs particles and the flavor physics constraints also overlap highly, which comes from the dependence on $\tan \beta$. When $\tan \beta$ is high, both the flavor physics constraints and the search for heavy neutral Higgs particles are strong.

Figure 8-19 summarizes the projection of the ATLAS experimental constraints on the SUSY particle mass. The models in the figure all pass the non-ATLAS experimental constraints. Figures 8-19(a) and 8-19(b) show the exclusion ability of the ATLAS experimental constraints on EWKino and the three-generation $\tilde{\ell}$. EWKino only considers the electroweak process in Figure 8-19(a), while Figure 8-19(b) considers the situation of being produced by $\tilde{g}$ or $\tilde{q}$ decay. It can be found that considering the process of strong interaction can greatly expand the constraint range of pMSSM model, but it does not expand the range of almost completely excluding pMSSM, and the lighter EWKino is still not completely excluded. Figure 8-19(c) shows that the pMSSM model in the range of $m(\tilde{g}) \leq 1 \text{ TeV}$ and $m(\tilde{q}) \leq 550 \text{ GeV}$ is almost completely excluded.

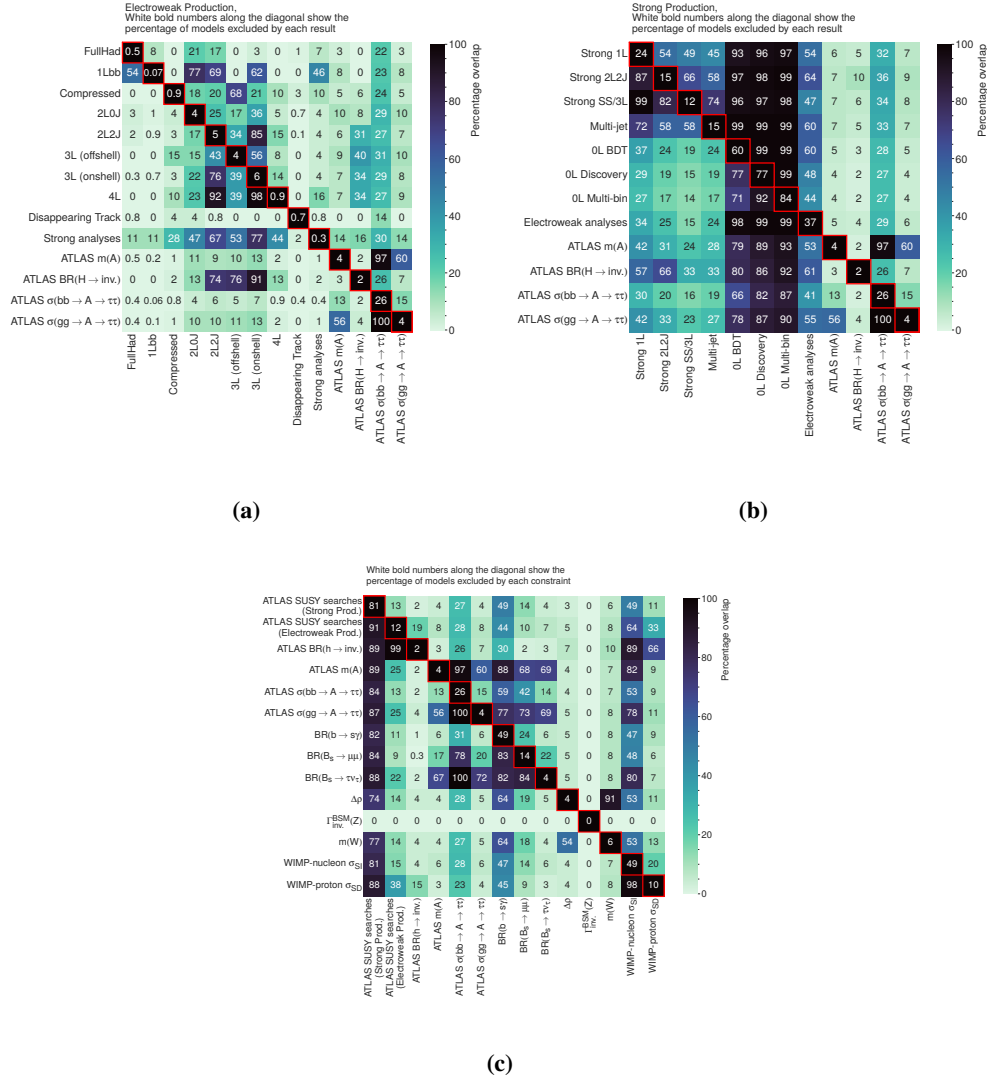


图 8-18 约束的重合度分布图。

对角线上的数字代表模型被此约束排除的比例，非对角线上的数字表示被纵坐标对应的约束排除的模型中有多少比例的模型也被横坐标对应的约束所排除：数字 = $100 \times N_{xy} / N_y$ ，其中 N_{xy} 表示同时被横、纵约束排除的模型数量， N_y 表示被纵坐标对应的约束排除的模型数量。

Figure 8-18 Percentage overlaps in the models excluded by each search and constraint.

For the diagonal entries, the number shows the percentage of all considered models excluded by that search/constraint. For each off-diagonal square, the number and bin colour indicates the percentage of the models excluded by the result on the x-axis that was also excluded by the result on the y-axis, i.e. = $100 \times N_{xy} / N_y$ where N_{xy} is the number of models excluded by the results on the x- and y-axes and N_y is the number of models excluded by the result on the y-axis.

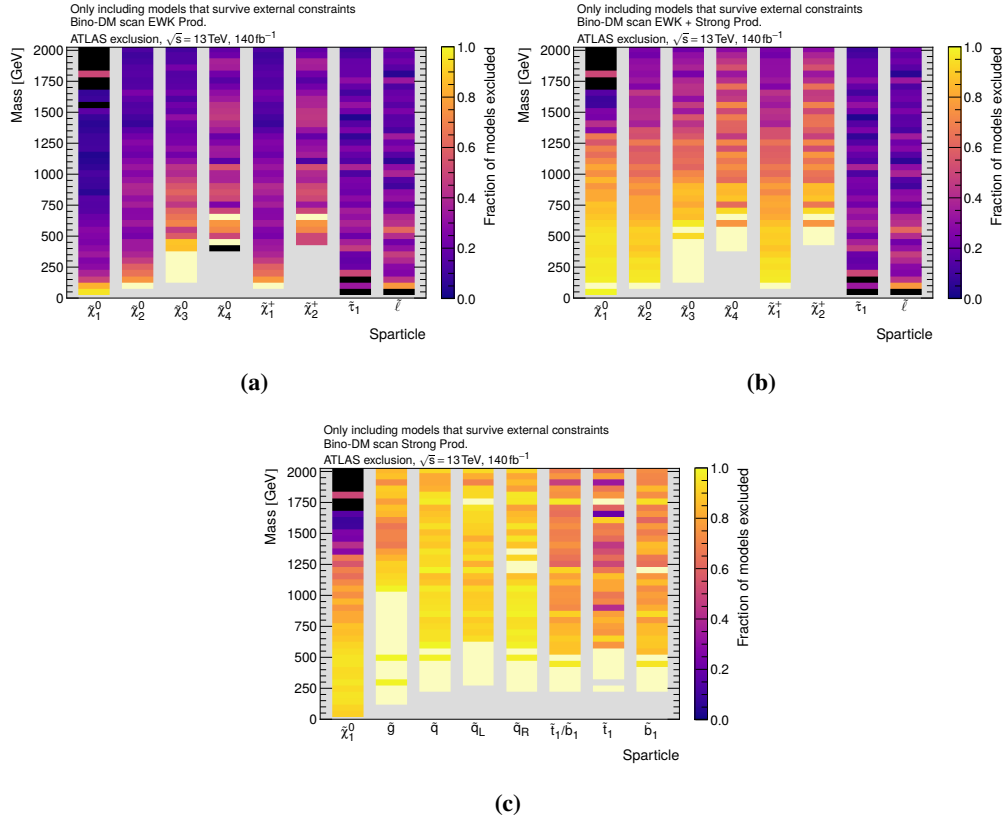


图 8-19 Bino-DM 被 ATLAS 实验约束排除的比例

在 SUSY 粒子质量一维分布上的投影，考虑了所有通过了非 ATLAS 实验约束的模型。(a) 展示了 EWKino 和三代 $\tilde{\ell}$ 只通过电弱过程产生的模型；(b) 展示了展示了 EWKino 和三代 $\tilde{\ell}$ 的情况，其中 EWKino 包括电弱过程产生和强过程产生的模型， $\tilde{\ell}$ 只考虑电弱过程产生的模型；(c) 展示了 $\tilde{\chi}_1^0$ 、 $\tilde{g}$ 和三代 $\tilde{q}$ 。

Figure 8-19 Summary plots showing the fraction of models excluded by ATLAS across the masses of each SUSY particles for models that satisfy external constraints. (a) shows the EWKinos and sleptons of EWK production, (b) considers EWK and Strong production for EWKinos, and (c) shows the summary of $\tilde{\chi}_1^0$, $\tilde{g}$, and third-generation $\tilde{q}$.

8.4 Results

This analysis shows the constraints on the pMSSM-19 model from the SUSY study of ATLAS in Run 2, the measurement of the Higgs particle width, and the study of Higgs particles beyond the standard model. This analysis only considers the pMSSM model with Bino mixing as the main LSP, which is more popular because it can provide a higher dark matter relic density. This analysis studies the constraints of the ATLAS experiment on the mass of SUSY particles in the pMSSM model and their impact on dark matter phenomenology, as well as the relationship between the constraints of collider experiments and non-collider experiments on the pMSSM model. The results show that: (1) The region where the ATLAS experiment completely excludes the mass parameters of SUSY particles in the pMSSM model is generally smaller than the constraints based on the simplified model, while the mass constraint on $\tilde{q}_L$ in the pMSSM model is slightly stronger than the constraints on the simplified model. This is mainly because $\tilde{g}$ is not decoupled in the pMSSM model, so the contribution of the $\tilde{g}\tilde{q}$ or $\tilde{g}\tilde{g}$ production process is higher; (2) The hypothesis of Bino-type LSP as a dark matter particle based on the annihilation mechanism of Z/h-funnel is almost completely excluded; (3) There is still a high probability that the SUSY model in the mass compression region has not been excluded. Future SUSY analysis still needs to continue to study this aspect, especially the EWKino particles in the mass compression region.

8.5 Conclusion

This analysis uses the supersymmetric search experiments of the ATLAS experiment during Run 2, the measurement of the Higgs particle decay width, the search experiments for Higgs particles beyond the standard model, and non-ATLAS experiments to constrain the pMSSM model. This analysis is not only a systematic summary of the experimental results during the ATLAS experiment Run 2, but also provides an important reference for future supersymmetric search experiments. This analysis found that the restrictions on the mass parameters of supersymmetric particles in the pMSSM-19 model by the ATLAS experiment are generally lower than the exclusion limits based on the simplified model, and the supersymmetric model with a mass spectrum in the mass compression region is still likely to be not excluded. For dark matter particle candidates, the Bino-type LSP based on the Z/h-funnel annihilation mechanism is less likely to be a dark matter particle, but the higher-mass Bino dark matter based on the joint annihilation mechanism of A/H-funnel and $\tilde{q}$, $\tilde{\chi}_2^0$, $\tilde{\chi}_2^\pm$ may still exist.

第9章 Summary and Outlook

Among all theories beyond the standard model, the supersymmetric model has the most advantages. It is perfectly compatible with quantum field theory, makes the coupling constants of the three gauge fields consistent at the grand unified energy scale, and can be used as part of the predictions of superstring theory and M theory. The main disadvantage of the supersymmetric model is that the current experiments to find supersymmetric particles have not found any signs, and of course, no particles predicted by other new physics have been found. In this regard, this paper conducts three related studies: (1) Searching for supersymmetric electroweak gauges, because their mass exclusion limit is low, there is still a large space to explore; (2) Studying the restrictions of double-tau or four-lepton analysis on the lifetime of supersymmetric particles and the R parity-breaking supersymmetric model with variable branching ratio. This paper selects the λ_{i33} term with variable coupling strength; (3) Studying the exclusion of supersymmetric models with more complex parameters, focusing on the model with Bino-type $\tilde{\chi}_1^0$ as LSP in the pMSSM-19 model.

The first part of this paper uses the proton collision data with a center-of-mass energy of 13 TeV and a total integrated brightness of 139 fb^{-1} collected by the ATLAS experiment during Run2 from 2015 to 2018 to search for the process in which $\tilde{\chi}_1^\pm \tilde{\chi}_2^0$ is produced in pairs and decays to the single-lepton double-tau state through W and h particles, respectively, and the process in which $\tilde{\chi}_1^\pm \tilde{\chi}_2^0 / \tilde{\chi}_1^\pm \tilde{\chi}_1^\mp$ is produced in pairs and decays to the double-tau state through $\tilde{\tau} / \tilde{\nu}_\tau$. Because the mass parameters of supersymmetric particles in these two analyses are relatively wide, each analysis defines the signal region for the low-mass region, the mass compression region, and the high-mass region, respectively. In terms of background estimation, the irreducible background dominated by the τ_{had} process with two injection misreconstructions was estimated by using the Fake factor method and the ABCD method, and the related errors were studied in detail. The remaining backgrounds were estimated by defining control regions or using verification regions to test the performance of MC simulation samples. Since no phenomena that obviously exceed the standard model were found in each signal region, this paper gives the mass exclusion limit based on the simplified model. For the process of gaugino decay through W and h , when the $\tilde{\chi}_1^0$ mass is 0, the region with a mass of $\tilde{\chi}_1^\pm / \tilde{\chi}_2^0$ lower than 330 GeV is excluded at 95% confidence. This is the first time that the ATLAS experiment has searched for this process and obtained the mass exclusion limit. For the process of gaugino decay through $\tilde{\tau}$ and $\tilde{\nu}_\tau$, when the mass of $\tilde{\chi}_1^0$ is 0, the region with a mass of $\tilde{\chi}_1^\pm$ lower than 970 GeV and the region with a mass-degenerate $\tilde{\chi}_1^\pm / \tilde{\chi}_2^0$ lower than 1160 GeV are excluded at a 95% confidence level. In addition, the addition

of the same-sign process greatly improves the ability to exclude the mass compression region.

The second part of this paper uses the analysis results of the ATLAS experiment during Run2 to search for the double tau state and the analysis results of the multi-lepton state to interpret the R parity violation process. This paper studies in detail the impact of λ_{i33} coupling on the Higgsino lifetime and branching ratio, and gives the latest theoretical upper limit of the λ_{i33} coupling coefficient. In terms of systematic errors, the paper studies in detail the systematic errors of shifted τ_{had} reconstruction, identification and correlation triggers. Finally, this paper gives the mass exclusion limit based on the simplified model of λ_{i33} . When $\tau_{\text{LSP}} = 0.01$ ns, the Higgsino mass in the range of 200 GeV to 600 GeV is excluded at 95% confidence; When τ_{LSP} is reduced to 0.001 ns, the region with Higgsino mass below 800 GeV is excluded; If the coupling strength continues to increase, the maximum mass exclusion limit of Higgsino is 900 GeV. It can be seen that the traditional signal region still has a certain constraint on the SUSY model with a certain lifetime and branching ratio change, and it decreases rapidly with the increase of lifetime.

In the last part of this paper, This paper describes the constraints on the pMSSM-19 model using the SUSY study of the ATLAS experiment during Run 2, the measurement of the Higgs particle width, the study of Higgs particles beyond the standard model, and the constraints of non-ATLAS experiments. The model that this paper focuses on is the model with Bino-type $\tilde{\chi}_1^0$ as LSP. By uniformly sampling the 19-dimensional parameter phase space, This paper finds that the ATLAS experiment's restrictions on the mass parameters of SUSY particles in the pMSSM model are generally lower than the results based on the simplified model. The SUSY model in the mass compression region of the mass spectrum is still likely to be not excluded, and the Bino-type LSP based on the Z/h -funnel annihilation mechanism is less likely to be a dark matter particle. In addition, the range of $\tilde{\chi}_1^\pm$ and $\tilde{\chi}_2^0$ in the pMSSM model is much smaller than the exclusion limit of the simplified model, and there is still a lot of room for exploration in the future search for $\tilde{\chi}_1^\pm$ and $\tilde{\chi}_2^0$.

On the basis of the current results, the above studies are worthy of further research in the future. For gaugino's research on the production process, adding experimental data from the ATLAS experiment Run3 will greatly increase the explorable range of high-quality areas. At the same time, it is also a very meaningful topic to use the experimental data of Run3 to expand the exploration scope to the mass compression region. The pMSSM study also shows that the current SUSY research has poor significance in the mass compression region. It is conceivable that the $E_{\text{T}}^{\text{miss}}$ in the mass compression region and the p_{T} of the final state physical object are both relatively low, so how to reduce the relevant background will become the biggest challenge. It would be helpful

to improve the reconstruction performance of low p_T physical objects, study methods that can improve the accuracy of background estimation, and introduce more efficient machine learning algorithms that can suppress the background. For the interpretation of R parity destruction process, Currently, there is no ability to exclude areas with higher τ_{LSP} . Therefore, introducing long-lived particle search experiments can not only limit the areas with higher τ_{LSP} , but also verify long-lived particles. Whether the search experiment and the traditional experiment complement each other cover all τ_{LSP} ranges. If these two analyzes are complementary, the significance of the signal can be further improved. On the contrary, it means that there is an τ_{LSP} area that has not been considered in the ATLAS experiment. How to study the related areas in the future will be a very interesting topic. . For the interpretation of the pMSSM-19 model, At present, this article has not considered the analysis of third-generation supersymmetric quarks and supersymmetric leptons. In the future, after adding them, we will get a more complete restriction of the pMSSM-19 model, and thus get a more accurate Run2 summary of the ATLAS experiment.

In the 1990s, theorists found that the minimum supersymmetric standard model predicted that the mass of the lightest Higgs boson would be less than 135 GeV [212, 213], In 2012, the ATLAS and CMS experiments discovered a Higgs boson with a mass of about 125 GeV, and the LHC lost the opportunity to rule out the minimum supersymmetric standard model. More than 30 years have passed, and how to find supersymmetric particles in the future with limited center-of-mass energy increase is a topic worth discussing.

(1) The production cross section of $\tilde{g}$ and $\tilde{q}$ decreases rapidly with the increase of their mass. In the future, when the energy increase of the center of mass of HL-LHC is limited ($\sqrt{S} = 14$ TeV), due to the limitation of PDF, the search ability for higher mass $\tilde{g}$ and $\tilde{q}$ is still weak. However, the search ability for $\tilde{\chi}_i^0$, $\tilde{\chi}_i^\pm$ and $\tilde{\ell}$ is still strong, and there is a large space to be explored. The pMSSM study in this paper also proves that the current experimental restriction range for $\tilde{\chi}_2^0$ and $\tilde{\chi}_1^\pm$ is far smaller than the interpretation based on the simplified model, so we should continue to search for supersymmetric particles produced by electroweak interaction. At the same time, because the lighter ewkino, smuon and stau can explain some "anomalous" phenomena currently observed in experiments, such as the anomalous magnetic moment of muons or dark matter particles, the physical motivation for searching for the process of electroweak interaction generation is also stronger.

(2) In terms of searching for SUSY models of stable LSP, the current analysis has a weak ability to exclude models in the mass compression region and cascade decay. Among them, the mass compression region is favored by the results of some non-collider experiments. Models in the mass compression region should be given priority,

especially the "Compressed Higgsino Scenario" corresponding to the Higgsino model.

It is difficult to optimize the signal area of such models, and more suitable machine learning algorithms need to be developed. At the same time, the reconstruction and identification performance of physical objects at low momentum needs to be improved.

(3) The interpretation of the R parity violation process in this paper shows that the traditional signal area can still restrict models within a certain lifetime range, but the signal significance decreases rapidly with the increase of the lifetime of supersymmetric particles. Therefore, most current SUSY experiments have weak restrictions on models with longer lifetimes. Finding long-lived particles with different characteristics is an important research aspect. At present, many theories tend to support the existence of long-lived SUSY particles, such as the GMSB model or the RPV model. At the same time, many other new physics models also predict the existence of long-lived particles.

(4) It is very meaningful to develop and improve tools that can replicate the analysis of collaborations such as ATLAS and CMS on other new physics models. If theorists can use replication tools to constrain new models, it will be very helpful for theoretical work. The Recast and Reana platforms that the ATLAS collaboration is continuously developing are good software. These software have been used in the pMSSM model research in this paper.

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附录一 Beam test and muon response of dual readout calorimeter

Future physics experiments on electron-positron colliders will require precise measurement of the jet quadruple momentum, such as the FCC-ee project [214] and the CEPC project [215]. Currently, particle flow algorithm-guided detector design and dual-readout calorimeter are two popular detector schemes that can improve the accuracy of jet measurement. This chapter will briefly introduce the preliminary research work of the dual-readout calorimeter based on the latter IDEA detector (Innovative Detector for Electron-positron Accelerator), which mainly includes beam testing in 2023 and related data analysis.

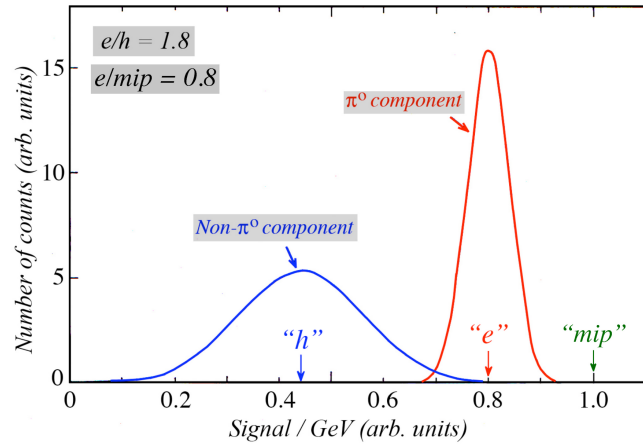
Detection principle of dual-readout calorimeter

The energy response of a calorimeter is defined as the efficiency ratio of particle energy deposition and signal generation, and the efficiency ratio is scaled to the efficiency ratio of the calorimeter to the smallest ionized particle (MIP) (e/mip), so the energy response of the calorimeter is a value between 0 and 1, and the energy response of the MIP is 1.

When the jet enters the detector, the π^0 or η mesons it contains or produced by secondary decay interact with the calorimeter material to produce electrons and photons, which will produce electromagnetic showers. This part of the energy is the electromagnetic part of the jet (Electromagnetic component, hereinafter abbreviated as em), and the remaining part of the energy is the non-electromagnetic part of the jet (Non-electromagnetic component, hereinafter abbreviated as non-em). More than 40% of the energy in non-em is absorbed by the calorimeter material as the binding energy of nucleons, thereby producing more secondary particles through nuclear reactions, and the energy fluctuation of non-em is large.

For non-compensated calorimeters, em has higher energy response and better energy resolution, while non-em has lower energy response and poorer energy resolution. Figure 2-0 [216] shows the distribution of em and non-em energy responses, where h represents the response of non-em and e represents the response of em. Because the energy responses of em and non-em in the uncompensated calorimeter are different ($e/h \neq 1$), when they are superimposed together, they will cause a wider distribution than the non-em response, resulting in a further decrease in energy resolution. If the average value of the em energy ratio in hadrons is recorded as $\langle f_{em} \rangle$, $\langle f_{em} \rangle$ is related to the properties of the detector material and the incident particles, then the total response of the calorimeter to hadrons can be expressed as: $[\langle f_{em} \rangle + (1 - \langle f_{em} \rangle)(h/e)]$.

In order to solve the problem of energy resolution degradation caused by invisible energy in non-em, the idea of a compensated calorimeter was proposed, which



附图 2-0 量能器的能量响应分布，能量响应已刻度到 MIP，其中 h 代表 non-em 的响应， e 代表 em 的响应 [216]。

App Figure 2-0 Shown are distributions of the signal per unit deposited energy, normalized to the response for minimum ionizing particles (MIP). The average values of the em and non-em distributions are the em response (e) and non-em response (h), respectively [216].

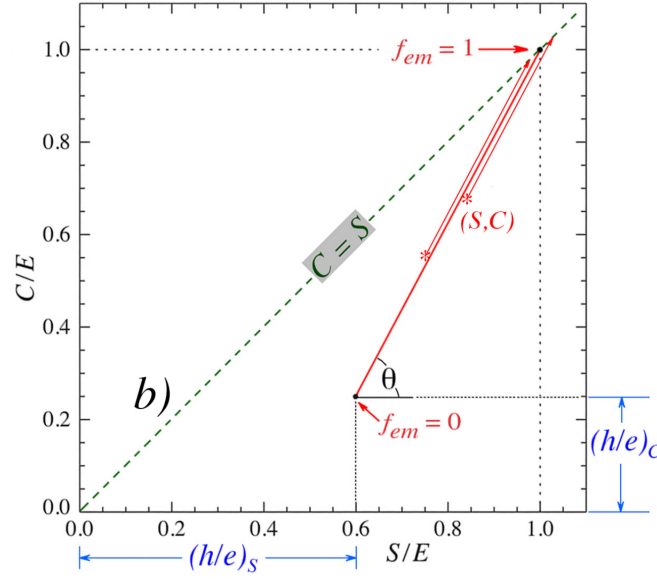
improves the performance of the calorimeter by designing $e/h \sim 1$. At the same time, there is another mechanism to improve the energy resolution of a non-compensated calorimeter in the case of $e/h \neq 1$: using Cherenkov light. In calorimeter materials, the energy of relativistic electrons can be as low as ~ 200 keV [217], but protons produced by non-em nuclear reactions are difficult to become relativistic particles and produce Cherenkov light. So in theory, by comparing the ratio of the total generated signal and the Cherenkov light generated signal, the f_{em} of an incident particle can be determined, and then the total response of the calorimeter to hadrons can be determined by measuring the detector response ratio e/h in advance. This is the measurement principle of the dual-readout calorimeter, which measures the total generation signal of non-em and em through scintillator or liquid argon and combines it with the Cherenkov light to measure the generation signal of em to measure f_{em} and thus determine the energy of the hadron.

Considering that the scintillator-generated signal and the Cherenkov-generated signal have better responses to electrons, the generated signals of the two can be calibrated by electrons: $\langle S \rangle = \langle C \rangle = E$, at which time the response ratio of the two to em is $R_{em} = 1$. After the calibration is completed, for any incident hadron, we can get:

$$\begin{aligned} S &= E[f_{em} + \frac{1}{(e/h)_S}(1 - f_{em})] \\ C &= E[f_{em} + \frac{1}{(e/h)_C}(1 - f_{em})] \end{aligned} \quad (\text{附 2-1})$$

Among them, $(e/h)_S$ and $(e/h)_C$ are obtained by advance measurement, and f_{em} can be measured only when they are not equal. It can be found that the distribution of S/E and C/E is on a line segment, and the specific position is determined by f_{em} , as shown in Figure 2-1 [216]. If the slope of the line segment is defined as χ , the hadron energy

can be measured by generating signals S and C : $E = (S - \chi C)/(1 - \chi)$, and χ is independent of the hadron energy and type.



附图 2-1 双读出量能器中 S/E 、 C/E 和 f_{em} 的关系 [216]。

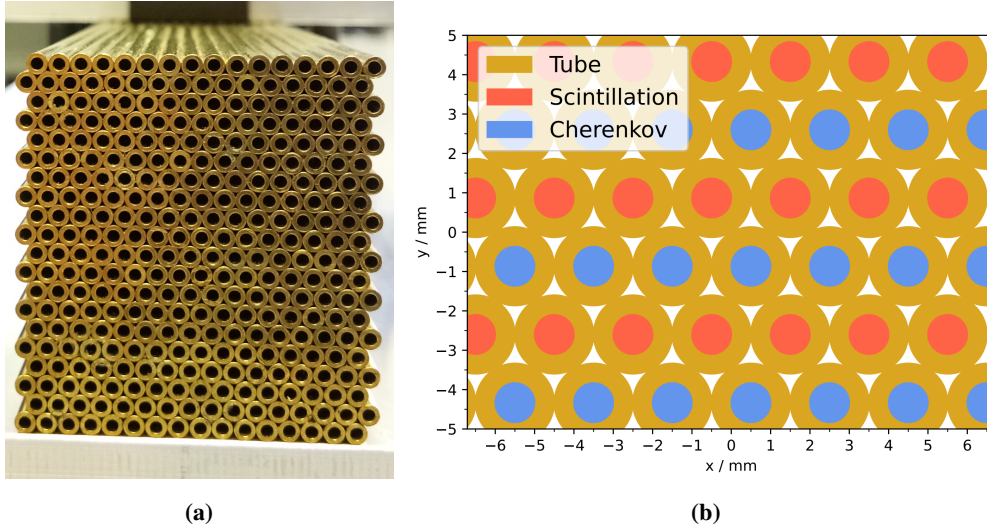
App Figure 2-1 The relation between S/E , C/E , and f_{em} the signals from a dual-readout calorimeter [216].

Capillary-tube-based Dual-readout Prototype

The capillary dual-readout calorimeter prototype tested in this study is a scintillator or plastic undoped fiber that passes through a thin copper-based tube with an outer diameter of 2 mm and an inner diameter of 1 mm. The plastic undoped fiber is used to absorb the Cherenkov light. After that, the copper tubes are glued together in a dense stack, which can greatly reduce the construction cost of the calorimeter. The prototype calorimeter module is 1 meter long, which can accommodate most of the electromagnetic shower energy, with a cross-section of $10 \times 10 \text{ cm}^2$, and contains a total of 16×20 tubes. Nine groups of calorimeter module prototypes are fixed together 3×3 , where the readout of the central module (M0) is a silicon photomultiplier tube (SiPM), and the readout of the outer eight modules (M1-8) is a photomultiplier tube (PMT). The addition of SiPM can read out the signal of each fiber of the central module [218], which has the ability to measure single photons. Figure 2-2 shows the arrangement of the tubes of a single module and the distribution of the two optical fibers.

Test beam

In order to measure the energy linear response, energy resolution and high-granularity readout characteristics of e^+ in the dual-readout calorimeter module prototype, and to measure the characteristics of μ and π in the module prototype, this study conducted beam tests on the detector module prototype. The beam tests were carried out on the H8 beam of the SPS at CERN. The experiments used e^+ with energies ranging from 10 GeV



附图 2-2 毛细管型双读出量能器模块原型铜细管排布，其中 (b) 展示了闪烁体光纤和塑料无掺杂光纤分布 [219]。

App Figure 2-2 Front view of the dual-readout calorimeter prototype, where (b) shows sketch of the front face of the calorimeter detailing the relative positions of the Cherenkov and scintillating fibres [219].

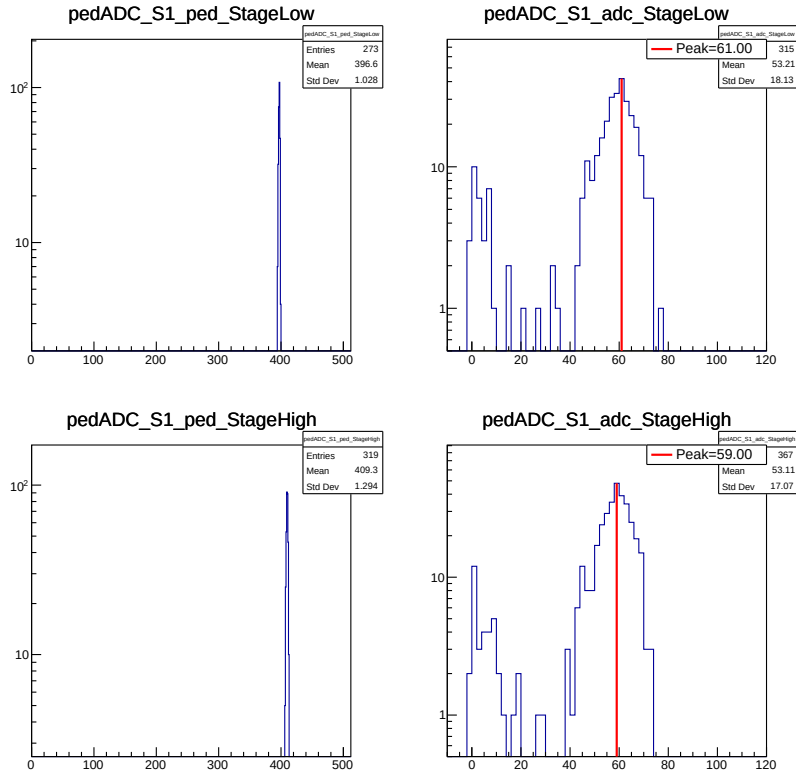
to 120 GeV, μ at 160 GeV, and π at 20 GeV to 180 GeV. Two Cherenkov detectors are placed after the beam to distinguish e^+ from π^+ . After that are three groups of scintillator detectors, two rectangular detectors are placed perpendicular to each other (T_1 and T_2), resulting in an overlapping area of $4 \times 4 \text{ cm}^2$. After this group of scintillator detectors is the third scintillator detector (T_3), which has a circular hole with a radius of 1 cm, thus forming the trigger condition: $(T_1 \wedge T_2) \wedge \bar{T}_3$. A group of multi-wire proportional chambers (DWC) are placed at the front and rear ends of the scintillator detector to provide particle track information, with a spacing of 174 cm. Behind the rear DWC is a pre-shower detector (PS) composed of lead and scintillator, which has the ability to generate and detect showers. After PS is the calorimeter prototype. The distance from the front end to the rear end DWC of the prototype is 245.5 cm. The prototype is placed on a platform that can rotate horizontally. Another scintillator detector is placed about 50 m away from the rear end of the prototype to measure muons (muon counter), and there is a concrete wall between the muon detector and the calorimeter prototype.

During the beam test, after every ten physical events are triggered, a signal-free reference event is generated for synchronization between the calibration and data acquisition subsystems. Finally, in terms of the muon beam, this beam test was conducted with the rear end of the detector raised by about 2.5° and the absolute horizontal angle (angle of the rotating platform) was $[-1^\circ, 2.5^\circ]$. About 80,000 physical events were collected at each angle. When the detector was placed horizontally, the beam test was conducted with the absolute horizontal angle $[-2.5^\circ, 1.5^\circ]$, and about 250,000 physical events were collected at each angle.

Equalisation of the response of a photomultiplier tube

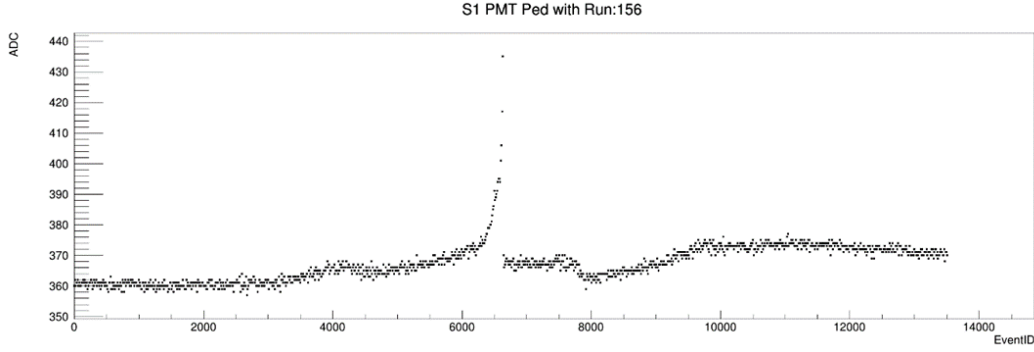
The readout balance of the SiPM was performed in the Desy laboratory. The PMT balance used the 20 GeV e^+ beam from H8. By adjusting the lateral and longitudinal positions of the platform where the calorimeter prototype is located, the beam was made to hit the center of the M0-8 module respectively.

The scintillator or Cherenkov light signal of the PMT is balanced separately. The ADC value of the physical case of the PMT of module M_i first needs to be subtracted from the ADC value of the reference case: $A_{M_i}^{S,C}(20 \text{ GeV}) = \text{ADC}_{\text{physics}} - \text{ADC}_{\text{pedestals}}$. The response and equilibrium constants can be obtained by scaling the peak of $A_{M_i}^{S,C}(20 \text{ GeV})$ to the M0 module: $P_{M_i}^{S,C}(20 \text{ GeV}) = a_i^{S,C} \times A_{M_i}^{S,C}(20 \text{ GeV}) = P_{M_0}^{S,C}(20 \text{ GeV})$, Figure 2-3 shows the response of Cherenkov light when the beam is in the middle of the M1 module. Since the ADC value of the benchmark event was observed to fluctuate at a specific time in the experiment, as shown in Figure 2-4, this study selected the area where the ADC distribution of the benchmark event has a small fluctuation and balanced it, named StageLow and StageHigh respectively. The two figures on the left are the benchmark event distributions of StageLow and StageHigh, respectively, and the right side is the corresponding $A_{M_1}^C(20 \text{ GeV})$ distribution. The peak position can be clearly seen, and the peak values of StageLow and StageHigh are close.



附图 2-3 M1 模块切伦科夫光的 ADC 分布。

App Figure 2-3 Distributions of ADC for the Cherenkov fibres in the M1 module.



附图 2-4 M1 模块切伦科夫光的基准事例 ADC 分布，横坐标为事例编号。

App Figure 2-4 The pedestal ADC as a function of the event number in the M1 module.

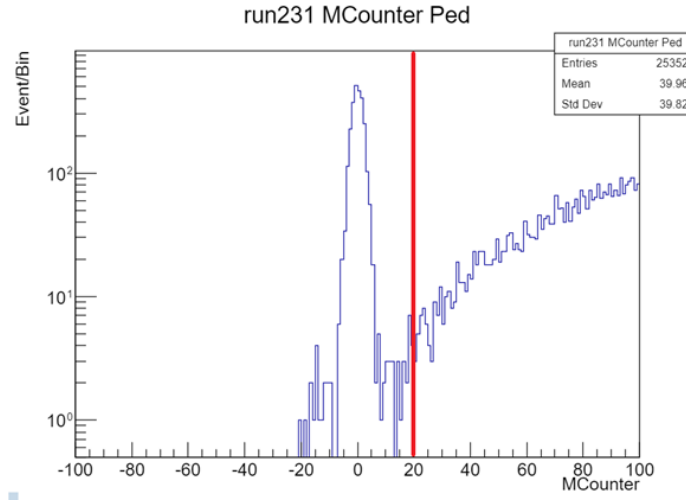
After balancing the energy responses of the nine modules M0-8, the next step is to correlate the responses with the incident positron energy. By using the experimental data of 20 GeV positrons incident on M0, combined with the energy absorption rate (Containment) of the entire calorimeter prototype obtained by Geant4 simulation is $\epsilon_{\text{module}} = 76\%$, we can finally obtain the number of photoelectrons measured by SiPM and the conversion coefficient of 1 GeV $F_{\text{PheToGeV}}^{S,C} = (P_{\text{M0}}^{S,C}(20 \text{ GeV})) / (\epsilon_{\text{module}} \times 20 \text{ GeV})$.

Muon Response

Thanks to the muon counter set up behind the calorimeter in this experiment, although the selection efficiency is not high because it is too far away from the detector and the area is smaller than $1 \times 1 \text{ m}^2$, it is precisely because of the long distance and the existence of the concrete block between the counter and the calorimeter that the background rejection rate is extremely high.

In order to select muon events, this study considered the following selection conditions. Figure 2-5 shows the distribution ΔADC of the muon counter physical event ADC minus the benchmark event ADC when the calorimeter platform is at an absolute horizontal angle of -0.5° . The peak of the muon-free event at the origin can be clearly seen. The selection condition of this study is $\Delta\text{ADC} > 20$. In addition, considering that muons have ionization energy loss in the calorimeter, the event also requires the energy of M0 to be higher than 0 GeV. Finally, in order to obtain the muons that are collimated and hit M0, this study also requires that the relative distance between the coordinates of the event in the two DWCs is less than 2 mm, that is: $\sqrt{\Delta X_{\text{DWC}}^2 + \Delta Y_{\text{DWC}}^2} < 2 \text{ mm}$, and the position of the event on each DWC is less than 9 mm from the center, that is: $\sqrt{X_{\text{DWC1(2)}}^2 + Y_{\text{DWC1(2)}}^2} < 9 \text{ mm}$.

Through the coordinates left by the event in the two DWCs, the position where the event hits the front end of the module (hereinafter abbreviated as Pred) can be calculated, and the excellent measurement performance of SiPM on each fiber makes it

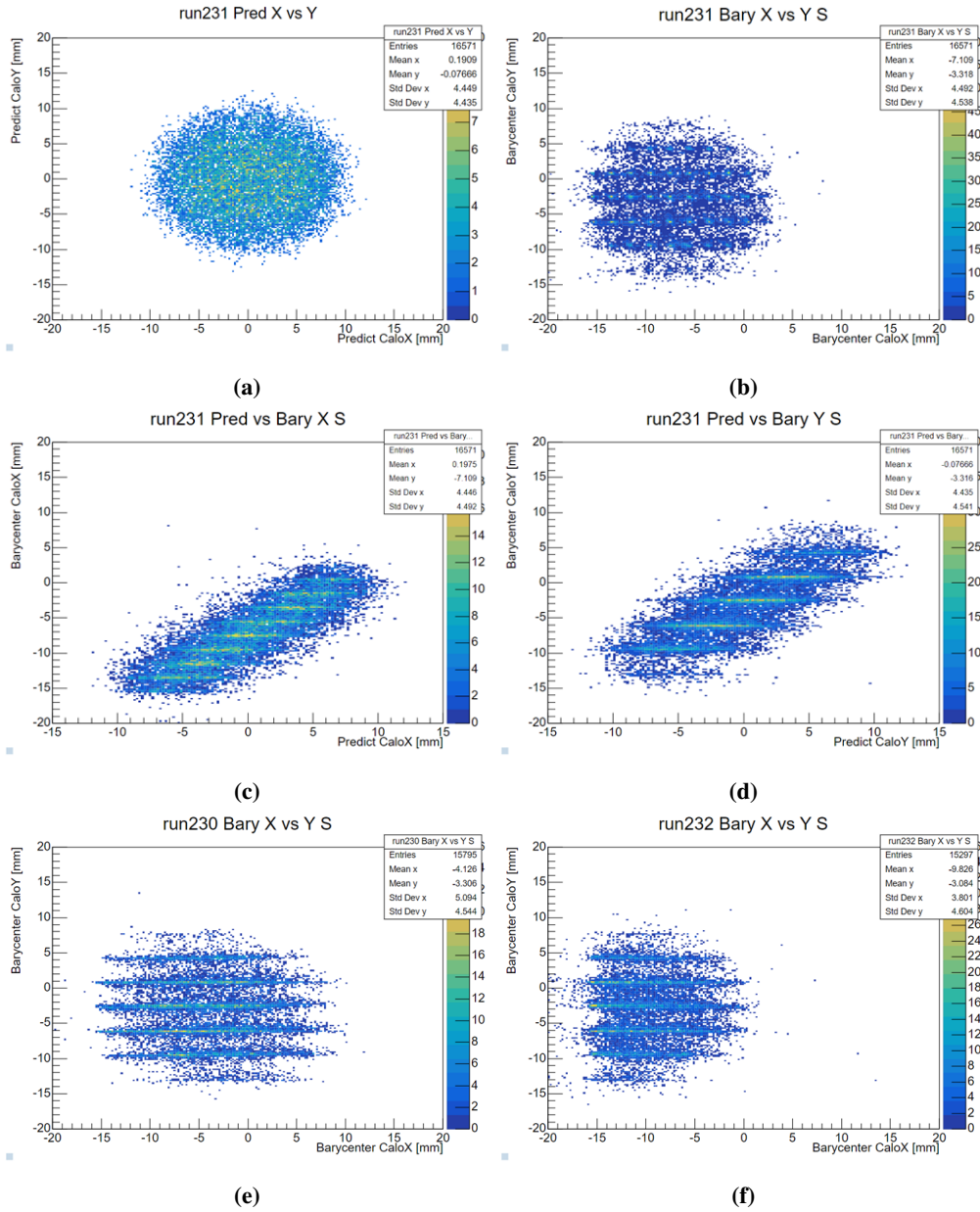


附图 2-5 缪子计数器中物理事例 ADC 减去基准事例 ADC 的分布。

App Figure 2-5 Distribution of ADC for physical events after removing ADC of baseline events in the muon counter.

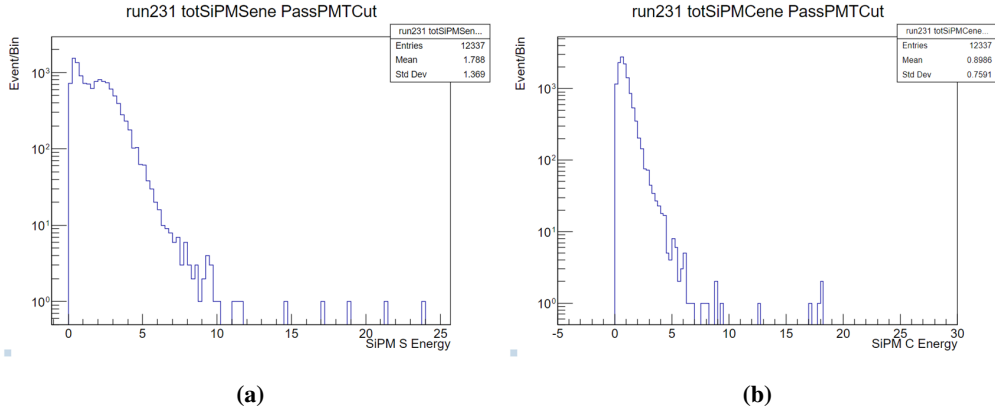
possible to calculate the energy response center (Barycenter, hereinafter abbreviated as Bary). Figure 2-6 shows the relationship between Pred and Bary. Figure 2-6a shows the two-dimensional distribution of Pred. It can be found that the distribution of the event after the DWC selection condition is more concentrated. Figure 2-6b shows the two-dimensional distribution of Bary. It can be found that Bary forms some point distributions more concentratedly. Each point corresponds to a scintillator fiber, with a horizontal spacing of about 2 mm and a vertical spacing of about 3.5 mm. SiPM's measurement of the energy response center shows the position of the optical fiber. Figures 2-6c and 2-6d respectively check the correspondence in the horizontal and vertical directions, and it can be clearly seen that Bary shows the distribution of the optical fiber. Figures 2-6e and 2-6f respectively check the distribution of Bary when the absolute angle of the rotating platform is 0° and -1.0° . It can be found that the horizontal distribution of the optical fiber is blurred at this time, because muons can pass through more optical fibers in the horizontal direction.

In order to further improve the measurement accuracy of muons, considering that it is impossible to accurately know at what value the absolute angle of the rotating platform is set when the relative angle between the beam and the calorimeter module in the horizontal direction is 0, this study further limits the PMT energy upper limit of the M4 and M5 modules located on the left and right sides of M0 to 0.20 GeV. Figure 2-7 shows the energy distribution collected by the M0 module scintillator and plastic undoped optical fiber after the PMT energy upper limit selection condition. It can be found that the peak values of the two distributions are both around 1 GeV. It is roughly estimated that the energy absorption rate of this calorimeter module for the directly incident muons is 0.6%.



附图 2-6 通过 DWC 信息计算事例的集中位置和 SiPM 相应能量中心的关系。

App Figure 2-6 Relationship between the predicted position calculated using DWC information and the energy barycenter of the SiPM.



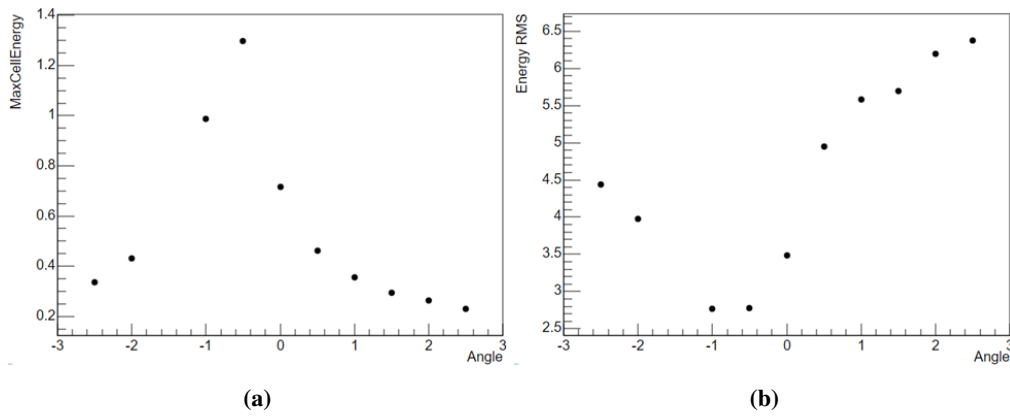
附图 2-7 缪子通过闪烁体 (a) 和塑料无掺杂光纤 (b) 收集到的能量分布。

App Figure 2-7 Energy distribution of muons collected by (a) scintillator fibres and (b) plastic undoped fibres.

Figure 2-8 shows the relationship between the absolute angle of the platform where the calorimeter is located and the highest energy of each fiber or the root mean square of the scintillator energy distribution. It can be seen that when the muon and the calorimeter are relatively aligned, the energy deposited by a single fiber may be higher, but the energy distribution is narrower, and the lowest is close to 2.8 mm, which is only slightly larger than the outer diameter of a single copper tube. This also indirectly reflects a feature of the dual-readout calorimeter: the energy resolution level drops rapidly when the fiber inside the calorimeter and the incident particle are aligned [217]. For example, for high-energy electrons with momentum higher than 100 GeV, most of the deposited energy of their electromagnetic shower is within the range of 4 mm [217], which is at the same order of magnitude as the fiber spacing of the dual-readout calorimeter. At this time, the deposited energy collected by the fiber is highly dependent on the position of the incident particle and is likely to be low, thereby greatly reducing the energy resolution level.

Conclusion

This study briefly introduced the beam test of the dual-readout calorimeter, and balanced the PMT module through the experimental data collected from the beam test. Preliminary results of the muon response were obtained, and it was found that when the muons and the optical fiber are aligned, the energy response center of the calorimeter can match the position of the optical fiber. This may have wider applications in the future, such as the study of shower structures, etc. This research will continue.



附图 2-8 量能器所在平台的绝对角度和 (a) 单光纤最高能量和 (b) 闪烁体能量分布均方根的关系。

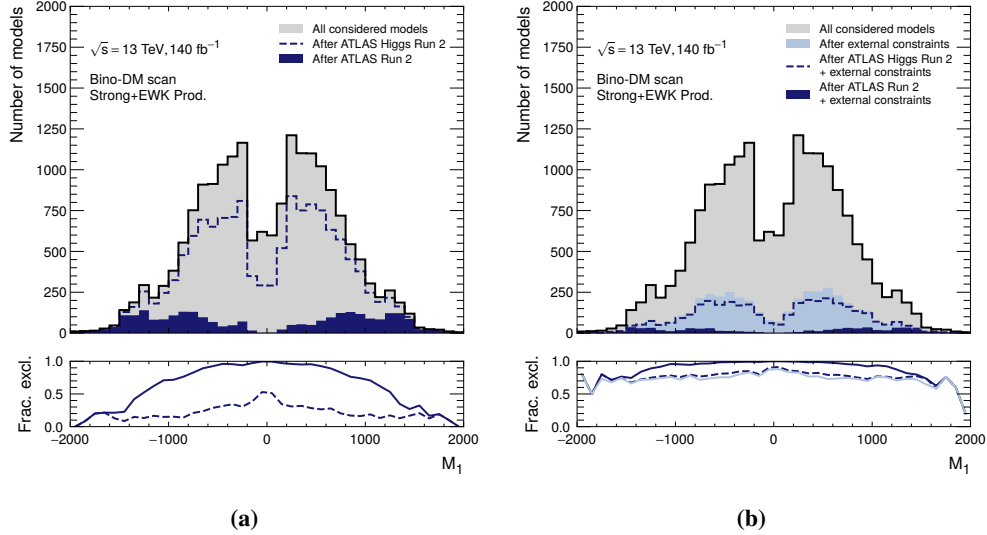
App Figure 2-8 Relationship between the absolute angle of the platform where the calorimeter is located and (a) the maximum energy of a single fibre and (b) the root mean square of the energy distribution collected by scintillator fibres.

附录二 pMSSM-19 model parameter distributions and exclusion ratios

This appendix is a supplement to Chapter 8, showing the distribution and constraints of some pMSSM-19 model parameters.

The one-dimensional distributions in this appendix are: (a) showing the distribution of all models before and after the addition of ATLAS experimental constraints, where the blue dashed line indicates only the constraints related to the Higgs study of ATLAS; (b) showing the distribution of all models after non-ATLAS experimental constraints, after non-ATLAS experimental constraints and ATLAS Higgs study constraints, and after non-ATLAS experimental constraints and ATLAS experimental constraints.

The two-dimensional distributions in this appendix are: (a) considering all models; (b) considering models constrained by non-ATLAS experiments; (c) considering models constrained by non-ATLAS experiments and ATLAS Higgs study constraints.



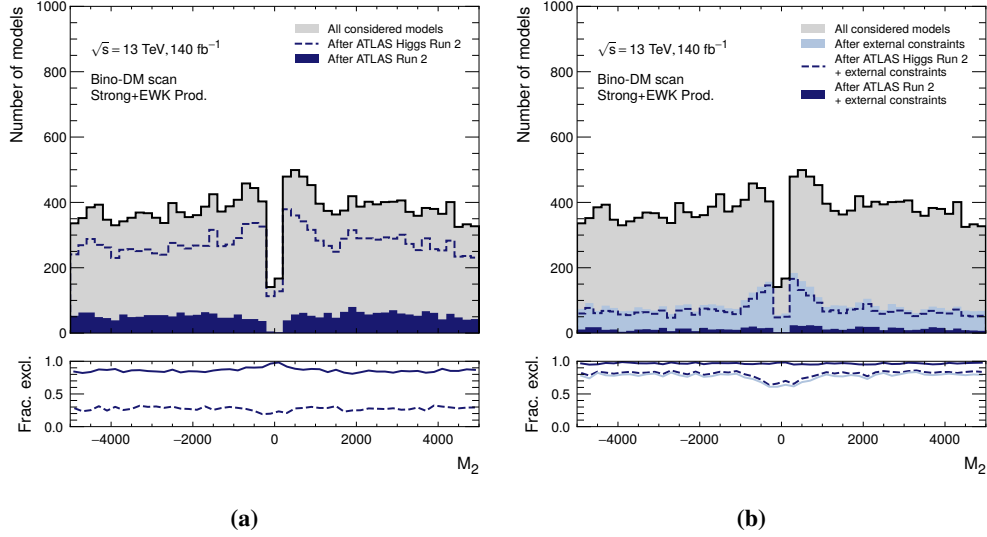
附图 3-1 Bino-DM 的 M_1 的分布与被排除的比例。

- (a) 展示了所有的模型在加入 ATLAS 实验的约束前后的分布，其中蓝色虚线表示只有 ATLAS 的 Higgs 研究相关的约束；(b) 展示了所有模型经过非 ATLAS 实验约束后的分布、经过非 ATLAS 实验约束后和 ATLAS 的 Higgs 研究约束、经过非 ATLAS 实验约束和 ATLAS 实验约束后的分布。

App Figure 3-1

Distributions of M_1 before and after the ATLAS Run 2 SUSY constraints are applied.

- (a) The distribution of all considered Bino-DM scan models before and after the ATLAS Run 2 constraints are applied, and the blue dashed line shows the remaining models after the ATLAS Higgs constraints applied. (b) The distribution of all considered Bino-DM scan models, the remaining models after all the external constraints are applied, the remaining models after all external constraints and the ATLAS Higgs constraints, and the remaining models after all external constraints and the ATLAS Run 2 constraints are applied.



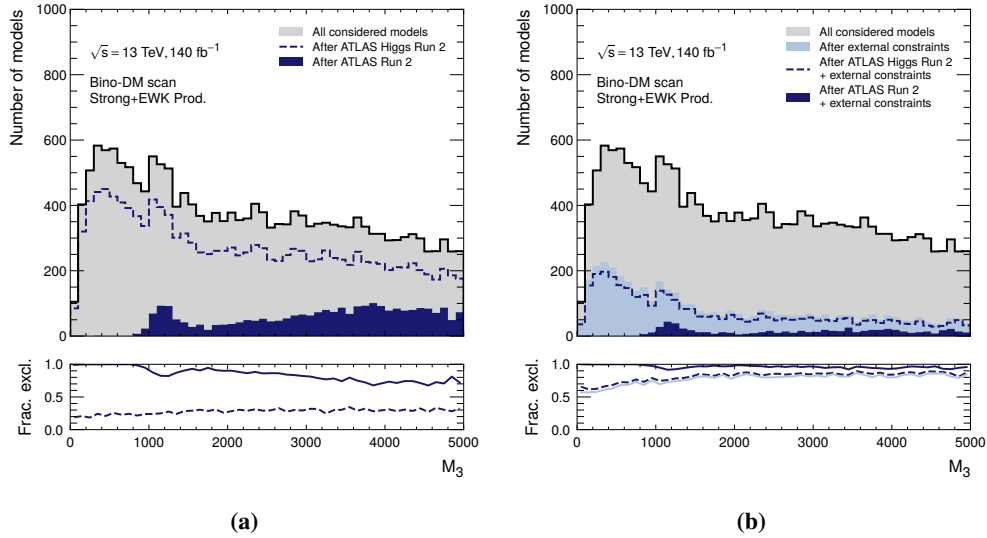
附图 3-2 Bino-DM 的 M_2 的分布与被排除的比例。

- (a) 展示了所有的模型在加入 ATLAS 实验的约束前后的分布，其中蓝色虚线表示只有 ATLAS 的 Higgs 研究相关的约束；(b) 展示了所有模型经过非 ATLAS 实验约束后的分布、经过非 ATLAS 实验约束后和 ATLAS 的 Higgs 研究约束、经过非 ATLAS 实验约束和 ATLAS 实验约束后的分布。

App Figure 3-2

Distributions of M_2 before and after the ATLAS Run 2 SUSY constraints are applied.

- (a) The distribution of all considered Bino-DM scan models before and after the ATLAS Run 2 constraints are applied, and the blue dashed line shows the remaining models after the ATLAS Higgs constraints applied. (b) The distribution of all considered Bino-DM scan models, the remaining models after all the external constraints are applied, the remaining models after all external constraints and the ATLAS Higgs constraints, and the remaining models after all external constraints and the ATLAS Run 2 constraints are applied.



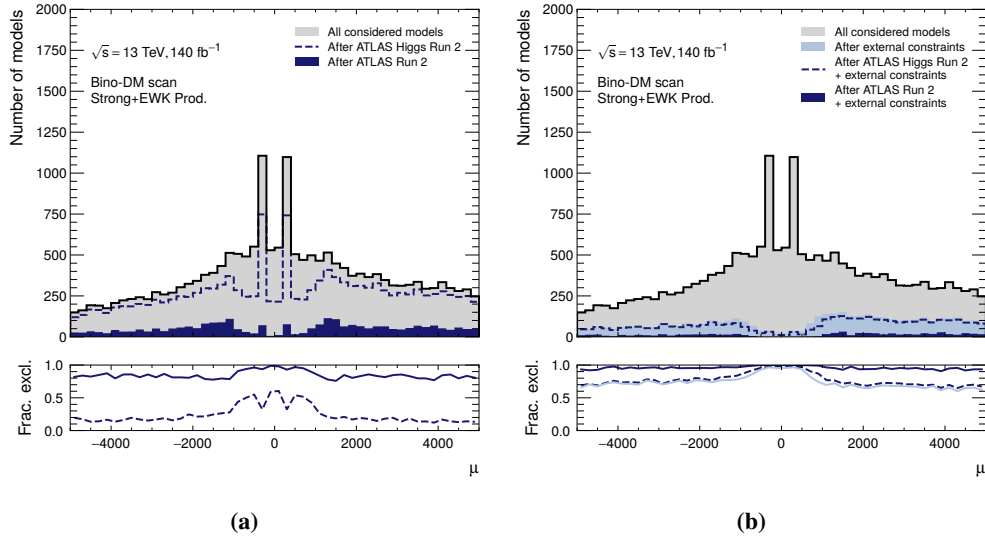
附图 3-3 Bino-DM 的 M_3 的分布与被排除的比例。

- (a) 展示了所有的模型在加入 ATLAS 实验的约束前后的分布，其中蓝色虚线表示只有 ATLAS 的 Higgs 研究相关的约束；(b) 展示了所有模型经过非 ATLAS 实验约束后的分布、经过非 ATLAS 实验约束后和 ATLAS 的 Higgs 研究约束、经过非 ATLAS 实验约束和 ATLAS 实验约束后的分布。

App Figure 3-3

Distributions of M_3 before and after the ATLAS Run 2 SUSY constraints are applied.

- (a) The distribution of all considered Bino-DM scan models before and after the ATLAS Run 2 constraints are applied, and the blue dashed line shows the remaining models after the ATLAS Higgs constraints applied. (b) The distribution of all considered Bino-DM scan models, the remaining models after all the external constraints are applied, the remaining models after all external constraints and the ATLAS Higgs constraints, and the remaining models after all external constraints and the ATLAS Run 2 constraints are applied.



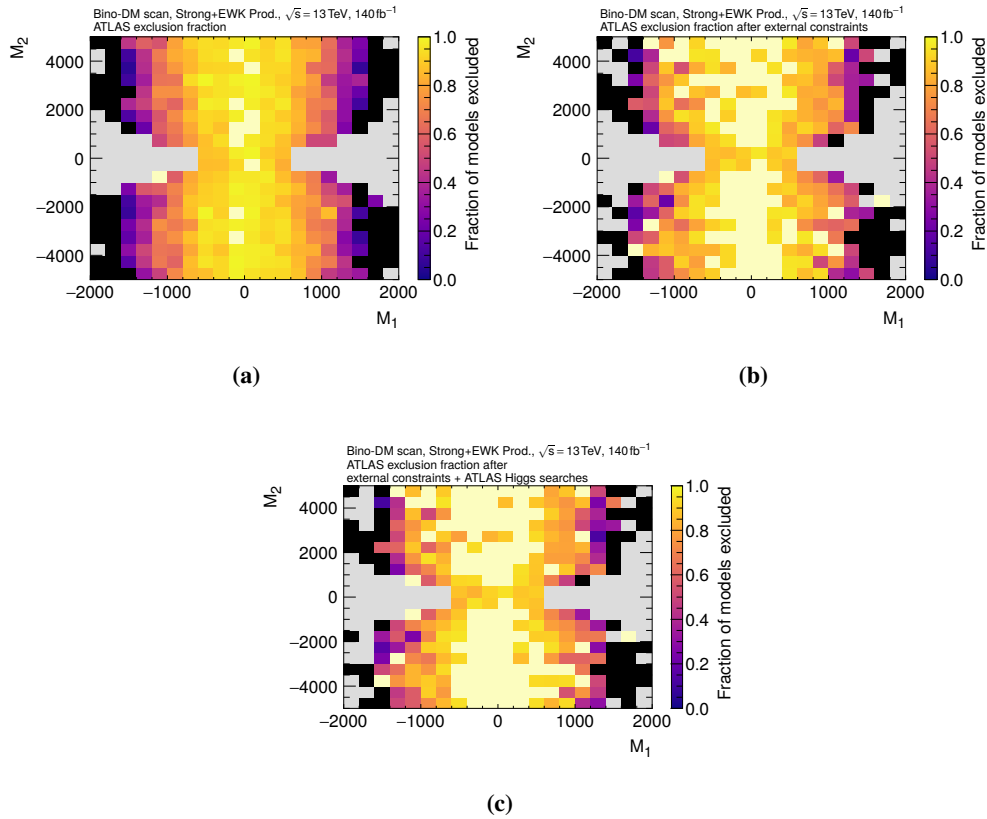
附图 3-4 Bino-DM 的 μ 的分布与被排除的比例。

- (a) 展示了所有的模型在加入 ATLAS 实验的约束前后的分布，其中蓝色虚线表示只有 ATLAS 的 Higgs 研究相关的约束；(b) 展示了所有模型经过非 ATLAS 实验约束后的分布、经过非 ATLAS 实验约束后和 ATLAS 的 Higgs 研究约束、经过非 ATLAS 实验约束和 ATLAS 实验约束后的分布。

App Figure 3-4

Distributions of μ before and after the ATLAS Run 2 SUSY constraints are applied.

- (a) The distribution of all considered Bino-DM scan models before and after the ATLAS Run 2 constraints are applied, and the blue dashed line shows the remaining models after the ATLAS Higgs constraints applied. (b) The distribution of all considered Bino-DM scan models, the remaining models after all the external constraints are applied, the remaining models after all external constraints and the ATLAS Higgs constraints, and the remaining models after all external constraints and the ATLAS Run 2 constraints are applied.



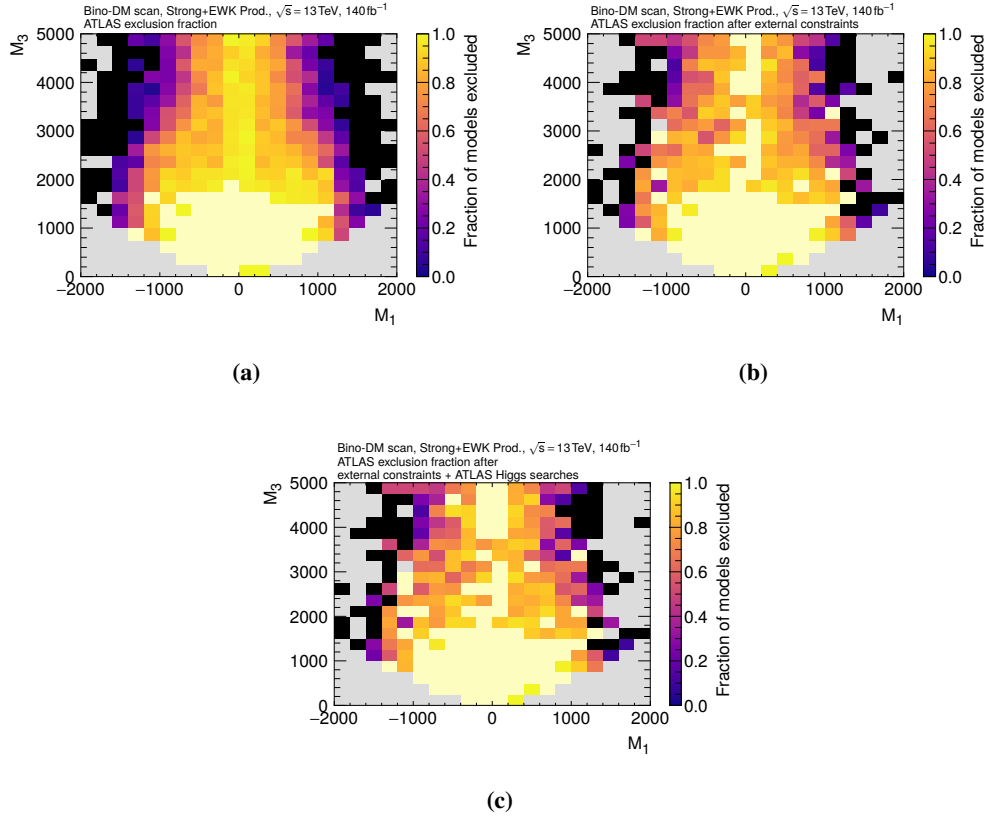
附图 3-5 Bino-DM 被 ATLAS 的 SUSY 研究约束排除的比例在 M_1 - M_2 平面的投影。

(a) 考虑了全部的 Bino-DM 模型，(d) 考虑了通过非 ATLAS 约束的模型，(c) 考虑了通过非 ATLAS 约束和 ATLAS 的 Higgs 研究的约束的模型。

App Figure 3-5 The fraction of

the Bino-DM scan models excluded by ATLAS SUSY results shown on the M_1 - M_2 plane.

(a) includes all considered models, (b) includes models that satisfy all external constraints, and (c) includes models that satisfy all external constraints and ATLAS Higgs constraints.



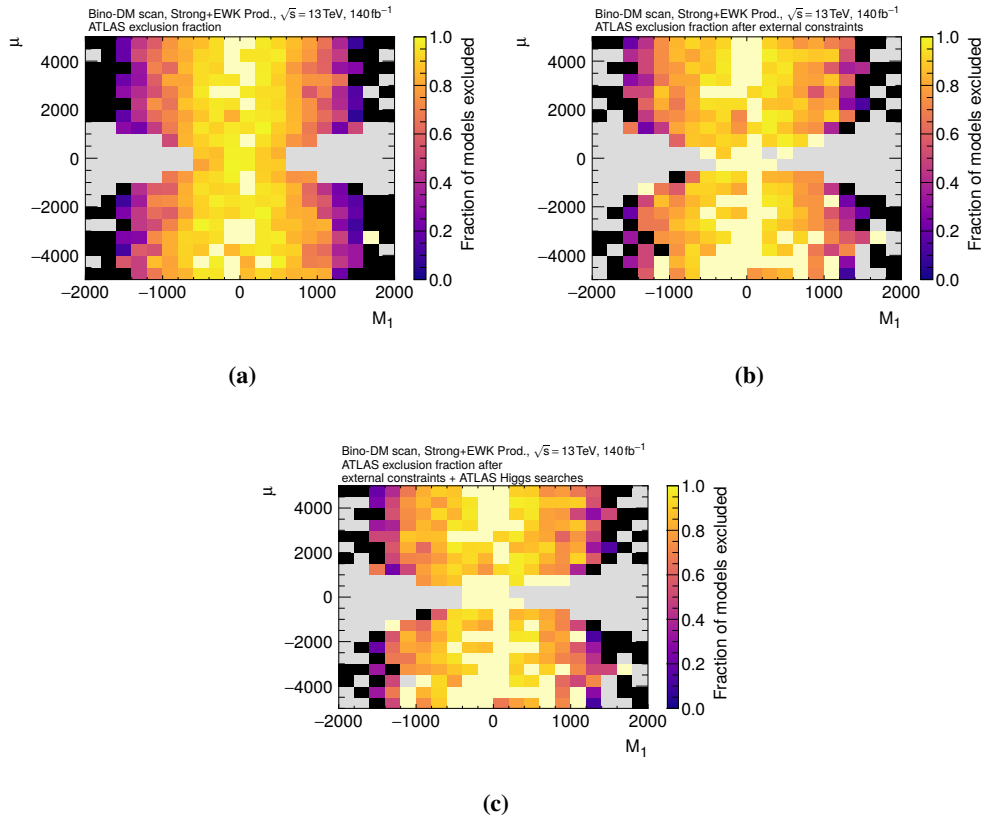
附图 3-6 Bino-DM 被 ATLAS 的 SUSY 研究约束排除的比例在 M_1 - M_3 平面的投影。

(a) 考虑了全部的 Bino-DM 模型，(d) 考虑了通过非 ATLAS 约束的模型，(c) 考虑了通过非 ATLAS 约束和 ATLAS 的 Higgs 研究的约束的模型。

App Figure 3-6 The fraction of

the Bino-DM scan models excluded by ATLAS SUSY results shown on the M_1 - M_3 plane.

(a) includes all considered models, (b) includes models that satisfy all external constraints, and (c) includes models that satisfy all external constraints and ATLAS Higgs constraints.



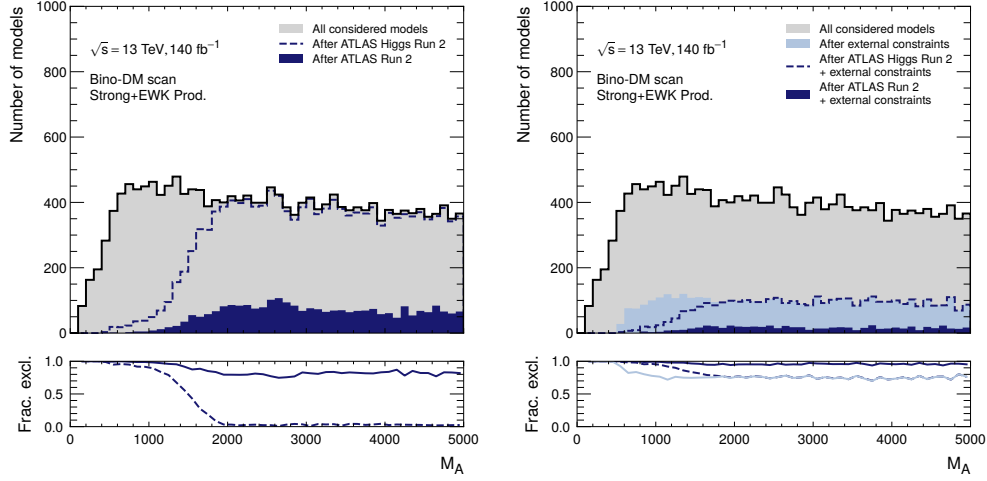
附图 3-7 Bino-DM 被 ATLAS 的 SUSY 研究约束排除的比例在 M_1 - μ 平面的投影。

(a) 考虑了全部的 Bino-DM 模型, (b) 考虑了通过非 ATLAS 约束的模型, (c) 考虑了通过非 ATLAS 约束和 ATLAS 的 Higgs 研究的约束的模型。

App Figure 3-7 The fraction of

the Bino-DM scan models excluded by ATLAS SUSY results shown on the M_1 - μ plane.

(a) includes all considered models, (b) includes models that satisfy all external constraints, and (c) includes models that satisfy all external constraints and ATLAS Higgs constraints.



(a)

(b)

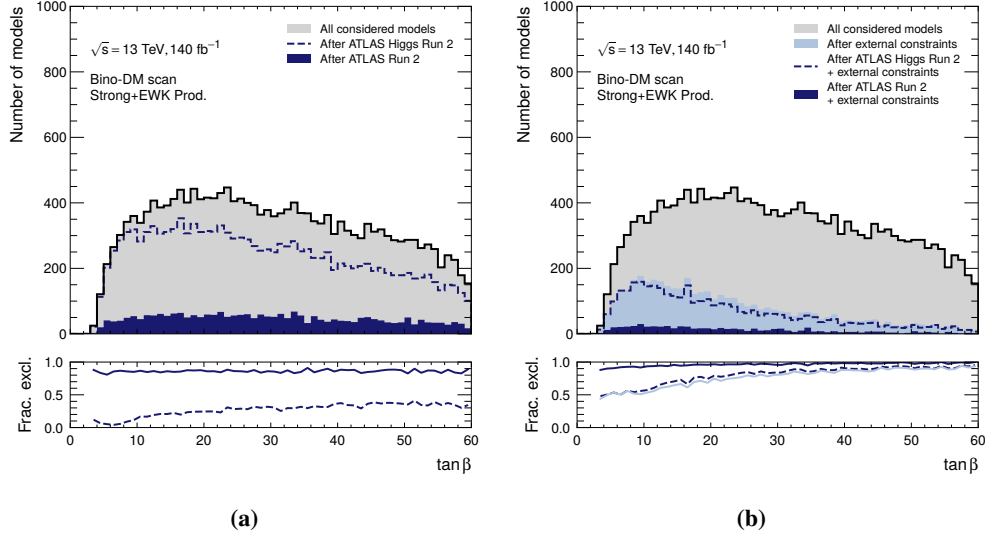
附图 3-8 Bino-DM 的 M_A 的分布与被排除的比例。

- (a) 展示了所有的模型在加入 ATLAS 实验的约束前后的分布，其中蓝色虚线表示只有 ATLAS 的 Higgs 研究相关的约束；(b) 展示了所有模型经过非 ATLAS 实验约束后的分布、经过非 ATLAS 实验约束后和 ATLAS 的 Higgs 研究约束、经过非 ATLAS 实验约束和 ATLAS 实验约束后的分布。

App Figure 3-8

Distributions of M_A before and after the ATLAS Run 2 SUSY constraints are applied.

- (a) The distribution of all considered Bino-DM scan models before and after the ATLAS Run 2 constraints are applied, and the blue dashed line shows the remaining models after the ATLAS Higgs constraints applied. (b) The distribution of all considered Bino-DM scan models, the remaining models after all the external constraints are applied, the remaining models after all external constraints and the ATLAS Higgs constraints, and the remaining models after all external constraints and the ATLAS Run 2 constraints are applied.



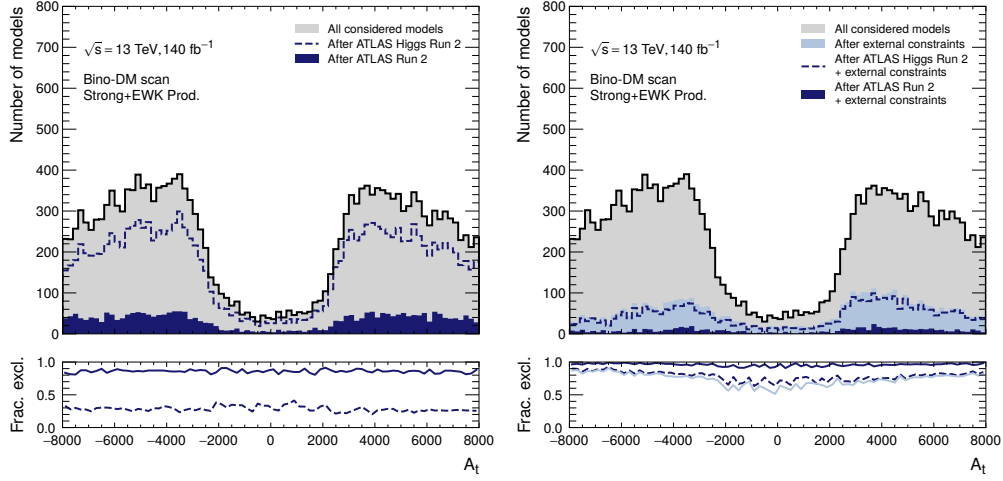
附图 3-9 Bino-DM 的 $\tan\beta$ 的分布与被排除的比例。

- (a) 展示了所有的模型在加入 ATLAS 实验的约束前后的分布，其中蓝色虚线表示只有 ATLAS 的 Higgs 研究相关的约束；(b) 展示了所有模型经过非 ATLAS 实验约束后的分布、经过非 ATLAS 实验约束后和 ATLAS 的 Higgs 研究约束、经过非 ATLAS 实验约束和 ATLAS 实验约束后的分布。

App Figure 3-9

Distributions of $\tan\beta$ before and after the ATLAS Run 2 SUSY constraints are applied.

- (a) The distribution of all considered Bino-DM scan models before and after the ATLAS Run 2 constraints are applied, and the blue dashed line shows the remaining models after the ATLAS Higgs constraints applied. (b) The distribution of all considered Bino-DM scan models, the remaining models after all the external constraints are applied, the remaining models after all external constraints and the ATLAS Higgs constraints, and the remaining models after all external constraints and the ATLAS Run 2 constraints are applied.



(a)

(b)

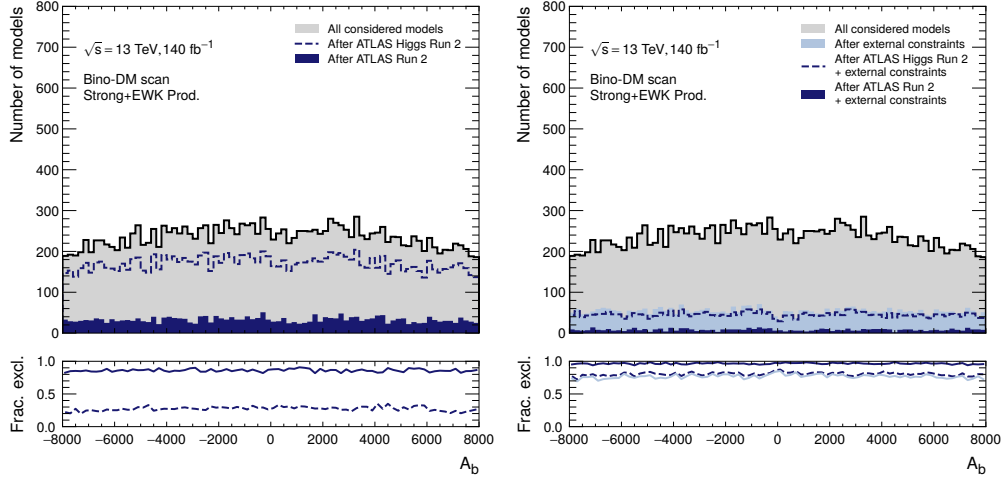
附图 3-10 Bino-DM 的 A_t 的分布与被排除的比例。

- (a) 展示了所有的模型在加入 ATLAS 实验的约束前后的分布，其中蓝色虚线表示只有 ATLAS 的 Higgs 研究相关的约束；(b) 展示了所有模型经过非 ATLAS 实验约束后的分布、经过非 ATLAS 实验约束后和 ATLAS 的 Higgs 研究约束、经过非 ATLAS 实验约束和 ATLAS 实验约束后的分布。

App Figure 3-10

Distributions of A_t before and after the ATLAS Run 2 SUSY constraints are applied.

- (a) The distribution of all considered Bino-DM scan models before and after the ATLAS Run 2 constraints are applied, and the blue dashed line shows the remaining models after the ATLAS Higgs constraints applied. (b) The distribution of all considered Bino-DM scan models, the remaining models after all the external constraints are applied, the remaining models after all external constraints and the ATLAS Higgs constraints, and the remaining models after all external constraints and the ATLAS Run 2 constraints are applied.



(a)

(b)

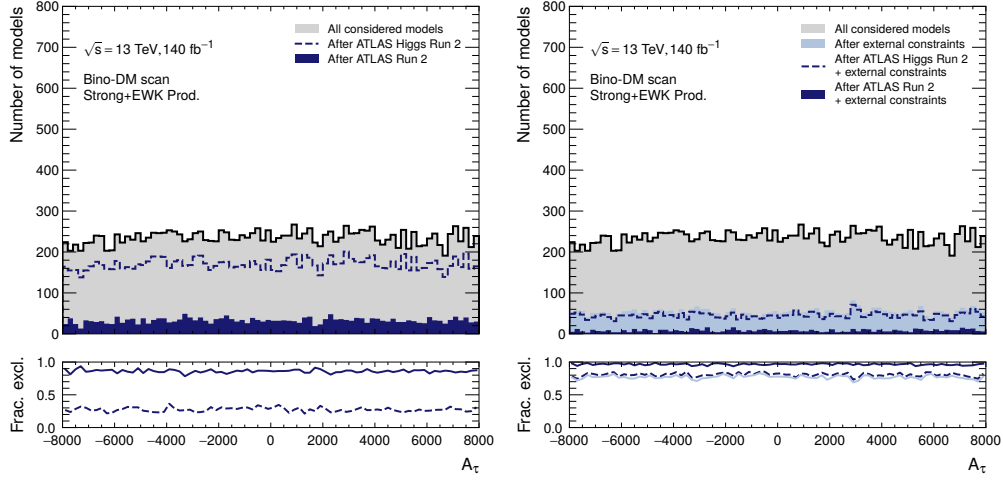
附图 3-11 Bino-DM 的 A_b 的分布与被排除的比例。

- (a) 展示了所有的模型在加入 ATLAS 实验的约束前后的分布，其中蓝色虚线表示只有 ATLAS 的 Higgs 研究相关的约束；(b) 展示了所有模型经过非 ATLAS 实验约束后的分布、经过非 ATLAS 实验约束后和 ATLAS 的 Higgs 研究约束、经过非 ATLAS 实验约束和 ATLAS 实验约束后的分布。

App Figure 3-11

Distributions of A_b before and after the ATLAS Run 2 SUSY constraints are applied.

- (a) The distribution of all considered Bino-DM scan models before and after the ATLAS Run 2 constraints are applied, and the blue dashed line shows the remaining models after the ATLAS Higgs constraints applied. (b) The distribution of all considered Bino-DM scan models, the remaining models after all the external constraints are applied, the remaining models after all external constraints and the ATLAS Higgs constraints, and the remaining models after all external constraints and the ATLAS Run 2 constraints are applied.



(a)

(b)

附图 3-12 Bino-DM 的 A_τ 的分布与被排除的比例。

- (a) 展示了所有的模型在加入 ATLAS 实验的约束前后的分布，其中蓝色虚线表示只有 ATLAS 的 Higgs 研究相关的约束；(b) 展示了所有模型经过非 ATLAS 实验约束后的分布、经过非 ATLAS 实验约束后和 ATLAS 的 Higgs 研究约束、经过非 ATLAS 实验约束和 ATLAS 实验约束后的分布。

App Figure 3-12

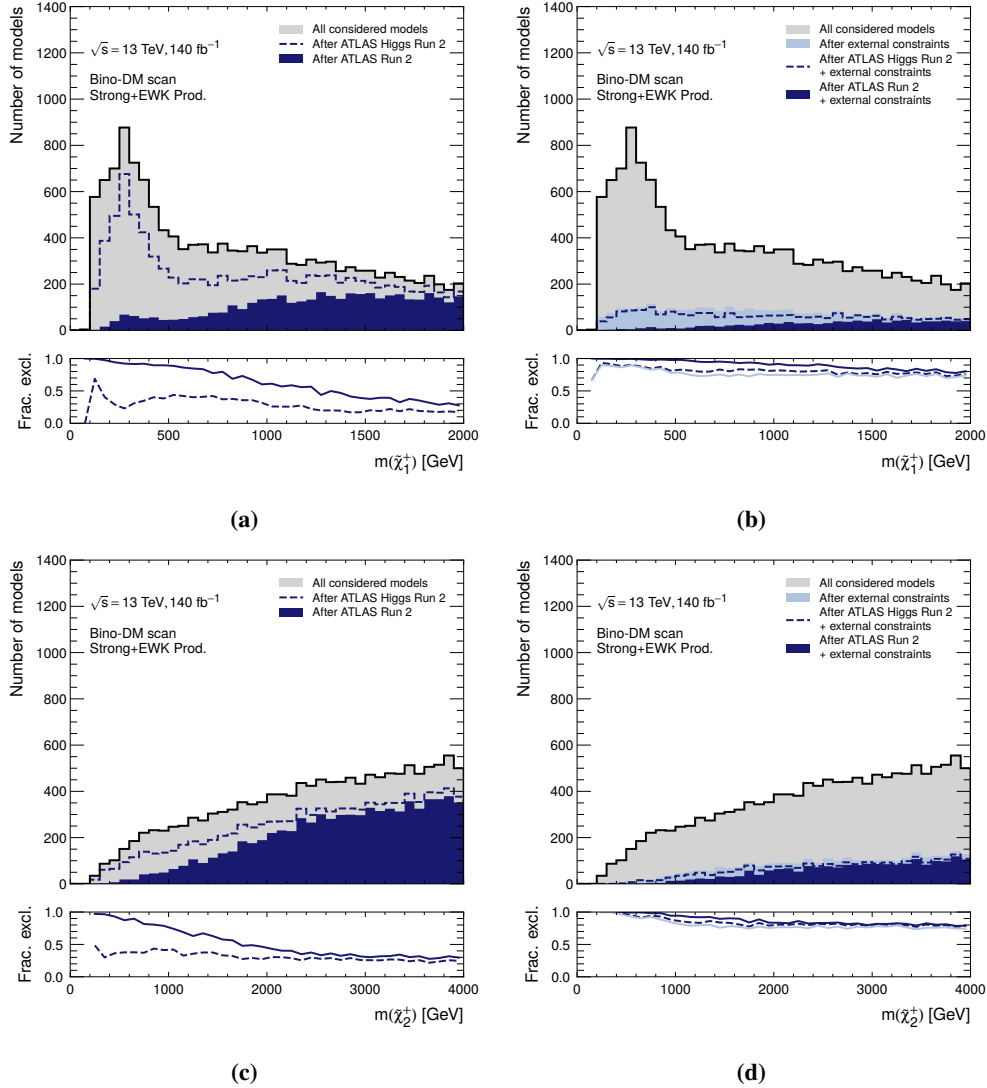
Distributions of A_τ before and after the ATLAS Run 2 SUSY constraints are applied.

- (a) The distribution of all considered Bino-DM scan models before and after the ATLAS Run 2 constraints are applied, and the blue dashed line shows the remaining models after the ATLAS Higgs constraints applied. (b) The distribution of all considered Bino-DM scan models, the remaining models after all the external constraints are applied, the remaining models after all external constraints and the ATLAS Higgs constraints, and the remaining models after all external constraints and the ATLAS Run 2 constraints are applied.

附录三 Mass distribution and exclusion ratio of sparticles in the pMSSM-19 model

This appendix is a supplement to Chapter 8, showing the one-dimensional distribution and constraints of supersymmetric particle masses of some pMSSM-19 models.

The one-dimensional distributions in this appendix are: the left column shows the distribution of all models before and after the ATLAS experiment constraints are added, where the blue dotted line indicates only the constraints related to the ATLAS Higgs study; the right column shows the distribution of all models after non-ATLAS experimental constraints, after non-ATLAS experimental constraints and ATLAS Higgs study constraints, and after non-ATLAS experimental constraints and ATLAS experimental constraints.

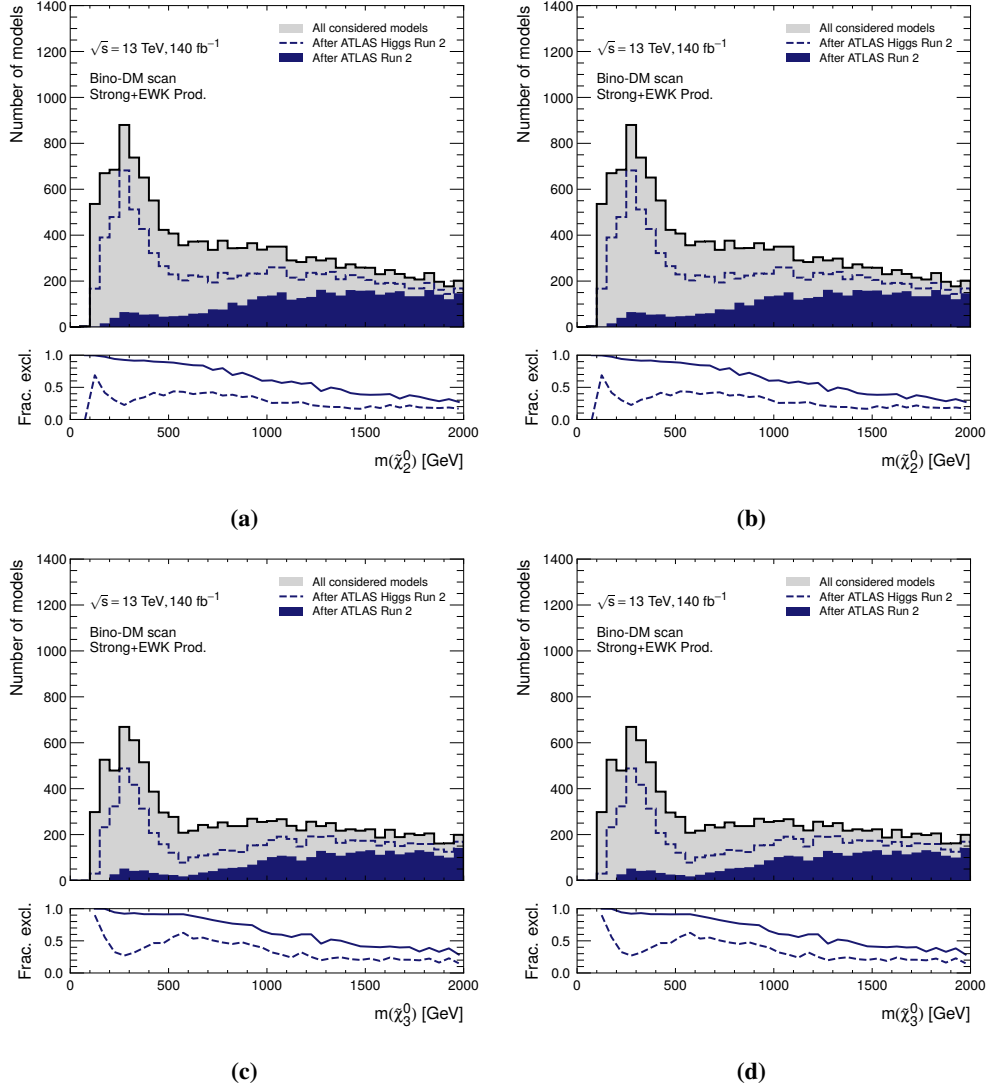


附图 4-2 Bino-DM, (a-b) 展示了 $\tilde{\chi}_1^\pm$ 的分布; (c-d) 展示了 $\tilde{\chi}_2^\pm$ 的分布。

(a)(c) 展示了所有的模型在加入 ATLAS 实验的约束前后的分布, 其中蓝色虚线表示只有 ATLAS 的 Higgs 研究相关的约束; (b)(d) 展示了所有模型经过非 ATLAS 实验约束后的分布、经过非 ATLAS 实验约束后和 ATLAS 的 Higgs 研究约束、经过非 ATLAS 实验约束和 ATLAS 实验约束后的分布。

App Figure 4-2 The distribution of the mass of (a-b) $\tilde{\chi}_1^\pm$ and (c-d) $\tilde{\chi}_2^\pm$.

(a)(c) The distribution of all considered Bino-DM scan models before and after the ATLAS Run 2 constraints are applied, and the blue dashed line shows the remaining models after the ATLAS Higgs constraints applied. (b)(d) The distribution of all considered Bino-DM scan models, the remaining models after all the external constraints are applied, the remaining models after all external constraints and the ATLAS Higgs constraints, and the remaining models after all external constraints and the ATLAS Run 2 constraints are applied.

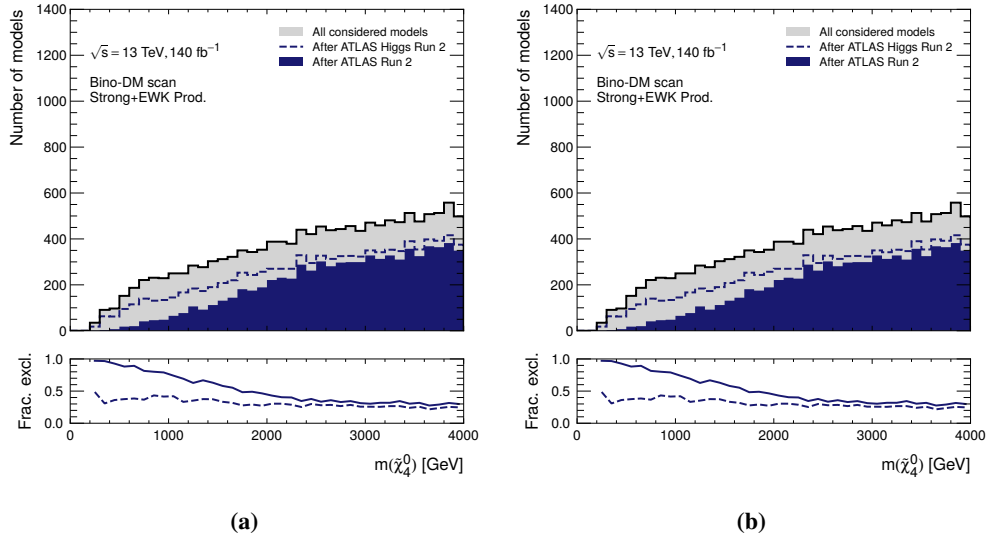


附图 4-3 Bino-DM, (a-b) 展示了 $\tilde{\chi}_2^0$ 的分布; (c-d) 展示了 $\tilde{\chi}_3^0$ 的分布。

左列展示了所有的模型在加入 ATLAS 实验的约束前后的分布, 其中蓝色虚线表示只有 ATLAS 的 Higgs 研究相关的约束; 右列展示了所有模型经过非 ATLAS 实验约束后的分布、经过非 ATLAS 实验约束和 ATLAS 的 Higgs 研究约束、经过非 ATLAS 实验约束和 ATLAS 实验约束后的分布。

App Figure 4-3 The distribution of the mass of (a-b) $\tilde{\chi}_2^0$ and (c-d) $\tilde{\chi}_3^0$.

The first column shows the distribution of all considered Bino-DM scan models before and after the ATLAS Run 2 constraints are applied, and the blue dashed line shows the remaining models after the ATLAS Higgs constraints applied. The second column shows the distribution of all considered Bino-DM scan models, the remaining models after all the external constraints are applied, the remaining models after all external constraints and the ATLAS Higgs constraints, and the remaining models after all external constraints and the ATLAS Run 2 constraints are applied.

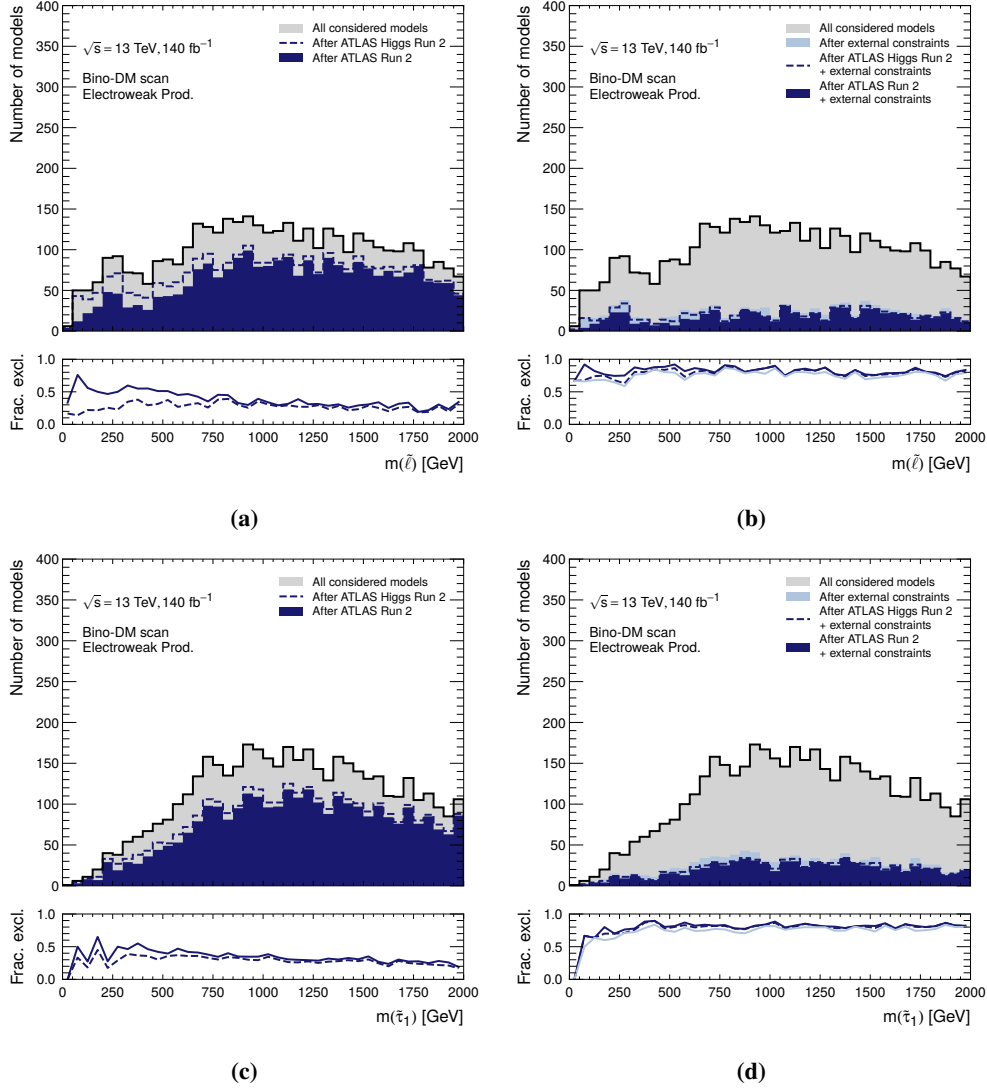


附图 4-4 Bino-DM, $\tilde{\chi}_4^0$ 的分布。

(a) 展示了所有的模型在加入 ATLAS 实验的约束前后的分布，蓝色虚线表示只有 ATLAS 的 Higgs 研究相关的约束；(b) 展示了所有模型经过非 ATLAS 实验约束后的分布、经过非 ATLAS 实验约束后和 ATLAS 的 Higgs 研究约束、经过非 ATLAS 实验约束和 ATLAS 实验约束后的分布。

App Figure 4-4 The distribution of the mass of $\tilde{\chi}_4^0$.

(a) shows the distribution of all considered Bino-DM scan models before and after the ATLAS Run 2 constraints are applied, and the blue dashed line shows the remaining models after the ATLAS Higgs constraints applied. (b) shows the distribution of all considered Bino-DM scan models, the remaining models after all the external constraints are applied, the remaining models after all external constraints and the ATLAS Higgs constraints, and the remaining models after all external constraints and the ATLAS Run 2 constraints are applied.

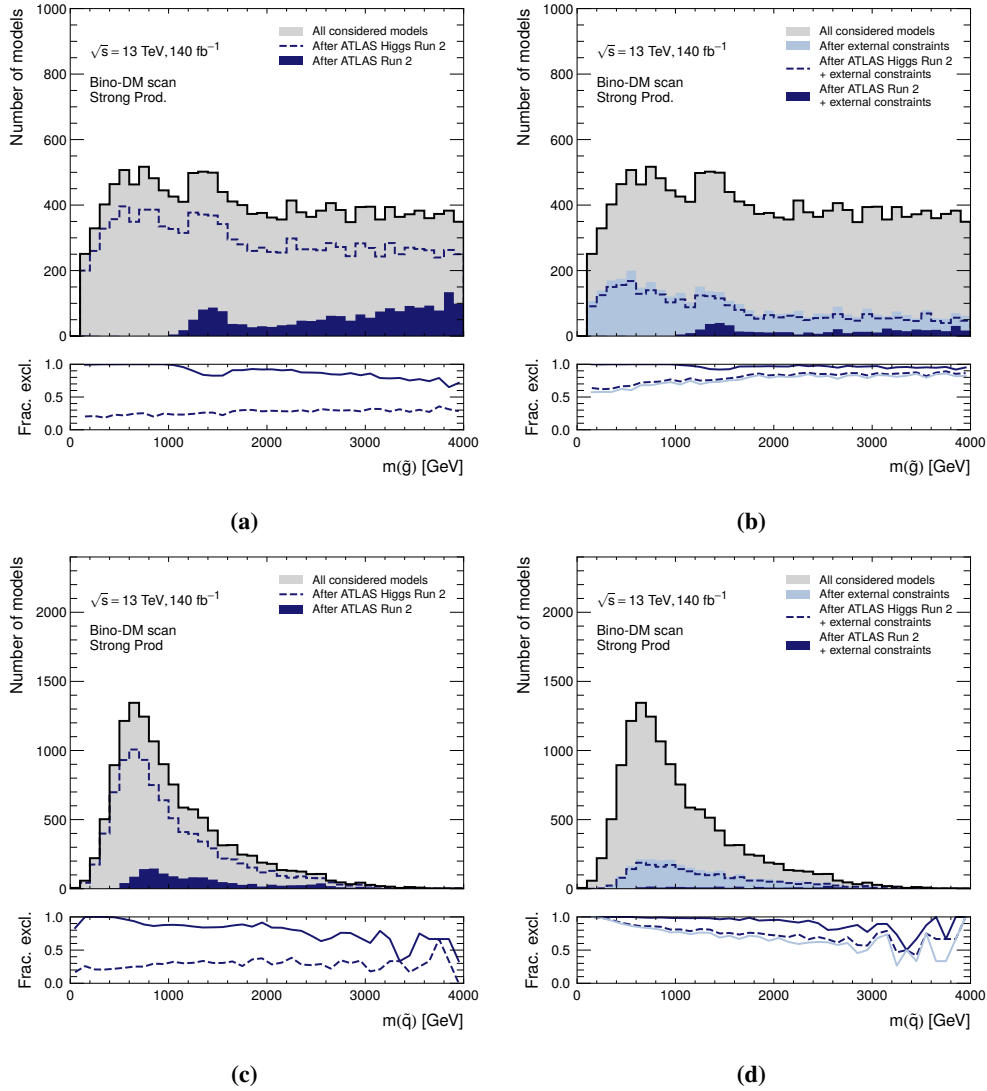


附图 4-5 Bino-DM, (a-b) 展示了 $\tilde{\ell}$ 的分布; (c-d) 展示了 $\tilde{\tau}$ 的分布。

左列展示了所有的模型在加入 ATLAS 实验的约束前后的分布, 其中蓝色虚线表示只有 ATLAS 的 Higgs 研究相关的约束; 右列展示了所有模型经过非 ATLAS 实验约束后的分布、经过非 ATLAS 实验约束后和 ATLAS 的 Higgs 研究约束、经过非 ATLAS 实验约束和 ATLAS 实验约束后的分布。

App Figure 4-5 The distribution of the mass of (a-b) $\tilde{\ell}$ and (c-d) $\tilde{\tau}$.

The first column shows the distribution of all considered Bino-DM scan models before and after the ATLAS Run 2 constraints are applied, and the blue dashed line shows the remaining models after the ATLAS Higgs constraints applied. The second column shows the distribution of all considered Bino-DM scan models, the remaining models after all the external constraints are applied, the remaining models after all external constraints and the ATLAS Higgs constraints, and the remaining models after all external constraints and the ATLAS Run 2 constraints are applied.

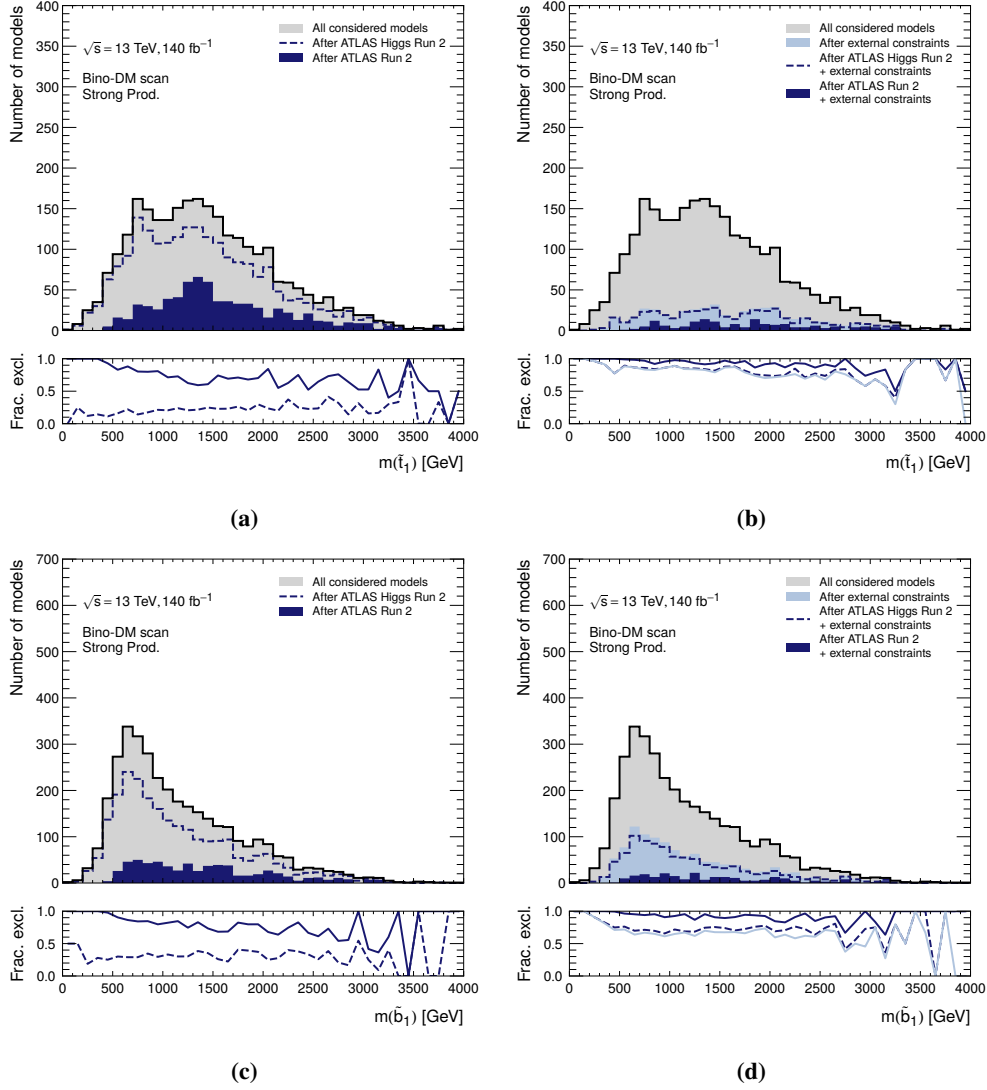


附图 4-6 Bino-DM, (a-b) 展示了 $\tilde{g}$ 的分布; (c-d) 展示了 $\tilde{q}$ 的分布。

左列展示了所有的模型在加入 ATLAS 实验的约束前后的分布, 其中蓝色虚线表示只有 ATLAS 的 Higgs 研究相关的约束; 右列展示了所有模型经过非 ATLAS 实验约束后的分布、经过非 ATLAS 实验约束后和 ATLAS 的 Higgs 研究约束、经过非 ATLAS 实验约束和 ATLAS 实验约束后的分布。

App Figure 4-6 The distribution of the mass of (a-b) $\tilde{g}$ and (c-d) $\tilde{q}$.

The first column shows the distribution of all considered Bino-DM scan models before and after the ATLAS Run 2 constraints are applied, and the blue dashed line shows the remaining models after the ATLAS Higgs constraints applied. The second column shows the distribution of all considered Bino-DM scan models, the remaining models after all the external constraints are applied, the remaining models after all external constraints and the ATLAS Higgs constraints, and the remaining models after all external constraints and the ATLAS Run 2 constraints are applied.

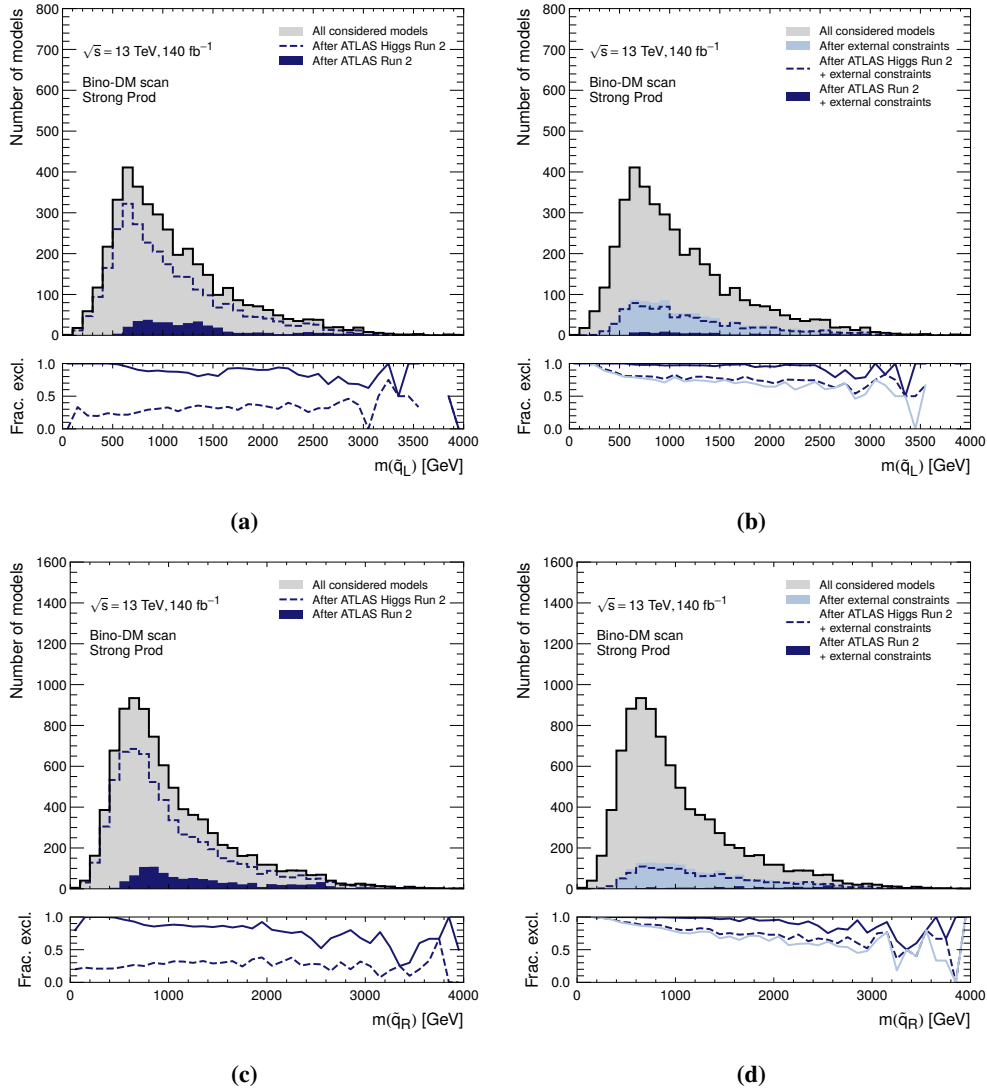


附图 4-7 Bino-DM, (a-b) 展示了 $\tilde{t}$ 的分布; (c-d) 展示了 $\tilde{b}$ 的分布。

左列展示了所有的模型在加入 ATLAS 实验的约束前后的分布, 其中蓝色虚线表示只有 ATLAS 的 Higgs 研究相关的约束; 右列展示了所有模型经过非 ATLAS 实验约束后的分布、经过非 ATLAS 实验约束后和 ATLAS 的 Higgs 研究约束、经过非 ATLAS 实验约束和 ATLAS 实验约束后的分布。

App Figure 4-7 The distribution of the mass of (a-b) $\tilde{t}$ and (c-d) $\tilde{b}$.

The first column shows the distribution of all considered Bino-DM scan models before and after the ATLAS Run 2 constraints are applied, and the blue dashed line shows the remaining models after the ATLAS Higgs constraints applied. The second column shows the distribution of all considered Bino-DM scan models, the remaining models after all the external constraints are applied, the remaining models after all external constraints and the ATLAS Higgs constraints, and the remaining models after all external constraints and the ATLAS Run 2 constraints are applied.



附图 4-8 Bino-DM, (a-b) 展示了 $\tilde{q}_L$ 的分布; (c-d) 展示了 $\tilde{q}_R$ 的分布。

左列展示了所有的模型在加入 ATLAS 实验的约束前后的分布, 其中蓝色虚线表示只有 ATLAS 的 Higgs 研究相关的约束; 右列展示了所有模型经过非 ATLAS 实验约束后的分布、经过非 ATLAS 实验约束后和 ATLAS 的 Higgs 研究约束、经过非 ATLAS 实验约束和 ATLAS 实验约束后的分布。

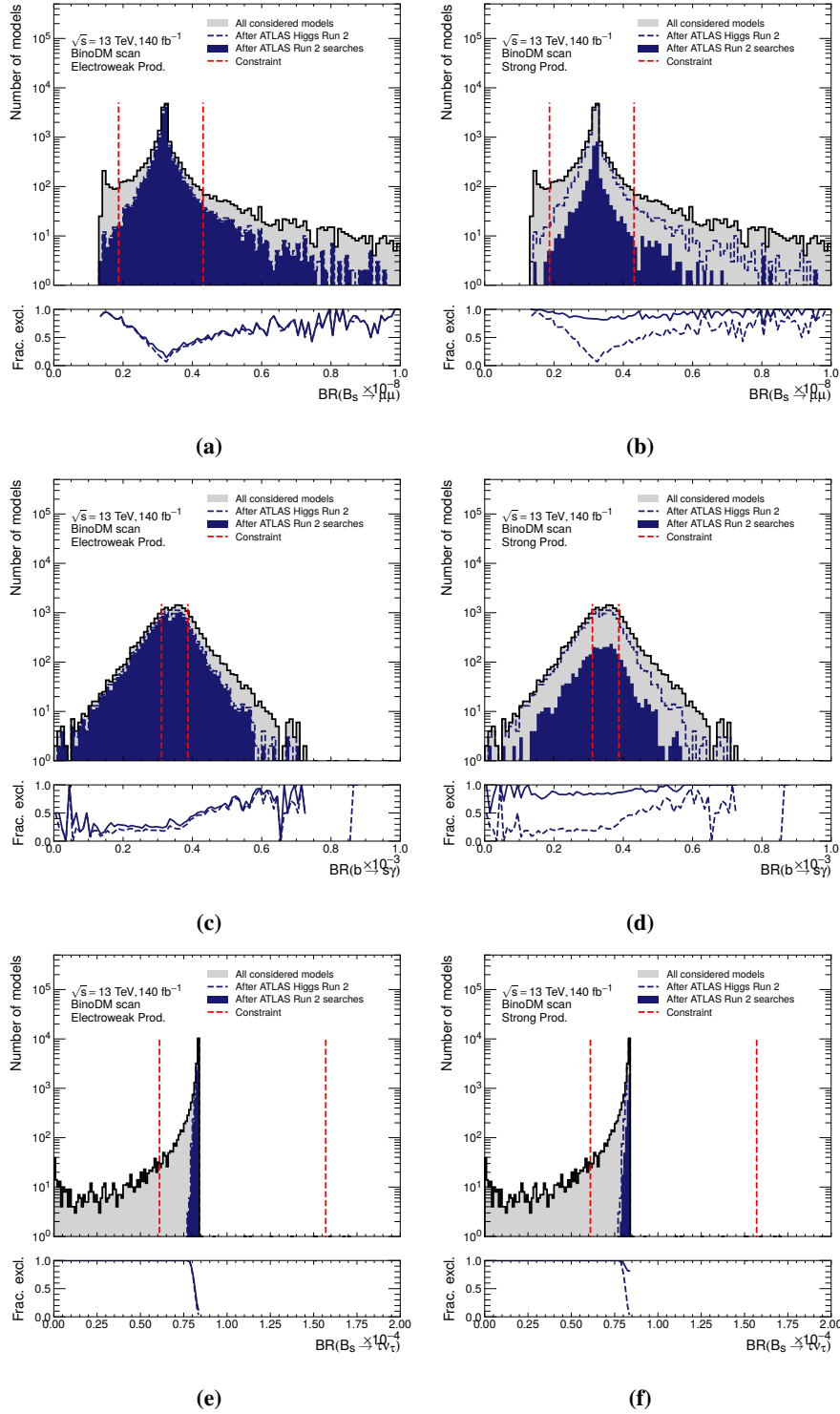
App Figure 4-8 The distribution of the mass of (a-b) $\tilde{q}_L$ and (c-d) $\tilde{q}_R$.

The first column shows the distribution of all considered Bino-DM scan models before and after the ATLAS Run 2 constraints are applied, and the blue dashed line shows the remaining models after the ATLAS Higgs constraints applied. The second column shows the distribution of all considered Bino-DM scan models, the remaining models after all the external constraints are applied, the remaining models after all external constraints and the ATLAS Higgs constraints, and the remaining models after all external constraints and the ATLAS Run 2 constraints are applied.

附录四 Constraints on the pMSSM-19 model from non-ATLAS SUSY experiments

This appendix is a supplement to Chapter 8, showing the distribution of flavor physics branch ratios, electroweak precise observation quantities, and dark matter direct detection experiment-related variables in Table 8-1 and the constraints on the pMSSM-19 model.

The one-dimensional distributions in this appendix are: the left column of pictures shows the electroweak interaction generation process of the pMSSM model; the right column of pictures shows the strong interaction generation process of the pMSSM model; All pictures show the distribution of the relevant models constrained by the ATLAS Higgs study and the ATLAS experiment.



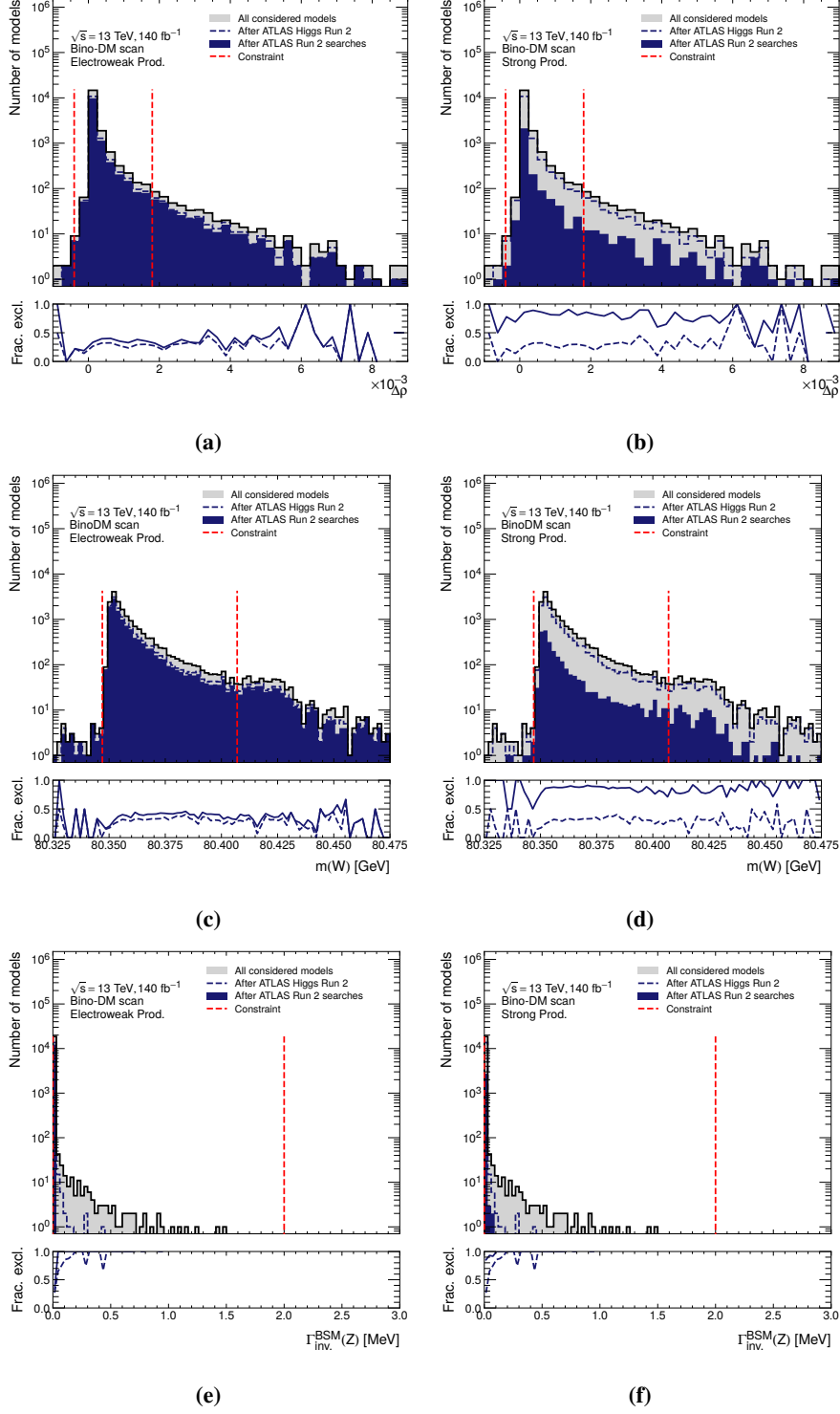
附图 5-3 Bino-DM，味物理相关分布。

每个分布分别展示了所有的模型在加入 ATLAS 实验的约束前后的分布，其中蓝色虚线表示只有 ATLAS 的 Higgs 研究相关的约束。左列只考虑了电弱作用产生过程；右列只考虑了强作用产生过程。

App Figure 5-3 Distributions of the variables

of flavour physics constraints before and after the ATLAS Run 2 constraints are applied.

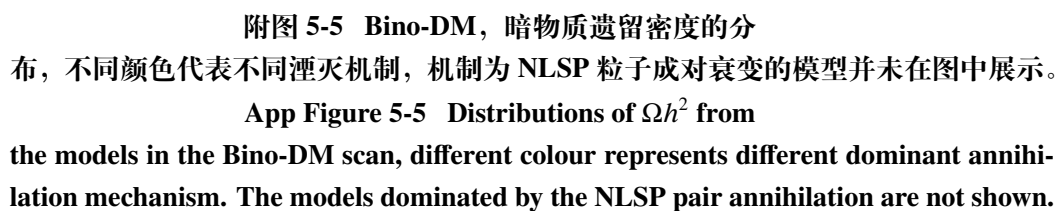
The blue dashed line shows the remaining models after the ATLAS Higgs constraints applied. The first column shows the distribution of the EWK production and the second column shows the distribution of the Strong production.

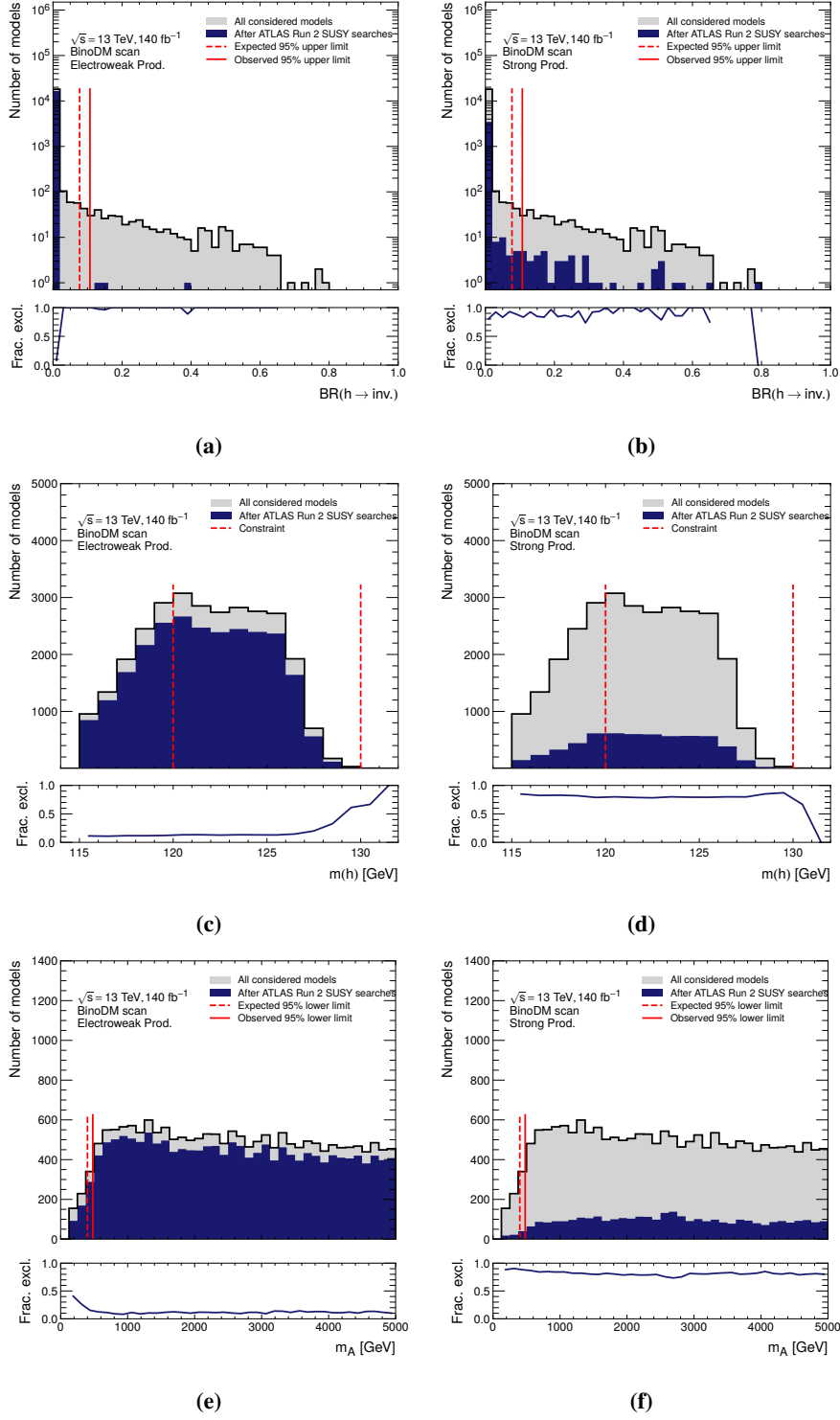


附图 5-4 Bino-DM，电弱精确测量值相关分布。

左列展示了所有的模型在加入 ATLAS 实验的约束前后的分布，其中蓝色虚线表示只有 ATLAS 的 Higgs 研究相关的约束，SUSY 研究只考虑了电弱作用产生过程；右列展示了所有的模型在加入 ATLAS 实验的约束前后的分布，其中蓝色虚线表示只有 ATLAS 的 Higgs 研究相关的约束，SUSY 研究只考虑了强作用产生过程。

App Figure 5-4 Distributions of the variables of precision electroweak observables constraints before and after the ATLAS Run 2 constraints are applied. The blue dashed line shows the remaining models after the ATLAS Higgs constraints applied. The first column shows the distribution of the EWK production and the second column shows the distribution of the Strong production.





附图 5-6 Bino-DM, 希格斯物理相关变量的分布。

左列展示了所有的模型在加入 ATLAS SUSY 实验的约束前后的分布，只考虑了电弱作用产生过程；右列展示了所有的模型在加入 ATLAS SUSY 实验的约束前后的分布，只考虑了强作用产生过程。

App Figure 5-6 Distributions of the variables

of ATLAS Higgs constraints before and after the ATLAS Run 2 constraints are applied.

The blue dashed line shows the remaining models after the ATLAS Higgs constraints applied. The first column shows the distribution of the EWK production and the second column shows the distribution of the Strong production.

Author Contributions

The author's contribution to the analysis of this article is as follows:

- Section 4.6 in-situ energy correction of tau: all analysis work.
- Chapter 5 Search for the final state gaugino particle of the single lepton and double tau: all analysis work (sample generation, background estimation, theoretical error, statistical interpretation, Recast and HepData; Derivation/Interpretation sample contact, Internal note editing, ATLAS Approval Talk.)
- Chapter 6 Search for the final state gaugino particle of the double tau: sample generation, theoretical error, statistical interpretation, SS-OS joint interpretation, Recast and HepData; Derivation/Interpretation sample contact, Internal note editing, ATLAS Approval Talk.
- Interpretation of the R parity violation process of lepton number non-conservation in Chapter 7: All analysis work, analysis leader, PUB note and Internal note editor, SUSY Approval Talk.
- Interpretation of the phenomenological minimal supersymmetric standard model in Chapter 8: All analysis work, Internal note editor, invited to give Approval Talk.
- Appendix — Beam test and muon response of the dual readout calorimeter: Beam test: Participated in the data acquisition software construction, platform construction and duty work during data acquisition for beam test; Analysis part: equalization and calibration of tower1-8, analysis of muon response.

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The author's resume and academic papers and other relevant academic achievements published during the degree program

作者简历:

2015 年 9 月——2019 年 6 月, 在南京大学物理学院获得学士学位。

2019 年 9 月——2024 年 6 月, 在中国科学院高能物理研究所攻读博士学位。

已发表 (或正式接受) 的学术论文:

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