

RICE UNIVERSITY

A Model Independent Search for New Bosons Decaying into Muons at LHC

By

Wei Shi

A THESIS SUBMITTED
IN PARTIAL FULFILLMENT OF THE
REQUIREMENTS FOR THE DEGREE

Doctor of Philosophy

APPROVED, THESIS COMMITTEE


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ABSTRACT

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A model independent search for pair production of new bosons in parameter space of mass, $0.21 < m < 60$ GeV, and lifetime, $0 < c\tau < 100$ mm, is reported using events with four muons. The dataset corresponds to 59.7 fb^{-1} of proton-proton collisions at $\sqrt{s} = 13$ TeV recorded during 2018 by the CMS experiment at the CERN LHC. No significant deviation from the predicted background is observed. A model independent upper limit on the product of the cross section, branching fraction, and acceptance is derived. The results are interpreted in the context of several benchmark models, namely, the axion-like particle model, dark supersymmetric models including those predicting a non-negligible lifetime of the new boson, and the next-to-minimal supersymmetric standard model.

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This thesis is written during the second half of the year 2020 when the COVID-19 pandemic is ongoing, convoluted with chaos in an untypical US election. I thank my fiancée, Qi Zhang, for being my companion during this time and for many helpful discussions on statistics. Finally, I thank my parents, without whom I would never be here.

Preface

The introduction (Chapter 1) collects physics topics I'm interested in during graduate school. In a sense, it is written for the education of myself. I only covered some important concepts in the Standard Model based on Mark Thomson's **Modern particle physics** textbook. The introduction on benchmark models is a re-worked version from the analysis note which is used internally in CMS.

When describing the experiment, I focused more on the algorithm (Chapter 3) than the detector technology (Chapter 2) as I want to get a full picture of the trigger and reconstruction at CMS, especially for muons. Chapter 4-8 are the main contents of the search. Chapter 4 contains a brief introduction to general Monte Carlo simulation in experiments like CMS as well as some work I did for the production of samples used in the thesis. Chapter 5 talks about the event selection criteria for signals, followed by background modeling in Chapter 6. All uncertainties are introduced in Chapter 7. Chapter 8 and Chapter 9 present the final result and summary. Many efforts didn't end up in the main thesis, some of them are put in the appendices with some discussions in the main body.

Throughout this thesis, unless specified, I used natural units in which the speed of light, as well as the Planck constant, equals one ($c = h = 1$). Consequently, mass, momentum, and energy are measured with the same unit. I will primarily use GeV, which is approximately the mass of the proton.

My biggest contribution to this model independent search is I expanded the searched new boson mass from 9 GeV up to 60 GeV while keeping a similar sensitivity to the previous search.

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Chapter 1

Introduction

Particle physics is the study of the most fundamental constituents of matter in nature. The beginning of modern particle physics dates to the late 19th century when J.J. Thomson first discovered the electron. For the first time, human beings started to understand matter at the subatomic level. Subsequent experimental and theoretical efforts have led to the discovery of many other particles thereafter [1]. Today, physicists are able to describe all the known fundamental particles with a mature theoretical model, the standard model (SM).

1.1 The Standard Model: Overview

As shown in Figure 1.1, the SM consists of three generations (I, II, III) of quarks (purple) and leptons (green). These are fermions, with a spin of $\frac{1}{2}$. Besides these, there are also spin-1 (vector) bosons (red) which mediate the forces between fermions. The most recently discovered member of the SM elementary particles is the spin-0 Higgs boson (yellow) observed in 2012 at the Large Hadron Collider (LHC) at CERN [2,3].

There are six flavors of quarks: up (u), down (d), top (t), bottom (b), strange (s), and charm (c). Each up-type quark (u, c, t) carries electric charge of $\frac{2}{3}$, while the down-type quarks each carries electric charge $-\frac{1}{3}$. There are also six flavors for the leptons. They are the three charged leptons: electron (e), muon (μ), and tau (τ); and

Standard Model of Elementary Particles

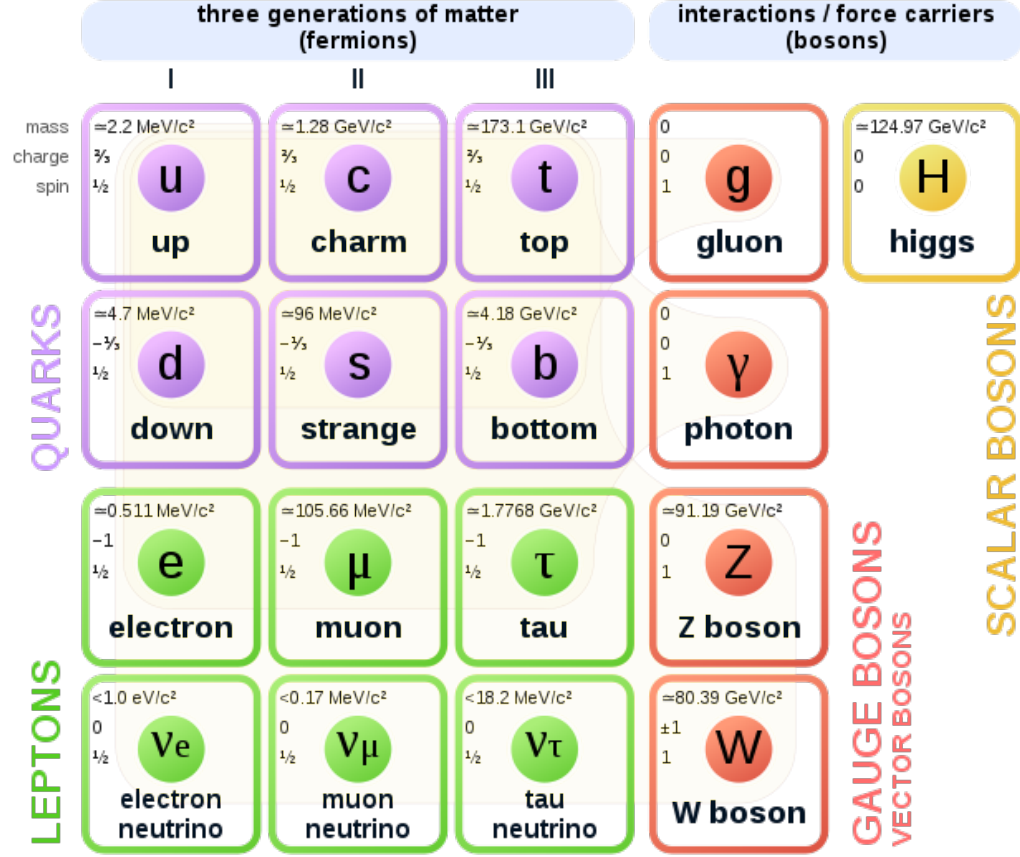


Figure 1.1 : Elementary Particles in the Standard Model [4].

the associated charge-neutral neutrinos: electron neutrino (ν_e), muon neutrino (ν_μ) and tau neutrino (ν_τ). The muons used in this thesis are a heavier (by a factor 200) version of the electrons.

All fermions in the SM can participate in weak interactions [5]. The weak forces are mediated by the massive W and the Z bosons. Fermions that are electrically charged (this excludes the neutrinos) can participate in the electromagnetic interactions, which are mediated by the exchange of massless photons (γ). Quarks are the

only fermions that carry a special kind of charge, called color charge, which is needed for strong interaction to happen. The force-carrying particle in strong interactions is called the gluon (g) which is massless [6].

In the modern language of quantum field theory (QFT), particles are excited states (quanta) of underlying fields. Quantum Electrodynamics (QED) [7] is the QFT version of the electromagnetic interaction. The intrinsic strength of the QED interactions is characterized by the fine-structure constant, $\alpha = 1/137$. The strong interactions are governed by quantum chromodynamics (QCD). The QCD interaction is stronger with $\alpha_s \sim 1$. This strength is found to vary depending on the momentum transfer, Q . For example, in QCD, at $Q^2 \sim 1 \text{ GeV}$, $\alpha_s(Q^2) \sim 1$; when Q^2 is above 100 GeV, which is the typical scale for modern high-energy collider experiments, $\alpha_s(Q^2) \sim 0.1$. This property of QCD interactions is called asymptotic freedom [8,9], which states that as the energy increases, the interactions become asymptotically weaker. For weak interactions, a familiar constant is the Fermi constant G_F [10], which is often used to characterize the strength of the weak interaction in the low-energy limit. It is related to the weak coupling constant, g_W , by

$$\frac{G_F}{\sqrt{2}} = \frac{g_W^2}{8m_W^2}. \quad (1.1)$$

Precise measurement of the Fermi constant from muon decays gives [11],

$$G_F = 1.1663787 \times 10^{-5} \text{GeV}^{-2}. \quad (1.2)$$

Using Eq. [1.1], the weak coupling constant g_W can be obtained using the precise measurement of W boson mass. The dimensionless coupling constant of the weak interaction is

$$\alpha_W = \frac{g_W^2}{4\pi} \approx \frac{1}{30}, \quad (1.3)$$

which is larger than the electromagnetic coupling constant ($\alpha = \frac{1}{137}$). The weak interaction is due to the presence of the large mass of the W boson. At the high-energy limit, the effect of the W boson mass becomes less important. The electromagnetic and weak interactions have similar strength.

So far, experiments haven't been able to observe free quarks. This is explained by the hypothesis of color confinement, which states that color charged particles cannot be isolated. A quark (q) can take one of three color charges: red, green, and blue. An antiquark ($\bar{q}$) has one of three anticolors: anti-red, anti-green, and anti-blue. Gluon carries a mixture of color and anti-color charge. As a result, quarks are always confined as color-neutral bound states called hadrons. Two types of hadrons exist, mesons and baryons. A meson ($q\bar{q}$) consists of a quark and an antiquark. Baryons, on the other hand, are composed of three quarks (qqq), such as protons (uud) and neutrons (udd).

By convention, quarks are categorized into light flavor quarks (u, d, s) and heavy flavor quarks (c, b, t) based on their masses. The measurement of the mass for the individual quark is difficult due to the color confinement. While the mass of heavy flavor quarks can be roughly estimated from hadronic states like same flavor mesons, assuming the binding energy is small compared to the quark mass, the light flavor quark mass could only be calculated from lattice QCD [11], which are based on first-principle calculations aimed to match the hadronic spectrum measured experimentally.

All massive spin- $\frac{1}{2}$ fermions (Dirac fermions) in the SM can be described by the Dirac equation [12],

$$(i\gamma^\mu\partial_\mu - m)u = 0, \quad (1.4)$$

which is the relativistic version of the Schrödinger equation for spin- $\frac{1}{2}$ massive par-

ticles. The symbol γ^μ represents four Dirac γ -matrices. They are usually written in the Dirac-Pauli representation as,

$$\begin{aligned} \gamma^0 &= \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & -1 & 0 \\ 0 & 0 & 0 & -1 \end{bmatrix}, \gamma^1 = \begin{bmatrix} 0 & 0 & 0 & 1 \\ 0 & 0 & 1 & 0 \\ 0 & -1 & 0 & 0 \\ -1 & 0 & 0 & 0 \end{bmatrix}, \\ \gamma^2 &= \begin{bmatrix} 0 & 0 & 0 & -i \\ 0 & 0 & i & 0 \\ 0 & i & 0 & 0 \\ -i & 0 & 0 & 0 \end{bmatrix}, \gamma^3 = \begin{bmatrix} 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & -1 \\ -1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \end{bmatrix}. \end{aligned} \quad (1.5)$$

The solution to the Dirac equation is called a four-component Dirac spinor, $u = u(E, \mathbf{p})$, which is a function of the energy and momentum of the particle. As in quantum mechanics, the four-vector probability current has the form,

$$j^\mu \propto \bar{u} \gamma^\mu u. \quad (1.6)$$

where $\bar{u}$ is the adjoint spinor defined as $\bar{u} = u^\dagger \gamma^0$. The four-vector current in Eq. [1.6](#) is known as vector current.

In general, four-vector currents are important in the description of particle interactions via the exchange of force-carrying particles. Fig. [1.2](#) shows a Feynman diagram [13](#) of two Dirac fermions scattering process $e^- \mu^- \rightarrow e^- \mu^-$. The left-hand side of the diagram represents the initial state of the electron and the muon. The right-hand side represents final states of the two fermions after the scattering. The QED scattering process is mediated by the γ in the middle.

It can be shown [5](#) that such QED process can be described by the Lorentz-

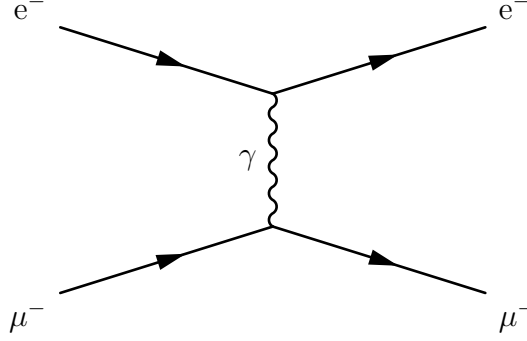


Figure 1.2 : The Feynman diagram for the QED scattering process $e^- \mu^- \rightarrow e^- \mu^-$.

invariant matrix element ($\mathcal{M}$),

$$\mathcal{M} \propto j_e \cdot j_\mu, \quad (1.7)$$

where j_e and j_μ are the vector currents for the electron and the muon. They are in the same form of the current shown in Eq. [1.6](#) as both the electron and the muon are Dirac fermions.

The SM predicts the neutrinos to be massless. However, there is established evidence [\[14, 15, 16\]](#) of neutrino oscillations from atmospheric and solar neutrino experiments indicating the neutrinos are massive. Neutrino oscillation arises from mixing between the flavor states (ν_e, ν_μ, ν_τ) and mass eigenstates (ν_1, ν_2, ν_3) of neutrinos. This is described by the Pontecorvo-Maki-Nakagawa-Sakata (PMNS) matrix. Similar mixing also happens in the quark sector that can be described by the Cabibbo-Kobayashi-Maskawa (CKM) matrix. It's worth mentioning the mixing in the quark sector is smaller than the neutrino sector [\[11\]](#). Consequently, the weak interactions of quarks between different generations are suppressed relative to those of the same generation. The suppression is largest for the couplings between the first and the third generation quarks.

A unique feature of the weak interaction in the SM is the violation of CP symmetry. Here, CP stands for the combination of charge conjugation (C) and parity (P)

operations. The C operation transforms a particle to its antiparticles and vice versa. The P operation inverts the spatial coordinates of the particle, $\mathbf{x} \rightarrow -\mathbf{x}$. CP symmetry means the physical laws remain unchanged under a CP operation. Experimental evidence from neutral kaon decays [17] show the CP symmetry is violated in weak interactions. This is directly related to the CP violation phase in the CKM matrix.

It is also worth pointing out, the weak interactions also violate the C and the P symmetries separately. For example, the violation of P symmetry can be illustrated using the probability current in weak interactions. The weak charged current due to the exchange of $W^\pm$ bosons has a current form of

$$j^\mu \propto \bar{u}(\gamma^\mu - \gamma^\mu \gamma^5)u. \quad (1.8)$$

It is a linear combination of a Lorentz-invariant vector current ($j_V^\mu \sim \bar{u}\gamma^\mu u$) and axial vector current ($j_A^\mu \sim \bar{u}\gamma^\mu \gamma^5 u$), termed V–A interaction. The symbol γ^5 represents a matrix which is defined as $\gamma^5 \equiv i\gamma^0\gamma^1\gamma^2\gamma^3$. When written in matrix form similar to Eq. [1.7], the coupling term $j_V^\mu \cdot j_A^\mu$ changes sign under a P transformation. This explains the observed P symmetry violation in the weak interactions [5, 18, 19].

The γ^5 matrix is related to the concept of chirality. Any Dirac spinor can be decomposed into left-handed (L) and right-handed (R) chiral components

$$u = \frac{1}{2}(1 + \gamma^5)u + \frac{1}{2}(1 - \gamma^5)u, \quad (1.9)$$

using the chiral projection operators, P_L and P_R , defined by

$$P_R = \frac{1}{2}(1 + \gamma^5), \quad P_L = \frac{1}{2}(1 - \gamma^5), \quad (1.10)$$

Specifically, for the weak interaction V–A current in Eq. [1.8], it includes the left-handed chiral projection operator P_L . Hence, only left-handed chiral particle states

and right-handed chiral antiparticle states participate in the charged-current weak interactions.

The SM can be further put in the context of the Yang-Mills gauge theory [20]. A gauge theory is a type of field theory in which the Lagrangian is invariant under local transformations of certain symmetry groups. Associated with these symmetry groups are the group generators. For each group generator, there is a corresponding field, called the gauge field. Gauge fields are included in the Lagrangian to ensure its invariance under the local group transformations (gauge invariance). In QFT, the quanta of these gauge fields are called gauge bosons. If the Lagrangian of a physics process is invariant under an identical transformation at every point in the spacetime, it is said to have a global symmetry. Local symmetry, on the other hand, is a much stronger requirement which states the Lagrangian needs to be invariant under a local transformation that depends on every point in the spacetime. The symmetry group for the SM can be written as $SU(3)_{\text{color}} \times SU(2) \times U(1)_Y$. Each group has a local gauge symmetry.

The gauge symmetry of $SU(2) \times U(1)_Y$ was first proposed in the 1960s by Glashow, Salam, and Weinberg (GSW) [21,22,23] to unify the QED and weak interactions. The $U(1)_Y$ is a local gauge symmetry,

$$\psi(x) \rightarrow \psi'(x) = e^{ig'\zeta(x)\frac{Y}{2}}\psi(x), \quad (1.11)$$

giving rise to a new gauge field B_μ that couples to a new kind of charge, called hypercharge (Y). The $\zeta(x)$ is a local phase as a function of spacetime.

The weak interaction is associated with invariance under $SU(2)$ local phase transformations,

$$\phi(x) \rightarrow \phi'(x) = e^{ig_W\boldsymbol{\alpha}(x)\cdot\mathbf{T}}\phi(x), \quad (1.12)$$

where $\boldsymbol{\alpha}(x)$ are three functions that specify the local phase at each point in spacetime and $\mathbf{T}$ represents three generators of the SU(2) group. Because the generators of the SU(2) gauge transformation are the Pauli matrices, the wavefunction $\phi(x)$ in Eq. [1.12](#) must be written in terms of two components, called weak isospin (T) doublet. The weak isospin doublets must contain different flavors of fermions differing by one unit of electric charge, for example,

$$\begin{bmatrix} \nu_e \\ e^- \end{bmatrix}_L, \begin{bmatrix} u \\ d' \end{bmatrix}_L, \quad (1.13)$$

where the subscript L indicates gauge transformation of Eq. [1.12](#) can affect only left-handed particles and right-handed antiparticles as we mentioned above. As a result, the symmetry group of the weak interaction is also written as SU(2)_L.

The required local gauge invariance can only be satisfied by the introduction of three gauge fields, corresponding to three gauge bosons, W_1 , W_2 , and W_3 . The physical W bosons can be identified as the linear combinations,

$$W^\pm = \frac{1}{\sqrt{2}}(W_1 \mp iW_2). \quad (1.14)$$

In the GSW model, the photon and Z boson are written as linear combinations of the B and neutral W_3 of the weak interaction,

$$\begin{bmatrix} \gamma \\ Z_0 \end{bmatrix} = \begin{bmatrix} \cos \theta_W & \sin \theta_W \\ -\sin \theta_W & \cos \theta_W \end{bmatrix} \begin{bmatrix} B \\ W_3 \end{bmatrix}, \quad (1.15)$$

where θ_W is the weak mixing angle. The angle can be measured in the forward-backward asymmetry of leptons produced in decay $Z \rightarrow l^+ l^-$. Currently, the value of $\sin \theta_W$ is measured to be 0.2229 [\[11\]](#). Since the Z boson is mixed from the weak gauge field W_3 , which only interacts with left-handed states, and the B_μ field, which treats left- and right-handed states equally, it can couple to both left-handed and

right-handed states. Exact couplings of the Z boson to the SM fermions can be found in [5]. Within the GSW model, the couplings of the γ , W, and Z in the SM are related by

$$e = g_W \sin \theta_W = g_Z \sin \theta_W \cos \theta_W. \quad (1.16)$$

The electric charge (q) arises as a linear combination of the weak hypercharge (Y) and the third component of weak isospin (T_3),

$$q = T_3 + \frac{1}{2}Y. \quad (1.17)$$

For the strong interaction in quantum field theory, the physics remains invariant under SU(3) local phase transformations,

$$\chi(x) \rightarrow \chi'(x) = e^{igs\boldsymbol{\alpha}(x) \cdot \hat{\mathbf{T}}} \chi(x). \quad (1.18)$$

The symbol $\hat{\mathbf{T}}$ represents eight generators (T^a) of the SU(3) group and $\boldsymbol{\alpha}(x)$ are eight functions of the spacetime coordinate. The eight new fields are the gluons of QCD [24].

With the gauge symmetry, the gauge bosons can't have mass as the mass terms of gauge fields in the Lagrangian would make it violate the invariance under local phase transformations. The Higgs mechanism [25, 26, 27] makes it possible to generate the masses of the electroweak gauge bosons in a manner that still preserves the local gauge invariance.

The Higgs mechanism is embedded in the $SU(2)_L \times U(1)_Y$ local gauge symmetry of the electroweak sector of the SM. The simplest Higgs model, which has the necessary four degrees of freedom, consists of two complex scalar fields. One of the scalar fields is neutral, written as ϕ^0 , and the other is charged (ϕ^+). They can be placed in a weak

isospin doublet,

$$\phi = \begin{bmatrix} \phi^+ \\ \phi^0 \end{bmatrix} = \frac{1}{\sqrt{2}} \begin{bmatrix} \phi_1 + i\phi_2 \\ \phi_3 + i\phi_4 \end{bmatrix}. \quad (1.19)$$

The Higgs potential is

$$V(\phi) = \mu^2 \phi^\dagger \phi + \lambda (\phi^\dagger \phi)^2. \quad (1.20)$$

For $\mu^2 < 0$, the potential looks like a Mexican hat (Fig. [1.3](#)) and has an infinite set of degenerate minima satisfying

$$\phi^\dagger \phi = -\frac{\mu^2}{2\lambda} = \frac{v^2}{2}, \quad (1.21)$$

where v is the vacuum expectation value (VEV) of the Higgs field. The Lagrangian is written as,

$$\mathcal{L}_{Higgs} = (\partial_\mu \phi)^\dagger (\partial^\mu \phi) - V(\phi). \quad (1.22)$$

The physical vacuum state will correspond to a particular point on the circle of minima, breaking the global symmetry of the Lagrangian. The Higgs mass is given by

$$m_H = \sqrt{2\lambda}v. \quad (1.23)$$

The masses of electroweak gauge bosons can be identified by writing the Lagrangian of Eq. [1.22](#) such that it respects the $SU(2)_L \times U(1)_Y$ local gauge symmetry by replacing the derivatives with the appropriate covariant derivatives,

$$\partial_\mu \rightarrow D_\mu = \partial_\mu + ig_W \mathbf{T} \cdot \mathbf{W}_\mu + ig' \frac{Y}{2} B_\mu. \quad (1.24)$$

where $\mathbf{T}$, $\mathbf{W}_\mu$, Y , B_μ are the generators and gauge fields of $SU(2)$ and $U(1)$ we introduced earlier. By identifying the terms in the Lagrangian that are quadratic in the gauge boson fields, we can find the mass of the W boson,

$$m_W = \frac{1}{2} g_W v. \quad (1.25)$$

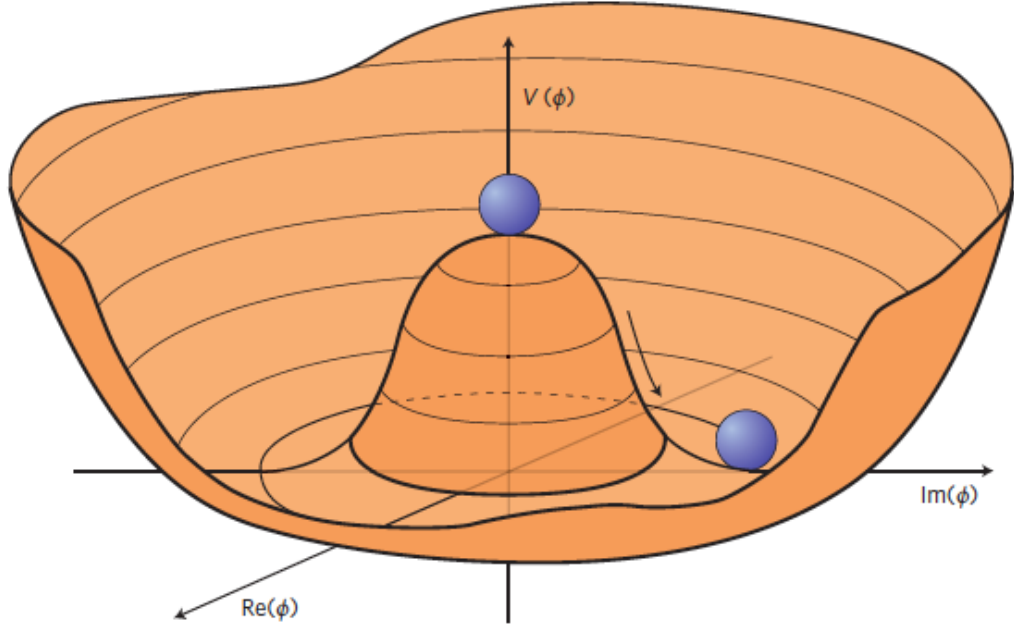


Figure 1.3 : Higgs potential. Illustration from [28].

The mass of the W boson is therefore determined by the coupling constant of the $SU(2)_L$ gauge interaction and the VEV of the Higgs field. The photon and the Z boson mass can be identified as,

$$m_\gamma = 0, \quad m_Z = \frac{v}{2} \frac{g_W}{\cos \theta_W}. \quad (1.26)$$

The Higgs mechanism also can be used to generate the masses of the fermions, characterized by the Yukawa coupling. The Yukawa couplings [29] of the Dirac fermions to the Higgs field, g_f , are given by

$$g_f = \sqrt{2} \frac{m_f}{v}. \quad (1.27)$$

1.2 Challenges to the Standard Model

While the SM has been successful in explaining many phenomena of nature, there are still many it failed to address. Currently, the SM has 26 parameters (assuming neutrinos are Dirac fermions like electrons) that need to be directly measured from the experiment. There are eight mixing parameters in total from the PMNS matrix in the leptons sector and the CKM matrix in the quarks sector, twelve fermion masses (or equivalently, Yukawa couplings to the Higgs field), three coupling constants for the gauge interactions (QED, weak, and strong interactions), two parameters for the Higgs potential (or equivalently its vacuum expectation value and the mass of the Higgs boson) [5], and finally, a phase that would lead to CP violation in the strong interaction which we will discuss more below. The abundance of arbitrary parameters in the theory leads many physicists to believe it is incomplete.

More challenges come from particle physics experimental searches. Abundant issues remain unsolved in neutrino physics. The measurement of neutrino mixing parameters is ongoing. They include three mixing angles (θ_{12} , θ_{23} , and θ_{13}), one phase angle (δ_{CP}) related to CP violation, and two squared mass difference parameters (Δm_{12}^2 and Δm_{23}^2) that come from wavefunctions of neutrino mass eigenstates [11]. It can be also found [5, 11] that the probability that a neutrino changes its flavor is related to the phase,

$$\frac{\Delta m_{ij}^2 L}{4E} = 1.27 \frac{\Delta m_{ij}^2}{\text{eV}^2} \frac{L}{\text{km}} \frac{\text{GeV}}{E}. \quad (1.28)$$

As a result, neutrino oscillation experiments need to measure oscillation probability over a distance L between the source and the detector for neutrinos of energy E . It is clear from Eq. 1.28 that if $E/L \gg |\Delta m_{ij}^2|$, the oscillation effect is not significant; if $E/L \ll |\Delta m_{ij}^2|$, many oscillation cycles can occur as it propagates the distance

L . The typical values of L/E for different types of neutrino experiments and the corresponding ranges of Δm^2 to which they can be most sensitive are summarized in Table 1.1.

Table 1.1 : Characteristic values of L and E for experiments performed using various neutrino sources and the corresponding ranges of $|\Delta m_{ij}^2|$ which they can be most sensitive to flavour oscillations in vacuum. Adapted from reference [11].

Experiment	L (m)	E (MeV)	$ \Delta m_{ij}^2 $ (eV ²)
Atmospheric	10^4 - 10^7	10^2 - 10^5	10^{-1} - 10^{-4}
Solar	10^{10}	1	10^{-10}
Reactor	SBL 10^2 - 10^3	1	10^{-2} - 10^{-3}
	LBL 10^4 - 10^5		10^{-4} - 10^{-5}
Accelerator	SBL 10^2	10^3 - 10^4	> 0.1
	LBL 10^5 - 10^6		10^{-2} - 10^{-3}

Aside from the atmospheric and solar neutrino experiments mentioned in Section 1.1, neutrinos can be also produced from accelerators by colliding high energy protons onto a target, producing pions and kaons which then decay into neutrinos. As a result, accelerator produced neutrinos dominantly contain muon neutrinos (or anti-neutrinos). As indicated in Table 1.1, there are two different scales of baselines for accelerator-based experiments to study different ranges of Δm^2 . The targeting mass splitting $\Delta m^2 \sim 10^{-3}$ eV² gives rise to the first oscillation maximum at $L/E \sim 500$ km/GeV. To study this parameter region with 1 GeV accelerator neutrino beam, a long baseline (LBL) of a few hundred to a thousand kilometers is necessary. Other experiments with smaller distance L are called short baseline (SBL) experi-

ments. The SBL experiments are important for the studies of anomalous neutrino appearance/disappearance as neutrino oscillation probability is expected to be small at short distances.

Nuclear reactors provide intense sources of electron anti-neutrinos ($\bar{\nu}_e$) in the MeV energy region, which are generated in the nuclear fission of heavy isotopes [11]. Charge current weak interaction cannot happen if a reactor $\bar{\nu}_e$ changes its flavor because its energy is not sufficient to produce heavier charged leptons. Thus, the disappearance of $\bar{\nu}_e$ is the only channel to study neutrino flavor change with reactor experiments [30]. More details on which parameters the current experiments are most sensitive to as well as the current measured value can be found in reference [11].

Neutrino oscillation experiments can also determine the neutrino mass ordering, defined by the sign of the squared mass difference, Δm_{ij}^2 , which remains unknown to us. Currently, there are two possible mass orderings, normal and inverted. The mass order is normal if the lightest neutrino is the one with the largest mixing with the electron flavor, or inverted in the opposite case. For example, the DUNE experiment in the US will be able to resolve the neutrino mass ordering issue after 7 years of data taking [31].

It is more challenging to measure the actual mass of each neutrino. Since the neutrino oscillation only depends on the difference of the squared masses of neutrinos, other experimental methods need to be exploited for this purpose. The KATRIN experiment is looking to perform direct measurement on the effective electron anti-neutrino mass [32]. With a designed sensitivity of 0.2 eV [33], it will be able to put a limit on the absolute mass scale of neutrinos by inspecting the energy spectrum of the tritium (^3H) beta decay process.

Other unsolved topics in neutrino physics include the search for evidence of the

Majorana neutrino via double beta neutrinoless decay at experiments like GERDA [34], EXO [35], KamLAND-Zen [36], and nEXO [37]. The PTOLEMY [38,39] experiment will be the first of its kind to look for cosmological neutrino relics, known as the cosmic neutrino background (CNB), via neutrino capture on ^3H .

The second challenge to the SM is the matter-antimatter asymmetry, which refers to the observed imbalance in the baryonic matter and antibaryonic matter in the observable universe [11]. It is characterized by the asymmetry parameter,

$$\eta_s = \frac{n_B - n_{\bar{B}}}{s}, \quad (1.29)$$

where n_B ($n_{\bar{B}}$) denotes the number density of baryons (antibaryons) and s denotes the entropy density of the universe. Assuming the universe started with no baryon asymmetry, the expected η_s today would be on the order of 10^{-20} [40]. However, current experiments [41] constrain $\eta_s \sim 10^{-10}$, ten orders larger than expected. The hypothesized physics process that happened during the early universe to produce this baryon asymmetry is generally phrased as baryogenesis. One cannot simply set this asymmetry as an initial condition as this would be washed out by inflation [42]. The Sakharov conditions [43] provide a recipe for the matter-antimatter creation: 1), baryon number violation; 2), violation of the C-symmetry and CP-symmetry; 3), interactions out of thermal equilibrium. One of the mechanisms proposed for the baryogenesis is the electroweak baryogenesis (EWBG) [44,45]. EWBG refers to any mechanism that produces an asymmetry in the density of baryons during the electroweak phase transition (EWPT) [46] of the universe. As the universe cools to temperatures below the electroweak scale, $T < 100$ GeV, the Higgs field acquires its nonzero VEV and breaks the symmetry, $\text{SU}(2)_L \times \text{U}(1)_Y$, into its $\text{U}(1)_{\text{em}}$ subgroup as we mentioned in Section 1.1.

Unfortunately, the SM falls short of the requirements of EWBG in many aspects.

In particular, the EWBG imposed an upper bound on the Higgs mass which is lighter than the recently discovered 125 GeV Higgs boson [47,48,49]. People found it easier to accommodate EWBG by adding a new singlet scalar field in models such as the NMSSM [50,51], which we will also mention in Section 1.4, as well as many other BSM scenarios [52,53,54,55]. Aside from EWBG, other proposals [42,56,57] to resolve the baryon asymmetry exist but are well out of reach of experiments today and the foreseeable future.

The third challenge from experiments is the so-called strong CP problem [58]. As I mentioned, CP violation plays a key role in the Sakharov conditions. In QCD, one source of CP violation could come from the non-zero value of the electric dipole moment (EDM) of hadrons, which is forbidden by both the time (T) invariant symmetry and P symmetry. However, current experiments put a stringent upper limit for the neutron EDM on the order of $10^{-26}|e|cm$ [59]. A hypothetical particle called axion was proposed as a potential candidate to solve the CP problem in QCD. The axion is the Goldstone boson after breaking of the Peccei-Quinn U(1) symmetry, first proposed by Peccei and Quinn [60,61], and later Weinberg and Wilczek [62,63], to cancel the CP violation term in the QCD Lagrangian. Such axions can be dark matter particle candidates [64,65] as we will discuss next.

The SM also failed to incorporate gravity. The so-called hierarchy problem, the vast separation between the electroweak energy scale and the Planck scale (where the gravity becomes strong). Models like supersymmetry [66] and extra dimensions [67] are proposed to address this issue. Other issues exist such as black holes [68] and dark energy.

1.3 Dark Matter

One of the most interesting, long-standing, and most relevant topic to this thesis is dark matter (DM) [69]. Early evidence for the existence of DM come from astrophysical observation of galactic rotation curves. Galactic rotation curves give a star's orbital velocity as a function of its distance from the center of the galaxy [70]. A discrepancy was found between the observed orbital velocity and the expected orbital velocity from the visible part of the galaxy. It was later determined that most DM in the universe cannot be black holes [69,70,71,72]. Although some modified theories of gravity were proposed as possible alternatives to the DM in the explanation of the galaxy rotations, more concrete evidence comes from increasingly precise astronomical measurements [73,74]. The most famous example is the bullet cluster. As a result of the collision of two clusters of galaxies, the distribution of mass is spatially separated from the hot x-ray emitting gas (which is mostly baryons). Fig. 1.4 shows the comparison of the weak lensing (green contours) and x-ray image (colored map). It reveals that the mass in this system does not match the distribution of baryons. Another source of gravitational potential, like that provided by dark matter, must instead dominate the mass of this system.

With the advance of cosmology in recent years, people can put constraints on the DM abundances based on the Big Bang nucleosynthesis [75] and cosmic microwave background (CMB) [76]. The most accurate measurement of the amount of DM in our universe so far comes from the CMB. Before the recombination epoch [46], photons and baryons are mixed as a hot plasma (like a fluid). The radiation pressure counterbalances the gravity pull of the baryonic matter. Such back-and-forth interactions create the so-called baryon acoustic oscillations (BAO) in the early universe. This process stopped at recombination when the universe was around 300000 years

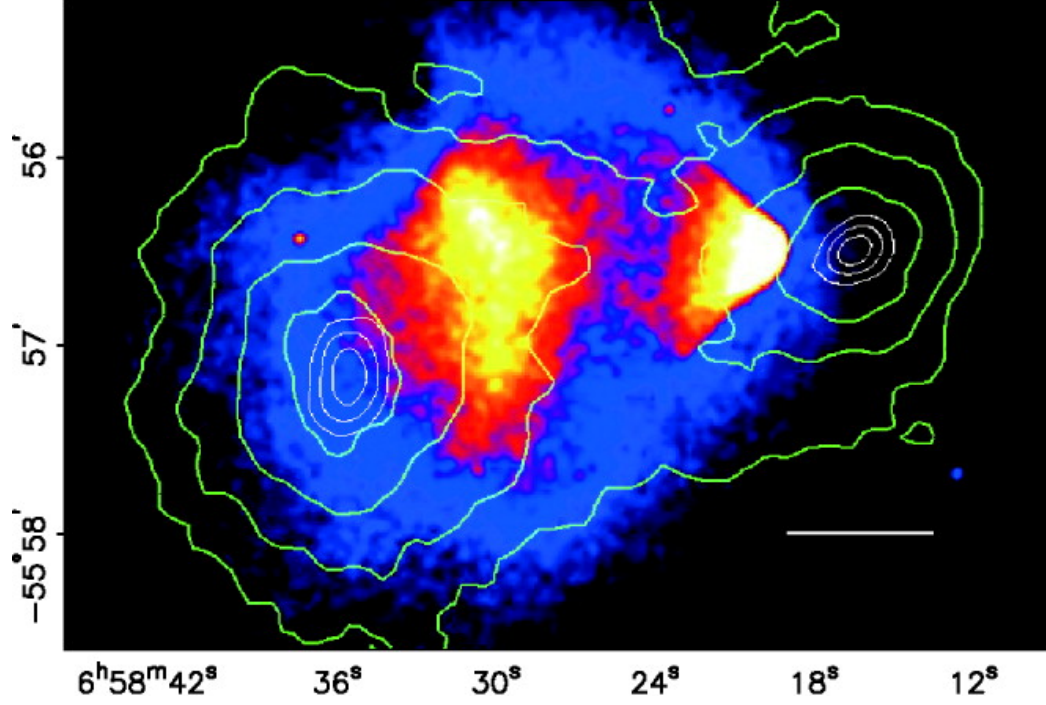


Figure 1.4 : The bullet cluster [73].

old. Atoms are formed and photons are decoupled from the plasma. This makes the ambient temperature fluctuations vary at different angular scales. Depending on the abundance of the DM, the BAO patterns as well as the temperature fluctuations we see today would be different.

The PLANCK data [76] gives the most precise small-scale temperature fluctuations in the CMB so far as shown in Fig. 1.5. The mean CMB temperature ($K_{CMB} = 2.72$ K) is subtracted from the map and only the differences are shown. A dipole anisotropy caused by motions of the Sun and the Earth relative to the CMB background is also subtracted. A power spectrum was obtained [41, 76] from the 2D map to show the BAO modes in Fig. 1.6. The power spectrum characterizes the size of the temperature fluctuations as a function of angular scale in the sky. The multi-

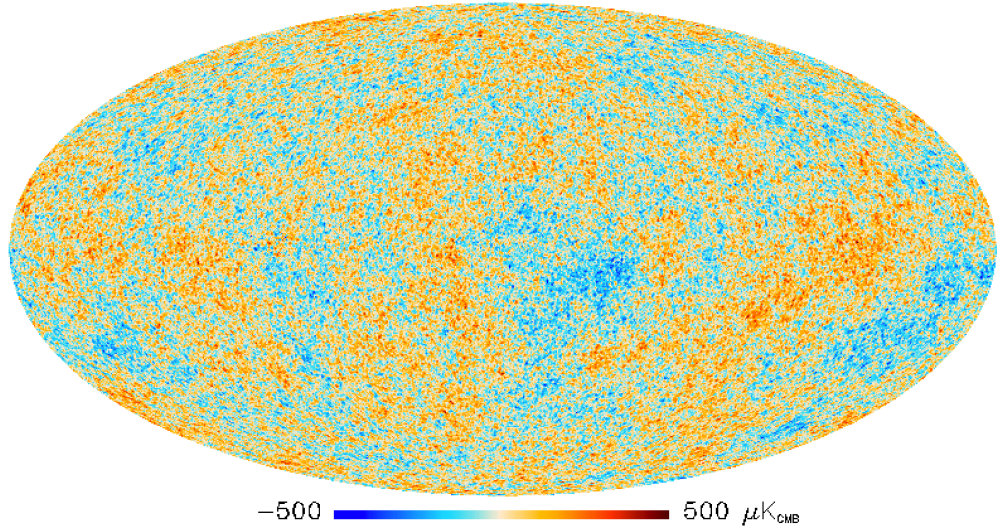


Figure 1.5 : Cosmic microwave background from 2013 Planck results [76].

pole moments (l) arise from a spherical harmonic decomposition of the fluctuations in Fig. 1.5. The reciprocal of l corresponds to the angular scale. The peaks show a unique identification of the universe's acoustic oscillation. Modes that reach extrema of oscillation at recombination epoch would carry enhanced temperature fluctuations. These modes represent the first, second, and third peaks respectively, much similar to sound waves in a cavity. By measuring the ratios of the heights of the first three peaks, the PLANCK collaboration has determined that our universe contains 26.8% dark matter (4.9% ordinary matter and 68.3% dark energy).

The most popular DM candidate is the so-called weakly interacting massive particle (WIMP) [77]. SuperCDMS [78] and Xenon1T [79] are among many experiments trying to detect WIMPs directly. It is based on the hypothesis that our solar system would be passing through a flux of DM particles which constitute the dark halo of the Milky Way galaxy. These DM particles could be detected via rare nuclei-WIMP interactions. The Xenon1T experiment is sensitive to DM particles with a mass of

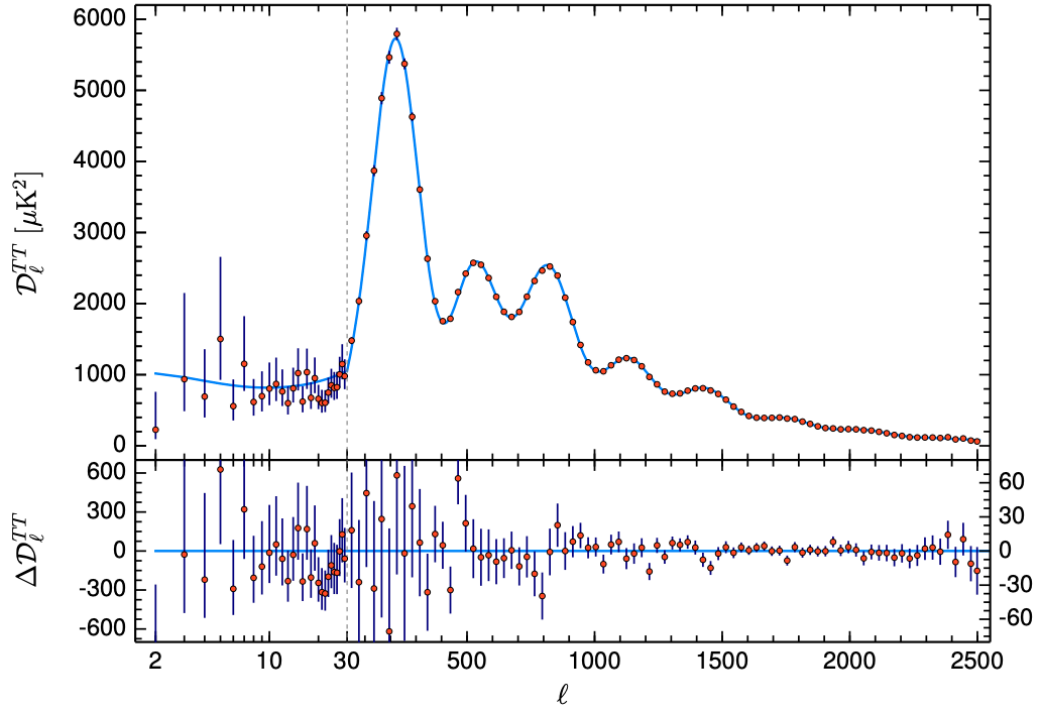


Figure 1.6 : Temperature power spectrum from 2018 Planck results [41].

$\mathcal{O}(1)$ keV- $\mathcal{O}(100)$ keV. More WIMP searches can be found in references [80, 81]. The KATRIN and the PTOLEMY experiments mentioned in Section 1.3 could also make use of tritium source to search for sterile neutrinos in the eV [38] to multi-keV [33] mass range constituting another classical candidate for DM. A comprehensive review of all other DM candidates and relevant searches can be found in references [77, 82].

1.4 Model Independent Search in This Thesis

This thesis explores the pair production of new bosons at high energy colliders. An illustration of the process is shown in Fig. 1.7. Two identical new bosons (a) are produced from the proton-proton (pp) collision and then decay to pairs of oppositely charged muons isolated from the rest of the activity (denoted by X) in the event. The

produced new boson, a , can also have a non-negligible lifetime so that it can travel a certain distance within the detector before decaying. A diagram of such a scenario is shown in Fig. 1.8. The intermediate portal (indicated by the large light blue circle) between the pp collision and the new boson could involve either an SM-like Higgs boson like the one discovered at the LHC, or some non-SM-like Higgs boson.

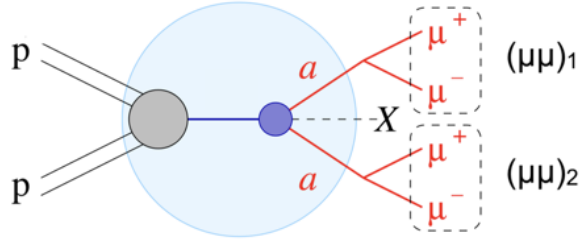


Figure 1.7 : Schematic example of the pp interaction that produces a pair of new bosons of which each decays into a muon pair.

Such new bosons, if discovered, could provide hints for the DM. A good DM particle candidate needs to be stable or has a lifetime comparable to the age of the universe, otherwise it would have already decayed away. The new boson searched in this thesis cannot be the DM particle as it decays to muons in a short time period. But it could act as a mediator of a new interaction between the DM particle and the SM particles.

The search is designed to be independent of details in specific models. Therefore, the search result can be interpreted in the context of any model predicting the same final state (denoted by red colors in Fig. 1.7). Model independent searches have become more important nowadays. First of all, this is prompted by massive data volume from colliders like LHC (introduced in Chapter 2). In this era of big data, the analysis of data needs to be more generalized to capture any discrepancy between the data and

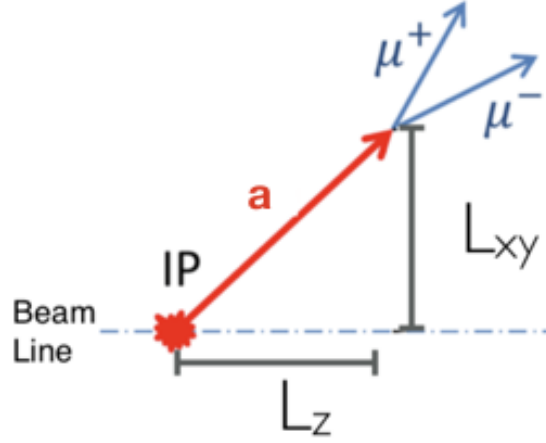


Figure 1.8 : Search for displaced signatures.

the SM predictions. Also, with the emergence of numerous theoretical models crafted to predict possible new physics, it becomes nearly impossible for experimentalists (e.g., the author of this thesis) to find evidence for all hypothetical particles in these models. Instead of testing each of them, model independent searches are favored to examine the common topology from several representative models. This provides the advantage of excluding many similar models if no evidence for the signal topology is found. This is also very important as the search will not be biased by any theoretical assumptions of the new physics. Experimentalists can avoid over-optimizing the search strategy for certain models and missing the true signal.

With model independent searches, experimentalists only need fewer parameters, such as the signal mass, lifetime, and decay rates that are much easier to examine in experiments. However, the main challenge for model independent searches is strong limitations when one analyzes the data. For example, a certain analysis method that works well on one model could fail to capture signal in another model that predicts the same event topology. I reserve the discussion of analysis methods to Chapter [5](#).

The expanded parameter space of this thesis is a huge leap from the previous result [83]. In this thesis, the upper mass bound of the probed new boson increases from 9 GeV to 60 GeV. Meanwhile, it keeps the sensitivity to new bosons with a lifetime up to 100 mm in the entire probed mass range with a much expanded fiducial volume. Last but not least, I also added a benchmark model of axion-like particle (described below) which puts even more stringent tests on the model independent search.

Previous searches for the pair production of new bosons decaying into muon pairs have been performed at the Tevatron with 4.2 fb^{-1} data sample [84] at $\sqrt{s} = 1.96 \text{ TeV}$ and more recently at the LHC with the CMS experiment with 35 pb^{-1} [85,86] (7 TeV), 5.3 fb^{-1} [87,88] (7 TeV), 20.7 fb^{-1} [89] (8 TeV) and 35.9 fb^{-1} [83] (13 TeV), and the ATLAS experiment with 1.9 fb^{-1} [90] (7 TeV) and 20.3 fb^{-1} [91] (8 TeV). The latest results from ATLAS and CMS consider models in which the new boson can be long-lived.

To demonstrate how model independent results from this analysis may be interpreted as well as verifying the independence of model parameters, I use three representative benchmark scenarios featuring either beyond the standard model (BSM) decays of the 125 GeV Higgs boson discovered at the LHC, or other non-SM Higgs-like bosons. These models are an axion-like particle (ALP) model, a supersymmetric model with additional dark sectors (i.e., dark SUSY) including cases with long-lived new particles, and the next-to-minimal supersymmetric standard model (NMSSM). Below I provide more details for these benchmarks, which are necessary for the final interpretation of the model independent result.

1.4.1 Benchmark Models

ALP

ALPs could, for example, explain the deviation of the measured muon anomalous magnetic moment $a_\mu = \frac{g_\mu - 2}{2}$ from its SM value [92, 93, 94]. When the ALP couples to the SM particles, it can also decay from the Higgs boson and could be discovered in the LHC [95].

In this thesis, I studied an ALP benchmark model [94] where the CP-odd ALP, a , could couple to the SM Higgs field and decay to SM leptons. The effective Lagrangian is written in the framework of effective field theory (EFT) [96] in a form like,

$$\mathcal{L} = \mathcal{L}_{\text{SM}} + \sum_{d \geq 5} \sum_{i=1}^{N_d} \frac{C_i}{\Lambda^{d-4}} \mathcal{O}_i^{(d)}, \quad (1.30)$$

where a series of operators ($\mathcal{O}_i^{(d)}$) with mass dimensions larger than four are added to the SM Lagrangian ($\mathcal{L}_{\text{SM}}$). Each operator is scaled by a dimensionless coupling constant called the Wilson coefficient (C_i), and a new physics scale (Λ). The operator $\mathcal{O}_i^{(d)}$ also has a mass dimension d . The decay width for ALP to leptons could be calculated from the effective Lagrangian [94] as,

$$\Gamma(a \rightarrow l^+ l^-) = \frac{|c_{ll}^{\text{eff}}|^2 m_l^2 m_a}{8\pi \Lambda^2} \sqrt{1 - \frac{4m_l^2}{m_a^2}}, \quad (1.31)$$

where the new physics scale Λ characterizes the scale of global symmetry breaking assumed to be above the weak scale, and c_{ll}^{eff} is the effective Wilson coefficient that describes the ALP couplings to SM lepton. This partial width includes both tree level and one loop mixing contributions from bosons shown in Fig. 1.9. Once kinematically allowed, the decay width is approximately linear to the mass of the ALP (m_a) as shown in Fig. 1.10.

The current phase space of the ALP in mass and its couplings to leptons is shown in

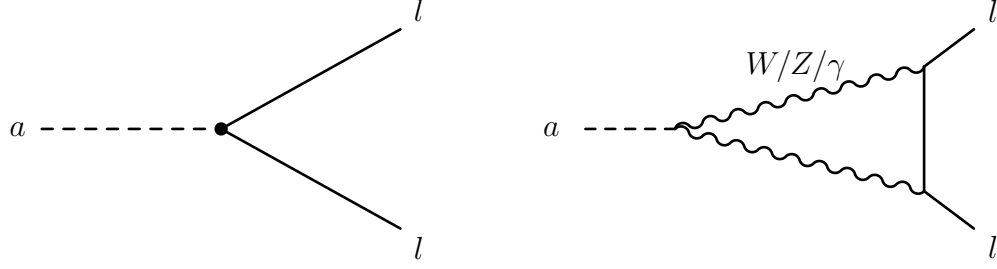


Figure 1.9 : Tree level and the one-loop Feynman diagrams contributing to the decay $a \rightarrow l^+ l^-$.

Fig. 1.11. The bounds from the Edelweiss collaboration (shaded purple) [97] searching for ALPs produced in the Sun by the Compton process $\gamma e^- \rightarrow e^- a$, by bremsstrahlung $e^- X \rightarrow e^- X a$ off electrons or hydrogen and helium nuclei in the plasma, and by ALP radiation from excited ions. In particular, the Edelweiss bounds assume that ALPs produced in the Sun do not decay on their way to Earth, which requires,

$$\frac{|c_{ee}^{\text{eff}}|}{\Lambda} < \frac{0.022}{\text{TeV}} \sqrt{\frac{E_a^2}{m_a^2} - 1} \left[\frac{m_a}{\text{MeV}} \right]^{-7/2}. \quad (1.32)$$

The dashed (dotted) lines intersecting the Edelweiss constraint indicate $E_a = 14$ keV (1 keV). Below these lines, ALPs are sufficiently long-lived to travel from the Sun to the Earth. Constraints from observations of Red Giants (shaded red) consider that ALP radiation can lead to the cooling of the cores of these stars, which leads to delayed Helium ignition and modifies the brightness-temperature relation [98]. Axion radiation from electron beams is further constrained by beam-dump experiments performed at SLAC (shaded blue) [99]. Assuming the approximate universality of the ALP-lepton couplings, a constraint can be derived from a dark-photon search in the channel $e^+ e^- \rightarrow \mu^+ \mu^- Z'$ performed by BaBar [100] assuming tree-level Wilson coefficient $C_{\gamma\gamma}$ equals zero, this gives rise to the bound shaded in gray.

The ALP couplings to the Higgs field that gives $h \rightarrow aa$ relevant to this analysis

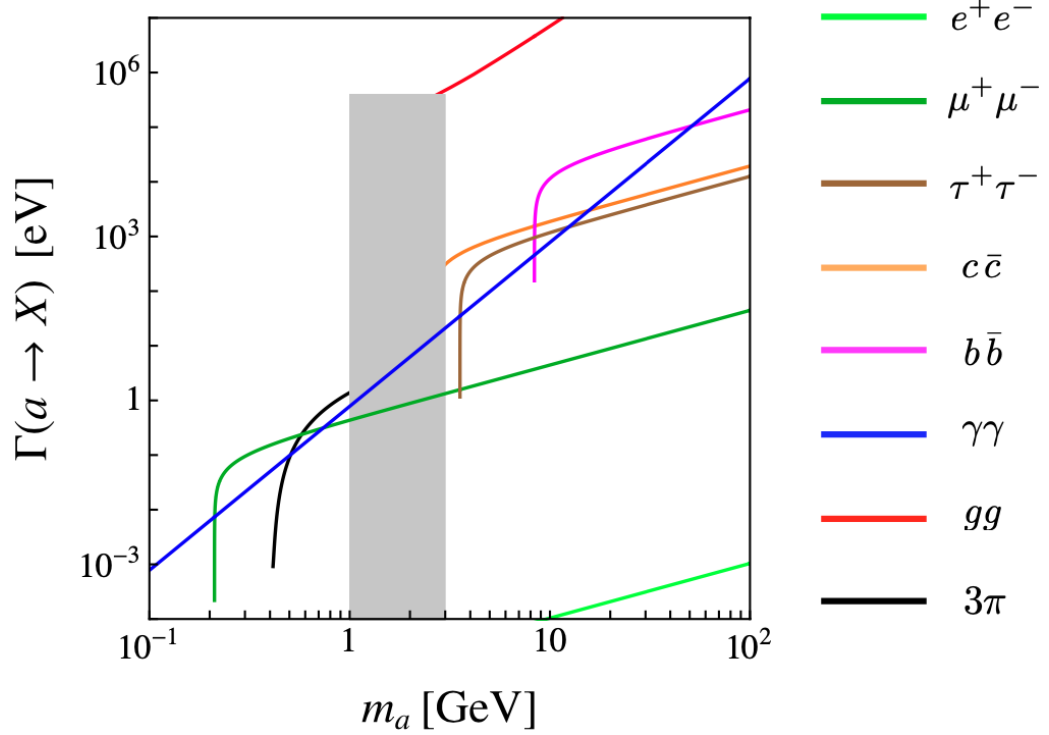


Figure 1.10 : ALP decay rates into pairs of SM particles obtained by setting the relevant effective Wilson coefficients to 1. The gray area between 1 and 3 GeV shows the region in which various exclusive hadronic decay channels open up and the decay rate of ALP to hadrons is expected to interpolate between the black and red lines. Figure taken from [94].

appear at operators of dimension 6,

$$\mathcal{L}_{eff}^{D \geq 6} = \frac{C_{ah}}{\Lambda^2} (\partial_\mu a) (\partial^\mu a) \phi^\dagger \phi + \frac{C'_{ah}}{\Lambda^2} m_{a,0}^2 a^2 \phi^\dagger \phi + \dots, \quad (1.33)$$

where C_{ah} is the portal coupling to the higgs at tree level and a is the gauge-singlet under the SM gauge group. The Higgs doublet is denoted as ϕ and $m_{a,0}$ is the mass from an explicit symmetry-breaking. The Higgs decay width to ALPs can be

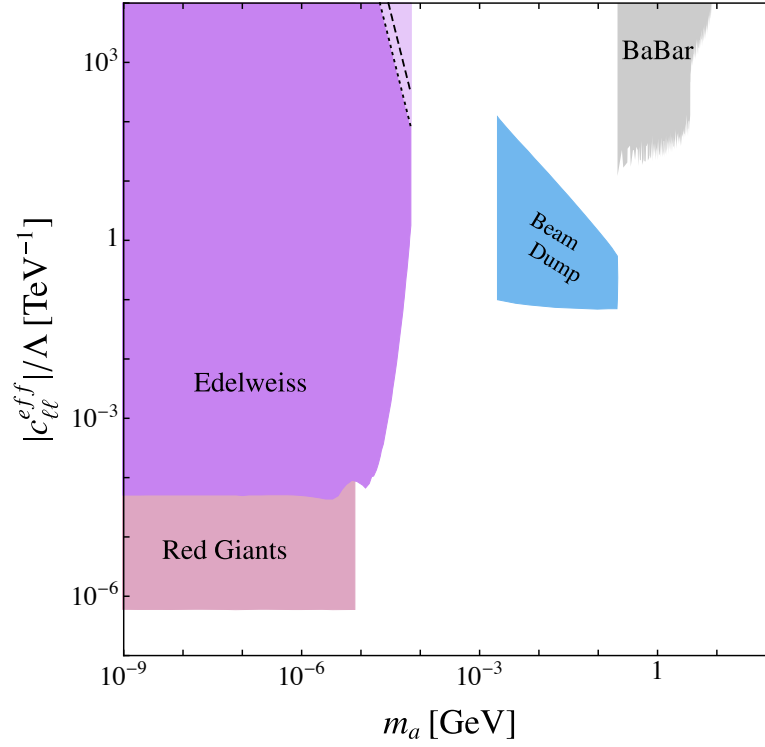


Figure 1.11 : Existing constraints on the ALP mass and coupling to leptons derived from various experiments. Figures by courtesy of authors of [94].

calculated from above as,

$$\Gamma(h \rightarrow aa) = \frac{|C_{ah}^{\text{eff}}|^2 v^2 m_h^3}{32\pi\Lambda^4} \left(1 - \frac{2m_a^2}{m_h^2}\right)^2 \sqrt{1 - \frac{4m_a^2}{m_h^2}}. \quad (1.34)$$

This includes the tree level as well as one-loop corrections from the SM fermions and bosons as shown in Fig. 1.12. Fig. 1.13 shows current limit on ALP-Higgs couplings from LHC searches [101, 102, 103]. In Chapter 8, we will show the new constraint from this thesis.

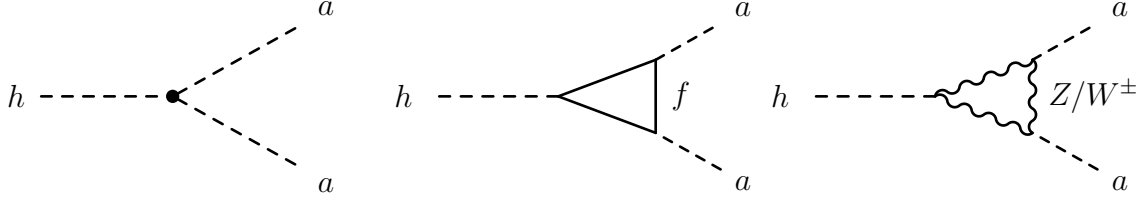


Figure 1.12 : Feynman diagrams contributing to the decay $h \rightarrow aa$. The last two diagrams are one-loop corrections from dimension 5 operators.

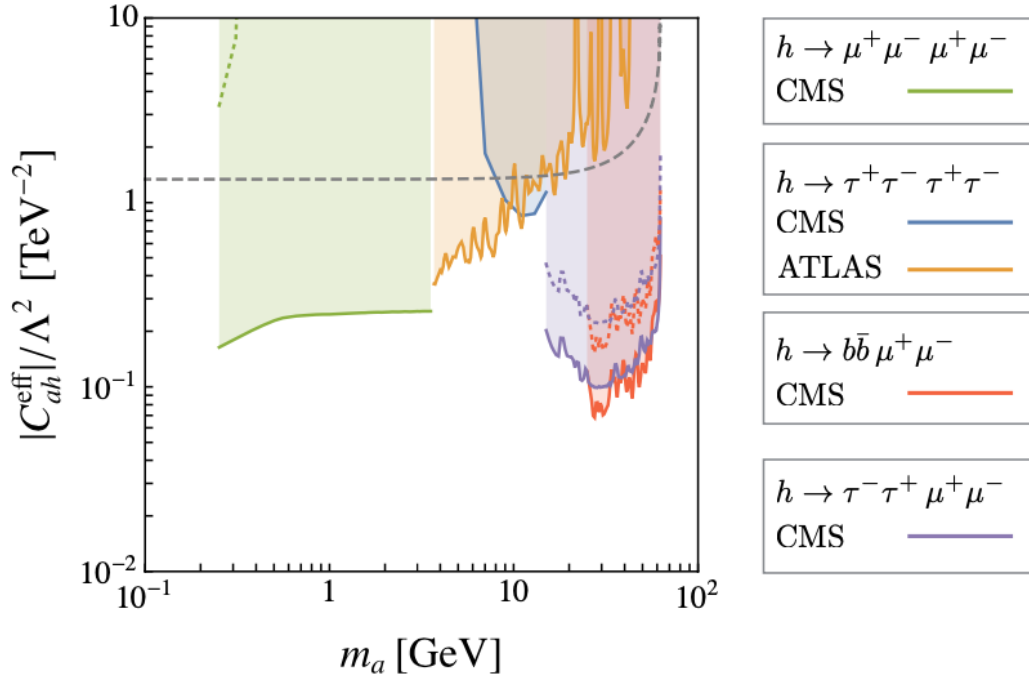


Figure 1.13 : Constraints from dedicated LHC searches for $h \rightarrow aa$ with subsequent ALP decays into fermion pairs. The solid contours assume $\mathcal{B}(a \rightarrow l^+ l^-) = 1$ if all fermions have the same flavor, and $\mathcal{B}(a \rightarrow \mu^+ \mu^-) = \mathcal{B}(a \rightarrow \tau^+ \tau^-) = \mathcal{B}(a \rightarrow b \bar{b}) = 0.5$ otherwise. The dotted contours correspond to $\mathcal{B}(a \rightarrow l^+ l^-) = 0.1$ if all fermions have the same flavor, and $\mathcal{B}(a \rightarrow \mu^+ \mu^-) = \mathcal{B}(a \rightarrow \tau^+ \tau^-) = \mathcal{B}(a \rightarrow b \bar{b}) = 0.9$ otherwise. The gray dashed lines indicate the model independent bounds $|C_{ah}| < 1.34 \left[\frac{\Lambda}{1 \text{ TeV}} \right]^2$ from current 95% CL upper limit $\mathcal{B}(h \rightarrow \text{BSM}) < 0.34$ [104].

Dark SUSY

The second benchmark scenario is dark SUSY [105, 106, 107]. In this scenario, a new hidden force can couple to the SM hypercharge through a kinetic mixing term [108, 109, 110] in Lagrangian:

$$L_{\text{KM}} \sim \frac{\epsilon}{2} F_{\mu\nu}^Y F^{\text{D}\mu\nu}, \quad (1.35)$$

where $F_{\mu\nu}^{\text{D}} = \partial_\mu A_\nu^{\text{D}} - \partial_\nu A_\mu^{\text{D}}$ and A^{D} is the dark gauge field [108, 109, 110] associated with a $U(1)_{\text{D}}$ symmetry. The breaking of this symmetry gives rise to a massive dark photon (γ_{D}). The SM particles also acquire an additional charge, ϵe , under the dark interaction. Note that in typical dark SUSY scenarios with kinetic mixing, the parameter ϵ is within the range $10^{-8} - 10^{-2}$. Assuming that γ_{D} can only decay to SM particles, the branching fraction $\mathcal{B}(\gamma_{\text{D}} \rightarrow \mu^+ \mu^-)$ can be as large as 45%, depending on the mass of the dark photon ($m_{\gamma_{\text{D}}}$) [107]. If the coupling to SM particles is highly suppressed then the γ_{D} can also have a non-negligible lifetime and travel some distance before decay. It is therefore important to use this benchmark to test our model independent search for long-lived signal bosons.

The dark SUSY process considered in this thesis is $h \rightarrow 2n_1 \rightarrow 2n_{\text{D}} + 2\gamma_{\text{D}} \rightarrow 2n_{\text{D}} + 4\mu$. The Feynman diagram is shown in Fig. 1.14. The neutralino, n_1 , is the lightest SUSY particle in the minimal supersymmetric standard model (MSSM) [111, 112, 113]. In MSSM, the Higgs boson decay to a pair of n_1 is strongly constrained due to the limits on invisible Higgs boson decays. However, if n_1 is no longer stable and decays into the hidden sector, the constraint is substantially weakened. In this case, the n_1 decays via $n_1 \rightarrow n_{\text{D}} + \gamma_{\text{D}}$, where n_{D} is a dark fermion called dark neutralino that escapes detection. There are large fractions of parameter space of n_1 with large branching fraction of $h \rightarrow n_1 n_1$. Similarly, the branching fraction can be moderate or even small, which could lead to an experimental observation of a Higgs boson

with only slightly reduced branching fractions in the channels dominating the LHC sensitivity to the SM Higgs boson. Distinguishing between the SM Higgs boson and the Higgs boson in this scenario can only be done by exploring final states sensitive to these exotic Higgs boson decays.

This benchmark model is only one possible scenario and is chosen as a single representation of a very wide range of available parameter space. It can be extended in many ways including more complex versions with dark Higgs, W, and Z bosons [114]. There are also many other allowed processes, such as $pp \rightarrow h \rightarrow Z_D Z / Z_D Z_D / Z a \rightarrow 4\mu$, for example. As said before, in this thesis, we present the results in a model independent way that allows for further reinterpretations in the framework of other models.

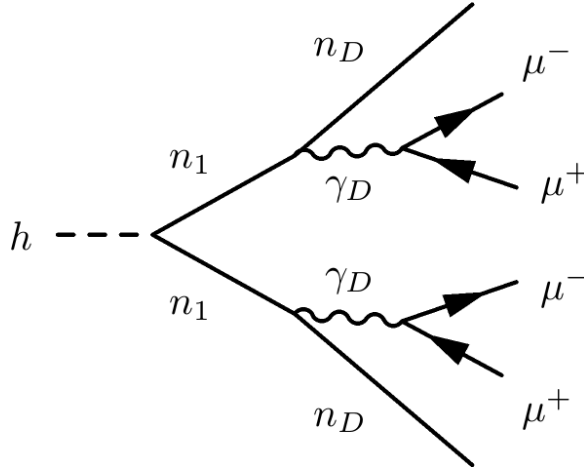


Figure 1.14 : Feynman diagram of the dark SUSY benchmark process $h \rightarrow 2n_1 \rightarrow 2n_D + 2\gamma_D \rightarrow 2n_D + 4\mu$.

It is shown in [115] that due to the kinetic mixing the dark photon will decay to

SM leptons with a partial width given by:

$$\Gamma_{\gamma_D \rightarrow \bar{l}l} = \frac{1}{3} \alpha \epsilon^2 m_{\gamma_D} \sqrt{1 - \frac{4m_l^2}{m_{\gamma_D}^2}} \left(1 + \frac{2m_l^2}{m_{\gamma_D}^2}\right), \quad (1.36)$$

where m_l is mass of the lepton and different decay modes start from $m_{\gamma_D} > 2m_l$.

Also, the dark photon will decay to SM hadrons for masses $m_{\gamma_D} > 2m_\pi$, with partial width:

$$\Gamma_{\gamma_D \rightarrow \text{hadrons}} = \frac{1}{3} \alpha \epsilon^2 m_{\gamma_D} \sqrt{1 - \frac{4m_\mu^2}{m_{\gamma_D}^2}} \left(1 + \frac{2m_\mu^2}{m_{\gamma_D}^2}\right) R(s = m_{\gamma_D}^2), \quad (1.37)$$

where $R = \sigma_{e^+e^- \rightarrow \text{hadrons}} / \sigma_{e^+e^- \rightarrow \mu^+\mu^-}$. The hadronic cross section data is available in recent compilation of various experimental measurements [11] but it is measured only starting at $\sqrt{s} = 0.36$ GeV which is above $2m_\pi = 0.28$ GeV threshold. Therefore, in the region where $2m_\pi < \sqrt{s} < 0.36$ GeV, we use the cross section for the $e^+e^- \rightarrow \pi^+\pi^-$ process evaluated using the technique presented in Ref. [116] and constants defined in Ref. [117]. Finally, for the region where $\sqrt{s} < 2m_\pi$, we sum only the lepton partial widths.

According to expressions (1.36) and (1.37), the partial width's dependences on ϵ and m_{γ_D} are factorized, i.e. $(\Gamma_{\gamma_D}/\epsilon^2)^{-1} = f(m_{\gamma_D})$, where $f(m_{\gamma_D})$ is a function of the dark photon mass only. Also, the branching ratio for the decay of the dark photon to a pair of muons $\mathcal{B}_{\gamma_D \rightarrow \mu\mu} = \Gamma_{\gamma_D \rightarrow \mu\mu} / \Gamma_{\gamma_D \text{Total}}$ does not depend on ϵ due to the factorized dependence on the ϵ .

The expressions for the partial widths allow for the calculation of the lifetime of the dark photon via

$$\tau_{\gamma_D} = \frac{\hbar}{\Gamma_{\gamma_D \text{Total}}} = \frac{1}{\Gamma_{\gamma_D \rightarrow e^+e^-} + \Gamma_{\gamma_D \rightarrow \mu^+\mu^-} + \Gamma_{\gamma_D \rightarrow \text{hadrons}}}. \quad (1.38)$$

The lifetime is directly related to the parameter ϵ and the mass of dark photon via

$$\tau_{\gamma_D}(\epsilon, m_{\gamma_D}) = \frac{1}{\epsilon^2} \times f(m_{\gamma_D}). \quad (1.39)$$

It is convenient to represent the lifetime τ_{γ_D} as a distance $c\tau_{\gamma_D}$, where c is speed of light. It is also convenient to measure $c\tau_{\gamma_D}$ in millimeters because the sensitivity to this variable is $\mathcal{O}(\text{mm})$ in this thesis. Including all unit-conversion coefficients, Eq. (1.39) becomes

$$c\tau_{\gamma_D}(\epsilon, m_{\gamma_D})[\text{mm}] = \frac{c[\text{mm/s}] \times \hbar[\text{GeV} \cdot \text{s}]}{\epsilon^2} \times f(m_{\gamma_D})[\text{GeV}^{-1}], \quad (1.40)$$

or numerically,

$$c\tau_{\gamma_D}(\epsilon, m_{\gamma_D})[\text{mm}] = \frac{1.97 \cdot 10^{-13}[\text{GeV} \cdot \text{mm}]}{\epsilon^2} \times f(m_{\gamma_D})[\text{GeV}^{-1}], \quad (1.41)$$

where $c = 3 \cdot 10^8 \text{ m/s} = 3 \cdot 10^{11} \text{ mm/s}$ and $\hbar = 1.055 \cdot 10^{-34} \text{ J}\cdot\text{s} = 6.58 \cdot 10^{-25} \text{ GeV}\cdot\text{s}$. The constraints on ϵ could be obtained from the constraints on the lifetime of the dark photon because they are directly related to each other.

As mentioned earlier, there is a connection between this thesis and many other searches for evidence of a dark sector. Low energy e^+e^- colliders and fixed-target experiments, including APEX [118], BaBar [119,120], HADES [121] and KLOE [122, 123] have performed complementary searches. These experiments search for slightly different topologies, such as the associated production of a dark photon and a photon where the dark photon then decays into SM fermions. This type of dark photon production could be detected as a narrow resonance in radiative $e^+e^- \rightarrow \gamma\ell^+\ell^-$ ($\ell = e, \mu$) events, and low energy e^+e^- colliders provide a clean environment in which to perform these searches. However, these searches involve two suppressed vertices and therefore scale with ϵ^4 (rather than ϵ^2 in this thesis), preventing the low energy experiments probing very small values of ϵ . Other experimental searches for γ_D have focused on the production of dark photons at the end of SUSY cascades at the Tevatron [124,125,126] and at the LHC [86]. The status of the recent experimental

constraints is reviewed in [127]. The exclusion limits in the 2D plane of ϵ^2 and m_{γ_D} from the previous search [83] is shown in Fig. 1.15.

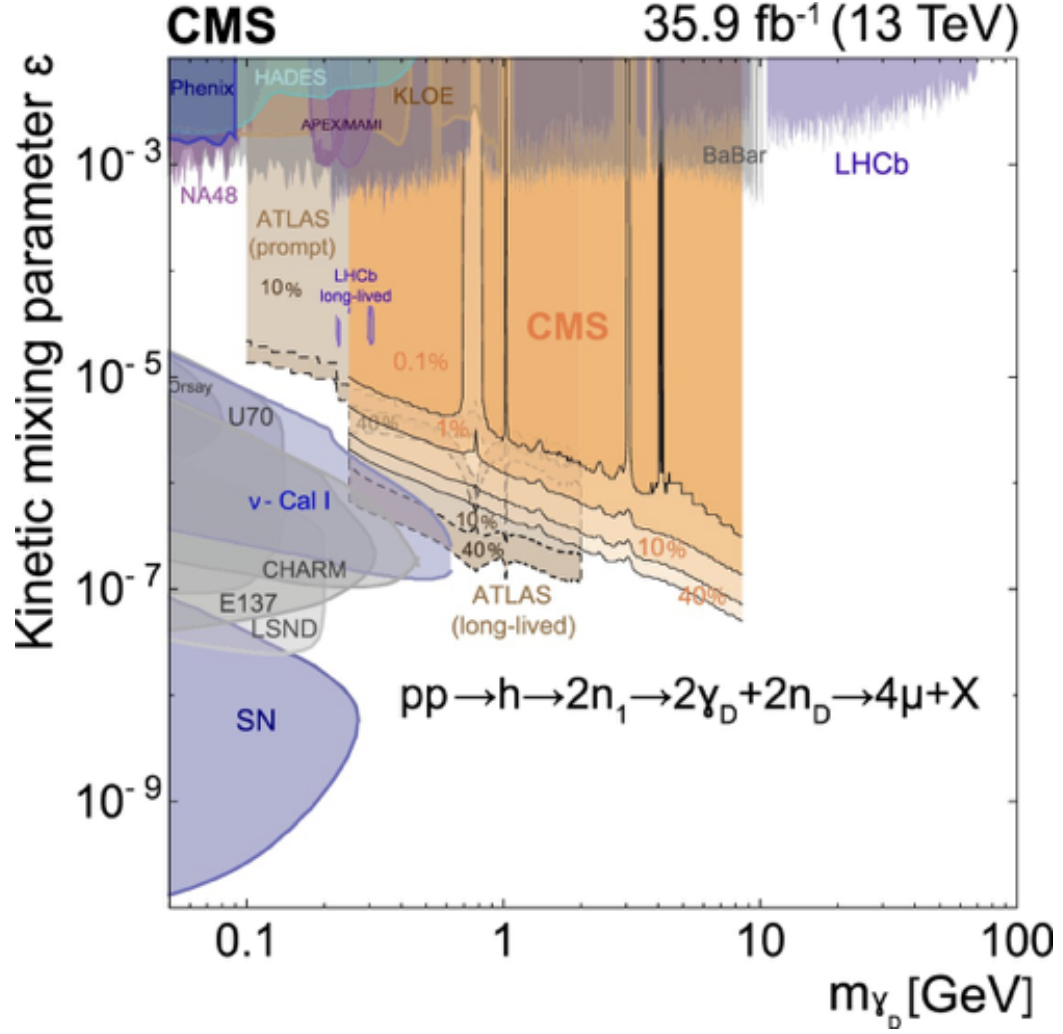


Figure 1.15 : 2016 search result for dark photon kinetic mixing parameter ϵ as a function of the dark photon mass [83].

NMSSM

The NMSSM [128, 129, 130, 131, 132, 133, 134, 135, 136] extends the MSSM by an additional gauge singlet field S under a new $U(1)_{\text{PQ}}$ (PQ stands for Peccei-Quinn) symmetry in the Higgs sector:

$$\mu \hat{H}_u \cdot \hat{H}_d \rightarrow \lambda \hat{S} \hat{H}_u \cdot \hat{H}_d + \frac{\kappa}{3} \hat{S}^3. \quad (1.42)$$

In this expression, the symbol μ is the mass parameter in the Higgs potential mentioned in Sec. 1.1. The Higgs fields for the up-type and down-type quarks are $\hat{H}_u$ and $\hat{H}_d$. The trilinear coupling constant between the singlet field S and the Higgs fields is λ . The strength of the self-interaction of the singlet field S is κ . Compared to the MSSM, the NMSSM naturally generates the mass parameter (μ) in the Higgs potential at the electroweak scale [58] and significantly reduces the amount of fine tuning required [137, 138, 139]. This leads to an extension of the Higgs sector compared to the MSSM. The Higgs sector of the NMSSM consists of 3 CP-even Higgs bosons ($h_{1,2,3}$) and 2 CP-odd Higgs bosons ($a_{1,2}$) [140, 141, 142, 143, 144]. The new Higgs boson a_1 can couple to the SM-like Higgs $h_{1,2}$ and substantially broaden the phenomenology of the Higgs sector. The CP-even Higgs bosons $h_{1,2}$ can thus decay via $h_{1,2} \rightarrow 2a_1$.

We follow the phenomenological studies published in [145, 146] and explore the scenario where h_1 and h_2 can decay via $h_{1,2} \rightarrow a_1 a_1$. There are no strong indications as to what the mass of a_1 should be, so very low masses are allowed. Because a_1 typically carries a large fraction of the NMSSM singlet field, the direct production $pp \rightarrow a_1$ is extremely suppressed. Other suppression [146, 147] also makes the a_1 boson decay to the heaviest pair of particles kinematically allowed. A plot of the branching ratio of the CP-odd Higgs boson a_1 is shown in Fig. 1.16. Below the $3m_\pi$ threshold, $\mathcal{B}(a_1 \rightarrow 2\mu)$ is expected to be close to 100% as hadronic decays are prohibited by spin

and hadronization effects and $\mathcal{B}(a_1 \rightarrow \gamma\gamma)$ is small. If $2m_\mu < m_{a_1} < 2m_\tau$, then it has a substantial branching fraction ($\mathcal{B}(a_1 \rightarrow \mu^+\mu^-) \sim 7.7\%$ for $m_{a_1} \sim 2$ GeV) for decays into muon pairs, and the $h_{1,2} \rightarrow a_1 a_1 \rightarrow 4\mu$ decay channel makes detection of a_1 in the muon channel viable at the LHC. The Feynman diagram of the NMSSM process $h_{1,2} \rightarrow 2a_1 \rightarrow 4\mu$ is shown in Fig. 1.17. If $2m_\tau < m_{a_1} < 2m_b$, then the $\mathcal{B}(a \rightarrow 2\mu)$ is suppressed by a factor $(m_\mu^2/m_\tau^2) / \left[\sqrt{1 - (2m_\tau/m_{a_1})^2} \right]$, the a_1 decays primarily to $\tau^+\tau^-$ [148, 149].

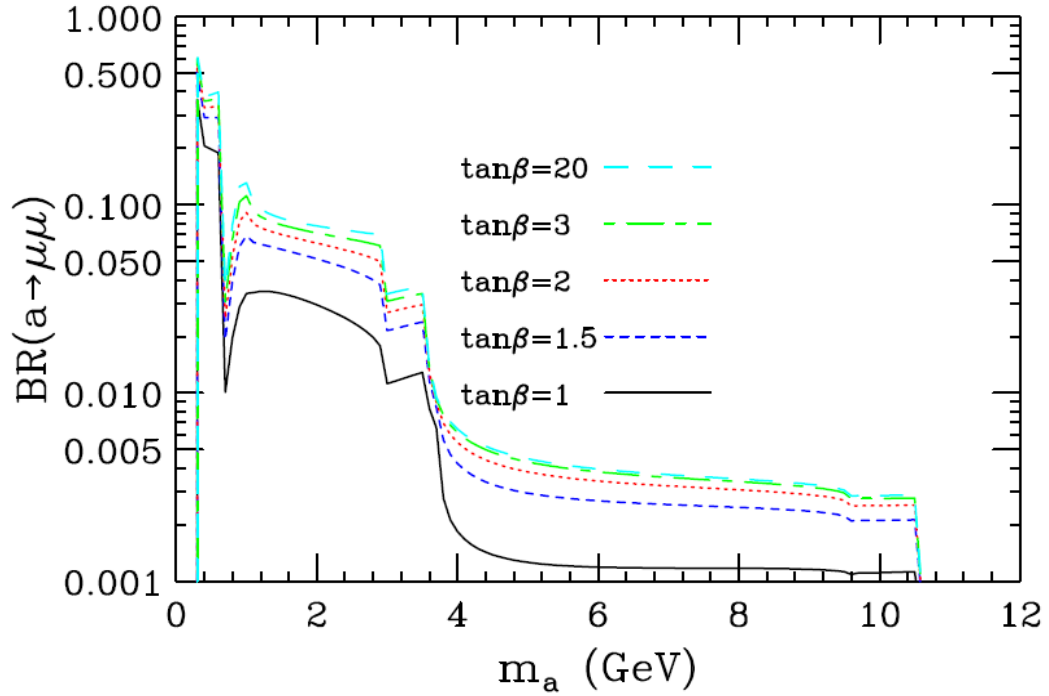


Figure 1.16 : Branching fraction of CP-odd Higgs boson $a_1 \rightarrow \mu\mu$ in the NMSSM scenario as a function of m_{a_1} for a variety of $\tan\beta$, which is defined as the ratio of two vacuum expectation values: $\tan\beta = \hat{H}_u/\hat{H}_d$. Plot excerpted from [146].

Both the production rate for the CP-even Higgs bosons $h_{1,2}$ (via gluon fusion predominantly) as well as the branching fraction for $h_{1,2} \rightarrow a_1 a_1$ can vary signifi-

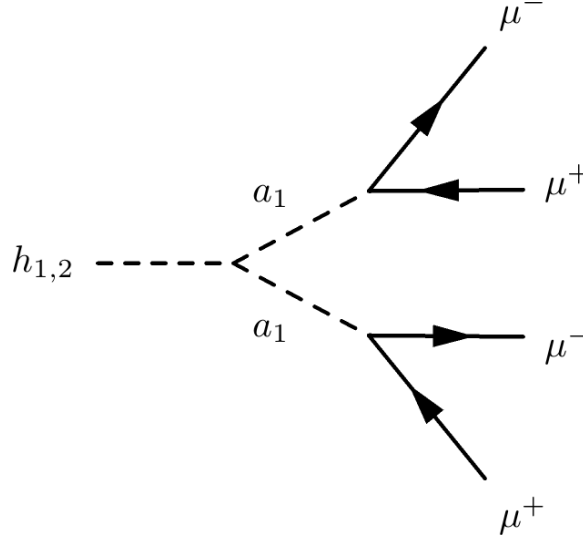


Figure 1.17 : Feynman diagram of the NMSSM benchmark process $h_{1,2} \rightarrow 2a_1 \rightarrow 4\mu$.

cantly depending on the chosen NMSSM parameters (notably the singlet fraction of $h_{1,2}$) [145]. Typical production cross sections $\sigma(pp \rightarrow h_{1,2})$ can range from ~ 0.05 to ~ 10 pb while $\mathcal{B}(h_{1,2} \rightarrow a_1 a_1)$ can be as high as 100% depending on the free parameters of the model.

Associated production of the CP-odd scalar bosons has been sought at e^+e^- colliders as in the case of BaBar [150,151] and BESIII [152,153] experiments, also at the Tevatron [154]. Direct production of the a_1 has been studied at the LHC [155], but in the framework of NMSSM the sensitivity of these searches is limited by the very weak coupling of the a_1 to SM particles. The most stringent limits on the Higgs sector of the NMSSM are provided by the WMAP data [156] and LEP searches [148,157,149] ($m_{h_1} > 86$ GeV). The result from the previous version of this search [83] is shown in Fig. 1.18. The result presented in this thesis has more sensitivity due to the larger center-of-mass energy and available integrated luminosity.

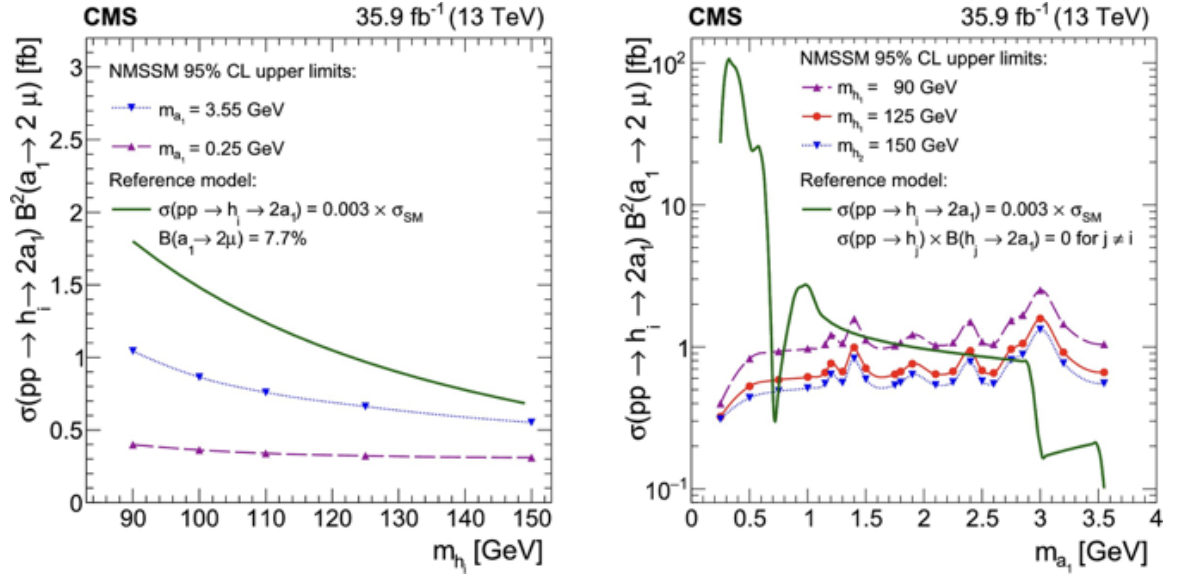


Figure 1.18 : 2016 search result for the CP-odd boson production cross section times branching ratio to muons as a function of the CP-even higgs mass (left) and the CP-odd boson mass (right) [83].

Chapter 2

Experiment: Apparatus

One of the key apparatuses for modern experimental particle physics is the accelerator. The search for new particles at accelerators often requires high energy and high luminosity. In the past century, many accelerators have been built for particle physics searches, dating back to the famous gold foil nuclei collision by Rutherford. The most powerful collider today is the LHC at CERN. The thesis is based on data taken at one of the experiments at the LHC.

2.1 LHC: the Accelerator

The CERN LHC is located at the border of France and Switzerland. A diagram of the CERN accelerator complex is shown in Fig. [2.1](#). The LHC has a circumference of 27 kilometers and sits about 100 meters underground. The designed center-of-mass energy is 14 TeV and the designed luminosity is $10^{34} \text{ cm}^{-2}\text{s}^{-1}$.

One of the many keys in accelerator design is rigidity, R , which is defined as $R = B\rho = p/q$. The B denotes the magnetic field strength and ρ is the gyroradius of a charged particle in the magnetic field. The particle charge is q and the momentum of the particle is p . Based on desired momentum and the type of particle that is accelerated, different working points of the needed magnet field strength and the size (circumference) of the tunnel exist. In the case of the LHC, since it used the tunnel left by the LEP, the magnetic field strength is around 8 Tesla.

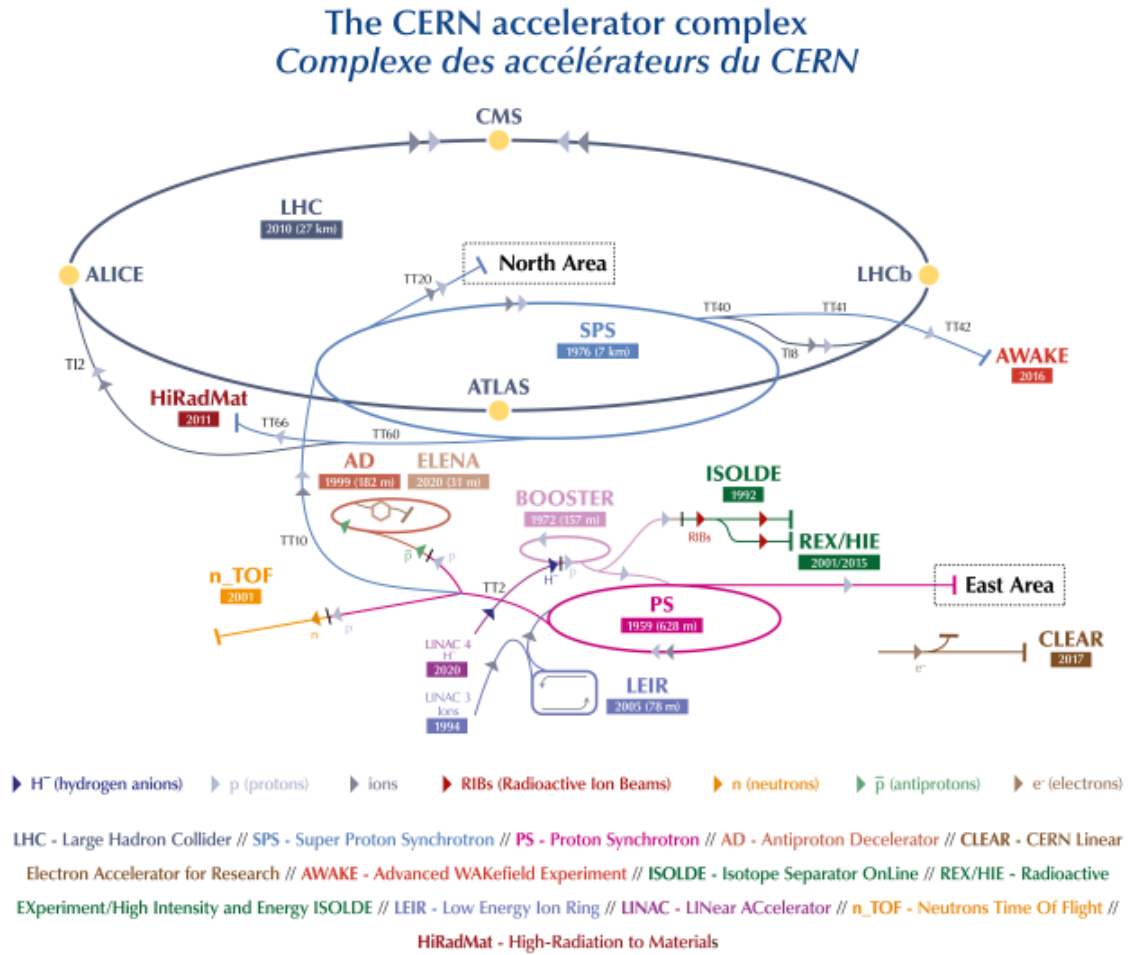


Figure 2.1 : The CERN accelerator complex from [158].

Alternate pairs of focusing and defocusing magnets (FODO cells) are primary components in focusing the beam in the transverse plane [159,160]. A total number of 1232 dipole magnets are used to bend the beam and 474 quadrupole magnets are used to focus the beam in the 27-kilometer circumference. All these magnets are superconducting, operating at a temperature around 2 K.

It takes around 90 microseconds for a proton to travel the circumference of LHC.

This corresponds to a revolution frequency of about 11 kHz. A bunching strategy was adopted to achieve a higher collision rate. A total number of 2556 bunches were used during Run 2 (2015-2018). These bunches are grouped in trains of 48 bunches spaced by 25 ns between bunches. There are larger gaps between trains. Every 25 ns, called one bunch crossing (BX), a collision happens between two proton bunches.

Multi-stage acceleration is necessary to achieve a collision energy of 6.5 TeV for each beam at the LHC [\[161\]](#). Typically, in a synchrotron with protons, the aperture size is determined by the lowest energy of the beam. As the proton beam gets accelerated, the beam size gets smaller. The magnetic field strength, on the other hand, is determined by the highest energy. The stored magnetic energy goes as the volume of the field times the square of the field strength [\[161\]](#). If a large aperture is used for the low energy and a high magnetic field is adopted for the high energy, the magnet stores more energy than needed, making it impractical to use a single synchrotron to accelerate particles from the lowest to the highest energy. A typical factor of 10–20 between the highest and lowest energy is adopted in one synchrotron acceleration stage. As shown in Fig. [2.1](#), an initial proton beam of 50 MeV from the linear accelerator (LINAC) is fed to the proton synchrotron booster (PSB). The PSB accelerates the beam to 1.4 GeV and then sends it to the Proton Synchrotron (PS). The beam is then accelerated in the PS up to 26 GeV. The SPS then accelerates the beam to 400 GeV and sends it to the LHC.

The beam intersects at four major points along the ring, corresponding to four major experiments, A Toroidal LHC Apparatus (ATLAS), Compact Muon Solenoid (CMS), A Large Ion Collider Experiment (ALICE), and LHC-beauty (LHCb). This

*The design energy was 7 TeV per beam, but retraining the magnets would take longer and limit the time for physics.

this thesis is done based on the 2018 data taken at the CMS detector.

2.2 CMS: the Detector

The CMS detector is a general-purpose particle detector. A cutaway view of the whole detector is shown in Fig. 2.2. It is around 21 meters long, 15 meters in diameter, and weighs about 14000 tonnes. A superconducting solenoid generates a magnetic field of 3.8 Tesla in the core and 2 Tesla outside. Massive steel yokes are used to support the entire detector as well as guiding the magnetic field lines.

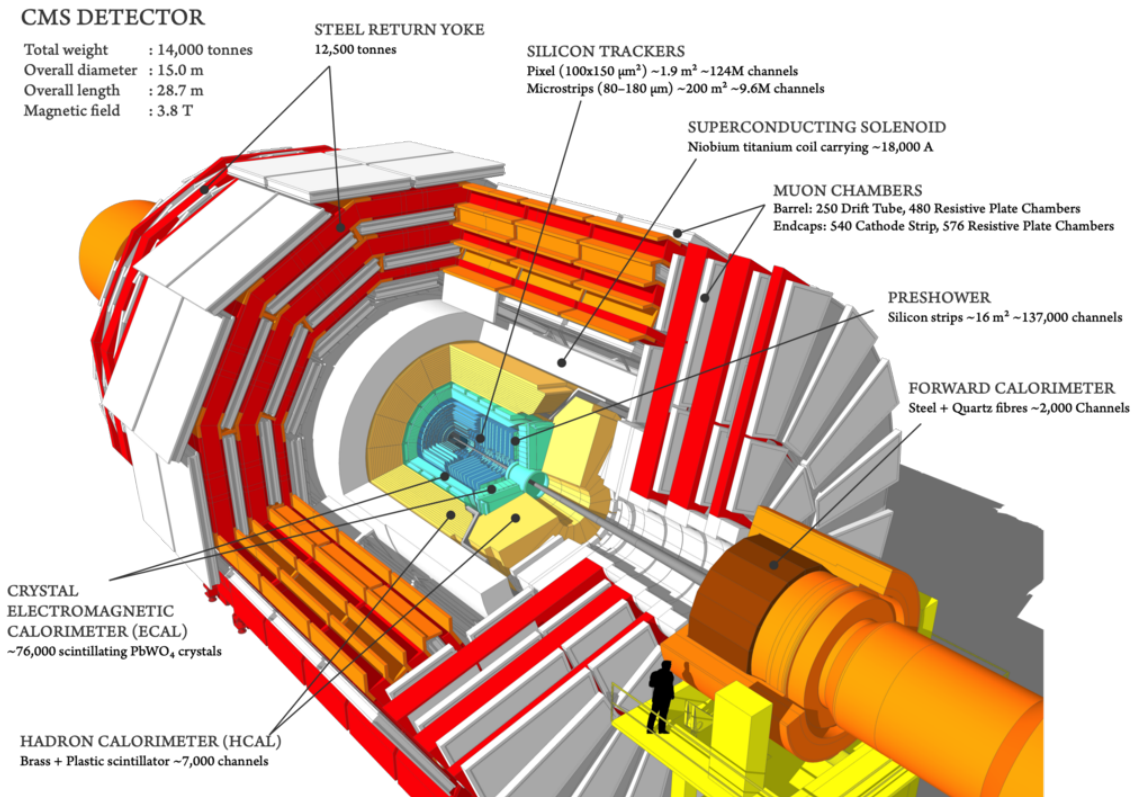


Figure 2.2 : The CMS detector cutaway view from [162].

Protons are primarily boosted along the beam axis at the LHC and the total

transverse momentum (p_T) is zero before each collision happens at CMS. Thus, any p_T must arise from the collision. The detector needs to measure the p_T and angle of particles as accurately as possible. In particle physics, pseudorapidity, η , is defined in Eq. (2.1) using the center-of-mass polar angle θ_{cm} with respect to the beamline. It is used to refer to detector geometry on the assumption that all collisions happen in the center of the CMS detector.

$$\eta \equiv -\ln\left[\tan\left(\frac{\theta_{cm}}{2}\right)\right] \quad (2.1)$$

In the limit where the particle is relativistic ($E \approx p$), the pseudorapidity η approximates the rapidity y via

$$y \equiv \frac{1}{2} \ln\left(\frac{E + p_L}{E - p_L}\right) \approx \frac{1}{2} \ln\left(\frac{|\mathbf{p}| + p_L}{|\mathbf{p}| - p_L}\right) = \text{artanh}\left(\frac{p_L}{|\mathbf{p}|}\right) = \eta. \quad (2.2)$$

In the case of Lorentz transformations with parallel boosts, the transformations commute with one another; thus, differences in rapidity are Lorentz invariant. In accelerated protons at LHC, partons with different longitudinal momentum fractions are all parallelly boosted. Thus rapidity is widely used in hadron collider physics because the measurement of the rapidity difference, Δy , does not depend on the longitudinal boosts of the rest frames of the partons.

Electrons, muons, photons, and hadrons can be detected at CMS. Particles that leave the detector without interaction, like neutrinos, can be inferred by observing momentum imbalance. More complicated objects can be reconstructed using dedicated algorithms (will be discussed in Chapter 3). Particle detectors on CMS generally fall into two categories: tracking detectors and calorimetry detectors.

2.2.1 Tracking Detectors

The interaction region at CMS could extend up to 24 cm away from the center of the detector in the case of high instantaneous luminosity. The tracking detectors, including the pixel and strip detectors, are the innermost detectors to the interaction region.

Silicon is widely used in the tracking system. The silicon atom needs 3.6 eV to be ionized. However, in the silicon solid, a continuous band is formed with an energy gap of 1.1 eV between the valence and the conduction band. A p-type semiconductor and n-type semiconductor are patched together to form a p-n junction. At the interface of p-type and n-type semiconductors, the difference in the Fermi levels causes diffusion of excessive carriers to the other material until thermal equilibrium is reached. This creates a depletion region without any charge carriers. An external voltage is applied so that electron-hole pairs are pulled out of the depletion zone to create a larger zone without charge carriers. The width of this zone is around 100-300 μm . When a charged particle passes through the depletion region, electron-hole pairs are formed in the depletion zone. They drift under the influence of the electric field. The signal is induced by the motion of the drifting charges and stops when they reach the electrodes.

As shown in Fig. [2.2](#), the pixel detector is the innermost part of the CMS detector. It is vital for the momentum measurement of charged particles as well as the identification of tracks and vertices coming from proton-proton collisions at the interaction point. The pixel detector was upgraded at the end of 2016. The comparison before and after the upgrade is shown in Fig. [2.3](#). Before the upgrade, the pixel detector had three barrel pixel (BPIX) layers in the central barrel region and two forward pixel (FPix) disks at each endcap. After the upgrade, the pixel system has a total of four

layers in the barrel, located at radii of 2.9 cm, 6.8 cm, 10.9 cm, and 16.0 cm; three layers in each endcap, located at a distance of 29.1 cm, 39.6 cm, and 51.6 cm from the interaction point. The innermost layer of the upgraded BPIX sits even closer to the collision point. To accommodate this configuration, the central section of the LHC beam pipe was replaced with a narrower version. The additional pixel layer improves the ability of CMS to track particles and vertices from each collision.

At a radius of 3 cm, the particle rate is around 600 MHz/cm^2 at peak LHC luminosity, $2 \times 10^{34} \text{ cm}^{-2}\text{s}^{-1}$. In the upgraded pixel detector, there are about 124 million channels in total [163], giving a channel occupancy on the order of 10^{-3} . This helps CMS deal with the increasing rate of collisions. The radiation tolerance of the upgraded pixel detector is about $3 \times 10^{14} \text{ neq/cm}^2/\text{year}$.

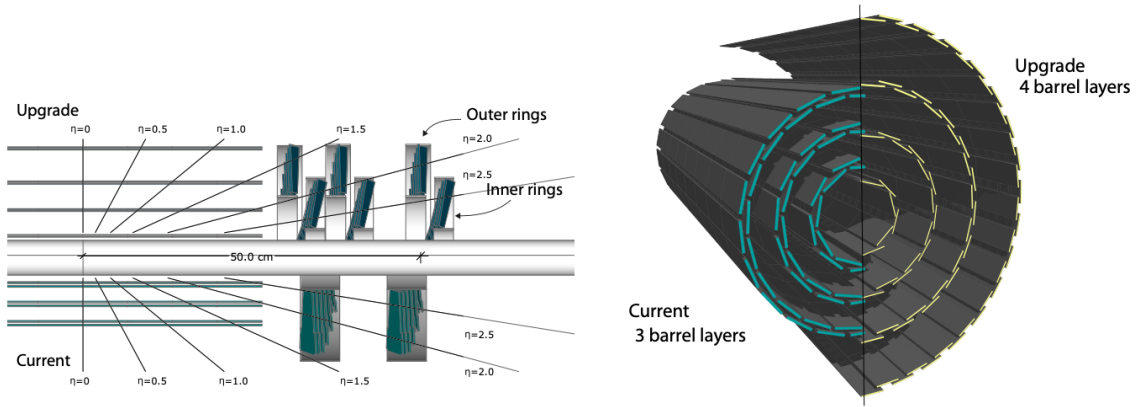


Figure 2.3 : Left: Conceptual layout comparing the different pixel layers and disks before and after the upgrade at the end of 2016. Right: Transverse-oblique view comparing the pixel barrel layers before and after the upgrade at the end of 2016 [163].

The silicon strip detector has 10 layers in the barrel with approximately $100 \mu\text{m}$ pitch going from a radius of 25 cm to 110 cm. It also has 9 disks in each endcap. The charge is sensed by long narrow strips of which the width is typically 20–100 μm . The

strip detector has 25000 sensors and about 10 M channels. The design occupancy is around 1–3%. The radiation tolerance is 1.5×10^{14} neq/cm²/year. The strip detector provides good momentum and energy measurement of the charged tracks. Both the pixel and the strip detector operates at -20 °C to improve its signal-to-noise ratio as well as its radiation tolerance.

The muon detectors are the outermost detector at CMS. They provide tracking and momentum measurement for muons. Because of the huge detection volume, the economic choice of gas chambers is adopted. Three different gas chambers are used in specific η regions. Cathode strip chambers (CSCs) are used in the endcap ($0.9 < |\eta| < 2.4$). Drift tube (DT) chambers are used in the barrel region ($0 < |\eta| < 1.3$). Resistive plate chambers (RPCs) are used in both the barrel and endcap, covering $0.9 < |\eta| < 2.1$. A diagram showing the CMS muon detectors is in Figure 2.4

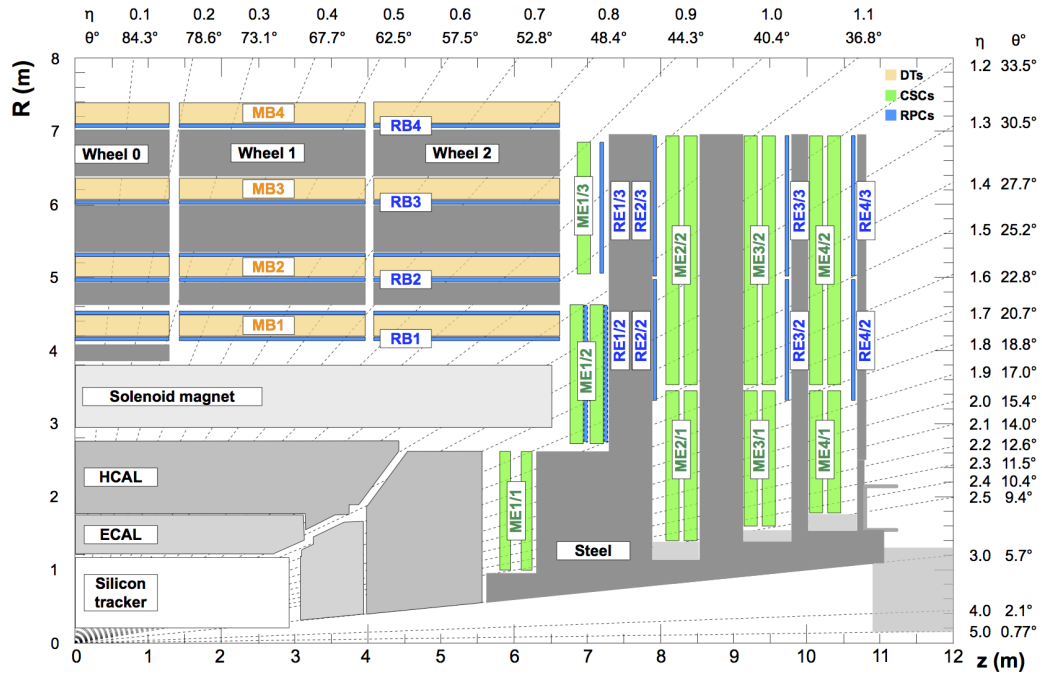


Figure 2.4 : R-z view of a quadrant of the CMS detector in Run 2 [164].

In gas chambers, as high energy particles pass through the gas chamber, gas atoms along its trajectory are ionized, creating pairs of electrons and positive ions. Most gas chambers work at the proportional region where the charge collected on the wire is proportional to the voltage. As electrons go to the immediate vicinity of the anode wire, an exponential increase of the number of electrons happens, causing the avalanche. The signal in the proportional region is sufficiently amplified. This greatly improves the signal-to-noise ratio of the gas detector and reduces requirements for subsequent electronic amplification. The DT and the CSC both work at the proportional region as a gas chamber, and hence the name proportional chambers. The chambers are filled with carefully chosen gas.

There are 540 trapezoidal CSCs in CMS endcaps. A CSC hit is reconstructed at the intersection points of hit strips and wire groups. In each CSC, six layers are used to record a hit pattern of the incident particle. The CSCs provide precise position measurements in the endcap where the magnetic field is uneven and the number of muons per second is high. Strips in contiguous layers are staggered (except in the ME1/1 chambers) to provide a spatial resolution of approximately 40-150 μm . Robust pattern recognition is achieved for the rejection of non-muon background and efficient matching of hits in other stations and the inner tracker.

DTs are used to detect muons in the barrel. Each 4-cm-wide drift tube contains a stretched wire within a gas volume. Each tube has a 2-mm-thick wall to separate contiguous tubes. Consecutive layers of tubes are staggered by half a tube. The spatial resolution per chamber could range from 80 to 120 μm . There are 240 DT chambers in the CMS barrel. They are segmented into 5 wheels longitudinally and 4 stations in the radial direction. Each station has 12 layers that are grouped into 3 superlayers, each consisting of 4 layers. Two superlayers are in the axial (r - ρ) plane

and one superlayer is in the longitudinal (r-z) plane.

The RPCs have a superior time resolution of ~ 3 ns which ensures unambiguous BX identification. They also serve as a redundant detection of muons. The position resolution is 0.8–1.2 centimeters. A total number of 480 chambers are in the barrel and 576 in the endcap. Each RPC consists of two parallel plates: a positively-charged anode and a negatively-charged cathode. Both plates are made of a very high resistivity plastic material and are separated by a gas mixture. Typically, the plate separation is on the order of a few millimeters. The entire structure is gas-tight.

The efficiency to reconstruct and identify muons is close to 100% [164]. Matching muons to tracks measured in the silicon tracker results in a relative p_T resolution of 1% in the barrel and 3% in the endcaps for muons with p_T up to 100 GeV. The p_T resolution in the barrel is better than 7% for muons with p_T up to 1 TeV.

2.2.2 Calorimetry Detectors

Calorimetry is widely used in chemistry where the total energy released within a chemical reaction can be measured by measuring the temperature difference. In particle physics, the energy of a particle is known by measuring the total energy absorption. The basic detection mechanism involves the formation of electromagnetic or hadronic showers in the detector. The energy is converted into ionization or excitation of the matter, usually in the form of charges, scintillation light, or Cherenkov light. At CMS, the calorimetry detectors are put inside the solenoid. This makes sure the energy measurement of particles is less affected by the magnet.

The electromagnetic calorimeter (ECAL) at CMS measures the energy and position of electrons, positrons, and photons. It uses approximately 76000 lead tungstate (PbWO_4) crystals as scintillation materials. High-energy electrons and photons pro-

duce electromagnetic showers in these crystals. Electrons lose most of their energy due to bremsstrahlung radiation. The radiated photon then goes through electron-positron ($e^\pm$) pair production. The cascade of $e^\pm$ pairs and photons goes on until the energy of the secondary electron falls below the critical energy. The critical energy is defined as the energy at which the ionization loss rate equals the bremsstrahlung loss rate. This is material dependent. The PbWO_4 crystal has low critical energy. It also provides a large cross section for bremsstrahlung. The longitudinal scale of bremsstrahlung is characterized by the radiation length (X_0). It defines the amount of material a high energy electron has to travel through until its energy is reduced to $1/e$ of its original energy. Once the electron energy drops below the critical energy, the electrons go through multiple scatterings. The lateral spread of the shower is characterized by the Molière radius (R_M). A cylinder with one R_M contains 90% of the shower cone. It's an important parameter for shower separation at CMS.

The light yield from the crystal is converted into an electric current and amplified by the attached photodetectors. The ECAL crystal light yield performance is deteriorated over the year. Crystal lattice defects can form due to the radiation. Although the thermal ambient environment could bring the deteriorated lattice back to normal slowly, it's necessary to apply the correction to the measured e/γ energy. Lasers are used during each abort gap when the beam cycles through the LHC orbit. The laser serves as input to the crystals installed in the detector and compare the output to the reference crystal to decide the corrections.

The energy resolution of calorimetry detectors is usually parametrized as

$$\left(\frac{\sigma(E)}{E}\right)^2 = \left(\frac{c_s}{\sqrt{E}}\right)^2 + \left(\frac{c_n}{E}\right)^2 + (c_c)^2, \quad (2.3)$$

where the c_s is a stochastic term that depends on intrinsic shower fluctuations, photoelectron statistics, dead material in front of calorimeters, and sampling fluctuations.

The noise term, c_n , comes from electronic noise and radioactivity. The final constant term (c_c) is due to inhomogeneities within the detector sensitivity, calibration uncertainties and radiation damage. At CMS ECAL, the stochastic term c_s is about 2.8%; the noise term c_n is 12.8%; the constant term c_c is 0.3% both in the barrel and the endcap.

The hadron calorimeter (HCAL) at CMS is designed to measure the energy and position of charged and neutral hadrons. Hadronic showers are produced by inelastic hadronic interactions of a primary hadron with the nuclei of the target material. Secondary particles undergo further interactions and produce more particles. Once the secondary particles' energies become too low for inelastic hadronic interactions, they lose energy due to the ionization and excitation of atoms. Hadronic showers can also be made more complicated by many other processes such as spallation. Neutral mesons like π^0 could also decay via the electromagnetic interaction and thus initiate an electromagnetic shower within the hadronic shower. The scale of a hadronic shower is determined by the nuclear interaction length, λ_I , which is the average distance a high energy hadron has to travel inside the material before a nuclear interaction occurs. In practice, the nuclear interaction length λ_I scales with $A^{1/3}$, where A is the mass number of the material. The HCAL is designed to be at least $10\lambda_I$ thick to avoid hadron punch-through which might affect muon detection.

The HCAL at CMS is a sampling calorimeter, meaning the material that produces the particle shower is distinct from the material that measures the deposited energy. As a result, only a fraction of the deposited energy is registered at HCAL. Compared to the ECAL, HCAL has limited energy resolution. It uses brass absorber plates for the shower and plastic scintillators with embedded wavelength-shifting plastic fibers for measuring the energy deposition. The brass segmentation in the HCAL has many

layers so that the shower direction and shape are measurable, which is important for jet analysis. In brass, the copper and zinc both have small mass numbers; they provide effective inelastic hadronic interactions. The HCAL provides coverage up to $|\eta| < 5.2$. Such hermeticity ensures a good measurement of missing transverse energy (MET). When the particle passes through the scintillator, it produces a light signal; this light signal is delivered to the hybrid photodiode, converted to electric currents, and amplified. The radiation could damage the light output of the plastic scintillators in HCAL as well as the photo-detectors.

Chapter 3

Experiment: Algorithms

During the running of the LHC, CMS (and other experiments at LHC) needs to synchronize to the LHC clock to keep track of the beam status. This is necessary for appropriate technical operations of sub-detectors at CMS as well as synchronized data-taking among these sub-detectors. The detector operation requirements could be quite different depending on the specific sub-detector and the beam status at LHC.

A Timing and Control Distribution System (TCDS) is used at CMS to communicate back and forth with the detector front-ends regarding the timing and control sequence [165]. The sub-detectors can provide basic status information back to TCDS. One of the most important parts of the TCDS is the trigger system.

3.1 Event Triggering and Reconstruction: An Overview

When stable beams are achieved at LHC, a proton-proton collision can happen at CMS every 25 ns (or 1 BX). In 2018, the raw data flow from the detector is over 1 MB per collision (or equivalently, per event). Every second, over 40 TB of raw data is generated at CMS. It is not possible to process all the data due to bandwidth constraints. Meanwhile, most of the collision data is not interesting. Therefore it is extremely important to select desired events using customized trigger algorithms.

A two-level trigger system is implemented at CMS. The level 1 (L1) trigger is based on hardware. After L1 trigger selection, the event rate drops from 40 MHz to

100 kHz. The event information is then sent to the High Level Trigger (HLT), which is purely based on filter software that is implemented in a computer farm of about 30000 CPU cores [166]. The event that passed HLT will be written to permanent storage space at CERN at a typical rate of several hundred Hz.

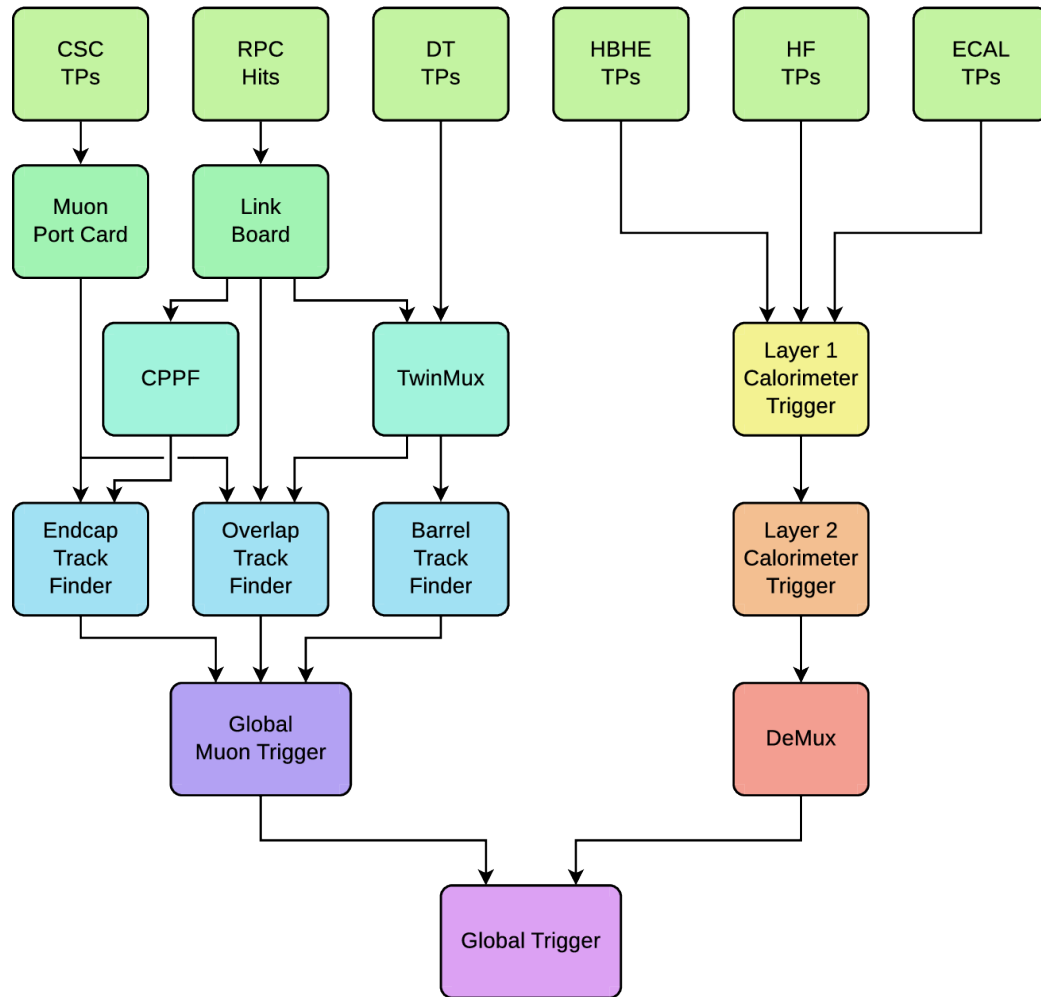


Figure 3.1 : Diagram of the upgraded CMS L1 trigger system during Run 2 [167].

A full diagram of the CMS L1 trigger system at the end of 2018 is shown in Figure 3.1. Given the differences in background rate and magnetic field uniformity at different $|\eta|$, the L1 muon trigger is composed of three separate muon track finders

(MTFs) covering different $|\eta|$ regions. The barrel muon track finder (BMTF) covers $|\eta| < 0.83$ region and receives data from the DTs and RPCs detectors. The endcap muon track finder (EMTF) receives data from the RPCs and CSCs in the region $1.24 < |\eta| < 2.4$. Finally, the overlap muon track finder (OMTF) receives data from the DTs, CSCs and RPCs in region $0.83 < |\eta| < 1.24$.

At the CSCs, a trigger primitive (TP) is a pattern of hits consistent with a muon crossing a CSC locally. The trigger primitives (TPs) are sent to the muon port card (MPC) before they are sent to the EMTF via optical links. The RPC hits are sent to the concentrator and preprocessor fanout (CPPF). It is designed to concentrate endcap RPC TPs for transmission onto higher-bandwidth optical links. The CPPF clusters RPC hits in adjacent strips into a single TP and computes their coordinates before transmitting to the EMTF.

The TwinMux merges DT TPs and RPC hits from the same station into so-called super-primitives. Super-primitives benefit from the better spatial resolution of the DT and more precise timing from the RPC. The TwinMux then sends super-primitives to the BMTF. Meanwhile, it transmits unmerged DT TPs and RPC hits to the OMTF.

The output of these three MTFs is collected by the Global Muon Trigger (GMT) which ranks muon tracks by p_T and quality, removes the reconstruction duplicates across boundary regions of two MTFs. The GMT also corrects the spatial coordinates of each muon by extrapolating the track from the muon stations back to the interaction region [167].

The ECAL and HCAL (including HCAL barrel (HB), endcap (HE), and forward (HF)) TPs are local energy deposits. These TPs are processed sequentially by the layer-1 and layer-2 calorimeter trigger algorithms. The layer-1 calorimeter trigger receives, calibrates, and sorts the TPs. The layer-2 trigger uses these TPs to recon-

struct and calibrate the physics objects such as electrons, tau leptons, jets, and energy sums. A demultiplexer (DeMux) board then reorders, reserializes, and formats the events for the global trigger (GT) processing. More details on the calorimeter trigger design can be found in reference [167].

All calorimeter and muon candidates are finally sent to the global trigger (GT). The GT calculates hundreds of trigger algorithms consisting of single physics objects or combinations of multiple types of objects. Decisions from all algorithms are then combined based on a final OR logic. Trigger rules can also be applied to suppress the GT decision for specific purposes. For example, one of the trigger rules prohibits data from two consecutive BXs to be accepted. Triggers can be prescaled, meaning that only a predefined fraction of events fulfilling the trigger condition is accepted. This typically happens for lower energy or momentum objects as they have a huge production rate at LHC.

The 2018 L1 trigger system is implemented on field-programmable gate arrays (FPGAs) on an advanced mezzanine card (AMC) in a MicroTCA (μ TCA) crate. One type of AMC, the AMC13, provides fast control signals from the TCDS to the trigger AMCs over the μ TCA backplane. TCDS sends out the L1 accept (L1A) signal to all components of the detector. This triggers the data acquisition system to read out all detector data stored in the buffer for the specified collision.

It is worth mentioning a maximum of 512 algorithms (the actual number is 350-400 in Run 2) can be implemented in the L1 trigger hardware [167]. The L1 trigger makes a trigger decision within 4 μ s. This is largely driven by the limited length of the silicon tracker readout pipeline. As shown in Figure 3.1, the existing L1 trigger system only exploits part of the detector. The information from pixel and strip detectors is not used in the L1 decision.

The HLT runs a simpler version of the offline reconstruction algorithms to be introduced in Sec. [3.2.4](#) to reduce the CPU consumption. For example, the reconstruction at HLT is restricted to a smaller region of interest (ROI) around the L1 or higher-level candidates. Tracking at HLT also uses a reduced number of tracking iterations. Still, with the full readout including tracking information (not available at L1), the HLT can improve the energy (or momentum) resolution of trigger objects.

Similar to the L1 trigger, the HLT runs hundreds of trigger paths. The running time is on the order of several hundred milliseconds. Each HLT path consists of a sequence of reconstruction and filtering modules aiming to reconstruct and select physics objects of interest to physicists. Each path is put into certain categories to take aimed data streams.

Three metrics are usually used when evaluating trigger performance: efficiency, rate, and timing. These metrics can be conflicting. In general, a higher trigger efficiency and lower trigger rate is favored. HLT also needs to be run fast without compromising too much on the goals of efficiency and rate. These requirements apply for the L1 trigger as well.

The event triggering and reconstruction comes hand in hand. Without appropriate reconstruction of the event or part of the event, it's not possible to trigger the desired event. The event reconstruction also needs to be further optimized after being triggered by using more refined methods with more information and computing resources.

The ultimate event reconstruction at CMS is performed by the particle-flow (PF) algorithm. It is one of the main and most important reconstruction algorithm used at CMS. The algorithm combines information from all CMS subdetectors to identify and reconstruct all individual particles for each event, including electrons, neutral

hadrons, charged hadrons, and muons. It's also able to calculate the isolation of specific physics objects for physics analysis. A full introduction to the PF algorithm can be found in reference [168].

3.2 Muon Triggers and Reconstruction

As this thesis is looking for signals decay to four muons in the final state, here I choose to write more on the triggering and reconstruction of muons at CMS. In Sec. 3.2.1, I will cover how muon tracks are built from detector signals at L1 trigger using EMTF as an example. Details on BMTF and OMTF can be found in [167]. In Sec. 3.2.2 and Sec. 3.2.3, I introduce the muon reconstruction at the HLT in two sequences (L2 and L3). Finally in Sec. 3.2.4, I talk about the offline reconstruction of muons at CMS as compared to reconstruction at the trigger level (online).

3.2.1 L1 Muon: Endcap Muon as an Example

As shown in Figure 3.1, the L1 muon starts from TPs at each muon detector. TPs provide coordinates, timing, and quality information from detector hits. The CSC TPs are also called LCTs, short for local charged tracks. In each CSC chamber, the cathode front-end board (CFEB) processes the hits from the strips while the anode front-end board (AFEB) processes the hits from the wires. They process the information from each chamber locally, called local triggers. The anode signals from the AFEB are used to define the timing. In the η direction, ALCT is built by pattern finding using wire digitized signals from 6 CSC layers. In the ϕ direction, CLCT is built by pattern finding in 6 CSC layers (half strip unit). The CSC LCT is built by combining ALCT and CLCT in the optical trigger motherboard (OTMB). Detailed definitions of the hit patterns can be found in reference [169].

The OTMB sends the two best LCTs to the MPC. The MPC receives the LCTs from all of the OTMB cards in one 60-degree azimuthal sector of one endcap muon station (30-degree subsector in station 1) and relays them over optical fiber links to the EMTF and OMTF as shown in Fig. [3.1](#).

The EMTF first builds each muon track using at most one TP (from CSC or RPC) per station. The algorithm first looks for CSC TPs correlated in ϕ in multiple stations consistent with the presence of a muon track, matching at least one of the predefined patterns. The pattern recognition runs in parallel in four zones in θ [\[169\]](#). After the patterns are found, the CSC or RPC TPs in each station closest to the pattern is taken for further processing. Resulting tracks are ranked according to their straightness and the number of stations with hits. Stations 1 and 2 are prioritized because the magnetic field is much stronger. A muon track with TPs in these two stations, therefore, has a more precise p_T assignment.

Ideally, the bending angles in ϕ and θ of the muon track can be used to infer the muon p_T . However, this relationship is complicated by several factors at the endcap. Low p_T muons tend to be produced more often at the endcap region. These muons could experience significant multiple scattering and energy loss. High momentum muons can initiate electromagnetic showers. Besides, the CMS magnetic field strength and direction vary with η outside the solenoid. The complicated dependencies make this an ideal case for machine learning. Starting in 2017, EMTF uses boosted-decision-trees (BDT) regression to perform the muon p_T and charge (q) assignment. The BDT input variables are compressed into 30 bits. The BDT output values are pre-evaluated and stored in a look-up-table (LUT) loaded in a 1 GB memory module of the EMTF electronics for fast determination. Additional details about the design, training, and implementation of the BDT can be found in [\[167\]](#), [\[170\]](#). The author

himself is heavily involved in the improvement of EMTF during 2017 and 2018.

3.2.2 L2 Muon in HLT

Of all objects accepted by the single muon L1 trigger, 10–20%, depending on the year, do not correspond to real muons [166]. To reject these fake objects and to reduce the trigger rate, more sophisticated muon reconstruction algorithms are employed in the HLT. The muon reconstruction at HLT is split into two sequences: the level-2 (L2) muon reconstruction that uses information from the muon detectors only, and the level-3 (L3) muon reconstruction that also incorporates information from the inner tracking detectors. These reconstruction sequences are followed by muon identification (ID) and isolation requirements. Here I focus on the L2 muon HLT algorithms used in 2017 and 2018 after the pixel detector upgrade. More details on muon reconstruction at HLT is available in reference [166].

The L2 muon reconstruction refines the initial estimate of the muon trajectory from the L1 reconstruction by using more precise algorithms that cannot be implemented in the hardware-based L1 trigger. Muons are first reconstructed using the Kalman filter technique [171]. This process uses the L1 trigger decision and refines the p_T measurement using isolation information from calorimeters. Muons are generally accompanied by other nearby particles, which can be suppressed by isolation cuts. Then, the muon trajectories are extended into the tracker system, which further refines the p_T measurement using isolation information from the tracker system. This is especially important as the L2 muons are used to seed the track reconstruction in the inner tracker in most L3 reconstruction algorithms.

The track building at L2 is also performed twice: first by proceeding from the innermost layer of the muon detector toward the outermost, and second from the

opposite direction. This allows the algorithm to remove possible biases from the initial seed. These wouldn't be possible at L1 due to limited time and hardware constraints.

3.2.3 L3 Muon in HLT

During 2017 and 2018, an iterative algorithm is used to reconstruct the L3 muons to accommodate the upgraded pixel detector. The details of algorithms and their performance are detailed in [166]. Here I briefly mention the algorithms in 2018 as it's the most relevant for this thesis.

Table 3.1 : Steps of the iterative algorithm for L3 muon reconstruction

Step	Direction	Seed
1	outside-in	L2 muons
2	inside-out	L2 muons
3	inside-out	L1 muons

The iterative algorithm for L3 muon consists of three steps executed in order as shown in Table 3.1. The outside-in (OI) reconstruction step uses L2 muons to start the search for track reconstruction seeds in the inner tracker. Using the parameters from the L2 muon, the trajectory is propagated to the outermost tracker layers using the stepping helix propagation to find the seed. The inside-out (IO) steps make use of the iterative tracking techniques, similar to those used for the tracker muon algorithm. The region of interest (ROI) is generated using both L2 and L1 muons depending on the step. As the uncertainties on the parameters of an L2 muon are much smaller than those of the L1 muons, the size of the ROI is much smaller for the

L2-seeded step. For the IO step seeded by an L2 muon, only those muons which were not reconstructed as an L3 muon in the OI step (i.e., step 1) are considered. For the L1 muon seeded IO step, all the L1 muons are used to maximize the efficiency of the final algorithm.

Each reconstruction step produces a collection of tracker tracks that are then combined, and duplicate tracks are removed. For the L2-seeded steps (i.e., step 1 and 2 in Tab. 3.1), the tracker tracks are matched to the L2 muon and a combined fit of the tracker and the muon track is performed to build an L3 muon. For the L1-seeded step (i.e., step 3 in Tab. 3.1), the tracker tracks are matched to hits in the muon system to create tracker muons.

Finally, extra muon ID requirements were introduced at the start of 2018 to the iterative algorithm to further decrease the rate and increase the purity of the L3 muons [166]. This removes a significant number of poorly reconstructed muon tracks. A looser version of the isolation based only on tracks has been used in some double muon triggers.

As the last step, the beam spot position is used to constrain the track parameters to improve the momentum resolution of tracks. However, this constraint is not applied in triggers targeting displaced or cosmic muons. For example, an L2 muon trigger is used in this thesis to collect events with displaced signal muons.

Fast algorithms are required for HLT to keep the overall processing time per event within the budget. The overall processing time for the full suite of triggers at CMS is 180 ms for 2017, and 196 ms for 2018 [166]. The increase in 2018 is mostly driven by the need to mitigate the effect of inoperative modules in the pixel detector. The L3 step of the 2018 iterative reconstruction algorithm consumes the most time. This is driven by many effects detailed in [166], including the increased number of

pixel detector layer combinations available for track seeding with the upgraded pixel detector.

3.2.4 Offline Muon Reconstruction

After the triggered event is written to tapes at CERN, the offline reconstruction of events starts using standard CMS software. Muons are reconstructed separately in the muon systems and inner tracker. In the muon system, hits within a station are combined into local segments. For example, a segment in a CSC is reconstructed from the hits on 6 layers of the CSC. Seeds made up of groups of CSC or DT segments are then used in the Kalman filter to reconstruct the muons, called standalone (SA) muons. A tracker muon is built inside-out by propagating tracker tracks to the muon system with loose matching to DT or CSC segments. If at least one muon segment matches the extrapolated track, the tracker track qualifies as a tracker muon track. A global muon is built outside-in by matching SA muon tracks with tracker tracks. The matching is done by comparing the parameters of the two tracks propagated onto a common surface [172]. A combined fit is performed with the Kalman filter. More details on these types of muons can be found in [164].

It is worth pointing out the muon segment used in offline reconstruction is different from the TP at online reconstruction mentioned in section 3.2.1. The CSC TPs are built from CSC local trigger electronics with simple pattern recognition, while segments are reconstructed offline CMS software with dedicated fit and charge weighting. Such different reconstruction choices are due to the time constraint of online event triggering. The fit generally takes more time and is not suitable to implement in triggers.

Reconstructed muons are fed into the CMS PF algorithm. It applies a set of

selection criteria to SA, global, or tracker muons. The requirements are based on various quality parameters from the muon reconstruction, as well as making use of information (e.g., isolation) from other CMS subdetectors.

High momentum muons have dedicated fitting methods because they start to lose energy from radiation and exceed the minimum ionization working point of the gas chambers for muon detection [173]. At low and intermediate momenta, below 100 GeV, the muon p_T resolution is dominated by the hits measured in the silicon tracker. In contrast, hits and segments measured in the muon chambers are significantly affected by multiple scattering of the muon trajectory while passing through the calorimeters and the flux-return yoke. This multiple scattering is reduced with increasing momentum, and above 200 GeV the muon chamber measurements start to improve on the measured p_T . The ultimate performance at high p_T is then determined by the precision of the muon chamber measurements and by the alignment of muon chambers relative to each other and the inner tracker.

Several muon ID criteria are developed to tune the desired balance between efficiency and purity (fake rate). Common muon ID types include loose, medium, tight, soft, and high momentum. The loose muon ID aims to identify prompt muons produced at the primary vertex, and muons from light and heavy flavor quarks decay, as well as maintain a low rate of the misidentification of charged hadrons as muons. A loose muon selected by the PF algorithm is also either a tracker or a global muon. This is also one of the main ID requirements for muons used in this thesis (Chapter 5). More details regarding how other ID types are defined can be found in reference [164] as they are not relevant or suitable for the search in this thesis. The tight muon ID for example is not suitable for this search because they have certain impact parameter restrictions that would reject our displaced muon signals.

A so-called Tune-P algorithm [164] is used by CMS to determine the muon momentum. For each muon, the Tune-P algorithm selects the p_T measurement from several refits based on goodness-of-fit and relative resolution ($\sigma(p_T)/p_T$). These fits include Inner-Track fit, Tracker-Plus-First-Muon-Station fit, Picky fit, and Dynamic-Truncation fit, more details can be found in reference [164]. The most relevant for this thesis is the Inner-Track fit. It determines the momentum using only information from the inner tracker. For muons p_T below 200 GeV, the contribution from the muon system to the momentum measurement is marginal. Therefore, the inner-track fit is highly favored by Tune-P at low momentum. In this thesis, the signal muons p_T are usually lower than 200 GeV, so this fit dominates.

The PF algorithm also refines the information from Tune-P, exploiting information from the full event, by selecting refits that significantly improve the balance of missing p_T and by using a postprocessing algorithm designed to preserve events that contain genuine missing energy.

Muon isolation is usually used to evaluate the activities around the muon. It is evaluated by summing up the energy in geometrical cones (ΔR), surrounding the muon. One strategy sums reconstructed tracks (track-based isolation), while another uses charged hadrons and neutral particles coming from PF (PF isolation). This thesis uses the former case, although it's slightly different as I will mention in Chapter 5.

3.3 Muon Triggers in This Search

The muon triggers for signal search in this thesis are shown in Tab. 3.2. The first trigger (index 1) is a double L2 muon trigger that requires two L2 muons with p_T threshold of 23 GeV. This trigger provides high efficiency for displaced muons. I also use three other triggers with lower p_T thresholds than the L2 muon trigger to

Table 3.2 : Muon Triggers in This Search

Index	HLT Name
1	HLT_DoubleL2Mu23NoVtx_2Cha_v*
2	HLT_Mu18_Mu9_SameSign_v*
3	HLT_TripleMu_12_10_5_v*
4	HLT_TrkMu12_DoubleTrkMu5NoFiltersNoVtx_v*

improve the trigger efficiency on signals. They include the `HLT_Mu18_Mu9_SameSign` trigger which requires two same-sign muons with p_T thresholds 18 GeV and 9 GeV. A triple muon trigger, `HLT_TripleMu_12_10_5`, which requires minimum p_T of 12 GeV, 10 GeV, and 5 GeV for each muon. The final trigger is a triple tracker muon trigger `HLT_TrkMu12_DoubleTrkMu5NoFiltersNoVtx` where the muons are required to have p_T above 12 GeV, 5 GeV, and 5 GeV. More details on the triple tracker muon trigger can be found in Appendix [G](#). Different versions exist because of the HLT algorithm update throughout the year. The performance of these triggers as well as other detailed studies will be included in Chapter [5](#) after I talk about the samples in the next chapter.

Chapter 4

Samples

4.1 Data

The dataset analyzed in this thesis comes from proton-proton collisions at a center of mass energy 13 TeV recorded by CMS in 2018. It was collected using the triggers in Tab. 3.2. These triggers were effective during the whole data taking period of 2018 when the LHC was providing stable beams. Events are collected in the `DoubleMuon` dataset shown in Tab. 4.1, which corresponds to an integrated luminosity of 59.7 fb^{-1} . Details on the dataset in Tab. 4.1 and on the data format used at CMS in general can be found in Sec. A.1 in Appendix A.

Table 4.1 : 2018 DoubleMuon dataset

Dataset	Events
/DoubleMuon/Run2018A-17Sep2018-v2/MINIAOD	75499908
/DoubleMuon/Run2018B-17Sep2018-v1/MINIAOD	35057758
/DoubleMuon/Run2018C-17Sep2018-v1/MINIAOD	34565869
/DoubleMuon/Run2018D-PromptReco-v2/MINIAOD	169225355
Total	314348890

4.2 Monte Carlo Samples

In Chapter [1](#), I introduced several benchmark models relevant for the search including the ALP, dark SUSY, and NMSSM models. The Monte Carlo (MC) samples of these signal models are vital to the search in terms of optimizing the event selection and checking the performance (Chapter [5](#)). It is also important to use MC samples of the SM background processes to understand the real data (Chapter [6](#)). Sec. [4.2.2](#) is an introduction to some work I did in 2017-2018 to implement the dark SUSY model which is necessary for its MC sample production. Finally, I summarize all MC samples used in the thesis in Sec. [4.2.3](#).

4.2.1 Overview

The first stage of MC sample production is event generation [\[174, 175\]](#). The most important part of this stage is the matrix element calculation of the hard scattering process of interest. In the scope of this thesis, it is the production of the two same signal bosons from pp collisions and their subsequent decay to four muons in each signal benchmark model. The cross section of the process could be obtained via the computation of the matrix element. However, it is important to mention that in this thesis, the calculation of the cross section for benchmark signal events is not required, as I set a model-independent 95% confidence level (CL) upper limit on the number of signal events (Chapter [8](#)).

The second step of event generation involves the modeling of the parton shower (PS). The generator deals with the evolution of partons (i.e., quarks and gluons) from the hard scattering process, including the initial-state radiation (ISR) and final-state radiation (FSR). The effect of all higher order processes, down to $\mathcal{O}(1)$ GeV energy scale, are simulated. By modeling such soft emissions from partons, PS complements

the description of partons from the hard scattering process.

It is challenging to unambiguously differentiate the processes in an event, which belong to the hard scattering and which should be described by the PS. A matching scheme is often used to separate these two components rigorously. For example, a FxFx jet matching scheme [176] implemented in aMC@NLO [177] is used for the Drell-Yan (DY)+jets MC sample introduced later in the thesis. There are also other common used schemes such as MLM [178,179] and CKKW [180]. The MLM scheme is used in the $t\bar{t}$ +jets background MC sample introduced later.

Event generation also involves the modeling of the underlying event (UE). UE refers to activities that are not associated with the particles from the hard scattering process. The ISR of the hard interaction, for example, is not included in UE. UE consists of beam-beam remnants (BBR) and particles arising from multi-parton interactions (MPI). BBR is what remains after a parton is scattered out of each of the two initial beam hadrons. The MPI is additional soft or semi-hard parton-parton scatterings that occur within the same hadron-hadron collision [181]. The UE simulation at CMS can be found in Sec. A.2 in Appendix A.

In all the processes mentioned above, parton distribution functions (PDF) play a central role. A function, $f_i(x, \mu_F)$, is often used to describe the probability to find a parton of species i with a momentum fraction x when a proton is probed at a factorization scale μ_F . This function cannot be calculated from first principles, since it depends on the non-perturbative physics of QCD. It is worth to point out the MPI mentioned above is expected to increase with the increase of energy scale μ_F . This is due to the violation of Bjorken scaling. At higher energies, the proton PDF shift toward low momentum fraction x , making MPI more likely to happen [5]. In Chapter 7, I will also assign a theoretical uncertainty due to the μ_F scale.

In the last step of event generation, hadronization happens where hadrons are formed from low momentum partons. Decays of these hadrons are also modeled.

Events generated with event generators are stored using the `HepMC` [182] format for simulation. The simulation of the generated particles traversing the CMS detector materials in the magnetic field is done with `GEANT 4` [183,184], which is implemented in standard CMS software. At CMS, the `HepMC` interfaces with `GEANT 4` and people can decide what particles to simulate from `HepMC` stored events. One of the main challenges I encountered during the MC sample production of dark SUSY is related to the interface between the `HepMC` event record and `GEANT 4`. Details can be found in Appendix B.

The digitized signals of the detector electronics as they respond to the `GEANT 4`-simulated hits are also simulated, which is followed by the simulation of the L1 and HLT decisions. I need to account for the different trigger effects on data and MC samples as a source of systematic uncertainty (see Chapter 7).

The pileup (PU) condition of the entire data taking period is also simulated. Different from the aforementioned MPI, PU refers to extra hadron-hadron collisions aside from the main hadron-hadron collision where MPI could happen. PU events mostly involve soft QCD processes. They can be simulated as minimum bias (MB) events, which refer to inclusive events that are selected with the minimum possible bias.

To simulate the desired luminosity profile of the data taking period, a distribution of the number of interactions per BX is chosen in advance. For each simulated event, the instantaneous luminosity is randomly chosen from the input distribution. Collisions from many BX before and after (out-of-time) the central BX (in-time) have to be included as well. The number of in-time and out-of-time interactions are

sampled from a Poisson distribution based on the chosen instantaneous luminosity and the total pp inelastic cross section [185,186]. Similarly, the systematic uncertainty due to the PU needs to be studied to characterize its different effects on data and MC samples. This will also be discussed in Chapter 7. A description of the PU simulation at CMS is available in Sec. A.3 in Appendix A.

The simulated events are finally reconstructed using the same algorithms that were used to reconstruct events collected in real data taking. A full list of setup commands for 2018 MC sample production is available in Sec. A.4 in Appendix A.

4.2.2 Dark SUSY Model Implementation

The ALP and dark SUSY benchmark models are first implemented in `FeynRules` [187] before they can be used in event generators. `FeynRules` is a `Mathematica`-based package that calculates Feynman rules for the physics model. The program computes the QFT Feynman rules directly from the Lagrangian of the model. As a user, I need to describe the new model in terms of a list of fields, parameters, and a Lagrangian. `FeynRules` enables models to go from theory to simulation and compare with experiment. While the ALP benchmark model is already available from our theorist colleagues [94] and I can directly use it in `MadGraph5` for event generation, the dark SUSY model needs to be implemented in `FeynRules` by us. Here I briefly describe the implementation work I did in 2017-2018.

The dark SUSY model implemented in `FeynRules` is called MSSMD^{*}. This is because I used the implemented `MSSM` model as a baseline. On top of that, I added the $U(1)_D$ gauge group with the subscript D indicating a dark sector. The $U(1)_D$

^{*}<https://feynrules.irmp.ucl.ac.be/wiki/MSSMD>

group is defined [†] as an Abelian group. The associated charge, $\mathbf{X}$, is the generator of the $U(1)_D$ symmetry group like the hypercharge for the $U(1)_Y$ group in the SM. This allows **FeynRules** to check charge conservation in the Lagrangian. The $U(1)_D$ gauge group coupling constant is **gd**. The name of the vector superfield associated with the $U(1)_D$ gauge group is written as **XSF**. In the context of SUSY models like MSSM, the gauge boson must be the vector component of the vector superfield. Thus, the superfield **XSF** is defined as,

$$\mathbf{XSF} := \text{GaugeBoson} \rightarrow \mathbf{AD}. \quad (4.1)$$

The coupling constant, **gd**, is defined as,

$$\begin{aligned} \mathbf{gd} := \{ & \text{ParameterType} \rightarrow \mathbf{External}, \text{ComplexParameter} \rightarrow \mathbf{False}, \text{Value} \rightarrow 0.001, \\ & \text{InteractionOrder} \rightarrow \{\mathbf{NP}, 1\} \}, \end{aligned} \quad (4.2)$$

Here, the nature of a parameter is specified by **ParameterType**. The allowed choices are **External** or **Internal**. By default, scalar parameters are considered as external and tensorial parameters as internal. The value of the coupling constant is set to 0.001 as default. This is adjustable later when one uses it in the event generator. Perturbative QFT allows one to compute the matrix element at a given order of the coupling constant. For the dark SUSY process (Fig. 1.14 in Chapter 1) considered in this thesis, I'm only considering the leading-order (LO) matrix element. This is indicated by $\text{InteractionOrder} \rightarrow \{\mathbf{NP}, 1\}$, where NP stands for the new physics; in this case, it refers to all vertices related to the dark sector coupling constant, **gd**. I

[†]**FeynRules** syntax: $U(1)_D := \text{Abelian} \rightarrow \mathbf{True}, \text{CouplingConstant} \rightarrow \mathbf{gd}, \text{Superfield} \rightarrow \mathbf{XSF}, \text{Charge} \rightarrow \mathbf{X}$.

also defined a maximum value for the power of a coupling to be allowed in the entire diagram,

$$\text{InteractionOrderLimit} = \{\text{NP}, 4\}; \quad (4.3)$$

This tells the generator that the largest power of **gd** appearing in the probability amplitude is 4. There is one **gd** factor from the vertex $n_1 \rightarrow \gamma_D + n_D$ and another from the vertex $\gamma_D \rightarrow \mu^+ \mu^-$. Since it is the pair production, I need to double the factors resulting in a power of 4. Finally, I need to provide the desired hierarchy of couplings. **FeynRules** needs this to order contributions to a process according to their relative importance and eventually only keep the largest one. For example, the SM interaction $d\bar{d} \rightarrow b\bar{b}$ has three LO diagrams, corresponding to the exchange of the g , the Z boson, and the γ . The contribution of the Z boson is only a small correction to the one involving g due to the hierarchy between the strong and the electroweak coupling constants. In MSSMD, the hierarchy is defined as,

$$\text{InteractionOrderHierarchy} = \{\{\text{QCD}, 1\}, \{\text{NP}, 2\}, \{\text{QED}, 2\}\}; \quad (4.4)$$

The numbers associated with the couplings give their relative importance, where the smaller number means it is more important. Here, one power of **gd** is considered equivalent to two powers of g_s (for QCD, the strong coupling constant $\alpha_s \propto g_s^2$). Because the subsequent decays after the Higgs in MSSMD do not involve QCD, this definition works well for us.

The broken $U(1)_D$ symmetry gives the dark photon (γ_D) as mentioned in Chapter [1](#). The physics field for the dark photon is defined as,

$$\begin{aligned} \gamma_D := & \{\text{ClassName} \rightarrow \text{AD}, \text{SelfConjugate} \rightarrow \text{True}, \text{Mass} \rightarrow \text{MAD}, \\ & \text{Width} \rightarrow \text{WAD}, \text{PDG} \rightarrow 3000022, \text{PropagatorType} \rightarrow \text{Sine}\}. \end{aligned} \quad (4.5)$$

Here the mass and the width of the γ_D are variables to be set at event generation. The `PropagatorType` attribute `Sine` indicates the dark photon has spin-1 so it propagates like the photon. It also registers a unique ID (3000022) similar to the PDG ID for SM particles.

The lightest neutralino n_1 from the MSSM decay via $n_1 \rightarrow n_D + \gamma_D$, where n_D is the dark neutralino in the dark sector. The physics field for the dark neutralino is,

$$n_D := \{\text{ClassName} \rightarrow \text{neuD}, \text{SelfConjugate} \rightarrow \text{True}, \text{Mass} \rightarrow \text{MneuD}, \\ \text{Width} \rightarrow \text{WneuD}, \text{PDG} \rightarrow 3000001, \text{PropagatorType} \rightarrow \text{Straight}\}. \quad (4.6)$$

Similarly, the mass and the width are changeable at event generation. The `PropagatorType` attribute `Straight` indicates the n_D has spin- $\frac{1}{2}$ so it propagates like a fermion. It has a unique ID (3000001) as well.

The Lagrangian term for vertex $n_1 \rightarrow \gamma_D + n_D$ is written as,

$$\mathcal{L}_{n_1 \rightarrow \gamma_D + n_D} := i \cdot \text{gd} \cdot (\bar{n}_1 \gamma^\mu n_D) \cdot (\gamma_D)_\mu. \quad (4.7)$$

The Lagrangian term for vertex for $\gamma_D \rightarrow \mu^+ \mu^-$ is,

$$\mathcal{L}_{\gamma_D \rightarrow \mu^+ \mu^-} := \text{gd}(\bar{\mu} \gamma^\mu \mu) \cdot (\gamma_D)_\mu, \quad (4.8)$$

and finally the total Lagrangian:

$$\mathcal{L}_{\text{MSSMD}} := \mathcal{L}_{\text{MSSM}} + \mathcal{L}_{n_1 \rightarrow \gamma_D + n_D} + \mathcal{L}_{\gamma_D \rightarrow \mu^+ \mu^-}. \quad (4.9)$$

Based on these, `FeynRules` does the calculation and outputs a UFO model which can be imported in `MadGraph5_aMC` for private event generation [\[1\]](https://github.com/weishi10141993/DarkSUSY_MC_MG5).

https://github.com/weishi10141993/DarkSUSY_MC_MG5

4.2.3 MC Samples in This Search

Events for the NMSSM benchmark model in this search are generated by `PYTHIA 8` [188] event generator (see settings in Appendix C). The dark SUSY and the ALP signal events are generated with `MadGraph5_aMC@NLO 2.4.2` [177,189] which outputs a so-called Les Houches Event (LHE) [190] file containing event contents of the hard scattering process. The LHE file is then interfaced with `PYTHIA 8` to finish the other steps of the event generation.

ALP, NMSSM, and dark SUSY MC samples are generated using only the dominant gluon-gluon fusion channel for SM-like Higgs boson production at LHC as shown in Fig. 4.1. The contribution from other Higgs production channels (Fig 4.2), including the vector-boson fusion, associated production with a vector boson, associated production with the top quark pair, are neglected. More details on the calculation of the Higgs boson production cross sections can be found in [191].

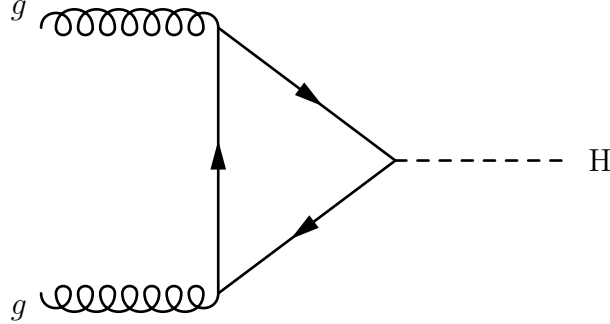


Figure 4.1 : Higgs boson production via the gluon-gluon fusion channel with a fermion triangle loop. The fermions in the loop are most likely the top quarks as they have the largest Yukawa coupling to the Higgs boson.

To make sure the generated events make sense, the kinematics of events in the LHE files are checked. For example, the p_T distributions of four muons from the decay of the generated dark photon signal are shown in Fig. 4.3.

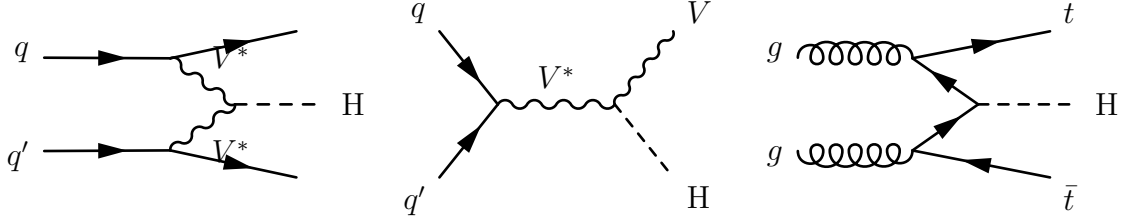


Figure 4.2 : Feynman diagrams for the Higgs boson production via vector boson fusion (left), associated production of Higgs boson production with a vector boson (middle), and the Higgs boson production associated with a top quark pair (right). V can be a Z or W boson.

Full lists of the ALP, dark SUSY and NMSSM signal MC samples in each year are available in Appendix [D](#), [E](#), and [F](#) respectively. As a summary, samples for the ALP benchmark model are generated with the mass of the ALP between 0.5 - 30 GeV while the Higgs boson mass (m_h) is fixed to 125 GeV. The global symmetry breaking scale, Λ , is set as 1 TeV and the Wilson coefficient, C_{ah}^{eff} , is set to 1, which is a quite realistic choice according current upper limits on $\mathcal{B}(h \rightarrow \text{BSM})$ in Fig.15 in [\[94\]](#). In the case of dark SUSY, samples are available with dark photon masses in the range $0.25 < m_{\gamma_D} < 60$ GeV while the masses of the Higgs boson, neutralino and dark neutralino are fixed to $m_h = 125$ GeV, $m_{n_1} = 60$ GeV and $m_{n_D} = 1$ GeV. In addition, for each mass point of dark photon, the nominal lifetime ($c\tau_{\gamma_D}$) are varied in the range 0 - 100 mm. This allows us to probe a wide range of the kinematic mixing parameter (ϵ) as described in Chapter [1](#). Samples for the NMSSM benchmark model are generated with the mass of the $h_{1,2}$ between 90–150 GeV and the mass of a_1 between 0.5–3 GeV.

Several SM MC samples are used for the background estimation above the Υ resonances. Although the details of the background estimation method will be explained in Chapter [6](#), I choose to describe the relevant MC samples here, which are listed in

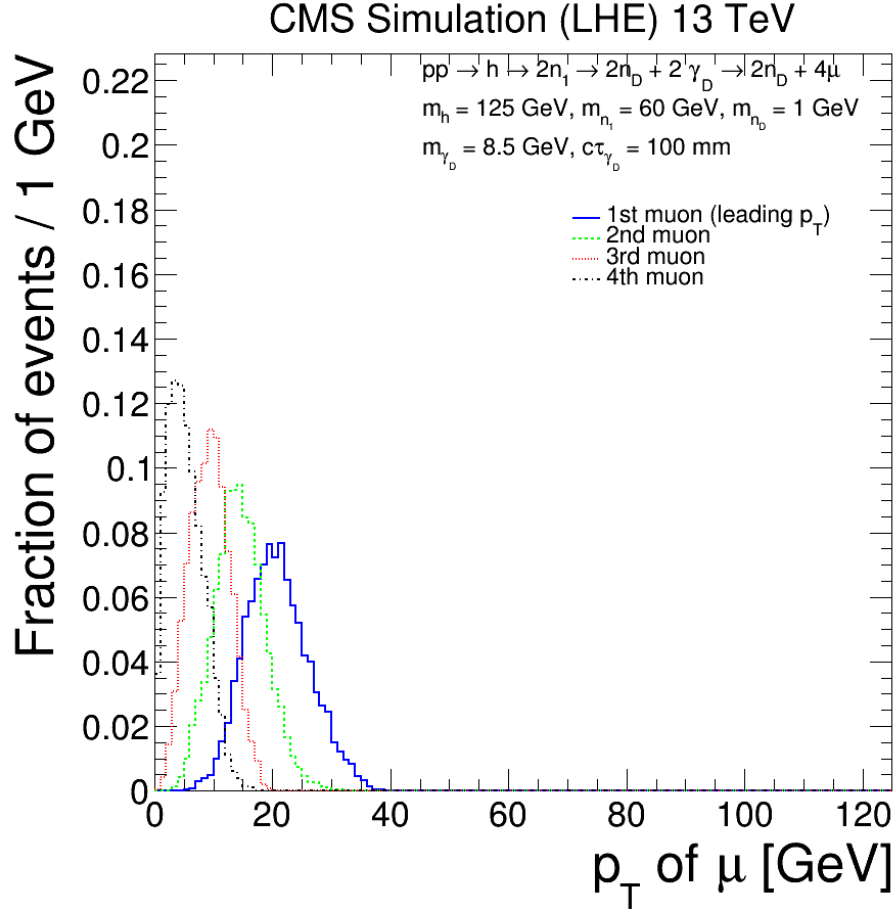


Figure 4.3 : p_T distributions of four generated muon from the LHE file for dark photon signal: $m_{\gamma_D} = 8.5$ GeV, $c\tau = 100$ mm.

Tab. [4.2](#)

Production of ZZ via quark-antiquark annihilation is generated at next-to-leading order (NLO) in perturbative QCD (pQCD) using POWHEG 2.0 [\[192,193,194,195\]](#) and PYTHIA 8. As this simulation covers a large range of ZZ invariant masses, dynamical QCD factorization and renormalization scales have been chosen, equal to m_{ZZ} . The $gg \rightarrow ZZ$ process is simulated at LO with MCFM [\[196,197\]](#). The showering for MCFM samples is performed with PYTHIA 8 settings, allowing only emissions up to the parton

level scale. The SM Higgs boson production via gluon fusion is generated at NLO pQCD using the POWHEG 2.0 generator by including quark mass effects [198]. The cross section is taken from Ref. [199]. The decay of the Higgs boson to four leptons is obtained using the JHUGen generator [200]. Showering of parton level events is done using PYTHIA 8.209, and matching is performed by allowing QCD emissions at all energies in the shower and vetoing them afterward according to the POWHEG internal scale.

The $t\bar{t}$ sample is simulated using the MadGraph5_aMC@NLO 2.4.2 which implements the relevant matrix elements at tree level with up to three additional partons. The MadSpin [201] package is used to incorporate spin correlation effects. The value of the top quark mass is fixed to 172.5 GeV. The generated events are subsequently processed with PYTHIA 8 for parton showering and hadronization. MadGraph5_aMC@NLO 2.6.0 is used to simulate the DY process at NLO. The DY process production rate is normalized to the predicted cross section calculated using the MadGraph5_aMC@NLO. All background samples are generated using the same proton PDF and UE tune as signal samples.

Table 4.2 : 2018 SM MC samples used in final background estimations above 11 GeV.

Dataset	$\sigma \cdot \mathcal{B}(\cdot, \epsilon_{\text{filter}})$ [fb]	Events
/ZZTo4L_13TeV_powheg_pythia8_TuneCP5/RunIIAutumn18MiniAOD-102X_upgrade2018_realistic_v15-v1/MINIAODSIM	1.325E+03	19089600
/GluGluToContInToZZTo4mu_13TeV_MCFM701_pythia8/RunIIAutumn18MiniAOD-102X_upgrade2018_realistic_v15-v2/MINIAODSIM	1.590E+00	911500
/GluGluHTToZZTo4L_M125_13TeV_powheg2_JHUGenV7011_pythia8/RunIIAutumn18MiniAOD-102X_upgrade2018_realistic_v15-v2/MINIAODSIM	1.218E+01	958000
/TTJets_DiLept_TuneCP5_13TeV-madgraphMLM-pythia8/RunIIAutumn18MiniAOD-102X_upgrade2018_realistic_v15-v1/MINIAODSIM	5.264E+04	28701360
/DYJetsToLL_2J_TuneCP5_13TeV-amcatnloFXFX-pythia8/RunIIAutumn18MiniAOD-102X_upgrade2018_realistic_v15-v1/MINIAODSIM	3.684E+05	61054774
/DYJetsToLL_1J_TuneCP5_13TeV-amcatnloFXFX-pythia8/RunIIAutumn18MiniAOD-102X_upgrade2018_realistic_v15-v1/MINIAODSIM	1.016E+06	96753082
/DYJetsToLL_0J_TuneCP5_13TeV-amcatnloFXFX-pythia8/RunIIAutumn18MiniAOD-102X_upgrade2018_realistic_v15-v1/MINIAODSIM	5.351E+06	93979507

Chapter 5

Event Selection

To get the model independent performance on signals and optimize the chance for signal discovery, the following event selections are applied. The general strategy is to achieve a preliminary model independent performance once I get two dimuon candidates. Then I ensure each one of the following selections is independent of model parameters. This is a stringent requirement for the analysis. As we will see, it limits many possible event selection options.

5.1 Trigger and Basic Event Selection

The offline muons used in the analysis are from the DoubleMuon dataset shown in Tab. 4.1. Muon candidates used in this analysis are primarily PF muons described in Chapter 3. They are required to satisfy baseline *Loose* selection requirements, namely, the PF reconstructed muon must be a tracker muon or global muon as well.

I also allow at most one (i.e., ≤ 1) of the four signal muons to be a SA muon only, meaning the muon is only reconstructed as an L2 muon and not reconstructed by the PF algorithm. This measure is necessary for the analysis to mitigate the low reconstruction efficiency of displaced muons in the tracker as I found in 2018 (see more details in Appendix H).

In accordance with the p_T requirement in signal triggers shown in Tab. 3.2, the offline p_T cuts are a bit above the trigger p_T threshold to ensure the efficiency is

relatively high and flat. To summarize, the basic muon selection requires,

- ≥ 3 PF *Loose* muons and ≤ 1 SA muon,
- two muons $p_T > 24$ GeV, $|\eta| < 2$,
- four muons $p_T > 8$ GeV, $|\eta| < 2.4$.

The requirement of two muons with p_T above 24 GeV and $|\eta|$ less than 2 is mainly dictated by the L2 muon trigger (HLT_DoubleL2Mu23NoVtx_2Cha) implementation requirement. This basic muon selection is applied offline as well as at the generator level for the signal MC samples. The combined efficiency of all signal triggers in Tab. 3.2 as a function of p_T and the transeverse displacement (L_{xy}) on one of the 2018 dark SUSY signal MC samples is shown in Fig. 5.1 and Fig. 5.2.

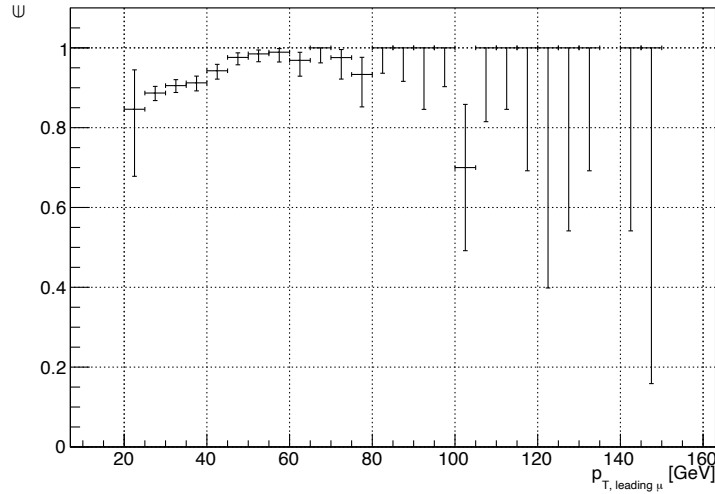


Figure 5.1 : Trigger efficiency, ϵ , as a function of the p_T of the leading p_T muon from a 2018 dark SUSY MC sample: dark photon mass (m_{γ_D}) = 25 GeV, $c\tau = 100$ mm.

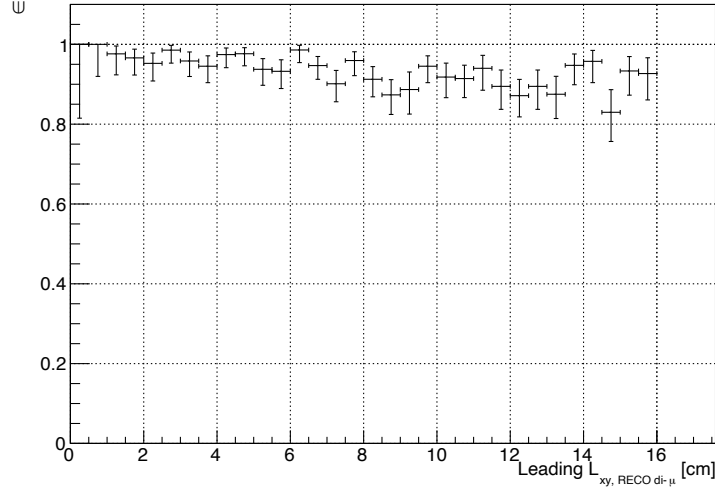


Figure 5.2 : Trigger efficiency, ϵ , as a function of the reconstructed dimuon transverse displacement (L_{xy}) from a 2018 dark SUSY MC sample: dark photon mass (m_{γ_D}) = 25 GeV, $c\tau = 100$ mm.

The trigger efficiency is high (over 90%) as a function of offline reconstructed leading muon p_T and of the leading transverse displacement (L_{xy}) of two reconstructed dimuons (discussed in the next section). The L2 muon trigger plays an important role in triggering large $c\tau$ signals as the displaced muons that failed to be reconstructed in the tracker can be picked up by the standalone muon reconstruction using only muon detectors. The slight drop in efficiency as L_{xy} increases is expected and acceptable. The mean trigger efficiency for all 2018 dark SUSY MC samples is shown in Fig 5.3. The trigger efficiency is high and consistent overall across the entire probed parameter space of the dark SUSY benchmark model.

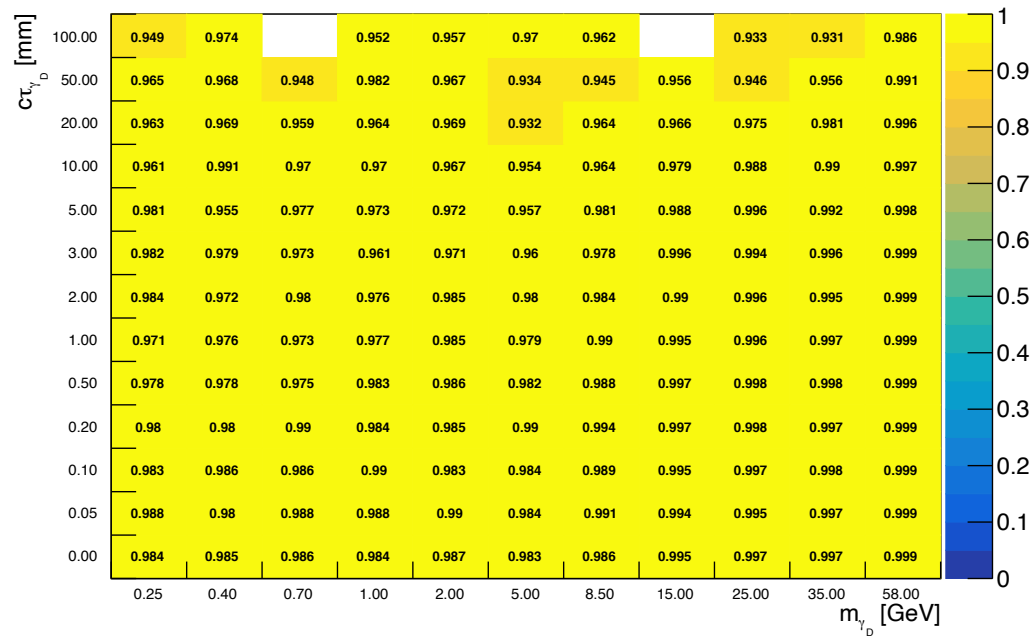


Figure 5.3 : Mean trigger efficiency on all 2018 dark SUSY MC samples.

5.2 Muon Pairing and Selection

Since the final state consists of oppositely charged muons as decay products of the mother boson, an algorithm is designed to pair muons and select two distinctive pairs as signal candidates. A flow chart of the algorithm is shown in Fig. 5.4.

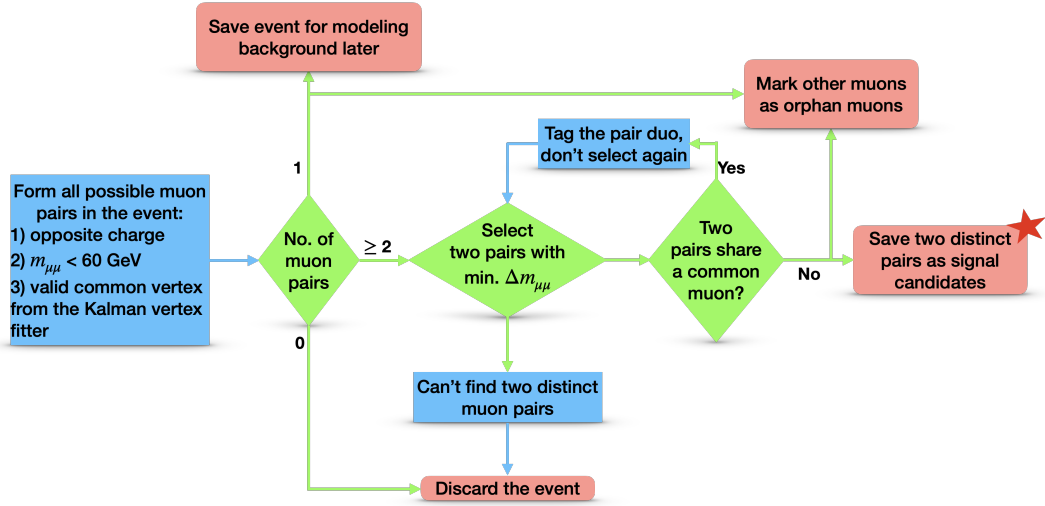


Figure 5.4 : Muon pairing and selection algorithm used in the analysis.

All muons in the event are looped over and any two of them with opposite charges are paired as long as their invariant mass is below 60 GeV. The upper mass cut is smaller than half of the discovered 125 GeV Higgs boson by about five times the detector resolution to ensure no detector effects on the highest probed mass. With this pairing method, one muon could be used in more than one pair. A Kalman vertex fitter is used to fit a common vertex for two muons in each pair. Those pairs with a valid fitted vertex are kept for further selection. This is necessary as muons far apart from each other in the detector could also have a correct mass of the signal.

Further selection of dimuons is made by finding the two dimuons that have the

minimum difference in their invariant mass. The absolute value of the difference of invariant masses of any two dimuons, $\Delta m_{\mu\mu}$, is calculated and then ordered from the lowest to the highest. An inspection is done for the two dimuons with the lowest $\Delta m_{\mu\mu}$ by checking whether or not they share a common muon. If they do not share one common muon, then they are used as signal candidates. If, for example, these two dimuons share one common muon, they are not considered as signal candidates and the inspection goes on to the next two dimuons in order. Such inspections are performed until two distinctive dimuons are found in one event. In the case no such two dimuons are found, all muons are marked as orphan muons. In cases where only one dimuon exists in the event, the rest of the muons are labeled orphan muons. Such one-dimuon events will be used for the background estimation in Chapter 6.

Note that no restriction on the number of orphan muons in the event is applied. While I could reject events with orphans, it would introduce unnecessary model dependency into the results. One example could be Higgs boson production in association with one or more energetic jet, where the probability of a non-muon track from a jet being incorrectly associated with some of the muon stubs available in the event resulting in a reconstructed orphan muon is not negligible.

5.3 Fiducial Volume for Displaced Signals

As mentioned in Chapter 1, certain long-lived signal bosons can be displaced from the pp interaction point before decaying. I use a fiducial volume based on the Phase-1 pixel detector volume with $L_{xy} < 16.0$ cm and $|L_z| < 51.6$ cm, corresponding to the radius from the center of the detector to the fourth layer in BPIX and the length to the third layer in FPIX respectively (see Fig. 2.3 in Chapter 2). For the two candidate dimuons, I require at least one muon in each dimuon has at least one valid hit in one

of the four BPIX layers or one valid hit in at least one of the three FPIX layers. For MC studies, the same cut on L_{xy} and L_z is required on the signal boson before they decay into muons.

5.4 Dimuon Vertex Fitted Probability

As mentioned in Sec. 5.2, the dimuon vertex is fitted by a Kalman vertex fitter^{*}. It is a fitter using the Kalman filter formalism [171]. The dimuon vertex fitting returns a probability based on the chi-square and degrees of freedom. I cut on the returned probability to achieve a preliminary model independent performance on signals. The probability cut is applied to each dimuon in the event. For each dimuon vertex with fitted probability $P_{\mu\mu}$, I require

$$P_{\mu\mu} > P(L_{xy}, f(\Delta R), N_{SA}), \quad (5.1)$$

where $P(L_{xy}, f(\Delta R), N_{SA})$ is a function of the dimuon transverse displacement, L_{xy} , the opening angle of two muons in the dimuon, $\Delta R = \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2}$, and the number of SA muon it contains, N_{SA} (≤ 1). The exact function is written as,

$$P(L_{xy}, f(\Delta R), N_{SA}) = P_0 \times (1 - N_{SA}) \times e^{-\left(\frac{L_{xy}}{R_0}\right)^2 \times f(\Delta R)}. \quad (5.2)$$

Here, the baseline probability $P_0 = 20\%$. The symbol R_0 represents a constant length of 10 cm and $f(\Delta R)$ is a polynomial function of degree 4:

$$f(\Delta R) = 8.54 - 50.46(\Delta R)^{1/2} + 109.83\Delta R - 92.74(\Delta R)^{3/2} + 36.84(\Delta R)^2. \quad (5.3)$$

The functions in Eq. 5.2 and Eq. 5.3 are semi-empirical. As I know, in general, the fitted probability is lower with the increase of the L_{xy} of the signal dimuon as

^{*}A comprehensive description of the Kalman filter technique can be found in CMS internal note 2003/008 and 2006/032.

well as the opening angle of two muons of the dimuon. These are addressed by the exponential decaying factor that couples the displacement and the opening angle, which relaxes the probability cut and keep the efficiency high for more displaced and massive signals. I still want to keep the events with one SA muon as I mention in basic muon selection. The factor $(1 - N_{SA})$ ensures zero probability cut is required on the dimuon if it has the only one SA muon ($N_{SA} = 1$) allowed in the event because I expect such dimuons have lower fitted vertex probability. After this selection, a preliminary model independent behavior is achieved over the entire parameter space of the dark SUSY signal as shown in Fig. 5.5.

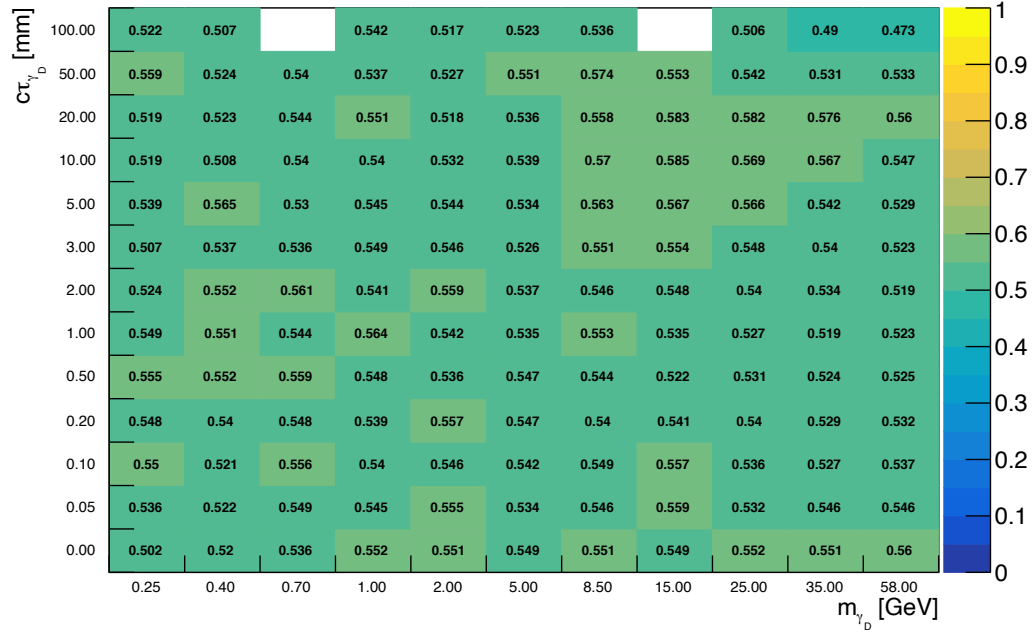


Figure 5.5 : Signal efficiency after the vertex probability requirement.

5.5 Dimuon Isolation

An isolation requirement on each dimuon is used. I use the absolute isolation of dimuons to suppress background events with muons from heavy-flavor $b\bar{b}$ and $t\bar{t}$ decays (Chapter 6). I choose to use the absolute isolation definition because the relative isolation is always p_T dependent, which would severely complicate a model independent interpretation of the results. The absolute dimuon isolation variable,

$$\text{Iso}_{\mu\mu} = \sum_{\text{tracks}} p_T(\text{track}), \quad (5.4)$$

sums over all reconstructed tracks with requirements:

- $p_T(\text{track}) > 0.5 \text{ GeV}$,
- $\Delta R(\text{track}, \mu\mu) < 0.4$,
- $|z_{\text{track}} - z_{\mu\mu}| < 0.1 \text{ cm}$,
- tracks associated with all four muons forming the two dimuons are excluded.

Here, the position of the signal boson production vertex at the beamline is written as $z_{\mu\mu}$. When defining $z_{\mu\mu}$, I assume that each signal boson is produced sufficiently close to the beamline but allow for a non-negligible lifetime before decaying to a muon pair. In other words, the candidate new boson's parent particle, in this case, the Higgs boson, can not be long-lived. I first calculate the 3D direction of the momentum of the signal boson candidate $\vec{p}_{\mu^+} + \vec{p}_{\mu^-}$ at the position of the reconstructed common vertex of the two muons (or, for muons with very close directions where the vertex is not reconstructed, at the points on the respective trajectories where the two tracks are the closest to each other in xy -plane). Next, I project a straight line along the dimuon direction vector from the common vertex (or the point in the middle of the

segment connecting the points on the trajectories where momenta of the two muons are calculated) towards the beamline. The z -coordinate of the projected line at the point of closest approach to the beamline in the xy -plane becomes the reconstructed $z_{\mu\mu}$ of the production vertex.

The distribution of the dimuon isolation in signal MC as well as in QCD processes are shown in Fig. 5.6 and Fig. 5.7, including QCD enriched dataset (Fig. 5.6) and MC samples (Fig. 5.7). The QCD enriched dataset consists of events from the DoubleMuon dataset where only one dimuon exists after the muon pairing step described in Sec. 5.2. The QCD MC samples include hard scattering processes with p_T above 15 GeV and are enriched in muons by applied muon filters. Full list of QCD samples can be found in Tab. J.1 in Appendix J.

I apply to each dimuon the requirement of isolation less than 2.3 GeV in a cone of $\Delta R < 0.4$. This choice keeps 90% efficiency for each signal dimuon and meanwhile rejects $\approx 71.8\%$ of the QCD background if using QCD enriched data and rejects $\approx 72.4\%$ QCD background if using QCD MC samples. The QCD data and MC show good agreement in terms of the background rejection performance. The cut is also independent of the signal lifetime as shown in Fig. 5.8.

Note that in events with one SA muon, the dimuon that contains the SA muon is not required to pass the above isolation requirement. This is because the reconstructed dimuon vertex $z_{\mu\mu}$ can be deviated from the MC truth due to the SA muon. There is also another technical caveat that prevents us from calculating the isolation variable for such dimuons. The reconstructed muon tracks in the DoubleMuon dataset are associated with PF muons, which is not available for a SA muon.

Studies were also done on single muon isolation, but it diminishes the model independent performance when the signal becomes displaced. More details can be

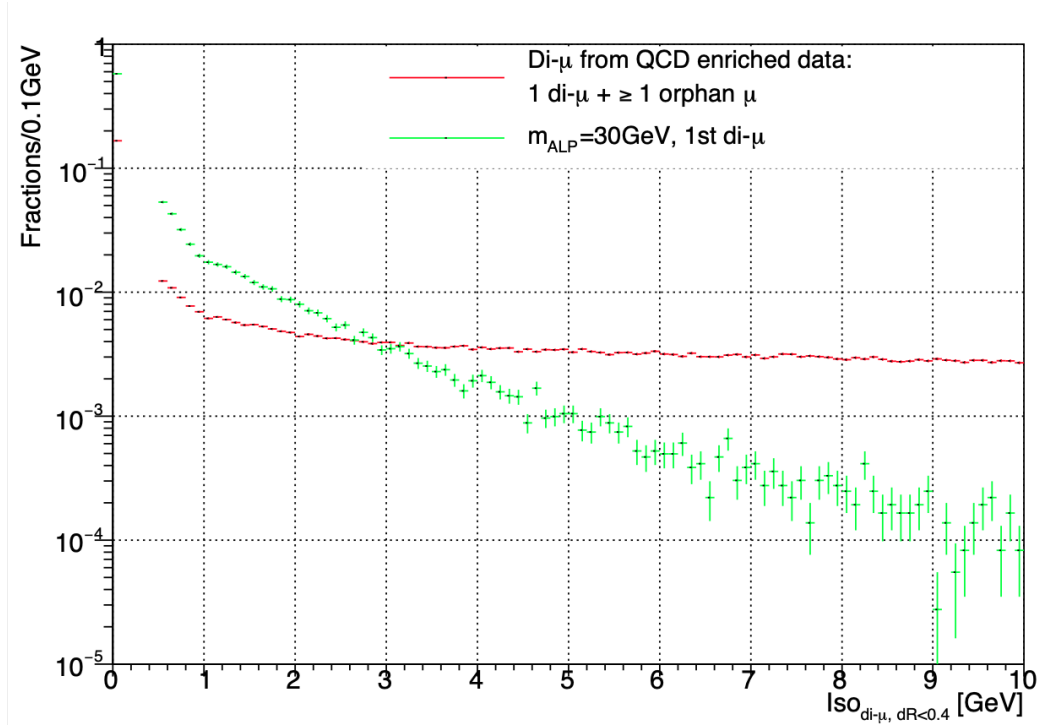


Figure 5.6 : First dimuon isolation in a cone of $\Delta R < 0.4$ in an ALP sample ($m_{\text{ALP}} = 30 \text{ GeV}$) compared with QCD enriched dataset.

found in Appendix [J](#).

5.6 Dimuon Mass Consistency

As the new boson couples to the SM particles weakly, they have narrow width. The shape of the dimuon invariant mass distribution is fully determined by the detector resolution and FSR from the muons. Ideally, one would fit the signal dimuon mass spectrum to extract its resolution and then set the mass window cut based on this resolution. In reality, the mass spectrum of our signals have radiative tails and reconstruction failures. These effects are strongly dependent on the mass and lifetime of the signal, making it hard to obtain a well-defined resolution for the model inde-

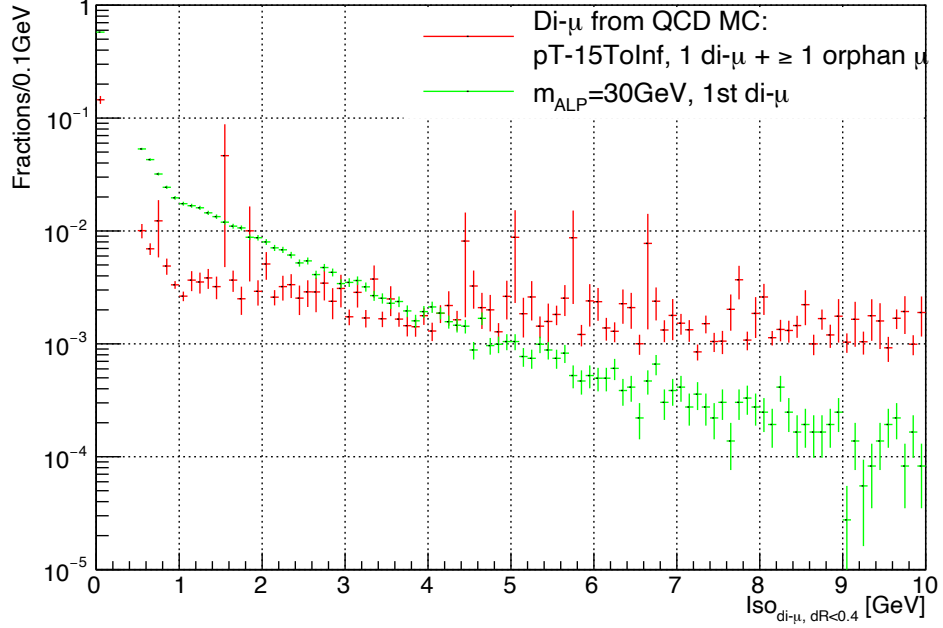


Figure 5.7 : First dimuon isolation in a cone of $\Delta R < 0.4$ in an ALP sample ($m_{\text{ALP}} = 30$ GeV) compared with muon enriched QCD MC samples.

pendent analysis. All plots of Crystal Ball function [202] fitting the dimuon mass spectrum for the dark SUSY signals as well as relevant discussions are available in Appendix I.

A method based on desired efficiency on prompt signals is used to calculate the mass window:

$$|m_1 - m_2| < W\left(\frac{m_1 + m_2}{2} \mid \text{efficiency on prompt signals}\right). \quad (5.5)$$

Signal MC samples are used to evaluate the needed mass window size for a desired efficiency. For example, for a 90% efficiency on prompt dark SUSY signals, the needed mass window, $W\left(\frac{m_1 + m_2}{2}\right)$, is shown in Tab. 5.1.

Linear interpolation is done between consecutive mass points in the table. Four

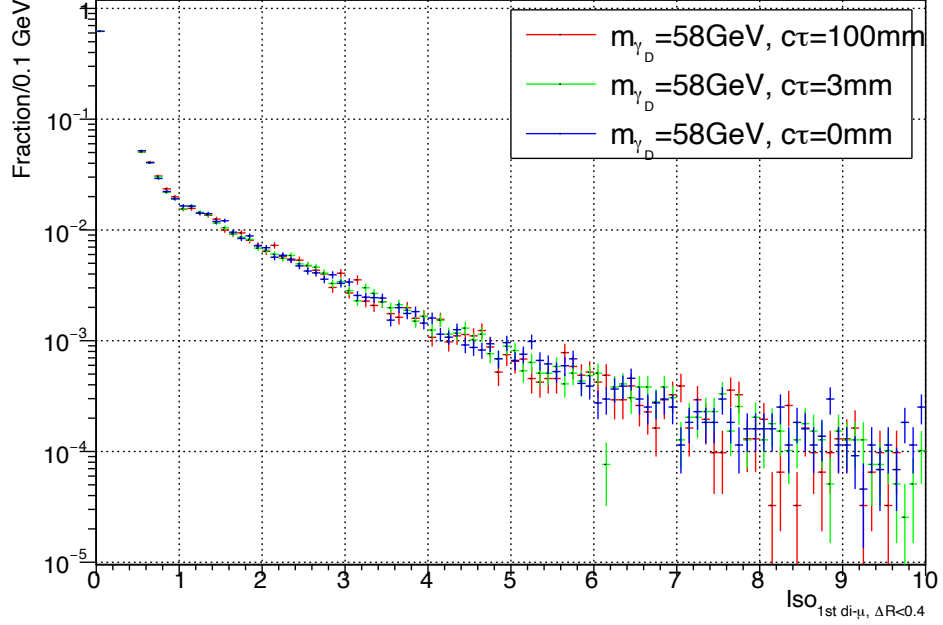


Figure 5.8 : Isolation distribution ($\Delta R < 0.4$) of the first dimuon from dark photon (MSSMD) signal MC with $m_{\gamma_D} = 58 \text{ GeV}$ with three different lifetime choices: 100 mm (red), 3 mm (green) and 0 mm (blue).

choices of signal efficiency are examined: 80%, 85%, 90%, and 95%. The significance of each mass window choice under specific signal efficiency is inspected to decide which mass window is the best. This is shown in Fig. 5.9.

From the plot, it is easy to tell the signal significance decreases as the signal becomes massive. This is expected behavior as the background events increase at a roughly constant rate as the mass window widens, but more massive signals have a smaller production cross section. It is also easy to see at small mass signals, the best significance is given by the mass window from 95% signal efficiency. This is however not the case at higher mass. With the help of zoomed-in plots in Fig. 5.10

Table 5.1 : Needed mass window $W(\frac{m_1+m_2}{2})$ for a 90% efficiency on prompt dark SUSY signals.

m_{γ_D} [GeV]	0.25	0.4	0.7	1	2	5	8.5	15	25	35	58
$W(\frac{m_1+m_2}{2})$ [GeV]	0.044	0.034	0.036	0.043	0.075	0.204	0.354	0.704	1.20	1.61	3.99

and Fig. 5.11, I can tell that changes in the signal significance are relatively small at low mass when varying the desired efficiency, but for the mass point of 35 GeV (Fig. 5.10), the 90% efficiency gives larger signal significance. For 58 GeV (Fig. 5.11), the signal significance is the largest at 80% signal efficiency. The final mass window choice is based on 90% prompt signal efficiency. The choice is made to balance the discovery potential over the entire probed mass range.

Other event selection also includes the requirement of at least one primary vertex with at least 4 tracks and with the vertex global z coordinate within 24 cm from the CMS origin. Discussions on several cut options that were considered but are not applied to this model independent search can be found in Appendix I.

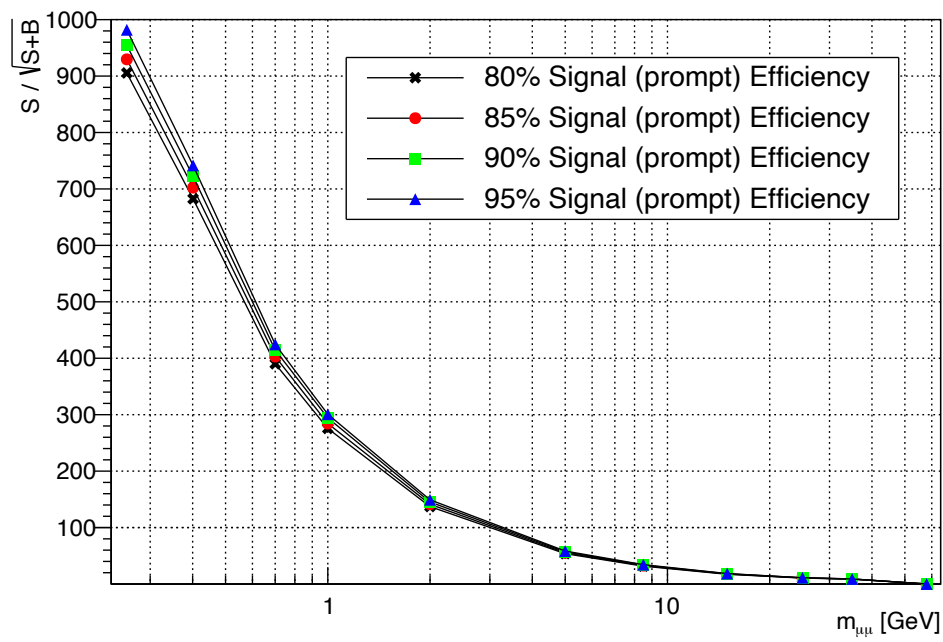


Figure 5.9 : Signal significance at different mass window choices based on desired efficiency on prompt signals. Four choices of efficiency are examined: 80% (black), 85% (red), 90% (green) and 95% (blue).

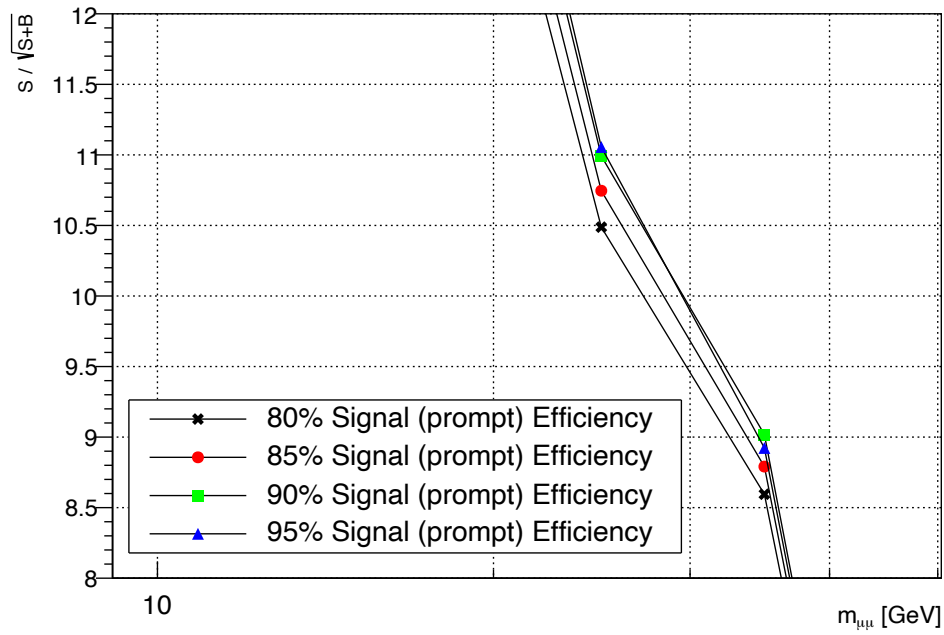


Figure 5.10 : Zoom in view of Fig. 5.9 at mass point 25 GeV and 35 GeV.

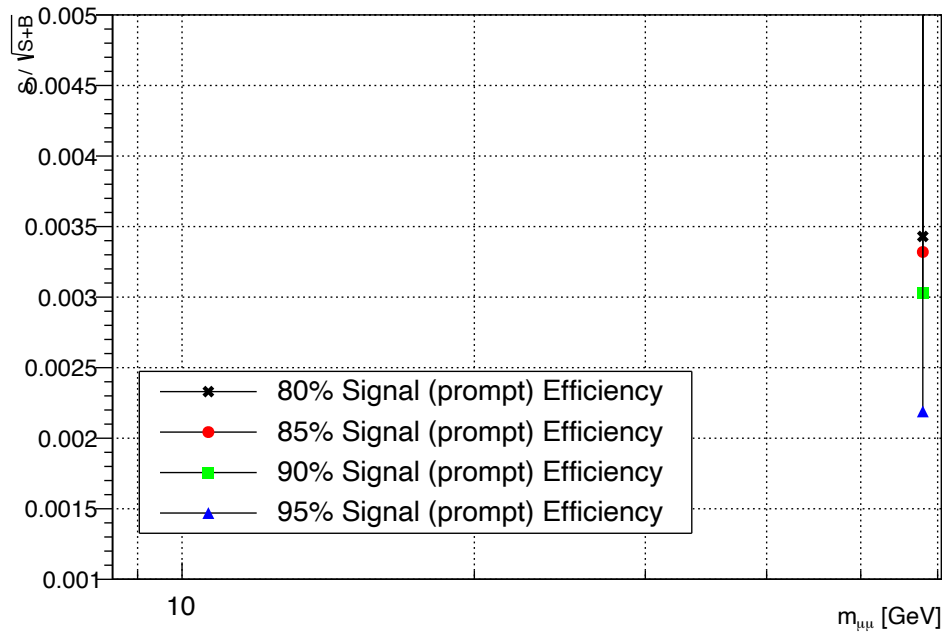


Figure 5.11 : Zoom in view of Fig. 5.9 at mass point 58 GeV.

5.7 Summary

To facilitate future reinterpretation of the results of this analysis in Chapter 8, I calculate the efficiency of generator level acceptance, α_{Gen} , using generator level information only:

$$\alpha_{\text{Gen}} = \frac{N_{\text{GEN Sel.}}}{N_{\text{Events}}}, \quad (5.6)$$

where N_{Events} is the total number of generated MC events, and $N_{\text{GEN Sel.}}$ is the number of events passing the generator level event selection requirements on η , p_T , and fiducial volume.

I also define the ratio of the efficiency of all analysis selections, ϵ_{Full} , as:

$$\epsilon_{\text{Full}} = \frac{N_{\text{RECO Sel.}}}{N_{\text{Events}}}, \quad (5.7)$$

where $N_{\text{RECO Sel.}}$ is the total number of events satisfying the full analysis selection including the muon selection requirements on η and p_T , exactly two dimuons in the event, one hit in one of the pixel barrel or endcap layers per dimuon, the isolation requirement, the requirement on the mass compatibility requirement, the requirement that the event fire the HLT as well as some requirements for background rejection to be discussed in Chapter 6.

These quantities, α_{Gen} and ϵ_{Full} , are useful for quantifying the sensitivity of this analysis in a model independent fashion. I check that the ratio $\epsilon_{\text{Full}}/\alpha_{\text{Gen}}$ is independent of the lifetime and mass of the dark photon in dark SUSY samples, of the masses of the $h_{1,2}$ and a_1 in NMSSM samples, and of the masses of the ALP in ALP samples. The final $\epsilon_{\text{Full}}/\alpha_{\text{Gen}}$ ratio plots are presented for all benchmark models in Fig. 5.12 (dark SUSY), Fig. 5.13 (ALP) and Fig. 5.14 (NMSSM). By verifying this ratio, $\epsilon_{\text{Full}}/\alpha_{\text{Gen}}$, is insensitive to variations of model parameters, I ensure that the analysis remains model independent. An overall $\epsilon_{\text{Full}}/\alpha_{\text{Gen}} = 0.418 \pm 0.001$ is found

by calculating the average value from all signal MC samples.

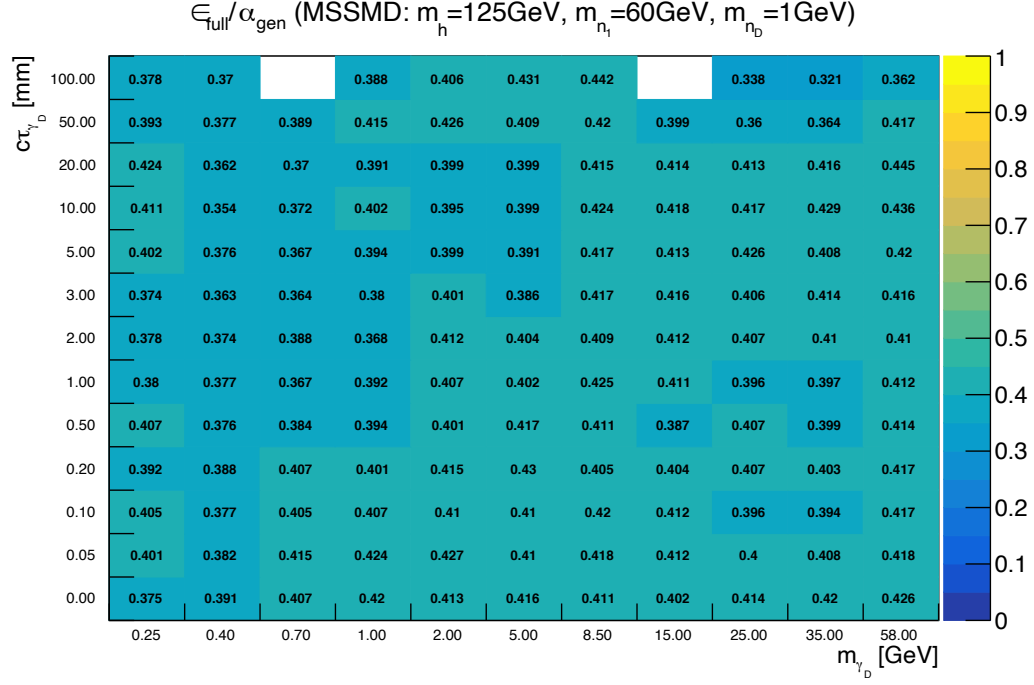


Figure 5.12 : Total selection efficiency over generator level selection efficiency as a function of the dark photon mass (m_{γ_D}) and lifetime ($c\tau_{\gamma_D}$) in dark SUSY model.

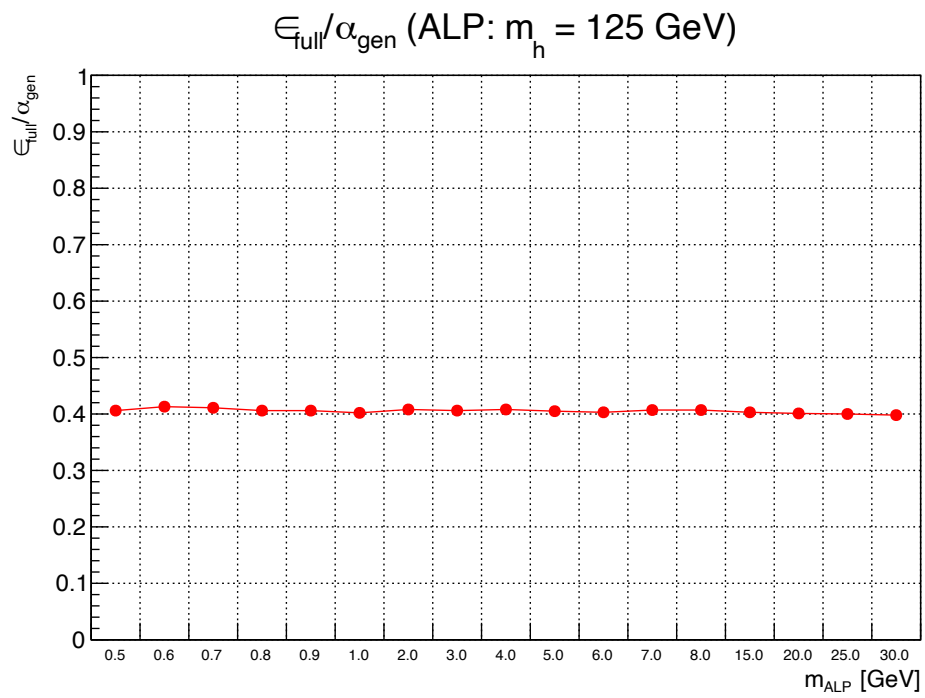


Figure 5.13 : Total selection efficiency over generator level selection efficiency as a function of the ALP mass (m_{ALP}) in ALP model.

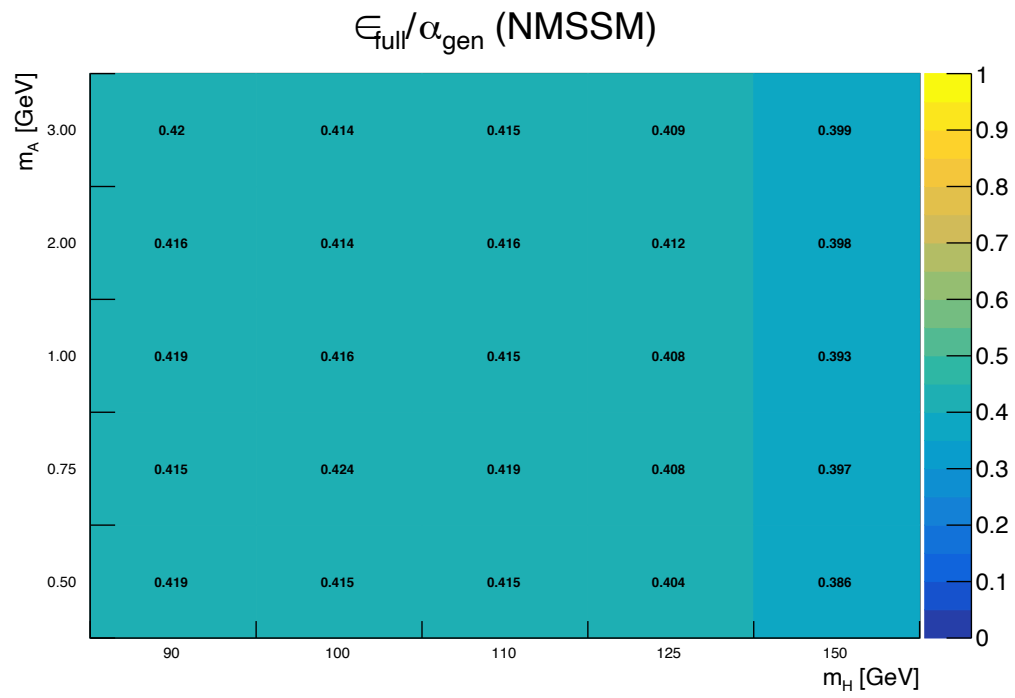


Figure 5.14 : Total selection efficiency over generator level selection efficiency as a function of the CP-even Higgs boson mass (m_H) and CP-odd Higgs boson mass (m_h) in NMSSM model.

Chapter 6

Background Modeling

6.1 Overview

As I am probing a mass range that spans over two orders of magnitude, many SM processes come into play. The background estimation method also varies depending on the probed mass region. For low masses, starting from invariant mass of two muons (i.e., ~ 0.21 GeV) up to 9 GeV (i.e., below the Υ resonances), the dominant background comes from QCD processes. Such QCD processes usually have large production cross sections at LHC and are hard to model precisely with MC samples because of the shortage of sample statistics. So a data-driven method is used to model the background shape and estimate its yield. For high masses, from 11 GeV (i.e., above the Υ resonances) up to 60 GeV (i.e., roughly half the Higgs boson mass), the four lepton background is dominated by electroweak processes where two Z bosons are produced and decay to muons. These processes are well understood and usually have a smaller production cross section because of the heavy Z boson. As a result, I use centrally produced MC samples to do background estimation. The Υ resonances are avoided in the search as well as the J/ψ resonances for reasons that will be explained later.

6.2 Low Mass Background: Below 9 GeV

The leading part of the QCD background contribution is dominated by events in which both b quarks decay to pairs of muons via double semi-leptonic decays or resonances, e.g. ω , ρ , ϕ , J/ψ , ψ . A smaller contribution comes from events with a true muon from semi-leptonic b quark decay and a charged track misidentified as another muon due to an occasional incorrect assignment of some of the true muon segments reconstructed in the muon system to a nearby track, resulting in two muon candidates. The fraction of these cases decreases as the momentum of the two muons increases. The isolation requirement imposed on dimuons candidates also ensures that two dimuons always come from two well-separated b jets.

6.2.1 Construct the 2D Background Template

I need to construct a 2D background template as a function of the invariant mass of each dimuon. To achieve this, I first construct two separate 1D mass templates with b quark enriched events. Then the 2D background template is formed by doing a product of two 1D mass templates based on the fact that in QCD processes, two b quarks decay independently.

A control data sample is used to construct the 1D background template. Events with only one dimuon and at least one orphan muon are selected from the same 2018 DoubleMuon dataset in Tab. [4.1](#). In case there are more than one orphan muons in the event, the one with the highest p_T is used. The requirement of an extra orphan muon in addition to the only dimuon is purely driven by the signal triggers because I used some triple muon triggers as shown in Tab. [3.2](#). The requirements on p_T and η are summarized here,

- ≥ 2 PF *Loose* muons and ≤ 1 SA muon,
- two muons $p_T > 24$ GeV, $|\eta| < 2$,
- three muons $p_T > 8$ GeV, $|\eta| < 2.4$.

Similar selections used for signal events are applied to the control sample, including the probability cut on fitted dimuon vertex, isolation cut on the dimuon, valid pixel hit requirement on either muon in the dimuon, and passing any one of the signal triggers in Tab. 3.2, etc. Depending on whether the orphan muon has p_T above 24 GeV, these events are separated into two categories. The first category (m_1) corresponds to those events where the two muons in the only dimuon both have p_T above 24 GeV and $|\eta| < 2$. The rest of the events belong to the second category (m_2) where the orphan muon has p_T above 24 GeV and $|\eta| < 2$. This follows the same criteria as I assign two signal dimuons. The mass distributions for two dimuons in 2018, m_1 and m_2 , are shown in Fig. 6.1 and Fig. 6.2.

I fitted the unbinned control data sample with a parametric function using extended unbinned likelihood. The parametric functions for below and above J/ψ are,

$$\begin{aligned}
\mathcal{F}_{\text{Below } J/\psi}(m; p_\eta, p_\omega, p_\phi, p_B, p_{06}, \dots, p_{66}) \\
= p_\eta G(m; m_{0,\eta}, \sigma_\eta) + p_\omega G(m; m_{0,\omega}, \sigma_\omega) + p_\phi G(m; m_{0,\phi}, \sigma_\phi) \\
+ p_B B(m; p_{06}, \dots, p_{66}) + p_{AH} G(m; m_{0,AH}, \sigma_{AH}) \\
+ p_{E0} \left[\left(\frac{m}{m_{0,min}} \right)^2 - 1 \right]^{p_{E1}} \times \exp \left[-p_{E2} \left[\left(\frac{m}{m_{0,min}} \right)^2 - 1 \right] \right],
\end{aligned} \tag{6.1}$$

$$\begin{aligned}
\mathcal{F}_{\text{Above } J/\psi}(m; p_\psi, p_B, p_{06}, \dots, p_{66}) \\
= p_\psi G(m; m_{0,\psi}, \sigma_\psi) + p_B B(m; p_{06}, \dots, p_{66}),
\end{aligned} \tag{6.2}$$

where η , ω , ϕ , and ψ resonances are parametrized using $G(m; m_0, \sigma)$, a Gaussian normalized to a unit integral in the region below and above the J/ψ depending on

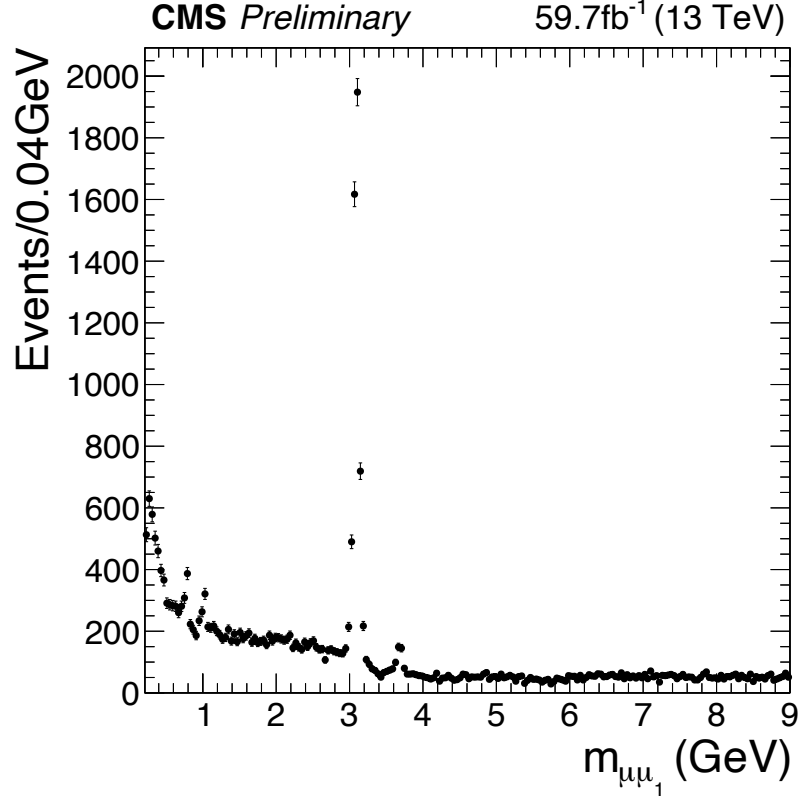


Figure 6.1 : The first dimuon mass m_1 distribution from the control data sample.

where the resonance locates. For each resonance, the mass m_0 is fixed to the corresponding PDG [11] mass and the resolution σ is fixed to the detector resolution. The mass (resolution) values are 0.548 (0.030) GeV for η , 0.782 (0.031) GeV for ω , 1.019 (0.033) for ϕ , and finally 3.686 (σ_ψ) GeV for ψ , where σ_ψ is allowed to float in the fits. For these SM resonances, only the normalization is allowed to vary, except the ψ resonance, where also the width is free to vary.

The bulk shape is described in both regions using $B(m; p_{06}, \dots, p_{66})$, a series expansion in the Bernstein polynomial basis* of power 6. A Gaussian and a decaying

*See <http://www.idav.ucdavis.edu/education/CAGDNotes/Bernstein-Polynomials.pdf>. Bernstein basis polynomials are positive-definite, thus, by providing n non-negative coefficients I can

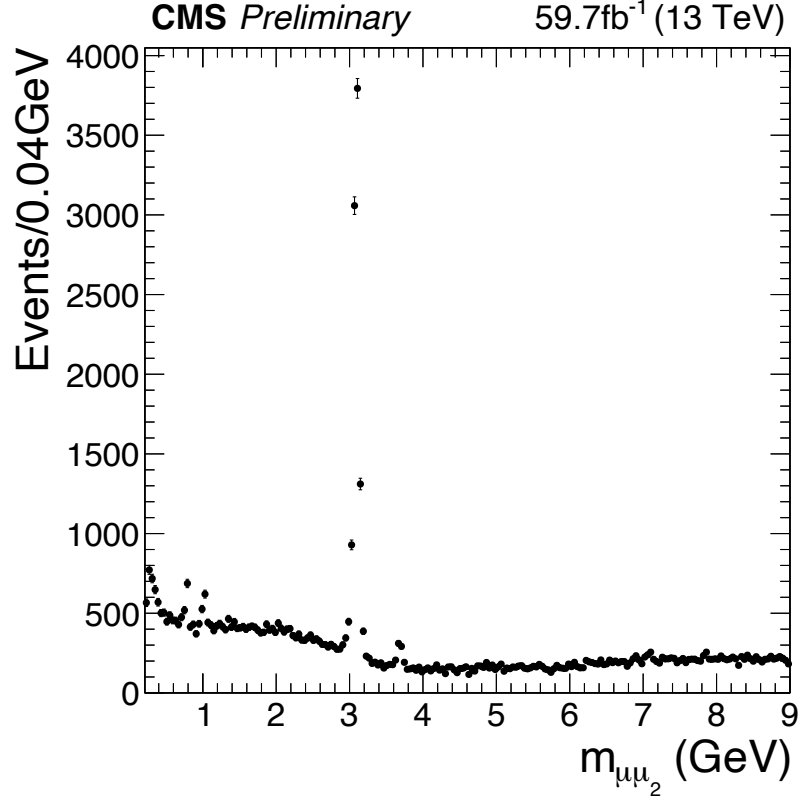


Figure 6.2 : The second dimuon mass m_2 distribution from the control data sample.

exponential was added in the low mass region (< 0.5 GeV) to model kinematic bumps in the low mass region ($m_{0,min} = 0.2113$ GeV). The p_η , p_ω , p_ϕ , and p_B are normalization factors for the resonances and bulk component respectively. They are also obtained from the fit as extended parameters. The fit, as well as the control data distributions for both dimuons below and above J/ψ , are shown in Fig. 6.3 for 2018. The fits are shown as solid red lines. The chi-square tests have been performed and have returned values showing the goodness of fit as described in the captions. Full lists of all fitted parameters are shown in Appendix K.

I excluded the J/ψ region (from 2.72 GeV to 3.24 GeV). One reason is that, if

get a well-behaving p.d.f. approximation. I used its implementation in RooFit.

there is a small signal from the new boson under a huge J/ψ peak, it is not going to be convincing. Such a scenario deserves a dedicated precise measurement on the J/ψ . The second argument follows from the first: the yield at J/ψ resonance dominates the template statistics while I'm more interested in the region outside the J/ψ peak.

The 1D fit of the control data sample for m_1 and m_2 is then multiplied to construct the 2D template below and above the J/ψ resonances shown in Fig. [6.4](#) and Fig. [6.5](#). The 2D background templates represent our expected background distributions in the 2D mass plane.

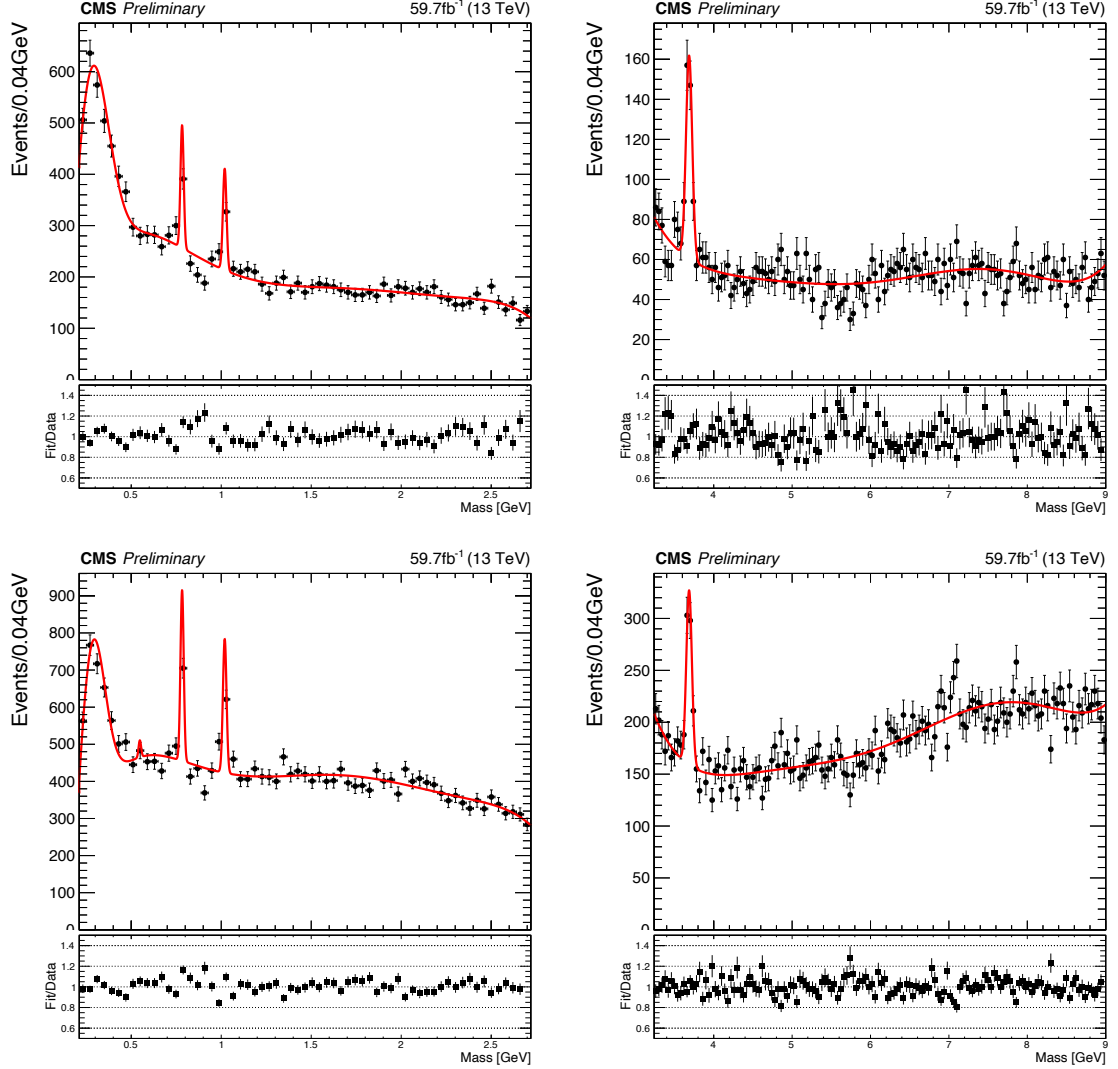


Figure 6.3 : Fit to 2018 control data. Top left: the first dimuon mass m_1 and fitted function below J/ψ , $\chi^2/\text{ndf} = 1.49$. Top right: the first dimuon mass m_1 and fitted function above J/ψ , $\chi^2/\text{ndf} = 1.18$. Bottom left: the second dimuon mass m_2 and fitted function below J/ψ , $\chi^2/\text{ndf} = 1.72$. Bottom right: the second dimuon mass m_2 and fitted function above J/ψ , $\chi^2/\text{ndf} = 1.33$.

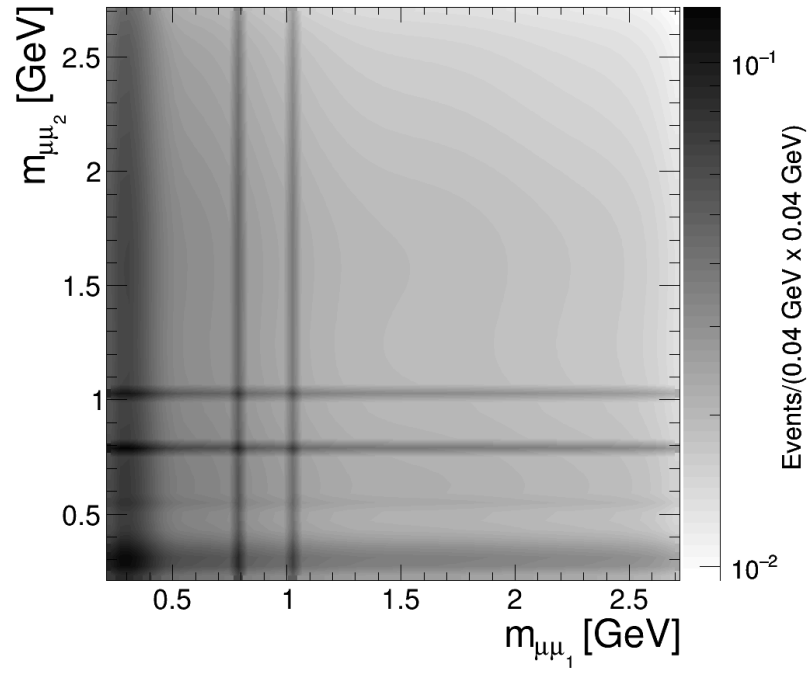


Figure 6.4 : 2D background template for 2018 below the J/ψ .

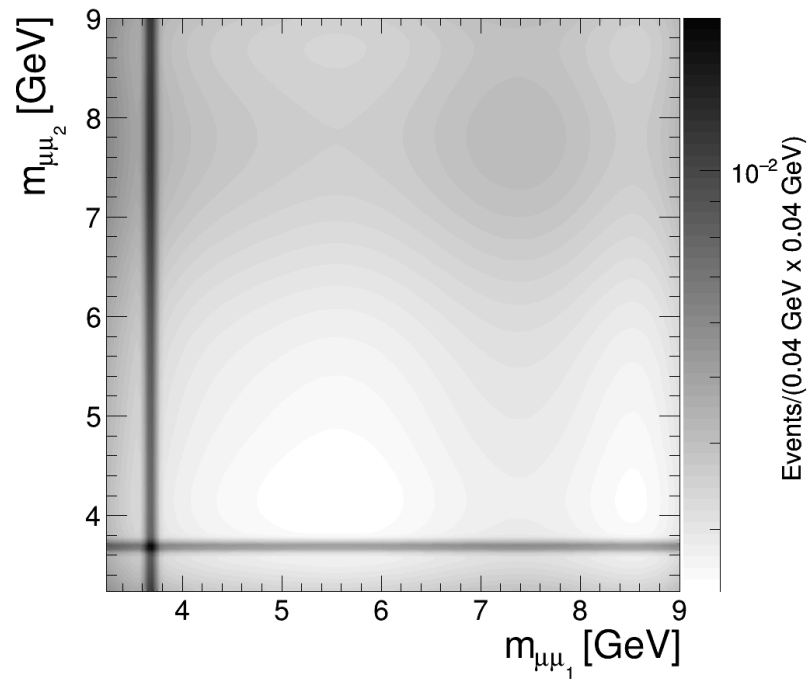


Figure 6.5 : 2D background template for 2018 above the J/ψ .

6.2.2 Estimated Background Events

I now overlay actual data events with two dimuons in the control region (CR) to calculate the estimated background yield in the signal region (SR). In Fig. 6.6 and Fig. 6.7, events with two dimuons passing all analysis selections except the mass consistency requirement from data are shown in the CR as empty circles. The 2D template is scaled to the data based on these events at CR. The SR bounded by dashed lines in the diagonal corridor is blinded at the moment. From the template, I can give the estimated number of background events in the SR based on the ratio of entries in SR and CR of the 2D template. The result is shown in Tab. 6.1.

Table 6.1 : Estimated background events in 2018 below the Υ Resonances

Region	Integral ratio (SR/CR)	CR data events	Est. events at SR	Stat. Unc.
Below J/ψ	0.043/0.969	98	4.34	0.44
Above J/ψ	0.035/0.965	66	6.16	0.76

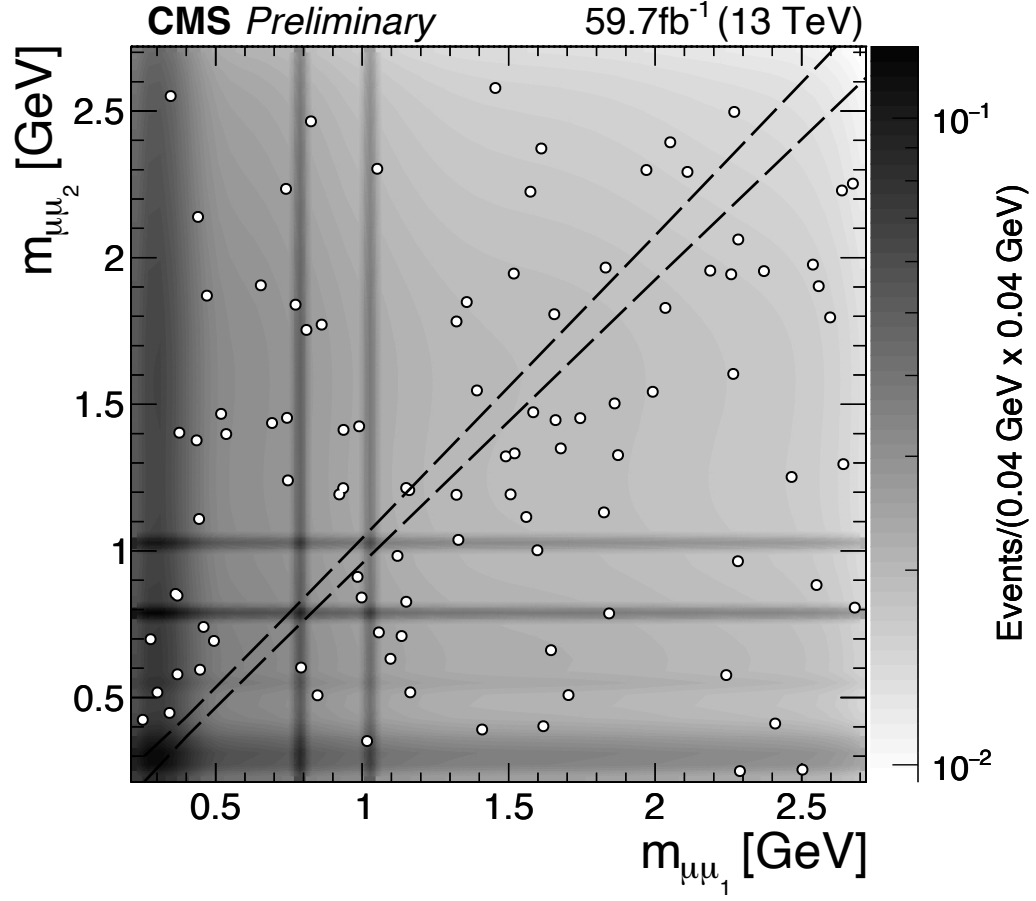


Figure 6.6 : 2D QCD background template for 2018 below the J/ψ overlaid with white circles that represent two-dimuon events from the 2018 DoubleMuon dataset in the control region. Signal regions (diagonal corridor bounded by dashed lines) is blinded here. A total number of 98 events are found in the off-diagonal control region.

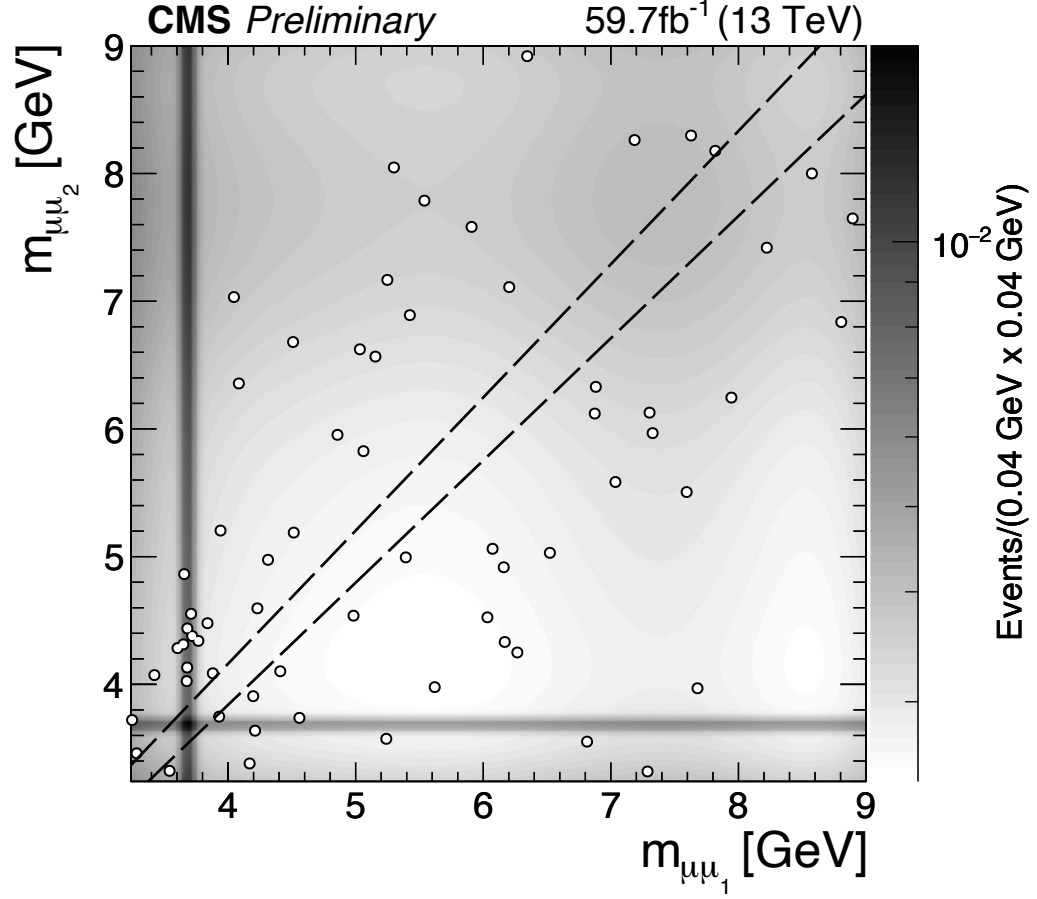


Figure 6.7 : 2D QCD background template for 2018 above the J/ψ overlaid with white circles that represent two-dimuon events from the 2018 DoubleMuon dataset in the control region. Signal regions (diagonal corridor bounded by dashed lines) is blinded here. A total number of 66 events are found in the off-diagonal control region above the J/ψ .

6.2.3 Validation of the Template

The statistical test method, Baker-Cousins (B-C) chi-square test [203], is used to do the compatibility test for the 2D background template and data at the CR shown in Fig. 6.6 and Fig. 6.7. Events from data at the CR are shown in Fig. 6.8 for both m_1 and m_2 for the region below J/ψ . Similarly, Fig. 6.9 shows those for the region above J/ψ . Meanwhile, the 2D template in the CR is projected into 1D histograms with the same binning as the data histograms. The total integral under the template is scaled to the actual data entries as well. A total of 98 and 66 events are in the control regions below J/ψ and above J/ψ , respectively. Normal statistical test methods are expected to fail with such low statistics and the returned probability value (p-value) should not be trusted. Instead, toy experiments are recommended to calibrate p-values returned by the method [203].

One million toy experiments are performed for each method by generating pseudo-data with the same entries and binning as original data based on the 1D projected template below and above the J/ψ . In each toy experiment, the test statistic is calculated by performing a statistical test on the generated pseudo-data and the template. In the case of the B-C test, the test statistic is the B-C chi-square. Distribution of the test statistic is obtained from all toy experiments. An example distribution of both test statistics from toy experiments for 2018 m_1 below and above the J/ψ is shown in Fig. 6.10 and Fig. 6.11. Finally, the calibrated p-value is calculated by integrating the part of the test statistic distribution where the test statistic is larger than the observed test statistic obtained from the actual data and the template. The results are shown in Tab. 6.2.

Note here the validation on signal-like events at the CR cannot be called a goodness-of-fit test because the fit function is already obtained by fitting to another

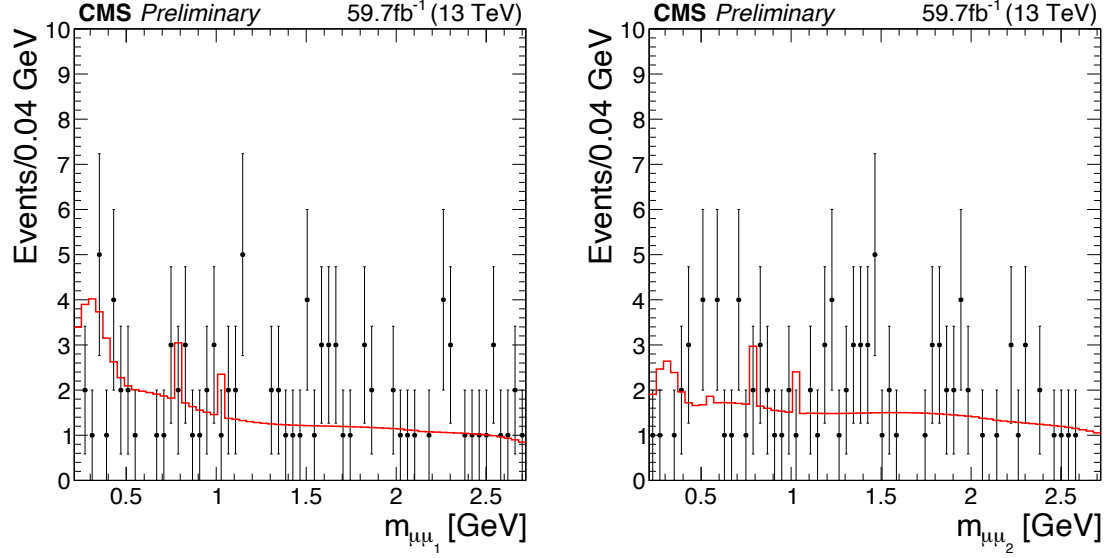


Figure 6.8 : 2018 2D background template and CR data projections into 1D m_1 (left) and m_2 (right) histograms below the J/ψ region. The integral of the 1D template (red) is scaled to data entries (black).

the control sample. For this validation, it is a compatibility test. Still, similar to goodness-of-fit tests, more than one statistical test is recommended [203]. In this case of no alternative hypothesis (i.e., I do not know the true shape for the data in the CR), it is hard to say which test method is the most powerful. The B-C chi-square test is sensitive to local deviations and targets low bin statistics and empty bins. Based on the corrected p-value from toy experiments, I conclude the two are compatible.

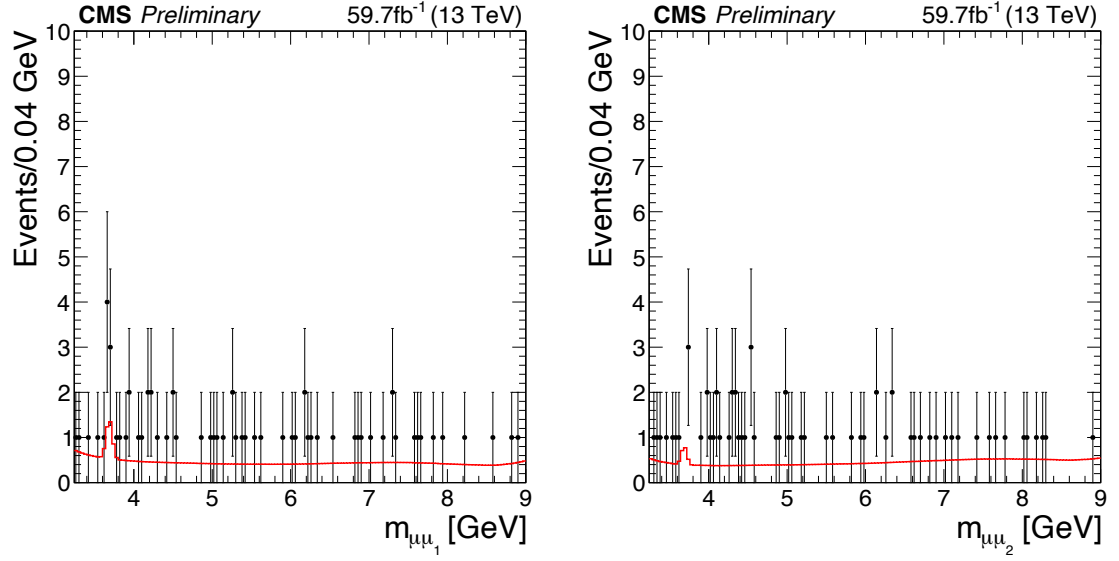


Figure 6.9 : 2018 2D background template and CR data projections into 1D m_1 (left) and m_2 (right) histograms above the J/ψ region. The integral of the 1D template (red) is scaled to data entries (black).

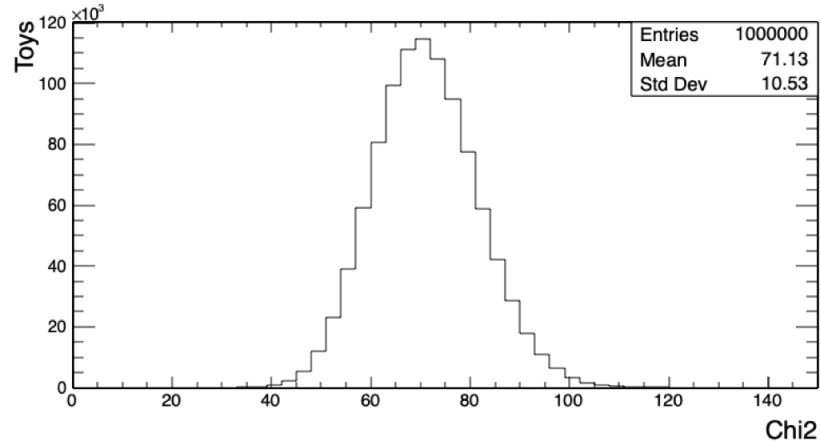


Figure 6.10 : Example distributions for test statistic chi-square in the Baker-Cousins test for 2018 m_1 below the J/ψ each using one million toy experiments.

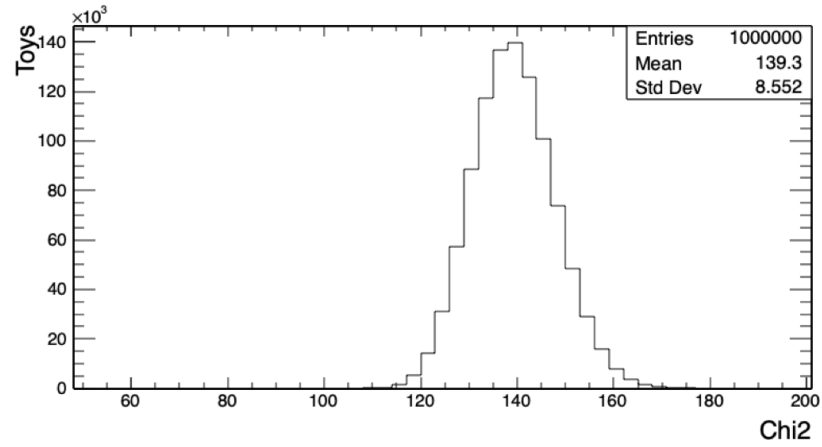


Figure 6.11 : Example distributions for test statistic chi-square in the Baker-Cousins test for 2018 m_1 above the J/ψ each using one million toy experiments.

Table 6.2 : Validate results for background templates

Region	Below J/ψ		Above J/ψ	
	m_1	m_2	m_1	m_2
Obs. Chisquare	81.53	81.46	133.63	139.27
1M toys Chisquare prob.	0.160	0.185	0.741	0.527

6.3 High Mass Background: Above 11 GeV

Theoretically, electroweak processes can contribute to the backgrounds at high mass. Similar to low mass, some QCD processes involving the top quark can also contribute. In practice, I compare data and MC sample yields in the CR to get an idea of what processes could contribute and how much they contribute to the SR. Many SM MC samples are checked by applying all analysis selections and those that have remaining events are scaled to data based on the cross section of the process and the luminosity of the DoubleMuon dataset. The most dominant ones are included in Tab. 4.2 when I introduce MC samples in Chapter 4. For other processes, the contributions are found negligible after scaling. A full list of these checked samples is listed in Appendix L.

6.3.1 Background Events from Drell-Yan Processes

The Feynman diagram of the DY process and an example of one extra jet production is shown in Fig. 6.12. Normally, events from the DY processes are not expected to contribute to the background as there are only two muons come from the hard scattering. The chance of two extra tracks in the event misidentified as muons are very small.

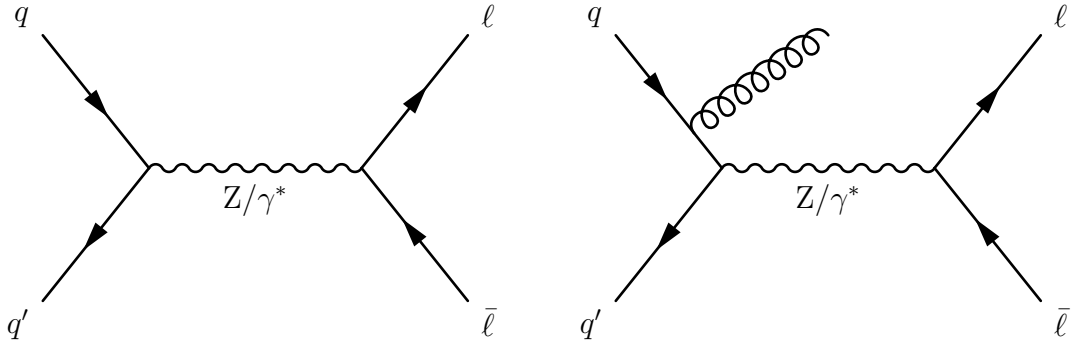


Figure 6.12 : Feynman diagram for the DY process (left) and the same process with extra gluon radiation from one of the initial quarks (right).

However, it is possible for a radiated photon in the DY process convert to a muon pair as shown in Fig. 6.13. Such events could mimic our signal event when a photon-converted muon is paired with a high p_T oppositely charged muon from the DY process. The display of two example events[†] from DY MC sample in the CMS event display are shown in Fig. 6.14 and Fig. 6.15, where the former event shows one of the incoming protons radiated a photon and the latter shows a radiated photon from one of the DY muons. For most of these events, they usually fail the mass consistency requirement and resides in the control region. Two such examples at the CR are also shown in Appendix M.

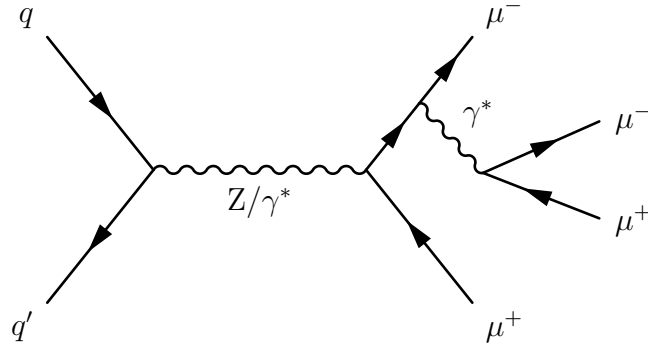


Figure 6.13 : Feynman diagram for the DY process with a high energy photon radiated from one of the muons produced in the hard scattering. The photon then converts to a pair of muons.

[†]Event 76792658, run 1, lumi 69121 in /store/mc/RunIIFall17MiniAODv2/DYJetsToLL_0J_TuneCP5_13TeV-amcatnloFXFX-pythia8/MINIAODSIM/PU2017_12Apr2018_94X_mc2017_realistic_v14-v1/40000/FAD7FA53-8489-E811-B7A8-3417EBE2F0C7.root

Event 10389531, run 1, lumi 9352 in /store/mc/RunIIFall17MiniAODv2/DYJetsToLL_0J_TuneCP5_13TeV-amcatnloFXFX-pythia8/MINIAODSIM/PU2017_12Apr2018_94X_mc2017_realistic_v14-v1/40001/7A185982-AF93-E811-9863-549F358EB7BD.root

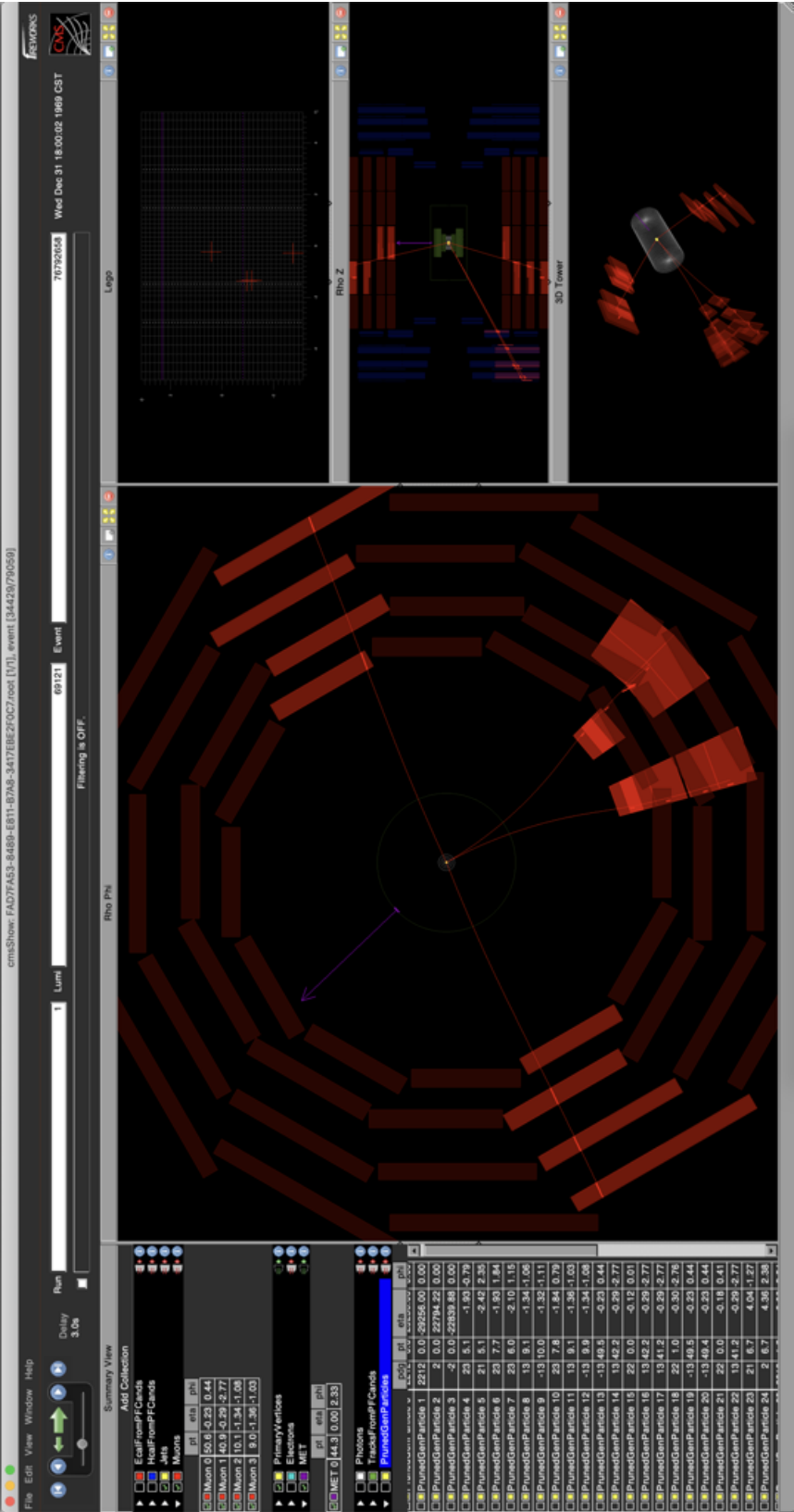


Figure 6.14 : Example 1: Display of an event from DY (0 jet) MC sample.

Considering the limited number of such events, it is difficult to model the shape of their distribution. Thus, it is necessary to veto these events and minimize the effect on the signal efficiency. The veto selection also needs to be model independent. A simple cut on the four-muon invariant mass, for example, is not a good choice because the four muons could come from a non-standard Higgs boson with a different mass from the 125 GeV Higgs boson, such as those predicted in the NMSSM benchmark model [135].

By comparing several variable distributions among the DY MC sample and all benchmark signal MC samples, I finally picked the so-called trailing mass and trailing ΔR variables from the alternative pairs. They are obtained as follows: once I get two dimuons from the normal muon pairing algorithm of the analysis, I re-pair these muons by taking one muon from each dimuon and find the oppositely charged muon in the other dimuon. Such alternative pairing restores the original muon pairs that come from the DY hard scattering process and the radiated photon. Because the muon pair converted from a photon usually has a very small invariant mass and also a small opening angle between the two muons, I call them trailing mass and trailing ΔR as opposed to the usually larger invariant mass and ΔR of the two muons from the DY hard scattering. By comparing signal efficiencies of various cut thresholds, a final requirement of trailing mass larger than 3 GeV, or trailing ΔR larger than 0.2, is used to veto these background events. This cut has a negligible effect on signals as shown in Fig 6.16. Machine learning techniques were considered for such vetoing but were not feasible because of limited statistics after basic analysis selection.

background.

6.3.2 Background Events due to the SA muon

As mentioned in the section on event selection, I allow at most one SA muon in two dimuons to recover lost signal efficiency due to the low reconstruction efficiency of displaced muons. This relaxation of one SA muon brings extra background from data, which is hard to model with MC. So I need to reject the SA muon induced backgrounds as much as possible without affecting the signal efficiency too much. The signal events that contain one SA muon usually happen at signals with high mass and long lifetime as I know from the signal MC. While in data, I found most background events with the SA muon have two dimuons that are very prompt. I reject events containing one SA muon if two dimuons in the event are both prompt-like with $L_{xy} < 0.1$ cm. This won't affect the prompt signals because the reconstruction is generally very good when the signal muons are prompt. Hence, fewer events contain SA muons in prompt signal MC.

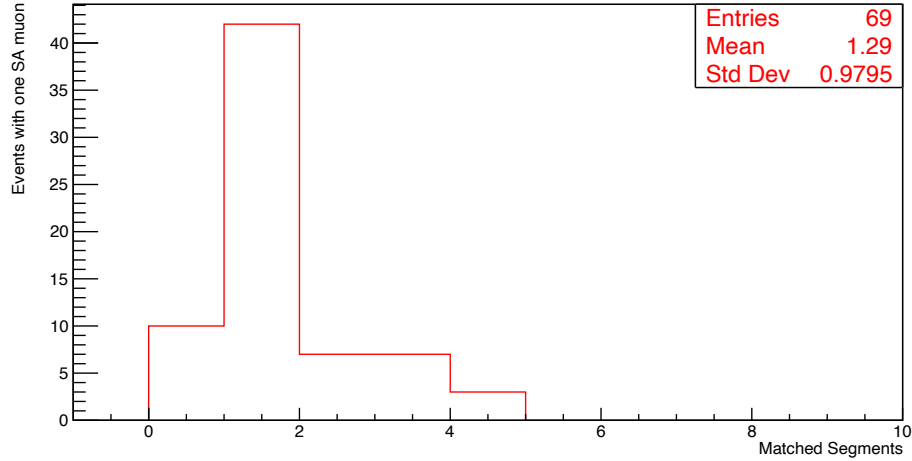


Figure 6.17 : Matched muon segments for the SA muon in two-dimuon events containing one SA muon in the DY (0-2 jets) MC.

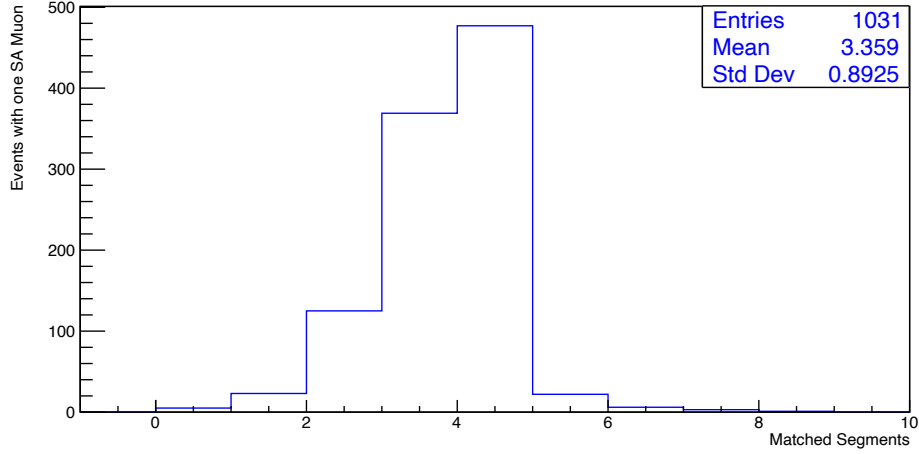


Figure 6.18 : Matched muon segments for the SA muon in two-dimuon events containing one SA muon in a dark SUSY signal MC (right): $m_{\gamma_D} = 35$ GeV, $c\tau = 100$ mm.

The SA muon in background events usually come from UE or punch-through. Such SA muons usually have limited reconstructed muon segments in the muon detector. The distributions of matched muon segments for the SA muon in the DY MC and the dark SUSY signal MC are shown in Fig. 6.17 and Fig. 6.18. It is clear that the matched number of muon segments for the SA muon in signals are usually larger than those from the background. As a result, I could cut on the matched segments for the SA muon to reject the background caused by the SA muon.

In summary, two-dimuon events containing one SA muon are rejected if either one of the two conditions below are satisfied,

- both dimuons $L_{xy} < 0.1$ cm,
- matched muon segments ≥ 2 for the SA muon.

These cuts have a negligible effect on signal efficiency as shown in Fig. 6.19. Other

cuts on the SA muon were considered including the track multiplicity and isolation around the SA muon, but are found to be model dependent and are not as good as the cuts adopted above.

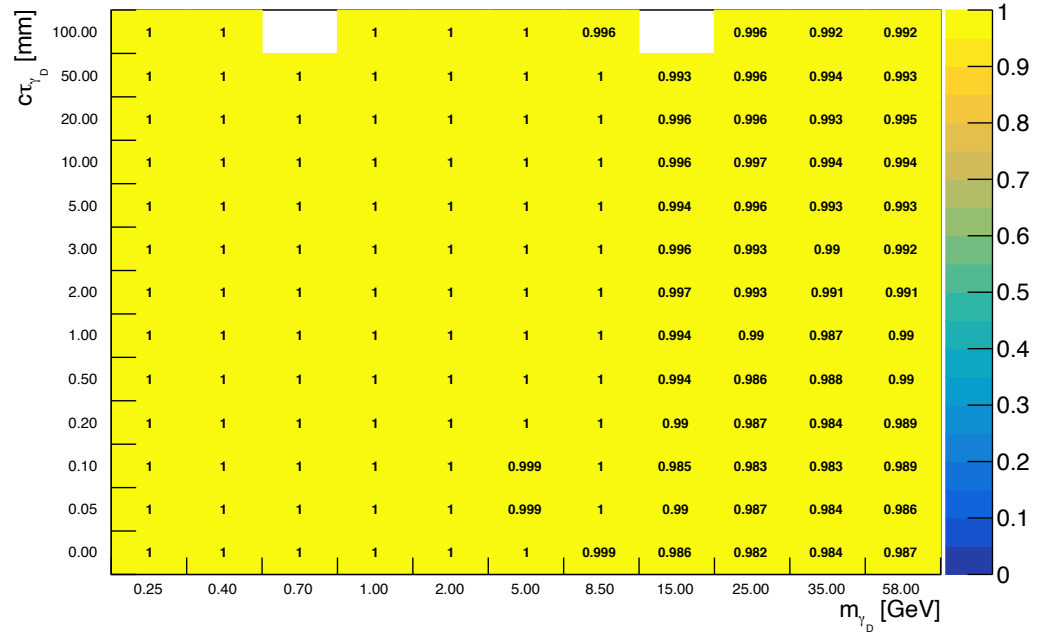


Figure 6.19 : Efficiency on dark SUSY signals with cut on SA muon events.

6.3.3 Estimated Background Events

Fig. 6.20 and Fig. 6.21 are 2018 data and MC comparisons of the CR for m_1 and m_2 . The same MC samples are then used for the estimation in the SR shown in Fig. 6.22 and Fig. 6.23. The relevant total number of events for both the CR and the SR is summarized in Tab. 6.3. The data-to-MC ratio in the CR is 1.05 ± 0.12 , indicating good agreement of the two. At the SR, m_1 (Fig. 6.22) and m_2 (Fig. 6.23) distributions show similar background shape and the contribution from each SM processes is similar as well. This matches my expectation as I required consistent mass for two dimuons. The MC contributions in the SR is then scaled based on the ratio of entries in MC and Data at CR as shown in Tab. 6.3. The final estimated number of background events at the SR is 12.28 ± 2.01 (stat.). The background shape used for the final shape-based limit calculation is described in Chapter 7.

Table 6.3 : Estimated background events in 2018: 11 - 60 GeV

Region	MC entries	Data entries	Data/MC	Est. events at SR
CR (m_1 or m_2)	136 ± 11 (stat.)	143 ± 12 (stat.)	1.05 ± 0.12 (stat.)	N/A
SR (m_1 or m_2)	11.67 ± 1.37 (stat.)	N/A (SR blinded)	N/A	12.28 ± 2.01 (stat.)

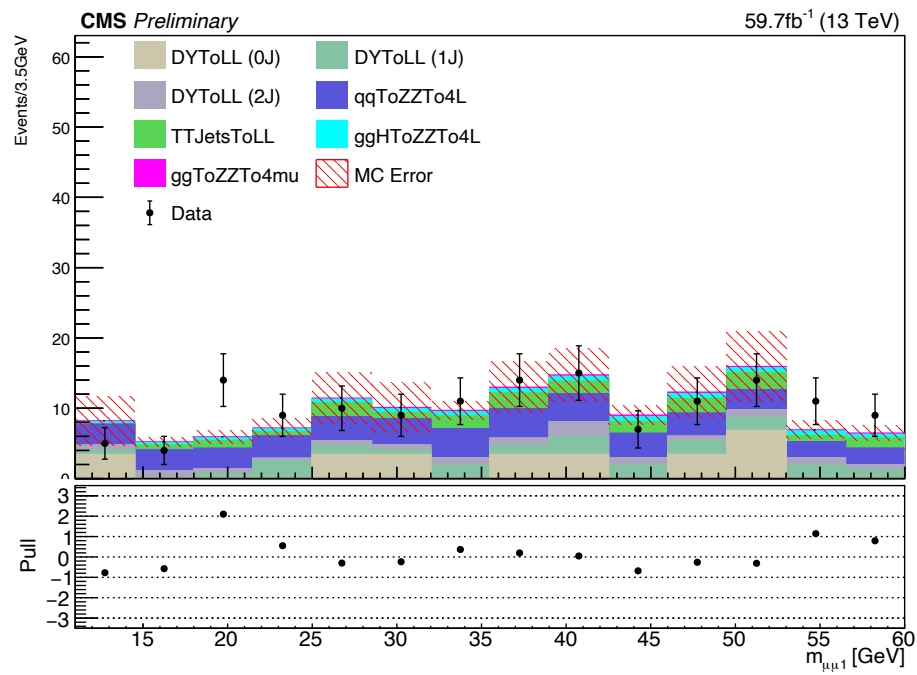


Figure 6.20 : MC and data distributions for m_1 in the control region after all analysis selection.

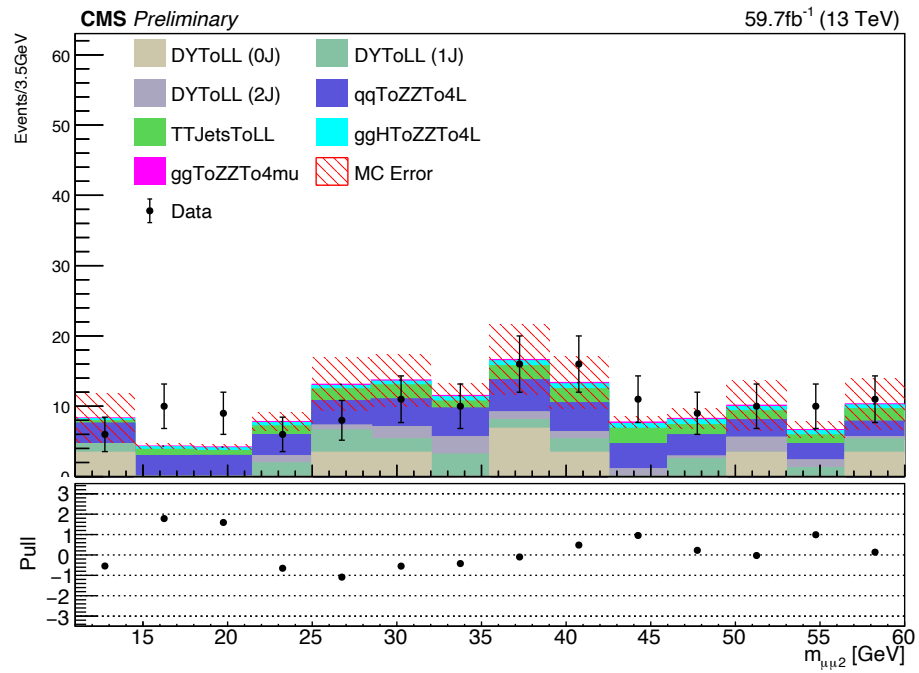


Figure 6.21 : MC and data distributions for m_2 in the control region after all analysis selection.

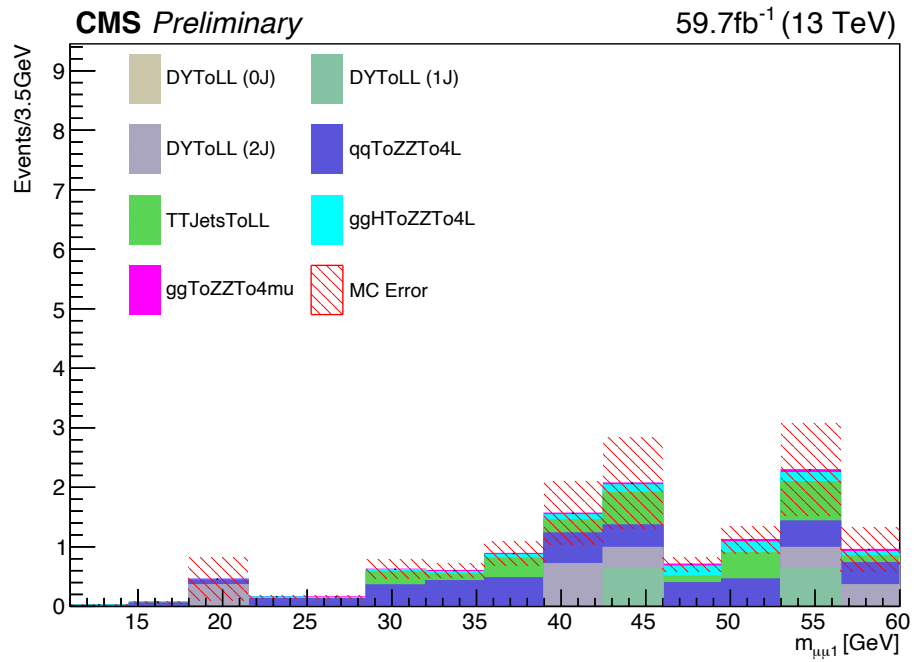


Figure 6.22 : MC distributions for m_1 in the signal region after all analysis selection.

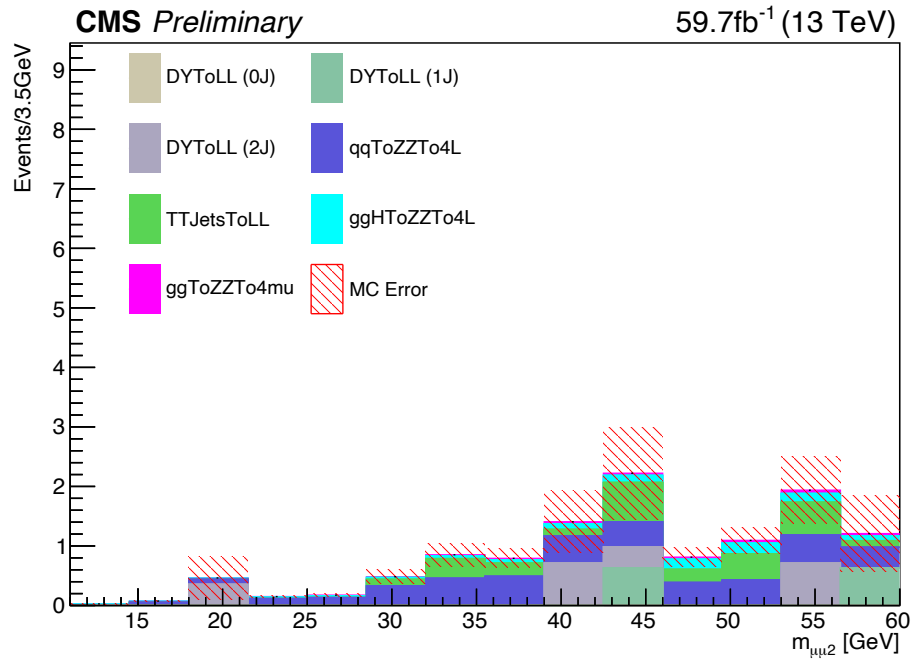


Figure 6.23 : MC distributions for m_2 in the signal region after all analysis selection.

6.4 Remarks

Overall, the analysis has close to zero background over the entire probed mass range. Still, understanding what processes constitute the background is important. The shape itself also gives me confidence that I did not make obvious mistakes.

Chapter 7

Systematic Uncertainties

Systematic uncertainties are categorized into experimental and theoretical uncertainties. Those related to the data taking, event selection, and event reconstruction are summarized as experimental uncertainties in Sec. [7.1](#). All uncertainties related to the MC sample are summarized as theoretical uncertainties in Sec. [7.2](#).

7.1 Experimental Uncertainties

Luminosity. The systematic uncertainty due to luminosity measurement is provided centrally by CMS. Briefly, the instantaneous luminosity ($\mathcal{L}_{inst}$) during 2018 data taking is determined with

$$\mathcal{L}_{inst} = R/\sigma_{vis}, \quad (7.1)$$

where R represents a rate of detector measured quantities such as hits or tracks in data taking periods and σ_{vis} is the visible cross section related to the detector. The determination of σ_{vis} is done through a special van der Meer (VdM) [204](#) scan using the same formula in Eq. [7.1](#) by measuring the luminosity and the rate. In the VdM scan, two separate beams are moved across each other and the rate R is measured; the luminosity can also be calculated to a good accuracy from the beam parameters. During normal running, this visible cross section and the measured hits can be used to determine the luminosity.

The measured σ_{vis} in the VdM scan suffers from many sources of systematic effects

like the x-y correlations of the beam. Details on all sources can be found in [204]. The total systematic uncertainty in the luminosity measurement is 2.5% for the dataset used in this thesis [204].

PU Effect. I introduced pileup in Sec. 4.2.1. Every time two proton bunches cross each other, more than one proton-proton collision takes place. PU affects the event selection performance. For example, the dimuon isolation selection loses efficiency in the high PU environment. To estimate the PU effect on signal, the entire PU range of 2018 is separated into the low ($\text{PU} < 25$), medium ($25 < \text{PU} < 45$), and high ($\text{PU} > 45$) PU regions. The number of events in each region is denoted as N_i ($i = \text{low, medium, high}$). The total number of events across the entire PU range is N_{tot} . To get the systematic uncertainty on the signal, we use a weighted standard deviation based on the number of events in each PU region. The final systematic uncertainty equals $\sqrt{\sum N_i (x_i - \bar{x})^2 / N_{\text{tot}}}$. Here $N_{\text{tot}} = \sum N_i$. The x_i is the $\epsilon_{\text{Full}}/\alpha_{\text{Gen}}$ in each of the three PU regions and the $\bar{x}$ is the average of $\epsilon_{\text{Full}}/\alpha_{\text{Gen}}$ at three PU regions. The PU effect on the event selection is estimated to be 1.8%. As the PU effect is minor, no PU mitigation techniques are applied.

PU Distribution. The systematic uncertainty due to the mischaracterization of the PU distribution in the MC was evaluated. The number of expected PU interactions in 2018 data is obtained from the per-BX luminosity and the nominal pp total inelastic cross section, $\sigma(pp)_{\text{nom}} = 69.2$ mb. Similar PU distribution is then derived with the cross section shifted 5% up and down from the nominal case. This corresponds to $\sigma(pp)_{\text{nom}-5\%} = 65.8$ mb and $\sigma(pp)_{\text{nom}+5\%} = 72.3$ mb. The PU distribution in data and the MC is normalized and divided to obtain weight as a function of the PU interactions. Such weights are applied to each event in the signal MC based on the number of PU interactions in the event.

The effect on $\varepsilon_{\text{Full}}/\alpha_{\text{Gen}}$ for a representative MC sample in each benchmark scenario is calculated for each of the three cases (nom-5%, nom, and nom+5%) [186]. The greatest absolute difference in the magnitude of $\varepsilon_{\text{Full}}/\alpha_{\text{Gen}}$ with respect to the nominal case is taken as the uncertainty. The final systematic uncertainty is determined to be 0.05%.

Muon Trigger. An orthogonal method described in [83] is used to estimate the overall scale factor of triggers for their different effects between data and MC samples in an unbiased way. The overall trigger scale factor is estimated to be 99.6% +/- 0.6% (stat.).

Muon ID. Loose muon ID is used for offline selections. The scale factor and its uncertainty for muon identification in data and MC samples are provided centrally by CMS. We assign a systematic uncertainty of 0.6% per muon [83].

Dimuon Isolation. The isolation is driven by UE activity. The isolation scale factor was also calculated using the same Tag-and-Probe method in [83]. A systematic error of 0.1% is obtained per muon. For the dimuon isolation used in the thesis, we assume its systematic uncertainty is two times the uncertainty of the single muon isolation.

Consistent Dimuon Masses. I use an uncertainty to cover the variation in $\varepsilon_{\text{Full}}/\alpha_{\text{GEN}}$ due to the mass consistency requirement. In Chapter 5 an overall $\varepsilon_{\text{Full}}/\alpha_{\text{Gen}} = 0.418 \pm 0.001$ is found by calculating the average value from all signal MC samples. This corresponds to an uncertainty of 0.24%.

Reconstruction of Close Muons in the Muon System. To account for correlated effects of muon reconstruction when two muons are close to each other in the muon system, we use the results of the studies in [85], where the systematic uncertainty associated with this effect was conservatively evaluated by comparing the

difference per leg efficiency for cases with and without a nearby muon present (so-called crossing and non-crossing topologies), which yielded a systematic uncertainty of 1.3% per muon in the endcap region only. No such effect was observed in the barrel region. As in our events, there is at most one dimuon in the endcap region, we assign an uncertainty of 2.6% per event to account for the uncertainties in reconstructing muons with overlapping trajectories in the muon system. There is only one relevant difference between muon identification requirements in this analysis and in [85], which is the requirement on the number of muon stubs per muon (at least two in this analysis, at least three in [85]). As the muon reconstruction is unchanged, it is only a matter of which muons each analysis picks out of the pool of reconstructed muons. As this analysis has a looser requirement, the importance of the effect of nearby muons becomes smaller (we find all muons that would have been found by [85] and more, which makes the loss of efficiency due to overlaps smaller). Therefore, the uncertainty of 2.6% per event is a conservative estimate of the effects related to overlaps in the muon system. And this uncertainty only applies to signal mass points below 9 GeV.

Reconstruction of Close Muons in the Tracker. In [85], a potential effect related to tracking was identified as low mass muon pairs at sufficiently high momentum can stay very close in the tracking volume leading to a reduced efficiency to reconstruct both tracks in the dimuon, due to merging of tracker hits into clusters. The assumption was that if the track hit size is larger in data than in the simulation by 20%, merging will be happening more frequently in data leading to lower efficiency to reconstruct both muons. As varying hit resolutions in simulation is a complicated endeavor, an easier but equivalent solution is to vary the momentum of the dimuon by the same 20%, which makes trajectories 20% closer and comparing efficiencies. We compared these efficiencies for reconstructed dimuon with transverse momenta from

16 to 60 GeV using Fig. 7 in [85]. As a result, the corresponding systematic uncertainty was estimated as 1.2% per dimuon. Similarly, this uncertainty only applies to signal mass points below 9 GeV.

Reconstruction of Displaced Tracks and Vertices. The systematic uncertainty on the reconstruction of displaced tracks and vertices is studied by another analysis group in CMS. They concluded the systematic uncertainty for a pair of displaced muons is 0.5% in 2018. As this search contains up to 2 possible displaced muon pairs, I use 1% as the systematic uncertainty of displaced track and vertex reconstruction.

7.2 Theoretical Uncertainties

PDF + α_s + QCD scales. The uncertainties related to the parton distribution functions (PDFs) and the knowledge of the strong coupling constant α_s were calculated in [205] by following the PDF4LHC recommendations [206]. Further, the uncertainty due to the PDF choice was found by varying parametrization within the PDF as well as investigating alternative PDFs and comparing the central values.

There are two important scales relevant for QCD, the renormalization scale (μ_R) and the factorization scales (μ_F). The factorization scale relevant for the parton distribution, $f_i(x, \mu_F)$, is mentioned previously in Sec. 4.2.1. Qualitatively, the factorization scale corresponds to the resolution with which the hadron is being probed. On the other hand, the renormalization scale is more relevant for the QCD coupling constant as mentioned in Sec. 1.1. It is introduced to resolve the ultraviolet (UV) divergence in the QCD amplitude calculations due to large momentum in the loops of the Feynman diagrams. The μ_R and μ_F scales are varied up and down by a factor of two to obtain their uncertainty on the signal acceptance.

All the uncertainties were treated as uncorrelated and added in quadrature. The final uncertainty was found to be 8% [83].

Higgs production cross section and branching ratio. Systematic errors on the Higgs production cross section for each production mechanism and all Higgs boson masses are fully defined in [191]; a total systematic uncertainty of 3.2 % (Higgs boson mass-independent) was obtained for this search. The uncertainty on the branching fraction of the Higgs boson to four leptons is taken to be 2% and assumed to be independent of the Higgs boson mass [205]. The total systematic uncertainty is 3.8%.

NNLO Higgs p_T re-weighting. The signal MC samples used in this analysis involve the production of the Higgs boson, which proceeds largely through heavy flavor quark loops as mentioned in Sec. 4.2.3. At the LHC, production of a Higgs boson can be characterized by its p_T . The p_T distribution is sensitive to multiple emissions from the initial state partons and its detailed knowledge is very important for the analysis. When $p_T \sim m_H$, the QCD radiative corrections can be evaluated through the standard fixed-order expansion. At $p_T \ll m_H$, the convergence of the perturbative expansion is spoiled by the presence of large logarithmic terms, called Sudakov logarithms [207], due to soft and collinear gluon emissions. To obtain reliable perturbative predictions over the whole p_T range, such terms must be resummed to all orders, and the result has to be consistently matched to the fixed-order result at $p_T \sim m_H$.

The exact p_T distribution at LO has been computed long ago. The NLO corrections are known only in the limit $m_t \rightarrow \infty$, where the quark loop becomes point-like. Recently the NNLO corrections in the gluon-gluon fusion channel have been evaluated [207]. The Higgs in signal MC samples used in the thesis is produced at NLO. Therefore it is important to estimate the effect of resummation and to account for the

effect that possible changes to the shape of the Higgs p_T could have on the kinematics and acceptance. To do this, we used NNLO re-weighting functions with respect to the Higgs p_T to evaluate changes in the signal acceptance after all selection requirements have been applied. The estimations for several signal MC samples were mostly found to be negligible. A conservative systematic of 2% is included to account for these deviations.

7.3 Background Uncertainties

Normalization. Normalization uncertainties for the background are considered. For the region below the J/ψ , the nominal number of expected background events is 4.34 ± 0.44 , which corresponds to an uncertainty of 10.1%. For the region between the J/ψ and the Υ resonances, the nominal number of expected background events is 6.16 ± 0.76 , which corresponds to an uncertainty of 12.3%. For the region above the Υ , the nominal number of expected background events is 12.28 ± 2.01 , which corresponds to an uncertainty of 16.4%.

Systematic uncertainty. Additionally, systematic uncertainties for the background are considered. They are obtained as follows. The dimuon isolation threshold is varied 5% up and down from the cut value of 2.3 GeV used in Chapter 5, corresponding to 2.415 GeV and 2.185 GeV. For each varied isolation cut, I recomputed the final expected number of background events in the signal region. For the region below the J/ψ , the 2D background template is recomputed. The nominal number of expected background events of 4.34 ± 0.44 changes to 4.52 ± 0.45 (for dimuon isolation < 2.415 GeV) and 4.34 ± 0.44 (for dimuon isolation < 2.185 GeV), corresponding to a systematic uncertainty of 4.1%. For the region between the J/ψ and the Υ resonances, similar procedures are done. The nominal number of expected background

events 6.16 ± 0.76 changes to 6.17 ± 0.76 (for dimuon isolation < 2.415 GeV) and 6.07 ± 0.75 (for dimuon isolation < 2.185 GeV), which corresponds to a systematic uncertainty of 1.5%. For the region above the Υ , the nominal number of expected background events 12.28 ± 2.01 changes to 12.56 ± 2.03 (for dimuon isolation < 2.415 GeV) and 12.24 ± 2.02 (for dimuon isolation < 2.185 GeV), corresponding to a systematic uncertainty of 2.3% for the background above the Υ .

Background Shape above 11 GeV and its uncertainty. Here I first describe the background shape in the signal region above 11 GeV. I implement a one-dimensional kernel estimation p.d.f.* which models the distribution of the MC sample dataset as a superposition of Gaussian kernels, one for each data point, each contributing $1/N$ to the total integral of the p.d.f. [208]. The kernel estimation is adopted to obtain a smooth background shape based on limited estimated background events in the signal region. The kernel estimation p.d.f. for each of the MC process is obtained and then summed up using the same weights† as in Fig. 6.22 and Fig. 6.23. The obtained smooth background p.d.f. for m_1 and m_2 are shown as the blue curve in Fig. 7.1.

To evaluate the background shape uncertainty, the weight for each MC sample is varied within the statistical uncertainty and several other smooth shapes are obtained as shown in Fig. 7.1. The weight variations are detailed in Tab. 7.1. The systematic uncertainty is defined as the deviation of these p.d.f. from the nominal p.d.f. (blue curve) divided by the nominal p.d.f. as shown in the lower panel in Fig. 7.1. All

*RooKeysPdf: the width of the Gaussian is adaptively calculated from the local density of events, i.e. narrow for regions with high event density to preserve details and wide for regions with low event density to promote smoothness. See: <https://root.cern.ch/doc/master/classRooKeysPdf.html>

†The weight is a multiplication of the MC-data scale factor and the number of MC events that pass all selection.

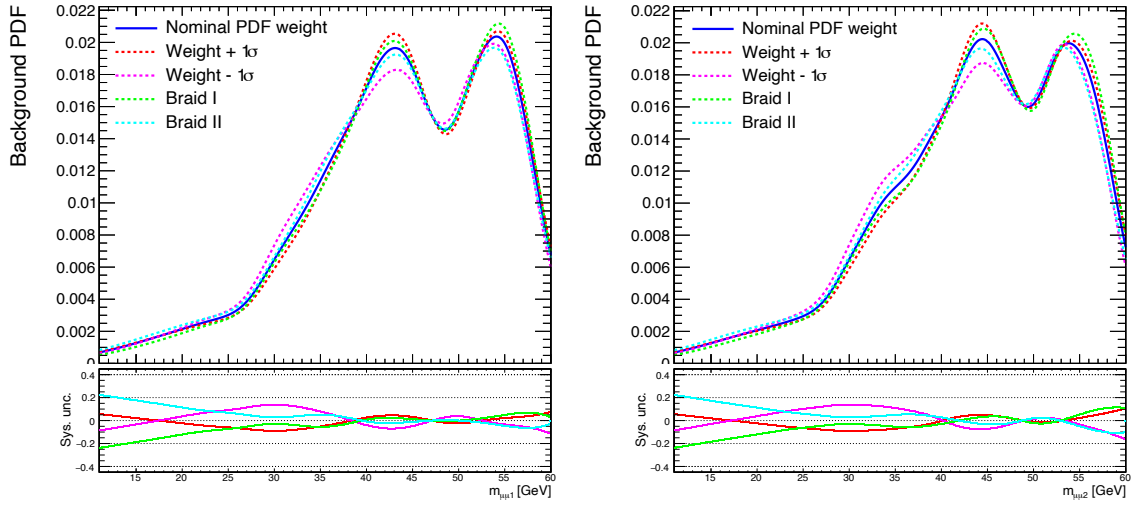


Figure 7.1 : Kernel estimation p.d.f for m_1 (left) and m_2 (right) in the signal region.

uncertainties are below 23.8%. Thus, I use a systematic uncertainty of 23.8% for the background shape. The nominal p.d.f. colored in blue is used to model the background shape in the next Chapter.

I further evaluate the impact of these different shapes on the expected limits before I unblind the data in the signal region. The expected 95% CL toy limits for mass points above 11 GeV using different shapes are summarized in Tab. [7.2](#). As shown in the last column, the standard deviation over the mean expected limit is below 3.7% for each mass point. I thus conclude that the impact of these varied background shapes on the expected limits is small.

Table 7.1 : Background p.d.f. using different MC weights

Weight Variations	Description
Nominal weight	use nominal MC weight (blue curve in Fig. 7.1)
Weight + 1σ	use nominal MC weight + 1σ (red dashed curve in Fig. 7.1)
Weight - 1σ	use nominal MC weight - 1σ (magenta dashed curve in Fig. 7.1)
Braid I	use nominal MC weight + or - 1σ alternatively for DY+1J, DY+2J, ZZTo4L, TTJetsToLL, ggHToZZTo4L, and ggToZZTo4mu processes, starting from nominal MC weight + 1σ for DY+1J (green dashed curve in Fig. 7.1)
Braid II	similar to Braid I but starts from nominal MC weight - 1σ for DY+1J (cyan dashed curve in Fig. 7.1)

Table 7.2 : Expected 95% CL limit using multiple weighted pdfs for background shapes above 11 GeV.

Mass [GeV]	Nom.	Nom.+1 σ	Nom.-1 σ	Braid I	Braid II	Mean	SD	SD/Mean
13	2.9434	3.1503	3.1130	3.1796	3.2521	3.1277	0.1149	0.0367
17	3.0191	3.1684	3.0632	3.0961	3.1040	3.0902	0.0550	0.0178
21	3.0566	3.1282	3.1896	3.1365	3.0605	3.1143	0.0561	0.0180
25	2.9564	3.0599	2.9403	3.1495	3.1535	3.0519	0.1018	0.0334
29	3.0555	3.0303	3.2073	3.1983	3.1646	3.1312	0.0826	0.0264
33	3.0680	3.1526	3.1872	3.1232	3.1615	3.1385	0.0456	0.0145
37	3.2113	3.3438	3.2757	3.2781	3.3376	3.2893	0.0541	0.0164
41	3.2420	3.3551	3.3122	3.2727	3.3829	3.3130	0.0577	0.0174
45	3.3398	3.4918	3.4517	3.4777	3.4637	3.4449	0.0607	0.0176
49	3.3245	3.5730	3.4541	3.4545	3.3619	3.4336	0.0966	0.0281
53	3.3561	3.5320	3.4453	3.5915	3.5604	3.4971	0.0958	0.0274
57	3.3346	3.5742	3.4394	3.4418	3.5387	3.4658	0.0943	0.0272
58	3.2983	3.6260	3.4710	3.5028	3.4909	3.4778	0.1173	0.0337

7.4 Summary

Tab. 7.3 summarizes uncertainties which will be used in the next Chapter.

Table 7.3 : Summary of uncertainties.

Source of uncertainty	Value
Experimental	
Integrated luminosity	2.5%
Muon ID	$4 \times 0.6\%$
Muon isolation	$2 \times 0.1\%$
Muon trigger	0.6%
Overlapping in tracker (signal below 9 GeV)	$2 \times 1.2\%$
Overlapping in muon system (signal below 9 GeV)	$2 \times 1.3\%$
Displaced track and vertex reconstruction	$2 \times 0.5\%$
Pileup distribution	0.05%
Pileup effect	1.8%
Dimuon mass consistency	0.24%
Theoretical	
PDF + α_s + QCD scales	8.0%
Higgs cross sec. and Br.	3.8%
NNLO Higgs p_T re-weighting	2.0%
Background below J/ψ: 0.21-2.72 GeV	
Normalization	10.1%
Systematic	4.1%
Background above J/ψ and below Υ: 3.24-9 GeV	
Normalization	12.3%
Systematic	1.5%
Background above Υ: 11-60 GeV	
Normalization	16.4%
Systematic	2.3%
Shape	23.8%

Chapter 8

Result

After full analysis selections are applied to the data sample from 2018, thirty events were observed in the signal region within the mass window after unblinding, which is consistent with the prediction. These events are shown in Fig. 8.1, Fig. 8.2, and Fig. 8.3.

In particular, for the signal region below 9 GeV, I observed 4 and 6 events below and above the J/ψ , respectively, shown in Fig. 8.1 and Fig. 8.2. This is consistent with the predicted background.

For the signal region above 11 GeV, twenty events are observed as shown in Fig. 8.3. This is consistent with the predicted background of 12.28 ± 2.01 (stat.) ± 2.94 (sys.) events. The systematic error of 2.94 already includes the background shape systematic uncertainty 23.8% obtained in Sec. 7.3. The pulls are within 2σ (only statistical errors are considered) when it's plotted in the 1D histograms as shown in Fig. 8.4 and Fig. 8.5.

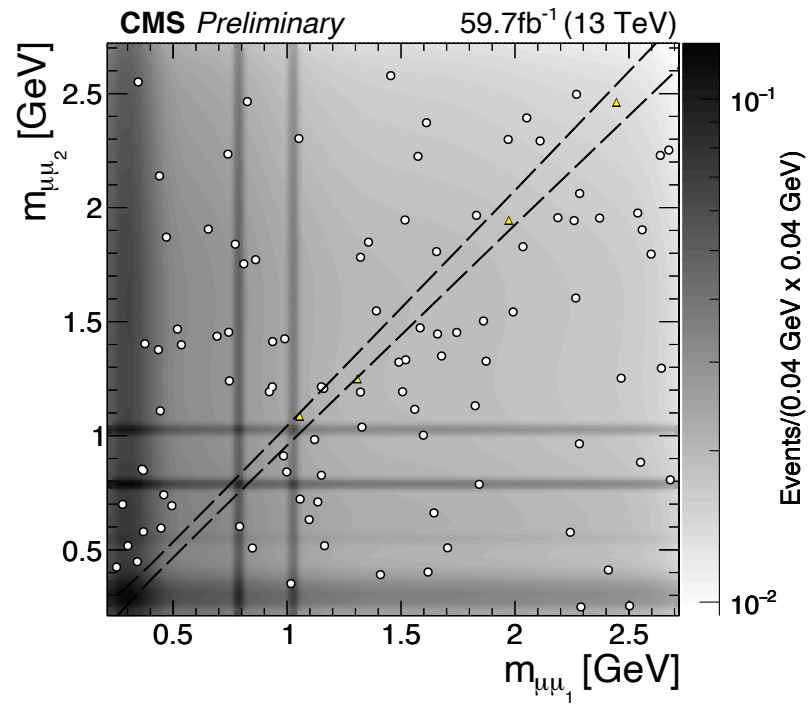


Figure 8.1 : Two-dimensional distribution of the invariant masses below the J/ψ resonance. The grayscale heatmap shows the normalized QCD background template; white dots represent data events that pass all selection criteria but fall outside the SR (outlined by dashed lines); triangles represent data events passing all selection criteria.

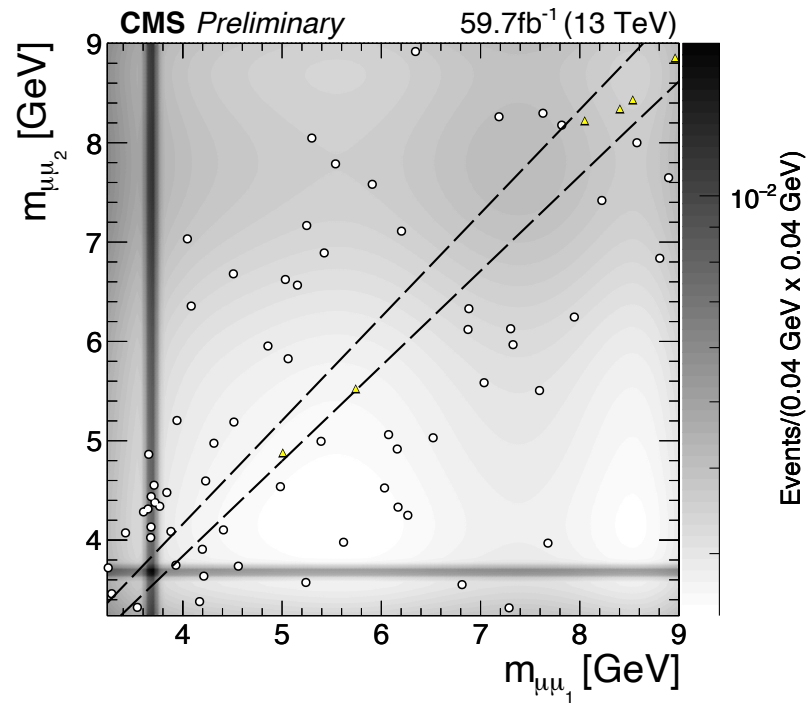


Figure 8.2 : Two-dimensional distribution of the invariant masses above the J/ψ resonance. The grayscale heatmap shows the normalized QCD background template; white dots represent data events that pass all selection criteria but fall outside the SR (outlined by dashed lines); triangles represent data events passing all selection criteria.

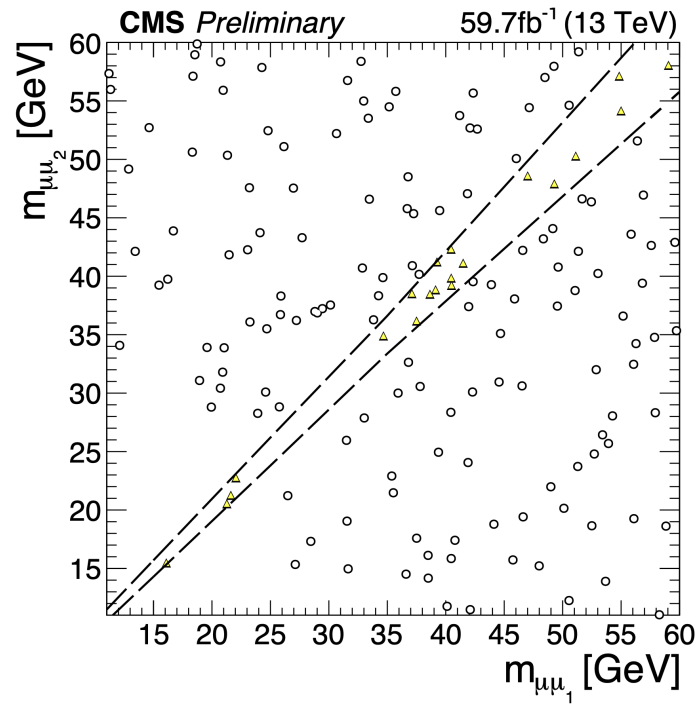


Figure 8.3 : Two-dimensional distribution of the invariant masses above the Υ resonances. White dots represent data events that pass all selection criteria but fall outside the SR (outlined by dashed lines); triangles represent data events passing all selection criteria.

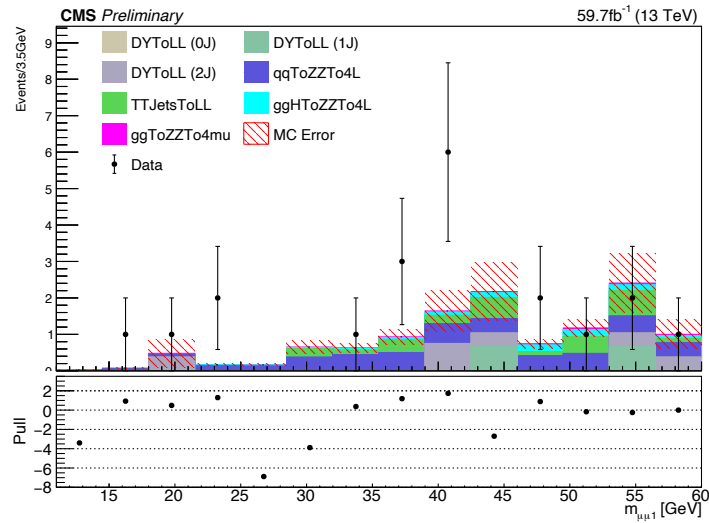


Figure 8.4 : MC and data distributions for m_1 in the signal region above 11 GeV after all analysis selection cuts are applied.

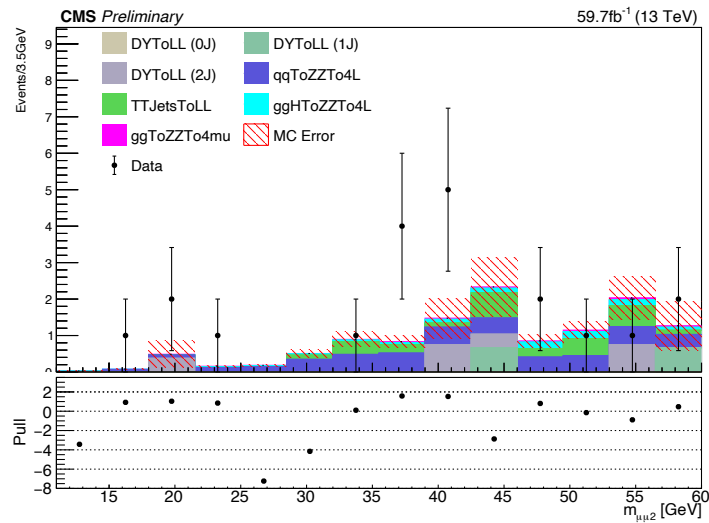


Figure 8.5 : MC and data distributions for m_2 in the signal region above 11 GeV after all analysis selection cuts are applied.

8.1 Model Independent Limit

For any new physics model predicting the signature investigated in this analysis, the results can be presented as the 95% confidence level (CL) upper limit on the product of cross section times branching fraction squared times kinematic and geometric acceptance of the analysis at generator level,

$$\sigma(pp \rightarrow 2a + X) \times \mathcal{B}^2(a \rightarrow 2\mu) \times \alpha_{\text{Gen}} \leq \frac{N_{\text{evt}}}{\mathcal{L} \times r}, \quad (8.1)$$

where N_{evt} is the 95% CL upper limit on the number of events. The calculation uses the integrated luminosity $L = 59.7 \text{ fb}^{-1}$, as measured in 2018 data, and takes the ratio r , which is given by,

$$r = \text{SF}_{\epsilon_{\text{Full}}} \times \epsilon_{\text{Full}}^{\text{MC}} / \alpha_{\text{Gen}}, \quad (8.2)$$

where $\text{SF}_{\epsilon_{\text{Full}}} = 0.996$ is a scale factor correcting for experimental effects not accounted for by simulation; it is a multiplicative product of the scale factors from muon ID, isolation and trigger described in Chapter [7](#). And $\epsilon_{\text{Full}}^{\text{MC}} / \alpha_{\text{Gen}} = 0.418$ is the ratio of full selection efficiency over full kinematic and geometric acceptance of the analysis at generator level averaged over all simulation samples.

The overall statistical methodology used in this analysis was developed by the ATLAS and CMS Collaborations in the context of the LHC Higgs Combination Group and is described in Refs. [\[209\]](#), [\[210\]](#), [\[211\]](#). The chosen test statistic is based on the profile likelihood ratio and is used to determine how signal-like or background-like the data are. Uncertainties described in Chapter [7](#) are treated as nuisance parameters according to the frequentist paradigm.

As final limit computation is performed based on a combination of signal and background, modeling the signal and background shapes are important. The signal shape used in limit calculations is modeled as a 2D shape by multiplying two identical

1D Crystal Ball functions from ROOT RooCShape, i.e., `PROD::signal(RooCShape m1, RooCShape m2)`. At each mass point, the σ parameter of the Crystal Ball function is extracted from the mass window used in the main analysis. Specifically, the mass window used in the analysis is based on a 90% signal efficiency; this roughly corresponds to ± 1.65 times the standard deviation (σ) [8]. As a result, the Crystal Ball function σ parameter is $\frac{W(\frac{m_1+m_2}{2})}{1.65 \times 2}$, where $W(\frac{m_1+m_2}{2})$ is the 90% mass window size mentioned in Chapter 5. The α parameter and the n parameter of the Crystal Ball function are fixed to 1.75 and 2 respectively following the choice of the previous publication [83]. The uncertainty for signal shape modeling is considered. The uncertainties for the Crystal Ball σ , α , and n are parameterized as a function of signal mass. Uncertainties from Crystal Ball fit to prompt dark photon signals (available in Appendix I) are linearly interpolated. These uncertainties are then treated as additional parametric uncertainties for the signal.

The background shape below 9 GeV is described in Chapter 6. The background shape above 11 GeV is described in Chapter 7 when we discuss the shape uncertainties.

To this end, toy models are generated assuming various masses of the new boson in the search region. The actual outputs of the statistical tool for the 95% CL upper limits on N_{evt} for dimuon mass points are obtained first. They are then used to derive the observed 95% CL limit on $\sigma(pp \rightarrow 2a + X) \times \mathcal{B}^2(a \rightarrow 2\mu) \times \alpha_{\text{Gen}}$ as shown in Fig. 8.6.

Generally, the reinterpretation of results in a specific BSM scenario requires there to be an evaluation of the signal acceptance. As mentioned above, this analysis has been designed in such a way that this is a simple procedure. Below I describe one approach to evaluate new models that only require the analyst to use generator level

*[https://en.wikipedia.org/wiki/Standard_normal_table#Cumulative_from_mean_\(0_to_Z\)](https://en.wikipedia.org/wiki/Standard_normal_table#Cumulative_from_mean_(0_to_Z))

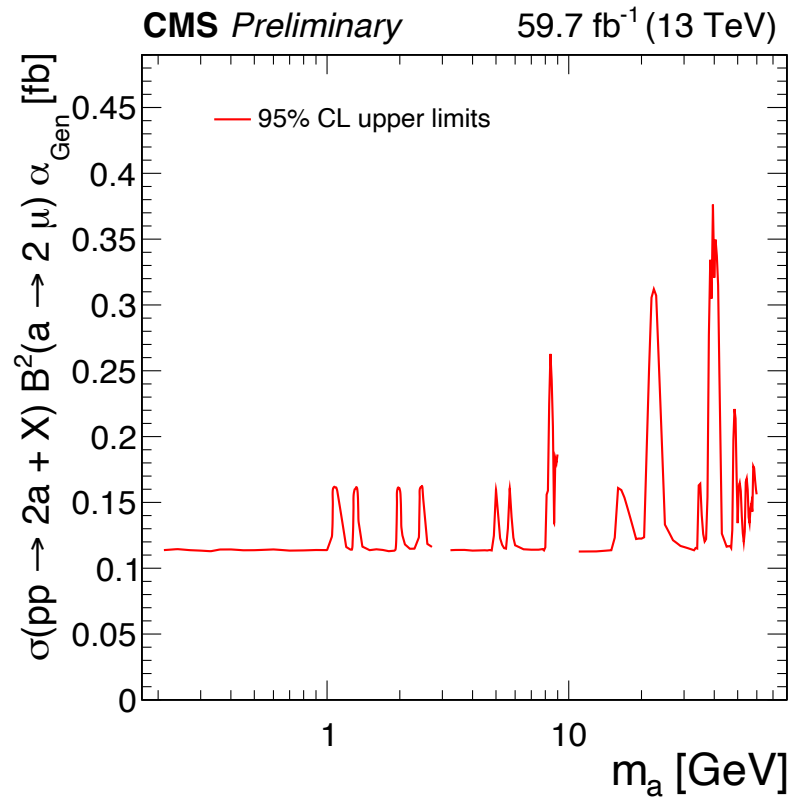


Figure 8.6 : Model independent 95% CL upper limit on the product of the cross section times branching fraction squared times acceptance at generator level.

information and does not require simulating the response from the CMS detector and reconstruction software.

8.2 Interpretation in Benchmark Models

Limit Interpretation in the ALP model.

The model independent limit in Fig. 8.6 can be further used to set the limit on the effective coupling of the ALP to the SM Higgs, C_{ah}/Λ^2 . Assume the production cross section for the SM Higgs via gluon gluon fusion at the LHC at 13 TeV, 48.52 pb, the branching fraction of the ALP to leptons is 100% or 10%, the upper limit on the branching fraction $\mathcal{B}(h \rightarrow aa)$ can be obtained using Eq. (8.1). Suppose the branching fraction follows,

$$\text{Br}(h \rightarrow aa) = \frac{\Gamma(h \rightarrow aa)}{\Gamma(h \rightarrow aa) + \Gamma(h \rightarrow \text{SM})}, \quad (8.3)$$

where $\Gamma(h \rightarrow \text{SM})$ is the partial width (4.1 MeV) for Higgs decaying to SM particles. Using Eq. (1.34), the VEV of the Higgs field (246 GeV), and the Higgs boson mass (125.10 GeV), I can obtain the 95% upper limit on the effective coupling of the ALP to the SM Higgs, C_{ah}/Λ^2 , as a function of the ALP mass. This is shown in Fig. 8.7. The sensitivity is better than Run 1 LHC searches shown in Fig. 1.13.

Similarly, I can also set limits on $\mathcal{B}(a \rightarrow \mu^+ \mu^-)$ assuming Eq. (8.3) with different choices of C_{ah}/Λ^2 : 1 TeV⁻², 0.1 TeV⁻² and 0.01 TeV⁻². This can be further transformed to limits on the effective coupling of the ALP to the SM leptons, c_u/Λ , as shown in Fig. 8.8. For simplicity, the total width of the ALP is fixed to 10⁻⁵ GeV for all mass points. Smaller width will give stronger limits on c_u/Λ according to Eq. (1.31). The limits are also shown in Fig. 8.9 in order to compare with other non-collider searches for the ALP.

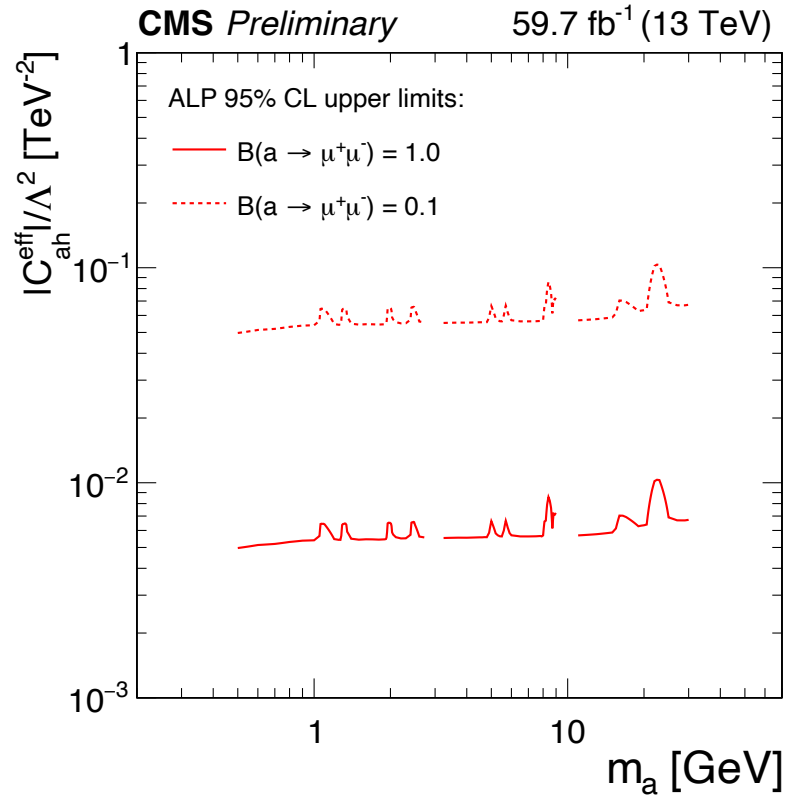


Figure 8.7 : Observed 95% CL upper limits on effective coupling of the ALP to the SM Higgs, C_{ah}/Λ^2 , assuming $\mathcal{B}(a \rightarrow \mu^+\mu^-) = 1$ (solid) and 0.1 (dashed), respectively.

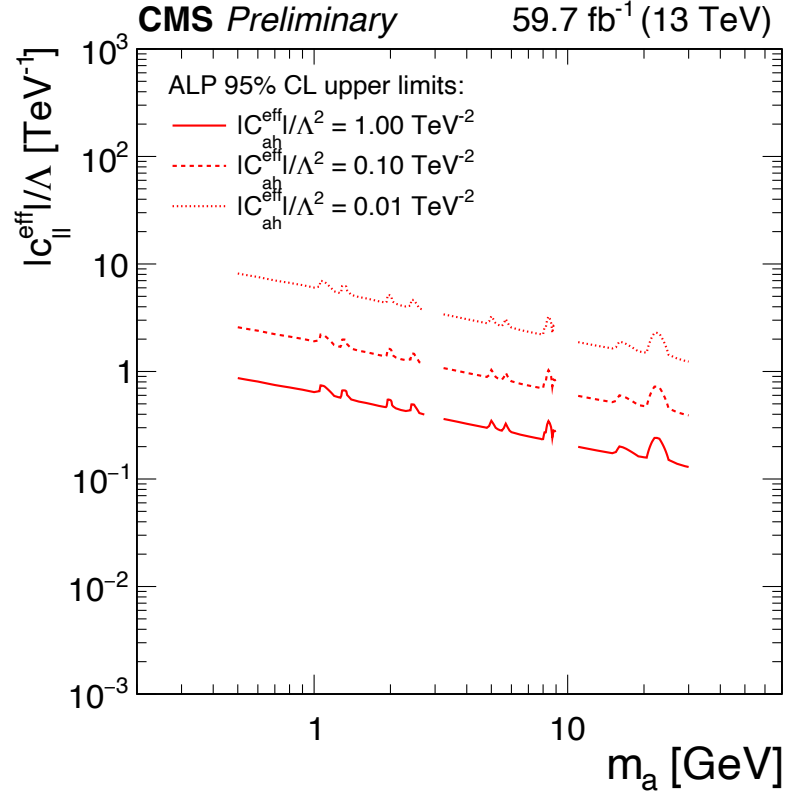


Figure 8.8 : Observed 95% CL upper limits on effective coupling of the ALP to the SM leptons, $c_{||}/\Lambda$, under different choices of C_{ah}/Λ^2 and ALP total width fixed to 10^{-5} GeV .

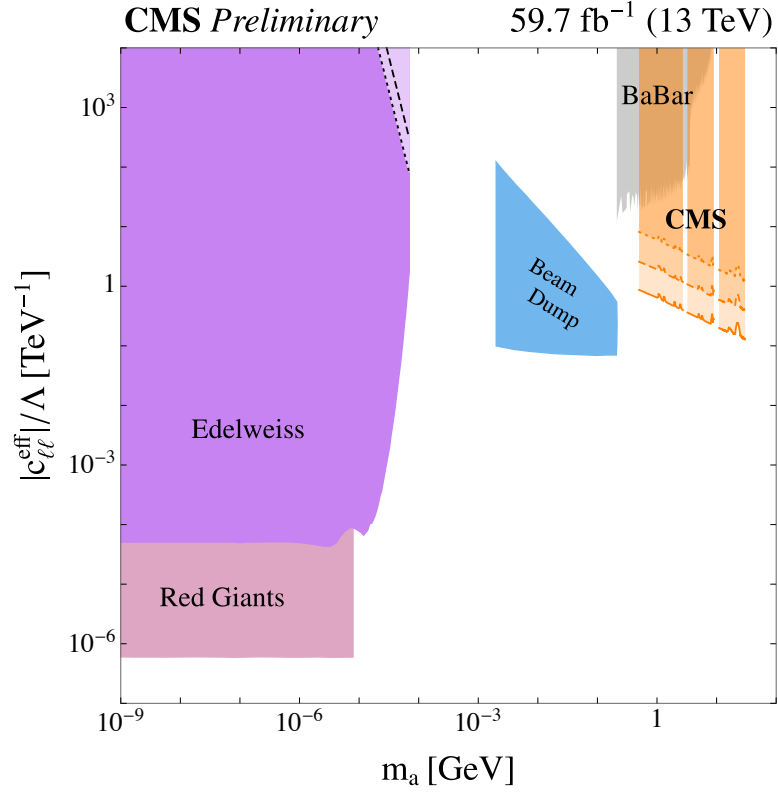


Figure 8.9 : Constraints on the ALP effective coupling to leptons, $c_{\ell\ell}/\Lambda$, as a function of the ALP mass. The orange shaded region represents the parameter space excluded by this analysis with 2018 data under three choices of C_{ah}/Λ^2 : 1 TeV⁻² (solid), 0.1 TeV⁻² (dashed) and 0.01 TeV⁻² (dotted).

Limit Interpretation in the Dark SUSY model.

The results of this analysis will allow us to set exclusion limits on currently unconstrained region of ϵ and m_{γ_D} plane, as described in Sec. [1](#). We set 95% CL limit on the product of Higgs production cross section and branching fraction of the Higgs decay to pair of dark photons (accompanied with something else, X) as follows,

$$\sigma(pp \rightarrow h) \times \mathcal{B}(h \rightarrow 2\gamma_D + X) < \frac{N(m_{\mu\mu})}{L \times r \times \alpha_{gen}(m_{\gamma_D}, c\tau_{\gamma_D}) \times \mathcal{B}_{\gamma_D \rightarrow \mu\mu}^2(m_{\gamma_D})}. \quad (8.4)$$

For this limit we normalize the product $\sigma(pp \rightarrow h) \times \mathcal{B}(h \rightarrow 2a + X)$ to the cross section of SM Higgs production $\sigma_{SM}(pp \rightarrow h_{125\text{GeV}})$ as follows,

$$\sigma(pp \rightarrow h) \times \mathcal{B}(h \rightarrow 2a + X) = \sigma_{SM}(pp \rightarrow h_{125\text{GeV}}) \times K, \quad (8.5)$$

where K could be interpreted as an effective branching fraction $\mathcal{B}(h \rightarrow 2a + X)$.

We will then use the parameter K to set limits on several choices of the branching fraction $\mathcal{B}(h \rightarrow 2\gamma_D + X)$ as follows,

$$\sigma_{SM}(pp \rightarrow h_{125\text{GeV}}) \times K < \frac{N(m_{\mu\mu})}{L \times r \times \alpha(m_{\gamma_D}, c\tau_{\gamma_D}) \times \mathcal{B}_{\gamma_D \rightarrow \mu\mu}^2(m_{\gamma_D})}. \quad (8.6)$$

The choices of parameter K (0.01, 0.1, 0.3) are color coded and represented in the z-axis. Using Eq. [1.41](#), we converted $(m_{\gamma_D}, c\tau_{\gamma_D})$ space to (m_{γ_D}, ϵ) space and represent the 95% CL limits in this plane. This is shown in Fig. [8.10](#). We can conclude that a large previously unconstrained area of the parameters space is excluded at 95% CL.

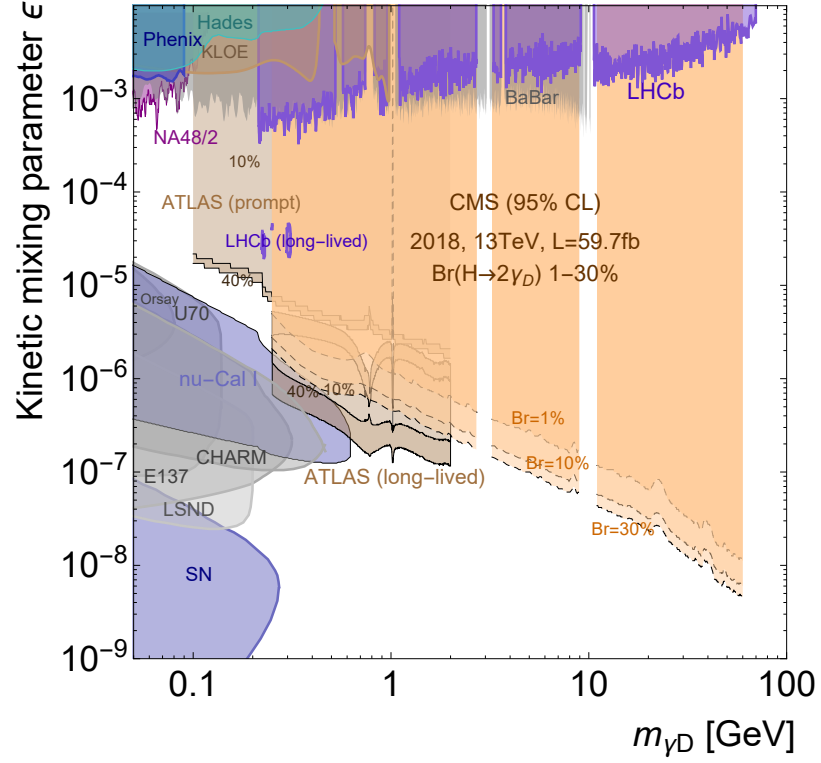


Figure 8.10 : The 95% CL limits from this analysis and other experimental constraints, in the plane of two parameters for the dark SUSY scenarios: ϵ and m_{γ_D} . Different colors represent different values of $\mathcal{B}(h \rightarrow 2\gamma_D)$. The limit goes from 0.25 to 60 GeV.

Limit Interpretation in the NMSSM model.

For the NMSSM scenario, the 95% CL upper limit is derived for $\sigma(pp \rightarrow h_{1,2} \rightarrow 2a_1) \times \mathcal{B}^2(a_1 \rightarrow 2\mu)$ as a function of m_{a_1} with $m_{h_1} = 90$ GeV (dashed curve), $m_{h_1} = 125$ GeV (dash-dotted curve), and $m_{h_2} = 150$ GeV (dotted curve) as shown in Fig. 8.11. It is assumed that all contributions come from either h_1 or h_2 ; there is no case in which both h_1 and h_2 decay to the a_1 .

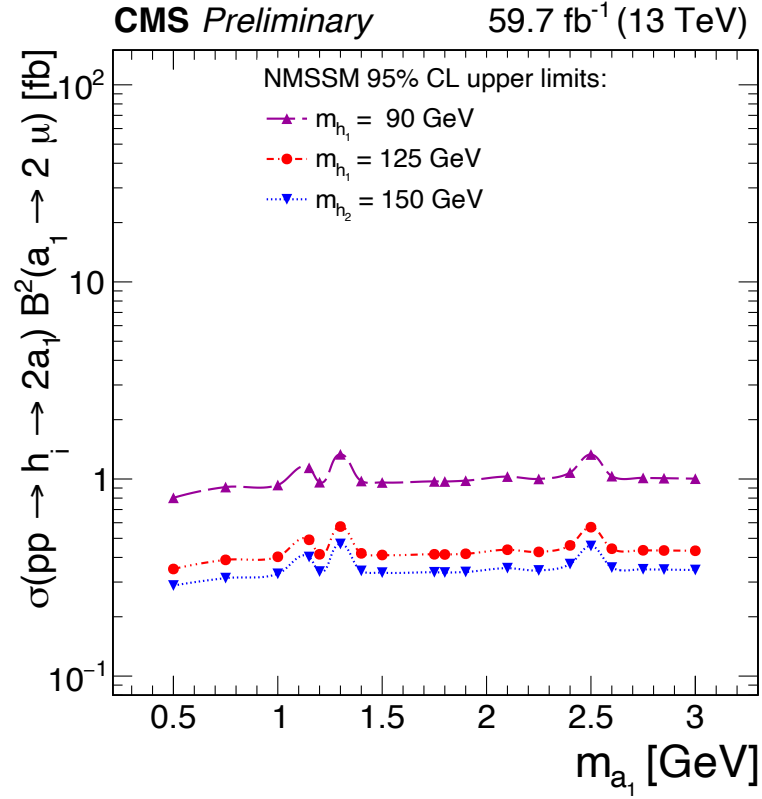


Figure 8.11 : The observed 95% CL upper limit for $\sigma(pp \rightarrow h_{1,2} \rightarrow 2a_1) \times \mathcal{B}^2(a_1 \rightarrow 2\mu)$ for the NMSSM as a function of m_{a_1} for three choices of $m_{h_{1,2}}$.

Chapter 9

Summary and Final Remarks

A search for pair production of a new boson that decays to a pair of oppositely charged muons has been presented in this thesis. The search is done based on a sample that corresponds to an integrated luminosity of 59.7 fb^{-1} collected by the CMS experiment in proton-proton collisions at $\sqrt{s} = 13 \text{ TeV}$ in 2018. No significant deviation from the predicted background is observed. A model independent 95% CL upper limit is set on $\sigma(pp \rightarrow 2a + X) \times \mathcal{B}^2(a \rightarrow 2\mu) \times \alpha_{\text{Gen}}$ for a signal boson mass from 0.21 GeV to 60 GeV and is found to vary between 0.11 and 0.38 fb. The model independent result of the analysis can be reinterpreted within a broad range of physics models predicting a similar topology. In this thesis, the result is interpreted in the context of the ALP, dark SUSY, and NMSSM benchmark models.

The result in this thesis will be combined with the previous published result [\[83\]](#) for new boson mass below 9 GeV. It is also foreseen that this result will be combined with the result of the search for prompt signal bosons using 2017 dataset collected by the CMS experiment. The combined result will put a even stronger limit on $\sigma(pp \rightarrow 2a + X) \times \mathcal{B}^2(a \rightarrow 2\mu) \times \alpha_{\text{Gen}}$.

Some improvements could be done in the future as I learned during this search. The DY background modeling could be improved by using simulation samples with more statistics which will improve the statistical uncertainty. To increase the signal acceptance, the trigger for displaced muons could be improved aiming at lower muon transverse momentum thresholds and relaxed eta restrictions. The triggers in the

current search should be kept as a backup for future searches. The muon selection could be improved to avoid the selection of SA muons as they introduce background events that are hard to model. The event selection could be improved to further improve the signal efficiency and minimize the background at the high mass region. Possible solutions could be machine learning techniques and data-driven methods in parallel with the current estimation which is purely based on simulation samples.

There are several possible directions to extend this search in the future. First of all, the search for more displaced signals in an expanded fiducial volume as well as more massive signals is favored in general. Also, non-Higgs portal scenarios would be interesting. We already knew from current studies that in heavy (much heavier than the SM Higgs boson, above 200 GeV) portal scenarios, the decay muons can have very high momentum and will no longer be minimum ionizing particles. For the signal boson with 5 GeV coming from these heavy portals, the mass window set in this thesis would be less than 90% efficient because of stronger radiative tails with high momentum muons.

One could also perform a general search for the production of two different new bosons in the entire 2D mass plane. In this case, the muon pairing can not rely on the minimum difference in the muon pair mass. One could pair muons purely based on the vertex probability (or equivalently, the chi-square and degrees of freedom from the vertex fit). The background estimation would be challenging as the control region used in this thesis is no longer available. For this purpose, one would probably resort to new variables such as the distance between two dimuon vertices.

Other directions worth exploring include a search for the production of triple new bosons with three dimuons in the final state. A search for a final state of muon jets with more than two muons in each jet will also be interesting for the HL-LHC.

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Appendix A

Samples Production at CMS

A.1 Data Format at CMS

The data flow at CMS during Run 2 is shown in Fig. [A.1](#). Raw data from the detectors were digitized (DIGI), and events were reconstructed (RECO). The DoubleMuon dataset contains events selected by a collection of triggers requiring at least two muon objects, including those shown in Tab. [3.2](#), during four data taking eras (A, B, C, and D) in 2018. The analysis object data (AOD) was generated with ~ 400 kilobytes per event. AOD is widely used for physics analysis at CMS during Run 1. With the increase of data volume in Run 2, the Mini-AOD format was designed to alleviate the data storage pressure at CMS. It is roughly 10% of the size of AOD. All samples used in this thesis are all formatted in Mini-AOD. Each physics analysis, including this analysis, use Mini-AOD samples to generate flat ntuples for specific needs of the analysis.

The contents of Mini-AOD are shown in Fig. [A.2](#). Mini-AOD contains particle candidates reconstructed by the PF algorithm as described in Chapter [3](#). It also contains high-level physics objects such as leptons, photons and jets. These physics objects are linked to the PF candidates from which it was reconstructed. This makes the calculation of certain variables more accurate, such as the isolation variable used in Chapter [5](#).

The simulated Mini-AOD is called Mini-AODSIM. In this case, extra information

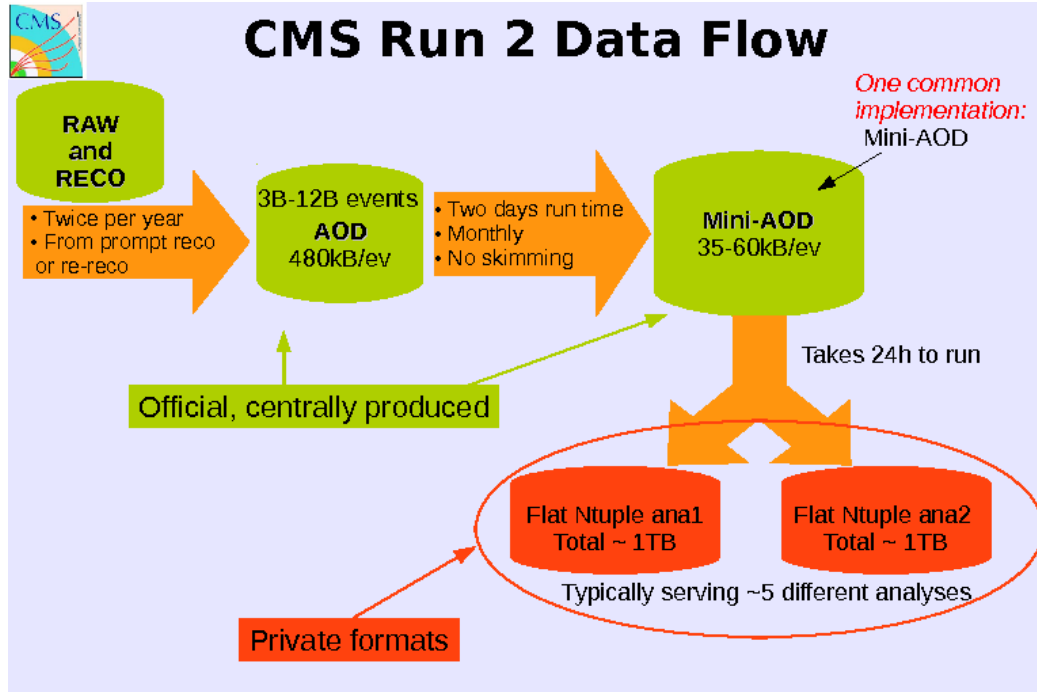


Figure A.1 : Data flow at CMS during Run 2. Plot from [212].

about simulated particles are stored. Because the simulated particles usually take a lot of space, only a subset of the simulated particles are stored in Mini-AODSIM, called pruned GenParticles. This includes the most important information of the simulated event and enables us to match reconstructed physics objects to simulated particles in the thesis.

Other miscellaneous information like the trigger, interaction vertices are also stored in Mini-AOD(SIM).

A.2 UE Simulation at CMS

A set of parameters related to the BBR and MPI, called a tune, are used to model the UE at CMS. In 2018, a so-called CP5 tune [181] is used for all signal MC sample used

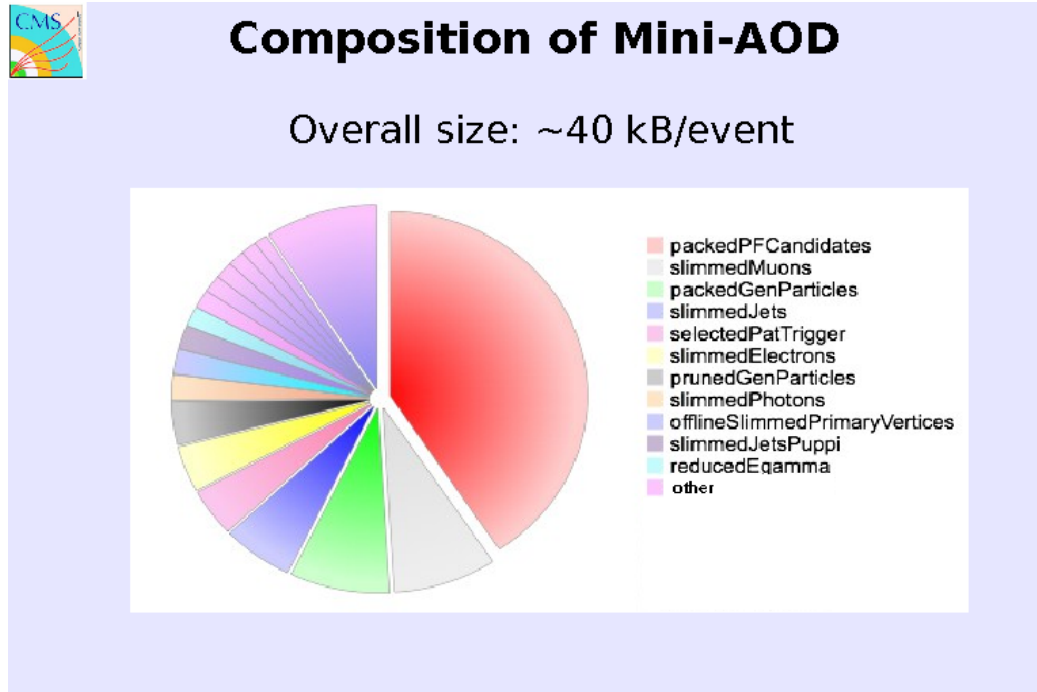


Figure A.2 : MiniAOD contents. Plot from [212].

in the thesis, where CP stands for CMS PYTHIA 8 [188]. The CP5 tune uses the PDF set, NNPDF3.1 [213], where NN stands for next-to-next-to-leading order (NNLO) in perturbative QCD. More details on the tune can be found in reference [181]. All signal MC samples used in this thesis use PYTHIA 8 for hadronization.

A.3 PU Simulation at CMS

Before Run 2, the simulation of the PU at CMS is done by accumulating GEANT 4-simulated hits from MB events and merging with signal hits before they are sent for further digitization. Typically, hundreds of MB events are used for each simulated signal event. This process requires large computing resources such as CPU and memory consumption. In 2018, the PU simulation at CMS is changed to a premixing

scheme where MB events are pre-mixed, digitized and simulated before they are used with a signal event. This saves disk space and gains computational speed.

A.4 MC Production and Data Analysis Settings

GEN-SIM Release: CMSSW_10_2_3

```
git clone git@github.com:cms-tamu/MuJetAnalysis_Generator.git

cmsDriver.py
Generator/python/Pythia8GeneratorFilter_13TeV_NMSSM_Hto2Ato4mu_mH_100_mA_0p25_cfi.py \
--fileout file:output.root --mc --eventcontent RAWSIM --datatier GEN-SIM \
--conditions 102X_upgrade2018_realistic_v11 --beamspot Realistic25ns13TeVEarly2018Collision \
--step GEN,SIM --nThreads 8 --geometry DB:Extended --era Run2_2018 \
--python_filename HIG-RunIIFall118GS-00006_1_cfg.py --no_exec \
--customise Configuration/DataProcessing/Utils.addMonitoring -n 1685
```

DIGI-HLT Release: CMSSW_10_2_5

```
cmsDriver.py step1 --filein file:input.root --fileout file:output.root \
--pileup_input
"dbs:/Neutrino_E-10_gun/RunIISummer17PrePremix-PUAutumn18_102X_upgrade2018_realistic_v15-v1/GEN-SIM-DIGI-RAW" \
--mc --eventcontent PREMIXRAW --datatier GEN-SIM-RAW --conditions 102X_upgrade2018_realistic_v15 \
--step DIGI,DATAMIX,L1,DIGI2RAW,HLT:@relval2018 --procModifiers premix_stage2 --nThreads 8 \
--geometry DB:Extended --datamix PreMix --era Run2_2018 \
--python_filename HIG-RunIIAutumn18DRPremix-00013_1_cfg.py --no_exec \
--customise Configuration/DataProcessing/Utils.addMonitoring -n 2626
```

RECO Release: CMSSW_10_2_5

```
cmsDriver.py step2 --filein file:input.root \
--fileout file:output.root --mc --eventcontent AODSIM \
--runUnscheduled --datatier AODSIM --conditions 102X_upgrade2018_realistic_v15 \
--step RAW2DIGI,L1Reco,RECO,RECOSIM,EI --procModifiers premix_stage2 --nThreads 8 \
--era Run2_2018 --python_filename HIG-RunIIAutumn18DRPremix-00013_2_cfg.py --no_exec \
--customise Configuration/DataProcessing/Utils.addMonitoring -n 2626
```


Mini-AODSIM Release: CMSSW_10_2_5

```
cmsDriver.py step1 --filein file:input.root --fileout file:output.root --mc \  
--eventcontent MINIAODSIM --runUnscheduled --datatier MINIAODSIM \  
--conditions 102X_upgrade2018_realistic_v15 --step PAT --nThreads 8 --geometry DB:Extended \  
--era Run2_2018 --python_filename HIG-RunIIAutumn18MiniAOD-00013_1_cfg.py \  
--no_exec --customise Configuration/DataProcessing/Utils.addMonitoring -n 8597
```

Analysis Release: CMSSW_10_2_5

GlobalTag MC: 102X_upgrade2018_realistic_v19

GlobalTag Data: 102X_dataRun2_v11 (Era A-C), 102X_dataRun2_Prompt_v14 (Era D)

Appendix B

Problem Encountered with MSSMD MC Generation

In all MSSMD samples with nonnegligible lifetime and with dataset name,

```
/MSSMD_mH_125_mN1_*_mGammaD_*_cT_*_TuneCP5_13TeV-madgraph-pythia8
/RunIIFall17MiniAODv2-PU2017_12Apr2018_94X_mc2017_realistic_v14-v1
/MINIAODSIM,
```

that were produced by the central CMS Monte Carlo production services we noticed issues with the simulation of displaced muons in the CMS detector. This issue was not present in previous MC simulation campaigns. In particular there were two classes of incorrect simulation of displaced muons:

1. a duplicate prompt SimTrack is associated to the displaced GenParticle, in addition to the true displaced SimTrack
2. only a prompt SimTrack is associated to the displaced GenParticle

These prompt SimTracks exhibited a track pattern close to the displaced SimTracks, but were clearly pointing back to the CMS center as opposed to the dark photon decay vertex. An example of each case is shown in Fig. [B.1](#) and Fig. [B.2](#). An example of correct simulation of displaced muons is shown in Fig. [B.3](#).

In the investigation of the problem we noticed that muon pairs with a transverse displacement L_{xy} larger than 2.87 cm showed duplicate SimTracks in CMS. Muon pairs with L_{xy} smaller than 2.87 cm were correctly simulated. This suggested a

link to the radius of the CMS beam pipe, $R = 2.9$ cm. By relaxing the vertex radius cut `RDecLenCut` from 2.9 cm to 100 cm in the module `g4SimHits`, previously incorrectly simulated muons were now correctly simulated. Further investigation into the problem revealed a relevant change to the Generator interface in CMS (<https://github.com/cms-sw/cmssw/pull/16366>). This pull request modified the tracking of `GEANT 4` for certain exotic particles. Particles with a `PDGId` between 1000000 and 4000000 (which includes dark photons) and with a status > 3 would have their status changed to 2 for `GEANT 4` tracking purposes if they decayed outside the CMS beam pipe. This effectively eliminated the simulation displaced muons when produced in the decay of long-lived dark photons with `PDGId 3000002`.

After reverting `PR16366` we noticed that the issue with the simulation had dissolved. Following the investigation and a proposal to resolve it to the CMS Simulation conveners, three pull requests (27765, 27766 and 27778) were made to different releases. After the fix to `CMSSW`, the produced displaced samples show good reconstruction of events as shown in Fig. [B.4](#) from one `MSSMD` displaced MC sample in 2018.

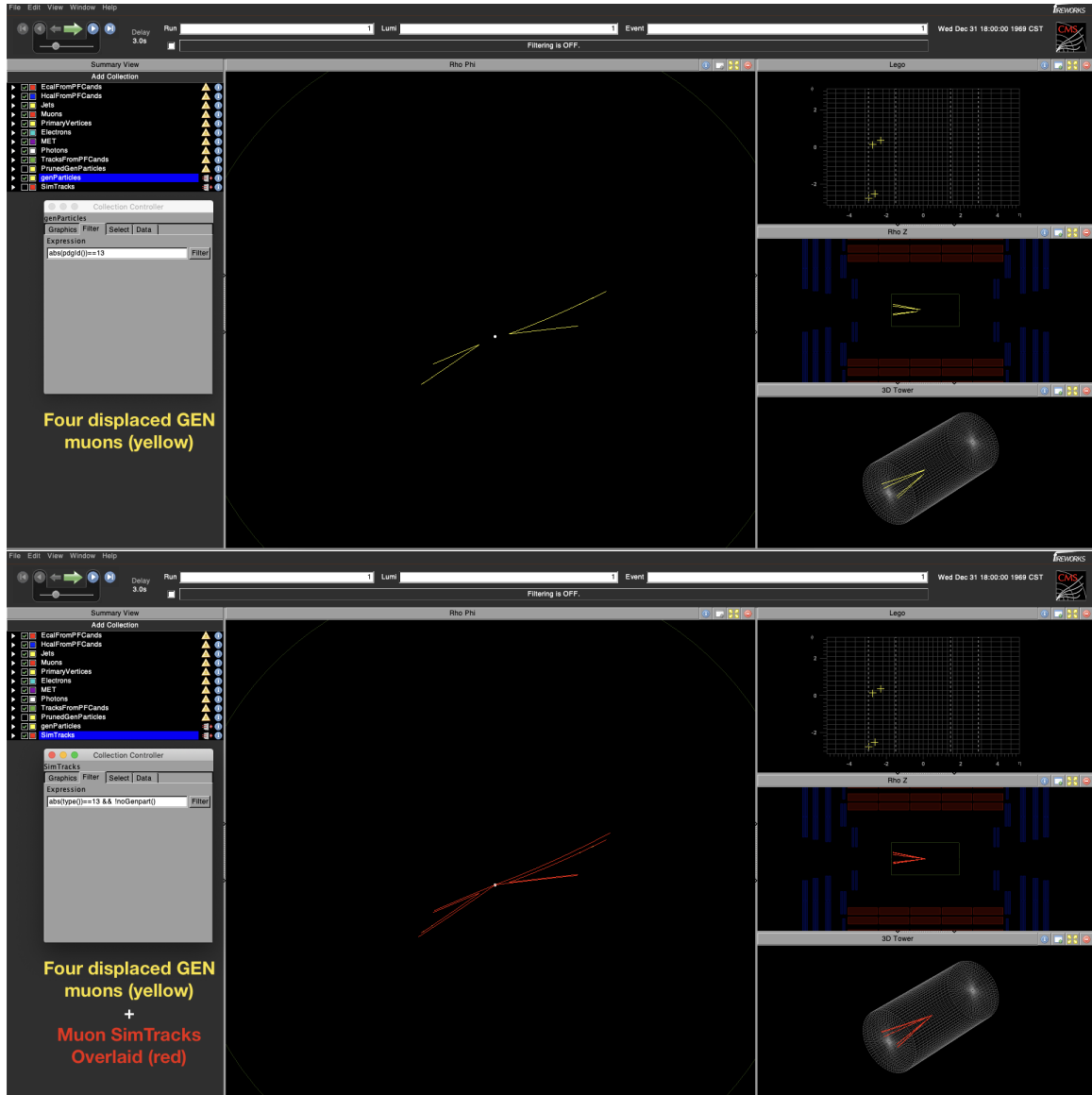


Figure B.1 : Case 1: generator level muon (yellow) is displaced. Both prompt and displaced SimTracks (red) exist in displaced MSSMD sample ($m = 5 \text{ GeV}$, $c\tau = 50 \text{ mm}$).

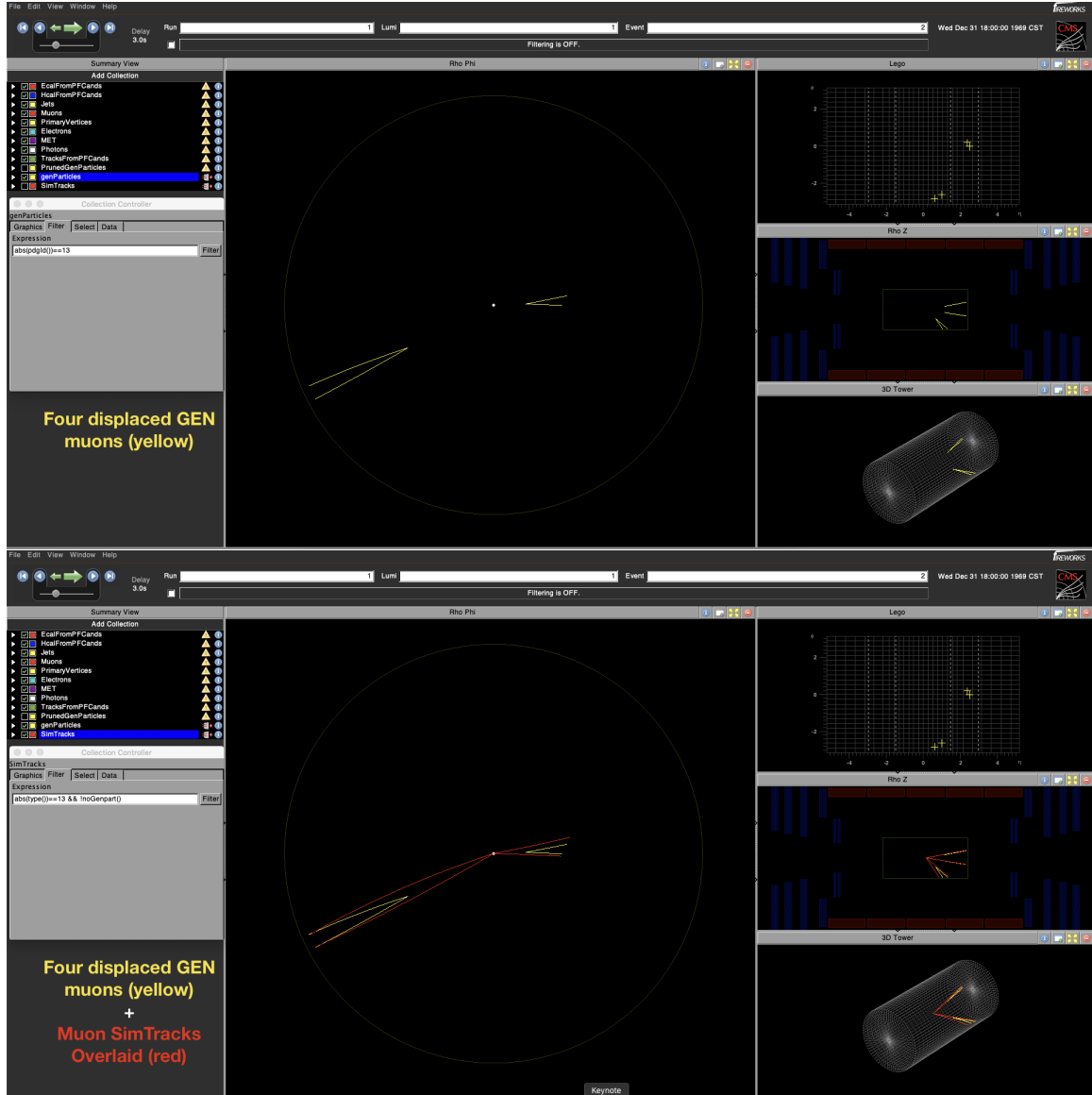


Figure B.2 : Case 2: generator level muon (yellow) is displaced. Only prompt SimTracks (red) exist in displaced MSSMD sample ($m = 5 \text{ GeV}$, $c\tau = 50 \text{ mm}$).

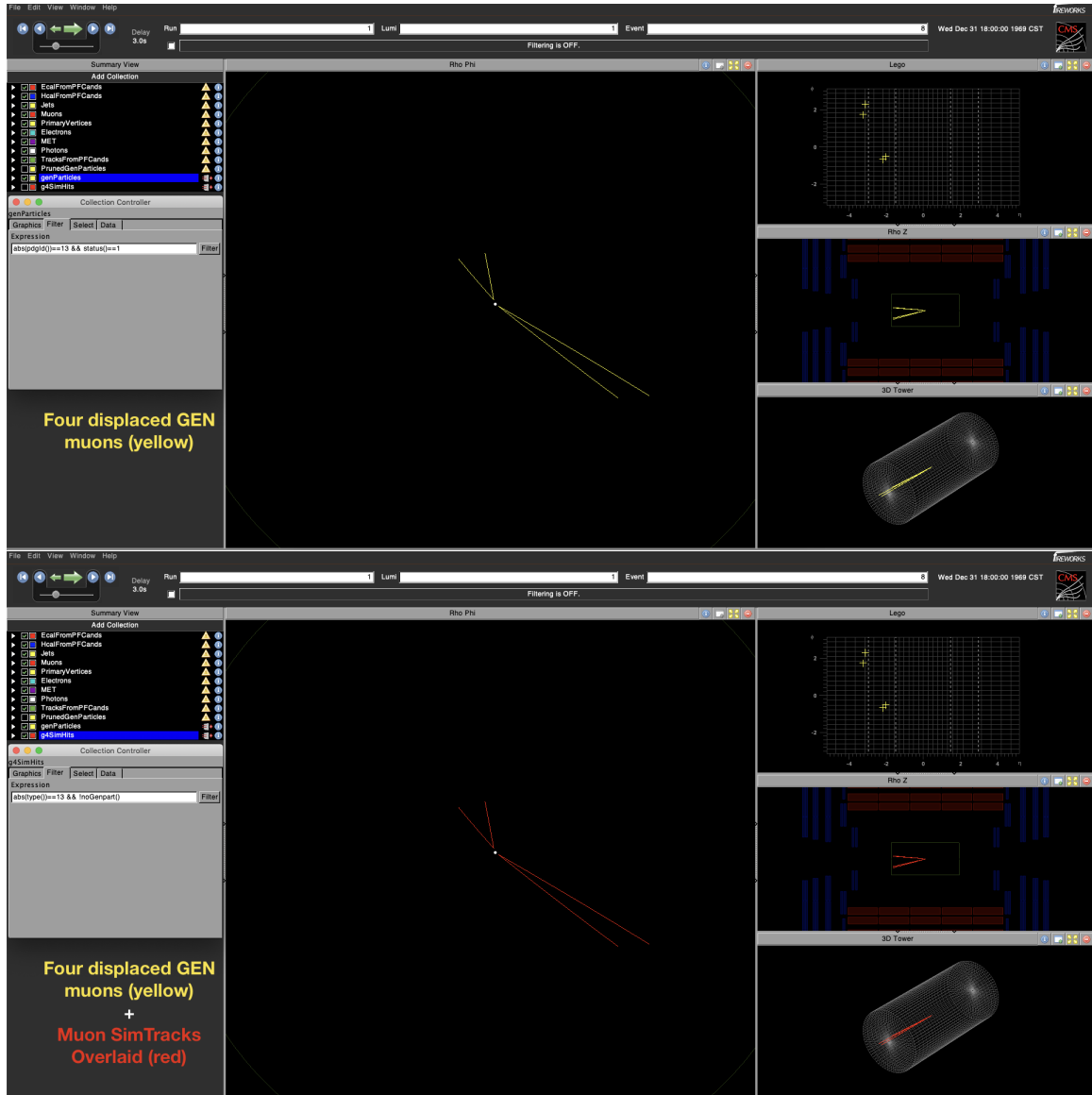


Figure B.3 : Example of correct simulation of displaced muons: generator level muon (yellow) is displaced. Two good displaced SimTracks (red) exist in displaced MSSMD sample ($m = 5 \text{ GeV}$, $c\tau = 50 \text{ mm}$).

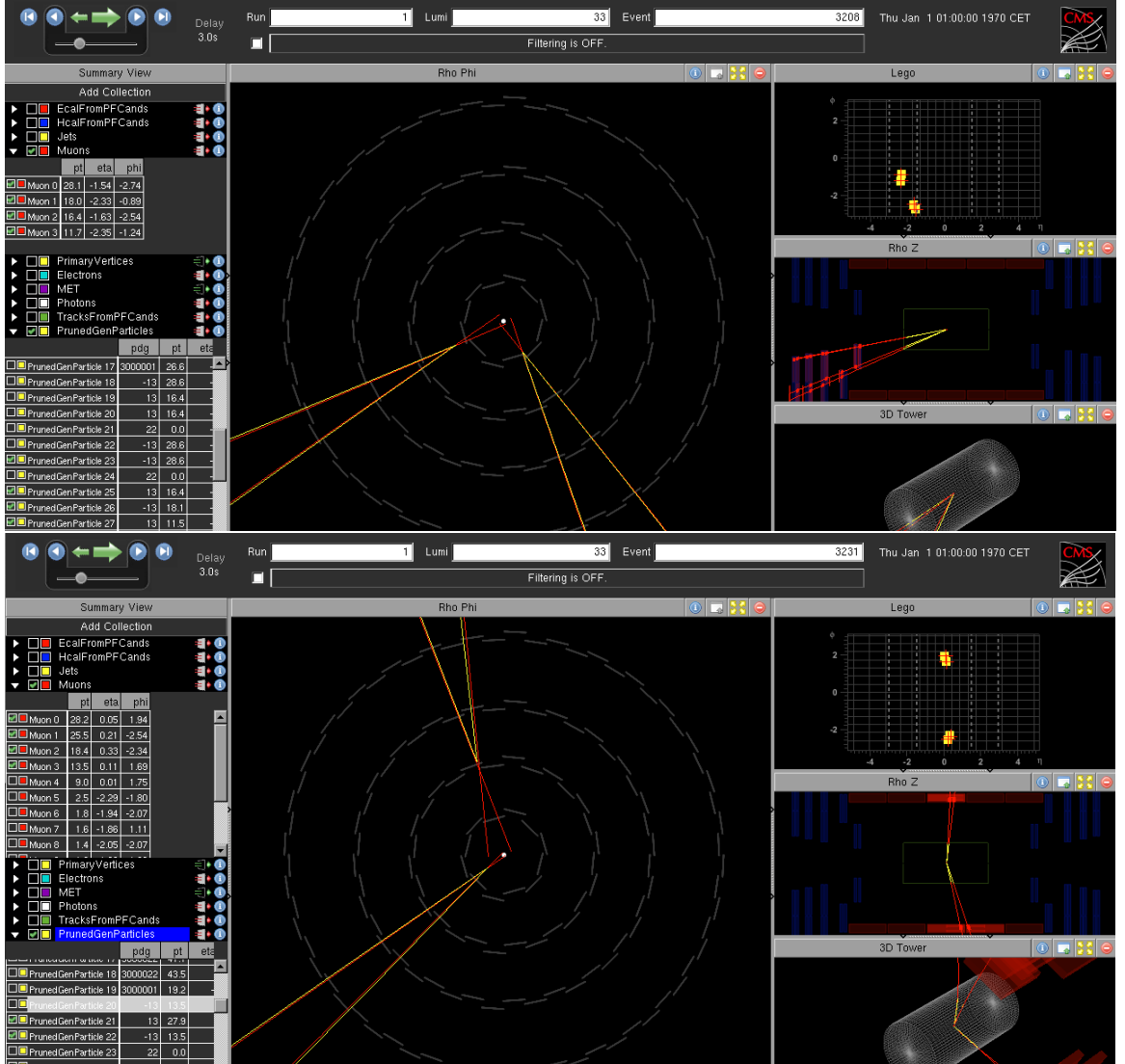


Figure B.4 : Two example events with good simulation of displaced muons after the fix in CMSSW in 2018 MSSMD MC sample ($m = 5$ GeV, $c\tau = 3$ mm). Yellow lines are muons at generator level. Red lines are reconstructed PF muons. The grey circles formed by staggered layers in the background of Rho-Phi view are pixel detectors in the barrel.

Appendix C

NMSSM Generator Settings with Pythia 8

C.1 Common Cases

Most NMSSM samples were produced with the following template configuration.

```
generator = cms.EDFilter('Pythia8GeneratorFilter',
    pythiaHepMCVerbosity = cms.untracked.bool(False),
    maxEventsToPrint = cms.untracked.int32(0),
    pythiaPylistVerbosity = cms.untracked.int32(1),
    filterEfficiency = cms.untracked.double(1.0),
    crossSection = cms.untracked.double(0.0),
    comEnergy = cms.double(13000.0),
    PythiaParameters = cms.PSet(
        pythia8CommonSettingsBlock,
        pythia8CP5SettingsBlock,
        pythiaUESettings = cms.vstring(),
        processParameters = cms.vstring(
            'Higgs:useBSM = on',
            'HiggsBSM:all = off',
            'HiggsBSM:gg2H2 = on',
            '35:m0 = 125.0',
            '36:m0 = 0.5',
            '35:onMode = off',
            '35:onIfMatch = 36 36',
            '36:onMode = off',
            '36:onIfMatch = 13 -13',
```



```

        'Init:showProcesses = on',
        'Init:showChangedSettings = on'),
parameterSets = cms.vstring(
    'pythiaUESettings',
    'pythia8CommonSettings',
    'pythia8CP5Settings',
    'processParameters')
    )
)

```

C.2 Special Cases

The NMSSM sample with $m_a = 0.25$ GeV was produced with a different template configuration than the one used in common cases.

```

generator = cms.EDFilter('Pythia8GeneratorFilter',
    pythiaPylistVerbosity = cms.untracked.int32(1),
    filterEfficiency = cms.untracked.double(1.0),
    pythiaHepMCVerbosity = cms.untracked.bool(False),
    comEnergy = cms.double(13000.0),
    crossSection = cms.untracked.double(1.0),
    maxEventsToPrint = cms.untracked.int32(1000),
    PythiaParameters = cms.PSet(
        pythia8CommonSettingsBlock,
        pythia8CP5SettingsBlock,
        pythiaUESettings = cms.vstring(),
        processParameters = cms.vstring(
            'Higgs:useBSM = on',
            'HiggsBSM:all = off',
            'HiggsBSM:gg2H2 = on',
            '35:m0 = 90',

```

```

'35:addChannel 1 0.01 100 54 54',

'35:onMode = off',

'35:onIfMatch = 54 54',

'54:isResonance = false',

'54:mWidth = 0',

'54:mMin = 0.1',

'54:m0 = 0.25',

'54:onMode = off',

'54:onIfMatch = 13 -13',

'Init:showProcesses = on',

'Init:showChangedSettings = on'),

parameterSets = cms.vstring('pythiaUESettings',

    'pythia8CommonSettings',

    'pythia8CP5Settings',

    'processParameters')

)

)

```

Appendix D

ALP MC Samples

Tab. D.1 shows all 2018 produced ALP MC samples.

Table D.1 : ALP 2018 MC samples.

Dataset	Events
/ALP_mH_125_mALP_0p5_PSWeights_TuneCP5_13TeV-madgraph-pythia8/RunIIAutumn18MiniAOD-102X_upgrade2018_realistic_v15-v2/MINIAODSIM	200000
/ALP_mH_125_mALP_0p6_PSWeights_TuneCP5_13TeV-madgraph-pythia8/RunIIAutumn18MiniAOD-102X_upgrade2018_realistic_v15-v2/MINIAODSIM	187000
/ALP_mH_125_mALP_0p7_PSWeights_TuneCP5_13TeV-madgraph-pythia8/RunIIAutumn18MiniAOD-102X_upgrade2018_realistic_v15-v2/MINIAODSIM	200000
/ALP_mH_125_mALP_0p8_PSWeights_TuneCP5_13TeV-madgraph-pythia8/RunIIAutumn18MiniAOD-102X_upgrade2018_realistic_v15-v2/MINIAODSIM	189000
/ALP_mH_125_mALP_0p9_PSWeights_TuneCP5_13TeV-madgraph-pythia8/RunIIAutumn18MiniAOD-102X_upgrade2018_realistic_v15-v2/MINIAODSIM	200000
/ALP_mH_125_mALP_1_PSWeights_TuneCP5_13TeV-madgraph-pythia8/RunIIAutumn18MiniAOD-102X_upgrade2018_realistic_v15-v2/MINIAODSIM	186000
/ALP_mH_125_mALP_2_PSWeights_TuneCP5_13TeV-madgraph-pythia8/RunIIAutumn18MiniAOD-102X_upgrade2018_realistic_v15-v2/MINIAODSIM	200000

Dataset	Events
/ALP_mH_125_mALP_3_PSWeights_TuneCP5_13TeV-madgraph-pythia8/RunIIAutumn18MiniAOD-102X_upgrade2018_realistic_v15-v2/MINIAODSIM	179000
/ALP_mH_125_mALP_4_PSWeights_TuneCP5_13TeV-madgraph-pythia8/RunIIAutumn18MiniAOD-102X_upgrade2018_realistic_v15-v2/MINIAODSIM	200000
/ALP_mH_125_mALP_5_PSWeights_TuneCP5_13TeV-madgraph-pythia8/RunIIAutumn18MiniAOD-102X_upgrade2018_realistic_v15-v2/MINIAODSIM	200000
/ALP_mH_125_mALP_6_PSWeights_TuneCP5_13TeV-madgraph-pythia8/RunIIAutumn18MiniAOD-102X_upgrade2018_realistic_v15-v2/MINIAODSIM	200000
/ALP_mH_125_mALP_7_PSWeights_TuneCP5_13TeV-madgraph-pythia8/RunIIAutumn18MiniAOD-102X_upgrade2018_realistic_v15-v2/MINIAODSIM	187000
/ALP_mH_125_mALP_8_PSWeights_TuneCP5_13TeV-madgraph-pythia8/RunIIAutumn18MiniAOD-102X_upgrade2018_realistic_v15-v2/MINIAODSIM	200000
/ALP_mH_125_mALP_15_PSWeights_TuneCP5_13TeV-madgraph-pythia8/RunIIAutumn18MiniAOD-102X_upgrade2018_realistic_v15-v2/MINIAODSIM	200000
/ALP_mH_125_mALP_20_PSWeights_TuneCP5_13TeV-madgraph-pythia8/RunIIAutumn18MiniAOD-102X_upgrade2018_realistic_v15-v2/MINIAODSIM	123000

Dataset	Events
/ALP_mH_125_mALP_25_PSWeights_TuneCP5_13TeV-madgraph-pythia8/RunIIAutumn18MiniAOD-102X_upgrade2018_realistic_v15-v2/MINIAODSIM	197000
/ALP_mH_125_mALP_30_PSWeights_TuneCP5_13TeV-madgraph-pythia8/RunIIAutumn18MiniAOD-102X_upgrade2018_realistic_v15-v2/MINIAODSIM	200000

Appendix E

Dark SUSY MC Samples

Tab. E.1 shows all 2018 produced MSSMD MC samples.

Table E.1 : Dark SUSY (MSSMD) 2018 MC samples.

Dataset	Events
/MSSMD_mH_125_mN1_60_mGammaD_0p25_cT_0_TuneCP5_13TeV-madgraph-pythia8/RunIIAutumn18MiniAOD-102X_upgrade2018_realistic_v15-v1/MINIAODSIM	100000
/MSSMD_mH_125_mN1_60_mGammaD_0p25_cT_0p05_TuneCP5_13TeV-madgraph-pythia8/RunIIAutumn18MiniAOD-102X_upgrade2018_realistic_v15-v1/MINIAODSIM	100000
/MSSMD_mH_125_mN1_60_mGammaD_0p25_cT_0p1_TuneCP5_13TeV-madgraph-pythia8/RunIIAutumn18MiniAOD-102X_upgrade2018_realistic_v15-v1/MINIAODSIM	100000
/MSSMD_mH_125_mN1_60_mGammaD_0p25_cT_0p2_TuneCP5_13TeV-madgraph-pythia8/RunIIAutumn18MiniAOD-102X_upgrade2018_realistic_v15-v1/MINIAODSIM	100000
/MSSMD_mH_125_mN1_60_mGammaD_0p25_cT_0p5_TuneCP5_13TeV-madgraph-pythia8/RunIIAutumn18MiniAOD-102X_upgrade2018_realistic_v15-v1/MINIAODSIM	100000
/MSSMD_mH_125_mN1_60_mGammaD_0p25_cT_100_TuneCP5_13TeV-madgraph-pythia8/RunIIAutumn18MiniAOD-102X_upgrade2018_realistic_v15-v1/MINIAODSIM	100000000
/MSSMD_mH_125_mN1_60_mGammaD_0p25_cT_10_TuneCP5_13TeV-madgraph-pythia8/RunIIAutumn18MiniAOD-102X_upgrade2018_realistic_v15-v1/MINIAODSIM	5000000

Dataset	Events
/MSSMD_mH_125_mN1_60_mGammaD_0p25_cT_1_TuneCP5_13TeV-madgraph-pythia8/RunIIAutumn18MiniAOD-102X_upgrade2018_realistic_v15-v1/MINIAODSIM	100000
/MSSMD_mH_125_mN1_60_mGammaD_0p25_cT_20_TuneCP5_13TeV-madgraph-pythia8/RunIIAutumn18MiniAOD-102X_upgrade2018_realistic_v15-v1/MINIAODSIM	10000000
/MSSMD_mH_125_mN1_60_mGammaD_0p25_cT_2_TuneCP5_13TeV-madgraph-pythia8/RunIIAutumn18MiniAOD-102X_upgrade2018_realistic_v15-v1/MINIAODSIM	300000
/MSSMD_mH_125_mN1_60_mGammaD_0p25_cT_3_TuneCP5_13TeV-madgraph-pythia8/RunIIAutumn18MiniAOD-102X_upgrade2018_realistic_v15-v1/MINIAODSIM	300000
/MSSMD_mH_125_mN1_60_mGammaD_0p25_cT_50_TuneCP5_13TeV-madgraph-pythia8/RunIIAutumn18MiniAOD-102X_upgrade2018_realistic_v15-v1/MINIAODSIM	50000000
/MSSMD_mH_125_mN1_60_mGammaD_0p25_cT_5_TuneCP5_13TeV-madgraph-pythia8/RunIIAutumn18MiniAOD-102X_upgrade2018_realistic_v15-v1/MINIAODSIM	1000000
/MSSMD_mH_125_mN1_60_mGammaD_0p4_cT_0_TuneCP5_13TeV-madgraph-pythia8/RunIIAutumn18MiniAOD-102X_upgrade2018_realistic_v15-v1/MINIAODSIM	100000
/MSSMD_mH_125_mN1_60_mGammaD_0p4_cT_0p05_TuneCP5_13TeV-madgraph-pythia8/RunIIAutumn18MiniAOD-102X_upgrade2018_realistic_v15-v1/MINIAODSIM	100000

Dataset	Events
/MSSMD_mH_125_mN1_60_mGammaD_0p4_cT_0p1_TuneCP5_13TeV-madgraph-pythia8/RunIIAutumn18MiniAOD-102X_upgrade2018_realistic_v15-v1/MINIAODSIM	100000
/MSSMD_mH_125_mN1_60_mGammaD_0p4_cT_0p2_TuneCP5_13TeV-madgraph-pythia8/RunIIAutumn18MiniAOD-102X_upgrade2018_realistic_v15-v1/MINIAODSIM	100000
/MSSMD_mH_125_mN1_60_mGammaD_0p4_cT_0p5_TuneCP5_13TeV-madgraph-pythia8/RunIIAutumn18MiniAOD-102X_upgrade2018_realistic_v15-v1/MINIAODSIM	100000
/MSSMD_mH_125_mN1_60_mGammaD_0p4_cT_100_TuneCP5_13TeV-madgraph-pythia8/RunIIAutumn18MiniAOD-102X_upgrade2018_realistic_v15-v2/MINIAODSIM	100000000
/MSSMD_mH_125_mN1_60_mGammaD_0p4_cT_10_TuneCP5_13TeV-madgraph-pythia8/RunIIAutumn18MiniAOD-102X_upgrade2018_realistic_v15-v1/MINIAODSIM	1000000
/MSSMD_mH_125_mN1_60_mGammaD_0p4_cT_1_TuneCP5_13TeV-madgraph-pythia8/RunIIAutumn18MiniAOD-102X_upgrade2018_realistic_v15-v1/MINIAODSIM	300000
/MSSMD_mH_125_mN1_60_mGammaD_0p4_cT_20_TuneCP5_13TeV-madgraph-pythia8/RunIIAutumn18MiniAOD-102X_upgrade2018_realistic_v15-v1/MINIAODSIM	100000000
/MSSMD_mH_125_mN1_60_mGammaD_0p4_cT_2_TuneCP5_13TeV-madgraph-pythia8/RunIIAutumn18MiniAOD-102X_upgrade2018_realistic_v15-v1/MINIAODSIM	300000

Dataset	Events
/MSSMD_mH_125_mN1_60_mGammaD_0p4_cT_3_TuneCP5_13TeV-madgraph-pythia8/RunIIAutumn18MiniAOD-102X_upgrade2018_realistic_v15-v1/MINIAODSIM	300000
/MSSMD_mH_125_mN1_60_mGammaD_0p4_cT_50_TuneCP5_13TeV-madgraph-pythia8/RunIIAutumn18MiniAOD-102X_upgrade2018_realistic_v15-v1/MINIAODSIM	30000000
/MSSMD_mH_125_mN1_60_mGammaD_0p4_cT_5_TuneCP5_13TeV-madgraph-pythia8/RunIIAutumn18MiniAOD-102X_upgrade2018_realistic_v15-v1/MINIAODSIM	300000
/MSSMD_mH_125_mN1_60_mGammaD_0p7_cT_0_TuneCP5_13TeV-madgraph-pythia8/RunIIAutumn18MiniAOD-102X_upgrade2018_realistic_v15-v1/MINIAODSIM	100000
/MSSMD_mH_125_mN1_60_mGammaD_0p7_cT_0p05_TuneCP5_13TeV-madgraph-pythia8/RunIIAutumn18MiniAOD-102X_upgrade2018_realistic_v15-v1/MINIAODSIM	100000
/MSSMD_mH_125_mN1_60_mGammaD_0p7_cT_0p1_TuneCP5_13TeV-madgraph-pythia8/RunIIAutumn18MiniAOD-102X_upgrade2018_realistic_v15-v1/MINIAODSIM	100000
/MSSMD_mH_125_mN1_60_mGammaD_0p7_cT_0p2_TuneCP5_13TeV-madgraph-pythia8/RunIIAutumn18MiniAOD-102X_upgrade2018_realistic_v15-v1/MINIAODSIM	100000
/MSSMD_mH_125_mN1_60_mGammaD_0p7_cT_0p5_TuneCP5_13TeV-madgraph-pythia8/RunIIAutumn18MiniAOD-102X_upgrade2018_realistic_v15-v1/MINIAODSIM	100000

Dataset	Events
/MSSMD_mH_125_mN1_60_mGammaD_0p7_cT_10_TuneCP5_13TeV-madgraph-pythia8/RunIIAutumn18MiniAOD-102X_upgrade2018_realistic_v15-v1/MINIAODSIM	2000000
/MSSMD_mH_125_mN1_60_mGammaD_0p7_cT_1_TuneCP5_13TeV-madgraph-pythia8/RunIIAutumn18MiniAOD-102X_upgrade2018_realistic_v15-v1/MINIAODSIM	200000
/MSSMD_mH_125_mN1_60_mGammaD_0p7_cT_20_TuneCP5_13TeV-madgraph-pythia8/RunIIAutumn18MiniAOD-102X_upgrade2018_realistic_v15-v1/MINIAODSIM	2000000
/MSSMD_mH_125_mN1_60_mGammaD_0p7_cT_2_TuneCP5_13TeV-madgraph-pythia8/RunIIAutumn18MiniAOD-102X_upgrade2018_realistic_v15-v1/MINIAODSIM	200000
/MSSMD_mH_125_mN1_60_mGammaD_0p7_cT_3_TuneCP5_13TeV-madgraph-pythia8/RunIIAutumn18MiniAOD-102X_upgrade2018_realistic_v15-v1/MINIAODSIM	200000
/MSSMD_mH_125_mN1_60_mGammaD_0p7_cT_50_TuneCP5_13TeV-madgraph-pythia8/RunIIAutumn18MiniAOD-102X_upgrade2018_realistic_v15-v1/MINIAODSIM	5000000
/MSSMD_mH_125_mN1_60_mGammaD_0p7_cT_5_TuneCP5_13TeV-madgraph-pythia8/RunIIAutumn18MiniAOD-102X_upgrade2018_realistic_v15-v1/MINIAODSIM	200000
/MSSMD_mH_125_mN1_60_mGammaD_15_cT_0_TuneCP5_13TeV-madgraph-pythia8/RunIIAutumn18MiniAOD-102X_upgrade2018_realistic_v15-v1/MINIAODSIM	100000

Dataset	Events
/MSSMD_mH_125_mN1_60_mGammaD_15_cT_0p05_TuneCP5_13TeV-madgraph-pythia8/RunIIAutumn18MiniAOD-102X_upgrade2018_realistic_v15-v1/MINIAODSIM	100000
/MSSMD_mH_125_mN1_60_mGammaD_15_cT_0p1_TuneCP5_13TeV-madgraph-pythia8/RunIIAutumn18MiniAOD-102X_upgrade2018_realistic_v15-v1/MINIAODSIM	100000
/MSSMD_mH_125_mN1_60_mGammaD_15_cT_0p2_TuneCP5_13TeV-madgraph-pythia8/RunIIAutumn18MiniAOD-102X_upgrade2018_realistic_v15-v1/MINIAODSIM	100000
/MSSMD_mH_125_mN1_60_mGammaD_15_cT_0p5_TuneCP5_13TeV-madgraph-pythia8/RunIIAutumn18MiniAOD-102X_upgrade2018_realistic_v15-v1/MINIAODSIM	100000
/MSSMD_mH_125_mN1_60_mGammaD_15_cT_10_TuneCP5_13TeV-madgraph-pythia8/RunIIAutumn18MiniAOD-102X_upgrade2018_realistic_v15-v1/MINIAODSIM	300000
/MSSMD_mH_125_mN1_60_mGammaD_15_cT_1_TuneCP5_13TeV-madgraph-pythia8/RunIIAutumn18MiniAOD-102X_upgrade2018_realistic_v15-v1/MINIAODSIM	100000
/MSSMD_mH_125_mN1_60_mGammaD_15_cT_20_TuneCP5_13TeV-madgraph-pythia8/RunIIAutumn18MiniAOD-102X_upgrade2018_realistic_v15-v1/MINIAODSIM	300000
/MSSMD_mH_125_mN1_60_mGammaD_15_cT_2_TuneCP5_13TeV-madgraph-pythia8/RunIIAutumn18MiniAOD-102X_upgrade2018_realistic_v15-v1/MINIAODSIM	100000

Dataset	Events
/MSSMD_mH_125_mN1_60_mGammaD_15_cT_3_TuneCP5_13TeV-madgraph-pythia8/RunIIAutumn18MiniAOD-102X_upgrade2018_realistic_v15-v1/MINIAODSIM	100000
/MSSMD_mH_125_mN1_60_mGammaD_15_cT_50_TuneCP5_13TeV-madgraph-pythia8/RunIIAutumn18MiniAOD-102X_upgrade2018_realistic_v15-v1/MINIAODSIM	300000
/MSSMD_mH_125_mN1_60_mGammaD_15_cT_5_TuneCP5_13TeV-madgraph-pythia8/RunIIAutumn18MiniAOD-102X_upgrade2018_realistic_v15-v1/MINIAODSIM	100000
/MSSMD_mH_125_mN1_60_mGammaD_15_cT_0_TuneCP5_13TeV-madgraph-pythia8/RunIIAutumn18MiniAOD-102X_upgrade2018_realistic_v15-v1/MINIAODSIM	100000
/MSSMD_mH_125_mN1_60_mGammaD_1_cT_0_TuneCP5_13TeV-madgraph-pythia8/RunIIAutumn18MiniAOD-102X_upgrade2018_realistic_v15-v1/MINIAODSIM	100000
/MSSMD_mH_125_mN1_60_mGammaD_1_cT_0p05_TuneCP5_13TeV-madgraph-pythia8/RunIIAutumn18MiniAOD-102X_upgrade2018_realistic_v15-v1/MINIAODSIM	100000
/MSSMD_mH_125_mN1_60_mGammaD_1_cT_0p1_TuneCP5_13TeV-madgraph-pythia8/RunIIAutumn18MiniAOD-102X_upgrade2018_realistic_v15-v1/MINIAODSIM	100000
/MSSMD_mH_125_mN1_60_mGammaD_1_cT_0p2_TuneCP5_13TeV-madgraph-pythia8/RunIIAutumn18MiniAOD-102X_upgrade2018_realistic_v15-v1/MINIAODSIM	100000
/MSSMD_mH_125_mN1_60_mGammaD_1_cT_0p5_TuneCP5_13TeV-madgraph-pythia8/RunIIAutumn18MiniAOD-102X_upgrade2018_realistic_v15-v1/MINIAODSIM	100000

Dataset	Events
/MSSMD_mH_125_mN1_60_mGammaD_1_cT_100_TuneCP5_13TeV-madgraph-pythia8/RunIIAutumn18MiniAOD-102X_upgrade2018_realistic_v15-v1/MINIAODSIM	10000000
/MSSMD_mH_125_mN1_60_mGammaD_1_cT_10_TuneCP5_13TeV-madgraph-pythia8/RunIIAutumn18MiniAOD-102X_upgrade2018_realistic_v15-v1/MINIAODSIM	1000000
/MSSMD_mH_125_mN1_60_mGammaD_1_cT_1_TuneCP5_13TeV-madgraph-pythia8/RunIIAutumn18MiniAOD-102X_upgrade2018_realistic_v15-v1/MINIAODSIM	200000
/MSSMD_mH_125_mN1_60_mGammaD_1_cT_20_TuneCP5_13TeV-madgraph-pythia8/RunIIAutumn18MiniAOD-102X_upgrade2018_realistic_v15-v1/MINIAODSIM	1000000
/MSSMD_mH_125_mN1_60_mGammaD_1_cT_2_TuneCP5_13TeV-madgraph-pythia8/RunIIAutumn18MiniAOD-102X_upgrade2018_realistic_v15-v1/MINIAODSIM	200000
/MSSMD_mH_125_mN1_60_mGammaD_1_cT_3_TuneCP5_13TeV-madgraph-pythia8/RunIIAutumn18MiniAOD-102X_upgrade2018_realistic_v15-v1/MINIAODSIM	200000
/MSSMD_mH_125_mN1_60_mGammaD_1_cT_50_TuneCP5_13TeV-madgraph-pythia8/RunIIAutumn18MiniAOD-102X_upgrade2018_realistic_v15-v1/MINIAODSIM	5000000
/MSSMD_mH_125_mN1_60_mGammaD_1_cT_5_TuneCP5_13TeV-madgraph-pythia8/RunIIAutumn18MiniAOD-102X_upgrade2018_realistic_v15-v1/MINIAODSIM	200000

Dataset	Events
/MSSMD_mH_125_mN1_60_mGammaD_25_cT_0_TuneCP5_13TeV-madgraph-pythia8/RunIIAutumn18MiniAOD-102X_upgrade2018_realistic_v15-v1/MINIAODSIM	100000
/MSSMD_mH_125_mN1_60_mGammaD_25_cT_0p05_TuneCP5_13TeV-madgraph-pythia8/RunIIAutumn18MiniAOD-102X_upgrade2018_realistic_v15-v1/MINIAODSIM	100000
/MSSMD_mH_125_mN1_60_mGammaD_25_cT_0p1_TuneCP5_13TeV-madgraph-pythia8/RunIIAutumn18MiniAOD-102X_upgrade2018_realistic_v15-v1/MINIAODSIM	100000
/MSSMD_mH_125_mN1_60_mGammaD_25_cT_0p2_TuneCP5_13TeV-madgraph-pythia8/RunIIAutumn18MiniAOD-102X_upgrade2018_realistic_v15-v1/MINIAODSIM	100000
/MSSMD_mH_125_mN1_60_mGammaD_25_cT_0p5_TuneCP5_13TeV-madgraph-pythia8/RunIIAutumn18MiniAOD-102X_upgrade2018_realistic_v15-v1/MINIAODSIM	100000
/MSSMD_mH_125_mN1_60_mGammaD_25_cT_100_TuneCP5_13TeV-madgraph-pythia8/RunIIAutumn18MiniAOD-102X_upgrade2018_realistic_v15-v1/MINIAODSIM	300000
/MSSMD_mH_125_mN1_60_mGammaD_25_cT_10_TuneCP5_13TeV-madgraph-pythia8/RunIIAutumn18MiniAOD-102X_upgrade2018_realistic_v15-v1/MINIAODSIM	300000
/MSSMD_mH_125_mN1_60_mGammaD_25_cT_1_TuneCP5_13TeV-madgraph-pythia8/RunIIAutumn18MiniAOD-102X_upgrade2018_realistic_v15-v1/MINIAODSIM	100000

Dataset	Events
/MSSMD_mH_125_mN1_60_mGammaD_25_cT_20_TuneCP5_13TeV-madgraph-pythia8/RunIIAutumn18MiniAOD-102X_upgrade2018_realistic_v15-v1/MINIAODSIM	300000
/MSSMD_mH_125_mN1_60_mGammaD_25_cT_2_TuneCP5_13TeV-madgraph-pythia8/RunIIAutumn18MiniAOD-102X_upgrade2018_realistic_v15-v1/MINIAODSIM	100000
/MSSMD_mH_125_mN1_60_mGammaD_25_cT_3_TuneCP5_13TeV-madgraph-pythia8/RunIIAutumn18MiniAOD-102X_upgrade2018_realistic_v15-v1/MINIAODSIM	100000
/MSSMD_mH_125_mN1_60_mGammaD_25_cT_50_TuneCP5_13TeV-madgraph-pythia8/RunIIAutumn18MiniAOD-102X_upgrade2018_realistic_v15-v1/MINIAODSIM	300000
/MSSMD_mH_125_mN1_60_mGammaD_25_cT_5_TuneCP5_13TeV-madgraph-pythia8/RunIIAutumn18MiniAOD-102X_upgrade2018_realistic_v15-v1/MINIAODSIM	100000
/MSSMD_mH_125_mN1_60_mGammaD_2_cT_0_TuneCP5_13TeV-madgraph-pythia8/RunIIAutumn18MiniAOD-102X_upgrade2018_realistic_v15-v1/MINIAODSIM	100000
/MSSMD_mH_125_mN1_60_mGammaD_2_cT_0p05_TuneCP5_13TeV-madgraph-pythia8/RunIIAutumn18MiniAOD-102X_upgrade2018_realistic_v15-v1/MINIAODSIM	100000
/MSSMD_mH_125_mN1_60_mGammaD_2_cT_0p1_TuneCP5_13TeV-madgraph-pythia8/RunIIAutumn18MiniAOD-102X_upgrade2018_realistic_v15-v1/MINIAODSIM	100000

Dataset	Events
/MSSMD_mH_125_mN1_60_mGammaD_2_cT_0p2_TuneCP5_13TeV-madgraph-pythia8/RunIIAutumn18MiniAOD-102X_upgrade2018_realistic_v15-v1/MINIAODSIM	100000
/MSSMD_mH_125_mN1_60_mGammaD_2_cT_0p5_TuneCP5_13TeV-madgraph-pythia8/RunIIAutumn18MiniAOD-102X_upgrade2018_realistic_v15-v1/MINIAODSIM	100000
/MSSMD_mH_125_mN1_60_mGammaD_2_cT_100_TuneCP5_13TeV-madgraph-pythia8/RunIIAutumn18MiniAOD-102X_upgrade2018_realistic_v15-v1/MINIAODSIM	10000000
/MSSMD_mH_125_mN1_60_mGammaD_2_cT_10_TuneCP5_13TeV-madgraph-pythia8/RunIIAutumn18MiniAOD-102X_upgrade2018_realistic_v15-v1/MINIAODSIM	1000000
/MSSMD_mH_125_mN1_60_mGammaD_2_cT_1_TuneCP5_13TeV-madgraph-pythia8/RunIIAutumn18MiniAOD-102X_upgrade2018_realistic_v15-v1/MINIAODSIM	200000
/MSSMD_mH_125_mN1_60_mGammaD_2_cT_20_TuneCP5_13TeV-madgraph-pythia8/RunIIAutumn18MiniAOD-102X_upgrade2018_realistic_v15-v1/MINIAODSIM	1000000
/MSSMD_mH_125_mN1_60_mGammaD_2_cT_2_TuneCP5_13TeV-madgraph-pythia8/RunIIAutumn18MiniAOD-102X_upgrade2018_realistic_v15-v1/MINIAODSIM	200000
/MSSMD_mH_125_mN1_60_mGammaD_2_cT_3_TuneCP5_13TeV-madgraph-pythia8/RunIIAutumn18MiniAOD-102X_upgrade2018_realistic_v15-v1/MINIAODSIM	200000

Dataset	Events
/MSSMD_mH_125_mN1_60_mGammaD_2_cT_50_TuneCP5_13TeV-madgraph-pythia8/RunIIAutumn18MiniAOD-102X_upgrade2018_realistic_v15-v1/MINIAODSIM	5000000
/MSSMD_mH_125_mN1_60_mGammaD_2_cT_5_TuneCP5_13TeV-madgraph-pythia8/RunIIAutumn18MiniAOD-102X_upgrade2018_realistic_v15-v1/MINIAODSIM	200000
/MSSMD_mH_125_mN1_60_mGammaD_35_cT_0_TuneCP5_13TeV-madgraph-pythia8/RunIIAutumn18MiniAOD-102X_upgrade2018_realistic_v15-v1/MINIAODSIM	100000
/MSSMD_mH_125_mN1_60_mGammaD_35_cT_0p05_TuneCP5_13TeV-madgraph-pythia8/RunIIAutumn18MiniAOD-102X_upgrade2018_realistic_v15-v1/MINIAODSIM	100000
/MSSMD_mH_125_mN1_60_mGammaD_35_cT_0p1_TuneCP5_13TeV-madgraph-pythia8/RunIIAutumn18MiniAOD-102X_upgrade2018_realistic_v15-v1/MINIAODSIM	100000
/MSSMD_mH_125_mN1_60_mGammaD_35_cT_0p2_TuneCP5_13TeV-madgraph-pythia8/RunIIAutumn18MiniAOD-102X_upgrade2018_realistic_v15-v1/MINIAODSIM	100000
/MSSMD_mH_125_mN1_60_mGammaD_35_cT_0p5_TuneCP5_13TeV-madgraph-pythia8/RunIIAutumn18MiniAOD-102X_upgrade2018_realistic_v15-v1/MINIAODSIM	100000
/MSSMD_mH_125_mN1_60_mGammaD_35_cT_100_TuneCP5_13TeV-madgraph-pythia8/RunIIAutumn18MiniAOD-102X_upgrade2018_realistic_v15-v1/MINIAODSIM	300000

Dataset	Events
/MSSMD_mH_125_mN1_60_mGammaD_35_cT_10_TuneCP5_13TeV-madgraph-pythia8/RunIIAutumn18MiniAOD-102X_upgrade2018_realistic_v15-v1/MINIAODSIM	300000
/MSSMD_mH_125_mN1_60_mGammaD_35_cT_1_TuneCP5_13TeV-madgraph-pythia8/RunIIAutumn18MiniAOD-102X_upgrade2018_realistic_v15-v1/MINIAODSIM	100000
/MSSMD_mH_125_mN1_60_mGammaD_35_cT_20_TuneCP5_13TeV-madgraph-pythia8/RunIIAutumn18MiniAOD-102X_upgrade2018_realistic_v15-v1/MINIAODSIM	300000
/MSSMD_mH_125_mN1_60_mGammaD_35_cT_2_TuneCP5_13TeV-madgraph-pythia8/RunIIAutumn18MiniAOD-102X_upgrade2018_realistic_v15-v1/MINIAODSIM	100000
/MSSMD_mH_125_mN1_60_mGammaD_35_cT_3_TuneCP5_13TeV-madgraph-pythia8/RunIIAutumn18MiniAOD-102X_upgrade2018_realistic_v15-v1/MINIAODSIM	100000
/MSSMD_mH_125_mN1_60_mGammaD_35_cT_50_TuneCP5_13TeV-madgraph-pythia8/RunIIAutumn18MiniAOD-102X_upgrade2018_realistic_v15-v1/MINIAODSIM	300000
/MSSMD_mH_125_mN1_60_mGammaD_35_cT_5_TuneCP5_13TeV-madgraph-pythia8/RunIIAutumn18MiniAOD-102X_upgrade2018_realistic_v15-v1/MINIAODSIM	100000
/MSSMD_mH_125_mN1_60_mGammaD_58_cT_0_TuneCP5_13TeV-madgraph-pythia8/RunIIAutumn18MiniAOD-102X_upgrade2018_realistic_v15-v1/MINIAODSIM	100000

Dataset	Events
/MSSMD_mH_125_mN1_60_mGammaD_58_cT_0p05_TuneCP5_13TeV-madgraph-pythia8/RunIIAutumn18MiniAOD-102X_upgrade2018_realistic_v15-v1/MINIAODSIM	100000
/MSSMD_mH_125_mN1_60_mGammaD_58_cT_0p1_TuneCP5_13TeV-madgraph-pythia8/RunIIAutumn18MiniAOD-102X_upgrade2018_realistic_v15-v1/MINIAODSIM	100000
/MSSMD_mH_125_mN1_60_mGammaD_58_cT_0p2_TuneCP5_13TeV-madgraph-pythia8/RunIIAutumn18MiniAOD-102X_upgrade2018_realistic_v15-v1/MINIAODSIM	100000
/MSSMD_mH_125_mN1_60_mGammaD_58_cT_0p5_TuneCP5_13TeV-madgraph-pythia8/RunIIAutumn18MiniAOD-102X_upgrade2018_realistic_v15-v1/MINIAODSIM	100000
/MSSMD_mH_125_mN1_60_mGammaD_58_cT_100_TuneCP5_13TeV-madgraph-pythia8/RunIIAutumn18MiniAOD-102X_upgrade2018_realistic_v15-v1/MINIAODSIM	300000
/MSSMD_mH_125_mN1_60_mGammaD_58_cT_10_TuneCP5_13TeV-madgraph-pythia8/RunIIAutumn18MiniAOD-102X_upgrade2018_realistic_v15-v1/MINIAODSIM	300000
/MSSMD_mH_125_mN1_60_mGammaD_58_cT_1_TuneCP5_13TeV-madgraph-pythia8/RunIIAutumn18MiniAOD-102X_upgrade2018_realistic_v15-v1/MINIAODSIM	100000
/MSSMD_mH_125_mN1_60_mGammaD_58_cT_20_TuneCP5_13TeV-madgraph-pythia8/RunIIAutumn18MiniAOD-102X_upgrade2018_realistic_v15-v1/MINIAODSIM	300000

Dataset	Events
/MSSMD_mH_125_mN1_60_mGammaD_58_cT_2_TuneCP5_13TeV-madgraph-pythia8/RunIIAutumn18MiniAOD-102X_upgrade2018_realistic_v15-v1/MINIAODSIM	100000
/MSSMD_mH_125_mN1_60_mGammaD_58_cT_3_TuneCP5_13TeV-madgraph-pythia8/RunIIAutumn18MiniAOD-102X_upgrade2018_realistic_v15-v1/MINIAODSIM	100000
/MSSMD_mH_125_mN1_60_mGammaD_58_cT_50_TuneCP5_13TeV-madgraph-pythia8/RunIIAutumn18MiniAOD-102X_upgrade2018_realistic_v15-v1/MINIAODSIM	300000
/MSSMD_mH_125_mN1_60_mGammaD_58_cT_5_TuneCP5_13TeV-madgraph-pythia8/RunIIAutumn18MiniAOD-102X_upgrade2018_realistic_v15-v1/MINIAODSIM	100000
/MSSMD_mH_125_mN1_60_mGammaD_58_cT_0_TuneCP5_13TeV-madgraph-pythia8/RunIIAutumn18MiniAOD-102X_upgrade2018_realistic_v15-v1/MINIAODSIM	100000
/MSSMD_mH_125_mN1_60_mGammaD_5_cT_0_TuneCP5_13TeV-madgraph-pythia8/RunIIAutumn18MiniAOD-102X_upgrade2018_realistic_v15-v1/MINIAODSIM	100000
/MSSMD_mH_125_mN1_60_mGammaD_5_cT_0p05_TuneCP5_13TeV-madgraph-pythia8/RunIIAutumn18MiniAOD-102X_upgrade2018_realistic_v15-v1/MINIAODSIM	100000
/MSSMD_mH_125_mN1_60_mGammaD_5_cT_0p1_TuneCP5_13TeV-madgraph-pythia8/RunIIAutumn18MiniAOD-102X_upgrade2018_realistic_v15-v1/MINIAODSIM	100000
/MSSMD_mH_125_mN1_60_mGammaD_5_cT_0p2_TuneCP5_13TeV-madgraph-pythia8/RunIIAutumn18MiniAOD-102X_upgrade2018_realistic_v15-v1/MINIAODSIM	100000

Dataset	Events
/MSSMD_mH_125_mN1_60_mGammaD_5_cT_0p5_TuneCP5_13TeV-madgraph-pythia8/RunIIAutumn18MiniAOD-102X_upgrade2018_realistic_v15-v1/MINIAODSIM	100000
/MSSMD_mH_125_mN1_60_mGammaD_5_cT_100_TuneCP5_13TeV-madgraph-pythia8/RunIIAutumn18MiniAOD-102X_upgrade2018_realistic_v15-v1/MINIAODSIM	300000
/MSSMD_mH_125_mN1_60_mGammaD_5_cT_10_TuneCP5_13TeV-madgraph-pythia8/RunIIAutumn18MiniAOD-102X_upgrade2018_realistic_v15-v1/MINIAODSIM	300000
/MSSMD_mH_125_mN1_60_mGammaD_5_cT_1_TuneCP5_13TeV-madgraph-pythia8/RunIIAutumn18MiniAOD-102X_upgrade2018_realistic_v15-v1/MINIAODSIM	100000
/MSSMD_mH_125_mN1_60_mGammaD_5_cT_20_TuneCP5_13TeV-madgraph-pythia8/RunIIAutumn18MiniAOD-102X_upgrade2018_realistic_v15-v1/MINIAODSIM	300000
/MSSMD_mH_125_mN1_60_mGammaD_5_cT_2_TuneCP5_13TeV-madgraph-pythia8/RunIIAutumn18MiniAOD-102X_upgrade2018_realistic_v15-v1/MINIAODSIM	100000
/MSSMD_mH_125_mN1_60_mGammaD_5_cT_3_TuneCP5_13TeV-madgraph-pythia8/RunIIAutumn18MiniAOD-102X_upgrade2018_realistic_v15-v1/MINIAODSIM	300000
/MSSMD_mH_125_mN1_60_mGammaD_5_cT_50_TuneCP5_13TeV-madgraph-pythia8/RunIIAutumn18MiniAOD-102X_upgrade2018_realistic_v15-v1/MINIAODSIM	100000
/MSSMD_mH_125_mN1_60_mGammaD_5_cT_100_TuneCP5_13TeV-madgraph-pythia8/RunIIAutumn18MiniAOD-102X_upgrade2018_realistic_v15-v1/MINIAODSIM	300000

Dataset	Events
/MSSMD_mH_125_mN1_60_mGammaD_5_cT_5_TuneCP5_13TeV-madgraph-pythia8/RunIIAutumn18MiniAOD-102X_upgrade2018_realistic_v15-v1/MINIAODSIM	100000
/MSSMD_mH_125_mN1_60_mGammaD_8p5_cT_0_TuneCP5_13TeV-madgraph-pythia8/RunIIAutumn18MiniAOD-102X_upgrade2018_realistic_v15-v1/MINIAODSIM	100000
/MSSMD_mH_125_mN1_60_mGammaD_8p5_cT_0p05_TuneCP5_13TeV-madgraph-pythia8/RunIIAutumn18MiniAOD-102X_upgrade2018_realistic_v15-v1/MINIAODSIM	100000
/MSSMD_mH_125_mN1_60_mGammaD_8p5_cT_0p1_TuneCP5_13TeV-madgraph-pythia8/RunIIAutumn18MiniAOD-102X_upgrade2018_realistic_v15-v1/MINIAODSIM	100000
/MSSMD_mH_125_mN1_60_mGammaD_8p5_cT_0p2_TuneCP5_13TeV-madgraph-pythia8/RunIIAutumn18MiniAOD-102X_upgrade2018_realistic_v15-v1/MINIAODSIM	100000
/MSSMD_mH_125_mN1_60_mGammaD_8p5_cT_0p5_TuneCP5_13TeV-madgraph-pythia8/RunIIAutumn18MiniAOD-102X_upgrade2018_realistic_v15-v1/MINIAODSIM	100000
/MSSMD_mH_125_mN1_60_mGammaD_8p5_cT_100_TuneCP5_13TeV-madgraph-pythia8/RunIIAutumn18MiniAOD-102X_upgrade2018_realistic_v15-v1/MINIAODSIM	300000
/MSSMD_mH_125_mN1_60_mGammaD_8p5_cT_10_TuneCP5_13TeV-madgraph-pythia8/RunIIAutumn18MiniAOD-102X_upgrade2018_realistic_v15-v1/MINIAODSIM	300000

Dataset	Events
/MSSMD_mH_125_mN1_60_mGammaD_8p5_cT_1_TuneCP5_13TeV-madgraph-pythia8/RunIIAutumn18MiniAOD-102X_upgrade2018_realistic_v15-v1/MINIAODSIM	100000
/MSSMD_mH_125_mN1_60_mGammaD_8p5_cT_20_TuneCP5_13TeV-madgraph-pythia8/RunIIAutumn18MiniAOD-102X_upgrade2018_realistic_v15-v1/MINIAODSIM	300000
/MSSMD_mH_125_mN1_60_mGammaD_8p5_cT_2_TuneCP5_13TeV-madgraph-pythia8/RunIIAutumn18MiniAOD-102X_upgrade2018_realistic_v15-v1/MINIAODSIM	100000
/MSSMD_mH_125_mN1_60_mGammaD_8p5_cT_3_TuneCP5_13TeV-madgraph-pythia8/RunIIAutumn18MiniAOD-102X_upgrade2018_realistic_v15-v1/MINIAODSIM	100000
/MSSMD_mH_125_mN1_60_mGammaD_8p5_cT_50_TuneCP5_13TeV-madgraph-pythia8/RunIIAutumn18MiniAOD-102X_upgrade2018_realistic_v15-v1/MINIAODSIM	300000
/MSSMD_mH_125_mN1_60_mGammaD_8p5_cT_5_TuneCP5_13TeV-madgraph-pythia8/RunIIAutumn18MiniAOD-102X_upgrade2018_realistic_v15-v1/MINIAODSIM	100000

Appendix F

NMSSM MC Samples

Tab. F.1 shows all 2018 NMSSM MC samples used in the analysis.

Table F.1 : NMSSM 2018 MC samples.

Dataset	Events
/NMSSM_HToAATo4Mu_mH_90_mA_0p5_PSWWeights_TuneCP5_13TeV-pythia8/RunIIAutumn18MiniAOD-102X_upgrade2018_realistic_v15-v2/MINIAODSIM	200000
/NMSSM_HToAATo4Mu_mH_90_mA_0p75_PSWWeights_TuneCP5_13TeV-pythia8/RunIIAutumn18MiniAOD-102X_upgrade2018_realistic_v15-v2/MINIAODSIM	193000
/NMSSM_HToAATo4Mu_mH_90_mA_1_PSWWeights_TuneCP5_13TeV-pythia8/RunIIAutumn18MiniAOD-102X_upgrade2018_realistic_v15-v2/MINIAODSIM	161000
/NMSSM_HToAATo4Mu_mH_90_mA_2_PSWWeights_TuneCP5_13TeV-pythia8/RunIIAutumn18MiniAOD-102X_upgrade2018_realistic_v15-v2/MINIAODSIM	200000
/NMSSM_HToAATo4Mu_mH_90_mA_3_PSWWeights_TuneCP5_13TeV-pythia8/RunIIAutumn18MiniAOD-102X_upgrade2018_realistic_v15-v2/MINIAODSIM	194000
/NMSSM_HToAATo4Mu_mH_100_mA_0p5_PSWWeights_TuneCP5_13TeV-pythia8/RunIIAutumn18MiniAOD-102X_upgrade2018_realistic_v15-v2/MINIAODSIM	200000
/NMSSM_HToAATo4Mu_mH_100_mA_0p75_PSWWeights_TuneCP5_13TeV-pythia8/RunIIAutumn18MiniAOD-102X_upgrade2018_realistic_v15-v2/MINIAODSIM	200000

Dataset	Events
/NMSSM_HToAATo4Mu_mH_100_mA_1_PSWWeights_TuneCP5_13TeV-pythia8/RunIIAutumn18MiniAOD-102X_upgrade2018_realistic_v15-v2/MINIAODSIM	190000
/NMSSM_HToAATo4Mu_mH_100_mA_2_PSWWeights_TuneCP5_13TeV-pythia8/RunIIAutumn18MiniAOD-102X_upgrade2018_realistic_v15-v2/MINIAODSIM	192000
/NMSSM_HToAATo4Mu_mH_100_mA_3_PSWWeights_TuneCP5_13TeV-pythia8/RunIIAutumn18MiniAOD-102X_upgrade2018_realistic_v15-v2/MINIAODSIM	196000
/NMSSM_HToAATo4Mu_mH_110_mA_0p5_PSWWeights_TuneCP5_13TeV-pythia8/RunIIAutumn18MiniAOD-102X_upgrade2018_realistic_v15-v2/MINIAODSIM	193000
/NMSSM_HToAATo4Mu_mH_110_mA_0p75_PSWWeights_TuneCP5_13TeV-pythia8/RunIIAutumn18MiniAOD-102X_upgrade2018_realistic_v15-v2/MINIAODSIM	196000
/NMSSM_HToAATo4Mu_mH_110_mA_1_PSWWeights_TuneCP5_13TeV-pythia8/RunIIAutumn18MiniAOD-102X_upgrade2018_realistic_v15-v2/MINIAODSIM	200000
/NMSSM_HToAATo4Mu_mH_110_mA_2_PSWWeights_TuneCP5_13TeV-pythia8/RunIIAutumn18MiniAOD-102X_upgrade2018_realistic_v15-v2/MINIAODSIM	200000
/NMSSM_HToAATo4Mu_mH_110_mA_3_PSWWeights_TuneCP5_13TeV-pythia8/RunIIAutumn18MiniAOD-102X_upgrade2018_realistic_v15-v2/MINIAODSIM	200000

Dataset	Events
/NMSSM_HToAATo4Mu_mH_125_mA_0p5_PSWeights_TuneCP5_13TeV-pythia8/RunIIAutumn18MiniAOD-102X_upgrade2018_realistic_v15-v2/MINIAODSIM	200000
/NMSSM_HToAATo4Mu_mH_125_mA_0p75_PSWeights_TuneCP5_13TeV-pythia8/RunIIAutumn18MiniAOD-102X_upgrade2018_realistic_v15-v2/MINIAODSIM	200000
/NMSSM_HToAATo4Mu_mH_125_mA_1_PSWeights_TuneCP5_13TeV-pythia8/RunIIAutumn18MiniAOD-102X_upgrade2018_realistic_v15-v2/MINIAODSIM	200000
/NMSSM_HToAATo4Mu_mH_125_mA_2_PSWeights_TuneCP5_13TeV-pythia8/RunIIAutumn18MiniAOD-102X_upgrade2018_realistic_v15-v2/MINIAODSIM	200000
/NMSSM_HToAATo4Mu_mH_125_mA_3_PSWeights_TuneCP5_13TeV-pythia8/RunIIAutumn18MiniAOD-102X_upgrade2018_realistic_v15-v2/MINIAODSIM	200000
/NMSSM_HToAATo4Mu_mH_150_mA_0p5_PSWeights_TuneCP5_13TeV-pythia8/RunIIAutumn18MiniAOD-102X_upgrade2018_realistic_v15-v2/MINIAODSIM	186000
/NMSSM_HToAATo4Mu_mH_150_mA_0p75_PSWeights_TuneCP5_13TeV-pythia8/RunIIAutumn18MiniAOD-102X_upgrade2018_realistic_v15-v2/MINIAODSIM	200000
/NMSSM_HToAATo4Mu_mH_150_mA_1_PSWeights_TuneCP5_13TeV-pythia8/RunIIAutumn18MiniAOD-102X_upgrade2018_realistic_v15-v2/MINIAODSIM	200000
/NMSSM_HToAATo4Mu_mH_150_mA_2_PSWeights_TuneCP5_13TeV-pythia8/RunIIAutumn18MiniAOD-102X_upgrade2018_realistic_v15-v2/MINIAODSIM	200000

Dataset	Events
/NMSSM_HToAATo4Mu_mH_150_mA_2_PSWeights_TuneCP5_13TeV-pythia8/RunIIAutumn18MiniAOD-102X_upgrade2018_realistic_v15-v2/MINIAODSIM	200000
/NMSSM_HToAATo4Mu_mH_150_mA_3_PSWeights_TuneCP5_13TeV-pythia8/RunIIAutumn18MiniAOD-102X_upgrade2018_realistic_v15-v2/MINIAODSIM	188000

Appendix G

Triple Tracker Muon Trigger

The original signal trigger for this search was summarized in Tab. [G.1](#). Three tracker muons need to pass the p_T threshold of 16, 6 and 6 GeV.

During the analysis, we found this trigger has limited efficiency at signals that are more displaced and boosted as shown in Fig. [G.1](#) and Fig. [G.2](#). An obvious drop in the trigger efficiency is observed as well after the third pixel barrel layer at 10.9 cm as indicated in Fig. [G.2](#).

As a result, we need to change triggers to use those in Tab. [3.2](#) for the main analysis. Nevertheless, the previous study on the triple tracker muon trigger trigger is documented below just for the record.

Table G.1 : Signal HLT HLT_TrkMu16_DoubleTrkMu6NoFiltersNoVtx changes in 2017 and 2018

Year	Version	Run range	Era	HLT Menu	fb ⁻¹
2017	v7	299368 - 299649	C	/cdaq/physics/Run2017/2e34/v2.0.0/HLT/V3	36.734 (C-F)
	v8	300079 - 302019			
	v9	302026 - 302494			
	v10	302509 - 306171			
	v11	306416 - 306460			
2018	v11	315252 - 315973	F	/cdaq/physics/Run2017/2e34/v4.2.1/HLT/V2	59.97 (All)
	v12	315974 - 325175			

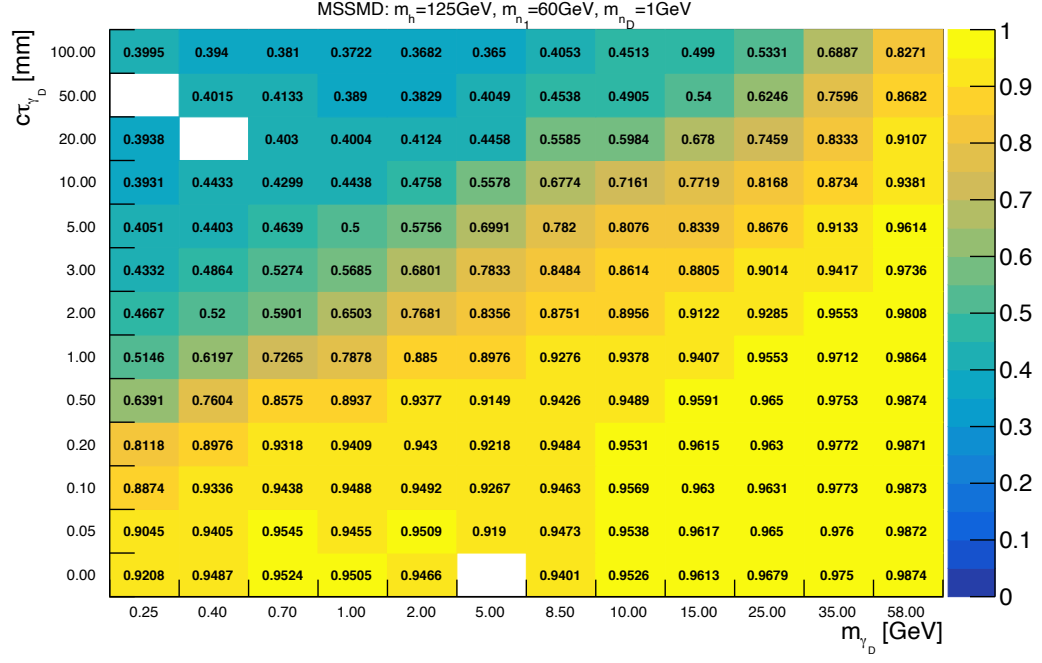


Figure G.1 : Triple tracker muon trigger efficiency on 2017 MSSMD signal MC samples. Similar behavior seen in 2018 signal MC as well.

Although the trigger performance is not ideal on displaced signals, it is still good on prompt signals such as the NMSSM signal. The efficiency on NMSSM MC from year 2017 and 2018 are shown in Fig. [G.3](#).

In order to facilitate the study of different effects of the trigger in data and MC samples, we deployed two single tracker muon control HLT paths in 2018. The p_T cuts mimics those in the signal HLT. A summary of the trigger information is in Tab. [G.2](#).

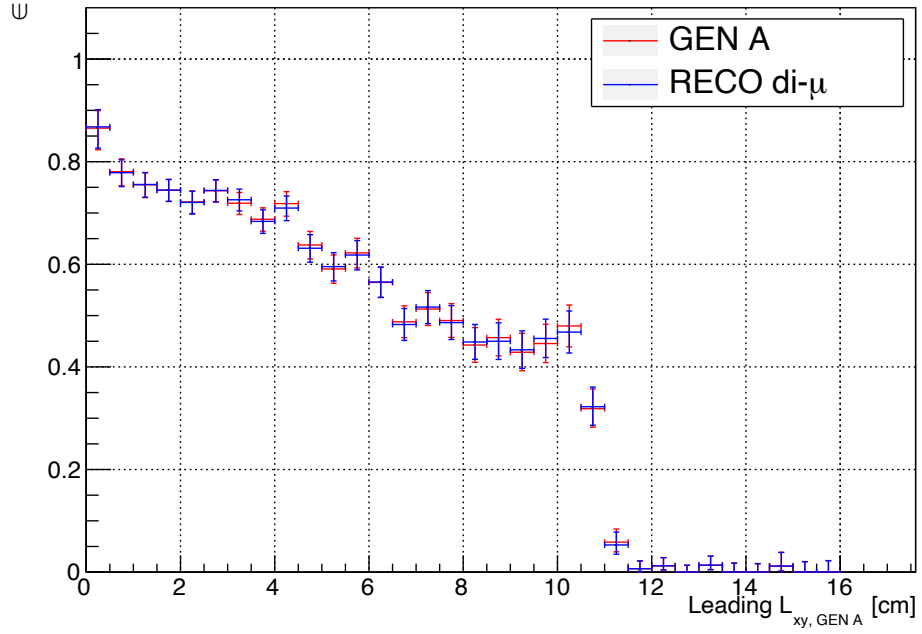


Figure G.2 : Triple tracker muon trigger efficiency as a function of leading transverse displacement (L_{xy}) of two dimuons at generator (red) and reconstructed level (blue) on one of the MSSMD signal MC sample: $m_{\gamma_D} = 25$ GeV, $c\tau = 100$ mm.

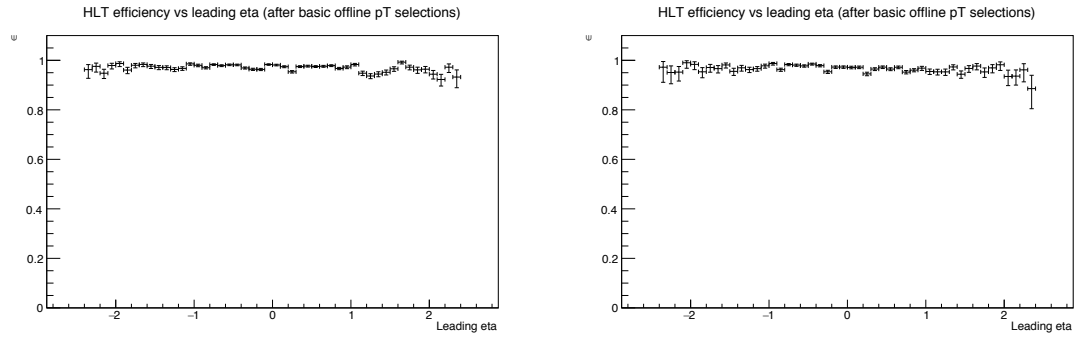


Figure G.3 : Per event signal HLT efficiency in 2017 (left) and 2018 (right) NMSSM MC samples with $m_H = 125$ GeV and $m_A = 3$ GeV.

Table G.2 : Triggers used in this analysis

HLT	Name	L1 seeds	L1 prescale
signal	HLT_TrkMu16_DoubleTrkMu6NoFiltersNoVtx_v*	L1_DoubleMu_15_5_SQ OR L1_DoubleMu_15_7 OR L1_TripleMu_5_3_3	N/A
control	HLT_TrkMu16NoFiltersNoVtx_v*	L1_SingleMu7	200
control	HLT_TrkMu6NoFiltersNoVtx_v*	L1_SingleMu3	22000

The trigger effects between data and MC can be characterized by a trigger scale factor, which will be used later when we interpret the limits using signal MC samples. The trigger scale factor for the signal HLT can be expressed by a product of control trigger efficiencies in Eq. (G.1). In this formula, only the relative efficiency of the control HLT over L1 filters are used. These control triggers can not address the inefficiencies at L1 trigger level, if any, because the L1 seeds used for control triggers and signal HLT are different. To ensure the strategy shown in Eq. (G.1) is fine, we went further to check the efficiency of L1 seeds used in the signal HLT in signal MC samples after all analysis selections (except firing the signal trigger). Such checks are shown in Fig. G.4 for 2017 and 2018 in NMSSM signal MC. This shows a close to 100% L1 efficiency for the L1 seeds used in signal HLT. So it is not necessary to worry about the inefficiency at L1 trigger when doing the interpretations in signal benchmark models. Thus, Eq. (G.1) can be safely used for this scale factor calculation.

$$\frac{\epsilon_{\text{signal HLT, DoubleMuon dataset}}}{\epsilon_{\text{signal HLT, Signal MC}}} = \frac{\epsilon_{\text{control HLT16/L1_SingleMu7, SingleMuon dataset}}}{\epsilon_{\text{control HLT16/L1_SingleMu7, Drell-Yan MC}}} \times \left(\frac{\epsilon_{\text{control HLT6/L1_SingleMu3, SingleMuon dataset}}}{\epsilon_{\text{control HLT6/L1_SingleMu3, Drell-Yan MC}}} \right)^2 \quad (\text{G.1})$$

To ensure that we characterize the trigger effects without any bias, the tag-and-probe (TnP) method [214] is used. SingleMuon dataset and DY MC from 2018 are used to study the control trigger efficiency. A summary of the dataset used are in Tab. G.3.

A final scale factor of 0.969 is quoted for the signal HLT with a statistical uncertainty of 1.5%. The statistical uncertainty on each efficiency measured using the TnP method is obtained based on the statistics of passing and total probes and then propagated through Eq. (G.1). The details are shown in Tab. G.4. Although above

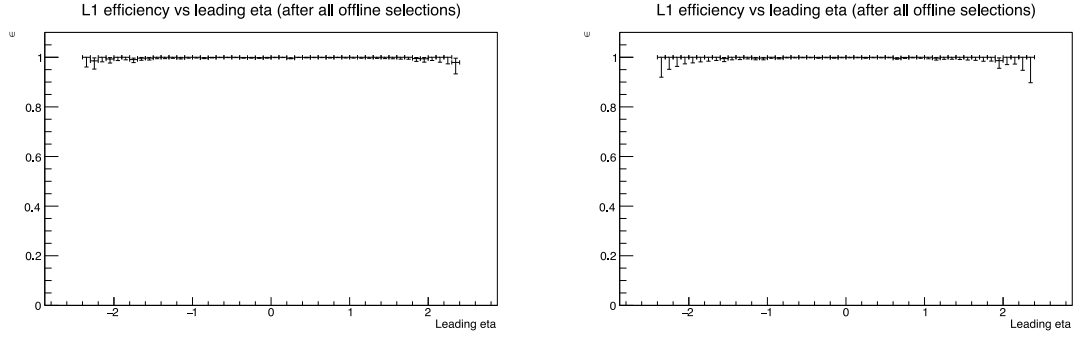


Figure G.4 : Efficiency of L1 triggers used in signal HLT after all analysis selections (except firing signal HLT) in 2017 (left) and 2018 (right) NMSSM MC samples with $m_H = 125$ GeV and $m_A = 3$ GeV.

scale factor is evaluated using 2018 data and MC only, it is also applied to 2017 data and MC since the tracker muon reconstruction algorithm remains same between 2017 and 2018 according to muon HLT group.

Here are more details about the TnP study (approved by trigger studies group). A full list of single muon triggers used for tag muons are listed in Tab. [G.5](#). We choose to use all of them in order to maximize the statistics for the study. 2018 Charmonium dataset is also checked but the statistics is worse than SingleMuon dataset as most Charmonium triggers are heavily prescaled at L1.

The relative efficiency for both control HLT are shown in Fig. [G.5](#) and Fig. [G.6](#).

The actual fit in TnP is shown in Fig. [G.7](#) and Fig. [G.8](#).

When using the TnP method to measure control trigger efficiencies, there is also a caveat that only the HLT relative to L1 efficiency can be measured. And the L1 efficiency (specifically on data) needs to be measured separately. This complication arises from the TnP method itself and is related to the L1 prescale of control triggers. But it is not the same argument that signal and control HLT have different L1

Table G.3 : 2018 datasets used in TnP study for control triggers.

Dataset	Run number
/SingleMuon/Run2018B-PromptReco-v1/AOD	317080-317696
/SingleMuon/Run2018B-PromptReco-v2/AOD	318070-319310
/SingleMuon/Run2018C-PromptReco-v1/AOD	319337-319349
/SingleMuon/Run2018C-PromptReco-v2/AOD	319449-319756
/SingleMuon/Run2018C-PromptReco-v3/AOD	319833-320191
/SingleMuon/Run2018D-PromptReco-v2/AOD	320500-325175
/DYJetsToLL_M-50_TuneCP5_13TeV- madgraphMLM-pythia8/RunIIAutumn18DRPremix- 102X_upgrade2018_realistic_v15-v1/AODSIM	N/A

seeds. When using TnP method, one tag muon and one probe muon are required to reconstruct the event of a Z boson decaying into two oppositely charged muons. To remove the trigger bias, the tag muon is usually required to fire a single muon trigger which is used to collect the SingleMuon dataset. These single muon triggers are usually not prescaled at L1. On the other hand, we require the probe muon to be the trigger object of the control trigger, which is heavily prescaled at L1. When measuring in data, if you do the TnP pass and fail measurement including the L1 filter, the measured efficiency tends to be zero. This does not mean that the efficiency is low. It is simply an effect brought by the control trigger prescales. In data taking, for a lot of events that the tag muon fired the single muon trigger, the probe muon does not fire the control trigger because of the prescale. If there is no such prescale at L1, the probe muon could have fired the control trigger. As a result, when you do the measurement, you need to exclude this effect of prescale at

Table G.4 : Signal HLT scale factor results

Sample	control HLT16/L1_SingleMu7		control HLT6/L1_SingleMu3	
	Eff. (ϵ)	Stat. Unc. ($\Delta\epsilon$)	Eff. (ϵ)	Stat. Unc. ($\Delta\epsilon$)
SingleMuon Dataset	0.9183	0.0008	0.916	0.010
Drell-Yan MC	0.9264	0.0006	0.9263	0.0006
Signal HLT Scale Factor (use Eq. (G.1)): 0.969 ± 0.015				

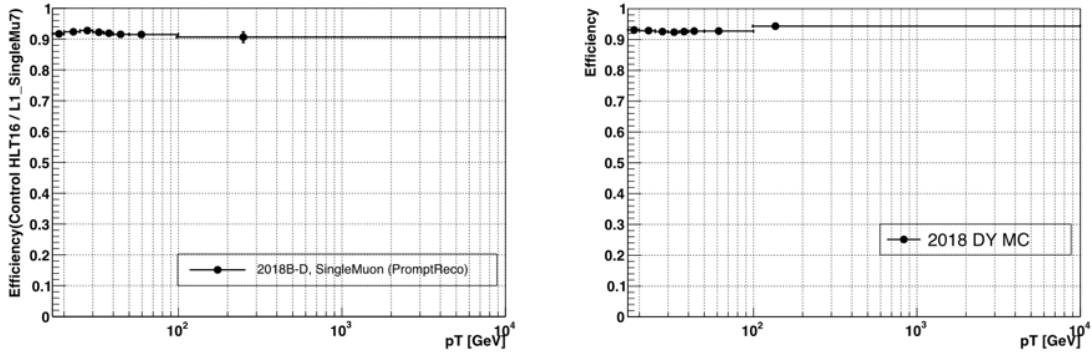


Figure G.5 : Relative efficiency (HLT/L1) of control trigger HLT_TrkMu16NoFiltersNoVtx_v* in 2018 SingleMuon dataset (left) and 2018 Drell-Yan MC (right).

L1 and only measure the efficiency of HLT relative to L1. Then, the L1 efficiency is measured separately by removing the prescale and re-emulate the L1 decisions in the data. The efficiency for L1 filter L1_SingleMu7 (L1_SingleMu3) in control trigger HLT_TrkMu16NoFiltersNoVtx_v* (HLT_TrkMu6NoFiltersNoVtx_v*) in 2018 data are shown in Fig. [G.9](#).

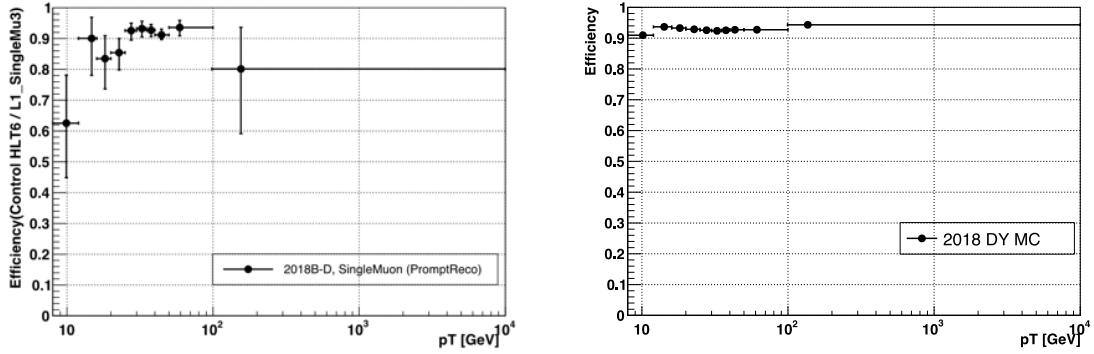


Figure G.6 : Relative efficiency (HLT/L1) of control trigger HLT_TrkMu6NoFiltersNoVtx_v* in 2018 SingleMuon dataset (left) and 2018 Drell-Yan MC (right).

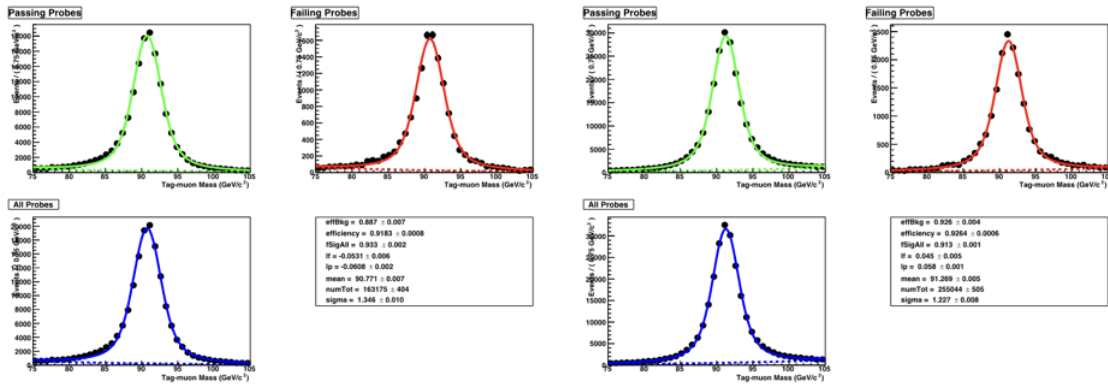


Figure G.7 : TnP fit plots (all p_T bins combined) to probe muons passing and failing the trigger object requirement of control trigger HLT_TrkMu16NoFiltersNoVtx_v* in 2018 SingleMuon dataset (left) and 2018 Drell-Yan MC (right).

Table G.5 : Single muon triggers used for tag muons in TnP method using the SingleMuon dataset.

Name
HLT_Mu8_v*
HLT_Mu12_v*
HLT_Mu15_v*
HLT_Mu17_v*
HLT_Mu19_v*
HLT_Mu20_v*
HLT_Mu27_v*
HLT_Mu50_v*
HLT_Mu55_v*
HLT_OldMu100_v*
HLT_TkMu100_v*
HLT_IsoMu20_v*
HLT_IsoMu24_v*
HLT_IsoMu27_v*
HLT_IsoMu30_v*

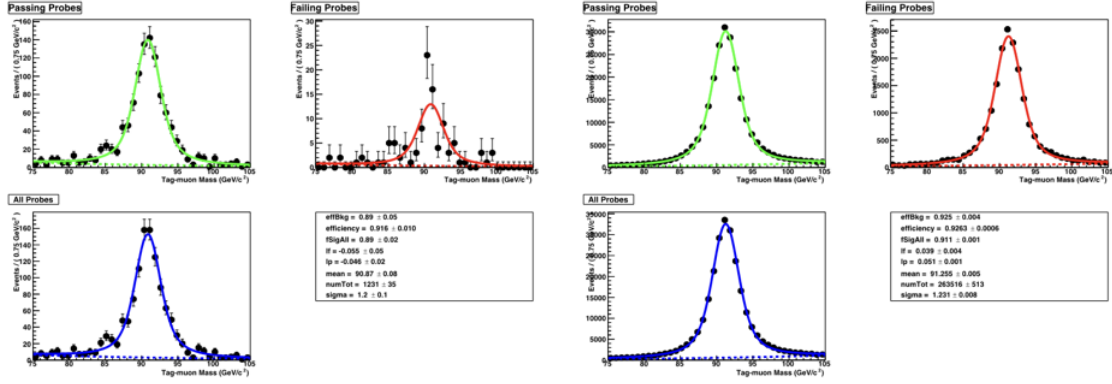


Figure G.8 : TnP fit plots (all p_T bins combined) to probe muons passing and failing the trigger object requirement of control trigger `HLT_TrkMu6NoFiltersNoVtx_v*` in 2018 SingleMuon dataset (left) and 2018 Drell-Yan MC (right).

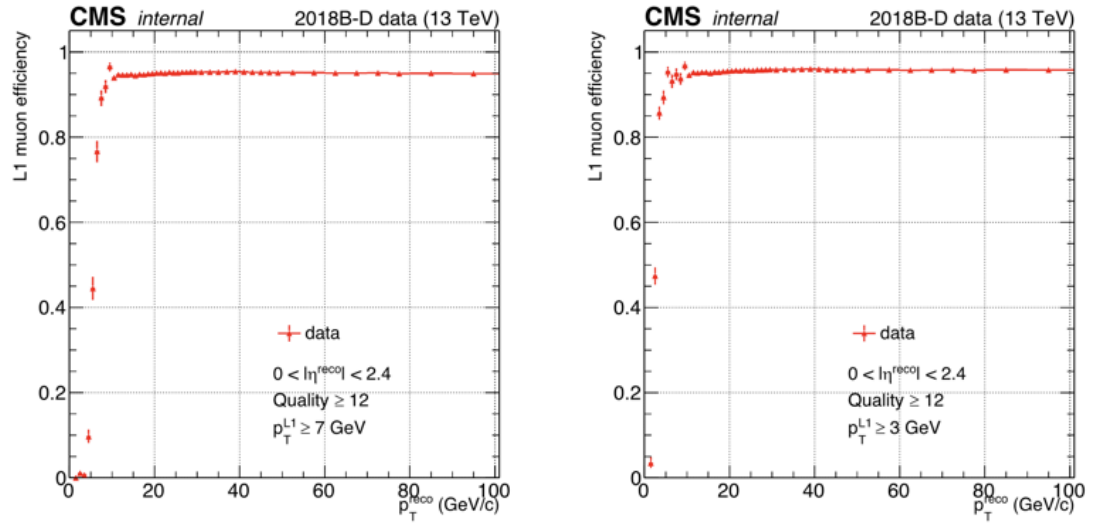


Figure G.9 : L1 filter efficiency of control trigger `HLT_TrkMu16NoFiltersNoVtx_v*` (left) and `HLT_TrkMu6NoFiltersNoVtx_v*` (right) in 2018 data taking by re-emulating L1 trigger decisions using the ZMu RAW-RECO dataset.

Appendix H

Reconstruction of Displaced Muons in Tracker

The requirement all four signal muons in the analysis was that they need to pass PF loose muon ID. We found in many displaced signal events one of the displaced signal muons (with generator level match) is reconstructed as a SA muon only which points back to the beamline as if it is a prompt muon. One example event is shown in Fig. [H.1](#).

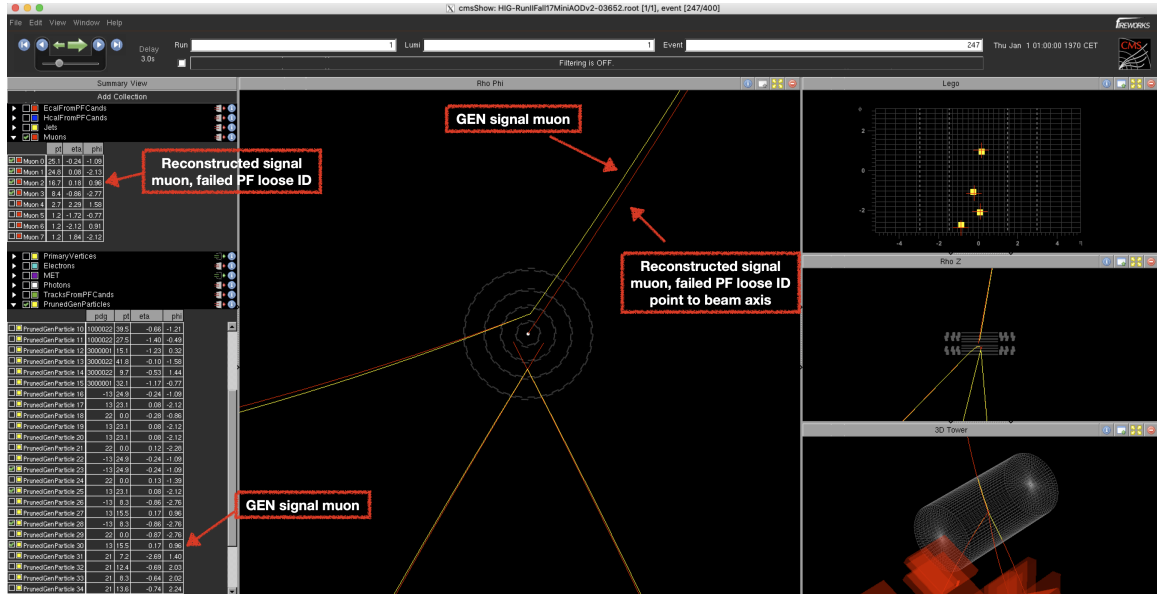


Figure H.1 : Event display for an MSSMD displaced signal event where one of the displaced muon is reconstructed as a standalone muon pointing back to the beam line.

This is due to the lower reconstruction efficiency of displaced muons in the tracker

volume as confirmed by the CMS muon physics object group (POG). As a result, we found low efficiency for the selection of four PF loose muon in the analysis. Tab. [H.1](#) shows the four muon selection efficiency if we require all of them to be PF loose muon.

Table H.1 : Selection of four leading p_T reconstructed (RECO) muons on a MSSMD signal MC: $m_{\gamma_D} = 25$ GeV, $c\tau = 100$ mm. A preselection of four leading p_T generator muons each with p_T above 8 GeV in the pixel detector volume is applied as a baseline before the selection of reconstructed muons.

RECO muon selection	Efficiency	
	4 PF loose muons	≥ 3 PF loose + ≤ 1 SA muons
$p_T > 8$ GeV		
1st muon	99.8%	99.9%
1st+2nd muon	97.5%	99.8%
1st+2nd+3rd muon	84.9%	97.5%
1st+2nd+3rd+4th muon	49.2%	80.1%

This can be mitigated by relaxing the muon ID requirement by allowing one SA muon in the two dimuons. The efficiency improvement after the relaxed requirement is shown in Tab. [H.1](#) as well. An efficiency gain of 30% is seen for four leading muon selection after such relaxation.

One could relax the muon selection even further to allow more than one SA muon. However, the gain in signal efficiency is negligible and more background are introduced as well as worse dimuon mass resolution.

Appendix I

Discussions on Event Selection

I.1 Crystal Ball fit to dimuon mass

We fit the dimuon invariant mass using the 2018 dark SUSY (MSSMD) MC samples. A Crystal Ball (CB) function is used in the fit for signals with different mass and lifetime as shown from Fig. [I.1](#) (58 GeV) to Fig. [I.11](#) (0.25 GeV).

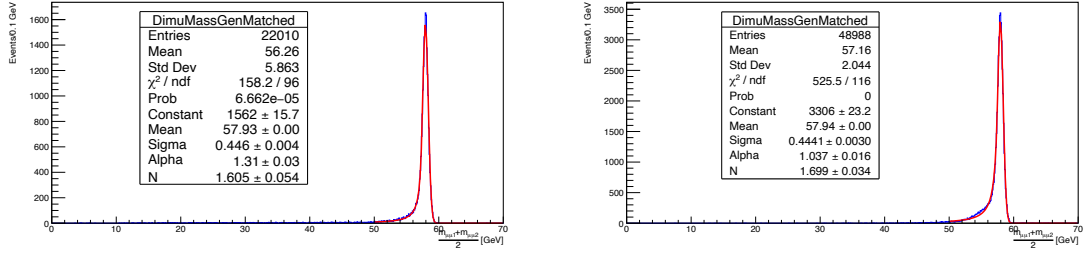


Figure I.1 : Crystal Ball function fit to the 2018 dark photon signal with $m_{\gamma_D} = 58$ GeV: $c\tau = 0$ mm (left) and 100 mm (right).

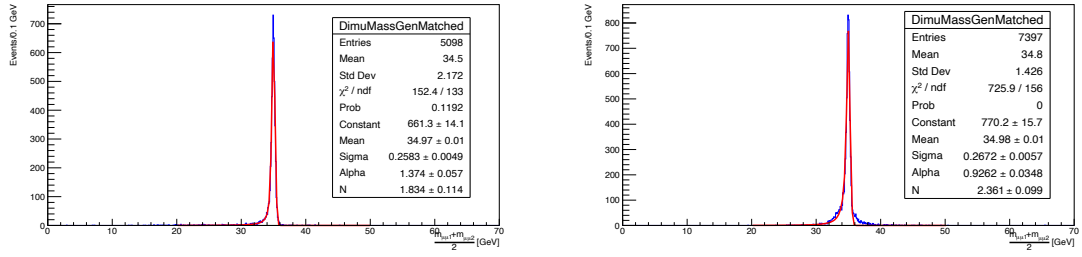


Figure I.2 : Crystal Ball function fit to the 2018 dark photon signal with $m_{\gamma_D} = 35$ GeV: $c\tau = 0$ mm (left) and 100 mm (right).

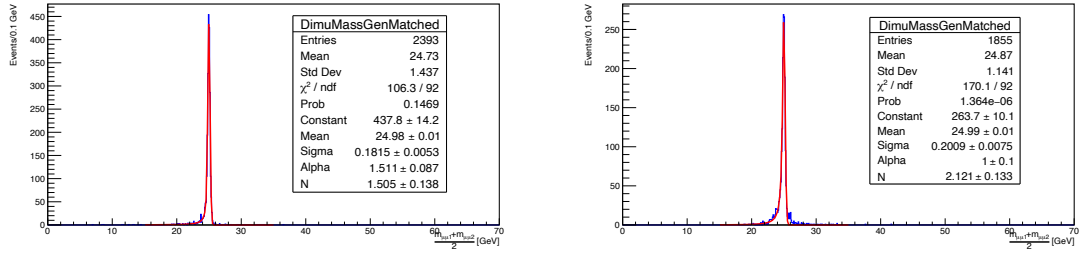


Figure I.3 : Crystal Ball function fit to the 2018 dark photon signal with $m_{\gamma_D} = 25$ GeV: $c\tau = 0$ mm (left) and 100 mm (right).

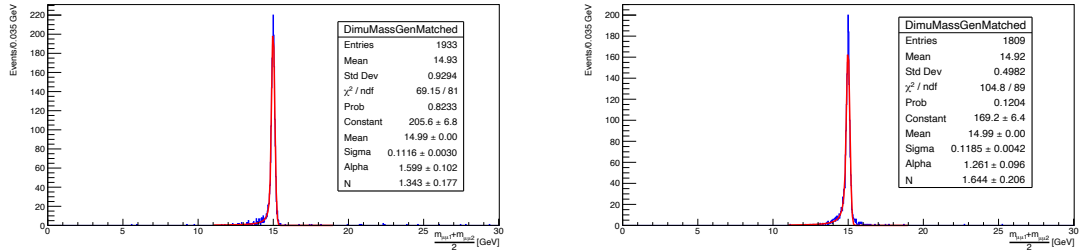


Figure I.4 : Crystal Ball function fit to the 2018 dark photon signal with $m_{\gamma_D} = 15$ GeV: $c\tau = 0$ mm (left) and 50 mm (right).

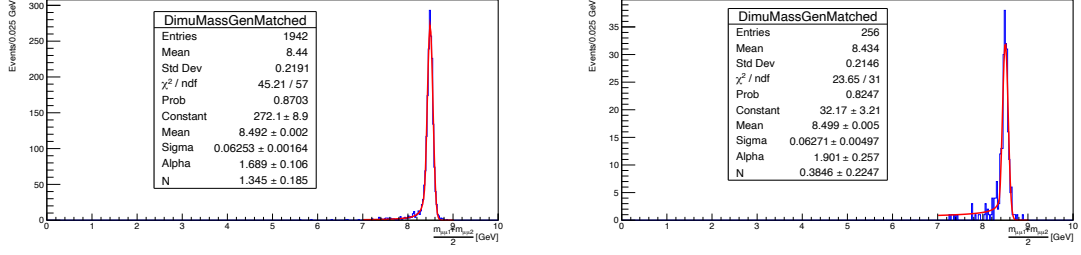


Figure I.5 : Crystal Ball function fit to the 2018 dark photon signal with $m_{\gamma_D} = 8.5$ GeV: $c\tau = 0$ mm (left) and 100 mm (right).

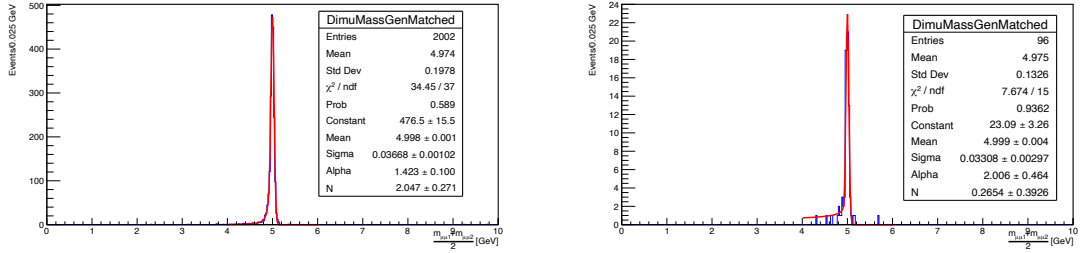


Figure I.6 : Crystal Ball function fit to the 2018 dark photon signal with $m_{\gamma_D} = 5$ GeV: $c\tau = 0$ mm (left) and 100 mm (right).

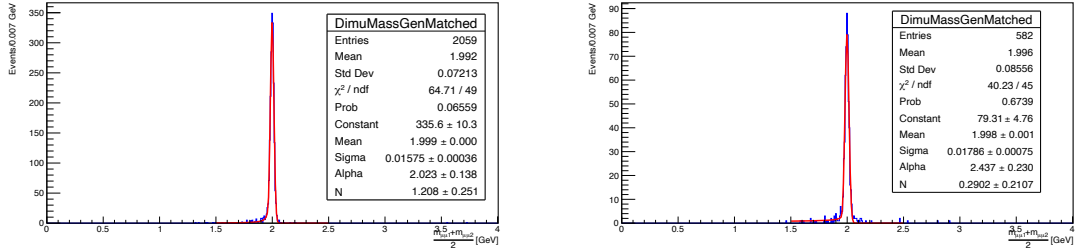


Figure I.7 : Crystal Ball function fit to the 2018 dark photon signal with $m_{\gamma_D} = 2$ GeV: $c\tau = 0$ mm (left) and 100 mm (right).

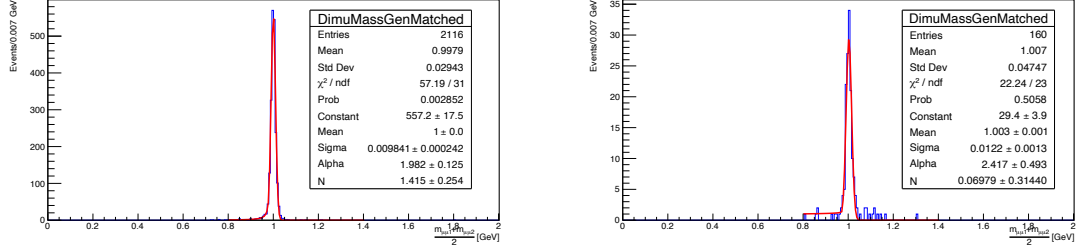


Figure I.8 : Crystal Ball function fit to the 2018 dark photon signal with $m_{\gamma_D} = 1$ GeV: $c\tau = 0$ mm (left) and 100 mm (right).

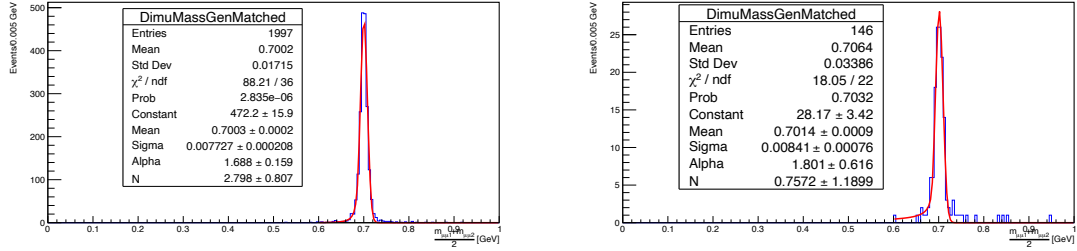


Figure I.9 : Crystal Ball function fit to the 2018 dark photon signal with $m_{\gamma_D} = 0.7$ GeV: $c\tau = 0$ mm (left) and 50 mm (right).

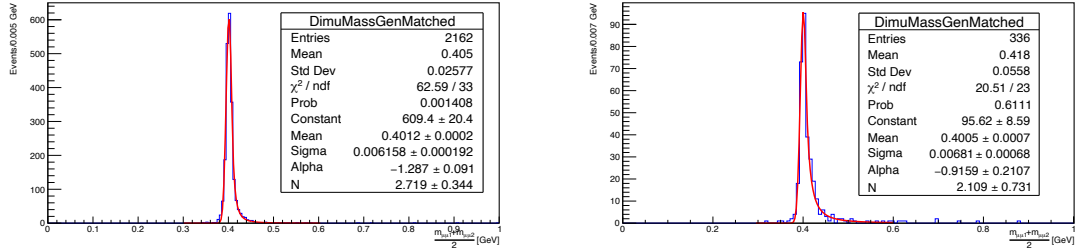


Figure I.10 : Crystal Ball function fit to the 2018 dark photon signal with $m_{\gamma_D} = 0.4$ GeV: $c\tau = 0$ mm (left) and 50 mm (right).

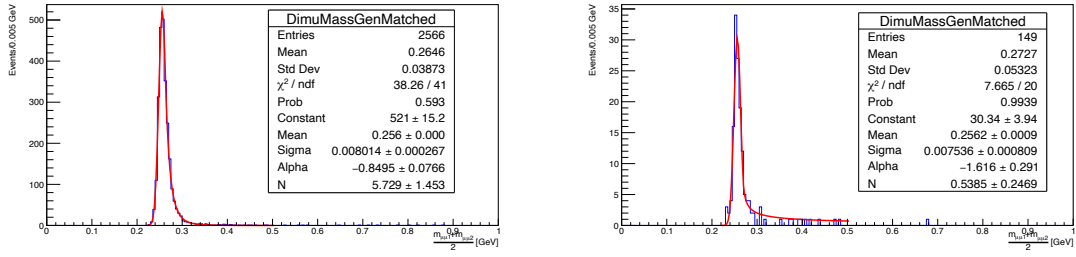


Figure I.11 : Crystal Ball function fit to the 2018 dark photon signal with $m_{\gamma_D} = 0.25$ GeV: $c\tau = 0$ mm (left) and 100 mm (right).

The CB fitted sigma as a function of the average dimuon mass for all dark photon signals are shown in Fig [I.12](#).

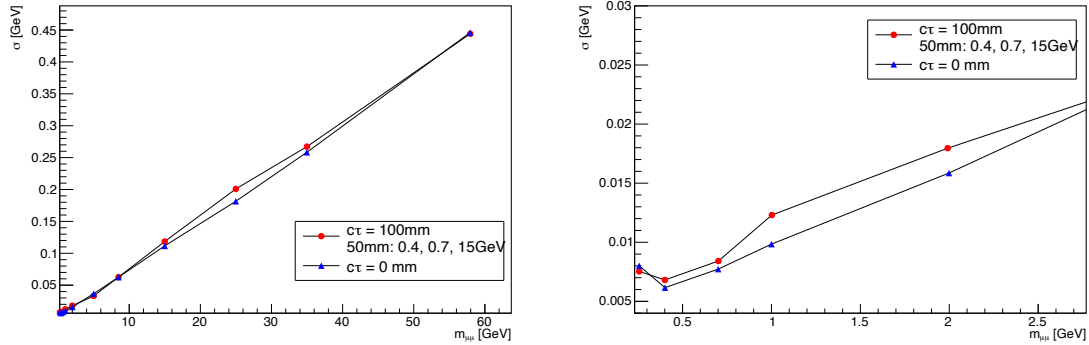


Figure I.12 : Left: Crystal Ball function fitted sigma (σ) as a function of average dimuon mass for prompt ($c\tau = 0$ mm) and displaced ($c\tau = 100$ mm or 50 mm) dark photon signals. Right: Zoom-in plot below the J/ψ resonances.

The relative mass resolution is shown in Fig. [I.13](#).

The asymmetry of the mass tails can be characterized by the α parameter from the CB fit. Its relationship as a function of the dimuon mass is also shown in Fig [I.14](#).

While the lower end tails for more massive signals are expected from radiation

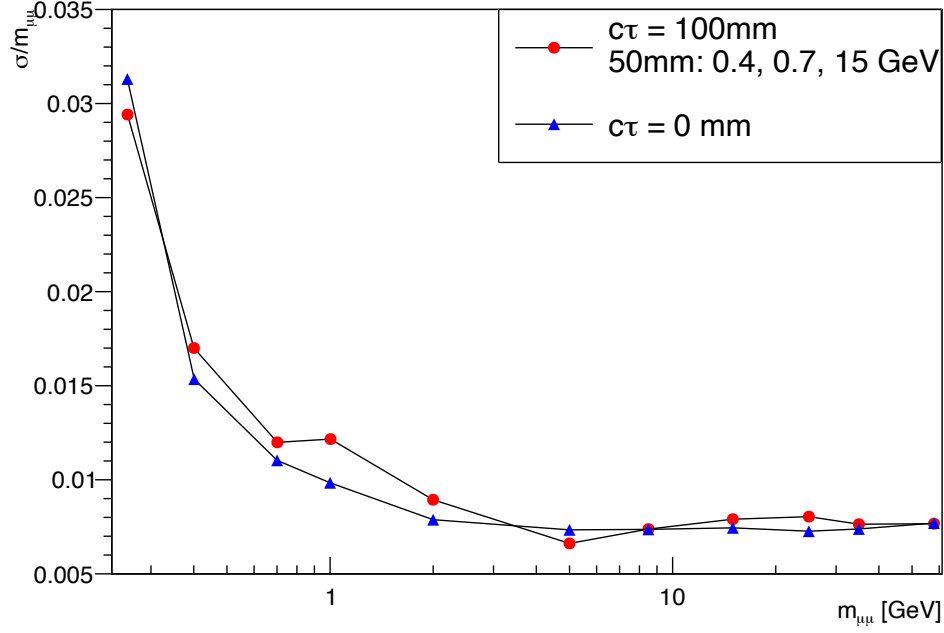


Figure I.13 : Relative mass resolution ($\sigma/m_{\mu\mu}$) as a function of the dimuon mass for prompt ($c\tau = 0$ mm) and displaced ($c\tau = 100$ mm or 50 mm) dark photon signals.

processes, it is interesting to observe the asymmetry at low mass with the tail appearing at the higher end of the mass spectrum ($\alpha < 0$). Such tails could possibly come from overestimated p_T for very boosted signals. Fig. [I.15](#) and Fig. [I.16](#) shows the difference in η , ϕ and p_T between the reconstructed and generated first four leading muons (both ordered in p_T) for the events at high end tails.

While the η and ϕ differences all peak at zero, it is obvious to see the mean difference of p_T is positive, especially for the leading p_T muon ($\Delta \bar{p}_T = 1.7$ GeV). With the approximation formula of invariant mass for highly relativistic particles,

$$M^2 = 2p_{T1}p_{T2}(\cosh(\eta_1 - \eta_2) - \cos(\phi_1 - \phi_2)). \quad (\text{I.1})$$

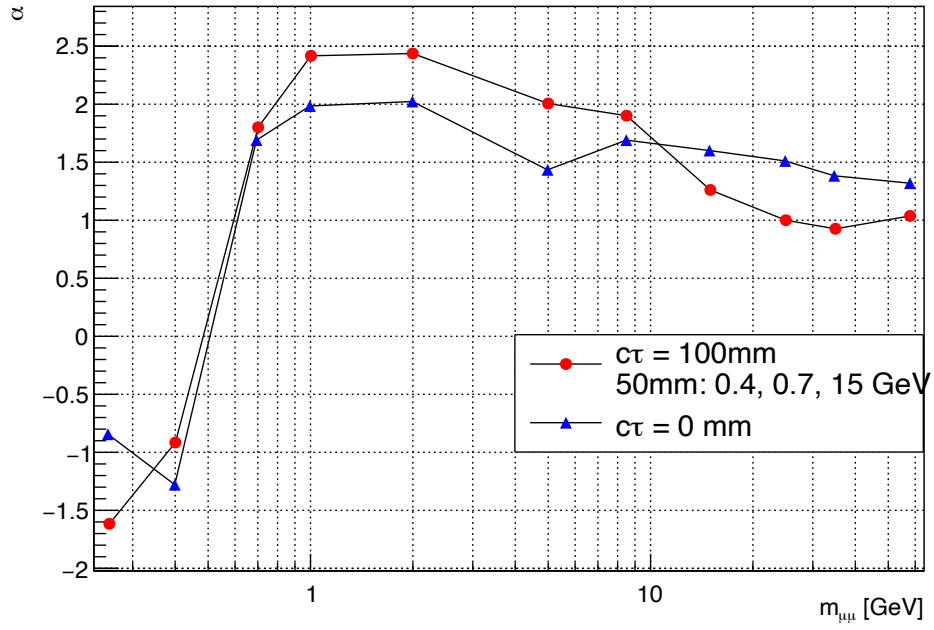


Figure I.14 : The CB fitted α parameter as a function of the dimuon mass for prompt ($c\tau = 0$ mm) and displaced ($c\tau = 100$ mm or 50 mm) dark photon signals.

the overestimate in p_T would lead to an overestimate of the dimuon mass, $M \propto \sqrt{p_{T1}p_{T2}}$.

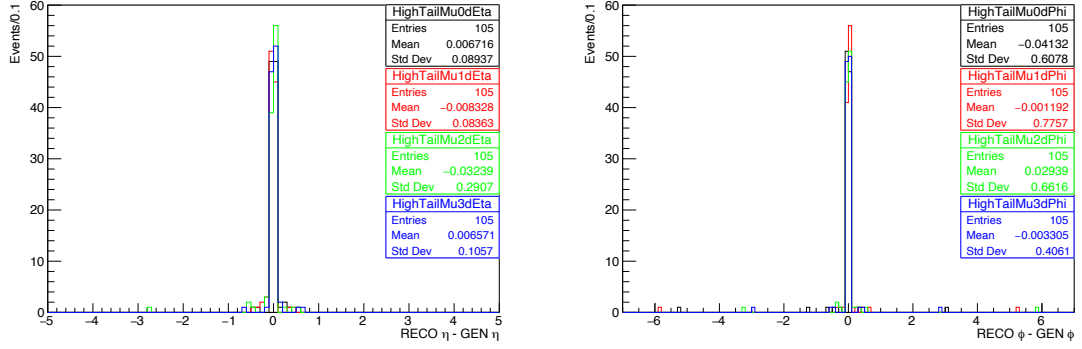


Figure I.15 : The difference in η and ϕ for 4 leading muons (ordered in p_T) at reconstruction level and generator level for events with $\frac{m_{\mu\mu 1} + m_{\mu\mu 2}}{2} > 0.3$ GeV in dark photon signal sample: $m_{\gamma_D} = 0.25$ GeV and $c\tau = 0$ mm.

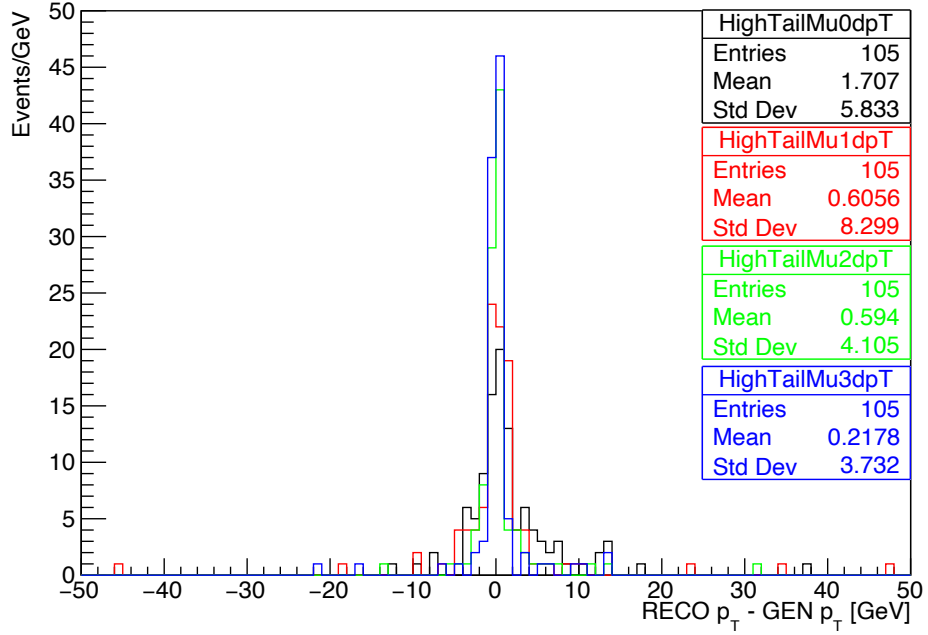


Figure I.16 : The difference in p_T for 4 leading muons (ordered in p_T) at reconstruction level and generator level for events with $\frac{m_{\mu\mu 1} + m_{\mu\mu 2}}{2} > 0.3$ GeV in dark photon signal sample: $m_{\gamma_D} = 0.25$ GeV and $c\tau = 0$ mm.

I.2 Asymmetric mass window

An asymmetric window was considered based on the the CB fitted resolution (σ), but it turns out such asymmetric mass window is not applicable and the mass window needs to be symmetric. A simple derivation is provided here.

Suppose two dimuons, each mass is m_1 and m_2 , for simplicity, let $m_1 > m_2$ (the derivation works similarly for $m_2 > m_1$), an asymmetric mass window cut is written as:

$$m_1 < \frac{m_1 + m_2}{2} + N_+ \times \sigma\left(\frac{m_1 + m_2}{2}\right). \quad (\text{I.2})$$

$$m_2 > \frac{m_1 + m_2}{2} - N_- \times \sigma\left(\frac{m_1 + m_2}{2}\right). \quad (\text{I.3})$$

This says that m_1 can not be larger than N_+ ($N_+ > 0$) times the resolution above the mean dimuon mass, and m_2 can not be smaller than N_- ($N_- > 0$) times the resolution below the mean dimuon mass. The mass resolution, $\sigma(\frac{m_1+m_2}{2})$, is a function of the mean dimuon mass that we can get from signal MC (for example, from the CB fit). For an asymmetric mass window, $N_+ \neq N_-$.

For the above two inequalities, if you move first term on the right side to the left, they become:

$$\frac{m_1 - m_2}{2} < N_+ \times \sigma\left(\frac{m_1 + m_2}{2}\right), \quad (\text{I.4})$$

$$\frac{m_2 - m_1}{2} > -N_- \times \sigma\left(\frac{m_1 + m_2}{2}\right), \quad (\text{I.5})$$

The second inequality can be written as

$$\frac{m_1 - m_2}{2} < N_- \times \sigma\left(\frac{m_1 + m_2}{2}\right), \quad (\text{I.6})$$

using the fact $m_1 > m_2$. So the asymmetric cuts are now equivalent to

$$\frac{m_1 - m_2}{2} < 2N_+ \times \sigma\left(\frac{m_1 + m_2}{2}\right), \quad (\text{I.7})$$

$$\frac{m_1 - m_2}{2} < 2N_- \times \sigma\left(\frac{m_1 + m_2}{2}\right). \quad (\text{I.8})$$

As you see, one of the two asymmetric cut is redundant depending on which one of N_+ and N_- is larger. Suppose $N_+ = 2.5$ and $N_- = 3$, the final mass window would be $\frac{m_1 - m_2}{2} < 6 \times \sigma\left(\frac{m_1 + m_2}{2}\right)$.

I.3 Discussion of the Old Muon Clustering Algorithm

The previous version of this search using the 2016 CMS data [83] adopted a different approach when selecting two signal dimuon candidates. An upper limit of 9 GeV was put on the invariant mass of each muon pair. All possible pairs of oppositely charged muons were selected with a Kalman vertex fit probability requirement of 1%. Then all muon pairs are examined and those that share a common muon are merged into single a muon jet. Such merge happens until there is no more muon pairs sharing a muon with the muon jet. In this way, muon jets are formed in the event. A final selection of two muon jets each with exactly two oppositely charged muons are applied.

Such an algorithm can not be adopted in the search of this thesis due to the expanded upper mass limit to 60 GeV. An example signal event is shown in Fig. I.17. Suppose the event contains four muons with a minimum p_T of 8 GeV, if you pair two muons back to back, the invariant mass is slightly above 11 GeV. Such pairs are not allowed because of the 9 GeV invariant mass cut in 2016 search. In this thesis, however, such pairings become possible if we still use the old algorithm. Furthermore, since $\mu_1^+ \mu_2^-$ and $\mu_3^+ \mu_4^-$ are actual signal pairs (i.e. invariant mass below 60 GeV), under

the old algorithm, they will be merged with $\mu_1^+ \mu_4^-$ and $\mu_2^- \mu_3^+$ because they all share common muons. This will result in a muon jet containing all four muons. To prevent this from happening, if one insists using the old algorithm, a minimum $p_T \sim 41$ GeV needs to be applied to each muon, which is too high for this search.

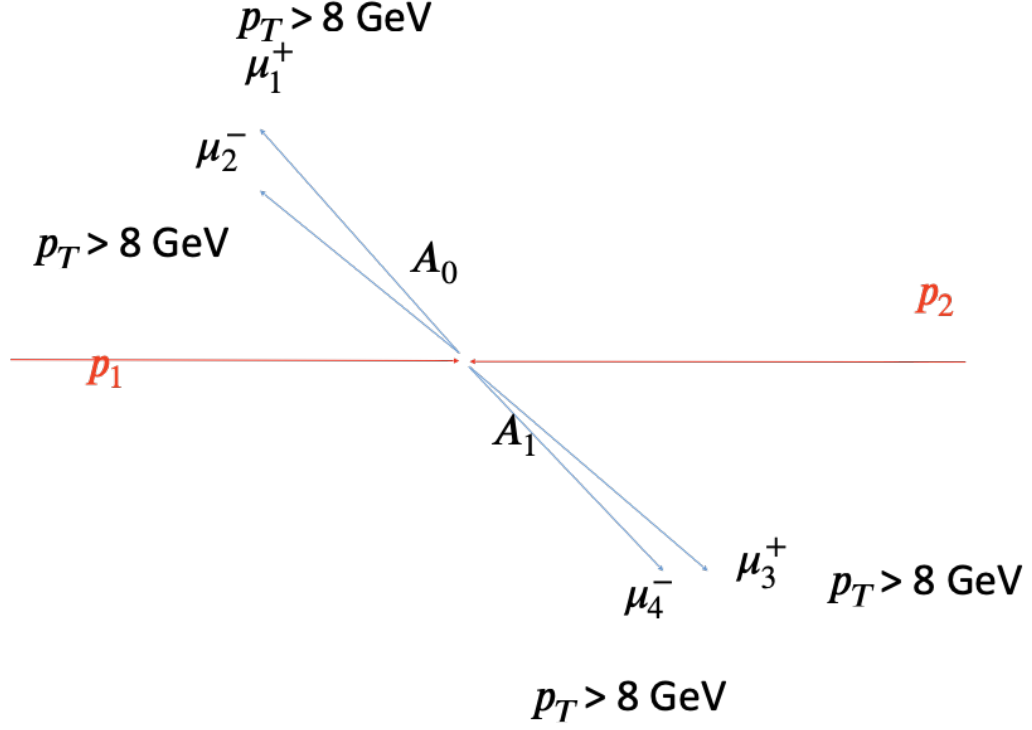


Figure I.17 : An example signal event with four muons $p_T > 8 \text{ GeV}$ produced from the proton proton collision. $\mu_1^+ \mu_2^-$ and $\mu_3^+ \mu_4^-$ are actual muon pairs decayed from the back-to-back signal bosons A_0 and A_1 , with $m_{A_0} = m_{A_1} < 60 \text{ GeV}$. If one accidentally pairs $\mu_1^+ \mu_4^-$ and/or $\mu_2^- \mu_3^+$, each pair will have an invariant mass larger than 11.3 GeV . This is not possible using the old algorithm since the muon pair invariant mass is limited to 9 GeV . However, this could happen with the muon pair invariant mass cut increased to 60 GeV . Furthermore, since $\mu_1^+ \mu_2^-$ and $\mu_3^+ \mu_4^-$ are actual signal pairs (i.e. invariant mass below 60 GeV), under the old algorithm, they will be merged with $\mu_1^+ \mu_4^-$ and $\mu_2^- \mu_3^+$ because they all share common muons. This will result in a muon jet containing all four muons.

I.4 Compatible dimuon vertices from the same pp collision

In earlier iterations of the analysis, two light boson candidates are required to be produced in the same pp collision with:

$$|\Delta z| = |z_{\mu\mu_1} - z_{\mu\mu_2}| < 0.1\text{cm}. \quad (\text{I.9})$$

As Higgs boson lifetime is negligible, in signal events $z_{\mu\mu}$ for each dimuon tags the primary vertex position and therefore the two positions should be consistent within the detector resolution. This requirement is loose enough to ensure that signal events are never rejected by this selection.

However, this cut is not used anymore in this 2018 analysis. We relaxed the muon selection to allow at most one SA muon to mitigate low reconstruction efficiency of displaced muons. As the SA muon usually have poorer position resolution when propagated back to the beam line, the reconstructed position of one dimuon is not necessarily in agreement with the other. Hence, the requirement of compatible dimuon production position became inappropriate for the model independent analysis we are pursuing. In principle, the cut affects the displaced signals more as there are larger fractions of events containing a SA muon. Nevertheless, we choose to document the compatibility requirement for reference.

Appendix J

Isolation of Muon and Dimuon

The single muon isolation requirement is not used in the main analysis due to its model dependent feature on the signal lifetime as shown in Fig. J.1. Nevertheless, we choose to document the relevant studies of single muon isolation and its comparison with the dimuon isolation here for reference.

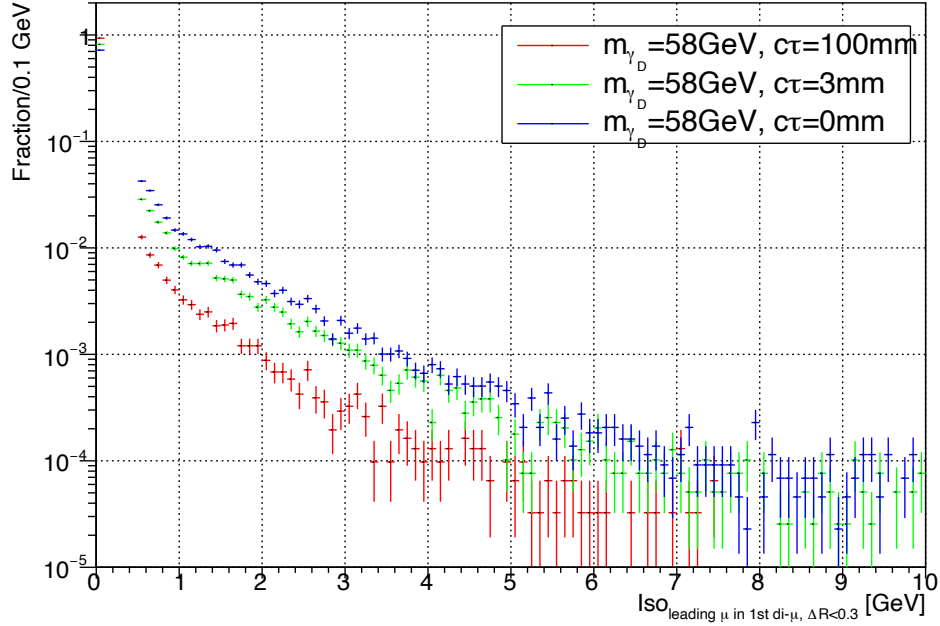


Figure J.1 : Leading muon isolation distribution ($\Delta R < 0.3$) of the first dimuon from dark photon (MSSMD) signal MC with $m_{\gamma_D} = 58$ GeV with three lifetime choices: 100 mm (red), 3 mm (green) and 0 mm (blue).

Similar to the dimuon isolation in the main text, the absolute muon isolation variable,

$$\text{Iso}_\mu = \sum_{\text{tracks}} p_T(\text{track}), \quad (\text{J.1})$$

sums over all reconstructed tracks with,

- $p_T(\text{track}) > 0.5 \text{ GeV}$,
- $\Delta R(\text{track}, \mu) < 0.3$,
- $|z_{\text{track}} - z_\mu| < 0.1 \text{ cm}$,
- tracks associated with all four muons forming the dimuon are excluded.

An absolute isolation less than 1.5 GeV in a cone of $\Delta R < 0.3$ is applied to the leading muon in each dimuon to reject background events from QCD processes. Fig. [J.2](#) shows such comparisons between an ALP sample and a QCD enriched dataset (left), or QCD MC samples (right). All QCD MC samples are listed in Tab. [J.1](#). This choice keeps 90% efficiency for each signal muon and meanwhile rejects $\sim 77.8\%$ QCD background if use QCD enriched data and rejects $\sim 82.4\%$ QCD background if using QCD MC samples. Other working points are also available corresponding to different efficiencies for signals and backgrounds based on such comparison plots.

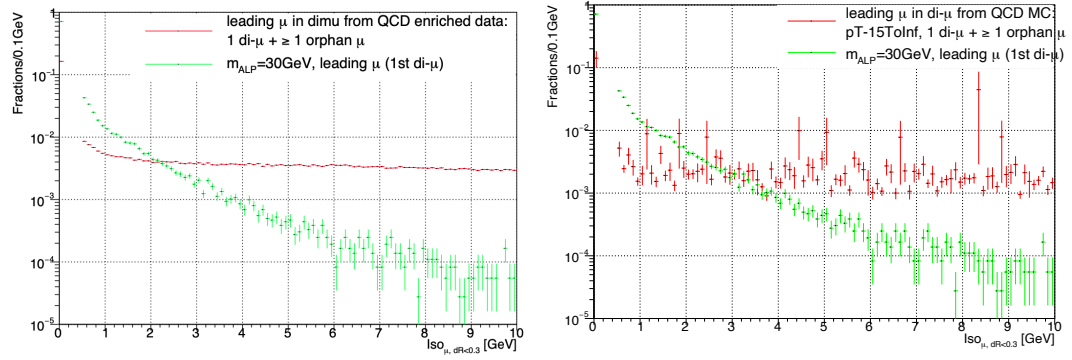


Figure J.2 : Leading muon isolation in a cone of $\Delta R < 0.3$ in the first dimuon of an ALP sample ($m_{\text{ALP}} = 30\text{GeV}$) compared with QCD enriched dataset (left) and QCD MC samples (right).

Table J.1 : QCD MC samples with enriched muons for isolation study.

Dataset	$\sigma \cdot Br(\epsilon_{filter})$ [fb]	Events
/QCD_Pt-15to20_MuEnrichedPt5_TuneCP5_13TeV_pythia8/RunIIFall17 MiniAODv2-PU2017_12Apr2018_94X_mc2017_realistic_v14-v1/MINIAODSIM	3.3360110E+09	5859904
/QCD_Pt-20to30_MuEnrichedPt5_TuneCP5_13TeV_pythia8/RunIIFall17 MiniAODv2-PU2017_12Apr2018_94X_mc2017_realistic_v14-v1/MINIAODSIM	3.9878549E+09	28070988
/QCD_Pt-30to50_MuEnrichedPt5_TuneCP5_13TeV_pythia8/RunIIFall17 MiniAODv2-PU2017_12Apr2018_94X_mc2017_realistic_v14-v1/MINIAODSIM	1.7053810E+09	29030324
/QCD_Pt-50to80_MuEnrichedPt5_TuneCP5_13TeV_pythia8/RunIIFall17 MiniAODv2-PU2017_12Apr2018_94X_mc2017_realistic_v14-v1/MINIAODSIM	3.9517800E+08	24068613
/QCD_Pt-80to120_MuEnrichedPt5_TuneCP5_13TeV_pythia8/RunIIFall17 MiniAODv2-PU2017_12Apr2018_94X_mc2017_realistic_v14-v1/MINIAODSIM	1.0688940E+08	23248995
/QCD_Pt-120to170_MuEnrichedPt5_TuneCP5_13TeV_pythia8/RunIIFall17 MiniAODv2-PU2017_12Apr2018_94X_mc2017_realistic_v14-v1/MINIAODSIM	2.3773610E+07	20774848
/QCD_Pt-170to300_MuEnrichedPt5_TuneCP5_13TeV_pythia8/RunIIFall17 MiniAODv2-PU2017_12Apr2018_94X_mc2017_realistic_v14-v1/MINIAODSIM	8.2929820E+06	46170668

Dataset	$\sigma \cdot Br(\epsilon_{filter})$ [fb]	Events
/QCD_Pt-300to470_MuEnrichedPt5_TuneCP5_13TeV_pythia8/RunIIFall17 MiniAODv2-PU2017_12Apr2018_94X_mc2017_realistic_v14-v1/MINIAODSIM	7.9735270E+05	17744779
/QCD_Pt-470to600_MuEnrichedPt5_TuneCP5_13TeV_pythia8/RunIIFall17 MiniAODv2-PU2017_12Apr2018_94X_mc2017_realistic_v14-v1/MINIAODSIM	5.6588300E+04	24243589
/QCD_Pt-600to800_MuEnrichedPt5_TuneCP5_13TeV_pythia8/RunIIFall17 MiniAODv2-PU2017_12Apr2018_94X_mc2017_realistic_v14-v1/MINIAODSIM	2.5095100E+04	17263676
/QCD_Pt-800to1000_MuEnrichedPt5_TuneCP5_13TeV_pythia8/RunIIFall17 MiniAODv2-PU2017_12Apr2018_94X_mc2017_realistic_v14-v1/MINIAODSIM	4.7074000E+03	17019127
/QCD_Pt-1000toInf_MuEnrichedPt5_TuneCP5_13TeV_pythia8/RunIIFall17 MiniAODv2-PU2017_12Apr2018_94X_mc2017_realistic_v14-v1/MINIAODSIM	1.6213000E+03	11596693

Note such isolation cut can not be applied to two muons in a dimuon at the same time because the selection efficiency would then be mass dependent. The opening angle of two muons in a dimuon varies a lot in the whole probed mass range. A generator level ΔR distribution for two muons coming from the first signal boson using MSSMD signal MC samples are shown in Fig. J.3. The average ΔR can go as low as 0.007 for very boosted signals ($m_{\gamma_D}=0.25\text{GeV}$) and as large as 2.66 in the case of high mass signals ($m_{\gamma_D}=58\text{GeV}$). For low mass signal boson decaying into boosted muons, isolation cones of two such boosted muons usually overlap. This is not true, however, for two muons coming from a high mass signal boson. An event display illustrates this in Fig. J.4.

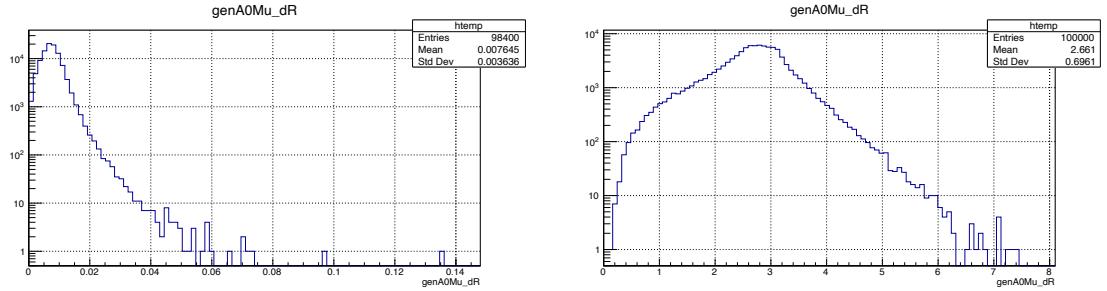


Figure J.3 : ΔR for two muons from the first dimuon with generator level signal boson mass 0.25 GeV (left) and 58 GeV (right) in MSSMD MC samples.

Different isolation cones are studied, including $\Delta R = 0.3$ (Fig. J.2), 0.4 (Fig. J.5) and 0.5 (Fig. J.6).

By requiring 90% efficiency on signals, the necessary cuts on the isolation of leading muon or the first dimuon as well as the corresponding performance of rejecting QCD backgrounds, if using QCD enriched dataset, are,

- $\text{Iso}_{\text{Leading } \mu, \Delta R < 0.3} < 1.5\text{GeV}$: rejects $\sim 77.8\%$ QCD background (adopted in

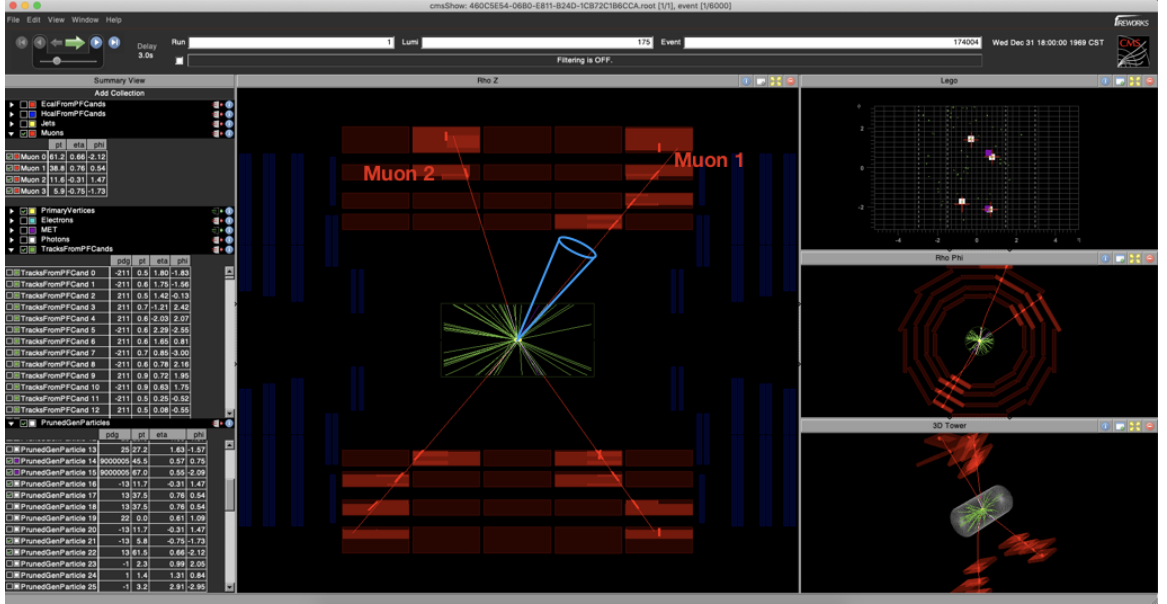


Figure J.4 : ΔR cone (blue) around a dimuon (signal boson) shown in an event from an ALP MC sample where $m_{\text{ALP}}=30$ GeV.

main analysis selections),

- $\text{Iso}_{\text{Leading } \mu, \Delta R < 0.4} < 2.3\text{GeV}$: rejects $\sim 78.3\%$ QCD background,
- $\text{Iso}_{\text{Leading } \mu, \Delta R < 0.5} < 3.4\text{GeV}$: rejects $\sim 77.4\%$ QCD background,
- $\text{Iso}_{1^{\text{st}} \text{ dimuon}, \Delta R < 0.4} < 2.3\text{GeV}$: rejects $\sim 71.8\%$ QCD background;

and if using QCD MC,

- $\text{Iso}_{\text{Leading } \mu, \Delta R < 0.3} < 1.5\text{GeV}$: rejects $\sim 82.4\%$ QCD background (adopted in main analysis selections),
- $\text{Iso}_{\text{Leading } \mu, \Delta R < 0.4} < 2.3\text{GeV}$: rejects $\sim 81.6\%$ QCD background,
- $\text{Iso}_{\text{Leading } \mu, \Delta R < 0.5} < 3.4\text{GeV}$: rejects $\sim 79.7\%$ QCD background,

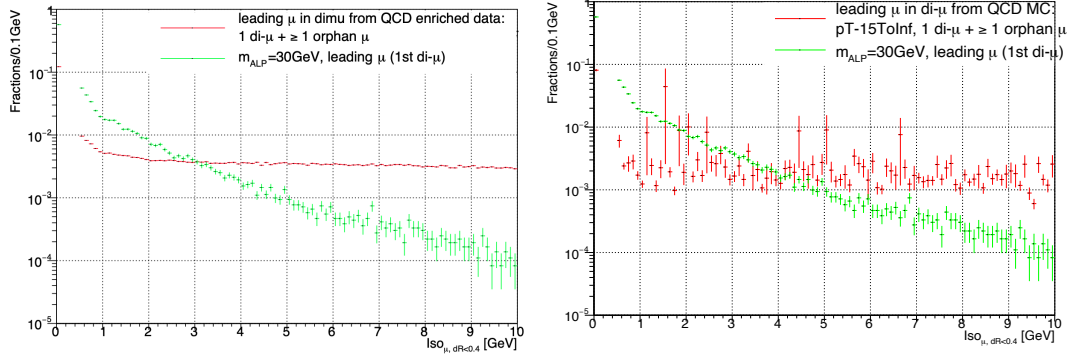


Figure J.5 : Leading muon isolation in a cone of $\Delta R < 0.4$ in the first dimuon of an ALP sample ($m_{\text{ALP}} = 30\text{GeV}$) compared with QCD enriched dataset (left) and QCD MC samples (right).

- $\text{Iso}_{1^{\text{st}} \text{ dimuon}, \Delta R < 0.4} < 2.3\text{GeV}$: rejects $\sim 72.4\%$ QCD background.

The QCD enriched data and MC show good agreement in terms of the cut and performance.

Some further comparisons are done in terms of signal muons only using signal MC samples. Fig. [J.7](#) ($\Delta R < 0.3$), Fig. [J.8](#) ($\Delta R < 0.4$) and Fig. [J.9](#) ($\Delta R < 0.5$) show that all four signal muons has similar isolation distributions under the same ΔR cone.

Fig. [J.10](#) shows that the leading muon isolation distributions are independent of signal mass of a specific signal model under the same ΔR cone.

Fig. [J.11](#) shows that the leading muon isolation distributions are independent of different signal masses from different signal models under the same ΔR cone. That means the leading muon isolation is model independent. (need to check displaced samples)

Fig. [J.12](#) shows that leading muon isolation in QCD processes does not vary much when the isolation cone size ΔR is changed except for the first bin which means zero

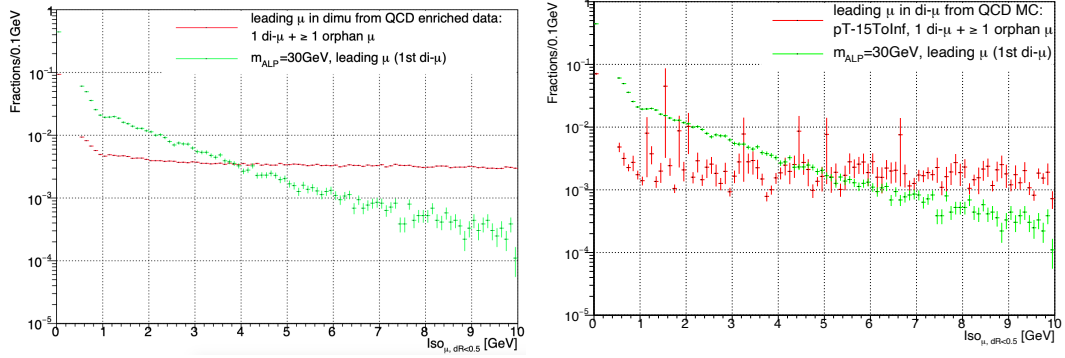


Figure J.6 : Leading muon isolation in a cone of $\Delta R < 0.5$ in the first dimuon of an ALP sample ($m_{\text{ALP}} = 30\text{GeV}$) compared with QCD enriched dataset (left) and QCD MC samples (right).

isolation.

When comparing the leading muon and dimuon isolation in QCD processes, Fig. [J.13](#) shows that the dimuon isolation distribution is slightly higher than the single muon isolation at small values.

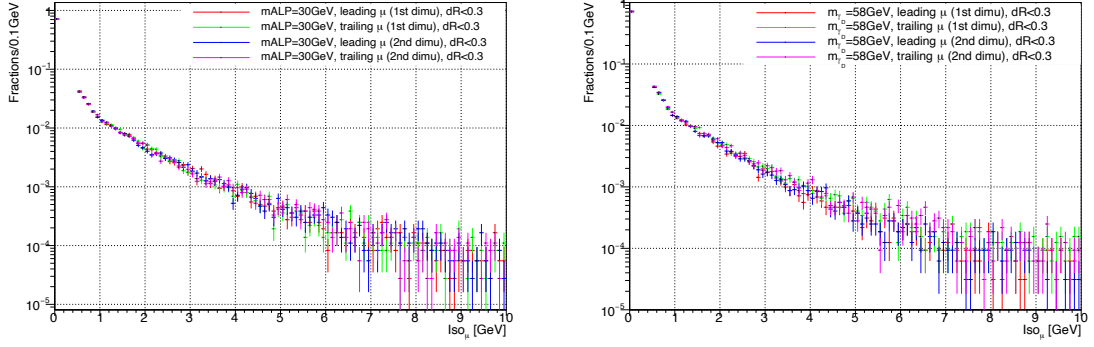


Figure J.7 : Isolation of four signal muons in a cone of $\Delta R < 0.3$ in an ALP MC sample of $m_{\text{ALP}} = 30\text{GeV}$ (left) and an MSSMD MC sample with $m_{\gamma_D} = 58\text{ GeV}$ (right).

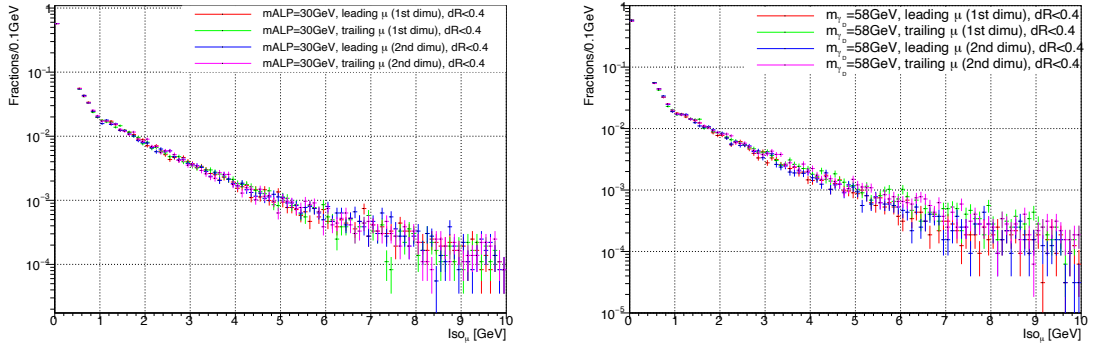


Figure J.8 : Isolation of four signal muons in a cone of $\Delta R < 0.4$ in an ALP MC sample of $m_{\text{ALP}} = 30\text{GeV}$ (left) and an MSSMD MC sample with $m_{\gamma_D} = 58\text{ GeV}$ (right).

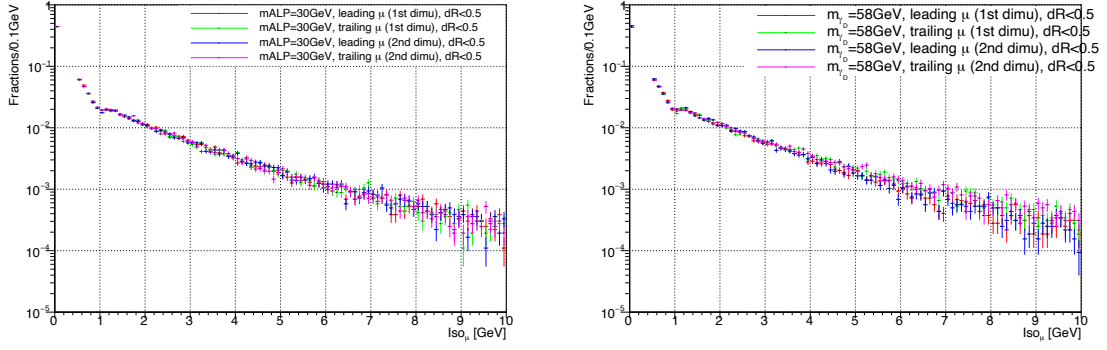


Figure J.9 : Isolation of four signal muons in a cone of $\Delta R < 0.5$ in an ALP MC sample of $m_{\text{ALP}} = 30\text{GeV}$ (left) and an MSSMD MC sample with $m_{\gamma_D} = 58\text{ GeV}$ (right).

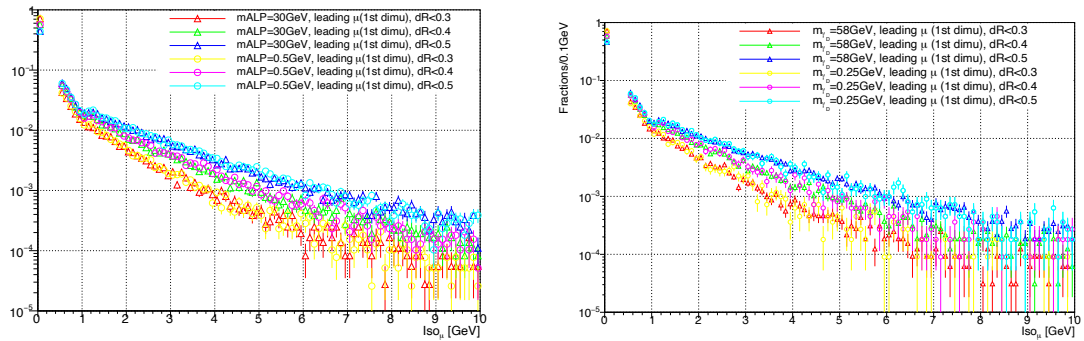


Figure J.10 : Isolation of leading muons in the first dimuon for different masses of signal boson in ALP (left) and MSSMD (right) MC.

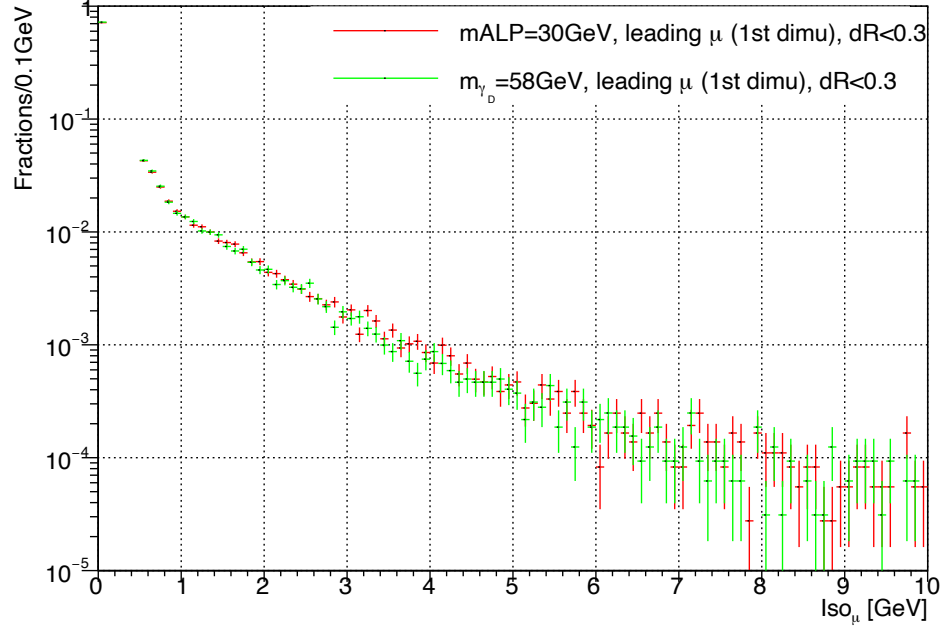


Figure J.11 : Isolation of leading muons in the first dimuon for different masses of signal boson in different signal models.

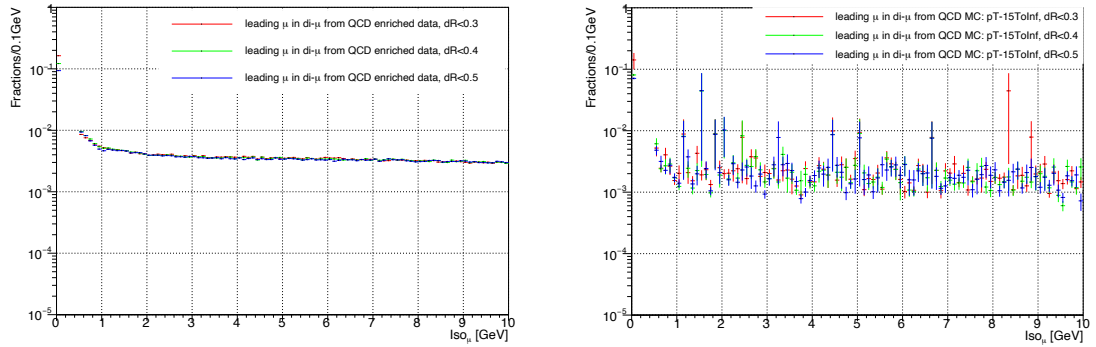


Figure J.12 : Isolation of leading muons in the first dimuon for QCD processes: QCD process enriched data (left) and QCD MC (right).

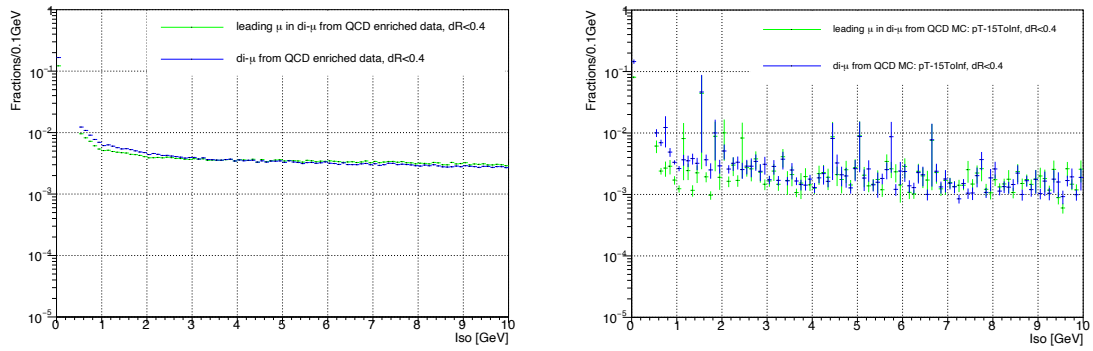


Figure J.13 : Isolation distributions of the leading muon and the first dimuon under the same cone size ($\Delta R < 0.4$) for QCD processes: QCD process enriched data (left) and QCD MC (right).

Appendix K

Low Mass 1D Templates Fit Results

The final fitted parameters for m_1 and m_2 in 2018 are shown in Tab. [K.1](#) and Tab. [K.2](#).

Table K.1 : Fit parameters for m1 templates in 2018.

Year	2018	
Below J/ψ		
Parameter	Final Value	Error
p_{E2}	6.3628e-03	6.15e-03
p_{E1}	1.1218e-01	1.17e-04
$m_{0,AH}$	2.8491e-01	4.01e-02
σ_{AH}	5.6957e-02	1.28e-02
p_{06}	7.1558e-01	4.31e+00
p_{16}	2.9277e+00	3.49e+00
p_{26}	-3.0825e+00	9.99e-01
p_{36}	4.3410e+00	2.59e+00
p_{46}	-7.9077e-01	4.45e+00
p_{56}	1.5603e+00	2.69e+00
p_{66}	2.9007e-01	1.39e+00
p_{E0}	1.9486e+04	3.94e+03
p_{AH}	1.3727e+03	1.10e+03
p_B	1.7365e+04	3.54e+03

Parameter	Final Value	Error
p_η	1.0490e-03	4.34e-01
p_ϕ	1.1818e+02	6.34e+01
p_ω	4.0327e+01	3.12e+01
Above J/ψ		
p_{06}	4.0132e+00	1.07e+00
p_{16}	-3.1169e+00	7.47e-01
p_{26}	3.6892e+00	8.57e-01
p_{36}	-1.8111e+00	5.48e-01
p_{46}	1.4147e+00	4.21e-01
p_{56}	1.1024e-01	1.98e-01
p_{66}	4.3063e-01	1.17e-01
p_B	6.0553e+03	8.15e+01
p_ψ	7.5763e+02	3.67e+01
σ_ψ	3.0097e-02	1.51e-03

Table K.2 : Fit parameters for m2 templates in 2018.

Year	2018	
Below J/ψ		
Parameter	Final Value	Error
p_{E2}	8.0674e-03	4.66e-04
p_{E1}	1.2566e-01	1.47e-01
$m_{0,AH}$	2.8242e-01	5.31e-03
σ_{AH}	2.4395e-02	5.65e-03

Parameter	Final Value	Error
p_{06}	6.6624e-01	5.43e-02
p_{16}	3.3967e-01	1.42e-01
p_{26}	-3.6159e-01	1.50e-01
p_{36}	1.9999e+00	5.75e-03
p_{46}	4.0046e-01	1.56e-01
p_{56}	11.2587e+00	1.56e-01
p_{66}	3.0988e-01	8.61e-02
p_{E0}	1.3978e+04	5.22e+02
p_{AH}	1.4632e+02	2.96e+01
p_B	1.4812e+04	5.13e+02
p_η	3.9999e+00	1.50e-02
p_ϕ	3.0321e+01	1.72e+01
p_ω	3.7792e+01	1.43e+01
Above J/ψ		
p_{06}	2.8110e+00	1.94e-01
p_{16}	-2.8859e+00	9.43e-02
p_{26}	3.3729e+00	6.83e-02
p_{36}	-2.0934e+00	1.20e-01
p_{46}	1.4872e+00	1.05e-01
p_{56}	-1.8570e-01	7.87e-02
p_{66}	2.8897e-01	3.77e-02
p_B	3.1347e+03	6.03e+01
p_ψ	4.6344e+02	3.11e+01

Parameter	Final Value	Error
σ_ψ	4.3996e-02	3.14e-03

Appendix L

Negligible Background Processes Above 11 GeV

Samples in Tab. [L.1](#) were checked and found to have negligible contributions to high mass background.

Table L.1 : Checked MC samples with negligible contributions to backgrounds above 11 GeV.

Dataset	$\sigma \cdot Br(\epsilon_{filter})$ [fb]	Events
/ZZTo2L2Nu_13TeV_powheg_pythia8/RunIIFall17MiniAODv2- PU2017_12Apr2018_94X_mc2017_realistic_v14-v1/MINIAODSIM	6.008E+02	8153257
/ZZTo2L2Q_13TeV_amcatnloFXFX_madspin_pythia8/RunIIFall17MiniAOD v2-PU2017_12Apr2018_94X_mc2017_realistic_v14-v1/MINIAODSIM	3.695E+03	21975845
/GluGluToContinToZZTo2mu2tau_13TeV_MCFM701_pythia8/RunIIFall17 MiniAODv2-PU2017_12Apr2018_94X_mc2017_realistic_v14-v1/MINIAODSIM	3.190E+00	487198
/GluGluToContinToZZTo4tau_13TeV_MCFM701_pythia8/RunIIFall17 MiniAODv2-PU2017_12Apr2018_94X_mc2017_realistic_v14_ext1- v2/MINIAODSIM	1.590E+00	476400
/GJets_DR-0p4_HT-100To200_TuneCP5_13TeV- madgraphMLM-pythia8_v2/RunIIFall17MiniAODv2- PU2017_12Apr2018_94X_mc2017_realistic_v14-v1/MINIAODSIM	5.026E+06	6355164
/GJets_DR-0p4_HT-200To400_TuneCP5_13TeV- madgraphMLM-pythia8_v2/RunIIFall17MiniAODv2- PU2017_12Apr2018_94X_mc2017_realistic_v14-v1/MINIAODSIM	1.123E+06	21232679

Dataset	$\sigma \cdot Br(\epsilon_{filter})$ [fb]	Events
/GJets_DR-0p4_HT-400To600_TuneCP5_13TeV-madgraphMLM-pythia8_v2/RunIIFall17MiniAODv2-PU2017_12Apr2018_94X_mc2017_realistic_v14-v1/MINIAODSIM	1.235E+05	13362765
/GJets_DR-0p4_HT-600ToInf_TuneCP5_13TeV-madgraphMLM-pythia8/RunIIFall17MiniAODv2-PU2017_12Apr2018_94X_mc2017_realistic_v14-v2/MINIAODSIM	4.058E+04	8392881
/ST_tWll_5f_LO_TuneCP5_PSweights_13TeV-madgraph-pythia8/RunIIFall17MiniAODv2-PU2017_12Apr2018_94X_mc2017_realistic_v14_ext1-v1/MINIAODSIM	1.102E+01	801000
/ST_s-channel_4f_leptonDecays_TuneCP5_13TeV-amcatnlo-pythia8/RunIIFall17MiniAODv2-PU2017_12Apr2018_94X_mc2017_realistic_v14-v2/MINIAODSIM	3.740E+03	6724642
/ST_t-channel_top_4f_inclusiveDecays_TuneCP5_13TeV-powhegV2-madspin-pythia8/RunIIFall17MiniAODv2-PU2017_12Apr2018_new_pmx_94X_mc2017_realistic_v14-v1/MINIAODSIM	1.133E+05	5189396

Dataset	$\sigma \cdot Br(\epsilon_{filter})$ [fb]	Events
/ST_tW_top_5f_NoFullyHadronicDecays_TuneCP5_13TeV-powheg-pythia8/RunIIFall17MiniAODv2-PU2017_12Apr2018_new_pmx_94X_mc2017_realistic_v14-v1/MINIAODSIM	3.491E+04	4907542
/ST_tW_top_5f_inclusiveDecays_TuneCP5_PSWeights_13TeV-powheg-pythia8/RunIIFall17MiniAODv2-PU2017_12Apr2018_new_pmx_94X_mc2017_realistic_v14-v1/MINIAODSIM	3.491E+04	3789309
/tZq_ll4f_ckm_NLO_TuneCP5_PSWeights_13TeV-amcatnlo-pythia8/RunIIFall17MiniAODv2-PU2017_12Apr2018_new_pmx_94X_mc2017_realistic_v14-v2/MINIAODSIM	7.358E+01	11067874
/TTGJets_TuneCP5_13TeV-amcatnloFXFX-madspin-pythia8/RunIIFall17MiniAODv2-PU2017_12Apr2018_94X_mc2017_realistic_v14-v2/MINIAODSIM	4.133E+03	4811179
/TTWJetsToLNu_TuneCP5_PSWeights_13TeV-amcatnloFXFX-madspin-pythia8/RunIIFall17MiniAODv2-PU2017_12Apr2018_new_pmx_94X_mc2017_realistic_v14-v1/MINIAODSIM	2.173E+02	4908905

Dataset	$\sigma \cdot Br(\cdot \epsilon_{filter})$ [fb]	Events
/TTWJetsToQQ_TuneCP5_13TeV-amcatnloFFX-madspin-pythia8/RunIIFall17MiniAODv2-PU2017_12Apr2018_94X_mc2017_realistic_v14-v2/MINIAODSIM	4.305E+02	811306
/TTZToQQ_TuneCP5_13TeV-amcatnlo-pythia8/RunIIFall17MiniAODv2-PU2017_12Apr2018_94X_mc2017_realistic_v14-v2/MINIAODSIM	5.104E+02	750000
/TTZToLL_M-1to10_TuneCP5_13TeV-amcatnlo-pythia8/RunIIFall17MiniAODv2-PU2017_12Apr2018_94X_mc2017_realistic_v14-v1/MINIAODSIM	5.324E+01	250000
/TTZToLLNuNu_M-10_TuneCP5_13TeV-amcatnlo-pythia8/RunIIFall17MiniAODv2-PU2017_12Apr2018_94X_mc2017_realistic_v14-v1/MINIAODSIM	2.529E+02	7563490
/TTJets_SingleLeptFromT_TuneCP5_13TeV-madgraphMLM-pythia8/RunIIFall17MiniAODv2-PU2017_12Apr2018_94X_mc2017_realistic_v14-v1/MINIAODSIM	1.091E+05	43589354

Dataset	$\sigma \cdot Br(\cdot \epsilon_{filter})$ [fb]	Events
/TTJets_SingleLeptFromTbar_TuneCP5_13TeV-madgraphMLM-pythia8/RunIIFall17MiniAODv2-PU2017_12Apr2018_94X_mc2017_realistic_v14-v1/MINIAODSIM	1.093E+05	55813019
/TTTT_TuneCP5_13TeV-amcatnlo-pythia8/RunIIFall17MiniAODv2-PU2017_12Apr2018_94X_mc2017_realistic_v14-v2/MINIAODSIM	8.213E+00	1000000
/WJetsToLNu_TuneCP5_13TeV-madgraphMLM-pythia8/RunIIFall17MiniAODv2-PU2017_12Apr2018_94X_mc2017_realistic_v14-v2/MINIAODSIM	5.257E+07	32955227
/WWTo4Q_NNPDF31_TuneCP5_13TeV-powheg-pythia8/RunIIFall17MiniAODv2-PU2017_12Apr2018_new_pmx_94X_mc2017_realistic_v14-v1/MINIAODSIM	4.773E+04	2000000
/WWToLNuQQ_NNPDF31_TuneCP5_13TeV-powheg-pythia8/RunIIFall17MiniAODv2-PU2017_12Apr2018_new_pmx_94X_mc2017_realistic_v14-v1/MINIAODSIM	4.599E+04	8712120
/WZTo1L1Nu2Q_13TeV-amcatnloFFX_madspin-pythia8/RunIIFall17MiniAODv2-PU2017_12Apr2018_94X_mc2017_realistic_v14-v2/MINIAODSIM	1.161E+04	18876735

Dataset	$\sigma \cdot Br(\epsilon_{filter})$ [fb]	Events
/WZTo2L2Q_13TeV-amcatnloFFFX_madspin_pythia8/RunIIFall17MiniAODv2-PU2017_12Apr2018_94X_mc2017_realistic_v14-v1/MINIAODSIM	6.297E+03	27108846
/WZTo3LNu_13TeV-powheg-pythia8/RunIIFall17MiniAODv2-PU2017_12Apr2018_94X_mc2017_realistic_v14-v2/MINIAODSIM	4.658E+03	976400
/WW_4F_TuneCP5_13TeV-amcatnlo-pythia8/RunIIFall17MiniAODv2-PU2017_12Apr2018_94X_mc2017_realistic_v14-v1/MINIAODSIM	2.086E+02	240000
/WWZ_4F_TuneCP5_13TeV-amcatnlo-pythia8/RunIIFall17MiniAODv2-PU2017_12Apr2018_94X_mc2017_realistic_v14-v1/MINIAODSIM	1.651E+02	250000
/WZZ_TuneCP5_13TeV-amcatnlo-pythia8/RunIIFall17MiniAODv2-PU2017_12Apr2018_94X_mc2017_realistic_v14-v1/MINIAODSIM	5.565E+01	250000
/ZZZ_TuneCP5_13TeV-amcatnlo-pythia8/RunIIFall17MiniAODv2-PU2017_12Apr2018_94X_mc2017_realistic_v14-v1/MINIAODSIM	1.398E+01	230118
/WZG_TuneCP5_13TeV-amcatnlo-pythia8/RunIIFall17MiniAODv2-PU2017_12Apr2018_94X_mc2017_realistic_v14-v1/MINIAODSIM	4.345E+01	1000000
/WWG_TuneCP5_13TeV-amcatnlo-pythia8/RunIIFall17MiniAODv2-PU2017_12Apr2018_94X_mc2017_realistic_v14-v1/MINIAODSIM	2.147E+02	970300

Appendix M

Drell-Yan Process with QED Radiation

Below shows two example Drell-Yan events [*](#) (Fig. [M.1](#) and Fig. [M.3](#)) where two additional muons are converted from a QED radiated photon. But both events fail the mass consistency requirement and reside in the control region.

*Event 110350579 from run 1, lumi 99326 in file: `/store/mc/RunIIFall17MiniA0Dv2/DYJetsToLL_0J_TuneCP5_13TeV-amcatnloFXFX-pythia8/MINIAODSIM/PU2017_12Apr2018_94X_mc2017_realistic_v14-v1/40000/5AADF3FD-FF8A-E811-8167-FA163E405DB4.root`

Event 110482780 from run 1, lumi 99445 in file: `/store/mc/RunIIFall17MiniA0Dv2/DYJetsToLL_0J_TuneCP5_13TeV-amcatnloFXFX-pythia8/MINIAODSIM/PU2017_12Apr2018_94X_mc2017_realistic_v14-v1/40000/922D9A3B-298E-E811-BE50-0242AC130002.root`

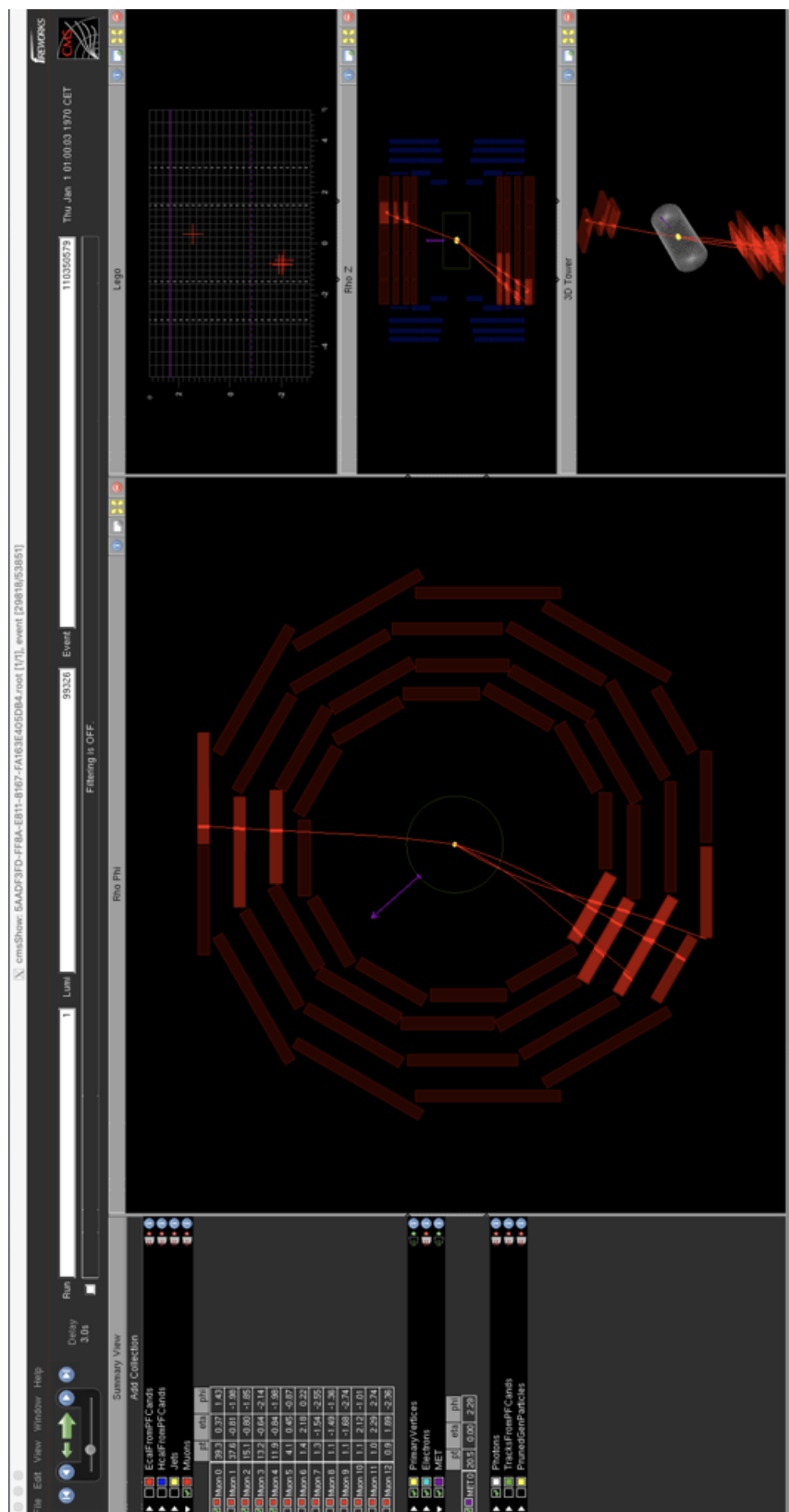


Figure M.1 : Example event 1 in CR: event display for a DY event. The generator level particles are listed in Fig. M.4

Begin processing the 29818th record. Run 1, Event 110350579, LumiSection 99326 at 10-Oct-2019

[ParticleListDrawer] analysing particle collection prunedGenParticles													
idx	ID	Name	Stat	Mo1	Mo2	Da1	Da2	nMo	nDa	pt	eta	phi	
0	2212	p-	4	-1	-1	2	69	0	24	0.000	29256.000	0.000	
1	2212	p-	4	-1	-1	3	93	0	26	0.000	-29256.000	0.000	
2	-3	sbar	21	0	0	4	4	1	1	0.000	22792.721	0.000	
3	3	s	21	1	1	4	4	1	1	0.000	-22812.619	0.000	
4	23	Z0	22	2	3	5	5	2	1	0.000	-22775.898	0.000	
5	23	Z0	44	4	4	6	6	1	1	10.949	-1.411	-3.090	
6	23	Z0	44	5	5	7	7	1	1	11.532	-1.277	2.812	
7	23	Z0	44	6	6	10	10	1	1	12.357	-1.219	-3.114	
8	4	c	51	0	1	11	11	2	1	3.627	1.295	2.495	
9	-4	cbar	51	0	1	12	12	2	1	3.589	1.140	-0.263	
10	23	Z0	44	7	7	24	24	1	1	11.488	-1.272	3.060	
11	4	c	44	8	8	13	13	1	1	4.611	1.419	2.573	
12	-4	cbar	44	9	9	14	14	1	1	2.395	0.795	-0.249	
13	4	c	44	11	11	15	15	1	1	4.933	1.351	2.324	
14	-4	cbar	44	12	12	16	16	1	1	2.485	0.760	-0.106	
15	4	c	44	13	13	17	17	1	1	5.110	1.316	2.333	
16	-4	cbar	44	14	14	18	18	1	1	2.437	0.779	-0.096	
17	4	c	44	15	15	23	69	1	3	5.040	1.330	2.336	
18	-4	cbar	44	16	16	26	26	1	1	2.450	0.774	-0.103	
19	4	c	31	21	21	20	20	1	1	0.000	23851.994	0.000	
20	4	c	33	1	19	22	22	2	1	1.189	7.516	-0.539	
21	4	c	42	27	27	19	19	1	1	0.000	40.461	-0.692	
22	4	c	44	20	20	28	28	1	1	1.186	7.480	-0.539	
23	4	c	51	17	17	25	25	1	1	4.151	1.473	2.328	
24	23	Z0	62	10	10	30	31	1	2	10.566	-1.343	2.951	
25	4	c	62	23	23	55	55	1	1	4.149	1.476	2.323	
26	-4	cbar	62	18	18	50	50	1	1	2.450	0.770	-0.099	
27	4	c	61	0	0	21	21	1	1	0.687	8.069	-1.237	
28	4	c	62	22	22	46	46	1	1	1.749	7.094	-0.788	
29	-4	cbar	63	0	0	61	61	1	1	0.148	7.060	2.852	
30	-13	mu+	23	24	24	32	38	1	2	39.832	-0.766	-1.983	
31	13	mu-	23	24	24	33	33	1	1	38.905	0.371	1.427	
32	22	gamma	51	30	30	34	35	1	2	19.065	-0.711	-2.134	
33	13	mu-	52	31	31	36	37	1	2	38.735	0.371	1.427	
34	13	mu-	1	32	32	-1	-1	1	0	13.113	-0.639	-2.143	
35	-13	mu+	1	32	32	-1	-1	1	0	11.892	-0.839	-1.980	
36	13	mu-	51	33	33	41	41	1	1	38.735	0.371	1.427	
37	22	gamma	1	33	33	-1	-1	1	0	0.000	0.388	1.392	
38	-13	mu+	52	30	30	39	40	1	2	14.968	-0.805	-1.847	
39	-13	mu+	1	38	38	-1	-1	1	0	14.968	-0.805	-1.847	
40	22	gamma	1	38	38	-1	-1	1	0	0.000	-1.007	-1.478	
41	13	mu-	1	36	36	-1	-1	1	0	38.735	0.371	1.427	
42	-3	sbar	73	0	1	64	64	2	1	1.763	-4.337	0.199	
43	21	g	72	0	1	-1	-1	2	0	10.007	0.656	-0.653	
44	21	g	72	1	1	-1	-1	1	0	6.320	-2.345	2.370	
45	-1	dbar	72	0	1	-1	-1	2	0	5.053	-0.054	-0.632	
46	4	c	71	28	28	47	47	1	1	1.749	7.094	-0.788	
47	413	D*+	2	0	46	70	71	2	2	1.466	6.922	-0.566	
48	2	u	71	0	1	72	73	2	2	2.349	0.149	0.271	
49	-3	sbar	71	0	1	72	73	2	2	1.145	2.732	-0.223	
50	-4	cbar	71	26	26	51	65	1	2	2.450	0.770	-0.099	
51	-423	D*bar0	2	0	50	74	75	3	2	2.203	0.867	0.052	

Figure M.2 : Particle list at generator level for the event in Fig. M.1. The DY process produced final state muons (index #39 and #41 from the bottom list) with invariant mass 56.63 GeV. The radiated photon (index #32) comes from one of the Drell-Yan muons and converted to two muons (index #34 and #35) with an invariant mass of 3.23 GeV. The analyzer gives candidate dimuons by pairing muons with index #34 and #39 (invariant mass is 4.75 GeV) and those with index #35 and #41 (invariant mass is 50.71 GeV). The invariant mass of all four muons is 92.21 GeV.

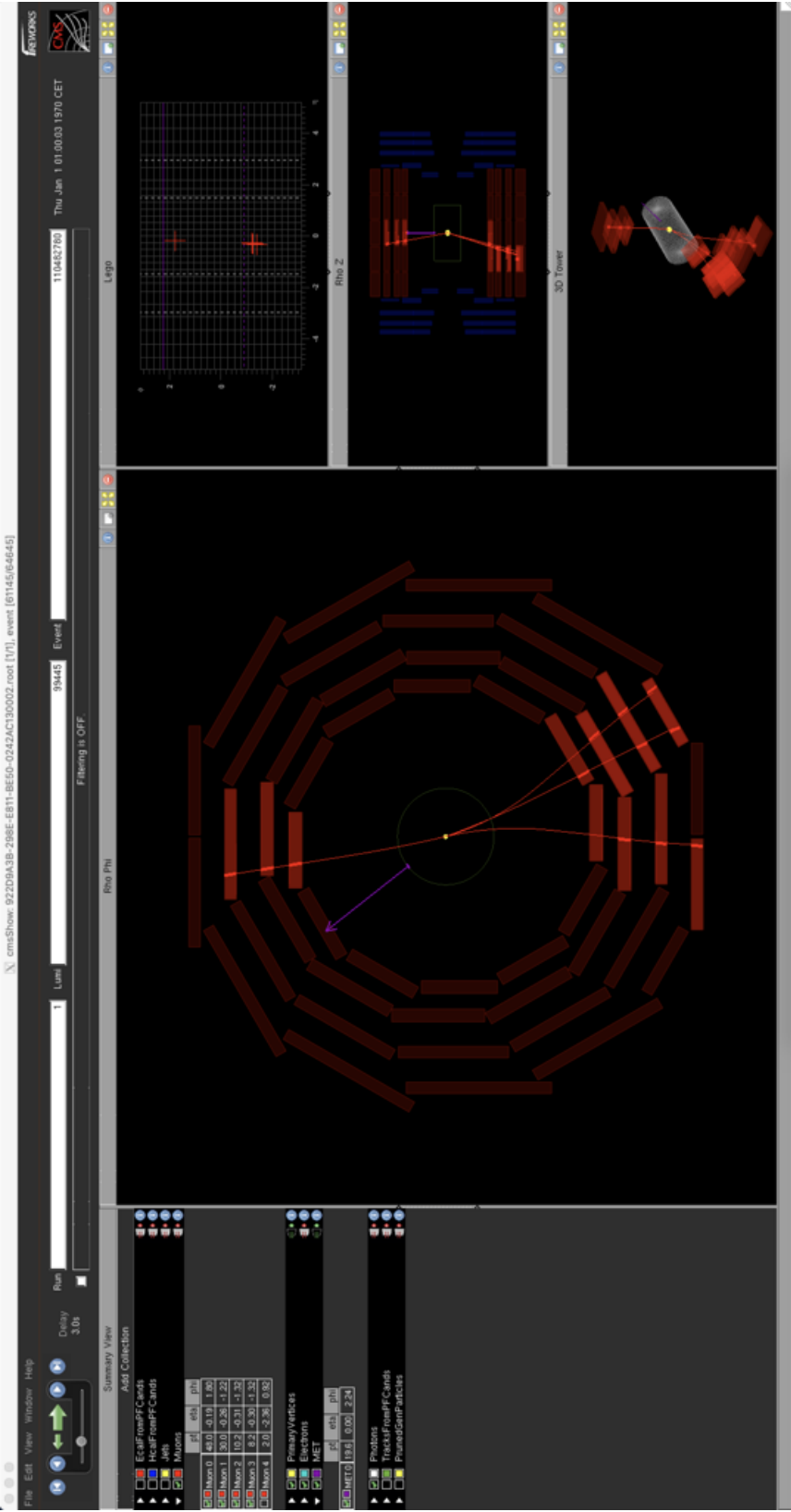


Figure M.3 : Example event 2 in CR: event display for a DY event. The generator level particles are listed in Fig. M.4

Begin processing the 61145th record. Run 1, Event 110482780, LumiSection 99445 at 10-Oct-2019

[ParticleListDrawer] analysing particle collection prunedGenParticles														
idx	ID	Name	Stat	Mo1	Mo2	Da1	Da2	nMo	nDa	pt	eta	phi		
0	2212 -	p+	4	-1	-1	2	57	0	23	0.000	29256.000	0.000		
1	2212 -	p+	4	-1	-1	3	57	0	23	0.000	-29256.000	0.000		
2	3 -	s	21	0	0	4	4	1	1	0.000	22794.127	0.000		
3	-3 -	sbar	21	1	1	4	4	1	1	0.000	-22816.840	0.000		
4	23 -	Z0	22	2	3	9	9	2	1	0.000	-22778.713	0.000		
5	-4 -	cbar	31	10	10	6	57	1	5	0.000	24255.111	0.000		
6	-4 -	cbar	33	1	5	11	11	2	1	0.911	8.081	-1.113		
7	4 -	c	31	12	12	8	57	1	5	0.000	22791.406	0.000		
8	4 -	c	33	1	7	13	13	2	1	0.306	5.368	-1.902		
9	23 -	Z0	62	4	4	14	15	1	2	3.972	-2.445	-0.016		
10	-4 -	cbar	61	0	0	5	5	1	1	0.666	8.414	-3.063		
11	-4 -	cbar	62	6	6	24	24	1	1	0.867	8.113	-1.850		
12	4 -	c	61	0	0	7	7	1	1	0.458	5.073	-2.378		
13	4 -	c	62	8	8	28	28	1	1	0.742	4.521	-2.196		
14	-13 -	mu+	23	9	9	17	17	1	1	47.585	-0.185	1.803		
15	13 -	mu-	23	9	9	16	20	1	2	48.712	-0.281	-1.260		
16	22 -	gamma	51	15	15	18	19	1	2	18.420	-0.309	-1.323		
17	-13 -	mu+	52	14	14	23	23	1	1	47.550	-0.185	1.803		
18	13 -	mu-	1	16	16	-1	-1	1	0	8.273	-0.301	-1.320		
19	-13 -	mu+	1	16	16	-1	-1	1	0	10.404	-0.313	-1.323		
20	13 -	mu-	52	15	15	21	22	1	2	30.058	-0.264	-1.221		
21	13 -	mu-	1	20	20	-1	-1	1	0	29.719	-0.264	-1.221		
22	22 -	gamma	1	20	20	-1	-1	1	0	0.339	-0.262	-1.250		
23	-13 -	mu+	1	17	17	-1	-1	1	0	47.549	-0.185	1.803		
24	-4 -	cbar	71	11	11	25	25	1	1	0.867	8.113	-1.850		
25	-411 -	D-	2	0	24	43	44	3	2	0.647	8.480	-1.982		
26	2 -	u	71	1	1	49	50	1	2	0.255	-6.239	-2.577		
27	-2 -	ubar	71	0	1	49	50	2	2	1.284	-0.945	-0.815		
28	4 -	c	71	13	13	29	29	1	1	0.742	4.521	-2.196		
29	423 -	D*0	2	0	28	45	46	3	2	0.649	4.205	-2.239		
30	333 -	phi	2	0	1	47	48	2	2	1.803	1.512	1.215		
31	1 -	d	71	0	0	33	57	1	4	0.293	1.681	-0.022		
32	-1 -	dbar	71	0	1	33	57	2	4	0.200	3.438	2.222		
33	2212 -	p+	1	0	32	-1	-1	6	0	1.350	5.322	2.107		
34	2 -	u	71	0	1	42	42	2	1	5.895	5.048	-1.895		
35	2 -	u	71	0	1	38	52	2	3	3.201	-1.468	-2.178		
36	3 -	s	71	0	1	38	52	2	3	0.705	-3.967	1.793		
37	1 -	d	71	0	1	38	52	2	3	1.317	4.134	-1.542		
38	2212 -	p+	1	0	37	-1	-1	5	0	1.383	-2.363	-3.001		
39	310 -	K_S0	1	0	1	-1	-1	2	0	2.564	2.022	1.158		
40	2212 -	p+	1	0	1	-1	-1	2	0	1.972	-1.758	-0.883		
41	2212 -	p+	1	0	32	-1	-1	6	0	0.453	2.875	2.940		
42	310 -	K_S0	1	0	34	-1	-1	3	0	1.623	-0.307	2.361		
43	10311 -	K*00	2	25	25	-1	-1	1	0	0.859	7.984	-1.977		
44	-211 -	pi-	1	25	25	-1	-1	1	0	0.212	7.938	1.181		
45	421 -	D0	2	29	29	53	55	1	3	0.615	4.180	-2.175		
46	111 -	pi0	2	29	29	-1	-1	1	0	0.053	4.133	-3.075		
47	321 -	K+	1	30	30	-1	-1	1	0	0.902	1.495	1.320		
48	-321 -	K-	1	30	30	-1	-1	1	0	0.911	1.519	1.110		
49	11 -	e-	1	26	27	-1	-1	2	0	0.120	-4.234	0.963		
50	-11 -	e+	1	26	27	-1	-1	2	0	0.014	-4.612	-0.213		

Figure M.4 : Particle list at generator level for the event in Fig. M.3. The DY process produced final state muons (index #21 and #23 from the bottom list) with invariant mass 75.11 GeV. The radiated photon (index #16) comes from one of the Drell-Yan muons and converted to two muons (index #18 and #19) with an invariant mass of 0.24 GeV. The analyzer gives candidate dimuons by pairing muons with index #18 and #23 (invariant mass is 39.73 GeV) and those with index #19 and #21 (invariant mass is 2.00 GeV). The invariant mass of all four muons is 95.99 GeV.