

A CROSS SECTION MEASUREMENT OF EVENTS WITH TWO MUONS AT THE Z^0 RESONANCE AND AT LEAST ONE HEAVY FLAVOUR JET AT THE ATLAS EXPERIMENT OF THE LARGE HADRON COLLIDER

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Kurzdarstellung

Der Large Hadron Collider (LHC) am europäischen Kernforschungszentrum (CERN) nahe Genf (Schweiz) wurde im Jahr 2010 erfolgreich in Betrieb genommen und präparierte Proton-Proton-Kollisionen bei einer Schwerpunktsenergie von $\sqrt{s} = 7\text{ TeV}$. Daten des LHC sollen die Beobachtung des Higgs-Boson, dem letzten unbekannten Baustein des Standardmodells der Teilchenphysik (SM), ermöglichen. Endzustände mit zwei Myonen und Jets, die von Bottom-Partonen initiiert wurden, stellen einen irreduziblen Untergrund für Suchen nach dem Higgsboson innerhalb oder außerhalb des SM dar. Zudem erlauben diese Endzustände weitreichende Tests für Vorhersagen der perturbativen Quantenchromodynamik (pQCD). Die hier vorgelegte Arbeit führt eine Messung des Wechselwirkungsquerschnittes $\sigma_{\text{incl}}(Z^0 + b)$ von Ereignissen mit einem Myonpaar nahe der Masse des Z^0 -Boson und mindestens einem rekonstruierten Jet, der von einem Bottom-Parton hervorgerufen wurde. Des weiteren wird das Verhältnis $\mathcal{R}$ der letztgenannten Observable und des Wechselwirkungsquerschnittes von Ereignissen mit einem Myonpaar und mindestens einem rekonstruierten Jet beliebigen Ursprungs durchgeführt. Dabei auftretende systematische Unsicherheiten und Akzeptanzkorrekturen wurden studiert und ein Vergleich mit aktuellen Theorievorhersagen vorgenommen. Der totale inklusive Wechselwirkungsquerschnitt $\sigma(\mu^+\mu^- + b)$ konnte zu $(4.15_{-0.89}^{+0.97}(\text{stat.})_{-0.53}^{+0.45}(\text{syst.}))\text{ pb}$ aus 36 pb^{-1} Daten bestimmt werden, was im Einklang mit pQCD-Rechnungen auf nächstführender Ordnung in der starken Kopplung α_s steht. Vergleiche mit Vorhersagen auf führender Ordnung zeigten Spannungen mit der präsentierten Messung. Das Verhältnis $\mathcal{R} = \frac{\sigma(\mu^+\mu^- + b)}{\sigma(\mu^+\mu^- + \text{jets})}$ wurde auf $(4.6_{-1.2}^{+1.4}(\text{stat.}) \pm 0.5(\text{syst.}))\%$ aus dem gleichen Datensatz bestimmt, was innerhalb präsentierter Unsicherheiten mit Vorhersagen auf nächstführender und führender Ordnung von α_s überein stimmt.

Abstract

In 2010, the Large Hadron Collider (LHC) at the European Organisation for Nuclear Research (CERN) near Geneva (Switzerland) came into full operation providing proton-proton collisions at a centre-of-mass energy of $\sqrt{s} = 7\text{ TeV}$. LHC data may allow the observation of the Higgs boson, the last unknown building block of the standard model of particle physics (SM). Di-muon final states containing heavy flavour jets pose an irreducible background for searches of the Higgs boson as predicted the SM or theories beyond. They also provide a unique testbed for tests of perturbative Quantum Chromo-Dynamics (pQCD). This thesis provides a measurement of the cross section of events with one di-muon pair with an invariant mass in the Z^0 mass region and at least one heavy flavour jet. Studies on acceptance and systematic effects of the experimental setup are presented as well as a comparison to theoretical predictions. The total inclusive cross section of $Z^0 + b$ events was observed as $\sigma(\mu^+\mu^- + b + X) = (4.15_{-0.89}^{+0.97}(\text{stat.})_{-0.53}^{+0.45}(\text{syst.}))\text{ pb}$ from the equivalent of 36 pb^{-1} of data. Agreement with pQCD predictions at next-to leading order (NLO) is found while tensions with leading order (LO) predictions are observed. Further, the cross-section ratio $\mathcal{R} = \frac{\sigma_{\text{incl}}(Z^0 + b)}{\sigma_{\text{incl}}(Z^0 + \text{jets})}$ with events containing two muons and at least one jet of any origin was measured to $\mathcal{R} = 4.6_{-1.2}^{+1.4}(\text{stat.}) \pm 0.5(\text{syst.})\%$. This is found to agree with NLO and LO calculations within known uncertainties.

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Chapter 1

Introduction

With the stable operation of the (LHC) in 2010, a new era of particle physics was introduced. Proton-proton collisions at unprecedented energies were provided at ever increasing world record rates of data delivery. This offers the opportunity to test again what is known as the Standard Model of Particle Physics and to search for unknown particles that may account for answers the standard model of particle physics (SM) is unable to provide on the nature of particle interactions. Since the LHC prepares hadron-hadron collisions at a centre-of-mass energy¹ of $\sqrt{s} = 7\text{ TeV}$, perturbative QCD (pQCD) builds the foundation for predicting the frequency of final states of any kind observed by one of the multi-purpose detectors (ATLAS and CMS) installed around the interaction points where the two proton beams are brought to collision. As will be discussed, a thorough understanding of pQCD predictions is essential to any searches for new elementary particles or related phenomena.

The search for the Higgs boson as predicted by the SM or theoretical extensions thereof is of central interest to the particle physics community. At the current state of knowledge, it is assumed to favour interactions with particles of high mass (such as the bottom quark) which has implication on its expected production and decay at the LHC. One irreducible background to Higgs searches in the low Higgs mass regime ($m_H = (114 - 160)\text{ GeV}$) are final states containing two muons and at least one bottom parton induced jet. It is thus mandatory to retain a detailed understanding of this final state to reliably search for new signals with similar signatures. Aside from this motivation, the origin of final states caused by bottom parton final states is yet theoretically unclear. Connected to this, the question if bottom partons are contained inside the proton remains experimentally unanswered.

The presented thesis discusses the current state of the art of available theoretical predictions. In order to provide experimental means to constrain or validate predictions, the measurement of the absolute cross section of di-muon events with an invariant mass in proximity to the mass of the Z^0 boson and at least one bottom parton induced jet is motivated ($Z^0 + b$ final states). Since this observable is expected to expose large uncertainties, an additional measurement of the ratio $\mathcal{R} = \frac{\sigma_{\text{incl}}(Z^0 + b)}{\sigma_{\text{incl}}(Z^0 + \text{jets})}$ of di-muon final states with at least one bottom parton induced jet and at least a jet of any origin.

This document starts with a discussion of the SM (chapter 2), followed by pQCD and concepts involved for predicting $Z^0 + b$ final states that discuss the motivation for the aforementioned measurement in detail including the involved theoretical uncertainties (chapter 3). Next, an overview

¹Through this study, natural units are used setting $c = \hbar = 1$

over the design and operation of the LHC is given followed by an introduction of the ATLAS experiment and its data taking (chapter 4). Subsequently, the dataset and simulated pseudo-data is reported (chapter 5) after which the selections applied to the data is described and discussed (chapter 6). The obtained event sample is made subject to a fit procedure used to estimate the observed number of events containing bottom flavour initiated jets (chapter 7) and the measurement with statistical uncertainties is quoted. Then, a thorough study of the involved sources of systematic uncertainty is conducted and their extend is evaluated (chapter 8). To conclude, the obtained measurement is compared with theoretical predictions and a discussion thereof provided (chapter 9).

Chapter 2

The Standard Model Of Particle Physics

The Standard Model (SM) of particle physics is the widely accepted and intensively tested theoretical framework to describe proton-proton collisions at high energies on the TeV scale. This chapter outlines its core features that build the foundation of modern understanding of nature including the central subjects of this thesis, the Z^0 boson [1, 2] and bottom quarks [3].

The development of the SM as a quantum field theory started with the unified description of electro-weak interactions by S. Glashow [4] in 1961 and lead to the subsequent implementation of spontaneous symmetry breaking [5, 6]. Today, it is known as the theoretical framework able to comprehensively describe electro-magnetic, weak and strong interactions on quantum scales. Its formulation postulates fundamental particles that have been observed experimentally and allow the interpretation or prediction of many natural phenomena. Its current form however still misses answers to many fundamental questions which shall be touched at the end of this chapter. Generally speaking, the content of the next chapters is the focus of many excellent text books whom shall be referred to here for relevant details and derivations [7–10].

2.1 Building Blocks

	leptons		quarks	
	name	mass	name	mass
1	electron-neutrino (ν_e)	$< 2\text{eV}$	up (u)	2.5MeV
	electron (e)	511keV	down (d)	5MeV
2	muon-neutrino (ν_μ)	$< 2\text{eV}$	charm (c)	1.3GeV
	muon (μ)	105.6MeV	strange (s)	101MeV
3	tau-neutrino (ν_τ)	$< 2\text{eV}$	top (t)	172GeV
	tau (τ)	1.78GeV	bottom (b)	4.2GeV

Table 2.1: Fermion particle content of the SM. For the purpose of illustration, particle masses [11] are rounded and attributed to flavour eigenstates.

The particles defined by the SM can be categorised following a hierarchy of quantum numbers. At first, a separation according to their spin S can be made. Half-integer spin particles (fermions) build up matter as we know it. Integer spin particles (bosons) mediate the gauge interaction between fermions. Due to their masses, fermions are divided into light (leptons) and heavy

(hadrons) types. The latter are found to be non-fundamental and made from a quark-anti-quark state (mesons) or three quark bound states (baryons) [12, 13]. All fermions¹ (leptons and quarks) are categorised into three generations (or flavours) according to their mass as listed in table 2.0.

	mass /GeV	charge /e	symmetry
photon γ	0	0	$U(1)_Y \otimes SU(2)_L$
Z^0	91.188	0	$U(1)_Y \otimes SU(2)_L$
$W^\pm$	80.4	± 1	$U(1)_Y \otimes SU(2)_L$
gluon g	0	0	$SU(3)_C$

Table 2.2: Gauge bosons of the SM. Particle masses are taken from [11] and rounded for illustration.

The SM is a quantum field theory based on the $U(1)_Y \otimes SU(2)_L \otimes SU(3)_C$ symmetry group under which it exposes local gauge invariance. Each symmetry represents an interaction whose associated gauge boson mediates it (see table 2.1). In other words, fermions can only interact through boson exchange if they adhere a common symmetry group and hold suitable quantum numbers as illustrated in the appendix' table A.0. For electro-magnetism ($U(1)_Q$) this quantum number is the electro-magnetic charge Q . Weak interactions ($SU(2)_L$) are described by means of the weak isospin $\vec{I}$ and strong interactions ($SU(3)_C$) by the colour charge.

2.2 Theoretical Formulation

The SM combines quantum mechanics with the theory of special relativity to formulate nature as a quantum field theory based on the principle of gauge invariance. It is described by a Lagrangian density, $\mathcal{L}_{SM}$, which is Lorentz invariant, containing terms of freely propagating as well as interacting fields:

$$\mathcal{L}_{SM} = \mathcal{L}_{EW} + \mathcal{L}_{QCD} + \mathcal{L}_{Higgs} + \mathcal{L}_{Yukawa}. \quad (2.1)$$

Equation 2.1 contains the free fermion and gauge bosons as well as fermion-boson and boson-boson interactions within $\mathcal{L}_{EW}$ for the $U(1)_Y \otimes SU(2)_L$ symmetry and the $SU(3)_C$ symmetry within $\mathcal{L}_{QCD}$. The Higgs and Yukawa terms, $\mathcal{L}_{Higgs}$ and $\mathcal{L}_{Yukawa}$, contain the mechanism to generate non-zero gauge boson and fermion masses while satisfying the local gauge invariance. In the following, the electro-weak interaction and the generation of masses is discussed briefly.

2.2.1 Electro-weak Interactions

The Glashow-Weinberg-Salam model [14] which predicts the existence of Z^0 bosons unifies the weak interaction and relativistic electro-magnetism. The $SU(2)_L$ symmetry of quantum fields can be described by projection operators P_L, P_R which retrieve the left-handed and right-handed components from fermion fields Ψ

$$\begin{aligned} L &= P_L \Psi, \\ R &= P_R \Psi. \end{aligned} \quad (2.2)$$

¹In this study, fermion nomenclature will be used in place of anti-fermions as well, e.g. "electron" refers to electrons or positrons, if not stated otherwise.

These projections satisfy $P_R \cdot P_L = P_L \cdot P_R = 0$, $P_R + P_L = 1$ and $P_L^2 = P_L, P_R^2 = P_R$. Left-handed fermions transform as $SU(2)_L$ doublets and are attributed weak-isospin $I_3 = \pm \frac{1}{2}$. Right-handed fermions transform as $SU(2)_L$ singlets, i.e. have $I_3 = 0$. This preference for left-handed interactions and the related P violations in beta decays has been experimentally known [15]. If the weak-isospin is considered as the charge of weak interactions analogous to electro-magnetism, left-handed fermions are positively or negatively charged, whereas right-handed ones are neutral. Like the photon in electro-magnetism, weak gauge bosons only interact with weakly charged fermions, i.e. left-handed ones.

$$\mathcal{L}_{EW} = i\bar{L}\gamma^\mu D_\mu L + i\bar{R}\gamma^\mu D_\mu R - \frac{B_{\mu\nu}B^{\mu\nu}}{4} - \frac{W_{\mu\nu}^i W_i^{\mu\nu}}{4} \quad (2.3)$$

Equation 2.3 denotes the electro-weak Lagrangian using Einstein's sum convention and the $U(1)_Y \otimes SU(2)_L$ covariant derivative D defined in

$$D_\mu = \partial_\mu + ig_1 \frac{Y}{2} B_\mu + ig_2 \tau_i W_\mu^i. \quad (2.4)$$

B_μ denotes the $U(1)_Y$ gauge field with coupling constant g_1 and symmetry group generator Y . $W_\mu^i (i = 1, 2, 3)$ represents the three weak gauge fields with coupling constant g_2 and associated three generators τ_i of the $SU(2)_L$ symmetry group. The definition of boson fields $B_{\mu\nu}$ and $W_{\mu\nu}^i$ follows from the compliance of the Lagrangian to local gauge invariance of the above stated symmetry groups. Gauge fields in equation 2.3 couple to left-handed fermions and to themselves (up to quartic self-couplings are allowed). Two of the mentioned $SU(2)_L$ gauge fields can be combined linearly through

$$W_\mu^\pm = \frac{1}{\sqrt{2}}(W_\mu^1 \mp iW_\mu^2) \quad (2.5)$$

to give the charged field mass eigenstates whose quanta were experimentally observed as $W^\pm$ bosons. Through the $SU(2)_L \otimes U(1)_Y$ symmetry breaking, the remaining neutral gauge boson of $SU(2)_L$ mixes with the $U(1)_Y$ gauge field as in

$$\begin{aligned} A_\mu &= B_\mu \cos \theta_W + W_\mu^3 \sin \theta_W, \\ Z_\mu &= -B_\mu \sin \theta_W + W_\mu^3 \cos \theta_W, \end{aligned} \quad (2.6)$$

where the Weinberg angle θ_W quantifies the degree of admixture. The quanta of A_μ correspond to the photon. The choice of $g_1 \sin \theta_W = g_2 \cos \theta_W = e$ satisfies this with e being the unit charge of the electron. The quanta of Z_μ are observed experimentally through the Z^0 boson. The hyper-charge Y of $U(1)_Y$ and the weak isospin are then related to the electric charge by $Q = \frac{1}{2}Y + I_3$, known as the Gell-Mann-Nishijima relation.

2.2.2 Particle Masses

A priori, the theoretical framework outlined above does not contain terms like $m^2 \bar{\Psi} \Psi$ that associate masses to all particles of the electro-weak standard model. This would break local gauge invariance of the $SU(2)_L$ symmetry due to left- and right-handed particles transforming differently under it. Consequently, explicit mass terms cannot be included in $\mathcal{L}_{EW}$. In a minimal scenario,

mass terms can be accommodated for by the introduction of a scalar boson field, a complex $SU(2)_L$ doublet, with non-vanishing vacuum expectation value as

$$\Phi = \begin{pmatrix} \phi^+ \\ \phi^0 \end{pmatrix}, \quad (2.7)$$

with the charge operator giving $Q(\phi^+) = +1$ and $Q(\phi^0) = 0$. The associated terms in the Lagrangian density have the form

$$\mathcal{L}_{Higgs} = |D_\mu \Phi|^2 - V(\Phi). \quad (2.8)$$

Equation 2.8 contains a kinematic term $|D_\mu \Phi|^2$ that denotes the interactions of Φ with other gauge fields. A potential $V(\Phi)$ is also given that regulates the total energy yield of $\mathcal{L}_{Higgs}$. It depends on two parameters μ and λ

$$V(\Phi) = -\mu^2 \Phi^\dagger \Phi + \lambda (\Phi^\dagger \Phi)^2. \quad (2.9)$$

The vacuum expectation value $\langle 0|\Phi|0 \rangle$ (vev) denotes states of Φ with minimal total energy being equivalent to the minimum of $V(\Phi)$ of equation 2.9. In order for the vev to remain non-zero, $\lambda > 0$ is set. Equation 2.8 is symmetric under $U(1)_Y \otimes SU(2)_L$ making it compliant to the electro-weak SM. Solving $\frac{dV(\Phi)}{d|\Phi|} = 0$ to obtain the minima of the Higgs potential gives

$$|\Phi_{min}| = \begin{cases} 0 & \text{if } \mu^2 \leq 0 \\ \sqrt{\frac{\mu^2}{2\lambda}} = \frac{v}{\sqrt{2}} & \text{if } \mu^2 > 0 \end{cases}. \quad (2.10)$$

For $\mu^2 \leq 0$, the vacuum expectation value of Φ is 0 which is invariant under $U(1)_Y \otimes SU(2)_L$. This symmetry is *spontaneously broken* [16–20] for $\mu^2 > 0$, where a non-zero vacuum expectation value $v = \mu/\sqrt{\lambda}$ is observed. For no positively charged Higgs has been observed yet or a vev for a charged state is assumed to be unphysical, Φ is

$$\Phi = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v \end{pmatrix}. \quad (2.11)$$

A thorough study [21] of equation 2.10 and 2.8 reveals a massive weak gauge boson with mass $m_H = v\sqrt{2\lambda}$ and cubic as well as quartic self-couplings. This particle was named Higgs particle and has couplings to fermions and gauge bosons of the electro-weak SM. The latter acquire their masses through the Higgs field, e.g. by

$$\begin{aligned} m_W &= \frac{1}{2}vg_2 \\ m_Z &= \frac{m_W}{\cos \theta_W} \\ m_\gamma &= 0 \end{aligned} \quad (2.12)$$

from $\mathcal{L}_{Higgs}$. Fermion masses related to the Higgs field must be inserted (manually) to $\mathcal{L}_{SM}$ by additional Yukawa terms, e.g. for the electron $m_e = \frac{g_e v}{\sqrt{2}}$ with the Higgs coupling to the electron g_e , that were already noted in equation 2.1 by $\mathcal{L}_{Yukawa}$. It must be stressed that the proportionality of the Higgs coupling to fermions with respective fermion masses is a general feature of the Higgs field.

2.3 Open Questions and Beyond

The formulation of the SM allowed for an unprecedented number of predictions in particle physics that were successfully confirmed by experiments since the 1970s. The only predicted particle that was not observed so far is the Higgs boson. The search for it was the pivotal motivation to construct the LHC and the experiments it hosts.

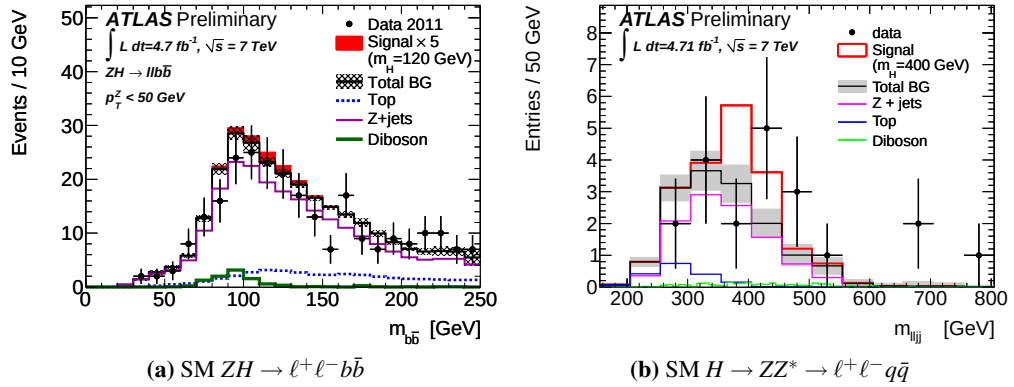


Figure 2.1: Invariant $b\bar{b}$ mass distribution (a) of SM Higgs boson search [22] associated production with a Z^0 $ZH \rightarrow \ell^+\ell^-b\bar{b}$ (Higgsstrahlung) with the Higgs particle decaying into bottom quark pairs. Four-particle invariant $\ell^+\ell^-q\bar{q}$ mass distribution of ATLAS search [23] for SM $H \rightarrow ZZ^* \rightarrow \ell^+\ell^-q\bar{q}$ final states depicted in (b). Both distributions have been plotted with different Higgs mass hypothesis. Where needed, the Higgs signal cross section has been scaled for illustration purposes.

Figure 2.1 shows two examples for SM Higgs searches that are conducted in invariant mass distributions of the Higgs decay products, i.e. of the reconstructed $b\bar{b}$ initiated jet pair (figure 2.0a) or the reconstructed final state of two oppositely charged same-flavour leptons and two jets. Figure 2.1 illustrates the small size of a possible Higgs signal expected in these distributions implying the use of complex statistical methods. The contribution of $Z^0 + \text{jets}$ final states as the dominant source of background for both Higgs searches shown underlines how essential the theoretically sound and experimentally well established knowledge of this final state is. This is one motivation for conducting the analysis at hand.

Up to the time of writing (April 2012), the SM Higgs boson was not unambiguously observed by either of the four LHC experiments. Results from two are depicted in figure 2.1.

Figure 2.1 displays a statistical view on the exclusion of the SM Higgs boson given a mass hypothesis for a wide range of hypothetical Higgs mass values within $m_H = (110 - 600)$ GeV. Figure 2.1 is the result from SM Higgs searches in $H \rightarrow \gamma\gamma, H \rightarrow b\bar{b}, H \rightarrow W^\pm W^\mp$ and $H \rightarrow Z^0 Z^*$ Higgs final states. While both experiments have not reported a discovery, ATLAS and CMS results from the decay channels just named show an excess of events above the background-only expectation at $m_H \approx 125$ GeV. In the quoted references [24, 25], it is introduced by results of the $H \rightarrow \gamma\gamma$ analysis of both experiments independent of each other. Statistically, all observed results are compatible with the background-only hypothesis within 2.5σ . The current status of the search for the SM Higgs boson provides tighter exclusions limits than reported by other experiments [26, 27].

Despite of its virtues, there are many questions on the nature of particle physics and cosmology that the SM fails to answer. The most important ones shall be summoned in the following list

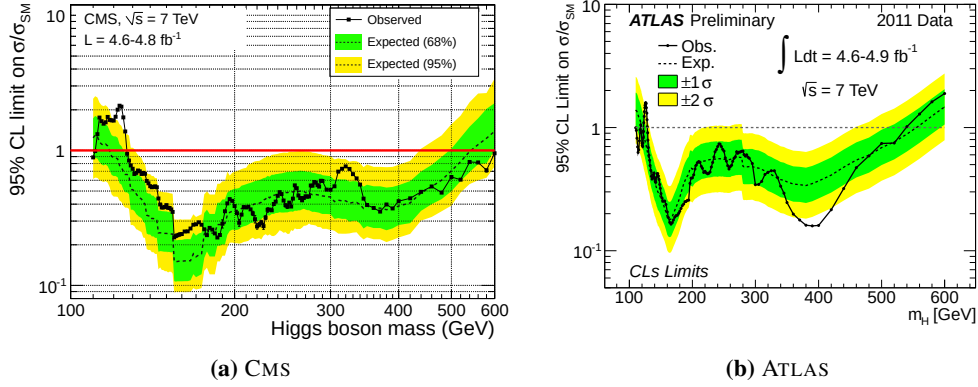


Figure 2.2: Observed excluded SM Higgs cross section at 95 % confidence level divided by the expected cross section of a SM Higgs boson in 2011 LHC data by CMS ((a) from [24]) and ATLAS ((b) from [25]). These figures combine the analyses of $H \rightarrow \gamma\gamma$, $H \rightarrow b\bar{b}$, $H \rightarrow W^+W^- \rightarrow \ell^+\nu_\ell\ell^-\bar{\nu}_\ell$, $H \rightarrow W^+W^- \rightarrow \ell\nu_\ell q\bar{q}$, $H \rightarrow Z^0Z^* \rightarrow \ell^+\ell^-\ell^+\ell^-$, $H \rightarrow Z^0Z^* \rightarrow \ell^+\ell^-\ell^+q\bar{q}$ and $H \rightarrow Z^0Z^* \rightarrow \ell^+\ell^-\nu_\ell\bar{\nu}_\ell$ of both LHC experiments.

briefly including theoretical suggestions to beyond the SM if available:

- Astrophysical observations indicate that 5 % of the universe are made of known SM particles. Interactions and particles within the SM cannot account for the origin of dark matter (or dark energy) assumed to populate 95 % of the universe. (Among others, the observation of constant rotation speed of spiral galaxies at larger radii from the centre indicates the presence of a substance in addition to the visible mass. Currently, the lightest super-symmetric particle forms a plausible candidate for this. Super-symmetry has however not been experimentally observed yet.)
- Why does the definition of SM particle masses fail at the Planck scale $m_{Planck} \approx 10^{19} \text{ GeV}$? (This question known as the *hierarchy problem* is connected to the fact, that contributions from Higgs self-interactions to the observed Higgs mass reach the order of m_{Planck}^2 if the Planck scale is reached, but the Higgs mass itself is assumed to be a constant parameter independent of scale. This problem is addressed by theoretical attempts to bridge the gap from weak energy scales m_W to the Planck scale 10^{19} GeV , e.g. Supersymmetry, Randall-Sundrum models and String Theory.)
- Why are particles categorised in fermions or bosons? (An undetected additional symmetry is assumed responsible for this named R-parity predicted by super-symmetric theories.)
- Why are there exactly three generations? (The notion of a fourth generation is suggested by Techni-colour theories that assume the Higgs boson to be non-elementary and constructed from Techni-colour fermions.)
- Why is the range of SM fermion masses so large stretching over eleven orders of magnitude from neutrino to top quark (table 2.0)? (Answers are based on the assumption that the SM exposes the low energy approximation of a grand unified theory which still has to be formulated.)
- How is gravitation linked to the interactions described by the SM?

The search for answers to them involves the identification of very rare processes given overwhelming background contributions (figure 2.0a). $Z^0 + \text{jets}$ and $Z^0 + b$ final states represent one of these contributions. It is thus of utmost importance that their magnitude and quality is precisely known. If this is not the case, any potential discovery will yet again be subject to the far future.

2.4 Quantum Chromo-Dynamics

Quantum chromo-dynamics (QCD) describes the strong interaction of partons. It contains a $SU(3)_C$ colour symmetry and is mediated by gauge bosons (gluons) between the strongly interacting fermionic constituents of matter (quarks). Quarks and gluons are referred to as partons for historical reasons [12, 13]. The QCD Lagrangian

$$\mathcal{L}_{QCD} = i\bar{q}_f \gamma^\mu D_\mu q_f - \frac{1}{4} G_{\mu\nu}^i G_i^{\mu\nu} \quad (2.13)$$

provides interactions of quark fields q of flavour f taking the form of colour triplets. The covariant derivative is given by

$$\mathcal{D}_\mu = \partial_\mu - \frac{i}{2} g_3 \lambda_i G_\mu^i. \quad (2.14)$$

The eight generators of $SU(3)_C$ are contained in the $\lambda_i (i = 1, \dots, 8)$. The term G_μ^i represents the affiliated gauge fields (gluons) with coupling constant g_3 . Commutation relations between the $SU(3)_C$ generators expose self-couplings of gluons with three and four gauge boson vertices occur. Quarks carry colour charge and gluons anti-colour as well. In QCD, $SU(3)_C$ symmetry is not broken and hence gluons are massless.

2.4.1 Renormalisation and the Strong Coupling Constant α_s

To relate theory (Lagrangians) and the experiment, the cross section $\sigma_{i \rightarrow f}$ is defined as the probability of an interaction of initial state i and final state f does occur. For the interaction of two incoming going to N outgoing particles it is defined as

$$\sigma_{2 \rightarrow N} = \int |\mathcal{M}|^2 d\phi \quad (2.15)$$

with the squared scattering matrix element $\mathcal{M}$ integrated over the available phase space $d\phi$ of initial and final state kinematics. The matrix element is obtained from first principles, e.g. the QCD Lagrangian, using perturbation theory. It is expressed as a perturbative series expansion in the coupling constant of the interaction. This method is widely referred to a perturbative QCD (pQCD).

Following Feynman [28], each element of the perturbative expansion can be described by a set of graphical interaction diagrams, *Feynman diagrams*, using translation rules, *Feynman rules*, which are derived from the above mentioned Lagrangian of equation 2.13. Calculations at lowest order of the coupling constant give leading order (LO) results. With more than lowest order, next-to-leading order (NLO) results are accessible. Of course, the perturbative expansions is an approximation to what is realised in nature where infinite orders in the coupling constants are realised.

Considering the evaluation of $\sigma(qg \rightarrow Z^0 + q)$ processes as illustrated by figure 2.2a, the cross section can be decomposed perturbatively into contributions from amplitudes A_i as in

$$\sigma = \alpha_{EW} \sum_{i=0}^{\infty} \alpha_s^i A_i. \quad (2.16)$$

The $i = 0$ term corresponds to LO calculations, $i = 1$ to NLO and every term $i > 1$ to the N^iLO level. Equation 2.15 notes the square of the matrix element which contain real and virtual terms

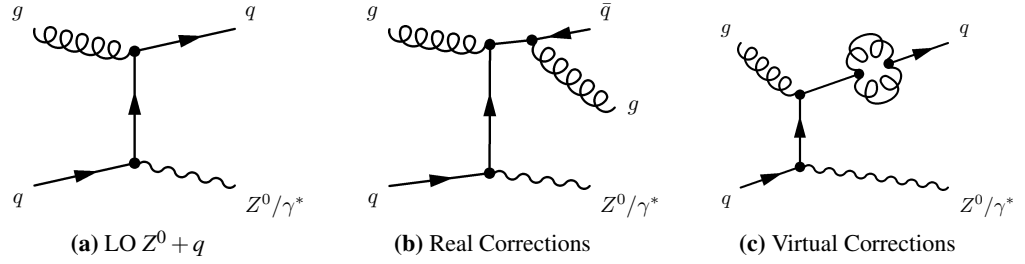


Figure 2.3: Examples of NLO real (b) and virtual corrections (c) to LO $qg \rightarrow Z^0 + q$ amplitudes (a).

that may expose a complex form. In Feynman's graphical representation, additional real contributions imply additional particles in the initial or final state (figure 2.2b), whereas virtual corrections can be described by loop diagrams of fermions or bosons (figure 2.2c). The particles' momenta contained in these loops are not observable - only the integral over all possible momenta of participating particles is. This leads to divergent terms in σ making this probability infinite which is unphysical.

The method of *Renormalisation* [29] resolves this divergence by redefining masses or coupling constants as the combination of a bare portion (appearing in $\mathcal{L}_{QCD}$) and the divergent terms. In renormalisable theories, e.g. the SM, the unobservable value of the bare parameter can be set such that divergences cancel to all orders of the perturbative expansion. Subsequently, the value of renormalised parameters depends on the energy scale (renormalisation scale μ_R) which defines the scale at which higher-order terms are absorbed by the redefinition of quantities of the Lagrangian. By definition, renormalised coupling constants obey renormalisation group equations at an interaction scale Q^2 [30]

$$Q^2 \frac{\partial \alpha}{\partial Q^2} = \beta(\alpha). \quad (2.17)$$

The β function denotes a power-series in α reading $\beta(\alpha)^{LO} = -\beta_0 \alpha^2$ at LO in perturbation theory. Solving equation 2.17 at LO gives

$$\alpha(Q^2) = \frac{\alpha(\mu^2)}{1 + \beta_0 \alpha(\mu^2) \log \frac{Q^2}{\mu^2}}. \quad (2.18)$$

Equation 2.18 generally concerns coupling constants in renormalisable theories. β_0 depends on the number of particles that enter virtual corrections. In QCD,

$$\beta_0^{QCD} = \frac{11C_A - 2n_f}{12\pi} \quad (2.19)$$

with a constant factor from gluon virtual corrections which is $C_A = 3$ required by the structure of $SU(3)$. The term $2n_f$ originates from fermion loops depending on the number of colour-charged fermions n_f (or the number of active flavours) with masses smaller than the interaction scale Q^2 . In the SM, this number is $n_f \leq 6$ which makes $\beta_0^{QCD} \geq \frac{7}{4\pi} > 0$. Evaluating equation 2.18, the strong coupling constant α_s decreases asymptotically towards 0 with increasing Q^2 . In other words, the strong coupling vanishes at higher energy transfers during an interaction, making quarks free particles with respect to QCD. This property was named *asymptotic freedom* [31, 32]. This can also be read from equation 2.17, where the right hand side is smaller than 0 already at LO.

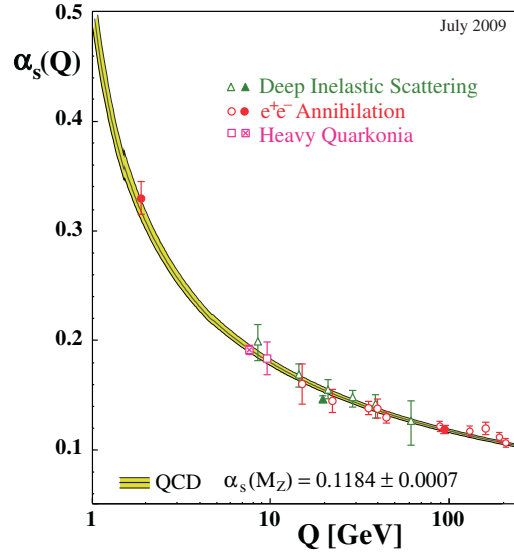


Figure 2.4: Summary of α_s measurements from ep (Deep Inelastic Scattering), e^+e^- and heavy quark-anti-quark experiments as a function of the energy scale Q from [33]. Open symbols indicate (resummed) NLO, and filled symbols NNLO QCD calculations used in the respective analysis for every measurement relies on a distinct theoretical model to fit the data with. The curves represent the QCD predictions for the combined world average value of $\alpha_s(m_Z)$.

On the other end of the energy scale, the strong coupling constant diverges towards infinity below the perturbation scale $\Lambda_{QCD} = 200\text{MeV}$. The dependence of α_s on the energy scale is referred to as running coupling constant (figure 2.3). The current world average at $Q = m_Z$ of α_s is $\alpha_s(m_Z) = 0.1189 \pm 0.0010$ [33].

Phenomena at $Q^2 < 1\text{ GeV}$ cannot be treated perturbatively anymore, e.g. the structure of hadrons. This effect of the coupling increasing to extremely high levels in soft energy regimes is generally interpreted as *confinement* of particles subject to QCD. Only phenomenological models or lattice QCD calculations [34] are able to make predictions in this regime.

Chapter 3

QCD Phenomenology and Monte Carlo Simulation

The following section will outline additional key features of QCD relevant for predictions of hadron-hadron collision events as encountered at modern particle colliders, e.g. LHC. Details that cannot be addressed within this brief and pragmatic overview can be found in [35–37].

3.1 Perturbative QCD

In practice, the evaluation of equation 2.16 is often impossible to all orders in α_s . Instead, the dominant contributions to σ are identified and taken into account, whereas others are ignored. However, this is not straightforward due to the relative importance of individual amplitudes depending on the process to study. Thus this section will review attempts to conduct calculations at fixed order, attempts to compute observables in the soft QCD limit to all orders in α_s and methods on how to combine the two.

3.1.1 Fixed-Order Calculations

The fundamental assumption of fixed-order calculations provides that the relative ordering of A_i terms in equation 2.16 follows from the fact that contributions of $\alpha_s^i A_i$ give smaller contributions than $\alpha_s^{i-1} A_{i-1}$ if $\alpha_s < 1$. In other words, it is sufficient to calculate 2.16 to NLO because higher orders will contribute at the level of $\alpha_s^{i>1}$ which is a small number. In this approach, the number of terms taken into account is limited by the availability of human ingenuity or computational resources.

In QCD, real parton emissions show divergences in the limit of two partons being collinear or having low transverse momentum with respect to each other. These divergences cancel in fixed-order calculations due to associated negative virtual terms of the same order [38]. Given a particle interaction at scale Q^2 (e.g. m_Z for $Z^0 + \text{jets}$) and two particles with relative four-momentum q^2 of one parton to another, the amplitude coefficients A_i assume the form

$$A_i = \sum_{j=0}^{2i} B_{ij} L^j \quad (3.1)$$

with L^j containing $\log \frac{Q^2}{q^2}$ terms that enhance A_i for $q^2 \rightarrow 0$. In this limit, higher order terms are not smaller than lower order terms as assumed due to these logarithms. So fixed-order calculations

are unable to describe the data at low q^2 , i.e. in the limit of soft/collinear emissions.

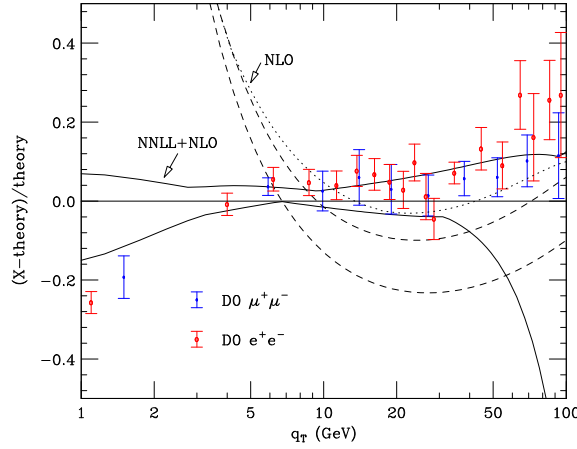


Figure 3.1: Relative difference of fixed-order NLO predictions ([39], dotted and black dashed which yields the theoretical uncertainties from scale variations) of $q\bar{q} \rightarrow Z^0/\gamma^* \rightarrow \ell^+\ell^-$ and DØ measurements of $q\bar{q} \rightarrow Z^0/\gamma^* \rightarrow e^+e^-$ ([40], red) and $q\bar{q} \rightarrow Z^0/\gamma^* \rightarrow \mu^+\mu^-$ ([41], blue) to the NNLL+NLO resummed predictions (horizontal line at $y = 0$) versus the transverse momentum of Z^0/γ^* noted q_T . The uncertainties from scale variations of NNLL+NLO calculation are depicted as well (bold solid lines).

Figure 3.0 shows a comparison of fixed order NLO predictions of $q\bar{q} \rightarrow Z^0/\gamma^* \rightarrow \ell^+\ell^-$ with measurements by the DØ collaboration in the electron and muon decay channel of a reconstructed Z^0/γ^* within $(70 < m_{\ell^+\ell^-} < 110)$ GeV. The fixed order prediction (NLO) fails to reproduce the data below $q_T < 6$ GeV in figure 3.0. To resolve this shortcoming, the perturbative expansion in α_s of equation 2.16 is reformulated to an expansion in the coupling constant and a logarithmic term ($\alpha_s \cdot L$). The nomenclature refers to $\alpha_s^i \cdot L^{2i}$ as *leading log* (LL) terms and $\alpha_s^i \cdot L^{2i-1}$ as *next-to leading log* (NLL). The structure of these logarithmic terms are found by analytical analysis of B_{ij} coefficients in equation 3.1. Figure 3.0 underlines that this theoretical assumption allows predictions that describe the data better at $q_T < 6$ GeV.

3.1.2 Parton Shower Calculations

Parton-shower (PS) methods provide an iterative method as an alternative to the analytical approach taken by resummation to include amplitude coefficients to all orders in α_s . Given the interaction of two initial state partons with n final state partons by a scattering matrix element (ME) calculation, the evaluation of $|\mathcal{M}|^2 = |\mathcal{M}_1 + \mathcal{M}_2 + \dots|^2$ of equation 2.15 from contributing ME $\mathcal{M}_1, \mathcal{M}_2, \dots$ yields interference terms. For example, these might expose one additional parton in the matrix element which is emitted from two different ME partons and hence described by two different contributions. In the soft/collinear limit, these interference terms vanish and the matrix element is approximated by $|\mathcal{M}|^2 = |\mathcal{M}_1|^2 + |\mathcal{M}_2|^2 + \dots$. Thus, every emission of an additional parton is distinct. The probabilities for this $1 \rightarrow 2$ splitting are described by the *Altarelli-Parisi* splitting functions [42] as well as the kinematics of the outgoing partons. These splitting functions depend on α_s and the renormalisation scale μ_R .

A PS is an algorithm for generating $1 \rightarrow 2$ parton emissions ordered by an evolution variable from a large starting value (*starting scale*) down to a small *cut-off scale*. Possible evolution parameters are

the virtuality of the incoming partons (Q^2 ordering), the relative transverse momentum of two partons (p_T ordering) or the angle between two partons (angular ordering). Iterating from the starting scale to the cut-off scale, the probability of an emission not to occur in a given segment is obtained from Sudakov form factors. The final decision per segment as well as the kinematic setup of the emitted partons (if any) is randomly drawn from a probability density function (PDF) according to the Sudakov factors aforementioned. The starting scale is typically a characteristic of the ME, e.g. $Q^2 = m_Z^2$ for $q\bar{q} \rightarrow Z^0/\gamma^* \rightarrow \ell^\pm \ell^\mp$ processes. The cut-off scale must be guaranteed to range in perturbative regimes in order to still obtain viable predictions. Values of $Q_{cut} = (1 - 2) \text{ GeV}$ are used from where the event is further evolved by non-perturbative hadronisation models.

One important difference between resummation and PS algorithms is the latter being less transparent. Due to the analytical approach of resummation, it is clear which terms are accounted for and which are not. Due to the parton shower evolution, information of this nature is not available. However, PS methods enable the prediction of exclusive or differential distributions which can be used to generate events by use of hadronisation models that interface with the PS output. Since this provides a tool to generate events with stable and observable particles that can be used as input to detector simulations (in contrast to final state partons from fixed-order calculations), PS methods have proven to be indispensable for particle physics.

The notion of providing predictions on hadron level allows for the automatic production of event-to-event records that include the four-momentum information and type of an ensemble of free, stable and observable particles. These can be used to obtain distributions of the predicted particles' properties. The data interface for this event record is standardised, [43, 44], and allows for coherent usage of the events by a variety of software packages. Naturally, the standardised event records just mentioned need not be restricted to store hadron level predictions.

3.1.3 Merging soft and hard QCD Phenomenology

This discussion of fixed-order versus all-order predictions of pQCD suggests that a combination of the two may provide a comprehensive tool to aid understanding pQCD at e.g. the LHC. Considering $q\bar{q} \rightarrow Z^0/\gamma^* \rightarrow \ell^+ \ell^-$, fixed-order calculations excel at high $p_t^{Z^0}$ and resummation does at low $p_t^{Z^0}$ as well as the PS approach [45]. Combining the two is not straight-forward due to the transition region in between with overlapping contributions from one and the other referred to as *double counting*.

For the analytical approach taken by resummation, double counting is overcome by subtracting terms of equal order in α_s from e.g. NLO and NLL calculations. For this, the resummed calculation is expanded in α_s again and compared to the fixed-order perturbation series.

Since the distinct information which PS emission contributes what at a given order in α_s are concealed in PS calculations, this procedure cannot be rigorously applied for combining fixed-order MEs and PS evolution. Of course, the combination for e.g. $q\bar{q} \rightarrow Z^0/\gamma^* \rightarrow \ell^\pm \ell^\mp$ is trivial for no double counting between the hard electro-weak process and PS may occur. As soon as additional partons are emitted from the ME and more QCD vertices arise, the removal of double counting is a complicated issue.

Generally, there are two approaches to translate between the PS and ME “language”. The subtraction term technique applied by the MC@NLO[46] and POWHEG[47] algorithms identifies the ME NLO terms that are accounted for by the PS and subtracts them a posteriori [46, 47]. These terms depend on the PS algorithm and the process of interest. However, for $q\bar{q} \rightarrow Z^0/\gamma^* \rightarrow \ell^\pm \ell^\mp$

it can lead to the situation that the Z^0/γ^* (leading jet) system is predicted at next-to leading (leading) order in α_s , but the sub-leading partons are generated by the PS in the soft/collinear limit only.

The alternative approach enables the process independent combination of ME and PS by transforming the ME output into an input state accepted by the PS. Such techniques do not include virtual loop corrections which have to be suppressed by requiring all partons to be well separated. The phase space volume that is unaccounted for by the ME is populated by the PS. Real contributions to the ME can be calculated up to order α_s^N with $N \leq 6$ as well as LL and some NLL terms to all orders of α_s . Prominent schemes to implement this ME+PS matching are the CKKW [48, 49] and MLM [50, 51] Merging. To remain brief, CKKW is based on a veto on single PS emissions during the evolution. Instead of altering the PS during evolution, the MLM approach rejects full events if the number of hard and well separated partons returned by the PS is unequal to the parton multiplicity of the ME. Further, CKKW uses the relative transverse momentum k_t to separate ME from PS phase space volumes, whereas MLM clusters objects by an $\Delta R = \sqrt{(\Delta\phi)^2 + (\Delta\eta)^2}$ criterion and cuts on their transverse momentum afterwards.

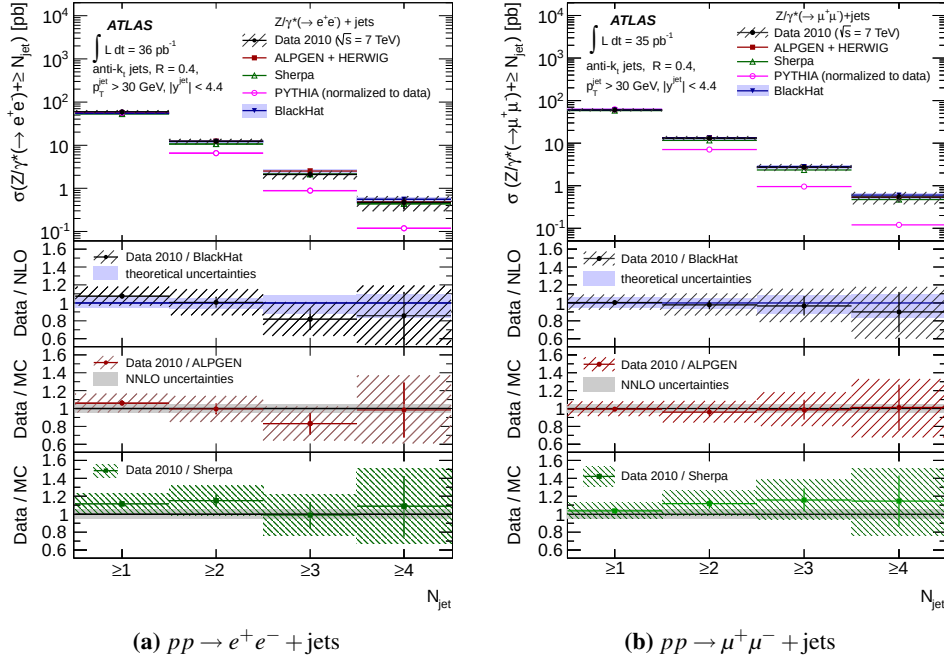


Figure 3.2: Measured differential cross section of $pp \rightarrow Z^0/\gamma^* + \text{jets}$ final states for $Z^0/\gamma^* \rightarrow e^+e^-$ (a) and $Z^0/\gamma^* \rightarrow \mu^+\mu^-$ (b) by ATLAS in bins of the inclusive jet multiplicity N_{jets} compared to LO (PYTHIA), LO+PS (ALPGEN+JIMMY, SHERPA) and NLO+PS (BLACKHAT) from [52].

Figure 3.1 illustrates how fixed-order calculations (e.g. predicted by PYTHIA) are inadequate to account for multi-parton final states. Good agreement with data is however found for predictions that merge fixed-order ME and PS.

3.2 Non-Perturbative QCD

pQCD provides methods to predict quark and gluon interactions at high momenta. Given QCD's property of confinement, the quanta of quark and gluon cannot be observed at low momentum. The elaborate techniques to predict e.g. $q\bar{q} \rightarrow Z^0/\gamma^* \rightarrow \ell^+\ell^-$ introduced in the last section cannot comprehensively describe proton-proton interactions. The *factorisation theorem* provides the notion that the high and low momentum regimes can be factorised. Given the observable σ for any process, the soft QCD contributions $\mathcal{N}$ can be separated from the hard scattering cross section $\hat{\sigma}$ as in

$$\sigma = \hat{\sigma} \otimes \mathcal{N}. \quad (3.2)$$

Moreover, the soft QCD contribution is independent from the hard partonic process. With this, $\mathcal{N}$ can be estimated experimentally and used in conjunction with pQCD for a wide range of processes. The boundary to define the transition between hard and soft QCD is referred to as factorisation scale μ_F . As for the renormalisation scale, the dependence of any result on μ_F is unphysical and would cancel in the exact solution for a given process. Thus, the more orders of α_s are included in a prediction, the lower the dependence on μ_F .

Generally, the transition from soft QCD (hadron regime) to hard QCD (parton level) is handled differently for initial (parton distribution functions) and final state (hadronisation). The following paragraphs give an overview on these methods and name additional aspects of soft QCD at hadron colliders that are required to obtain a comprehensive theoretical picture of proton-proton collisions.

3.2.1 Parton Distribution Functions

Parton Distribution Functions (PDF, [53]) represent the relationship between incoming hadrons and partons interacting in high energy scattering processes. They describe the probability of finding a parton p inside a hadron h carrying a fraction x ($0 < x < 1$) of the incoming hadron's longitudinal momentum. Since the focus of this analysis is on LHC data, the incoming hadron is assumed to be a proton here. The PDF $f_p^h(x, Q^2)$ depends on x and the energy at which the hadron is probed Q^2 . It is defined in the soft QCD limit below μ_F^2 , so equation 3.2 applies. If the probed energy scale Q^2 is however larger than μ_F^2 , the DGLAP [42, 54, 55] equations enable a transformation of the PDF to Q^2 . Thus, PDFs absorb effects at lower scales than μ_F^2 which cannot be handled by a pQCD treatment of the ME into a parametrised form, i.e. a parametrisation of the proton's partonic structure.

The observable cross section of e.g. $pp \rightarrow q\bar{q} \rightarrow Z^0/\gamma^* \rightarrow \ell^\pm \ell^\mp$ can hence be expressed as

$$\sigma = \sum_q \int dx_1 \int dx_2 [f_q^p(x_1, \mu_F^2) f_{\bar{q}}^p(x_2, \mu_F^2) + f_{\bar{q}}^p(x_1, \mu_F^2) f_q^p(x_2, \mu_F^2)] \hat{\sigma} \quad (3.3)$$

depending on respective PDFs and the partonic cross section $\hat{\sigma}$, containing the sum over all available quark flavours q and the integrals over the infinitesimal phase space volume for the extracted partons dx_1 and dx_2 . The available partonic squared centre-of-mass energy $\hat{s}$ of proton-proton interactions can thus be defined by

$$\hat{s} = x_1 x_2 s \quad (3.4)$$

as the product of the squared proton-proton centre-of-mass energy s and the momentum fractions x_1, x_2 as defined above. In practise, equation 3.3 is also used to determine PDFs for processes where $\hat{\sigma}$ is known well theoretically and σ was measured with high precision. Also, equation 3.3 allows to make hadron level predictions for σ from a known partonic process $\hat{\sigma}$.

Extracting PDF from data is performed by means of a global fit to a wide range of measurements. The PDF parametrisation versus x is not known and has to be extracted from data using constraints from theoretical arguments (and experience) [56, 57] or machine learning techniques [58]. However, both methods introduce dependencies on the perturbative order of $\hat{\sigma}$ as well as the numerical value of α_s . The bulk of data that enter PDF fits originates from $ep \rightarrow eX$ deep-inelastic scattering (DIS) experiments at the HERA collider. Multi-jet as well as vector boson asymmetry measurements performed at the Tevatron and many low energy fixed target experiments are taken into account.

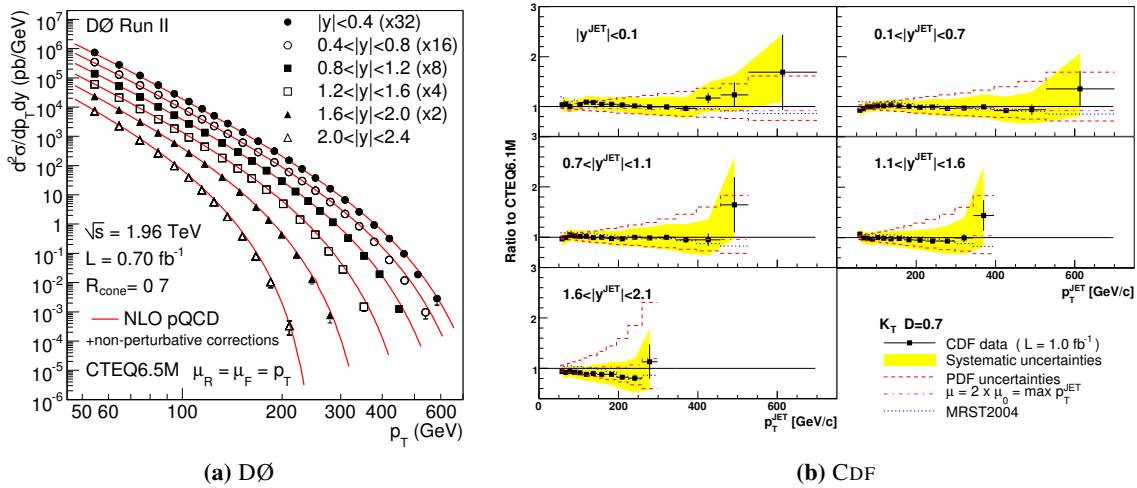


Figure 3.3: Double differential cross section of inclusive $p\bar{p} \rightarrow N \cdot \text{jets}$ ($N > 0$) final states measured by D0 (a) [59] and CDF (b) [60] versus jet transverse momentum in bins of jet rapidity y . The observed cross sections are compared with CTEQ6.5M (a) as well as CTEQ6.1M and MSTW2004 (b).

Figure 3.2 compares measured inclusive jet cross sections at the Tevatron with NLO predictions based on PDF functions that were obtained from DIS data by HERA experiments. The excellent match of predictions and observations for a large phase space volume is a strong indicator that equation 3.2 paraphrases a valid assumption and exposes a general concept independent of the scattering process of interest. PDFs are hence universal quantities.

The definition as PDFs originated from measurements of hadron structure functions in neutrino-nucleon scatterings [61, 62] and the hereby created quark-parton model. These measurements experimentally prove the proton to be made up of two u and one d quark if probed at low energy scales Q (valence quarks), i.e. the proton is made from three point-like parton objects if the dimension of the proton probe is “large” ($\Delta x \sim 1/Q$). If the scale is increased (i.e. the proton probe’s spatial extension is decreased), quarks of different flavours (sea quarks, [63]) and gluons are observed.

3.2.2 Hadronisation

To establish accurate predictions of stable, observable hadrons' occurrence, kinematics and type that are produced through partonic interactions, perturbative methods cannot be applied for the energy scale of the hadronisation process is of the size of Λ_{QCD} . Thus, phenomenological models have to be utilised. The simplest of which is *independent hadronisation*. It defines the probability to produce a hadron h from parton p by a function $f_p^h(z, k_T^2)$. This probability depends on the parton's momentum fraction z ($0 < z < 1$) the hadron receives as well as the hadron's relative momentum k_T with respect to p after its generation. The parameters of $f_p^h(z, k_T^2)$ have to be tuned from data by comparing it to hadron level predictions, e.g. $e^+e^- \rightarrow Z^0/\gamma^* \rightarrow \text{hadrons}$ based on calculations of $e^+e^- \rightarrow Z^0/\gamma^* \rightarrow q\bar{q}$. Electron-positron collisions offer a clean initial state that does not require hadron-to-parton transitions through the PDF formalism. However, independent hadronisation was found to yield imprecise predictions when confronted with $e^+e^- \rightarrow Z^0/\gamma^* \rightarrow q\bar{q}g$ processes (observed by the JADE experiment [64]). This is due to correlations between hadronisation from close-by quarks and gluons that independent hadronisation cannot account for by definition.

Further developments of hadronisation models employ the fact that hadrons are only produced as observable states if they form a colour singlet state. With this, they are not subject to QCD and propagate as free particles (referred to as *colour transparency*). Given a partonic event as predicted by ME+PS calculations, the *Lund string model* [65] assumes strings according to the colour field spanned by two quarks. Each string is hadronised on grounds of a hadronisation functions $f_p^h(z, k_T^2)$. Another suggested approach forces all gluons in the event to evolve and split until no gluons are left in the event. A cluster finding algorithm combines neighbouring pairs of quarks and fragments them into hadrons. This procedure is referred to as *cluster hadronisation* [66]. Both models were shown to reproduce e^+e^- data well [67].

In order to avoid dependencies on the ME calculation and to remain independent from the hard scattering process, the parametrisation of hadronisation models are extracted from data using predictions from ME+PS calculations. With this, the fragmentation model is dependent on the PS cut-off scale which is the factorisation scale that separates effects accounted for the PS and those described by the hadronisation (equation 3.2). Since hadronisation models require the incoming partons to be at μ_F , they cannot be applied to results from fixed order calculations that only yield partons at higher scales.

For the analysis at hand, the cluster hadronisation model as implemented in SHERPA and HERWIG was used for the simulated signal MC samples, see section 5.1.1. The background pseudo-datasets comprise cluserisation used within the PYTHIA and MC@NLO package. A significant impact of these choices on the final result is however not expected, since the measurement at hand lacks the precision for this.

3.2.3 Underlying Event

The term *underlying event* (not defined by a rigorous theoretical language) historically refers to the experimentally observable particle activity per hadron-hadron collision that is not accounted for by the experimentally defined hard scale $2 \rightarrow N$ process of interest. Thus, the precise limits of the underlying event are partly subject to arbitrariness. To disentangle possible contributions, the composition of hadron-hadron interactions as provided by LHC and Tevatron collider will be discussed in the following paragraphs.

The total cross section of a single hadron-hadron interaction σ^{total} given the squared centre-of-mass energy s of an interaction can be accounted for by:

$$\sigma^{tot}(pp \rightarrow X) = \sigma^{elas}(pp \rightarrow pp) + \underbrace{\sigma^{SD}(pp \rightarrow pX) + \sigma^{DD}(pp \rightarrow XX) + \sigma^{ND}(pp \rightarrow X)}_{\sigma^{inelas}(pp \rightarrow X)}. \quad (3.5)$$

For this, hadron-hadron interactions (using the example of proton-proton collisions) are categorised in an elastic part and an inelastic part. The elastic scattering is of no interest here since the scattering occurs at very low angles and the proton-proton final state escapes detection in the direction of the incoming particles. The inelastic scattering can be categorised into colour-exchange processes denoted by the non-diffractive term $\sigma^{ND}(pp \rightarrow X)$ (including the hard ME interaction) and colourless interactions described by the single-diffractive component $\sigma^{SD}(pp \rightarrow pX)$ (dissociation of one proton) and double-diffractive term $\sigma^{DD}(pp \rightarrow XX)$ (dissociation of two protons). The relative frequency of elastic and diffractive interactions is multiple orders of magnitude larger than the non-diffractive portion which is of interest. To give an indication, the cross section of inelastic proton-proton scattering was recently measured to be $\sigma^{inelas}(pp \rightarrow X) = 69.4 \pm 2.4(exp.) \pm 6.9(theo.)$ mb [68]. The elastic proton-proton scattering cross section was observed to be $\sigma^{elas}(pp \rightarrow pp) = 98.3 \pm 0.2(stat) \pm 2.8(syst)$ mb [69]. Both values are ten orders of magnitude larger than what is expected of $\sigma_{incl}(Z^0 + b)$.

Even if a non-diffractive interaction occurred, additional soft QCD process may still be initiated from the proton remnants in parallel to the hard $2 \rightarrow N$ partonic interaction. The latter phenomenon is referred to as *multiple parton interaction* (MPI). To model it [70], the incoming proton's PDFs are accessed corresponding to the colour and momentum that remains after the hard interaction. Then, secondary interactions are initiated by $2 \rightarrow 2$ QCD processes (assumed to have considerably larger cross sections than comparable electro-weak interactions) until the available momentum reaches a lower cut-off that prevents the $\sigma^{QCD}(2 \rightarrow 2)$ to diverge. As with hadronisation and PDF models, the inherent parameters for modelling the generation of secondary interactions have to be tuned with data.

Due to the experimental setup of hadron colliders (LHC and Tevatron) the collision of proton bunches rather than individual particles is conducted, see section 4.1. Thus, the possibility that multiple proton-proton interactions occur if two proton bunches are brought to collision is non-negligible (referred to as *pile-up*). The number of proton-proton interactions to occur in parallel (if any) depends on the beam conditions with which the high energetic experiment is prepared at the interaction point. Further details will be discussed in section 4.1.2. As implied by equation 3.5, the bulk of pile-up interactions are provided by elastic or diffractive proton-proton collisions since they have a very large cross section compared to $\sigma^{ND}(pp \rightarrow X)$.

Given the discussion above, the underlying event comprises contributions from MPI and pile-up among others. Through its non-perturbative setting and modelling, the underlying event contribution to hadron-hadron interactions must be tuned with data [71, 72]. For this analysis, the underlying event parameter settings contained in SHERPA (1.1.3 with CTEQ6.6, [73]) and ALPGEN [74] MC generators are used.

3.2.4 Event Generators

An event generator is a package of computer code that generates a list of initial state and final states particles including their type and Lorentz kinematics mimicking the expected abundance in high energy collision events prepared for particle physics experiments. These events are produced in such a way that their kinematic properties collected in histograms from the created event sample are identical to those predicted by the theoretical calculation of the particle interaction of interest. To achieve this, equation 2.15 is evaluated in an automated way using Monte Carlo techniques and events are generated by random draws from the involved phase space volume of available initial and final states with respect to the frequency distinct Feynman diagrams contribute. These Monte Carlo generators include routines to conduct the above mentioned integration for a variety of processes and the capability to generate the event record of particles and their properties introduced above. Available programs may produce event record including partons only (parton level generators) or including stable observable hadrons as well (hadron level generators). The following paragraphs will give an outline of software packages used to generate the pseudo-data used for this analysis.

MC@NLO

MC@NLO[46] is a Fortran based code which merges NLO ME predictions with a PS. As for ALPGEN, the HERWIG package is used for PS and JIMMY is used to add MPI to the event record provided by MC@NLO.

MCFM

MCFM[75] is a Fortran based software that provides parton-level events based on a fixed-order calculation at LO and NLO for a variety of processes. For $Z^0/\gamma^* + N \cdot \text{jets}$ final states, it provides final states at NLO with $N \leq 2$ and at LO with $N \leq 3$.

PYTHIA

The PYTHIA[76] software bundle is written in Fortran and includes a LO ME element generator on particle level as well as a p_t -ordered parton shower algorithm. For Z^0/γ^* final states, the first PS emission is reweighted to match LO $Z^0/\gamma^* + 1\text{jet}$ fixed order predictions. The hadronisation is based upon the Lund string model. The MPI model includes the MPI partons in the parton shower. PYTHIA has been rewritten to C++ partially [77].

ALPGEN

ALPGEN [74] is a Fortran written collection of software packages that provide an ensemble of matrix element generators. These may calculate LO ME with up to 6 additional jets besides the $2 \rightarrow 1$ or $2 \rightarrow 2$ processes. In order to produce ME+PS events, it has to be interfaced to dedicated codes (HERWIG+JIMMY, PYTHIA) for parton showering, MPI and hadronisation. The MLM merging scheme is used to avoid double counting and CKKW-style reweighting to smoothen the transition between ME and PS phase space.

HERWIG including JIMMY

HERWIG [78] is a particle-level Fortran-based event generator similar to PYTHIA. It contains an angular-ordered PS and a cluster hadronisation model. As with PYTHIA, the first PS emission in Z^0/γ^* final states is reweighted to LO $Z^0/\gamma^* + 1 \cdot \text{jet}$ calculations. However, two different schemes

are applied for this reweighting at low and high p_t . In the hard regime, the parton shower result is reweighted to mimic the first NLO emission from a real contributions. In the soft regime, the leading parton shower emission is reweighted to match the leading emission of the LO ME to smooth the transition between ME and PS. Although HERWIG offers its own underlying event model it is often interfaced with the MPI generator JIMMY. HERWIG has been rewritten to C++ recently [79].

SHERPA

SHERPA ([73], version lower than 1.3) is a C++-based event generator offering a full ME+PS description of high energy collisions. The CKKW merging scheme is used to match ME predictions with a virtuality ordered PS. A cluster model is applied for hadronisation. The MPI model generates $2 \rightarrow 2$ processes from the hard scattering's left-over objects as long as their transverse momentum is at a perturbative scale.

Recent developments ([80, 81], version higher than 1.3) show that a selection of processes can be calculated at NLO in SHERPA. With this, a new parton shower mechanism was established as well as new underlying event tune so that these versions can be considered to base on an entirely new theoretical ansatz.

3.3 Theoretical Predictions of $Z^0 + b$ Final States

The current state of the art predicting Z^0 boson inclusive cross sections are NNLO calculations [82]. For $Z^0 + \text{jets}$ final states, a multitude of NLO predictions are available [83, 84] predicting up to three additional emissions. A comparison of NLO results with LHC data yielded good agreement [52]. The calculation of $Z^0 + b$ final states has ever been troublesome due to the comparably large mass of the b parton involved. The following section will outline theoretical approaches to $Z^0 + b$ final states. Finally, approaches to estimate theoretical uncertainties associated with LO and NLO predictions of $Z^0 + b$ final states will be addressed.

The goal of this analysis is to measure the cross section $\sigma_{\text{incl}}(Z^0 + b)$ and the related ratio $\mathcal{R} = \frac{\sigma_{\text{incl}}(Z^0 + b)}{\sigma_{\text{incl}}(Z^0 + \text{jets})}$. All quoted cross section refer to inclusive quantities, i.e. to contain one Z^0 boson and at least one bottom parton induced jet. The distinction between inclusive final states $Z^0 + b + X$ and exclusive final states $Z^0 + b$ is from here on collapsed to $Z^0 + b$ if not stated otherwise. The equivalent holds for $Z^0 + \text{jets}$ which refer to events exposing one Z^0 and at least one jet.

3.3.1 Description of $Z^0 + b$ Final States

The soft and collinear divergences entering pQCD calculations occur only in processes where the participating quark mass can be neglected due to a comparably high scale Q^2 involved. This is a sound approximation since light¹ flavour quark masses are of the order of $m_s = 101 \text{ MeV}$ or lower, see table 2.0. For heavy flavour partons (c, b), this hypothesis does not hold. The treatment of LO matrix elements is hence free of divergences due to vanishing parton transverse momentum because the quark mass regulates it proportional to $\log m_q^2$. While this being a virtue, the fixed-order calculations become much more complicated with it.

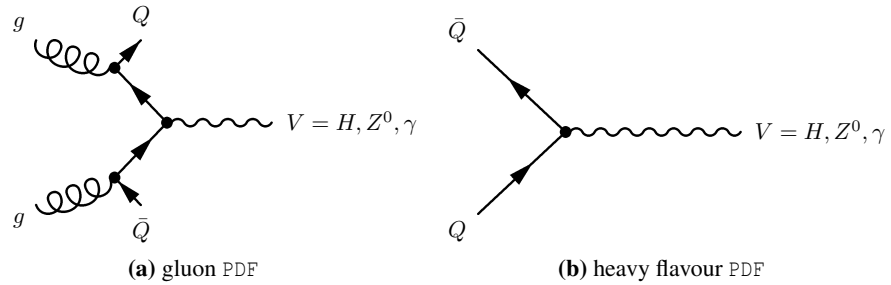


Figure 3.4: Feynman representation of SM LO gauge boson production from heavy flavour partons Q . Either heavy partons are produced by gluon splitting in the initial state (a) and auxiliary $Q, \bar{Q}$ partons escape detection or by fusion of heavy quarks that are contained in the proton bPDF (b).

To resolve this, the tendency that high energetic hadron-hadron collisions probe the proton sea quark PDF is exploited. Figure 3.3a illustrates the canonical assumption that heavy quarks are not (or rarely) contained in the proton. Thus, heavy partons producing Z^0 bosons or alike must be generated by gluon splittings. Folding or resumming the gluon splitting back into the proton's PDF yields a much simpler picture of the matter, figure 3.3b, and implies the existence of a bottom quark parton density function (bPDF).

¹Light refers to u, d, s flavour partons.

For comparison to experimental observations, the production of heavy flavour partons in addition to the Z^0 boson in 3.3a must be integrated over the full parton phase space to yield contributions for inclusive Z^0 or up to $Z^0 + 2 \text{ jets}$ final states. The gluon splitting approach is referred to as *fixed flavour number scheme* (FFS, figure 3.3a) and the alternative as *variable number scheme* (VFS, figure 3.3b). In the full theory, i.e. calculations to infinite order of α_s , any difference between the two must be resolved. However, LO order calculations are expected to expose a non-negligible impact from using the two schemes.

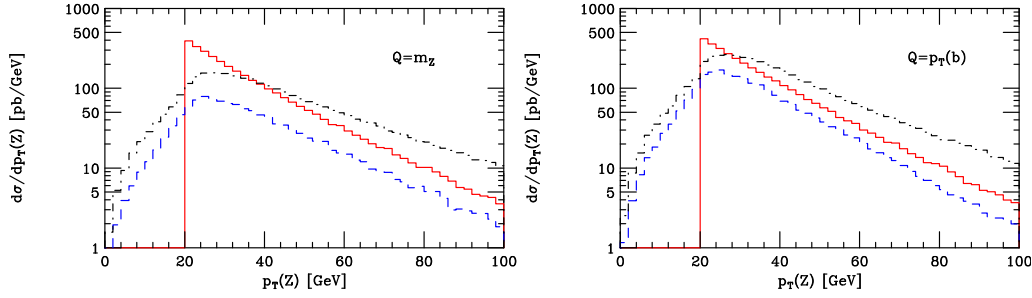


Figure 3.5: Differential LO cross section estimates of $Z^0 + b$ final states from $p\bar{p}$ collisions versus Z^0 transverse momentum from [85] for a hard scale $Q = m_{Z^0}$ (left) and a soft scale $Q = p_T(b)$ (right). For both, the final state bottom quarks are restricted to $p_T(b) > 20 \text{ GeV}$ and $|\eta(b)| < 2.5$. The VFS is represented by the red solid curve. The blue dashed line reports the FFS prediction. The black dot-dashed curve represents the contribution from $q\bar{q} \rightarrow Z^0 b\bar{b}$ common to both approaches.

Figure 3.4 illustrates the impact of the presented calculation schemes on the cross section of $Z^0 + b$ at LO for $p\bar{p}$ collisions. The VFS prediction vanishes below $p_T(Z^0) = 20 \text{ GeV}$ due to the kinematic constraints imposed on final state partons. However, the FFS and VFS predictions yield a substantially different cross section. Similar studies for $\gamma + b$ final states have shown a different behaviour where the two schemes give comparable predictions at LO [86]. Thus, measurements of $Z^0 + b$ observables can help discriminate both approaches that are lively discussed [87] and help to a better understanding of heavy flavour physics in association with gauge bosons. It is of special interest for calculations of inclusive Higgs production $b\bar{b} \rightarrow H$ [88, 89], single top final states $qb \rightarrow q't$ [90], charged Higgs production $gb \rightarrow H^- t$ [91] and other Higgs final states within the SM or beyond [92].

The controversies of calculating heavy flavour final states sketched above have further implications for determination of PDF (section 3.2.1). Recalling equation 3.3, which forms the basis of PDF global fits from experimental data, the number of active flavours in the proton is an important quantity for it enters the sum over all flavours. Depending on the flavour content of the proton, the global fit results may rearrange the extent of PDF at various scales differently due to different net content of parton flavours [93]. This has important consequences if e.g. a MC simulation based on a 4-flavour FFS calculation is conducted with 5-flavour PDF as input.

Figure 3.5 underlines the dramatic impact that VFS or FFS calculations have when prediction the SM Higgs NLO and NNLO cross section at the LHC. Theoretical uncertainties of 20% over a wide range of m_H are reported. In addition, the mean cross sections of VFS and FFS diverge with higher m_H .

Measurements by DØ [94] and CDF [95, 96] have not succeeded in obtaining a statistical precision

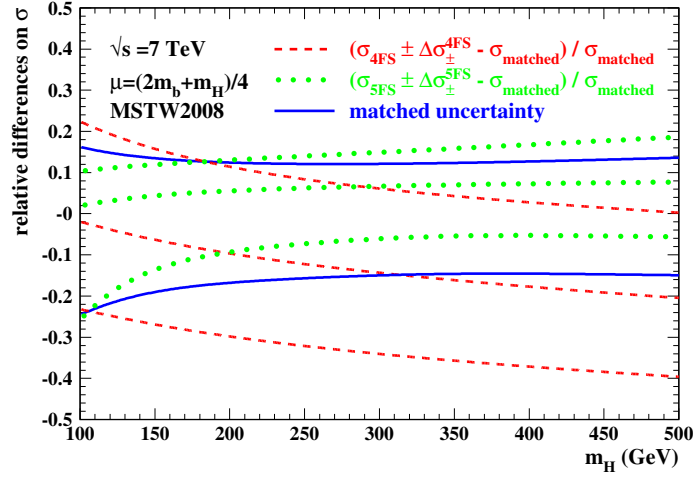


Figure 3.6: Relative deviation of the expected SM Higgs cross section for b-associated productions at LHC with $\sqrt{s} = 7$ TeV from a joint “matched” prediction. Taken from [92].

to be able to discriminate between both calculation schemes, so were early measurements by CMS [97] and ATLAS [98]. Thus, the measurement of $\sigma_{\text{incl}}(Z^0 + b)$ can be considered an essential contribution not only to understanding background contributions in Higgs related final states, but also to establishing insight into heavy flavour QCD in the perturbative (VFS vs. FFS) and non-perturbative (bPDF) regime.

3.3.2 NLO Calculations of $Z^0 + b$ with MCFM

The NLO parton-level calculation by MCFM (version 6.2) is used to obtain predictions for $Z^0 + b$ and $Z^0 + \text{jets}$ cross sections. For $Z^0 + b$ final states, the following calculations are conducted and summed afterwards to obtain $\sigma_{\text{incl}}(Z^0 + b)$ as outlined in [99, 100]:

- $pp \rightarrow Z^0 + b$ at NLO (process 261, $m_b = 0$)
- $pp \rightarrow Z^0 + b + \bar{b}$ at LO (process 263, $m_b \neq 0$, one bottom quark $\bar{b}$ is outside the defined phase space definition)
- $pp \rightarrow Z^0 + b + \bar{b}$, real emission at NLO (process 266, $m_b = 0$).

For all of the processes above, the Z^0 boson is required to decay into e^+e^- . Given lepton universality, this is assumed to give a small difference to equivalent results with the Z^0 boson decaying into a muon pair. The calculations are carried out using CTEQ6.6 (NLO, [101]) and MSTW200868cl (NLO, [57]) PDF distributions. The choice of PDF is driven by the requirement to remain as close as possible to the SHERPA calculation (see section 3.3.3). Further, the MSTW2008NLO PDF offers distributions with a varied bottom mass m_b used for extracting the PDF from data [93].

A dynamic scale of $H_T = \sum_i p_{T,i}$ is chosen [102] per event representing the sum over all final state parton momenta generated to give the hard scale Q^2 of the process. This choice is driven by the current state of MCFM which does not allow for other dynamic scales. In addition, the mass of the bottom quark is assumed non-zero at 4.75 GeV where indicated. In this setup, a VFS calculation is implemented by MCFM.

The $Z^0 + \text{jets}$ cross section is calculated by the dedicated process 41 inclusively. At NLO, the dominantly contributing final state diagrams are listed in table 3.0.

LO Feynman diagram	fraction of $\sigma_{\text{incl}}(Z^0 + \text{jets}) / \%$
$gq \rightarrow Z^0(\mu^+\mu^-) + \text{jets}$	50.96
$g\bar{q} \rightarrow Z^0(\mu^+\mu^-) + \text{jets}$	27.45
$q\bar{q} \rightarrow Z^0(\mu^+\mu^-) + \text{jets}$	27.23

Table 3.1: Fractional contribution to the total $\sigma_{\text{incl}}(Z^0 + \text{jets})$ at NLO estimated by MCFM. The dominant positive contributions are listed only. The sum of all contributions adds to more than 100% for virtual corrections yield negative corrections and are not listed. In the definition given here, they yield -5% .

The dominating diagrams for $\sigma_{\text{incl}}(Z^0 + b)$ predictions compared to table 3.0 are similar but different in the size. For $Z^0 + b$ final states, also the gg initial state contributes a dominant part.

In order to comply to the phase space definition used for this analysis, parton level objects are required to pass the requirements discussed in section 7.4.2. All final state partons are limited to $p_t > 25 \text{ GeV}$, $|\eta| < 2.5$ and $\Delta R(\text{jet}, \ell^\pm) > 0.5$. All generated leptons are required to fall inside $p_t > 20 \text{ GeV}$, $|\eta| < 2.5$ and the invariant mass of an event must be $(71 < m_{\ell^+\ell^-} < 111) \text{ GeV}$. For prediction of $Z^0 + \text{jets}$, MCFM was used with process 41 defined in inclusive mode which gives an inclusive cross section of $Z^0 + \text{jets}$.

Table 3.1 lists the expected NLO cross sections provided by the MCFM setup outlined above. The total cross sections provided by two different PDF configurations differ by 7% for $Z^0 + b$

PDF	$\sigma_{incl}(Z^0 + b) / pb$	$\sigma_{incl}(Z^0 + \text{jets}) / pb$
CTEQ6.6	4.26 ± 0.01	70.2 ± 0.1
MSTW2008NLO	4.57 ± 0.01	70.9 ± 0.1

Table 3.2: Predicted NLO cross section of $Z^0 + b$ as calculated by MCFM with different PDF setups. The uncertainty given corresponds to the statistical uncertainty of the phase space integration by the finite number of samplings.

and 1% for $Z^0 + \text{jets}$. The noted relative uncertainty on $\sigma_{incl}(Z^0 + b)$ coincides with the relative difference on the b PDF as shown in figure 3.7 later. Similar or higher discrepancies were observed by equivalent studies of other processes at the LHC [103]. Also, the implementation of the VFS for extracting PDF from the data (MSTW2008NLO PDF) seems to have a further impact on the predicted cross section [104]. The difference between CTEQ6.6 and MSTW2008NLO for $Z^0 + \text{jets}$ final states are smaller for this process accesses light parton PDF.

3.3.3 LO Calculations of $Z^0 + b$ with SHERPA

For predictions of $Z^0 + b$ at LO, hadron level calculations by SHERPA 1.1.3 are used. The SHERPA 1.1.3 underlying event model was tuned with CTEQ6.6(NLO PDF) and CTEQ6L1(LO PDF) [73], which implies to use it as baseline PDF. To study the dependency on the assumed value of m_b , MSTW2008NLO (NLO PDF) is employed in addition. The SHERPA configuration at hand is identical to the one applied for producing the signal samples noted in section 5.1.1 - the only difference being the PDF configured (see section 5.1.1 for further details). The produced event ensemble was analysed within the Rivet software framework (1.8.0, [105]). As for the event samples with the complete ATLAS detector simulation, the SHERPA default scale calculation via the CKKW scheme [48] is used. The fraction of events containing bottom and charm quarks in the initial and final states is enhanced by a factor of 10 compared to their nominal contribution. Each event that exposes a bottom and charm quark is assigned a weight of 0.1, so that the total event sample corresponds to an inclusive $Z^0 + \text{jets}$ data set with the Z^0 decaying into $\mu^+\mu^-$.

LO Feynman diagram	fraction of $\sigma_{incl}(Z^0 + \text{jets}) / \%$
$gq \rightarrow Z^0(\mu^+\mu^-) + \text{jets}$	47.8
$q\bar{q} \rightarrow Z^0(\mu^+\mu^-) + \text{jets}$	32.9
$g\bar{q} \rightarrow Z^0(\mu^+\mu^-) + \text{jets}$	19.3

Table 3.3: Fractional contribution to the total $\sigma_{incl}(Z^0 + \text{jets})$ at LO estimated by SHERPA 1.1.3. Only $2 \rightarrow 3$ Feynman diagrams are considered for illustration purposes here.

The dominant Feynman diagrams contributing on in the LO ME+PS calculation conducted by SHERPA 1.1.3 are listed in table 3.2. Again, the qg initiated process provides the dominant part of $\sigma_{incl}(Z^0 + \text{jets})$. Compared to NLO, $q\bar{q}$ initial diagrams expose a higher fraction of the $\sigma_{incl}(Z^0 + \text{jets})$ at LO. This can be interpreted as the effect of virtual corrections not presented in table 3.0. Along the same line of argument, a comparison on a by Feynman diagram basis can also be misleading for it neglects effects due to interferences that enter quite differently at NLO compared to LO.

PDF	$\sigma_{incl}(Z^0 + b) / pb$	$\sigma_{incl}(Z^0 + \text{jets}) / pb$
CTEQ6L1	3.41 ± 0.07	55.7 ± 0.5
CTEQ6.6	3.75 ± 0.08	59.4 ± 0.6
MSTW2008NLO	3.75 ± 0.08	60.0 ± 0.6

Table 3.4: Predicted LO cross section of $Z^0 + b$ and $Z^0 + \text{jets}$ as calculated by SHERPA 1.1.3 with different PDF. The uncertainty given corresponds to the statistical uncertainty of the phase space integration due to the finite number of samplings.

Table 3.3 summarises the LO ME+PS predictions on hadron-level obtained from SHERPA 1.1.3. They were obtained by making the same requirements on final state objects (muons and jets) as introduced in the last section for NLO predictions. The cross sections predictions using the LO CTEQ6L1 PDF remain lower than those obtained at NLO because the CTEQ6L1 PDF set remains smaller than CTEQ6.6 in the most populated phase space points in x .

Figure 3.6 compares the gluon PDF (g_{PDF}) of CTEQ6L1 (at LO) and CTEQ66 (NLO) for it is probed in initial states that contribute dominantly to $\sigma_{incl}(Z^0 + \text{jets})$ (see tables 3.2 and 3.0). Over a wide range of x values, CTEQ6L1 remains below CTEQ66 (reaching down to 50% of CTEQ66).

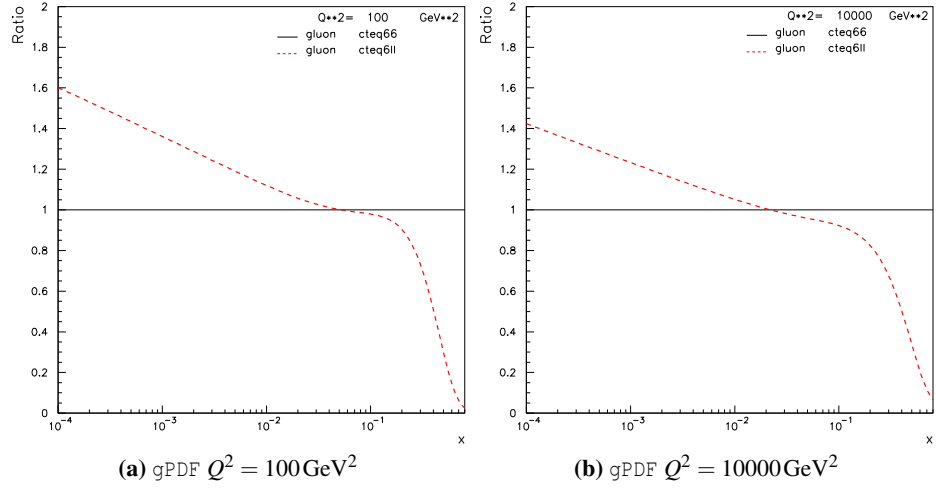


Figure 3.7: Ratio of the gluon PDF ($gPDF$) from CTEQ6L1 (red dashed line) at LO relative to CTEQ66 (black solid) in NLO at $Q^2 = 100 GeV^2$ (a) and $Q^2 = 10000 GeV^2$ (b) from [106].

The $\sigma_{incl}(Z^0 + b)$ and $\sigma_{incl}(Z^0 + jets)$ predictions using NLO PDFs (CTEQ66 and MSTW2008NLO) give comparable within their statistical uncertainties. This observation indicates that the underlying event model that was tuned to CTEQ6.6 and CTEQ6L1 only does not play a dominant role given the e.g. high momentum requirement of the final state jets of $p_{t,jet} > 25 GeV$. This was also found by the ATLAS $Z^0 + b$ analysis [98].

3.4 Theoretical Uncertainties of $Z^0 + b$ Predictions

In order to estimate the uncertainty of these theoretical predictions, the following sources are studied:

- uncertainties connected to the choice of PDF and intrinsic uncertainties thereof following estimations suggested in [107]
- uncertainties from the dependence on the assumed mass of the bottom quark
- uncertainties due to the choice of renormalisation and factorisation scale
- uncertainties of α_s used

The total theoretical uncertainty is obtained by adding the above mentioned contributions quadratically in order to obtain a conservative estimate. This may or may not represent a confidence interval that is rigorously justified [108]. Alternative methods introduced in the latter reference were not accessible at the time of writing.

3.4.1 PDF Uncertainties

To evaluate the uncertainties on the presented (N)LO predictions due to the statistical uncertainties entailed by the global fit to data for extracting a PDF, the recommendations offered by [107, 109] are pursued. Given a theoretical prediction on grounds of a fixed PDF set O_{PDF} , its computation must be re-evaluated for each variation of the PDF according to its uncertainty eigenvectors i (available with the PDF, [57, 101]) to obtain $O_{PDF,i}$. To yield the total upward or downward uncertainty for a given calculation $\sigma(O_{PDF})^\pm$, the maximum of upward and downward variations for a given eigenvector is summed quadratically over all eigenvectors as in

$$\sigma(O_{PDF})^\pm = \sqrt{\sum_i (\max[\pm 1 \cdot (O_{PDF,i}^+ - O_{PDF}), \pm 1 \cdot (O_{PDF,i}^- - O_{PDF}), 0])^2}. \quad (3.6)$$

PDF	$\sigma_{incl}(Z^0 + b) / \%$		$\sigma_{incl}(Z^0 + \text{jets}) / \%$	
	NLO	LO	NLO	LO
CTEQ6.6 $^\pm$	3.4	5.2	2.3	1.5
	-4.1	-15.0	-3.7	-7.6
MSTW2008NLO $^\pm$	3.9	8.5	0.9	4.9
	-1.3	-5.4	-1.7	2.9

Table 3.5: Relative variation according to equation 3.6 of the predicted (N)LO cross section of $Z^0 + b$ (and $Z^0 + \text{jets}$) from predictions of MCFM and SHERPA with different PDF setups.

The extent of theoretical uncertainties due to the used PDF in table 3.4 are larger for $\sigma_{incl}(Z^0 + b)$ than for $\sigma_{incl}(Z^0 + \text{jets})$. This implies that calculations of $Z^0 + \text{jets}$ probe PDF more frequently in phase space regions that are known with smaller uncertainties than for $Z^0 + b$ final states. This is due to Feynman diagrams with light flavour partons in the initial state that contribute more for $Z^0 + \text{jets}$ than for $Z^0 + b$ final states due to the large abundance of valence quarks in the protons. Similar uncertainties of NLO calculations due to PDF variations of $\sigma_{incl}(Z^0 + \text{jets})$ were also reported by a dedicated ATLAS analysis [52].

The PDF uncertainty observed in NLO and LO cross section predictions documented in table 3.4 are asymmetric. A comparison of PDF uncertainty bands can guide an interpretation of this observation.

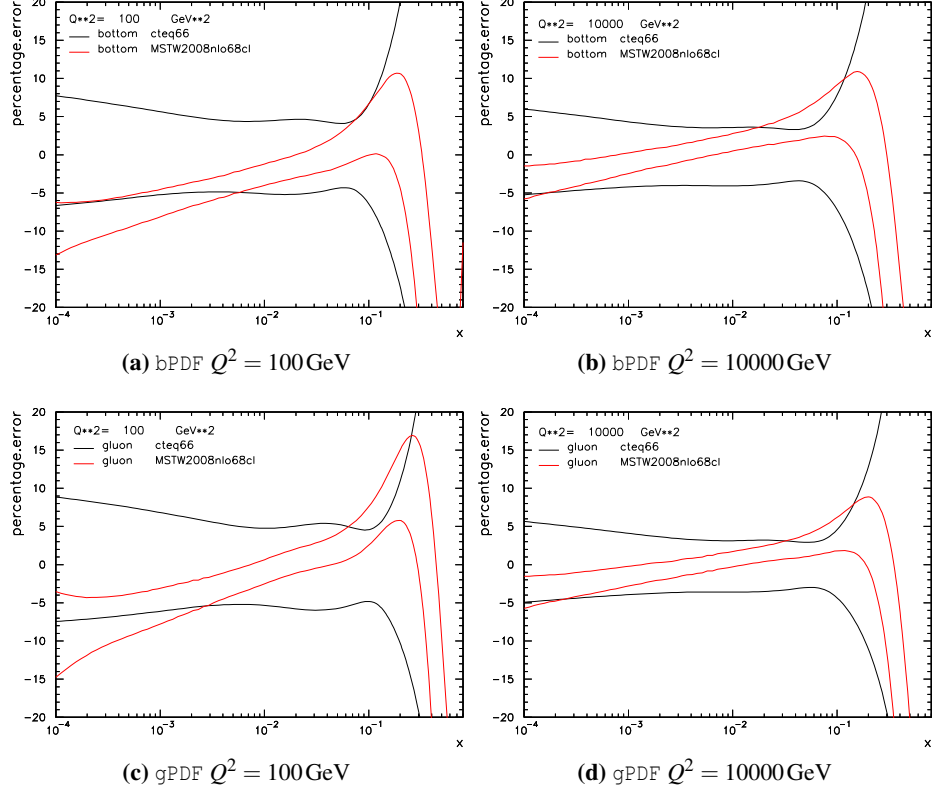


Figure 3.8: Bottom and gluon PDF uncertainty bands obtained from [106] of CTEQ6.6 and MSTW2008NLO normalised to the CTEQ6.6 central value. Two energy scales are depicted, $Q^2 = 100 \text{ GeV}$ close to m_b (a, c) and $Q^2 = 10000 \text{ GeV}$ close to m_{Z^0} (b, d) to illustrate the scaling in Q^2 . The error bands are obtained from equation 3.6.

Figure 3.7 shows the uncertainties of bPDF and gPDF of CTEQ6.6 compared to MSTW2008NLO. The error bands of MSTW2008NLO exhibit a different shape than those for CTEQ6.6 at low and high values of x . Figure 3.7 suggests, that the relative uncertainty is distributed asymmetrically around the central expectation of MSTW2008NLO and CTEQ6.6. This is also supported by the reversed asymmetric uncertainty bands between CTEQ6.6 and MSTW2008NLO noted in table 3.4. Further, the deviations of NLO calculations are observed to be smaller than for LO predictions. This aspect can be correlated with the direct scaling of the LO calculation that is not counter acted by any higher order terms (as at NLO).

3.4.2 Uncertainties from m_b

One further source of theoretical uncertainty is the pole mass of the bottom quark. This is studied as independent source of theoretical uncertainty here to illustrate the effect on the final cross section prediction. It is however not used to derive the total theoretical uncertainty at the end of this chapter to provide consistency with existing publications [98, 99] for PDF with varied m_b are only available for MSTW2008NLO, i.e. the MSTW2008NLO_mbrange PDF sets.

Both, SHERPA and MCFM provide the capability to take massive bottom flavour partons into account. The assumed bottom quark pole mass was varied within $m_b = 4.0, 5.5$ GeV within the given MSTW2008NLO_mbrange sets and also within the ME calculations at hand for MCFM only.

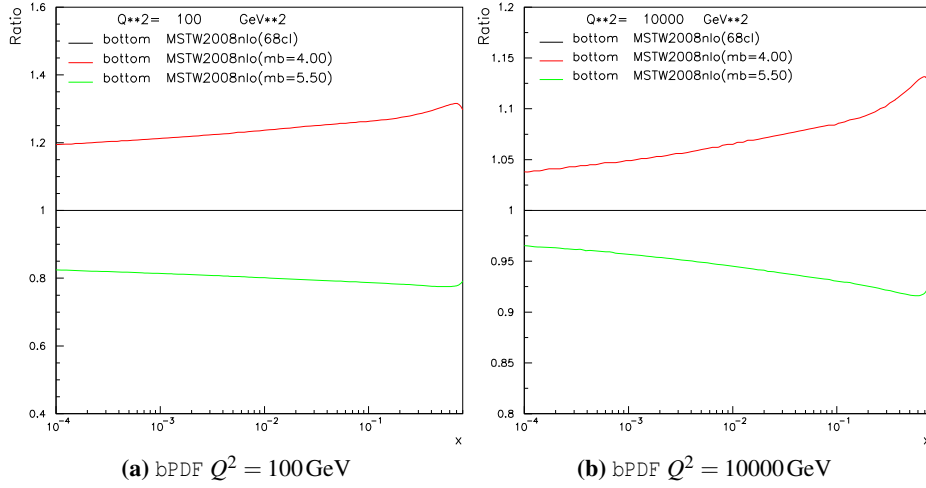


Figure 3.9: Ratio of MSTW2008NLO bottom PDF assuming $m_b = 4.0, 5.5$ GeV (red, green) relative to the nominal MSTW2008NLO PDF with $m_b = 4.75$ GeV (black) at energy scale $Q^2 = 100 \text{ GeV}$ close to m_b (a) and $Q^2 = 10000 \text{ GeV}$ close to m_{Z^0} (b). Distributions were produced by [106].

Figure 3.8 illustrates the impact of the available maximal and minimal bottom quark mass variations available with MSTW2008NLO_mbrange PDF sets. At energies close to m_b a difference of 20% compared to the nominal bPDF is observed. For higher Q^2 , this effect decreases to below 10%. This behaviour can be attributed to a discussion introduced in section 3.1.1 that applies here as well. Terms of the form $\log \frac{Q^2}{q^2}$ in the fixed-order calculation (assuming partons to be massless) transform to $\log \frac{Q^2}{q^2 - m^2}$ (with partons being massive). The parton mass enables a damping of the collinear/soft divergence of these logarithms. The lower Q^2 , the stronger the impact of m^2 . With a difference in the ME used to obtain a PDF fit, all parton flavours described by a PDF set change accordingly. Effects as those of figure 3.8 can be observed for the gluon PDF and light quark PDF as well but are not shown here [93].

PDF	$\sigma_{incl}(Z^0 + b) / \%$	$\sigma_{incl}(Z^0 + \text{jets})$
	NLO	NLO
MSTW2008NLO $_{-}^{+}$	7.1	0.0
	-8.4	-0.4

Table 3.6: Relative variation of the predicted (N)LO cross section of $Z^0 + b$ (and $Z^0 + \text{jets}$) as calculated by MCFM with MSTW2008NLO_mbrange PDF corresponding to $m_b = 4.0 - 5.5$ GeV. The bottom quark mass was also altered in the fixed-order NLO calculation for consistency. The maximal deviation from the nominal result with $m_b = 4.75$ GeV is used as an estimate of the attributed theoretical uncertainty.

Table 3.5 lists how NLO predictions follow a variation of m_b . The expected $\sigma_{incl}(Z^0 + b)$ can change by up to 8.4%. This reflects how the individual calculations substantially rely on a precise

knowledge of the bottom quark content of the proton. The considerable extent of the theoretical uncertainty attributed to m_b emphasizes again the central motivations of this analysis.

The effect of different m_b values on $\sigma_{incl}(Z^0 + \text{jets})$ is reported negligible due to the low rate of $Z^0 + b$ final states contained in the ensemble of $Z^0 + \text{jets}$ events. As reported in section 3.4.5, the expectation of $\mathcal{R}$ at NLO gives 6.5 %. Thus, an additional uncertainty of up to 8.4 % becomes 0.5 % and thus close to the statistical precision of the calculation.

3.4.3 Uncertainties from scale choices

The dominant contribution to the theoretical uncertainty is expected from renormalisation and factorisation scale variations [83, 99, 100]. To estimate them, the respective scales have been multiplied by 1/4, 1/2, 1, 2, 4 coherently on an event-by-event basis yielding four estimates different from the nominal one with $\mu_{ren} = \mu_{fac} = 1$. To account for the total uncertainty due to these variations, the maximum value of this set of predictions is used.

PDF	$\sigma_{incl}(Z^0 + b) / \%$		$\sigma_{incl}(Z^0 + \text{jets}) / \%$	
	NLO	LO	NLO	LO
CTEQ6.6 $^{\pm}$	16.4	16.0	6.1	9.9
	-3.8	-8.6	-7.2	-8.5
MSTW2008NLO $^{\pm}$	17.0	4.7	7.6	3.1
	7.2	-10.5	-6.1	-13.1

Table 3.7: Relative Variation of the predicted (N)LO cross section of $Z^0 + b$ (and $Z^0 + \text{jets}$) as calculated by MCFM (and SHERPA) with MSTW2008NLO PDF setups corresponding to renormalisation and factorisation scale variations of $\mu_{ren}, \mu_{fac} = 1/4, 1/2, 1, 2, 4$. The maximal deviation from the nominal result $\mu_{ren} = \mu_{fac} = 1$ is used as an estimate of the theoretical uncertainty.

Although the procedure applied to obtain the results of table 3.6 is a standard procedure, the interpretation of its outcome is vague. Both scales at hand parametrise short-comings of the pQCD description at very soft (factorisation) and very hard scales (renormalisation), see sections 2.4.1 and 3.2 above. Both scales are unphysical by definition and merely offer an approximation in regimes which cannot be described rigorously in pQCD. Thus, their variation allows to probe phase space regions that may not be properly taken into account due to these approximations made for a given calculation. Estimating an uncertainty by a source that the nominal calculation was not intended for is questionable [108]. Due to a lack of alternatives, the above mentioned recipe is applied here and its results are used without further comment.

It must be stressed that the schemes to calculate the scale Q^2 per event is different for the chosen setup of SHERPA and MCFM. At NLO, H_T was used that provides a very high scale (all partons per event are summed). At LO, the CKKW scale is used that is by definition a parton shower scale (very soft regime). The scaling behaviour of both predictions is therefore very different and difficult to compare besides other fundamental differences (fixed-order versus ME+PS approach).

3.4.4 Uncertainties from α_s

The predictions of $Z^0 + b$ and $Z^0 + \text{jets}$ have to be made subject to a deviation according to the uncertainties of α_s [33]. The procedures outlined in [109] are applied to ensure that uncertainties

in α_s and PDF choices are treated consistently.

PDF	$\sigma_{incl}(Z^0 + b) / \%$		$\sigma_{incl}(Z^0 + \text{jets}) / \%$	
	NLO	LO	NLO	LO
CTEQ6.6 $^+_{-}$	0.7	3.3	0.6	1.9
	-1.8	-0.6	-0.8	-1.4
MSTW2008NLO $^+_{-}$	1.0	1.2	2.3	0.1
	-2.4	-2.1	-0.1	-1.7

Table 3.8: Relative Variation of the predicted (N)LO cross section of $Z^0 + b$ (and $Z^0 + \text{jets}$) as calculated by MCFM (and SHERPA) with CTEQ6.6 and MSTW2008NLO PDF setups corresponding to $\alpha_s(m_{Z^0}) \pm \sigma(\alpha_s(m_{Z^0}))_{exp}$ based on the experimental uncertainty noted in [33].

Since the absolute uncertainty on α_s is itself small, the deviation of the presented calculations of table 3.7 is so too.

3.4.5 Total Uncertainties

In order to combine the uncertainty estimates reported above, their individual extent is added in quadrature to give the total uncertainty of the theoretical predictions. In order to retain comparability, only the CTEQ6.6 predictions are used further on and results for MSTW2008NLO are shown here for completeness. Table 3.8 adds the computation of $\mathcal{R} = \frac{\sigma_{incl}(Z^0+b)}{\sigma_{incl}(Z^0+jets)}$ to the combination

PDF	$\sigma_{incl}(Z^0 + b) / pb$		$\sigma_{incl}(Z^0 + jets) / pb$		$\mathcal{R} = \frac{\sigma_{incl}(Z^0+b)}{\sigma_{incl}(Z^0+jets)} / \%$	
	NLO	LO	NLO	LO	NLO	LO
CTEQ6.6	$4.26^{+0.63}_{-0.22}$	$3.75^{+0.64}_{-0.65}$	$(70.2^{+4.7}_{-5.6})$	$59.4^{+6.0}_{-6.8}$	$6.07^{+0.99}_{-0.58}$	$6.31^{+1.25}_{-1.31}$
MSTW2008NLO	$4.57^{+0.70}_{-0.45}$	$3.75^{+0.47}_{-0.61}$	$(70.9^{+5.7}_{-4.2})$	$60.0^{+4.4}_{-8.1}$	$6.50^{+1.11}_{-0.74}$	$6.25^{+0.91}_{-1.32}$

Table 3.9: Expected cross section $\sigma_{incl}(Z^0 + b)$, $\sigma_{incl}(Z^0 + jets)$ and cross section ratio $\mathcal{R}$ as predicted from a fixed NLO MCFM 6.3 calculation and from a ME+PS LO generation by SHERPA 1.1.3. The quoted uncertainties include the variation of renormalisation and factorisation scales independently for NLO and coherently for LO, different assumption of the bottom quark mass (only MSTW2008NLO), variations due to experimental uncertainties of α_s and due to the uncertainties of the respective PDF CTEQ6.6 and MSTW2008NLO. The uncertainties from $\sigma_{incl}(Z^0 + b)$ and $\sigma_{incl}(Z^0 + jets)$ entering in $\mathcal{R} = \frac{\sigma_{incl}(Z^0+b)}{\sigma_{incl}(Z^0+jets)}$ have been combined under the assumption of full correlation.

of theoretical uncertainties in $\sigma_{incl}(Z^0 + b)$ and $\sigma_{incl}(Z^0 + jets)$. The uncertainties are combined quadratically to give the uncertainty of the cross section ratio $\mathcal{R}$. It must again be made clear that a fair comparison of results obtained with CTEQ6.6 versus those with MSTW2008NLO cannot be made due to latter containing the contribution from varying m_b in addition.

In general, the theoretical uncertainties obtained for $\sigma_{incl}(Z^0 + b)$ are large and range within 7 – 19 % for both NLO and LO. From an experimental point of view, this requires an experimental measurement to validate phenomenological models and fixed-order calculations and thus drive their improvement. The theoretical uncertainties on $\sigma_{incl}(Z^0 + jets)$ were observed to be 6 – 7 % at NLO and 7 – 14 % at LO. The uncertainties of $\mathcal{R}$ are 10 – 17 % at NLO and 14 – 20 % at LO. For all listed final states the choice of the renormalisation and factorisation scale discussed in section 3.4.3 exposes the largest contribution to the theoretical uncertainty.

Due to the variation of the bottom quark pole mass, the relative uncertainty of $\sigma_{incl}(Z^0 + b)$ estimated with MSTW2008NLO is by 5 – 100 % larger than obtained with CTEQ6.6. This again underlines how theoretical predictions of $Z^0 + b$ contain intrinsic high uncertainties due to the involved heavy flavour parton properties and their treatment.

The reported theoretical uncertainties motivate a measurement of $\sigma_{incl}(Z^0 + b)$ and $\mathcal{R}$ not only to study the QCD at play in $Z^0 + b$ final states, but also to help reduce the theoretical uncertainties that are connected to the calculations of it. As mentioned in section 2.3, precise knowledge of bottom quark associated boson production processes at the LHC is essential for an efficient and effective search for the Higgs boson predicted by the SM or extensions of it.

Chapter 4

Experimental Setup

To lay the ground for any interpretation of recorded events, this chapter introduces the *Large Hadron Collider* (LHC) installed underground at the “Conseil Européen de la Recherche Nucléaire” (CERN) near Geneva, Switzerland. This facility provided proton-proton collisions in 2010 that were recorded by one of the multi-purpose detectors, *A Toroidal LHC Apparatus* (ATLAS), whose design will be outlined afterwards and whose data of 2010 was analysed. In order to mediate a precise understanding of the data taking and collision event reconstruction, these are briefly discussed at the end of this chapter.

4.1 The Large Hadron Collider (LHC)

The LHC is a circular proton-proton collider of 26659m circumference located 50 – 150m underground. Depending on the geographic location, the exact depth varies with respect to mean sea level.

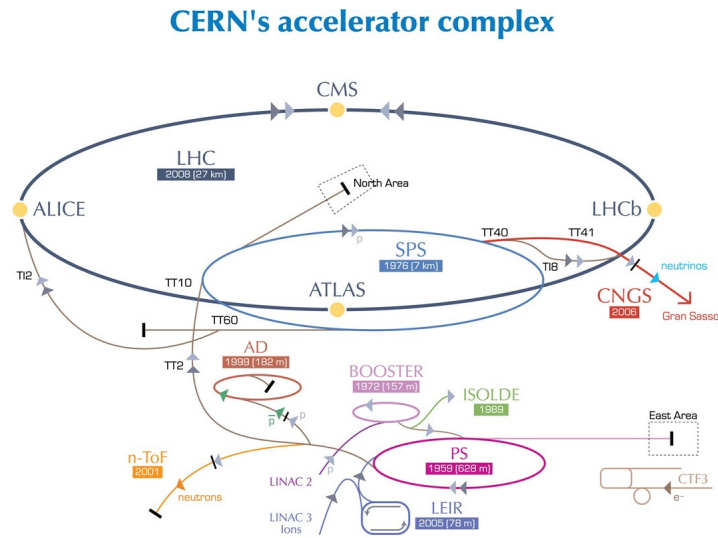


Figure 4.1: Illustration of the LHC accelerator facilities at CERN (Geneva, Switzerland) [110].

4.1.1 Collider Facilities

As figure 4.0 illustrates, the LHC represents the last stage in an accelerator facility at CERN that consists of the following components (ordered by acceleration sequence, including the proton beam's extraction energy E_p upon leaving the respective facility):

1. Linac2, $E_p \rightarrow 50\text{MeV}$
2. Proton Synchrotron Booster (PSB), $E_p \rightarrow 1.4\text{GeV}$
3. Proton Synchrotron (PS), $E_p \rightarrow 25\text{GeV}$
4. Super Proton Synchrotron (SPS), $E_p \rightarrow 450\text{GeV}$
5. LHC, $E_p \rightarrow (0.45 - 14)\text{TeV}$

Due to the Helium leak accident in 2008 [111] and subsequent repairs [112], the LHC came into operation in physics mode in 2010. The proton-proton *centre-of-mass* energy $\sqrt{s}$ (CME) was increased carefully from 450GeV to 7TeV in 2010 to prevent damage as occurred in 2008. At the time of writing (April 2012), the LHC commences the 2012 season of proton-proton collisions at $\sqrt{s} = 8\text{TeV}$.

The LHC was built inside the LEP tunnel [113] to settle the search for the Higgs particle and answer fundamental questions of particle physics as introduced in section 2.3 [114]. For this the LHC collider tunnel hosts caverns that encase two multi-purpose experiments, ATLAS at interaction point IP1 and CMS [115] at IP5 as well as two specialised detectors, ALICE [116] at IP2 and LHCb [117] at IP8.

The LHC accelerator consists of 1232 super-conducting dipole magnets whose magnet coils are made of a niobium-titanium alloy and are operated at a 1.9 K in a super-fluid helium filled vessel [110]. These dipole magnets provide a 8.33 T magnetic field to keep the proton beam upon its orbit and collimated to a small beam profile. The magnetic field strength is thus the limiting factor on the CME - higher values of which demand stronger dipole magnets to keep protons on their circular track.

Figure 4.1a illustrates the design of the LHC dipole magnets. The beam pipe is encased by super-conducting coils that provide the magnetic field. The iron return yoke operated with super-fluid helium provides the cooling and allows for a homogeneous magnetic field. In addition to these dipole magnets, the LHC consists of a wealth of magnets that provide higher order magnetic field symmetries (quadrupoles, sextupoles, octupoles etc.) all of which serve to optimise the beam and proton bunch shape. See [110] for further details on the LHC design.

4.1.2 Beam Conditions

At the envisaged operating point of the original design, the LHC will circulate 2808 proton bunches each filled with approximately 10^{11} protons in two beams of opposite direction. The proton bunch spacing at design operation will be provide collisions every 25 ns. As outlined above, the motivation to build the LHC can be paraphrased by the search of very rare processes, i.e. with a small cross section σ .

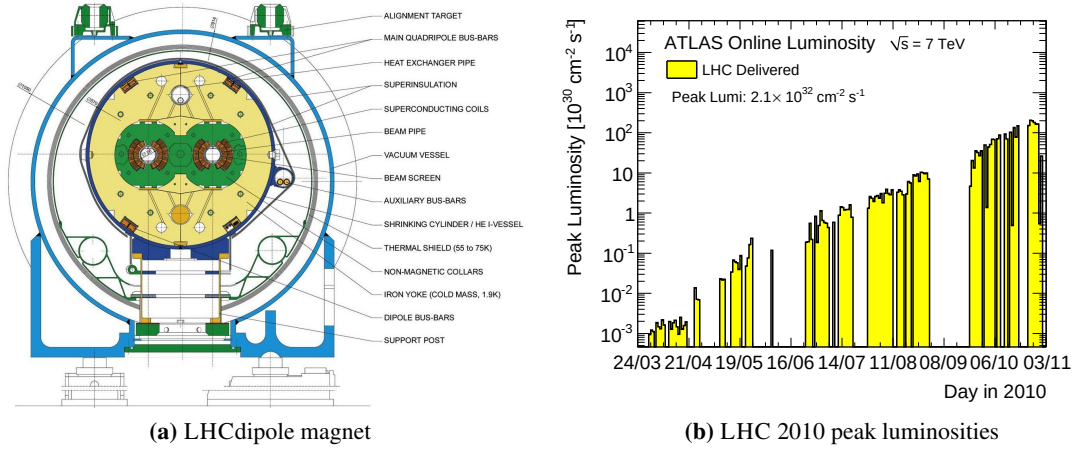


Figure 4.2: Illustration of the LHC dipole magnet [110] in cross section (a). Each dipole magnet measures 15 m of length and 35 t of mass. The beam pipe has a diameter of 50 – 53 mm. Depicted in (b), the LHC peak luminosities delivered to ATLAS versus operation date in 2010 [118].

To relate the rate $R = \frac{dN_p}{dt}$ of proton-proton collisions per time unit (machine parameter) to a cross section (particle physics parameter), the instantaneous luminosity $\mathcal{L}$ is defined as

$$R = \mathcal{L} \cdot \sigma. \quad (4.1)$$

Assuming a Gaussian beam profile, the luminosity [110] can be written as a function of the accelerator's interaction frequency f , the number of protons stored in each bunch N_p , the number of bunches circulating per beam n_b , the relativistic gamma factor γ_r , the normalised transverse beam emittance ϵ_n , the beta function at each collision point β^* and a correction factor F associated to the crossing angle at each IP

$$\mathcal{L} = \frac{N_p^2 n_b f \gamma_r F}{4\pi \epsilon_n \beta^*}. \quad (4.2)$$

During 2010 operation, the LHC instantaneous luminosity was steadily increased, starting from below $10^{27} \text{ cm}^{-2} \text{ s}^{-1}$ to finalise at a peak luminosity of $2.1 \cdot 10^{32} \text{ cm}^{-2} \text{ s}^{-1}$ as illustrated by figure 4.1b.

LHC operation of 2010 can be viewed as a three stage process [119] whose transition coincide with luminosity gaps reported in figure 4.1b:

1. Commissioning the beams to $E = 3.5 \text{ TeV}$ each and first collisions at $\sqrt{s} = 7 \text{ TeV}$ at $\beta^* = 2 \text{ m}$. The number of bunches (filled with $N_{beam} = 10^{10}$ protons) was increased from $n_b = 2$ to $n_b = 13$. Peak instantaneous luminosities of $(10^{27} - 10^{29}) \text{ cm}^{-2} \text{ s}^{-1}$ were reached. This period ended June 5th, 2010 (ATLAS run 156682).
2. Further squeezing of the beam ($\beta^* = 3.5 \text{ m}$) while increasing the number of protons per bunch to $N_{beam} = 10^{11}$. The number of proton bunches per beam was increased to $n_b = 50$. Peak instantaneous luminosities ranging within $(10^{29} - 10^{31}) \text{ cm}^{-2} \text{ s}^{-1}$ were observed. This period ended August 29th, 2010 (ATLAS run 162882).
3. Bunch trains are introduced so groups of eight proton bunches with a time separation of 150 ns are collectively injected into LHC. The total number of bunches per fill thus increased

to $n_b = 368$. The peak luminosity of 2010 as mentioned above was observed. (ATLAS data taking period G onwards)

Aside from proton-proton collisions (pp), the LHC facilities were also filled with lead ions in 2010 which were subsequently brought to collisions [120].

4.2 A Toroidal LHC Apparatus (ATLAS)

The ATLAS experiment [121] as displayed in figure 4.3 was designed to offer a multi-purpose detector to suit the identification and selection of rare proton-proton interactions. It measures 25 m in diameter, 44 m in length and approximately 7000 t in weight. The following section introduces the key detector components of the ATLAS detector that are essential for the analysis of $Z^0 + b$ final states, starting with the coordinate system onto the *InnerDetector*, the *Calorimeter* and the *MuonSpectrometer*. However, the discussion will remain qualitative and thus not cover the wealth of all engineering and physics details as given in [121–123].

4.2.1 Coordinate System and Conventions

By convention, the ATLAS experiment uses a right-handed coordinate system with the positive x-axis pointing from the nominal interaction point IP to the centre of the circle described by the LHC tunnel. The positive y-axis points from the IP upwards. The z-axis is defined by the anti-clockwise direction of the beam normal to the x-y plane. The detector half at $z > 0$ is referred to as *A-side* and for $z < 0$ as *C-side*. Three dimensional space points can be defined in polar coordinates as well with the radial distance $r = \sqrt{x^2 + y^2 + z^2}$, the polar angle $\theta = \arccos(z/r)$ and the azimuthal angle $\phi = \arctan(y/x)$.

The rapidity is defined as

$$y = -\frac{1}{2} \ln \frac{E + p_z}{E - p_z}. \quad (4.3)$$

with E denoting a particles energy and p_z its three-momentum component in z-direction, i.e. along the beam. For massless objects, the rapidity converges towards the pseudo-rapidity as defined by

$$\eta = -\ln \tan \left(\frac{\theta}{2} \right). \quad (4.4)$$

The convention to describe charged particles' trajectories (referred to as *tracks*) as measured by ATLAS are parametrised by five quantities: q/p with q giving the charge and p the total momentum of a particle; the azimuthal ϕ and polar angle θ of a trajectory given at the origin of the track; the transverse impact parameter of the track given by the distance of closest approach in the $x - y$ plane with respect to the track origin (typically the nominal interaction point at $(0, 0, 0)$); the closest intersection of a trajectory with the z axis. These five parameters are necessary because charged particles do not follow precisely a spiral trajectory in the experiment's magnetic field. It is bent or tilted due to the magnetic field inhomogeneity, energy loss and multiple scattering.

Another quantity often referred to is the missing transverse energy, E_T . Upon the observation that the incoming protons do not have transverse momentum, the vectorial sum of all transverse momentum or transverse energy measurements is not required to give 0 if particles escape detection (shower in uninstrumented detector volume or are outside the detector acceptance) or cannot be detected at all (e.g. neutrinos).

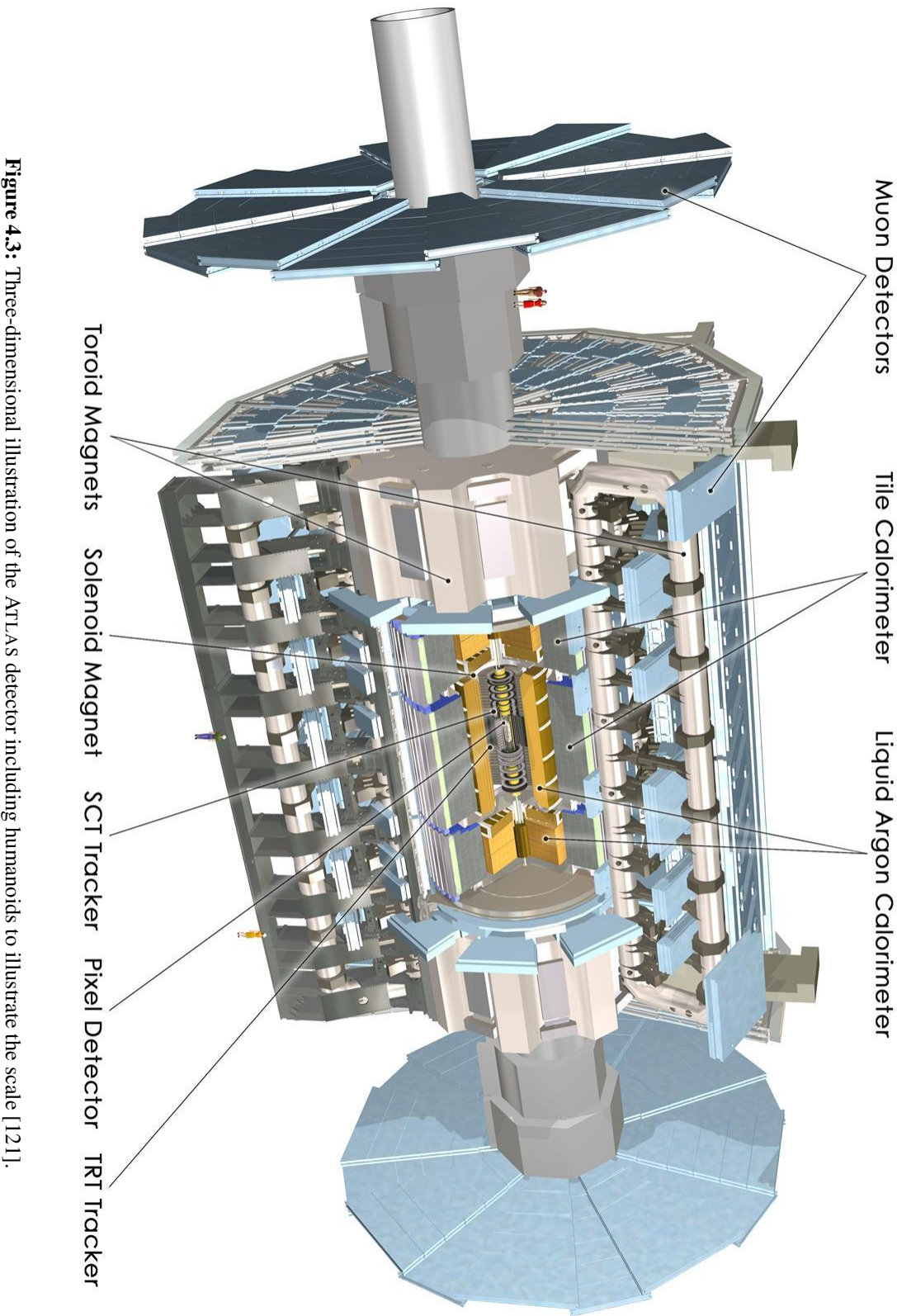


Figure 4.3: Three-dimensional illustration of the ATLAS detector including humanoids to illustrate the scale [121].

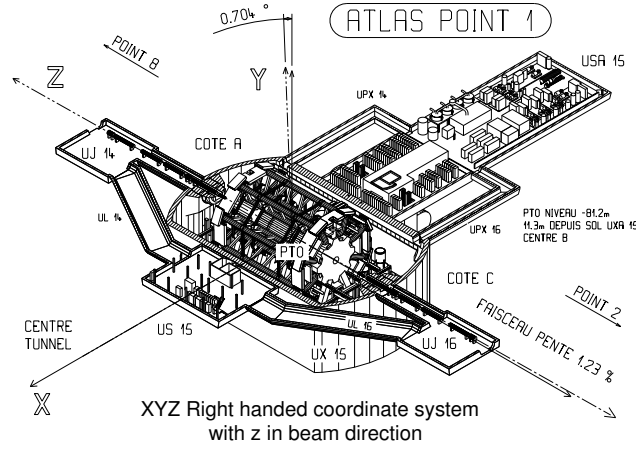


Figure 4.4: ATLAS right-handed coordinate system illustrated by a pictorial representation of experimental cavern at IP1 [122, 123].

4.2.2 Inner Detector Systems

The inner most tracking detectors of the experiment (figure 4.3) are referred to as *InnerDetector* and comprise three sub-detectors: the *Silicon Pixel Detector (Pixel)*, the *Semi-Conductor Tracker (SCT)* and the *Transition Radiation Tracker (TRT)*. They are designed to detect the position and momentum of charged particles from pp interactions passing through with high accuracy and efficiency. The track reconstruction efficiency was observed to reach 78 % for tracks with $p_t = 500\text{MeV}$ and more than 85 % for charged particles at $p_t > 10\text{GeV}$ [124].

The transverse momentum resolution of $\sigma(p_t)/p_t = (0.05 \cdot p_t/\text{GeV} \oplus 1) \%$ and a transverse impact parameter resolution of $10\mu\text{m}$ in central regions ($\eta = 0$) [121] can only be reached through the rigorous exploitation of this subsystem's design virtues as discussed below.

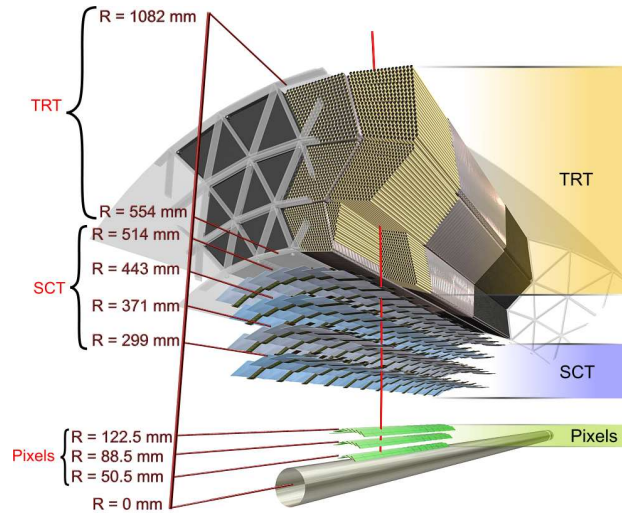


Figure 4.5: Illustration of the LHC *InnerDetector* sub-detector setup [121]. From radii of 5 cm to 108 cm, the *Pixel*, *SCT* and *TRT* barrel module at $\eta = 0.3$ is depicted as well as parts of the support structures. The cooling and electronic systems are not shown for illustrative purposes.

Silicon Pixel Detector (*Pixel*)

The *Pixel* consists of three concentric barrel layers. The innermost one is located at 5 cm (see figure 4.4) from the beam pipe and referred to as beam pipe layer (or *b-layer*) due to its importance for accurately determining the transverse impact parameter which is essential for b-tagging performance, see section 4.3.4. Three additional disks of pixel sensors normal to the beam axis build the end-cap stations. Each *Pixel* layer is divided into modules (1744 in total) that form the fundamental unit of data acquisition. A module contains 47232 pixels of mostly $50 \times 400 \mu\text{m}^2$ surface area. In total the *Pixel* contains $80 \cdot 10^6$ channels and exposes a geometric acceptance of $|\eta| \leq 2.5$.

Each *Pixel* sensor contains a $250 \mu\text{m}$ thick layer of a $n^+ - n - p^+$ semi-conducting compound material that provides the fiducial volume. A high voltage is applied to this transition regions which (ideally) implies a charge depletion from it. If a highly energetic particle traverses this charge free volume, ionisation effects induce additional charge carriers, i.e. a voltage arises over the depletion zone that can be measured.

Every module is read-out by 16 radiation hard front-end chips which are bump-bonded to the sensor. In addition to read-out electronics, the *Pixel* is equipped with a comprehensive cooling system installed so the sensors operate between $-(5 - 10)^\circ\text{C}$. The cooling system removes about 24 kW of dissipation heat from the detector which in turn helps minimising leakage currents and degradation of doping concentration due to thermal effects. The *Pixel* detector provides a spatial resolution in ϕ of

$$\begin{aligned}\sigma(\phi)/\phi &= 10 \mu\text{m} \text{ and} \\ \sigma(z)/z &= 115 \mu\text{m}\end{aligned}\tag{4.5}$$

in z [121].

Semi-Conductor Tracker (*SCT*)

The *SCT* is separated in four concentric double layers of silicon micro strips in the ATLAS barrel. In the end-cap volumes, it consists of nine disks covering the full azimuthal angle on each side of the IP. In total, the *SCT* hosts $6.3 \cdot 10^6$ micro-strip channels. Each *SCT* plane is made from two discs that expose micro strips at a tilted angle with respect to each other. This geometric property aids the precise location of a hit in the transverse x-y plane. The *SCT* barrel layers are positioned at radii $r = 29.9 - 56.0 \text{ cm}$ as illustrated by figure 4.4.

Similar to the *Pixel*, the read-out of the *SCT* is segmented in 4088 modules. Every sensor is assigned a characteristic threshold voltage above which it is read out. The *SCT* is only read-out entirely if a higher level trigger *Pass* signal has been acquired. These data acquisition techniques are necessary to keep read-out occupancies (dead times) as low as possible given the large number of channels.

The *SCT* may provide measurements up to $|\eta| \leq 2.5$ with a total hit resolution of

$$\begin{aligned}\sigma(\phi)/\phi &= 17 \mu\text{m} \text{ and} \\ \sigma(z)/z &= 580 \mu\text{m}\end{aligned}\tag{4.6}$$

in z [121].

Transition Radiation Tracker (*TRT*)

The *TRT* encapsulates the silicon detectors and is comprised of 76 layers from longitudinal straw tubes (parallel to the beam axis) in the barrel and 160 radial straw planes one in each end-cap. As shown in figure 4.4, the *TRT* extends from $r = 56.3 - 108.0$ cm. The *TRT* end-caps were are designed to cover the domain of $1 < |\eta| < 2$. In total, 298,304 drift tubes, 4 mm in diameter, are read out by split anodes on each side. The barrel *TRT* is segmented into 3 radial layers and 32 ϕ sectors, the end-cap counterpart into 18 modules.

The *TRT* was designed to provide position measurement of passing charged particles as well as identification capabilities. To achieve this, it is setup in a fashion that particles with $p_t > 500$ MeV and pseudo-rapidity $|\eta| < 2$ pass 30 straws on average. By interleaving polypropylene fibres (barrel *TRT*) or polypropylene foils (end-cap *TRT*) into it, electron identification from transition radiation emitted by respective particle candidates is made possible. The detection principle of the *TRT* is based on ionisation. The straw tubes are filled with a mixture of Xe (70%), CO_2 (27%) and O_2 (3%). In addition, a voltage is applied between the cylindrical walls of a tube and an anode wire at its centre. If a charged particle (or energetic photon from transition radiation) passes the gaseous volume, charge carriers are produced. Due to the electric potential within the tube, they drift towards the anode wire or the cathode wall. This introduces a current in the attached electric circuit that can be recorded.

The production of transition radiation in this environment is limited to relativistic particles travelling with a Lorentz factor $\gamma = \frac{E}{m}$ above 1000. This can essentially only be fulfilled by electrons. Thus, the *TRT* is used to separate electron candidates from other hadrons (mostly pions) at high speeds by means of a threshold that separates mostly ionising particles from those that emit transition radiation in addition. Further details about particle identification with the *TRT* can be found in [121, 125].

The *TRT* may provide measurements up to $|\eta| \leq 2$. with an intrinsic hit resolution of

$$\sigma(\phi)/\phi = 140 \mu\text{m} \quad (4.7)$$

given that the wire position is known at an accuracy better than $50 \mu\text{m}$ [121].

4.2.3 Magnet Systems

The ATLAS magnet system houses two different types of magnets that provide magnetic fields of solenoidal and toroidal symmetry. The *Central Solenoid* magnet system is built around the *InnerDetector* in a cylindrical shape and generates a 2 T axial magnetic field around the interaction region. Thus, charged particle trajectories passing the *InnerDetector* are bent in the x-y plane and their momentum can be measured.

In addition, the ATLAS is equipped with one *Barrel Toroid* and two *End-cap toroid* systems. Each provides a toroidal magnetic field of 0.5 – 1 T for the muon detectors in the respective volumes of ATLAS. It is important to underline that this design provides the exceptional feature that charged particle trajectories are bent in the transverse $x - y$ plane within the solenoid field and (if their energy is sufficient) in the $r - z$ plane in the toroidal magnetic field.

4.2.4 Calorimetry Systems

The calorimetry systems are installed outside the solenoid magnet. They are designed to measure the position and energy of charged as well as neutral particles energy depositions. The calorimetry's design follows the dichotomy to record particles of electro-magnetic origin (electrons and photons) or hadronic origin (pions, kaons, etc.) respectively. The electro-magnetic calorimeter is a liquid argon sampling detector. The hadronic counterpart was engineered using two approaches: a plastic scintillator (active material) and iron (absorber) is used in the barrel; in the end-cap regions, liquid argon (as active material) and copper/copper-tungsten (as absorber) sampling calorimeters were installed.

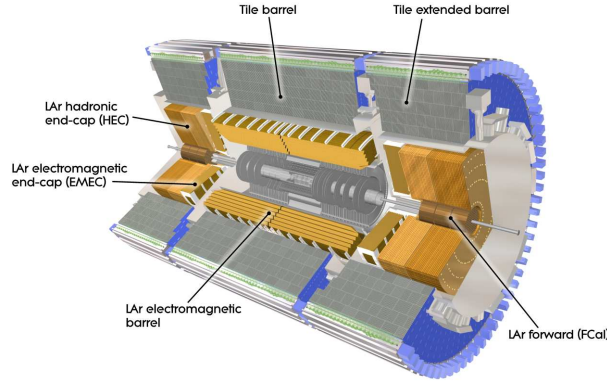


Figure 4.6: Three dimensional illustration of the ATLAS *Calorimeter* sub-detector setup for barrel and end-cap. Liquid-Argon based technology is marked in gold and Tile calorimetry in dark grey. Taken from [121].

Electro-magnetic Calorimetry

A lead-liquid argon sampling detector built in an accordion geometry provides the electro-magnetic calorimeter of ATLAS with full ϕ coverage (simply referred to as *LAr*). It is made of alternating absorber material (lead) so charged particles irradiate photons in a shower-like behaviour and the active material (liquid argon) provide the energy measurement thereof.

The detector within $|\eta| \leq 1.475$ is referred to as Barrel *LAr*, whereas two coaxial detector wheels on each side of the IP provide the End-cap *LAr* (outer wheel: $1.375 \leq |\eta| \leq 2.5$, inner wheel: $2.5 \leq |\eta| \leq 3.2$). In order to ensure full containment of electro-magnetic showers (caused by electrons and photons predominantly), the barrel *LAr* has a total thickness of more than 22 radiation lengths (X_0). The latter is defined as the mean distance in which a particle loses all but $1/e$ of its energy. The end-cap counter parts have a thickness of above $22 X_0$. Moving from the IP outwards, the calorimeters are segmented into three sections (or *samplings*), see figure 4.6, each built up of calorimeter cells that are the fundamental unit of read-out.

The first sampling has the highest granularity of cells with a radiation thickness of $4.3 X_0$ allows to pre-shower electro-magnetic particles, so photons can be separated. The second sampling has a depth of $16 X_0$ and represents the largest part of *LAr*. Most of a particles energy will be deposited there. While the pre-shower is a rather coarse detector, this sampling has a very fine granularity. Each cell has the size of $\Delta\phi \times \Delta\eta = 0.025 \times 0.025$ up to $|\eta| \leq 2.5$. The last (third) sampling has less granularity by a factor of 2 because electro-magnetic showers tend to be wide spread here. At

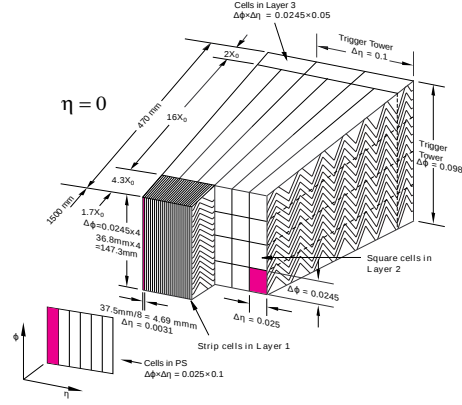


Figure 4.7: Three dimensional illustration of the ATLAS *LAr* setup at $\eta = 0$ projected into $\eta - \phi - r$ space. Taken from [121].

large pseudo-rapidities in the barrel ($\eta \approx 1$), an additional pre-sampler is installed between *LAr* and *InnerDetector* to allow an improved measurement due to the energy loss of particles in the *InnerDetector* and the cryostat located between *LAr* and IP.

The *LAr* provides an energy resolution of

$$\frac{\sigma_E}{E} = \left(\frac{10}{\sqrt{E/\text{GeV}}} \oplus 0.7 \right) \% \quad (4.8)$$

The first term of equation 4.8 represents the stochastic response of a sampling calorimeter. The last term gives resolution effects due to non-conformities of the calorimeter [121].

Hadronic Calorimetry

As presented by figure 4.5, the hadronic calorimeters encase the electro-magnetic facilities in r in the ATLAS barrel and in z in both end-cap volumes. As introduced above, the hadronic systems are composed of four subsystems that are based on two techniques. Within $|\eta| \leq 1.7$ referred to as *Tile*, the detector consists of scintillating plastic and iron tiles. At larger η of $1.5 \leq |\eta| \leq 3.2$ i.e. in close proximity of the beam pipe, the hadronic end-cap calorimeter (HEC) uses copper plates interleaved with liquid argon gaps. Closest to the beam at $3.1 \leq |\eta| \leq 4.9$, the forward calorimeter (FCAL) is installed made from copper-tungsten absorbers and liquid argon scintillation gaps.

The thickness of the hadronic detectors is expressed in units of λ which notes the mean free path of a particle before being subject to an interaction that is neither elastic nor quasi-elastic (i.e. does not change the projectiles energy) in a given medium. The *Tile* and HEC have a thickness of 9.7λ and the FCAL stretches 11λ . For *Tile* and HEC, an energy resolution of

$$\frac{\sigma_E}{E} = \left(\frac{50}{\sqrt{E/\text{GeV}}} \oplus 3 \right) \% \quad (4.9)$$

was observed. The FCAL yields [121]

$$\frac{\sigma_E}{E} = \left(\frac{100}{\sqrt{E/\text{GeV}}} \oplus 10 \right) \% \quad (4.10)$$

4.2.5 Muon Spectrometer Systems

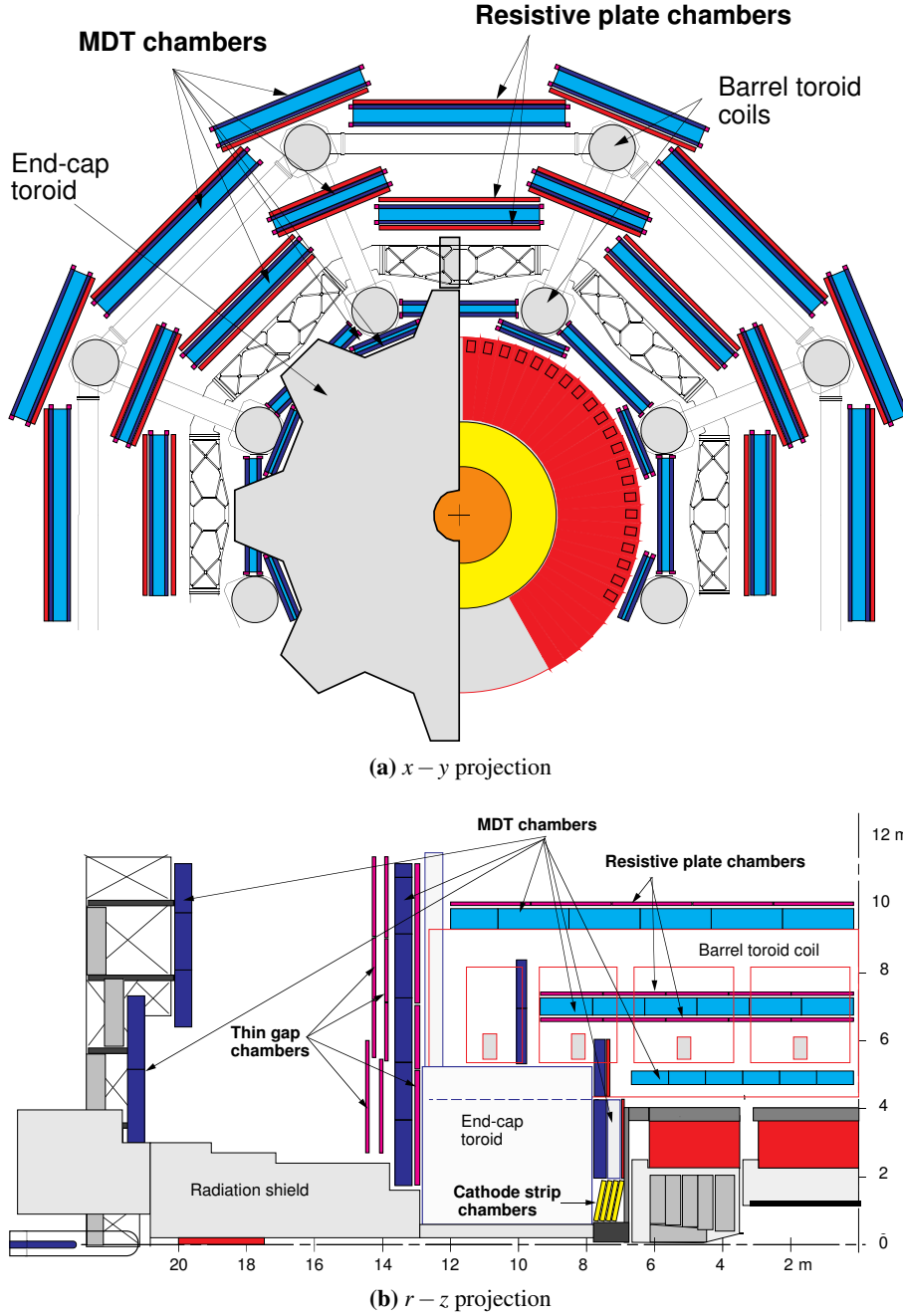


Figure 4.8: Transverse and longitudinal projection of the ATLAS *MuonSpectrometer*. Adapted from [121].

The muon spectrometer system (*MuonSpectrometer*) is shown in figure 4.7. It is installed in-between the toroid magnet coils of the barrel and end-cap magnet systems. Due to its distance to the IP and the amount of material (active or passive) in-between, predominantly muons are capable to reach it. As for the other sub-detectors, the *MuonSpectrometer* is separated into a barrel segment ($|\eta| \leq 1.05$) equipped with Monitored Drift Tubes (MDT) and Resistive Plate Chambers (RPC), see figure 4.7b, and the end-cap *MuonSpectrometer*. The latter provides sensitivity out to $|\eta| \leq 2.7$ and hosts Thin Gap Chambers (TGC) and Cathode Strip Chambers (CSC). Each *MuonSpectrometer* segment is capable of providing high precision position information and trigger information.

Due to its size and equipment, the *MuonSpectrometer* is able to provide an autonomous track measurement within the toroid magnetic field just as the *InnerDetector* is capable of in the solenoid field.

Monitored Drift Tubes (MDT)

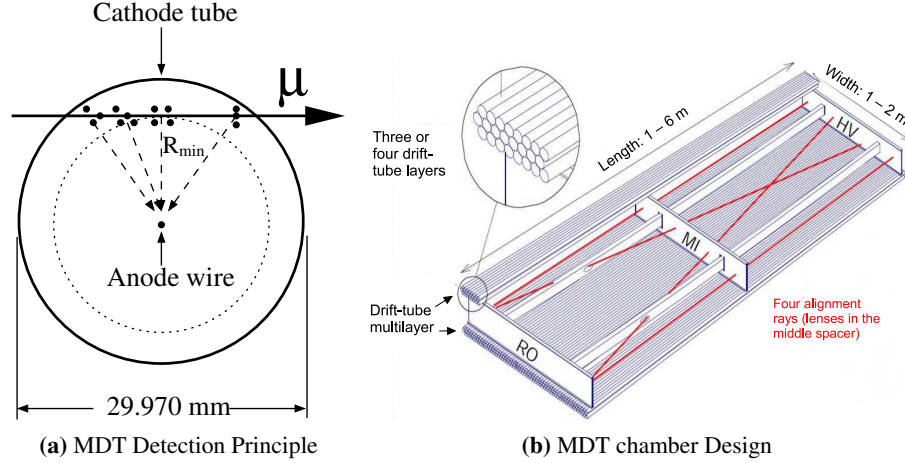


Figure 4.9: Working principle of a drift tube (a) and structural design of a muon chamber with MDT multilayers on each side (b). Besides the mechanical supports, the MDT chambers are equipped with an internal laser alignment system highlighted in red. Taken from [121].

In the barrel *MuonSpectrometer*, the MDTs provide a position measurement of charged particles in the $x - y$ plane with high precision $60 - 100 \mu\text{m}$ (depending on the irradiation of a tube). The tubes, 30 mm in diameter, are setup in multi-layers (mostly three or four layers) mounted on both sides on a muon chamber. The latter vary in size and provide the MDTs with a rigid support structure as well as a built-in alignment monitor by means of a three-dimensional diode laser system. This system can provide information on the deformation of the muon chamber during data taking which is essential information for track reconstruction. The chambers have a width of 1 – 2 m and a length of 1 – 6 m. This heterogeneous composition is due to the toroid magnet coils that the muon system has to adapt to.

The detecting principle of the drift tubes is similar to a proportional chamber. The MDTs are made from aluminium and filled with a $\text{Xe}(93\%)\text{-CO}_2(7\%)$ gas mixture. A rhenium-tungsten wire is strained in its centre. A high voltage is applied between the wire and the aluminium wall which depletes the gas of free charge carriers. If an ionising muon passes the tube, charge carriers are created in an avalanche drifting towards the wire. For the time of an interaction and the drift velocities of charge carriers in the gas are known, the position of the intersection of the particle can be evaluated in $x - y$ given the time a signal needs from the tube into the read-out electronics. The identification of the z position of the particle's intersection is hard to obtain for it is mutually exclusive with obtaining $x - y$ in this setup.

The Cathode Strip Chambers are not build from mechanically isolated tubes, but rather consist of multi-wire proportional chambers. Due to the radiation hardness of their design, they are located at $2.0 < |\eta| \leq 2.7$ closer to the beam pipe. The average drift times of charge avalanches for MDTs are 300 ns and for CSC around 30 ns. For passage through read-out electronics in addition, MDT and CSC technology cannot be used for providing a trigger signal. Therefore, the barrel and end-cap *MuonSpectrometer* is equipped with dedicated sub-detectors that allow for this.

Resistive Plate Chambers (RPC)

As illustrated by figure 4.7a, the MDT chambers are sandwiches by one or two RPC units depending on the position in r . The RPC is a gaseous parallel electrode-plate detector. Two plates of phenolic-melamine plastic laminate are positioned parallel to each other at 2 mm distance kept by spacers, see figure 4.9. Between them, an electric field of 4.9 kV/mm forces any charge carriers from ionisation of passing muons to avalanche towards the graphite anodes glued on top of the resistive plates. This signal is recorded by capacitive coupling for each anode strip. The gas mixture used is $C_2H_2F_4/Is - C_4H_{10}/SF_6((94.7/5/0.3)\%)$.

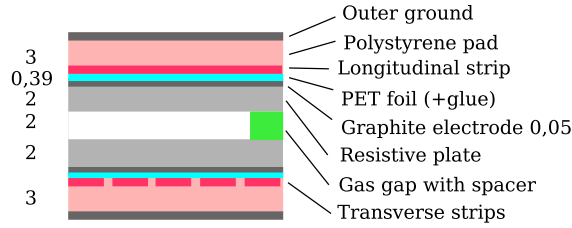


Figure 4.10: Schematic view of a RPC module illustrating the mechanical structure. All dimensions are given in mm and are not to scale. Taken from [121].

As sketched in figure 4.9, each gas gap is sandwiched by a longitudinal and transverse anode strip array. RPC chambers can provide position measurements in three coordinates with high precision. For each gas gap, the spatial resolution was observed to be 10 mm in z and ϕ respectively. Since every RPC unit houses two gas gaps, two position measurements in close proximity can be provided. The intrinsic timing resolution per chamber is 1.5 ns which is well within a bunch crossing separation of 25 ns.

In this setup, the RPC signals are read-out once per pp interaction and directly used as input to the trigger logic and the offline data acquisition system in parallel. With this, the RPC position information can be used for trigger and track reconstruction purposes.

Thin Gap Chambers (TGC)

The TGCs are multi-wire proportional chambers with a wire-cathode distance of 1.4 mm and a wire-wire separation of 1.8 mm. The gas volume is delimited by a graphite layer with a mixture of CO_2 and $n-C_5H_{12}$ within. On each side, copper pick-up strips are mounted to provide a measurement of ϕ . The wires within the gas yield the radial coordinate of a passing muon. The TGC is mounted in two concentric rings at each side of the ATLAS experiment. An outer (end-cap) ring covers $1.05 < |\eta| \leq 1.92$ in pseudo-rapidity and a forward ring reaching to $1.92 < |\eta| \leq 2.4$.

The TGC provide measurements with a resolution of 2 – 6 mm in r and 3 – 7 mm in ϕ . Each chamber can be read-out within 4 ns and the signal is again used as input to the trigger logic and the offline data acquisition, so that this information can be used for offline track reconstruction.

4.2.6 Luminosity Systems

In addition to the main ATLAS detector inside the experimental cavern at IP1, the experiment has three additional components that are situated at $z = \pm 17$ m (LUCID), $z = \pm 140$ m (ZDC) and $z = \pm 240$ m (ALFA) in copies of two along the LHC beam line.

The *L*uminosity measurement using *C*erenkov *I*ntegrating *D*etector (LUCID) represents the main relative luminosity monitor of ATLAS. It registers inelastic proton-proton scattering at very high η that can be linearly correlated with the total number of collisions that occurred. The Zero-Degree Calorimeter (ZDC) is responsible for detecting forward neutrons produced in heavy-ion collisions. The *A*bsolute *L*uminosity *f*or ATLAS detector (ALFA) consists of scintillating fibre trackers. These are mounted inside Roman pots that can be moved as close as 1 mm to the beam. ALFA provides the absolute luminosity measurement for ATLAS by exploiting the optical theorem. The latter relates the elastic proton-proton amplitude with the very forward scattered protons. This allows to measure the absolute luminosity delivered to ATLAS.

The luminosity measurement of 2010 proton-proton collisions used in this analysis was provided by the LUCID detector [118].

4.2.7 Trigger Systems

If the LHC provides proton-proton collisions at an event rate of 40 MHz at the design parameters, the ATLAS data acquisition is not able to record every event. The limit of data is set by the performance of data storage size and its speed. The maximum rate to conduct a full read-out of ATLAS is 75 kHz and the peak rate of saving events is limited to 200 Hz. The ensemble of proton-proton interactions is dominated by known elastic proton-proton and inelastic scatterings to a large fraction (see section 3.2.3). Thus, collision events of interest must be selected from all delivered collisions to reduce the rate of candidates to be considered for further processing.

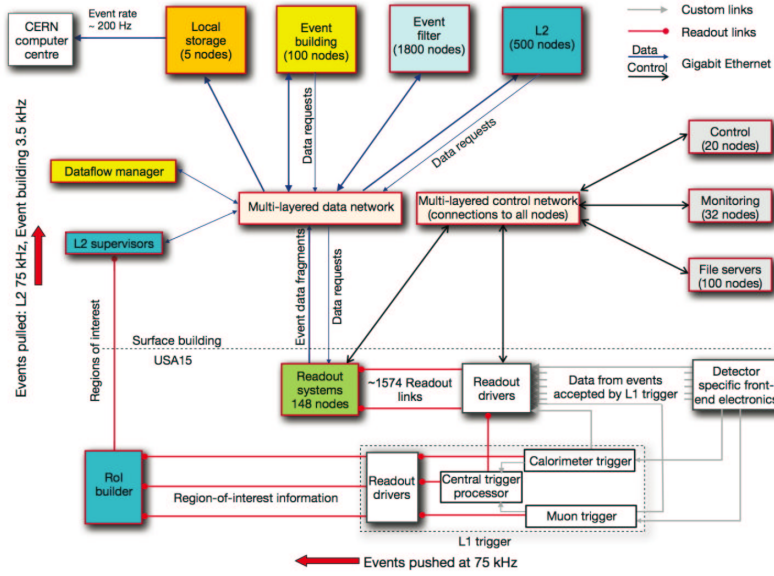


Figure 4.11: ATLAS trigger and data acquisition scheme denoting the stages of read-out on L1 underground as well as above ground for offline and higher level trigger processing. Taken from [121].

Figure 4.10 gives a general overview on the ATLAS three-stage trigger strategy as well as the flow of information for data acquisition. The first trigger stage is referred to as Level 1 (LVL1) and consists of a hardware-based logic that is integrated in the detector electronics [122]. The higher level trigger stages comprise the Level 2 (LVL2) and Event Filter (EF) which are based on algorithms performed on dedicated computer farms. Each level of the above refines the requirements an event must fulfil to obtain the respective *Pass* flag. If all three stages evaluate a *Pass* signal for a given event, it is stored for offline processing.

Level 1

In order to reduce the input rate of 40 MHz to 75 kHz, the LVL1 trigger has to provide a decision within $2.5\mu\text{s}$. For this, it has access to specialised sub-detectors (e.g. RPC and TGC) or a reduced granularity of available measurements e.g. through trigger towers of the calorimeters ($\Delta\phi \times \Delta\eta = 0.1 \times 0.1$).

The LVL1 calorimeter takes the energy of trigger towers above certain thresholds and their multiplicities into account to provide a decision upon the quantity and quality of found electro-magnetic clusters, tau lepton candidates, jet candidates, the missing transverse energy E_T , the scalar sum of

energies $\sum E_T$ and the total transverse energy of jets $\sum^{N_{jets}} E_T$ in the event. The trigger decision from the *MuonSpectrometer* is based upon the comparison of hit occupancy patterns that passing muons above predefined transverse momentum thresholds would create.

If an event acquires the LVL1 *Pass*, the event data is moved through the Readout Driver (ROD) into the Readout Buffer (ROB) for temporary storage (bottom section of figure 4.10).

Level 2

Given a LVL1 *Pass* in a detector volume, this signal is used as seed to define a Region-of-Interest (ROI) that is the input to the LVL2 trigger stage. Based on the LVL1 *Pass*, a ROI is affiliated to a transverse momentum threshold and a $\eta - \phi$ position. To evaluate the LVL2 *Pass* or *Fail* the detector within this volume is read-out at full granularity and hits are reconstructed on a custom PC farm. This stage reduces the event rate below 3.5 kHz with an average trigger processing time of 40 ms.

Event Filter

The final stage of trigger decision is provided by the EF. The algorithms used on this stage are typically identical to those used in the the offline reconstruction running on a custom PC farm. A LVL2 *Pass* for a given ROI is used as seed. The EF reduces the event rate to 200 Hz which is equivalent to 300 MB/s storage access.

Naming Conventions

For every trigger stage, trigger items of predefined momentum thresholds or multiplicities thereof are available. These items may be seeded by only one item of the previous stage but may invoke multiple items on the next, e.g. one LVL1 item may induce multiple LVL2 algorithms.

The nomenclature to denote trigger items used for this analysis follows

$$\{1\}_{-}[a][b]$$

Here, $\{1\}$ denotes the trigger stages, e.g. *L1*, *L2*, *EF*. $[a]$ refers to the trigger item used, e.g. *mu* for muon triggers. $[b]$ represents the threshold a candidate event or object has to pass for a *Pass* to be obtained, e.g. 15 for a 15 GeV threshold.

Prescales

In due course of operation, the definitions of trigger items will be superseded in a sense that their defined threshold result in a rate of events obtaining *Pass* that is too high to store all the events' information at [126]. Thus, the ATLAS trigger systems distributes pre-scale factors N that only one out of N events of declared to *Pass* by a specific trigger are allowed to proceed. The pre-scale factors can be applied on all three trigger levels individually.

4.3 ATLAS Data Taking

If an event was stored, the measurements provided by individual sub-detectors do not allow a straight analysis in terms of muon or jet candidates. An extensive software framework [127] was created that allows the reconstruction of these events and a subsequent storage of events for physics analysis among other capabilities. The following sections will introduce the key algorithms needed to perform an analysis of $Z^0 + b$ final states of LHC collisions with ATLAS data.

4.3.1 Inner Detector Tracking

Based on the high spatial resolution the *InnerDetector* components may provide (equations 4.5, 4.6 and 4.7) at close proximity to the interaction point, the hits collected are subject to track reconstruction algorithms. The *InnerDetector* track reconstruction [128] is comprised of a multi-stage pattern recognition algorithm combined with a Kalman filter [129] to remove ghost tracks¹, loopers² and V_0 ³ yielding good performance [130].

The track objects created by the *InnerDetector* track reconstruction are also input to the primary vertex (PV) finding algorithm [131]. For this, intersections of tracks with more than or equal to two tracks attached to it are searched for. Among the ensemble of proto vertices thus created, the object with maximal squared scalar track transverse momentum sum $\sum |p_t|^2$ is declared the primary vertex of the interaction, which proved to be a valid assumption [132].

4.3.2 Muon Reconstruction

As outlined in section 4.2.5, the *MuonSpectrometer* is able to provide hit position measurements that allow an autonomous track reconstruction. For this, two algorithms are available: *Moore* [133] and *MuonBoy* [134]. The general strategy of both follows a bottom-up approach. First straight line track segments are searched for in each muon chamber individually. On these small scales, the track curvature due the magnetic field is negligible, thus straight line segments are formed. Segments from at least two muon chambers are then combined and refitted to yield a full track on *MuonSpectrometer* level. The fit algorithm itself accounts for the introduced bending and multiple scattering.

To select *MuonSpectrometer* hits as input to the segment finding, the *Moore* algorithm performs a Hough transform [135] on the ensemble of hits per event in the bending ($r - z$) and non-bending ($x - y$) planes that categorises viable hit candidates inside *roads*. Straight line segments are formed from at least three MDT chamber hits and RPC hits in the associated units, see 4.2.5. Segment patterns are found by an additional Hough transform and a 5-parameter trajectory is fitted on this ensemble (with at least six MDT hits).

The *MuonBoy* algorithm is different in the details. First regions of activity are defined from the RPC (or TGC) information only. Then straight line segments are formed and the combination of segments from different stations is finally subject to a global fit.

¹Reconstruction effect due to combination of hits that are located near charged particle depositions by coincidence.

²Trajectories of particles with small momentum and thus unable to pass the *InnerDetector*.

³Electron-Positron pairs from photon conversions, K_s or Λ decays inside the detector volume.

The ATLAS experiments comprises multiple muon identification algorithms. The observation that predominantly muons have the energy loss profile to reach the muon chambers provides a strong argument in order for *MuonSpectrometer* only tracks to be regarded as muon candidates. Further, measurements from the *InnerDetector* and/or *Calorimeter* are used also to provide combined muon candidates. These can be categorised in three families upon the type of object they create [136]:

- *Calorimeter based algorithms*
These use the complete *InnerDetector* track and affiliated *Calorimeter* cluster measurement satisfying the requirement of a minimum ionising particle.
- *Segment-Tagged Algorithms* (MuGirl and MuTag)
An *InnerDetector* track and muon segments from the inner muon chamber layers (see figure 4.7b) that can be affiliated to the *InnerDetector* track are used as input here.
- *Combined Muon Algorithms* (Muid and Staco)
Given a *InnerDetector* and *MuonSpectrometer* track, the combined muon candidate object is the result of a complete refit (Muid) or the statistical combination of the two (Staco).

The optimal reconstruction purity $P = \frac{N_{\mu cand}(rec|not\ from\ muon)}{N_{\mu cand}(rec)}$ per generated muon particles is expected from combined muon algorithm candidates. The Moore combined (Muid) and standalone algorithm yield

$$P_{Moore}(\text{combined}) = 0.11\%$$

$$P_{Moore}(\text{standalone}) = 15.6\%$$

in $t\bar{t}$ events with pile-up expected for a LHC luminosity of $\mathcal{L} = 10^{33} \text{ cm}^{-2} \text{ s}^{-1}$ [137]. The approach of using information from both detectors (*InnerDetector* and *MuonSpectrometer*) exploits the virtues of each while being able to damp their respective short-comings as illustrated by figure 4.11.

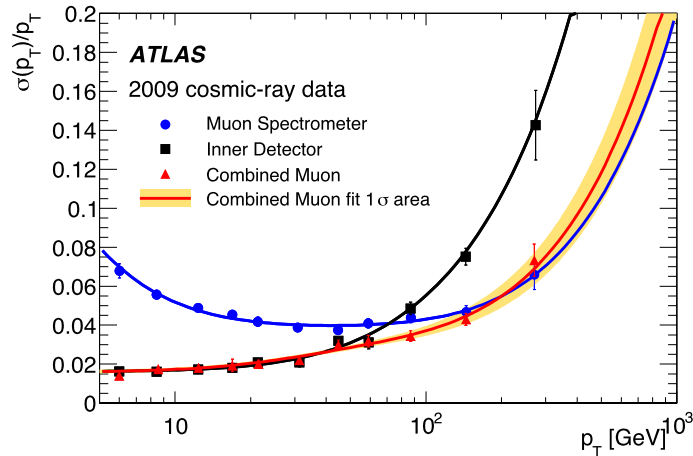


Figure 4.12: Transverse momentum resolution observed in 2009 cosmic data taking for *InnerDetector* and *MuonSpectrometer* only tracks as well as combined muon candidate objects. Taken from [138].

At low muon momenta below 60 GeV, the low resolution of muon hit information (compared to the *InnerDetector*) in conjunction with the large volume of the *MuonSpectrometer* does not allow for a precise momentum measurement and reaches 8% transverse momentum resolution while

the *InnerDetector* is able to estimate the momentum with 2% resolution. In the high momentum regime above 100 GeV, the particle trajectories become rather straight that the small volume and magnetic field of the *InnerDetector* has not enough lever arm to result in a precise fit of the spiral trajectory even though it offers spatial resolutions better than the *MuonSpectrometer* by factor of 10. Here, the *MuonSpectrometer* tracking exposes a better resolution. For this analysis on the Z^0 resonance, a mean muon transverse momentum of 45 GeV is expected. Thus, the muon candidates used here are located within the transition region reported by figure 4.11.

4.3.3 Clustering and Jet Finding

Contrary to leptons, partons produced in pp events are not observed as freely propagating particles, see section 2.4.1. The production of partons in proton-proton interactions results in the generation of an ensemble of hadronic objects which can be observed as sprays of particles traversing the detector in a specific sub-volume - see section 3.2.2 for a discussion thereof. In order to consistently and automatically characterise these jet objects, dedicated algorithms are applied that are discussed in dedicated reviews [139, 140].

From an experimental point of view, the input to these jets is crucial for it affects the energy measurement and angular direction of a jet object dominantly. The ATLAS jet reconstruction is able to process inputs from four difference categories which are combined upon a *recombination scheme* [140], i.e. their Lorentz vectors are added within the canonical Minkowski metric. Calorimeter measurements are obtained by clusterisation algorithms to provide a four-momentum entity of zero mass as input to the jet reconstruction. *InnerDetector* tracks may also be used as unclustered input to jet reconstruction comprising the measured momentum and the π meson assumption concerning their mass. A discussion of track jets can be found in [141].

Calorimeter Towers

The simplest approach in clustering *Calorimeter* measurements provided in cells is to use a geometric criterion ($\Delta\phi \times \Delta\eta = 0.1 \times 0.1$) without further corrections for noise, so called towers. Being applied at DØ [142] and CDF [143] experiments, the method introduces artifacts due to noise fluctuations that may give rise to jet objects with negative energy. This is caused by the requirement of having four-momentum objects as input given large fluctuations of the energy measurement but assuming the mass to be zero. Thus, ad hoc schemes have to be introduced that correct for this short coming and e.g. combine negative mass clusters with nearby clusters until a cluster of positive energy is obtained.

Topological Clusters

Topological clusters [144] are the result of a iterative combination algorithm that forms three-dimensional objects seeded by a *Calorimeter* cell whose measured energy is four times larger than the expected noise level $|E_{cell}| > (\mu_{noise} + 4\sigma_{noise})$ given by the average noise μ_{noise} and its standard deviation σ_{noise} . The quantification of a cell's energy distribution due to noise is obtained from randomly selected events which must not coincide with a pp interaction. Neighbouring cells satisfying $|E_{cell}| > 2\sigma_{noise}$ are then added to the cluster until no nearest neighbouring cell satisfies this criteria anymore. Finally, all remaining nearest-neighbour cells are added. The resulting clusters can be split or merged whether local minima or maxima are found within. Negative energy clusters are rejected in this approach.

Noise-suppressed towers

Noise-suppressed towers are obtained from an angular $\Delta\phi \times \Delta\eta = 0.1 \times 0.1$ grid just as Tower clusters are, but their energy is evaluated from cells that were selected using a topological clustering. They henceforth combine the simplicity of tower clusters with the noise-suppression provided by a topological clustering.

The anti-kt jet Algorithm

Jets are bundles of four-momentum objects [140]. This definition is not restricted to combine *Calorimeter* clusters only. It is meant in a broad sense that has important implications in theory and experiment. The choice of a jet algorithm that does not adequately take soft radiation in proximity of a jet or that cannot distinguish close-by jets efficiently leads to infrared or collinear unsafe results when compared to theory.

The collinear and infrared safe *anti-kt* algorithm [145] used for this analysis is defined upon a distance metric $d_{i,j}$ and an angular metric $\Delta R_{i,j}$ between two particles i, j with respective four-momenta and the distance to the beam $d_{i,B}$ of particle i :

$$\Delta R_{i,j}^2 = (y_i - y_j)^2 + (\phi_i - \phi_j)^2 \quad (4.11)$$

$$d_{i,j} = \min(p_{t,i}^{-2}, p_{t,j}^{-2}) \frac{\Delta R_{i,j}}{R^2} \quad (4.12)$$

$$d_{i,B} = p_{t,i}^{-2} \quad (4.13)$$

The *anti-kt* algorithm given an event of N four-momenta (i.e. particles) and a critical metric R is as follows:

1. Evaluate $d_{i,B}$ and $d_{i,j}$ for all entities in the event
2. Find the minimum of all values $d_{i,B}$ and $d_{i,j}$
3. If the minimum found . . .
 - is a $d_{i,j}$, recombine i and j into a single new particle and return to 1.
 - is a $d_{i,B}$, declare i to be a final state particle and remove it from the list of particles to consider, return to 1.
4. Stop if no particles are left.

Due to the inverse transverse momentum entering in equation 4.12, the *anti-kt* algorithm grows jet objects from high p_t particles downwards in momentum. Since the angular distance enters as well, this approach is considered collinear safe (small angles from collinear branchings result in small $d_{i,j}$). Due to its grow from the hardest seed outwards, this algorithm is infrared-safe as well. For ATLAS physics analysis, the default value for R is 0.4 [146].

Jet Energy Calibration

The resulting object from the *anti-kt* algorithm with *Calorimeter* clusters as input does not yield the energy that corresponds to the sum of momenta of particles it originated from. The thus obtained jet energy must be calibrated. The simplest approach transforms the measured energy E_{rec} to the equivalent energy of the electro-magnetic level E_{EM} [147–152]. During test beams studies [147, 151, 153, 154] most parts of the ATLAS *Calorimeter* have been subject to electron and photon beam irradiation of known energy and angle. With this, the response of the calorimeter design, its read-out and material to an electro-magnetic shower was evaluated. The EM calibration was obtained from comparing the measured E_{rec} with the incidents beam energy E_{EM} . This calibration is available for the *LAr*, *Tile* and *FCAL* calorimeters.

Hadronic objects that are the proponents of jets induced by partons, do not provide the same shower behaviour than electro-magnetic particles. Therefore, an additional calibration to the EM scale must be applied (referred to as JES, [155]). It entails corrections for partial measurements of the energy deposited by hadrons (calorimeter non-compensation), energy losses in inactive parts of the detector (dead material), additional energy deposits from particles not contained in the calorimeter (leakage) and energy deposits of particles that are not picked up by the reconstruction (out-of-cone).

To recover the defects named above, a η -dependent EM+JES calibration scheme was applied to 2010 data. It is based on Monte Carlo simulation while its application was validated in 2010 data and consists of three fundamental steps

1. The mean energy surplus observed if multiple interactions take place is subtracted from the energy measurement in detector volumes close to the beam pipe (the extent of this correction was obtained in data),
2. The jet position is corrected to point to the primary vertex instead to the nominal IP and kinematics of each cluster is recalculated,
3. The reconstructed jet energy and position are corrected by comparing data with Monte Carlo simulation.

For the EM+JES calibration, the last of these three steps is the most important. It is driven by the jet response R_{jet} defined by the reconstructed energy in data divided by the generated energy E_{gen} of a jet with equivalent properties after reconstruction in MC events.

$$R_{jet} = \frac{E_{rec}}{E_{gen}} \quad (4.14)$$

R_{jet} is recorded in bins of E_{rec} and η_{rec} and fitted by a Gaussian *PDF*. It can be defined with respect to a specific calibration entailed on reconstructed jets, e.g. $R_{jet,EM}$ on EM level. The resulting mean values are used to derive a parametrisation of the response calibration F_{calib} in a jet's pseudo-rapidity. The final calibration can then be performed as

$$E_{rec}^{EM+JES} = \frac{E_{rec}^{EM}}{F_{calib}}. \quad (4.15)$$

Figure 4.12 illustrates the extent to which jet energy measurements as observed by the detector are corrected. Figure 4.12a shows that corrections are more dramatic for softer jets. The correction factors may reach down to 50 %. Given the ensemble of sources for additional energy deposits or drains, if the jet energy is small, the effect can be considerable. Figure 4.12b illustrates this behaviour again with the correction ascending to 200 %. It is also noteworthy that $\langle R_{JES} \rangle$ decreases at higher η bins. This behaviour is attributed to the geometric effect (η is a logarithmic function of θ) that a jet of fixed angular width $\Delta R = 0.4$ covers less volume at high η than it does at low. Further, the material budget at high pseudo-rapidity is lower than e.g. for central detector volumes - see figure 4.13.

The resulting *EM+JES* calibration was validated using $\gamma^* + jets$ event topologies in 2010 data [157]. For this, the kinematic balance between photons and reconstructed jets is used to determine the jet energy scale with respect to the photon energy measurement in the electromagnetic

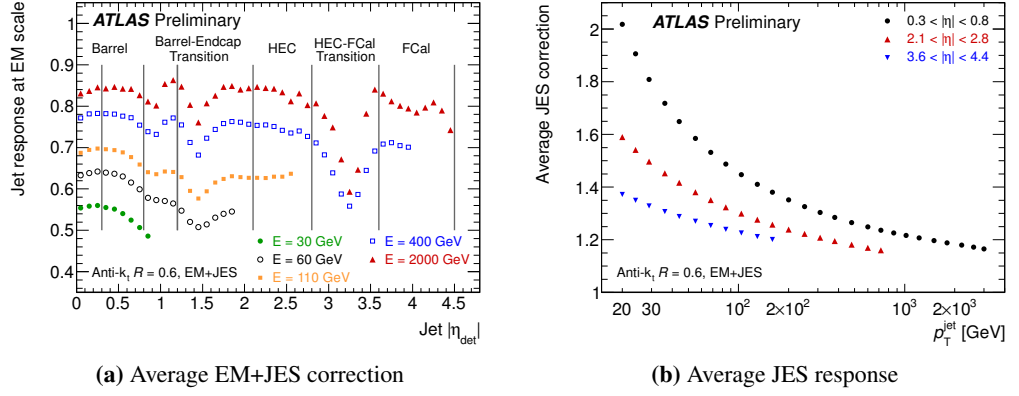


Figure 4.13: Jet response at EM scale for EM+JES calibrated jets estimated in simulation (a). Jet energy scale corrections as a function of the calibrated jet transverse momentum and pseudo-rapidity. Taken from [156].

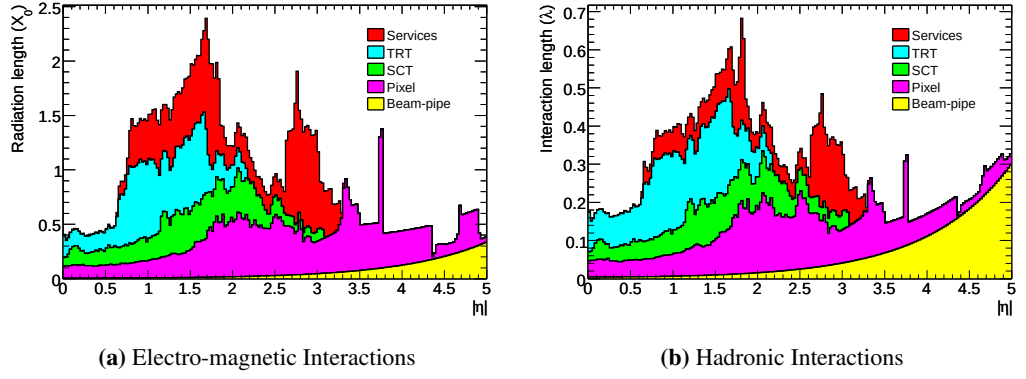


Figure 4.14: InnerDetector material budget in units of electro-magnetic interaction lengths X_0 (a) and hadronic interaction lengths λ (b) from [121].

calorimeter. From this measurement, correction factors to be applied to simulated events have been calculated.

Figure 4.14 illustrates that data to MC corrections for EM+JES corrected jets remain below 3 % being a solid proof of this calibration's viable performance.

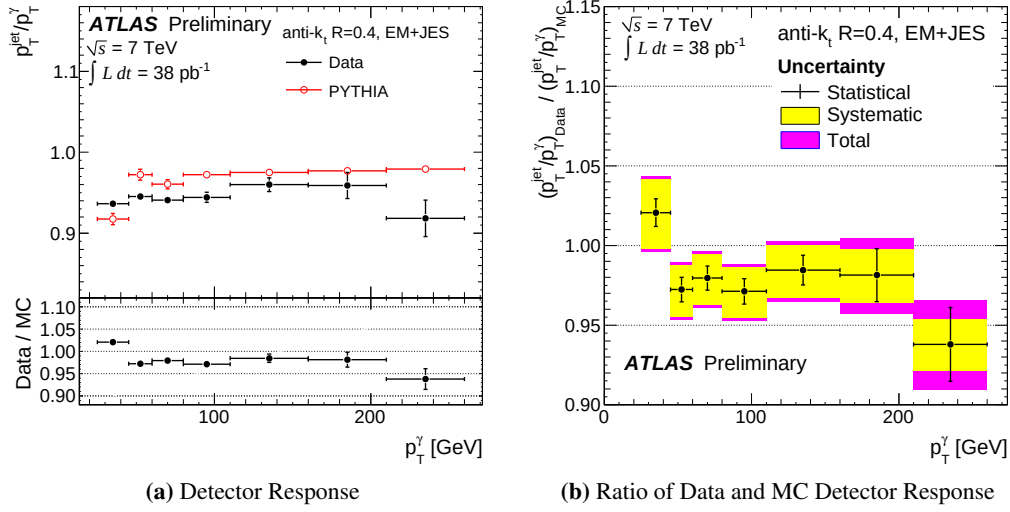


Figure 4.15: Jet detector response p_T^{jet}/p_T^γ in data and simulated events (a) and corresponding Data/MC scale factors (b) of reconstructed *anti-kt*(0.4) *EM+JES* jets in 2010 ATLAS data, from [157].

4.3.4 Heavy Flavour Tagging

One of the main goals of this analysis is the efficient selection of reconstructed jets that were induced by heavy flavour partons (*charm*, *bottom* quarks). These fragment dominantly into excited heavy flavour baryons which decay further into affiliated ground states.

hadron type	$f_{hadrons}/\%$	m/MeV	$c\tau/\mu m$
B^+ or B^0	40.0 ± 1.2	$m_{B^+} = (5279.17 \pm 0.29 5279 \pm 0.4)$ $m_{B^0} = (5279.5 \pm 0.5)$	$c\tau _{B^+} = 491.1$ $c\tau _{B^0} = 457.2$
B_s^0	11.5 ± 1.3	(5366.3 ± 0.6)	441
$b-hadrons$	8.5 ± 2.1		

Table 4.1: Combined fragmentation fractions $f_{hadrons}$ and related uncertainties of b partons to b hadrons obtained from e^+e^- at LEP and $p\bar{p}$ collisions at Tevatron [158]. The respective meson's masses and lifetimes given were taken from [11].

Table 4.0 reports the current experimental observations on b parton fragmentation ratios. The high mass of B mesons and a lifetime on the level of $500\mu m$ offer observables that can be exploited for b hadron identification. For example, a B meson with $E = 50\text{GeV}$ exposes a Lorentz boost that results in a visible flight length of 3 mm in the laboratory's frame of motion. The latter results in the advent of secondary vertices (SV) of charged particles which are displaced from the PV in jets initiated by heavy flavour partons, see figure 4.15.

Comparing the magnitude of B meson flight paths from above with the resolution offered by the *InnerDetector* detectors allows the conclusion that SV from B meson decays can be observed experimentally. It is characterised by an impact parameter with respect to the PV.

Generally, the latter is given as the distance of a track or vertex (the SV in this case) to a reference point (e.g. IP at (0,0,0) or the PV) in the $r-z$ plane referred to as the longitudinal impact parameter or in the $x-y$ plane referred to as the transverse impact parameter. At ATLAS, they are defined as:

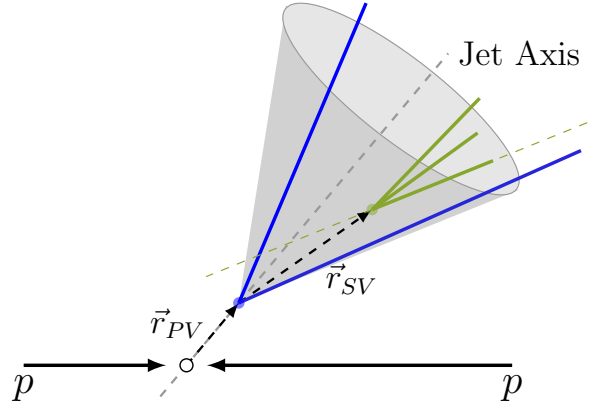


Figure 4.16: Illustration of a heavy flavour jet produced in pp collision and a selection of charged constituents exposing a primary (PV, blue) and a displaced secondary vertex (SV, dark green). Relative dimensions not to scale. The three-dimensional positions of the PV and the SV (with respect to the PV) are given as well.

$$IP_z = z_0 \sin \theta \quad (4.16)$$

$$IP_t = \text{sign}(d_0) \cdot d_0. \quad (4.17)$$

Here, $\text{sign}(d_0)$ is defined to be $+1$ if the intersection of a tracks' extrapolations with the jet axis lies in the hemisphere of the point of closest approach with respect to the PV. Otherwise, $\text{sign}(d_0)$ is -1 .

Among others [159], two approaches that are of concern for this analysis are used to identify jets with displaced vertices:

lifetime tagging The ensemble of tracks associated to the jet is searched for common vertices by a Kalman filter algorithm [129, 160] that are significantly displaced from the PV given the experimental resolution. If a SV is found, its properties like the longitudinal or transverse impact parameter significance with respect to the PV can be used as discriminant.

impact parameter tagging Given the existence of a displaced vertex in a jet, the number of tracks with large impact parameters is higher than compared with jets without a SV.

For the analysis at hand, a combined tagging algorithm (IP3D+SV1, the linear combination of SV1 and IP3D) and a simple lifetime tagging algorithm (SV0) were used. Due to the low momenta that are expected from B meson daughter particles, the ensemble of tracks entering these algorithms is cleaned to avoid fake reconstructions. The corresponding requirements are listed in the appendix section B.1. These tracks are henceforth associated by an angular criterion to the jet $\Delta R(\text{track}, \text{jet}) < R$, where R is given by the critical metric of the jet finding algorithm (see section 4.3.3). All of the above mentioned algorithms express the likelihood of a jet being initiated by a b parton as a one dimensional quantity - the b -tagging weight w (not limited to $[0, 1]$). For the SV0 and SV1 algorithms this weight is defined by the signed longitudinal impact parameter $\vec{L}$ divided by its uncertainty :

$$w_{SV} = \frac{\text{sign}(\vec{L}) \cdot \vec{L}}{\sigma(L)}. \quad (4.18)$$

$\vec{L}$ is defined as the longitudinal projection of $\vec{r}_{SV}$ (figure 4.15) onto the jet axis. $sign(\vec{L})$ is negative if $\vec{r}_{SV}$ is in-between the PV and IP. If that is not the case, $sign(\vec{L}) > 0$. During the search for the SV, SV0 allows for negative values of $sign(\vec{L}) \cdot \vec{L}$, i.e. SVs that were resolved to lie in the opposite hemisphere than the jet constitutes with respect to the PV. The SV1 does not allow this.

The impact parameter tagging algorithms use distribution of IP_z and IP_t for tracks contained in bottom, charm or light flavour initiated jets in MC simulation. Since MC simulated events are available at a large number, the probability density functions $f_b(IP_t), f_c(IP_t), f_l(IP_t)$ and equivalently for IP_z can be obtained. For N tracks associated to a reconstructed jet, an estimator for the heavy flavour likelihood can be noted by using the Neyman-Pearson lemma [161]:

$$L(IP) = \frac{\prod_{i=1}^N f_b(IP_i)}{\prod_{i=1}^N f_l(IP_i)}. \quad (4.19)$$

Implementing this likelihood with two-dimensional probability density functions depending on IP_z and IP_t gives the IP3D b-tagging weight as

$$w_{IP3D} = \log L(IP_t, IP_z) = \log \frac{\prod_{i=1}^N f_b(IP_{t,i}, IP_{z,i})}{\prod_{i=1}^N f_l(IP_{t,i}, IP_{z,i})}. \quad (4.20)$$

To conclude, the SV0 algorithm provides a simple and robust scheme to obtain a figure of merit for the likelihood of a jet to be heavy flavour induced. Thus it was among the early taggers used for ATLAS data [162]. The IP3D+SV1 uses a composite ansatz and relies on MC reference information. The latter requires a more thorough validation before it can be used for physics analysis [159].

4.3.5 Simulation And Computing Model

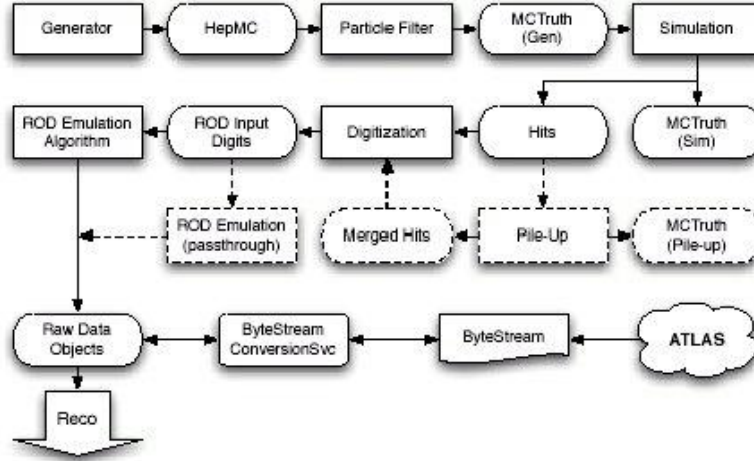


Figure 4.17: Illustration of the data flow of the ATLAS computing model for data taking and simulation. Adapted from [163].

Figure 4.16 illustrates the ATLAS computing model that builds the back bone of data taking, simulation and data analysis at the ATLAS experiment. This model represents the computational workflow necessary to provide simulated or experimentally observed events. For this, the data stream from the ATLAS experiment is marked in light grey. The event are read-out from the experiment in a byte-stream format and are subsequently stored as Raw Data Object (RDO) files. In

order to offer simulated events that are the result of MC calculations as discussed in chapter 3, the data path taken by the signal a particle leaves in the detector is mapped onto the simulation.

For this, MC software provides an ensemble of simulated events according to a prediction. These are filtered if a specific final state cannot be generated exclusively. The events enter the simulation that is based on the Geant4 toolkit [164, 165] in which the entire ATLAS detector is digitally mapped into. The simulation performs the passage of the generated particles through the active and inactive material of the detector and produces particle hits. At this stage, the possibility of overlaying this single proton-proton interaction with multiple ones to emulate pile-up conditions and cavern background radiation. These hits are hence digitised and enter the simulation of the read-out electronics. From here, the passage through the trigger logic is simulated and added to the data stream until finally an event can be saved in RDO as if it would have been recorded by the detector. Due to the RDO event size of 1.6MB combined with the high rate of events delivered by the LHC, the data storage, processing and analysis of the simulated and recorded events is non-trivial. International distributed computing storage and computing resources are required for this [163, 166, 167].

Chapter 5

Datasets

To establish the basis for a detailed description of the analysis approach, the observed and simulated data set analysed is introduced. For this, signal and background final states used in simulation are noted, after which the applied pile-up simulation is discussed. Then, the experimental data taking conditions ranging from LHC collision delivery to ATLAS detector status are concisely illustrated.

5.1 Simulated Pseudo-Datasets

The available simulated pseudo data (see section 4.3.5) contains the Monte Carlo prediction of signal and background processes at detector level expected to contribute to $Z^0 + \text{jets}$ and $Z^0 + b + X$ final states. The notation chosen here highlights the fact that this study's focus is on the selection of events yielding a Z^0 boson and at least one bottom quark induced jet. The ensemble of events complying to this requirement are denoted $Z^0 + b + X$ final states, where X encompasses any additional hadronic or leptonic activity in the event, so $Z^0 + b + X$ is entirely contained in $Z^0 + \text{jets}$.

From here onward, a rigorous distinction between Monte Carlo (MC) pseudo data and simulation is lifted and the term MC is used for both onwards. These MC datasets contain the complete detector response and reconstruction results expected from equivalent events in real data taking, see section 4.3.2. The section at hand will state the respective MC generator and configurations used for event generation.

5.1.1 Signal Datasets

One motivation for this study is to provide a measurement to test the validity of two competing calculation schemes to predict the production of $Z^0 + b + X$ at hadron colliders. For this, two leading-order matrix element plus parton shower MC generators were used: SHERPA and ALPGEN. In the setup used for this study, both generators use different schemes to extract bottom flavour partons from given PDF sets as highlighted also in section 3.3.1. Furthermore, both signal samples contain Z^0/γ^* resonances decaying into muon pairs.

With SHERPA 1.1.3 (see [73]), a dedicated $\ell^+\ell^- + N \text{ jets}$ ($0 \leq N_{\text{jets}} \leq 3$) sample for $\ell = e, \mu, \tau$ lepton flavours has been produced. Here, all diagrams exhibiting bottom or charm flavour partons in final or initial state receive an additional event weight of 10 and thus the bottom/charm final state

content of the event sample is enhanced. For simulating proton-proton collisions, the SHERPA generator was setup with LO CTEQ6L PDF (error PDF set 1, [168]) and an additional requirement on the invariant lepton-lepton mass $m_{\ell^+\ell^-} > 60\text{ GeV}$ on matrix element level constraining the available phase space to suppress excited photon plus jets diagrams, $\gamma^* + \text{jets}$, at low values of $m_{\ell^+\ell^-}$. The CKKW parton-shower matrix element merging as introduced in section 3.1.3 was conducted with $Q_{CKKW} = 20\text{ GeV}$.

Pseudo data sets of $\ell^+\ell^- + N_{\text{partons}}$ parton ($0 \leq N_{\text{partons}} \leq 5$) with $\ell = e, \mu, \tau$ were produced with ALPGEN 2.13 [74]. A matching scale in energy of $E_{t,MLM} = 20\text{ GeV}$ and angular distance of $\Delta R_{MLM} > 0.6$ was used for MLM matrix element parton shower matching. All ALPGEN $Z^0 + \text{jets}$ samples were generated with $40\text{ GeV} < m_{\ell^+\ell^-} < 2000\text{ GeV}$. The LO CTEQ6L1 PDF set was used for ALPGEN MC events. This event sample is split into samples per number of partons N_{parton} that satisfy $E_{t,\text{parton}} > E_{t,MLM}$.

In order to enrich bottom quark related final state events, an additional sample of $\ell^+\ell^- + b\bar{b} + X$ ($0 \leq N_{\text{partons}} \leq 3$) was generated with ALPGEN 2.13 and admixed to $\ell^+\ell^- + N_{\text{partons}}$ parton ($0 \leq N_{\text{partons}} \leq 5$) events. However, both $\ell^+\ell^- + b\bar{b} + X$ and $\ell^+\ell^- + N_{\text{partons}}$ parton ($0 \leq N_{\text{partons}} \leq 5$) event samples contain events with $\ell^+\ell^- + b\bar{b}$ final states and thus combining the two results in an overlap. The procedure applied [98, 169, 170] is adopted where $\ell^+\ell^- + b\bar{b}$ type events are selected based on a $\Delta R(b, b)$ criterion and henceforth coherently removed to resolve the overlap. It is important to note that ALPGEN implements a 4-FFS, but was configured using a 5-flavour PDF.

Sample	σ_{LO}/pb	σ_{NNLO}/pb	Event Yield
SHERPA $Z^0 + \text{jets}$ [73] $m_{\ell^+\ell^-} > 60\text{ GeV}$, enhanced b/c fraction, CTEQ6L	1012.41	989 [171]	181309.8
ALPGEN $Z^0 + \text{jets}$ [74] $40\text{ GeV} < m_{\ell^+\ell^-} < 2\text{ TeV}$, CTEQ6L1		1036 [171]	
$N_{\text{parton}} = 0$	669.68		2038316
$N_{\text{parton}} = 1$	134.64		1333531
$N_{\text{parton}} = 2$	40.749		402812
$N_{\text{parton}} = 3$	11.246		109917
$N_{\text{parton}} = 4$	2.8462		29962
$N_{\text{parton}} \leq 5$	0.76319		9993
ALPGEN $Z^0 + b\bar{b}$ [74], $40\text{ GeV} < m_{\ell^+\ell^-} < 2\text{ TeV}$, CTEQ6L1	12.4 [171]		
$N_{\text{parton}} = 0$	6.5283		149923
$N_{\text{parton}} = 1$	2.469		99930
$N_{\text{parton}} = 2$	0.88279		38950
$N_{\text{parton}} = 3$	0.3857		9994

Table 5.1: Collection of simulated data samples used for signal processes for $\mu^+\mu^- + \text{jets}$ topologies, their generated LO and NNLO cross section as well as the effective event yield available for this analysis.

Where possible, LO cross sections have been normalised to corresponding values from higher

order calculations. Table 5.0 shows cross section and event contents of signal MC samples. It is important to note here that LO MC datasets that contain weighted events are summed up accordingly. The SHERPA dataset yields a total (effective) event yield of 181309.8 which represents the sum over all event weights. ALPGEN $Z^0 + \text{jets}$ and $Z^0 + b\bar{b}$ samples have been normalised to $\sigma_{NNLO}(Z^0 + \text{jets}) = 1036\text{pb}$ and $\sigma_{NNLO}(Z^0 + b\bar{b} + X) = 12.4\text{pb}$ respectively after all LO sub-samples have been added. Although the latter named calculations were conducted using massless partons, its use in conjunction with a LO prediction with massive quarks is considered a good approximation.

5.1.2 Background Datasets

For a di-lepton selection and subsequent jet analysis at $m_{\ell^+\ell^-} = m_{Z^0}$, the dominant background final states to be expected are: $t\bar{t}$, single Top, $W^\pm + \text{jets}$, $WW/ZZ/WZ$ and QCD multi-jet¹ events.

Table 5.2 summarises simulated background samples used for this analysis indicating corresponding results from higher order α_s calculations. Also the experimentally observed cross sections are listed which still yield errors comparable or larger than theory predictions. All MC samples are renormalised to theoretical cross sections.

Due to the high computing requirements on producing the accounted number of events in table 5.2, their configurations, input PDF sets and decisions on their specific theory model implied there are not subject for further optimisation for this analysis. For PYTHIA6 [76] MC datasets, the given variable Q_{kin} represents the configuration parameter `ckin` and thus transverse momentum transfer at the hard scattering vertex.

5.1.3 Pile-up Description and Beam conditions

All simulated pseudo data sets used for this study were produced with ATLAS production tag `_r1831` - which carries reference to the beam conditions setup that was used for simulation. Here, proton-proton collisions delivered by the LHC at a bunch spacing of $\Delta t = 150\text{ns}$ and a mean number of interactions per bunch crossing of $\mu_{BX} = 2.2$ were assumed. The nominal hard scattering provided by the MC generator was overlaid with PYTHIA Minimum Bias events to produce pile-up conditions as observed in 2010 ATLAS data taking which proved to be a close but not exact description of the observed data. Hence, all MC samples are reweighted to yield a better description of beam conditions contained in 2010 data as will be described in section 5.2.3.

¹The term QCD multi-jet refers to $2 \rightarrow N$ final states in which only partons of any flavour participate.

Sample	σ_{LO}/pb	σ_{NNLO}/pb	σ_{obs}/pb	Event Yield
PYTHIA6 QCD multi-jet ([76],MRST2007 LMod, $N_\mu > 1$, $p_{T,\mu} > 8\text{ GeV}$, $ \eta_\mu < 3$.)				
8 GeV $< Q_{kin} < 17\text{ GeV}$	986.026 $\cdot 10^6$			966681
17 GeV $< Q_{kin} < 35\text{ GeV}$	677.889 $\cdot 10^6$			996624
35 GeV $< Q_{kin} < 70\text{ GeV}$	40985 $\cdot 10^3$			479766
70 GeV $< Q_{kin} < 140\text{ GeV}$	2195.5 $\cdot 10^3$			498714
140 GeV $< Q_{kin} < 280\text{ GeV}$	87659.6			498475
280 GeV $< Q_{kin} < 560\text{ GeV}$	2345.58			492066
560 GeV $< Q_{kin} < 1120\text{ GeV}$	33.592			9968
PYTHIA6 $W^\pm$ + jets ([76],MRST2007 LMod, min. 1 lepton with $ \eta_\ell < 2.5$)				
$W^\pm \rightarrow e\nu_e$	8937.8	10455 [171]	10207 $\pm$ 403 [172]	996690
$W^\pm \rightarrow \mu\nu_\mu$	8940	10455 [171]	10207 $\pm$ 403 [172]	998683
$W^\pm \rightarrow \tau\nu_\tau$	8936.6	10455 [171]	10207 $\pm$ 403 [172]	998692
ALPGEN 2.13 $WW/ZZ/WZ$ ([74],CTEQ6L1, $0 < N_{parton} < 4$)				
$WW (W^\pm W^\pm \rightarrow \ell^+ \nu_\ell \ell^- \bar{\nu}_\ell)$	3.655	4.421 [75]	4.3 $^{+2.2}_{-1.7}$ [173]	99917
$ZW (Z^0 W^\pm \rightarrow \ell^+ \ell^- + X)$	1.377	1.664 [75]	2.25 $^{+0.38}_{-.33}$ [174]	
$ZZ (Z^0 Z^0 \rightarrow \ell^+ \ell^- + X)$	0.835	1.008 [75]	.85 $^{+28}_{-.23}$ [175]	
MC@NLO 3.41 ([46],CTEQ6.6)				
$t\bar{t} (t\bar{t} \rightarrow \ell^\pm \nu_\ell + 2b + X)$	80.201 (NLO)	89.02 $^{+6.23}_{-8.01}$ [176]	95.6 $^{+8.5}_{-7.1}$ [177]	771295
single Top (t-channel)	21.3972 (NLO)	21.48 $^{+1.10}_{-0.87}$ [178]	29.2 $^{+9.8}_{-7.1}$ [170]	132008
single Top (s-channel)	1.44 (NLO)	1.50 $\pm$ 0.09 [179]		24517
$Wt (bg \rightarrow W^\pm t \rightarrow X)$	14.581 (NLO)	15.74 $^{+1.34}_{-1.36}$ [180]		264894
SHERPA 1.1.3 (CTEQ6L)				
$\ell^+ \ell^- + N \text{ jets } (0 \leq N_{jets} \leq 3) (\ell = e, \tau, m_{\ell+\ell^-} > 60\text{ GeV})$	2024.82	1978 [171]		374801.3

Table 5.2: Collection of simulated data samples used for background processes for $\mu^+ \mu^-$ + jets topologies, their generated (N)LO, NNLO and observed cross sections (where accessible) as well as the effective event count available for this analysis.

5.2 Experimental Dataset

During data taking, subsystems of the ATLAS detector may show varying performance or even fail. For this, a careful selection of data taking periods needs to be conducted in order to guarantee high data quality. Then, trigger signals are checked to allow a selection of $\mu^+\mu^-$ events and to reduce background contributions. After this, the effective luminosity analysed for this measurement can be calculated.

5.2.1 Data Quality

For a high quality event the following detector systems are required to operate at good performance in online (during data taking) and offline monitoring (using fast reconstruction of selected events) in the ATLAS barrel and endcap volumes:

- solenoid magnet and toroid magnet
- *InnerDetector*
- *Calorimeter*
- *MuonSpectrometer*

Furthermore, the quality of all related reconstruction algorithms need to show good performance in offline monitoring in the ATLAS barrel and endcap volumes:

- *InnerDetector* tracking
- *MuonSpectrometer* tracking
- Muon and Staco combined reconstruction
- life-time b-tagging
- jet reconstruction
- E_T calculation

The detailed query for 2010 ATLAS data quality selection can be found in appendix C.2 which has also been applied for [52, 98].

5.2.2 Trigger

After the selection of an ensemble of good quality data events, the rejection of high-rate reducible background events has to be ensured by requiring muon trigger signals at event filter level (see section 4.2.7) to yield *Pass* in a given event. During 2010 ATLAS data taking, low momentum threshold trigger items were constantly prescaled (see section 4.2.7) due to beam conditions and event rates above expectations.

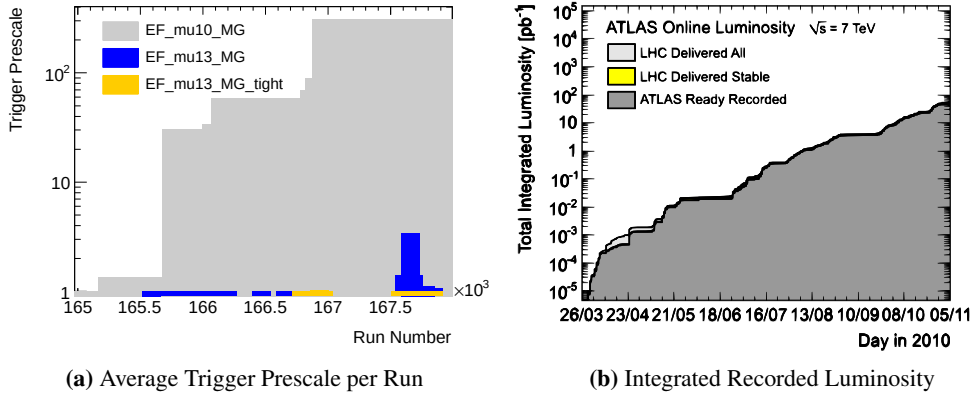


Figure 5.1: Trigger prescales for event filter muon triggers versus ATLAS run period (a) and total integrated luminosity [118] on tape by data (b). Both figures are in log scale.

Figures 5.0 illustrate the increase of prescale factors for event filter bits `EF_mu10_MG` and `EF_mu13_MG` during data taking due to the increasing amount of data collected per time unit. It is worth noting, that due to the ever increasing luminosity higher trigger thresholds had to be put to operation, for example `EF_mu13_MG_tight` is only available from run 166786 onwards (figure 5.0a). On the same line of argument, trigger prescales increased dramatically, e.g. up to values of 311 for `EF_mu10_MG`, in late 2010 data taking.

In order to retain large amounts of non-prescaled events (thus minimal or no statistical uncertainties), the data taking was split up into three main trigger periods.

trigger period	muon trigger	run numbers (periods)	mean prescale	scale factor
1	L1_MU10	152166 – 160879 (<i>A – E3</i>)	1.	1.028 ± 0.005 1.013 ± 0.005
2	EF_mu10_MG	160899 – 165632 (<i>E4 – G1</i>)	1.	
3	EF_mu13_MG	160899 – 167576 (<i>G2 – I1</i>)	1.	
4	EF_mu13_MG_tight	167607 – 167844 (<i>I1 – I2</i>)	1.	

Table 5.3: Collection of muon trigger items and data taking periods that were applied on a per-event basis. In addition, the average trigger item prescale used for recording events and the trigger efficiency scale factor [181] is shown.

Table 5.2 illustrates how average trigger prescales of single muon trigger items remain at 1.0 by choosing the appropriate trigger item per data taking period. As will be documented in table 5.3, trigger period 1 (periods *A – E3*) yields a negligible fraction of luminosity and is thus dropped from further consideration. In order to guarantee a reliable simulation of noted trigger items, the trigger efficiency was evaluated in MC and data in the ATLAS inclusive Z^0 boson cross section

measurement [181]. The muon object kinematic selection there is equivalent to the selection at hand (see section 6.1). The trigger efficiency scale factors from [181] are thus adopted. Their small uncertainties will later be accounted for as systematic uncertainty.

5.2.3 Reconstructed Vertices and Pile-up Reweighting

Besides the trigger requirements introduced in the last section, an event is considered for further analysis if it contains at least one vertex that has more than two *InnerDetector* tracks matched to it in order to retain a vertex finding efficiency of $> 99\%$, see [124].

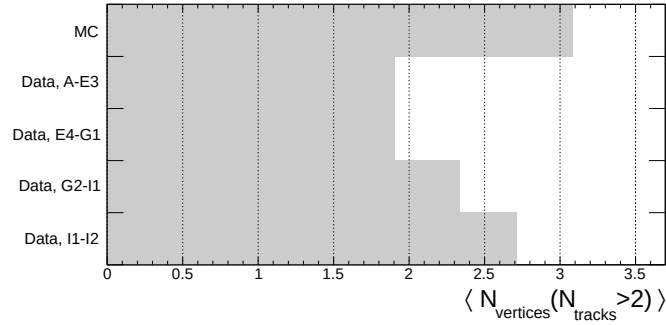


Figure 5.2: Mean multiplicity of reconstructed vertices that have at least 3 adjoined tracks in 2010 data as well as signal simulation. Pile-up increases throughout the 2010 data taking from periods A – I2. The MC simulation overestimates $N_{vertices}$ on average.

Figure 5.1 illustrates the vertex multiplicity in events containing at least one muon candidate with transverse momentum $p_{T,\mu} > 15 \text{ GeV}$ and $|\eta_\mu| < 2.5$ from data. Here, data periods from A – I2 exhibit a rise in the mean number of vertices per event, $\langle N_{vertices} \rangle$. The value of $\langle N_{vertices} \rangle$ in data does not exceed the one simulated in MC; simulation overestimates it on average. This is due to an assumption that was made for MC mass production [167] on the average number of interactions per bunch crossing, $\mu_{BX} = \langle N_{BX}(vertices) \rangle$ (see section 4.1.2).

Figure 5.0b showed a constant rise of luminosity provided by the LHC accelerator which followed from an increased collision rate and optimised beam optics. This in turn increased the number of interactions per bunch crossing accordingly. To adapt to this difference, a procedure to reweight events in simulation was used to ensure that this effect can be neglected in simulated events. First, events in data are selected that have a matching trigger requirement and have at least one reconstructed combined $Muid$ muon candidate that satisfies $p_{T,\mu} > 15 \text{ GeV}$ and $|\eta_\mu| < 2.5$. For this selection, the number of vertices is histogrammed in figure 5.1 per trigger run period of 2010 data, see table 5.2. The same selection is applied to the signal MC samples. A weight factor per event can be computed by:

$$\begin{aligned}
 w(N_{vertices}) &= \sum_i \frac{\mathcal{L}_i}{\mathcal{L}_{total}} \cdot \frac{N_{Data,i}(N_{vertices})}{N_{MC,scaled,i}(N_{vertices})} \\
 &= f(N_{vertices})
 \end{aligned} \tag{5.1}$$

where $w(N_{vertices})$ refers to the distribution of weights per good vertex multiplicity $n(vertex)$. It is derived from a weighted sum of the number of events $N_{Data,i}(N_{vertices})$ by data taking period

i with integrated luminosity $\mathcal{L}_i$. The vertex multiplicity $N_{MC,scaled,i}(N_{vertices})$ denotes the comparable quantity from simulated signal events which has been scaled to the luminosity for period i according to the trigger selection applied, see section 5.2.4. Integrating equation 5.1 over all possible values of $N(N_{vertices})$ drives the ratio of data to MC to unity and thus shows that $\sum_{vertices} w(N_{vertices}) = 1$. This procedure does not alter any normalisation contained in MC by construction.

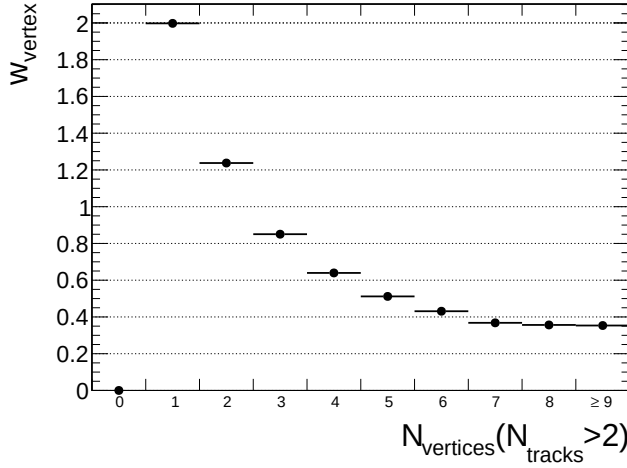


Figure 5.3: Weighting factors $w_{vertices}$ per multiplicity of reconstructed vertices $N_{vertices}$ as described to correct simulation to data as introduced in equation 5.1. For low values of $N_{vertices}$, MC overestimates the data. For high values, MC underestimates the data.

As can be seen in figure 5.2 (values added in appendix C, table C.0), at low values of $N_{vertices}$ the pile-up weight $w_{vertices}$ is larger than 1 and the simulation underestimates pile-up here. At medium and higher multiplicities ($N_{vertices} \geq 3$), the pile-up weight is smaller than 1 and thus simulation overestimates the vertex multiplicity here. This reweighting procedure ensures that simulated events are not discarded but rather their composition is adjusted to that observed in data.

5.2.4 Luminosity

Following the definition of the data taking quality and trigger, an effective data luminosity $\mathcal{L}_{eff} = \epsilon_{trigger} \cdot \mathcal{L}_{recorded}$ can be evaluated.

As illustrated in figure 5.0b, the LHC collider provided ever increasing yields of delivered luminosity during its operation in 2010. Given the trigger requirements from section 4.2.7, table 5.3 notes the effective luminosities corresponding to the events in data. The dominant portion of the data ensemble can be found in periods ($G2 - I2$) with runs of period $I2$ containing the most events per run. Although events of trigger period 1 are not prescaled, the effective luminosity of this period yields 1.8% of the total luminosity available. It is hence dropped from the analysis at this point.

trigger period	muon trigger	run numbers (periods)	$\mathcal{L}_{eff}/pb^{-1}$
1	L1_MU10	152166 – 160879 ($A - E3$)	0.699 ± 0.024
2	EF_mu10_MG	160899 – 165632 ($E4 - G1$)	2.91 ± 0.1
3	EF_mu13_MG	160899 – 167576 ($G2 - I1$)	15.3 ± 0.5
4	EF_mu13_MG_tight	167607 – 167844 ($I1 - I2$)	17.97 ± 0.61
Total (2 – 4)		160899 – 167844 ($E4 - I2$)	36.13 ± 1.23

Table 5.4: Collection of muon trigger items and effective luminosity. Luminosity uncertainties of $\pm 3.4\%$ were calculated as in [118].

Chapter 6

Selection of Reconstructed Objects

Before any cross section can be determined, it has to be ensured that the observed data provides a considerable amount of events of the desired final state to investigate and that possible background contributions are under control. This chapter introduces selection criteria for muon candidates and jet objects. Optimal cut values are searched for by evaluating

$$Q = \frac{s}{\sqrt{s+b}}. \quad (6.1)$$

that is derived in appendix D.1 from the number of events from signal MC s and those from background final states b . The description of the event selection finishes with a definition of reconstructed Z^0 boson candidates as well as bottom quark induced jets.

Throughout this chapter, all distributions including signal MC are made from ALPGEN MC events due to the increased size of the respective event sample compared to its SHERPA counterpart (table 5.0). Figures or tables that are accessible with SHERPA MC are added in appendix D.

6.1 Muon Candidate Selection

The following section describes the selection applied to reconstructed muon candidates to create a event sample with a high signal efficiency and high purity sample of objects that enter the creation of Z^0 candidate from lepton pairs later.

6.1.1 Muon Reconstruction Algorithm and Detector Requirements

A selection was applied to data and simulation that ensured a vanishing contribution of fake reconstructed muon candidates, e.g. from high energetic punch-through kaons or pions whose decay products penetrate the *MuonSpectrometer*, or misreconstructions due to detector mismeasurements.

At the time of writing, the ATLAS experiment's reconstruction software contained muon objects from two algorithm families, *Muid* and *Staco* (see section 4.3.2) that both produced independent muon candidate objects in data and simulation events. A comparison of muon object yields for combined muon objects from these families is shown in table 6.0.

Combined muon candidates by *Muid* produce a higher Q than *Staco* candidates. Table 6.0 notes that the Z^0 candidate yield with *Muid* reconstructed objects in data is five standard deviations

Algorithm	Signal / 10^3	Q	Data / 10^3
Muid	13.38 ± 0.05	111.2 ± 0.6	13.3 ± 0.1
Staco	12.68 ± 0.05	108.5 ± 0.5	12.7 ± 0.1

Table 6.1: Comparison of number of combined muon candidate pairs after full muon selection and combination to Z^0 candidate lepton pairs (see section 6.2) using reconstructed objects by the Muid and Staco algorithm family. A comparison of pair yields in ALPGEN signal MC events as well as the 2010 dataset is made.

higher than for Staco candidates. It has been shown in [182], that Muid combined muons are reconstructed at a higher efficiency than Staco whereas the latter produces Z^0 muon object ensembles with higher purity. Since this analysis aims at measuring $Z^0 + b + X$ events in 2010 data which are expected at a small frequency, the algorithm with (at best) an overall high yield and purity must be chosen. Therefore, Muid family combined muon candidates are chosen as baseline muon candidate objects for this analysis.

In addition, the objects satisfying “tight” quality criteria are used only which requires objects to satisfy:

- reconstructed by the MuidCombined algorithm or
- reconstructed by the MuidStandalone algorithm if $|\eta_{MS,track}| > 2.5$ or
- reconstructed by the MuGirl algorithm

Quality criteria on the *InnerDetector* track used for combination with the *MuonSpectrometer* track are applied as well. They comprise limits on the number of measurements per detector volume $N_{detector}(hits)$ as well as the number of holes $N_{detector}(holes)$. A hole refers to an expected detector hit at a position where the a posteriori interpolated reconstructed track passed sensitive material but no hit signal was recorded. The number of track outliers is also considered, representing detector measurements that could not be attributed to or have a unfavourable matching χ^2 to a reconstructed track.

These quality criteria are listed below:

- $N_{Pixel}(hits) + N_{Pixel}(holes) > 1$
- $N_{SCT}(hits) + N_{SCT}(holes) > 5$
- $N_{SCT}(holes) + N_{Pixel}(holes) < 2$
- $\langle N_{Pixel,B-Layer}(hits) \rangle > 0$ (expected number of *Pixel* B-Layer hits derived from extrapolating the *MuonSpectrometer* track to the primary vertex, PV)
- $N_{Pixel,B-Layer}(hits) > 0$
- TRT hits where $f_{TRT} = N_{TRT,outliers} / (N_{TRT,outliers} + N_{TRT}(hits))$
 - if $|\eta_{MS}| < 1.9$ (within TRT acceptance): $N_{TRT}(hits) > 5 \cap f_{TRT} < 0.9$
 - if $|\eta_{MS}| \geq 1.9 \cap N_{TRT}(hits) > 5$: $f_{TRT} < 0.9$
 - if $|\eta_{MS}| \geq 1.9 \cap N_{TRT}(hits) \leq 5$: no additional requirement

The ensemble of reconstructed muon candidates can be contaminated by cosmic rays traversing the ATLAS detector within the *MuonSpectrometer* or *InnerDetector* read-out window imminent to a proton-proton collision. Thus, their chance of being recorded with or in place of a collision event is non-zero. The rate of cosmic muons at 100m below ground can be approximated to $f_{\text{cosmic}} \leq 10\text{Hz}$ from the average flux per m^2 of muons with at least 3 GeV energy given in [11]. As illustrated in section 4.2.5, the MDT read-out window is $t = 2.5\mu\text{s}$. Using this as an upper limit, the maximum rate of events to be read-out from the *MuonSpectrometer* is $f_{\text{RO}} = 4 \cdot 10^5\text{Hz}$.

Hence, every recorded collision event has a probability of $p_{\text{cosmic}} = f_{\text{cosmic}}/f_{\text{RO}} = 2.5 \cdot 10^{-3}$ to contain cosmic muons. These being rare and independent processes, the probability of observing at least one cosmic muons in the data sample can be evaluated using a Poisson distribution: $P_{\text{Poisson}}(N > 0, \lambda = p_{\text{cosmic}}) = 1 - P_{\text{Poisson}}(N = 0, \lambda = p_{\text{cosmic}}) = 2.497 \cdot 10^{-3}$. With every 2500 recorded events, at least one cosmic muon event can be expected on average.

A signal from this source will expose itself as equally distributed around the nominal IP. In order to validate this hypothesis, cosmic muon events were analysed that were recorded during 2010 ATLAS data taking. For these events, the trigger requirements discussed above and muon object selection was applied.

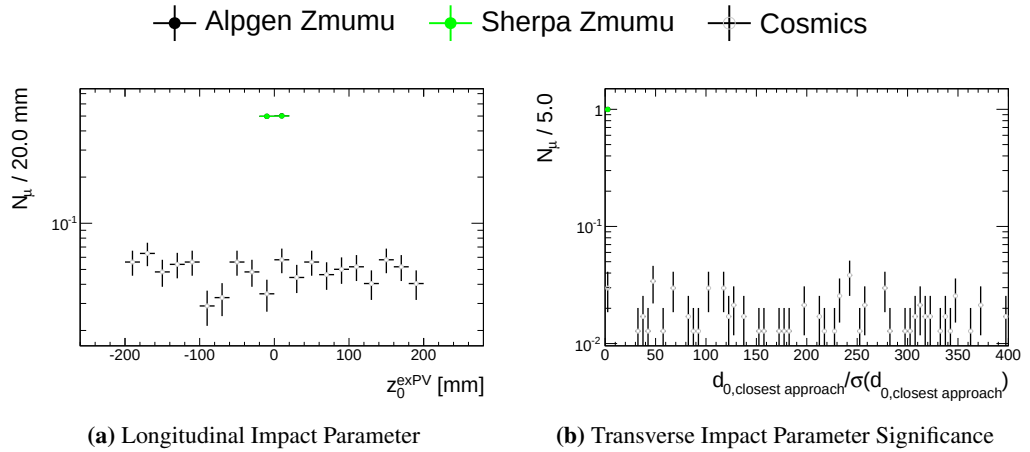


Figure 6.1: Muon track impact parameters from muon candidate combined tracks that have been extrapolated to the primary vertex in cosmic muon events overlaid with signal MC $Z^0 \rightarrow \mu^+\mu^-$. Sub-figure (a) depicts the longitudinal impact parameter z_0 . Sub-figure (b) depicts the transverse impact parameter significance $\frac{d_0}{\sigma(d_0)}$. All distributions have been normalised to unit area.

Figure 6.0a depicts the distribution of longitudinal impact parameters z_0^{exPV} of muon candidate tracks in cosmic muon events that have been extrapolated to the events PV. The distribution is equally distributed between $\pm 200\text{mm}$. This distance from the nominal interaction point IP marks the longitudinal acceptance boundary of the *InnerDetector*. Muon candidates from signal MC events yield values of z_0^{exPV} close to 0. To suppress cosmic muon contamination, the longitudinal impact parameter of a muon candidate is limited to $|z_0^{exPV}| < 10\text{mm}$. This reduces the probability of a cosmic muon candidate to enter the Z^0 selection by a factor of 20.

In addition, the transverse impact parameter significance of the extrapolated combined muon track is restricted to $|d_0^{PV}|/\sigma_{d_0^{exPV}} < 10$. The uncertainty $\sigma_{d_0^{exPV}}$ used here, is obtained from the 5-parameter track extrapolation with respect to the primary vertex of the inner detector. As documented in figure 6.0b, 2% of cosmic muons yield values of $|d_0^{exPV}|/\sigma_{d_0^{exPV}} < 10$ whereas muon

candidates from the Z^0 signal MC accumulate here. To conclude, the above mentioned cuts on z_0^{exPV} and $|d_0^{PV}|/\sigma_{d_0^{exPV}}$ further reduce the probability of a cosmic muon to interfere with or in place of a reconstructed Z^0 candidate by an additional 3 orders of magnitude. So, the probability for a cosmic muon to enter the sample of selected muons amounts to $p_{cosmic} = 2.497 \cdot 10^{-6}$ without any requirement on the mimicked di-muon mass which reduces this probability further. Thus, the contribution from cosmic muons to the reconstructed Z^0 sample can be neglected.

6.1.2 Muon Candidate Kinematic Cuts

Due to the known acceptance of the ATLAS *MuonSpectrometer*, the pseudo-rapidity of muon candidates is restricted to $|\eta_\mu| < 2.4$. This ensures a high efficiency and allows for a robust unfolding of the data to particle level, for it contains the bulk of the *MuonSpectrometer* acceptance, see figure 6.3b below. With the limits of acceptance excluded, this provides a flat reconstruction efficiency distribution without large migrations due to boundary effects.

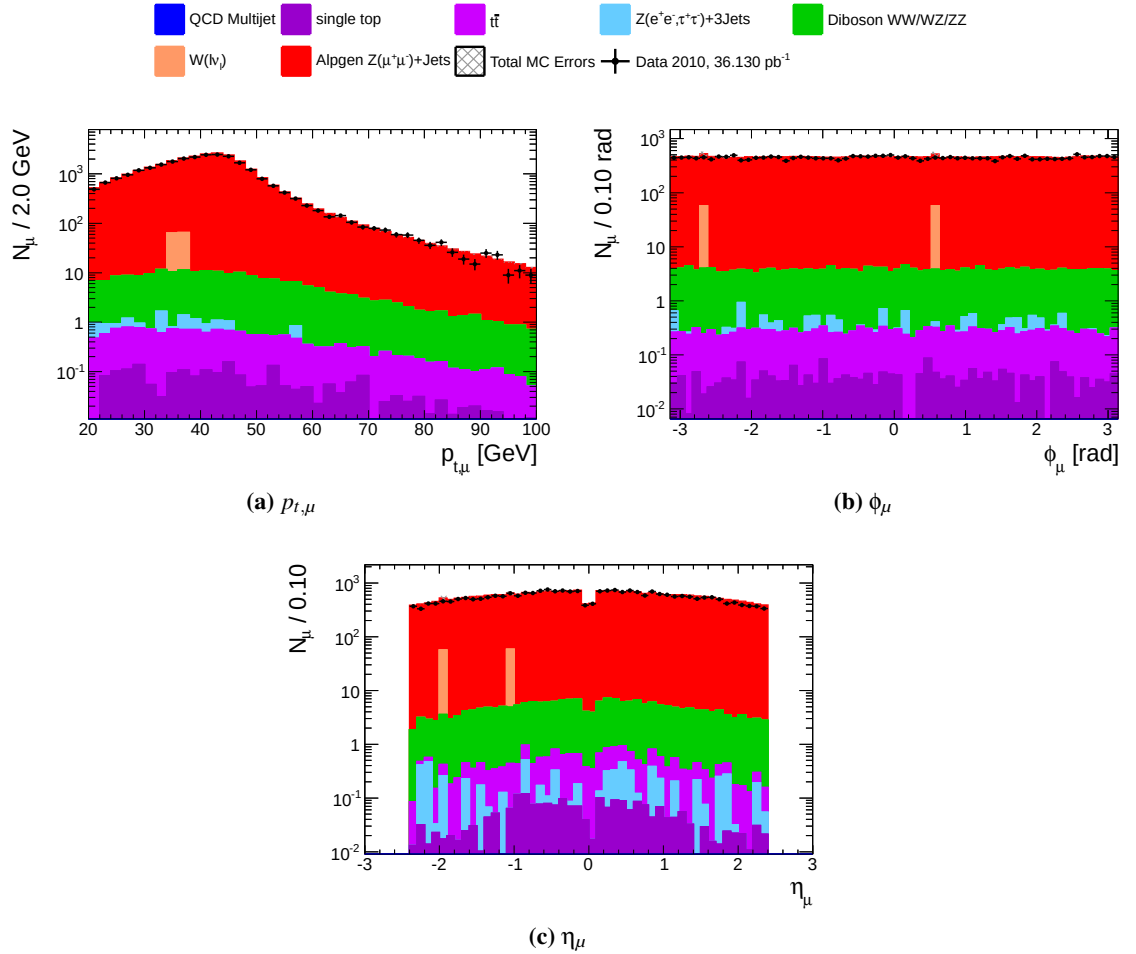


Figure 6.2: Distribution of muon candidate $p_{t,\mu}$ (a), ϕ_μ (b) and η_μ (c) for 2010 data and simulation. The plots include all muon object cuts passing di-muon selection described in section 6.2. Although not visible, the total statistical uncertainty of the MC prediction is included.

Figure 6.1 holds distinct features of the Z^0 two-body decay into muons. First, the distribution of muon candidates in the polar coordinate ϕ of figure 6.1b is flat, indicating no preferred angle of decay for the Z^0/γ^* leptons. Second, the maximum of figure 6.1a can be identified as the Jacobian peak at $m_{\mu^+\mu^-} = \frac{1}{2}m_{Z^0}$ of the two-body decay of the Z^0 . The third observation is the reduced muon object abundance at $\eta = 0$ due to detector volume without instrumentation, i.e. the crack region (see section 4.2). Missing instrumentation implies a lower muon object reconstruction efficiency which results in comparably less muon objects reconstructed here. Given the large number of events available and a vanishing statistical uncertainty of the MC prediction, the good agreement between observed and expected muon distributions in all three kinematic variables is striking.

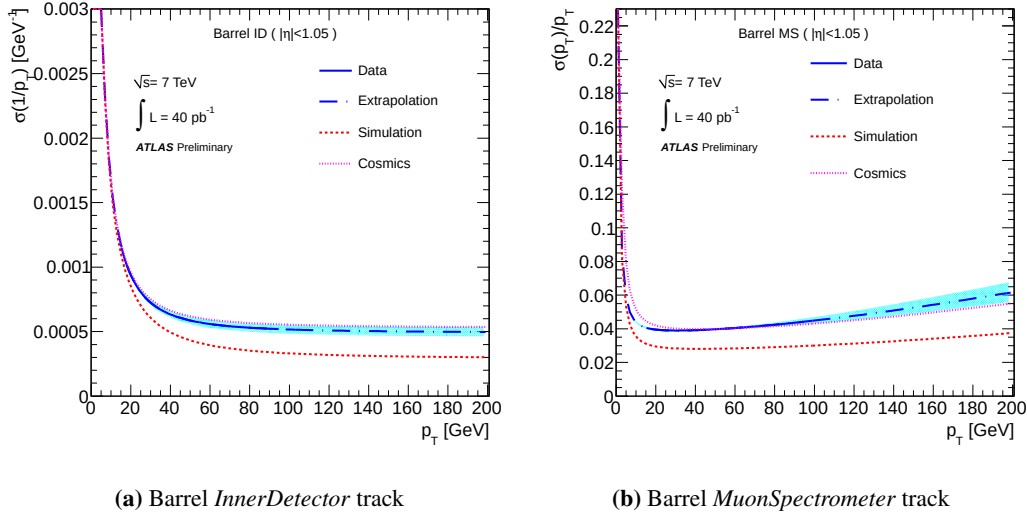


Figure 6.3: Muon momentum resolution derived from muon candidates found in reconstructed $Z^0 \rightarrow \mu^+\mu^-$ decay events taken from [183]. A comparison between transverse momentum resolution of *InnerDetector* tracks (a) versus *MuonSpectrometer* tracks (b) in the ATLAS barrel region is shown.

Studies of the mass resolution in the di-muon invariant mass spectrum at m_{Z^0} in [183] indicated that the momentum resolution of the ATLAS muon reconstruction decreases dramatically for transverse momenta below 20 GeV, but shows almost constant behaviour for higher momenta. These findings were obtained from a fit to the reconstructed Z^0 invariant mass peak in data and a comparison with the theoretically well known resonance shape of the Z^0 boson.

Figure 6.2 recapitulates a steep decrease of the relative momentum uncertainty for muon candidates (especially the *InnerDetector* component) within $(0 < p_{t,\mu} < 20)$ GeV. The resolution for muons with $p_{t,\mu} > 100$ GeV is deduced by extrapolating results from Z^0 decays for the available muon momentum is limited here. The available statistics for $p_{t,\mu} > 100$ GeV from Z^0 is poor as can be observed from figure 6.1a. Further, figure 6.2b exposes a linear increase of the track momentum resolution for objects reconstructed in the *MuonSpectrometer* as opposed to those in the *InnerDetector* (figure 6.2a).

It is important to note, that the momentum resolution contained in simulated events does not coincide with that observed in collision or cosmic data. This issue is addressed by a dedicated calibration described in the next section, 6.1.3.

Because muons at low transverse momentum expose large transverse momentum uncertainties and the single muon trigger threshold is set to 10 – 13 GeV (see section 5.2.2), a lower bound to the muon transverse momentum of $p_{t,\mu} > 20$ GeV is set. This will aid to suppress background processes, e.g. $\gamma^* + jets$, ISR/FSR muons or muons produced in jets that are non-negligible at low muon momenta.

6.1.3 Muon Calibration

The ATLAS 2010 data set was the first bulk of proton-proton collisions recorded by the ATLAS experiment. Although the performance of all muon related systems and software algorithms was studied extensively in cosmics data [138], the measurement of Z^0 bosons provided a tool to study the performance of reconstruction efficiency and muon momentum resolution in collision events.

The Tag-And-Probe Method

The production rate of Z^0/γ^* resonances in proton-proton collisions is large compared to other standard model final states, such as top quark production or $WW/ZZ/WZ$ final states. In addition, Z^0 events exposed one of the first measurements to rediscover the SM at the LHC [172], for it is known with high precision from LEP measurements [184]. The two-body decay of a neutral particle such as the Z^0 with a well defined resonant peak in the invariant mass spectrum of its decay particles offers a unique tool. This is used to select a sample of Z^0 events without e.g. requiring information from the *MuonSpectrometer* for one decay lepton and using this sample of events as *tag*. The same events are used as reference to compare with Z^0 candidates reconstructed including the *MuonSpectrometer* hits for both lepton candidates to construct a *probe* ensemble.

In more detail, events containing a high quality muon candidate (*tag*) and a high quality *InnerDetector* track (*probe*) were recorded if the invariant mass of both objects fell into the proximity of m_{Z^0} , denoted $N(\text{tag-and-probe})$. The probe track is not required to be a muon candidate. The requirement of the invariant mass between tag-and-probe implies this by definition.

In the very same event, the *probe* is used to test whether it can be matched to another muon candidate of equal charge, i.e. not the *tag* muon. The ensemble of events with a successful reconstruction of a *tag-and-probe* pair $N(\text{probe matched}|\text{tag-and-probe})$ allows for an estimation of the muon reconstruction efficiency $\epsilon_{rec,\mu}$. The latter is accomplished by matching a reconstructed muon to the probe *InnerDetector* track to yield

$$\epsilon_{rec,\mu} = \frac{N(\text{probe matched}|\text{tag-and-probe})}{N(\text{tag-and-probe})}. \quad (6.2)$$

The efficiency described here can now be evaluated for data and simulation. Any difference between data and MC must hence be interpreted as non-optimal simulation of the detector response, its read-out or subsequent reconstruction algorithms. This provides means to compare simulation with data and provide correction factors where needed.

Muon Reconstruction Efficiency Calibration

As indicated in the last section, a *tag-and-probe* analysis was used to extract the muon reconstruction efficiency from data and MC [185, 186].

Figure 6.3 shows results of a *tag-and-probe* determination of muon reconstruction efficiencies in ATLAS data and simulation [185]. Discrepancies in $\epsilon_{\mu,rec}$ are observed for low and very high muon transverse momenta, figure 6.3a. In addition, efficiencies at $\eta = 0$ (the crack region) and $|\eta| \simeq 1$ (ATLAS barrel to endcap transition) expose reconstruction deficiencies due to lack of instrumentation in the *MuonSpectrometer* but not in the *InnerDetector*. In these regions, the bulk of

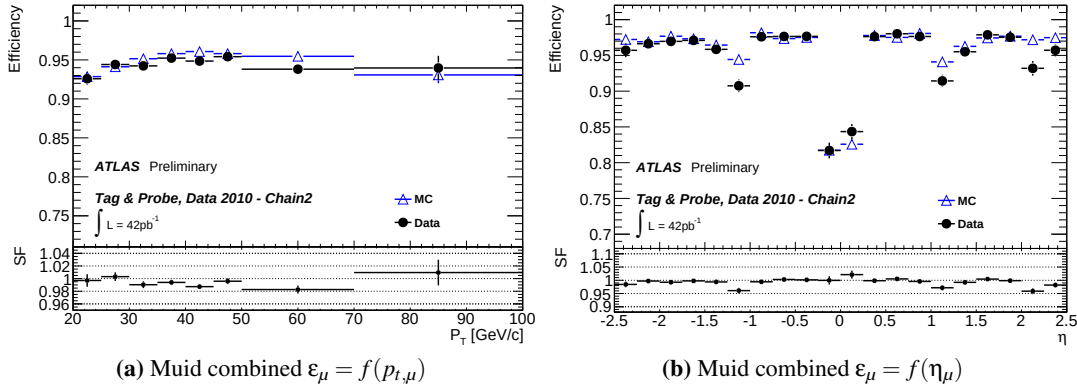


Figure 6.4: Muon candidate *tag-and-probe* reconstruction efficiency as a function of $p_{t,\mu}$ (a) and η_{μ} (b) in data and MC from [185]. “Chain 2” hereby refers to `Muid` combined muon candidates. The scale factor defined in equation 6.3 is also plotted exposing values that differ from 1 by less than 5%.

differences between simulation and data is found.

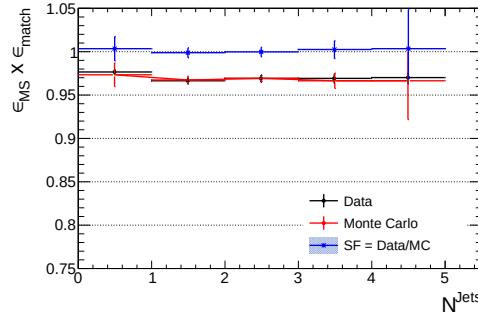


Figure 6.5: Muon candidate *tag-and-probe* reconstruction efficiency as a function of the number of jets N^{jets} taken from [186]. The muon reconstruction efficiency shows no significant dependency on N^{jets} .

In the context of $Z^0 + \text{jets}$ analyses, the muon reconstruction efficiency is required to show no correlation with the number of reconstructed jets in the event. A flat muon reconstruction efficiency as a function of the number of jets was found by [186] as demonstrated in figure 6.4.

In general, figures 6.3 and 6.4 show the relative difference of data reconstruction efficiency $\epsilon_{\mu,rec}^{Data}$ and $\epsilon_{\mu,rec}^{MC}$ found in simulation to be below 5%. It shows small variations with $p_{t,\mu}$, whereas N_{jets} and η_{μ} exhibit a constant offset only. In order to correct for this short-coming when analysing simulated events, scale factors SF are calculated for a given $p_{t,\mu}$ and η_{μ} per muon candidate that may correct the abovementioned relative difference of simulation compared to data as in

$$SF(p_{t,\mu}, \eta_{\mu}) = \frac{\epsilon_{rec,\mu}^{Data}(p_{t,\mu}, \eta_{\mu})}{\epsilon_{rec,\mu}^{MC}(p_{t,\mu}, \eta_{\mu})}. \quad (6.3)$$

It is important to note that the reconstruction efficiency scale factors shown in figure 6.3 expose values with less than 5% deviations from unity. In order to achieve a match between simulated and data events, a MC event weight $w_{\epsilon_{\mu}}$ is calculated from the above-mentioned scale factors for

all selected muon candidates per event,

$$w_{\epsilon_\mu} = \prod_{\mu} SF_{\mu}. \quad (6.4)$$

This procedure is well established and has been used in studies of similar final states to $Z^0 + b$ [52, 98, 181]. Scale factors from [185] are henceforth applied to simulated events containing corrections for combined muon objects and hence correcting muon reconstruction with respect to the *InnerDetector* and the *MuonSpectrometer*.

Muon Momentum Scale Calibration

The Z^0 resonance shape and normalisation (i.e. its production cross section) are well-known physics observables with high-precision measurements available from LEP [184]. The abundance of $Z^0 \rightarrow \mu^+\mu^-$ events measured in 2010 ATLAS data [181] allows to extract the muon momentum resolution through a fit to the invariant $\mu^+\mu^-$ mass distribution in data. This was done for simulated and data events in [183], see figure 6.2. The high yield of Z^0 boson candidates allowed to bin Z^0 resonance fit results in $p_{t,\mu}$. This uncovered a mismatch between data and MC muon resolutions. This could only be accounted for by new simulation of generated events which was inaccessible within the time frame of this study. Thus, corrections to muon kinematics have been applied in simulated events using reference information from [183] by randomly smearing the simulated muon momenta per reconstructed object.

6.1.4 Muon Isolation

As already outlined, the main expected backgrounds for $Z^0 + \text{jets}$ final states are QCD multi-jet, $W^\pm + \text{jets}$ and $t\bar{t}$ topologies - all of which contain high momentum muons either from $W^\pm$ decays or highly boosted hadron decays inside jets. Thus, events of the latter type may considerably fake the signature of $\mu^+\mu^- + \text{jets}$. To suppress this effect, each muon candidate taken into account is required to exhibit a cone-like fiducial volume around it with no significant detector activity, i.e. the muon candidate needs to be isolated.

In order to provide a parameter to quantify this property, there are three approaches possible to calculate the isolation parameter i :

Relative Pt Cone Given a cone of metric $\Delta R < 0.2$ around a muon candidate track, the sum of transverse momenta of all tracks inside this volume except tracks affiliated with the muon candidate itself is calculated and divided by the muon candidates momentum.

$$i_{ptcone} = \frac{\sum_{tracks} p_t(track) | \Delta R(\mu, track) < 0.2}{p_{t,\mu}} \quad (6.5)$$

Relative Et Cone Given a cone of $\Delta R < 0.2$ around a muon candidate track, the sum of transverse energies of all calorimeter clusters inside this volume except the cluster affiliated with the muon candidate itself is calculated and divided by the muon candidates momentum.

$$i_{etcone} = \frac{\sum_{caloclusters} E_t(clusters) | \Delta R(\mu, track) < 0.2}{p_{t,\mu}} \quad (6.6)$$

Number Cone The number of tracks in a cone-like volume of $\Delta R < 0.2$ around a muon candidate track is used:

$$i_{nucone} = N(tracks | \Delta R(\mu, track) < 0.2) \quad (6.7)$$

As already indicated in equations 6.5, 6.6 and 6.7, the cone size of $\Delta R < 0.2$ is used for the analysis at hand to retain comparability to already published ATLAS measurements [52, 98]. Also, relative momentum and energy isolation parameters are chosen, for their absolute equivalents showed correlations with the size of pile-up per event, i.e. the number of proton-proton interactions per bunch crossing [187].

All three approaches provide different signal selection efficiencies and sample purities as illustrated by figure 6.5. At this point, i_{nucone} and i_{etcone} show inferior performance compared to i_{ptcone} for they retain QCD multi-jet events for all possible values of the isolation parameter. Opposed to that, i_{ptcone} already separates QCD (high i_{ptcone}) from Z^0 events ($i_{ptcone} = 0$). The muon isolation cut is motivated by reducing large jet backgrounds such as QCD multi-jet. For this, the signal significance Q (see equation 6.1) was studied for simulated events applying all quality and kinematic cuts stated above to the muon sample and composing Z^0 candidate pairs using 3 sets of isolation requirements, $i_{etcone} < 0.2$, $i_{ptcone} < 0.2$ and $i_{nucone} < 0.1$.

As shown by table 6.1, all isolation criteria result in different admixtures of background components to the selected sample culminating in a vanishing QCD contribution for $i_{ptcone} < 0.1$. While the signal content remains unchanged within statistical uncertainties for all isolation requirements presented, $i_{ptcone} < 0.1$ gives the highest Q value while retaining a sizable sample of signal events which differs with less than 1 % from the sample selected by $i_{ptcone} < 0.2$. It should be highlighted that due to the high luminosity scale factor for QCD multi-jet type events and the large rejection

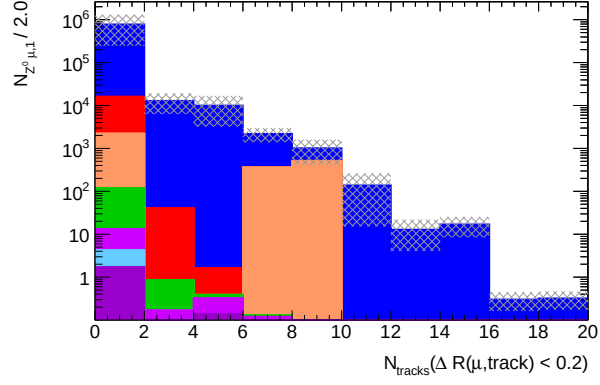
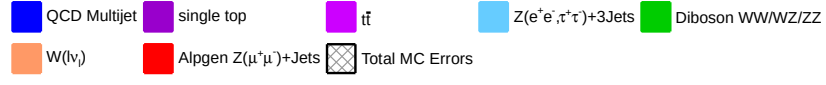
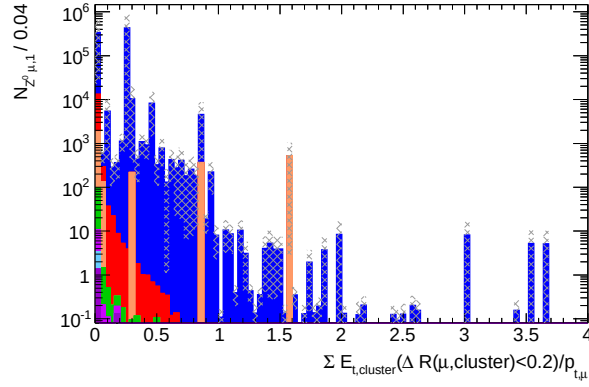
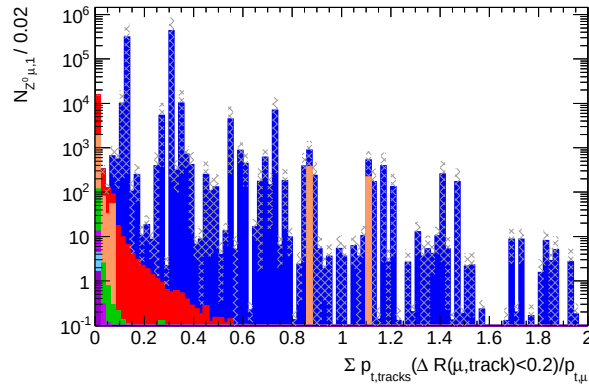
(a) i_{nucone} (b) i_{etcone} (c) i_{ptcone}

Figure 6.6: Distributions of reconstructed muon isolation parameter. The isolation parameter of one muon per Z^0 candidate after the full muon object selection was conducted except a requirement on muon isolation.

final state	$i_{etcone} < 0.2$	$i_{ptcone} < 0.2$	$i_{ptcone} < 0.1$
$Z^0 + \text{jets}$	13724 ± 14	13768 ± 14	13665 ± 14
QCD multi-jet	$(14.7 \pm 11.0) \cdot 10^3$	$(10.2 \pm 9.8) \cdot 10^3$	0
Q	81 ± 16	88 ± 18	116.17 ± 0.26

Table 6.2: Total number of Z^0 candidates for $Z^0 + \text{jets}$ and QCD multi-jet MC events selected by isolation criteria $i_{etcone} < 0.2$, $i_{ptcone} < 0.2$ and $i_{ptcone} < 0.1$. As indicated in the text, the expected number of QCD multi-jet events vanishes due to a high rejection rate obtained by $i_{ptcone} < 0.1$ and a subsequent shortcoming of MC statistics.

rate obtained by requiring $i_{ptcone} < 0.1$, the available QCD multi-jet MC pseudo-data sample does not yield enough events to make a prediction anymore and hence only provides an indication. The observations made above suggest $i_{ptcone} < 0.1$ as optimal isolation requirement.

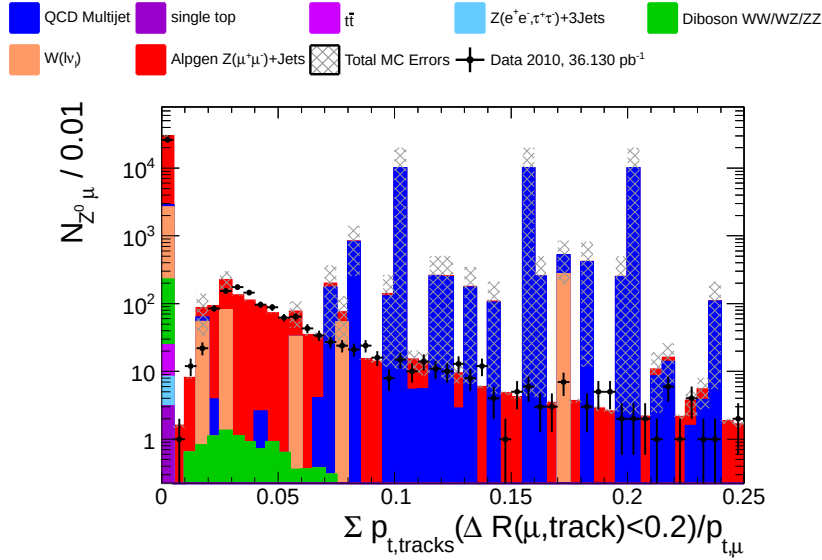


Figure 6.7: Muon candidate isolation i_{ptcone} from data and ALPGEN signal MC as well as expected background contributions. Only muon candidates that have been successfully combined to a Z^0 boson candidate enter here. No requirement on the proximity or existence of additional jets in the event was made.

Any estimation of scale factors to correct simulation to data regarding muon candidate isolation was not published yet. The observation that data and MC agree very well for the inclusive Z^0 selection (relying on an isolation requirement), figure 6.6, provides convincing evidence that the i_{ptcone} isolation efficiency correction is small. This was indeed observed as reported in the ATLAS $Z^0 + \text{jets}$ publication [52]. The comparison of isolation efficiencies in data and simulation discussed there showed no statistically significant effect. Thus, no muon isolation scale factors are applied to MC here as well. However, a systematic uncertainty of $\pm 1.8\%$ on $\sigma_{incl}(Z^0 + b)$ and $\sigma_{incl}(Z^0 + \text{jets})$ on muon isolation is adopted from [52] to account for the assumption of vanishing data to simulation corrections.

6.2 Boson Candidate Selection

For the reconstruction of Z^0 candidates, all muon objects left after the selection presented in section 6.1 are combined into pairs. Then only pairs are selected that exhibit opposite charges of both leptons, $q_{\mu,1} \cdot q_{\mu,2} < 0$. To further constrain the sample, the invariant mass of both leptons, $m_{\mu^+\mu^-}$, is required to yield a result close to the Z^0 resonance, i.e. $m_{Z^0} = 91.1876 \text{ GeV}$ [11].

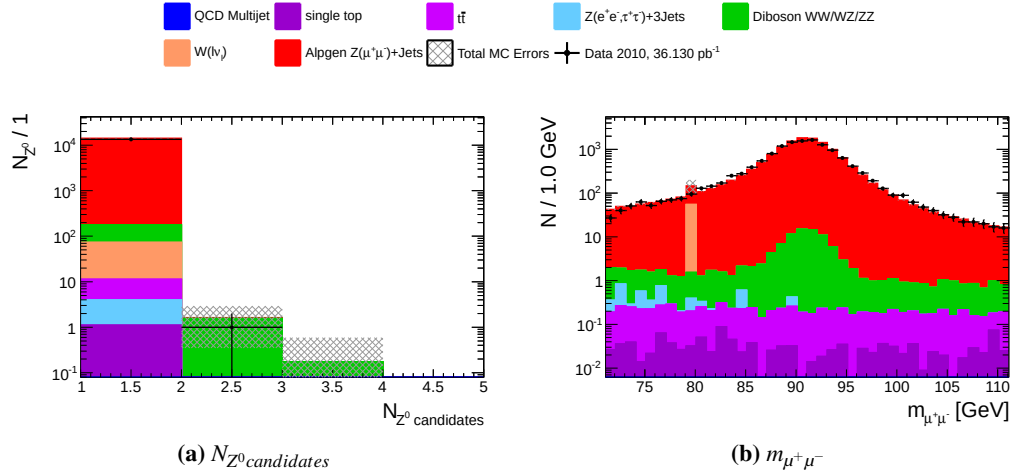


Figure 6.8: Number of reconstructed Z^0 candidates per event and di-muon invariant mass spectrum for ALPGEN signal plus expected background MC and data. The Z^0 resonance can be identified at $m_{\mu^+\mu^-} = 91 \text{ GeV}$.

Figure 6.7 illustrates the number of Z^0 candidates in data compared to simulated signal and background events. Both exhibit the characteristic Z^0 resonance peak at $m_{\mu^+\mu^-} = 91 \text{ GeV}$. Data and simulation shape and normalisation agree to the sub-percent level providing confidence in the applied reweighting and original simulation. The contribution of events that yield more than one Z^0 candidate is negligible.

The main background contributions can also be identified: $Z \rightarrow \tau^+\tau^-$, *Diboson* and *top* final states. In addition, one $W^\pm + \text{jets}$ event is exposed in the invariant mass spectrum. It must be noted that one event is statistically compatible with zero. Due to the one order of magnitude larger cross section of $W^\pm + \text{jets}$ events compared to $Z^0 + \text{jets}$, the event observed here receives a large luminosity weight and hence a large statistical uncertainty. With this, the expectation in this bin is yet compatible with the observed number of events. Thus, this is considered a mere statistical fluctuation and not subject to detailed studies.

In order to study the effect of the mass window window per Z^0 candidate, its width is varied with values of $|m_{\mu^+\mu^-} - m_{Z^0}| < 10, 15, 20, 25 \text{ GeV}$ and the signal significance Q as well as the total event yield is studied.

Figure 6.8 shows the increase of signal events versus the width of the invariant mass requirement imposed on reconstructed Z^0 candidates. While the shallow increase of Q from varying $|m_{\mu^+\mu^-} - m_{Z^0}|$ does not favour any of the given values, the signal yield, N_s , underlines again that a choice of $|m_{\mu^+\mu^-} - m_{Z^0}| = 20 \text{ GeV}$ does hold the highest signal significance and yet provides a large number of events from the signal. Thus, the invariant mass selection window for any given Z^0 candidate is set to 20 GeV .

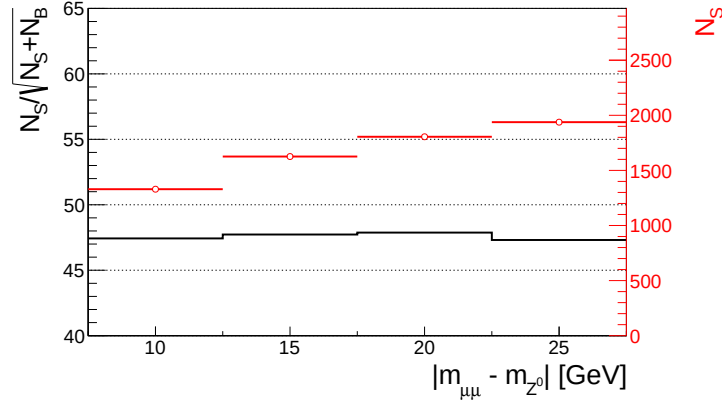


Figure 6.9: Event yields for four invariant mass windows of $|m_{\mu^+\mu^-} - m_{Z^0}| < 10, 15, 20, 25$ GeV in ALPGEN plus expected background topologies. The MC signal yields N_S (red) and the $Q = N_S / \sqrt{N_S + N_B}$ distance (black) are shown.

At this point, any distinction (while being well justified) between a reconstructed muon pair that satisfies the aforementioned requirements and a Z^0 is dropped in favour of brevity.

6.3 Jet Object Selection

The muon selection reflects the basis of reconstructing Z^0 boson candidates. Jets are also required for this study of $\sigma_{incl}(Z^0 + b)$ and $\sigma_{incl}(Z^0 + \text{jets})$. The following section will summarise the steps taken to select a well-reconstructed and well-understood sample of jets - starting from clustering, continuing onto jet cleaning, the kinematic selection and concluding by discussing the pile-up energy corrections applied.

6.3.1 Clustering and Calibration

For this study, jets were reconstructed from topological calorimeter clusters using the *anti-kt* algorithm with a distance measure of $R = 0.4$ (further denoted *anti-kt* for simplicity). All objects' kinematics are corrected for the position of the PV and calibrated onto the EM+JES energy scale, see section 4.3.3. Only reprocessed data samples have been used that already contain the above mentioned corrections from $\gamma^* + \text{jets}$ analyses [157].

6.3.2 Clean Jet Selection

During data taking, increasing pile-up (and subsequent out-of-time effects as described in section 4.2.4) and detector failures were observed during data-taking. With this, reconstructed jets were found showing large energy or angle mismeasurements due to calorimeter cell bursts or calorimeter cell readout failures as well as jets that had not been caused by sprays of particles from the interaction point at all. A detailed analysis of these features [188] suggests two categories of malformed jet measurements: non-collision jets and mismeasured jets.

For characterising these measurements, quantities have to be defined to describe energy depositions in active material of ATLAS or the detector response to this:

- f_X denotes the energy fraction measured in detector component X (e.g. *Tile*, *LAr*) or attributed to the jet constituent X (e.g. clusters, charged tracks). For $f_X = 1$, the entire jet's energy measurement was obtained from detector X .
- q_X describes the *LAr* quality of the calorimeter energy measurement available. It notes the fraction of cells with quality factor $Q_{LAr} > 4000$ divided by the total number of cells that contributed to the measurement. As illustrated in section 4.2.4, the energy measurement per cell is obtained by a fit to the recorded pulse shape a . The cell quality measures the difference between the expected versus the observed pulse shape over all recorded samples via $Q_{LAr} = \sum_{\text{sample}} (a_i^{\text{measured}} - a_i^{\text{predicted}})^2$. Thus, an energy measurement of detector X can be considered poorer the higher q_X evaluates.
- the energy-weighted time average of cells per jet is denoted as t
- E_{negative} describes the total measurement of negative energy clusters per jet due to pedestal or noise subtraction.

In the following, the key properties of the above mentioned malformed jet measurements are outlined.

non-collision jets refers to jets caused by mismeasurements in the endcap calorimeters (HEC spikes), by coherent electromagnetic noise in the calorimeters or non-collision backgrounds or influences from cosmic rays. These jets are characterised as:

- $(f_{HEC} > 0.5 \cap |q_{HEC}| > 0.5 \cap |E_{negative}| > 60 \text{ GeV}) \cup f_{HEC} > (1 - |q_{HEC}|)$

If a spatially concentrated array of calorimeter cells suffers from large high-voltage fluctuations, massive energy mis-measurements can be triggered (HEC spikes), that are read-out and reconstructed as jets objects but without high energetic particle origin.

- $f_{EM} > 0.9 \cap |q_{LAR}| > 0.8 \cap |\eta_{jet}| < 2.8$

A similar effect can occur in the electromagnetic calorimeters, if large volumes of cells experience electronic noise or fluctuations of it and record this as an energy measurement.

- $|t_{jet}| > 10 \text{ ns} \cup (f_{EM} < 0.05 \cap f_{tracks} < 0.1 \cap |\eta_{jet}| < 2) \cup (f_{EM} > 0.95 \cap f_{tracks} < 0.05 \cap |\eta_{jet}| < 2) \cup (|\eta_{jet}| < 2 \cap f_{max,sampling} > 0.99)$

This requirement is motivated by cosmic muons that induce jets either due to their high momentum or if they hadronically scatter off detector material or the cavern wall material. The timing of the latter would be askew of the LHC interaction and thus yield values of $|t_{jet}| > 10 \text{ ns}$. In addition, nuclear reactions known as cavern background can also induce energy measurements of this type.

mismeasured jets refers to jets that were measured in fiducial volumes of ATLAS where the energy measurement was not accurate. These jets can be characterised by:

- the jet's energy fraction in the *Tile gap 3* $f_{tilegap3} < 0.5$
This detector region is known to expose bad performance in 2010 data [188].
- the jet's energy fraction from dead cells or cells receiving large corrections $f_{dead \cup bad \text{ cells}} > 0.5$

By definition, dead cells do not deliver (correct) energy measurements. This also applies to masked cells or cells that are known to yield mismeasurements quite often. Thus, if a jet's energy was measured predominantly by these cells, it is considered uncertain.

For this analysis, jets falling into both categories are discarded in data only if the detector description in MC was inaccurate to allow a clear correspondence to observations during data taking.

6.3.3 Pile-Up Corrections

Out-of-time energy measurements due to time integration of calorimeter cell pulses leads to an overestimation of jets' energy deposit at high jet pseudo-rapidity η close to the beam-pipe. Here, the impact of beam halo and multiple interactions is the most dominant with increasing number of interactions per bunch crossing. Since this effect is uncorrelated with the bunch crossing during a given read-out, the effect can be translated to an average offset that needs to be subtracted from a jet's reconstructed energy.

Figure 6.9 shows the absolute energy offset per jet depending on η_{jet} in data which underlines the expected behaviour - increasing energy offset with increasing η_{jet} (up to $\eta_{jet} \simeq 3.2$) until a saturation is reached. The detector geometry limits the offset in the forward region (within $|\eta_{jet}| > 3.2$). As shown in section 5.2.3, the analysis at hand contains events with an average number of vertices of $\langle N_{vertices} \rangle = 1.9 - 2.7$. As will be discussed later, the use of b-tagging requires reconstructed jets to be inside $|\eta_{jet}| < 2.5$. Thus, figure 6.9 suggests a mean electro-magnetic energy offset of $0.1 - 1.2 \text{ GeV}$.

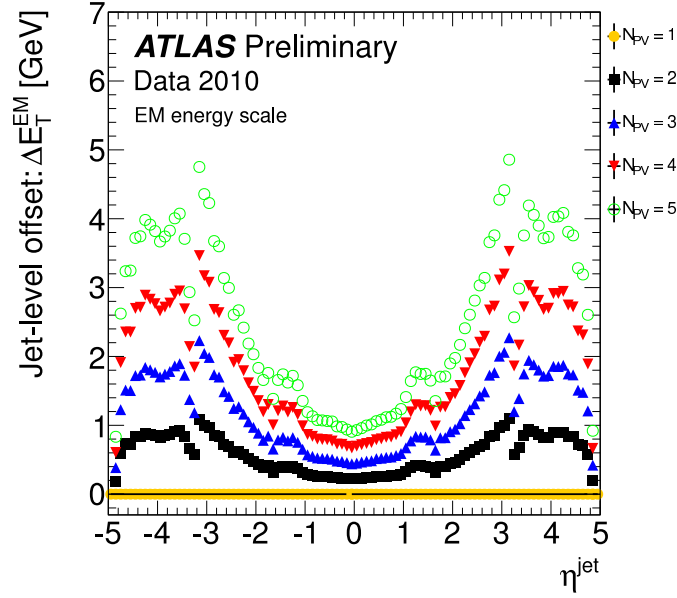


Figure 6.10: Jet energy offset of *anti-kt*(0.4) topo-cluster jets in 2010 ATLAS data versus jet pseudo-rapidity η_{jet} for different multiplicities of interactions per bunch crossing N_{PV} , from [189]. Pile-up effects on jet energy measurement are increasing with higher $|\eta_{jet}|$.

Figure 6.9 illustrates the constant rise of the energy correction with the observed number of vertices per event. A comparable observation can be made from figure 6.10, where increasing vertex multiplicities cause increasing energy offsets. This behaviour is shown to be of comparable dimension for a wide range of jet transverse momenta.

Figures 6.9 and 6.10 denote the number of interactions per bunch crossing as number of primary vertices, N_{PV} . For technically there is only one primary vertex per bunch crossing, this refers to the number of reconstructed track vertices that have at least five tracks attached to them. The track multiplicity requirement ensures that counted vertices have been reconstructed with an efficiency above 99% as documented in [124]. It has to be noted at this point that the definition of a good vertex with at least five associated tracks given here represents a measure of the magnitude of pile-up (e.g. the number of proton-proton interactions per bunch crossing) experienced per event. Since this definition is not used to discard events or jets but rather to apply energy corrections in fiducial volumes close to the beam pipe, the mismatch with the vertex requirement given in section 5.2.3 has no effect.

For this analysis, all jets' kinematics are corrected on per jet basis according to [189] taking all effects stated above into account before being subject for additional selection criteria.

6.3.4 Kinematic Selection

Constraining jet kinematics for a measurement of $\sigma_{incl}(Z^0 + b)$ and $\sigma_{incl}(Z^0 + \text{jets})$ limits the statistical power of the measurement itself. Taking this aspect into account, only jets within jet rapidity of $|\eta_{jet}| < 2.5$ are used. This cut is motivated by the *InnerDetector* tracking acceptance that constrains b-tagging for jets to this pseudo-rapidity. Second, the jet's transverse momentum

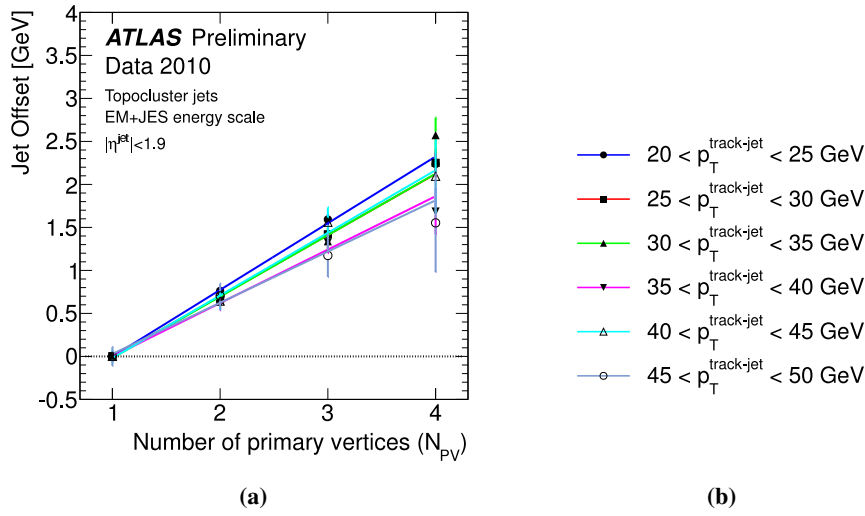


Figure 6.11: Jet energy offset of *anti-kt*(0.4) topo-cluster jets in 2010 ATLAS data versus multiplicities of interactions per bunch crossing N_{PV} for different bins of jet transverse momentum, from [189].

is required to be $p_{t,jet} > 25 \text{ GeV}$ because the uncertainties of jet energy scale and resolution are only available for jets above this threshold.

In addition to kinematic constraints, a jet-muon isolation requirement is imposed on all jet objects. Jets with an angular distance of $\min(\Delta R(jet, Z^0 \text{lepton})) < 0.5$ with regard to either lepton of the reconstructed Z^0 candidate are dropped from the event in order to uphold comparability with published ATLAS results as in [52, 98]. Discarding this requirement would imply a detailed understanding of muon isolation in the proximity of heavy flavour initiated jets which is inaccessible with the amount of 2010 ATLAS data presented and therefore not within the scope of this study.

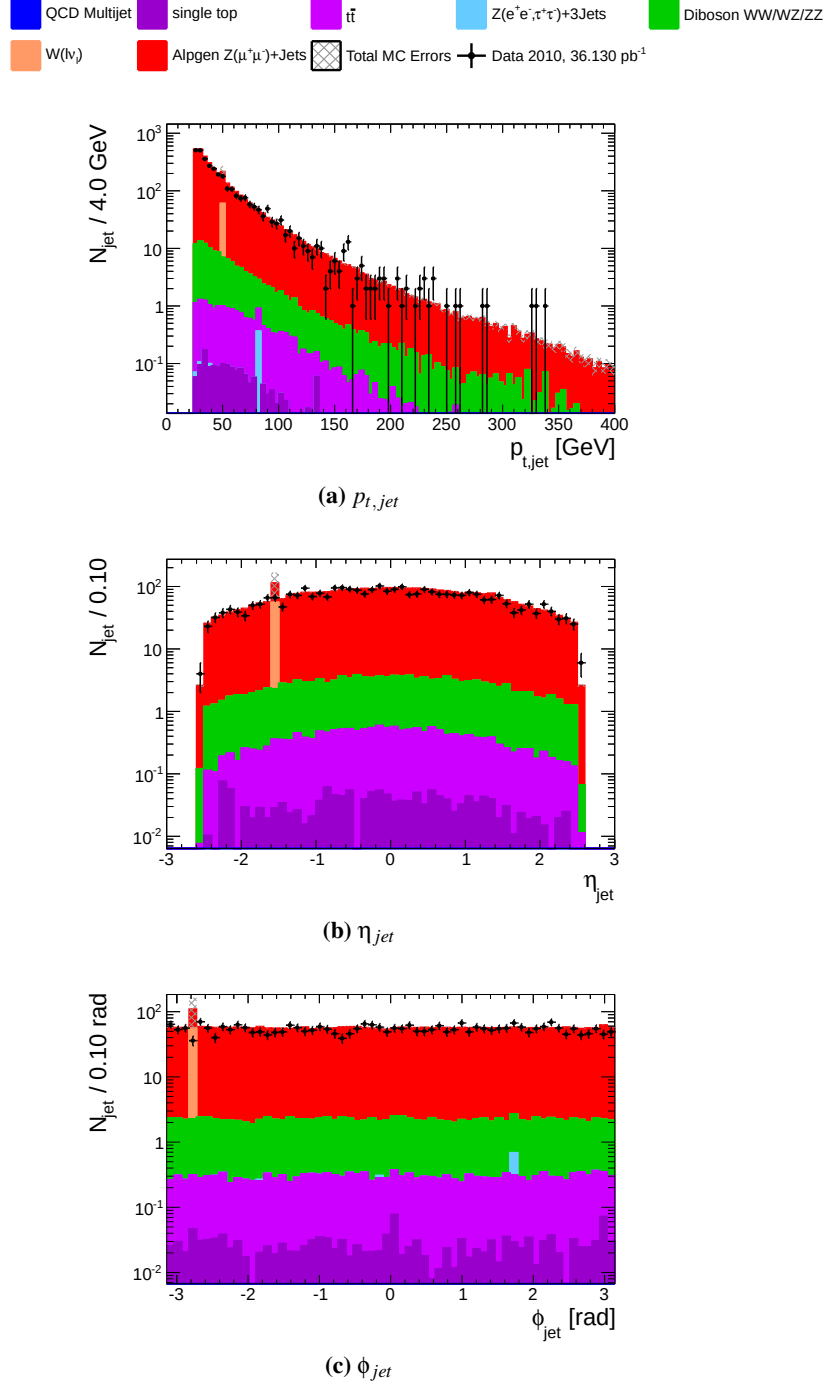


Figure 6.12: Distributions of jet kinematics observables $p_{t,jet}$ (a), ϕ_{jet} (c) and η_{jet} (b) for 2010 data and simulation. The plots include all jet object cuts as well as the di-muon selection described in section 6.2.

6.3.5 Summary

To summarise this section, a cutflow is shown that lists the number of jet objects passing a given level of requirement. The absolute cut efficiency ϵ_{abs} for this describes the number of objects passing all selection steps up to a given one compared to the initial number of objects. The relative cut efficiency ϵ_{rel} is also given that notes the portion of objects that passed only one given criteria with respect to the event ensemble without it.

	N_{jets}	ϵ_{abs}	ϵ_{rel}
<i>anti-kt</i> (0.4) Topo jet	28999.2 ± 170		
$p_{t,jet} > 25 \text{ GeV}$	3987 ± 63	0.137 ± 0.002	0.137 ± 0.002
$ \eta_{jet} < 2.5$	3650 ± 60	0.126 ± 0.002	0.915 ± 0.021
$\min(\Delta R(jet, Z^0 \text{lepton})) < 0.5$	3285 ± 57	0.113 ± 0.002	0.900 ± 0.022

Table 6.3: Cut-flow for absolute jet multiplicities N_{jets} , absolute ϵ_{abs} and relative cut efficiencies ϵ_{rel} thereof for simulated events using the ALPGEN $Z^0 + jets$ MC yielding at least one Z^0 candidate.

	N	ϵ_{abs}	ϵ_{rel}
<i>anti-kt</i> (0.4) Topo jet	27096		
not non-collision jet	25892	0.96	0.96
not mismeasured jet	25892	0.96	1.00
$p_{t,jet} > 25 \text{ GeV}$	3891	0.144	0.150
$ \eta_{jet} < 2.5$	3528	0.130	0.907
$\min(\Delta R(jet, Z^0 \text{lepton})) > 0.5$	3175	0.117	0.900

Table 6.4: Cut-flow for absolute jet multiplicities N_{jets} , absolute ϵ_{abs} and relative cut efficiencies ϵ_{rel} thereof for events in 2010 ATLAS data yielding at least one Z^0 candidate.

The total jet selection cutflow is listed in table 6.2 for simulation and in table 6.3 for data. The data at hand did not yield any mismeasured jets which can be attributed to the rigorous data-quality requirements imposed on analysed events in data and the small number of jets that may be subject to this issue. As expected, the cut on transverse jet momenta has the largest impact on the jet object count due to the steeply falling $p_{t,jet}$ spectrum which is illustrated in figure 6.11a. As a side note, the cut efficiencies in simulation and data agree within 1 – 2 standard deviations. This again shows how accurate the simulation of jet kinematics is. Since, an event is only selected if a Z^0 boson candidate was found and at least one jet satisfied the above listed criteria, the invariant mass of the di-muon system is a good indicator of data-simulation agreement.

Figure 6.12 illustrates again a good agreement of the total expected and observed events with $N_{jets} > 0$. Figure 6.12 exhibits a decrease in signal statistics from $N_{Z^0,MC} = 13665 \pm 14$ to $N_{Z^0+jets,MC} = 2442.2 \pm 22.5$ in simulation compared to figure 6.7b. This observation is due to the reduced cross section of events with additional jet(s) that are potentially subject to an additional pQCD vertex increasing the order of α_s by one. The selection efficiency of requiring at least one additional jet is $\epsilon_{sel}(N_{jets} > 0|Z^0) = 0.1849 \pm 0.0003$.

Regarding background contamination given in table 6.4, the statistical significance $Q(Z^0 + X) = 116.2 \pm 0.3$ and $Q(Z^0 + jets) = 48.2 \pm 0.7$ are observed. As dominant backgrounds, electro-weak

final state	$N \pm \sigma_N$	N/N_{MC}
$Z^0 + \text{jets}$	2457.3 ± 3.9	0.95
$WW/ZZ/WZ$	67.1 ± 0.9	0.03
$W^\pm + \text{jets}$	53.2 ± 53.2	0.02
$t\bar{t}$	7.3 ± 0.2	0.00
single Top	1.1 ± 0.1	
Q	48.2 ± 0.7	
Total MC	2586.3 ± 53.3	
Data	2420	

Table 6.5: Event yields after complete selection of $Z^0 + \text{jets}$ events. The event counts have been collected from ALPGEN signal MC and expected background contributions. In addition, the ratio of individual event topologies to the total MC prediction N/N_{MC} is given for illustrative purposes. Only statistical uncertainties of the MC event samples used are noted.

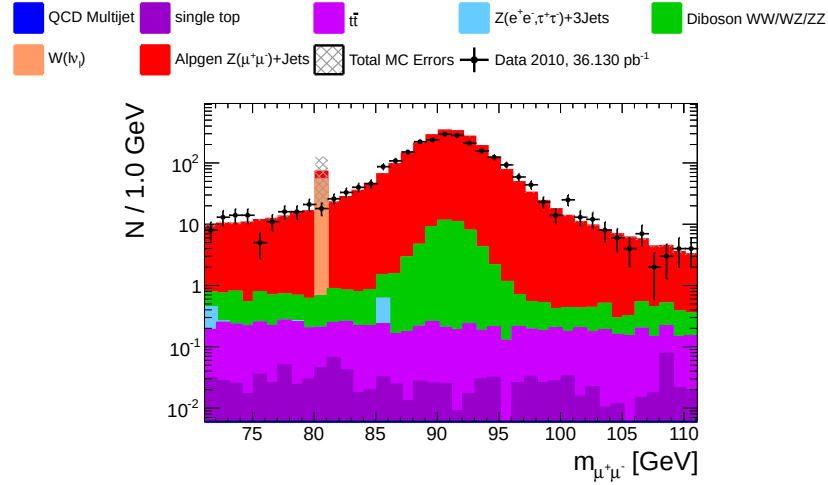


Figure 6.13: Invariant di-muon mass spectrum for events in data, ALPGEN signal plus expected background topologies that contain at least one Z^0 boson candidate in addition to at least one selected jet.

boson ($WW/ZZ/WZ$) and top quark ($t\bar{t}$) pair production can be identified. The contribution of $W^\pm + \text{jets}$ is caused by one single event that passes the selection presented here which receives a high luminosity weight due to the large cross section of $W^\pm + \text{jets}$ versus $Z^0 + \text{jets}$ topologies at the LHC and the low rate of jets faking muon candidates, see table 5.0 and 5.2.

The unsatisfactory account of the total predicted number of $Z^0 + \text{jets}$ compared to the observed one by 3 standard deviations of the prediction's statistical uncertainty was also observed by a dedicated ATLAS analysis [52]. The account given there can be reproduced here and was found to be due to modelling uncertainties.

Figure 6.13 illustrates the Z^0 candidate rapidity distribution from reconstructed muon candidates as well as from generator level muon objects. While the distribution on detector level does expose a good agreement, the distribution on generator level reports a significant difference between the SHERPA and ALPGEN MC for rapidities near 0. Although the PDF sets utilised for the signal event samples are identical (see table 5.0), the Z^0 rapidity distributions in events with at least one jet

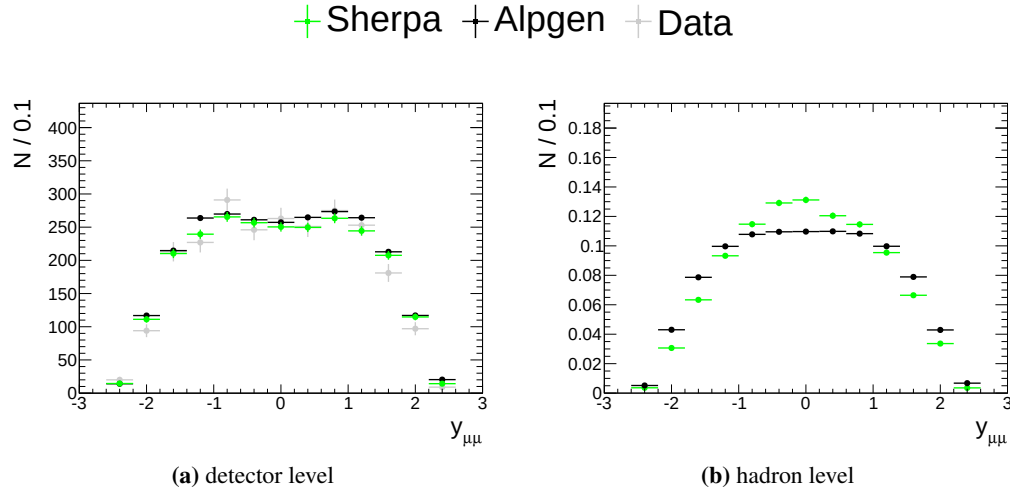


Figure 6.14: Reconstructed Z^0 candidate rapidity distribution on detector level or hadron level in events with at least one reconstructed jet (a) or one generated jet (b).

differs. Further, the effect of mixing (N)LO predictions with (N)LO PDF in $Z^0 + \text{jets}$ final states has been shown [103] to result in deviations of the size than observed here. The precise identification of the theoretical source for this discrepancy is henceforth not considered part of this analysis since the normalisation of the simulated $Z^0 + N_{jets}$ jets event sample does not enter the evaluation of $\mathcal{R}$ and has negligible effect on $\sigma_{incl}(Z^0 + b)$.

Events passing the requirements listed up to this point will be further denoted as $Z^0 + N_{jets}$ jets to indicate a sample of events with a reconstructed Z^0 candidate and $N_{jets} > 0$ selected jets that have not been subject to a b-tagging requirement.

6.4 Bottom Flavour Tagging

To select bottom parton induced jets, each reconstructed jet object is subject to a b-tagging algorithm and a corresponding estimator, the b-tagging weight, is calculated as introduced in section 4.3.4. The b-tagging weight is used as a cut variable to obtain a set of viable heavy flavour jet candidates. For the study at hand, a baseline tagger is used as well as an alternative algorithm to allow better comparability with recent ATLAS publications [98] and to facilitate inter-comparability between a highly efficient and a high purity selection. This section will thus introduce the working points used, show control distributions of $m_{\mu^+\mu^-}$, $p_{t,jet}$ and η_{jet} in events with at least one tagged jet to illustrate data-to-MC comparability and finally introduce the procedure applied in order to calibrate MC simulation to data performance similar to muons in section 6.1.

6.4.1 Tagging Algorithms

As indicated, the extraction of $\sigma_{incl}(Z^0 + b)$ is conducted on two b-tagged sub-samples of $Z^0 + N_{jets}$ jets events using two different tagging algorithm weight cuts. The high efficiency advanced tagger IP3D+SV1 is used at its working point of $\epsilon_b^{t\bar{t}} = 80\%$ requiring each jet to have a tagging weight of $w_{IP3D+SV1} > -0.85$ (further denoted as IP3D+SV1(80%)). As an alternative, jets in events with at least one Z^0 boson have to pass a SV0 weight selection of $w_{SV0} > 5.85$ corresponding to $\epsilon_b^{t\bar{t}} = 50\%$ (further denoted as SV0(50%)). Here, the b-tagging efficiency is given as deduced from $t\bar{t}$ MC events.

The tagging efficiency ϵ_b is defined as

$$\epsilon_b = \frac{N_{jets}(tagged|generated\ b)}{N_{jets}(generated\ b)} \quad (6.8)$$

the ratio of all reconstructed and tagged jets inside the number of reconstructed jets that were successfully found to contain generated b hadrons. $t\bar{t}$ final states in simulation and in data offer standard candle type measurements for b-tagging analysis for they contain at least two bottom flavour induced jets due to the dominant decay of the top quark through $t \rightarrow W^+ \bar{b}$ ($\bar{t} \rightarrow W^- b$). Therefore, the b-tagging working points given above are quantified by reporting the total b-tagging efficiency in $t\bar{t}$ MC event, $\epsilon_b^{t\bar{t}}$.

The b-tagging efficiencies given here correspond to results from dedicated studies on simulated $t\bar{t}$ events as available from [159, 190]. Before the 2010 data taking, the performance of b-tagging could not been validated with collision data. As introduced in section 4.3.4, b-tagging algorithms use a multitude of information from the *InnerDetector* systems which in turn had to be studied with the first bulk of data taken and required validation of respective simulations.

With b-tagging, the selection of a pure sample of bottom quark induced jets in data is non-trivial. Either complicated algebraic methods have to be applied, e.g. *System8* [191], or semi-leptonic decays of B hadrons have to be utilised (*ptrel*-method [190]) which tend to yield a small reference sample. For the bulk 2010 data set, the *ptrel*-method was conducted on QCD multi-jet events in data and MC which allowed to calculate scale factors to adjust the simulated b-tagging performance. Thus, the *ptrel*-method shall be outlined here briefly.

For the *ptrel*-method, a high purity sample of jets caused by b-quark fragmentation is selected by relying on the semi-leptonic B hadron decays with branching fractions of $\mathcal{BR}(B^+ \rightarrow \ell^+ \nu_\ell + X) = (10.99 \pm 0.28)\%$ or $\mathcal{BR}(B^0 \rightarrow \ell^+ \nu_\ell + X) = (10.33 \pm 0.28)\%$ [11], where a soft lepton can be found inside the jet. The reconstructed lepton transverse momentum with respect to the jet axis,

$p_{t,rel}$, can be used to discriminate heavy flavour (momenta of leptons correlated with B hadron momentum) from light flavour (momenta of leptons more along the jet axis) jets as illustrated in figure 6.14a. This in turn allows to extract the efficiency to successfully tag a generated bottom quark induced jet by means of b-tagging, ϵ_b . The $p_{t,rel}$ -method can be conducted on data and simulated events. Obtaining the ϵ_b from both allows to calculate scale factors that correct simulated b-tagging performance with the same algorithm's response in data.

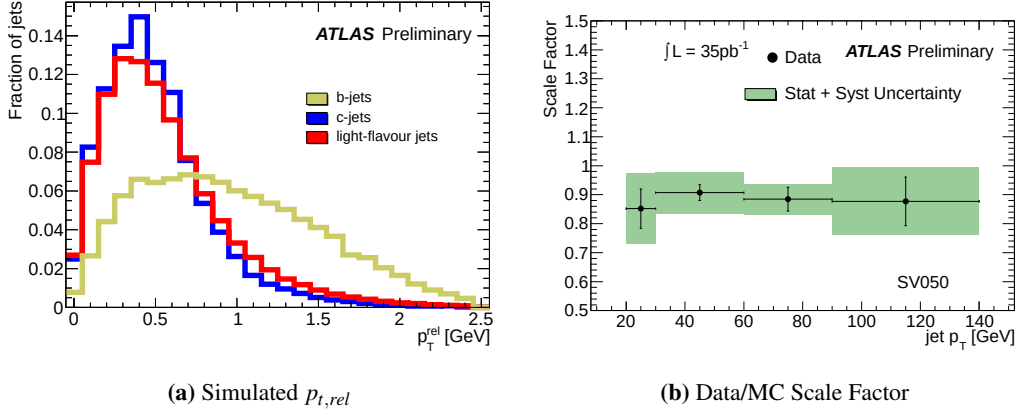


Figure 6.15: Simulated $p_{t,rel}$ spectrum for light, charm and bottom quark induced jets (left) and ϵ_b Data/MC scale factors (right) from [190].

Figure 6.14b shows ϵ_b scale factors for SV0(50%) that range within (80 – 95) %. It must be emphasised at this point that scaling ϵ_b in simulation does not only alter the number of generated bottom quark induced jets tagged here, but also changes the abundance of light and charm quark induced ones in the tagged jet sample. Thus, in order to correctly apply this scale factor to MC, all jets that have been subject to b-tagging need to be taken into account. Scale factors are hence evaluated on a per-jet level depending on the simulated flavour F of the jet. A tagged jet is accounted for by

$$w_b(jet|tagged) = \frac{\epsilon_{b-tag}^{Data}(F|tagged)}{\epsilon_{b-tag}^{MC}(F|tagged)}. \quad (6.9)$$

For an untagged jet, the purity (or mistag efficiency) has to be taken into account as in

$$w_b(jet|\overline{tagged}) = \frac{1 - \epsilon_b^{Data}(F|\overline{tagged})}{1 - \epsilon_b^{MC}(F|\overline{tagged})}. \quad (6.10)$$

From [190] and [159], the measured estimates of $\epsilon_{b-tag}^{Data}(F)$ are available in bins of $p_{t,jet}$ and η_{jet} including statistical and systematic uncertainties. Thus, equations 6.9 and 6.10 are used to calculate an event weight by evaluating

$$w_{b-tag} = \prod_i^{jets} w_{b,i}. \quad (6.11)$$

The difference in statistics in figure 6.15 (left/right subfigures) is due to the b-tagging performance of SV0 compared to IP3D+SV1 that fall into the selected regimes of w_{SV0} or $w_{IP3D} + w_{SV1}$. Since SV0(50%) was utilised at a low efficiency working point, the statistics that passes $w_{SV0} > 5.85$ is low (large statistical uncertainties of figure 6.15a). This is not the case for the high efficient IP3D+SV1(80%) working point at $w_{IP3D} + w_{SV1} > -0.85$ (small statistical uncertainties of figure

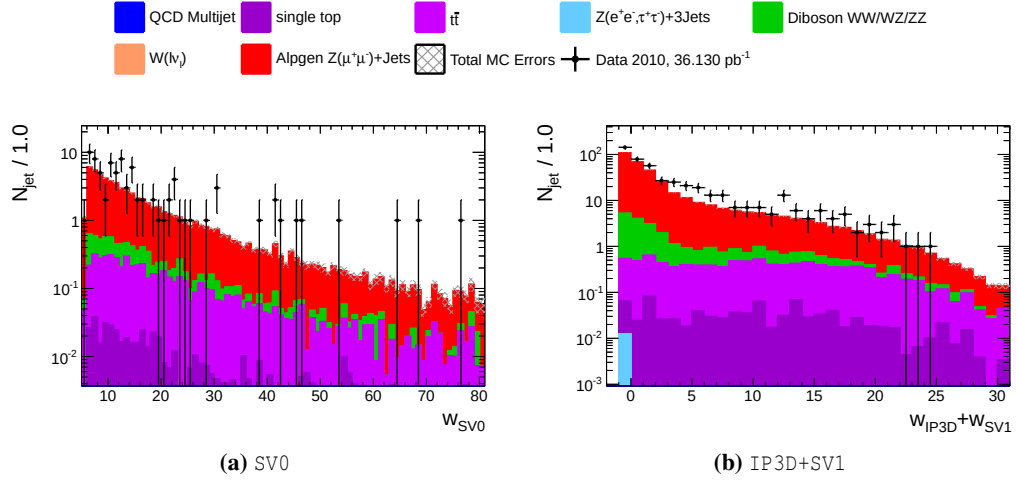


Figure 6.16: B-tagging weight distributions per jet of selected $Z^0 + b + X$ samples using the SV0(50%) (a) and IP3D+SV1(80%) (b) tagging algorithm requirement and one reconstructed Z^0 per event. The shown mismatch of data and MC is explained by a mis-modelling of b-tagging efficiency and mistag rates in MC as compared to observations in data. No correction for b-tagging performance was applied for events shown here.

6.15b).

Figure 6.15 shows a mismatch of b-tagging weight distributions for events with at least one Z^0 candidate and one b-tagged jet. This is caused by the b-tagging efficiencies differing in MC and in data. Dedicated analyses by the ATLAS experiment [159] have suggested that it can be primarily attributed to a better impact parameter resolution modelled in MC than observed in data. In order to quantitatively describe the reported mismatch, the Fisher distance

$$t = \frac{\langle N_{MC} \rangle - \langle N_{Data} \rangle}{\sqrt{\sigma(N_{Data})^2 + \sigma(N_{MC})^2}} \quad (6.12)$$

calculated from the expectation value of simulated ($\langle N_{MC} \rangle$) and observed ($\langle N_{Data} \rangle$) event distribution as well as the variance of the latter ($\sigma(N_{Data}), \sigma(N_{MC})$) is used.

sample	Data	Simulation	t
SV0	86 ± 9	89 ± 2.5	-0.32
IP3D+SV1	474 ± 28	353.9 ± 1.4	4.3

Table 6.6: Total integral of b-tagging weight distributions as observed in data and MC as illustrated in figure 6.15.

Table 6.5 lists the total normalisations for these quantities which are of central interest for the measurement of the total cross section. Besides the obvious difference in the chosen test statistic, the Fisher distance for IP3D+SV1 selected events is higher than those from SV0 selection. Thus, a careful study of possible scale factors is required. The difference in event yields listed in table 6.5 is caused by the different working points at which IP3D+SV1 ($\epsilon_b(t\bar{t}) = 50\%$) and SV0 ($\epsilon_b(t\bar{t}) = 80\%$) are used. Higher b-tagging efficiencies induce higher event yields that pass the respective requirement.

Events passing these requirements of either SV0 (or IP3D+SV1) will be further denoted as $Z^0 + N_{SV0}$ jets ($Z^0 + N_{IP3D+SV1}$ jets) indicating a sample of events yielding a reconstructed Z^0 candidate and $N_{SV0} > 0$ (or $N_{IP3D+SV1} > 0$) selected and b-tagged jets. To denote either event sample, $Z^0 + N_{b-tag}$ jets is used.

6.4.2 Performance and Calibration

In order to validate the use of scale factors, b-tagging efficiencies for bottom ϵ_b , charm ϵ_c and light flavour jets ϵ_l (equation 6.8) were evaluated for all selected jets in simulated $Z^0 + \text{jets}$ events. This is motivated by the observation that jet kinematics as well as the flavour composition of partons inducing jets do differ in $Z^0 + b + X$ compared to $t\bar{t}$ final states. To illustrate this and its consequences, simulated events with jets that pass the IP3D+SV1 requirement are studied that have not been subject to a Z^0 selection in order to retain a high statistics sample, figure 6.16.

In order to identify a heavy flavour induced jet on hadron level the following definition was used: if a non-excited bottom hadron (denoted B) is found with $p_{t,B} > 5 \text{ GeV}$ and within $\Delta R(B, \text{jet}) < 0.3$, a jet is considered bottom induced. if no B hadron is found, the jet's proximity is searched for charm hadrons (denoted D) required to have $p_{t,D} > 5 \text{ GeV}$ and within $\Delta R(D, \text{jet}) < 0.3$. If this is not successful, the jet is considered to be light quark or gluon induced. The listing of all generator level particle identifiers [11] used to identify B or D in MC events are given in appendix E.1.

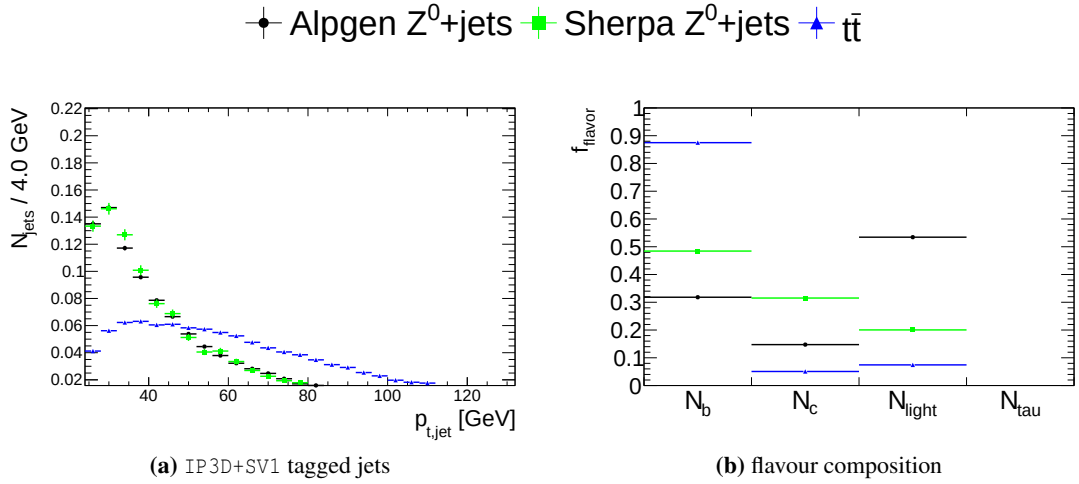


Figure 6.17: Bottom parton labelled jets' transverse momentum and parton flavour composition in events of signal MC and top background samples with at least one IP3D+SV1 jet but without prior Z^0 reconstruction. All distributions are normalised to unity.

Bottom flavour induced jets in $t\bar{t}$ events are produced in decays of top quarks themselves $t \rightarrow W^\pm b$. Due to the high mass of the top, the produced bottom flavour jet has a large kinematic phase space available and obtains high momenta on average. In figure 6.16a, the ensemble means are $\langle p_t(\text{tagged}|\text{bottom})^{t\bar{t}} \rangle = 63.6 \pm 0.1 \text{ GeV}$ and $\langle p_t(\text{tagged}|\text{bottom})^{Z^0 + \text{jets}} \rangle = 47.2 \pm 0.3 \text{ GeV}$. In $Z^0 + \text{jets}$ events, the bottom quark recoils against the Z^0 which is produced almost at rest during the collision. Thus, the produced bottom quark momenta differ greatly. The flavour composition of $Z^0 + \text{jets}$ or $t\bar{t}$ differs as well, for the production vertex in $Z^0 + \text{jets}$ events is dominated by pQCD whereas the production of additional flavour jets (besides the bottom quark from the top decay) in $t\bar{t}$ events is primarily due to the hadronic decay of the $W^\pm$ boson.

Figure 6.16b and table 6.6 list the number of IP3D+SV1 b-tagged jets per parton flavour. As listed in table 5.2, the $t\bar{t}$ MC events contain topologies where at least one $W^\pm$ decays leptonically. Further, the difference in flavour composition comparing ALPGEN and SHERPA is attributed to the fact that both generators use competing approaches in calculating $Z^0 + b + X$ final states. In the massless four-flavour FFS scheme implemented by ALPGEN, final state bottom partons can only be

sample	$f_b/[\%]$	$f_c/[\%]$	$f_{light}/[\%]$
SHERPA $Z^0 + \text{jets}$	48	32	20
ALPGEN $Z^0 + \text{jets}$	32	15	53
MC@NLO $t\bar{t}$	87	5	7

Table 6.7: Parton flavour fractions composition in events of signal MC and top background samples with at least one IP3D+SV1 jet but without prior Z^0 reconstruction as depicted in figure 6.16b.

produced by gluon splitting $g \rightarrow b\bar{b}$. SHERPA as setup for the MC used here generates events upon a massive five-flavour VFS scheme. Within the latter, final state bottom quarks can be generated by gluon splitting and might also be obtained from the bPDF directly (see section 3.3). Therefore, the bottom flavour fraction in SHERPA is larger than in ALPGEN. In addition, the latter described process $gb \rightarrow Z^0 b$ exposes one order of α_s while the dominant process in the FFS used by the ALPGEN MC exposes two in $q\bar{q} \rightarrow Z^0 b\bar{b}$. The differences reported in table 6.6 originate from two effects that yield different bottom flavour fractions. Similar observations can be made on the generator level $Z^0 + b$ count that are reported in the appendix section D.5.

The scale factors used to calibrate the b-tagging response in simulation $w_b(jet)$ as introduced in equations 6.9 and 6.10 as well as their statistical and systematic uncertainties are obtained from reference histograms and evaluated for every simulated event. They are binned in reconstructed jet p_t and η . For the latter, the distribution of *InnerDetector* sensitive material with η motivates this choice. With higher jet momentum, the varying abundance and kinematics of charged particles inside jets also suggest a different response of b-tagging algorithms in this jet variable. A dependency versus ϕ_{jet} is not expected due to the homogeneous layout of sensitive material in the ATLAS experiment.

In order to obtain scale factors according to jet kinematics observed in $Z^0 + N_{b-tag}$ jets events, b-tagging efficiencies have been deduced from signal MC and used for calculating $w_b(jet)$ and w_{b-tag} for this study.

Figure 6.17 depicts the b-tagging efficiencies yielded from SHERPA and ALPGEN signal MC events and MC@NLO $t\bar{t}$. For bottom and light flavour jets, $t\bar{t}$ samples do show up to 20% higher efficiencies than signal Z^0 samples. For the case of SV0 efficiencies of charm and light flavour initiated jets, the absolute difference in efficiency reaches a factor of two. The b-tagging efficiency is calculated in two dimensions, $p_{t,jet}$ and η_{jet} as shown in appendix D.5, and scale factors are evaluated using equations 6.9 and 6.10 with $\epsilon_b^{MC, Z^0 + jets}$ for ALPGEN and SHERPA signal samples.

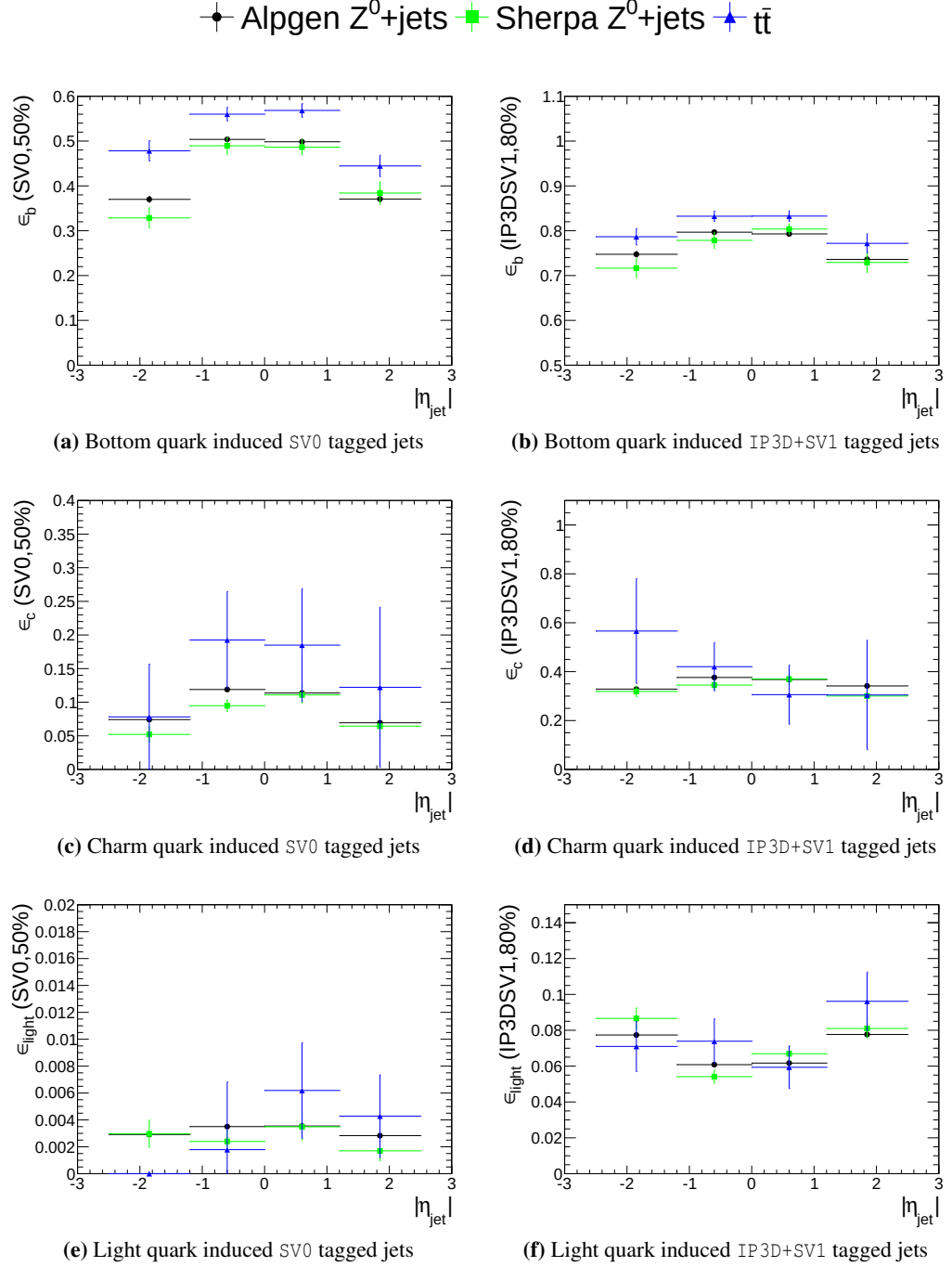


Figure 6.18: B-tagging efficiency for bottom (a,b), charm (c,d) and light (e,f) flavour induced jet as a function of η_{jet} for SV0(50%) (left) and IP3D+SV1(80%) b-tagged jets (right). The efficiency was evaluated for simulated $Z^0 + jets$ and $t\bar{t}$ samples.

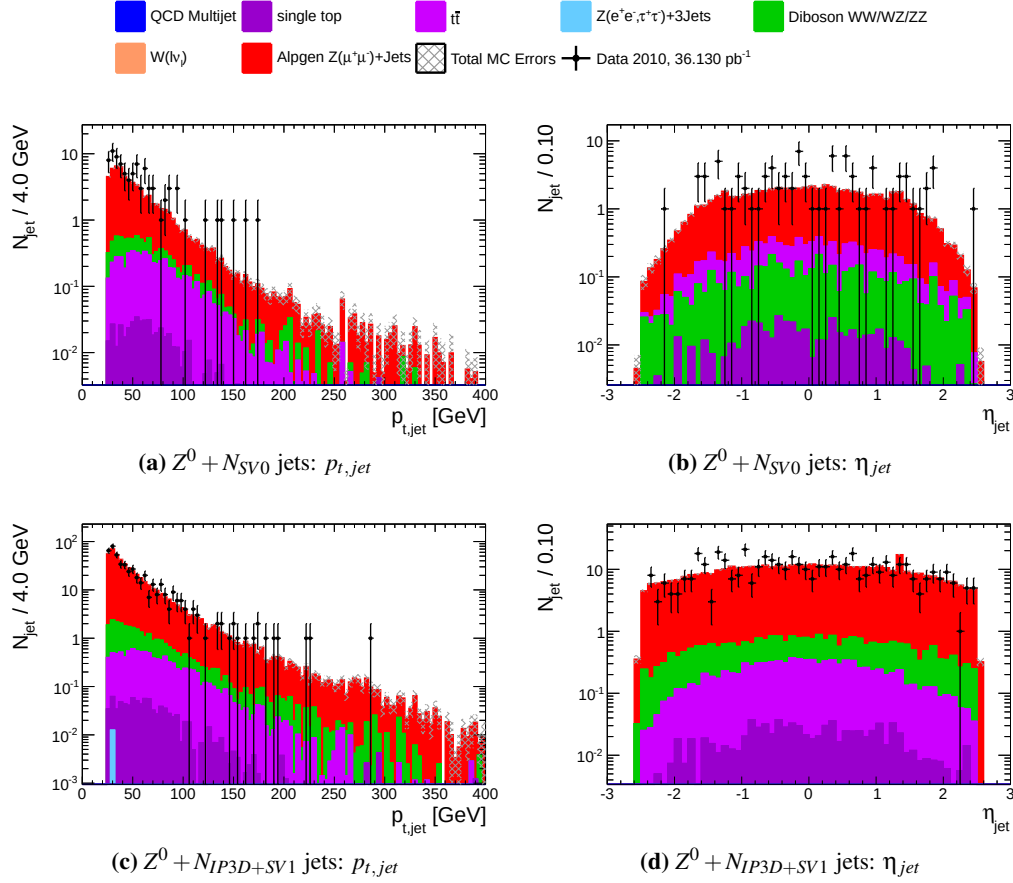


Figure 6.19: $SV0$ tagged jet transverse momentum (a) and pseudo-rapidity (b) as well as $IP3D+SV1$ tagged jet transverse momentum (c) and pseudo-rapidity (d) distributions in events with a reconstructed Z^0 boson candidate for ALPGEN signal plus expected background topologies compared to data. The b-tagging efficiency calibration in MC has been conducted using $Z^0 + \text{jets}$ events.

Figure 6.18 underline the well described jet kinematics by both SHERPA and ALPGEN MC generators and subsequent detector simulation after reweighting.

sample	Data	Simulation	t
SV0	86	86.3 ± 2.5	-0.03
IP3D+SV1	474	473.4 ± 1.9	0.03

Table 6.8: Total integral of b-tagging weight distributions as observed in data and MC after b-tagging reweighting was applied.

Comparing tables 6.7 and 6.5 provides good evidence that applying scale factors to b-tagged $Z^0 + b + X$ yields improved MC to data comparability. The mismatch between data and MC in the IP3D+SV1 sample is reported to vanish if the $Z^0 + \text{jets}$ based calibration is applied. The SV0 event sample shows to be invariant under this correction of b-tagging efficiencies. Since the SV0 sample is dominated by bottom flavour initiated jets and vice versa, the IP3D+SV1 sample contains a majority of light jets, the reported data/MC mismatch could be correlated to light flavour induced jets is hereby reported but not followed upon any further.

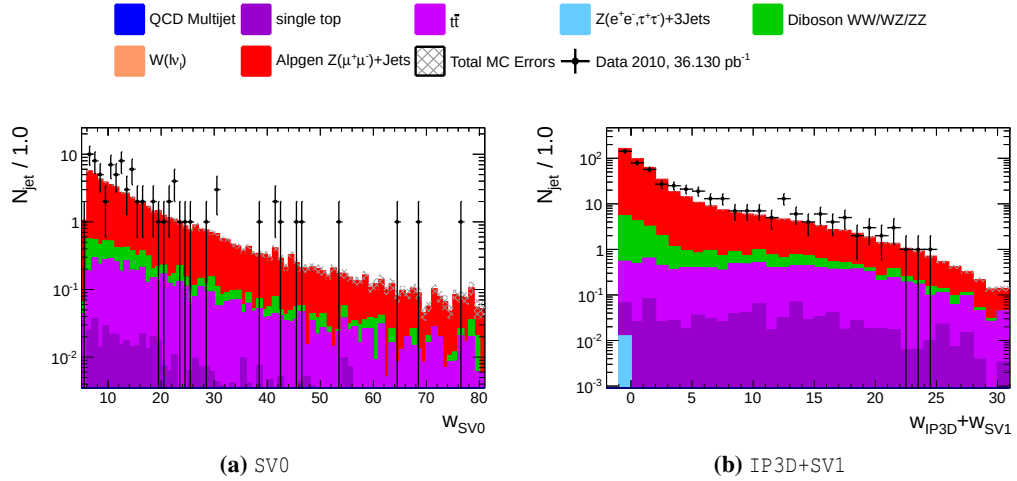


Figure 6.20: B-tagging weight distributions for selected $Z^0 + b + X$ samples using the SV0(50%) (a) and IP3D+SV1(80%) (b) tagging algorithm requirement requiring at one reconstructed Z^0 per event. A weight has been assigned to events entering here to correct b-tagging performance in simulation to that observed in data.

Figure 6.19 shows the b-tagging weight distributions of jets from events satisfying the $Z^0 + N_{SV0}$ jets and $Z^0 + N_{IP3D+SV1}$ jets selection that have been corrected with b-tagging efficiency scale factors as discussed above. The effect on jets tagged by the SV0 algorithm is negligible due to the small statistics of the $Z^0 + N_{SV0}$ jets event sample. However, the overestimate observed in figure 6.15b is removed for this sample contains a high fraction of light jets which yield a smaller b-tagging in $Z^0 + \text{jets}$ than in $t\bar{t}$ MC events as illustrated in figure 6.17f. Finally, the total b-tagging efficiencies for the two working points obtained from $Z^0 + \text{jets}$ events are:

- SV0 : $\epsilon_b^{MC, Z^0 + jets} = (45.2 \pm 0.5) \%$
- IP3D+SV1 : $\epsilon_b^{MC, Z^0 + jets} = (77.7 \pm 0.7) \%$.

6.5 Event Yields

At this stage, the object and event selection is concluded. Any further selections would potentially increase the purity of the selected event sample, but inevitably lead to a decrease of total statistics. In 2010 data, two categories of events have been selected that will facilitate the evaluation of $\sigma_{incl}(Z^0 + b)$ and $\sigma_{incl}(Z^0 + \text{jets})$: $Z^0 + N_{jets}$ jets and $Z^0 + N_{b-tag}$ jets ($Z^0 + N_{IP3D+SV1}$ jets and $Z^0 + N_{SV0}$ jets) type events. Here, two b-tagged event samples are retained in order to make the analysis robust against any mis-modelling or mis-simulation of b-tagging related quantities. Effects from bottom quark induced jets or the b-tagging performance thereof are expected to have strong impact in $Z^0 + N_{SV0}$ jets events whereas the effect due to light quark initiated jets would surface in $Z^0 + N_{IP3D+SV1}$ jets events.

final state	$N \pm \sigma_N$	N/N_{MC}	final state	$N \pm \sigma_N$	N/N_{MC}
$Z^0 + \text{jets}$	56.8 ± 0.5	0.87	$Z^0 + \text{jets}$	435.6 ± 1.8	0.95
$t\bar{t}$	4.4 ± 0.1	0.07	$WW/ZZ/WZ$	17.3 ± 0.4	0.04
$WW/ZZ/WZ$	3.6 ± 0.2	0.06	$t\bar{t}$	6.4 ± 0.2	0.01
single Top	0.5 ± 0.0	0.01	single Top	0.8 ± 0.0	0.00
Q	7.0 ± 0.1		Q	20.3 ± 0.1	
Total MC	61.3 ± 0.5		Total MC	460.2 ± 1.9	
Data	80		Data	435	

(a) SV0(50%)

(b) IP3D+SV1(80%)

Table 6.9: Event yields after complete selection of $Z^0 + N_{b-tag}$ jets selection with high efficiency trigger IP3D+SV1(80%) (sub-table 6.8b) and high purity trigger SV0(50%) (sub-table 6.8a). The event counts have been collected from ALPGEN signal MC and noted background contributions. In addition, the ratio of individual event topologies contributing to the total MC prediction N/N_{MC} is given ordered by magnitude for illustration.

Tables 6.8a and 6.8b show the low statistics inferred by a $Z^0 + b + X$ selection in 2010 ATLAS data. Data and simulation do not coincide within the quoted statistical uncertainties which underlines the importance of using a fit to extract the number of observed bottom induced jets. The impact of high efficient versus high purity selection is also visible: SV0(50%) gives a low statistic ensemble, the IP3D+SV1(80%) yields 4 times more events. The fact that also Q values differ substantially should not disclose that signal yields contain far more light flavour induced jets in the IP3D+SV1 than in SV0 selection respectively. This is further underlined by the observation that $t\bar{t}$ plays a more dominant role for the latter.

Comparing the results noted in table 6.8 with the event yields for $Z^0 + \text{jets}$ presented in table 6.4 illustrates the high reduction of selected events by applying a b-tagging requirement. Here, the selection efficiencies for events containing at least one b-tagged jet versus events containing at least one jet in simulated signal events are: $\epsilon_{sel}(SV0|Z^0 \cap N_{jets} > 0) = 0.0210 \pm 0.0002$ for SV0 and $\epsilon_{sel}(IP3D+SV1|Z^0 \cap N_{jets} > 0) = 0.1674 \pm 0.0008$ for IP3D+SV1 type events.

To conclude, this chapter has illustrated the selection imposed on 2010 ATLAS data and simulation in order to select a sample of $Z^0 + \text{jets}$ events. Simulated events have been reweighted to published data-driven performance estimates of the ATLAS detector as much as possible. From this, a good agreement of distribution shapes between MC prediction and data was shown. Selected events of $Z^0 + \text{jets}$ have been categorised into two samples of b-tagged $Z^0 + b$ final states, a high purity sample with low statistics ($Z^0 + N_{SV0}$ jets) and a high efficiency sample with high statistics

($Z^0 + N_{IP3D+SV1}$ jets) which may overlap. The normalisation of the used MC samples was found to insufficiently describe the data which again provides a motivation to conduct a cross section measurement of $\sigma_{incl}(Z^0 + b)$ and $\mathcal{R}$ as envisioned.

Chapter 7

Measurement of Cross Section and Cross Section Ratios

The number of observed $Z^0 + \text{jets}$ events containing bottom quark induced jets has to be estimated from data because b-tagging algorithms provide object ensembles that are not populated by heavy flavour initiated jets at high purity. This estimate will be possible by means of an extended maximum likelihood fit to a parameter that is sensitive to b-tagging. Here, the b-tagging weight cannot be used because it is subject of a cut criteria (providing truncated distributions that are difficult to fit). Therefore, the parameter to apply the fit in is expected to be correlated with the content of heavy flavour induced jets and thus with the b-tagging weight, but provide distributions with high separation power and yielding robust fit performance.

This chapter first validates the description of irreducible background contributions that will eventually be part of the fitted distribution. Then suitable parameters are studied that may provide distributions for the log-likelihood fit procedure. Further, the chosen fit ansatz is validated for its statistical properties and possible short-comings. The chapter concludes by the definition of fiducial phase space volumes before the results for $\sigma_{incl}(Z^0 + b)$ and $\mathcal{R} = \frac{\sigma_{incl}(Z^0 + b)}{\sigma_{incl}(Z^0 + \text{jets})}$ are reported including statistical uncertainties only.

7.1 Background Contributions

The dominant backgrounds for this analysis are: $WW/ZZ/WZ$ and $t\bar{t}$. QCD multi-jet events might also have an impact. Due to their large cross section (table 5.2) and the high rejection obtained by the selection outlined in chapter 6, it is not possible to make predictions based on the available QCD multi-jet MC due to a lack of events.

7.1.1 QCD multi-jet background

From PYTHIA QCD multi-jet MC, the expected number of observed $Z^0 + N_{jets}$ jets, $Z^0 + N_{SV0}$ jets and $Z^0 + N_{IP3D+SV1}$ jets events is zero. Since the MC statistics at hand is not sufficient, the QCD prediction has to be re-evaluated using data-driven methods. In order to estimate the QCD background a tiling method [52, 98] is set up.

It is assumed that QCD final states enter the ensemble of selected events if they pass the lepton isolation requirements (by mismeasurements in the calorimeter systems or their read-out) or by charge mismeasurements per muon object in close proximity or within jet objects in case of high

lepton momenta or due to *InnerDetector-MuonSpectrometer* track matching ambiguities. Both plausible causes are very unlikely but not impossible. For QCD multi-jet events may yield pairs of muon objects with arbitrary charges, their abundance is expected to follow a two-dimensional distribution in muon pair charge $q_{\mu,1} \cdot q_{\mu,2}$ versus lepton isolation requirement i_{ptcone} (see section 6.1.4) with non-negligible contributions to all bins. This behaviour contrasts that of $Z^0 + \text{jets}$ events which yield vanishing entries from same-sign muon pair selections. Thus, four sub-samples of the observed data are constructed retaining all object requirements from chapter 6 except those for muon isolation and di-muon pair charge:

tile	final state	lepton charge product	lepton isolation
A	$N(os iso)$	$q_{\mu,1} \cdot q_{\mu,2} < 0$	$i_{ptcone} < 0.1$
B	$N(os \overline{iso})$	$q_{\mu,1} \cdot q_{\mu,2} < 0$	$i_{ptcone} > 0.1$
C	$N(ss iso)$	$q_{\mu,1} \cdot q_{\mu,2} > 0$	$i_{ptcone} < 0.1$
D	$N(ss \overline{iso})$	$q_{\mu,1} \cdot q_{\mu,2} > 0$	$i_{ptcone} > 0.1$

Table 7.1: Notation of lepton pair populations for different requirements on lepton pair charge and lepton object isolation requirements.

QCD multi-jet events contain dominantly opposite sign lepton pairs (*os*), but also same sign pairs (*ss*) to some extent. Given that lepton isolation criteria are uncorrelated with the charge product of a lepton pair, the probabilities for obtaining isolated versus non-isolated leptons in QCD multi-jet events can be assumed to be the same. The assumptions just made for the $q_{\mu,1} \cdot q_{\mu,2}$ -isolation parameter space can be expressed as

$$\frac{N(os|iso)}{N(ss|iso)} = \frac{N(os|\overline{iso})}{N(ss|\overline{iso})}. \quad (7.1)$$

Here, *iso* refers to both leptons of the di-muon pair are isolated, whereas $\overline{iso}$ indicates that they are anti-isolated (by inverting the isolation requirement introduced in section 6.1.4). Equation 7.1 may yield the expected QCD multi-jet contribution to $\langle N(os|iso) \rangle_{QCD}$ in the signal region A because the remaining volume of the $q_{\mu,1} \cdot q_{\mu,2}$ -isolation parameter space is expected to be dominated by QCD.

tile	final state	$Z^0 + N_{jets} \text{ jets}$	$Z^0 + N_{SV0} \text{ jets}$	$Z^0 + N_{IP3D+SV1} \text{ jets}$
A	$\langle N(os iso) \rangle_{QCD}$	1.4 ± 1.4	$0 + 1.1$	$0 + 1.1$
B	$N(os \overline{iso})$	29 ± 5	2 ± 1	7 ± 3
C	$N(ss iso)$	1 ± 1	$0 + 1.1$	$0 + 1.1$
D	$N(ss \overline{iso})$	20 ± 4	2 ± 1	7 ± 3

Table 7.2: Estimated QCD contribution of opposite sign isolated muon pairs in 2010 ATLAS data in $Z^0 + N_{jets} \text{ jets}$, $Z^0 + N_{SV0} \text{ jets}$ and $Z^0 + N_{IP3D+SV1} \text{ jets}$ selected events. For vanishing event counts, an upper limit for the number of expected events calculated from a Poisson distribution with mean $\lambda = 0$ is given as uncertainty for upwards fluctuations.

Table 7.1 shows that this data-driven approach fails if $N(ss|iso) = 0$. For the $Z^0 + N_{jets} \text{ jets}$ selection, only one event contributed to $N(ss|iso)$ and hence the estimate of QCD contributing here can be given as $\langle N(os|iso) \rangle_{QCD} = 1.4 \pm 1.4$ (being compatible with zero). Given the studied number of QCD events, the contribution of QCD multi-jet in $Z^0 + N_{b-tag} \text{ jets}$ events is assumed to

be zero. This assumption is made based on the observations of section 6.5 that the event selection efficiency by introducing a b-tagging requirement is 2.1 % (16.7 %). Therefore, the expectation of QCD multi-jet events in the selected $Z^0 + N_{b\text{-tag}}$ jets event sample extrapolated from $Z^0 + N_{jets}$ jets final states can be assessed to be 0.03 ± 0.03 (0.2 ± 0.2) events. Dedicated heavy-flavour QCD multi-jet samples have also been subject to the $Z^0 + N_{b\text{-tag}}$ jets selections discussed here, but yielded no events passing this selection. The latter provides good evidence that fake lepton events entering the $Z^0 + N_{b\text{-tag}}$ jets ensemble from heavy flavour QCD multi-jet are negligible.

7.1.2 Top related backgrounds

As illustrated in tables 6.8a and 6.8b of section 6.5, $t\bar{t}$ topologies represent 33 – 50 % of the total background contribution in observed $Z^0 + N_{b\text{-tag}}$ jets final states. For the data ensemble at hand is small and the $t\bar{t}$ cross section was measured in ATLAS data with good agreement to existing predictions in [177], the approximate NNLO normalisation [176] and distribution shapes from NLO MC are taken as a good description of this background contribution. The total uncertainty of the approximate NNLO cross section is used as systematic uncertainty of the prediction (see table 5.2).

7.1.3 Di-boson background

Di-boson ZZ final states represent the dominant background for this analysis, for it is irreducible in the invariant mass spectrum of $Z^0 + jets$ events for one Z^0 on average escapes the selection or decays hadronically or different lepton flavours than muons. Again, available measurements [175] have yielded results that compare well to state-of-the-art theory predictions [75]. Therefore, $WW/ZZ/WZ$ backgrounds are normalised to NLO and distribution shapes are taken from LO MC samples as described in table 5.2 of section 5.1.2. The total uncertainty of the NLO cross section is used as systematic uncertainty of the prediction, see table 5.2.

7.2 Heavy Flavour Observables

In order to enable an estimation of the number of observed $Z^0 + b + X$ events from data, variables are needed that provide good discrimination of heavy flavour jets from light or charm induced jets. In addition, these variables must have low or no dependence on the b-tagging weight that was used to select heavy flavour jets in order to avoid possible bias. In other 2010 ATLAS heavy flavour jet analyses [98, 169, 192], the secondary vertex mass was used for this. This section will thus review possible choices.

For studying different observables, the ALPGEN signal MC sample is split into 3 sub-samples utilising the definition of heavy flavour induced jets introduced in section 6.4.2:

$Z^0 + b + X$ The event contains at least one reconstructed Z^0 candidate and at least one (b-tagged) jet that was successfully identified as bottom quark induced on generator level (by $b, \bar{b}$ partons).

$Z^0 + c + X$ The event contains at least one reconstructed Z^0 candidate and at least one (b-tagged) jet that was successfully identified as charm induced (by $c, \bar{c}$ partons) and no jet was found that was induced by a bottom quark on generator level.

$Z^0 + light + X$ The event contains at least one reconstructed Z^0 candidate and at least one (b-tagged) jet that was successfully identified as light induced (by $u, d, s, \bar{u}, \bar{d}, \bar{s}, g$ partons) and no jet was found that was induced by either a bottom or a charm quark.

These samples are labelled with an additional $+X$ as in $Z^0 + b + X$ to indicate that they may contain other jets induced by quarks of lighter flavours than considered. Thus, $Z^0 + b + X$ may contain charm or light quark initiated jets and $Z^0 + c + X$ may contain light quark induced jets respectively. With this, the categorisation ensures that these samples are exclusive with respect to heavy flavour quark jets.

For the quantitative measure to describe the separation of two given distributions. e.g. bottom induced jet distributions versus light or charm induced distributions, the Fisher distance introduced in equation 6.12 is used again. In order to estimate the number of observed $Z^0 + b + X$ events, the following observables are compared:

- scalar sum of reconstructed track momenta per jet
- number of tracks per jet (track multiplicities)
- reconstructed secondary vertex mass
- sum of reconstructed secondary vertex masses per event
- number of tracks associated to jets per event.

In the following, studies on these observables with signal MC normalised to the integrated luminosity recorded by the ATLAS experiment in 2010 are reported briefly before a summarising discussion is given.

7.2.1 Scalar Sum of Reconstructed Track Momenta per Jet

Bottom mesons decay predominantly to charm mesons and other observable particles, e.g.

- $\mathcal{BR}(B^0 \rightarrow \bar{D}^0 + X) = (0.474 \pm 0.028) [11]$
- $\mathcal{BR}(B^+ \rightarrow \bar{D}^0 + X) = (0.79 \pm 0.04) [11]$.

Hereby produced charm mesons decay again to charged particles with the dominant part of their branching fraction. The number of decay prongs measured in the detector from bottom mesons is hence expected to be higher than those from charm mesons on average. Therefore, the number of tracks must be sensitive to the flavour of the meson produced in a jet and potentially to the parton that caused it as well. If the track multiplicity increases (figure 7.1), the sum of all track transverse momenta does so as well (figure 7.0).

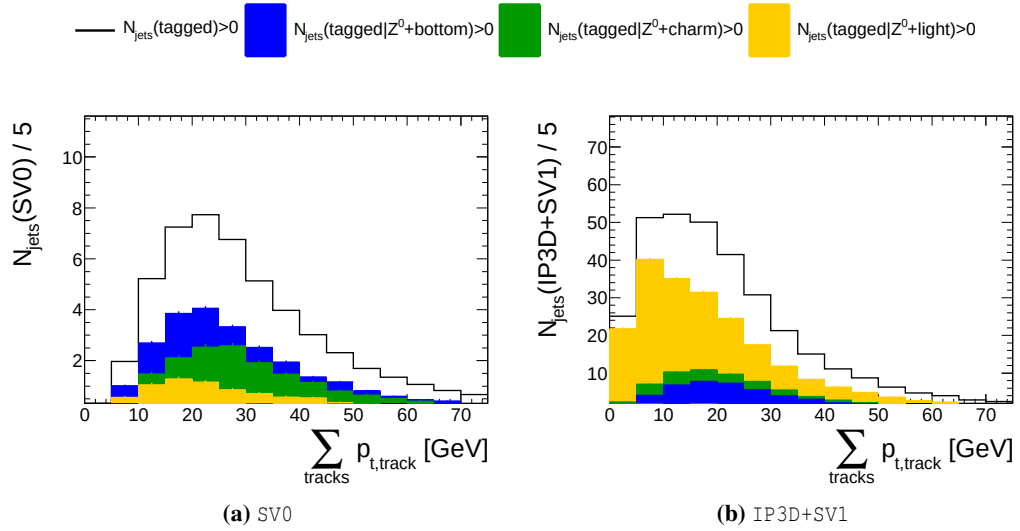


Figure 7.1: Scalar sum of reconstructed transverse momenta of tracks within a jet that was tagged with the SV0 b-tagging algorithm (a) or SV1 b-tagging algorithm (b) in events with at least one reconstructed Z^0 bosons from ALPGEN signal MC. All figures have been normalised to the integrated luminosity recorded by the ATLAS experiment in 2010.

$\sum_{tracks \in jet} p_{t,track}$	SV0	IP3D+SV1
$t(light, bottom)$	0.02 ± 0.02	0.253 ± 0.006
$t(charm, bottom)$	-0.093 ± 0.014	0.056 ± 0.008

Table 7.3: Fisher distance t for figures (a) and (b) from equation 6.12.

The sum of track momenta poorly discriminates jets initiated by different parton flavours. Although figure 7.1 supports the notion that heavy flavour induced jets contain more charged particle tracks than light flavour initiated objects, the larger amount of transverse momentum available to heavy flavour objects and their decay products is equally distributed upon neutral and charged particles within the jet depending on the decay channel. This is supported by the width of the $n_{tracks \in jet}$ distributions for heavy flavour jets in figure 7.1 which indicates that similar track multiplicities than for light flavour jets are equally probable than higher multiplicities. In addition, any remaining difference between heavy and light flavour induced jets in transverse momentum can

be diluted by their decay products' energy loss passing the detector material and reconstruction resolution or efficiency effects.

7.2.2 Track Multiplicity per Jet

The absolute track multiplicity per reconstructed jet is studied. As for the sum of track momenta, this observable is expected to yield large values for bottom quark induced jets due to the high mass of B hadrons as shown in figure 7.1.

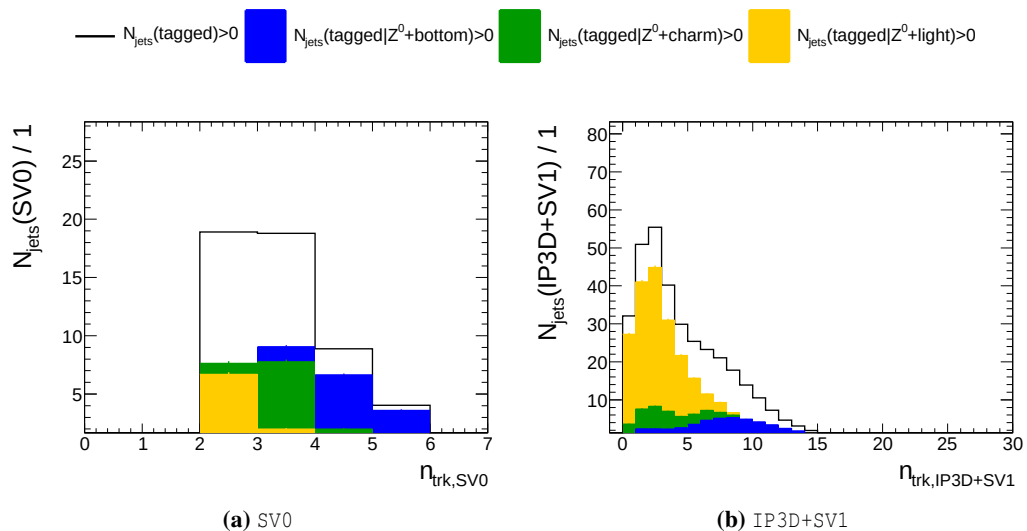


Figure 7.2: Number of tracks per tagged jet with the SV0 b-tagging algorithm (a) and SV1 b-tagging algorithm (b). All figures have been normalised to the integrated luminosity recorded by the ATLAS experiment in 2010.

$n_{tracks \in jet}$	SV0	IP3D+SV1
$t(light, bottom)$	0.95 ± 0.02	0.891 ± 0.007
$t(charm, bottom)$	0.61 ± 0.01	0.456 ± 0.008

Table 7.4: Fisher distance t for figures (a) and (b) from equation 6.12.

As discussed in the previous section, figure 7.1 shows that heavy flavour induced jets do yield higher charged particle multiplicities than objects initiated by light quark flavours. However, the distributions of track multiplicities of various flavour origin overlap considerably which decreases the separation power. This overlap extends to up to e.g. 90% of the bottom induced distribution's integral with respect to the light one in figure 7.1b.

7.2.3 Secondary Vertex Mass

This section studies the distribution of the invariant mass reconstructed from all tracks that were successfully associated to a secondary vertex found inside a jet. For SV0 and IP3D+SV1 use different ensembles of tracks for finding secondary vertices and estimating their invariant mass, the shape and yield of the secondary vertex mass for SV0 and IP3D+SV1 is expected to differ. Especially in the case of IP3D+SV1, a successful calculation of the IP3D weight does not require the SV1 algorithm to have found a secondary vertex. Thus, the distribution of secondary vertex masses has to be observed including the default value (-1) that is yielded if no secondary vertex was found.

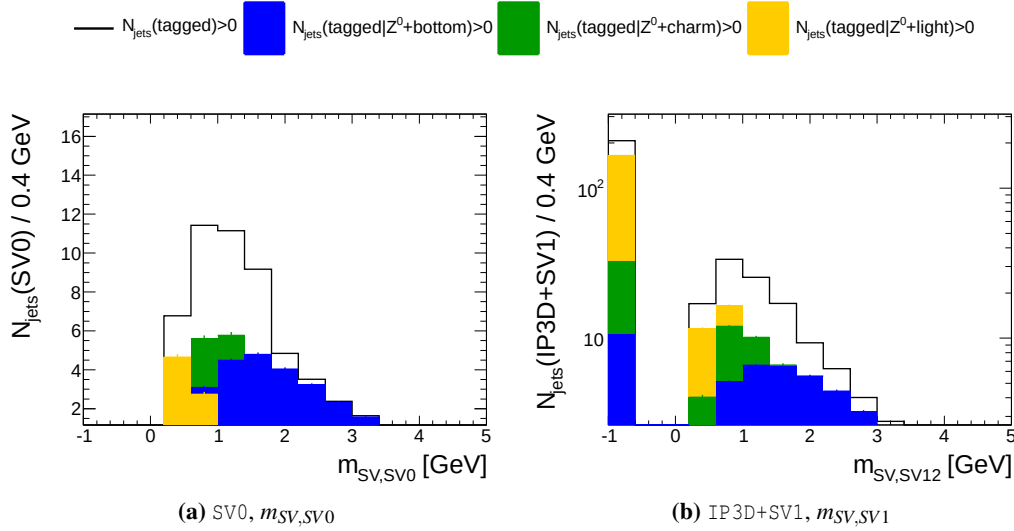


Figure 7.3: Invariant mass of all tracks associated to a secondary vertex in the jet. The SV0 mass is shown in figure (a) and SV1 mass in figure (b). All figures have been normalised to the integrated luminosity recorded by the ATLAS experiment in 2010.

	SV0, $m_{SV,SV0}$	IP3D+SV1, $m_{SV,SV1}$
$t(\text{light}, \text{bottom})$	1.11 ± 0.02	1.071 ± 0.007
$t(\text{charm}, \text{bottom})$	0.78 ± 0.01	0.633 ± 0.008

Table 7.5: Fisher distance t for figures (a) and (b) from equation 6.12.

Figure 7.2 shows the secondary vertex mass distribution from two b-tagging algorithms, SV0 in figure 7.2a and SV1 in figure 7.2b. Again, the estimators describing the separation power of this variable are shown in table 7.4.

Comparing to results from sections 7.2.2 (table 7.3) and 7.2.1 (table 7.2), the secondary vertex mass yields a good light-bottom separation with values of $t > 1$ contrary to the track multiplicity or the sum of track momenta. Also the discrimination of charm induced signals is superior to that found for $n_{\text{tracks} \in \text{jet}}$ or $\sum_{\text{tracks} \in \text{jet}} p_{t, \text{track}}$. This can be explained by the fact that m_{SV} provides a direct handle on the highest mass hadron that is produced inside the jet which is naturally correlated with parton flavour that initiated a jet. Also the invariant mass differences between e.g. B and D hadrons tend to be larger than 1 GeV depending on the particles at hand. This provides enough phase space of the decay products' transverse momentum to not be hidden by detector or

reconstruction effects.

The scope of this analysis is to observe the average number of $Z^0 + b + X$ events in data described by a cross section. Single jet observables as described in sections 7.2.1 to 7.2.3 do allow an estimation of $Z^0 + b + X$ type events only for $Z^0 + 1 \cdot \text{jet}$ topologies. If there is more than one reconstructed and selected jet per event, these observables do not yield accurate frequencies of $Z^0 + b + X$ type events. It must be ensured that also $Z^0 + b\bar{b}$ events or events with additional (light or charm) jets as in $Z^0 + b + \text{jets}$ event signatures are accounted for correctly. The forthcoming sections thus study distributions that yield the sum of heavy flavour observables over all selected jets found in an event.

7.2.4 Sum of Secondary Vertex Masses

The sum of secondary vertex masses per event is considered in order to facilitate the fit to the number of events yielding $Z^0 + b + X$. The origin of events on generator level can be categorised following the description noted at the beginning of this section 7.2.

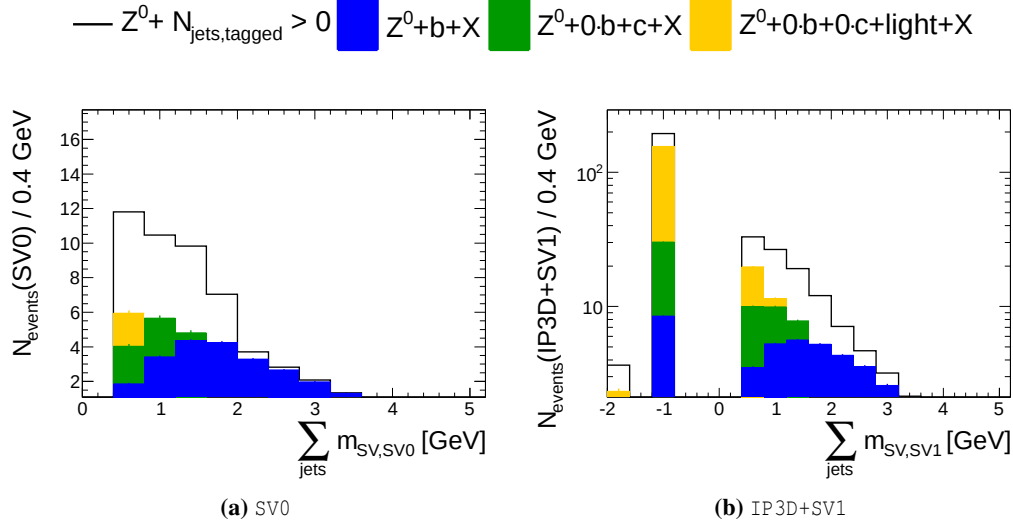


Figure 7.4: Sum of all tagged jets' secondary vertex mass yields per event. The SV0 mass sum is shown in figure (a) and SV1 mass in figure (b). The sample is split into inclusive sub-samples, $Z^0 + b + X$, $Z^0 + c + X$ and $Z^0 + \text{light} + X$. All figures have been normalised to the integrated luminosity recorded by the ATLAS experiment in 2010.

	SV0, $\sum_{\text{jets}} m_{SV,SV0}$	IP3D+SV1, $\sum_{\text{jets}} m_{SV,SV1}$
$t(\text{light}, \text{bottom})$	1.07 ± 0.01	1.069 ± 0.007
$t(\text{charm}, \text{bottom})$	0.77 ± 0.01	0.639 ± 0.008

Table 7.6: Fisher distance t for figures (a) and (b) from equation 6.12.

Studying figures 7.3b, the appearance of negative masses can be observed. This reflects the composite nature of IP3D+SV1. If IP3D yields a high weight and SV1 does not successfully identify a secondary vertex, this distribution is still filled with the default secondary mass of $m_{SV,SV1} = -1$ per jet. This implies that $\sum_{\text{jets}} m_{SV,SV1}$ may yield values of $-1 \cdot N_{\text{jets}}$ per event. In figure 7.3b -2 is filled. Figure 7.3a does not show negative masses for the histogram is only filled if at least one SV0 tagged jet was found in the event which in turn requires that also a secondary vertex was found with a non-zero secondary vertex mass.

The sum of secondary vertex masses provides a viable quantity to estimate the contained number of $Z^0 + b + X$ in an event for m_{SV} is proportional to the parton flavour from which a jet originated from. Thus, the sum of m_{SV} for an event hosting a heavy flavour object must be larger than for an event without it. Implicitly, this interpretation is the cause of the substantial tail, that e.g. the bottom quark induced distribution of figure 7.3a shows. This feature can be exploited to successfully estimate the number of $Z^0 + b + X$ events in data.

7.2.5 Number of Tracks Associated to Jets per Event

As an alternative, the sum of all track multiplicities per jet $\sum_{jets} n_{trk}$ in an event is considered. Again, it must be noted, that the b-tagging algorithms SV0 and IP3D+SV1 use different quality criteria imposed in *InnerDetector* tracks to enter. Thus, the shape and content of $\sum_{jets} n_{trk}$ distributions is expected to differ comparing the two algorithms.

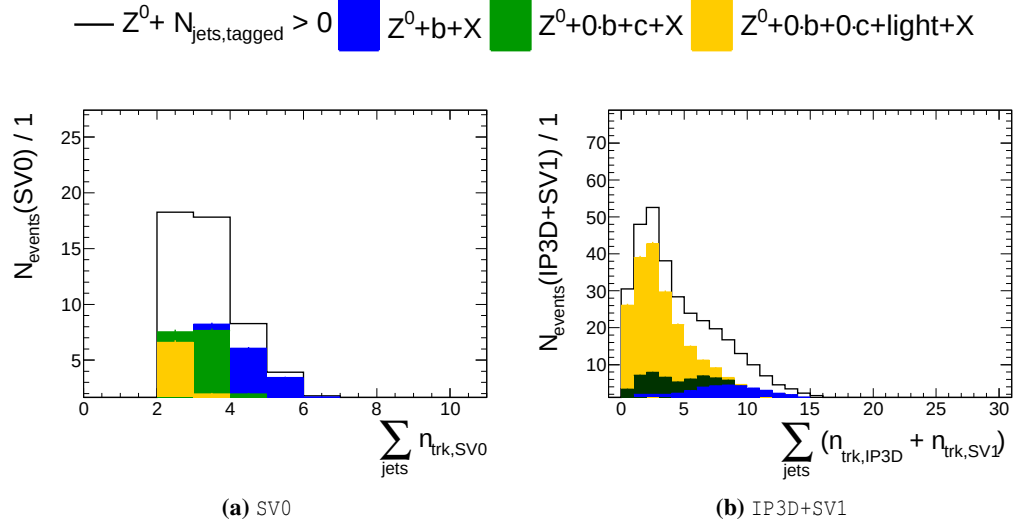


Figure 7.5: Sum of all tagged jet track multiplicities with the SV0 b-tagging algorithm (a) and IP3D+SV1 b-tagging algorithm figure (b). The sample is split into inclusive sub-samples, $Z^0 + b + X$, $Z^0 + c + X$ and $Z^0 + light + X$. All figures have been normalised to the integrated luminosity recorded by the ATLAS experiment in 2010.

$\sum_{jets} n_{tracks \in jet}$	SV0	IP3D+SV1
$t(light, bottom)$	0.87 ± 0.01	0.908 ± 0.007
$t(charm, bottom)$	0.64 ± 0.01	0.502 ± 0.008

Table 7.7: Fisher distance t for figures (a) and (b) from equation 6.12.

Comparing tables 7.5 and 7.6, the separation of light and charm from bottom flavour induced jets is superior including uncertainties of t if $\sum_{jets} m_{SV}$ is used. At this point, $\sum_{jets} m_{SV}$ is chosen as the variable in which to perform a template fit.

7.3 Parameter Estimation

This section introduces the binned extended likelihood technique that was used to conduct a template fit to the distribution of $\sum_{jets} m_{SV}$ observed in data. Further, statistical tests on the robustness of the method, behaviour upon different choices of binning, the linear scaling of results and possible measures of goodness of fit are examined. Finally, the fitted number of events in selected IP3D+SV1 and SV0 data is noted.

7.3.1 Ansatz

In order to estimate the number of observed $Z^0 + b + X$ events from a sample of $Z^0 + N_{b-tag}$ jets events, a simultaneous binned fit of four contributing distributions (templates) has to be conducted. Since the observed shape is composed of the linear sum of the shapes of the underlying models, this procedure can be reduced to fitting the normalisations observed in data for each contribution. Thus a binned extended log-likelihood minimisation is conducted with four model distributions yielding the total expected data distribution.

To illustrate this method, a binned histogram of N bins and j templates is assumed. The histogram's joint probability density function (*PDF*) can be given by the product of a Poisson probability density function (*PDF*) giving the normalisation and a multinomial *PDF* of N independent outcomes for the shape of the histogram as

$$f_{joint}(\vec{n}, \vec{v}) = \frac{v_{tot}^{n_{tot}} \cdot e^{-v_{tot}}}{n_{tot}!} \frac{n_{tot}!}{n_1! \dots n_N!} \left(\frac{v_1}{v_{tot}} \right)^{n_1} \dots \left(\frac{v_N}{v_{tot}} \right)^{n_N}. \quad (7.2)$$

In equation 7.2 the notion is provided that the total number of events is considered to be a Poisson random variable with an expectation value of $v_{tot} = \sum_{i=1}^N v_i$ and an observed value of $n_{tot} = \sum_{i=1}^N n_i$ by summing over all bins i . In short, this reduces to a product of Poissonian *PDFs* as in

$$f_{joint}(\vec{n}, \vec{v}) = \prod_{i=1}^N \frac{v_i^{n_i} \cdot e^{-v_i}}{n_i!}. \quad (7.3)$$

The joint *PDF* $f_{joint}(\vec{n}, \vec{v})$ depends on the expectation values $\vec{v} = (v_1, \dots, v_j)$ deduced from j models and all observations $\vec{n} = (n_1, \dots, n_N)$. The log-likelihood function (LLH) to minimise follows directly from equation 7.3 because $L = f_{joint}(\vec{n}, \vec{v})$ and can be written as

$$-\log L(v_{tot}, \vec{\beta}) = v_{tot} - \sum_{i=1}^N n_i \log v_i(v_{tot}, \vec{\beta}). \quad (7.4)$$

Terms that only include n_i are discarded for they only shift the likelihood function in dimensions independent of v_i . This formulation as likelihood includes the expectation values per bin v_i that are functions of v_{tot} and the vector of normalisations $\vec{\beta}$ for the given model *PDFs*. Given a template distribution t_j for model j that is normalised to unity, the expected total number of events v_i for a given bin x_i with lower bin bound x_i^{min} and upper bound x_i^{max} can be expressed in terms of

$$v_i(v_{tot}, \vec{\beta}) = \sum_{j=1}^{models} \left(\beta_j \int_{x_i^{min}}^{x_i^{max}} dx t_j(x) \right). \quad (7.5)$$

When a *PDF* is stored as an histogram, the information on the unbinned shape of *PDF* is lost. The exact curvature per bin is stored as the integral over the *PDF* within a bins boundary. The fre-

quency density of a *PDF* $t_j = f(X)$ for a given bin i with limits $[x_i^{min}, x_i^{max}]$ is given by $\int_{x_i^{min}}^{x_i^{max}} dx t_j(x) = T_j(x_i)$. Thus equation 7.5 transforms to

$$v_i(v_{tot}, \vec{\beta}) = \sum_{j=1}^{models} (\beta_j T_j(x_i)). \quad (7.6)$$

The fit itself then yields the vector $\vec{\beta} = \beta_1, \dots, \beta_j$ of j absolute model normalisations observed in data. For this, a custom software package [193] was composed that implements the definition of equations 7.4 and 7.6 and conducts a minimisation using the `TMinuit2` package [194]. In the following, symmetric as well as asymmetric uncertainty estimates of the fitted normalisations will be used.

7.3.2 Template Distributions and Minimisation Procedure

Each category of events introduced at the beginning of section 7.2 yields a template distribution, i.e. $Z^0 + b + X$ for bottom quark induced events, $Z^0 + c + X$ for charm quark induced events and $Z^0 + light + X$ for light quark induced events. In addition, the total observed background is represented by a template distribution as well.

Figures 7.5 compare the template shapes used in the extended likelihood fit for both signal generators, ALPGEN and SHERPA. The template distributions exhibit the expected behaviour of $Z^0 + b + X$ type events to accumulate at high m_{SV} , $Z^0 + c + X$ events at medium m_{SV} and $Z^0 + light + X$ topologies at low or zero values of the secondary vertex mass. Due to the fact that the sum is plotted, especially events from the IP3D+SV1 selection can yield negative values which seem unphysical but can directly be accounted for with the software setup of the related b-tagging algorithm (section 7.2.4).

Further, template distributions in figure 7.5e and 7.5f exhibit a vague mass peak at $m_{SV} \approx 0.5 \text{ GeV}$ which can be identified as K^0 mesons that contribute here. It has zero charm and bottom baryon number and was measured to have invariant masses of $m_{K^0} = 497.614 \pm 0.024 \text{ MeV}$ [11] as well as high branches ratios into charged particles.

Charm induced templates show similar mass peaks at $m_{SV} \approx 1.1 \text{ GeV}$ and $m_{SV} \approx 1.8 \text{ GeV}$ that could be correlated to ϕ ($m_\phi = 1.01946 \pm 0.00002 \text{ GeV}$ [11]), $D^\pm$ ($m_{D^\pm} = 1.8696 \pm 0.00016 \text{ GeV}$ [11]) or D^0 ($m_{D^0} = 1.8648 \pm 0.00014 \text{ GeV}$ [11]) on generator level which both yield high branching ratios into charged particles. A precise identification of mesons or baryons contained in these jets through the reconstructed $\sum_{jets} m_{SV}$ distributions is however not within the scope of this study and not permissible with the MC statistics provided.

final state	KS distance (P-Value) /%	
	SV0, $\sum_{jets} m_{SV,SV0}$	IP3D+SV1, $\sum_{jets} m_{SV,SV1}$
$Z^0 + b + X$	82.6(67.4)	42.3(37.3)
$Z^0 + c + X$	43.4(21.7)	65.7(41.9)
$Z^0 + light + X$	12.5(4.2)	37.8(17.5)

Table 7.8: Quantitative shape comparison of template distributions from ALPGEN and SHERPA depicted in figure 7.5 using the Kolmogorov-Smirnov (KS) distance. The p-value for the hypothesis that the same KS test result is due to a statistical fluctuation of one of the distributions is given as well.

In order to judge the comparability of template distributions from SHERPA and ALPGEN, the Kolmogorov-Smirnov test (d_{KS} , see e.g. [195, 196]) was conducted for each pair of distributions depicted in figure 7.5. For this, each comparison was repeated in 1000 pseudo-experiments to define the distribution of all possible Kolmogorov-Smirnov distances from statistically fluctuations and hence derive a p-value $p(d_{KS})$ for a given Kolmogorov-Smirnov distance d_{KS} . Further, d_{KS} can be translated into a probability that is uniformly distributed within $[0, 1]$.

The values of d_{KS} and $p(d_{KS})$ for the normalised template distributions in figure 7.5 are given in table 7.7. Here, templates with high statistics and hence less statistical fluctuations in the central values give good agreement between the 2 generators, ($42.3 \leq d_{KS} \leq 82.6$) % with fair p-values of ($37.3 \leq p(d_{KS}) \leq 67.4$) %. For $Z^0 + light + X$ from both selections and $Z^0 + c + X$ from SV0, the MC statistics is poor and the distributions do not hold many filled bins. Thus, d_{KS} is near 0 with

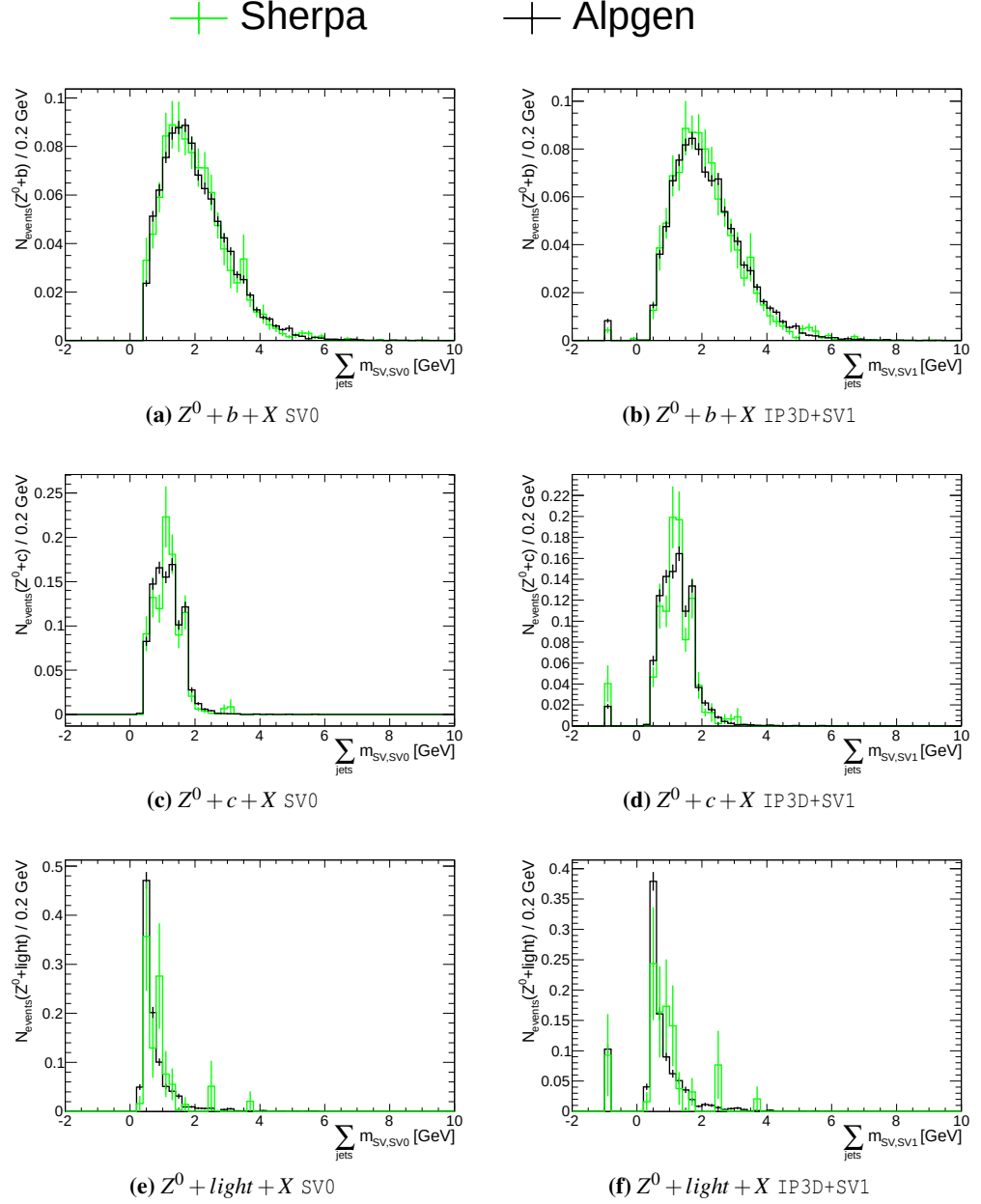


Figure 7.6: Sum of all tagged jets' secondary vertex mass per event using the SV0 (a, c, e) and IP3D+SV1 (b, d, f) selections and their corresponding mass definitions. All distributions are normalised to unit area and were obtained from ALPGEN or SHERPA signal MC events that passed all selection criteria discussed in chapter 6.

values of $p(d_{KS})$ implying that this observed mismatch between ALPGEN and SHERPA is not only of statistical nature. However, large uncertainties of the SHERPA template (which are not taken into account for calculating d_{KS} or $p(d_{KS})$ in the Kolmogorov-Smirnov test above) motivate the conclusion that a lack of MC statistics is the cause of the observed mismatch.

Since the template fit described above does not take the size of the statistical uncertainties of the template distributions into account, ALPGEN generated template distributions are further used for discussing the fit procedure and performance. The final results are obtained by using ALPGEN and SHERPA MC templates independently and a systematic uncertainty is assigned to the result due to shape uncertainties of the two.

As documented above, the minimisation is performed through a custom software package [193] accessing the TMinuit2 [194] minimisation interface provided by the ROOT library [197]. The tolerance to find a minimum in the LLH function is set to $5 \cdot 10^{-4}$. Further, the number of calls to the LLH function is limited to $< 1 \cdot 10^6$ and the number of iterations is constrained to $1 \cdot 10^5$.

In order to estimate the uncertainties of a fitted parameter, the Minos engine of TMinuit2 is used. This algorithm constructs the uncertainty bounds of a parameter in question by varying it until $-\log(L)_{min} + 1/2$ alongside the fitted minimum $-\log(L)_{min}$ are reached. The uncertainties evaluated in this way can be asymmetric.

As described above, the fit is conducted using three template distributions whose normalisation parameters are to be estimated without additional constraints. Also, the expected contribution from background processes through $WW/ZZ/WZ$ and $t\bar{t}$ events is part of the fit procedure, but it is left at a fixed normalisation given by the (N)NLO cross section predictions. Due to the large statistical uncertainties of the fit results expected for the amount of 2010 data, advanced methods to model the constraint of background contributions was not studied.

Starting values for all parameters are set to the expected normalisation known from MC. The step width for each parameter was set to be 0.1.

7.3.3 Pseudo Experiments and Statistical Stability

In order to study the stability of the fit procedure introduced in the last section, pseudo experiments are created and fitted subsequently.

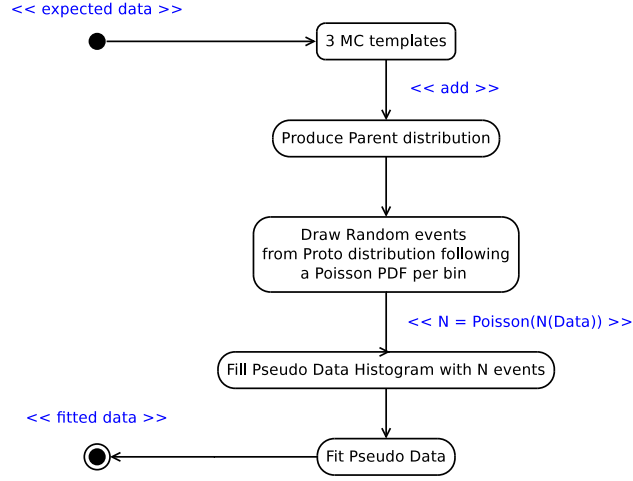


Figure 7.7: UML activity diagram illustrating the creation of pseudo experiments from a total of three MC templates.

With reference to figure 7.6, if a set of j MC templates with normalisations $N_{j,MC}$ and $PDFs$ $f_j(x)$ is given, the algorithm to conduct one pseudo experiment is as follows:

1. A proto distribution $\mathcal{P}(x)$ is produced as $\mathcal{P}(x) = \sum_j \langle N_{j,MC} \rangle \cdot f_j(x)$.
2. The toy experiment's total normalisation $n_{toy} = f_{Poisson}(\lambda = N_{data})$ is given by a random draw from a Poisson PDF $f_{Poisson}(\lambda)$ with mean $\lambda = N_{data}$ using the sum of observed events N_{data} .
3. The pseudo data histogram is filled by drawing pseudo-events over x from $\mathcal{P}(x)$ for n_{toys} times where each bin of $\mathcal{P}(x)$ is modelled by a Poisson PDF .
4. The fit is performed with the MC templates that will be applied to data.
5. The fitted values and uncertainties are stored.

In order to validate the fit outputs from pseudo experiments, the pull estimator is used [198]. Given pseudo data that were generated according to a Poisson distribution with mean at τ_g , the pull $p(\tau)$ can be calculated from the fitted parameter τ_m and its uncertainty σ_m as in

$$p(\tau) = \frac{\tau_g - \tau_m}{\sigma_m}. \quad (7.7)$$

The distribution of p then follows a normal distribution, if the fitted values and uncertainties reflect the behaviour of a random variable and the range $\tau_m \pm \sigma_m$ covers 68.27 %, i.e. one standard deviation, of the τ_m PDF . In addition, relation 7.7 only holds if the fit is of unconstrained nature and the uncertainty of τ_g vanishes, i.e. in the limit of large numbers of pseudo experiments. The minimization engine, TMinuit2, was used for parameter estimation with its capability to provide asymmetric uncertainties. Hence, the definition of equation 7.7 has to be revised

$$p(\tau) = \begin{cases} \frac{\tau_g - \tau_m}{\sigma_{m,down}} & \text{if } \tau_m > \tau_g \\ \frac{\tau_g - \tau_m}{\sigma_{m,up}} & \text{if } \tau_m \leq \tau_g \end{cases}. \quad (7.8)$$

This definition guarantees that the fraction of pulls within $[-1, +1]$ does coincide with the coverage of the uncertainty band given by the upper ($\sigma_{m,up}$) and lower ($\sigma_{m,down}$) uncertainty limits of 68.27 %. For further details on the deduction of equation 7.8 can be found in [198].

In addition, the bias of the fit as in

$$b = \tau_m - \tau_g \quad (7.9)$$

is used to validate the consistency of the LLH estimator. It is expected that the LLH ansatz provides an unbiased estimate only in the limit of large event counts. Thus, it is expected that a bias can be observed, for the pseudo experiments are conducted on grounds of the limited sample size observed in data, [196, 199].

Bias of Pseudo Experiments

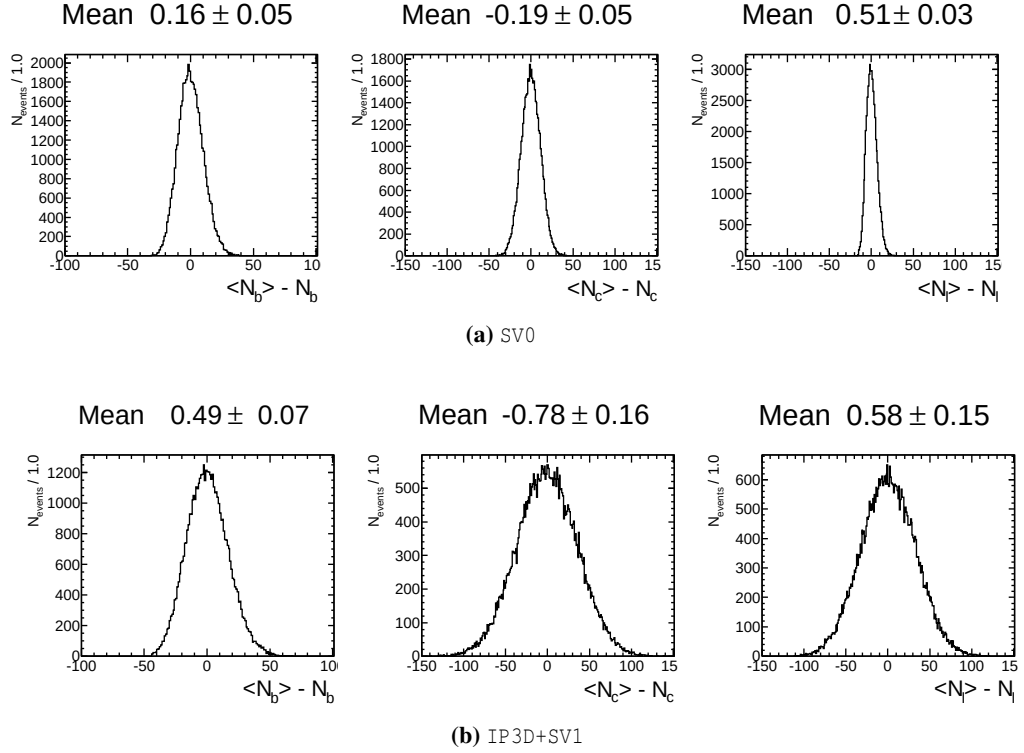


Figure 7.8: Distributions of bias as defined in equation 7.9 per fitted normalisations of bottom (N_b), charm (N_c) and light flavour templates (N_l) in $\sum_{jets} m_{SV,SV0}$ (a) and $\sum_{jets} m_{SV,SV1}$ (b) from 50000 pseudo experiments. The template for the total background contribution remained fixed during the fit and is not shown. Templates extracted from ALPGEN signal MC are used.

With the large statistics in figure 7.7, the mean given of quantity x was calculated as sample mean by $\bar{x} = 1/n \cdot \sum_{i=1}^n x_i$ for n bins with entries x_i [161]. Figures 7.7 demonstrate a good agreement between the mean fitted value and the generated one, i.e. the distributions yield an average bias that is compatible with 0 given the binning on the x axis of 1. Hence, the fit can be regarded as unbiased. However, a small notion of skewness can be observed in all distributions due to bias of LLH estimators faced with small statistics mentioned above.

Pulls of Pseudo Experiments

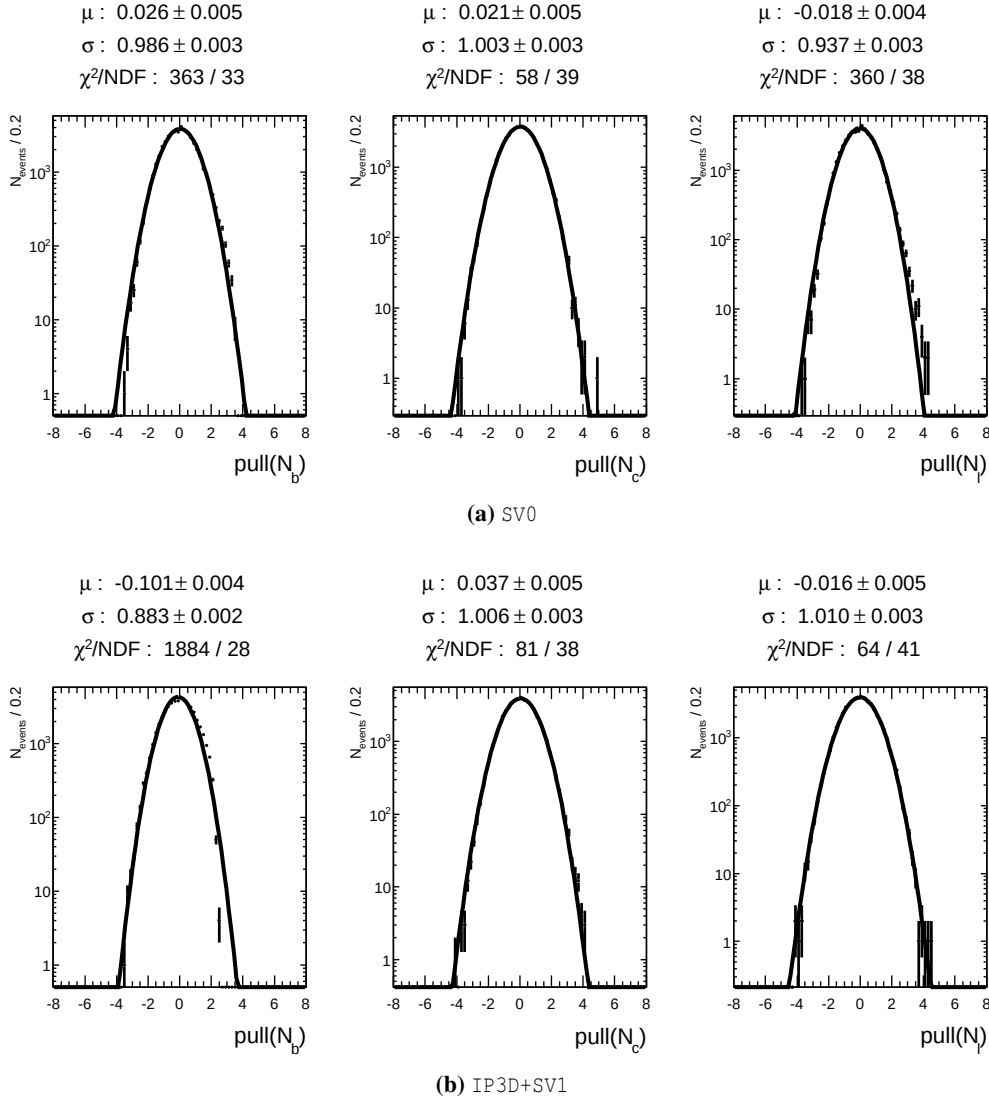


Figure 7.9: Pull distributions as defined in equation 7.8 per fitted normalisations of bottom (N_b), charm (N_c) and light flavour templates (N_l) in $\sum_{jets} m_{SV,SV0}$ (a) and $\sum_{jets} m_{SV,SV1}$ (b) from 50000 pseudo experiments. The template for the total background contribution remained fixed during the fit and is not shown. Templates extracted from ALPGEN signal MC are used. The distributions are plotted on a logarithmic scale on the y axis. Results from a fit with a Gaussian *PDF* as defined in the text are shown as addition.

The pull distributions shown in figures 7.8 have been fitted with a Gaussian distribution $f(x|\mu, \sigma) = \frac{1}{\sqrt{2\pi}} \exp -\frac{(x-\mu)^2}{2\sigma^2}$ in order to test the hypothesis that the fitted mean and fit result uncertainty perform as described in the introduction of this section.

For both observables, the pull distributions for bottom templates disagree most from a normal *PDF*. This is not only underlined by a high χ^2 compared to the number of degrees of freedom (*NDF*), but also observed by deviations of the width from 1 of up to 11.7% (figure 7.8b). Most notably, the mean of fitted values N_b is located at -0.1 instead of 0 which resembles a deviation of 20 times its variance. However, this deviation is not a large quantitative effect, for the pull

describes the bias normalized to the fit uncertainty. Therefore, a deviation of 0.1 reports a bias of 10 % of the given fit result's uncertainty. In practice, this can be considered negligible in comparison to the size of the measurement's large systematic uncertainties.

Further, pull distributions for both $Z^0 + c + X$ and $Z^0 + light + X$ normalisations show deviations from a normal *PDF* in both observables, *SV0* (figure 7.8a) and *IP3D+SV1* (figure 7.8b). The pulls for light templates perform better for *IP3D+SV1*, which is expected as light flavour induced final states contribute most in the event sample of the *IP3D+SV1* selection.

In order to test the hypothesis that the imperfect behaviour of the LLH fit in pseudo experiments is due to the fact that a LLH estimator is biased if the statistics is not large, the amount of pseudo-events per toy experiment was increased by a factor of 150 emulating the amount of data corresponding to the recorded luminosity by the ATLAS experiment in 2011.

Figure 7.9 provides positive evidence for this hypothesis because the fitted normal distributions to all pull distributions are compatible with a mean of 0 and a width of 1. For this, the aforementioned bias of the fit is not considered anymore.

Correlations of Fitted Parameters

Another aspect of the analysis of pseudo-experiments is the study of correlations between fitted parameter values. For this, the individual results of the fit are recorded comparing N_{Z^0+b} versus N_{Z^0+c} , N_{Z^0+b} versus $N_{Z^0+light}$ and N_{Z^0+c} versus $N_{Z^0+light}$. From this, the correlations matrix $\rho_{m,n}$ can be constructed from

$$\rho_{m,n} = \begin{pmatrix} C_{b,b} & C_{b,c} & C_{b,light} \\ \ddots & C_{c,c} & C_{c,light} \\ \ddots & \ddots & C_{light,light} \end{pmatrix} \quad (7.10)$$

where, $C_{m,n}$ denotes the correlation coefficient for fitted value m versus n . By definition, the matrix $\rho_{m,n}$ is symmetric with the diagonal elements yielding unity. Thus, the study of correlations can be broken down to studying the three relations as introduced above.

The correlation matrix for $SV0$ templates, ρ_{SV0} , and for $IP3D+SV1$ templates, $\rho_{IP3D+SV1}$, are obtained from figure 7.10

$$\rho_{SV0} = \begin{pmatrix} 1. & -0.534 & 0.112 \\ -0.534 & 1. & -0.463 \\ 0.112 & -0.463 & 1. \end{pmatrix}, \quad (7.11)$$

$$\rho_{IP3D+SV1} = \begin{pmatrix} 1. & -0.530 & 0.256 \\ -0.530 & 1. & -0.703 \\ 0.256 & -0.703 & 1. \end{pmatrix}. \quad (7.12)$$

The interpretation of correlations reported in equations 7.11 and 7.12 adds a quantitative foundation to the observation made on the differences in template shape made for figure 7.5 and on the statistical distances noted in table 7.5 of section 7.2.4.

For $SV0$ templates, the anti-correlation of about -50% for $\rho_{b,c}$ and $\rho_{c,light}$ can be explained by the charm template spanning the abscissa, i.e. $\sum_{jets} m_{SV,SV1}$, and overlapping with light quark templates completely here. In addition charm templates overlap with one standard deviation of the bottom template distribution. Such constellations of templates manifest in high correlation of the respective fit results since LLH varies strongly if the normalisations of overlapping template *PDFs* are altered in the same direction. If one is increased while the other is decrease, the LLH converges more rapidly. The small correlation in $\rho_{b,light}$ must hence be caused by the large Fisher distance between light and bottom template distributions of more than one standard variation, see table 7.5 of section 7.2.4. Thus, during the minimisation of the likelihood function normalisations of both templates can be effectively varied independent of each other.

The correlations for $IP3D+SV1$ template distributions can be interpreted on the same basis as those for $SV0$. It is interesting that $\rho_{b,c}$ shows a stronger correlation. This can be assigned to the fact that bottom and charm templates are statistically closer together, $t(charm, bottom)_{SV0} = 0.77 \pm 0.01$ versus $t(charm, bottom)_{IP3D+SV1} = 0.639 \pm 0.008$ in table 7.5 of section 7.2.4. To conclude, the study of correlations in pseudo-experiments gives the heuristic picture on the interplay between the fitted normalisation of quark flavours in $Z^0 + N_{b-tag}$ jets events found in figure 7.5 a quantitative basis and serves as an important consistency measure.

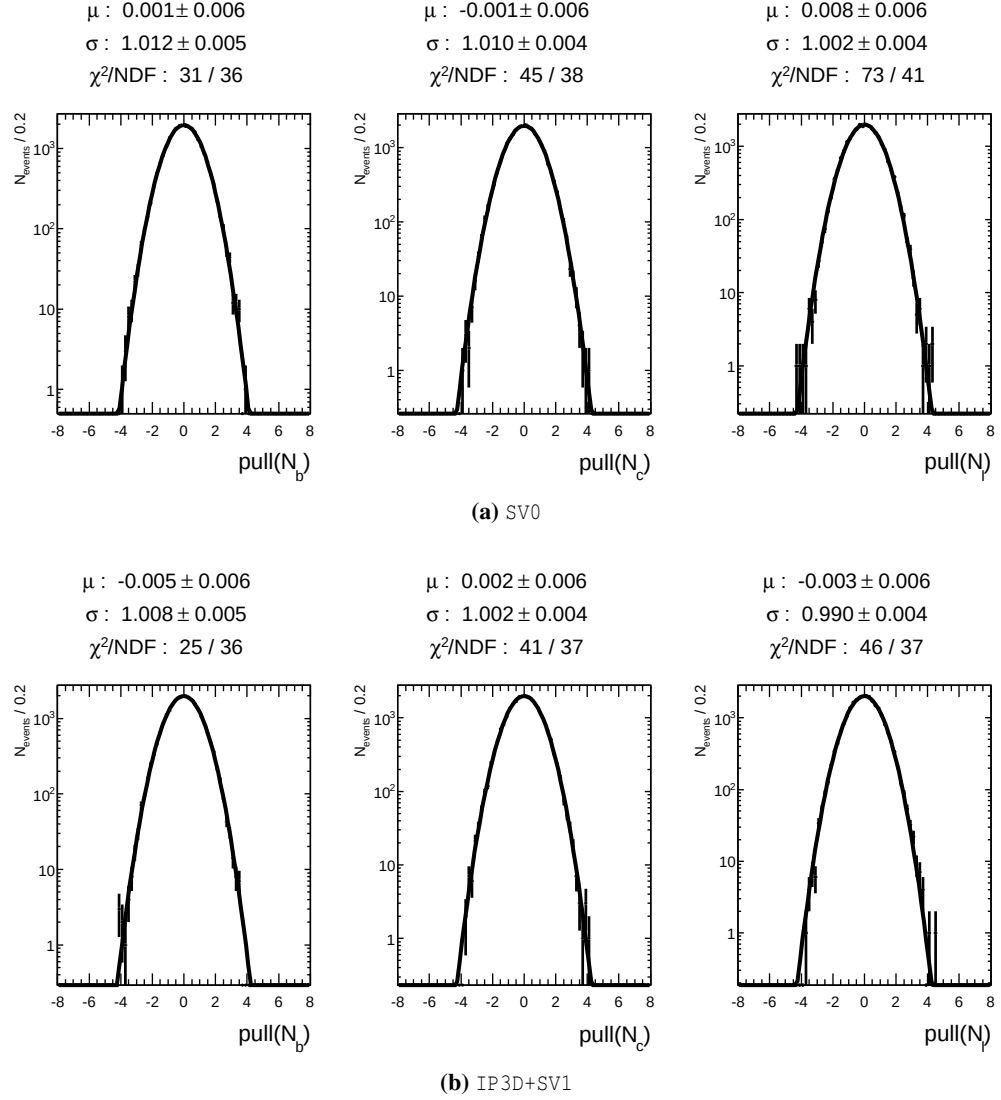


Figure 7.10: Distributions of pulls as defined in equation 7.8 per fitted normalisations of bottom (N_b), charm (N_c) and light flavour templates (N_l) in $\sum_{jets} m_{SV,SV0}$ (a) and $\sum_{jets} m_{SV,SV1}$ (b) from 50000 pseudo experiments. The template for the total background contribution remained fixed during the fit and is not shown. Templates extracted from ALPGEN signal MC are used. The pseudo experiments were conducted assuming 150 times more data than was recorded in 2010 by the ATLAS experiment.

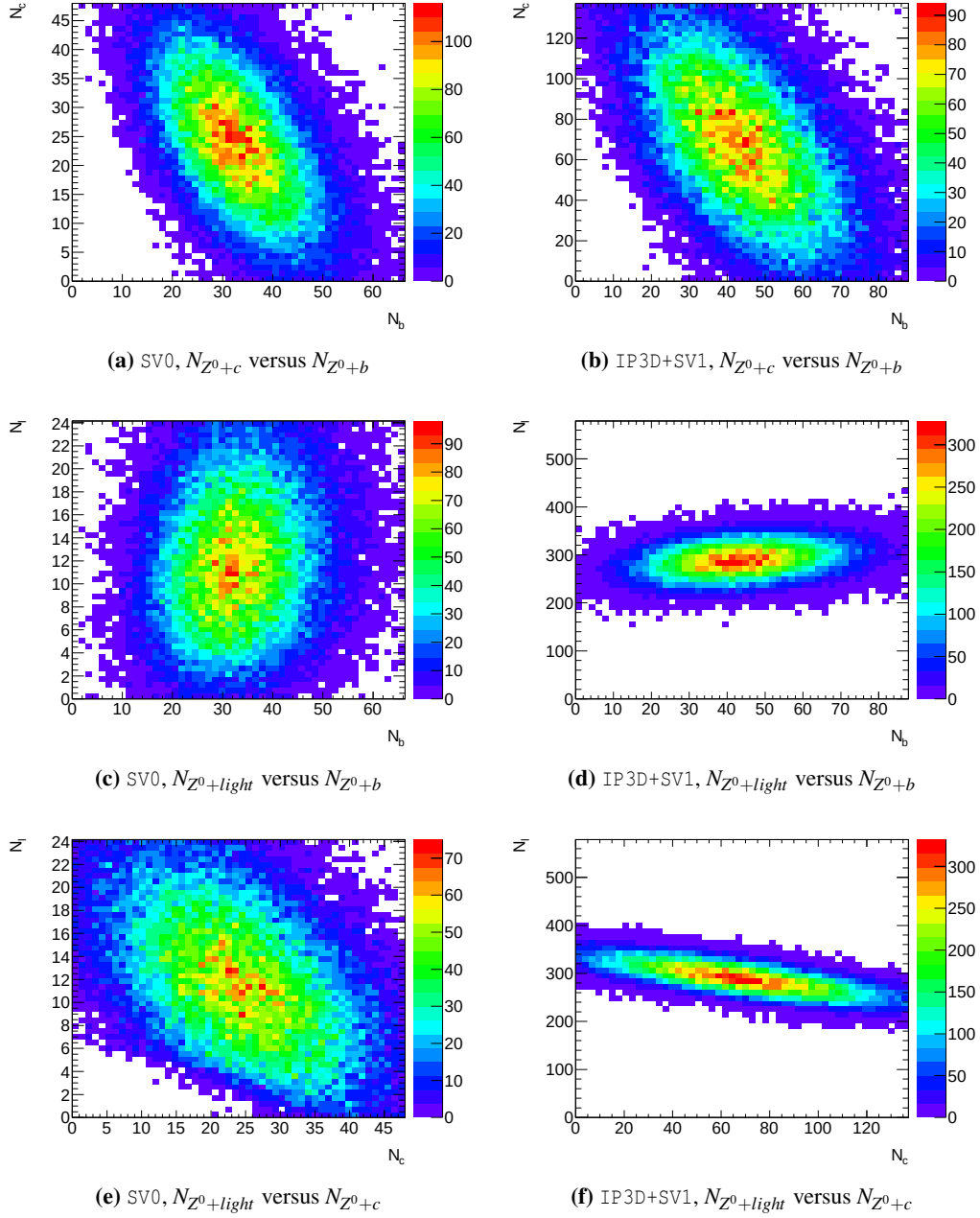


Figure 7.11: Distributions of fitted N_{Z^0+b} versus N_{Z^0+c} (figure a and b), N_{Z^0+b} versus $N_{Z^0+light}$ (figure c and d) and N_{Z^0+c} versus $N_{Z^0+light}$ (figure e and f) per experiment recorded for pseudo-experiments using ALPGEN MC.

7.3.4 Bottom Fraction Linearity

For an estimator to be consistent, it is expected to yield the generated (or true) parameter on average. To study this, the bottom fraction contained in pseudo experiments, i.e. when building the proto distribution $\mathcal{P}(x)$ section 7.3.3), is varied following $N = (f_b \cdot N_b) + N_c + N_l$ by a fixed fraction f_b . Ideally the fit procedure should adapt and yield exactly the bottom fraction that was generated by each set of pseudo experiments within given statistical bounds. Five working points of f_b are chosen, i.e. 0.5, 0.75, 1., 1.25, 1.5. For each setting, 20000 pseudo experiments have been conducted.

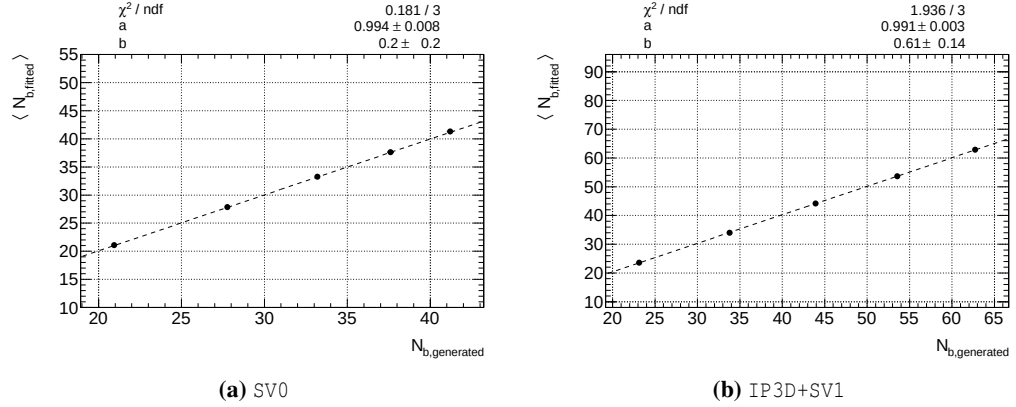


Figure 7.12: Fitted bottom normalisation $N_{b, \text{fitted}}$ versus the generated bottom content $N_{b, \text{generated}}$. The distributions were produced with ALPGEN templates for the SV0 mass (a) and for IP3D+SV1 mass (b) and are fitted with a 1st order polynomial of the form $f(x) = a \cdot x + b$. Each point represents the evaluation of 20000 pseudo-experiments where the x coordinate gives the generated number of $Z^0 + b + X$ events (including its uncertainty) and the y axis notes the mean number of fitted $Z^0 + b + X$ events including the error on the mean.

Figure 7.11 depicts the average result $\langle N_{b, \text{fitted}} \rangle$ of the fit procedure compared to the generated number of $Z^0 + b + X$ type events from 20000 pseudo-experiments. This distribution is fitted with a linear function, $f(x) = a \cdot x + b$ by means of a χ^2 minimisation. Figure's 7.11a fit result complies within the given uncertainties with an optimal fit procedure that is expected to follow $a = 1$ and $b = 0$.

The deficiencies with respect to a linear rise of 1 in figure 7.11b must be attributed to the bias observed in the previous section 7.3.3. The repetition of the linearity test with 150 times the statistics of 2010 ATLAS data yielded optimal results, see appendix E.0.1. To conclude, linearity is observed for fits with $\sum_{jets} m_{SV, SV0}$ (7.11a) and $\sum_{jets} m_{SV, SV1}$ (7.11b) except for small deviations that were found to be negligible.

7.3.5 Bin Size Linearity

One of the weak aspects of binned fits is the choice of bin size w . At best, the chosen estimator for N_b is invariant under changes of w chosen for the observable in which the fit is conducted. This is only the case if the *PDF* at hand does not show too steep rises or falls. The reason for this is that the curvature or shape of a *PDF* (being a continuous function) is collapsed to one value (the integral within a bin's limits) if a sample of events is drawn from the *PDF* and histogrammed. Thus, the bin size can have direct influence on the fit result if the *PDF* exposes steep rises or falls so that the integral per bin is no longer similar to the central *PDF* value per bin. Upon these grounds, a bias that depends upon the choice of the bin width can be introduced. In order to study this effect, the fit procedure was repeated with different choices of the bin size.

The lower bound for w is motivated by the invariant mass resolution of *InnerDetector* tracks. This is known from J/ψ decays [200] to span from $\sigma_{ID}(m_{J/\psi}) = (46 \pm 1) \text{ MeV}$ at central rapidities ($|y_{J/\psi}| < 0.75$) to $\sigma(m_{J/\psi}) = (111 \pm 2) \text{ MeV}$ at large rapidities ($2.0 < |y_{J/\psi}| < 2.4$) of the reconstructed J/ψ meson. Since J/ψ mesons receive high Lorentz boosts at the LHC and the tracks of the decay leptons are produced close-by in solid angle, the observations of J/ψ decays also hold for heavy flavour hadron decays inside jets. The binning w in $\sum_{jets} m_{SV,SV1}$ or $\sum_{jets} m_{SV,SV0}$ is varied from 200 MeV to 800 MeV and for each point, a set of pseudo experiments is conducted.

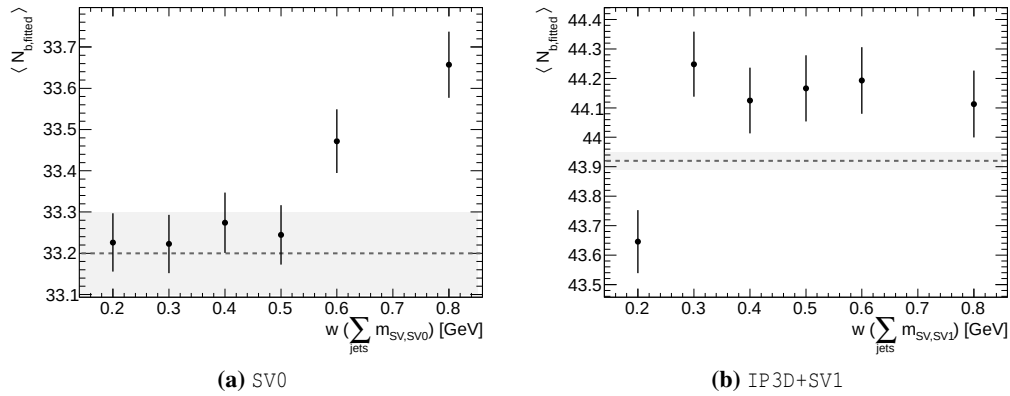


Figure 7.13: Mean fitted bottom normalisation $N_{b,fitted}$ from 20000 pseudo experiments versus the set bin size per template in $\sum_{jets} m_{SV,SV0}$ (a) and $\sum_{jets} m_{SV,SV1}$ (b). The dashed horizontal line indicates the true bottom content that was contained in the signal MC including its statistical uncertainty (grey filled area).

Figure 7.12 compares the average fit result for N_b from 20000 pseudo experiments versus the chosen bin size in $\sum_{jets} m_{SV,SV0}$ (7.12a) and $\sum_{jets} m_{SV,SV1}$ (7.12b) respectively. It should be highlighted at this point, that the error bars of figure 7.12 reflect the error of the mean fitted value $\langle N_{b,fitted} \rangle$ from all pseudo experiments per bin size setup.

For figure 7.12a, the mean fitted values are oriented along the generated value - illustrated by a grey dashed line. Above bin widths of 500 MeV, the mean fitted value increases. This behaviour can be understood by the effect of charm and bottom templates becoming more and more indistinguishable. Figure 7.12b exposes a different behaviour, here all mean fit results for binnings above 300 MeV remain above the generated value. This again indicates the observed bias of the fit. Repeating this test with 150 more statistics per pseudo-experiment than recorded in 2010 by ATLAS resolves this shortcoming, see appendix E.0.2.

In order to avoid possible mismeasurements, the bin size of 500 MeV is used as default.

7.3.6 Goodness of fit

The goodness of fit is quantified by using the distribution of all minima of the LLH function $f(-\log(L)_{\min}) = f(L_{\min})$ found in pseudo experiments as a reference to the statistical behaviour of the fit result itself. Given a measurement of τ_m in data with estimated minimum of the LLH function of $-\log(L)_{\min} = L_m$, the p-value is given by:

$$p_m = \frac{\int_{L_m}^{\infty} f(L_{\min}) dL}{\int_{-\infty}^{\infty} f(L_{\min}) dL}. \quad (7.13)$$

This figure is bound between $p_m \in [0, 1]$ and an established procedure in the literature [161].

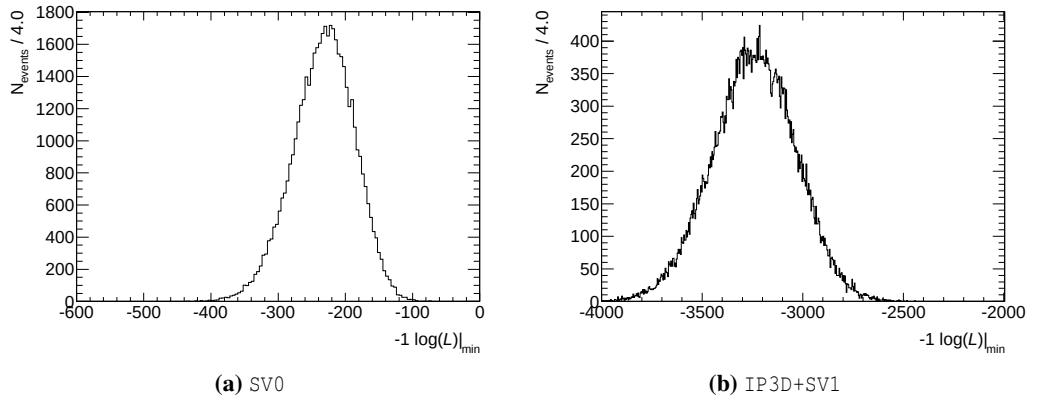


Figure 7.14: Maximum of log-likelihood function per pseudo experiment for SV0 (a) and IP3D+SV1 template fit (b) using ALPGEN signal MC.

The distributions of L_m depicted in figure 7.13 show different means for they were extracted from fits to $\sum_{jets} m_{SV,SV0}$ (7.13a) and $\sum_{jets} m_{SV,SV1}$ (7.13b) respectively which are independent minimisations and hence have independent properties.

7.3.7 Results

To conclude, the estimation procedure for N_b in data was introduced in this section and tests on the precision of the estimation procedure using the extended likelihood method were conducted. The chosen approach proved to be both consistent and unbiased in the limit of large statistics.

parameter	$\sum_{jets} m_{SV,SV0}$	$\sum_{jets} m_{SV,SV1}$
N_b	$39.7^{+11.5}_{-10.2}$	$71.9^{+20.2}_{-18.3}$
N_c	$28.7^{+11.5}_{-11.3}$	$148.6^{+40.9}_{-40.2}$
N_{light}	$3.3^{+5.2}_{-3.8}$	$177.2^{+32.5}_{-32.2}$
$N_{Background}$	8.3	38.4
p_m	0.56	0.172

Table 7.9: Fitted normalisations from 2010 ATLAS data using ALPGEN template distributions to estimate the frequency of events with bottom, charm and light flavour initiated jets in selected b-tagged $Z^0 + b + X$ events. The expected background contributions was fixed during the fit procedure. The goodness of fit measure p_m is given as defined in section 7.3.6.

parameter	$\sum_{jets} m_{SV,SV0}$	$\sum_{jets} m_{SV,SV1}$
N_b	$40.8^{+11.5}_{-10.2}$	$76.6^{+20.7}_{-19.0}$
N_c	$26.2^{+11.4}_{-11.2}$	$149.8^{+37.6}_{-36.8}$
N_{light}	$3.8^{+6.1}_{-4.7}$	$174.5^{+29.2}_{-28.8}$
$N_{Background}$	8.5	38.4
p_m	0.577	0.280

Table 7.10: Fitted normalisations from 2010 ATLAS data using SHERPA template distributions to estimate the frequency of events with bottom, charm and light flavour initiated jets in selected b-tagged $Z^0 + b + X$ events. The expected background contributions was fixed during the fit procedure. The goodness of fit measure p_m is given as defined in section 7.3.6.

Tables 7.9 and 7.8 present the fit results that were obtained on data. Both tables note the respective background contributions without uncertainties to highlight that this template has been kept at a fixed normalisation during the fit procedure. The given uncertainties on the parameters correspond to 68 % confidence intervals around the minimal value of $-\log L$. These range from 25 % to 27 % of the fitted value of N_b . The measurement of the cross section will be dominated by this source of uncertainty.

As discussed earlier, the fit results reflect the flavour composition to be expected for the high-purity and high-efficiency selections. While for $SV0$ selections, the bottom contribution dominates over results for different flavours, this observation turns opposite by studying the results of fits to $IP3D+SV1$ selected events due to the different b-tagging efficiencies noted in section 6.4.2. Comparing the use of two different generators, the fit results of N_b are consistent within given error bands for both tagging algorithms.

Further, both estimates of N_b from the fit to $\sum_{jets} m_{SV,SV0}$ distributions yield almost optimal p-values and can be considered good fits. This effect is not surprising for this distribution holds the largest ratio of bottom flavour induced jets compared to charm or light while possessing comparable separation power as $\sum_{jets} m_{SV,SV1}$, see section 7.2.4.

7.4 Cross Section Definition

In order to extract a cross section from numbers given in the previous section, the phase space must be defined for which the cross section is obtained. From this, the definition of the measurements acceptance follows which extrapolates the observed number of events to those expected for the selected phase space.

The algebraic formulation of the cross section of events containing a $Z^0 \rightarrow \mu^+ \mu^-$ and at least one bottom quark induced jet can be given as

$$\sigma(Z^0 + b + X) = \frac{N_{Z^0+b+X, \text{fitted}}}{\mathcal{A}_{Z^0+b+X} \cdot \mathcal{L}_{\text{int}}} \quad (7.14)$$

The acceptance $\mathcal{A}$ contains the geometric acceptance of the ATLAS detector as well as any efficiency involved in reconstructing or selecting $Z^0 + N_{b\text{-tag}}$ jets event topologies in data. Since the number of observed $Z^0 + b + X$ is obtained from a fit to the data, no background subtraction is needed. Equation 7.14 contains three variables that are subject to systematic uncertainties which add quadratically under the assumption of uncorrelated contributions. Therefore, a ratio measurement of $\mathcal{R} = \frac{\sigma_{\text{incl}}(Z^0+b)}{\sigma_{\text{incl}}(Z^0+\text{jets})}$ can provide a way to suppress systematic influences, most notably in the integrated luminosity $\mathcal{L}_{\text{int}}$. The ratio can be given as

$$\begin{aligned} \mathcal{R} &= \frac{\sigma(Z^0 + b + X)}{\sigma(Z^0 + \text{jets})} \\ &= \frac{N_{Z^0+b+X, \text{fitted}}}{\mathcal{A}_{Z^0+b+X} \cdot \mathcal{L}_{\text{int}}} \cdot \left(\frac{N_{Z^0+\text{jets}, \text{data}} - N_{Z^0+\text{jets}, \text{background}}}{\mathcal{A}_{Z^0+\text{jets}} \cdot \mathcal{L}_{\text{int}}} \right)^{-1} \\ &= \frac{N_{Z^0+b+X, \text{fitted}}}{\mathcal{A}_b \cdot (N_{Z^0+\text{jets}, \text{data}} - N_{Z^0+\text{jets}, \text{background}})}. \end{aligned} \quad (7.15)$$

$N_{Z^0+\text{jets}, \text{data}}$ accounts for the number of $Z^0 + N_{\text{jets}}$ jets events observed in data and $N_{Z^0+\text{jets}, \text{background}}$ refers to the expected or measured background contribution therein. Given a measurement of $Z^0 + \text{jets}$ via $N_{Z^0+\text{jets}}$ and the observation that $Z^0 + b + X$ events are a subset of $Z^0 + \text{jets}$ events, the acceptance of $Z^0 + N_{b\text{-tag}}$ jets events factorises into

$$\mathcal{A}_{Z^0+b+X} = \mathcal{A}_{Z^0+\text{jets}} \cdot \mathcal{A}_b. \quad (7.16)$$

$\mathcal{A}_b$ gives the acceptance that is introduced by requiring at least one bottom quark induced jet on generator level in the ensemble of selected $Z^0 + N_{b\text{-tag}}$ jets events. As motivated earlier, equation 7.15 has no connection to the integrated luminosity and hence its uncertainty is removed.

7.4.1 Acceptances

An acceptance $\mathcal{A}$ incorporates the effect of a geometrically limited sensitive detector volume, the imprecision of reconstructing objects from detector signals as well as the known loss of information by selecting only a well understood sample of signal candidate events from the data in a defined phase space ϕ . The acceptance is thus a convolution of many aspects involved to observe a specific final state. In order to calculate it, MC simulations are used providing information on the theoretical final state of a proton-proton collision as well as on the measured final state as illustrated in chapters 3 and 4.3.5. Assuming this view, an acceptance describes the loss by trans-

forming a generated (gen) event to a measured (selected) event in simulation. Hence, it can be written as

$$\mathcal{A} = \frac{N(\text{gen} \cap \text{sel} | \phi)}{N(\text{gen} | \phi)} \quad (7.17)$$

Here, $N(\text{gen} \cap \text{sel} | \phi)$ describes events that fall into the selected phase space ϕ and show the generated as well as selected signature. $N(\text{gen} | \phi)$ notes the number of events that exhibit the generated event topology in the given phase space without requiring the very same event to pass the selection introduced in chapter 6. As mentioned earlier, $\mathcal{A}_{Z^0+b+X}$ gives the ratio of observed events that follow the hadron-level selection described in the previous section, 7.4.2. Since the number of selected bottom quark jets is always a sub-sample of the number of observed jets, this acceptance factorises into $\mathcal{A}_{Z^0+jets} \cdot \mathcal{A}_b$. The latter is defined as

$$\mathcal{A}_b = \frac{N(Z^0 + b + X \cap \text{tagged} | \phi)}{N(Z^0 + b + X | \phi)}. \quad (7.18)$$

Equation 7.18 describes the ratio of $Z^0 + N_{b\text{-tag}}$ jets events in the ensemble of $Z^0 + N_{jets}$ jets final states containing generated bottom quark induced jets.

The unfolding of results from detector to hadron level is performed through the definition of the acceptances above. The acceptances' reference event ensemble are defined on hadron level (represented by ϕ in equations 7.17 and 7.18) prior to selecting reconstructed objects. Further, the acceptance numerator counts the number of events passing the selection on detector level within the hadron level ensemble. Thus, an extrapolation from detector to hadron level is performed. For the hadron level phase space definition is oriented as close as possible after the requirements on reconstructed objects, the phase space extrapolated over is small.

7.4.2 Phase Space Definition

The extrapolation from the measured cross section to its correspondence in phase space via $\mathcal{A}$ introduces systematic uncertainties. To keep these low, the definition of the phase space for this analysis accommodates the experimental selection. The phase space is defined on hadron level at this point and will later be extended to particle level for a comparison with NLO predictions. It should be highlighted, that the phase space definition at hand is imposed on generator level for signal MC events.

Muons are selected with $p_{t,\mu} > 20 \text{ GeV}$ and $|\eta_\mu| < 2.4$. Any muon with radiated photons in a cone of $\Delta R(\mu, \gamma) < 0.1$ is not discarded and will enter the selected sample.

Anti-kt(0.4) jets reconstructed on generated hadronic objects are required to have $p_{t,jet} > 25 \text{ GeV}$ and $|\eta_{jet}| < 2.5$. As for the experimental selection, jet objects with $\Delta R(jet, \mu^\pm) < 0.5$ are vetoed and hence removed from the selected sample. In order to separate bottom quark induced jets from charm or light, the definitions made in section 6.4.2 are used on detector and hadron level.

7.5 Measurements

This section presents the observed total $Z^0 + b + X$ cross section $\sigma_{incl}(Z^0 + b)$ observed in data as well as the cross section ratio $\mathcal{R} = \frac{\sigma_{incl}(Z^0 + b)}{\sigma_{incl}(Z^0 + \text{jets})}$ on hadron level. The fitted number of $Z^0 + b + X$ events are given and used as input to equations 7.14 and 7.15 respectively. The unfolding from detector to hadron level is performed using SHERPA for the fit results obtained with SHERPA templates and using ALPGEN for results obtained with ALPGEN template distributions.

All measurements are compared to predictions from SHERPA and ALPGEN LO plus parton shower simulations estimated at hadron level. Systematic uncertainties are not included at this point, but will be the subject of chapter 8. The expected results for $\sigma_{incl}(Z^0 + b)$ and $\mathcal{R}$ are obtained by conducting the LLH fit with pseudo-data from luminosity weighted distributions extracted from signal and background MC events. To calculate the hadron level predictions, no fit is conducted. The number of $Z^0 + b$ events generated on hadron level, $N_{Z^0+b,generated}$ is used instead of $N_{Z^0+b,fitted}$ in equation 7.14. For the prediction of equation 7.15, $N_{Z^0+jets,data} - N_{Z^0+jets,background}$ is replaced by $N_{Z^0+jets,generated}$ as well.

7.5.1 Total $Z^0 + b + X$ Cross Section $\sigma_{incl}(Z^0 + b)$

	SV0		IP3D+SV1	
	SHERPA	ALPGEN	SHERPA	ALPGEN
$N_{Z^0+b+X,fitted}$	$40.8^{+11.5}_{-10.2}$	$39.4^{+11.5}_{-10.2}$	$76.6^{+20.7}_{-19.0}$	$71.9^{+20.2}_{-18.3}$
$\mathcal{A}_{Z^0+b+X}$	0.34 ± 0.02	0.33 ± 0.004	0.60 ± 0.04	0.71 ± 0.004
$\mathcal{L}_{int}$	36.13 pb^{-1}			
$\sigma_{incl}(Z^0 + b) / pb$	$3.33^{+0.93}_{-0.83}$	$3.29^{+0.96}_{-0.84}$	$3.54^{+0.96}_{-0.88}$	$2.82^{+0.79}_{-0.71}$
$\langle \sigma(Z^0 + b + X) \rangle / pb$	$4.04^{+0.97}_{-0.87}$	$2.36^{+0.82}_{-0.71}$	$4.15^{+0.97}_{-0.89}$	$2.04^{+0.71}_{-0.64}$
SHERPA $\sigma(Z^0 + b + X)_{hadron} / pb$	$3.90 \pm 0.26 \text{ pb}$			
ALPGEN $\sigma(Z^0 + b + X)_{hadron} / pb$	$2.28 \pm 0.02 \text{ pb}$			

Table 7.11: Total hadron-level SV0 or IP3D+SV1 $Z^0 + b + X$ cross section observed in 2010 ATLAS data. Statistical uncertainties are given only. In addition, the expectations of $\sigma_{incl}(Z^0 + b)$ deduced from signal and background MC events $\langle \sigma(Z^0 + b + X) \rangle$ as well as the hadron level predictions of SHERPA and ALPGEN signal MC $\sigma(Z^0 + b + X)_{hadron}$ are listed. The quoted hadron level prediction was obtained from an LO+PS event sample that was renormalised to the NNLO inclusive $Z^0 + \text{jets}$ cross section.

Table 7.10 collects the obtained results for $\sigma_{incl}(Z^0 + b)$ including statistical uncertainties from the fit procedure only. The statistical uncertainty of the acceptance correction to hadron level is given for illustration.

All measured cross section estimates are within one standard deviation of each other. In addition, statistical uncertainties of 24 – 29 % are reported on $\sigma_{incl}(Z^0 + b)$ which reflects the high uncertainties yielded by the template fit. All measurements agree within one standard deviation with expectations from signal and background MC samples. The latter are obtained by using MC events as input to the cross section extraction entirely. Also, observations made using SHERPA yield smaller statistical uncertainties which implies that SHERPA generated template distributions

match the data better in shape.

A comparison with hadron level predictions from SHERPA and ALPGEN indicates that SHERPA and ALPGEN hadron-level predictions reproduce the observed cross sections within one standard deviation respectively. It is interesting to note that results obtained with SHERPA templates and acceptances are not sufficiently supported by ALPGEN hadron level predictions and vice versa. In this context, hadron level predictions from SHERPA tend to overestimate observed central values, whereas figures with ALPGEN underestimate them. Given the calculations of section 3.3.3, the difference between $\sigma_{incl}(Z^0 + b)$ quoted in table 7.10 and in table 3.3 is due to the different PDF configuration used for the SHERPA samples at hand. As discussed in section 5.1.1, the available SHERPA sample with the full ATLAS detector simulation used the CTEQ6L PDF [168] while all numbers in section 3.3 were obtained with PDF sets that the SHERPA 1.1.3 underlying event model was tuned to.

7.5.2 Cross Section Ratio $\mathcal{R} = \frac{\sigma_{incl}(Z^0+b)}{\sigma_{incl}(Z^0+jets)}$

	SV0		IP3D+SV1	
	SHERPA	ALPGEN	SHERPA	ALPGEN
$N_{Z^0+b+X,fitted}$	$40.8^{+11.5}_{-10.2}$	$39.7^{+11.5}_{-10.2}$	$76.7^{+20.7}_{-19.0}$	$71.9^{+20.2}_{-18.3}$
$\mathcal{A}_b$	0.44 ± 0.03	0.40 ± 0.005	0.78 ± 0.05	0.84 ± 0.006
$N_{Z^0+jets,data}$	2420			
$N_{Z^0+jets,background}$	258 ± 55			
$\mathcal{R} = \frac{\sigma_{incl}(Z^0+b)}{\sigma_{incl}(Z^0+jets)} / \cdot 10^{-2}$	$4.3^{+1.2}_{-1.1}$	$4.6^{+1.4}_{-1.2}$	$4.6^{+1.2}_{-1.1}$	$3.9^{+1.1}_{-1.0}$
$\langle \mathcal{R} \rangle / \cdot 10^{-2}$	$4.6^{+1.1}_{-1.0}$	$2.8^{+1.0}_{-0.8}$	4.7 ± 1.1	2.4 ± 0.8
SHERPA $\mathcal{R}_{hadron} / \cdot 10^{-2}$	5.78 ± 0.37			
ALPGEN $\mathcal{R}_{hadron} / \cdot 10^{-2}$	3.24 ± 0.03			

Table 7.12: Hadron-level cross section ratio $\mathcal{R} = \frac{\sigma_{incl}(Z^0+b)}{\sigma_{incl}(Z^0+jets)}$ observed in 2010 ATLAS data with SV0 or IP3D+SV1 events. Only statistical uncertainties are given. In addition, the expectations of $\sigma_{incl}(Z^0+b)$ deduced from signal and background MC events $\langle \mathcal{R} \rangle$ as well as the hadron level predictions of SHERPA and ALPGEN signal MC $\mathcal{R}_{hadron}$ are listed. The quoted hadron level prediction was obtained from an LO+PS event sample that was renormalised to the NNLO inclusive $Z^0 + jets$ cross section.

Table 7.11 lists the observed and expected values of $\mathcal{R} = \frac{\sigma_{incl}(Z^0+b)}{\sigma_{incl}(Z^0+jets)}$. The assigned statistical uncertainty on $\mathcal{R} = \frac{\sigma_{incl}(Z^0+b)}{\sigma_{incl}(Z^0+jets)}$ ranges from 25 % to 30 %. The low relative frequency of bottom quark induced jets in ALPGEN MC compared to SHERPA increases the statistical uncertainty of $\mathcal{A}_b$ above that for SHERPA. The SV0 results obtained with SHERPA templates and IP3D+SV1 results with ALPGEN distributions expose highest statistical precision.

Comparing expectation and observation, all results are compatible with each other within one standard deviation of the statistical uncertainty. Judging hadron level results in table 7.11 one must take into account that SHERPA events contain $\ell^+\ell^- + N$ jets ($0 \leq N_{jets} \leq 3$) final states on LO matrix element level, whereas ALPGEN was setup to predict $\ell^+\ell^- + N$ jets ($0 \leq N_{jets} \leq 5$) final states. Again, ALPGEN predictions tend to underestimate the data while SHERPA expectations on hadron-level remain above it.

Chapter 8

Systematic Uncertainties

The study of systematic uncertainties introduced by detection, reconstruction, analysis of the data and the calculation of observables is required to complete the measurement envisioned. Beginning with a metrological motivation, this chapter will discuss the uncertainties related to reconstructing leptonic objects (muons) and hadrons (jets) used for this measurement. Next, the uncertainties related to heavy flavour tagging are assessed. Last, the influences of theoretical assumptions made for background estimation, template models and acceptance corrections are reviewed, before all estimates of systematic uncertainties are combined.

8.1 Motivation and Approach

Systematic uncertainties are metrological influences on a measurement that do not vanish with acquiring more data [199]. They can be caused by crude or false assumptions, detector inefficiencies, low signal resolutions or statistical biases. Clearly, all of these should be avoided by the detector layout and analysis strategy a priori to the measurement. Since the observation of proton-proton collisions at a centre-of-mass energy of $\sqrt{s} = 7\text{ TeV}$ is a task not trivial and was endeavoured by means of complex detector systems, e.g. ATLAS or CMS, and accelerator facilities, i.e. the LHC, a measurement without systematic uncertainties is never achieved. Although the size of which is given by the required precision, their knowledge and characterisation related to an obtained result θ is an elementary as well as essential task that is part of every measurement.

Possible sources of systematic uncertainties can be categorised into two types following [201]:

- stochastic sources (*Class 1*)
- coherent sources (*Class 2*)

Stochastic sources (*Class 1*) of systematic uncertainties are effects that alter a measurement in a random way. These effects are caused e.g. by estimators that enter the measurement which were deduced from a limited dataset themselves. For example, calibration constants whose uncertainty is entirely statistical or dominated by statistics such as the muon reconstruction efficiency scale factors (section 6.1.3) or the trigger efficiency scale factors (section 5.2.2). These are known within their statistical uncertainties.

The exact *PDF* connected to this stochastic behaviour is rarely known or difficult to obtain. Therefore, these *PDFs* effect on the cross section result is evaluated by applying the aforementioned calibration constants on the basis of a random draw from a Gaussian *PDF* with mean $\mu = c_{calib}$

and variance $\sigma = \sigma(c_{calib})$. This procedure is conducted on the full MC dataset for signal and background events and repeated 100 times, i.e. with 100 pseudo-experiments. From each pseudo-experiment, a measurement on θ is collected into a histogram whose mean value yields the expected result again and whose root-mean-squared represents the systematic uncertainty. The number of pseudo-experiments was set to 100 due to constraints of computational power.

A coherent source of uncertainty is represented by effects that alter input parameters to θ in a way that may not be considered random. As an example, the uncertainty on the jet energy scale can be considered as a coherent source of uncertainty. The extent to which a coherent source influences the presented measurement is evaluated by conducting the analysis of $\sigma_{incl}(Z^0 + b)$ or $\mathcal{R} = \frac{\sigma_{incl}(Z^0 + b)}{\sigma_{incl}(Z^0 + jets)}$ with simulated events in which relevant objects (e.g. jets) have been subject to alternations (e.g. all jets' energy were varied up by the known uncertainty of the energy itself) before any selection is applied. Then, the analysis outlined in chapters 5, 6 and 7 was conducted on this sample in order to estimate the measurement's outcome due to the given source, e.g. by mis-modelling of detector effects in simulation or uncertainties of calibrations constants. The systematic uncertainty is then given by the deviation from the nominal expected result.

Systematic uncertainties caused by theoretical assumptions that cannot be verified by the data are treated as Class 2 effects. As an example, the prediction for background contributions discussed in sections 7.1.2 and 7.1.3 yields a theoretical uncertainty. Also the statistical uncertainty of the acceptance correction based on ALPGEN or SHERPA distributions can be loosely considered a theoretical uncertainty. These systematic uncertainties are studied by coherent variation (for the cross section uncertainties).

In order to treat all correlations of the template fit results and acceptance corrections coherently, the systematic uncertainties are evaluated for $\sigma_{incl}(Z^0 + b)$ and $\mathcal{R}$ directly. For this, the analysis procedure of chapter 6 and 7 is conducted on simulated signal and background events whose reconstructed objects have been "smeared" due to a given source of uncertainty. The method to calculate the cross section thus must be adopted.

$$\sigma(Z^0 + b + X) = \frac{N_{Z^0+b+X,pseudo-data}}{\mathcal{A}'_{Z^0+b+X} \cdot \mathcal{L}_{int}} \quad (8.1)$$

$$\mathcal{R} = \frac{N_{Z^0+b+X,pseudo-data}}{\mathcal{A}'_b \cdot (N_{Z^0+jets,pseudo-data} - N'_{Z^0+jets,background})} \quad (8.2)$$

To illustrate this, equations 8.1 and 8.2 are based on the formulae given in section 7.4. Quantities decorated with ' have been obtained from simulated events whose content has been altered according to a given source of uncertainty. For a *Class 1* systematic, $N_{Z^0+b+X,pseudo-data}$ was obtained from the expectation value of N_b in pseudo-experiments where the pseudo-data was generated from unaltered input and the templates used were obtained from systematically shifted objects. The acceptance correction was adopted directly from systematically altered entities in simulation. This approach for *Class 1* systematics ensures that uncertainties affecting the template shape and the event sample normalisation are accounted for at the same time.

For studying *Class 2* type sources, the template fit is conducted on each of the 100 samples analysed. For each pass of the analysis, the remaining variables entering equations 8.1 and 8.2 are obtained from the 100 event samples respectively whereas only simulated signal and background MC events are used. The measurements θ being $\sigma(Z^0 + b + X)$ or $\mathcal{R}$ are histogrammed and fitted by Gaussian *PDF* with mean $\mu = c_{calib}$ and variance $\sigma = \sigma(c_{calib})$ as stated above.

8.2 Muon Measurement Uncertainties

As introduced in chapter 6, reconstructed muon objects are subject to two calibrations to correct simulation to data: muon efficiency correction and muon momentum scale calibrations. While the first was deduced from a *tag-and-probe* analysis and hence yields only statistical uncertainties (see section 6.1.3, *Class 2* systematic uncertainty), the latter was obtained by fits to the invariant di-muon mass at the Z^0 resonance. The muon momentum calibrations used in section 6.1.3 expose uncertainties that were obtained by fits with different assumptions on the material budget of the ATLAS detector as well as different track alignment constants. Therefore, these calibrations yield a coherent source of systematic uncertainties (*Class 1* systematic uncertainty).

8.2.1 Muon Reconstruction Efficiency $\epsilon_{\mu,rec}$

As described in section 6.1.3, the scaling of the muon reconstruction efficiency is provided by an event weight. This weight $w_{muon,rec}$ is calculated from the product of all selected muon objects' scale factors $SF(p_{t,\mu}, \eta_\mu)$ (see equation 6.3 and 6.4). Each scale factor hereby comprises a statistical uncertainty that will decrease with more data collected and used for obtaining these calibrations by the ATLAS experiment. The impact of this uncertainty on the measurement of $\sigma_{incl}(Z^0 + b)$ and $\mathcal{R}$ is considered as a stochastic uncertainty. It is obtained by drawing the scale factor per muon object and per event from a Gaussian *PDF* with mean $\mu = SF(p_{t,\mu}, \eta_\mu)$ and variance $\sigma = \sigma(SF(p_{t,\mu}, \eta_\mu))$. As discussed above, 100 toy experiments are conducted with MC events. The variance of the latter results give the size of the systematic uncertainty.

The influence of this uncertainty can be expected to be small, which was shown in multiple ATLAS publications [52, 98, 169]. Figures 6.3 and 6.4 expose uncertainties below $\pm 5\%$. The maximal deviation is observed in regions of the phase space that are least populated and also not contributed significantly to any systematic deviation. However, the event weight described by equation 6.4 can act as a scale to the number of events within the invariant mass window of this analysis and thus is a potential source of systematic uncertainties to be investigated.

variation	$Z^0 + N_{SV0} \text{ jets}$		$Z^0 + N_{IP3D+SV1} \text{ jets}$	
	SHERPA	ALPGEN	SHERPA	ALPGEN
$\Delta\sigma_{Z^0+b+X}(\epsilon_{\mu,rec})$	$\pm 0.5\%$	$\pm 0.2\%$	$\pm 0.6\%$	$\pm 0.2\%$
$\Delta\mathcal{R}(\epsilon_{\mu,rec})$	$\pm 0.5\%$	$\pm 0.2\%$	$\pm 0.6\%$	$\pm 0.2\%$

Table 8.1: Collection of relative variations $\Delta\sigma_{Z^0+b+X}$ and $\Delta\mathcal{R}$ from 100 measurements on pseudo-data where the muon efficiency correction $\epsilon_{\mu,rec}$ has been drawn from a Gaussian *PDF* according to its mean and statistical uncertainty reported in section 6.1.3.

Table 8.0 lists the obtained systematic deviations on the expected cross sections $\sigma_{incl}(Z^0 + b)$ and ratios $\mathcal{R}$ obtained from MC simulation if the muon efficiency scale factor per selected muon object was randomly drawn from a Gaussian *PDF* with mean at the muon efficiency scale factor described by equation 6.4 and standard deviation set to its statistical uncertainty. As outlined in the introduction, the measurement on pseudo-data was conducted 100 times and the yielded cross section (or cross section ratio) was estimated and histogrammed. The resulting distribution was fitted with a Gaussian *PDF* via a binned maximum likelihood fit. The fitted Gaussian standard

deviation is used as systematic uncertainty. Two examples of these fits are displayed in figure 8.0 for illustration. The appendix section F.1 contains the remaining distributions related to table 8.0.

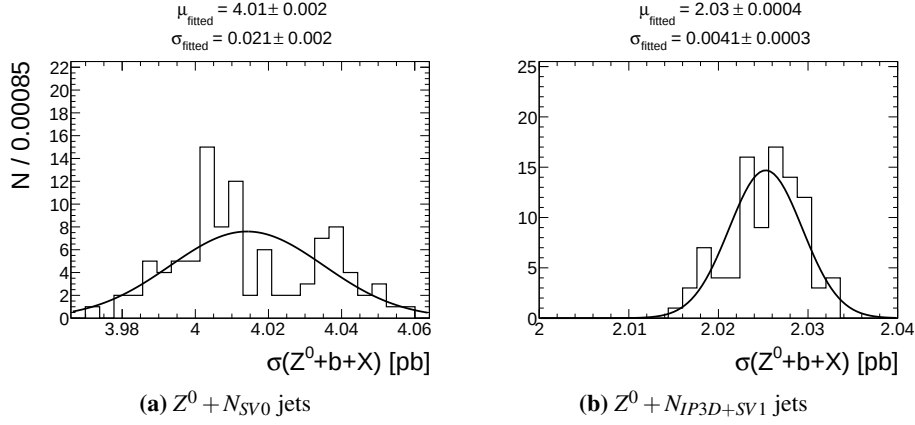


Figure 8.1: Distribution of estimated $\sigma_{incl}(Z^0 + b)$ yields from 100 pseudo-data experiments from the $Z^0 + N_{SV0}$ jets analysis (figure a using SHERPA MC) and $Z^0 + N_{IP3D+SV1}$ jets analysis (figure b using ALPGEN) after variations of the muon reconstruction efficiency corrections. All histograms are fitted with a Gaussian *PDF* by a binned minimum log-Likelihood procedure. The fit results for the Gaussian mean μ and standard deviation σ are also given.

All cross section variations listed in table 8.0 are below 0.6%. This reflects the size of muon efficiency scale factors' statistical uncertainty as observed in [185, 186] (figures 6.3 and 6.4 of section 6.1.3) which is typically below 2%. The difference between $Z^0 + N_{IP3D+SV1}$ jets and $Z^0 + N_{SV0}$ jets is of statistical nature. For example, the number $Z^0 + N_{IP3D+SV1}$ jets events not scaled to luminosity in SHERPA amounts to 8113 and in ALPGEN to 103553. The two statistics differ by a factor of 13. Hence, a random draw from the same Gaussian *PDF* (i.e. the muon efficiency scale factor *PDF*) must yield a deviation $\Delta_{Alp\text{gen}} \approx \Delta_{Sherpa} / \sqrt{13} = \Delta_{Sherpa} / 3.6$ by definition of a Gaussian *PDF*'s variance. This ratio is not exactly but approximately reproduced by table 8.0 due to rounding effects.

The relative deviations listed in table 8.0 will enter the statistical uncertainty of the measurement for they are expected to decrease with more ATLAS data used to derive muon efficiency correction factors.

8.2.2 Muon Energy Scale $p_{t,\mu}$

As discussed in chapter 6, the reconstructed muon candidate transverse momenta are smeared in simulation following muon momentum scale estimates from invariant mass fits [183]. These fits were performed on invariant mass distributions using combined muon candidates as well as using *MuonSpectrometer* or *InnerDetector* only track candidates. For each, the systematic uncertainty of the estimated momentum scale was assessed by re-evaluating the momentum correction with different misalignment schemes and *InnerDetector* material budget scenarios. Uncertainties of the muon momentum scale are given as upward or downward error bands on the *MuonSpectrometer* and *InnerDetector* momentum measurement and are *Class 2* type coherent sources of uncertainty. Their extent is below 5 % of the muon transverse momentum.

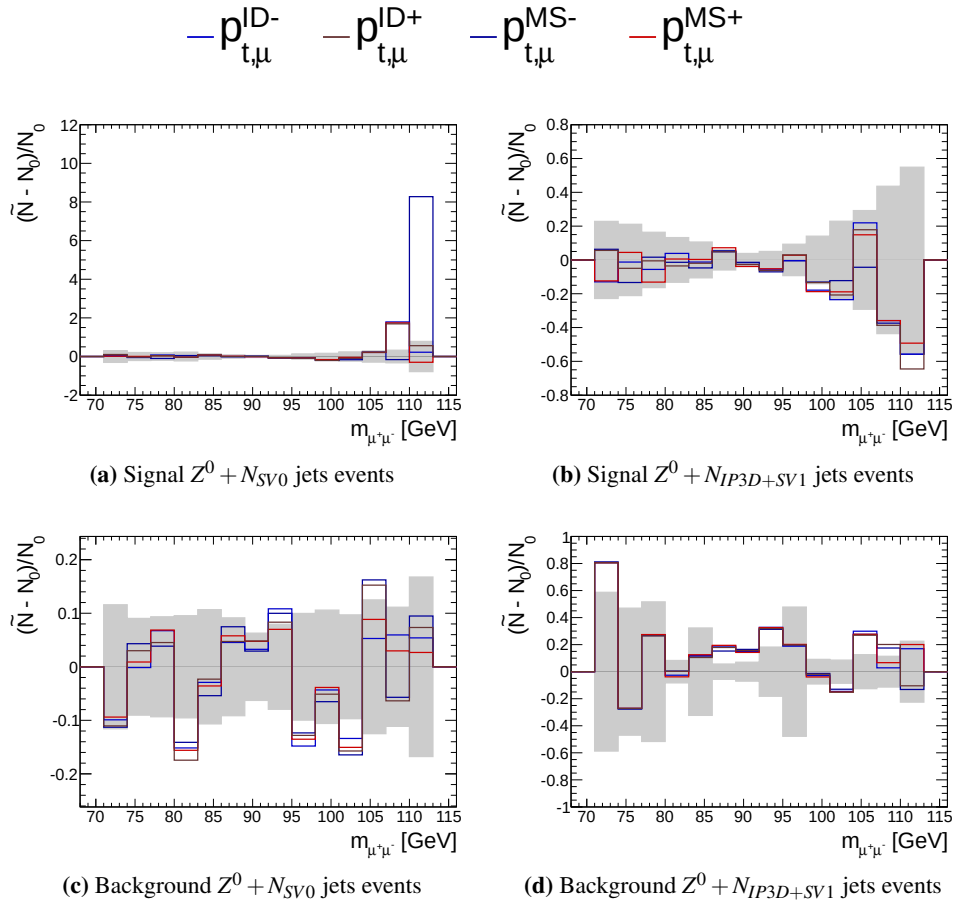


Figure 8.2: Relative difference of event yields to nominal value in $Z^0 + N_{SV0}$ jets (a, c) and $Z^0 + N_{IP3D+SV1}$ jets (b, d) selected events per bin of the reconstructed muon-muon invariant mass. For each distribution, the muon candidates histogrammed were subject to extra muon momentum smearings of the *InnerDetector* component of a combined muon track ($p_{t,\mu}^{ID\pm}$) and of the *MuonSpectrometer* component ($p_{t,\mu}^{MS\pm}$) according to the respective uncertainties. The grey shaded area indicates the statistical uncertainty of the unaltered event sample.

Figure 8.1 illustrates the extent to which the variation of *InnerDetector* or *MuonSpectrometer* momenta effects the invariant mass distribution of reconstructed Z^0 candidates. Due to the small size of the variation per muon object of 1 % [183], the effect is only visible towards the boundaries of the chosen invariant mass window (see section 6.2) where relative differences of more than 100 % are shown. Here, the absolute event count in the nominal sample per bin is however negligible

(statistical uncertainty of 90 %, see section 6.5) which explains why migrations of neighbouring bins imply an increase of bin content up to 800 %. Further, all variations are within one standard deviation of the statistical uncertainty of the nominal event sample. The influence on the total cross section measurement and the cross section ratio is thus small and remains below 3 %.

variation	$Z^0 + N_{SV0}$ jets		$Z^0 + N_{IP3D+SV1}$ jets	
	SHERPA	ALPGEN	SHERPA	ALPGEN
$\Delta\sigma_{Z^0+b+X}(p_{t,\mu}^{ID-})$	-1.9 %	-0.9 %	-2.0 %	-2.5 %
$\Delta\sigma_{Z^0+b+X}(p_{t,\mu}^{ID+})$	-1.6 %	-0.7 %	-2.0 %	-2.4 %
$\Delta\sigma_{Z^0+b+X}(p_{t,\mu}^{MS-})$	-1.8 %	-0.8 %	-1.4 %	-2.4 %
$\Delta\sigma_{Z^0+b+X}(p_{t,\mu}^{MS+})$	-1.7 %	-0.6 %	-1.9 %	-2.4 %
$\Delta\mathcal{R}(p_{t,\mu}^{ID-})$	-2.3 %	-1.1 %	-2.4 %	-2.8 %
$\Delta\mathcal{R}(p_{t,\mu}^{ID+})$	-1.9 %	-0.9 %	-2.3 %	-2.6 %
$\Delta\mathcal{R}(p_{t,\mu}^{MS-})$	-2.1 %	-1.0 %	-1.7 %	-2.6 %
$\Delta\mathcal{R}(p_{t,\mu}^{MS+})$	-2.1 %	-1.0 %	-2.3 %	-2.8 %

Table 8.2: Collection of relative systematic variations assuming pseudo-data in which the muon momentum scale $p_{t,\mu}^\pm$ has been corrected according to its systematic uncertainty.

Table 8.1 lists the relative variations due to different setups for calibrating the momentum scale of reconstructed muons. All values indicate a decrease in $\sigma_{incl}(Z^0 + b)$ as well as in $\mathcal{R}$ by up to 3 %. Although this can be considered negligible compared to the overall statistical uncertainty of the measurement, the $Z^0 + N_{IP3D+SV1}$ jets samples is most sensitive to this variation. This is due to its larger statistics and the high content of light flavour jets in this sample which imply Z^0 boson kinematics that produce muons that are subject to larger corrections.

Figure 8.2 illustrates how the increased sample size of $Z^0 + N_{IP3D+SV1}$ jets events leads to a higher frequency of muon objects (e.g. at $p_{t,\mu} = 45$ GeV) that are subject to corrections. As illustrated by figure 8.1d, the expected background increases for all muon momentum variations around $m_{\ell^+\ell^-} = 91$ GeV compared to the signal event yield of this sample. Since the fit procedure of chapter 7 uses a fixed background template normalisation, more background events induce less fitted signal events. Thus, the systematic variations of table 8.1 are below zero.

Figure 8.3 compares the reconstructed muon momentum distribution after the $Z^0 + N_{jets}$ jets, $Z^0 + N_{SV0}$ jets and $Z^0 + N_{IP3D+SV1}$ jets event selection on SHERPA signal MC events. Compared to the $Z^0 + N_{jets}$ jets sample, reconstructed muons in events with bottom quark induced jets (i.e. with tagged jets here) produce are more soft, figure 8.3b. This is a consequence of the massive bottom quark that holds a momentum balance against the produced Z^0 boson. Also, the $Z^0 + N_{SV0}$ jets sample yields much fewer muon candidates at the most probable muon transverse momentum of a Z^0 decay at $p_{t,\mu} \approx (35 - 45)$ GeV. On the other hand, muon candidates from the $Z^0 + N_{IP3D+SV1}$ jets event sample expose a (more) equivalent transverse momentum spectrum than from the $Z^0 + N_{jets}$ jets event sample. The latter must be identified as the cause of the higher systematic uncertainty for a negative deviation in figures 8.2b can be seen at $p_{t,\mu} \approx (35 - 45)$ GeV as well.

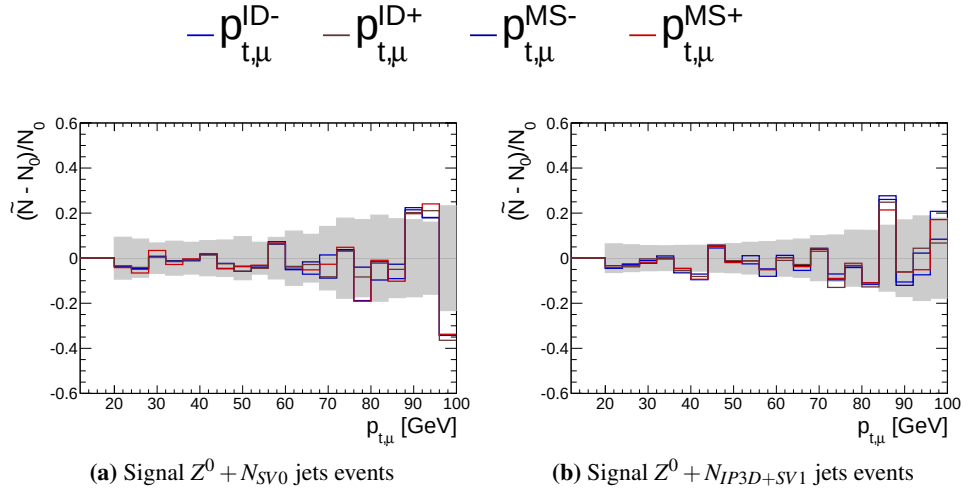


Figure 8.3: Relative difference of event yields to nominal value in $Z^0 + N_{SV0}$ jets (a) and $Z^0 + N_{IP3D+SV1}$ jets (b) selected events per bin of the reconstructed muon-muon invariant mass. For each distribution, the muon candidates histogrammed were subject to extra muon momentum smearings of the *InnerDetector* component of a combined muon track ($p_{t,\mu}^{\text{ID}\pm}$) and of the *Muon-Spectrometer* component ($p_{t,\mu}^{\text{MS}\pm}$) according to the respective uncertainties. The grey shaded area indicates the statistical uncertainty of the unaltered event sample.

8.2.3 Muon Isolation Efficiency $\epsilon_{\mu,iso}$

As discussed in section 6.1.4, any corrections of data to MC discrepancies versus the muon isolation i_{ptcone} is not taken into account for this analysis. To account for this assumption, a systematic uncertainty of $\pm 1.8\%$ is adopted from [52] for $\sigma_{incl}(Z^0 + b)$ and $\pm 2.5\%$ for the cross section ratio $\mathcal{R}$ where this uncertainty enters twice.

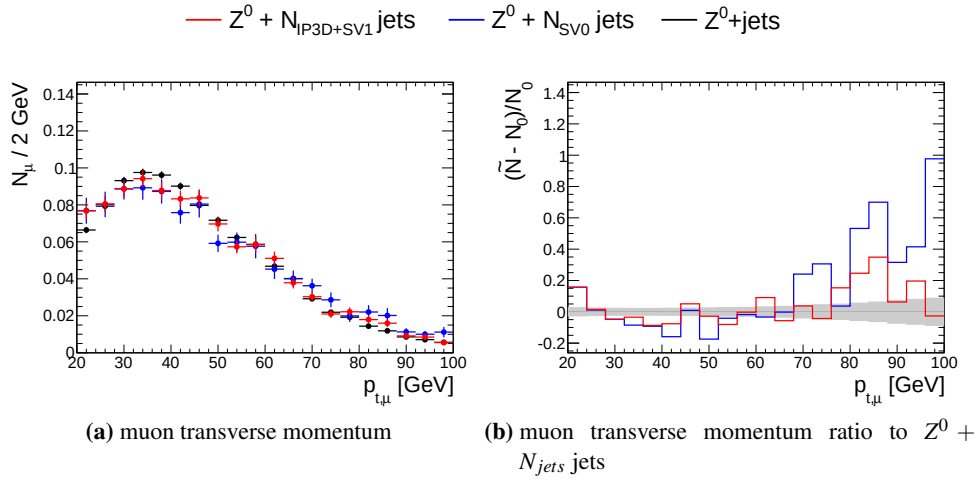


Figure 8.4: Reconstructed muon transverse momentum distribution in SHERPA signal MC in $Z^0 + N_{jets}$ jets, $Z^0 + N_{SV0}$ jets and $Z^0 + N_{IP3D+SV1}$ jets selected events (a). All distributions have been normalised to unit integral. The relative variation with respect to the untagged muon sample is displayed as well (b).

8.2.4 Muon Trigger Response $\epsilon_{\mu,trigger}$

In section 5.2.2, the muon trigger response was corrected in simulated events to match the performance observed in data. For the uncertainties of this correction are again of stochastic nature, the approach of section 8.2.1 is followed to estimate their impact on the final result.

variation generator	$Z^0 + N_{SV0}$ jets		$Z^0 + N_{IP3D+SV1}$ jets	
	SHERPA	ALPGEN	SHERPA	ALPGEN
$\Delta\sigma_{Z^0+b+X}(\epsilon_{\mu,trigger})$	$\pm 0.5\%$	$\pm 0.2\%$	$\pm 0.6\%$	$\pm 0.2\%$
$\Delta\mathcal{R}(\epsilon_{\mu,trigger})$	$\pm 0.5\%$	$\pm 0.2\%$	$\pm 0.6\%$	$\pm 0.2\%$

Table 8.3: Collection of relative variations from 100 measurements on pseudo-data where the muon trigger efficiency correction $\epsilon'_{\mu,trigger}$ has been drawn from a Gaussian *PDF* according to its mean and statistical uncertainty. The distributions from which the reported numbers were obtained can be found in the appendix F.1.

As discussed in an related published ATLAS analysis [181], the uncertainties on the trigger efficiency scale factors are below 1 %. Since the trigger efficiency corrections are applied on the event selection level, their effect is expected to directly scale the estimated cross section $\sigma_{incl}(Z^0 + b)$ and $\mathcal{R}$.

Table 8.2 lists the relative deviations in the measured quantities from the expected cross section obtained from Gaussian fits to 100 pseudo-experiments. The yielded differences remain below 1 %. The impact and behaviour due to this source of uncertainty is equivalent to the one discussed in section 8.2. Since the uncertainties discussed here are of stochastic origin, their extent on $\sigma_{incl}(Z^0 + b)$ and $\mathcal{R}$ is added in quadrature to the total statistical uncertainty of the measurement.

8.3 Jet Reconstruction Uncertainties

The jet momentum recorded by the ATLAS experiment with respect to its corresponding value on hadron level is parametrised via the response function $\langle \mathcal{R}_{EM+JES} \rangle = f(E_{t,jet}, \eta_{jet})$ (see equation 4.15) in bins of jet transverse energy and pseudo-rapidity, see section 4.3.3. A fit of $\mathcal{R}_{EM+JES}$ is performed which yields this absolute scale by which the observed momentum has to be shifted ($\langle p_{t,jet} \rangle$). $\langle \mathcal{R}_{EM+JES} \rangle$ is thus a random variable. Its standard deviation is taken as the jet energy resolution uncertainty ($\sigma(p_{t,jet})$) and must be regarded as *Class 1* source of uncertainty.

The uncertainty of the jet energy scale is estimated by performing the analysis of $\langle \mathcal{R}_{EM+JES} \rangle$ under different assumptions (material budget, hadronisation model) or with different experimental setups (calorimeter maskings and calibrations). Thus it represents a coherent source of uncertainty (*Class 2*).

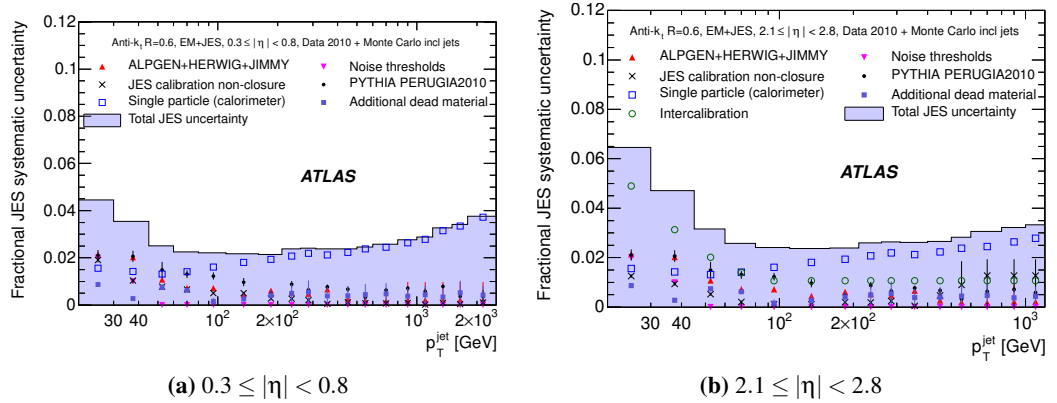


Figure 8.5: Expected jet energy uncertainties obtained from 2010 multi-jet events versus p_T^{jet} for $0.3 \leq |\eta| < 0.8$ (a) and $2.1 \leq |\eta| < 2.8$ (b) reported in [202].

Figure 8.4 illustrates the expected size of systematic uncertainties affiliated to the EM+JES calibrated jet energy measurement at ATLAS in 2010 data. As shown in figure 6.11 and 6.18, the most probable value of jet transverse momentum in reconstructed $Z^0 + \text{jets}$ events is 50.6 GeV, 55.7 GeV in $Z^0 + N_{SV0}$ jets and 51.9 GeV in $Z^0 + N_{IP3D+SV1}$ jets events observed in data. Therefore, uncertainties of 2 – 3 % on the jet energy scale are to be expected. Figures 6.11 and 6.18 also show a steep decrease of the jet transverse momentum spectrum which indicates that any alternations of the jet transverse momentum may imply considerable migrations.

At central pseudo-rapidity (figure 8.4a), the dominant source of uncertainty is the underlying event tune and the simulation of single particle responses of the *Calorimeter*. For more forward jets (figure 8.4b), the inter-calibration method to estimate the jet energy scale in data and the single particle responses of the *Calorimeter* contribute most to the total jet energy uncertainty.

8.3.1 Jet Energy Scale Uncertainty $\langle p_{t,jet} \rangle$

For this analysis, the jet energy scale uncertainties reported in [156, 157] are used. Therein, the effect of flavour composition, close-by jet cross talk, pile-up effects, calorimeter response and non-closure are taken into account. For jets induced by bottom quarks on hadron level, the jet energy

scale uncertainty is increased by 2.5% relative to its nominal value to account for the unknown calorimeter response of heavy flavour initiated jets [203].

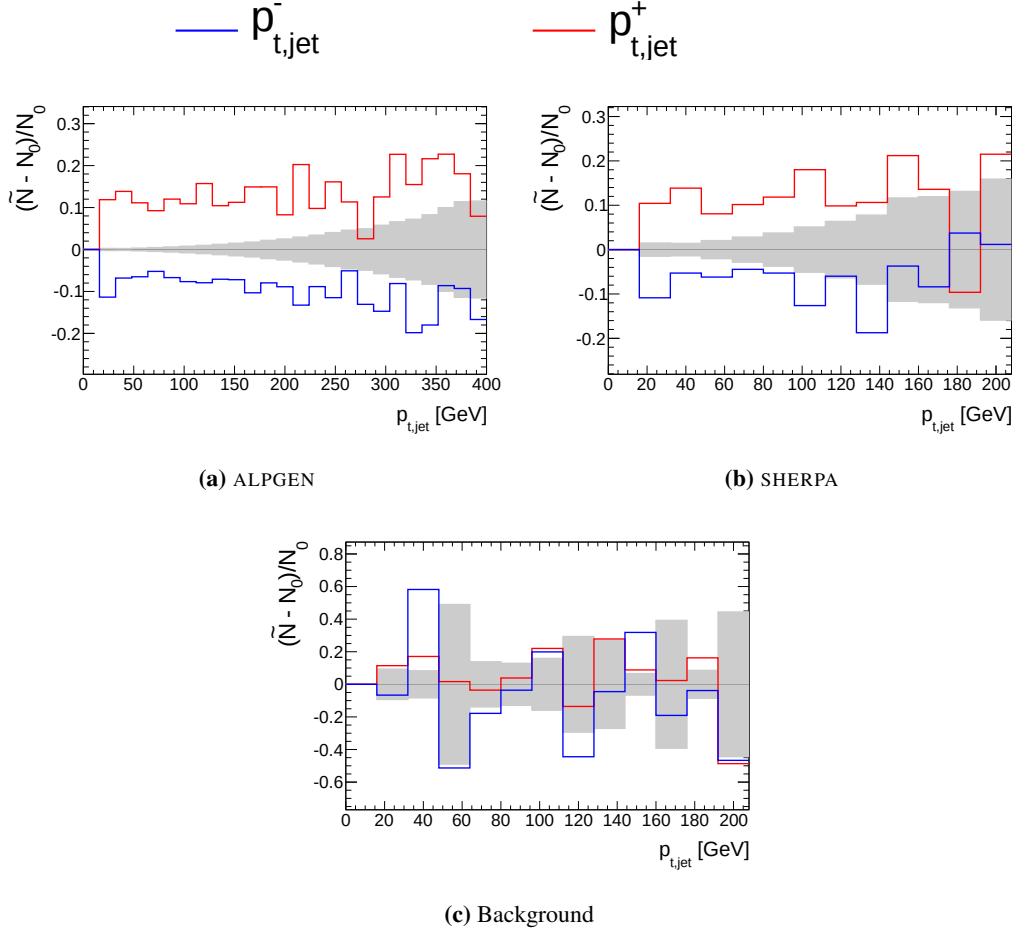


Figure 8.6: Relative difference of event yields to nominal value per bin versus the reconstructed jet transverse momentum after the jet energy scale was added (subtracted) from the observed value in ALPGEN (a) and SHERPA (b) signal MC as well as background MC events (c). Only events that contain at least one selected jet and a di-muon candidate that satisfies the invariant mass requirement discussed in chapter 6 were used. The grey shaded area indicates the statistical uncertainty of the unaltered (nominal) event sample.

Figure 8.5 shows the relative deviation of the number of observed jets in bins of jet transverse momentum after a $Z^0 + N_{jets}$ jets selection where the jet energy scale uncertainty is added or subtracted from the expected jet momentum in MC events. For a wide range of values, the observed systematic shift is constant around $\pm 10\%$. This sizable difference to figure 8.4 is caused by migrations due to the steeply falling jet transverse momentum spectrum. For background MC events, no coherent effect can be observed. Larger deviations in specific bins of the latter are due to migration of $W^\pm + jets$ events into the sample in the soft jet transverse momentum regime as was already observed in figure 6.11a.

The interpretation of the systematic deviations noted in table 8.3 is counter-intuitive for the cross section deviations from the $Z^0 + N_{SV0}$ jets analysis. Downward variations of the jet energy scale tend to induce upward deviations of the cross section (or ratio) and vice versa. The $Z^0 + N_{SV0}$ jets events yield a very pure sample of $Z^0 + b$ final states, i.e. events that contain a high fraction of bottom flavour initiated jets. Deviations of light and charm template shapes result in different

variation	$Z^0 + N_{SV0}$ jets		$Z^0 + N_{IP3D+SV1}$ jets	
	SHERPA	ALPGEN	SHERPA	ALPGEN
$\Delta\sigma_{Z^0+b+X}(\langle p_{t,jet}^+ \rangle)$	-6.3 %	-2.4 %	-1.0 %	+0.6 %
$\Delta\sigma_{Z^0+b+X}(\langle p_{t,jet}^- \rangle)$	+3.3 %	+1.6 %	-2.3 %	-3.1 %
$\Delta\mathcal{R}(\langle p_{t,jet}^+ \rangle)$	-2.6 %	+1.1 %	+3.0 %	+4.2 %
$\Delta\mathcal{R}(\langle p_{t,jet}^- \rangle)$	-0.6 %	-1.7 %	-6.0 %	-6.3 %

Table 8.4: Collection of relative variations after to coherent variation of the jet energy scale $p_{t,jet}^\pm$.

fitted values of N_{Z^0+b} . Especially in the $Z^0 + N_{SV0}$ jets selection with small event yields, different charm and light flavour templates have sizable effects.

For the $Z^0 + N_{IP3D+SV1}$ jets event sample, the deviations of $\sigma_{incl}(Z^0 + b)$ show a different behaviour which is driven by migrations of the light jet ensemble contained in events entering here. In any case, the systematic variations observed for $\mathcal{R}$ show how the deviations that enter from the $Z^0 + N_{jets}$ jets sample tend to dominate all other. This is implied by almost all listed $\mathcal{R}$ deviations of table 8.3 being proportional to the change in the jet energy scale itself. In general, the numbers reported in table 8.3 suggest that a change in jet energy scale induces different template distributions in such a way that the fit result follows in a complex manner that is not straight forward to account for.

The $\sum_{jets} m_{SV,SV0}$ template distributions (figure 8.6) experience large deviations (up to 100 % or more) in the non-bottom flavour templates ($Z^0 + c$ and $Z^0 + light$). These amount to multiples of the statistical uncertainty and henceforth influence the fit result. The bottom flavour template displays a flat and stable shift. These two effects produce more fitted light (or charm) flavour events which induces a decrease of the fitted number of observed bottom final states in turn. This behaviour propagates to $\sigma_{incl}(Z^0 + b)$.

Figure 8.7 displays the relative deviation due to jet energy scale variations for $Z^0 + N_{IP3D+SV1}$ jets events. The impact of different jet energy scales is not as severe for the $\sum_{jets} m_{SV,SV1}$ shape compared to the $\sum_{jets} m_{SV,SV0}$ distributions of figure 8.6. The jet energy scale uncertainties on $\sigma_{incl}(Z^0 + b)$ for the $Z^0 + N_{IP3D+SV1}$ jets analysis is smaller than for the $Z^0 + N_{SV0}$ jets estimates, table 8.3. For $\mathcal{R}$ this is not the case, because $N_{b,fitted}$ and $N_{jets,data}$ are more correlated due to a high light parton flavour content.

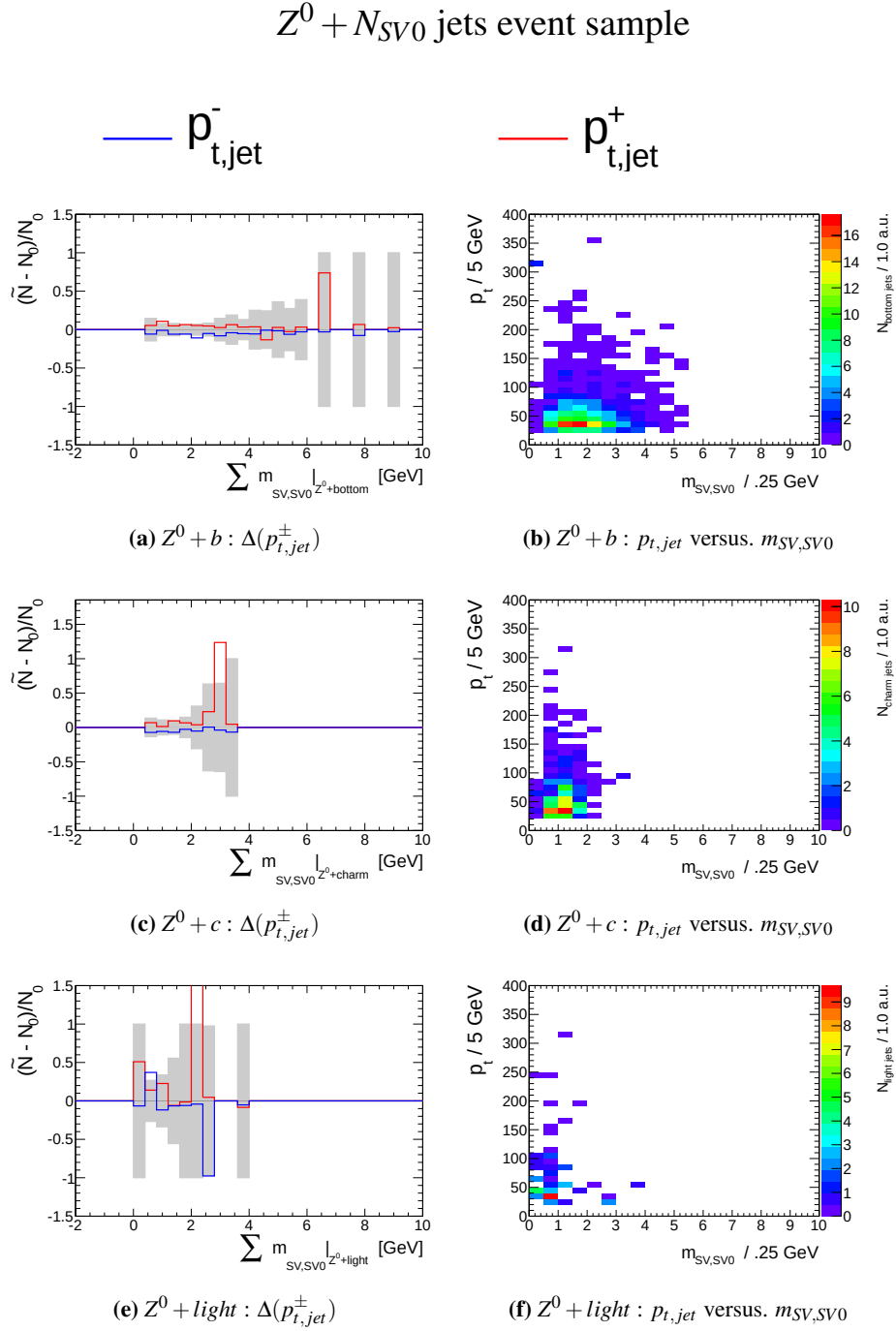


Figure 8.7: Relative difference of event yield to nominal value per $\sum_{jets} m_{SV,SV0}$ bin for events containing $Z^0 + b$ (a), $Z^0 + c$ (c) and $Z^0 + light$ (e) final state events passing all $Z^0 + N_{SV0}$ jets selection requirements. The grey shaded area indicates the statistical uncertainty of the unaltered event sample. Further, the reconstructed jet transverse momentum versus the secondary mass $m_{SV,SV0}$ is displayed for generator level identified $Z^0 + b + jets$ (b), $Z^0 + c + X$ (d) and $Z^0 + light + X$ (f) final state events passing all $Z^0 + N_{SV0}$ jets selection requirements.

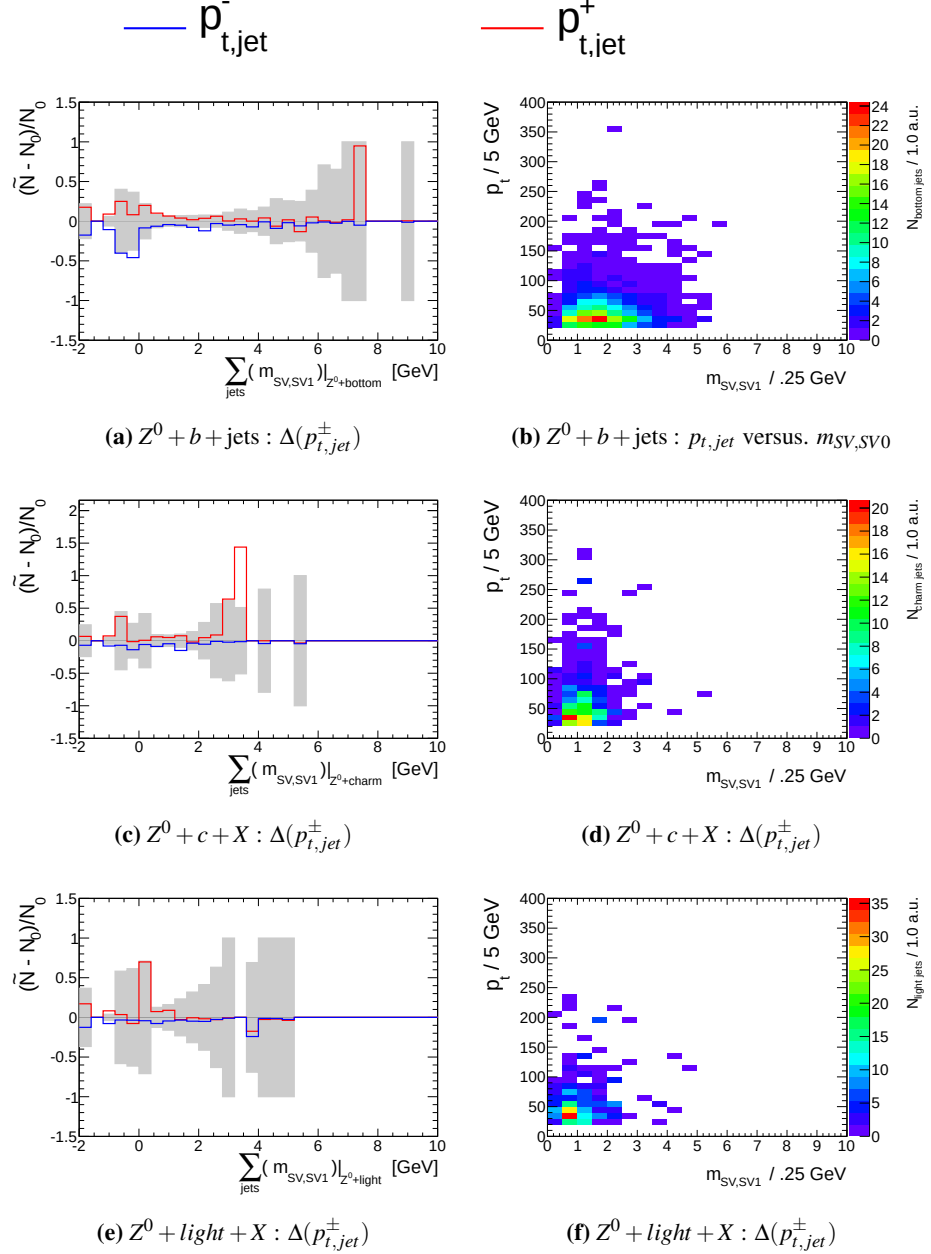
$Z^0 + N_{IP3D+SV1} \text{ jets event sample}$


Figure 8.8: Relative difference of event yield to nominal value per $\sum_{jets} m_{SV,SV1}$ bin for events containing $Z^0 + b + \text{jets}$ (a), $Z^0 + c + X$ (c) and $Z^0 + \text{light} + X$ (e) final state events passing all $Z^0 + N_{SV0}$ jets selection requirements. The grey shaded area indicates the statistical uncertainty of the unaltered event sample. Further, the reconstructed jet transverse momentum versus the secondary mass $m_{SV,SV1}$ is displayed for generator level identified $Z^0 + b + \text{jets}$ (b), $Z^0 + c + X$ (d) and $Z^0 + \text{light} + X$ (f) final state events passing all $Z^0 + N_{IP3D+SV1}$ jets selection requirements.

8.3.2 Jet Energy Resolution Uncertainty $\sigma(p_{t,jet})$

Contrary to the coherent nature of jet energy scale uncertainties, the jet energy resolution is of stochastic origin (*Class I*). Therefore, the analysis and result extraction was performed 100 times. Each time, the jet energy was smeared by a draw from a Gaussian *PDF* with the mean set to the reconstructed jet energy (in simulation) and the variance fixed at the jet energy resolution known from [202].

variation	$Z^0 + N_{SV0}$ jets		$Z^0 + N_{IP3D+SV1}$ jets	
	SHERPA	ALPGEN	SHERPA	ALPGEN
$\Delta\sigma_{Z^0+b+X}(\sigma(p_{t,jet}))$	$\pm 0.6\%$	$\pm 0.2\%$	$\pm 0.6\%$	$\pm 0.2\%$
$\Delta\mathcal{R}(\sigma(p_{t,jet}))$	$\pm 0.7\%$	$\pm 0.2\%$	$\pm 0.6\%$	$\pm 0.3\%$

Table 8.5: Relative variations from 100 measurements on pseudo-data where the jet energy per object has been drawn from a Gaussian *PDF* according to the jet energy resolution $\sigma(p_{t,jet})$ given by [202]. The quoted numbers were obtained from fits to the distributions of 100 measurements shown in the appendix F.2.

Table 8.4 lists deviations of $\sigma_{incl}(Z^0 + b)$ and $\mathcal{R}$ for the random variation of the jet energy scale according to its resolution. Since this variation affects only events that contain reconstructed jets close to the transverse momentum threshold described in section 6.3.4 at $p_{t,jet} > 25 \text{ GeV}$, its effect is small. The effect is of the order of 1 % which was also observed in [98]. Since the uncertainties discussed here are of stochastic origin, their influence on $\sigma_{incl}(Z^0 + b)$ and $\mathcal{R}$ is added in quadrature to the total statistical uncertainty of the measurement.

8.4 Flavour Tagging Uncertainties

As outlined in the introduction of this chapter, the approach to study systematic effects is categorised into three types of sources. The scale factors used for calibrating b-tagging in MC to data introduce statistical uncertainties as well as systematic uncertainties. With this, they contain uncertainties of classes 1 and 2 and are treated according to the prescription of section 8.1.

8.4.1 Coherent Uncertainties of b-tagging efficiency corrections $\langle \epsilon_b \rangle$

The efficiency corrections [159, 190] required to correct b-tagging performance in simulation to that observed in data were obtained by the *ptrel* method (section 6.4.1). For this, a sample of QCD di-jet events was analysed that were selected that contain a muon candidate and that were tagged by the $\sum_{jets} m_{SV,SV0}$. Low momentum leptons are more frequently produced in charm and bottom flavour induced jets due to the semi-leptonic decay of associated mesons ($B^\pm, D^*, D^\pm$) compared to light jets. Thus, the *ptrel* method exposes efficiencies in data and simulated events with correlated uncertainties for charm and bottom flavour jets and anti-correlated uncertainties for heavy flavour with respect to light flavour initiated jets.

The custom calibration presented in section 6.4.2 does follow the same approach as [159, 190] with $Z^0 + \text{jets}$ simulated events. Since this implies comparable systematic uncertainties on jet properties in $Z^0 + \text{jets}$ events as in QCD di-jet events, their relative size is used here as coherent source of uncertainty on the b-tagging efficiency scale factors in $Z^0 + N_{SV0}$ jets and $Z^0 + N_{IP3D+SV1}$ jets events.

variation	$Z^0 + N_{SV0}$ jets		$Z^0 + N_{IP3D+SV1}$ jets	
	SHERPA	ALPGEN	SHERPA	ALPGEN
$\Delta\sigma_{Z^0+b+X}(\langle \epsilon_{b,heavy}^- \rangle)$	+9.0 %	+10.4 %	+9.6 %	+9.7 %
$\Delta\sigma_{Z^0+b+X}(\langle \epsilon_{b,heavy}^+ \rangle)$	-10.8 %	-9.8 %	-11.9 %	-13.3 %
$\Delta\sigma_{Z^0+b+X}(\langle \epsilon_{b,light}^- \rangle)$	-2.0 %	-1.4 %	-1.8 %	-1.1 %
$\Delta\sigma_{Z^0+b+X}(\langle \epsilon_{b,light}^+ \rangle)$	-1.8 %	-0.2 %	-2.1 %	-4.0 %
$\Delta\mathcal{R}(\langle \epsilon_{b,heavy}^- \rangle)$	+9.0 %	+10.4 %	+9.6 %	+9.7 %
$\Delta\mathcal{R}(\langle \epsilon_{b,heavy}^+ \rangle)$	-10.8 %	-9.8 %	-11.9 %	-13.3 %
$\Delta\mathcal{R}(\langle \epsilon_{b,light}^- \rangle)$	-2.0 %	-1.4 %	-1.8 %	-1.1 %
$\Delta\mathcal{R}(\langle \epsilon_{b,light}^+ \rangle)$	-1.8 %	-0.2 %	-2.1 %	-4.0 %

Table 8.6: Relative deviations after coherent variation of heavy $\langle \epsilon_{b,heavy}^\pm \rangle$ and light $\langle \epsilon_{b,light}^\pm \rangle$ flavour jet related uncertainties of the b-tagging corrections applied during the analysis.

Table 8.5 summarises the effect of the variation of the b-tagging efficiency systematics on this measurement. The listed deviations are driven by the response of the acceptance on varied input templates prior to the LLH fit. Both acceptance definitions in equation 8.1 and 8.2 are directly dependent on the heavy flavour b-tagging efficiency and hence linearly respond to any variation therein. Further, alternations of $\epsilon_{b,light}$ may not necessarily induce more or less bottom flavour partons to enter the cross section evaluation. The fit procedure may account for any variation in $\epsilon_{b,light}$ by adjusting the number of charm over bottom flavour jet yields. Which one occurs strongly

depends on the specific shape of the template distributions used in the fit procedure.

Figure 8.8 demonstrates the anti-correlation of heavy to light flavour b-tagging efficiency uncertainties: the deviations due to light flavour b-tagging efficiency uncertainty is large in figure 8.8f whereas the heavy flavour efficiency corrections dominates in figure 8.8b. The latter governs the overall b-tagging systematic uncertainties with variations of approximately 10% over large parts of $\sum_{jets} m_{SV,SV1}$.

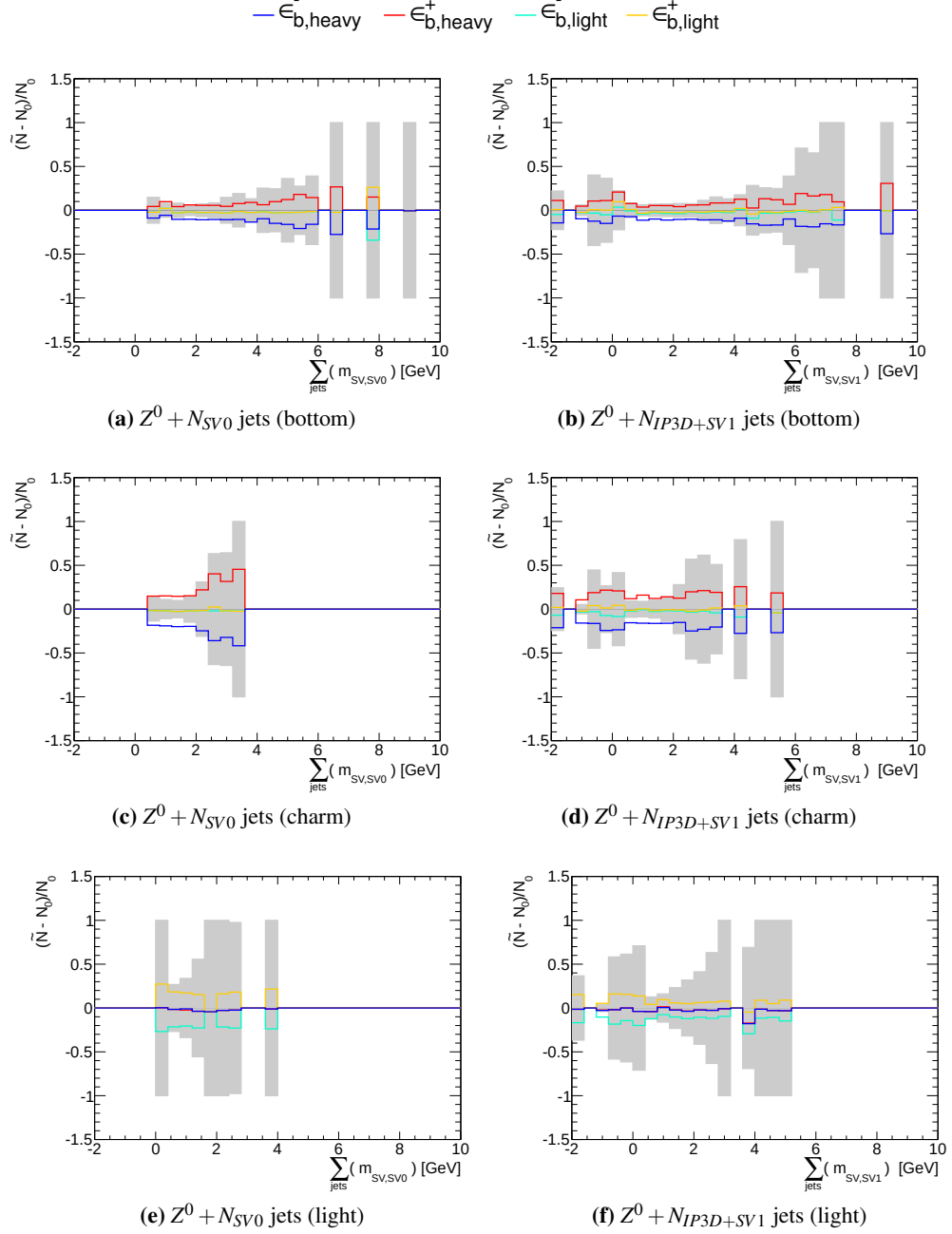


Figure 8.9: Relative difference of event yield to nominal value per $\sum_{\text{jets}} m_{SV,SV1}$ or $\sum_{\text{jets}} m_{SV,SV0}$ bin for events containing $Z^0 + b + \text{jets}$ (a) and (b), $Z^0 + c + X$ (c) and (d) or $Z^0 + \text{light} + X$ (e) and (f) final state events due to variations of the heavy $\epsilon_{b,\text{heavy}}^\pm$ and light flavour b-tagging efficiency $\epsilon_{b,\text{light}}^\pm$. The grey shaded area indicates the statistical uncertainty of the unaltered event sample.

8.4.2 Statistical Uncertainties of b-tagging efficiency corrections $\sigma(\epsilon_b)$

In the calibration procedure documented in section 6.4.2, the mean statistical uncertainty of the b-tagging calibration constants is below $\pm 5\%$, see figure 8.9.

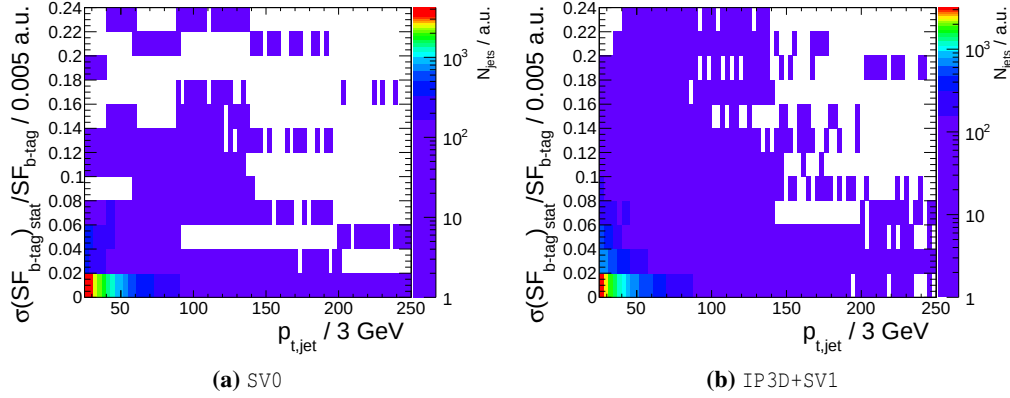


Figure 8.10: Relative statistical uncertainty $\sigma(SF_{b-tag})/SF_{b-tag}$ of the b-tagging calibration weight versus jet transverse momentum for SV0 (a) and IP3D+SV1 (b) selected jets in SHERPA MC events as computed from the algorithm discussed in section 6.4.2.

Figure 8.9 illustrates the distribution of relative statistical uncertainty of the b-tagging efficiency scale factors per jet object without requiring a specific parton flavour that initiated the jets. The average relative statistical uncertainty for figure 8.9a is 2.1 % and 3.7 % for figure 8.9b. These uncertainties enter the estimate of $\sigma_{incl}(Z^0 + b)$ and $\mathcal{R}$ by the acceptance correction $\mathcal{A}$ and will hence be studied briefly as *Class 1* uncertainties since they are of stochastic origin.

variation	$Z^0 + N_{SV0}$ jets		$Z^0 + N_{IP3D+SV1}$ jets	
	SHERPA	ALPGEN	SHERPA	ALPGEN
$\Delta\sigma_{Z^0+b+X}(\sigma(\epsilon_b))$	$\pm 0.5\%$	$\pm 0.2\%$	$\pm 0.7\%$	$\pm 0.2\%$
$\Delta\mathcal{R}(\sigma(\epsilon_b))$	$\pm 0.5\%$	$\pm 0.2\%$	$\pm 0.7\%$	$\pm 0.6\%$

Table 8.7: Relative variations due to random variations of the b-tagging corrections $\sigma(\epsilon_b)$ applied within their statistical uncertainties.

Table 8.6 collects the deviation of $\sigma_{incl}(Z^0 + b)$ and $\mathcal{R}$ due to random variations of the nominal b-tagging calibration constants. The effects reported are small. The relative effect remains below $\pm 1\%$. This again underlines how the LLH fit procedure reacts mildly upon systematic variations of any kind. Even if the acceptance is affected by a deviation on any sort, this may not induce differences in $\sigma_{incl}(Z^0 + b)$ and $\mathcal{R}$ because a jitter on the denominators of a few percent does not have a large impact on the general result of equations 8.1 and 8.2.

8.4.3 Correlations

Due to the essential role that (b-tagged) jets play for this analysis, the correlations between the most dominant sources of uncertainty (jet energy scale and b-tagging efficiency corrections) are evaluated.

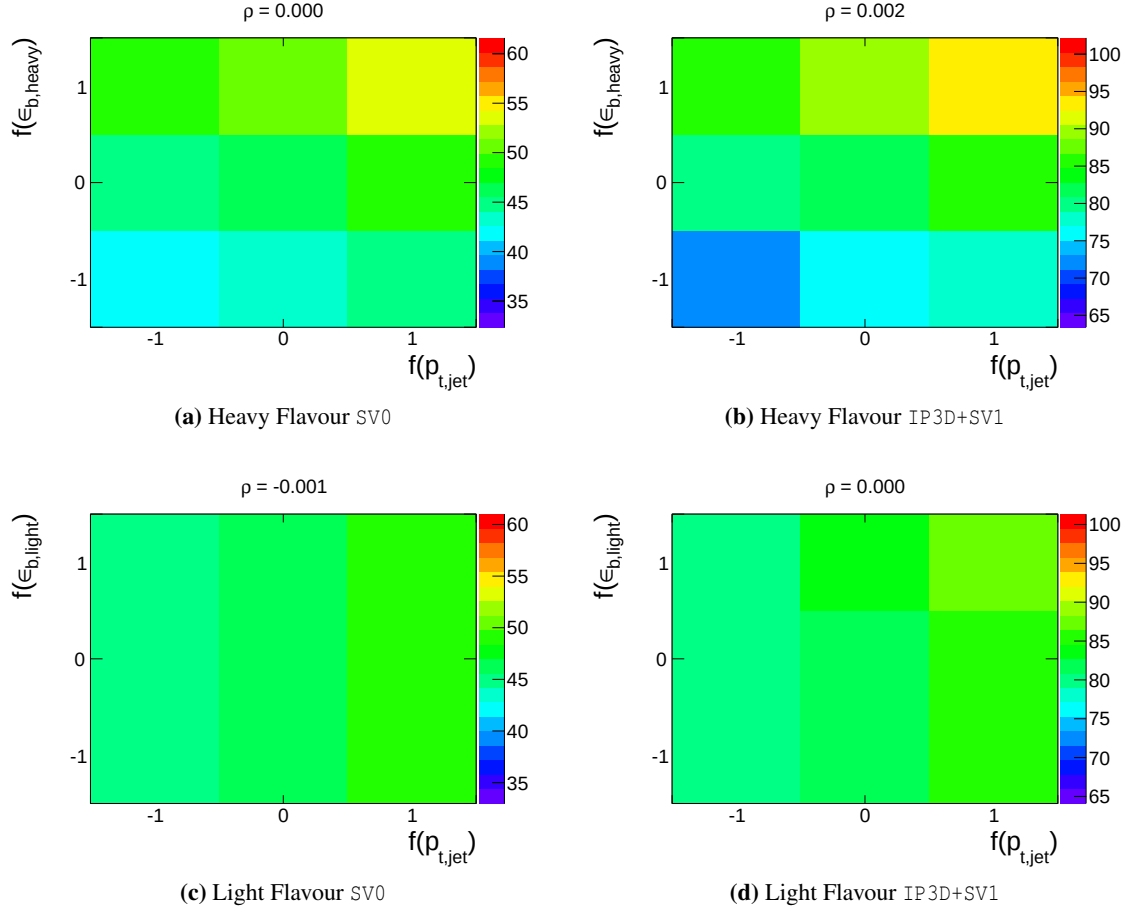


Figure 8.11: Event yield after $Z^0 + N_{SV0}$ jets (left) and $Z^0 + N_{SV0}$ jets (right) analysis from SHERPA signal MC. For each analysis, the systematic uncertainty was added to ($f(p_{t,jet}) = +1$) or subtracted from ($f(p_{t,jet}) = -1$) the reconstructed jet energy scale as well as was the b-tagging efficiency correction for heavy ($f(\epsilon_{b,heavy})$) or light ($f(\epsilon_{b,light})$) flavour initiated jets. Pearson's correlation coefficient ρ [204] acquired for each analysis is given respectively.

Figure 8.10 shows event yields for the $Z^0 + N_{IP3D+SV1}$ jets and $Z^0 + N_{SV0}$ jets selection in SHERPA MC events for different coherent variations of $p_{t,jet}, \epsilon_{b,light}, \epsilon_{b,heavy}$. Pearson's correlation coefficients [204] deduced from these indicate no correlation between these variables. If any, they are statistically small compared to the bulk of the ensemble and are caused by the momentum distributions of reconstructed jet objects in this sample. Thus, correlations at the permille level are observed that affect the treatment of the systematic uncertainties to second or third order studied so far.

An impact of correlations between muon objects and (b-tagged) jets on the event yield are not expected since the fiducial veto of jets within $\min(\Delta R(jet, \mu)) < 0.5$ makes any interaction very unlikely if not impossible.

8.5 Luminosity Uncertainties

The total integrated luminosity used for this study is $\mathcal{L}_{eff} = 36.13 \pm 1.23 \text{ pb}^{-1}$ as documented in section 5.2.4. The uncertainty quoted of $\pm 3.4\%$ was evaluated [118] and is taken from there. For this being a coherent source of uncertainty, it is added to the total systematic uncertainty in quadrature.

8.6 Theoretical Uncertainties

Complementing section 3.3, the following section summarises the quality and quantity of uncertainties that are caused by theoretical assumptions entering the evaluation of equations 7.14 and 7.15 on hadron level.

8.6.1 Background Normalisation Uncertainties

For performing the LLH fit on data, the template from background final states such as $WW/ZZ/WZ$, $t\bar{t}$ and QCD multi-jet is kept as a fixed offset (see sections 7.1 and 7.1.1). Therefore, the normalisation of these final states to (N)NLO enters directly in the calculation of $\mathcal{R}$ and $\sigma_{incl}(Z^0 + b)$. Table 5.2 shows that the theoretical uncertainties on the aforementioned final states are still smaller than experimental uncertainties of respective measurements. Thus, the theoretical errors of the $WW/ZZ/WZ$, $t\bar{t}$ and QCD multi-jet cross sections are added in quadrature neglecting correlations and are used as coherent source of systematic uncertainty on $\mathcal{R}$ and $\sigma_{incl}(Z^0 + b)$.

variation	$Z^0 + N_{SV0}$ jets		$Z^0 + N_{IP3D+SV1}$ jets	
	SHERPA	ALPGEN	SHERPA	ALPGEN
$\Delta\sigma_{Z^0+b+X}(\sigma_{background}^-)$	+1.6 %	+2.7 %	+2.0 %	+3.5 %
$\Delta\sigma_{Z^0+b+X}(\sigma_{background}^+)$	-1.6 %	-2.6 %	-2.0 %	-3.4 %
$\Delta\mathcal{R}(\sigma_{background}^-)$	+0.3 %	+1.4 %	+0.7 %	+2.3 %
$\Delta\mathcal{R}(\sigma_{background}^+)$	-0.5 %	-1.6 %	-0.9 %	-2.4 %

Table 8.8: Relative deviations due to coherent variation of the total expected background contributions ($\sigma_{background}^\pm$) from $WW/ZZ/WZ$, $t\bar{t}$ and QCD multi-jet cross section uncertainties.

Table 8.7 lists the impact on $\sigma_{incl}(Z^0 + b)$ and $\mathcal{R}$ of varying the total background normalisation estimated by $\pm 11\%$ according to the theoretical uncertainties listed in table 5.2. This affects the result of $\sigma_{incl}(Z^0 + b)$ more than $\mathcal{R}$ due to the background uncertainty entering only in $N_{b,fitted}$ of $\sigma_{incl}(Z^0 + b)$, equation 8.1. This linear proportionality is compensated for $\mathcal{R}$ since $\sigma_{background}$ enters in the denominator as well, equation 8.2. Also, if the background contribution is varied up, $\sigma_{incl}(Z^0 + b)$ and $\mathcal{R}$ are varied down and vice versa. This behavior is driven by the LLH fit, where a contribution of more non-bottom like events implies fewer bottom like events to be minimised from the input distribution.

8.6.2 Monte Carlo Uncertainties

To correct the observation from detector to hadron level, the acceptance correction of $\sigma_{incl}(Z^0 + b)$ and $\mathcal{R}$ are deduced from signal MC events. Both acceptances of equation 7.17 and 7.18 describe the portion of events which yield $Z^0 + b + \text{jets}$ before any particles enter the full simulation and reconstruction of the ATLAS detector compared to the number of $Z^0 + b + \text{jets}$ events that are positively reconstructed and selected as such. The latter process can be described by mapping an ensemble of hadron to detector level events. It involves influences from the theoretical model applied concerning matrix element evaluation and parton shower approach, as both affect transverse momentum and rapidity distributions of jets in the predicted final state. Further, detector simulation (material budget, sub-detector alignment and energy loss), reconstruction effects (intercalibration of jets, misreconstruction of tracks), energy mis-calibrations, geometric effects and the selection efficiency enter the evaluation of the acceptance.

The simulated signal MC samples used here were subject to an identical setup of detector simulation, digitisation and object reconstruction algorithms. Thus, any deviation of acceptance corrections observed must be attributed to the two different theoretical frameworks in which the prediction of $Z^0 + b + X$ final states was carried out. In the literature, the treatment of this effect received no [97] or fair attention [98, 169]. The latter publications used a custom model of generated jet momenta in $Z^0 + b$ events to reweight simulated pseudo-data until a given MC event sample agreed with the data. The difference between reweighted simulation and original simulation was considered as the model dependent systematic uncertainty that is discussed in this section.

This approach is expected to overestimate the theoretical uncertainty that arises from correcting the data to hadron level for many reasons. Most importantly, this approach misses any scientific motivation on why the nominal theoretical model (SHERPA or ALPGEN) should have been used as reference for reweighting in the first place. A more pragmatic approach would be to acknowledge the fact that the uncertainty of hadron level correction is primarily caused by the finite size of signal MC samples used. For the study at hand, the calculated acceptance corrections are therefore varied up or down following the statistical uncertainty of $\mathcal{A}$ obtained from simulation. Besides, any difference between acceptance corrections obtained from SHERPA and ALPGEN must occur, for the simulated Z^0 boson kinematics show significant differences, see figure 6.13.

The effect just mentioned concerning the finite size of the used MC event samples is quantified by toy MC methods. For each toy experiment, all MC template distributions are generated by a Poisson draw for each bin independently with the generated mean given by the expected bin content from the nominal MC sample. Since the template distributions were generated containing 10 – 30 filled bins, the assumption of all bins being independent is valid. Quantities (acceptance corrections) that enter the calculation of $\sigma_{incl}(Z^0 + b)$ and $\mathcal{R}$ are also drawn from a Poisson *PDF* with the mean value λ set to the value exposed by the un-altered MC sample. Thus, all input distributions (i.e. template distributions) are generated by a Poisson *PDF*. For obtaining the fitted number of toy experiments, the un-altered pseudo-data (including signal and background samples) is used as input to the template fit of chapter 7 using the the Poisson smeared template distributions. The calculated $\sigma_{incl}(Z^0 + b)$ and $\mathcal{R}$ of 1000 toy experiments are filled into a histogram and the variance of which gives the systematic uncertainty.

This procedure can be considered pragmatic. By individually drawing a Poisson *PDF* for each quantity entering equations 8.1 and 8.2 any correlation inbetween is neglected. Hence, this procedure needs not give the expected cross section and ratios noted in tables 7.10 and 7.11 because the acceptance correction and fit templates are smeared independent of each other but the pseudo data

remains the same. However, this approach comprises shape uncertainties affiliated to the template distributions in an model independent way for the individual bin contents are drawn from a Poisson *PDF*.

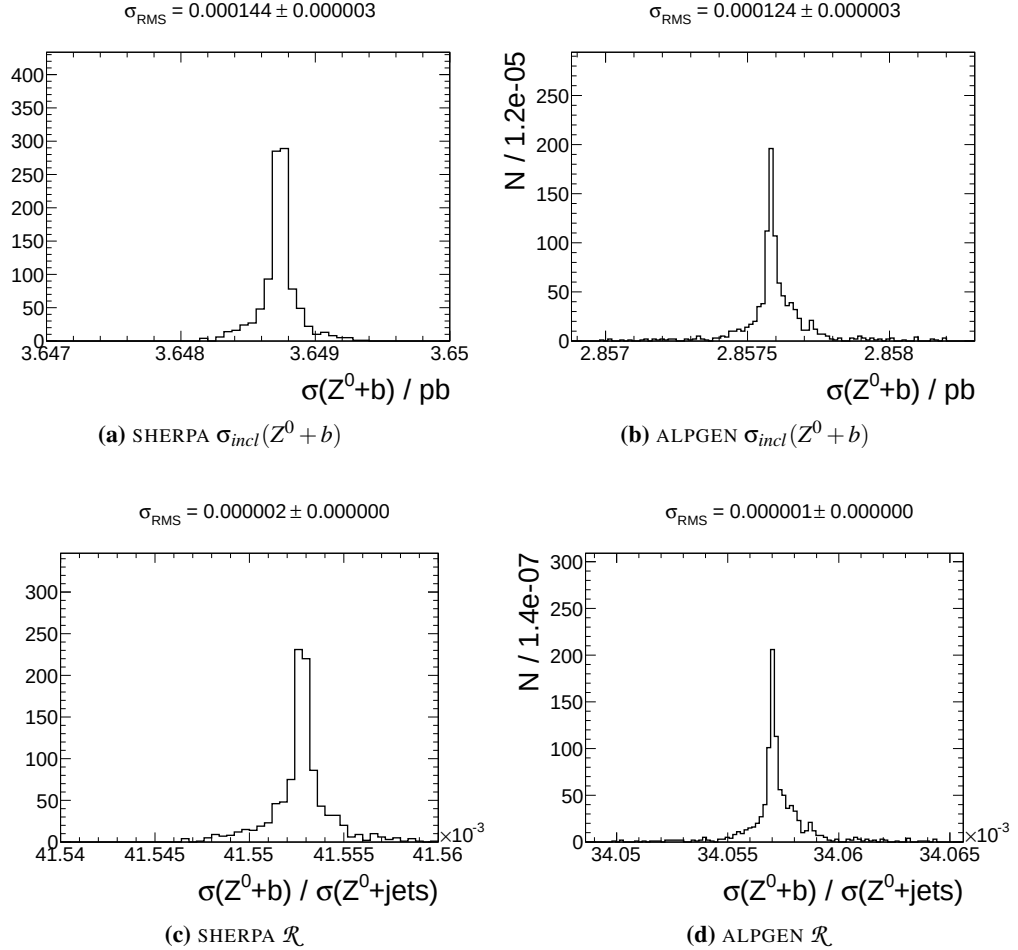


Figure 8.12: $\sigma_{incl}(Z^0 + b)$ (top) and $\mathcal{R}$ (bottom) yields after $Z^0 + N_{SV0}$ jets analysis from SHERPA (left) and ALPGEN (right) signal MC. For each, input quantities to equations 8.1 and 8.2 were drawn from a Poisson *PDF* to study shape dependencies in 1000 toy experiments. The reported variance σ was calculated as the root-mean-square of the displayed distributions.

Figure 8.11 displays the obtained distributions of $\sigma_{incl}(Z^0 + b)$ and $\mathcal{R}$. The distributions themselves contain a dominant peak at the expected values of $\sigma_{incl}(Z^0 + b)$ and $\mathcal{R}$ with a broader distribution underneath. The shape uncertainties that can be estimated from this by the root-mean-square of the shown distributions are at the sub-per-mill level ($\pm 0.01\%$) with respect to their mean. This underlines the stability of the fit procedure applied. Equivalent results for the $Z^0 + N_{IP3D+SV1}$ jets final state are collected in appendix section F.3. Due to the small size of these uncertainties, they are discarded from further consideration.

Finally, the acceptance corrections entering equations 8.1 and 8.2 yield statistical uncertainties that are caused by the finite sample of MC events being available. These uncertainties are not taken into account by the calculation of $\sigma_{incl}(Z^0 + b)$ and $\mathcal{R}$ presented in chapter 7. They are considered as coherent systematic uncertainties and can be adopted from section 7.5 through error

propagation.

variation	$Z^0 + N_{SV0}$ jets		$Z^0 + N_{IP3D+SV1}$ jets	
	SHERPA	ALPGEN	SHERPA	ALPGEN
$\Delta\sigma_{Z^0+b+X}(\text{MC Statistics})$	5.8 %	0.9 %	6.6 %	0.8 %
$\Delta\sigma_{Z^0+b+X}(\text{MC Statistics})$	6.8 %	0.7 %	6.4 %	0.7 %

Table 8.9: Relative deviations due to available MC statistics as reported in tables 7.10 and 7.11.

Table 8.8 lists the statistical uncertainties of the acceptance corrections presented in section 7.5. The larger statistics contained in the ALPGEN MC samples by a factor of 13 comes to play here again. The uncertainties of SHERPA are larger than for ALPGEN. Also, the uncertainties on $\mathcal{A}$ for $\sigma_{incl}(Z^0 + b)$ and $\mathcal{R}$ differ. This is related to the definition of the acceptance correction in equations 7.17 and 7.18 that are taken into account respectively having different event samples as input.

8.7 Summary

In the following, the discussed uncertainties of this chapter are collected and combined appropriately. Since no correlations between them are known, all uncertainties are treated independent of each other. In order to choose one MC event sample over the other for quoting the final result of this analysis, the total uncertainties of each are used.

$\sigma_{incl}(Z^0 + b)$ (SV0)				
	SHERPA		ALPGEN	
	statistical unc. / pb (up,down)	systematic unc. / pb (up,down)	statistical unc. / pb (up,down)	systematic unc. / pb (up,down)
Fit to 2010 data	0.93(28.1%), 0.83(24.9%)	0.	0.96(29.2%), 0.85(25.7%)	0.
$\epsilon'_{\mu,rec}$	0.02(0.5%)	—	0.01(0.2%)	—
$\epsilon'_{\mu,trigger}$	0.02(0.5%)	—	0.01(0.2%)	—
$\epsilon_{\mu,iso}$	—	0.06(1.8%)	—	0.06(1.8%)
$p_{t,\mu}^{MS+}$	—	0.(0.%), 0.0522(1.6%)	—	0.(0.%), 0.0230(0.7%)
$p_{t,\mu}^{MS-}$	—	0.(0.%), 0.0632(1.9%)	—	0.(0.%), 0.0296(0.9%)
$p_{t,\mu}^{ID-}$	—	0.(0.%), 0.0565(1.7%)	—	0.(0.%), 0.0197(0.6%)
$p_{t,\mu}^{ID+}$	—	0.(0.%), 0.0609(1.8%)	—	0.(0.%), 0.0263(0.8%)
$p_{t,jet}^+$	—	0.(0.%), 0.2095(6.3%)	—	0.(0.%), 0.0790(2.4%)
$p_{t,jet}^-$	—	0.1097(3.3%), 0.(0.%)	—	0.0527(1.6%), 0.(0.%)
$p_{t,jet}$	0.02(0.6%)	—	0.01(0.2%)	—
$\epsilon_{b,heavy}^+$	—	0.(0.%), 0.3592(10.8%)	—	0.(0.%), 0.3225(9.8%)
$\epsilon_{b,heavy}^-$	—	0.2976(8.9%), 0.(0.%)	—	0.3423(10.4%), 0.(0.%)
$\epsilon_{b,tight}^+$	—	0.(0.%), 0.0612(1.8%)	—	0.(0.%), 0.0066(0.2%)
$\epsilon_{b,tight}^-$	—	0.(0.%), 0.0655(2.0%)	—	0.(0.%), 0.0461(1.4%)
ϵ_b'	0.02(0.5%)	—	0.01(0.2%)	—
$\sigma_{background}^+$	—	0.(0.%), 0.0532(1.6%)	—	0.(0.%), 0.0856(2.6%)
$\sigma_{background}^-$	—	0.0532(1.6%), 0.(0.%)	—	0.0889(2.7%), 0.(0.%)
MC Statistics	—	0.1929(5.8%)	—	0.0296(0.9%)
Luminosity	0.	0.12(3.4%)	0.	0.12(3.4%)
Quadratic Sum	0.94(28.1%), 0.83(24.9%)	0.3963(11.9%), 0.5010(15.1%)	0.96(29.2%), 0.85(25.7%)	0.38(11.6%), 0.37(11.3%)
Total Uncertainty	1.02(30.5%), 0.97(29.1%)		1.03(31.4%), 0.93(28.1%)	

Table 8.10: Collection of statistical and systematic uncertainty of $\sigma_{incl}(Z^0 + b)$ from the $Z^0 + N_{SV0}$ jets selection with input from SHERPA and ALPGEN MC event samples.

$\mathcal{R} = \frac{\sigma_{incl}(Z^0+b)}{\sigma_{incl}(Z^0+jets)} \text{ (SV0)}$			
	SHERPA	ALPGEN	
	statistical unc. / 10^{-2} (up,down)	systematic unc. / 10^{-2} (up,down)	statistical unc. / 10^{-2} (up,down) systematic unc. / 10^{-2} (up,down)
Fit to 2010 data	1.21(28.2%), 1.08(25.0%)	0.	1.35(29.3%), 1.19(25.9%) 0.
$\epsilon'_{\mu,rec}$	0.02(0.5%)	—	0.01(0.2%) —
$\epsilon'_{\mu,trigger}$	0.02(0.5%)	—	0.01(0.2%) —
$\epsilon_{\mu,iso}$	—	0.11(2.5%)	— 0.11(2.5%)
$p_{t,\mu}^{D+}$	—	0.(0.%), 0.10(2.3%)	— 0.(0.%), 0.04(0.9%)
$p_{t,\mu}^{D-}$	—	0.(0.%), 0.08(1.9%)	— 0.(0.%), 0.06(1.2%)
$p_{t,\mu}^{MS+}$	—	0.(0.%), 0.09(2.1%)	— 0.(0.%), 0.05(1.0%)
$p_{t,\mu}^{MS-}$	—	0.(0.%), 0.09(2.1%)	— 0.(0.%), 0.05(1.0%)
$p_{t,jet}^+$	—	0.(0.%), 0.11(2.5%)	— 0.05(1.1%), 0.(0.%)
$p_{t,jet}^-$	—	0.(0.%), 0.28(6.4%)	— 0.(0.%), 0.08(1.7%)
$p_{t,jet}'$	0.03(0.7%)	—	0.01(0.2%) —
$\epsilon_{b,heavy}^+$	—	0.(0.%), 0.46(10.8%)	— 0.(0.%), 0.45(9.8%)
$\epsilon_{b,heavy}^-$	—	0.38(8.9%), 0.(0.%)	— 0.48(10.4%), 0.(0.%)
$\epsilon_{b,light}^+$	—	0.(0.%), 0.08(1.8%)	— 0.(0.%), 0.01(0.2%)
$\epsilon_{b,light}^-$	—	0.(0.%), 0.08(1.9%)	— 0.(0.%), 0.06(1.4%)
ϵ_b'	0.02(0.5%)	—	0.01(0.2%) —
$\sigma_{background}^+$	—	0.(0.%), 0.02(0.5%)	— 0.(0.%), 0.08(1.6%)
$\sigma_{background}^-$	—	0.01(0.3%), 0.(0.%)	— 0.07(1.4%), 0.(0.%)
MC Statistics	—	0.29(6.8%)	— 0.03(0.7%)
Quadratic Sum	1.05(28.2%), 0.93(25.0%)	0.50(11.5%), 0.67(15.5%)	1.35(29.3%), 1.19(25.9%) 0.50(10.9%), 0.49(10.7%)
Total Uncertainty	1.31(30.5%), 1.27(29.5%)	—	1.44(31.2%), 1.29(28.0%)

Table 8.11: Collection of statistical and systematic uncertainty of $\mathcal{R} = \frac{\sigma_{incl}(Z^0+b)}{\sigma_{incl}(Z^0+jets)}$ from the $Z^0 + N_{SV0}$ jets selection with input from SHERPA and ALPGEN MC events.

$\sigma_{incl}(Z^0 + b)$ (IP3D+SV1)					
	SHERPA		ALPGEN		
	statistical unc. / pb (up,down)	systematic unc. / pb (up,down)	statistical unc. / pb (up,down)	systematic unc. / pb (up,down)	
Fit to 2010 data	0.96(27.0%), 0.88(24.8%)	0.	0.79(28.0%), 0.72(25.4%)	0.	
$\epsilon'_{\mu rec}$	0.02(0.6%)	—	0.01(0.2%)	—	
$\epsilon'_{\mu trigger}$	0.02(0.6%)	—	0.01(0.2%)	—	
$\epsilon_{\mu iso}$	—	0.06(1.8%)	—	0.05(1.8%)	
$p_{t,\mu}^{ID+}$	—	0.(0.%), 0.07(2.0%)	—	0.(0.%), 0.07(2.4%)	
$p_{t,\mu}^{ID-}$	—	0.(0.%), 0.07(2.0%)	—	0.(0.%), 0.07(2.5%)	
$p_{t,\mu}^{MS+}$	—	0.(0.%), 0.07(2.0%)	—	0.(0.%), 0.07(2.4%)	
$p_{t,\mu}^{MS-}$	—	0.(0.%), 0.05(1.4%)	—	0.(0.%), 0.07(2.4%)	
$p_{t,jet}^+$	—	0.(0.%), 0.04(1.0%)	—	0.02(0.6%), 0.(0.%)	
$p_{t,jet}^-$	—	0.08(2.2%), 0.(0.%)	—	0.(0.%), 0.09(3.1%)	
$p_{t,jet}$	0.02(0.6%)	—	0.01(0.2%)	—	
$\epsilon_{b,heavy}^+$	—	0.(0.%), 0.42(11.9%)	—	0.(0.%), 0.38(13.3%)	
$\epsilon_{b,heavy}^-$	—	0.34(9.6%), 0.(0.%)	—	0.27(9.7%), 0.(0.%)	
$\epsilon_{b,tight}^+$	—	0.(0.%), 0.07(2.1%)	—	0.(0.%), 0.11(4.0%)	
$\epsilon_{b,tight}^-$	—	0.(0.%), 0.06(1.8%)	—	0.(0.%), 0.03(1.2%)	
ϵ_b	0.03(0.7%)	—	0.01(0.2%)	—	
$\sigma_{background}^+$	—	0.(0.%), 0.07(2.0%)	—	0.(0.%), 0.10(3.4%)	
$\sigma_{background}^-$	—	0.07(2.0%), 0.(0.%)	—	0.10(3.5%), 0.(0.%)	
MC Statistics	—	0.23(6.6%)	—	0.02(0.7%)	
Luminosity	0.	0.12(3.4%)	0.	0.10(3.4%)	
Quadratic Sum	0.96(27.1%), 0.88(24.8%)	0.45(12.6%), 0.53(15.1%)	0.79(28.0%), 0.72(25.4%)	0.31(11.1%), 0.45(15.9%)	
Total Uncertainty	1.06(29.9%), 1.03(29.0%)		$\pm 0.85(30\%)$		

Table 8.12: Collection of statistical and systematic uncertainty of $\sigma_{incl}(Z^0 + b)$ from the $Z^0 + N_{IP3D \pm SV1}$ jets selection with input from SHERPA and ALPGEN MC events.

$\mathcal{R} = \frac{\sigma_{incl}(Z^0+b)}{\sigma_{incl}(Z^0+\text{jets})} \text{ (IP3D+SV1)}$			
	SHERPA	ALPGEN	
	statistical unc. / 10^{-2} (up,down)	systematic unc. / 10^{-2} (up,down)	statistical unc. / 10^{-2} (up,down) systematic unc. / 10^{-2} (up,down)
Fit to 2010 data	1.24(27.2%), 1.14(24.9%)	—	1.11(28.1%), 1.01(25.5%) —
$\epsilon'_{\mu,rec}$	0.02(0.6%)	—	0.01(0.2%) —
$\epsilon'_{\mu,trigger}$	0.02(0.6%)	—	0.01(0.2%) —
$\epsilon_{\mu,iso}$	—	0.11(2.5%)	— 0.10(2.5%)
$p_{t,\mu}^{ID+}$	—	0.(0.%), 0.11(2.3%)	— 0.(0.%), 0.01(0.3%)
$p_{t,\mu}^{ID-}$	—	0.(0.%), 0.11(2.4%)	— 0.(0.%), 0.11(2.8%)
$p_{t,\mu}^{MS+}$	—	0.(0.%), 0.11(2.3%)	— 0.(0.%), 0.11(2.8%)
$p_{t,\mu}^{MS-}$	—	0.(0.%), 0.08(1.7%)	— 0.(0.%), 0.10(2.6%)
$p_{t,jet}^+$	—	0.14(3.0%), 0.(0.%)	— 0.16(4.2%), 0.(0.%)
$p_{t,jet}^-$	—	0.(0.%), 0.27(6.0%)	— 0.(0.%), 0.25(6.3%)
$p_{t,jet}'$	0.02(0.6%)	—	0.01(0.3%) —
$\epsilon_{b,heavy}^+$	—	0.(0.%), 0.54(11.9%)	— 0.(0.%), 0.52(13.3%)
$\epsilon_{b,heavy}^-$	—	0.44(9.6%), 0.(0.%)	— 0.38(9.7%), 0.(0.%)
$\epsilon_{b,light}^+$	—	0.(0.%), 0.10(2.1%)	— 0.(0.%), 0.16(3.9%)
$\epsilon_{b,light}^-$	—	0.(0.%), 0.08(1.8%)	— 0.(0.%), 0.05(1.2%)
ϵ_b'	0.03(0.7%)	—	0.02(0.6%) —
$\sigma_{background}^+$	—	0.(0.%), 0.04(0.9%)	— 0.(0.%), 0.09(2.4%)
$\sigma_{background}^-$	—	0.03(0.7%), 0.(0.%)	— 0.09(2.3%), 0.(0.%)
MC Statistics	—	0.29(6.4%)	— 0.03(0.8%)
Quadratic Sum	1.24(27.2%), 1.14(25.0%)	0.56(12.2%), 0.73(15.9%)	1.11(28.1%), 1.01(25.5%) 0.44(11.2%), 0.65(16.4%)
Total Uncertainty	1.36(29.8%), 1.35(29.6%)	—	1.19(30.3%), 1.20(30.4%)

Table 8.13: Collection of statistical and systematic uncertainty of $\mathcal{R} = \frac{\sigma_{incl}(Z^0+b)}{\sigma_{incl}(Z^0+\text{jets})}$ from the $Z^0 + N_{IP3D+SV1}$ jets selection with input from SHERPA and ALPGEN MC events.

In general, the total uncertainties assigned to the measurement of $\sigma_{incl}(Z^0 + b)$ or $\mathcal{R}$ are dominated by the statistical uncertainties provided by the fit procedure. The expectation that systematic uncertainties of the measurement of $\mathcal{R}$ are smaller than for $\sigma_{incl}(Z^0 + b)$ was not met due to various reasons outlined in this chapter. The b-tagging efficiency corrections and jet energy scale uncertainties can be identified as largest sources of systematic uncertainty contributing the most. For SHERPA MC samples, the third largest contributions is the finite size of the event sample. For ALPGEN MC, this is not the case. Systematic uncertainties related to muon reconstruction do not play an important role for this measurement.

Future analyses of equivalent final states with more data should thus focus predominantly on reducing uncertainties related to b-tagging and jet energy calibration. An improved understanding of the muon reconstruction performance can reduce overall systematic uncertainties in addition, but will not result in a large increase of precision.

For the $Z^0 + N_{SV0}$ jets ensemble (tables 8.10 and 8.11), results obtained with ALPGEN or SHERPA MC events resulted in comparable total uncertainties of $\sigma_{incl}(Z^0 + b)$. For $\mathcal{R}$, the uncertainties with ALPGEN MC are smaller than those deduced with SHERPA. Comparing results from the $Z^0 + N_{IP3D+SV1}$ jets set of events (tables 8.12 and 8.13) shows that uncertainties obtained using SHERPA MC events predict $\sigma_{incl}(Z^0 + b)$ and $\mathcal{R}$ with smaller uncertainties than with .

Combining the measurements of $\sigma_{incl}(Z^0 + b)$ and $\mathcal{R}$ provided by the $Z^0 + N_{SV0}$ jets and $Z^0 + N_{IP3D+SV1}$ jets event samples requires a thorough study of all involved correlations. Since the total uncertainties are very large, this is not conducted here. Instead, the measurements with smallest uncertainties is chosen as the baseline result for this analysis. For $\sigma_{incl}(Z^0 + b)$, the results using SHERPA MC and the $Z^0 + N_{IP3D+SV1}$ jets selection is used. The measurement of $\mathcal{R}$ will be given by that obtained with ALPGEN $Z^0 + N_{SV0}$ jets MC events.

Chapter 9

Results

This chapter will conclude the presented analysis of $pp \rightarrow Z^0 + b$ final states and report the final results obtained. Following this, a comparison with theoretical predictions at LO and NLO will be noted. The hereby initiated discussion will be concluded by a summary and an outlook.

9.1 Comparison with Theoretical Predictions

To compare the NLO calculations presented in chapter 3 with experimental observations at detector level, the acceptance correction to hadron level must be complemented by an equivalent procedure onto parton level. For the analysis at hand, this is comprised by the evaluation of all non-perturbative corrections C_{NPC} with which the NLO cross sections will be multiplied with. In this way, the NLO prediction is transformed to its equivalent on hadron level and can be compared to the measurement.

To obtain C_{NPC} , the SHERPA 1.1.3 generator was used to generate two distinct samples of events: one event sample comprising the full LO ME+PS prediction including underlying event and hadronisation (referred to as *hadron sample*); the other sample used the same setup as the latter but discarded underlying event and hadronisation (referred to as *parton sample*). Both event samples are subject to the Rivet [105] analysis introduced in section 3.3.3 with the only difference, that for the parton level events the identification of *bottom* quark induced jets is based on bottom partons exclusively rather than hadrons.

The non-perturbative correction C_{NPC} is hence given by

$$C_{NPC} = \frac{\sigma_{hadron}}{\sigma_{parton}}. \quad (9.1)$$

Here, σ_{hadron} notes the cross section (or any other observable) obtained from the *hadron sample* while σ_{parton} does so for the *parton sample*. For SHERPA 1.1.3, the non-perturbative correction thus obtained is 0.91 which is in agreement to findings from the ATLAS $Z^0 + b$ analysis [98]. The discussion in the latter reference illustrates the uncertainties related to C_{NPC} . The same line of argument is followed here and an uncertainty of 7% is taken from [98] that will be attributed to the NLO theory prediction. The use of a one dimensional correction factor despite a multi-dimensional unfolding is justified by the goal of this measurement which is to obtain the total the cross section (again a one-dimensional quantity).

For giving the theoretical predictions used for $Z^0 + b$ final states discussed in section 3.4.5 in tables 9.0 and 9.1, SHERPA 1.1.3 calculations at LO with CTEQ6.6 on hadron level are used. For

comparison, the equivalent expectations obtained from MCFM at NLO corrected to hadron level by C_{NPC} using CTEQ6.6 is reported.

9.2 Total Cross Section $\sigma_{incl}(Z^0 + b)$ of $Z^0 + b$ final states

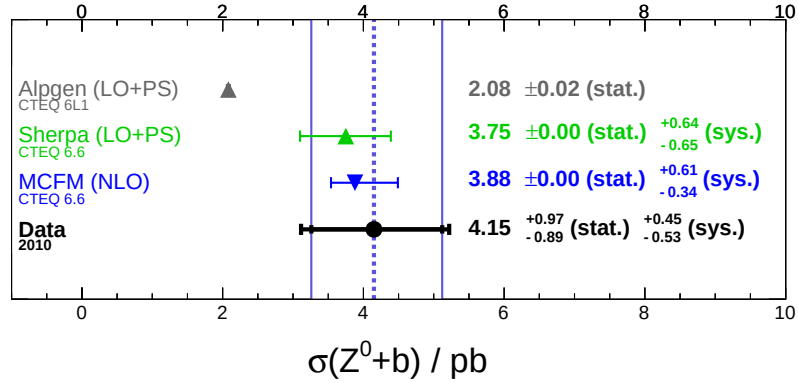


Figure 9.1: Summary of experimental and theoretical hadron level results of $\sigma_{incl}(Z^0 + b)$.

Table 9.0 and figure 9.0 summon the measurement of $\sigma_{incl}(Z^0 + b)$ and theoretical predictions thereof provided by the study at hand. The theoretical uncertainties quoted are of substantial size and almost comparable to those obtained with data. An effort from the theory community is required to prevent it from becoming the dominant uncertainty in an interpretation of future data. LO predictions by SHERPA and NLO results from MCFM are within one standard deviation of the measurement. For both, SHERPA and MCFM, the estimated theoretical uncertainties of section 3.3 are quoted.

The expected $\sigma_{incl}(Z^0 + b)$ from the ALPGEN generator is almost two standard deviations apart from the measurement. Only statistical uncertainties related to the available event sample size are given in table 9.0 and 9.0. This cannot only be attributed to the effect of different PDF sets utilised. As discussed in section 5.1, the above-mentioned SHERPA results were generated with CTEQ6.6 while the fully simulated ALPGEN MC samples used CTEQ6L1. In addition, the expected uncertainties due to the PDF as discussed in section 3.4.1 are too small to account for the observed deviation. It must be concluded that ALPGEN does not describe the data very well in this respect. Studies of $W^\pm + b$ of ATLAS [169] and $Z^0 + b$ at CDF [96] have reported similar deficits of the ALPGEN MC generator package. More data and theoretical studies are required in order to extend the latter observation in favour or against the four flavour FFS versus the five flavour VFS

	$\sigma_{incl}(Z^0 + b) / pb$
This analysis	$4.15^{+0.97}_{-0.89}(stat.)^{+0.45}_{-0.53}(syst.)$
NLO MCFM (corrected to hadron level)	$3.88^{+0.61}_{-0.34}(theo.)$
LO SHERPA	$3.75^{+0.64}_{-0.65}(theo.)$
LO ALPGEN	$2.28 \pm 0.02(stat.)$

Table 9.1: Hadron level measurement from 2010 ATLAS data and predictions of $\sigma_{incl}(Z^0 + b)$ at NLO and LO. The calculations of MCFM and SHERPA are quoted including the theoretical uncertainties estimated in section 3.4.5. The NLO MCFM prediction is corrected to hadron level with non-perturbative correction factors discussed in section 9.1. The statistical uncertainty of the ALPGEN prediction from the finite MC event sample size is given.

calculation schemes.

9.3 Cross Section Ratio $\mathcal{R}$ of $Z^0 + b$ and $Z^0 + \text{jets}$ final states

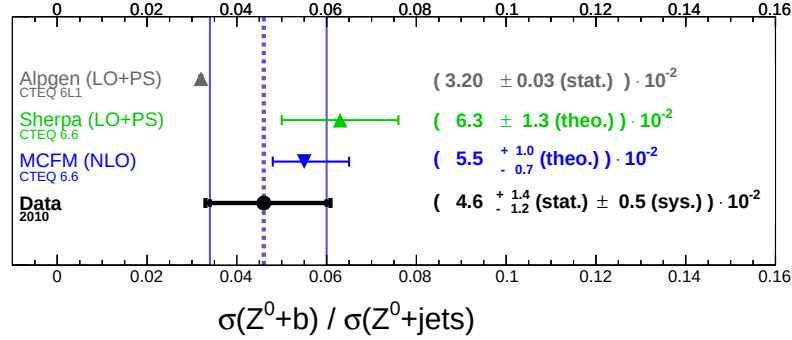


Figure 9.2: Summary of experimental and theoretical hadron level results of $\mathcal{R} = \frac{\sigma_{\text{incl}}(Z^0+b)}{\sigma_{\text{incl}}(Z^0+\text{jets})}$.

The experimental and theoretical results of $\mathcal{R}$ listed in table 9.1 and figure 9.1 give a very mixed picture. While all theoretical predictions are within one standard deviation limits around the measured value, SHERPA and MCFM predictions overestimate the data while ALPGEN calculations underestimate it. The calculations of SHERPA at LO and MCFM at NLO include ME final states with up to three additional jets. For both predictions, the estimated theoretical uncertainties of section 3.3 is given. The simulated ALPGEN event sample provides a prediction for ME final states with up to five jets. Only the statistical uncertainty of the ALPGEN event sample are given.

A straight forward interpretation of this outcome is difficult for it involves the theoretical description of $Z^0 + b$ and $Z^0 + \text{jets}$ final states produced at the LHC. The uncertainties of the ratio measurement provided are driven by the statistical uncertainty from fitting the number of observed $Z^0 + b$ in data. The relative systematic uncertainties are only marginally smaller than those obtained for $\sigma_{\text{incl}}(Z^0 + b)$. As for $\sigma_{\text{incl}}(Z^0 + b)$, the amount of data used by this analysis is insufficient to draw significant conclusions on whether the presented theoretical descriptions of $\mathcal{R}$ at LO or NLO provide results that describe the data.

	$\mathcal{R} = \frac{\sigma_{\text{incl}}(Z^0+b)}{\sigma_{\text{incl}}(Z^0+\text{jets})} / 10^{-2}$
This analysis	$4.6^{+1.4}_{-1.2}(\text{stat.}) \pm 0.5(\text{syst.})$
NLO MCFM (corrected to hadron level)	$5.52^{+1.00}_{-0.65}(\text{theo.})$
LO SHERPA	$6.31^{+1.25}_{-1.31}(\text{theo.})$
LO ALPGEN	$3.24 \pm 0.03(\text{stat.})$

Table 9.2: Hadron level measurement from 2010 ATLAS data and predictions of $\mathcal{R}$ at NLO and LO. The calculations of MCFM and SHERPA are quoted including the theoretical uncertainties estimated in section 3.4.5. The NLO MCFM prediction is corrected to hadron level with non-perturbative correction factors discussed in section 9.1. The statistical uncertainty of the ALPGEN prediction from the finite MC event sample size is given.

Chapter 10

Summary and Outlook

The description of $pp \rightarrow Z^0 + b$ interactions at high centre-of-mass energies provided by the LHC requires sophisticated pQCD computations especially if bottom flavour final state partons are assumed massive. At the time of writing, two competing calculation schemes motivate an account for the kinematics and cross section of $Z^0 + b$ final state events. Either all initial state bottom partons are generated from gluon splittings $g \rightarrow b\bar{b}$ within the fixed-flavour number (FFS) scheme or any initial state bottom flavour is assumed to be found inside the proton as by the variable-flavour number scheme (VFS). With this, both schemes represent opposite attitudes towards the question if bottom partons reside inside the proton, i.e. if a partial description of the proton by a bPDF is a valid approach. Theoretical uncertainties estimated on LO and NLO calculations of $Z^0 + b$ final states still suffer from large uncertainties and thus a measurement can aid substantially to resolve the just mentioned theoretical inconsistencies. These uncertainties are on the other hand of essential importance for experimental searches for the Higgs boson as described with or beyond the SM. This analysis aims at measuring of the absolute cross section of $Z^0 + b$ final states $\sigma_{incl}(Z^0 + b)$ and the cross section ration $\mathcal{R} = \frac{\sigma_{incl}(Z^0 + b)}{\sigma_{incl}(Z^0 + \text{jets})}$ of $Z^0 + b$ versus $Z^0 + \text{jets}$ in 2010 LHC proton-proton collisions at $\sqrt{s} = 7 \text{ TeV}$ recorded by the ATLAS experiment.

The data, corresponding to 36 pb, was analysed and subject to two dedicated selections. Common to both is the selection of Z^0 boson candidates constructed from two observed muon candidates in data within an invariant muon-muon mass window of $\Delta m_{\mu^+\mu^-} = 20 \text{ GeV}$ around the Z^0 boson mass. Events that contain a Z^0 boson candidates are required to expose at least one high momentum jet to give a $Z^0 + N_{jets}$ jets event sample. The results of two bottom flavour tagging algorithms are subsequently analysed. The first, SV0, of which yields a high purity sample of bottom flavour initiated jets but with a low efficiency. The second, IP3D+SV1, constructed from a combined likelihood of two sub-algorithms, IP3D and SV1, selects an ensemble of b-tagged jets with lower purity but higher efficiency than SV0. With this, two event ensembles were constructed from $Z^0 + N_{SV0}$ jets and $Z^0 + N_{IP3D+SV1}$ jets events. All event ensembles thus obtained were henceforth corrected for known deficiencies of data and MC simulation. No significant deviation between MC and data was found that was not accounted for.

Since b-tagging algorithms are designed to discriminate heavy flavour from light flavour jets but fail to separate bottom induced from charm induced jets, the number of observed bottom quark initiated jets in Z^0 events was obtained from a binned maximum log-likelihood fit to the distribution of the sum of all observed secondary vertex masses per event: $\sum_{jets} m_{SV,SV0}$ (in $Z^0 + N_{SV0}$ jets events) and $\sum_{jets} m_{SV,SV1}$ (in $Z^0 + N_{IP3D+SV1}$ jets events). The template distributions were obtained from SHERPA and ALPGEN simulated events. A thorough study of the stability and unbiasedness of the fit procedure chosen revealed no features of the fit results that compromise their reliability.

Further, a study of systematic uncertainties was performed to obtain a thorough understanding of the effect calibrations and assumptions made during the selection discussed above imply on the obtained results. The b-tagging efficiency corrections and jet calibration uncertainties were found to be the dominant sources of systematic uncertainties. The total uncertainty of the presented measurement was found to be limited by statistics of the available data. This motivates a most precise result of $Z^0 + b$ analysis with coming ATLAS data.

The measured value of $\sigma_{incl}(Z^0 + b)$ was evaluated to $(4.15^{+0.97}_{-0.89}(stat.)^{+0.45}_{-0.53}(syst.))$ pb. The predicted cross sections by MCFM at NLO and by SHERPA at LO fall within one standard deviation of the total uncertainty of the measurement. The LO prediction by the ALPGEN MC was found to be more than two standard deviations apart from the measurement. This observation provides decisive hints to the tension of FFS versus VFS calculation schemes for describing $Z^0 + b$ final states at the LHC.

Finally, the cross section ratio $\mathcal{R}$ was obtained to take advantage of reduced uncertainties that cancel in the ratio of $\sigma_{incl}(Z^0 + b)$ and $\sigma_{incl}(Z^0 + \text{jets})$. It was observed in data as $(4.6^{+1.4}_{-1.2}(stat.) \pm 0.5(syst.))\%$. All presented LO predictions (by SHERPA and ALPGEN MC generators) as well as NLO calculations reproduce this measurement with one standard deviation of its uncertainty. However, the spread of theoretical predictions at LO is wide which again supports the notion that predictions from the two implementing competing calculation schemes (FFS and VFS) provide an inconsistent description. The amount of data analysed in this study is however insufficient to resolve it.

Due to the relevance of the bPDF for predictions of Higgs boson production at the LHC, the presented measurement must be conducted on more LHC data. At the time of writing, 150 times more integrated luminosity equivalent was recorded by the ATLAS experiment in 2011 and 305 times more are expected for 2012. This may potentially reduce the statistical uncertainty of the absolute cross section to below 5% of what this measurement obtained. In addition, more data may provide means to estimate differential cross sections, e.g. in Z^0 transverse momentum p_{t,Z^0} , Z^0 rapidity or angular correlations of the Z^0 and the leading heavy flavour jet, which gives a direct handle to the theoretical calculation as well as a probe to the initial state PDF (e.g. the bPDF). This paves the way to discriminate the FFS and VFS calculation schemes and provide an opportunity that experiment improves our knowledge of the nature of the proton by constraining the bPDF. In order to achieve this, a robust and well understood fit procedure is an essential necessity as this analysis showed. Further, a precise knowledge of b-tagging algorithms, their performance and jet calibration will reduce related systematic uncertainties.

Appendix A

Theory of the SM and QCD

A.1 The Standard Model of High-Energy Physics

In the beginning of this analysis, the Standard Model of High-Energy Physics was introduced and the symmetries found therein (section 2.1).

	particles			Q/e	I_3	$SU(3)_C$	$SU(2)_L$	$U(1)_Y$
Quarks	$\begin{pmatrix} u \\ d' \end{pmatrix}_L$	$\begin{pmatrix} c \\ s' \end{pmatrix}_L$	$\begin{pmatrix} t \\ b' \end{pmatrix}_L$	$\frac{2}{3}$	$\frac{1}{2}$	3	2	$\frac{1}{3}$
	u_R	c_R	t_R	$-\frac{1}{3}$	$-\frac{1}{2}$	3	1	$\frac{4}{3}$
	d_R	s_R	b_R	$\frac{2}{3}$	0	3	1	$\frac{4}{3}$
				$-\frac{1}{3}$	0	3	1	$-\frac{2}{3}$
Leptons	$\begin{pmatrix} \nu_e \\ e \end{pmatrix}_L$	$\begin{pmatrix} \nu_\mu \\ \mu \end{pmatrix}_L$	$\begin{pmatrix} \nu_\tau \\ \tau \end{pmatrix}_L$	0	$\frac{1}{2}$	1	2	-1
	e_R	μ_R	τ_R	-1	$-\frac{1}{2}$	3	1	-2
				-1	0	3	1	-2
				0	0	3	1	-2

Table A.1: SM Fermion quantum numbers from [11]. Left-handed (L) and Right-handed (R) eigenstates are distinguished by their weak interactions. In addition, quark flavour eigenstates, e.g. d', s', b' , are given which have to be related through the Cabibbo-Kobayashi-Maskawa matrix to their mass eigenstates d, s, b . For the experimental proof of neutrino masses is still missing, right-handed neutrinos are not listed.

Table A.0 notes the quantum numbers affiliated to lepton and quarks that are described by the SM.

Appendix B

Experiment

B.1 Object Reconstruction

B-tagging algorithms were introduced in section 4.3.4. The ensemble of tracks that are considered for matching to reconstructed jets and further input to searches for secondary vertices are subject to quality criteria listed in table B.0.

	IP3D	SV0,SV1
transverse momentum /GeV	> 1	0.3
IP_{rz}/mm	< 1	< 25.0
$IP_{xy}/\mu m$	< 1.5	< 5.0
Error on IP_{rz}/mm		< 5.0
Error on $IP_{xy}/\mu m$		< 1.0
Track fit quality χ^2/n_{dof}		< 3
Number of B-layer hits	> 1	> 0
Number of <i>Pixel</i> hits	> 2	> 4
Number of <i>SCT</i> hits	> 0	> 1
Number of <i>SCT+Pixel</i> hits	> 7	> 7

Table B.1: *InnerDetector* selection requirements for tracks used by the IP3D,SV0 and SV1 algorithms.

Appendix C

Dataset

C.1 Pile-Up Reweighting

The description of the simulated pile-up conditions in proton-proton collisions in MC event samples was found to inadequately reproduce the data (section 5.1.3). There, a scheme was outlined how simulated events may be reweighted to present a comparable vertex multiplicity as observed in data.

N_{vertex}	1	2	3	4	5
w_{vertex}	(1.998 ± 0.005)	(1.238 ± 0.003)	(0.850 ± 0.002)	(0.640 ± 0.002)	(0.512 ± 0.002)
N_{vertex}	6	7	8	≥ 9	
w_{vertex}	(0.431 ± 0.004)	(0.368 ± 0.006)	(0.357 ± 0.006)	(0.35 ± 0.02)	

Table C.1: Weighting factors w_{vertex} per multiplicity of reconstructed vertices N_{vertex} as introduced in section 5.2.3.

Table C.0 gives the results that are also shown by figure 5.2.

C.2 Data Quality Flags

The query used for generating the event list containing data that entered this analysis was as follows:

```
find run data10_7TeV.periodAllYear and
partition ATLAS and db DATA and
ptag data10_7TeV and
dq global_status DEFECTS#DetStatus-v21-pro05 g and
dq atlsol DEFECTS#DetStatus-v21-pro05 g and
dq atltor DEFECTS#DetStatus-v21-pro05 g and
dq trig_muon DEFECTS#DetStatus-v21-pro05 g and
dq cp_mu_mmuidcb DEFECTS#DetStatus-v21-pro05 g and
dq cp_mu_mstaco DEFECTS#DetStatus-v21-pro05 g and
dq trig_ele DEFECTS#DetStatus-v21-pro05 g and
dq cp_eg_electron_barrel DEFECTS#DetStatus-v21-pro05 g and
dq cp_eg_electron_endcap DEFECTS#DetStatus-v21-pro05 g and
dq cp_eg_electron_forward DEFECTS#DetStatus-v21-pro05 g and
dq trig_jet DEFECTS#DetStatus-v21-pro05 g and
```

```
dq cp_jet_jetb DEFECTS#DetStatus-v21-pro05 g and
dq cp_jet_jetea DEFECTS#DetStatus-v21-pro05 g and
dq cp_jet_jetec DEFECTS#DetStatus-v21-pro05 g and
dq cp_jet_jetfa DEFECTS#DetStatus-v21-pro05 g and
dq cp_jet_jetfc DEFECTS#DetStatus-v21-pro05 g and
dq trig_met_metcalo DEFECTS#DetStatus-v21-pro05 g and
dq cp_met DEFECTS#DetStatus-v21-pro05 g and
dq cp_btag_life DEFECTS#DetStatus-v21-pro05 g and
dq pix0 DEFECTS#DetStatus-v21-pro05 g and
dq cp_tracking DEFECTS#DetStatus-v21-pro05 g and
dq idvx DEFECTS#DetStatus-v21-pro05 g and
dq idbs DEFECTS#DetStatus-v21-pro05 g and
dq lumi DEFECTS#DetStatus-v21-pro05 g
```

Appendix D

Selection of Reconstructed Objects

Chapter 6 introduced and discussed the selection requirements on reconstructed lepton and jet objects to create a sample of viable $Z^0 + b$ events. For this, the results of from SHERPA and ALPGEN simulation were used, but only ALPGEN results were depicted in the above mentioned chapter. This appendix lists the remaining illustrations obtained with SHERPA MC events.

D.1 Definition of a Figure of Merit for Measurements

Given an ensemble of events that contain both signal and background type events, one may study it using different observables $\vec{x} = x_1, x_2, \dots, x_n$, e.g. $p_{t,\text{leading jet}}, m_{\mu^+\mu^-}$ etc. In order to separate signal from background, a set of critical values $\vec{x}_c$ is chosen such that the amount of signal events is separable from background, e.g. $m_{\ell^+\ell^-} > 60 \text{ GeV}$. Choosing $\vec{x}_c$ under consideration of a figure of merit or estimator is referred to as cut-based selection approach. A critical value x_c is referred to as a *cut*.

The estimator of choice is hereby derived from a likelihood-ratio ansatz, which yields the most powerful test statistic or estimator for a simple hypothesis, see [161, 196]. In this section, optimal values of $\vec{x}_c$ are to be set, which is a simple hypothesis test. Assuming the (pseudo) data at hand consists of events from two Poisson populations, the likelihood that n events are drawn from the hypothetical sample n_{hyp} is given by $L(n, n_{hyp}) = \frac{n_{hyp}^n}{n!} \cdot e^{-n_{hyp}}$. The construction of the two likelihood functions is straight-forward given the perfect knowledge of signal (s) and background (b) yields:

- for an ensemble including signal and background, $n_{hyp} = s + b$,
- for an ensemble including background only, $n_{hyp} = b$.

From this, the observable λ can be constructed through a likelihood ratio by Wilk's theorem [205] as in

$$\begin{aligned}
 \lambda &= -2 \ln \frac{L(n, s+b)}{L(n, b)} \\
 &= -2 \ln \left(\frac{(s+b)^n}{n!} \cdot e^{-(s+b)} \frac{n!}{(b)^n} \cdot e^b \right) \\
 &= -2 \ln \left(\frac{(s+b)^n}{b^n} \cdot e^s \right) \\
 &= -2 \left(n \ln \left(\frac{s+b}{b} \right) - s \right). \tag{D.1}
 \end{aligned}$$

The mean and variance of λ follow from equation D.1.

$$\langle \lambda \rangle = -2 \langle n \rangle \ln \frac{s+b}{b} \tag{D.2a}$$

$$\sigma^2(\lambda) = 4 \cdot \left(\ln \frac{s+b}{b} \right)^2 \cdot \sigma^2(n) \tag{D.2b}$$

Given the definition of λ in equation D.1, an estimator Q (or distance measure) can be constructed that suits the requirement of a measurement (instead of a search), i.e. it yields higher values the more separated the mean of signal and background versus the background mean is compared to the total variance of the signal and background PDF. Q is defined as

$$Q = \frac{\langle \lambda_b \rangle - \langle \lambda_{s+b} \rangle}{\sigma_{s+b}(\lambda)}. \tag{D.3}$$

The expectation value of n is set to b for λ_b and to $s+b$ for λ_{s+b} or $\sigma_{s+b}(\lambda)$ which assumes that n is a Poisson random variable. Using equations D.2a and D.2b, equation D.3 can be written as

$$Q = \frac{s}{\sqrt{s+b}}. \tag{D.4}$$

D.2 Muon Candidate Selection

This section is supplement to section 6.1 and shows distributions obtained from SHERPA MC events.

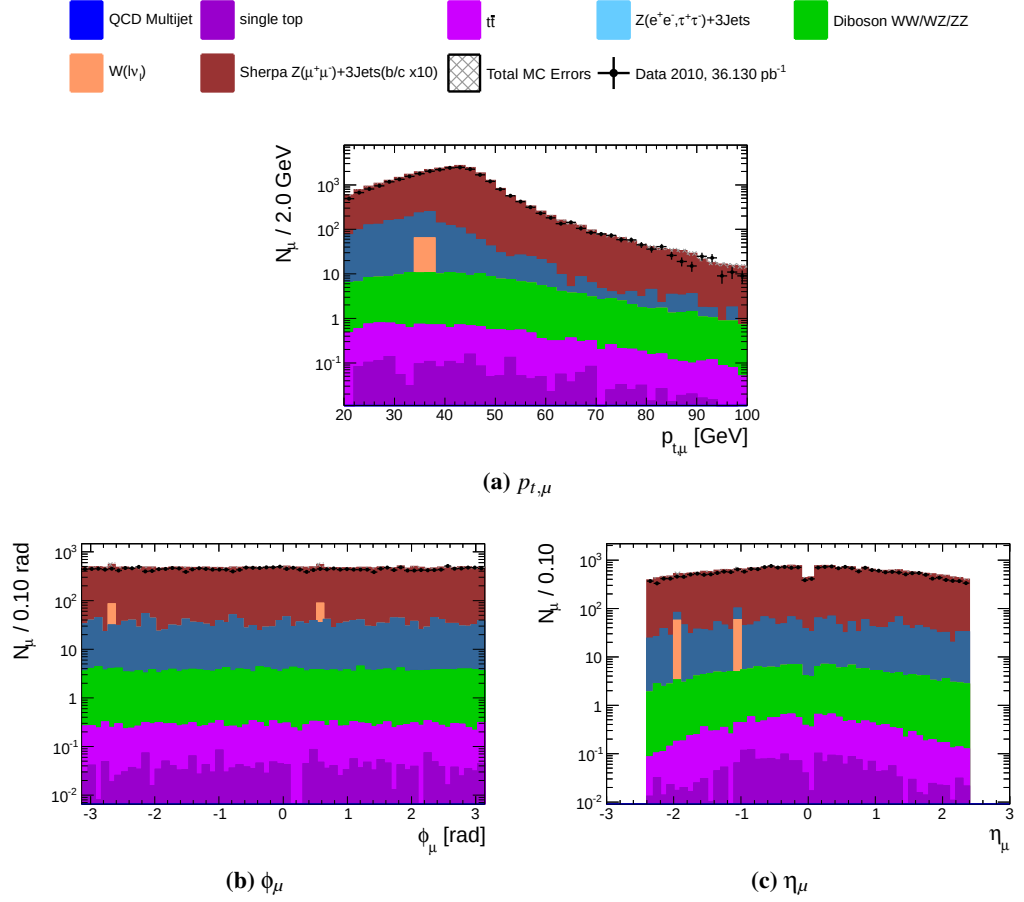


Figure D.1: Distribution of muon kinematics observables $p_{t,\mu}$ (D.0a), ϕ_μ (D.0b) and η_μ (D.0c) for 2010 data and simulation. The plots include all muon object cut as well as the di-muon selection described in section 6.2.

D.3 Jet Candidate Selection

This section is supplement to section 6.3 and shows distributions and numbers obtained from SHERPA MC events.

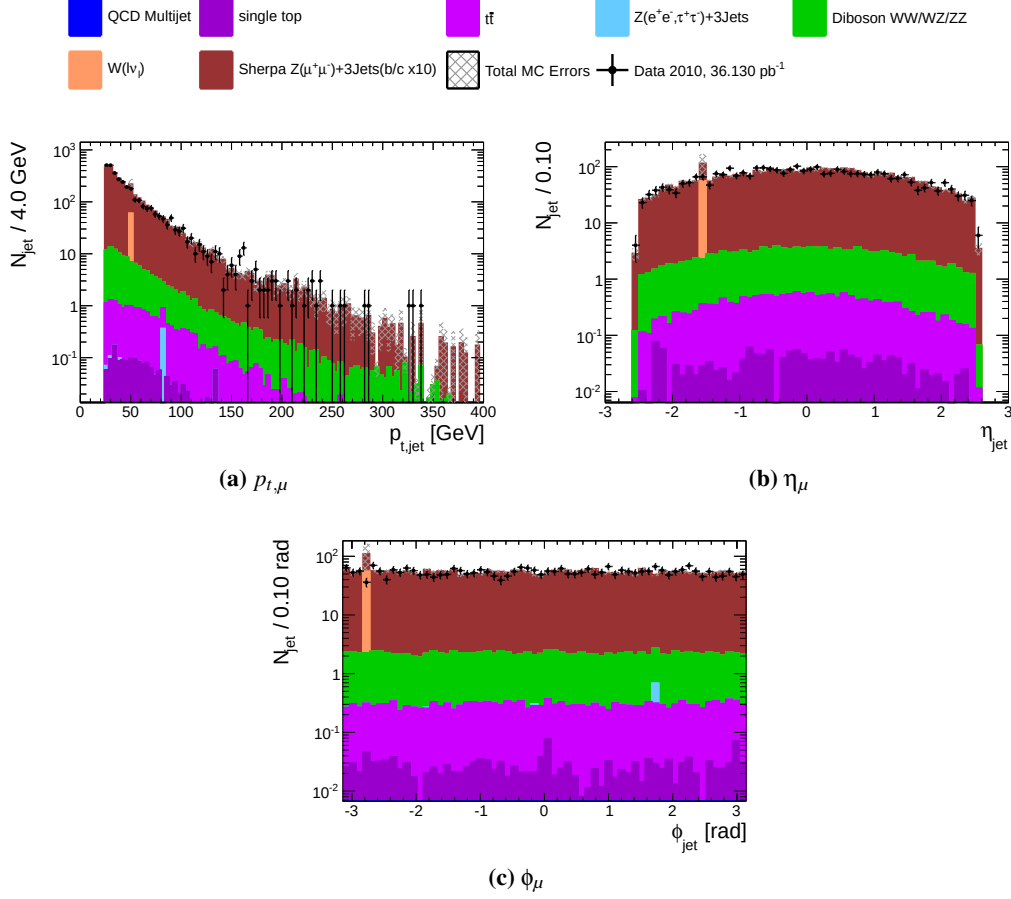


Figure D.2: Distribution of jet kinematics observables $p_{t,jet}$ (D.1a), ϕ_{jet} (D.1c) and η_{jet} (D.1b) for 2010 data and simulation. The plots include all jet object cuts as well as the di-muon selection described in section 6.2.

	N	ϵ_{abs}	ϵ_{rel}
<i>anti-kt</i> (0.4) Topo jet	20725 ± 144	1.00 ± 0.10	1.00 ± 0.10
not non-collision jet	20725 ± 144	1.00 ± 0.10	1.00 ± 0.10
not mismeasured jet	20725 ± 144	1.00 ± 0.10	1.00 ± 0.10
$p_{jet,t} > 25.$	3624 ± 60	0.17 ± 0.06	0.17 ± 0.06
$ \eta_{jet} < 2.5$	3303 ± 57	0.16 ± 0.05	0.9 ± 0.1
$\min(\Delta R(jet, Z^0 \text{lepton})) > 0.5$	3027 ± 55	0.15 ± 0.05	0.9 ± 0.2

Table D.1: Cut-flow for absolute jet multiplicities N_{jets} passing cut, absolute ϵ_{abs} as well as relative cut efficiencies ϵ_{rel} thereof for events in simulated events using the SHERPA MC.

D.4 Z^0 Boson Selection

This section is supplement to section 6.2 and shows distributions and numbers obtained from SHERPA MC events.

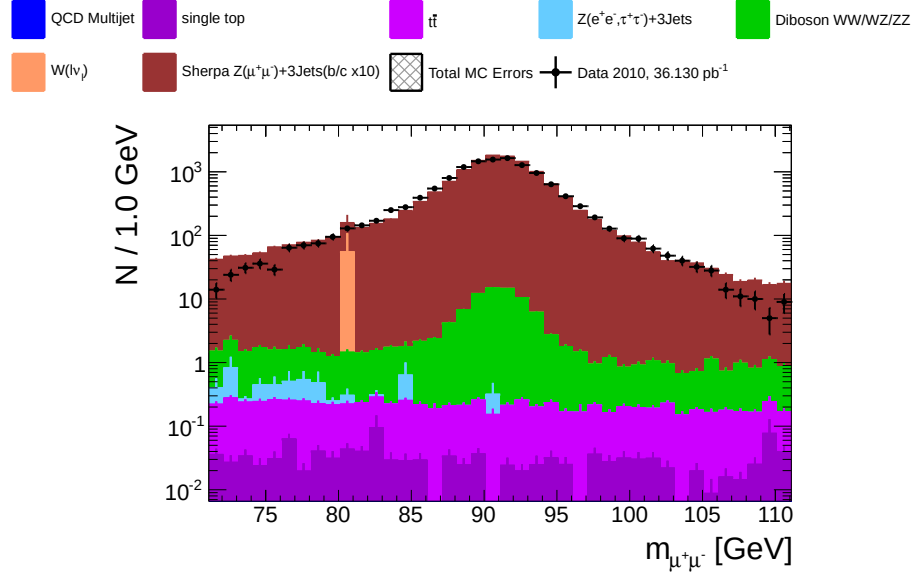


Figure D.3: Invariant mass spectrum for SHERPA signal plus expected background topologies for objects from muon selection that have been combined to Z^0 boson candidates without cuts on jet multiplicity.

final state	$N \pm \sigma_N$	N/N_{MC}
$Z^0 + \text{jets}$	2441.9 ± 22.5	0.95
$WW/ZZ/WZ$	67.1 ± 0.9	0.03
$W^\pm + \text{jets}$	53.2 ± 53.2	0.02
$t\bar{t}$	7.3 ± 0.2	0.00
single Top	1.1 ± 0.1	
Q	48.2 ± 0.7	
Total MC	2570.9 ± 57.8	
Data	2420.0	

Table D.2: Event yields after complete selection of $Z^0 + \text{jets}$ events. The event counts have been collected from SHERPA signal MC and expected background contributions. In addition, the ratio of individual event topologies to the total MC prediction N/N_{MC} is given for illustrative purposes.

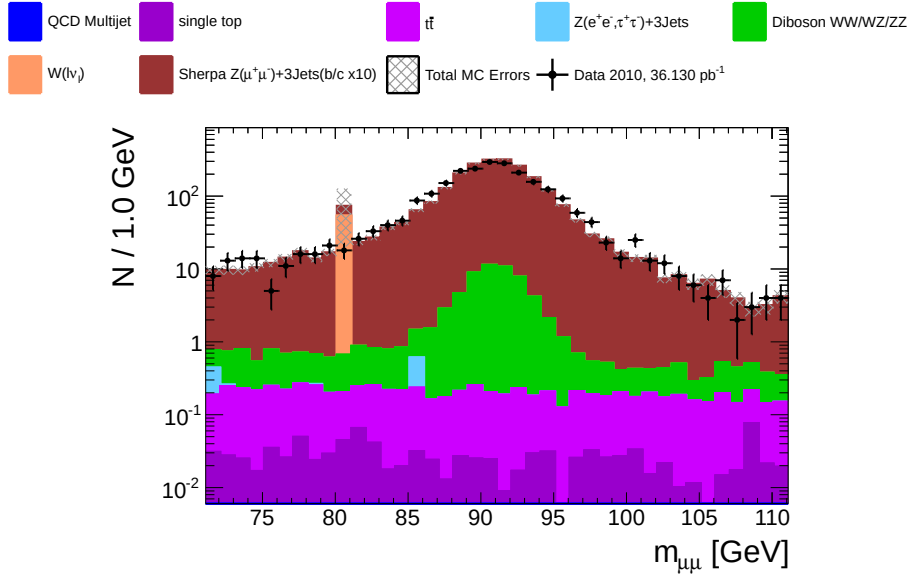


Figure D.4: Invariant mass spectrum for events from data SHERPA signal plus expected background topologies for objects from muon selection that have been combined to a Z^0 boson candidates requiring at least 1 selection jet.

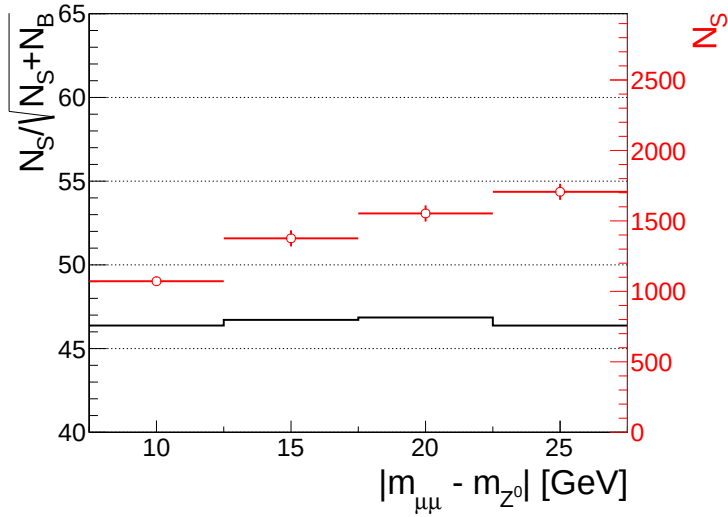


Figure D.5: Event yields for four invariant mass windows of $|m_{\mu^+\mu^-} - m_{Z^0}| < 10, 15, 20, 25$ GeV in SHERPA signal (D.4) plus expected background topologies. The MC signal yields scaled to the yield at $|m_{\mu^+\mu^-} - m_{Z^0}| = 10$ GeV (in red) and the overall $N_S / (N_S + N_B)$ (in black) is depicted for comparison.

D.5 Bottom Flavour Tagging

Section 6.4 reported a difference in flavour fraction (bottom to charm, bottom to light) comparing inclusive IP3D+SV1 jet rates (no Z^0 requirement) of ALPGEN and SHERPA.

	SHERPA	ALPGEN
$Z^0 + b$	20 %	9 %
$Z^0 + c$	52 %	83 %
$Z^0 + light$	28 %	8 %

Table D.3: Fraction of generator level events in SHERPA and ALPGEN events containing a generated Z^0 boson and at least one hadron-level defined bottom, charm or light parton induced jet exclusively. The generated objects entering this estimate of the flavour fractions must fulfil the hadron-level phase space definitions noted in section 7.4.2.

As illustrated in section 3.3, ALPGEN implements a 4-flavour FFS calculation. With this, all final state bottom partons must be generated from gluon splittings. The 5-flavour VFS scheme in SHERPA includes additional Feynman diagrams for producing a heavy flavour parton (c or b) in the final state. Depending on the PDF used, the relative fraction of bottom flavour partons per final state can be expected to be larger.

Table D.2 shows, that SHERPA MC events contain more $Z^0 + b$ events than ALPGEN. To conclude, the competing theoretical assumptions made within ALPGEN and SHERPA lead to different abundances of generated bottom flavour final state partons. This in turn leads to e.g. different statistical uncertainties when calculating b-tagging efficiencies or hadron level acceptance corrections if a finite sample of MC events is available.

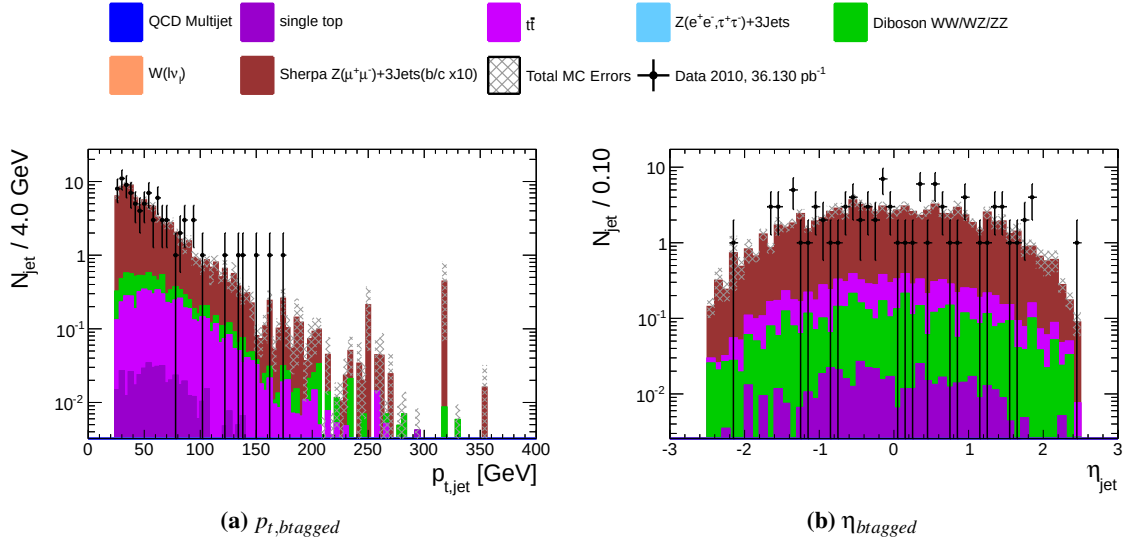


Figure D.6: Transverse momentum (D.6a) and pseudo-rapidity (D.6b) distribution for selected SV0 tagged jets in events with a reconstructed Z^0 boson candidate for SHERPA signal plus expected background topologies compared to data as described in section 6.4.2.

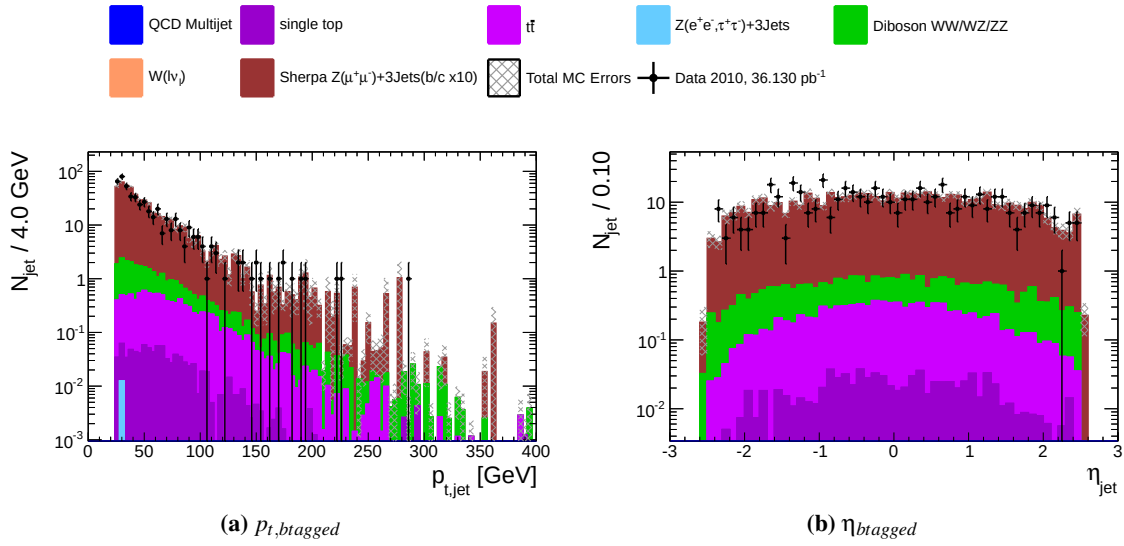
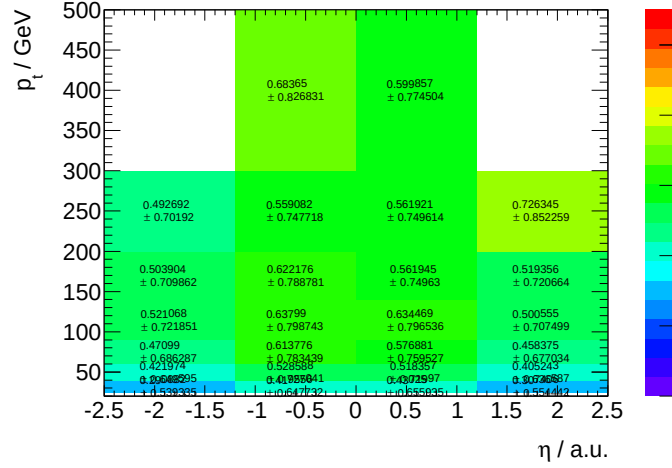
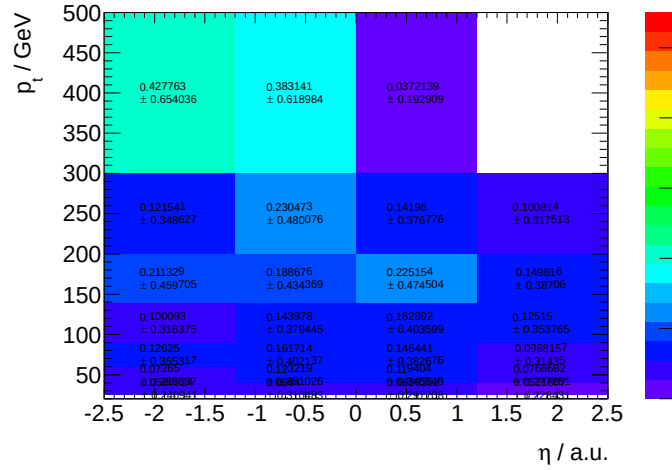


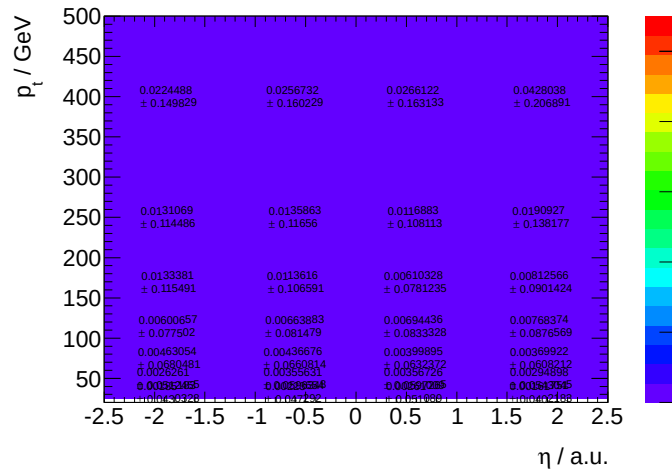
Figure D.7: Transverse momentum (D.6a) and pseudo-rapidity (D.6b) distribution for selected IP3D+SV1 tagged jets in events with a reconstructed Z^0 boson candidate for SHERPA signal plus expected background topologies compared to data as described in section 6.4.2.



(a) bottom

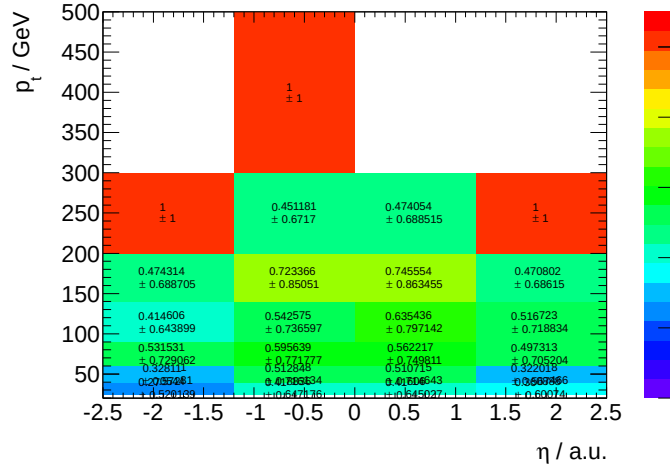


(b) charm

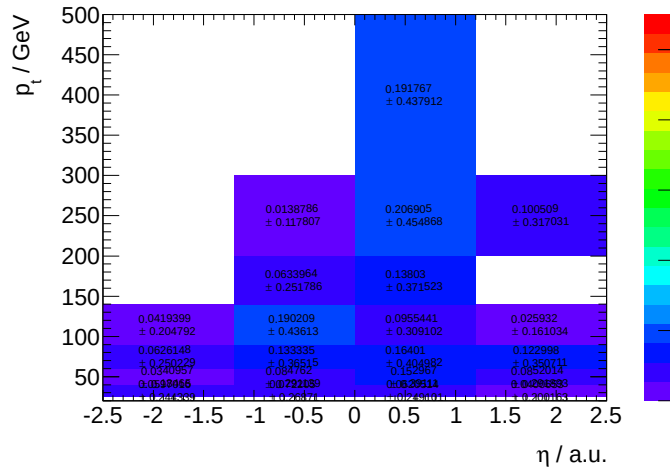


(c) light

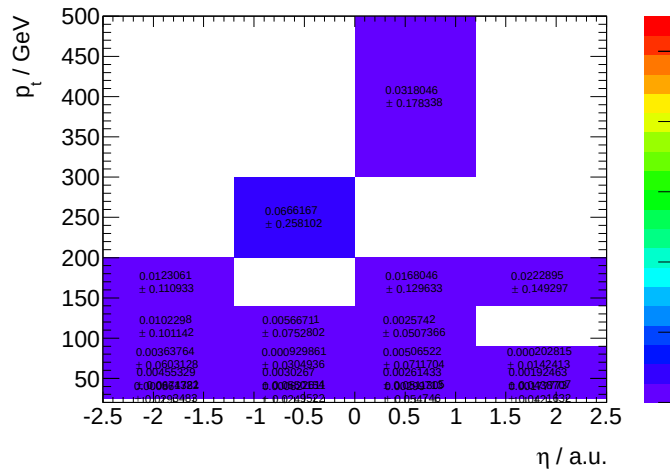
Figure D.8: B-tagging efficiencies for bottom (D.7a), charm (D.7b) and light (D.7c) parton induced jets that have been tagged with SV0(50%) from ALPGEN MC.



(a) bottom

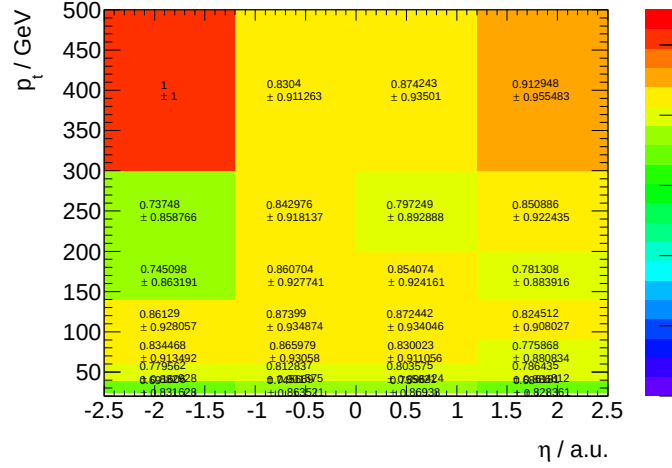


(b) charm

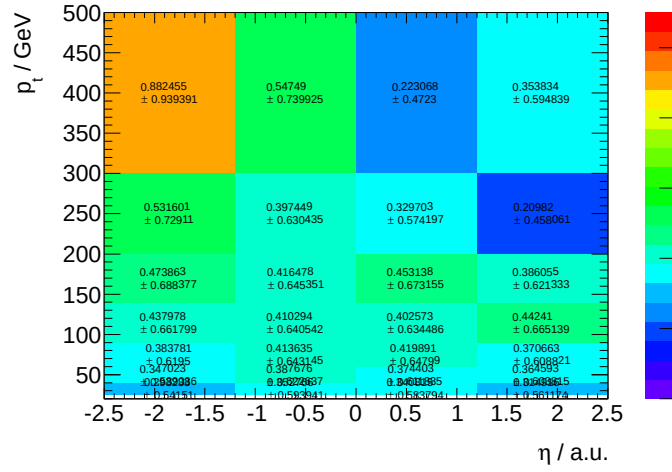


(c) light

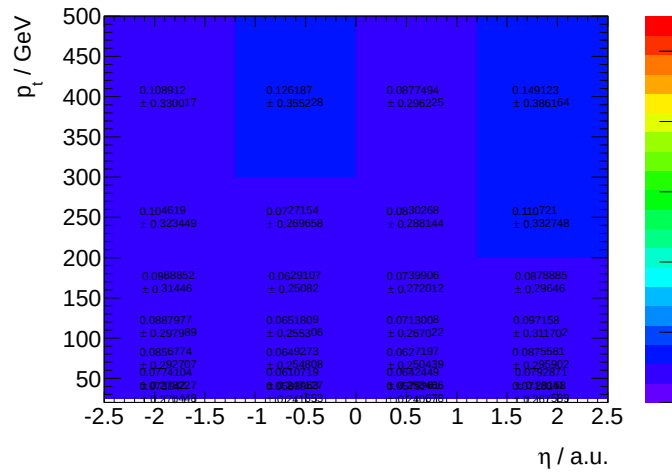
Figure D.9: B-tagging efficiencies for bottom (D.8a), charm (D.8b) and light (D.8c) parton induced jets that have been tagged with $SV0(50\%)$ from SHERPA MC.



(a) bottom

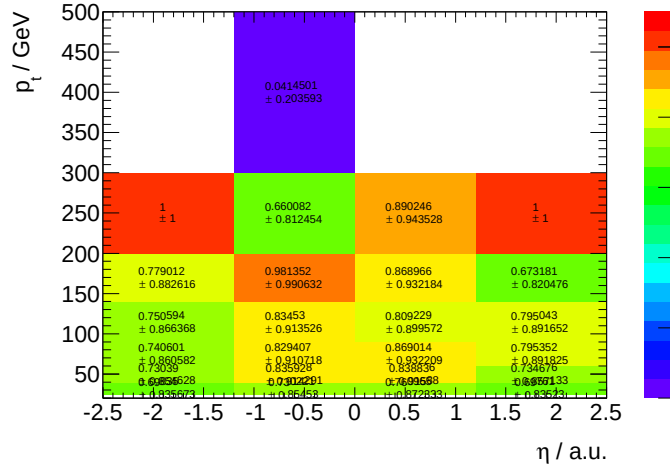


(b) charm

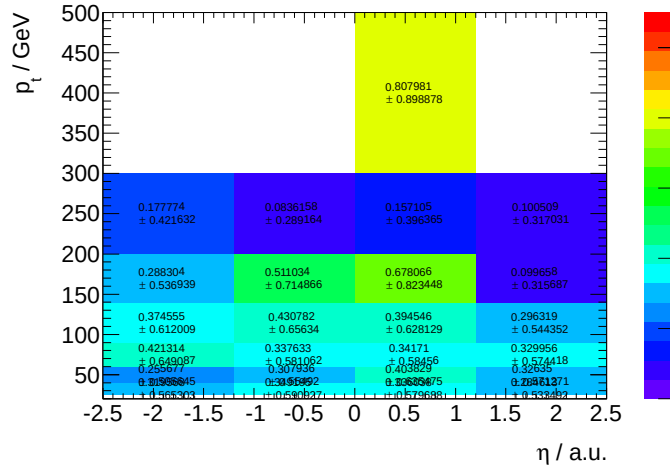


(c) light

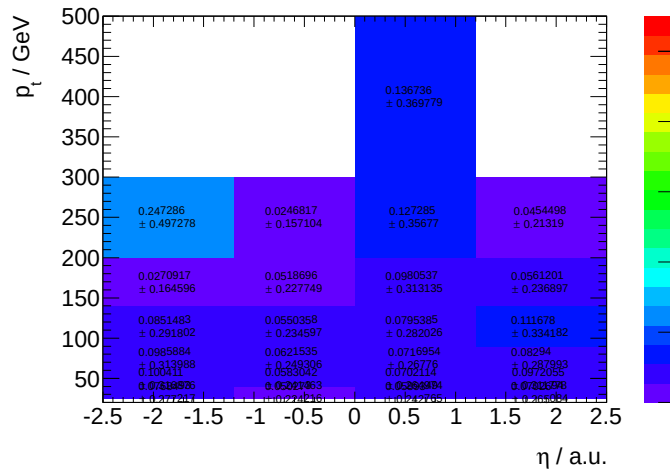
Figure D.10: B-tagging efficiencies for bottom (D.9a), charm (D.9b) and light (D.9c) parton induced jets that have been tagged with IP3D+SV1(80%) from ALPGEN MC.



(a) bottom



(b) charm



(c) light

Figure D.11: B-tagging efficiencies for bottom (D.10a), charm (D.10b) and light (D.10c) parton induced jets that have been tagged with IP3D+SV1(80%) from SHERPA MC.

Appendix E

Extraction of Cross Section

E.0.1 Bottom Fraction Linearity

The bottom normalisation yield of the presented maximum LLH fit of chapter 7 was found to almost give linear behaviour with the small statistics available. Here, the bottom flavour count is obtained again but with 150 times the statistics of pseudo-data (equivalent to 2011 ATLAS data).

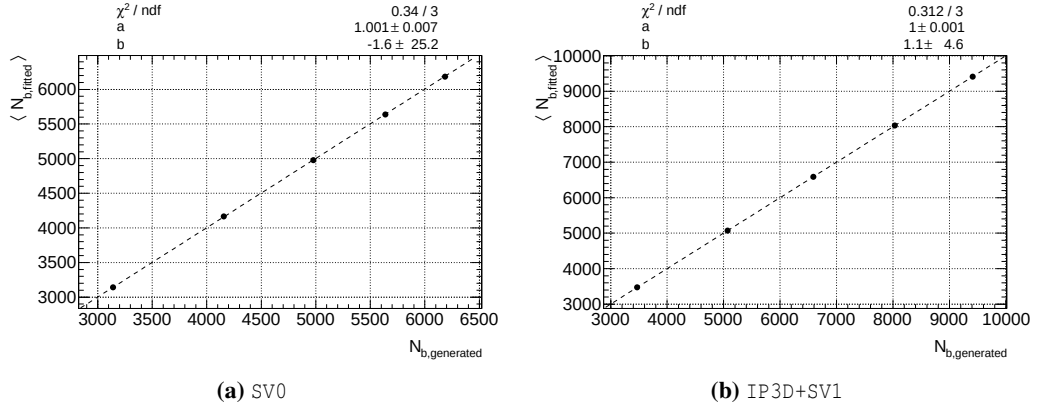


Figure E.1: Fitted bottom normalisation $N_{b, \text{fitted}}$ versus the generated bottom content $N_{b, \text{generated}}$. The distributions were produced with ALPGEN templates for the SV0 mass (7.11a) and for IP3D+SV1 mass (7.11b) and are fitted with a 1st order polynomial of the form $f(x) = a \cdot x + b$. Each point represents the evaluation of 20000 pseudo-experiments where the x coordinate gives the generated number of $Z^0 + b + X$ events (including its uncertainty) and the y axis notes the mean number of fitted $Z^0 + b + X$ events including the error on the mean. The number of available events in data per pseudo-experiment was enhanced by a factor of 150 compared to figure 7.11.

E.0.2 Bin Size Linearity

Also, the maximum LLH fit of chapter 7 fit was found to almost give linear behaviour with varied bin sizes of the distribution of the sum of secondary vertex masses. With 150 times the statistics of pseudo-data (equivalent to 2011 ATLAS data), the bin size linearity is obtained to high precision.

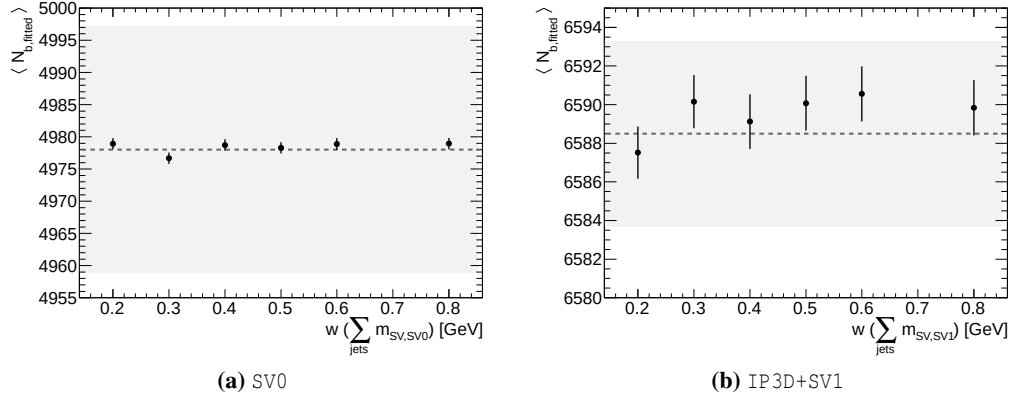


Figure E.2: Mean fitted bottom normalisation $N_{b, \text{fitted}}$ from 20000 pseudo experiments versus the set bin size per template in $\sum_{\text{jets}} m_{SV, SV0}$ (7.12a) and $\sum_{\text{jets}} m_{SV, SV1}$ (7.12b). The dashed horizontal line indicates the true bottom content that was contained in the signal MC including its statistical uncertainty.. The number of available events in data per pseudo-experiment was enhanced by a factor of 150 compared to figure 7.12.

E.1 Acceptance Definition

For the definition of the phase space that the measurement of $\sigma_{incl}(Z^0 + b)$ and $\mathcal{R} = \frac{\sigma(\mu^+\mu^-+b+X)}{\sigma(\mu^+\mu^-+\text{jets})}$ refers to, the identification of bottom or charm partons is specified with respect to bottom or charm hadrons. The following tables list the individual hadrons including their particle data identity number and measured mass [11].

name	$N(PDGID)$	m	name	$N(PDGID)$	m
B^0	511	5.27953 GeV	Ξ_{bc+}	5242	7.00575 GeV
B^{*0}	513	5.32510 GeV	Ξ'_{b-}	5312	5.96000 GeV
B^{*20}	515	5.74690 GeV	Ξ^{*}_{b-}	5314	5.97000 GeV
B^+	521	5.27915 GeV	Ξ'_{b0}	5322	5.96000 GeV
B^{*2+}	525	5.74690 GeV	Ξ^{*}_{b0}	5324	5.97000 GeV
B_{s0}	531	5.36630 GeV	Ω_{b-}	5332	6.12000 GeV
B^{*}_{s0}	533	5.41280 GeV	Ω^{*}_{b-}	5334	6.13000 GeV
B^{*2s0}	535	5.83970 GeV	Ω_{bc0}	5342	7.19099 GeV
B_{c+}	541	6.27600 GeV	Ξ'_{bc0}	5412	7.03724 GeV
B^{*}_{c+}	543	6.60200 GeV	Ξ^{*}_{bc0}	5414	7.04850 GeV
B^{*2c+}	545	7.35000 GeV	Ξ'_{bc+}	5422	7.03724 GeV
η_b	551	9.40000 GeV	Ξ^{*}_{bc+}	5424	7.04850 GeV
Υ	553	9.46030 GeV	Ω'_{bc0}	5432	7.21101 GeV
χ_{2b}	555	9.91220 GeV	Ω^{*}_{bc0}	5434	7.21900 GeV
Σ_{b-}	5112	5.81520 GeV	Ω_{bcc+}	5442	8.30945 GeV
Σ^{*}_{b-}	5114	5.83640 GeV	Ω^{*}_{bcc+}	5444	8.31325 GeV
Λ_{b0}	5122	5.62020 GeV	Ξ^{*}_{bb-}	5514	1.04414e + 01 GeV
Ξ_{b-}	5132	5.79240 GeV	Ξ_{bb0}	5522	1.04227e + 01 GeV
Ξ_{bc0}	5142	7.00575 GeV	Ξ^{*}_{bb0}	5524	1.04414e + 01 GeV
Σ_{b0}	5212	5.80780 GeV	Ω_{bb-}	5532	1.06021e + 01 GeV
Σ^{*}_{b0}	5214	5.82900 GeV	Ω^{*}_{bb-}	5534	1.06143e + 01 GeV
Σ_{b+}	5222	5.80780 GeV	Ω_{bbc0}	5542	1.17077e + 01 GeV
Σ^{*}_{b+}	5224	5.82900 GeV	Ω^{*}_{bbc0}	5544	1.17115e + 01 GeV
Ξ_{b0}	5232	5.79240 GeV	Ω^{*}_{bbb-}	5554	1.51106e + 01 GeV

Table E.1: Bottom Hadron PDG identifiers used to match a reconstructed jet on detector or particle level to a bottom quark hadron [11].

name	$N(PDGID)$	m
D^+	411	1.86962 GeV
D^{*+}	413	2.01027 GeV
D^{*2+}	415	2.46010 GeV
D^0	421	1.86484 GeV
D^{*0}	423	2.006970 GeV
D^{*20}	425	2.46110 GeV
D_{s^+}	431	1.96850 GeV
$D^{*}_{s^+}$	433	2.11230 GeV
$D^{*2}_{s^+}$	435	2.57260 GeV
J/Ψ_{di}	440	0.00000 GeV
η_c	441	2.98030 GeV
χ_{2c}	445	3.55620 GeV
Σ_{c0}	4112	2.45376 GeV
Σ^{*}_{c0}	4114	2.51800 GeV
Λ_{c^+}	4122	2.28646 GeV
Ξ_{c0}	4132	2.47100 GeV
Σ_{c^+}	4212	2.45290 GeV
$\Sigma^{*}_{c^+}$	4214	2.51750 GeV
$\Sigma_{c^{++}}$	4222	2.45402 GeV
$\Sigma^{*}_{c^{++}}$	4224	2.51840 GeV
Ξ_{c^+}	4232	2.46790 GeV
cs_0	4301	2.15432 GeV
Ξ'_{c0}	4312	2.57800 GeV
Ξ^{*}_{c0}	4314	2.64610 GeV
Ξ'_{c^+}	4322	2.57570 GeV
$\Xi^{*}_{c^+}$	4324	2.64660 GeV
Ω_{c0}	4332	2.69750 GeV
Ω^{*}_{c0}	4334	2.76830 GeV
Ξ_{cc^+}	4412	3.59798 GeV
$\Xi^{*}_{cc^+}$	4414	3.65648 GeV
$\Xi_{cc^{++}}$	4422	3.59798 GeV
$\Xi^{*}_{cc^{++}}$	4424	3.65648 GeV
Ω_{cc^+}	4432	3.78663 GeV
$\Omega^{*}_{cc^+}$	4434	3.82466 GeV
$\Omega^{*}_{ccc^{++}}$	4444	4.91594 GeV

Table E.2: Charm Hadron PDG identifiers used to match a reconstructed jet on detector or particle level to a charm quark hadron [11].

Appendix F

Systematic Uncertainties

F.1 Muon Measurement Uncertainties

In section 8.2, the expected systematic uncertainty due to the statistical uncertainty of the muon reconstruction efficiency and muon trigger efficiency MC-to-data corrections was obtained by randomly drawing correction factors per muon object and conducting the presented analysis 100 times. Individual results were stored in a histogram whose standard deviation is used as account of the related systematic uncertainty.

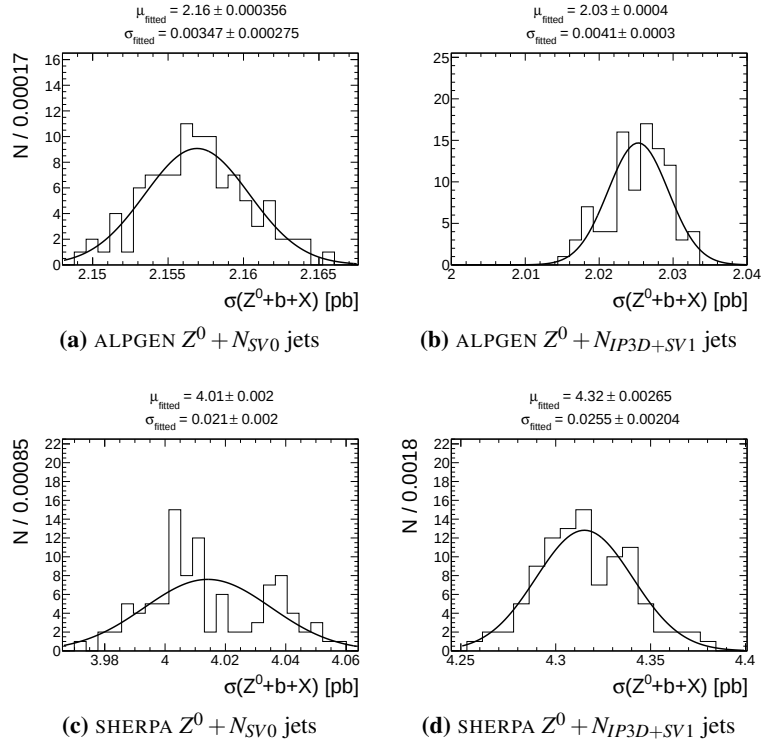


Figure F.1: Distribution of estimated $\sigma_{incl}(Z^0 + b)$ yields from 100 pseudo-data experiments with ALPGEN (a),(b) and SHERPA (c),(d) template distributions after variations of the muon reconstruction efficiency corrections. All histograms are fitted with a Gaussian PDF by a binned minimum log-Likelihood procedure. The fit results for the Gaussian mean μ and standard deviation σ are also given.

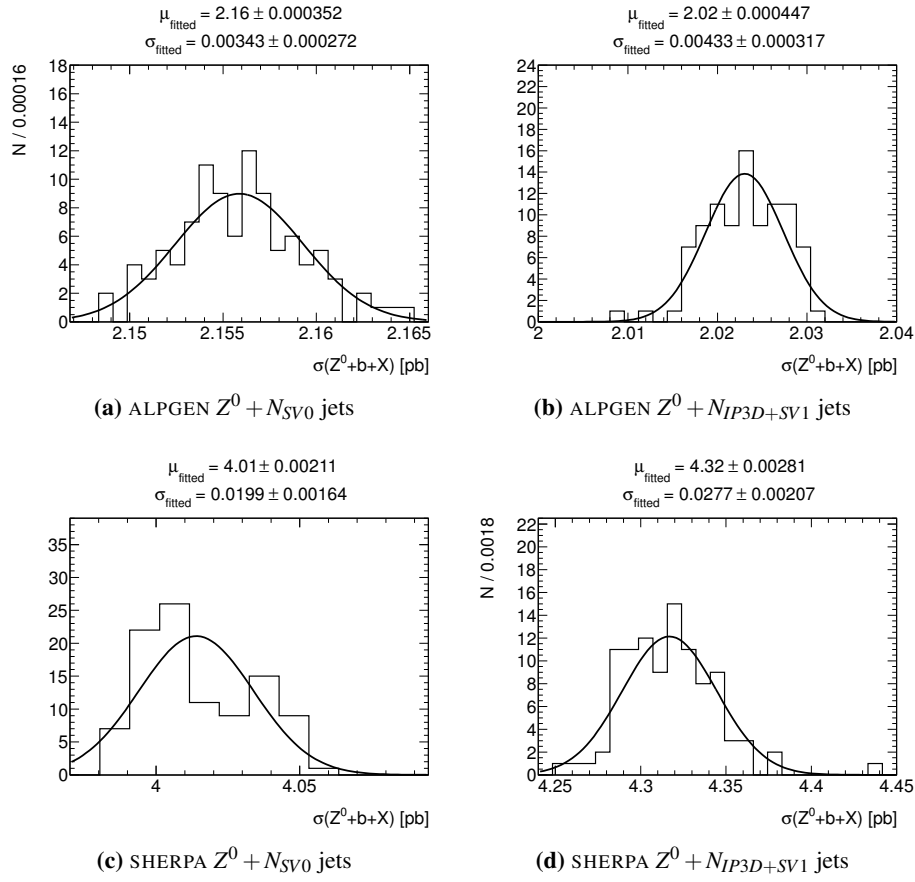


Figure F.2: Distribution of estimated $\sigma_{incl}(Z^0 + b)$ yields from 100 pseudo-data experiments with ALPGEN (a),(b) and SHERPA (c),(d) template distributions due to variations of the muon trigger efficiency corrections. All histograms are fitted with a Gaussian PDF by a binned minimum LLH procedure. The fit results for the Gaussian mean μ and standard deviation σ are also given.

F.2 Jet Measurement Uncertainties

In section 8.3, the expected systematic uncertainty due to the jet energy resolution was obtained by randomly drawing smeared jet energies per jet object and conducting the presented analysis 100 times. Individual results were stored in a histogram whose standard deviation is used as account of the related systematic uncertainty.

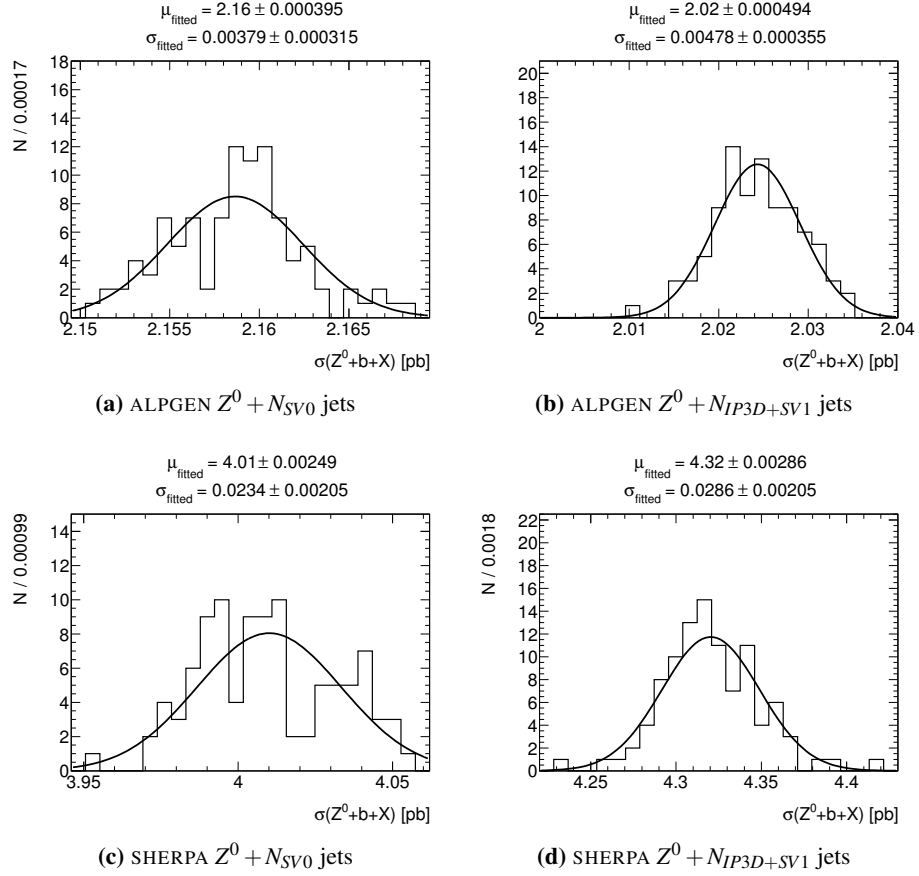


Figure F.3: Distribution of estimated $\sigma_{incl}(Z^0 + b)$ yields from 100 pseudo-data experiments with ALPGEN (a),(b) and SHERPA (c),(d) template distributions due to variations of the jet energy scale resolution. All histograms are fitted with a Gaussian PDF by a binned minimum LLH procedure. The fit results for the Gaussian mean μ and standard deviation σ are also given.

F.3 Theoretical Uncertainties

In section 8.6.2, the expected systematic uncertainty due to the finite size of the used MC event sample was obtained by randomly drawing acceptance correction factors $\mathcal{A}$ and conducting the presented analysis 1000 times. Individual results were stored in a histogram whose standard deviation is used as account of the related systematic uncertainty.

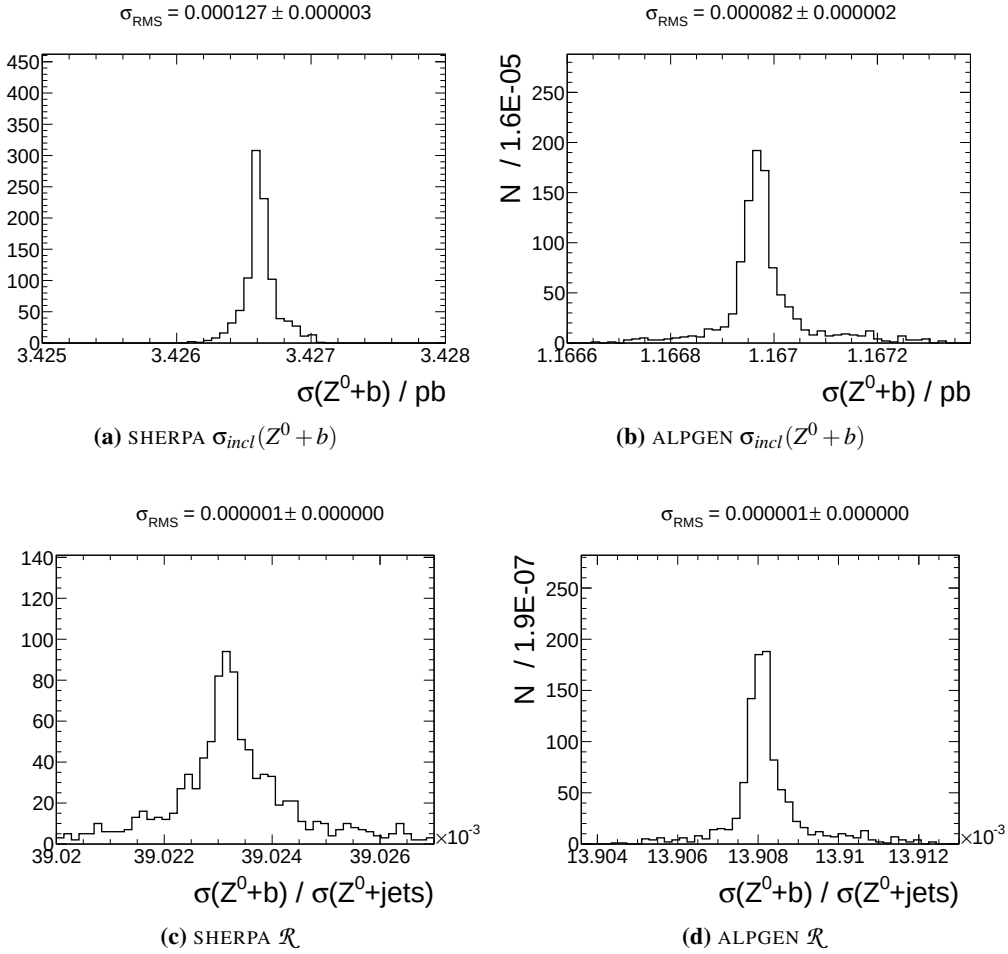


Figure F.4: $\sigma_{incl}(Z^0 + b)$ (top) and $\mathcal{R}$ (bottom) yields after $Z^0 + N_{IP3D+SV1}$ jets analysis from SHERPA (left) and ALPGEN (right) signal MC. For each, input quantities to equations 8.1 and 8.2 were drawn from a Poisson PDF to study shape dependencies in 1000 toy experiments. The obtained distributions of $\sigma_{incl}(Z^0 + b)$ and $\mathcal{R}$ were fitted with a Gaussian PDF to expose their mean and variance.

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Eidesstattliche Erklärung

Hiermit versichere ich, dass ich die vorliegende Arbeit ohne unzulässige Hilfe Dritter und ohne Benutzung anderer als der angegebenen Hilfsmittel angefertigt habe; die aus fremden Quellen direkt oder indirekt übernommenen Gedanken sind als solche kenntlich gemacht. Die Arbeit wurde bisher weder im Inland noch im Ausland in gleicher oder ähnlicher Form einer anderen Prüfungsbehörde vorgelegt.

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