

SEARCH FOR DISPLACED HADRONIC VERTICES IN
THE ATLAS INNER DETECTOR AND MUON
SPECTROMETER IN P-P COLLISIONS AT $\sqrt{s} = 13$ TEV
AT THE LHC

A Dissertation Presented

by

MARGARET S. LUTZ

Submitted to the Graduate School of the
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of the requirements for the degree of

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Physics

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DEDICATION

NMS

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ABSTRACT

SEARCH FOR DISPLACED HADRONIC VERTICES IN THE ATLAS INNER DETECTOR AND MUON SPECTROMETER IN P-P COLLISIONS AT $\sqrt{s} = 13$ TEV AT THE LHC

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A search is performed for long-lived neutral particles using 33 fb^{-1} of 13 TeV proton-proton collision data produced by the LHC and collected by the ATLAS detector during 2016. This search focuses on the topology in which pairs of displaced hadronic jets are produced, with one in the inner detector and the other in the muon spectrometer. Special techniques are used to reconstruct the displaced decays. One event is found passing the full signal selection, which is consistent with the background estimation. Limits are set at a 95% upper confidence level on the $BR \times \sigma$ for a SM Higgs, or scalar boson Φ of mass 200 to 1000 GeV, to decay to long-lived hidden sector particles of masses 8 to 400 GeV. The limits placed on the branching ratio of the Higgs boson and the $BR \times \sigma$ of a 200 GeV Φ to several long-lived neutral

scalars extend existing exclusion limits between long-lived particle lifetimes from 5 cm to 1 m.

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INTRODUCTION

In particle physics, the Standard Model (SM) is the best current description of the universe around us. The SM consists of the fundamental particles of matter, and the quantizations of the fields that regulate their interactions. The final piece of the SM was found with the discovery of the Higgs boson by the ATLAS and CMS experiments at CERN [1, 2]. Thus far the SM has withstood (nearly) every experimental test.

In many ways, however, the SM is an unsatisfactory description. The SM does not provide answers for many existing questions, such as why gravity is much weaker than other forces and why there is more baryonic matter than anti-matter, and it does not include dark matter particles. In order to fill in the gaps, there are a variety of beyond-SM (BSM) theories that propose solutions, and there are many robust experimental programs searching for evidence of these theories.

Many of these BSM searches have taken place at particle colliders, using detectors like those at the Large Hadron Collider (LHC) at CERN. These searches have not yet yielded evidence for BSM theories and have set strong limits on the existence of many BSM particles. However, the searches have primarily focused on BSM particles that decay promptly, because most reconstruction software is optimized to reconstruct decays that point back to a common interaction point. This means that theories containing long-lived particles (LLPs) have been less explored, and there is still plenty of potential for discovery when searching for long-lived BSM particles. Long-lived BSM theories are thus very intriguing, if one can surmount the experimental challenges of searching for them.

At CERN many researchers are part of a collaborative community searching for evidence of LLPs, and results have been published from a variety of LLP searches

performed during the first [3, 4, 5, 6, 7, 8, 9, 10] and second [11, 12, 13, 14, 15] data-taking runs of the LHC.

Of particular importance to the analysis described here are three such searches which looked for evidence of the same BSM model as this analysis and which used similar reconstruction techniques. The first, Ref. [4], is an analysis from the first data-taking run of the LHC. The analysis looked for evidence of LLPs that had decayed in the inner detector (ID) (the innermost sub-system) and the muon spectrometer (MS) (the outermost sub-system) of the ATLAS detector, and was the first ATLAS search for Hidden Sector particles. The search in Ref. [4] used similar techniques as this analysis to select and reconstruct events of interest, in particular the methods for reconstructing the displaced decays in the muon spectrometer.

Thus far in the second data-taking run of the LHC, two searches for the Hidden Sector have been published. The MS analysis [13] searches for decays of one or two LLPs in the muon spectrometer, and the CR analysis [14] searches for pairs of LLP decays that occur in the hadronic calorimeter (located between the ID and the MS).

The analysis presented here searches for the same topology of one displaced decay in the inner detector and one in the muon spectrometer as the search in Ref. [4], and extends the work of the MS analysis to have greater sensitivity at lower LLP lifetimes. The results of this analysis are combined with the results of the CR and MS analyses, providing the strongest limits to date on the branching ratio of the Higgs boson, and other scalar bosons, to Hidden Sector particles.

The following dissertation lays out the theoretical motivation and background for the analysis in Chapter 1. The ATLAS detector is described in detail in Chapter 2, and the data and Monte Carlo samples used are detailed in Chapter 3. Special techniques are needed to reconstruct the displaced decays in the ID and the MS, and these are described, along with the standard ATLAS reconstruction used, in Chapter 4. The selection criteria which are then used to separate signal-like decays

from the background to the search are explained in Chapter 5. The estimation method used to predict how many events from background survive the selection criteria, and the validation of this background estimation method are laid out in Chapter 6. The systematic uncertainties that impact this search are detailed in Chapter 7. Finally, the results of the analysis are shown in Chapter 8.

CHAPTER 1

THEORY MOTIVATION

1.1 Standard Model

The Standard Model in particle physics is the best and most thorough description of the known particles and their interactions that has been developed so far. The fundamental particles making up the SM are the fermion matter particles, the quarks and leptons, which have spin $J = n(\hbar/2)$ where n is odd [16]; the force carrying gauge bosons which have spin $J = n(\hbar/2)$ where n is even; and the Higgs boson, which has a spin of 0, and gives mass to the (massive) gauge bosons through electroweak symmetry breaking [17, 18, 19, 20]. The fermions and bosons, their properties, and their interactions are laid out in Figure 1.1.

Below is a brief overview of the key attributes of these particles and their interactions:

- Quarks

Quarks are fermions that have an electric charge of either $\pm 2/3$ or $\mp 1/3$ (thus interacting via electromagnetism). An important and unique property of quarks is that they also carry a color charge, this enables three otherwise identical quarks to exist in bound states without violating Fermi statistics [16]. Quarks therefore interact via the strong force, mediated by the gluon (quarks can also interact via the weak force, mediated by the $W^\pm$ and Z bosons).

Quarks may exist in one of three colors (R, B, and G, in analog to real colors), and are confined to exist only in colorless states, either in baryons - strongly

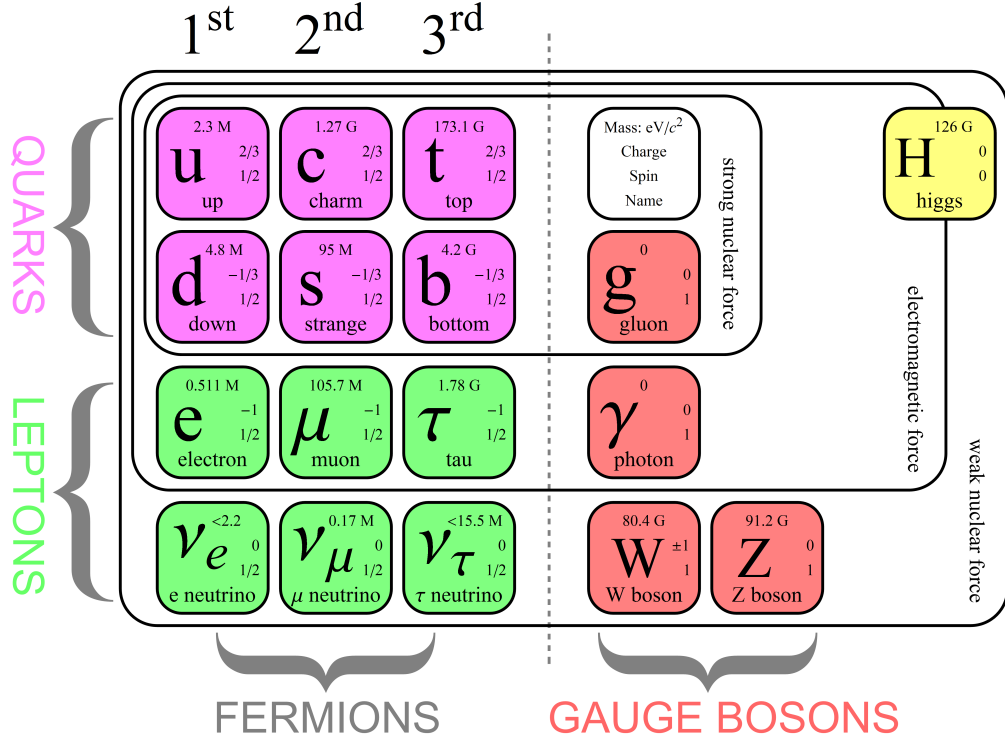


Figure 1.1: The quarks, leptons, and bosons that are the fundamental building blocks in the SM, including their spin, and the interactions between the fermions and the gauge bosons [21].

interacting fermion states composed of three quarks with one of each color (or occasionally four quarks and one anti-quark), or in mesons - strongly interacting boson states composed of a quark and an anti-quark with one color and one anti-color. In interactions in the SM, the baryon number (assigned ± 1 for baryons and their anti-particles, $\pm 1/3$ for (anti-)quarks and 0 for everything else) is conserved.

Quarks always confine into these bound hadronic states of two or three (or five) quarks which are neutral in color. When a meson or a baryon decays, the components will hadronize, forming new hadronic bound states of quarks.

- Leptons

Leptons are fermions that interact via the weak force, they carry no baryon number but rather a lepton number of ± 1 . There are two classes of leptons. The charged leptons, electrons (e^{-1} 's), muons (μ^{-1} 's), and taus (τ^{-1} 's), interact via electromagnetism in addition to the weak force. The e^{-1} 's, μ^{-1} 's, and τ^{-1} 's are massive, with the electron being the lightest, and the tau being the heaviest. The second class of leptons are the uncharged neutrinos, which interact via the weak force. For each of the e^{-1} 's, μ^{-1} 's, and τ^{-1} 's, there is a very light neutrino (ν) with a corresponding “flavor” to the charged leptons.

Lepton number is conserved in the SM, as is lepton flavor, with the exception of neutrino flavor oscillation.

- Gauge Bosons

Photons (γ) are quanta of the electromagnetic field, they have spin 1, carry no mass, and no electric (or color) charge. They mediate the electromagnetic field and interact with charged particles.

Gluons are quanta of the color field that mediate the interactions between quarks. Gluons have spin 1, carry no mass or electric charge, but have a color charge, meaning that gluons can self interact and bind together. This self interaction of the gluons leads to asymptotic freedom; at extremely short distances the strong force between two quarks is very low, but as the quarks are pulled apart, gluon-gluon pairs are generated which increases the force between the quarks. The strength of the force grows asymptotically until distance scales of approximately one fm. The energy needed to pull two quarks completely apart is less than the energy needed to create a quark - anti-quark pair, so instead of separating into individual quarks, the quarks will confine into two mesons.

The strong interactions of quarks and gluons in QCD (quantum chromodynamics) contribute a $SU(3)$ color group to the gauge group of the Standard Model, formed by the triplet of the three color charges.

The $W^\pm$ and Z gauge bosons are the mediators of the weak force. They are massive spin-1 bosons, with a charge of ± 1 and 0 respectively. The $W^\pm$ bosons interact with charged fermions, and the Z bosons interact with charged and neutral fermions. Because of the masses of the $W^\pm$ and Z bosons, decays through weak interactions are slower (the particles have longer lifetimes) than those which proceed through the strong force. The masses also lead to a limited range of the weak interaction.

The $W^\pm$ and Z bosons mix with the γ to create the $SU(2) \times U(1)$ gauge group, with W_1, W_2, W_3 bosons making up the former and a B boson making up the latter. The W_i and B bosons relate to the $W^\pm, Z$, and γ via the weak mixing angle such that
$$\begin{pmatrix} \gamma \\ Z \end{pmatrix} = \begin{pmatrix} \cos \theta_W & \sin \theta_W \\ -\sin \theta_W & \cos \theta_W \end{pmatrix} \begin{pmatrix} B \\ W_3 \end{pmatrix} \text{ and } W^\pm = \frac{1}{\sqrt{2}}(W_1 \mp iW_2).$$

- The Higgs Boson

The electroweak symmetry of the $SU(2) \times U(1)$ group is broken through the interaction with the Higgs field, thus giving mass to the $W^\pm$ and Z bosons but not the γ . The scalar potential responsible for this is:

$$V(\Phi) = m^2 \Phi^\dagger \Phi + \lambda (\Phi^\dagger \Phi)^2 \quad [22]. \quad (1.1)$$

The Φ is the self-interacting, complex, Higgs field, with $\Phi = \frac{1}{\sqrt{2}} \begin{pmatrix} \sqrt{2}\phi^+ \\ \phi^0 + ia^0 \end{pmatrix}$, in which ϕ^0 and a^0 are the neutral CP-even and CP-odd components of the Higgs doublet, and ϕ^+ is the charged and complex component. The electroweak symmetry breaking results from the non-zero vacuum expectation value of the

complex Higgs doublet, $\langle \Phi \rangle = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v \end{pmatrix}$, in which $m^2 = -\lambda v^2$, and $m_H = \sqrt{2\lambda}v$. In the SM, λ is a free parameter, but since the Higgs mass has been experimentally measured to be $m_H \simeq 125$ GeV, it can be determined that $|m| \simeq 88.8$ GeV, and $\lambda \simeq 0.13$.

The fermions in the SM also acquire mass through the couplings between the fermions and the Higgs field, via the Yukawa interactions:

$$\mathcal{L}_{\text{Yukawa}} = -\hat{h}_{d_{ij}} \bar{q}_{L_i} \Phi d_{R_j} - \hat{h}_{u_{ij}} \bar{q}_{L_i} i\sigma_2 \Phi^* u_{R_j} - \hat{h}_{l_{ij}} \bar{l}_{L_i} \Phi e_{R_j} + h.c.... \quad [22] \quad (1.2)$$

where q, u, d and l, e are the quarks and (non-neutrino) leptons. There is no particular allowance here for the mass hierarchy of the quarks and leptons, or for neutrino mass.

In summary, the SM is an $SU(3) \times SU(2) \times U(1)$ gauge group containing 6 quarks, 6 leptons, 3 gauge bosons, and the Higgs boson, which describes (very nearly) everything that we see, and whose predictions have been confirmed experimentally to high precision.

1.2 BSM and the Hidden Sector

So, why should anyone spend time searching for BSM physics? Because there are many open questions that the SM cannot answer.

- The SNO collaboration's measurement of the ν_e flux compared to the total ν_x flux from solar neutrinos [23], was the first observation of the oscillation of neutrino flavors and led to the conclusion that there are two different mass splittings between three neutrino masses. The SM does not explicitly allow for this mass splitting (implying non-zero neutrino mass) or the resulting oscillations between the three neutrino flavors.

- There is an imbalance in the baryonic and anti-baryonic matter in the universe. If baryon number is conserved in SM interactions, how can this arise? The SM does not have an allowance for the development of this imbalance, so the asymmetric abundance of baryonic matter necessitates BSM physics [24].
- The existence of dark matter, which was first proposed by Fritz Zwicky in 1933 to explain the motion of galaxies in the COMA cluster [25], was confirmed in 1978 when Rubin, Ford, and Thonnard [26] determined that the rotational curves of galaxies must be due to non-luminous mass in addition to the ‘optical galaxy’ that was observed. Since the SM makes no allowance for the existence of dark matter, there must be another model or set of models to be able to explain it.
- The hierarchy problem is the idea that it is unnatural that the force due to gravity is 10^{24} times weaker than the electroweak force. Of particular interest in particle physics is the manifestation of this problem in the mass calculation of the Higgs boson. The Higgs boson, as discovered by the ATLAS and CMS experiments, is found to have a mass of 125 GeV, however because of the first order loop correction to the mass of the Higgs, the expectation from the Standard Model is that the observed mass of the Higgs boson should be $m_{obs}^2 = m_{free}^2 + \mathcal{O}(\Lambda)$ [27], where Λ is taken to be the Planck scale $\mathcal{O}(10^{19})$ [22]. This means that in order to have a Higgs mass of $\mathcal{O}(10^2)$, the free parameter m_{free} would have to undergo a huge amount of fine tuning. Alternatively, there could be, for instance, a BSM partner to the top quark, whose loop contribution would cancel out the loop correction to the Higgs boson mass calculation. This would thus very neatly solve the problem.

There are many models that have been developed to try to fill in some of the gaps, many of which include LLPs. These models include, but aren’t limited to, supersym-

metry (SUSY) [28, 29, 30, 31], right-handed (heavy) neutrinos [32, 33], models of neutral naturalness (NN) [34, 35, 36], and hidden sector (HS) models [37, 38, 39, 40]. The HS may arise in connection with SUSY [38, 41] and NN [42] models.

1.2.1 The Hidden Sector

Hidden Sector models, (or sometimes Hidden Valley (HV) models) are models which may be easily constructed in several ways, are compatible with solutions to the hierarchy problem, and may produce long-lived particles with little fine tuning [37, 38]. Additionally, if the HS particles are stable they could be dark matter candidates.

The HS models are characterized by some BSM sector of relatively light mass particles, which is connected to the SM through some relatively heavy mediator, hence causing the BSM sector to be hidden. The large center of mass energy in the collisions provided by the LHC could help overcome this and allow the HV particles to be created at non-trivial rates, as shown schematically in Figure 1.2.

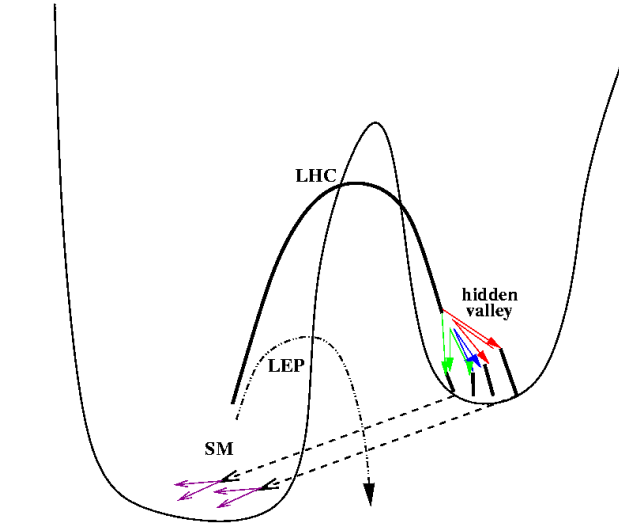


Figure 1.2: The schematic visualization of the Hidden Valley, from Ref. [39], representing the (potential) relative energy scales of the SM, Hidden Valley, the energy barrier between the two, and the possible reach of the LEP and LHC colliders.

In Hidden Valley models, the SM is extended to include a non-abelian gauge group, G_{HV} [37]. Neutral HV scalars are charged under G_{HV} but not under G_{SM}

(although they do carry mass) and most SM particles which are charged under G_{SM} are neutral under G_{HV} , with the possible exception of the Higgs, Z' , and/or some heavy scalar which may be charged under both G_{SM} and G_{HV} and act as a mediator, allowing some coupling between the HV and the SM.

In a confining HV model, the HV fundamental particles will combine into neutral (under G_{HV}) states in analog to hadrons in QCD, with a potentially wide range of final states. These final states could be stable, in which case they could make up dark matter, or they could be unstable, and decay through a mediator (not necessarily the same one via which they arose) back to neutral pairs of SM fermions. In some cases the decays are predominately to heavy flavor (as is the focus of this analysis, see Section 1.2.1.1), but in some cases decays may be to $\mu^+\mu^-$ or e^+e^- pairs, gluons, or pairs of W^+W^- or ZZ . The lifetimes of the HV states are relatively unconstrained.

To demonstrate how a Hidden Valley could relate to the SM, a simple HV scenario is described below.

The SM can be extended by a gauge group $U(1) \times SU(n_{HV})$, which confines at a Λ_{HV} scale between 1 GeV and 1 TeV. The $U(1)$ symmetry is broken via the scalar expectation value $\langle\phi\rangle$, the coupling with ϕ gives mass to the HV “quarks” $Q_1, \bar{Q}_1$ and $Q_2, \bar{Q}_2$, and three stable right-handed neutrinos. One can consider a situation in which the two HV quark flavors are light - $m_{Q_1} \sim m_{Q_2} \ll \Lambda_{HV}$, as in the framework that was the basis for the Run 1 version of this search, presented in [4].

In this two-light-flavor scenario, the HV quarks form HV hadrons, which decay either to HV nucleons or an HV isospin triplet $\pi_{HV}^\pm, \pi_{HV}^0$ as shown in Figure 1.3. These HV “pions” are all neutral under G_{SM} and are charged and neutral, respectively, under G_{HV} .

In this scenario, the π_{HV}^0 is unstable, formed from the HV-quark wave function $Q_1\bar{Q}_1 - Q_2\bar{Q}_2$, and can decay back to the SM via a heavy Z' such that $Q\bar{Q} \rightarrow Z' \rightarrow f\bar{f}$,

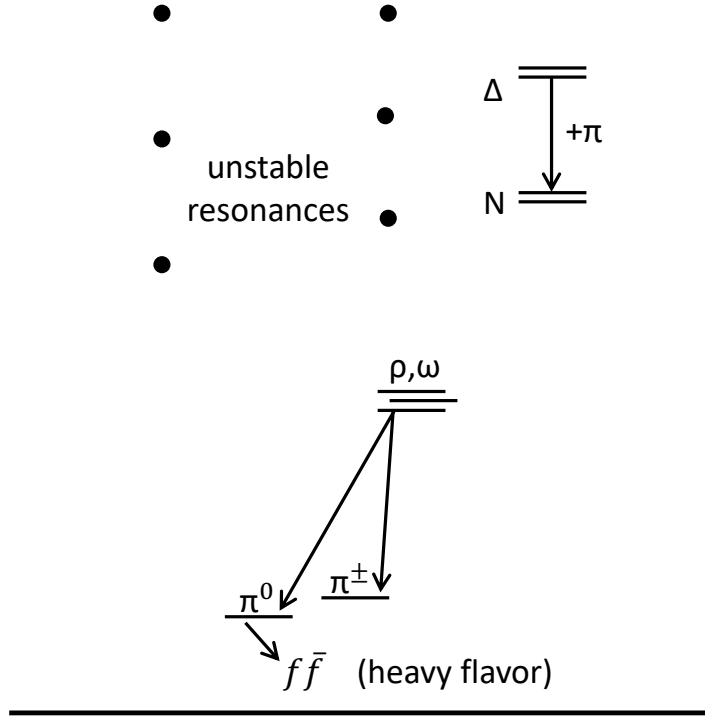


Figure 1.3: Decay modes in a Hidden Valley scenario in which there are two light HV “quarks” which combine to form HV “hadrons” which are stable or decay back to SM fermion pairs (Figure recreated from the left-hand side of Figure 1 in Ref. [37]).

in which f are SM fermions. The decays are principally to heavy flavor, and will be dominantly to $b\bar{b}$ provided that $2m_b < m_{\pi_{HV}} < 2m_t$.

Since the Higgs boson is not fully constrained to decay to the SM [43], it is intriguing to consider the Higgs as the portal to the HV. The connection to the HV is then through the mixing of the Higgs and the HV ϕ scalar which gives mass to the HV quarks, with a potential

$$V = -\mu^2|H|^2 - \hat{\mu}^2|\phi|^2 + \lambda|H|^4 + \tau|\phi|^4 + \zeta|\phi|^2|H|^2 \quad [38]. \quad (1.3)$$

Here, $\hat{v} = \sqrt{2}\langle\phi\rangle$, $\gamma = \hat{v}/v \sim 1/10 - 1/20$, and $\zeta \sim \lambda\gamma^2 \sim \tau$, leading to a mixing angle of $> \mathcal{O}(0.1)$ without significant fine-tuning.

1.2.1.1 Simplified HS model

In order to increase the chances of discovery for new physics, it is important to search in a somewhat model-independent way. Thus instead of focusing on the exact structure of the hidden sector, this search is performed using a simplified HS model, and focusing primarily on what the final state looks like in the ATLAS detector. In the simplified HS model used by this analysis, the mediator between the SM and the HS is taken to be Φ which is either the SM Higgs boson, or some heavy scalar boson. The Φ decays to the neutral long-lived HS scalars s , as shown in Figure 1.4, which in turn decay back to SM fermion pairs, without considering any further complexity to the HS. Because a Yukawa coupling is assumed between the s and the SM particles, the s decay to heavy flavor, following the branching ratio of the SM Higgs decays: $b\bar{b}$, $c\bar{c}$, $\tau^+\tau^-$ at 85:5:8, when kinematically viable. As mentioned previously, the lifetimes of the long-lived s are unconstrained, aside from the upper limit of $c\tau \lesssim 10^8$ m from Big Bang Nucleosynthesis [44, 45].

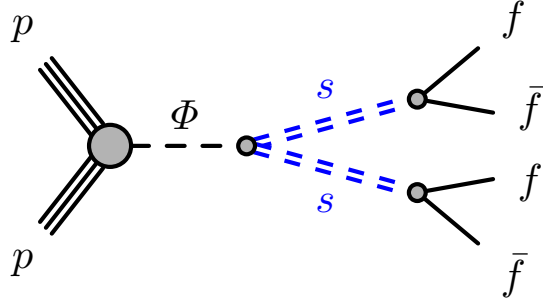


Figure 1.4: Diagram for a Higgs or heavy scalar decaying to displaced hadronic jets via a hidden sector [13].

CHAPTER 2

THE ATLAS EXPERIMENT AT THE LHC

The Large Hadron Collider is located at CERN, just outside of Geneva, Switzerland. The LHC is the world's largest particle collider, designed to produce high energy proton-proton and heavy ion collisions [46]. The LHC has two hadron beams circulating in opposite directions, which are designed to collide at four points on the LHC ring where four main experiments are located: ATLAS (A LHC Toroidal Apparatus), ALICE (A Large Ion Collider Experiment), CMS (Compact Muon Solenoid), and LHCb (Large Hadron Collider beauty). There have been two LHC running periods thus far, Run 1, which spanned 2010-2012, and Run 2, spanning 2016-2018. In Run 2 of the LHC, during the data taking used for this analysis, the LHC provided proton-proton collisions with a bunch-spacing of once every 25 ns, and a center of mass energy of 13 TeV.

2.1 ATLAS

The ATLAS detector is a general-purpose particle detector which was designed to probe the proton-proton and ion-ion collisions produced by the LHC [47]. ATLAS is a forward-backward symmetric cylindrical detector and covers a solid angle of nearly 4π . In ATLAS a right-handed coordinate system is used, centered on the proton-proton interaction point (IP). The $(+)x$ -axis points towards the center of the LHC ring, the $(+)y$ -axis points upwards, and the z -axis points along the LHC beamline. The $(+)z$ side of the ATLAS detector is referred to as side-A while the $(-)z$ side is referred to as side-C.

It is often convenient to refer to a cylindrical coordinate system within the cylindrical detector. In this case, the azimuthal angle ϕ is defined in the x - y plane with $\phi = 0$ along the x -axis, and the polar angle θ is defined from the z -axis (along the beamline). The pseudorapidity is then defined as $\eta = -\ln \tan \theta/2$.

The ATLAS detector, as shown in Figure 2.1, is made up of three main sub-detectors, the inner detector, the calorimeters, and the muon spectrometer, and is submerged in a magnetic field provided by toroid and solenoid magnets.

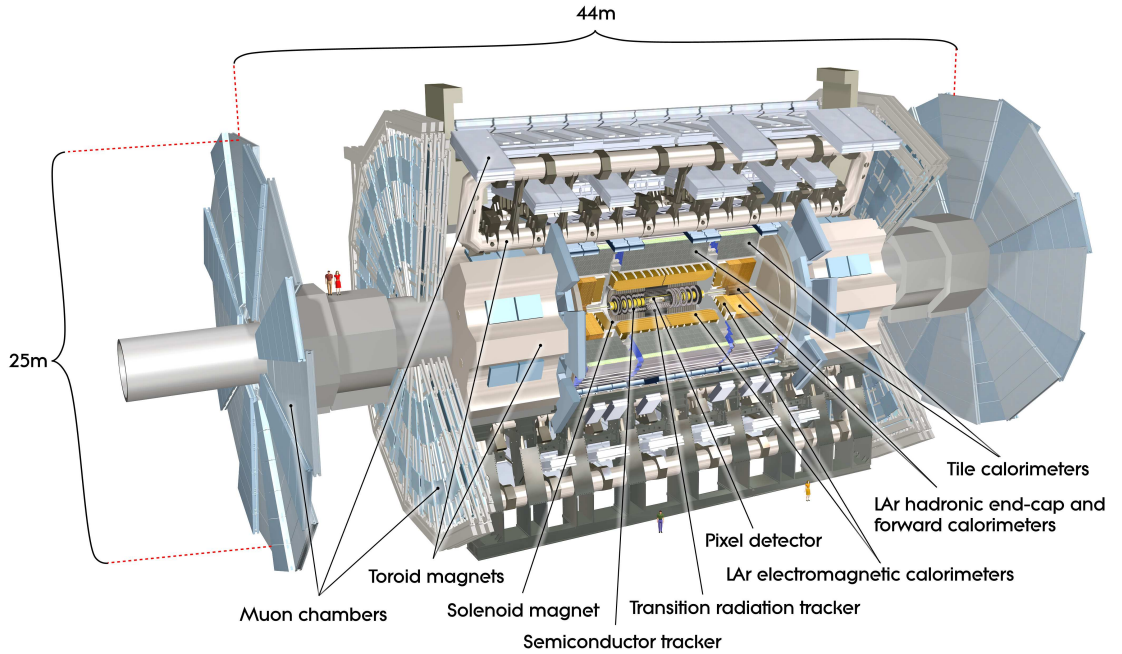


Figure 2.1: The ATLAS detector [47]. People for scale.

2.1.1 Inner Detector

The inner detector is used primarily for the tracking of charged particles. The ID consists of three sub-systems, the silicon pixel and silicon micro-strip (SCT) detectors, and the Transition Radiation Tracker (TRT), which are immersed in a 2 T magnetic field provided by the solenoid magnet [47]. The pixel detector has four cylindrical layers in the barrel (including the Insertable B -Layer (IBL) which was included after

the end of Run 1) and three endcap disks on each side, as shown in Figure 2.2 [48]. The SCT likewise has 4 cylindrical layers in the barrel, and 9 disks in each endcap. The pixel and SCT detector provide precision tracking for $|\eta| < 2.5$. The pixel barrel (endcaps) provides coverage for $R < 122.5$ mm ($R < 149.6$ mm) and $|z| < 400.5$ mm ($495 < |z| < 650$ mm), and the SCT barrel (endcaps) provides coverage for $299 < R < 514$ mm ($275 < R < 560$ mm) and $|z| < 749$ mm ($839 < |z| < 2,735$ mm). The layers of the pixel detector are segmented in $R - \phi$ and z , with a minimum pixel size of $50 \times 400 \mu\text{m}^2$ in $R - \phi \times z$ and intrinsic accuracies of $10 \mu\text{m}$ in $R - \phi$ and $115 \mu\text{m}$ in z (R) in the barrel (endcaps). The exception to this is the IBL, which is more finely segmented than the rest of the pixel layers with a pixel size of $50 \times 250 \mu\text{m}^2$ in $R - \phi \times z$ [48].

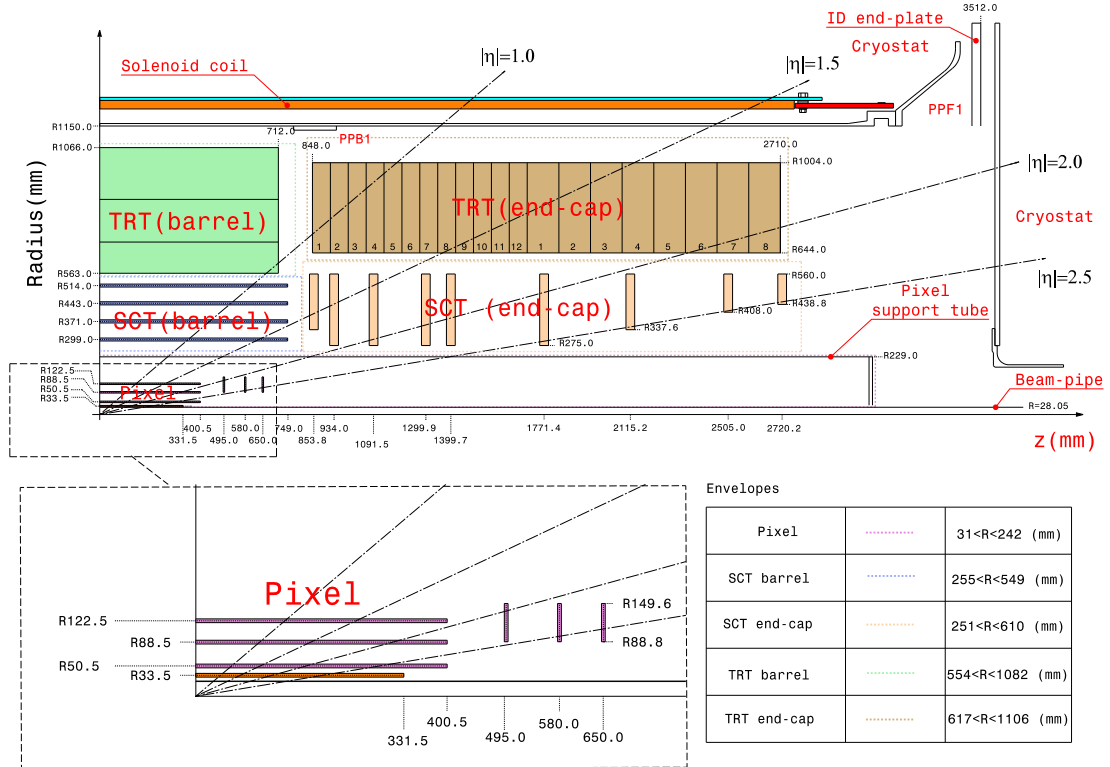


Figure 2.2: The $R - z$ cross-section of the ID of the ATLAS detector [48]. The lower-left inset shows an enlarged version of the barrel of the pixel detector, and the lower-right inset displays a table describing the radial coverage of the three ID sub-systems.

The layers in the SCT consist of micro-strip modules. Each module has two micro-strips with a stereo-angle of 40 mrad to provide space points with R , z , and ϕ information. The intrinsic accuracies of these modules in the barrel (endcaps) are $17\text{ }\mu\text{m}$ ($R - \phi$) and $580\text{ }\mu\text{m}$ (z) ($17\text{ }\mu\text{m}$ ($R - \phi$) and $580\text{ }\mu\text{m}$ (R)).

The TRT is located outside of the pixel and SCT detectors (Figure 2.2). It consists of layers of 4 mm diameter straw tubes which provide high precision momentum measurements and electron identification for tracks in a region $|\eta| < 2.0$. The straw tubes are 144 cm long in the barrel and 37 mm long in the endcaps, and thus only provide 2 coordinates per hit ($R - \phi$ in the barrel and $z - \phi$ in the endcaps). Due to the fact the TRT provides only two coordinates per hit, it is difficult to seed tracks for track reconstruction (explained in Section 4.1.3), however the TRT provides an average of 36 additional hits per track to the tracks which are seeded in the silicon sub-systems.

2.1.2 Calorimeters

Calorimetry is provided by liquid argon (LAr) electromagnetic and scintillator-tile and LAr hadronic calorimeters [47]. The electromagnetic calorimeter (ECal) covers the region $|\eta| < 1.475$ in the barrel and $1.375 < |\eta| < 3.2$ in the endcaps, with the ECal barrel divided into two by a 4 mm wide gap at $z = 0$ and the ECal endcaps divided into inner and outer wheels covering the regions $1.375 < |\eta| < 2.5$ and $2.5 < |\eta| < 3.2$ respectively. The ECal has an accordion shaped geometry, designed to prevent cracks in ϕ coverage. An active LAr pre-sampler detector covers the region $|\eta| < 1.8$ to correct for energy lost to upstream electrons and photons.

The HCal is located just outside of the ECal. A tile calorimeter barrel provides hadronic calorimetry for $|\eta| < 1.0$ and an extended tile barrel covers $0.8 < |\eta| < 1.7$. The HCal is a sampling calorimeter which uses a steel absorber in addition to the active scintillating tiles.

Like the ECal, the HCal uses LAr cryostats in the endcaps. A Hadronic Endcap Calorimeter, is found just outside of the ECal in $|z|$ with two wheels of wedge-shaped modules providing coverage from $|\eta| = 1.5$ to $|\eta| = 3.2$ [47], and a Forward LAr endcap extending the pseudorapidity coverage of the calorimeters out to $|\eta| < 4.9$.

2.1.3 Muon Spectrometer

The muon spectrometer consists of four sub-systems, which are shown in Figure 2.3. Precision tracking is provided in the barrel and endcaps by the Monitored Drift Tubes (MDTs) up to $|\eta| < 2.7$, and in the endcaps by the Cathode Strip Chambers (CSCs) in a range $2.0 < |\eta| < 2.7$. Triggering and additional tracking information is provided in the barrel up to $|\eta| < 1.05$ by the Resistive Plate Chambers (RPCs) and by the Thin Gap Chambers (TGCs) in the endcaps for $1.05 < |\eta| < 2.7$ (the triggering capabilities extend to $|\eta| < 2.4$) [47].

The MDTs in the barrel are arranged in three cylindrical layers, at radii of 5 m, 7.5 m, and 10.0 m (like in the calorimeter, there is a small gap at $|z| = 0$), and in three endcap layers on each side at $|z|$ positions of 7.4 m, 14.0 m and 21.5 m [47]. The CSCs are located in the endcaps at $|z|$ positions at 7.4 m. The MDTs in the barrel are submerged in a magnetic field providing 1.5-5.5 Tm of bending power, whereas the MDTs located in the endcaps are all outside of the magnetic field regions provided by the endcap toroids [49]. The tubes in the MDTs are arranged in two multi-layers (MLs), with 3-4 layers of drift tubes each. These tubes are 30 mm in diameter and can measure the drift radius of a charged particle with a resolution of $80 \mu\text{m}$, but are 2-5 m long and thus can only provide very rough measurements in ϕ . The ϕ coordinates are therefore taken from measurements in the RPCs and TGCs.

In order to provide triggering information, the RPCs are arranged in three layers in the MS barrel at 7.820 m, 8.365 m, and 10.229 m. Each layer of RPCs has two detector layers, each providing η and ϕ measurements (meaning there are two measurements

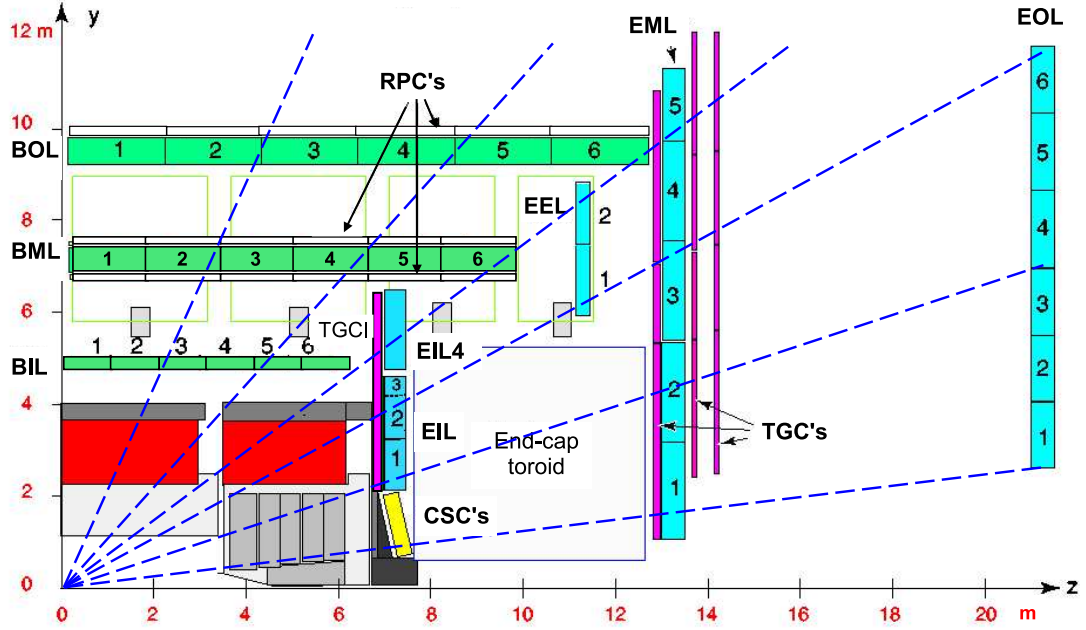


Figure 2.3: The $R-z$ cross-section of the MS of the ATLAS detector [49]. The MDTs are shown as green (cyan) blocks in the barrel (endcaps), the CSCs are represented in yellow, the TGCs in purple, and the RPCs as black lines. The dashed blue lines represent possible paths of high energy μ 's through the MS.

of η and ϕ provided for each RPC layer a charged particle passes through). The large gap between the middle and outer layers facilitates triggering on charged particles with high transverse momentum (p_T), of $9 < p_T < 35$ GeV, and the smaller gap between the inner and middle layers allows for a low- p_T trigger.

In the endcaps, the TGCs are arranged in 9 total layers on each side, a doublet layer just before the innermost MDT layer, and two doublets and a triplet surrounding the central MDT layer (see Figure 2.3). The TGC chambers are equipped with anode wires and cathode strips which provide precision η and ϕ measurements respectively. The cathode strips are arranged to have an azimuthal granularity of 2-3 mrad, and the anode wires to have a wire-to-wire distance of 1.8 mm, in order to have a sufficient granularity for the required momentum resolution of the triggers.

2.1.4 Trigger System

In Run 2 of the LHC, the ATLAS experiment made use of a two-level trigger system, with a level-1 (L1) hardware trigger and a high level software trigger (HLT), which reduced the event collision rate of 40 MHz to 100 kHz and then to approximately 1 kHz [50], demonstrated schematically in Figure 2.4.

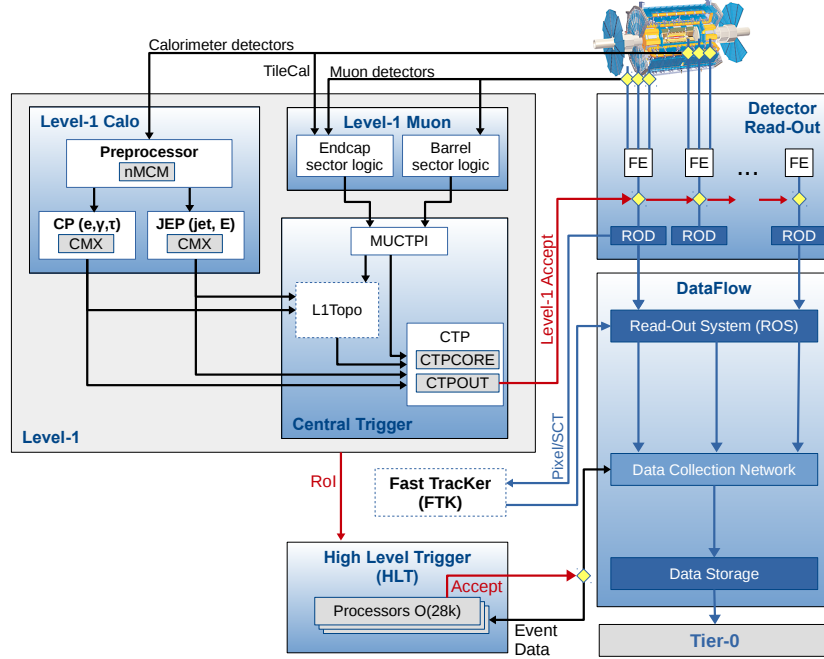


Figure 2.4: A schematic representation of the ATLAS L1 and HLT trigger system [50]. The FTK shown here is still being commissioned and was not employed during 2016 data taking.

The L1 trigger is based on hardware, taking inputs from the calorimeters and MS, as well as the Minimum Bias Trigger Scintillators [51], the LUCID detector [52], and the Zero-Degree Calorimeter [53]. A Central Trigger Processor (CTP) takes the information from these sub-detectors and selects events based on an input trigger menu of different trigger options. The triggers in this menu may be pre-scaled, in other words to reduce the rate of triggers which may arrive very frequently, the CTP can be told to only select a certain fraction of events passing a given trigger. The L1 trigger will identify and pass along information about Regions-of-Interest (RoIs) which are

$\eta - \phi$ regions around interesting features in the event such as high energy μ 's, γ 's, etc. The L1 trigger can either apply a simple or complex dead-time to reduce the trigger rates. A simple dead-time enforces a minimum number of non-accepted events after each L1 trigger, while the complex dead-time restricts the number of events passing the L1 trigger over the course of a given number of total bunch-crossings.

The HLT is a software-based trigger which takes as input the event and RoI information from L1 and uses it to perform limited object reconstruction. The HLT uses a more complex trigger menu to apply a final selection to events, which are then exported for permanent storage and offline reconstruction. Pre-scaling may also be applied to triggers at the HLT.

CHAPTER 3

SAMPLES

3.1 Data

The data samples used by this analysis were proton-proton events collected by the ATLAS detector in 2016. In 2016, the LHC delivered an integrated luminosity of 38.5 fb^{-1} , 35.6 fb^{-1} of which were collected by the ATLAS detector, as shown in Figure 3.1a. Of the data collected, 33.0 fb^{-1} passing data quality standards are used for this analysis. In the proton-proton collision data collected by the ATLAS detector, the number of mean interactions per crossing $\langle\mu\rangle$ was designed to be much greater than one to increase the likelihood of interesting physics occurring in any given bunch crossing. During the 2016 data collection period, the average $\langle\mu\rangle$ in ATLAS events was 24.9, as shown in Figure 3.1b.

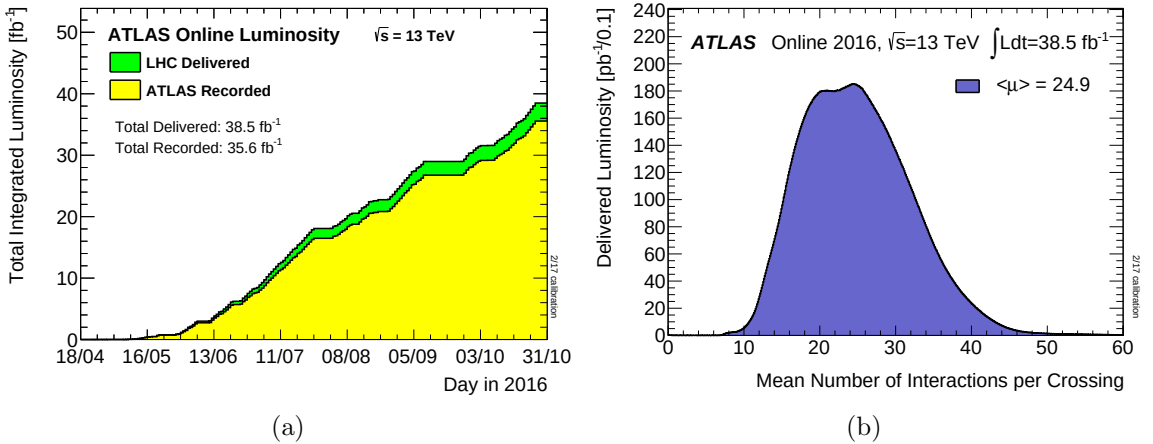


Figure 3.1: The (a) integrated luminosity delivered by the LHC and collected by the ATLAS detector in 2016 p-p data and (b) the mean number of interactions per crossing in the events in ATLAS during that time [54].

The data used by this analysis was collected as part of the ‘RPVLL’ filter stream, which is a collection of triggers and offline filter requirements used by groups of analyses looking for non-standard physics signatures. The importance of the RPVLL filter stream is that all the data events collected in this stream underwent the specialized displaced tracking and vertex reconstruction described in Section 4.

The data used by this analysis was collected by two triggers. The data used in the signal region was collected by the muon RoI cluster trigger, described in Section 5.1.1, which was designed specifically to select events with a displaced hadronic decay after the last layer of the HCal and in the MS. The data in the signal region is also required to contain reconstructed vertices in the MS and ID, described in Sections 5.2 and 5.3 respectively.

Events collected by the muon RoI cluster trigger are also used in a modified ABCD plane used for the background estimation (Section 6) and the regions used to validate the background estimation method.

The other trigger used in this analysis was the `HLT_mu26_ivarmedium` trigger, which selects a medium muon (described in Section 4.1.2) with $p_T \geq 26$ GeV. This trigger is used as part of a background event selection designed to minimize the signal contamination.

3.2 Simulation

3.2.1 Generation of MC samples

In order to study the performance of reconstruction techniques, to understand the trigger and selection efficiencies, and to determine appropriate selection requirements for the analysis, generated Monte Carlo (MC) samples are used. Creating MC samples is a multi-step process that begins with the calculation of the matrix elements of the physics processes of interest. The matrix elements are typically calculated to leading

order (LO) or next-to-leading order (NLO) from the partons¹ in the proton-proton collision, using parton distribution functions (PDFs). The partons are then showered, and the constituents of the parton showers are formed into colorless hadrons.

In addition to the physics process of interest, underlying event (UE) is generated. The UE can include initial and final state radiation, interactions with the beam remnants, and additional hard scatters [55]. The generation of the UE is not as well understood as much of the rest of the MC generation, which is in part why using a data-driven background estimation is important.

After the generation is complete, hadrons are made to travel through the detector, and the interactions with the detector are simulated using GEANT4 [56]. Finally, the MC events are digitized, the energy deposits left on the layers of simulated detector material are turned into detector signals like those that would be found in the real ATLAS detector.

Samples are also generated to model the $\langle\mu\rangle$ found in the data events, and these samples are overlaid on the signal MC samples. The $\langle\mu\rangle$ distribution generated is not exactly equal to that found in data, so a pileup reweighting (PRW) is applied to make the $\langle\mu\rangle$ distribution in the MC events match the $\langle\mu\rangle$ distribution in data, as shown in Figure 3.2.

3.2.2 Signal MC samples

The signal MC events used for this search were generated using MadGraph5_aMC@NLO 2.2.3 [57]. The decay products in the events were then showered using Pythia 8.210 [58], using the EvtGen 1.2.0 [59] generator to simulate the properties of the b - and c - hadron decays and using the A14 set of tuned parameters [60] and the

¹Partons are the constituents of a hadron, the quarks, the gluons that hold the quarks together, and a “sea” of virtual quark and anti-quark pairs that are generated by the gluons.

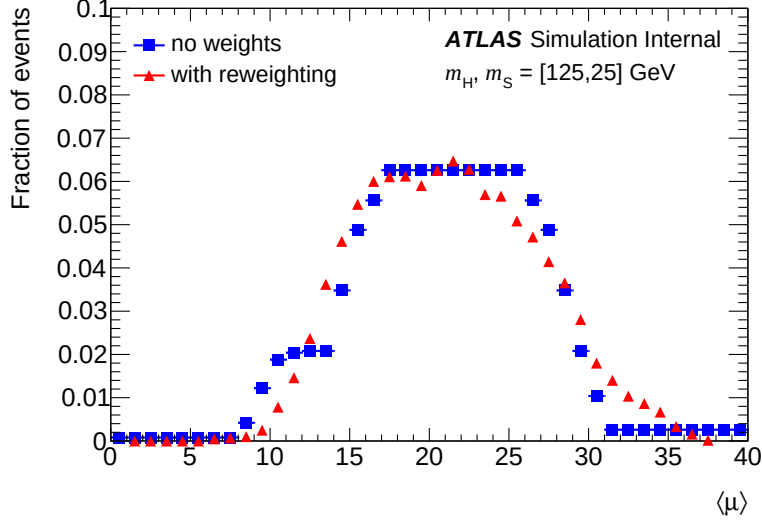


Figure 3.2: The $\langle\mu\rangle$ distribution in a MC sample, without pileup re-weighting applied (blue squares) and with the re-weighting applied (red triangles).

NNPDF2.3LO PDF set [61] for the UE and hadronization. All the signal MC samples underwent the same special reconstruction as the data events.

As discussed in Section 1.2.1, this analysis uses a simplified HS model (Figure 1.4), in which a heavy scalar propagator Φ connects the SM to the HS, where it will decay to long-lived scalars, which eventually decay back to the SM. The Φ was chosen to be either the SM Higgs, with a mass of 125 GeV, or a heavier scalar ranging in mass from 200 to 1000 GeV. The LLP masses range from 8 GeV to 400 GeV, depending on the mass of the Φ . All the mass points are laid out in Table 3.1. The lower limit on the LLP mass is determined by the reconstruction efficiency and background rejection for the inner detector vertices, while the upper limit on the LLP masses relate to the kinematics of each Φ decaying to two LLPs.

Two mean lab-frame lifetimes were generated for each signal MC mass point (the mean lab-frame lifetimes were held constant by adjusting the generated mean proper lifetime for each mass point). The signal MC samples were shared by this analysis, concerned with decays in the ID, as well as the CR and MS analyses which focused

Higgs or Φ mass [GeV]	LLP mass [GeV]	5m lab-frame lifetime $c\tau$ [m]	9m lab-frame lifetime $c\tau$ [m]
125	8	0.200	0.375
125	15	0.580	0.710
125	25	0.760	1.210
125	40	1.180	1.900
125	55	1.540	2.730
200	8	0.170	0.290
200	25	0.540	0.950
200	50	1.070	1.900
400	50	0.700	1.260
400	100	1.460	2.640
600	50	0.520	0.960
600	150	1.720	3.140
1000	50	0.380	0.670
1000	150	1.170	2.110
1000	400	3.960	7.200

Table 3.1: Signal MC samples - mass points and proper and lab-frame lifetimes.

on decays in the HCal and MS. The mean lab-frame lifetime of 5 m was chosen because there were approximately equal numbers of LLP decays in each of the sub-detectors. The second lab-frame lifetime of 9 m was chosen to provide more statistics for studies focused on the outer sub-detectors in ATLAS. Because the 5 m samples provided better statistics for the inner detector, these were used for most of the studies performed for this analysis, while the 9 m samples were used for verification of a lifetime extrapolation method (described in Section 8.1.1). The generated $c\tau$ for the 5 m and 9 m mean lab-frame lifetimes for each mass point are listed in Table 3.1.

3.2.3 Di-jet MC samples

A second set of MC samples are used in this analysis; QCD di-jet MC samples are used to compare the reconstruction of K_S^0 vertices in data and in MC events (described in detail in Section 7.1). The di-jet samples were also used by the MS analysis to determine scale factors to make up for differences in the trigger efficiency in data and in MC samples (as described in Section 5.1.1.1). The QCD di-jet samples

were generated using Pythia 8.186, again using the A14 tuned parameters and the NNPDF2.3LO PDF set.

While the cross-section for QCD jet production falls with increasing jet p_T , the di-jet samples are generated in p_T ‘slices’ of approximately one million events each in order to have sufficient statistics across the p_T range. The p_T range of each slice is shown in Table 3.2, along with the the production cross-section and the generator level filter² efficiency. To cause the shape of the jet p_T distribution in the di-jet MC samples to match the QCD jet p_T distribution in data, a scale factor of

$$\frac{\text{event weight} \times \text{cross-section} \times \text{filter efficiency} \times \text{luminosity}}{\text{number of events}} \quad (3.1)$$

is determined. The number of events is the total number of di-jet MC events used, the luminosity is that of the data sample that the di-jet MC events are compared to, and the event weights are weights applied to the events during event generation (for example an event weight of -1 may be applied during a NLO calculation to avoid duplication of processes produced both at LO and NLO).

slice	low p_T [GeV]	high p_T [GeV]	cross-section [nb]	filter efficiency
JZ0W	0	20	7.8420×10^7	1.0240×10^0
JZ1W	20	60	7.8420×10^7	6.7198×10^{-4}
JZ2W	60	160	2.4334×10^6	3.3264×10^{-4}
JZ3W	160	400	2.6454×10^4	3.1953×10^{-4}
JZ4W	400	800	2.5464×10^2	5.3009×10^{-4}
JZ5W	800	1300	4.5536×10^0	9.2325×10^{-4}
JZ6W	1300	1800	2.5752×10^{-1}	9.4016×10^{-4}
JZ7W	1800	2500	1.6214×10^{-2}	3.9282×10^{-4}

Table 3.2: The di-jet MC sample slices’ p_T ranges, cross-sections, and filter efficiencies.

²A filter may be applied to generated MC events, it is a factor that takes into account that the full cross-section of a given physics process is not being generated, but rather a subset of events that are more likely to pass some selection criteria.

CHAPTER 4

RECONSTRUCTION

4.1 Standard objects

4.1.1 Jets

In the ATLAS detector, jets are reconstructed from energy deposits in the ECal and the HCal. Nearby calorimeter cells with energy above a noise threshold are built into three-dimensional topological clusters [62]. The energy of the calorimeter cells is measured at the electromagnetic energy scale, assuming the energy is associated to electrically charged particles. The jets are reconstructed using the software FASTJET 2.4.3 [63]. Jets with $p_T > 7$ GeV are reconstructed using the anti- k_t algorithm [64].

The anti- k_t algorithm is a jet clustering algorithm which clusters particles according to

$$\begin{aligned}
 d_{ij} &= \min(k_{ti}^{2p}, k_{tj}^{2p}) \frac{\Delta_{ij}^2}{R^2}, \\
 d_{iB} &= k_{ti}^{2p}, \\
 p &= -1
 \end{aligned}
 \tag{4.1}$$

in which d_{ij} is the distance between particles and d_{iB} is the distance between a particle and the beam, R is the radius parameter of the jet, and $\Delta_{ij} = (y_i - y_j)^2 + (\phi_i - \phi_j)^2$ (k_{ti} and y_i are the transverse momentum and rapidity of a given particle). The particles are clustered together based on the smallest d_{ij} or d_{iB} until there are none left. The $p = -1$ is what defines the “anti- k_t ” method, which is resilient to the pileup and UE in the LHC [64]. The jets used in this search are reconstructed with $R = 0.4$.

4.1.2 Muons

Muons are reconstructed in the ATLAS inner detector, making use of the same standard tracking as is used for all charged particles (described in the following Section 4.1.3), as well as in the muon spectrometer. Muon tracks in the MS are built primarily from hits left in the MDT chambers and the nearby triggering (RPC or TGC) chambers [65] (the CSC provides some coverage in the high η region, $|\eta| > 2.0$). Straight-line segments are reconstructed using the hits in each MDT chamber, and a Hough transform [66] is used to search for corresponding hits along a plane based on the particle's momentum in the magnetic field in the MS. The hits from the RPC and TGC chambers provide the η and ϕ measurements which are orthogonal to this plane.

Candidates for muon tracks are created by combining the individual straight-line segments from different chambers. The muon tracking algorithm starts with the segments in the middle layers of the detector, where there are the most trigger hits, and then extends to the outer and inner layers. The segments are matched based on their relative positions and directions, and are subjected to hit multiplicity and fit quality criteria, as well as being required to point back to the approximate region of the IP. In general, a muon track candidate requires at least two matching segments, with the exception of candidates in the barrel-endcap transition region of the MS, where one high quality segment may be used. During the muon track creation, one segment is allowed to be associated to multiple tracks. These shared segments may be either assigned to the muon track with which it has the better fit, or may be allowed to be shared by the muon tracks in certain situations. For example, if two muon tracks have segments in three different layers, they are allowed to share segments in two of those layers so long as they diverge in the third. This allows for higher efficiency in cases when muons are very close together.

The hits in the muon track candidates are fitted using a global χ^2 fit, and the track candidate is accepted given that this χ^2 passes the selection criteria for the muon. Hits may be removed from the muon track candidate if they contribute very poorly to the fit, and hits along the track trajectory may be added into the track; in both these cases, the χ^2 fit is redone after the addition or removal of the hits.

Muon tracks may then be combined with the tracks formed in the ID in one of several different ways.

Combined Muons (CB muons) may be formed when independently reconstructed tracks in the ID are matched to the muon tracks reconstructed in the MS, with a global refit that uses the tracks in both sub-detectors. CB muons are typically formed when a track in the MS is extrapolated inwards and matched to a track in the ID, but some CB tracks are formed by extrapolating the ID tracks outwards.

Segment-tagged muons (ST muons) may be formed when tracks in the ID are matched with at least one MDT or CSC segment. ST muons are useful for muon tracks that have a low p_T and therefore are not able cross multiple layers in the MS, or for regions with poor MS coverage.

In some cases when there is no reconstructed track in the MS, a *Calorimeter-tagged muon* (CT muon) may be reconstructed. This is the case when an energy deposit in the calorimeters consistent with a muon is matched to a track in the ID. While the fake rate of muons reconstructed in this manner is higher than for other types of muon reconstruction, CT muons increase the efficiency to reconstruct muon tracks in regions of the detector in which the MS loses some coverage in order to make room for cables and other services for the ID and the calorimeters, specifically in the region of $|\eta| < 0.1$.

Finally, *Extrapolated muons* (ME muons) are formed when the muon track is reconstructed solely in the MS, and is required to be pointing roughly towards the IP. In order to provide track measurements, the ME muons must pass through at

least two layers of MS chambers, and at least three if they are reconstructed in the forward region. ME muons extend the ability to reconstruct muons in the the region $2.5 < |\eta| < 2.7$, which is not covered by the ID.

If multiple muons reconstructed using different methods share the track in the ID, CB muons are chosen over ST muons and ST muons over CT. If multiple muons reconstructed using different methods share the track in the MS, overlaps are resolved based on the of hits per track and the track quality.

Once muon tracks have been reconstructed, they are given an identification based on certain quality criteria. In general, muons used in analyses are *medium* muons (like the muons used in the background event selection, as mentioned in Section 3.1). Medium muons use only CB and ME muons. Medium CB muons are required to have ≥ 3 hits in two or more MDT layers throughout most of the detector, and in at least one MDT layer and $\leq$ one MDT hole in the region $|\eta| < 0.1$. ME medium muons are required to have $\geq$ three MDT or CSC layers and are required to be in the $2.5 < |\eta| < 2.7$ region, outside the ID η acceptance. Furthermore, in order to reduce the contamination from misidentified hadrons, the q/p significance, the absolute value of the q/p of the muons over their uncertainties, must be < 7 .

Muons may be identified as *loose*, a category which contains all medium CB and ME muons, as well as ST and CT muons in the region $|\eta| < 0.1$. Loose muons are used in situations that call for maximum efficiency. *Tight* muons are used in situations calling for a maximum purity at the expense of some efficiency. Tight muons consider only CB muons with hits in at least two different MS stations, which satisfy the medium requirements, and have a normalized χ^2 which is < 8 . Tight muons also have an extra selection on the q/p significance and the difference of the p_T of the ID and MS tracks, as a function of the CB muon p_T . Finally, *high* p_T muons are those CB muons which pass the medium selection and have ≥ 3 hits in three different MS

stations. The high p_T muon identification is meant to optimize muons with $p_T > 100$ GeV.

4.1.3 Standard tracks

Tracks are reconstructed in the inner detector using the hits deposited by charged particles. The main standard tracking pass used by the ATLAS experiment reconstructs tracks in an *inside-out* manner. In this *inside-out* tracking pass, track seeds, collections of three space points¹, are formed in three distinct layers in the pixel and SCT sub-detectors (seeds may be made of all pixel or all SCT space points, or a combination from both sub-detectors) [67]. Seeds must pass some requirements on momentum and impact parameter, as well as on the distances between the space points (tracking parameters are estimated assuming a perfectly helical track structure, ignoring any radiative energy loss, etc). If the seeds pass these requirements, a window search is performed, and all hits in the window are put into a combinatorial Kalman filter [68] in order to create track candidates. A seed may only lead to one track candidate, and for the candidate search to be successful, the track candidate must have a minimum number of hits and those hits must not be associated to another track candidate.

Successful track candidates are passed through an ambiguity solver. The purpose of this ambiguity solver is to cut down on the incidence of fake tracks, formed from combinatorial collections of hits rather than hits left by a true particle passing through the inner detector. This is achieved by assigning a score to the track candidates. These scores are based on the hits in the track candidates (weighted by where in the detector

¹Space points may be created from one cluster in the pixel detector, which gives local 2-dimensional coordinates (on a module, giving 3-dimensional coordinates overall). In the SCT however, a cluster on a single strip will not give enough information, so space points are formed from a pair of SCT clusters on corresponding strips in the axial and stereo directions [67].

the hits were), with the score being lowered by the existence of any holes² in the track. The track scores also take into account the χ^2 of the track fit. Track candidates that survive the ambiguity solver also must pass the track parameter requirements listed for ‘standard’ tracks in Table 4.1.

Successful track candidates may be extended into the TRT (all tracks are passed through the TRT extension, tracks which fail the extension are kept in the final track collection). The straw tube structure of the TRT means that each TRT hit can only provide a set of two-dimensional coordinates, however it can provide an average of 36 additional hits to existing tracks that are extended into the TRT. In the TRT extension, hits compatible with the existing track candidate are assigned to that track, the quality of this extension is then evaluated using the track fit and a scoring similar to that used in the ambiguity solver. If the TRT extension has at least 9 TRT hits and improves the quality of the track fit, then the track is considered to have been successfully extended into the TRT. The TRT extension may fail if the track is unable to be extended into the TRT, in this case the track is still kept (this may happen if the $|\eta|$ of the track is too high, as the $|\eta|$ limits of the TRT are smaller than those of the silicon sub-detectors). Furthermore, the track extension may be rejected, this may be due to the presence of too many TRT outliers³ or a too high fraction of TRT tube hits⁴.

There is a second standard tracking pass known as the *outside-in* tracking pass. In this tracking pass, standalone segments in the TRT are seeded with deposits in the ECal. The standalone TRT segments may be extended back into the silicon

²A hole is where a silicon hit was expected but none was found.

³Initially, a TRT outlier is a hit for which the track associated to it passes outside of the straw tube by $\geq 100\mu\text{m}$. After a TRT extension is rejected, all TRT hits associated to it will be marked as outliers.

⁴A TRT tube hit is one for which the signal has no leading edge, or one for which the track does not pass through the drift circle of the tube.

sub-detectors, using the hits that were not used during the inside-out pass (non-extended TRT standalone segments are kept and used for photon conversions). These tracks may be slightly displaced, but are still subject to the same impact parameter requirements as the inside-out tracks listed in Table 4.1.

4.2 Displaced tracking

The standard track reconstruction in ATLAS is optimized for the reconstruction of tracks left by prompt decays in the inner detector, however the efficiency falls rapidly with the displacement of the decay. For this reason, a third tracking pass is run, known as a *large radius* tracking pass (LRT), using the hits leftover from the standard tracking passes. This large radius tracking is performed in a similar manner to the inside-out tracking, but with looser requirements on various track parameters in order to increase the efficiency of reconstructing highly displaced tracks [69]. The differences between the requirements on track parameters and number of hits in the standard and large radius tracking passes are laid out in Table 4.1. The requirements on the longitudinal and transverse impact parameters, $|d_0|$ and $|z_0|$ are relaxed from 10 mm to 300 mm, and from 250 mm to 1500 mm respectively. The requirements on the number of unshared silicon hits are also relaxed in order to increase the efficiency of the large radius tracking. The seed extension furthermore uses a sequential instead of a combinatorial Kalman filter, due to the increase in the possible number of track candidates for any given seed.

As with the standard tracks, the large radius tracks candidates within the appropriate $|\eta|$ range are also extended into the TRT. After the large radius tracking pass is complete, the large radius tracks are merged into a final track collection containing both the standard and large radius tracks.

Figure 4.1 demonstrates the impact of large radius tracking pass on the resulting vertex reconstruction efficiency in one of the samples used for the analysis. As demon-

Track parameter	Standard	large radius
Maximum $ d_0 $ [mm]	10	300
Maximum $ z_0 $ [mm]	250	1500
Minimum p_T [MeV]	400	500
Maximum $ \eta $	2.7	5.0
Minimum silicon hits	7	7
Minimum unshared silicon hits	6	5
Maximum silicon holes	2	2
Seed extension	Combinatorial	Sequential

Table 4.1: Track parameter requirements for inside-out standard and large radius tracks

strated, the vertex reconstruction efficiency without large radius tracks is greatly reduced after 10-20 mm compared to those with the large radius tracks.

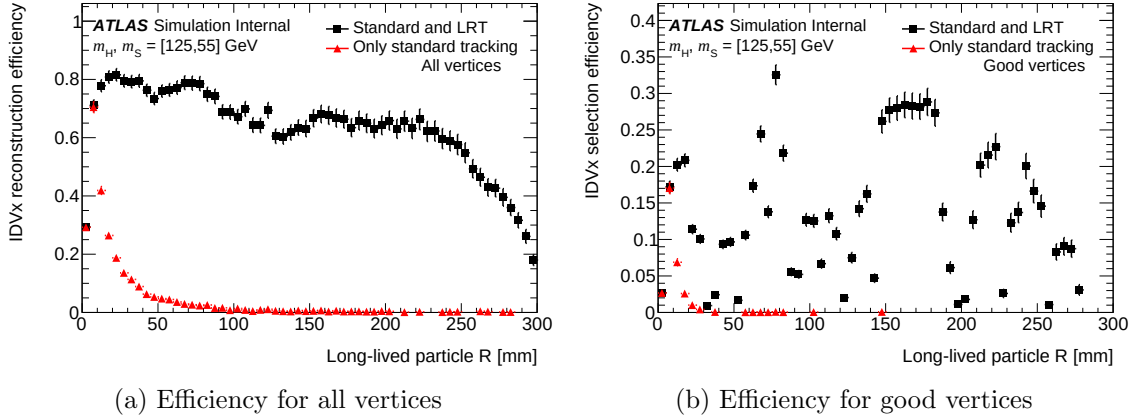


Figure 4.1: Comparison of the vertex reconstruction efficiency for a Higgs boson decaying to a 55 GeV mass LLP, using only standard tracking vs using standard and large radius tracking for (a) all reconstructed vertices in the signal MC samples and (b) vertices passing the IDVX selection criteria used in the analysis.

The large radius tracking pass is very CPU intensive and thus is not run by default. The large radius tracking has to be specially reconstructed on all samples used for the analysis described here. Information about the performance studies conducted on the large radius tracking is presented in Appendix A.

4.3 Displaced vertices in the ID

In addition to the specialized large radius tracking, a special secondary vertexing algorithm is used to reconstruct the decays of the LLPs in the ID. This special vertexing algorithm takes tracks from the combined track collection which have a $|d_0|$ of ≥ 2 mm [11] (a provision which is intended to exclude tracks from prompt decays). The tracks used for the vertexing are also required to have a $p_T > 1$ GeV, and have either ≥ 2 pixel hits or a successful TRT extension, in order to increase the quality of the tracks used in the displaced vertices.

The vertexing algorithm takes these tracks and forms a set of two-track vertex-seeds of all possible pairs of intersecting tracks using an iterative process based on the incompatibility-graph method [70]. The tracks in the vertex-seeds are required to have no hits on layers of the inner detector before the position of the vertex (between the IP and the vertex), and are required to have a hit on the next available layer of material (unless the vertex position is within or very close to the next available layer). Any track that is shared between two or more different vertex-seeds is assigned to the one with which it has the best fit. This process is continued until each track is only assigned to one vertex-seed.

The vertex-seeds are merged in a multi-step process. First, any two vertex-seeds that are within $d/\sigma_d < 3$ of each other will be merged (d refers to the 3-dimensional distance between the vertex-seeds, and σ_d is the uncertainty in the distance). This continues until all seed vertices within $d/\sigma_d < 3$ of another seed-vertex are merged together. During this merging step, the fits of the tracks in the newly merged vertices are re-evaluated, and poorly associated tracks are removed from the merged vertices. All vertices are required to have a $\chi^2/\text{nDoF} < 5$. Finally, all vertices within 1 mm of each other are merged and the tracks are again re-tested for their fit with the merged vertices.

4.4 Displaced vertices in the MS

The standard vertex reconstruction algorithms in the MS are designed to reconstruct decays from muons, which look very different from the displaced, hadronic decays of LLPs. A special reconstruction algorithm was developed in Run 1 to be optimized for these decays with large numbers of low p_T decay products [49]. This algorithm makes use of the MLs in each of the MDT chambers. Straight-line segments are constructed with ≥ 3 hits in each of the MLs, and then the straight-line segments from the two MLs are matched to create tracklets in each chamber (see Figure 4.2).

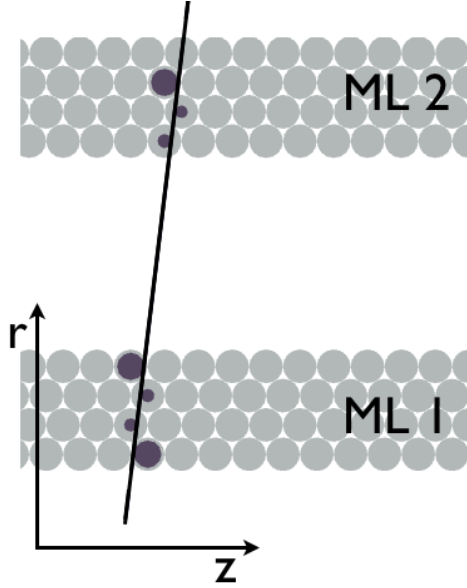


Figure 4.2: The construction of tracklets from straight-line segments in each ML of the MDT chambers [49].

The tracklets within $\Delta\eta < 0.7$, $\Delta\phi < \pi/3$, are then grouped into clusters using a cone algorithm [13], making use of the ϕ information in the RPC (TGC) chambers in the barrel (endcaps). The LLP line of flight is calculated in η and ϕ , and the tracklet clusters are mapped into a single r - z plane based on the ϕ line of flight. The vertexing then proceeds differently in the barrel and in the endcaps due to the fact the MDT chambers in the barrel are submerged in the magnetic field, and the MDT chambers in the endcaps are not. In the barrel, tracklets are extrapolated back

towards the IP through the magnetic field, and the position of the vertex is taken to be the radius and the z-position on the line with the largest number of tracklets used to create the vertex. The vertices are required to have a χ^2 probability of $> 5\%$, if it is less than 5% , the worst fitting tracklet is dropped and the vertex position is recalculated. This process is repeated until the χ^2 probability is sufficiently high, or until the number of tracklets is < 3 , at which point the vertex is discarded. In the endcap, the tracklets are extrapolated back linearly to the endcap toroid, and the vertex position is calculated using a least-squares fit. If tracklets are > 30 cm from the vertex, they are dropped and the vertex position is recalculated. Vertices are again required to have ≥ 3 tracklets.

One repercussion of having two different vertex reconstruction algorithms in the barrel and the endcaps of the MDTs is that LLP decays in the crack region between the barrel and the endcaps may have their decay products split between algorithms. This sometimes results in one LLP decay being reconstructed as two separate vertices in the MS, but commonly the splitting of the decay products means that there are not enough tracklets in either the barrel or in the endcap to reconstruct a single vertex. For this reason, the $|\eta|$ region $0.8 \leq |\eta| \leq 1.3$ is excluded from the fiducial region of the muon spectrometer vertices (MSVXs) [13].

CHAPTER 5

SELECTION

It is necessary to employ measures to sift through the many events collected by the ATLAS detector, to eliminate events with bad data quality and to examine only the events that are likely to contain interesting signal. Similarly, many vertices may be reconstructed that are from SM decays or from other background processes, and there must be a way to find those that are interesting amongst the noise.

5.1 Event Selection

A *good run list* (GRL) is prepared by a dedicated group working in the ATLAS experiment, which includes only ATLAS runs meeting certain data quality standards related to hardware and data-taking issues. The events used in the analysis must be included in the GRL and must pass the quality standards for the SCT, LAr, and Tile sub-detectors. In addition, the events are required to include a primary vertex (PV), a vertex associated with the IP with at least two tracks of p_T of ≥ 400 MeV. If more than one vertex exists meeting these criteria, the PV is taken to be the one with the highest combined p_T of all tracks in the vertex.

5.1.1 Trigger

The events included in the signal region of this analysis must pass a special muon RoI cluster trigger designed during Run 1 for the search for displaced decays in the MS [71]. The trigger employed during Run 2 differs from the Run 1 trigger only in that the trigger used in this search no longer includes the isolation requirements described in [71].

This trigger uses an L1 trigger which looks for 2 muon RoIs¹. Once there is some level of activity guaranteed in the MS, at the HLT the trigger searches for evidence of the LLP decays. Long-lived particle decays after the end of the HCal and before the first trigger plane of the MS are characterized by clusters of muon RoIs around the LLP line of flight. Thus, at the HLT the trigger looks for clusters of 3 (4) muon RoIs in a $\Delta R = \sqrt{\Delta\eta^2 + \Delta\phi^2} = 0.4$ cone in the barrel (endcaps) of the MS. Due to the specialized nature of the muon RoI cluster trigger leading to a relatively low acceptance rate, there were no further event level requirements needed to reduce the rate of the data collection.

The events that pass the triggers used in the event selection from the CR analysis [14] are vetoed for this analysis (these triggers were designed to select late decaying jets which are trackless and which leave a large fraction of their energy in the HCal as opposed to the ECal.). These events were explicitly vetoed in order to facilitate combining the results of the two searches.

5.1.1.1 Scale factors for the muon RoI cluster trigger

The simulation of the L1 muon RoI efficiency is not exactly the same as the trigger efficiency in data, thus scale factors were developed by the MS analysis [13] to compensate for these differences. In order to determine appropriate scale factors for this trigger, punch-through jets (jets that punch through from the calorimeters into the muon spectrometer) were used. High-energy punch-through jets are likely to create clusters of muon RoIs in the MS just as the signal vertices would, and are identifiable in both data and in MC samples. The average number of muon RoI clusters in a $\Delta R = 0.4$ cone around jets with $E_T > 400$ GeV were calculated in data and in di-jet MC samples. The number of clusters around the jets was found to be

¹A muon RoI is a coincidence of hits in at least 3 of the 4 inner RPC layers (the outer 2 TGC layers) in a $0.2 \times 0.2 \Delta\eta \times \Delta\phi$ ($0.1 \times 0.1 \Delta\eta \times \Delta\phi$) in the MS barrel (endcap).

independent of both the η (besides the barrel vs endcap distinction) and the p_T of the jet in question, so flat scale factors were set for triggers in the MS barrel and endcaps of 1.13 ± 0.01 and 1.04 ± 0.02 , respectively.

5.2 MS vertex selection

Events that pass the event level selections are required to include a reconstructed MSVX meeting several requirements which were refined by the MS analysis [13]. The MSVX must be matched within $\Delta R < 0.4$ cone to the muon RoI cluster that fired the trigger. The MSVX must also be in the fiducial volume $|\eta| < 0.8$ or $|\eta| > 1.3$ as described in Section 4.4. Due to the presence of a crack region in the HCal overlapping with the excluded MDT crack region, and the prevalence of punch-through jets (a source of background for the MSVXs), the excluded $|\eta|$ region is expanded to $0.7 \leq |\eta| \leq 1.3$.

In order to discriminate between the MSVXs left by LLP decays, and between background coming from cosmic particles, noise bursts, and high energy QCD jets that punch through into the MS, the MSVXs are each required to have between 300 and 3000 associated hits in the MDT chambers, and to have at least 250 associated hits in the RPC (TGC) chambers in the barrel (endcaps).

To reduce the contribution of multi-jet background, the MSVXs are required to be isolated from activity in the inner detector and calorimeters. The MSVX thus must be isolated by $\Delta R > 0.3$ (0.6) in the barrel (endcaps) from any tracks in the inner detector that have a $p_T > 5$ GeV. The Σp_T of all inner detector tracks in a $\Delta R = 0.2$ cone around the MSVX must be < 10 GeV. (The tracks used in the isolation are those that are considered to be associated to the PV).

Furthermore, the MSVXs are required to be isolated by $\Delta R > 0.3$ (0.6) in the barrel (endcaps) from jets that have a $p_T > 30$ GeV. The jets used in the isolation are required to be matched to the PV using a jet vertex tagger (JVT) discriminant [72].

The application of the JVT selection is designed to suppress jets from pileup by taking into account the scalar Σp_T of all tracks associated to the jet which stem from the PV, compared to the scalar Σp_T of the tracks associated to the jet coming from pileup interactions. The jets used in the isolation are also required to have $\log_{10}(E_{\text{HAD}}/E_{\text{EM}}) < 0.5$, which ensures that the jets deposited the majority of their energy in the ECal. This is enforced because hadronic decays from LLPs which occur late in the HCal may leave enough energy in the MS to form a valid MSVX, and these decays should not be excluded from the signal region.

All of the selection requirements on the MSVXs are summarized in Table 5.1

MSVX parameter	Barrel	Endcap
ΔR separation from trigger cluster	< 0.4	< 0.4
MSVX $ \eta $	< 0.7	> 1.3
Number of precision hits	$300 < n_{\text{MDT hits}} < 3000$	
Number of trigger hits	$n_{\text{RPC hits}} > 250$	$n_{\text{TGC hits}} > 250$
Isolation from > 5 GeV tracks	$\Delta R > 0.3$	$\Delta R > 0.6$
Σp_T of tracks in a $\Delta R = 0.2$ cone	< 10 GeV	< 10 GeV
Isolation from > 30 GeV jets	$\Delta R > 0.3$	$\Delta R > 0.6$

Table 5.1: Requirements of the MSVXs in events used in the analysis, from the work presented in [13].

5.3 ID vertex selection

Events are also required to contain a displaced vertex in the inner detector (IDVX) which passes a variety of requirements in order to discriminate against background vertices that arise from prompt decays, interactions with the material in the inner detector, and fake vertices from the random crossing of tracks or the accidental crossing of a track over a real vertex. All selections described below are collected in Table 5.2.

The IDVXs are required to have a $\chi^2/n_{\text{DoF}} < 5$ for a measure of basic quality control. IDVXs also must be separated from the PV by a radial distance of > 4 mm in order to eliminate as many prompt b -decays as possible.

IDVX parameter	Requirement
χ^2/n_{DoF}	< 5
Radius from PV	$> 4 \text{ mm}$
Vertex R	$< 300 \text{ mm}$
Vertex $ z $	$< 300 \text{ mm}$
Pass material veto and disabled module veto	
m_{IDVX}	$> 3 \text{ GeV}$
Vertex n_{trk}	≥ 4
ΔR from nearest good MSVX	$\Delta R > 0.4$

Table 5.2: Requirements of the IDVXs in events used in the analysis.

The IDVXs considered are those within a fiducial volume of $R < 300 \text{ mm}$ and $|z| < 300 \text{ mm}$. The limit in R is related to the natural limit of the track reconstruction algorithm stemming from the minimum number of silicon hits required during the track reconstruction. The limit in z stems from the limits of the existing material maps created from data.

The interaction of particles traversing through the inner detector with detector material is a large source of displaced hadronic decays which could mimic the signature of an LLP decaying in the inner detector.

To remove this significant source of background, a 3-dimensional material map was created from displaced vertices in minimum-bias data, from which the decays of known hadrons had been removed [11]. The projections of the resulting material map into the $x-y$ and $R-z$ planes are shown in Figure 5.1. Using this material map, a material veto is applied, which rejects vertices that fall in regions found to contain material. This material veto leads to a loss of 42% of the $\pi \times (30 \text{ cm})^2 \times 60 \text{ cm} = 169\,646 \text{ cm}^3$ of fiducial volume within the $R < 300 \text{ mm}$ and $|z| < 300 \text{ mm}$ limits [11]. While this fiducial volume loss is significant, it is also necessary due to the difficulty in distinguishing the decays from material interactions and true displaced decays. The requirement of the material veto reduces the number of events in the signal region which contain IDVXs from background by more than a factor of 50.

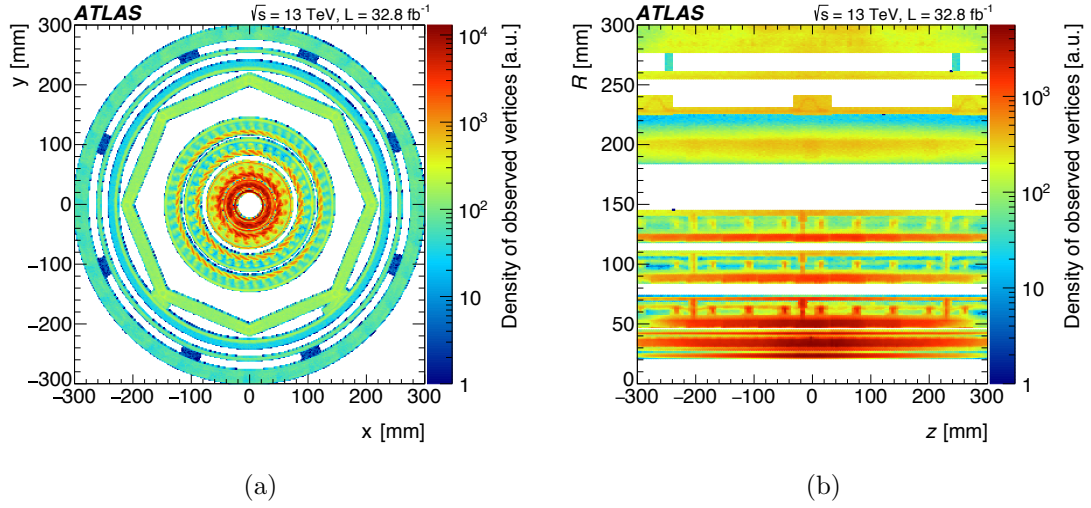


Figure 5.1: Material maps created from displaced vertices in minimum bias data [11].

In addition to the material veto, there is a disabled module veto. This disabled module veto is employed in the MC simulation in order to mimic the effect of disabled modules in the actual detector on the ability to reconstruct the IDVXs (if a disabled module exists, it may cause a track to fail the requirement of having a hit in the next available material layer after the IDVX). The disabled module veto rejects vertices in regions just inside of the disabled modules. This disabled module veto leads to a fairly minor loss in fiducial volume of 2.3%.

An important method of discrimination between hadronic decays and background from fake vertices is to consider the number of tracks associated to the IDVX (n_{trk}). Vertices resulting from the decay of an LLP to hadrons should have a fairly large number of tracks, while completely fake vertices (created from unrelated tracks) will most likely have only two tracks. Figure 5.2 demonstrates the impact of requiring $n_{\text{trk}} > 2$ as opposed to $n_{\text{trk}} \geq 2$ on the fraction of IDVXs which are matched or un-matched to true (generated) vertices in one of the MC signal samples used for the analysis. The IDVXs considered have no restrictions besides the fiducial selection of $R, |z| < 300$ mm. A truth-matched vertex in this case is defined to be one which falls

within $d < 5$ mm (where d is the 3-dimensional distance) to the decay of a generated particle whose truth information was preserved. The dashed red lines in the plot represent positions of material layers in the pixel and SCT sub-detectors. It is clear to see that requiring even just three tracks in the vertex instead of two can greatly reduce the fraction of fake vertices (the small spike in the un-matched fraction at 122 mm corresponds to a pixel material layer, this area will be removed by the material veto).

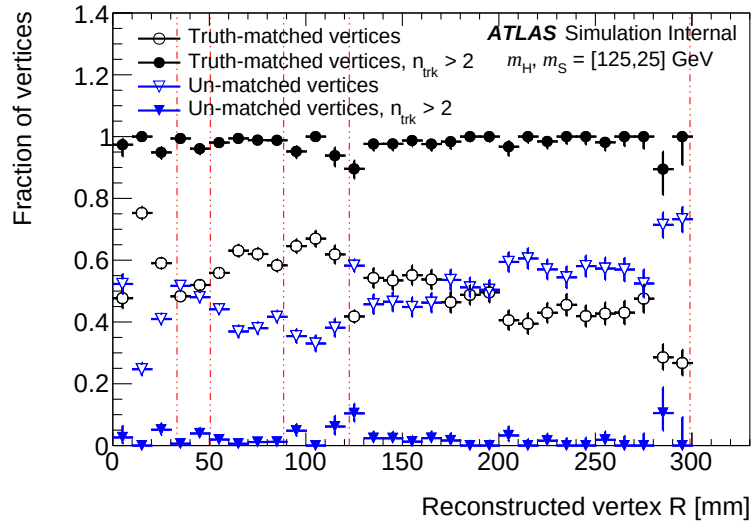


Figure 5.2: Un-matched and truth-matched vertex fractions versus vertex R [mm] for one signal MC mass point. The fractions are shown with and without the restrictions to $n_{\text{trk}} > 2$. The dashed lines represent the positions of the layers of the pixel detector and the first layer of the SCT.

In order to find the best requirement on n_{trk} to discriminate between background vertices and vertices from the LLP decays, distributions of the n_{trk} for signal-matched vertices in the signal MC samples, and vertices in data background samples are compared. The background data vertices are vertices in events used for the background estimation method described in Section 6. In the signal MC samples, for an IDVX to be considered to be signal-matched, it must both meet the requirement of falling

within $d < 5$ mm of the LLP decay, and also must have ≥ 2 tracks in the reconstructed IDVX which are matched² to decay products of the LLP.

Figures 5.3 and 5.4 compare the (linear and logarithmic) distributions of number of tracks associated to the vertex between these signal-matched IDVXs in signal MC samples and the vertices in background events, which pass all the requirements listed in Table 5.2 except for the selection on the number of tracks. These figures again confirm that background vertices predominately have two tracks each, and also have orders of magnitude more vertices with three tracks than with four or more tracks. From these comparisons, a preliminary selection of ≥ 4 tracks per vertex was placed on the IDVXs.

In order to further confirm that a selection of ≥ 4 tracks per IDVX would optimize the signal selection over background, the number of IDVXs from the signal MC samples and from the background data sample can be scaled to the number that are expected to be found in the final signal region. The number of vertices from background are scaled by the number of events in region D (Section 6), the events used to estimate the background, and the number of events in region B , the number of events that pass the muon RoI cluster trigger requirements and have a good MSVX matched to that trigger. The scale factor for the number of background vertices is $\frac{N_B}{N_D}$. The number of vertices from signal are scaled by dividing by the number of MC sample events, and then applying a scale factor based on the integrated luminosity of the data sample used, the efficiency of events to pass the trigger and MSVX related requirements in the event, and the $\sigma \times \text{BR}$, which is based on existing limits on the signal (for the case of a Higgs propagator, the Higgs gluon-gluon fusion cross section of $\sigma_{ggF} = 48.58$ pb is used). The overall scale factor used for the signal vertices is

²For a track to be considered matched, the weighted fraction of hits in the reconstructed track that are matched to energy deposits from generated particles over all hits in the reconstructed track must be > 0.5 .

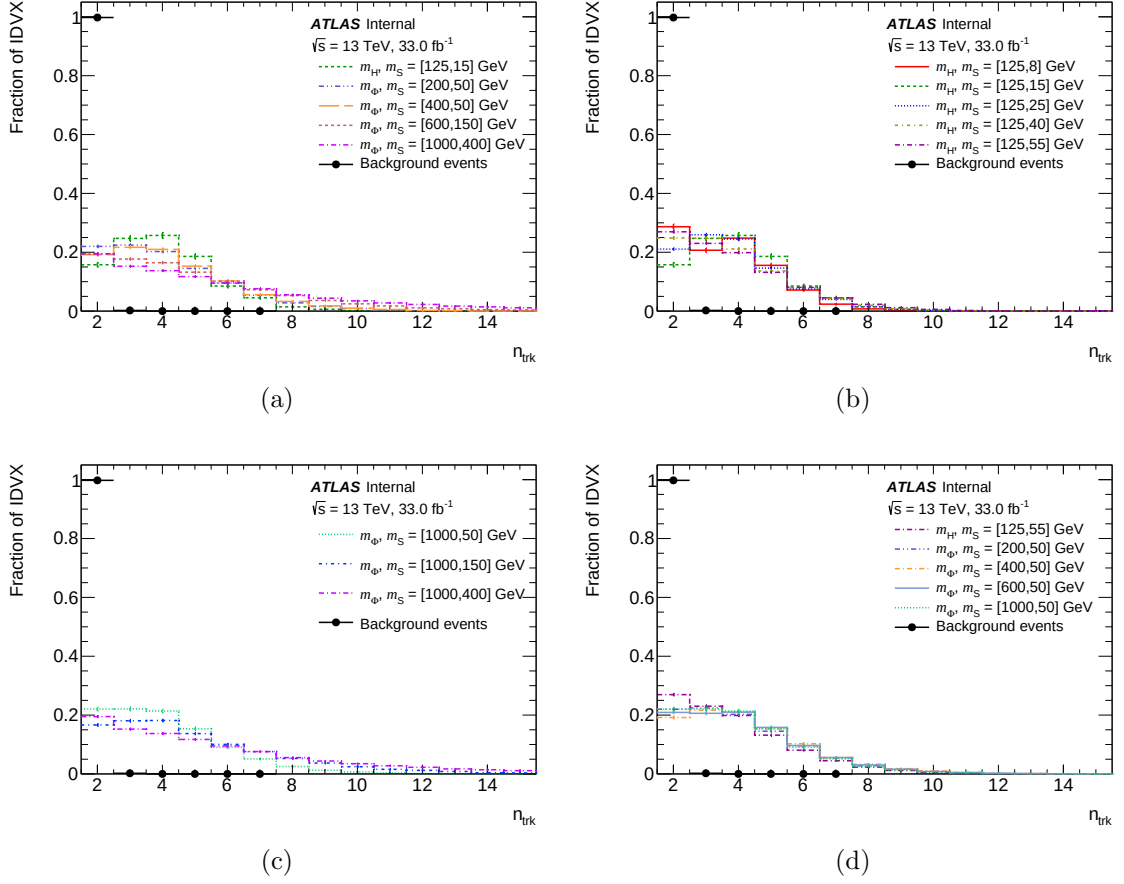


Figure 5.3: Linear distributions of n_{trk} for signal MC samples and RPVLL background events, for vertices which pass all other selection requirements in Table 5.2. Each curve is normalized to unity. A range of mass points are shown in (a), (b) shows 125 GeV Higgs $\rightarrow ss$ samples, (c) shows Φ mass 1000 GeV $\rightarrow ss$, (d) shows LLP mass 50-55 GeV.

$$\frac{33 \text{ fb}^{-1} \times \sigma \times \text{BR} \times \varepsilon_{\text{trig+MSVX}}}{N_{\text{MC}}}. \quad (5.1)$$

Figure 5.5 demonstrates the quantity $\frac{S}{\sqrt{S+B}}$, in which S is the scaled number of signal vertices and B is the scaled number of background vertices, for all vertices that pass a given n_{trk} selection (as well as passing the other IDVX selection selections outlined in Table 5.2). Figure 5.5a shows $\frac{S}{\sqrt{S+B}}$ for all of the signal MC samples with a Higgs propagator that were used in this analysis, considering a branching ratio of 0.01, while Figure 5.5b shows a Φ mass of 200 GeV and and LLP mass of

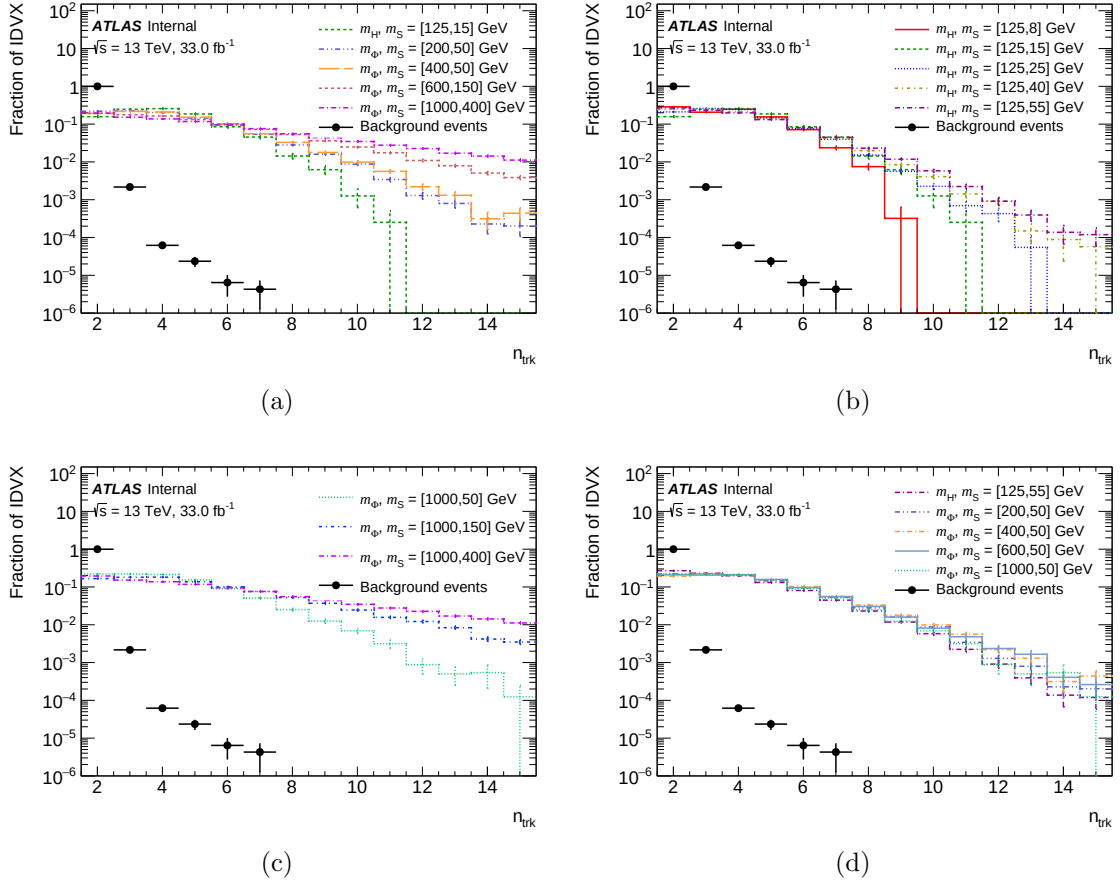


Figure 5.4: Logarithmic distributions of numbers of tracks per vertex for signal MC samples and RPVLL background events, for vertices which pass all other selection requirements in Table 5.2. Each curve is normalized to unity. A range of mass points are shown in (a), (b) shows 125 GeV Higgs $\rightarrow ss$ samples, (c) shows Φ mass 1000 GeV $\rightarrow ss$, (d) shows LLP mass 50-55 GeV.

8 GeV, considering a $\sigma \times \text{BR}$ of 0.3. These masses in particular are examined for optimization, because this analysis is better suited to search for lower mass LLPs than other similar analyses, due to the presence of the second vertex in the event which suppresses background and allows for looser selections on the reconstructed mass of the IDVX (m_{IDVX}) and n_{trk} than would be feasible in an 1-vertex analysis.

The same methods are employed to determine the optimal selection on m_{IDVX} , calculated under the assumption that the charged tracks making up the vertex are charged pions. Figure 5.6 shows the normalized signal and background m_{IDVX} distri-

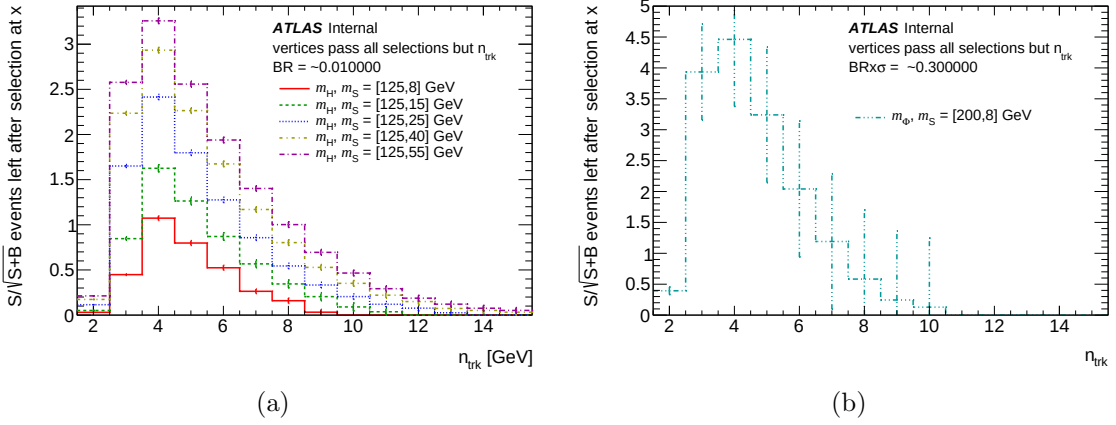


Figure 5.5: The quantity $\frac{S}{\sqrt{S+B}}$, in which S is the scaled number of signal vertices and B is the scaled number of background vertices, for all vertices that pass a given n_{trk} selection (as well as passing the other IDVX selection requirements outlined in Table 5.2), for (a) a Higgs mass propagator and (b) a Φ mass of 200 GeV and and LLP mass of 8 GeV.

butions, and indicates that the optimal m_{IDVX} selection for most of the signal MC mass points would be between 3 and 4 GeV.

The quantity $\frac{S}{\sqrt{S+B}}$ was once again examined to better understand the optimal m_{IDVX} selection. Figure 5.7 demonstrates $\frac{S}{\sqrt{S+B}}$ for all vertices that pass a given vertex mass selection, for a mass range of 0-80 GeV, and a zoomed in mass range of 0-10 GeV.

Figure 5.7 indicates that a looser selection on m_{IDVX} would be preferable, particularly for the lower LLP masses. The selection is thus chosen to be at 3 GeV instead of 4 GeV. It is better to have a mass selection at 3 GeV rather than none at all, even though no mass selection would have been ideal for the lowest LLP masses, in order to restrict the predicted number of background events to $\mathcal{O}(1)$.

One final requirement is placed on the IDVXs in the signal region. The IDVX is required to be $\Delta R > 0.4$ from the nearest existing good MSVX in the event, to reduce the likelihood that a single high-energy QCD decay would create a signal-like vertex both in the inner detector and in the muon spectrometer. A selection of $\Delta R > 0.4$

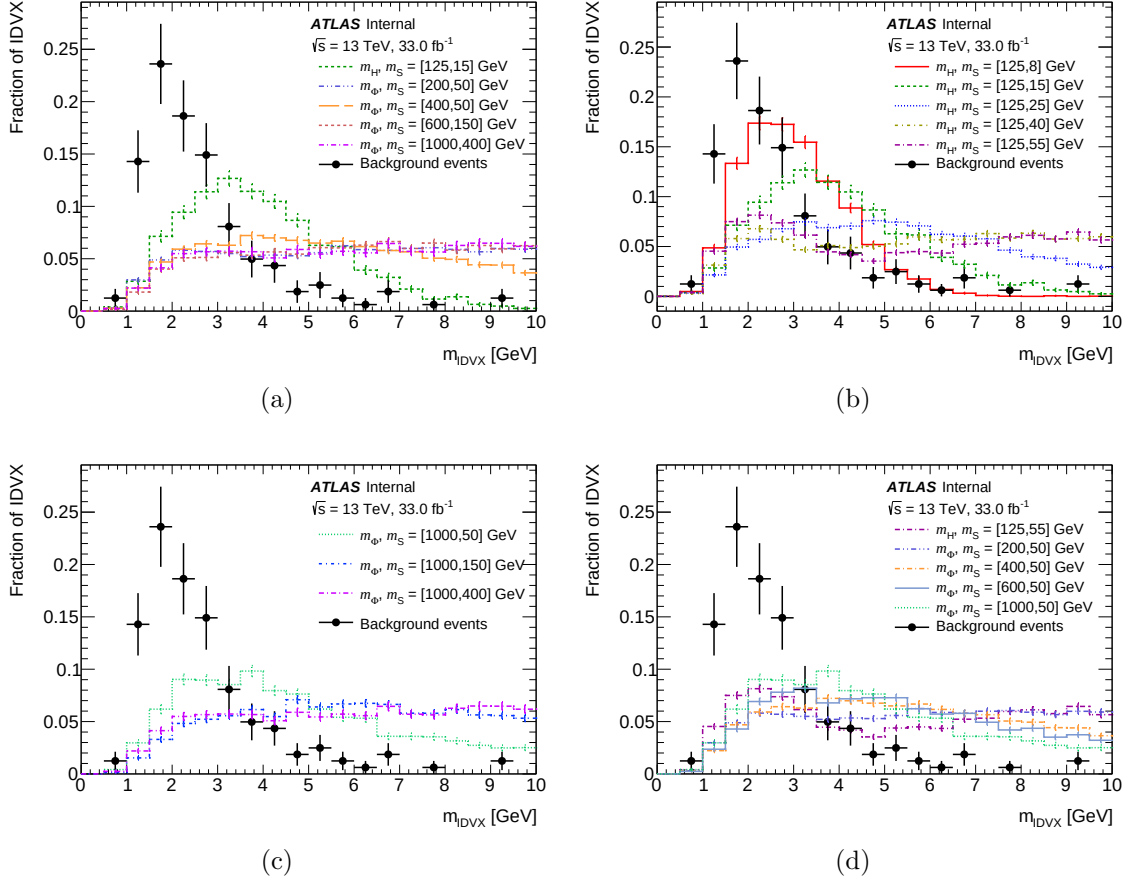


Figure 5.6: Distributions of m_{IDVX} for signal MC samples and RPVLL background events, for vertices which pass all other selection requirements in Table 5.2. Each curve is normalized to unity. A range of mass points are shown in (a), (b) shows 125 GeV Higgs $\rightarrow ss$ samples, (c) shows Φ mass 1000 GeV $\rightarrow ss$, (d) shows LLP mass 50-55 GeV.

is naively imposed due to the fact that $\Delta R = 0.4$ is the typical size of the jet cone used for reconstructing QCD jets. It is impossible to optimize this selection using data vertices without essentially unblinding (by looking for events containing a good MSVX and a good IDVX), however it is still possible to examine the ΔR distributions in signal MC samples, as shown in Figure 5.8. The two LLPs are produced back-to-back in the reference frame of the propagator decay, so in the frame of the ATLAS detector, one would expect that the LLPs are fairly back-to-back as long as the LLPs are relatively boosted. Figure 5.8 shows that for the majority of samples this is true,

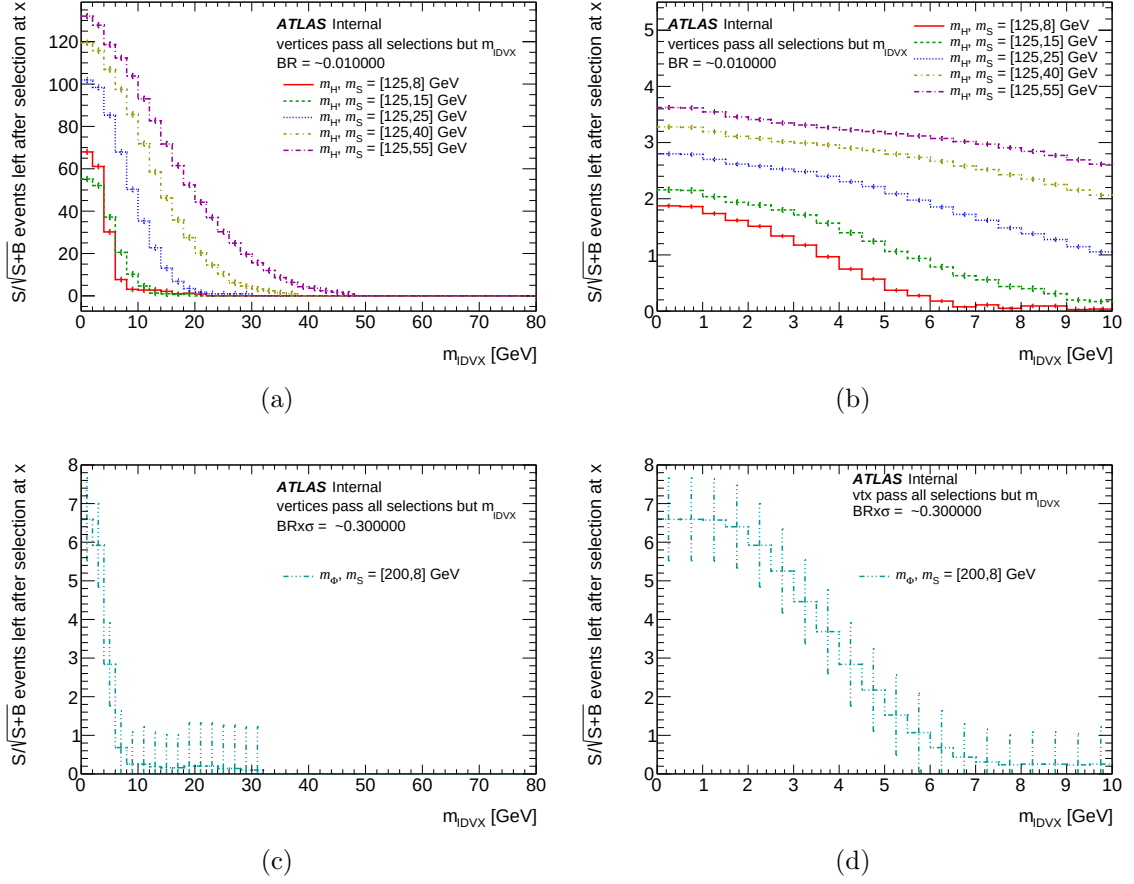


Figure 5.7: The quantity $\frac{S}{\sqrt{S+B}}$, in which S is the scaled number of signal vertices and B is the scaled number of background vertices, for all vertices that pass a given vertex mass selection (as well as passing the other IDVX selection requirements outlined in Table 5.2), for (a),(b) a Higgs mass propagator and (c),(d) a Φ mass of 200 GeV and and LLP mass of 8 GeV.

except for the very low boosted sample of a Higgs boson decaying to LLPs of mass 55 GeV. Other than for this sample, a selection of $\Delta R > 0.4$ has very little impact on the selection efficiency for signal IDVXs, thus it is chosen as the final requirement.

After unblinding, the angular separation was examined between IDVXs and MSVXs in data. Figure 5.9 shows the ΔR (Figure 5.9a), $\Delta\phi$ (Figure 5.9b), and $\Delta\eta$ (Figure 5.9c), separation between good MSVXs and IDVXs passing all selections in Table 5.2 except those on n_{trk} and the IDVX-MSVX separation. The data events used are those in region B in the ABCD plane described in Section 6, those events that

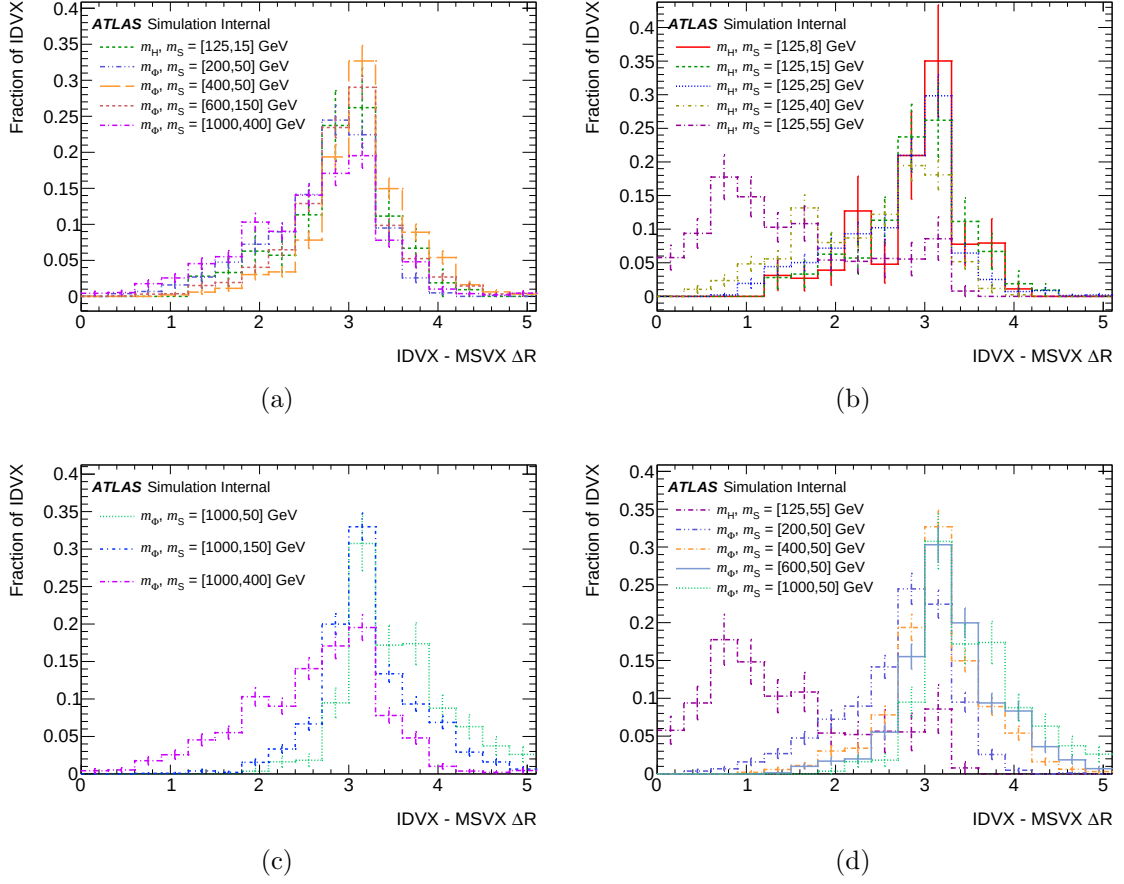


Figure 5.8: Distributions of the distance in ΔR between a good IDVX and the nearest good MSVX in the event, for vertices which pass all other selection requirements in Table 5.2. Each curve is normalized to unity. A range of mass points are shown in (a), (b) shows 125 GeV Higgs $\rightarrow$ ss samples, (c) shows Φ mass 1000 GeV $\rightarrow$ ss, (d) shows LLP mass 50-55 GeV.

pass event selection requirements except for the requirement of a good IDVX. Figure 5.10 shows the ΔR separation for IDVXs with $n_{\text{trk}} = 2$ (Figure 5.10a), $n_{\text{trk}} = 3$ (Figure 5.10b), $n_{\text{trk}} \geq 4$ (Figure 5.10c). After unblinding it is evident that the selection on the IDVX-MSVX separation does not remove any events for IDVXs with $n_{\text{trk}} \geq 3$. While this information cannot be used to adjust the selection of this analysis (since it was discovered after unblinding the signal region), it could be useful for future iterations of the search.

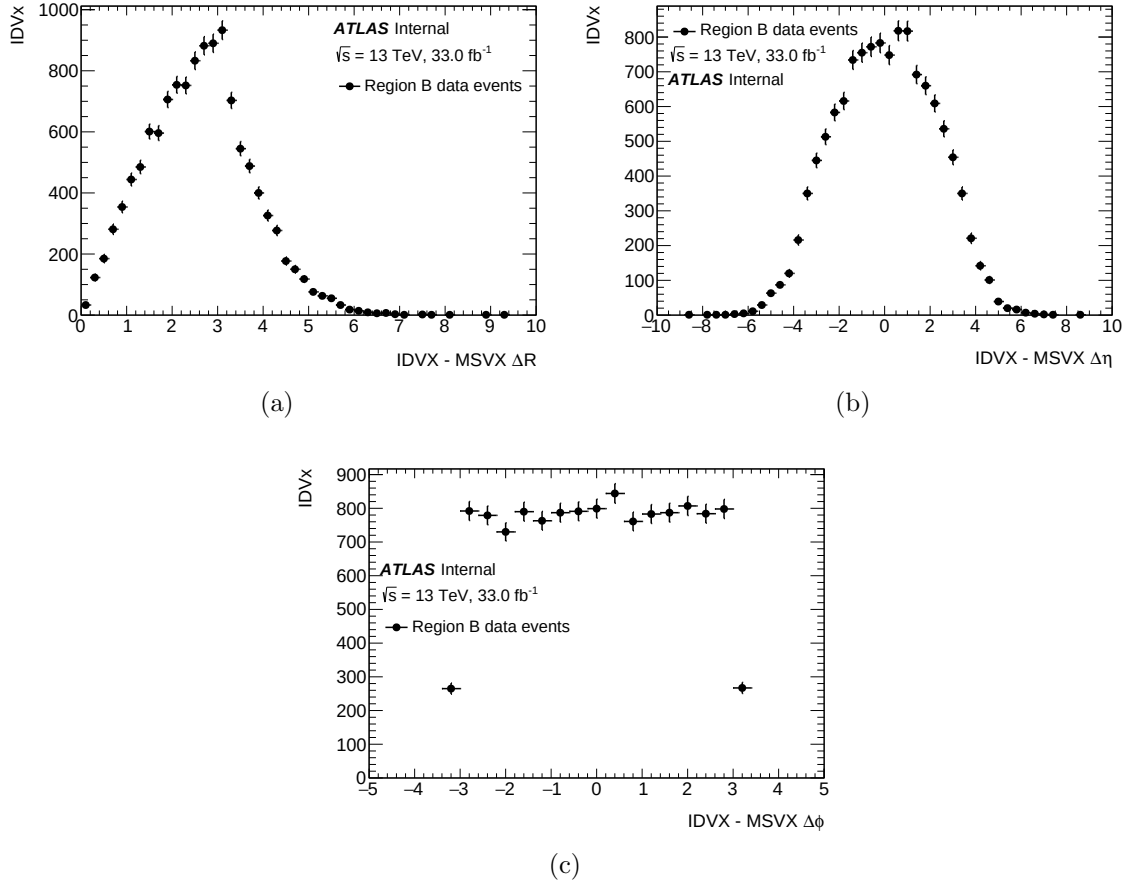


Figure 5.9: The ΔR (a), $\Delta\eta$ (b), and $\Delta\phi$ (c) separation between good MSVXs and (otherwise) good IDVXs with any number of tracks in unblinded region B events in data.

5.3.1 IDVX reconstruction efficiency

The impact of the different requirements on the selection efficiency of the IDVXs, defined as

$$\varepsilon_{IDVX} = \frac{\text{IDVX}_{\text{reco}} \text{ passing vtx reqs. in Table 5.2, matched to LLP decay}}{\text{All LLP decays in fid. volume from Table 5.3}} \quad (5.2)$$

is demonstrated in Figures 5.11, 5.12, and 5.13 vs the LLP decay R [mm] and the LLP decay z [mm]. In these figures, the true LLP decays are constrained to decay within the fiducial volume laid out in Table 5.3.

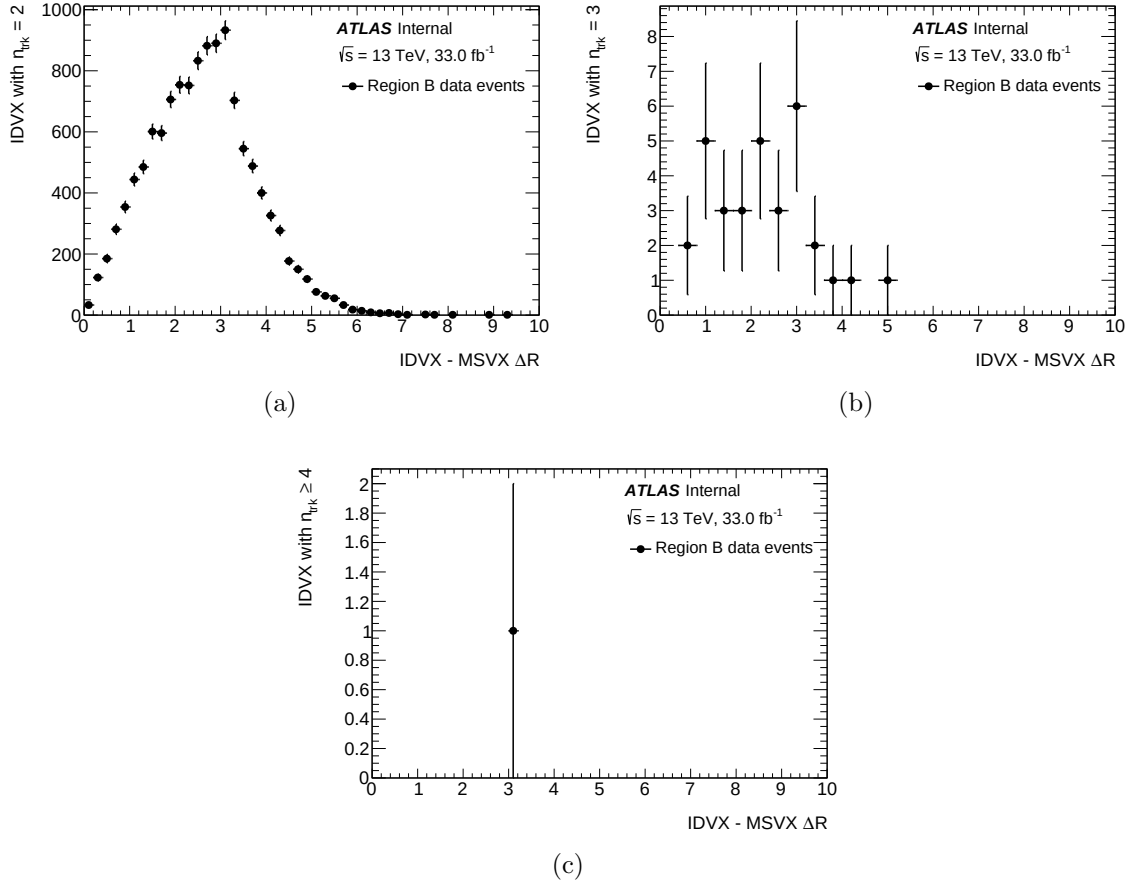


Figure 5.10: The ΔR separation between good MSVXs and (otherwise) good IDVXs in which the IDVXs have (a) $n_{\text{trk}} = 2$, (b) $n_{\text{trk}} = 3$, and (c) $n_{\text{trk}} \geq 4$.

Detector	Fiducial Volume
ID barrel/endcaps	$L_{xy} < 300 \text{ mm}, L_z < 300 \text{ mm}$ $ \eta < 2.5$
MS barrel	$L_{xy} < 10 \text{ m}, \eta < 0.7$
MS endcaps	$5 \text{ m} < L_z < 15 \text{ m}, 1.3 < \eta < 2.5$

Table 5.3: Fiducial volume considered for LLP decays in the ID and MS

Figure 5.11 shows the IDVX selection efficiency for signal MC samples that have a Higgs propagator, while Figure 5.12 shows the IDVX selection efficiency for those samples that have a Φ propagator with a mass of 1000 GeV. Both of these figures demonstrate that the selection efficiency is highly correlated with the mass of the

LLP. This is due in part to the requirement on the vertex mass of 3 GeV; the higher the mass of the LLP, the more likely it is that there will be enough visible and reconstructed decay products to pass the mass selection.

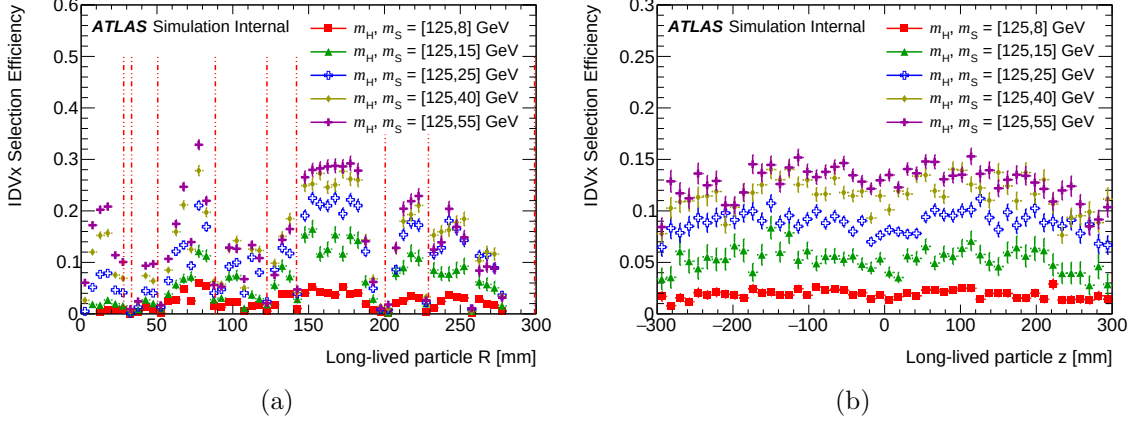


Figure 5.11: Vertex selection efficiency (Eq. 5.2) for Higgs $\rightarrow ss$ mass points, vs LLP decay R (a) and z (b), the reconstruction vertices are required to meet all good vertex for IDVXs in Table 5.2, the LLP decays meet the fiducial volume requirements in Table 5.3. To be considered matched the vertex must be within 5 mm of the LLP decay position and at least two of the tracks in the vertex must be signal matched. The dashed red lines represent some of the layers of the inner detector material.

Figure 5.13 shows that very highly boosted samples have a lower IDVX selection efficiency. If an LLP is very boosted, more of the tracks in the resulting decay will point back towards the IP, and thus will be less likely to be included in the IDVX when the vertex is reconstructed, due to the minimum $|d_0|$ of 2 mm.

The distinctive shape of the IDVX selection efficiency vs R is due to the material veto. This is demonstrated explicitly in Figure 5.14a. Figure 5.14a demonstrates the IDVX selection efficiency without any of the selections from Table 5.2 enforced, compared to when just the selection on the distance from the PV, just the selection on the χ^2/n_{DoF} , or just the material veto has been enforced. This demonstrates the dramatic impact of the material veto in terms of the fiducial volume lost (although this loss is necessary due to the difficulty discussed in distinguishing between decays

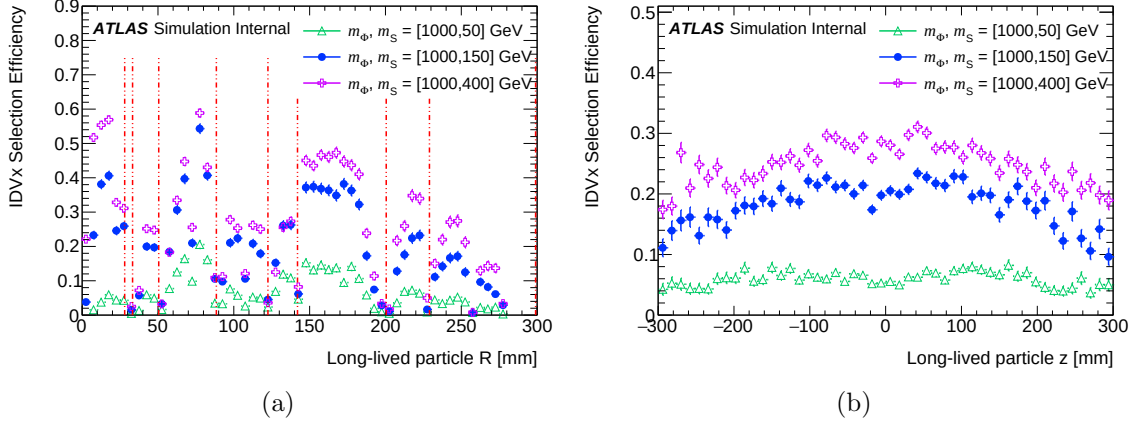


Figure 5.12: Vertex selection efficiency (Eq. 5.2) for 1000 GeV $\Phi \rightarrow ss$ mass points, vs LLP decay R (a) and z (b), the reconstruction vertices are required to meet all good vertex for IDVXs in Table 5.2, the LLP decays meet the fiducial volume requirements in Table 5.3. To be considered matched the vertex must be within 5 mm of the LLP decay position and at least two of the tracks in the vertex must be signal matched. The dashed red lines represent some of the layers of the inner detector material.

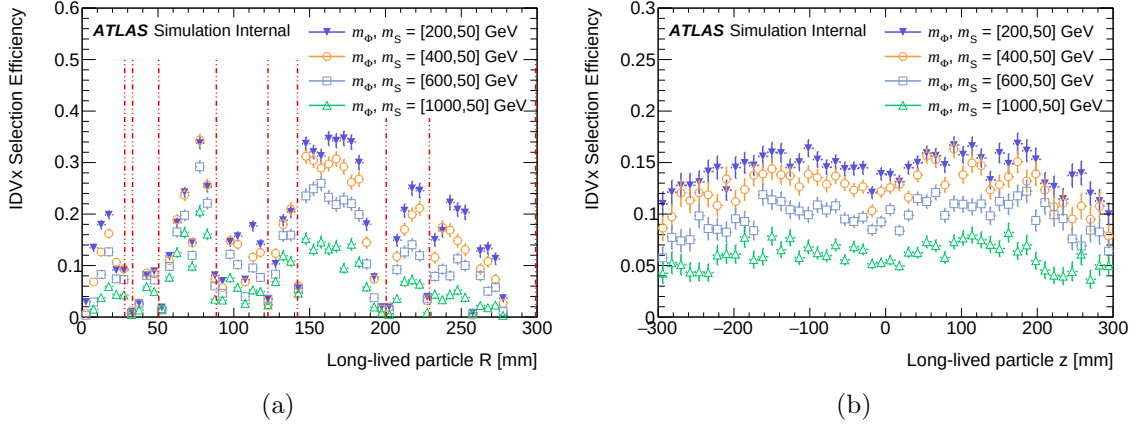


Figure 5.13: Vertex selection efficiency (Eq. 5.2) for mass points with a 50 GeV LLP, vs LLP decay R (a) and z (b), the reconstruction vertices are required to meet all good vertex for IDVXs in Table 5.2, the LLP decays meet the fiducial volume requirements in Table 5.3. To be considered matched the vertex must be within 5 mm of the LLP decay position and at least two of the tracks in the vertex must be signal matched. The dashed red lines represent some of the layers of the inner detector material.

from signal and from material interactions). Figure 5.14b demonstrates the impacts of the selections on the number of tracks and on the vertex mass on the IDVX selection

efficiency compared to no selections at all. For this particular mass point, the selection on the number of tracks has a much larger individual impact than the selection on the vertex mass (although this varies depending on the mass of the Φ and of the LLP).

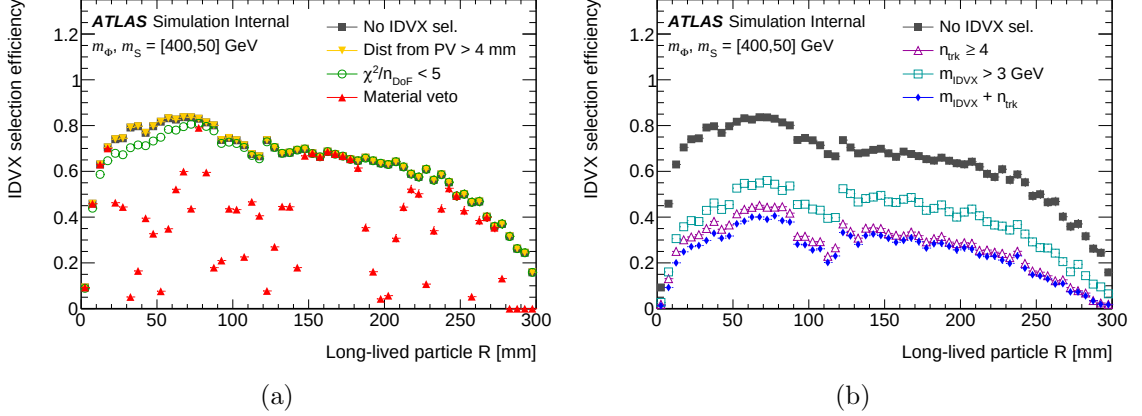


Figure 5.14: Impact on the IDVX selection efficiency of the (a) distance from the PV, χ^2/n_{dof} , or material veto, (b) number of tracks then vertex mass requirements from Table 5.2, compared to having no selection requirements on the vertices in the sample with a 400 GeV Φ decaying to a 50 GeV scalar.

Figure 5.15 demonstrates the impact of all of the different individual selections on the IDVXs from Table 5.2 for the signal MC mass point of $m_\Phi = 400$ GeV and $m_s = 50$ GeV.

5.3.2 IDVX residuals

Figures 5.16 and 5.17 show the IDVX residuals plots for signal samples with Higgs and 1000 GeV mass Φ propagators. The residuals are given by the signed difference in the LLP radial (longitudinal) decay position and the reconstructed radial (longitudinal) decay position and are shown in mm. In Figures 5.16 and 5.17 each curve has been normalized to one.

Figure 5.16 shows the residuals for LLP - IDVX r and z for the Higgs samples. The IDVXs that pass all the selection requirements in Table 5.2 except those on the IDVX mass and number of tracks are shown in Figures 5.16a and 5.16c, and for

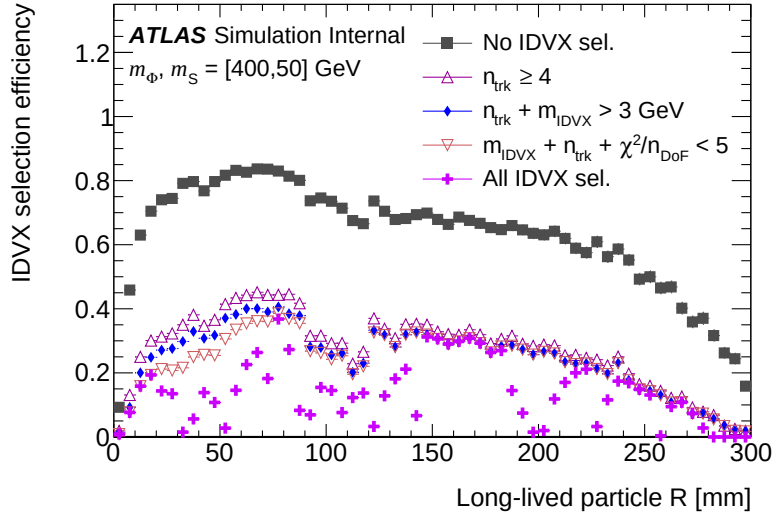


Figure 5.15: Impact of the all selections from Table 5.2 on the IDVX selection efficiency, starting with the selection on number of tracks in the sample with a 400 GeV Φ decaying to a 50 GeV scalar.

vertices which then pass selections on $n_{\text{trk}} \geq 4$ and $m_{\text{IDVX}} > 3$ GeV in Figures 5.16b and 5.16d.

Figure 5.16 demonstrates that for the 125 GeV Higgs MC samples, the reconstructed IDVX position is typically within 0.5 mm of the true decay position in both R and z, even before the requirement on the number of tracks and vertex mass, and this is further improved when the selections on the number of tracks and vertex mass are enforced.

Figure 5.17 shows these same plots for a Φ with a mass of 1000 GeV. Once again, the majority of reconstructed IDVXs are within 0.5 mm in both r and z of the true LLP decay positions, and the residuals are better after the requirement of at least 4 tracks per vertex and a vertex mass of at least 3 GeV. It is also evident that the higher boosted LLPs have broader residuals distributions than those with lower boost, this is clear both from examining the different LLP mass points for the 1000 GeV Φ propagator in Figure 5.17, and in comparing the distributions for the LLPs with a mass of 50 or 55 GeV in Figures 5.16 and 5.17.

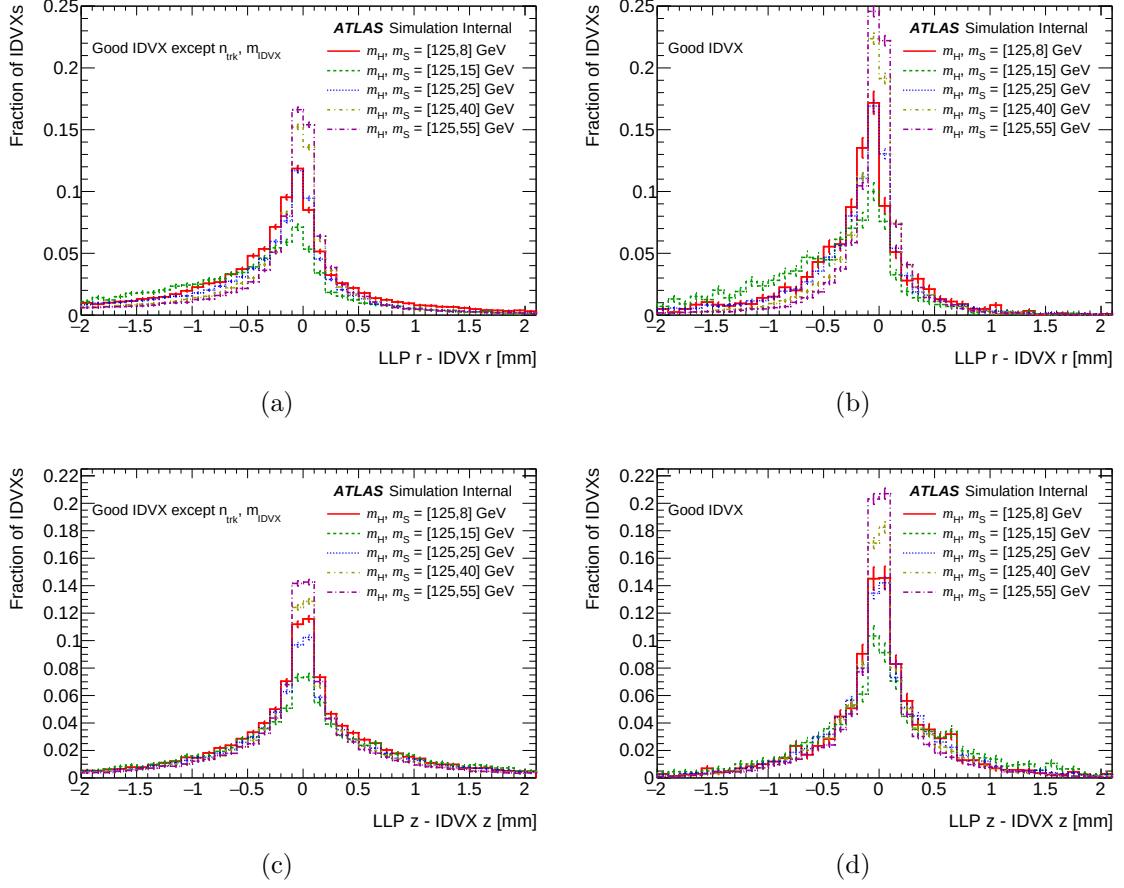


Figure 5.16: IDVX residuals distributions for (a),(b) LLP r - IDVX r (c),(d) LLP z - IDVX z for vertices that pass all the vertex selection requirements in Table 5.2 except those on n_{trk} and m_{IDVX} (a),(c) and considering those vertices passing a selection of $m_{\text{IDVX}} > 3$ GeV and $n_{\text{trk}} \geq 4$ (b),(d) in samples with a 125 GeV Higgs.

5.4 Overall event cutflow

A cutflow plot visually demonstrates the impact of each of the event and vertex selections on the efficiency to select signal events. In Figure 5.18 the cutflow plots are shown for the signal MC samples with a 125 GeV Higgs propagator (Figure 5.18a), a 1000 GeV Φ propagator (Figure 5.18b), and samples with LLP masses of 50-55 GeV (Figure 5.18c). In Figure 5.18, ‘Good events’ refers to events that pass the PV and event cleaning requirements, ‘Pass trigger’ refers to events that pass the muon RoI cluster trigger and pass the veto on triggers used to select displaced decays in the

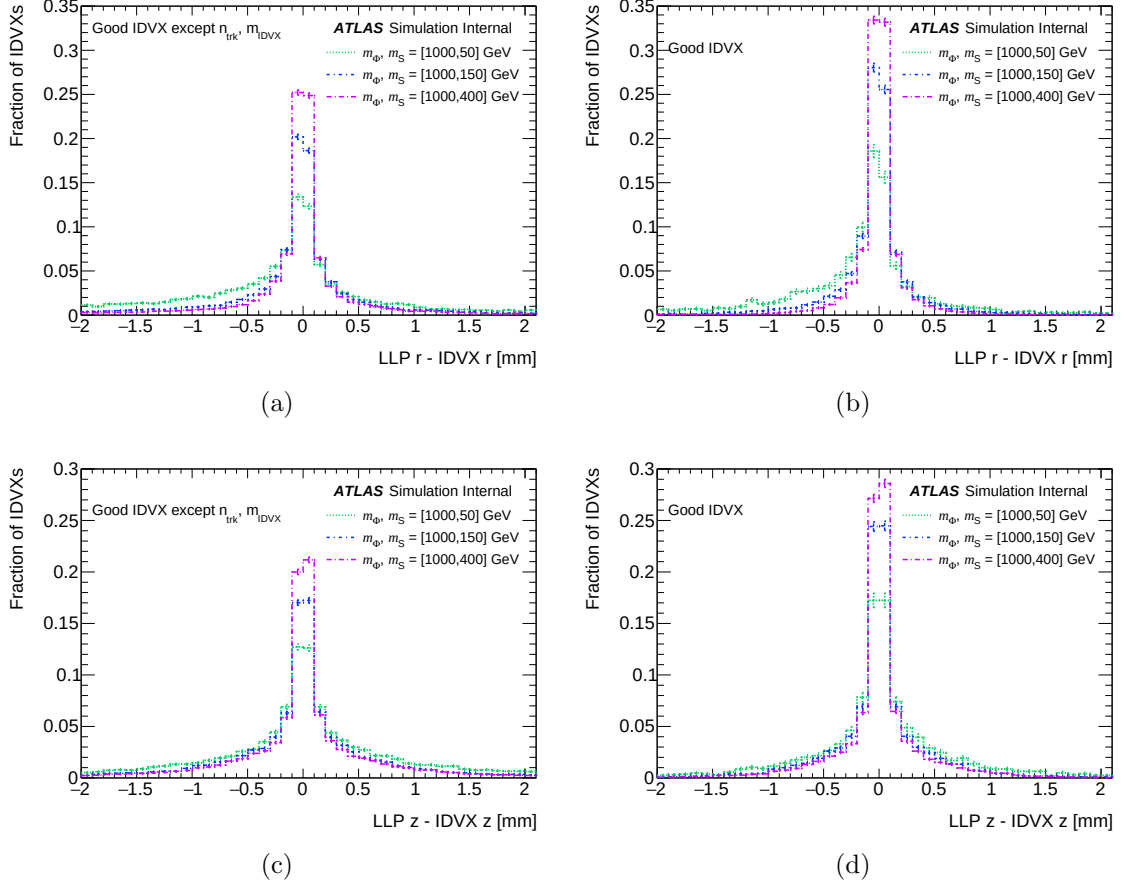


Figure 5.17: IDVX residuals distributions for (a),(b) LLP r - IDVX r (c),(d) LLP z - IDVX z for vertices that pass all the vertex selection requirements in Table 5.2 except those on n_{trk} and vertex mass (a),(c) and considering those vertices passing a selection of $m_{\text{IDVX}} > 3$ GeV and $n_{\text{trk}} \geq 4$ (b),(d) in samples with a 1000 GeV Φ .

HCal, ‘Good MSVX’ refers to events containing an MSVX passing all requirements in Table 5.1, and ‘IDVX’ refers to events containing an IDVX passing all selections in Table 5.2, except for those on tracks and vertex mass, which are shown separately. Figure 5.18 demonstrates the impact that the trigger and MSVX requirements have on the different mass points compared to the impact that the IDVX requirements have. While the lower LLP mass is correlated to a lower IDVX reconstruction efficiency, samples with a very low boost are less likely to pass the muon RoI cluster trigger and contain a good MSVX matched to the triggering cluster.

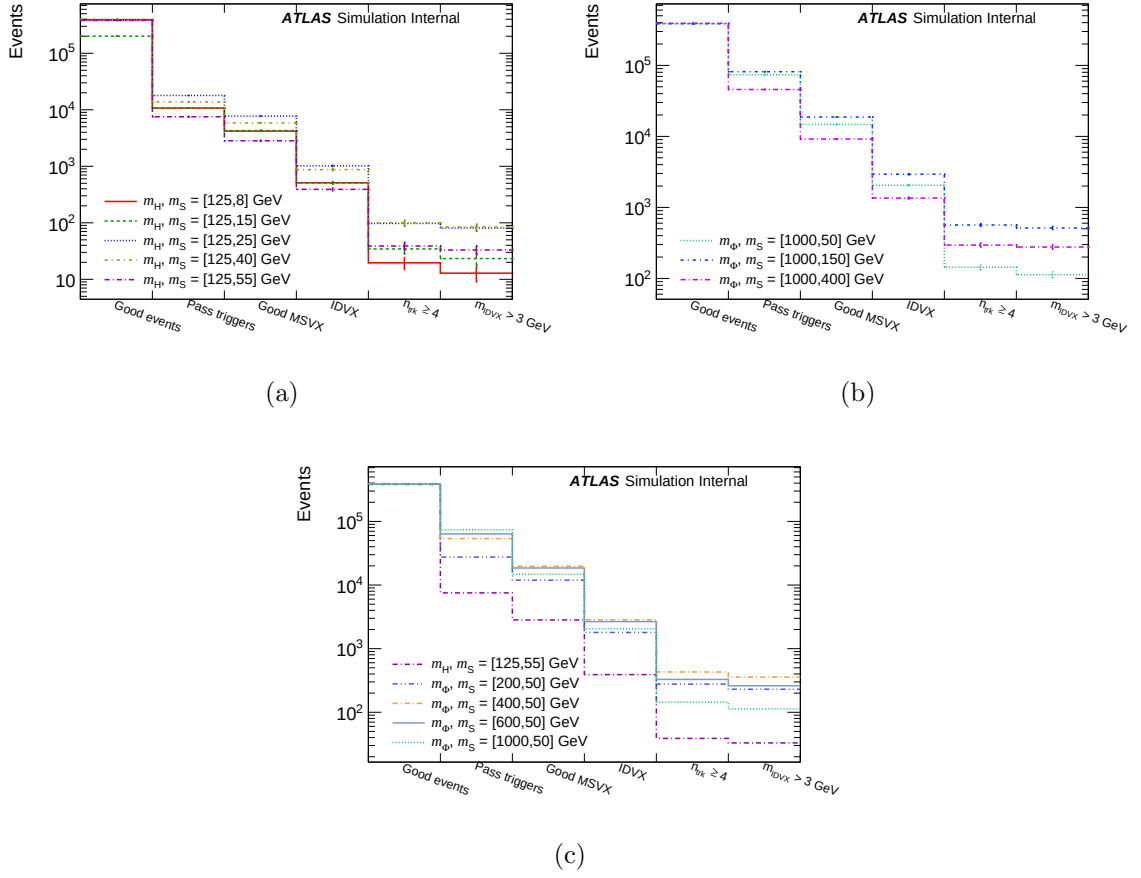


Figure 5.18: The cutflow for all is shown for all Higgs $\rightarrow ss$ mass points (a), for all 1000 GeV $\Phi \rightarrow ss$ mass points (b), and for all is shown for all mass points with a 50-55 GeV LLP (c). Here, ‘Good MSVX’ includes all the MSVX selection selections described in Table 5.1 and ‘IDVX’ includes all selections in Table 5.2 except those on vertex mass and number of tracks, which are shown in the subsequent two histogram bins.

One impact on the efficiency loss is the need for one of the LLPs to be decaying in the muon spectrometer and in the inner detector. The lab-frame lifetime of 5 m of the samples was designed to allow for approximately equal numbers of decays per mass point in the inner detector, the calorimeters, and the muon spectrometer of the ATLAS detector, because the MC samples were shared by analyses searching for decays in all of those regions. Due to this, many of the MC samples do not have an LLP decaying in the fiducial volume of the muon spectrometer at all, and therefore

are not able to fire the muon RoI cluster trigger. In order to understand the impact of the different selections on events in which one LLP decays in the fiducial volume of the inner detector and one LLP decays in the fiducial volume of the muon spectrometer (as defined in Table 5.3), the cutflows were remade. Figure 5.19 demonstrates the difference in the cutflows for mass points with a 1000 GeV Φ propagator, with and without the fiducial volume requirements on the LLPs, in which each curve has been normalized to the first bin.

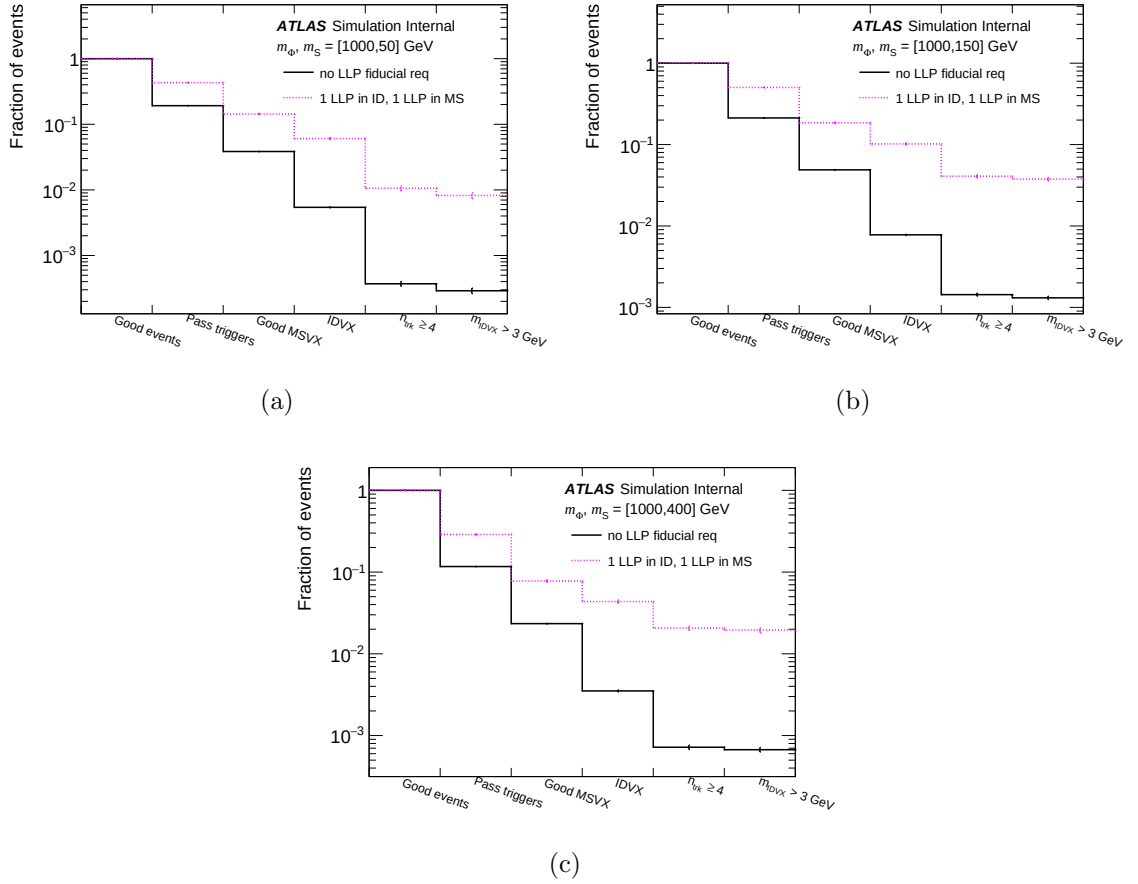


Figure 5.19: Comparisons between the cutflows for MC signal samples with a Φ mass 1000 GeV, showing the difference in the impact of the different selections in the cutflow with and without fiducial requirements on the LLP decays. Curves are normalized to the number of events in first bin.

In Figure 5.19 it is clear that part of the apparent inefficiency in the muon RoI cluster trigger (and the requirement of reconstructed MSVXs and IDVXs) is due to the fact that not all of the events contain an LLP decay in the fiducial volume of the MS (and the ID).

Cutflow plots for the signal selection in data (created after unblinding) and the IDVX selection in background events in data are shown in Figure 5.20. For the signal selection, the selections with the largest impact on the total number of data events are those requiring a good MSVX that is matched to the muon RoI cluster that caused the trigger to fire, and on the requirement that the IDVX in the event have $n_{\text{trk}} \geq 4$ (although if the order of the n_{trk} selection and the m_{IDVX} selection were reversed, the m_{IDVX} selection would appear to have a greater impact than it currently does). The background events in the first column in Figure 5.20b are those that are in region D of the modified ABCD plane defined in Section 6, while those in the last column are C , those background events which contain an IDVX passing the full signal selection. In Figure 5.20b it is once again evident that the requirement for the IDVXs to have $n_{\text{trk}} \geq 4$, reduces the number of background events by nearly four orders of magnitude.

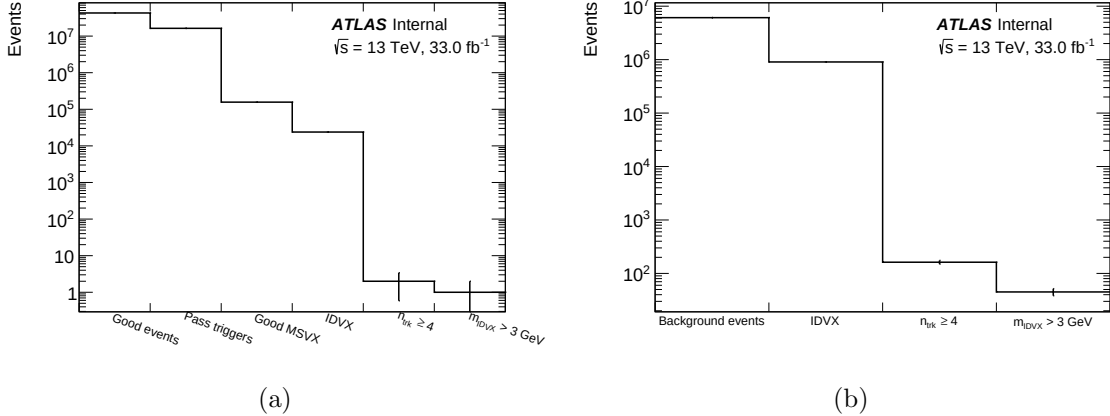


Figure 5.20: Cutflows for signal (a) and background (b) events in data. For the full signal region selection, and the IDVX selection, respectively.

The numbers of events left after each selection and the relative percentages of events passing each selection for several signal MC samples are presented in Appendix B.

CHAPTER 6

BACKGROUND

As mentioned previously in Section 5.3, one of the main sources of background in a search for displaced hadronic vertices in the inner detector is the interactions with the material constituting the inner detector, both the active layers, and the support material. The vertices resulting from these material interactions should predominantly be removed with the application of the material veto, although there is still a small possibility of a reconstructed vertex escaping the material veto, or resulting from the interaction with some gas that leaked out of the detector tubes.

Other sources of background include combinatorial fakes - vertices that are made of fake tracks, or real tracks from different decays that happen to overlap, and vertices that were accidentally crossed by a track to cause the number of tracks and mass of the vertex to seem larger than it should. Most completely fake vertices are excluded by the requirement of at least 4 tracks per vertex, and a minimum vertex mass of at least 3 GeV.

A data driven method is used to estimate the combination of all sources of background, including those which may not be easily modeled in MC samples. Using a data-driven background estimation method also removes the complication of data/MC related systematic uncertainties.

6.1 Estimation method

The background estimation used can be presented as a modified ABCD plane, as shown in Figure 6.1. The ABCD plane is used to determine the fraction of background

events which contain an IDVX (presumably from background) which passes the full IDVX selection, and then to apply that fraction to events which pass the full event selection except for the requirement of an IDVX. In this way, the number of events in the final signal region which contain an IDVX due to background can be estimated.

In the ABCD plane, region A events are those which pass the full event selection, that have a PV and pass event cleaning, pass the trigger requirements (pass the muon RoI cluster trigger, do not pass the HCal jets triggers used by the CR analysis), contain a good MSVX matched to the triggering cluster, and contain an IDVX passing the full IDVX selection requirements. Region B events are those events which pass all the signal selection requirements through the existence of the MSVX, but are agnostic to the presence of any IDVX.

Has IDVX passing the full signal selection	C	A
Agnostic with respect to IDVXs	D	B
	Background events	Muon RoI cluster trigger events with a good MSVX

Figure 6.1: The ABCD plane, with events passing the signal region requirements through the presence of a good MSVX, either containing or agnostic to signal region IDVXs (A and B), and background events, which contain or are agnostic to signal region IDVXs (C and D).

The ‘background events’ in regions C and D are constructed to contain as few signal decays as possible. The background events are required to pass the HLT trigger looking for a medium muon with a $p_T \geq 26$ GeV and to pass vetos on the muon RoI cluster trigger and the HCal jets triggers used by the CR analysis. The background events are also required to contain at least two muons, with $p_T \geq 25, 20$ GeV, in which both muons are isolated from other activity in the event such that $\frac{\Sigma_{cone40pT}}{\mu_{onpT}} < 0.30$, the total combined p_T in a cone of $\Delta R < 0.4$ around the muon must be less than 30%

of the muon p_T . The combination of these requirements minimizes the possibility of signal contamination in the background events, to the extent that $< 0.1\%$ of the signal MC samples pass the background event requirements, as demonstrated in Figure 6.2. In region D , the selection on the background events is agnostic to the presence of any IDVXs, whereas in region C events, these background events are required to contain an IDVX passing the IDVX event selection laid out in Table 5.2, including $m_{\text{IDVX}} > 3 \text{ GeV}$, and $n_{\text{trk}} \geq 4$.

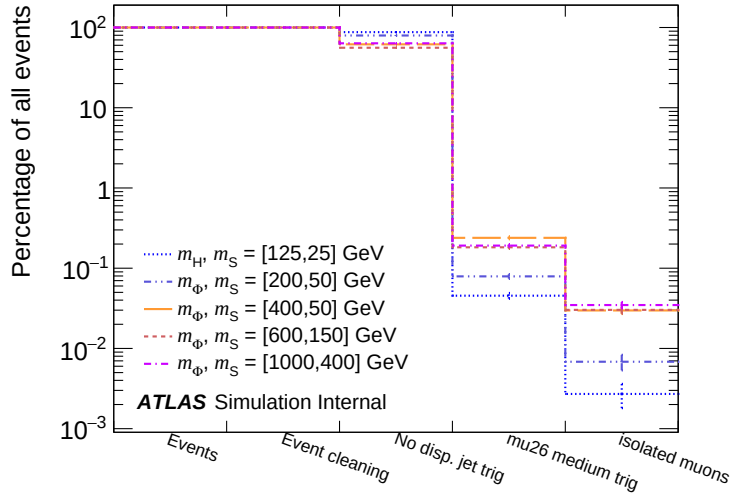


Figure 6.2: The percentage of signal MC events selected by the background event requirements.

In the plane presented in Figure 6.1, a factor

$$F = N_C/N_D \quad (6.1)$$

can be calculated, representing the likelihood of any of the background events to contain an IDVX that passes the signal IDVX selection, based on the number of region C and D events, N_C and N_D respectively. This F , when applied to the number

of events in region B (N_B) should give the number of events in region A (N_A) which pass the full signal selection but contain an IDVX from background,

$$N_A^{\text{pred.}} = N_B \times F = N_B \times N_C/N_D. \quad (6.2)$$

There are 6,099,660 events used to populate region D and 45 of these events contain an IDVX which passes the full selection, including $n_{\text{trk}} \geq 4$ and $m_{\text{IDVX}} > 3$ GeV, thus resulting in 45 region C events. Therefore, $F = N_C/N_D = 45/6,099,660 = (7.38 \pm 1.10(\text{stat})) \times 10^{-6}$. There are a total of 156,805 barrel and endcap combined events which pass the non-IDVX related event selections in 2016 data¹. So we expect $N_A^{\text{pred.}} = N_B \times F = N_B \times N_C/N_D = (156,805 \pm 400) \times (7.38 \pm 1.10) \times 10^{-6} = 1.16 \pm 0.18(\text{stat})$.

6.2 Validation of the background estimation

In order to validate the background estimation method, a set of control regions is introduced, as demonstrated in Figure 6.3. Here, region C' events are background events, but instead of being agnostic to the presence of any IDVXs, such as those in region D , and instead of being required to contain an IDVX passing the full signal selection, such as those in region C , they are required to contain an IDVX passing the full signal selection, except for the requirement on the number of tracks, which has been changed from ≥ 4 tracks, to exactly 2 tracks. Similarly, the region B' events are required to pass the full requirements for the signal region, except the IDVX has to have $n_{\text{trk}} = 2$ instead of $n_{\text{trk}} \geq 4$. IDVXs with $n_{\text{trk}} = 2$ are chosen because the 2-track IDVXs should be dominated by background, even in events otherwise passing the signal selection.

¹The total number of events in region B is slightly different from the number of events calculated by the MSVX team in [13] due to small changes in the quality definitions for the tracks and jets used in the MSVX isolation.

Has IDVX, $n_{\text{trk}} \geq 4$, $m_{\text{IDVX}} > 3 \text{ GeV}$	C	A
Has IDVX, $n_{\text{trk}} = 2$, $m_{\text{IDVX}} > 3 \text{ GeV}$	C'	A'
Agnostic with respect to IDVXs	D	B
	Background events	Muon RoI cluster trigger events with a good MSVX

Figure 6.3: The ABCD plane, with the addition of the B' and C' regions, containing IDVXs with a $m_{\text{IDVX}} > 3 \text{ GeV}$ and $n_{\text{trk}} = 2$.

Like the factor F that was calculated using the plane in Figure 6.1, a factor F' can be calculated using the new control regions in the plane in Figure 6.3. Here,

$$F' = N_{C'}/N_D, \quad (6.3)$$

and the expected number of events in region A' is

$$N_{A'}^{\text{pred.}} = N_B \times F' = N_B \times N_{C'}/N_D. \quad (6.4)$$

It is found that 438,351 of the region D events contain at least one 2-track IDVX as described above, thus $F' = N_{C'}/N_D = 438,351/6,099,660 = (7.19 \pm 0.011 \text{ (stat)}) \times 10^{-2}$. Therefore, the predicted number of region A' events becomes $N_{A'}^{\text{pred.}} = N_B \times F' = N_B \times N_{C'}/N_D = (156,805 \pm 400) \times (7.19 \pm 0.011) \times 10^{-2} = 11,268.8 \pm 46.1 \text{ (stat)}$. The actual number of events found in region A' was 11,470, which is within 2% of the predicted number.

There are sufficient statistics to examine the distributions of the 2-track vertices that are found in the A' and C' validation regions to ensure that there isn't any significant bias introduced by the selection of the background events. Figure 6.4 shows the normalized R and z distributions for the 2-track vertices found in the validation regions A' and C' , as well as the ratios of the of the normalized A' distributions to the C' distributions. Along both the vertex R and z , the ratio of the normalized

distributions is fairly consistent with one, after taking into account the statistical uncertainties. Any additional differences in the R and z distributions would be covered by a systematic uncertainty of $\geq \pm 10\%$ (as represented by the red dashed lines in the ratio plots).

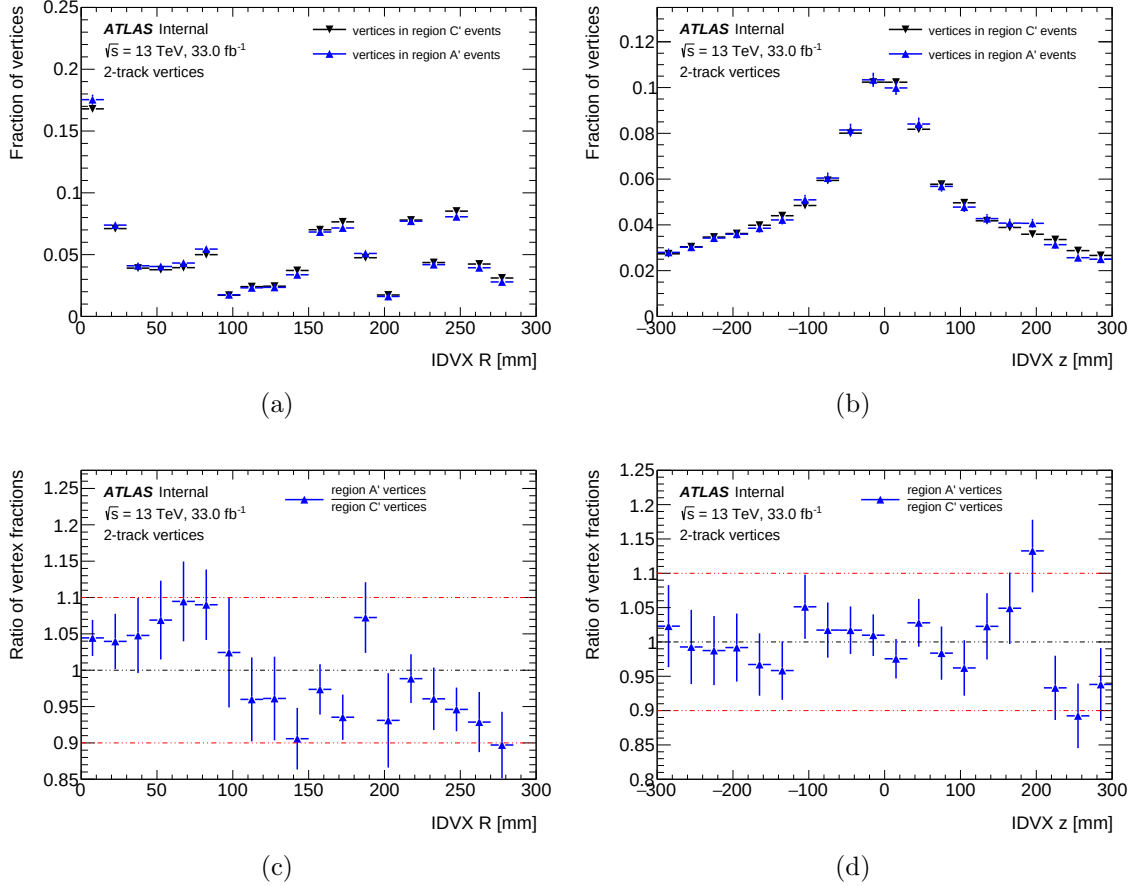


Figure 6.4: The normalized distributions of the (a) R and (b) z positions of the 2-track vertices for regions A' and C' , and (c),(d) the ratios of the A' region to the C' region. The red dashed lines in (c) and (d) represent 1 ± 0.1 .

Figure 6.5 shows the normalized η and ϕ distributions for the 2-track vertices found in the validation regions A' and C' , as well as the ratios of the of the normalized A' distributions to the C' distributions. The ratios of the normalized distributions vs η and ϕ are also mostly consistent with one within the statistical uncertainties. Once

again, any differences in the vertex distributions introduced by the different event selections are easily covered by a small systematic.

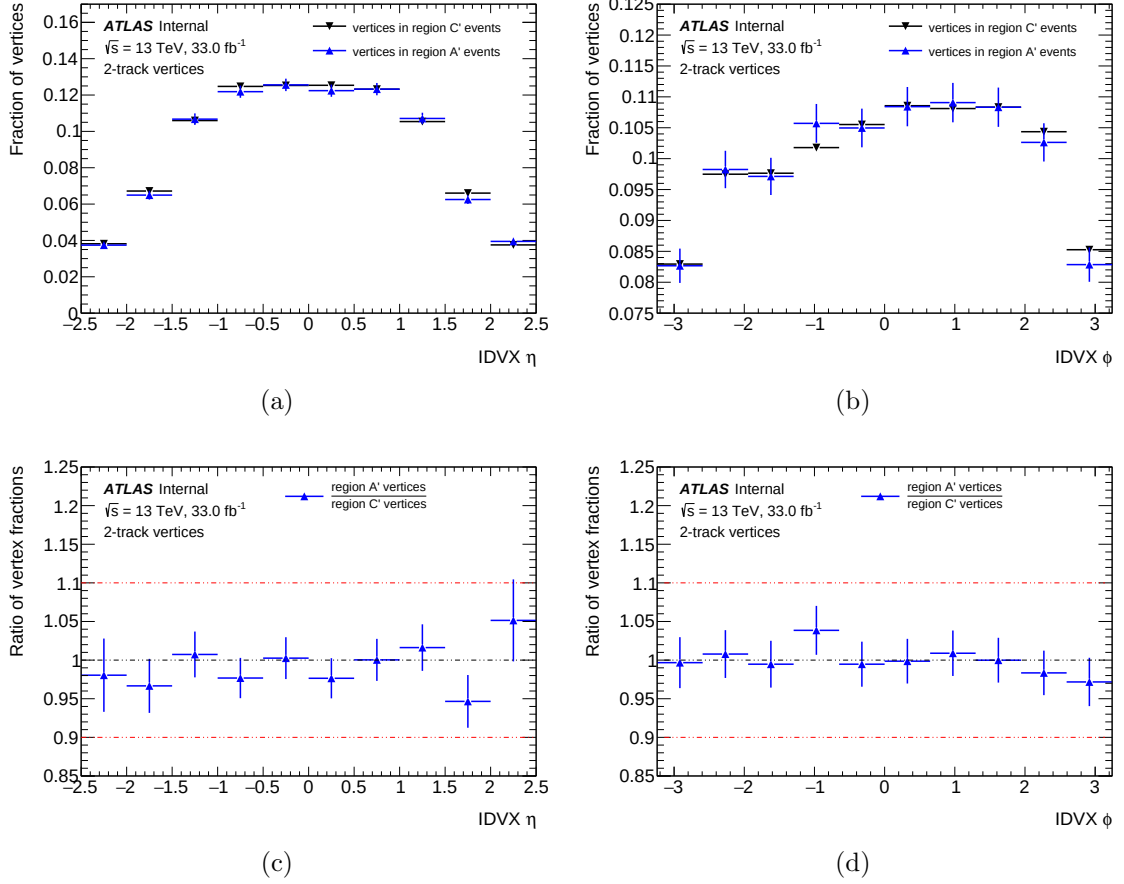


Figure 6.5: The normalized distributions of the (a) η and (b) ϕ of the 2-track vertices for regions A' and C' , and (c),(d) the ratio of the A' region to the C' region. The red dashed lines in (c) and (d) represent 1 ± 0.1 .

Figure 6.6 shows the normalized 2-track vertex distributions versus the vertex mass as well as the ratio of the normalized distributions. Although the statistics become very limited for $m_{\text{IDVX}} > 10$ GeV, the ratio is approximately consistent with one within statistical uncertainties. Figures 6.4, 6.5, and 6.6 demonstrate that there is no significant bias in the distributions of the vertices in the validation regions introduced by the background event selection compared to the signal selection. This increases the confidence in the use of the background events to develop the background estimation.

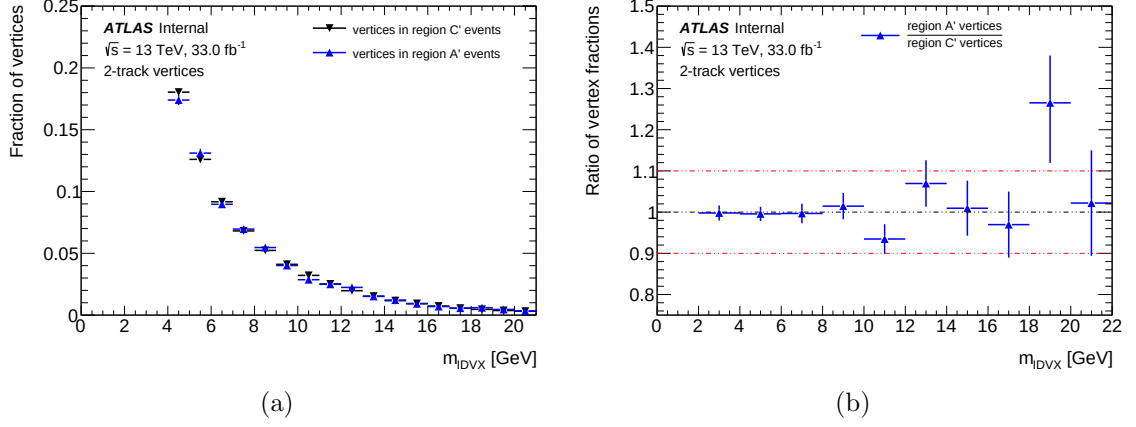


Figure 6.6: The normalized distributions of the m_{IDVX} of 2-track vertices for regions A' and C' (a), and the ratio of the A' region to the C' region (b). The red dashed lines in (b) represent 1 ± 0.1 .

Due to the fact that different sources of background are likely to be the main contributors to IDVXs with $n_{\text{trk}} = 2$, compared to IDVXs with a higher number of tracks, a second set of control regions was developed, which are demonstrated in Figure 6.7.

Has IDVX, $n_{\text{Trks}} \geq 4$, mass > 3 GeV	C		A
Has IDVX, $n_{\text{Trks}} = 3$, $1 < \text{mass} < 3$ GeV	C''	A''	
Agnostic with respect to IDVXs	D	B''	B
	Background events	Muon RoI cluster trigger events agnostic to MSVXs	Muon RoI cluster trigger events w/ a good MSVX

Figure 6.7: The ABCD plane, with the addition of the A'' , B'' and C'' regions, containing IDVXs with $1 \text{ GeV} < m_{\text{IDVX}} < 3 \text{ GeV}$ and $n_{\text{trk}} = 3$, and events that pass the muon RoI cluster trigger but that don't necessarily contain any good MSVXs.

Here, the region C'' events are background events containing an IDVX passing all the IDVX requirements described in Table 5.2 except those on the vertex mass and on the number of tracks, instead these vertices are required to have a vertex mass just lower than those in the signal region, $1 < m_{\text{IDVX}} < 3$ GeV, and exactly 3 tracks. A new type of events is added; region B'' , events that pass all the trigger requirements used for the events in the signal region, but which are agnostic to the presence of any MSVXs.

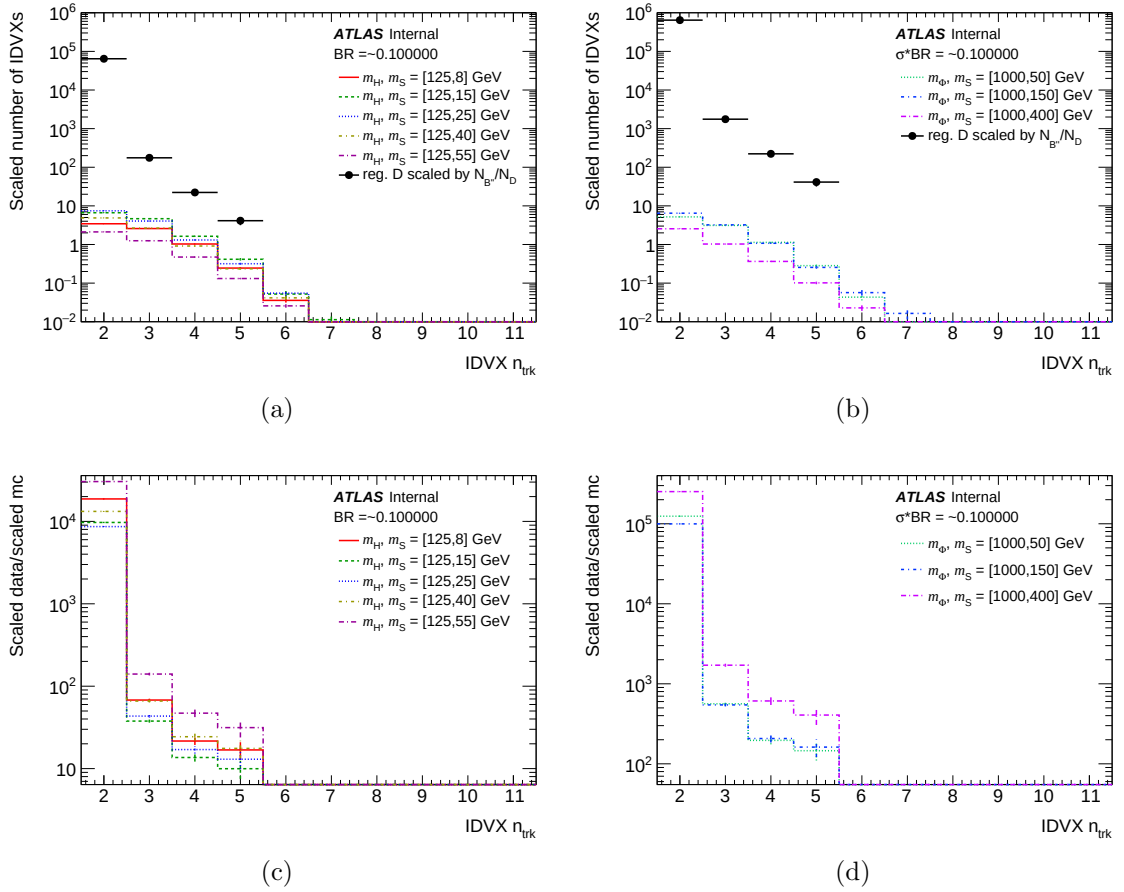


Figure 6.8: Scaled distributions of signal (from signal MC samples) and background (from region D) vertices expected to be found in region B'' . Shown for (a) 125 GeV $H \rightarrow ss$ and (b) 1000 GeV $\Phi \rightarrow ss$ (b). The IDVXs are required to have vertex mass $1 < \text{mass} < 3$ GeV and exactly 3 tracks. The ratios of the scaled number of background vertices/scaled number of signal vertices are shown in (c) and (d).

As shown in Figure 6.8 in these events the amount of signal contamination for the 3-track, lower mass IDVXs described above is determined to be at most 3%, based on current limits, which is significantly lower than it would have been in region B type events, and so it is safe to proceed with validation of the background estimation. Region A'' is thus defined as events passing the muon RoI cluster trigger (and not the HCal jets triggers), which contain a low-mass, 3-track vertex.

Once again, a factor F'' can be defined, $F'' = N_{C''}/N_D$. In this case, out of the 6,099,660 events used to populate region D , 765 events were found to contain a low mass, 3-track vertex, thus $F'' = 765/6,099,660 = (1.25 \pm 0.045(stat)) \times 10^{-4}$. There were 13,953,316 events used to populate region B'' , so the predicted number of events in A'' becomes $N_{A''}^{pred.} = N_{B''} \times F'' = N_{B''} \times N_{C''}/N_D = (1.3953316 \times 10^7 \pm 3.7 \times 10^3) \times (1.25 \pm 0.045) \times 10^{-4} = 1,750 \pm 64(stat)$. The total number of events found to be in region A'' was 2,132, which is within 25% of the predicted number of events. To be conservative, because the second set of validation regions are similar to, but not exactly like the ABCD regions, the systematic uncertainty on the background estimation method is taken to be 50%.

6.2.1 Jet multiplicity impact on the background estimation

The jet multiplicity distributions are not exactly the same in the different regions used in the modified ABCD plane, so to provide more confidence that this difference will not impact the accuracy of the background estimation, the impact on the background estimation of the jet multiplicities is examined. The jets considered are those that pass standard jet cleaning selections and have a $p_T \geq 20$ GeV. The jet multiplicities are examined separately considering jets that are selected to have passed the JVT selection and with the selection agnostic to the JVT requirement. The inclusion of the JVT requirement reduces the contribution from the pileup jets in the events.

Jet multiplicities are compared between the three ABCD regions (and validation regions) that are agnostic to the presence of vertices: D , B , and B'' .

Figure 6.9 shows the overall jet multiplicity distributions in regions D , B , and B'' , considering all jets (passing the jet cleaning and p_T requirements) in Figure 6.9a and jets that additionally pass the JVT requirement in Figure 6.9b. The normalized distributions are shown in Figures 6.10a and 6.10b respectively.

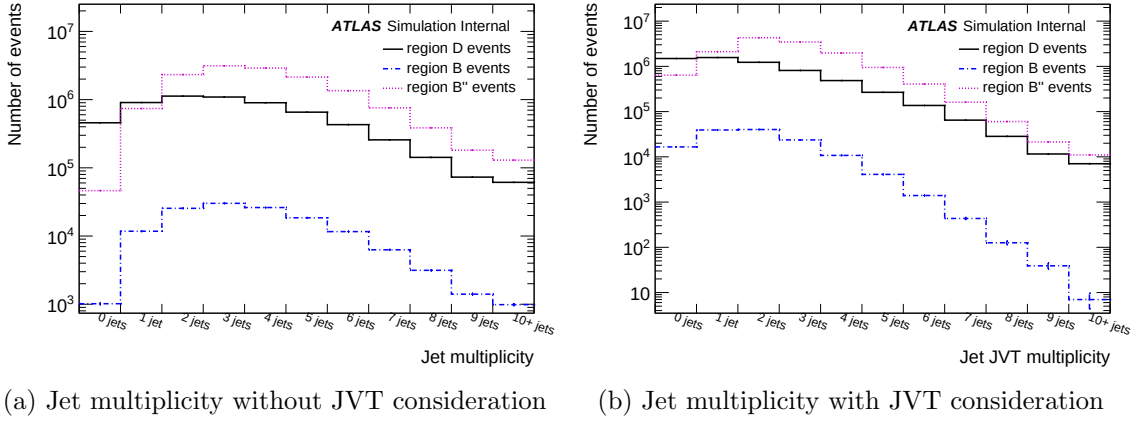


Figure 6.9: The jet multiplicity in events used in the background estimation, for region D , B , and B'' events. Jet multiplicities (a) agnostic to and (b) passing the JVT requirement.

From Figures 6.9 and 6.10 it can be seen that a greater proportion of the events populating region D have no jets (whether taking into account or not the JVT requirement), than of the events in regions B or B'' . Region D also has a greater fraction of events with 9 or more jets than region B . This is particularly clear in the ratios of the normalized distributions, Figures 6.10c and 6.10d, which show the increased fraction of region D events compared to region B events with 0-1 or ≥ 9 jets. The validation region, region B' , also has somewhat different jet multiplicity distributions than those found in the region B events, tending to have more jets per event. This difference is expected, as there are isolation requirements placed on the MSVX found in the region B events, which are not required in the region B'' events,

these isolation requirements which reject MSVXs which are produced nearby to jet activity in the event, will disfavor events with higher jet multiplicities.

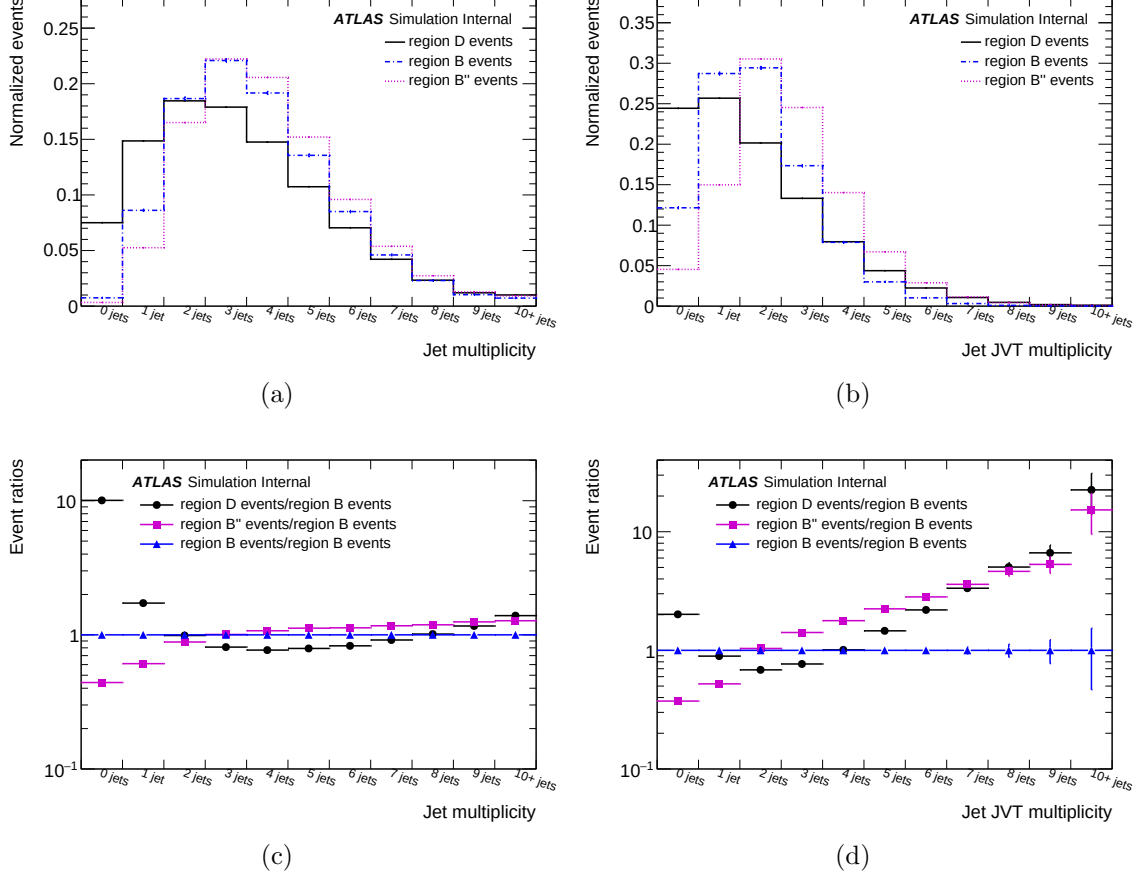


Figure 6.10: The normalized jet multiplicity distributions agnostic to (a) and passing (b) the JVT requirement on the jets in regions D , B , and B'' . The ratios of the normalized distributions are shown in (c) and (d).

To examine how these differences in the jet multiplicities in the different ABCD regions impact the background estimation, the factors F'' and F' are compared versus the jet multiplicity. As defined in Equations 6.3 and 6.4, $F' = N_{C'}/N_D$, and since it is predicted that $N_{A'} = N_B \times F'$, it is possible to compare $F' = N_{C'}/N_D$ and $F' = N_{A'}/N_B$. Similarly it is possible to compare the F'' factors calculated from $F'' = N_{C''}/N_D$ or from $F'' = N_{A''}/N_{B''}$.

Figure 6.11 demonstrates the F' factors based on regions C' and D compared to A' and B as a function of the jet multiplicity in the region B and D events. There is a positive correlation between the jet multiplicity in the events and the magnitude of the F' factors, meaning the increased jet multiplicity increases the likelihood that a given event will contain at least one 2-track vertex. The increase of the F' factors are similar within statistical uncertainties vs the jet multiplicity for F' based on regions C' and D or A' and B .

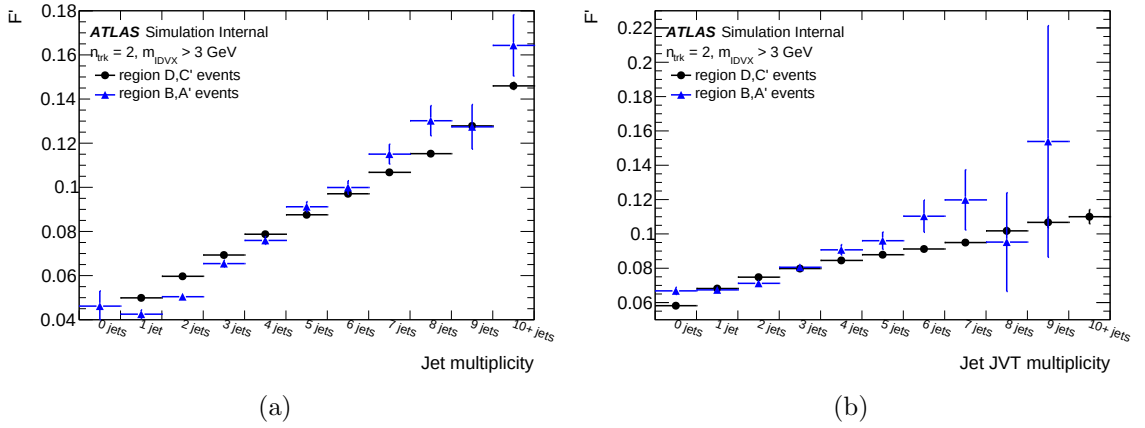


Figure 6.11: The factor $F' = N_{C'}/N_D$, $F' = N_{A'}/N_B$, vs the jet multiplicity, considering jets (a) agnostic to or (b) passing the JVT selection.

The dependence of the F'' factors on the jet multiplicity in the events is shown in Figure 6.12. The F'' factors show a stronger dependence on the jet multiplicity than the F' because the 2-track vertices are more likely to be formed from the random crossing of two unrelated (fake or real) tracks, while vertices with three tracks are more likely to be associated with activity in the calorimeters. Once again the functions of F'' factors calculated based on the C'' and D regions and the A'' and B'' regions vs jet multiplicity are somewhat similar within statistical uncertainties. Both the consistency within the two F'' factors and the approximately linear relationship between the F'' factor and the jet multiplicity in the B'' and D events are stronger

for jet multiplicity taking into account only jets passing the JVT requirement; the number of non-pileup jets in the events.

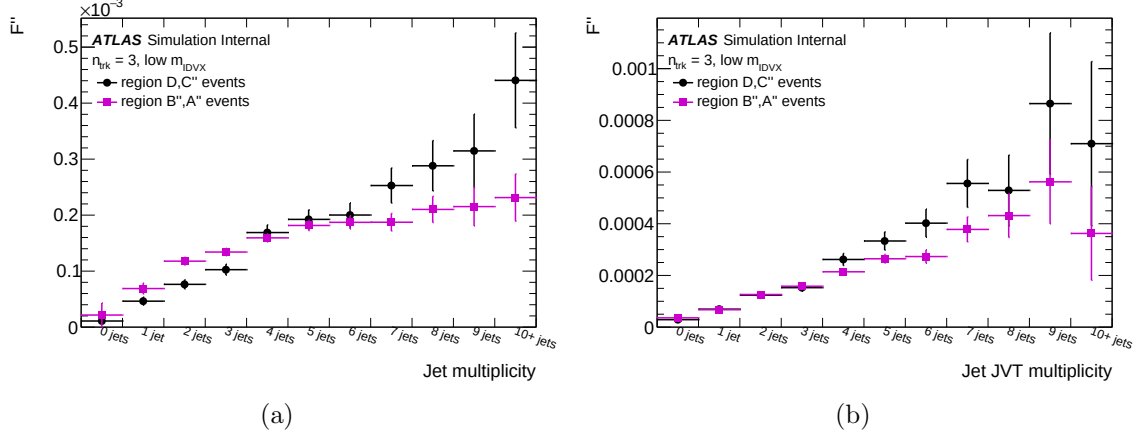


Figure 6.12: The factor $F'' = N_{C''}/N_D$, $F'' = N_{A''}/N_{B''}$, vs the jet multiplicity, considering jets (a) agnostic to or (b) passing the JVT selection.

As discussed in Section 6.2, the actual number of events in A' is within 2% of the predicted number of events based on the F' factor, while the predicted number of events in region A'' is within 25% of the actual number found. To determine the impact of the scaling the jet multiplicity in all regions to that found in the region B events, the total F'' factors can be calculated from the events in each region in each jet multiplicity bin, and then recalculated based on the scaling.

The overall F'' factors based on regions C'' and D , and A'' and B'' can be calculated as

$$F'' = \frac{\sum^{bin} N_{C''}^{bin}}{\sum^{bin} N_D^{bin}} \quad (6.5)$$

and

$$F'' = \frac{\sum^{bin} N_{A''}^{bin}}{\sum^{bin} N_{B''}^{bin}} \quad (6.6)$$

respectively, where the bins are the jet multiplicity bins. Additional per-bin factors can be calculated based on the ratios of the normalized jet multiplicity distributions shown in Figures 6.10c and 6.10d, such that $f_{B''}^{bin} = N_B^{bin}/N_{B''}^{bin}$ or $f_D^{bin} = N_B^{bin}/N_D^{bin}$.

The f''^{bin} factors allow the jet multiplicity in the events to be rescaled to match the jet multiplicity in the region B events since the factor F is applied to the region B events in the final background estimation.

The rescaled F'' factors then are calculated via

$$F'' = \frac{\sum^{\text{bin}} f''^{\text{bin}}_{B''} \times N^{\text{bin}}_{A''}}{\sum^{\text{bin}} f''^{\text{bin}}_{B''} \times N^{\text{bin}}_{B''}} \quad (6.7)$$

and

$$F'' = \frac{\sum^{\text{bin}} f''^{\text{bin}}_D \times N^{\text{bin}}_{C''}}{\sum^{\text{bin}} f''^{\text{bin}}_D \times N^{\text{bin}}_D}. \quad (6.8)$$

The rescaled F'' factors can be calculated using the jet multiplicities agnostic to, or considering, the JVT jet requirements.

As shown in Figure 6.13, the total F'' factor calculated from the C'' and D regions differs significantly from the total F'' factor calculated from the A'' and B'' regions even after taking into account the statistical uncertainties (as shown by the black points). The recalculated F'' factors taking into account the jet multiplicities that are agnostic to the JVT requirement, represented by the blue filled triangles in Figure 6.13, differ only by about 4%, as shown by the green dashed line, which is within the statistical uncertainty. The recalculated F'' factors taking into account the jet multiplicities that take into account the JVT requirement, represented by the blue open triangles, agree within 5%, which is also within the statistical uncertainties, shown by the purple dashed line. Thus, re-scaling by the jet multiplicity differences between the regions (scaling to match the jet multiplicity in region B), provides closure, reducing the differences between the F'' factors calculated from the C'' and D regions or A'' and B'' regions to within the statistical uncertainties. This is true whether the jet multiplicity used for the scaling takes into account the JVT requirement or not.

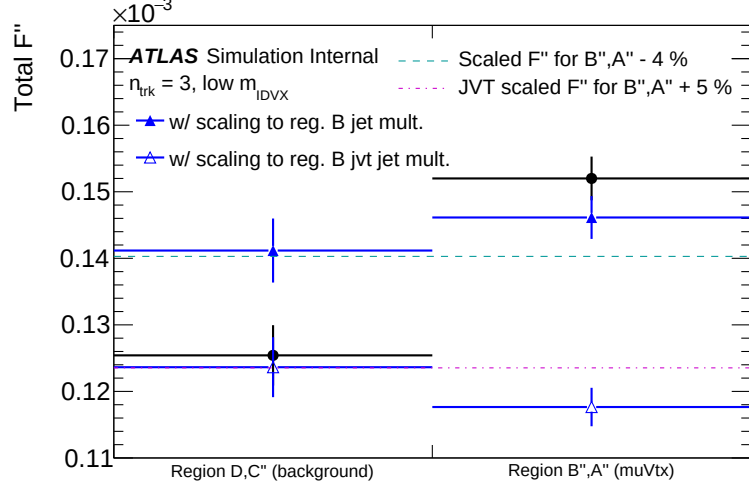


Figure 6.13: The overall factor F'' , for the 3 track vertices, low mass vertices, unscaled (black points), scaled based on the region B events jet multiplicity (blue filled triangles), and scaled based on the region B jet multiplicity taking into account JVT requirements (blue open triangles). Dashed lines indicate the level of agreement between the calculations of F'' , before and after scaling to the region B events jet multiplicity.

If the same scaling method is applied to the factor F that is used to predict the number of background events found in region A , the rescaled

$$F_{rescale} = \frac{\sum^{bin} f^{bin} \times N_C^{bin}}{\sum^{bin} f^{bin} \times N_D^{bin}}, \quad (6.9)$$

using $f^{bin} = N_B^{bin}/N_D^{bin}$. The rescaled F factor calculated when considering the jet multiplicity agnostic to the JVT selection, $F_{rescale} = 8.6 \times 10^{-6}$, differs from the unscaled $F = (7.38 \pm 1.10(stat)) \times 10^{-6}$ by 15%, and is approximately within the statistical uncertainty on the unscaled F . Considering the rescaled F factor calculated using the multiplicity of jets passing the JVT selection, $F_{rescale} = 8.1 \times 10^{-6}$, differs from the unscaled F by 9.2%, less than the statistical uncertainty. Thus, while the closure provided in the 3-track validation regions after the jet multiplicity scaling provides more confidence in the effectiveness of the background estimation method and validation, the impact on the final background estimate is ultimately very small

(within statistical uncertainty). Since the jet multiplicity scaling would have such a small impact on the background estimation method, it was determined that it was more straightforward to leave the estimate unscaled, and take the systematic uncertainty to be based on the largest difference between the predicted and observed numbers of events found in the unscaled validation regions.

6.3 Expected number of background events

As discussed previously, the predicted number of events from background passing the full signal region requirements is $N_A^{\text{pred.}} = N_B \times F = N_B \times N_C/N_D$. The total number of events in region B is 156,805, thus the predicted number of region A events becomes $N_A = N_B \times F = N_B \times N_C/N_D = (156,805 \pm 400) \times (7 \pm 1.1) \times 10^{-6} = 1.2 \pm 0.2 (stat) \pm 0.6 (syst.)$.

CHAPTER 7

SYSTEMATIC UNCERTAINTIES

Many sources of statistical uncertainties are introduced during an experimental search for new particles. Systematic uncertainties may come from a variety of sources such as the parton distribution functions (PDFs) used to create the MC samples, and the differences introduced by using MC samples for studies and ultimately performing the search in data. Uncertainties from the differences in the reconstruction efficiency in data and in MC samples, from the trigger scale factors, the pileup re-weighting, and the PDF fits are summarized in the following section. None of the studies described here were performed by the author, but are necessary to the final result, credit is given to the analyses and analyzers who performed the studies.

7.1 Systematic uncertainties on displaced tracking and vertex reconstruction in the ID

In order to determine any systematic uncertainties introduced by the differences in the reconstruction of the displaced IDVXs, reconstructed vertices from $K_S^0 \rightarrow \pi^+\pi^-$ decays were compared in data and in MC samples¹. The K_S^0 vertices are expected to be well modeled in MC simulation and may be reconstructed with standard tracks and/or tracks reconstructed during the large radius tracking pass. Because the systematic uncertainties due to the standard tracking algorithm are understood well by the ATLAS collaboration [73], comparing the K_S^0 vertices with two standard tracks

¹This study comparing the $K_S^0 \rightarrow \pi^+\pi^-$ decays in data and in MC samples was performed by University of Massachusetts Amherst student, Jackson Burzynski.

and the K_S^0 vertices with two large radius tracks provides an estimate of the systematic uncertainties introduced by the large radius tracking and displaced vertexing algorithms.

The data events used for this study were those events in the RPVLL filter stream (all the events selected to be reconstructed with the large radius tracking and displaced IDVX algorithms), that pass the GRL and the quality standards for the SCT, LAr, and Tile sub-detectors. The di-jet MC events used are those in the p_T slices outlined in Table 3.2. These p_T slices are chosen so that the shape of the jet p_T distribution in the di-jet slices most closely matched the shape of the jet p_T distribution in the signal region in data (see Figure 7.1). No further requirements are placed on either the data or MC sample events used, in order to minimize the impact of the statistical uncertainty.

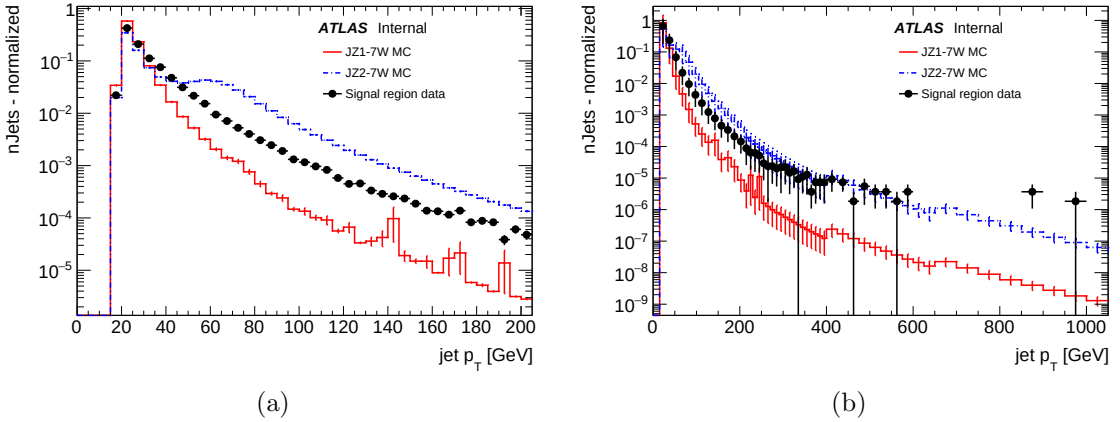


Figure 7.1: The comparison of the jet p_T distributions in the di-jet MC samples and in the signal region in data (minus the requirement of an IDVX). The jet p_T region from 0-200 GeV is shown in (a) and an expanded region from 0-1000 GeV is shown in (b). The jet p_T distribution in data is compared to the jet p_T distributions using the di-jet slices JZ1W-JZ7W or JZ2W-JZ7W to show that the inclusion of the JZ1W slice is important to for the shape of the low p_T distribution to match that found in data.

Preliminary K_S^0 vertex candidates are selected as those displaced vertices that pass the fiducial volume selections described in Section 5.3, K_S^0 $R, |z| < 300$ mm,

radial distance from the PV > 4 mm, and passing the material and disabled module vetos. The preliminary K_S^0 vertex selection also requires $\chi^2/\text{nDoF} < 5$. Furthermore, the preliminary K_S^0 vertex candidates are required to have exactly 2 tracks, a decay length ≥ 15 mm, and an invariant mass of $450 \text{ MeV} < m_{\text{vertex}} < 550 \text{ MeV}$. The last two selections reduce the potential signal contamination to a trivial level without significantly impacting the efficiency to select K_S^0 vertices.

Any potential background is calculated by subtracting the number of vertices in the invariant mass sidebands of $350 \text{ MeV} < m_{\text{vertex}} < 450 \text{ MeV}$ and $550 \text{ MeV} < m_{\text{vertex}} < 650 \text{ MeV}$, from the number of vertices in the $450 \text{ MeV} < m_{\text{vertex}} < 550 \text{ MeV}$ invariant mass region. The total number of final K_S^0 vertex candidates is thus computed via Equation 7.1,

$$N_{K_S^0} = N_{450 < m < 550} - \frac{N_{350 < m < 450} + N_{550 < m < 650}}{2}. \quad (7.1)$$

The distributions of the K_S^0 candidate decay radius R [mm], longitudinal decay position z [mm], decay length [mm], and invariant mass [GeV] are shown in Figure 7.2. The vertices shown in Figure 7.2 have no requirement on the tracking algorithm used to reconstruct the constituent tracks. There is good agreement demonstrated between the K_S^0 candidate distributions in data and in MC samples, confirming that the K_S^0 vertices are well modeled in MC simulation.

The yield of the K_S^0 vertices reconstructed with large radius tracks only is shown in Figure 7.3, as a function of the K_S^0 decay radius R [mm]. The distribution in data is normalized so that the total vertex collections in data events and in MC sample events had the same number of K_S^0 vertex candidates reconstructed using only standard tracks. This is done to account for any differences in the total number of K_S^0 candidates existing in the data and MC samples. The normalization is applied to the distribution in data rather than to the distribution in the di-jet MC samples due to a limitation in the MC statistics.

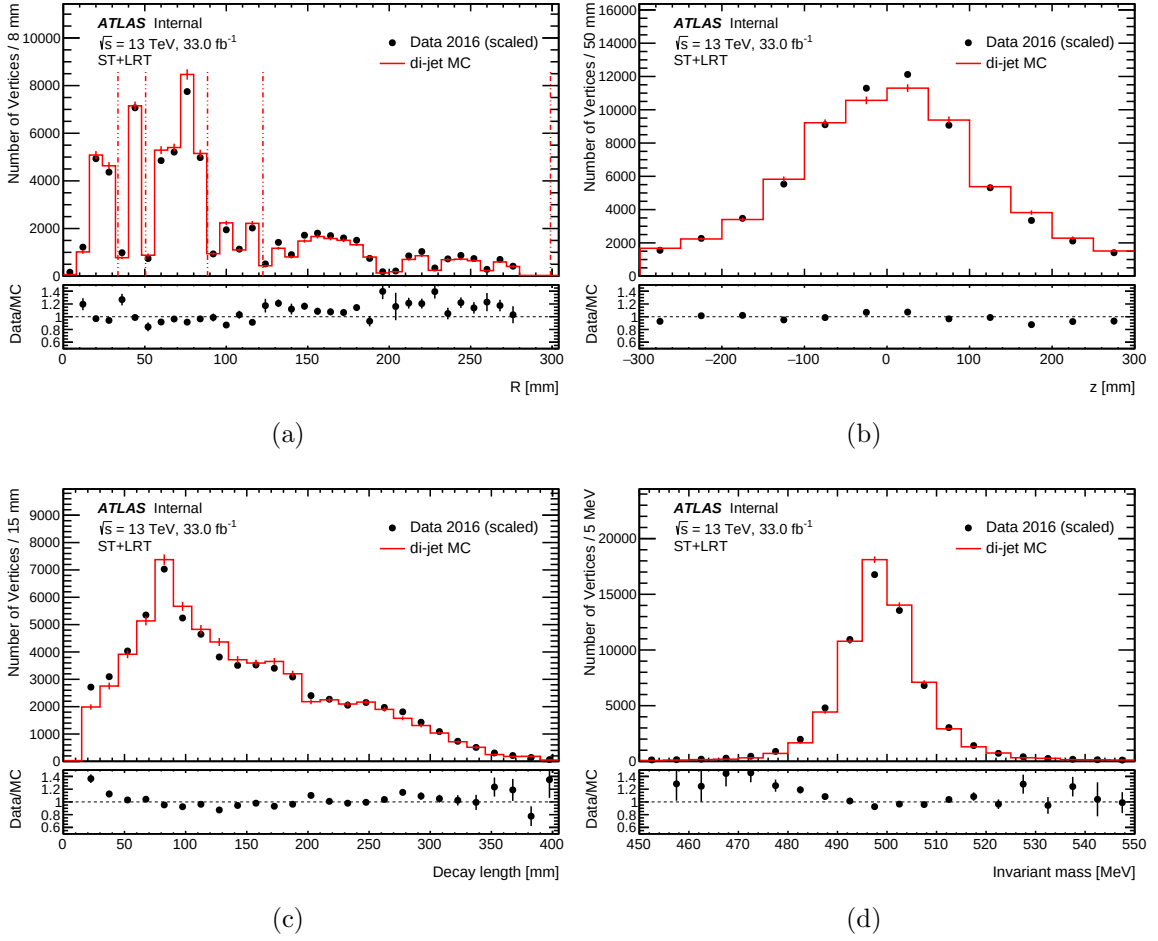


Figure 7.2: The data vs MC comparison of the radial decay position of the K_S^0 vertices, R [mm] is shown in (a), the longitudinal decay position of the vertices, z [mm] is shown in (b), the decay length of the vertices [mm] is shown in (c), and the invariant mass of the vertices [MeV] is shown in (d). The dashed lines shown in (a) represent the radial position of the layers of material in the pixel detector and the first layer of the SCT. All reconstructed K_S^0 candidates are included, whether they were reconstructed with standard or large radius tracks. *Figures were created by J. Burzynski.*

Figure 7.3 demonstrates the ratio of large radius-track-only K_S^0 candidates in data to those in MC samples in each of five decay radius R [mm] bins. The largest difference from one in any bin is approximately 20%. To be conservative, a systematic uncertainty of 20% is applied to the IDVX reconstruction efficiency.

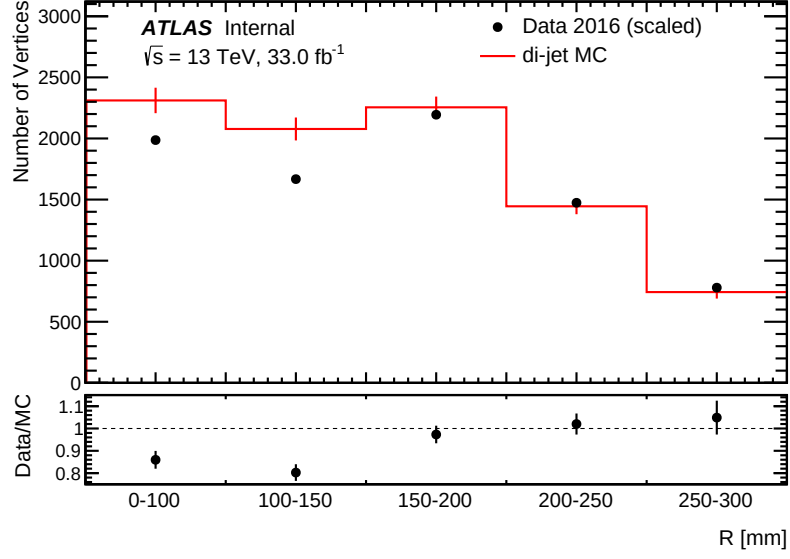


Figure 7.3: The yield of the K_S^0 vertices reconstructed with only large radius tracks, as a function of the radial decay position of the vertex, R [mm]. The vertex collection in data is normalized such that the data and MC sample events each had the same number of vertices reconstructed using only standard tracks. *Figure was created by J. Burzynski.*

7.2 Uncertainty on integrated luminosity

The uncertainty on the integrated luminosity for the 2016 dataset is 2.2%. This uncertainty is derived using a methodology like that which is described in Ref. [74], using the LUCID-2 detector [52] to perform baseline luminosity measurements from a calibration of the luminosity scaling using x-y beam-separation scans.

7.3 MSVX reconstruction efficiency

The MS analysis used punch-through jets in data and di-jet MC events to assess the systematic uncertainty associated to the MSVX reconstruction. The average number of muon segments found in the punch-through jet cones were compared between data and MC events as a function of the leading jet p_T . The data/MC ratio was found to be consistent with one in both the barrel and the endcaps, so there is no systematic uncertainty applied.

7.4 Muon RoI cluster trigger, scale factor uncertainty

The trigger scale factors described in Section 5.1.1.1 introduce a systematic uncertainty. To assess these systematic uncertainties, the MS analysis varied the trigger scale factor up and down by the uncertainty of the fit, $\pm 1\sigma$. The trigger efficiency was then evaluated using the nominal trigger scale factor, and the trigger scale factor $\pm 1\sigma$. The uncertainty was found to be flat vs the LLP radial (longitudinal) decay position in barrel (endcaps), so a flat systematic uncertainty was applied to the trigger efficiency per mass point. The largest systematic uncertainty due to the trigger scale factors on any mass point, in the barrel or endcaps, was 4.6%. These systematic uncertainties are included in the combined systematic uncertainties listed in Table 7.1 and 7.2.

7.5 Pileup uncertainty

As discussed in Section 3.2.1, the pileup distribution in data does not exactly match the pileup modeled in the MC samples, so a PRW is applied to correct the disagreement. This PRW introduces a source of systematic uncertainty that impacts the trigger and vertex reconstruction efficiency. The impact from the pileup should already be included in the systematic applied to the IDVX reconstruction described in Section 7.1. The impact of the PRW on the trigger efficiency and the MSVX reconstruction was evaluated by the MS analysis. The impact of the systematic uncertainty due to the PRW was determined using the same method to determine the systematic uncertainty due to the trigger scale factors. The PRW was varied up and down by its uncertainty, and the trigger efficiency and MSVX reconstruction efficiency were compared to the efficiency calculated using the nominal PRW. The impact was found to be flat compared to the LLP decay position, so a single systematic was applied to the trigger or MSVX reconstruction efficiency in the barrel and endcaps for each mass point. The largest impact on the trigger efficiency for any mass point

in the barrel or endcap was found to be 1%, and the largest impact on the MSVX reconstruction efficiency was found to be 5.5%. These systematic uncertainties are included in the combined uncertainties displayed in Tables 7.1 and 7.2.

7.6 PDF uncertainty

The signal MC samples were generated using the parton distribution function (PDF) with QED corrections NNPDF23_lo_as-0120_qed. A central PDF value is used based on 100 PDF fits, which introduces another source of systematic uncertainty that impacts the trigger efficiency and vertex reconstruction efficiency. The MS analysis determined these systematic uncertainties by comparing the trigger efficiency and the MSVX reconstruction efficiency using each of the 100 PDF fits compared to the efficiencies obtained using the central value. The ratio of the efficiencies obtained using the different PDF fits compared to the efficiencies obtained using the central value were found to be approximately flat as a function of the LLP decay position. A systematic uncertainty was applied to the trigger efficiency and the MSVX reconstruction efficiency in the barrel and the endcaps in each mass point, the largest of these was found to be 1.2%. The systematic uncertainties due to the PDF fits are included in the total combined systematic uncertainties in Tables 7.1 and 7.2.

The impact of the PDF fits on the IDVX reconstruction efficiency was not evaluated as it would be trivial compared to the uncertainty determined after comparing the K_S^0 reconstruction in data and MC samples.

m_Φ	m_s	Total Systematic uncertainties			
		Trig. eff (B)	Trig. eff (E)	MSVX reco eff (B)	MSVX reco eff (E)
125	8	$\pm 2.3\%$	$+4.8, -4.1\%$	$+0.3, -1.8\%$	$+0.07, -0.1\%$
125	15	$+2.1, -2.3\%$	$+4.6, -4.1\%$	$+5.5, -0.7\%$	$+0.2, -0.5\%$
125	25	$\pm 2.1\%$	$+3.8, -3.4\%$	$+0.1, -0.2\%$	$\pm 0.1\%$
125	40	$+1.9, -1.8\%$	$+3.3, -3.4\%$	$+0.4, -0.7\%$	$+0.1, -0.08\%$

Table 7.1: Systematic uncertainties associated to the MSVX reconstruction and the muon RoI cluster trigger in the Higgs scalar boson signal samples, resulting from the trigger reconstruction, the pileup and the PDF uncertainties. Listed separately for the barrel (B) and the endcaps (E).

m_Φ	m_s	Total Systematic uncertainties			
		Trig. eff (B)	Trig. eff (E)	MSVX reco eff (B)	MSVX reco eff (E)
200	8	$+2.1, -2.3\%$	$+4.6, -3.8\%$	$+5.5, -0.7\%$	$+0.2, -0.5\%$
200	25	$\pm 2.1\%$	$+3.8, -3.4\%$	$+0.1, -0.2\%$	$\pm 0.1\%$
200	50	$+1.9, -1.8\%$	$+3, -2.5\%$	$+0.4, -0.7\%$	$+0.1, -0.08\%$
400	50	$\pm 1.5, \%$	$\pm 2.4\%$	$+1.2, -0.3\%$	$\pm 0.2\%$
400	100	$\pm 1.6\%$	$+3, -2.5$	$+0.08, -0.3\%$	$\pm 0.1\%$
600	50	$+1.5, -1.4\%$	$+2.5, -2.2\%$	$+0.8, -0.2\%$	$\pm 0.3\%$
600	150	$+1.3, -1.5\%$	$\pm 2.1\%$	$+0.9, -0.3\%$	$+0.2, -0.3\%$
1000	50	$+1.1, -1.4\%$	$\pm 1.9\%$	$+0.05, -0.9\%$	$+0.6, -0.8\%$
1000	150	$\pm 1.1\%$	$+1.4, -1.7\%$	$+0.2, -0.3\%$	$+0.3, -0.6\%$
1000	400	$+1.4, -1.7\%$	$+2.1, -2.2\%$	$+0.2, -2.5\%$	$\pm 1.2\%$

Table 7.2: Systematic uncertainties associated to the MSVX reconstruction and the muon RoI Cluster trigger in the Φ scalar boson signal samples, resulting from the trigger reconstruction, the pileup and the PDF uncertainties. Listed separately for the barrel (B) and the endcaps (E).

CHAPTER 8

RESULTS

8.1 Global Efficiency

It is computationally forbidding to produce a statistically useful number of events at a large range of lifetime points, therefore in order to understand the event selection efficiency and the limits on a given mass and cross-section across a range of lifetimes, an extrapolation method must be used.

8.1.1 Lifetime Extrapolation

To evaluate the efficiency of the full event selection as a function of the proper lifetime of the LLP, a re-weighting procedure is used. Each LLP in each event is given a weight according to Eq. 8.1,

$$w_l(t) = \frac{\tau_{gen}}{\exp(\frac{-t_l}{\tau_{gen}})} \cdot \frac{\exp(\frac{-t_l}{\tau_{new}})}{\tau_{new}}, \quad (8.1)$$

in which τ_{gen} is the lifetime of the signal MC sample, τ_{new} is an arbitrary lifetime point, and t is the proper decay time, based on the three-dimensional decay position, the β , and the γ of the LLP.

Since the LLPs are pair-produced, the weight for each event becomes $w_{ev} = w_1 \cdot w_2$, and the overall efficiency to select an event at any given lifetime is

$$\epsilon = \frac{\sum_{ev} \text{event weight}_{ev} \times \text{pass}_{ev} \times w_{ev} \times SF_{trig}}{\sum_{all}}, \quad (8.2)$$

where the term SF_{trig} takes into account the data/MC trigger scale factor depending on whether the MSVX was in the barrel or the endcap of the MS, and ‘event weight’

takes into account weighting to make the MC events match the data events (such as the PRW). The results of the lifetime extrapolation starting from a mean lab-frame lifetime of 5 m are shown in Figure 8.1.

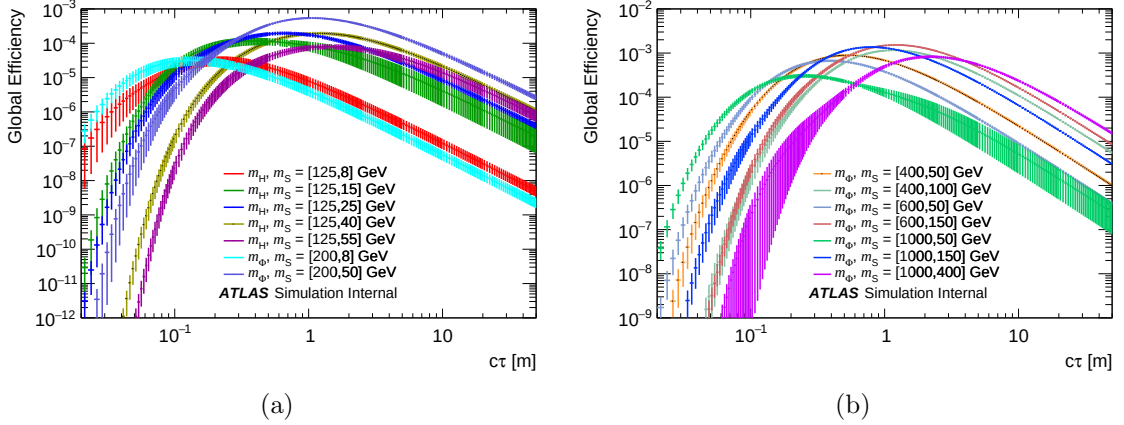


Figure 8.1: Global efficiency vs $c\tau$ [m] for Higgs or $\Phi = 200 \text{ GeV} \rightarrow ss$ (a) and for $\Phi = 400, 600, 1000 \text{ GeV} \rightarrow ss$ (b).

Confirmation of the effectiveness of the lifetime extrapolation method was evaluated by comparing the extrapolated efficiency from the 5 m mean lab-frame lifetime sample to the efficiency found in the 9 m mean lab-frame lifetime sample (at the nominal lifetime), as well as by comparing the lifetime extrapolation curves derived from both the 5 m lab-frame lifetime and 9 m lab-frame lifetime samples. Comparisons of the lifetime extrapolations from the 5 m and 9 m mean lab-frame lifetime samples are shown in Figure 8.2.

Figure 8.2 demonstrates agreement of the lifetime extrapolation curves from the 5 m and 9 m lab-frame lifetime samples over a wide range of the extrapolated $c\tau$. The extrapolated efficiency generally agrees within the statistical uncertainties. The statistical uncertainties are fairly large, particularly for the mass points with the lowest LLP masses, due to the limitations of the IDVX reconstruction and the requirement that the IDVX mass must be $> 3 \text{ GeV}$. There is some further disagreement in the lifetime extrapolation curves at low $c\tau$; it is expected that the extrapolation from the

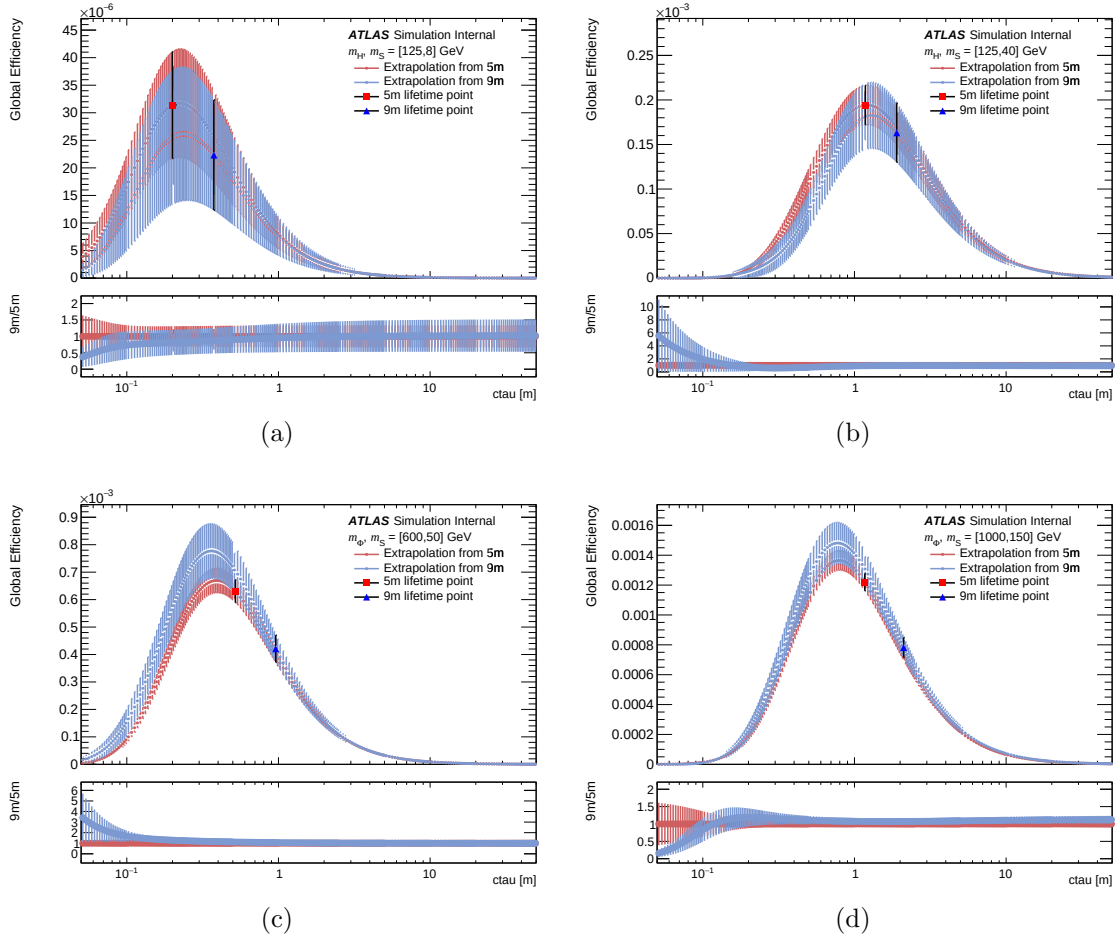


Figure 8.2: The comparison of the lifetime extrapolation starting from the 5 m lab-frame lifetime sample (red), and starting from the 9 m lab-frame lifetime sample (blue). The efficiency at the mean generated lifetimes for each sample are included as the red (blue) points. The comparison is shown for mass points with a 125 GeV Higgs decaying to an 8 GeV (a) or 40 GeV LLP (b), for a 600 GeV Φ to a 50 GeV LLP (c), and for a 1000 GeV Φ to a 150 GeV LLP (d) Uncertainties are statistical only.

9 m mean lab-frame lifetime will do a worse job at very low $c\tau$ due to the fact the low decay length regions will be less populated for these samples and the fact that the extrapolation is further from the nominal lifetime of the sample.

At the $c\tau$ of the 9 m mean lab-frame lifetime point, the extrapolated efficiency from the 5 m mean lab-frame lifetime samples agreed with the nominal efficiency found

in the 9 m mean lab-frame lifetime samples within at most 1.3 times the combined statistical uncertainties from the efficiency and extrapolation computations.

8.2 Observed signal region events

One event was observed in the signal region. The observed event is visualized in Figure 8.3.

Given that the background estimate, described in Section 6, predicted $1.2 \pm 0.2 (stat) \pm 0.56 (syst.)$ events from background to be in the signal region, this observation is consistent with background. Since no excess is observed, limits are set on the production cross section of the Φ times the branching ratio (BR) for the decay of the Φ to the LLPs.

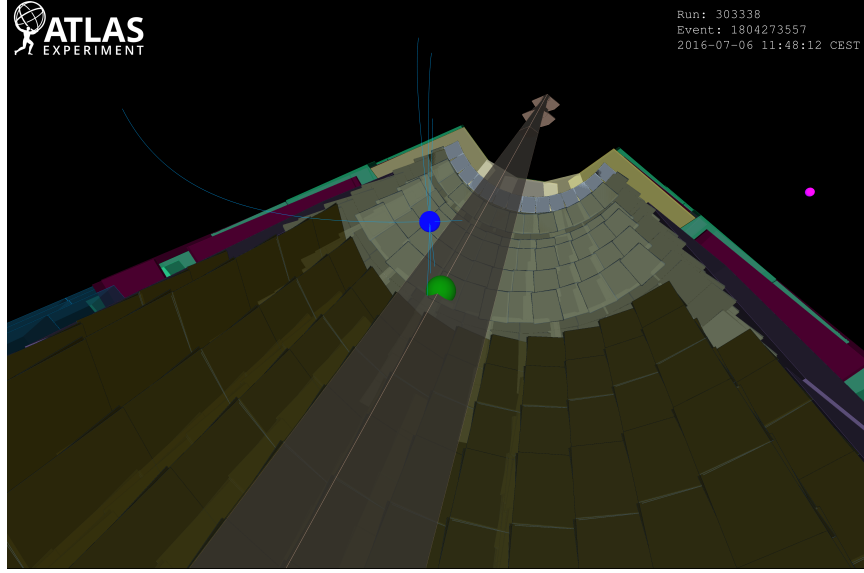
8.3 Limits

8.3.1 Limit setting procedure

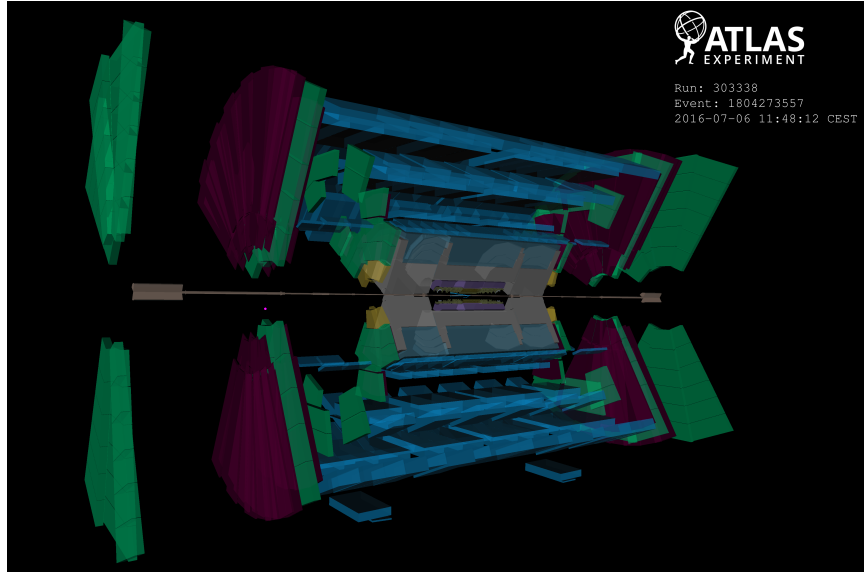
Upper limits are set at a 95% confidence level (CL) using the CL_s method [75, 76]. The CL_s method is a popular method of setting limits in particle physics designed to take into account the two different goals of particle physics experiments, exclusion and discovery.

A test statistic can be developed which is the ratio of the likelihoods for the exclusion and discovery hypotheses. The denominator is the null, or background only, hypothesis, that the data can be explained using only existing physics. The numerator is the alternative, or signal plus background hypothesis, that to explain the data necessitates new physics.

The CL_s method can be considered as $P(n_{s+b} \leq n_o)/P(n_b \leq n_o)$, the probability that the number of observed events is $\leq$ the number of events predicted from background and signal processes combined, over the probability that the number of



(a)



(b)

Figure 8.3: The event observed in the signal region, Event number 1804273557 in Run 303338. The IDVX is shown as a dark blue sphere and the associated tracks are shown in light blue. The MSVX is shown in purple, and the PV is shown in green. The event is shown in (a) zoomed in from the endcaps and in (b), zoomed out from outside the barrel. The IDVX has 4 associated tracks, a mass of 3.34 GeV, and is located at an (R,z) of (29.07,142.92) mm and detector (η,ϕ) of (2.30,0.014). The MSVX is located at an (R,z) of (4.97,12.45) m and a detector (η,ϕ) of (1.65,-2.94).

observed events is $\leq$ the number of events from background processes only. This is typically written out as $CL_s = CL_{s+b}/CL_b$.

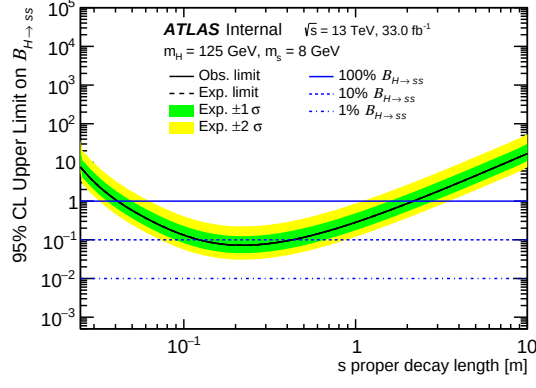
For this analysis, the calculation of the test statistic was done using pseudo-experiments and a Poisson probability term is used to describe the number of observed events¹. The systematic uncertainties on the signal efficiency, estimated number of background events, and luminosity, are treated as nuisance parameters with assigned Gaussian constraints. The limit is extrapolated to each $c\tau$ point using the lifetime extrapolation method described in Section 8.1.1.

8.3.2 Limits from this analysis

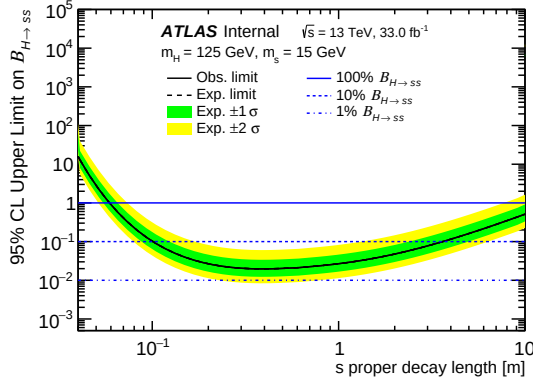
Limits are set on all mass points listed in Table 3.1. Limits on the SM Higgs decaying to LLPs are placed on the BR to the LLPs, assuming the gluon-gluon fusion production cross-section for the Higgs, $\sigma_{ggF} = 48.58$ pb [77]. These limits are shown including $\pm 1\sigma$ (green) and $\pm 2\sigma$ (yellow) error bands in Figure 8.4, and are summarized in Figure 8.5. The expected and observed limits are both displayed in Figure 8.4, but overlap very closely due to the agreement between the expected background and the observed number of events in the signal region.

There are two LLP mass points studied here that are identical to those studied in the Run 1 version of this search. The excluded $c\tau$ [m] ranges for the Higgs to LLPs at a 15% BR are shown for this search compared to the Run 1 search for a Higgs decaying to hidden valley pions with a topology of one decay in the ID and one in the MS or two decays in the MS. This search alone slightly extends the limits on the BR to a lower $c\tau$. The excluded range presented here does not extend to as high a $c\tau$ as those presented in Run 1 due to the inclusion of the 2-MSVX topology in the Run 1 results.

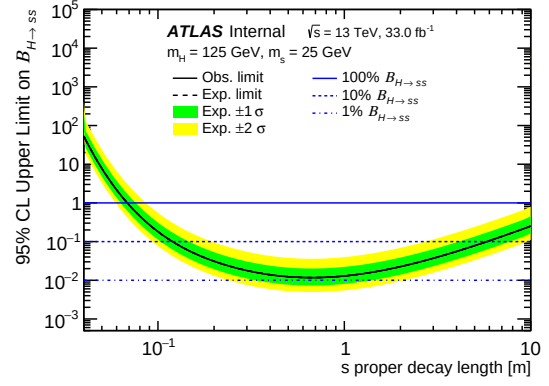
¹The limits studies were performed by Jackson Burzynski.



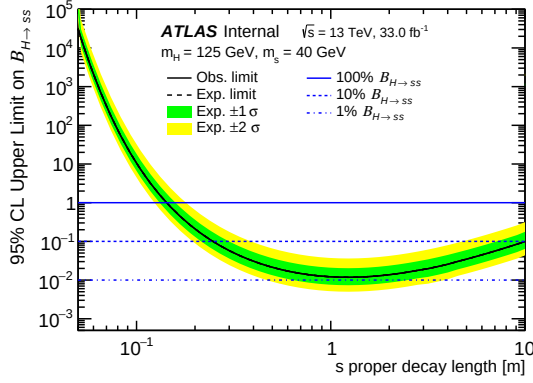
(a)



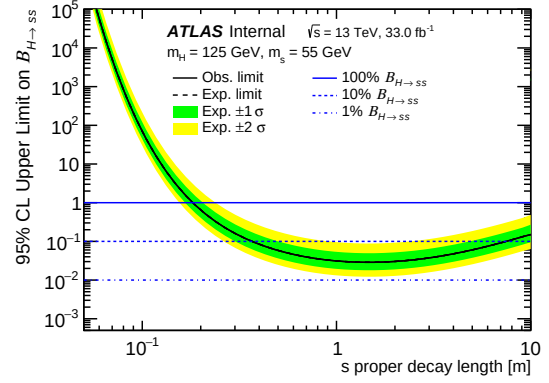
(b)



(c)



(d)



(e)

Figure 8.4: CL $_s$ limits on BR for Higgs $\rightarrow ss$, assuming a σ for the Higgs equal to that of the SM Higgs produced via ggF. The limits on the BR are shown for the Higgs decaying to an (a) 8 GeV LLP, a (b) 15 GeV LLP, a (c) 25 GeV LLP, a (d) 40 GeV LLP, and an (e) 55 GeV LLP. The green and yellow bands represent the $\pm 1\sigma$ and $\pm 2\sigma$ error bands. *Figures were created by J. Burzynski.*

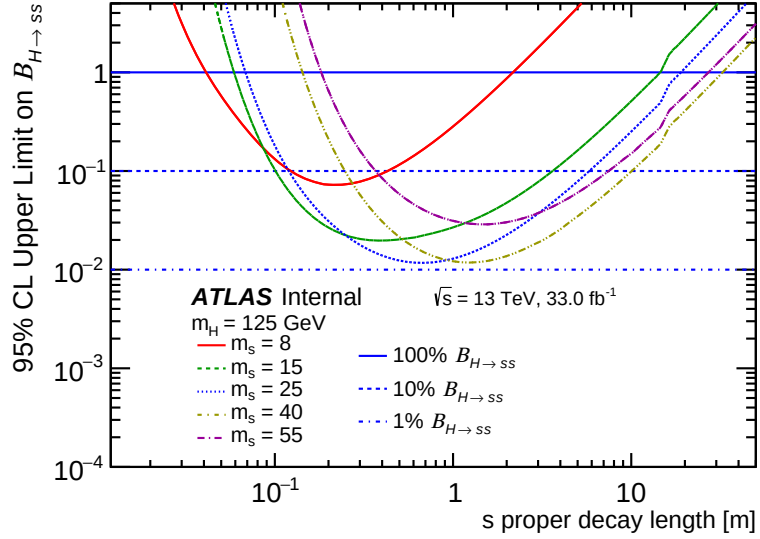


Figure 8.5: CL_s limits on BR for $H \rightarrow ss$, assuming a SM Higgs produced via ggF. *Figure was created by J. Burzynski.*

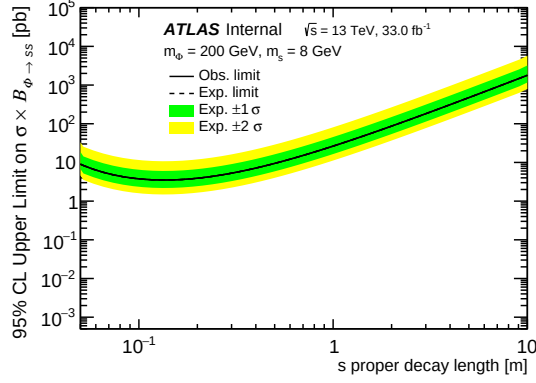
m_s [GeV]	Excluded $c\tau$ range [m]	
	Run 1	Run 2
	15% BR	
25	0.28-32.8	0.11-7.46
40	0.68-55.5	0.22-12.83

Table 8.1: Excluded $c\tau$ [m] ranges for the Higgs to LLPs at a 15% BR , from the Run 1 search for a Higgs to hidden valley scalar decaying in the ID and MS or MS, compared to those set by this search alone.

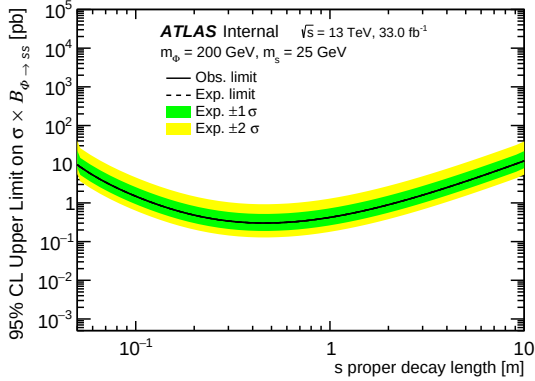
Limits on the $\sigma \times BR$ are shown for a 200 GeV Φ in Figure 8.6 and for a 400 GeV Φ in Figure 8.7, and are summarized in Figure 8.8.

Limits on the $\sigma \times BR$ are shown for a 600 GeV Φ in Figure 8.9 and for a 1000 GeV Φ in Figure 8.10, and are summarized in Figure 8.11.

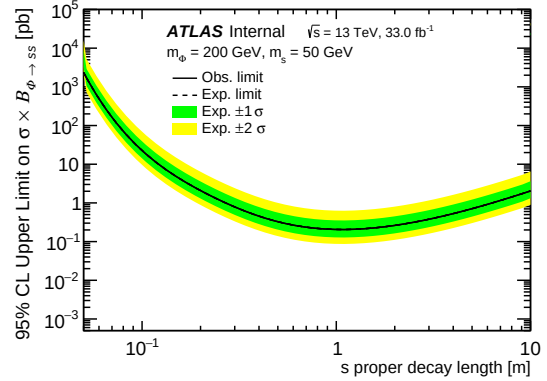
The only overlapping $\Phi \rightarrow ss$ mass points that are common between this analysis and the Run 1 search are the $m_\Phi = 600$ GeV mass points. For these two mass points, the excluded region for $\sigma \times BR \leq 1$ is extended to a slightly lower $c\tau$ in the limits from this analysis alone, than that presented in the Run 1 search.



(a)



(b)



(c)

Figure 8.6: CL_s limits on $\sigma \times BR$ for 200 GeV $\Phi \rightarrow ss$. The limits on the $\sigma \times BR$ are shown for the 200 GeV Φ decaying to an (a) 8 GeV LLP, a (b) 25 GeV LLP, and a (c) 50 GeV LLP. The green and yellow bands represent the $\pm 1\sigma$ and $\pm 2\sigma$ error bands. *Figures were created by J. Burzynski.*

8.3.3 Combined limits

The limits from this search alone can be combined with the limits presented in searches for a Higgs or heavy scalar Φ decaying to neutral scalars, which produced decay vertices in the HCal [14] or in the MS [13]. The event selection used in this search was designed to be explicitly orthogonal to that used by the search for displaced hadronic jets in the HCal, by placing a veto on the triggers used to define the signal region in that analysis (as described in Section 5.1.1). The search for displaced hadronic jets decaying in the MS was broken into two topologies, 2 MSVXs (MS2)

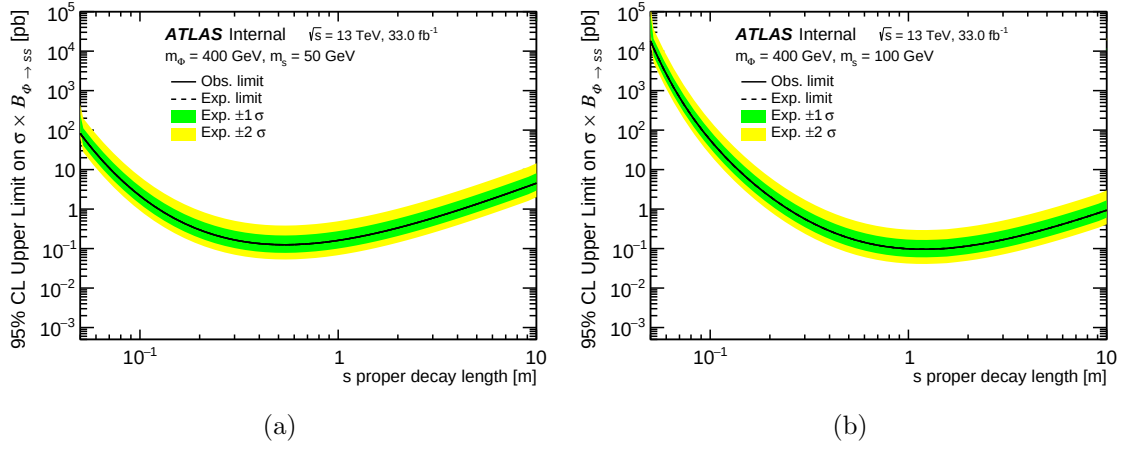


Figure 8.7: CL_s limits on $\sigma \times BR$ for 400 GeV $\Phi \rightarrow ss$. The limits on the $\sigma \times BR$ are shown for the 400 GeV Φ decaying to an (a) 50 GeV LLP and a (b) 100 GeV LLP. The green and yellow bands represent the $\pm 1\sigma$ and $\pm 2\sigma$ error bands. *Figures were created by J. Burzynski.*

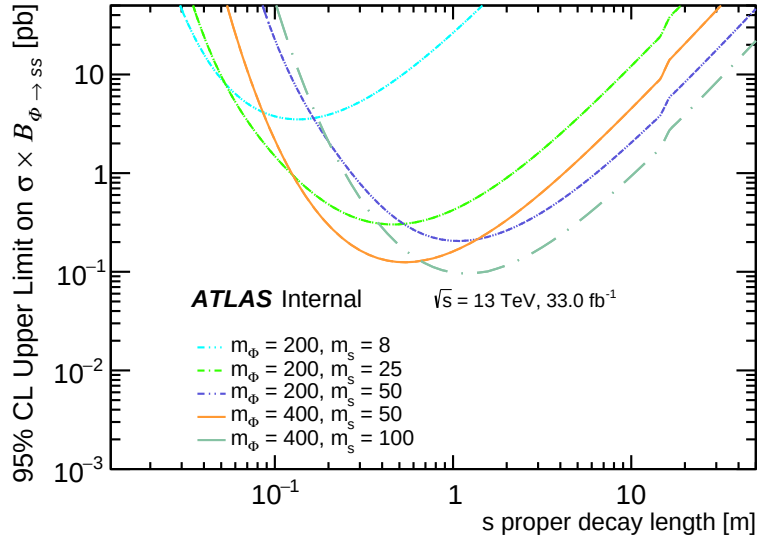


Figure 8.8: CL_s limits on $\sigma \times BR$ for 200 and 400 GeV $\Phi \rightarrow ss$. *Figure was created by J. Burzynski.*

or one MSVX as well as missing transverse energy (E_T) in the event (MS1). This analysis is approximately orthogonal to the MS2 topology, as only a few events in two of the signal MC samples contained 2 good MSVXs as well as a good IDVX (and the removal of these events has no impact on the combined limits), however there is

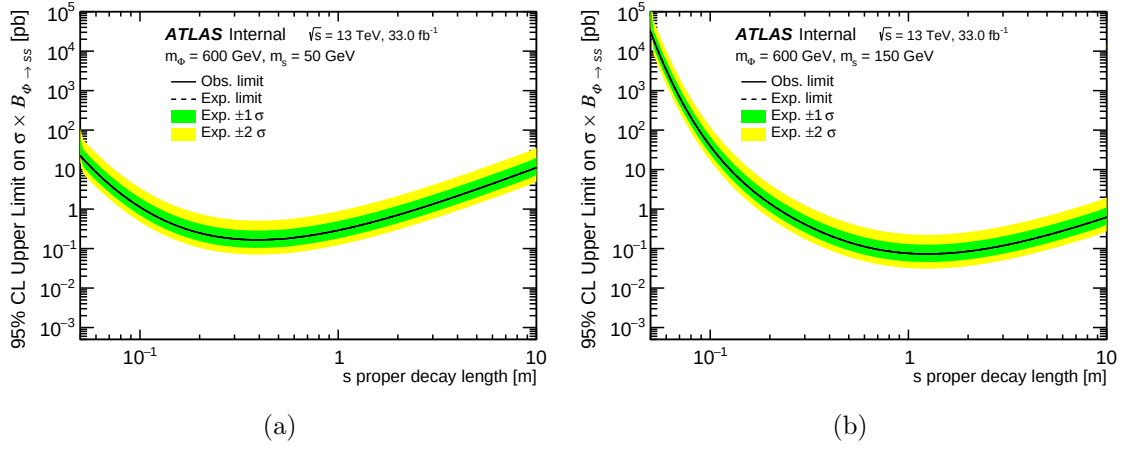


Figure 8.9: CL_s limits on $\sigma \times BR$ for 400 GeV $\Phi \rightarrow ss$. The limits on the $\sigma \times BR$ are shown for the 600 GeV Φ decaying to an (a) 50 GeV LLP and a (b) 150 GeV LLP. The green and yellow bands represent the $\pm 1\sigma$ and $\pm 2\sigma$ error bands. *Figures were created by J. Burzynski.*

a significant overlap in the events selected in the signal region of the MS1 topology and in the signal region presented here. Thus limits from the CR analysis and the limits from the MS2 topology from the MS analysis can be combined with the limits presented in Section 8.3.1, but the limits from the MS1 topology are excluded.

The limits are combined using a simultaneous fit of the profile likelihood functions from each of the individual analyses. The signal strength and the nuisance parameter associated with the systematic uncertainty in the integrated luminosity are chosen to be the same for each, while the signal uncertainties are dominated by different sources in each search and are thus chosen to be uncorrelated. The background estimations used by all of the searches are data-driven and thus also uncorrelated. The limits are calculated using a global fit in which the combined profile likelihood function is the product of each individual likelihood function.

The limits on the BR of a SM Higgs to Hidden Sector LLPs set by this search (as presented in Figures 8.4 and Figure 8.5), are shown versus the combined limits from the CR and MS analyses, and compared to the combined limits from this search,

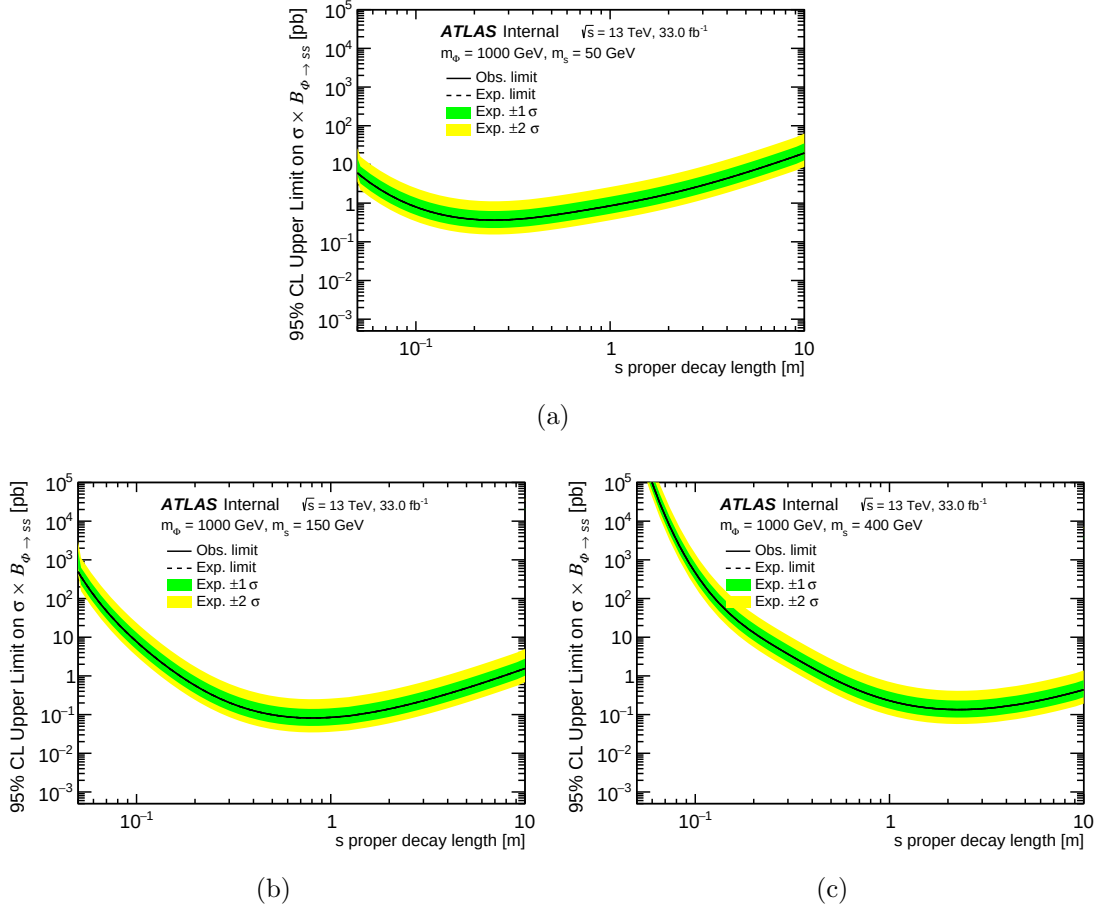


Figure 8.10: CL_s limits on $\sigma \times BR$ for 200 GeV $\Phi \rightarrow ss$. The limits on the $\sigma \times BR$ are shown for the 200 GeV Φ decaying to a (a) 50 GeV LLP, a (b) 150 GeV LLP, and a (c) 400 GeV LLP. The green and yellow bands represent the $\pm 1\sigma$ and $\pm 2\sigma$ error bands. *Figures were created by J. Burzynski.*

the CR analysis, and the MS2 topology from the MS analysis in Figure 8.12. The expected and observed limits are shown for the individual and the combined limits, and the shaded areas represent $\pm 1\sigma$ error bands. The limits on the branching ratio for a Higgs decaying to a 55 GeV LLP are shown for the CR analysis only instead of the CR and MS analyses because the MS analysis did not place limits on the BR for this mass point.

At low $c\tau$, the limits set by this search outperform the combined limits from the CR and MS analyses very slightly for the Higgs decay to a 8 or 15 GeV LLP

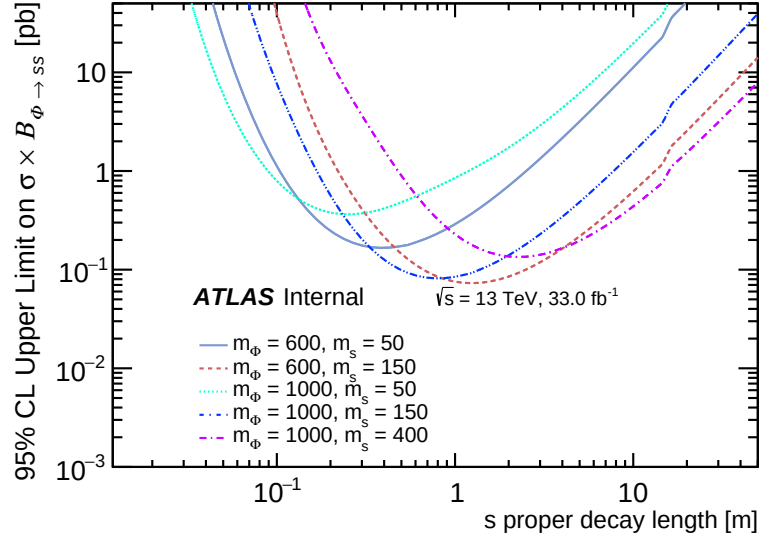


Figure 8.11: CL_s limits on $\sigma \times BR$ for 600 and 1000 GeV $\Phi \rightarrow ss$. Figure was created by J. Burzynski.

(Figures 8.12a and 8.12b), and more significantly for decays of the Higgs to 25 GeV (Figure 8.12b), 40 GeV (Figure 8.12b), and 55 GeV (Figure 8.12b) LLPs. Thus, the combined ID+CR+MS2 limits represent the strongest limits yet set on the decay of a SM Higgs to neutral LLPs, at these mass points, which hadronically decay back to SM fermions.

The inclusion of the results from this analysis do not strengthen the combined limits significantly for the decays of the SM Higgs to an 8 or 15 GeV LLP due to the limitations in the IDVX reconstruction and selection efficiency for lower mass LLPs. The selection on the LLP mass in particular significantly restricts the IDVX reconstruction efficiency for the 8 GeV LLP due to the similarity in the vertex mass distributions for the reconstructed vertices matched to 8 GeV LLPs and the IDVXs found in background (see Figure 5.6b). The inclusion of the results from this analysis for the Higgs decay to LLPs with mass ≥ 25 GeV strengthen the combined limits more notably, due to the increased IDVX reconstruction efficiency with increased

LLP mass for a constant Φ , allowing the IDVX+MSVX topology to make a bigger improvement over the limits set by the MS1 topology at low $c\tau$.

The combined limits on the $\sigma \times BR$ for a 200 GeV Φ and a 400 GeV Φ are shown in Figure 8.13 and for a 600 GeV Φ and a 1000 GeV Φ are shown in Figure 8.14.

Once again, limitations of the IDVX selection for low mass LLPs limited the impact of the inclusion of the results from this analysis on the limits for the $\sigma \times BR$ for a 200 GeV Φ to an 8 GeV LLP. The results from this analysis however strengthened the limits significantly for a 200 GeV Φ to 25 or 50 GeV scalars compared to the combined limits from the CR and MS analyses at low $c\tau$.

The CR analysis treated the lower mass Φ ($m_H = 125$ GeV and $m_\Phi = 200$ GeV) differently from the higher mass Φ ($m_\Phi \geq 400$ GeV), using a Low- E_T selection for the former and a High- E_T selection for the latter [14]. This scheme was devised to optimize the selection for the lower mass samples without sacrificing background discrimination for the higher mass samples. The trigger used in the High- E_T selection was both more efficient for selecting the signal decays, and the integrated luminosity used for the High- E_T trigger was greater than that for the Low- E_T trigger (due to the late development and implementation of the Low- E_T trigger). These factors resulted in stronger limits being set by the CR analysis for mass points with $m_\Phi \geq 400$ GeV than for mass points with $m_\Phi \leq 200$ GeV. For this reason, despite the higher selection efficiency in this analysis for mass points with higher m_Φ (as demonstrated in Figure 5.18c), the results from this analysis did not have an impact on the total combined limits for mass points with $m_\Phi \geq 400$ GeV.

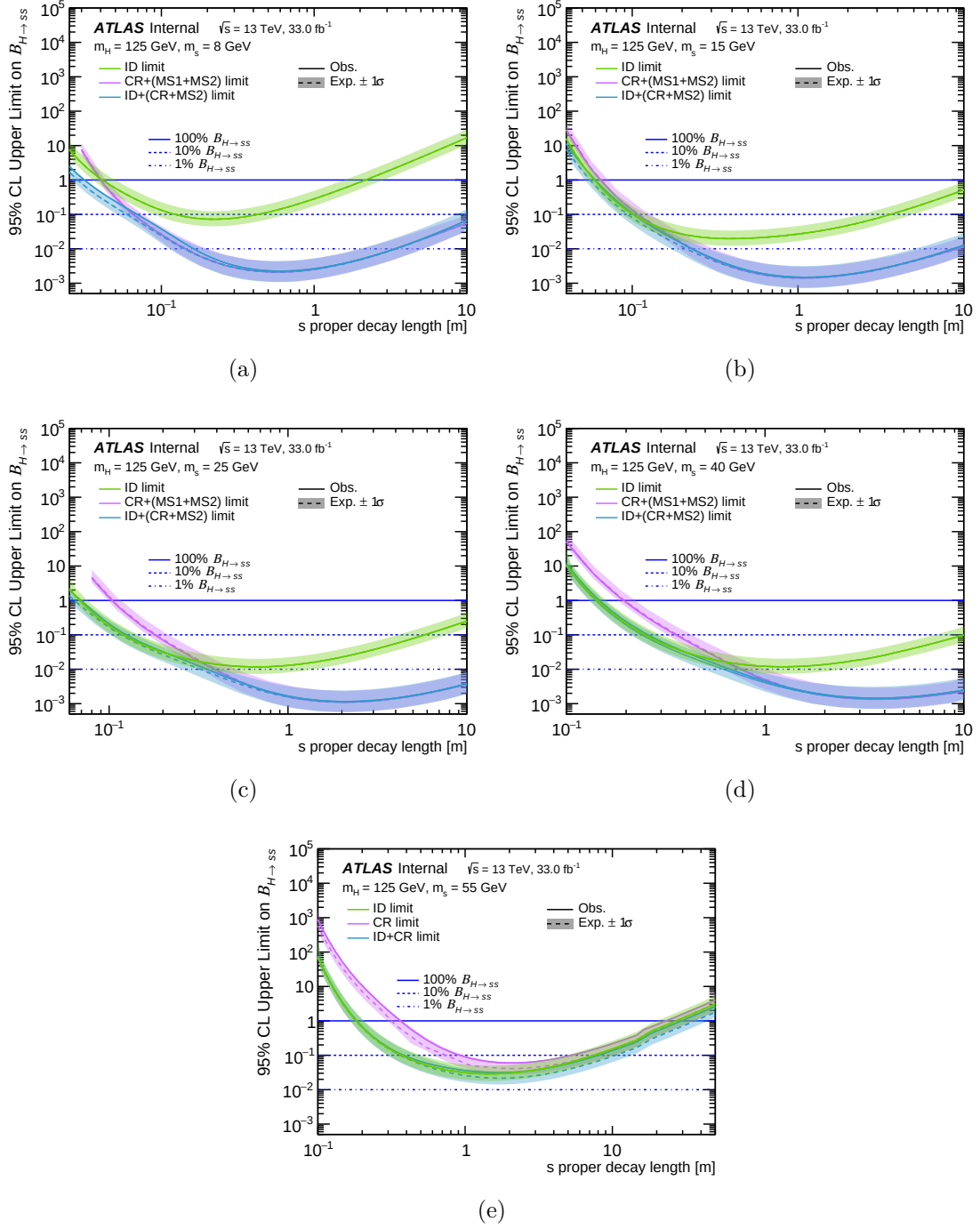
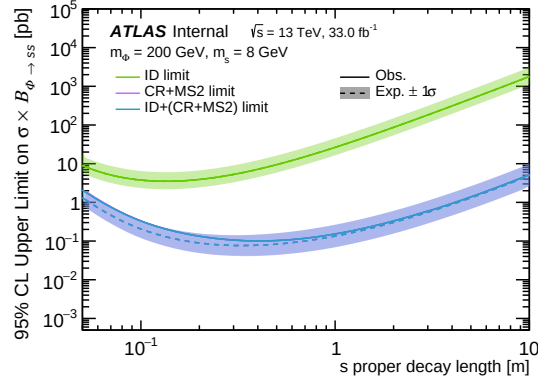
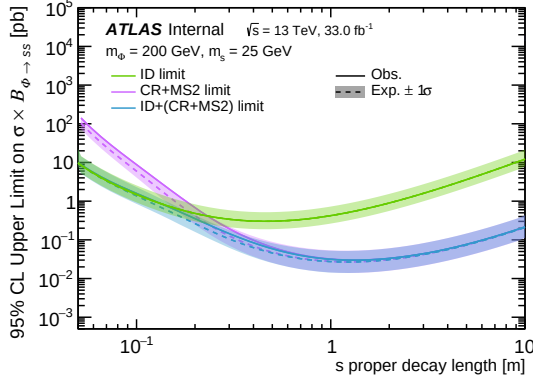


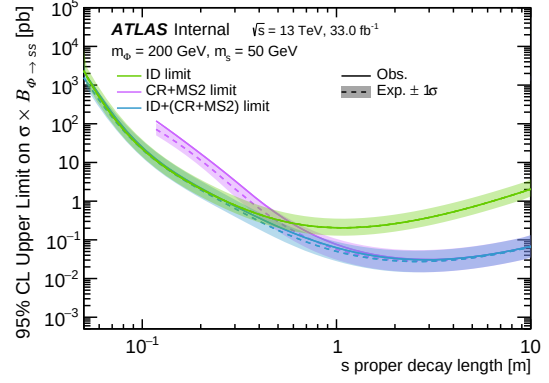
Figure 8.12: CL_S limits on BR for $H \rightarrow ss$, assuming a σ for the Higgs equal to that of the SM Higgs produced via ggF. The limits are shown for the Higgs decaying to an (a) 8 GeV LLP, a (b) 15 GeV LLP, a (c) 25 GeV LLP, a (d) 40 GeV LLP, and an (e) 55 GeV LLP. The limits set by this analysis (green) are compared with those set by the CR+(MS1+MS2) analyses (purple), as well as the combination of all three analyses (blue). *Figures were created by J. Burzynski.*



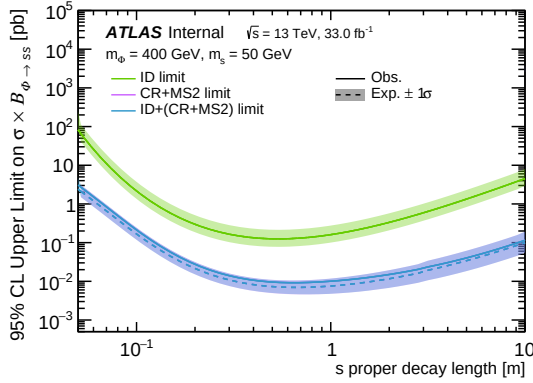
(a)



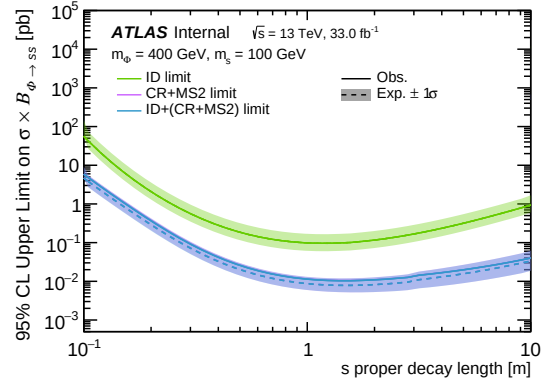
(b)



(c)



(d)



(e)

Figure 8.13: CL_S limits on $\sigma \times BR$ for a 200 GeV Φ decaying to an (a) 8 GeV LLP, (b) 25 GeV LLP, and a (c) 50 GeV LLP, and for a 400 GeV Φ decaying to a (d) 50 GeV LLP and an (e) 100 GeV LLP. The limits set by this analysis (green) are compared with those set by the CR+(MS1+MS2) analyses (purple), as well as the combination of all three analyses (blue). *Figures were created by J. Burzynski.*

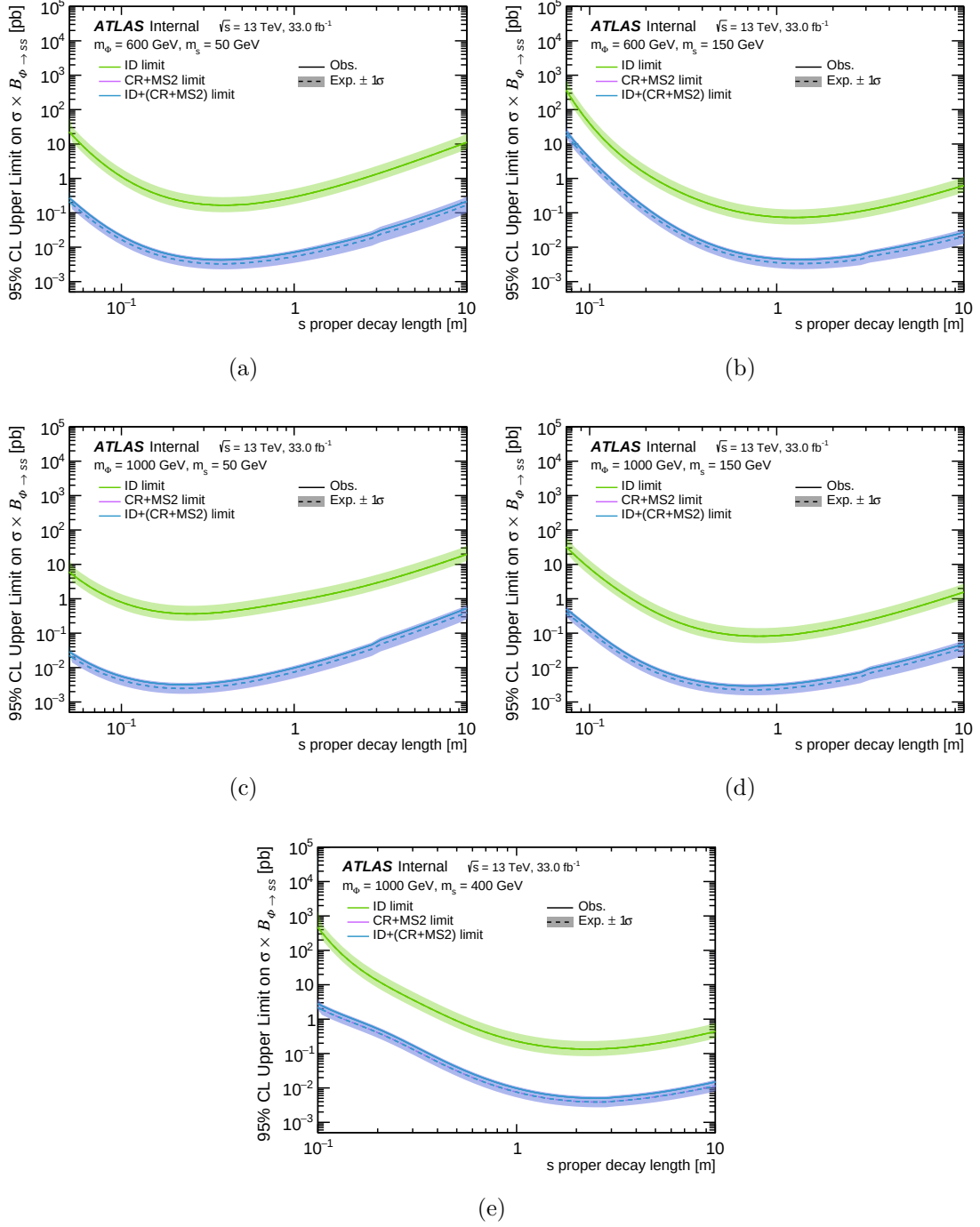


Figure 8.14: CL_S limits on $\sigma \times BR$ for a 600 GeV Φ decaying to an (a) 50 GeV LLP, (b) 150 GeV LLP, and for a 1000 GeV Φ decaying to a (c) 50 GeV LLP, a (d) 150 GeV LLP, and an (e) 100 GeV LLP. The limits set by this analysis (green) are compared with those set by the CR+(MS1+MS2) analyses (purple), as well as the combination of all three analyses (blue). *Figures were created by J. Burzynski.*

CHAPTER 9

CONCLUSION

A search has been presented for neutral long-lived particles using 33.0 fb^{-1} of proton-proton collision data provided by the LHC and collected by the ATLAS detector in 2016. The search used a benchmark model of a Higgs or heavy scalar Φ mediator, decaying to neutral HS scalars which in turn decayed through the mediator back to heavy SM fermions. This search focused on a topology of one displaced hadronic vertex in the inner detector and the other in the muon spectrometer. The combination of the inner detector and muon spectrometer vertices was designed to extend the sensitivity of a muon spectrometer-only search to lower long-lived particle lifetimes while taking advantage of a customized long-lived particle trigger used in the muon spectrometer.

To collect the data used in this search, a special trigger was used that was designed to identify events with hadronic decays after the last layer of the hadronic calorimeter. In order to reconstruct the displaced hadronic decays, a customized vertex reconstruction algorithm was necessary to reconstruct the hadronic decays in the muon spectrometer, as well as specialized tracking and vertex reconstruction algorithms to reconstruct the decay vertices in the inner detector.

The observed number of events in the signal region was found to be approximately equal to the predicted number of events owing to background. In the absence of an excess, limits were set at a 95% confidence level on the $\sigma \times BR$ for the decay of a range of Φ mass from 125 to 1000 GeV to LLPs ranging in mass from 8 to 400 GeV.

The results from this search definitively strengthened combined limits on the $\sigma \times BR$ for propagators of masses 125 and 200 GeV to LLPs of mass ≥ 25 GeV at $c\tau$ s in the range from a few cm to approximately 1 m depending on the mass point.

The impact of this analysis on the sensitivity to lower mass scalars was limited by the similarity of the vertex mass distribution for scalars of mass ≤ 8 GeV and vertices from background. This analysis may be improved by changes to the vertex reconstruction algorithm that were made for the 2017-2018 data taking periods, designed to allow the reconstructed vertices to include a greater number of tracks.

Future iterations of this analysis could benefit by the addition of a topology of one inner detector vertex with one hadronic jet in the calorimeter, which would allow further sensitivity to the lower $c\tau$ lifetimes. The development of an inner detector long-lived particle trigger could also benefit the analysis by allowing for an inner detector-only topology without relying on associated production of the Higgs (which has lower production σ than the gluon-gluon fusion production used in this search, but allows for use of lepton-triggers) or multi-jet triggers (which have limited efficiency for low mass Φ and LLPs).

APPENDIX A

LARGE RADIUS TRACKING

The performance of the large radius tracking was examined by a small analysis team including the author, and this performance was documented in the ATLAS public note [69].

Two models were used to evaluate the performance of the large radius tracking. In one of the models, a split-SUSY model (shown in Figure A.1a), long-lived gluinos decay to a quark and a virtual squark, the latter of which decay to neutralinos and quarks, leading to displaced hadronic jets (*displaced hadrons*). In the other model (shown in Figure A.1b), a squark decays to a quark and a neutralino, and the neutralino then decays to displaced leptons (*displaced leptons*). While the displaced lepton model allows for decays to ee , $\mu\mu$, and $e\mu$, only decays to $\mu\mu$ were considered for the performance study.

In addition to the difference in the displaced decay products, the two samples were chosen due to the differences in the kinematic properties of those decay products in order to provide a wide array of signal decays for testing purposes. The production radius (r_{prod}) and p_{T} of the signal particles (decay products which result from the signal processes diagrammed in Figure A.1) are shown in Figure A.2. The signal particles in the displaced leptons sample have production radii predominantly between 0 and 200 [mm], which are quite displaced. The signal particles in the displaced hadrons sample are even more displaced on average, with a range of production radii extending to over 400 mm, which allows the performance studies of the LRT to probe the entire range of the pixel and the first layers of the SCT (Figure A.2a). The decay

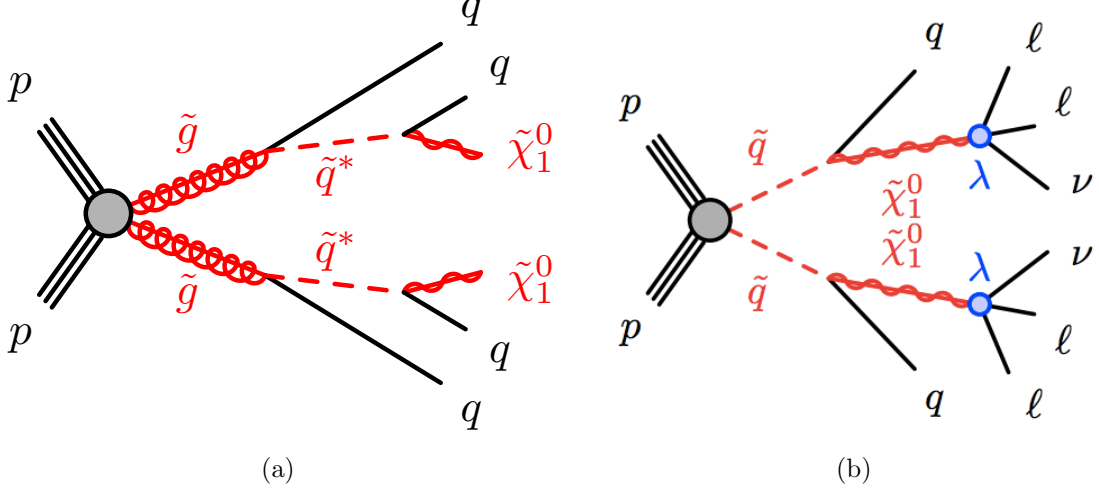


Figure A.1: The (a) displaced hadron and (b) displaced lepton samples used for the LRT performance evaluation in Ref. [69].

products in the displaced hadrons sample are fairly soft while the decay products in the displaced leptons sample are much harder, allowing the LRT performance to be tested for decay vertices with a wide range of boost (Figure A.2b).

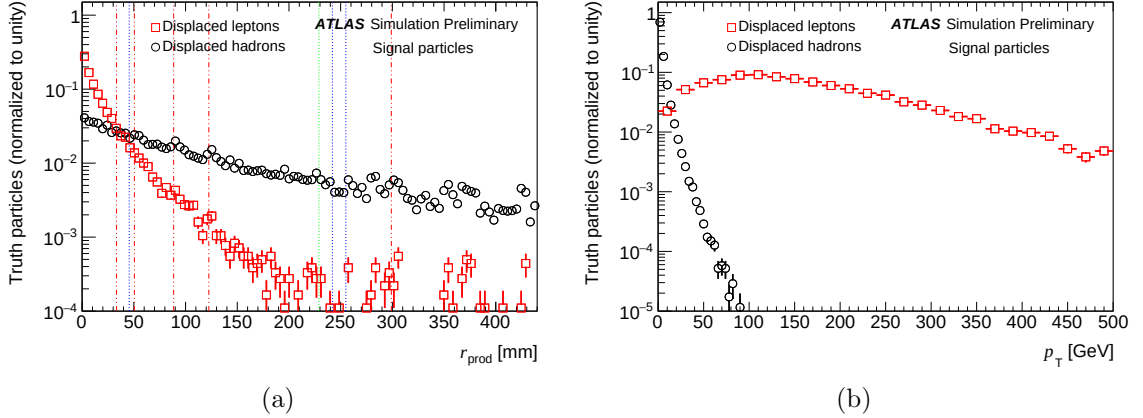


Figure A.2: The (a) production radius [mm] and (b) p_T [GeV] of the signal particles in the displaced hadron and displaced leptons samples used for the LRT performance. Plots were created by the author and published in [69].

The efficiency to reconstruct the displaced hadrons and displaced leptons is shown versus the decay product production radius in Figure A.3. The efficiency is defined

as the fraction of the generated signal particles which are matched to reconstructed tracks. To be matched to a reconstructed track, the weighted fraction of hits left by the generated particle that are included in the reconstructed track must be ≥ 0.5 . The hits are weighted according to the sub-detector they are found in to account for the different resolutions of the different sub-detectors. The generated particles are required to be in the fiducial volume, within $r_{\text{prod}} < 440$ mm, $|\eta| < 2.5$. The generated particles are also required to have $p_T > 1$ GeV, must be charged, and must be decay products of the signal process. The reconstruction efficiency is shown for the LRT (blue points) and the standard tracking (red circles) individually, and for the combined track collection (black triangles).

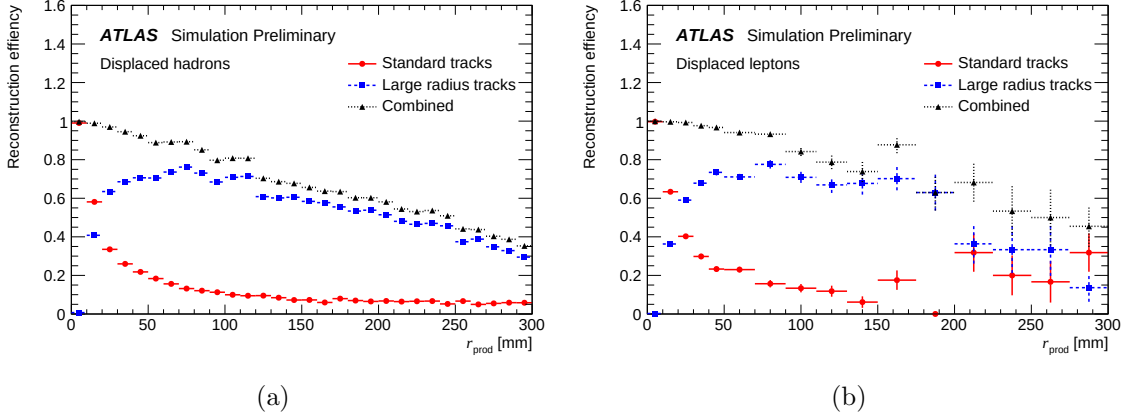


Figure A.3: Reconstruction efficiency of the displaced decay products in the (a) displaced hadrons and (b) displaced leptons signal test samples, as published in [69]. The blue squares represent the reconstruction efficiency of the decay products using only large radius tracks, the red circles represent the reconstruction efficiency using only standard tracks, and the black triangles use both the standard and large radius tracks.

The generated particles are primarily reconstructed using the standard tracking for production radii < 10 -20 mm, after which point the large radius tracking reconstructs the majority of the decay products out to a radius of approximately

200 mm. The reconstruction efficiency decreases as the production radius increases. This is due to the reconstruction requirement of ≥ 7 silicon hits per track.

As shown in Figure 2.2, particles that are produced after the last layer of the pixel detector and particularly after the first layer of the SCT are unlikely to traverse the necessary number of layers of silicon in order to have at least 7 silicon hits, this will inevitably cause a reduction in the reconstruction efficiency. To evaluate the reconstruction efficiency of reconstructable particles, a technical efficiency is examined.

In Figure A.4, the technical efficiency is determined in the same manner as the reconstruction efficiency, except the generated signal particles are required to have left energy deposits on at least 7 silicon layers. As in Figure A.3, the blue squares represent the efficiency using only the large radius tracks, and the black squares represent the technical efficiency taking into account all reconstructed tracks.

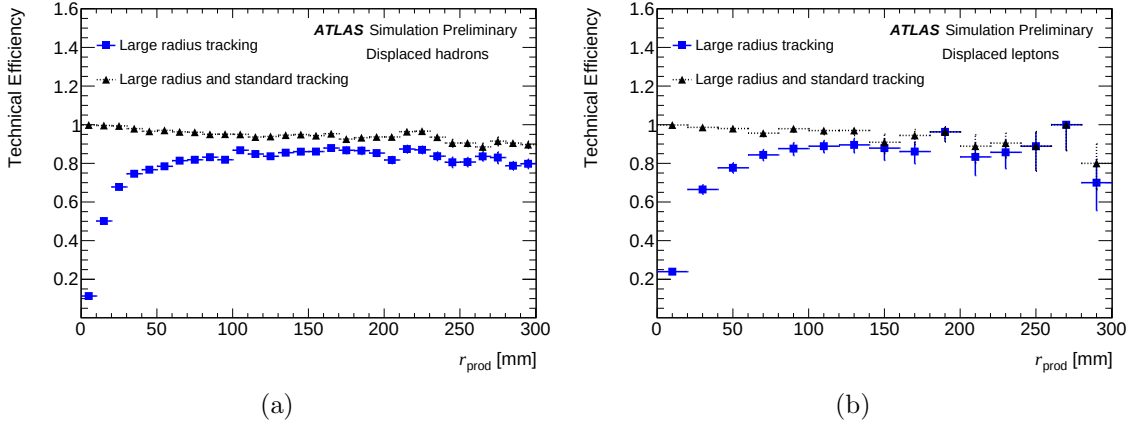


Figure A.4: The technical efficiency of the displaced decay products in the (a) displaced hadrons and (b) displaced leptons signal test samples. Plots were created by the author and published in [69]. The blue squares represent the technical efficiency using only large radius tracks and the black triangles represent the technical efficiency using the combined track collection.

The technical efficiency for reconstructing generated signal particles which leave at least 7 energy deposits on silicon layers is consistently high versus the production radius of the particle. After a production radius of 20 mm, the signal particles are

predominately reconstructed by the large radius tracking, and the total technical efficiency is at least 80% out to a production radius of 300 mm. Of the particles that are reconstructable considering the requirement of at least 7 silicon hits, most are reconstructed using the combination of the standard and large radius tracking. While the reconstruction efficiency is what ultimately is important for analyses concerned with displaced decays, the technical efficiency is important to consider when evaluating the performance of the algorithm.

While the efficiency for reconstructing signal particles is high, the large radius tracking algorithm produces a large quantity of poor-quality tracks (a poor-quality track is a track that is not matched to a generated particle) and consequently has a very high CPU usage. Due to this, the LRT algorithm can only be run on a small subset of events and was not able to be run at trigger level in Run 2. Several studies were performed both before and after the publication of the public note [69] to determine methods to reduce the rate of poor-quality track reconstruction.

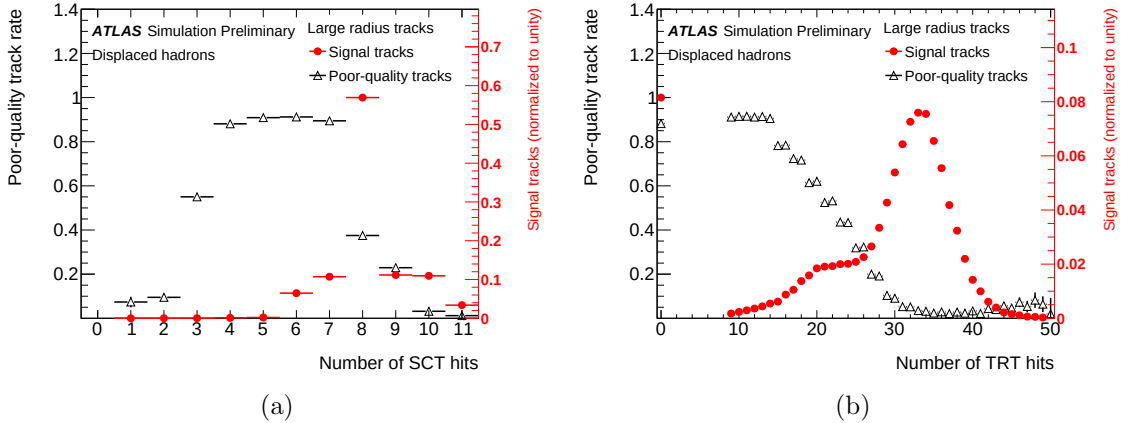


Figure A.5: The fraction of reconstructed tracks which are poor-quality (open black triangles) compared to the fraction of reconstructed tracks which are matched to generated signal particles (red circles) compared to (a) the number of SCT hits used in the reconstructed track and (b) the number of TRT hits in the TRT extension of the track (if it is successful). Plots were created by the author and published in [69].

Figure A.5 shows the fraction of reconstructed tracks which are poor-quality (open black triangles) compared to those which are matched to generated signal particles (red circles) versus the number of SCT hits in the reconstructed tracks (Figure A.5a) and the number of TRT hits in the TRT extension (Figure A.5b). If the TRT extension fails the number of hits is 0.

Figure A.5b demonstrates that the fraction of poor-quality tracks would be reduced if the number of TRT hits in a TRT extension was increased (and the TRT extension was required to be successful assuming the tracks are reconstructed in the $|\eta|$ range of the TRT), without significantly decreasing the fraction of reconstructed tracks which are matched to generated signal particles. Figure A.5a demonstrates likewise that the fraction of poor-quality tracks would be reduced if the number of SCT hits was increased to 8. The number of SCT hits becomes an important consideration for highly displaced tracks which may only have one or two reconstructed hits in the pixel detector. The addition of a minimum SCT hit requirement in addition to a minimum silicon hit requirement requires more careful study due to the increased dependence on the function of the SCT detector.

The average pileup increased throughout Run 2, so the dependence of the LRT reconstruction efficiency on $\langle\mu\rangle$ needed to be considered. Figure A.6 shows the reconstruction efficiency versus $\langle\mu\rangle$ for the reconstruction efficiency using the large radius tracking (open points) and the combined track collection (filled points). Figure A.6 demonstrates that there is a negative correlation between the amount of $\langle\mu\rangle$ and the reconstruction efficiency; this difference is predominately due to the LRT reconstructed tracks. By increasing the minimum p_T for the LRT, the dependence on $\langle\mu\rangle$ is slightly mitigated, which has a greater impact for sets of data with $\langle\mu\rangle$ over 60, as was produced in 2018. The mitigation of the decrease in efficiency is due to the removal of the low p_T poor-quality tracks which are created, using hits which belong to tracks from decays of interest.

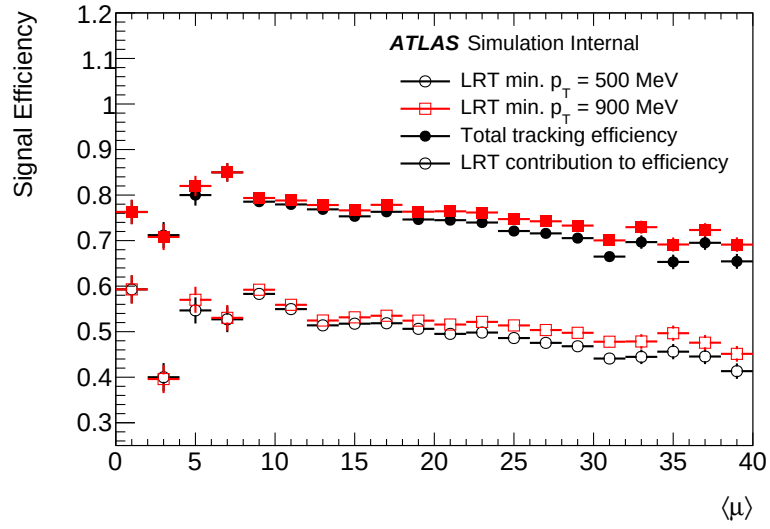


Figure A.6: The reconstruction efficiency from the large radius tracking (open points) and the combined track collection (filled points) considering a minimum p_T of 500 MeV (black circles) or 900 MeV (red squares).

APPENDIX B

ANALYSIS CUTFLOWS

Tables B.1 and B.2 demonstrate the number of events left after each of the different cutflow selections, and the relative efficiency of each selection, respectively. In these tables, the trigger requirements are broken into the selection to pass the muon RoI cluster trigger (MS trigger), and the veto on the CR triggers (no CR trigger). ‘Good MSVX’ includes all the MSVX selection requirements described in Table 5.1 and ‘IDVX’ includes all selections in Table 5.2 except those on vertex mass and number of tracks, which are listed separately.

m_H, m_Φ in GeV	m_{LLP}	Good events	MS trigger	no CR trigger	Good MSVX	IDVX	n_{trk} ≥ 4	m_{IDVX} > 3 GeV
125	8	392,995	11,213	10,669	4,196	526	19	12
125	15	199,996	11,314	10,720	4,305	510	32	20
125	25	384,997	18,815	17,910	7,785	1,038	95	77
125	40	399,396	14,513	13,852	5,879	866	97	84
125	55	380,995	8,147	7,553	2,859	406	41	35
200	50	390,996	30,096	27,617	11,929	1,827	274	230
400	50	392,994	66,500	53,958	19,718	2,868	411	343
600	50	386,995	83,852	65,568	18,458	2,684	328	257
1000	50	385,996	107,101	74,177	14,848	2,093	143	112

Table B.1: Cutflow numbers for all samples with a Higgs propagator or LLP with a mass of approximately 50 GeV. Here, ‘Good MSVX’ includes all the MSVX selection requirements described in Table 5.1 and ‘IDVX’ includes all selections in Table 5.2 except those on vertex mass and number of tracks.

In tables B.1 and B.2 it is once again apparent that the mass of the LLP is highly correlated with the efficiency to pass the selections of the requirement of an IDVX in the event as well as on the number of tracks associated to the IDVX and the mass

m_H, m_Φ in GeV	m_{LLP}	Good events	MS trigger	no CR trigger	Good MSVX	IDVX	n_{trk} ≥ 4	m_{IDVX} > 3 GeV
125	8	-	2.9 %	95 %	39 %	13 %	3.6 %	63 %
125	15	-	5.7 %	95 %	40 %	12 %	6.3 %	63 %
125	25	-	5.4 %	95 %	43 %	13 %	9.2 %	81 %
125	40	-	3.6 %	95 %	42 %	15 %	11 %	87 %
125	55	-	2.1 %	93 %	38 %	14 %	10 %	85 %
200	50	-	7.7 %	92 %	43 %	15 %	15 %	84 %
400	50	-	17 %	81 %	37 %	15 %	14 %	83 %
600	50	-	22 %	76 %	29 %	15 %	12 %	78 %
1000	50	-	28 %	69 %	20. %	14 %	6.8 %	78 %

Table B.2: Cutflow numbers for all samples with a Higgs propagator or LLP with a mass of approximately 50 GeV. Here, ‘Good MSVX’ includes all the MSVX selection requirements described in Table 5.1 and ‘IDVX’ includes all requirements in Table 5.2 except those on vertex mass and number of tracks.

of the IDVX. The boost of the LLP (or the mass of the Φ considering a constant LLP mass) is approximately negatively correlated with the efficiency of the IDVX selections. The boost and the mass of the LLP are positively correlated with the efficiency to pass the muon RoI cluster trigger, although the boost of the LLP is negatively correlated with the likelihood that events passing the MS trigger contain an MSVX.

As discussed, not all the signal MC events contain LLPs which decay in the fiducial volumes of the inner detector and the muon spectrometer. In Table B.3, the events are required to include LLPs decaying the fiducial volumes, and like in Figure 5.19, it is apparent that in this case the relative efficiency of every selection is increased, except for the final selection on the mass of the IDVX. The relative efficiency of the final IDVX selection is generally unaffected by the fiducial volume requirements because in very few cases is there an IDVX passing the n_{trk} requirements that is not matched to an LLP decay (in a few cases it is not matched at all and in a small number of other cases it is, but the IDVX is in the fiducial volume and the LLP decay is just outside the fiducial volume).

m_H, m_Φ in GeV	m_{LLP} in GeV	Good events	MS trigger	no CR trigger	Good MSVX	IDVX	n_{trk} ≥ 4	m_{IDVX} > 3 GeV
125	8	-	10 %	99 %	48 %	31 %	9.8 %	63 %
125	15	-	14 %	100 %	51 %	42 %	17 %	63 %
125	25	-	15 %	99 %	54 %	45 %	22 %	82 %
125	40	-	13 %	100 %	51 %	49 %	27 %	867 %
125	55	-	9.3 %	100 %	42 %	51 %	28 %	85 %
200	50	-	23 %	99 %	56 %	52 %	32 %	85 %
400	50	-	38 %	97 %	54 %	50 %	30 %	84 %
600	50	-	44 %	94 %	45 %	48 %	27 %	79 %
1000	50	-	48 %	89 %	33 %	42 %	17 %	77 %

Table B.3: Relative efficiency for each selection for all samples with a Higgs propagator or LLP with a mass of approximately 50 GeV, taking into account fiducial volume restrictions on the generated LLP decays. Here, ‘Good MSVX’ includes all the MSVX selection requirements described in Table 5.1 and ‘IDVX’ includes all selections in Table 5.2 except those on vertex mass and number of tracks.

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