Search for compressed mass Higgsino production with soft lepton tracks with the CMS experiment in proton-proton collision data at $\sqrt{s} = 13$ TeV

Von der Fakultät für Physik der Universität Hamburg zur Erlangung des akademischen Grades eines Doktors der Naturwissenschaften genehmigte Dissertation

vorgelegt von

Yuval Nissan

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Universität Hamburg

DER FORSCHUNG | DER LEHRE | DER BILDUNG

Abstract This is the abstract

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Introduction

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Search for compressed Higgsinos with soft lepton tracks

6.1 Motivation

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6.3 Signal models

The signal models considered in this analysis are based on **FiXme Note: fill in signal model stuff**.

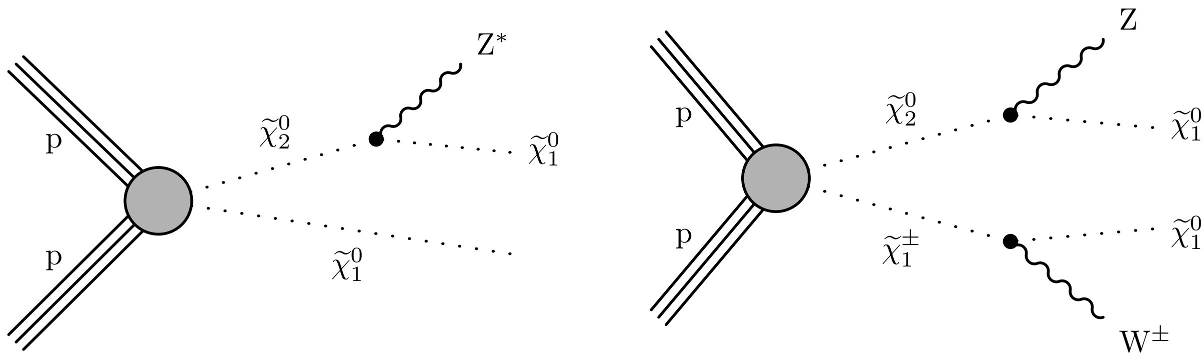

Figure 6.1: Production and decay of electroweakinos in the higgsino simplified model through $\widetilde{\chi}_2^0\,\widetilde{\chi}_1^0$ (left) and $\widetilde{\chi}_2^0\,\widetilde{\chi}_1^\pm$ (right).

6.4 Signal signature and base selection

To build an effective analysis strategy, the signal kinematics must be studied and exploited. The electroweakino production in question exhibit unique features which can be used in order to discriminate between the signal and the Standard Model (SM) background. It is important to explore these signal distributions in order to define a preselection, or a base cut, that will serve the purpose of retaining as much signal as possible while rejecting as much background. All of the following distributions were plotted by weighting the simulation to Run II luminosity of $\mathcal{L} = 135\,\mathrm{fb}^{-1}$ and requiring at least one jet in the event with $p_\mathrm{T} \geq 30\,\mathrm{GeV}$. Further selection might apply and will be listed in each section in that case.

6.4.1 Missing Transverse Energy

One property that essentially all Dark Matter (DM) searches have in common is the presence of a DM candidate in the production. The exact identity and properties of said particle (or particles in the case multiple DM candidates) vary, but they do share a lot in common. The DM candidate in our Supersymmetry (SUSY) search is the neutralino, which is a type of DM candidate referred to as a Weakly Interacting Massive Particle (WIMP). A WIMP, broadly speaking, is a new elementary particle which interacts via gravity and any other force (or forces), potentially not part of the SM itself, which is as weak as or weaker than the weak nuclear force, but also non-vanishing in its strength. That essentially means that such candidate is neutral, and therefore not interacting via the electromagnetic force. A neutral particle that interacts neither electromagnetically nor via the strong force (i.e. colorless) will escape detection and will leave traces in the form of a transverse momentum imbalance, which we refer to as $E_{\mathrm{T}}^{\mathrm{miss}}$ (Missing Transverse Energy or Missing Transverse Momentum). Our signal contains two DM candidates in the production, which are the Lightest SUSY Particles (LSPs), the neutralinos $\widetilde{\chi}_1^0$. We therefore expect the signal to contain considerable magnitude of $E_{\mathrm{T}}^{\mathrm{miss}}$. As described in 6.7.3, **FiXme Note: make sure we described both met and mht** we are more interesting in $H_{\mathrm{T}}^{\mathrm{miss}}$, which is highly correlated with $E_{\mathrm{T}}^{\mathrm{miss}}$, due to our definition of lepton isolation and its use in the background estimation methods. Nonetheless, we will look at both $E_{\mathrm{T}}^{\mathrm{miss}}$ and $H_{\mathrm{T}}^{\mathrm{miss}}$ observables. **FiXme Note: make sure we define the different deltaM somewhere**

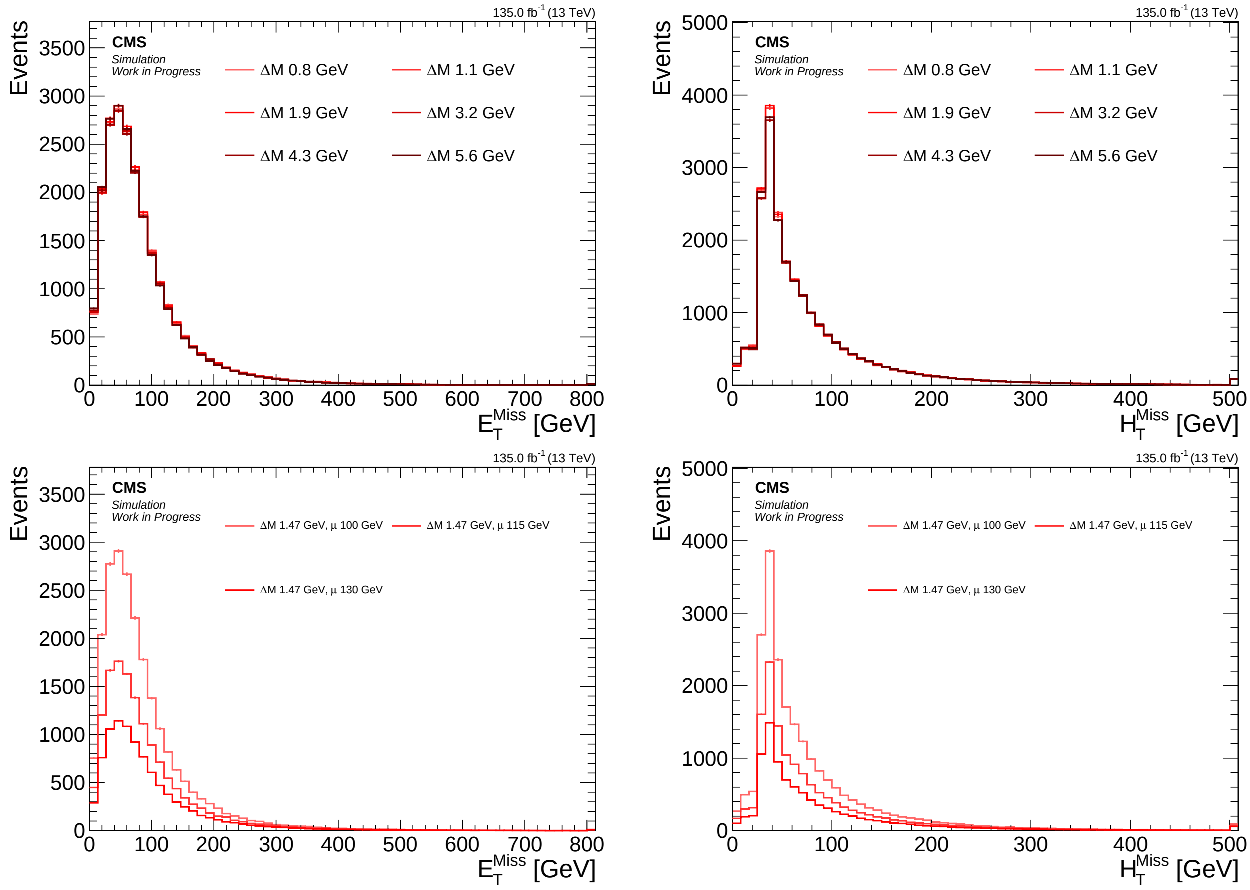

Figure 6.2: Signal distributions for $E_{\mathrm{T}}^{\mathrm{miss}}$ (left) and $H_{\mathrm{T}}^{\mathrm{miss}}$ (right) comparing various Δm with a fixed higgsino parameter $\mu = 100\,\mathrm{GeV}$ (upper), and comparing various higgsino parameters μ with fixed $\Delta\mathrm{m} = 1.47\,\mathrm{GeV}$ (lower).

As we expect, $E_{\mathrm{T}}^{\mathrm{miss}}$ and $H_{\mathrm{T}}^{\mathrm{miss}}$ are hardly affected by the different choices for Δm, while the higgsino parameter μ affect the distributions above all through its lower production cross section for higher higgsino parameter μ. As discuss at 6.8, the region of interest lie at $H_{\mathrm{T}}^{\mathrm{miss}} \geq 220$ for triggering purposes. Even though this is quite a harsh and inefficient cut, one must look also at the SM background at the regions of $H_{\mathrm{T}}^{\mathrm{miss}} < 220$ and $H_{\mathrm{T}}^{\mathrm{miss}} \geq 220$ to conclude that most of the sensitivity comes from the $H_{\mathrm{T}}^{\mathrm{miss}} \geq 220$ region, since the production of real $H_{\mathrm{T}}^{\mathrm{miss}}$ (or $E_{\mathrm{T}}^{\mathrm{miss}}$) result from the production of neutrinos in the event, and these are much less common than Quantum Chromodynamics (QCD) events which swarm the $H_{\mathrm{T}}^{\mathrm{miss}} < 220$ region. Therefore, cutting at $H_{\mathrm{T}}^{\mathrm{miss}} \geq 220$ might be inefficient, but results in high sensitivity.

6.4.2 Jets and hardronic activity

Since the neutralinos $\widetilde{\chi}_1^0$ escaping the detector are the contributors to the $H_{\mathrm{T}}^{\mathrm{miss}}$ and in doing so the drivers of the sensitivity in high $H_{\mathrm{T}}^{\mathrm{miss}}$ region, we want them to be as boosted as possible, i.e., with the highest transverse momentum p_{T} as possible. A widely used approach is to require **FiXme Note: add citation** an Initial State Radiation (ISR) jet in the event. An ISR jet is formed when one of the incoming protons emit radiation (such as a photon or a gluon) before the interaction **FiXme Note: add citation and maybe reference to other section**. If a jet with high enough p_{T} is emitted, the rest of the interaction is recoiled against this jet and boosting it in the other direction. This way, the boosted neutralinos $\widetilde{\chi}_1^0$ will result in higher $H_{\mathrm{T}}^{\mathrm{miss}}$. As described in **FiXme Note: ref**, we require the jets to have $p_{\mathrm{T}} \geq 30\,\mathrm{GeV}$ and be located within the tracker acceptance ($|\eta| < 2.4$). We require at least one such jet in the event.

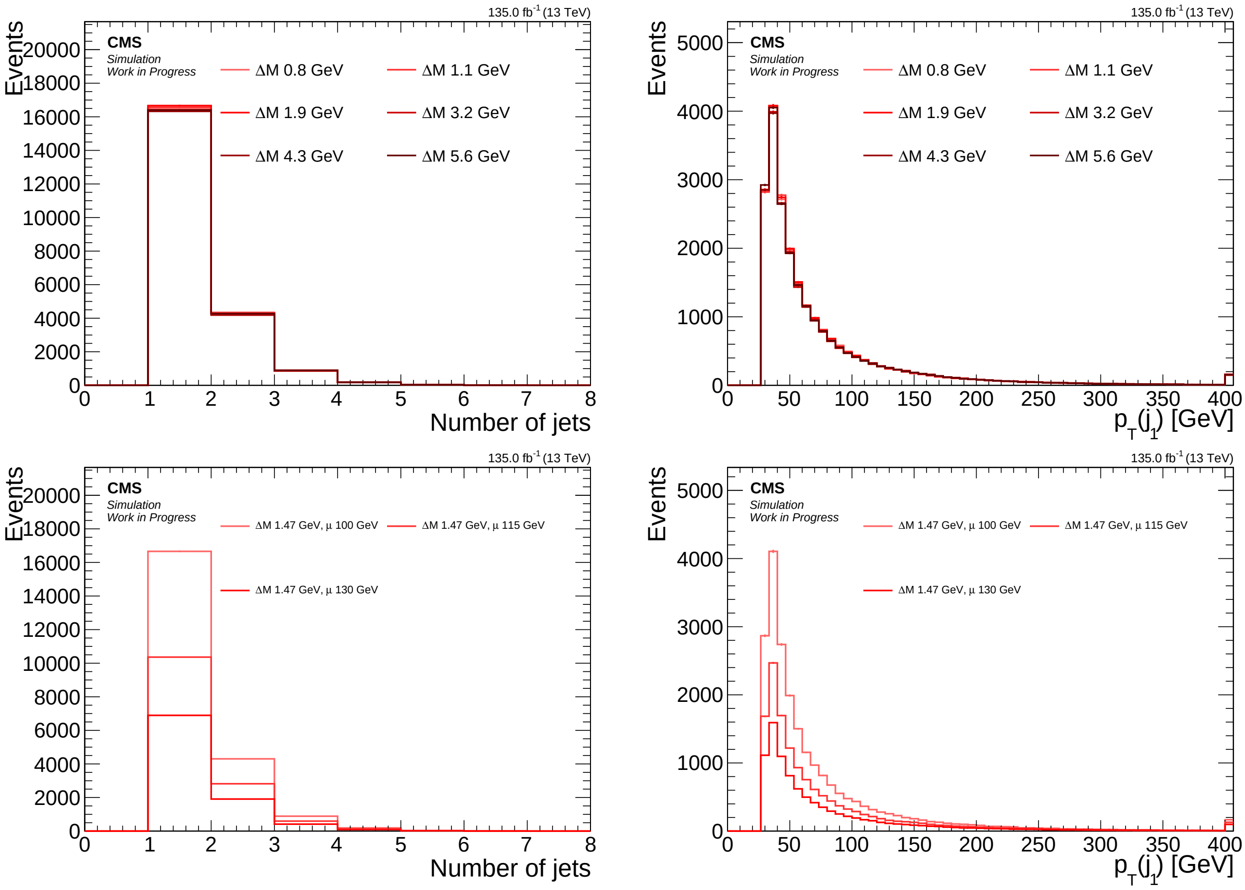

Figure 6.3: Signal distributions for *number of jets* (left) and *leading jet* p_{T} (right) comparing various Δm with a fixed higgsino parameter $\mu = 100\,\mathrm{GeV}$ (upper), and comparing various higgsino parameters μ with fixed $\Delta\mathrm{m} = 1.47\,\mathrm{GeV}$ (lower).

Our signal signature does not include a b-jet, i.e., a jet resulting from a bottom quark hadronization (either resulting from a top quark or not). We therefore seek to exploit this knowledge by vetoing b-tagged jets in the event. As described in **FiXme Note: add ref** we are using DeepCSV flavor tagging discriminant with a medium working point. As can be seen in these distributions, most of the signal lie in the 0 bin, and we will therefore veto any b-tagged jet, which retains most of the signal, but rejects a lot of SM background, such as arising from $t\bar{t}$ events.

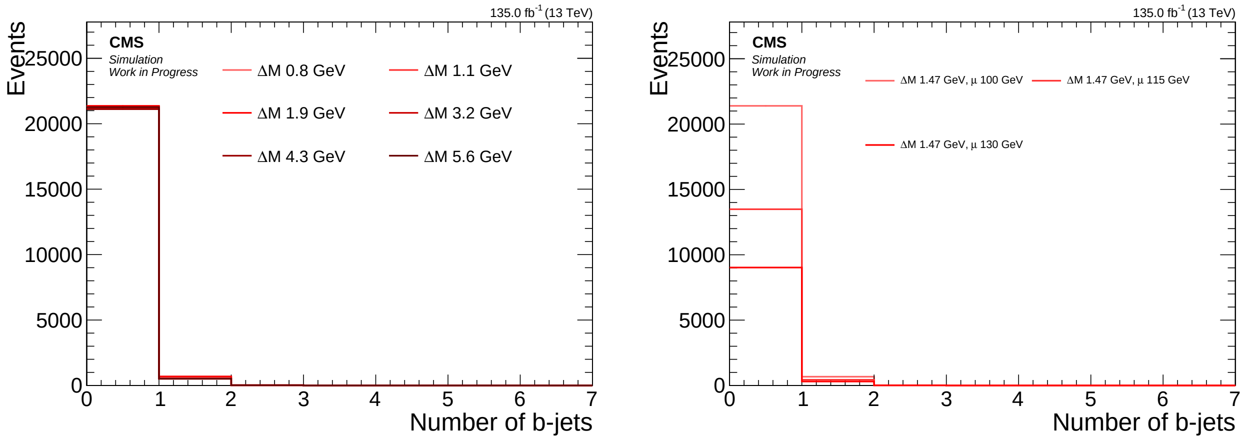

Figure 6.4: Signal distributions for *number of b-tagged jets* comparing various Δm with a fixed higgsino parameter $\mu = 100\,\text{GeV}$ (left), and comparing various higgsino parameters μ with fixed $\Delta\text{m} = 1.47\,\text{GeV}$ (right).

Since we are requiring an ISR jet in the event, we expect the $E_{\text{T}}^{\text{miss}}$ and the $H_{\text{T}}^{\text{miss}}$ to point in the opposite direction of the jet, or at least in an angel close to π. Events with multiple jets in the SM background such as arising from QCD will not exhibit such a feature. In order to reduce QCD background, we require $\min \Delta\phi \left(H_{\text{T}}^{\text{miss}}, \text{jets}\right) > 0.4$.

6.4.3 Base selection

We recap the section by summarizing the base selection of our analysis. This base selection, or preselection as we might use call it interchangeably, is applied to all analysis categories.

Table 6.1: Base selection applied to all analysis categories

Variable	Value
$H_{\text{T}}^{\text{miss}}$ [GeV]	≥ 220
$N_{\text{jets}}\left(p_{\text{T}} \geq 30\,\text{GeV and } \lvert\eta\rvert < 2.4\right)$	≥ 1
$N_{\text{b-jets}}\left(p_{\text{T}} \geq 30\,\text{GeV and } \lvert\eta\rvert < 2.4\right)$	0
$\min \Delta\phi \left(H_{\text{T}}^{\text{miss}}, \text{jets}\right)$	> 0.4

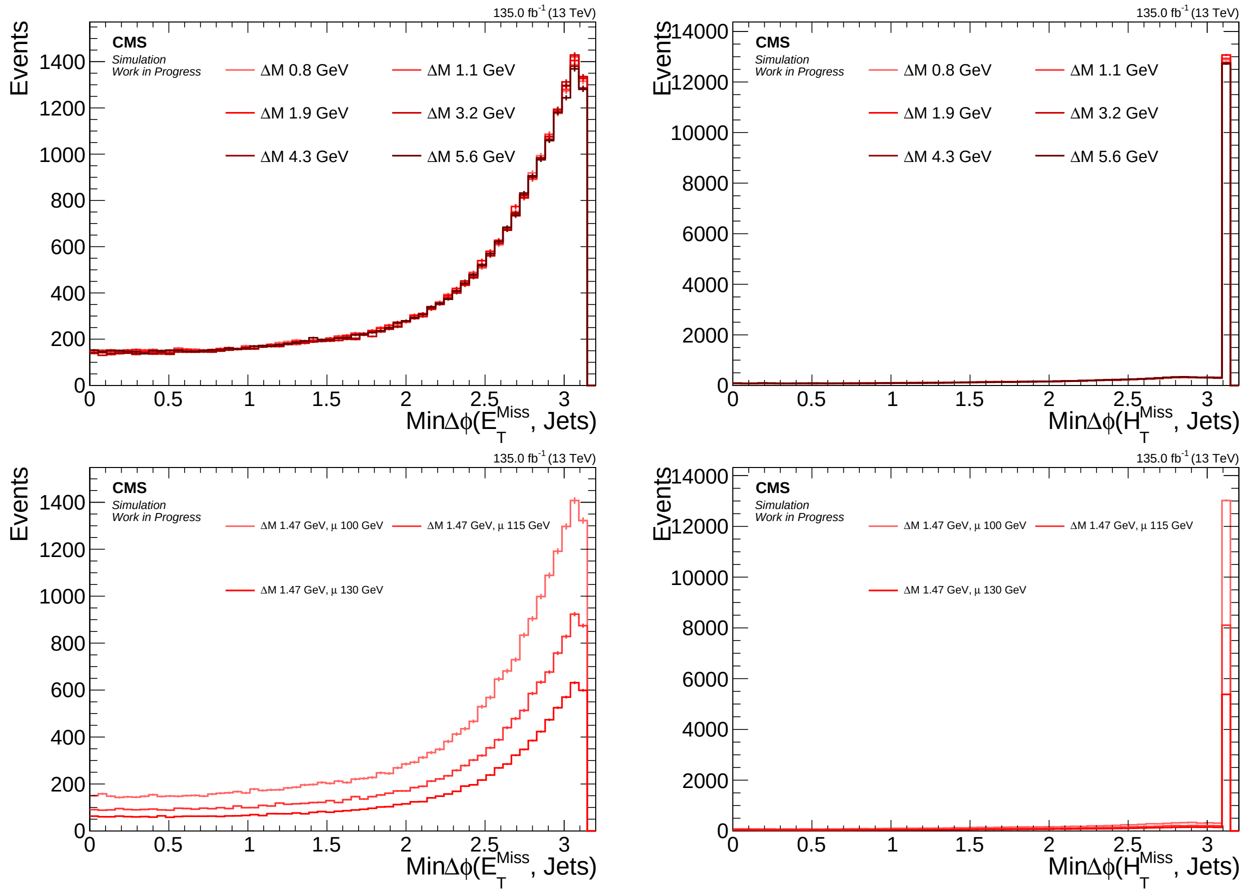

Figure 6.5: Signal distributions for $\min \Delta\phi \left(E_{\mathrm{T}}^{\mathrm{miss}}, \mathrm{jets}\right)$ (left) and $\min \Delta\phi \left(H_{\mathrm{T}}^{\mathrm{miss}}, \mathrm{jets}\right)$ (right) comparing various Δm with a fixed higgsino parameter $\mu = 100\,\mathrm{GeV}$ (upper), and comparing various higgsino parameters μ with fixed $\Delta\mathrm{m} = 1.47\,\mathrm{GeV}$ (lower).

6.5 Search strategy

6.6 Simulated samples

6.6.1 Standard Model simulated samples

6.6.2 Signal simulated samples

6.7 Object Definition and Selection

6.7.1 Electrons

Signal Electron Selection

Additional Electron Veto

6.7.2 Muons

Signal Muon selection

Additional Muon veto

6.7.3 Missing transverse energy

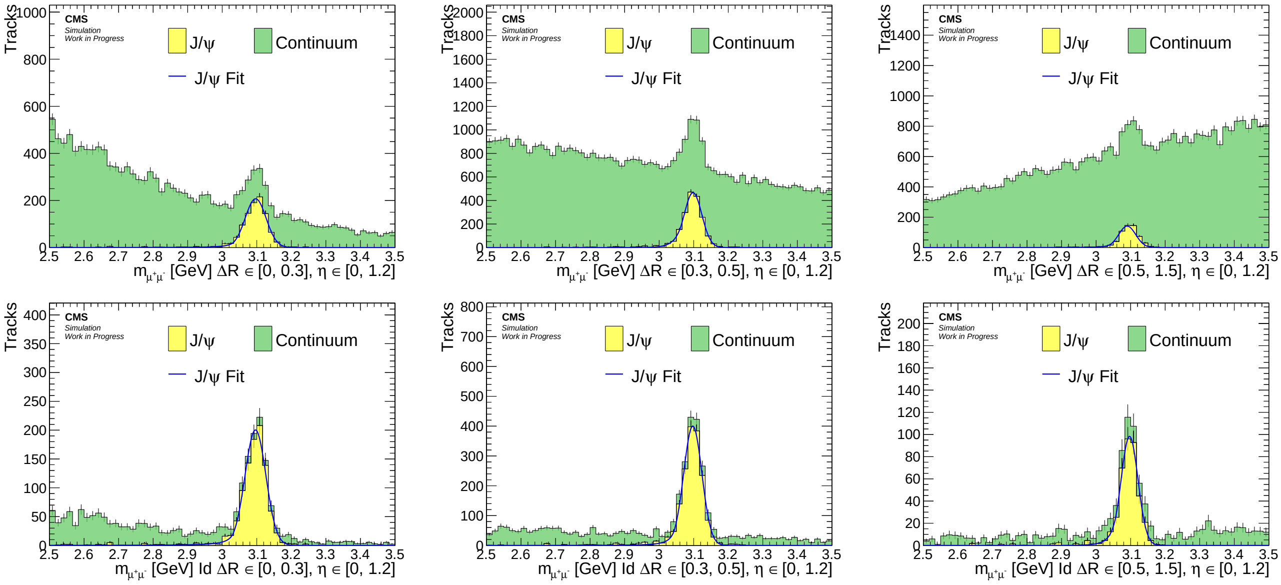

Figure 6.6: Barrel Muons BG

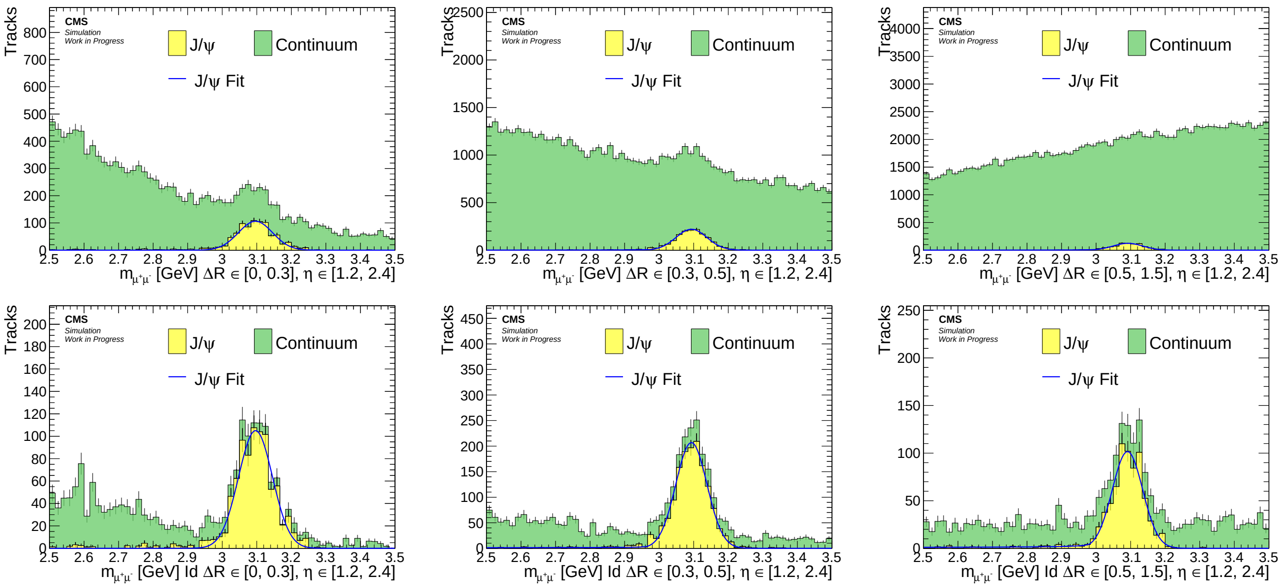

Figure 6.7: Endcaps Muons BG

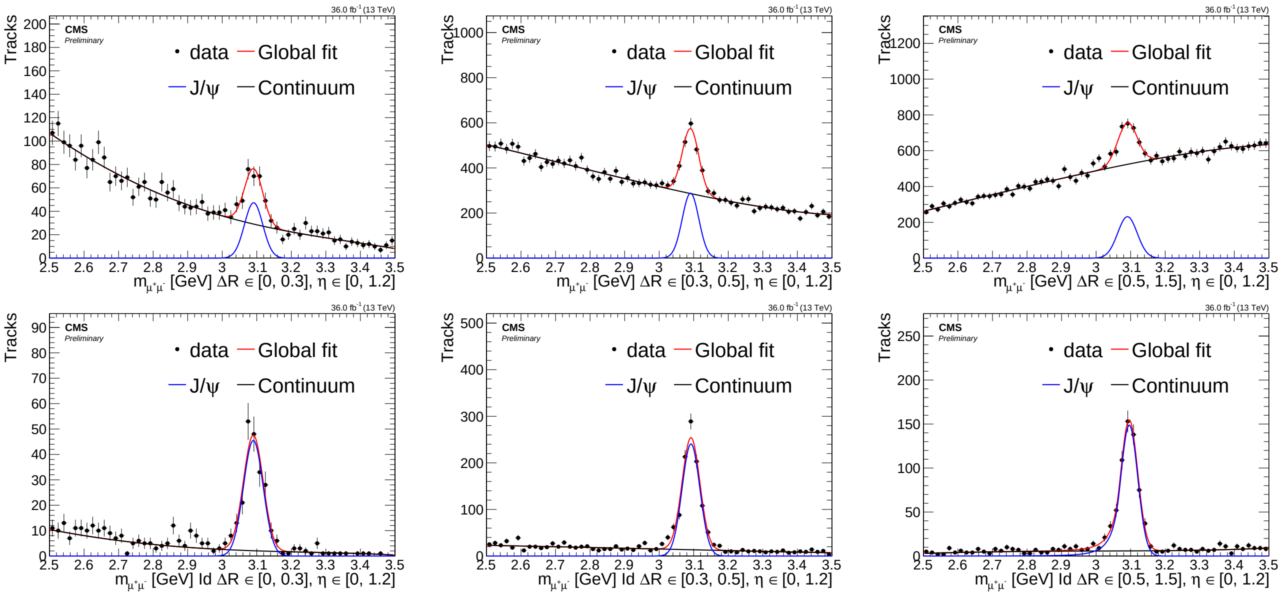

Figure 6.8: Barrel Muons Data

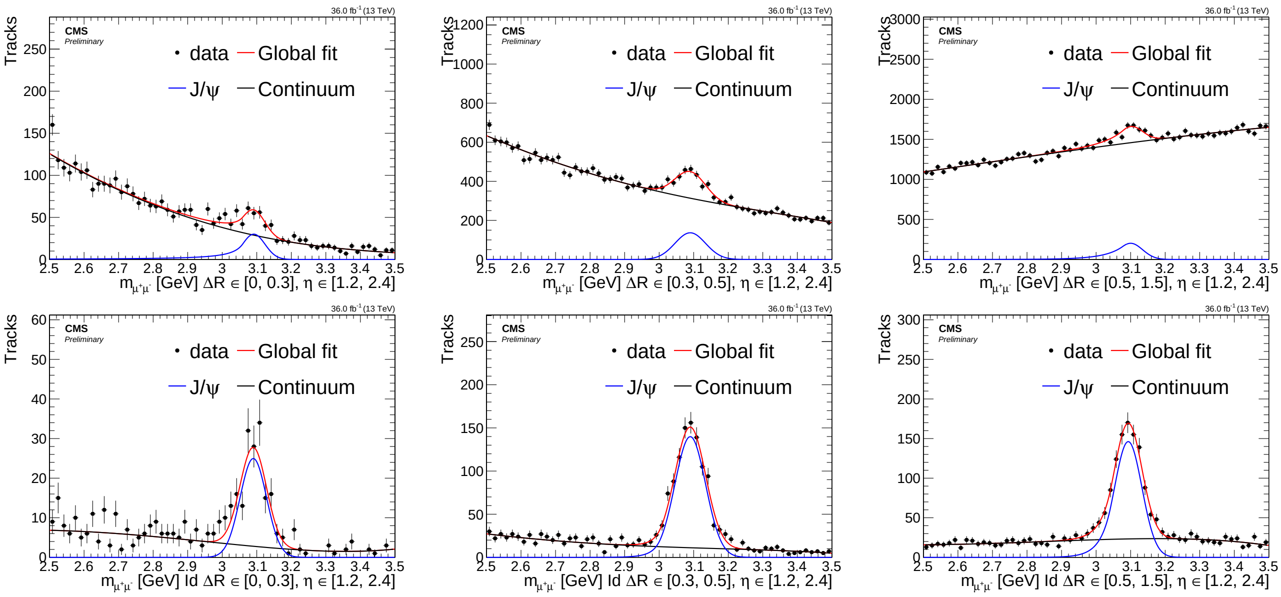

Figure 6.9: Endcaps Muons Data

Scale factors

6.7.4 Tracks and multivariate selection

6.7.5 Isolation

6.8 Trigger

6.9 Event Selection

6.9.1 Preselection

6.9.2 Selection Efficiencies

6.9.3 Boosted Decision Trees

6.10 Characterisation and Estimation of the Standard Model Backgrounds

6.11 Optimisation of Sensitivity

6.12 Results

6.13 Interpretation

Chapter 7

Jet Isolation and Non-Isolated Background Estimation

7.1 Jet Isolation

7.1.1 Optimisation

7.2 Non-Isolated Background

Chapter 8

Summary

Chapter 9

Latex stuff

9.1 Some examples

9.1.1 Multiline comment

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9.1.2 Fixme note

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9.1.3 Tables

Table 9.1: Table captions are above the table whereas figure captions are below.

Parameter	Value 1	Value 2
s	10.0	20.0
t	20.0	30.0
u	30.0	40.0

9.1.4 Cross References

9.1.4 23 section 9.1.4

9.1.5 Particles

Hello World $\tilde{\chi}_1^0\pi\eta_{\mathrm{c}}$ GeV$E_{\mathrm{T}}^{\mathrm{miss}}$ hey GeV $E_{\mathrm{T}}^{\mathrm{miss}}$ π new one $\tilde{\chi}_1^0$ $\tilde{\chi}_1^0$

9.1.6 Citing

[1] SOS analysis

9.1.7 Glossary

Using glossary for compter computer plural form computers upper case first Computer upper case first plural Computers. To use for symbol π

9.1.8 Acronyms

First use of acronym Soft-Opposite-Sign (SOS) and second SOS. You can reset this and do again Soft-Opposite-Sign (SOS) and second time again SOS. Long version Soft-Opposite-Sign. Full version Soft-Opposite-Sign (SOS). Short version SOS.

List of Corrections

Glossary

computer is a programmable machine that receives input, stores and manipulates data, and provides output in a useful format. 21

$\boldsymbol{E_{\mathrm{T}}^{\mathrm{miss}}}$ add description. 12, 13

$\boldsymbol{H_{\mathrm{T}}^{\mathrm{miss}}}$ add description. 12, 13

neutralino add description. 12, 13

$\boldsymbol{\pi}$ ratio of circumference of circle to its diameter. 21

$\boldsymbol{p_{\mathrm{T}}}$ Transverse momentum. 13

Acronyms

DM Dark Matter. 12

ISR Initial State Radiation. 13

LSP Lightest SUSY Particle. 12

QCD Quantum Chromodynamics. 13

SM Standard Model. 11–13

SOS Soft-Opposite-Sign. 22

SUSY Supersymmetry. 12

WIMP Weakly Interacting Massive Particle. 12

Bibliography

[1] **CMS** Collaboration, A. Tumasyan *et al.*, "Search for supersymmetry in final states with two or three soft leptons and missing transverse momentum in proton-proton collisions at $\sqrt{s} = 13$ TeV," *JHEP* **04** (2022) 091, `arXiv:2111.06296 [hep-ex]`.

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