Search for chargino and neutralino production in final states with two same-sign leptons, jets and missing transverse momentum at $\sqrt{s} = 13$ TeV with the ATLAS detector

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March 15, 2019

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Introduction

Standard Model : Fundamental Particles

- Standard Model(SM) is the current mainstream theory to describe the electromagnetic force, weak force and strong force.

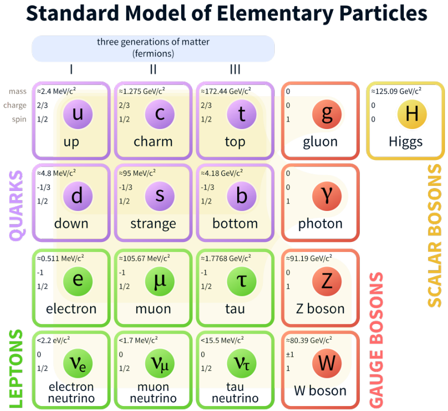


Figure: The "periodic" table for all fundamental particles in SM.

Standard Model : Fundamental Interaction

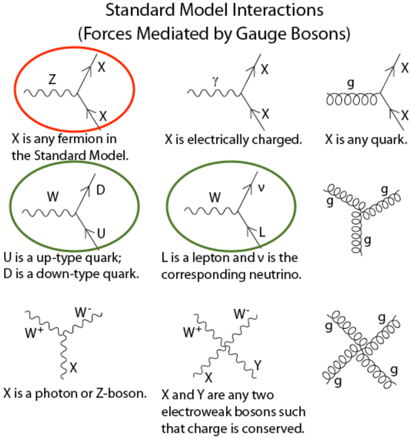


Figure: All allowed fundamental Feynman vertices in SM, except higgs-related vertices.

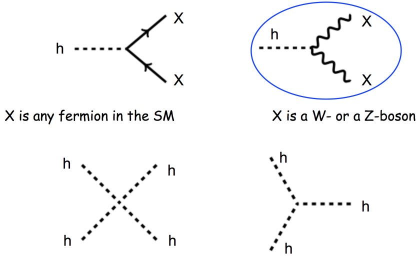


Figure: All allowed fundamental higgs-related Feynman vertices in SM.

Standard Model : Success

- SM gained huge successes in providing experimental predictions.
- With the W boson explaining the beta decay, the existence of the neutral Z boson was predicted and discovered later in 1983.
- The existence of a third generation of quarks is predicted in 1973 and top quark was discovered in 1995.
- Higgs boson is proposed in 1964 and discovered recently in 2012.

Standard Model : Limitation

- SM cannot explain the nature of dark matter.
- The hierarchy problem
  - Why the weak force is stronger than the gravity by 10^{24}.
  - At very high energy scale ($\sim 10^{19}$ GeV), the Higgs boson mass is strongly sensitive to quantum corrections.
- The electroweak interaction and the strong interaction have not been unified in SM.

Supersymmetry

- Supersymmetry(SUSY) is a theoretical extension of the Standard Model.
- It is one of the most promising theory.
- It can solve the hierarchy problem of Higgs mass.
- It can explain the nature of dark matter.
- It unifies the electroweak interaction and the strong interaction at $\sim 10^{16}$ GeV. The gauge couplings change with the energy scale.

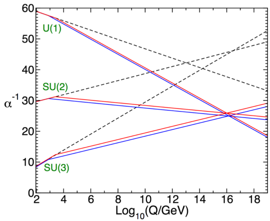


Figure: Black dashed lines are for SM. Red and blue lines are for the MSSM.

Supersymmetry : MSSM

- Minimal Supersymmetric Standard Model(MSSM) is the simplest realization of the supersymmetry.
- It predicts that each particle in the Standard Model has its own partner particle, called the superpartner.
- The spin of the superpartner will differ from the Standard Model particle by 1/2.
- A symmetry between the fermions and bosons.

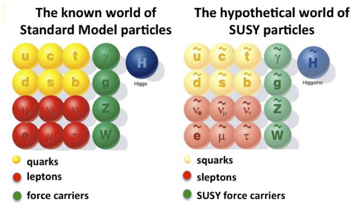


Figure: The particles in Standard Model and their corresponding superpartners and their names.

Supersymmetry : Superpartners

- In the MSSM, We need two neutral Higgs fileds (H_u^0 and H_d^0) and two charged Higgs fileds (H_u^+ and H_d^-).
- In SM electro-weak bosons, there are in total 4 neutral bosons: γ, Z, H_u^0 and H_d^0, and 4 charged bosons: W^+, W^-, H_u^+ and H_d^-.
- The superpartners of the 4 neutral bosons together form 4 mass eigenstates, called neutralinos: $\tilde{\chi}_1^0$, $\tilde{\chi}_2^0$, $\tilde{\chi}_3^0$ and $\tilde{\chi}_4^0$.
- The superpartners of the 4 charged bosons together form two mass eigenstates with electric charge ±1, called charginos: $\tilde{\chi}_1^\pm$ and $\tilde{\chi}_2^\pm$.

Type	SM particle	Symbol	Spin	R-parity	Superpartner	Symbol	Spin	R-parity
Fermions	Quark	q	$\frac{1}{2}$	+1	Squark	$\tilde{q}$	0	-1
	Lepton	l	$\frac{1}{2}$	+1	Slepton	$\tilde{l}$	0	-1
Gluon	Gluon	g	1	+1	Gluino	$\tilde{g}$	$\frac{1}{2}$	-1
Neutral EW Bosons	Photon	γ	1	+1				
	Z Boson	Z	1	+1	Neutralinos	$\tilde{\chi}_1^0$, $\tilde{\chi}_2^0$, $\tilde{\chi}_3^0$, $\tilde{\chi}_4^0$	$\frac{1}{2}$	-1
	Neutral Higgs	H_u^0, H_d^0	0	+1				
Charged EW Bosons	W Boson	W^+, W^-	1	+1	Charginos	$\tilde{\chi}_1^\pm$, $\tilde{\chi}_2^\pm$	$\frac{1}{2}$	-1
	Charged Higgs	H_u^+, H_d^-	0	+1				

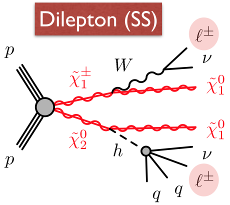
Table: The spin and R-parity for the Standard Model particles and their superpartners.

Supersymmetry : R-parity

- In order to agree with the experimental result that we never observe the proton decay, a quantum number R-parity is introduced. All SM particles have R-parity $+1$, while all SUSY particles have R-parity -1.
- If the R-parity is conserved, the lightest supersymmetric particle (LSP) cannot decay (stable).
- If the LSP is electrically neutral and interacts with matter only by the weak interaction and gravity, it could be a candidate for dark matter, for example the lightest neutralinos $\tilde{\chi}_1^0$.
- In this thesis, the R-parity is assumed to be conserved, and the lightest neutralino $\tilde{\chi}_1^0$ is assumed to be the LSP.
- Due to the conservation of R-parity, the supersymmetric particles can only be pair-produced, and will eventually decay into SM particles and the lightest neutralino $\tilde{\chi}_1^0$ (i.e. LSP).

Our Signal Scenario : Motivation

- In the recent searches for SUSY particles involved in strong interaction, their masses are suggested to be larger than 1 TeV.
- In this case, the direct pair production of SUSY electroweak boson $\tilde{\chi}_1^\pm$ and $\tilde{\chi}_2^0$ may be the dominant SUSY production process at the LHC, if their masses are below 1 TeV.
- In this thesis, their masses are assumed to be the same, and denoted by $m_{\tilde{\chi}_1^\pm, \tilde{\chi}_2^0}$.



Our Signal Scenario : Decay Processes

- If all the slepton ($\tilde{l}$) are heavier than $\tilde{\chi}_1^{\pm}$ and $\tilde{\chi}_2^0$:
  1. $\tilde{\chi}_1^{\pm}$ will decay to W boson and $\tilde{\chi}_1^0$:
     $\tilde{\chi}_1^{\pm} \rightarrow W^{\pm} + \tilde{\chi}_1^0$
  2. $\tilde{\chi}_2^0$ will decay to the lightest MSSM Higgs boson h and $\tilde{\chi}_1^0$:
     $\tilde{\chi}_2^0 \rightarrow h + \tilde{\chi}_1^0$

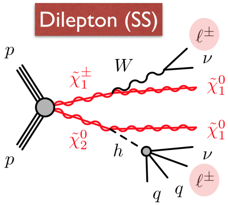
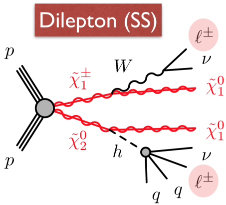


Figure: The Feynman diagram for our Wh same-sign signal scenario.

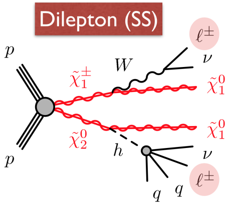
Our Signal Scenario : Decay Processes

- The W boson will further decay to one lepton (electron or muon) and one neutrino with the SM branching ratio :
$W^{\pm} \to \ell^{\pm} + \nu$
- The Higgs boson h will eventually decay to one lepton (electron or muon), quarks (i.e. jets) and neutrino(s) by various decay modes with the SM branching ratios. (For example, $h \to W^{+}W^{-}$)
- From now on, a lepton $\ell^{\pm}$ only refer to an electron or muon, but not τ lepton or neutrino.



Our Signal Scenario : Signal Signature in the Final State

- In this thesis, we search for two same-sign(SS) leptons, in order to reduce the SM backgrounds.
- A large missing energy is expected, due to the undetected neutralinos $\tilde{\chi}_1^0$ and neutrinos ν.
- Each quark will eventually become a particle shower within a narrow cone, called a jet, by the process of hadronization.
- The mass difference between the two lightest neutralinos $(m_{\tilde{\chi}_2^0} - m_{\tilde{\chi}_1^0})$ should be larger than the Higgs mass ($\sim$ 125 GeV).



Our Signal Scenario : Sensitive Region

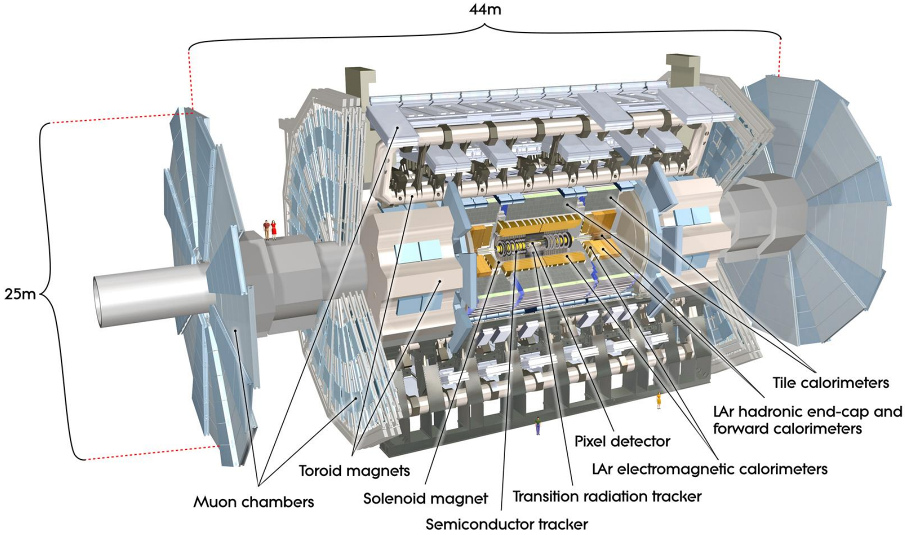
- If the mass difference $(m_{\tilde{\chi}_1^\pm, \tilde{\chi}_2^0} - m_{\tilde{\chi}_1^0})$ is slightly larger than the Higgs mass, it is called the compressed region.
- In the compressed region, one of the lepton may have low energy, due to the low momentum of the Higgs boson, and hence it may not be detected.
- In this case, only 2 out of 3 leptons are detected.
- In the compressed region, the signal will be more sensitive than the 3-leptons channel that searched for final states with 3 leptons. We can pick up their signal.

Experimental Setup

Experimental Setup : LHC

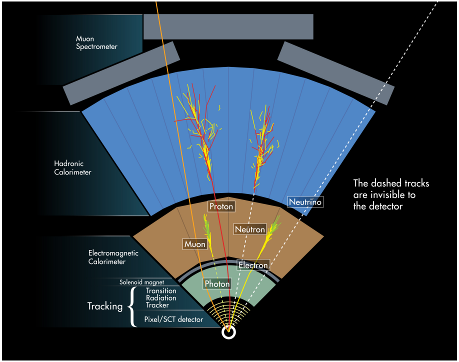
- The Large Hadron Collider (LHC) is the most powerful circular particle accelerator in the world.
- Its circumference is 27 km.
- Two beams of protons will be accelerated in opposite direction to centre-of-mass energy 13 TeV.
- They will be finally collided at the ATLAS detector.

Experimental Setup : ATLAS detector



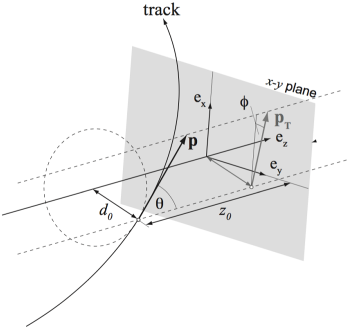
Experimental Setup : ATLAS detector

- The ATLAS detector consists of 3 main components:
  1. Inner detector: It is a particle tracker. It measures the tracks of charged particles.
  2. Calorimeter: It measures the energy of the particle and stops the particle. It consists of electromagnetic and hadronic calorimeters.
  3. Muon spectrometer: It is a particle tracker for muons.



Basic kinematic variables

- The z-axis is in the proton beam direction.
- The direction of the momentum **p** of the particle can by specified by the azimuthal angle ϕ and the polar angle θ, as usual in the spherical coordinate system.

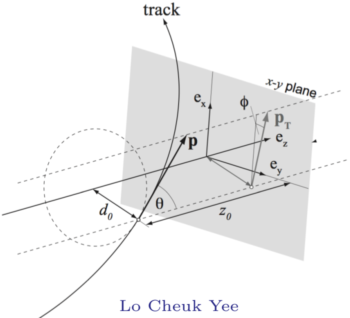


Basic kinematic variables

- The transverse momentum $\mathbf{p_T}$ is the projection of $\mathbf{p}$ onto the x-y plane. The magnitude of $\mathbf{p_T}$ is denoted by p_T

$$p_T = \sqrt{p_x^2 + p_y^2}$$

- p_T^1 and p_T^2 are p_T of the two leptons, with $p_T^1 \geq p_T^2$. The lepton with larger p_T is called the leading lepton, while the lepton with smaller p_T is called the sub-leading lepton.



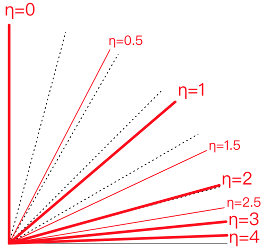
Basic kinematic variables

- The pseudorapidity η is defined by

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

- The angle separation ΔR of two particles is defined as:

$$\Delta R = \sqrt{(\Delta\phi)^2 + (\Delta\eta)^2} = \sqrt{(\phi_2 - \phi_1)^2 + (\eta_2 - \eta_1)^2}$$



Challenges of Background Estimatation

In order to search for SUSY, we need to understand the SM background very well.

1. Reducible SM background: They are due to the limitation of our detector and the wrong identification of the particle. There are two dominant reducible SM backgrounds, which are estimated by the data-driven method.
    - Charge flip background
    - Fake lepton background (dominant background)
2. Irreducible SM background: They are estimated by Monte Carlo (MC)
    - VV: WZ, WW, ZZ
    - tt+V
    - Rare: VVV, multitop, Higgs

Charge Flip Background

Charge Flip Background : Sources

- The charge flip background is due to the mis-identification of the sign of the charge of a lepton (mainly electron) in the reconstruction.
- The sign of the charge is determined by the direction of the curvature of the track. The charge may be reversed, or flipped.

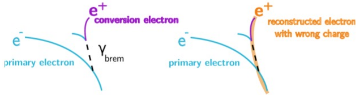


Figure: Bremsstrahlung and γ conversion.

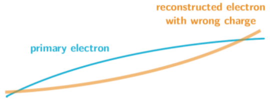


Figure: Track with high velocity

Charge Flip Background : Charge Flip Rate

- The probability that the charge of an electron is flipped is denoted by the charge-flip rate ϵ_i, where the index i represents the dependency on the p_T and $|\eta|$ of the electron.
- The value of index i is defined by the index of the following grids in the table.

Variable	Boundary of the bins
p_T (GeV)	25, 60, 90, 130, 150, 1000
$\|\eta\|$	0, 0.50, 1.00, 1.37, 1.52, 1.80, 2.00, 2.47

Table: Binning in p_T and $|\eta|$ for the charge-flip rate ϵ_i.

- The probability p_{ij} that an OS data event becomes a SS data event (with the leading lepton in bin i and the subleading lepton in bin j) is

$$p_{ij} = (1 - \epsilon_i)\epsilon_j + (1 - \epsilon_j)\epsilon_i$$

- It is called the charge flip weight.

Charge Flip Background : Charge Flip Rate

- The charge flip rates are measured by the likelihood method described in the next slide.
- After getting the charge flip rates, the charge flip background can be estimated by applying the charge flip weights on all OS events in data.

Charge Flip Background : Likelihood Method

- The charge flip rate ϵ_i is measured by using the data in the control region, within the Z mass window cut of 80-100 GeV.
- The events inside the Z mass window is then subtracted by the non-Zee processes, by using the sideband technique.
- After the subtraction, the total number of event is denoted by N^{ij}, and the number of events with two same-sign leptons is denoted by N^{ij}_{SS}.
- The expected value of N^{ij}_{SS} is then given by $\lambda = N^{ij}p_{ij}$. And, if N^{ij}_{SS} is described by a Poisson distribution, then

$$P(N^{ij}_{SS}|N^{ij}, \epsilon_i, \epsilon_j) = \frac{(N^{ij}p_{ij})^{N^{ij}_{SS}} e^{-N^{ij}p_{ij}}}{N^{ij}_{SS}!}$$

Charge Flip Background : Likelihood Method

- Converting it to the likelihood function L and taking the negative natural log yields

$$
\begin{aligned}
-\ln L &= -\ln \prod_{ij} P(N_{SS}^{ij} | N^{ij}, \epsilon_i, \epsilon_j) \\
&= -\sum_{ij} \Big[N_{SS}^{ij} \ln(N^{ij}[\epsilon_i(1-\epsilon_j) + (1-\epsilon_i)\epsilon_j]) \\
&\quad - N^{ij}[\epsilon_i(1-\epsilon_j) + (1-\epsilon_i)\epsilon_j] \Big] + \text{constant}
\end{aligned}
$$

- where the summation over i and j is taken over all p_T and $|\eta|$ bins of both electrons.
- By minimizing this likelihood, the charge-flip rate can be estimated.

Charge Flip Background : Result for Charge Flip Rate

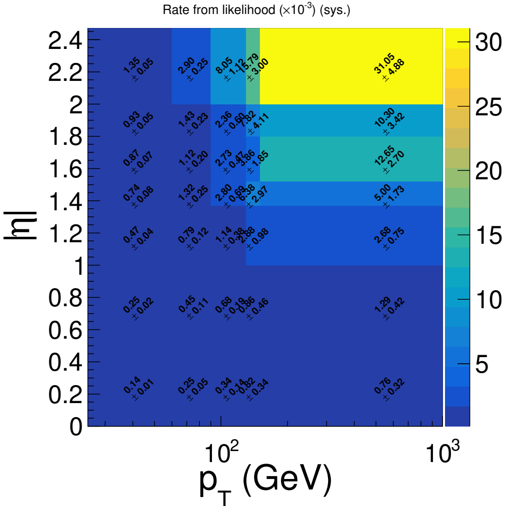


Figure: The measured values of the charge-flip rate ϵ_i in data, with total uncertainties.

Fake Lepton Background

Fake Lepton Background : Sources

The source of the fake lepton is that other object (like jet and photon) is mis-identified as a lepton. Thay can be mainly classified into 3 types:

- Heavy-flavor fakes:
  - It comes from semi-leptonic decays of heavy-quark (b or c) hadrons.
- Light-flavor fakes:
  - It comes from semi-leptonic decays of light-quark hadrons.
    OR
  - It is due to mis-reconstructions of light-quark hadrons.
- photon conversion:
  - It comes from the pair production of leptons from a photon

Fake Lepton Background : Matrix Method

- The fake leptons is estimated by the matrix method.
- The probability that a real lepton passes the tight selection criteria (i.e. tight lepton) is denoted by the real efficiency ϵ.
- The probability that a real lepton does not pass the tight selection criteria (i.e. loose lepton) is denoted by $\bar{\epsilon} = 1 - \epsilon$.
- The probability that a fake lepton passes the tight selection criteria (i.e. tight lepton) is denoted by the fake efficiency f.
- The probability that a fake lepton does not pass the tight selection criteria (i.e. loose lepton) is denoted by $\bar{f} = 1 - f$.

$$\begin{pmatrix} N_T \\ N_L \end{pmatrix} = \begin{pmatrix} \epsilon & f \\ \bar{\epsilon} & \bar{f} \end{pmatrix} \begin{pmatrix} N_R \\ N_F \end{pmatrix}$$

Fake Lepton Background : Matrix Method

Suppose we know $\begin{pmatrix} N_T \\ N_L \end{pmatrix}$, we can find N_F by inverting the matrix.

$$\begin{pmatrix} 0 \\ N_F \end{pmatrix} = \begin{pmatrix} 0 & 0 \\ 0 & 1 \end{pmatrix} \begin{pmatrix} N_R \\ N_F \end{pmatrix} = \begin{pmatrix} 0 & 0 \\ 0 & 1 \end{pmatrix} \begin{pmatrix} \epsilon & f \\ \bar{\epsilon} & \bar{f} \end{pmatrix}^{-1} \begin{pmatrix} N_T \\ N_L \end{pmatrix}$$

Then, we can find the number of tight lepton due to the fake lepton, N'_T

$$\begin{pmatrix} N'_T \\ N'_L \end{pmatrix} = \begin{pmatrix} \epsilon & f \\ \bar{\epsilon} & \bar{f} \end{pmatrix} \begin{pmatrix} 0 \\ N_F \end{pmatrix}$$

$$= \begin{pmatrix} \epsilon & f \\ \bar{\epsilon} & \bar{f} \end{pmatrix} \begin{pmatrix} 0 & 0 \\ 0 & 1 \end{pmatrix} \begin{pmatrix} \epsilon & f \\ \bar{\epsilon} & \bar{f} \end{pmatrix}^{-1} \begin{pmatrix} N_T \\ N_L \end{pmatrix}$$

Fake Lepton Background : Matrix Method

We can generalize the one-lepton case to the two-leptons case.

$$\begin{pmatrix} N_{TT} \\ N_{TL} \\ N_{LT} \\ N_{LL} \end{pmatrix} = \begin{pmatrix} \epsilon_1\epsilon_2 & \epsilon_1 f_2 & f_1\epsilon_2 & f_1 f_2 \\ \epsilon_1\bar{\epsilon_2} & \epsilon_1\bar{f_2} & f_1\bar{\epsilon_2} & f_1\bar{f_2} \\ \bar{\epsilon_1}\epsilon_2 & \bar{\epsilon_1} f_2 & \bar{f_1}\epsilon_2 & \bar{f_1} f_2 \\ \bar{\epsilon_1}\bar{\epsilon_2} & \bar{\epsilon_1}\bar{f_2} & \bar{f_1}\bar{\epsilon_2} & \bar{f_1}\bar{f_2} \end{pmatrix} \begin{pmatrix} N_{RR} \\ N_{RF} \\ N_{FR} \\ N_{FF} \end{pmatrix}$$

where ϵ_1 is the probability that a leading real lepton passes the signal selection (i.e. tight lepton), ϵ_2 is the probability that a subleading real lepton passes the signal selection (i.e. tight lepton), etc.

Fake Lepton Background : Matrix Method

Similarly, we can find the number of tight-tight leptons due to the fake leptons, N'_{TT}

$$\begin{pmatrix} N'_{TT} \\ N'_{TL} \\ N'_{LT} \\ N'_{LL} \end{pmatrix} = \begin{pmatrix} \epsilon_1\epsilon_2 & \epsilon_1 f_2 & f_1\epsilon_2 & f_1 f_2 \\ \epsilon_1\bar{\epsilon_2} & \epsilon_1\bar{f_2} & f_1\bar{\epsilon_2} & f_1\bar{f_2} \\ \bar{\epsilon_1}\epsilon_2 & \bar{\epsilon_1}f_2 & \bar{f_1}\epsilon_2 & \bar{f_1}f_2 \\ \bar{\epsilon_1}\bar{\epsilon_2} & \bar{\epsilon_1}\bar{f_2} & \bar{f_1}\bar{\epsilon_2} & \bar{f_1}\bar{f_2} \end{pmatrix} \begin{pmatrix} 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix}$$

$$\begin{pmatrix} \epsilon_1\epsilon_2 & \epsilon_1 f_2 & f_1\epsilon_2 & f_1 f_2 \\ \epsilon_1\bar{\epsilon_2} & \epsilon_1\bar{f_2} & f_1\bar{\epsilon_2} & f_1\bar{f_2} \\ \bar{\epsilon_1}\epsilon_2 & \bar{\epsilon_1}f_2 & \bar{f_1}\epsilon_2 & \bar{f_1}f_2 \\ \bar{\epsilon_1}\bar{\epsilon_2} & \bar{\epsilon_1}\bar{f_2} & \bar{f_1}\bar{\epsilon_2} & \bar{f_1}\bar{f_2} \end{pmatrix}^{-1} \begin{pmatrix} N_{TT} \\ N_{TL} \\ N_{LT} \\ N_{LL} \end{pmatrix}$$

Fake Lepton Background : Results of Fake Efficiencies

The method for measuring the fake efficiencies is described in the backup slides.

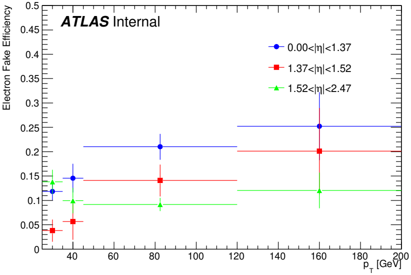


Figure: Electron fake efficiency

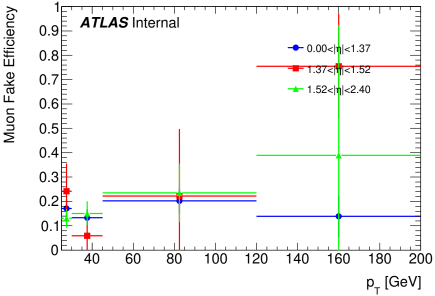


Figure: Muon fake efficiency

Signal Region

Signal Region: Challenges

Estimation of the signal sensitivity

- Cross section for our signal ~ 0.1 pb
- Total luminosity in one year $\sim 10^4$ pb^{-1}
- Expected number of signal events in one year $\sim 10^3$

- Time interval between each collision $= 25$ ns
- Total number of events in one year $\sim 10^{15}$
- The probability to have a signal event $\sim 10^{-12}$
- Conclusion: the SUSY signal is very rare.

Signal Region : Strategy

In order to extract the signal, the following strategies are used.

- A trigger system are used when taking the data (online), to only store the interested events in the disk.
  (40 MHz $\rightarrow$ 100 kHz $\rightarrow$ 1 kHz)
- Some discriminant variables (based on the kinematic variables) are defined, to help distinguish the signal and the background.
- Two dedicated signal regions are defined (SRjet1 and SRjet23) based on the discriminant variables, to maximize the signal sensitivity.

Signal Region : discriminant variable

- n_{jets}: Number of signal jets:
- $n_{\text{b-jets}}$: Number of b-jets (jet from b quark).
- $\Delta\eta_{ll}$ is designed to estimate the angle between the two leptons.

$$\Delta\eta_{ll} = |\eta_1 - \eta_2|$$

- m_{eff} is designed to estimate the total energy and momentum of the charginos $\tilde{\chi}_1^{\pm}$ and neutralinos $\tilde{\chi}_2^0$.

$$m_{\text{eff}} = p_T^1 + p_T^2 + E_T^{\text{miss}} + \sum_{\text{signal jets}} p_T$$

- m_{ll}: The invariant mass of the 4-momentum sum of the two leptons

$$(m_{ll})^2 = (p_1 + p_2)^2$$

Signal Region : discriminant variable

- The missing momentum $\mathbf{p}^{\text{miss}}$ due to undetected particles is defined by

$$\mathbf{p}^{\text{miss}} = - \sum_{\text{All detected particles}} \mathbf{p}$$

- E_T^{miss} or MET: The transverse missing erengy is designed to estimate the missing energy from undetected particles.

$$E_T^{\text{miss}} = |\mathbf{p}_T^{\text{miss}}| = \sqrt{(p_x^{\text{miss}})^2 + (p_y^{\text{miss}})^2}$$

Signal Region : discriminant variable

- m_T: It is designed to reconstruct the mass of the W boson.

$$m_T = \sqrt{2p_T^1 E_T^{\text{miss}}(1 - \cos\Delta\phi)}$$

where $\Delta\phi$ is the azimuthal angle between the leading lepton and the missing transverse momentum.

- m_{T2}: It is designed to set a lower bound on the masses of the unseen pair of charginos $\tilde{\chi}_1^{\pm}$ and neutralinos $\tilde{\chi}_2^0$.

$$m_{T2} = \min_{\mathbf{q}_T}\left[\max\left(m_T(\mathbf{p}_T^1, \mathbf{q}_T), m_T(\mathbf{p}_T^2, \mathbf{p}_T^{\text{miss}} - \mathbf{q}_T)\right)\right]$$

$$m_T(\mathbf{p}_T, \mathbf{q}_T) = \sqrt{2p_T q_T(1 - \cos\Delta\phi)}$$

Signal Region : discriminant variable

- m_{lj} or m_{ljj}: It is designed to reconstruct the mass of the Higgs boson.

$$p_{\text{jet-system}} = \begin{cases} p_{\text{jet1}} & \text{for SRjet1 (1 jet)} \\ p_{\text{jet1}} + p_{\text{jet2}} & \text{for SRjet23 (2 or 3 jets)} \end{cases}$$

$$p_{\text{closest-lepton}} = \begin{cases} p_{\ell 1} & \text{if } \Delta R(p_{\ell 1}, p_{\text{jet-system}}) \leq \Delta R(p_{\ell 2}, p_{\text{jet-system}}) \\ p_{\ell 2} & \text{if } \Delta R(p_{\ell 1}, p_{\text{jet-system}}) > \Delta R(p_{\ell 2}, p_{\text{jet-system}}) \end{cases}$$

$$(m_{lj(j)})^2 = (p_{\text{closest-lepton}} + p_{\text{jet-system}})^2$$

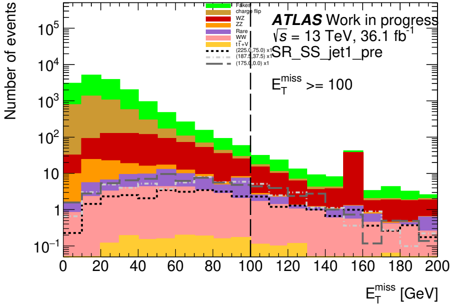
Signal Region : Pre-selection

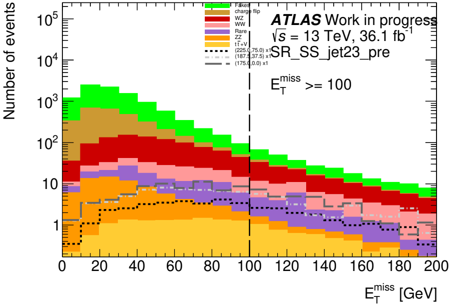
- Signal Region(SR) is a set of cuts of the discriminant variables, such that the signal sensitivity is high.
- By trying different sets of cuts, the signal region with the highest signal sensitivity can be found. This process is called the signal region optimization.
- In the SR optimization, the MC signal and background are used to study the expected sensitivity.

The following cuts are the pre-selection, before the signal region optimization.

- Exactly 2 leptons with $p_T > 25$ GeV.
- Electron: $|\eta| < 2.47$; Muon: $|\eta| < 2.4$
- The two leptons are same-sign in electric charge (SS).
- $n_{\text{b-jets}} = 0$, to reduce the SM background from top quark.
- Two signal regions: SRjet1 with $n_{\text{jets}} = 1$, SRjet23 with $n_{\text{jets}} = 2$ or 3.

Signal Region : Pre-selection plots





Signal Region : Optimizied Event Selection

	SRjet1	SRjet23
n_{jets}	1	2 or 3
Leading lepton p_T [GeV]	≥ 25	≥ 25
Sub-leading lepton p_T [GeV]	≥ 25	≥ 25
$\lvert\Delta\eta_{ll}\rvert$	< 1.5	-
$E_{\mathrm{T}}^{\mathrm{miss}}$ [GeV]	≥ 100	≥ 100
m_{eff} [GeV]	≥ 260	≥ 240
m_{T}^{l1} [GeV]	≥ 140	≥ 120
m_{lj}/m_{ljj} [GeV]	< 180	< 130
m_{T2} [GeV]	≥ 80	≥ 70

Signal Region : Expected Yields

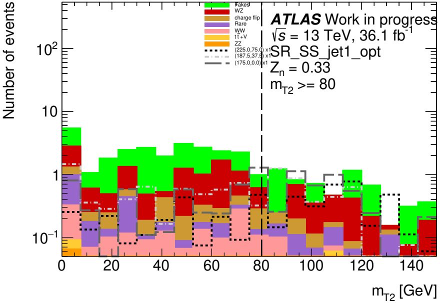
	Number of events	Significance
Fakes	3.295 ± 0.819	
WZ	2.176 ± 0.398	
charge flip	0.472 ± 0.053	
Rare	0.444 ± 0.111	
WW	0.166 ± 0.023	
$t\bar{t} + V$	0.125 ± 0.046	
ZZ	0.055 ± 0.028	
Total BG	6.733 ± 0.921	
(225.0,75.0)	3.33 ± 0.60	**0.74**
(187.5,37.5)	3.77 ± 0.95	0.86
(175.0,0.0)	4.29 ± 0.73	0.98

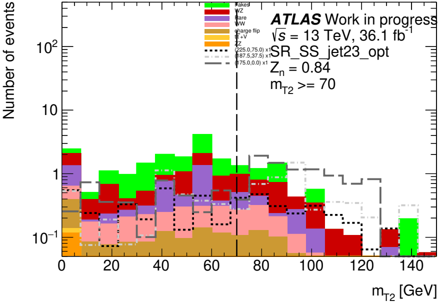
Table: Yields in SRjet1

	Number of events	Significance
WZ	1.849 ± 0.273	
Fakes	1.765 ± 0.709	
Rare	0.731 ± 0.195	
WW	0.514 ± 0.037	
charge flip	0.267 ± 0.029	
$t\bar{t} + V$	0.142 ± 0.031	
ZZ	0.067 ± 0.025	
Total BG	5.335 ± 0.787	
(225.0,75.0)	2.35 ± 0.34	0.57
(187.5,37.5)	4.72 ± 0.74	**1.26**
(175.0,0.0)	8.60 ± 1.51	2.24

Table: Yields in SRjet23

Signal Region : N-1 plots





Validation Region

Validation Region: Introduction

- The validation region(VR) is designed to ensure that the estimation of background is reliable.
- Method: The backgrounds are compared with the data, to see whether they agree with each other.
- One VR is defined for each SR: VRjet1 and VRjet23.

There are three requirements for the validation regions:

- The signal contribution should be small.
- The validation region is orthogonal to the corresponding signal region.
- The background composition is similar to the corresponding signal region.

Validation Region: Method

- In order to make it orthogonal to SR, E_T^{miss}/m_T cut is inverted.
- Adjust its lower cut, to have a similar background composition.
- Invert the m_{lj}/m_{ljj} cut, to reduce the signal.
- Remove m_{T2} and m_{eff} cuts, to increase statistics.

Cut	VRjet1	VRjet23
n_{jets}	1	$[2,3]$
$\Delta\eta_{ll}$	< 1.5	$-$
E_T^{miss} [GeV]	$[70,100]$	> 100
m_T [GeV]	> 140	$[65,120]$
m_{eff} [GeV]	$-$	> 240
$m_{lj(j)}$ [GeV]	> 130	> 130
m_{T2} [GeV]	$-$	$-$

Validation Region: Yield

Process	VRjet1	VRjet23
Rare	$0.775 \pm 0.389^{+0.661}_{-0.362}$	$2.469 \pm 0.674^{+0.998}_{-0.899}$
$t\bar{t}V$	$0.039 \pm 0.013^{+0.018}_{-0.012}$	$0.959 \pm 0.082^{+0.152}_{-0.146}$
ZZ	$0.298 \pm 0.060^{+0.089}_{-0.063}$	$0.247 \pm 0.045^{+0.113}_{-0.047}$
WZ	$4.909 \pm 0.530^{+0.960}_{-0.899}$	$19.325 \pm 0.643^{+4.393}_{-4.346}$
WW	$0.801 \pm 0.051^{+0.123}_{-0.060}$	$10.477 \pm 0.176^{+0.796}_{-0.726}$
Charge flip	$1.997 \pm 0.128^{+0.260}_{-0.260}$	$2.065 \pm 0.085^{+0.166}_{-0.166}$
Fakes	$8.021 \pm 1.390^{+5.806}_{-5.806}$	$19.990 \pm 2.013^{+13.461}_{-13.461}$
Total BG	$16.839 \pm 1.545^{+5.915}_{-5.912}$	$55.534 \pm 2.228^{+14.396}_{-14.332}$
Data	17	54

Table: The uncertainties include the statistical and systematic uncertainties.

The distribution plots for different variables are in the backup slides.

Results

Results: Observed Events

- The observed events are consistent with the SM.

	Number of events
Fakes	3.295 ± 2.100
WZ	2.176 ± 0.398
charge flip	0.472 ± 0.053
Rare	0.444 ± 0.111
WW	0.166 ± 0.023
$t\bar{t} + V$	0.125 ± 0.046
ZZ	0.055 ± 0.028
Total BG	6.733 ± 2.142
Data	2

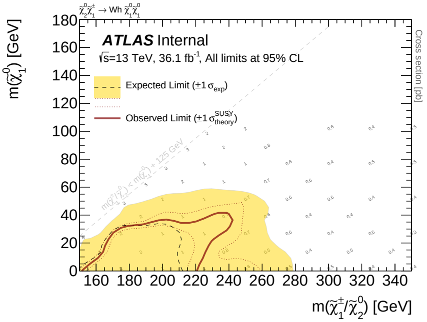
Table: Yields in SRjet1

	Number of events
WZ	1.849 ± 0.273
Fakes	1.765 ± 1.460
Rare	0.731 ± 0.195
WW	0.514 ± 0.037
charge flip	0.267 ± 0.029
$t\bar{t} + V$	0.142 ± 0.031
ZZ	0.067 ± 0.025
Total BG	5.335 ± 1.499
Data	8

Table: Yields in SRjet23

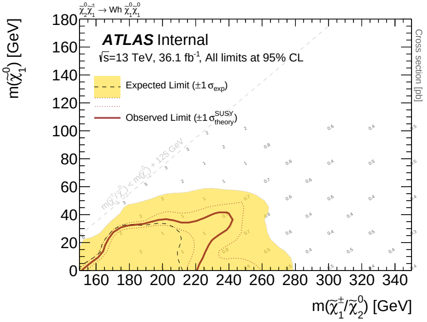
Results: Exclusion Limits

- New exclusion limits were set, by combining the two SR.
- The contour line is in 95% confidence level.



Results: Exclusion Limits

- The exclusion limits for the masses of $\tilde{\chi}_1^{\pm}$ and $\tilde{\chi}_2^0$ are extended up to 245 GeV, and the exclusion limits for the mass of $\tilde{\chi}_1^0$ are extended up to 40 GeV.
- This means that the mass points inside the contour line are rejected with 95% confidence level.



Conclusion

- We searched for the electroweak pair production of a chargino and a neutralino ($p + p \to \tilde{\chi}_1^{\pm} + \tilde{\chi}_2^0$), with the Wh channel $\tilde{\chi}_1^{\pm} \to \tilde{\chi}_1^0 + W$ and $\tilde{\chi}_2^0 \to \tilde{\chi}_1^0 + h$, and the same-sign channel.
- By using the ATLAS data with total integrated luminosity 36.1 fb^{-1}.
- The dominant BG (fake lepton BG and charge flip BG) were estimated by the data-driven method.
- All the results were consistent with the SM.
- New exclusion limits were set, by combining the two SR.

Thank You

Backup

Supersymmetry : R-parity

- The baryon number B is defined by $\frac{1}{3}(n_q - n_{\bar{q}})$, where n_q is the number of quarks and $n_{\bar{q}}$ is the number of anti-quarks.
- The lepton number L is defined by $n_l - n_{\bar{l}}$, where n_l is the number of leptons and $n_{\bar{l}}$ is the number of anti-leptons.
- In SM, $(B - L)$ is conserved. But in MSSM, it is no longer conserved.
- To keep $(B - L)$ conservation and prevent the proton decay, the R-parity P_R is introduced.

$$P_R = (-1)^{3(B-L)-2s}$$

where s is the spin.

Charge Flip Background : Likelihood Method

Likelihood Method : Method

- The probability that the charge of an electron is flipped is denoted by the charge-flip rate ϵ_i, where the index i represents the dependency on the p_T and $|\eta|$ of the electron.
- The value of index i is defined by the index of the following grids in the table.

Variable	Boundary of the bins
p_T (GeV)	25, 60, 90, 130, 150, 1000
$\|\eta\|$	0, 0.50, 1.00, 1.37, 1.52, 1.80, 2.00, 2.47

Table: Binning in p_T and $|\eta|$ for the charge-flip rate ϵ_i.

- The probability p_{ij} that an OS data event becomes a SS data event (with the leading lepton in bin i and the subleading lepton in bin j) is

$$p_{ij} = (1 - \epsilon_i)\epsilon_j + (1 - \epsilon_j)\epsilon_i$$

Likelihood Method : Definition of Control Region

A control region is defined.

- Trigger requirement
- exactly 2 signal leptons
- 2 electrons
- $25 < p_T < 1000$
- $|\eta| < 2.47$

Likelihood Method : Method

- The charge flip rate ϵ_i is measured by using the data in the control region, within the Z mass window cut of 80-100 GeV.
- The events inside the Z mass window is then subtracted by the non-Zee processes, by using the sideband technique.
- After the subtraction, the total number of event is denoted by N^{ij}, and the number of events with two same-sign leptons is denoted by N^{ij}_{SS}.
- The expected value of N^{ij}_{SS} is then given by $\lambda = N^{ij}p_{ij}$. And, if N^{ij}_{SS} is described by a Poisson distribution, then

$$P(N^{ij}_{SS}|N^{ij}, \epsilon_i, \epsilon_j) = \frac{(N^{ij}p_{ij})^{N^{ij}_{SS}} e^{-N^{ij}p_{ij}}}{N^{ij}_{SS}!}$$

Likelihood Method : Method

- Converting it to the likelihood function L and taking the negative natural log yields

$$
\begin{aligned}
-\ln L &= -\ln \prod_{ij} P(N_{SS}^{ij}|N^{ij}, \epsilon_i, \epsilon_j) \\
&= -\sum_{ij} \Big[N_{SS}^{ij} \ln(N^{ij}[\epsilon_i(1-\epsilon_j) + (1-\epsilon_i)\epsilon_j]) \\
&\quad - N^{ij}[\epsilon_i(1-\epsilon_j) + (1-\epsilon_i)\epsilon_j] \Big] + \text{constant}
\end{aligned}
$$

- where the summation over i and j is taken over all p_T and $|\eta|$ bins of both electrons.
- By minimizing this likelihood, the charge-flip rate can be estimated.

Likelihood Method : Background Subtraction

Both for data and MC

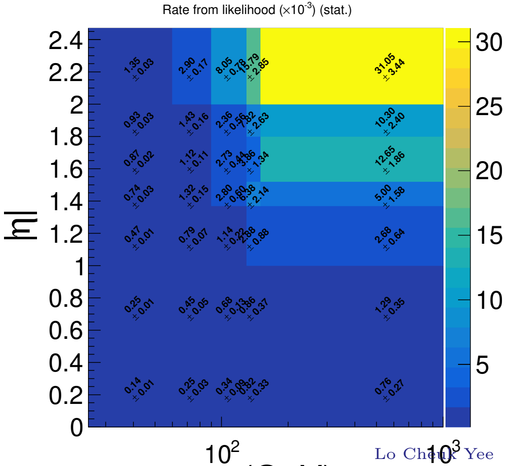
- Central region: 80 - 100 GeV
- Sideband region: 60 - 80 and 100 - 120
  (Sideband width 20 GeV)

$$N_{Central} = N_{Central} - \frac{20}{20+20} N_{SB}$$

- Background subtraction is done both on N^{ij} and N^{ij}_{SS}

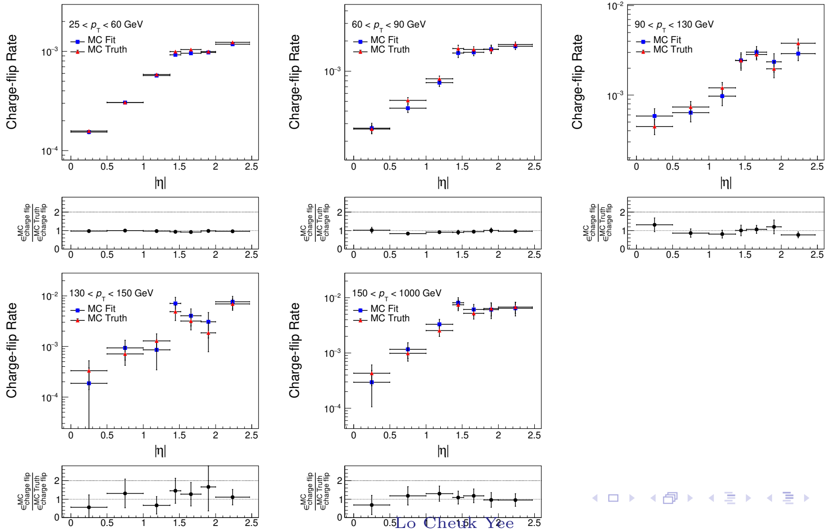
Likelihood Method : Result for Charge Flip Rate (statistical error only)

- Results by likelihood method from data, $\epsilon_{\text{lik,data}}$
- The error is statistical only, from likelihood method, $\sigma_{\text{lik,data}}$.



Likelihood Method : MC Truth Validation

- Results by likelihood method from MC (blue points)
- Results by MC truth (red points)

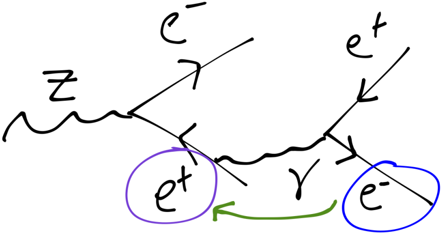


Likelihood Method : MC Truth Matching

- It is a complicated part, because we do not know the original charge of the reconstructed electron for some cases.
- The reconstructed electrons match the truth particle by the smallest ΔR ($\Delta R < 0.1$).
- No match for reconstructed electrons if no any truth particle is inside $\Delta R < 0.1$. (cannot find the original charge)
- If the truth particle is matched, the truth particle is not electron. (fake lepton, not charge flip)

Likelihood Method : MC Truth Matching

- If the truth particle is electron, the (grand)mother particle is not Z Boson. (ignore it)
- If (grand)mother particle is Z Boson, the daughter of the Z Boson is not electron. (ignore it)
- If the daughter of the Z Boson is electron, the charge of that electron is the original charge.



Likelihood Method : Systematic uncertainties due to likelihood method

For each bin, the systematic uncertainties due to likelihood method are estimated by the difference between the likelihood method and the MC truth method.
For MC,

$$\sigma_{\text{truth,MC}} = \left|\epsilon_{\text{lik,MC}} - \epsilon_{\text{MC truth}}\right|$$

For data,

$$\sigma_{\text{truth,data}} = \epsilon_{\text{lik,data}} \times \frac{\sigma_{\text{truth,MC}}}{\epsilon_{\text{lik,MC}}}$$

Likelihood Method : Systematic uncertainties due to background substraction

Nominal:

- Central region: 80 - 100 GeV, Sideband width: 20 GeV

Variations:

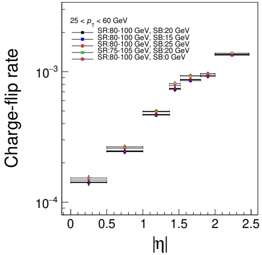
- Central region: 80 - 100 GeV, Sideband width: 15 GeV
- Central region: 80 - 100 GeV, Sideband width: 25 GeV
- Central region: 75 - 105 GeV, Sideband width: 20 GeV
- Central region: 80 - 100 GeV, no background subtraction

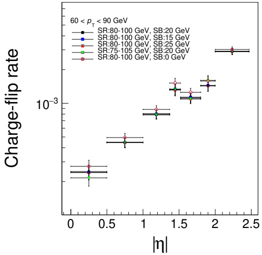
For each bin, the largest deviation from the nominal among these variations is the systematic uncertainty due to background substraction.

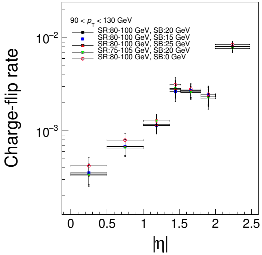
$$\sigma_{\text{bgk}} = max\{|\sigma_{\text{nominal}} - \sigma_{\text{variation}}|\}$$

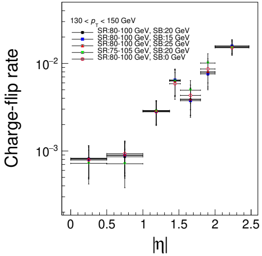
Likelihood Method : Result for different variation

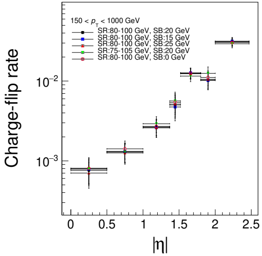
- Results for different variations











Likelihood Method : Total uncertainties

$$\sigma_{\text{sys}} = \sqrt{\sigma^2_{\text{truth}} + \sigma^2_{\text{bgk}}}$$

$$\sigma_{\text{tot}} = \sqrt{\sigma^2_{\text{lik}} + \sigma^2_{\text{sys}}}$$

Likelihood Method : MC Validation Plots

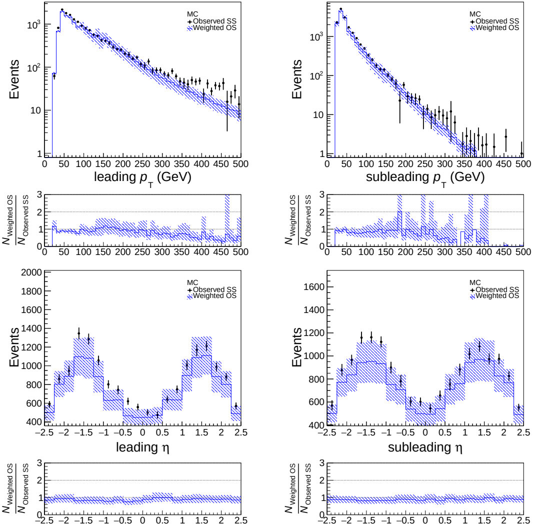


Figure: The comparison between the weighted OS events and the SS events, with different variables.

Likelihood Method : MC Validation Plots

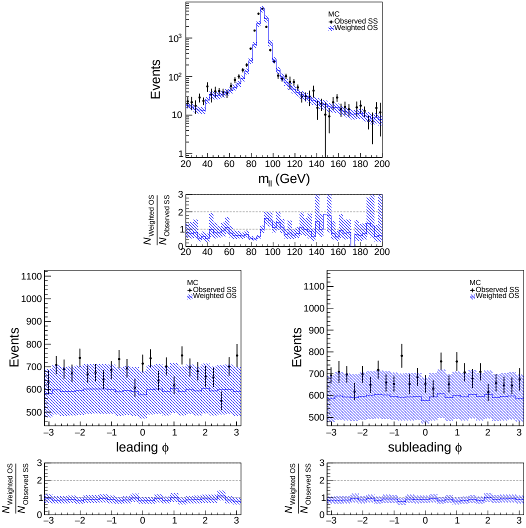


Figure: The comparison between the weighted OS events and the SS events, with different variables.

Fake Lepton Background : Matrix Method

Fake Lepton Background : Matrix Method

We can generalize the one-lepton case to the two-leptons case.

$$\begin{pmatrix} N_{TT} \\ N_{TL} \\ N_{LT} \\ N_{LL} \end{pmatrix} = \begin{pmatrix} \epsilon_1\epsilon_2 & \epsilon_1 f_2 & f_1\epsilon_2 & f_1 f_2 \\ \epsilon_1\bar{\epsilon_2} & \epsilon_1\bar{f_2} & f_1\bar{\epsilon_2} & f_1\bar{f_2} \\ \bar{\epsilon_1}\epsilon_2 & \bar{\epsilon_1}f_2 & \bar{f_1}\epsilon_2 & \bar{f_1}f_2 \\ \bar{\epsilon_1}\bar{\epsilon_2} & \bar{\epsilon_1}\bar{f_2} & \bar{f_1}\bar{\epsilon_2} & \bar{f_1}\bar{f_2} \end{pmatrix} \begin{pmatrix} N_{RR} \\ N_{RF} \\ N_{FR} \\ N_{FF} \end{pmatrix}$$

where ϵ_1 is the probability that a leading real lepton passes the signal selection (i.e. tight lepton), ϵ_2 is the probability that a subleading real lepton passes the signal selection (i.e. tight lepton), etc.

Fake Lepton Background : Matrix Method

We can find N_{RF}, N_{FR}, N_{FF} by inverting the matrix.

$$\begin{pmatrix} 0 \\ N_{RF} \\ N_{FR} \\ N_{FF} \end{pmatrix} = \begin{pmatrix} 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} N_{RR} \\ N_{RF} \\ N_{FR} \\ N_{FF} \end{pmatrix}$$

$$= \begin{pmatrix} 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} \epsilon_1\epsilon_2 & \epsilon_1 f_2 & f_1\epsilon_2 & f_1 f_2 \\ \epsilon_1\bar{\epsilon_2} & \epsilon_1\bar{f_2} & f_1\bar{\epsilon_2} & f_1\bar{f_2} \\ \bar{\epsilon_1}\epsilon_2 & \bar{\epsilon_1}f_2 & \bar{f_1}\epsilon_2 & \bar{f_1}f_2 \\ \bar{\epsilon_1}\bar{\epsilon_2} & \bar{\epsilon_1}\bar{f_2} & \bar{f_1}\bar{\epsilon_2} & \bar{f_1}\bar{f_2} \end{pmatrix}^{-1} \begin{pmatrix} N_{TT} \\ N_{TL} \\ N_{LT} \\ N_{LL} \end{pmatrix}$$

Fake Lepton Background : Matrix Method

Then, we can find the number of tight-tight leptons due to the fake leptons, N'_{TT}

$$\begin{pmatrix} N'_{TT} \\ N'_{TL} \\ N'_{LT} \\ N'_{LL} \end{pmatrix} = \begin{pmatrix} \epsilon_1\epsilon_2 & \epsilon_1 f_2 & f_1\epsilon_2 & f_1 f_2 \\ \epsilon_1\bar{\epsilon_2} & \epsilon_1\bar{f_2} & f_1\bar{\epsilon_2} & f_1\bar{f_2} \\ \bar{\epsilon_1}\epsilon_2 & \bar{\epsilon_1}f_2 & \bar{f_1}\epsilon_2 & \bar{f_1}f_2 \\ \bar{\epsilon_1}\bar{\epsilon_2} & \bar{\epsilon_1}\bar{f_2} & \bar{f_1}\bar{\epsilon_2} & \bar{f_1}\bar{f_2} \end{pmatrix} \begin{pmatrix} 0 \\ N_{RF} \\ N_{FR} \\ N_{FF} \end{pmatrix}$$

$$= \begin{pmatrix} \epsilon_1\epsilon_2 & \epsilon_1 f_2 & f_1\epsilon_2 & f_1 f_2 \\ \epsilon_1\bar{\epsilon_2} & \epsilon_1\bar{f_2} & f_1\bar{\epsilon_2} & f_1\bar{f_2} \\ \bar{\epsilon_1}\epsilon_2 & \bar{\epsilon_1}f_2 & \bar{f_1}\epsilon_2 & \bar{f_1}f_2 \\ \bar{\epsilon_1}\bar{\epsilon_2} & \bar{\epsilon_1}\bar{f_2} & \bar{f_1}\bar{\epsilon_2} & \bar{f_1}\bar{f_2} \end{pmatrix} \begin{pmatrix} 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix}$$

$$\begin{pmatrix} \epsilon_1\epsilon_2 & \epsilon_1 f_2 & f_1\epsilon_2 & f_1 f_2 \\ \epsilon_1\bar{\epsilon_2} & \epsilon_1\bar{f_2} & f_1\bar{\epsilon_2} & f_1\bar{f_2} \\ \bar{\epsilon_1}\epsilon_2 & \bar{\epsilon_1}f_2 & \bar{f_1}\epsilon_2 & \bar{f_1}f_2 \\ \bar{\epsilon_1}\bar{\epsilon_2} & \bar{\epsilon_1}\bar{f_2} & \bar{f_1}\bar{\epsilon_2} & \bar{f_1}\bar{f_2} \end{pmatrix}^{-1} \begin{pmatrix} N_{TT} \\ N_{TL} \\ N_{LT} \\ N_{LL} \end{pmatrix}$$

Method for measuring real efficiencies

Control Region for Real Efficiencies

It uses the Z tag-and-probe method to measure the real efficiencies of electrons and muons.

Pre-selection:

- Trigger requirement
- exactly 2 baseline leptons
- same flavour and opposite charge ($Z \to ee$, $Z \to \mu\mu$)
- $80 < m_{ll} < 100$
- $p_T > 20$
- $|\eta| < 2.47$ for electron, $|\eta| < 2.5$ for muon

Requirements for tag lepton

- $p_T > 25$
- pass signal requirement

Permutation of tag and probe

Check the probe lepton:
Tight lepton: pass signal requirement
Loose lepton: pass baseline requirement (include tight lepton)
4 possible cases: (slightly simplified)

- TL: fill loose hist by the subleading lepton
- LT: fill loose hist by the leading lepton
- TT: fill both loose and tight hist by the both leading and subleading lepton
- LL: do nothing

The real eff is calculated by

$$\epsilon = \frac{N_{\text{tight}}}{N_{\text{loose}}}$$

Fake Lepton Background : Results of Real Efficiencies

The method for measuring the real efficiencies is described in the backup slides.

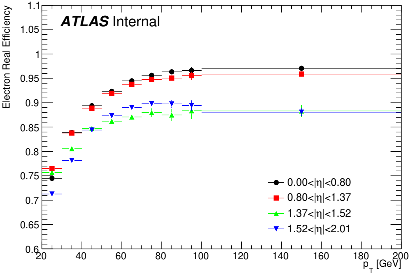


Figure: Electron real efficiency

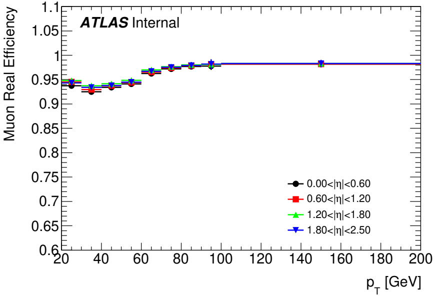


Figure: Muon real efficiency

Method for measuring fake efficiencies

Control Region for fake eff for muon

It uses the heavy-flavour fake-enriched region to measure the fake efficiencies of electrons and muons.
For muon fake eff, it uses the muon-muon events.
Pre-selection for muon-muon events:

- Trigger requirement
- exactly 2 baseline muons
- SS
- at least 1 jet
- at least 1 b-jet
- $p_T > 20$
- $|\eta| < 2.5$

Requirements for the tag lepton

- $p_T > 40$
- pass signal requirement

Control Region for fake eff for electron

For electron fake eff, it uses the muon-electron events.
Pre-selection for muon-electron events:

- Trigger requirement
- exactly 1 baseline electron and 1 baseline muon
- SS
- at least 1 jet
- at least 1 b-jet
- $p_T > 20$
- $|\eta| < 2.5$

Requirements for the tag lepton

- muon
- $p_T > 40$
- pass signal requirement

Calculate the fake eff

The fake eff is calculated by

$$\epsilon = \frac{N_{\text{tight}}^{\text{data}} - N_{\text{tight}}^{\text{prompt MC}}}{N_{\text{loose}}^{\text{data}} - N_{\text{loose}}^{\text{prompt MC}}}$$

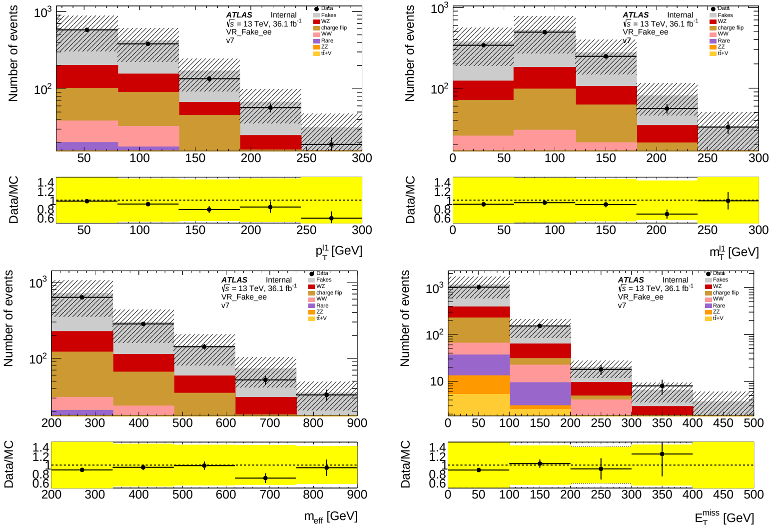
The prompt lepton is estimated from MC by using the truth information. The prompt lepton is defined by the MCTruthClassifier, with the ParticleType = IsoElectron or IsoMuon.

Validation plots for fake lepton background

ee channel

	Number of events	
Fakes	$860.738787 \pm 14.359660 \pm 630.863451$ (9663)	
WZ	201.069385 ± 3.094538 (39857)	
charge flip	167.954322 ± 1.110819 (86972)	
WW	45.176809 ± 0.401964 (21140)	
Rare	30.757392 ± 3.403960 (1268)	
ZZ	8.351345 ± 0.345416 (6466)	
$t\bar{t} + V$	8.346022 ± 0.254296 (4158)	
Total BG	$1322.394062 \pm 15.130843 \pm 630.863451$ (169524)	
Data	1201	

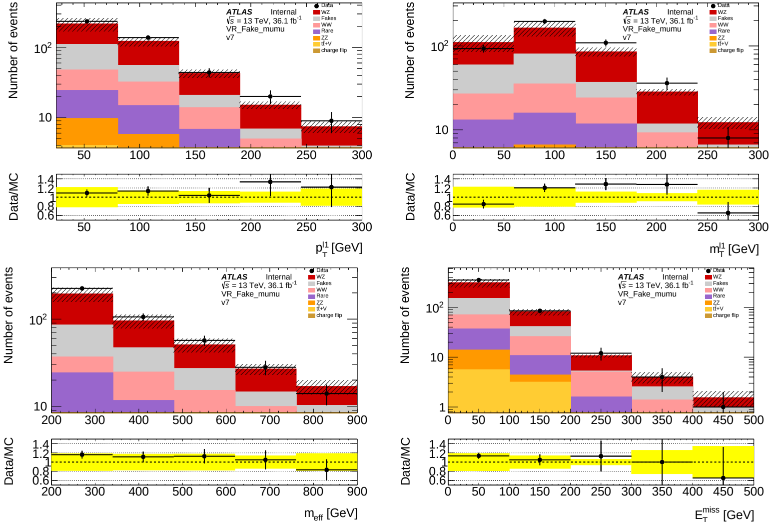
ee channel


ATLAS Internal
$\sqrt{s}$ = 13 TeV, 36.1 fb^{-1}
VR_Fake_ee
v7
Data
Fakes
WZ
charge flip
WW
Rare
ZZ
$t\bar{t}$+V
Number of events
Data/MC
p_T^{l1} [GeV]
m_T^{l1} [GeV]
m_{eff} [GeV]
E_T^{miss} [GeV]

mumu channel

	Number of events	
WZ	209.219829 ± 2.994737 (42458)	
Fakes	$96.203916 \pm 5.013796 \pm 70.510979$ (1160)	
WW	53.675707 ± 0.409851 (25092)	
Rare	30.460547 ± 4.359663 (1361)	
ZZ	9.474511 ± 0.534342 (7674)	
$t\bar{t}+V$	9.369165 ± 0.284944 (4801)	
charge flip	0.000000 ± 0.000000 (0)	
Total BG	$408.403674 \pm 7.324477 \pm 70.510979$ (82546)	
Data	454	

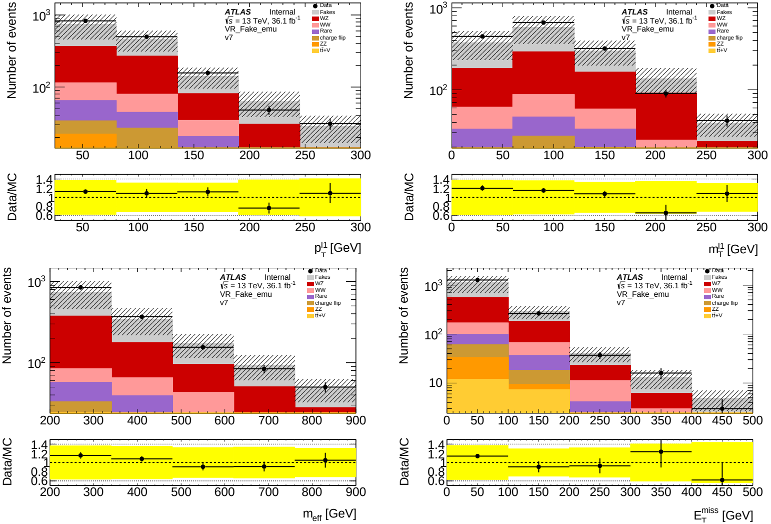
mumu channel



emu channel

	Number of events	
Fakes	$702.995427 \pm 13.784203 \pm 515.248212$ (8544)	
WZ	516.828375 ± 33.696304 (94571)	
WW	110.280002 ± 0.578575 (51615)	
Rare	58.742111 ± 4.005608 (3037)	
charge flip	36.901490 ± 0.479301 (36998)	
ZZ	23.391749 ± 0.482387 (16698)	
$t\bar{t} + V$	20.739252 ± 0.424107 (10526)	
Total BG	$1469.878407 \pm 36.639692 \pm 515.248212$ (221989)	
Data	1593	

emu channel


ATLAS Internal
√s = 13 TeV, 36.1 fb-1
VR_Fake_emu
v7
Data
Fakes
WZ
WW
Rare
charge flip
ZZ
tt+V
Number of events
Data/MC
p_T^l1 [GeV]
m_T^l1 [GeV]
m_eff [GeV]
E_T^miss [GeV]

Pre-selection plots

Yields in pre-selection

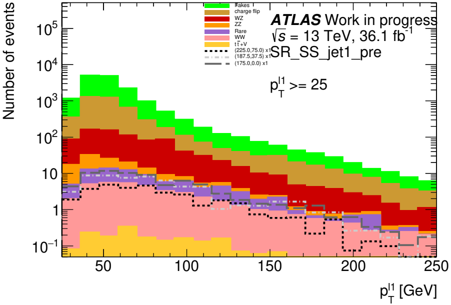
	Number of events
Fakes	$11580.965417 \pm 45.775452$ (107219)
charge flip	3622.756937 ± 2.810481 (3375964)
WZ	691.333566 ± 34.238864 (68626)
ZZ	66.945860 ± 1.049840 (21749)
Rare	47.371873 ± 4.082859 (1662)
WW	38.128141 ± 0.388221 (15666)
$t\bar{t}+V$	1.971267 ± 0.138488 (671)
Total BG	$16049.473060 \pm 57.389305$ (3591557)
(225.0,75.0)	33.08 ± 1.57 (676)
(187.5,37.5)	62.09 ± 3.13 (568)
(175.0,0.0)	74.30 ± 3.57 (556)

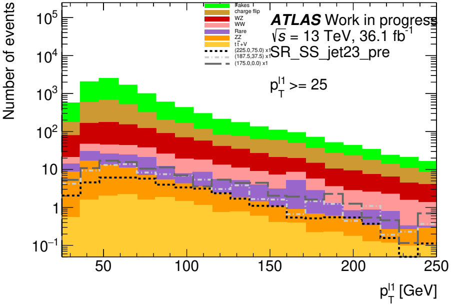
Table: Yields in SRjet1

	Number of events
Fakes	$6848.284248 \pm 36.074557$ (66096)
charge flip	2074.427691 ± 2.680118 (1679673)
WZ	776.282836 ± 5.978666 (147413)
WW	153.455294 ± 0.679752 (72175)
Rare	92.181843 ± 6.338615 (3011)
ZZ	62.932966 ± 1.198123 (35945)
$t\bar{t}+V$	16.375388 ± 0.359456 (6082)
Total BG	$10023.940266 \pm 37.235816$ (2010395)
(225.0,75.0)	45.01 ± 1.76 (937)
(187.5,37.5)	86.02 ± 3.84 (754)
(175.0,0.0)	107.96 ± 5.14 (743)

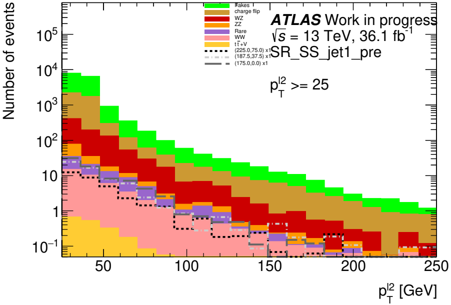
Table: Yields in SRjet23

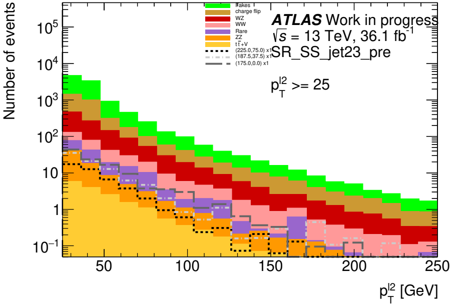
p_T^{l1}


Fakes
charge flip
WZ
ZZ
Rare
WW
$t\bar{t}$+V
(225.0,75.0) x1
(187.5,37.5) x1
(175.0,0.0) x1
ATLAS Work in progress
$\sqrt{s}$ = 13 TeV, 36.1 fb^{-1}
SR_SS_jet1_pre
p_T^{l1} >= 25
Number of events
p_T^{l1} [GeV]

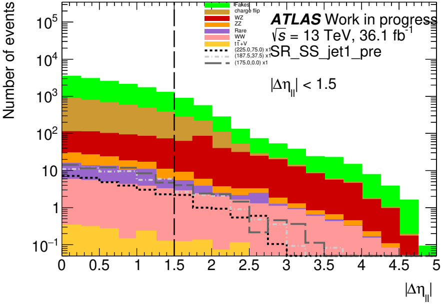

Fakes
charge flip
WZ
WW
Rare
ZZ
$t\bar{t}$+V
(225.0,75.0) x1
(187.5,37.5) x1
(175.0,0.0) x1
ATLAS Work in progress
$\sqrt{s}$ = 13 TeV, 36.1 fb^{-1}
SR_SS_jet23_pre
p_T^{l1} >= 25
Number of events
p_T^{l1} [GeV]

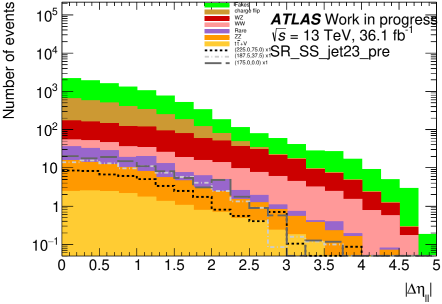
p_T^{l2}


Fakes
charge flip
WZ
ZZ
Rare
WW
$t\bar{t}+V$
(225.0,75.0) x1
(187.5,37.5) x1
(175.0,0.0) x1
ATLAS Work in progress
$\sqrt{s}$ = 13 TeV, 36.1 fb^{-1}
SR_SS_jet1_pre
p_T^{l2} >= 25
Number of events
p_T^{l2} [GeV]

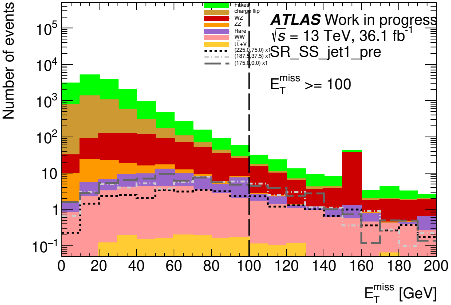

Fakes
charge flip
WZ
WW
Rare
ZZ
$t\bar{t}+V$
(225.0,75.0) x1
(187.5,37.5) x1
(175.0,0.0) x1
ATLAS Work in progress
$\sqrt{s}$ = 13 TeV, 36.1 fb^{-1}
SR_SS_jet23_pre
p_T^{l2} >= 25
Number of events
p_T^{l2} [GeV]

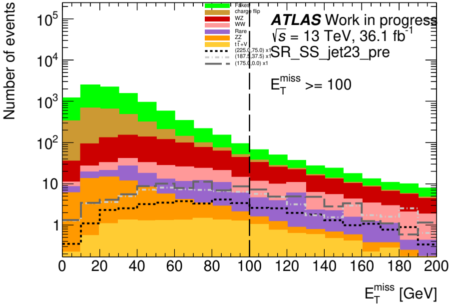
$|\Delta\eta_{ll}|$


Fakes
charge flip
WZ
ZZ
Rare
WW
t t̄+V
(225.0,75.0) x1
(187.5,37.5) x1
(175.0,0.0) x1
ATLAS Work in progress
√s = 13 TeV, 36.1 fb-1
SR_SS_jet1_pre
|Δη_ll| < 1.5
Number of events
|Δη_ll|

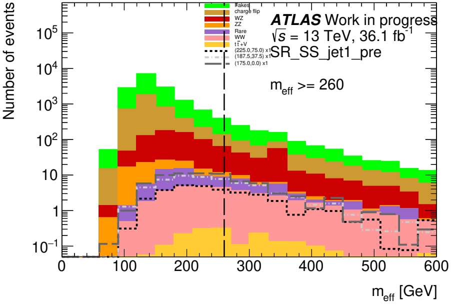

Fakes
charge flip
WZ
WW
Rare
ZZ
t t̄+V
(225.0,75.0) x1
(187.5,37.5) x1
(175.0,0.0) x1
ATLAS Work in progress
√s = 13 TeV, 36.1 fb-1
SR_SS_jet23_pre
Number of events
|Δη_ll|

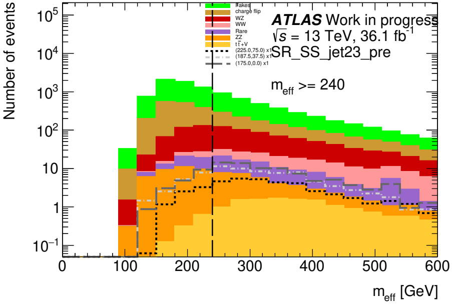
E_T^{miss}


ATLAS Work in progress
√s = 13 TeV, 36.1 fb-1
SR_SS_jet1_pre
ETmiss >= 100
Fakes
charge flip
WZ
ZZ
Rare
WW
tt̄+V
(225.0,75.0) x1
(187.5,37.5) x1
(175.0,0.0) x1
Number of events
ETmiss [GeV]

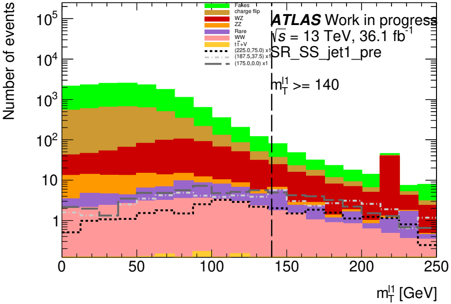

ATLAS Work in progress
√s = 13 TeV, 36.1 fb-1
SR_SS_jet23_pre
ETmiss >= 100
Fakes
charge flip
WZ
WW
Rare
ZZ
tt̄+V
(225.0,75.0) x1
(187.5,37.5) x1
(175.0,0.0) x1
Number of events
ETmiss [GeV]

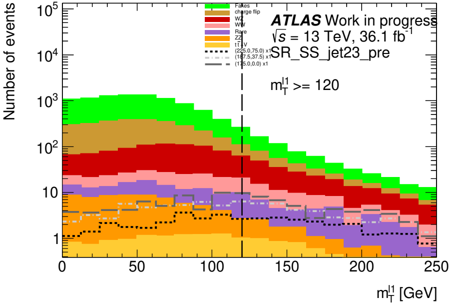
m_{eff}


Fakes
charge flip
WZ
ZZ
Rare
WW
$t\bar{t}$+V
(225.0,75.0) x1
(187.5,37.5) x1
(175.0,0.0) x1
ATLAS Work in progress
$\sqrt{s}$ = 13 TeV, 36.1 fb^{-1}
SR_SS_jet1_pre
m_{eff} >= 260
Number of events
m_{eff} [GeV]

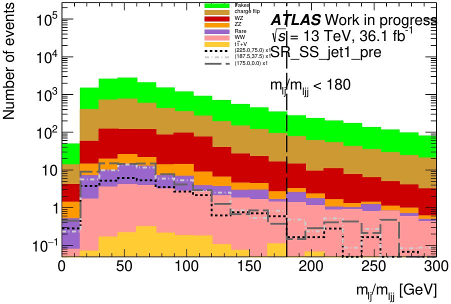

Fakes
charge flip
WZ
WW
Rare
ZZ
$t\bar{t}$+V
(225.0,75.0) x1
(187.5,37.5) x1
(175.0,0.0) x1
ATLAS Work in progress
$\sqrt{s}$ = 13 TeV, 36.1 fb^{-1}
SR_SS_jet23_pre
m_{eff} >= 240
Number of events
m_{eff} [GeV]

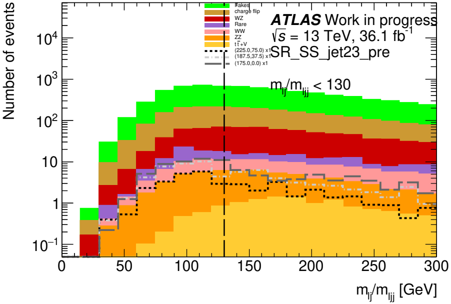
m_{T}^{l1}


ATLAS Work in progress
√s = 13 TeV, 36.1 fb-1
SR_SS_jet1_pre
mT l1 >= 140
Fakes
charge flip
WZ
ZZ
Rare
WW
tt+V
(225.0,75.0) x1
(187.5,37.5) x1
(175.0,0.0) x1
Number of events
mT l1 [GeV]

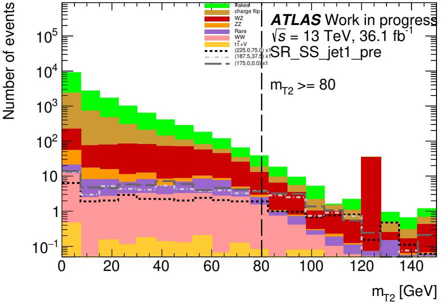

ATLAS Work in progress
√s = 13 TeV, 36.1 fb-1
SR_SS_jet23_pre
mT l1 >= 120
Fakes
charge flip
WZ
WW
Rare
ZZ
tt+V
(225.0,75.0) x1
(187.5,37.5) x1
(175.0,0.0) x1
Number of events
mT l1 [GeV]

m_{lj}/m_{ljj}

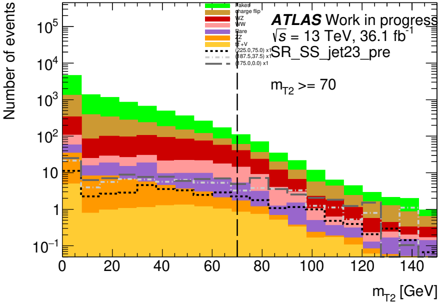

ATLAS Work in progress
√s = 13 TeV, 36.1 fb-1
SR_SS_jet1_pre
mlj/mljj < 180
Fakes
charge flip
WZ
ZZ
Rare
WW
tt̄+V
(225.0,75.0) x1
(187.5,37.5) x1
(175.0,0.0) x1
Number of events
mlj/mljj [GeV]


ATLAS Work in progress
√s = 13 TeV, 36.1 fb-1
SR_SS_jet23_pre
mlj/mljj < 130
Fakes
charge flip
WZ
Rare
WW
ZZ
tt̄+V
(225.0,75.0) x1
(187.5,37.5) x1
(175.0,0.0) x1
Number of events
mlj/mljj [GeV]

m_{T2}



Number of events
Fakes
charge flip
WZ
ZZ
Rare
WW
$t\bar{t}$+V
(225.0,75.0) x1
(187.5,37.5) x1
(175.0,0.0) x1
ATLAS Work in progress
$\sqrt{s}$ = 13 TeV, 36.1 fb^{-1}
SR_SS_jet1_pre
m_{T2} >= 80
m_{T2} [GeV]



Number of events
Fakes
charge flip
WZ
WW
Rare
ZZ
$t\bar{t}$+V
(225.0,75.0) x1
(187.5,37.5) x1
(175.0,0.0) x1
ATLAS Work in progress
$\sqrt{s}$ = 13 TeV, 36.1 fb^{-1}
SR_SS_jet23_pre
m_{T2} >= 70
m_{T2} [GeV]

N-1 plots

Yields in SR

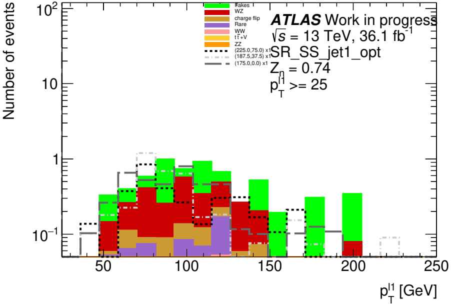
	Number of events	Significance
Fakes	3.295434 ± 0.819175 (24)	
WZ	2.176292 ± 0.397871 (257)	
charge flip	0.472185 ± 0.052737 (265)	
Rare	0.443536 ± 0.111301 (56)	
WW	0.165504 ± 0.023455 (67)	
$t\bar{t}+V$	0.124898 ± 0.046227 (36)	
ZZ	0.055330 ± 0.027713 (31)	
Total BG	6.733178 ± 0.920855 (736)	
(225.0,75.0)	3.33 ± 0.60 (60)	**0.74**
(187.5,37.5)	3.77 ± 0.95 (31)	0.86
(175.0,0.0)	4.29 ± 0.73 (36)	0.98

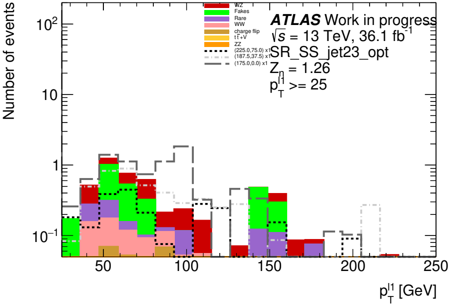
Table: Yields in SRjet1

	Number of events	Significance
WZ	1.848838 ± 0.273025 (319)	
Fakes	1.764693 ± 0.709215 (20)	
Rare	0.731015 ± 0.195114 (48)	
WW	0.514488 ± 0.036878 (235)	
charge flip	0.267485 ± 0.029086 (274)	
$t\bar{t}+V$	0.141679 ± 0.030772 (67)	
ZZ	0.067226 ± 0.024995 (24)	
Total BG	5.335425 ± 0.787005 (987)	
(225.0,75.0)	2.35 ± 0.34 (58)	0.57
(187.5,37.5)	4.72 ± 0.74 (47)	**1.26**
(175.0,0.0)	8.60 ± 1.51 (58)	2.24

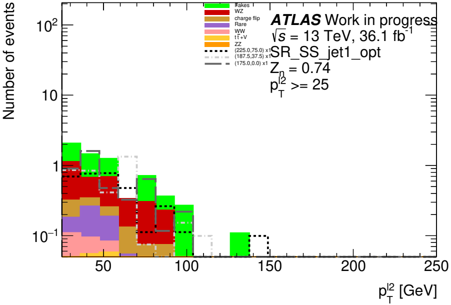
Table: Yields in SRjet23

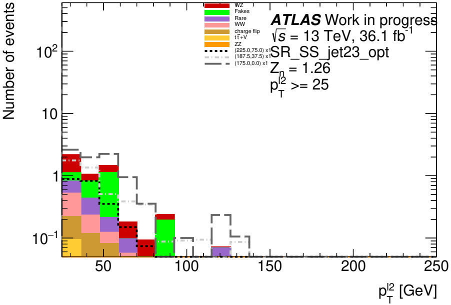
p_T^{l1}


Number of events
10^2
10
1
10^{-1}
Fakes
WZ
charge flip
Rare
WW
$t\bar{t}+V$
ZZ
(225.0,75.0) x1
(187.5,37.5) x1
(175.0,0.0) x1
ATLAS Work in progress
$\sqrt{s}$ = 13 TeV, 36.1 fb^{-1}
SR_SS_jet1_opt
Z_n = 0.74
p_T^{l1} >= 25
50
100
150
200
250
p_T^{l1} [GeV]

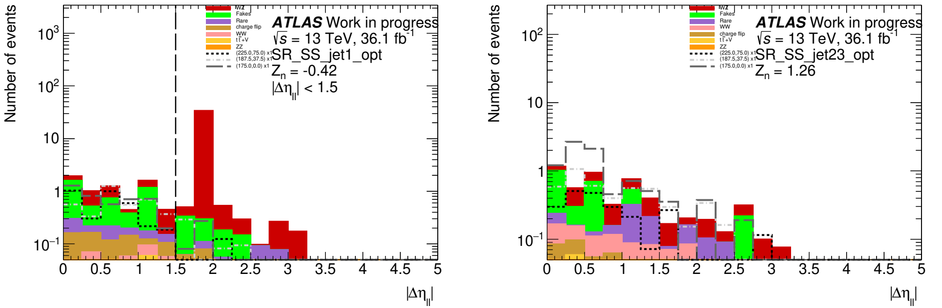

Number of events
10^2
10
1
10^{-1}
WZ
Fakes
Rare
WW
charge flip
$t\bar{t}+V$
ZZ
(225.0,75.0) x1
(187.5,37.5) x1
(175.0,0.0) x1
ATLAS Work in progress
$\sqrt{s}$ = 13 TeV, 36.1 fb^{-1}
SR_SS_jet23_opt
Z_n = 1.26
p_T^{l1} >= 25
50
100
150
200
250
p_T^{l1} [GeV]

p_T^{l2}

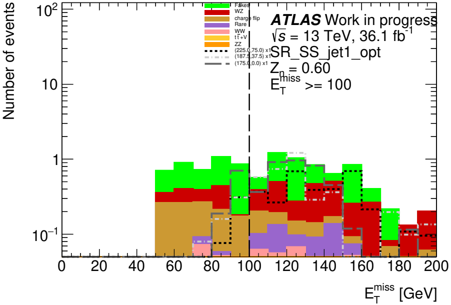

Fakes
WZ
charge flip
Rare
WW
t t̄+V
ZZ
(225.0,75.0) x1
(187.5,37.5) x1
(175.0,0.0) x1
ATLAS Work in progress
√s = 13 TeV, 36.1 fb-1
SR_SS_jet1_opt
Zn = 0.74
pT l2 >= 25
Number of events
pT l2 [GeV]

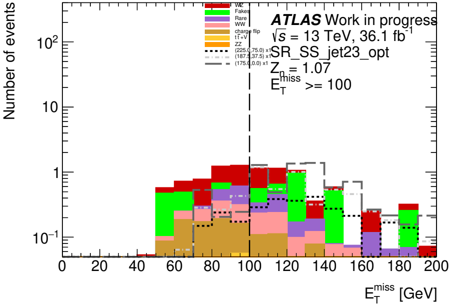

WZ
Fakes
Rare
WW
charge flip
t t̄+V
ZZ
(225.0,75.0) x1
(187.5,37.5) x1
(175.0,0.0) x1
ATLAS Work in progress
√s = 13 TeV, 36.1 fb-1
SR_SS_jet23_opt
Zn = 1.26
pT l2 >= 25
Number of events
pT l2 [GeV]

$|\Delta\eta_{ll}|$

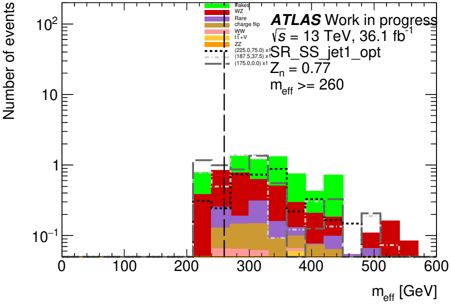

Number of events
WZ
Fakes
Rare
charge flip
WW
tt̄+V
ZZ
(225.0,75.0) x1
(187.5,37.5) x1
(175.0,0.0) x1
ATLAS Work in progress
√s = 13 TeV, 36.1 fb-1
SR_SS_jet1_opt
Zn = -0.42
|Δηll| < 1.5
|Δηll|
SR_SS_jet23_opt
Zn = 1.26

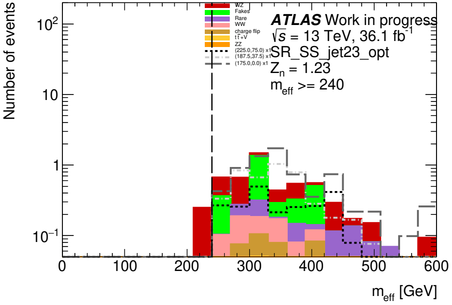
$E_{\mathrm{T}}^{\mathrm{miss}}$



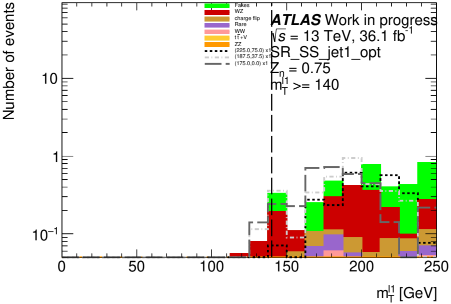


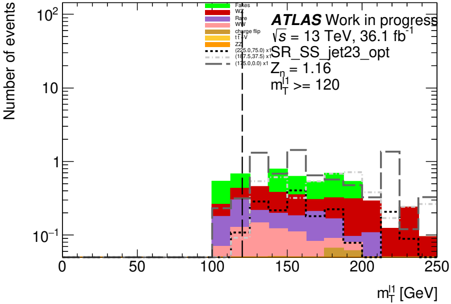
m_{eff}


Fakes
WZ
Rare
charge flip
WW
$t\bar{t}$+V
ZZ
(225.0,75.0) x1
(187.5,37.5) x1
(175.0,0.0) x1
ATLAS Work in progress
$\sqrt{s}$ = 13 TeV, 36.1 fb^{-1}
SR_SS_jet1_opt
Z_n = 0.77
m_{eff} >= 260
Number of events
m_{eff} [GeV]

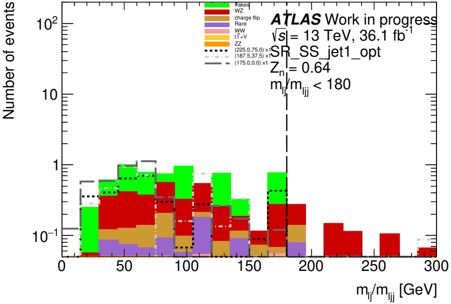

WZ
Fakes
Rare
WW
charge flip
$t\bar{t}$+V
ZZ
(225.0,75.0) x1
(187.5,37.5) x1
(175.0,0.0) x1
ATLAS Work in progress
$\sqrt{s}$ = 13 TeV, 36.1 fb^{-1}
SR_SS_jet23_opt
Z_n = 1.23
m_{eff} >= 240
Number of events
m_{eff} [GeV]

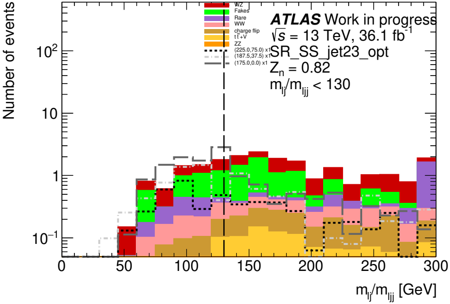
m_{T}^{l1}


Fakes
WZ
charge flip
Rare
WW
$t\bar{t}$+V
ZZ
(225.0,75.0) x1
(187.5,37.5) x1
(175.0,0.0) x1
ATLAS Work in progress
$\sqrt{s}$ = 13 TeV, 36.1 fb^{-1}
SR_SS_jet1_opt
Z_n = 0.75
m_T^{l1} >= 140
Number of events
m_T^{l1} [GeV]
0
50
100
150
200
250
10^{-1}
1
10

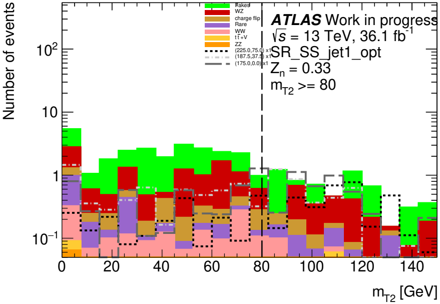

Fakes
WZ
Rare
WW
charge flip
$t\bar{t}$+V
ZZ
(225.0,75.0) x1
(187.5,37.5) x1
(175.0,0.0) x1
ATLAS Work in progress
$\sqrt{s}$ = 13 TeV, 36.1 fb^{-1}
SR_SS_jet23_opt
Z_n = 1.16
m_T^{l1} >= 120
Number of events
m_T^{l1} [GeV]
0
50
100
150
200
250
10^{-1}
1
10
10^2

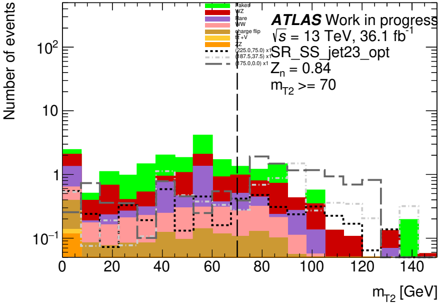
m_{lj}/m_{ljj}


Number of events
Fakes
WZ
charge flip
Rare
WW
tt̄+V
ZZ
(225.0,75.0) x1
(187.5,37.5) x1
(175.0,0.0) x1
ATLAS Work in progress
√s = 13 TeV, 36.1 fb-1
SR_SS_jet1_opt
Zn = 0.64
mlj/mljj < 180
mlj/mljj [GeV]


Number of events
WZ
Fakes
Rare
WW
charge flip
tt̄+V
ZZ
(225.0,75.0) x1
(187.5,37.5) x1
(175.0,0.0) x1
ATLAS Work in progress
√s = 13 TeV, 36.1 fb-1
SR_SS_jet23_opt
Zn = 0.82
mlj/mljj < 130
mlj/mljj [GeV]

m_{T2}


Fakes
WZ
charge flip
Rare
WW
tt̄+V
ZZ
(225.0,75.0) x1
(187.5,37.5) x1
(175.0,0.0) x1
ATLAS Work in progress
√s = 13 TeV, 36.1 fb⁻¹
SR_SS_jet1_opt
Zn = 0.33
mT2 >= 80
Number of events
mT2 [GeV]


Fakes
WZ
Rare
WW
charge flip
tt̄+V
ZZ
(225.0,75.0) x1
(187.5,37.5) x1
(175.0,0.0) x1
ATLAS Work in progress
√s = 13 TeV, 36.1 fb⁻¹
SR_SS_jet23_opt
Zn = 0.84
mT2 >= 70
Number of events
mT2 [GeV]

Validation Region

Validation Region: Check for Signal Contribution

The signal contribution is below 12% and 10% for VRjet1 and VRjet23 respectively.

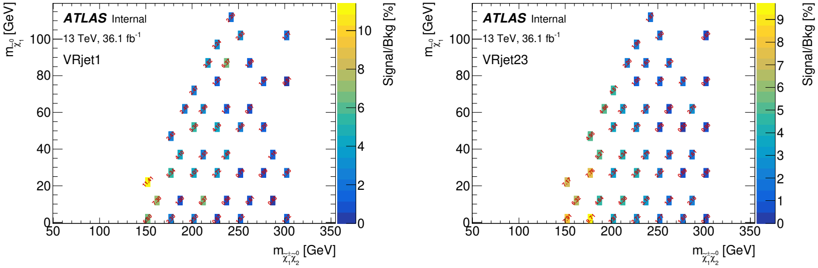


Figure: Percentages of signal contribution are shown for the VRjet1 (left) and VRjet23 (right).

Validation Region: Check for Background Composition

The background compositions for VRjet1 and SRjet1 are similar.

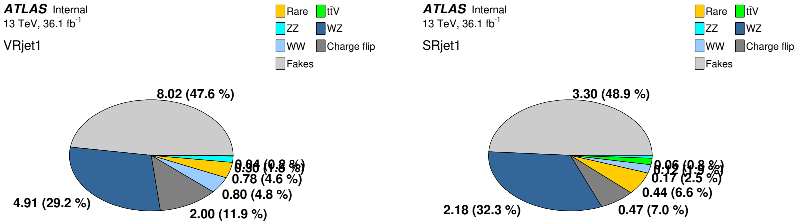


Figure: Background composition for the VRjet1 (left) and SRjet1 (right).

Validation Region: Check for Background Composition

The background compositions for VRjet23 and SRjet23 are similar.

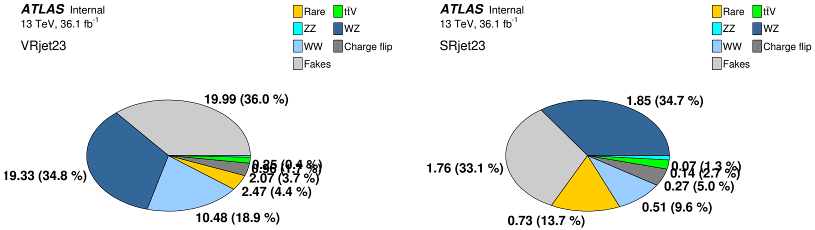
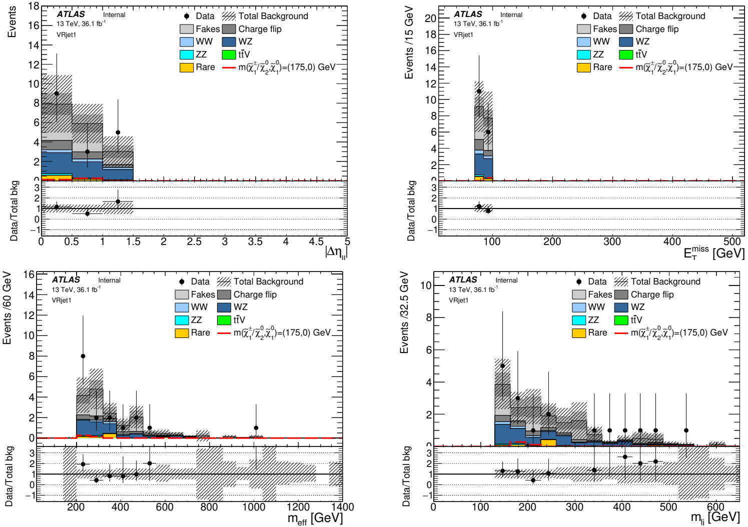
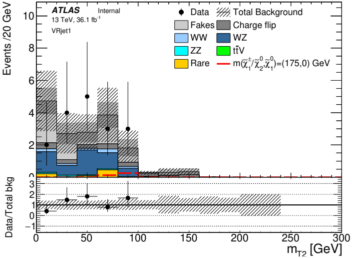


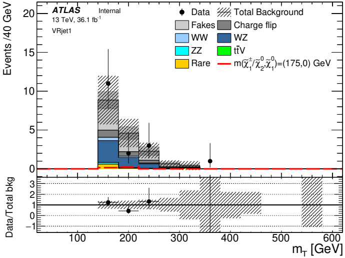
Figure: Background composition for the VRjet23 (left) and SRjet23 (right).

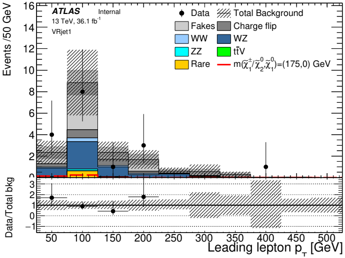
Validation Region : Plots for different variables (VRjet1)

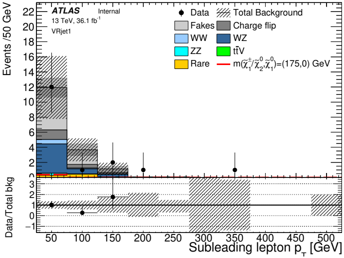


Validation Region : Plots for different variables (VRjet1)

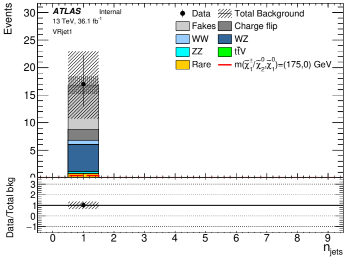




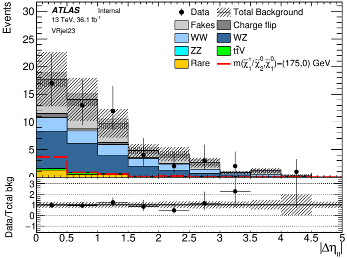


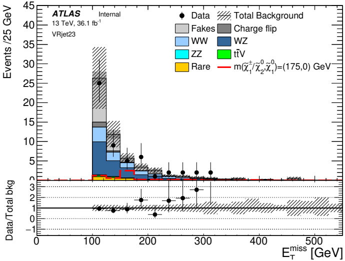


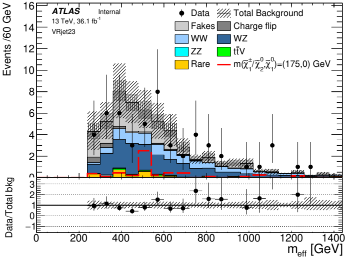
Validation Region : Plots for different variables (VRjet1)

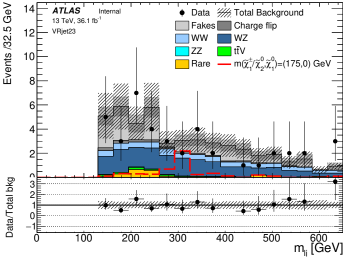


Validation Region : Plots for different variables (VRjet23)

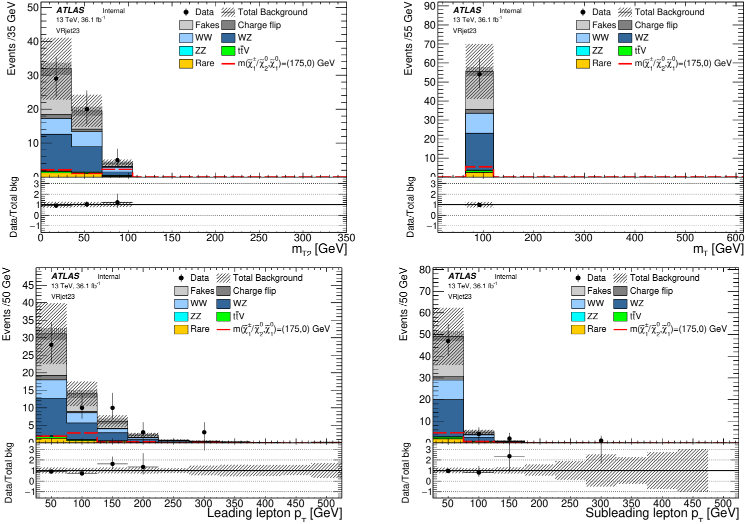








Validation Region : Plots for different variables (VRjet23)



Validation Region : Plots for different variables (VRjet23)