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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Introduction

Standard Model : Fundamental Particles

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

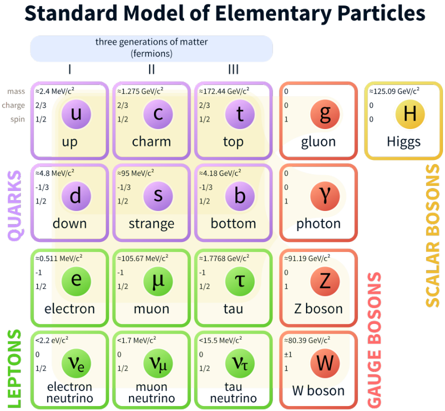


Figure: The “periodic” table for all fundamental particles in SM.

Standard Model : Fundamental Interaction

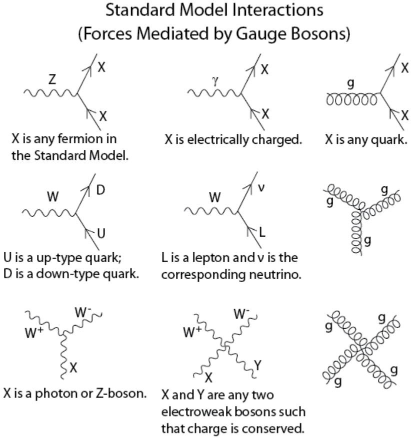


Figure: All allowed fundamental Feynman vertices in SM, except higgs-related vertices.

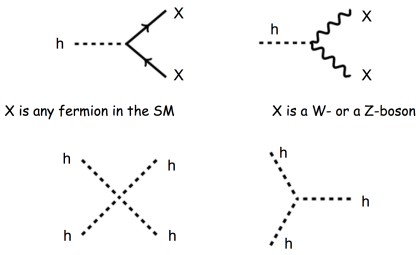


Figure: All allowed fundamental higgs-related Feynman vertices in SM.

Standard Model : Limitation

- SM cannot explain gravity.
- SM cannot explain the nature of dark matter.
- The hierarchy problem
  - Why the weak force is stronger than the gravity by 10^{24}.
  - Why the Higgs mass is much lighter than the Planck mass.
  - At very high energy scale, the Higgs boson mass is strongly sensitive to quantum corrections.

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.

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.

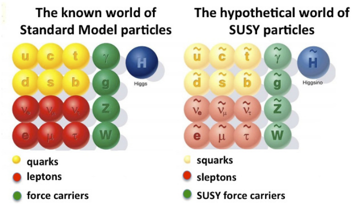


Figure: The particles in Standard Model and their corresponding superpartners and their names.

Supersymmetry : Superpartners

- In the MSSM, one more neutral Higgs filed H and two more charged Higgs fileds H^+, H^- needed to be introduced.
- In SM electro-weak bosons, there are in total 4 neutral bosons: γ, Z, h and H, and 4 charged bosons: W^+, W^-, H^+ and H^-.
- 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	Neutralinos	$\tilde{\chi}_1^0$, $\tilde{\chi}_2^0$, $\tilde{\chi}_3^0$, $\tilde{\chi}_4^0$	$\frac{1}{2}$	-1
	Z Boson	Z	1	+1				
	Neutral Higgs	h,H	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^+, H^-	0	+1				

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

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.

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

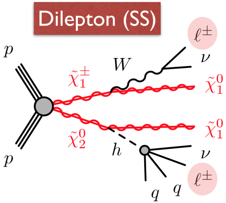
where s is the spin.

Supersymmetry : R-parity

- 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 and is 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 the squarks ($\tilde{q}$) and gluinos ($\tilde{g}$), the masses of gluinos and the first and second generation squarks are suggested to be larger than 1 TeV, while the masses of the third generation squarks are still allowed to be below 1 TeV.
- In this case, the direct pair production of $\tilde{\chi}_1^{\pm}$ and $\tilde{\chi}_2^0$ may be the dominant SUSY production process at the LHC, if the masses of them 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 $\tilde{\chi}_1^0$:
     $\tilde{\chi}_2^0 \rightarrow h + \tilde{\chi}_1^0$

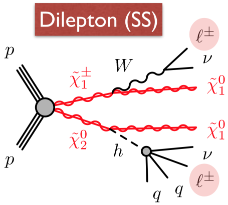
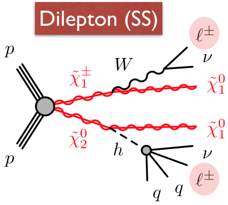


Figure: The Feynman diagram for our Wh same-sign signal scenario.

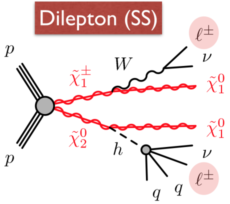
Our Signal Scenario : Decay Processes

- The W boson will further 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, $h \to W^{+}W^{-}$ and $h \to \tau^{+}\tau^{-}$)
- 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 only search for two same-sign(SS) leptons, in order to suppress 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

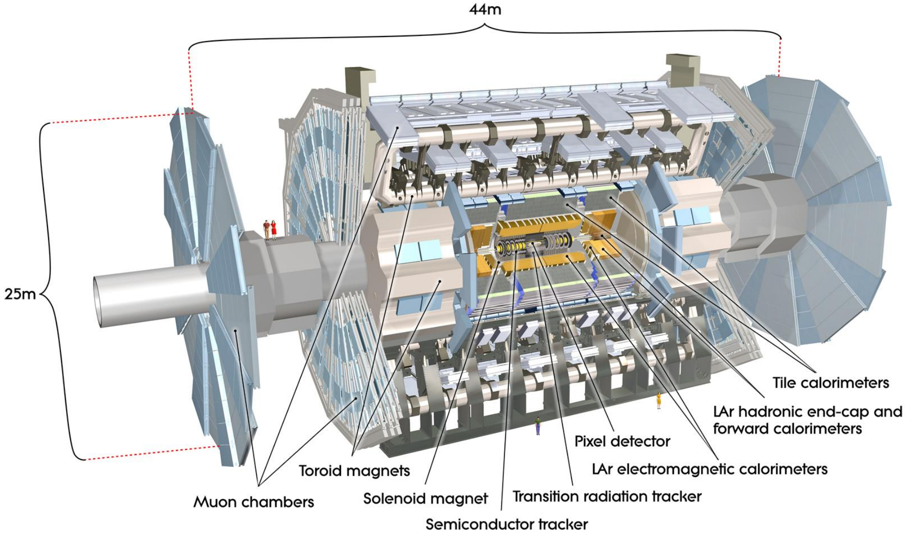
- If the mass difference $(m_{\tilde{\chi}_1^{\pm},\tilde{\chi}_2^0} - m_{\tilde{\chi}_1^0})$ is slightly larger than the Higgs mass, it is called the compressed region.
- In the compressed region, one of the lepton may have low energy, due to the low momentum of the Higgs boson, and hence it may not be detected.
- In this case, there may be originally 3 leptons, but only 2 leptons are detected.
- This allows more decay modes for Higgs boson, which produce two leptons. (For example, $h \to ZZ$)
- Hence, the signal will be more sensitive in the compressed region.

Experimental Setup

Experimental Setup : LHC

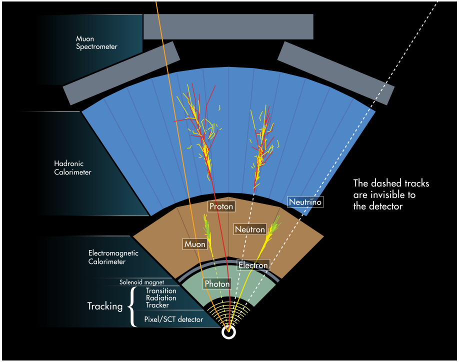
- The Large Hadron Collider (LHC) is the most powerful circular particle accelerator in the world.
- Its circumference is 27 km.
- Two beams of protons will be accelerated in opposite direction to centre-of-mass energy 13 TeV.
- They will be finally collided at the ATLAS detector.

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.

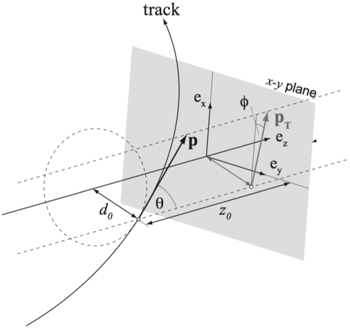


Challenges of Background Estimatation

- Before we search for the signal, we need to understand and estimate the background first.
- Our detector is not perfect. There are two types of background in the data, which is due to the limitation of our detector.
  - Charge flip background
  - Fake lepton background
- They are due to the wrong identification of the particle.

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.

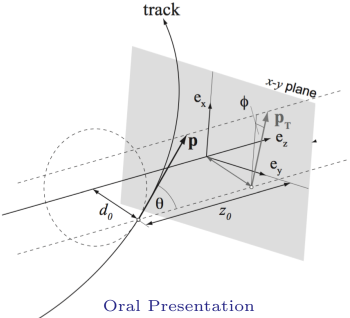


Basic kinematic variables

- 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.



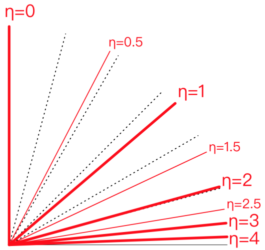
Basic kinematic variables

- The pseudorapidity η is defined by

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

- The values of pseudorapidity η have reflective symmetry about the x-y plane. (Negetive value for $90^\circ < \theta < 180^\circ$)
- The angle separation ΔR of two particles is defined as:

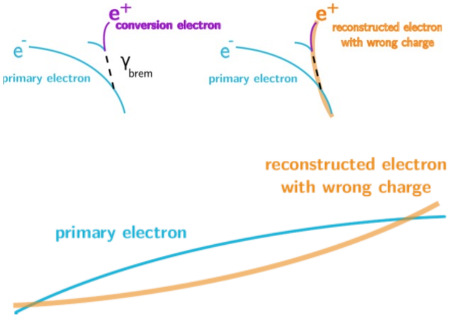
$$\Delta R = \sqrt{(\Delta\phi)^2 + (\Delta\eta)^2} = \sqrt{(\phi_2 - \phi_1)^2 + (\eta_2 - \eta_1)^2}$$



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.



Charge flip Background : charge flip rate

- The probability that the charge of an electron is flipped, called the charge flip rate $\epsilon(p_T, |\eta|)$, depends on the p_T and $|\eta|$ of the electron.
- The charge flip rates are measured by the likelihood method described in the backup slides.
- After getting the charge flip rates, the charge flip background can be found by applying the charge flip rates on the OS events in data.
- The probability that an OS data event becomes a SS data event, which is the charge of one of the leptons is flipped, is given by

$$\begin{aligned} & P(p_T^1, |\eta^1|, p_T^2, |\eta^2|) \\ & = [1 - \epsilon(p_T^1, |\eta^1|)] \cdot \epsilon(p_T^2, |\eta^2|) + [1 - \epsilon(p_T^2, |\eta^2|)] \cdot \epsilon(p_T^1, |\eta^1|) \\ & = (1 - \epsilon_1)\epsilon_2 + (1 - \epsilon_2)\epsilon_1 \end{aligned}$$

- It is called the charge flip weight. The charge flip weight is applied on all OS data events to estimate the charge flip background.

Charge flip Background : Result for Charge Flip Rate

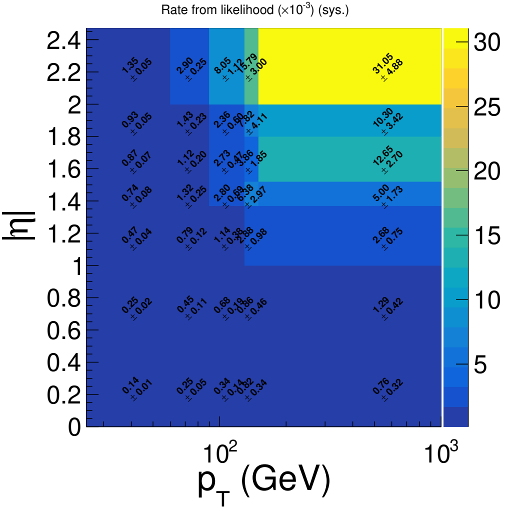


Figure: The measured values of the charge-flip rate ϵ_i in data, with total uncertainties.

Charge flip Background : MC Validation Plots

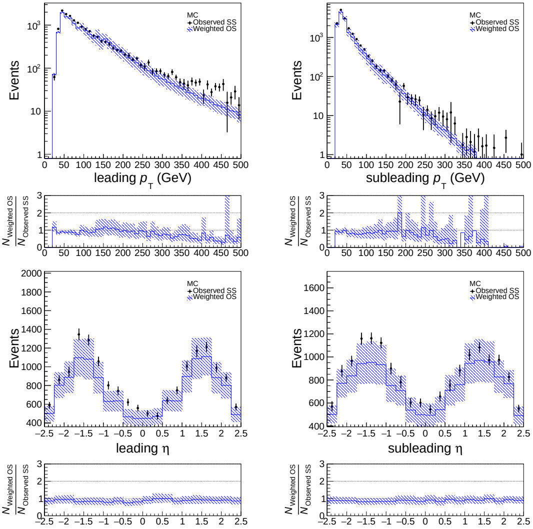


Figure: The comparison between the weighted OS events and the SS events, with different variables.

Charge flip Background : MC Validation Plots

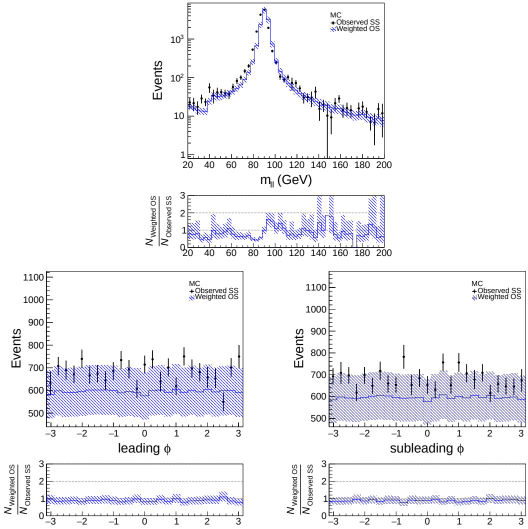


Figure: The comparison between the weighted OS events and the SS events, with different variables.

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 hardware 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 (i.e. noise).
- Two dedicated signal regions are defined based on the discriminant variables, to maximize signal sensitivity (like the signal-to-noise ratio).

Signal Region : discriminant variable

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

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

- The transverse missing erengy, denoted by E_T^{miss} or MET, is defined by

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

Signal Region : discriminant variable

- n_{jets}: Number of signal jets:
- $n_{\text{b-jets}}$: Number of b-jets (jet from b quark).
- $$\Delta\eta_{ll} = |\eta_1 - \eta_2|$$
- $$m_{\text{eff}} = p_T^1 + p_T^2 + E_T^{\text{miss}} + \sum_{\text{signal jets}} p_T$$
- 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

- 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.

$$p_{\text{jet-system}} = \begin{cases} p_{\text{jet1}} & \text{for SRjet1} \\ p_{\text{jet1}} + p_{\text{jet2}} & \text{for SRjet23} \end{cases}$$

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

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

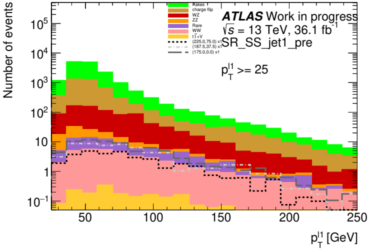
Signal Region : Pre-selection

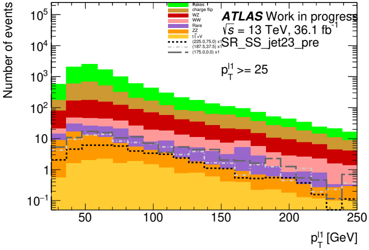
- Signal Region(SR) is a set of cuts of the discriminant variables, such that the signal sensitivity is high.
- By trying different sets of cuts, the signal region with the highest signal sensitivity can be found. This process is called the signal region optimization. The following cuts are the pre-selection, before the signal region optimization.

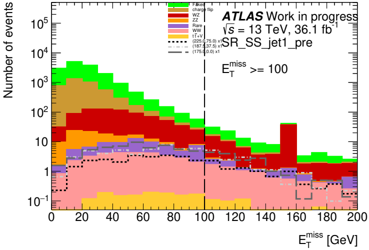
Pre-selection:

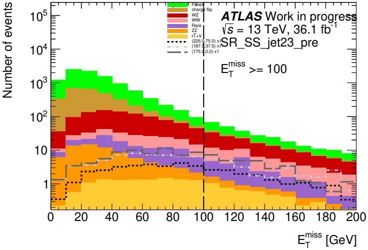
- Exactly 2 leptons with $p_T > 25$ GeV.
- The two leptons are same-sign in electric charge (SS).
- $n_{\text{b-jets}} = 0$, to reduce the SM background from top quark.
- Two signal regions: SRjet1 with $n_{\text{jets}} = 1$, SRjet23 with $n_{\text{jets}} = 2$ or 3.

Signal Region : Pre-selection plots





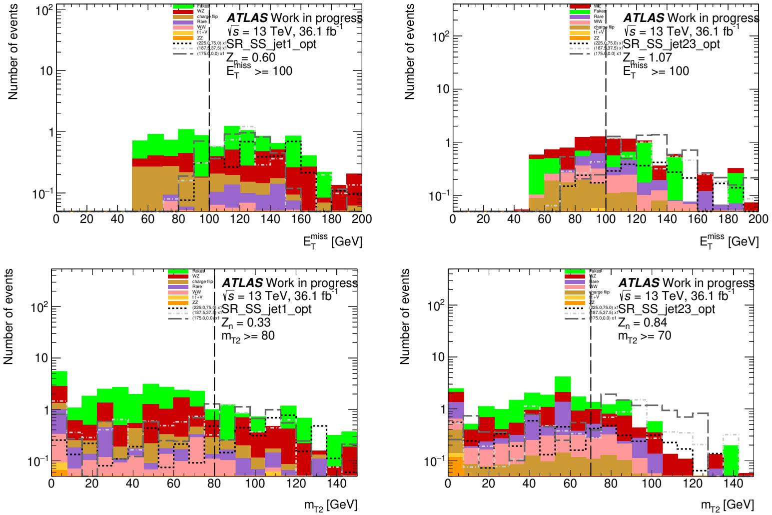




Signal Region : cut result

	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 : N-1 plots



Backup

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

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

- 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

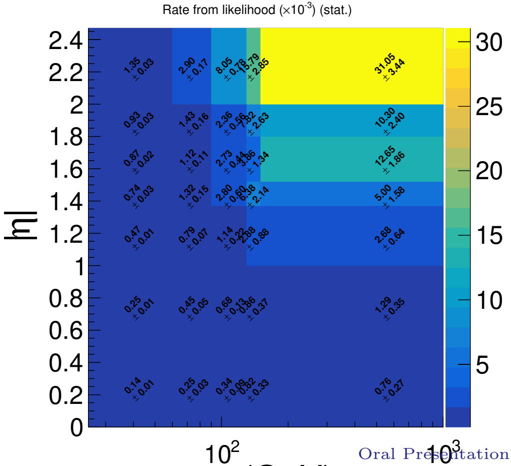
- Central region: 80 - 100 GeV
- Sideband region: 60 - 80 and 100 - 120
  (Sideband width 20 GeV)

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

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

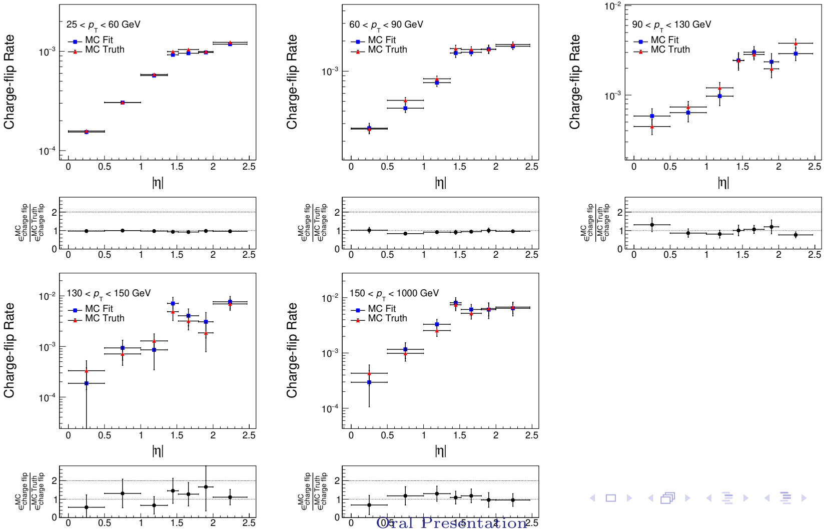
Likelihood Method : Result for Charge Flip Rate (statistical error only)

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



Likelihood Method : MC Truth Validation

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

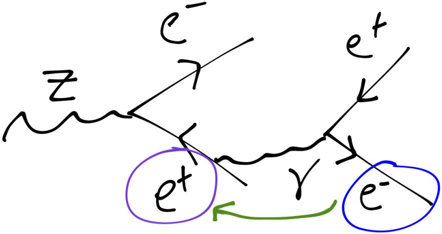


Likelihood Method : MC Truth Matching

- 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:

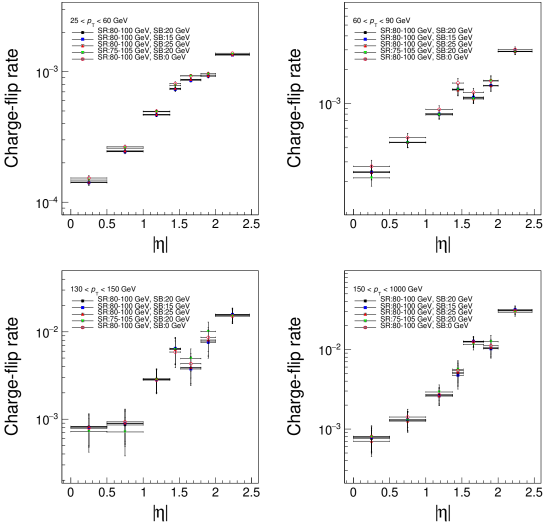
- Central region: 80 - 100 GeV, Sideband width: 15 GeV
- Central region: 80 - 100 GeV, Sideband width: 25 GeV
- Central region: 75 - 105 GeV, Sideband width: 20 GeV
- Central region: 80 - 100 GeV, no background subtraction

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

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

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

Pre-selection plots

Yields in pre-selection

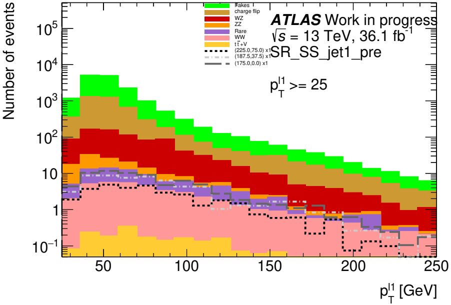
	Number of events
Fakes	11580.965417 ± 45.775452 (107219)
charge flip	3622.756937 ± 2.810481 (3375964)
WZ	691.333566 ± 34.238864 (68626)
ZZ	66.945860 ± 1.049840 (21749)
Rare	47.371873 ± 4.082859 (1662)
WW	38.128141 ± 0.388221 (15666)
$t\bar{t} + V$	1.971267 ± 0.138488 (671)
Total BG	16049.473060 ± 57.389305 (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)

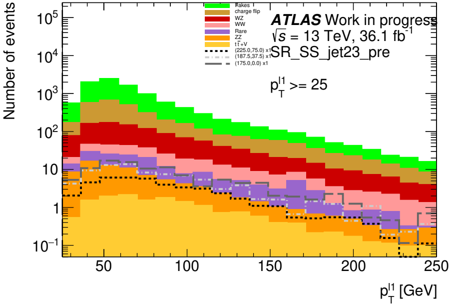
Table: Yields in SRjet1

	Number of events
Fakes	6848.284248 ± 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 ± 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)

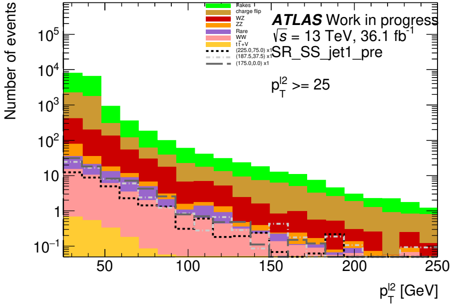
Table: Yields in SRjet23

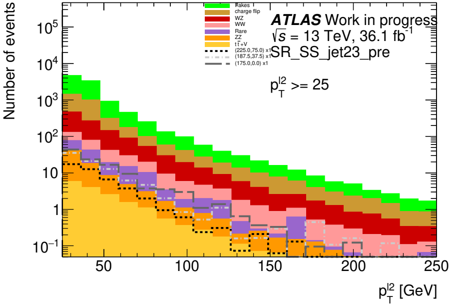
p_T^{l1}


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]

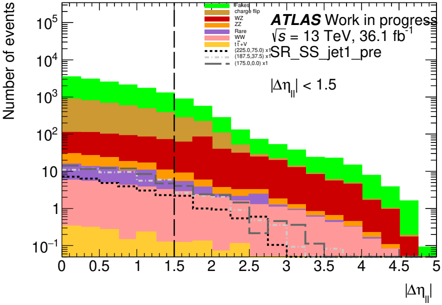

Fakes
charge flip
WZ
WW
Rare
ZZ
$t\bar{t}$+V
(225.0,75.0) x1
(187.5,37.5) x1
(175.0,0.0) x1
ATLAS Work in progress
$\sqrt{s}$ = 13 TeV, 36.1 fb^{-1}
SR_SS_jet23_pre
p_T^{l1} >= 25
Number of events
p_T^{l1} [GeV]

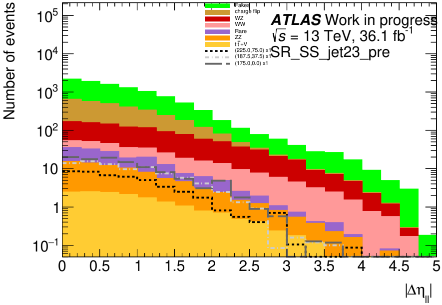
p_T^{l2}


Fakes
charge flip
WZ
ZZ
Rare
WW
tt̄+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
pT l2 >= 25
Number of events
pT l2 [GeV]

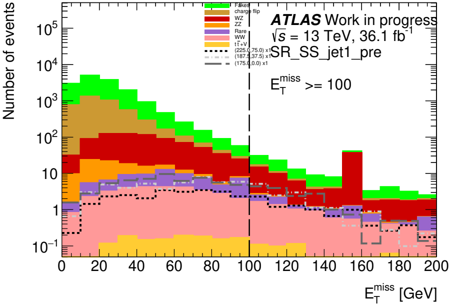

Fakes
charge flip
WZ
WW
Rare
ZZ
tt̄+V
(225.0,75.0) x1
(187.5,37.5) x1
(175.0,0.0) x1
ATLAS Work in progress
√s = 13 TeV, 36.1 fb-1
SR_SS_jet23_pre
pT l2 >= 25
Number of events
pT l2 [GeV]

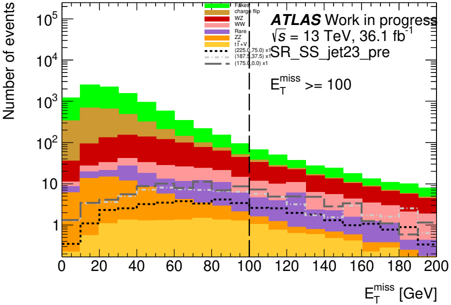
$|\Delta\eta_{ll}|$


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
$|\Delta\eta_{ll}| < 1.5$
$|\Delta\eta_{ll}|$

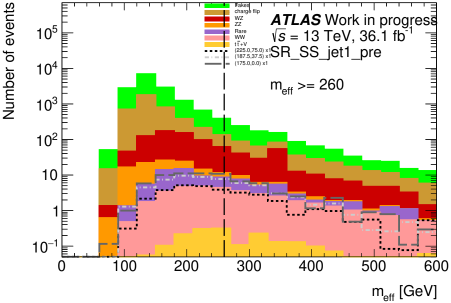

Number of events
Fakes
charge flip
WZ
WW
Rare
ZZ
$t\bar{t}$+V
(225.0,75.0) x1
(187.5,37.5) x1
(175.0,0.0) x1
ATLAS Work in progress
$\sqrt{s}$ = 13 TeV, 36.1 fb^{-1}
SR_SS_jet23_pre
$|\Delta\eta_{ll}|$

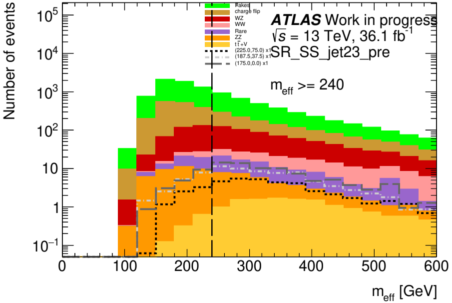
$E_{\mathrm{T}}^{\mathrm{miss}}$



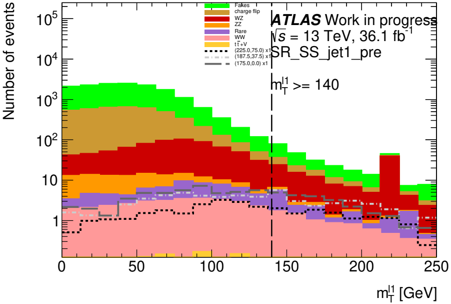


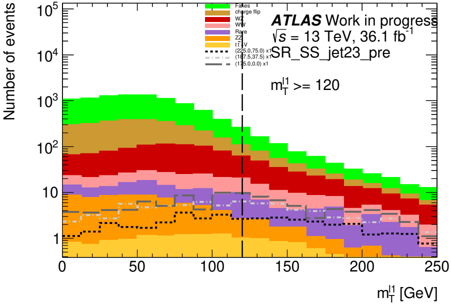
m_{eff}


Number of events
Fakes
charge flip
WZ
ZZ
Rare
WW
tt̄+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
meff >= 260
meff [GeV]

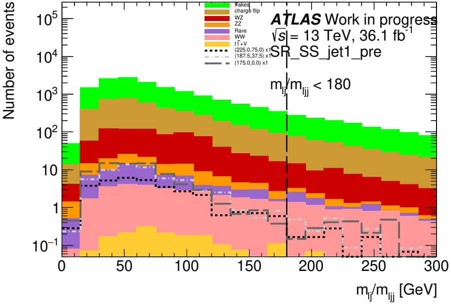

Number of events
Fakes
charge flip
WZ
WW
Rare
ZZ
tt̄+V
(225.0,75.0) x1
(187.5,37.5) x1
(175.0,0.0) x1
ATLAS Work in progress
√s = 13 TeV, 36.1 fb-1
SR_SS_jet23_pre
meff >= 240
meff [GeV]

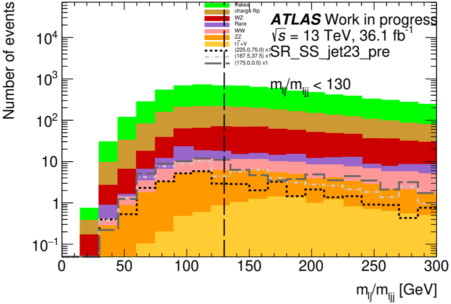
m_{T}^{l1}


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
m_T^{l1} >= 140
Number of events
m_T^{l1} [GeV]

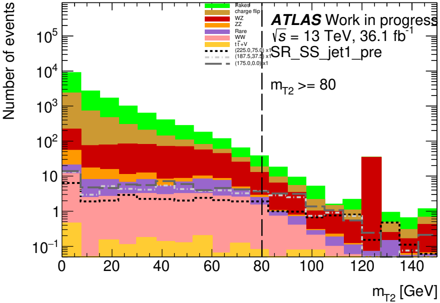

Fakes
charge flip
WZ
WW
Rare
ZZ
$t\bar{t}$+V
(225.0,75.0) x1
(187.5,37.5) x1
(175.0,0.0) x1
ATLAS Work in progress
$\sqrt{s}$ = 13 TeV, 36.1 fb^{-1}
SR_SS_jet23_pre
m_T^{l1} >= 120
Number of events
m_T^{l1} [GeV]

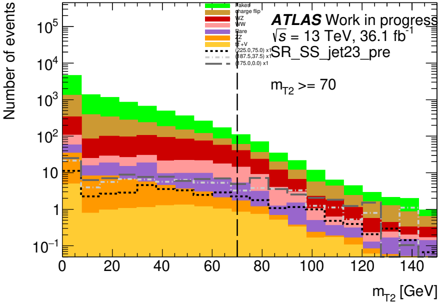
m_{lj}/m_{ljj}


Number of events
Fakes
charge flip
WZ
ZZ
Rare
WW
tt̄+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
mlj/mljj < 180
mlj/mljj [GeV]


Number of events
Fakes
charge flip
WZ
Rare
WW
ZZ
tt̄+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
mlj/mljj < 130
mlj/mljj [GeV]

m_{T2}


ATLAS Work in progress
√s = 13 TeV, 36.1 fb-1
SR_SS_jet1_pre
mT2 >= 80
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
mT2 [GeV]


ATLAS Work in progress
√s = 13 TeV, 36.1 fb-1
SR_SS_jet23_pre
mT2 >= 70
Number of events
mT2 [GeV]

N-1 plots

Yields in SR

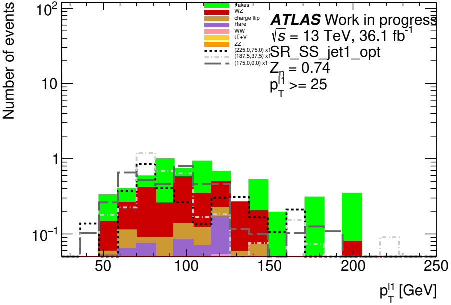
	Number of events	Significance
Fakes	3.295434 ± 0.819175 (24)	
WZ	2.176292 ± 0.397871 (257)	
charge flip	0.472185 ± 0.052737 (265)	
Rare	0.443536 ± 0.111301 (56)	
WW	0.165504 ± 0.023455 (67)	
$t\bar{t} + V$	0.124898 ± 0.046227 (36)	
ZZ	0.055330 ± 0.027713 (31)	
Total BG	6.733178 ± 0.920855 (736)	
(225.0,75.0)	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

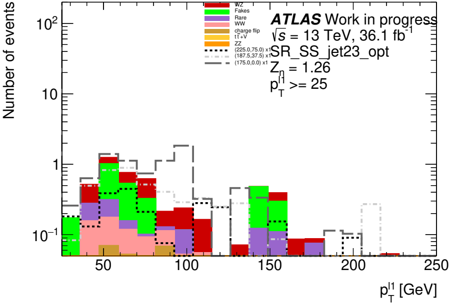
Table: Yields in SRjet1

	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

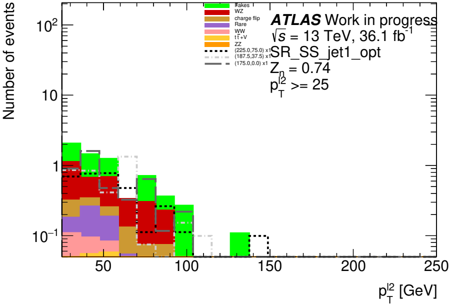
Table: Yields in SRjet23

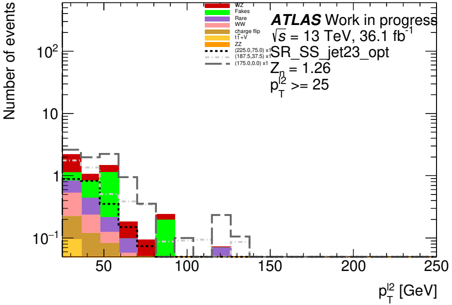
p_T^{l1}


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]

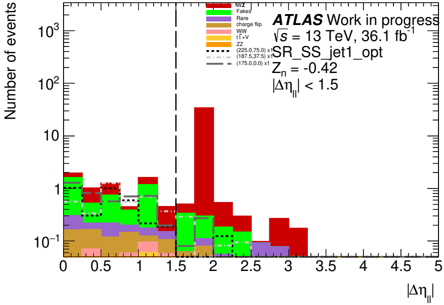

Number of events
10^2
10
1
10^{-1}
WZ
Fakes
Rare
WW
charge flip
$t\bar{t}$+V
ZZ
(225.0,75.0) x1
(187.5,37.5) x1
(175.0,0.0) x1
ATLAS Work in progress
$\sqrt{s}$ = 13 TeV, 36.1 fb^{-1}
SR_SS_jet23_opt
Z_n = 1.26
p_T^{l1} >= 25
50
100
150
200
250
p_T^{l1} [GeV]

p_T^{l2}

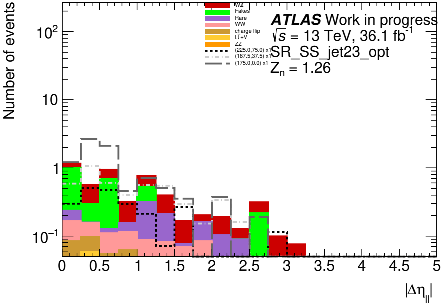

Fakes
WZ
charge flip
Rare
WW
tt̄+V
ZZ
(225.0,75.0) x1
(187.5,37.5) x1
(175.0,0.0) x1
ATLAS Work in progress
√s = 13 TeV, 36.1 fb-1
SR_SS_jet1_opt
Zn = 0.74
pT l2 >= 25
Number of events
pT l2 [GeV]


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 = 1.26
pT l2 >= 25
Number of events
pT l2 [GeV]

$|\Delta\eta_{ll}|$

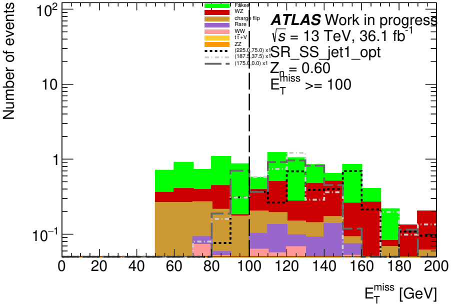


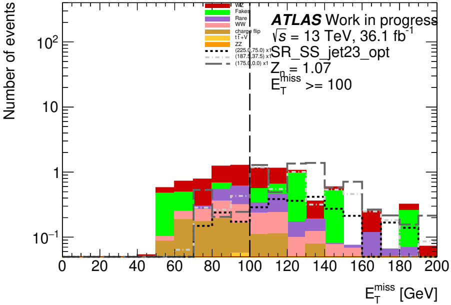
Number of events
WZ
Fakes
Rare
charge flip
WW
tt̄+V
ZZ
(225.0,75.0) x1
(187.5,37.5) x1
(175.0,0.0) x1
ATLAS Work in progress
√s = 13 TeV, 36.1 fb⁻¹
SR_SS_jet1_opt
Z_n = -0.42
|Δη_ll| < 1.5
|Δη_ll|



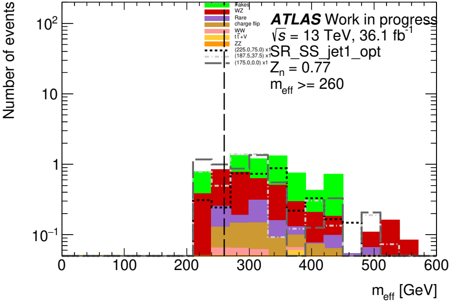
Number of events
WZ
Fakes
Rare
WW
charge flip
tt̄+V
ZZ
(225.0,75.0) x1
(187.5,37.5) x1
(175.0,0.0) x1
ATLAS Work in progress
√s = 13 TeV, 36.1 fb⁻¹
SR_SS_jet23_opt
Z_n = 1.26
|Δη_ll|

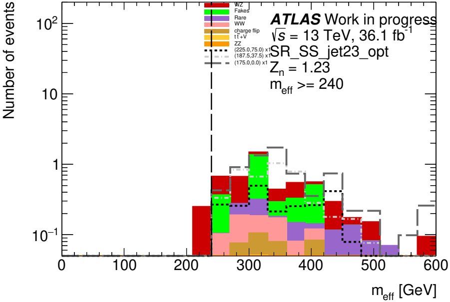
$E_{\mathrm{T}}^{\mathrm{miss}}$



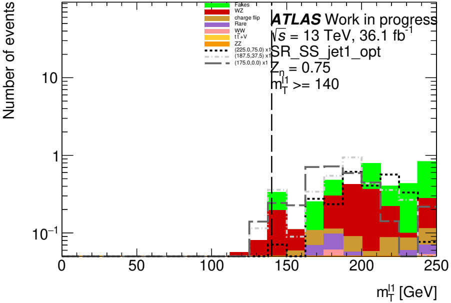


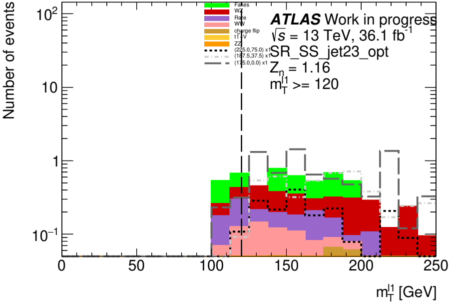
m_{eff}


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
10^2
10
1
10^{-1}
0
100
200
300
400
500
600
m_{eff} [GeV]

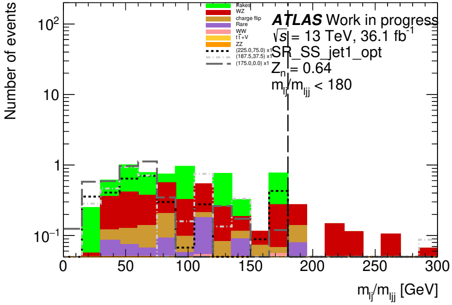

WZ
Fakes
Rare
WW
charge flip
$t\bar{t}$+V
ZZ
(225.0,75.0) x1
(187.5,37.5) x1
(175.0,0.0) x1
ATLAS Work in progress
$\sqrt{s}$ = 13 TeV, 36.1 fb^{-1}
SR_SS_jet23_opt
Z_n = 1.23
m_{eff} >= 240
Number of events
10^2
10
1
10^{-1}
0
100
200
300
400
500
600
m_{eff} [GeV]

m_{T}^{l1}

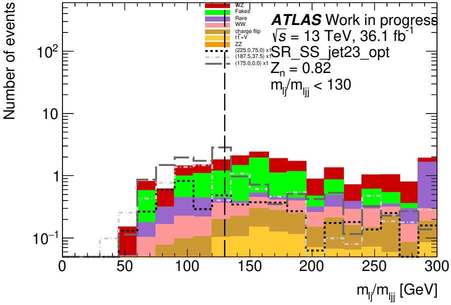

Fakes
WZ
charge flip
Rare
WW
t t̄+V
ZZ
(225.0,75.0) x1
(187.5,37.5) x1
(175.0,0.0) x1
ATLAS Work in progress
√s = 13 TeV, 36.1 fb-1
SR_SS_jet1_opt
Zn = 0.75
mT l1 >= 140
Number of events
10
1
10−1
0
50
100
150
200
250
mT l1 [GeV]


Fakes
WZ
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 = 1.16
mT l1 >= 120
Number of events
10^2
10
1
10−1
0
50
100
150
200
250
mT l1 [GeV]

m_{lj}/m_{ljj}

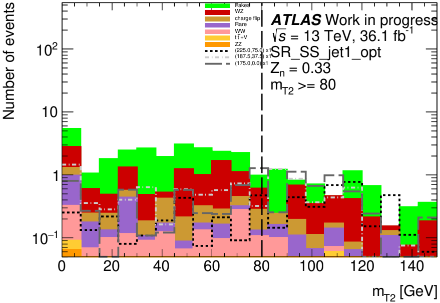


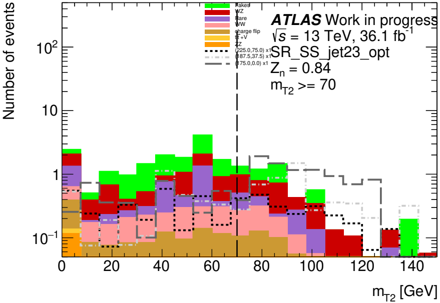
Fakes
WZ
charge flip
Rare
WW
tt̄+V
ZZ
(225.0,75.0) x1
(187.5,37.5) x1
(175.0,0.0) x1
ATLAS Work in progress
√s = 13 TeV, 36.1 fb⁻¹
SR_SS_jet1_opt
Zn = 0.64
mlj/mljj < 180
Number of events
mlj/mljj [GeV]



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
Number of events
mlj/mljj [GeV]

m_{T2}


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 = 0.33
m_{T2} >= 80
Number of events
10^2
10
1
10^{-1}
0
20
40
60
80
100
120
140
m_{T2} [GeV]


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 = 0.84
m_{T2} >= 70
Number of events
10^2
10
1
10^{-1}
0
20
40
60
80
100
120
140
m_{T2} [GeV]