Search for the Doubly Charged Higgs Decaying to $W^{\pm}W^{\pm}$ with the ATLAS Detector

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Higgs Doublet Triplet Model

- Neutrinos are massless in the SM which is in contrast to various experimental observations.
- To allow mass for neutrinos, a triplet is introduced to the Higgs doublet.

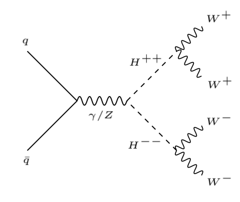
$$\mathcal{L} = (D_\mu H)^\dagger (D^\mu H) + Tr(D_\mu \Delta)^\dagger (D^\mu \Delta) - V(H, \Delta) + \mathcal{L}_{Yukawa} \quad (1)$$

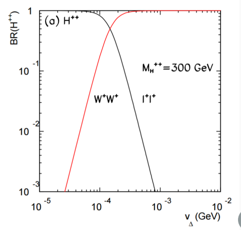
$$\begin{aligned} V(H, \Delta) = & - m_H^2 H^\dagger H + \frac{\lambda}{4}(H^\dagger H)^2 \\ & + m_\Delta^2 Tr(\Delta^\dagger \Delta) + [\mu(H^\dagger i\sigma^2 \Delta^\dagger H) + h.c.] \\ & + \lambda_1 (H^\dagger H) Tr(\Delta^\dagger \Delta) + \lambda_2 (Tr\Delta^\dagger \Delta)^2 \\ & + \lambda_3 Tr\left(\Delta^\dagger \Delta\right)^2 + \lambda_4 H^\dagger \Delta \Delta^\dagger H. \end{aligned}$$

- The electroweak symmetry breaking can still be achieved with certain constraints on model parameters.
- The EWSB will result in seven scalar bosons: $H^{\pm\pm}$, $H^\pm$, A^0 (CP odd), H^0 (CP even) and h^0 (CP even).

Higgs Doublet Triplet Model

- Two major production modes, pair production and associated production.
- This analysis focus on the pair production mode.
- First search for $H^{\pm\pm}$ via $H^{\pm\pm} \to W^{\pm}W^{\pm}$.
- In this analysis, the vacuum expected value is constrained to enlarge the branching ratio of $H^{\pm\pm} \to W^{\pm}W^{\pm}$.



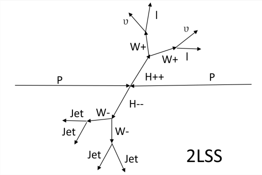


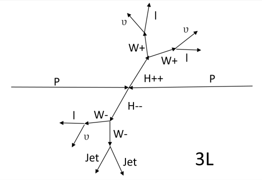
Type II Seeaw

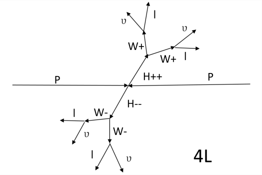
- Data with a centre-mass-energy of 13 TeV and integrated luminosity of $36.1 fb^{-1}$ is utilized.

Analysis Methodology

- Events are split into three categories according to different final states: $2\ell^{SS}, 3\ell$ and 4ℓ.







- $M_{H^{\pm\pm}}$ from 200$\sim$700 GeV considered.
- Full 2015+2016 dataset with centre-mass-energy of 13 TeV and luminosity of 36.1 fb^{-1} utilized.

$2\ell^{SS}$ **Overview**

- Two same sign lepton in final state.
- Three sub-channels according to the flavor of the leptons(ee, $\mu\mu$ and eμ).
- Background originate from fake leptons, charge flip and prompt same-sign di-leptons.
    - Background due to electron's charge flip such as Z+jets and $W^{\pm}W^{\mp}$ are estimated with electron's charge flip rates.
    - Background due to fake leptons like $Z + Jets$ and t$\bar{t}$ are estimated with the fake factor method.
    - Background with prompt same sign di-leptons like WZ are estimated with MC simulation.

Event Selection

Trigger requirement
Two tight leptons with same sign , $p_T > 30$, 20 GeV respectively.
$|M_{\ell\ell}| <$80 GeV or $\|M_{\ell\ell}\| >$ 100 GeV for ee channel
No b-jet (a multivariate algorithm utilized)
Njets $\geq$ 3
$E_T^{miss} >$ 70 GeV

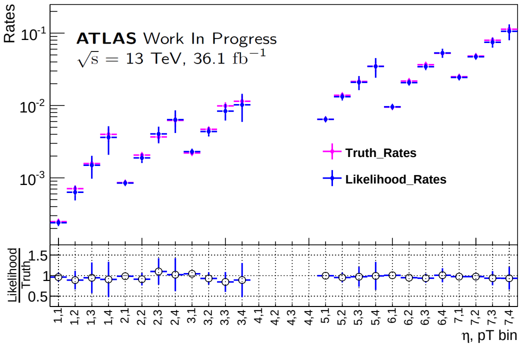
- Single lepton trigger with p_T threshold 27 GeV (electron) and 21 GeV (muon) applied.
- Tight and loose selections are designed for leptons using mainly shower shape information.
- Leptons pass loose selections but fail tight selections are denoted as LooseNotTight.

Electron's Charge Mis-Identification

- Electron charge mis-ID rate(ϵ) measured with likelihood method.
- Tight electrons' charge flip rates are measured in tight+tight region with fine binning.
- LooseNotTight electrons' charge flip rates are measured in tight+looseNotTight region with coarse binning.
- Fine binning:
    - $|\eta|$: 0., 0.6, 1.1, 1.37, 1.52, 1.7, 2.3, 2.47.
    - p_T [GeV]: 20., 60., 90., 130., 1000.
- Coarse binning:
    - $|\eta|$: 0., 1.37, 1.52, 2.47.
    - p_T [GeV]: 20., 60., 1000.
- Uncertainties of the rates include statistical uncertainty, uncertainty due to background contamination and uncertainty due to kinematic difference.

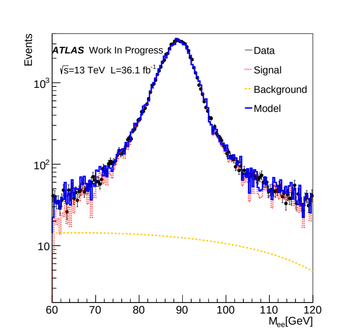
Closure for ChargeFlip Rates

- Electron QMisID measured with the fraction of same-sign events in using $Z \rightarrow ee$ Powheg MC sample.
- Truth Match method based on MC as closure.

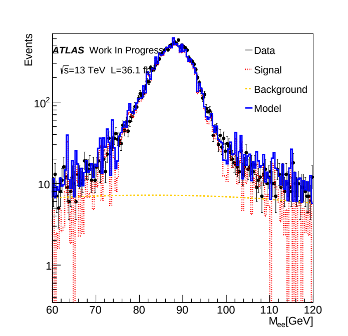


Background Contamination

- Events used to measure the rates are contaminated by background events, its impact on rates is studied with the Template Fit Method and is treated as an additional systematic.
- Plot on left is for N_{ss} with two same sign tight electrons, plot on right is for N_{ss} with looseNotTight electron in barrel region and tight electron in end-cap region.



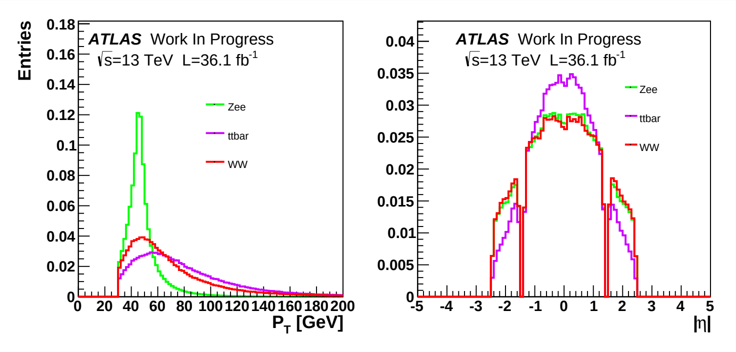
Signal purity is 97.8%.



Signal purity is 93.2%.

Kinematic Difference

- Electron's kinematic is different among Z+jets, $t\bar{t}$ and $W^{\pm}W^{\mp}$ which are main source of charge mis-id background in this analysis, the kinematic difference results in another systematic on rates.



Final Uncertainty of ChargeFlip Rates

	$20 < p_T < 60$	$60 < p_T < 90$	$90 < p_T < 130$	$130 < p_T < 1000$
$0< \|\eta\| <0.6$	25.7	27.7	31.1	32.6
$0.6< \|\eta\| <1.1$	25.3	26.7	29.2	28.3
$1.1< \|\eta\| <1.37$	25.3	26.5	28.9	30.0
$1.52< \|\eta\| <1.7$	25.2	26.1	27.9	28.8
$1.7< \|\eta\| <2.3$	25.1	25.2	25.6	25.9
$2.3< \|\eta\| <2.47$	25.0	25.4	26.4	28.3

	$20 < p_T < 60$	$60 < p_T < 1000$
$0< \|\eta\| <1.37$	38.33	37.29
$1.52< \|\eta\| <2.47$	35.02	35.23

Uncertainties of the electron's charge flip rates, numbers are in %. Table on top is for tight electrons while table on the bottom is for looseNotTight electrons.

Fake Factor Method

- The method is based on a control region enriched by fake leptons selected with one tight lepton and one looseNotTight lepton.
- The amount of background due to fake leptons is estimated with this control region and a projection factor, "Fake Factor".
- The fake factor is defined as: $\theta_\ell = \frac{N_{\ell\ell}}{N_{\ell\not{\ell}}}$
- Fake factors are measured in low E_T^{miss} region.
- Muon fake factor is measured in $\mu\mu$ channel and electron fake factor is measured in eμ channel(To reduce the contamination from electron's chargeflip).

Muon Fake Factor

$$\theta_\mu = \frac{N_{\mu\mu}}{N_{\mu\not{\mu}}}(\mathrm{E}_T^{miss} < 70) = \frac{N_{\mu\mu}^{Data} - N_{\mu\mu}^{\mathrm{P}rompt\ SS}}{N_{\mu\not{\mu}}^{Data} - N_{\mu\not{\mu}}^{\mathrm{P}romt\ SS}} \tag{2}$$

	data	VV_Prompt	VH	ttH+ttV	Vgamma
Numerator	139	75.2±4.5	1.5±0.6	7±0.2	0
Denominator	416	20.4±2	0	0.94±0.09	0

Estimation for Prompt SS and data for muons in tight+tight and tight+looseNotTight region, uncertainty here is statistical only.

Muon fake factor: 0.14±0.03.

Electron Fake Factor

$$\theta_e = \frac{N_{\mu e}}{N_{\mu \not{e}}}(\mathrm{E}_T^{miss} < 70) = \frac{N_{\mu e}^{Data} - N_{\mu e}^{\mathrm{P}rompt\ SS} - N_{\mu e}^{\mathrm{Q}MisId} - N_{\mu e}^{\mathrm{F}akeMuon}}{N_{\mu \not{e}}^{Data} - N_{\mu \not{e}}^{\mathrm{P}rompt\ SS} - N_{\mu \not{e}}^{\mathrm{Q}MisId}} \tag{3}$$

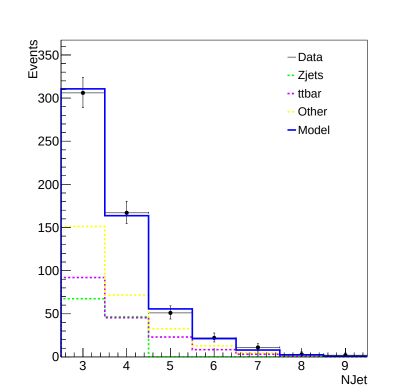
	data	VV_Prompt	VH	ttV	QMisID	Fake Muon
Numerator	444	135.3±5.6	4.0±1.2	11.3±0.3	47.9±1.2	71.5±3.3
Denominator	434	22.3±2.3	1±0.6	1.4±0.1	50±2.2	

Estimation for Prompt SS, QMisID, fake muon contamination and data for electrons in tight+tight and tight+looseNotTight region, uncertainly here is stat-only.

Electron fake factor: 0.48±0.07

"Jet Composition" Uncertainty

- Fake factors especially muon fake factor are affected by the heavy-flavor/light-flavor jets fractions.
- A template fit is performed on the events passing pre-selection region to study the ratio of Z+jets and $t\bar{t}$ contributions.
- Z+Jets yield: 113.9±40; $t\bar{t}$ yield: 172.5±43.7.
- Variate the fractions by their uncertainties, the impact on fake factors is treated as the jet composition uncertainty.



Uncertainties of Fake Factor

Source	Effect in %
Jet flavour composition	14
Pile_Up reweighting	1.5
JVT	7.4
B-jet veto	3.1
MC cross section	32
Lepton ID	3.4
Object Reconstruction	38
Statistic	23
Total	56

Uncertainties of muon fake factor.

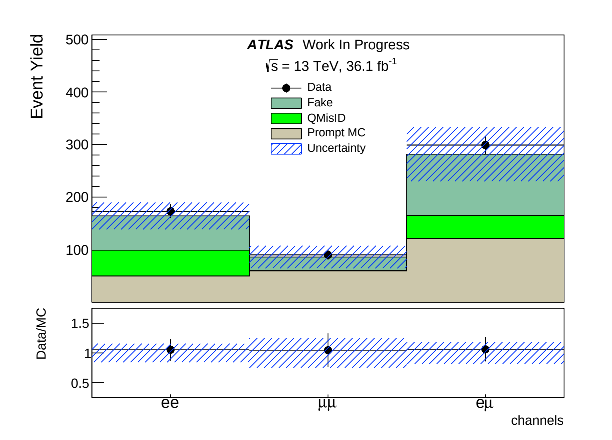
Source	Effect in %
QMisID	10
Fake	21
Jet composition	2
Pile_Up reweighting	1.2
JVT	4.7
B-jet veto	1.8
MC cross section	18
Electron ID	2
Muon ID	0.8
Object Reconstruction	11
Statistic	14
Total	35

Uncertainties of electron fake factor.

The "Object Reconstruction" term is one important systematic, it's mainly from jet reconstruction.

Preselection Level Data-Background comparison

- Comparison between data and SM background at event pre-selection level. The estimated SM background agrees with the data.



Background estimation at event pre-selection level for $2\ell^{ss}$ channel.

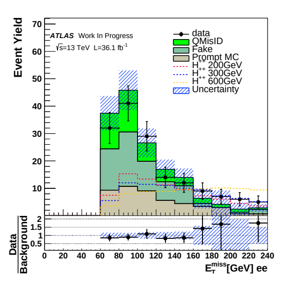
Event Topology

- On top of pre-selection, 6 variables are designed to further separate signal from background.
  - M_{jj}^{W}: the invariant mass of the two jets closest to the mass of W boson.
  - M_{jets}: the invariant mass of all jets, only the leading four jets are considered is there are more than four jets.
  - $M_{\ell\ell}$: the invariant mass of the two leptons.
  - $\Delta R_{\ell\ell}$: the distance in $\eta - \phi$ plane between the two leptons.
  - $\Delta\phi(\ell\ell, E_T^{miss})$: difference in azimuth between the di-lepton system and E_T^{miss}.
  - RMS: variable used to describe the "spreads" of the azimuth angles of leptons, jets and E_T^{miss}:

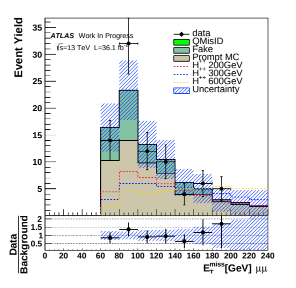
$$\mathrm{RMS} = \frac{\mathrm{R.M.S.}(\phi_{\ell_1}, \phi_{\ell_2}, \phi_{E_T^{miss}}) * \mathrm{R.M.S.}(\phi_{j1}, \phi_{j2}, \cdots)}{\mathrm{R.M.S.}(\phi_{\ell_1},, \phi_{\ell_2}, \phi_{E_T^{miss}}, \phi_{j1}, \phi_{j2}, \cdots)}, \quad (4)$$

E_T^{miss} and $M_{\ell\ell}$ Distributions

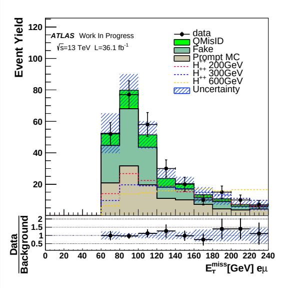
E_T^{miss} ee



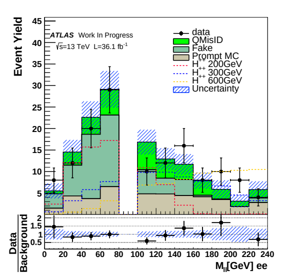
E_T^{miss} $\mu\mu$



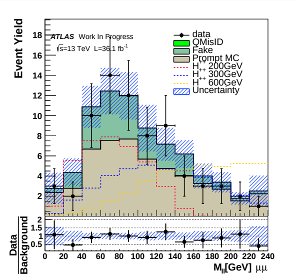
E_T^{miss} $e\mu$



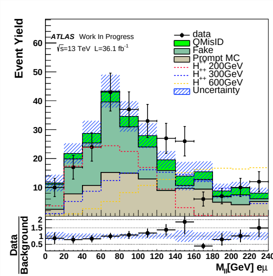
$M_{\ell\ell}$ ee



$M_{\ell\ell}$ $\mu\mu$



$M_{\ell\ell}$ $e\mu$



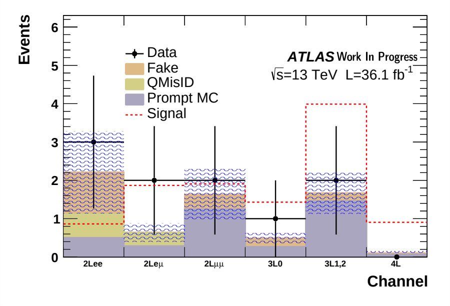
3ℓ and 4ℓ channel

- 3ℓ channel: backgrounds are events with fake leptons and prompt tri-leptons.
  - Similar to the $2\ell^{SS}$ channel, fake factor method is used to estimated fake lepton background.
  - Prompt backgrounds, WZ and ZZ, are estimated with MC.
- 4ℓ channel: backgrounds are events from fake leptons and prompt four-leptons.
  - Prompt backgrounds are estimated with MC.
  - Fake lepton background is estimated with the "Fake Scale Factor Method", i.e. scale the MC fake in heavy/light enriched region to data.

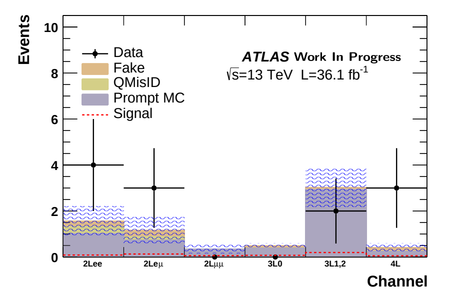
Signal Region

- Expected and observed yield in the signal regions:

$M_{H^{\pm\pm}} = 200$ GeV



$M_{H^{\pm\pm}} = 500$ GeV



Systematics

- Systematics included:

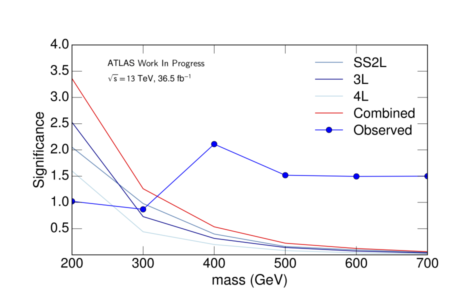
PDF, factorization scale and parton shower	$\sim$15% for signal
Cross section measurements	20%$\sim$30%
Luminosity	$\sim$3%
Data-driven background estimation	30%$\sim$80% for $2\ell^{SS}$ and $\sim$50% for 3ℓ, 4ℓ
Reconstruction of the physics objects	5%$\sim$40%

- Major uncertainty is from the data-driven background estimation.

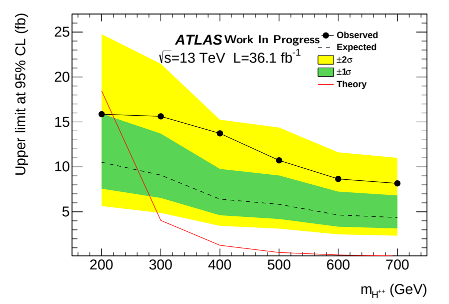
Significance and Limits

- Limits are computed with the likelihood ratio test.
- The model is excluded at 95% CL for $M_{H^{\pm\pm}} < 220\mathrm{GeV}$.

Significance



Limit



Expected (Observed) significances as a function of the mass of $H^{\pm\pm}$(left) and expected (observed) limits for the combination of $2\ell^{SS}$, 3ℓ and 4ℓ channels(right).

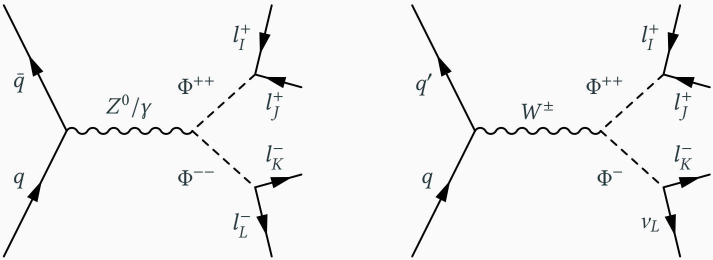
Summary

- First analysis of the $H^{\pm\pm} \rightarrow W^{\pm}W^{\pm}$ at colliders with data collected by ATLAS at $\sqrt{s}$ =13 TeV of 36.1 fb^{-1}
- No significant signal observed, limits are derived.
    - The model is excluded at 95% CL for $M_{H^{\pm\pm}} < 220\mathrm{GeV}$.
    - The paper is circulated in the collaboration.

Backup

Other $H^{\pm\pm}$ Search

CMS: Search for $H^{\pm\pm}$ in three and four lepton final state: ▸ CMS $H^{\pm\pm}$
Limits on the $M_{H^{\pm\pm}}$ derived for different assumptions on branching ratio to leptons. 535∼820 GeV for 100% decaying to leptons with 95% CL.



ATLAS: Search for $H^{\pm\pm}$ via $H^{\pm\pm} \to \ell^\pm\ell^\pm$: ▸ arXiv:1710.09748 [hep-ex]
660∼870 GeV for 100% decaying to leptons with 95% CL.

CH Lepton Definition

Electron	Loose	Tight
p_T	10 GeV	10 GeV
η	[0, 1.37] & [1.52, 2.47]	[0, 1.37] & [1.52, 2.47]
ID	LooseLH	TightLH
Isolation	Loose	FixedCutTight
$\|d0Sig\| <$	5	5
$\|z0\sin(\theta)\| <$	0.5 mm	0.5 mm

Table 1: Loose and Tight definitions for electrons

Muon	Loose	Tight
p_T	10 GeV	10 GeV
η	[0, 2.5]	[0, 2.5]
ID	Loose	Loose
Isolation	LooseTrackOnly	FixedCutTightTrackOnly
$\|d0Sig\| <$	3	3
$\|z0\sin(\theta)\| <$	0.5 mm	0.5 mm

Table 2: Loose and Tight definitions for muons

Trigger

2015	**2016**
HLT_e26_lhmedium_L1EM20VH for data set	HLT_e26_lhtight_nod0_ivarloose
HLT_e60_lhmedium	HLT_e60_lhmedium_nod0
HLT_e120_lhloose	HLT_e140_lhloose_nod0
HLT_mu20_iloose_L1MU15	HLT_mu26_ivarmedium
HLT_mu50	HLT_mu50

Table 3: Summary of triggers used by data taking period.

Signal Region $2\ell^{SS}$

mass	ch.	$M_{jets} >$	$M_{jets} <$	RMS $<$	$\Delta R(\ell, \ell) <$	$\Delta\phi(\ell\ell, E_T^{miss}) <$	$M_{\ell\ell} <$	$M_{\ell\ell} >$	$E_T^{miss} >$
200	ee	140	770	0.3	0.8	1.1	130	25	100
300	ee	180	770	0.4	1.4	2.1	340	105	200
400	ee	280	1200	0.6	2.2	2.4	340	105	200
500-700	ee	440	∞	1.1	2.6	2.6	730	105	250
200	$\mu\mu$	95	310	0.3	1.8	1.3	150	15	100
300	$\mu\mu$	130	640	0.4	1.8	2.4	320	80	200
400	$\mu\mu$	220	1200	0.6	1.8	2.4	350	80	200
500-700	$\mu\mu$	470	∞	1.1	2.2	2.4	440	110	250
200	eμ	95	640	0.2	0.9	1.3	150	35	100
300	eμ	130	640	0.4	1.8	2.4	320	80	200
400	eμ	220	1200	0.5	1.8	2.4	350	80	200
500-700	eμ	470	∞	1.1	2.2	2.4	440	110	250

Table 4: Cut values for the definition of the signal regions. All numbers for masses and E_T^{miss} are in unit of GeV.

Event Preselection 3ℓ

Step	Selection Criteria
A	Three leptons with $P_T^{0,1,2} > 10, 20, 20\text{GeV}$
B	$\|M_{\ell+\ell-} - M_Z\| > 10$ GeV $M_{\ell+\ell-} > 15$ GeV $E_T^{miss} > 30$ GeV $N_{\text{jet}} >= 2$
C	$N_{\text{b-jet}} = 0$

Table 5: Event pre-selections for the 3ℓ channel.

Signal Region 3ℓ

	SFOS 0	SFOS 1,2	Data	Prompt	Fakes	H++200GeV
1	$0.15 < \Delta R_{\ell\ell ss} < 1.57$ and $E_T^{miss} > 45$ GeV	$0.00 < \Delta R_{\ell\ell ss} < 1.52$ and $E_T^{miss} > 45$ GeV	0.198 ± 0.046	0.191 ± 0.025	0.16 ± 0.06	0.670 ± 0.004
2	$M_{3\ell} > 160$ GeV and $0.08 < \Delta R_{\ell j} < 1.88$	$M_{3\ell} > 170$ GeV and $0.07 < \Delta R_{\ell j} < 1.31$	0.061 ± 0.050	0.084 ± 0.027	0.038 ± 0.057	0.498 ± 0.005
3	$P_T^{\text{leading jet}} > 80$ GeV	$P_T^{\text{leading jet}} > 55$ GeV	0.751 ± 0.026	0.772 ± 0.014	0.709 ± 0.034	0.821 ± 0.003
4		All cuts	0.008 ± 0.05	0.006 ± 0.019	0.003 ± 0.073	0.330 ± 0.006
5		Factorised efficiency 1234	0.011	0.012 ± 0.000	0.004 ± 0.000	0.274 ± 0.000

Table 6: The optimized cut values and their individual efficiencies. The correlated variables are grouped together. The "All cuts" line displays the nominal efficiency when all cuts are applied while the last line "Factorized efficiency" shows the product of the efficiencies of the three groups. Only statistical errors are shown. The systematic uncertainties are not included in this table.

Stability of Fake Factors

- A test is performed to check the stability of fake factors among different control regions, whose selections are the same as nominal control region except that the cuts on E_T^{miss} are different. The results of the closure test are shown in Figure 1, fake factors are quite stable among different control regions.

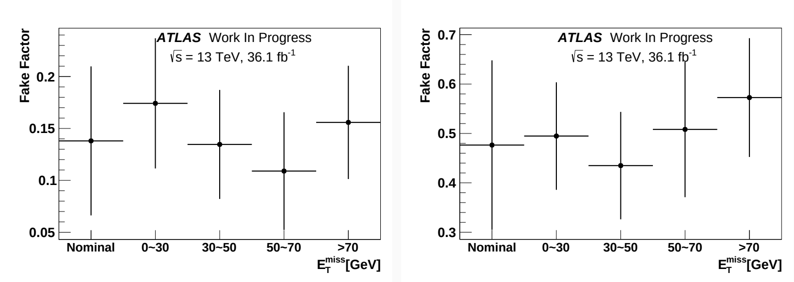
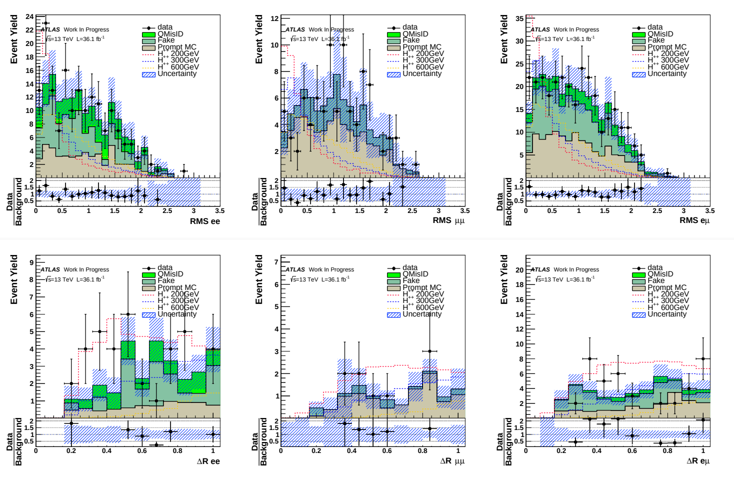


Figure 1: Stability of muon(left) and electron(right) fake factors. The fake factors are measured in control regions with different E_T^{miss} requirements.

Uncertainties of Fake Factor

- For fake factors, considered uncertainties are:
  - The statistical uncertainty on fake factors.
  - The uncertainty due to jet flavor composition.
  - The uncertainty of the QMisID estimation.
  - The uncertainty due to MC modeling of the prompt processes(variations of lepton identification scale factors, cross sections for normalizations and jet/E_T^{miss} energy scales).
  - For electron factor, there is an additional uncertainty from muon fake factor. This uncertainty will be taken into account as correlated for the final signal fit.

Distributions



Distributions