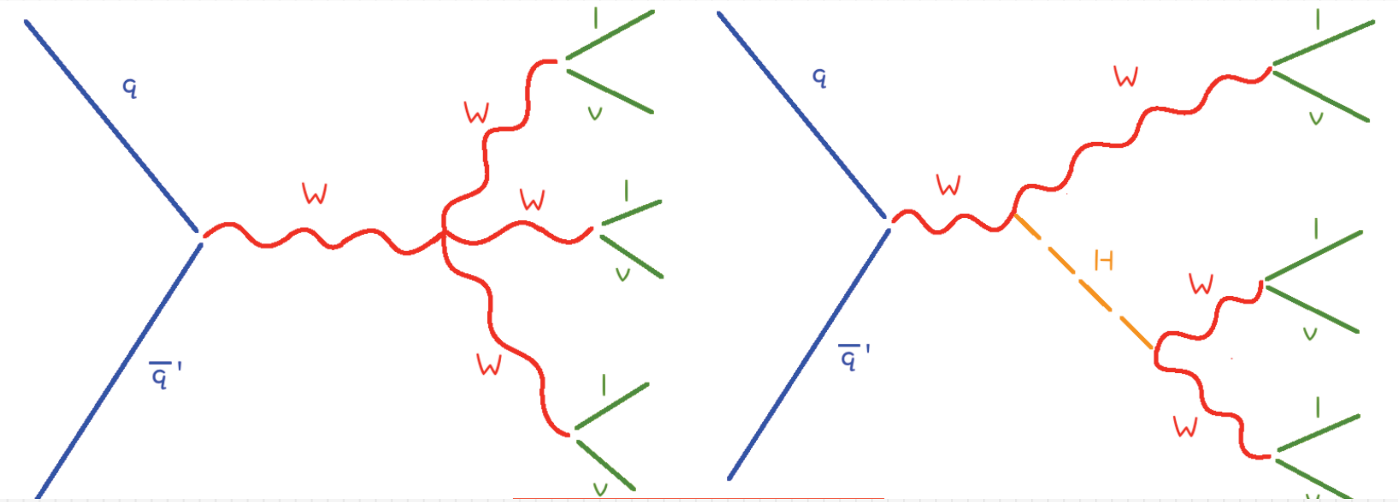
WWW Analysis with Run I Data

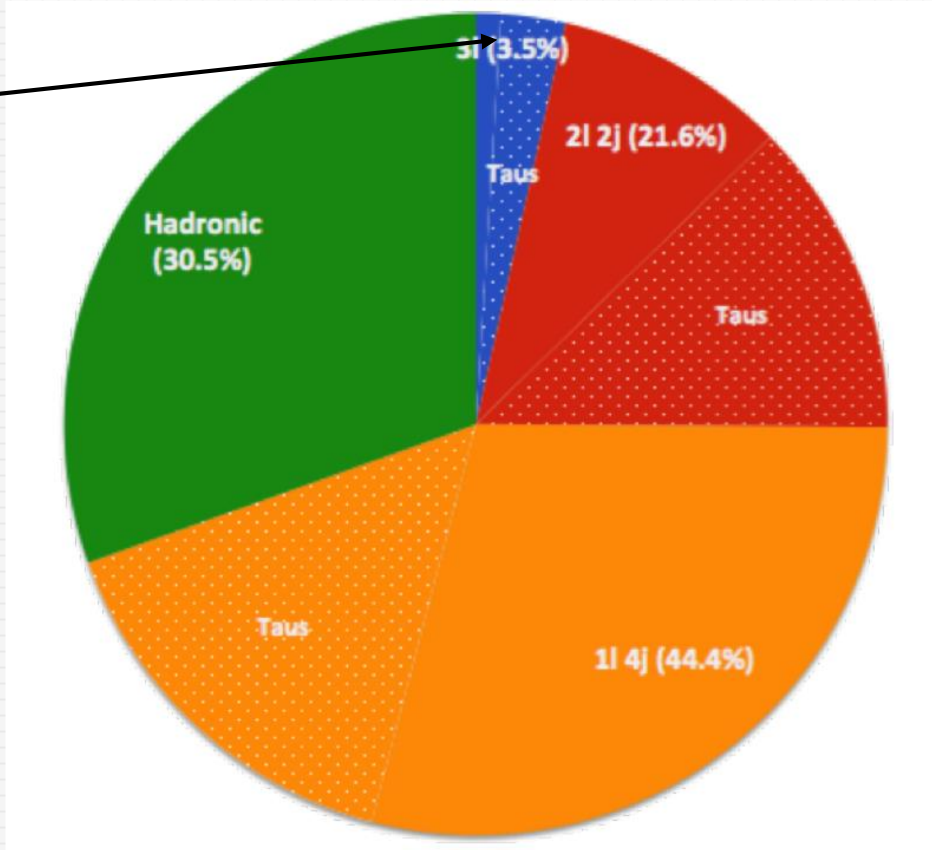
Cristinel Diaconu, Yanwen Liu, Emmanuel Monnier, Ruiqi Zhang

WWW Full Leptonic Analysis

Introduction

- Seeking first measurement of WWW production cross section
- Use 20.3 fb-1 of 8 TeV data collected at the LHC in 2012
- Search in fully leptonic channel: cleanest signature
  - ~40% due to SM ~60% due to Higgs production





Sample		Cross-section [fb]
MadGraph NLO	$W^+W^-W^+ \rightarrow$ Anything	59.47 ± 0.11
	$W^-W^+W^- \rightarrow$ Anything	28.069 ± 0.076
	$W^+H \rightarrow W^+W^+W^-(*) \rightarrow$ Anything	99.106 ± 0.019
	$W^-H \rightarrow W^-W^+W^-(*) \rightarrow$ Anything	54.804 ± 0.010

- Internal note:
  - ATL-COM-PHYS-2015-601
  - https://cds.cern.ch/record/2030159

Event Pre-Selection of full leptonic channel

- Pre-selection:
  - Data quality
    - Data must pass a selection ensuring that the detector and LHC conditions were good enough to introduce no selection bias.
  - Primary vertex
    - The event must contain a primary vertex with 3 tracks.
  - Trigger
    - High pt leptons with medium or tight quality, with various pT thresholds(25 GeV, 60 GeV) and isolation criteria.
  - 3 lepton selection
    - Exactly 3 leptons with Pt>20 GeV

Backgrounds

WZ->lllν
Simulated using Powheg +Pythia 8 with three lepton filter. Charge mis-id contribution determined in data.

Fake Lepton (W,Z,WW,ttbar)
Uses data-driven estimate via Generalized Matrix Method.

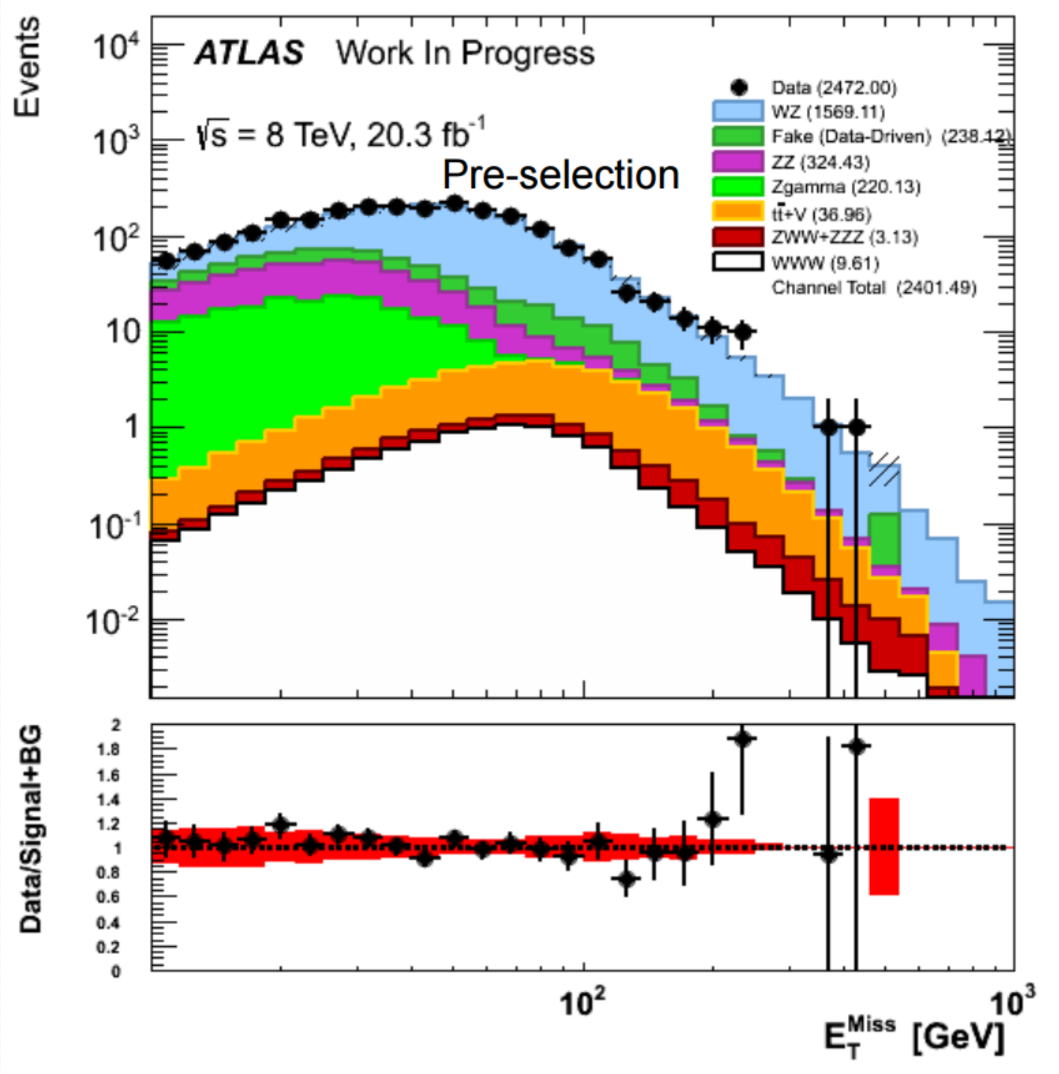
ZZ->llll
Estimated in same manner as WZ.

Zgamma
Estimated with MC using Sherpa.

ttbarV
Estimated from MC using Madgraph + Pythia samples with three lepton filter.

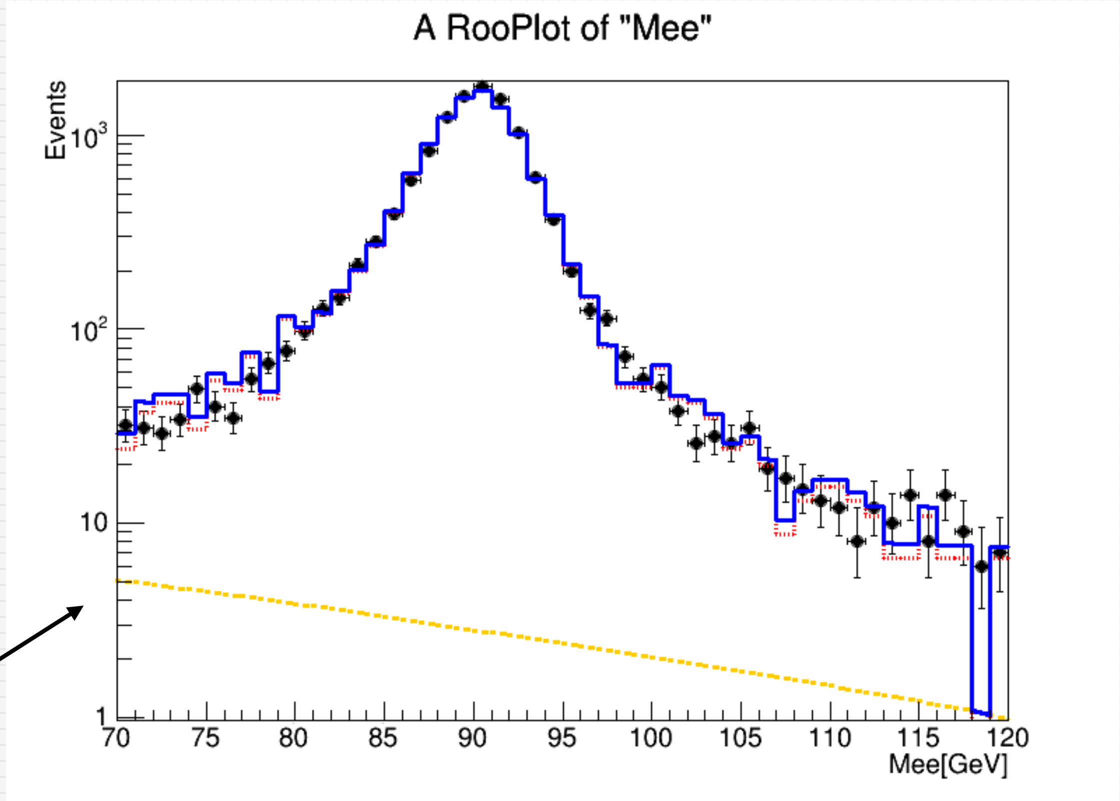
ZWW+ZZZ
Estimated using Madgraph+ Pythia.

WWW Signal
Estimated using VBFNLO + Pythia 8.



Electron Charge Mis-Identification

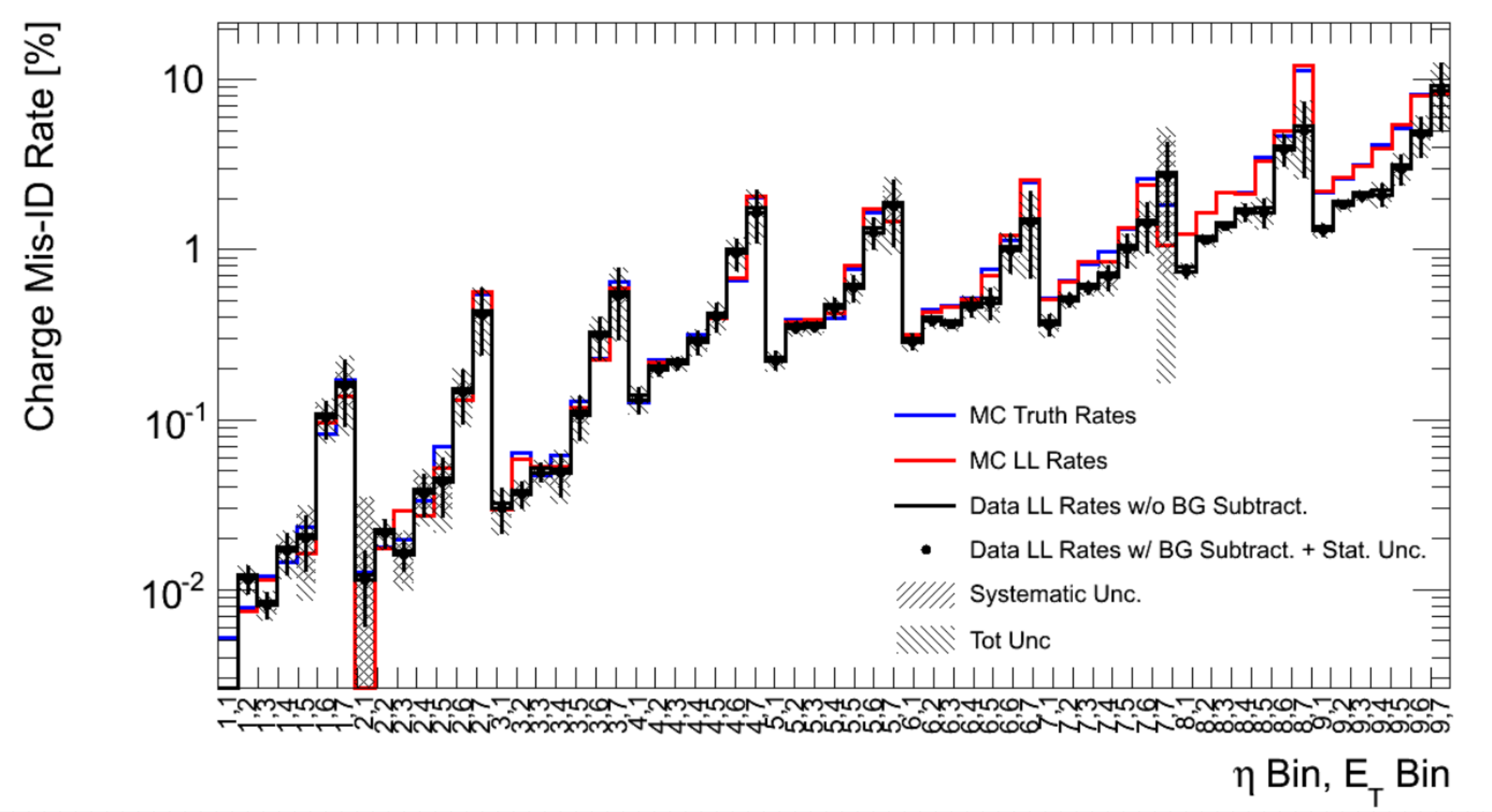
- Electrons' charge can be mis-identified because of bremsstrahlung.
- Evaluate the mis-identified rate as a function of Pt and η using two methods.
  - Truth: Compared reconstructed electrons to truth electrons.
  - Likelihood method:
    - Count the number of events in data around Z->ee peak with same sign pairs, Nss, and the total number N.
    - Using Poisson probability to construct log-likelihood distribution.
    - $lnL = \sum_{i,j=1}\{N_{ss}^{i,j}\ln\left[N^{i,j}(\varepsilon_i+\varepsilon_j)\right]-N^{i,j}(\varepsilon_i+\varepsilon_j)\}$
    - Maximize log-likelihood to extract rates.
- Then use the data-driven rates to reweight di-boson MC in 0SFOS region.
- Background subtraction performed using template fit.
  - Perform background subtraction for both Nss and N.
- Get a set of new rates without background contamination.
  - The difference with raw rate is treated as systematic.



Blue is fit.
Red is Signal.
Orange is polynomial function.
Black is data.

Electron Charge Mis-Identification

- Use rates measured from data with likelihood method as central values.
- Difference between truth and likelihood methods in MC used as systematic along with effect of background subtraction in data.
- MC Truth rate is compatible with MC likelihood rate which means likelihood method is implemented correctly.

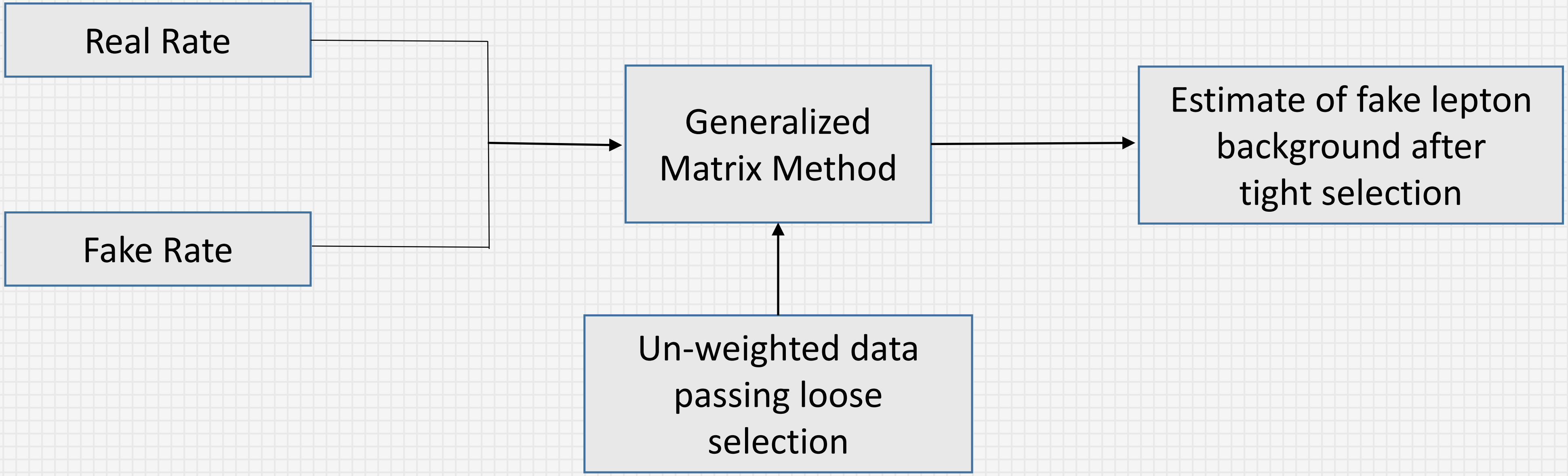


Fake Lepton Background

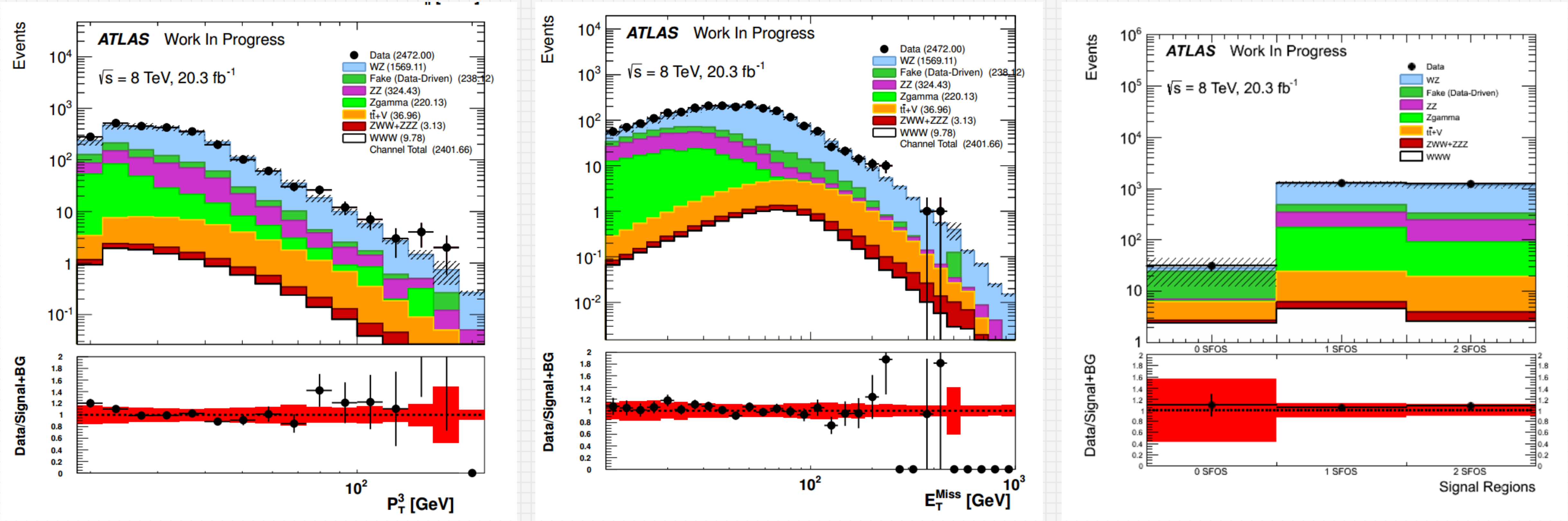
- Using Generalized Matrix Method to estimate any number of fake leptons.
- Adapted from estimation in SUSY analysis: ATL-COM-PHYS-2013-887
- Backgrounds can be split into two categories: Real and Fake.

$$\text{Fake Rate} = \frac{\#\text{Tight probes in data - }\#\text{Tight probes in real lepton MC}}{\#\text{All probes in data - }\#\text{All probes in real lepton MC}} \qquad \text{Real Rate} = \frac{\#\text{Tight probes in data}}{\#\text{All probes in data}}$$

- Rates are determined in control regions using tag and probe method enriched in either real or fake probe leptons.



Estimates at Pre-selection

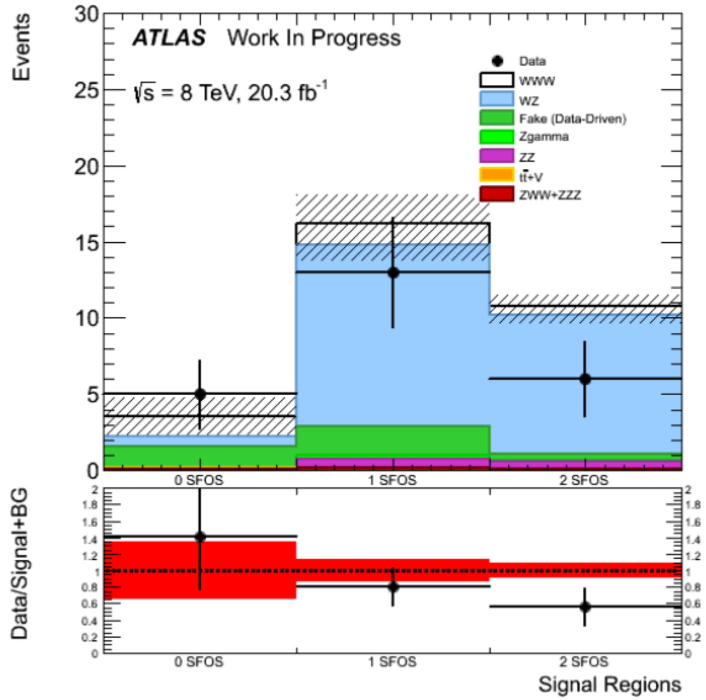


- From left to right: Minimum lepton Pt, MET and signal regions.
  - SFOS: same flavor opposite sign lepton pair
- Backgrounds are well modeled.

Signal Region

	0 SFOS	1 SFOS	2 SFOS
Pre-selection	Exactly 3 leptons with $P_T > 20$ GeV where at least one is trigger matched. (See Section 6.1)		
b-tagged Jet Veto	$N_{b-jet} = 0$ (85 % b-tagging efficiency)		
Same-Flavor Mass	$m_{SF} > 20$ GeV		
Z-Veto ($m_Z = 91.1876$ GeV)	$\lvert m_{ee} - m_Z\rvert > 15$ GeV	No m_{SFOS} with $m_Z - 35\text{GeV} < m_{SFOS} < m_Z + 20$ GeV	$\lvert m_{SFOS} - m_Z\rvert > 20$ GeV
Missing E_T		$E_T^{Miss} > 45$ GeV	$E_T^{Miss} > 55$ GeV
Lepton-Missing E_T Angle	$\lvert\phi(3l) - \phi(E_T^{Miss})\rvert > 2.5$		
Inclusive Jet veto	$N_{jet} \leq 1$		

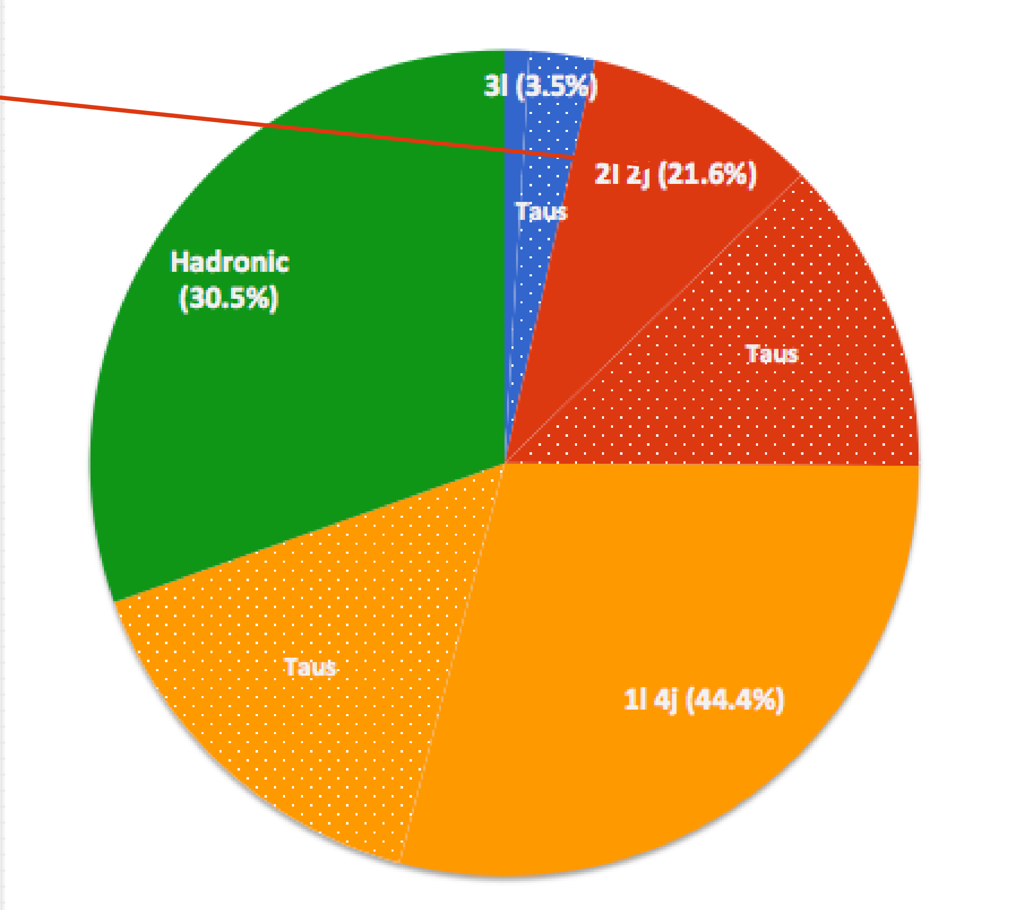
Table 15: Optimized signal selection split by number of Same-Flavor Opposite-Sign (SFOS) lepton pairs.



WWW Combination

Full Leptonic+Semi Leptonic

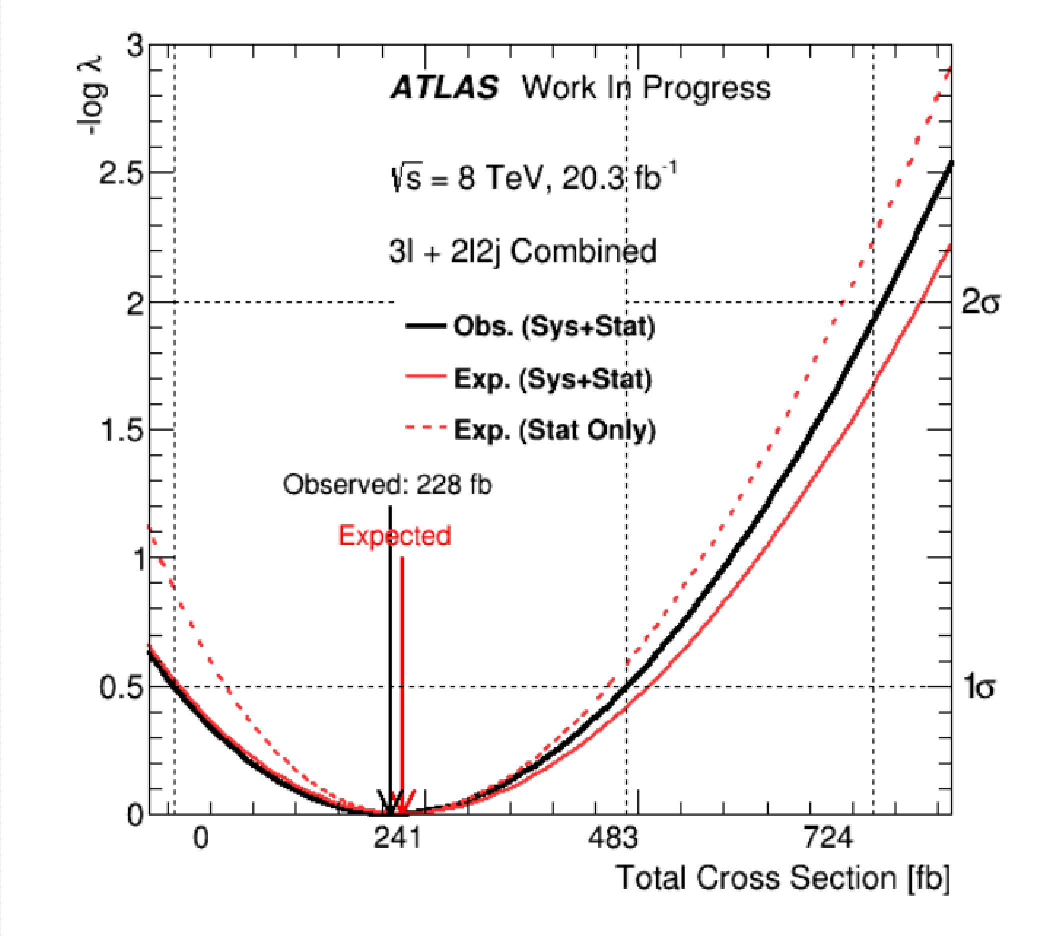
- There is another WWW analysis with 2l2j final state.
- Two analyses are now combined for cross section measurement and aQGC study.
- Now there are two separate internal notes for both analyses and also a combined note:
  - Semi leptonic internal note
    - ATL-COM-PHYS-2015-1374
    - https://cds.cern.ch/record/2022894
  - Combined internal note
    - ATL-COM-PHYS-2015-500
    - https://cds.cern.ch/record/2093523
- Will show the combined cross section measurement and the aQGC limits extraction.
- WWW combination:
  - Much of the treatment between the two analyses is similar.
  - Unify the systematics treatment.
  - Combine the channels of both analyses.



WWW Cross Section Measurement

- The discovery significance is tested using frequentist statistics to estimate the degree of compatibility with the background only hypothesis.
- The measurement and uncertainty are evaluated by using the shape of the profile likelihood ratio which is a function of the data and the signal strength.
- Combine the channels of both analyses to get the best possible measurement.
  - Full leptonic+Semi leptonic

- Observed total cross section is:
  - $227.66^{+201}_{-198}(Stat.)^{+155}_{-160}(Syst.)fb$
- Expected total cross section is:
  - $241.47^{+232}_{-199}(Stat.)^{+152}_{-153}(Syst.)fb$



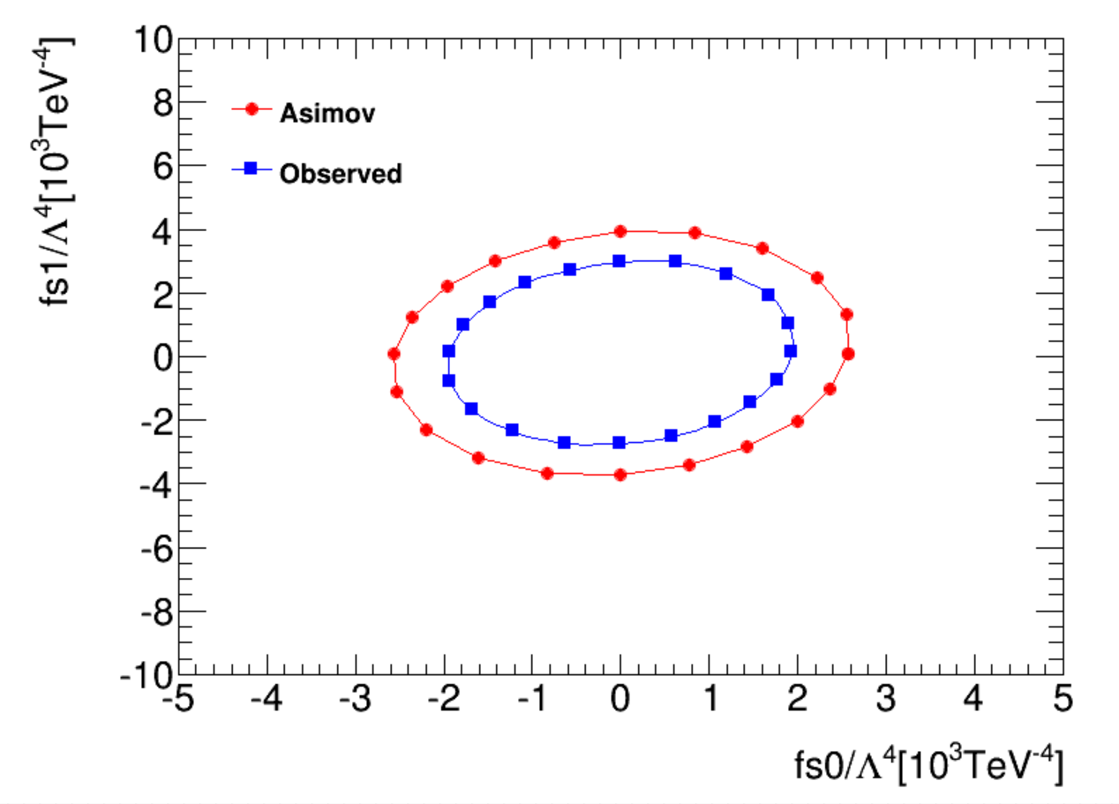
Anomalous Quartic Gauge Couplings

$$\mathcal{L}_{S,0} = \frac{f_0}{\Lambda^4}\left[(D_\mu\Phi)^\dagger D_\nu\Phi\right] \times \left[(D^\mu\Phi)^\dagger D^\nu\Phi\right]$$

$$\mathcal{L}_{S,1} = \frac{f_1}{\Lambda^4}\left[(D_\mu\Phi)^\dagger D^\mu\Phi\right] \times \left[(D_\nu\Phi)^\dagger D^\nu\Phi\right]$$

- Seek limits on the following dimension-8 operators in an effective field theory:
- Use TGClim to calculate the limits.
  - Calculate expected and observed limits.
- First set of non-unitarized combined limits are shown below:

	WWW(Combined)	
	$fs0/\Lambda^4$ [10^3TeV^{-4}]	$fs1/\Lambda^4$ [10^3TeV^{-4}]
Expected limits	[-2.527,2.540]	[-3.655,3.850]
Observed limits	[-1.9710,1.9533]	[-2.7973,3.0289]



- Unitarized limits now under study.

Conclusion and Future

- My contribution in this analysis：
  - Measurement of electron charge misID rate which has been finished.
  - aQGC limit extraction now on the way.

- Status of this analysis:
  - Already have 4 Editorial Board meetings.
  - SM approval on 10th Dec.
  - Looking forward for closure after Chrismas.

- Plan for Run II:
  - Plan to join the HWW group and work on 3-lepton channel.
  - Now getting started with HWW framework.

BACKUP

Object Selection of full leptonic channel

- Electrons:
  - (author is 1 or 3) and Tight++
  - PT > 10 GeV § $|\eta| < 1.37$ or $1.52 < |\eta| < 2.47$
  - I ETcone20/ET < 0.10 for pT > 20GeV
  - I ETcone20/ET < 0.07 for pT < 20GeV
  - I pTcone20/pT < 0.04
  - |d0/sigma d0| < 3.0
  - |z0/sigma z0| < 0.5mm
  - No duplicate μ or e within $\Delta R < 0.1$
- Jets:
  - Anti-kT 4 LC Topo Jets
  - PT > 25 GeV
  - $|\eta| < 4.5$
  - JVF > 0.5 for jets with $|\eta| < 2.4$ and PT < 50GeV
  - No duplicate μ or e within $\Delta R < 0.2$
- Muons:
  - Tight STACO Combined
  - PT > 10 GeV
  - $|\eta| < 2.5$
  - MCP ID Hits selection
  - I ETcone20/ET < 0.10 for pT > 20GeV
  - I ETcone20/ET < 0.07 for pT < 20GeV
  - I pTcone20/pT < 0.04
  - |d0/sigma d0| < 3.0
  - |z0/sigma z0| < 0.5mm
  - No duplicate e within $\Delta R < 0.1$

Backgrounds at Pre-selection of lll

	eee	$ee\mu$	$e\mu\mu$	$\mu\mu\mu$
WZ	240.85 ± 0.67	339.17 ± 0.82	422.07 ± 0.87	567.0 ± 1
ZZ	60.21 ± 0.13	54.1 ± 0.2	118.60 ± 0.31	91.48 ± 0.17
$Z\gamma$	70.1 ± 2.7	0.47 ± 0.22	149.4 ± 3.9	0.17 ± 0.12
$ZWW + ZZZ$	0.436 ± 0.019	0.834 ± 0.027	1.00 ± 0.03	0.864 ± 0.028
$t\bar{t} + V$	4.854 ± 0.044	9.549 ± 0.064	12.047 ± 0.072	10.510 ± 0.066
Fake (data-driven)	45.1 ± 2.2	37.8 ± 1.6	112.7 ± 2.8	42.5 ± 1.2
WWW	0.784 ± 0.011	3.077 ± 0.023	4.041 ± 0.026	1.876 ± 0.018
Expected Background	421.6 ± 3.5	441.9 ± 1.8	815.8 ± 4.9	712.5 ± 1.6
Expected Signal + Background	422.4 ± 3.6	445.0 ± 1.8	819.8 ± 4.9	714.4 ± 1.6
Observed Data	426 ± 21	468 ± 22	821 ± 29	757 ± 28

Table 39: Expected and observed event yields binned by lepton flavor combination at event pre-selection. Only statistical uncertainties are shown.

Fiducial cross section for full leptonic channel

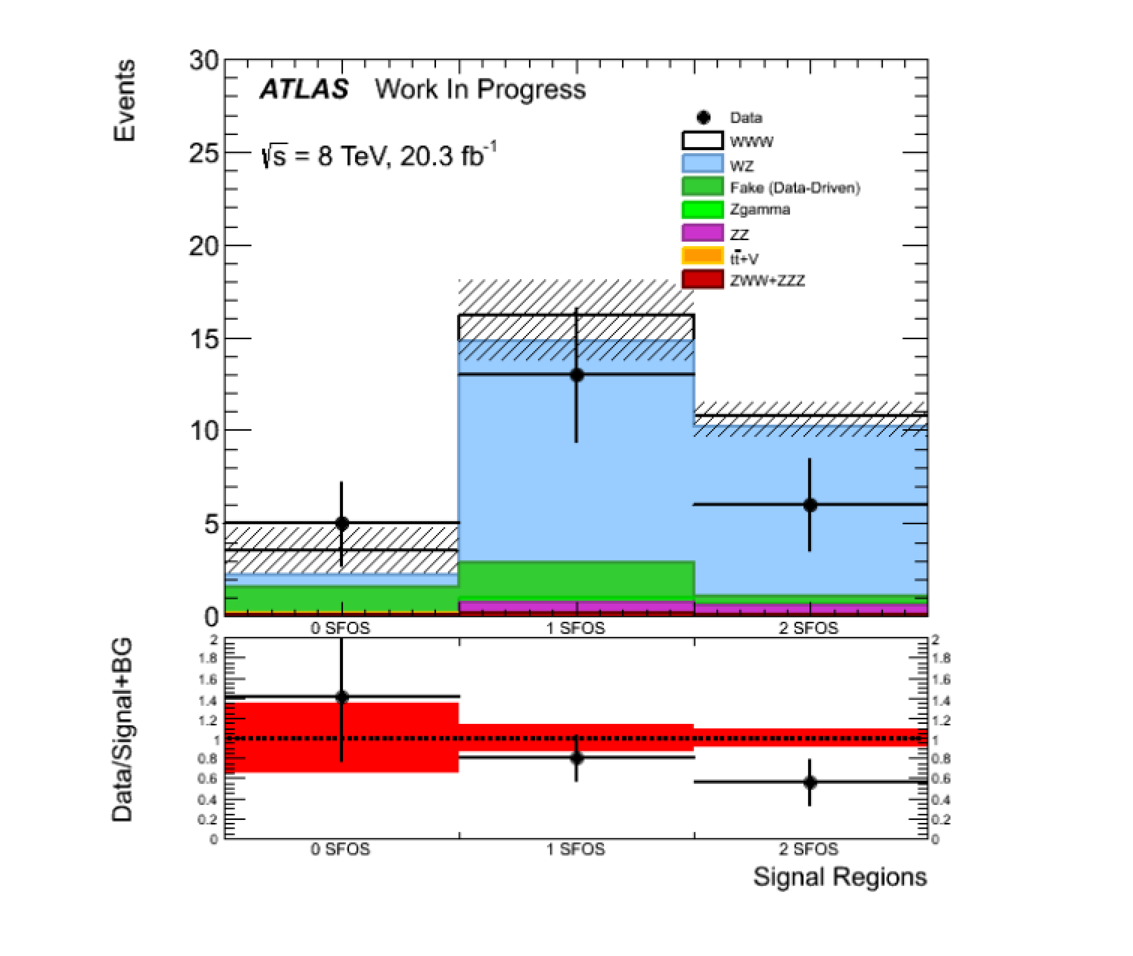
	0 SFOS	1 SFOS	2 SFOS
All	All		
Tau Veto	$N_\tau < 1$		
Fiducial Leptons	Exactly 3 leptons with $p_T > 20$ GeV and $\|\eta\| < 2.5$		
Lepton Overlap Removal	$\Delta R(\ell\ell) > 0.1$		
Same-Flavor Mass	$m_{\mathrm{SF}} > 20$ GeV		
Z-Veto ($m_Z = 91.1876$ GeV)	$\|m_{ee} - m_Z\| > 15$ GeV	No m_{SFOS} with $m_Z - 35\mathrm{GeV} < m_{\mathrm{SFOS}} < m_Z + 20$ GeV	$\|m_{\mathrm{SFOS}} - m_Z\| > 20$ GeV
Missing E_T		$E_T^{Miss} > 45$ GeV	$E_T^{Miss} > 55$ GeV
Lepton-Missing E_T Angle	$\|\phi(3l) - \phi(E_T^{Miss})\| > 2.5$		
Inclusive Jet veto	$N_{jet} \leq 1$ with fiducial jets of $p_T > 25$ GeV and $\|\eta\| < 4.5$		

Table 16: Fiducial regions based on optimized selection.

Sample	Fiducial Cross-section [fb]			
	0 SFOS	1 SFOS	2 SFOS	All
$W^+W^-W^+$	0.0384 ± 0.0029	0.0374 ± 0.0028	0.0141 ± 0.0019	0.0900 ± 0.0048
$W^-W^+W^-$	0.0212 ± 0.0025	0.0199 ± 0.0025	0.0065 ± 0.0015	0.0476 ± 0.0043
$W^+H \to W^+W^+W^-(*)$	0.0414 ± 0.0016	0.0521 ± 0.0018	0.01791 ± 0.00095	0.1114 ± 0.0029
$W^-H \to W^-W^+W^-(*)$	0.02261 ± 0.00085	0.02740 ± 0.00093	0.01028 ± 0.00054	0.0603 ± 0.0015
Sum	0.1236 ± 0.0047	0.1369 ± 0.0047	0.0488 ± 0.0029	0.3092 ± 0.0072

Table 17: Fiducial cross-sections for NLO MadGraph samples with CT10 NLO pdfs calculated in the three different signal regions and for the sum of all three signal regions. Cross-sections are shown separately for the different charge modes and for resonant and non-resonant production along with their sum.

Signal Regions



- Yields after full selection for 0,1,2 SFOS regions.

Fiducial cross section for semi leptonic channel

Cut Name	Details
Tau Veto	Remove any events associated with Tau's
Lepton Selection	At least 2 leptons with $P_T > 15$ GeV
Jet Selection	At least 2 jets with $P_T > 15$ GeV
Same-sign Leptons	Leptons must have the same electric charge
Final Lepton Selection	Exactly Two leptons with $P_T > 30$ GeV, $\lvert\eta\rvert < 2.5$
$\Delta R_{\ell\ell}$	$\Delta R_{\ell\ell} > 0.1$ to remove any possible faulty lepton containers
$M_{\ell\ell}$	$M_{\ell\ell} > 40$ GeV
Z Veto	$\lvert M_{ee} - M_Z\rvert < 20$ GeV (only for the ee channel)
Final Jet Selection	Leading(Sub) jet $P_T > 30$ (20) GeV and $\lvert\eta\rvert < 2.5$
$\Delta R_{\ell j}$	min $\Delta R_{\ell j} > 0.3$
MET	MET > 55 GeV (Not applied for the $\mu\mu$ channel)
b-jet Veto	Remove any events that contain any b-tagged jets
ΔR_{jj}	$\Delta R_{jj} < 1.5$ to make sure that the two jets come from the W boson decay
W mass window cut	Two leading jets should have 65 GeV $< M_{jj} <$ 105 GeV
jet-jet rapidity	$\lvert\Delta y(jj)\rvert < 1.5$

Table 4: Description of fiducial selection for each of the semi-leptonic channels.

	Channel	Fiducial Cross-section [ab]
Fully-leptonic	0 SFOS	123.6 ± 4.7
	1 SFOS	136.9 ± 4.7
	2 SFOS	48.8 ± 2.9
Semi-leptonic	ee	50.4 ± 2.5
	$e\mu$	125.2 ± 3.8
	$\mu\mu$	129.9 ± 3.9

Fake Lepton Background

- Using Generalized Matrix Method to estimate any number of fake leptons.
- Adapted from estimation in SUSY analysis: ATL-COM-PHYS-2013-887
- Backgrounds can be split into two categories: Real and Fake.

$$\text{Fake Rate} = \frac{\#\text{Tight probes in data - \# Tight probes in real lepton MC}}{\#\text{All probes in data - \#All probes in real lepton MC}}$$

$$\text{Real Rate} = \frac{\#\text{Tight probes in data}}{\#\text{All probes in data}}$$

- Rates are determined in control regions using tag and probe method enriched in either real or fake probe leptons.

	Electrons	Muons
Loose	Central electrons (author is 1 or 3) P_T > 10 GeV $\lvert\eta\rvert$ < 1.37 or 1.52 < $\lvert\eta\rvert$ < 2.47 Medium++ Object quality flag $\lvert d_0/\text{sigma } d_0\rvert < 3.0$ $\lvert z_0 \sin(\theta)\rvert$ < 0.5 mm	Tight STACO Combined P_T > 10 GeV $\lvert\eta\rvert$< 2.5 MCP ID Hits selection $\lvert d_0/\text{sigma } d_0\rvert < 3.0$ $\lvert z_0 \sin(\theta)\rvert$ < 0.5 mm
Tight	Tight++ P_T cone 20 / P_T < 0.04 E_T cone 20 / E_T < 0.07 if P_T < 20 GeV E_T cone 20 / E_T < 0.10 if P_T > 20 GeV	P_T cone 20 / P_T < 0.04 E_T cone 20 / E_T < 0.07 if P_T < 20 GeV E_T cone 20 / E_T < 0.10 if P_T > 20 GeV

Fake Rate Dilepton Control Regions

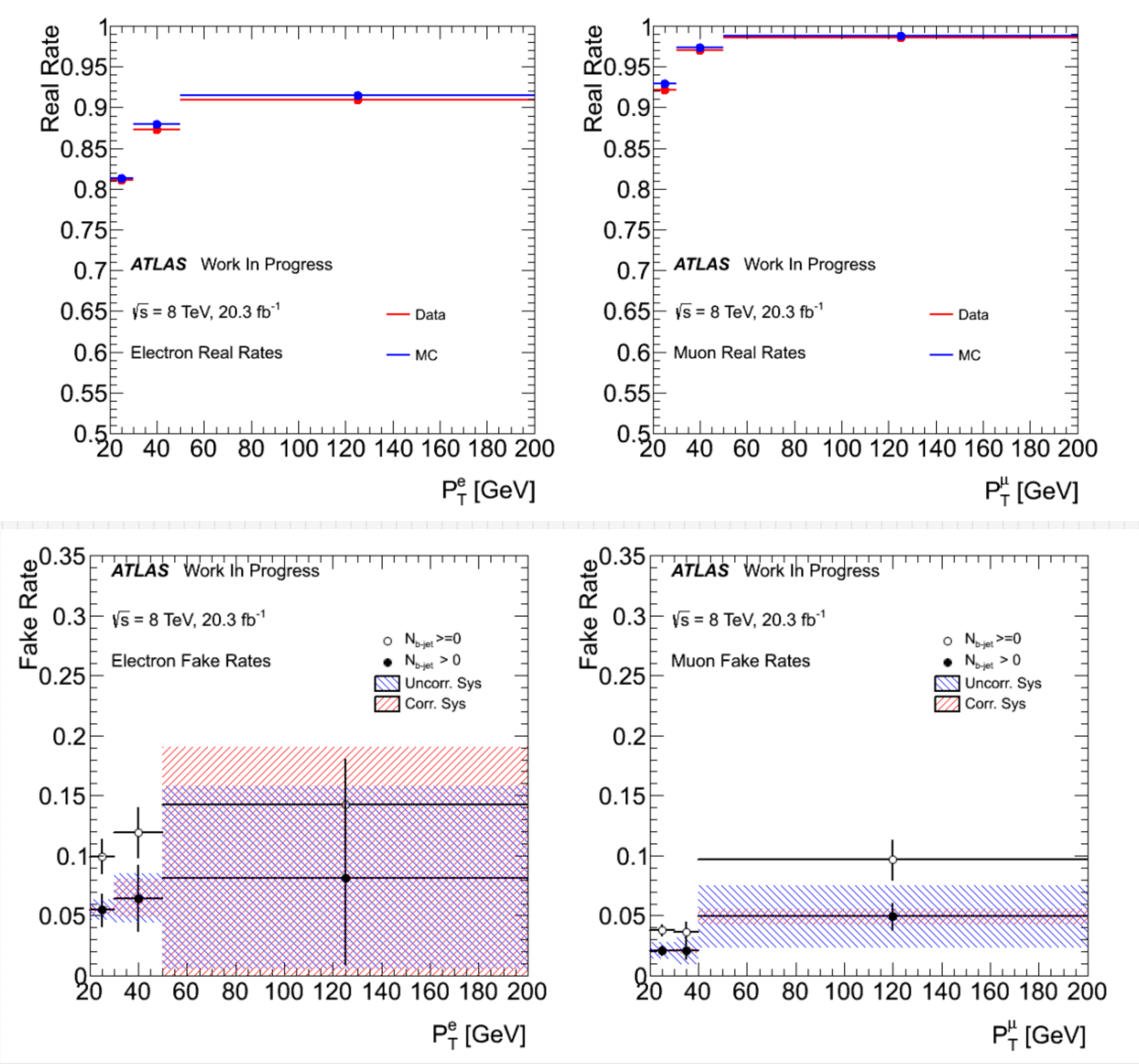
Event Selection	▪ Single lepton trigger ▪ Exactly 2 Loose leptons ▪ Both leptons required to have same sign ▪ MET > 10 GeV
Electron CR	**Tag**: Tight μ that is trigger matched. P_T > 40 GeV **Probe**: Loose e
Muon CR	**Tag**: Tight μ that is trigger matched. P_T > 40 GeV **Probe**: Loose μ

Real Rate Dilepton Control Regions

Event Selection	▪ Single lepton trigger ▪ At least 1 Loose SFOS pair inside Z-window of |m-90 GeV| < 15 GeV
Electron CR	**Tag**: Tight e that is Trigger Matched **Probe**: Loose e
Muon CR	**Tag**: Tight μ that is trigger matched **Probe**: Loose μ

Real and Fake Rate

- Final real rates are evaluated in both data and in MC.
- The difference is taken as a systematic.



- The final fake rates are evaluated along with some systematic variations:
  - Composition: Change b-jet selection in control regions
  - Correlated: Scale Real and MC estimates by +/- 20%
  - Uncorrelated: Vary Pt and MET cuts