Search for Tribosons in ATLAS

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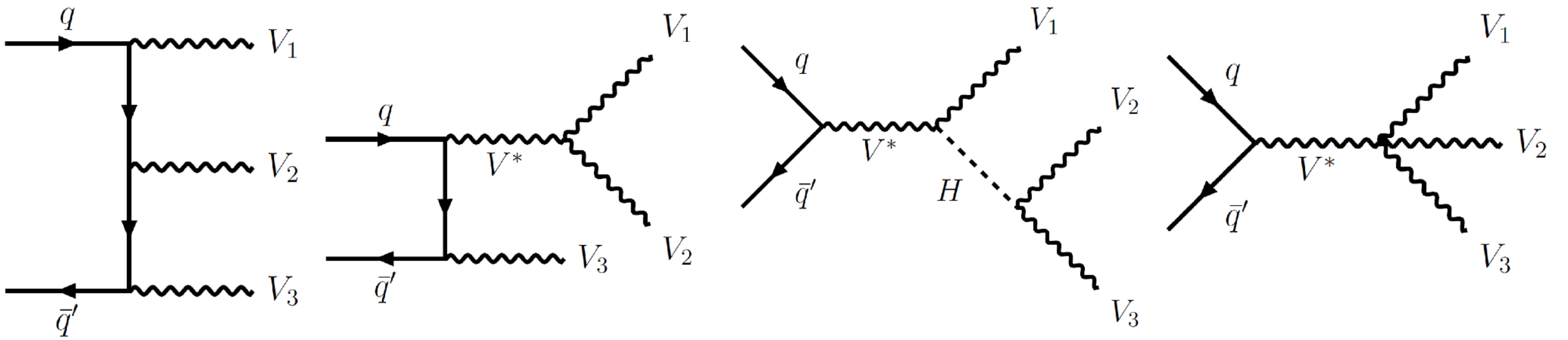
ATLAS EXPERIMENT

Why Tri-Bosons

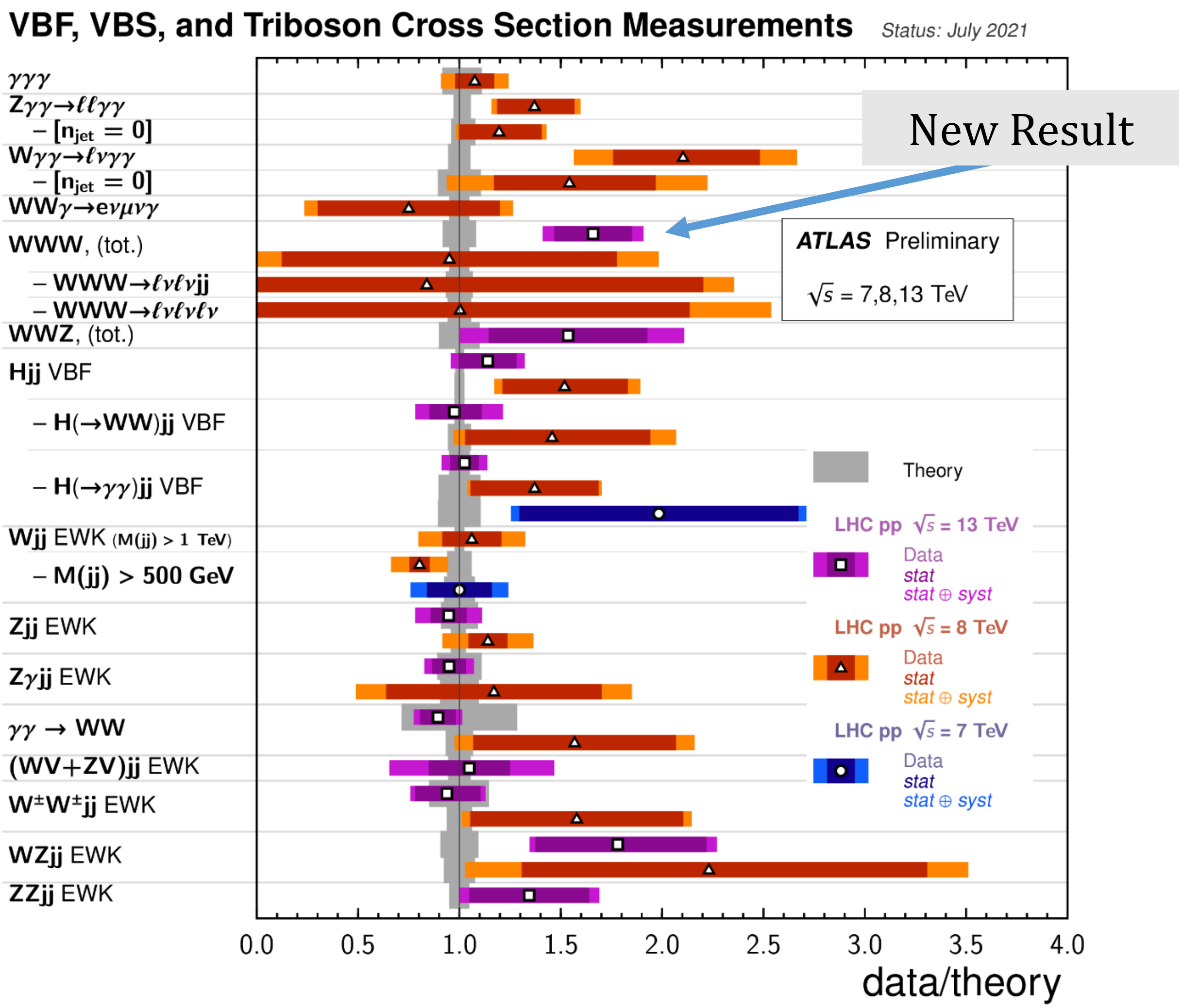
- Direct measurement of gauge boson self-coupling and precision test of SM



- Finely balanced cancellations between QGC, TGC, Higgs amplitudes is needed to preserve unitarity at high CM energies.
- Any anomalous HVV, QGC and TGC coupling can disturb the balance and create large cross-sections at high energies.
- Complementary to vector boson scattering measurements

Summary of Triboson Measurements

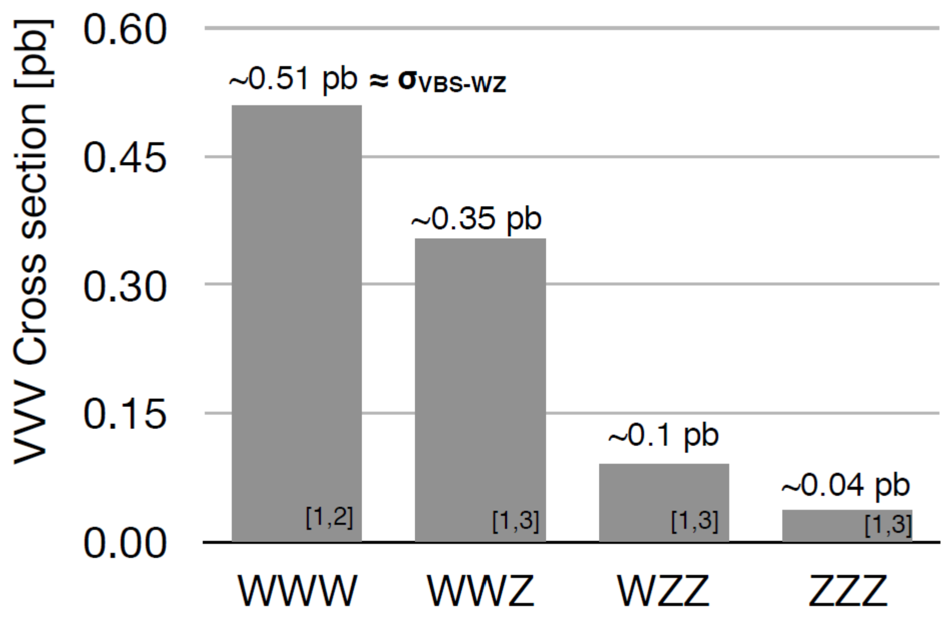
- Photon have no electric charge and Z have no weak-hyper charge
- Only charged TGC and QGC are allowed in SM:
  - WWZ, WWγ
  - WWWW, WWZZ, WWZγ, WW γ γ
- Prevalence of ISR and FSR photons hamper constraints on aQGC in channels with photons



Summary of Previous Triboson Measurements

- First evidence for WWW and WWZ at ATLAS in 2019
  - Partial Run 2 dataset 80 fb^{-1}
  - Observed: WVV 4.1 σ, WWW 3.2σ
  - Physics Letter B. 2019

- First observation of VVV at CMS in 2020
  - Full Run 2 dataset 137 fb^{-1}
  - Observed: VVV 5.7σ, WWW 3.3σ
  - Physics Review Letters 2020



From Philip Chang
https://indico.cern.ch/event/823181/contributions/3466223/attachments/1886506/3110079/PhilipChang20190725_LPCMBWorkshop.pdf

New WWW Cross-Section Measurement

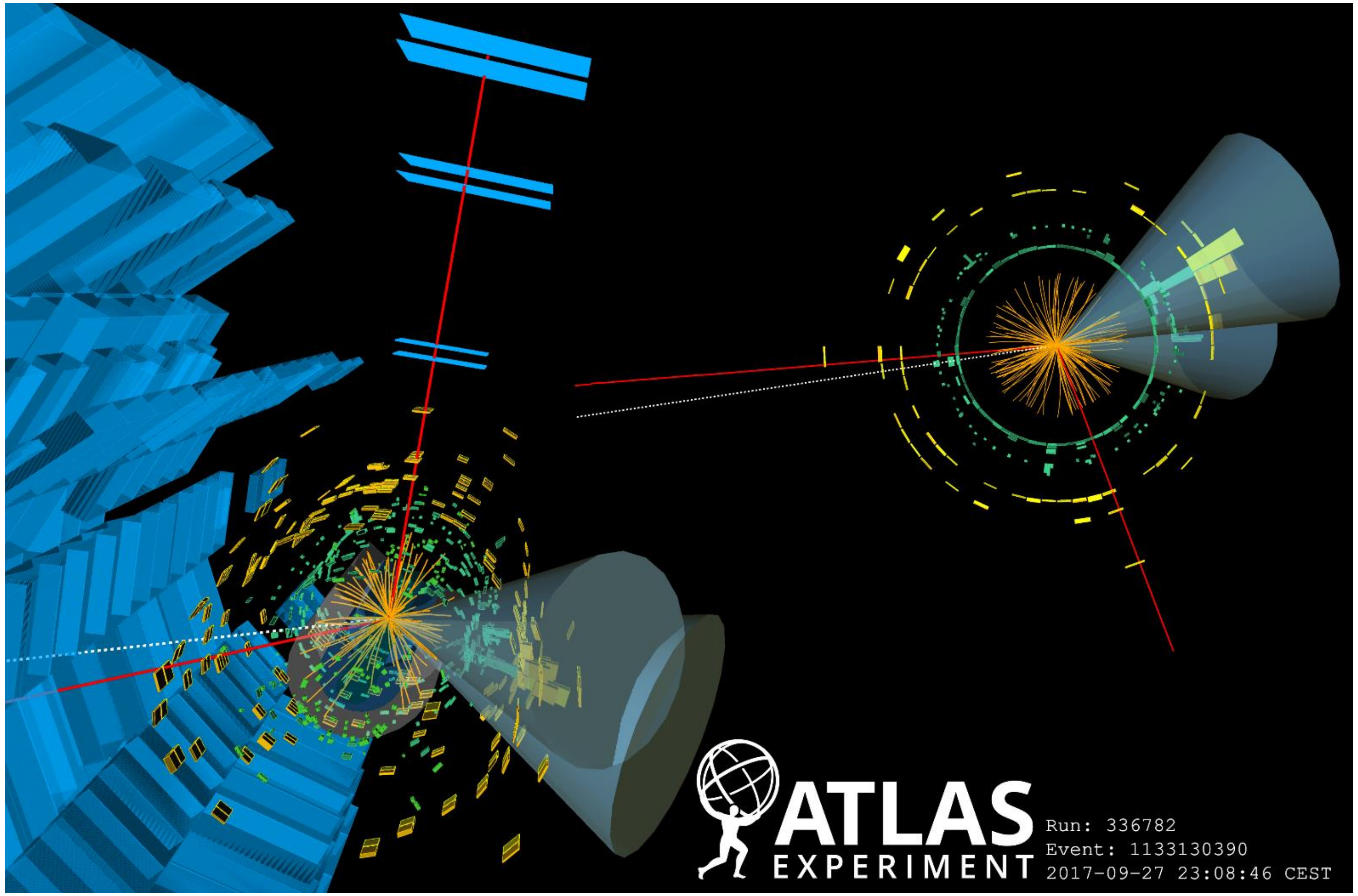
- Analysis principle: Avoid opposite signed, same flavor pairs of leptons (OSSF)
  - Avoids SM processes that pair produce oppositely charged leptons

	Detector Signatures			
$W^{\pm}W^{\pm}W^{\mp} \to 2l2\nu 2j$	$e^{\pm}e^{\pm}jj + E_T^{miss}$	$e^{\pm}\mu^{\pm}jj + E_T^{miss}$		$\mu^{\pm}\mu^{\pm}jj + E_T^{miss}$
$W^{\pm}W^{\pm}W^{\mp} \to 3l3\nu$	$e^{\pm}e^{\pm}\mu^{\mp} + E_T^{miss}$		$\mu^{\pm}\mu^{\pm}e^{\mp} + E_T^{miss}$	

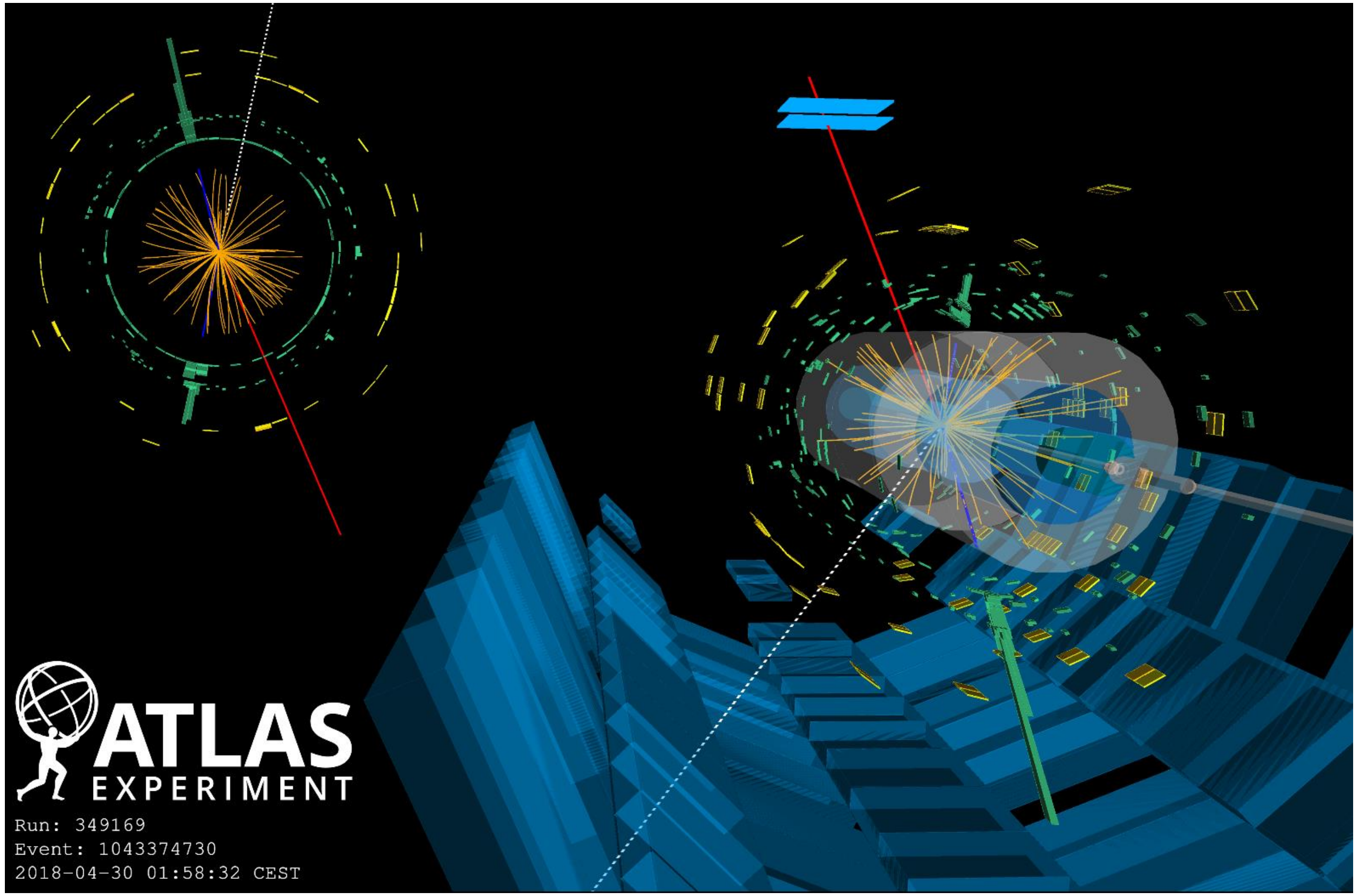
- Same signed lepton pair from the two same signed W
- Two jets or a lepton of a different flavor from the third W
- Missing transverse energy from the neutrinos

- https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/CONFNOTES/ATLAS-CONF-2021-039/

WWW → μνμνjj Candidate



WWW → μνeνeν Candidate



WWW Simulation

- WWW Monte Carlo used for the WWW analysis are simulated to NLO accuracy in QCD and LO accuracy in EW

	Generator	Accuracy QCD	Accuracy EW
On-Shell WWW	Sherpa 2.2.2	NLO	LO
WH → WWW*	Powheg (ME) + Pythia 8 (PS)	NLO	LO

- Inclusive theoretical cross-section is 511 $\pm$ 42 fb calculated with NLO electroweak correction is used as the baseline theoretical cross-section
- N3LO QCD + NLO EWK correction predicts 505 fb for the total inclusive cross-section
  - $pp \rightarrow W^-W^+W^+$ $\quad 136^{+6}_{-5}$ (scale) $\pm$ 4 (PDF) fb
  - $pp \rightarrow W^+W^-W^-$ $\quad 76^{+4}_{-3}$ (scale) $\pm$ 2 (PDF) fb
  - $pp \rightarrow WH \rightarrow WWW^*$ $\quad 293^{+1}_{-2}$ (scale) $^{+6}_{-5}$ (PDF) fb

Major Backgrounds

1. SM process that produce > 3 leptons but one is lost
   - WZ, ZZ where a lepton is not detected
   - WZ, ZZ where $Z \rightarrow \tau\tau$
2. Non-prompt leptons originating from hadronic jets
3. $V\gamma$ events where the photon is misidentified as an electron
4. Electron charge mis-identification

(1: estimated by normalizing MC to data)

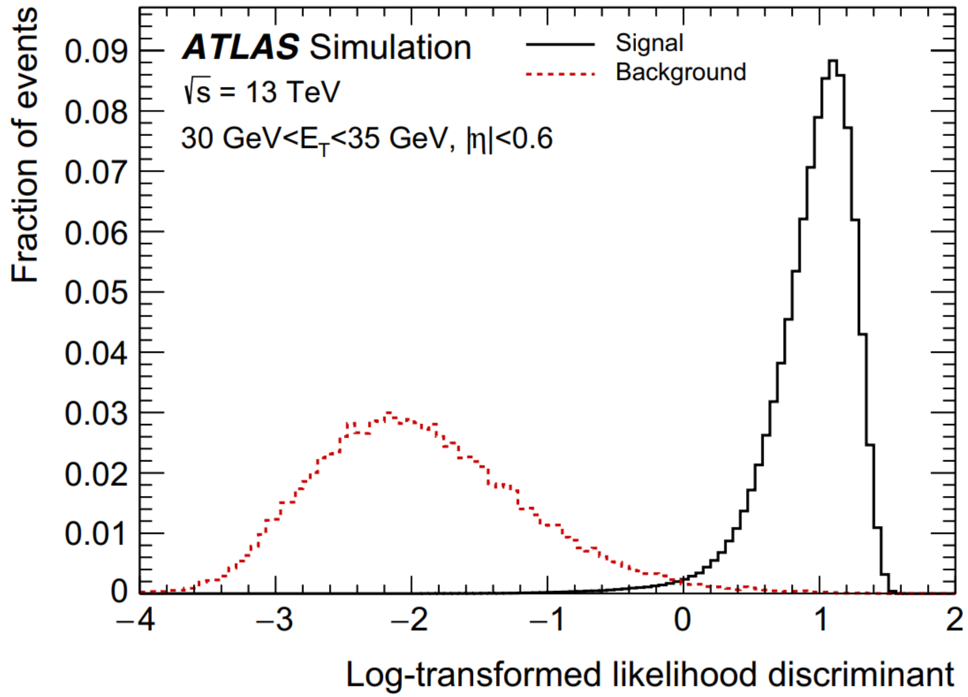
(2–4: Fully estimated in-situ using data)

Selecting High Quality Electron/Muons

- Selection of high quality leptons is critical for minimizing the rate of background due to mis-reconstruction

- Require electron + muon objects have high reconstruction "quality"
- Require that the electron+muons are isolated from other activities in the detector
- Reject electrons who's charge may have been mis-identified

Electron Reconstruction "Quality"



https://link.springer.com/content/pdf/10.1140/epjc/s10052-019-7140-6.pdf

2l2j Signal Region Design

Rejects non-prompt bkg from J/ψ, ϒ, γ^* + jets

Rejects Charge Flip Electrons from $Z \to ee$

Rejects non-prompt lepton from b-decays (tt, wt etc)

Rejects WW VBS

2l2ν2j Signal Region		
$e^\pm e^\pm$	$e^\pm \mu^\pm$	$\mu^\pm \mu^\pm$
No SFOS pairs, no 3rd lepton		
Leading lepton pT > 27 GeV		
$40 < m_{ll} < 400$ GeV		
$m_{ee} < 80$GeV || 100 GeV $< m_{ee}$		
≥ 2 jets, $m_{jj} < 160$ GeV, $\lvert\Delta\eta_{jj}\rvert < 1.5$		
no b quark jet		
E_T^{miss} significance > 3		

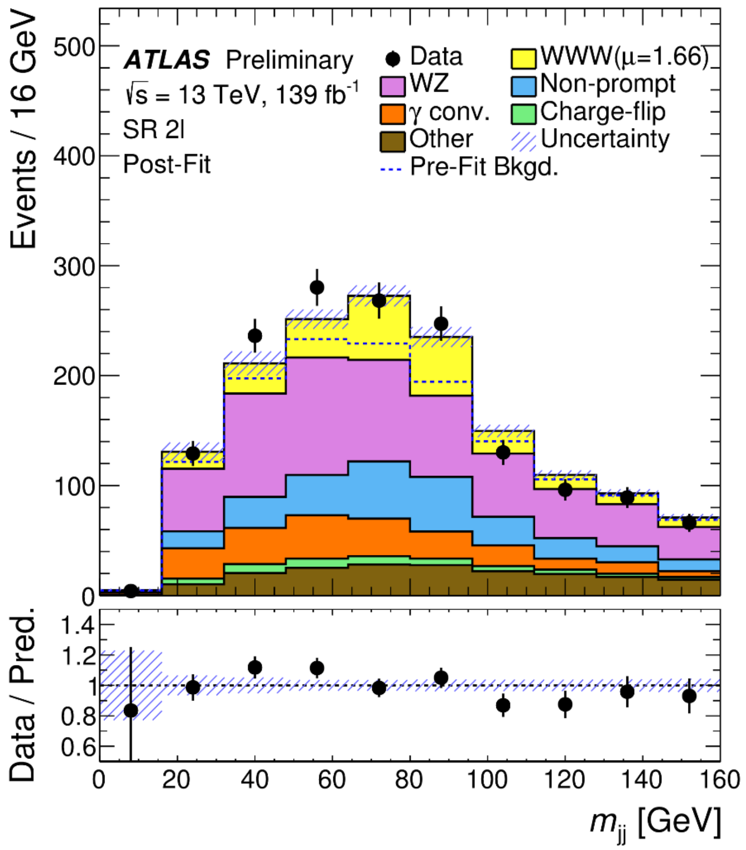
3l3ν Signal Region

3l3ν Signal Region
$e^{\pm}e^{\pm}\mu^{\mp}$ or $e^{\mp}\mu^{\pm}\mu^{\pm}$
No OSSF pairs
No 4th lepton
Leading lepton pT $>$ 27 GeV
Sum of lepton charge $= 1$ ($++-$ or $--+$)
no b-jets

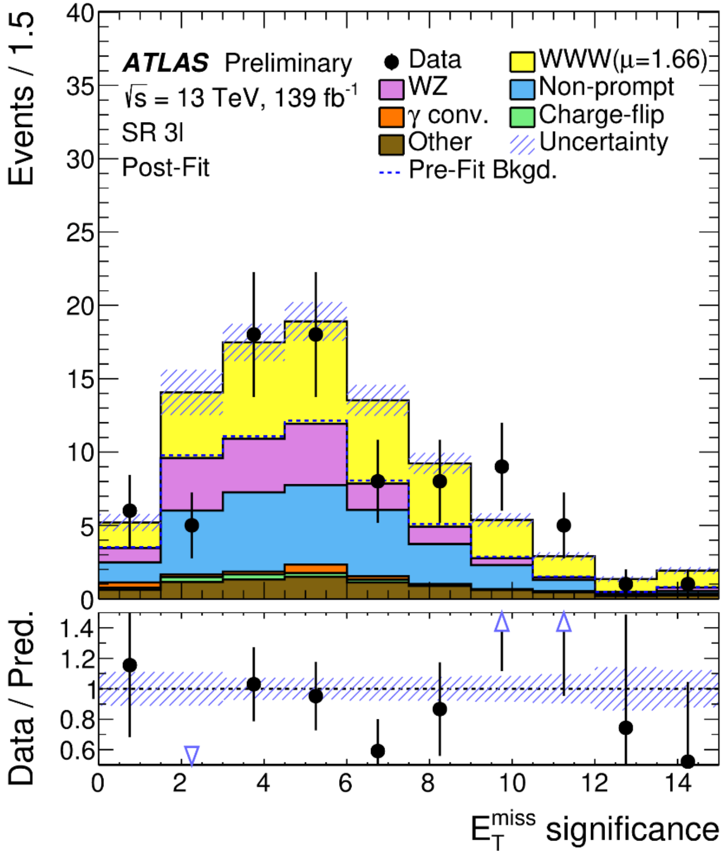
Rejects non-prompt lepton from b-decays (tt, wt etc)

Signal Region Distributions

2l2j Signal Region

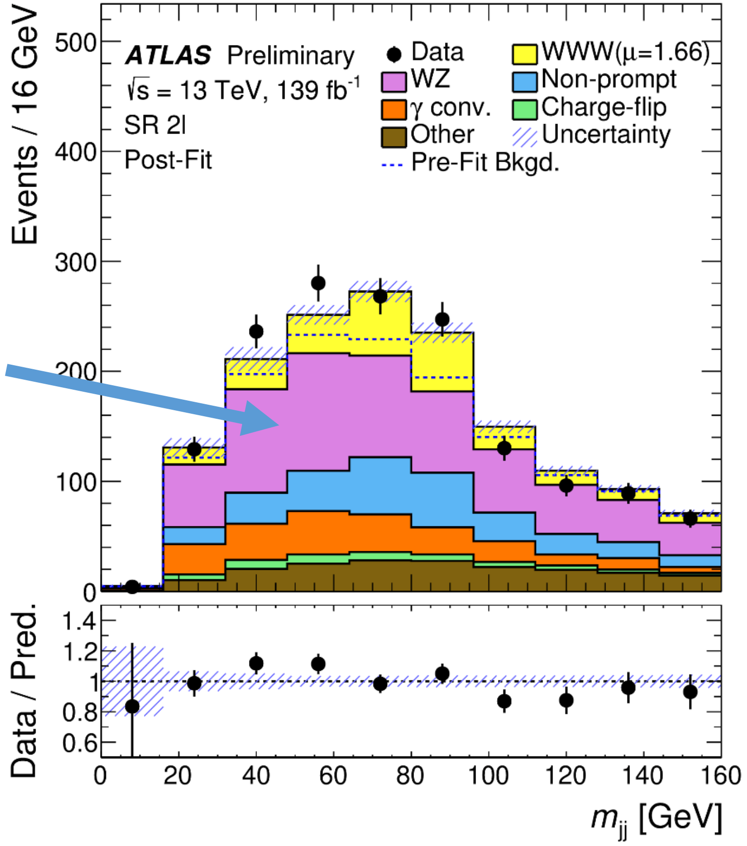


3l3ν Signal Region



Background Estimation: WZ

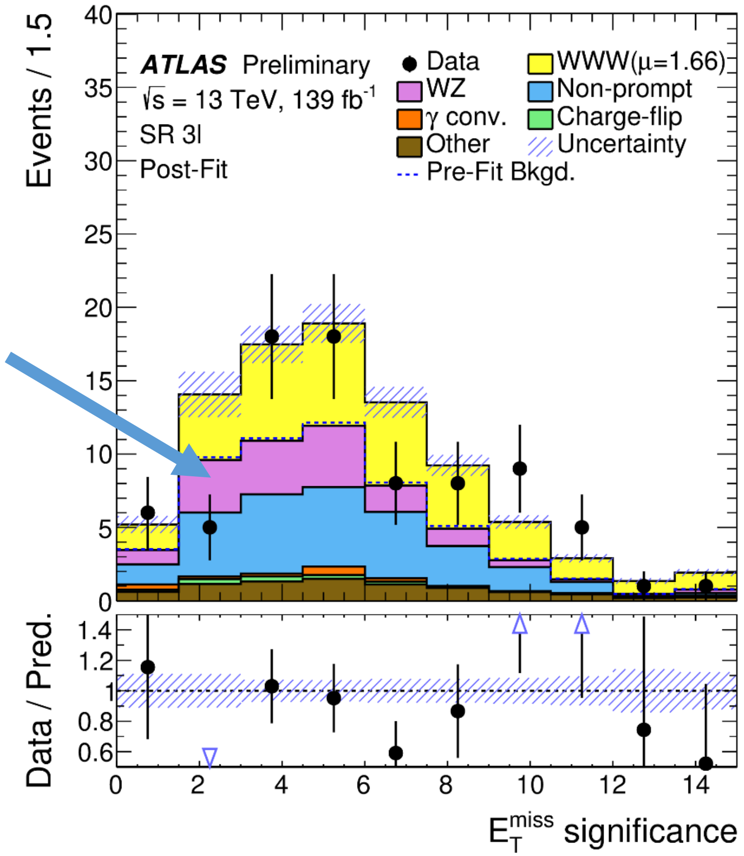
2l2j Signal Region



Mainly
WZ + 2jets

1 lost lepton
or Z→ττ

3l3ν Signal Region



Mainly
WZ + 0jets

Mainly
Z→ττ

WZ Control Region

WZ 0 jet CR	WZ 1 jet CR	WZ 2 jet CR
3 leptons with 1 $e^{\pm}e^{\mp}$ or $\mu^{\pm}\mu^{\mp}$ pair		
Triggering Lepton must have pT > 27 GeV		
No 4th lepton		
No b-quark jets		
E_T^{miss} significance > 3		
110 GeV < m_{lll} < 500 GeV		
0 jets	1 jet	≥ 2 jets

Reject Z/γ^{*} + jets → (E_T^{miss} significance > 3; 110 GeV < m_{lll} < 500 GeV)

WZ Monte Carlo Scale Factors

Signal Strength	Normalization Factors		
$\mu(WWW)$	$WZ + 0$ jets	$WZ + 1$ jet	$WZ + \geq 2$ jets
1.66 ± 0.28	1.12 ± 0.11	0.98 ± 0.04	0.88 ± 0.18

WZ Monte Carlo is generated with Sherpa 2.2.2 to NLO accuracy in QCD
The WZ MC is scaled according to the number of jets in the event

WZ + 0 jet and WZ + 1 jet dominate the 3l3ν signal region
WZ+2jet dominate the 2l2j signal region

Background Estimation: Non-prompt Lepton

- Background where b-hadrons, c-hadrons decaying semi-leptonically are mis-reconstructed as prompt leptons
- $t\bar{t}$ is the main contributor to the 3l3ν channel
- $t\bar{t}$ and W+b-jets are the main contributors to the 2l2j channel
- Estimated in data using control region rich in $t\bar{t}$

Control Region rich in $t\bar{t}$	Factor Derivation in Control Region	
2l2j selection + 1 b-jet	2 high quality leptons ←	1 lepton that fail some quality/isolation section
3l3ν selection + 1 b-jet	3 high quality leptons ←	1 lepton that fail some quality/isolation selection

- Simultaneous fit to # of data events in green and yellow regions derives the factor between # of leptons that fail quality selection vs # of lepton that pass but originate from hadrons

Non-Prompt Background Estimation

Signal Region	Apply factor		
2l2j signal region selection	2 high quality leptons	←	1 lepton that fail some quality/isolation section
3l3ν signal region selection	3 high quality leptons	←	1 lepton that fail some quality/isolation selection

- Applying the derived factor to the data events in yellow predicts the # of events in green

Photon Mis-ID Background Estimation

- Estimated in region rich in $Z\gamma$ events where the photon originates from FSR $Z \rightarrow ll\gamma$

- Photons can convert to electrons through scattering off of detector material
- "electrons" without a hit on the inner most tracker layer are more likely to be mis-identified photons

	Factor Derivation in Control Region	
Control Region rich in $Z\gamma$	All high quality leptons ←	1 electron don't have hit in the inner most layer of the tracker

- Simultaneous fit to # of data events in green and yellow regions derives the factor between electrons that fail quality selection vs # of electrons that pass but are actually mis-identified photons

Photon Mis-ID Background Estimation

Signal Region	Apply factor	
2l2j signal region selection	2 high quality leptons ←	1 electron don't have hit in the inner most layer of the tracker
3l3ν signal region selection	3 high quality leptons ←	1 electron don't have hit in the inner most layer of the tracker

- Applying the derived factor to the data events in yellow predicts the # of events in green due to photon mis-identification

Electron Charge-Flip Background Estimation

- Electron charge can be mis-reconstructed for example when electron path is changed due to bremsstrahlung

- Estimated in region rich in $Z \rightarrow$ ee events

	Factor Derivation in Control Region	
Control Region rich in $Z \rightarrow ee$	Same-signed ee ←	Opposite signed electrons

- Simultaneous fit to # of data events in green and yellow regions derives the factor between electrons that fail quality selection vs # of electrons that pass but are actually mis-identified photons

Electron Charge-Flip Background Estimation

Signal Region	Apply factor	
2l2j signal region selection	2 same signed leptons ←	Opposite signed electron
3l3ν signal region selection	No opposite signed, same flavor lepton pairs ←	Opposite signed electron

- Applying the derived factor to the data events in yellow predicts the # of events in green due to electron charge flip

Signal Region Yields

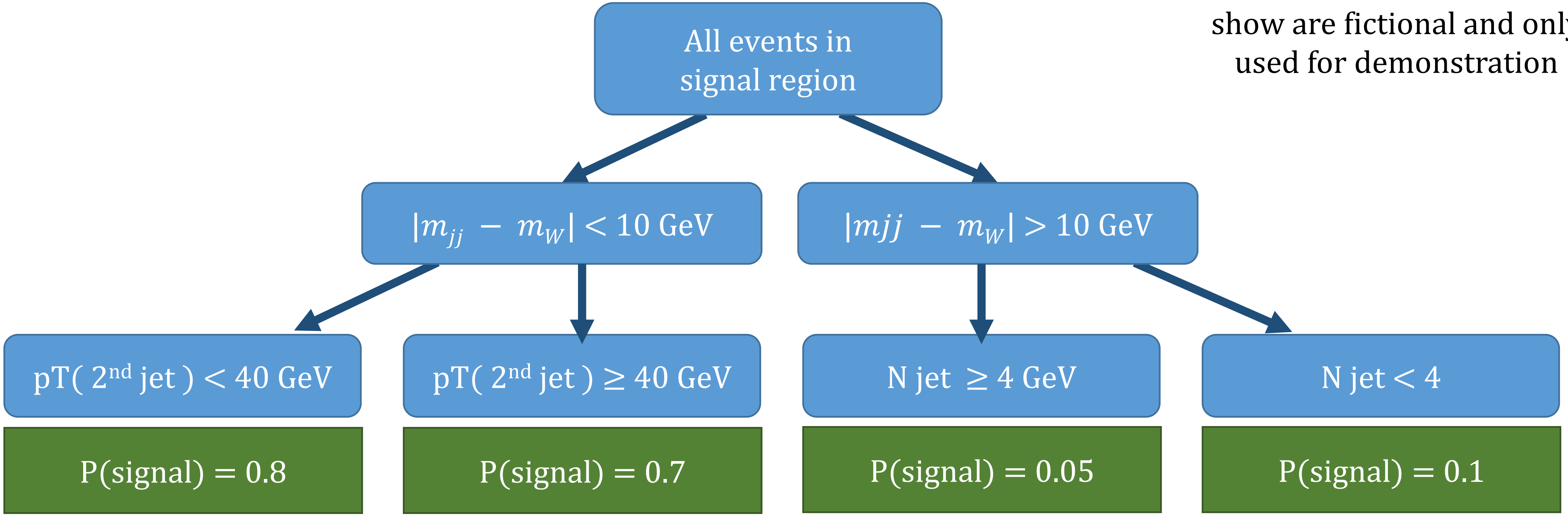
	$e^{\pm}\ e^{\pm}$	$e^{\pm}\mu^{\pm}$	$\mu^{\pm}\mu^{\pm}$	3ℓ
WWW	29.3 ± 4.4	128 ± 19	84 ± 12	35.8 ± 5.2
WZ	80.6 ± 5.7	344 ± 22	171 ± 10	16.4 ± 1.4
Charge-flip	30.3 ± 7.2	18.8 ± 4.5	–	1.7 ± 0.4
γ conversions	62.1 ± 8.7	142 ± 15	–	1.5 ± 0.1
Non-prompt	16.6 ± 4.1	138 ± 24	98 ± 21	26.3 ± 2.9
Other	22.8 ± 3.7	102 ± 15	59.7 ± 9.0	8.0 ± 0.9
Total predicted	242 ± 11	872 ± 22	414 ± 17	89.7 ± 5.4
Data	242	885	418	79

Boosted Decision Tree

- We apply a boosted decision tree to the signal regions to further separate signal from background
- Two BDTs are trained for the 2l2j and 3l3ν signal regions
- We used the package XGBoost:
  - https://dl.acm.org/doi/pdf/10.1145/2939672.2939785

Decision Trees

*Numbers and selections show are fictional and only used for demonstration



Ensemble of Decision Trees

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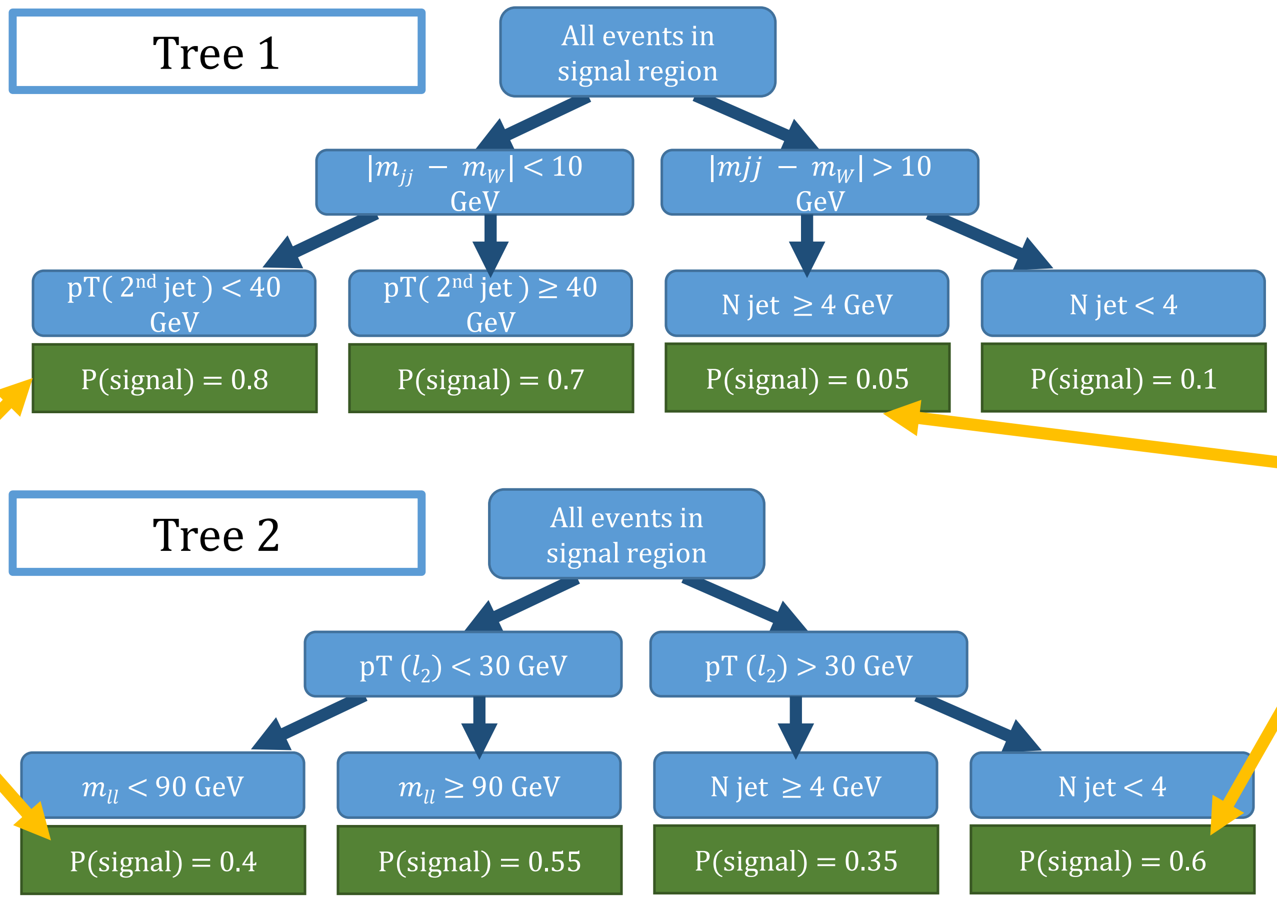


10th event belongs to these two "leafs"

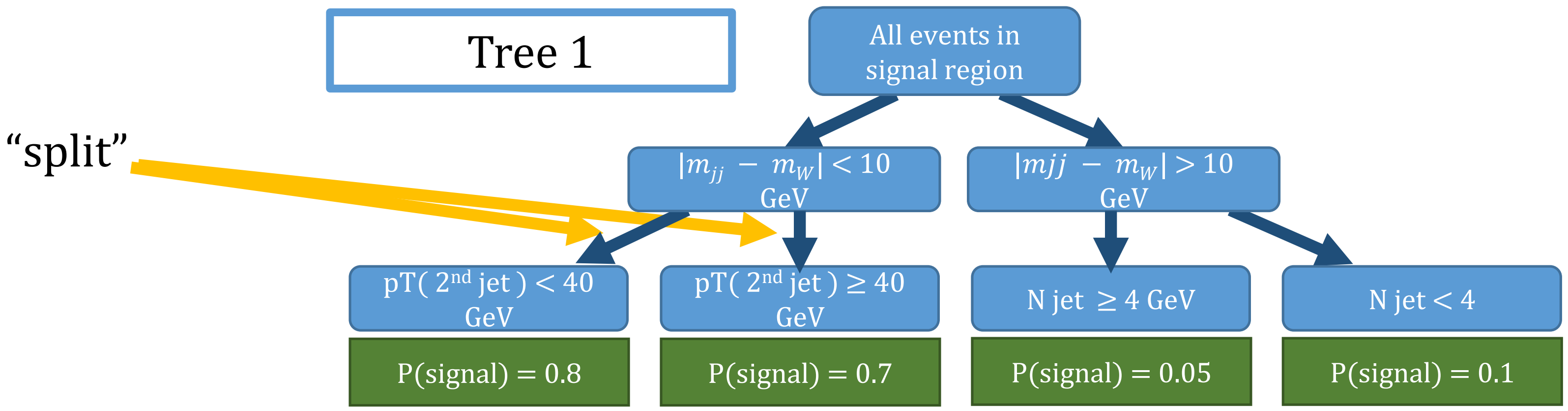
10th event 'score' $= 0.8 + 0.6 = 1.4$

11th event belongs to these two "leafs"

11th event 'score' $= 0.05 + 0.6 = 0.65$

An ensemble of individual weak classifiers can make a strong classifier*

Tree Optimization



*Numbers and selections show are fictional and only used for demonstration

- Algorithmically pick the best variables to "split" on and use gradient decent to find the most optimal value to cut.
- The BDT is optimized to minimize the "loss"

$$\mathcal{L}(\phi) = \sum_i l(\hat{y}_i, y_i) + \sum_k \Omega(f_k) \quad \text{where } \Omega(f) = \gamma T + \frac{1}{2}\lambda \|w\|^2$$

# of leaves

Avoid single extreme weights

Sum of loss over i events

Sum of loss over k trees

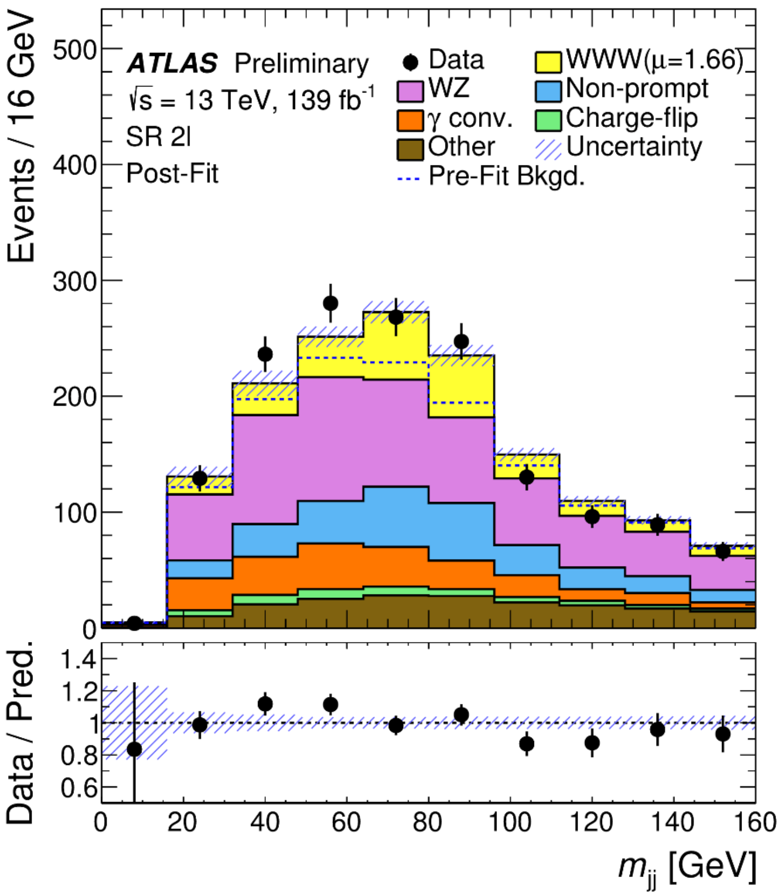
Penalty for k-th tree's complexity

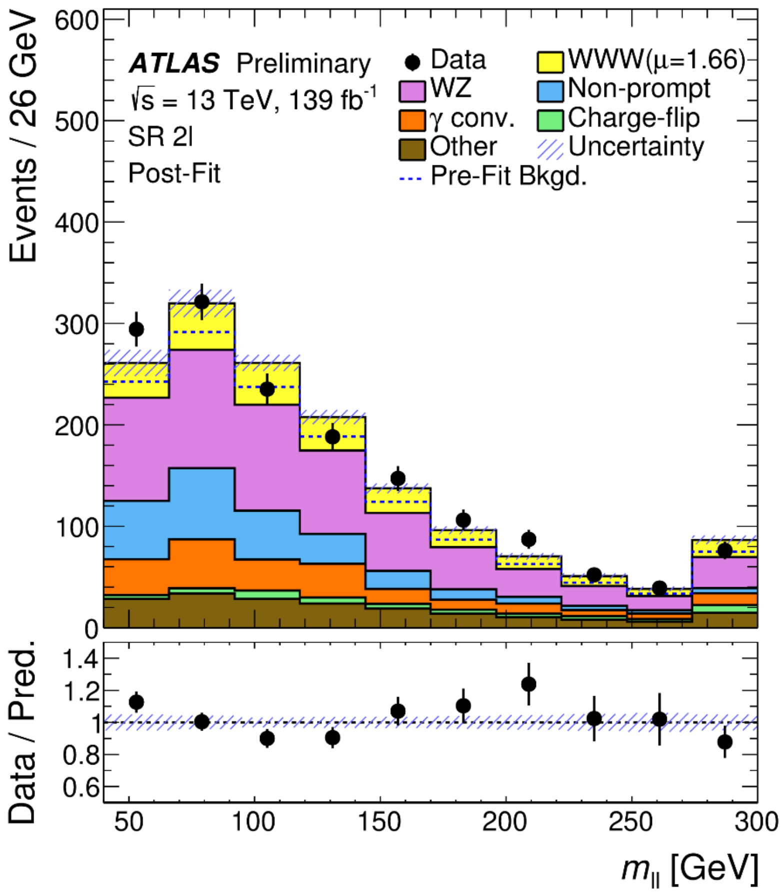
Boosted Decision Tree Variables

- Input variables are chosen for their feature importance and lack of correlation with other variables
- Importance = increase in purity caused by splitting on that variable
- More important variables are listed first

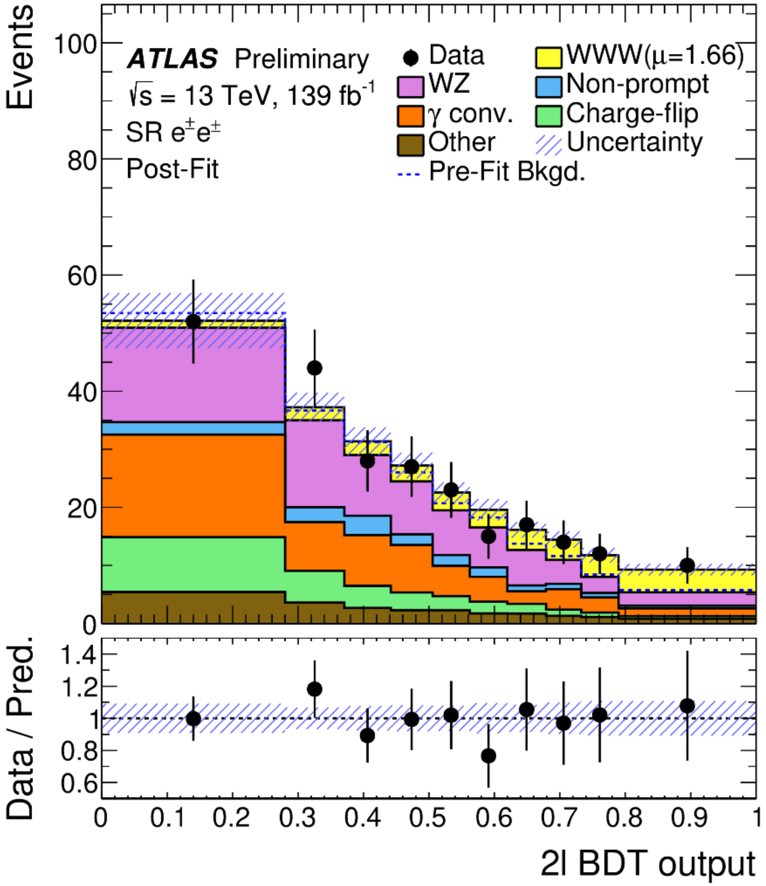
2ℓ	3ℓ
$\lvert m_{jj} - m_W \rvert$	$E_{\mathrm{T}}^{\mathrm{miss}}$ significance $\times 10 / E_{\mathrm{T}}^{\mathrm{miss}}$
p_{T} (forward jet)	$p_T(\ell_2)$
$E_{\mathrm{T}}^{\mathrm{miss}}$ significance	N(jets)
$p_T(j_2)$	same flavor $m_{\ell\ell}$
minimum $m(\ell, j)$	$m_T(\ell\ell\ell, E_{\mathrm{T}}^{\mathrm{miss}})$
$m(\ell_2, j_1)$	$m(\ell_2, \ell_3)$
N(jets)	$\Delta\phi(\ell\ell\ell, E_{\mathrm{T}}^{\mathrm{miss}})$
p_{T} (ℓ_2)	minimum $\Delta R(\ell, \ell)$
$m_{\ell\ell}$	p_{T} (ℓ_3)
$\lvert \eta(\ell_1) \rvert$	$m_T(\ell_2, E_{\mathrm{T}}^{\mathrm{miss}})$
N(leptons in jets)	$E_{\mathrm{T}}^{\mathrm{miss}}$ significance
$m(\ell_1, j_1)$	

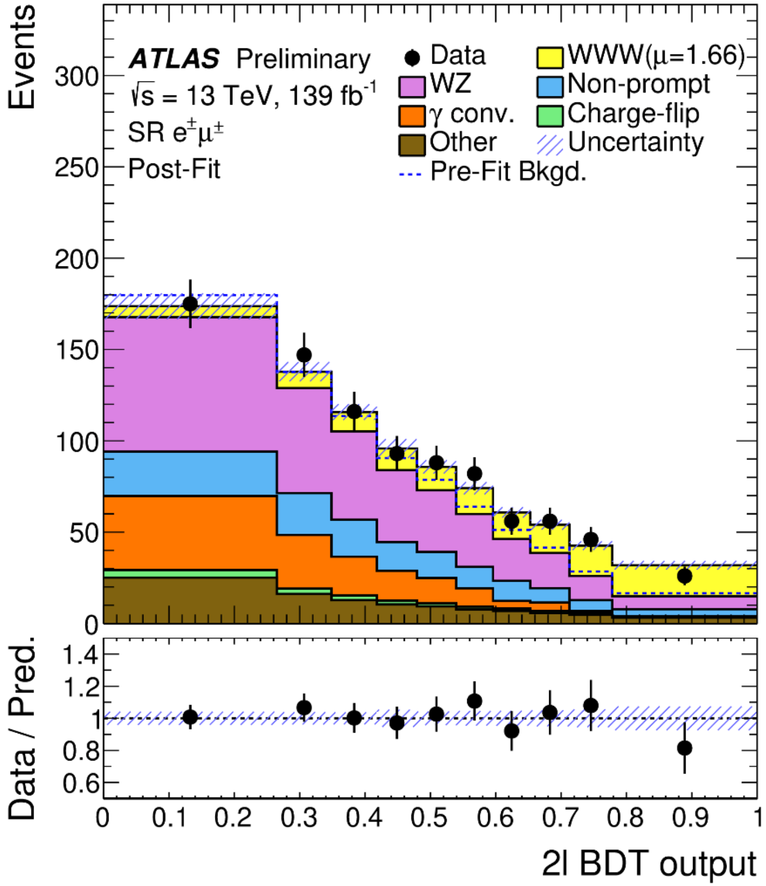
Distributions of BDT Input Variables



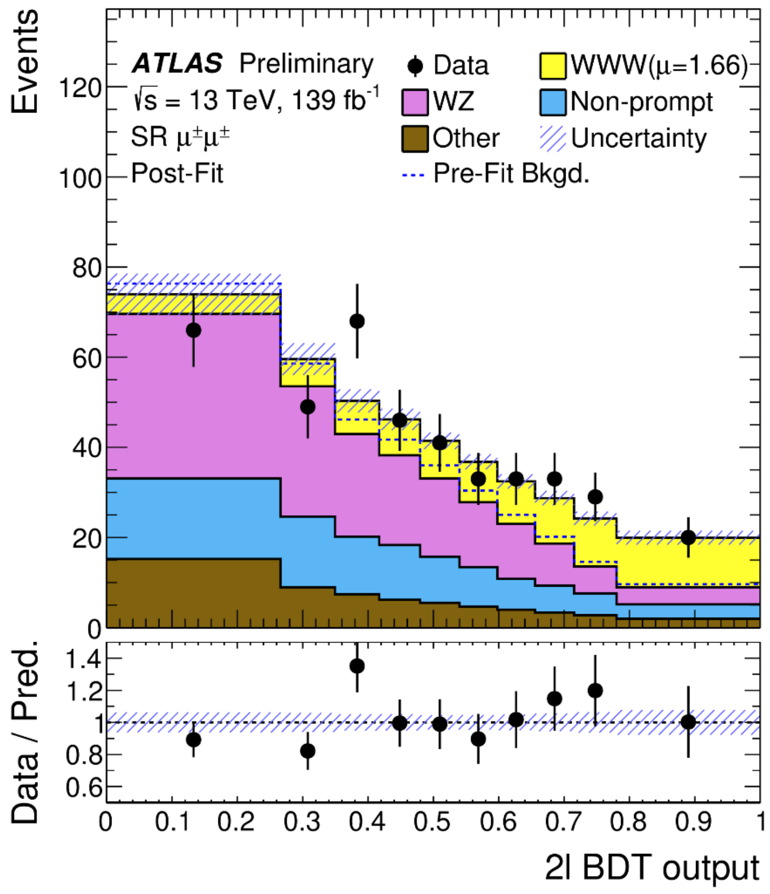


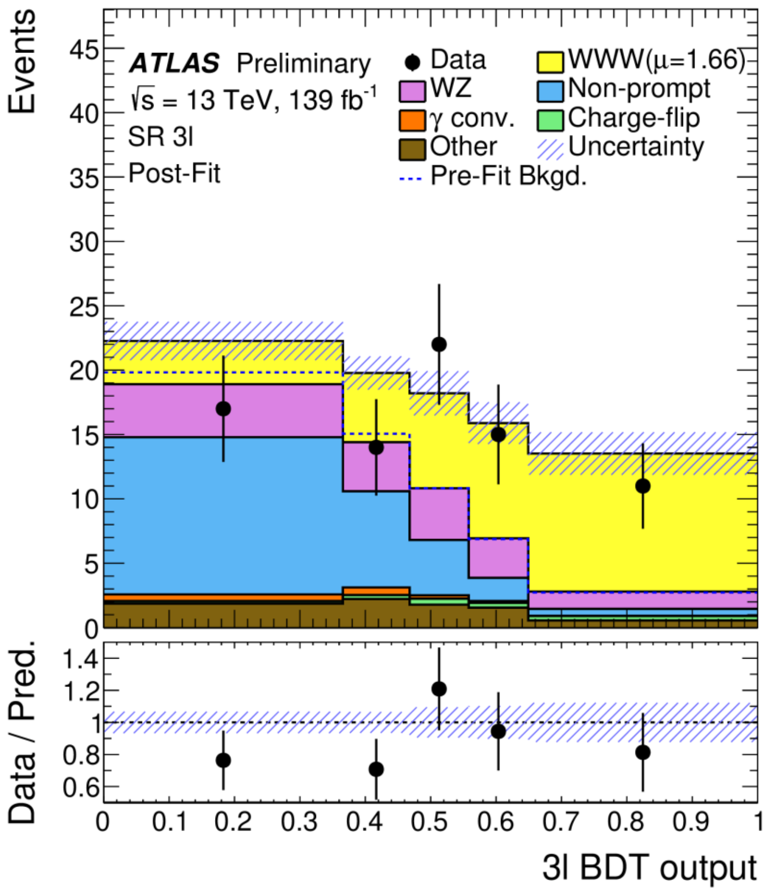
BDT Distribution in Signal Region





BDT Distribution in Signal Region



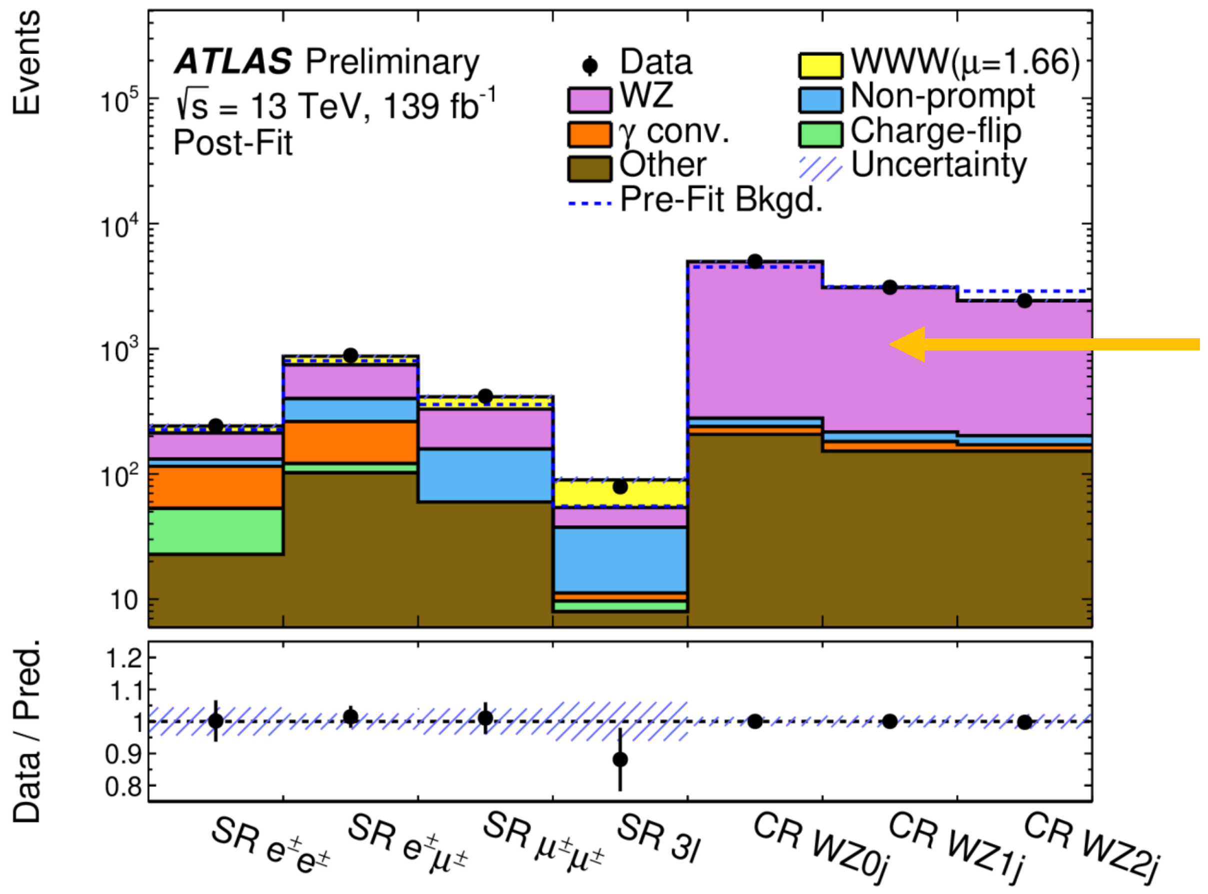


Fitting and Signal Strength Extraction

Fitted Regions	Fitted Distributon	N_{bins}
$e^{\pm}e^{\pm}jj$ signal region	BDT	10
$e^{\pm}\mu^{\pm}jj$ signal region	BDT	10
$\mu^{\pm}\mu^{\pm}jj$ signal region	BDT	10
$3l3\nu$ signal region	BDT	5
WZ 0 jet control region	m_{lll}	5
WZ 1 jet control region	m_{lll}	5
WZ 2 jet control region	m_{lll}	5

- Signal strength is extracted by simultaneous binned log-likelihood fitting of all signal regions and the WZ control regions

Signal and Control Region Yields



Much higher statistics in WZ control region serves to constrain the WZ rate in the signal region

Observed Signal Strength

Fit	Observed (expected) significances [σ]	$\mu(WWW)$
$e^{\pm}e^{\pm}$	2.3 (1.4)	1.69 ± 0.79
$e^{\pm}\mu^{\pm}$	4.6 (3.1)	1.57 ± 0.40
$\mu^{\pm}\mu^{\pm}$	5.6 (2.8)	2.13 ± 0.47
2ℓ	6.9 (4.1)	1.80 ± 0.33
3ℓ	4.8 (3.7)	1.33 ± 0.39
Combined	**8.2 (5.4)**	$\mathbf{1.66 \pm 0.28}$

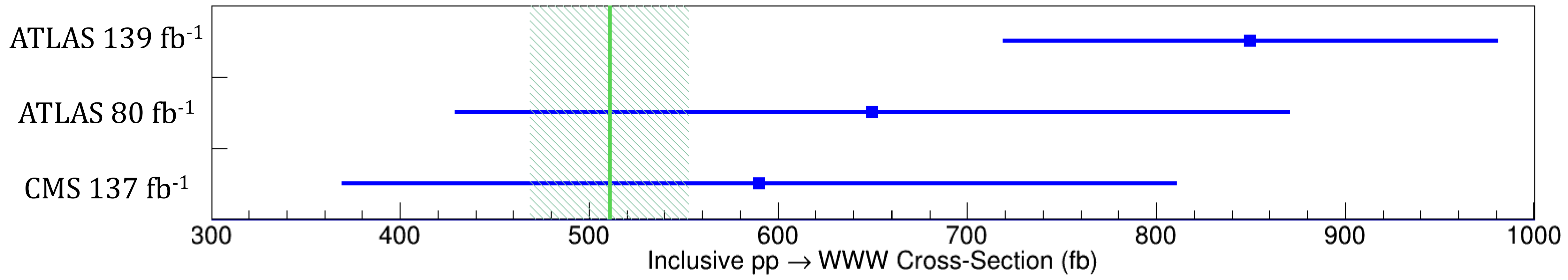
The inclusive WWW production cross section is measured to be
850 ± 100 (stat.) $\pm$ 80 (syst.) fb
Standard model predicts 511 ± 42 fb

Systematic Uncertainties

Uncertainty source	$\Delta\sigma/\sigma$ [%]
Data-driven background	5.3
Prompt-lepton-background modeling	3.3
Jets and $E_{\mathrm{T}}^{\mathrm{miss}}$	2.8
MC statistics	2.8
Lepton	2.1
Luminosity	1.9
Signal modeling	1.5
Pile-up modeling	0.9
Total systematic uncertainty	9.5
Data statistics	11.2
WZ normalizations	3.3
Total statistical uncertainty	11.6

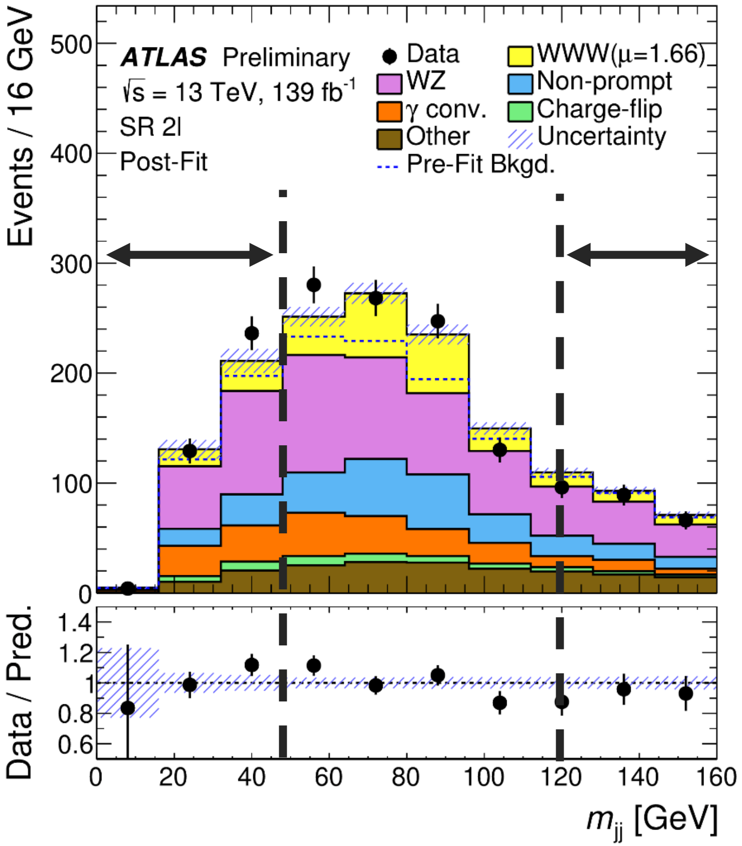
Comparison with Previous WWW Results

Analysis	μ	σ[pb]	Reference
ATLAS @ 139fb^{-1}	1.66 ± 0.28	0.85 ± 0.13	CDS
ATLAS @ 80fb^{-1}	1.29 ± 0.44	0.65 ± 0.22	Physics Let. B. 2019
CMS @ 137fb^{-1}	1.15 ± 0.45	0.59 ± 0.22	Physics Rev. L. 2020



Cross-Checks Performed

- Signal region was originally blinded.
- All BDT bins with signal/bkg > 0.05 are blinded
- Background normalization was check in the W-mass side band region before unblinding
- BDT shape was checked in all background control regions and validation region before unblinding

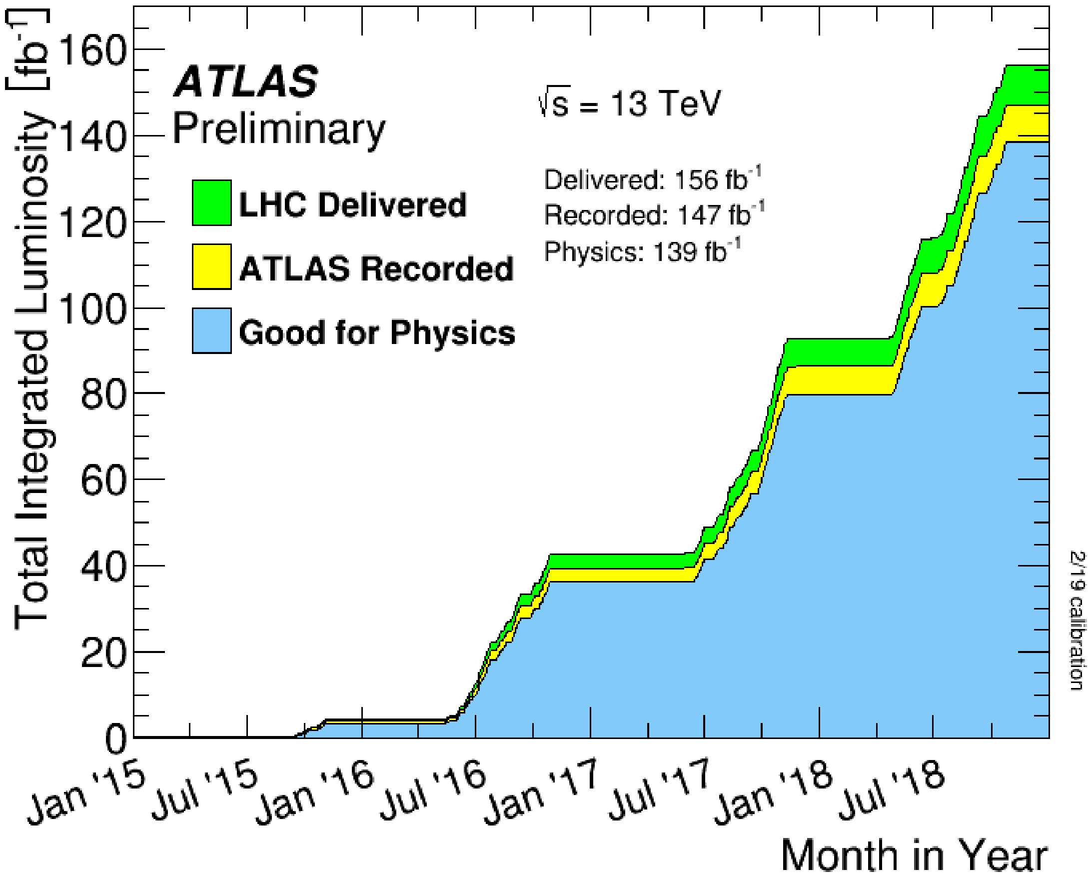


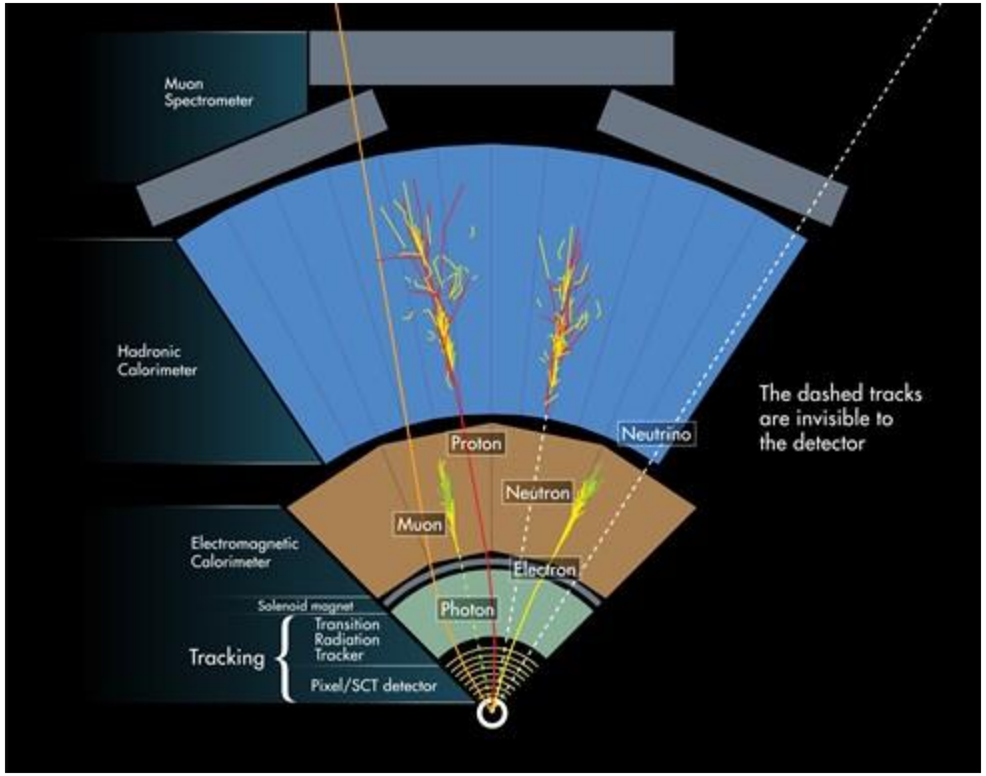
- we measured the signal strengths for $e^{\pm}e^{\pm}$, $e^{\pm}\mu^{\pm}$, $\mu^{\pm}\mu^{\pm}$ and 3l3ν SR separately;
- we divided events into three independent data-taking periods;
- we performed 80 fb^{-1} measurement using BDT and compared to the evidence paper results without BDT;
- we performed measurements with cut-based analysis
- all results were found to be consistent with each other.

Summary

- ATLAS and CMS are entering into a new era in the direct measurements of tribosons.
- This is a vital step in constraining aQGCs and search for BSM physics
- Deep dive into the resent first observation of inclusive WWW production at ATLAS
  - Observed cross-section: 850 ± 100 (stat.) $\pm$ 80 (syst.) fb
  - Observed signal strength: $\mu = 1.66 \pm 0.28$
  - Observed significance: 8.2 standard deviations
  - Expected significance: 5.4 standard deviations

ATLAS Detector and Data





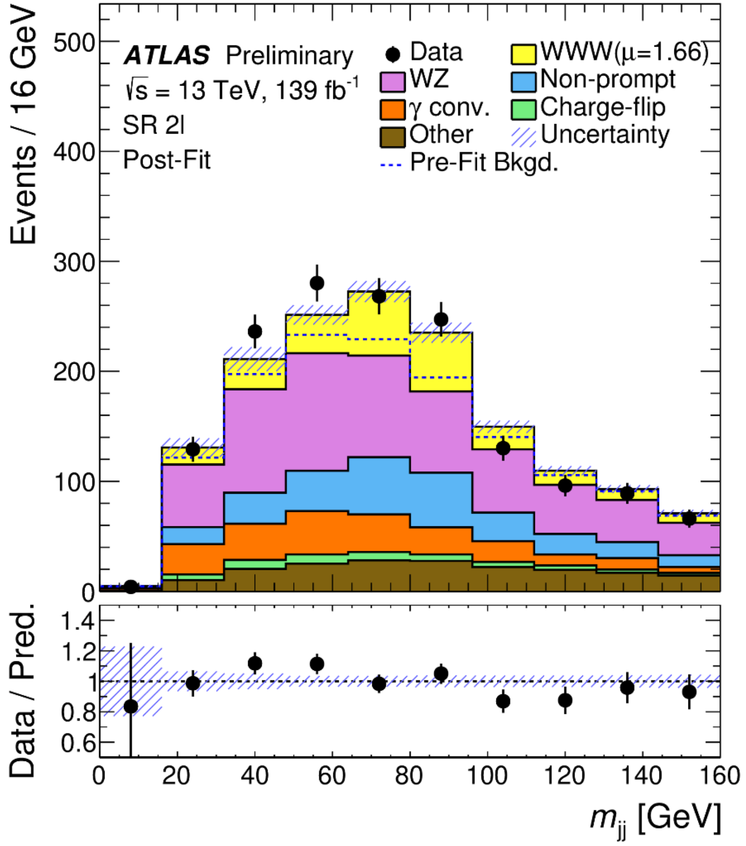
139 fb^{-1} ATLAS Analysis

2l2v2j Signal Region		
$e^\pm e^\pm$	$e^\pm \mu^\pm$	$\mu^\pm \mu^\pm$
No SFOS pairs, no 3rd lepton		
Leading lepton pT > 27 GeV		
$40 < m_{ll} < 400$ GeV		
$m_{ee} < 80$GeV || 100 GeV $< m_{ee}$		
≥ 2 jets, $m_{jj} < 160$ GeV, $\|\Delta\eta_{jj}\| < 1.5$		
no b quark jet		
E_T^{miss} significance > 3		

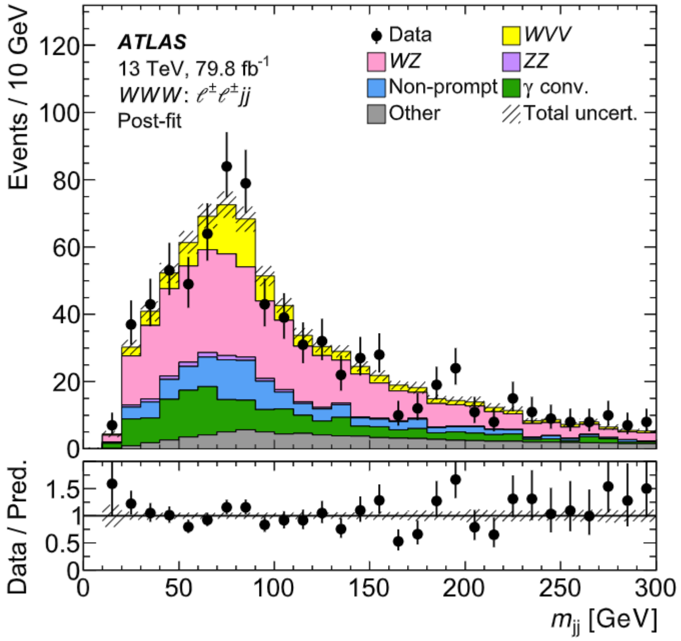
80 fb^{-1} ATLAS Analysis

$\ell^\pm\nu\ell^\pm\nu jj$ **Signal Region**		
$e^\pm e^\pm$ channel	$e^\pm \mu^\pm$ channel	$\mu^\pm \mu^\pm$ channel
Two same-sign leptons with $p_T >$ (20) 27 GeV		
3^{rd} lepton veto		
≥ 2 jets with $p_T >$ (20) 30 GeV and $\|\eta\| < 2.5$		
b-jet veto		
$40 < m_{\ell\ell} < 80$ GeV $100 < m_{\ell\ell} < 400$ GeV	$40 < m_{\ell\ell} < 400$ GeV	
$\|\Delta\eta_{jj}\| < 1.5$		
$m_{jj} < 300$ GeV		
$E_T^{miss} > 55$ GeV	None	

139 fb^{-1} ATLAS



80 fb^{-1} ATLAS



80 fb^{-1} vs 139 fb^{-1}

139 fb^{-1} ATLAS

	$e^{\pm} e^{\pm}$	$e^{\pm}\mu^{\pm}$	$\mu^{\pm}\mu^{\pm}$	3ℓ
WWW	29.3 ± 4.4	128 ± 19	84 ± 12	35.8 ± 5.2
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80 fb^{-1} ATLAS

Table 2
Post-fit background, signal and observed yields for the $\ell\nu\ell\nu qq$ and $\ell\nu\ell\nu\ell\nu$ channels. Uncertainties in the predictions include both statistical and systematic uncertainties added in quadrature; correlations among systematic uncertainties are taken into account in the calculation of the total.

	ee	$e\mu$	μe	$\mu\mu$	$\mu ee + e\mu\mu$
WWW	9.9 ± 3.3	26 ± 9	23 ± 8	30 ± 10	15 ± 5
WZ	37.4 ± 2.2	121 ± 6	96 ± 5	119 ± 6	8.6 ± 0.5
ZZ	0.46 ± 0.05	5.11 ± 0.25	3.44 ± 0.18	4.12 ± 0.24	0.69 ± 0.03
Non-prompt	6.1 ± 3.0	35 ± 5	17 ± 9	37 ± 7	9.4 ± 1.5
γ conv.	20.9 ± 1.9	35.0 ± 3.1	76 ± 7	–	1.06 ± 0.11
Other	12.9 ± 1.0	25.7 ± 1.7	20.3 ± 1.3	25.3 ± 1.6	3.5 ± 0.4
Total	88 ± 4	249 ± 9	237 ± 10	216 ± 9	38 ± 4
Data	87	239	235	237	27

Ensure High Quality Muons

Signal Muon Selection
$pT > 20$ GeV
$\lvert\eta\rvert < 2.5$
“Medium” muon quality[1]
Longitudinal impact parameter $\lvert z_0 \times \sin\theta \rvert < 0.5$ mm
Transverse impact parameter: $\left\lvert \frac{d_0}{\sigma_{d_0}} \right\rvert < 3$
Reject muons suspected to originate from hadrons [2]

[1] Muon Quality: https://link.springer.com/article/10.1140%2Fepjc%2Fs10052-016-4120-y
[2] Non-prompt lepton BDT: https://journals.aps.org/prd/pdf/10.1103/PhysRevD.97.072003

Ensure High Quality Electrons

Signal Electron Selection
pT > 20 GeV
$\|\eta\| < 2.47$ but not in crack region $1.37 < \|\eta\| < 1.52$
Tight Likelihood[1]
Longitudinal impact parameter $\|z_0 \times \sin\theta\| < 0.5$ mm
Transverse impact parameter: $\left\|\frac{d_0}{\sigma_{d_0}}\right\| < 5$
Reject electrons suspected to originate from hadrons [2]
Reject electrons with suspected mis-measured charge [3]

[1] Electron quality: https://doi.org/10.1088/1748-0221/14/12/P12006
[2] Non-prompt lepton BDT: https://journals.aps.org/prd/pdf/10.1103/PhysRevD.97.072003
[3] charge mis-id tagger: https://doi.org/10.1140/epjc/s10052-019-7140-6

Anti-ID Muon

Signal Muon Selection	"Anti-ID" Muon Selection
pT > 20 GeV	pT > 20 GeV
$\|\eta\| < 2.5$	$\|\eta\| < 2.5$
High quality reconstructed tracks in most regions + Segment/calorimeter tagged muons in regions with limited detector coverage	High quality reconstructed tracks in most regions + Segment/calorimeter tagged muons in regions with limited detector coverage
Longitudinal impact parameter $\|z_0 \times \sin\theta\| < 0.5$ mm	Longitudinal impact parameter $\|z_0 \times \sin\theta\| < 0.5$ mm
Transverse impact parameter: $\left\|\frac{d_0}{\sigma_{d_0}}\right\| < 3$	Transverse impact parameter: $\left\|\frac{d_0}{\sigma_{d_0}}\right\| < 10$
Reject muons suspected to originate from hadrons	Do not reject muons suspected to originate from hadrons Must not pass signal muon selection

Anti-ID Electron

Signal Electron Selection	"Anti-ID" Electron Selection
pT > 20 GeV	pT > 20 GeV
$\lvert\eta\rvert < 2.47$ but not in crack region $1.37 < \lvert\eta\rvert < 1.52$	$\lvert\eta\rvert < 2.47$ but not in crack region $1.37 < \lvert\eta\rvert < 1.52$
Tight Likelihood	Medium Likelihood
Longitudinal impact parameter $\lvert z_0 \times \sin\theta\rvert < 0.5$ mm	Longitudinal impact parameter $\lvert z_0 \times \sin\theta\rvert < 0.5$ mm
Transverse impact parameter: $\left\lvert \frac{d_0}{\sigma_{d_0}} \right\rvert < 5$	Transverse impact parameter: $\left\lvert \frac{d_0}{\sigma_{d_0}} \right\rvert < 5$
Reject electrons suspected to originate from hadrons	Do not reject electrons suspected to originate from hadrons
Reject electrons with suspected mis-measured charge	Do not reject electrons with suspected mis-measured charge

Non-Prompt Enriched Region

3l3ν 1 bjet Control Region	
eeμ or eμμ	
No SFOS pairs or SFOS pairs with $m_{ll} < 70$ GeV or $m_{ll} > 110$ GeV	
No 4th lepton	
Leading lepton pT > 27 GeV	
Sum of lepton charge = 1 (++ − or −− +)	
1 bjet	
3 Signal Leptons ←	2 Signal + 1 antiID lepton

2l2ν2j 1 bjet Control Region		
$e^{\pm}e^{\pm}$	$e^{\pm}\mu^{\pm}$	$\mu^{\pm}\mu^{\pm}$
No SFOS pairs, no 3rd lepton		
Leading lepton pT > 27 GeV		
$40 < m_{ll} < 400$ GeV		
$m_{ee} < 80$GeV || 100 GeV $< m_{ee}$		
≥ 2 jets		
1 b quark jet		
2 Signal Leptons ←	1 Signal + 1 antiID lepton	

Derive non-prompt factor by performing simultaneous fits to the data in the Signal lepton+antiID lepton and all signal lepton control regions

Non-Prompt Enriched Region

3l3ν Signal Region	
eeμ or eμμ	
No SFOS pairs	
No 4th lepton	
Leading lepton pT > 27 GeV	
Sum of lepton charge = 1 (++ − or −− +)	
no b-jets	
3 Signal Leptons ←	2 Signal + 1 antiID lepton

2l2ν2j Signal Region		
$e^{\pm}e^{\pm}$	$e^{\pm}\mu^{\pm}$	$\mu^{\pm}\mu^{\pm}$
No SFOS pairs, no 3rd lepton		
Leading lepton pT > 27 GeV		
$40 < m_{ll} < 400$ GeV		
$m_{ee} < 80$GeV || 100 GeV $< m_{ee}$		
≥ 2 jets, $m_{jj} < 160$ GeV, $\|\Delta\eta_{jj}\| < 1.5$		
no b quark jet		
E_T^{miss} significance > 3		
2 Signal Leptons ←	1 Signal + 1 antiID lepton	

Apply non-prompt factor to amount of data observed in the antiID region
to predict number expected in the signal region

Background Estimation: Photon Misidentification

- $V\gamma$ + jets events where the photon is mis-identified as an electron
- Photons can convert to electrons through scattering off of detector material

Signal Electron
$pT > 20$ GeV
$\lvert\eta\rvert < 2.47$ && not in crack: $1.37 \leq \lvert\eta\rvert \leq 1.52$
Tight Likelihood
Transverse impact parameter $\left\lvert \frac{d_0}{\sigma_{d_0}} \right\rvert < 5$ Longitudinal impact par. $\lvert z0 \times \sin\theta \rvert < 0.5$ mm
Reject electrons suspected to originate from hadrons
Reject electrons with suspected mis-measured charge

"Photon-like" Electron
$pT > 20$ GeV
$\lvert\eta\rvert < 2.47$ && not in crack: $1.37 \leq \lvert\eta\rvert \leq 1.52$
Tight Likelihood except no inner most tracker layer hit
Transverse impact parameter $\left\lvert \frac{d_0}{\sigma_{d_0}} \right\rvert < 5$ Longitudinal impact par. $\lvert z0 \times \sin\theta \rvert < 0.5$ mm
Reject electrons suspected to originate from hadrons
Reject electrons with suspected mis-measured charge

Predicting Photon Misidentification Rate

Zγ Control Region
$e^{\pm}e^{\mp}$ or $\mu^{\pm}\mu^{\mp}$ opposite signed pair
one additional electron
Leading lepton pT > 27 GeV
No b-quark jets
$80 < m_{lll} < 100$ GeV

3l3ν Signal Region
eeμ or eμμ
No SFOS pairs
No 4^{th} lepton
Leading lepton pT > 27 GeV
Sum of lepton charge = 1 ($++-$ or $--+$)
no b-jets

All electrons are signal electrons	←	One electron is "photon-like"

Derive Mis-ID rate

All electrons are signal electrons	←	One electron is "photon-like"

Apply Mis-ID rate

Similarly for 2l2j signal regions*

Background Estimation: Electron Charge flip

Charge flip control region
ee
No 3rd lepton
Leading lepton pT > 27 GeV
$75 < m_{ee} < 105$ GeV

3l3ν Signal Region
eeμ
No SFOS pairs
No 4th lepton
Leading lepton pT > 27 GeV
Sum of lepton charge = 1 (++ − or −− +)
no b-jets

Same signed electrons	←	Opposite signed electrons

Derive charge flip rate

Same signed electrons	←	Opposite signed electrons

Apply charge flip rate

Similarly for 2l2j signal regions*