Precision Measurements of Electroweak Theory

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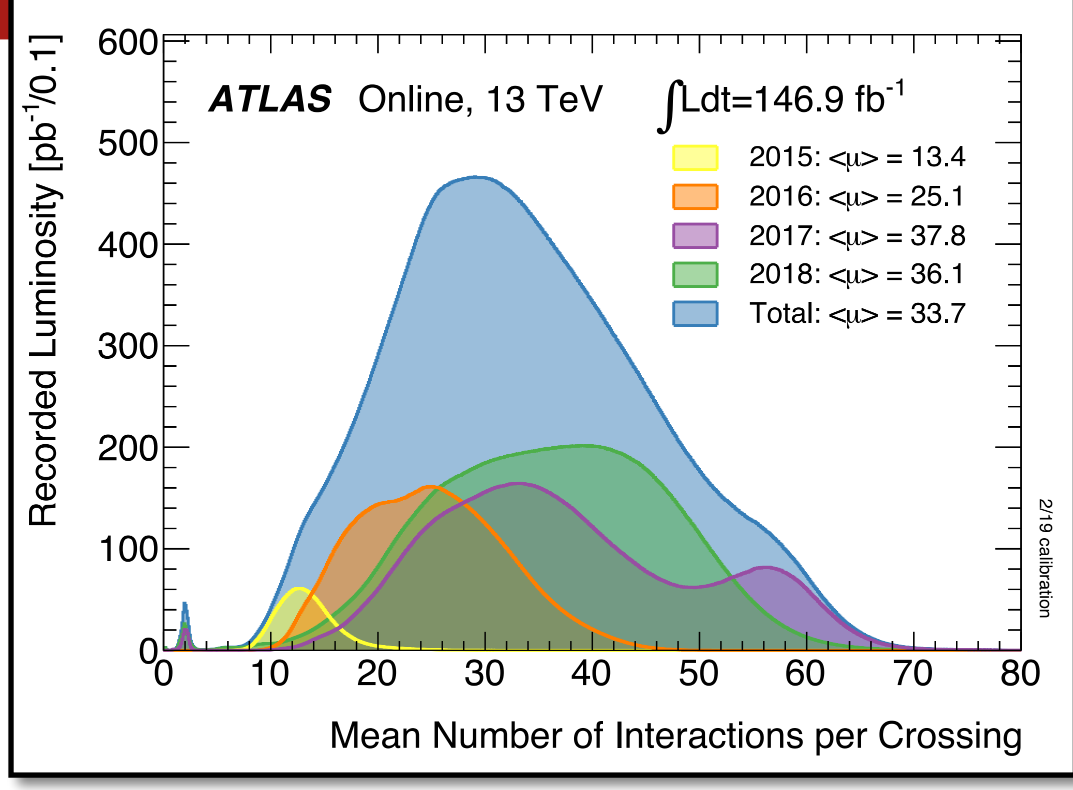
ATLAS EXPERIMENT

UNIVERSITY OF OREGON

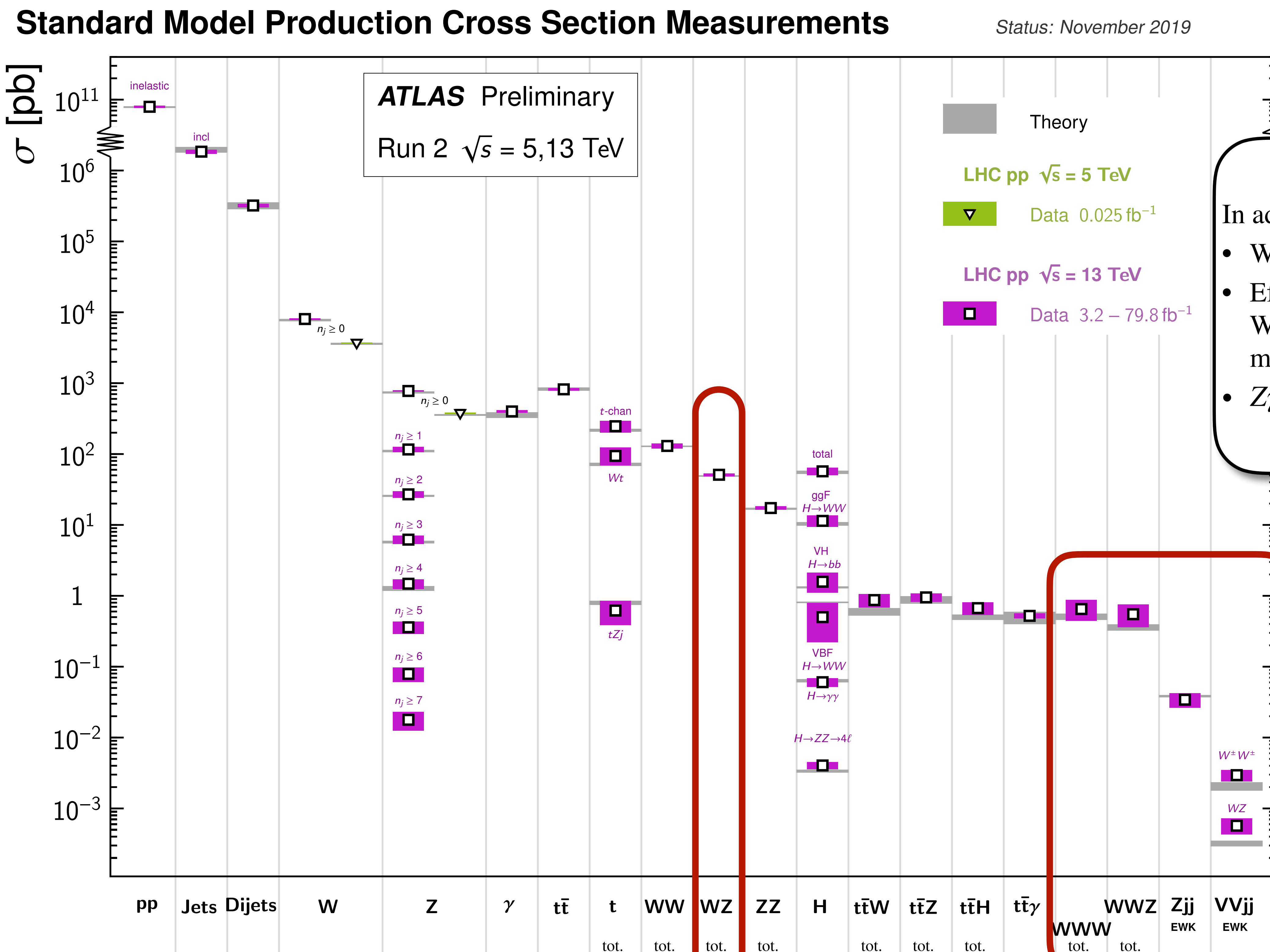
Introduction



- Doing precision measurements at hadronic colliders are challenging.
  - Experimental: Pile-up, Detector Uncertainties etc.
  - Theory: PDF's, Other Theoretical Uncertainties etc.
- **ATLAS** has been able to successfully tackle this problem .
- At 7 TeV **ATLAS** has collected 4.1 fb^{-1} and at 8 TeV **ATLAS** collected 20.2 fb^{-1} of good for physics data.
  - Effective Leptonic Weak Angle Mixing: ATLAS-CONF-2018-037 (8 TeV 20.2 fb^{-1})
  - W Mass Measurement: Eur. Phys. J. C 79 (2019) 535 (7 TeV 4.6 fb^{-1})
- At 13 TeV Till now the **ATLAS** has collected 139 fb^{-1} collisions data.
- **ATLAS** can now do polarization measurements on electroweak gauge-bosons:
  - Inclusive WZ polarization and X-section measurements: Eur. Phys. J. C 79 (2019) 535 (13 TeV 36.1 fb^{-1})
- And **ATLAS** started tackling rare electroweak processes.
  - Observation EWK-ZZjj: ATLAS-CONF-2019-033 (13 TeV 139 fb^{-1})
  - Observation of EWK-ssWWjj: Phys. Rev. Lett. 123 (2019) 161801 (13 TeV 36.1 fb^{-1})
  - Observation of EWK-WZjj: Phys. Lett. B 793 (2019) 469 (13 TeV 36.1 fb^{-1})
  - Evidence EWK-Zγjj arXiv:1910.09503 [Submitted to PLB] (13 TeV 36.1 fb^{-1})
  - First Evidence of WVV Production: Phys. Lett. B 798 (2019) 134913 (13 TeV 79.8 fb^{-1})

ATLAS Standard Model X-Section Measurements

Today, we will cover only a sub-set of ATLAS results.



In addition:

- W mass measurement
- Effective Leptonic Weak Mixing Angle measurement
- *Zγ* EWK

Measurement of Effective Leptonic Weak Mixing Angle

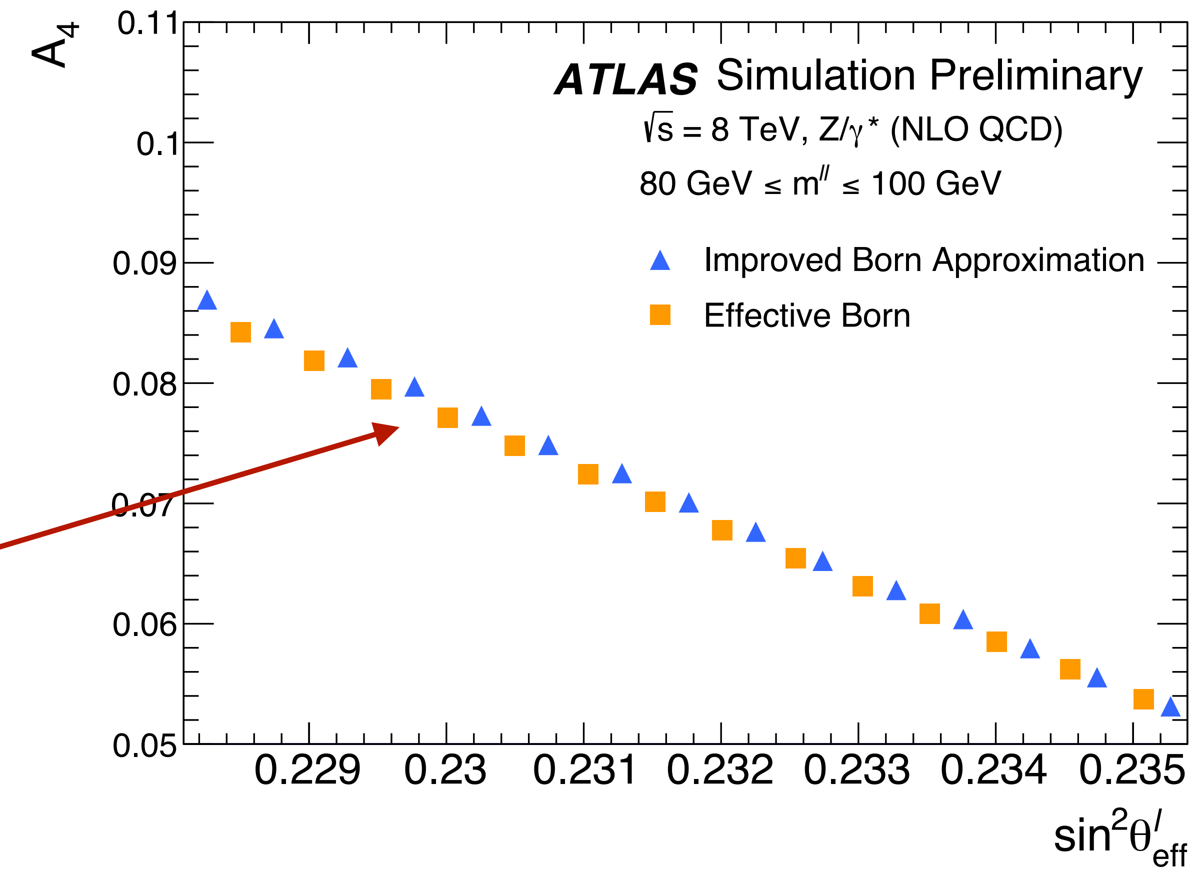
ATLAS-CONF-2018-037

Measurement of Effective Leptonic Weak Mixing Angle

Leading Order Differential Cross-Section of $pp \to Z/\gamma^* \to \ell^+\ell^-$

$$\frac{d\sigma}{dp_T^{\ell\ell}\, dy^{\ell\ell}\, dm^{\ell\ell}\, d\cos\theta\, d\phi} = \frac{3}{16\pi}\frac{d\sigma^{U+L}}{dp_T^{\ell\ell}\, dy^{\ell\ell}\, dm^{\ell\ell}}$$
$$\Big\{(1+\cos^2\theta) + \frac{1}{2}A_0(1-3\cos^2\theta) + A_1\sin 2\theta\cos\phi$$
$$+\frac{1}{2}A_2\sin^2\theta\cos 2\phi + A_3\sin\theta\cos\phi + \boxed{A_4\cos\theta}$$
$$+A_5\sin^2\theta\sin 2\phi + A_6\sin 2\theta\sin\phi + A_7\sin\theta\sin\phi\Big\}.$$

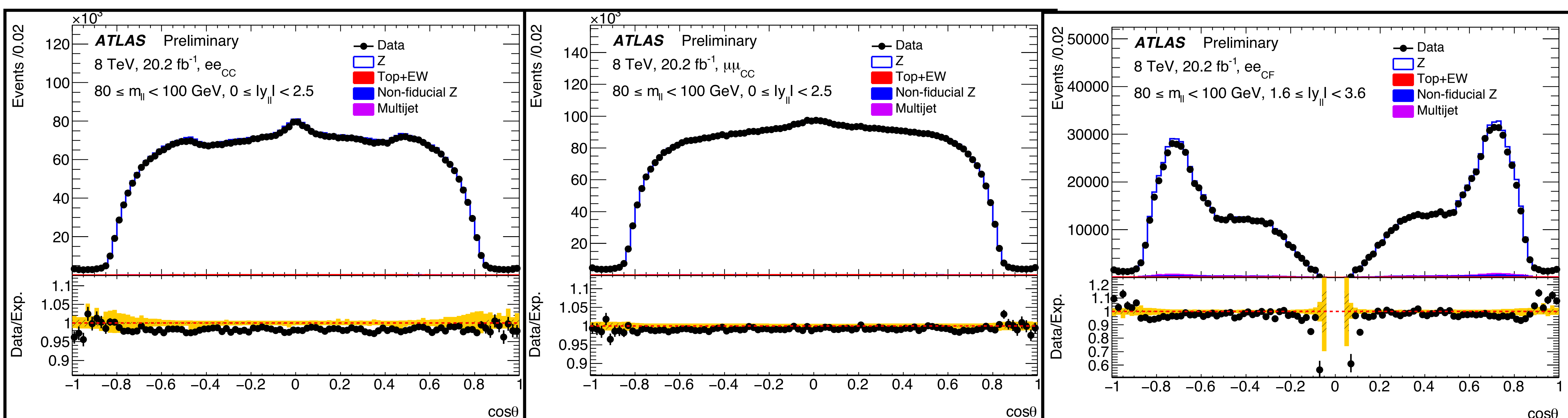
- The differential equation is composed of nine harmonic polynomials with 8 dimensionless angular coefficients ($A_{0\text{-}7}$)
- Coefficients $A_{3\text{-}4}$ are sensitive to $\sin^2\theta^\ell_{\text{eff}}$, but A_3 is much weaker then A_4.
- A_4 can be modeled as a functions of $\sin^2\theta^\ell_{\text{eff}}$



Measurement of Effective Leptonic Weak Mixing Angle

Reconstructing the Z Boson and Extracting the angular coefficients

- The analysis has been constructed at 8 TeV with an integrated luminosity of 20.2 fb^{-1}
- In order to reconstruct the Z boson:
  - Two opposite leptons are selected and categorized according to their orientation. (Forward (f) or Central (c))
    - $e_{\mathrm{c}}^{\pm}e_{\mathrm{c}}^{\mp}$, $\mu_{\mathrm{c}}^{\pm}\mu_{\mathrm{c}}^{\mp}$, $e_{c}^{\pm}e_{\mathrm{f}}^{\mp}$
  - These leptons are used to reconstruct a Z boson mass and a Z window cut is applied.
    - $70 < m_{\ell\ell} < 125$ GeV
  - All lepton categories are treated separately and binned in $m_{\ell\ell}$ and $|y_{\ell\ell}|$.



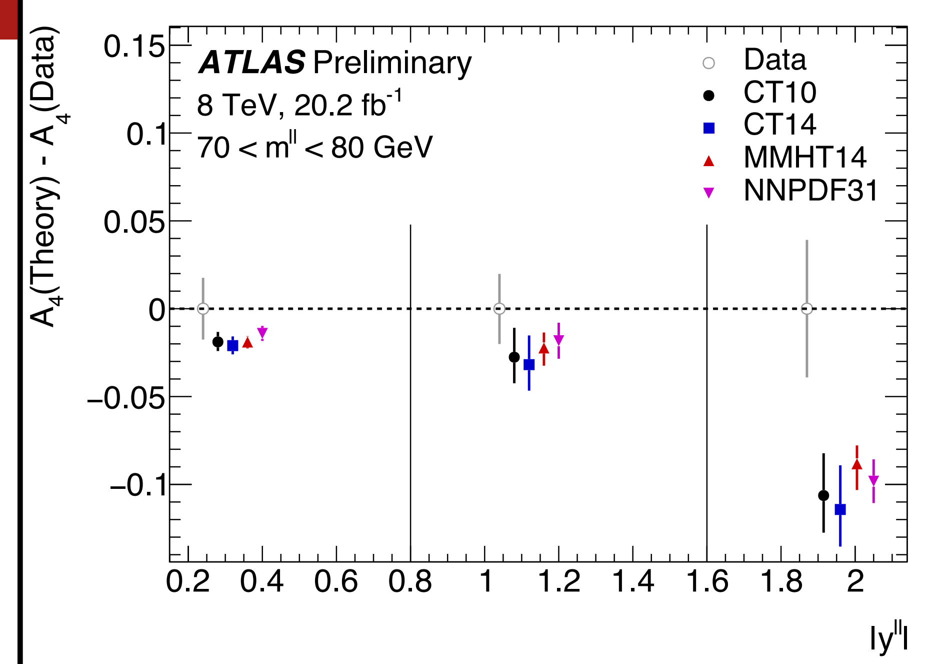
Measurement of Effective Leptonic Weak Mixing Angle

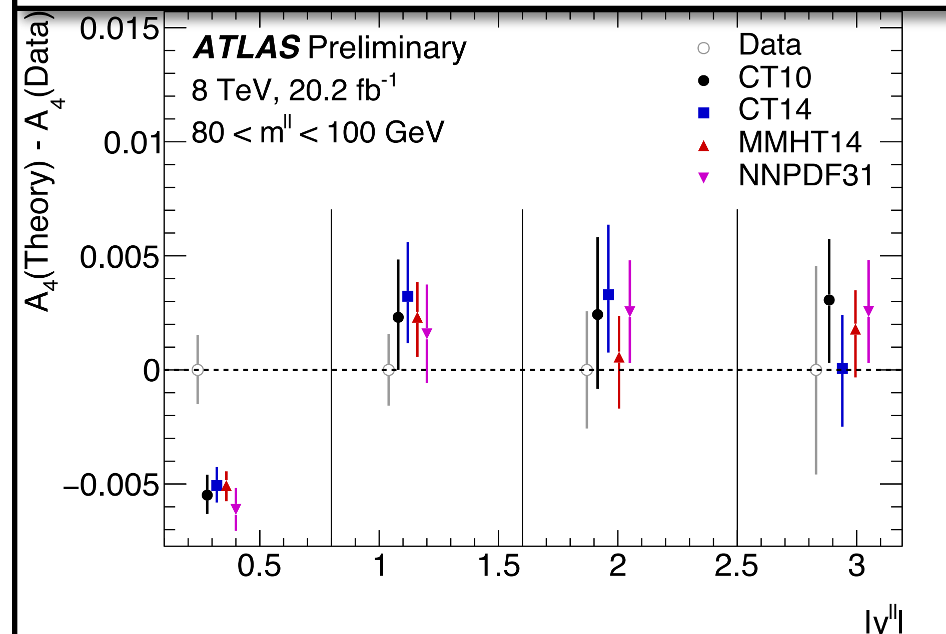
Extracted A_4 Value

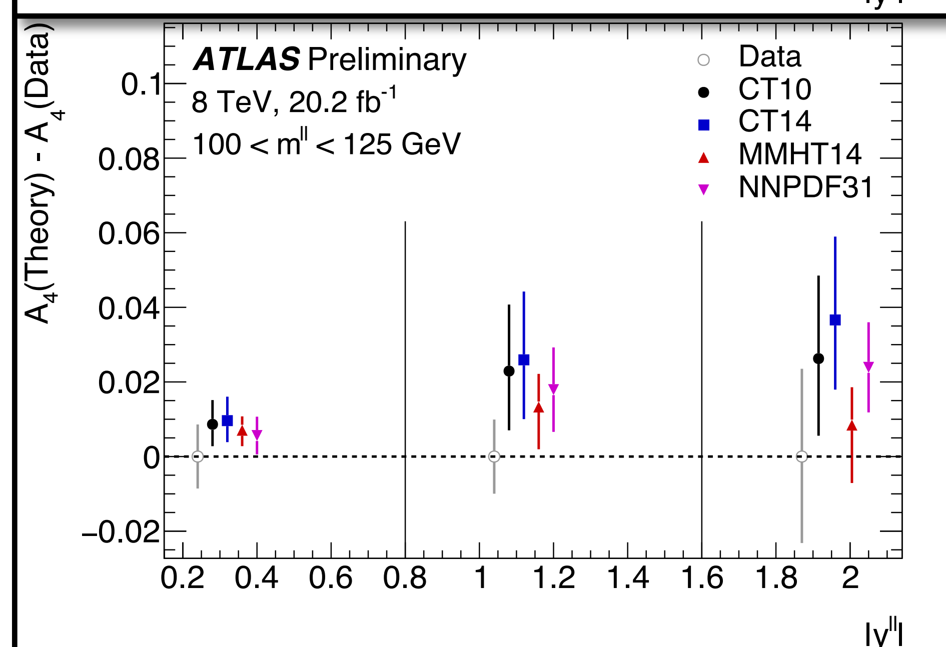
- The A_4 values is extracted through a template fit.
- A template is created for each A_i value in 4 dimensions: $\cos\theta$, ϕ, $m_{\ell\ell}$ and $y_{\ell\ell}$
- The number of expected events in a bin (n) is given by:

$$N^n_{\mathrm{exp}}(A,\sigma,\theta) = \left\{ \sum_{j=0}^{\mathrm{N_{bins}}} \sigma_j \times L \times \left[t^n_{8j}(\beta) + \sum_{i=0}^{7} A_{ij} \times t^n_{ij}(\beta) \right] \right\} \times \gamma^n + \sum_{B}^{\mathrm{bkgs}} T^n_B(\beta),$$

  - The fits are done for both individual channels as well as combined fit.
- The most sensitive channel is $e_c^{\pm} e_f^{\mp}$

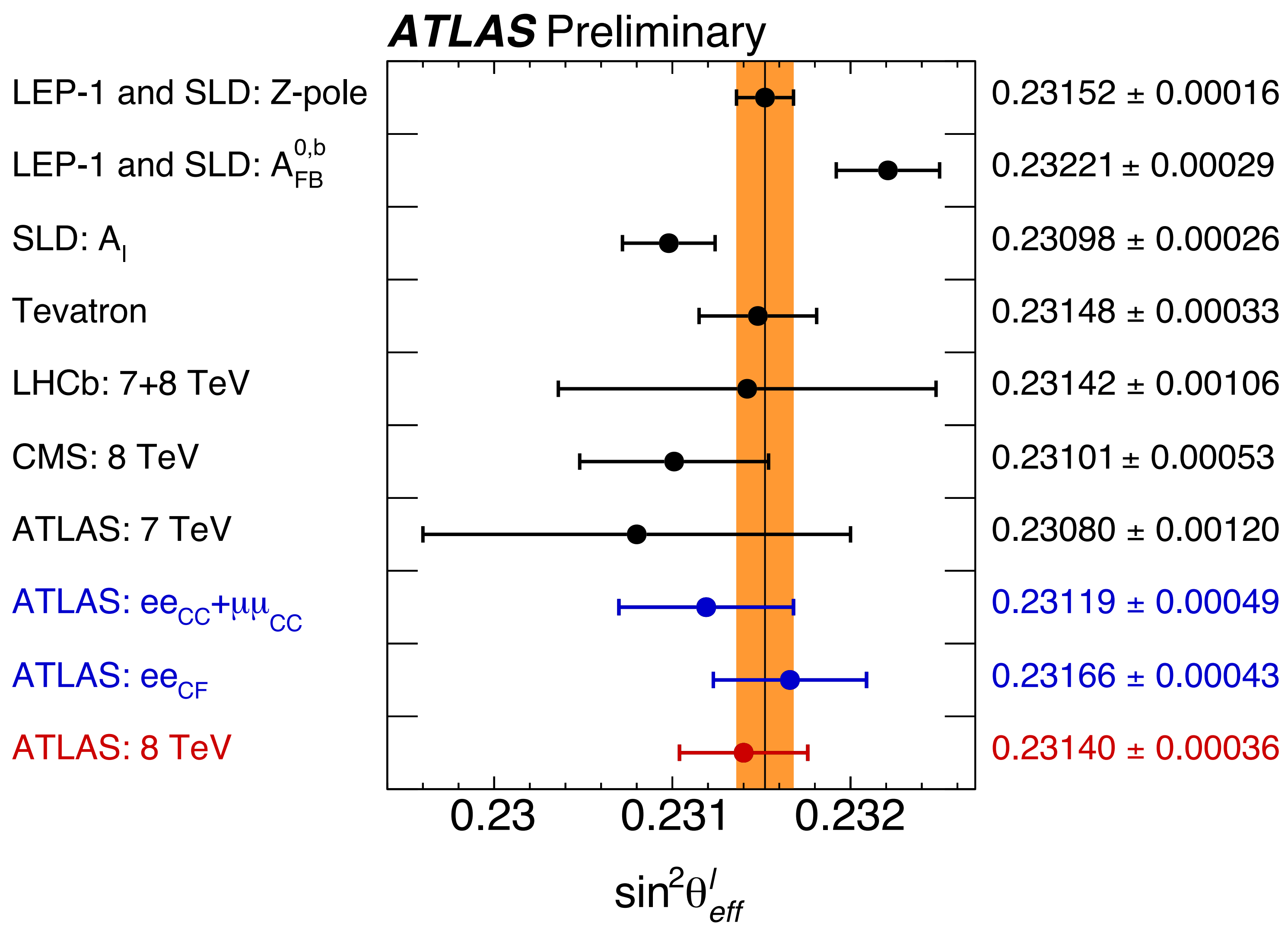






Measurement of Effective Leptonic Weak Mixing Angle

Measured Effective Leptonic Weak Mixing Angle



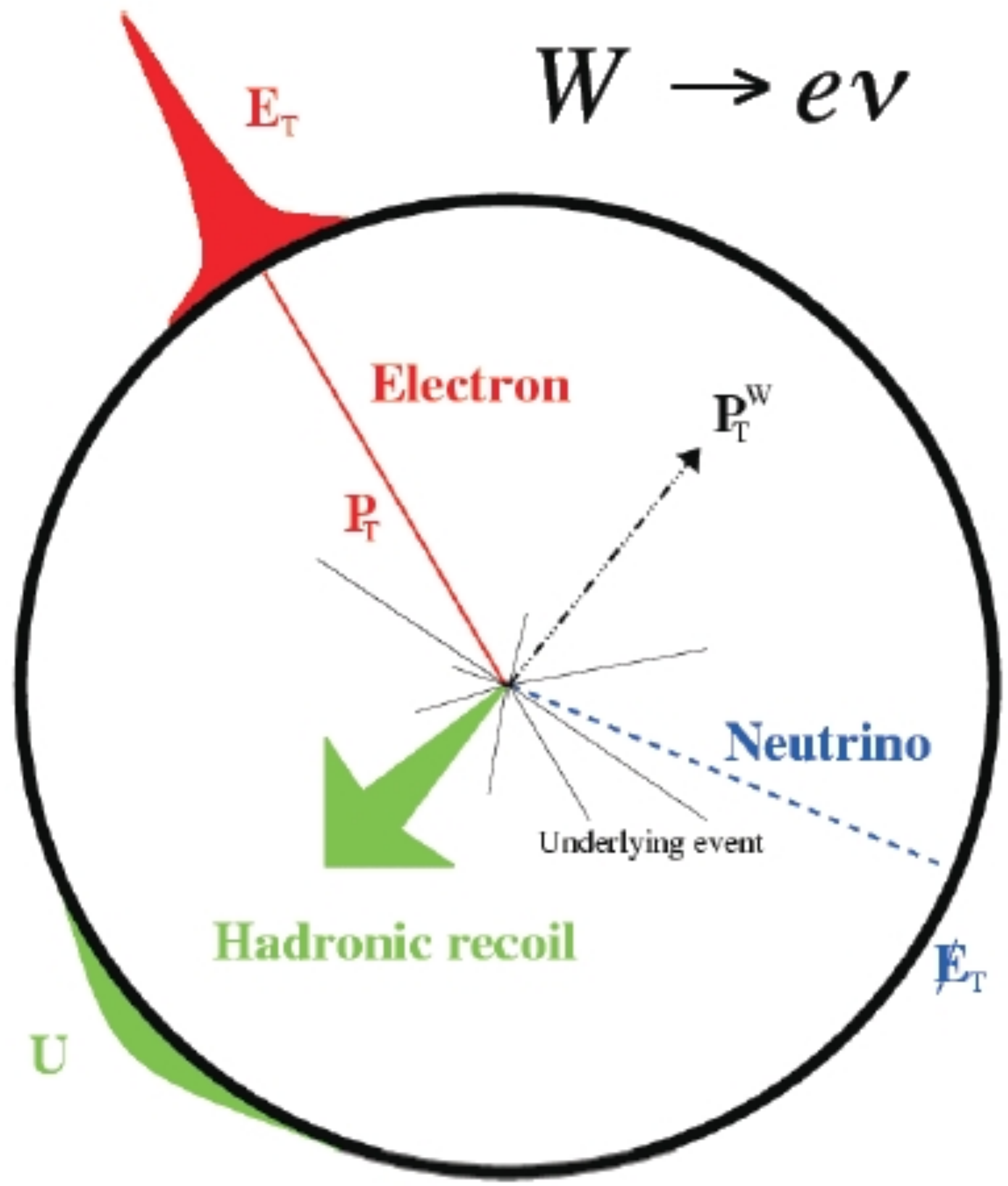
Combined $\sin^2\theta^{\ell}_{\mathrm{eff}} = 0.23140 \pm 0.00021(\mathrm{stat.}) \pm 0.00024(\mathrm{PDF}) \pm 0.00016(\mathrm{syst.})$

Measurement of the W-boson mass in pp collisions at 7 TeV with the ATLAS detector

Eur. Phys. J. C 78 (2018) 110

Measurement of the W-Boson Mass

- Measuring the W boson mass is really challenging in LHC.
  - Exact mass of the W-boson cannot be directly extracted since the neutrinos go undetected.
- Instead the W mass is extracted by generating MC samples with different masses and doing template fits with these MC samples on m_T^W, p_T^ℓ.

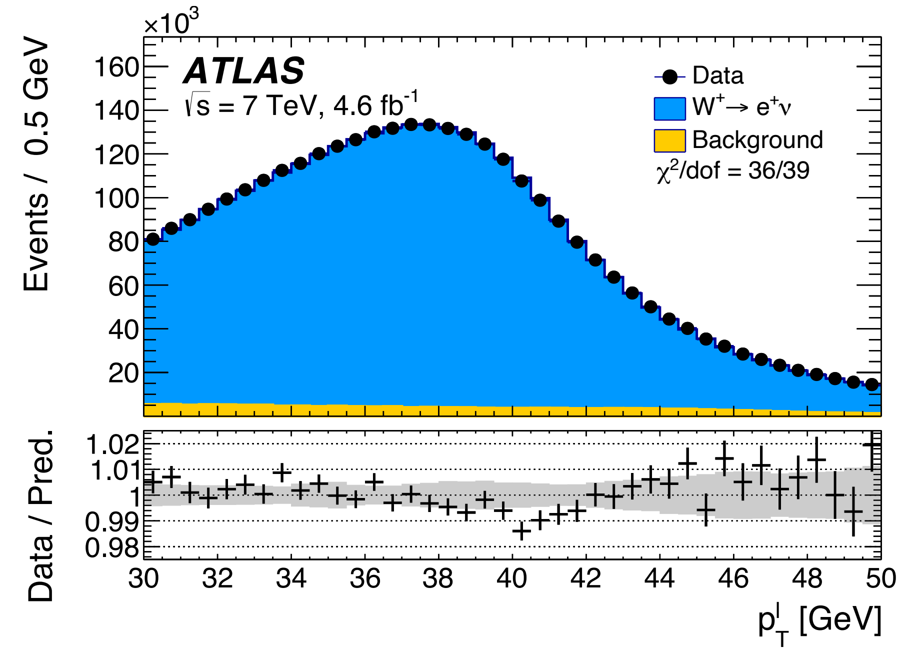


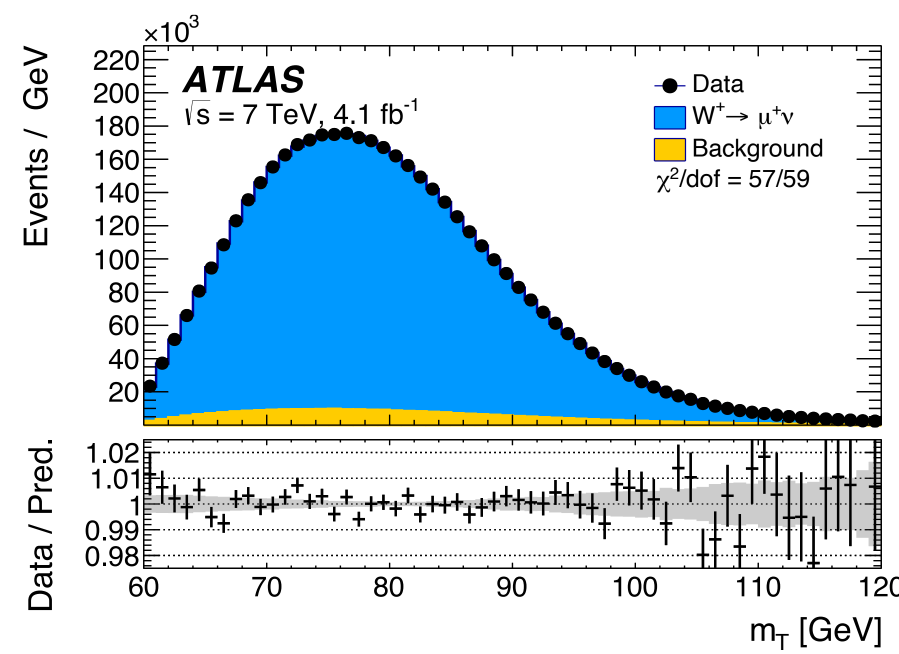
*Plot by Tommaso Dorigo From:
https://www.science20.com/quantum_diaries_survivor/blog/thats_my_plot_damnit_reprise

Measurement of the W-Boson Mass

Template Fits and the Extraction of the W-Boson Mass

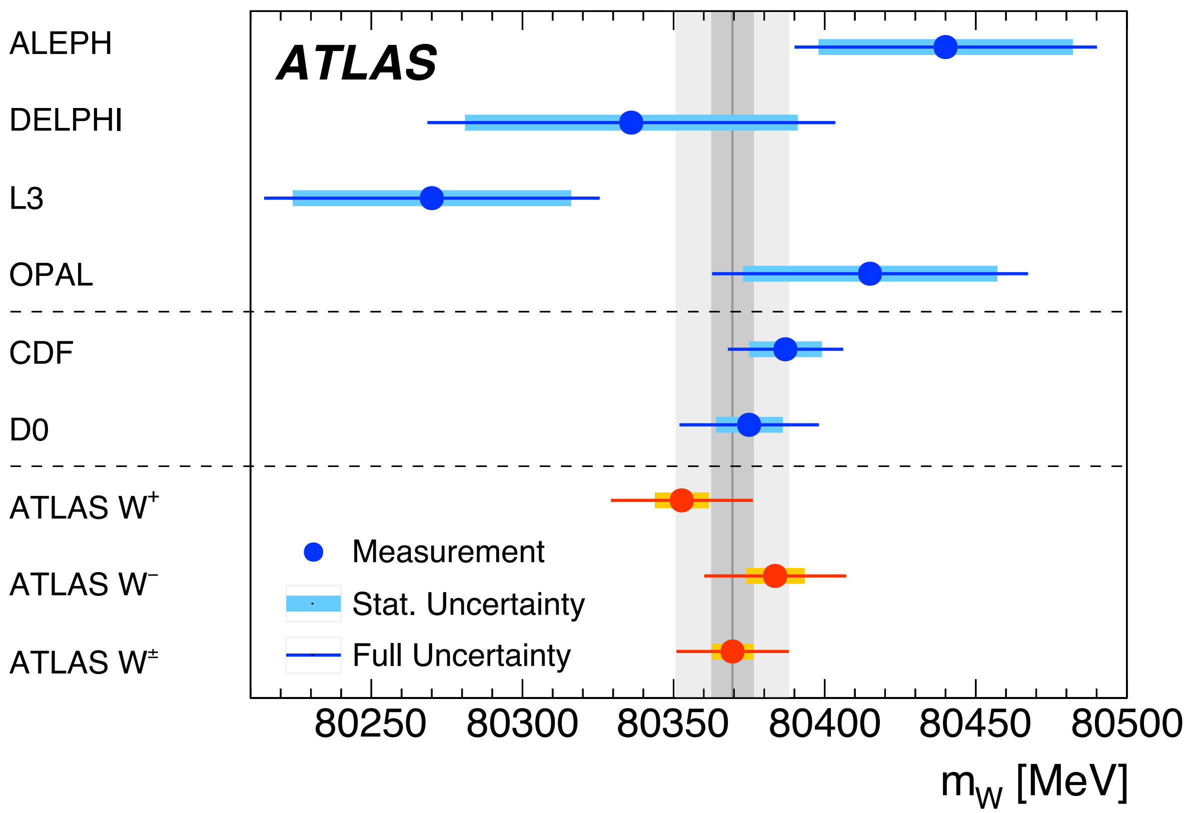
- This analysis is conducted at 7 TeV with the luminosity of 4.6 fb^{-1}
- Template fitting to extract the W-boson mass is simple but comes with large uncertainties:
  - Detector Uncertainties,
  - Physics Modelling: PDF, W Prod, W Decay …
- To reduce these uncertainties as well as to reduce the background events, certain kinematic requirements are applied
  - $p_T^{\ell} > 30$ GeV , $E_T^{\text{miss}} > 30$ GeV
  - $m_T^W > 60$ GeV
  - $p_T^W < 30$ GeV
- Leptonic Z-boson decay is used to constrain the experimental uncertainties as well to test the W-mass extraction method.
- Recoil calibration is done to correct m_T modeling.

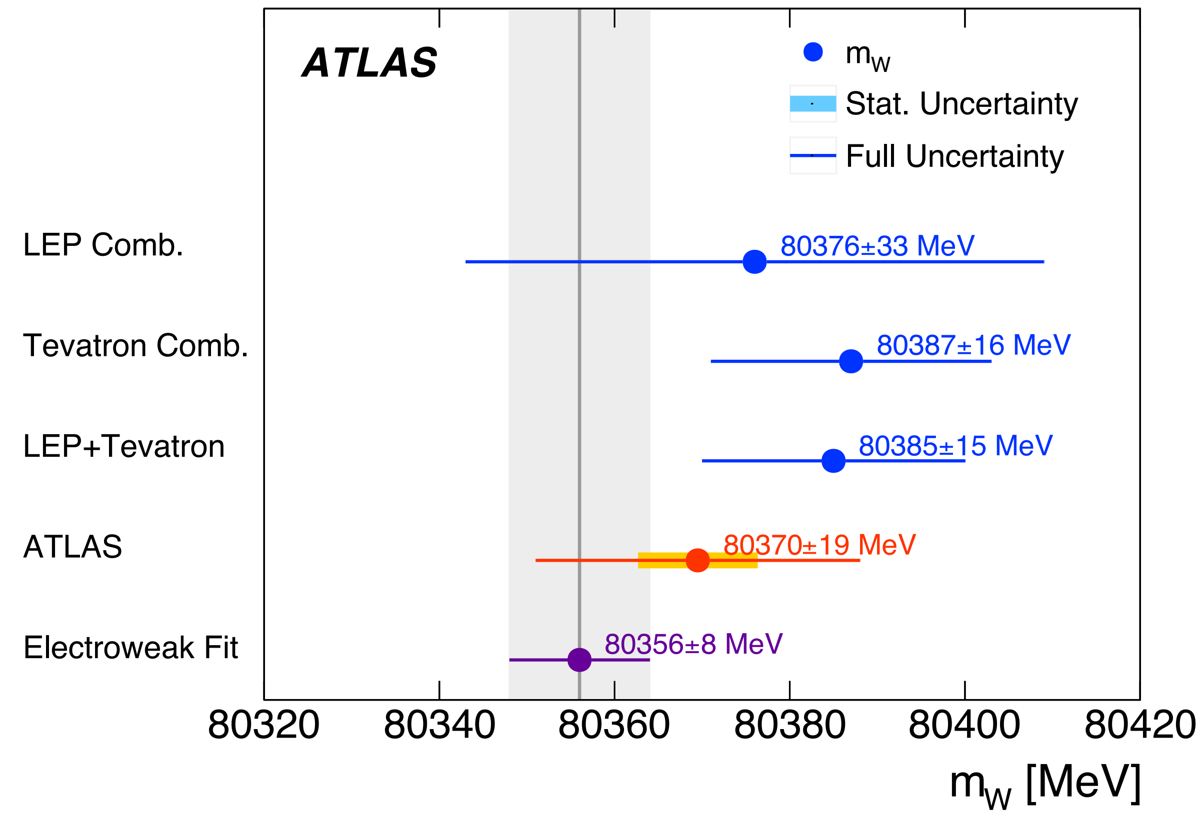




Measurement of the W-Boson Mass

Results





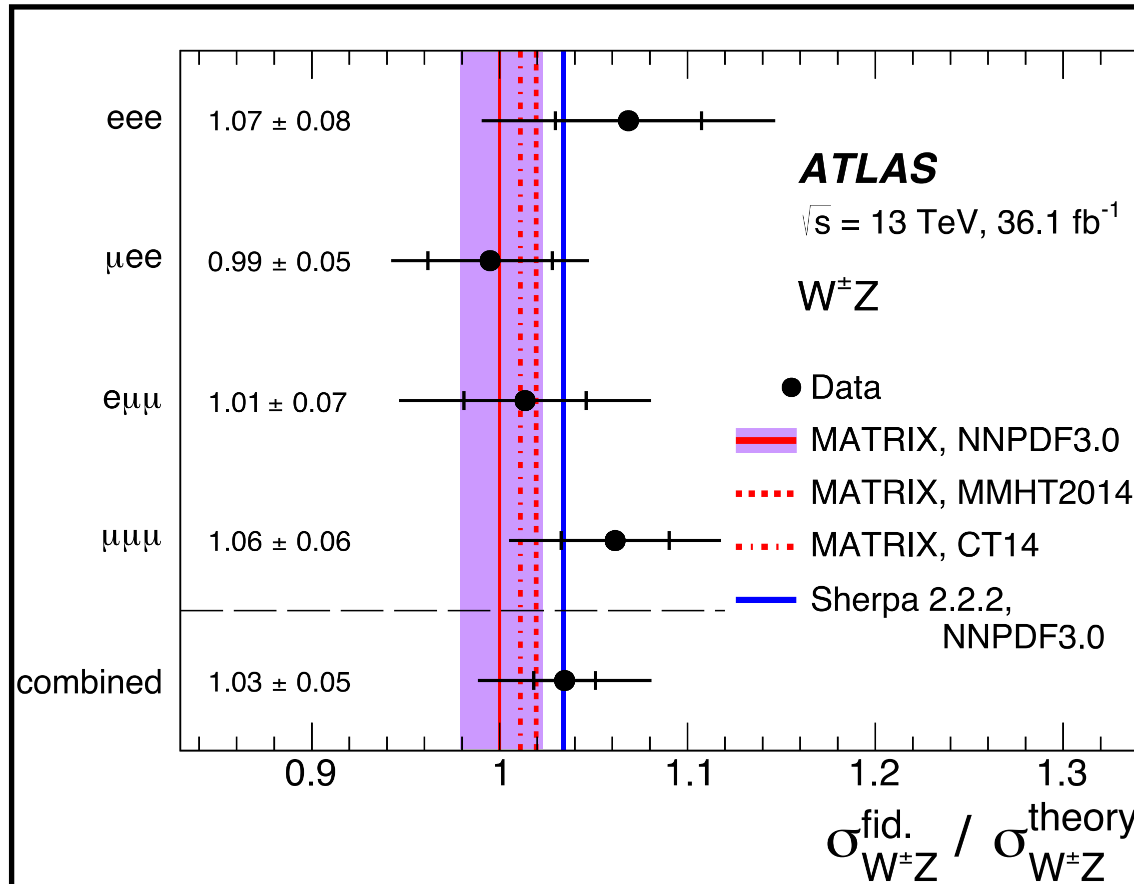
- $m_W = 80370 \pm 7\ (\text{stat.}) \pm 11\ (\text{exp sys.}) \pm 14\ (\text{mod. syst.})\ \text{MeV} = 80370 \pm 19\ \text{MeV}$
- The measured values is compatible with the world average with similar precision made by the CDF and D0 collaborations.

Measurement of $W^{\pm}Z$ production cross sections and gauge boson polarisation in pp collisions at 13TeV with the ATLAS detector.

Eur. Phys. J. C 79 (2019) 535

WZ Prod. X-Sections and Gauge Boson Polarisations

- The longitudinal polarization of the W and Z bosons are the results of the EWSB.
  - While the W polarization are helpful for testing CP violation.
- WZ production channel is sensitive to these polarization observables, due to its reliance on gauge boson self interactions.
- In addition the asymmetry between $W^{+}Z$ and $W^{-}Z$ are sensitive to PDF distributions.
- The analysis is conducted at 13 TeV with integrated luminosity 36.1 fb^{-1}.
- Events are selected according to:
  - Exactly 3 Leptons, $W \to \ell^{\pm}, Z \to \ell^{+}\ell^{-}$
  - $|m_{Z\to\ell\ell} - m_{Z}| < 10$ GeV
  - $m_{T}^{W} > 30$ GeV



- The using the extracted yields, the fiducial cross-section is calculated to be: $\sigma^{fid}_{WZ\to lvll} = 63.7 \pm 1.0$ (stat.) $\pm$ 2.3 (exp. syst.) $\pm$ 0.3 (mod. syst) $\pm$ 1.4 (lumi.) fb
- The total cross-section is estimated to be: $\sigma^{tot.}_{WZ} = 51.0 \pm 0.8$ (stat.) $\pm$ 1.8 (exp. syst.) $\pm$ 0.9 (mod. syst.) $\pm$ 1.1(lumi.) pb

The $W^{+}Z$ vs. $W^{-}Z$ asymmetry has also been measured as:

- $\sigma_{W^{+}Z}/\sigma_{W^{-}Z} = 1.47 \pm 0.05$ and has been found to be consistent with theory

WZ Prod. X-Sections and Gauge Boson Polarisations

Precision Measurements

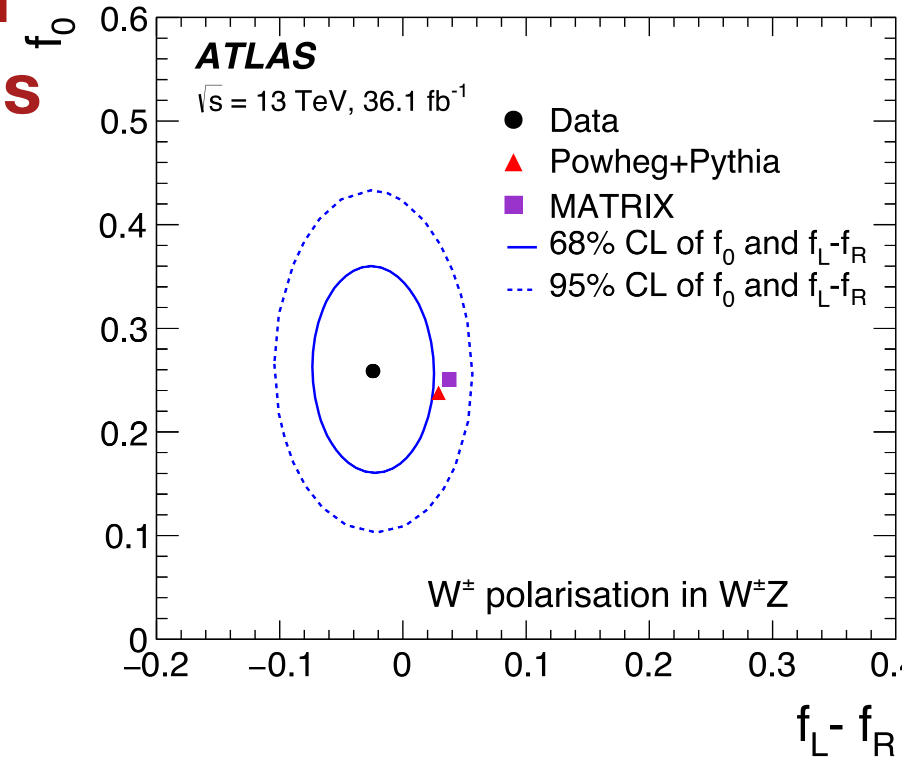
- Polarisation of the gauge bosons can be determined using the angular distributions of the decay products.

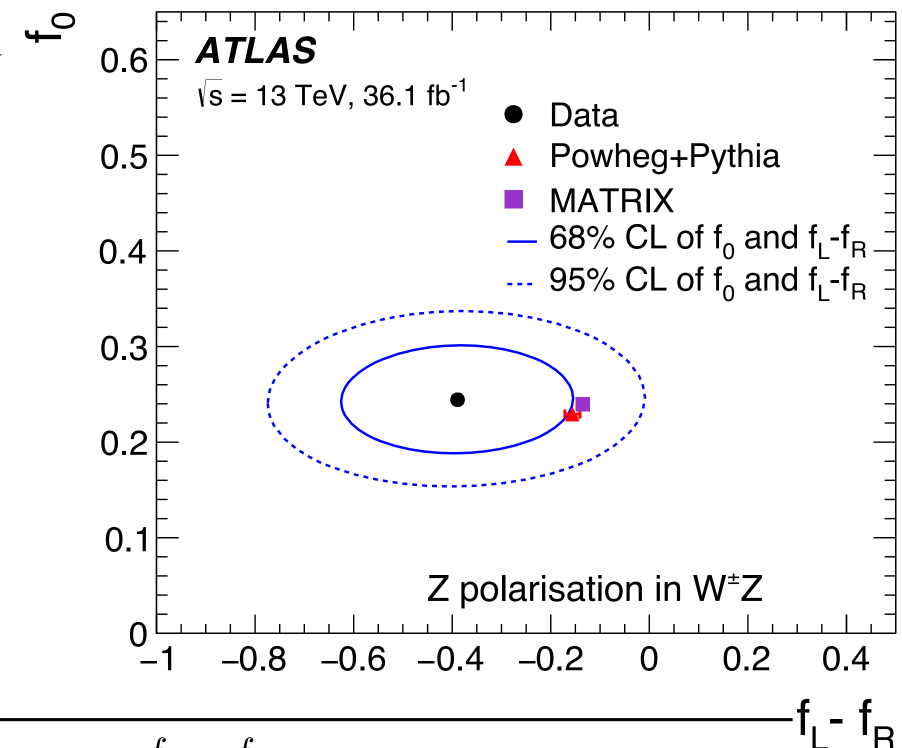
For W decay:

$$\frac{1}{\sigma_{WZ}}\frac{d\sigma_{W^{\pm}Z}}{d\cos\theta_{\ell,W}} = \frac{3}{8}f_L(1\mp\cos\theta_{\ell,W})^2 + \frac{3}{8}f_R(1\pm\cos\theta_{\ell,W})^2 + \frac{3}{4}f_0\sin^2\theta_{\ell,W}$$

Where $f_{L,R,0}$ are left handed, right handed and longitudinal helicity fractions.

- A template fit of three different helicity states is used to extract the helicity fractions in the differential distributions.





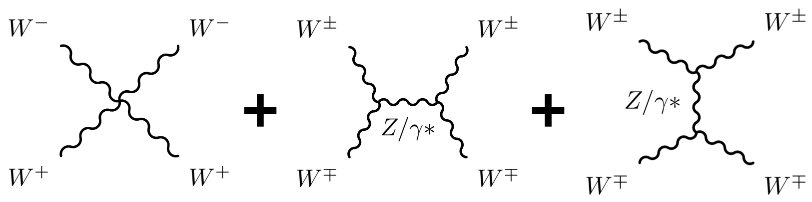
	f_0 Data	f_0 Powheg+Pythia	f_0 MATRIX	$f_L - f_R$ Data	$f_L - f_R$ Powheg+Pythia	$f_L - f_R$ MATRIX
W^+ in W^+Z	0.26 ± 0.08	0.233 ± 0.004	0.2448 ± 0.0010	−0.02 ± 0.04	0.091 ± 0.004	0.0868 ± 0.0014
W^- in W^-Z	0.32 ± 0.09	0.245 ± 0.005	0.2651 ± 0.0015	−0.05 ± 0.05	−0.063 ± 0.006	−0.034 ± 0.004
$W^\pm$ in $W^\pm Z$	0.26 ± 0.06	0.2376 ± 0.0031	0.2506 ± 0.0006	−0.024 ± 0.033	0.0289 ± 0.0022	0.0375 ± 0.0011
Z in W^+Z	0.27 ± 0.05	0.225 ± 0.004	0.2401 ± 0.0014	−0.32 ± 0.21	−0.297 ± 0.021	−0.262 ± 0.009
Z in W^-Z	0.21 ± 0.06	0.235 ± 0.005	0.2389 ± 0.0015	−0.46 ± 0.25	0.052 ± 0.023	0.0468 ± 0.0034
Z in $W^\pm Z$	0.24 ± 0.04	0.2294 ± 0.0033	0.2398 ± 0.0014	−0.39 ± 0.16	−0.156 ± 0.016	−0.135 ± 0.006

Vector Boson Scattering Studies

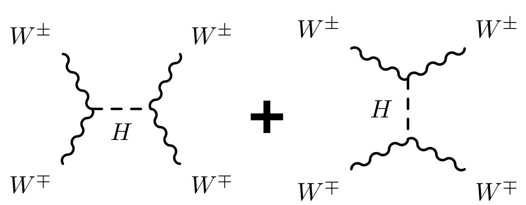
Vector Boson Scattering

- With the discovery of the Higgs, precision measurement of the electroweak triple and quartic gauge couplings offers us key to probe EWSB.

- An example is the longitudinal WW scattering. $W_L W_L \to W_L W_L$

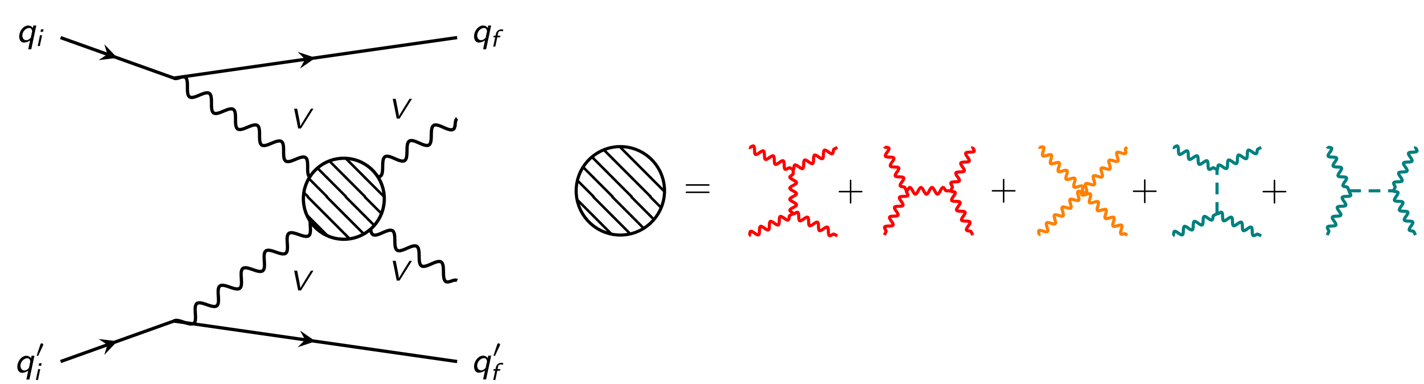


$$\propto 1/m_W^2(s+t)$$



$$\propto -1/m_W^2\left(\frac{s^2}{s-m_H^2}+\frac{t^2}{t-m_H^2}\right)$$

- The VBS channels are really promising to study EW triple and quartic gauge couplings.
  - Good signal-to-background ratio.
  - Possible to separate the QCD and EWK components



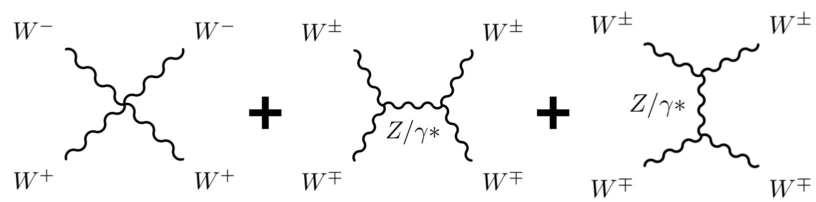
*Graphic by Franziska Iltzsche

Ismet Siral, University Of Oregon

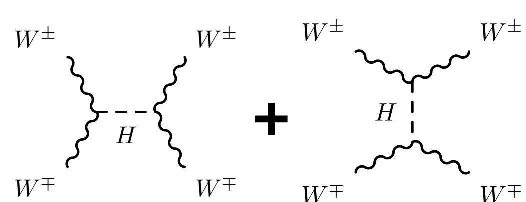
Vector Boson Scattering

- With the discovery of the Higgs, precision measurement of the electroweak triple and quartic gauge couplings offers us key to probe EWSB.

- An example is the longitudinal WW scattering. $W_L W_L \rightarrow W_L W_L$

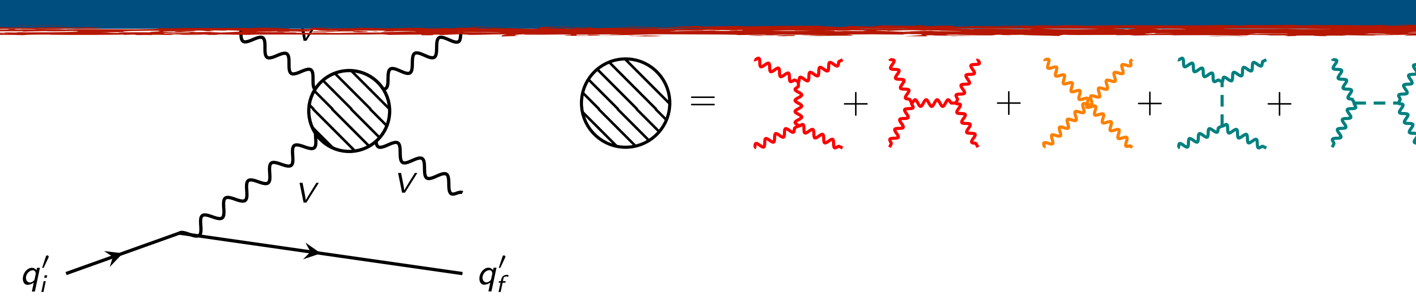


$$\propto 1/m_W^2(s+t)$$



$$\propto -1/m_W^2\left(\frac{s^2}{s-m_H^2}+\frac{t^2}{t-m_H^2}\right)$$

We are not there yet to measure $W_L W_L \rightarrow W_L W_L$, but we now have access to WW final states.



*Graphic by Franziska Iltzsche

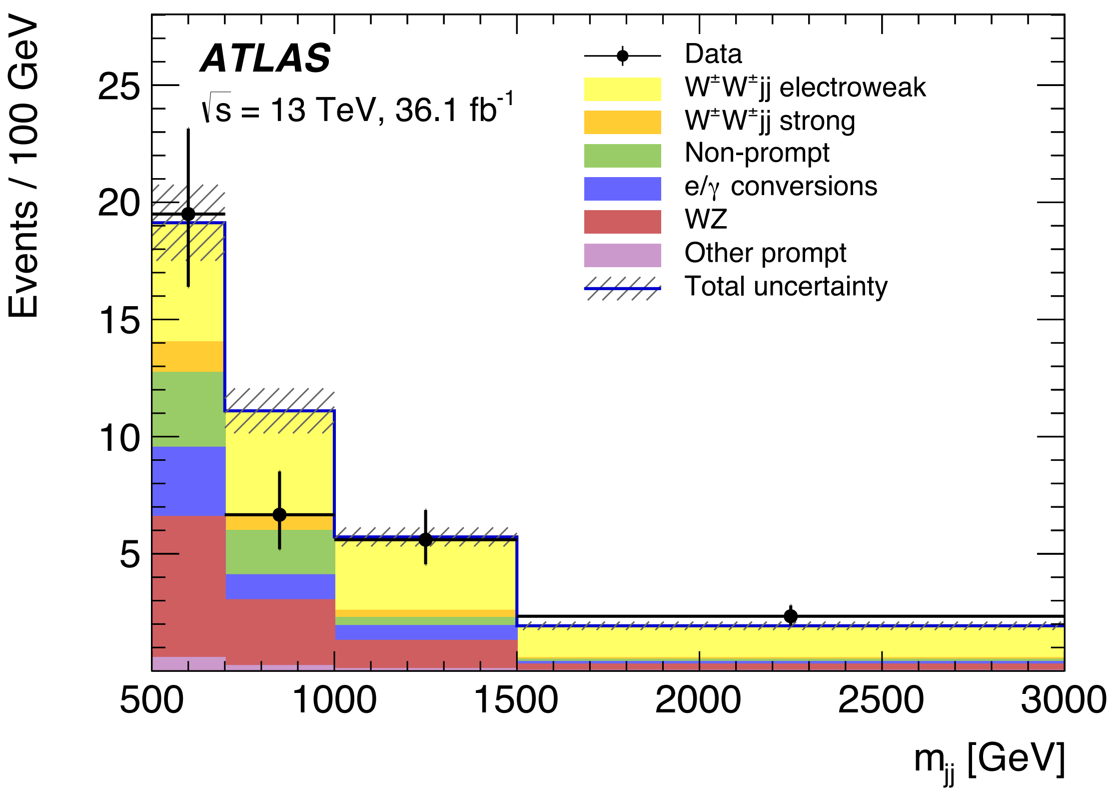
Observation of electroweak production of a same-sign W-boson pair in association with two jets in pp collisions at 13 TeV with the ATLAS detector

Phys. Rev. Lett. 123 (2019) 161801

Observation of EWK Same-Sign WW Production

Event Selection

- This study is done at 13 TeV with with an integrated luminosity of 36.1 fb^{-1}.
  - The first evidence for the EWK ssWW processes 8 TeV by ATLAS: Phys. Rev. Lett.113, 141803 (2014)
  - The first observation for the EWK ssWW processes at 13TeV by CMS: Phys. Rev. Lett.120, 081801 (2018)



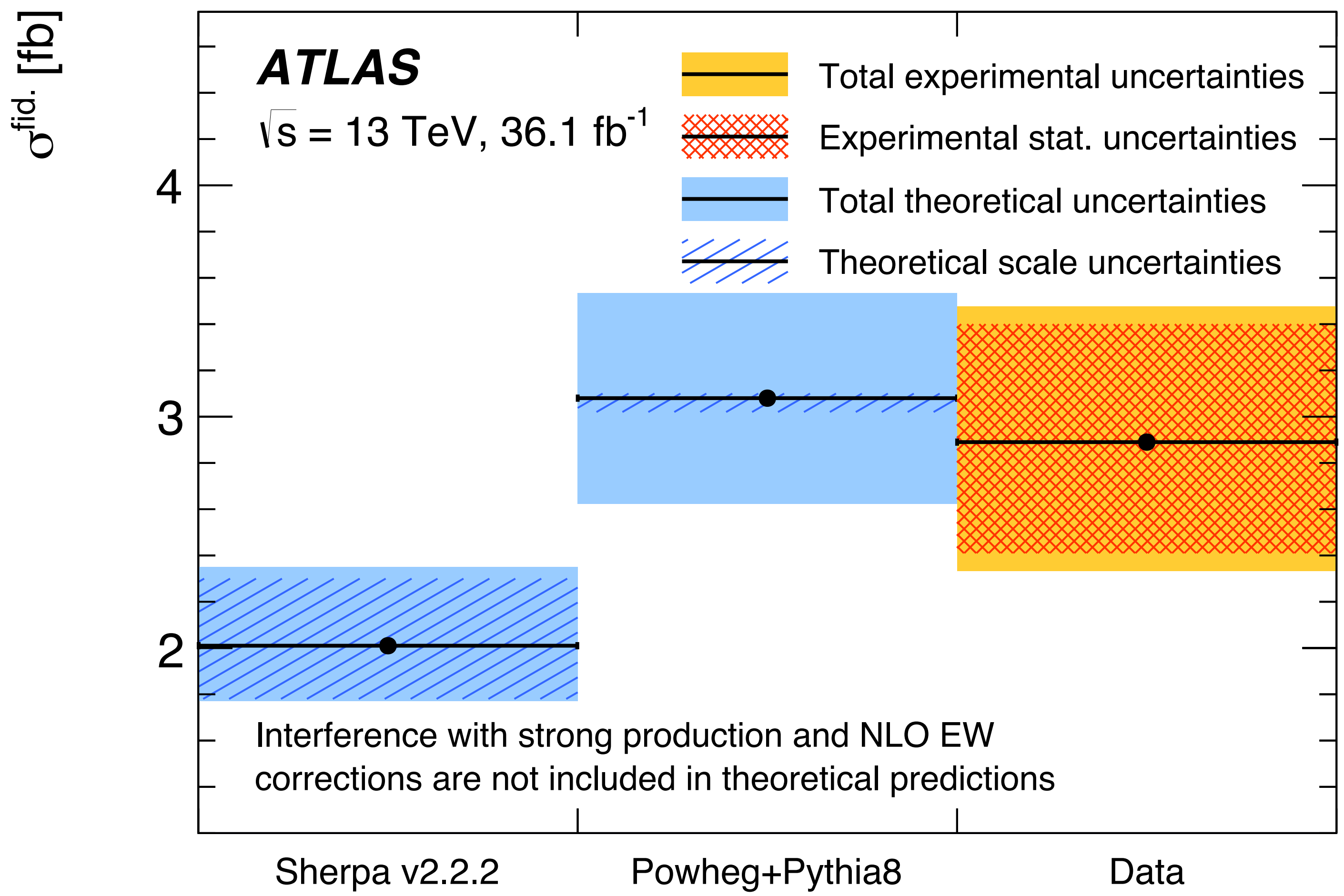
Event Selection

- Exactly two ss leptons: $e^{\pm}e^{\pm}, \mu^{\pm}\mu^{\pm}, e^{\pm}\mu^{\pm}$
- $E_T^{\text{miss}} > 30$ GeV
- Two jets with $m_{jj} > 500$ GeV, with rapidity separation. ($|\Delta y_{jj}| > 2$)
  - $500 > m_{jj} > 200$ GeV is used for validation.

$$\frac{\sigma_{obs.}}{\sigma_{exp.}^{\text{sherpa}}} = 1.44^{+0.26}_{-0.24}\,(\text{Stat.})^{+0.28}_{-0.22}\,(\text{syst.})$$

Observation of EWK Same-Sign WW Production

Observed and Expected Fiducial Cross-Sections



$$\sigma^{\text{fid}}_{\text{obs}} = 2.89^{+0.51}_{-0.48}(\text{stat.})^{+0.24}_{-0.22}(\text{exp. syst.})^{+0.14}_{-0.16}\text{mod. syst.}^{+0.08}_{-0.06}(\text{lumi.})\text{ fb}$$

Background only hypothesis has been rejected with a significance of 6.5σ (4.4 σ exp. with Sherpa)

Observation of electroweak $W^{\pm}Z$ boson pair production in association with two jets in pp collisions at 13TeV with the ATLAS Detector

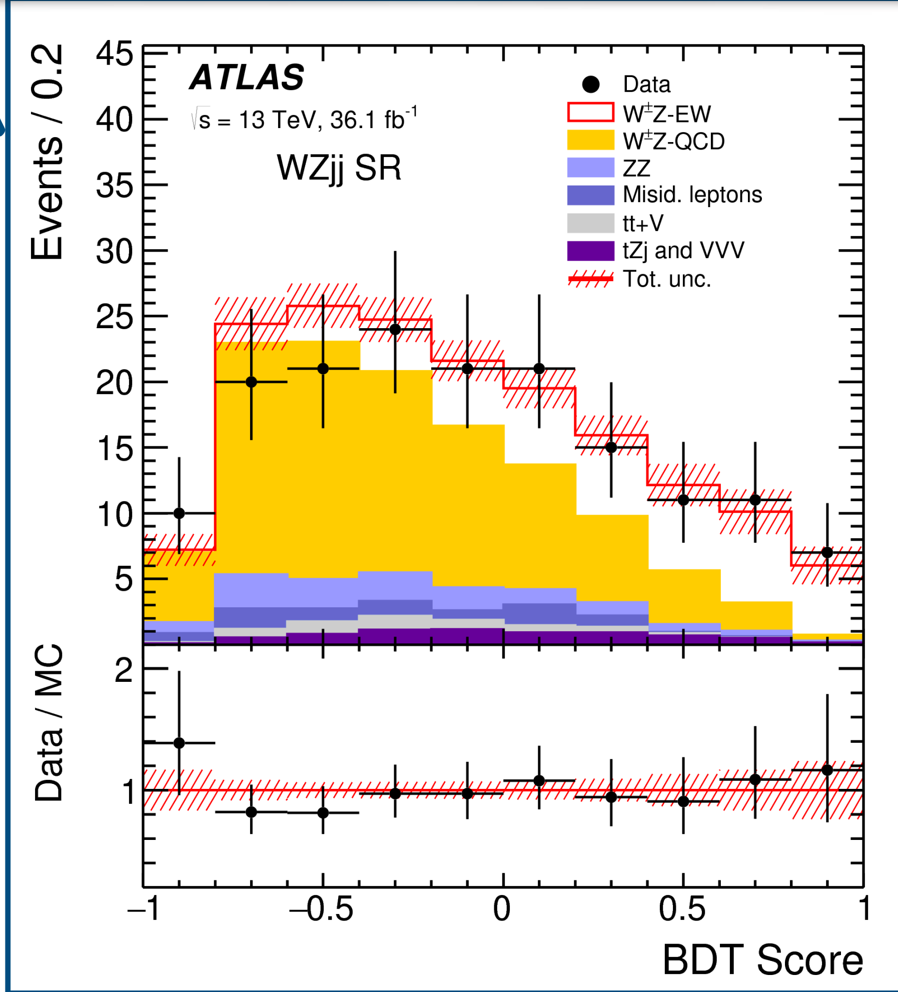
Phys. Lett. B 793 (2019) 469

Observation of VBS Production of WZ

- In addition to the inclusive WZ cross-section measurement, the VBS measurement is also conducted.
- The cuts are really similar with an additional jet requirements.
- A BDT is implemented to split the QCD and EW production of the WZ.
  - The BDT variable is then used to extract the significance.

Event Selection

- Exactly three leptons
- One Z boson candidate: $|m_{\ell\ell}^{\mathrm{SFOS}} - M_Z| < 10$ GeV
- One W boson candidate: $m_T^W > 30$ GeV
- Two high p_T jets with $m_{jj} > 500$ GeV



$$\mu_{WZjj}^{\mathrm{EWK}} = 1.77^{+0.44}_{-0.40}\,(\mathrm{stat.})^{+0.15}_{-0.12}\,(\mathrm{exp.})^{+0.15}_{-0.13}\,(\mathrm{mod.})^{+0.04}_{-0.02}\,(\mathrm{lumi})$$

Backg. only hypothesis is rejected with 5.3 σ (3.2 σ expected)

$$\sigma_{WZjj\text{–}\mathrm{EW}}^{\mathrm{fid.}} = 0.57^{+0.14}_{-0.13}\,(\mathrm{stat.})^{+0.05}_{-0.04}\,(\mathrm{exp.})^{+0.05}_{-0.04}\,(\mathrm{mod.})^{+0.01}_{-0.01}\,(\mathrm{lumi})\ \mathrm{fb}$$

$$\sigma_{WZjj}^{\mathrm{fid.}} = 1.68 \pm 0.25\ \mathrm{fb}$$

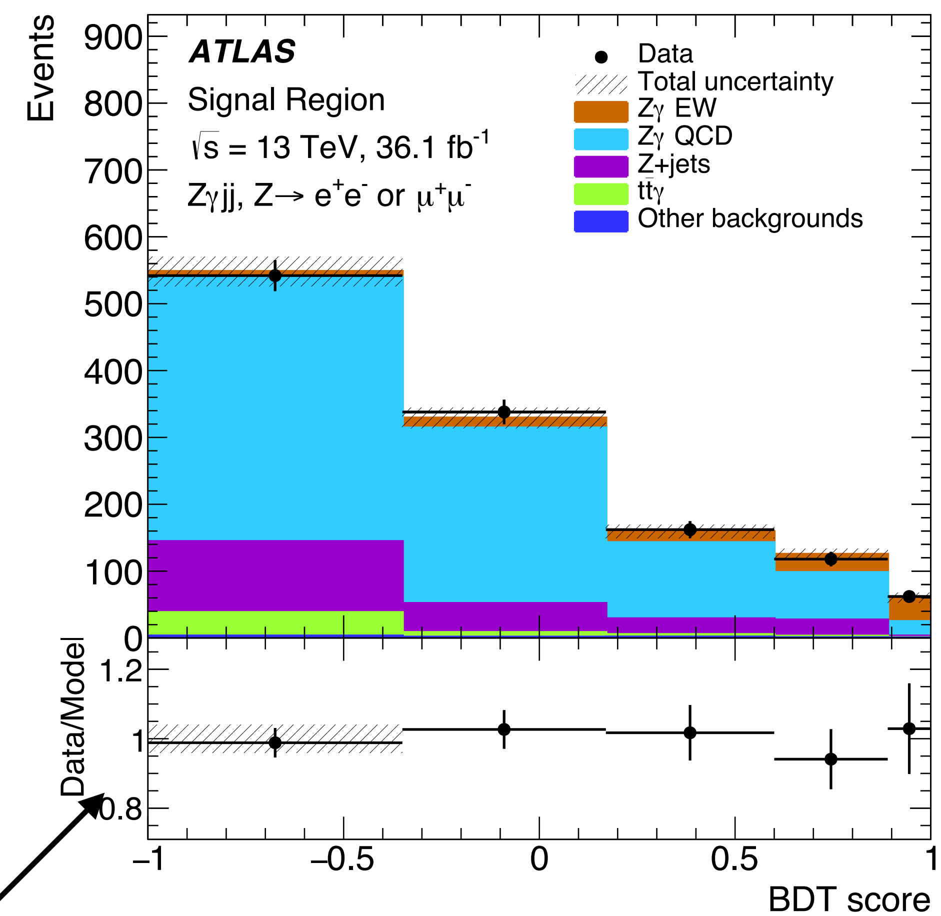
Evidence for electroweak production of two jets in association with a Zγ pair in collisions at 13 TeV with the ATLAS detector

arXiv:1910.09503 [Submitted to PLB]

Evidence of VBS Production of Zγ

Conducted at 13 TeV with an integrated lumi. 36.1 fb^{-1}

- Similar to other VBS productions, $Z\gamma$ is sensitive to triple and quartic gauge boson couplings.
- Event selection:
  - Two same-flavor opposite sign leptons: $e^{\pm}e^{\mp}, \mu^{\pm}\mu^{\mp}$
  - Two back-to-back high-p_T jets with $m_{jj} > 150$ GeV
  - $m_{\ell\ell} > 40$ GeV and $(m_{\ell\ell} + m_{\ell\ell\gamma}) > 182$ GeV
- Produced by both Electroweak and QCD induced processes.
  - In order to differentiate these two processes a BDT based discriminant is used.



$$\mu_{Z\gamma jj-EW} = 1.00 \pm 0.19\ (\text{stat.}) \pm 0.13\ (\text{syst.})^{+0.13}_{-0.10}\ (\text{mod.})$$

Consistent with LO SM Theory !!

$$\sigma^{\text{fid}}_{Z\gamma jj-EW} = 7.8 \pm 1.5\ (\text{stat.}) \pm 1.0\ (\text{syst.})^{+1.0}_{-0.8}\ (\text{mod.})\ \text{fb}$$

Background only hypothesis excluded with 4.1 σ (4.1 σ expected).

Evidence of VBS Production of Zγ

Conducted at 13 TeV with an integrated lumi. 36.1 fb^{-1}

- Similar to other VBS productions, $Z\gamma$ is sensitive to triple
  and
- F
  -
  -
  -
- F
  p

Fiducial $Z(\rightarrow \ell\ell)\gamma$ cross-section is also measured in ATLAS in a separate paper as:
$\sigma_{\text{fid.}} = 533.7 \pm 2.1$ (stat.) $\pm\ 12.4$ (syst.) $\pm\ 9.1$ (lumi.) fb
(arXiv:1911.04813)

$\mu_{Z\gamma jj}$

Consistent with LO SM Theory !!

$\sigma^{\text{fid}}_{Z\gamma jj-EW} = 7.8 \pm 1.5\ (\text{stat.}) \pm 1.0\ (\text{syst.})^{+1.0}_{-0.8}\ (\text{mod.})$ fb

Background only hypothesis excluded with 4.1 σ (4.1 σ expected).

Observation of electroweak production of two jets in association with a Z-boson pair in pp collisions at 13 TeV with the ATLAS detector

ATLAS-CONF-2019-033

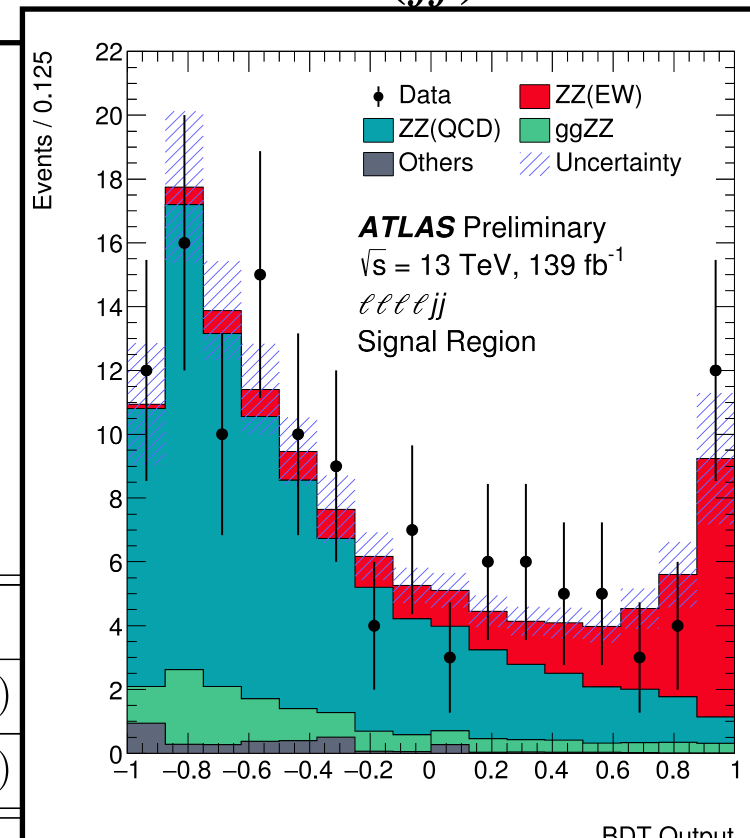
Observation of VBS Production of ZZ

Conducted at 13 TeV with an integrated lumi. 139 fb^{-1}

- The search for the VBS ZZ production is conducted in two decay channels: $ZZjj \rightarrow \ell\ell\ell\ell jj$, $ZZjj \rightarrow \ell\ell\nu\nu jj$
  - $ZZjj \rightarrow \ell\ell\ell\ell jj$:
    - 4 Leptons with smallest $|m^1_{\ell\ell} - m_z| + |m^2_{\ell\ell} - m_z|$
    - Both Z candidates: $66 < m_{\ell\ell} < 116$ GeV
    - Two high-p_T jets with $m_{jj} > 300$ GeV and $\Delta Y(jj) > 2$
  - $ZZjj \rightarrow \ell\ell\nu\nu jj$:
    - Exactly 2 leptons with $80 < m_{\ell\ell} < 110$ GeV
    - E_T^{miss}sig. > 12
    - Two high-p_T jets with $m_{jj} > 400$ GeV and $\Delta Y(jj) > 2$
- A BDT is trained to separate the QCD and EWK production modes.

	μ_{EW}	$\mu^{\ell\ell\ell\ell jj}_{QCD}$	Significance Obs. (Exp.)
$\ell\ell\ell\ell jj$	1.54 ± 0.42	0.95 ± 0.22	5.48 (3.90) σ
$\ell\ell\nu\nu jj$	0.73 ± 0.65	-	1.15 (1.80) σ
Combined	1.35 ± 0.34	0.96 ± 0.22	5.52 (4.30) σ

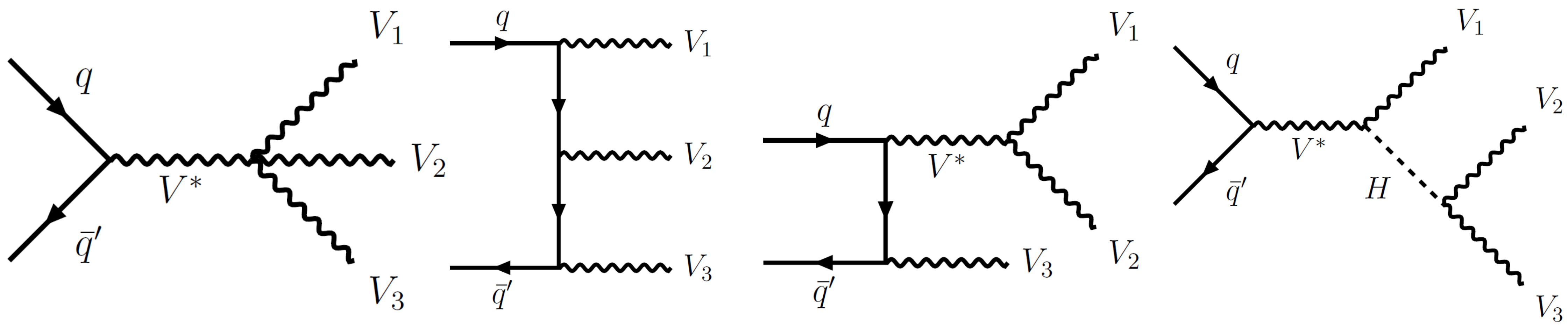
	Measured fiducial σ [fb]	Predicted fiducial σ [fb]
$\ell\ell\ell\ell jj$	1.27 ± 0.12(stat) ± 0.02(theo) ± 0.07(exp) ± 0.01(bkg) ± 0.03(lumi)	1.14 ± 0.04(stat) ± 0.20(theo)
$\ell\ell\nu\nu jj$	1.22 ± 0.30(stat) ± 0.04(theo) ± 0.06(exp) ± 0.16(bkg) ± 0.03(lumi)	1.07 ± 0.01(stat) ± 0.12(theo)



Evidence for the production of three massive vector bosons with the ATLAS detector

Phys. Lett. B 798 (2019) 134913

Evidence for Tri-Boson Production



$$WWW \rightarrow \ell\nu\ell\nu\ell\nu \quad WZZ \rightarrow qq\ell\ell\ell\ell \quad WWZ \rightarrow \ell\nu\ell\nu\ell\ell$$
$$WWW \rightarrow \ell\nu\ell\nu qq \quad WZZ \rightarrow \ell\nu qq\ell\ell \quad WWZ \rightarrow \ell\nu qq\ell\ell$$

- **Each channel has an individual significance of ~1–2 σ.**
- **These final states are sensitive to triple gauge couplings, quartic gauge couplings and Higgs production.**
  - **Only cross-section measurements are made**
  - **aQGCs is considered for the full data-set.**

Evidence for Tri-Boson Production

WVZ Analysis

BDT Based

All backgrounds are MC

W V Z

Categorize according to 3ℓ or 4ℓ end-states

Always reconstruct a Z boson with 2 leptons

3ℓ Analysis

- At least one jet with b-jet veto.
- One BDT is trained per jet category:
  - 1, 2, 3+ jets.

4ℓ Analysis

- 4 leptons with a total charge of 0
- One BDT is trained for each category:
  - Same-flavor on-shell
  - Same-flavor off-shell
  - Different-flavor

WWW Analysis

Cutflow Based

Uses data driven backgrounds

W W W

Avoid Z bosons:

2ℓ2j Analysis - Two same sign leptons

3ℓ Analysis - 0 same flav. opposite sign lep.

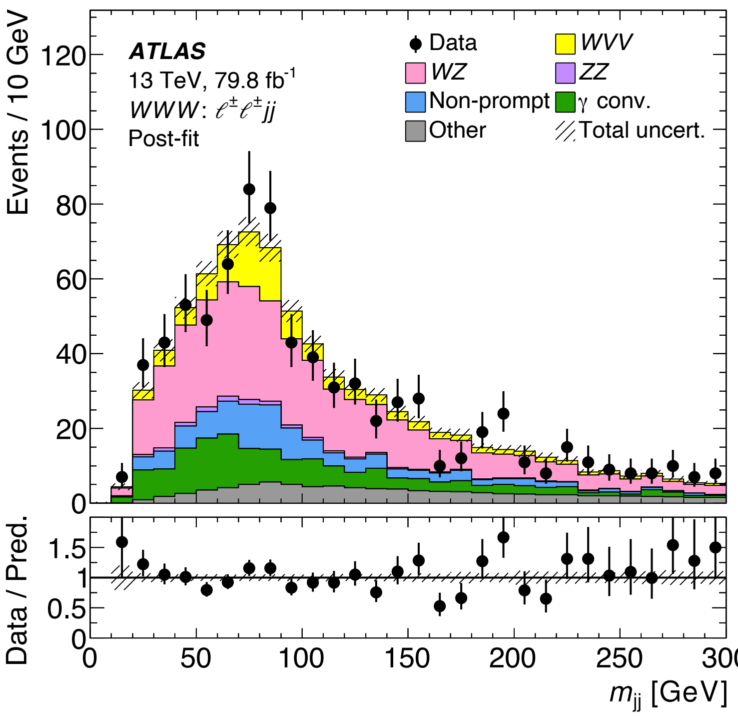
2ℓ2j Analysis

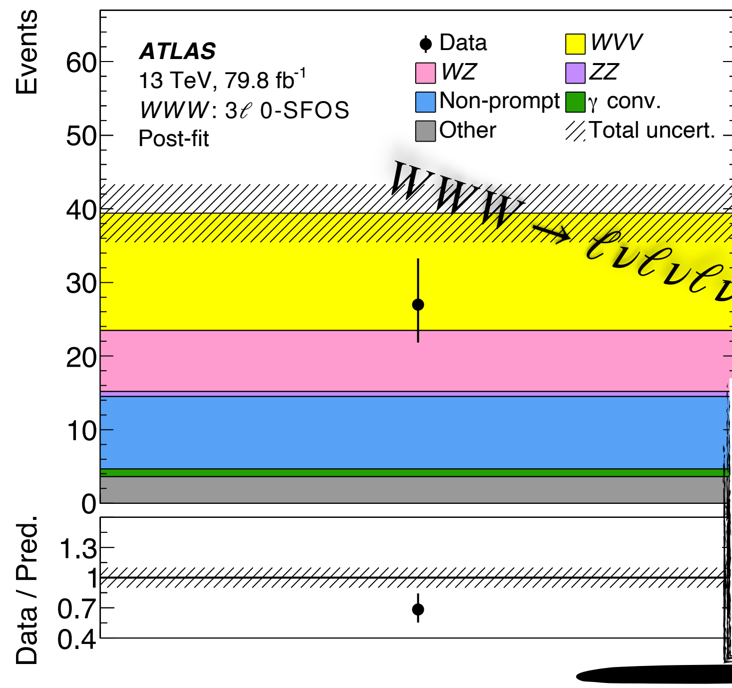
- At least 2 jets with b-jet veto.
  - Mjj is used as the discriminant
- Specific cuts to veto ssWW

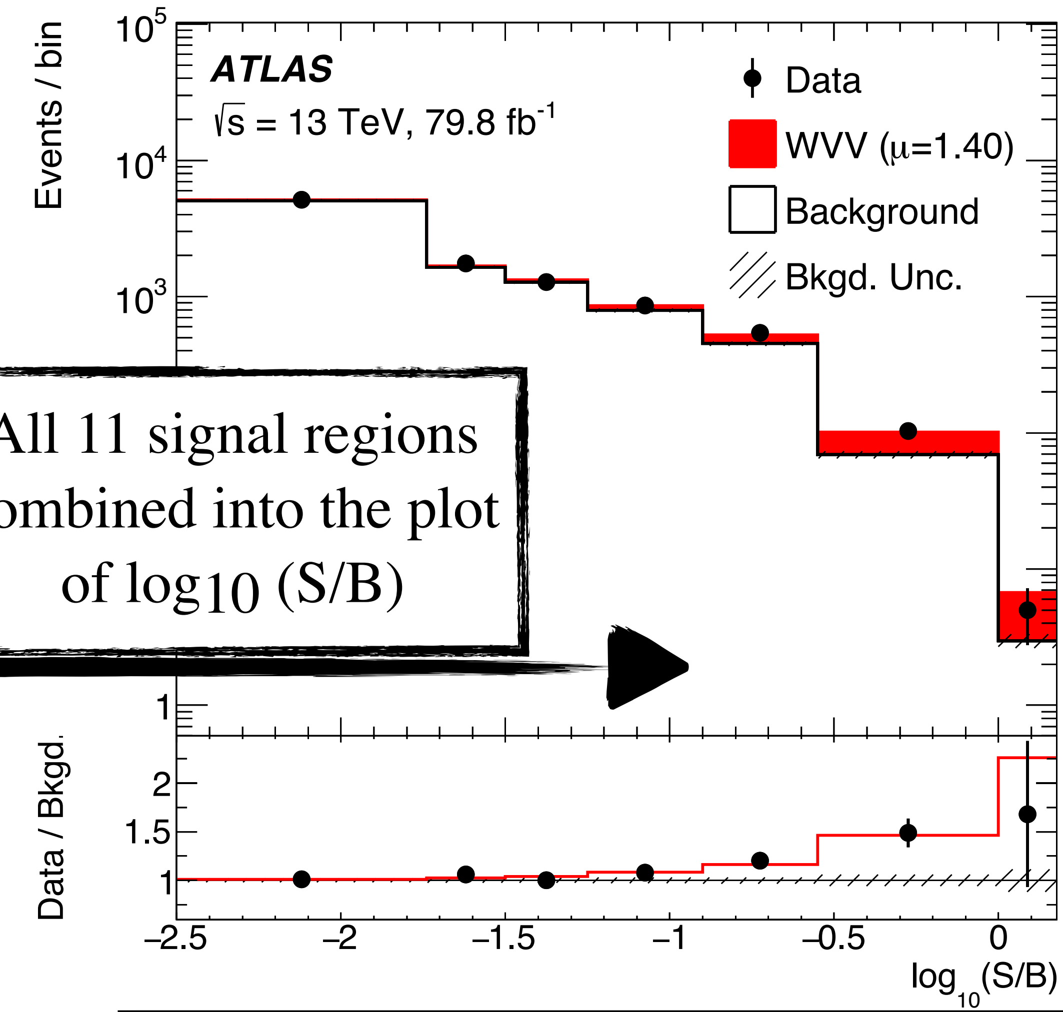
3ℓ Analysis

- 0SFOS suppresses majority of backgrounds.
- b-jet veto is additionally applied to veto ttbar events.

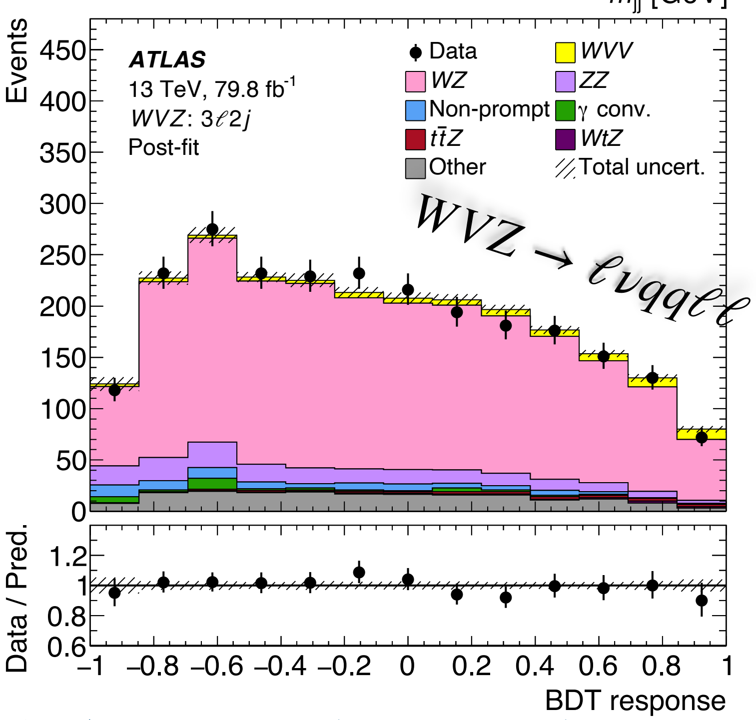
Evidence for Tri-Boson Production

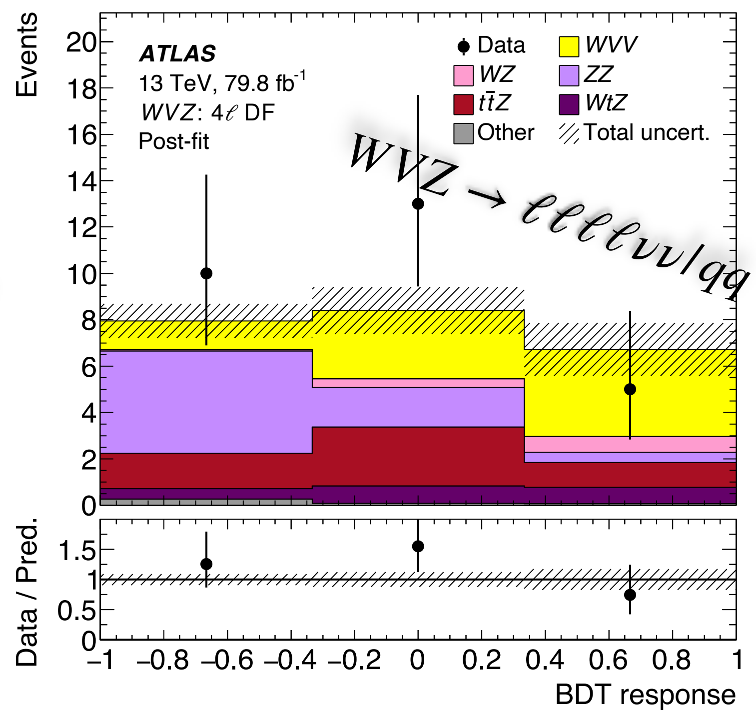


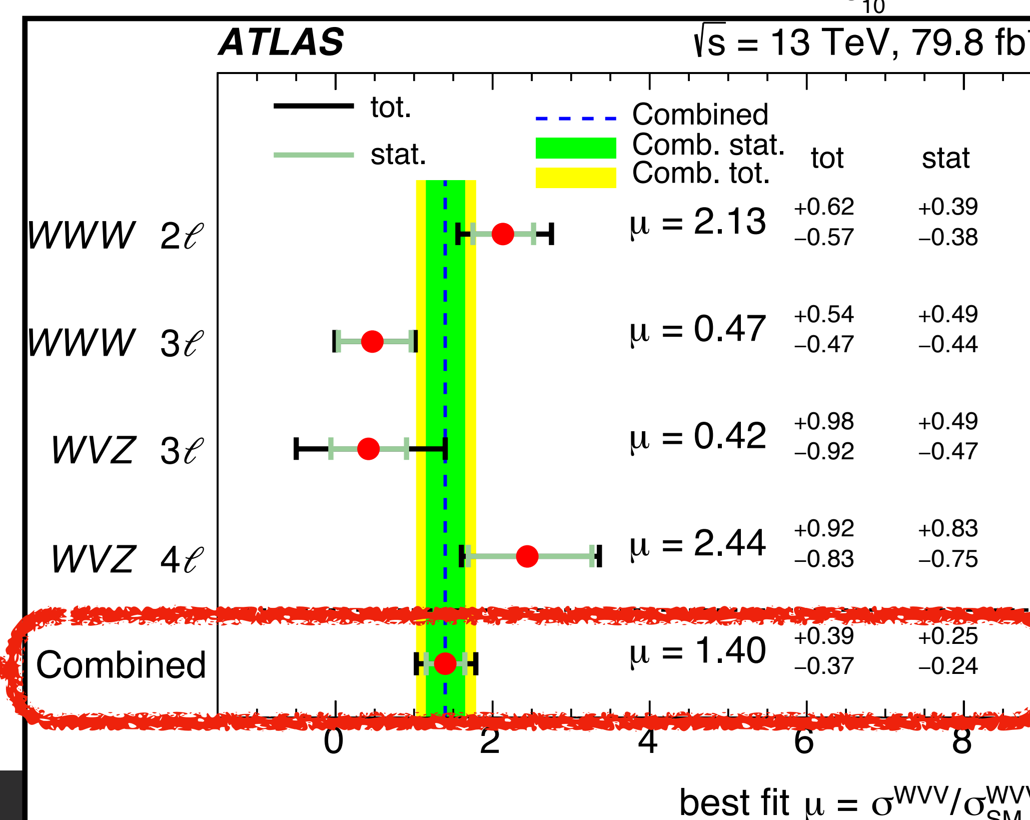




All 11 signal regions combined into the plot of $\log_{10}$ (S/B)







First evidence of VVV production in *pp* events has been observed with a significance of 4 σ compared to expected 3.1 σ.

$$\sigma_{WWW} = 0.65^{+0.23}_{-0.21}\ \text{pb};\ \sigma_{WWZ} = 0.55^{+0.21}_{-0.19}\ \text{pb}$$

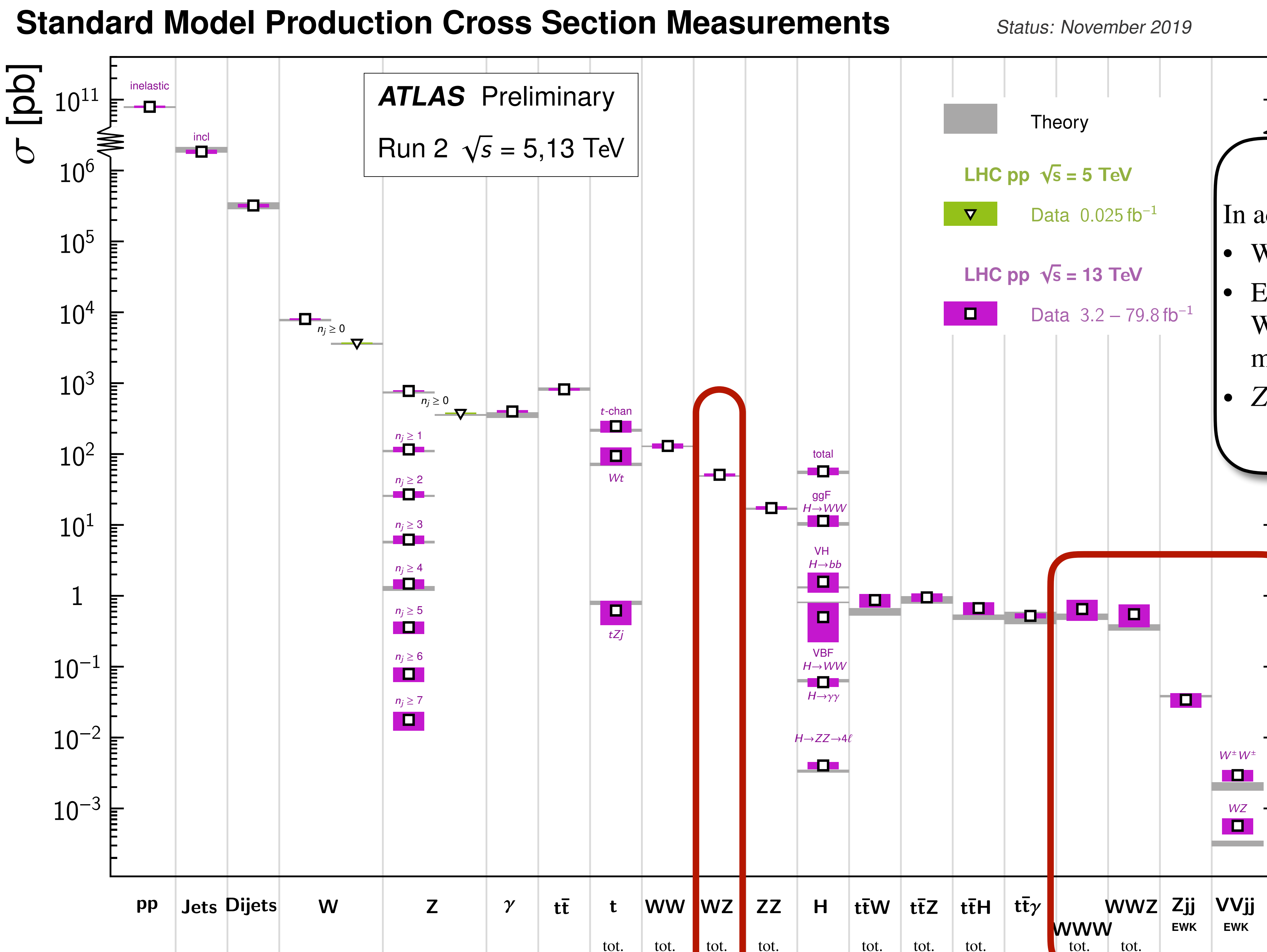
Conclusion

- ATLAS is now able to compete in precision measurements with previous experiments. (m_W and $\sin^2\theta^{\ell}_{\text{eff}}$)
  - More results are soon to follow with 8 TeV and 13 TeV datasets.
  - Special studies are being conducted to reduce both theoretical and experimantal uncertainties.
- Triple and Quartic gauge couplings are being probed now, and we are getting the first evidences/ observation of EW di-boson / tri-boson final states.
  - In the long term, we will reach observation level for majority of these final states and these results will allow us to probe the EWSB.

More results are coming
Standard Model Is Still Exiting :)

ATLAS Standard Model X-Section Measurements

Today, we will cover only a sub-set of ATLAS results.



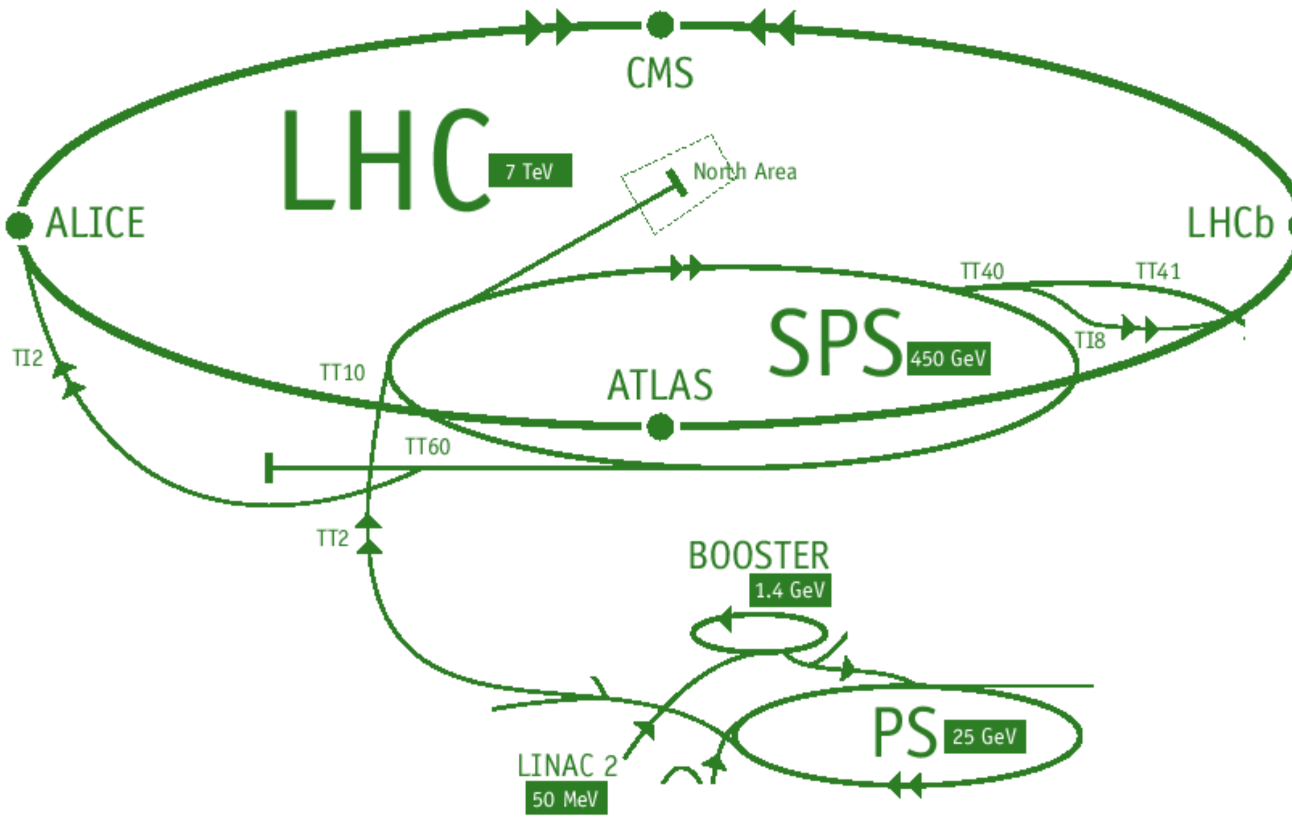
In addition:

- W mass measurement
- Effective Leptonic Weak Mixing Angle measurement
- $Z\gamma$ EWK

Backup Slides

The Large Hadron Collider

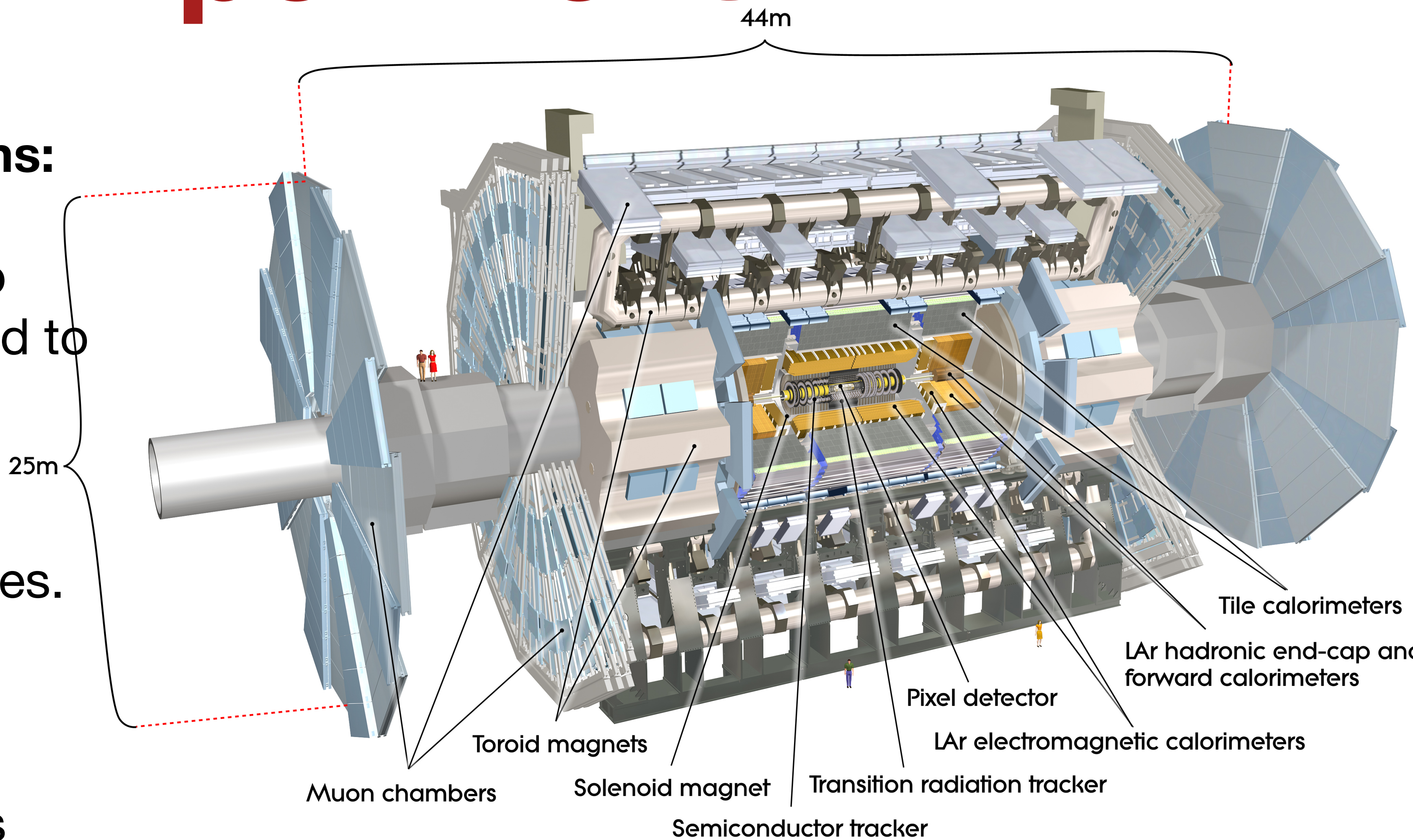
- The LHC is a 27km particle collider that can collide protons and lead ions.
- Protons are accelerated to:
  - Linac 2 - 50 MeV
  - PS - 25 GeV
  - BOOSTER -1.4 GeV
  - SPS - 450 GeV
  - LHC - 6.5 TeV
- It houses the experiments:
  - ATLAS, CMS, ALICE, LHCb
  - TOTEM, LHCf, MoEDAL



Parameters	2010	2011 - 2012	2015 - 2018	Design
Beam Energy [TeV]	3.5	4	6.5	7
Integrated Luminosity [fb^{-1}]	0.048	28.3	156	
Max Peak Luminosity [$10^{34} cm^{-2} s^{-1}$]	0.021	0.77	2.14	1
Bunch Spacing [ns]	150	50	25	25

The ATLAS Experiment

- **The ATLAS Detector is composed of 4 major systems:**
  - **Inner Detector**
    - The inner detector aims to track charged particles and to measure their momenta.
  - **Calorimeters**
    - Calorimeters measure the energy of incoming particles.
  - **Muon Spectrometer**
    - The muon spectrometer tracks the particles that penetrate the calorimeters and measure their momenta.



- **Magnet System**
  - The magnet system provides magnetic field to the inner detector and the muon spectrometer.
    - Solenoid Magnet - Inner Detector - 2 Tesla
    - Toroid Magnet - Muon Spectrometer - 4 Tesla

* Image from https://cds.cern.ch/record/1095924/.

Measurement of Effective Leptonic Weak Mixing Angle

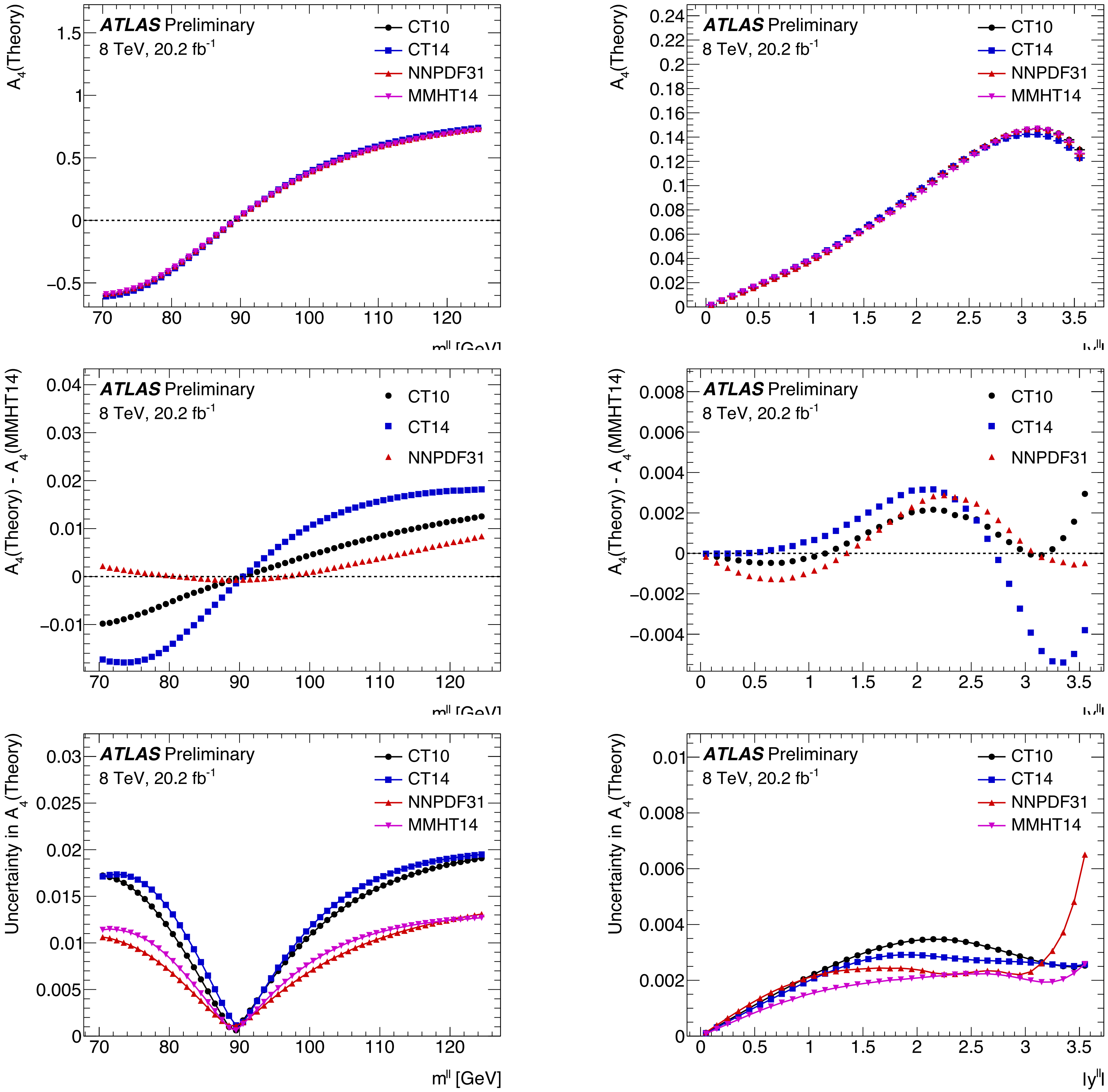
Backup Slides

Measurement of Effective Leptonic Weak Mixing Angle

Input Parameters used by Dizet to calculate effective mixing angles

Parameter	Value	Description
	Measured	
m_Z	91.1876 GeV	Mass of Z boson
m_H	125.0 GeV	Mass of Higgs boson
m_t	173.0 GeV	Mass of top quark
m_b	4.7 GeV	Mass of b quark
$1/\alpha(0)$	137.0359895(61)	QED coupling constant in Thomson limit
G_μ	$1.166389(22) \cdot 10^{-5}$ GeV^{-2}	Fermi constant from muon lifetime
	Calculated	
m_W	80.353 GeV	Mass of W boson
$\sin^2\theta_W$	0.22351946	On mass-shell-value of weak mixing angle
$\alpha(m_Z^2)$	0.00775995	
$1/\alpha(m_Z^2)$	128.86674175	
$ZPAR(6) - ZPAR(8)$	0.23175990	$sin^2\theta^{\ell}_{eff}(m_Z^2)$ (e, μ, τ)
$ZPAR(9)$	0.23164930	$sin^2\theta^{u}_{eff}(m_Z^2)$ (up quark)
$ZPAR(10)$	0.23152214	$sin^2\theta^{d}_{eff}(m_Z^2)$ (down quark)

Measurement of Effective Leptonic Weak Mixing Angle
Uncertainties on A4 Predictions



Measurement of Effective Leptonic Weak Mixing Angle
A4 Predictions With PDF uncertainteis

	$70 < m^{\ell\ell} < 80$ GeV			$80 < m^{\ell\ell} < 100$ GeV				$100 < m^{\ell\ell} < 125$ GeV		
$\|y^{\ell\ell}\|$	$0-0.8$	$0.8-1.6$	$1.6-2.5$	$0-0.8$	$0.8-1.6$	$1.6-2.5$	$2.5-3.6$	$0-0.8$	$0.8-1.6$	$1.6-2.5$
Central value (NNLO QCD)	-0.0870	-0.2907	-0.5970	0.0144	0.0471	0.0928	0.1464	0.1045	0.3444	0.6807
ΔA_4 (NNLO - NLO QCD)	0.0003	0.0010	0.0021	-0.0001	-0.0005	-0.0009	-0.0015	-0.0007	-0.0022	-0.0041
ΔA_4 (EW)	0.0008	0.0028	0.0056	0.0002	0.0007	0.0015	0.0026	-0.0008	-0.0026	-0.0048
$\Delta \sin^2\theta^{\ell}_{\rm eff}$ (EW)	0.00129	0.00130	0.00133	0.00024	0.00024	0.00025	0.00026	-0.00120	-0.00123	-0.00119
	Uncertainties			Uncertainties				Uncertainties		
Total	0.0035	0.0094	0.0137	0.0007	0.0017	0.0021	0.0021	0.0040	0.0102	0.0140
PDF	0.0034	0.0092	0.0127	0.0007	0.0016	0.0020	0.0019	0.0039	0.0100	0.0131
QCD scales	0.0006	0.0019	0.0052	0.0003	0.0003	0.0004	0.0008	0.0005	0.0022	0.0049

Measurement of Effective Leptonic Weak Mixing Angle

Expected vs Observed uncertainties on A4 and their brakdown based on MMHT14 pseudo-data

Expected

$m^{\ell\ell}$ (GeV)	70 − 80			80 − 100				100 − 125		
$—y^{\ell\ell}—$	0 − 0.8	0.8 − 1.6	1.6 − 2.5	0 − 0.8	0.8 − 1.6	1.6 − 2.5	2.5 − 3.6	0 − 0.8	0.8 − 1.6	1.6 − 2.5
Prediction (MMHT14)	−0.0870	−0.2907	−0.5970	0.0144	0.0471	0.0928	0.1464	0.1045	0.3444	0.6807
	Uncertainties			Uncertainties				Uncertainties		
Total	0.0176	0.0202	0.0404	0.0015	0.0015	0.0025	0.0044	0.0083	0.0098	0.0230
Stat.	0.0153	0.0164	0.0333	0.0013	0.0013	0.0021	0.0036	0.0072	0.0078	0.0188
Syst.	0.0087	0.0117	0.0229	0.0007	0.0008	0.0013	0.0025	0.0041	0.0060	0.0133
PDF (meas.)	0.0013	0.0049	0.0048	0.0001	0.0002	0.0004	0.0007	0.0007	0.0016	0.0043
p_T^Z modelling	0.0002	0.0004	< 0.0001	< 0.0001	< 0.0001	< 0.0001	< 0.0001	0.0001	< 0.0001	0.0002
Leptons	0.0023	0.0059	0.0118	0.0002	0.0001	0.0003	0.0007	0.0014	0.0037	0.0070
Background	0.0004	0.0011	0.0064	< 0.0001	< 0.0001	< 0.0001	0.0001	0.0004	0.0017	0.0031
MC stat.	0.0082	0.0088	0.0179	0.0007	0.0007	0.0012	0.0023	0.0038	0.0041	0.0100

Observed

	$70 < m^{\ell\ell} < 80$ GeV			$80 < m^{\ell\ell} < 100$ GeV				$100 < m^{\ell\ell} < 125$ GeV		
$\|y^{\ell\ell}\|$	0 − 0.8	0.8 − 1.6	1.6 − 2.5	0 − 0.8	0.8 − 1.6	1.6 − 2.5	2.5 − 3.6	0 − 0.8	0.8 − 1.6	1.6 − 2.5
Central value	−0.0681	−0.2684	−0.5087	0.0195	0.0448	0.0923	0.1445	0.0975	0.3311	0.6722
	Uncertainties			Uncertainties				Uncertainties		
Total	0.0176	0.0199	0.0391	0.0015	0.0016	0.0026	0.0046	0.0086	0.0099	0.0234
Stat.	0.0149	0.0160	0.0324	0.0013	0.0013	0.0021	0.0037	0.0073	0.0079	0.0188
Syst.	0.0093	0.0119	0.0220	0.0008	0.0008	0.0014	0.0027	0.0045	0.0062	0.0139
PDF (meas.)	0.0004	0.0044	0.0046	0.0001	0.0002	0.0004	0.0008	0.0009	0.0015	0.0050
p_T^Z modelling	0.0028	0.0031	0.0058	0.0003	0.0003	0.0004	0.0007	0.0014	0.0015	0.0033
Leptons	0.0044	0.0063	0.0095	0.0004	0.0003	0.0005	0.0010	0.0019	0.0040	0.0071
Background	< 0.0001	0.0008	0.0040	< 0.0001	0.0001	< 0.0001	0.0001	0.0006	0.0015	0.0023
MC stat.	0.0083	0.0089	0.0180	0.0007	0.0007	0.0012	0.0023	0.0038	0.0042	0.0102

Measurement of Effective Leptonic Weak Mixing Angle

Expected vs Obs. uncertainties on Effective Mixing Angle and their brakdown based on MMHT14 pseudo-data

Expected

Channel	ee_{CC}	$\mu\mu_{CC}$	ee_{CF}	$ee_{CC} + \mu\mu_{CC}$	$ee_{CC} + \mu\mu_{CC} + ee_{CF}$
Total	65	59	42	48	34
Stat.	47	39	29	30	21
Syst.	45	44	31	37	27
	Uncertainties in measurements				
PDF (meas.)	7	7	7	7	4
p_{T}^{Z} modelling	< 1	< 1	1	< 1	< 1
Lepton scale	5	4	6	3	3
Lepton resolution	3	1	3	1	2
Lepton efficiency	1	1	1	1	1
Electron charge misidentification	< 1	0	< 1	< 1	< 1
Muon sagitta bias	0	4	0	2	1
Background	1	1	1	1	1
MC. stat.	25	22	18	16	12
	Uncertainties in predictions				
PDF (predictions)	36	37	21	32	22
QCD scales	5	5	9	4	6
EW corrections	3	3	3	3	3

Observed

Channel	ee_{CC}	$\mu\mu_{CC}$	ee_{CF}	$ee_{CC} + \mu\mu_{CC}$	$ee_{CC} + \mu\mu_{CC} + ee_{CF}$
Central value	0.23148	0.23123	0.23166	0.23119	0.23140
	Uncertainties				
Total	68	59	43	49	36
Stat.	48	40	29	31	21
Syst.	48	44	32	38	29
	Uncertainties in measurements				
PDF (meas.)	8	9	7	6	4
p_{T}^{Z} modelling	0	0	7	0	5
Lepton scale	4	4	4	4	3
Lepton resolution	6	1	2	2	1
Lepton efficiency	11	3	3	2	4
Electron charge misidentification	2	0	1	1	< 1
Muon sagitta bias	0	5	0	1	2
Background	1	2	1	1	2
MC. stat.	25	22	18	16	12
	Uncertainties in predictions				
PDF (predictions)	37	35	22	33	24
QCD scales	6	8	9	5	6
EW corrections	3	3	3	3	3

Measurement of Effective Leptonic Weak Mixing Angle
Data MC Samples

Signature	Generator	PDF	References
$Z/\gamma^* \to \ell\ell$	Powheg-Box + Pythia 8	CT10 NLO	[21,22,23,24,42,41]
$Z/\gamma^* \to \tau\tau$	Sherpa	CT10 NLO	[45,46,47,48]
$t\bar{t}$	Powheg-Box + Pythia 6	CTEQ6L1	
Single top quark (Wt channel)	Powheg-Box + Pythia 8	CTEQ6L1	
Dibosons	Herwig	CTEQ6L1	[49]
$\gamma\gamma \to \ell\ell$	Pythia 8	MRST2004QED NLO	[50]

Measurement of Effective Leptonic Weak Mixing Angle
Yields After Cuts

$\|y_{ll}\|$	Data	Top+EW	Multijets	Non-fiducial Z
	$70 < m_{ll} < 80$ GeV			
0-0.8	106 718	0.023	0.015	0.010
0.8-1.6	95 814	0.015	0.020	0.010
1.6-2.5	47 078	0.012	0.041	0.009
	$80 < m_{ll} < 100$ GeV			
0-0.8	2 697 316	0.003	0.001	< 0.001
0.8-1.6	2 084 856	0.002	0.001	< 0.001
1.6-2.5	839 424	0.002	0.002	< 0.001
	$100 < m_{ll} < 125$ GeV			
0-0.8	106 855	0.034	0.016	0.023
0.8-1.6	80 403	0.025	0.019	0.027
1.6-2.5	28 805	0.015	0.025	0.029

Two Central Electrons

$\|y_{ll}\|$	Data	Top+EW	Multijets	Non-fiducial Z
	$70 < m_{ll} < 80$ GeV			
0-0.8	124 050	0.019	0.017	0.009
0.8-1.6	137 984	0.015	0.014	0.014
1.6-2.5	74 976	0.010	0.011	0.019
	$80 < m_{ll} < 100$ GeV			
0-0.8	2 866 016	0.002	0.001	< 0.001
0.8-1.6	2 948 371	0.002	0.001	< 0.001
1.6-2.5	1 314 890	0.002	0.001	< 0.001
	$100 < m_{ll} < 125$ GeV			
0-0.8	119 650	0.030	0.023	0.023
0.8-1.6	122 775	0.020	0.015	0.023
1.6-2.5	55 886	0.010	0.005	0.022

Two Central Muons

$\|y_{ll}\|$	Data	Top+EW	Multijets	Non-fiducial Z
	$80 < m_{ll} < 100$ GeV			
1.6-2.5	702 142	0.001	0.010	0.017
2.5-3.6	441 104	0.001	0.011	0.013

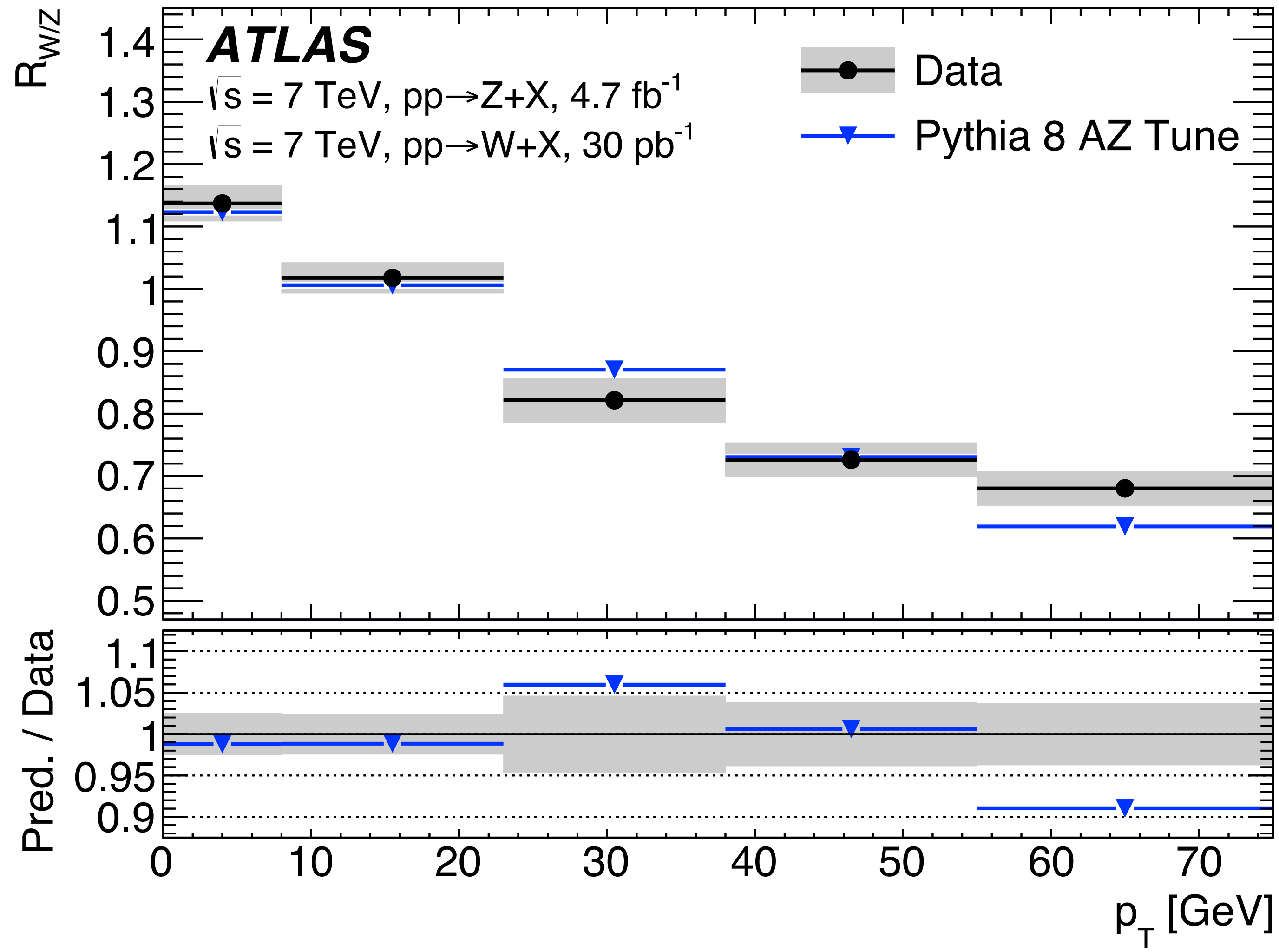
One Central Electron
One Forward Electron

Measurement of the W-Boson Mass

Backup Slides

Measurement of the W-Boson Mass

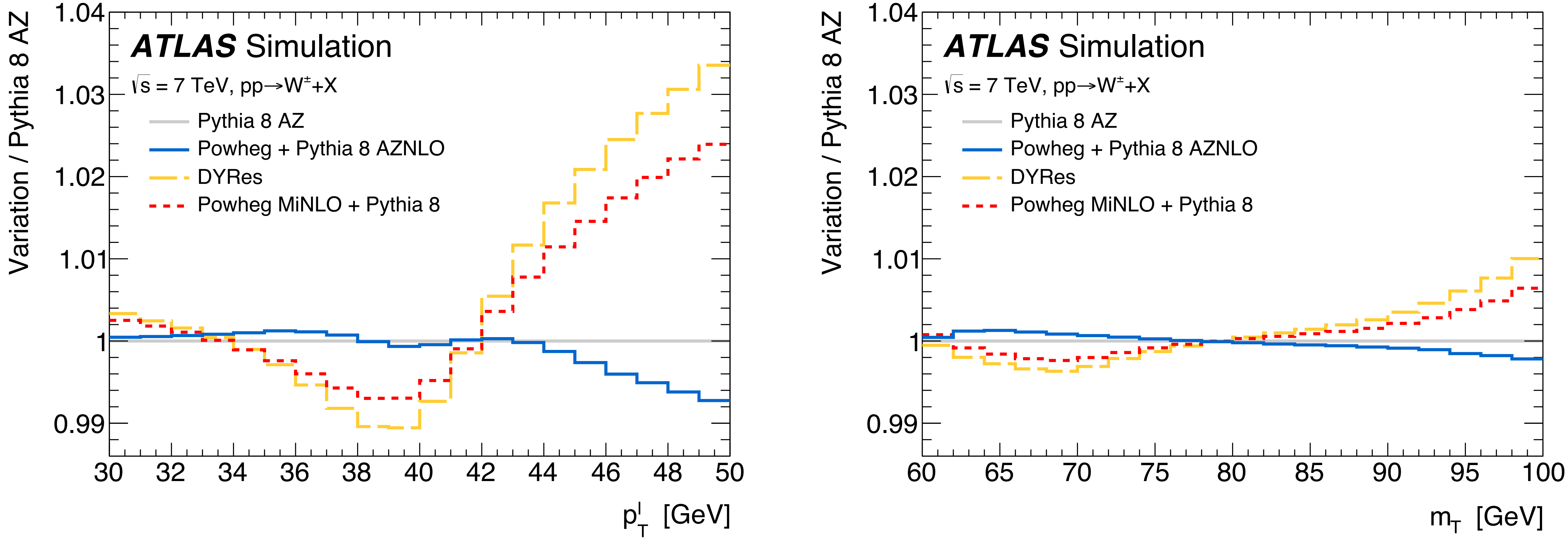
Differential Cross -Section Ratios between W and Z



The theoretical prediction is in agreement with experimental measurements

Measurement of the W-Boson Mass

Modeling Differences Between Different Generators



The discrepancy at high p_T justifies the cut on $p_T < 30$ GeV

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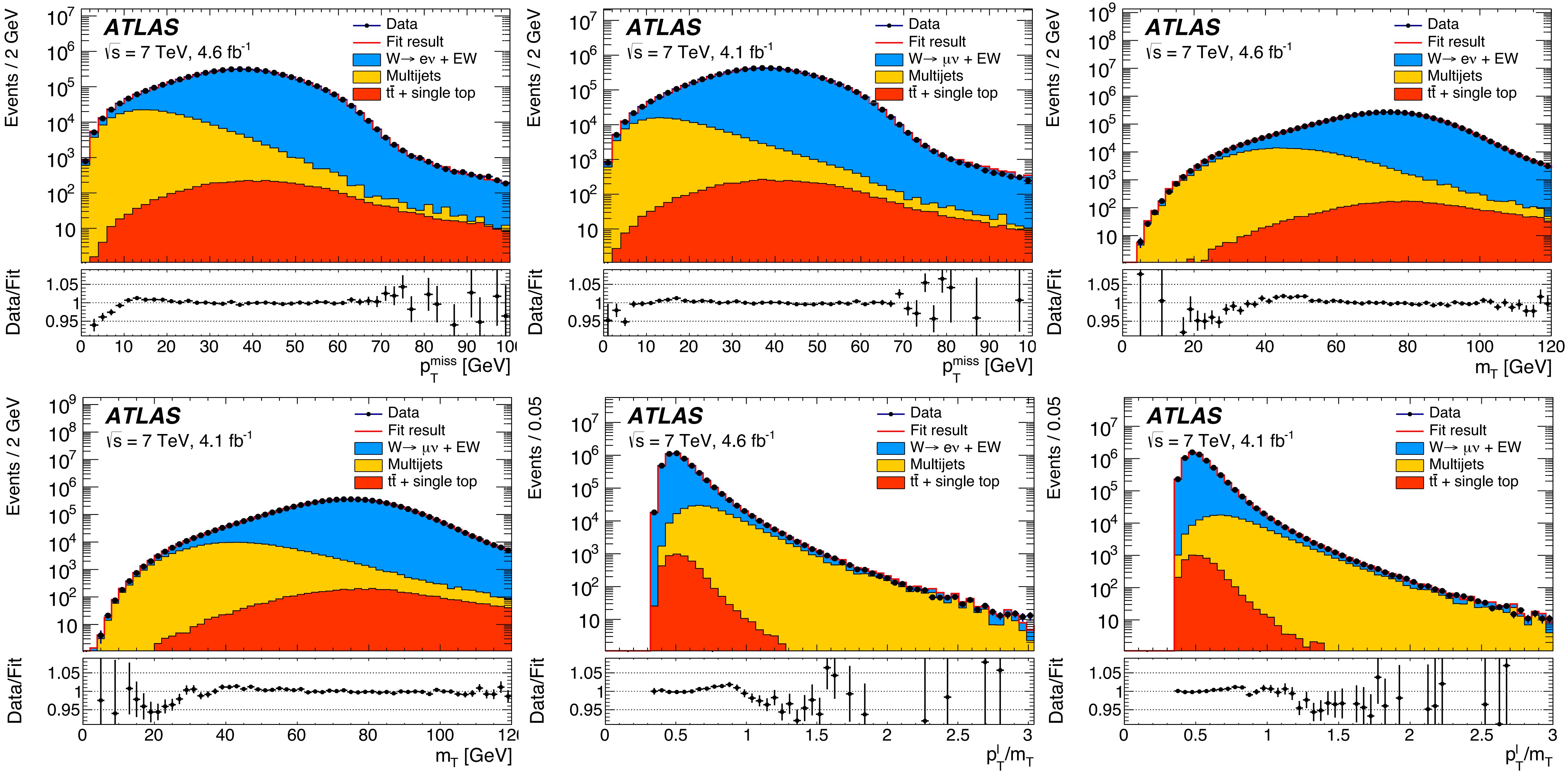
Measurement of the W-Boson Mass

Templates



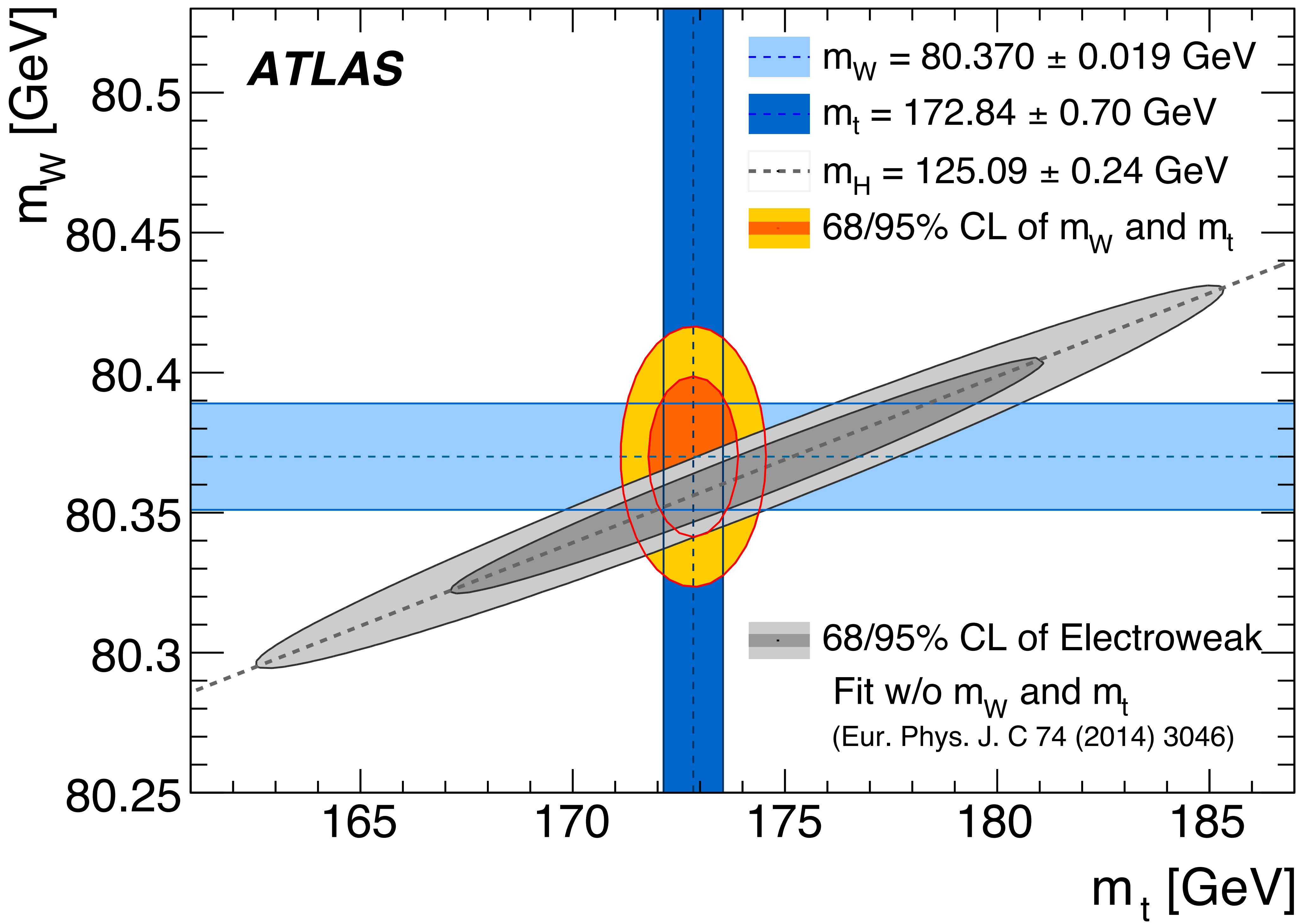
Measurement of the W-Boson Mass

Final Mass Values For Individual Fits

Channel	m_W	Stat.	Muon	Elec.	Recoil	Bckg.	QCD	EW	PDF	Total
m_T-Fit	[MeV]	Unc.	Unc.	Unc.	Unc.	Unc.	Unc.	Unc.	Unc.	Unc.
$W^+ \to \mu\nu, \|\eta\| < 0.8$	80371.3	29.2	12.4	0.0	15.2	8.1	9.9	3.4	28.4	47.1
$W^+ \to \mu\nu, 0.8 < \|\eta\| < 1.4$	80354.1	32.1	19.3	0.0	13.0	6.8	9.6	3.4	23.3	47.6
$W^+ \to \mu\nu, 1.4 < \|\eta\| < 2.0$	80426.3	30.2	35.1	0.0	14.3	7.2	9.3	3.4	27.2	56.9
$W^+ \to \mu\nu, 2.0 < \|\eta\| < 2.4$	80334.6	40.9	112.4	0.0	14.4	9.0	8.4	3.4	32.8	125.5
$W^- \to \mu\nu, \|\eta\| < 0.8$	80375.5	30.6	11.6	0.0	13.1	8.5	9.5	3.4	30.6	48.5
$W^- \to \mu\nu, 0.8 < \|\eta\| < 1.4$	80417.5	36.4	18.5	0.0	12.2	7.7	9.7	3.4	22.2	49.7
$W^- \to \mu\nu, 1.4 < \|\eta\| < 2.0$	80379.4	35.6	33.9	0.0	10.5	8.1	9.7	3.4	23.1	56.9
$W^- \to \mu\nu, 2.0 < \|\eta\| < 2.4$	80334.2	52.4	123.7	0.0	11.6	10.2	9.9	3.4	34.1	139.9
$W^+ \to e\nu, \|\eta\| < 0.6$	80352.9	29.4	0.0	19.5	13.1	15.3	9.9	3.4	28.5	50.8
$W^+ \to e\nu, 0.6 < \|\eta\| < 1.2$	80381.5	30.4	0.0	21.4	15.1	13.2	9.6	3.4	23.5	49.4
$W^+ \to e\nu, 1{,}8 < \|\eta\| < 2.4$	80352.4	32.4	0.0	26.6	16.4	32.8	8.4	3.4	27.3	62.6
$W^- \to e\nu, \|\eta\| < 0.6$	80415.8	31.3	0.0	16.4	11.8	15.5	9.5	3.4	31.3	52.1
$W^- \to e\nu, 0.6 < \|\eta\| < 1.2$	80297.5	33.0	0.0	18.7	11.2	12.8	9.7	3.4	23.9	49.0
$W^- \to e\nu, 1.8 < \|\eta\| < 2.4$	80423.8	42.8	0.0	33.2	12.8	35.1	9.9	3.4	28.1	72.3
p_T-Fit										
$W^+ \to \mu\nu, \|\eta\| < 0.8$	80327.7	22.1	12.2	0.0	2.6	5.1	9.0	6.0	24.7	37.3
$W^+ \to \mu\nu, 0.8 < \|\eta\| < 1.4$	80357.3	25.1	19.1	0.0	2.5	4.7	8.9	6.0	20.6	39.5
$W^+ \to \mu\nu, 1.4 < \|\eta\| < 2.0$	80446.9	23.9	33.1	0.0	2.5	4.9	8.2	6.0	25.2	49.3
$W^+ \to \mu\nu, 2.0 < \|\eta\| < 2.4$	80334.1	34.5	110.1	0.0	2.5	6.4	6.7	6.0	31.8	120.2
$W^- \to \mu\nu, \|\eta\| < 0.8$	80427.8	23.3	11.6	0.0	2.6	5.8	8.1	6.0	26.4	39.0
$W^- \to \mu\nu, 0.8 < \|\eta\| < 1.4$	80395.6	27.9	18.3	0.0	2.5	5.6	8.0	6.0	19.8	40.5
$W^- \to \mu\nu, 1.4 < \|\eta\| < 2.0$	80380.6	28.1	35.2	0.0	2.6	5.6	8.0	6.0	20.6	50.9
$W^- \to \mu\nu, 2.0 < \|\eta\| < 2.4$	80315.2	45.5	116.1	0.0	2.6	7.6	8.3	6.0	32.7	129.6
$W^+ \to e\nu, \|\eta\| < 0.6$	80336.5	22.2	0.0	20.1	2.5	6.4	9.0	5.3	24.5	40.7
$W^+ \to e\nu, 0.6 < \|\eta\| < 1.2$	80345.8	22.8	0.0	21.4	2.6	6.7	8.9	5.3	20.5	39.4
$W^+ \to e\nu, 1{,}8 < \|\eta\| < 2.4$	80344.7	24.0	0.0	30.8	2.6	11.9	6.7	5.3	24.1	48.2
$W^- \to e\nu, \|\eta\| < 0.6$	80351.0	23.1	0.0	19.8	2.6	7.2	8.1	5.3	26.6	42.2
$W^- \to e\nu, 0.6 < \|\eta\| < 1.2$	80309.8	24.9	0.0	19.7	2.7	7.3	8.0	5.3	20.9	39.9
$W^- \to e\nu, 1.8 < \|\eta\| < 2.4$	80413.4	30.1	0.0	30.7	2.7	11.5	8.3	5.3	22.7	51.0

Measurement of the W-Boson Mass

2-D Contours of ATLAS meas. of top and W masses



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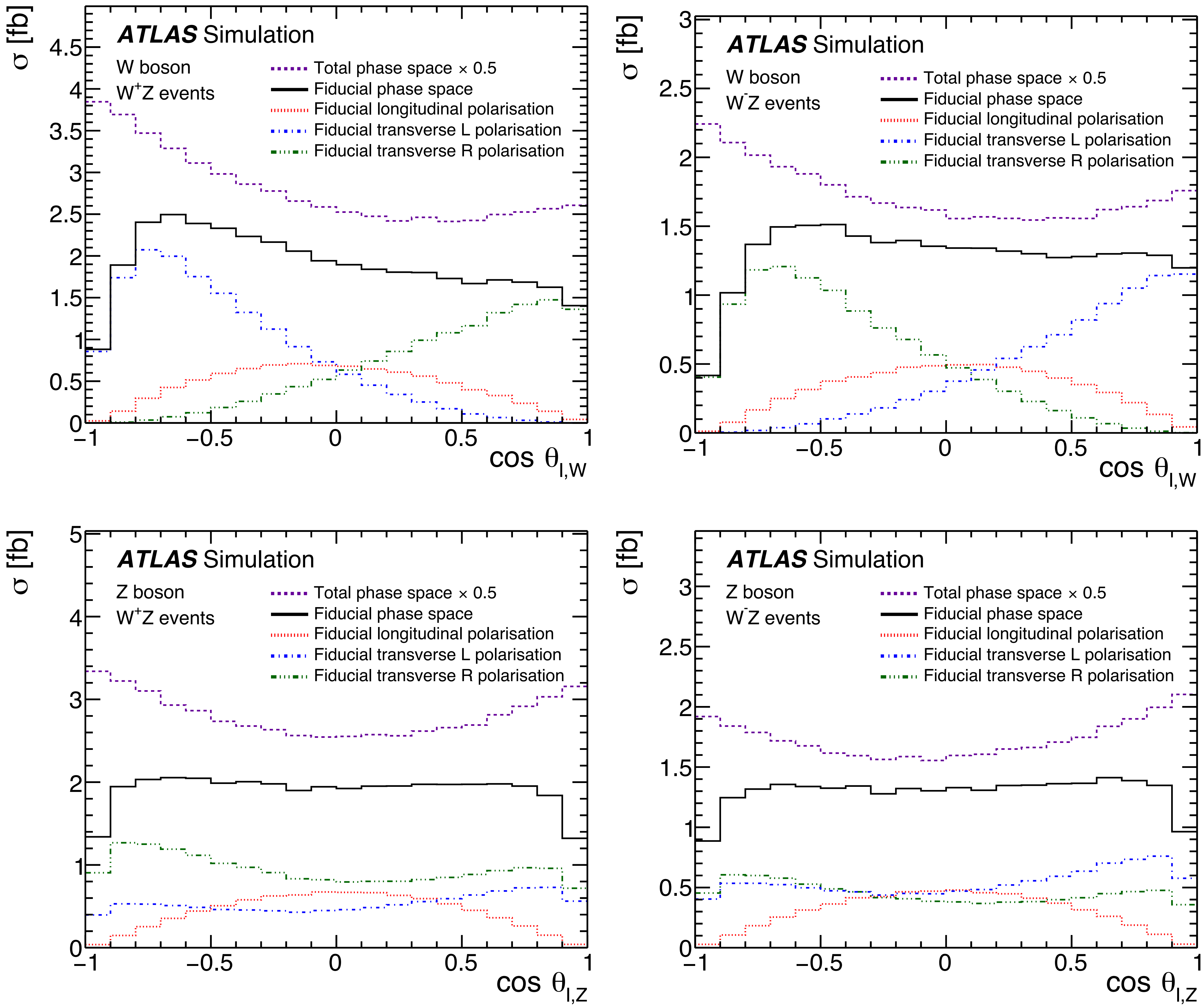
WZ Prod. X-Sections and Gauge Boson Polarisations

Backup Slides

WZ Prod. X-Sections and Gauge Boson Polarisations

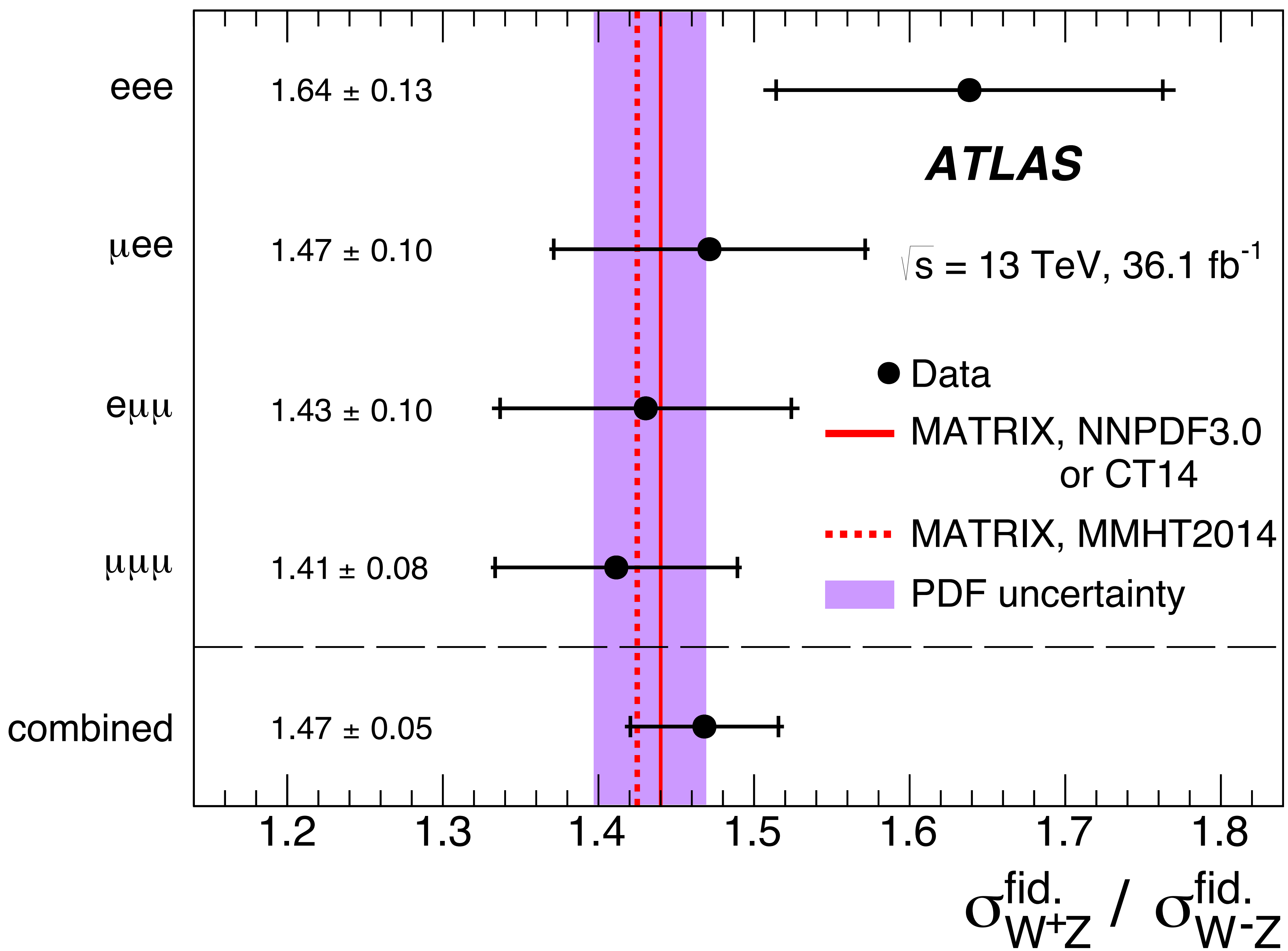
Helicity Simulations through POWHEG+PYTHIA



WZ Prod. X-Sections and Gauge Boson Polarisations

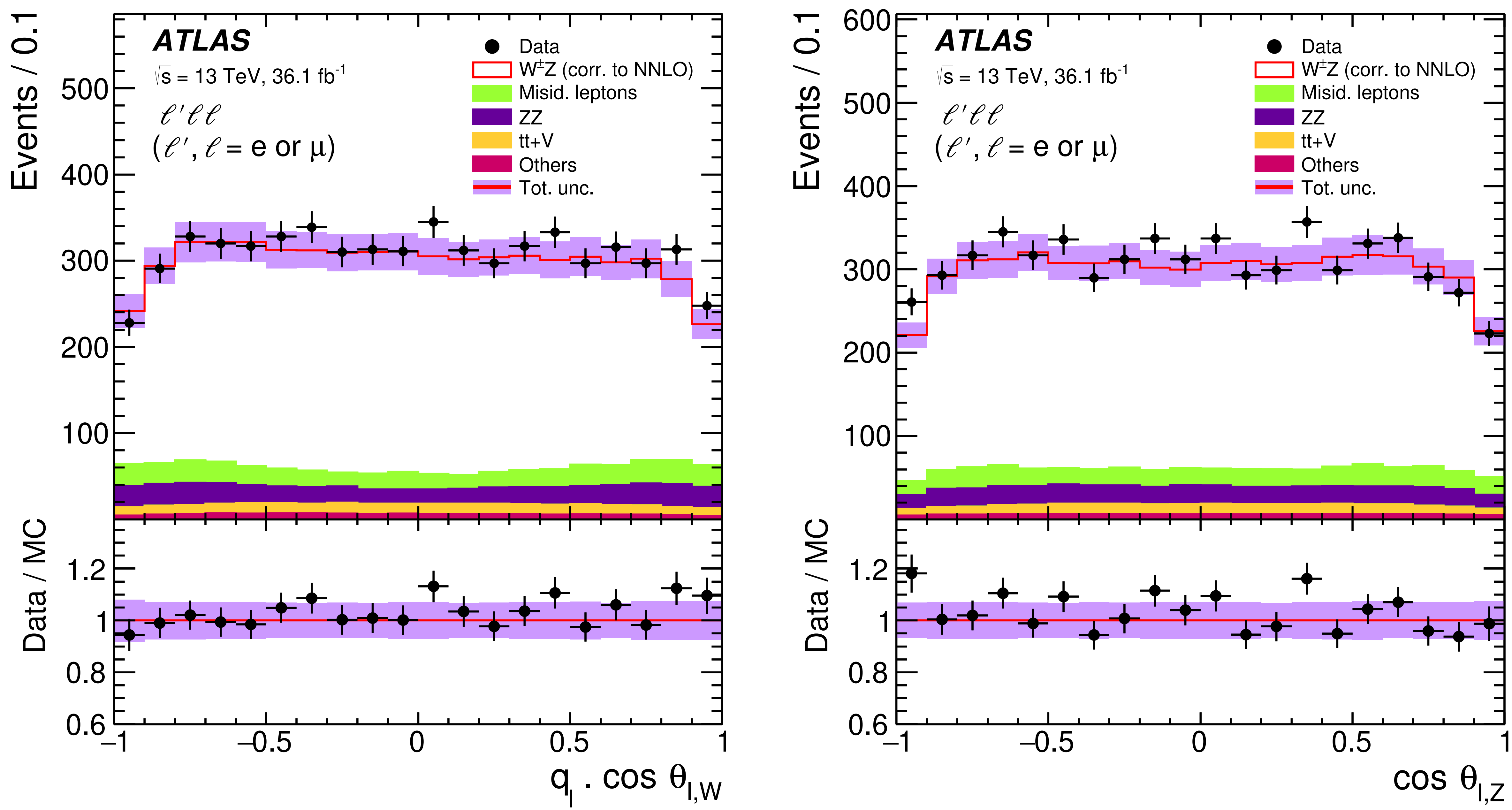
Charge Asymmetry

- The $W^{+}Z$ vs. $W^{-}Z$ asymmetry has also been measured as $\sigma_{W^{+}Z}/\sigma_{W^{-}Z} = 1.47 \pm 0.05$ and has been found to be consistent with theory



WZ Prod. X-Sections and Gauge Boson Polarisations

Detector level distributions for decay angles



WZ Prod. X-Sections and Gauge Boson Polarisations

C-Factors

Channel	C_{W^-Z}	C_{W^+Z}	$C_{W^\pm Z}$
eee	0.399 ± 0.003	0.394 ± 0.003	0.396 ± 0.002
μee	0.470 ± 0.004	0.469 ± 0.003	0.469 ± 0.002
$e\mu\mu$	0.548 ± 0.004	0.541 ± 0.003	0.544 ± 0.003
$\mu\mu\mu$	0.660 ± 0.005	0.663 ± 0.004	0.662 ± 0.003

Yields

Channel	eee		μee		$e\mu\mu$		$\mu\mu\mu$		All	
Data	1279		1281		1671		1929		6160	
Total Expected	1221	± 7	1281	± 6	1653	± 8	1830	± 7	5986	± 14
WZ	922	± 5	1077	± 6	1256	± 6	1523	± 7	4778	± 12
Misid. leptons	138	± 5	34	± 2	193	± 5	71	± 2	436	± 8
ZZ	86	± 1	89	± 1	117	± 1	135	± 1	426	± 3
$t\bar{t}$+V	50.0	± 0.7	54.0	± 0.7	56.1	± 0.7	63.8	± 0.8	225	± 1
tZ	23.1	± 0.4	24.8	± 0.4	28.8	± 0.4	33.5	± 0.5	110	± 1
VVV	2.5	± 0.1	2.8	± 0.1	3.2	± 0.1	3.6	± 0.1	12.0	± 0.2

WZ Prod. X-Sections and Gauge Boson Polarisations

Systematic Uncertainties

	eee	μee	$e\mu\mu$	$\mu\mu\mu$	Combined
Relative uncertainties [%]					
e energy scale	0.2	0.1	0.1	< 0.1	0.1
e id. efficiency	2.8	1.8	1.0	< 0.1	1.1
μ momentum scale	< 0.1	< 0.1	< 0.1	< 0.1	< 0.1
μ id. efficiency	< 0.1	1.3	1.6	2.8	1.5
$E_{\mathrm{T}}^{\mathrm{miss}}$ and jets	0.2	0.2	0.3	0.5	0.3
Trigger	< 0.1	< 0.1	0.2	0.3	0.2
Pile-up	1.0	1.5	1.2	1.5	1.3
Misid. leptons background	4.7	1.1	4.5	1.6	1.9
ZZ background	1.0	1.0	1.1	1.0	1.0
Other backgrounds	1.6	1.5	1.4	1.2	1.4
Uncorrelated	0.7	0.6	0.7	0.5	0.3
Total systematic uncertainty	6.0	3.5	5.4	4.1	3.6
Luminosity	2.2	2.2	2.2	2.2	2.2
Theoretical modelling	0.5	0.5	0.5	0.5	0.5
Statistics	3.6	3.3	3.2	2.7	1.6
Total	7.3	5.3	6.6	5.3	4.5

Data Driven Background is the leading source of uncertainty.

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WZ Prod. X-Sections and Gauge Boson Polarisations

Absolute Uncertainties in Helicity Fractions

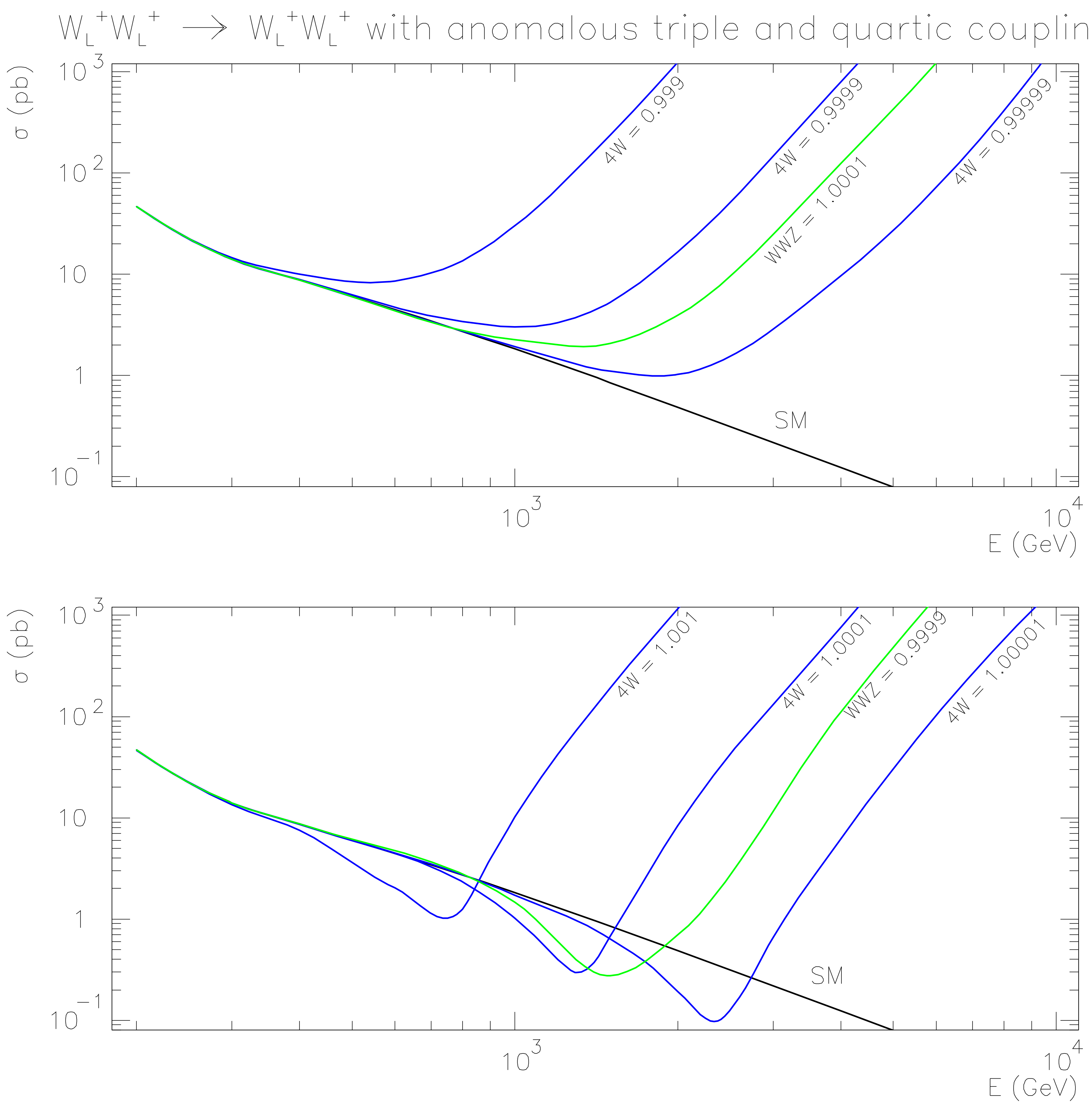
	$W^{\pm}$ in $W^{\pm}Z$		Z in $W^{\pm}Z$	
	f_0	$f_L - f_R$	f_0	$f_L - f_R$
e energy scale and id. efficiency	0.0024	0.0004	0.005	0.0021
μ momentum scale and id. efficiency	0.0013	0.0027	0.0018	0.008
E_T^{miss} and jets	0.0024	0.0010	0.0017	0.005
Pile-up	0.005	0.00009	0.0014	0.005
Misid. lepton background	0.031	< 0.001	0.007	0.019
ZZ background	0.009	0.0004	0.0007	0.0012
Other backgrounds	0.0012	0.0005	0.0018	0.005
QCD scale	0.0008	0.0013	0.0004	0.008
PDF	0.0011	0.0009	0.00004	< 0.00001
Modelling	0.004	0.007	0.0015	0.0028
Total systematic uncertainty	0.033	0.008	0.009	0.024
Luminosity	0.0015	< 0.0001	< 0.0001	0.0008
Statistics	0.06	0.032	0.04	0.15
Total	0.06	0.033	0.04	0.16

Observation of EWK Same-Sign WW Production

Backup Slides

WW Scattering Cross-sections

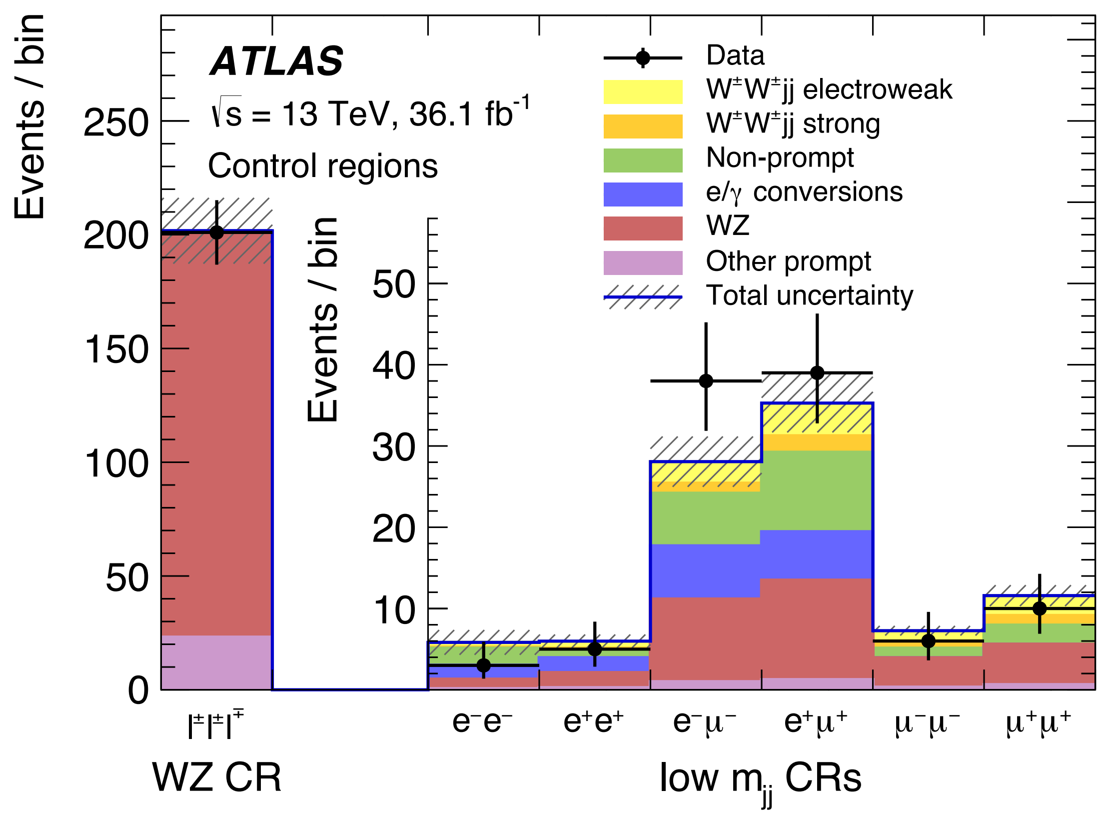
Sensitivity for Anomalous Gauge Couplings

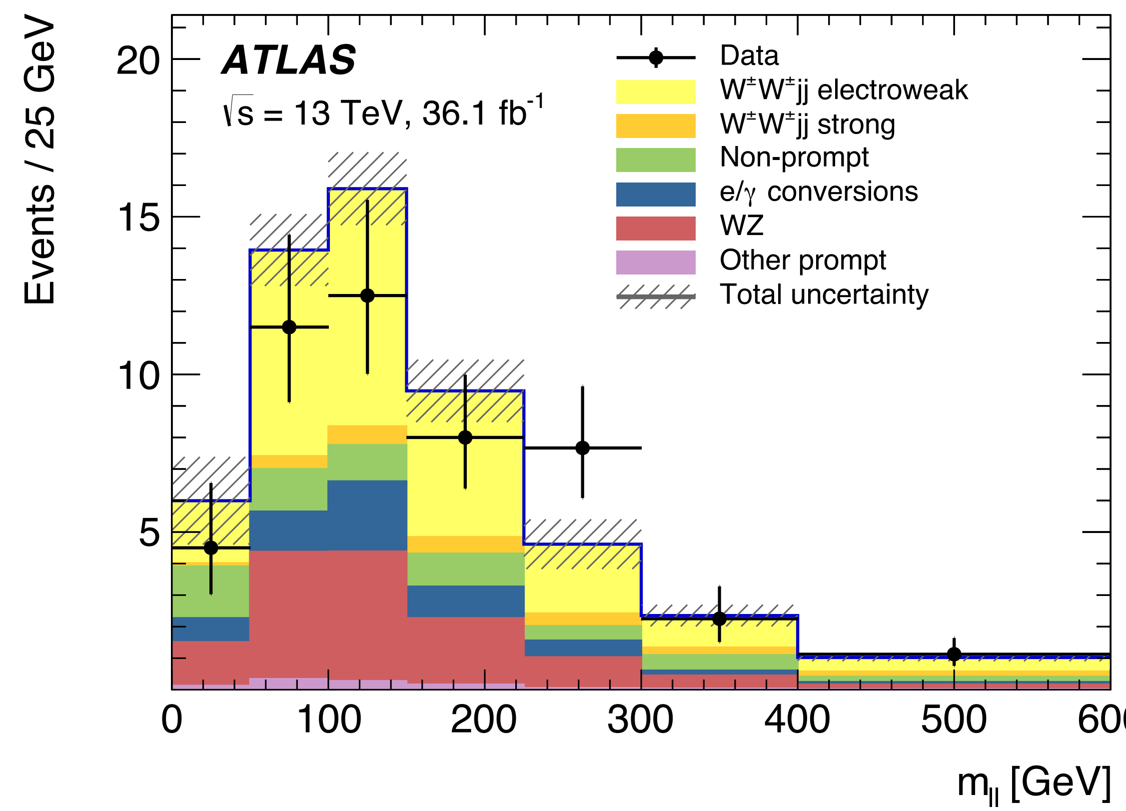


* Plots from https://arxiv.org/abs/1412.8367v2

Observation of EWK Same-Sign WW Production

Other Plots and Yields





	e^+e^+	e^-e^-	$e^+\mu^+$	$e^-\mu^-$	$\mu^+\mu^+$	$\mu^-\mu^-$	Combined
WZ	1.48 ± 0.32	1.09 ± 0.27	11.6 ± 1.9	7.9 ± 1.4	5.0 ± 0.7	3.4 ± 0.6	30 ± 4
Non-prompt	2.2 ± 1.1	1.2 ± 0.6	5.9 ± 2.5	4.7 ± 1.6	0.56 ± 0.05	0.68 ± 0.13	15 ± 5
e/γ conversions	1.6 ± 0.4	1.6 ± 0.4	6.3 ± 1.6	4.3 ± 1.1	—	—	13.9 ± 2.9
Other prompt	0.16 ± 0.04	0.14 ± 0.04	0.90 ± 0.20	0.63 ± 0.14	0.39 ± 0.09	0.22 ± 0.05	2.4 ± 0.5
$W^{\pm}W^{\pm}jj$ strong	0.35 ± 0.13	0.15 ± 0.05	2.9 ± 1.0	1.2 ± 0.4	1.8 ± 0.6	0.76 ± 0.25	7.2 ± 2.3
Expected background	5.8 ± 1.4	4.1 ± 1.1	28 ± 4	18.8 ± 2.6	7.7 ± 0.9	5.1 ± 0.6	69 ± 7
$W^{\pm}W^{\pm}jj$ electroweak	5.6 ± 1.0	2.2 ± 0.4	24 ± 5	9.4 ± 1.8	13.4 ± 2.5	5.1 ± 1.0	60 ± 11
Data	10	4	44	28	25	11	122

Observation of EWK Same-Sign WW Production

Systematics

Source	Impact [%]
Experimental	
Electrons	0.6
Muons	1.3
Jets and $E_{\mathrm{T}}^{\mathrm{miss}}$	3.2
b-tagging	2.1
Pileup	1.6
Background, statistical	3.2
Background, misid. leptons	3.3
Background, charge misrec.	0.3
Background, other	1.8
Theory modeling	
$W^{\pm}W^{\pm}jj$ electroweak-strong interference	1.0
$W^{\pm}W^{\pm}jj$ electroweak, EW corrections	1.4
$W^{\pm}W^{\pm}jj$ electroweak, shower, scale, PDF & α_s	2.8
$W^{\pm}W^{\pm}jj$ strong	2.9
WZ	3.3
Luminosity	2.4

Observation of EWK WZ Production

Backup Slides

Observation of EWK WZ Production

Pre-Post Fit Yields

Pre-Fit

	SR	$WZjj$–QCD CR	b-CR	ZZ-CR
Data	161	213	141	52
Total predicted	200 $\pm$ 41	290 $\pm$ 61	160 $\pm$ 14	45.2 $\pm$ 7.5
$WZjj$–EW (signal)	24.9 $\pm$ 1.4	8.45 $\pm$ 0.37	1.36 $\pm$ 0.10	0.21 $\pm$ 0.12
$WZjj$–QCD	144 $\pm$ 41	231 $\pm$ 60	24.4 $\pm$ 1.7	1.43 $\pm$ 0.22
Misid. leptons	9.8 $\pm$ 3.9	17.7 $\pm$ 7.1	30 $\pm$ 12	0.47 $\pm$ 0.21
$ZZjj$–QCD	8.1 $\pm$ 2.2	15.0 $\pm$ 3.9	1.96 $\pm$ 0.49	35 $\pm$ 11
tZj	6.5 $\pm$ 1.2	6.6 $\pm$ 1.1	36.2 $\pm$ 5.7	0.18 $\pm$ 0.04
$t\bar{t}+V$	4.21 $\pm$ 0.76	9.11 $\pm$ 1.40	65.4 $\pm$ 10.3	2.8 $\pm$ 0.61
$ZZjj$–EW	1.80 $\pm$ 0.45	0.53 $\pm$ 0.14	0.12 $\pm$ 0.09	4.1 $\pm$ 1.4
VVV	0.59 $\pm$ 0.15	0.93 $\pm$ 0.23	0.13 $\pm$ 0.03	1.05 $\pm$ 0.30

Post-Fit

	SR	$WZjj$–QCD CR	b-CR	ZZ-CR
Data	161	213	141	52
Total predicted	167 $\pm$ 11	204 $\pm$ 12	146 $\pm$ 11	51.3 $\pm$ 7.0
$WZjj$–EW (signal)	44 $\pm$ 11	8.52 $\pm$ 0.41	1.38 $\pm$ 0.10	0.211 $\pm$ 0.004
$WZjj$–QCD	91 $\pm$ 10	144 $\pm$ 14	13.9 $\pm$ 3.8	0.94 $\pm$ 0.14
Misid. leptons	7.8 $\pm$ 3.2	14.0 $\pm$ 5.7	23.5 $\pm$ 9.6	0.41 $\pm$ 0.18
$ZZjj$–QCD	11.1 $\pm$ 2.8	18.3 $\pm$ 1.1	2.35 $\pm$ 0.06	40.8 $\pm$ 7.2
tZj	6.2 $\pm$ 1.1	6.3 $\pm$ 1.1	34.0 $\pm$ 5.3	0.17 $\pm$ 0.04
$t\bar{t}+V$	4.7 $\pm$ 1.0	11.14 $\pm$ 0.37	71 $\pm$ 15	3.47 $\pm$ 0.54
$ZZjj$–EW	1.80 $\pm$ 0.45	0.44 $\pm$ 0.10	0.10 $\pm$ 0.03	4.2 $\pm$ 1.2
VVV	0.59 $\pm$ 0.15	0.93 $\pm$ 0.23	0.13 $\pm$ 0.03	1.06 $\pm$ 0.30

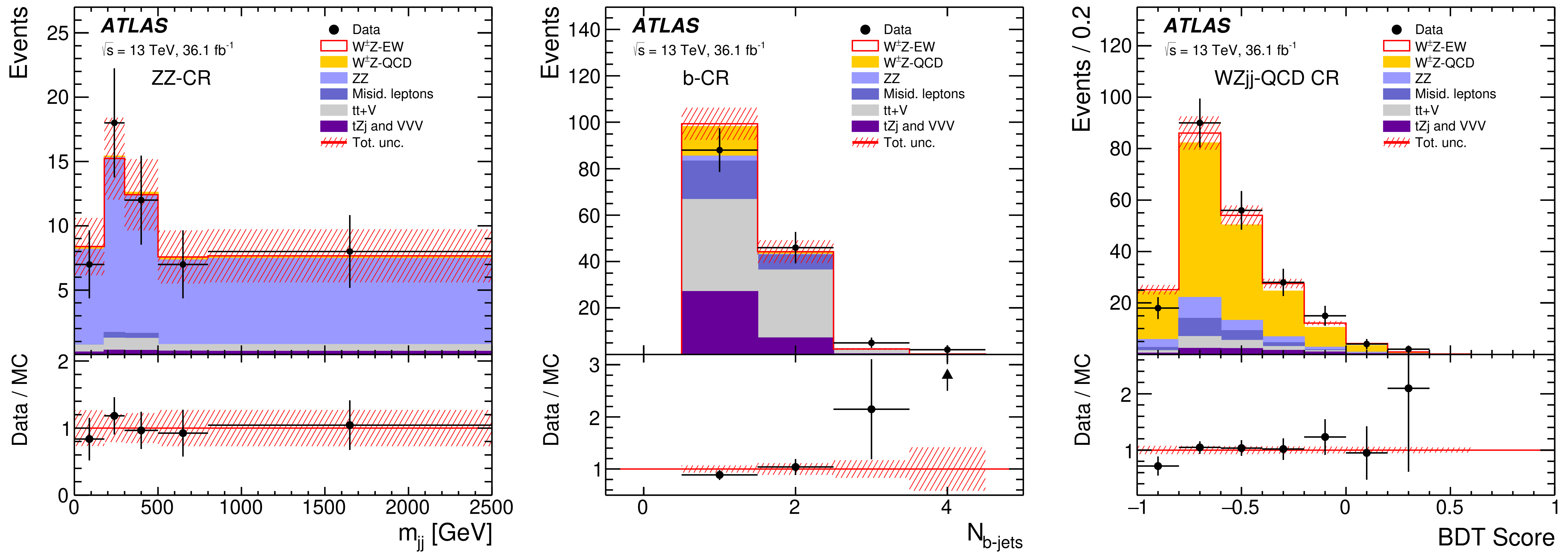
Observation of EWK WZ Production

Systematic Uncertainties

Source	Uncertainty [%]
$WZjj$–EW theory modelling	4.8
$WZjj$–QCD theory modelling	5.2
$WZjj$–EW and $WZjj$–QCD interference	1.9
Jets	6.6
Pile-up	2.2
Electrons	1.4
Muons	0.4
b-tagging	0.1
MC statistics	1.9
Misid. lepton background	0.9
Other backgrounds	0.8
Luminosity	2.1
Total Systematics	10.7

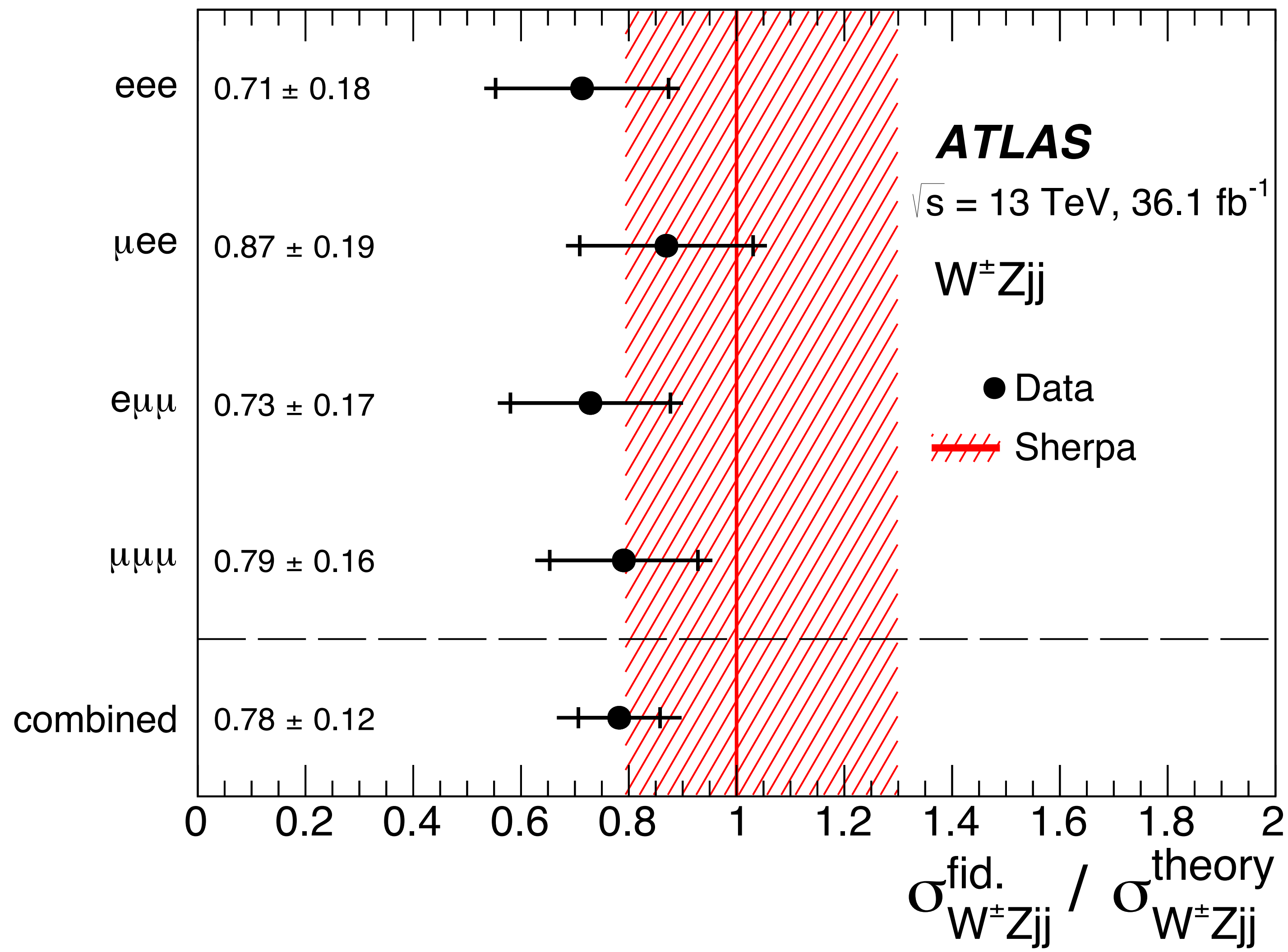
Observation of EWK WZ Production

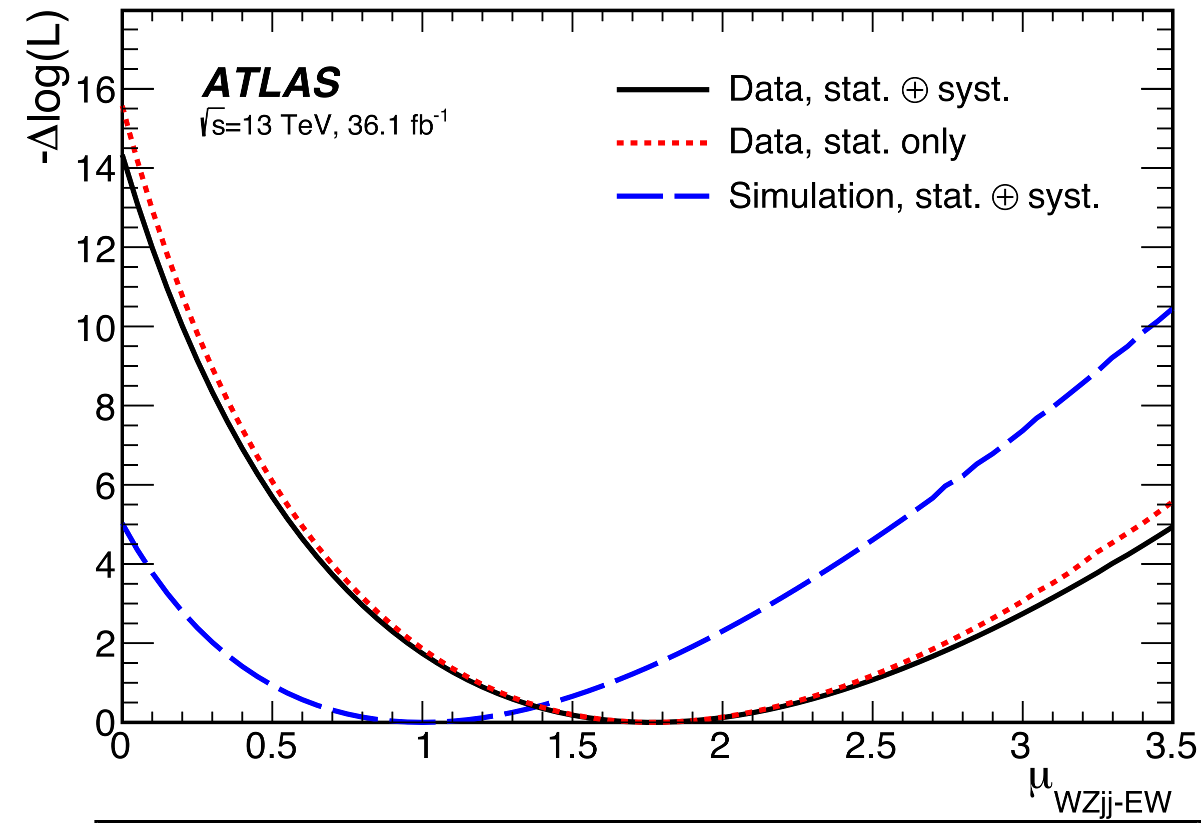
Backgrounds



Observation of EWK WZ Production

Fit Results





m_T^{WZ} [GeV]	150 – 200	200 – 250	250 – 300	300 – 400	≥ 400
$\Delta\sigma^{\text{fid.}}_{W^\pm Zjj}$ [fb]	0.49	0.64	0.24	0.21	0.06
Relative Uncertainties [%]					
Statistics	24.7	19.3	31.0	33.6	63.1
All systematics	16.9	11.8	10.6	9.9	18.4
Luminosity	2.8	2.3	2.4	2.5	3.0
Total	29.9	22.6	32.7	35.0	65.7
Uncorrelated syst.	4.2	0.7	1.0	1.4	5.6
Unfolding	5.2	9.1	6.0	2.0	8.6
Electrons	1.5	1.4	2.0	2.3	3.0
Muons	1.8	1.9	2.2	2.3	3.5
Jets	8.0	5.5	6.0	6.5	3.4
Red. Background	6.1	0.5	0.5	1.9	5.5
Irred. Background	10.6	3.0	4.3	4.6	11.9
Pileup	1.4	0.8	0.9	0.8	1.4

Evidence of VBS Production of Zγ

Backup Slides

Evidence of VBS Production of Zγ

Yields and Systematic Uncertainties

Source	Uncertainty [%]
Statistical	$^{+19}_{-18}$
$Z\gamma jj$−EW theory modelling	$^{+10}_{-6}$
$Z\gamma jj$−QCD theory modelling	±6
$t\bar{t} + \gamma$ theory modelling	±2
$Z\gamma jj$−EW and $Z\gamma jj$−QCD interference	$^{+3}_{-2}$
Jets	±8
Pile-up	±5
Electrons	±1
Muons	$^{+3}_{-2}$
Photons	±1
Electrons/photons energy scale	±1
b-tagging	±2
MC statistical uncertainties	±8
Other backgrounds normalisation (including Z+jets)	$^{+9}_{-8}$
Luminosity	±2
Total uncertainty	±26

	SR		b-CR	
Data	1222		388	
Total expected	1222	±35	389	±19
$Z\gamma jj$−EW (signal)	104	±26	5	± 1
$Z\gamma jj$−QCD	864	±60	82	± 9
Z+jets	200	±40	19	± 4
$t\bar{t} + \gamma$	48	±10	280	±21
Other backgrounds	7	± 1	4	± 1

Evidence of VBS Production of Zγ

Event Selection & BDT Variables

	$\ell^+\ell^-\gamma jj$ preselection
Lepton	$p_T^{\ell} > 20$ GeV
	$\lvert\eta_\ell\rvert < 2.47(2.5)$ for $e(\mu)$
	remove e if $\Delta R(e,\mu) < 0.1$
	$N_\ell = 2$
Boson	$m_{\ell^+\ell^-} > 40$ GeV
	$m_{\ell^+\ell^-} + m_{\ell^+\ell^-\gamma} > 182$ GeV
Photon	$E_T^{\gamma} > 15$ GeV
	$\lvert\eta_\gamma\rvert < 2.37$ (excl. $1.37 < \lvert\eta_\gamma\rvert < 1.52$)
	remove γ if $\Delta R(\ell,\gamma) < 0.4$
	$N_\gamma \geq 1$
b-jet	$p_T^{\text{jet}} > 25$ GeV , $\lvert\eta_{\text{jet}}\rvert < 2.5$
Jet	$p_T^{\text{jet}} > 50$ GeV , $\lvert\eta_{\text{jet}}\rvert < 4.5$
	$N_{\text{Jets}} \geq 2$
	remove jets if $\Delta R(\ell,\text{jet}) < 0.4$ OR $\Delta R(\gamma,\text{jet}) < 0.4$
	$\lvert\Delta\eta_{jj}\rvert > 1.0$
	$m_{jj} > 150$ GeV
b-CR	$\ell^+\ell^-\gamma jj$ preselection
	$\zeta(\ell\ell\gamma) < 5$
	Nb−jet>0
Signal Region	$\ell^+\ell^-\gamma jj$ preselection
	$\zeta(\ell\ell\gamma) < 5$
	Nb−jet=0

Reco Level

	$\ell^+\ell^-\gamma jj$ preselection
Lepton	$p_T^{\ell} > 20$ GeV
	$\lvert\eta_\ell\rvert < 2.5$
	remove e if $\Delta R(e,\mu) < 0.1$
	$N_\ell \geq 2$
Boson	$m_{\ell^+\ell^-} > 40$ GeV
	$m_{\ell^+\ell^-} + m_{\ell^+\ell^-\gamma} > 182$ GeV
Photon	$E_T^{\gamma} > 15$ GeV
	$\lvert\eta_\gamma\rvert < 2.37$
	remove γ if $\Delta R(\ell,\gamma) < 0.4$
	$N_\gamma \geq 1$
Jet	$p_T^{\text{jet}} > 50$ GeV , $\lvert\eta_{\text{jet}}\rvert < 4.5$
	$N_{\text{Jets}} \geq 2$
	remove jets if $\Delta R(\ell,\text{jet}) < 0.3$ OR $\Delta R(\gamma,\text{jet}) < 0.4$
	$\lvert\Delta\eta_{jj}\rvert > 1.0$
	$m_{jj} > 150$ GeV
Signal Region	$\ell^+\ell^-\gamma jj$ preselection
	$\zeta(\ell\ell\gamma) < 5$

Particle Level

Variable used in the BDT
m_{jj}
$\Delta\eta_{jj}$
$\zeta(\ell\ell\gamma)$
$m_{\ell\ell\gamma}$
$p_T^{\ell\ell\gamma}$
$m_{\ell\ell}$
$p_T^{\ell\ell}$
$p_T^{\text{lead lep}}$
$p_T^{\text{lead jet}}$
$\eta^{\text{lead jet}}$
$min\Delta R(\gamma,j)$
$\Delta\phi(\ell\ell\gamma,jj)$
$\Delta R(\ell\ell\gamma,jj)$

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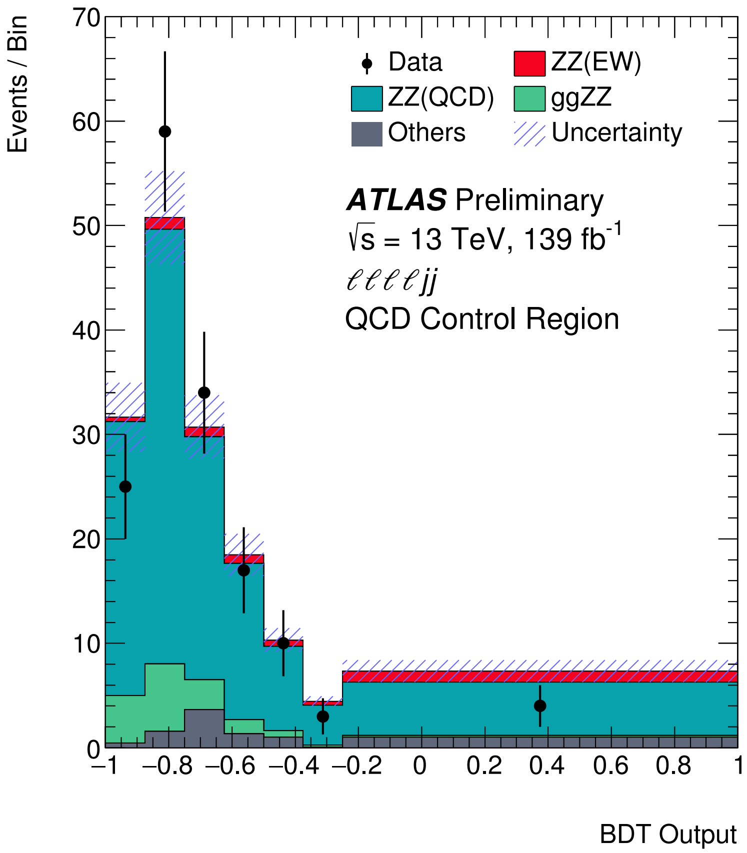
arXiv:1910.09503

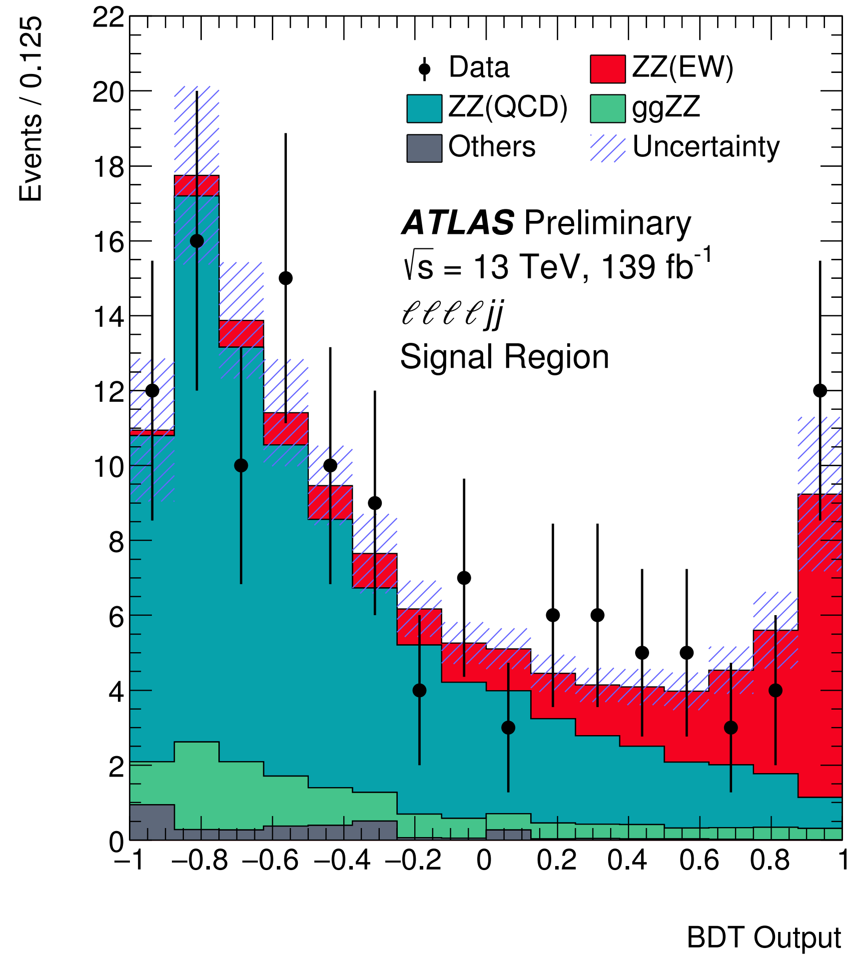
Observation of VBS Production of ZZ

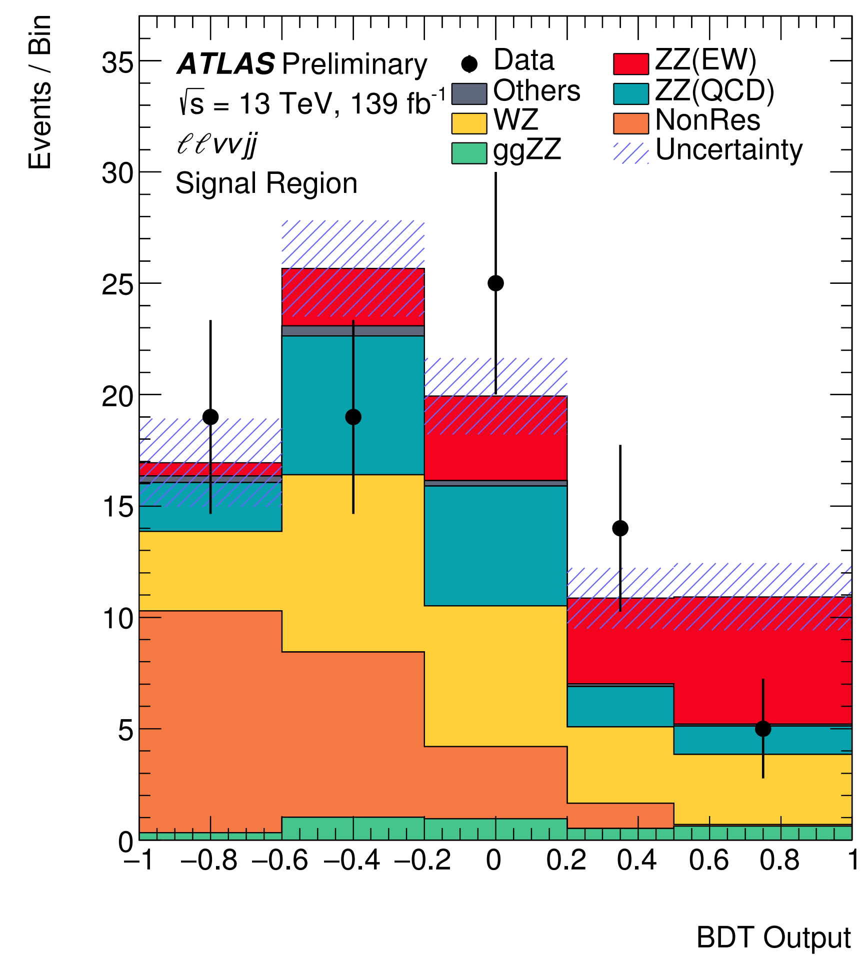
Backup Slides

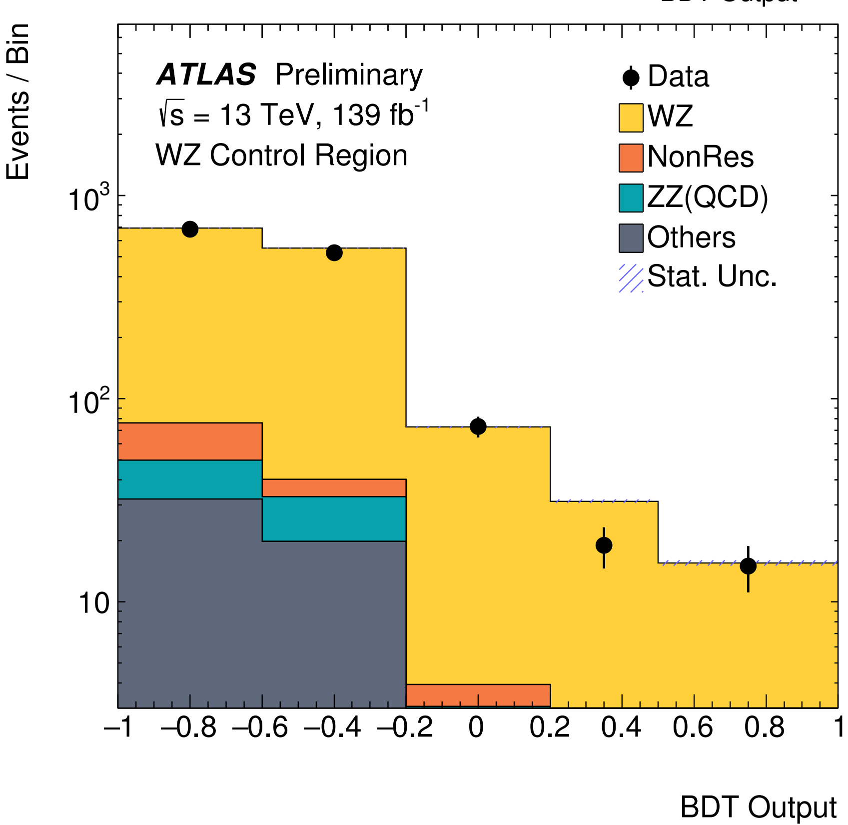
Observation of VBS Production of ZZ

BDT Discriminants









Observation of VBS Production of ZZ

Event Selection and Yields

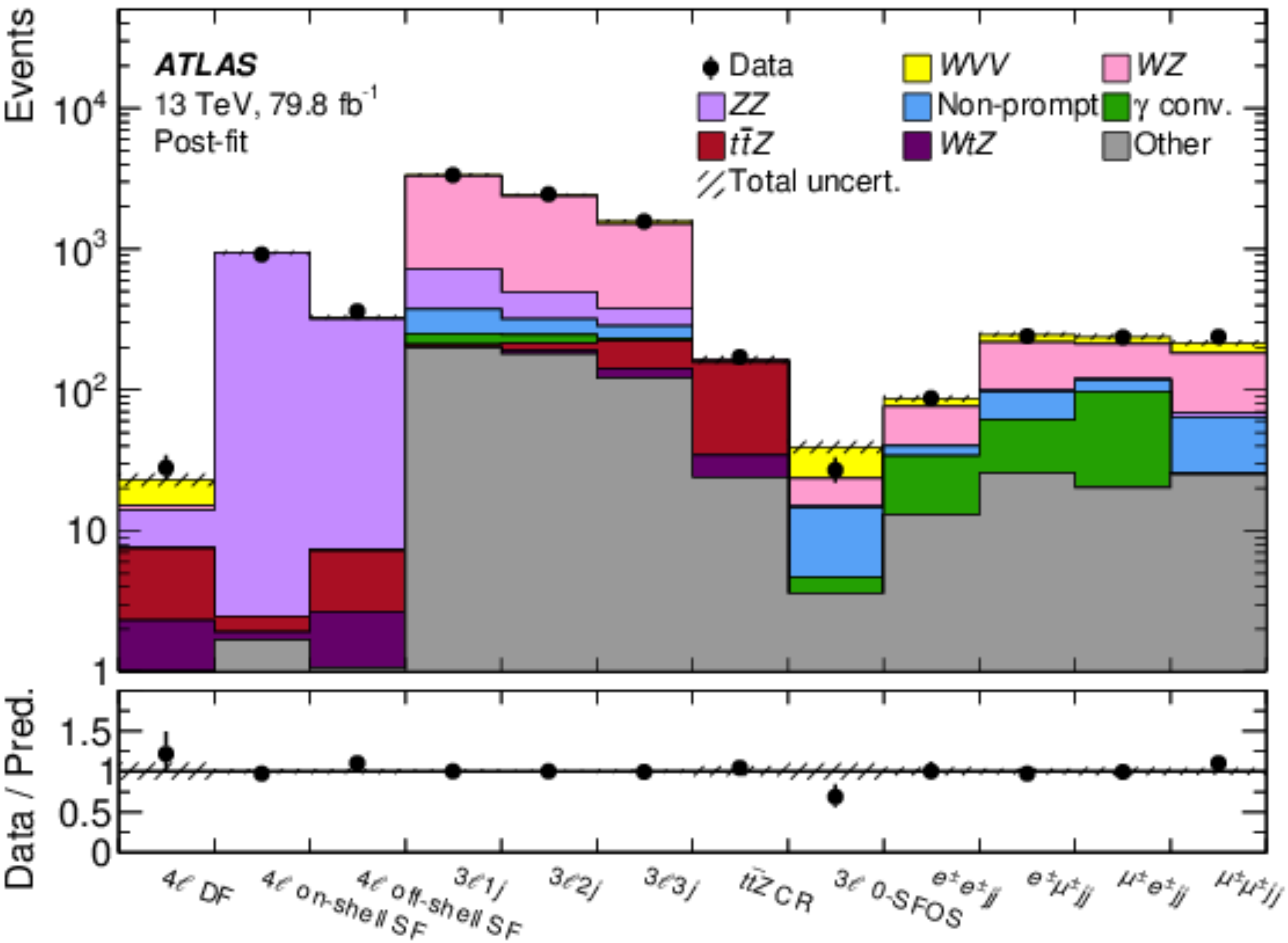
	$\ell\ell\ell\ell jj$	$\ell\ell\nu\nu jj$
Electrons	$p_{\mathrm{T}} > 7$ GeV, $\lvert\eta\rvert < 2.47$ $\lvert d_0/\sigma_{d_0}\rvert < 5$ and $\lvert z_0 \times \sin\theta\rvert < 0.5$ mm	
Muons	$p_{\mathrm{T}} > 7$ GeV, $\lvert\eta\rvert < 2.7$ $\lvert d_0/\sigma_{d_0}\rvert < 3$ and $\lvert z_0 \times \sin\theta\rvert < 0.5$ mm	$p_{\mathrm{T}} > 7$ GeV, $\lvert\eta\rvert < 2.5$
Jets	$p_{\mathrm{T}} > 30$ (40) GeV for $\lvert\eta\rvert < 2.4$ ($2.4 < \lvert\eta\rvert < 4.5$)	$p_{\mathrm{T}} > 60$ (40) GeV for the leading (sub-leading) jet
ZZ selection	$p_{\mathrm{T}} > 20, 20, 10$ GeV for the leading, sub-leading and third leptons Two OSSF lepton pairs with smallest $\lvert m_{\ell^+\ell^-} - m_Z\rvert + \lvert m_{\ell'^+\ell'^-} - m_Z\rvert$ $m_{\ell^+\ell^-} > 10$ GeV for lepton pairs $\Delta R(\ell, \ell') > 0.2$ $66 < m_{\ell^+\ell^-} < 116$ GeV	$p_{\mathrm{T}} > 30$ (20) GeV for the leading (sub-leading) lepton One OSSF lepton pair and no third leptons $80 < m_{\ell^+\ell^-} < 100$ GeV No b-tagged jets $E_{\mathrm{T}}^{\mathrm{miss}}$ significance > 12
Dijet selection	Two most energetic jets with $y_{j_1} \times y_{j_2} < 0$ $m_{jj} > 300$ GeV and $\Delta y(jj) > 2$	$m_{jj} > 400$ GeV and $\Delta y(jj) > 2$

Process	$\ell\ell\ell\ell jj$	$\ell\ell\nu\nu jj$
EW $ZZjj$	20.6 ± 2.5	12.3 ± 0.7
QCD $ZZjj$	77.4 ± 25.0	17.2 ± 3.5
QCD $ggZZjj$	13.1 ± 4.4	3.5 ± 1.1
Non-resonant-$\ell\ell$	-	21.4 ± 4.8
WZ	-	22.8 ± 1.1
Others	3.2 ± 2.1	1.2 ± 0.9
Total	114.3 ± 25.6	78.4 ± 6.2
Data	127	82

Evidence for Tri-Boson Production

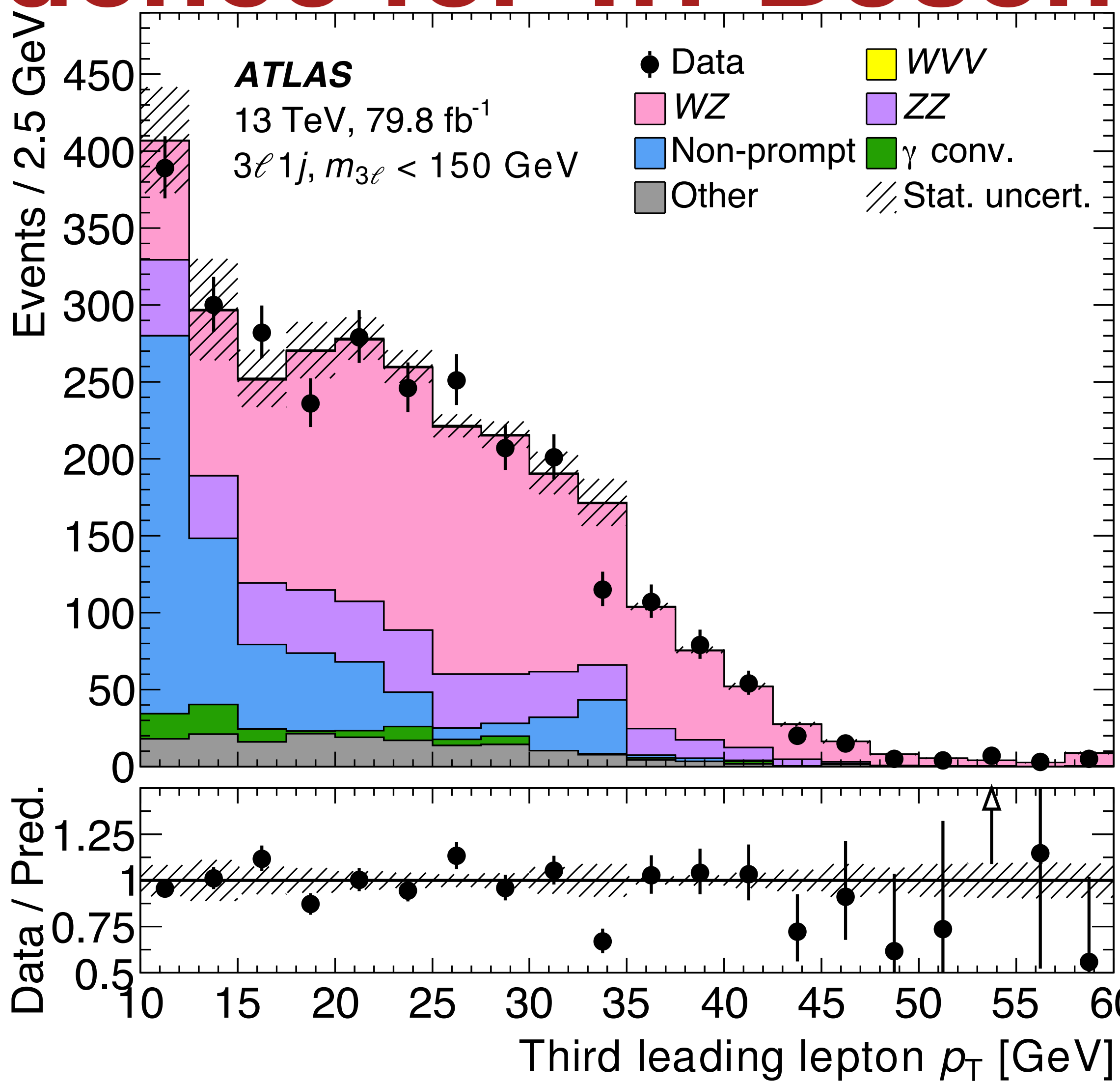
Backup Slides

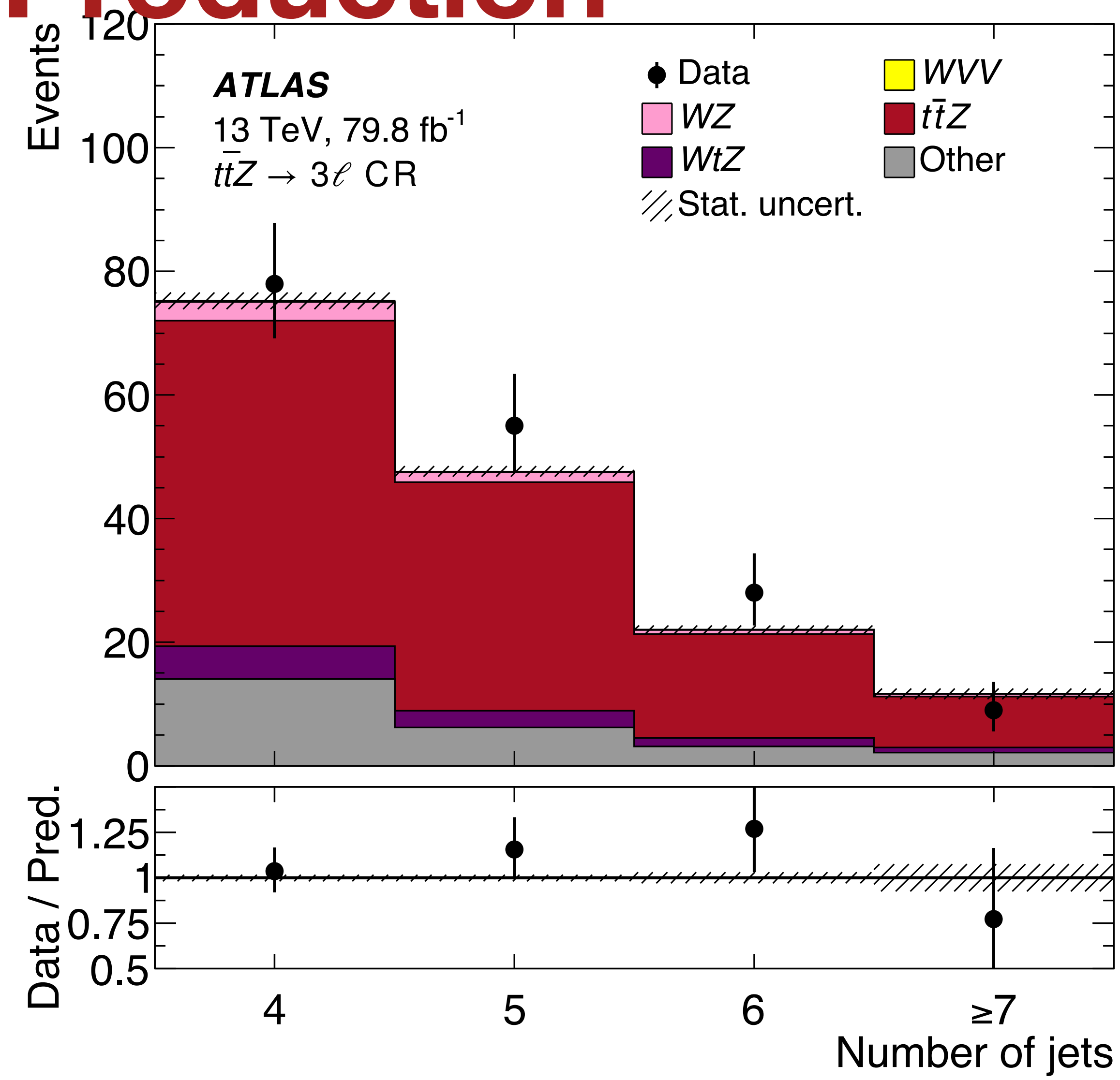
Evidence for Tri-Boson Production
All Signal Regions



Uncertainty source	$\Delta\mu_{WVV}$	
Data-driven	+0.14	–0.14
Theory	+0.15	–0.13
Instrumental	+0.12	–0.09
MC stat. uncertainty	+0.06	–0.04
Generators	+0.04	–0.03
Total systematic uncertainty	+0.30	–0.27

Evidence for Tri-Boson Production





	4ℓ-DF	4ℓ-SF-Z	4ℓ-SF-noZ	3ℓ-1j	3ℓ-2j	3ℓ-3j	$t\bar{t}Z$ CR
WVZ	9.6 ± 3.5	5.0 ± 1.8	10 ± 4	62 ± 23	85 ± 30	84 ± 30	–
WZ	1.11 ± 0.13	–	1.08 ± 0.14	2580 ± 80	1830 ± 60	1110 ± 50	5.7 ± 0.4
ZZ	6.7 ± 0.4	933 ± 28	310 ± 10	344 ± 12	182 ± 13	98 ± 12	0.58 ± 0.06
$t\bar{t}Z$	5.1 ± 0.5	0.55 ± 0.08	4.5 ± 0.5	7.6 ± 1.1	22.6 ± 2.5	82 ± 8	122 ± 9
tWZ	1.9 ± 0.4	0.23 ± 0.10	1.6 ± 0.4	4.2 ± 0.9	11.2 ± 2.2	20 ± 4	10.3 ± 0.8
Non-prompt	–	–	0.18 ± 0.12	130 ± 50	77 ± 28	59 ± 24	0.47 ± 0.18
γ conv.	–	–	–	42 ± 8	32 ± 7	9.6 ± 3.4	0.4 ± 0.6
Other	0.4 ± 0.4	1.8 ± 1.1	1.0 ± 0.7	200 ± 15	182 ± 16	120 ± 10	24.4 ± 2.5
Total	24.8 ± 3.5	941 ± 27	329 ± 10	3370 ± 70	2430 ± 40	1580 ± 40	160 ± 10
Data	28	912	360	3351	2438	1572	170

Evidence for Tri-Boson Production

WVZ BDT Discriminants

Variable	3ℓ-1j	3ℓ-2j	3ℓ-3j	4ℓ DF	4ℓ SF on-shell	4ℓ SF off-shell
$p_T(\ell_1)$	×	×				
$p_T(\ell_2)$	×	×	×			
$p_T(\ell_3)$	×	×	×			
Sum of $p_T(\ell)$	×	×	×			
$m_{\ell_1\ell_2}$	×	×				
$m_{\ell_1\ell_3}$	×	×				
$m_{\ell_2\ell_3}$	×	×				
$m_{\ell\ell}$ of best Z					×	×
$m_{\ell\ell}$ of other leptons				×	×	×
$m_{3\ell}$	×	×	×			
$m_{4\ell}$				×	×	×
Sum of lepton charges	×	×	×			
$p_T(j_1)$	×	×				
$p_T(j_2)$		×	×			
Sum of $p_T(j)$			×			
Number of jets			×	×	×	×
$m_{j_1j_2}$		×				
$m_T(W_\ell)$		×				
m_{jj} of best W			×			
Smallest m_{jj}			×			
E_T^{miss}		×	×	×	×	×
H_T	×	×			×	×
Leptonic H_T				×		
Hadronic H_T				×		
Invariant mass of all leptons, jets and E_T^{miss}	×		×			
Invariant mass of the best Z leptons and j_1	×					

Evidence for Tri-Boson Production

Lepton defintion	Quality	Minimum p_{T}	Isolation	Maximum $\lvert d_0\rvert/\sigma_{d_0}$	Maximum $\lvert z_0 \sin\theta\rvert$	n.p.l. BDT	ch.mis. BDT
Nominal e	Tight	15 GeV	Fix (Loose)	5	0.5 mm	yes	yes
Nominal μ WWW	Medium		Gradient	3			–
Nominal μ WVZ	Loose		FixCutLoose	3			–
Loose e	Loose	15 GeV	no	5	0.5 mm	no	no
Loose μ				3			–
Veto e	Loose	7 GeV	no	no	no	no	no
Veto μ	Loose and $\lvert\eta\rvert < 2.7$						–
Fake e	Medium not Tight	15 GeV	no	5	0.5 mm	no	no
Fake μ	Not nominal WWW			10			–
Photon-like e	Defined as for nominal, but no hit in first pixel layer					no	no

Evidence for Tri-Boson Production

Event Selection Criteria WWW

	$WWW \to \ell\nu\ell\nu qq$	$WWW \to \ell\nu\ell\nu\ell\nu$
Lepton	Two leptons with $p_{\mathrm{T}} > 27(20)\,GeV$ and one same-sign lepton pair	Three leptons with $p_{\mathrm{T}} > 27(20, 20)\,GeV$ and no same-flavour opposite-sign lepton pairs
$m_{\ell\ell}$	$40 < m_{\ell\ell} < 400\,\mathrm{GeV}$	–
Jets	At least two jets with $p_{\mathrm{T}} > 30(20)\,GeV$ and $\lvert\eta\rvert < 2.5$	–
m_{jj}	$m_{jj} < 300\,\mathrm{GeV}$	–
$\Delta\eta_{jj}$	$\lvert\Delta\eta_{jj}\rvert < 1.5$	–
$E_{\mathrm{T}}^{\mathrm{miss}}$	$E_{\mathrm{T}}^{\mathrm{miss}} > 55\,\mathrm{GeV}$ (only for ee)	–
Z boson veto	$m_{ee} < 80\,\mathrm{GeV}$ or $m_{ee} > 100\,\mathrm{GeV}$ (only for ee and μee)	
Lepton veto	No additional lepton with $p_{\mathrm{T}} > 7\,\mathrm{GeV}$ and $\lvert\eta\rvert < 2.5$	
b-jet veto	No b-jets with $p_{\mathrm{T}} > 25\,\mathrm{GeV}$ and $\lvert\eta\rvert < 2.5$	

Evidence for Tri-Boson Production

Event Selection Criteria WVZ

	$WVZ \to \ell\nu qq\ell\ell$	$WVZ \to \ell\nu\ell\nu\ell\ell/qq\ell\ell\ell\ell$
Z boson	At least one OS lepton pair with $\lvert m_{\ell\ell} - 91.2\,\text{GeV}\rvert < 10\,\text{GeV}$	
Low mass veto	$m_{\ell\ell} > 12\,\text{GeV}$ for any OS lepton pair	
b-jet veto	No b-jets with $p_{\text{T}} > 25\,\text{GeV}$ and $\lvert\eta\rvert < 2.5$	
Leptons	One additional nominal lepton	One additional OS lepton pair; third and fourth lepton nominal
H_{T}	$H_{\text{T}} > 200\,\text{GeV}$	–

Evidence for Tri-Boson Production

Event Selection Criteria For Control Regions

WZ control region	Three nominal leptons with one SFOS pair No b-tagged jets $E_{\mathrm{T}}^{\mathrm{miss}} > 55$ GeV $m_{\ell\ell\ell} > 110$ GeV
W sideband validation region	Same as the $WWW \to \ell\nu\ell\nu qq$ SR, with $m_{jj} < 50$ GeV or $m_{jj} > 120$ GeV
$t\bar{t}Z$ control region	Same as the 3ℓ-3j SR region, except: no requirement on H_{T}, at least four jets, at least two b-tagged jets.
WZ+jets and Z+jets validation regions	Same as the 3ℓ-1j SR region, except: no requirement on H_{T}; third-highest-p_{T} lepton has 10 GeV $< p_T <$ 15 GeV; $m_{\ell\ell\ell} < 150$ GeV.

Measurement of the Zγ production cross-section

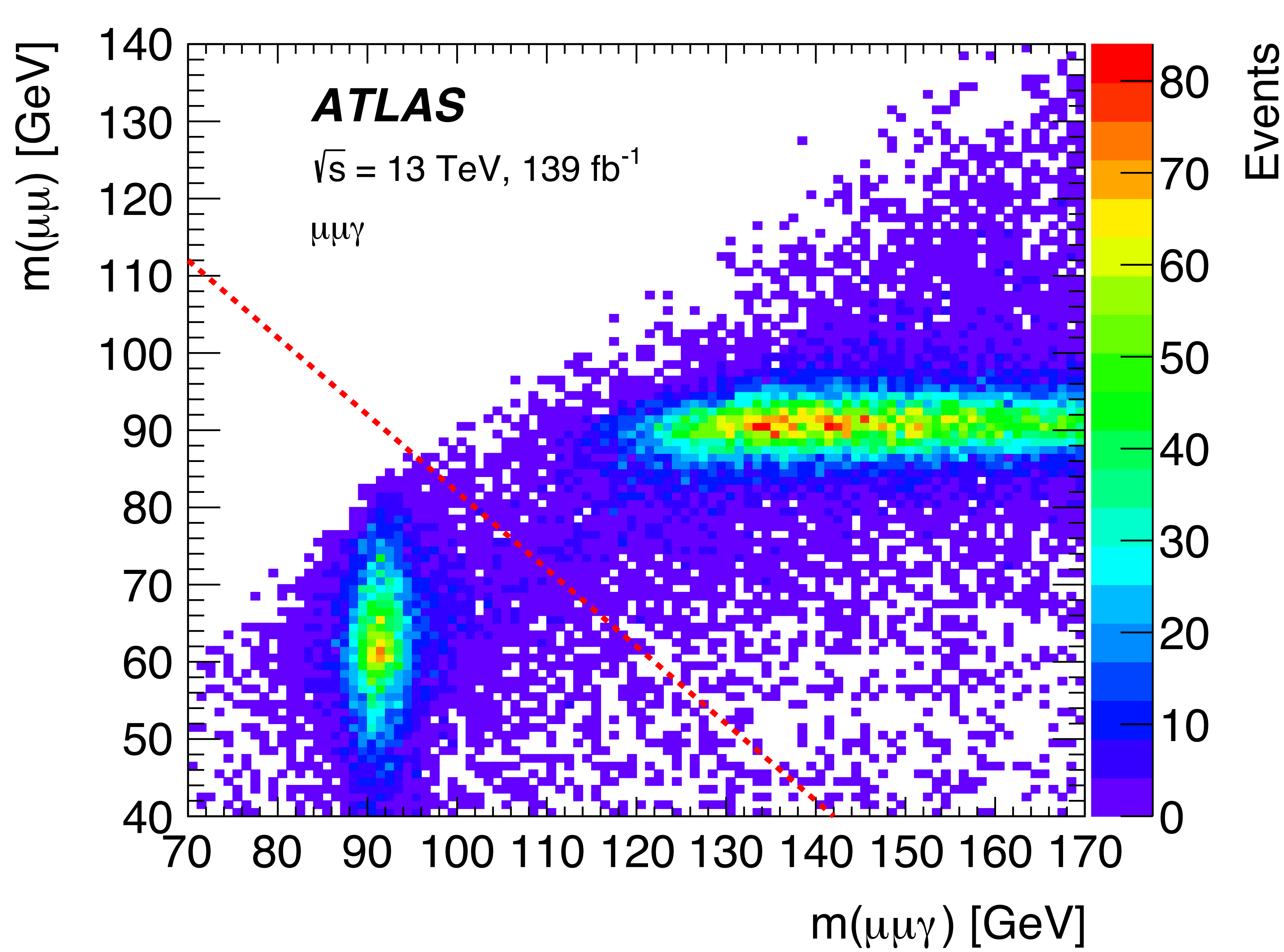
Backup Slides

Measurement of the Zγ production cross-section

Cuts

Photons	Electrons/Muons
$E_T^\gamma > 30$ GeV	$p_T^\ell > 30, 25$ GeV
$\lvert\eta^\gamma\rvert < 2.37$	$\lvert\eta^\ell\rvert < 2.47$
$E_T^{\text{cone}0.2}/E_T^\gamma < 0.07$	dressed leptons
$\Delta R(\ell, \gamma) > 0.4$	
Event selection	
$m(\ell\ell) > 40\,GeV$	
$m(\ell\ell) + m(\ell\ell\gamma) > 182\,GeV$	

	Photons	Electrons	Muons
Kinematics:	$E_T > 30$ GeV	$p_T > 30, 25$ GeV	$p_T > 30, 25$ GeV
	$\lvert\eta\rvert < 2.37$	$\lvert\eta\rvert < 2.47$	$\lvert\eta\rvert < 2.5$
	excl. $1.37 < \lvert\eta\rvert < 1.52$	excl. $1.37 < \lvert\eta\rvert < 1.52$	
Identification:	Tight [55]	Medium [55]	Medium [56]
Isolation:	FixedCutLoose [55]	FCLoose [55]	FCLoose_FixedRad [56]
	$\Delta R(\ell, \gamma) > 0.4$	$\Delta R(\mu, e) > 0.2$	
Event selection:	$m(\ell\ell) > 40\,GeV$, $m(\ell\ell) + m(\ell\ell\gamma) > 182\,GeV$		



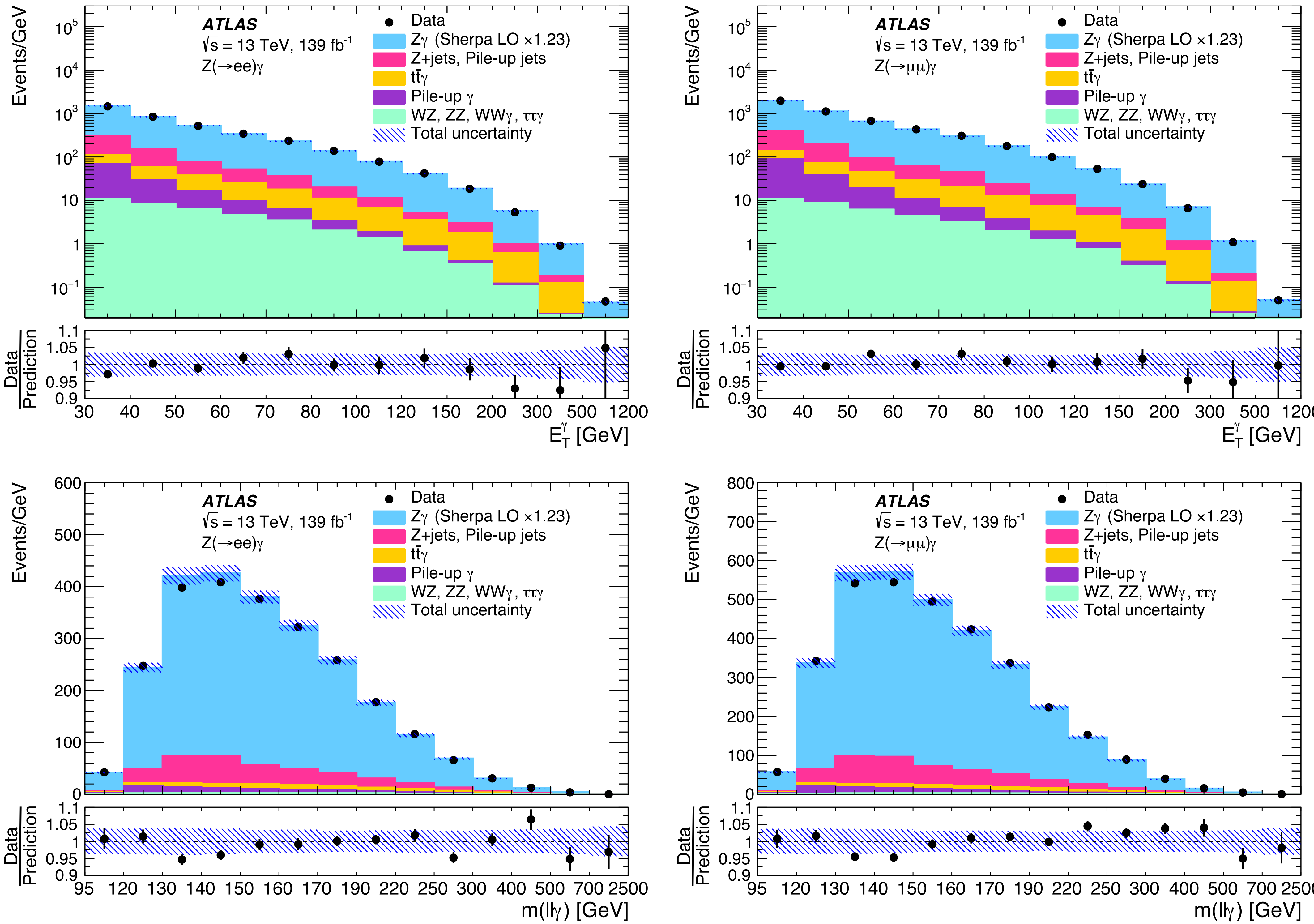
Measurement of the Zγ production cross-section

Uncertainties

Source	Uncertainty [%] $e^+e^-\gamma$	Uncertainty [%] $\mu^+\mu^-\gamma$	Correlation
Trigger efficiency	–	0.2	no
Photon identification efficiency	1.0	1.0	yes
Photon isolation efficiency	0.9	0.9	yes
Electron identification efficiency	1.4	–	no
Electron reconstruction efficiency	0.3	–	no
Electron–photon energy scale	0.9	0.6	partial
Muon isolation efficiency	–	0.4	no
Muon identification efficiency	–	0.7	no
$Z +$ jets background	1.3	1.3	yes
Pile-up background	0.6	0.6	yes
Other backgrounds	0.8	0.7	partial
Monte Carlo event statistics	0.4	0.4	no
Integrated luminosity	1.7	1.7	yes
Systematic uncertainty	3.2	2.9	
Statistical uncertainty	0.6	0.5	
Total uncertainty	3.2	3.0	

Measurement of the Zγ production cross-section

Fiducial Distributions



Measurement of the Zγ production cross-section

Yields and Cross-Sections

	$e^+e^-\gamma$	$\mu^+\mu^-\gamma$
N_{obs}	41343	54413
$N_{Z+\text{jets}}$	4130 ± 440	5470 ± 580
(includes $N_{\text{PU,jets}}$	870 ± 170	1140 ± 230)
$N_{\text{PU},\gamma}$	1030 ± 210	1360 ± 270
$N_{t\bar{t}\gamma}$	1650 ± 250	1980 ± 300
N_{WZ}	254 ± 76	199 ± 60
N_{ZZ}	64 ± 19	102 ± 31
$N_{WW\gamma}$	92 ± 28	112 ± 34
$N_{\tau\tau\gamma}$	46 ± 15	39 ± 12
$N_{\text{obs}} - N_{\text{bkg}}$	34080 ± 590	45150 ± 750

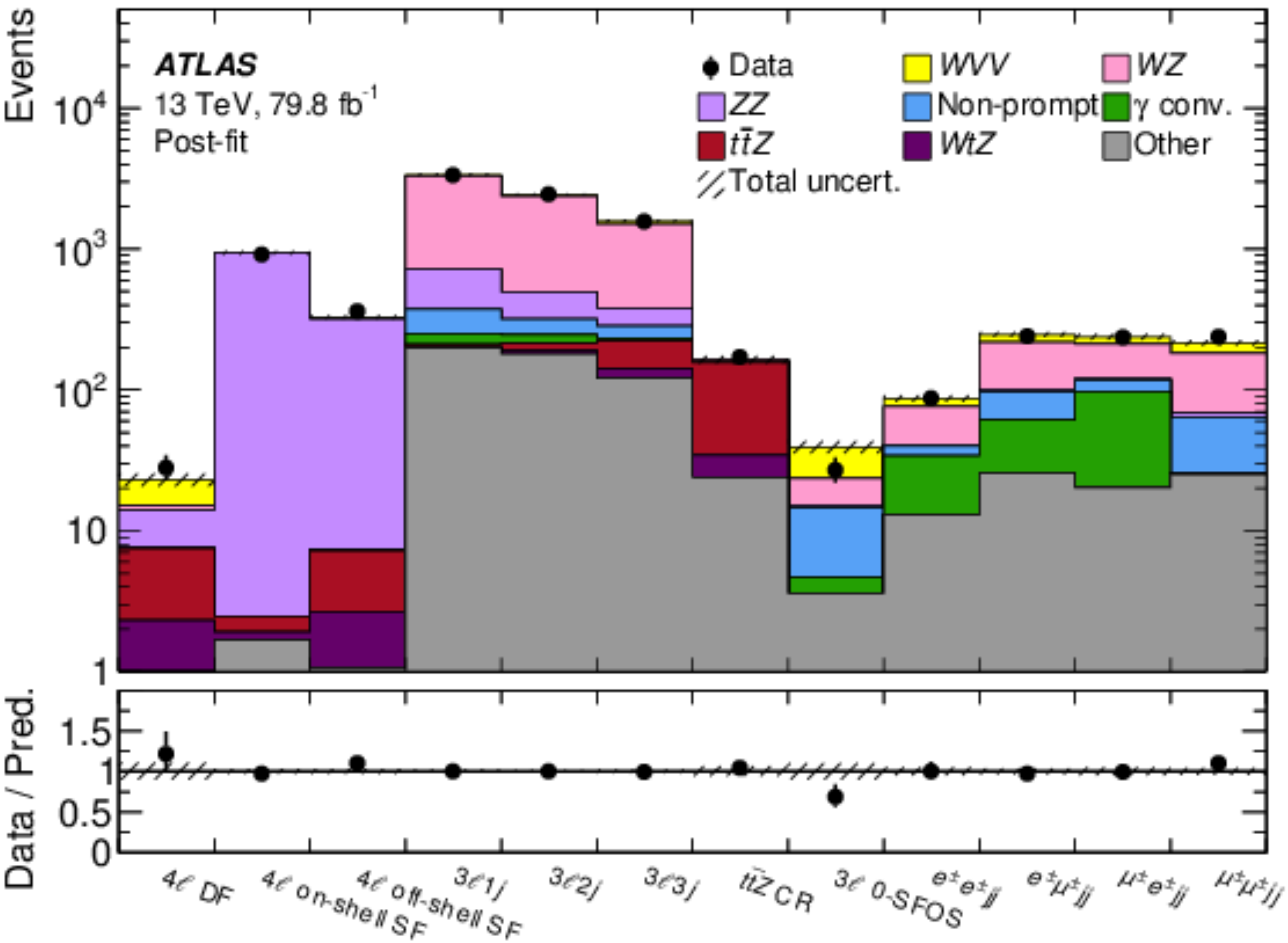
$$C_{e^{\pm}e^{\mp}\gamma} = 0.426 \pm 0.007(\text{uncor}) \pm 0.008(\text{corr})$$
$$C_{\mu^{\pm}\mu^{\mp}\gamma} = 0.607 \pm 0.005(\text{uncor}) \pm 0.009(\text{corr})$$

			Cross-section [fb]
$e^+e^-\gamma$	530.4	± 9.0 (uncorr)	± 11.7 (corr) ± 9.0 (lumi)
$\mu^+\mu^-\gamma$	535.0	± 6.1 (uncorr)	± 11.5 (corr) ± 9.1 (lumi)
$\ell^+\ell^-\gamma$	533.7	± 5.1 (uncorr)	± 11.6 (corr) ± 9.1 (lumi)
Sherpa LO	438.9	± 0.6 (stat)	
Sherpa NLO	514.2	± 5.7 (stat)	
MadGraph NLO	503.4	± 1.8 (stat)	
Matrix NLO	444.3	± 0.1 (stat)	± 4.3 (C_{theory}) ± 8.8 (PDF) $^{+16.8}_{-18.9}$ (scale)
Matrix NNLO	518.7	± 2.7 (stat)	± 5.0 (C_{theory}) ± 10.8 (PDF) $^{+16.4}_{-14.9}$ (scale)
Matrix NNLO × NLO EW	510.1	± 2.7 (stat)	± 5.0 (C_{theory}) ± 10.8 (PDF) $^{+16.4}_{-14.9}$ (scale)
Matrix NNLO + NLO EW	515.3	± 2.7 (stat)	± 5.0 (C_{theory}) ± 10.8 (PDF) $^{+16.4}_{-14.9}$ (scale)

Evidence for Tri-Boson Production

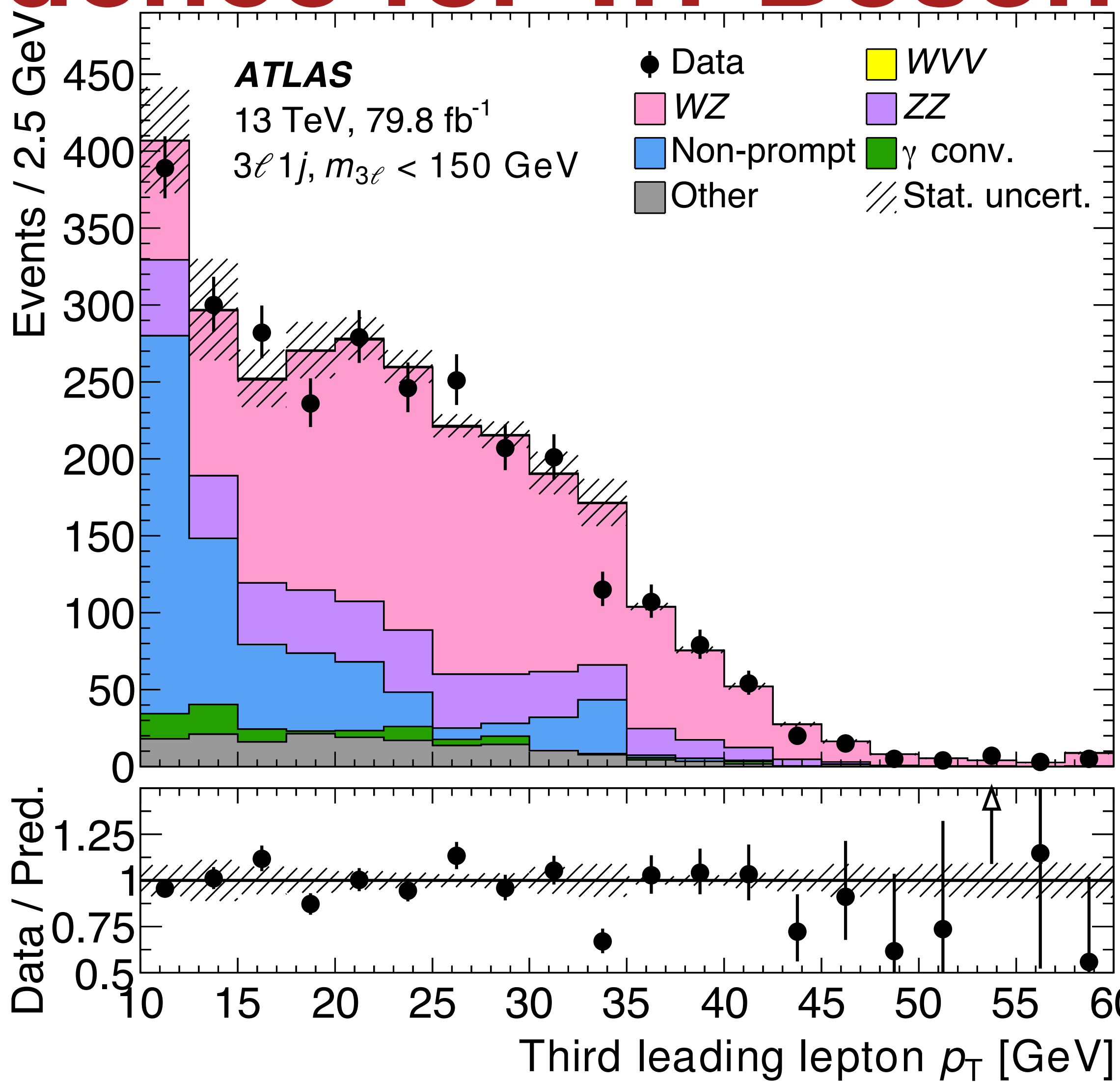
Backup Slides

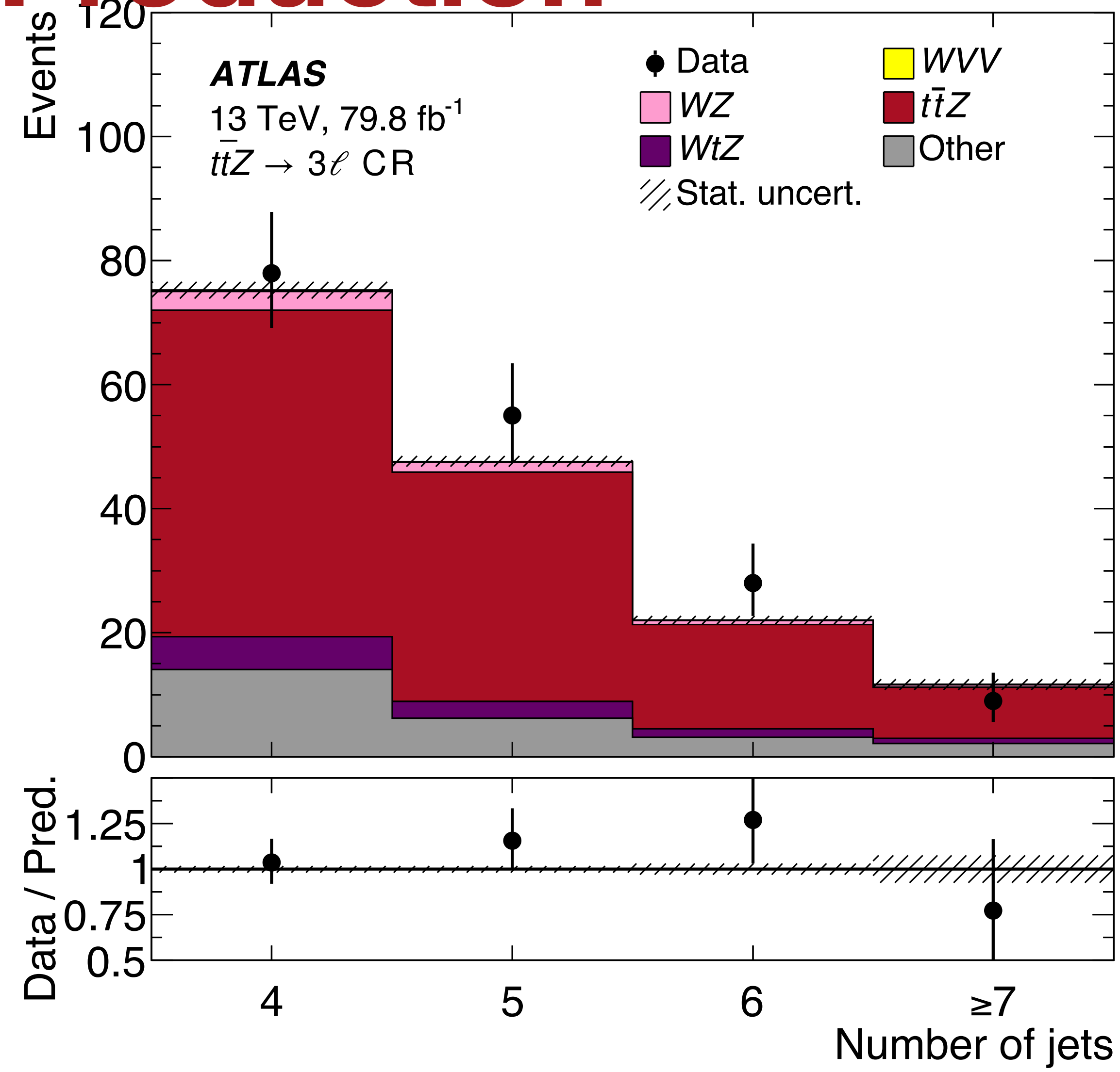
Evidence for Tri-Boson Production
All Signal Regions



Uncertainty source	$\Delta\mu_{WVV}$	
Data-driven	+0.14	–0.14
Theory	+0.15	–0.13
Instrumental	+0.12	–0.09
MC stat. uncertainty	+0.06	–0.04
Generators	+0.04	–0.03
Total systematic uncertainty	+0.30	–0.27

Evidence for Tri-Boson Production





	4ℓ-DF	4ℓ-SF-Z	4ℓ-SF-noZ	3ℓ-1j	3ℓ-2j	3ℓ-3j	$t\bar{t}Z$ CR
WVZ	9.6 ± 3.5	5.0 ± 1.8	10 ± 4	62 ± 23	85 ± 30	84 ± 30	–
WZ	1.11 ± 0.13	–	1.08 ± 0.14	2580 ± 80	1830 ± 60	1110 ± 50	5.7 ± 0.4
ZZ	6.7 ± 0.4	933 ± 28	310 ± 10	344 ± 12	182 ± 13	98 ± 12	0.58 ± 0.06
$t\bar{t}Z$	5.1 ± 0.5	0.55 ± 0.08	4.5 ± 0.5	7.6 ± 1.1	22.6 ± 2.5	82 ± 8	122 ± 9
tWZ	1.9 ± 0.4	0.23 ± 0.10	1.6 ± 0.4	4.2 ± 0.9	11.2 ± 2.2	20 ± 4	10.3 ± 0.8
Non-prompt	–	–	0.18 ± 0.12	130 ± 50	77 ± 28	59 ± 24	0.47 ± 0.18
γ conv.	–	–	–	42 ± 8	32 ± 7	9.6 ± 3.4	0.4 ± 0.6
Other	0.4 ± 0.4	1.8 ± 1.1	1.0 ± 0.7	200 ± 15	182 ± 16	120 ± 10	24.4 ± 2.5
Total	24.8 ± 3.5	941 ± 27	329 ± 10	3370 ± 70	2430 ± 40	1580 ± 40	160 ± 10
Data	28	912	360	3351	2438	1572	170

Evidence for Tri-Boson Production

WVZ BDT Discriminants

Variable	3ℓ-1j	3ℓ-2j	3ℓ-3j	4ℓ DF	4ℓ SF on-shell	4ℓ SF off-shell
$p_{\mathrm{T}}(\ell_1)$	×	×				
$p_{\mathrm{T}}(\ell_2)$	×	×	×			
$p_{\mathrm{T}}(\ell_3)$	×	×	×			
Sum of $p_{\mathrm{T}}(\ell)$	×	×	×			
$m_{\ell_1\ell_2}$	×	×				
$m_{\ell_1\ell_3}$	×	×				
$m_{\ell_2\ell_3}$	×	×				
$m_{\ell\ell}$ of best Z					×	×
$m_{\ell\ell}$ of other leptons				×	×	×
$m_{3\ell}$	×	×	×			
$m_{4\ell}$				×	×	×
Sum of lepton charges	×	×	×			
$p_{\mathrm{T}}(j_1)$	×	×				
$p_{\mathrm{T}}(j_2)$		×	×			
Sum of $p_{\mathrm{T}}(j)$			×			
Number of jets			×	×	×	×
$m_{j_1j_2}$		×				
$m_{\mathrm{T}}(W_\ell)$		×				
m_{jj} of best W			×			
Smallest m_{jj}			×			
$E_{\mathrm{T}}^{\mathrm{miss}}$		×	×	×	×	×
H_{T}	×	×			×	×
Leptonic H_{T}				×		
Hadronic H_{T}				×		
Invariant mass of all leptons, jets and $E_{\mathrm{T}}^{\mathrm{miss}}$	×		×			
Invariant mass of the best Z leptons and j_1	×					

Evidence for Tri-Boson Production

Lepton defintion	Quality	Minimum p_{T}	Isolation	Maximum $\lvert d_0\rvert/\sigma_{d_0}$	Maximum $\lvert z_0 \sin\theta\rvert$	n.p.l. BDT	ch.mis. BDT
Nominal e	Tight	15 GeV	Fix (Loose)	5	0.5 mm	yes	yes
Nominal μ WWW	Medium		Gradient	3			–
Nominal μ WVZ	Loose		FixCutLoose	3			–
Loose e	Loose	15 GeV	no	5	0.5 mm	no	no
Loose μ				3			–
Veto e	Loose	7 GeV	no	no	no	no	no
Veto μ	Loose and $\lvert\eta\rvert < 2.7$						–
Fake e	Medium not Tight	15 GeV	no	5	0.5 mm	no	no
Fake μ	Not nominal WWW			10			–
Photon-like e	Defined as for nominal, but no hit in first pixel layer					no	no

Evidence for Tri-Boson Production

Event Selection Criteria WWW

	$WWW \to \ell\nu\ell\nu qq$	$WWW \to \ell\nu\ell\nu\ell\nu$
Lepton	Two leptons with $p_{\mathrm{T}} > 27(20)\,GeV$ and one same-sign lepton pair	Three leptons with $p_{\mathrm{T}} > 27(20,20)\,GeV$ and no same-flavour opposite-sign lepton pairs
$m_{\ell\ell}$	$40 < m_{\ell\ell} < 400\,\mathrm{GeV}$	–
Jets	At least two jets with $p_{\mathrm{T}} > 30(20)\,GeV$ and $\lvert\eta\rvert < 2.5$	–
m_{jj}	$m_{jj} < 300\,\mathrm{GeV}$	–
$\Delta\eta_{jj}$	$\lvert\Delta\eta_{jj}\rvert < 1.5$	–
$E_{\mathrm{T}}^{\mathrm{miss}}$	$E_{\mathrm{T}}^{\mathrm{miss}} > 55\,\mathrm{GeV}$ (only for ee)	–
Z boson veto	$m_{ee} < 80\,\mathrm{GeV}$ or $m_{ee} > 100\,\mathrm{GeV}$ (only for ee and μee)	
Lepton veto	No additional lepton with $p_{\mathrm{T}} > 7\,\mathrm{GeV}$ and $\lvert\eta\rvert < 2.5$	
b-jet veto	No b-jets with $p_{\mathrm{T}} > 25\,\mathrm{GeV}$ and $\lvert\eta\rvert < 2.5$	

Evidence for Tri-Boson Production

Event Selection Criteria WVZ

	$WVZ \to \ell\nu qq\ell\ell$	$WVZ \to \ell\nu\ell\nu\ell\ell/qq\ell\ell\ell\ell$
Z boson	At least one OS lepton pair with $\lvert m_{\ell\ell} - 91.2\,\text{GeV}\rvert < 10\,\text{GeV}$	
Low mass veto	$m_{\ell\ell} > 12\,\text{GeV}$ for any OS lepton pair	
b-jet veto	No b-jets with $p_{\text{T}} > 25\,\text{GeV}$ and $\lvert\eta\rvert < 2.5$	
Leptons	One additional nominal lepton	One additional OS lepton pair; third and fourth lepton nominal
H_{T}	$H_{\text{T}} > 200\,\text{GeV}$	–

Evidence for Tri-Boson Production

Event Selection Criteria For Control Regions

WZ control region	Three nominal leptons with one SFOS pair No b-tagged jets $E_{\mathrm{T}}^{\mathrm{miss}} > 55$ GeV $m_{\ell\ell\ell} > 110$ GeV
W sideband validation region	Same as the $WWW \to \ell\nu\ell\nu qq$ SR, with $m_{jj} < 50$ GeV or $m_{jj} > 120$ GeV
$t\bar{t}Z$ control region	Same as the 3ℓ-3j SR region, except: no requirement on H_{T}, at least four jets, at least two b-tagged jets.
WZ+jets and Z+jets validation regions	Same as the 3ℓ-1j SR region, except: no requirement on H_{T}; third-highest-p_{T} lepton has 10 GeV $< p_T <$ 15 GeV; $m_{\ell\ell\ell} <$ 150 GeV.