Observation and Measurements of Vector-Boson Pair Production with ATLAS

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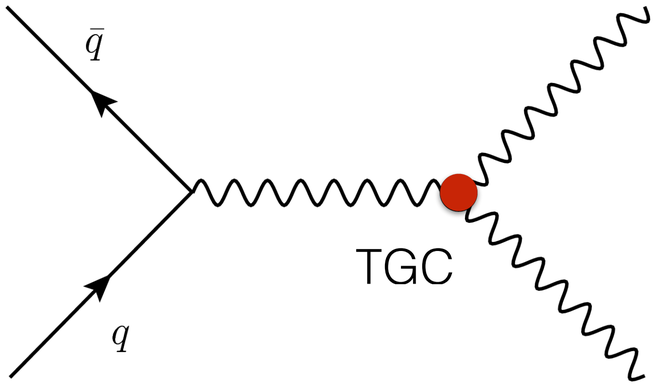
ATLAS EXPERIMENT

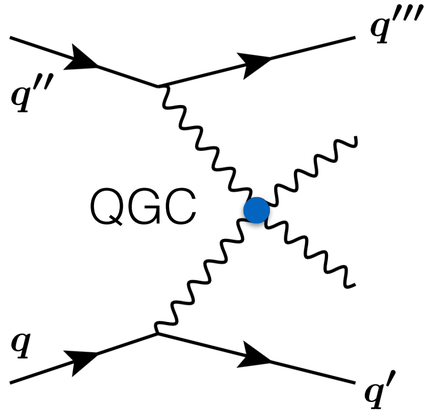
Motivation

- The ATLAS detector has recently been used to study a number of electroweak vector-boson pair production processes.
- Among these processes are the invisible Z, VBS and inclusive $W^{\pm}Z$, inclusive $W^{+}W^{-}$ and VBS $W^{\pm}W^{\pm}$.
- Using these vector-boson pair production processes we can,
  - Probe the electroweak sector of the Standard Model.
  - Investigate the mechanism responsible for electroweak symmetry breaking.
  - Study triple and quartic gauge-boson interactions.
  - Search for evidence of new physics (BSM, aTGC, aQGC, etc.)

Triple Gauge Coupling



Quartic Gauge Coupling

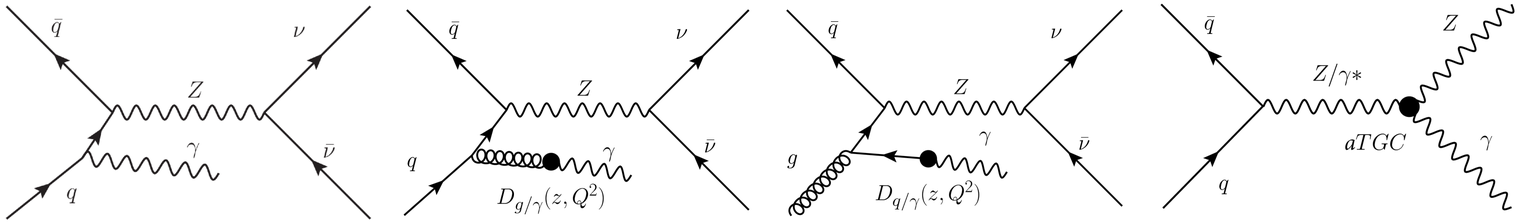


- Data conditions for all of the included measurements:
  - High energy proton-proton collisions recorded in 2015-2016 at $\sqrt{s}$ = 13 TeV and $\mathscr{L}$ = 36.1 fb^{-1}.

Zγ → νν̄γ — Z Boson Production in Association with a High Energy Photon

arXiv:1810.04995

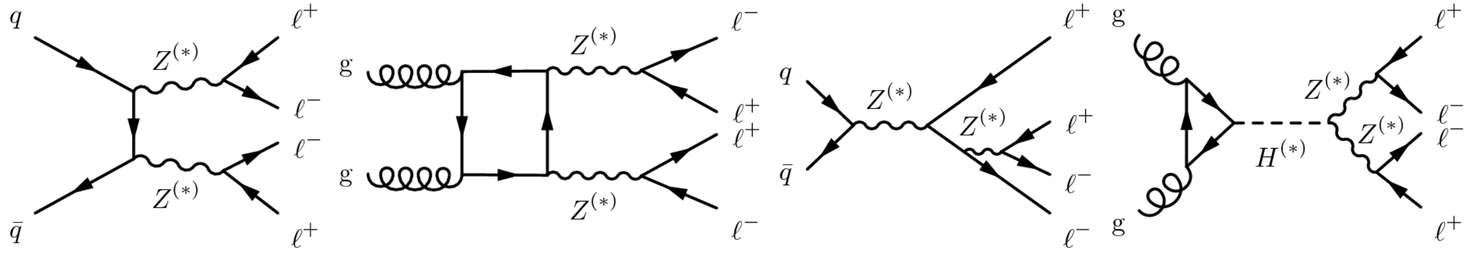
- $Z\gamma \to \nu\bar{\nu}\gamma$ events with exactly one tight isolated photon and no leptons.
- Events are selected in an inclusive region ($N_{jets} \geq 0$) and an exclusive region ($N_{jets} = 0$).



pp → 4ℓ — Four-lepton (pp → 4ℓ) Production

arXiv:1902.05892

- A set of processes with four leptons in the final state ($pp \to 4\ell$).
- 4ℓ = 4e, 4μ or 2e2μ.



Inc. W±Z — Inclusive W±Z Production

arXiv:1902.05759

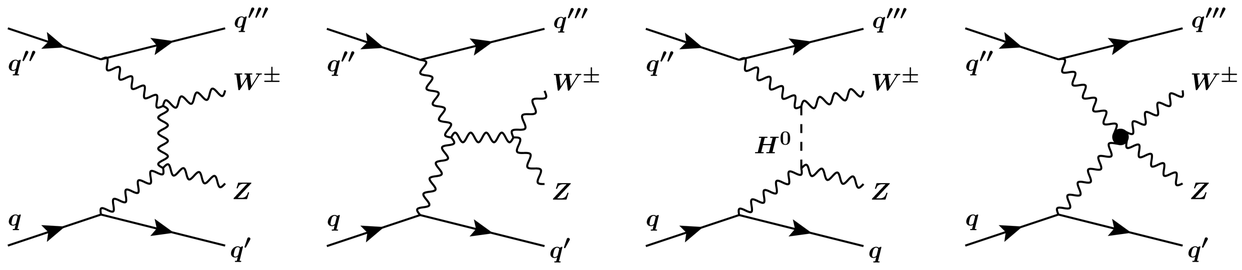
- W±Z production characterized by a decay to three leptons and a neutrino.
- $W^{\pm} \to \ell^{\pm}\nu$ (ℓ = e or μ) and $Z \to \ell\ell$ (ℓℓ = e^+e^- or $\mu^+\mu^-$)
- Events include any number of jets.

The Signals

VBS W±Z — Electroweak VBS W±Zjj Production

arXiv:1812.09740

- The purely electroweak scattering of two vector bosons yielding a W± boson, a Z boson and two jets (W±Zjj-EW).
- The W± and Z bosons decay into three leptons and a neutrino. $W^{\pm} \to \ell^{\pm}\nu$ and $Z \to \ell\ell$, (ℓ = e and/or μ).



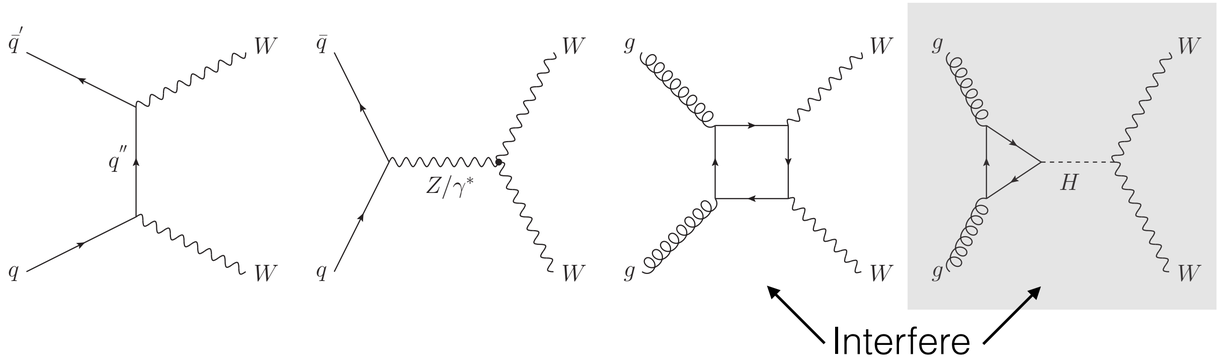
Inc. W+W- — Inclusive Opposite-Sign W Boson Pair Production

ATL-COM-PHYS-2018-1487

- W+W- production characterized by a decay to two leptons, two neutrinos and no jets.

$$W^{+}W^{-} \to e^{\pm}\nu\mu^{\mp}\nu$$

- This analysis is orthogonal to the recent H → WW* analysis.



Suppressed by invariant mass ($m_{\ell\ell}$) cut

VBS W±W± — VBS Same-Sign W Boson Pair Production

ATLAS-CONF-2018-030

- The electroweak scattering of two vector bosons yielding two same-sign W bosons and two jets.
- Each W boson decays into a lepton and a neutrino. $W^{\pm} \to \ell^{\pm}\nu$, (ℓ = e and/or μ).

- In invisible Z boson (Zγ → νν̄γ) analysis, both the fiducial and differential cross-sections are measured in an extended fiducial region where many of the analysis cuts have been relaxed, (including the lepton veto).

The Fiducial Cross-Section:

- The measured fiducial cross-sections are listed in the table to the right.
- The measured fiducial cross-sections agree within one standard deviation with the SM prediction.

The Differential Cross-Section:

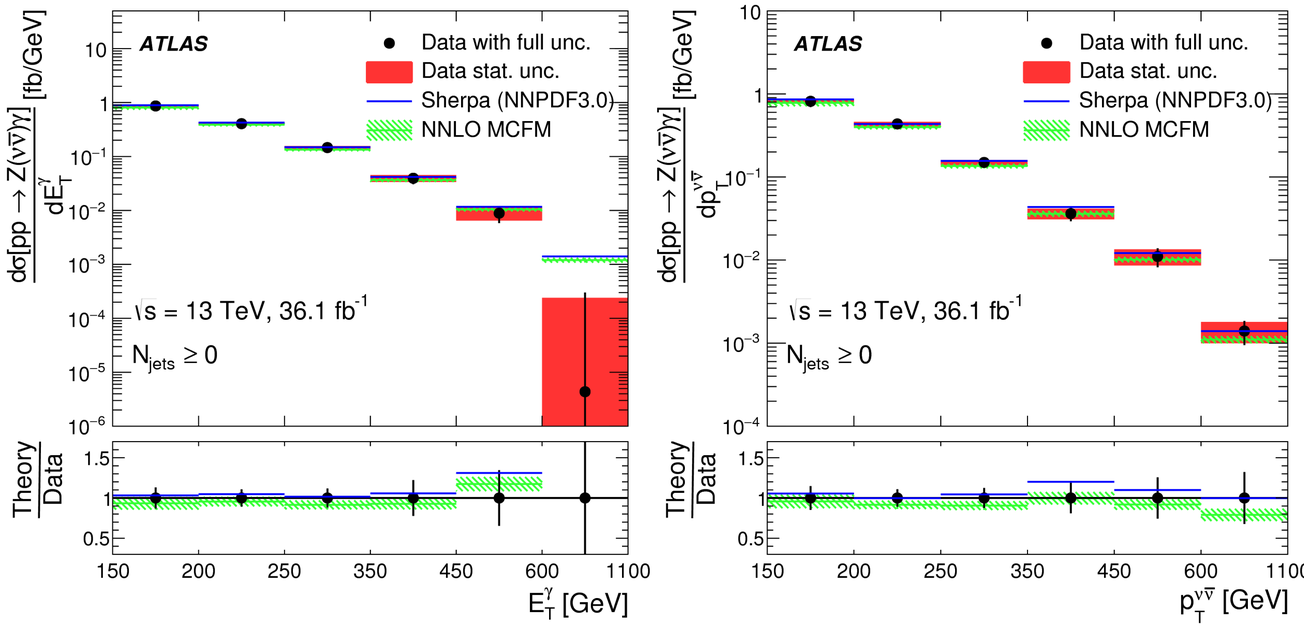
- The differential cross-sections are extracted using an iterative Bayesian unfolding method.
- The measured differential cross-sections generally show good agreement with the SM prediction.
  - The disagreement in the last bin of the E_{T}^{γ} distribution is due to statistical fluctuation.

Fiducial Cross-Sections

$\sigma^{\text{ext.fid.}}$ [fb] Measurement	$\sigma^{\text{ext.fid.}}$ [fb] NNLO MCFM Prediction
$N_{\text{jets}} \geq 0$	
$83.7^{+3.6}_{-3.5}\ (\text{stat.})^{+6.9}_{-6.2}\ (\text{syst.})^{+1.7}_{-2.0}\ (\text{lumi.})$	$78.1 \pm 0.2(\text{stat.}) \pm 4.7(\text{syst.})$
$N_{\text{jets}} = 0$	
$52.4^{+2.4}_{-2.3}\ (\text{stat.})^{+4.0}_{-3.6}\ (\text{syst.})^{+1.2}_{-1.1}\ (\text{lumi.})$	$55.9 \pm 0.1(\text{stat.}) \pm 3.9(\text{syst.})$

arXiv:1810.04995

Inclusive Differential Cross-Sections



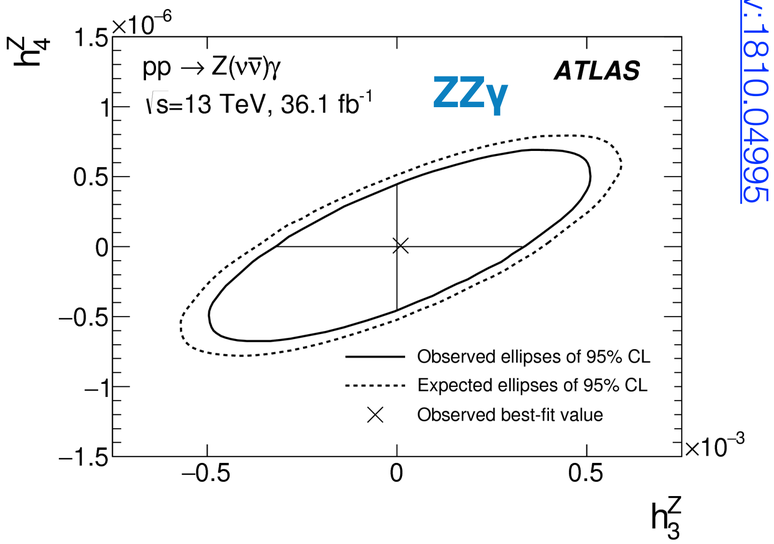
- In the framework of the effective vertex function approach, this analysis parameterizes aTGC contributions as follows.
  - CP-violating: h_1^V and h_2^V
  - CP-conserving: h_3^V and h_4^V

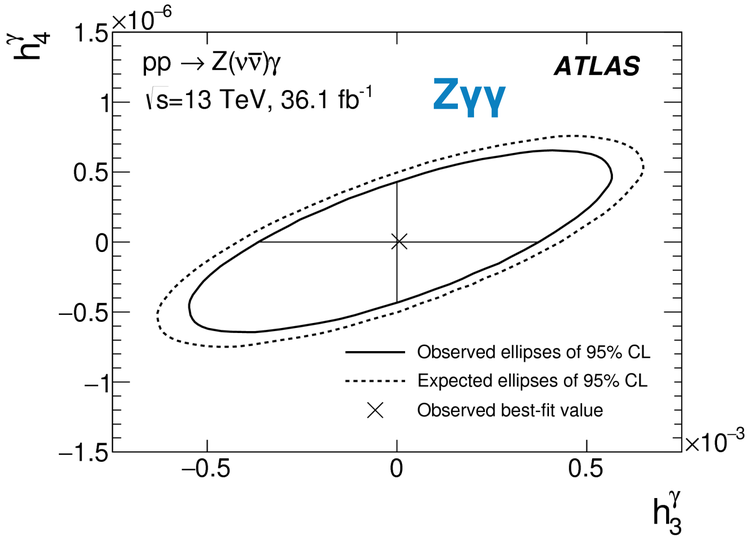
  } V = Z or γ, where, { Z = ZZγ vertex; γ = Zγγ vertex
- The CP-violating and the CP-conserving parameters do not interfere and are nearly identical.
- To optimize the sensitivity to aTGCs, the exclusive region (N_{jets} = 0) is used with the additional requirement that E_T^γ > 600 GeV.
- Shown here are the 1D 95% confidence level limits for the CP-conserving parameters.

Parameter	Limit 95% CL	
	Measured	Expected
h_3^γ	$(-3.7 \times 10^{-4}, 3.7 \times 10^{-4})$	$(-4.2 \times 10^{-4}, 4.3 \times 10^{-4})$
h_3^Z	$(-3.2 \times 10^{-4}, 3.3 \times 10^{-4})$	$(-3.8 \times 10^{-4}, 3.8 \times 10^{-4})$
h_4^γ	$(-4.4 \times 10^{-7}, 4.3 \times 10^{-7})$	$(-5.1 \times 10^{-7}, 5.0 \times 10^{-7})$
h_4^Z	$(-4.5 \times 10^{-7}, 4.4 \times 10^{-7})$	$(-5.3 \times 10^{-7}, 5.1 \times 10^{-7})$

- This analysis did not observe anomalous couplings.
- When compared with previous analyses, this analysis imposes 3-7 times more stringent limits on anomalous couplings.

95% CL Ellipses





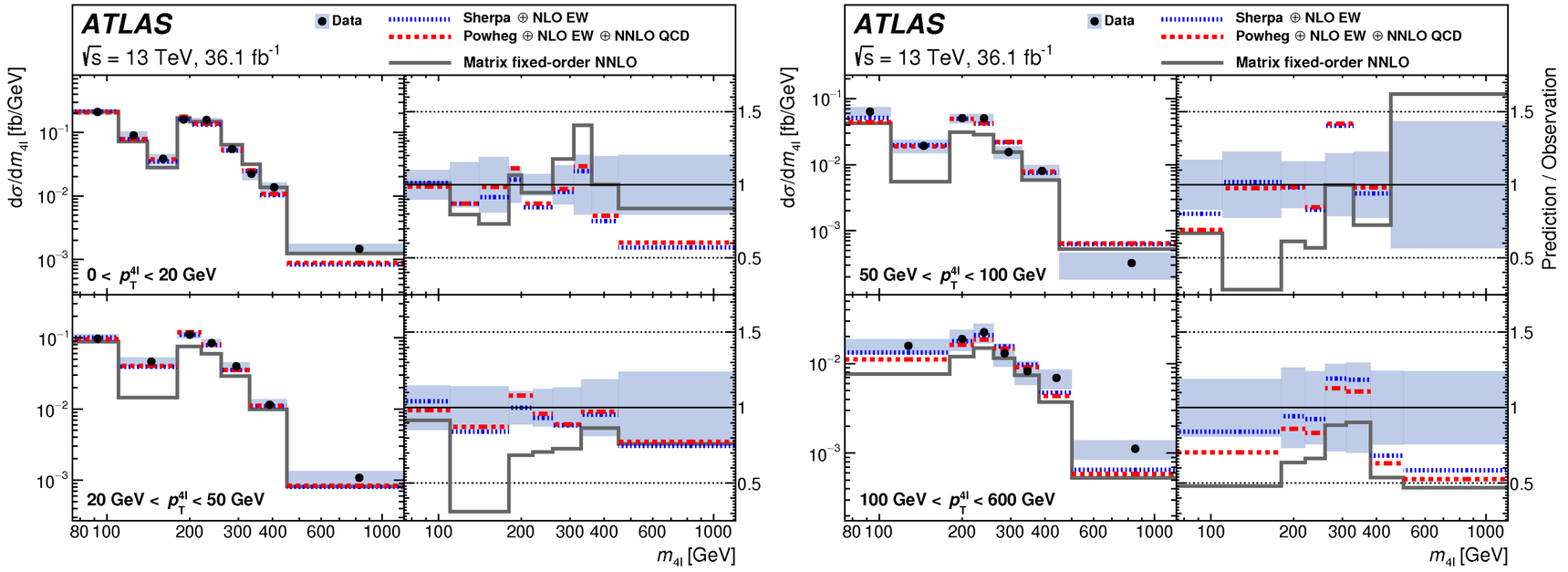
arXiv:1810.04995

arXiv:1902.05892

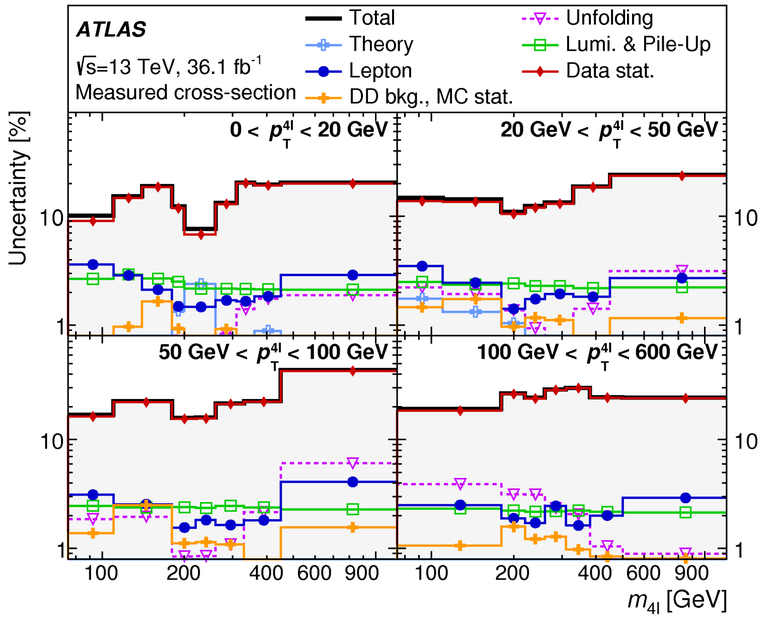
Differential Cross-Section:

- In the four lepton (pp → 4ℓ) analysis, the differential cross-section is determined as a function of the invariant mass, $m_{4\ell}$.
- Overall, good agreement exists between the unfolded data and the predictions found using Sherpa and Powheg.
  - The MATRIX prediction shows the effect of additional higher-order corrections and QED final state radiation.
- As can be seen to the right below, the overall cross-section uncertainty is dominated by the statistical uncertainty.

Measured Differential Cross-Section as a Function of $m_{4\ell}$, in Bins of $p_T^{4\ell}$



Leading Sources of Uncertainty in Cross-Section in Bins of $p_T^{4\ell}$



Signal strength for gluon-induced 4ℓ production ($gg \to 4\ell$).

- Is determined relative to an uncorrected leading-order precision MCFM prediction.

$$\mu_{gg}^{\mathrm{LO}} = \frac{\sigma_{gg\to 4\ell}^{\mathrm{measured}}}{\sigma_{gg\to 4\ell}^{\mathrm{SM,\ LO\ QCD}}}$$

	ATLAS at √s = 13 TeV	ATLAS at √s = 8 TeV
Measured	2.7 ± 0.9	2.4 ± 1.4
Expected	2.2 ± 0.9	

arXiv:1902.05892

Branching Fraction of $Z \to 4\ell$

- Is determined in a region that is dominated by single Z boson production.

  $80 < m_{4\ell} < 100$ GeV and $m_{\ell\ell} > 4$ GeV

Measurement	$\mathcal{B}_{Z\to 4\ell}/10^{-6}$
ATLAS, $\sqrt{s}$ = 7 TeV and 8 TeV [8]	$4.31 \pm 0.34(\mathrm{stat}) \pm 0.17(\mathrm{syst})$
CMS, $\sqrt{s}$ = 13 TeV [6]	$4.83\ ^{+0.23}_{-0.22}(\mathrm{stat})\ ^{+0.32}_{-0.29}(\mathrm{syst}) \pm 0.08(\mathrm{theo}) \pm 0.12(\mathrm{lumi})$
ATLAS, $\sqrt{s}$ = 13 TeV	**$4.70 \pm 0.32(\mathrm{stat}) \pm 0.21(\mathrm{syst}) \pm 0.14(\mathrm{lumi})$**

Constraint on Off-Shell Higgs Boson Signal Strength

- Is determined using the double-differential distribution for $m_{4\ell}$ in terms of D_{ME} (matrix-element discriminant) at high mass ($m_{4\ell} > 180$ GeV).

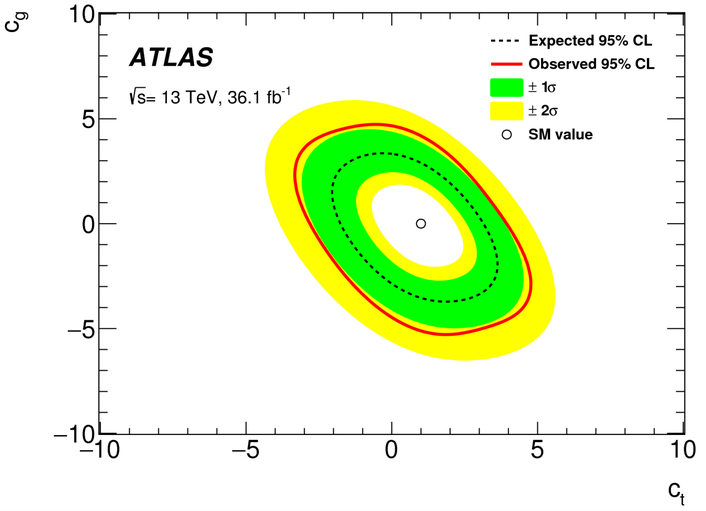
	95% CL Upper Limit for Off-Shell Higgs Boson Signal Strength
Observed	6.5
Expected	5.4

- The observed value of the 95% CL upper limit agrees with the expected within $\pm 1\sigma$ uncertainty.

Constraint on Modified Higgs Boson Couplings

- Is determined at high mass (> 180 GeV) for two BSM couplings.
  - c_t ($t\bar{t}H$) and c_g (ggH)
- The parameter space outside of the observed contour is excluded at 95% CL.

95% CL Exclusion Contours

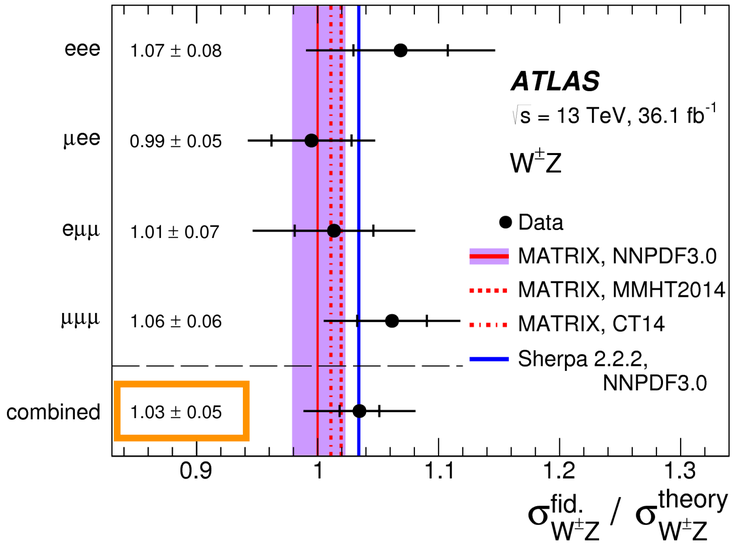


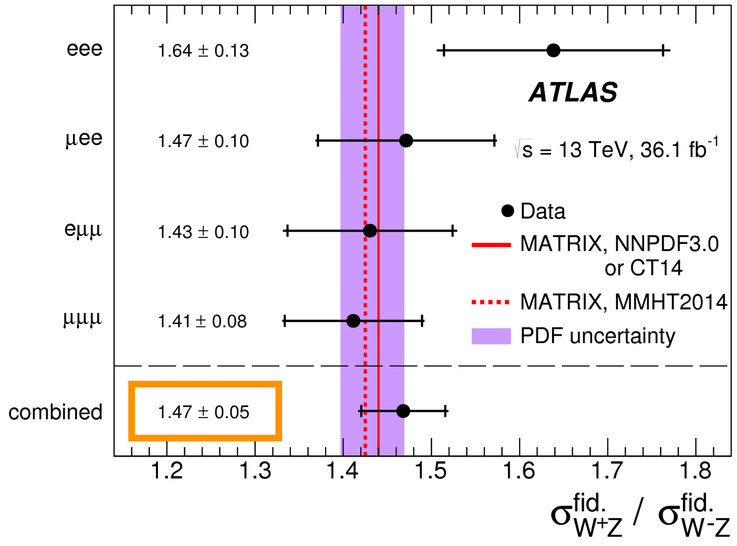
The Fiducial Cross-Section:

- In the inclusive $W^{\pm}Z$ analysis, the fiducial cross section is determined separately in the different lepton channels for $W^{-}Z$, $W^{+}Z$ and $W^{\pm}Z$.

$$\sigma^{\text{fid.}}_{W^{\pm}Z \to \ell'\nu\ell\ell} = \frac{N_{\text{data}} - N_{\text{bkg}}}{\mathcal{L} \cdot C_{\text{WZ}}} \times \left(1 - \frac{N_{\tau}}{N_{\text{all}}}\right)$$

- A χ^2 minimization method is used to combine the results from the four lepton channels.

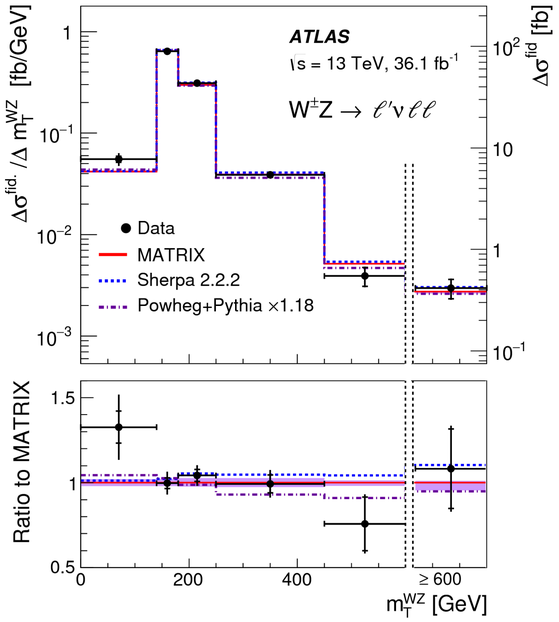


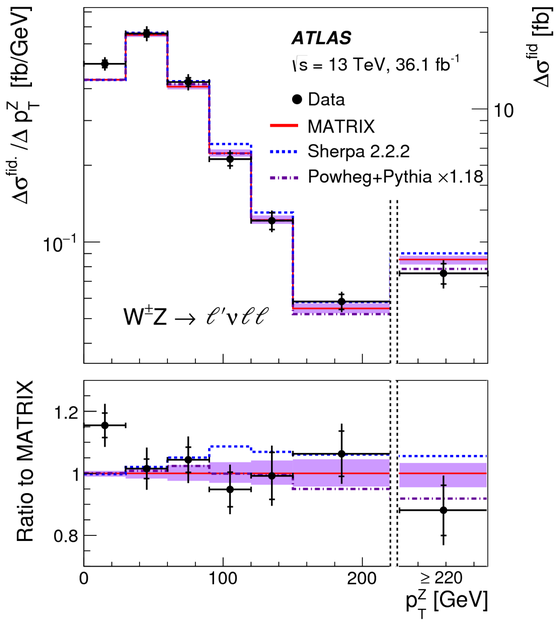


arXiv:1902.05759

The Differential Cross-Section:

- The differential cross-section is determined for a combination of all four lepton channels as a function of several variables.
- Good agreement exits between the unfolded data and the prediction for each of the resulting distributions.
- The high energy tails of the m_T^{WZ} and p_T^{Z} distributions are sensitive to aTGC.
- As shown here, there is no excess of data events in the associated bins and thus no evidence of aTGC.





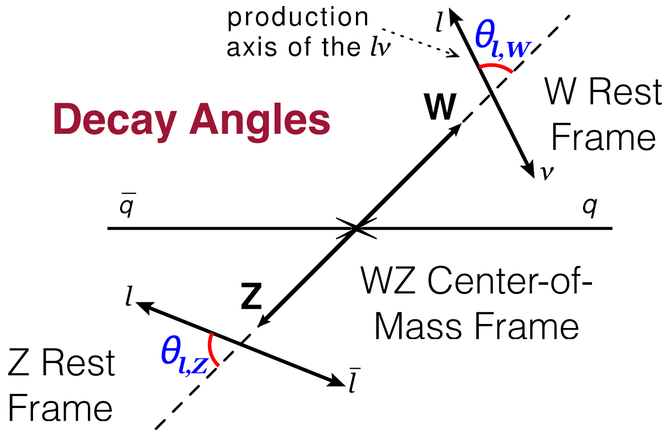
Polarization of WZ Events:

- The W and Z boson polarization measurements are performed on a sum of the four lepton channels (eee, eμμ, μee, and μμμ).
- Binned profile-likelihood fits are performed of templets of the helicity states.
- The helicity parameters, f_0 and f_L - f_R, are extracted from fits of $q_\ell \cdot \cos(\theta_{\ell,W})$ and $\cos(\theta_{\ell,Z})$ for W and Z separately.
- The resulting significance of the longitudinal helicity fractions, f_0:

	Significance	
	Observed	Predicted
$W^\pm$	4.2σ	3.8σ
Z	6.5σ	6.1σ

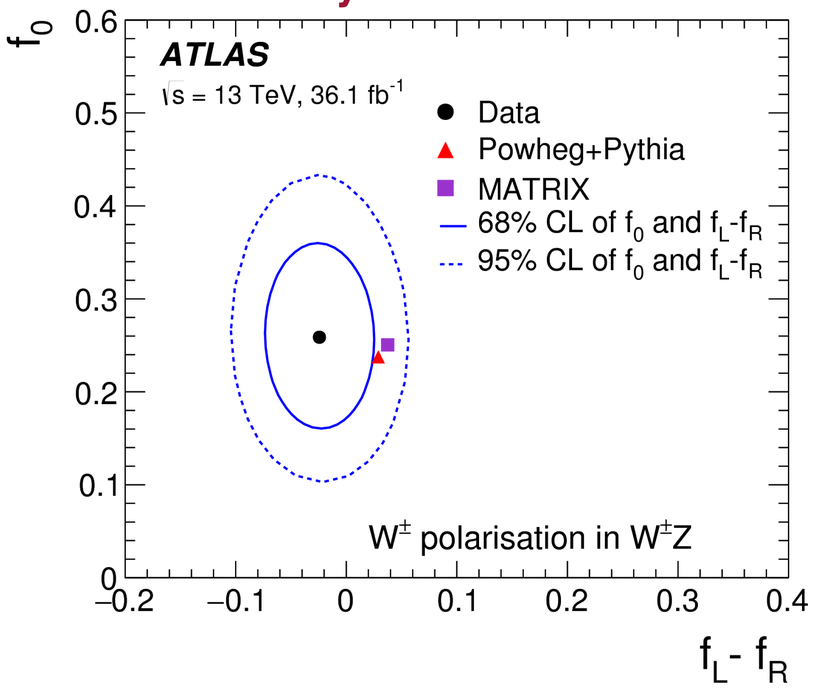
- Note that the f_0 for the W is more difficult to extract and thus has greater uncertainty.
- This analysis successfully observed longitudinally polarized W bosons.

Decay Angles

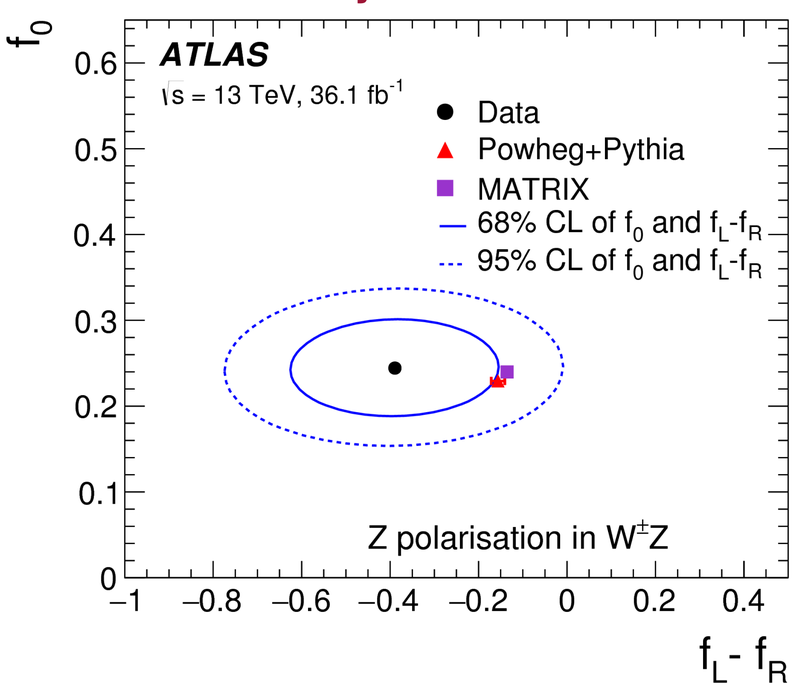


arXiv:1902.05759

Helicity Fractions for W±



Helicity Fractions for Z



arXiv:1812.09740

Fiducial Cross-Section:

- In the electroweak VBS W±Zjj analysis, two fiducial cross-sections are determined.
- The BDT score is used to extract the signal significance ($\mu_{\text{WZjj-EW}}$). The fiducial cross-section for W±Zjj-EW production is then derived from $\mu_{\text{WZjj-EW}}$.

$$\mu_{\text{WZjj-EW}} = \frac{N_{\text{data}}^{\text{signal}}}{N_{\text{MC}}^{\text{signal}}} = \frac{\sigma_{\text{WZjj-EW}}^{\text{fid.}}}{\sigma_{\text{WZjj-EW}}^{\text{fid.,MC}}}$$

  - Signal Significance: $\mu_{WZjj-\text{EW}} = 1.77\ ^{+0.44}_{-0.40}\,(\text{stat.})\ ^{+0.15}_{-0.12}\,(\text{exp. syst.})\ ^{+0.15}_{-0.12}\,(\text{mod. syst.})\ ^{+0.04}_{-0.02}\,(\text{lumi.}) = 1.77\ ^{+0.49}_{-0.43}$
  - Measured cross-section: $\sigma^{\text{fid.}}_{WZjj-\text{EW}} = 0.57\ ^{+0.14}_{-0.13}\,(\text{stat.})\ ^{+0.05}_{-0.04}\,(\text{exp. syst.})\ ^{+0.05}_{-0.04}\,(\text{mod. syst.})\ ^{+0.01}_{-0.01}\,(\text{lumi.})\ \text{fb} = 0.57\ ^{+0.16}_{-0.14}\ \text{fb}$
  - Predicted cross-section: $\sigma^{\text{fid., Sherpa}}_{WZjj-\text{EW}} = 0.321 \pm 0.002\,(\text{stat.}) \pm 0.005\,(\text{PDF})^{+0.027}_{-0.023}\,(\text{scale})\ \text{fb}$

- The integrated fiducial cross-section for all W±Zjj production (W±Zjj-EW and W±Zjj-QCD) can be expressed as,

$$\sigma^{\text{fid.}}_{W^{\pm}Zjj} = \frac{N_{\text{data}} - N_{\text{bkg}}}{\mathcal{L} \cdot C_{\text{WZjj}}} \times \left(1 - \frac{N_{\tau}}{N_{\text{all}}}\right)$$

  - Measured cross-section: $\sigma^{\text{fid.}}_{W^{\pm}Zjj} = 1.68 \pm 0.16\,(\text{stat.}) \pm 0.12\,(\text{exp. syst.}) \pm 0.13\,(\text{mod. syst.}) \pm 0.044\,(\text{lumi.})\ \text{fb} = 1.68 \pm 0.25\ \text{fb}$
  - Predicted cross-section: $\sigma^{\text{fid., Sherpa}}_{W^{\pm}Zjj} = 2.15 \pm 0.01\,(\text{stat.}) \pm 0.05\,(\text{PDF})^{+0.65}_{-0.44}\,(\text{scale})\ \text{fb}$

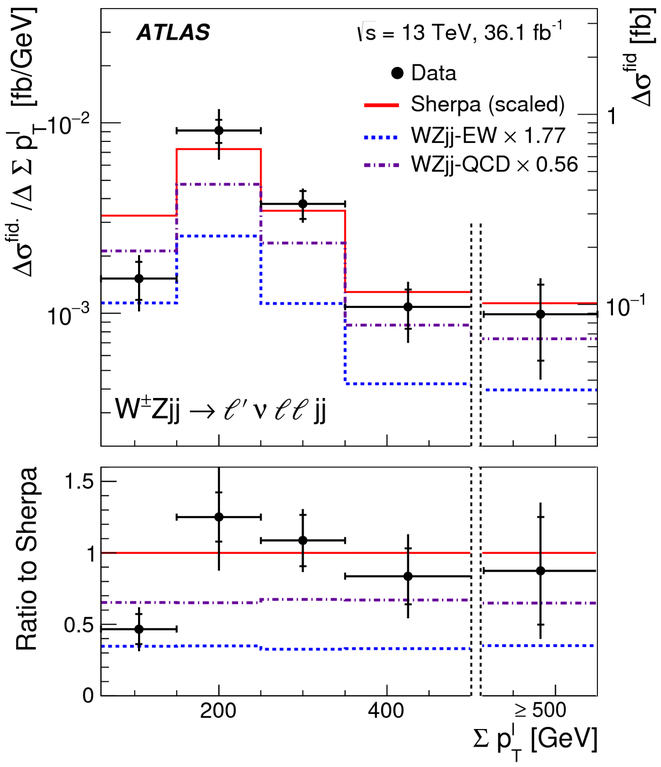
- Both measured fiducial cross-sections include interference effects between W±Zjj-QCD and W±Zjj-EW.
- Neither of the predicted fiducial cross-sections include interference effects between W±Zjj-QCD and W±Zjj-EW. They are also determined at LO and do not include NLO Electroweak corrections.

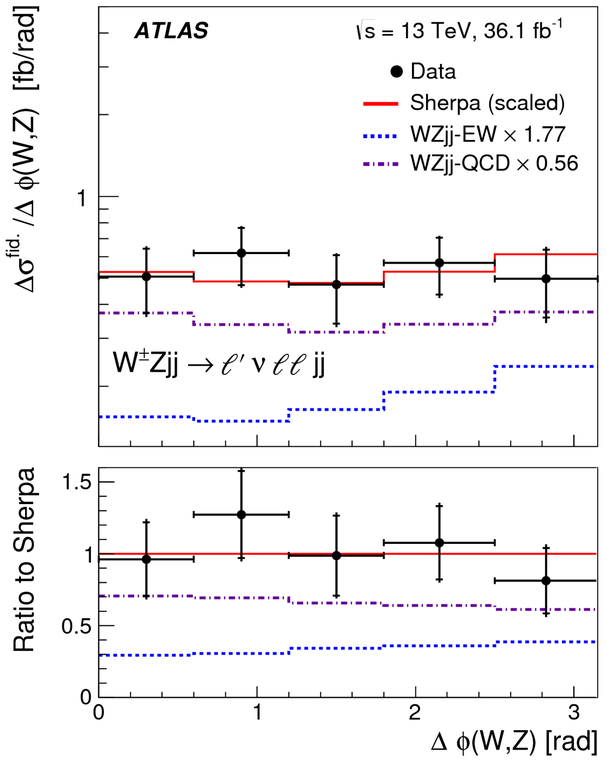
arXiv:1812.09740

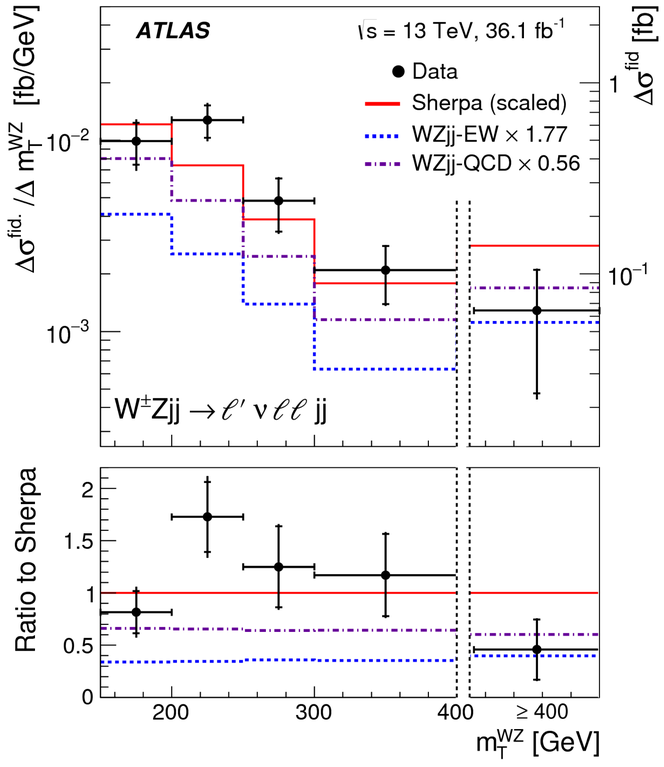
Differential Cross-Section:

- An iterative Bayesian unfolding is performed to measure the W±Zjj differential cross-section.
- Shown here is the differential cross-section as a function of three variables that are sensitive to aQGCs.
- The WZjj-EW and WZjj-QCD predicted cross-sections have been scaled by their respective signal strengths to more closely model data and minimize unfolding uncertainties.
- Sherpa samples for WZjj-EW and WZjj-QCD have also been added together and similarly scaled.

Differential Cross-Section as a Function of Σp_T^{ℓ}, $\Delta\phi$(W,Z) and m_T^{WZ}







- For the inclusive W^+W^- analysis:

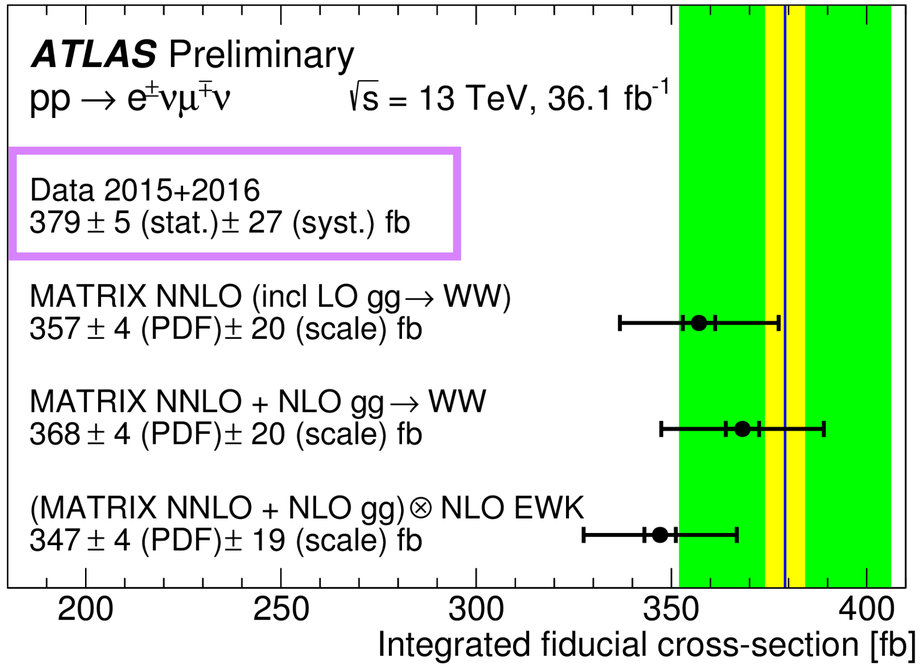
Fiducial Cross-Section:

- The measured and predicted fiducial cross-sections for the $W^+W^- \rightarrow e^{\pm}\nu\mu^{\mp}\nu$ signal process are shown here.

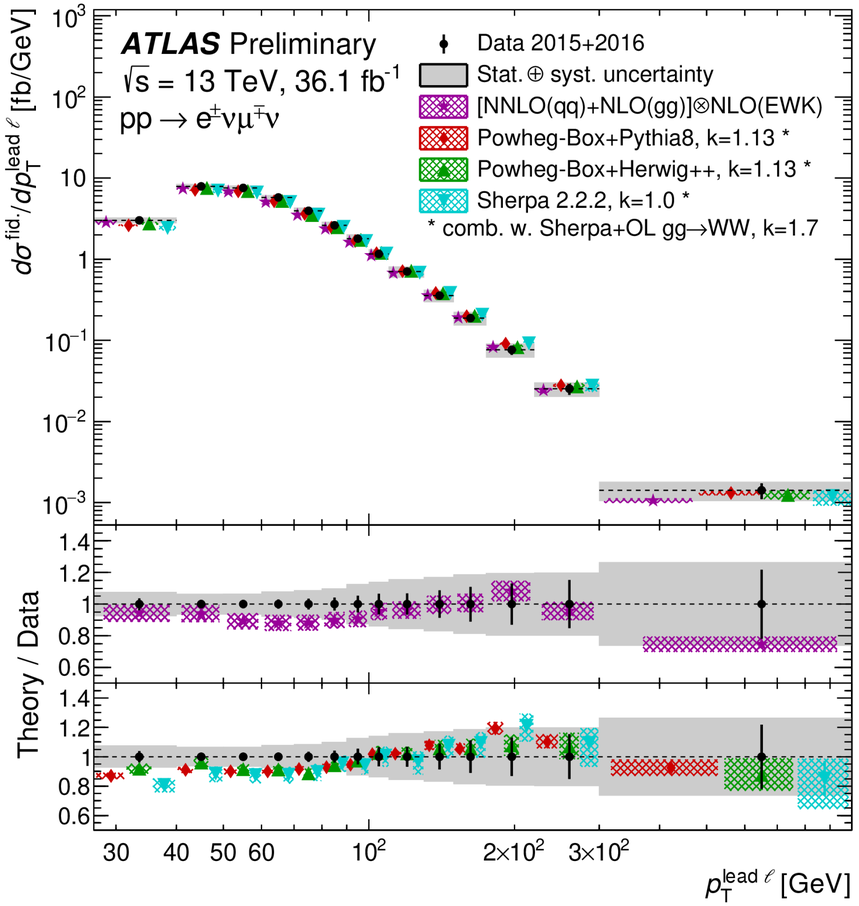
$$\sigma^{\text{fid.}}_{WW \rightarrow e\mu} = \frac{N_{\text{obs}} - N_{\text{bkg}}}{C \times \mathcal{L}}$$

- Good agreement exists between the measured and predicted fiducial cross-sections.

Comparison of the Measured and Predicted Fiducial Cross-Sections



Differential Cross-Section as a Function of Leading Lepton p_T



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Differential Cross-Section:

- An iterative Bayesian unfolding procedure is used to find the differential cross-section as a function of a number of lepton based observables.
- All of the predictions for each of the observables do a fair job of predicting the unfolded data. However, as seen here at low leading lepton p_T, there is a tendency to under predict the data.

Measurements

- In the framework of effective field theory (EFT) there are five dimension six operators, $\mathcal{O}_i$, that can generate aTGCs from purely electroweak processes.

$$\mathcal{L} = \mathcal{L}_{\mathrm{SM}} + \sum_i \frac{c_i}{\Lambda^2}\mathcal{O}_i$$

- Using the unfolded leading lepton p_T distribution it is possible constrain the five associated EFT coefficients, c_i.
- The observed and expected 95% CL intervals for these coefficients are listed in the table.
- The plot to the right is a breakdown of the sources of uncertainty on the leading lepton p_T distribution.
- Sensitivity to anomalous couplings is greatest in the high leading lepton p_T bins.
- Since these bins are statistics dominated, further improvements to the constraints on the EFT coefficients will require a significant improvement in statistics.

Parameter	Observed 95% CL [TeV^{-2}]	Expected 95% CL [TeV^{-2}]
c_{WWW}/Λ^2	[−3.4 , 3.3]	[−3.0 , 3.0]
c_W/Λ^2	[−7.4 , 4.1]	[−6.4 , 5.1]
c_B/Λ^2	[−21 , 18]	[−18 , 17]
$c_{\tilde{W}WW}/\Lambda^2$	[−1.6 , 1.6]	[−1.5 , 1.5]
$c_{\tilde{W}}/\Lambda^2$	[−76 , 76]	[−91 , 91]

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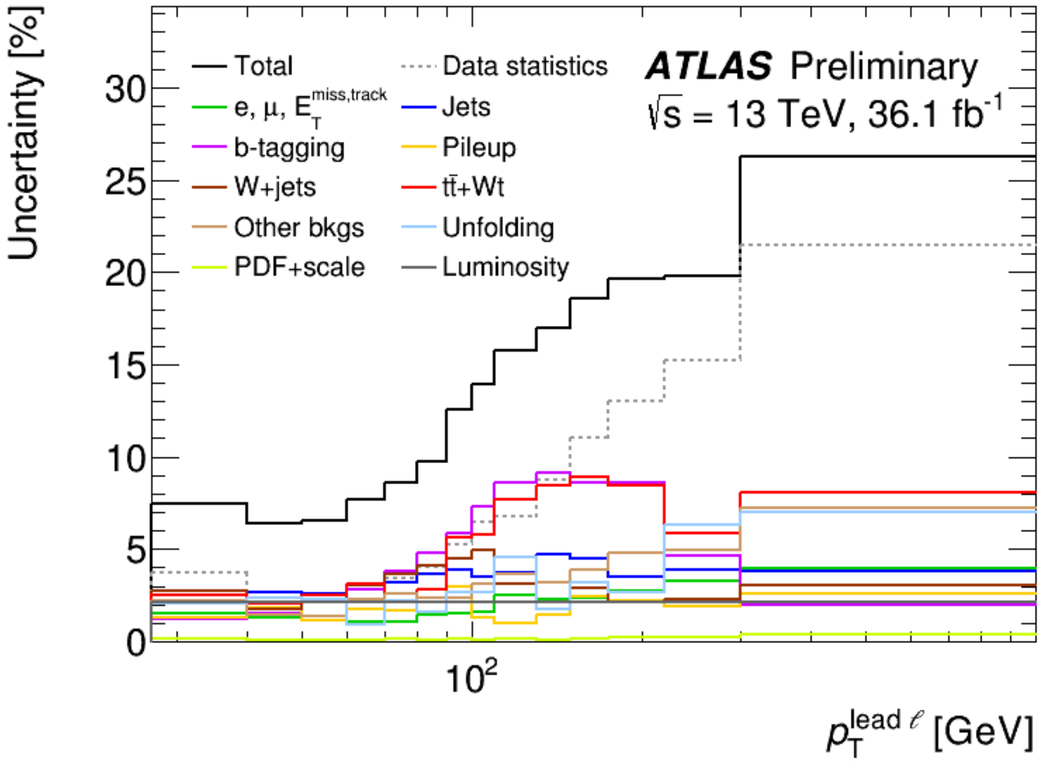
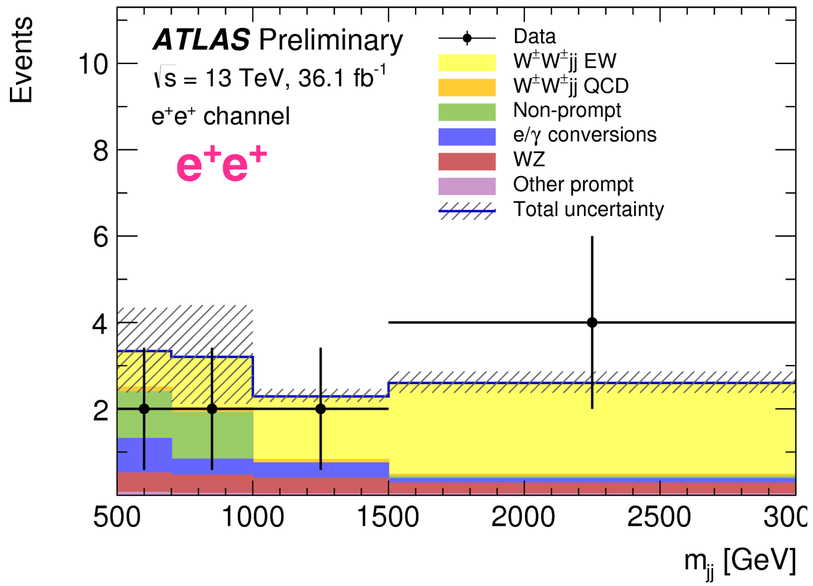
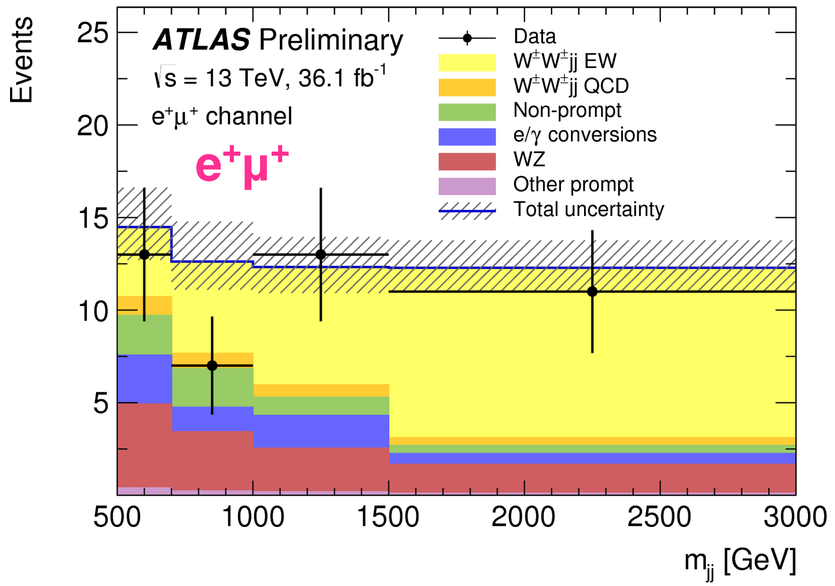
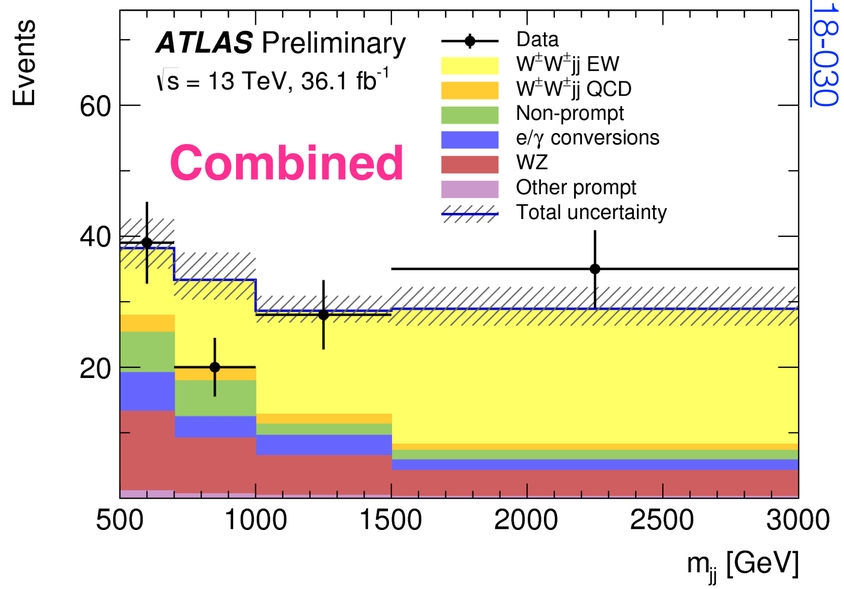


Measurements

- For the VBS same-sign WW analysis, to increase sensitivity to the electroweak signal, events are grouped according to lepton decay channel, ($e^{\pm}e^{\pm}$, $\mu^{\pm}\mu^{\pm}$, and $e^{\pm}\mu^{\pm}$).
- Shown here are m_{jj} distributions for two of the six lepton decay channels. Also shown is the combined result.







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- Shown here is a breakdown of the total number of expected signal and background events along with the number of observed data events for all lepton channels.
- Based on this, the electroweak $W^{\pm}W^{\pm}jj$ signal is observed and the background-only hypothesis is rejected with a significance of 6.9σ.

	Events
Expected Background	78 ± 15
$W^{\pm}W^{\pm}jj$-EW	40.9 ± 2.9
Data	122

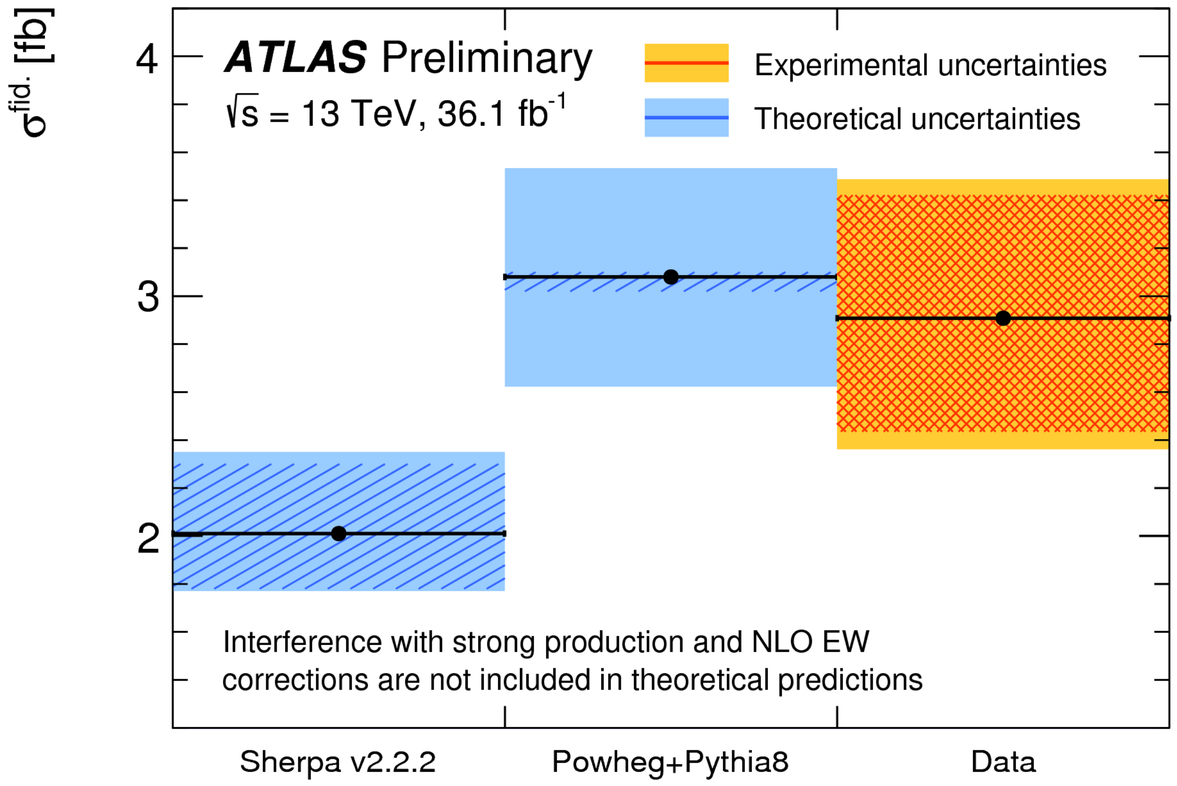
Fiducial Cross-Section:

- The fiducial cross-section is extracted from a profile likelihood fit of the m_{jj} distribution.
  - Measured cross-section:

$$\sigma^{fid} = 2.91^{+0.51}_{-0.47}\ (\text{stat.}) \pm 0.27\ (\text{syst.})\ \text{fb}$$

- Shown to the right is a comparison of the observed and predicted values for the fiducial cross-section.
- The observed cross-section includes interference between the electroweak and strong production.
- The predictions do not include strong interference effects and they do not include NLO electroweak corrections.

Observed & Predicted Fiducial Cross-Section



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Conclusion

- As part of its ongoing studies into the nature of the particles produced in high energy proton-proton collisions, the ATLAS detector has been used to perform the following set of recent measurements involving electroweak vector-boson pair production:
  - The fiducial and differential cross-sections for invisible Z production and limits on the parameters in the effective vertex function approach to describing aTGC contributions.
  - The differential cross-section as a function of the four-lepton invariant mass $m_{4\ell}$, the strength of gluon-induced 4ℓ production, the branching fraction of $Z \to 4\ell$, constraints on the off-shell Higgs boson signal strength and constraints on some modified Higgs boson couplings.
  - The fiducial and differential cross-sections of inclusive $W^{\pm}Z$ production and the longitudinal helicity fractions for $W^{\pm}$ and Z bosons.
  - The fiducial and differential cross-sections of electroweak $W^{\pm}Zjj$ production.
  - The fiducial and differential cross-sections for leptonically decaying $W^{+}W^{-}$ and constraints on the associated five EFT dimension six operators.
  - The fiducial cross-section for leptonically decaying VBS same-sign $W^{\pm}W^{\pm}$ production and a rejection of the background-only hypothesis.

References

- For an in-depth discussion of the analysis and results presented in this talk, please see the following:
  - The ATLAS Collaboration. Measurement of the $Z\gamma \rightarrow \nu\bar{\nu}\gamma$ production cross section in pp collisions at √s = 13 TeV with the ATLAS detector and limits on anomalous triple gauge-boson couplings. High Energy Phys. (2018) 2018: 10. https://doi.org/10.1007/JHEP12(2018)010.
  - The ATLAS Collaboration. Measurement of the four-lepton invariant mass spectrum in 13 TeV proton-proton collisions with the ATLAS detector. High Energy Phys. (2019) 2019: 48. https://doi.org/10.1007/JHEP04(2019)048.
  - The ATLAS Collaboration. Measurement of W±Z production cross sections and gauge boson polarisation in pp collisions at √s = 13 TeV with the ATLAS detector. eprint arXiv:1902.05759 [hep-ex].
  - The ATLAS Collaboration. Observation of electroweak W±Z boson pair production in association with two jets in pp collisions at √s= 13 TeV with the ATLAS detector. eprint arXiv:1812.09740 [hep-ex].
  - The ATLAS Collaboration. Measurement of fiducial and differential W+W− production cross sections at √s = 13 TeV with the ATLAS detector. CDS Record: ATL-COM-PHYS-2018-1487.
  - The ATLAS Collaboration. Observation of electroweak production of a same-sign W boson pair in association with two jets in pp collisions at √s = 13 TeV with the ATLAS detector. CDS Record: ATLAS-CONF-2018-030.

Backup