VBF and VBS Measurements in ATLAS

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On behalf of the ATLAS Collaboration

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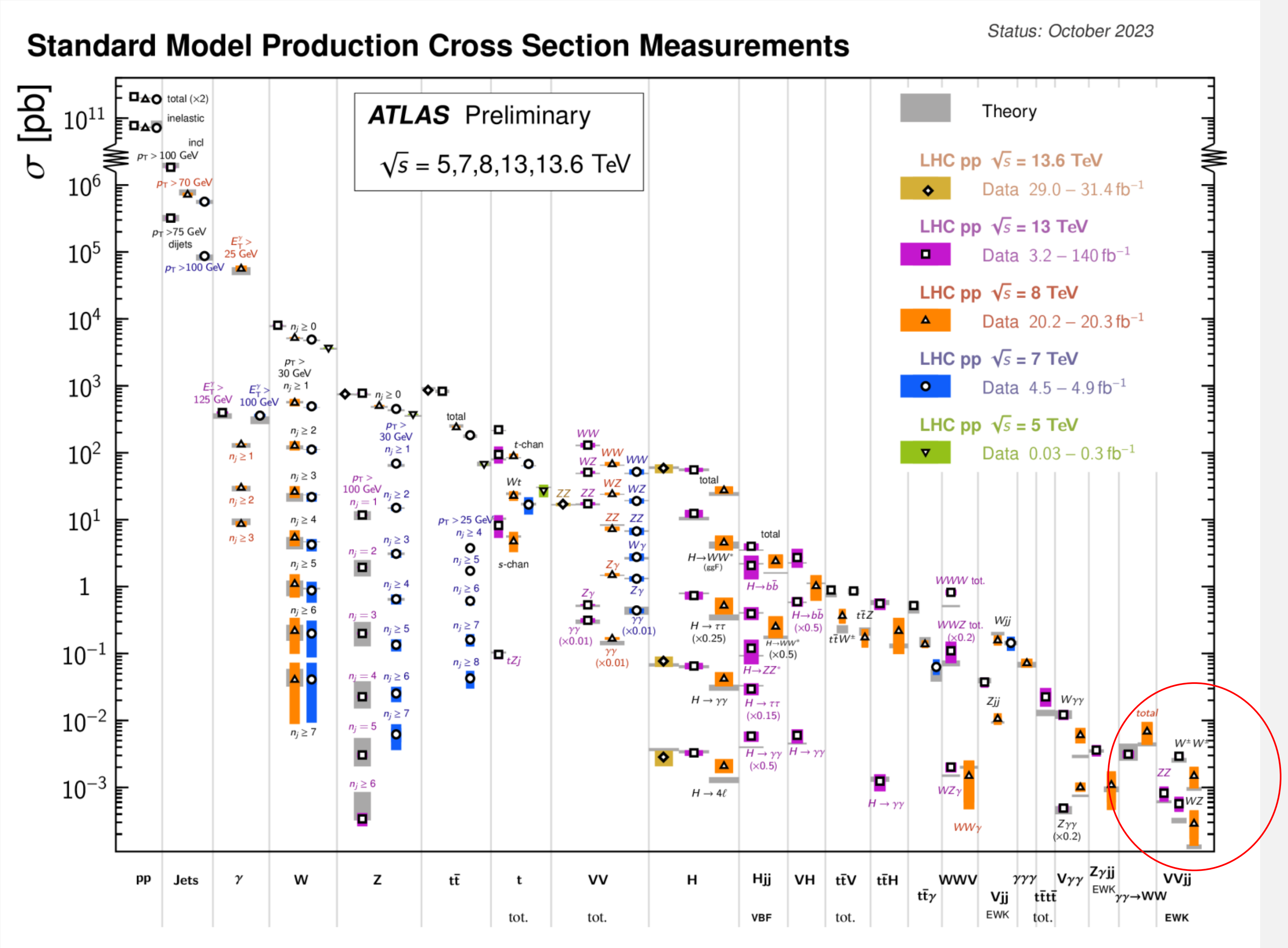
Motivation

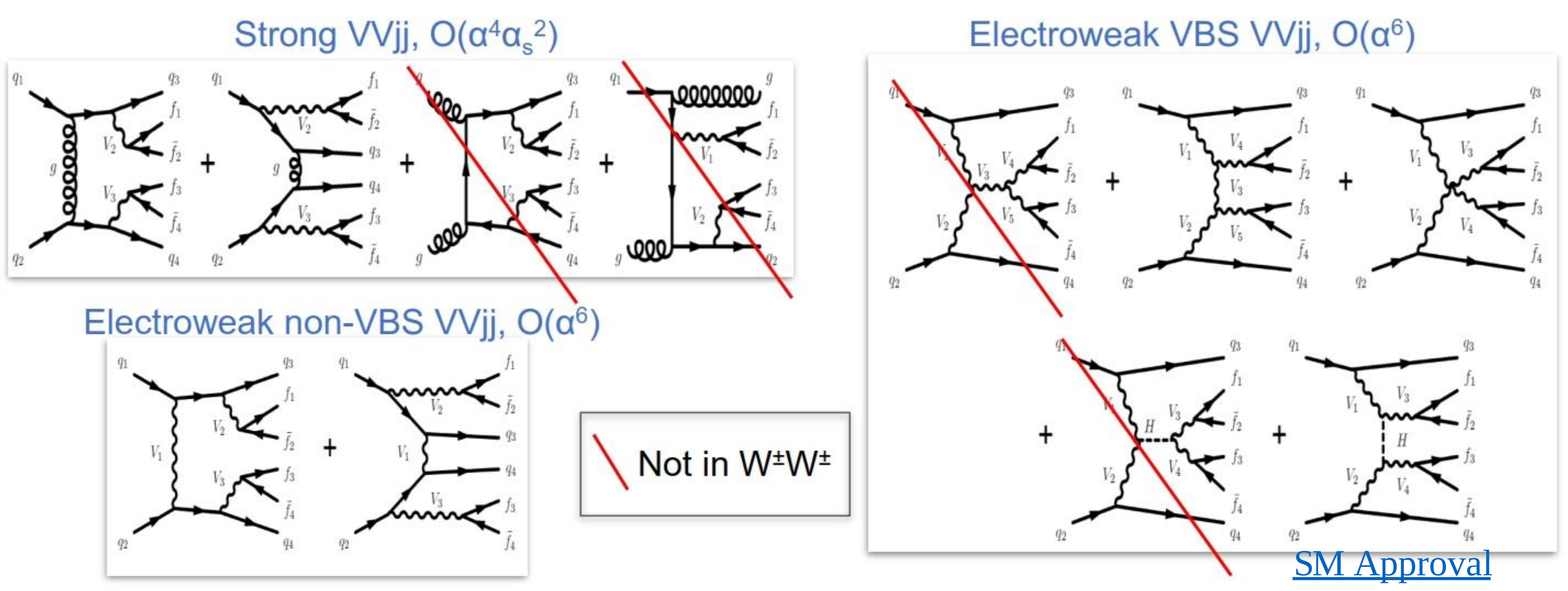


- Direct probes of boson interactions, both in standard model and beyond
- Allows to test SM predictions to triple and quartic gauge couplings
- Looking at the smallest EW cross-sections

https://arxiv.org/abs/2312.00420

Same-sign $W^{\pm}W^{\pm}jj$

- Motivation:
  - Probes mechanism of electroweak symmetry breaking (EWSB) in the Standard Model (SM)
  - Unique sensitivity for new physics phenomena



SM Approval

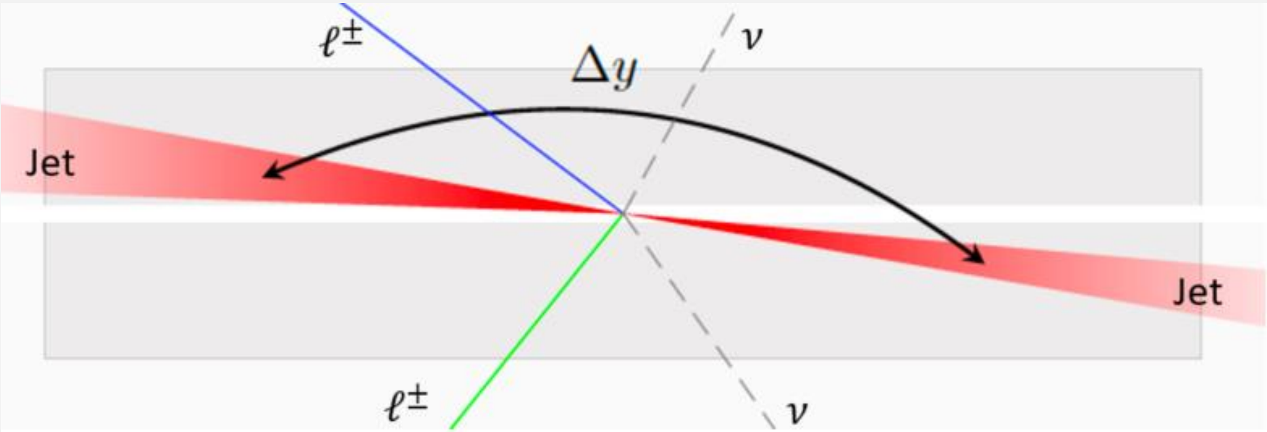
- $W^{\pm}W^{\pm}jj$ final states has largest EW to QCD xsection ratio because of the suppression of QCD-induced background
- EW measures both VBS and non-VBS process, inclusive measurements include EW + QCD + interference

Same-sign $W^{\pm}W^{\pm}jj$ Strategy

- SR selections:
  - Two isolated same-sign leptons with transverse momentum $p_T > 27\ GeV$
  - Large missing energy due to presence of neutrinos $E_T^{miss} > 30\ GeV$
  - Jet transverse momentum $p_T^{leading} > 65\ GeV$ $p_T^{sub-leading} > 30\ GeV$ and b-veto
  - VBS signature: $m_{jj} > 500\ GeV$ & $|\Delta y_{jj}| > 2$

- WZ CR (improve modelling from QCD-induced $W^{\pm}Zjj$ events):
  - One more lepton with $p_T > 15\ GeV$
  - $m_{jj} > 200\ GeV$ & $m_{lll} > 106\ GeV$ (suppress radiative Z decay)

- Low-m_{jj} CR (control uncertainties of major background in signal extraction fit):
  - $200\ GeV < m_{jj} < 500\ GeV$



- Backgrounds modelled with MC and data-driven method:
  - $WZ/\gamma^{*}jj$
  - Non-prompt lepton & lepton charge mis-identification
  - Remaining background…

Same-sign $W^{\pm}W^{\pm}jj$ Fiducial Cross Section

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- Fiducial region defined as closely as possible to the analysis selections
- Separate maximum likelihood fits with free parameter μ_{sig}^{EW} ($\mu_{sig}^{EW+Int+QCD}$) performed to measure the EW and inclusive cross sections. $\mu^{QCD\,WZ}$ used as normalization coefficient for QCD $W^{\pm}Zjj$
- SR and CRs are split into four regions depending on lepton flavors : ee, $e\mu, \mu e, \mu\mu$

Description	$\sigma_{\text{fid}}^{\text{EW}}$ [fb]	$\sigma_{\text{fid}}^{\text{EW+Int+QCD}}$ [fb]
Measured cross section	2.92 ± 0.22 (stat.) ± 0.19 (syst.)	3.38 ± 0.22 (stat.) ± 0.19 (syst.)
MG5_aMC+Herwig7	2.53 ± 0.04 (PDF) $^{+0.22}_{-0.19}$ (scale)	2.92 ± 0.05 (PDF) $^{+0.34}_{-0.27}$ (scale)
MG5_aMC+Pythia8	2.53 ± 0.04 (PDF) $^{+0.22}_{-0.19}$ (scale)	2.90 ± 0.05 (PDF) $^{+0.33}_{-0.26}$ (scale)
Sherpa	2.48 ± 0.04 (PDF) $^{+0.40}_{-0.27}$ (scale)	2.92 ± 0.03 (PDF) $^{+0.60}_{-0.40}$ (scale)
Sherpa ⊗ NLO EW	2.10 ± 0.03 (PDF) $^{+0.34}_{-0.23}$ (scale)	2.54 ± 0.03 (PDF) $^{+0.50}_{-0.33}$ (scale)
Powheg Box+Pythia	2.64	–

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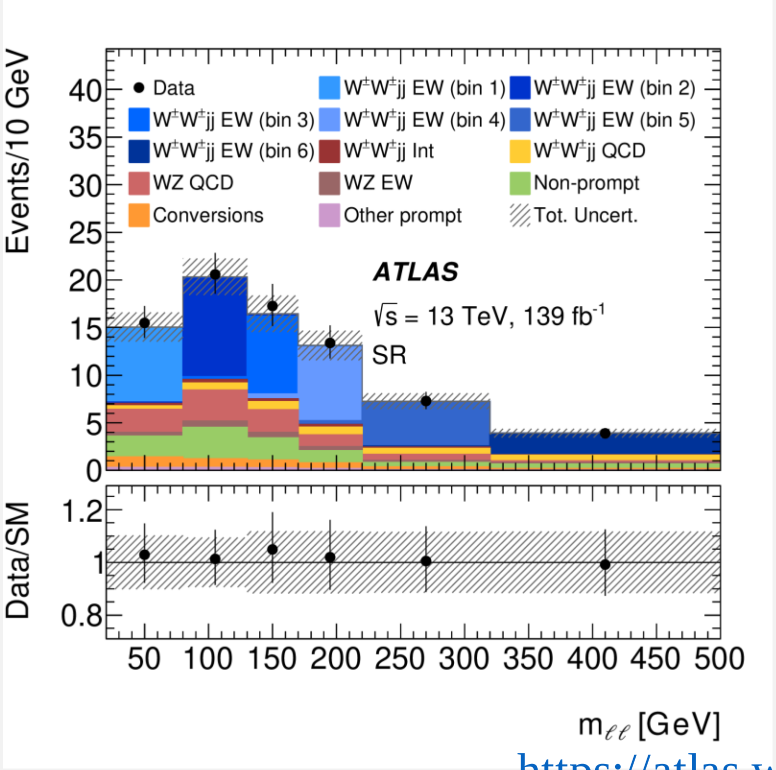
- Predictions agree with the observed data within uncertainties generally
- Observed cross section is slightly higher than predicted cross section

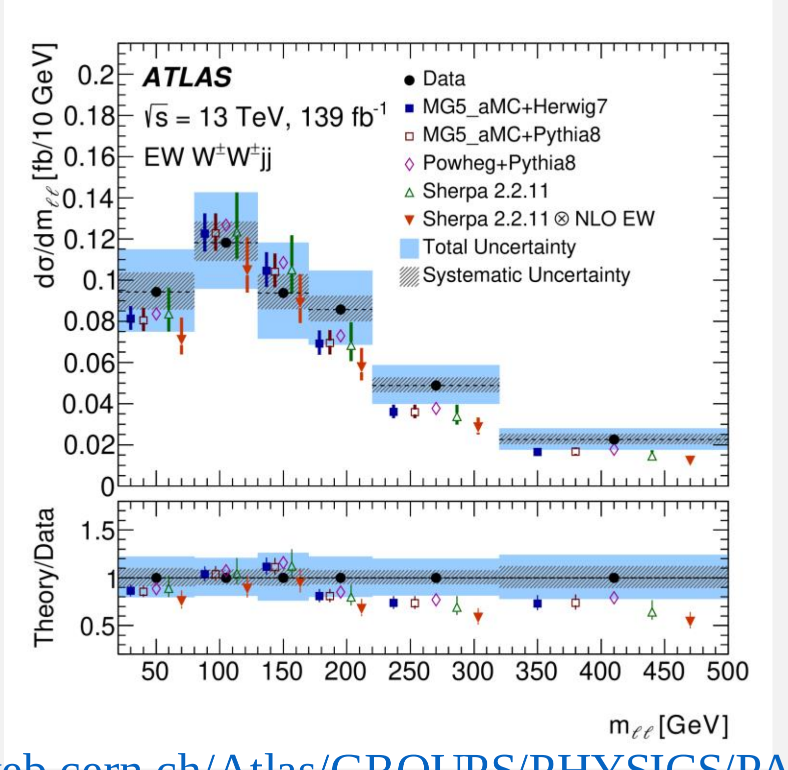
Same-sign $W^{\pm}W^{\pm}jj$ Differential Cross Section

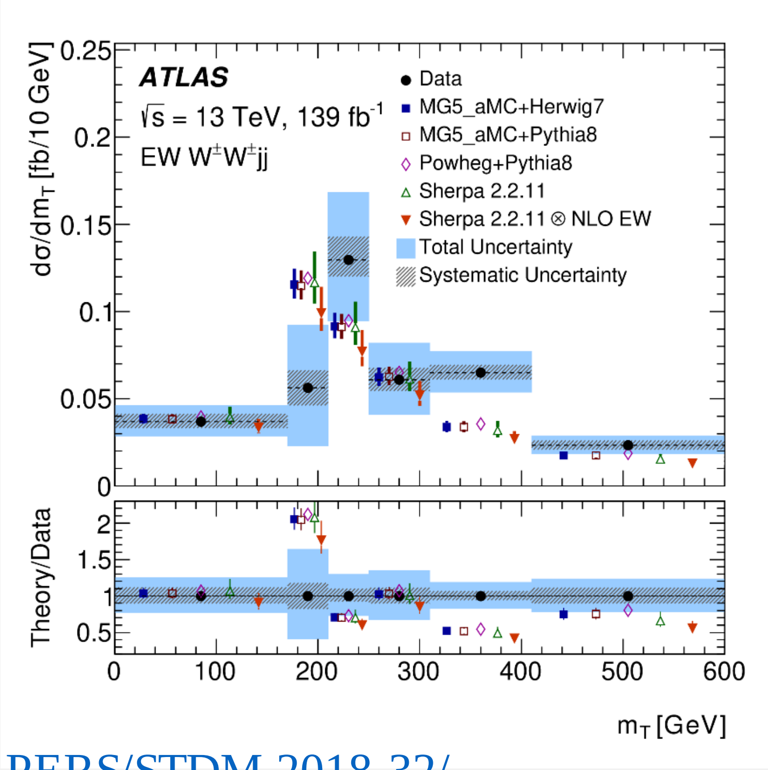
$$m_T = \sqrt{\left(E_T^{\ell\ell} + E_T^{\text{miss}}\right)^2 - \left|\vec{p}_T^{\,\ell\ell} + \vec{E}_T^{\text{miss}}\right|^2}$$

$$\xi_{j3} = \left|\frac{\eta_{j3} - \frac{1}{2}(\eta_{j1} + \eta_{j2})}{\eta_{j2} - \eta_{j1}}\right|$$

- Same fiducial space is used for extraction of differential cross section
- A maximum-likelihood fit is performed to do the cross section unfolding
- Five observables $m_{ll}, m_T, m_{jj}, N_{gapjets}$ and ξ_{j3} are studied







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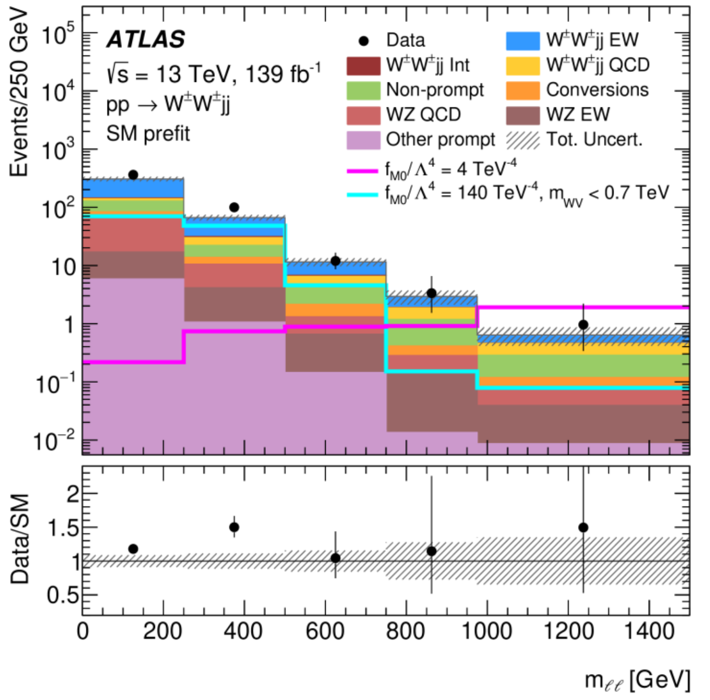
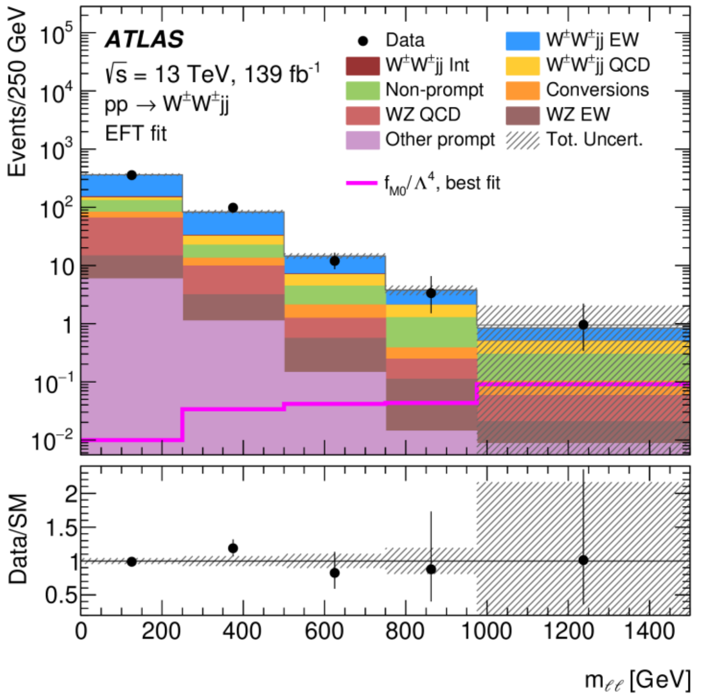
- Prediction underestimates data but is in good agreements within uncertainties
- Have observed overprediction and underprediction in distribution of m_T

Same-sign $W^{\pm}W^{\pm}jj$ EFT Interpretation

- Measurement could be used to search for new physics affect WWWW coupling
- Sensitivity is quantified by setting limits on D-8 EFT operators



Prefit distribution



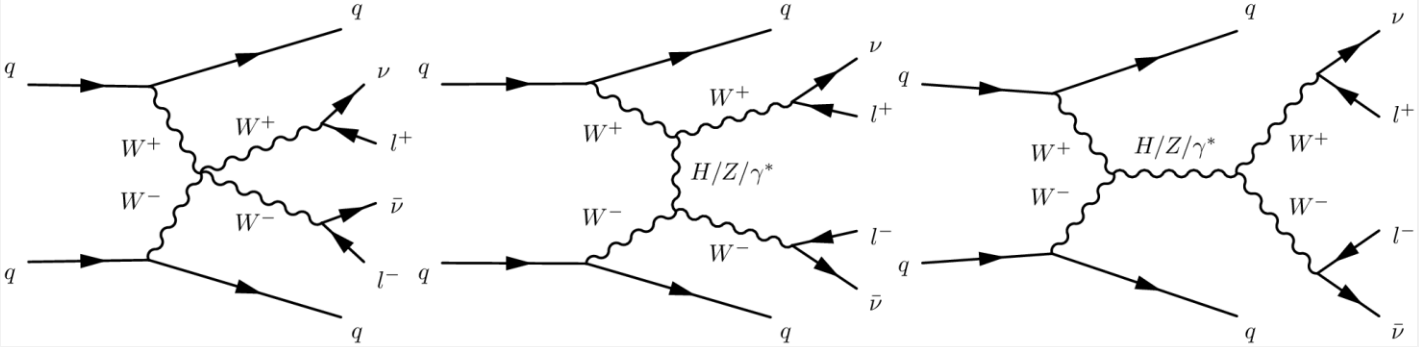
Postfit distribution

Coefficient	Type	No unitarisation cut-off [TeV^{-4}]	Lower, upper limit at the respective unitarity bound [TeV^{-4}]
f_{M0}/Λ^4	Exp.	[-3.9, 3.8]	-64 at 0.9 TeV, 40 at 1.0 TeV
	Obs.	[-4.1, 4.1]	-140 at 0.7 TeV, 117 at 0.8 TeV
f_{M1}/Λ^4	Exp.	[-6.3, 6.6]	-25.5 at 1.6 TeV, 31 at 1.5 TeV
	Obs.	[-6.8, 7.0]	-45 at 1.4 TeV, 54 at 1.3 TeV
f_{M7}/Λ^4	Exp.	[-9.3, 8.8]	-33 at 1.8 TeV, 29.1 at 1.8 TeV
	Obs.	[-9.8, 9.5]	-39 at 1.7 TeV, 42 at 1.7 TeV
f_{S02}/Λ^4	Exp.	[-5.5, 5.7]	-94 at 0.8 TeV, 122 at 0.7 TeV
	Obs.	[-5.9, 5.9]	–
f_{S1}/Λ^4	Exp.	[-22.0, 22.5]	–
	Obs.	[-23.5, 23.6]	–
f_{T0}/Λ^4	Exp.	[-0.34, 0.34]	-3.2 at 1.2 TeV, 4.9 at 1.1 TeV
	Obs.	[-0.36, 0.36]	-7.4 at 1.0 TeV, 12.4 at 0.9 TeV
f_{T1}/Λ^4	Exp.	[-0.158, 0.174]	-0.32 at 2.6 TeV, 0.44 at 2.4 TeV
	Obs.	[-0.174, 0.186]	-0.38 at 2.5 TeV, 0.49 at 2.4 TeV
f_{T2}/Λ^4	Exp.	[-0.56, 0.70]	-2.60 at 1.7 TeV, 10.3 at 1.2 TeV
	Obs.	[-0.63, 0.74]	–

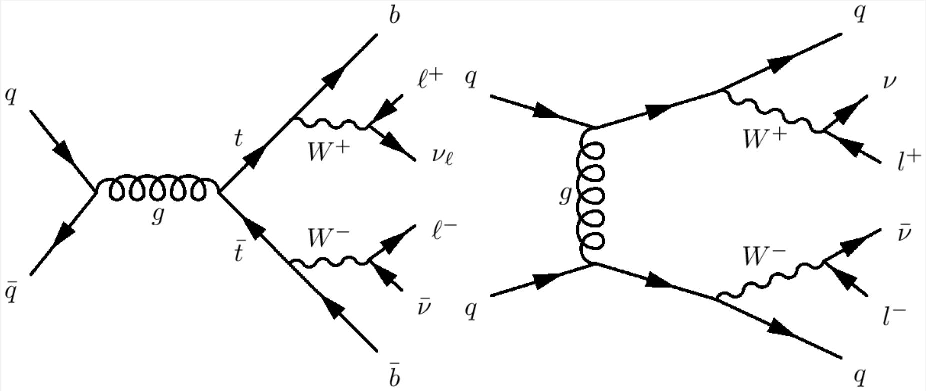
EFT limits with and without unitarisation cut-off

Opposite-sign W^+W^-jj

- First observation of EW W^+W^-jj in ATLAS
- Opposite-sign W^+W^-jj has small cross sections and large background contributions
- Two neural networks trained to separate signal from $t\bar{t}$ and Strong W^+W^-jj backgrounds
- Interesting events should contain two leptons, two or three jets and missing transverse energy



EW W^+W^-jj



$t\bar{t}$ and Strong W^+W^-jj

Opposite-sign W^+W^-jj Strategy

- One signal region, one control region to constrain top backgrounds
- Apply cuts before the neural network training
- Two NNs for two-jet and three-jet cases in SR, validation checks performed in low NN-score region (<0.6) on:
  - DATA/MC agreement and correlations between variables
- Uncertainty estimations:
  - Experimental uncertainties: jet energy scale, b-tagging efficiency, jet flavor composition and jet energy scale dependence on pile-up
  - Theoretical uncertainties on signal, top and QCD
  - Statistical uncertainties

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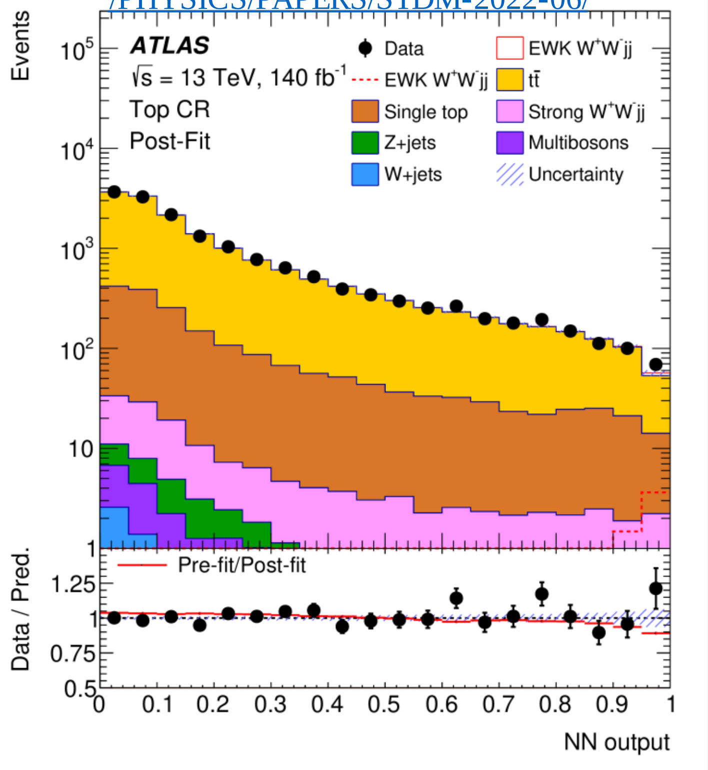
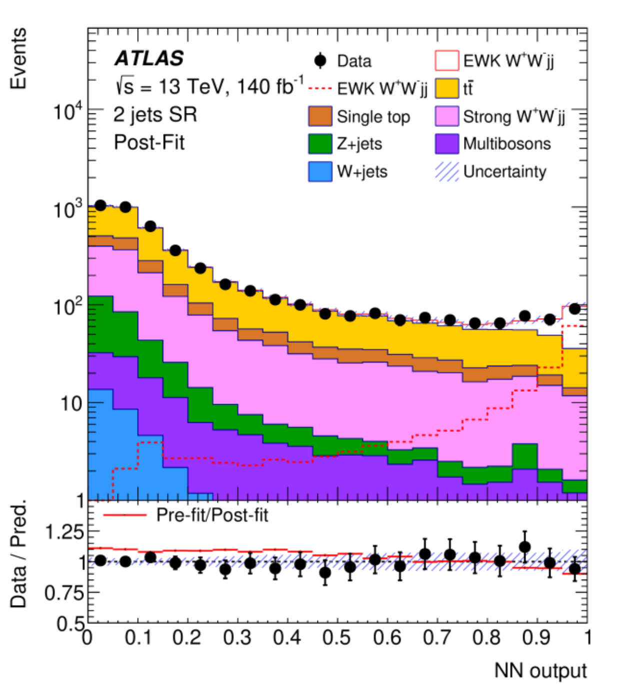
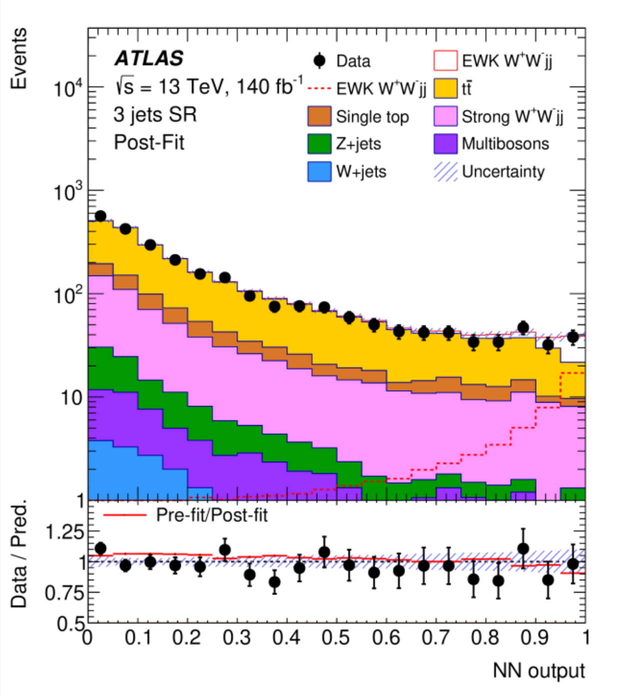
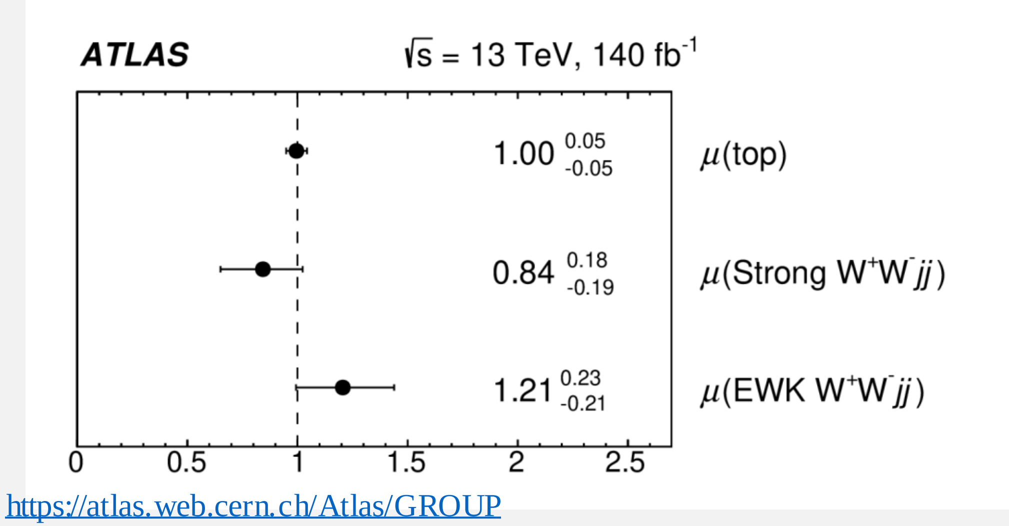


Opposite-sign W^+W^-jj Fiducial Cross Section

- A profile likelihood fit is performed on the NN output simultaneously in the SR and CR
- The fiducial region is defined with selections similar to reconstructed signal region with extra cut on $m_{jj} > 500\ GeV$







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- The NN modelling is in good agreement with data
- The observed (expected) significance is 7.1σ (6.2σ), for both 2 and 3 jets combined.

Differential $ZZjj$

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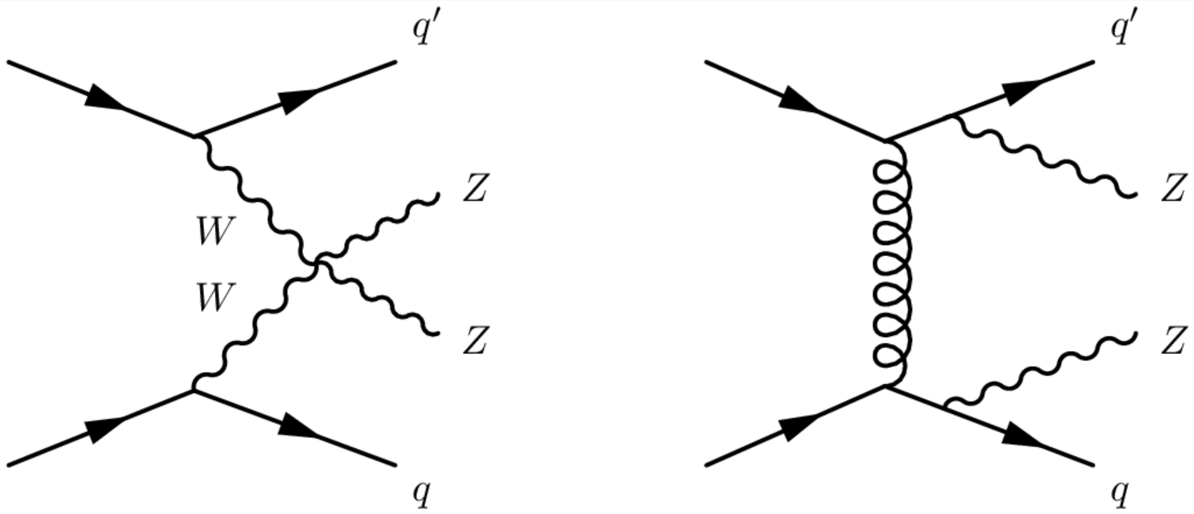
- EW $ZZjj$ sensitive to WWZ and WWZZ weak-boson self-interactions
- Theoretical prediction of QCD $ZZjj$ sensitive to the accuracy of perturbative QCD calculation (overall production rate and kinematic properties of the final states)



Pure-EW $ZZjj$ Strong $ZZjj$

- Goals:
  - Unfolded differential cross section measurement of interesting kinematic observables
  - Limits on triple and quartic gauge couplings

Differential $ZZjj$ Strategy

- Selections:
  - Same-flavor opposite-charge (SFOC) lepton pairs ordered by $|m_{ll} - m_Z|$
  - Four lepton system invariant mass $m_{4l} > 130\ GeV$
  - Leading (sub-leading) jets with transverse momentum $> 40\ (30)\ GeV$, dijet invariant mass and separation angle $m_{jj} > 300\ GeV$ & $|\Delta y_{jj}| > 2.0$

$$\zeta = \frac{(y_{4l} - 0.5(y_{j_1} + y_{j_2}))}{\Delta y_{jj}}$$

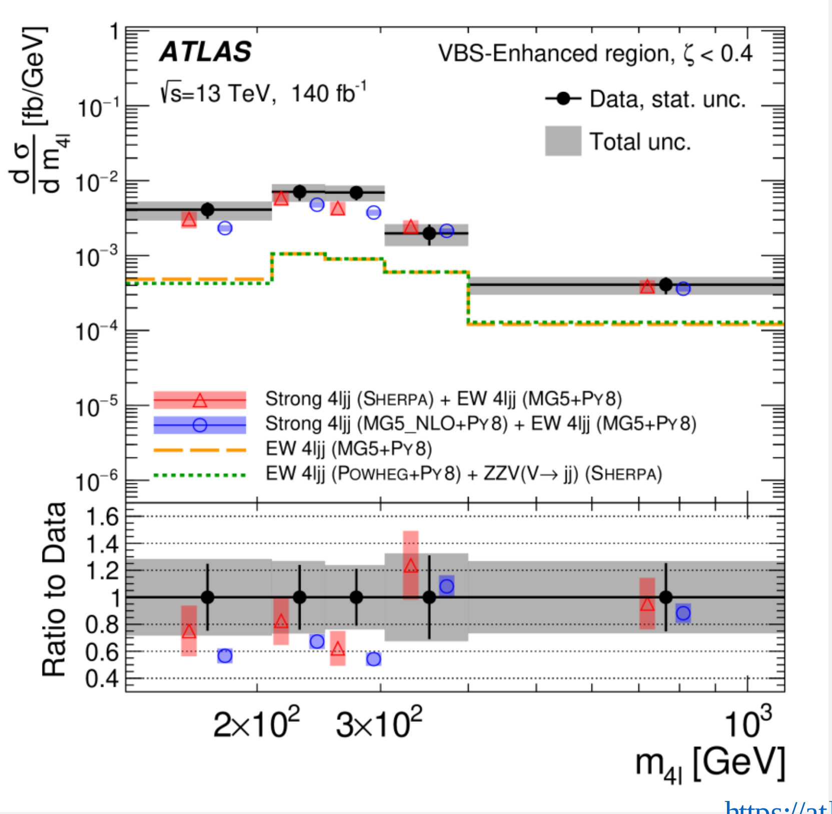
  - Events further categorized into VBS-enhanced ($\zeta < 0.4$) and VBS-suppressed ($\zeta > 0.4$) regions

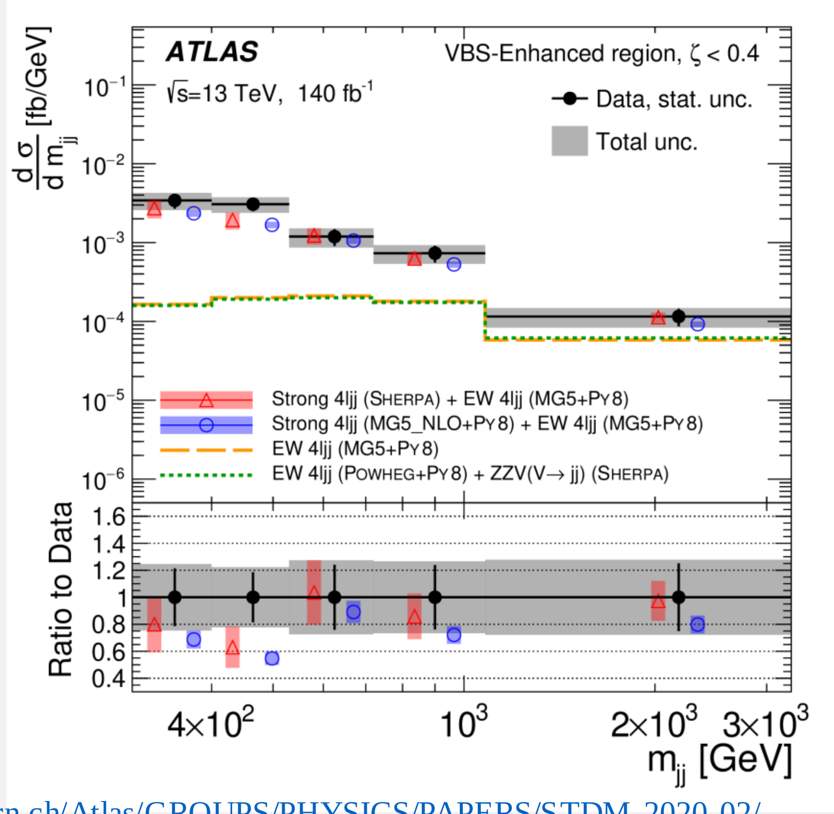
- Inclusive measurements on both EW and strong $ZZjj$ production

- Samples:
  - Nominal strong $ZZjj$: SHERPA
  - Alternative strong $ZZjj$: MG5_NLO+PY8
  - Nominal EW $ZZjj$: MG5+PY8
  - Alternative EW $ZZjj$: POWHEG+PY8

Differential $ZZjj$ Differential Cross Section

- Particle-level measurements in both VBS-enhanced and VBS-suppressed fiducial regions
- Unfolding done with iterative Bayesian method to correct the detector effect





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- Generally good agreement between Data and MC prediction
- MG5_NLO+PY8 underestimates the observed data especially in low m_{4l} and m_{jj}

Differential $ZZjj$ EFT Interpretation

- Unfolded distribution for the search of physics beyond the SM
- m_{4l} and m_{jj} are used to set limits on dim-8 and dim-6 EFT operators

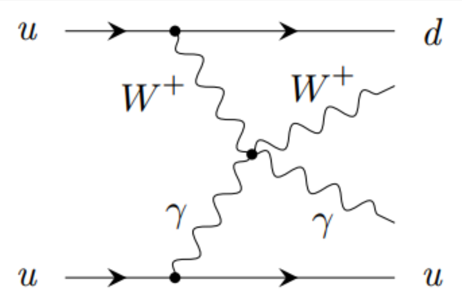
Wilson coefficient	$\|\mathcal{M}_{d8}\|^2$ Included	95% confidence interval [TeV^{-4}] Expected	Observed
$f_{T,0}/\Lambda^4$	yes	[-0.98, 0.93]	[-1.00, 0.97]
	no	[-23, 17]	[-19, 19]
$f_{T,1}/\Lambda^4$	yes	[-1.2, 1.2]	[-1.3, 1.3]
	no	[-160, 120]	[-140, 140]
$f_{T,2}/\Lambda^4$	yes	[-2.5, 2.4]	[-2.6, 2.5]
	no	[-74, 56]	[-63, 62]
$f_{T,5}/\Lambda^4$	yes	[-2.5, 2.4]	[-2.6, 2.5]
	no	[-79, 60]	[-68, 67]
$f_{T,6}/\Lambda^4$	yes	[-3.9, 3.9]	[-4.1, 4.1]
	no	[-64, 48]	[-55, 54]
$f_{T,7}/\Lambda^4$	yes	[-8.5, 8.1]	[-8.8, 8.4]
	no	[-260, 200]	[-220, 220]
$f_{T,8}/\Lambda^4$	yes	[-2.1, 2.1]	[-2.2, 2.2]
	no	[-4.6, 3.1]$\times10^4$	[-3.9, 3.8]$\times10^4$
$f_{T,9}/\Lambda^4$	yes	[-4.5, 4.5]	[-4.7, 4.7]
	no	[-7.5, 5.5]$\times10^4$	[-6.4, 6.3]$\times10^4$

- Generally Wilson coefficients are consistent with zero when pure D8 contribution is included
- Wilson coefficients associated with T,0 and T,1 operators are most tightly constrained

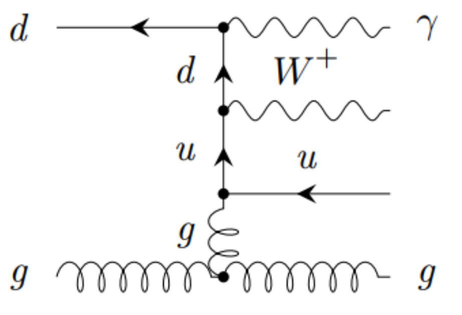
VBS $W\gamma$ jj

- **Analysis targets:**
  - Observation of EWK Wy+jj production
  - Differential cross-section measurements of EWK Wy+jj production
  - Unfold $m_{jj}, p_T^{jj}, \Delta\phi_{jj}, p_T^{lep}, \Delta\phi_{l\gamma}, m_{l\gamma}$
  - EFT Interpretation targeting dimension-8 operators

Signal:

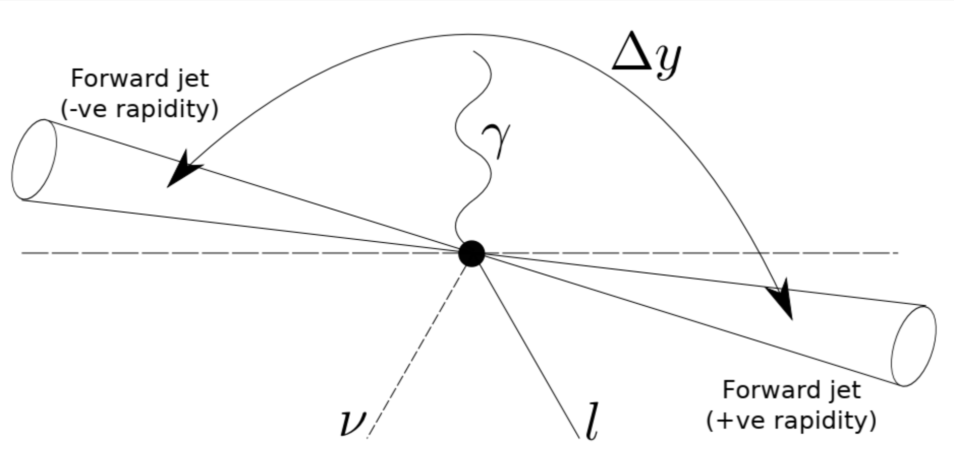


QCD Background:



Typical diagrams

Measurements performed in VBS-enhanced phase-space



No hadronic activity in central region between two jets, γ and W boson produced in central regions.
Apply high-dijet mass, large forward jet rapidity gap…

VBS $W\gamma$ jj Strategy

- Selections:
  - Single lepton and missing momentum with $p_T^l > 30\ GeV$ & $E_T^{miss} > 30\ GeV$
  - One photon with $p_T^\gamma > 22\ GeV$ and two jets with $p_T^j > 50\ GeV$
  - VBS signature with large $m_{jj} > 500\ GeV$ and $|\Delta y_{jj}| > 2$
- Data-driven background estimations:
  - Jet faking photons with template fit method
  - Jet faking electron/muons with fake factor method
  - Electron faking photons with tag and probe method
- Observation:
  - NN trained using events after $m_{jj} > 500\ GeV$ & $N_{gapjets} = 0$
  - Profile likelihood fit to the NN score
- Differential measurement:
  - Extract signal + constrain QCD simultaneously
  - Use bootstrapping to evaluate statistical significance of systematic uncertainties
- EFT interpretation:
  - Iterative Bayesian unfolding to correct detector effects
  - Unfolded distribution for setting limits on dim-8 operators

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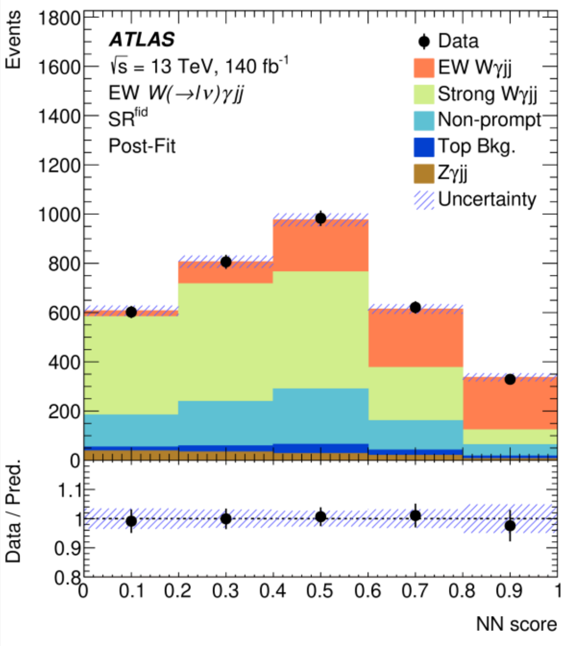

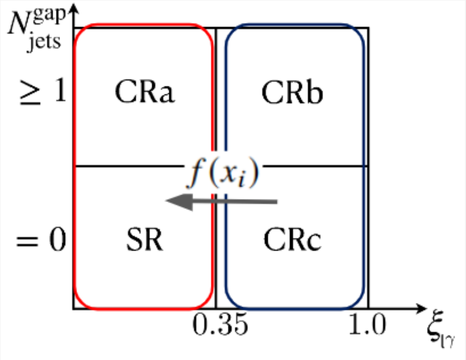

VBS $W\gamma$ jj Measurements

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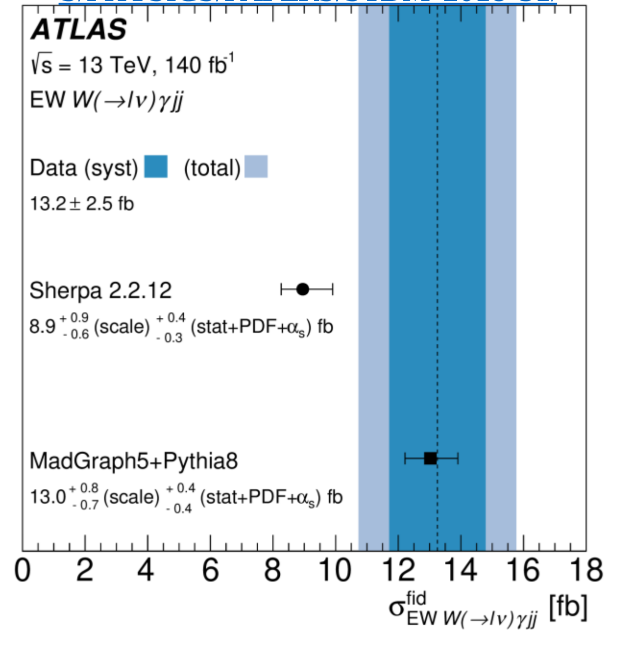
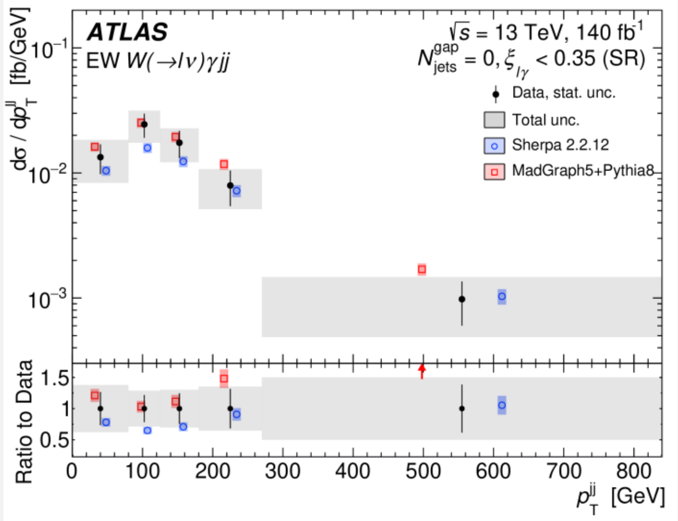
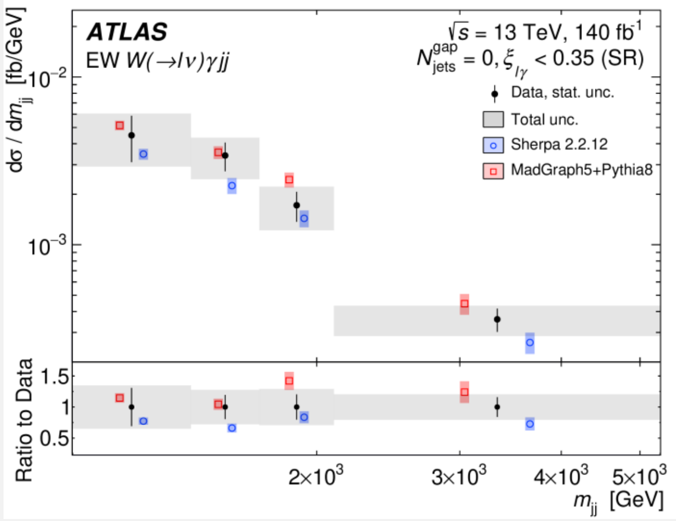


- Fiducial measurements:
  - The observed significance is well above 6 standard deviation compared to the expected significance of 6.3σ
  - MadGraph5+PYthia8 is in good agreements with data while Sherpa underestimates data within 2 standard deviations
- Differential measurements:
  - Cross sections as a function of $m_{jj}, p_T^{jj}, \Delta\phi_{jj}, p_T^{lep}, \Delta\phi_{l\gamma}, m_{l\gamma}$ are studied
  - Both Sherpa and Madgraph are in good agreement with data within uncertainties
  - MG overshoot at high m_{jj} & p_T^{jj}
  - Sherpa underestimates all six observables
- Analysis is sensitive to 16 dim-8 EFT operators. Aim to set limits on couplings in Warsaw basis.
- Using EFT samples with full detector simulation





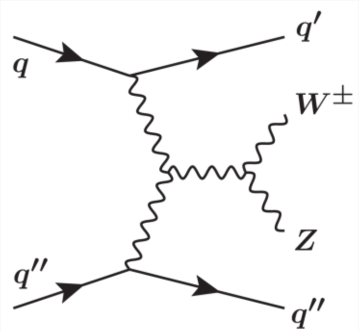
VBS WZ jj

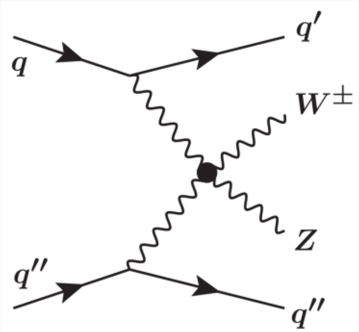
- First observation using 2015-2016 data

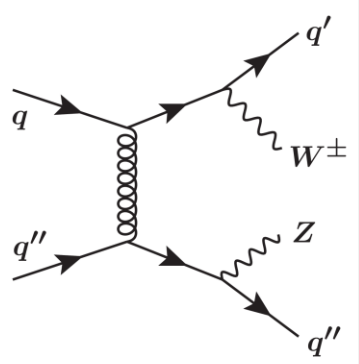
- EWK $WZjj$ production:
  - Better precision on fiducial cross section measurement
  - Perform the first EW $WZjj$ differential cross section measurement
  - Simultaneously measure $\sigma_{WZjj-EW}$ and $\sigma_{WZjj-strong}$ in the SR

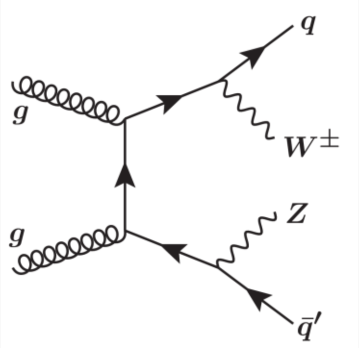
- Inclusive $WZjj$ production:
  - Better precision on differential cross section measurements
  - Unfold BDT score distribution

- Interpretation of results on EFT frame:
  - Detector level limits using 2D template of $M_T^{WZ} - BDT$ score









VBS WZ jj Strategy

Same BDT score distribution is used in all SRs

- $WZjj - EW$ and $WZjj - Strong$ integrated measurements:
  - Separate the signal region into two categories of different N_{jets}
  - Maximum likelihood fit performed on BDT score distribution

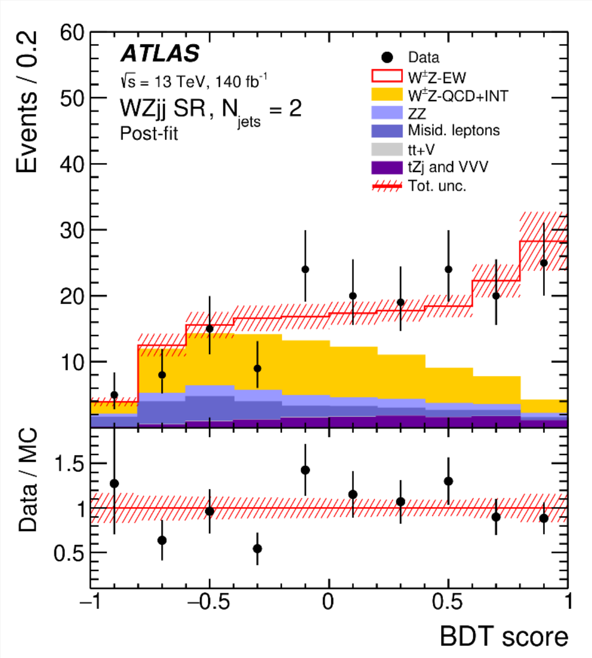
- $WZjj - EW$ and $WZjj - Strong$ differential measurements:
  - SR separated into bins of N_{jets} and m_{jj}
  - Simultaneous fit to the data of the BDT score distribution of events in each bin is performed

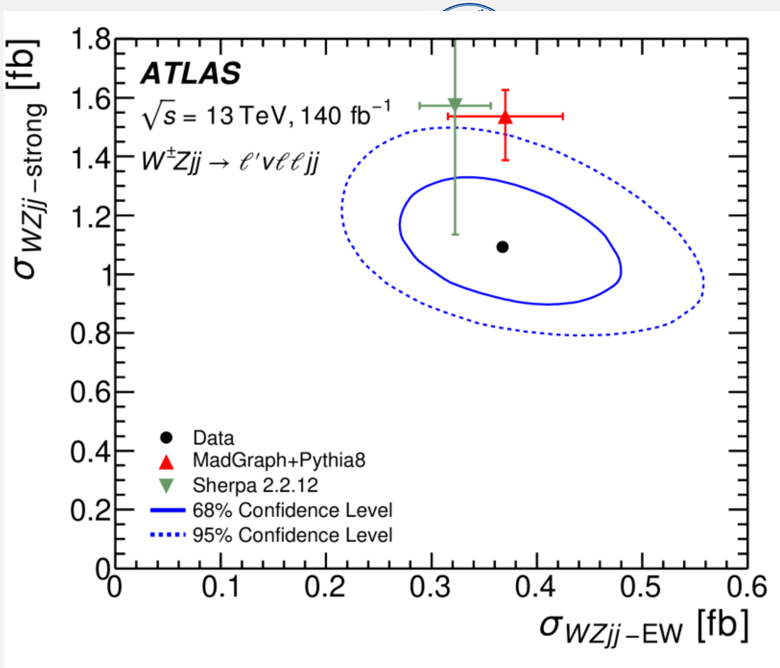
- Differential $WZjj$ measurements:
  - Iterative Bayesian method with 3 iterations used to correct detector effects
  - MC scaled to data to better model the data and minimize unfolding uncertainty
  - Variables: $M_T^{WZ}, \Delta\phi(W,Z), N_{jets}, m_{jj}, \Delta y_{jj}, \Delta\phi_{jj}, N_{jets(gap)}, Z_{j3}, BDT\ score$

VBS WZ jj Results

- $WZjj - EW$ and $WZjj - Strong$ integrated measurements:

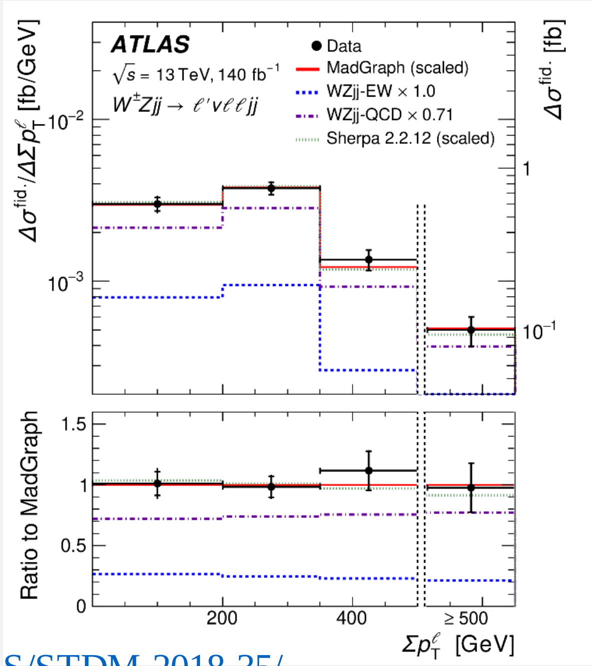
$$\begin{aligned}\sigma_{WZjj\text{-EW}} &= 0.368 \pm 0.037\,(\text{stat.}) \pm 0.059\,(\text{syst.}) \pm 0.003\,(\text{lumi.})\ \text{fb} \\ &= 0.37 \pm 0.07\ \text{fb}, \\ \sigma_{WZjj\text{-strong}} &= 1.093 \pm 0.066\,(\text{stat.}) \pm 0.131\,(\text{syst.}) \pm 0.009\,(\text{lumi.})\ \text{fb} \\ &= 1.09 \pm 0.14\ \text{fb},\end{aligned}$$

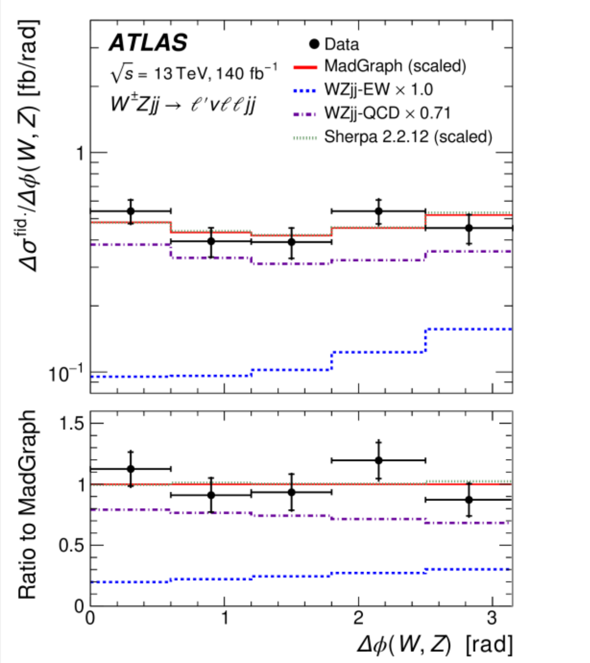




- Good agreement found between MC predictions of different generators and the measured cross sections

- Differential $WZjj$ measurements:





https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/PAPERS/STDM-2018-35/

VBS WZ jj Results EFT

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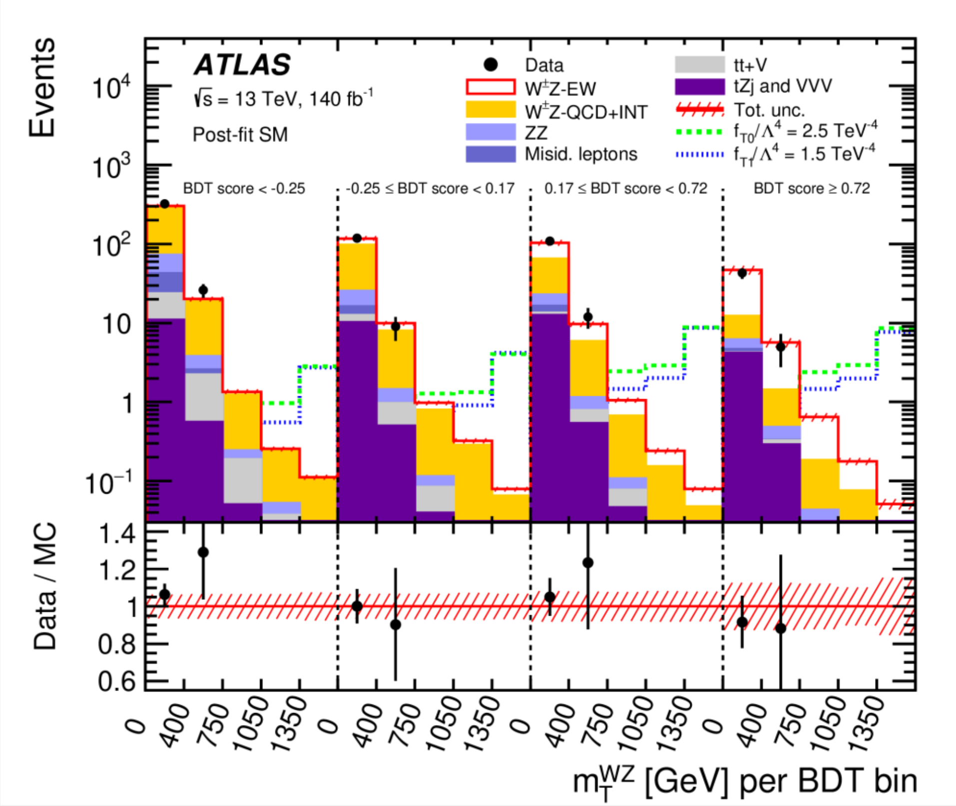
- No deviation with respect to the SM predictions is observed
- Two dimensional distribution $M_T^{WZ} - BDT$ used for extraction of limits



	Expected [TeV $^{-4}$]	Observed [TeV $^{-4}$]
f_{T0}/Λ^4	[-0.80, 0.80]	[-0.57, 0.56]
f_{T1}/Λ^4	[-0.52, 0.49]	[-0.39, 0.35]
f_{T2}/Λ^4	[-1.6, 1.4]	[-1.2, 1.0]
f_{M0}/Λ^4	[-8.3, 8.3]	[-5.8, 5.6]
f_{M1}/Λ^4	[-12.3, 12.2]	[-8.6, 8.5]
f_{M7}/Λ^4	[-16.2, 16.2]	[-11.3, 11.3]
f_{S02}/Λ^4	[-14.2, 14.2]	[-10.4, 10.4]
f_{S1}/Λ^4	[-42, 41]	[-30, 30]

Expected and observed lower and upper 95% CL limits on the Wilson coefficients

Binning optimization:
BDT: [-1.0, -0.25, 0.17, 0.72, 1.0]
M_T^{WZ}: [0, 400, 750, 1050, 1350, ∞]

Coefficients associated to T0 and T1 are the most tightly constraint

Summary

- Several measurements are reported about EW or inclusive production of different final states
- Generally the observed data has good agreements with predictions
- Limits on EFT operators are set in most cases
- Results are bringing challenge to electroweak cross section calculations and kinematic modellings

谢 谢 ！