Massive Diboson Measurements from ATLAS and CMS

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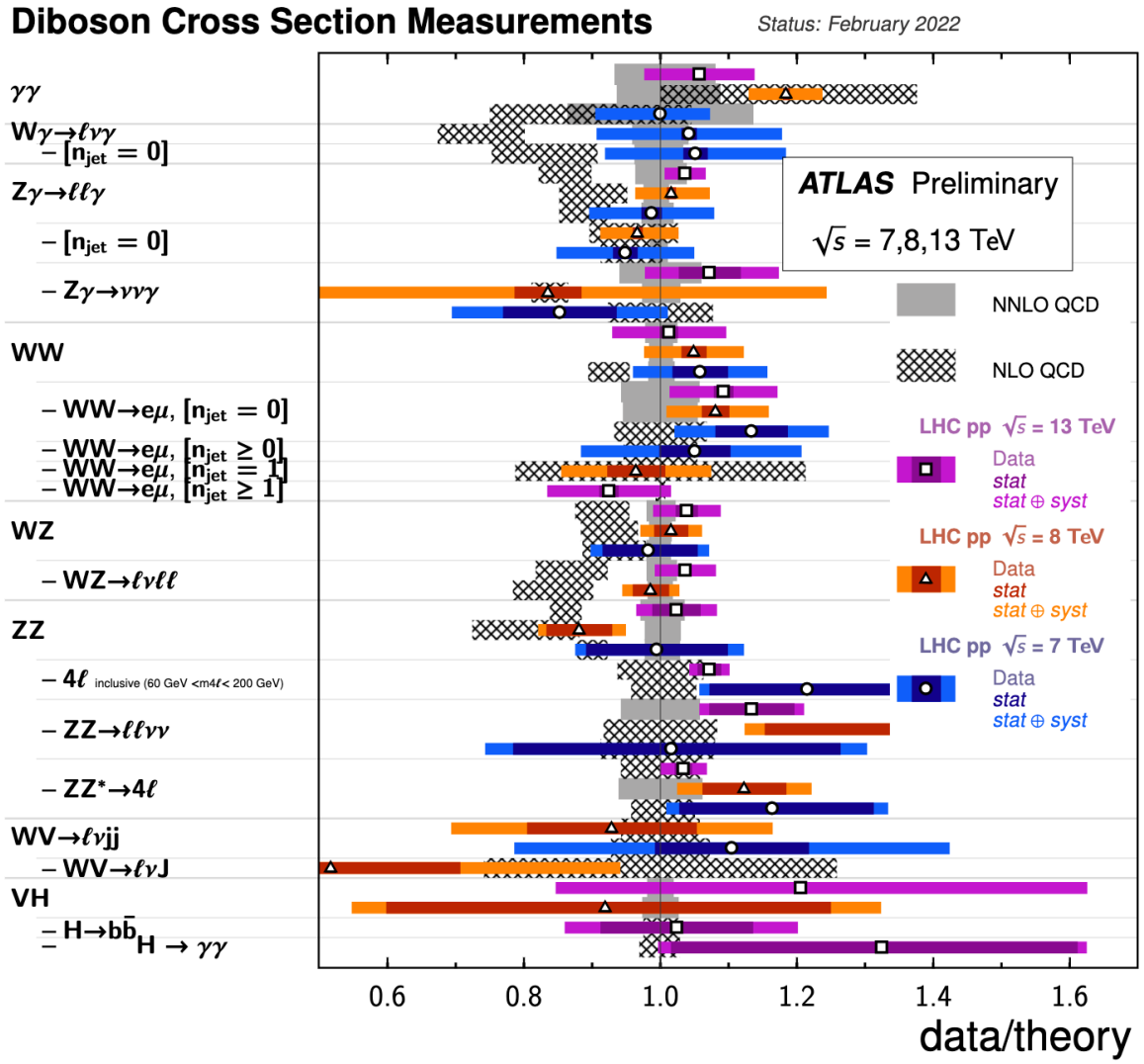
Contents

- Latest massive di-boson measurements from ATLAS and CMS include inclusive and differential cross-sections, EFT interpretations, polarization measurements and CP studies.
- Latest ATLAS di-boson measurements (total six analyses):
  - The channels include $ZZjj$, (Same sign) $W^{\pm}W^{\pm}jj$, (Opposite Sign) $W^{+}W^{-}$ and with associated jets, (Opposite Sign) $W^{+}W^{-}jj$, $W^{\pm}Z$.
- Latest CMS diboson measurements (total five analyses):
  - $W^{\pm}Z, WVjj$ Semi-leptonic, $ZZ + jets$, (Opposite Sign) $W^{+}W^{-}jj$, $\gamma\gamma \rightarrow WW$ and $\gamma\gamma \rightarrow ZZ$.

Previous Diboson Searches in Run 2: ATLAS



Ref: http://cds.cern.ch/record/2804061/files/ATL-PHYS-PUB-2022-009.pdf

1 $4\ell + jj$ Measurement Introduction

arXiv:2308.12324

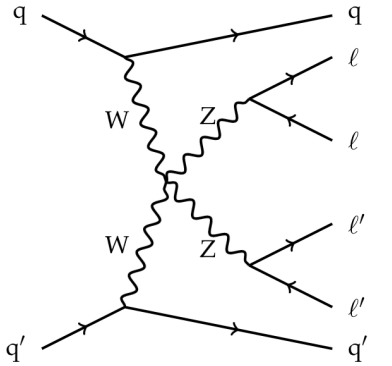
- $ZZjj$ observation with 139 fb^{-1}: 5.7 sigma (5.9 sigma) observed (expected) in Feb 2023. *Nature Physics* **19**, 237–253 (2023)
- The latest analysis with an integrated luminosity of 140 fb^{-1} contains:
  - Differential cross-section measurements for the production of four charged leptons in association with two jets
  - limits on the anomalous weak boson self interactions..

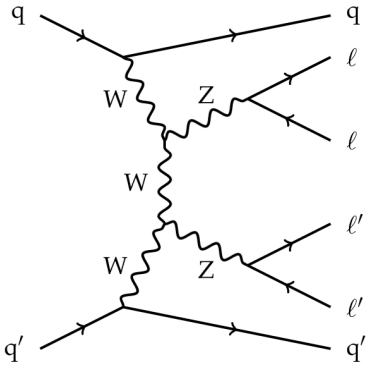
Event Selection:

- $m_{4\ell} > 130$ GeV
- At least two jets: Dijet system is defined as two leading jets in the event with $\eta_{j_1} \times \eta_{j_2} < 0$, $\Delta y_{jj} > 2.0$ and $m_{jj} > 300$ GeV.
- VBS-enhanced and VBS-suppressed regions:
  - $\zeta < 0.4$ (VBS enhanced) and $\zeta > 0.4$ (VBS suppressed)

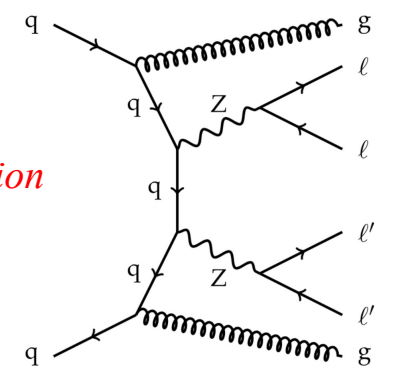
$$\zeta = \frac{(y_{4\ell} - 0.5(y_{j_1} + y_{j_2}))}{\Delta y_{jj}}$$

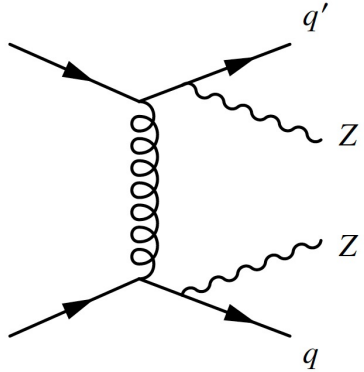
EW Production





Strong Production





Backgrounds:

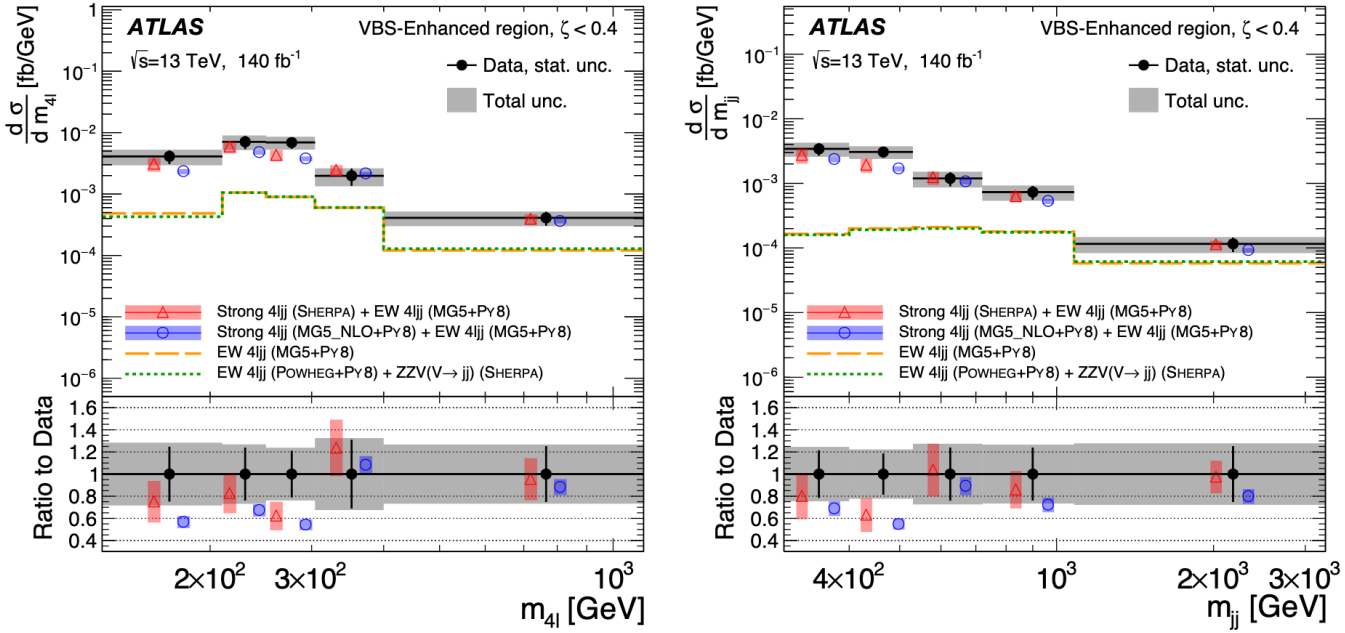
- **Prompt Background (15% of signal yield):** Processes with leptons that do not originate from the decay of a Z boson ($t\bar{t}Z, WWZ, WZZ$)
- **Non-prompt Background (2.4% of signal yield):** One or more non-prompt leptons ($WZjj, t\bar{t}$). Estimated using data-driven method.

$4\ell + jj$ Differential Cross-section

arXiv:2308.12324

- Differential cross-section measurement as a function of observables:
  - Sensitive to the VBS process
  - those sensitive to the Z boson polarization and
  - those sensitive to the QCD interactions (higher order real emission of quarks and gluons).
- The distributions Unfolded using the iterative Baysian unfolding procedure.
- Unfolding is performed in both VBS-enhanced and VBS-suppressed regions.

Source	Uncertainty (%)
Luminosity	0.8 – 1.3
Leptons	0.8 – 1.6
Jets	2.7 – 18
Pile-up	0.0 – 2.5
Backgrounds	0.9 – 9.0
Theory modelling	0.6 – 8.8
Unfolding method	0.9 – 12
Total systematic	5 – 22



The differential cross sections for inclusive $4\ell jj$ production in the VBS-enhanced region as a function of $m_{4\ell}$ and m_{jj}.

Results:

- EW contribution: 20% in VBS enhanced (50% in high m_{jj} and 5% in low m_{jj} region.)
- No significant difference observed between two different generators for EW $ZZjj$ distributions.

$4\ell + jj$ EFT Interpretations

arXiv:2308.12324

- SM extended with new interactions included in the dim-8 operators of EFT formalism.

$$\mathcal{L} = \mathcal{L}_{SM} + \sum_i \frac{f_{T,i}}{\Lambda^4} O_{T,i}$$

- Squared scattering amplitude for EFT prediction:

$$|\mathcal{M}|^2 = |\mathcal{M}_{SM}|^2 + 2\,\mathrm{Re}(\mathcal{M}_{SM}{}^* \mathcal{M}_{d8}) + |\mathcal{M}_{d8}|^2$$

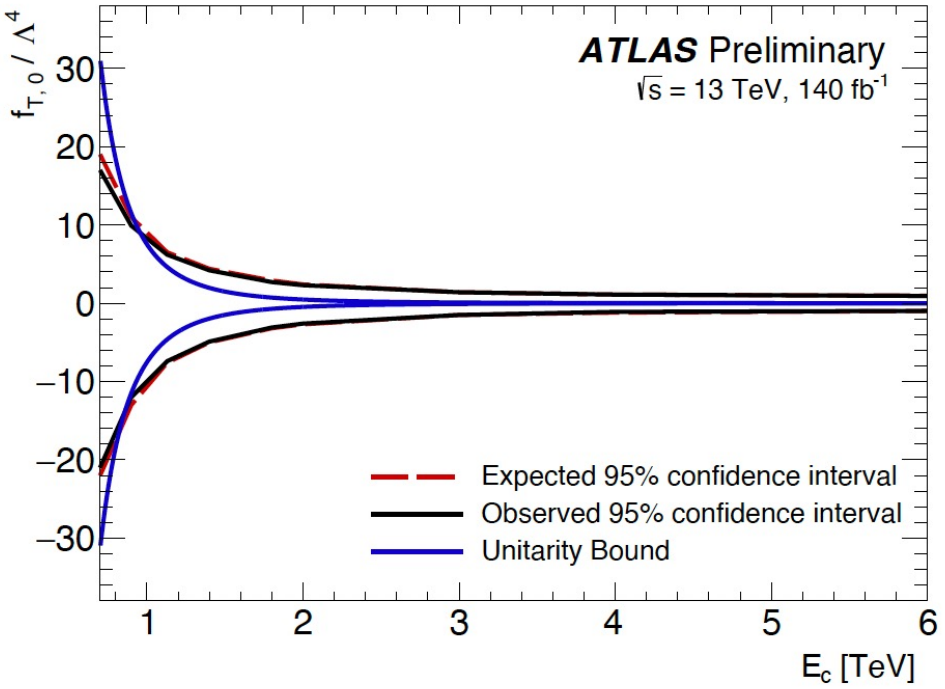
- aQGC self interactions appear in lowest order as Dim-8 operators.
- Assumption is that contribution from dim-6 operators is 0 i.e. already constrained from diboson and VBF production (for completeness limits on dim-6 operators are also set.)
- The 95% confidence intervals and upper limits on the dimension-eight Wilson coefficients are calculated using a two-dimensional fit to the $4\ell jj$ differential cross-section as a function of $m_{4\ell}$ and m_{jj}.

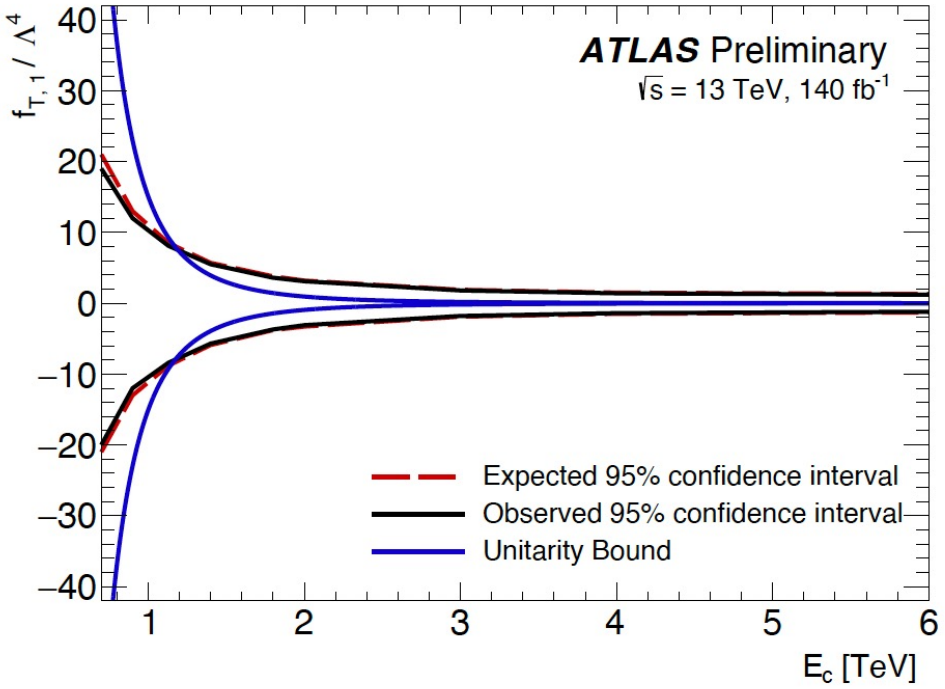
Wilson coefficient	$\lvert\mathcal{M}_{d8}\rvert^2$ Included	95% confidence interval [TeV^{-4}] Expected	Observed
$f_{T,0}/\Lambda^4$	yes	[-0.98, 0.93]	[-1.00, 0.97]
	no	[-23, 17]	[-19, 19]
$f_{T,1}/\Lambda^4$	yes	[-1.2, 1.2]	[-1.3, 1.3]
	no	[-160, 120]	[-140, 140]
$f_{T,2}/\Lambda^4$	yes	[-2.5, 2.4]	[-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	$[-7.5, 5.5]\times10^4$	$[-6.4, 6.3]\times10^4$

$4\ell + jj$ EFT Interpretations

arXiv:2308.12324

- The inter- and pure dim-eight- contributions have $m_{4\ell} < E_c$.

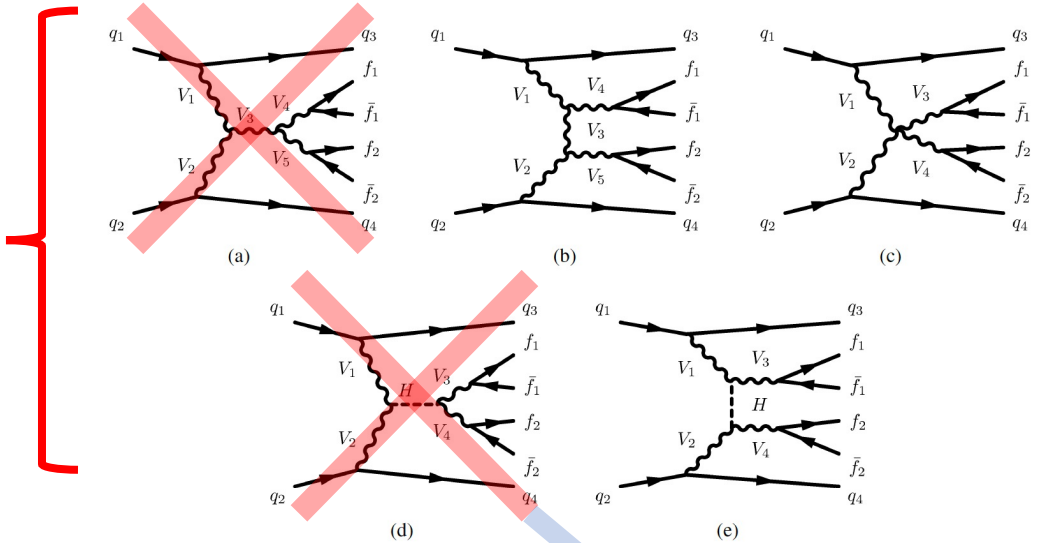




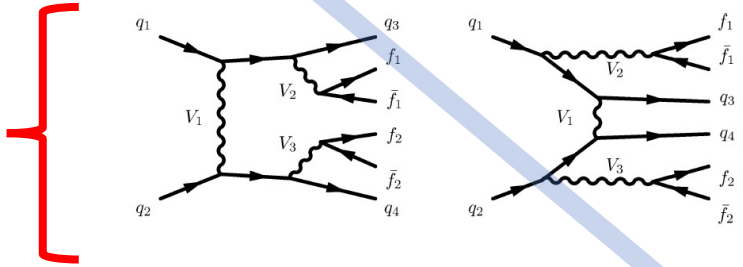
Exp and Obs 95% confidence interval for the Wilson coefficients as a function of a cut-off scale, E_c.

2 (Same sign) $W^{\pm}W^{\pm}jj$ Cross-section Measurement

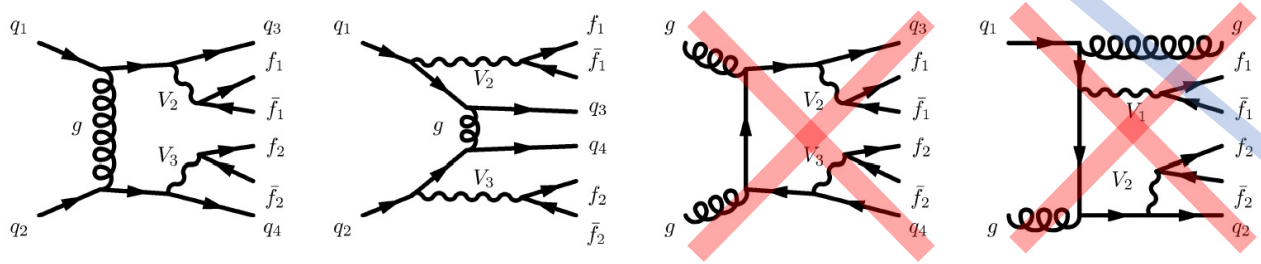
Electroweak VBS VVjj



Electroweak non-VBS VVjj



Strong VVjj



Forbidden in the SM and/or for $W^{\pm}W^{\pm}jj$

- Largest ratio of Electroweak to Strong productions cross-section compared to other VBS diboson processes (~5 for the fiducial region of this analysis).
- Observed before with 36.1 fb^{-1}: obs significance of 6.5σ (PRL 123 (2019) 161801).

- Measurements performed using integrated luminosity of 139 fb^{-1}:
  - EW and Inclusive (EW+Int+QCD) accuracy Inclusive and Differential Cross-sections in the fiducial phase space.
  - Limits on anomalous quartic gauge couplings
  - Limits on doubly charged Higgs production

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(Same sign) $W^{\pm}W^{\pm}jj$ Cross-section Measurement

Event Selection:

- Expected purity of the EW, QCD and interference is 52%, 5.4% and 1.7%.
- Exactly two signal leptons
  - $m_{\ell\ell'} \geq 20$ GeV
  - 3rd lepton veto
- $E_T^{miss} \geq 30$ GeV
- At least two jets, b-jet veto applied
  - $m_{jj} \geq 500$ GeV: suppresses triboson production with resonant decay to two jets
  - $|\Delta y_{jj}| > 2$

Backgrounds:

- WZ/γ^* (22% of the signal event yield): One lepton escaping the third lepton veto requirement.
- Non-Prompt Lepton Background (12% of the signal event yield): $W + jets$, semi-leptonic $t\bar{t}$. Estimated using data-driven method
- Electron charge misidentification background: From Z and dileptonic $t\bar{t}$.
- Other backgrounds: $V\gamma$(2.4%), ZZ, $t\bar{t}V$, VVV (total 1.6%)

Uncertainties with Significant Impact:

- Experimental: 6.7% (Misidentified Lepton Bkg: 3.1%)
- Modelling: 7.4% (EW $W^{\pm}W^{\pm}jj$, QCD corrections: 3.5%, QCD $W^{\pm}W^{\pm}jj$ theory uncertainties: 2.3%)
- Statistical: 7.4%
- Total: 10%

(Same sign) $W^{\pm}W^{\pm}jj$ Cross-section Measurement

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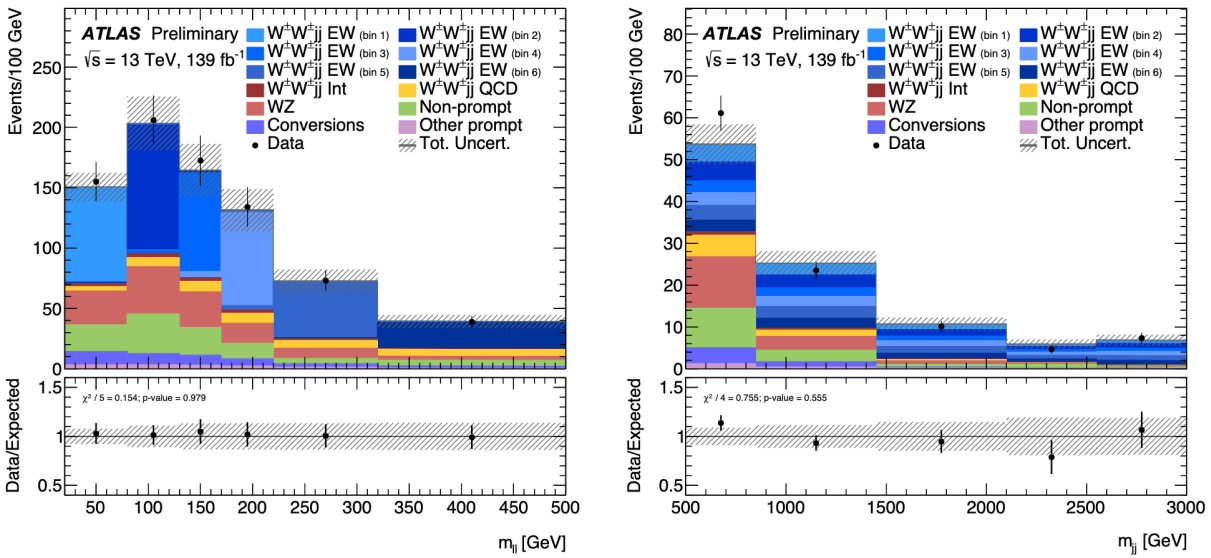
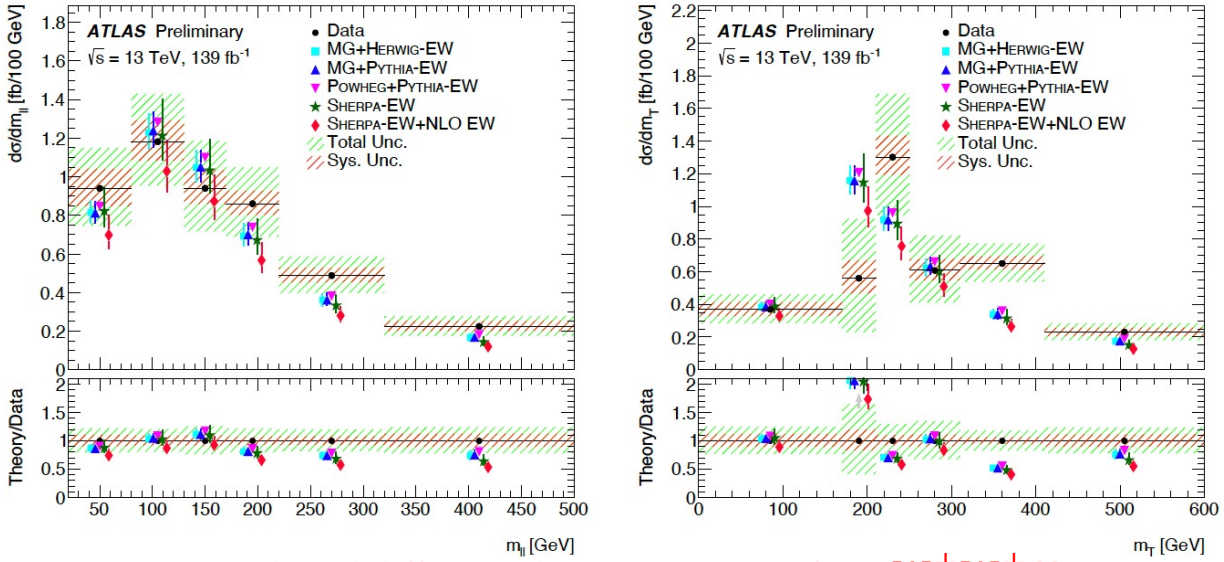
- Fiducial Cross-section measurement: Fiducial region defined as close to analysis signal region and detector acceptance as possible.
  - Signal region split in 4 regions according to the lepton flavors in the final state

Description	$\sigma_{\text{fid}}^{\text{EW}}$, fb	$\sigma_{\text{fid}}^{\text{EW+Int+QCD}}$, fb
Measured cross section	$2.88 \pm 0.21\,(\text{stat.}) \pm 0.19\,(\text{syst.})$	$3.35 \pm 0.22\,(\text{stat.}) \pm 0.20\,(\text{syst.})$
MG_aMC@NLO+Herwig	$2.53 \pm 0.04\,(\text{PDF}) \pm^{0.22}_{0.19}\,(\text{scale})$	$2.93 \pm 0.05\,(\text{PDF}) \pm^{0.34}_{0.27}\,(\text{scale})$
MG_aMC@NLO+Pythia	$2.55 \pm 0.04\,(\text{PDF}) \pm^{0.22}_{0.19}\,(\text{scale})$	$2.94 \pm 0.05\,(\text{PDF}) \pm^{0.33}_{0.27}\,(\text{scale})$
Sherpa	$2.44 \pm 0.03\,(\text{PDF}) \pm^{0.40}_{0.27}\,(\text{scale})$	$2.80 \pm 0.03\,(\text{PDF}) \pm^{0.53}_{0.36}\,(\text{scale})$
Powheg Box +Pythia	2.67	–

- Likelihood based unfolding.
- P-values range from 0.014 to 0.623 across five variables used showing good Data-MC agreement.



Post-fit distributions of $m_{\ell\ell}$ and m_{jj} for fiducial cross-section measurement



Fiducial differential cross sections of EW $W^{\pm}W^{\pm}jj$ production as a function of $m_{\ell\ell}$ and m_T.

(Same sign) $W^{\pm}W^{\pm}jj$ EFT Interpretations

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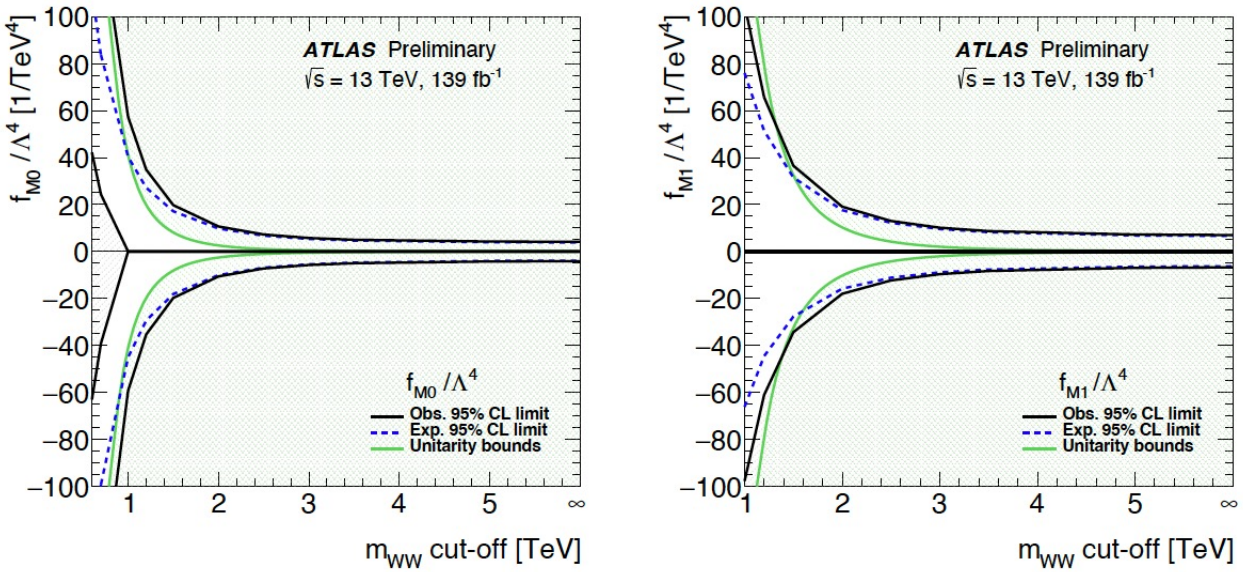
- Maximum likelihood fits are performed by keeping other coefficients to zero and maximizing the likelihood with respect to the nuisance parameters.
- The 95% CLs are calculated on the Wilson Coefficients for dimension-8 operators with and without unitary bounds.



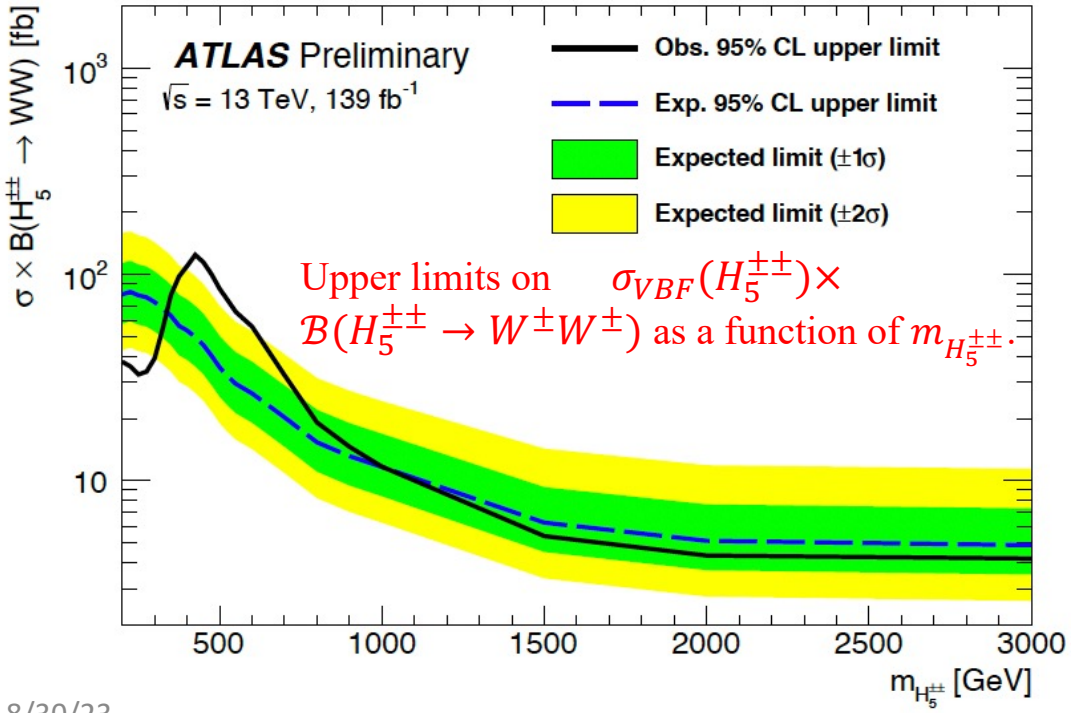
Limits at 95% CL as a function of the cut-off scale

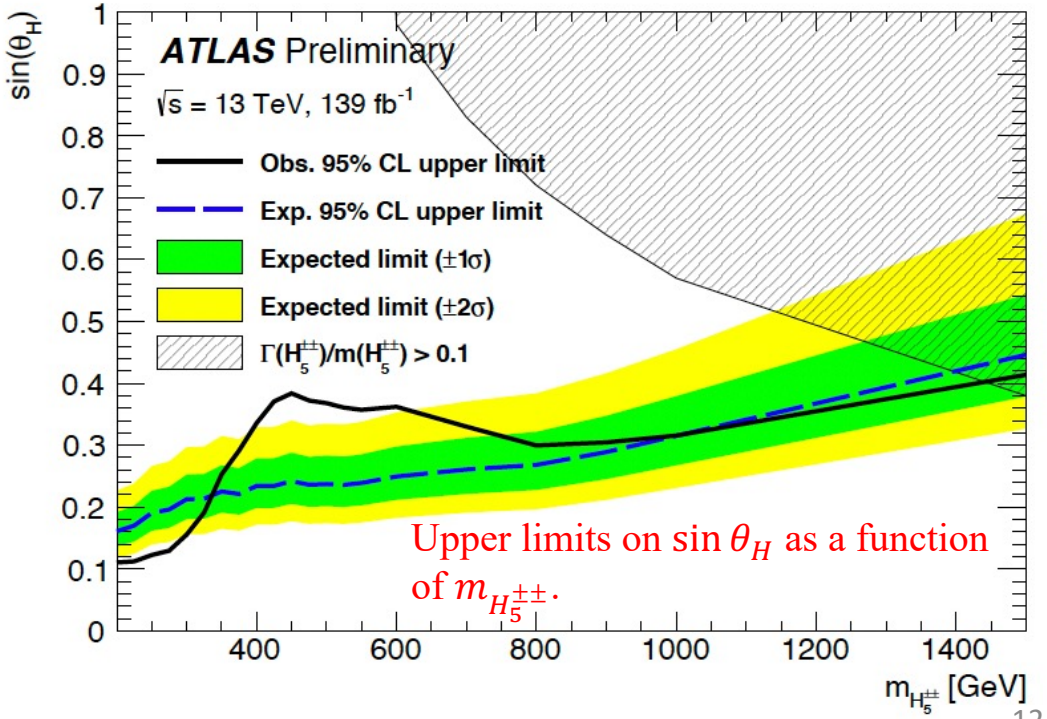
Coefficient	Type	No unitarisation cut-off [TeV^{-4}]	Lower and upper limit at the respective unitarity bound [TeV^{-4}]
f_{M0}/Λ^4	exp.	[-3.9, 3.8]	-64 at 0.9 TeV, 40 at 1.0 TeV
	obs.	[-4.1, 4.1]	-140 at 0.7 TeV, 117 at 0.8 TeV
f_{M1}/Λ^4	exp.	[-6.3, 6.6]	-25.5 at 1.6 TeV, 31 at 1.5 TeV
	obs.	[-6.8, 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]	–

- Limits at 95% confidence level (CL) are extracted, including their effects both on EW $W^{\pm}W^{\pm}jj$ and EW $W^{\pm}Zjj$ (ATL-PHYS-PUB-2023-002).
- Including the effect of the EFT operators on the EW $W^{\pm}Zjj$ production, the limits improve by ~1-4%.

(Same sign) $W^{\pm}W^{\pm}jj$ Search for Doubly Charged Higgs

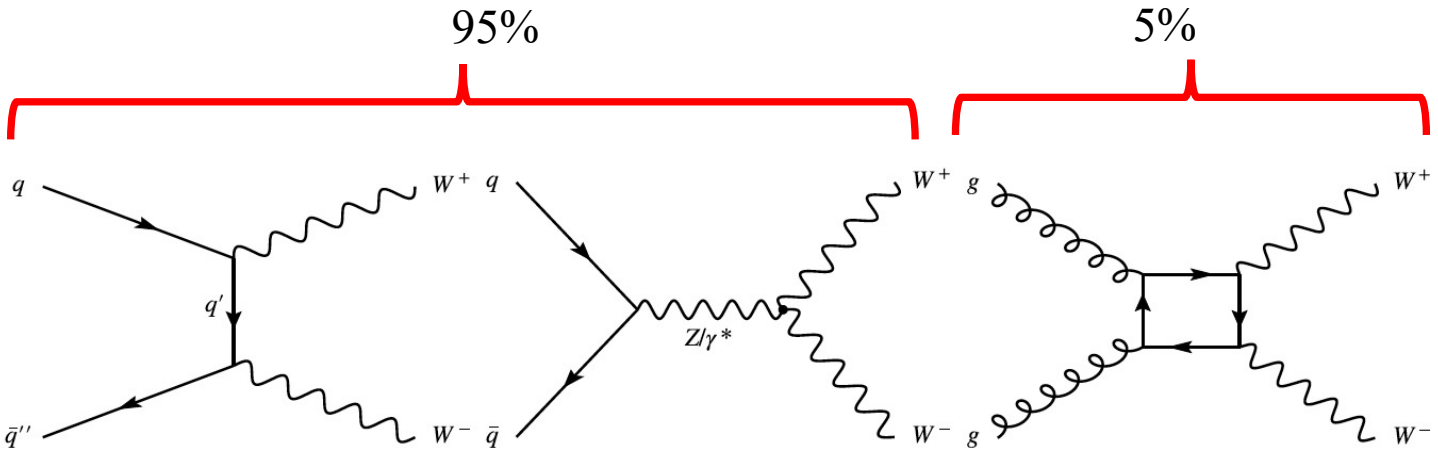
- Model independent upper limits calculated on $\sigma_{VBF}(H_5^{\pm\pm})\times\mathcal{B}(H_5^{\pm\pm} \to W^{\pm}W^{\pm})$.
- Also interpreted in the context of the Georgi–Machacek (GM) model giving upper limit on $\sin\theta_H$ parameter (characterises the contribution of the isotriplet scalar fields to the masses of the W and Z bosons) as a function of $m_{H_5^{\pm\pm}}$.
- These exclude parameter values greater than 0.11-0.41 for the $m_{H_5^{\pm\pm}}$ range of 200 to 1500 GeV.
- They show a local excess at a resonance mass of around 450 GeV with local significance of 3.2σ and global significance of 2.5σ.





3 (Opposite Sign) W^+W^- Cross-section Measurement

- W^+W^- cross-section measurement is performed without any requirements on the jets (first jet-inclusive measurement). This allows for precise comparison with theory.
- Using integrated luminosity of 140 fb^{-1}.
- Fully leptonic final state with different flavor opposite charge leptons: $W^{\pm}W^{\mp} \rightarrow e^{\pm}\nu\mu^{\mp}\nu$



Event Selection:

- Exactly two opposite charge leptons: one electron and one muon
- No additional lepton with $p_T > 10$ GeV.
- 0 b-jets
- $m_{\ell\ell'} > 85$ GeV

Backgrounds:

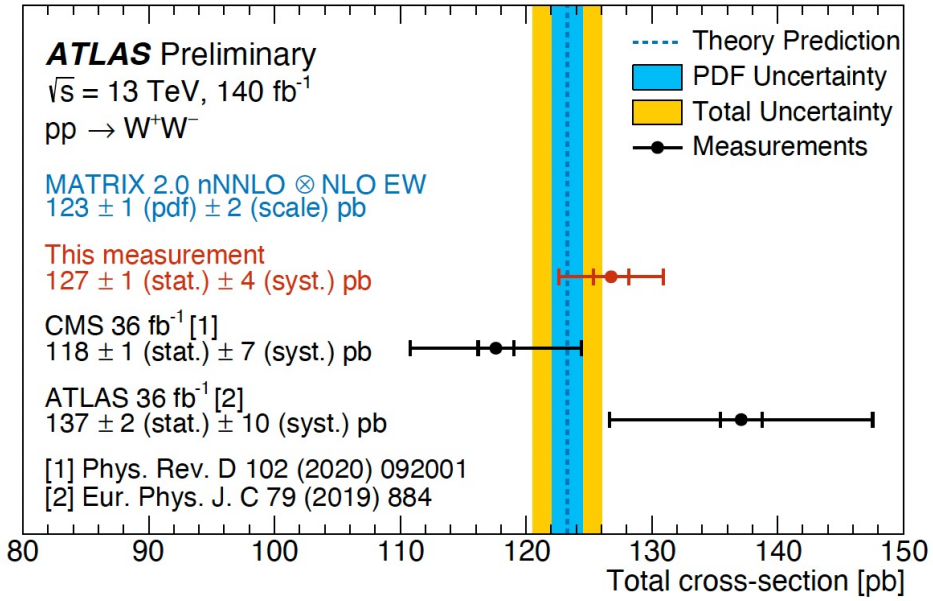
- 60% of all events is background
- $t\bar{t}$ or single top Wt (80% of the total background)

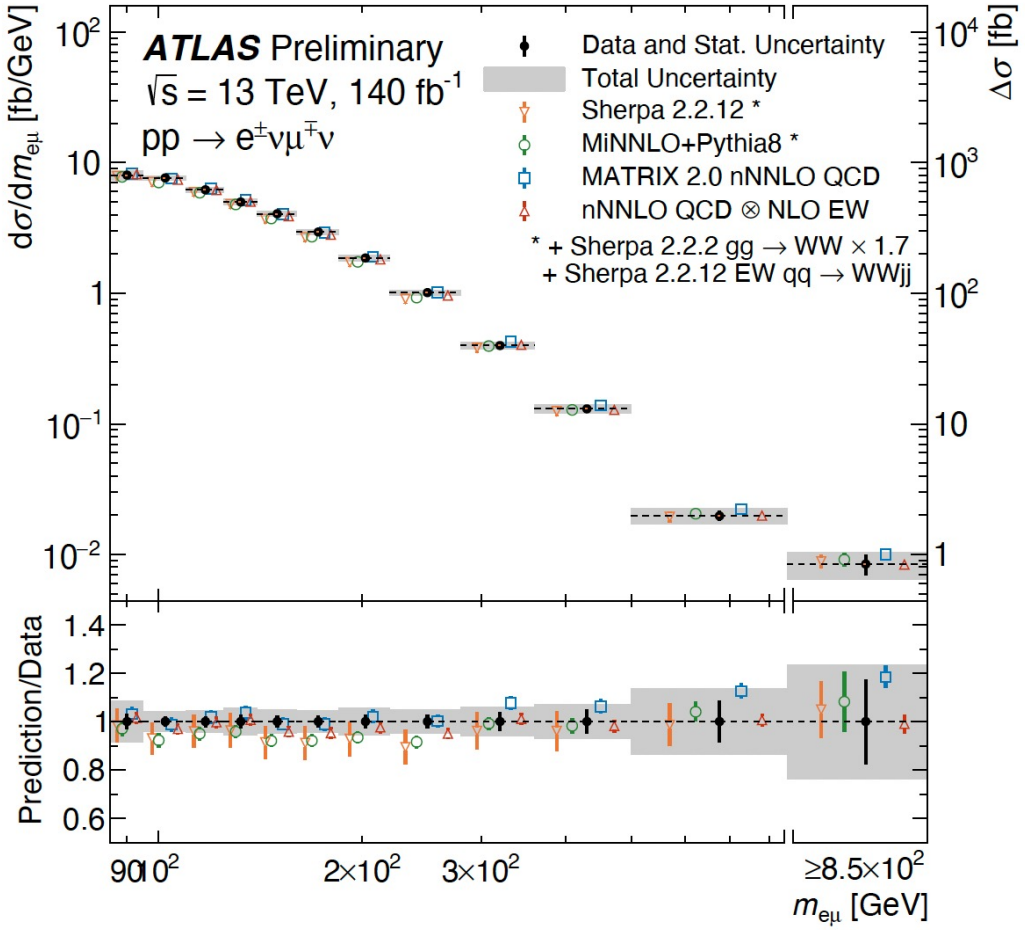
Other backgrounds: Z+jets production, events with non-prompt or misidentified leptons, and diboson production ($WZ, W\gamma, ZZ$, and $Z\gamma$).

(Opposite Sign) W^+W^- Cross-section Measurement

- The fiducial integrated and differential cross-section measurements with 12 observables (in backup):
  - The fiducial cross-section extrapolated to the total cross-section measurement:

    $127 \pm 1\ (stat.) \pm 4\ (syst.)\ pb$
- Improved data-driven estimates of top and fake backgrounds reduce uncertainty in the fiducial region to 3.1%.





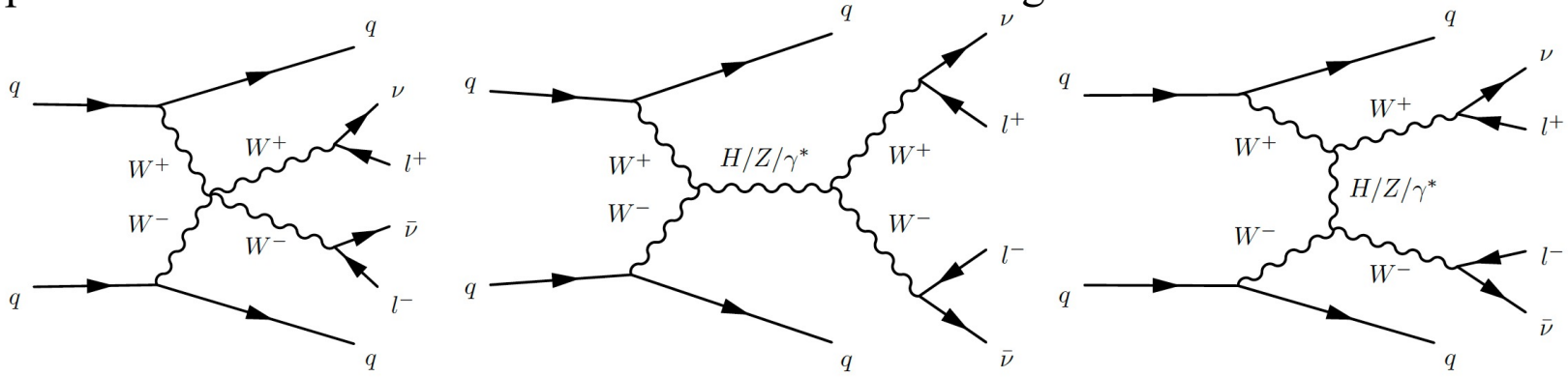
Fiducial differential cross-section as a function of $m_{e\mu}$.

4 (Opposite Sign) Electroweak Production of W^+W^-jj

ATLAS-CONF-2023-039

Electroweak Production of (opposite sign) W^+W^- associated with jets.

Fully leptonic, opposite flavor oppositely charged leptons are selected: $W^{\pm}W^{\mp}jj \rightarrow e^{\pm}\nu\mu^{\mp}\nu jj$. This has enhanced sensitivity compared to the same flavor channel. Low Drell-Yan Background.



Event Selection:

- Signal process tends to produce events with positive lepton centrality.
  - Centrality $\zeta = \min\{[\min(\eta_{\ell_1}, \eta_{\ell_2}) - \min(\eta_{j_1}, \eta_{j_2})], [max(\eta_{j_1}, \eta_{j_2}) - max(\eta_{\ell_1}, \eta_{\ell_2}]\} > 0.5$.
  - The Signal to background ratio is enhanced with this cut.
- $m_{e\mu} > 80$ GeV
- $E_T^{miss} > 15$ GeV
- No b-jets

Backgrounds:

- Top background: 66% of the inclusive region. Modelled using simulation and constrained using data in a dedicated CR.
- Strong production of W^+W^-jj: 24% of the inclusive region
- $Z + jets$ (4%)
- Multiboson (2%)
- $W + jets$ where one jet is mis-identified as a lepton (below 1%).

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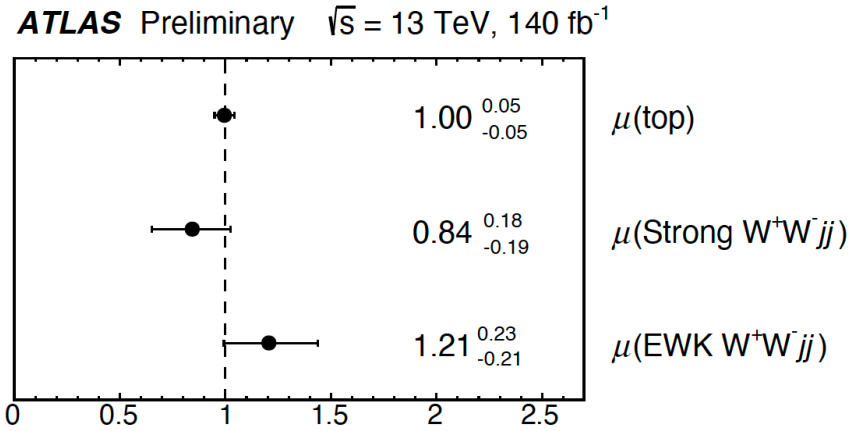
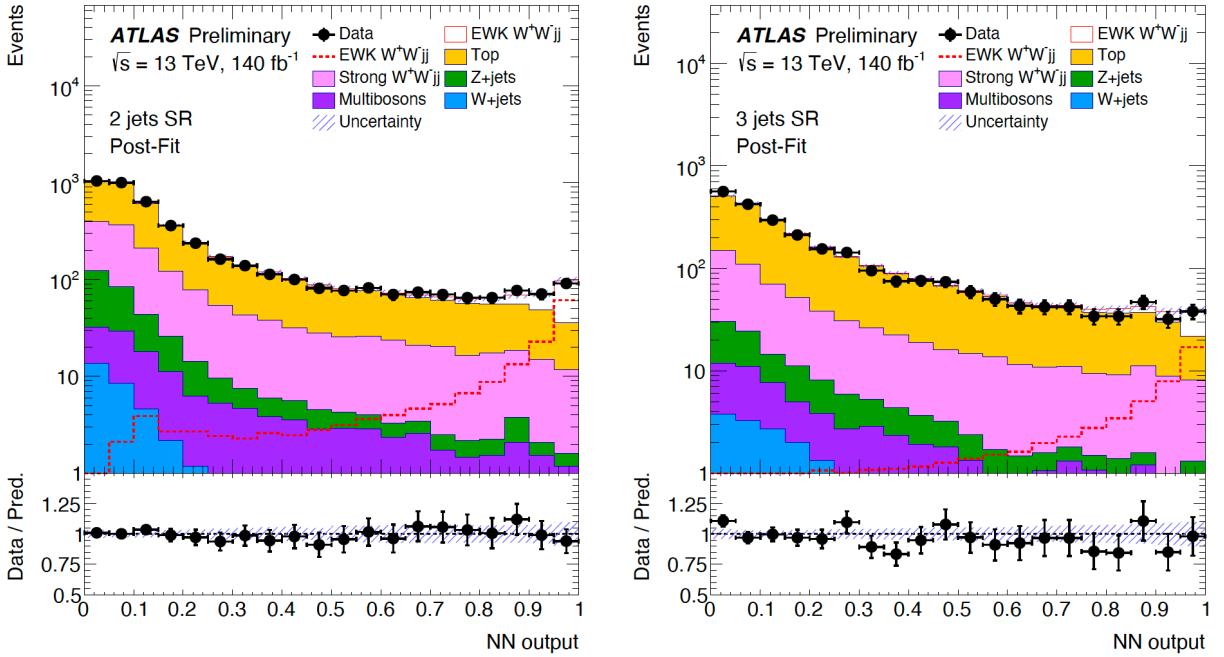
(Opposite Sign) EW W^+W^-jj: Signal Extraction and Cross-section Measurement

- The Signal and other SM processes are separated using a Neural Network. The backgrounds considered are the dominant top quark and strong W^+W^- processes as backgrounds
- Output is between 0 (background-like) and 1 (signal-like)
- The Neural Network is trained for 2 jets and 3 jets categories separately.



Signal strengths as floating params for bkg ans signal processes



(a) Two jets (b) Three jets

NN output distribution in the signal region (SR)

Results:

- The Signal has been observed with an observed (expected) significance of 7.1σ (6.2 σ).
- Cross section in a signal-enriched fiducial volume $2.65^{+0.52}_{-0.48}\ fb$ (Powheg Box predictor $2.20^{+0.14}_{-0.13}\ fb$.
- Dominant uncertainty comes from the data statistics.

5

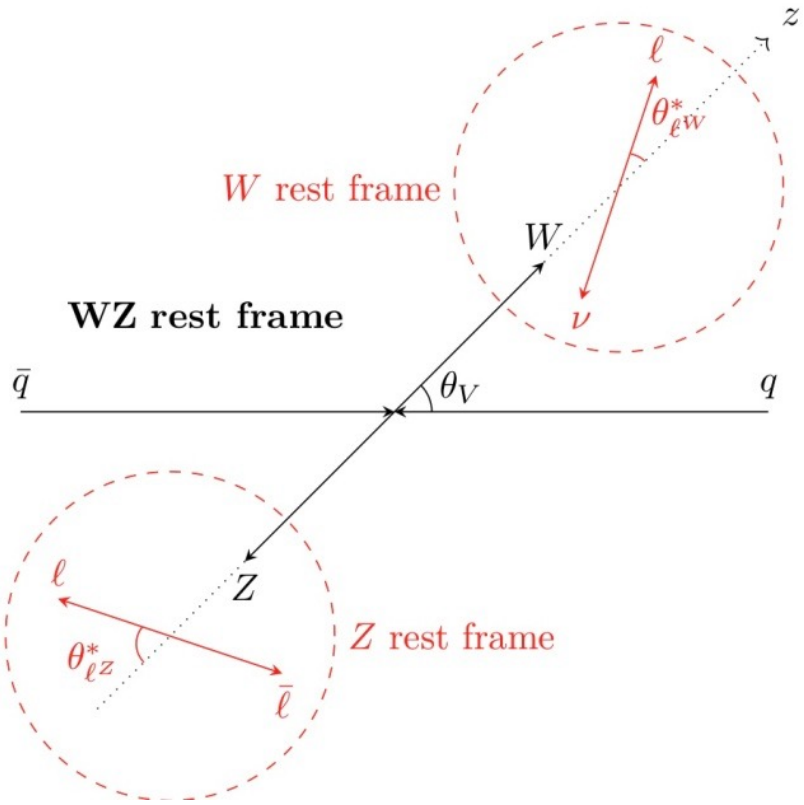
$W^{\pm}Z$ Polarization Studies in ATLAS

PLB 843 (2023) 137895

- **First-ever observation of longitudinal-longitudinal joint polarization state in diboson production.**
- Experimental Signature: $p\,p \rightarrow \ell\,\bar{\ell}\,\ell'\,\nu_{\ell'} + X$
- Inclusive Fiducial phase space for cross-section measurement and joint and single polarization fraction extraction
- Modified Helicity frame used for defining polarization (not Lorentz Invariant)
- p_z^{ν} reconstruction: New DNN-based method.
  - Reasonable p_z^{ν} estimate for which analytical method fails
  - 10% decrease in RMS due to improved p_z^{ν} resolution.

Backgrounds:

- **Irreducible background** (all candidates are prompt or from τ-lepton) 18%:
  - Using MC samples
  - ZZ – 7.5%, Main background (QCD+EW)
  - ttV: 4%
  - $WZ \rightarrow \tau\ell\ell \rightarrow \ell\nu\ell\ell$: 3%
  - Others: $t + Z$, triboson $VVV, VBS\ WZ, W^{\pm}\gamma^{*}$ produced outside of total phase space.
- **Reducible background** (at least one non-prompt lepton):
  - Using data-driven method
  - Misidentified leptons: $Z + \gamma$, $t\bar{t}$, Z+jets



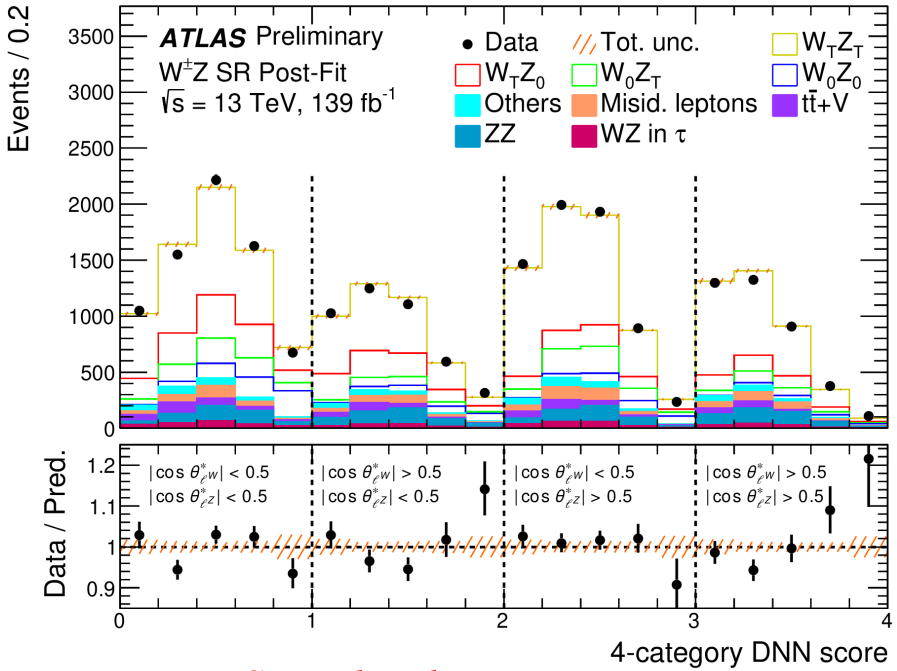
Modified Helicity Frame

$W^{\pm}Z$: Polarization Templates

PLB 843 (2023) 137895

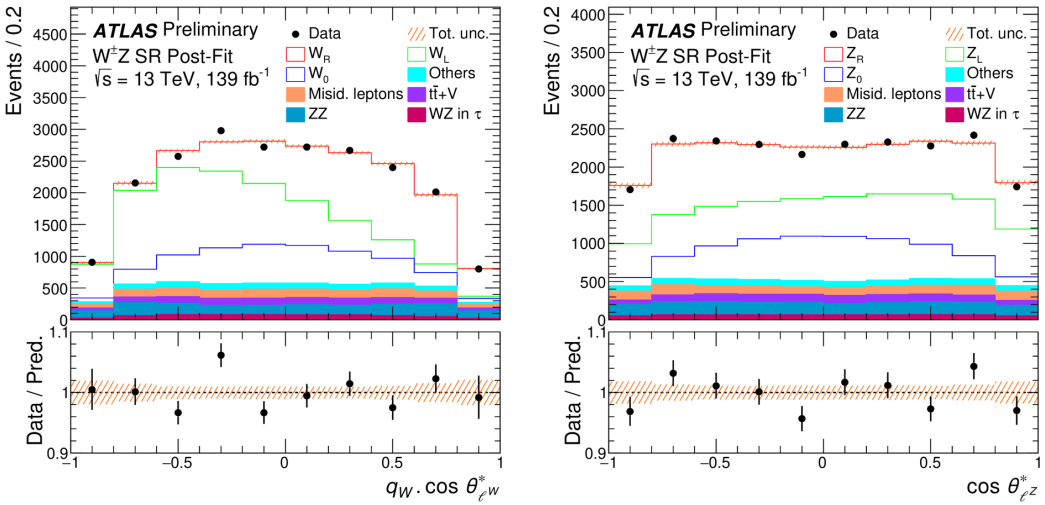
Joint Polarization:

- Polarized samples are produced at LO with WZ+0,1 jets.
- NLO-accurate polarization templates are required.
- 4 Categories were used for training 4 DNNs.
- Many validations are done to get NLO-accurate templates using LO polarized samples.

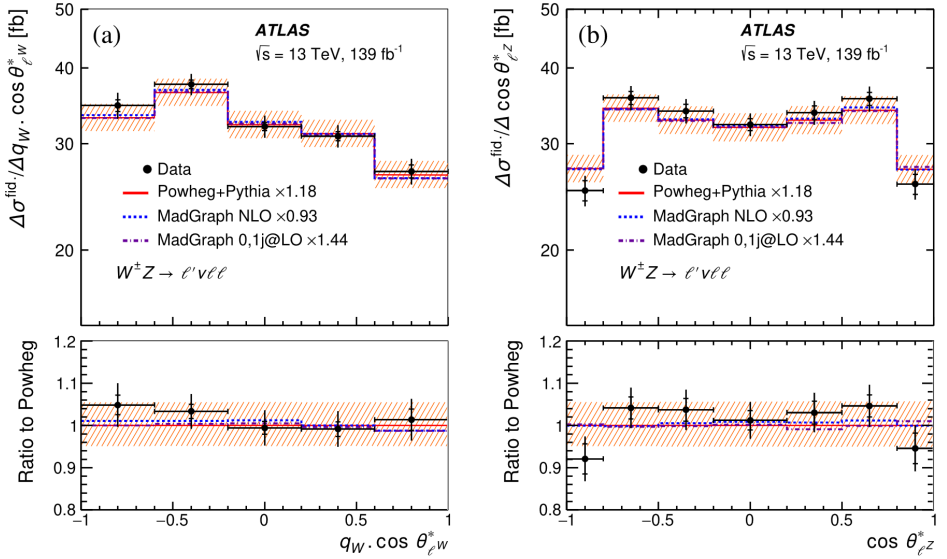


DNN Score distributions in 4 categories

Single Polarization templates using analytical reweighting: Agreement of fitted templates with



Iterative Bayesian unfolding for differential cross-section measurements in the fiducial phase space.



$W^{\pm}Z$ Polarization Fractions Results

PLB 843 (2023) 137895

Joint Polarization:

- **First ever observation of V_0V_0.**

Fraction	Significance: Observed (Expected)
f_{00}	7.1σ (6.2σ)
f_{0T}	3.4σ (5.4σ)
f_{T0}	7.1σ (6.6σ)
f_{TT}	11σ (9.7σ)

	Data	POWHEG+PYTHIA	NLO QCD
		$W^{\pm}Z$	
f_{00}	0.067 ± 0.010	0.0590 ± 0.0009	0.058 ± 0.002
f_{0T}	0.110 ± 0.029	0.1515 ± 0.0017	0.159 ± 0.003
f_{T0}	0.179 ± 0.023	0.1465 ± 0.0017	0.149 ± 0.003
f_{TT}	0.644 ± 0.032	0.6431 ± 0.0021	0.628 ± 0.004
		$W^{+}Z$	
f_{00}	0.072 ± 0.016	0.0583 ± 0.0012	0.057 ± 0.002
f_{0T}	0.119 ± 0.034	0.1484 ± 0.0022	0.155 ± 0.003
f_{T0}	0.153 ± 0.033	0.1461 ± 0.0022	0.147 ± 0.003
f_{TT}	0.66 ± 0.04	0.6472 ± 0.0026	0.635 ± 0.004
		$W^{-}Z$	
f_{00}	0.063 ± 0.016	0.0600 ± 0.0014	0.059 ± 0.002
f_{0T}	0.11 ± 0.04	0.1560 ± 0.0027	0.166 ± 0.003
f_{T0}	0.21 ± 0.04	0.1470 ± 0.0027	0.152 ± 0.003
f_{TT}	0.62 ± 0.05	0.6370 ± 0.0033	0.618 ± 0.004

Single Polarization:

	f_0			$f_L - f_R$	
	Data	POWHEG+PYTHIA	NLO QCD	Data	POWHEG+PYTHIA
W in W^+Z	0.23 ± 0.05	0.2044 ± 0.0024	0.211 ± 0.002	0.071 ± 0.023	0.0990 ± 0.0015
W in W^-Z	0.19 ± 0.05	0.217 ± 0.004	0.225 ± 0.001	0.026 ± 0.027	-0.0491 ± 0.0020
W in $W^{\pm}Z$	0.22 ± 0.04	0.2094 ± 0.0016	0.217 ± 0.001	0.059 ± 0.016	0.0390 ± 0.0011
Z in W^+Z	0.223 ± 0.025	0.1971 ± 0.0019	0.206 ± 0.002	-0.20 ± 0.10	-0.217 ± 0.006
Z in W^-Z	0.240 ± 0.029	0.2065 ± 0.0023	0.211 ± 0.001	0.10 ± 0.13	0.092 ± 0.007
Z in $W^{\pm}Z$	0.231 ± 0.019	0.2009 ± 0.0014	0.208 ± 0.001	-0.10 ± 0.08	-0.092 ± 0.005

- Here the NLO QCD predictions are from Denner&Pellicioli [arXiv:2010.07149]
- Better than 2σ agreement for joint polarization fractions.
- f_0 agrees within 1σ
- $f_L - f_R$ agrees within 1.5 σ, except W^-Z (2.8 σ)

Spin-correlations between longitudinal W and Z:

- Measured $R_c = {}^{f_{00}}/_{(f_0^W f_0^Z)} = 1.54 \pm 0.35$ (Obs. Significance 1.6σ wrt $R_c = 1$ hypothesis)
- Predicted (NLO QCD) $R_c = 1.3$.

Cross-section in inclusive fiducial phase space (also measured differentially):

- Measured: $\sigma^{fid}_{W^{\pm}Z\to\ell'\nu\ell\ell} = 64.6 \pm 2.1$ fb
- NNLO Expectation: $\sigma^{fid}_{W^{\pm}Z\to\ell'\nu\ell\ell} = 64.0^{+1.5}_{-1.3}$ fb

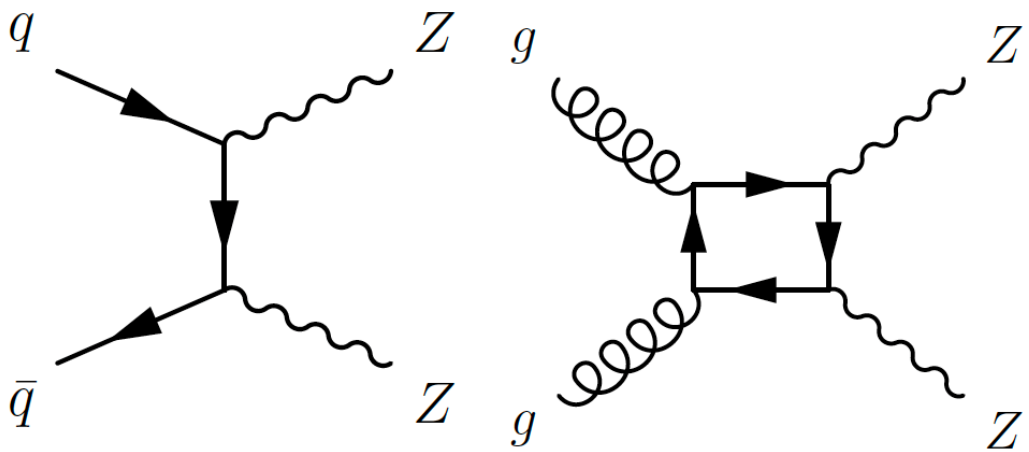
6 ZZ Polarization and CP Property Measurement

ATLAS-CONF-2023-038

- **Measurement of $Z_L Z_L$** (both longitudinally polarized). Helps probing the EWSB and new physics searches.

- **Measurement of CP-sensitive observables** in diboson production for exploring new sources of CP violation.
- In this analysis, unfolded differential cross-section measured for an Optimal Observable (OO). Results are interpreted to constrain aNTGC using an effective vertex function approach. aNTGC vertex can be parameterised with two coupling parameters f_Z^4 and f_γ^4 that violate CP symmetry.

- Fully leptonic final states: $ZZ \to \ell^+\ell^-\ell'^+\ell'^-$, the leptons can be electron or muon (SFOC leptons).
- possible combinations SFOC pairs + invariant mass of Z constraint.
- $m_{4\ell} > 180$ GeV.



$q\bar{q}$ initiated *gg initiated*

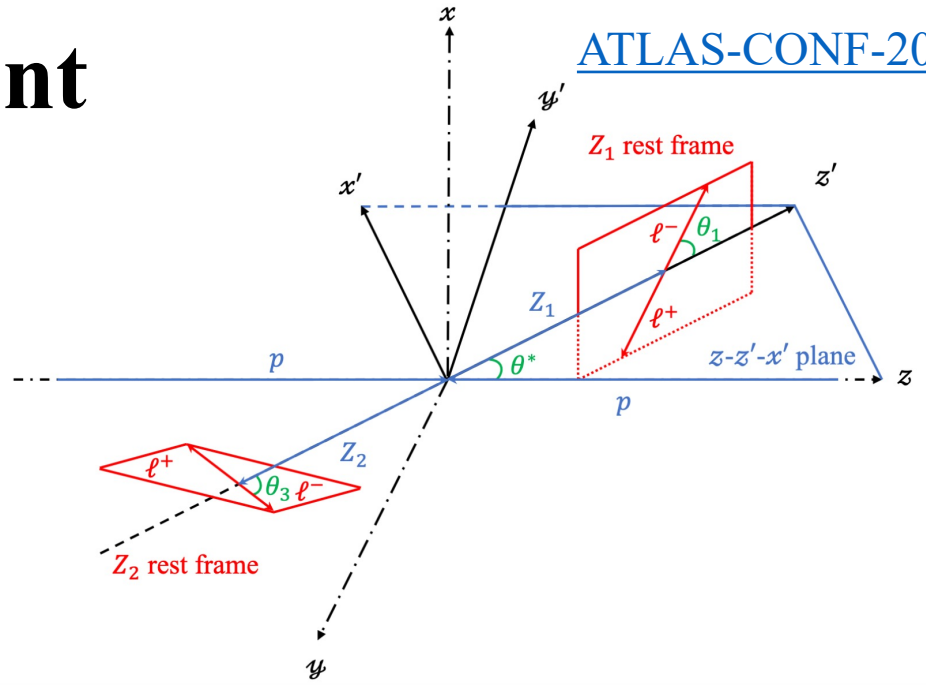
Backgrounds:

- Reducible (8-9% of $Z_L Z_L$ events): non-prompt leptons from hadron decays, charge misidentification, or photon conversion. Fake-factor determination done using Z+jets and $t\bar{t}$ CR.
- Irreducible (9-10% of $Z_L Z_L$ events): $t\bar{t}Z, VVZ$.

$Z_L Z_L$: Cross-section Measurement

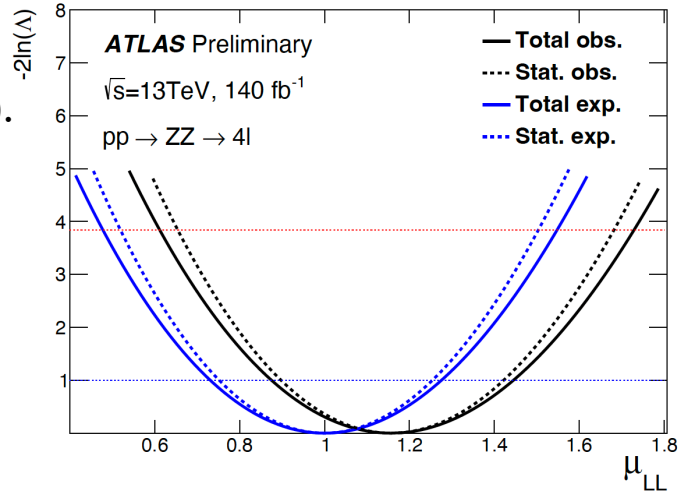
ATLAS-CONF-2023-038

- For the extraction of $Z_L Z_L$ cross-section, multivariate technique based on Boosted Decision Trees (BDT).
- To reduce theoretical modelling uncertainties, only angular variables were used in BDT training.
- Higher order corrections, QCD+EW are applied. Theoretical calculations taken from https://link.springer.com/article/10.1007/JHEP10(2021)097.
  - 1D reweighting for each polarization
  - 1D reweighting for the interference effect
  - 2D reweighting for residual higher order corrections

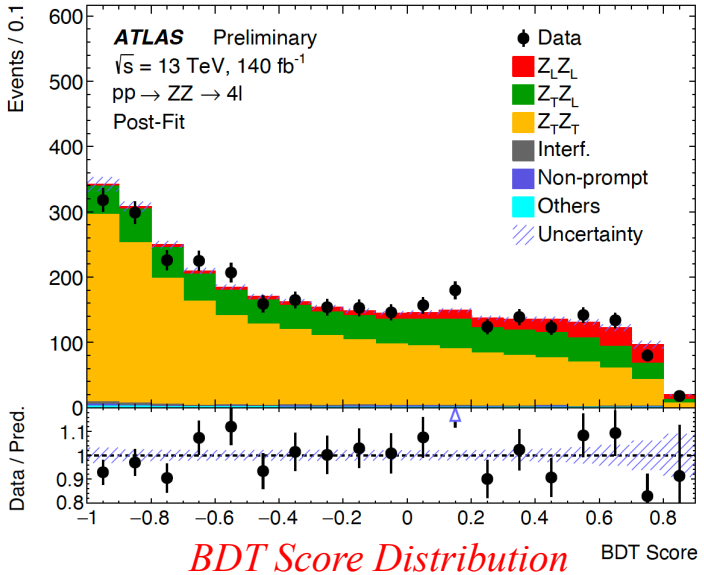


Results:

- Obs (exp) significance of 4.3σ (3.8σ).
- An additional likelihood fit is performed to convert signal strength to cross-section:
- Obs: $\sigma_{Z_L Z_L}^{obs.} = 2.44 \pm 0.59\ fb$
- SM Pred: $\sigma_{Z_L Z_L}^{pred.} = 2.09 \pm 0.10\ fb$.



Likelihood Scan For Signal Strength



BDT Score Distribution

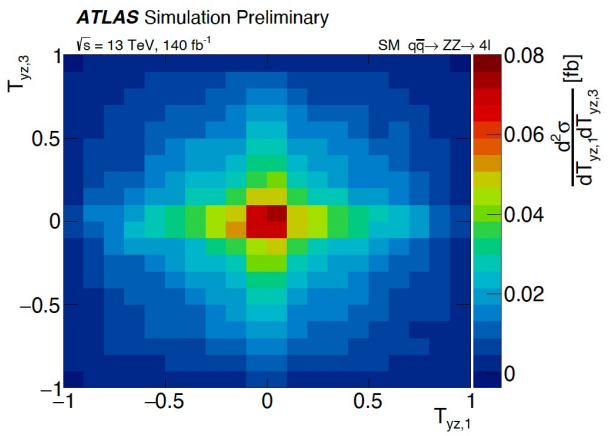
ZZ: Study of CP Property

ATLAS-CONF-2023-038

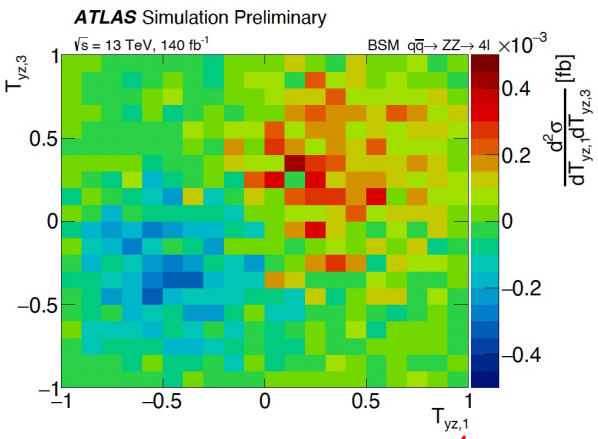
- The differential cross-sections $\theta_1(\theta_3)$ and $\phi_1(\phi_3)$ are symmetric in the SM but asymmetric in the presence of the two CP-odd aNTGC. (1 and 3 correspond to the negatively charged leptons of the ZZ system).
- $\mathcal{O}_{T_{yz,1},T_{yz,3}}$ defined from 2D distribution of T_{yz} by grouping sensitive and non-sensitive bins (here $T_{yz,1(3)} = sin\phi_{1(3)} \times cos\theta_{1(3)}$, maximizing asymmetry for each Z boson system).
- Miss-paired leptons have smaller impact on the CP sensitivity.
- The distributions are unfolded using the iterative Bayesian unfolding method.
- Exp and Obs 95% confidence intervals on CP-odd Operator:

$$\sigma^i = \sigma^i_{\text{SM}} + c \cdot \sigma^i_{\text{interference}} + c^2 \cdot \sigma^i_{\text{quadratic}}$$

Xsec in a bin of CP sensitive observable

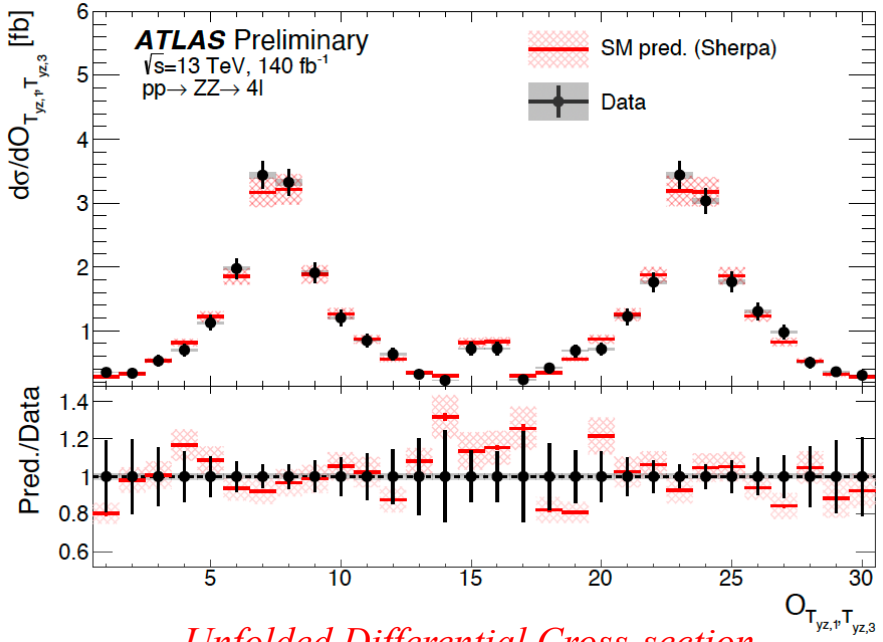


SM



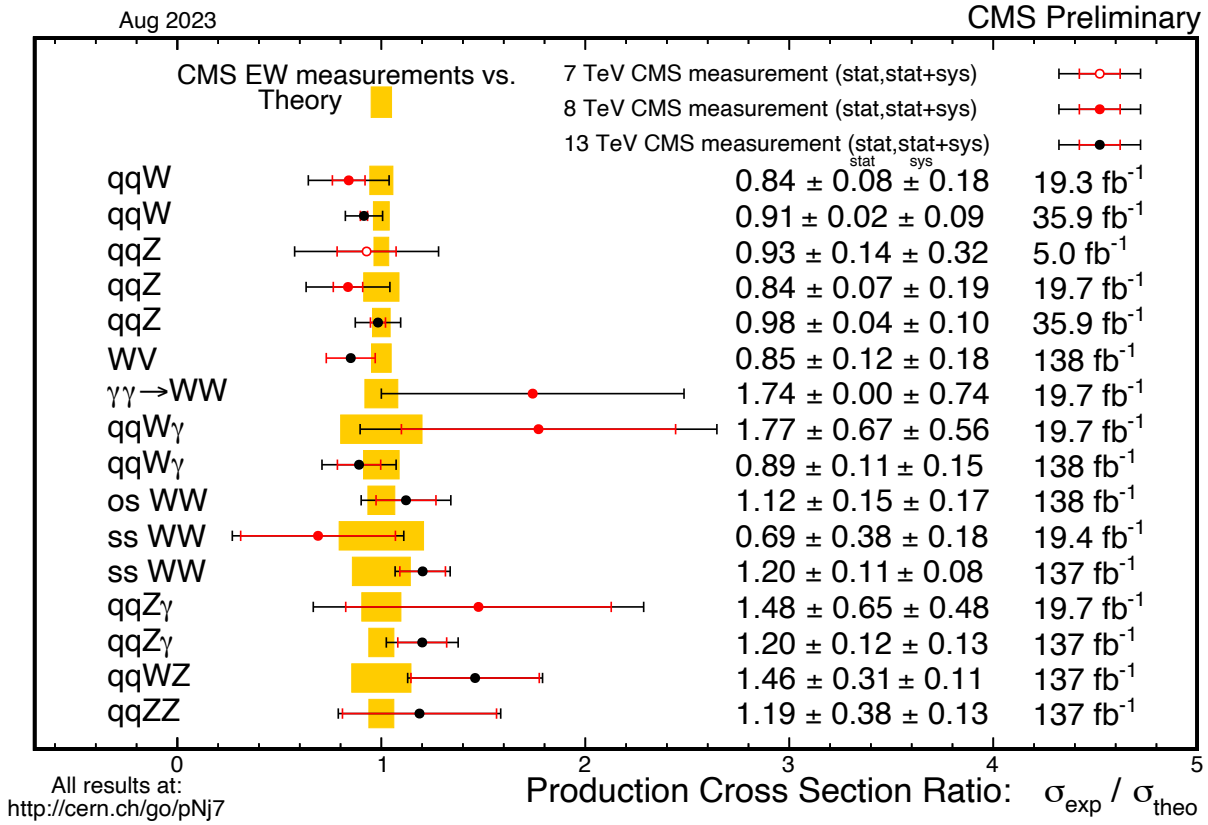
with BSM aNTGC vertex: $f_Z^4 = 1$

aNTGC parameter	Interference only		Full	
	Expected	Observed	Expected	Observed
f_Z^4	$[-0.16, 0.16]$	$[-0.12, 0.20]$	$[-0.013, 0.012]$	$[-0.012, 0.012]$
f_γ^4	$[-0.30, 0.30]$	$[-0.34, 0.28]$	$[-0.015, 0.015]$	$[-0.015, 0.015]$

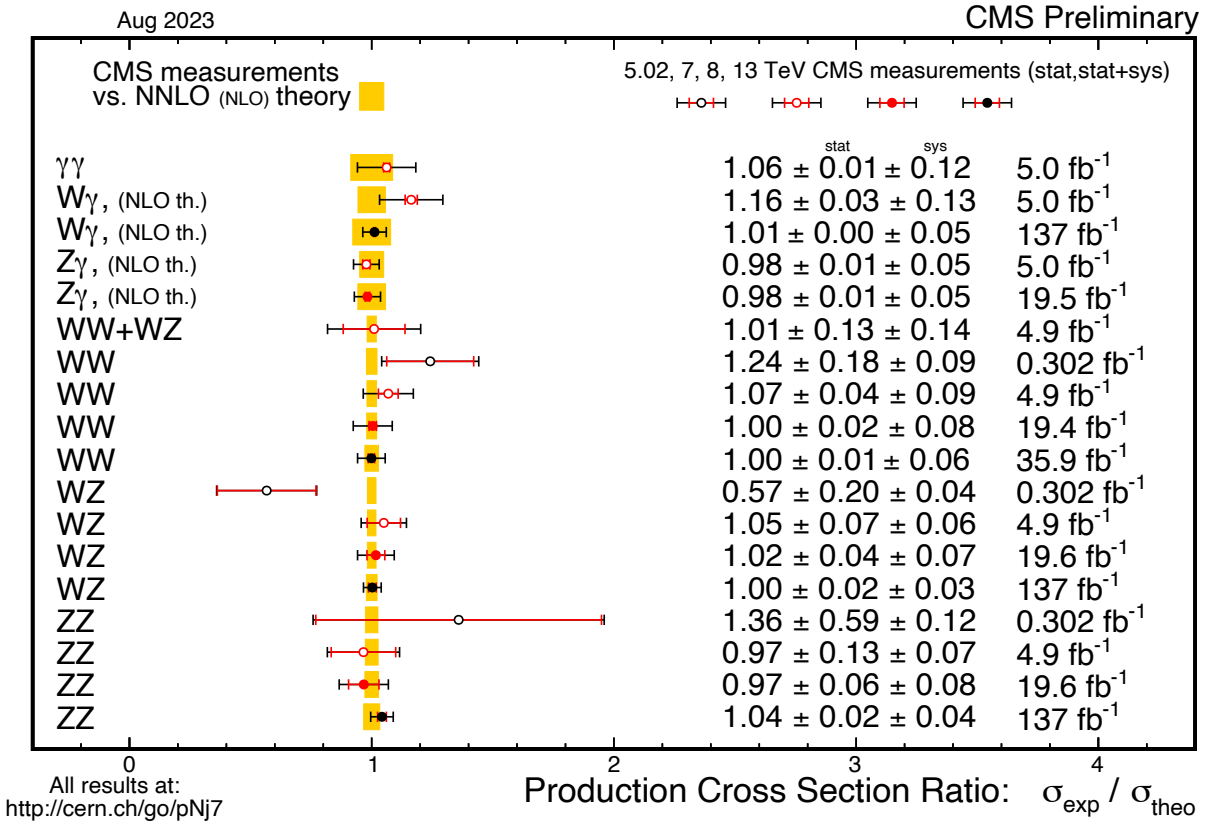


Unfolded Differential Cross-section

Diboson Searches Summary: CMS



EW Diboson Cross-sections Vs Theory



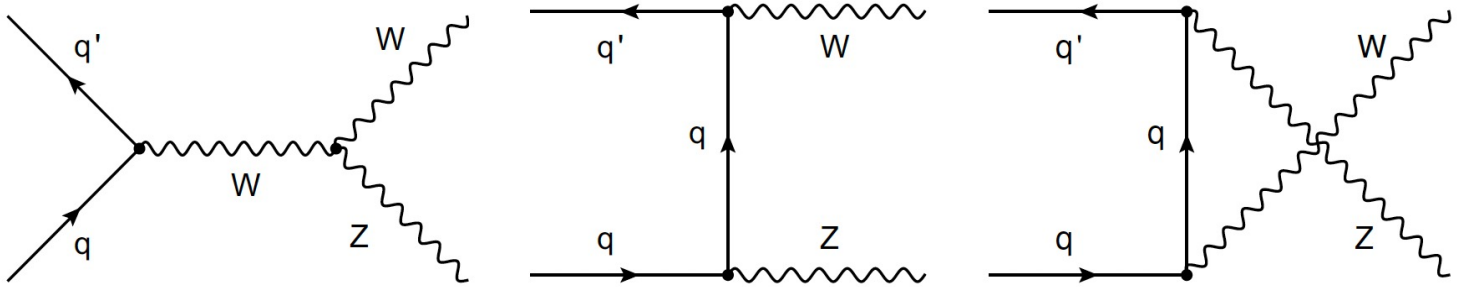
Diboson Cross-sections Vs Theory

Ref:https://twiki.cern.ch/twiki/pub/CMSPublic/PhysicsResultsCombined/CMSCrossSectionSummaryBarChart.pdf

1 $W^{\pm}Z$ Introduction

JHEP 07 (2022) 032

- WZ is a dominant SM contribution to the trilepton final states, hence a background in many multileptonic final states
- Measurements performed:
  - inclusive cross section
  - charge asymmetry measurement
  - Boson polarization measurement
  - differential cross section
  - the search for anomalous triple gauge couplings



Event Selection:

- $N_\ell = 3$
- Number of opposite sign same flavor leptons ≥ 1.
- $p_T^{miss} > 30$ GeV
- No b-tagged jets
- $\min\left(M(\ell\ell')\right) > 4\ GeV$: For infrared safety and avoid contribution from low mass resonances.
- $M(\ell_{Z1}, \ell_{Z2}, \ell_W) > 100$ GeV

Backgrounds:

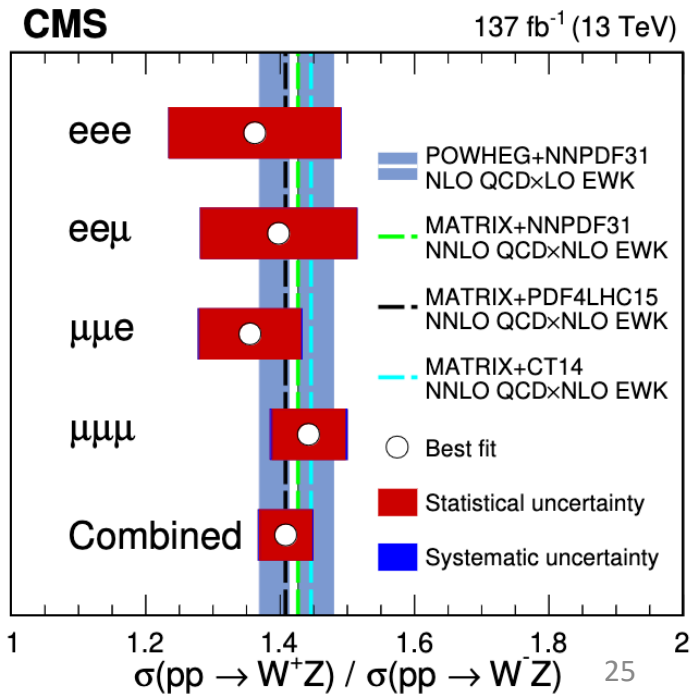
- Reducible: Estimated using right-to-loose data-driven method method. Includes $Z + jets$ and $t\bar{t}$.
- Irreducible:
  - ZZ (6% of the SR yield), $t\bar{t}Z$ and tZq (3.2% of the SR yield), $X\gamma$ (1.5% of the total SR yield),

$W^{\pm}Z$ Cross-section Measurement

JHEP 07 (2022) 032

- Inclusive Cross-section measurement performed in flavour inclusive (combined) and in separate flavor categories ($eee, ee\mu, \mu\mu e, \mu\mu\mu$).
- Maximum likelihood fit is used for obtaining WZ yields in the SR.
  - $\sigma_{tot}(pp \rightarrow WZ) = 50.6 \pm 0.8\,(stat) \pm 1.4\,(syst) \pm 1.1\,(lumi) \pm 0.5\,(theo)\,pb$
- The normalization of the WZ process is kept as an unconstrained parameter in the fit for the cross-section measurement
- Charge asymmetry ratio is also measured (resulting from dominant qq' production): $A_{WZ}^{+-} = \frac{\sigma_{fid}(pp \rightarrow W^+Z)}{\sigma_{fid}(pp \rightarrow W^-Z)} = 1.41 \pm 0.04$.
- Consistency of the asymmetry ratio with different PDF sets is also calculated

Category or source	Total cross section
POWHEG	$42.5^{+1.6}_{-1.4}$ (scale) $\pm$ 0.6 (PDF) pb
MATRIX, NNLO QCD	$51.2^{+1.2}_{-1.0}$ (scale) pb
MATRIX, NNLO QCD $\times$ NLO EWK	$50.7^{+1.1}_{-1.0}$ (scale) pb
eee (Measured)	53.2 $\pm$ 2.7 (stat) $\pm$ 2.3 (syst) $\pm$ 1.1 (lumi) $\pm$ 0.5 (theo) pb
eeμ (Measured)	48.1 $\pm$ 1.7 (stat) $\pm$ 1.8 (syst) $\pm$ 1.1 (lumi) $\pm$ 0.4 (theo) pb
$\mu\mu$e (Measured)	50.6 $\pm$ 1.3 (stat) $\pm$ 1.5 (syst) $\pm$ 1.1 (lumi) $\pm$ 0.5 (theo) pb
$\mu\mu\mu$ (Measured)	50.8 $\pm$ 1.0 (stat) $\pm$ 1.5 (syst) $\pm$ 1.1 (lumi) $\pm$ 0.5 (theo) pb
Combined (Measured)	50.6 $\pm$ 0.8 (stat) $\pm$ 1.5 (syst) $\pm$ 1.1 (lumi) $\pm$ 0.5 (theo) pb



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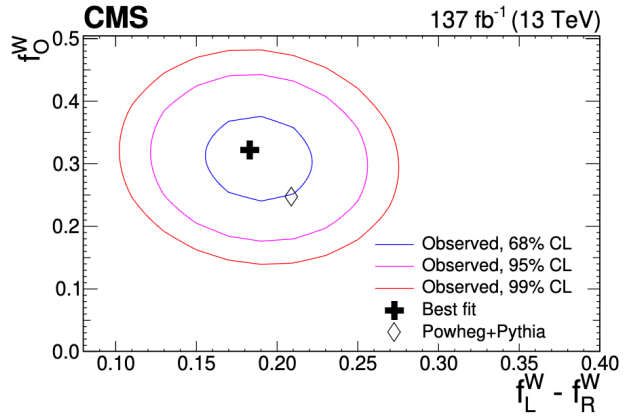
$W^{\pm}Z$ Polarization and Differential Cross-section

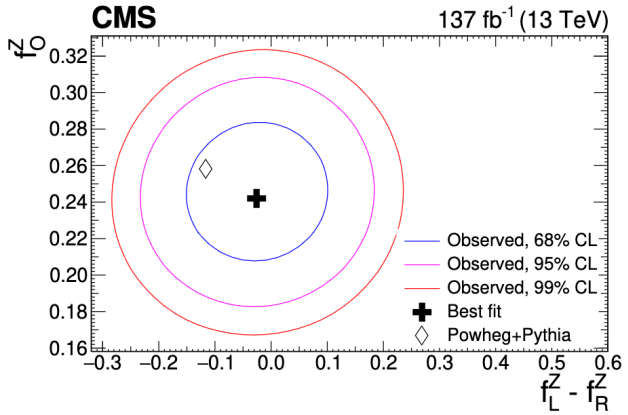
Single boson polarization measurement:

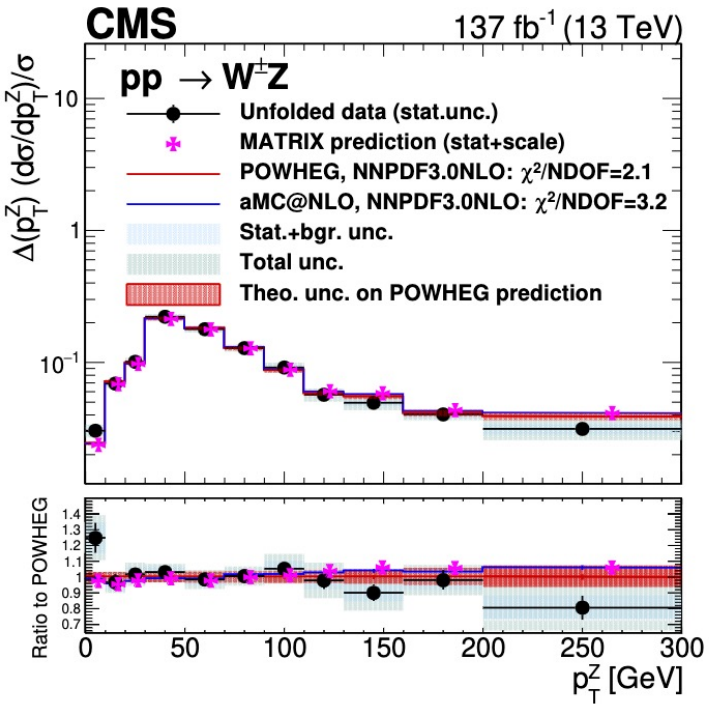
- Observation of longitudinally polarized W boson with obs (exp) significance of 5.6σ (4.3σ)
- Observation of longitudinal Z, obs and exp above 5σ.

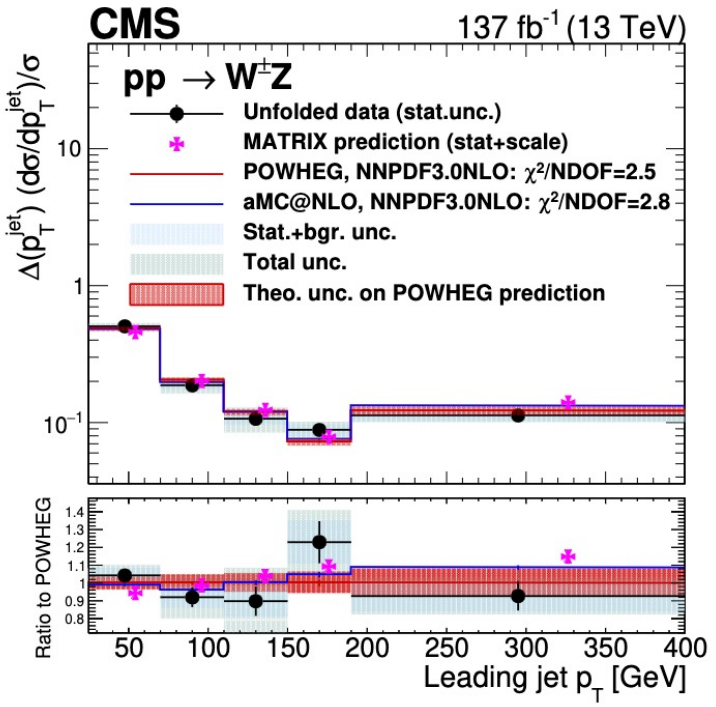
Differential Cross-section measurement:

- based on a least squares fit as implemented in the TUnfold software package









$W^{\pm}Z$ aQGC Limits

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- Anomalous couplings search is based on $M(WZ)$. Two different 95% confidence limits are set:
  - Both purely dimension-eight BSM contribution and dimension-six interference term are included to compute the EFT effect in the high tails of M(WZ)
  - Only dimension-six interference term is included
- Better than best previous limits
- Limits on three CP-conserving parameters ($c_{WWW}/\Lambda^2, c_W/\Lambda^2, c_b\ /\Lambda^2$) and two CP-violating parameters ($\tilde{c}_{WWW}/\Lambda^2, \tilde{c}_W\ /\Lambda^2$)

Parameter	95% CI, exp. (TeV^{-2})	95% CI, obs. (TeV^{-2})	Best fit, obs. (TeV^{-2})
c_{w}/Λ^2	$[-2.0, 1.3]$	$[-2.5, 0.3]$	-1.3
$c_{\mathrm{www}}/\Lambda^2$	$[-1.3, 1.3]$	$[-1.0, 1.2]$	0.1
c_{b}/Λ^2	$[-86, 125]$	$[-43, 113]$	44
$\widetilde{c}_{\mathrm{www}}/\Lambda^2$	$[-0.76, 0.65]$	$[-0.62, 0.53]$	-0.03
$\widetilde{c}_{\mathrm{w}}/\Lambda^2$	$[-46, 46]$	$[-32, 32]$	0

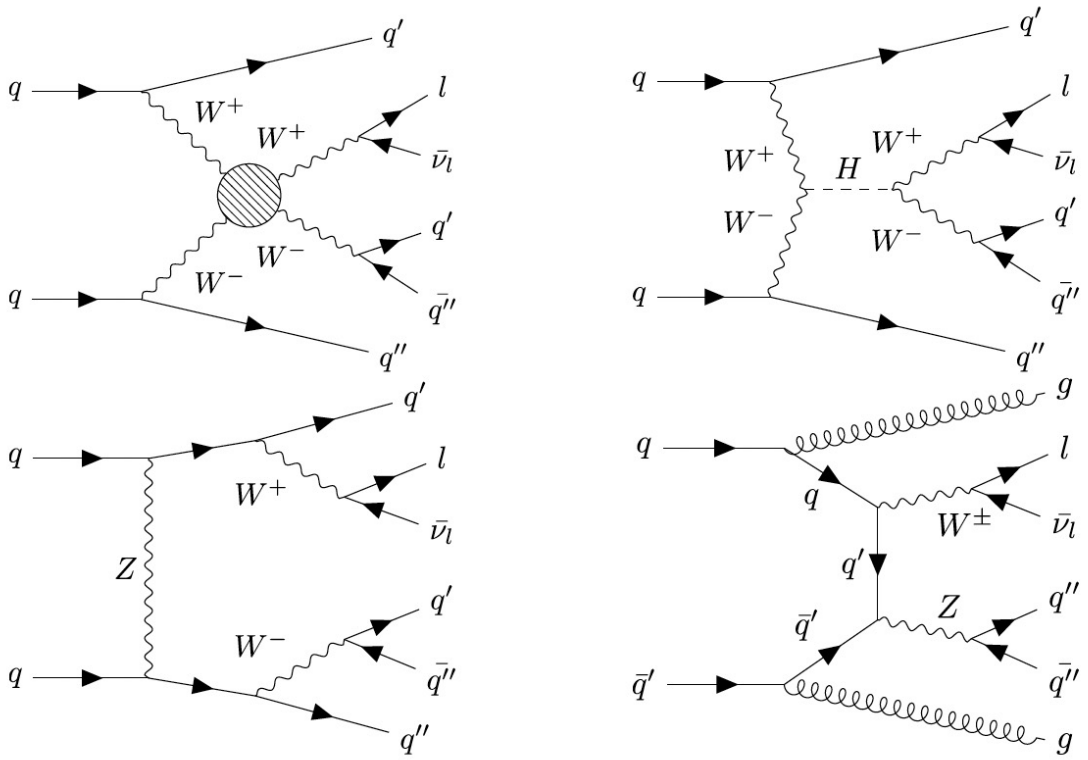
2 $WVjj$: Cross-section Measurements

PLB 834 (2022) 137438

- First LHC evidence of SM electroweak $\ell\nu qq$ production with two jets.
- $W^{\pm} \rightarrow \ell^{\pm}\nu_{\ell}$ and V $(W^{\pm}/Z) \rightarrow q\bar{q}$.
- The signature consists of 4 jets, 1 lepton and missing E_T.

Event Selection:

- Two categories:
  - Resolved: Four anti-k_T jets with distance parameter $\Delta R = 0.4$ (AK4)
  - Boosted: Two anti-k_T jets with $\Delta R = 0.4$ and one jet with $\Delta R = 0.8$ (AK8).
- $m_{jj}^{VBS} > 500$ GeV and $\Delta\eta_{jj}^{VBS} > 2.5$ for tag jets (enhances VBS events)
- No b-jets should be found in the signal region



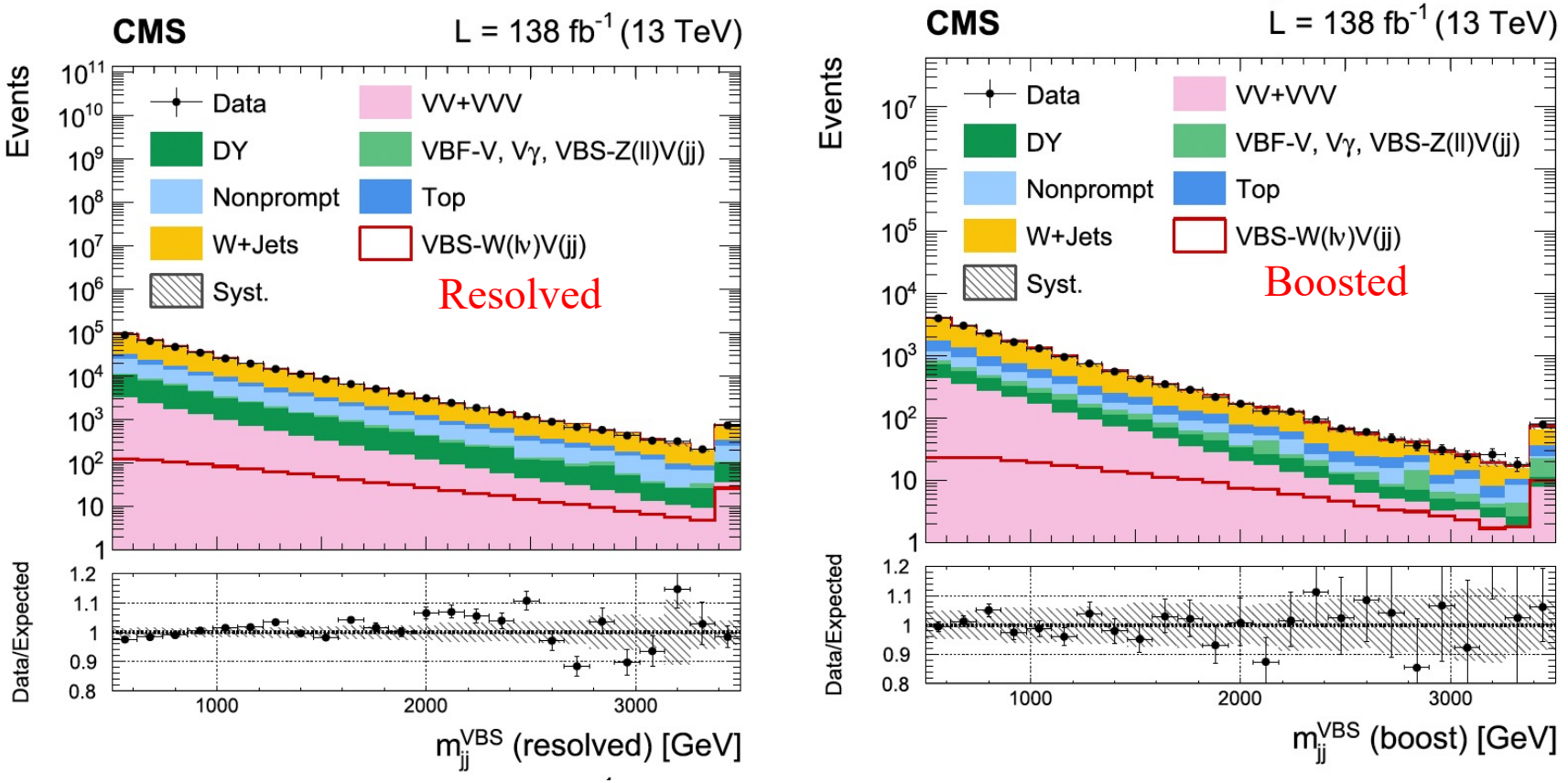
Backgrounds:

- $W + jets$ (data-driven method) using dedicated CRs.
- Top quark background, QCD-multijet
- VBF-V Single vector boson EW production (2% in resolved, 4% in boosted
- Other: QCD VBS WV production, Drell-Yan, VVV, $V\gamma$, VBS Z($\ell\ell$)V(jj)

PLB 834 (2022) 137438

$WVjj$: Cross-section Measurements

- Deep Neural Network (DNN) used for signal extraction.
- It increases the sensitivity of the analysis by a factor of 3 over a fit to the shape of the m_{jj}^{VBS} variable (most sensitive variable).

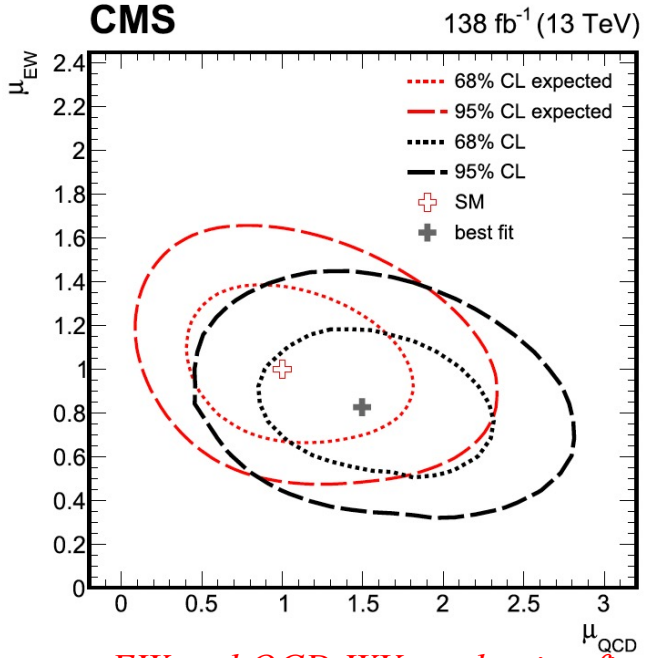


Post-fit distributions of m_{jj}^{VBS} in the resolved and boosted categories.

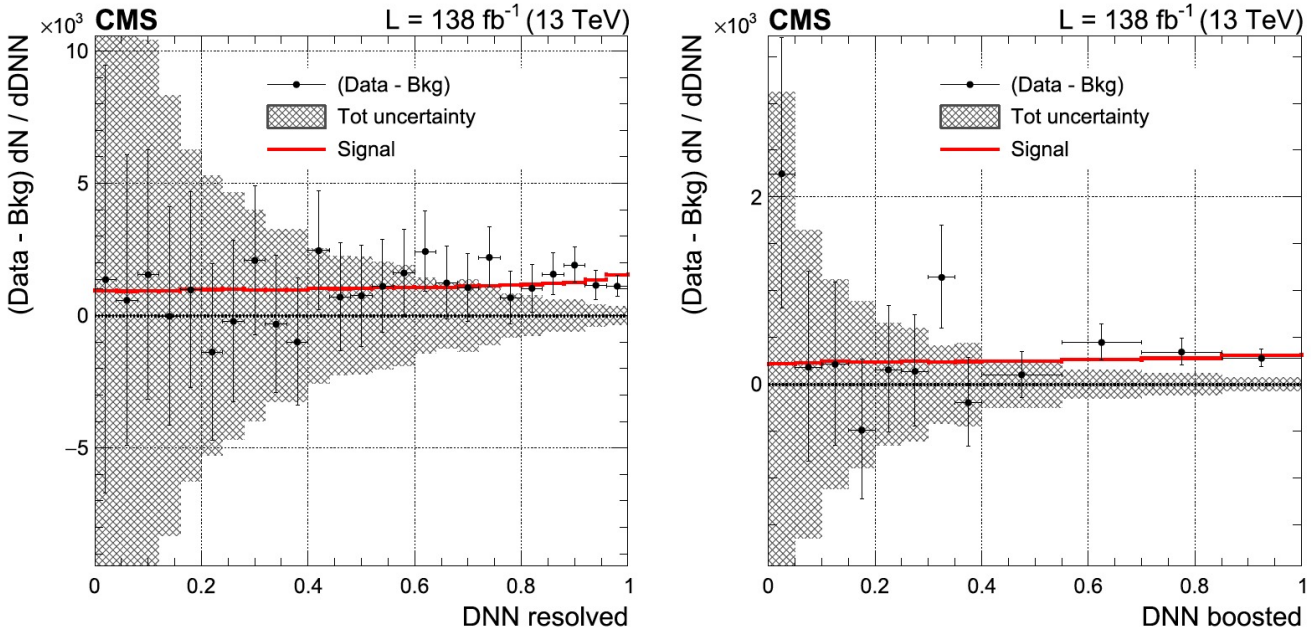
$WVjj$: Cross-section Measurements

PLB 834 (2022) 137438

- The cross-section measured at a fiducial phase space defined at parton level.
- Cross-section measurement:
  - Measured: $1.90^{+0.53}_{-0.46}\ pb$
  - Expected: $2.23^{+0.08}_{-0.11}\ (scale)\ \pm 0.05\ (PDF)\ pb$
- Observed EW signal strength: $\mu_{EW} = 0.85 \pm 0.12\ (stat)^{+0.19}_{-0.17}(syst)$ with an obs (exp) significance of 4.4σ ($5.1\ \sigma$), with QCD associated diboson production fixed to SM prediction.
- EW + QCD associated signal strength: $0.97 \pm 0.06\ (stat)^{+0.19}_{-0.21}(syst)$.



Simultaneous EW and QCD WV production fit: Exp and Obs 68% and 95% CL contours for signal strengths



DNN Score Distribution

3

$ZZ + jets$: Differential Cross-section Measurement

CMS PAS SMP-22-001

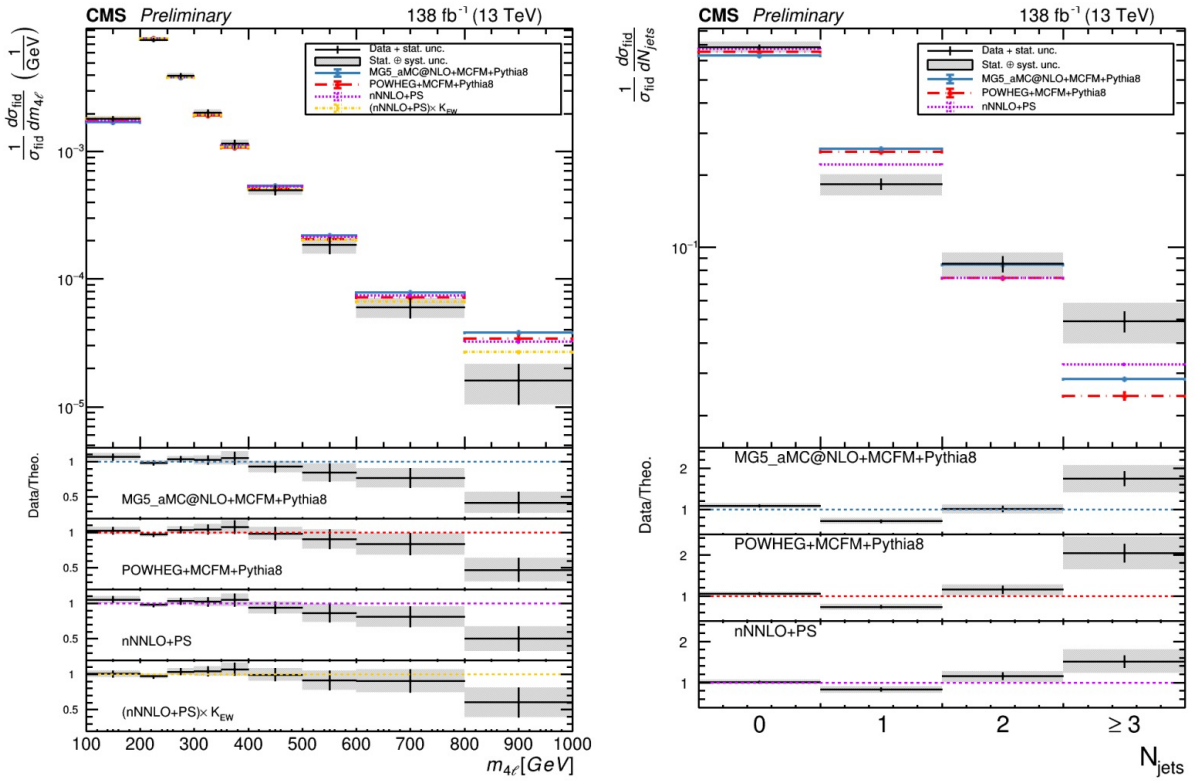
- Differential production cross-section of $ZZ + jets$ as a function of multiple variables.
- Signal includes $qq \rightarrow ZZ$ sample, $gg \rightarrow ZZ$ samples, EW production sample (which includes vector boson fusion (VBF) Higgs events and their interference with non-Higgs EW production), and the $gg \rightarrow H \rightarrow ZZ$ samples

Event Selection:

- Fully leptonic final states. Lepton-lepton and jet-lepton (or photon) overlaps are taken care of. Four-lepton candidates of SFOC pairs are considered.
- Jets with $p_T > 30$ GeV and $|\eta| < 4.7$.

Backgrounds:

- Well reconstructed and isolated lepton candidates suppress backgrounds to a great extent
- Backgrounds dominated by $Z + jets$, $WZ + jets$, $t\bar{t}$, VVV.



Differential cross-section for $m_{4\ell}$ and N_{jets}.

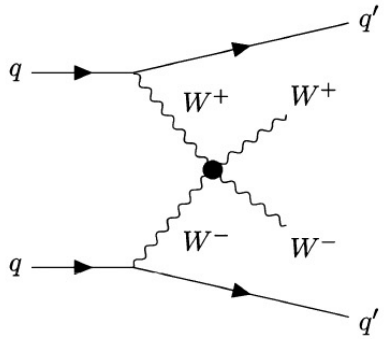
- Unfolding using the iterative D'Agostini's method
- EW corrections improves the description of the $m_{4\ell}$ distribution.

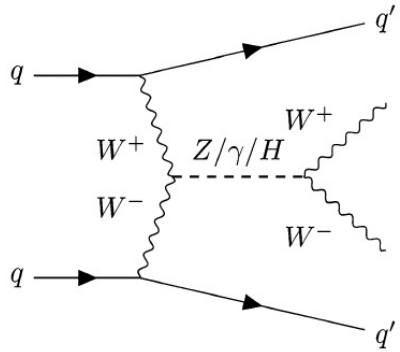
4 (Opposite Sign) EW W^+W^-jj Measurement

PLB 841 (2023) 137495

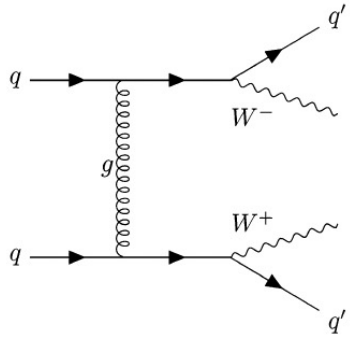
- Electroweak production of W^+W^- associated with two jets.

EW production





QCD Induced production



Event Selection:

- Fully leptonic final states. Split into different flavor SRs: $e^+e^-, \mu^+\mu^-, e^\pm\mu^\mp$.
  - exactly two opposite-sign leptons (electrons or muons) $m_{\ell\ell} > 50$ GeV and $p_T^{\ell\ell} > 30$ GeV
  - two jets with large pseudorapidity separation and high dijet invariant mass: $m_{jj} > 300$ GeV and $|\Delta\eta_{jj}| > 2.5$
  - $p_T^{miss} > 20$ GeV
  - SR split acc to the final state lepton flavors, Zeppenfeld variable: $Z_{\ell\ell} = \frac{1}{2}|Z_{\ell 1} + Z_{\ell 2}|$, where $Z_\ell = \eta_\ell - \frac{1}{2}(\eta_{j_1} + \eta_{j_2})$.

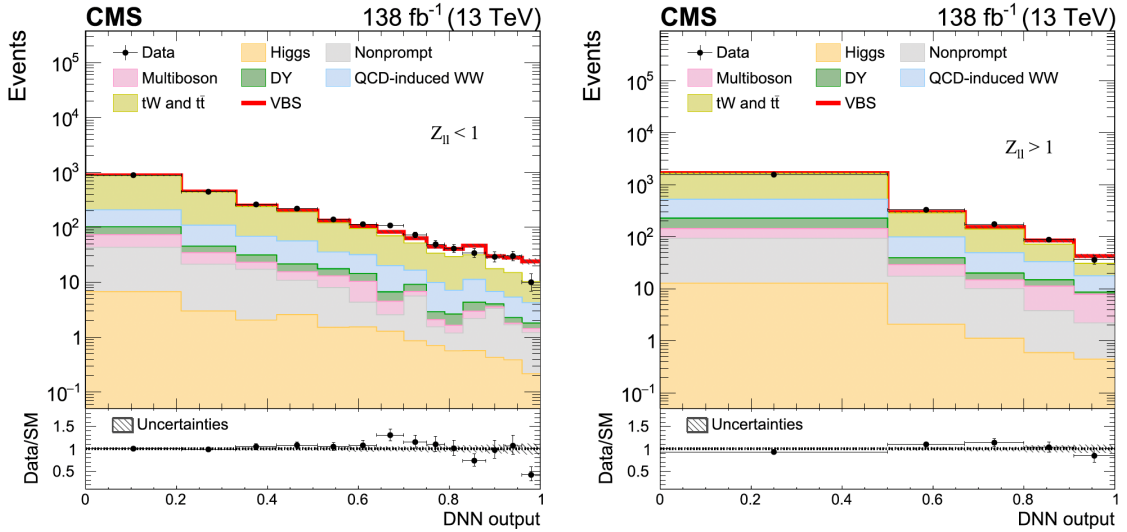
Backgrounds:

- $t\bar{t}$: estimated with a $t\bar{t}$ CR
- Drell-Yan production: estimated with dedicated CRs
- QCD induced W^+W^-: Normalization is left floating in the fit
- Non-prompt leptons: $W + jets$ - From data, $Z + jets$ – From simulation
- Higgs and multiboson production: using simulation

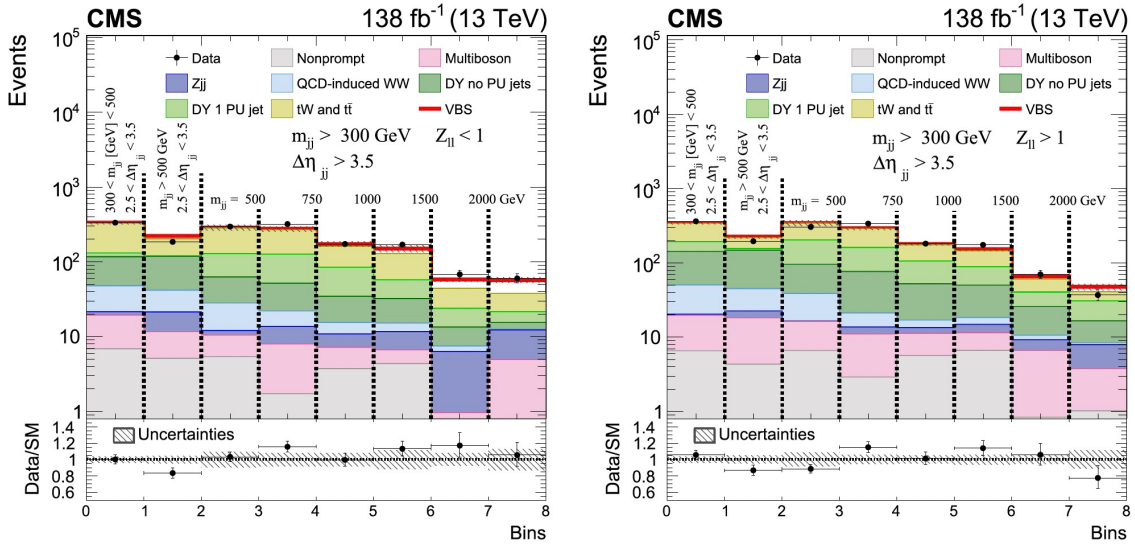
(Opposite Sign) EW W^+W^-jj Measurement

PLB 841 (2023) 137495

- In the $e\mu$ category, a feed forward deep neural network (DNN) is used to distinguish signal from $t\bar{t}$ and QCD induced W^+W^-.
- Separate models built for $Z_{\ell\ell} < 1$ (less background, signal enriched) and $Z_{\ell\ell} > 1$.
- Binary cross-entropy loss function is minimized in both the models
- $\mu_{EW} = \sigma^{obs}/\sigma^{SM}$ is the parameter of interest. Translated to cross-section in two fiducial volumes.
- A maximum-likelihood fit is performed to get the cross-sections:
- The background only hypothesis (without contribution from EW W^+W^-) rejected with obs (exp) significance of 5.6σ ($5.2\ \sigma$).
  - More inclusive region: $99\ \pm 20\ fb$ (LO pre-diction of $89\ \pm 5\ (scale) fb$
  - Closer to the preselection region: $10.2\ \pm 2.0\ fb$ (LO theoretical prediction is $9.1\ \pm 0.6\ (scale)\ fb$)



DNN Output Distribution in Diff Flavor (eμ) Channel

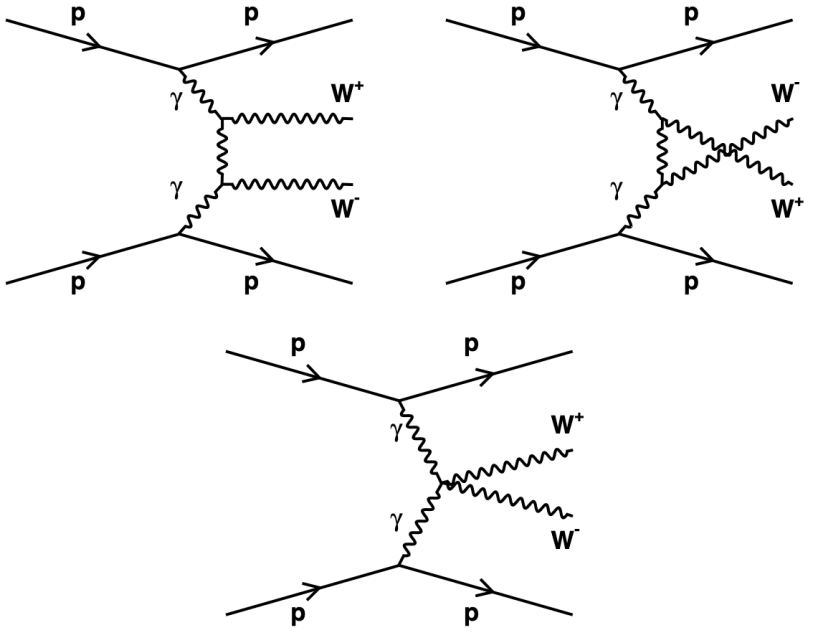


Regions in m_{jj} and $|\Delta\eta_{jj}|$ same Flavor (ee and μμ)

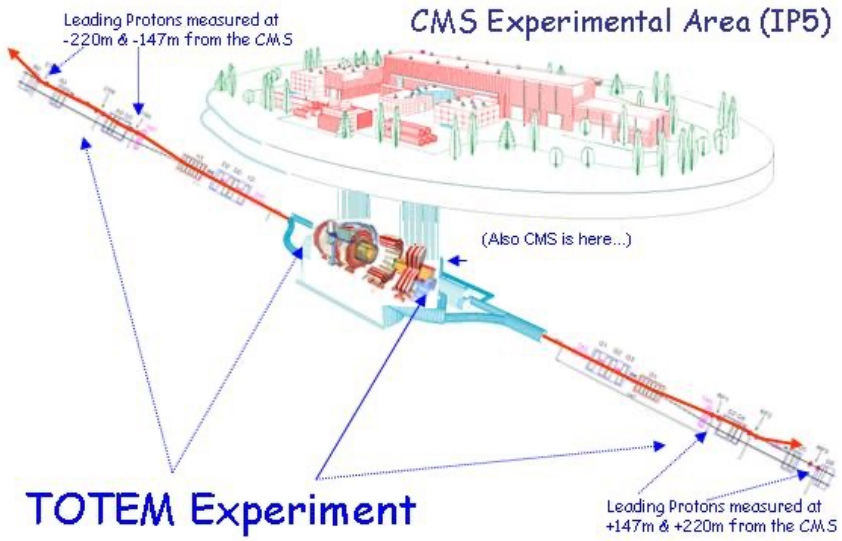
5 $\gamma\gamma \rightarrow WW$ and $\gamma\gamma \rightarrow ZZ$ CMS+TOTEM

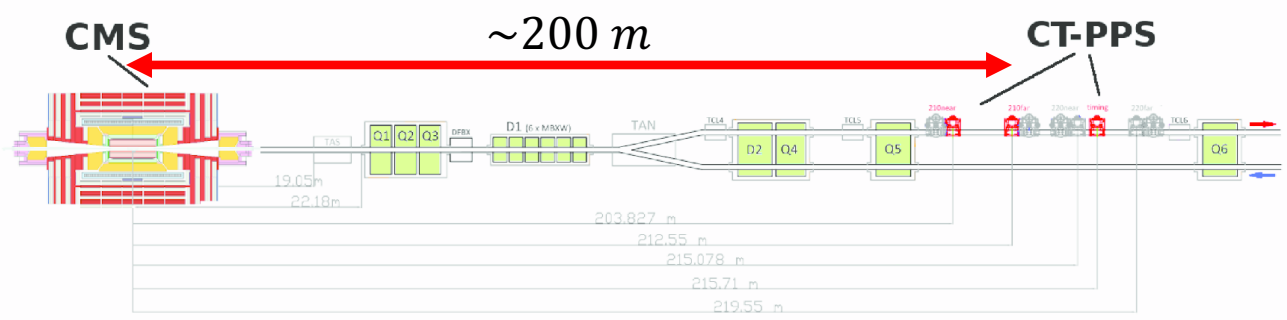
arXiv:2211.16320v2

- Search for exclusive high mass $\gamma\gamma \rightarrow WW$ and $\gamma\gamma \rightarrow ZZ$ production in pp collisions with an integrated luminosity of 100 fb^{-1}.
- Using intact forward protons reconstructed in near-beam detectors
- Both weak bosons decaying into boosted and merged jets



- The protons radiate quasireal high-energy photons and remain intact. Only the two photons interact, and the protons are scattered at very small angles.
- The scattered protons are measured using a Precision Proton Spectrometer (PPS) of CMS-TOTEM collaboration.





$\gamma\gamma \rightarrow WW$ and $\gamma\gamma \rightarrow ZZ$: EFT interpretations

arXiv:2211.16320v2

Event Reco and selection:

- The scattered protons are reconstructed using "Multi-RP Algorithm". which combines tracks reconstructed in both tracking Roman pots in each arm of PPS.
- Both weak bosons decaying into boosted and merged jets.
- Proton jet matching is performed, and signal regions are defined using variables $1 - m(VV)/m(pp)$ and $y(pp) - y(VV)$.

Backgrounds:

- QCD multijet, $W + jets, Z + jets, t\bar{t}$. Have to rely on data for background estimate as the protons predominantly arise from diffractive pileup interactions, which are not well modelled.

Coupling	Observed (expected) 95% CL upper limit No clipping	Observed (expected) 95% CL upper limit Clipping at 1.4 TeV
$\lvert a_0^W/\Lambda^2\rvert$	$4.3\ (3.9) \times 10^{-6}\,\mathrm{GeV}^{-2}$	$5.2\ (5.1) \times 10^{-6}\,\mathrm{GeV}^{-2}$
$\lvert a_C^W/\Lambda^2\rvert$	$1.6\ (1.4) \times 10^{-5}\,\mathrm{GeV}^{-2}$	$2.0\ (2.0) \times 10^{-5}\,\mathrm{GeV}^{-2}$
$\lvert a_0^Z/\Lambda^2\rvert$	$0.9\ (1.0) \times 10^{-5}\,\mathrm{GeV}^{-2}$	—
$\lvert a_C^Z/\Lambda^2\rvert$	$4.0\ (4.5) \times 10^{-5}\,\mathrm{GeV}^{-2}$	—

Expected and observed limits on dimension-6 AQGC operators

$\gamma\gamma \to WW$ and $\gamma\gamma \to ZZ$: EFT interpretations

- Translation to linear dimension-8 mixed AQGCs (contain both covariant derivatives of the Higgs field and field strength tensor) in case of processes involving photons:

$$a_0^{\mathrm{W}} = -\frac{m_{\mathrm{W}}}{\pi\alpha_{\mathrm{em}}}\left[s_w^2\frac{f_{M,0}}{\Lambda^2} + 2c_w^2\frac{f_{M,2}}{\Lambda^2} + s_w c_w\frac{f_{M,4}}{\Lambda^2}\right].$$

- The limits are obtained for a fiducial region of $0.04 < \xi < 0.20$ and diboson invariant mass $m(VV) > 1$ TeV, and correspond to the diboson production cross section before decays into hadrons (p_{nom} nominal beam momentum, p scattered proton momentum).

$$\xi = (p_{\mathrm{nom}} - p)/p_{\mathrm{nom}}$$

- Upper exclusion limits on AQGC like signal at 95% CL obs (exp):
  - $\sigma(pp \to pWWp) < 67(53^{+34}_{-19})fb$
  - $\sigma(pp \to pZZp) < 43(62^{+33}_{-20})\,fb.$

Coupling	Observed (expected) 95% CL upper limit No clipping	Observed (expected) 95% CL upper limit Clipping at 1.4 TeV
$\lvert f_{M,0}/\Lambda^4\rvert$	66.0 (60.0) TeV^{-4}	79.8 (78.2) TeV^{-4}
$\lvert f_{M,1}/\Lambda^4\rvert$	245.5 (214.8) TeV^{-4}	306.8 (306.8) TeV^{-4}
$\lvert f_{M,2}/\Lambda^4\rvert$	9.8 (9.0) TeV^{-4}	11.9 (11.8) TeV^{-4}
$\lvert f_{M,3}/\Lambda^4\rvert$	73.0 (64.6) TeV^{-4}	91.3 (92.3) TeV^{-4}
$\lvert f_{M,4}/\Lambda^4\rvert$	36.0 (32.9) TeV^{-4}	43.5 (42.9) TeV^{-4}
$\lvert f_{M,5}/\Lambda^4\rvert$	67.0 (58.9) TeV^{-4}	83.7 (84.1) TeV^{-4}
$\lvert f_{M,7}/\Lambda^4\rvert$	490.9 (429.6) TeV^{-4}	613.7 (613.7) TeV^{-4}

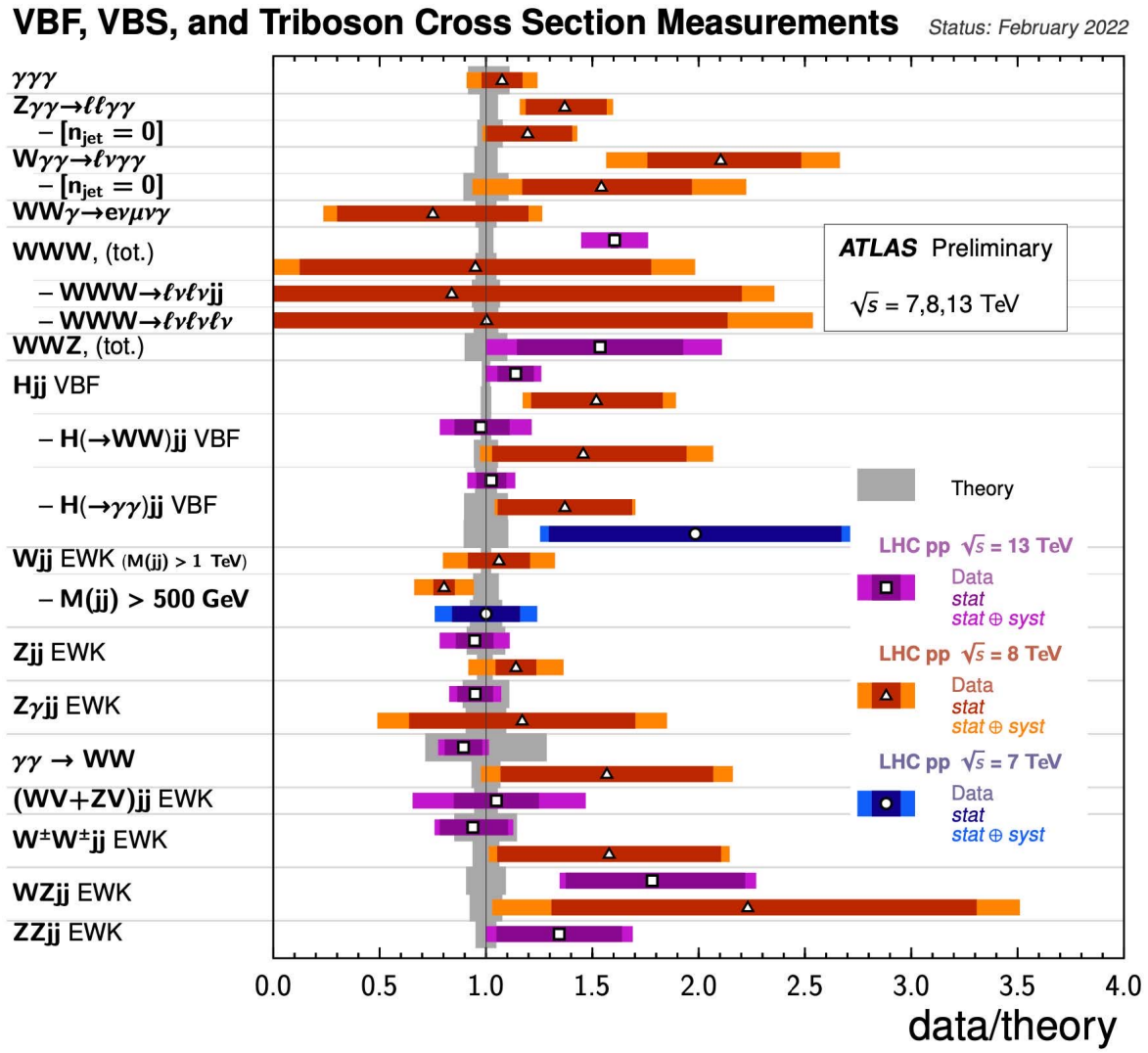
Conversion of limits to dim-8 operators with assumption that all $f_{M,i}$ except one are equal to zero.

Summary

- Overview (not exhaustive) of the latest massive diboson final state analyses from 2022 and 2023 performed at the ATLAS and CMS collaborations.
- Many jet associated diboson processes are observed with a more than 5σ with respect to the background only hypothesis.
- More precise limits on anomalous couplings with EFT interpretations (dim-6 and dim-8 operators) in many different channels are performed.
- First diboson longitudinal-longitudinal measurements performed for WZ and ZZ, with first observation of WZ longitudinal-longitudinal in ATLAS.
- Other BSM searches, study of CP properties, etc are also performed.
- Many more analyses coming soon with polarization measurements, EFT interpretations and BSM searches in the massive diboson channels.

Backup

Previous Multiboson Searches in Run 2: ATLAS



This talk includes latest results for:

- $ZZjj$: Differential Cross-section and EFT Interpretations
- Measurement of Longitudinal-longitudinal ZZ (Z_L, Z_L) and Study of CP Property
- (Same sign) $W^{\pm}W^{\pm}jj$:
- (Opposite Sign) $W^{+}W^{-}$
- (Opposite Sign) $W^{+}W^{-}jj$
- $W^{\pm}Z$ Joint Polarization Measurements

EFT Interpretations: Dimension-six op

Wilson coefficient	$\lvert\mathcal{M}_{d6}\rvert^2$ Included	95% confidence interval [TeV^{-2}] Expected	Observed
c_W/Λ^2	yes	[-1.3, 1.3]	[-1.2, 1.2]
	no	[-32, 32]	[-37, 28]
$c_{\widetilde{W}}/\Lambda^2$	yes	[-1.3, 1.3]	[-1.2, 1.2]
	no	[-17, 17]*	[0, 30]*
c_{HWB}/Λ^2	yes	[-16, 7]	[-16, 6]
	no	[-12, 12]	[-15, 10]
$c_{H\widetilde{W}B}/\Lambda^2$	yes	[-1.3, 1.3]	[-1.2, 1.2]
	no	[-67, 67]*	[-25, 130]*
c_{HB}/Λ^2	yes	[-13, 13]	[-12, 12]
	no	[-38, 38]	[-38, 38]
$c_{H\widetilde{B}}/\Lambda^2$	yes	[-13, 13]	[-12, 12]
	no	[-420, 420]*	[-200, 790]*

(Same sign) $W^{\pm}W^{\pm}jj$ ATLAS

ATLAS-CONF-2023-023

Event Selection:

- Expected purity of the EW, QCD and interference is 52%, 5.4% and 1.7%.

Exactly two signal leptons with $p_{\mathrm{T}} > 27$ GeV and the same electric charge with $\lvert\eta\rvert < 2.5$ for muons and with $\lvert\eta\rvert < 2.47$ excluding $1.37 \leq \lvert\eta\rvert \leq 1.52$ for electrons with $\lvert\eta\rvert < 1.37$ in the ee channel
$m_{\ell\ell'} \geq 20$ GeV 3rd lepton veto $\lvert m_{ee} - m_Z\rvert > 15$ GeV in the ee-channel
$E_{\mathrm{T}}^{\mathrm{miss}} \geq 30$ GeV
At least two jets Leading and subleading jets satisfying $p_{\mathrm{T}} > 65$ GeV and $p_{\mathrm{T}} > 35$ GeV, respectively b-jet veto for jets with $p_{\mathrm{T}} > 20$ GeV and $\lvert\eta\rvert < 2.5$ $m_{\mathrm{jj}} \geq 500$ GeV $\lvert\Delta y_{\mathrm{jj}}\rvert > 2$

Backgrounds:

- WZ/γ^* (22% of the signal event yield): One lepton escaping the third lepton veto requirement.
- Non-Prompt Lepton Background (12% of the signal event yield): W+jets, semi-leptonic $t\bar{t}$. Estimated using data-driven method
- Electron charge misidentification background: From Z and dileptonic $t\bar{t}$.
- Other backgrounds: $V\gamma$(2.4%), ZZ, $t\bar{t}V$, VVV (except same sign WW) (total 1.6%)

Same sign WWjj uncertainties

Source	Impact [%]
Experimental	
Electron calibration	0.4
Muon calibration	0.5
Jet energy scale and resolution	1.8
$E_{\mathrm{T}}^{\mathrm{miss}}$ scale and resolution	0.2
b-tagging inefficiency	0.7
Background, misid. leptons	3.1
Background, charge misrec.	0.8
Pileup modelling	0.2
Luminosity	1.9
Modelling	
EW $W^{\pm}W^{\pm}jj$, shower, scale, PDF & α_s	0.8
EW $W^{\pm}W^{\pm}jj$, QCD corrections	3.5
EW $W^{\pm}W^{\pm}jj$, EW corrections	0.8
Int $W^{\pm}W^{\pm}jj$, shower, scale, PDF & α_s	0.1
QCD $W^{\pm}W^{\pm}jj$, shower, scale, PDF & α_s	2.3
QCD $W^{\pm}W^{\pm}jj$, QCD corrections	0.9
Background, WZ scale, PDF & α_s	0.2
Background, WZ reweighting	1.7
Background, other	1.0
Model statistical	1.8
Experimental and modelling	6.7
Data statistical	7.4
Total	10.0

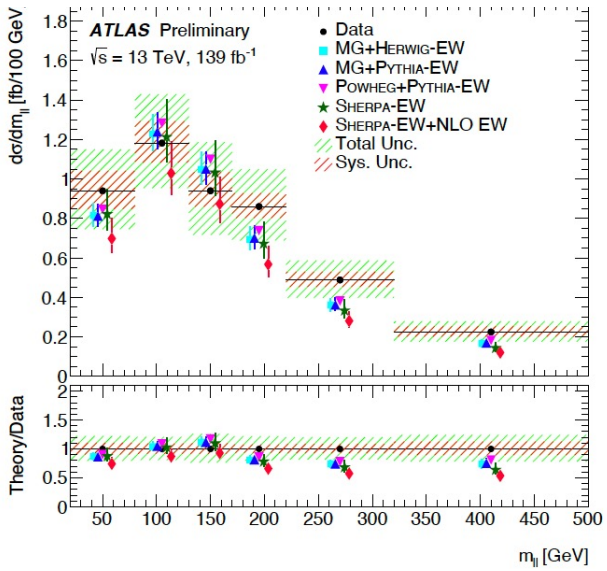
(Same sign) $W^{\pm}W^{\pm}jj$ ATLAS

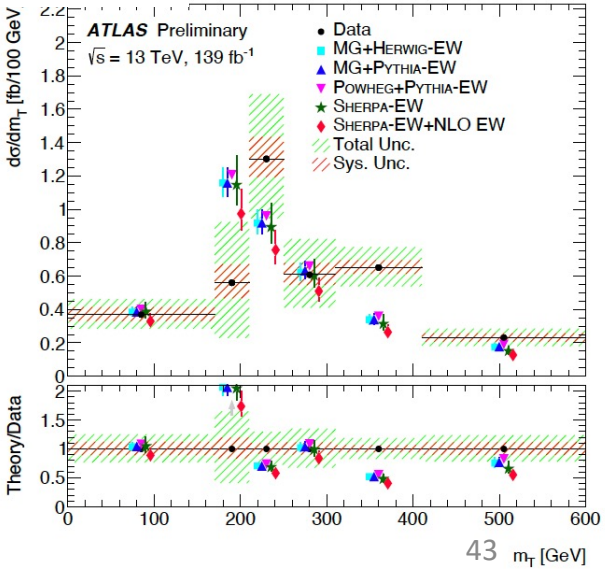
ATLAS-CONF-2023-023

- Fiducial Cross-section measurement: Fiducial region defined as close to analysis signal region and detector acceptance as possible.
  - Signal region split in 4 regions according to the lepton flavors in the final state

Description	$\sigma_{\text{fid}}^{\text{EW}}$, fb	$\sigma_{\text{fid}}^{\text{EW+Int+QCD}}$, fb
Measured cross section	$2.88 \pm 0.21\,(\text{stat.}) \pm 0.19\,(\text{syst.})$	$3.35 \pm 0.22\,(\text{stat.}) \pm 0.20\,(\text{syst.})$
MG_aMC@NLO+Herwig	$2.53 \pm 0.04\,(\text{PDF}) \pm^{0.22}_{0.19}\,(\text{scale})$	$2.93 \pm 0.05\,(\text{PDF}) \pm^{0.34}_{0.27}\,(\text{scale})$
MG_aMC@NLO+Pythia	$2.55 \pm 0.04\,(\text{PDF}) \pm^{0.22}_{0.19}\,(\text{scale})$	$2.94 \pm 0.05\,(\text{PDF}) \pm^{0.33}_{0.27}\,(\text{scale})$
Sherpa	$2.44 \pm 0.03\,(\text{PDF}) \pm^{0.40}_{0.27}\,(\text{scale})$	$2.80 \pm 0.03\,(\text{PDF}) \pm^{0.53}_{0.36}\,(\text{scale})$
Powheg Box +Pythia	2.67	–

- Differential cross-section measurement. Likelihood based unfolding used to get particle level distributions
- Good agreement between data/MC within uncertainties. χ^2 and p-value measured to check data-MC compatibility. P-values range from 0.014 to 0.623 across five variables used: $m_{\ell\ell}$, m_{jj}, m_T, $N_{gap\ jets}$(num of jets between two signal jets in rapidity) and Zeppenfeld variable.

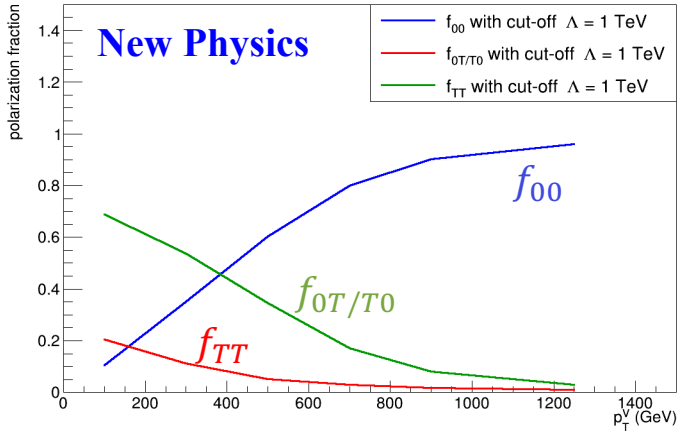




$W^{\pm}Z$ Polarization Studies in ATLAS

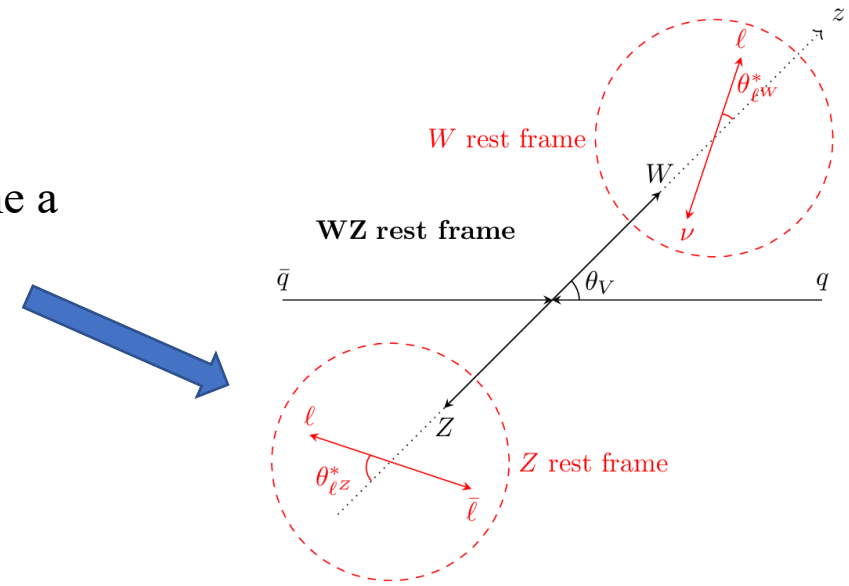
arXiv:2211.09435

- **Motivation:**
  - Goldstone Boson Equivalence Theorem: a phenomenon at high energies (PRD 103 (2021) 053007)
  - The V_0V_0 (both longitudinally polarized bosons) are the only polarization states that exhibit quadratic energy growth for BSM amplitudes, thus giving us a handle to search for new physics. (JHEP 02 (2018) 111)

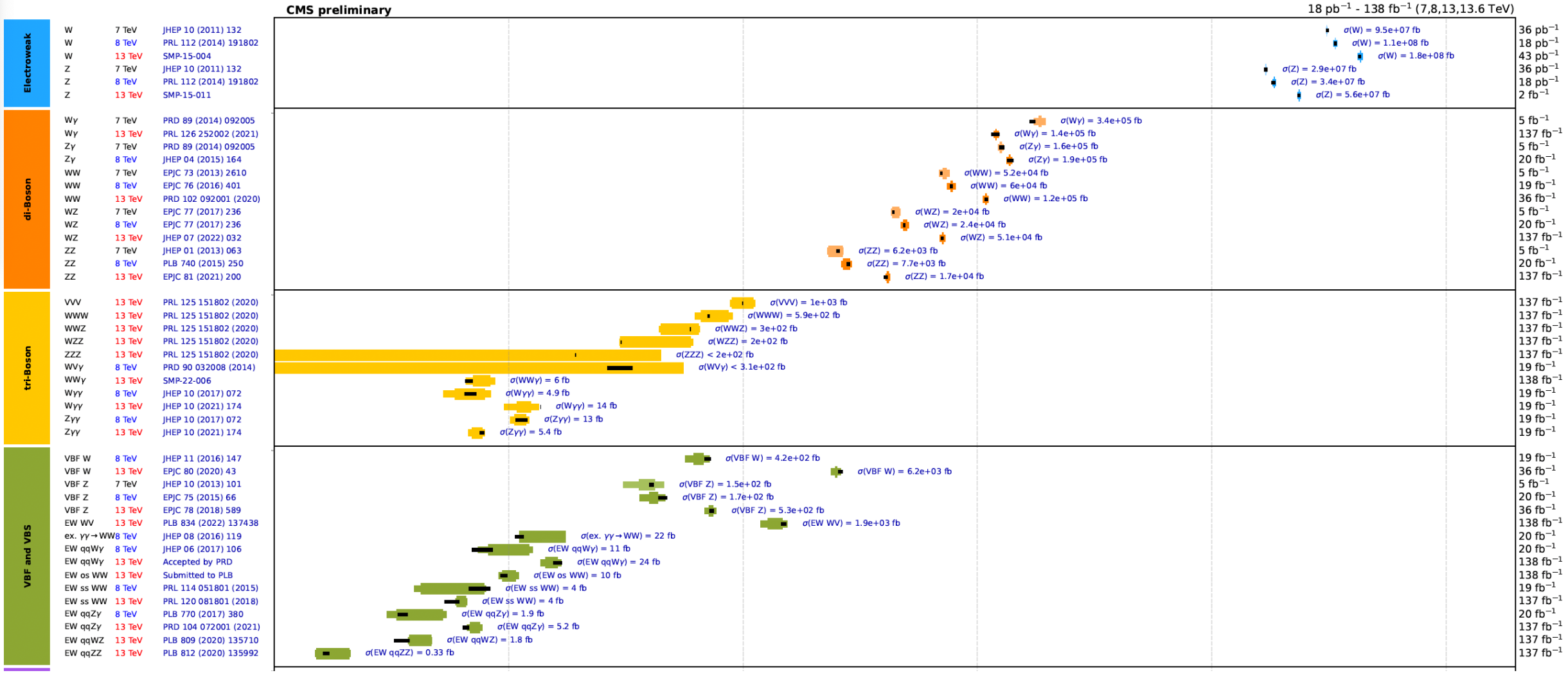


Polarization fractions as a function of p_T^V for a new physics model with a cut off $\Lambda = 1\,TeV$ using calculations from PRD 99 (2019) 055001

- **This is the first-ever observation of longitudinal-longitudinal joint polarization state in diboson production.**
- **Some of the challenges:**
  - The definition of polarization is not Lorentz invariant, so must define a frame – modified helicity frame
  - Should discriminate both bosons at once. Combining L and R polarization there are 4 configurations to distinguish (W_0Z_0, W_0Z_T, W_TZ_0, W_TZ_T, where 0 is longitudinal and T is transverse)



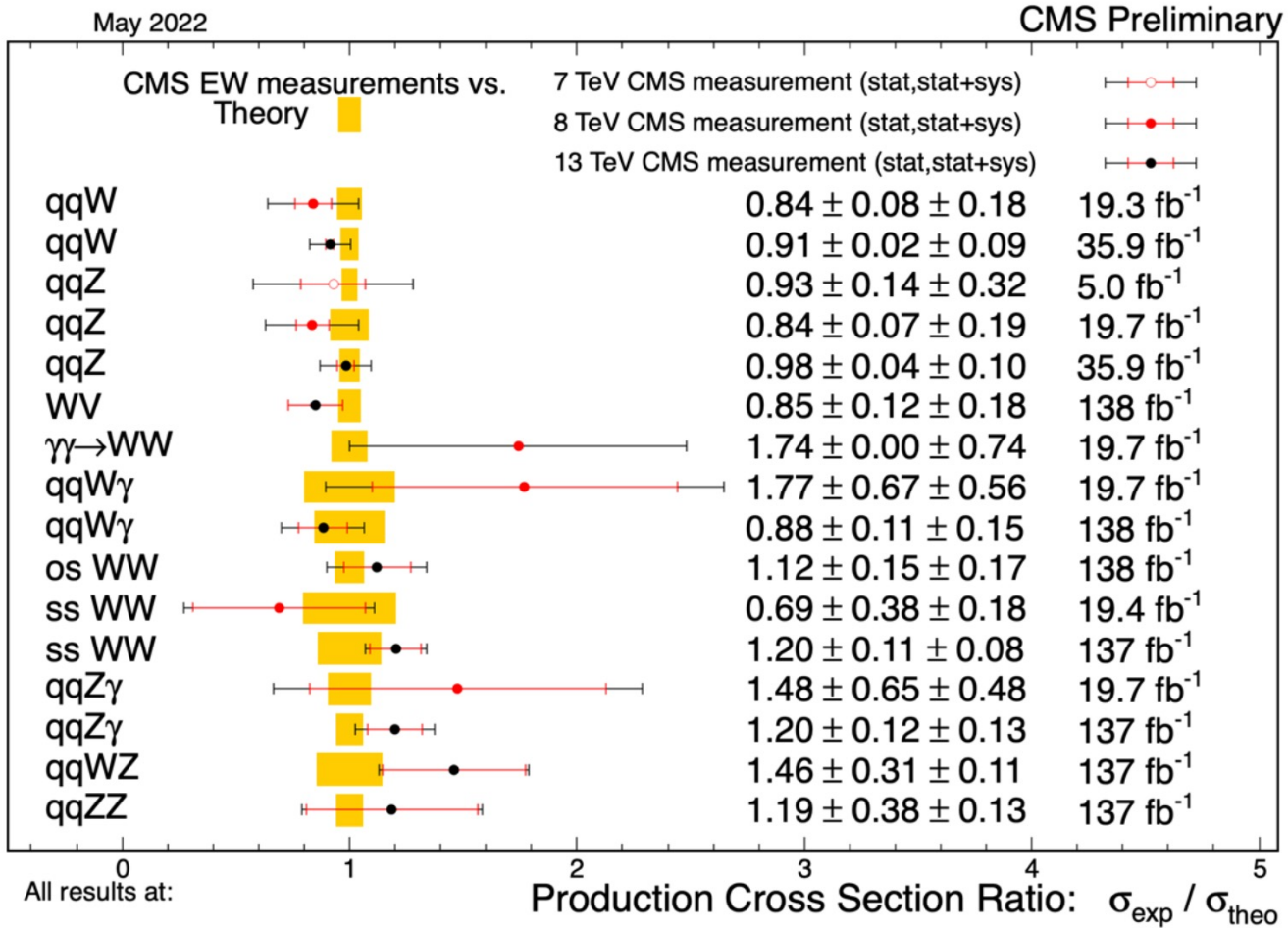
Previous Multiboson Searches in Run 2: CMS



X-axis: $\sigma(fb)$

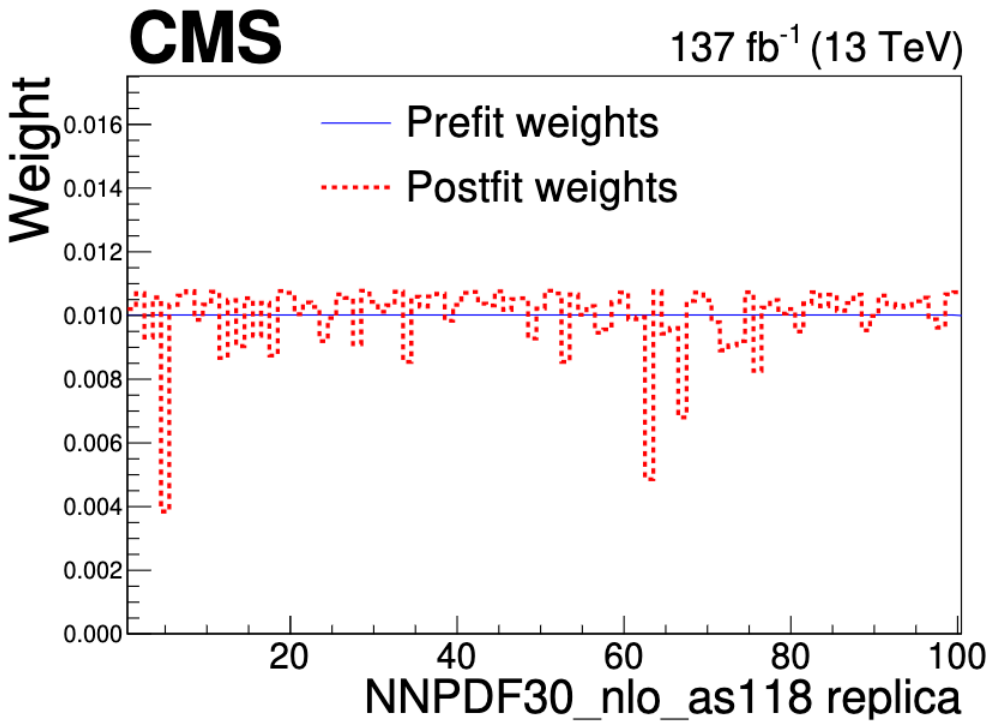
Ref:https://twiki.cern.ch/twiki/pub/CMSPublic/PhysicsResultsCombined/CMSCrossSectionSummaryBarChart.pdf

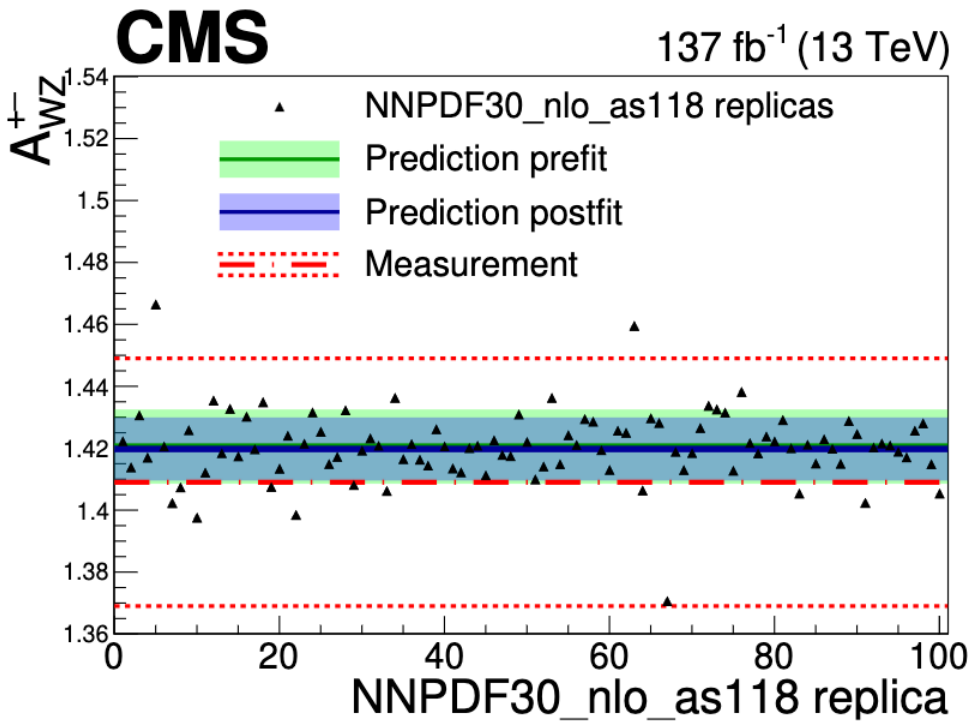
Previous Multiboson Searches in Run 2: CMS



Ref:https://twiki.cern.ch/twiki/pub/CMSPublic/PhysicsResultsCombined/CMSCrossSectionSummaryBarChart.pdf

WZ CMS


CMS
137 fb-1 (13 TeV)
Weight
Prefit weights
Postfit weights
0.016
0.014
0.012
0.010
0.008
0.006
0.004
0.002
0.000
20
40
60
80
100
NNPDF30_nlo_as118 replica

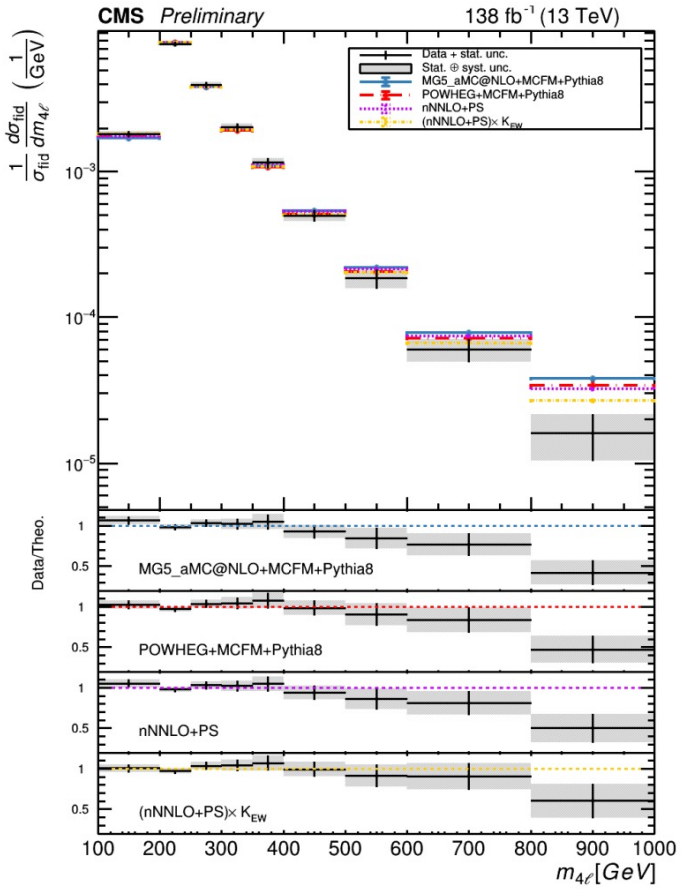

CMS
137 fb-1 (13 TeV)
A±WZ
NNPDF30_nlo_as118 replicas
Prediction prefit
Prediction postfit
Measurement
1.54
1.52
1.5
1.48
1.46
1.44
1.42
1.4
1.38
1.36
0
20
40
60
80
100
NNPDF30_nlo_as118 replica

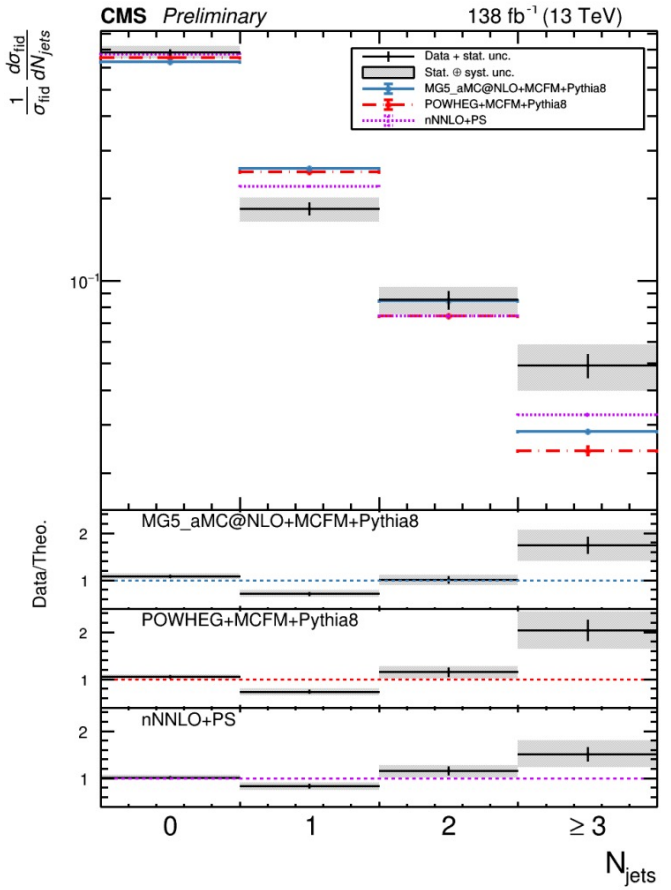
$ZZ + jets$ CMS

CMS PAS SMP-22-001

- Unfolding using the iterative D'Agostini's method including correction for background contributions.
- Differential cross-section measured for: number of jets, jets transverse momentum and pseudorapidity, invariant mass of dijet system and pseudorapidity difference of the highest-pT and second-highest-pT jets, invariant mass of the four leptons with different jet multiplicities in the events

- The nNNLO+PS prediction describes the distribution of jet multiplicities better than MadGraph5 aMC@NLO and POWHEG
- the inclusion of EW corrections improves the description of the $m_{4\ell}$ distribution.
- Further improvement of the predictions is required to describe the ZZ+jet production in the whole phase space.





Zjj CMS: EFT Limits

$$-0.24 < f_{T0}/\Lambda^4 < 0.22$$
$$-0.31 < f_{T1}/\Lambda^4 < 0.31$$
$$-0.63 < f_{T2}/\Lambda^4 < 0.59$$
$$-0.43 < f_{T8}/\Lambda^4 < 0.43$$
$$-0.92 < f_{T9}/\Lambda^4 < 0.92$$

$\gamma\gamma \rightarrow WW$ and $\gamma\gamma \rightarrow ZZ$: EFT interpretations

arXiv:2211.16320v2

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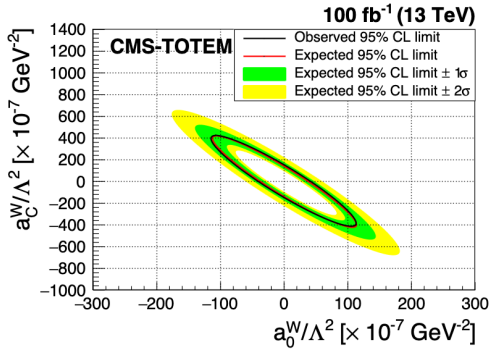
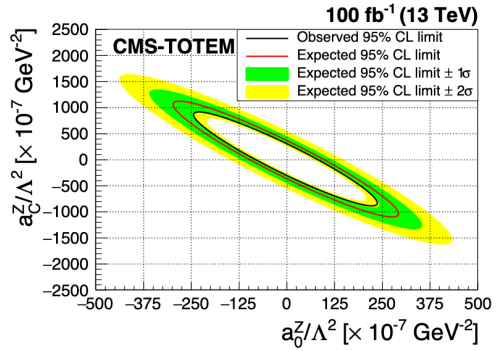
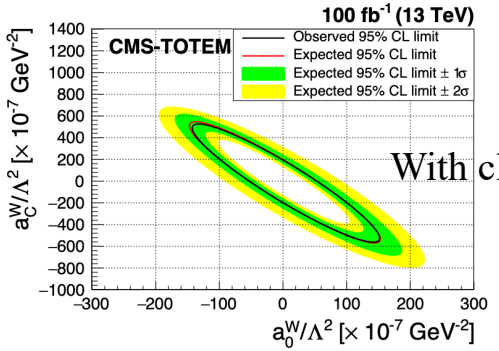
$\lvert a_0^Z/\Lambda^2\rvert$	$0.9\ (1.0) \times 10^{-5}\,\text{GeV}^{-2}$	—
$\lvert a_C^Z/\Lambda^2\rvert$	$4.0\ (4.5) \times 10^{-5}\,\text{GeV}^{-2}$	—







With clipping imposed

Expected and observed limits on dimension-6 AQGC operators