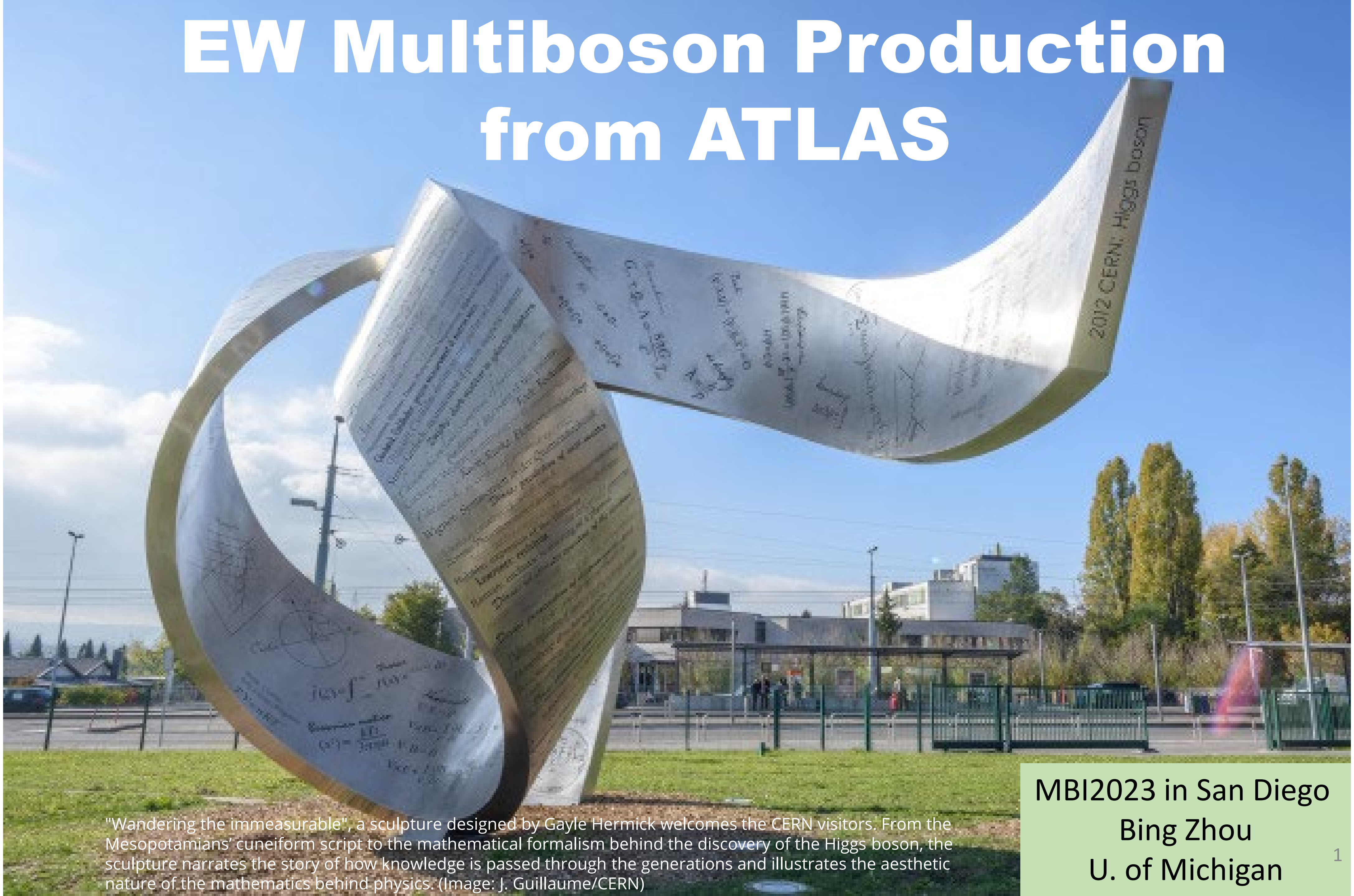
EW Multiboson Production from ATLAS



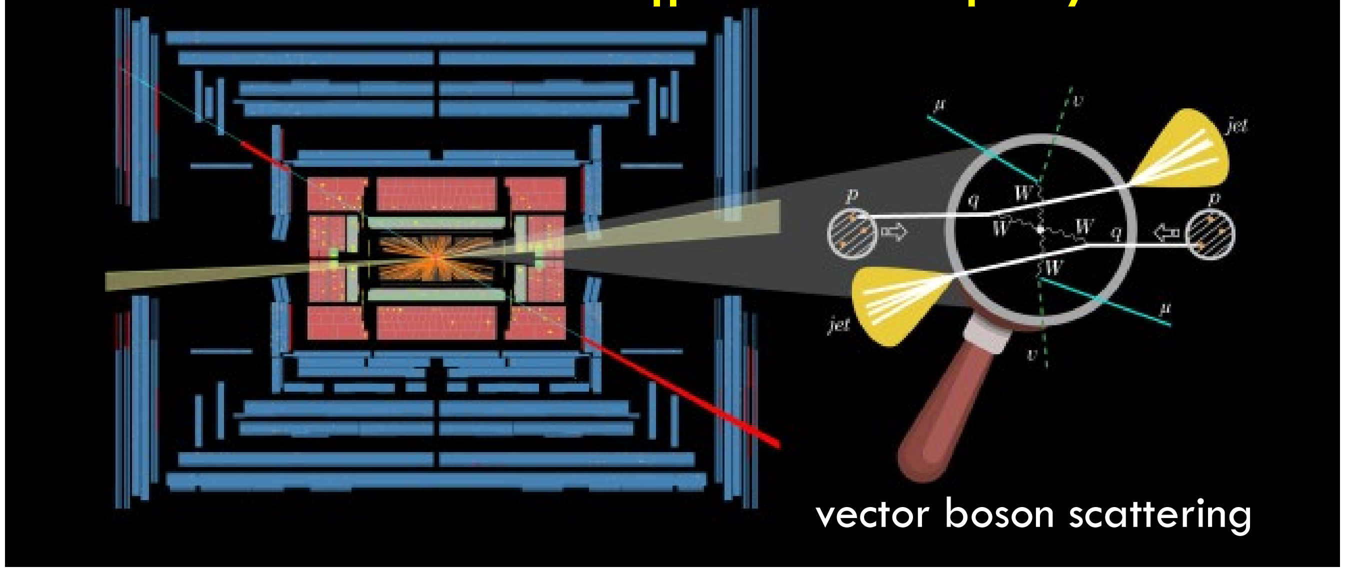
"Wandering the immeasurable", a sculpture designed by Gayle Hermick welcomes the CERN visitors. From the Mesopotamians' cuneiform script to the mathematical formalism behind the discovery of the Higgs boson, the sculpture narrates the story of how knowledge is passed through the generations and illustrates the aesthetic nature of the mathematics behind physics. (Image: J. Guillaume/CERN)

MBI2023 in San Diego
Bing Zhou
U. of Michigan

Introduction

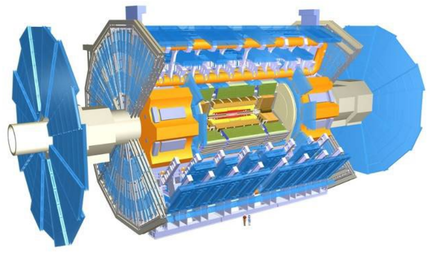
- Study multi-boson interactions, by high-precision measurements and probing rare processes, to test SM and search for its breakdown.
- Particularly, by studying vector boson scattering, physicists can investigate the Higgs mechanism in the highest energy domain accessible, where there may be signs of new physics.

ATLAS WWjj Event Display



Outline

Recent new results

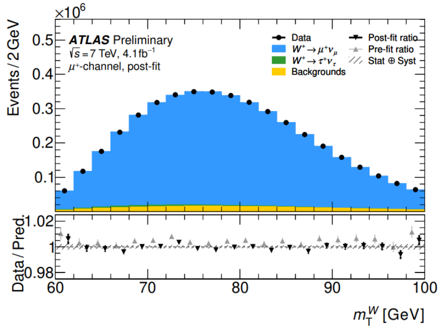


The ATLAS Experiment at the LHC

Physics runs since 2009 (Run 1, 2, 3,…)

Single W and Z

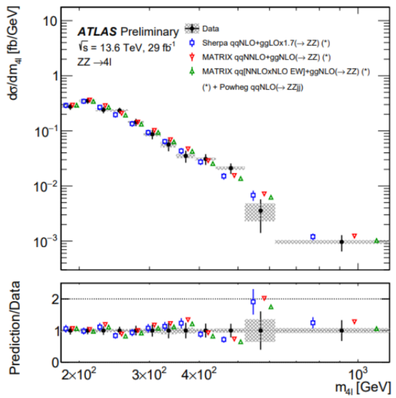
W mass



ATLAS-CONF-2023-004

Di-boson

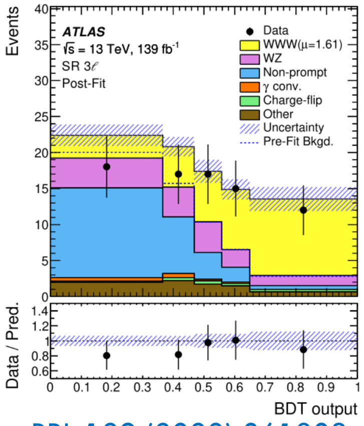
ZZ (Run 3)



ATLAS-CONF-2023-062

Tri-boson

WWW



PRL 129 (2022) 061803

Single Z and W production -- Standard Candles

Large production cross-section, enabling high-precision measurements of SM parameters, m_Z, m_W, $\sin^2\theta_W$, α_s, PDF, detector calibration, E, and P scales, …

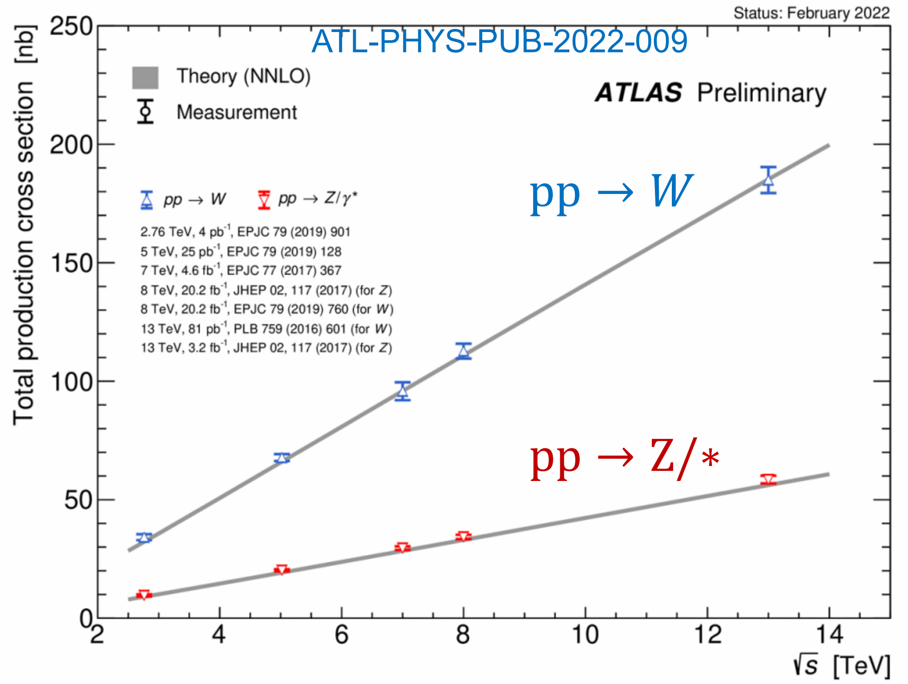
$Z \rightarrow \ell\ell$ and $W \rightarrow \ell\nu$

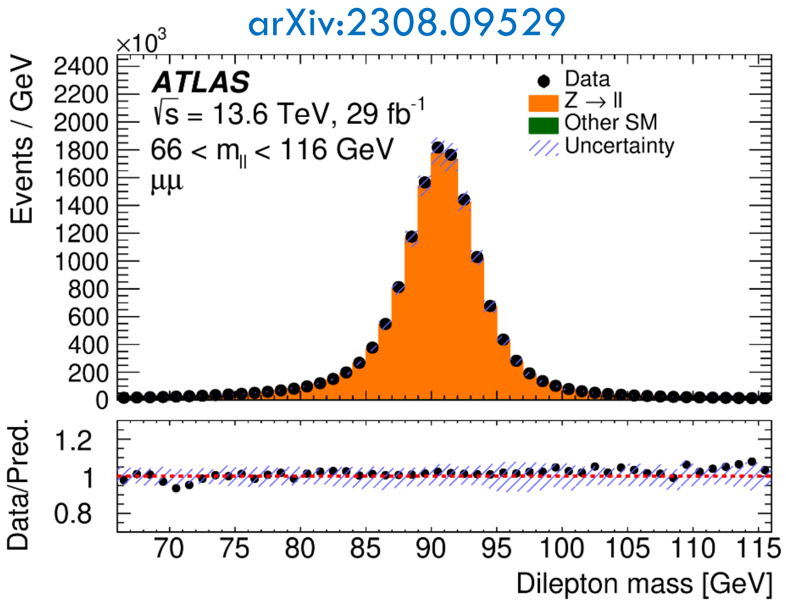
$m_{\ell\ell}$ of two high p_T isolated leptons (e,μ):

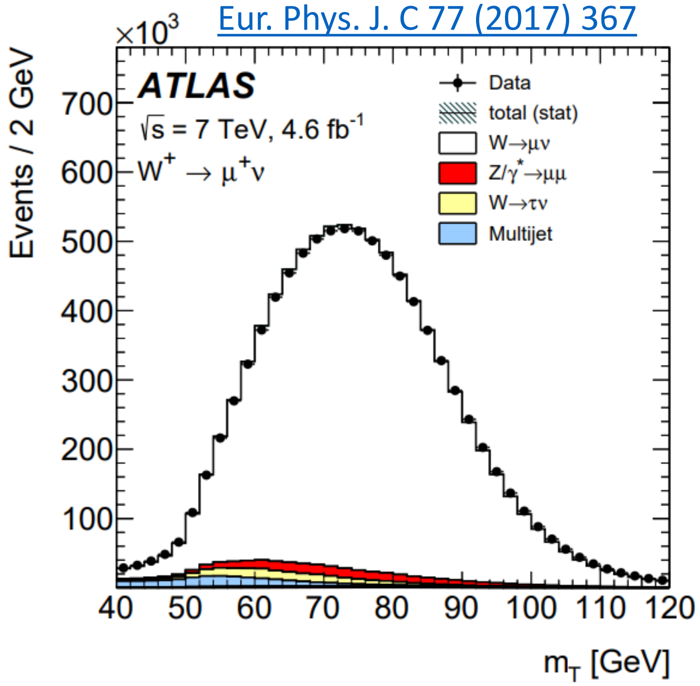
$$m_{\ell\ell}^2 = (E_{\ell 1} + E_{\ell 2})^2 - (\vec{p}_{\ell 1} + \vec{p}_{\ell 2})^2$$
$$\approx 2E_{\ell 1}E_{\ell 2}(1-\cos\alpha)$$

For $W \rightarrow \ell\nu$ decays, full mass reconstruction is not possible. Instead, a transverse mass is reconstructed:

$$m_T = \sqrt{2E_T^{\ell}\not{E}_T(1-\cos\phi_{\ell\nu})}$$







Recent new results

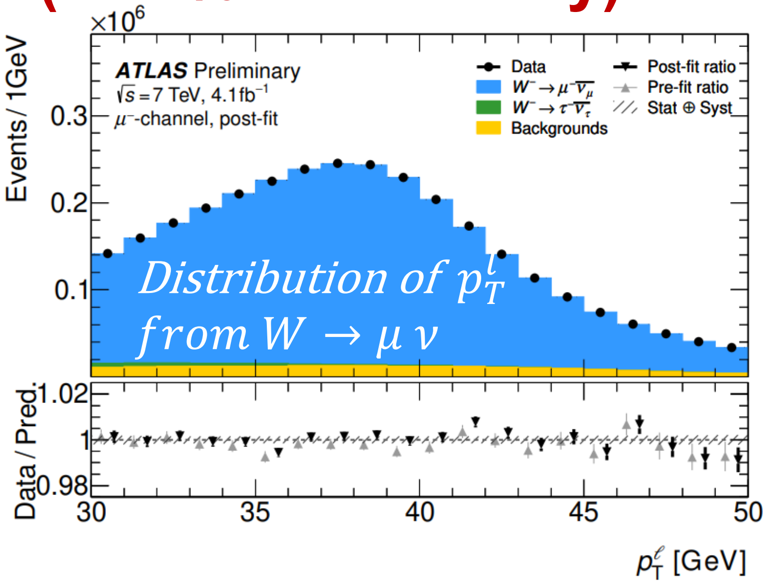
pT: sensitive to higher-order corrections

- m_W (ATLAS-CONF-2023-004)
- $\alpha_s(m_Z)$(ATLAS−CONF−2023−015)
- Z pT and Y at 8 TeV(ATLAS-CONF-2023-013)
- W pT and Z pT with low pile-up data (ATLAS-CONF-2023-028)

W mass re-measurement from ATLAS

m_W =80360 ± 5 (stat.) ± 15 (syst.) = 80360 ± 16 MeV (0.02% uncertainty)

- The revisited measurement from 2017, using the same data, to determine m_W from the distributions of p^l_T and m_T
- Using a more advanced physics model and profile likelihood fitting: Reduce systematic uncertainties from 19 MeV to 16 MeV



Physics modeling

Baseline: Pythia AZ tune (based on Z boson)

- Z boson data, Parton Shower variations

New verifications:

- AZ tune describes hadronic recoils spectrum of W's in low-pileup data at 5 TeV within experimental uncertainties
- DTRurbo (resumption) agrees with AZ tune

Treatment of angular coeff. Unchanged

Parton Distribution Functions:

- Studied full set of available PDF Sets at NNLO: CT10, CT14, CT18, MMHT2014, MSHT20, NNPDF3.1, NNPDF4.0
  - **New Baseline: CT18**

Analysis improvements

Multijet background estimation

- Systematic shape variations using PCA
- New transfer function from CR to SR
- Reduction of uncertainty by 2 MeV

EWK uncertainty evaluated at reco. level:

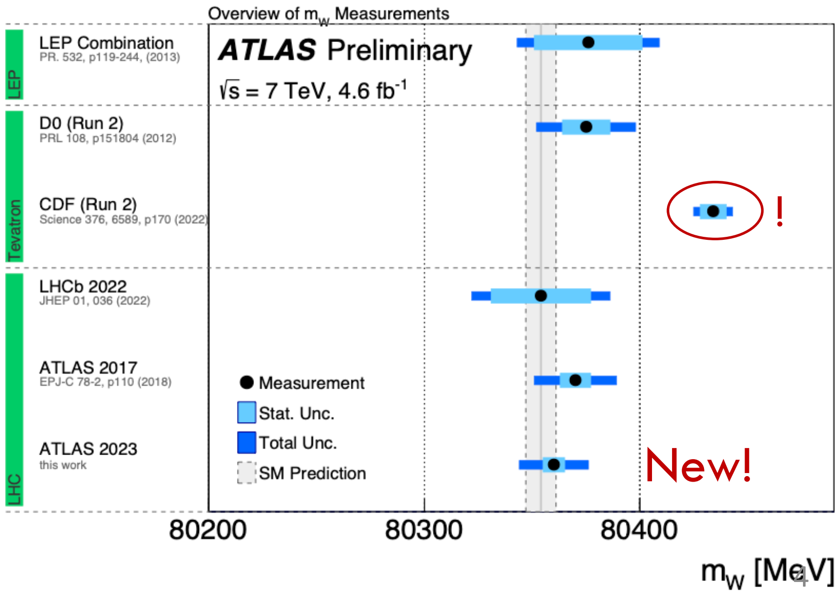
- Increased uncertainty by 1-2 MeV

Recovery data in the electron channel

- Increased statistics by 1.5%

Add W width as NP parameter

Improving random generator setup for the electron energy calibration



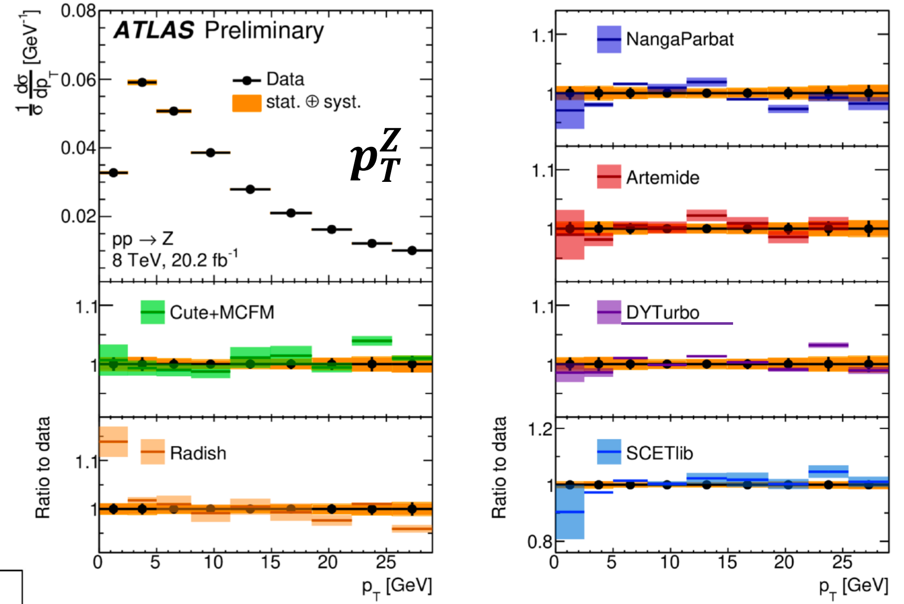
p_T^Z and $\alpha_s(M_Z)$ Measurement (8 TeV)

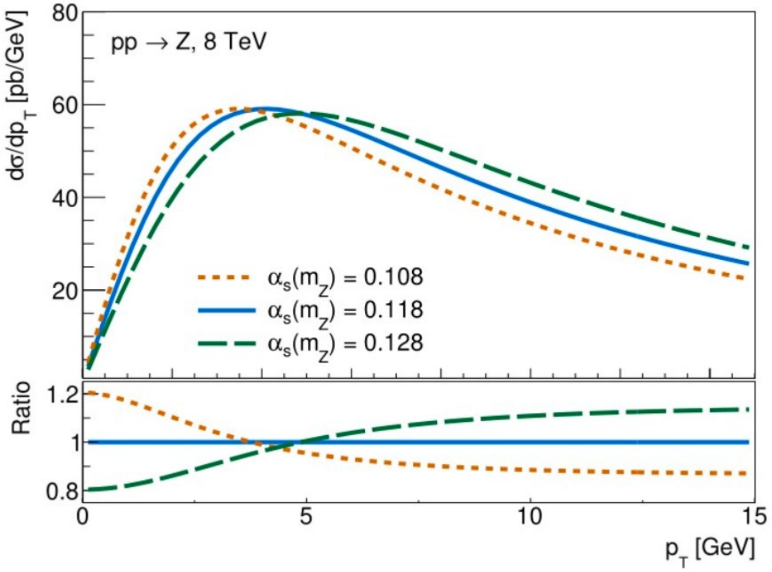
ATLAS-CONF-2023-013

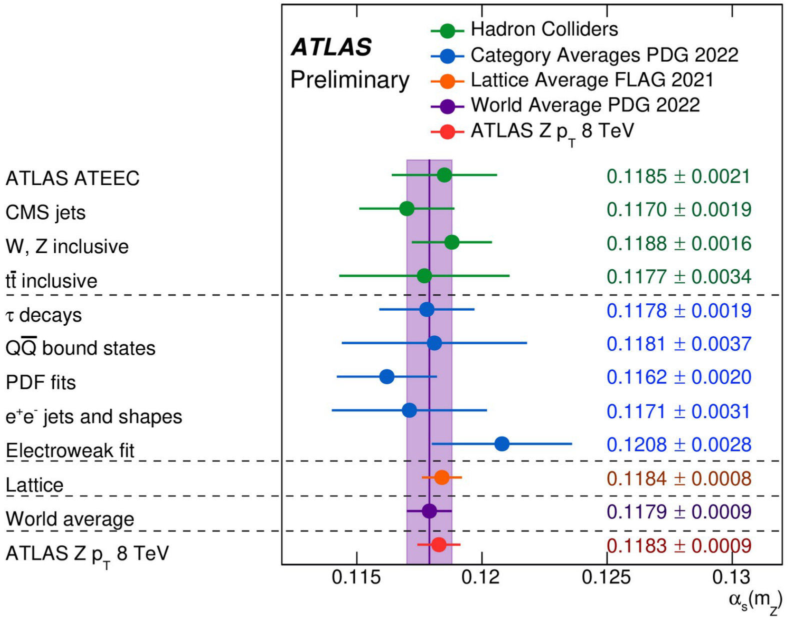
ATLAS−CONF−2023−015

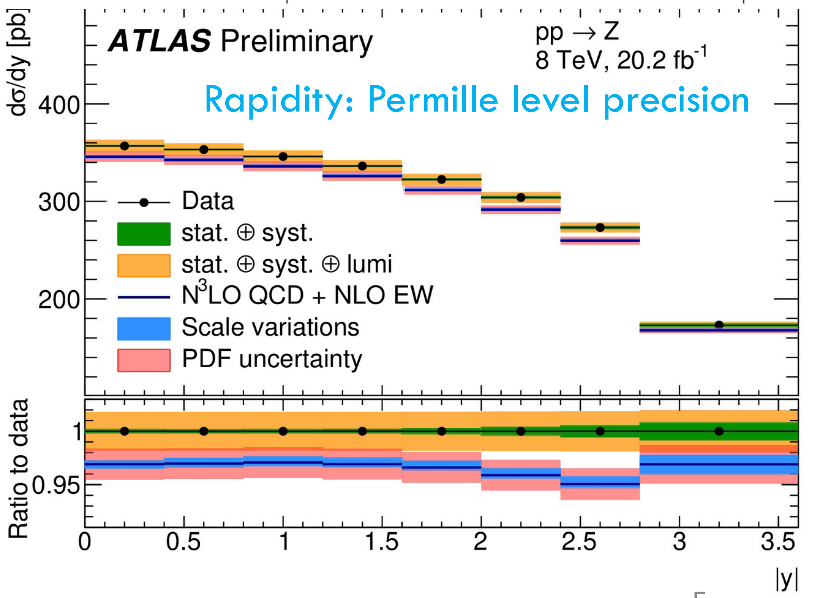
- **Differential cross-section measurements: pT and rapidity Y**
  - The first comparison to N³LO QCD predictions and N⁴LL resummation
  - Stringent test of the state-of-art QCD theories
- **Measurement of $\alpha_s(m_Z)$ from the Z pT**
  - Z bosons produced in hadron collisions recoil against QCD initial-state radiation: ISR gluons will boost the Z in the transverse plane
  - Most precise experimental determination of $\alpha_s(m_Z)$ (uncertainty~0.7%)

$$\alpha_s(M_Z) = 0.11828^{+0.00084}_{-0.00088}$$









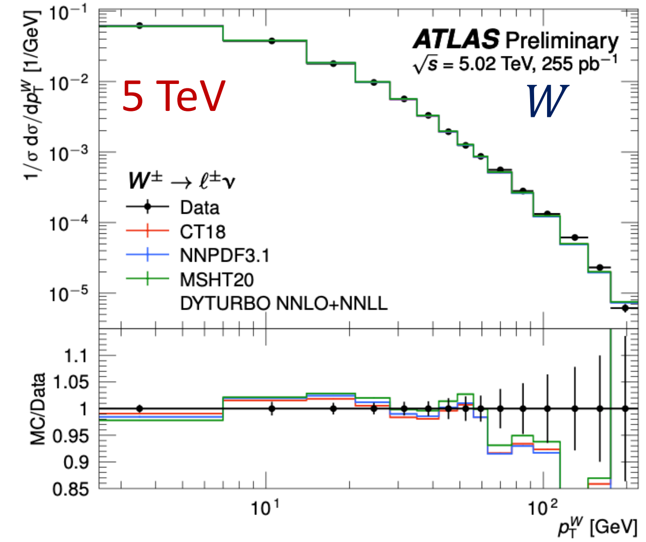
W and Z Production at 5 and 13 TeV

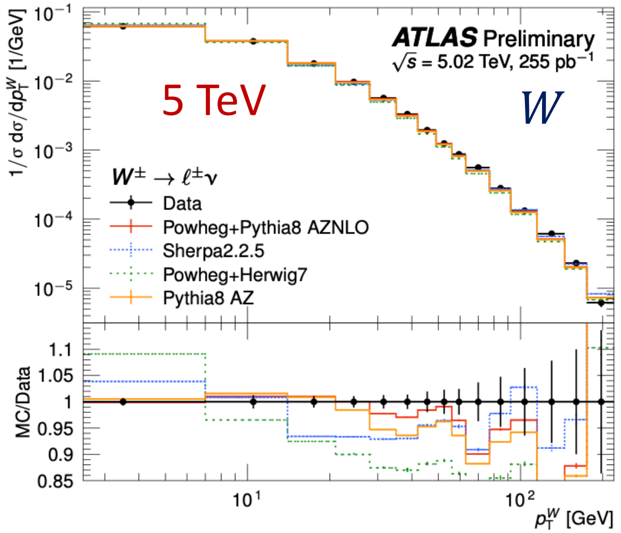
Precision pT measurement

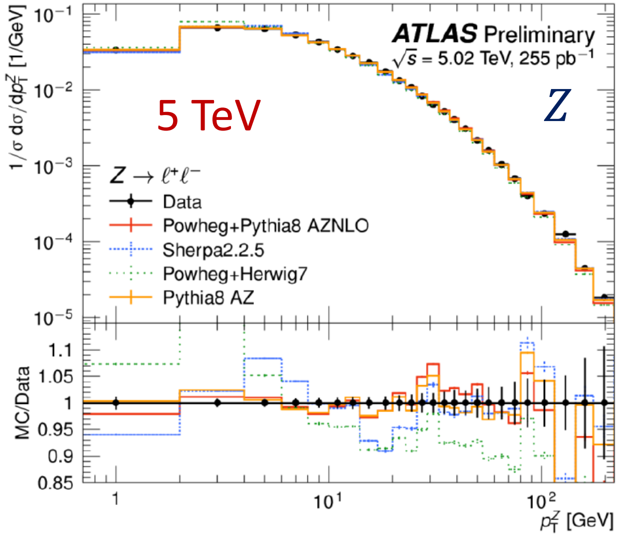
ATLAS-CONF-2023-028

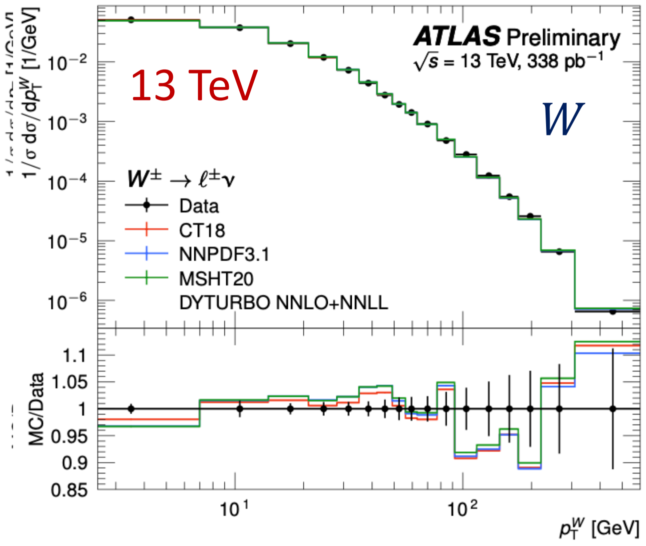
Compared to DYTURBO predictions with different PDF sets

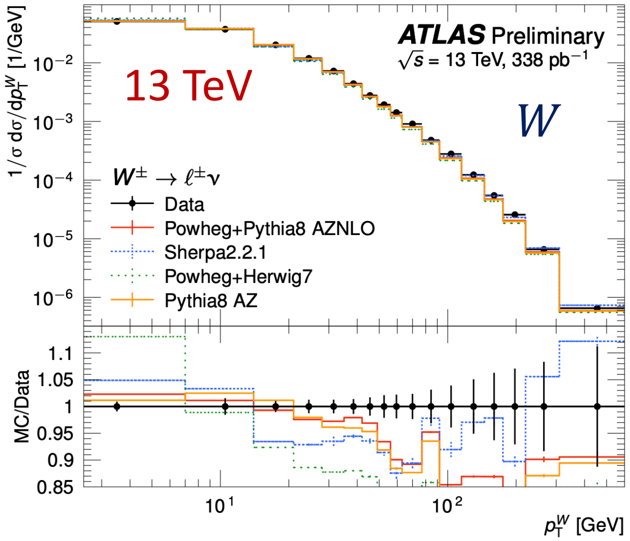
Compared with different Monte Carlo predictions

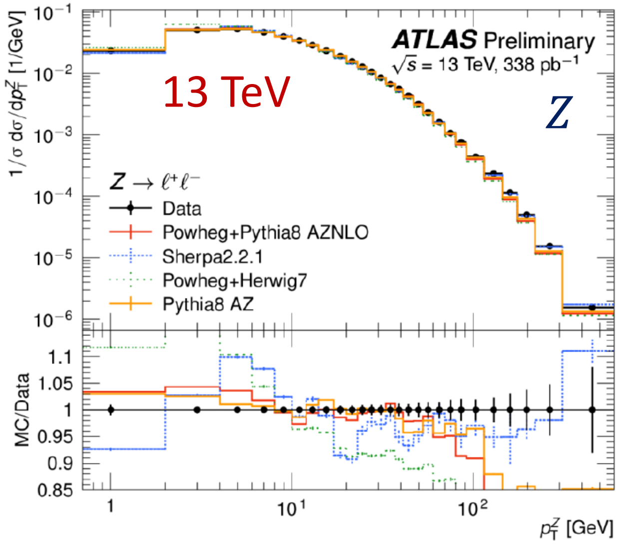








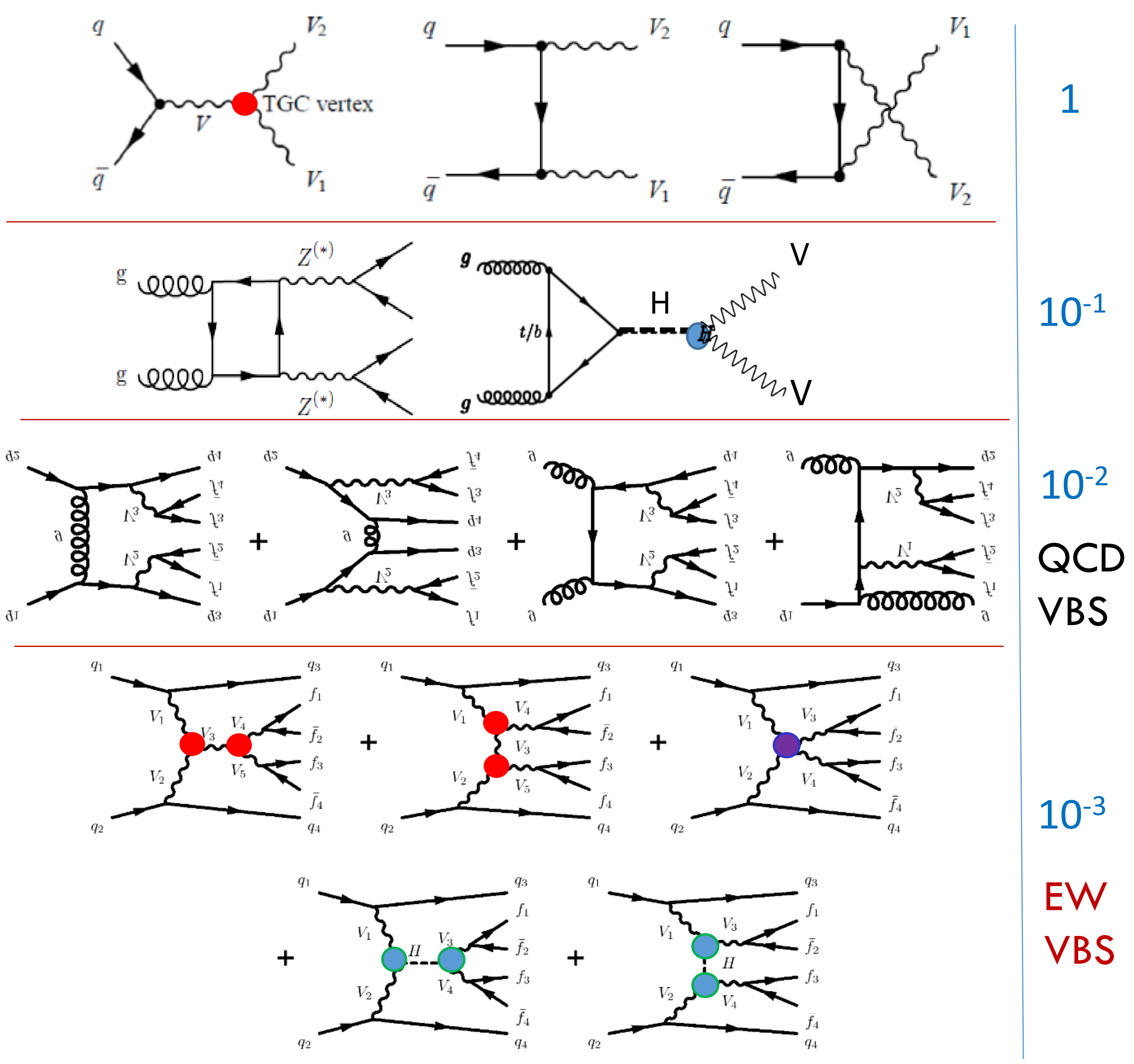




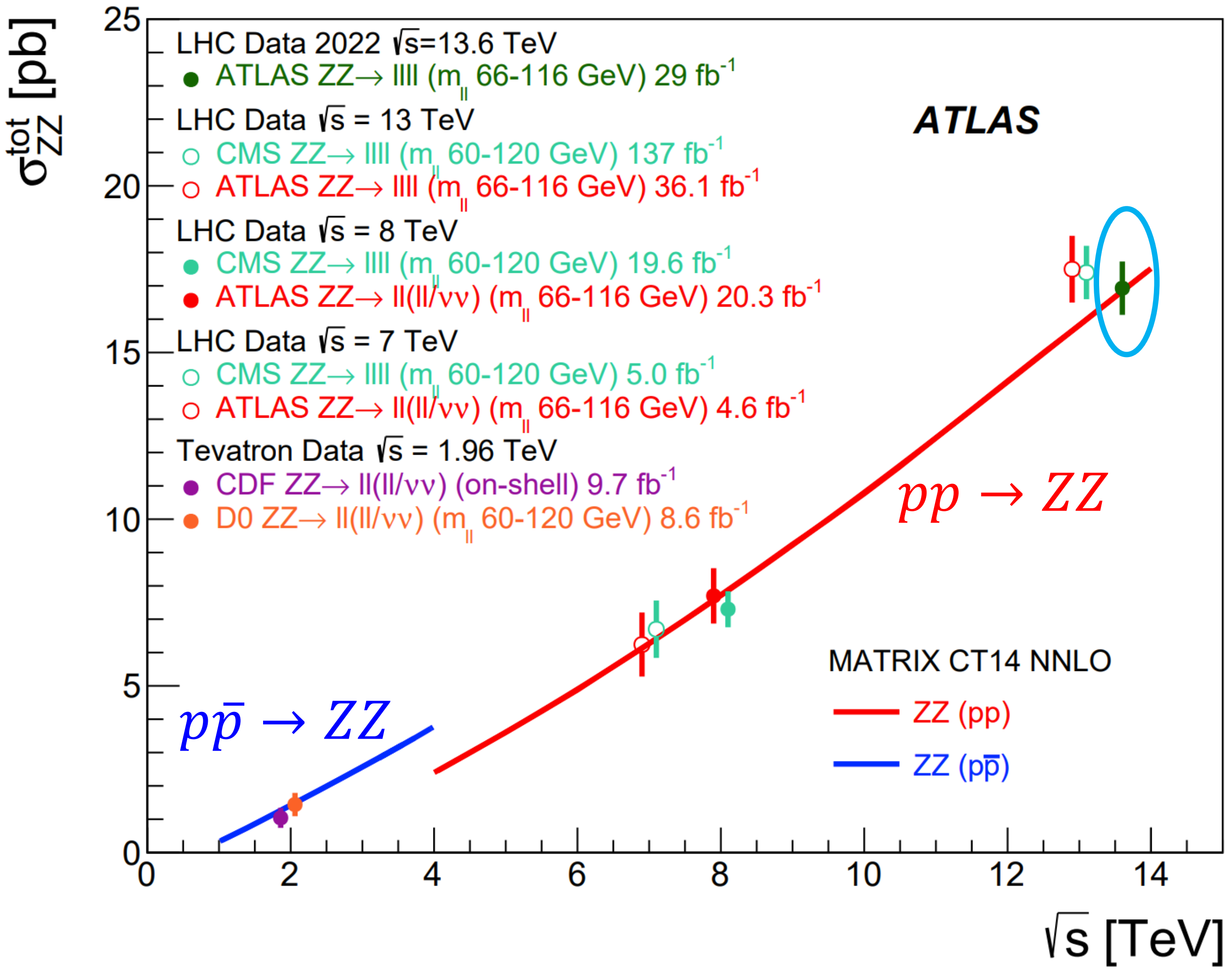
Diboson Production at the LHC

- Studying of VV (V= W/Z/γ) production has been an active research area at the LHC
- Vector-boson scattering and fusion is the production of VV involving EW triple and quartic gauge couplings, and Higgs boson exchange at tree level. Provides a test of EW Symmetry Breaking - still to be proven that the presence of discovered Higgs boson preserves the unitarity of the longitudinal polarized VV scattering.
- VBS/VBF processes measurement at the energy frontier is important to test the SM through the interplay of electroweak and QCD
- Strong (+ EW) interactions result in the irreducible background for pure EW processes
- Clean signature with two forward jets with large dijet invariant mass and $|\Delta\eta|$ gap

Production diagrams and rel. rates



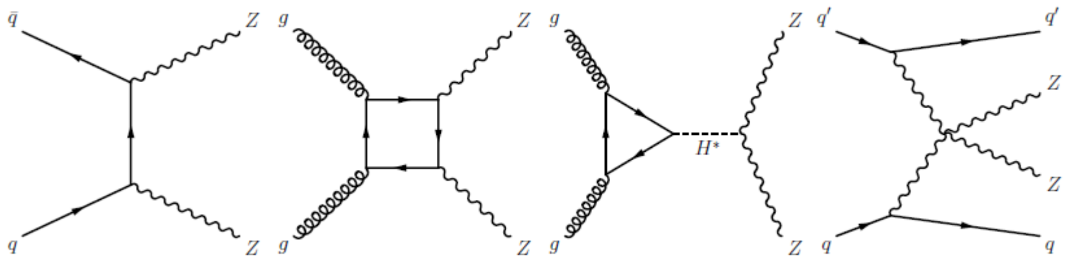
Total ZZ production cross-section vs $\sqrt{s}$



New from Run 3

Diboson ZZ Production at 13.6 TeV

ATLAS-CONF-2023-062

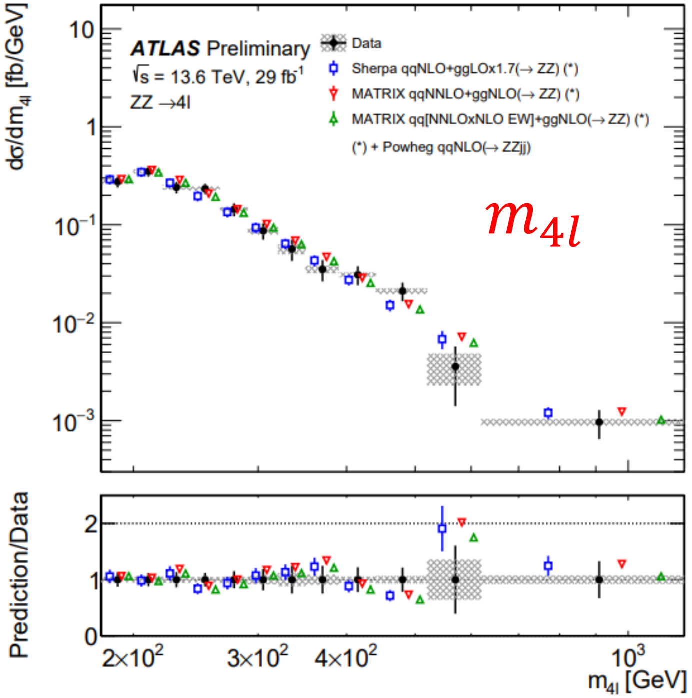


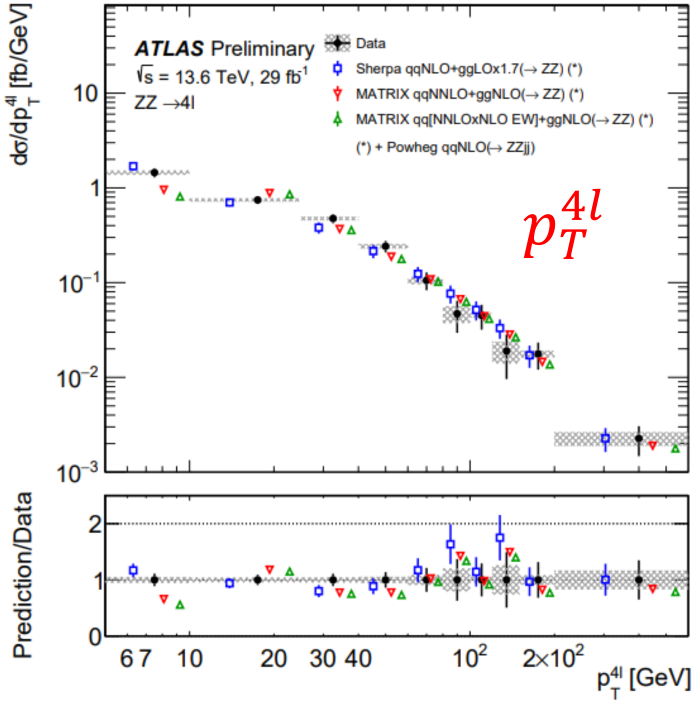
	Fiducial phase space	Total lepton phase space
Muon selection	Bare, $p_T > 5$ GeV , $\|\eta\| < 2.5$	Born
Electron selection	Dressed, $p_T > 7$ GeV , $\|\eta\| < 2.47$	Born
Four-lepton signature	≥ 2 SFOC pairs	≥ 2 SFOC pairs
Lepton kinematics	$p_T > 27/10$ GeV	
Lepton separation	$\Delta R(\ell_i, \ell_j) > 0.05$	
J/ψ veto	$m_{ij} > 5$ GeV	$m_{ij} > 5$ GeV
Z mass window	$66 < m_{\ell\ell,1}, m_{\ell\ell,2} < 116$ GeV	$66 < m_{\ell\ell,1}, m_{\ell\ell,2} < 116$ GeV
ZZ on-shell	$m_{4l} > 180$ GeV	

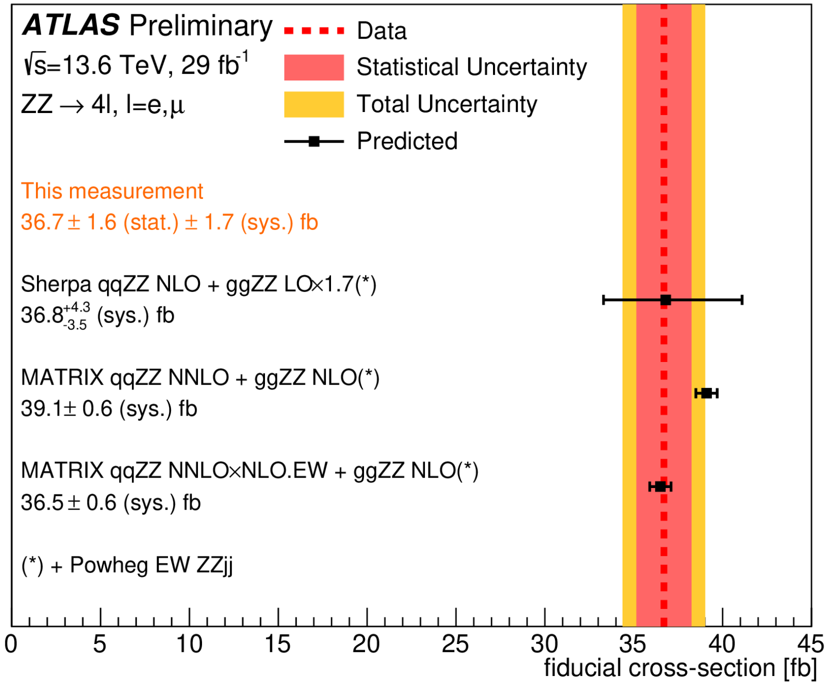
$29\ \text{fb}^{-1}$

Process	$q\bar{q} \to ZZ$	$gg \to ZZ$	EW $qq \to ZZ + 2j$	$t\bar{t}Z$	VVV	Reducible	Total	Data
Yield	514.8 ± 49.6	73.6 ± 44.3	4.7 ± 1.0	5.5 ± 0.8	2.1 ± 0.2	25.4 ± 8.1	626.1 ± 88.4	625

The measurements are well described by the calculations from fixed-order calculations with accuracies up to NNLO QCD+NLO EW







Observation and Cross-section Measurement of EW VBS ZZ Production

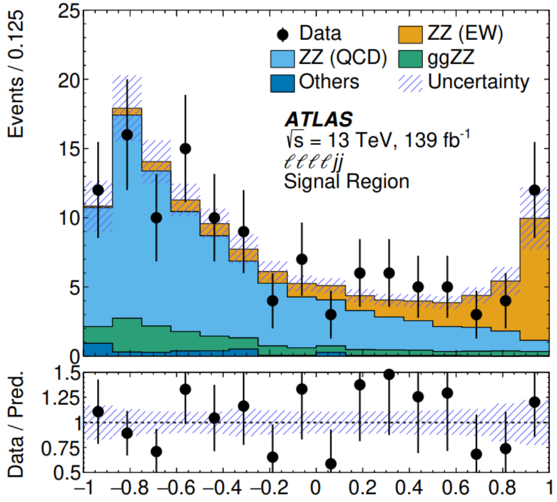
1st obsservation [Nature Physics 19 (2023) 237–253]; Differential cross-section: arVix:2308.12324

- Extracting inclusive cross-section in two SRs
- SR: EW selection + Z-mass (ll) window; 2 jets with $y_{j_1} \cdot y_{j_2} < 0$, $m_{jj} > 400/300$ GeV, $|\Delta y_{jj}| > 2$
- Large bkg. from WZ and non-resonant ll in llvvjj

- **Using BDT to separate EW and QCD ZZjj**
- Also fitting QCD CR to constrain background
- **EW ZZjj cross-section : 0.70 ± 0.18 fb**
  (one of the smallest measured by ATLAS)

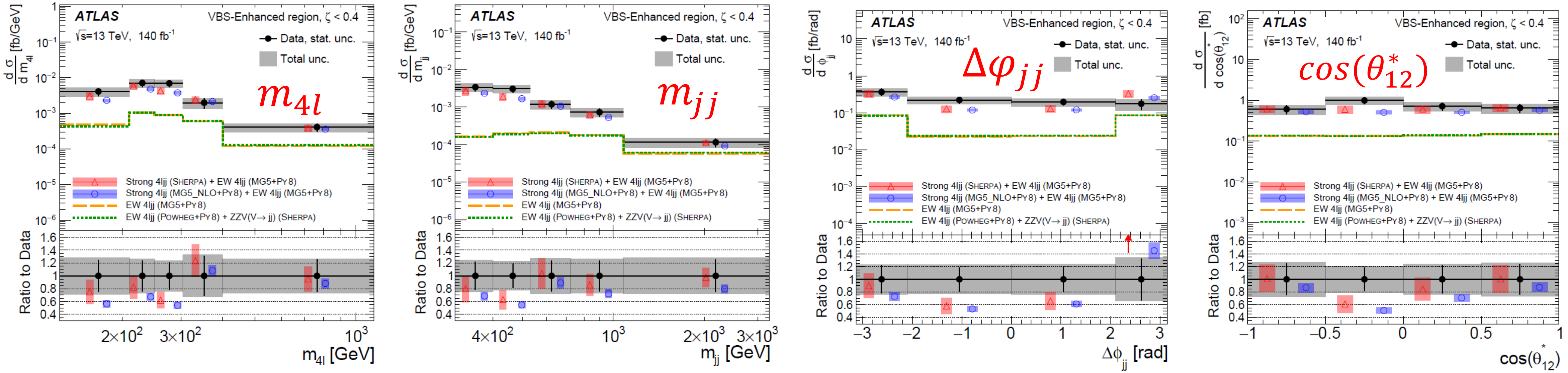
Significance of EW $ZZjj$ processes: **5.7σ**

Process	$\ell\ell\ell\ell jj$	$\ell\ell\nu\nu jj$
EW $ZZjj$	31.4 ± 3.5	15.0 ± 0.8
QCD $ZZjj$	77 ± 25	17.2 ± 3.5
QCD $ggZZjj$	13.1 ± 4.4	3.5 ± 1.1
Non-resonant-$\ell\ell$	–	21.4 ± 4.8
WZ	–	24.6 ± 1.1
Others	3.2 ± 2.1	1.2 ± 0.9
Total	124 ± 26	82.9 ± 6.4
Data	127	82



Boosted decision trees

Unfolded differential cross sections

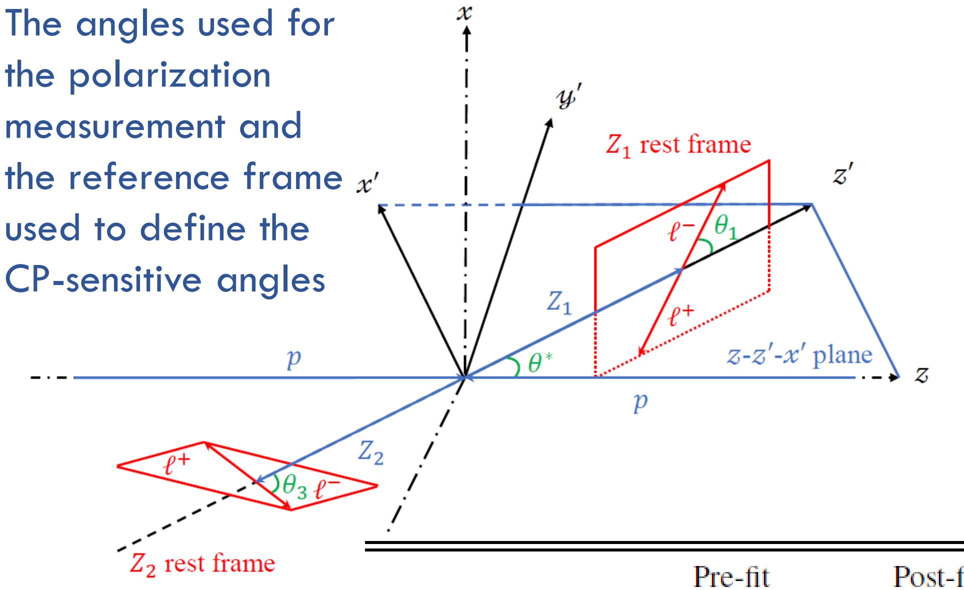


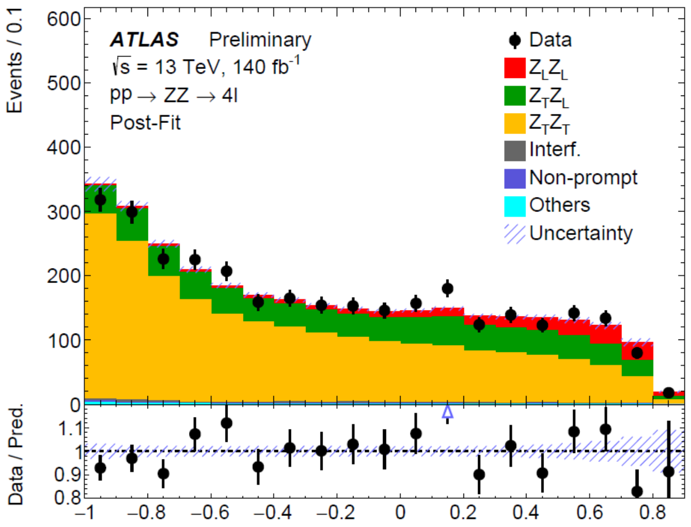
ATLAS-CONF-2023-038

Evidence of longitudinally polarized $Z_L Z_L$ production

The polarization measurement of massive weak bosons is a direct probe of the EWSB, through which the W and Z bosons obtain the longitudinally polarized state. Diboson polarization measurements and especially those probing longitudinally polarized vector bosons provide unique sensitivity to new physics beyond the SM.

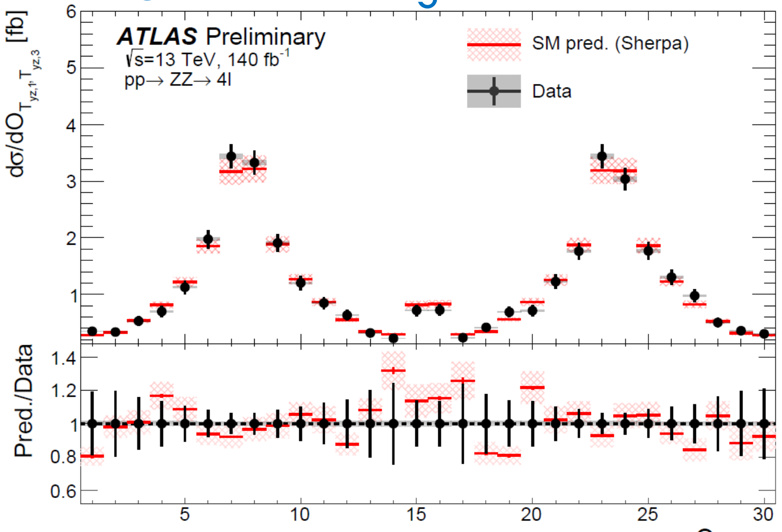
The angles used for the polarization measurement and the reference frame used to define the CP-sensitive angles





Boosted decision trees

a CP-sensitive angular observable



Defined from the 2D distribution of Tyz

$$T_{yz,1(3)} = \sin\phi_{1(3)} \times \cos\theta_{1(3)}$$

		Pre-fit	Post-fit
ZZ	$Z_L Z_L$	189.1 ± 8.8	220 ± 53
	$Z_T Z_L$	710 ± 29	711 ± 29
	$Z_T Z_T$	2170 ± 120	2146 ± 60
	Interference	34.2 ± 3.1	33.8 ± 2.9
Non-prompt		18.7 ± 7.1	18.5 ± 7.0
Others		20.0 ± 3.7	19.9 ± 3.7
Total		3140 ± 150	3149 ± 57
Data		3149	3149

The production of two longitudinally polarized Z_L Z_L is measured with a significance of **4.3σ**, and its cross-section is measured in fiducial phase space to be **2.44±0.59 fb**, consistent with the next-to-leading order Standard Model prediction of 2.09 ±0.10 fb.

No significant deviations from SM were observed. Excluded anomalous CP-odd neutral triple gauge coupling f_Z^4 outside [-0.012, 0.012].

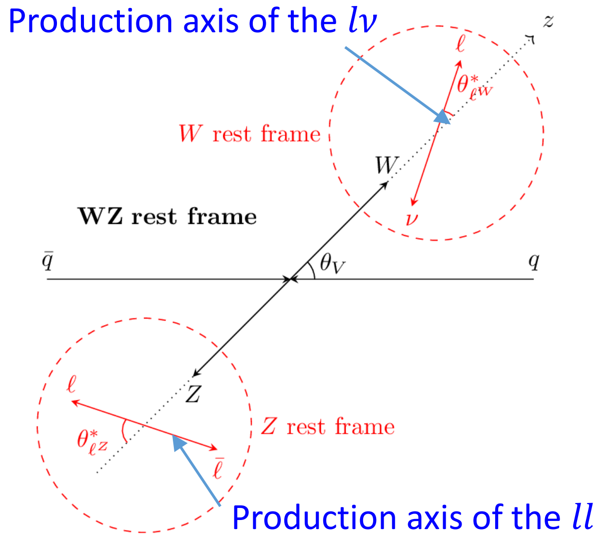
First measurement of joint $W_L Z_L$ polarization

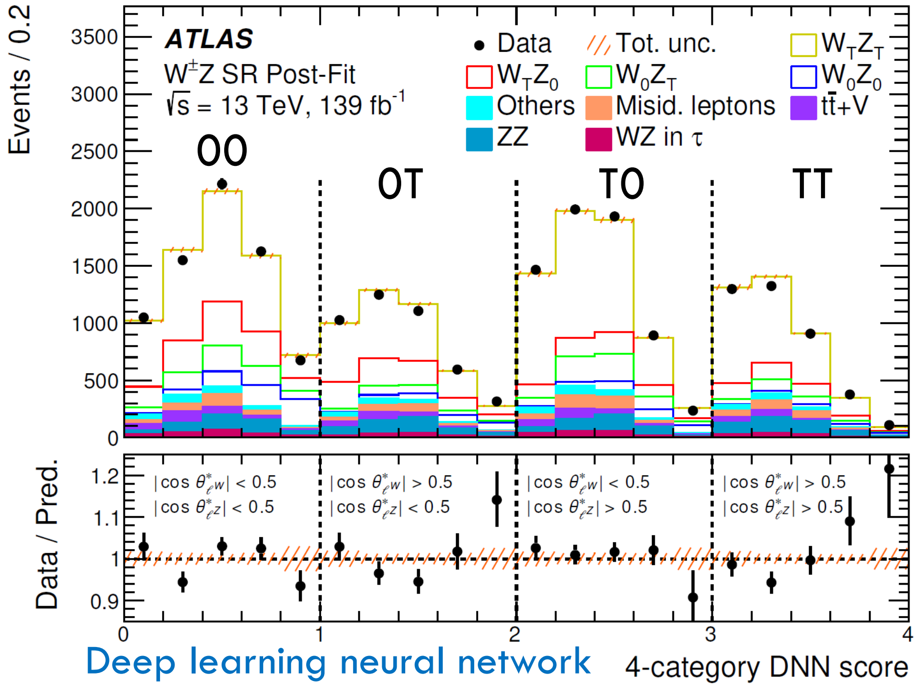
PLB 843 (2023) 137895

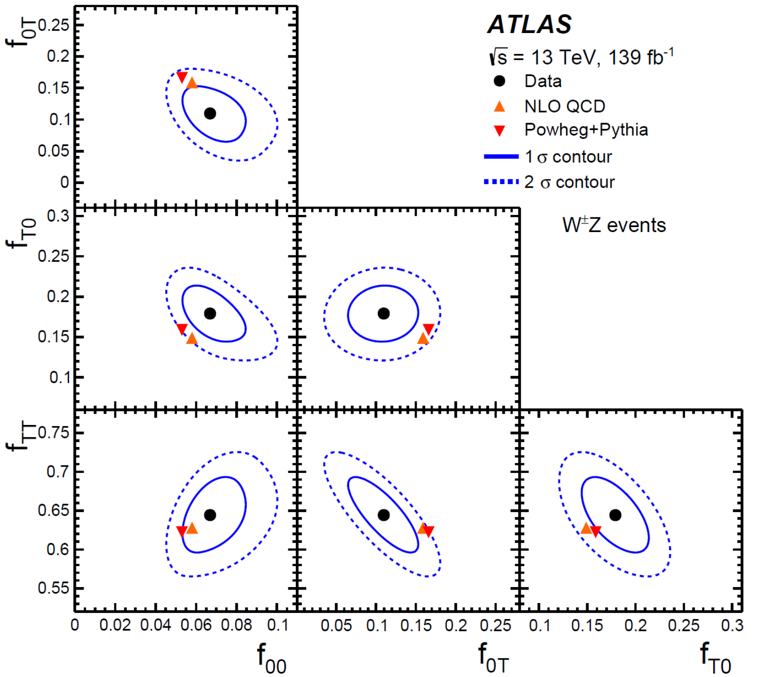
- Measure joint/individual helicity fractions. **Observed 7% $W_L Z_L$ events**
- Use WZ rest frame to extract fraction of events where both bosons are longitudinally/transversally polarized or mixed states

long. + long.	$f_{00} = \rho_{0000}$,	$f_{00} = 0.067 \pm 0.010$
transv. + transv.	$f_{TT} = \rho_{++--} + \rho_{--++} + \rho_{----} + \rho_{++++}$	$f_{TT} = 0.644 \pm 0.032$
long. + transv.	$f_{0T} = \rho_{00--} + \rho_{00++}$,	$f_{0T} = 0.110 \pm 0.029$
transv. + long.	$f_{T0} = \rho_{--00} + \rho_{++00}$.	$f_{T0} = 0.179 \pm 0.023$

- Derive DNN sensitive to 00, 0T, T0, and TT in 4 categories of $|\cos\theta_{lW}|$ $|\cos\theta_{lZ}|$ using W, Z and WZ transverse momenta and angular variables







	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}	0.152 ± 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

Most Precise W^+W^- Production Cross-Section Measurement

- Measurement of inclusive WW and VBS WW productions has been a high-profile physics program. The first WW cross-section measurement was based on 8 observed events at 7 TeV (PRL 107 (2011) 041802). ATLAS conducted many measurements on WW+jets (including HF) with much-improved precision since then. These measurements provide a test of the predictions of perturbative QCD, PDF, and the electroweak theory.
- **The latest measurements in ATLAS are performed using 140 fb^{-1} data at from LHC pp collisions at $\sqrt{s}$ = 13 TeV**

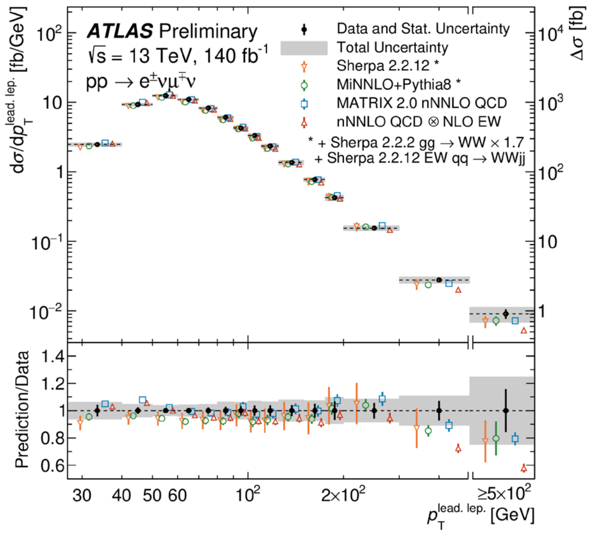
Select events contain isolated $e^{\pm}\mu^{\mp}$(no 3rd lepton), and $m_{e\mu} > 85\ GeV$, veto b-jets.

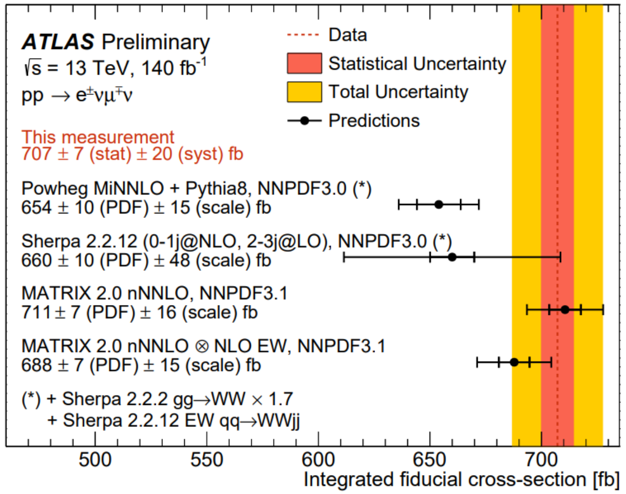
First use of fully jet-inclusive phase space

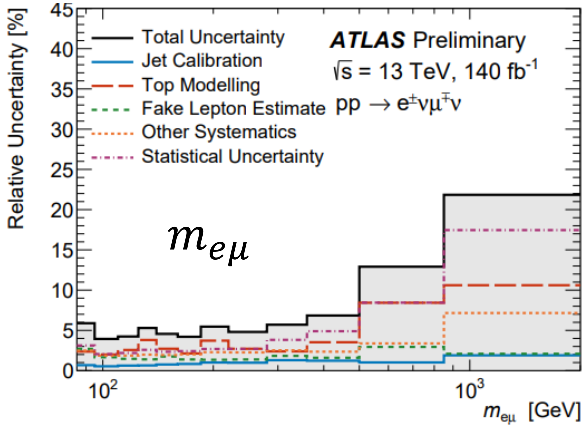
Most precise WW cross-section measurement in hadron-hadron collisions: 3.1% uncertainty vs 6-7% from previous measurements

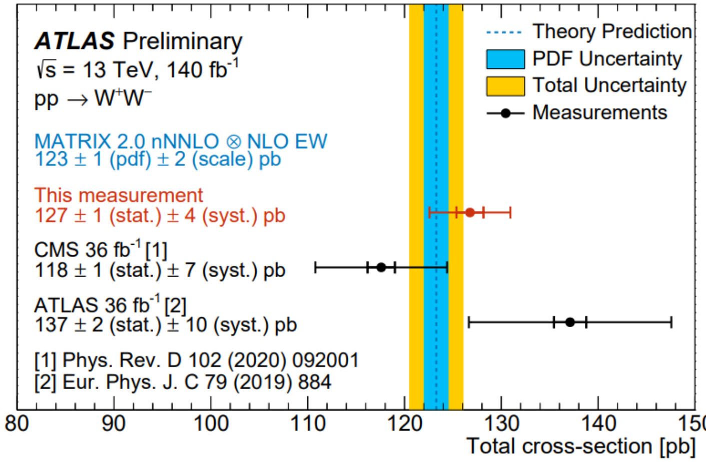
Category	Event yield	
Data	144221	
Total SM	139700 ± 2400	
WW	56900 ± 1100	41%
Total bkg.	82600 ± 2100	59%
Top	66500 ± 1900	48%
Drell-Yan	6500 ± 400	5%
Fakes	5000 ± 1300	4%
$WZ,ZZ,V\gamma$	4500 ± 600	3%

Uncertainty source	Effect
Total uncertainty	3.1%
Stat. uncertainty	1.1%
Top modelling	1.6%
Fake lepton background	1.5%
Flavour tagging	0.7%
Other background	0.9%
Signal modelling	1.0%
Jet calibration	0.6%
Luminosity	0.8%
Other systematic uncertainties	0.9%









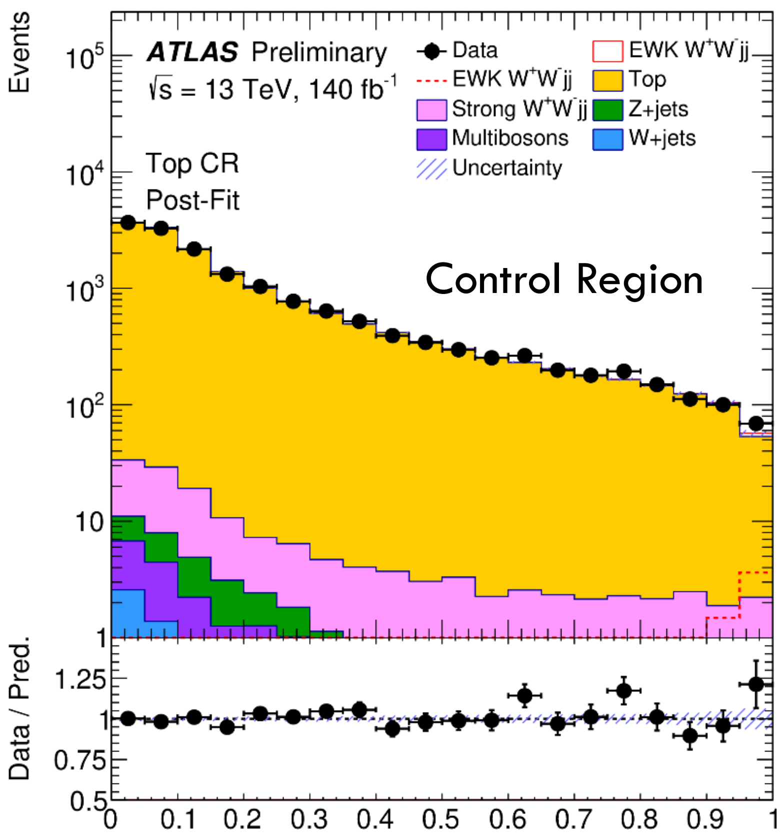
Observation of EW VBS W^+W^-jj Production

W^+W^-jj measurement is sensitive to the scattering of W bosons, which is of particular interest as it can be used to probe the electroweak symmetry-breaking mechanism of the SM. This signal has been observed for **the first time** in the ATLAS experiment with a significance of **7.1σ** (expected 6.2σ). The observed cross-section has been determined in a signal-enriched fiducial volume and is found to be **$2.65^{+0.52}_{-0.48}$ fb**, while the theoretical prediction from POWHEG is $2.20^{+0.13}_{-0.14}$ fb.

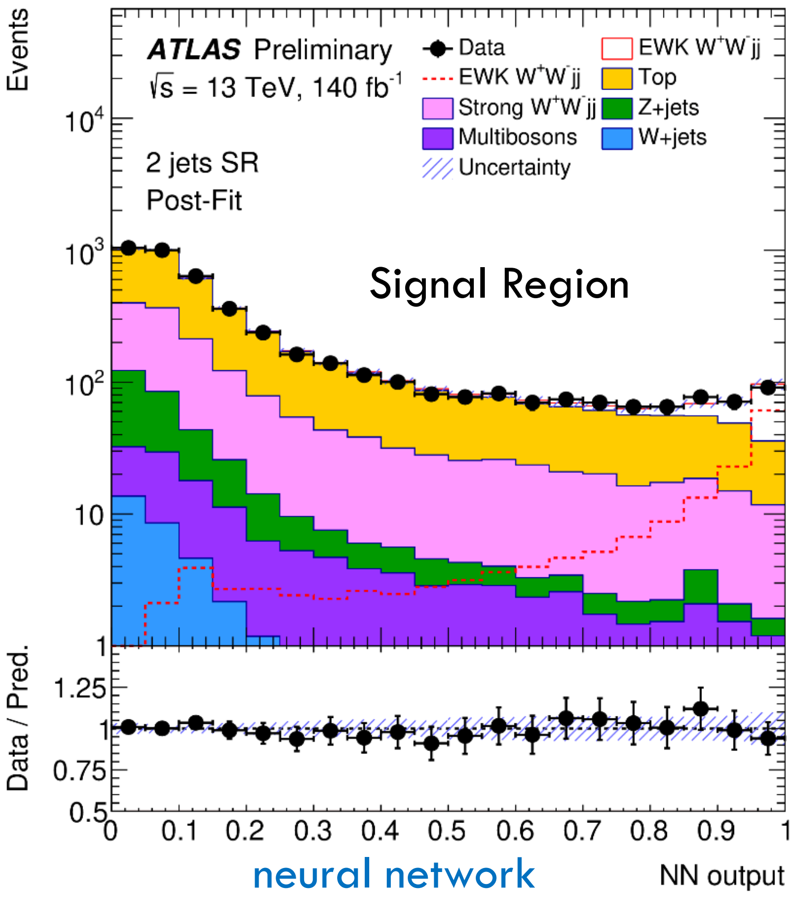
One electron and one muon with opposite charges
No additional lepton
$p_T^{\text{dressed}\ \ell} = p_T^{\ell} + \sum_i p_T^{\gamma_i}$ if $\Delta R(\ell, \gamma_i) < 0.1$
Leptons p_T: $p_T > 27$ GeV
Lepton η: $|\eta| < 2.5$
Two or three jets with $p_T > 25$ GeV and $|\eta| < 4.5$
$p_T^{miss} > 15$ GeV
$m_{jj} > 500$ GeV
centrality > 0.5
$m_{e\mu} > 80$ GeV
b-jet veto

Fiducial phase space

Process	Event yields $n_{\text{jets}} = 2$	$n_{\text{jets}} = 3$
EWK W^+W^-jj	158 ± 27	54 ± 13
Top quark	2885 ± 214	1851 ± 131
Strong W^+W^-jj	1214 ± 256	514 ± 121
W+jets	37 ± 97	19 ± 48
Z+jets	216 ± 62	65 ± 25
Multiboson	101 ± 5	42 ± 3
SM prediction	4610 ± 77	2546 ± 48
Data	4610	2533



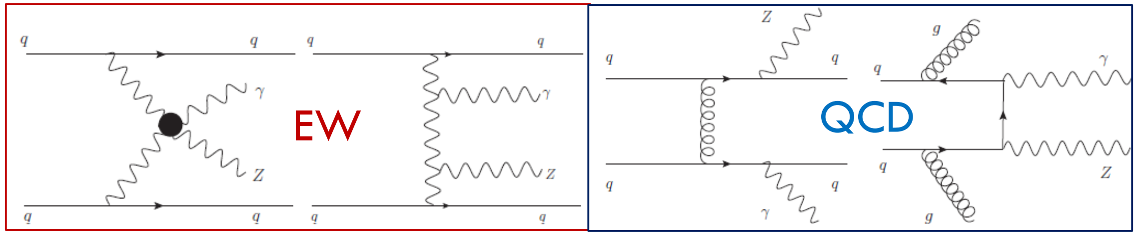
neural network



neural network

Observation and Measurement of VBS Zγ jj Production

The first observation ATLAS-CONF-2021-38; Diff. Cross-section measurements arXiv:2305.19142

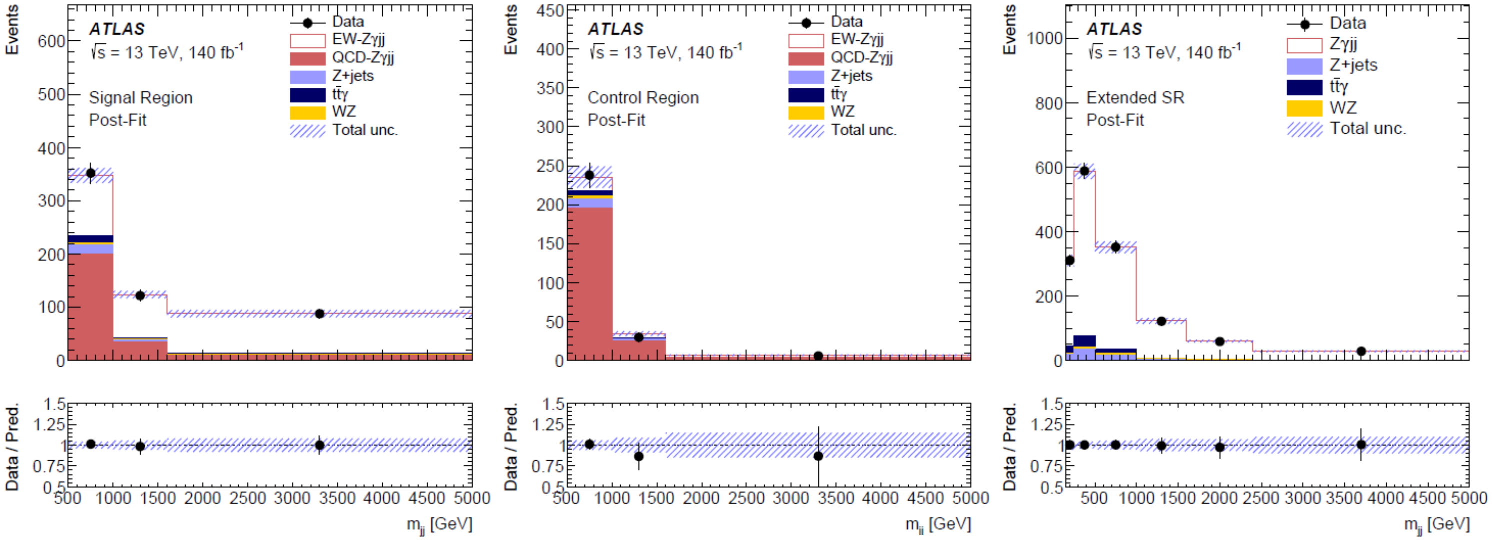


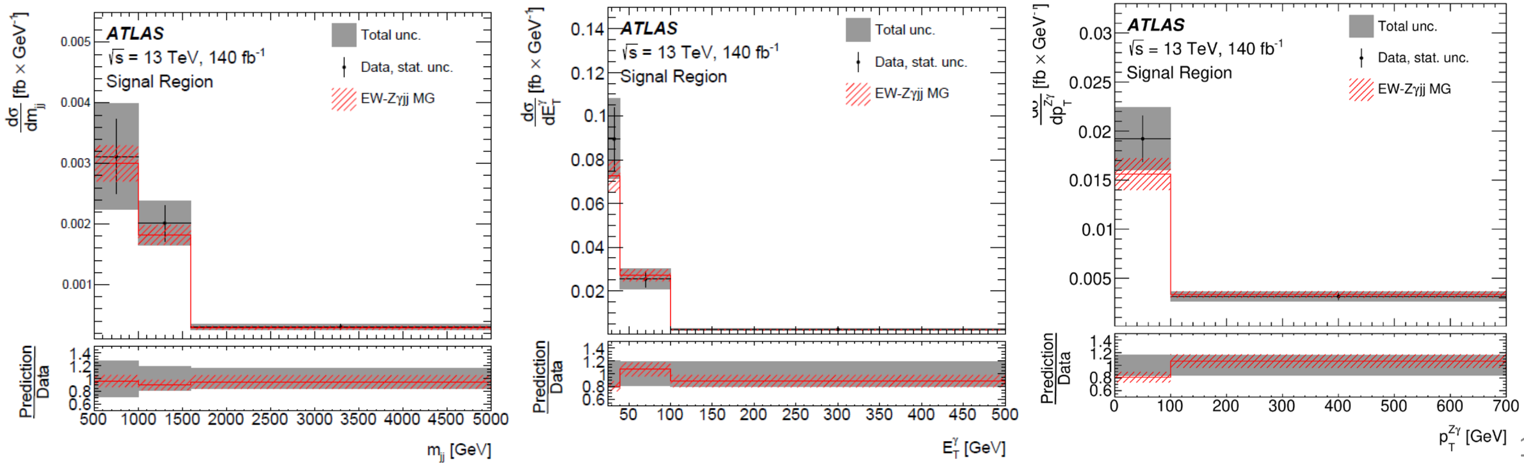
- **EW production in fid. P.S. σ is measured to be 3.6 ± 0.5 fb.**
- **The inclusive fiducial σ is measured to be $16.8^{+2.0}_{-1.8}$ fb**

$$\sigma^{pred}_{Z\gamma} = 15.7^{+5.0}_{-2.6}\ \text{fb}$$

Lepton	$p_T^\ell > 20, 30$(leading) GeV, $\lvert\eta_\ell\rvert < 2.5$ $N_\ell \geq 2$
Photon	$E_T^\gamma > 25$ GeV, $\lvert\eta_\gamma\rvert < 2.37$ $E_T^{\text{cone20}} < 0.07 E_T^\gamma$ $\Delta R(\ell,\gamma) > 0.4$
Jet	$p_T^j > 50$ GeV, $\lvert y_j\rvert < 4.4$ $\lvert\Delta y\rvert > 1.0$ $m_{jj} > 150$ GeV or $m_{jj} > 500$ GeV Remove jets if $\Delta R(\gamma, j) < 0.4$ or if $\Delta R(\ell, j) < 0.3$
Event	$m_{\ell\ell} > 40$ GeV $m_{\ell\ell} + m_{\ell\ell\gamma} > 182$ GeV $\zeta(Z\gamma) < 0.4$ $N_{\text{jets}}^{\text{gap}} = 0$

Sample	SR, $m_{jj} > 150$ GeV	SR, $m_{jj} > 500$ GeV	CR, $m_{jj} > 500$ GeV
$N_{\text{EW}-Z\gamma jj}$		269 ± 27	25 ± 6
$N_{\text{QCD}-Z\gamma jj}$		245 ± 21	224 ± 18
$N_{Z\gamma jj}$	1292 ± 50		
$N_{Z+\text{jets}}$	78 ± 30	21 ± 8	16 ± 5
$N_{t\bar{t}\gamma}$	73 ± 11	16 ± 2	8 ± 1
N_{WZ}	17 ± 3	9 ± 2	4 ± 1
Total	1461 ± 38	560 ± 23	277 ± 17
N_{obs}	1461	562	274





Observation and Measurements of EW $W^{\pm}W^{\pm}jj$

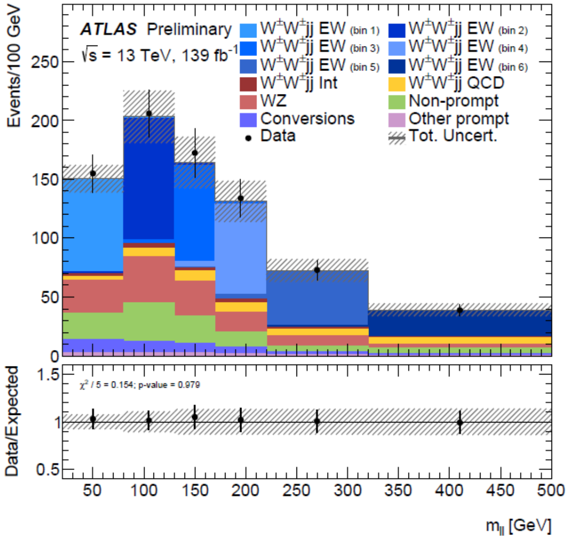
Evidence (4.5σ): PRL 113, 141803 (2014), Observation (6.5σ): PRL 123, 161801 (2019), Measurements: ATLAS-CONF-2023-023

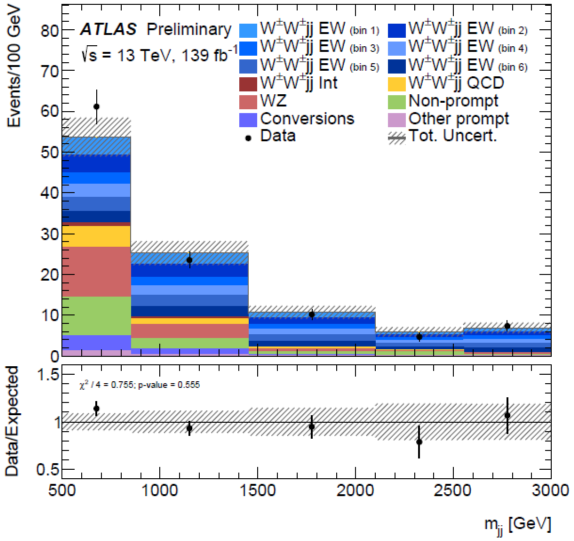
The analysis is performed by selecting two same-charge $e^{\pm}\mu^{\pm}, e^{\pm}e^{\pm}, \mu^{\pm}\mu^{\pm}$, and at least two jets with a large invariant mass ($m_{jj} > 500\ GeV$) and rapidity difference ($|\Delta y_{jj}| > 2$). No b-jet in the event.

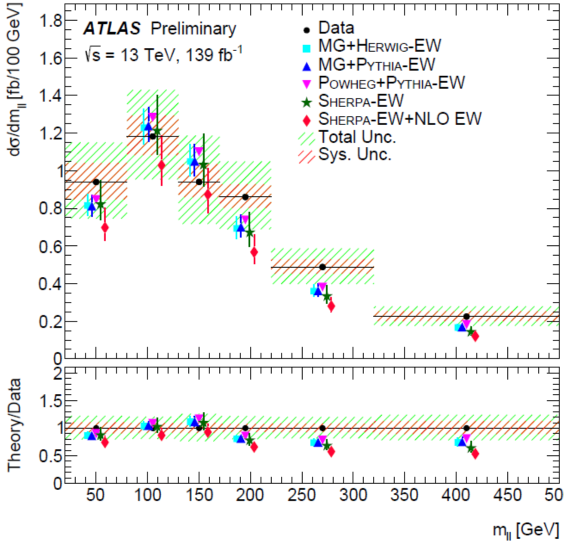
Process	Pre-fit yield	Post-fit yield
$W^{\pm}W^{\pm}jj$ EW	235 ± 27	278 ± 30
$W^{\pm}W^{\pm}jj$ QCD	24 ± 6	27 ± 7
$W^{\pm}W^{\pm}jj$ Int	7.6 ± 0.6	8.1 ± 0.7
$W^{\pm}Zjj$	98 ± 11	71 ± 8
Non-prompt	56 ± 11	55 ± 11
$V\gamma$	11 ± 4	13 ± 5
Charge misid.	10.1 ± 3.4	11.0 ± 3.5
Other prompt	7.1 ± 2.4	6.7 ± 1.9
Total Expected	448 ± 34	470 ± 40
Data	475	

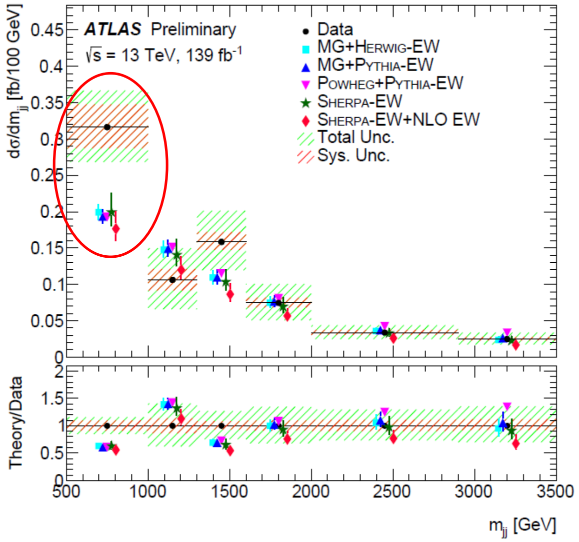
Description	$\sigma_{\text{fid}}^{\text{EW}}$, fb	$\sigma_{\text{fid}}^{\text{EW+Int+QCD}}$, fb
Measured cross section	$2.88 \pm 0.21\,(\text{stat.}) \pm 0.19\,(\text{syst.})$	$3.35 \pm 0.22\,(\text{stat.}) \pm 0.20\,(\text{syst.})$
MG_AMC@NLO+HERWIG	$2.53 \pm 0.04\,(\text{PDF}) \pm^{0.22}_{0.19}\,(\text{scale})$	$2.93 \pm 0.05\,(\text{PDF}) \pm^{0.34}_{0.27}\,(\text{scale})$
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	–

The measurements are used to constrain anomalous quartic gauge couplings by extracting confidence level intervals of 95% on dimension-8 operators.



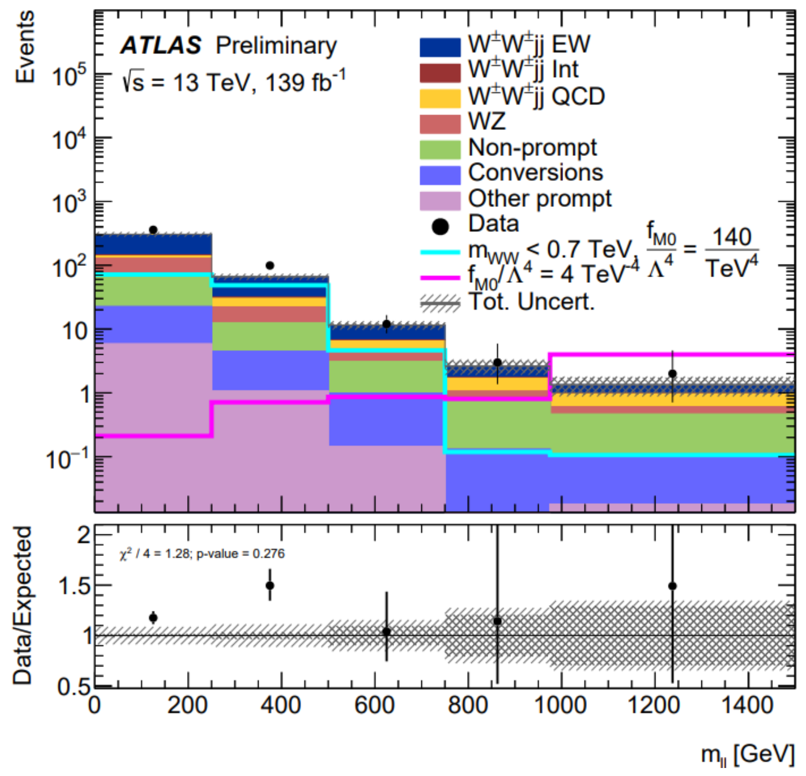






Limits on anomalous QGC

ATLAS-CONF-2023-023

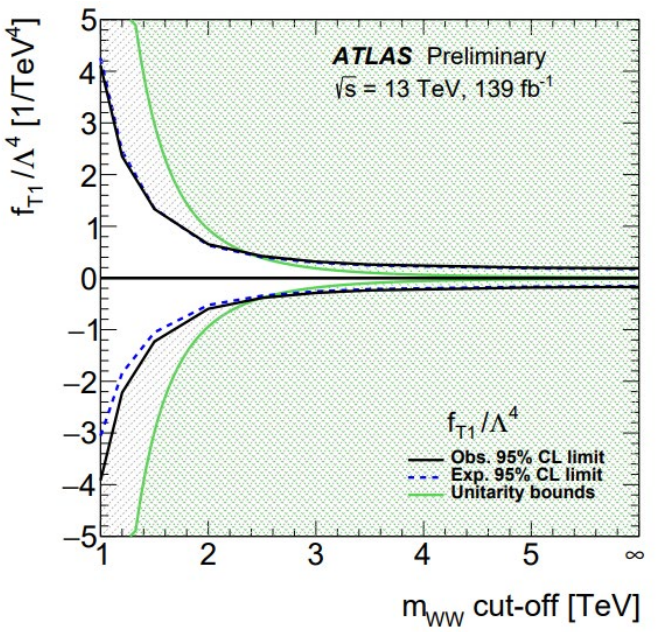


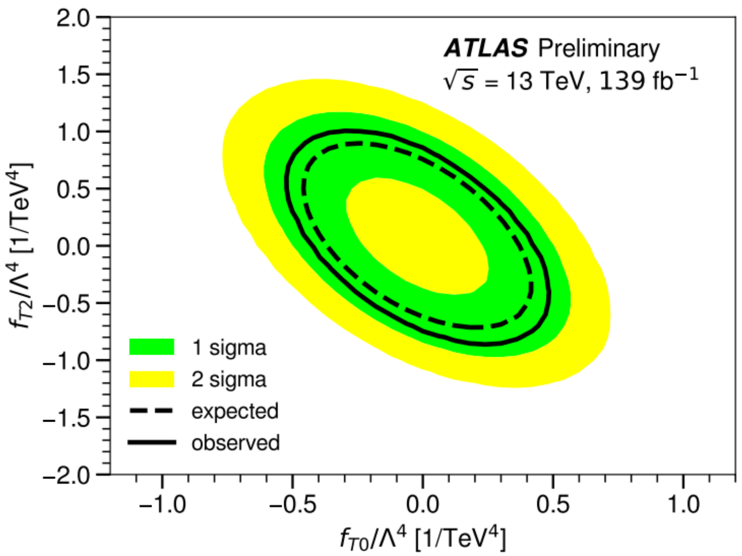
Variable	EW $W^\pm W^\pm jj$ χ^2/N_{dof}	EW $W^\pm W^\pm jj$ p-value	Inclusive $W^\pm W^\pm jj$ χ^2/N_{dof}	Inclusive $W^\pm W^\pm jj$ p-value
$m_{\ell\ell}$	4.4/6	0.623	7.0/6	0.322
m_{T}	12.9/6	0.045	15.9/6	0.014
m_{jj}	7.2/6	0.300	7.8/6	0.250
$N_{\mathrm{gap\ jets}}$	2.3/2	0.316	2.3/2	0.316
ξ_{j3}	4.3/5	0.511	5.2/5	0.396

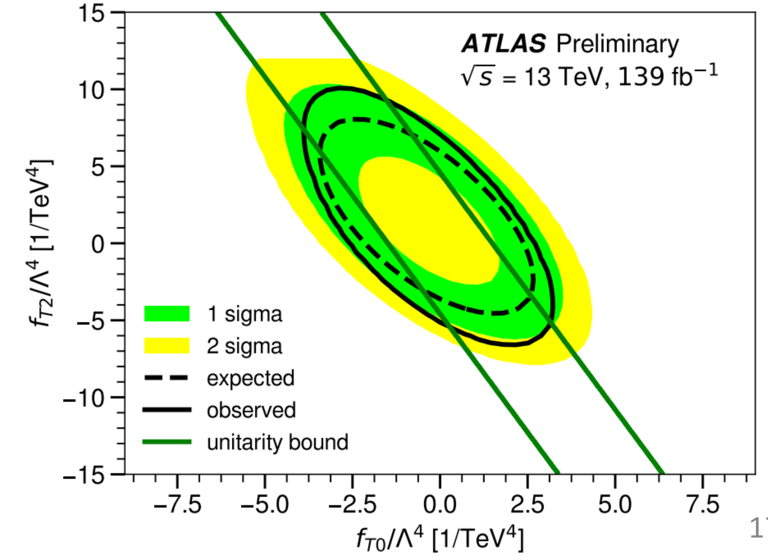
- **Data agree with the prediction**
- Limits on dim-8 EFT operators to probe aQGC

$$\mathcal{L}_{\mathrm{eff}} = \mathcal{L}_{\mathrm{SM}} + \sum_i \frac{f_i^{(6)}}{\Lambda^2} O_i^{(6)} + \sum_j \frac{f_j^{(8)}}{\Lambda^4} O_j^{(8)} + \ldots$$

- Limits are set w/ and w/o UV preservation treatment (cut-off scale of 1.5TeV and compare with UV bound)
- Limit evolution vs cut-off scale is scanned

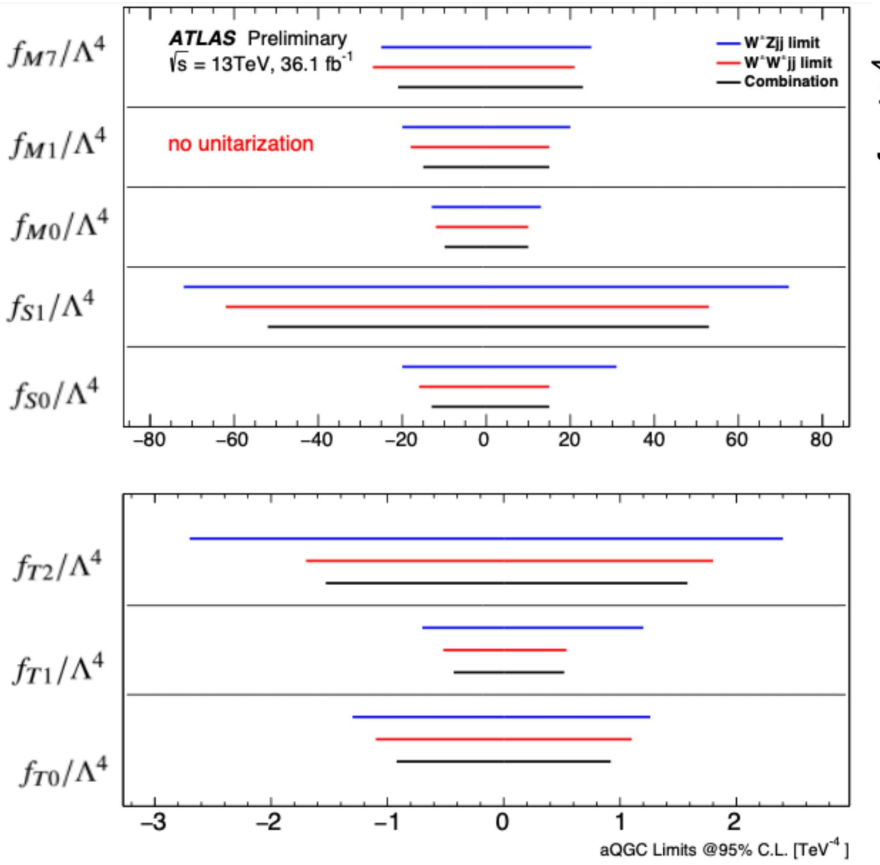


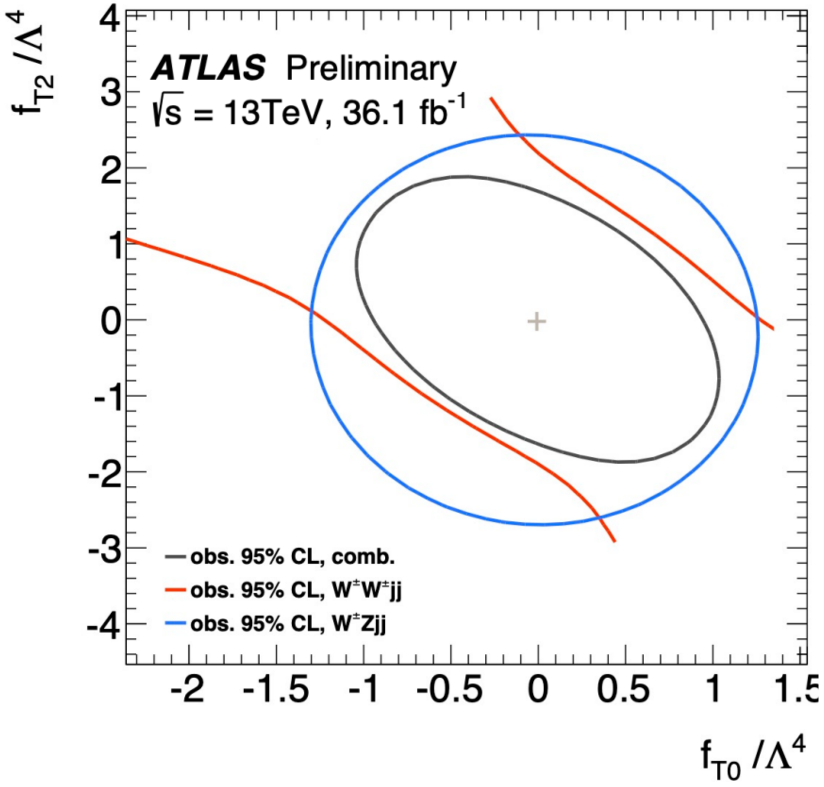


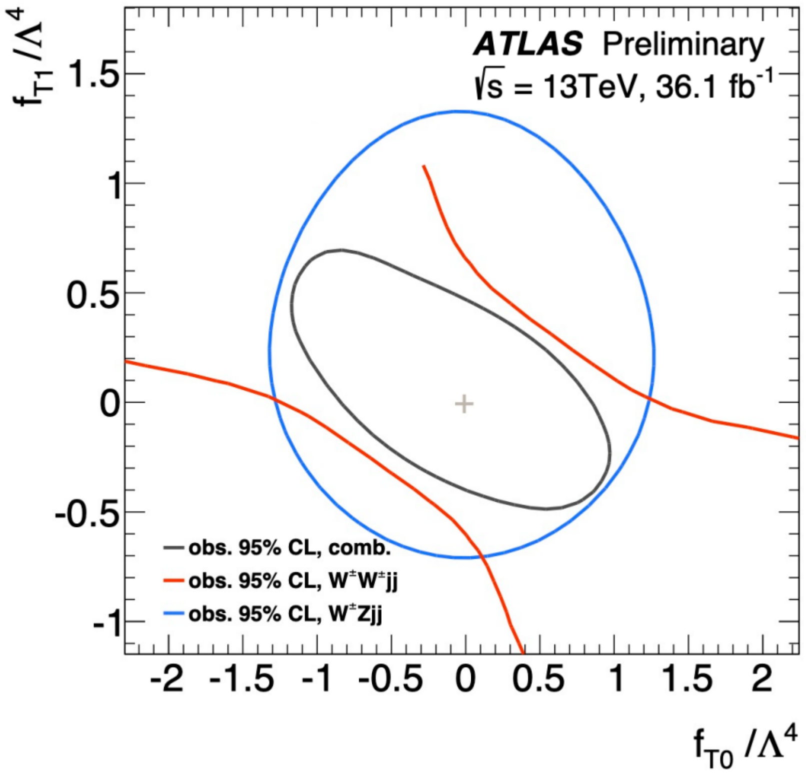


The aQGC EFT interpretation of Combined Measurements $W^{\pm}Zjj$ & $W^{\pm}W^{\pm}jj$

An EFT interpretation of the two fully leptonic $W^{\pm}Zjj$ and $W^{\pm}W^{\pm}jj$ measurements is performed to constrain anomalous Quartic Gauge Couplings. Both measurements are based on 36.1 fb^{-1} data collected at $\sqrt{s}$= 13TeV. Confidence Level intervals of 95% on dimension-8 EFT operators are extracted for the individual channels and for the combination.



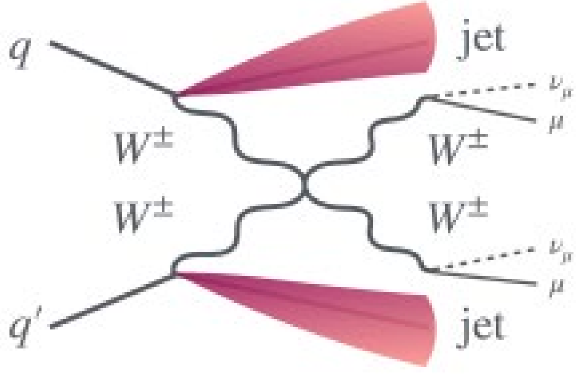




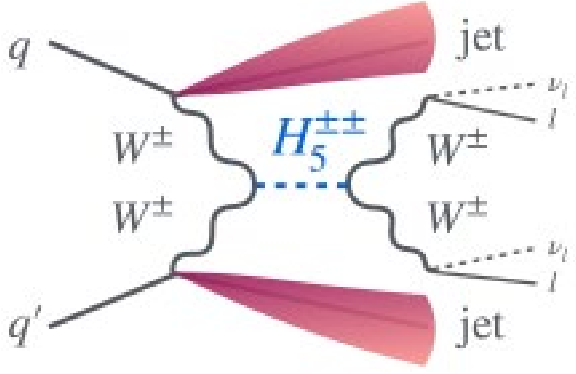
Hunting for new physics in the scattering of the same-sign W bosons

ATLAS-CONF-2023-023

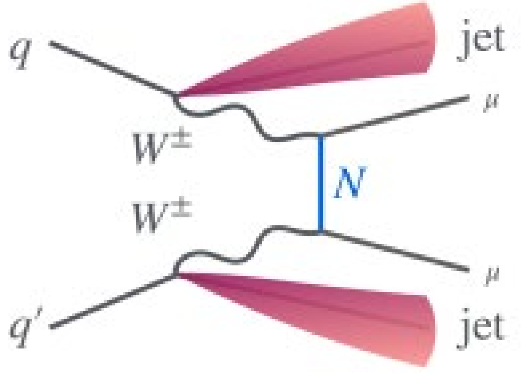
Measurement and interpretation of same-sign W boson pair production in association with two jets in pp collisions at a center-of-mass energy of 13 TeV with the ATLAS detector



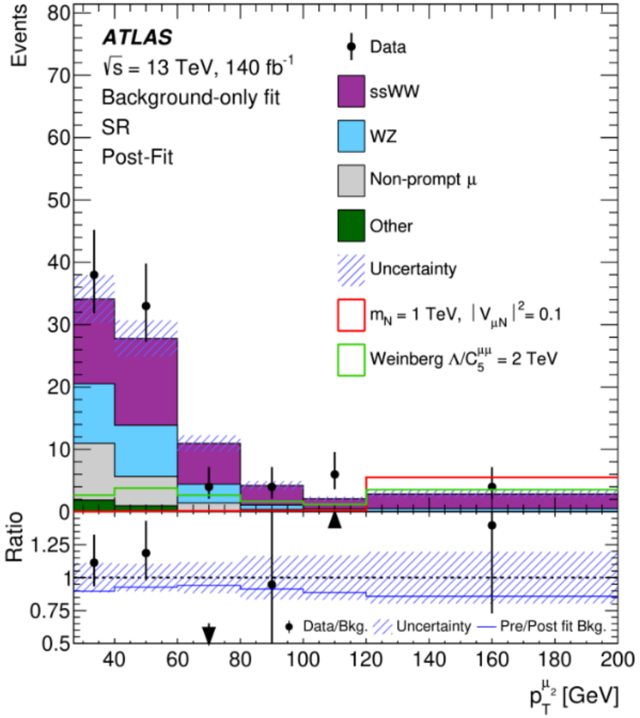
EW ss WWjj production

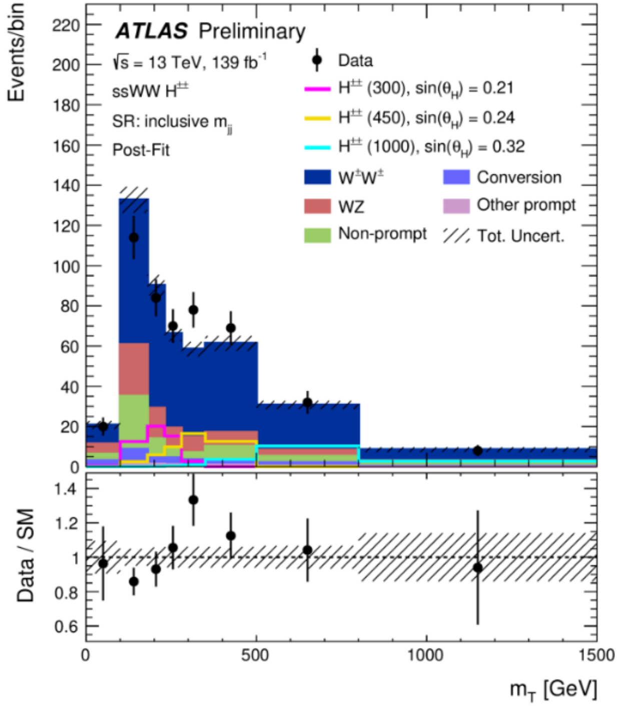


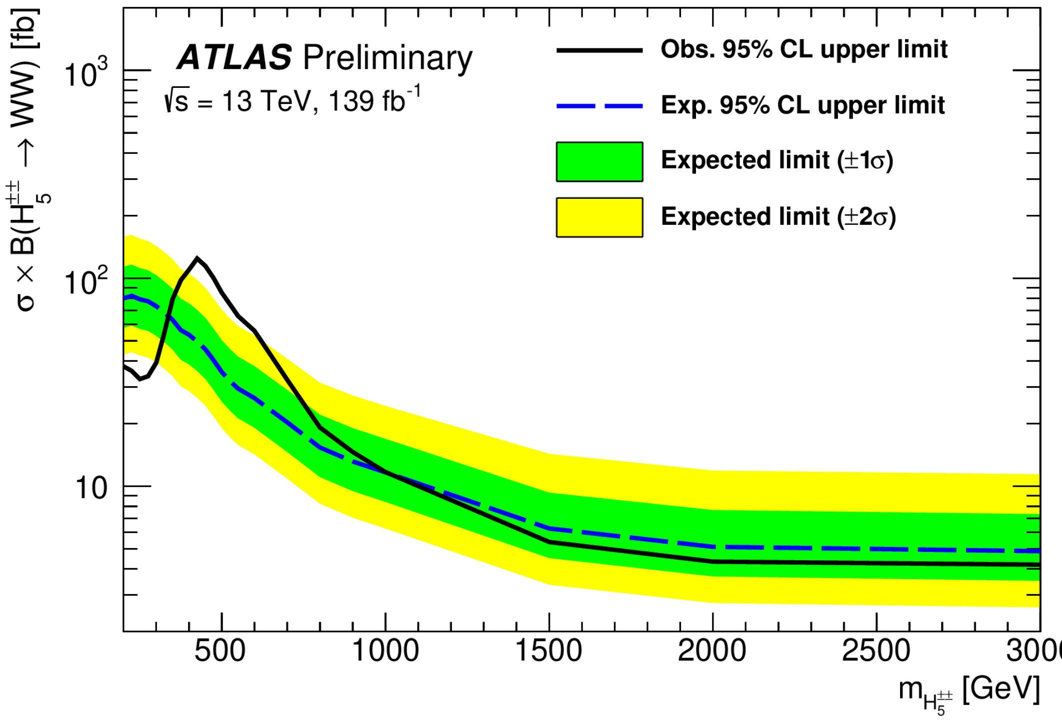
Georgi– Machacek model charged Higgs bosons production



Majorana neutrino (mediator)



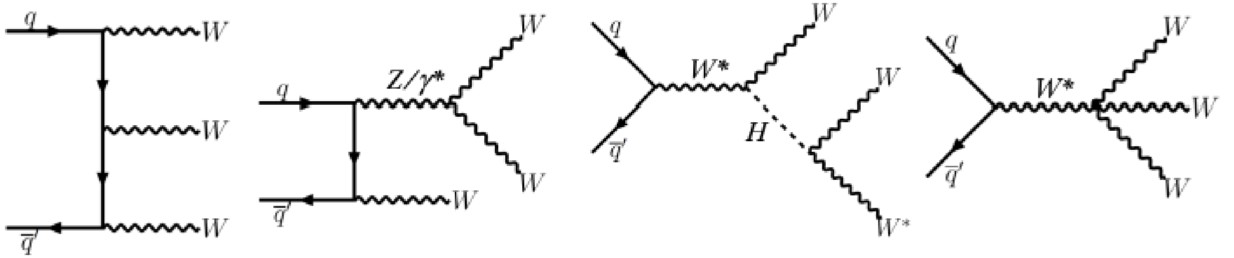




The First Observation of Triboson – WWW Production

PRL 129 (2022) 061803

Measurements of triboson production at colliders directly probe the strength of gauge boson self-interactions within the SM via triple gauge couplings and quartic gauge couplings



σ=820±100(stat.)±80(syst.)820±100(stat.)±80(syst.) fbSM σ (511±18511±18 fb)

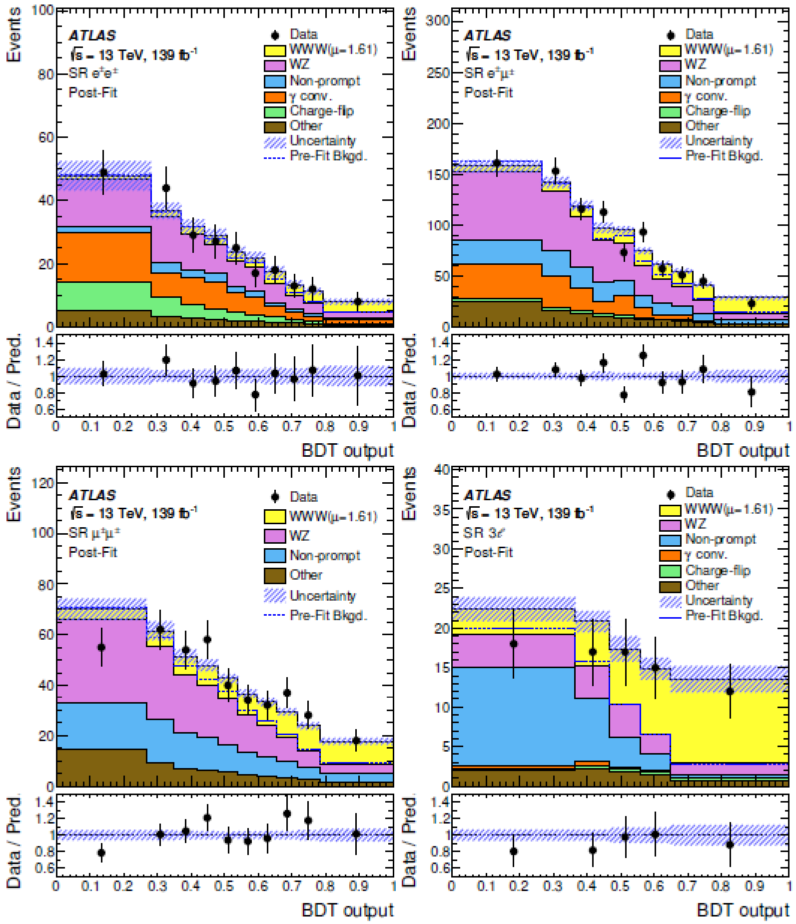
Two analysis channels

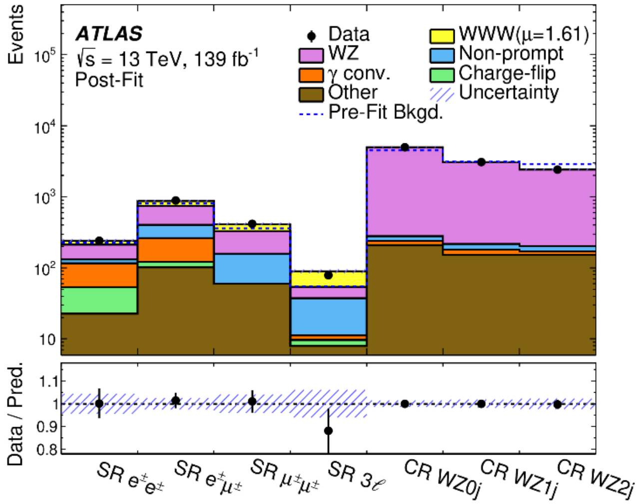
1) $WWW \rightarrow l^{\pm}\nu\, l'^{\pm}\nu' jj$
2) $WWW \rightarrow l^{\pm}\nu\, l'^{\mp}\nu' l^{\mp}\nu$

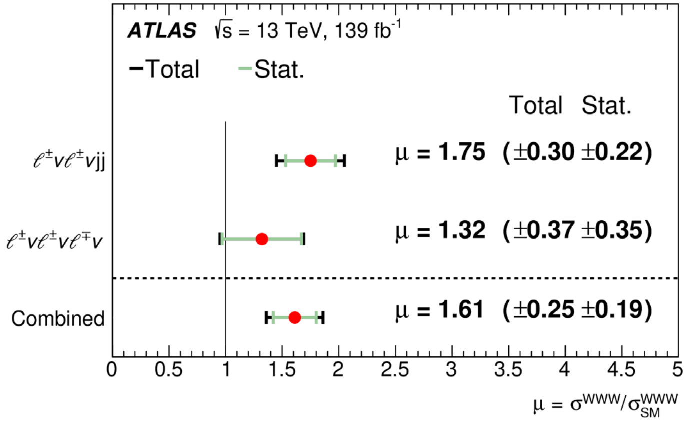
	$e^{\pm}e^{\pm}$	$e^{\pm}\mu^{\pm}$	$\mu^{\pm}\mu^{\pm}$	3ℓ
WWW signal	28.4 ± 4.3	124 ± 19	82 ± 12	34.8 ± 5.2
WZ	81.1 ± 5.7	346 ± 22	170 ± 10	16.4 ± 1.5
Charge-flip	31.1 ± 7.3	19 ± 5	-	1.7 ± 0.4
γ conversions	60.8 ± 8.5	139 ± 15	-	1.5 ± 0.1
Nonprompt	17.0 ± 4.0	145 ± 23	104 ± 21	26.6 ± 2.9
Other	22.3 ± 2.4	100 ± 10	58 ± 6	8.0 ± 0.9
Total predicted	241 ± 11	873 ± 22	415 ± 17	89.0 ± 5.4
Data	242	885	418	79

BDT is used to fit SR and CRs simultaneously

Fit	$\mu(WWW)$	Significance observed (expected)
$e^{\pm}e^{\pm}$	1.54 ± 0.76	2.2 (1.4) σ
$e^{\pm}\mu^{\pm}$	1.44 ± 0.39	4.1 (3.0) σ
$\mu^{\pm}\mu^{\pm}$	2.23 ± 0.46	5.6 (2.7) σ
2ℓ	1.75 ± 0.30	6.6 (4.0) σ
3ℓ	1.32 ± 0.37	4.8 (3.8) σ
Combined	**1.61 ± 0.25**	**8.0 (5.4) σ**







Triboson Production Involving Photons: Wγγ, Zγγ, WZγ

Joseph Lambert will report the “Multiboson Physics with Photons in ATLAS” in this conference

- **Observation Wγγ production (5.6s)**

  arXiv:2308.03041

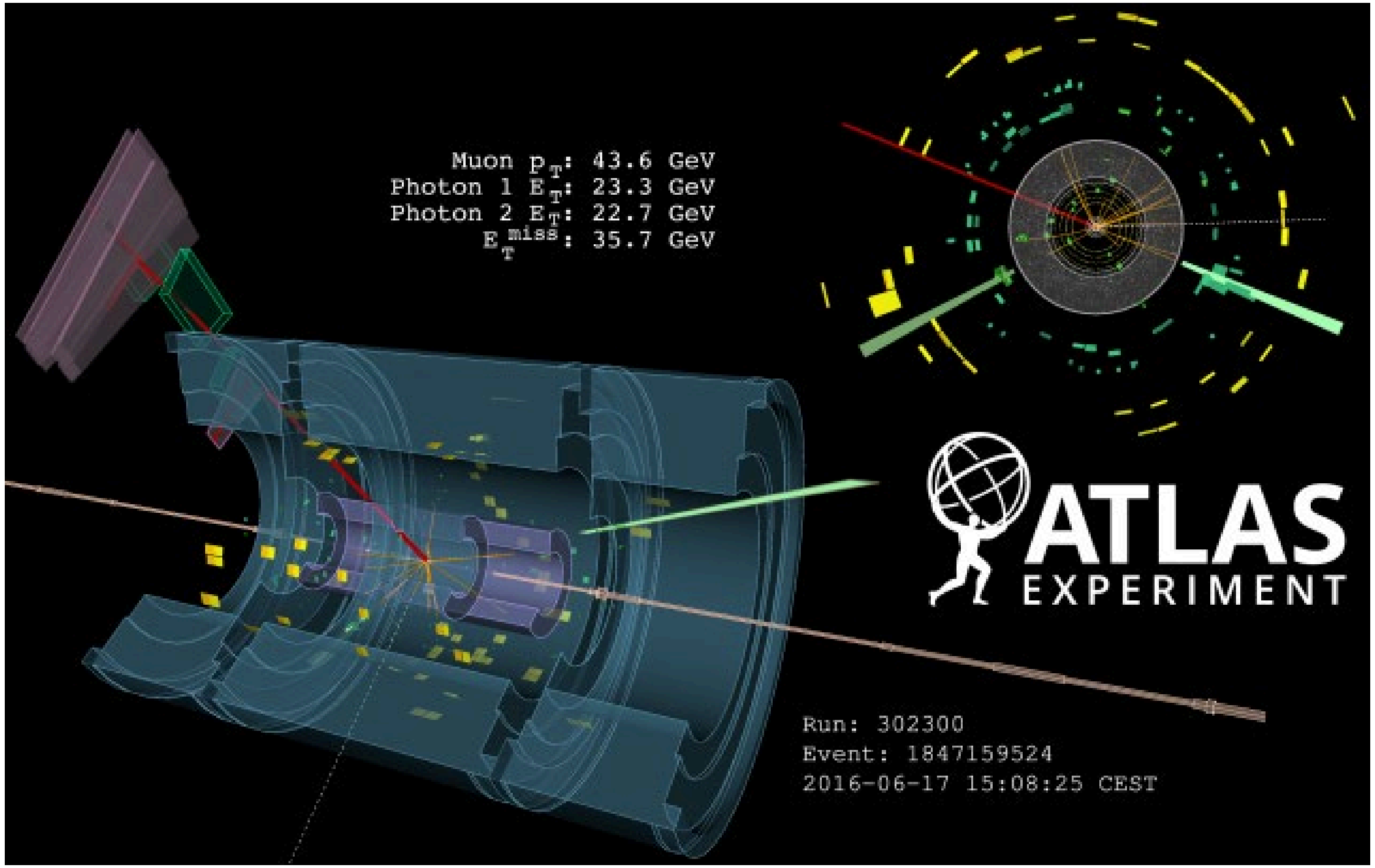
- **Observation WZγ production (6.3s)**

  arXiv:2305.16994

- **Measurement of Zγγ production cross-section**

  EPJC 83 (2023) 539

Event display: Wγγ candidate event



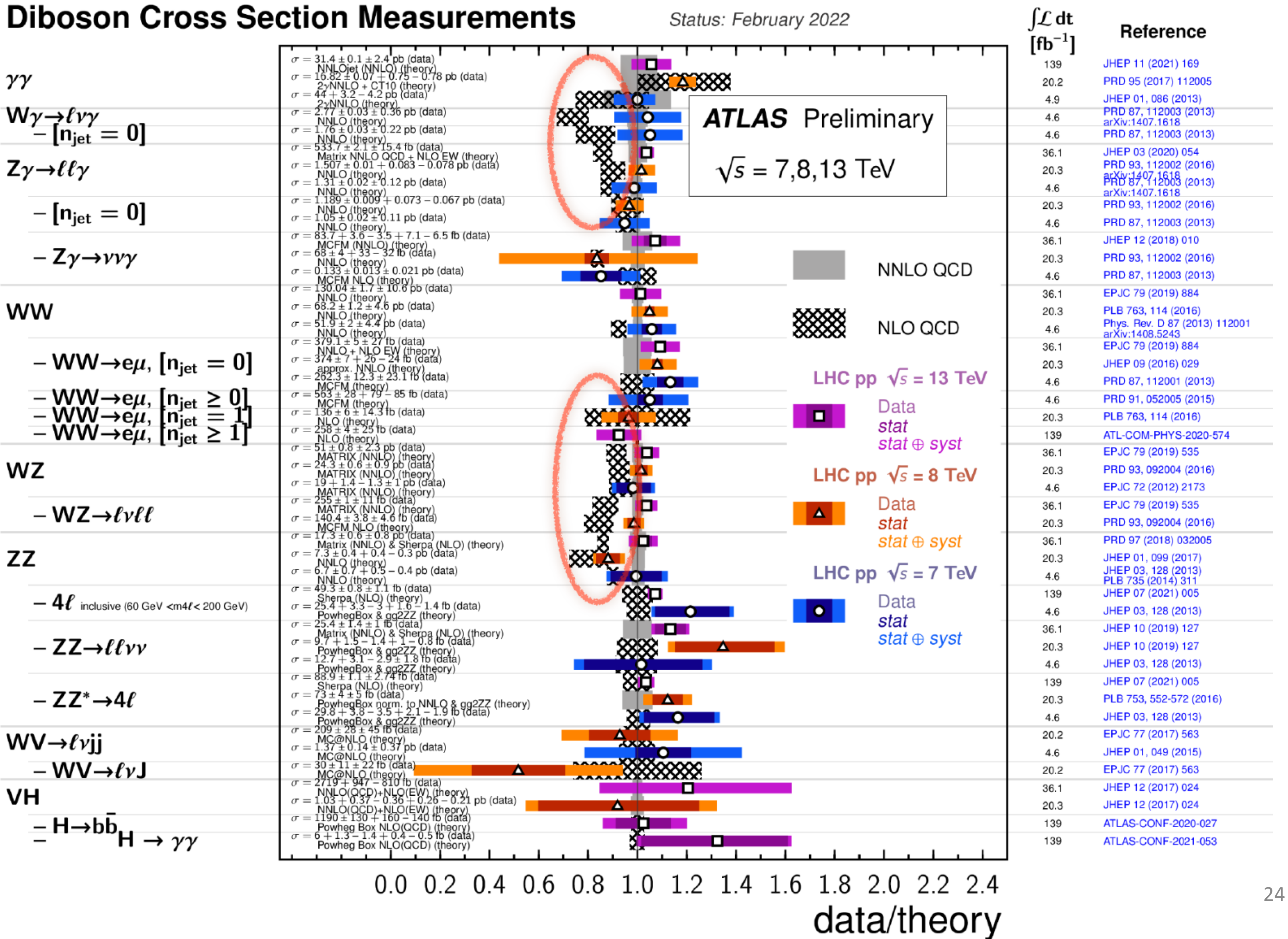
Summary

- Studying multiboson production and interactions is a very active research area at the LHC. Precision SM parameters, such as m_W, $\sin^2\theta_W$, and α_s, are measured; Many rare processes are observed for the first time, and differential cross-sections are measured to study the process in depth. So far, the data is consistent with SM prediction (with state-of-art calculations). Search for new physics, directly and indirectly (through the EFT framework) are performed

- These remarkable measurements significantly advance our understanding of EW interactions and were enabled due to
  - Excellent LHC performance at 7, 8, 13, and 13.6 TeV, luminosity has doubled the designed luminosity
  - Accurate detector calibrations on luminosity, leptons, photons, and jets (including b-jet) to reduce the systematic uncertainties
  - Active involvement from the theoretical community, providing precise cross-section prediction (fixed-order, mixed QCD/EW, with resummation), development of precise event generators for complex multi-scale processes
  - Development of the most powerful analysis techniques: profile-likelihood fits can deal with multiple floating "signals" and "background", state-of-art machine learning algorithms to maximize separation between signal and background to probe the smallest experimental signals

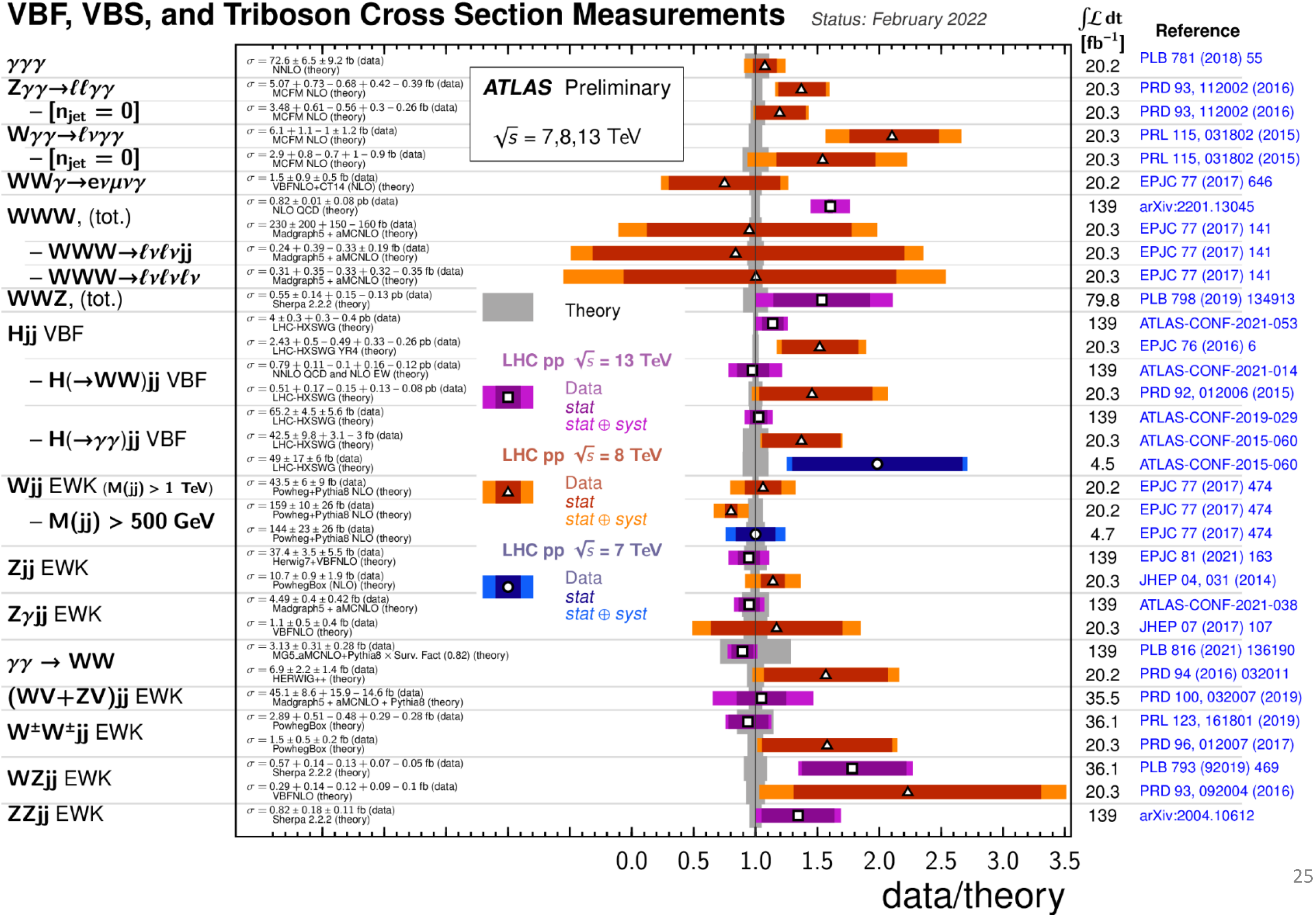
Spare slides

Experimental results demanded higher precision theoretical calculations



VBF, VBS, and Triboson Cross Section Measurements

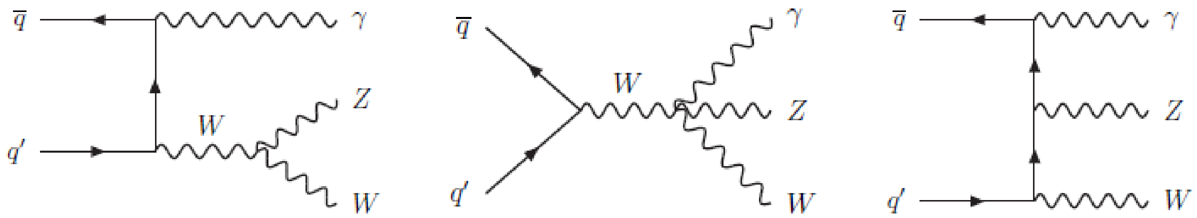
Status: February 2022



Observation of WZγ Production

arXiv:2305.16994

Submitted to PRL



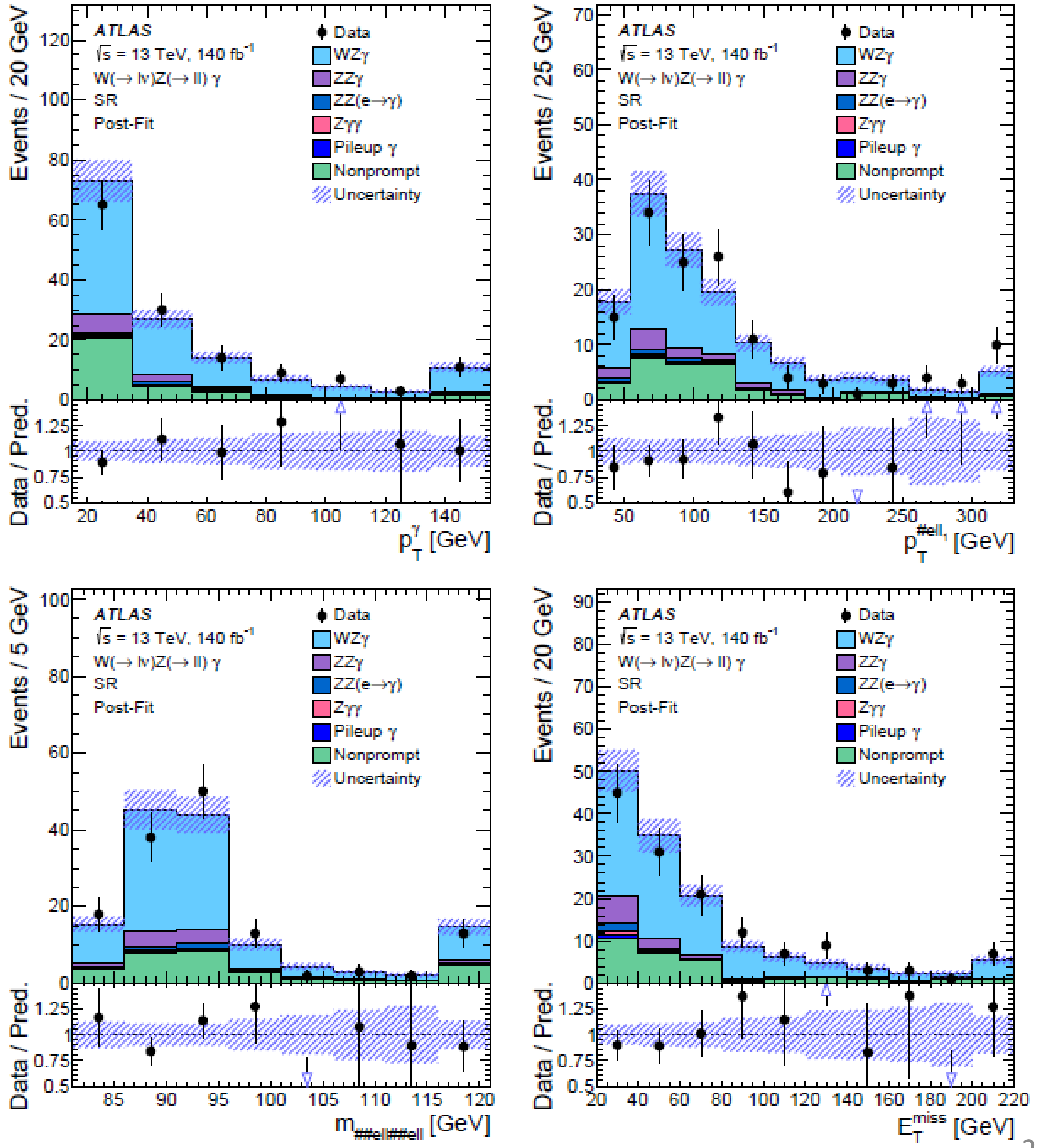
WZγ production observed with 6.3σ (exp. 5.0σ)

$$\sigma^{fid} = 2.01 \pm 0.30(stat) \pm 0.16(syst)\ fb$$

$$\sigma^{SM} = 1.50 \pm 0.06\ fb$$

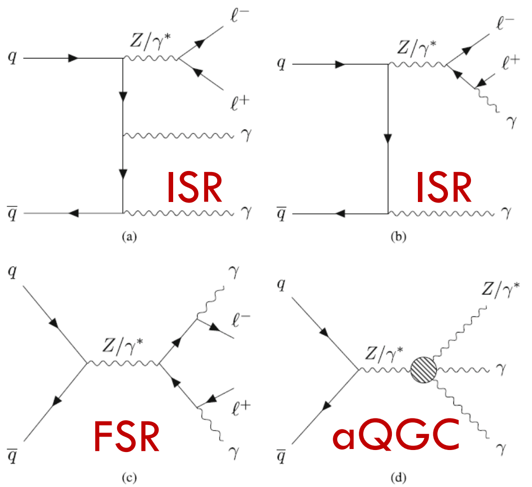
- Select events: $Z \rightarrow l^+l^-\ (m_{ll} > 81\ GeV), W \rightarrow l'\nu, isolated\ \gamma$
- Non-prompt γ/l: estimation from data; ZZ(γ) SF from CR

Process	SR	$ZZ\gamma$ CR	$ZZ(e\rightarrow\gamma)$ CR
$WZ\gamma$	92 ± 15	0.21 ± 0.07	0.56 ± 0.14
$ZZ\gamma$	10.7 ± 2.3	23 ± 5	1.8 ± 0.4
$ZZ(e\rightarrow\gamma)$	3.0 ± 0.6	0.028 ± 0.020	30 ± 6
$Z\gamma\gamma$	1.05 ± 0.32	0.15 ± 0.06	0.29 ± 0.10
Nonprompt background	30 ± 6	-	-
Pileup γ	1.9 ± 0.7	-	-
Total yield	139 ± 12	23 ± 5	33 ± 6
Data	139	23	33

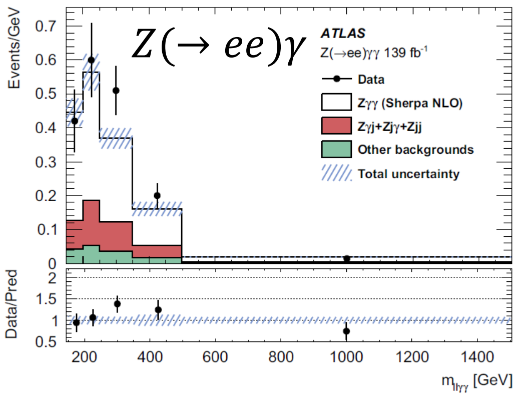


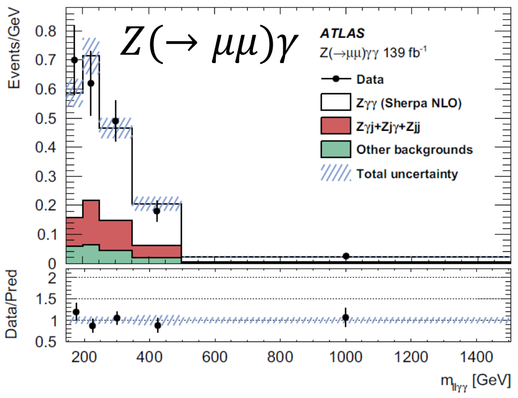
EPJC 83 (2023) 539

Observation of Zγγ Production

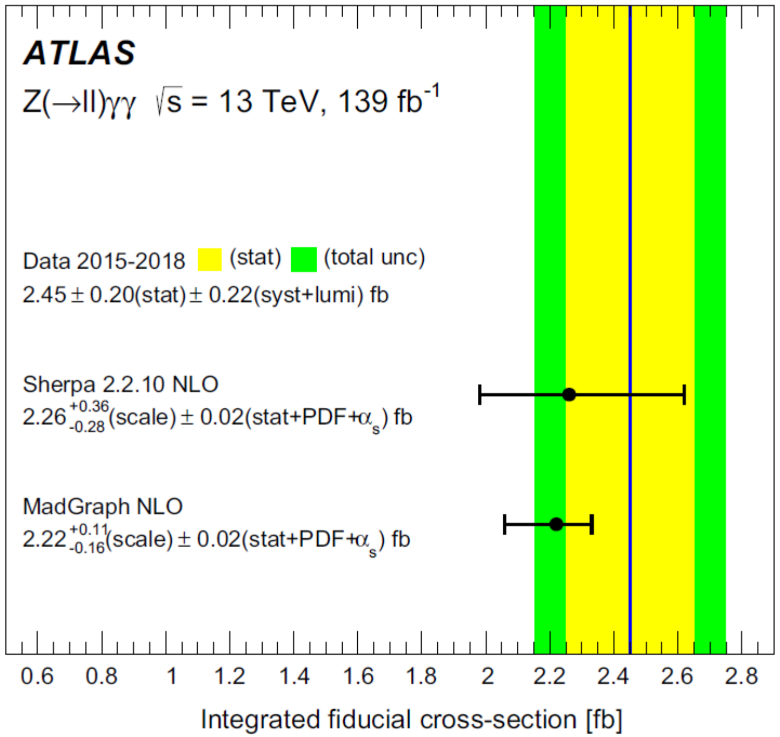


Remove FSR $m_{\ell\ell} + \min(m_{\ell\ell\gamma_1}, m_{\ell\ell\gamma_2}) > 2m_Z$

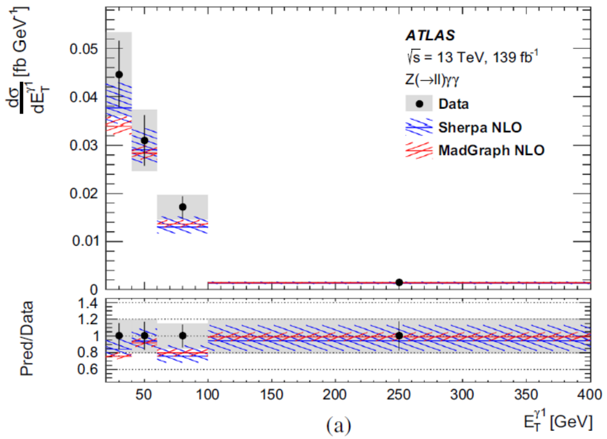


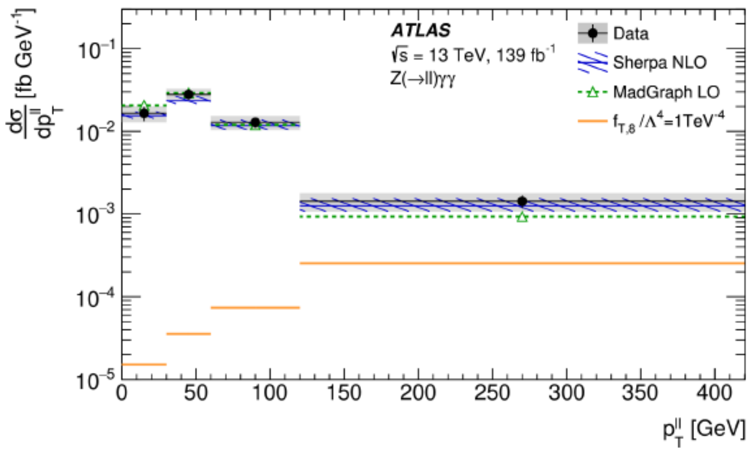


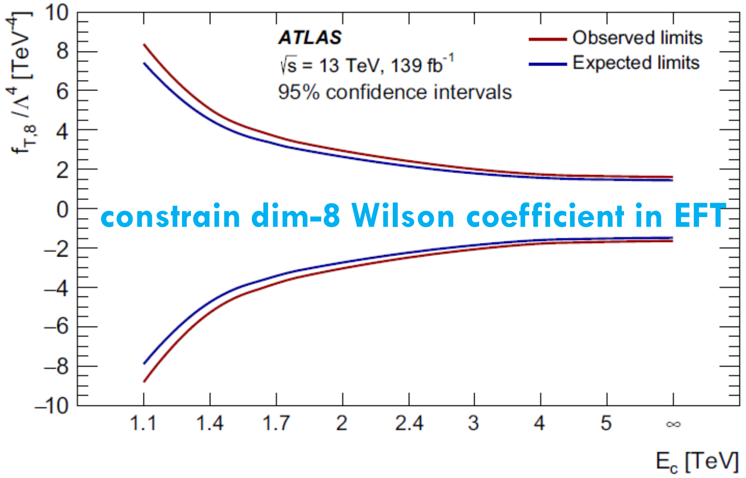
Measured σ



	$e^+e^-\gamma\gamma$	$\mu^+\mu^-\gamma\gamma$
Data	148	171
Data – background (Non-prompt γ)	105.5 ± 12.2 (stat.) ± 8.1 (sys.)	120.4 ± 13.1 (stat.) ± 9.4 (sys.)
Signal predictions		
SHERPA NLO	91.5 ± 0.9 (stat.)	119.5 ± 1.0 (stat.)
MADGRAPH5_AMC@NLO	91.0 ± 1.0 (stat.)	118.1 ± 1.2 (stat.)



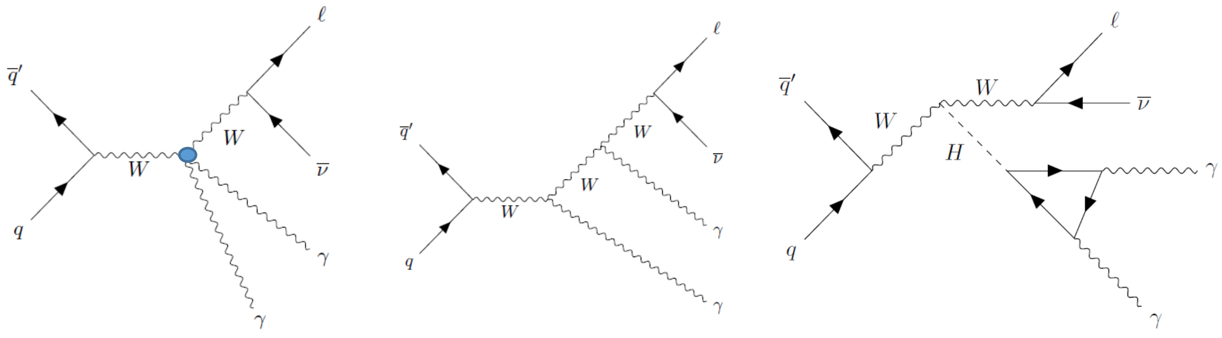


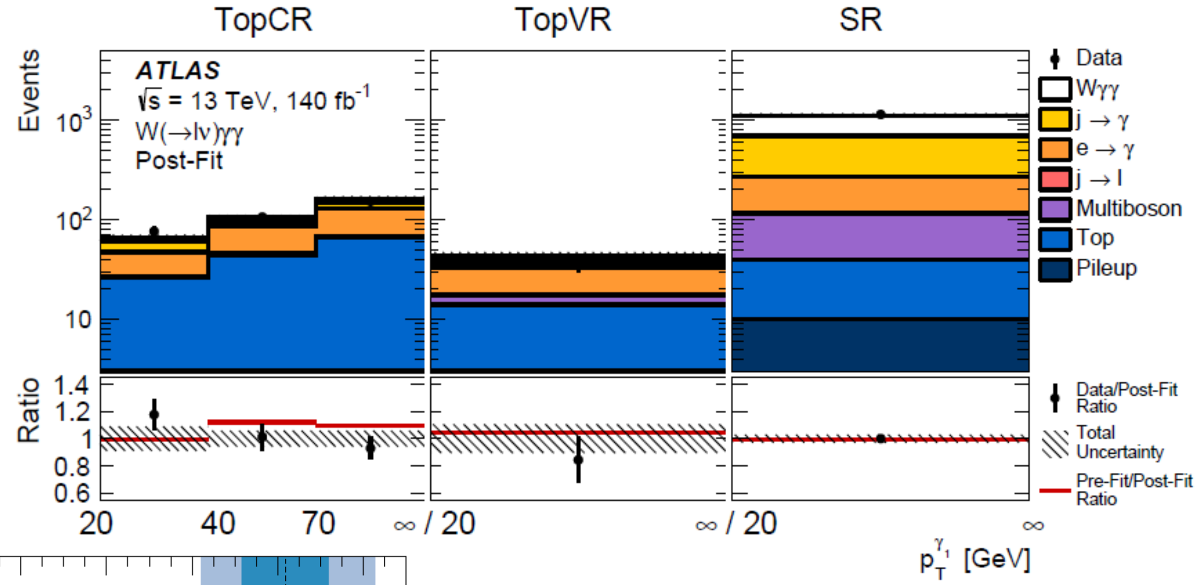


Observation of Wγγ Production

arXiv:2308.03041

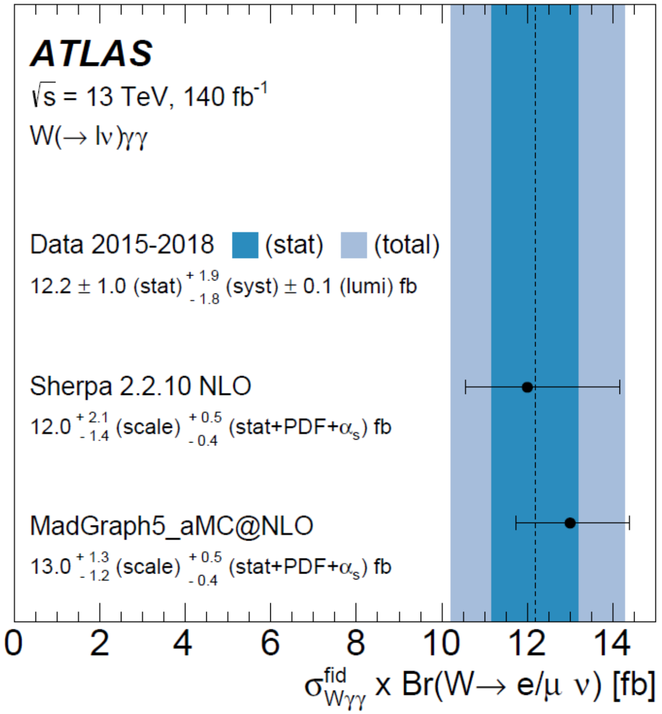
Submitted to PLB

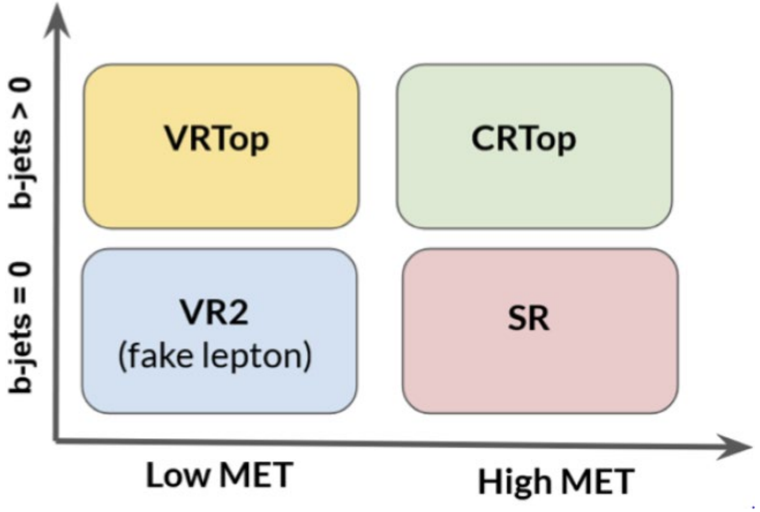




The first observation of $W(\rightarrow l\nu)\gamma\gamma$ (5.6σ observed and predicted)!

Source	SR	TopCR
$W\gamma\gamma$	410 ± 60	28 ± 5
Non-prompt $j \rightarrow \gamma$	420 ± 50	42 ± 20
Misidentified $e \rightarrow \gamma$	155 ± 11	120 ± 9
Multiboson ($WH(\gamma\gamma)$, $WW\gamma$, $Z\gamma\gamma$)	76 ± 13	5.2 ± 1.7
Non-prompt $j \rightarrow \ell$	35 ± 10	–
Top ($tt\gamma$, $tW\gamma$, $tq\gamma$)	30 ± 7	136 ± 32
Pileup	10 ± 5	–
Total	$1\,136 \pm 34$	332 ± 18
Data	$1\,136$	333





The Standard Model only allows a specific set of combinations of four-gauge-boson self-interactions: WWWW, WWγγ, WWZγ and WWZZ, forbidding interactions among four neutral bosons.

	WWWW	WWγγ	WWZγ	WWZZ
$W^{\pm}W^{\pm}jj$	✓			
WZjj				✓
ZZjj				✓
Zγjj			✓	
WW (via γγ)		✓		