Multiboson Production

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On behalf of ATLAS and CMS collaborations

QCD@LHC 2022

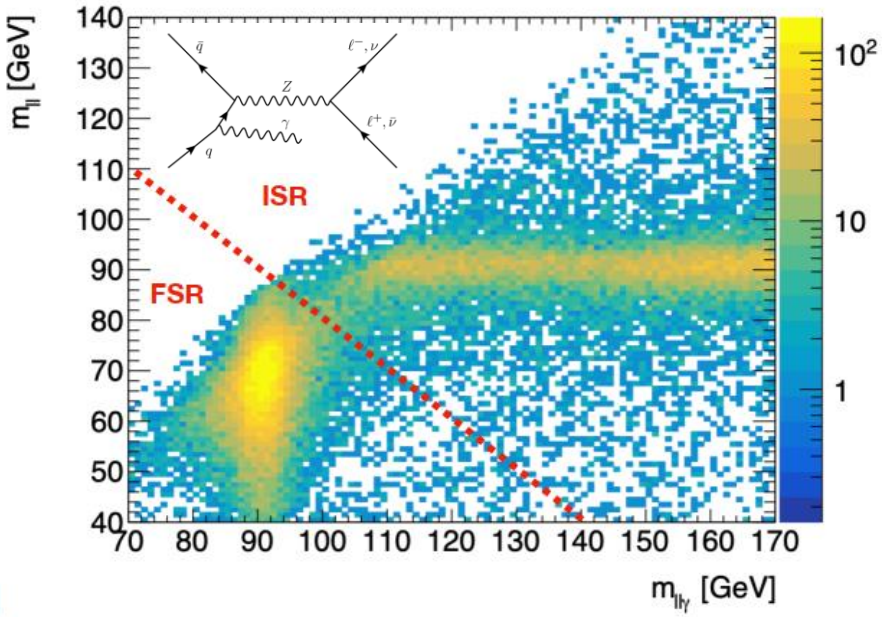
Introduction

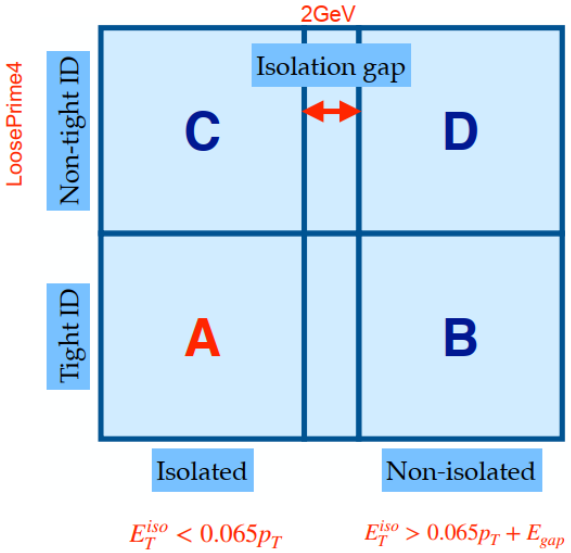
- Multiboson production:
  - Di-boson production: Zγ, Wγ, WZ, WW, and so on
  - Vector boson scattering (VBS): EWK Zγ, Wγ, WW and so on → *More VBS specific results in Michael's talk!*
  - Tri-boson production such as WWW and Zγγ
- Observation of rare processes predicted by SM but never seen before
- Precision measurement of SM such as inclusive/differential cross-section and polarization
- Validation of EWK & QCD modelling and search for SM breakdown (beyond SM)
- Sensitive probe to BSM and crucial inputs for effective field theory (EFT) study
  - Constraints to anomalous **t**riple and **q**uartic **g**auge **c**oupling (aTGC/aQGC)

*cartoon from *higgstan*

Differential Z(→ll)γ

- Inputs and constraints on the modeling of additional QCD activity in di-boson events: e.g. improvement of ZZ estimation on DM searches
- Meaningful for EFT and Z-boson polarization study
- Signal: Z→ll with photon from initial state radiation (ISR)
- Background:
  - Final state rad. process → removed with $m_{ll} + m_{ll\gamma} > 182GeV$
  - $t\bar{t}\gamma$ process → modelling checked with $e\mu\gamma$ region
  - Z+jets and pileup→ data-driven estimation

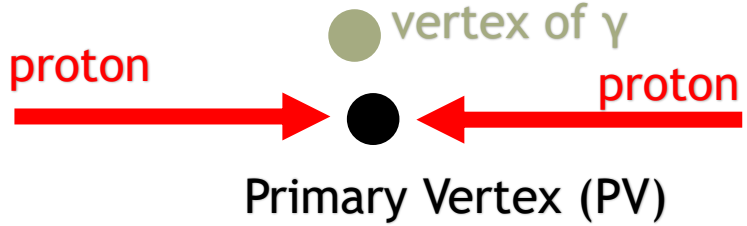




$$N^{Z+jets} = (N_A^{data} - N_A^{bkg}) \times (1 - \frac{N_A^{sig}}{N_A^{data} - N_A^{bkg}})$$

purity

$$f_{PU} = \frac{1}{N_{\text{Data, pixel conv}}} \cdot \frac{N^{|\Delta z|>50\,\text{mm}}_{\text{Data, pixel conv}} - N^{|\Delta z|>50\,\text{mm}}_{Z\gamma\text{MC, pixel conv}}}{P(\Delta z > 50\ \text{mm}) = \mathbf{0.32}}$$



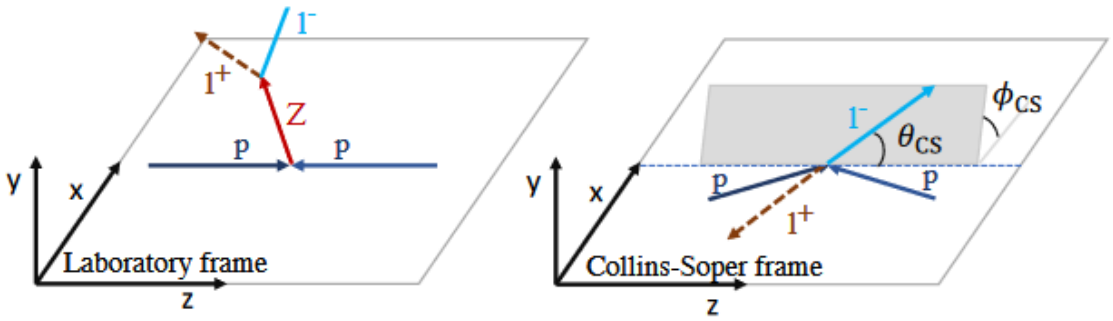
$$\Delta Z = Z_\gamma - Z_{PV}$$

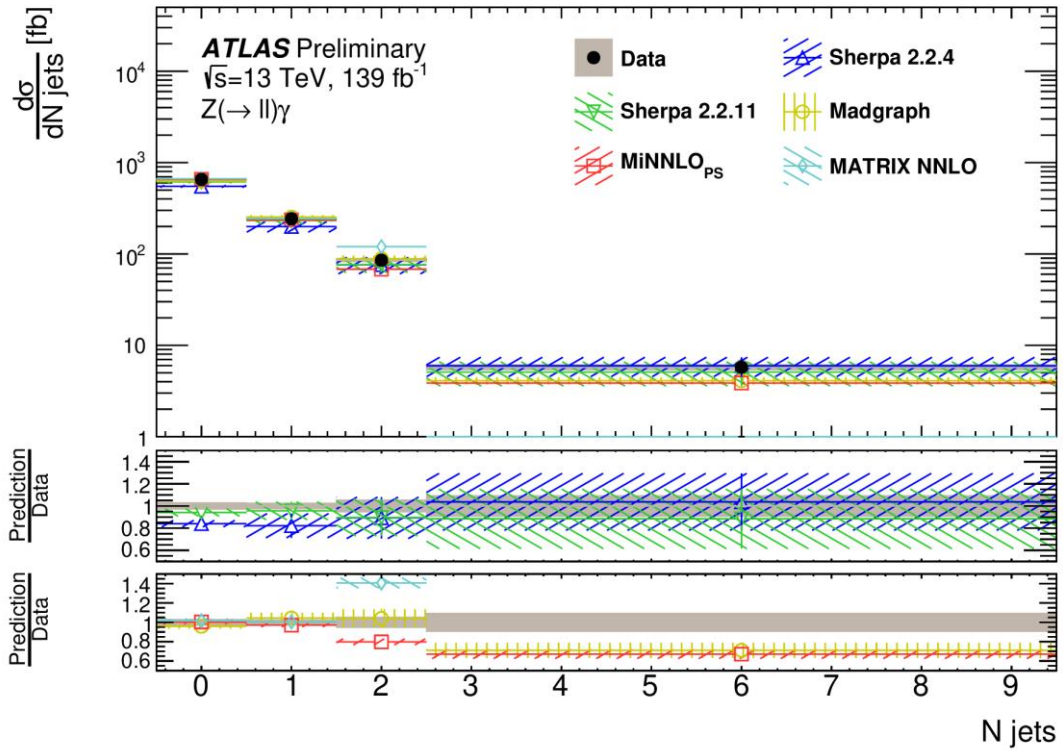
Differential Z(→ll)γ

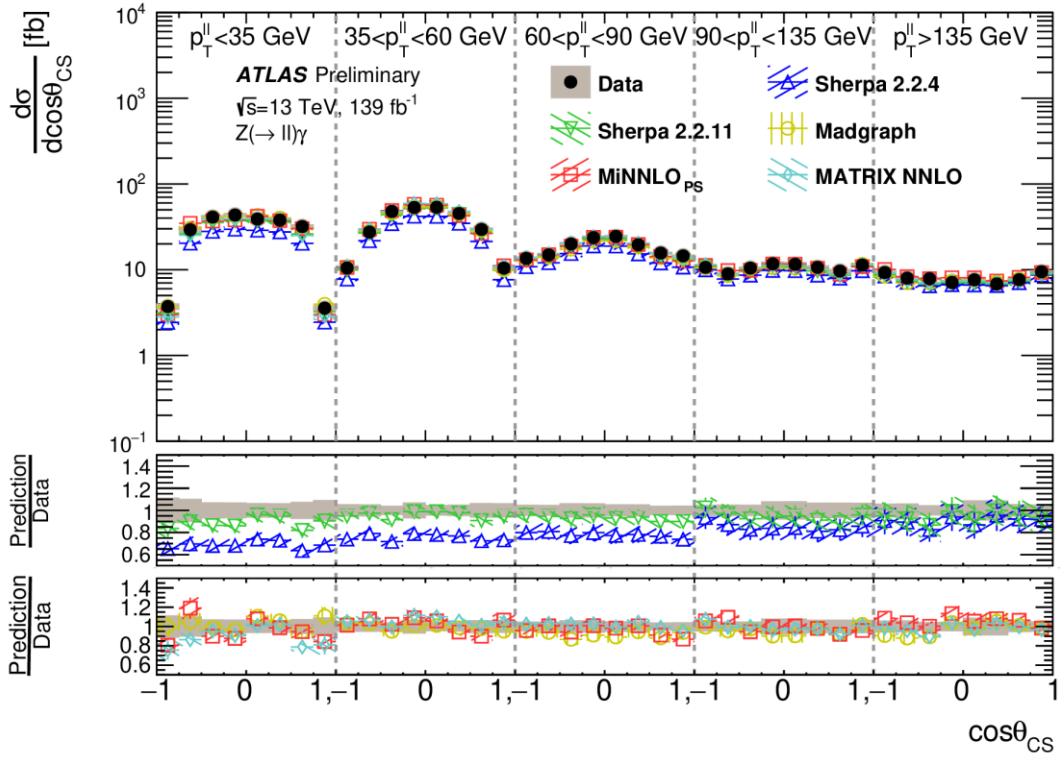
- Measured plenty of observables:
  - 1D variables for QCD study and analyses like ZH(→inv):

    N_{jets}, p_T^j, m_{jj}, HT, $\Delta\Phi(jet,\gamma)$, $\Delta R(l,l)$, $p_T^{Z\gamma}$, …
  - 2D variables sensitive for QCD: eg. $p_T^{Z\gamma}/m_{Z\gamma}$ in $m_{Z\gamma}$ slices
  - **2D variables for polarization study: $\cos\theta_{CS}$ and ϕ_{CS} in p_T^Z slices**
    - **First time to measure the lepton angular coefficient in DY events with γ**

Polarization angle in CS frame







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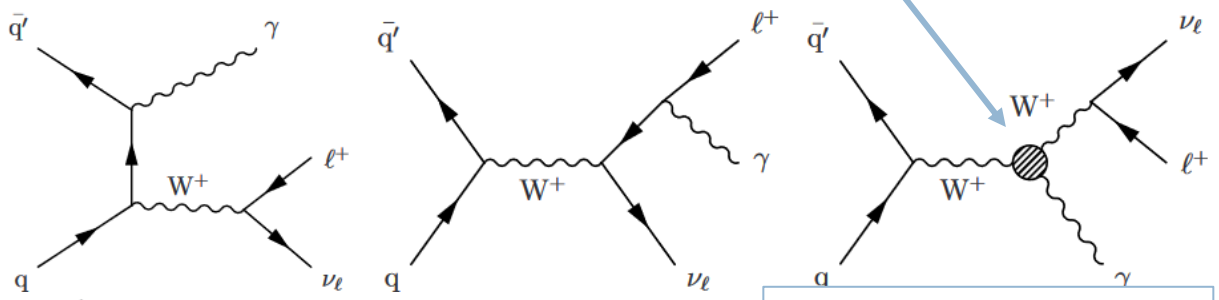
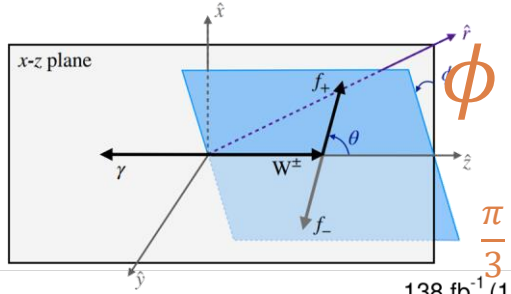
Differential W(→lν)γ

- Important test of SM and probe of WWγ TGC vertex
- Radiation amplitude zero (RAZ) observed: the suppression at $\Delta\eta(l,\gamma) = 0$
- Interference resurrection: sensitivity to interference improved by measuring the lepton angle information and photon momentum
- Limits set on O_{3W} EFT operator: C_{3W} coeff

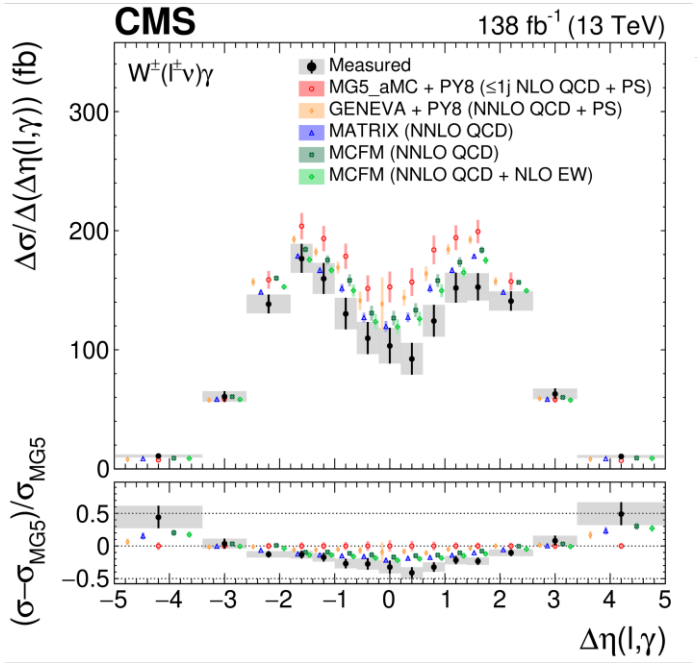
TGC vertex



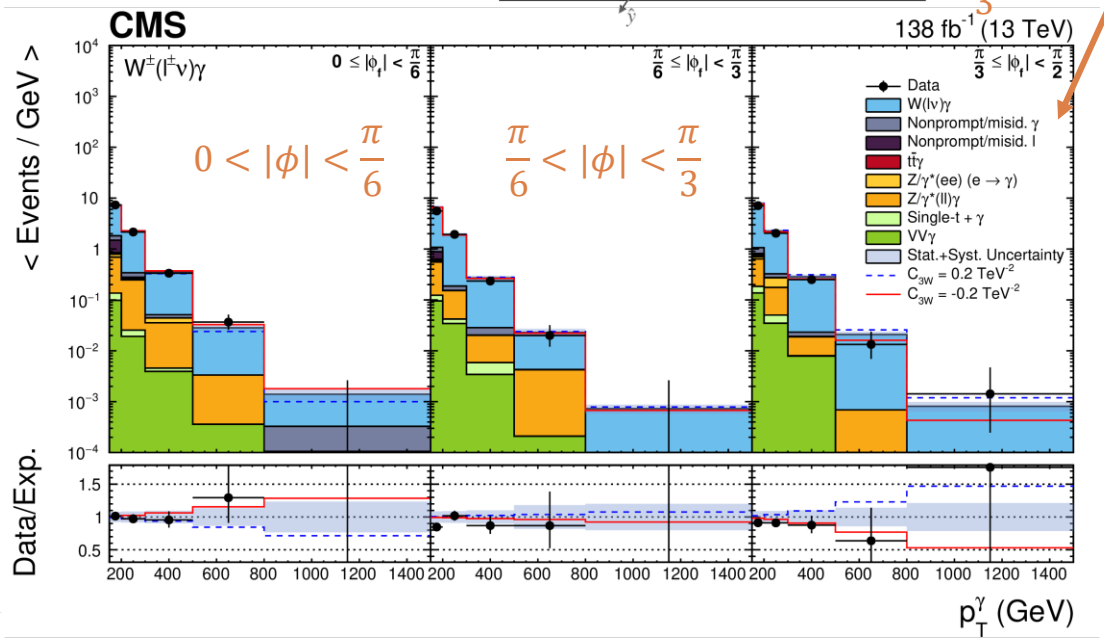


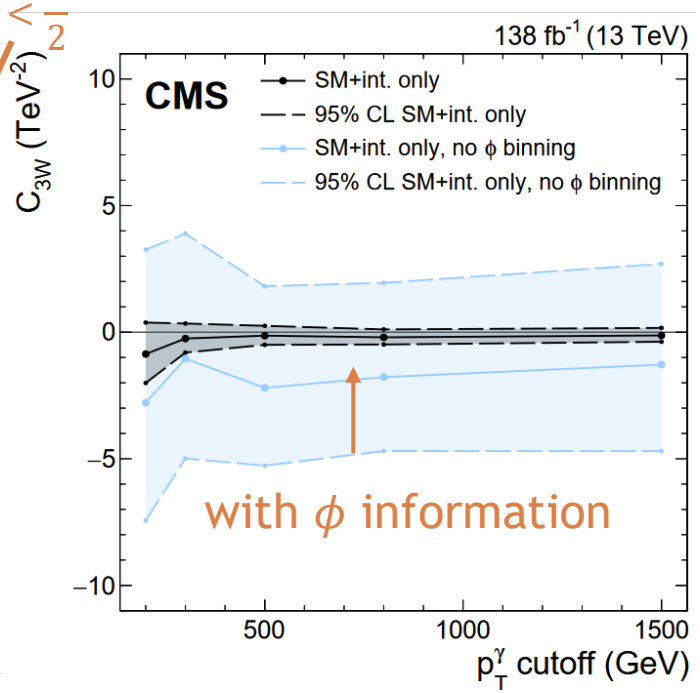
$$\mathcal{O}_{3W} = \epsilon^{ijk} W_\mu^{i\nu} W_\nu^{j\rho} W_\rho^{k\mu}$$

$$\sigma(C_{3W}) = \sigma^{SM} + C_{3W}\sigma^{int} + C_{3W}^2\sigma^{BSM}$$



$\frac{\pi}{3} < |\phi| < \frac{\pi}{2}$





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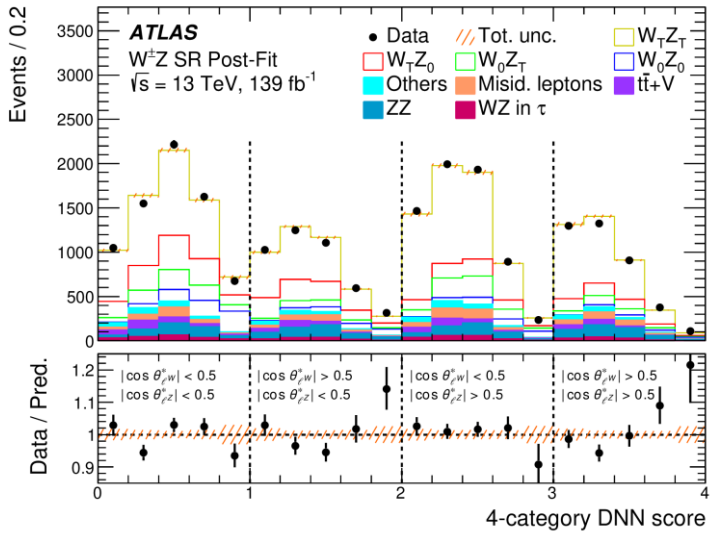
Polarized $W^{\pm}Z$

- Joint-polarisation states of W and Z gauge bosons in $W^{\pm}Z$ production (leptonic mode)
- Rare process: about 17000 WZ with full Run2 and joint-polarized events about 1000
- Signal:
  - Inclusive WZ using Powheg-Box v2 NLO + **reweighting to polarized state**
  - Polarized WZ using MadGraph 2.7.3 LO (WZ+0,1j@LO) used to train the **reweighting deep neural network**
- Background: 3 or more lepton (ZZ, $t\bar{t}V$, τll, so on), fake lepton (Z+jets, so on)
- Deep neural network trained to separate different polarization states
  - Input with leading importance: $|y_{lW} - y_Z|$, p_T^{WZ}, p_T^{lW}, $\Delta\Phi(lW, lv)$

	Signal Region	
	Pre-fit	Post-fit
WZ in τ	620 ± 60	630 ± 60
ZZ	1420 ± 120	1630 ± 50
$t\bar{t}+V$	870 ± 130	830 ± 120
Misid. leptons	1170 ± 230	1010 ± 220
Others	800 ± 90	790 ± 90
W_0Z_0	920 ± 40	1190 ± 160
W_0Z_T	2670 ± 50	1900 ± 500
W_TZ_0	2670 ± 60	3100 ± 400
W_TZ_T	10200 ± 230	10900 ± 600
Total MC	21400 ± 600	21950 ± 170
Data	—	21936



	f_{00}
e energy scale and id. efficiency	0.00019
μ energy scale and id. efficiency	0.0004
E_T^{miss} and jets	0.0017
Pile-up	0.00031
Misidentified lepton background	0.0012
ZZ background	0.0004
Other backgrounds	0.0016
Parton Distribution Function	0.00017
QCD scale	0.00010
Modelling	0.005
Total systematic uncertainty	0.005
Luminosity	0.00015
Statistical uncertainty	0.007
Total	0.010

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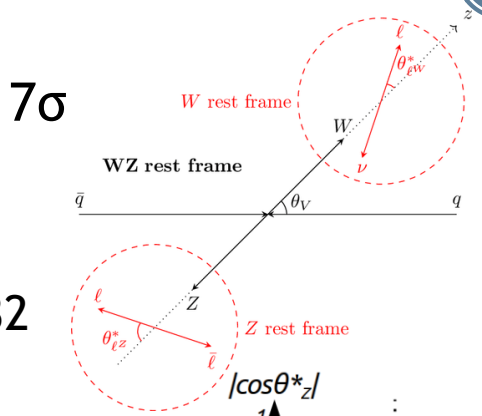
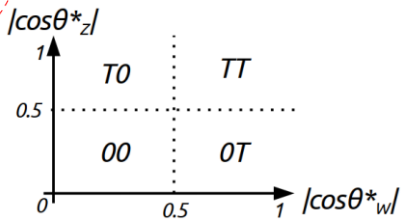
Polarized $W^{\pm}Z$

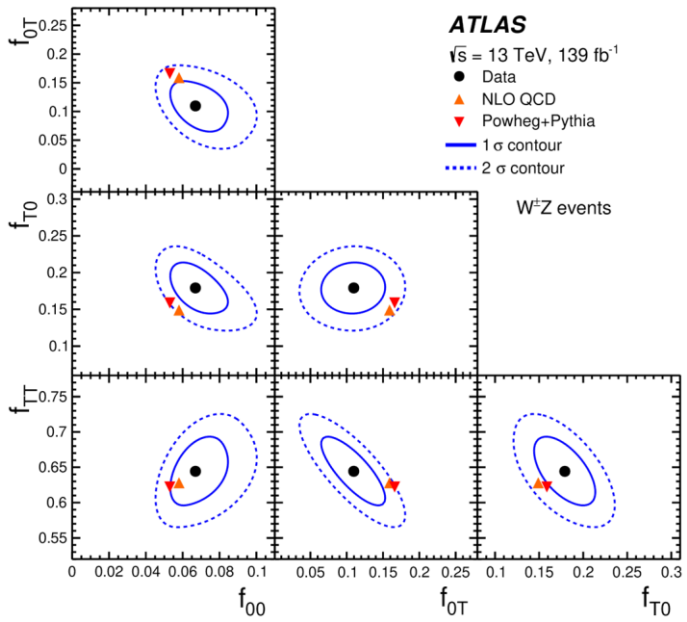
- Simultaneous pair-production of longitudinally polarized vector bosons : 7σ
- Joint helicity fractions integrated over the fiducial region measured
  → agrees SM at NLO
  - f_{00}=0.067±0.010, f_{0T} =0.110±0.029, f_{T0} =0.179±0.023 and f_{TT} =0.644±0.032
  - Individual helicity fractions also measured and consistent within **correlations**

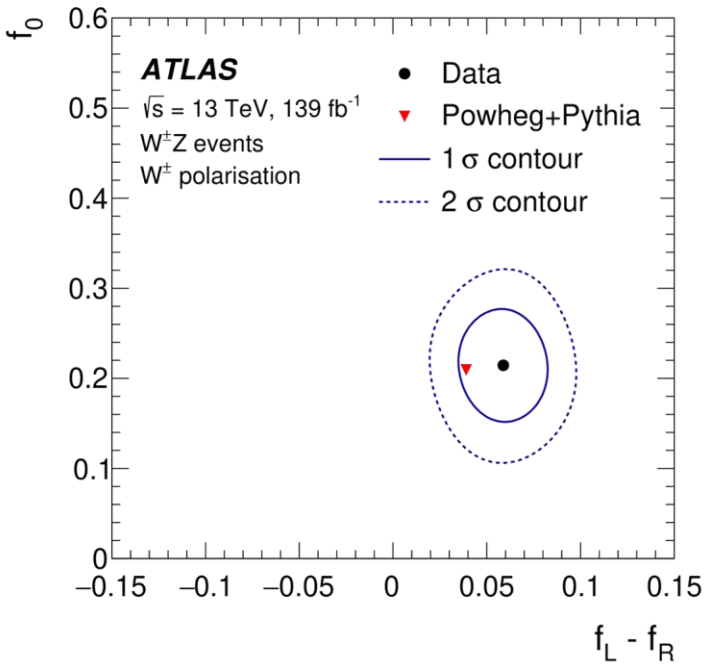
longitudinal-longitudinal

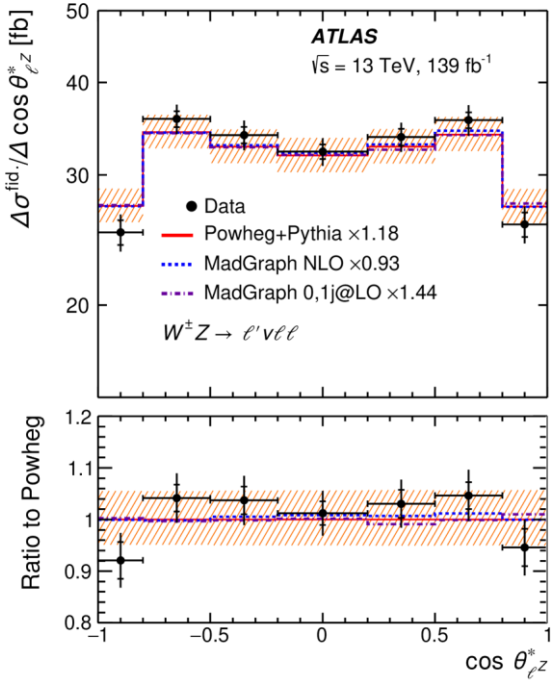
- Inclusive $\sigma^{\text{fid.}}_{W^{\pm}Z\to\ell'\nu\ell\ell} = 64.6 \pm 2.1$ fb **VS** NNLO QCD SM prediction = $64.0^{+1.5}_{-1.3}$ fb
- Differential cross-section measured for polarization sensitive variables











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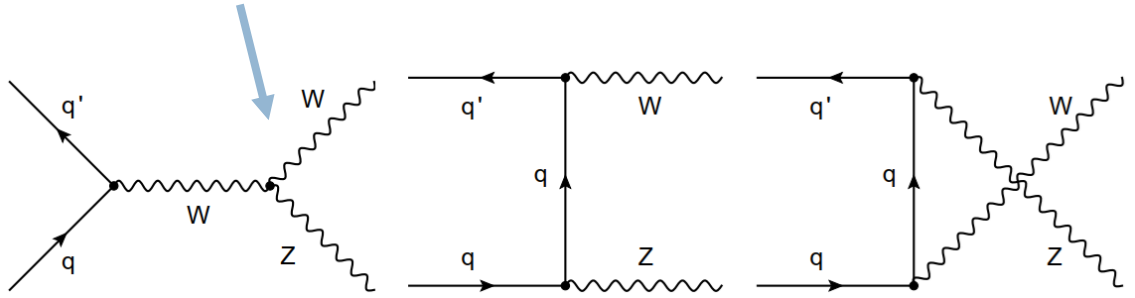
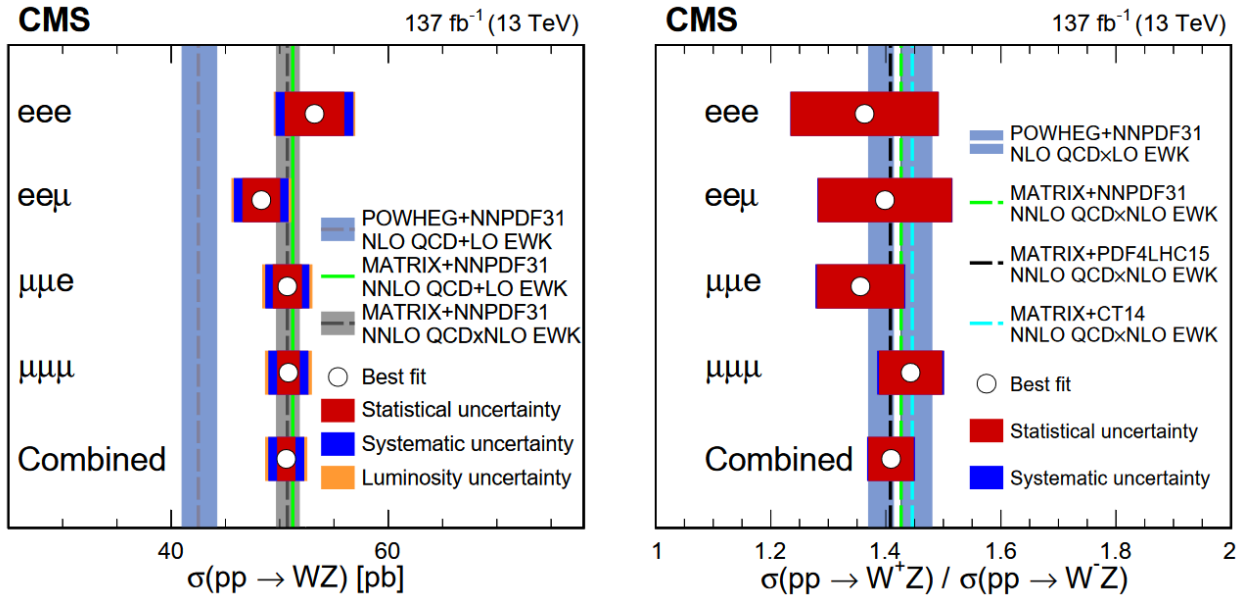
Measurement of WZ

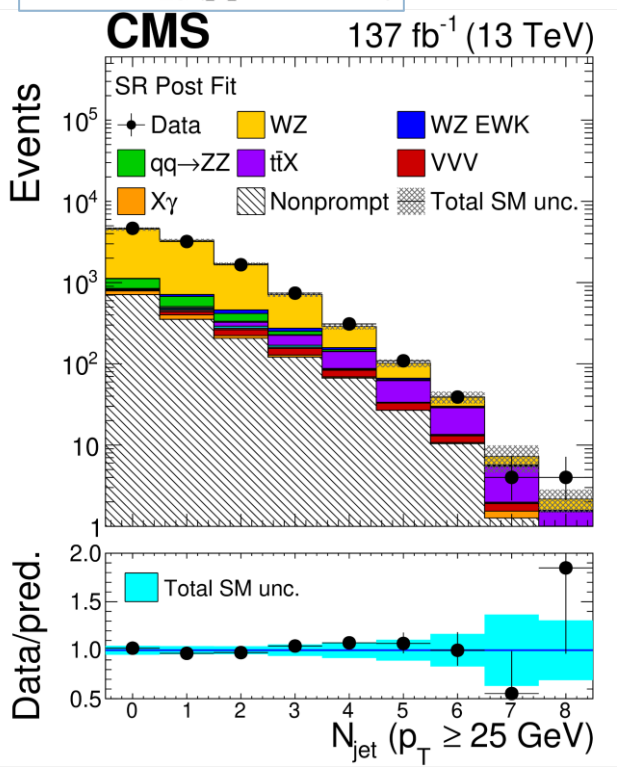
- Measure the WZ associated production (leptonic decaying)
- Dominant bkg. from Z+jets and $t\bar{t}$ [2.4%] , V V and $t\bar{t}$V [14%]
- Inclusive cross-section measured 50.6 ± 0.8 (stat) ± 1.4 (syst) ± 1.1 (lumi) ± 0.5 (theo) pb = 50.6 ± 1.9pb
- Agrees with SM from MATRIX at NNLO QCD and NLO EWK ($50.7^{+1.1}_{-1.0}$ pb) ; consistent with earlier ATLAS/CMS results
- Compatible charge asymmetry ratio $A^{\pm}_{WZ}$=1.41 ± 0.04 observed with SM calculated with POWHEG at NLO QCD and previous measurement

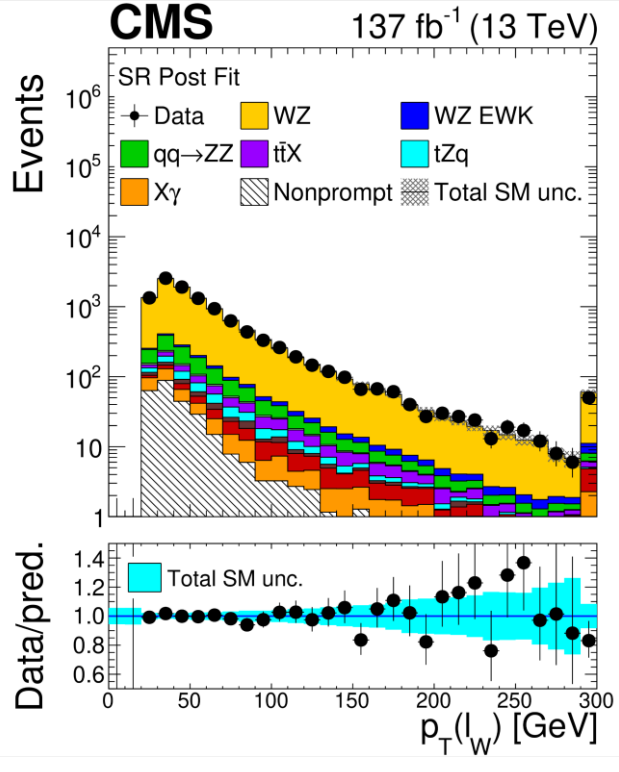
Triple gauge coupling(TGC)



$$A^{+-}_{WZ} = \frac{\sigma_{\text{fid}}(pp \to W^+Z)}{\sigma_{\text{fid}}(pp \to W^-Z)}$$







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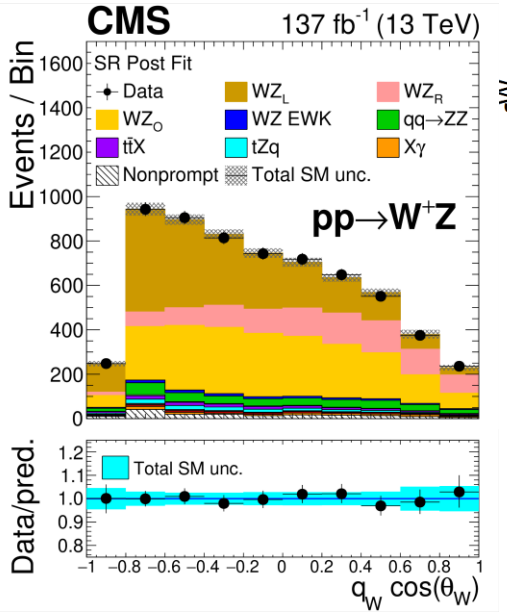
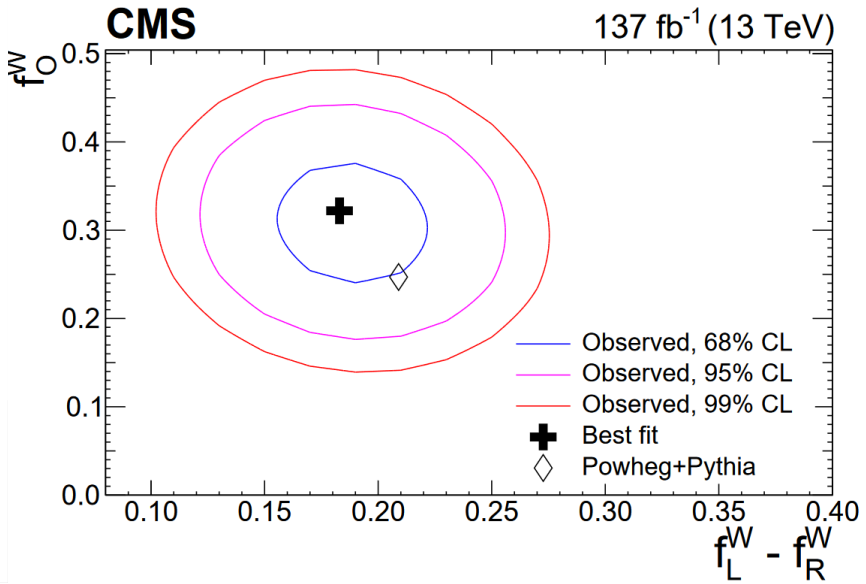
Measurement of WZ

- Vector boson polarization fraction measured in the helicity frame with charge inclusive/exclusive final states
- Longitudinally polarized W bosons in WZ production: first observation at 5.6σ (4.3σ expected)!
- Longitudinally polarized Z bosons: well beyond 5σ

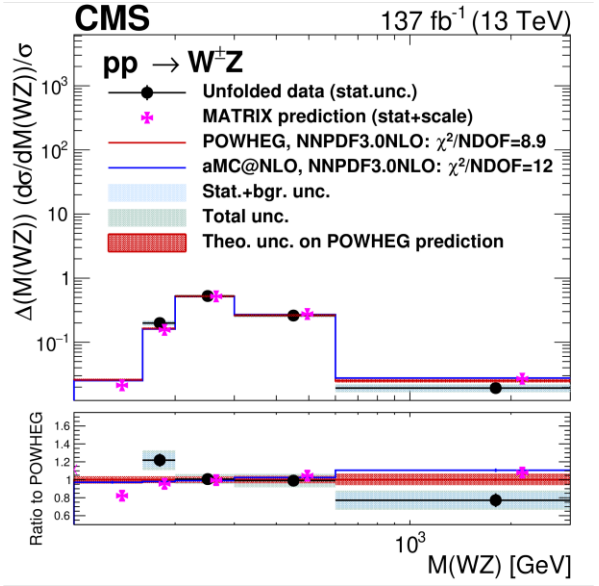
Polarization fraction

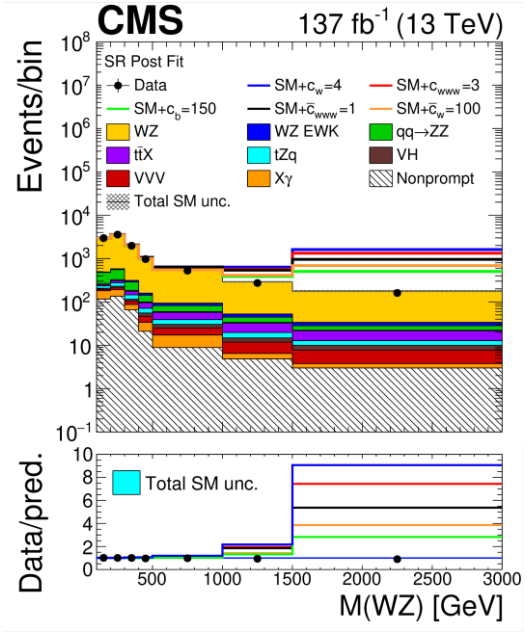
$$\frac{1}{\sigma}\frac{\mathrm{d}\sigma}{\mathrm{d}\cos\theta_{\mathrm{W}^{\pm}}} = \frac{3}{8}\left\{[1\mp\cos(\theta_{\mathrm{W}^{\pm}})]^2 f_{\mathrm{L}}^{\mathrm{W}} + [1\pm\cos(\theta_{\mathrm{W}^{\pm}})]^2 f_{\mathrm{R}}^{\mathrm{W}} + 2\sin^2(\theta_{\mathrm{W}^{\pm}}) f_{0}^{\mathrm{W}}\right\}$$





- Differential cross-section measured and data favor MATRIX over POWHEG
- New constraints on charged anomalous triple gauge coupling (aTGC, dim-6): 2x stronger than previous





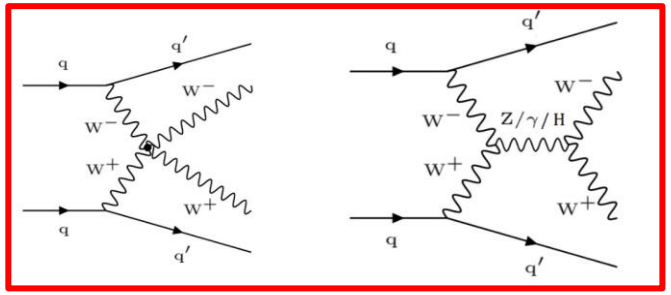
Parameter	95% CI, exp. (TeV^{-2})	95% CI, obs. (TeV^{-2})	Best fit, obs. (TeV^{-2})
c_{W}/Λ^2	$[-2.0, 1.3]$	$[-2.5, 0.3]$	-1.3
$c_{\mathrm{WWW}}/\Lambda^2$	$[-1.3, 1.3]$	$[-1.0, 1.2]$	0.1
c_{b}/Λ^2	$[-86, 125]$	$[-43, 113]$	44
$\tilde{c}_{\mathrm{WWW}}/\Lambda^2$	$[-0.76, 0.65]$	$[-0.62, 0.53]$	-0.03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

Observation of EWK $W^{\pm}W^{\mp}$ (leptonic decay)

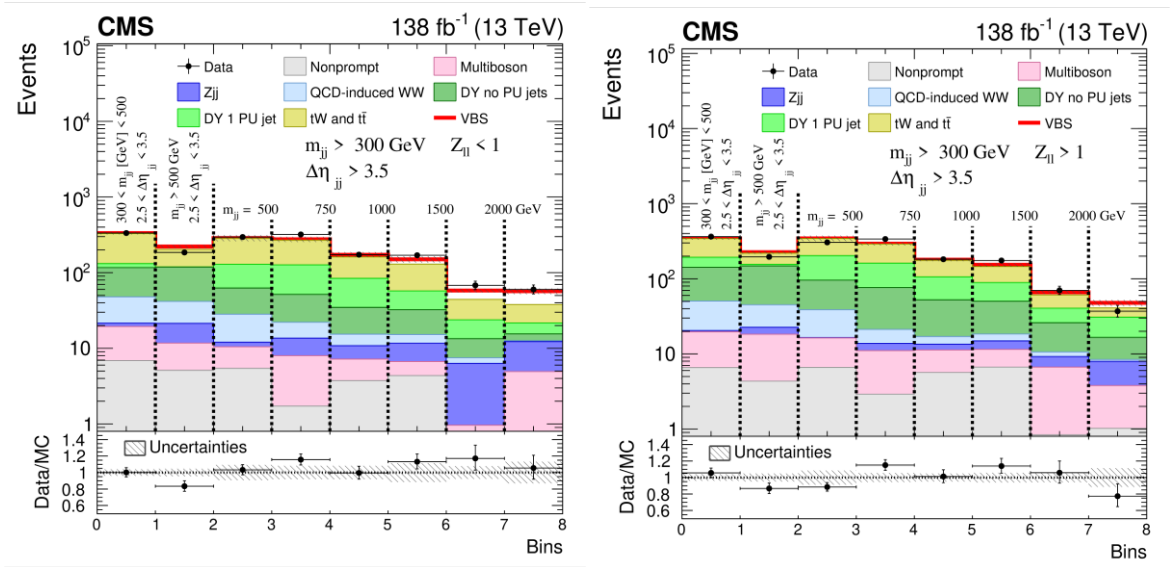
- EW scattering: study EW symmetry breaking and probe of BSM
- Exactly 2 opposite sign lepton and 2 jets with large Δη and high m_{jj}
- Signal enriched with small Zeppenfeld: $Z_{l1l2} = \frac{1}{2}\left|\left(\eta_{l1} - \frac{1}{2}(\eta_{j1}+\eta_{j1})\right) + \left(\eta_{l1} - \frac{1}{2}(\eta_{j1}+\eta_{j1})\right)\right|$
- Background from QCD WW, $t\bar{t}$ (tW), DY and non-prompt lepton (W+jets)

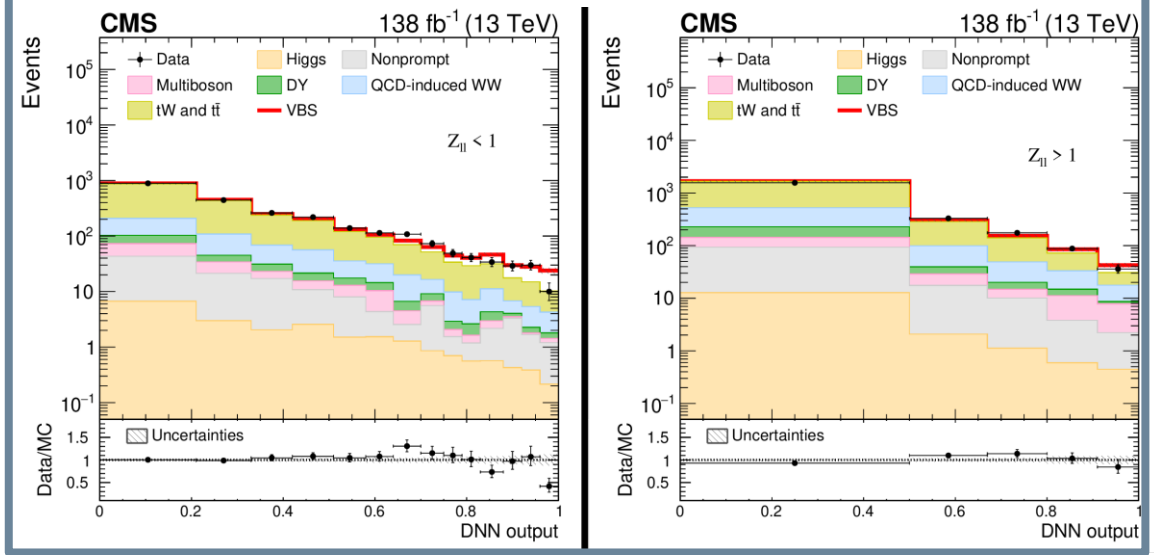
➢ DNN trained for different lepton flavor region

- **Observed with 5.6σ (5.2σ expected)**
- Fiducial cross-section measured 10.2 ± 2.0 fb, consistent with SM prediction of 9.1 ± 0.6 fb



Variable	Description
m_{jj}	Invariant mass of the two tagging jets pair
$\Delta\eta_{jj}$	Pseudorapidity separation between the two tagging jets
$p_T^{j_1}$	p_T of the highest p_T jet
$p_T^{j_2}$	p_T of the second-highest p_T jet
$p_T^{\ell\ell}$	p_T of the lepton pair
$\Delta\phi_{\ell\ell}$	Azimuthal angle between the two leptons
Z_{ℓ_1}	Zeppenfeld variable of the highest p_T lepton
Z_{ℓ_2}	Zeppenfeld variable of the second-highest p_T lepton
$m_T^{\ell_1}$	Transverse mass of the $(p_T^{\ell_1}, p_T^{miss})$ system



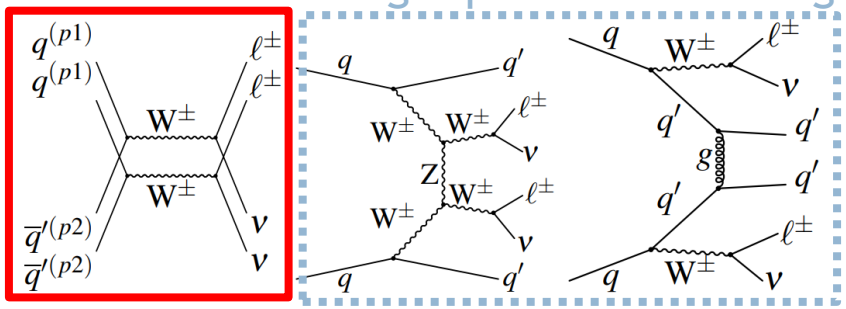


SMP-21-013 (*Phys. Rev. Lett. accepted*)

Double parton scattering $W^{\pm}W^{\pm}$

- First observation of $W^{\pm}W^{\pm}$ bosons from double parton scattering (significance 6.2σ)
- Probe the transverse profile of the proton and its energy evolution
- Angular and momentum uncorrelated final states and information encoded in the σ_{eff}
- Clear leptonically decaying and little additional jet (suppress single parton process)
- Multivariate discriminants(BDT) used to distinguish the signal from background

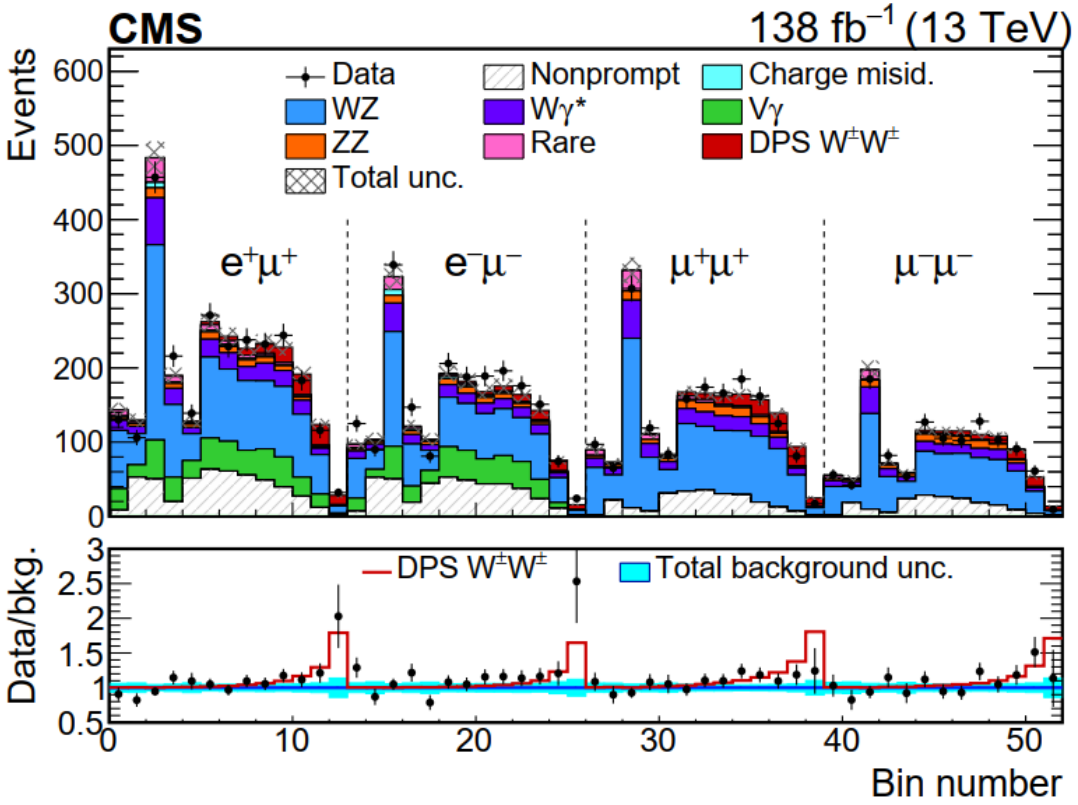
single parton scattering



$$80.7 \pm 11.2\,(\text{stat})^{+9.5}_{-8.6}\,(\text{syst}) \pm 12.1\,(\text{model})\ \text{fb}$$

(leptonic decaying)

$$\sigma_{DPS} = \frac{1}{2}\frac{\sigma^2_{incl}}{\sigma_{eff}}$$



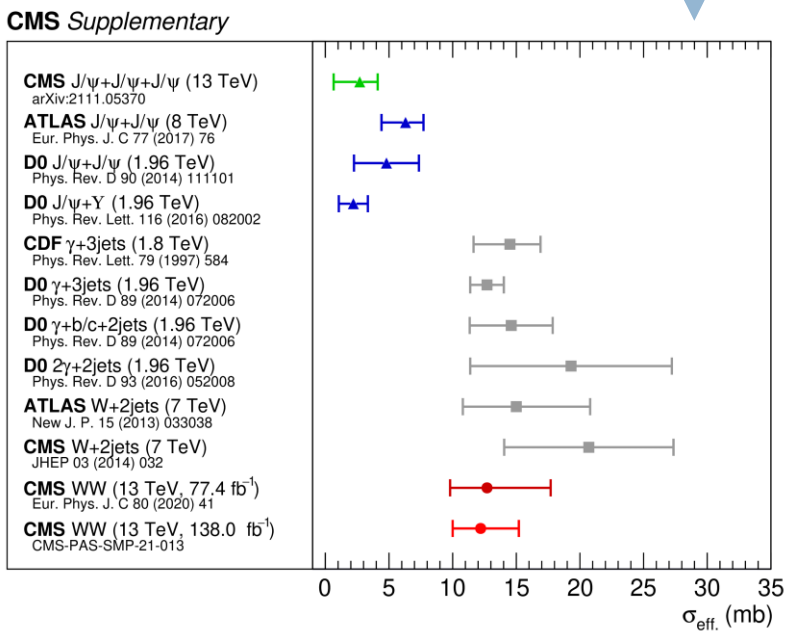
WZ: Dominant bkg.
Suppressed by veto 3rd lepton or tau
Controlled by enriched 3L region

Non-prompt(W+jets,multijets, tt~)
Supp. by MET>15GeV, m_ll>12GeV and b

ZZ: controlled by 4L region

Vγ and DY process:
Supp. by pT_ll>20GeV in emu region

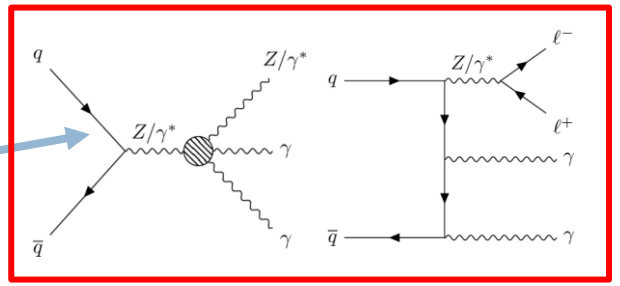
Signal:simulated at LO
with **Pythia**+CUETP8M1(for 2016)
/CP5(for 2017-2018) with NNPDF 2.3
Alternatively simu. with HERWIG++
and dShower (considers **dPDF**)

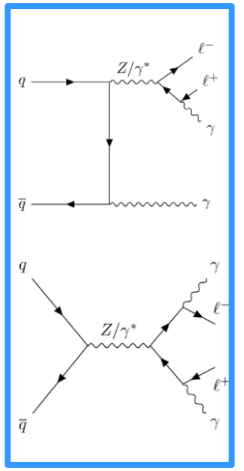


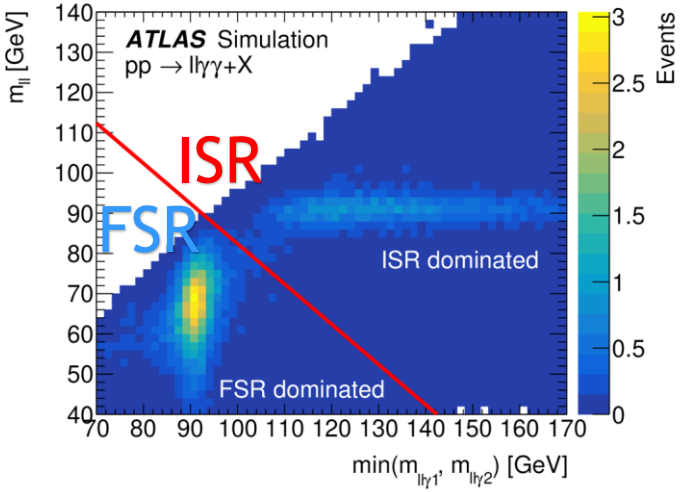
Measurement of Z(→ll)γγ

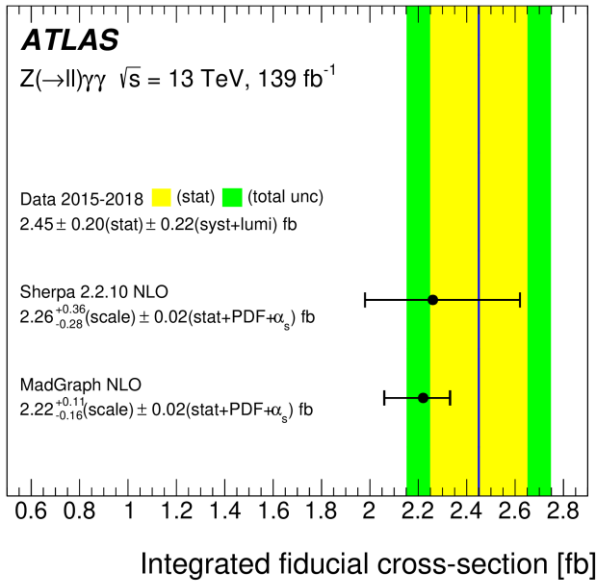
- First measurement of fully ISR Zγγ production
- Signal generated using Sherpa2.2.10 (0j@NLO, 1,2j@LO)
- FSR photon explicitly removed with $\mathbf{min}(m_{ll\gamma 1}, m_{ll\gamma 2}) + m_{ll} > 2m_Z$
- Largest(20%) bkg. is non-prompt photons estimated from data
- Integrated cross-section measured with a precision of 12%
- Differential meas. good with SM except discrepancy at high-$p_T^{ll\gamma\gamma}$
- Limits set on Wilson coeff. of dim-8 EFT operator using p_T^{ll}

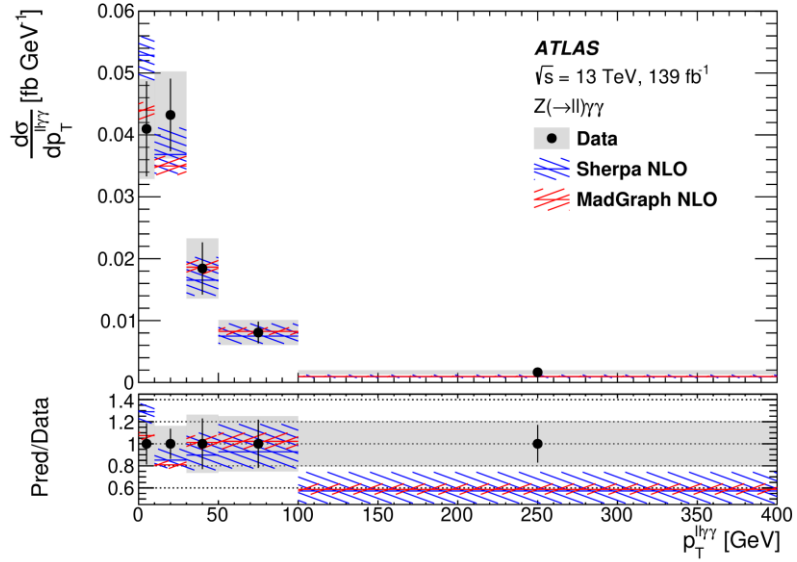
aQGC

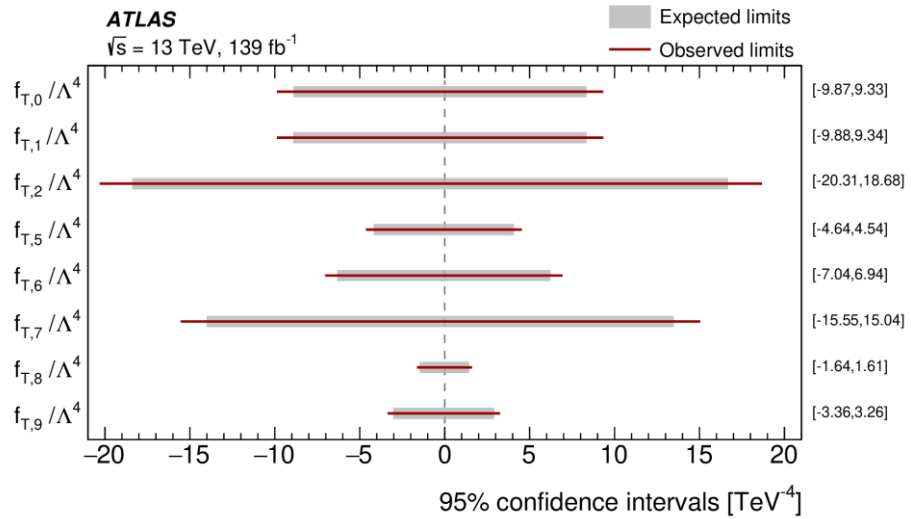








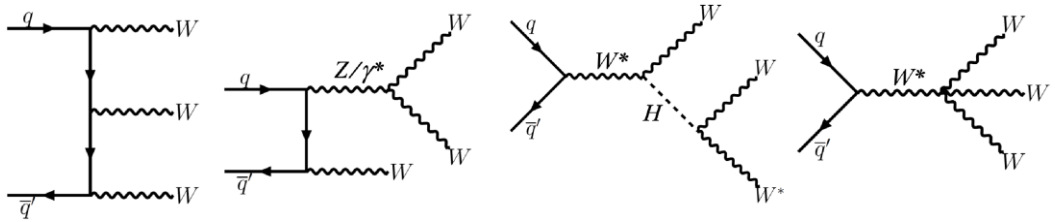


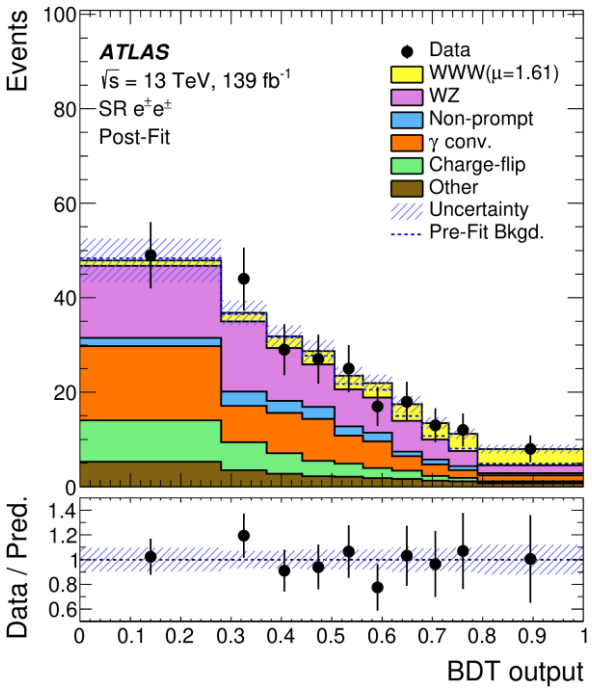


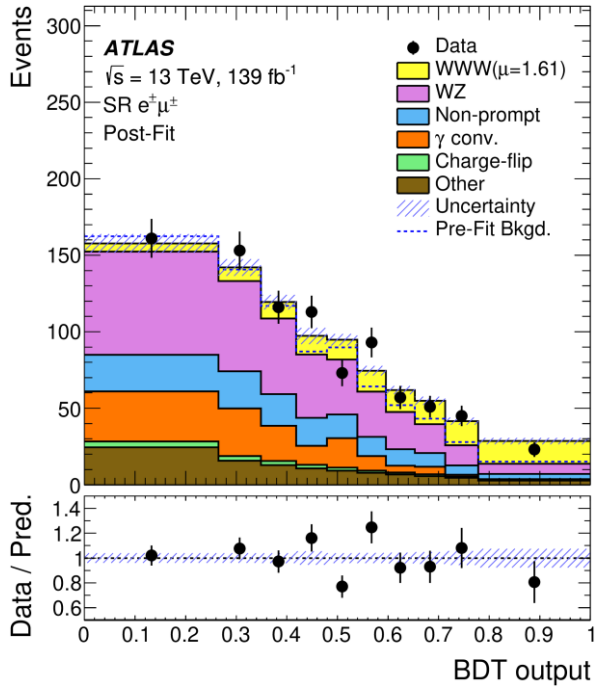
Phys. Rev. Lett. 129 (2022) 061803

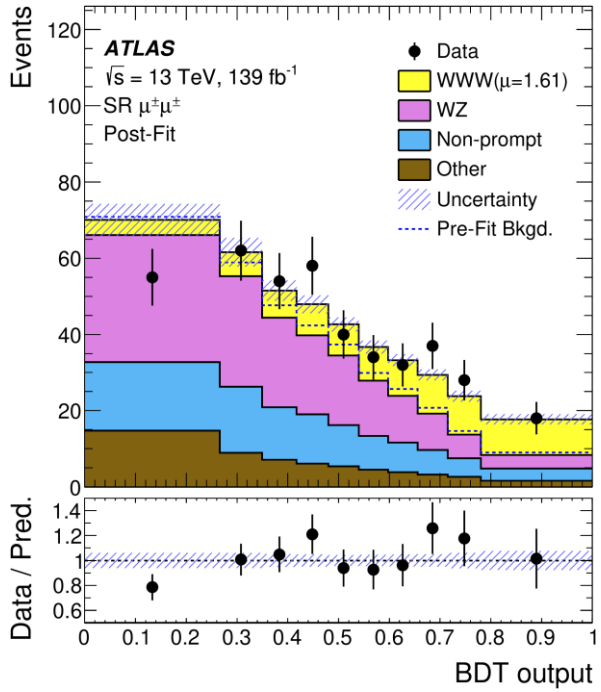
Observation of $W^{\pm}W^{\mp}W^{\mp}$

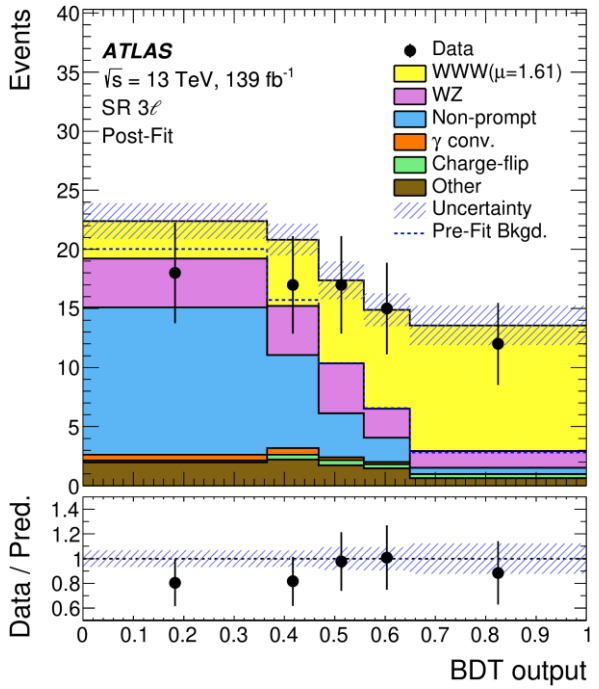
- Test of SM boson self-interactions via triple and quartic gauge coupling and search for BSM hint
- Final states with 2L ($l\mp\nu\, l\mp\nu\, jj$) or 3L ($l\pm\nu\, l\, \mp\nu\, l\, \mp\nu$)
- Background from WZ, non-prompt ($t\bar{t}$), photon-conversion, charge-flip — Data-driven estimation
- Multivariate technique (BDT) trained to separate signal/background — constrained by $l\, e^+\, e^-$ or $l\, \mu^+\, \mu^-$ control region
- Binned maximum-likelihood fit performed to extract the signal







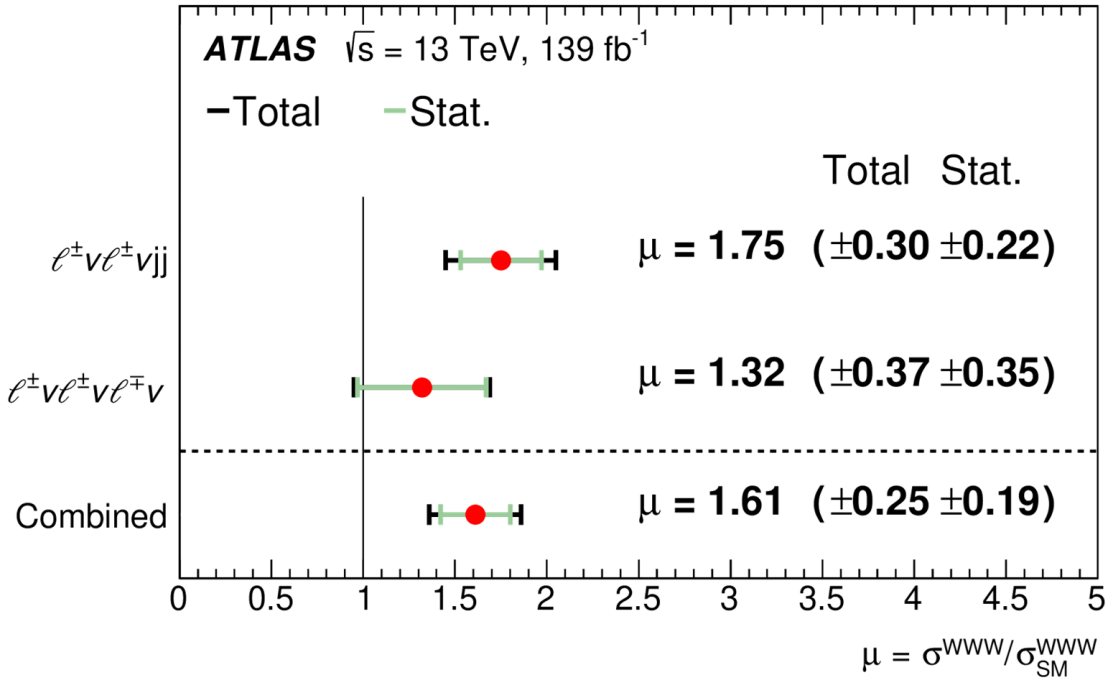




Phys. Rev. Lett. 129 (2022) 061803

Observation of $W^{\pm}W^{\mp}W^{\mp}$

- Largest systematic uncertainty from non-prompt data-driven estimation of and WZ modelling
- WWW production observed with 8.0σ (5.4σ expected)
- Inclusive cross-section 820 ± 100 (stat) ± 80 (syst) fb
  - SM Prediction: 511 ± 18 fb at NLO QCD and LO EW
  - **2.6σ derivation from SM prediction**



Uncertainty source	$\Delta\sigma/\sigma$ [%]
Data-driven background	6.0
Prompt-lepton-background modeling	3.0
Jets and $E_{\mathrm{T}}^{\mathrm{miss}}$	2.6
MC statistics	2.5
Lepton	2.2
Luminosity	1.9
Signal modeling	1.5
Pile-up modeling	1.0
Total systematic uncertainty	9.9
Data statistics	11.6
WZ normalizations	3.1
Total statistical uncertainty	12.0

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	$\mathbf{1.61 \pm 0.25}$	**8.0 (5.4) σ**

Summary

- Recent results from ATLAS and CMS experiments of multiboson production presented
  - Measurement of **differential cross-section** of $Z(\rightarrow ll)\gamma$
  - Measurement of **differential cross-section** of $W(\rightarrow l\nu)\gamma$ dim-6 EFT interpretation
  - Measurement of **joint-polarized** $W^{\pm}Z$ production
  - Measurement of WZ production NNLO QCD dim-6 EFT interpretation
  - **Observation** of electroweak production of $W^{\pm}W^{\mp}$
  - **Observation** of $W^{\pm}W^{\pm}$ production from **double parton scattering**
  - Measurement of **differential cross-section** of $Z(\rightarrow ll)\gamma\gamma$ dim-8 EFT interpretation
  - **Observation** of $W^{\pm}W^{\mp}W^{\mp}$ production 2.6σ derivation from SM prediction

More electroweak specific results in Michael's talk!

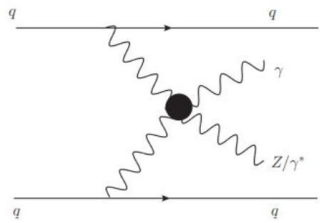
- No significant deviation from SM prediction
- Limits on aQGC and aTGC refreshed with new precise measurement
- Run3 data with higher stats will allow for more precise measurement of SM and better sensitivity for BSM including EFT interpretation → worth looking forward to!

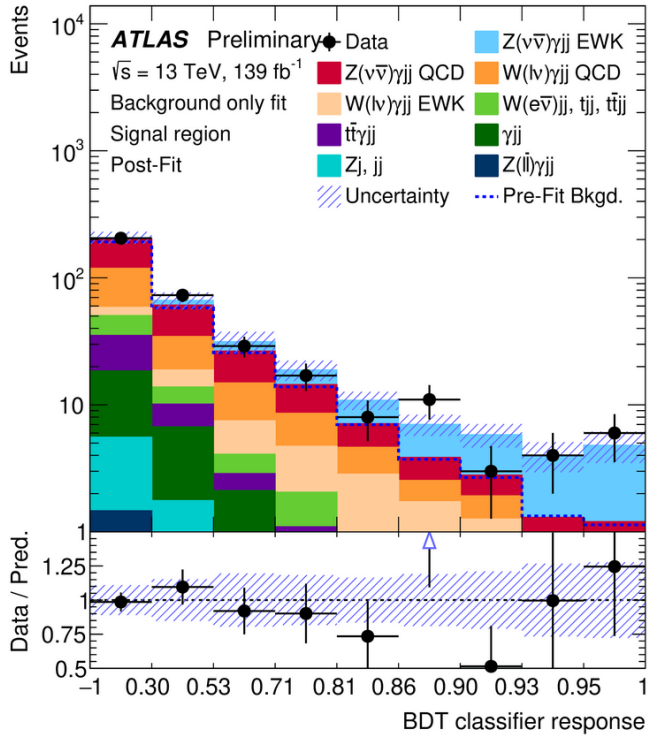
Backups

2208.12741 More on Michael's talk!

EW Z(→νν)γjj

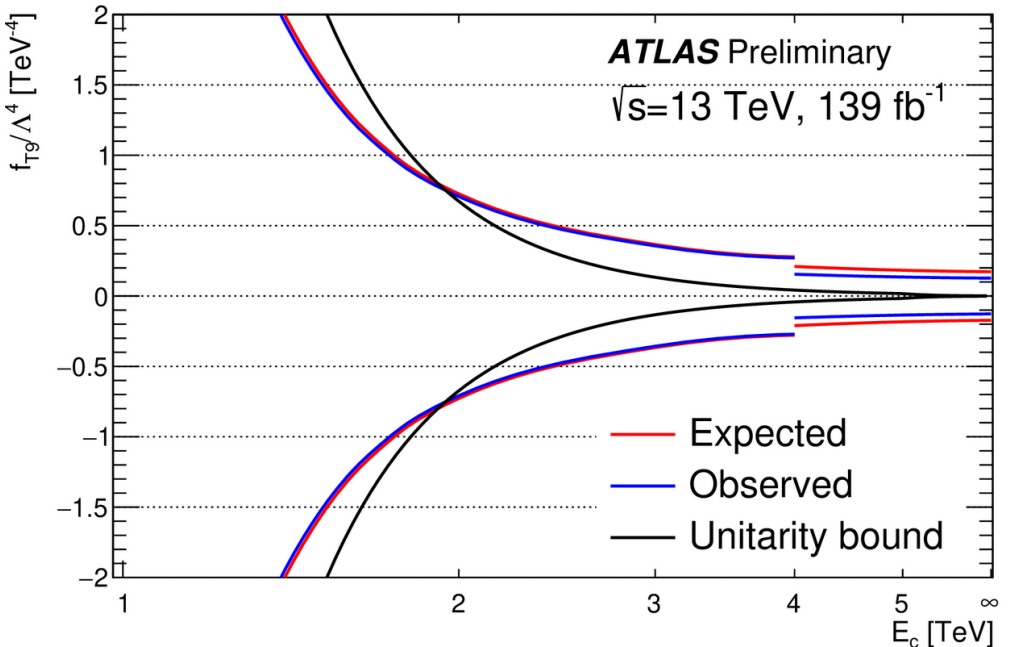
- EW Z(→νν)γjj previously observed in ATLAS [EPJC. 82, 105 (2022)]
  - 5.2σ significance with $p_T^\gamma \in [15, 110]$ GeV
- Measurement of EW $Z(\rightarrow \nu\nu)\gamma jj$ with high p_T^γ >150GeV
  - Sensitive phase space to aQGC study
- Dominant background from QCD Z(→νν)γ and W(lν)γ/ttγ
- Fake photon and MET bkg. estimated with data-driven
- Boosted decision tree developed to increase S/B and used as fitting discriminant in SR
- No significant deviation observed from SM prediction
- Limit set on EFT dim-8 operator, in particular strong limit on f_{T5}/Λ^4, f_{T8}/Λ^4 and f_{T9}/Λ^4



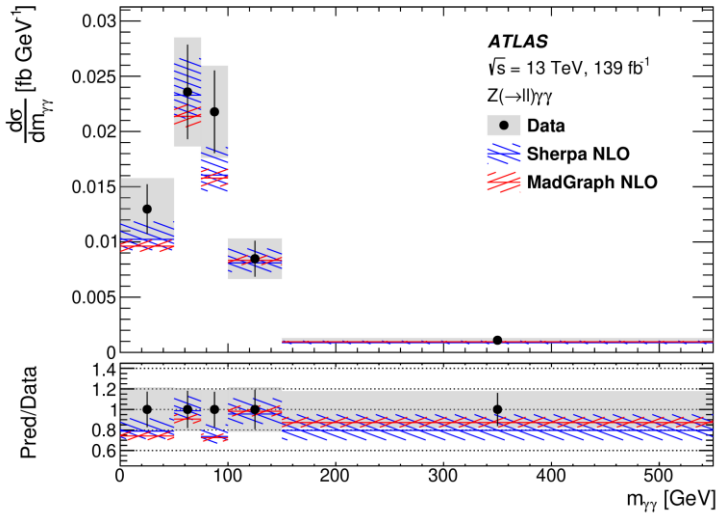


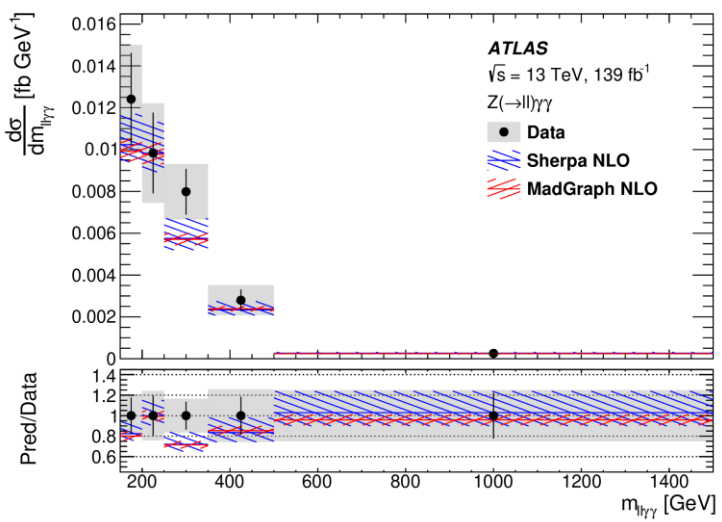
unitarity-preserving

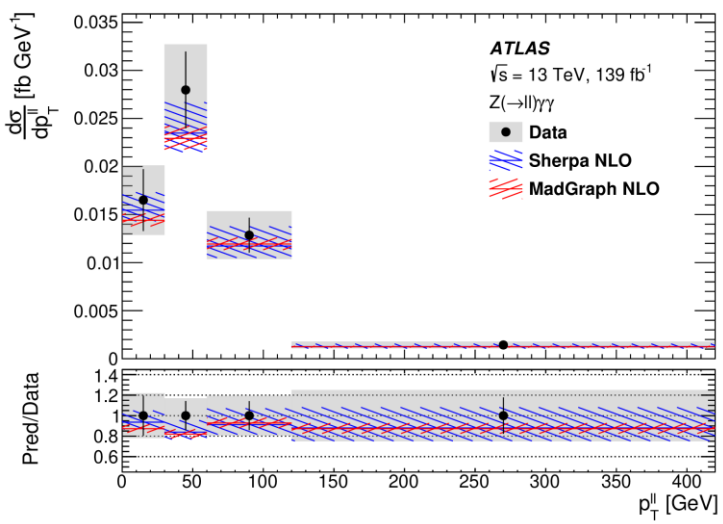
Coefficient	E_c [TeV]	Observed limit [TeV^{-4}]	Expected limit [TeV^{-4}]
f_{T0}/Λ^4	1.7	$[-8.7, 7.1] \times 10^{-1}$	$[-8.9, 7.3] \times 10^{-1}$
f_{T5}/Λ^4	2.4	$[-3.4, 4.2] \times 10^{-1}$	$[-3.5, 4.3] \times 10^{-1}$
f_{T8}/Λ^4	1.7	$[-5.2, 5.2] \times 10^{-1}$	$[-5.3, 5.3] \times 10^{-1}$
f_{T9}/Λ^4	1.9	$[-7.9, 7.9] \times 10^{-1}$	$[-8.1, 8.1] \times 10^{-1}$
f_{M0}/Λ^4	0.7	$[-1.6, 1.6] \times 10^{2}$	$[-1.5, 1.5] \times 10^{2}$
f_{M1}/Λ^4	1.0	$[-1.6, 1.5] \times 10^{2}$	$[-1.4, 1.4] \times 10^{2}$
f_{M2}/Λ^4	1.0	$[-3.3, 3.2] \times 10^{1}$	$[-3.0, 3.0] \times 10^{1}$

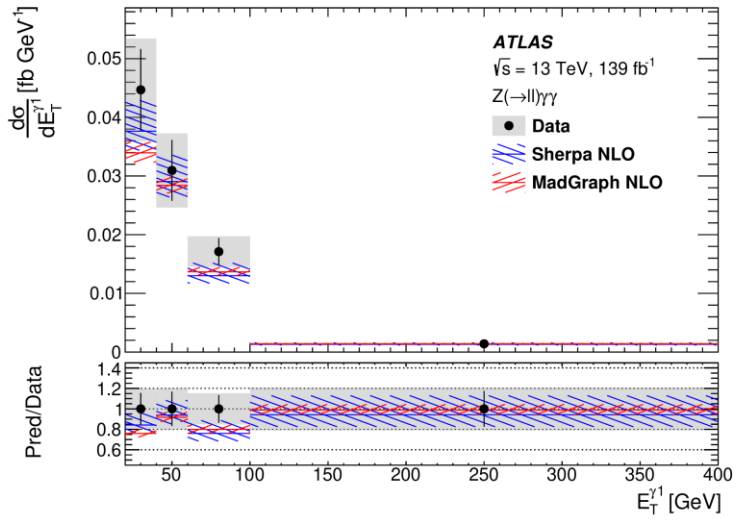


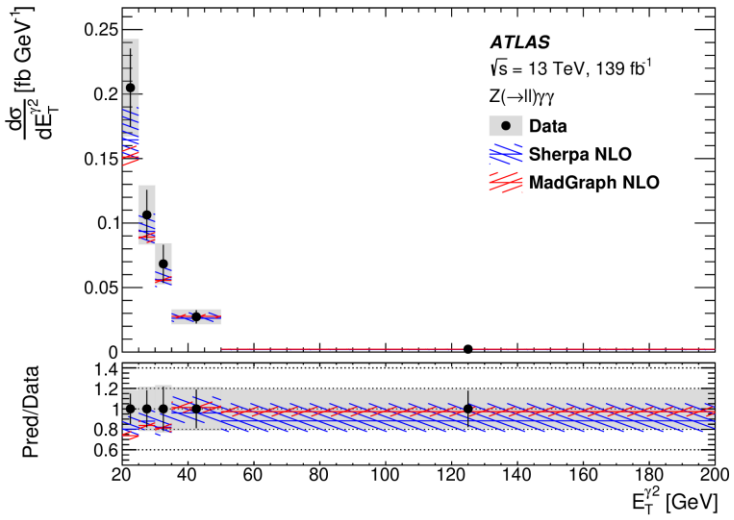
Measurement of Z(→ll)γγ

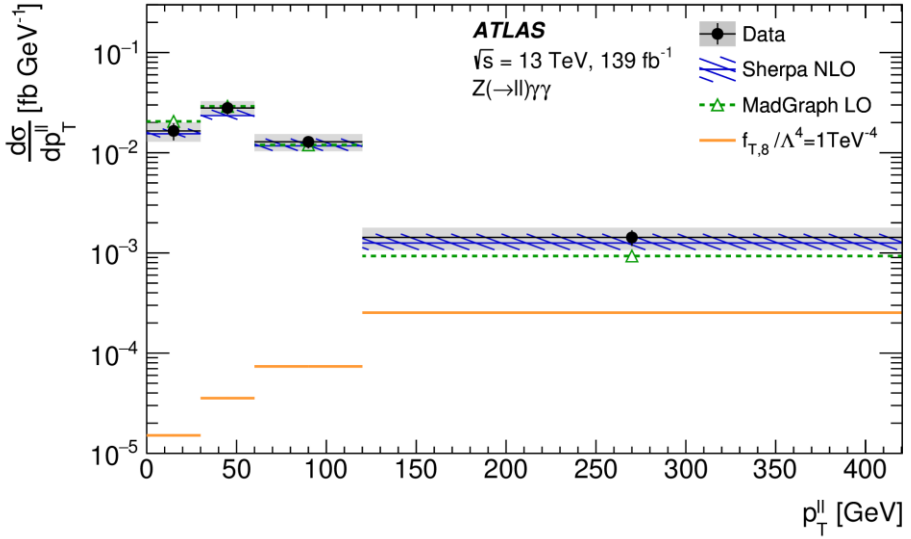












Measurement of Z(→ll)γγ

	$e^+e^-\gamma\gamma$	$\mu^+\mu^-\gamma\gamma$
Data	148	171
	Background predictions	
$Z\gamma j + Zj\gamma + Zjj$	29.8±5.7 (stat.)±5.5 (sys.)	34.4±6.6 (stat.)±6.3 (sys.)
$t\bar{t}\gamma\gamma$	6.4±0.4 (stat.)±1.4 (sys.)	8.4±0.5 (stat.)±1.8 (sys.)
$ZZ \to \ell\ell\ell\ell$	1.03±0.10 (stat.)±0.51 (sys.)	1.24±0.11 (stat.)±0.62 (sys.)
$WZ\gamma \to \ell\nu\ell\ell\gamma$	0.69±0.06 (stat.)±0.35 (sys.)	0.52±0.05 (stat.)±0.26 (sys.)
$Z(\to \ell\ell)H(\to \gamma\gamma)$	1.08±0.01 (stat.)±0.22 (sys.)	1.38±0.01 (stat.)±0.28 (sys.)
$Z\gamma + \gamma$	2.07±0.16 (stat.)±0.72 (sys.)	2.74±0.21 (stat.)±0.96 (sys.)
$Z + \gamma\gamma$	1.44±0.04 (stat.)±0.39 (sys.)	1.90±0.05 (stat.)±0.51 (sys.)
Data – background	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.)

	Process	Generator	Order	PDF Set	PS/UE/MPI
Signal	$\ell\ell\gamma\gamma$	Sherpa 2.2.10	NLO	NNPDF3.0nnlo	Sherpa 2.2.10
	$\ell\ell\gamma\gamma$	MadGraph5_aMC@NLO 2.7.3	NLO	NNPDF3.0nlo	Pythia 8.244
Background	$Z\gamma$ + jets	Sherpa 2.2.4	LO	NNPDF3.0nnlo	Sherpa 2.2.4
	Z + jets	Powheg Box v1	NLO	CT10nlo	Pythia 8.186
	$t\bar{t}\gamma$	MadGraph5_aMC@NLO 2.3.3	LO	NNPDF2.3lo	Pythia 8.212
	$ZZ \to \ell\ell\ell\ell$	Sherpa 2.2.2	NLO	NNPDF3.0nnlo	Sherpa 2.2.2
	$WZ\gamma \to \ell\nu\ell\ell\gamma$	Sherpa 2.2.5	NLO	NNPDF3.0nnlo	Sherpa 2.2.5
	$Z(\to \ell\ell)H(\to \gamma\gamma)$	Powheg Box v2	NLO	NNPDF3.0nlo	Pythia 8.212
	γ + jets	Sherpa 2.2.2	NLO	NNPDF3.0nnlo	Sherpa 2.2.2
	$\gamma\gamma$ + jets	Sherpa 2.2.2	NLO	NNPDF3.0nnlo	Sherpa 2.2.2

Photons	Leptons
$p_{\mathrm{T}}^{\gamma} > 20$ GeV	$p_{\mathrm{T}}^{\ell 1} > 30$ GeV, $p_{\mathrm{T}}^{\ell 2} > 20$ GeV
$\lvert\eta^{\gamma}\rvert < 2.37$	$\lvert\eta^{\ell}\rvert < 2.47$
$E_{\mathrm{T}}^{\mathrm{iso}}/p_{\mathrm{T}}^{\gamma} < 0.07$	dressed leptons
Event	
$\Delta R(\gamma, \ell) > 0.4$, $\Delta R(\gamma, \gamma) > 0.4$	
$m_{\ell\ell} > 40$ GeV	
$m_{\ell\ell} + \min(m_{\ell\ell\gamma_1}, m_{\ell\ell\gamma_2}) > 2m_Z$	

Source	Relative uncertainty [%]	
	$e^+e^-\gamma\gamma$	$\mu^+\mu^-\gamma\gamma$
Photon identification efficiency	2.5	2.6
Photon isolation efficiency	2.0	2.0
Electron–photon energy resolution	0.2	0.1
Electron–photon energy scale	0.8	0.6
Electron identification efficiency	2.0	-
Electron reconstruction efficiency	0.3	-
Muon isolation efficiency	-	0.4
Muon reconstruction efficiency	-	0.4
Muon trigger efficiency	-	0.3
Muon momentum scale	-	0.2
Pile-up reweighting	2.8	2.9
Monte Carlo signal statistics	1.1	1.0
Signal modelling	1.1	1.1
Integrated luminosity	1.7	1.7
$j \to \gamma$ backgrounds	7.5	7.6
Other backgrounds	1.7	1.9
Total systematic uncertainty	8.6	7.5
Data statistical uncertainty	11.5	10.9
Total uncertainty	14.5	13.3

Measurement of Z(→ll)γγ