Multiboson production at the LHC

(diboson, triboson)

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on behalf of the ATLAS and CMS Collaborations

PANIC 2021 (22nd ed.)

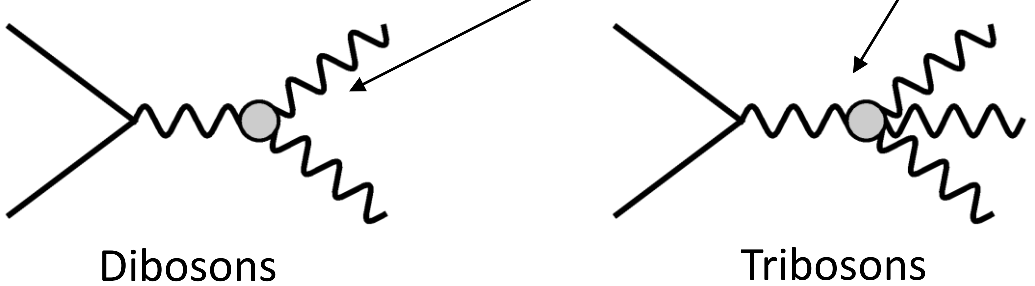
Introduction

- Multibosons: two or more electroweak bosons - W, Z, γ
- Why measure multibosons?
  - ➢ Test Standard Model predictions
    - – State of the art theory is at NNLO QCD, with NLO EW corrections
  - ➢ Check for BSM effects
    - – BSM typically formulated in the language of EFT →

$$L_{\text{EFT}} = L_{\text{SM}} + \sum_i \frac{\bar{C}_i^{(6)}}{\Lambda^2}\mathcal{O}_i^{(6)} + \sum_i \frac{\bar{C}_i^{(8)}}{\Lambda^4}\mathcal{O}_i^{(8)} + \dots$$

    - – Concentrate on operators modifying TGCs and QGCs

Many approaches:
dim-6 or dim-8?
Operator basis? Model assumptions?
Method to restore unitarity?
Enhance SM-EFT interference?
Fits to reconstructed or truth level distributions?
…



Today's talk

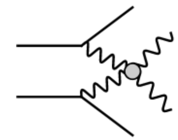
Biased towards more recent and full Run 2 based results:

- WW + 1 jet
- ◦ WZ
- Four-lepton differential (ZZ)
- ◦ WW, WZ and ZZ at 5 TeV
- Z γ
- ◦ Wγ
- γγ
- Observation of WWW
- ◦ Observation of Vγγ

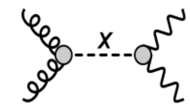
- • ATLAS
- ◦ CMS

Talk does NOT include:

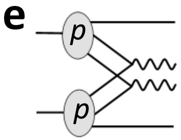
- Vector boson scattering (VBS) measurements



- Diboson resonance searches



- Dibosons via double parton scattering

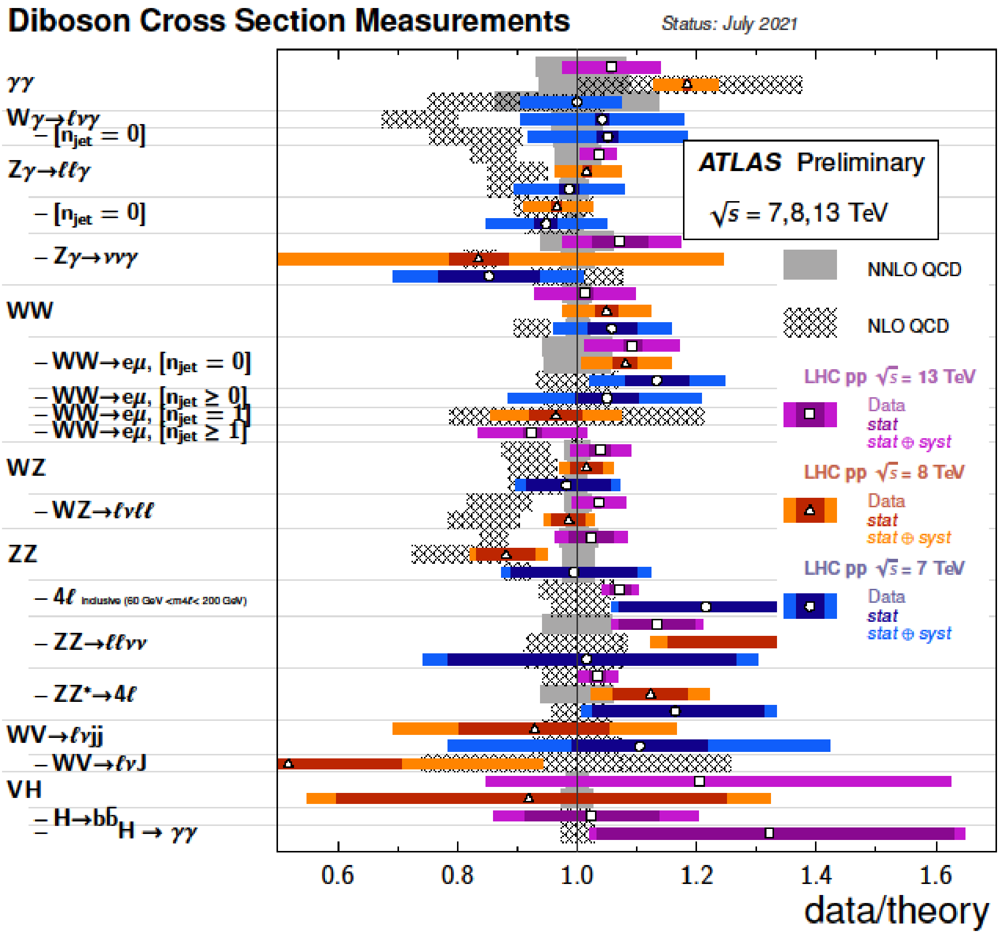


Related talks:

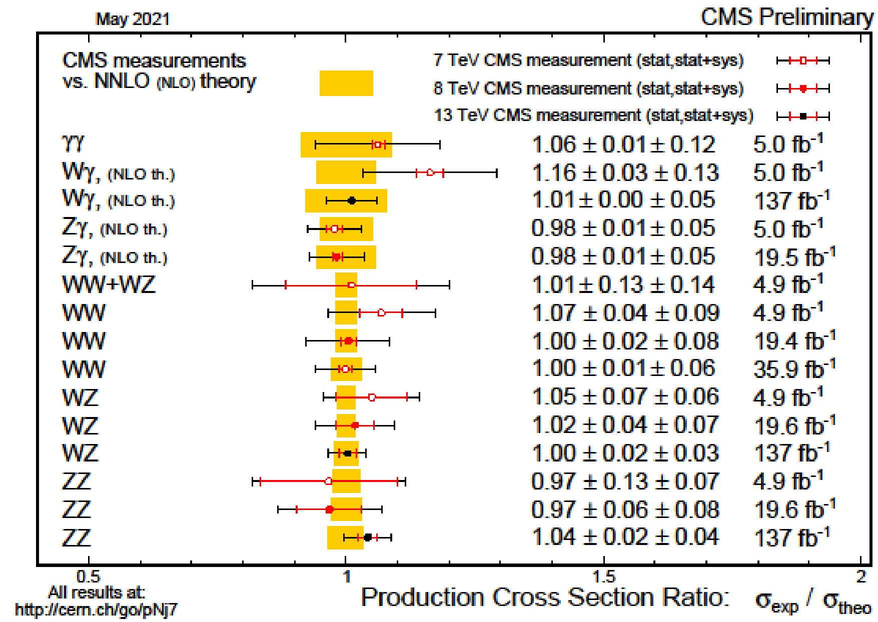
- S. Li, Status of VBS measurements at the LHC
- J. Rojo, Combined SMEFT interpretation of Higgs, diboson, and top quark data from the LHC
- D. Duda, Search for heavy resonances at the LHC

Diboson measurements overview

[ATL-PHYS-PUB-2021-032]



[https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsCombined]



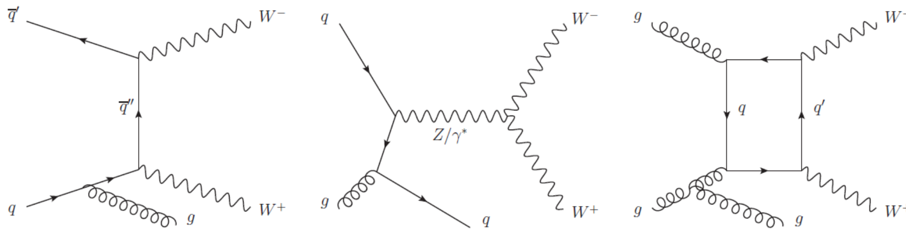
- Remarkable agreement between measured diboson cross sections and NNLO QCD predictions

WW + ≥1 jet

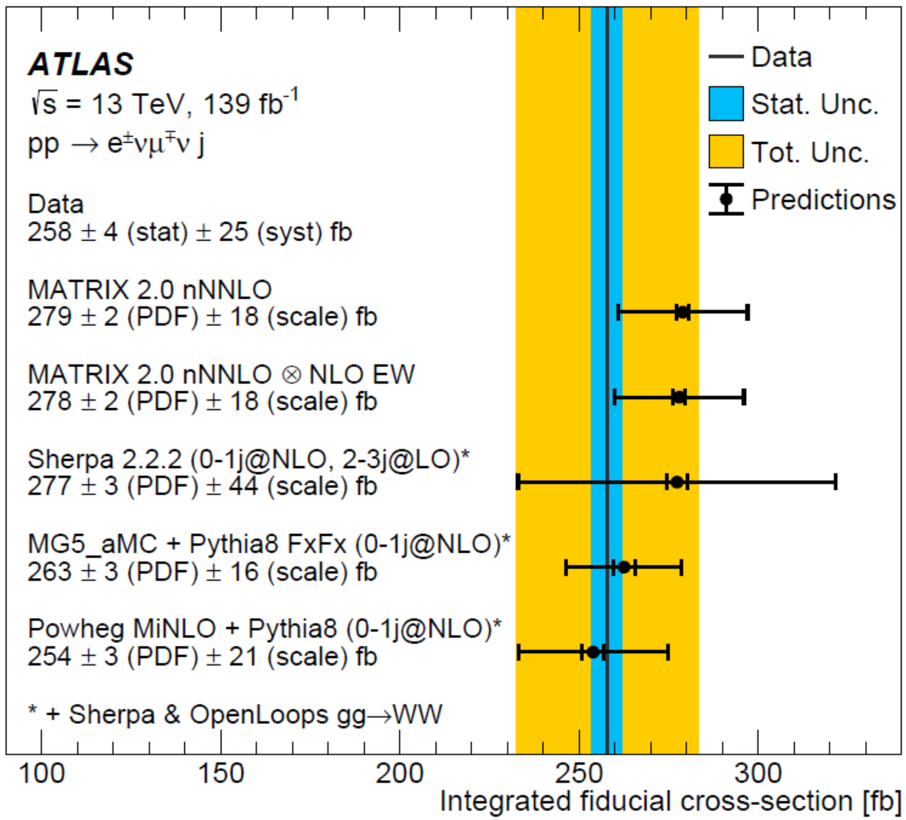
JHEP 06 (2021) 003

ATLAS, 13 TeV, 139 fb^{-1}

$e^{\pm}\mu^{\mp}, m(e\mu) > 85$ GeV
b-jet veto (20 GeV)
>=1 jet (35 GeV)



- Extra jet: enhance EFT-SM interference
- Robust estimate of the (dominant) ttbar background using b-jet counting method in 1- and 2 b-jet regions
- Precise measurement: 10% fiducial cross section uncertainty
  - Dominant systematic uncertainty: jet calibration (6%)
- Measurement agrees with state-of-the art theory predictions

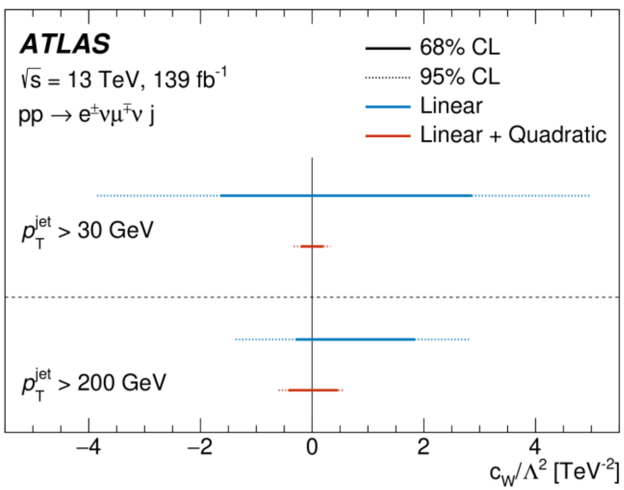


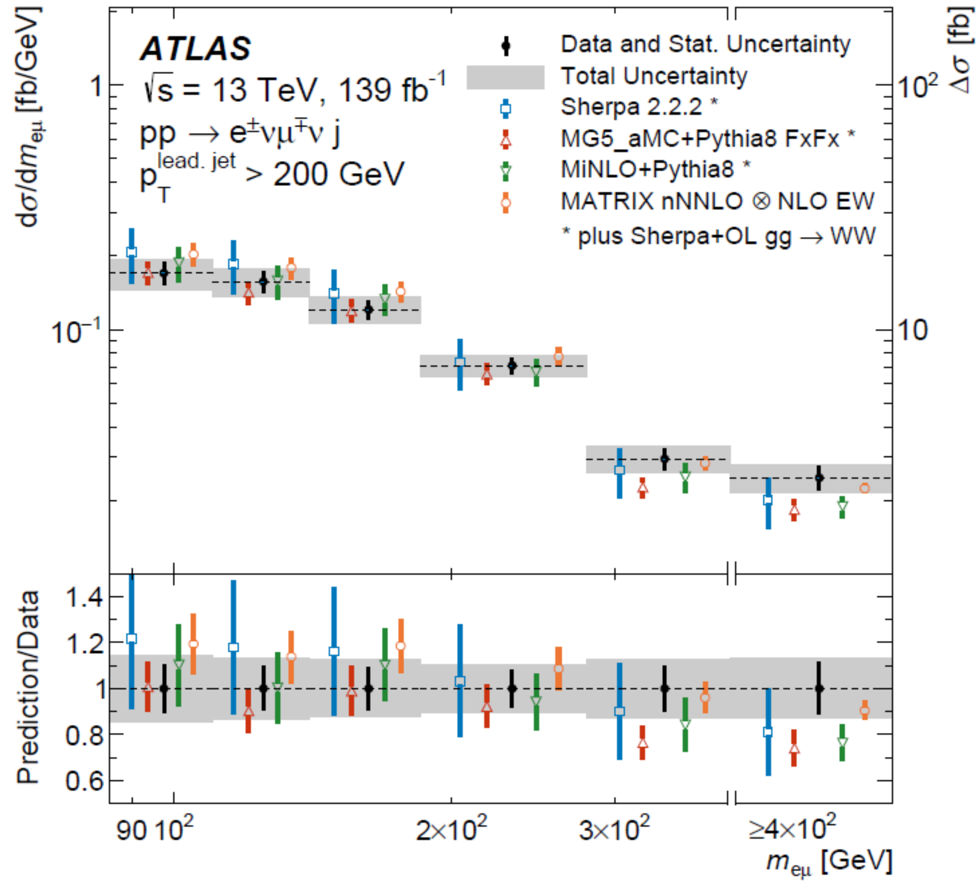
WW + ≥1 jet

JHEP 06 (2021) 003

ATLAS, 13 TeV, 139 fb^{-1}

- Fiducial and differential cross sections (12 variables)
  - Also: extra differential cross sections in high-$p_T^{\text{lead. jet}}$ (>200 GeV) and high-$p_T^{\text{lead. lep}}$ (>200 GeV) regions
- Interpreted within the EFT dim-6 using unfolded $m_{e\mu}$
  - High-$p_{T,\text{jet}}$ region helps to further enhance SM-EFT Interference term: $\sigma(c_W) = \sigma_{SM} + c_W\sigma_{int} + c_W^2\sigma_{BSM}$
- Limits on c_W for linearized and quadratic EFT fit
  - Λ = 1 TeV:



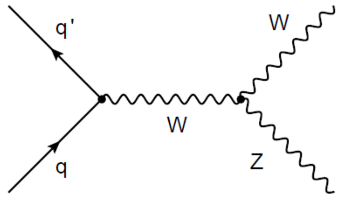


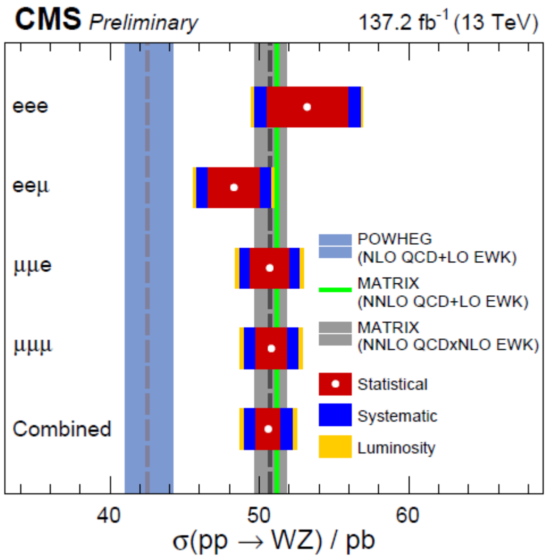
Inclusive WZ measurement

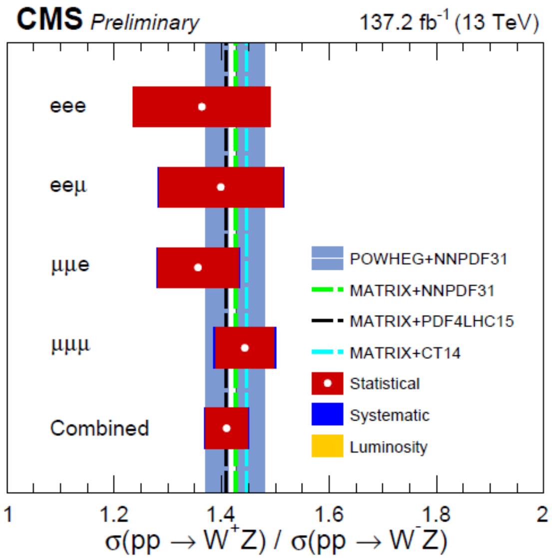
CMS-PAS-SMP-20-014

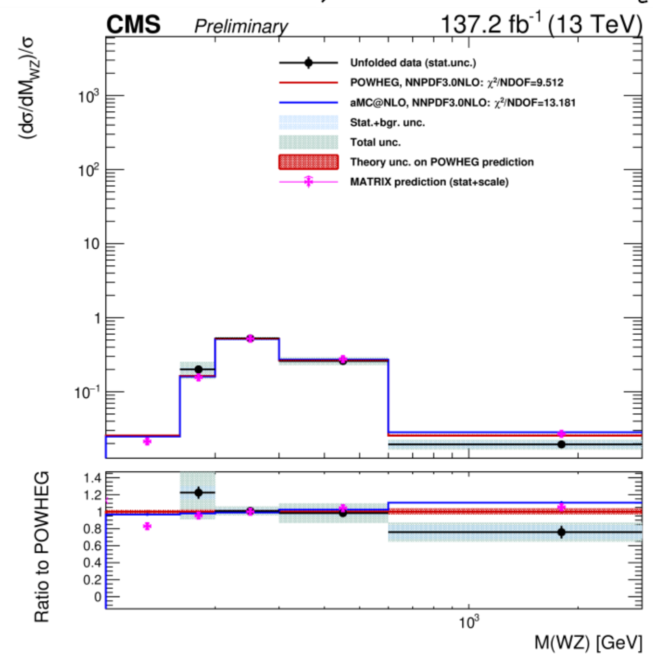
CMS, 13 TeV, 137 fb^{-1}

- WZ production at 13 TeV with leptonic final states
- Exhaustive study of WZ production:
  - ➢ Total and differential cross sections
  - ➢ Polarization fractions measurements
  - ➢ Charge asymmetry measurements









A factor 2 stronger limits compared to previous iteration of the analysis thanks to increased statistics

- ➢ aTGC limits formulated in dim-6 EFT (5 parameters)
  - – Using M(WZ) at the reconstructed level

Parameter	95% CI, Exp. (TeV^{-2})	95% CI, Obs. (TeV^{-2})	Best fit, Obs. (TeV^{-2})
c_{w}/Λ^2	$[-2.05, 1.27]$	$[-2.52, 0.33]$	-1.34
c_{www}/Λ^2	$[-1.27, 1.33]$	$[-1.04, 1.19]$	0.15
c_{b}/Λ^2	$[-86.0, 125.0]$	$[-42.7, 113.0]$	43.6
$\tilde{c}_{www}/\Lambda^2$	$[-0.76, 0.65]$	$[-0.62, 0.53]$	-0.03
$\tilde{c}_{w}/\Lambda^2$	$[-46.1, 46.1]$	$[-45.9, 45.9]$	0.0

Inclusive WZ measurement

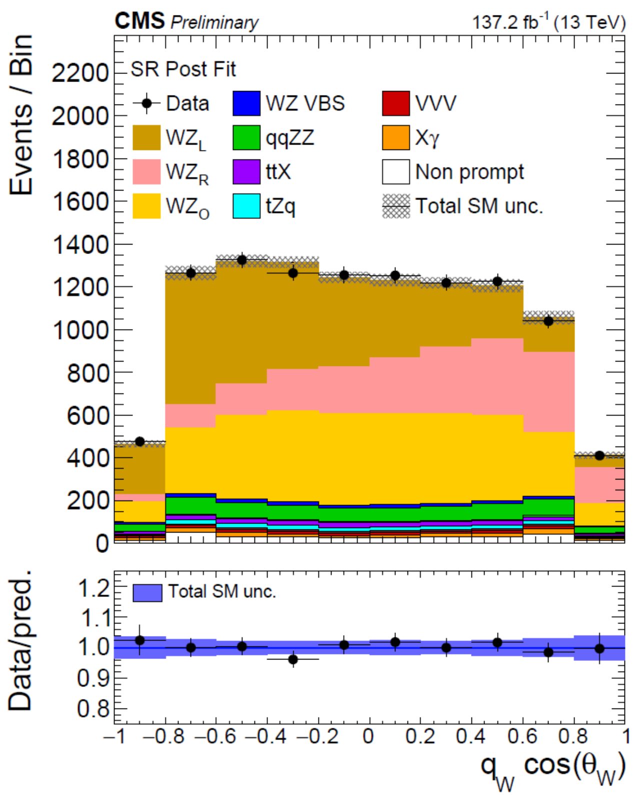
CMS-PAS-SMP-20-014

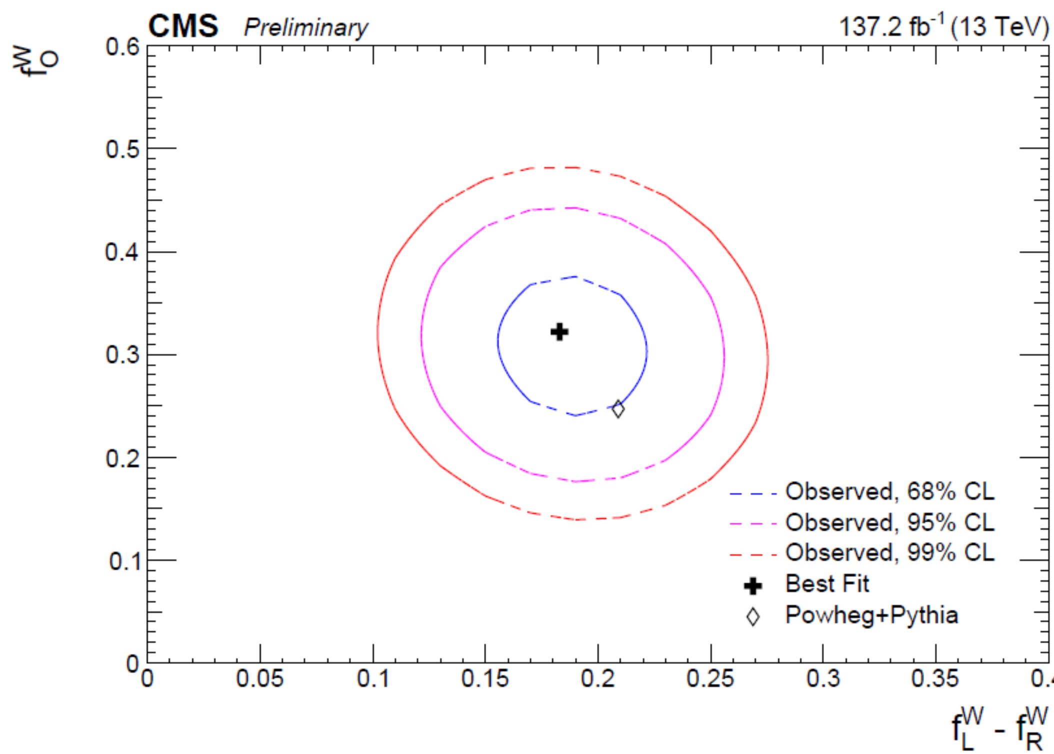
CMS, 13 TeV, 137 fb^{-1}

- First observation of longitudinally polarized W bosons in WZ production
- 5.6σ (4.3σ) observed (expected), studied in helicity frame

$$\frac{d\sigma}{\sigma d\cos\theta^{W\pm}} = \frac{3}{8}\left[(1 \mp \cos(\theta^{W\pm}))^2 f_L^W + (1 \pm \cos(\theta^{W\pm}))^2 f_R^W + 2\sin^2(\theta^{W\pm}) f_0^W\right]$$

$$f_L + f_R + f_0 = 1$$



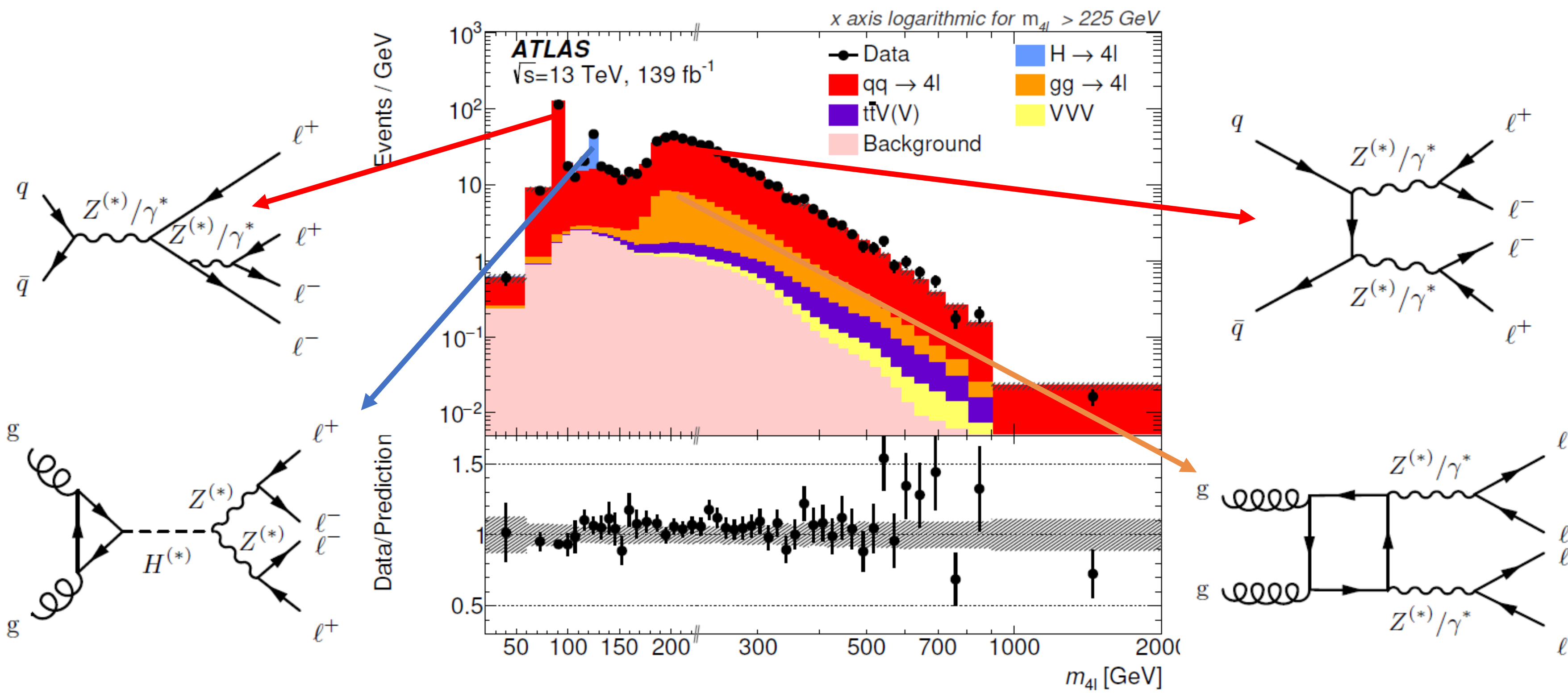


Four-lepton measurement

JHEP 07 (2021) 005

ATLAS, 13 TeV, 139 fb^{-1}

- 4 leptons with two same-flavour opposite-charge dileptons
- Signal includes on- and off-shell *ZZ*, resonant *Z* and *H* decays, tribosons and $t\bar{t}V(V)$ events -> broad definition, good for reinterpretations
- Background = non-prompt leptons



Four-lepton measurement

[JHEP 07 (2021) 005](#)

ATLAS, 13 TeV, 139 fb^{-1}

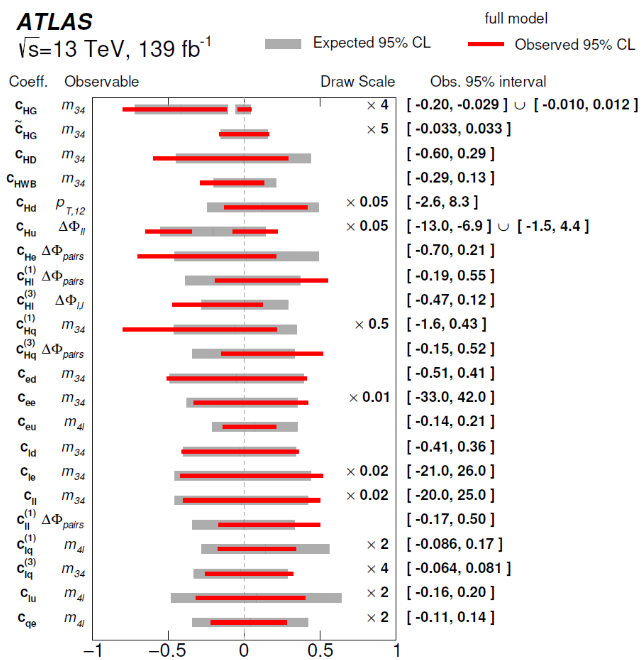
- Integrated and differential cross sections (also in different regions of m_{4l})
- Comprehensive interpretation of results:

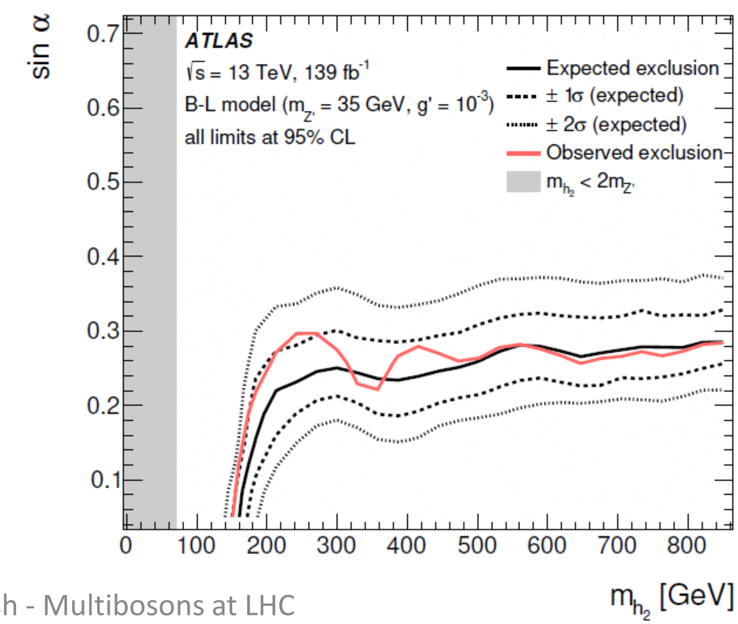
1. Most precise to date $Z \rightarrow 4l$ branching ratio measurement

$$\mathcal{B}_{Z\rightarrow 4\ell} = (4.41 \pm 0.13\,(\text{stat.}) \pm 0.23\,(\text{syst.}) \pm 0.09\,(\text{theory}) \pm 0.12\,(\text{lumi.})) \times 10^{-6}$$
$$= (4.41 \pm 0.30) \times 10^{-6},$$

   - ➢ Thanks to 130% acceptance gain compared to previous ATLAS measurement

2. EFT dim-6 limits (22 parameters) using Warsaw basis
3. Limits on parameters of a BSM with a spontaneously broken B-L gauge symmetry





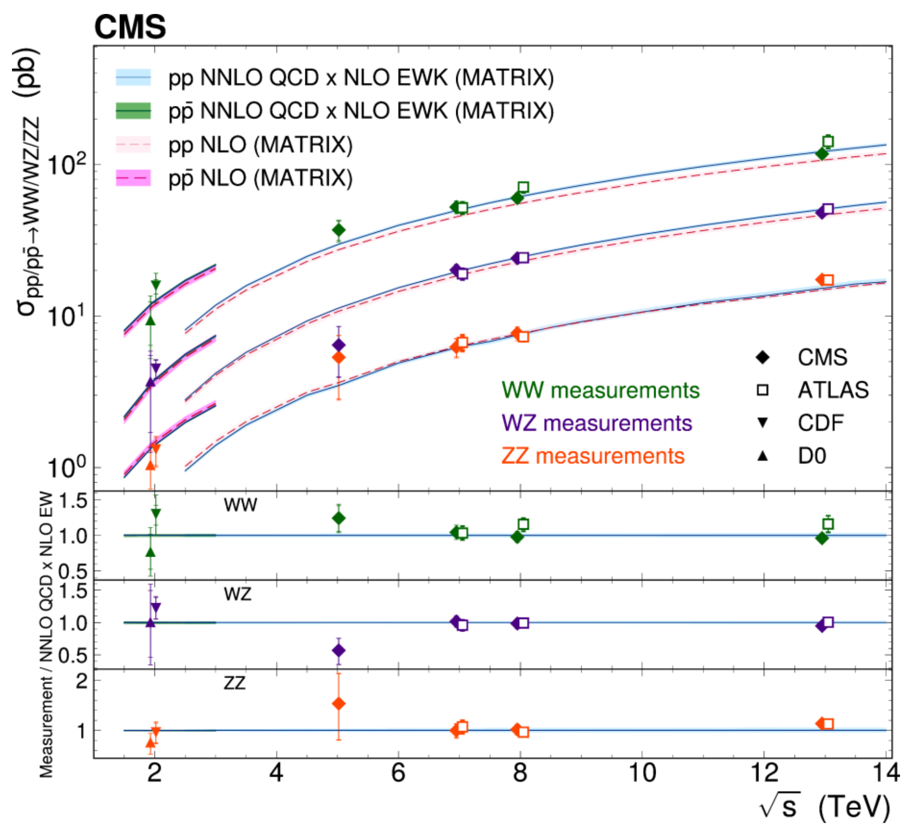
WW, WZ and ZZ at 5 TeV

CMS-SMP-20-012 Submitted to PRL

CMS, 5.02 TeV, 302 pb^{-1}

- First measurement of VV cross sections at 5 TeV
  - ➢Using *pp* low-pileup run (reference run for heavy ions)
  - ➢Leptonic final states
  - ➢Integrated cross sections

- Reduces the gap between Tevatron and LHC measurements
- Measurements agree with NNLO QCD NLO EWK predictions
- Dominant uncertainty source: limited data statistics

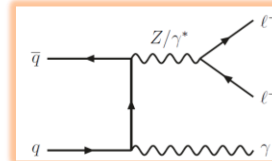


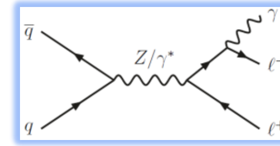
Zγ

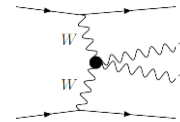
JHEP 03 (2020) 054

ATLAS, 13 TeV, 139 fb^{-1}

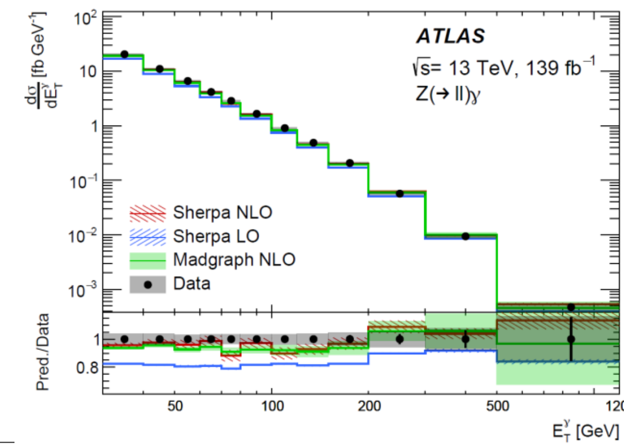
- $e^+e^-\gamma$, $\mu^+\mu^-\gamma$
- No VZγ TGC in SM -> LO diagrams are ISR and FSR
  - ➢ Small contribution from VBS at higher EW orders
- Pileup photon background estimated using converted photons
- Integrated and differential cross sections compared to a number of MC and fixed-order predictions
  - ➢ Generally good description by MATRIX NNLO

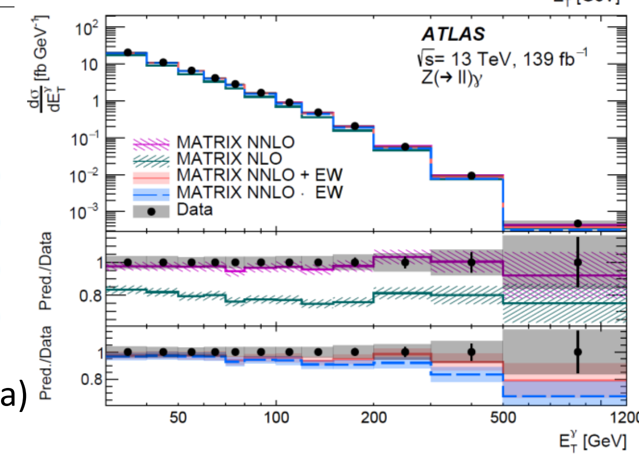






Condition
$m(ll) + m(ll\gamma) > 182$ GeV
applied to suppress FSR





2.9% precision!

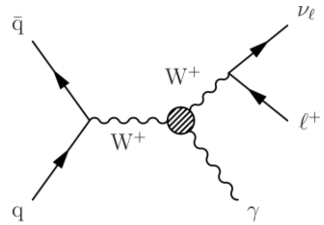
$\ell^+\ell^-\gamma$	533.7	± 5.1 (uncorr)	± 11.6 (corr) ± 9.1 (lumi)
Sherpa LO	438.9	± 0.6 (stat)	
Sherpa NLO	514.2	± 5.7 (stat)	
MadGraph NLO	503.4	± 1.8 (stat)	
Matrix NLO	444.2	± 0.1 (stat)	± 4.3 (C_{theory}) ± 8.8 (PDF) $^{+16.8}_{-18.9}$ (scale)
Matrix NNLO	518.9	± 2.0 (stat)	± 5.1 (C_{theory}) ± 10.8 (PDF) $^{+16.4}_{-14.9}$ (scale)
Matrix NNLO × NLO EW	513.5	± 2.0 (stat)	± 2.7 (C_{theory}) ± 10.8 (PDF) $^{+16.4}_{-14.9}$ (scale)
Matrix NNLO + NLO EW	518.3	± 2.0 (stat)	± 2.7 (C_{theory}) ± 10.8 (PDF) $^{+16.4}_{-14.9}$ (scale)

*C_{theory} is a parton-to-particle level correction factor (~0.9, obtained from Sherpa)

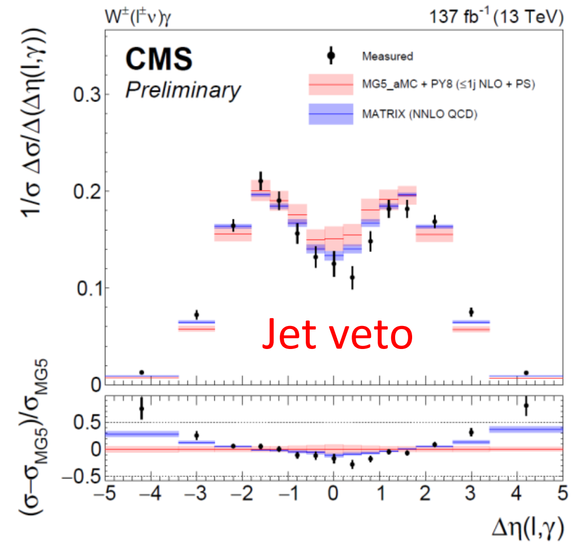
Wγ

[CMS-PAS-SMP-20-005](CMS-PAS-SMP-20-005)

CMS, 13 TeV, 137 fb^{-1}

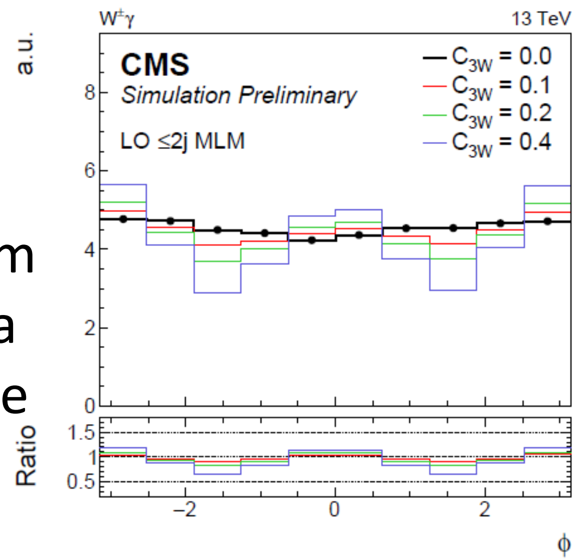


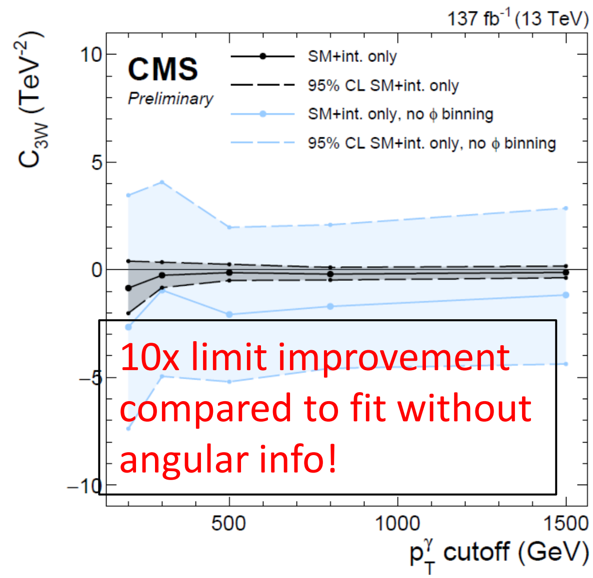
- Probes WWγ vertex
- Cross section at $\Delta\eta(l,\gamma) = 0$ at LO vanishes due to interference -> "radiation valley"
  - ➢ BSM processes could make the minimum less pronounced
  - ➢ SM NNLO QCD describes the shape well



- Interpreted within EFT dim-6 framework
  - ➢ Limits are set on C_{3W}

- SM-EFT interference term resurrected by going to a Wγ centre-of-mass frame and including angular information in the fit

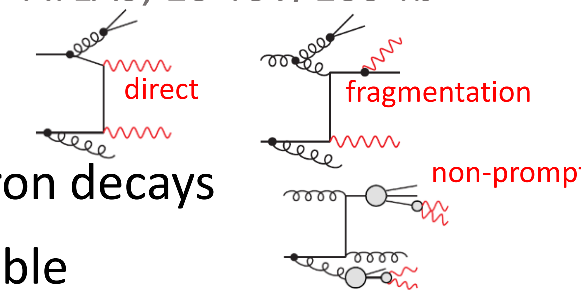




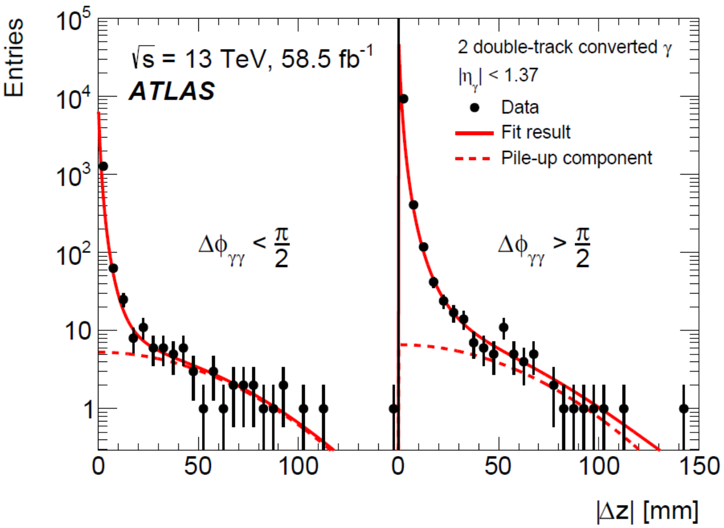
γγ

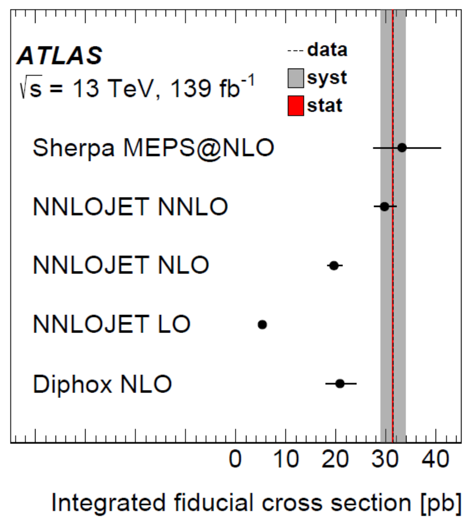
[STDM-2017-30](#) Submitted to JHEP

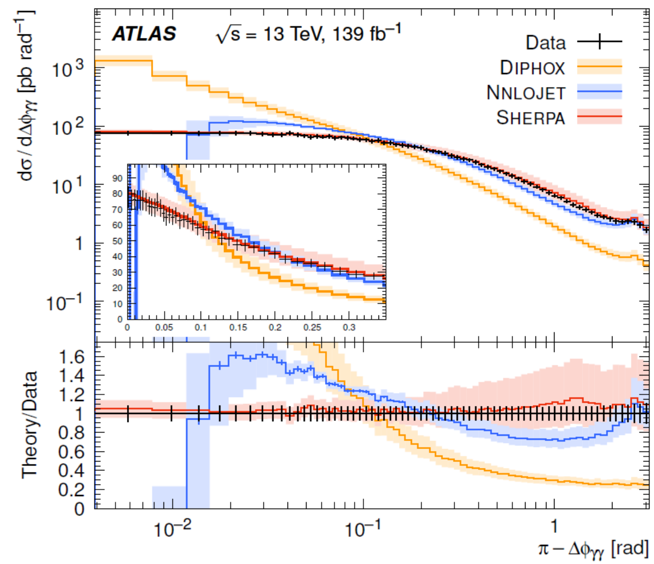
ATLAS, 13 TeV, 139 fb^{-1}



- Signal includes direct and fragmentation photons
- Dominant background: non-prompt photons from hadron decays
- Pileup background normalization from events with double conversions, by fitting $|\Delta z| = |z_{\gamma 1} - z_{\gamma 2}|$



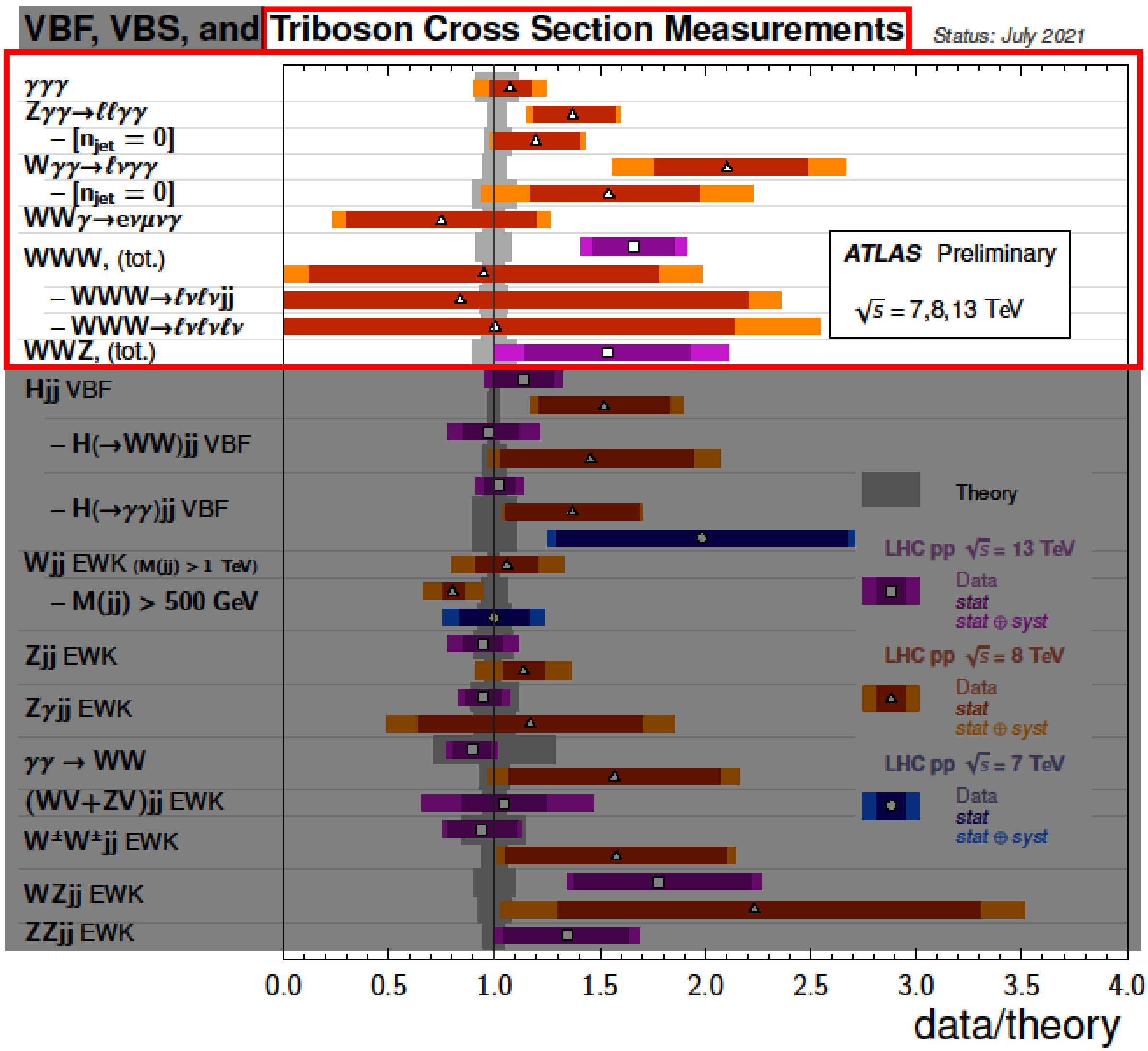




- Integrated cross section described well by Sherpa NLO and NNLOJET NNLO
  - ➢ LO and NNLO results differ by a factor of 6!
- Differential cross sections described best by Sherpa
  - ➢ Fixed-order predictions fail when the photons are back-to-back -> region sensitive to resummation effects

Triboson measurements overview

ATL-PHYS-PUB-2021-032



- ~2 sigma disagreement between measurement and theory for Wγγ and WWW
  - No NNLO calculations (yet)

WWW observation

ATLAS-CONF-2021-039

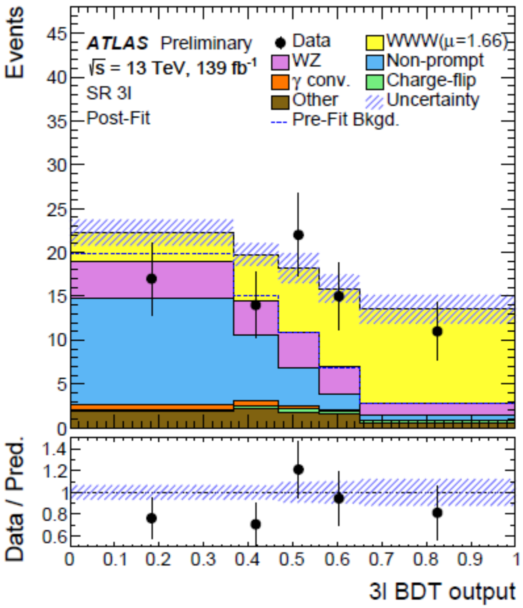
ATLAS, 13 TeV, 139 fb^{-1}

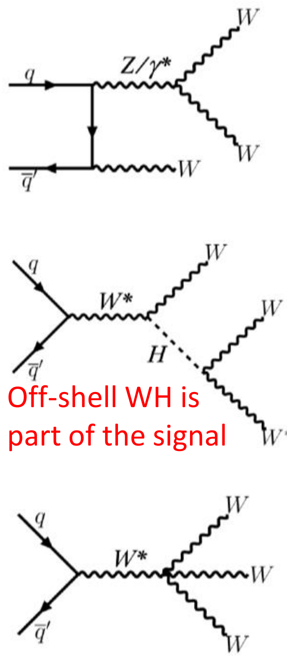
- $l^{\pm}\nu l^{\pm}\nu jj$ and $l^{\pm}\nu l^{\pm}\nu l^{\mp}\nu$
  - No same-flavour opposite-sign leptons
- Signal from the fit of the BDT score distribution
- Measured cross section

$$\sigma(pp \to WWW) = 850 \pm 100\,(\text{stat.}) \pm 80\,(\text{syst.})\ \text{fb}$$

- Higher-order predictions:
  - WWW at NLO QCD + NLO EW, WH at N3LO QCD + NLO EW:

505 fb (uncertainty up to 6% or ~30 fb)

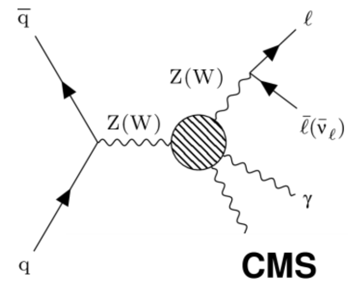




Fit	Observed (expected) significances [σ]	$\mu(WWW)$
$e^{\pm}e^{\pm}$	2.3 (1.4)	1.69 ± 0.79
$e^{\pm}\mu^{\pm}$	4.6 (3.1)	1.57 ± 0.40
$\mu^{\pm}\mu^{\pm}$	5.6 (2.8)	2.13 ± 0.47
2ℓ	6.9 (4.1)	1.80 ± 0.33
3ℓ	4.8 (3.7)	1.33 ± 0.39
Combined	**8.2 (5.4)**	**1.66 ± 0.28**

Uncertainty source	$\Delta\sigma/\sigma$ [%]
Data-driven background	5.3
Prompt-lepton-background modeling	3.3
Jets and $E_{\mathrm{T}}^{\mathrm{miss}}$	2.8
MC statistics	2.8
Lepton	2.1
Luminosity	1.9
Signal modeling	1.5
Pile-up modeling	0.9
Total systematic uncertainty	9.5
Data statistics	11.2
WZ normalizations	3.3
Total statistical uncertainty	11.6

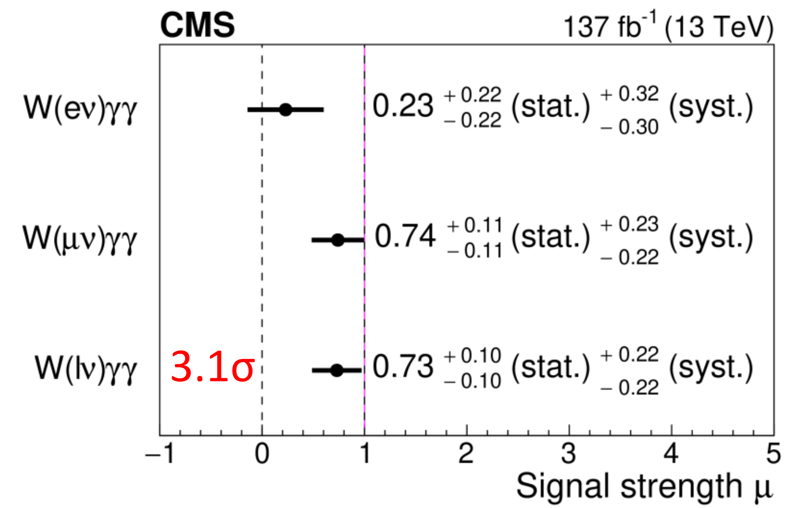
Observation of Vγγ

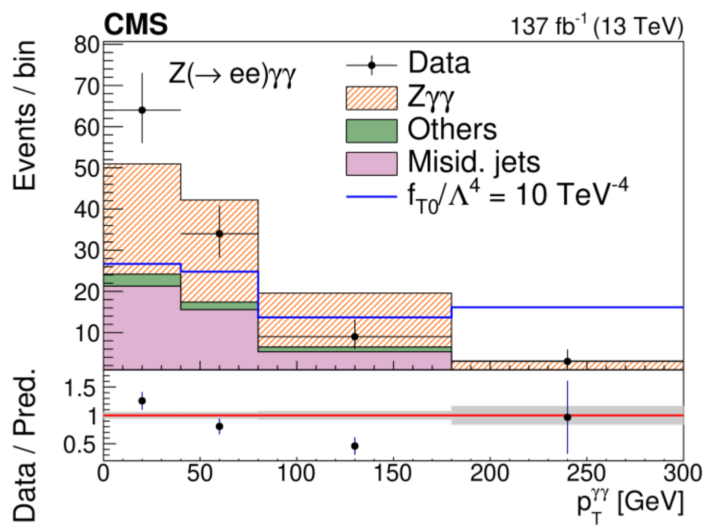


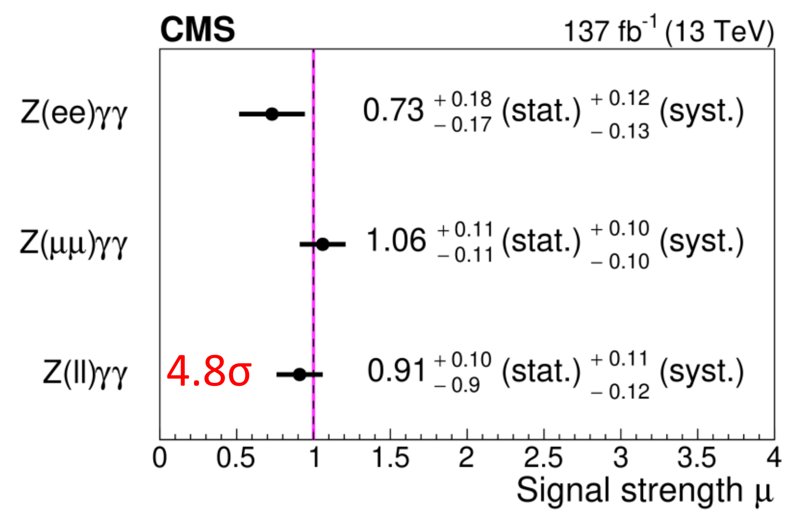
[SMP-19-013](SMP-19-013) Accepted by JHEP

CMS, 13 TeV, 137 fb^{-1}

- First observation of Vγγ cross section at 13 TeV
- W/Z leptonic decays (electrons and muons)
- Probes QGC
- Results interpreted using dim-8 EFT using diphoton p_T at the reconstructed level







Summary

- LHC Run 2 based results continuing to come
- Integrated diboson cross sections measurements dominated by systematic uncertainties
- First observations of WWW and Vγγ with full LHC Run 2 data
- Multibosons in Run 2: not only about aTGC/aQGC at 13 TeV -> rich area for different kinds of SM measurements
- BSM interpretations:
  - No hints for BSM physics
  - Including interpretations in measurement papers one benefits from knowledge of correlations; publishing detailed results important for later reinterpretations/combinations
- Run 3 and 4 data will allow for more precise differential cross section measurements -> more stringent tests of the Standard Model & better sensitivity to potential BSM effects

Backup

Analyses overview (13 TeV)

Final state	Experiment	Signal in SR	Dominant background	Signal extraction; precision of int. cross. sec.	Dominant uncertainty	Results
Wγ	CMS	50%	Non-prompt γ (25%), non-prompt l(5%)	Fit signal strength differentially (5-8%?)	Misid. Muon (16-42%), jet -> γ misid (10-45%)	-diff. cross. sec -radiation amplitude zero -EFT dim-6
WW + ≥1 jet	ATLAS	42%	Top (51%)	Data-bkg (10%)	Jet calib. (6.3%), Top modelling (4.5%)	-tot. and diff. cross. sec -EFT dim-6
4l	ATLAS	96%	Non-prompt l (4%): the only bkg.	Data-bkg (3.4%)	Syst. (2.6%), lumi (1.7%)	-tot. and diff. cross. sec -EFT dim-6 -Z' and h2 limits
WZ	CMS	83%	Irreducible (ZZ and ttbar+V, 13%), reducible (4%)	Fig signal strength and major bkg normalizations in SR and CRs (3.6%)	Lumi (2.1%), B-tagging (1.6%), stat. (1.5%)	-tot. and diff. cross. sec -charge asymmetry, PDF unc. reduction -EFT dim-6
Zγ	ATLAS	85%	Z+jets faking γ (10%), pileup jets and γ (4-5%)	Data-bkg (2.9%)	Lumi (1.7%), e id eff. (1.4%), Z+jets bg (1.3%)	-int. and diff. cross. sec
γγ	ATLAS	60.4%	γj (20%), jγ (10%), jj (6%), electron (2.6%), pileup (0.6%)	Fit of signal and bkg. normalizations in SR and CRs (7.6%)	Bkg. Estimation (4.3%), photon isolation (4.1%)	-int. and diff. cross. sec
WWW	ATLAS	16% (2l), 40% (3l)	WZ (40%), γ conv., fakes in 2l; non-prompt (30%), WZ (18%) in 3l	Fit of signal and bkg. normalizations in SR and CRs using BDT output (15%)	Statistics (11.6%), data-driven bkg. est. (5.3%)	-observation (8.2 sigma) -int. cross. sec.
Vγγ	CMS	17% (W), 59% (Z)	Misid. j & e (75%) in W, misid. j (37%) in Z	Fit of signal using diphoton pT (33% W, 16% Z)	j-γ. misid (21%), stat. (14%) in W; j-γ. misid (6%), Zγ cross. sec. (6%), stat. (10.7%) in Z	-observation (>5 sigma) -int. cross. sec. -EFT dim-8

EFT interpretations overview

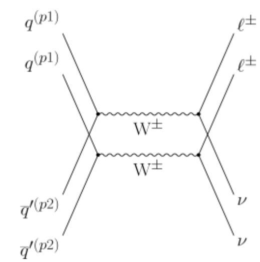
Final state	Experiment	EFT dim	Operators / coefficients	Variable	Interference resurrection	Unitarization / EFT validity
Wγ	CMS	6, int, int + pure	C_{3W} (WWγ) in Warsaw basis	Unfolded p_{T}^{γ}, $\lvert\varphi_f\rvert$	Angular info in Wγ CoM frame	Upper cut on p_{T}^{γ}
WW + ≥1 jet	ATLAS	6, int, int + pure	c_W in Warsaw basis	Unfolded $m_{e\mu}$	High jet p_{T} region	-
4-lepton	ATLAS	6, int. int + pure	22 coeff. in Warsaw basis	Unfolded 1d, 2d comb. of $\lvert\varphi_{ll}\rvert$, $\lvert\varphi_{\mathrm{pairs}}\rvert$, m_{4l}, m_{34}, $p_{\mathrm{T},12}$	-	-
WZ	CMS	6, int. int + pure	5 coeff. in HISZ basis	$M(WZ)$ reco	-	Clipping
Vγγ	CMS	8	10 coeff., Eboli 2006	$p_{\mathrm{T},\gamma\gamma}$ reco	-	-
ZZ->4l	CMS	8	4 aTGC param. transformed to dim-8 EFT param. Degrande 2014	m_{4l} reco	-	-

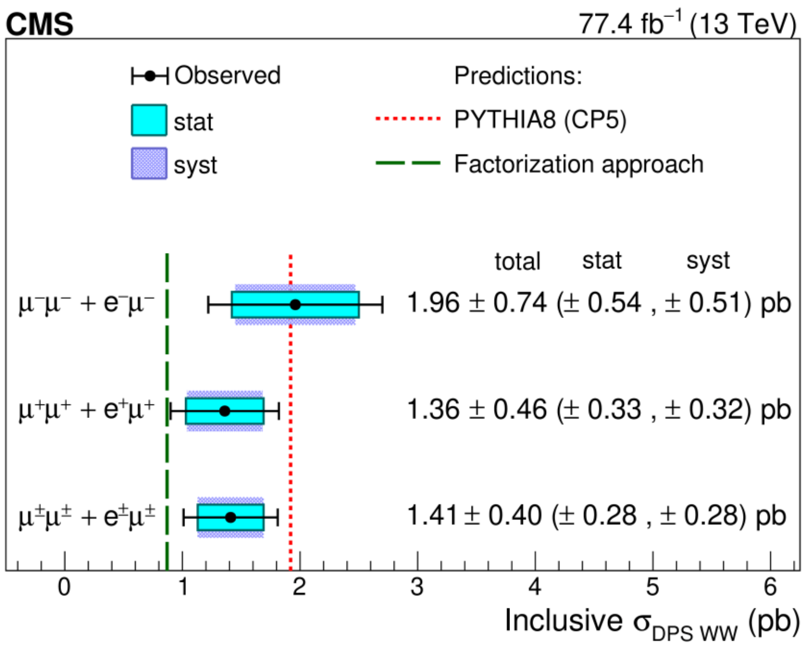
WW in DPS

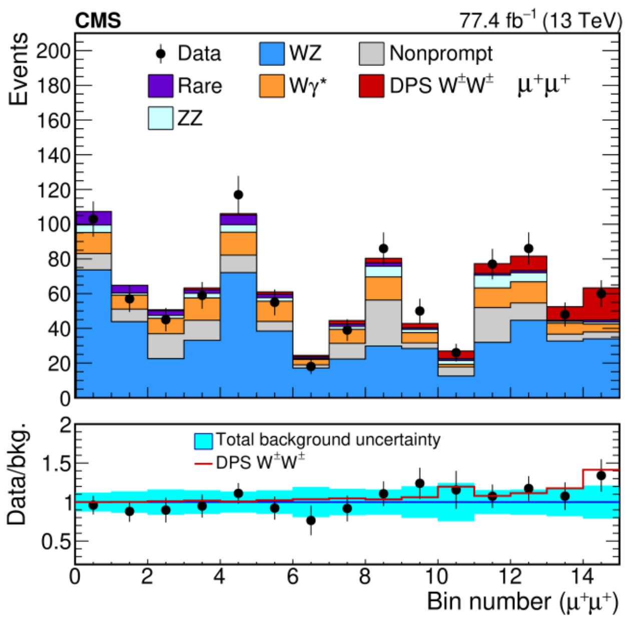
Eur. Phys. J. C 80 (2020) 41

CMS, 13 TeV, 77.4 fb^{-1}

- Same sign WW to $e^{\pm}\mu^{\pm}$ or $\mu^{\pm}\mu^{\pm}$
- Same-sign leptons -> smaller single-parton scattering (SPS) background
- First evidence for WW production via double parton scattering (DPS), 3.9σ
- Dominant background: WZ via SPS
- Compared to Pythia predictions and factorized scatterings
- Measurement statistically limited
- Effective cross section extracted, $\sigma_{eff} = 12.7^{+5.0}_{-2.9}$ mb





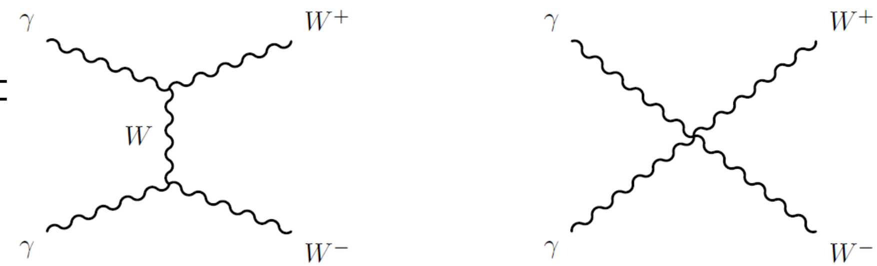


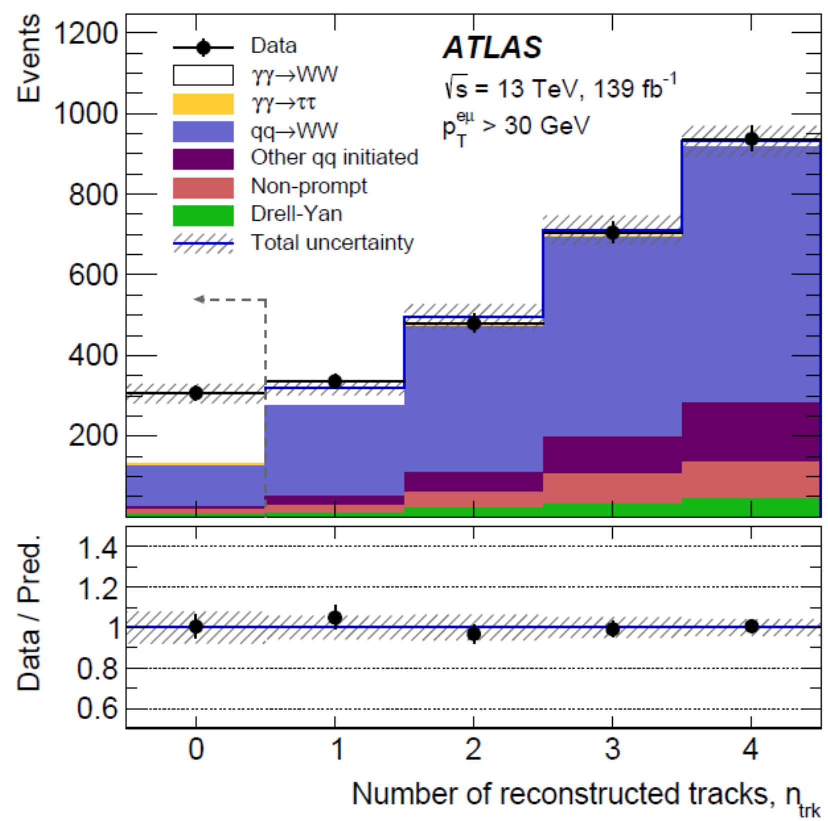
Observation of γγ→WW

Phys. Lett. B 816 (2021) 136190

ATLAS, 13 TeV, 139 fb^{-1}

- Opposite-sign, opposite-flavour $e^{\pm}\mu^{\mp}$
- Intact or dissociated protons
- Exclusive production; exclusivity defined using central detector cuts, $n_{trk} = 0, p_{T,track} > 500$ MeV
- At LO, process only proceeds via EW gauge boson self-couplings
- Largest background: inclusive $qq \to WW$
- Proton dissociation not included in the signal model -> data-driven correction





Observation of γγ→WW

Phys. Lett. B 816 (2021) 136190

ATLAS, 13 TeV, 139 fb^{-1}

- Many non-standard corrections:
  - ➢ Vertex definition (ATLAS vertex reconstruction biased for exclusive vertices)
  - ➢ MC beamspot width rescaled to data
  - ➢ MC pileup mismodelling correction
  - ➢ Charged particle multiplicity correction
- Fit to data yields in SR and 3 CRs based on values of and
- Measured fiducial cross section

  3.13 ±0.31(stat.) ±0.28(syst.) fb

  - ➢ Agrees with theory corrected for a proton survival factor

Observed signal significance: 8.4σ