Electroweak physics: current status from the experiment side

Oleg Kuprash

on behalf of ATLAS, CDF, CMS, D0, LHCb Collaborations

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UNI FREIBURG

Outline

Electroweak measurements at hadron colliders

Electroweak parameters

Single vector boson cross sections and properties

Diboson measurements

Electroweak production of bosons

Triboson production

EFT interpretation

Electroweak parameters - introduction

- Electroweak sector of the Standard Model has five parameters
  - α_{em}, G_{F}, m_{W} , m_Z, $\sin\theta^{\ell}_{\mathrm{eff}}$
  - Only three of them are independent
  - Two relations, at tree level:

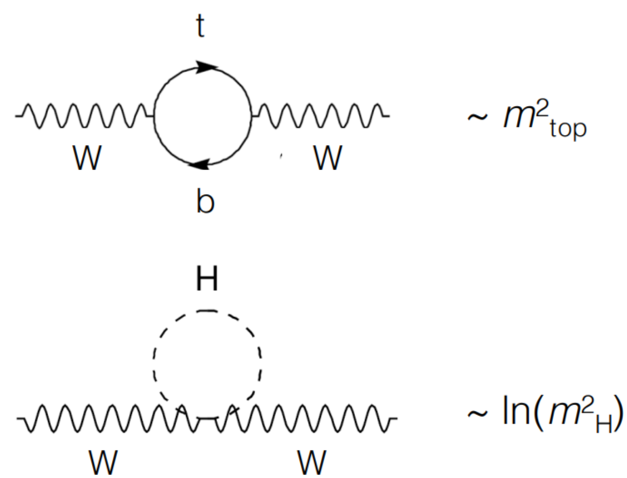
$$\sin^2\theta_W = 1 - \frac{m_W^2}{m_Z^2}$$

$$m_W^2 \sin^2\theta_W = \frac{\pi\alpha}{\sqrt{2}G_F}$$

Electroweak parameters - introduction

- Tree-level relations are not sufficient when confronting measurements
- Impact of loop corrections included in EW form factors
- Correction factor Δr includes dependence on m_t^2 and $\ln M_H^2$

$$m_W^2 = \frac{m_Z^2}{2}\left(1+\sqrt{1-\frac{\sqrt{8}\pi\alpha(1+\Delta r)}{G_F m_Z^2}}\right)$$



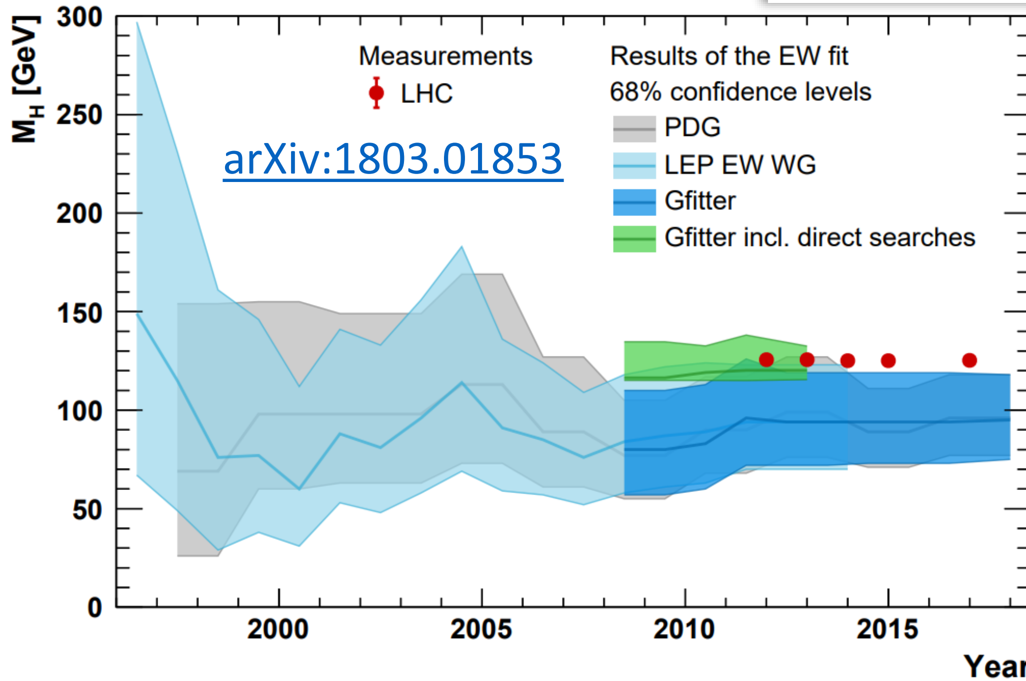
$$\Delta r \sim -\frac{3\alpha}{16\pi s^4}\frac{M_t^2}{M_Z^2} + \frac{11\alpha}{24\pi s^2}\ln\left(\frac{M_H}{M_Z}\right) + \cdots$$

Electroweak parameters - introduction

- Global electroweak fits to LEP and later to Tevatron data allowed prediction of the Higgs boson mass, thanks to loop contributions

For the first time, the data also give non−trivial bounds on M_H: independently of m_t CERN-TH. 5817/90:

$$1.8 \text{ GeV} < M_H < 6 \text{ TeV} \qquad (68\% \text{ C.L.})$$



- Fitted value* from 2009: - three years before the Higgs boson discovery at the LHC!

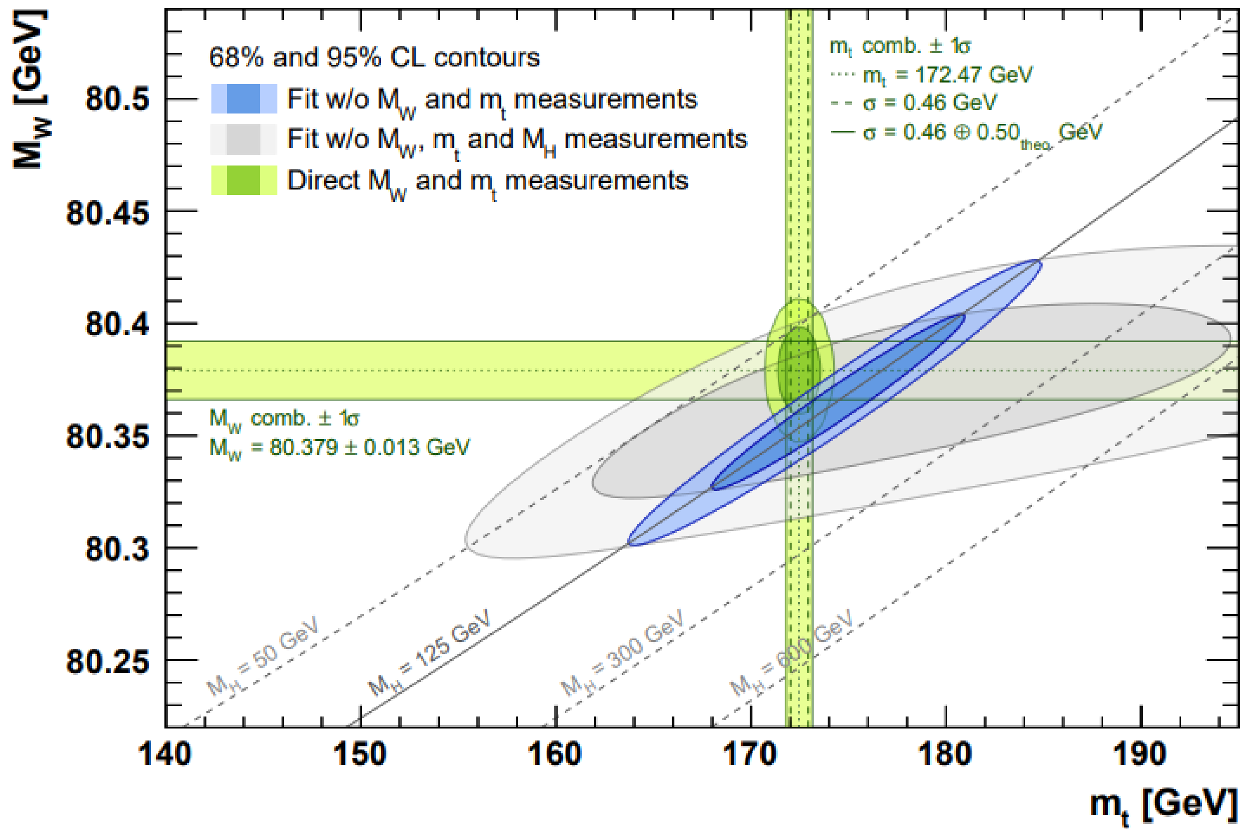
$$M_H = 116.4^{+18.3}_{-1.3} \text{ GeV}$$ arXiv:0811.0009 *including direct searches

- After Higgs boson discovery, global electroweak fits turned into a true SM self-consistency check
  - ➢ With a potential to constrain or find new physics!

W boson mass measurements

- Individual EW parameter measurements are of a limited interest
- But when put in context can say a lot about the theory consistency!

arXiv:1803.01853

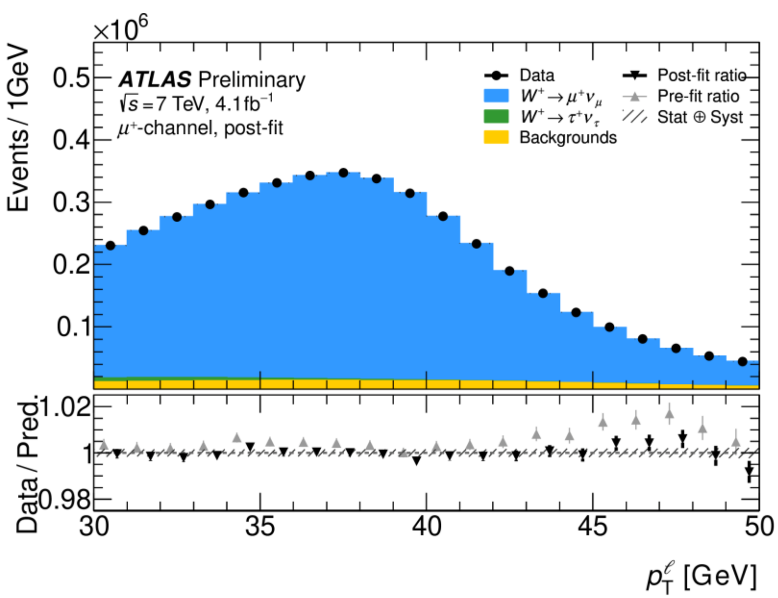


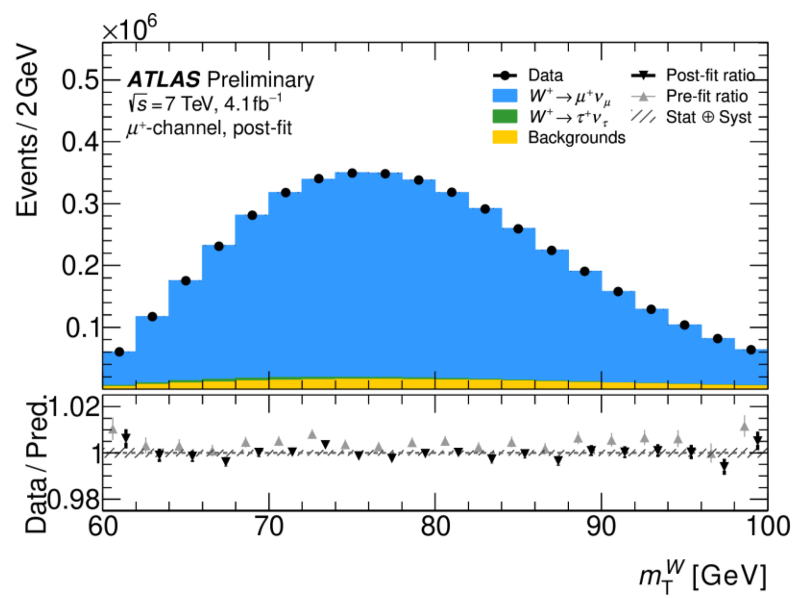
ATLAS W mass reanalysis

ATLAS-CONF-2023-004

ATLAS, 7 TeV, 4.6 fb^{-1}

- Strategy:
  - Leptonic (electron and muon) W decays
  - Use dilepton p_{T} and m_{T} dependence on m_W
  - Use signal MC templates for a range of m_W values - obtained by reweighting the reference MC according to the Breit-Wigner parameterisation of W
  - Z, W→τν, VV, top background estimated using MC; data-driven multijet bkg
  - Final m_W is a combination of m_W values obtained from separate p_{T} and m_{T} fits
- Reanalysis of the data used for the 2017 m_W measurement (worlds best at the time); reanalysis effort started back in 2018





ATLAS W mass reanalysis

ATLAS-CONF-2023-004

ATLAS, 7 TeV, 4.6 fb^{-1}

- Comparison of approaches between the new and 2017 measurement:

	ATLAS m_W 2017	ATLAS m_W 2023	Effect on central value	Effect on uncertainty
Statistical interpretation	χ^2 fit with stat-only uncertainties, systematics added aposteriori	Profile max. likelihood (ML) fit - for the first time in context of m_W measurements; O(1000) NPs reduced to ~200 NPs with PCA	-16.3 MeV	↓
Baseline PDF	CT10	CT18	+4.6 MeV	↑
Electroweak theory unc.	Evaluated at truth level	Evaluated at detector level		↑
Multijet background	2023: Systematic shape variations using PCA, new transfer function from CR to SR		+1.9 MeV	↓
Detector calibration	Unchanged			
EW and top background	Unchanged			

Good compatibility between χ^2 and ML fits

- New ATLAS result

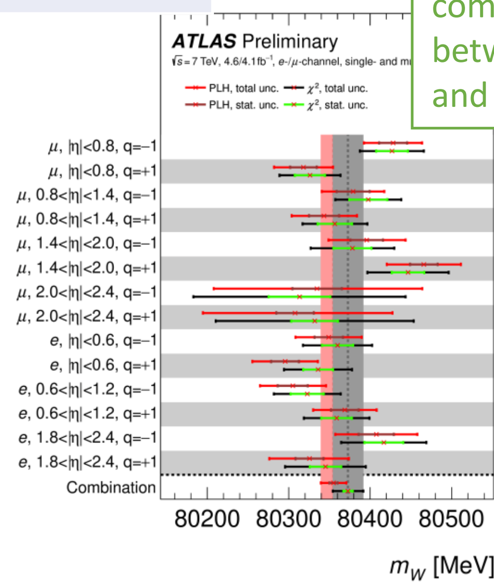
$$m_W = 80360 \pm 5(\text{stat.}) \pm 15(\text{syst.}) = 80360 \pm 16 \text{ MeV}$$

- Supersedes the 2017 result

$$80370 \pm 19 \text{ MeV}$$

- New result agrees slightly better with the SM prediction

$$m_W^{\text{pred.}} = 80354 \pm 7 \text{ MeV}$$



LHCb W mass measurement

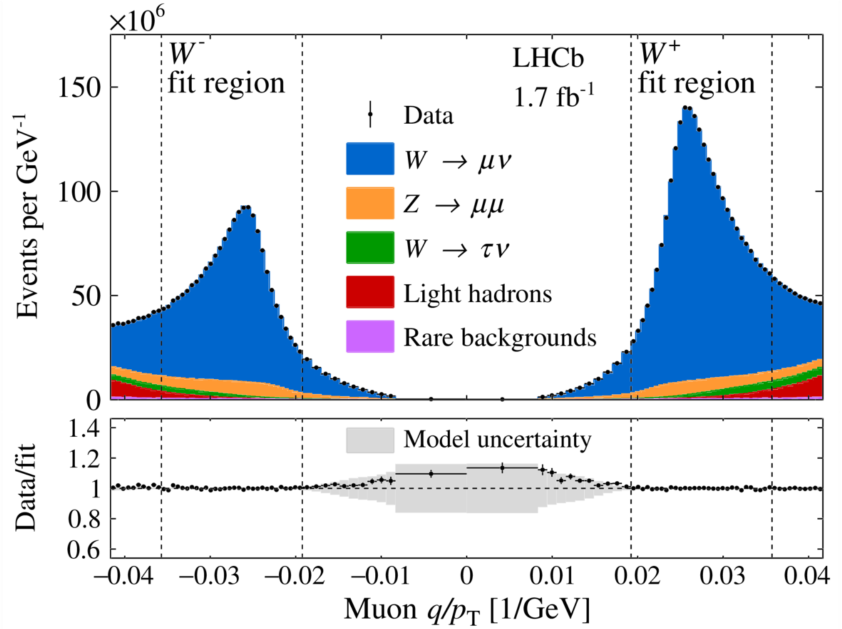
JHEP 01 (2022) 036

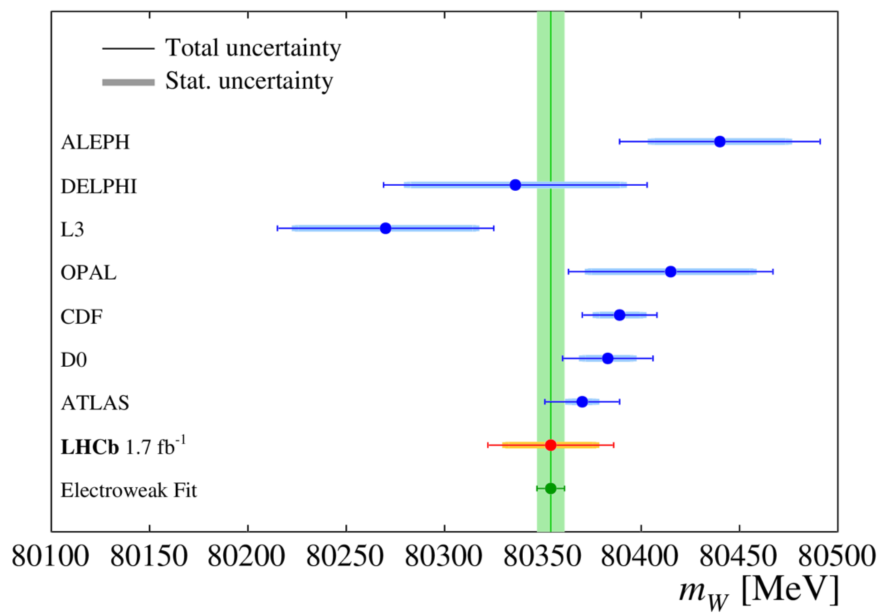
LHCb, 13 TeV, 1.7 fb^{-1}

- Simultaneous fit of the muon q/p_T distribution of a sample of W→μν decays and the ϕ∗ distribution of a sample of Z→μμ decays
- Result averaged over three recent PDF sets

$$m_W = 80354 \pm 23_{\text{stat}} \pm 10_{\text{exp}} \pm 17_{\text{theory}} \pm 9_{\text{PDF}} \text{ MeV}$$

- First proof-of-principle of a measurement of m_W with the LHCb experiment
  - ➢ Potential to decrease the statistical uncertainty by using full Run 2 data (3x lumi)
- LHCb acceptance almost orthogonal to the one of ATLAS & CMS
  - ➢ Partial anti-correlations can reduce PDF uncertainty by a factor of 2





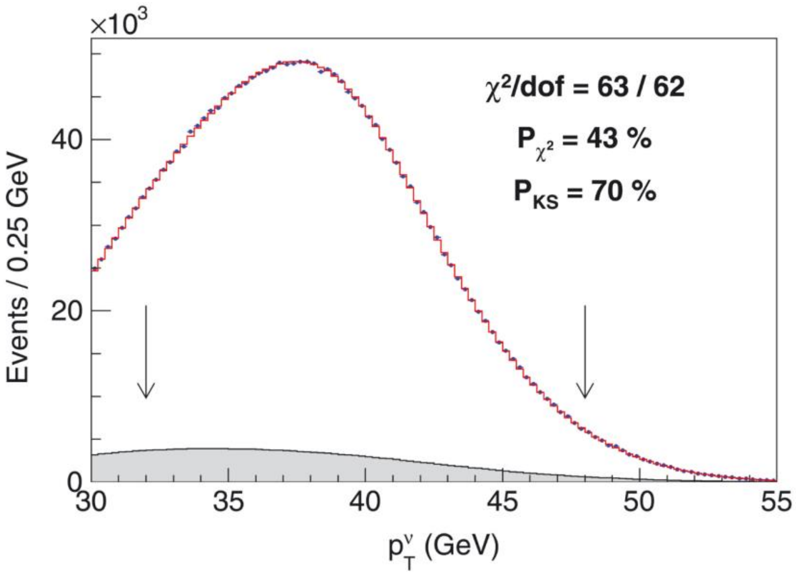
CDF W mass measurement

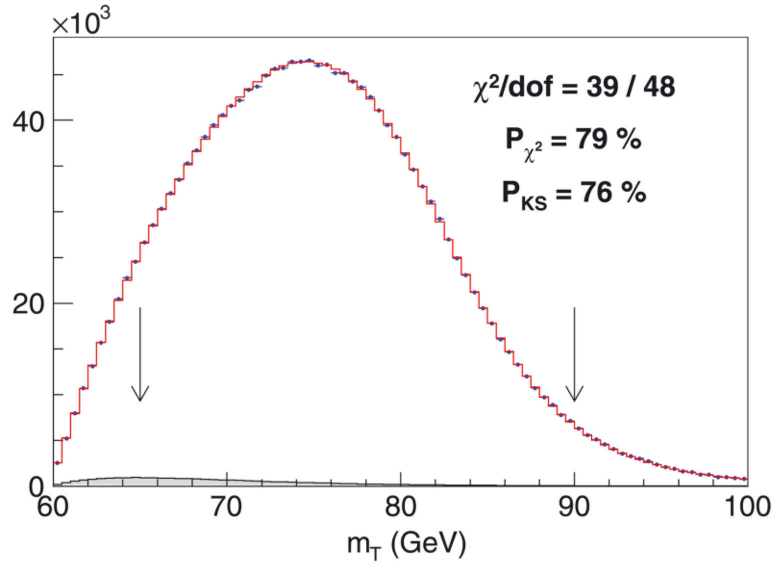
Science 376 (2022) 6589, 170-176

CDF, 1.96 TeV, 8.8 fb^{-1}

7 pages paper with 45 pages supplementary material

- Most precise m_W measurement to date
  - More precise than all other measurements combined
- Uses full Run II Tevatron data
- All experimental aspects controlled by the analysis team:
  - Reconstruction, alignment, calibration, simulation, analysis
- Significant systematics reduction mainly thanks to using cosmic data in ways not employed previously:
  - Tracking detector alignment & drift model
  - Uniformity of the EM calo response and resolution model
- Custom detector response simulation (not full simulation unlike LHC experiments)
- Six m_W values from template fits to m_T, p_T^ℓ and p_T^ν distributions in e and mu channels
  - Final m_W is the combination, χ^2/dof = 7.4/5





CDF W mass measurement

Science 376 (2022) 6589, 170-176

CDF, 1.96 TeV, 8.8 fb^{-1}

- Result:

$$M_W = 80,433.5 \pm 9.4\ \mathrm{MeV},$$

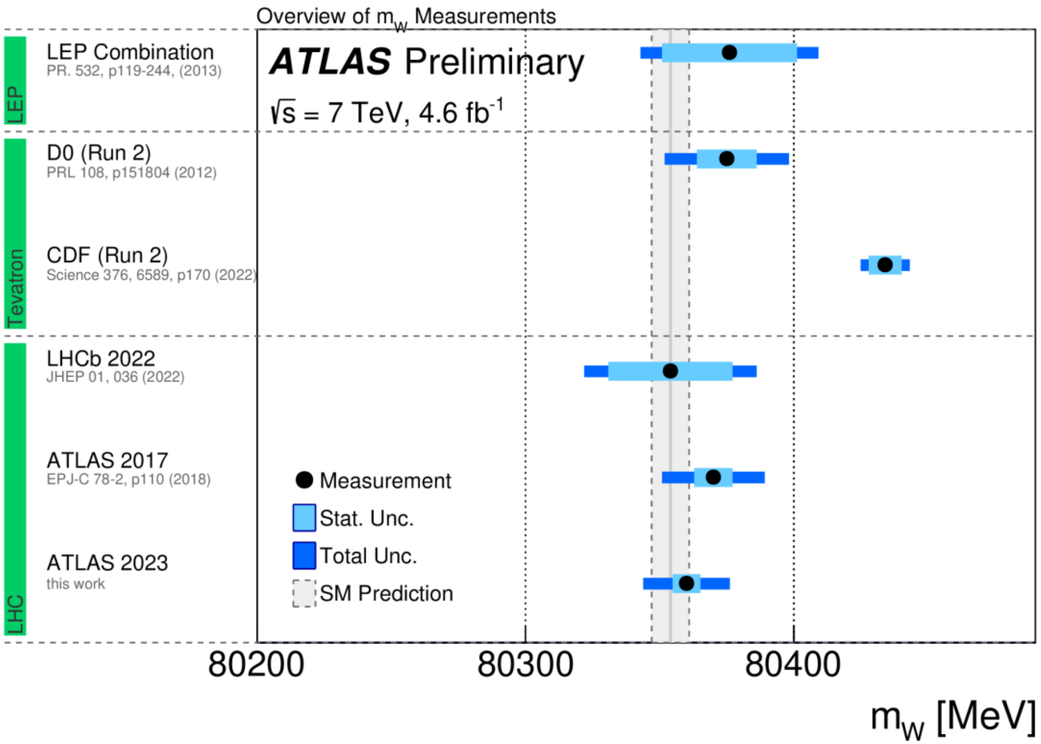
- Tension with SM-predicted mW value at the level of 7 standard deviations!

$$m_W^{\mathrm{pred.}} = 80354 \pm 7\ \mathrm{MeV}$$

CDF uncertainty breakdown

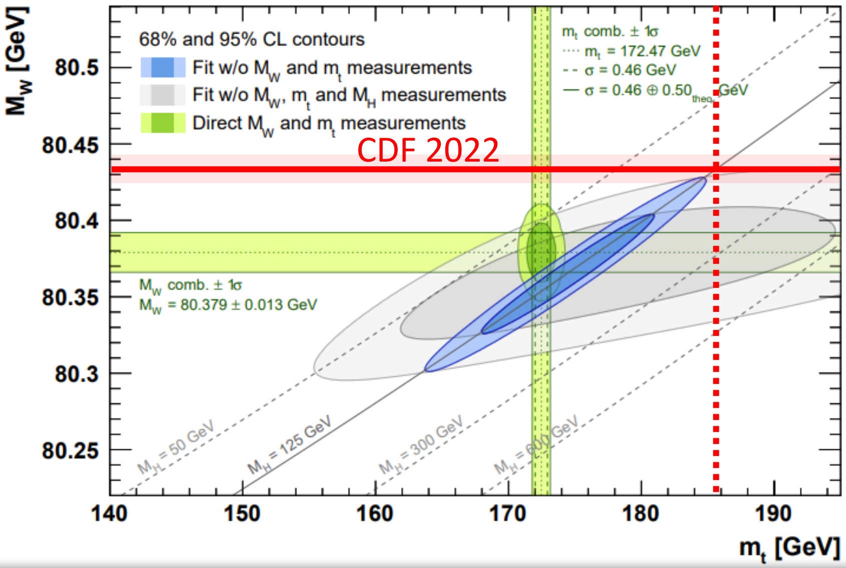
Table 2. Uncertainties on the combined M_W result.

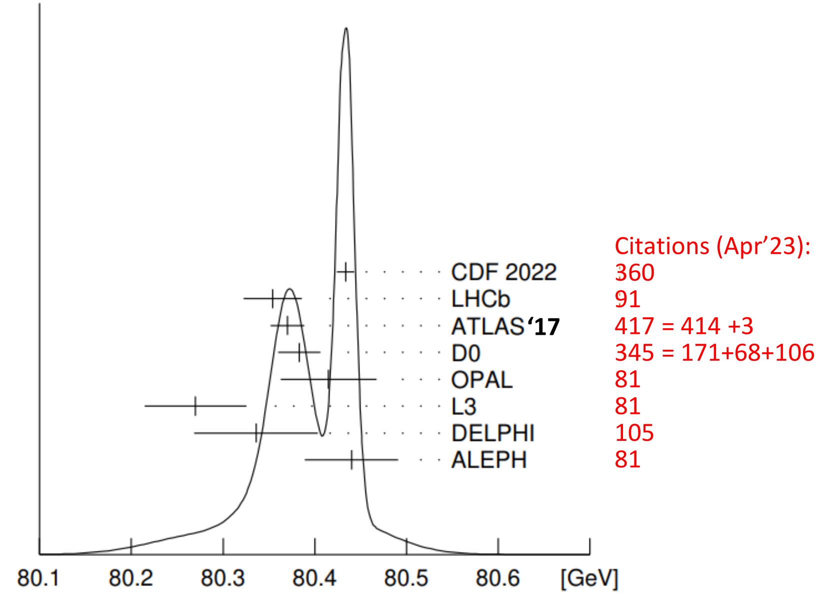
Source	Uncertainty (MeV)
Lepton energy scale	3.0
Lepton energy resolution	1.2
Recoil energy scale	1.2
Recoil energy resolution	1.8
Lepton efficiency	0.4
Lepton removal	1.2
Backgrounds	3.3
p_T^Z model	1.8
p_T^W/p_T^Z model	1.3
Parton distributions	3.9
QED radiation	2.7
W boson statistics	6.4
Total	9.4



W mass measurements

Let’s take a step back and look at these results again





PDG2022:

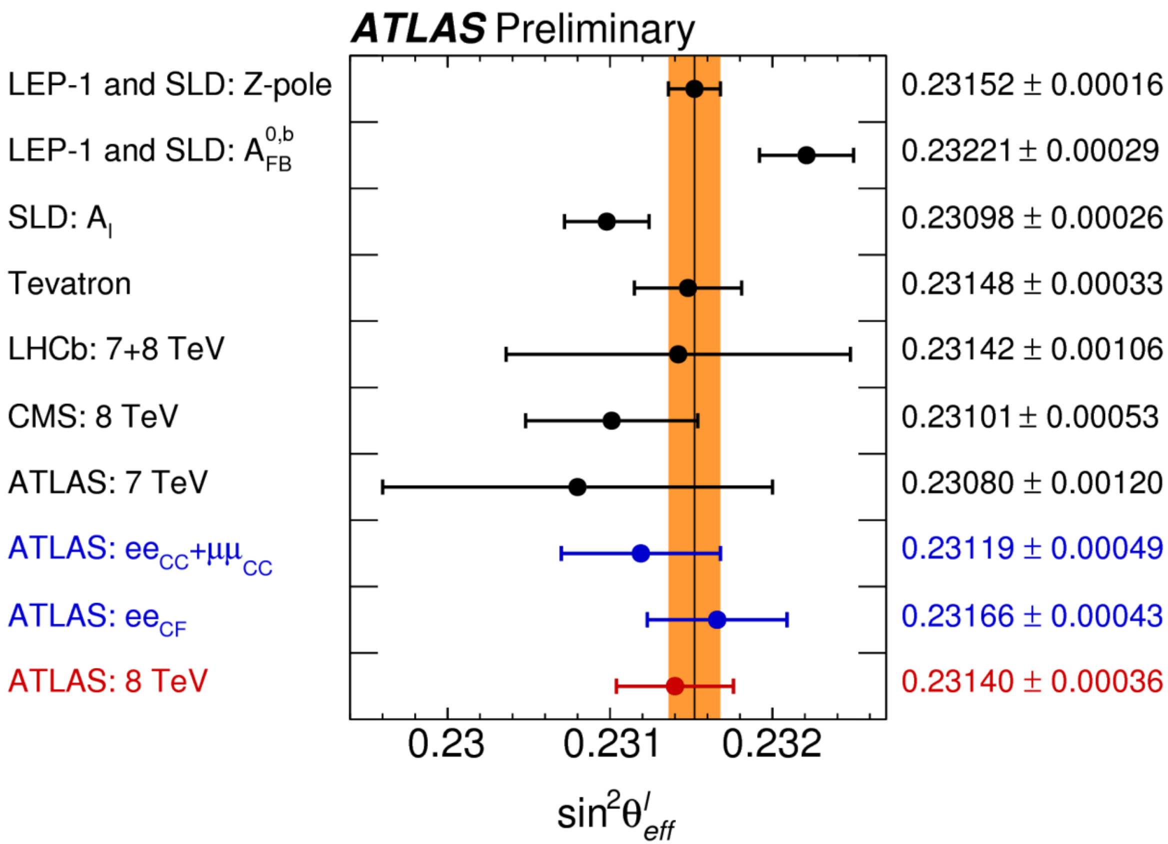
For calculating a new world average, replacing the old CDF Run-II result [3] by the new one [11], the uncertainties of all results need to be scaled by a factor of about two in order to achieve a χ^2 per degree of freedom of unity …

… A detailed understanding of the results and their correlations is needed. Corresponding studies are currently being undertaken by the experiments.

- Tevatron/LHC W-boson mass Combination WG issued a preliminary note (CERN-LPCC-2022-06) summarizing methodological and modelling considerations towards a combination

Measurements of $\sin\theta^{\ell}_{\text{eff}}$

- Measured from forward-backward lepton asymmetry in $q\bar{q} \to Z/\gamma \to l^+l^-$
- Tevatron combination gives the most precise measurement from hadron colliders
- ATLAS and CMS measurements so far based on Run 1 LHC data only
- Expecting improved LHC measurements using Run 2 data and updated PDF



Phys. Rev. D 97, 112007

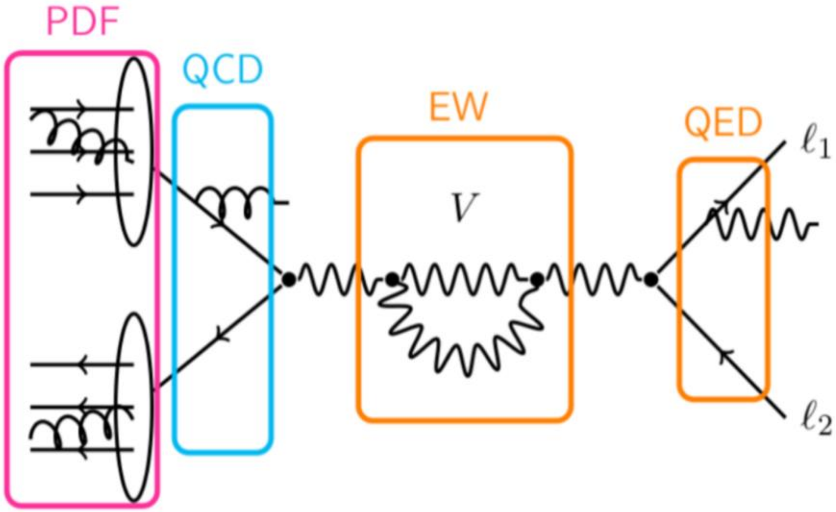
JHEP 1511(2015) 190

Eur. Phys. J. C 78 (2018) 701

ATLAS-CONF-2018-037

Single vector boson production - introduction

- Drell-Yan process enables electroweak precision measurements and stress test of QCD calculations
- One of the best understood processes at LHC
- State of the art theory predictions at NNLO QCD with partial N4LL resummation and NLO EW corrections

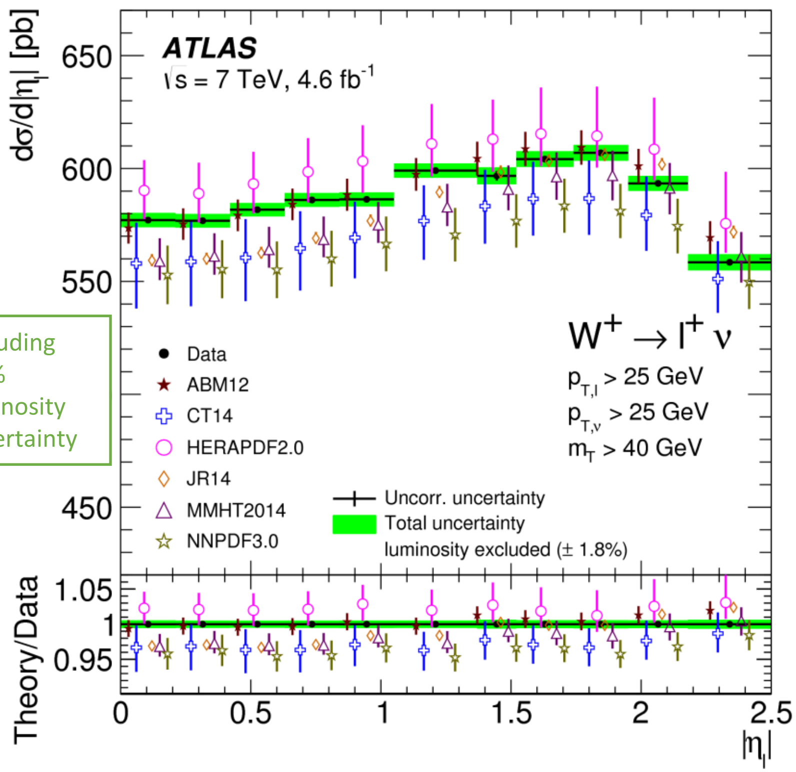


- pT(V) modelling is so much sensitive to QCD that it enabled the most precise single α_S measurement! ATLAS-CONF-2023-015
- Differential cross sections of single W, Z production is the main source of proton PDF constraints from LHC side - routinely used by PDF fitting groups

Drell-Yan cross section measurements

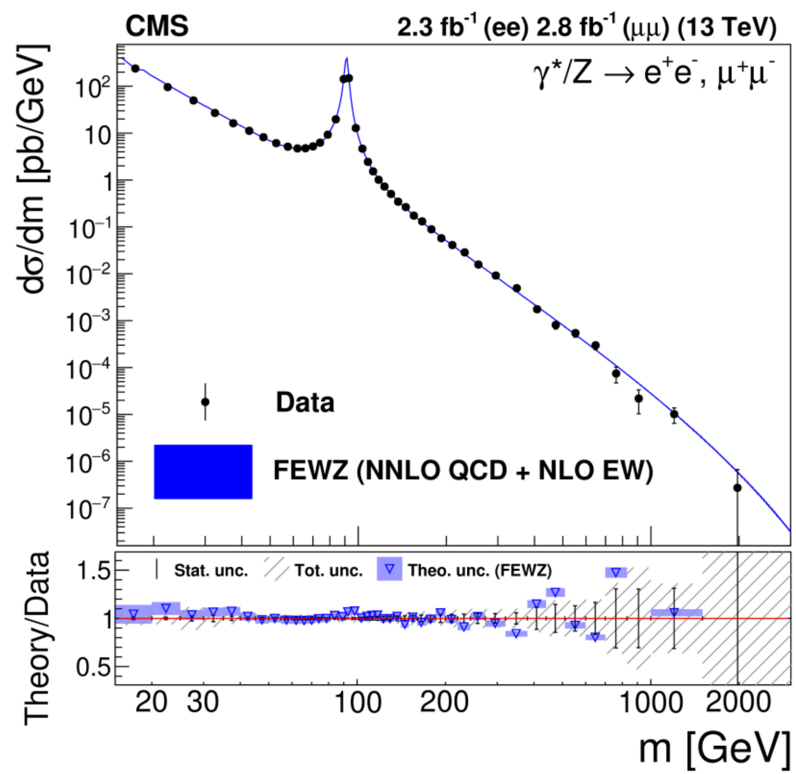
- Thorough measurements by both ATLAS and CMS at 7, 8, 13 TeV
- LHC provides most precise Drell-Yan cross sections
- Just two examples out of many measurements:

W and Z cross differential cross sections with sub-percent precision at 7 TeV by ATLAS, Eur. Phys. J. C 77 (2017) 367



Excluding 1.8% luminosity uncertainty

Drell-Yan cross sections at 13 TeV in the dilepton mass range 15 to 3000 GeV by CMS, JHEP 12 (2019) 059



Z boson invisible width

Accepted by PLB

CMS, 13 TeV, 36.3 fb^{-1}

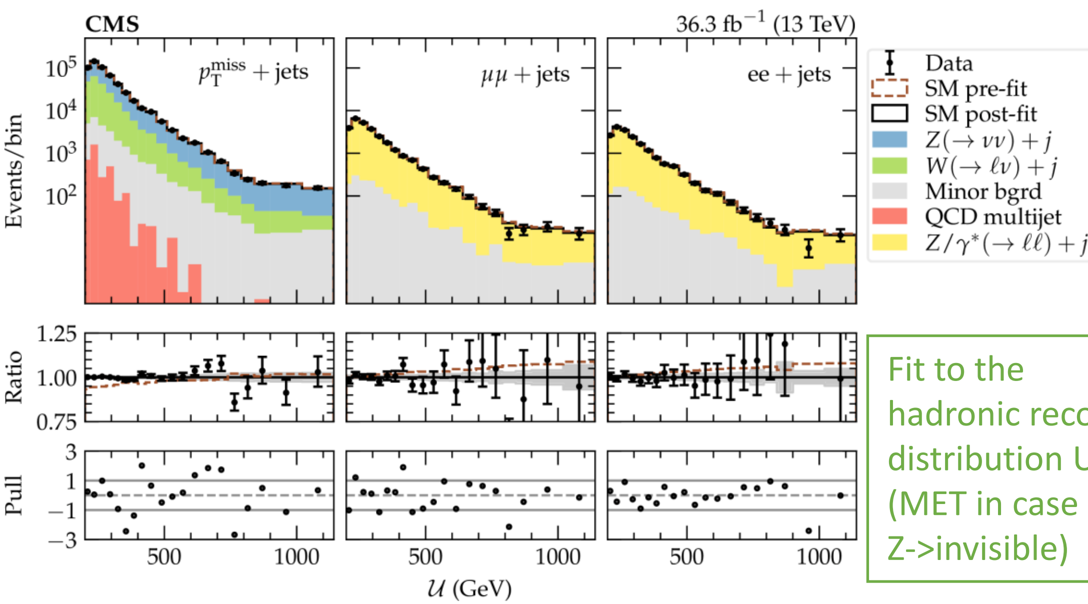
- First precise measurement of the invisible width of the Z boson at a hadron collider
- The single most precise direct measurement to date
  - ➢ competitive with the combined result of the direct measurements from the LEP experiments

$$\Gamma_{\rm inv} = 523 \pm 3\,({\rm stat}) \pm 16\,({\rm syst})\,{\rm MeV}$$

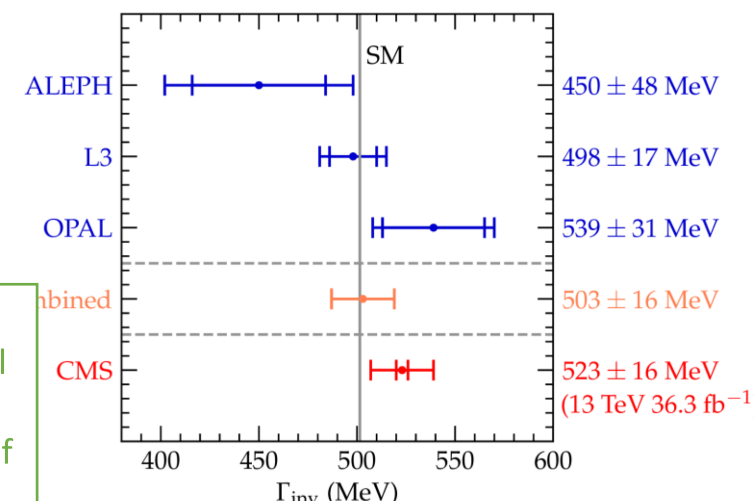
- Obtained from the simultaneous fit to kinematic distributions of two data samples:
  - ➢ Dominated by invisible Z decays
  - ➢ Dominated by $Z \rightarrow ee$ and $Z \rightarrow \mu\mu$

$$\Gamma(Z \to \nu\bar{\nu}) = \frac{\sigma(Z{+}{\rm jets})\mathcal{B}(Z \to \nu\bar{\nu})}{\sigma(Z{+}{\rm jets})\mathcal{B}(Z \to \ell\ell)}\Gamma(Z \to \ell\ell)$$

Dominant systematic contributions from muon ID (2.1%) and jet energy scale (1.9%)



Fit to the hadronic recoil distribution U (MET in case of Z->invisible)



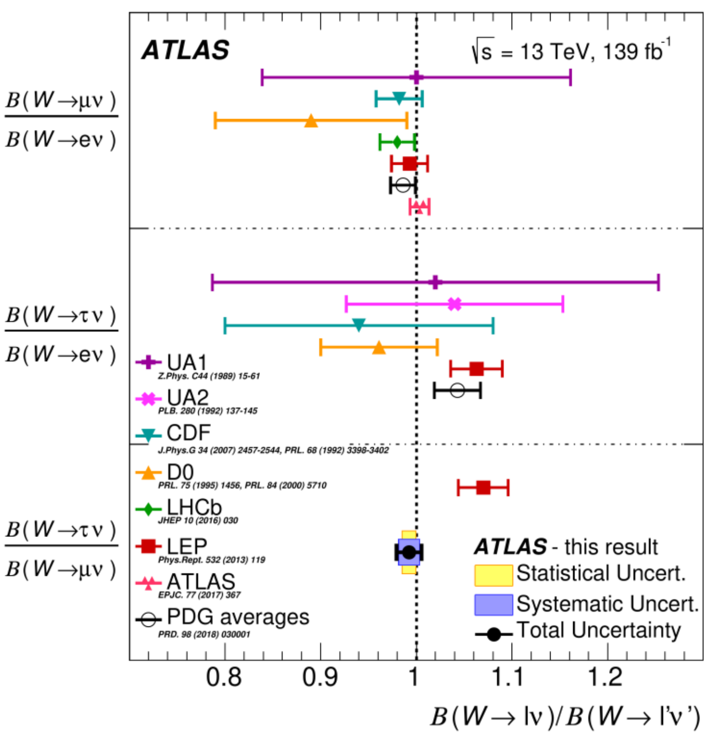
W boson R(τ/μ)

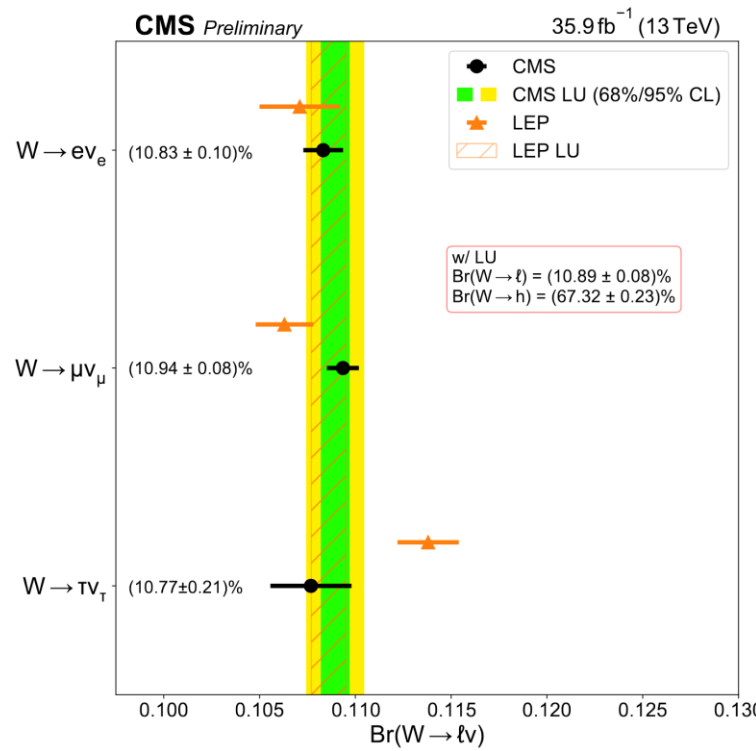
ATLAS: Nature Phys. 17 (2021) 813
CMS: CMS-PAS-SMP-18-011

- All charged leptons couple to W boson equally
- LEP combined result has shown 2.6σ tension between W decay branching ratio to τν and lν (l = e, μ)

$$R_{\tau/\ell} = \frac{2\,\mathcal{B}(\mathrm{W}\to\tau\overline{\nu}_\tau)}{\mathcal{B}(\mathrm{W}\to \mathrm{e}\overline{\nu}_\mathrm{e}) + \mathcal{B}(\mathrm{W}\to\mu\overline{\nu}_\mu)} = 1.066 \pm 0.025,$$

- ATLAS measured the ratio with a better precision than LEP using ttbar events, in consistence with the Standard Model
- CMS confirms lepton universality using events with two or one W boson

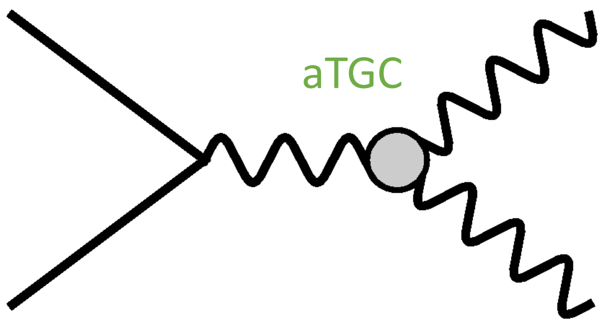


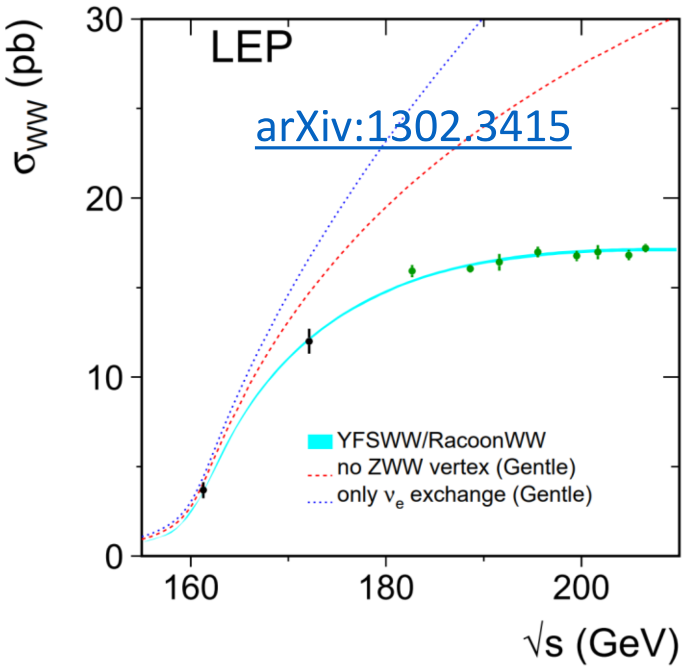


Diboson measurements - introduction

Motivation to measure diboson production:

- Test Standard Model:
  - State of the art predictions at NNLO in pQCD, with NLO EW corrections
- Sensitive to anomalous triple gauge boson couplings (aTGC)
- aTGC modify total production cross section as well as kinematic distributions -> used in data interpretation, typically in form of dimension-6 EFT limits
- TGCs were accessible at LEP -> LHC allows reaching higher $\sqrt{s}$



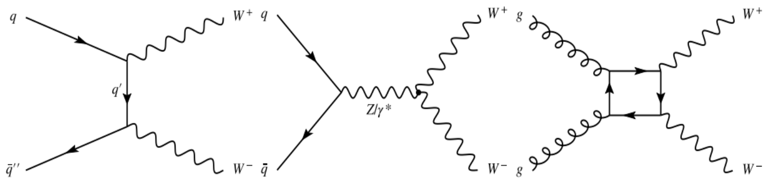


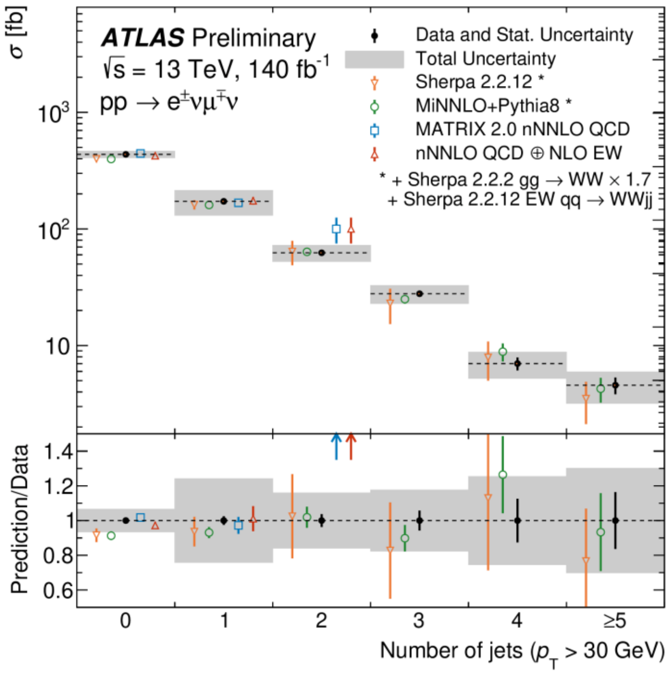
W^+W^- measurement

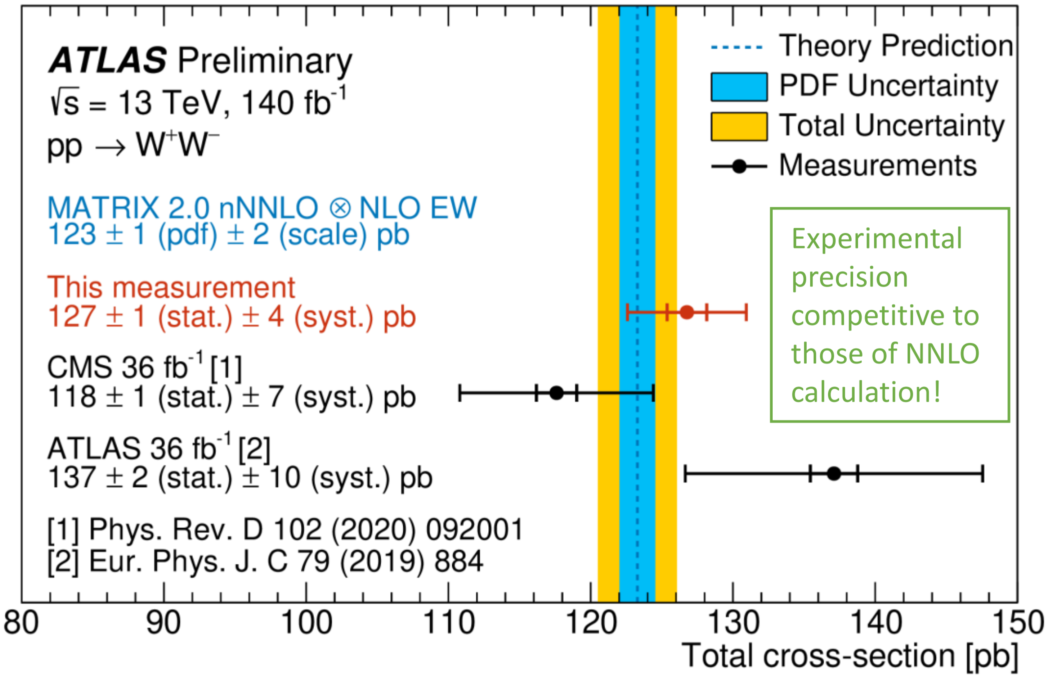
ATLAS-CONF-2023-012

ATLAS, 13 TeV, 140 fb^{-1}

- Most precise measurement of inclusive W^+W^- production at LHC with 3.1% relative uncertainty on the fiducial cross section
  - ➢ No jet veto requirement applied
- Dominant top background estimated using data driven b-tag counting method
- Excellent agreement with the NNLO QCD + NLO EW prediction



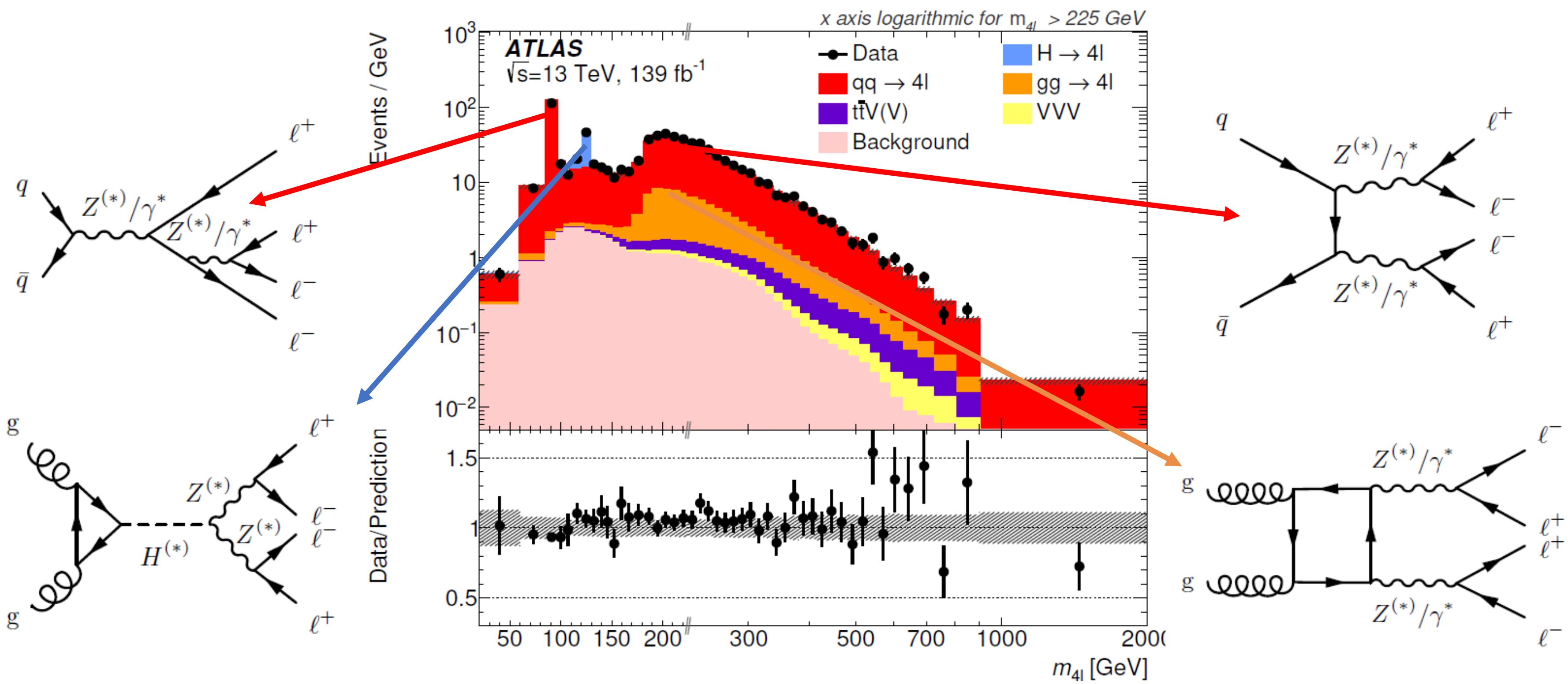




Four-lepton measurement

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}

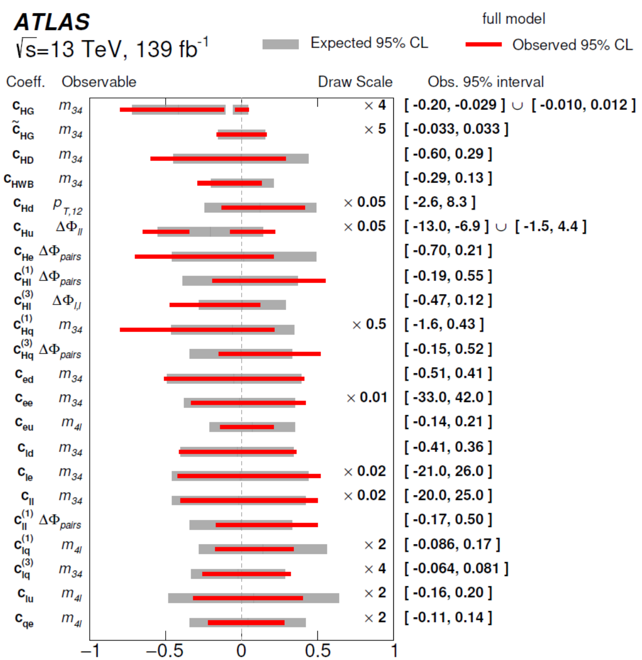
- Integrated and differential cross sections (also in different regions of m_{4l})
- Comprehensive interpretation of results:

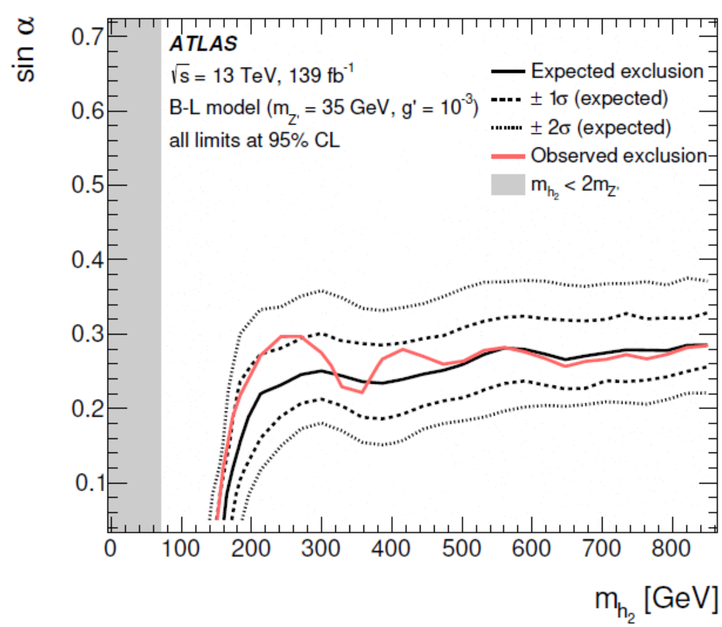
1. Most precise to date $Z \to 4l$ branching ratio measurement

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

   - ➢ 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

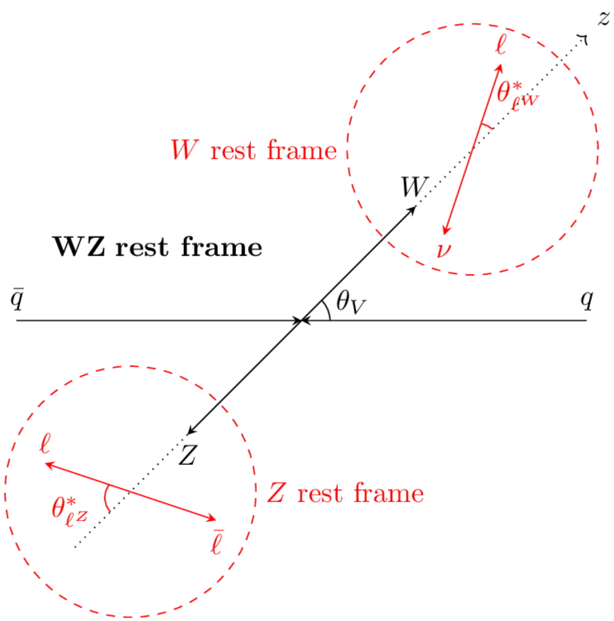


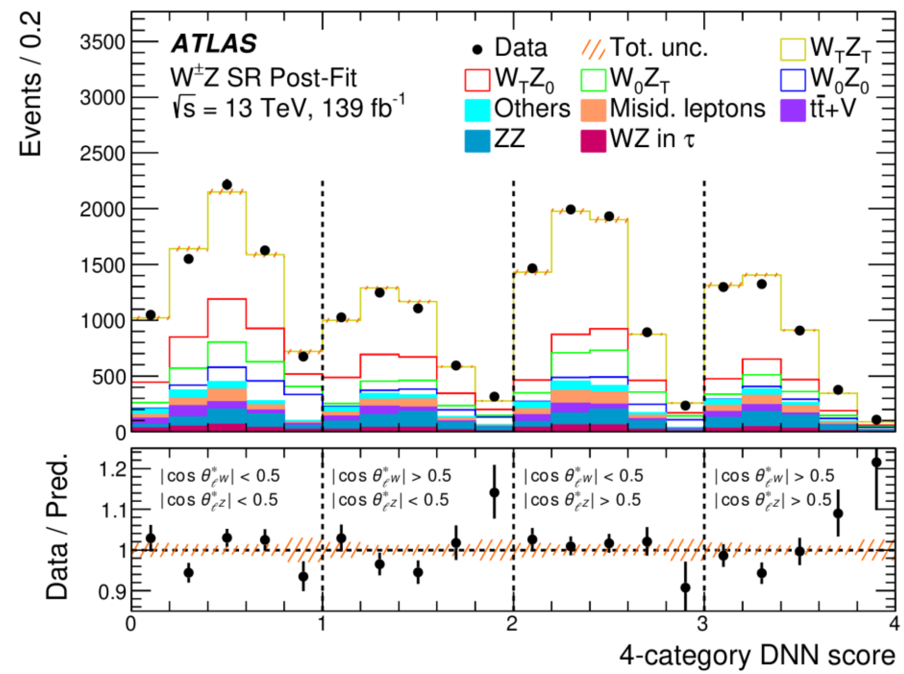


WZ joint polarisation

Accepted by PLB , 2211.09435
ATLAS, 13 TeV, 139 fb^{-1}

- Observation of joint polarisation states of W and Z boson in WZ production
- Boson polarisations defined in WZ rest frame
- 4-category DNN score to distinguish between all possible joint polarisation states
- Unpolarized WZ prediction available at NLO QCD
- Polarized signal templates from 0, 1j @LO merged MG+Pythia
  - ➢ Missing virtual NLO corrections found to be crucial -> see next page



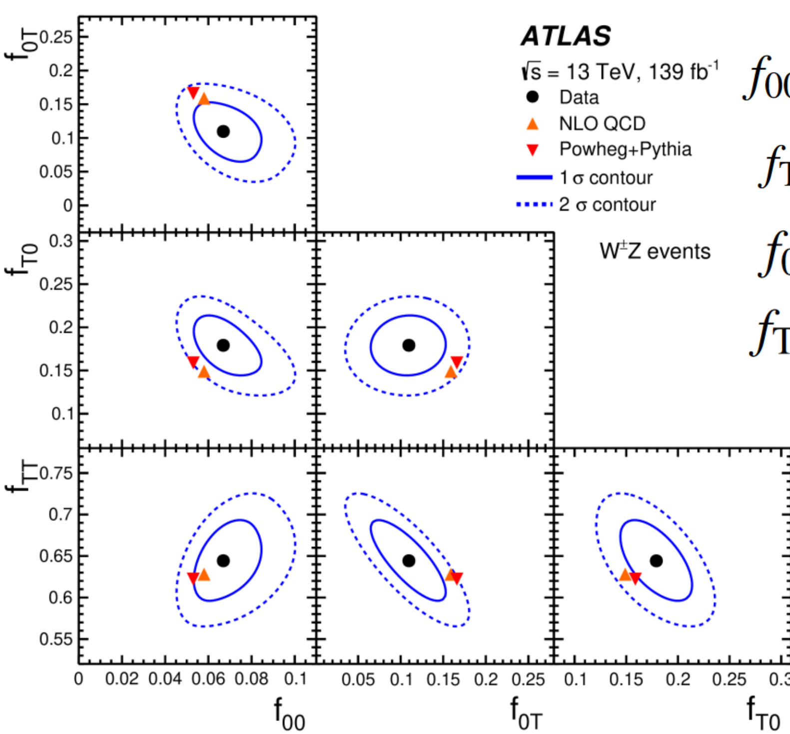


WZ joint polarisation

Accepted by PLB

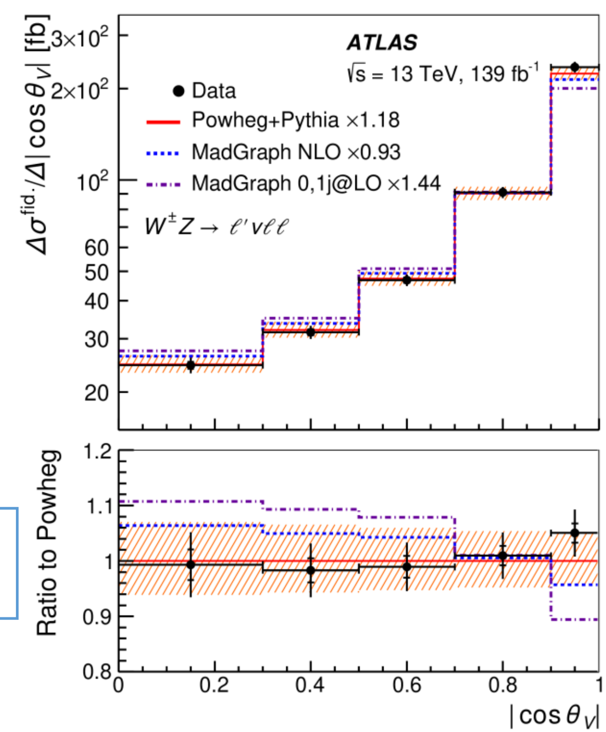
ATLAS, 13 TeV, 139 fb^{-1}

- LO (up to 1 extra jet) polarised signal templates are reweighted with dedicated DNN scores to obtain NLO-matched templates
    - One DNN per diboson polarization state
    - Procedure cross checked with bin-by-bin correction factors
- First observation of $W_L Z_L$ production with a significance of 7.1σ (6.2σ observed)
    - Milestone towards observation of doubly-longitudinal VV final states in VBS-like configurations!



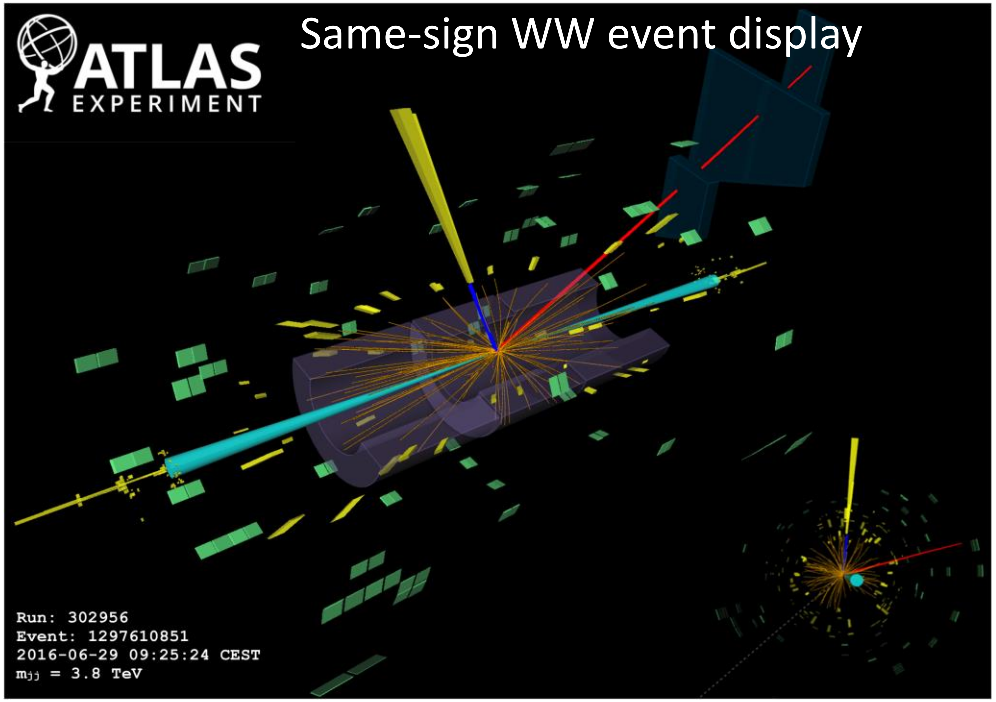
$$f_{00} = 0.067 \pm 0.010$$
$$f_{TT} = 0.644 \pm 0.032$$
$$f_{0T} = 0.110 \pm 0.029$$
$$f_{T0} = 0.179 \pm 0.023$$

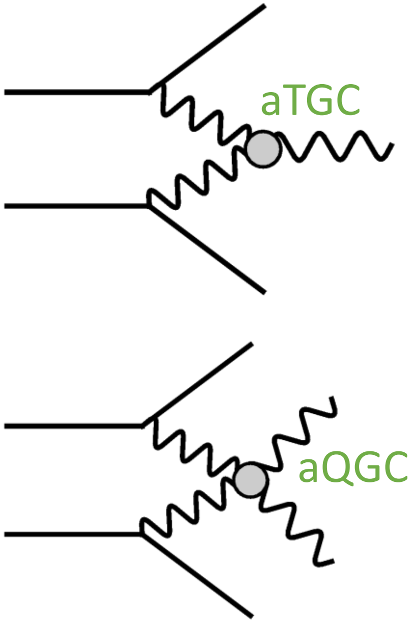
CMS single polarisation: CMS-PAS-SMP-20-014



Electroweak production of bosons - introduction

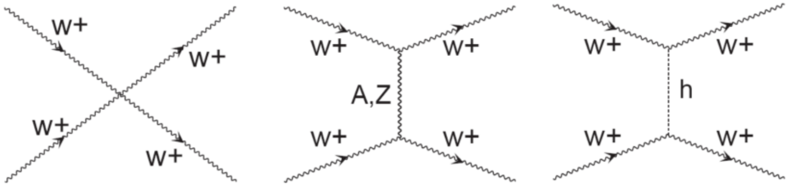
- Electroweak production:
  - Single vector boson -> vector boson fusion (VBF)
  - Two vector bosons -> vector boson scattering (VBS)
- Sensitive to anomalous triple and quartic gauge boson couplings (aQGC)
- Kinematic signature at LHC: (di)boson decay products accompanied by two forward jets
  - Typical "VBS phase space": $m_{jj} > 500\ \mathrm{GeV}$, $|\Delta y_{jj}| > 2$

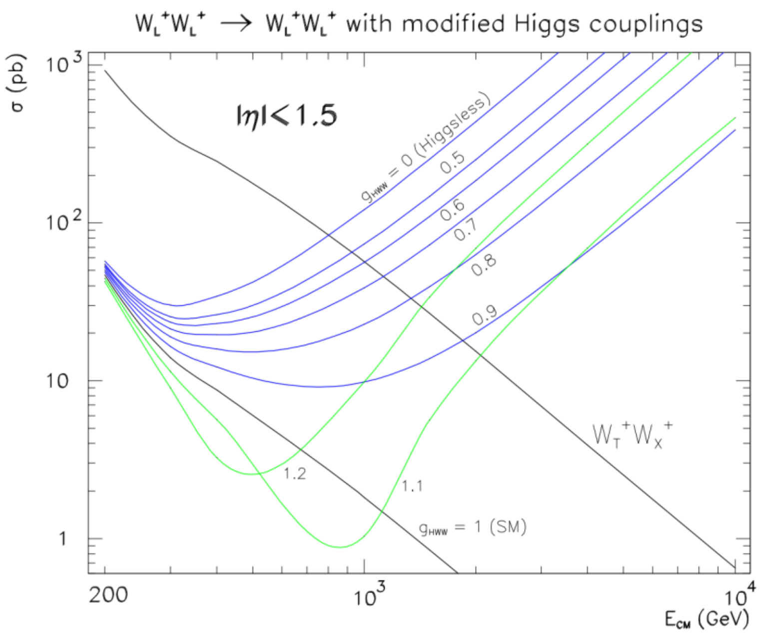




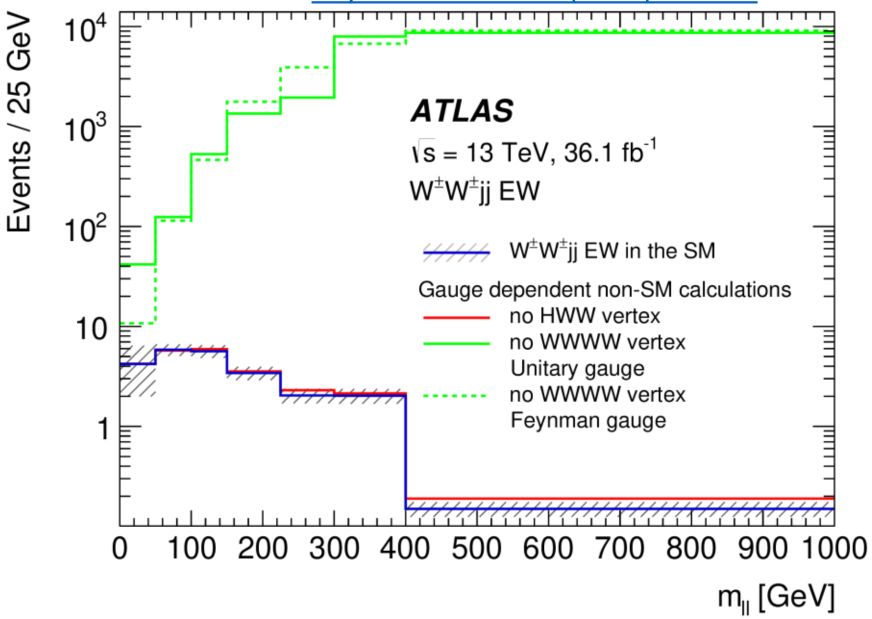
Vector boson scattering

- Test electroweak symmetry breaking
- Higgs boson contributions regularize amplitude of the $V_L V_L \rightarrow V_L V_L$ scattering (V = W, Z)
- QGCs became for the first time within the reach at LHC
- Typically, provide most stringent dim-8 EFT limits
- $W^{\pm}W^{\pm}$ final state has the largest EW/QCD ratio among other VV VBS processes





[Phys. Rev. Lett. 123 (2019) 161801]

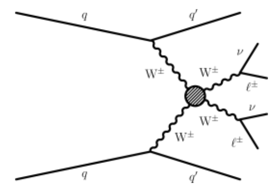


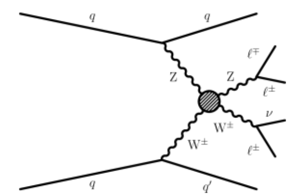
$W^{\pm}W^{\pm}jj$ and $W^{\pm}Zjj$

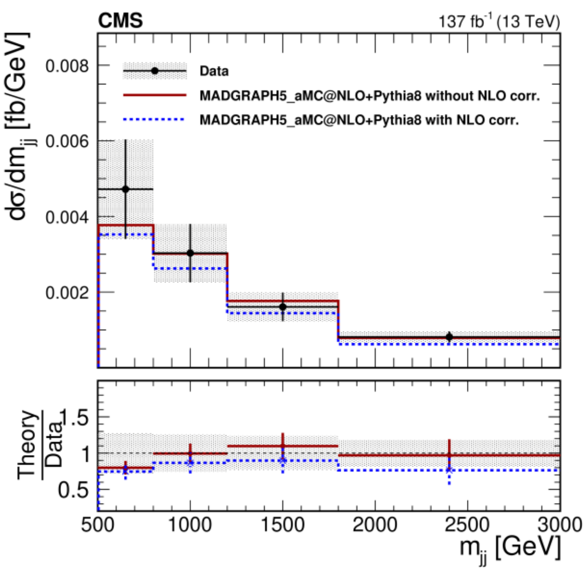
Phys.Lett.B 809 (2020) 135710

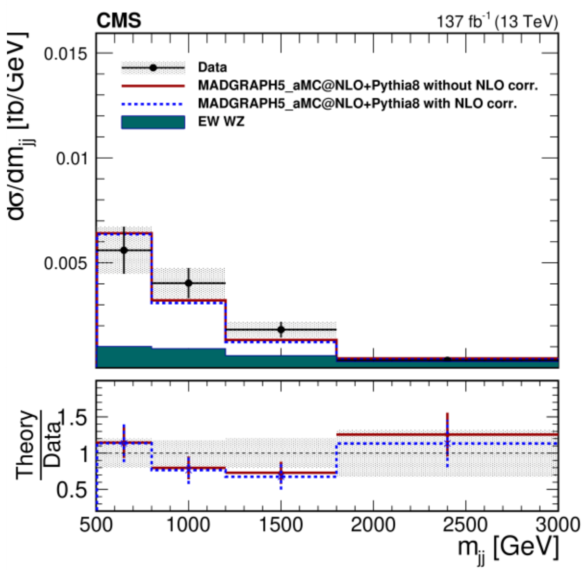
CMS, 13 TeV, 137 fb^{-1}

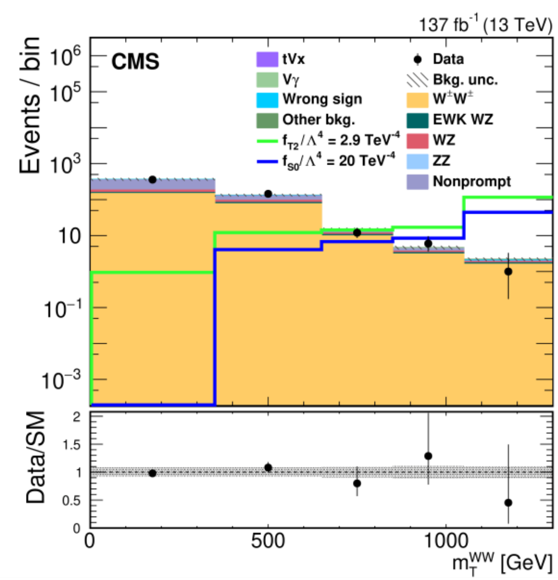
- WZ is the second-largest background to $W^{\pm}W^{\pm}$ (after non-prompt lepton background)
- Simultaneous cross section measurement of inclusive (i.e. sum of EW, QCD, and interference) $W^{\pm}W^{\pm}$ and WZ cross sections
- Absolute and normalized cross sections
- Dim-8 EFT limits at the reconstructed level









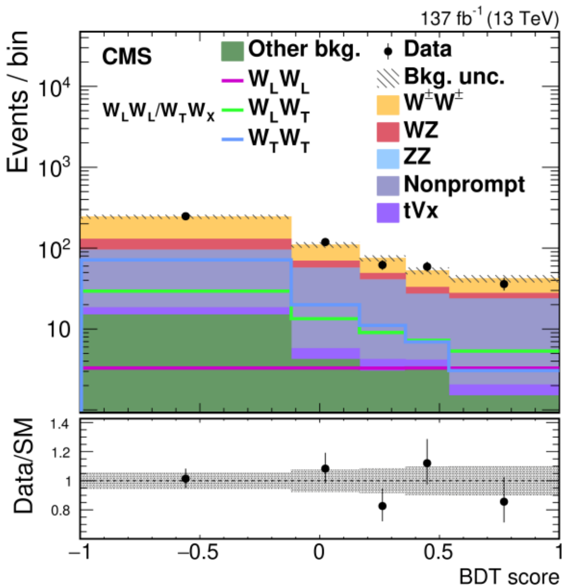


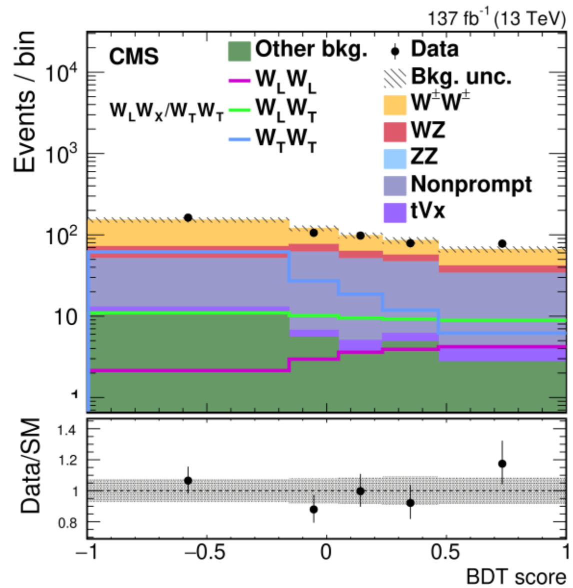
Electroweak $W^{\pm}W^{\pm}$ polarization

[Phys. Lett. B 812 (2020) 136018](https://doi.org/10.1016/j.physletb.2020.136018)

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

- First cross section measurement for polarized same-sign WW scattering
- Different diboson polarization states distinguished with the help of machine learning





- Cross section too low to obserwe $W_L^{\pm}W_L^{\pm}$ production yet
- Measured $W_L^{\pm}W_X^{\pm}$ signal significance of 2.3σ (3.1σ expected)

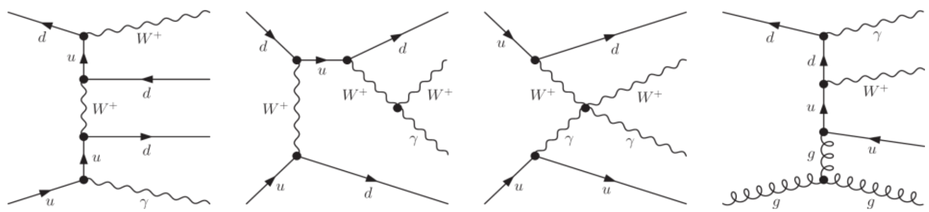
Process	$\sigma\mathcal{B}$ (fb)	Theoretical prediction (fb)
$W_L^{\pm}W_L^{\pm}$	$0.32^{+0.42}_{-0.40}$	0.44 ± 0.05
$W_X^{\pm}W_T^{\pm}$	$3.06^{+0.51}_{-0.48}$	3.13 ± 0.35
$W_L^{\pm}W_X^{\pm}$	$1.20^{+0.56}_{-0.53}$	1.63 ± 0.18
$W_T^{\pm}W_T^{\pm}$	$2.11^{+0.49}_{-0.47}$	1.94 ± 0.21

Electroweak Wγjj measurement

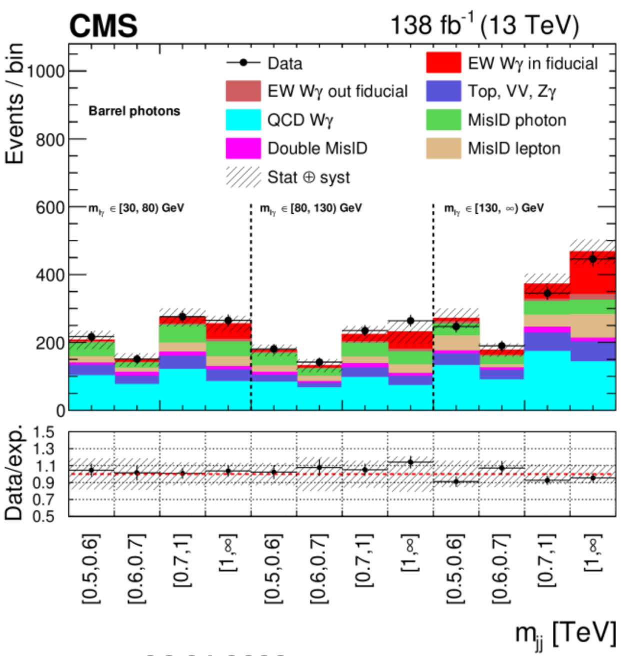
[Accepted by PRD](#)

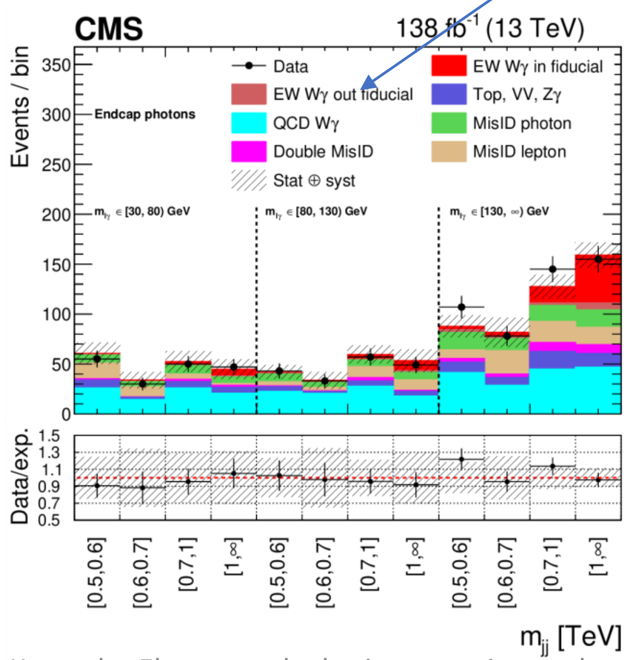
CMS, 13 TeV, 138 fb^{-1}

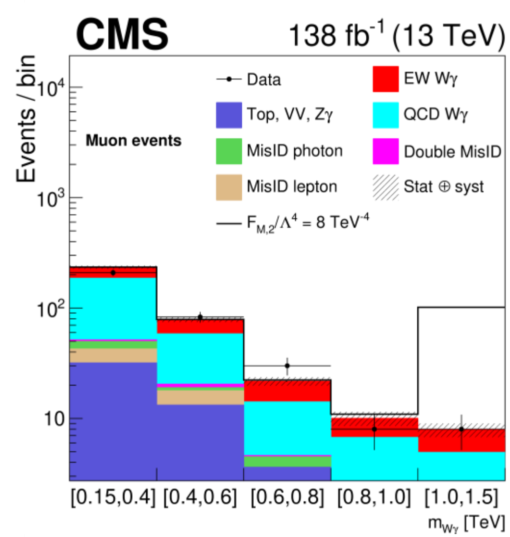
- Electroweak Wγjj signal observed with a significance of 6.0σ (6.8σ expected)
- Signal extracted from mjj, mlγ 2D-fit (2D fit provides better expected significance)
- Differential cross sections of EW-only and EW+QCD Wγjj measured (4 bins)
- Most stringent limits on dim-8 EFT operators M2-5, T6-7



Out-of-fiducial EW Wγjj contributions (17% of the total EW Wγjj) treated as background







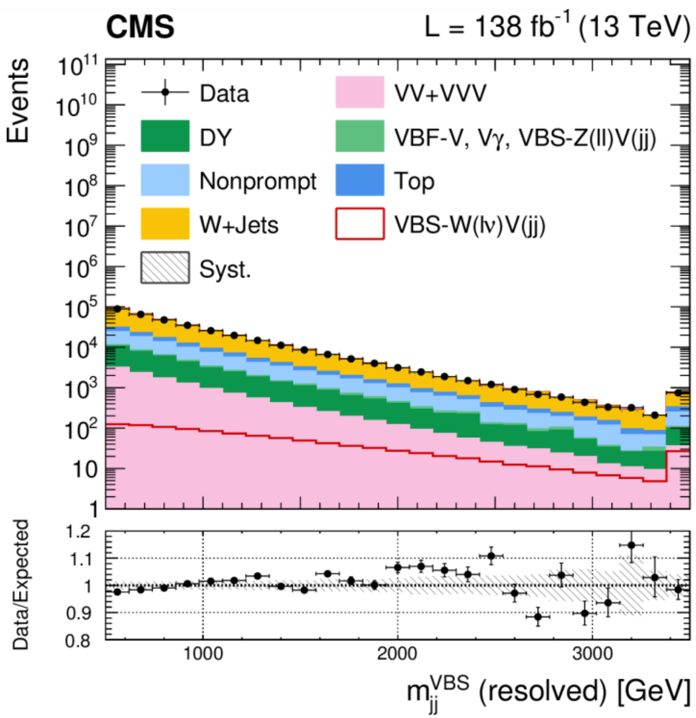
Evidence for semileptonic WVjj

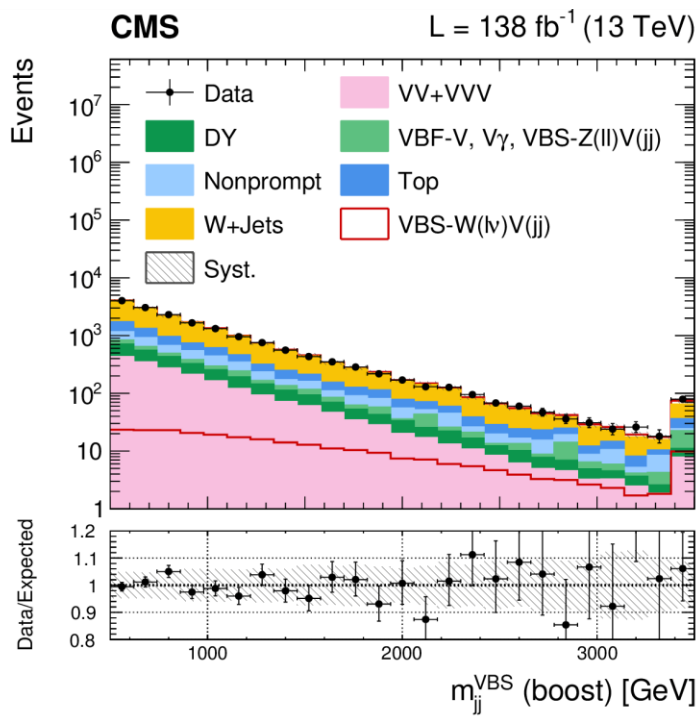
[Phys. Lett. B 834 (2022) 137438](#)

CMS, 13 TeV, 138 fb^{-1}

- First evidence for electroweak production of $WVjj \rightarrow l\nu qq\ (V = W,\ Z)$ at LHC
- Large background & complex topology -> use DNN to separate signal and bkg
  - A factor 3 improvement of the sensitivity compared to the most sensitive variable m_{jj}
- Two signal regions for resolved and boosted event categories

$$\mu_{EW} = \frac{\sigma^{obs}}{\sigma^{SM}} = 0.85 \pm 0.12\,(\text{stat})^{+0.19}_{-0.17}\,(\text{syst}) = 0.85^{+0.23}_{-0.21}$$





Observed significance 4.4σ (5.1σ expected)

Dominant systematics from theory modelling (LO)

γγ→ττ and anomalous τ magnetic moment

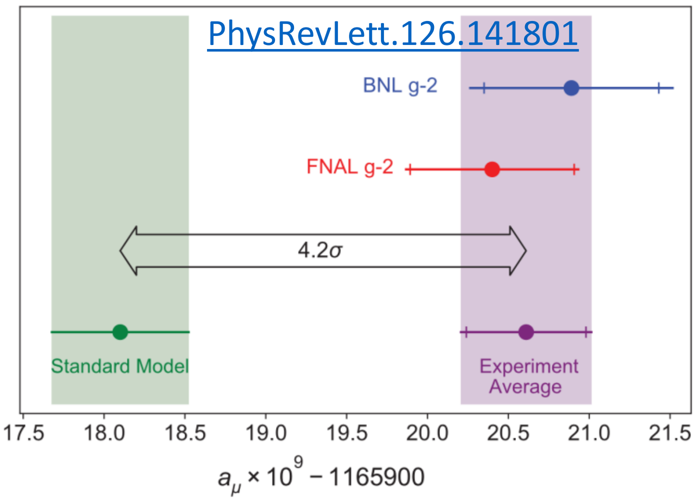
arXiv:2204.13478

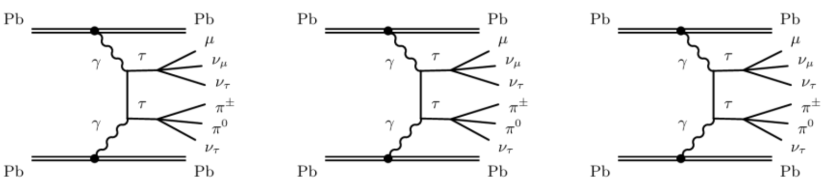
ATLAS, 5.02 TeV
Pb+Pb, 1.44 nb^{-1}

- Anomalous magnetic moment of leptons has unique sensitivity to New Physics contributions

$$a_\ell = \frac{1}{2}(g_\ell - 2)$$

- Interest significantly attracted by a tension with the SM reported by Fermilab Muon g-2 experiment

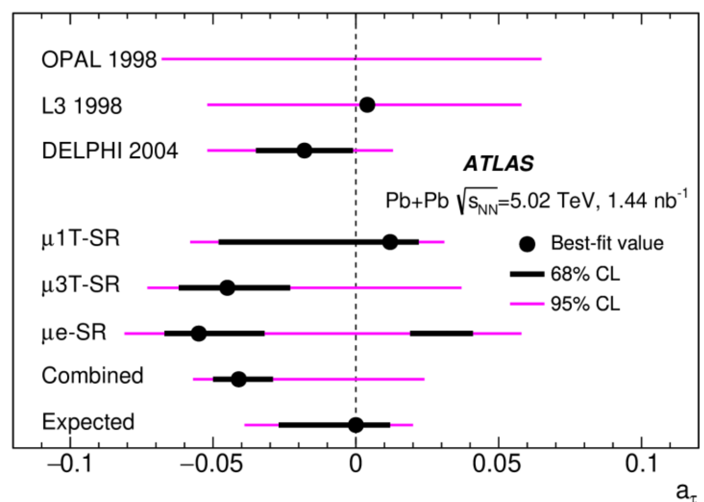




- ATLAS reports observation of the γγ→ττ process in Pb+Pb collisions with a significance exceeding 5σ and uses to set 95% CL limits on a_μ:

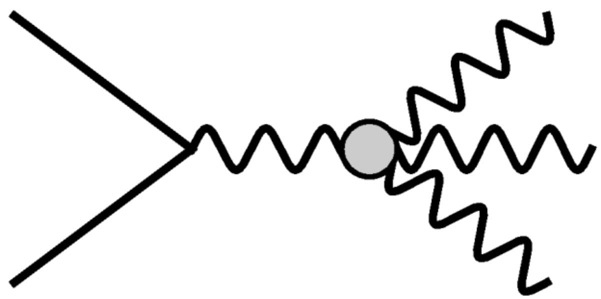
$$-0.057 < a_\mu < 0.024$$

In agreement with the Standard Model



Triboson production - introduction

- Similarly to VBS, sensitive to aQGC, but typically to a lower extent
- SM does not allow fully neutral QGC (not necessarily true for BSM)
  - ➢ SM processes sensitive to QGC will contain at least one W boson
- LHC allowed observing heavy triboson production for the first time

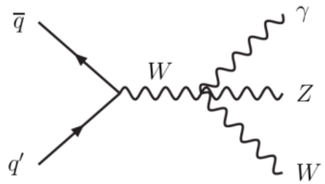


- Almost all triboson combinations observed at LHC already
  - ➢ With the exception of ZZy and ZZZ

Triboson WZγ & Wγγ observation

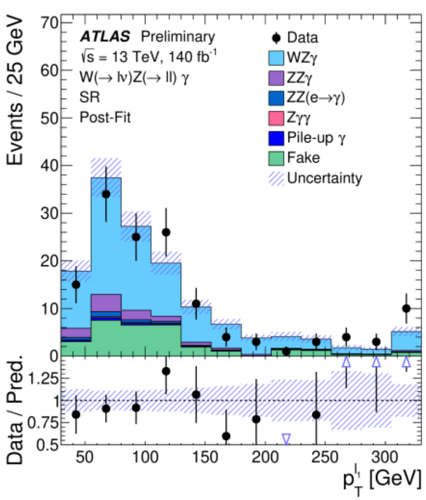
WZγ: ATLAS-CONF-2023-014
Wγγ: ATLAS-CONF-2023-005
ATLAS, 13 TeV, 140 fb^{-1}

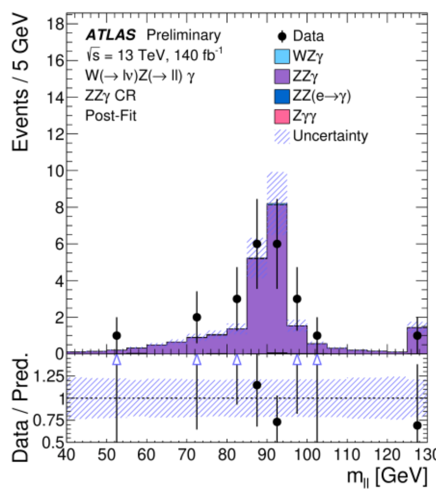
Wzγ observed with 6.3σ (expected 5.0σ)



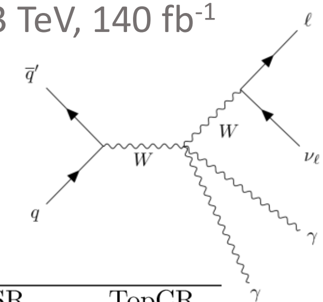
$$\mu_{WZ\gamma} = 1.34 \pm 0.21\,(\text{stat.}) \pm 0.10\,(\text{syst.}) \pm 0.07\,(\text{theory})$$

Process	SR	$ZZ\gamma$ CR	$ZZ(e\to\gamma)$ 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
$ZZ(e\to\gamma)$	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
Non-prompt background	30 ± 6	-	-
Pile-up γ	1.9 ± 0.7	-	-
Total prediction	139 ± 12	23 ± 5	33 ± 6
Data	139	23	33





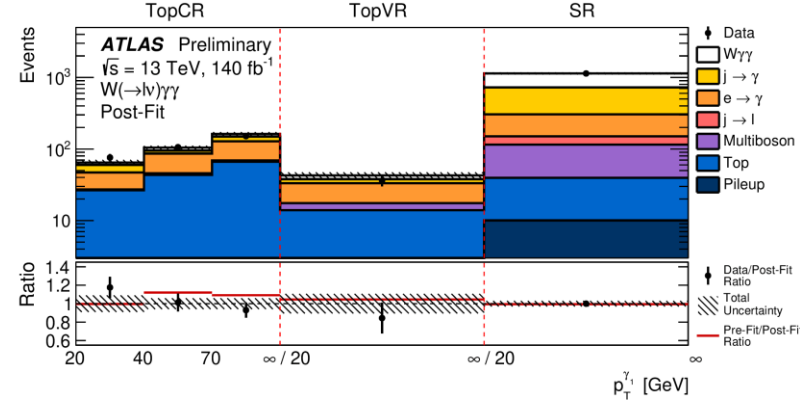
Wγγ observed with 5.6σ (expected 5.6σ)



$$\mu = 1.01^{+0.17}_{-0.16}$$

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

Systematic	15
Statistical	8.3
Total	17

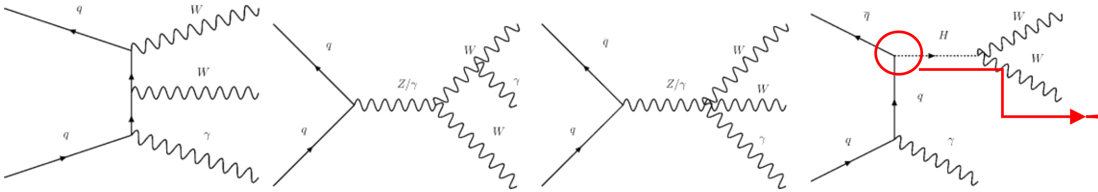


Dominant systematics for both measurements due to misidentified photons and leptons

Triboson WWγ observation

SMP-22-006

CMS, 13 TeV, 138 fb^{-1}



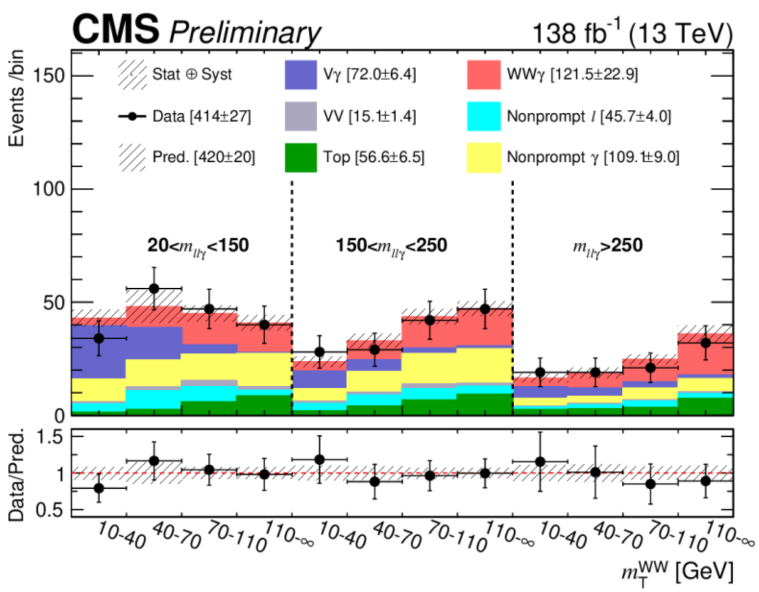
Process	σ_{up} pb exp.(obs.)	Yukawa couplings limits exp.(obs.)
$u\bar{u} \to H + \gamma \to e\mu\gamma$	0.067 (0.085)	$\lvert\kappa_u\rvert \leq 13000$ (16000)
$d\bar{d} \to H + \gamma \to e\mu\gamma$	0.058 (0.072)	$\lvert\kappa_d\rvert \leq 14000$ (17000)
$s\bar{s} \to H + \gamma \to e\mu\gamma$	0.049 (0.068)	$\lvert\kappa_s\rvert \leq 1300$ (1700)
$c\bar{c} \to H + \gamma \to e\mu\gamma$	0.067 (0.087)	$\lvert\kappa_c\rvert \leq 110$(200)

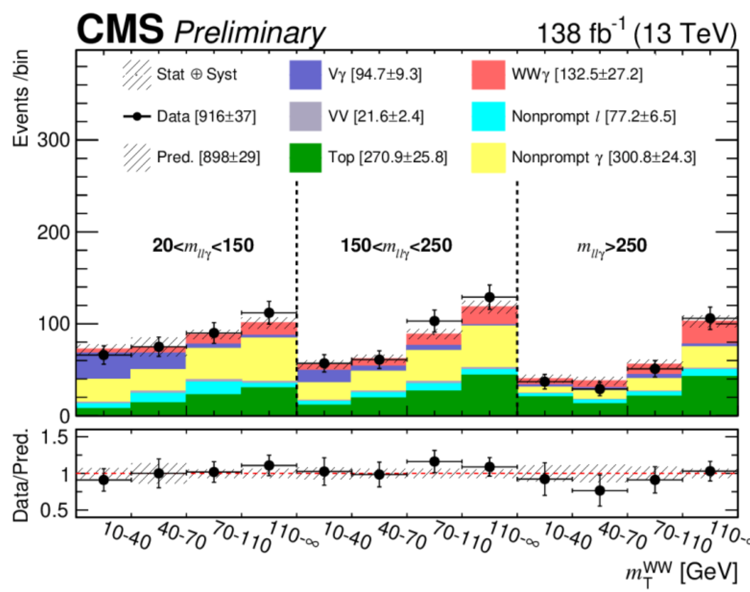
- Wwy observed with 5.6σ (4.7σ expected)

$$\mu^{obs.}_{combined} = 1.31 \pm 0.17\,(\text{stat}) \pm 0.21\,(\text{syst})$$

- Study extended to set limits on Higgs boson couplings to light quarks, in a subset of the SR

Process	Signal region	SSWWγ CR	Topγ CR
WWγ	254.0±47.3	1.2±0.2	12.8±2.7
QCD Vγ	166.7±13.8	12.2±2.2	12.6±1.2
VV	36.7±3.5	24.9±1.7	2.0±0.3
Top	327.5±32.2	2.4±0.6	2433.5±85.2
Nonprompt ℓ	122.9 ±9.7	196.6±13.6	39.8±10.7
Nonprompt γ	409.9 ±31.7	19.9±1.6	793.2±62.1
Expected	1318±43	257±14	3294±57
Observed	1330±46	259±20	3287±59



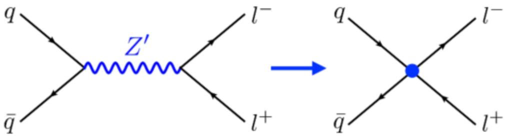


EFT interpretations - introduction

- New physics effects parameterised by extra operators in the Lagrangian with the mass dimension d > 4
- Generic parameterisation not attached to a specific model

$$\mathcal{L}_{\text{SMEFT}} = \mathcal{L}_{\text{SM}} + \frac{1}{\Lambda}\mathcal{L}_5 + \frac{1}{\Lambda^2}\mathcal{L}_6 + \frac{1}{\Lambda^3}\mathcal{L}_7 + \frac{1}{\Lambda^4}\mathcal{L}_8 + \ldots \qquad \mathcal{L}_n = \sum_k C_k\, O_k^{(d=n)}$$

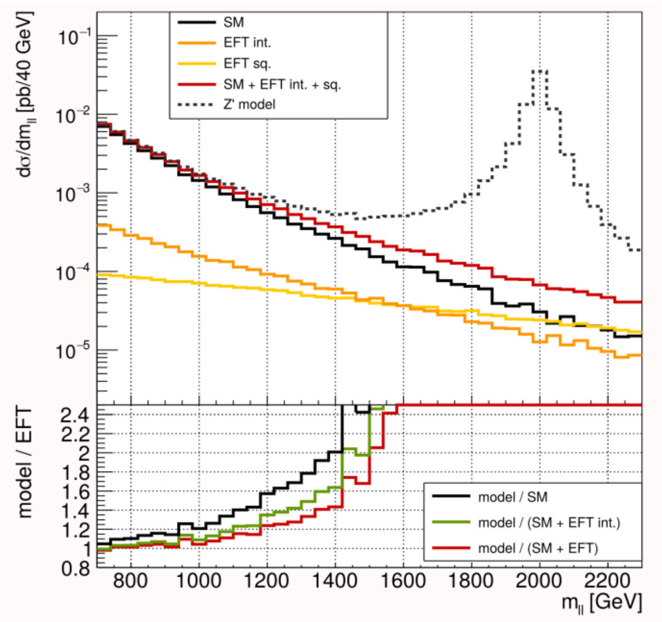
Lambda is the new physics scale, e.g. Z' boson mass



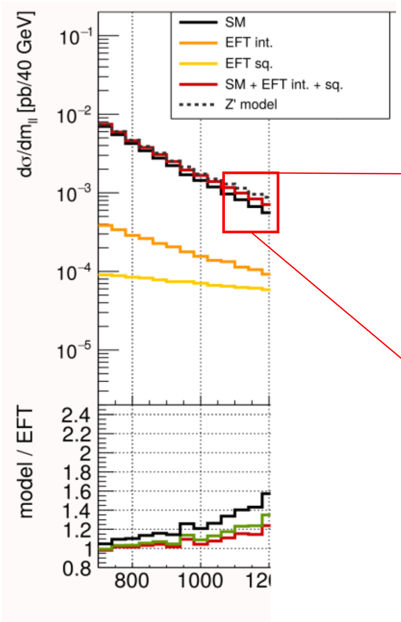
- Using effective interactions (new resonance integrated out)
- EFT approximation is only valid far away from the resonance mass
- Allows looking for new particles without having them produced (beyond the centre-of-mass energy reach)

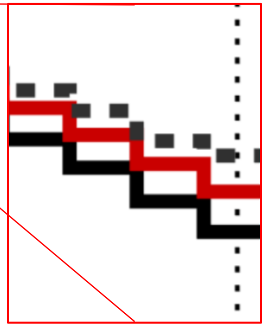
At LHC, mostly cases of n=6, 8 are considered

I. Brivio



EFT limits at LHC: Search for deviations from data in tails of kinematic distributions





EFT interpretation of multibosons

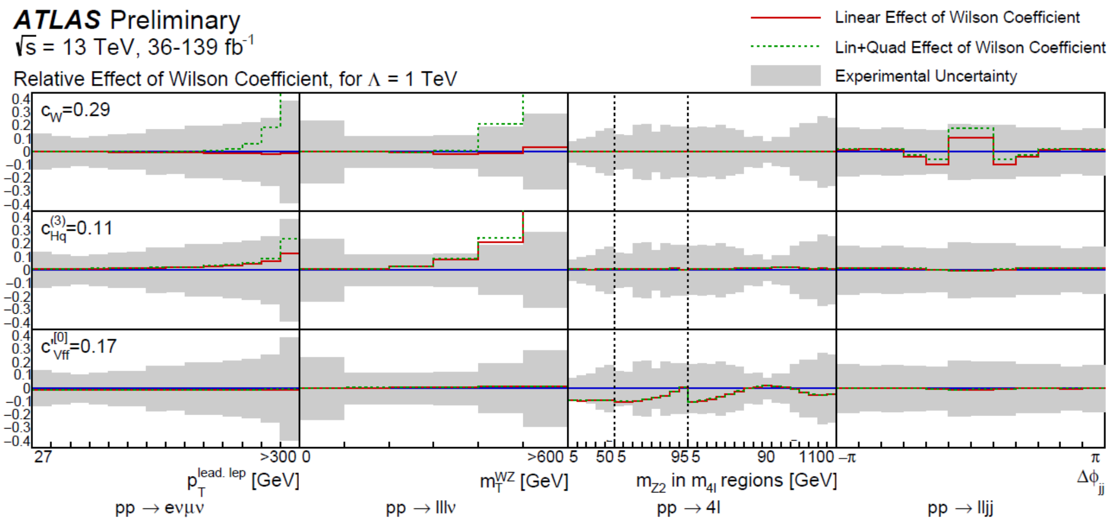
- Combined analysis of ATLAS published measurements:
  - Zjj via Vector Boson Fusion (VBF) with 139 fb^{-1}, Eur. Phys. J. C 81 (2021) 163
  - Diboson WW with 36 fb^{-1}, Eur. Phys. J. C 79 (2019) 884
  - Diboson WZ with 36 fb^{-1}, Eur. Phys. J. C 79 (2019) 535
  - Inclusive four-lepton with 139 fb^{-1}, JHEP 07 (2021) 005
- EFT dimension-6 with 33 CP-even operators, using Warsaw basis
- The information contained in data is not sufficient to constrain all 33 operators
- Identify sensitive directions from eigenvalue decomposition of the covariance matrix
  - Construct a modified basis with linear combinations of the Warsaw basis operators
  - Linear combinations of operators constrained (two Wilson coefficients c_W and $c_{Hq}^{(3)}$ and 13 combinations of other Wilson coefficients)
- The expansion of the cross section contains linear and quadratic terms in Wilson coefficients $c_i^{(6)}$:

$$\sigma \propto |\mathcal{M}_{\mathrm{SMEF}} = |\mathcal{M}_{\mathrm{SM}}|^2 + \sum_i \frac{c_i^{(6)}}{\Lambda^2} 2\mathrm{Re}\left(\mathcal{M}_i^{(6)} \mathcal{M}_{\mathrm{SM}}^*\right) + \sum_i \frac{\left(c_i^{(6)}\right)^2}{\Lambda^4} \left|\mathcal{M}_i^{(6)}\right|^2 + \sum_{i<j} \frac{c_i^{(6)} c_j^{(6)}}{\Lambda^4} 2\mathrm{Re}\left(\mathcal{M}_i^{(6)} \mathcal{M}_j^{(6)*}\right) + O\left(\Lambda^{-4}\right)$$

- Quadratic terms are of the same order as those of EFT dimension-8 interfering with the SM
  - EFT dim-8 not considered in the model -> report limits based on linear and linear+quadratic fits; difference gives estimate of missing $1/\Lambda^4$ terms

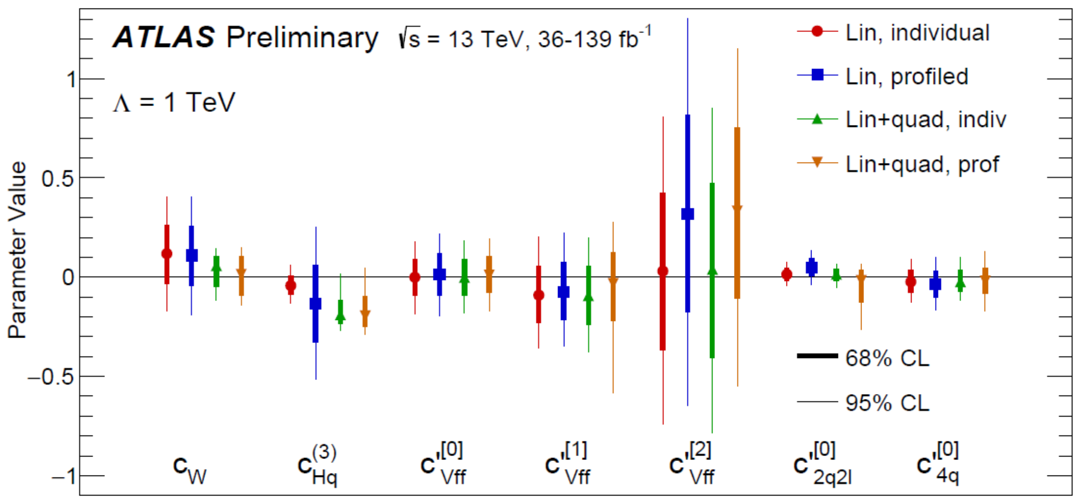
EFT interpretation

ATL-PHYS-PUB-2021-022



- Correlation of systematics between measurements taken into account

Correlated Uncertainty Source	WW	WZ	4ℓ	VBF Z
Luminosity (correlated part)	✓	✓	✓	✓
Luminosity 2015/16	✓	✓	✓	✓
Luminosity 2017/18			✓	✓
Lepton efficiency (correlated part)	✓	✓	✓	✓
Pile-up modelling	✓	✓	✓	✓
Pile-up jet suppression	✓			✓
Jet energy scale (Pile-up modelling)	✓			✓
Jet energy scale η-inter-calibration	✓			✓



$c'^{[0]}_{Vff} \approx 0.81c_{HWB} + 0.38c_{HD} + 0.13c^{(1)}_{Hl} + 0.37c^{(3)}_{Hl} - 0.14c^{(1)}_{ll} + 0.12c^{(1)}_{Hq}$

$c'^{[1]}_{Vff} \approx 0.73c^{(1)}_{Hl} - 0.28c^{(3)}_{Hl} - 0.48c_{He} + 0.38c^{(1)}_{ll} + 0.13c^{(1)}_{Hq}$

$c'^{[2]}_{Vff} \approx 0.37c_{HWB} + 0.17c_{HD} - 0.31c^{(1)}_{Hl} - 0.53c^{(3)}_{Hl} + 0.25c_{He} + 0.59c^{(1)}_{ll} - 0.21c^{(1)}_{Hq}$

$c'^{[0]}_{2q2l} \approx -0.37c^{(1)}_{lq} + 0.89c^{(3)}_{lq} - 0.11c_{lu} - 0.21c_{eu} - 0.13c_{qe}$

$c'^{[0]}_{4q} \approx 0.11c^{(11)}_{qq} + 0.22c^{(18)}_{qq} + 0.95c^{(31)}_{qq} - 0.2c^{(38)}_{qq}$

- Limits at 95% CL for linear and linear+quadratic fits (to illustrate the effect of truncation of EFT expansion)
- Fits of individual coefficients (with others set to zero) as well as combined fit
- No deviations from SM found

Step forward towards global EFT interpretations!

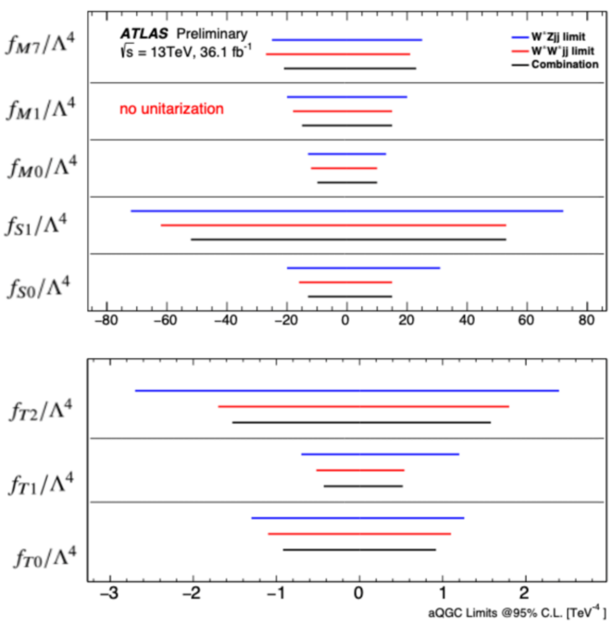
EFT interpretation of EW diboson

ATL-PHYS-PUB-2023-002

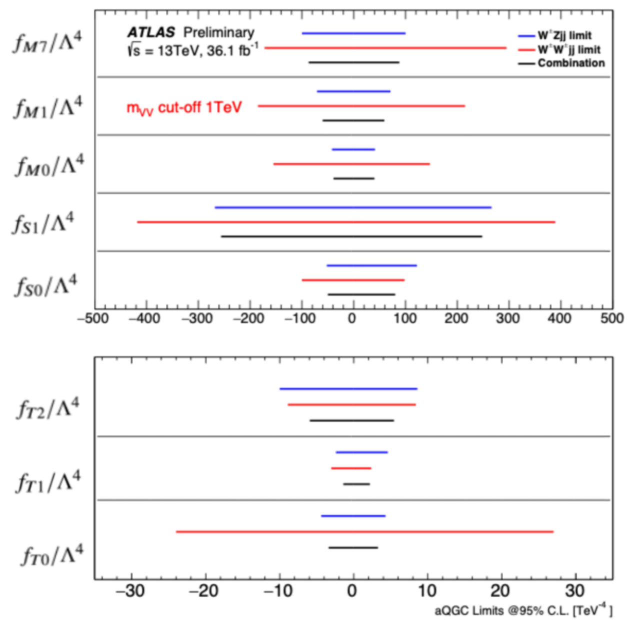
ATLAS, 13 TeV, 36 fb^{-1}

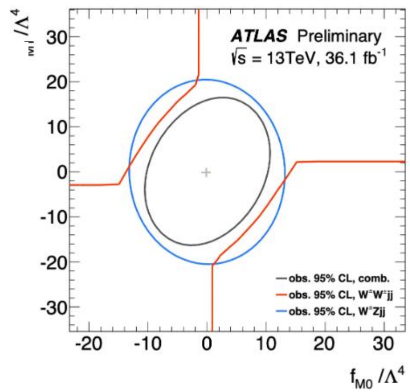
- Joint dim-8 EFT interpretation of partial Run 2 $W^{\pm}W^{\pm}$ and WZ ATLAS results
  - ➢ $W^{\pm}W^{\pm}$: Reco M_{ll} distribution
  - ➢ WZ: Unfolded cross sections
  - ➢ Preserving systematic correlations between two measurements
- 1D and 2D limits
- Also "unitarized" 1D limits, with EFT contributions clipped above 1 TeV

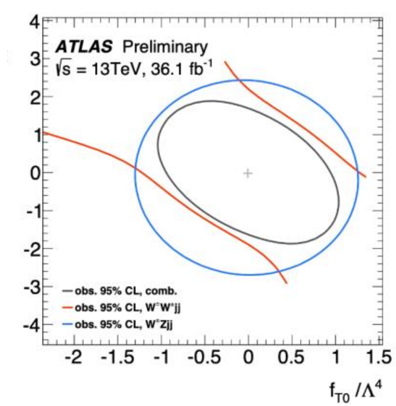
Without EFT clipping



With EFT clipping







When clipping EFT contributions, the limits get weaker -> constraints from partial-wave unitarity are stronger than the experimental ones

First ATLAS global EFT fit

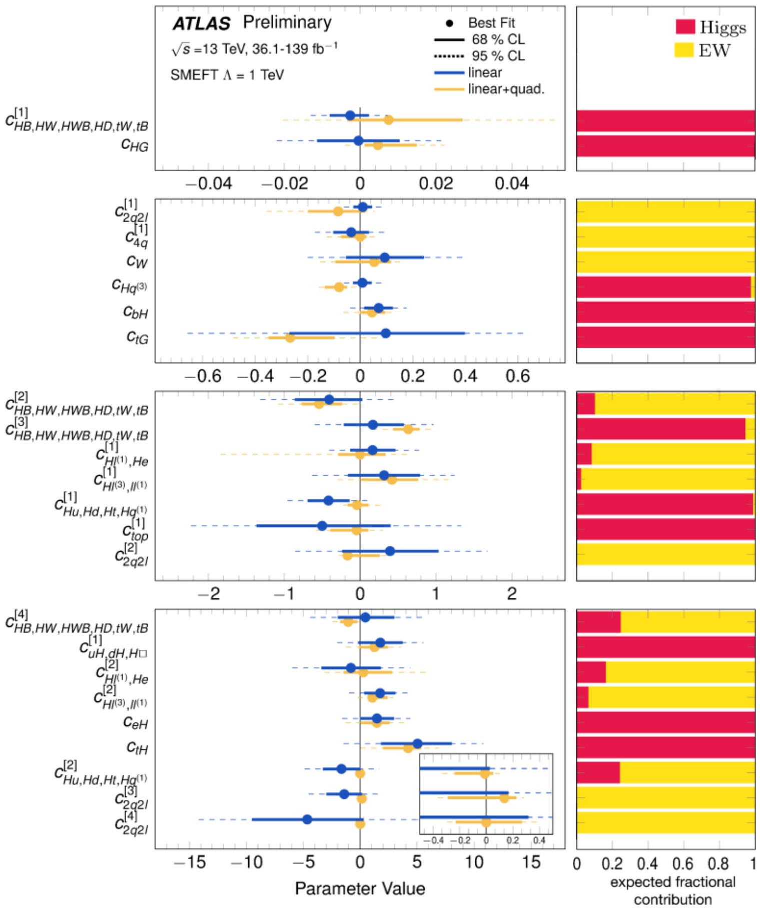
ATL-PHYS-PUB-2022-037

ATLAS, 13 TeV, 36-139 fb^{-1}

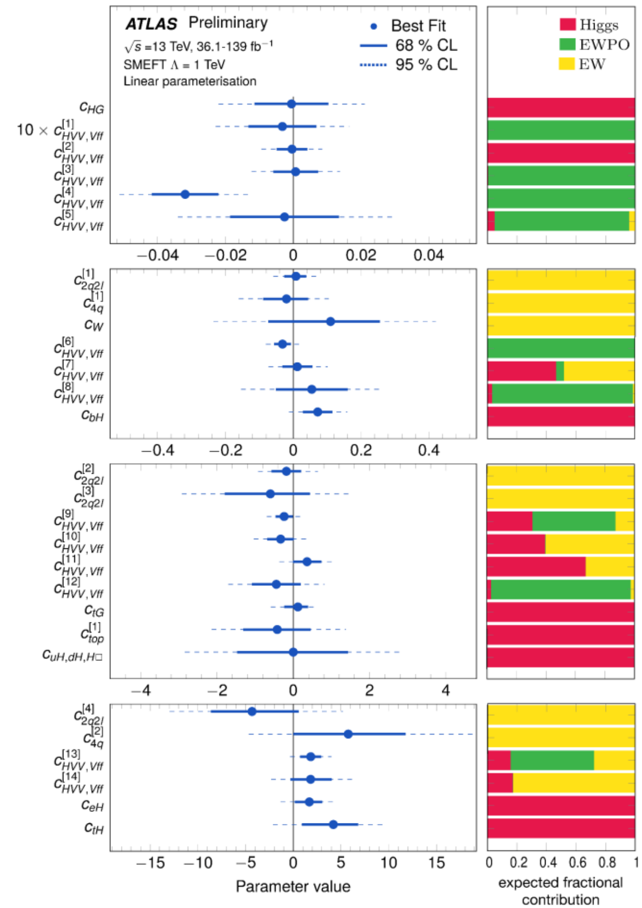
Including ATLAS, LEP and SLC data

- Global dim-6 EFT interpretation of multiple measurements:
  - ➢ Higgs boson production and decay in form of STXS; differential cross sections of weak boson production; electroweak precision observables from LEP and SLC
- Constraints on 28 Wilson coefficients and their linear combinations

ATLAS only



ATLAS + LEP, SLC precision EW

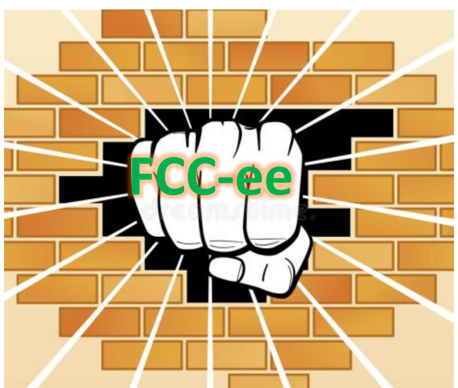


No signs for BSM contributions

Predicting future is hard…

CERN/AC/93–03(LHC)
8 November 1993

LEP is almost certainly the last in the line of circular machines of colliding leptons. Lepton beams emit energy while following a circular path. This synchrotron radiation, though it has extraordinarily useful properties for other applications, is a great drain in the operation of machines for particle physics. It increases dramatically as the beam energy rises and a machine like LEP would be extremely expensive to operate much above 100 GeV per beam.



frontiers | Frontiers in Physics

ORIGINAL RESEARCH
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Future Circular Collider: Integrated Programme and Feasibility Study

Michael Benedikt and Frank Zimmermann*

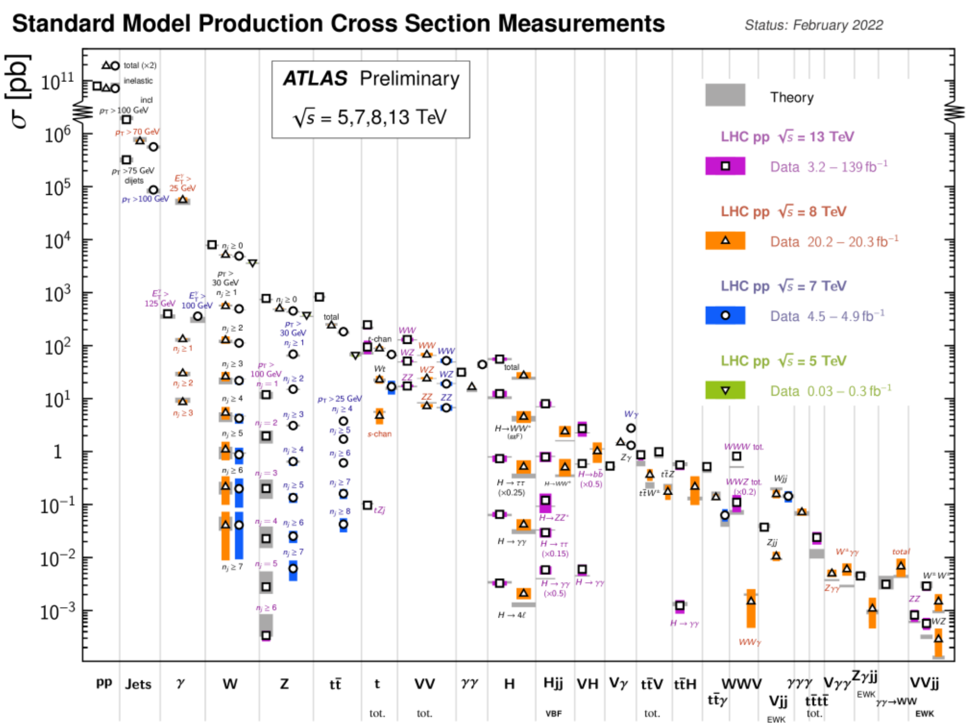
CERN, Geneva, Switzerland

The Future Circular Collider (FCC) Integrated Project foresees, in a first stage, a high-luminosity high-energy electron-positron collider, serving as Higgs, top and electroweak factory, and, in a second stage, an energy frontier hadron collider, with a centre-of-mass energy of at least 100 TeV. This programme well matches the highest priority future requests issued by the 2020 Update of the European Strategy for Particle Physics. In 2021, with the support of the CERN Council, a five-year FCC Feasibility Study was launched. In this article, we present the FCC integrated project and the preparations for the FCC Feasibility Study.

… but in either case…

Summary

- Electroweak measurements provide a powerful way to explore nature
- m_W measurements is certainly one of the largest excitements of the decade in HEP
- LHC entered precision race with LEP measuring electroweak observables
- Reach spectrum of single- and multiple electroweak boson production measurements at LHC:
  - ➢ Single W, Z -> electroweak parameters, PDF, α_S
  - ➢ Diboson -> NNLO QCD, polarized diboson final states, aTGC limits
  - ➢ Electroweak single & double V production; triboson -> aTGC and aQGC limits
- EFT interpretation is a compelling method for model-independent searches of New Physics



HL-LHC will extend the vertical axis range of this plot by two orders of magnitude

Improved statistics of weak boson production

\+

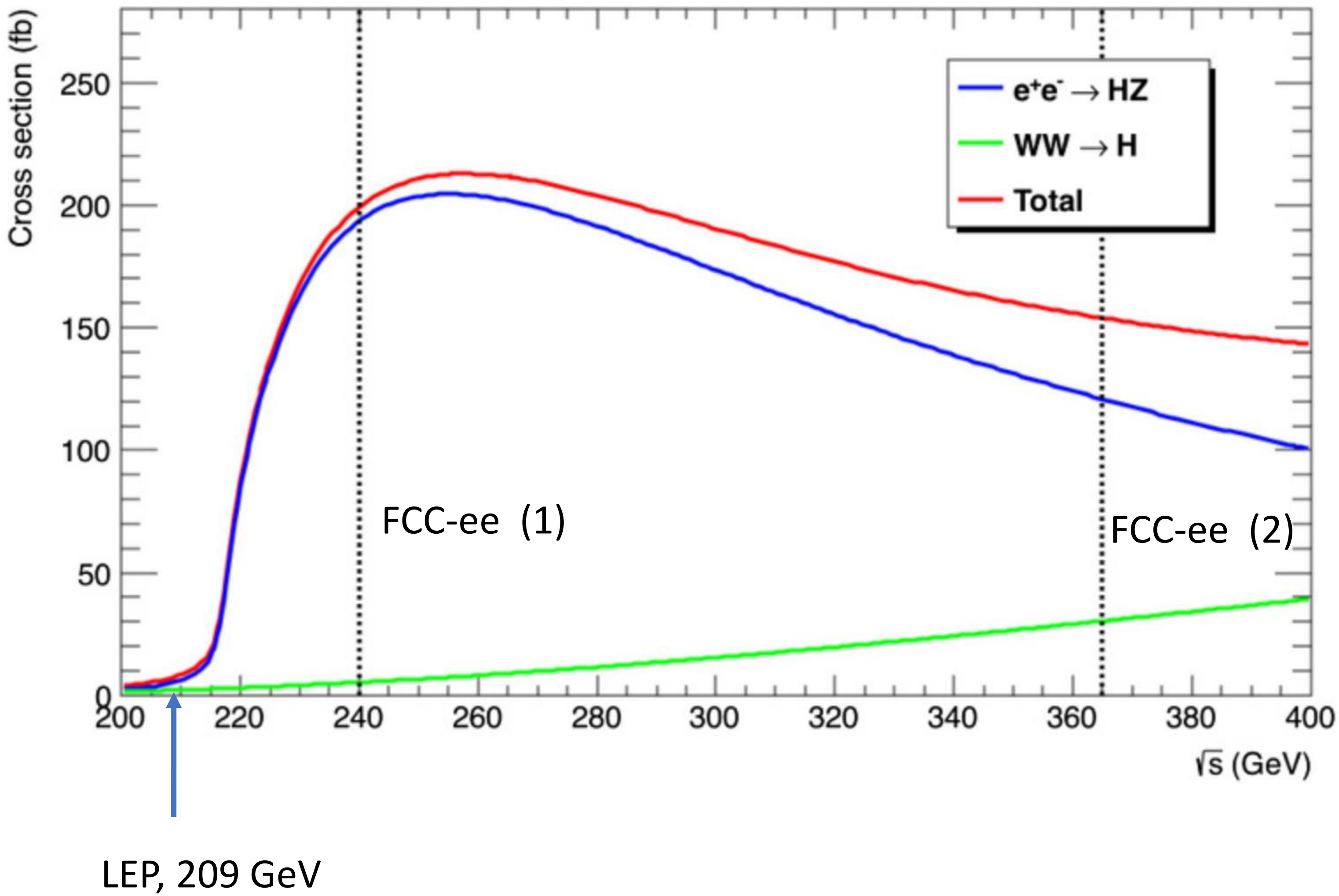
New rare processes within reach

=

New knowledge

Backup

FCC-ee



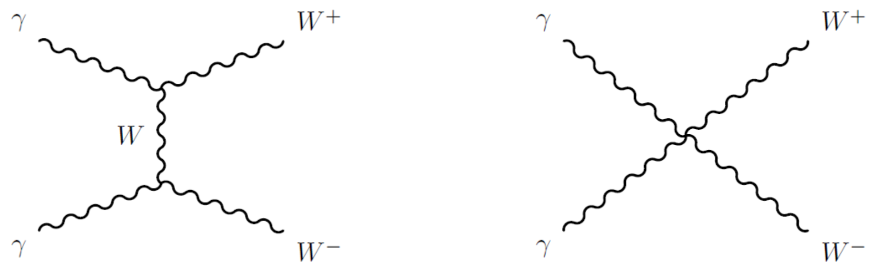
Cross section (fb)
250
200
150
100
50
0
200
220
240
260
280
300
320
340
360
380
400
√s (GeV)
e+e- → HZ
WW → H
Total
FCC-ee (1)
FCC-ee (2)
LEP, 209 GeV

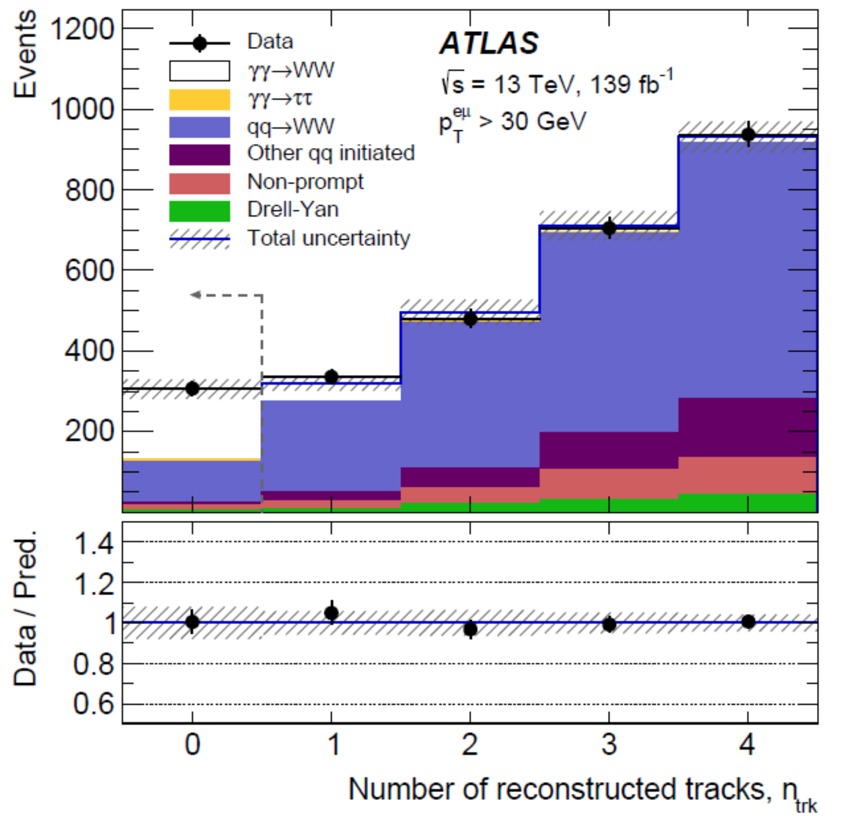
Observation of γγ→WW

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





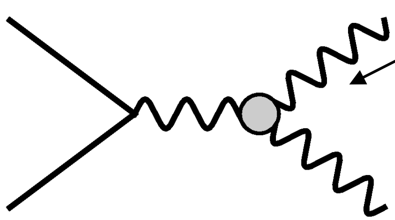
Electroweak parameters

- 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

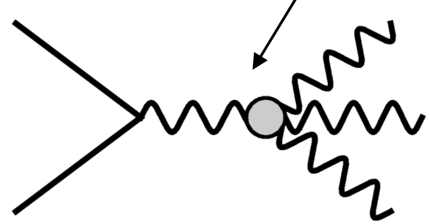
$$L_{\text{EFT}} = L_{\text{SM}} + \sum_i \frac{\bar{C}_i^{(6)}}{\Lambda^2}\mathcal{O}_i^{(6)} + \sum_i \frac{\bar{C}_i^{(8)}}{\Lambda^4}\mathcal{O}_i^{(8)} + \dots$$

    - 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?
…



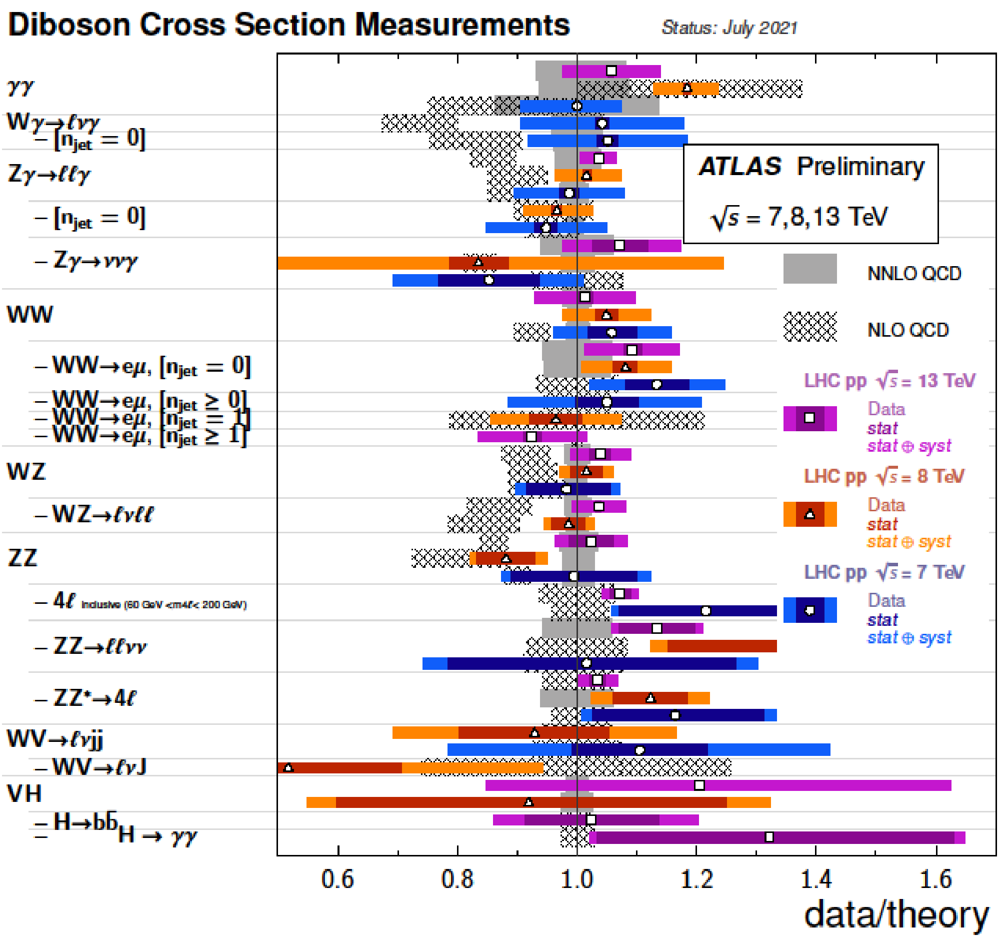
Dibosons



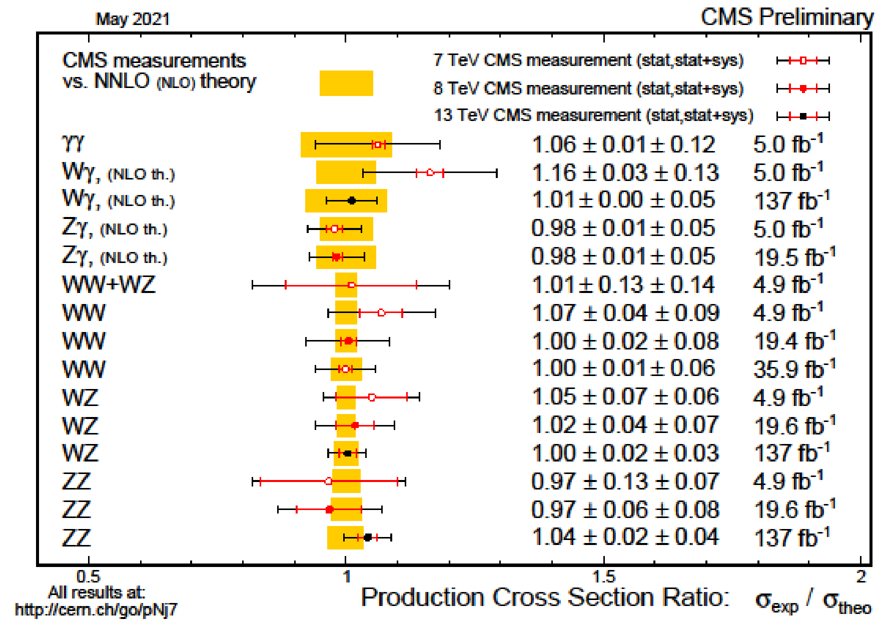
Tribosons

Diboson measurements overview

ATL-PHYS-PUB-2021-032



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



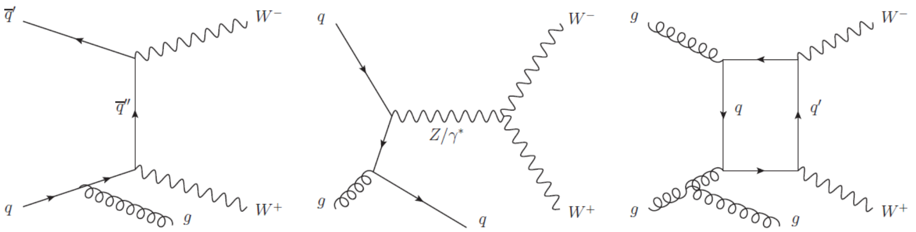
- Remarkable agreement between measured diboson cross sections and NNLO QCD predictions

WW + ≥1 jet

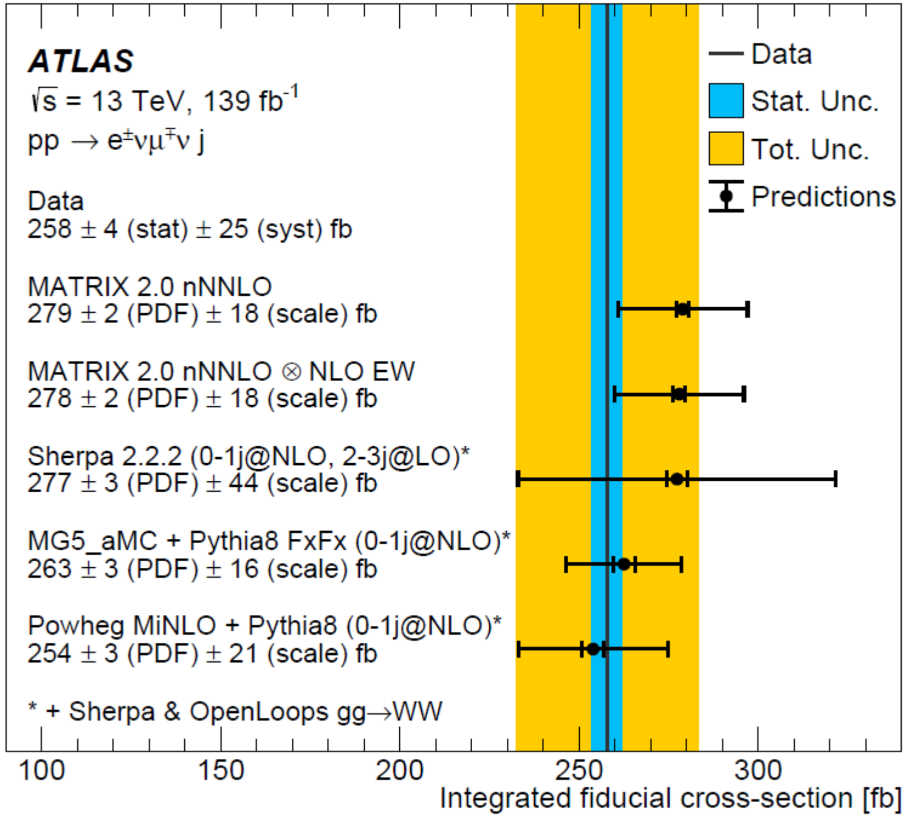
JHEP 06 (2021) 003

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

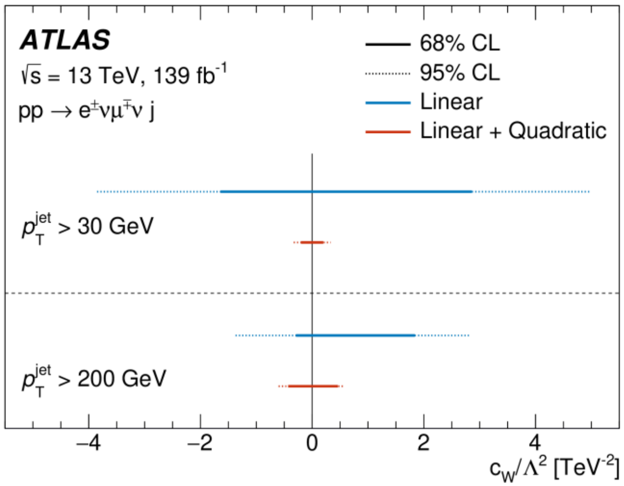


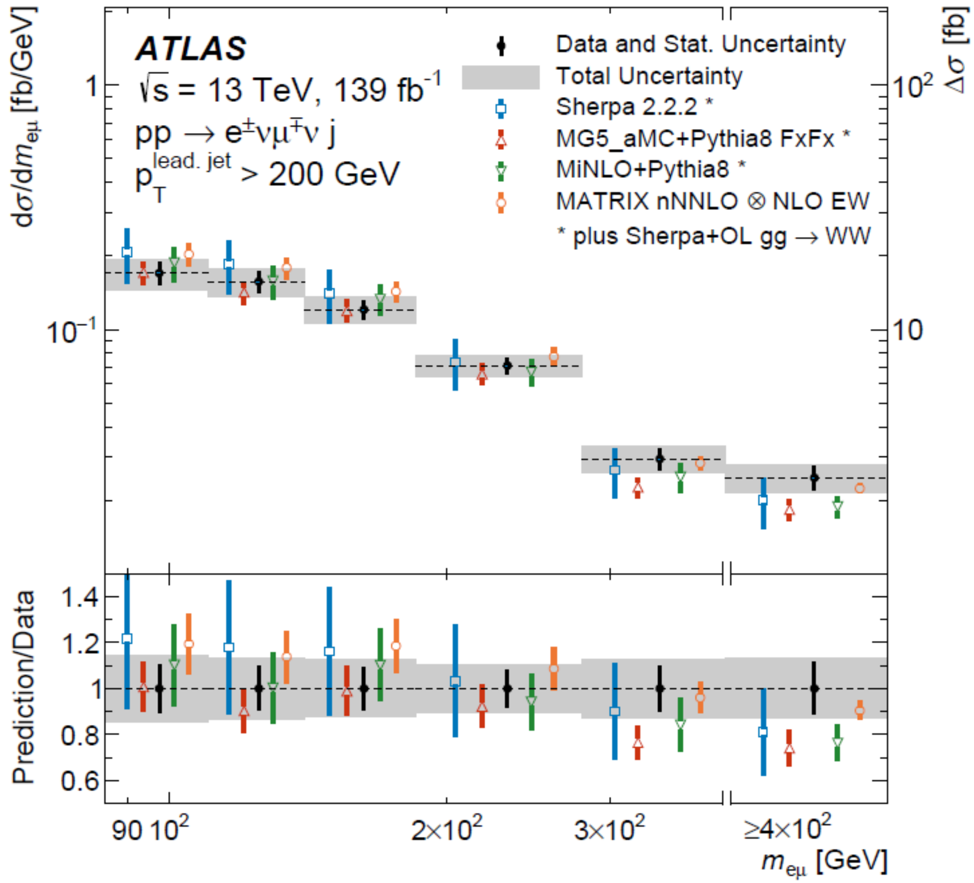
WW + ≥1 jet

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:



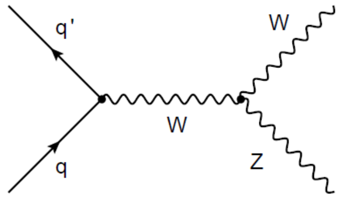


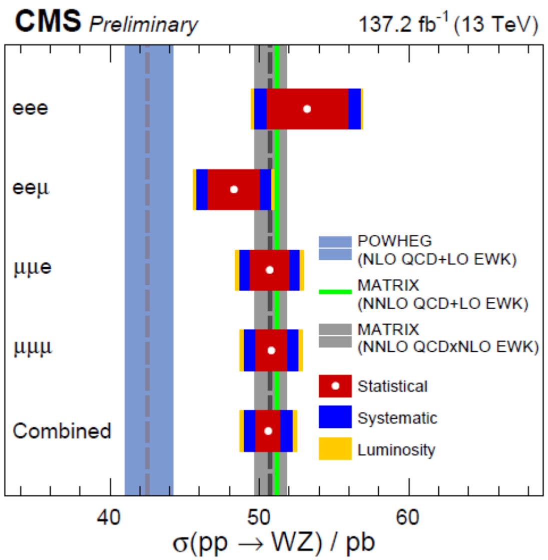
Inclusive WZ measurement

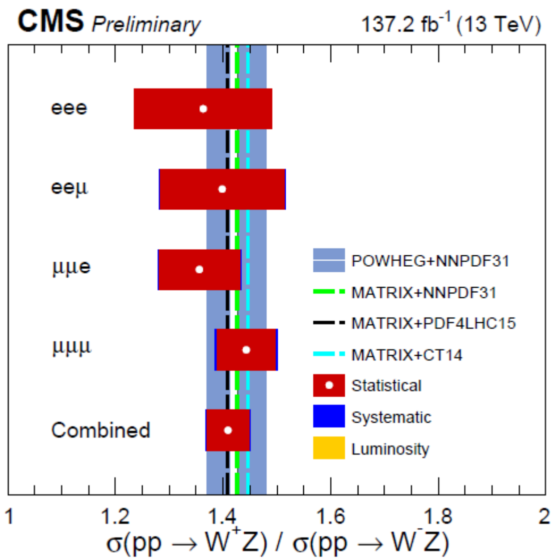
CMS-PAS-SMP-20-014

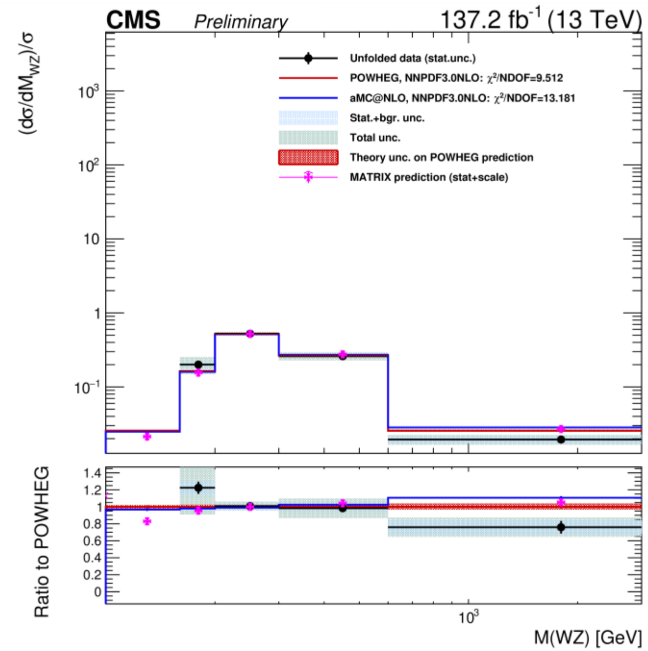
CMS, 13 TeV, 137 fb^{-1}

- 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

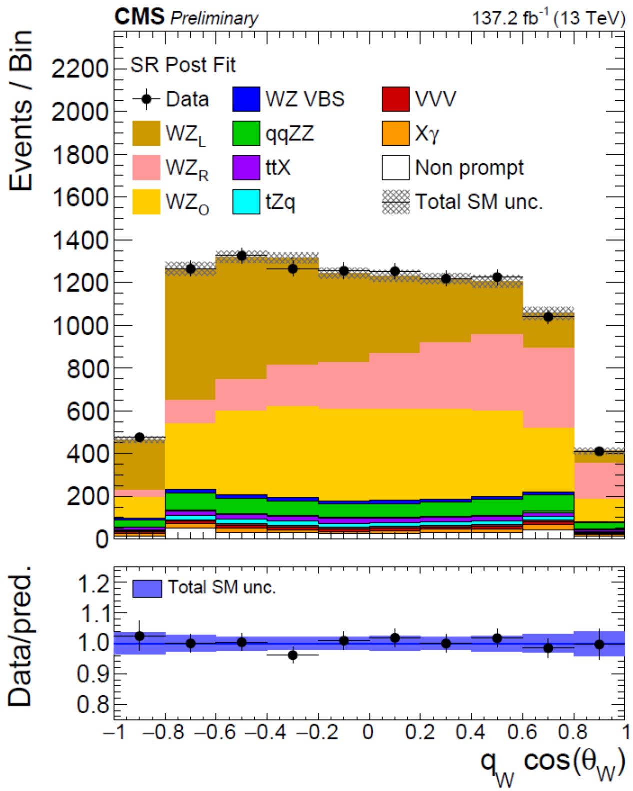
Inclusive WZ measurement

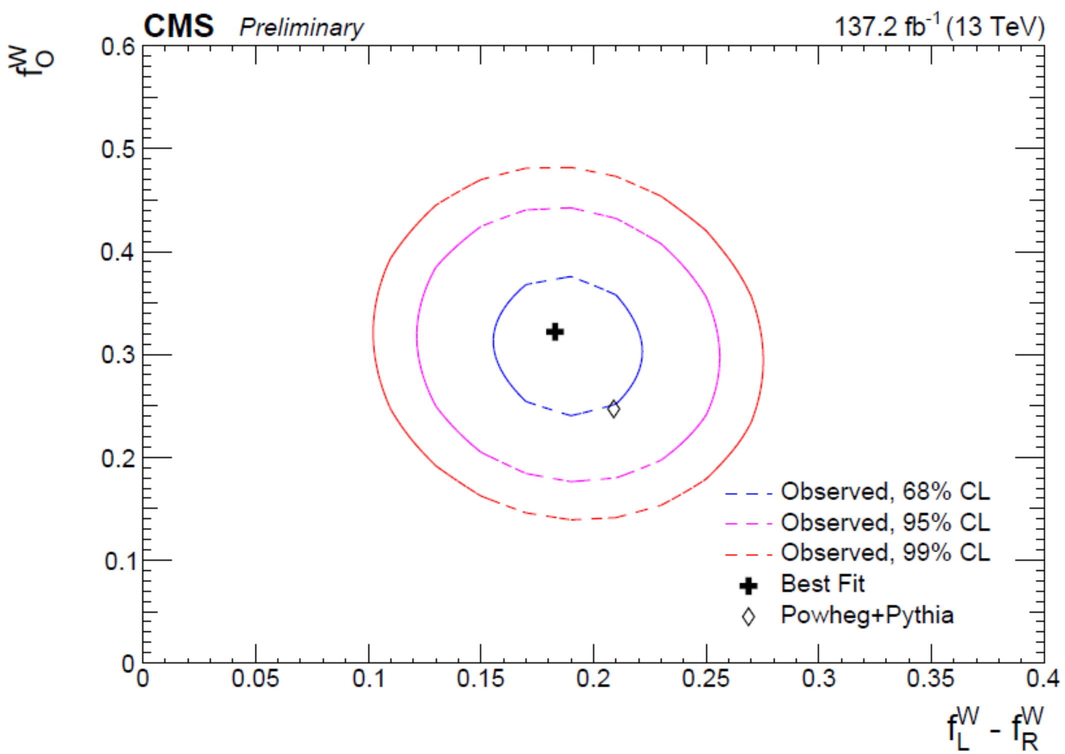
CMS-PAS-SMP-20-014
CMS, 13 TeV, 137 fb^{-1}

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

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

$$f_L + f_R + f_0 = 1$$





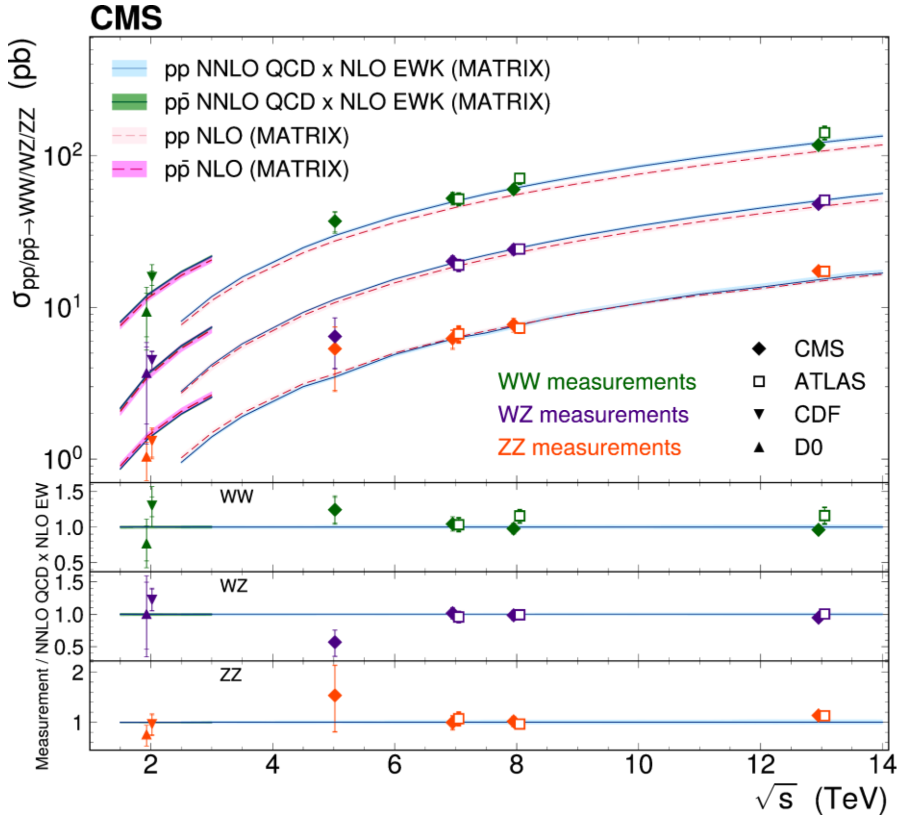
WW, WZ and ZZ at 5 TeV

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

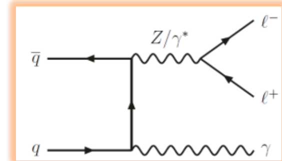


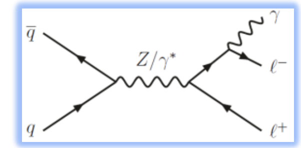
Zγ

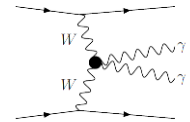
[JHEP 03 (2020) 054](https://doi.org/10.1007/JHEP03(2020)054)

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

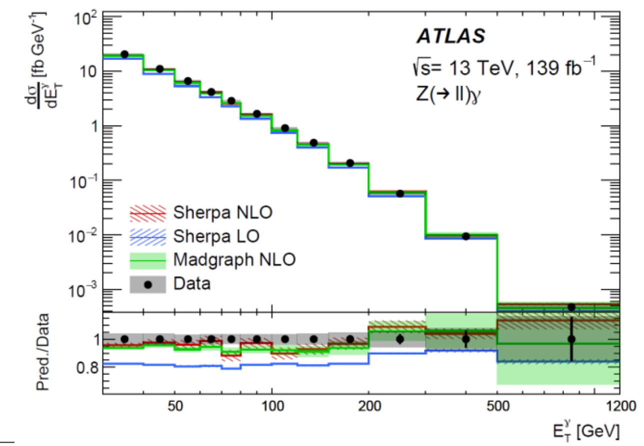
- $e^+e^-\gamma$, $\mu^+\mu^-\gamma$
- No VZγ TGC in SM -> LO diagrams are ISR and FSR
  - Small contribution from VBS at higher EW orders
- Pileup photon background estimated using converted photons
- Integrated and differential cross sections compared to a number of MC and fixed-order predictions
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

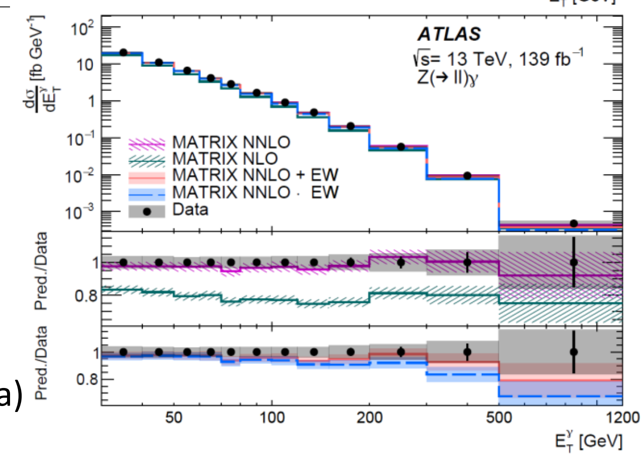






Condition $m(ll) + m(ll\gamma) > 182$ GeV applied to suppress FSR



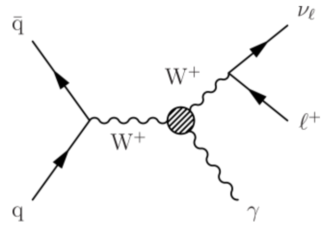


2.9% precision!

$\ell^+\ell^-\gamma$	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)

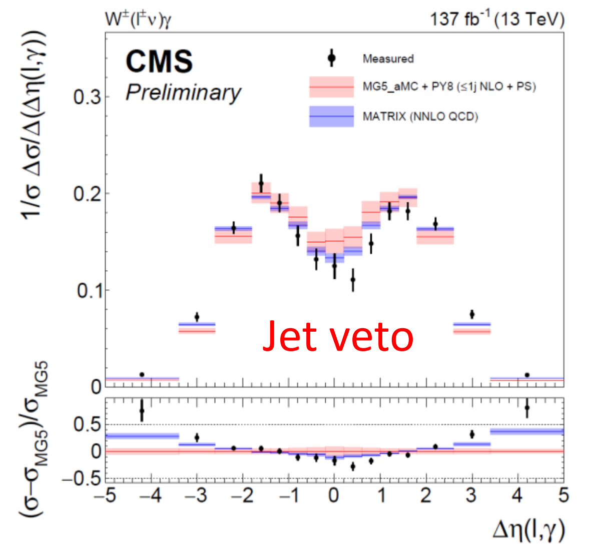
Wγ



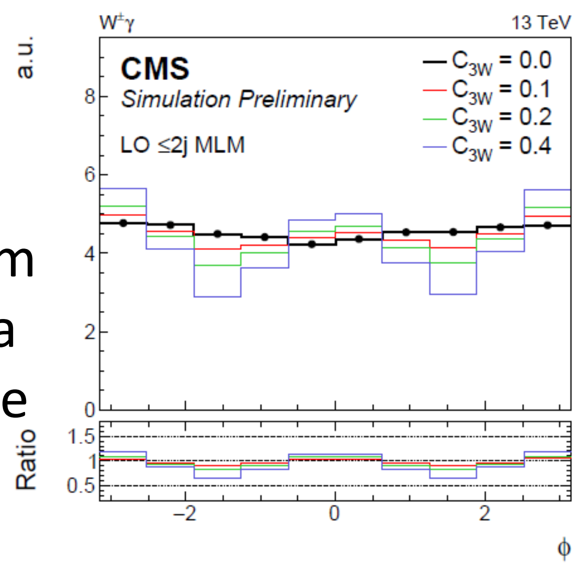
CMS-PAS-SMP-20-005

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

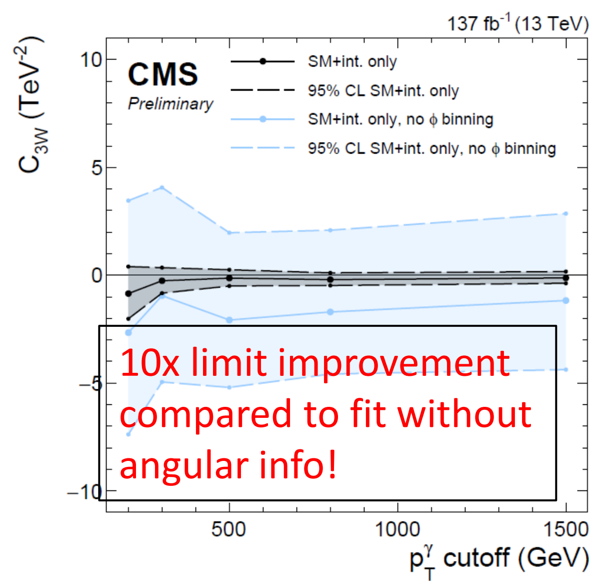
- Probes WWγ vertex
- Cross section at $\Delta\eta(l,\gamma) = 0$ at LO vanishes due to interference -> "radiation valley"
  - ➢ BSM processes could make the minimum less pronounced
  - ➢ SM NNLO QCD describes the shape well



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



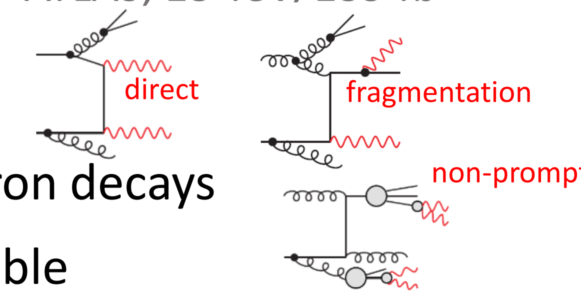
- SM-EFT interference term resurrected by going to a Wγ centre-of-mass frame and including angular information in the fit



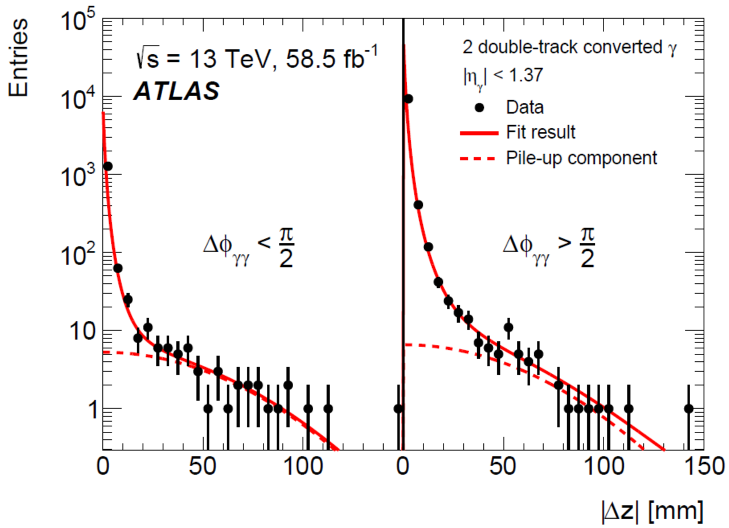
γγ

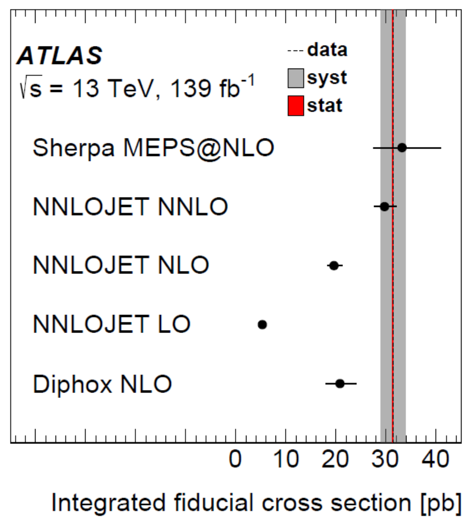
[STDM-2017-30](#) Submitted to JHEP

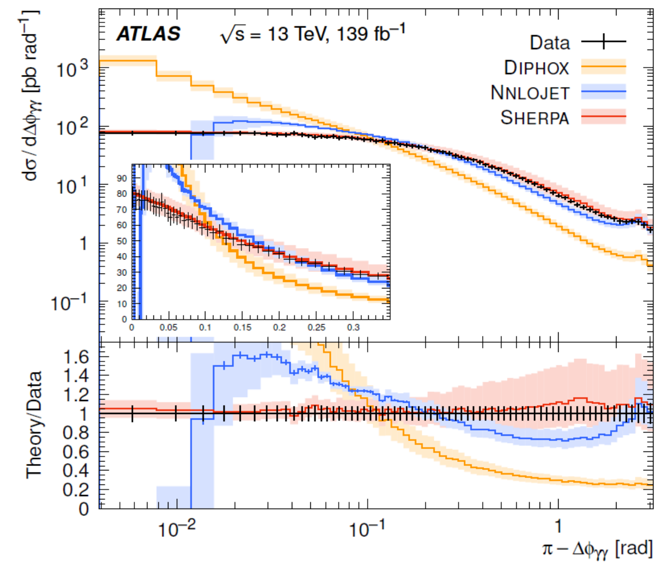
ATLAS, 13 TeV, 139 fb^{-1}



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



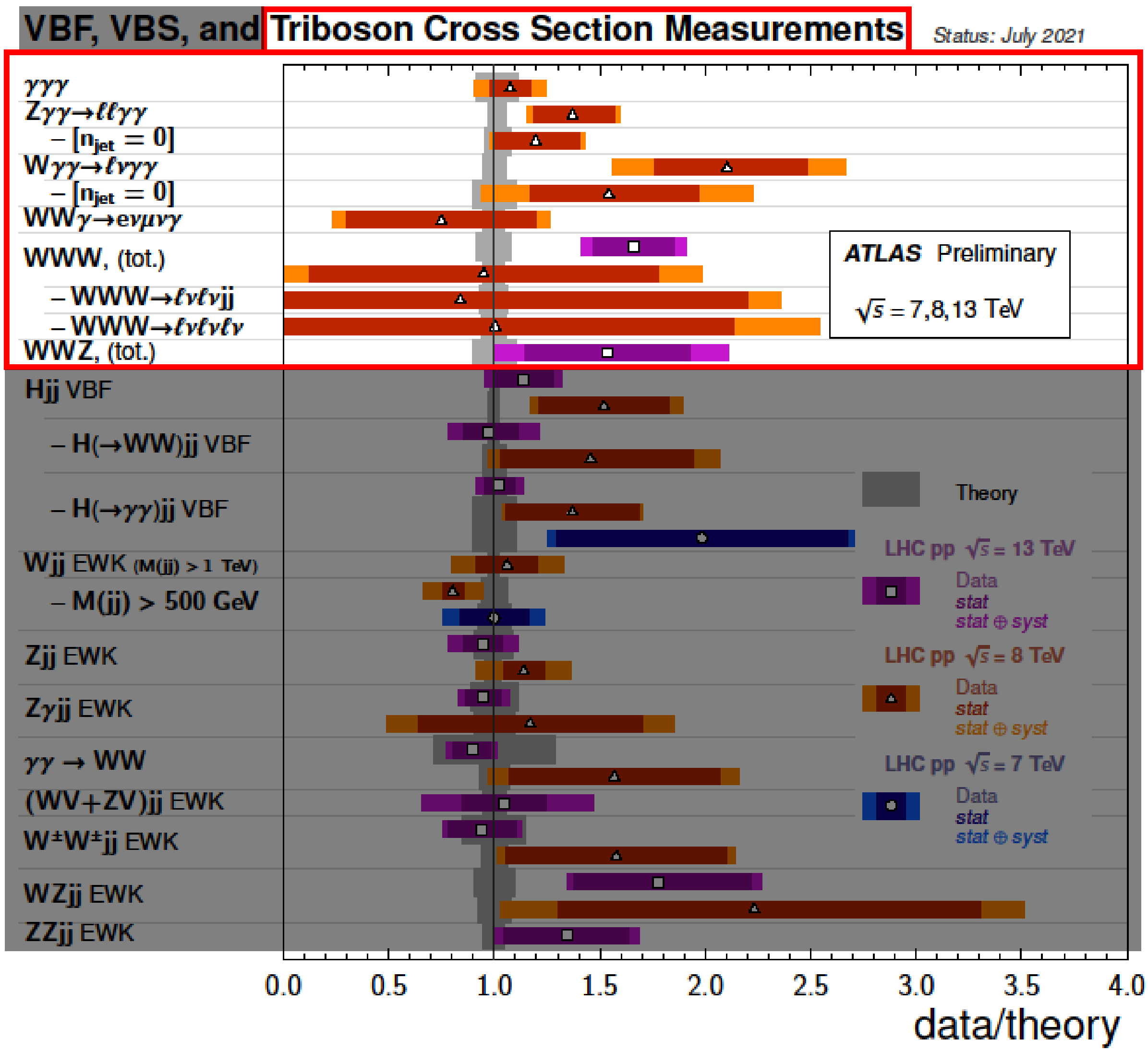




- Integrated cross section described well by Sherpa NLO and NNLOJET NNLO
  - ➢ LO and NNLO results differ by a factor of 6!
- Differential cross sections described best by Sherpa
  - ➢ Fixed-order predictions fail when the photons are back-to-back -> region sensitive to resummation effects

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

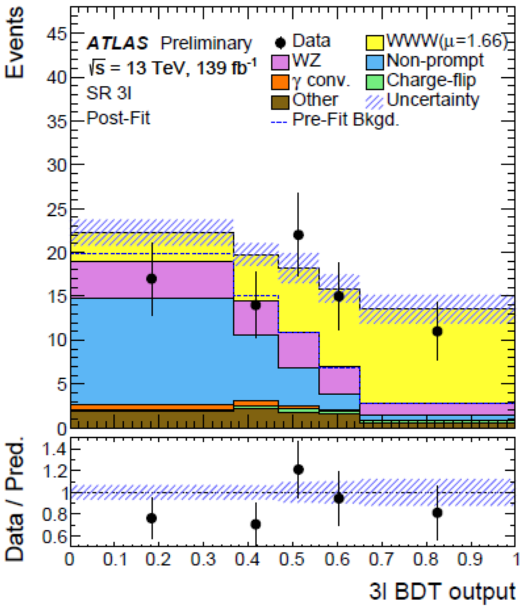
ATLAS, 13 TeV, 139 fb^{-1}

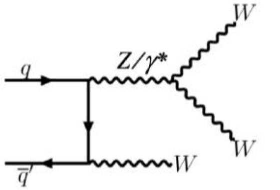
- $l^{\pm}\nu l^{\pm}\nu jj$ and $l^{\pm}\nu l^{\pm}\nu l^{\mp}\nu$
  - ➢ No same-flavour opposite-sign leptons
- Signal from the fit of the BDT score distribution
- Measured cross section

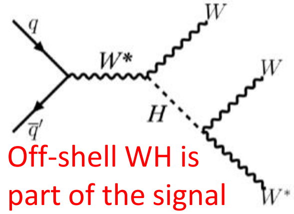
$$\sigma(pp \to WWW) = 850 \pm 100\,(\text{stat.}) \pm 80\,(\text{syst.})\ \text{fb}$$

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

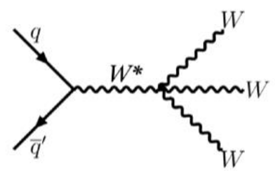
505 fb (uncertainty up to 6% or ~30 fb)







Off-shell WH is part of the signal



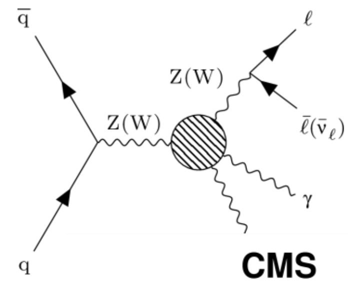
Uncertainty source	$\Delta\sigma/\sigma$ [%]
Data-driven background	5.3
Prompt-lepton-background modeling	3.3
Jets and E_T^{miss}	2.8
MC statistics	2.8
Lepton	2.1
Luminosity	1.9
Signal modeling	1.5
Pile-up modeling	0.9
Total systematic uncertainty	9.5
Data statistics	11.2
WZ normalizations	3.3
Total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

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**

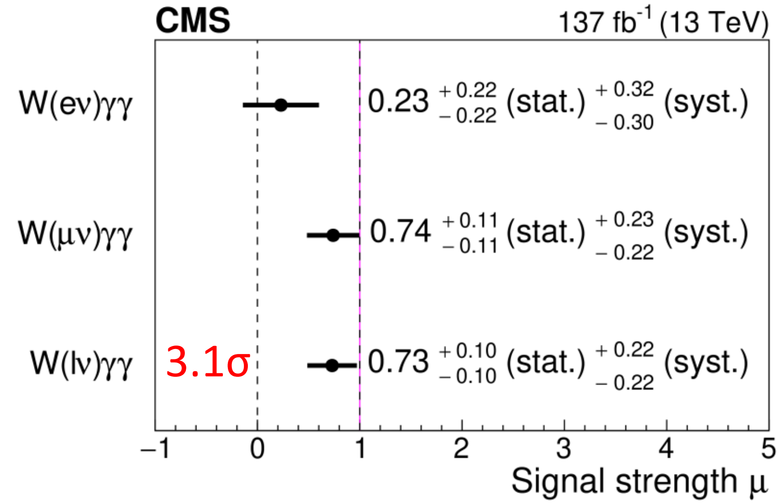
Observation of Vγγ

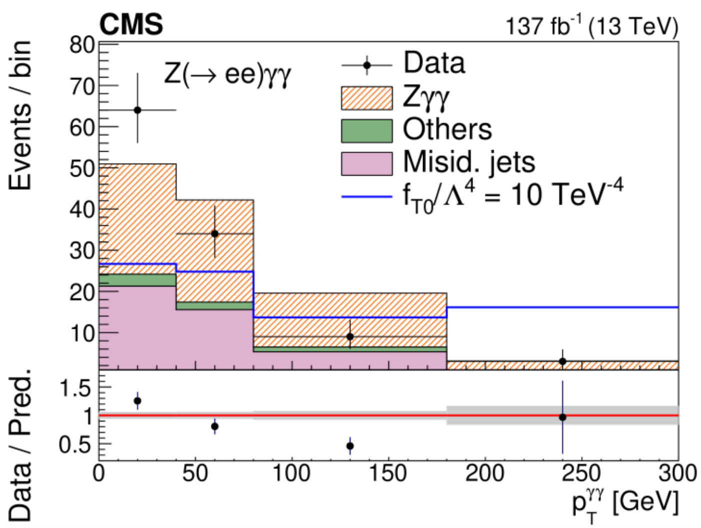
[SMP-19-013](SMP-19-013) Accepted by JHEP

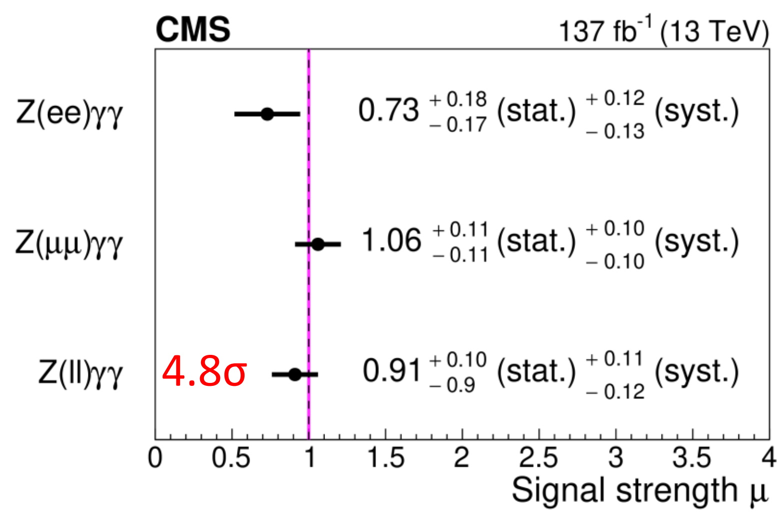
CMS, 13 TeV, 137 fb^{-1}



- 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







First Higgs mass prediction

CERN–TH. 5817/90

New bounds on m_t and first bounds on M_H from precision electroweak data

John Ellis and G. L. Fogli[†]

CERN, CH-1211 Geneva 23, Switzerland

Abstract

We present new results from a global analysis of all the electroweak data including precision measurements of the Z^0 mass and decays from LEP. Data from both low–energy and high–energy experiments indicate independently that the top quark mass $m_t \sim 100$ to 160 GeV. When combined they give

$$m_t = 127 \begin{array}{c} +24 \\ -30 \end{array} \text{ GeV},$$

for the Higgs mass $M_H = M_Z$. For the first time, the data also give non–trivial bounds on M_H: independently of m_t

$$1.8 \text{ GeV} < M_H < 6 \text{ TeV} \qquad (68\% \text{ C.L.}),$$

with the preferred value of M_H being below M_Z. Furthermore, if the top quark were found below the above central value, the data would provide a stronger upper bound:

$$\ln\left(\frac{M_H}{M_Z}\right) < 3.97 - 8.90\left(\frac{m_t}{M_Z}\right) + 5.56\left(\frac{m_t}{M_Z}\right)^2 \qquad (68\% \text{ C.L.}),$$

which gives $M_H < 600$ GeV for $m_t \leq 120$ GeV.

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

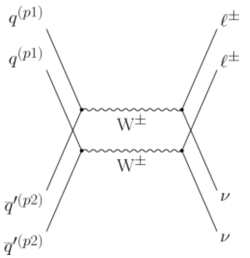
Final state	Experiment	EFT dim	Operators / coefficients	Variable	Interference resurrection	Unitarization / EFT validity
Wγ	CMS	6, int, int + pure	C_{3W} (WWγ) in Warsaw basis	Unfolded p_{T}^{γ}, $\lvert\varphi_f\rvert$	Angular info in Wγ CoM frame	Upper cut on p_{T}^{γ}
WW + ≥1 jet	ATLAS	6, int, int + 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	-	-

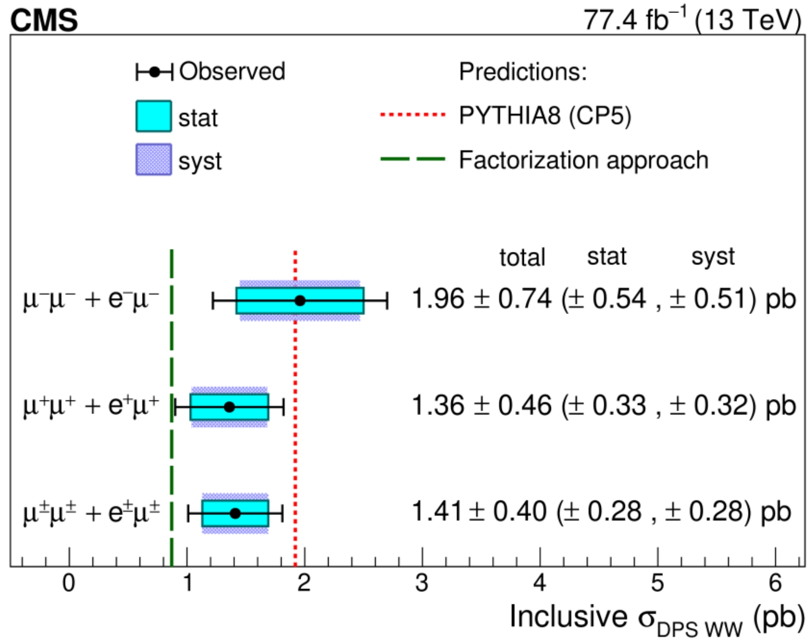
WW in DPS

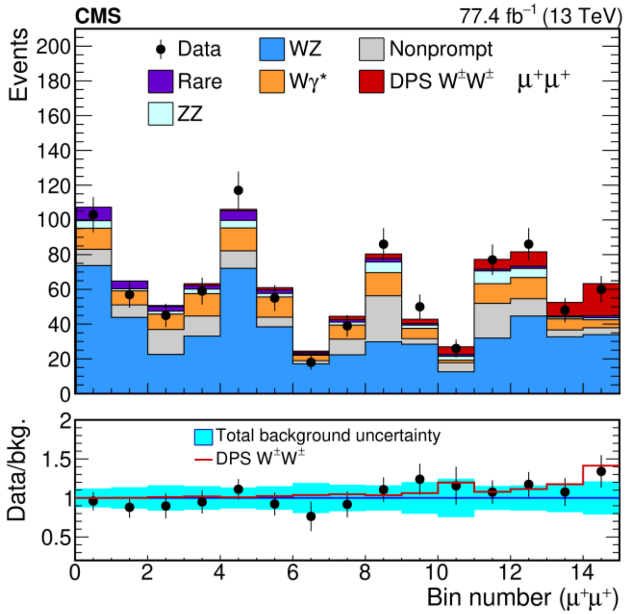
[Eur. Phys. J. C 80 (2020) 41]

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





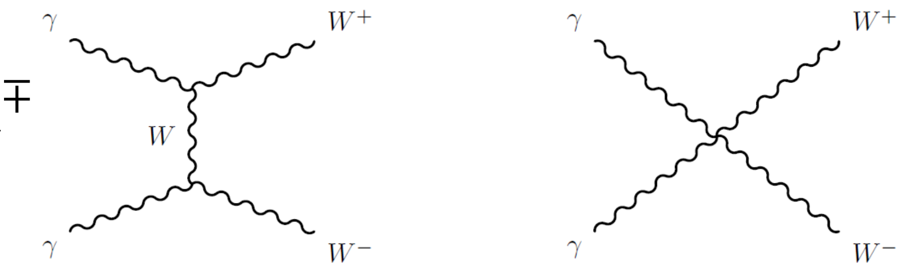


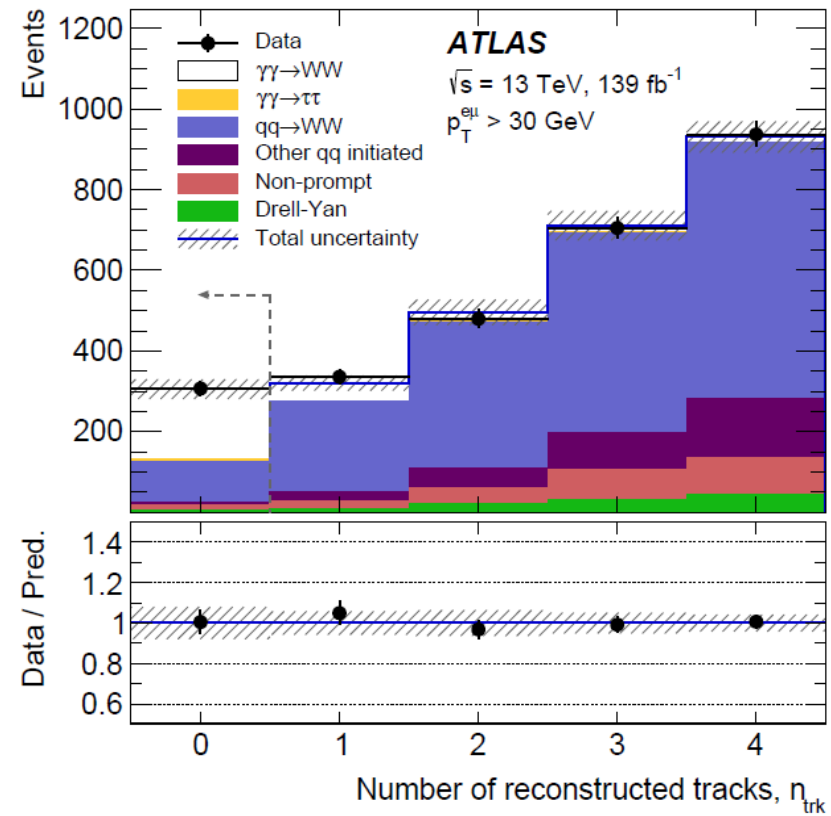
Observation of γγ→WW

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

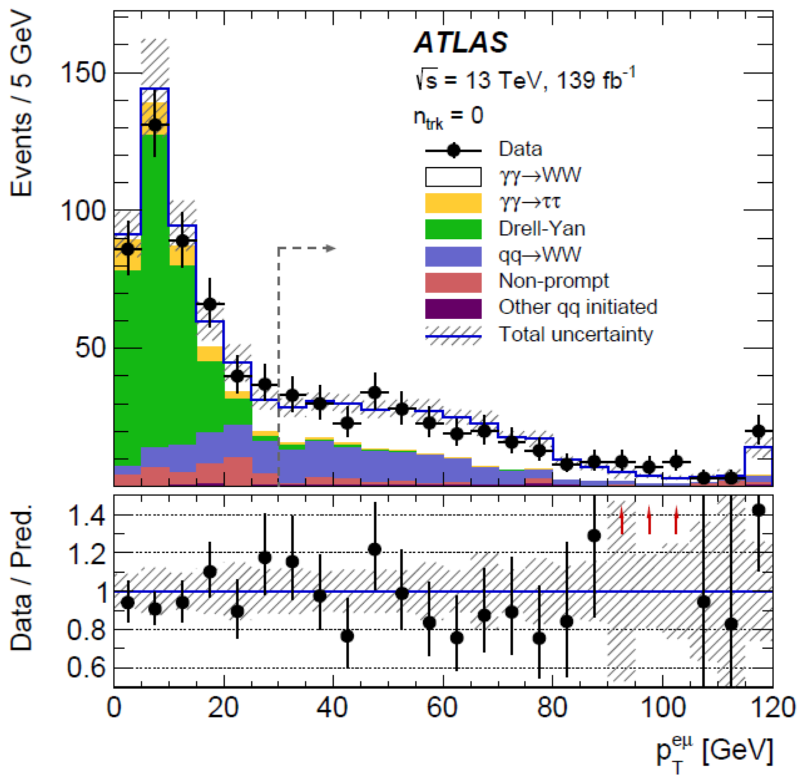
ATLAS, 13 TeV, 139 fb^{-1}

- 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



Where do we stand

Quantity/process	LHC expected	Achieved
syst. unc. of mW, MeV	10	15
stat. unc. of sinTheta	0.00015	0.00021
syst. unc. of sinTheta	0.00024	0.00024

Inputs to EW fits

Parameter	Input value	Free in fit	Results from global EW fits: *Standard fit*	*Complete fit*	*Complete fit w/o exp. input in line*
M_Z [GeV]	91.1875 ± 0.0021	yes	91.1874 ± 0.0021	91.1877 ± 0.0021	$91.2001^{+0.0174}_{-0.0178}$
Γ_Z [GeV]	2.4952 ± 0.0023	–	2.4959 ± 0.0015	2.4955 ± 0.0015	2.4950 ± 0.0017
$\sigma^0_{\rm had}$ [nb]	41.540 ± 0.037	–	41.477 ± 0.014	41.477 ± 0.014	41.468 ± 0.015
R^0_ℓ	20.767 ± 0.025	–	20.743 ± 0.018	20.742 ± 0.018	$20.717^{+0.029}_{-0.025}$
$A^{0,\ell}_{\rm FB}$	0.0171 ± 0.0010	–	0.01638 ± 0.0002	0.01610 ± 0.9839	0.01616 ± 0.0002
A_ℓ $^{(\star)}$	0.1499 ± 0.0018	–	$0.1478^{+0.0011}_{-0.0010}$	$0.1471^{+0.0008}_{-0.0009}$	–
A_c	0.670 ± 0.027	–	$0.6682^{+0.00046}_{-0.00045}$	$0.6680^{+0.00032}_{-0.00046}$	$0.6680^{+0.00032}_{-0.00047}$
A_b	0.923 ± 0.020	–	$0.93470^{+0.00011}_{-0.00012}$	$0.93464^{+0.00008}_{-0.00013}$	$0.93464^{+0.00008}_{-0.00011}$
$A^{0,c}_{\rm FB}$	0.0707 ± 0.0035	–	0.0741 ± 0.0006	$0.0737^{+0.0004}_{-0.0005}$	$0.0737^{+0.0004}_{-0.0005}$
$A^{0,b}_{\rm FB}$	0.0992 ± 0.0016	–	0.1036 ± 0.0007	$0.1031^{+0.0007}_{-0.0006}$	0.1036 ± 0.0005
R^0_c	0.1721 ± 0.0030	–	0.17224 ± 0.00006	0.17224 ± 0.00006	0.17225 ± 0.00006
R^0_b	0.21629 ± 0.00066	–	$0.21581^{+0.00005}_{-0.00007}$	0.21580 ± 0.00006	0.21580 ± 0.00006
$\sin^2\theta^\ell_{\rm eff}(Q_{\rm FB})$	0.2324 ± 0.0012	–	0.23143 ± 0.00013	$0.23151^{+0.00012}_{-0.00010}$	$0.23149^{+0.00013}_{-0.00009}$
M_H [GeV] $^{(\circ)}$	Likelihood ratios	yes	$80^{+30[+75]}_{-23[-41]}$	$116.4^{+18.3[+28.4]}_{-1.3[-2.2]}$	$80^{+30[+75]}_{-23[-41]}$
M_W [GeV]	80.399 ± 0.025	–	$80.382^{+0.014}_{-0.016}$	80.364 ± 0.010	$80.359^{+0.010}_{-0.021}$
Γ_W [GeV]	2.098 ± 0.048	–	$2.092^{+0.001}_{-0.002}$	2.091 ± 0.001	$2.091^{+0.001}_{-0.002}$
$\overline{m}_c$ [GeV]	1.25 ± 0.09	yes	1.25 ± 0.09	1.25 ± 0.09	–
$\overline{m}_b$ [GeV]	4.20 ± 0.07	yes	4.20 ± 0.07	4.20 ± 0.07	–
m_t [GeV]	172.4 ± 1.2	yes	172.5 ± 1.2	172.9 ± 1.2	$178.2^{+9.8}_{-4.2}$
$\Delta\alpha^{(5)}_{\rm had}(M_Z^2)$ $^{(\dagger\triangle)}$	2768 ± 22	yes	2772 ± 22	2767^{+19}_{-24}	2722^{+62}_{-53}
$\alpha_s(M_Z^2)$	–	yes	$0.1192^{+0.0028}_{-0.0027}$	$0.1193^{+0.0028}_{-0.0027}$	$0.1193^{+0.0028}_{-0.0027}$
$\delta_{\rm th} M_W$ [MeV]	$[-4, 4]_{\rm theo}$	yes	4	4	–
$\delta_{\rm th}\sin^2\theta^\ell_{\rm eff}$ $^{(\dagger)}$	$[-4.7, 4.7]_{\rm theo}$	yes	4.7	−1.3	–
$\delta_{\rm th}\rho^f_Z$ $^{(\dagger)}$	$[-2, 2]_{\rm theo}$	yes	2	2	–
$\delta_{\rm th}\kappa^f_Z$ $^{(\dagger)}$	$[-2, 2]_{\rm theo}$	yes	2	2	–

$^{(\star)}$Average of LEP ($A_\ell = 0.1465 \pm 0.0033$) and SLD ($A_\ell = 0.1513 \pm 0.0021$) measurements. The *complete fit* w/o the LEP (SLD) measurement gives $A_\ell = 0.1472^{+0.0008}_{-0.0011}$ ($A_\ell = 0.1463 \pm 0.0008$). $^{(\circ)}$In brackets the 2σ errors. $^{(\dagger)}$In units of 10^{-5}. $^{(\triangle)}$Rescaled due to α_s dependency.