Status of electroweak physics at the LHC

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On behalf of ATLAS, CMS, and LHCb

28th Rencontres de Blois
Particle Physics and Cosmology
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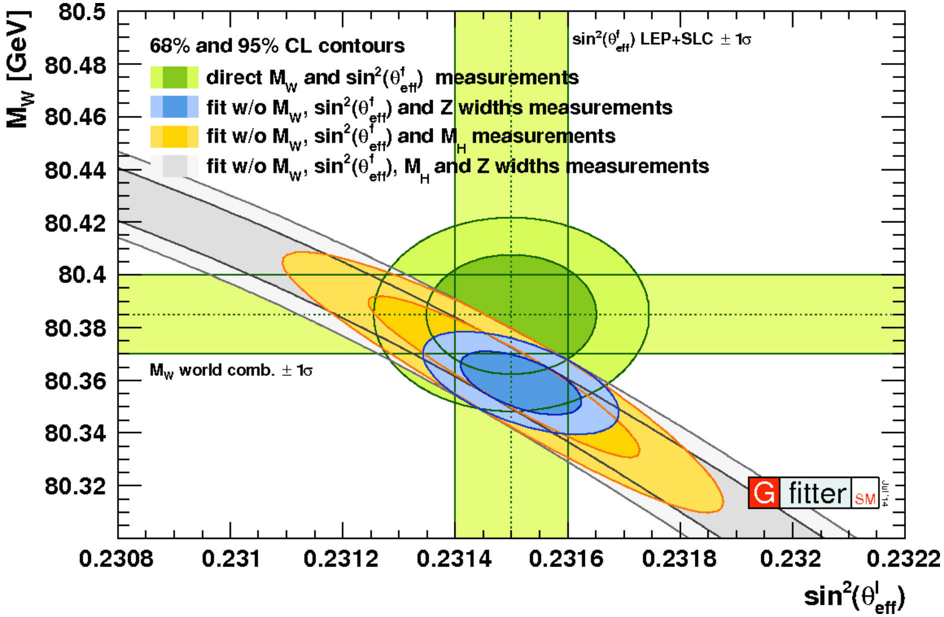
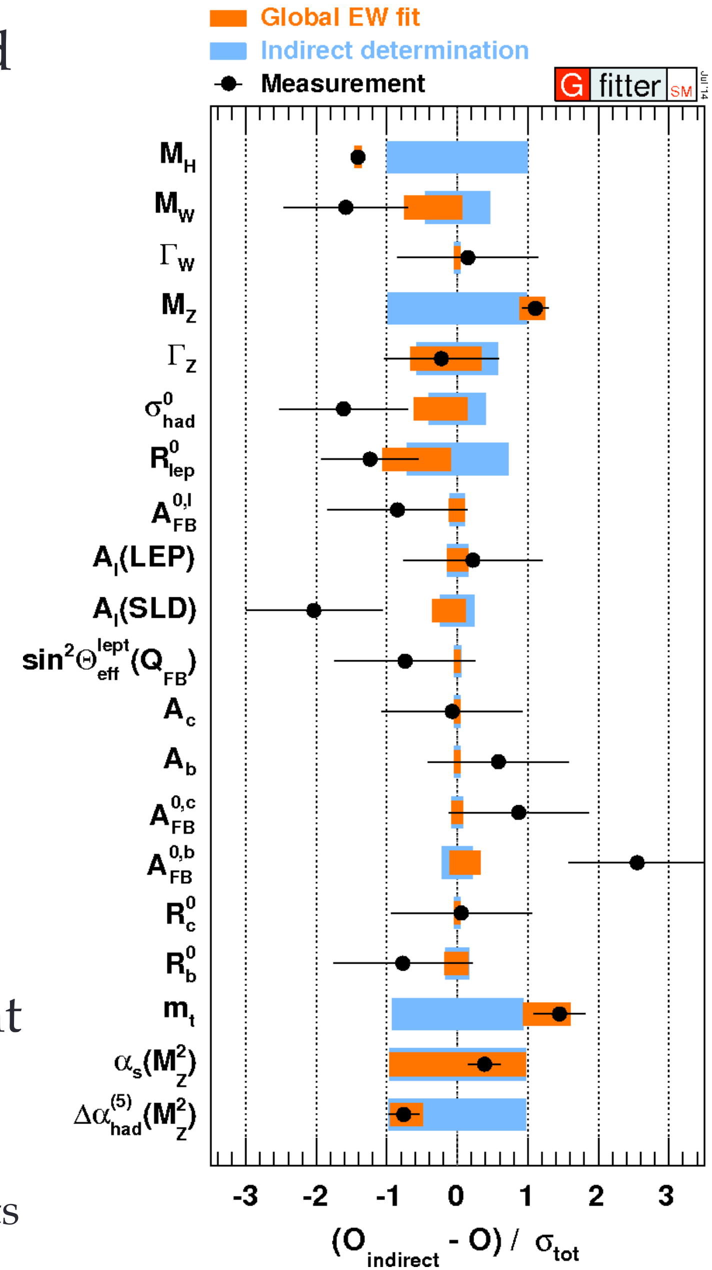
- Electroweak precision observables: M_W, $\sin^2\theta_{eff}$
- Multiboson production and gauge couplings

Global electroweak fit

- With Higgs mass, model is over-constrained
  - — precision EW measurements provide crucial consistency test for theory
  - — deviations can indicate new physics

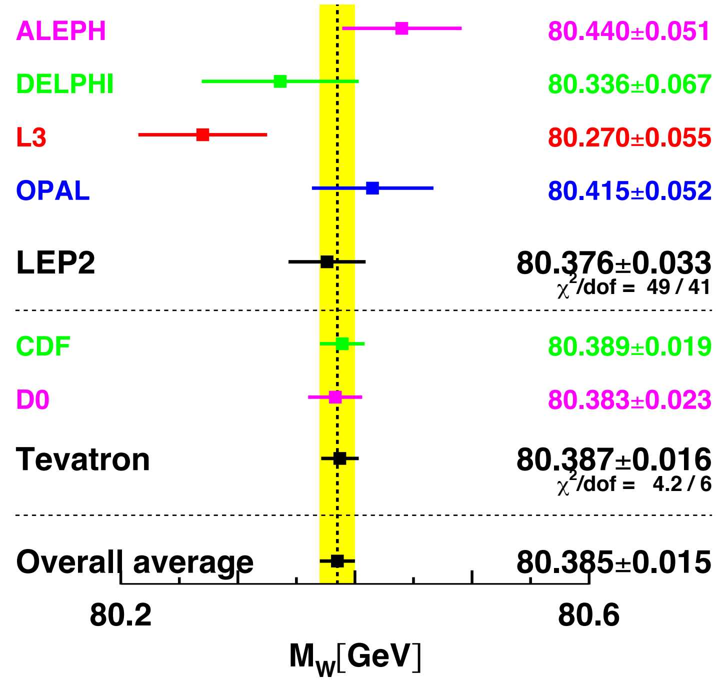


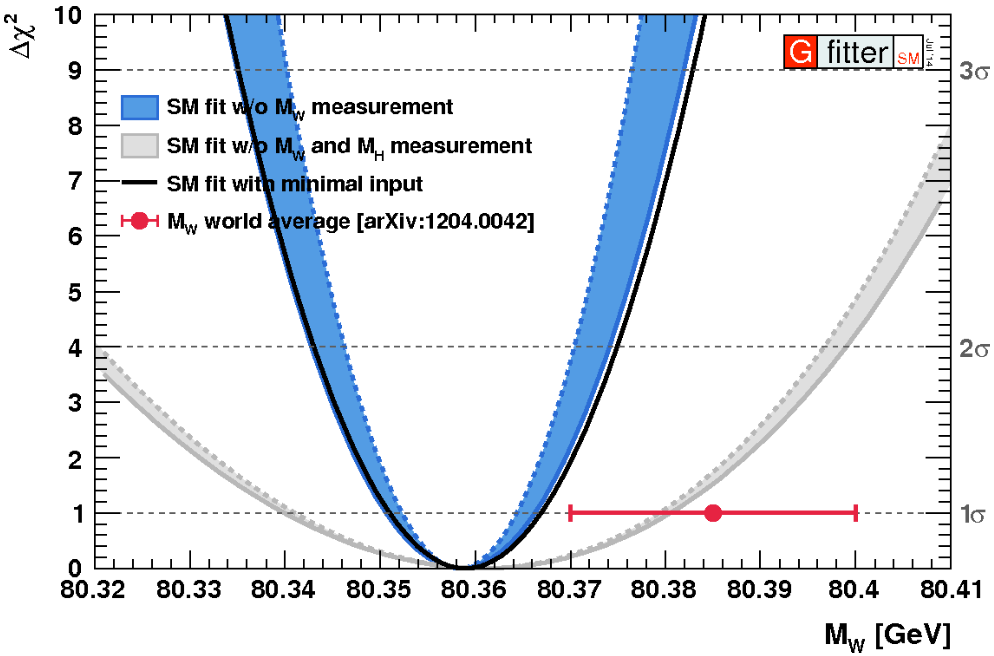


- Improved precision of direct m_W measurement and $\sin^2\theta_{eff}$ could probe BSM contributions
  - — improved precision for $\sin^2\theta_{eff}$ could also resolve discrepancy between two most precise LEP-SLD results

W mass

- M_W — a key EWK parameter
- World average of direct measurements: **80385 ± 15 MeV** precision dominated by CDF and D0
- Precise indirect determination from the SM fit: **80358 ± 8 MeV**

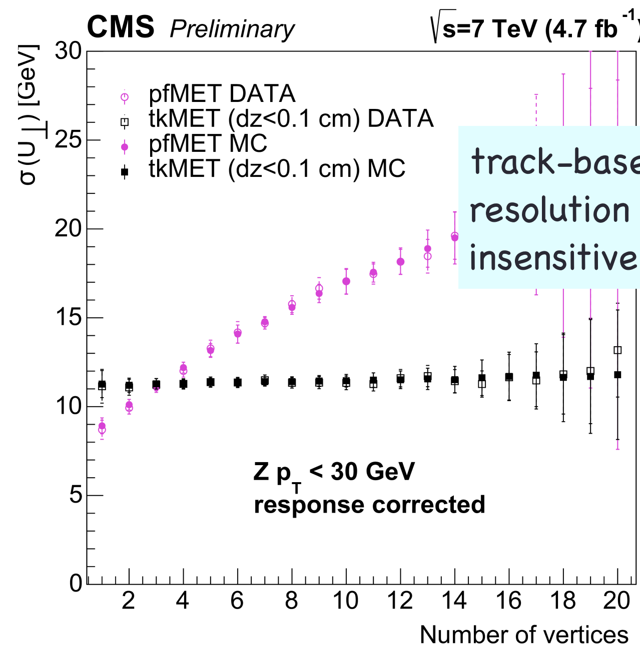




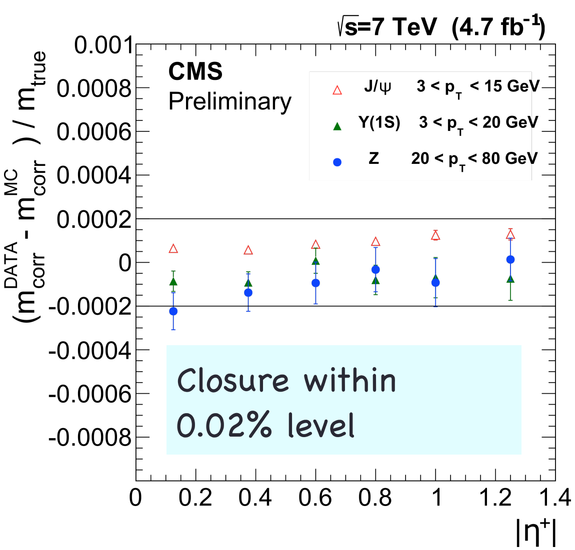
- Precise measurements of M_W at the LHC is crucial
- Ongoing effort by experiments in close cooperation with theory community

W mass at LHC

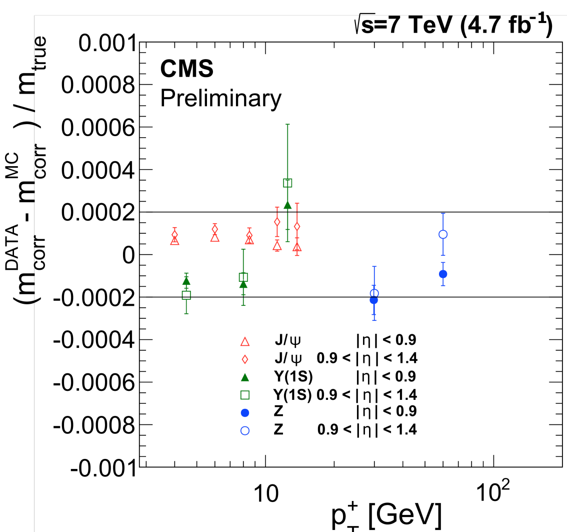
- Precision goal: ~O(10MeV)
- Measurement approach:
  - — template fit of lepton p_T, $\not{E}_T$ or m_T
  - — affected differently by experimental, PDF, and theory systematics
- Controlling all uncertainties to required level
  - — multi-step iterative process
  - — various precise measurements needed to improve modeling of W production and decay and constrain PDFs



track-based recoil resolution is insensitive to pileup



Closure within 0.02% level



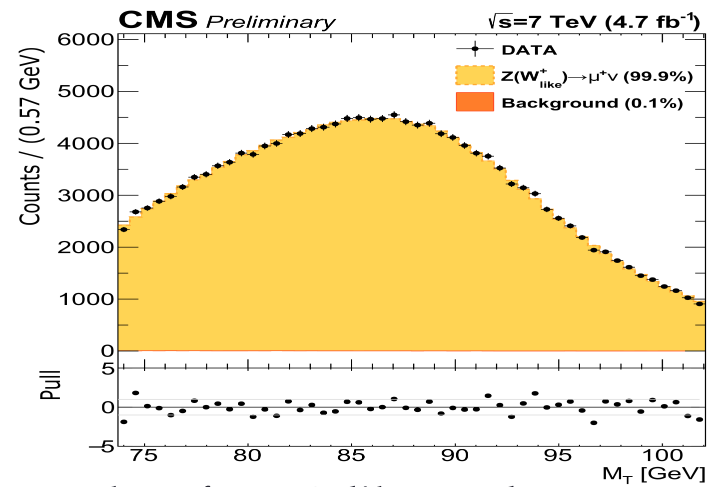
- A lot of progress made towards achieving required experimental precision
  - — track-based $\not{E}_T$
  - — lepton energy calibration

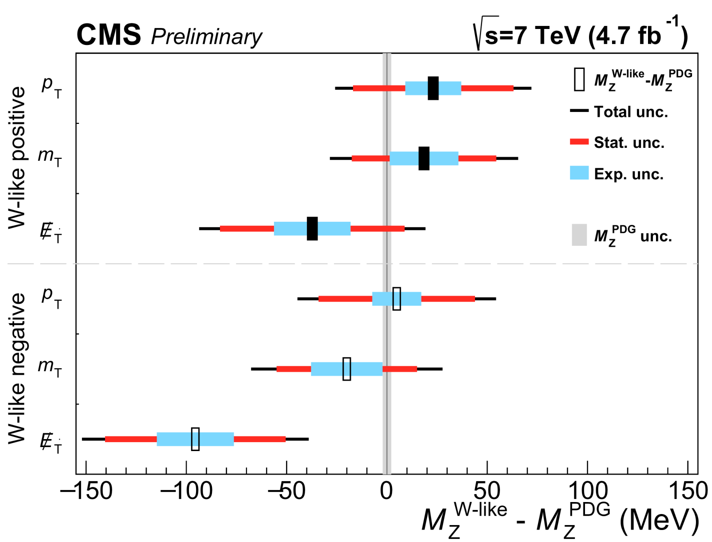
First milestone: W-like mass

CMS-SMP-14-007

- Measure mass of the Z boson using W-like setup — removed one lepton from event

- Important first step and quantitative assessment of common experimental uncertainties:
  - — lepton p_T and recoil scale and resolution





Indicative numbers from W-like results

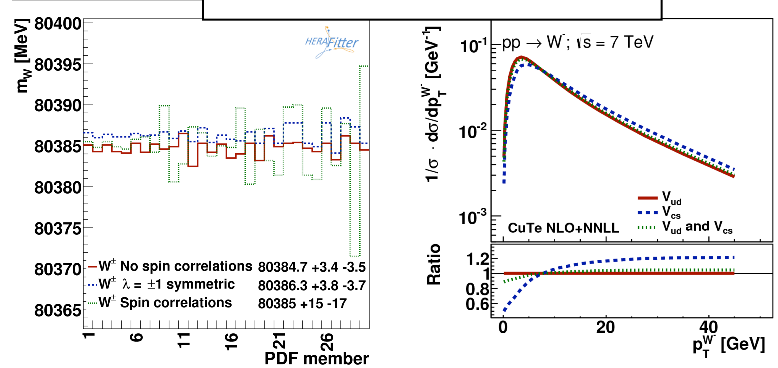
σ_{stat} ~ 40 MeV — not a problem with real W
σ_{exp} ~ 15 MeV — shall be improved
σ_{model} ~ 30 MeV — conservative EW radiation unc.

Number of additional sources for real W analysis, not considered in this test (polarization, boson p_T..), or specific to real *W* (backgrounds, Z → W ext.)

— physics modeling is expected to be main challenge in real W measurement

— comprehensive studies performed on various components of theory uncertainties →

ATL-PHYS-PUB-2014-015

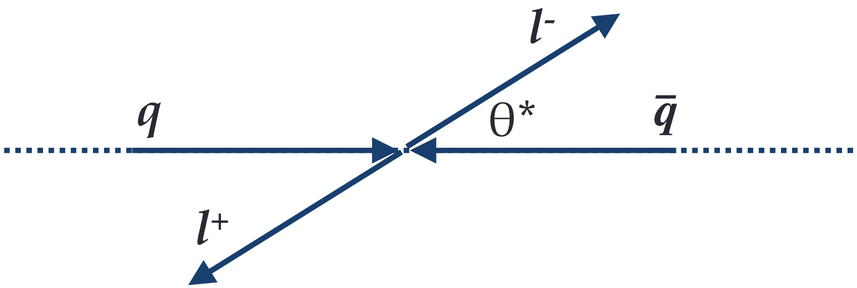


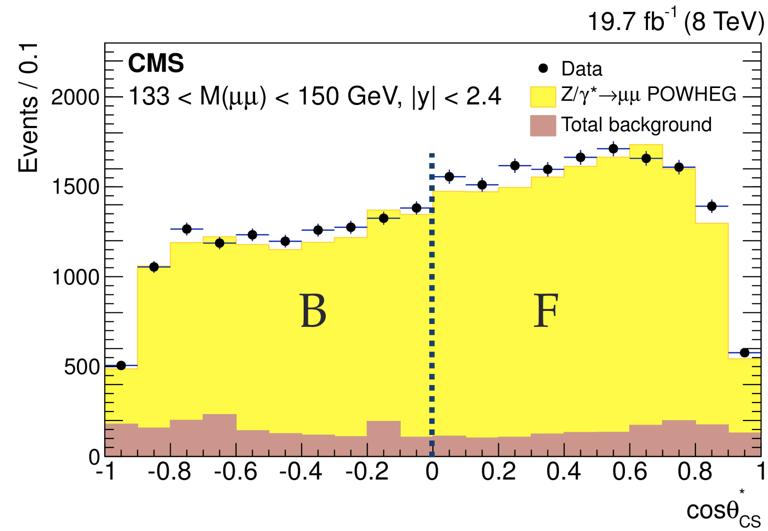
A_{FB} in pp collisions

arXiv:1601.4768

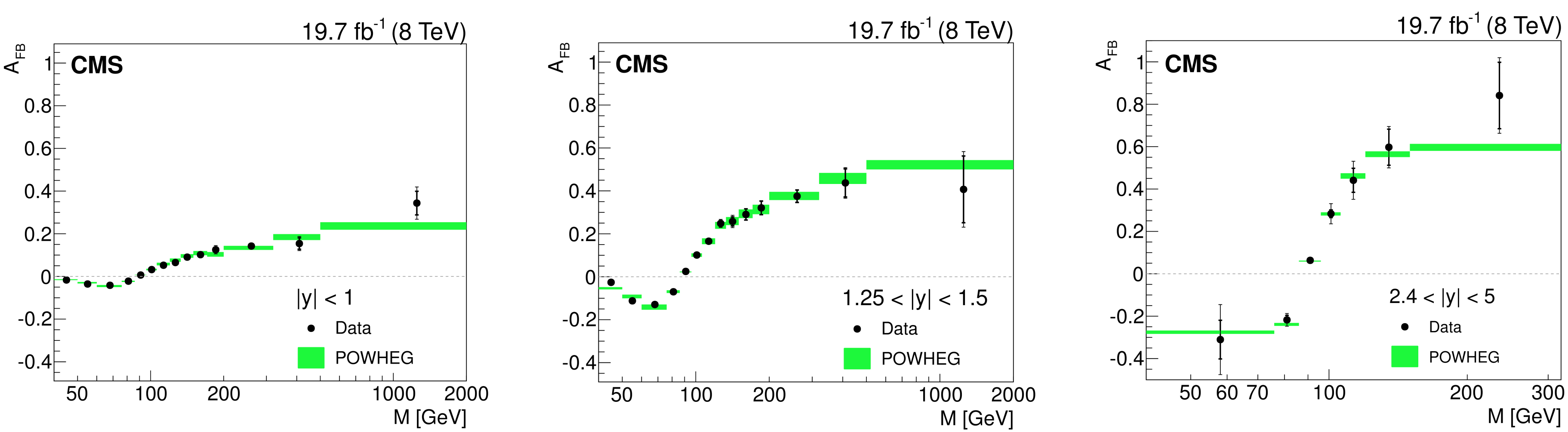
- Drell Yan dilepton events: $pp \to Z/\gamma^* \to l^+l^-$

  vector and axial vector couplings of Z/γ^* to fermions $\to$ $$A_{FB} = \frac{\sigma_F - \sigma_B}{\sigma_F + \sigma_B}$$





- In pp unknown incoming quark direction
  - — assumed in dilepton boost direction
  - — large y_{ll}-dependent dilution

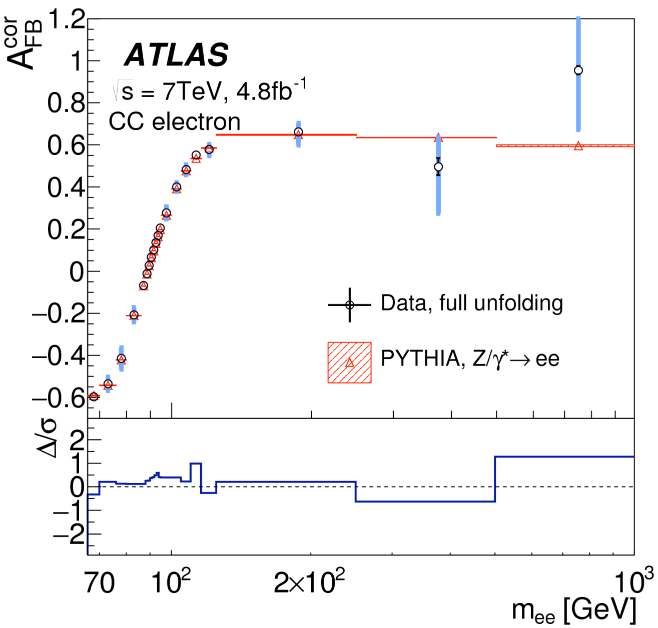


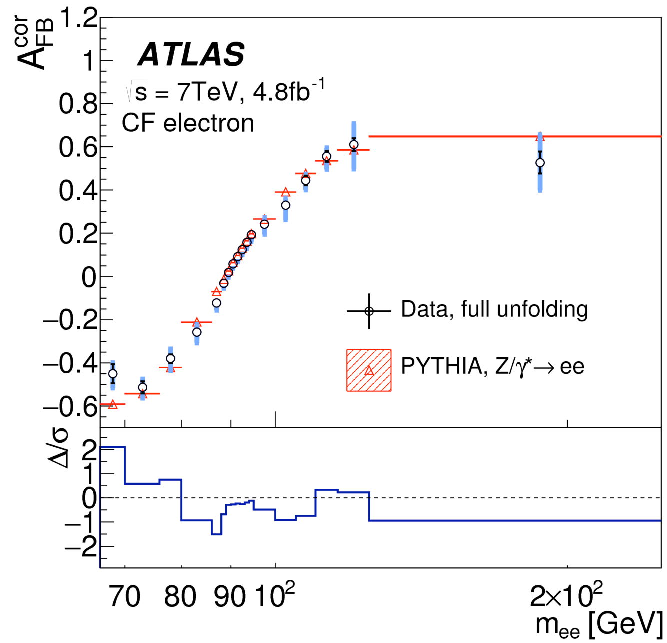
A_{FB} and $\sin^2\theta_{eff}$

JHEP 1509 (2015) 049

- A_{FB} near Z peak sensitive to $\sin^2\theta_{eff}$
- ATLAS measurement from 7 TeV data with 4.8 fb^{-1}
- μμ and ee pairs, including forward electrons

Forward rapidities suffer less from dilution





	$\sin^2\theta_{eff}^{lept}$
CC electron	$0.2302 \pm 0.0009(\text{stat.}) \pm 0.0008(\text{syst.}) \pm 0.0010(\text{PDF}) = 0.2302 \pm 0.0016$
CF electron	$0.2312 \pm 0.0007(\text{stat.}) \pm 0.0008(\text{syst.}) \pm 0.0010(\text{PDF}) = 0.2312 \pm 0.0014$
Muon	$0.2307 \pm 0.0009(\text{stat.}) \pm 0.0008(\text{syst.}) \pm 0.0009(\text{PDF}) = 0.2307 \pm 0.0015$
El. combined	$0.2308 \pm 0.0006(\text{stat.}) \pm 0.0007(\text{syst.}) \pm 0.0010(\text{PDF}) = 0.2308 \pm 0.0013$
Combined	$0.2308 \pm 0.0005(\text{stat.}) \pm 0.0006(\text{syst.}) \pm 0.0009(\text{PDF}) = 0.2308 \pm 0.0012$

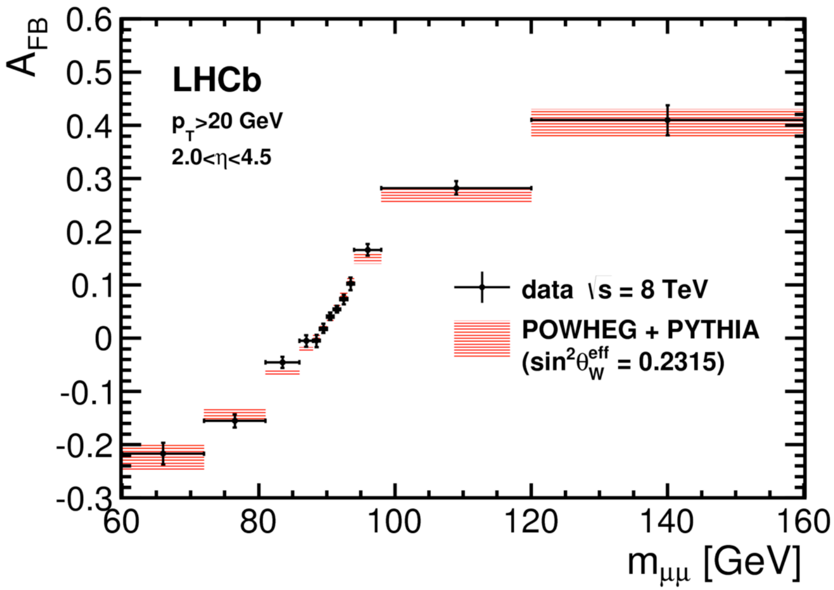
Leading uncertainties from PDFs

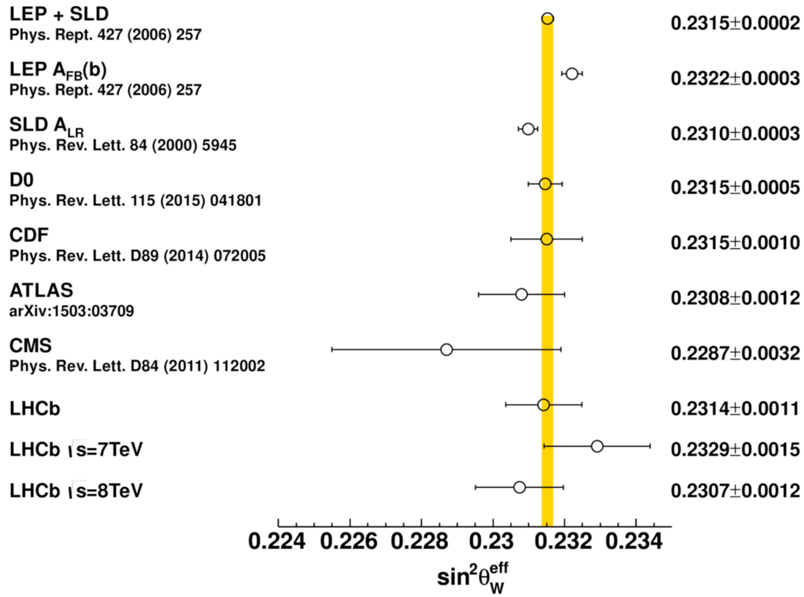
A_{FB} and $\sin^2\theta_{eff}$

JHEP 1511 (2015) 190

- LHCb, 7 and 8 TeV datasets
- Use A_{FB} in forward dimuon events to extract $\sin^2\theta_{eff}$

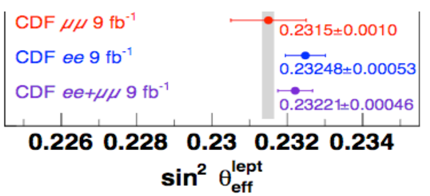
$$\sin^2\theta_W^{eff} = 0.23142 \pm \underset{\text{(stat)}}{0.00073} \pm \underset{\text{(exp)}}{0.00052} \pm \underset{\text{(theory+pdf)}}{0.00056}$$





- Precision of $\sin^2\theta_{eff}$ dominated by LEP and SLD

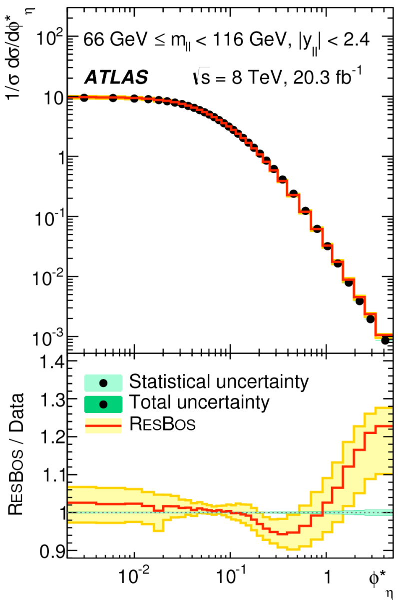
Recent combined ee+μμ results from CDF: arxiv:1605.02719

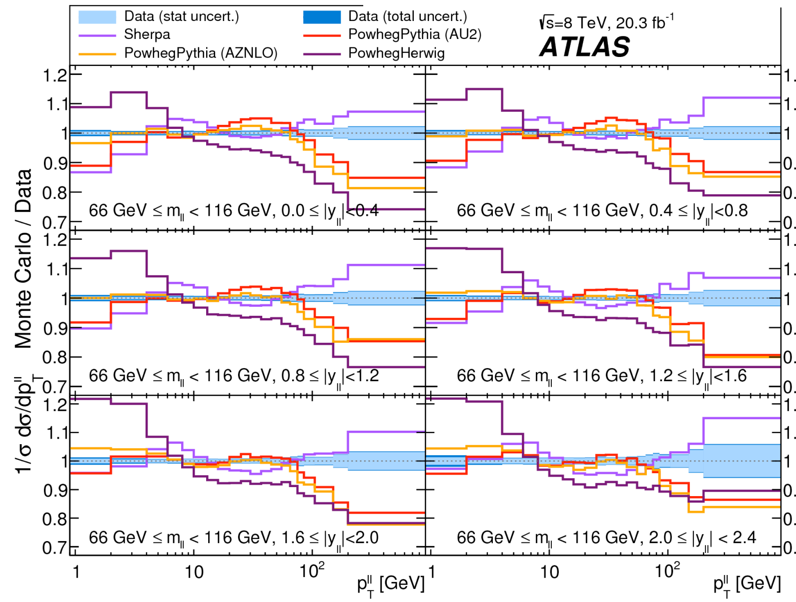


- Measurements from hadron colliders are becoming more precise

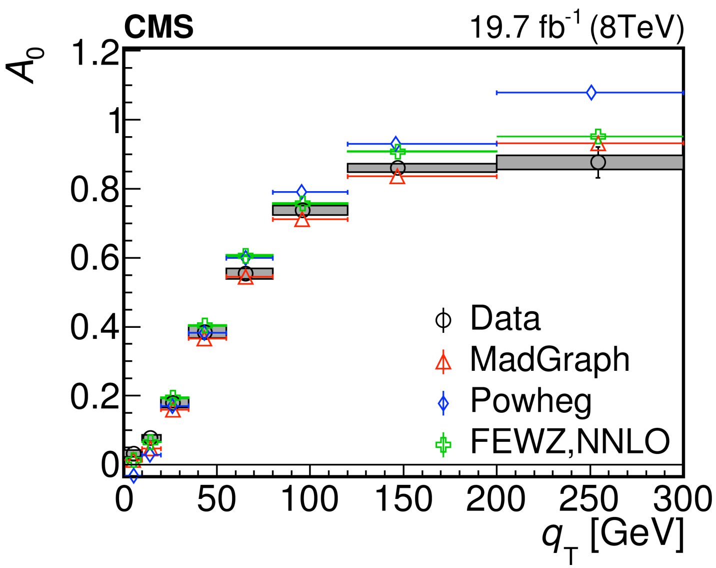
Z p_T and angular coefficients

arXiv:1512.02192





Phys.Lett. B750 (2015) 154-175



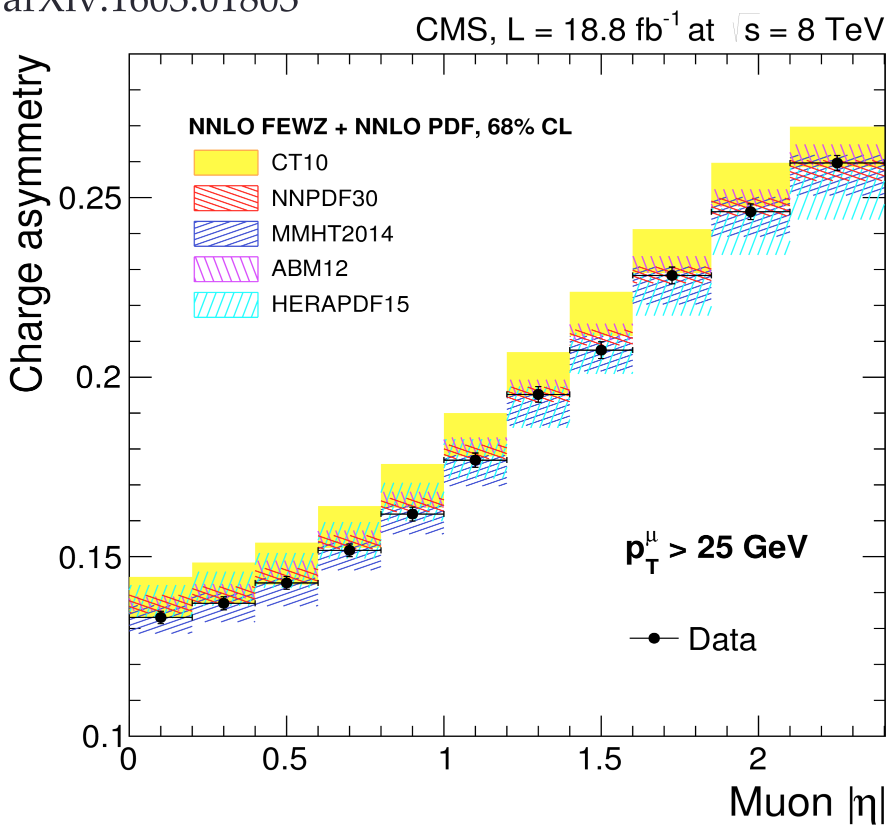
$$\frac{d\sigma}{d\cos\theta} \propto (1+\cos^2\theta) + \frac{1}{2}A_0(1-3\cos^2\theta) + A_4\cos\theta$$

Accurate modeling of QCD effects is crucial for precision EW measurements

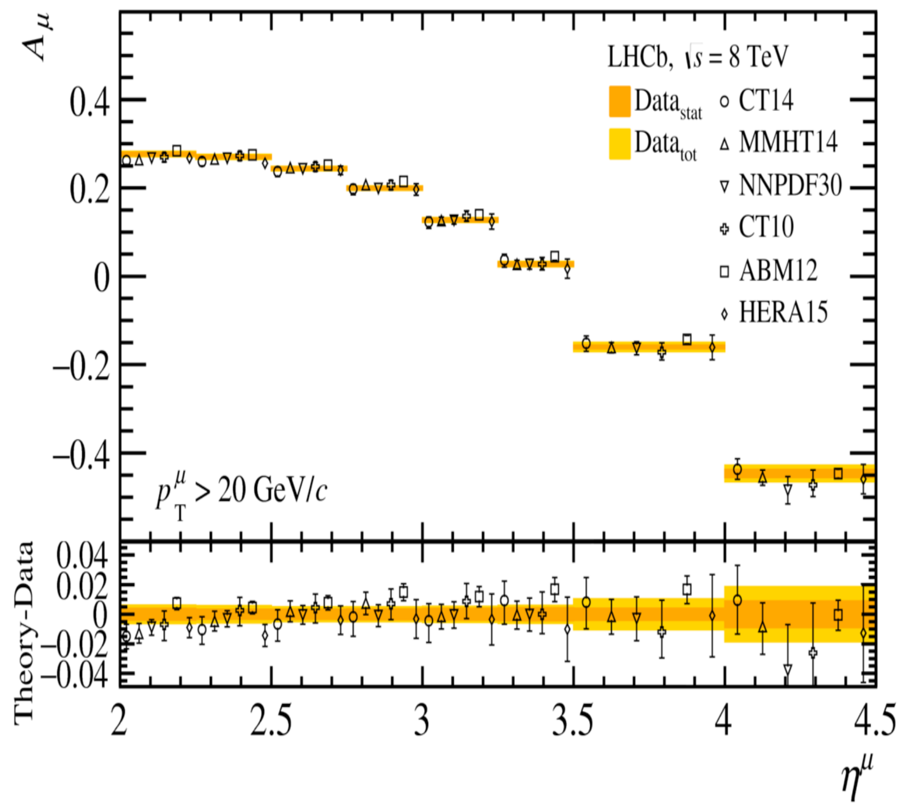
W charge asymmetry

W charge asymmetry sensitive to valence and sea quark densities in the proton

arXiv:1603.01803



JHEP 1601 (2016) 155

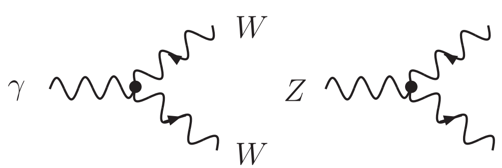


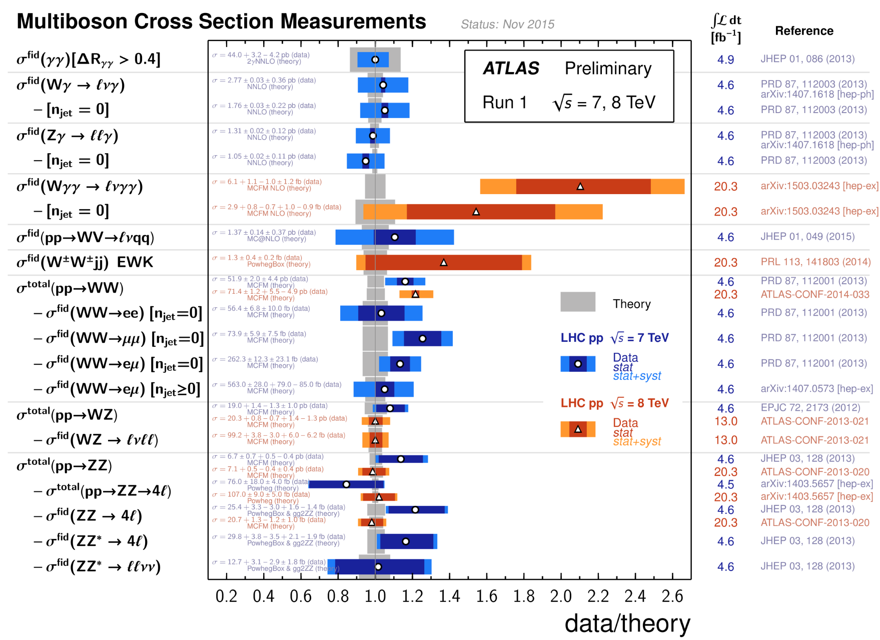
Precision measurements at the LHC are used to constrain PDFs that in turn are needed by other precision measurements

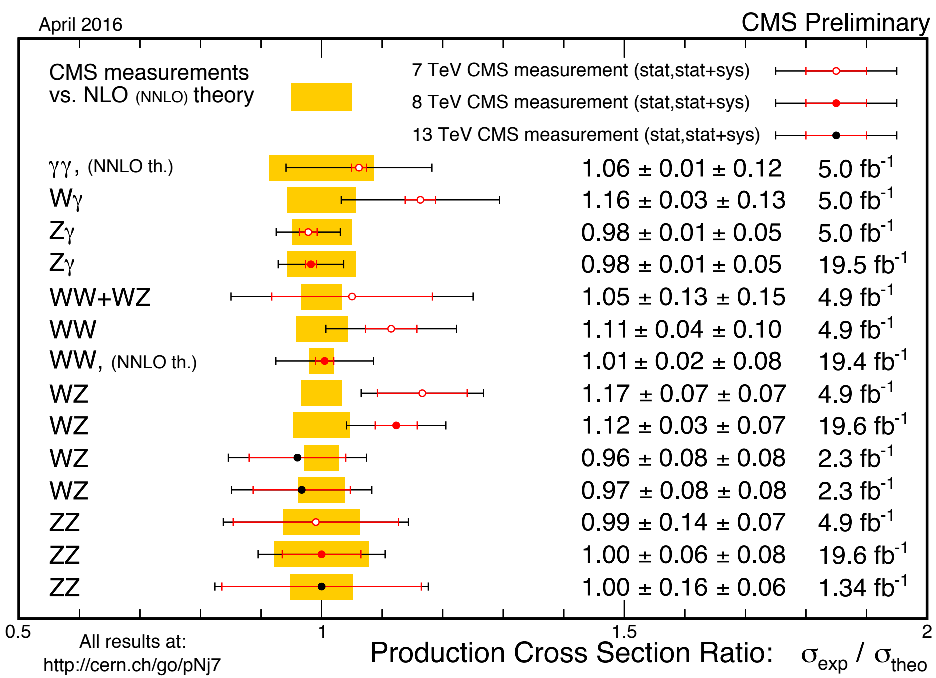
Diboson and triboson studies

- Diboson and triboson processes provide unique test for the electroweak sector

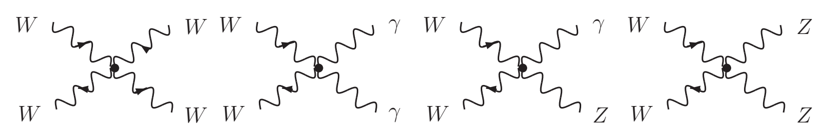
- Diboson final states probe triple gauge couplings (TGC)







- Vector boson scattering (VBS) and triboson production topologies probe quartic gauge couplings (QGC)

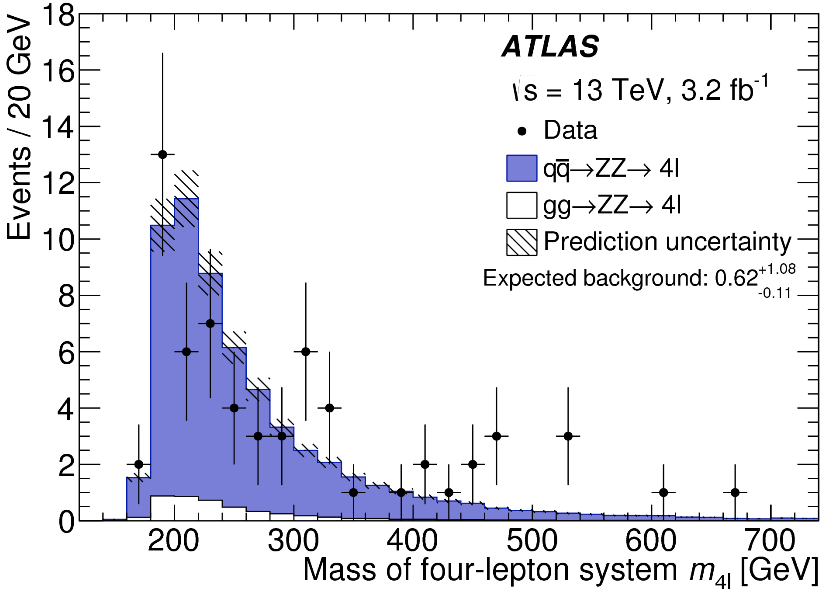


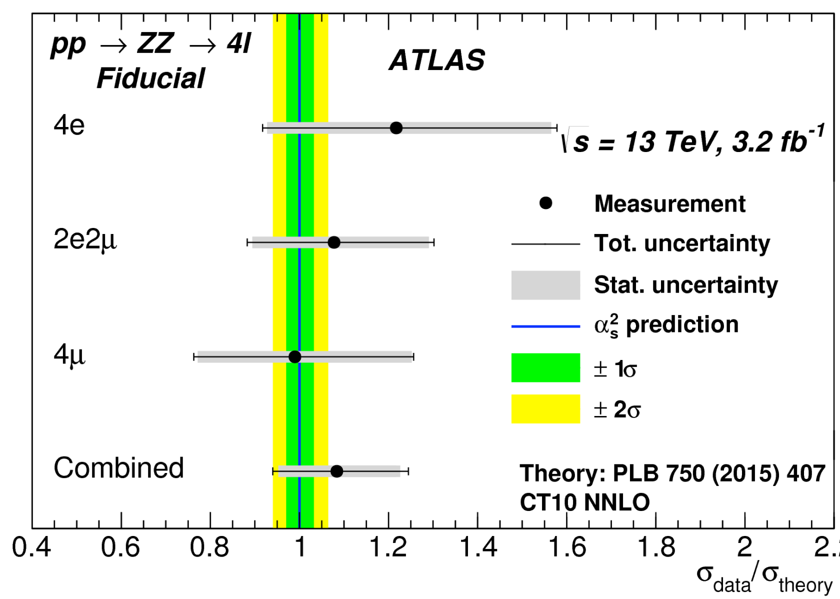
- Search for excesses from new physics via anomalous TGC and QGC

ZZ at 13 TeV

Phys. Rev. Lett. 116, 101801 (2016)

- Fiducial and total $\sigma(pp \rightarrow ZZ \rightarrow 4l)$ @ 13 TeV, L_{int}=3.2 fb^{-1}
- Two dielectron or dimuon pairs each with 66 GeV < M_{ll} < 116 GeV

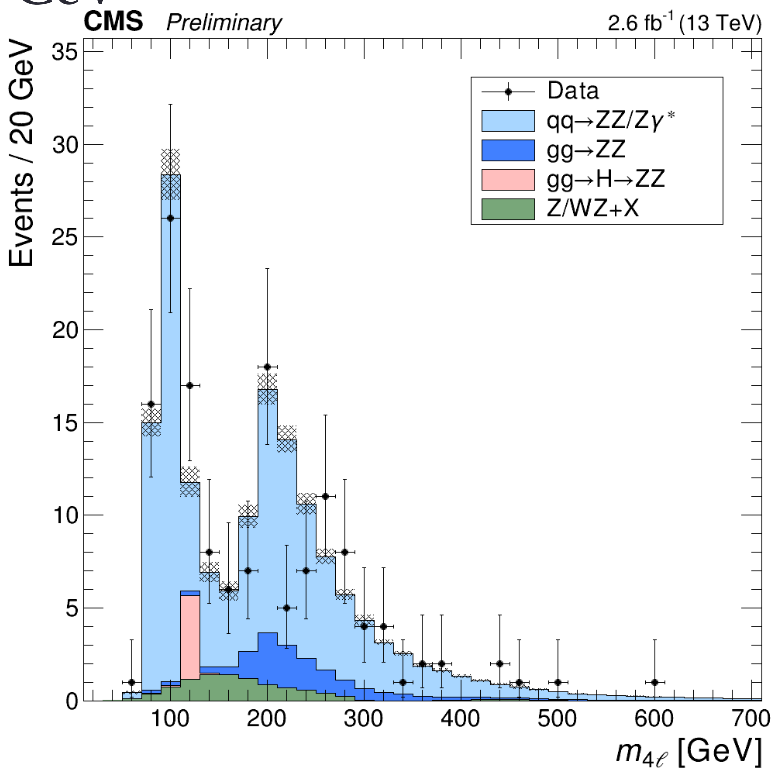


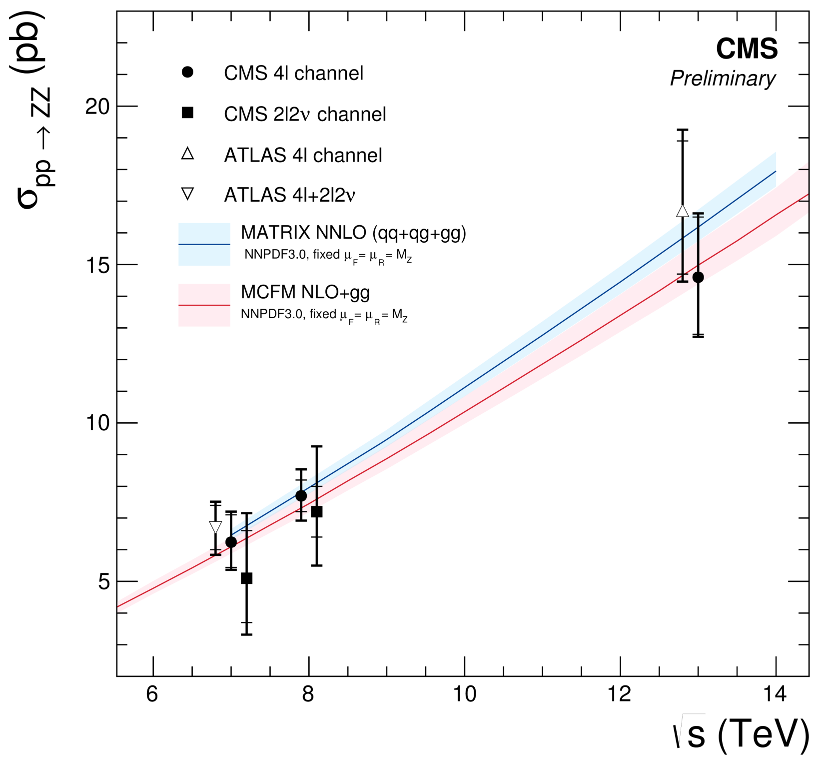


	Measurement	$\mathcal{O}(\alpha_s^2)$ prediction
$\sigma^{\text{fid}}_{ZZ\rightarrow e^+e^-e^+e^-}$	$8.4\ ^{+2.4}_{-2.0}(\text{stat.})\ ^{+0.4}_{-0.2}(\text{syst.})\ ^{+0.5}_{-0.3}(\text{lumi.})$ fb	$6.9^{+0.2}_{-0.2}$ fb
$\sigma^{\text{fid}}_{ZZ\rightarrow e^+e^-\mu^+\mu^-}$	$14.7\ ^{+2.9}_{-2.5}(\text{stat.})\ ^{+0.6}_{-0.4}(\text{syst.})\ ^{+0.9}_{-0.6}(\text{lumi.})$ fb	$13.6^{+0.4}_{-0.4}$ fb
$\sigma^{\text{fid}}_{ZZ\rightarrow \mu^+\mu^-\mu^+\mu^-}$	$6.8\ ^{+1.8}_{-1.5}(\text{stat.})\ ^{+0.3}_{-0.3}(\text{syst.})\ ^{+0.4}_{-0.3}(\text{lumi.})$ fb	$6.9^{+0.2}_{-0.2}$ fb
$\sigma^{\text{fid}}_{ZZ\rightarrow \ell^+\ell^-\ell'^+\ell'^-}$	$29.7\ ^{+3.9}_{-3.6}(\text{stat.})\ ^{+1.0}_{-0.8}(\text{syst.})\ ^{+1.7}_{-1.3}(\text{lumi.})$ fb	$27.4^{+0.9}_{-0.8}$ fb
σ^{tot}_{ZZ}	$16.7\ ^{+2.2}_{-2.0}(\text{stat.})\ ^{+0.9}_{-0.7}(\text{syst.})\ ^{+1.0}_{-0.7}(\text{lumi.})$ pb	$15.6^{+0.4}_{-0.4}$ pb

ZZ at 13 TeV

- $\sigma(pp \to \mathbf{ZZ} \to 4l)$ for electrons & muons with 60 GeV < M_{ll} < 120 GeV
- $\mathcal{B}$ranching fraction($\mathbf{Z} \to 4l$) for 80 GeV < M_{4l} < 100 GeV and M_{ll} > 4 GeV





$$\sigma(pp \to ZZ) = 14.6^{+1.9}_{-1.8}\,(\text{stat})^{+0.5}_{-0.3}\,(\text{syst}) \pm 0.2\,(\text{theo}) \pm 0.4\,(\text{lum})\ \text{pb}$$

$\sigma_{NNLO} = 16.5^{+0.7}_{-0.5}$ pb

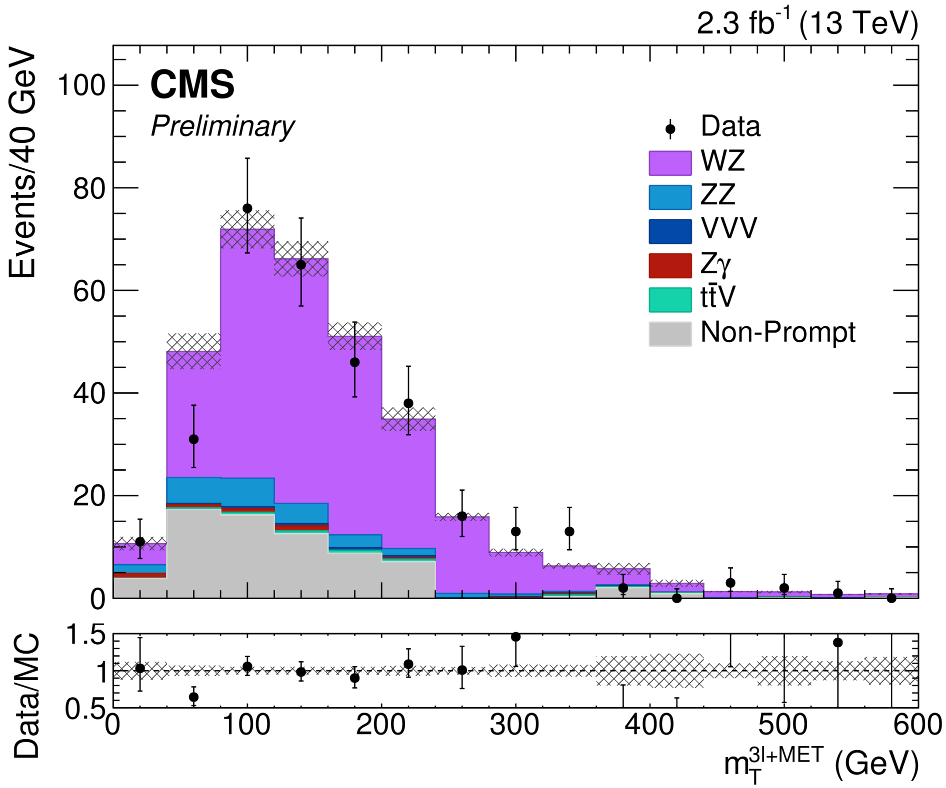
$$\mathcal{B}(Z \to \ell\ell\ell'\ell') = (4.9^{+0.8}_{-0.7}\,(\text{stat})^{+0.3}_{-0.2}\,(\text{syst})^{+0.2}_{-0.1}\,(\text{theo}) \pm 0.1\,(\text{lum})) \times 10^{-6}$$

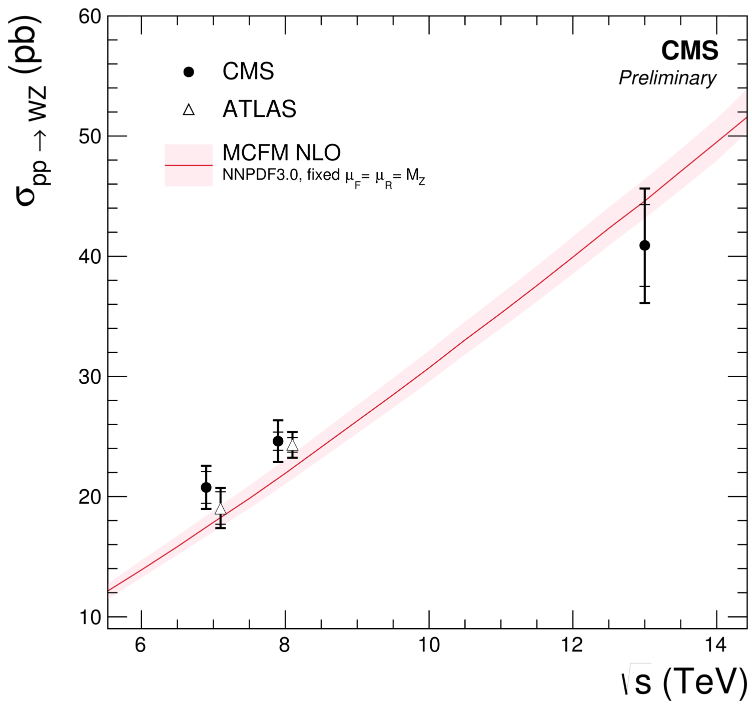
$\mathcal{B}_{NLO} = 4.6 \times 10^{-6}$

WZ at 13 TeV

CMS-PAS-SMP-16-002

- $\sigma(pp \rightarrow \mathbf{WZ} \rightarrow l\nu l'l')$ @ 13 TeV, L_{int}=2.3 fb^{-1}
- l,l' = e, μ; 60 GeV < M_Z < 120 GeV





NLO predictions

$$\sigma_{\text{fid}}(pp \rightarrow WZ \rightarrow \ell\nu\ell'\ell') = 265 \pm 22\,(\text{stat})^{+20}_{-22}\,(\text{syst}) \pm 9\,(\text{lum})\text{ fb}$$

σ_{fid} =274$^{+11}_{-10}$ fb

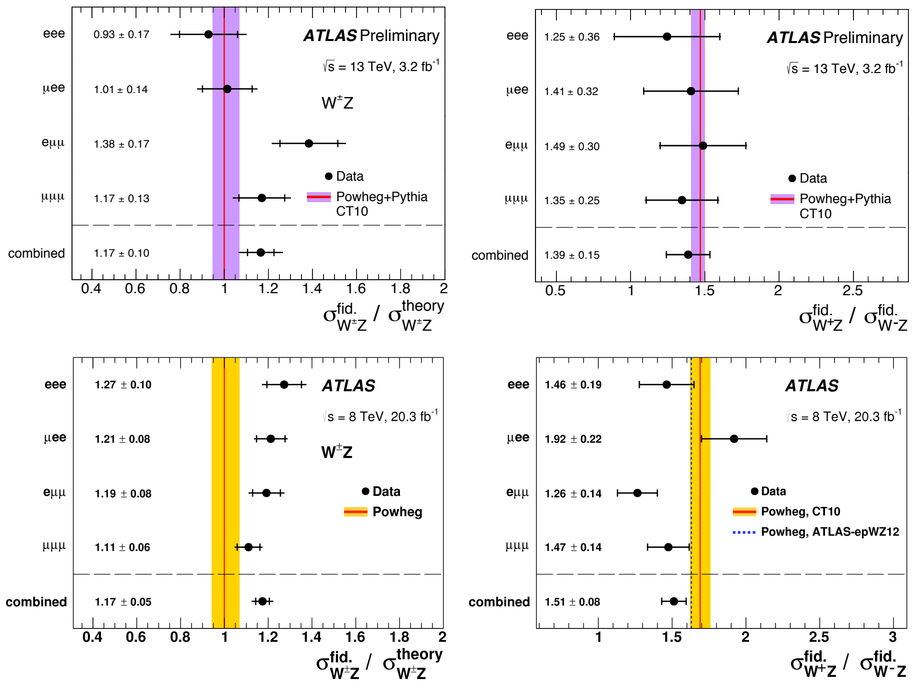
$$\sigma(pp \rightarrow WZ) = 40.9 \pm 3.4\,(\text{stat})^{+3.1}_{-3.3}\,(\text{syst}) \pm 0.4\,(\text{theo}) \pm 1.3\,(\text{lum})\text{ pb}$$

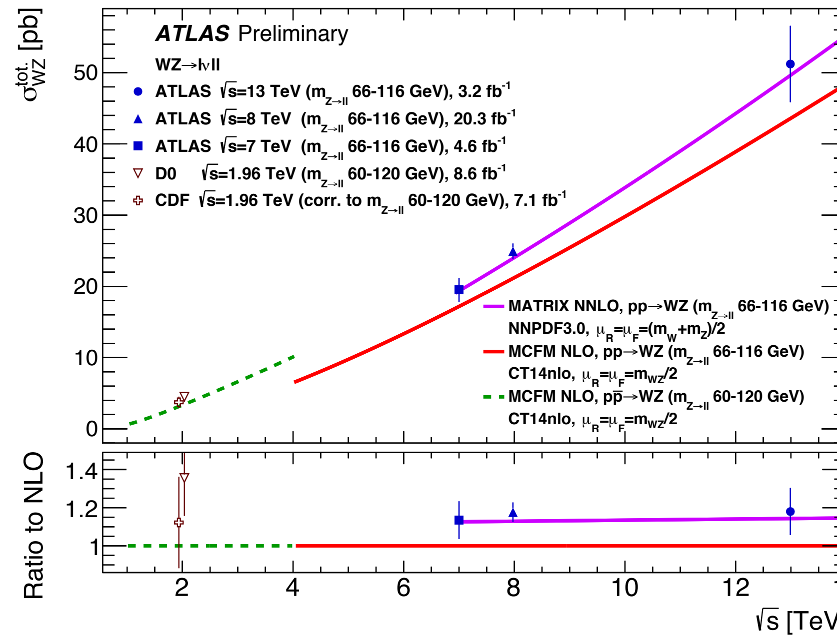
σ_{tot} =42.6$^{+1.6}_{-0.8}$ pb

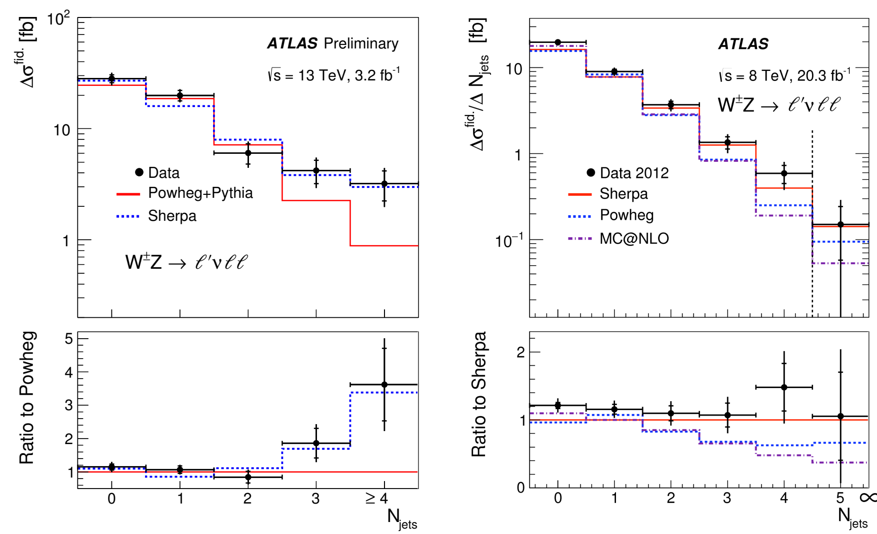
WZ at 13 and 8 TeV

STDM-2015-19
Phys. Rev. D 93, 092004 (2016)

- Total and fiducial σ(pp → *WZ* → *l′νll*)
- Differential measurements







– Consistent pictures at 8 and 13 TeV

– NLO predictions somewhat low,
NNLO predictions well describe data

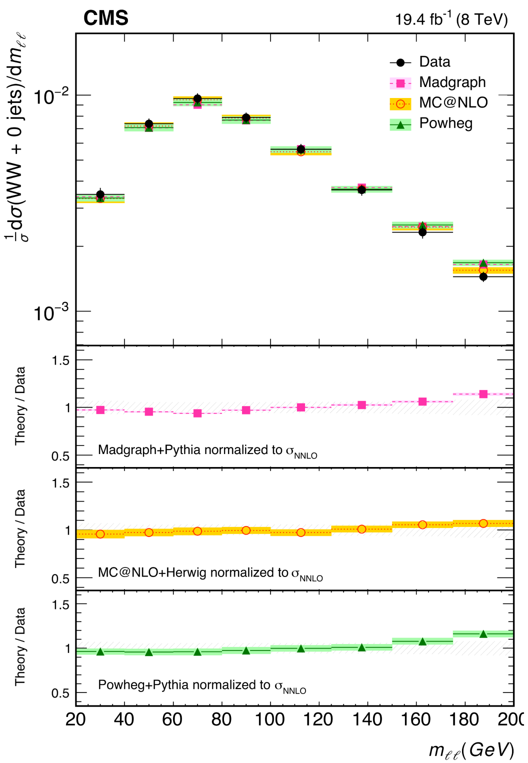
– Good description of jet multiplicity by Sherpa

WW at 8 TeV

arXiv:1507.03268

arXiv:1603.01702

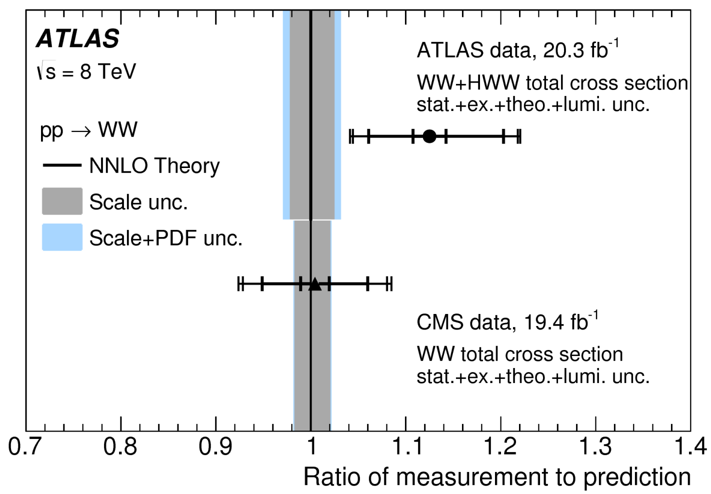
- Total and fiducial σ(pp → *WW* → *lνlν*) @ 8 TeV

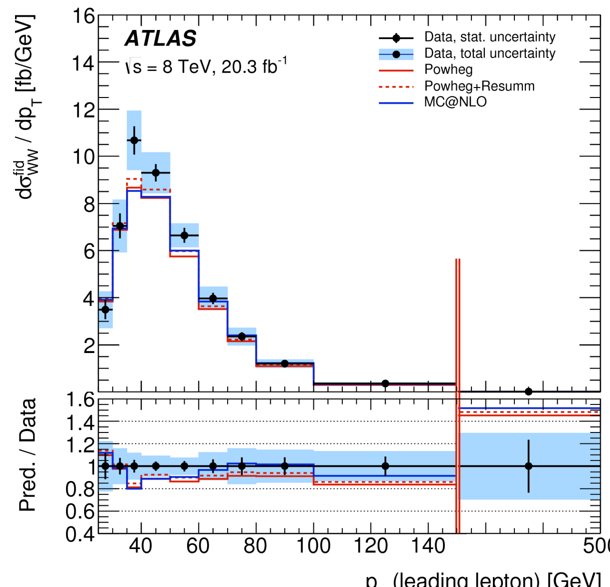


MC WW p_T re-weighted to NNLL calculation to improve modeling of jet veto efficiency

$$\sigma_{W^+W^-} = 60.1 \pm 0.9\,(\text{stat}) \pm 3.2\,(\text{exp}) \pm 3.1\,(\text{theo}) \pm 1.6\,(\text{lumi})\,\text{pb} = 60.1 \pm 4.8\,\text{pb}$$

$$\sigma^{\text{NNLO}}(pp \to W^+W^-) = 59.8^{+1.3}_{-1.1}\,\text{pb}$$





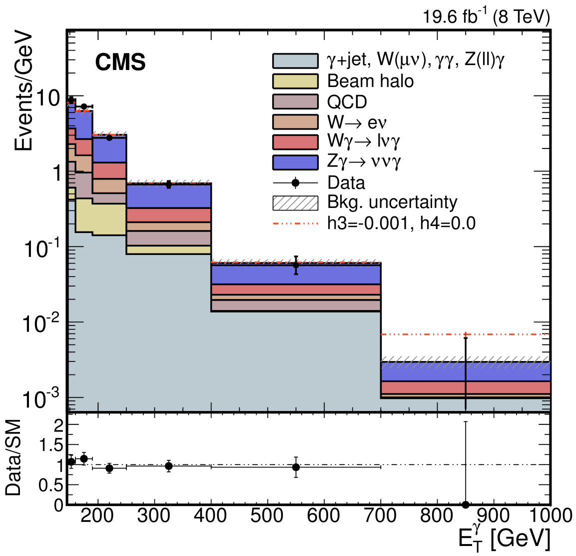
- Theory predictions significantly improved from NLO to NNLO QCD calculations
- Two measurements in agreement

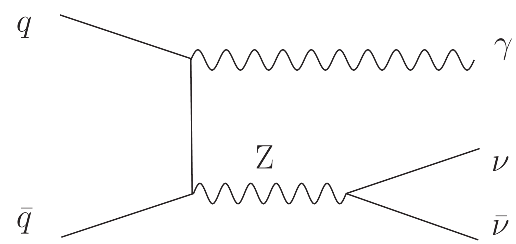
Zγ at 8 TeV

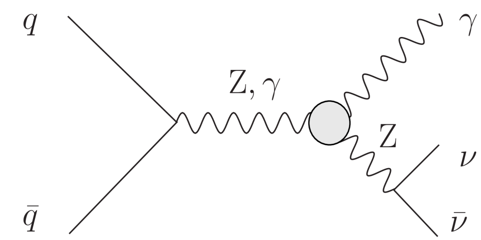
arXiv:1602.07152

arXiv:1604.05232

- $pp \to Z\gamma \to \nu\bar{\nu}\gamma$ @ 8 TeV







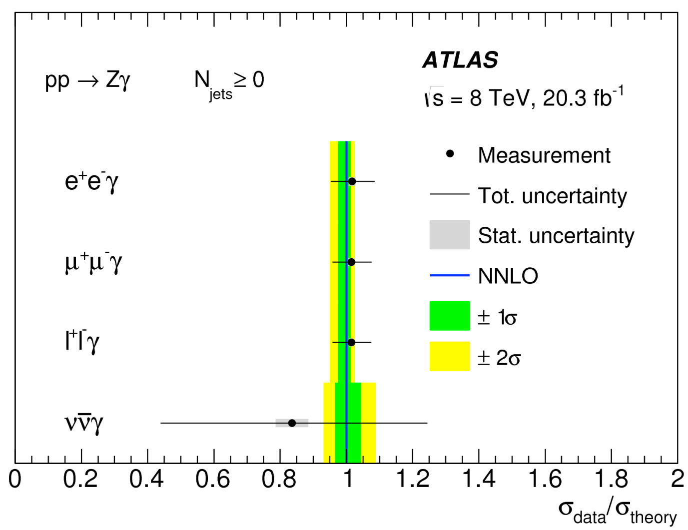
Fid: photon E_T>145 GeV, |η|<1.44

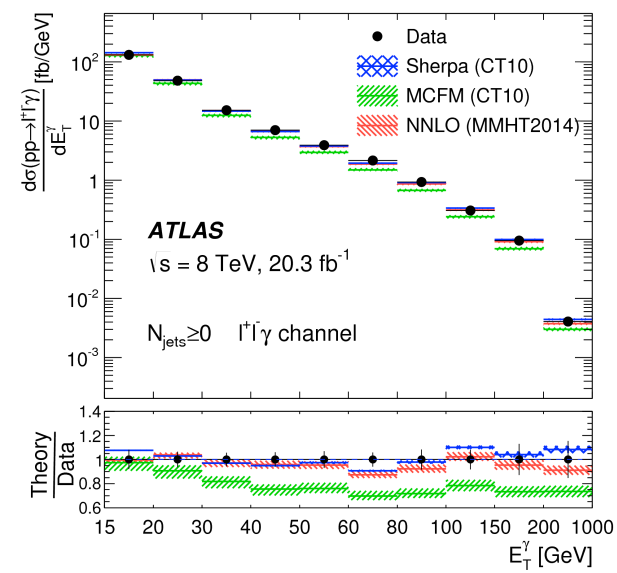
$\sigma_{fid} = 52.7 \pm 2.1\,(stat) \pm 6.4\,(syst) \pm 1.4\,(lumi)$ fb

$\sigma_{NNLO} = 50.0^{+2.4}_{-2.2}$ fb

Use photon E_T to set limits on anomalous TGC

- Inclusive & exclusive (N_{jet}=0) $\sigma(pp \to Z\gamma \to ll\gamma, \nu\nu\gamma)$
- differential measurements



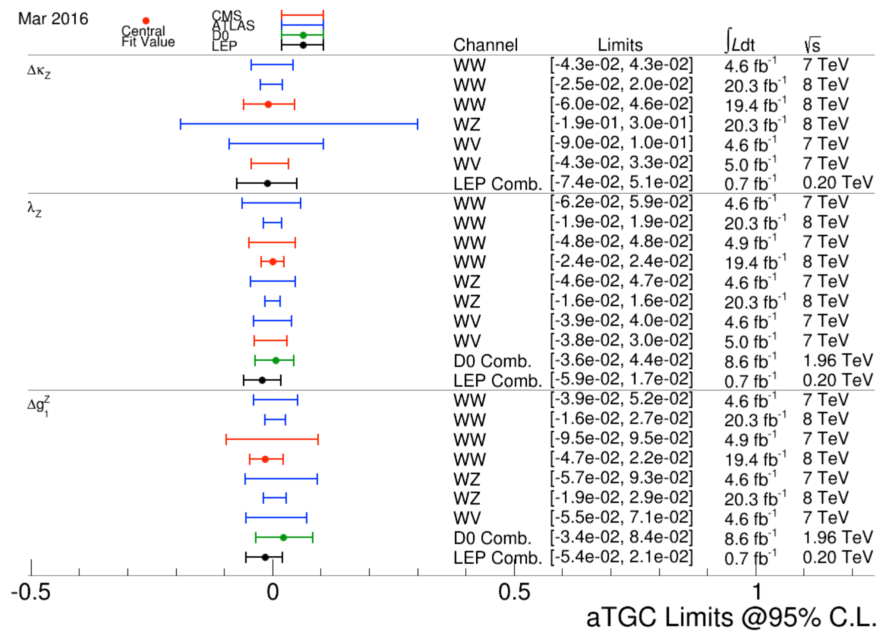


Anomalous TGC

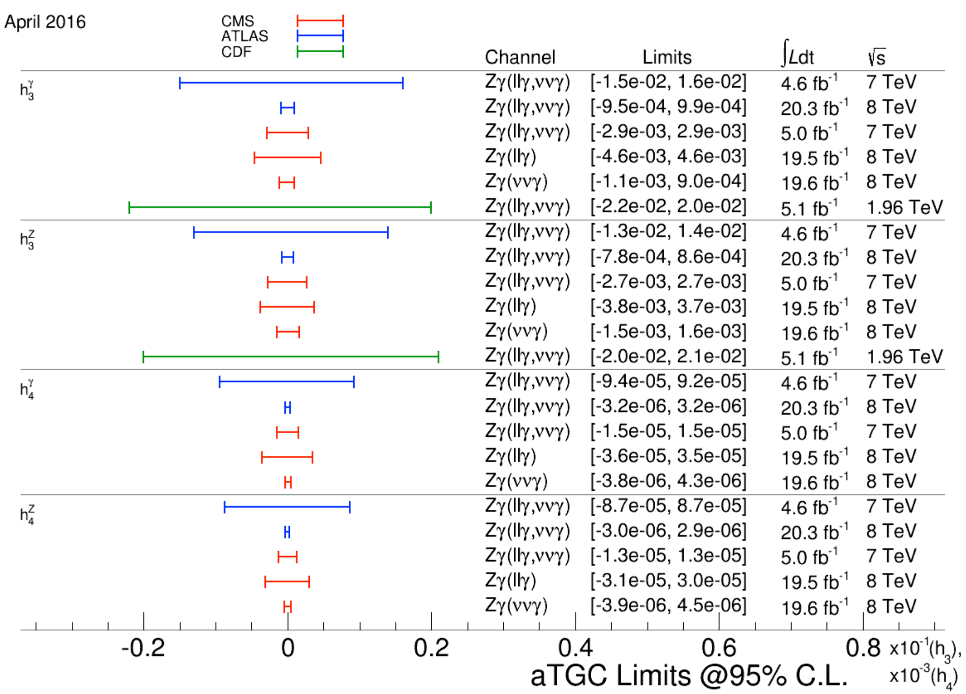
https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsSMPaTGC

Summary of charged and neutral aTGC limits from various measurements with diboson final states

Limits on *WWZ* aTGC couplings



Limits on neutral $Z\gamma\gamma$ and $ZZ\gamma$ couplings

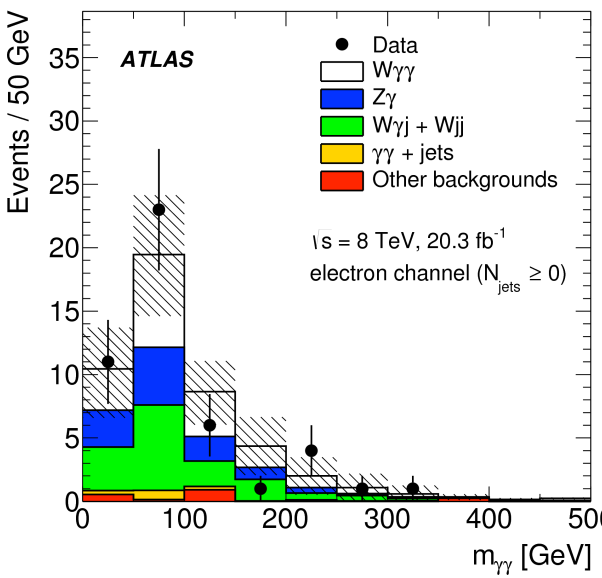


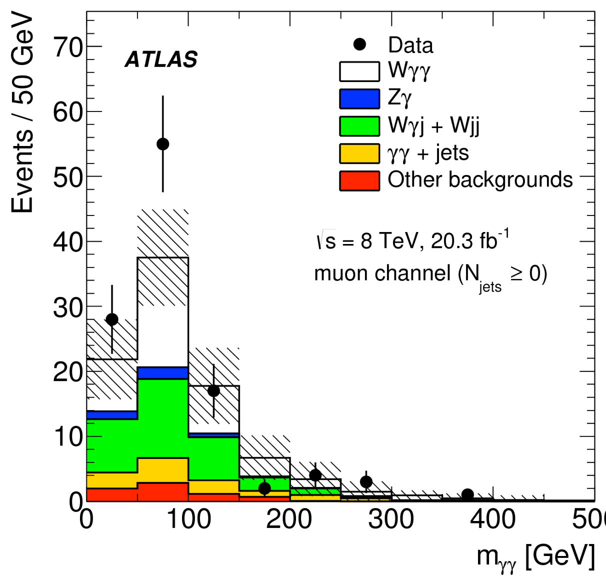
- LHC data now set most stringent constraints on anomalous couplings

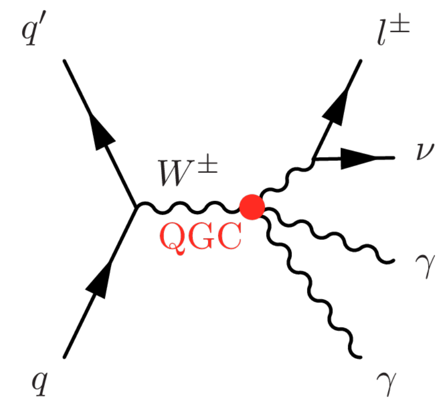
Tribosons: $W\gamma\gamma$

Phys. Rev. Lett. 115, 031802 (2015)

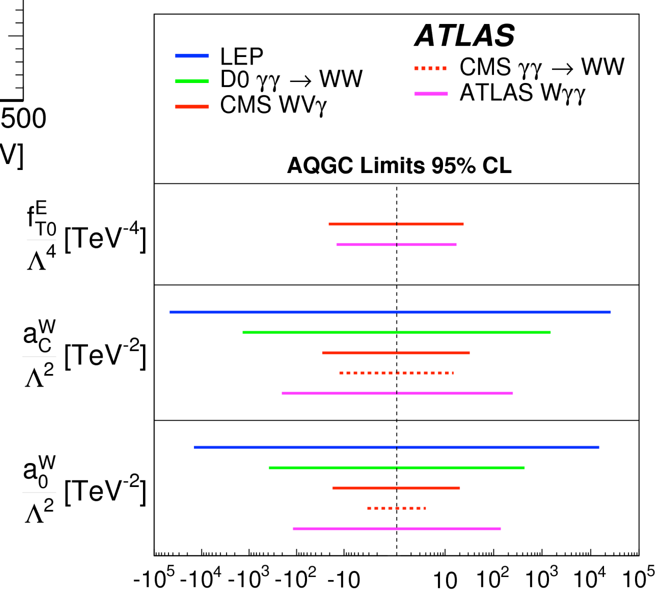
- Evidence of pp → $W\gamma\gamma \rightarrow l\nu\gamma\gamma$ @ 8 TeV
  - significance > 3σ
- Use photon $m_{\gamma\gamma}$ to set limits on anomalous Quartic GC







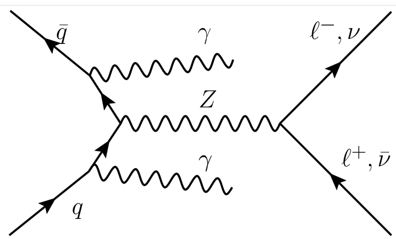
	σ^{fid} [fb]	σ^{MCFM} [fb]
Inclusive ($N_{\text{jet}} \geq 0$)		
$\mu\nu\gamma\gamma$	$7.1\ ^{+1.3}_{-1.2}$ (stat.) ± 1.5 (syst.) ± 0.2 (lumi.)	
$e\nu\gamma\gamma$	$4.3\ ^{+1.8}_{-1.6}$ (stat.) $^{+1.9}_{-1.8}$ (syst.) ± 0.2 (lumi.)	2.90 ± 0.16
$\ell\nu\gamma\gamma$	$6.1\ ^{+1.1}_{-1.0}$ (stat.) ± 1.2 (syst.) ± 0.2 (lumi.)	
Exclusive ($N_{\text{jet}} = 0$)		
$\mu\nu\gamma\gamma$	3.5 ± 0.9 (stat.) $^{+1.1}_{-1.0}$ (syst.) ± 0.1 (lumi.)	
$e\nu\gamma\gamma$	$1.9\ ^{+1.4}_{-1.1}$ (stat.) $^{+1.1}_{-1.2}$ (syst.) ± 0.1 (lumi.)	1.88 ± 0.20
$\ell\nu\gamma\gamma$	$2.9\ ^{+0.8}_{-0.7}$ (stat.) $^{+1.0}_{-0.9}$ (syst.) ± 0.1 (lumi.)	

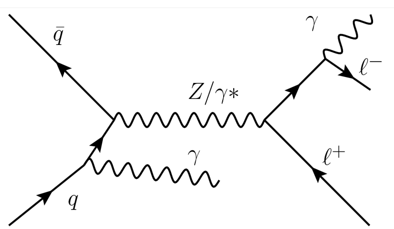


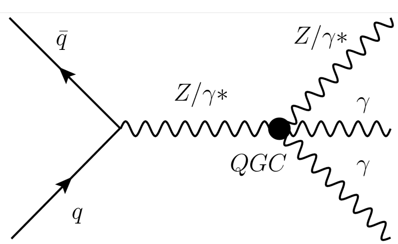
Tribosons: $Z\gamma\gamma$

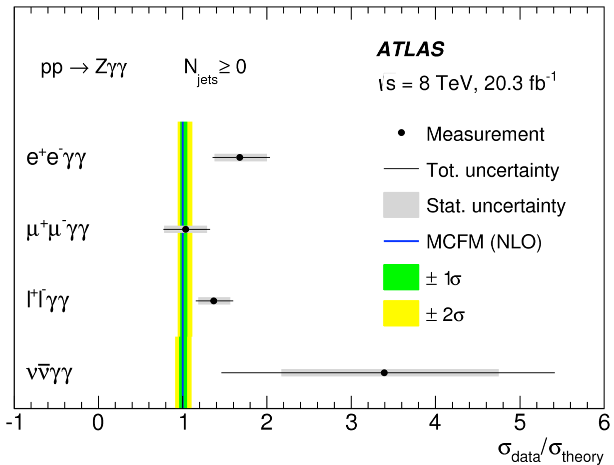
arXiv:1604.05232

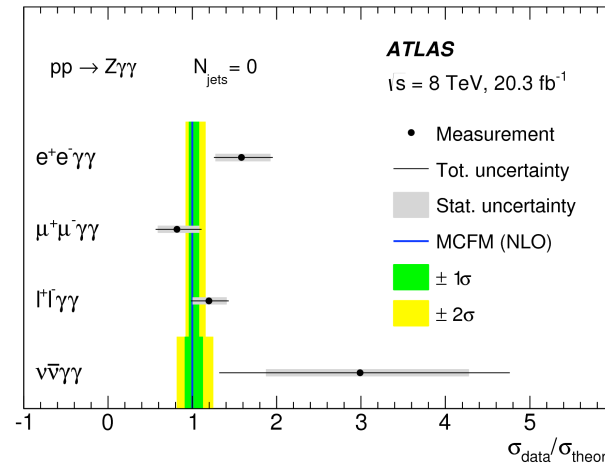
- Triboson production of $Z\gamma\gamma \rightarrow ll\gamma\gamma, \nu\nu\gamma\gamma$ @ 8 TeV
  - significance > 5σ
- Use photon $m_{\gamma\gamma}$ to set limits on QGC

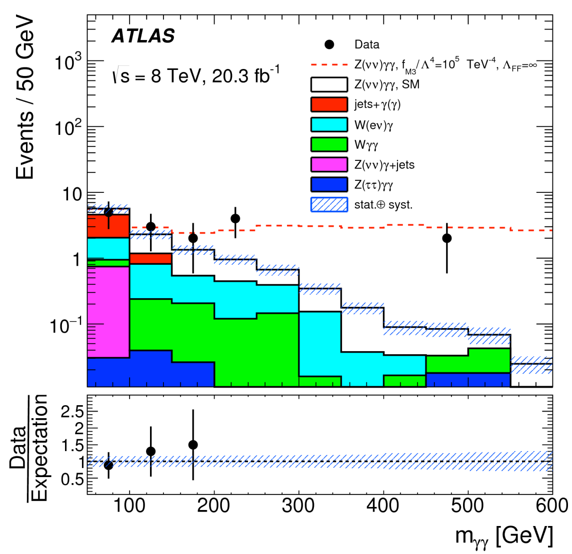


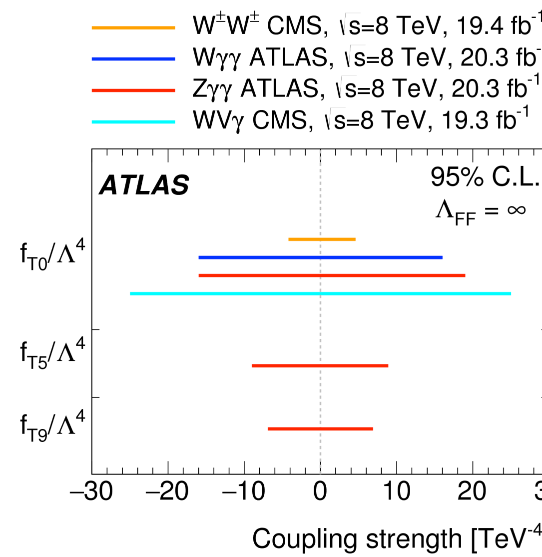






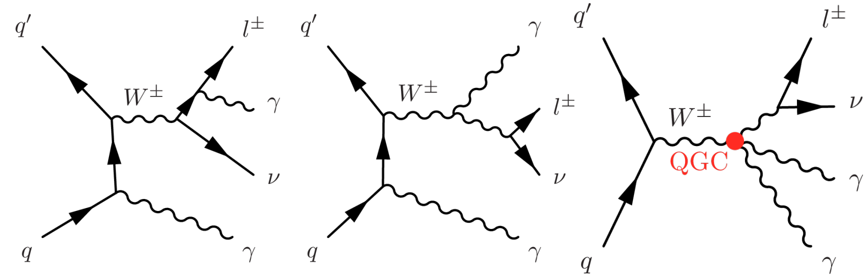




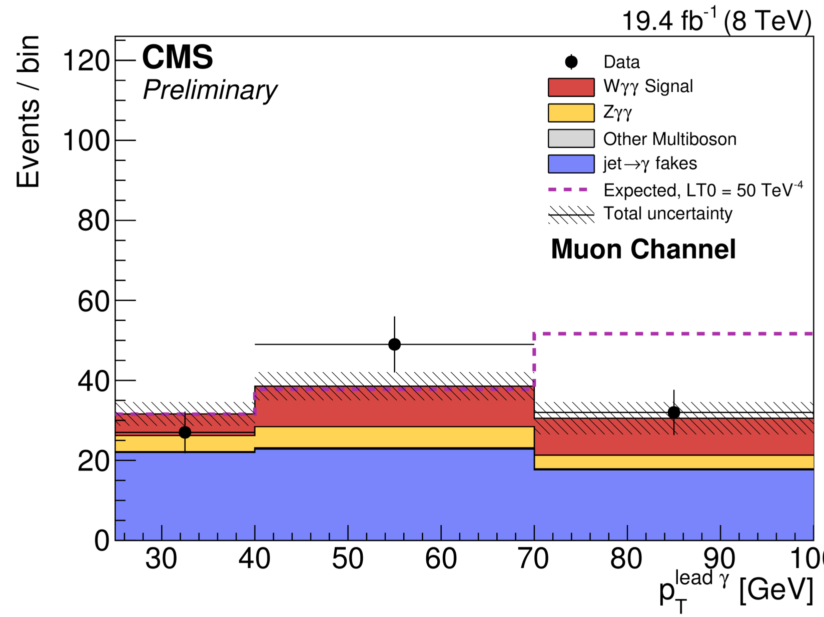


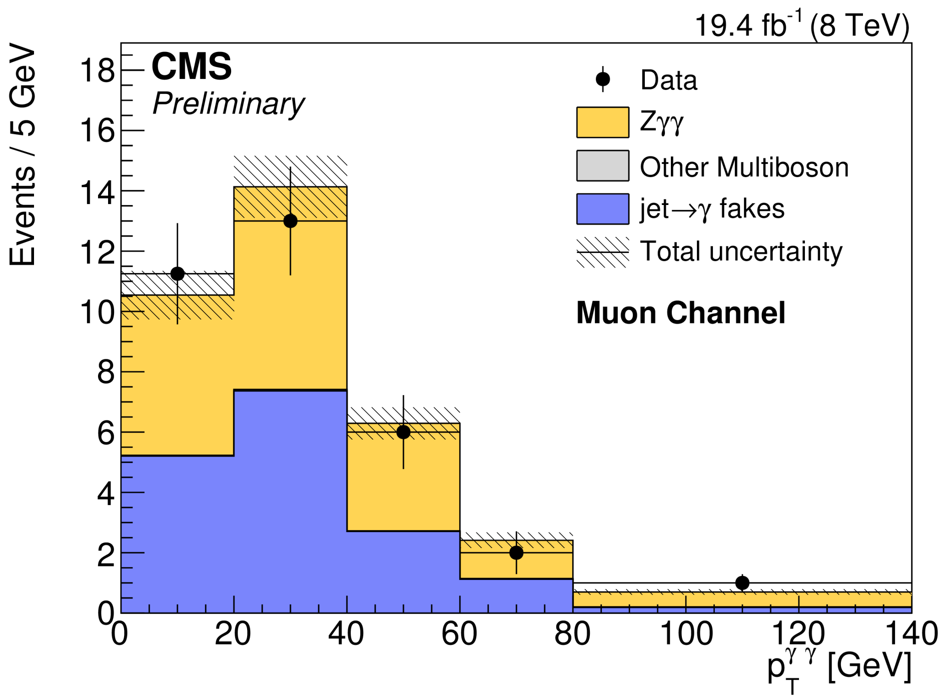
Tribosons: $W\gamma\gamma$ and $Z\gamma\gamma$ CMS-SMP-15-008

- $W\gamma\gamma \rightarrow \mu\nu\gamma\gamma$ @ 8 TeV
    - observed with significance 2.4σ
    - σ_{fid} = 6.0 ± 1.8 (stat) ± 2.3 (syst) ± 0.2 (lumi) fb
    - σ_{NLO} = 4.76 ± 0.53 fb



- $Z\gamma\gamma \rightarrow l\nu\gamma\gamma$ @ 8 TeV
    - observed with significance 5.9σ
    - σ_{fid} = 12.7 ± 1.4 (stat) ± 1.8 (syst) ± 0.3 (lumi) fb
    - σ_{NLO} = 12.95 ± 1.47 fb

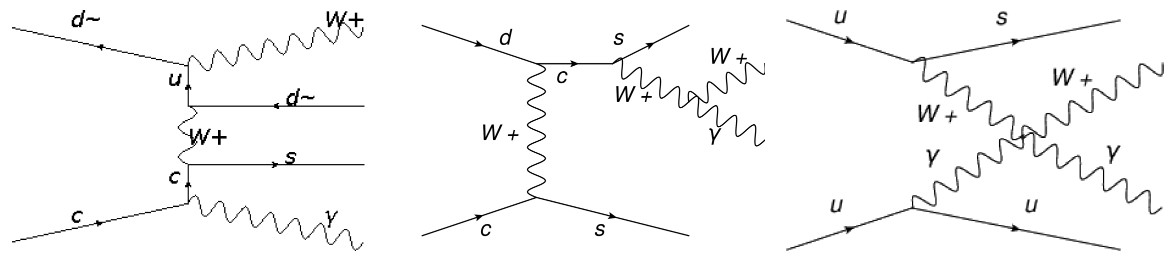




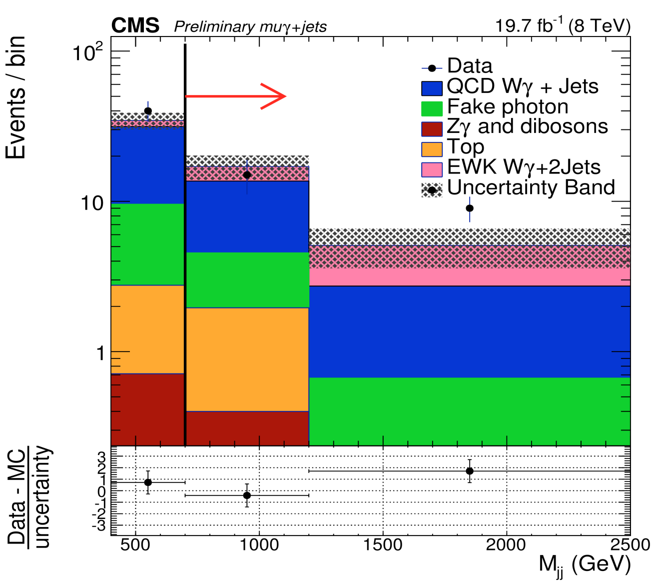
Expected Limits (TeV^{-4})	Observed Limits (TeV^{-4})
$-30.5 < \frac{f_{T0}}{\Lambda^4} < 31.1$	$-37.5 < \frac{f_{T0}}{\Lambda^4} < 38.1$
$-36.9 < \frac{f_{T1}}{\Lambda^4} < 37.5$	$-46.1 < \frac{f_{T1}}{\Lambda^4} < 46.9$
$-83.2 < \frac{f_{T2}}{\Lambda^4} < 83.2$	$-103 < \frac{f_{T2}}{\Lambda^4} < 103$
$-623 < \frac{f_{M2}}{\Lambda^4} < 603$	$-751 < \frac{f_{M2}}{\Lambda^4} < 729$
$-1080 < \frac{f_{M3}}{\Lambda^4} < 1110$	$-1290 < \frac{f_{M3}}{\Lambda^4} < 1340$

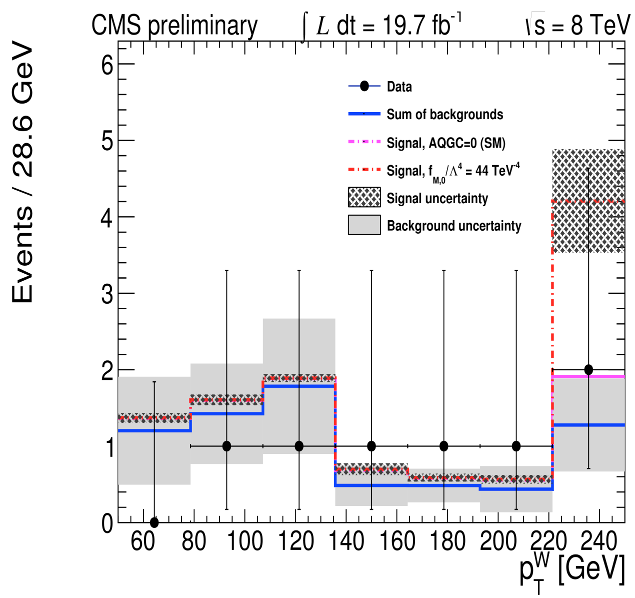
VBS: Wγjj

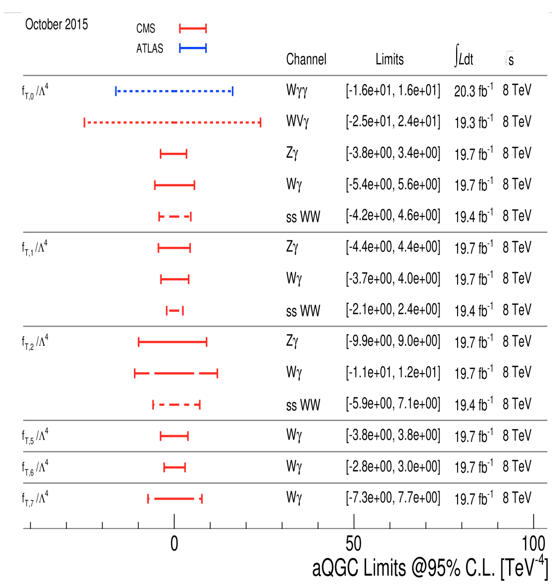
- EWK-induced Wγjj
  - $\Delta\eta_{jj} > 2.4$
  - $M_{jj} > 700$ GeV



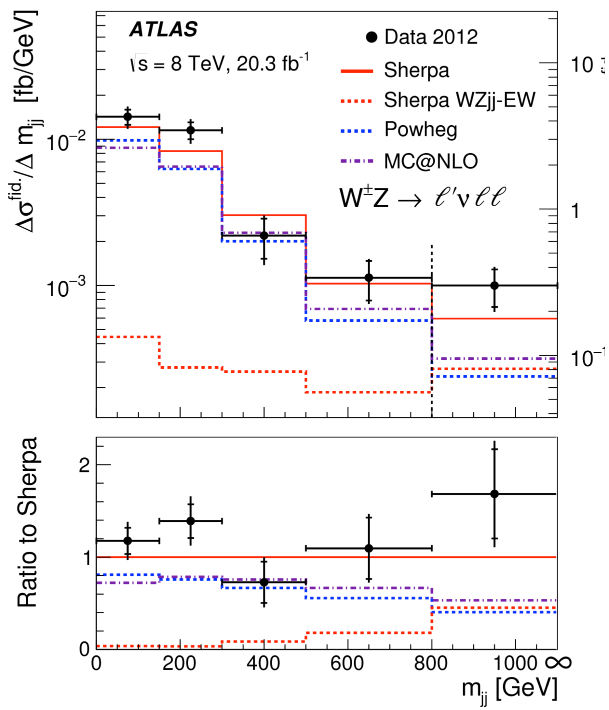
Items	EWK measurement	EWK+QCD measurement
$\hat{\mu}$	$1.78^{+0.99}_{-0.76}$	$0.99^{+0.21}_{-0.19}$
EWK fraction (search region)	100%	27.1%
EWK fraction (fiducial region)	100%	25.8%
Observed (Expected) significance	$2.67(1.52)\,\sigma$	$7.69(7.49)\,\sigma$
Theory cross section (fb)	6.1 ± 1.2 (scale) ± 0.2 (PDF)	23.5 ± 6.6 (scale) ± 0.8 (PDF)
Measured cross section (fb)	10.8 ± 4.1 (stat.) ± 3.4 (syst.) ± 0.3 (lumi.)	23.2 ± 4.3 (stat.) ± 1.7 (syst.) ± 0.6 (lumi.)



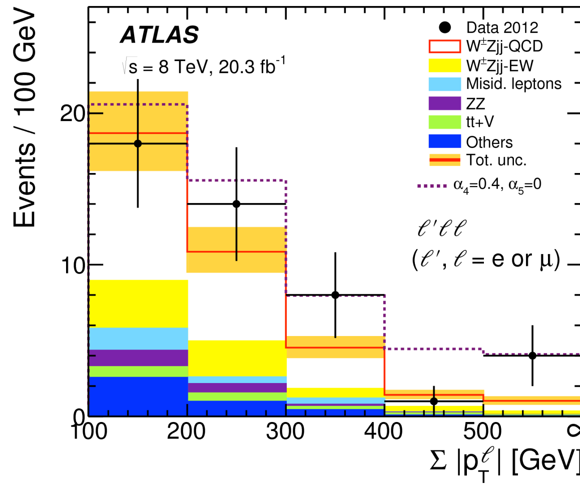


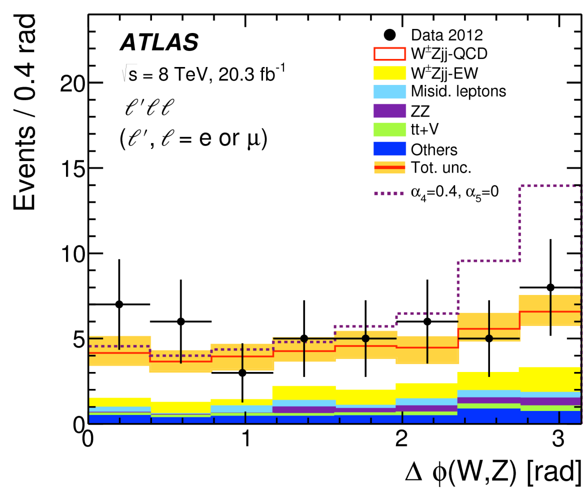


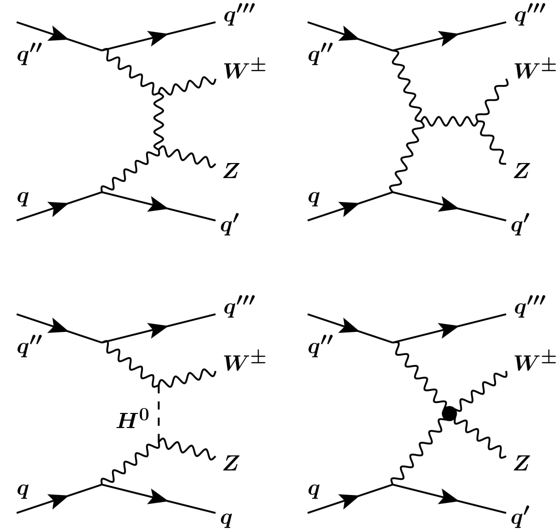
VBS pp → WZjj at 8 TeV
- W(l′ν) and Z(ll) with
- Two jets (p_T >30GeV) with m_{jj}>500 GeV

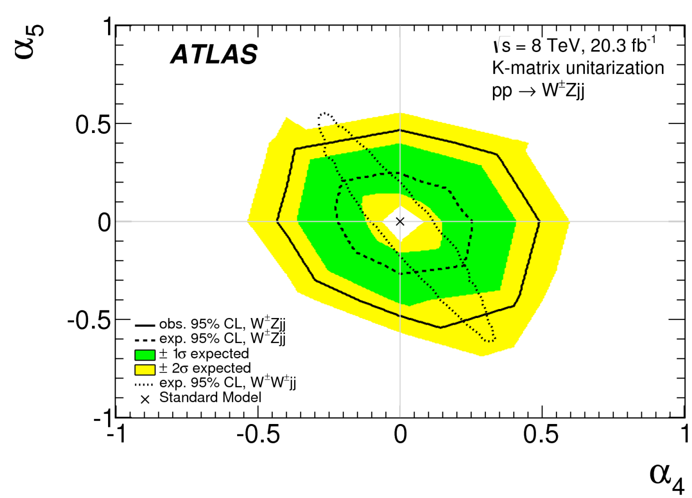


Δ φWZ (>2) and Σp^l_T (>250) used to set limits on aQGC





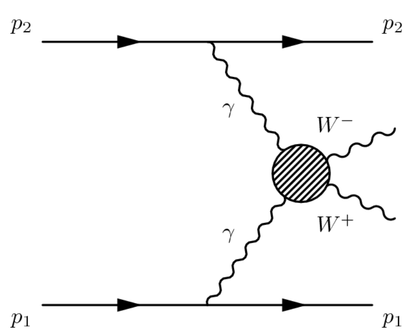


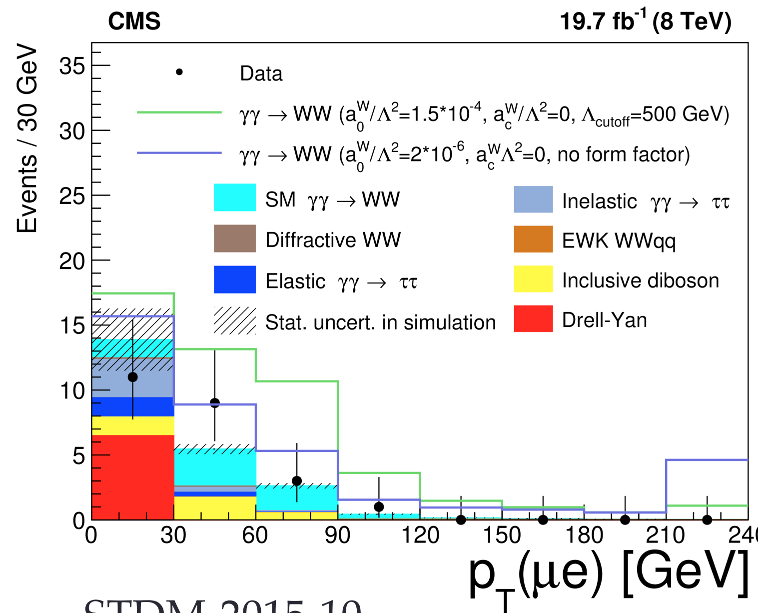


Exclusive $\gamma\gamma \to WW$

arXiv:1604.04464

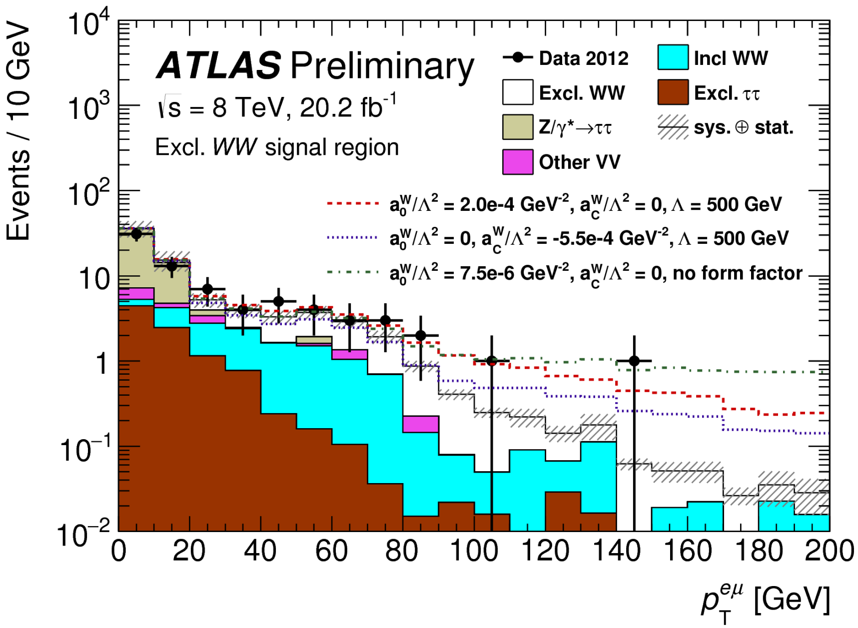
- $pp \to p^{(*)}W^+W^-p^{(*)} \to p^{(*)}\mu^{\pm}e^{\mp}\, p^{(*)}$
- Combined CMS 7&8 TeV, with 3.4σ

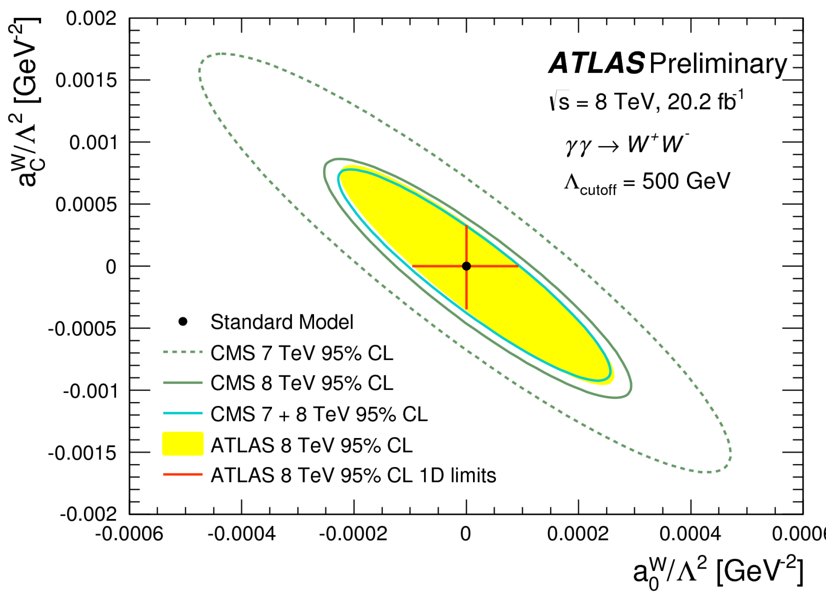




- (new) ATLAS equivalent analysis at 8 TeV

STDM-2015-10





Summary

- Electroweak precision measurements
  - A lot of progress in theoretical and experimental components of precision W mass measurement at the LHC

  - Precise measurements of sin2θeff
    - uncertainties dominated by PDFs and statistics
    - both can be improved with more LHC data

- Multiboson studies
  - Extensive amount of Run-1 (7,8 TeV) measurements with dibosons
  - Observations of triboson and VBS processes
  - Stringent limits on anomalous couplings
  - First diboson cross section measurements from Run-2 (13 TeV)
  - Still a lot more to come with new data