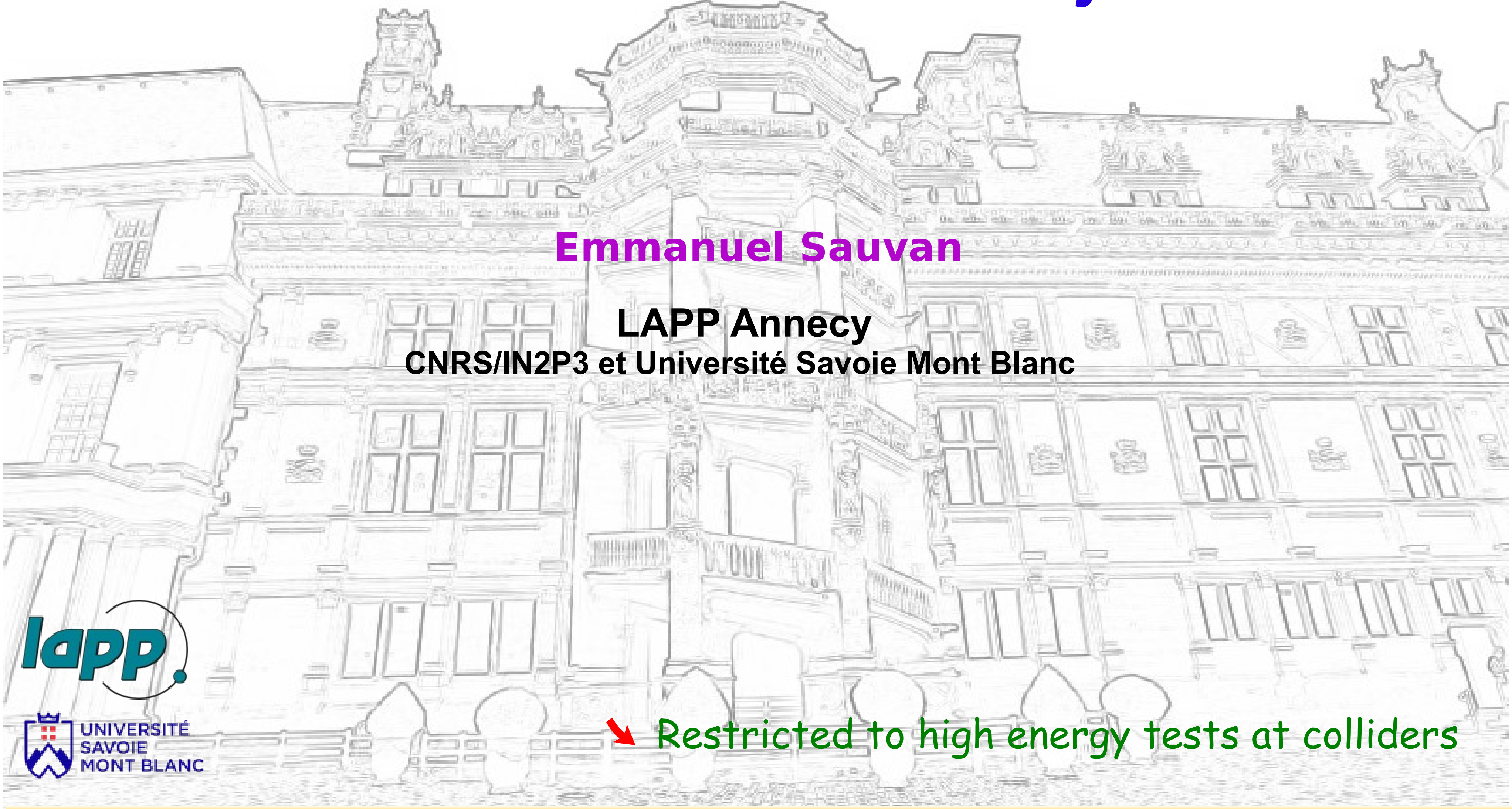
Status of Electroweak Physics



Emmanuel Sauvan

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CNRS/IN2P3 et Université Savoie Mont Blanc

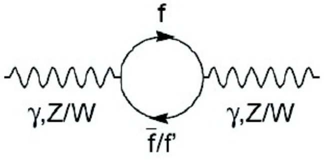
↘ Restricted to high energy tests at colliders

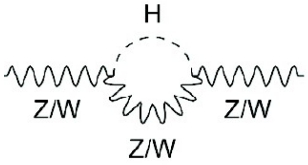
The Standard Electroweak Model

Parameters

➔ Related to Z, W properties

- 3 parameters at tree level: $M_Z = \frac{\enclose{circle}{v}\sqrt{\enclose{circle}{g}^2+\enclose{circle}{g'}^2}}{2}$ $\quad M_W = \frac{v|g|}{2}$ $\quad \cos\theta_W = \frac{M_W}{M_Z}$
- + radiative corrections $M_W^2 = \frac{M_Z^2}{2}\left(1+\sqrt{1-\frac{\sqrt{8}\pi\alpha(1+\Delta r)}{G_F M_Z^2}}\right)$



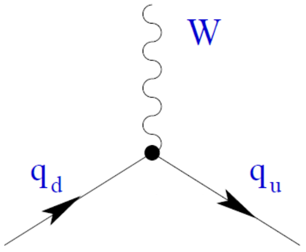


➔ With m_H, the model is over-constraint

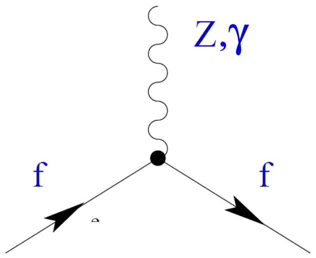
➔ EW precision measurements allows consistency checks of the theory

Interactions

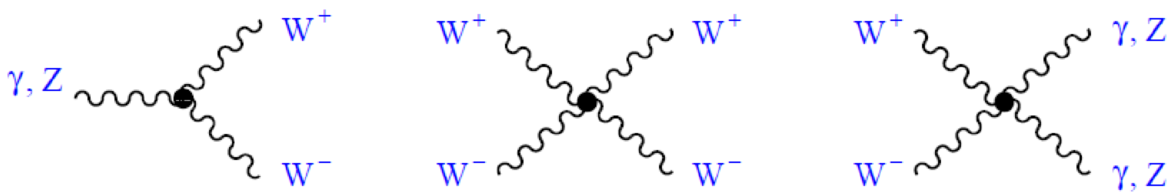
Charged current



Neutral current



Gauge self-interactions



➔ Not precisely measured

➔ Direct test of the gauge structure

Global Electroweak Fit

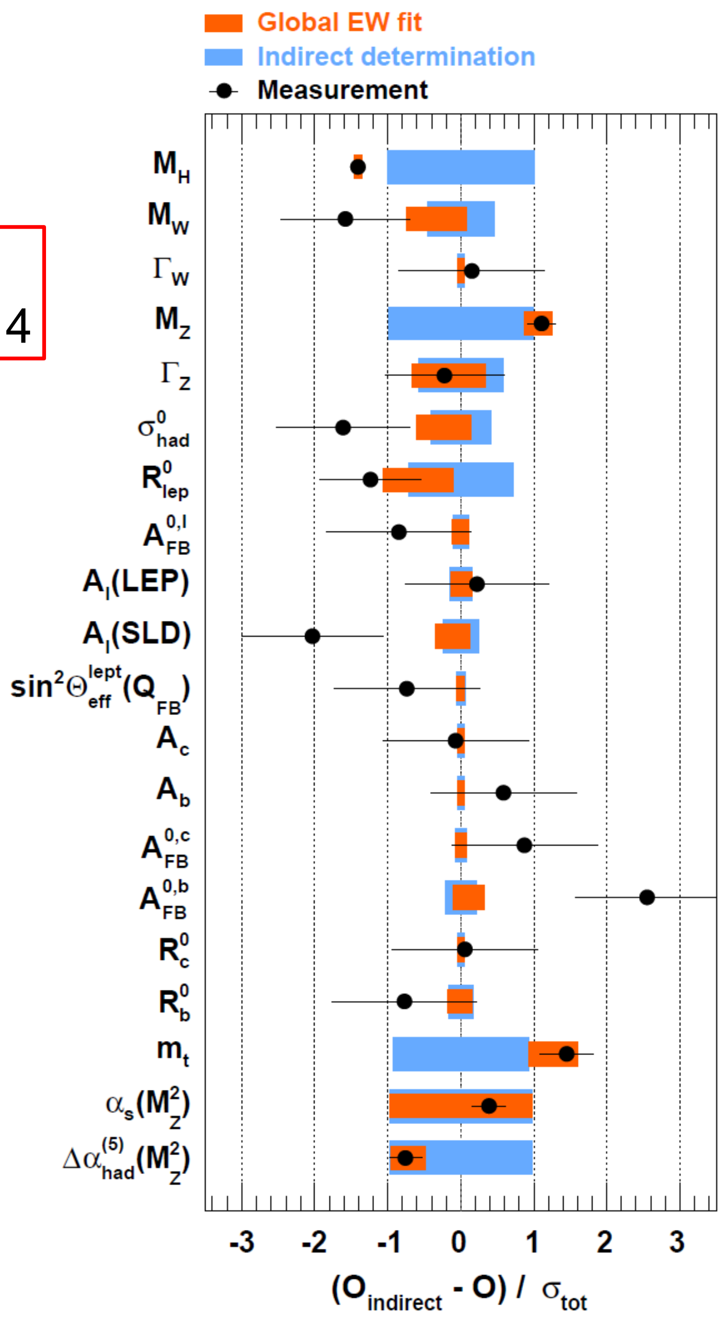
[http://cern.ch/gfitter]

- Radiative corrections:
  - ➔ W, Z measurements sensitive to m_t, m_H

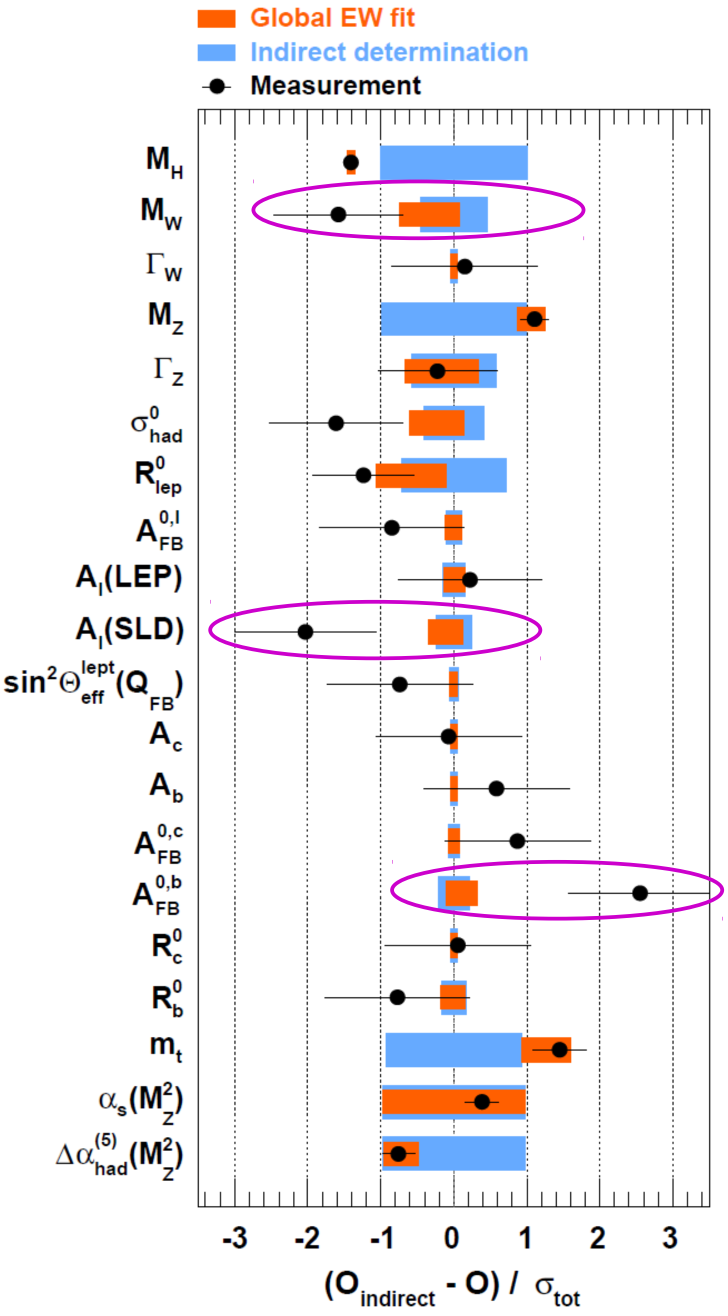
Free parameters in fit

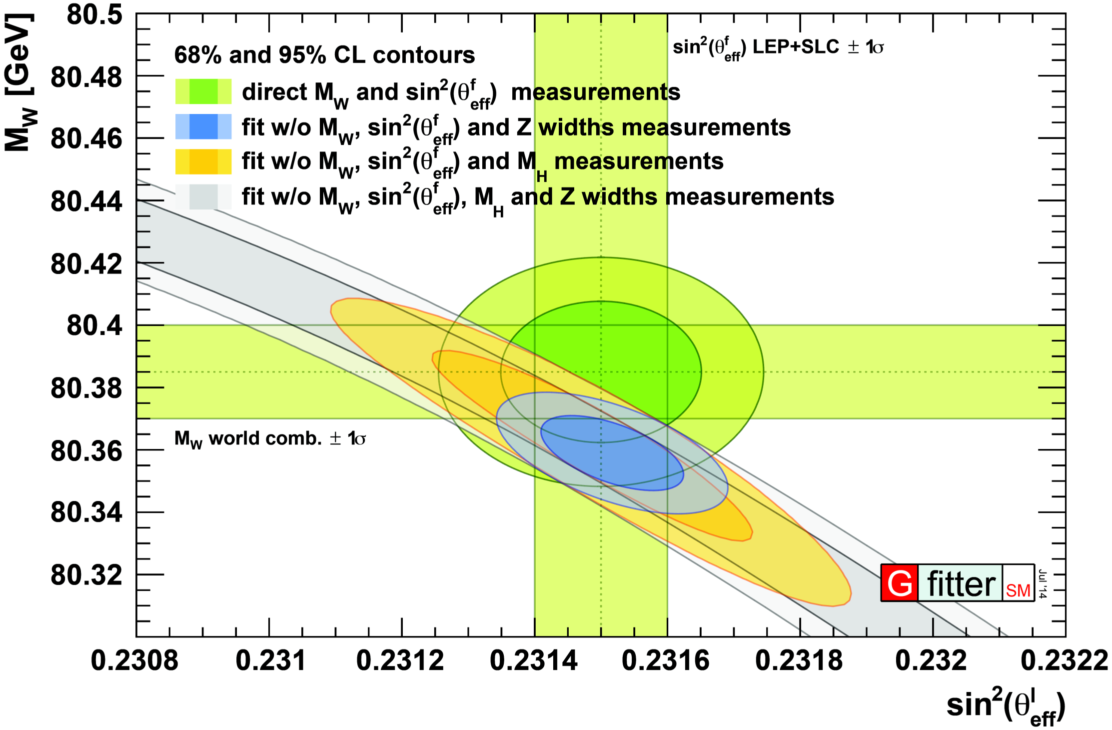
M_H [GeV]	125.14 ± 0.24	LHC
M_W [GeV]	80.385 ± 0.015	Tev.
Γ_W [GeV]	2.085 ± 0.042	
M_Z [GeV]	91.1875 ± 0.0021	LEP
Γ_Z [GeV]	2.4952 ± 0.0023	
$\sigma^0_{\rm had}$ [nb]	41.540 ± 0.037	
R^0_ℓ	20.767 ± 0.025	
$A^{0,\ell}_{\rm FB}$	0.0171 ± 0.0010	
A_ℓ $^{(\star)}$	0.1499 ± 0.0018	SLD
$\sin^2\theta^\ell_{\rm eff}(Q_{\rm FB})$	0.2324 ± 0.0012	
A_c	0.670 ± 0.027	SLD
A_b	0.923 ± 0.020	
$A^{0,c}_{\rm FB}$	0.0707 ± 0.0035	LEP
$A^{0,b}_{\rm FB}$	0.0992 ± 0.0016	
R^0_c	0.1721 ± 0.0030	
R^0_b	0.21629 ± 0.00066	
$\Delta\alpha^{(5)}_{\rm had}(M^2_Z)$	2757 ± 10	low E
$\overline{m}_c$ [GeV]	$1.27^{+0.07}_{-0.11}$	
$\overline{m}_b$ [GeV]	$4.20^{+0.17}_{-0.07}$	
m_t [GeV]	173.34 ± 0.76	Tev.+LHC

χ^2 / n.d.f.
= 17.8 / 14



Global Electroweak Fit

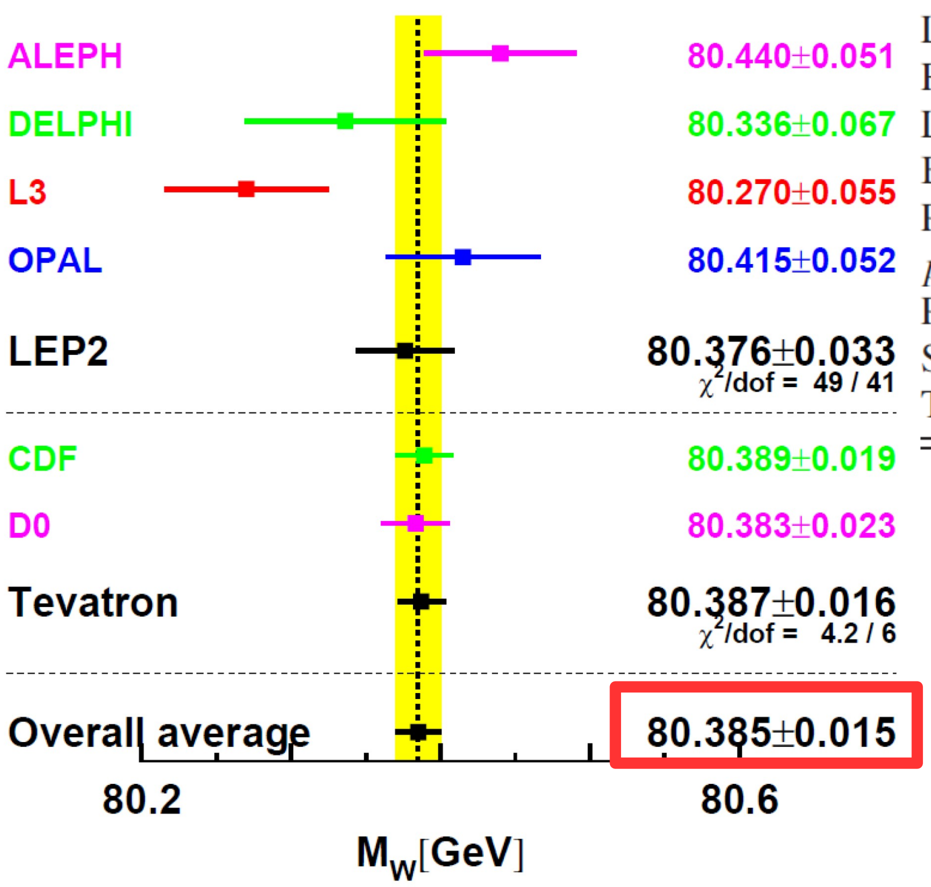




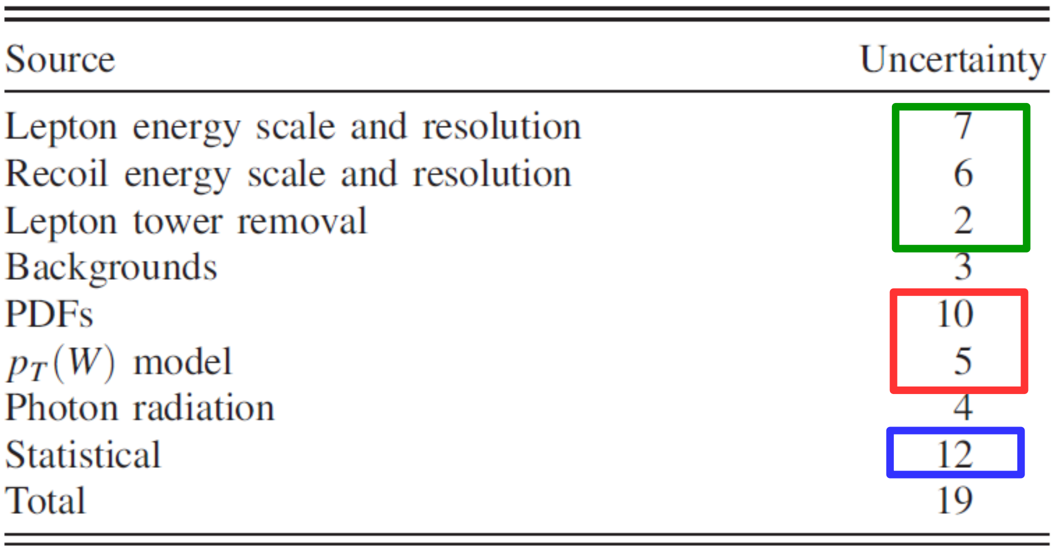
- ➔ m_W has the leading exp. uncertainty in consistency test
- ➔ Discrepancies between asymmetry measurements
  - ➘ Indirect constraints now superior to precise W, Z (m_W, $\sin^2\theta_W$) measurements

Precision on m_W

- $\delta(m_W) < 10$ MeV → Independent check of $\sin^2 \theta^l_{eff}$
- Tevatron is still leading this measurement : $\delta(m_W) = 16$ MeV



[Chin. Phys. C38 (2014) 090001]



Source	Uncertainty
Lepton energy scale and resolution	7
Recoil energy scale and resolution	6
Lepton tower removal	2
Backgrounds	3
PDFs	10
$p_T(W)$ model	5
Photon radiation	4
Statistical	12
Total	19

→ Presently δ(stat.) ~ δ(inst.) ~ δ(QCD)

- Measurement is ongoing at the LHC

→ Facing δ(QCD) > δ(inst.) > δ(stat.)

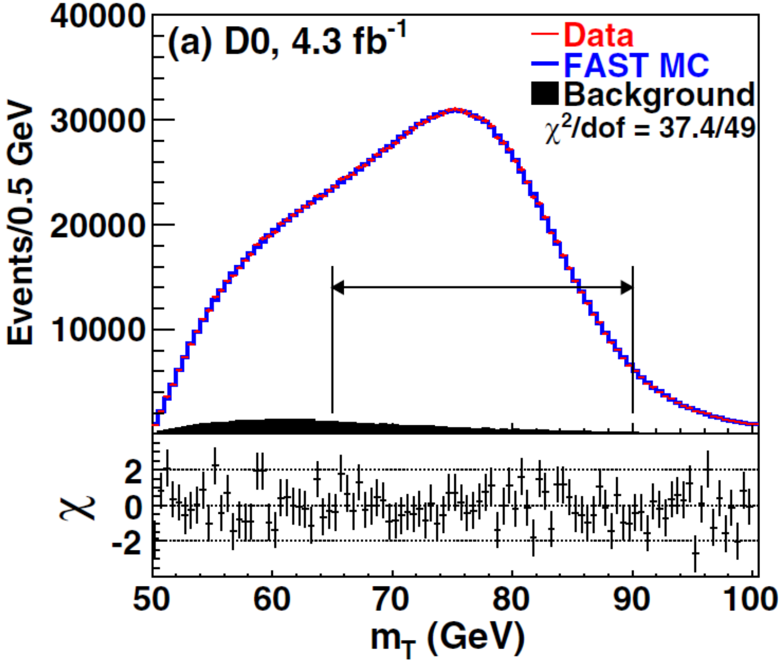
↘ m_W measurements now dominated by modeling

m_W Measurement Strategy

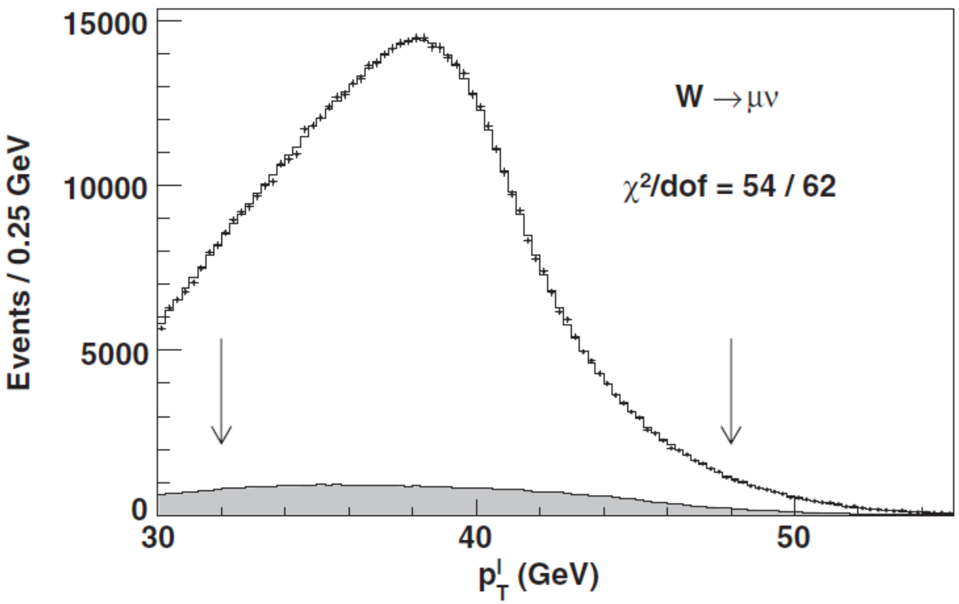
- Fits to transverse distributions: p_T^{lepton}, p_T^{ν}, m_T^W

$$m_T = \sqrt{2 p_T^{\ell} p_T^{\nu} (1 - \cos\Delta\phi)}$$

[D0, PRD 89 (2014) 012005]



[CDF, PRD 89 (2014) 072003]



➔ m_T^W more sensitive to experimental effects (pile-up at the LHC)

➔ p_T^{lepton} more sensitive to theory uncertainties: PDFs, p_T^W modeling

➘ Constraint the physics model

➘ Minimise the model dependence in the analysis

PDF effects on p_T^l, m_T^W distributions

- Effect of u_v, d_v and sea uncertainties on W polarisation

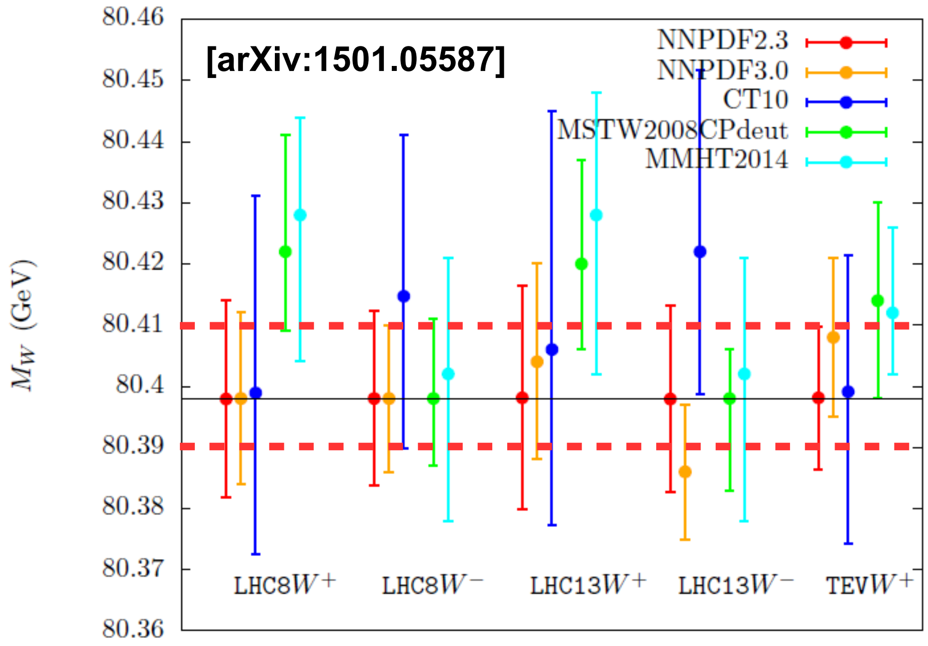
→ More pronounced in pp than $p\bar{p}$

→ Directly affect p_T^{lepton}

[Krasny et al, EPJ C69 (2010) 379]

- Effect of charm initiated W production

→ Harder p_T^W

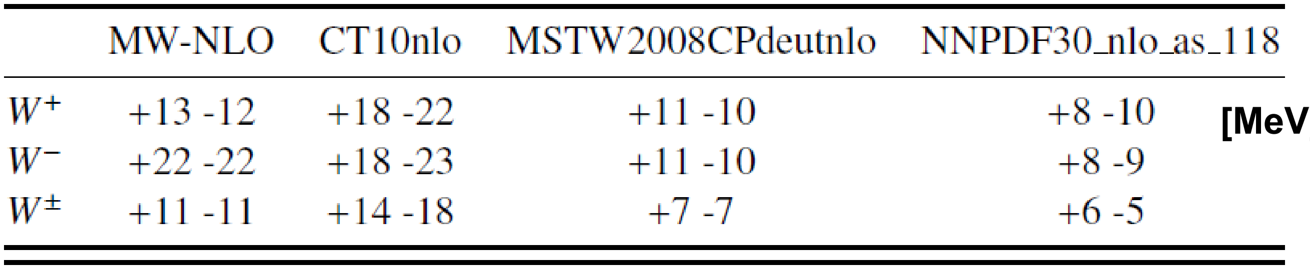


[arXiv:1501.05587]

➘ ~ 10 MeV uncertainty

➘ But 20-30 MeV from differences between PDF sets

PDF uncertainties on m_W



	MW-NLO	CT10nlo	MSTW2008CPdeutnlo	NNPDF30_nlo_as_118
W^+	+13 -12	+18 -22	+11 -10	+8 -10
W^-	+22 -22	+18 -23	+11 -10	+8 -9
$W^\pm$	+11 -11	+14 -18	+7 -7	+6 -5

[MeV]

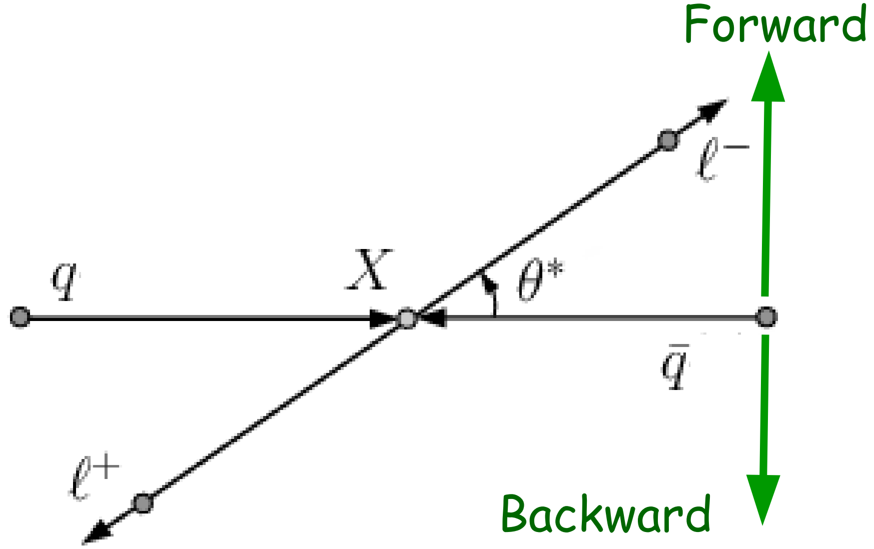
[ATL-PHYS-PUB-2014-015]

Measurement of $\sin^2\theta_W$ in pp or $p\bar{p}$

- In Drell-Yan Z events $q\bar{q} \rightarrow Z/\gamma^* \rightarrow \ell^+\ell^-$

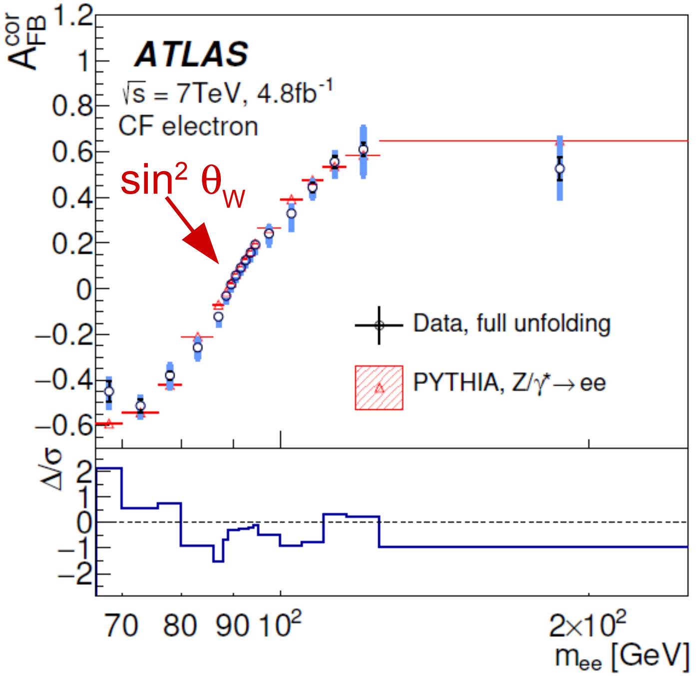
➔ Vector and axial-vector couplings

➔ Asymmetry in the distribution of negative lepton polar angle wrt. axis of the incoming quark, in the dilepton CM,



- Forward-Backward asymmetry:

$$A_{FB} = \frac{\sigma_F - \sigma_B}{\sigma_F + \sigma_B}$$



➔ A_{FB} depends on flavour, charge of initial partons

➘ PDF dependence

➔ In pp: direction of q ambiguous

➘ Dilution

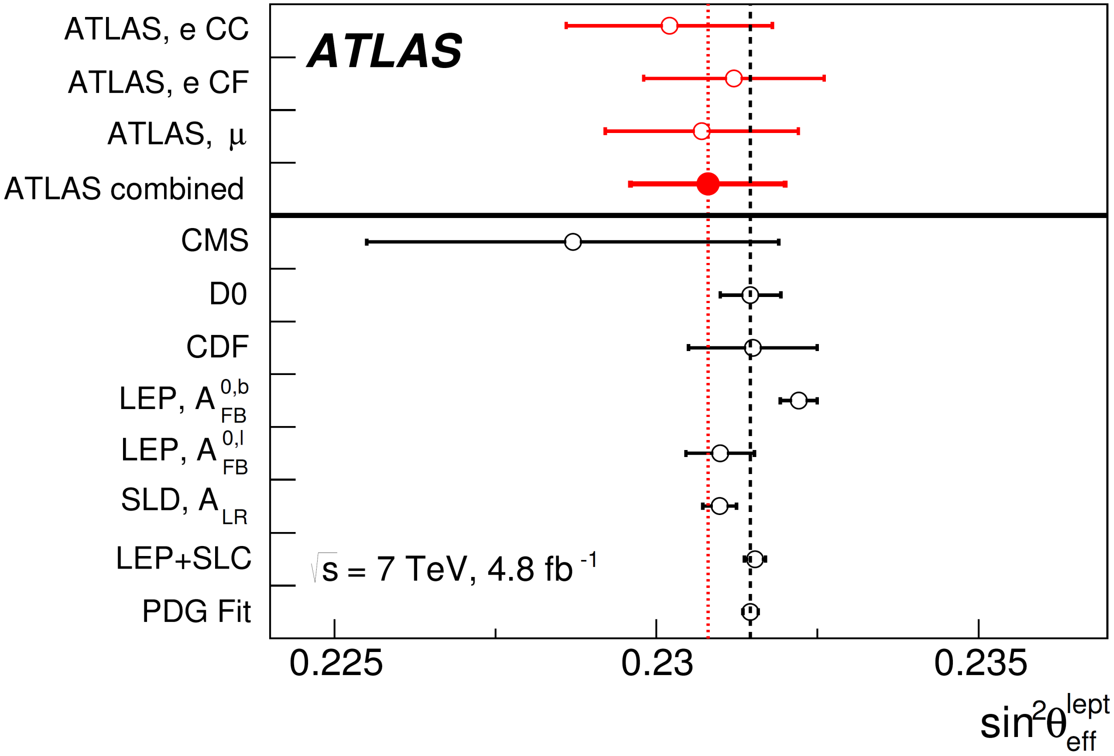
$\sin^2\theta_W$: a recent measurement at LHC

[ATLAS arXiv:1503.03709]

- Use of forward electrons with central-forward topologies

  ➔ Best sensitivity

Uncertainty source	CC electrons $[10^{-4}]$	CF electrons $[10^{-4}]$	Muons $[10^{-4}]$	Combined $[10^{-4}]$
PDF	10	10	9	9
MC statistics	5	2	5	2
Electron energy scale	4	6	–	3
Electron energy resolution	4	5	–	2
Muon energy scale	–	–	5	2
Higher-order corrections	3	1	3	2
Other sources	1	1	2	2
Stat.	9	7	9	5



- Agreement with PDG value at 0.6 σ
- D0 and CDF measurements also with a large PDF uncertainty.

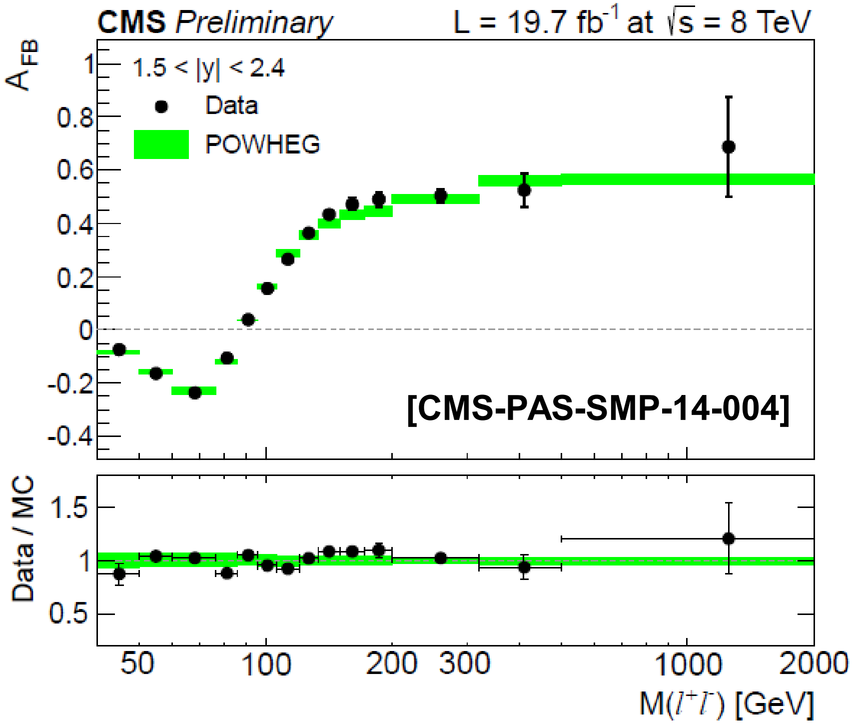
[CDF PRD 89 (2014) 072003]
[D0 arXiv:1408.5016]

➘ Future precision limited by PDFs

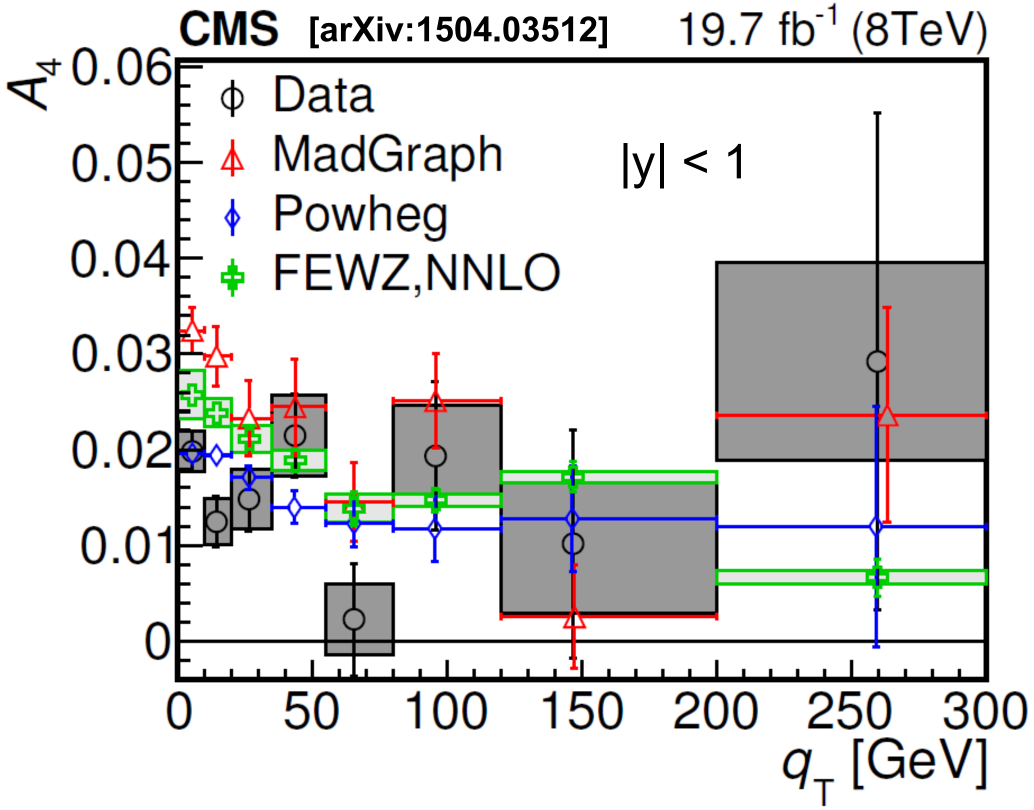
Drell-Yan lepton pairs at 8 TeV

- Recent A_{FB} measurement at 8 TeV by CMS

➔ Muon and electrons pairs



- As well as Z angular coefficients



➔ Muon pairs only

➔ A_4 sensitive to sin θ_W

[CDF PRD 88 (2013) 072002]

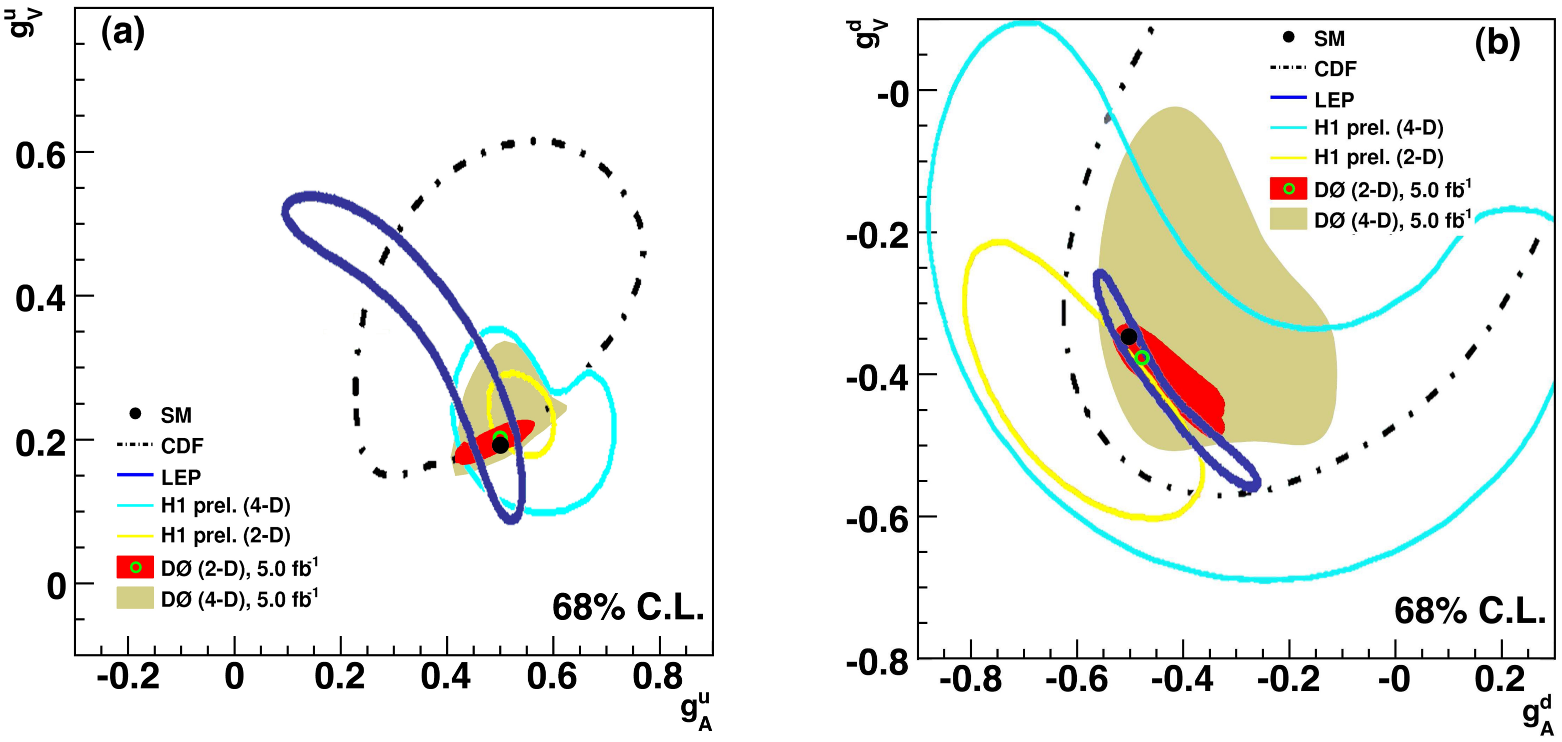
➘ Next step: $\sin^2 \theta_{eff}^{lept}$

Quark couplings

[D0 PRD 84 (2011) 012007]
[H1 prelim-10-042 (2010)]

- DY Z events also sensitive to Z-q couplings

➔ Obtained by fixing Z-l couplings and $\sin^2\theta_W$

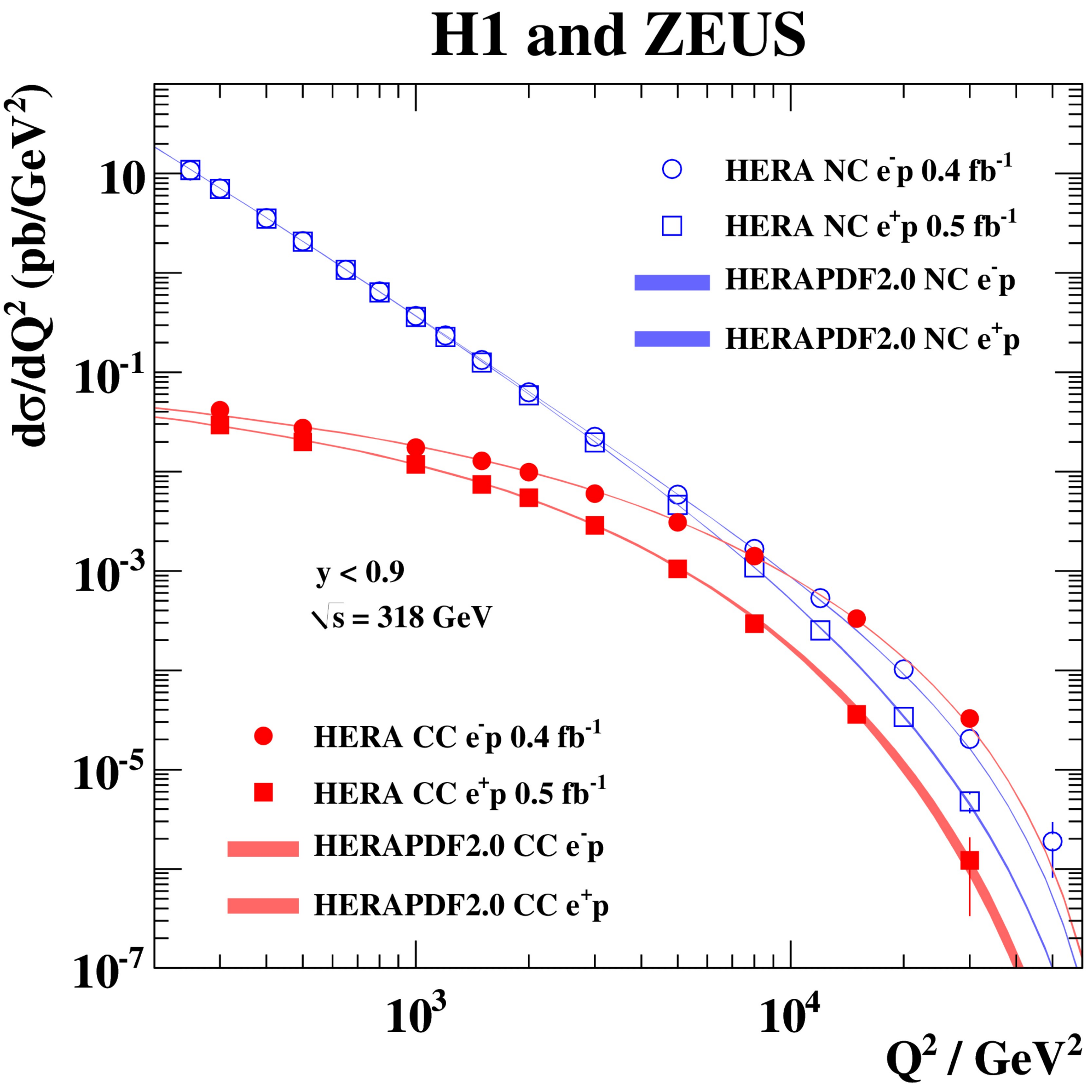


➘ Most precise measurements

- Neutral Current and Charge current in e-p interactions can also be exploited

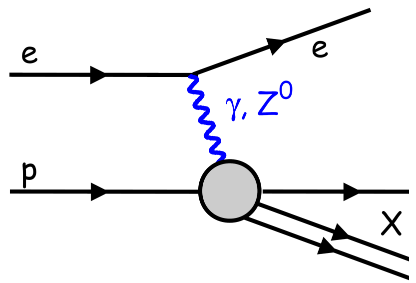
NC, CC Interactions: Electroweak Unification

- A legacy textbook picture from HERA

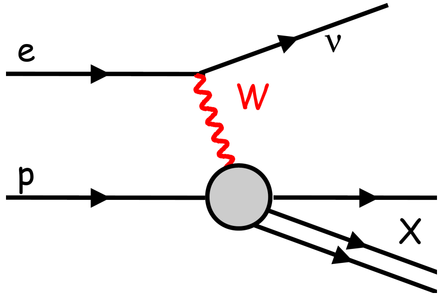


➘ Final HERA result

Neutral current



Charged current

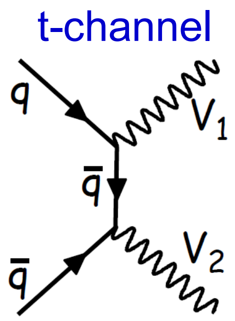


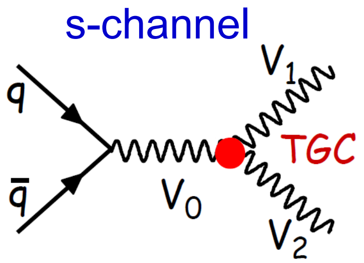
- At hight scales CC and NC become of similar magnitude

Triple Gauge Boson Self Couplings

- First observed at LEP, Tevatron

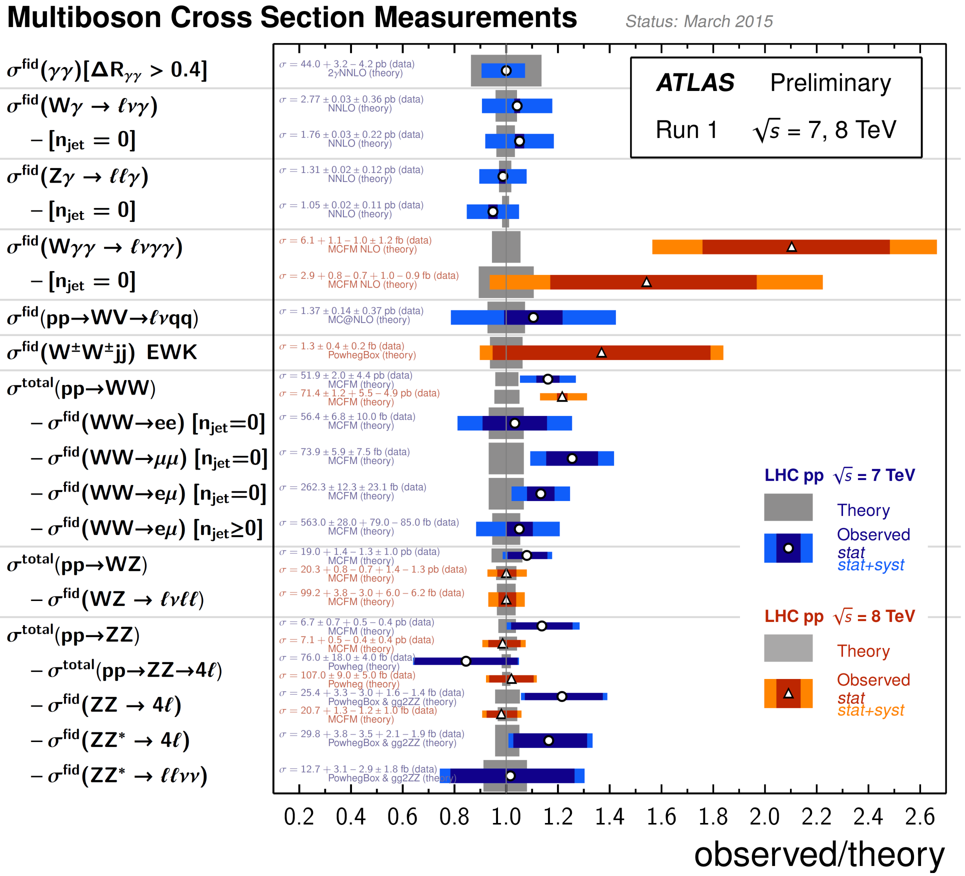
➔ Diboson final states:
γγ, Wγ, Zγ, WW, WZ, ZZ



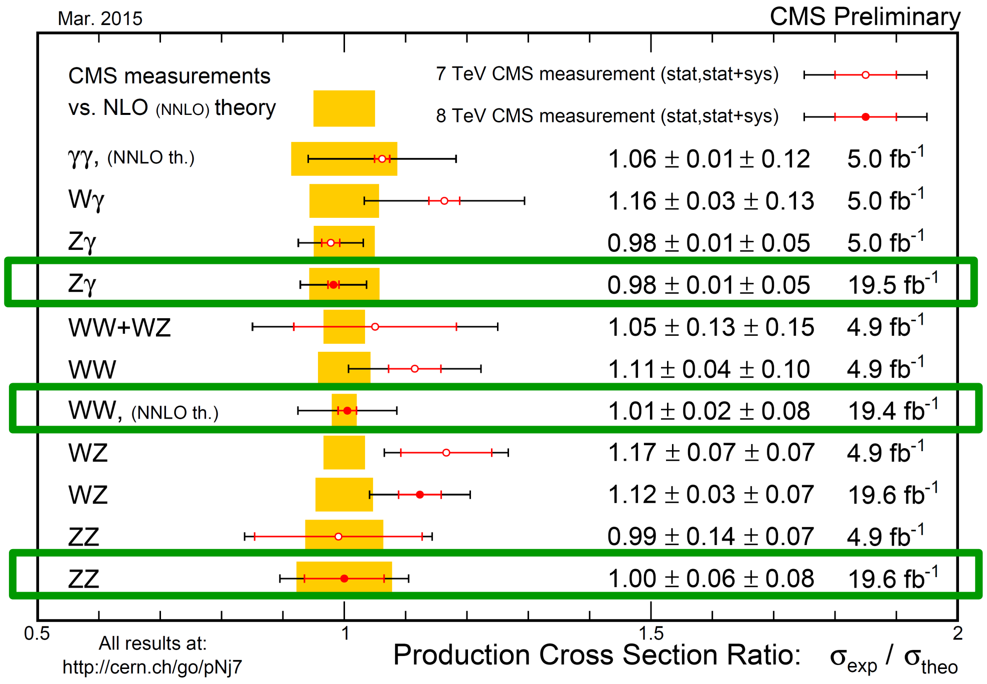


In SM: only charged TGCs
(Wγ, WW, WZ)

ATLAS



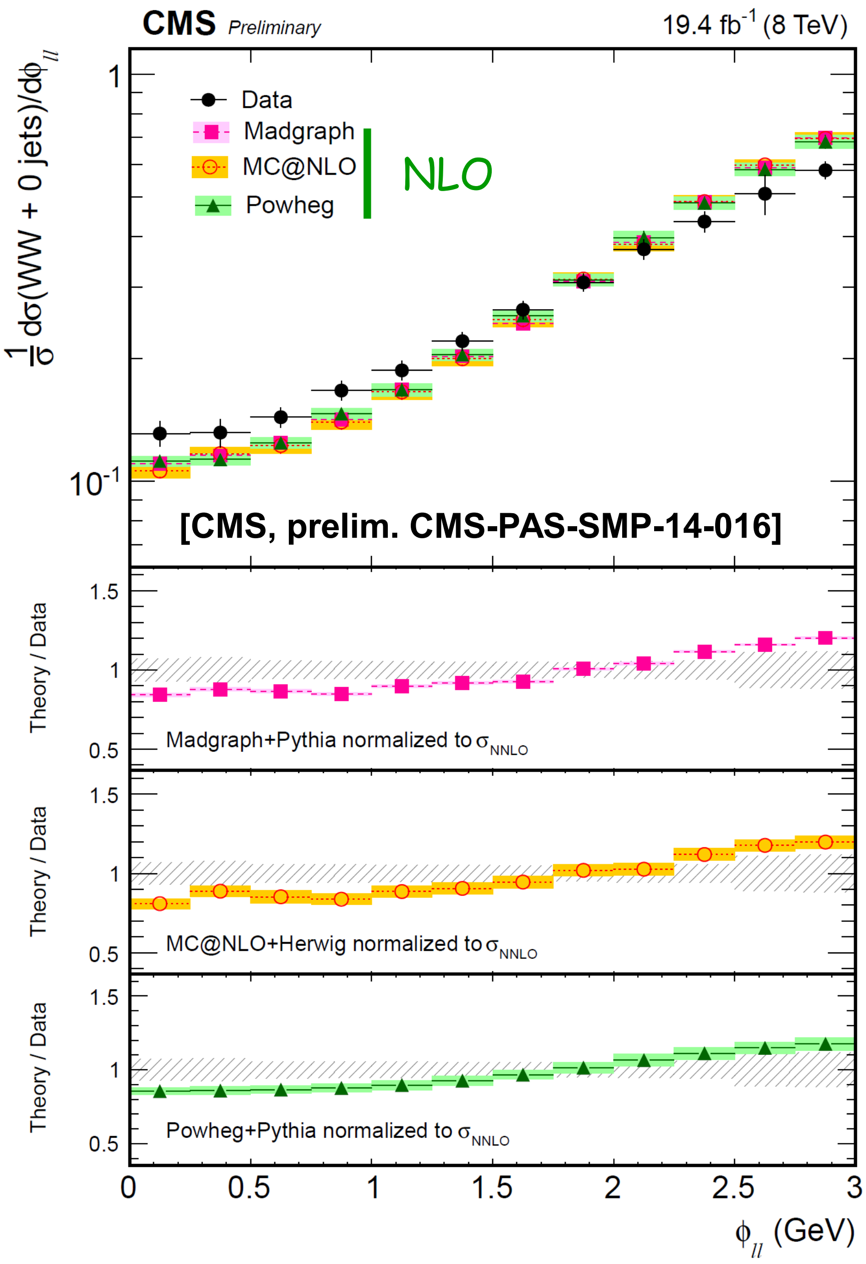
CMS



➘ Now, from observation to precision measurements at LHC

$WW \rightarrow 2l\ 2\nu$

- Large statistics with LHC 8 TeV data



[CMS, prelim. CMS-PAS-SMP-14-016]

➔ Precise differential measurements

- Total cross section:

CMS: $\sigma_{tot.} = 60.1 \pm 0.9\,(\text{stat.}) \pm 3.2\,(\text{exp.})$
$\boxed{\pm 3.1\,(\text{th.})} \pm 1.6\,(\text{lumi.})$ pb

ATLAS: (H → WW* included)

$$\sigma_{tot.} = 71.4 \pm 1.2\,(\text{stat.})^{+5.0}_{-4.4}\,(\text{sys.})^{+2.2}_{-2.1}(\text{lumi.})\ \text{pb}$$

[ATLAS-CONF-2014-033]

Predicted:

$$\sigma^{NNLO}_{th.} = 59.8 \pm 2.1\ \text{pb}$$

$$\sigma^{H \rightarrow WW*}_{th.} = 4.1 \pm 7.5\ \text{pb}$$

➔ Agreement with NNLO prediction

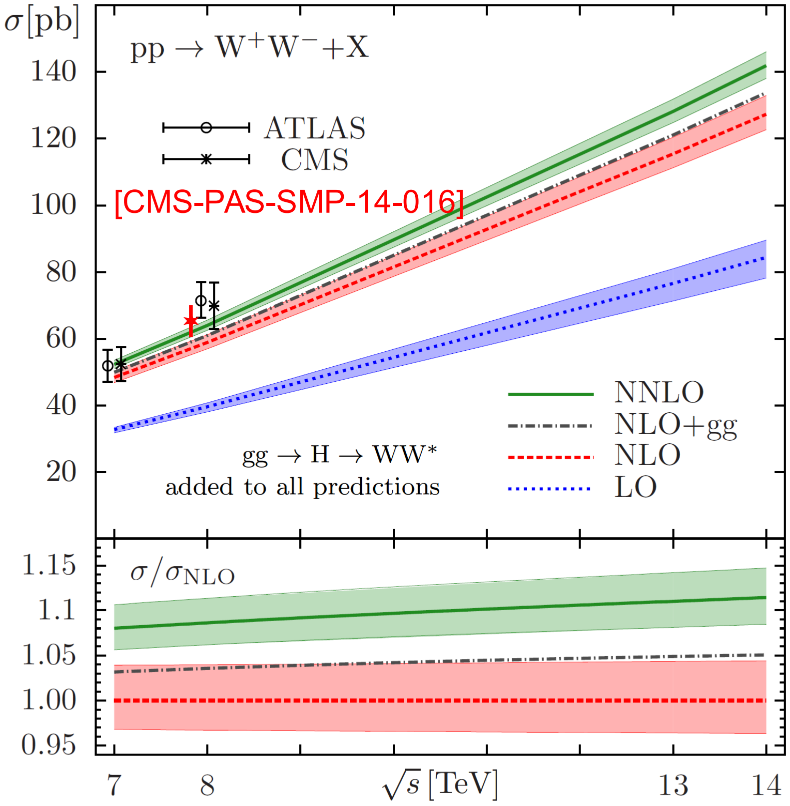
➔ Theory uncertainties affects the measurement

➘ *A fair assessment of theory uncertainties is needed to compare to data*

WW: theory limitations

- Large NNLO QCD corrections (9-12%)

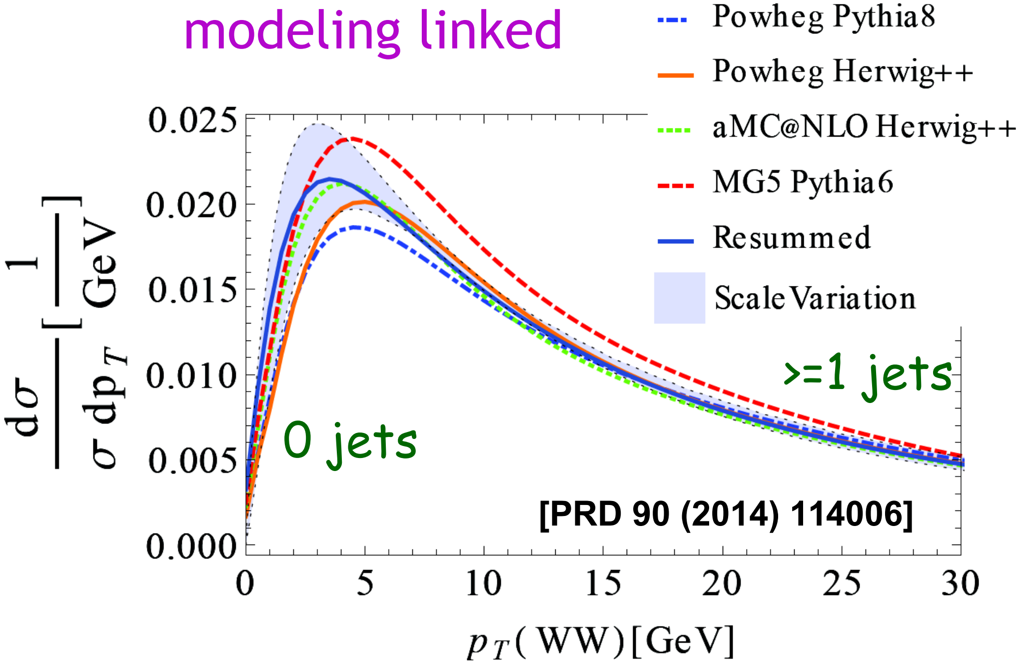
[PRL 113 (2014) 212001]



[CMS-PAS-SMP-14-016]

- NLO EW corrections also important
  - ➔ Calculations for WW including leptons decays **[arXiv:1310.1564]**

- 0-jet veto used to reduce $t\bar{t}$ background
  - ➔ Enhance sensitivity to QCD corrections **[PRD 90 (2014) 073009] [arXiv:1410.4745]**
  - ➔ Jet multiplicity and p_T^{WW} modeling linked



[PRD 90 (2014) 114006]

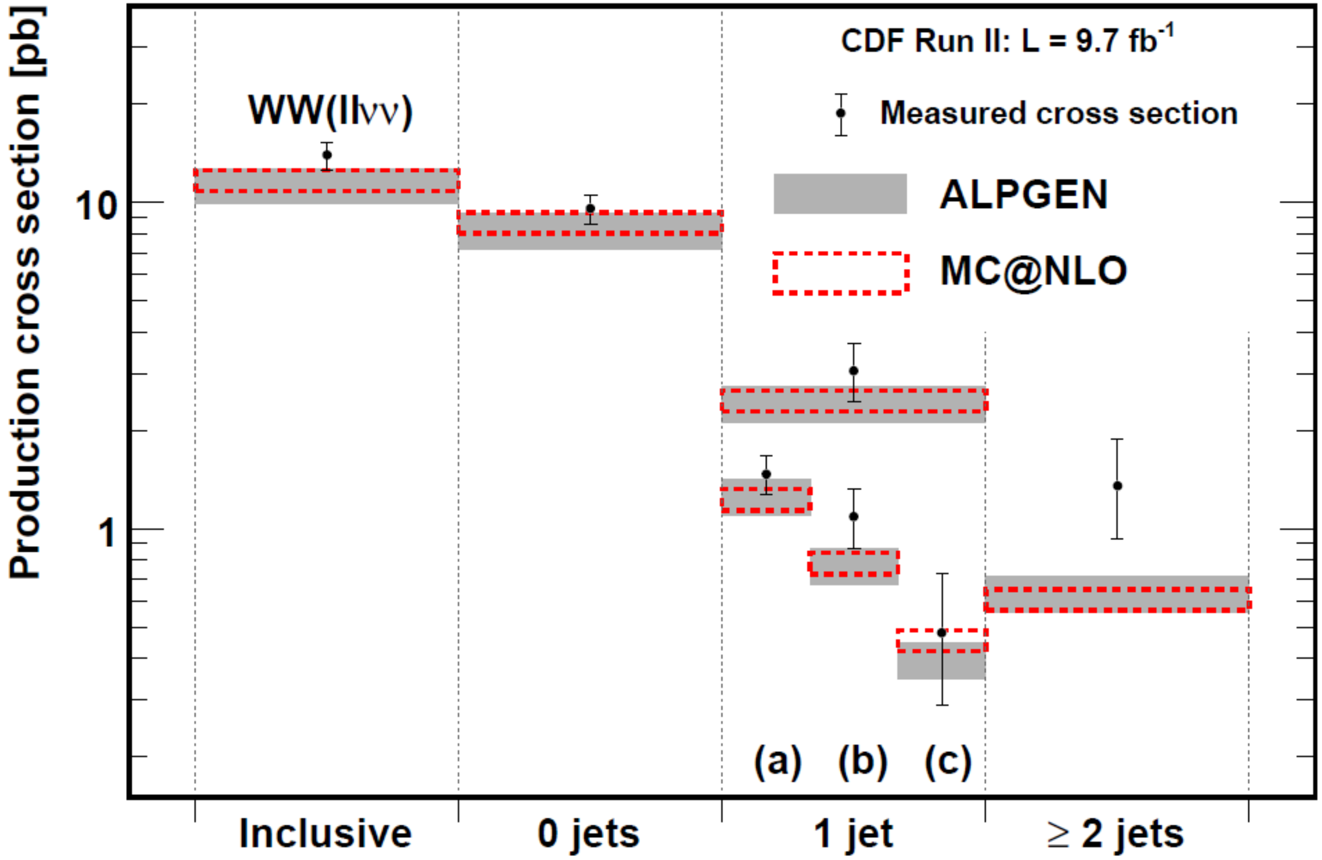
➘ Better compare fiducial than total cross sections

WW: jet multiplicity measurement

[CDF, arXiv:1505.00801]

- At the Tevatron, using the full Run II data set

➔ b-jet tag and neural network used to reduce $t\bar{t}$ background



(a): 15 < E_T^{jet} < 25 GeV

(b): 25 < E_T^{jet} < 45 GeV

(c): E_T^{jet} > 45 GeV

ZZ and Zγ

[CMS, PLB 740 (2015) 250]
[CMS, arXiv:1503.05467]

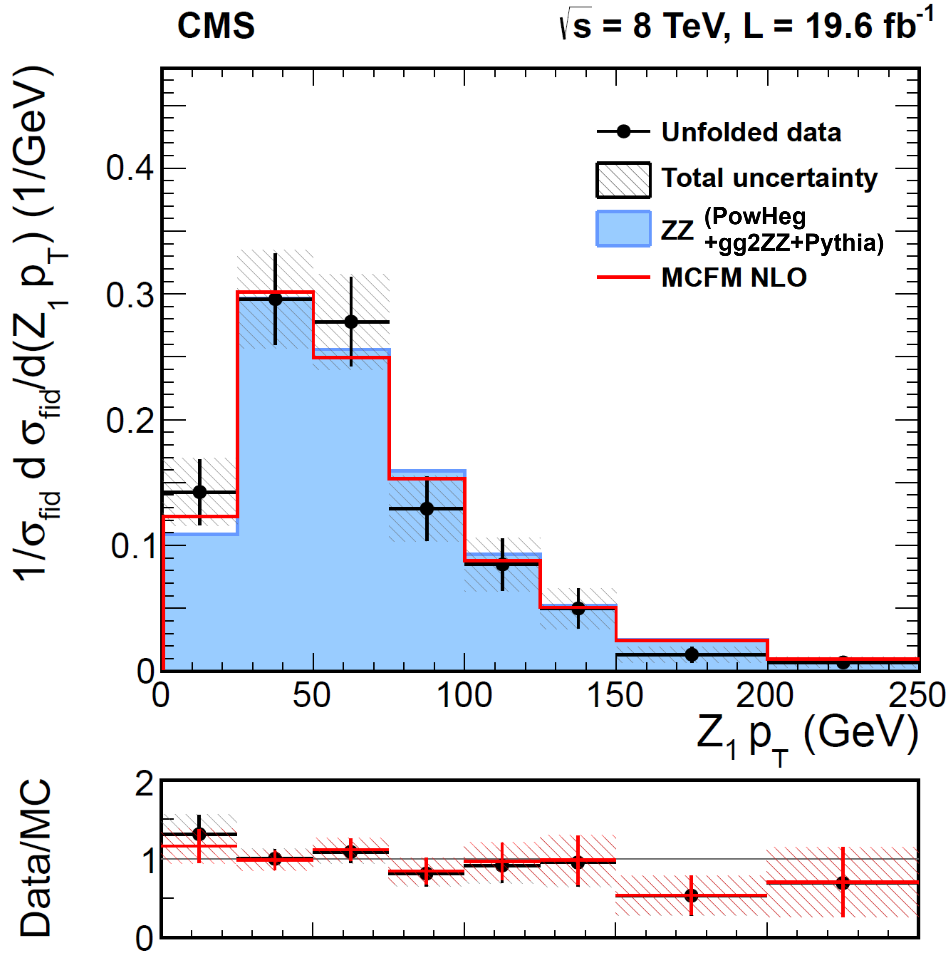
[CMS, JHEP 04 (2015) 164]

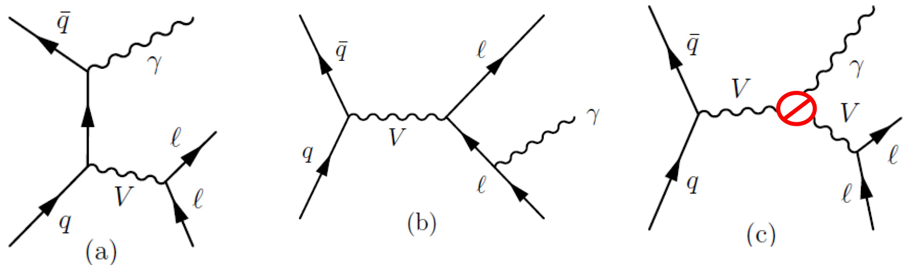
➔ Exploit the full 8 TeV data

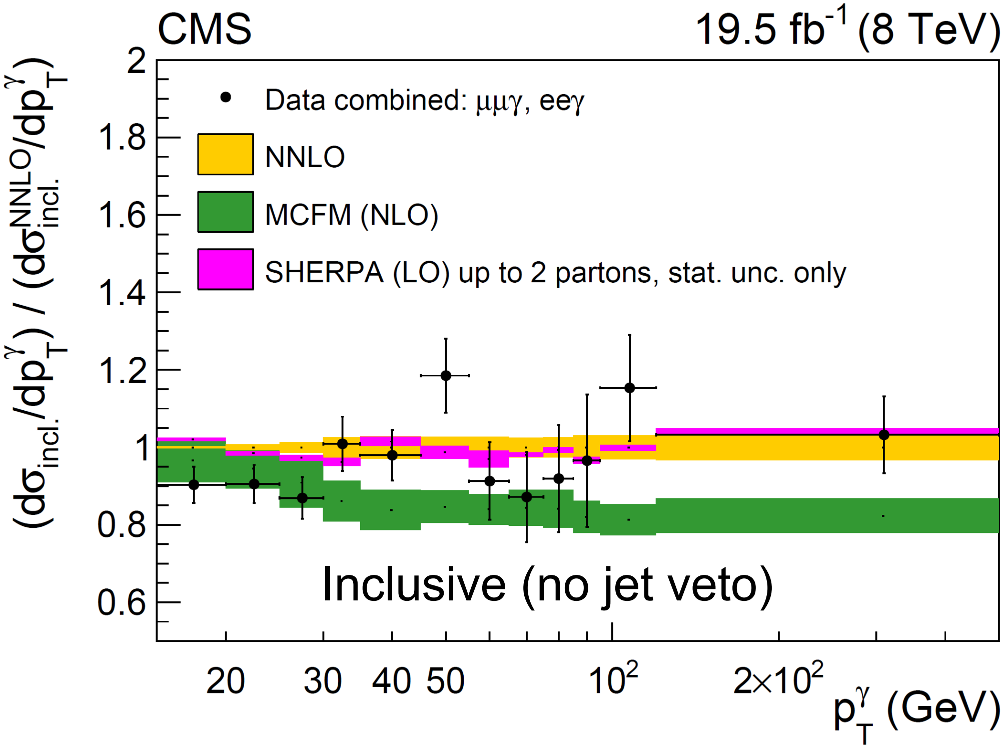
- ZZ → llll and ZZ → llνν

➔ tau decays also considered

- Zγ → llγ







➘ Agreement with NNLO

Charged Anomalous Triple Gauge Couplings

➔ Low energy effects from high scale New Physics

- General Lagrangian for WWV conserving C and P

$$\begin{aligned}\mathcal{L}^{\text{eff}}_{WWV} &= ig_{WWV}\Big[\boxed{g_1^V}(W^+_{\mu\nu}W^{-\mu} - W^{+\mu}W^-_{\mu\nu})V^\nu \\ &\quad + \boxed{\kappa_V}W^+_\mu W^-_\nu V^{\mu\nu} \\ &\quad + \frac{\boxed{\lambda_V}}{M_W^2}W^{+\nu}_\mu W^{-\rho}_\nu V^\mu_\rho\Big]\end{aligned}$$

- For SM: $g_1^\gamma = g_1^Z = \kappa_\gamma = \kappa_Z = 1$

$$\lambda_\gamma = \lambda_Z = 0$$

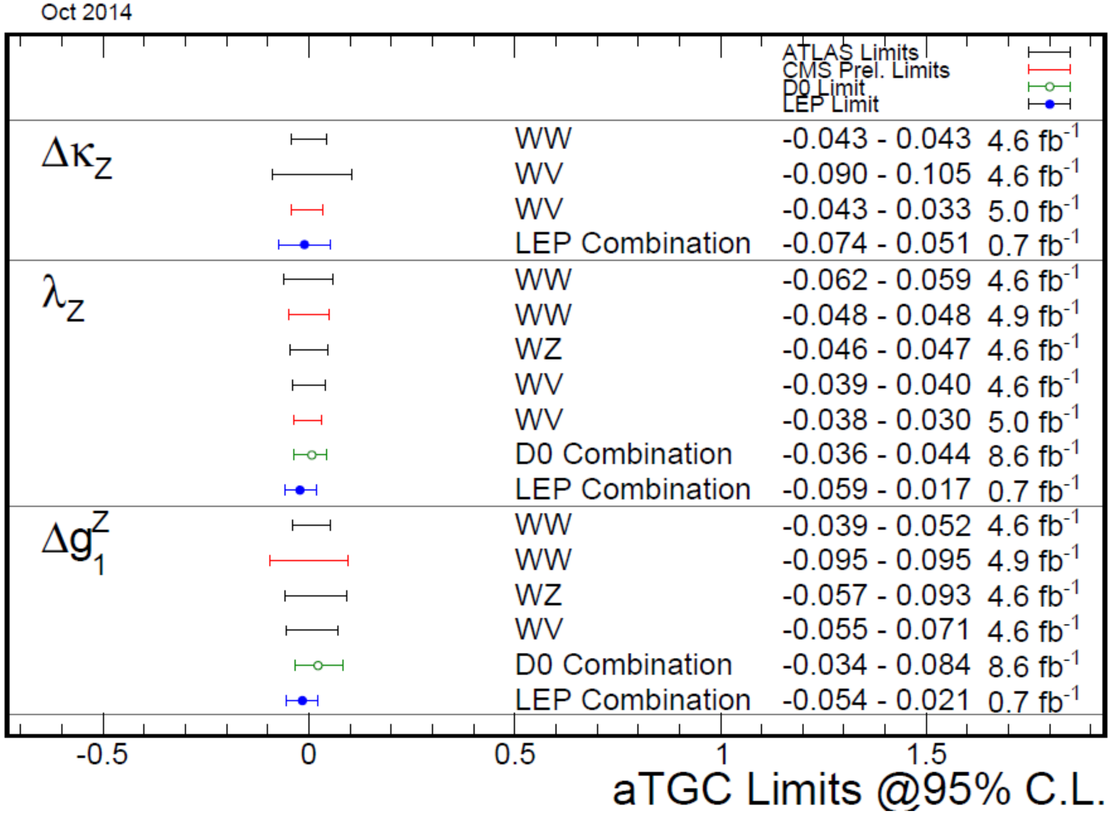
- W magnetic moment:

$$\mu_W = \frac{e}{2m_W}(1 + \kappa_\gamma + \lambda_\gamma)$$

- W electric quadrupole moment:

$$Q_W = -\frac{e}{m_W^2}(\kappa_\gamma - \lambda_\gamma)$$

- Charged aTGCs WWZ



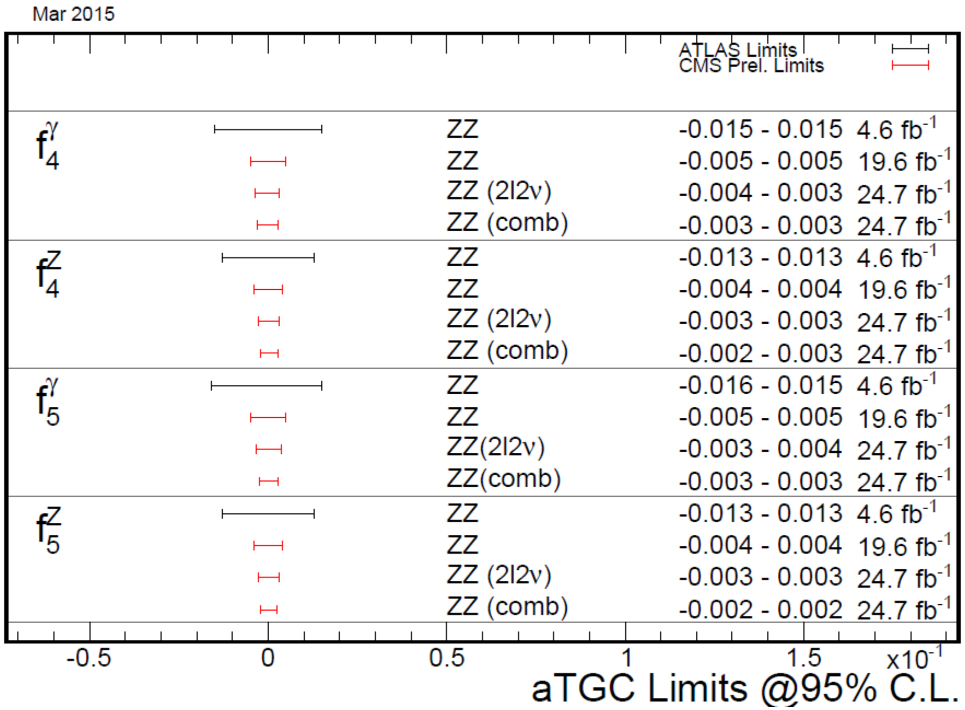
$\Delta\kappa_Z$	WW	-0.043 - 0.043	4.6 fb^{-1}
	WV	-0.090 - 0.105	4.6 fb^{-1}
	WV	-0.043 - 0.033	5.0 fb^{-1}
	LEP Combination	-0.074 - 0.051	0.7 fb^{-1}
λ_Z	WW	-0.062 - 0.059	4.6 fb^{-1}
	WW	-0.048 - 0.048	4.9 fb^{-1}
	WZ	-0.046 - 0.047	4.6 fb^{-1}
	WV	-0.039 - 0.040	4.6 fb^{-1}
	WV	-0.038 - 0.030	5.0 fb^{-1}
	D0 Combination	-0.036 - 0.044	8.6 fb^{-1}
	LEP Combination	-0.059 - 0.017	0.7 fb^{-1}
Δg_1^Z	WW	-0.039 - 0.052	4.6 fb^{-1}
	WW	-0.095 - 0.095	4.9 fb^{-1}
	WZ	-0.057 - 0.093	4.6 fb^{-1}
	WV	-0.055 - 0.071	4.6 fb^{-1}
	D0 Combination	-0.034 - 0.084	8.6 fb^{-1}
	LEP Combination	-0.054 - 0.021	0.7 fb^{-1}

➘ Only using 7 TeV data, LHC limits are now as stringent as LEP or Tevatron ones

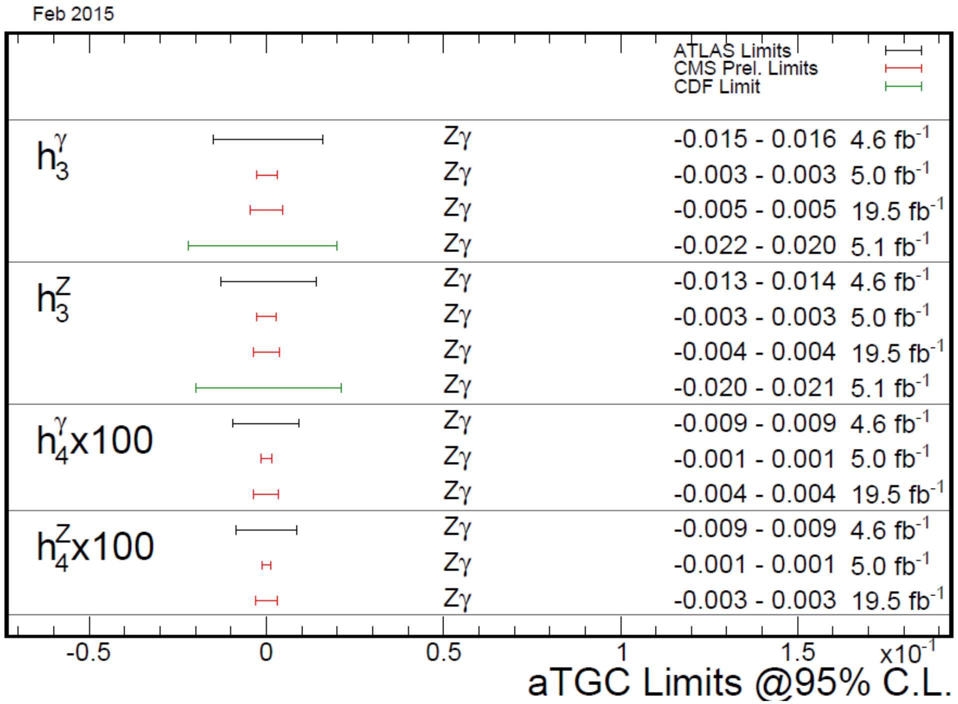
Neutral aTGCs

- Forbidden in the SM when all particles are on shell

➔ ZZZ, ZγZ

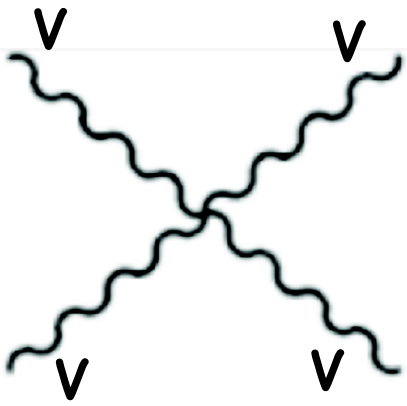


➔ ZZγ, Zγγ



➘ LHC limits now dominate

Quartic Gauge Boson Self Couplings



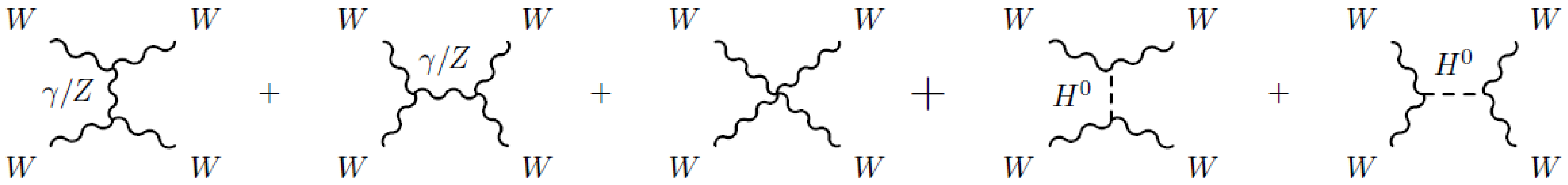
Probed via:

- 3 bosons productions
- γγ exclusive production γγ → WW
- Vector Boson Scattering

➘ First evidences with 8 TeV LHC data

- Vector Boson Scattering

$$\mathcal{A}(W_L W_L \to W_L W_L) \propto \frac{g_W^2}{v^2}\left[-s-t+\frac{s^2}{s-m_H^2}+\frac{t^2}{t-m_H^2}\right]$$

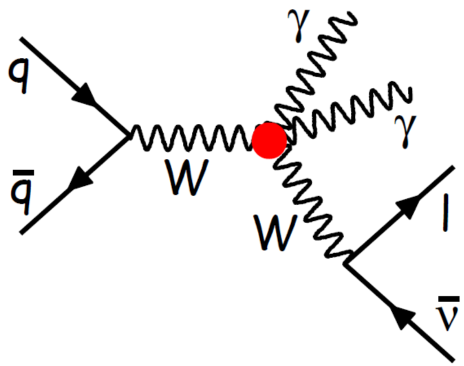


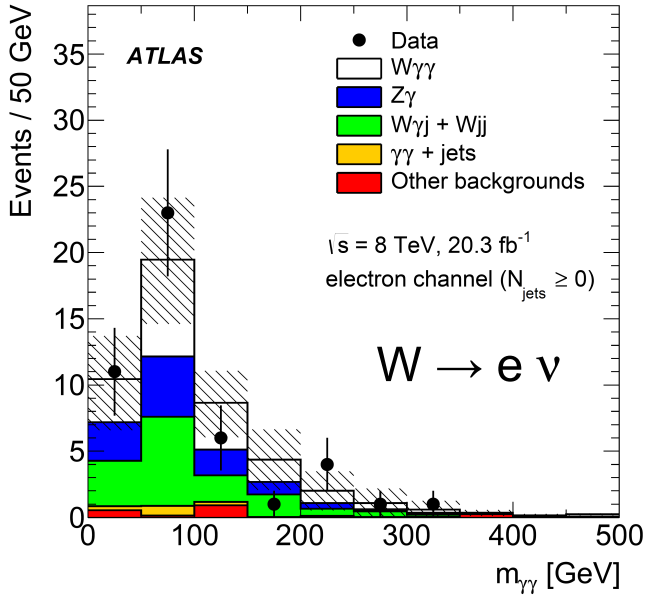
➔ Direct probe of the nature of the EWSB mechanism

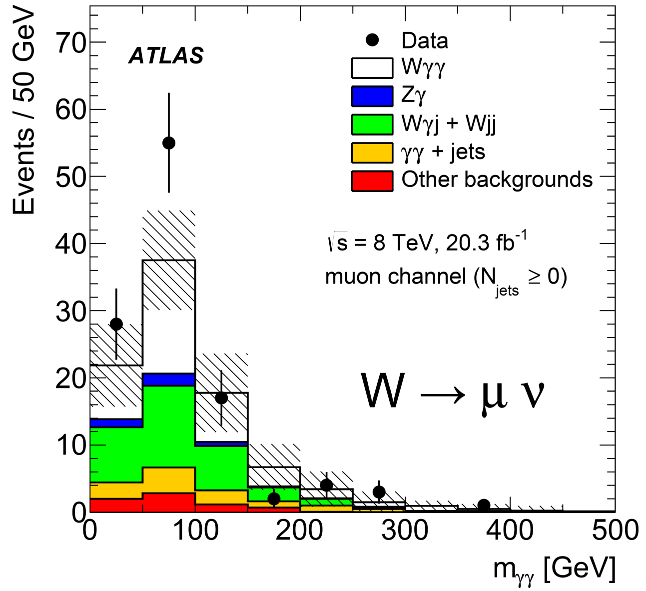
Wγγ production

[ATLAS, arXiv:1503.03243]

- A first evidence of 3 bosons production







➔ Inclusive and exclusive cross sections

[NLO]

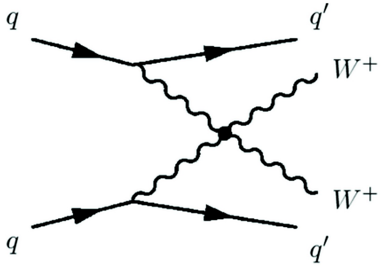
	σ^{fid} [fb]	σ^{MCFM} [fb]
Inclusive ($N_{\text{jet}} \geq 0$)		
$\mu\nu\gamma\gamma$	$7.1\ ^{+1.3}_{-1.2}$ (stat.) ± 1.5 (syst.) ± 0.2 (lumi.)	Incl. 2.90 ± 0.16
$e\nu\gamma\gamma$	$4.3\ ^{+1.8}_{-1.6}$ (stat.) $^{+1.9}_{-1.8}$ (syst.) ± 0.2 (lumi.)	
$\ell\nu\gamma\gamma$	$6.1\ ^{+1.1}_{-1.0}$ (stat.)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

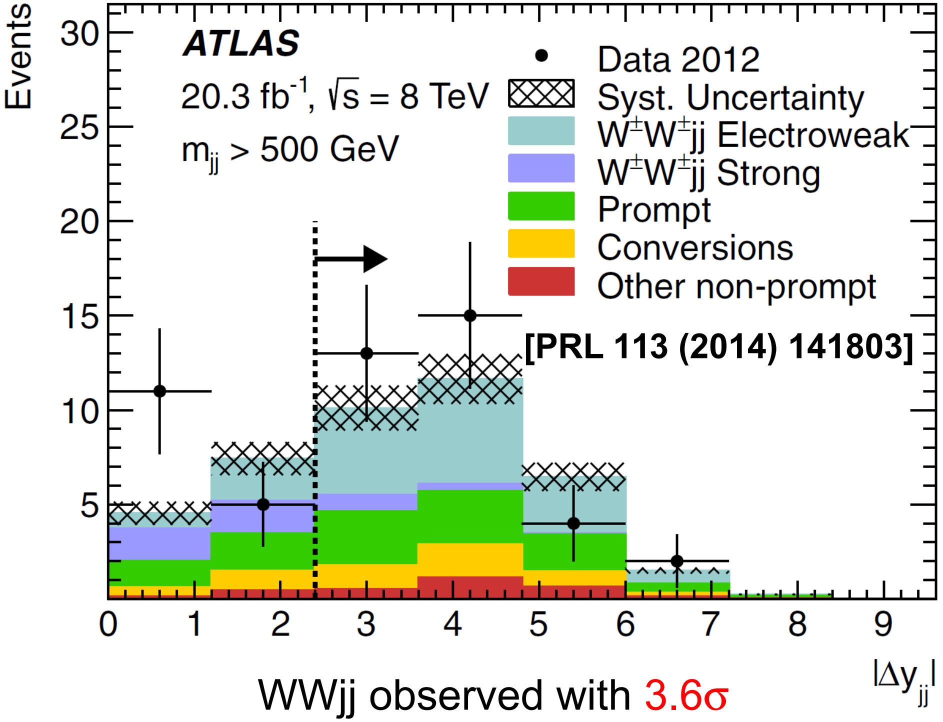
- As for Wγ, NNLO QCD corrections are important

➔ 19 – 26% for Wγ [arXiv:1504.01330]

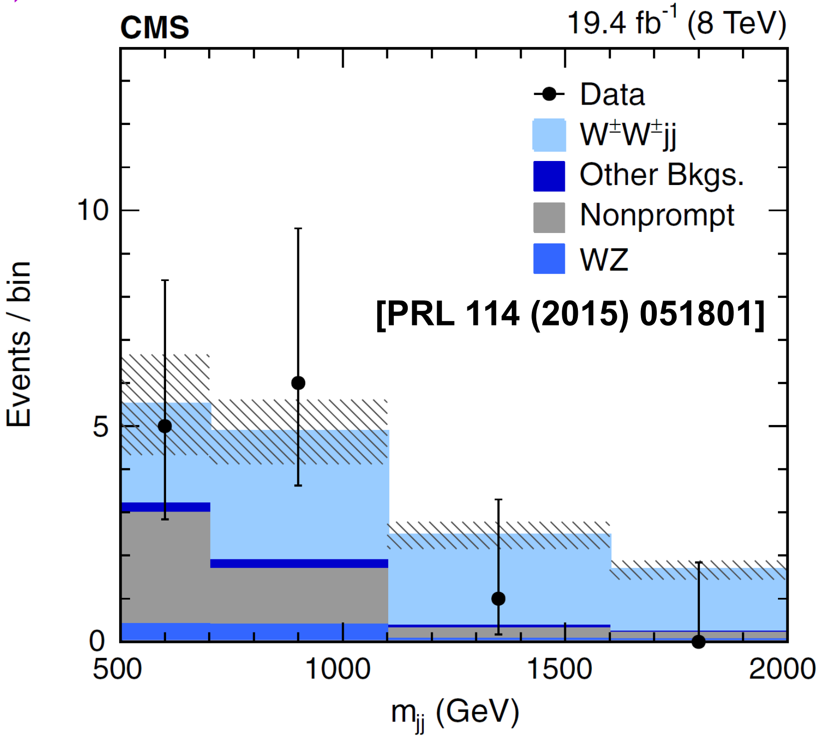
Vector Boson Scattering

- First evidence in same sign WW
  - ➔ Same sign dileptons
  - ➔ 2 high pT jets with $|\Delta\eta_{jj}|$ > 2.4 (2.5)





WWjj observed with 3.6σ



WWjj observed with 2σ

- WWjj production (QCD+EW)

CMS: $\sigma_{\rm fid}(W^\pm W^\pm jj) = 4.0^{+2.4}_{-2.0}(\text{stat})^{+1.1}_{-1.0}(\text{syst})$

Predicted: $5.8 \pm 1.2\ \text{fb}$

- WWjj EW production:

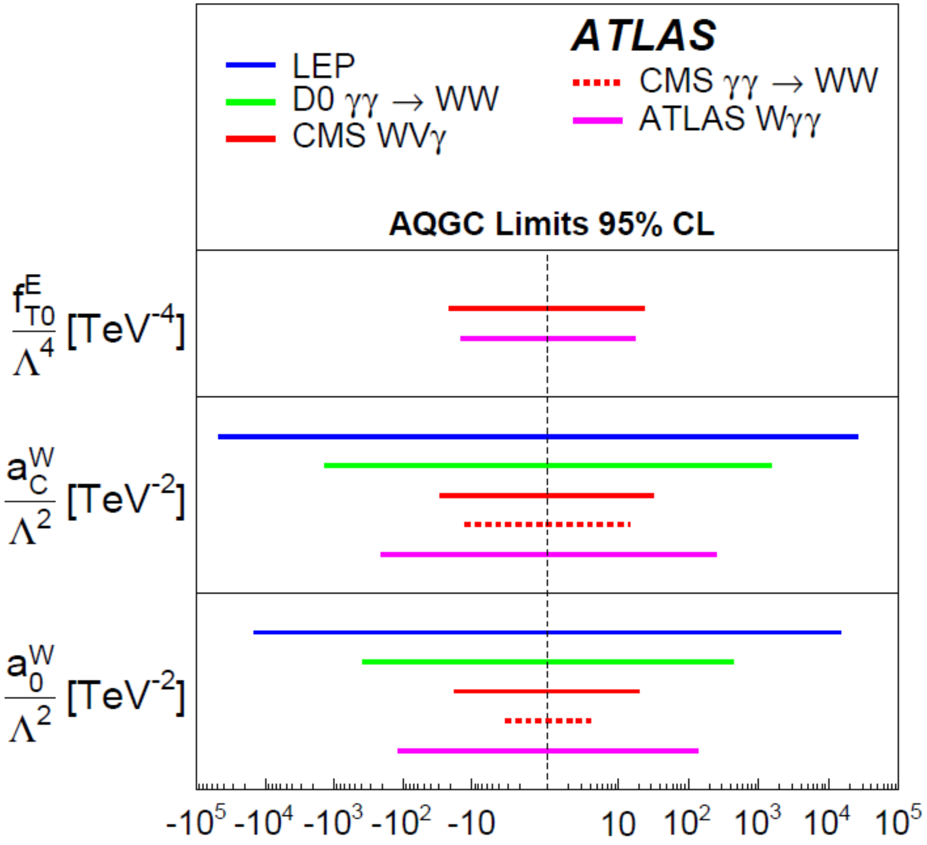
ATLAS: $\sigma^{\rm fid} = 1.3 \pm 0.4(\text{stat}) \pm 0.2(\text{syst})\ \text{fb}$

Predicted: $0.95 \pm 0.06\ \text{fb}$

Anomalous Quartic Gauge Couplings

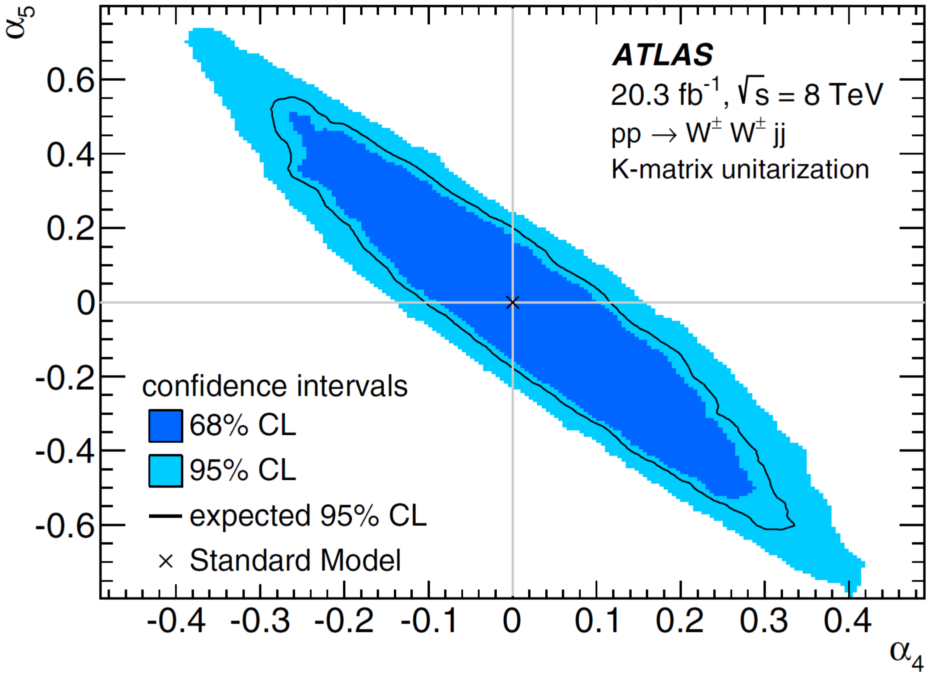
- 3 bosons final state or VBS used to set limits on dim. 8 EFT operators: $f_{T,0}$, $f_{M,i}$, α_4, α_5 ($\leftrightarrow$ $f_{S,0}$, $f_{s,1}$)

$$\mathcal{L}_{EFT} = \mathcal{L}_{SM} + \sum_{i=WWW,W,B,\Phi W,\Phi B} \frac{c_i}{\Lambda^2}\mathcal{O}_i + \sum_{j=1,2} \frac{f_{S,j}}{\Lambda^4}\mathcal{O}_{S,j} + \sum_{j=0,\ldots,9} \frac{f_{T,j}}{\Lambda^4}\mathcal{O}_{T,j} + \sum_{j=0,\ldots,7} \frac{f_{M,j}}{\Lambda^4}\mathcal{O}_{M,j}$$



(a$_{W0,C}$ = parametrised $f_{M,2,3}$ to match LEP and CMS conventions)

➔ First limits on α_4, α_5 using pp → $W^\pm W^\pm$ jj



Summary

Parameters

- m_W and sin θ_W: W and Z precision measurements

➔ Improved PDF constraints are critical

Interactions

- Triple Gauge couplings: towards precision measurements

➔ Experimental precision match theory one

➔ NNLO QCD + NLO EW Monte Carlo desirable

- Quartic Gauge couplings: the observations started

➔ The movement will be amplified with 13 TeV data
(~ x3 larger cross sections)

➘ Next Challenges in EW physics at colliders are in PDFs, QCD and theory

[Apologizes for subjects or results not shown]