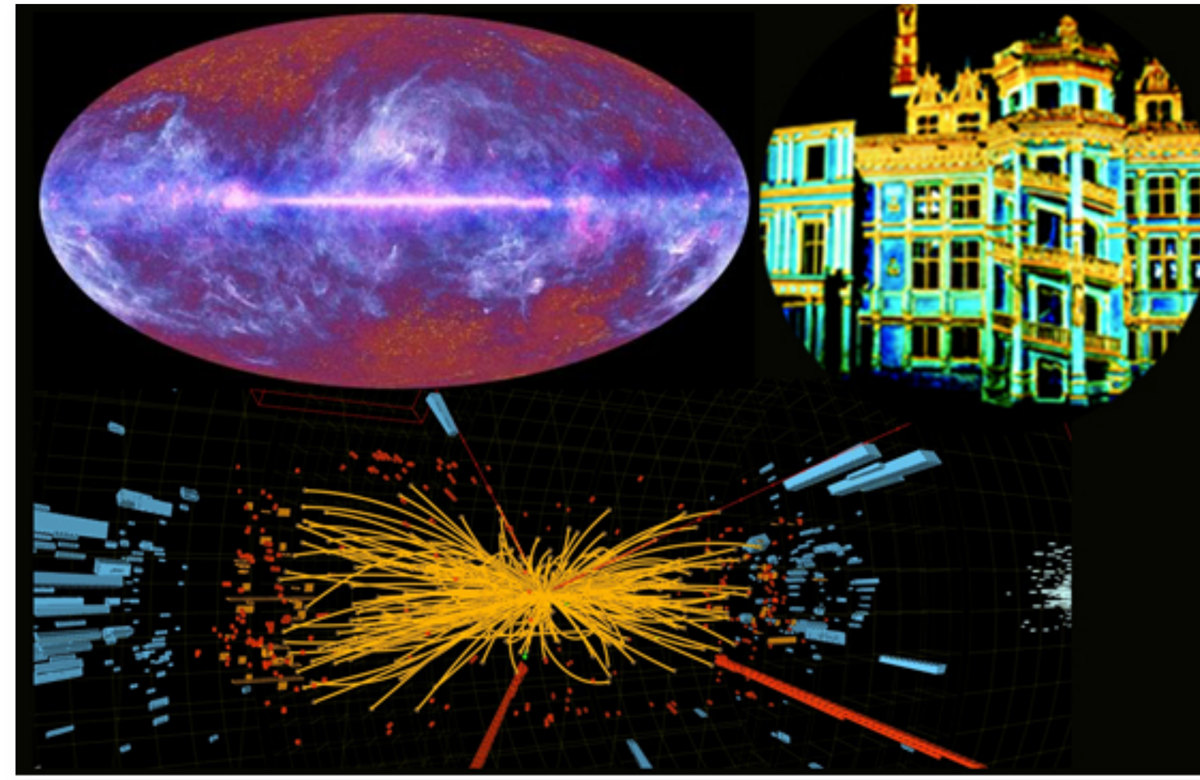

Electroweak tests at the LHC

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on behalf of ATLAS and CMS collaborations

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Institut de recherche sur les lois fondamentales de l'Univers

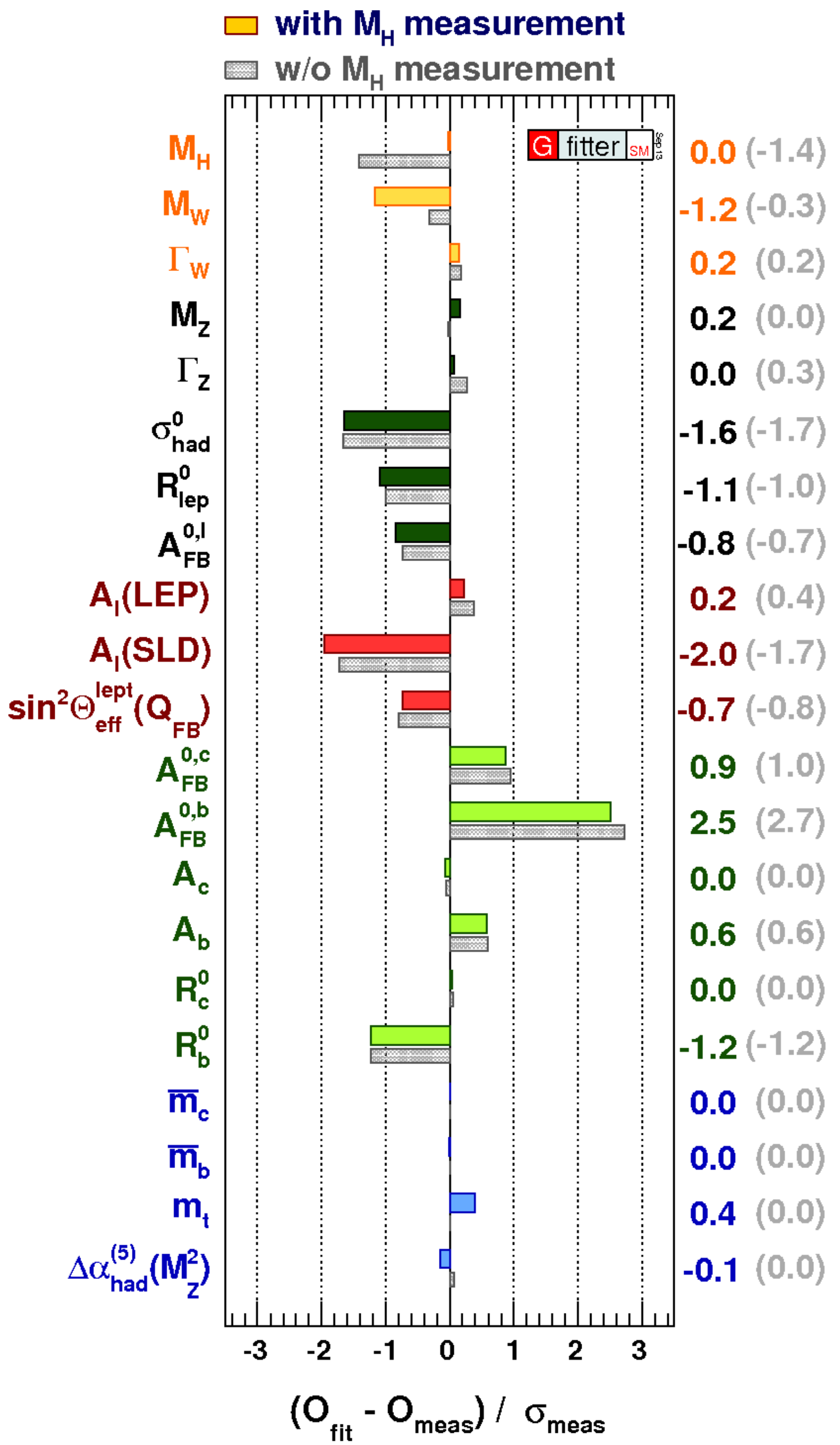
ATLAS

CMS

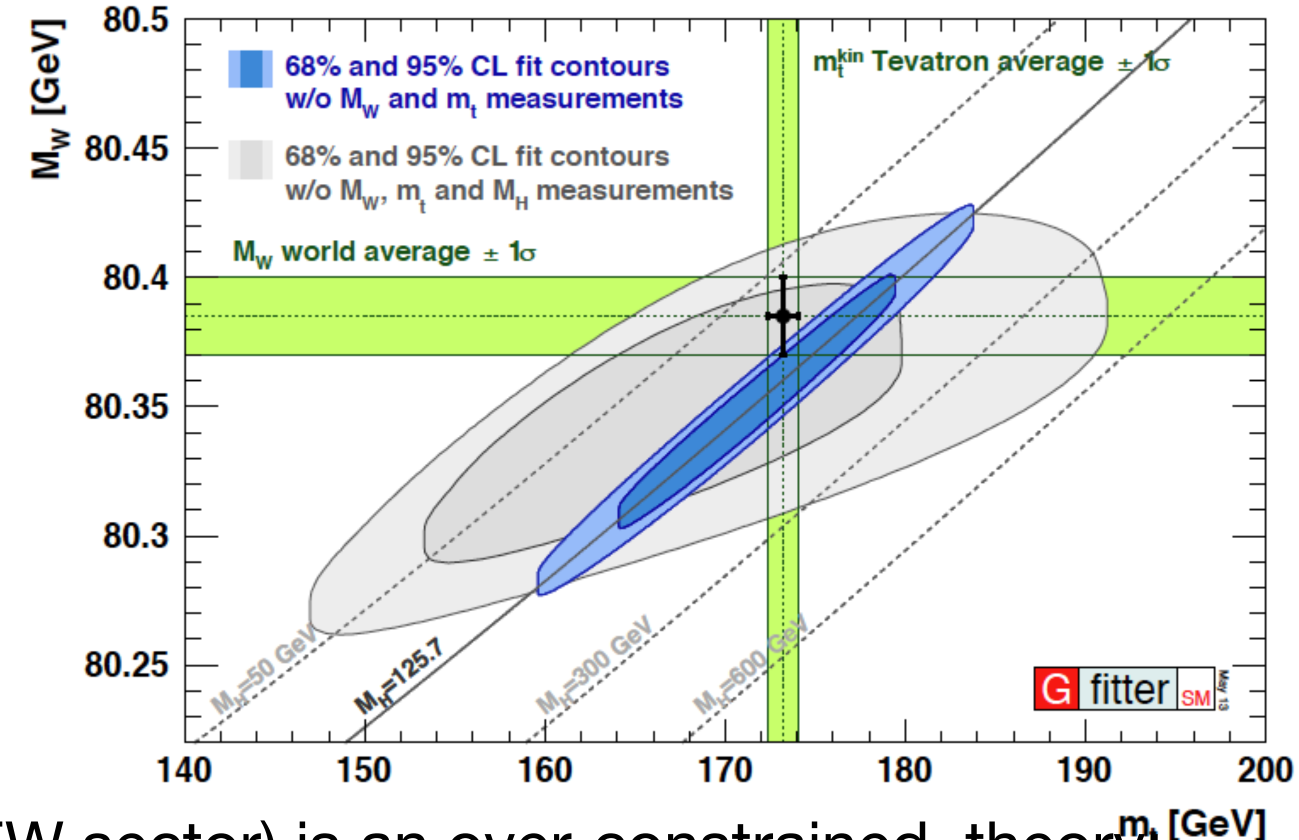
OUTLINE

- Two topics
  - Prospects for W mass measurement at the LHC
  - Electroweak tests with anomalous couplings
- W mass:
  - Very basics of the measurement, Tevatron results, statistical precision with Run-1
  - Supporting measurements: p_TZ, p_TW, Parton Shower tunes and strange quark PDF
- Gauge boson couplings:
  - Probing gauge bosons' self couplings with dibosons production, Vector boson scattering and electroweak Z+2jet production
  - Leptonic final states (electrons and muons), photons and MET
  - Limits on anomalous couplings mainly with full 7 TeV data, 8 TeV yet to come
    - Channel combination would increase sensitivity.

ELECTROWEAK PARAMETERS

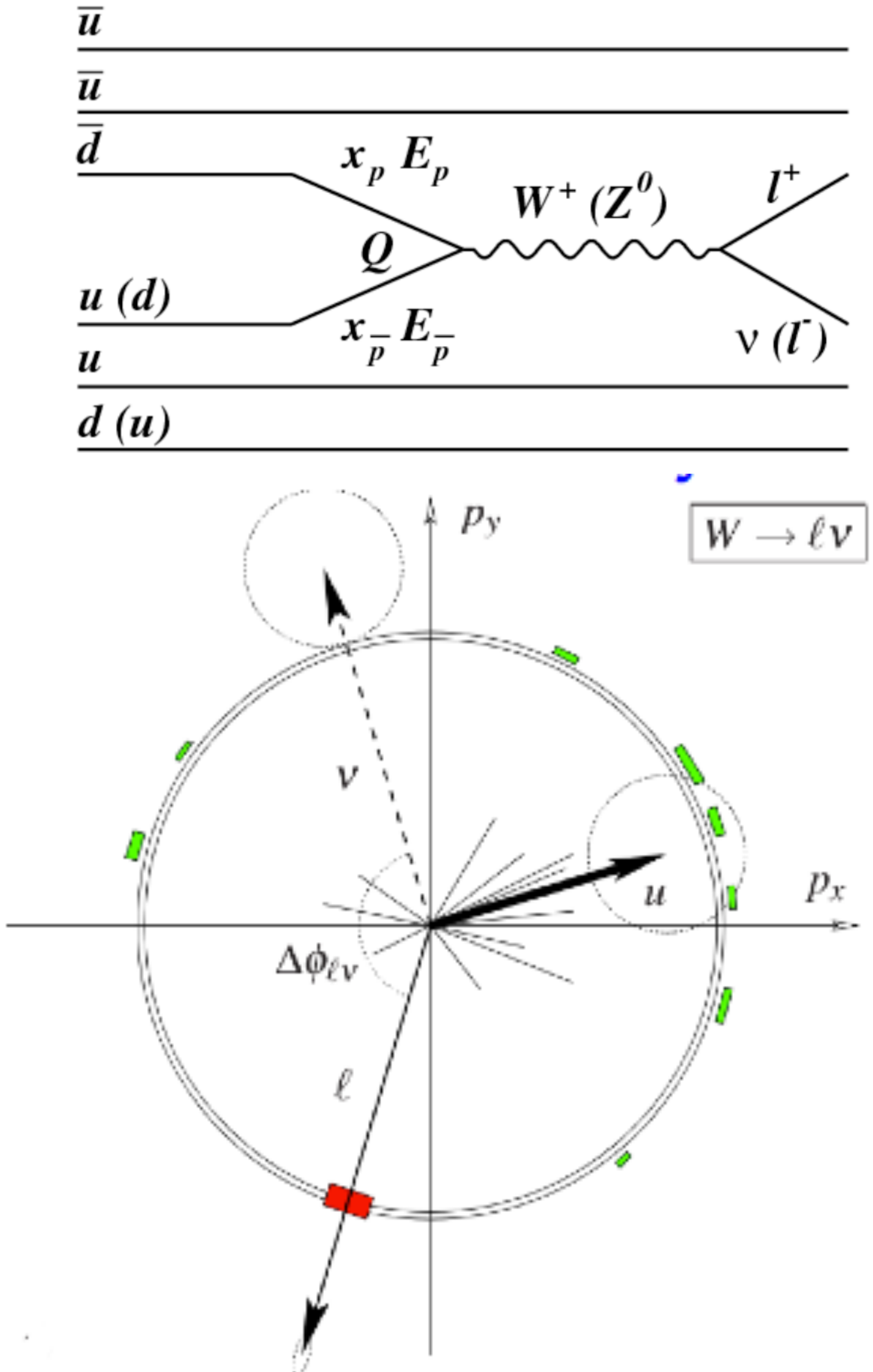


Plot inspired by Eberhardt et al. [arXiv:1209.1101]



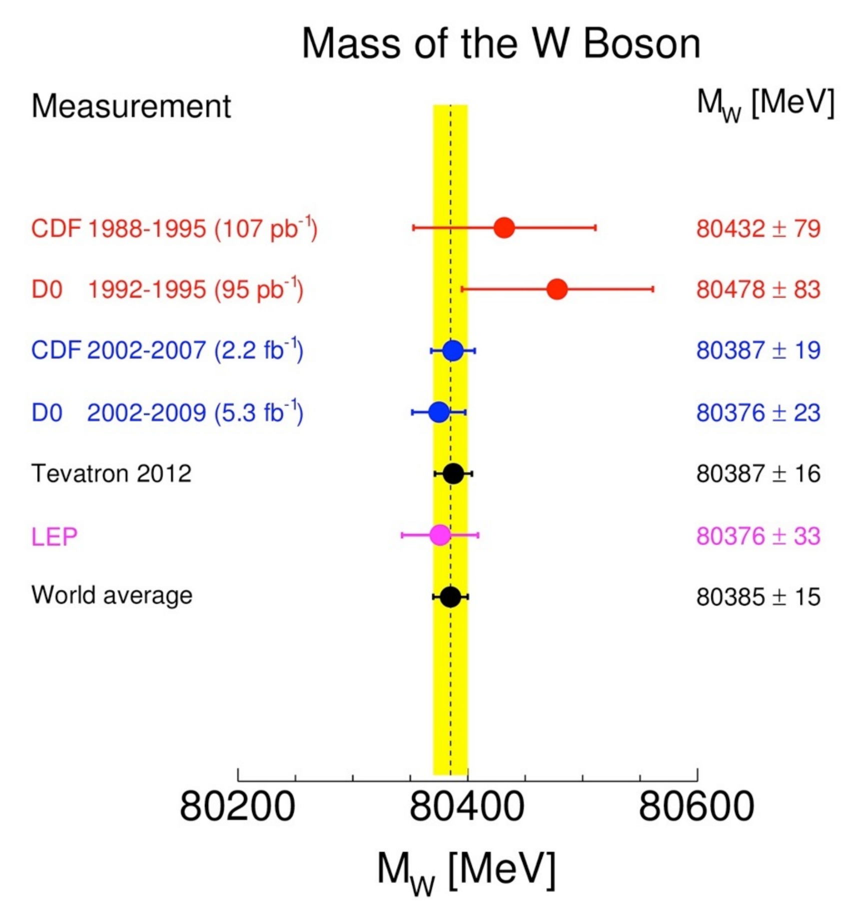
- SM (EW sector) is an over-constrained theory: 3 parameters at the tree level (α_{em}, G_F, M_Z)
  - Precise measurement probe loop diagrams => radiative corrections
- Mass depend on M^2_{top} and $\ln(M_H)$, but also any new particle with weak charge.
- Precise measurement of top and W mass constrain Higgs mass:
  - Current ΔM_H and ΔM_{top}, require experimental precision of **~10 MeV** uncertainty on W mass (cf. plenary talk by S. Tkazyuk)

W MASS: ANALYSIS STRATEGY



- Many components needed for Mw measurement: ***a very complex measurement***
  - ISR (transverse) and PDFs (longitudinal boson momentum)
  - V-A couplings: angular distributions
  - FSR affects lepton momentum
- Experimental inputs
  - In situ calibration of the lepton momentum scale and hadronic recoil resolution
- Three observables:
  - **lepton p_T**
  - **neutrino p_T (MET)**
  - **Transverse mass: $m^2_T = 2 p_T MET\ (1 - \cos \Delta\phi)$**
- Some systematic uncertainties more affecting measurement with one observable then the other (consistency check)

PRECISION



CDF+D0 ==>16

Systematic (MeV)	Electrons	Muons	Common
Lepton Energy Scale	10	7	5
Lepton Energy Resolution	4	1	0
Recoil Energy Scale	6	6	6
Recoil Energy Resolution	5	5	5
$u_{\|\|}$ efficiency	2	1	0
Lepton Removal	0	0	0
Backgrounds	3	5	0
$p_T(W)$ model (g_2, g_3, α_s)	9	9	9
Parton Distributions	9	9	9
QED radiation	4	4	4
Total	19	18	16

Systematics, systematics, systematics!

Table above: **D0** p_T lepton fit only, no statistics.

(N.B: many systematics statistically limited)

- **Each experiment @ LHC** should reach 7 MeV precision with 10fb^{-1} @14 TeV
  - Each experiment should reach ***few MeV statistical*** precision with Run-1
- Desired Experimental systematics (lepton calibration for example, cf M_H measurement in 4 lepton channel) should be within reach
- PDF and other uncertainties more critical.

$$\frac{\partial m_W}{\partial_{rel}\alpha_\ell} \sim 800\ \text{MeV}/\%,$$

momentum scale

$$\frac{\partial m_W}{\partial_{rel}\sigma_\ell} = 0.8\ \text{MeV}/\%$$

momentum resolution

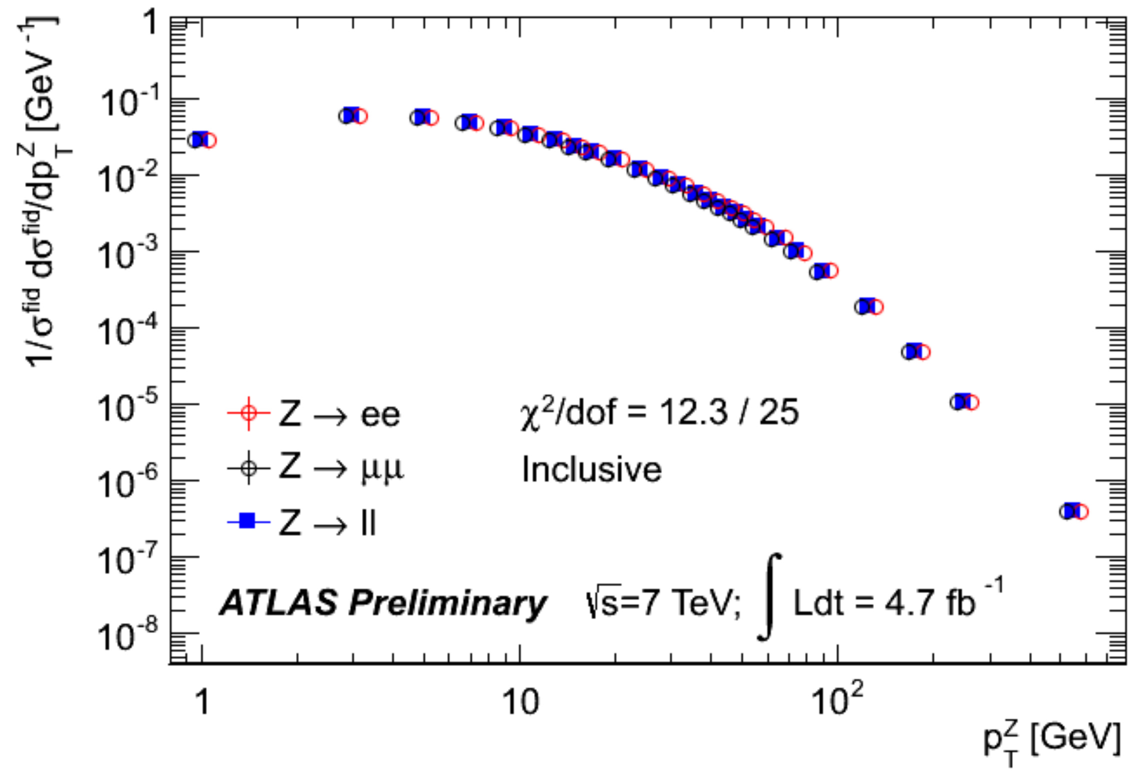
Eur.Phys.J. C57 (2008) 627-651

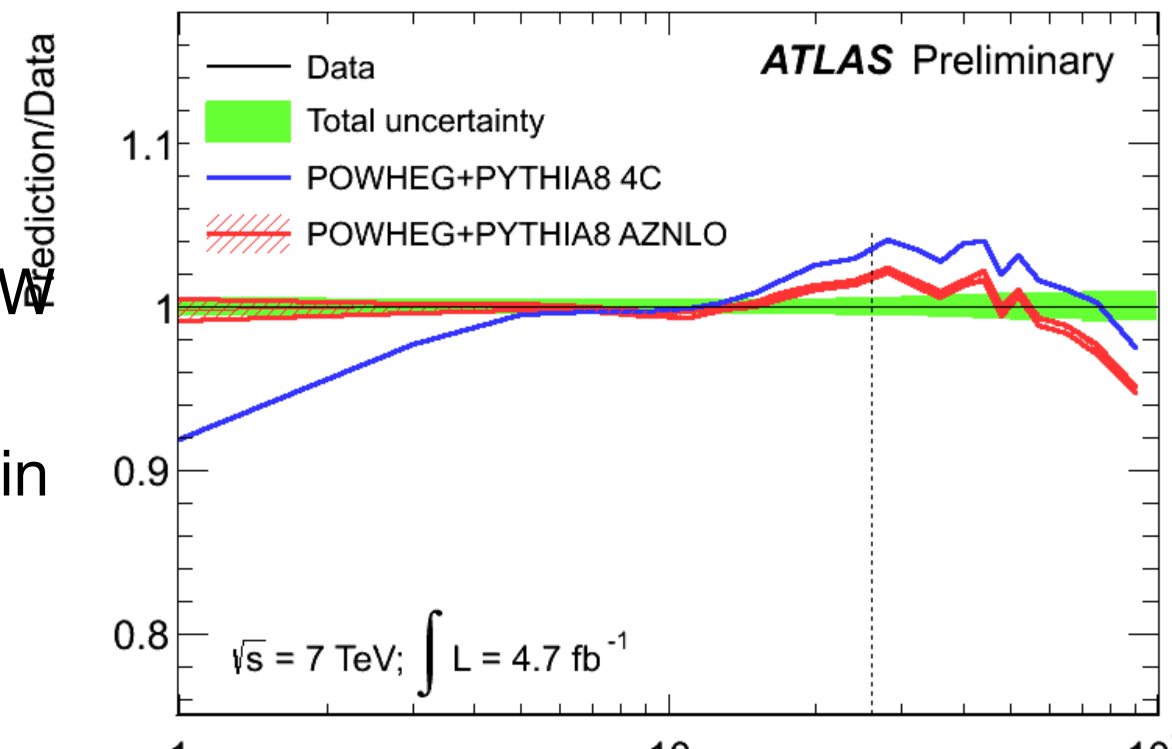
arXiv:0805.2093v2 [hep-ex]

CERN/LHCC 2006-021

SUPPORTING MEASUREMENTS

- ***Physics modelling***
  - $p_T Z$ (and $p_T W$) measurement
  - QED, NLO EW corrections
  - Polarization coefficients
- ***$p_T Z$ measurement***
  - soon public result on full 2011 data
  - In combination with φ^*
- ***Parton Shower (PS) tuning***
  - $p_T Z$ and $p_T W$ the same QCD, difference in EW less important
  - Tune PS on $p_T Z$ to get better description of $p_T W$
  - Exploit the high precision of the $p_T Z$ and the complementary Z φ^* measurements to constrain the parton shower models
  - New ATLAS tune based on ATLAS φ^* (ee) and $p_T Z$ (μμ) uncorellated measurements
- ***QED and EWK corrections***

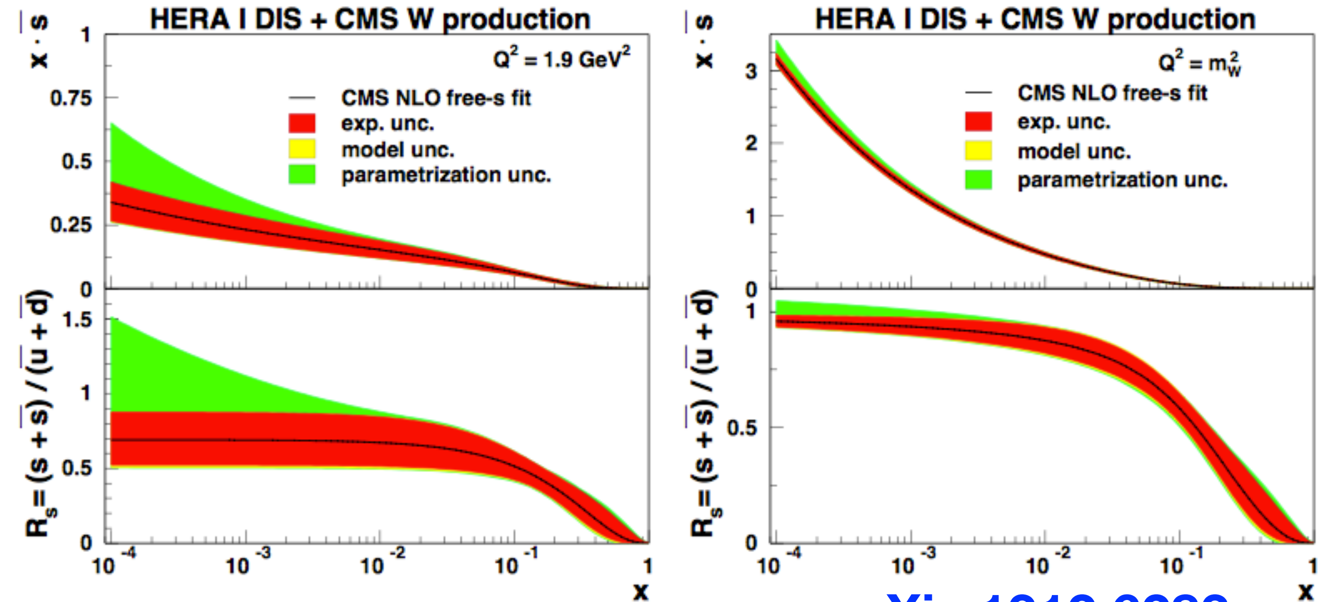




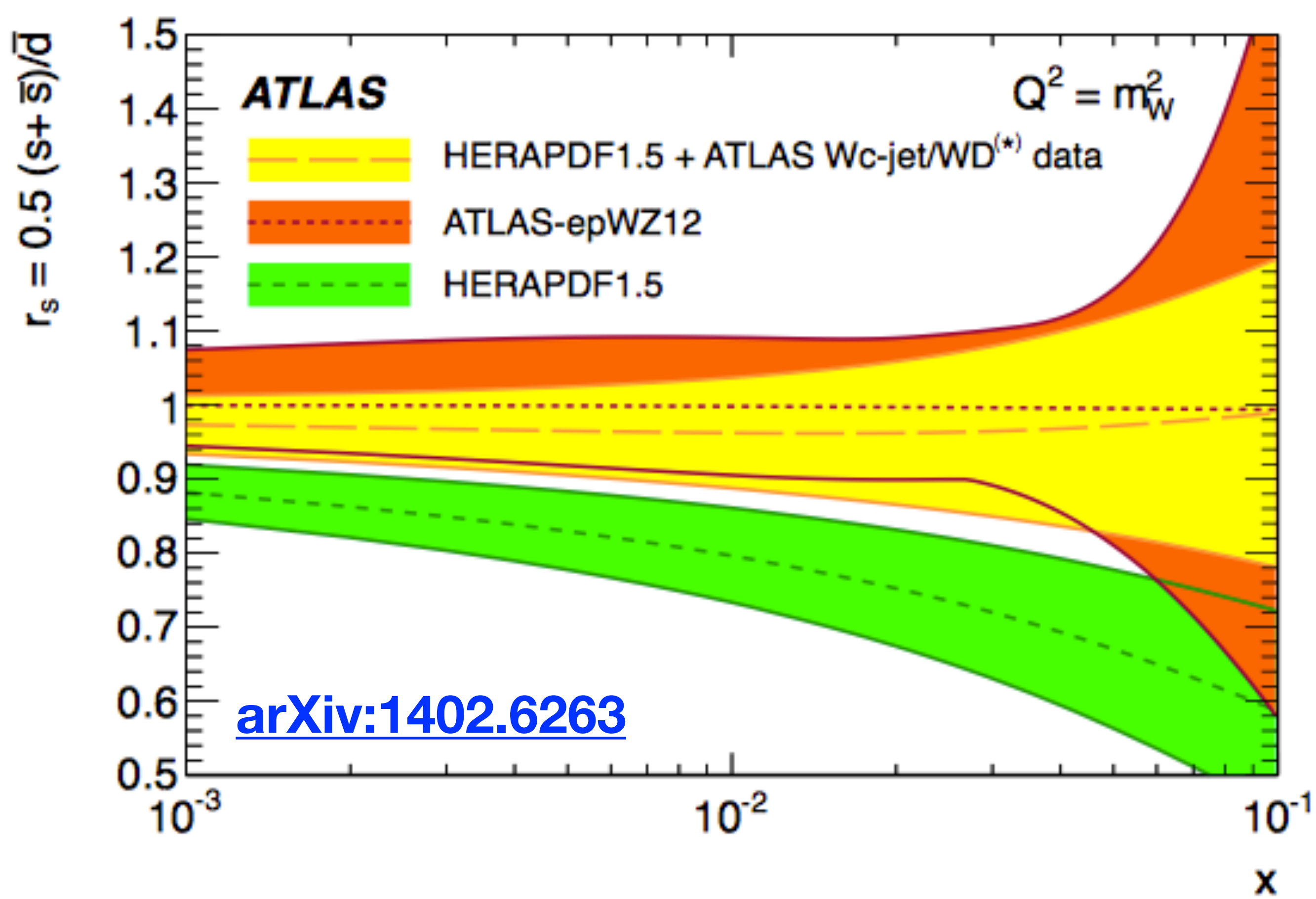
Paper in preparation
Preliminary results here

SUPPORTING MEASUREMENTS

- ***Constrain PDFs***
    - double differential W and Z cross section measurement
    - strange quark density
- ***ATLAS***
    - Use W+c, W± asymmetry, Z rapidity
    - Use HERA DIS (v1.5) as baseline
    - Strange PDF parameterised by one variable
- ***CMS***
    - Use W+c & 5fb^{-1} W$^{\pm}$ asymmetry
    - Use HERA DIS (v1.0) as baseline
    - Allow strange PDF shape and normalization
- Similar CMS and ATLAS measurements using different methodologies!
- Small tension over strange-suppression between ATLAS & CMS result

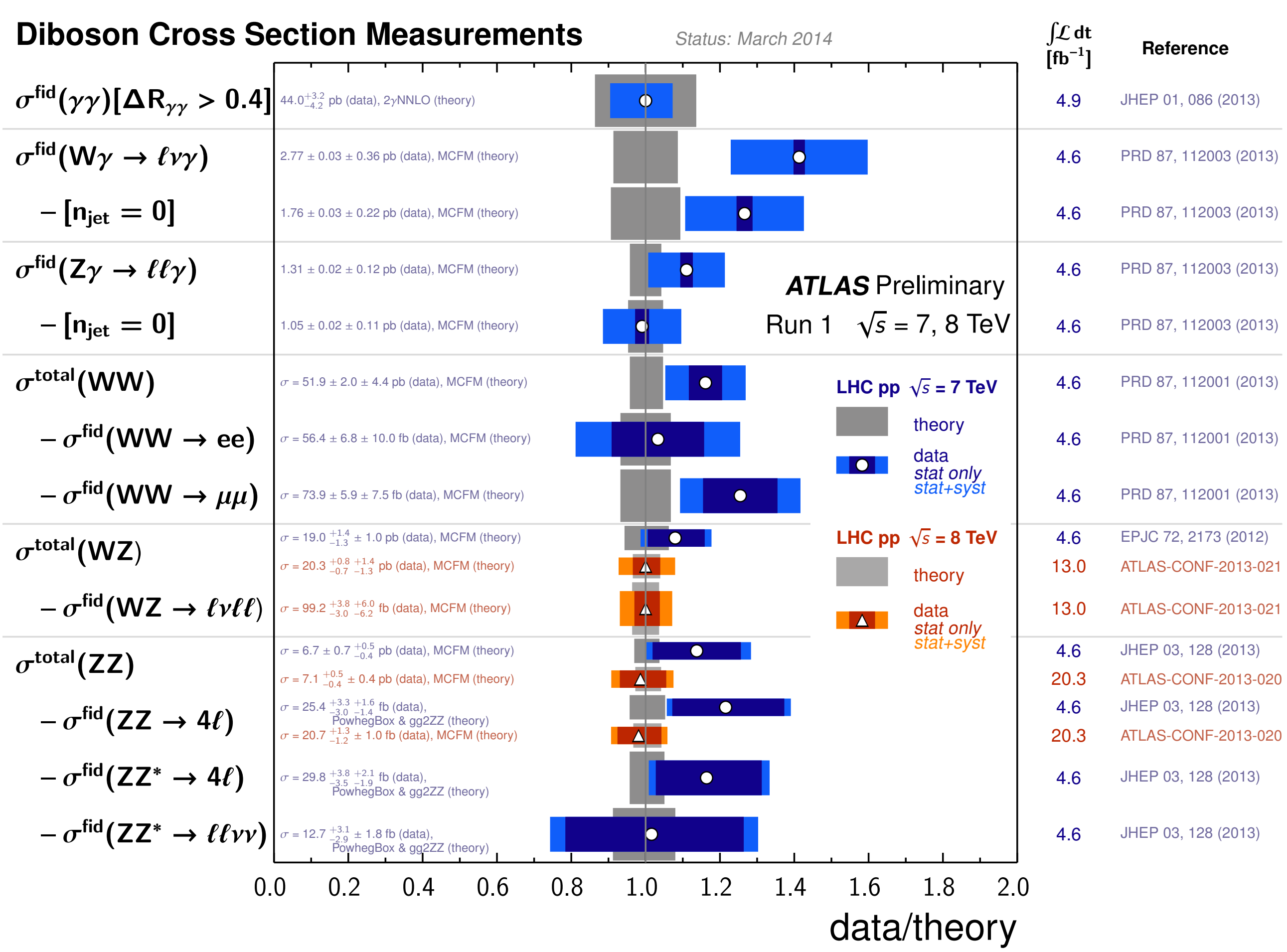


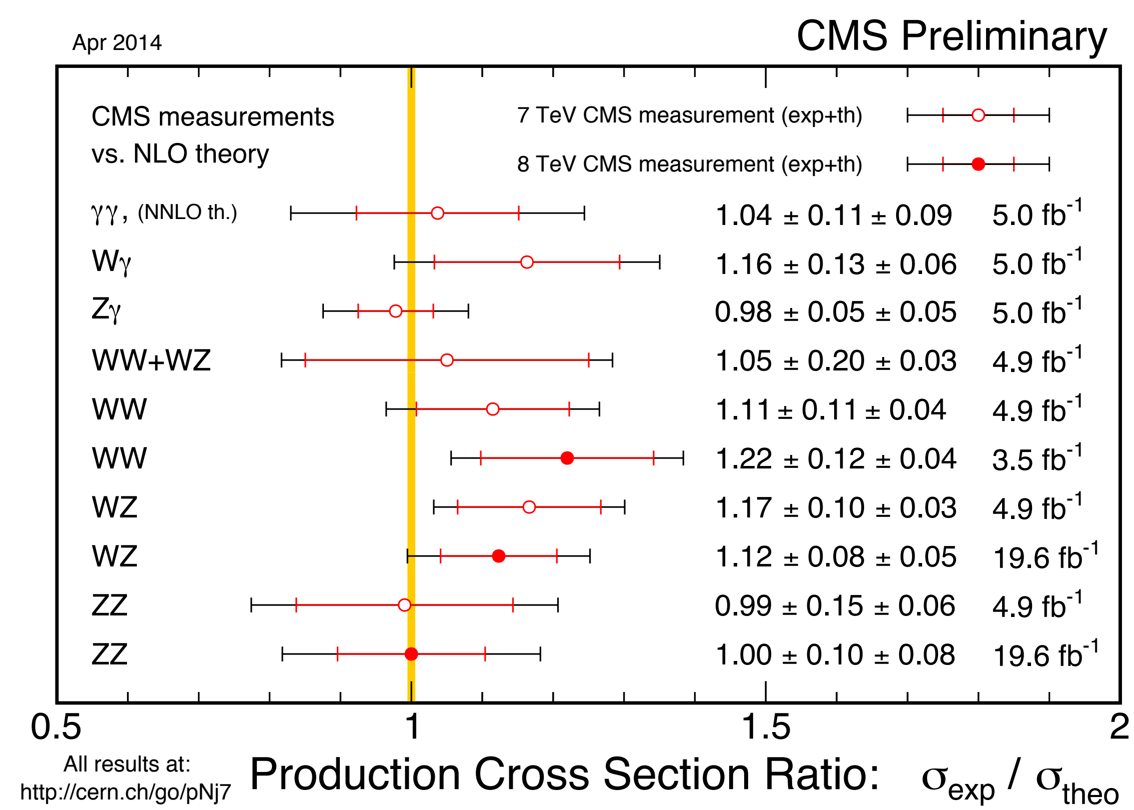
arXiv:1312.6283



GAUGE BOSON COUPLINGS

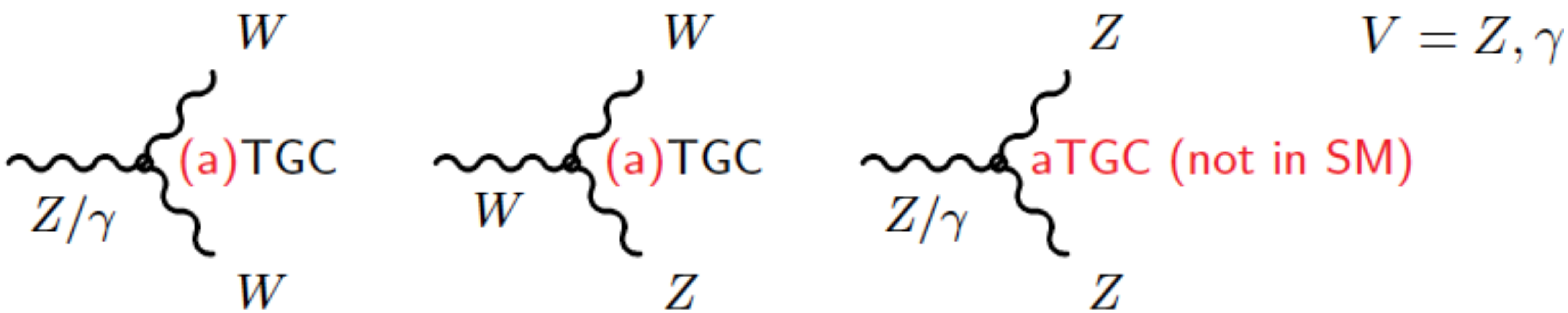
- Fundamental test of Standard Model:
  - Self interactions of gauge bosons manifest themselves as a couplings of three (TGC) of four (QGC) gauge bosons (WWZ, WWγ, WWZγ, WWγγ, WWZZ, WWWW)
  - Structure of TGC and QGC completely determined by $SU(2)_L x U(1)_Y$ symmetry
  - Precision measurement of TGC and QGC either confirm SM or indicate presence of New Physics at the mass scale through the discovery of anomalous couplings
  - **Anomalous couplings manifest as increase of total cross sections and differential cross sections at high invariant mass and high transverse**





More in the talk by H.L. Brun, this session.

ANOMALOUS TGC



- Beyond SM physics modelled by effective Lagrangian with anomalous TGC (**aTGC)** parameters
- Values of the parameters are 0 in the SM
- Charged aTGC (*WWV*): **in SM**
  - measurements in *WW, WZ, Wγ* diboson processes + *Zjj*
  - $\frac{\mathcal{L}_{WWV}}{g_{WWV}} = ig_1^V(W^+_{\mu\nu}W^{\mu}V^{\nu} - W^+_{\mu}V_{\nu}W^{\mu\nu}) + i\kappa_V W^+_{\mu}W_{\nu}V^{\mu\nu} + \frac{i\lambda_V}{m_W^2}W^+_{\lambda\mu}W^{\mu}_{\nu}V^{\nu\lambda}$
  - 5 parameters: $\Delta g_1^Z \ (= g_1^Z - 1)$, $\Delta\kappa_Z \ (= \kappa_Z - 1)$, $\Delta\kappa_\gamma \ (= \kappa_\gamma - 1)$, λ_Z, λ_γ
- Neutral aTGC (*ZZV*): **not in SM**
  - measurement using ZZ and Zγ
  - $\mathcal{L}_{ZZV} = -\frac{e}{M_Z^2}\left(f_4^V(\partial_4^V V^{\mu\beta})Z_\alpha(\partial^\alpha Z_\beta) + f_5^V(\partial^\sigma V_{\sigma\mu})\tilde{Z}^{\mu\beta}Z_\beta\right)$
  - 8 parameters h_3^V, h_4^V, f_4^V, f_5^V
- avoid unitarity violation via dipole form factors $\mathcal{F}(s) = \frac{1}{(1+\hat{s}/\Lambda^2)^n}$
  - CMS follows non-form factor convention, ATLAS shows both

$WW \to l\nu l\nu$

- Cross section slightly above NLO predictions.
  - H→WW*→lνlν 3% (not included in this plot)
- aTGC
  - sensitive to both WWγ and WWZ couplings
  - assume some relations between the couplings, 3 “scenarios” for the limits:
    - “LEP scenario” (explicit $SU(2)_L \times U(1)_Y$ invariance, 3 parameters)

$$\lambda_\gamma = \lambda_Z \text{ and } \Delta\kappa_Z = \Delta g_1^Z - \Delta\kappa_\gamma \tan^2\theta_W$$

    - “HISZ” (2 param)

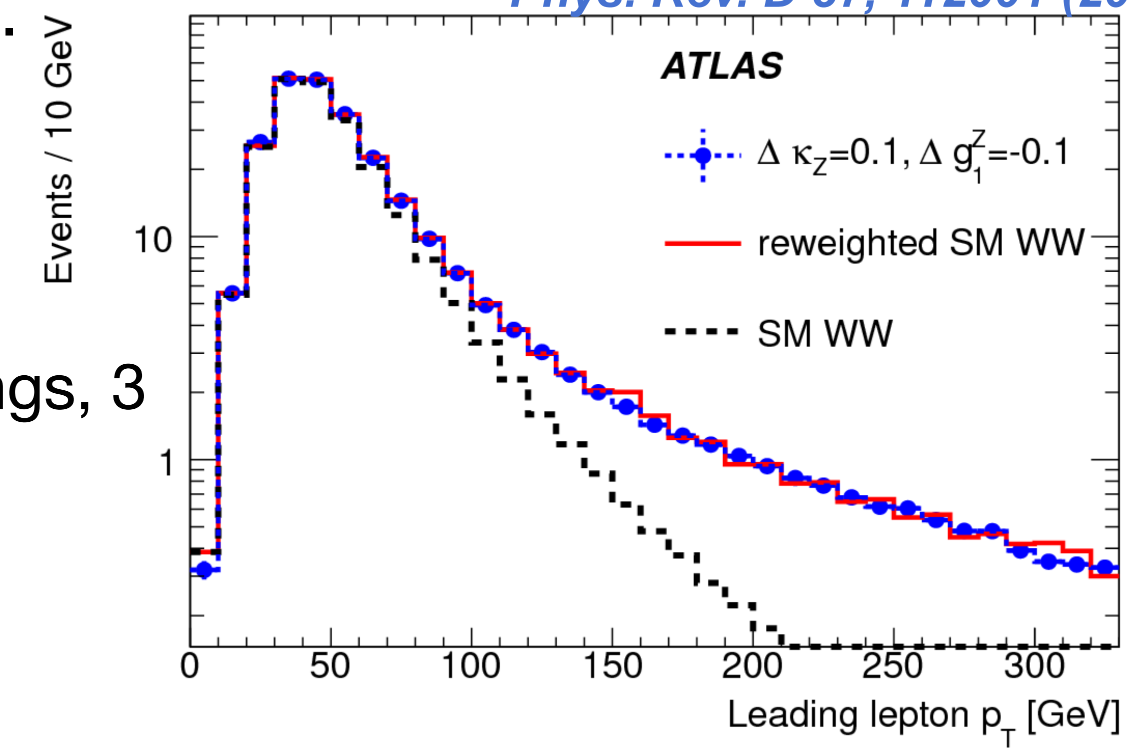
$$\Delta g_1^Z = \frac{1}{2\cos^2\theta_W}\Delta\kappa_\gamma,\quad \Delta\kappa_Z = \frac{1}{2}(1-\tan^2\theta_W)\Delta\kappa_\gamma\ ,\quad \lambda_Z = \lambda_\gamma$$

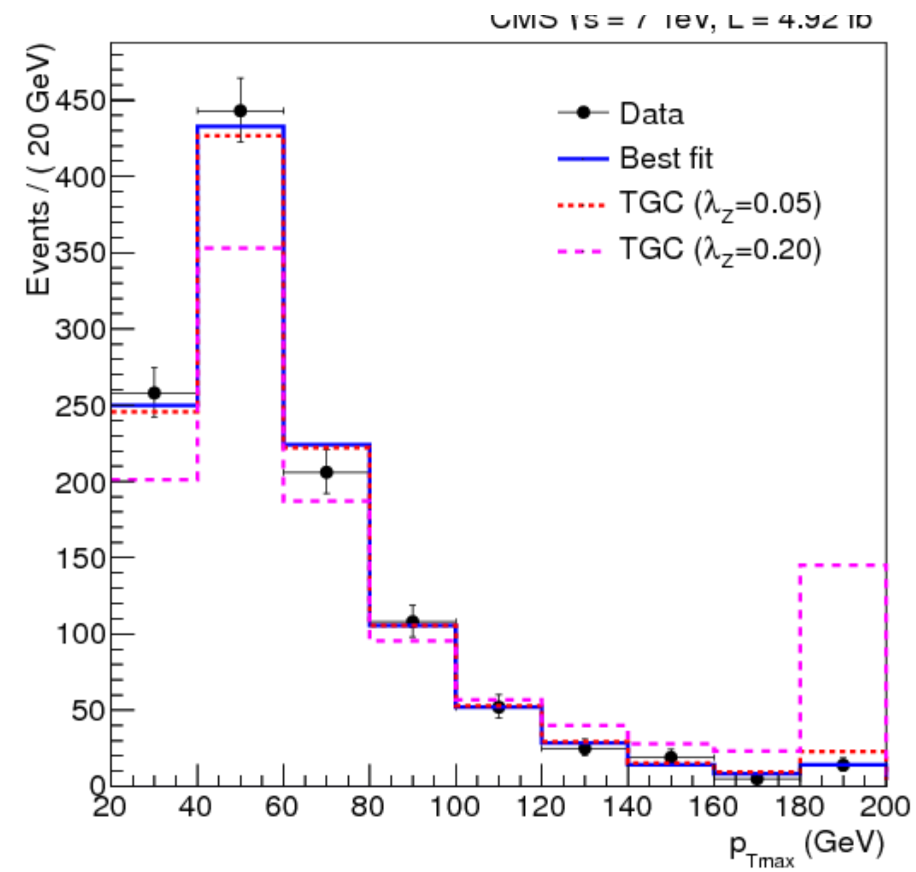
    - equal coupling scenario (2 parameters)

$$\Delta\kappa = \Delta\kappa_\gamma = \Delta\kappa_Z \text{ and } \lambda = \lambda_\gamma = \lambda_Z$$

- 95% C.L. limits on aTGC extracted for Λ = 6 TeV and $\Lambda = \infty$
  - Leading lepton p_T, statistics is still limited @ 7 TeV
  - Limits better than Tevatron, LEP still most stringent limits

Phys. Rev. D 87, 112001 (2013)

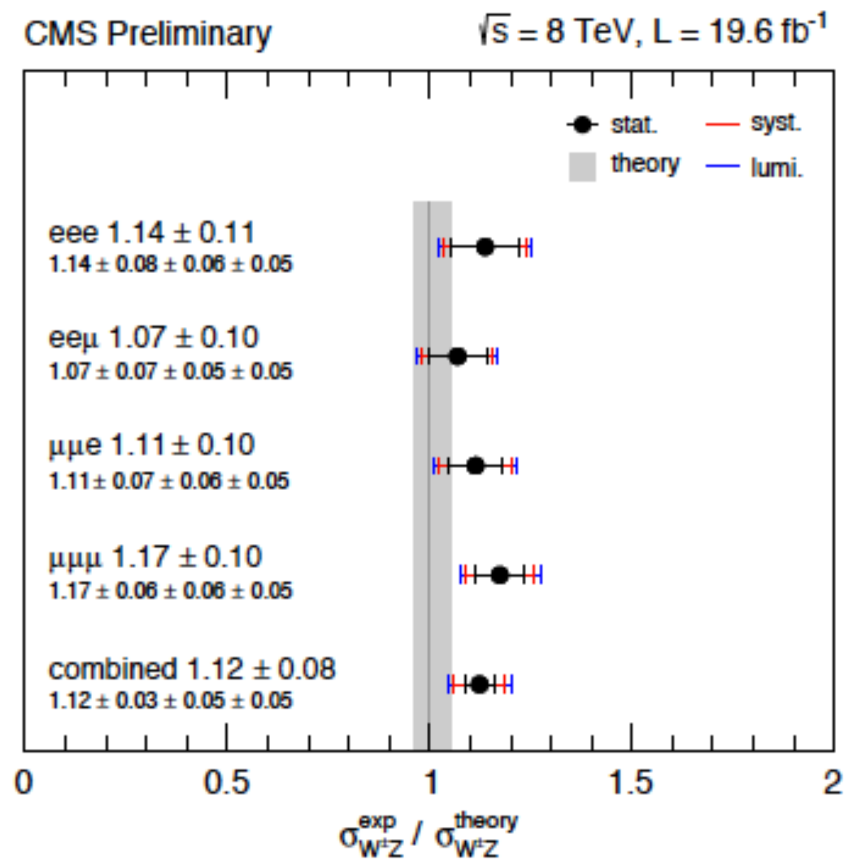




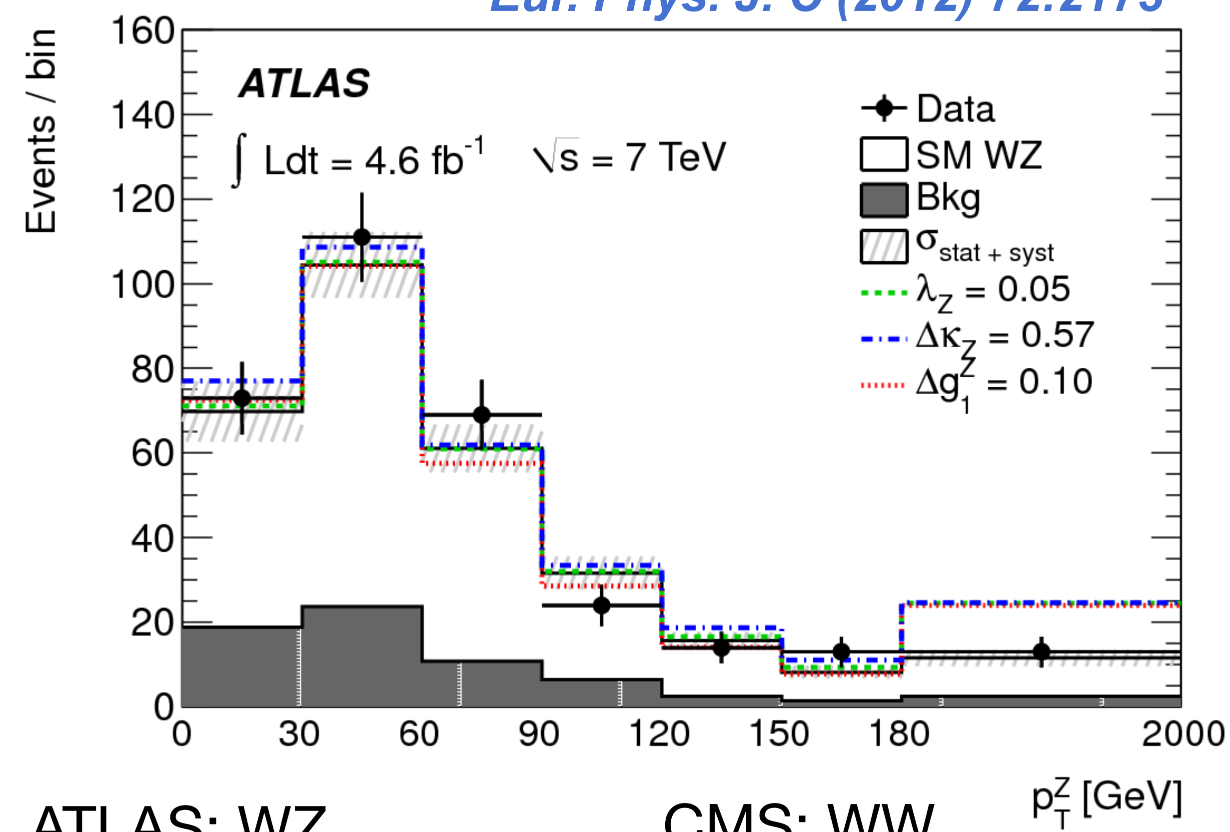
Eur.Phys.J. C73 (2013) 2610

$WZ \to l\nu ll$

CMS-PAS-SMP-12-006



Eur. Phys. J. C (2012) 72:2173



ATLAS: WZ

$$\Delta g_1^Z \in [-0.057, 0.093]$$
$$\Delta\kappa_Z \in [-0.37, 0.57]$$
$$\lambda_Z \in [-0.046, 0.047]$$

CMS: WW

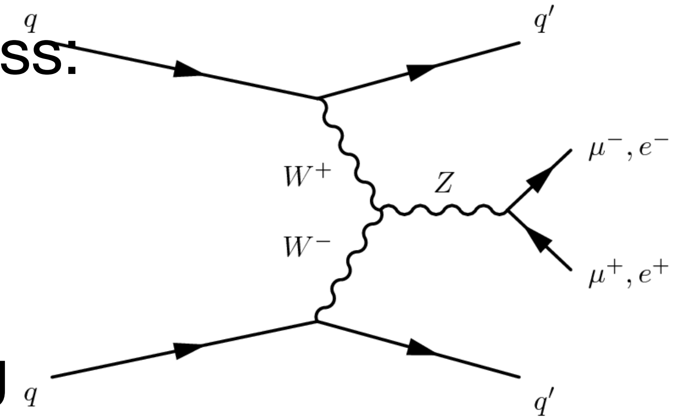
$$-0.048 \leq \lambda_Z \leq 0.048,$$
$$-0.095 \leq \Delta g_1^Z \leq 0.095,$$
$$-0.21 \leq \Delta\kappa_\gamma \leq 0.22.$$

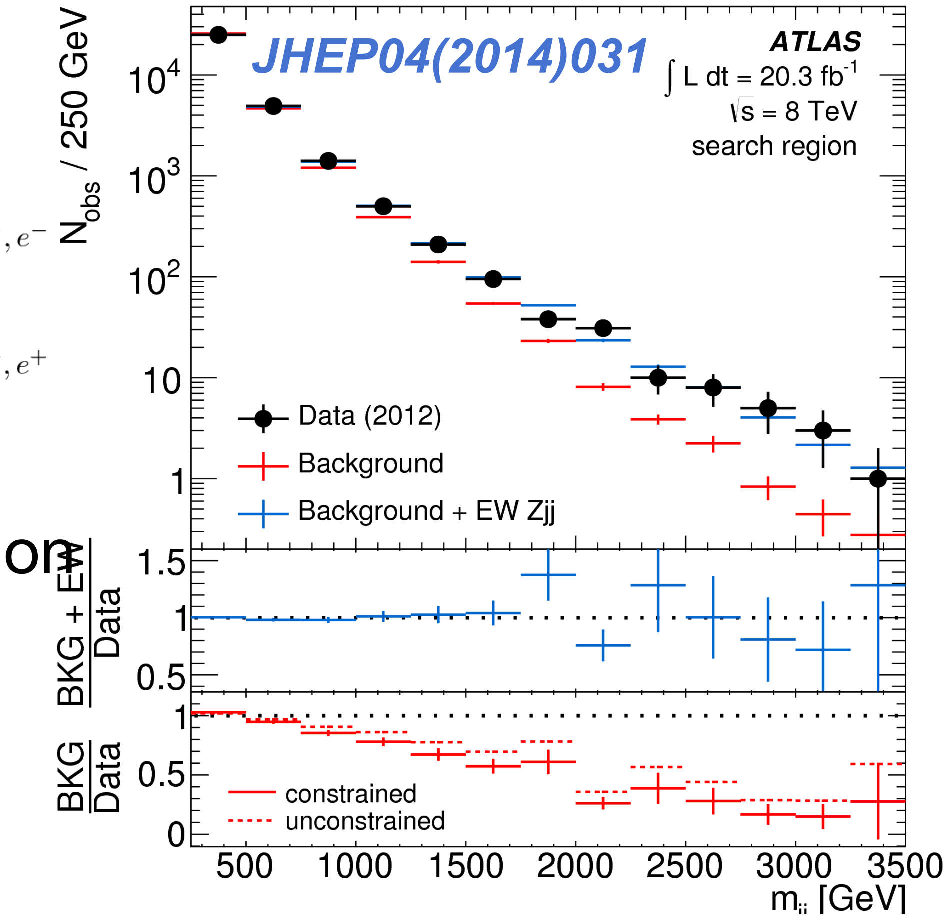
- aTGC
  - sensitive to WWZ coupling:
  - p_TZ correlated to ŝ, used to set limits on aTGC
  - Dominated by statistical uncertainty.
  - Improvement with 8 TeV expected

- in WW $\Delta\kappa_V$ ~ ŝ/M^2w, while in WZ and Wγ as √ ŝ/Mw
  - more sensitivity to $\Delta\kappa_V$

$Zjj \to lljj$

- Production of Zjj events via the t-channel exchange is a purely EWK process: vector boson fusion (VBF), Z-boson bremsstrahlung non-resonant production
  - VBF sensitive to WWZ coupling



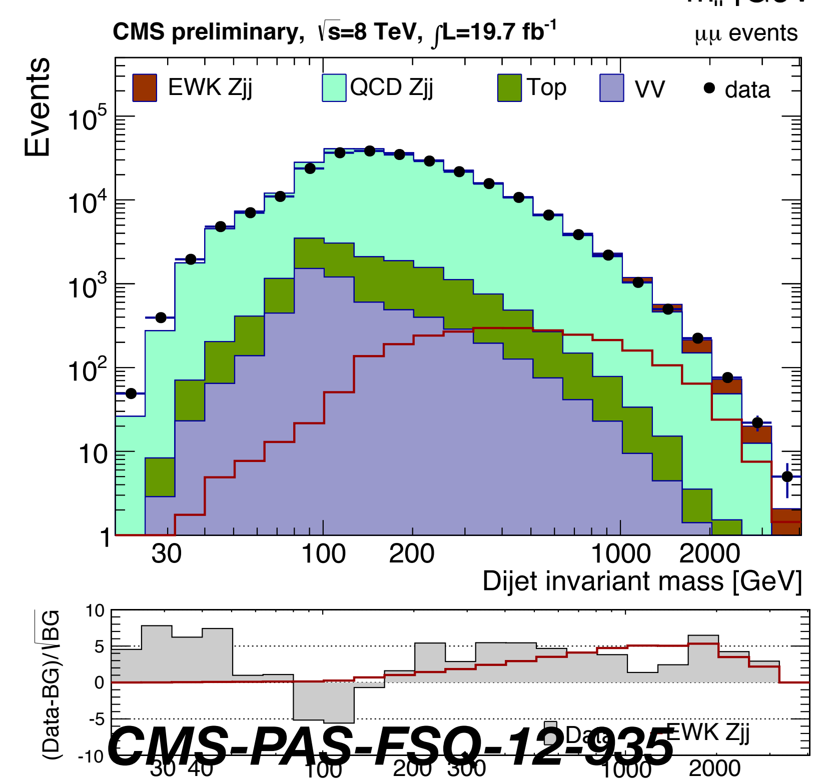


- Boson propagators present in electroweak Zjj production are different from those in VV production.
- Electroweak *Zjj* production therefore offers a complementary test of aTGCs
- Good agreement with SM!

aTGC	$\Lambda = 6\,\text{TeV}$ (obs)	$\Lambda = 6\,\text{TeV}$ (exp)	$\Lambda = \infty$ (obs)	$\Lambda = \infty$ (exp)
$\Delta g_{1,Z}$	$[-0.65, 0.33]$	$[-0.58, 0.27]$	$[-0.50, 0.26]$	$[-0.45, 0.22]$
λ_Z	$[-0.22, 0.19]$	$[-0.19, 0.16]$	$[-0.15, 0.13]$	$[-0.14, 0.11]$

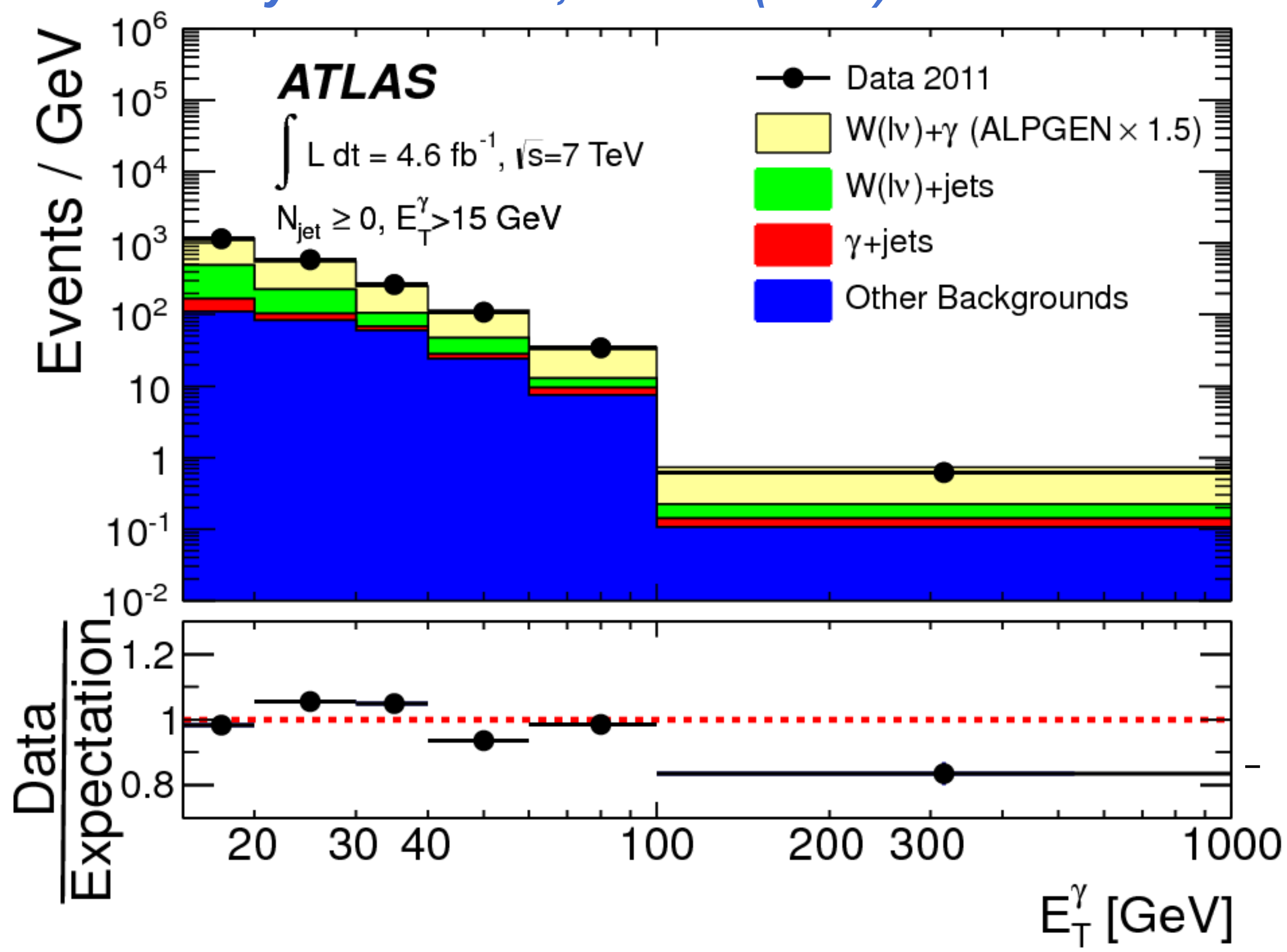
- CMS: BDT analysis, muon channel only,
  - NNLO fiducial cross section estimation 239 fb, agrees with the measurement:

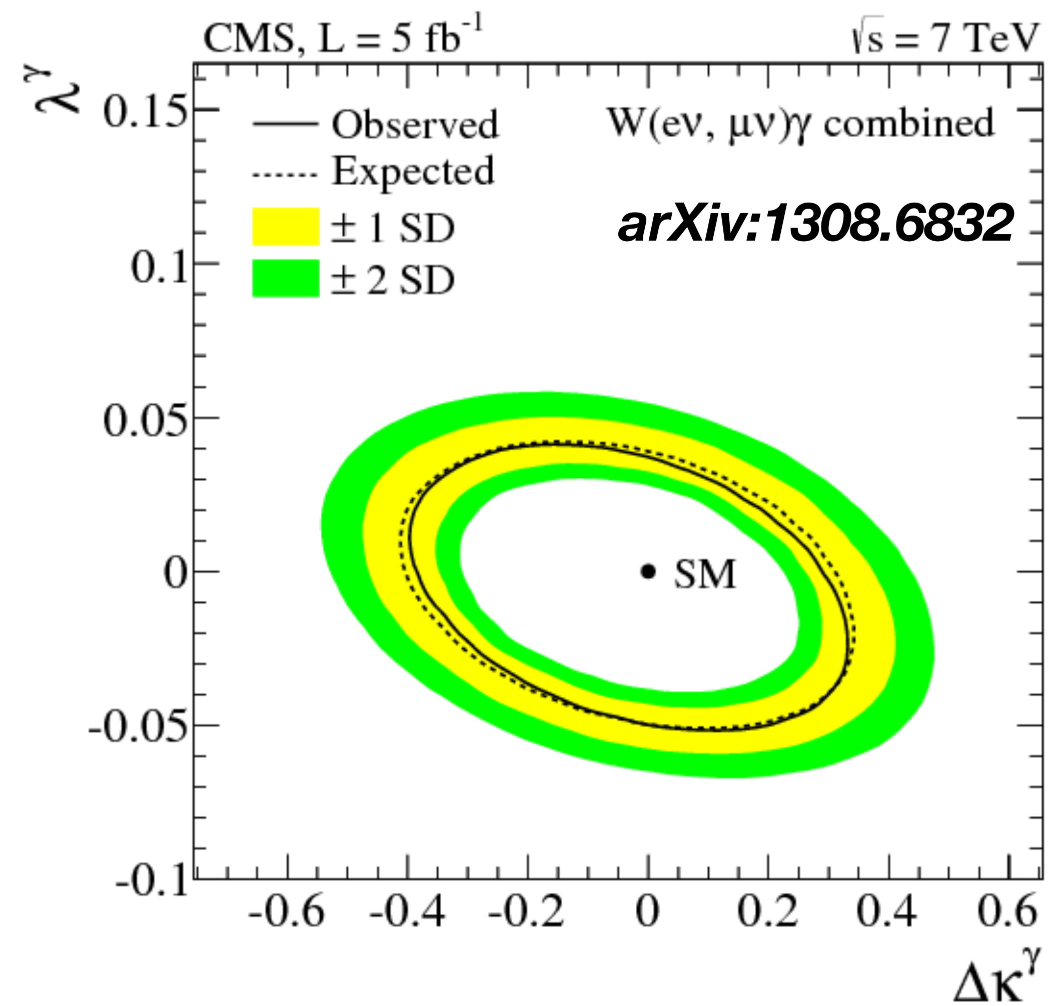
$$\sigma(\text{EWK } \ell\ell\text{jj}) = 226 \pm 26_{\text{stat}} \pm 35_{\text{syst}} \text{ fb}$$



$W\gamma \to l\nu\gamma$

Phys. Rev. D 87, 112003 (2013)





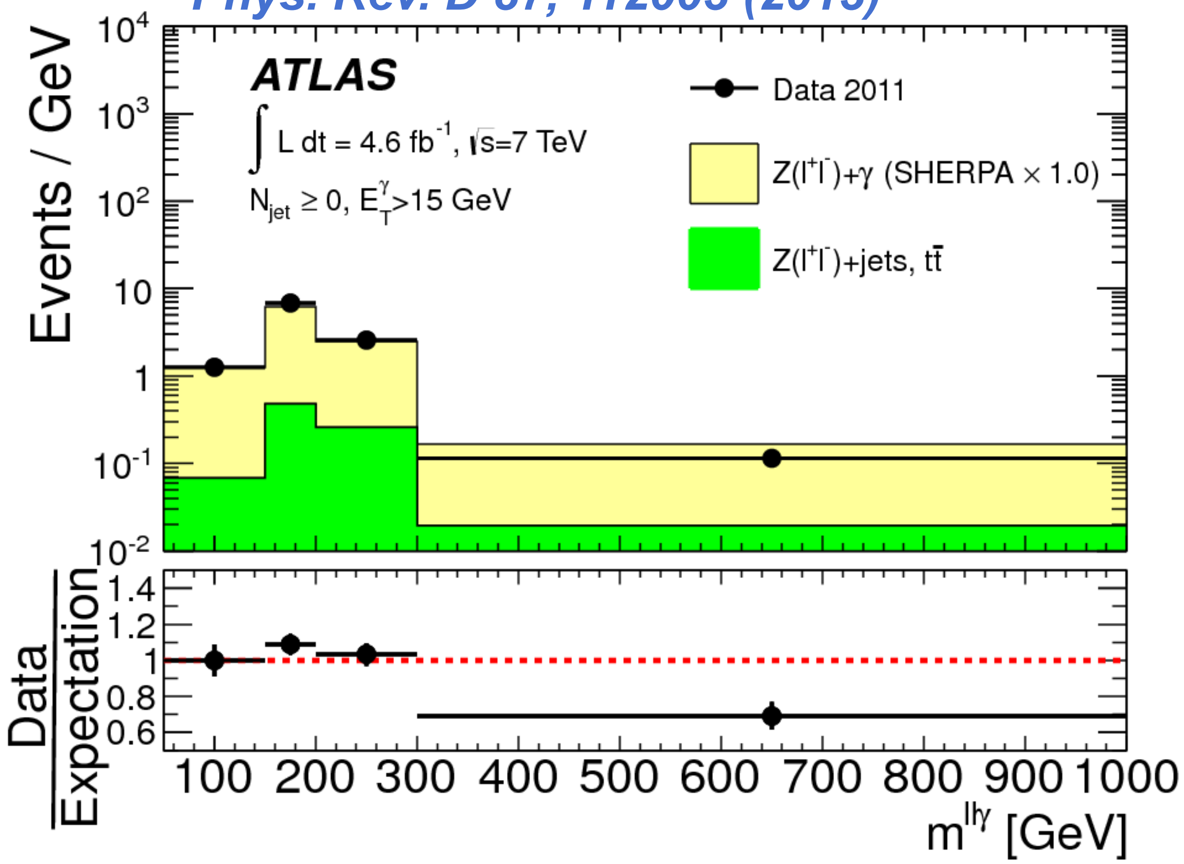
- Leptonic final state, suppress FSR: ΔR(l,γ)>0.7
- aTGC extracted from $E_T\gamma$ observable
  - Uncertainties due to backgrounds and physics modelling
  - Supersedes Tevatron limits, still not competitive with LEP.

	$\Delta\kappa_\gamma$	λ_γ
$W\gamma \to e\nu\gamma$	$[-0.45, 0.36]$	$[-0.059, 0.046]$
$W\gamma \to \mu\nu\gamma$	$[-0.46, 0.34]$	$[-0.057, 0.045]$
$W\gamma \to \ell\nu\gamma$	$[-0.38, 0.29]$	$[-0.050, 0.037]$

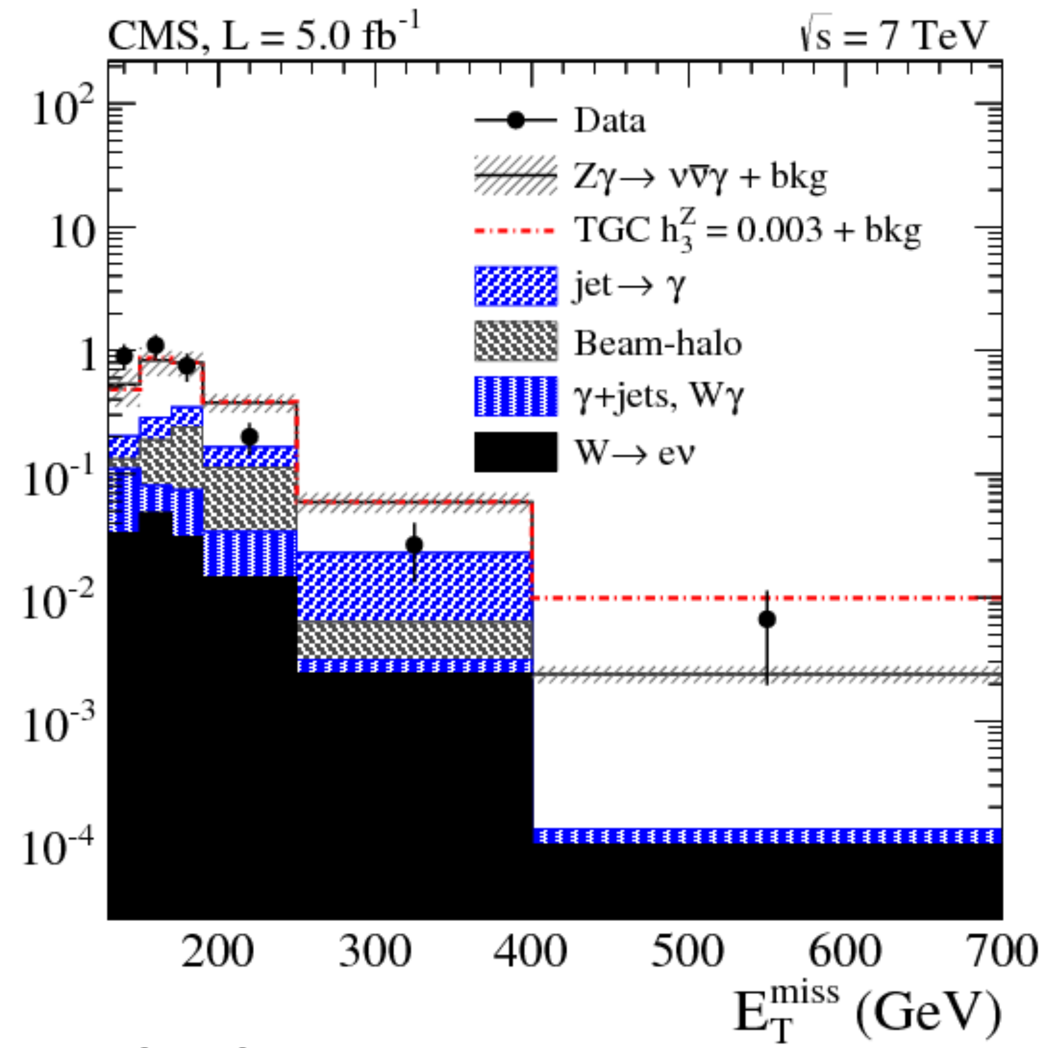
processes	Measured $pp \to \ell\nu\gamma$	Expected $pp \to \ell\nu\gamma$
Λ	∞	∞
$\Delta\kappa_\gamma$	$(-0.41, 0.46)$	$(-0.38, 0.43)$
λ_γ	$(-0.065, 0.061)$	$(-0.060, 0.056)$
Λ	6 TeV	6 TeV
$\Delta\kappa_\gamma$	$(-0.41, 0.47)$	$(-0.38, 0.43)$
λ_γ	$(-0.068, 0.063)$	$(-0.063, 0.059)$

$Z\gamma \to ll\gamma, \nu\nu\gamma$

Phys. Rev. D 87, 112003 (2013)



	Measured	Expected
processes	$pp \to \nu\nu\gamma$ and $pp \to \ell^+\ell^-\gamma$	
Λ	∞	∞
h_3^{γ}	$(-0.015, 0.016)$	$(-0.017, 0.018)$
h_3^{Z}	$(-0.013, 0.014)$	$(-0.015, 0.016)$
h_4^{γ}	$(-0.000094, 0.000092)$	$(-0.00010, 0.00010)$
h_4^{Z}	$(-0.000087, 0.000087)$	$(-0.000097, 0.000097)$
Λ	3 TeV	3 TeV
h_3^{γ}	$(-0.023, 0.024)$	$(-0.027, 0.028)$
h_3^{Z}	$(-0.018, 0.020)$	$(-0.022, 0.024)$
h_4^{γ}	$(-0.00037, 0.00036)$	$(-0.00043, 0.00042)$
h_4^{Z}	$(-0.00031, 0.00031)$	$(-0.00037, 0.00036)$



CMS: llγ + vvγ, no form factor

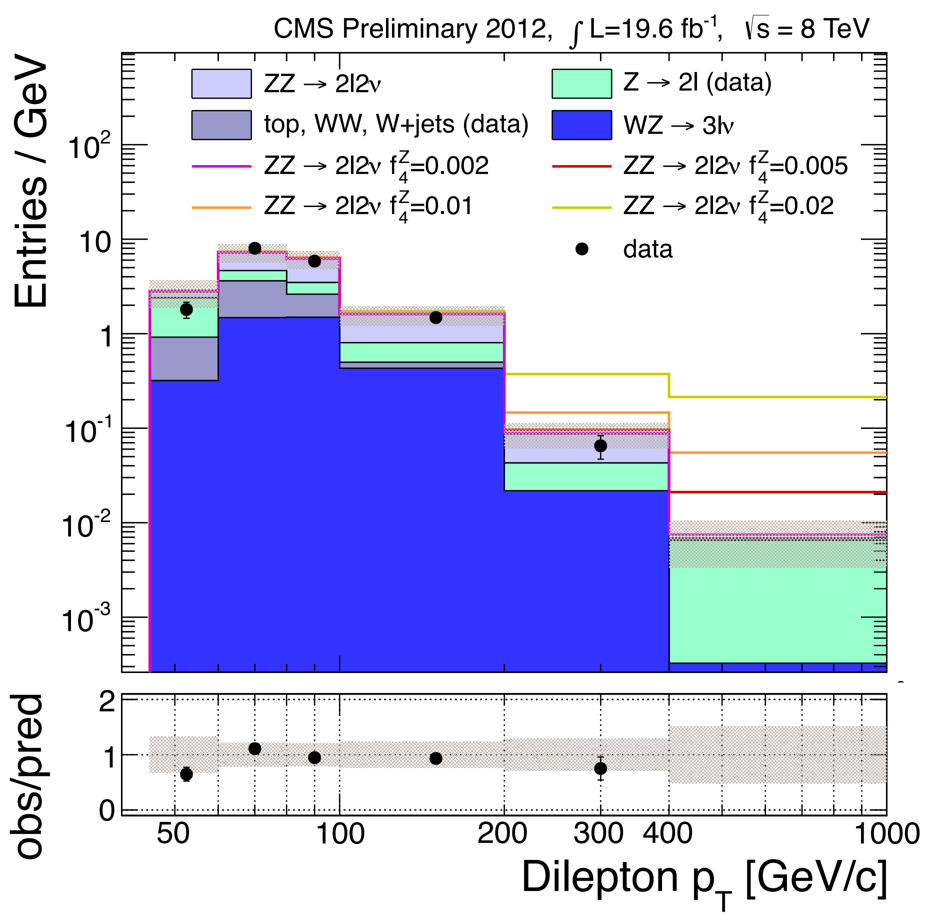
h	h	h	h
2.7x10	1.3x10	2.9x10	2.5x10

The results from the vvγ analysis dominate the sensitivity to anomalous TGCs in Zγ production.

J. High Energy Phys. 10 (2013) 164
arXiv:1308.6832

$ZZ \to llll, ll\nu\nu$

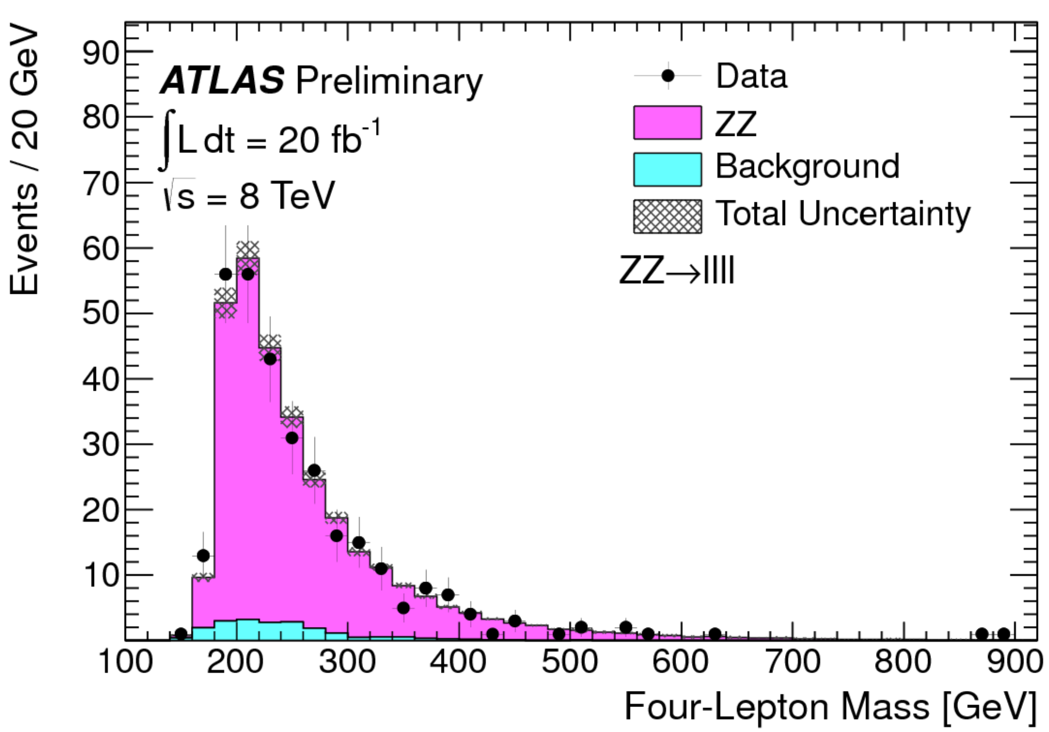
CMS-PAS-SMP-13-005



- ZZγ and Zγγ forbidden at the tree level
  - aTGC simulated using Sherpa
  - $p_T Z$ of the leading lepton pair used to estimate parameter values
  - Dominated by statistical uncertainty
  - Much stringent limits with respect to Tevatron and LEP

Dataset	f_4^Z	f_4^γ	f_5^Z	f_5^γ
7 TeV	[-0.0088; 0.0085]	[-0.0098; 0.011]	[-0.0096; 0.0096]	[-0.011 ; 0.010]
8 TeV	[-0.0038; 0.0040]	[-0.0049; 0.0039]	[-0.0041; 0.0038]	[-0.0049; 0.0046]
Combined	[-0.0030; 0.0034]	[-0.0039; 0.0031]	[-0.0036; 0.0032]	[-0.0038; 0.0038]
Expected (7 and 8 TeV)	[-0.0040; 0.0045]	[-0.0054; 0.0046]	[-0.0045; 0.0049]	[-0.0048; 0.0052]

$0.004 < f_4^Z < 0.004, \; -0.005 < f_5^Z < 0.005, \; -0.004 < f_4^\gamma < 0.004, \; -0.005 < f_5^\gamma < 0.005.$



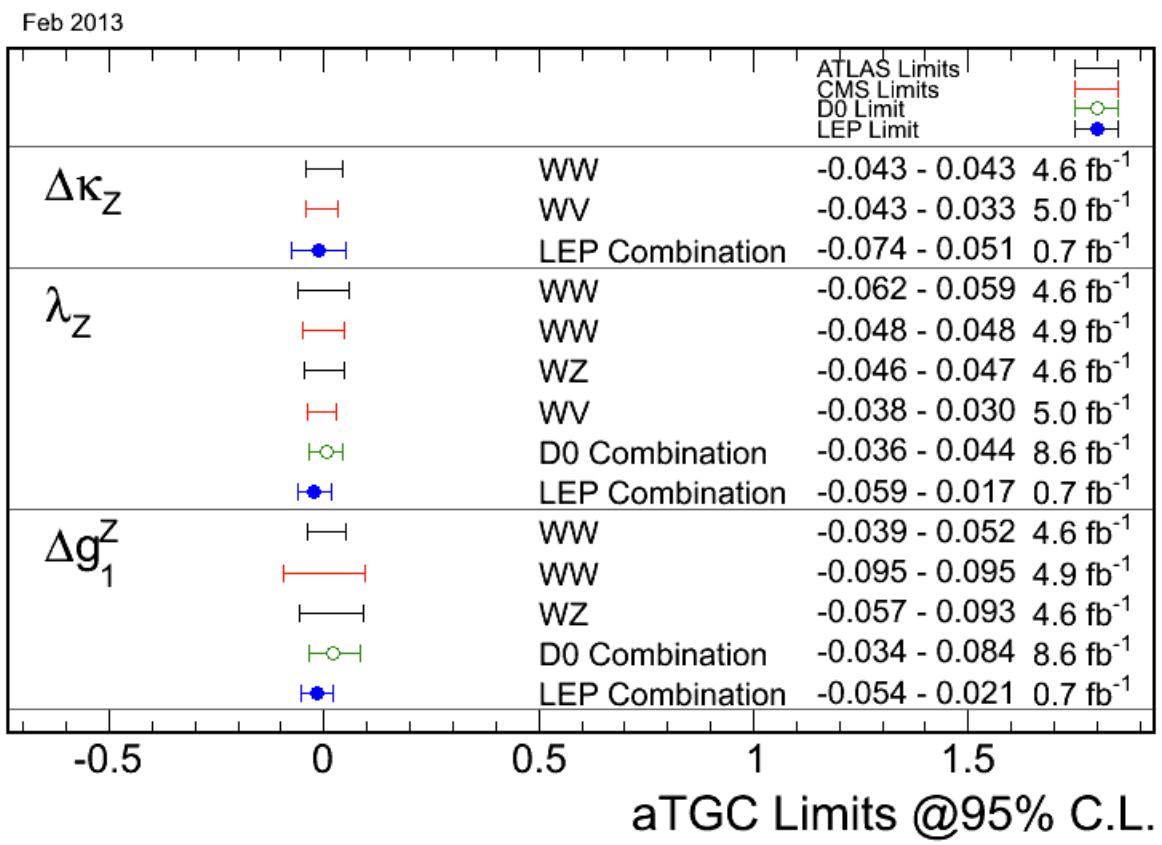
$$\sigma^{\text{fid}}_{ZZ\to\ell^-\ell^+\ell^-\ell^+} = 20.7^{+1.3}_{-1.2}(\text{stat.}) \pm 0.8(\text{syst.}) \pm 0.6(\text{lumi.})\ \text{fb}$$
$$\sigma^{\text{tot}}_{ZZ} = 7.1^{+0.5}_{-0.4}(\text{stat.}) \pm 0.3(\text{syst.}) \pm 0.2(\text{lumi.})\ \text{pb}$$

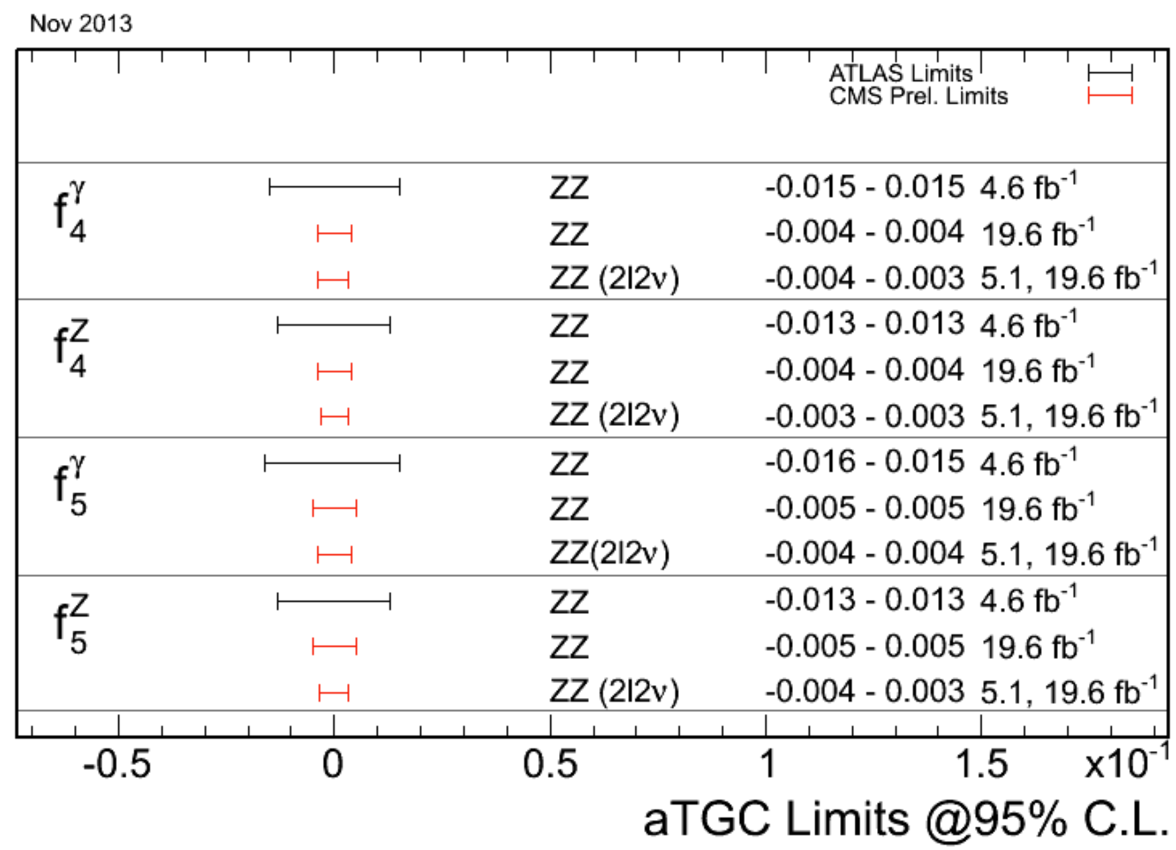
- In agreement with SM expectations (MCFM)
  - 7.2 + 0.3 -0.2 pb

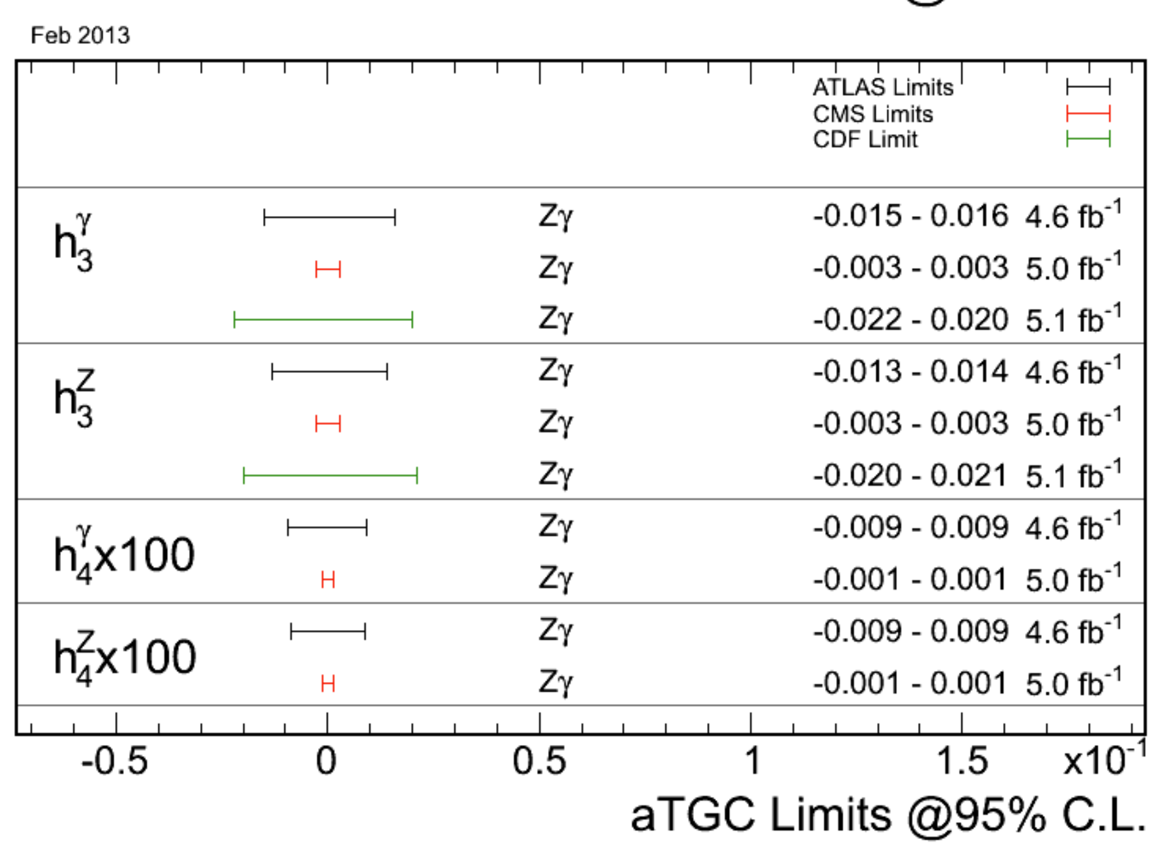
ATLAS-CONF-2013-020

JHEP03(2013)128

aTGC : SUMMARY







- ***No deviation from SM observed!***
- ***Limits on aTGC are mostly published with 7 TeV data (CMS ZZ is notable exception)***
  - Better sensitivity for neutral couplings wrt to LEP and Tevatron
  - Competitive with Tevatron for charge TGC.
- ***Improvement in sensitivity with 20fb^{-1} @ 8 TeV***
  - *Also through combination in channels.*

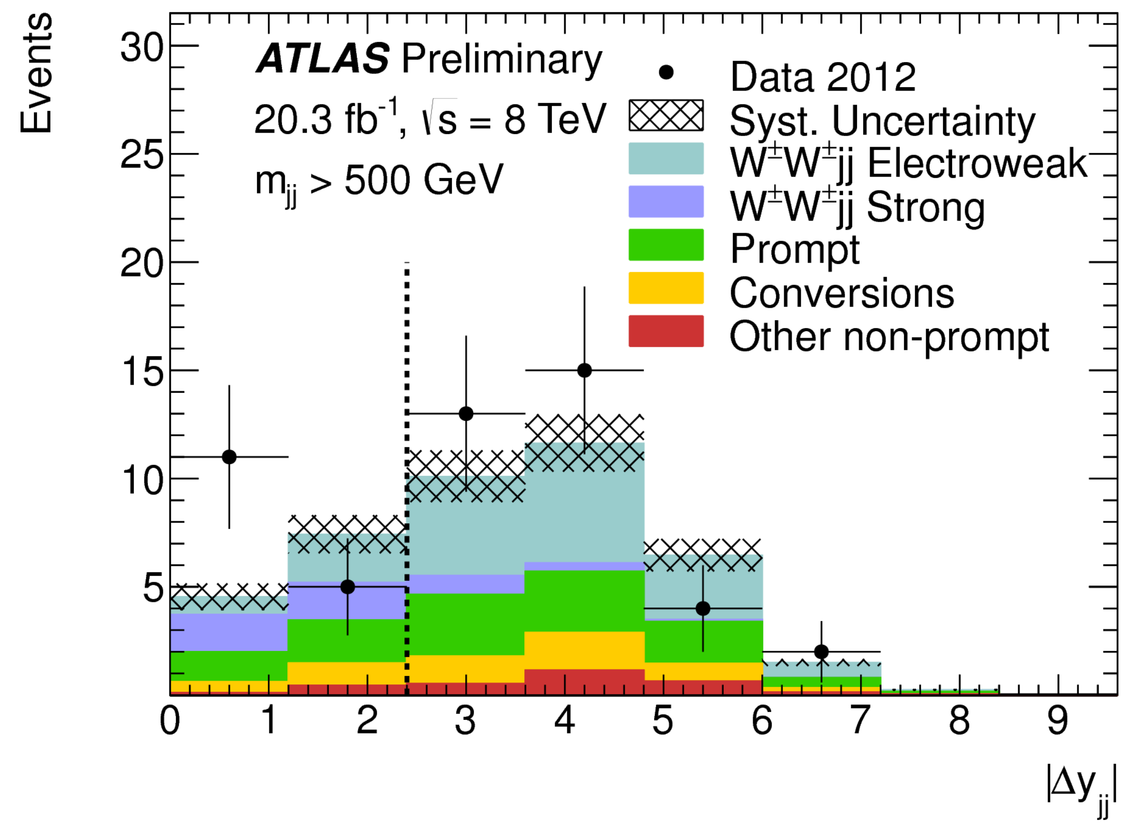
$W^{\pm}W^{\pm}jj \to l\nu l\nu jj$

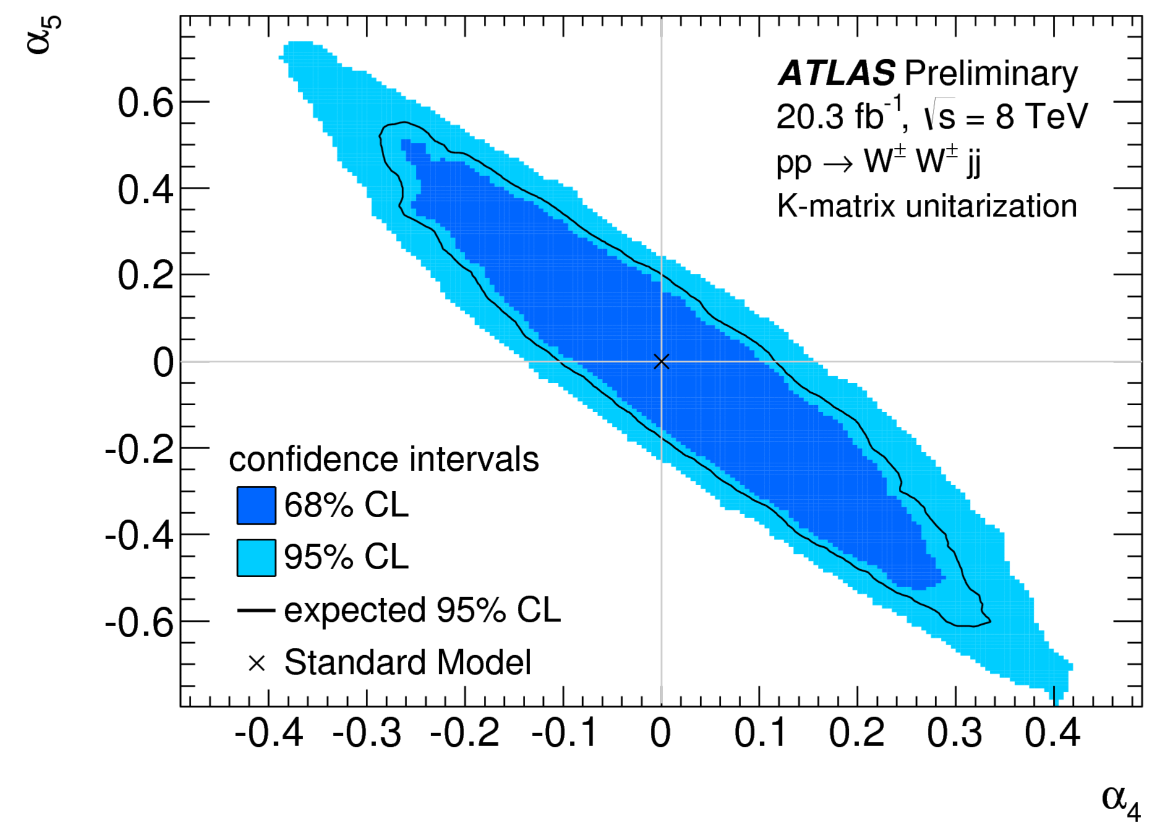
- V V→V V scattering is a key process for understanding of EWK symmetry breaking
  - Strong and EW production of WWjj
  - Same sign W production, strong production does not dominate
- Preselection:
  - exactly 2 same-charge leptons (p_T> 25 GeV)
  - ≥ 2 jets, p_T> 30 GeV
  - MET > 40 GeV, no b-jets
  - **m_{jj} > 500 GeV, $|\Delta y_{jj}|$ > 2.4 (applied only for VBS)**
- Main backgrounds:prompt lepton (WZ/γ*+j), conversion (Wγ+j), non-prompt
- Evidence of *WWjj* and EWK *WWjj* are observed with with 4.6 and 3.6σ respectively
  - Probe of *WWWW* coupling
- Cross section measurement

$$\sigma^{EW}_{W^\pm W^\pm jj} = 1.3 \pm 0.4(\text{stat}) \pm 0.2(\text{syst})\ \text{fb}$$

$$\text{SM:}\quad \sigma^{EW}_{W^\pm W^\pm jj}(\text{NLO}) = 0.95 \pm 0.06\ \text{fb}$$

ATLAS-CONF-2014-013

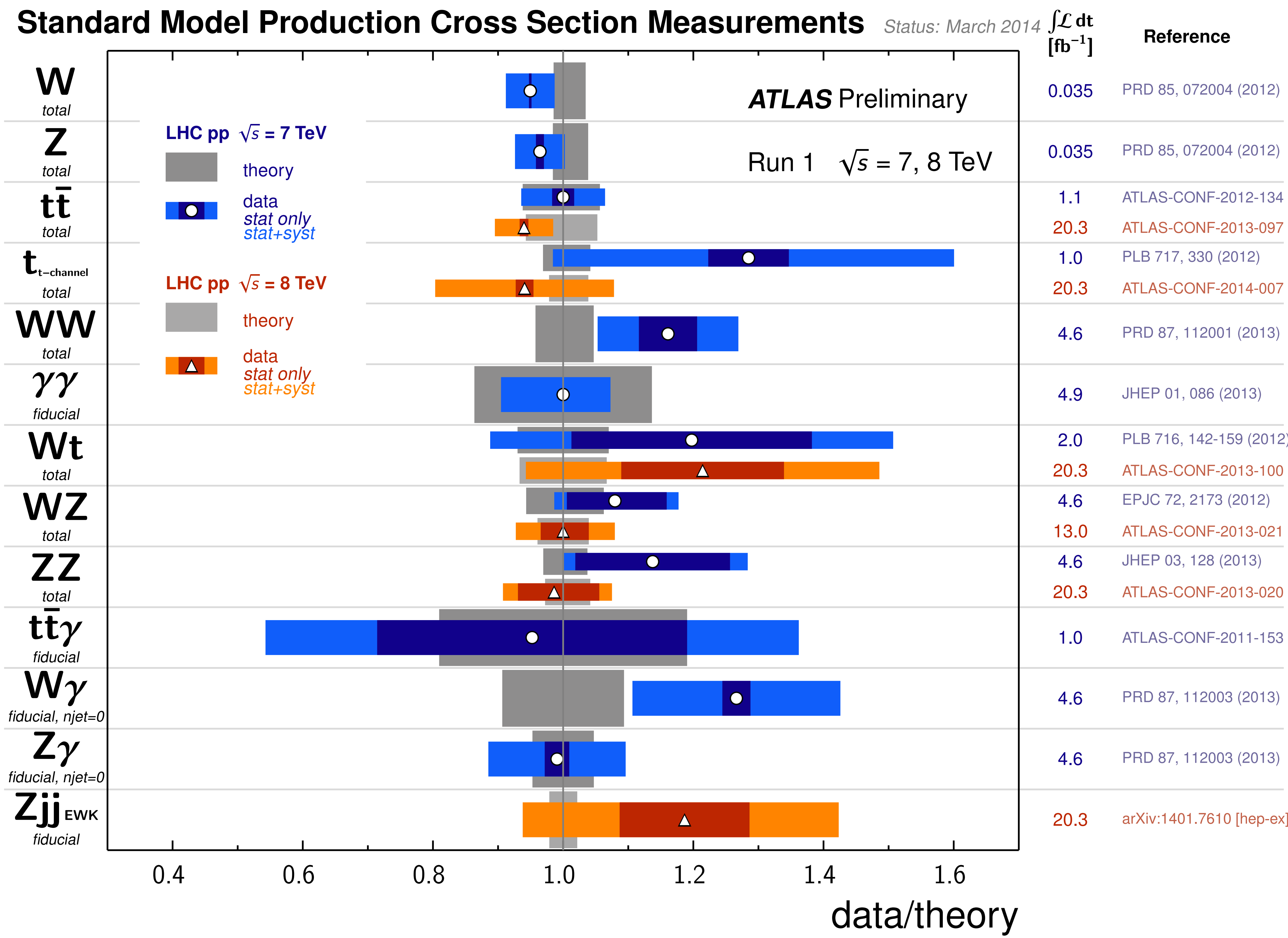




SUMMARY

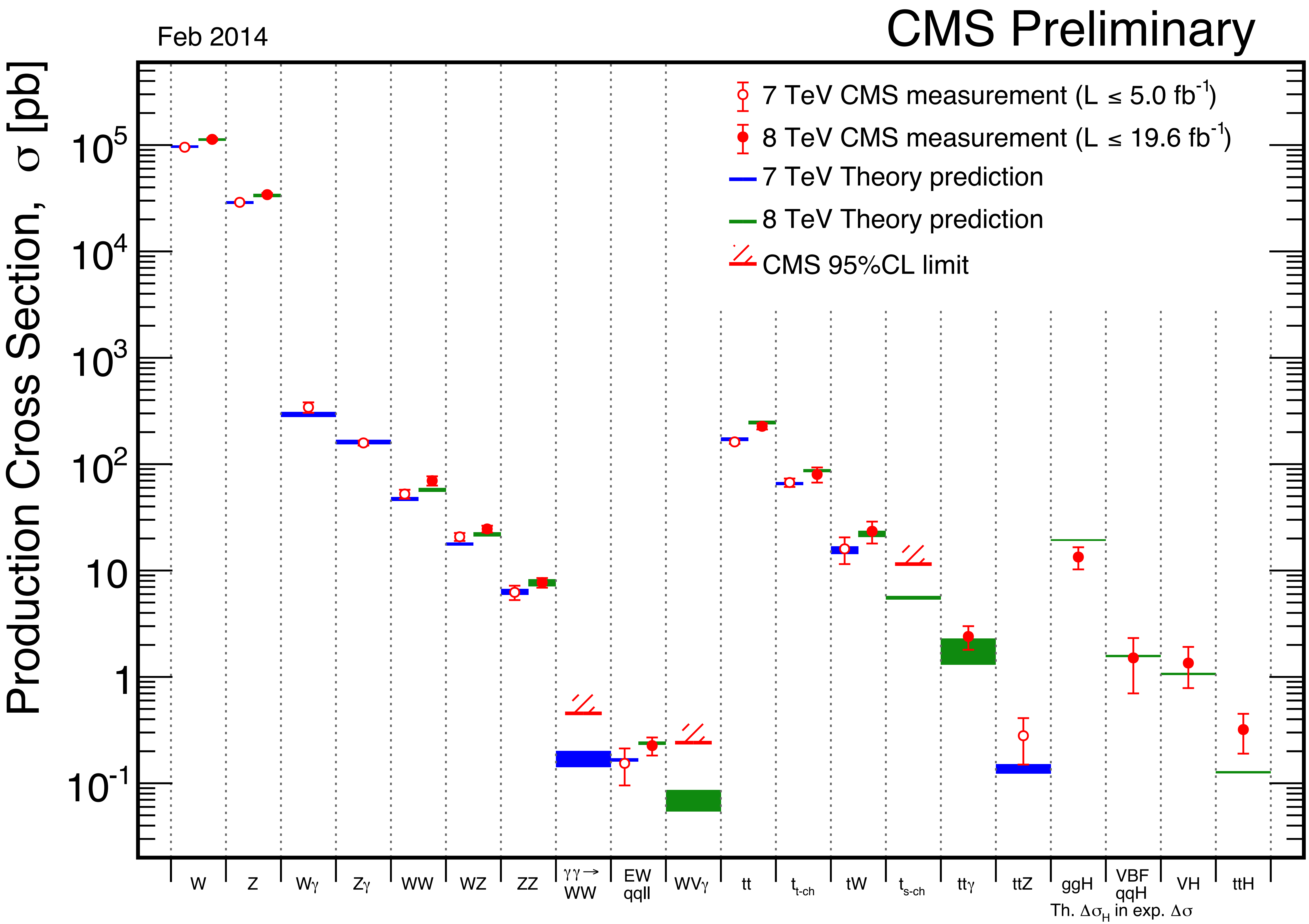
- Exciting time for electroweak physics at the LHC
- Prospects for W boson mass measurement:
  - Huge accumulated statistics of leptonic W bosons decays should give few MeV statistical uncertainty on W mass measurement.
  - Experimental systematic uncertainties: lepton momentum scale/resolution, hadronic recoil resolution.
  - Physics modelling benefits from supporting measurement such as $P_T Z$, $p_T W$, Parton shower tunes…
  - W/Z double differential cross section measurements and strange quark density help constraining PDF uncertainties.
- Multiboson production: test self couplings of gauge bosons.
  - New energy regime: no deviation with respect to SM predictions
- Limits on anomalous couplings mostly at full 7 TeV dataset.
  - Still most of the LHC data at 8 TeV to be analysed more results with improved precision expected soon.

BACKUP



Standard Model Production Cross Section Measurements
Status: March 2014
∫ℒ dt [fb⁻¹]
Reference
ATLAS Preliminary
Run 1 √s = 7, 8 TeV
LHC pp √s = 7 TeV
theory
data
stat only
stat+syst
LHC pp √s = 8 TeV
theory
data
stat only
stat+syst
W total
Z total
tt̄ total
t t−channel total
WW total
γγ fiducial
Wt total
WZ total
ZZ total
tt̄γ fiducial
Wγ fiducial, njet=0
Zγ fiducial, njet=0
Zjj EWK fiducial
0.035 PRD 85, 072004 (2012)
0.035 PRD 85, 072004 (2012)
1.1 ATLAS-CONF-2012-134
20.3 ATLAS-CONF-2013-097
1.0 PLB 717, 330 (2012)
20.3 ATLAS-CONF-2014-007
4.6 PRD 87, 112001 (2013)
4.9 JHEP 01, 086 (2013)
2.0 PLB 716, 142-159 (2012)
20.3 ATLAS-CONF-2013-100
4.6 EPJC 72, 2173 (2012)
13.0 ATLAS-CONF-2013-021
4.6 JHEP 03, 128 (2013)
20.3 ATLAS-CONF-2013-020
1.0 ATLAS-CONF-2011-153
4.6 PRD 87, 112003 (2013)
4.6 PRD 87, 112003 (2013)
20.3 arXiv:1401.7610 [hep-ex]
0.4 0.6 0.8 1.0 1.2 1.4 1.6
data/theory

XSEC


CMS Preliminary
Feb 2014
Production Cross Section, σ [pb]
10^5
10^4
10^3
10^2
10
1
10^{-1}
7 TeV CMS measurement (L ≤ 5.0 fb^{-1})
8 TeV CMS measurement (L ≤ 19.6 fb^{-1})
7 TeV Theory prediction
8 TeV Theory prediction
CMS 95%CL limit
W
Z
Wγ
Zγ
WW
WZ
ZZ
γγ→WW
EW qqll
WVγ
tt
$t_{t\text{-}ch}$
tW
$t_{s\text{-}ch}$
ttγ
ttZ
ggH
VBF qqH
VH
ttH
Th. $\Delta\sigma_H$ in exp. $\Delta\sigma$

ELECTROWEAK FITS

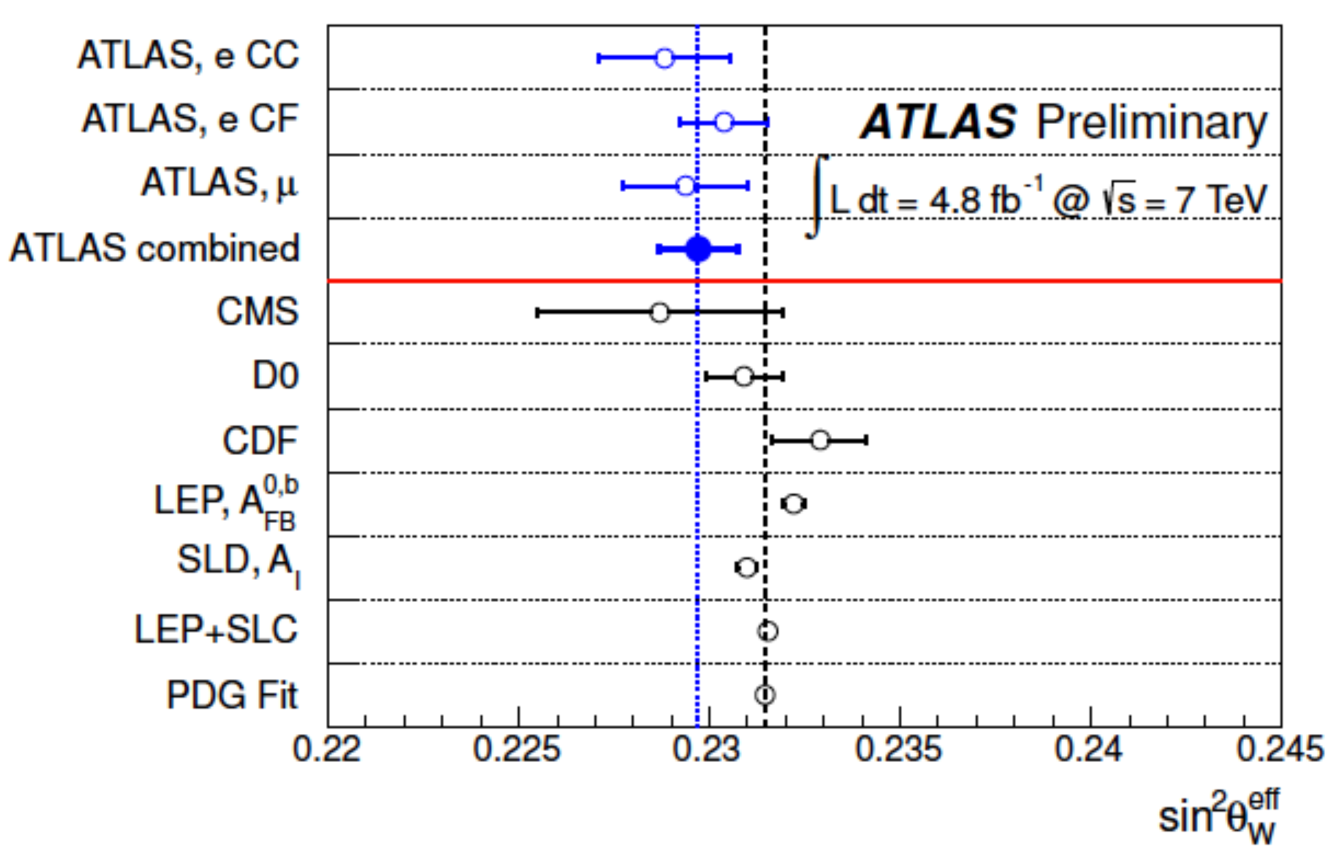
- From the Gfitter Group, EPJC 72, 2205 (2012)
- Left: full fit incl. M_H
- Middle: not incl. M_H
- Right: fit incl M_H, not the row

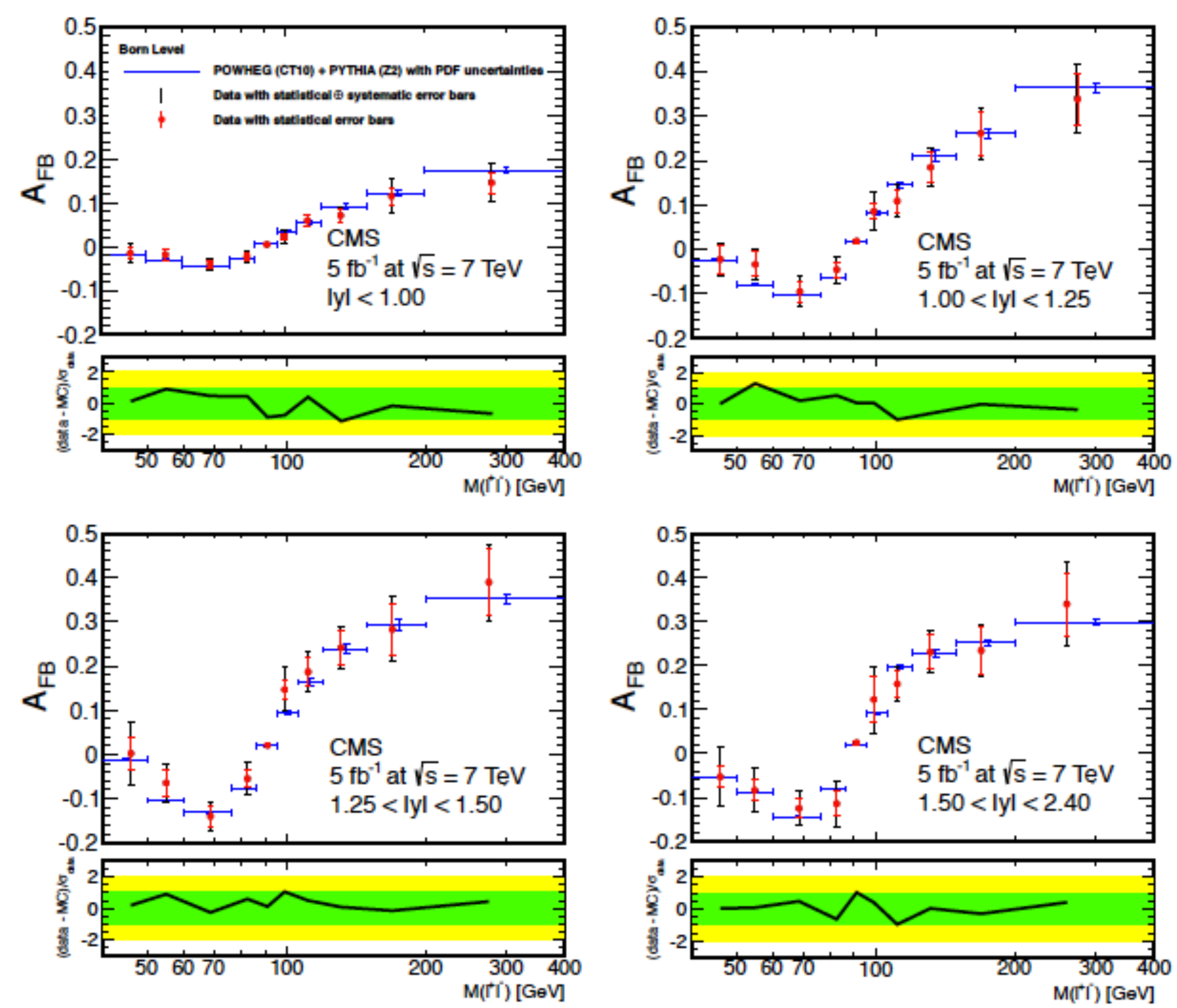
Parameter	Input value	Free in fit	Fit Result	Fit without M_H measurements	Fit without exp. input in line
M_H [GeV]°	$125.7^{+0.4}_{-0.4}$	yes	$125.7^{+0.4}_{-0.4}$	94.7^{+25}_{-22}	94.7^{+25}_{-22}
M_W [GeV]	80.385 ± 0.015	–	$80.367^{+0.006}_{-0.007}$	$80.367^{+0.006}_{-0.007}$	80.360 ± 0.011
Γ_W [GeV]	2.085 ± 0.042	–	2.091 ± 0.001	2.091 ± 0.001	2.091 ± 0.001
M_Z [GeV]	91.1875 ± 0.0021	yes	91.1878 ± 0.0021	91.1878 ± 0.0021	91.1978 ± 0.0114
Γ_Z [GeV]	2.4952 ± 0.0023	–	2.4954 ± 0.0014	2.4954 ± 0.0014	2.4950 ± 0.0017
$\sigma^0_{\rm had}$ [nb]	41.540 ± 0.037	–	41.479 ± 0.014	41.479 ± 0.014	41.471 ± 0.015
R^0_ℓ	20.767 ± 0.025	–	20.740 ± 0.017	20.740 ± 0.017	20.715 ± 0.026
$A^{0,\ell}_{\rm FB}$	0.0171 ± 0.0010	–	$0.01626^{+0.0001}_{-0.0002}$	$0.01626^{+0.0001}_{-0.0002}$	0.01624 ± 0.0002
A_ℓ $^{(\star)}$	0.1499 ± 0.0018	–	0.1472 ± 0.0007	0.1472 ± 0.0007	–
$\sin^2\theta^\ell_{\rm eff}(Q_{\rm FB})$	0.2324 ± 0.0012	–	$0.23149^{+0.00010}_{-0.00008}$	$0.23149^{+0.00010}_{-0.00008}$	0.23150 ± 0.00009
A_c	0.670 ± 0.027	–	$0.6679^{+0.00034}_{-0.00028}$	$0.6679^{+0.00034}_{-0.00028}$	0.6680 ± 0.00031
A_b	0.923 ± 0.020	–	$0.93464^{+0.00005}_{-0.00007}$	$0.93464^{+0.00005}_{-0.00007}$	0.93463 ± 0.00006
$A^{0,c}_{\rm FB}$	0.0707 ± 0.0035	–	0.0738 ± 0.0004	0.0738 ± 0.0004	0.0737 ± 0.0004
$A^{0,b}_{\rm FB}$	0.0992 ± 0.0016	–	0.1032 ± 0.0005	0.1032 ± 0.0005	0.1034 ± 0.0003
R^0_c	0.1721 ± 0.0030	–	0.17223 ± 0.00006	0.17223 ± 0.00006	0.17223 ± 0.00006
R^0_b	0.21629 ± 0.00066	–	0.21548 ± 0.00005	0.21548 ± 0.00005	0.21547 ± 0.00005
$\overline{m}_c$ [GeV]	$1.27^{+0.07}_{-0.11}$	yes	$1.27^{+0.07}_{-0.11}$	$1.27^{+0.07}_{-0.11}$	–
$\overline{m}_b$ [GeV]	$4.20^{+0.17}_{-0.07}$	yes	$4.20^{+0.17}_{-0.07}$	$4.20^{+0.17}_{-0.07}$	–
m_t [GeV]	173.20 ± 0.87	yes	173.53 ± 0.82	173.53 ± 0.82	$176.11^{+2.88}_{-2.35}$
$\Delta\alpha^{(5)}_{\rm had}(M^2_Z)$ $^{(\dagger\triangle)}$	2757 ± 10	yes	2755 ± 11	2755 ± 11	2718^{+49}_{-43}
$\alpha_s(M^2_Z)$	–	yes	$0.1190^{+0.0028}_{-0.0027}$	$0.1190^{+0.0028}_{-0.0027}$	0.1190 ± 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	-0.6	-0.5	–

FB SYMMETRY AND WEAK MIXING ANGLE

$$\text{On-shell: } \sin^2\theta_W = 1 - \frac{M_W^2}{M_Z^2}$$

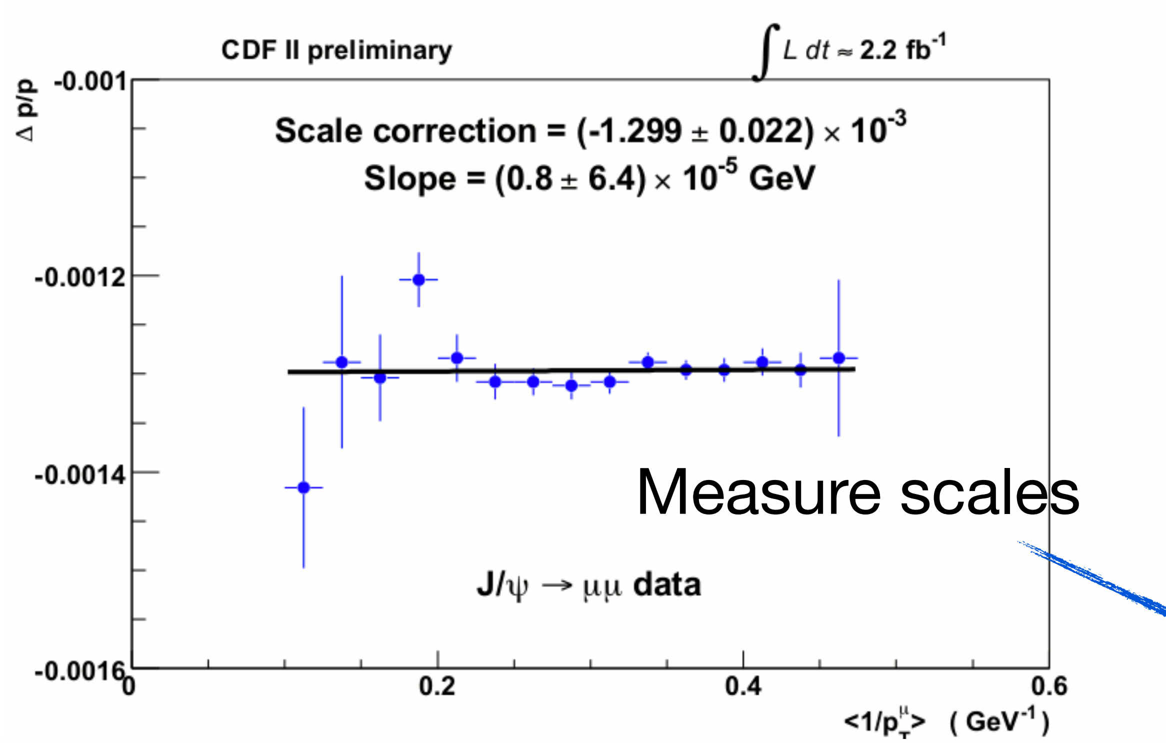
- Can be measured at colliders in asymmetries:
  - CMS: 1.1 fb^{-1}, ATLAS 4.6 fb^{-1} (preliminary)
  - g_A and g_V interference leads to asymmetry in polar angle w.r.t quark
    pp collision: where does the quark come from?
- AFB @ CMS, no Z- mass constrained, results consistent with SM

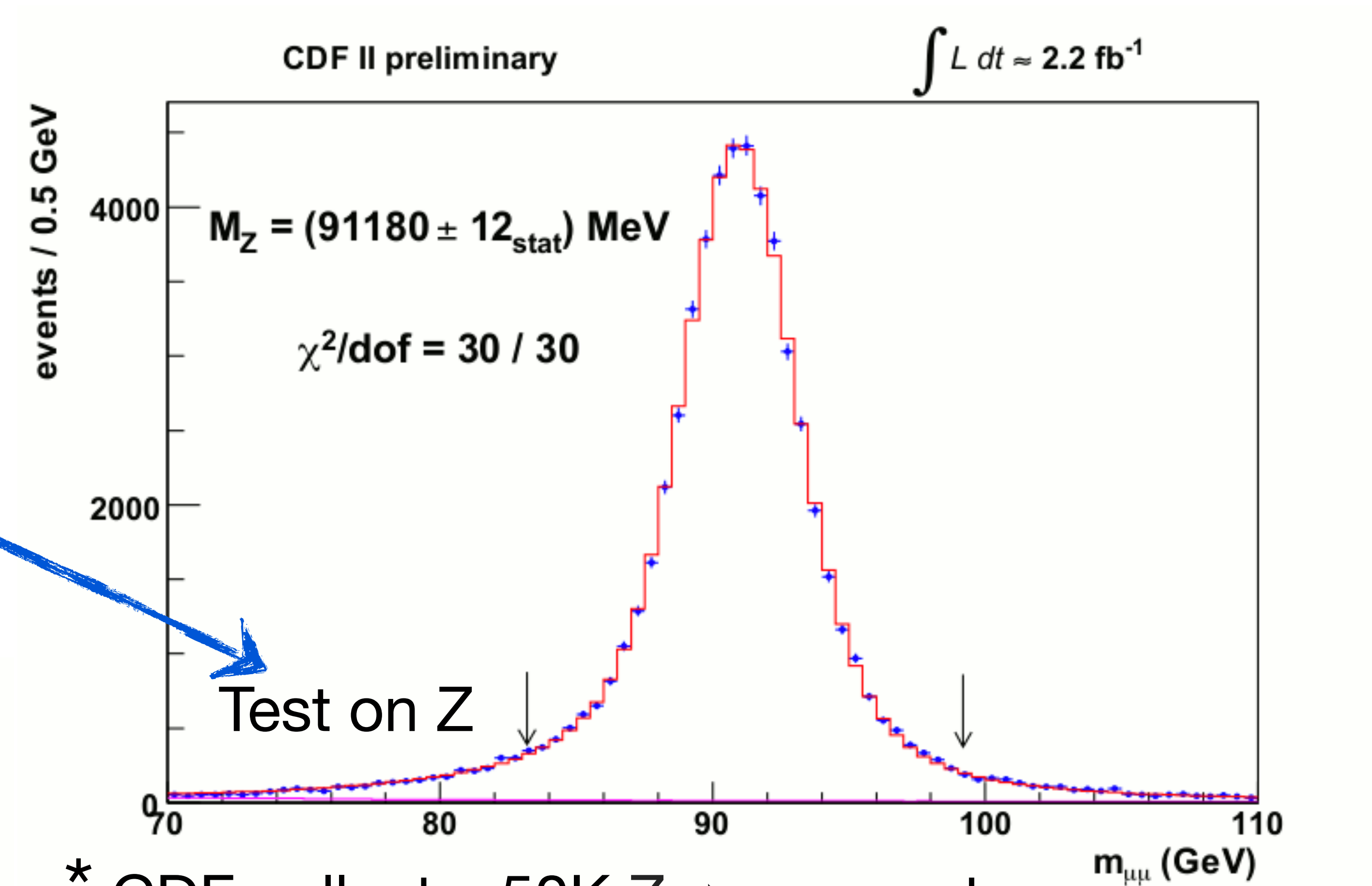


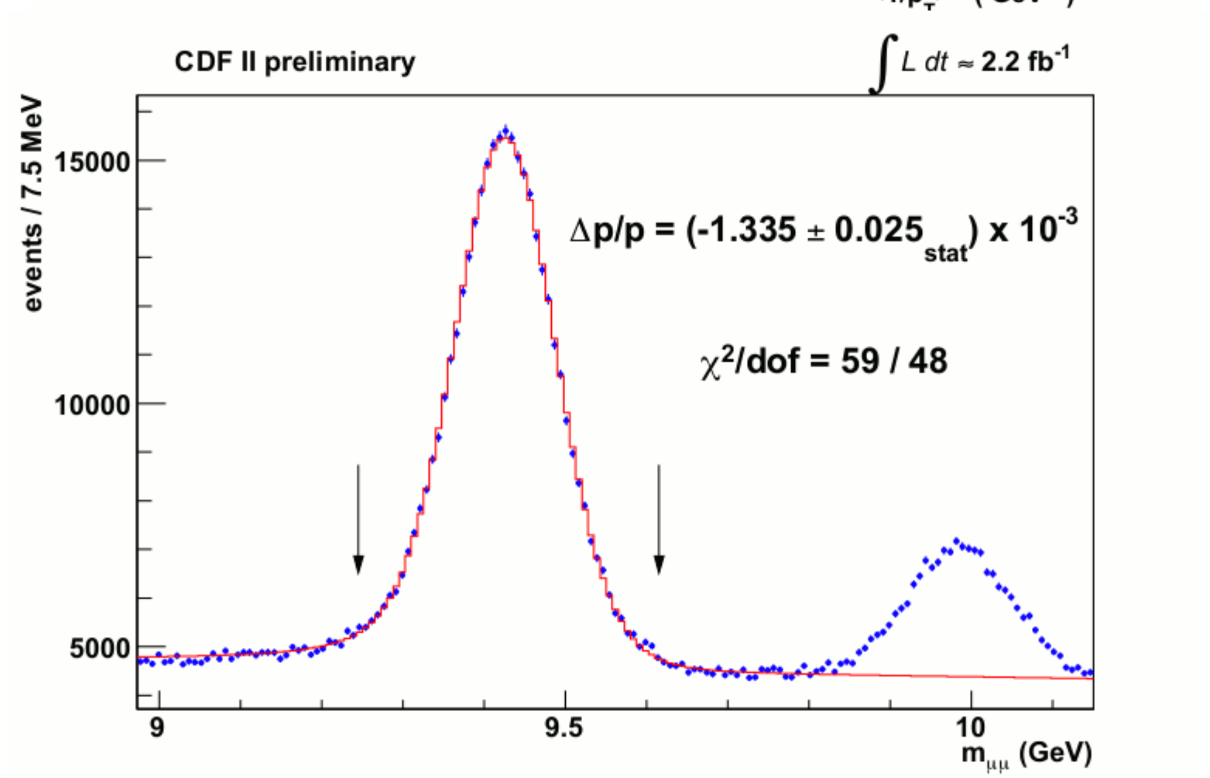


TEVATRON LEPTON SCALE UNCERTAINTY

- Tevatron experience: use J/ψ→ μμ (and Υ), but p_T<5-10 GeV, test scale on Z→ μμ





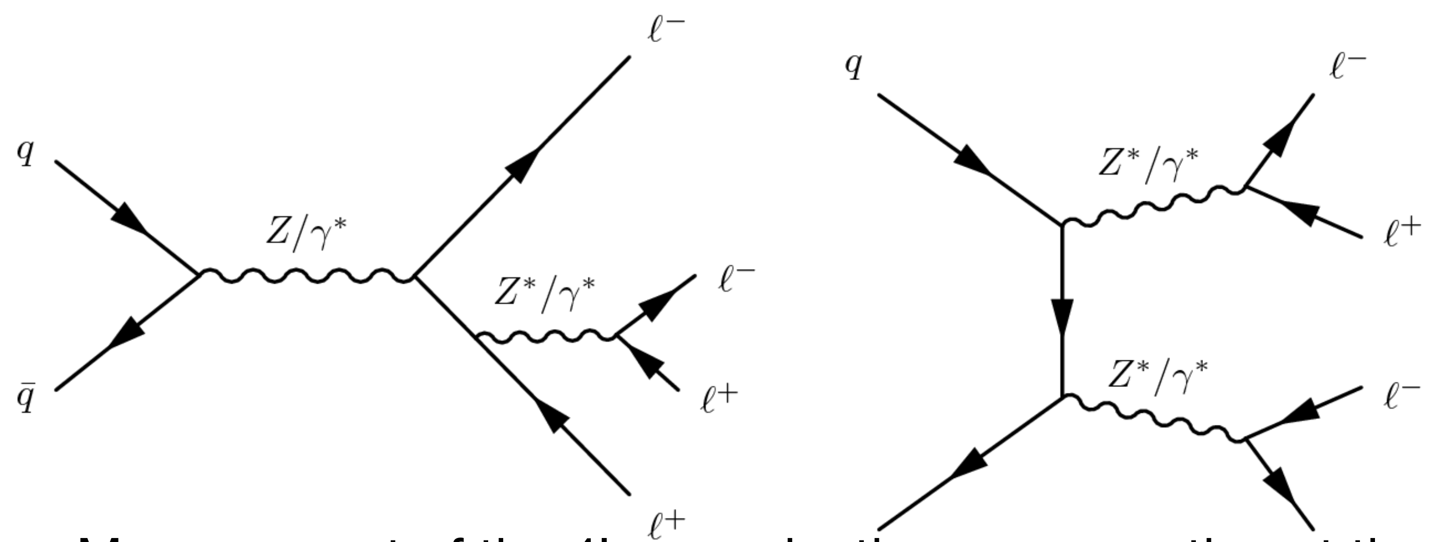


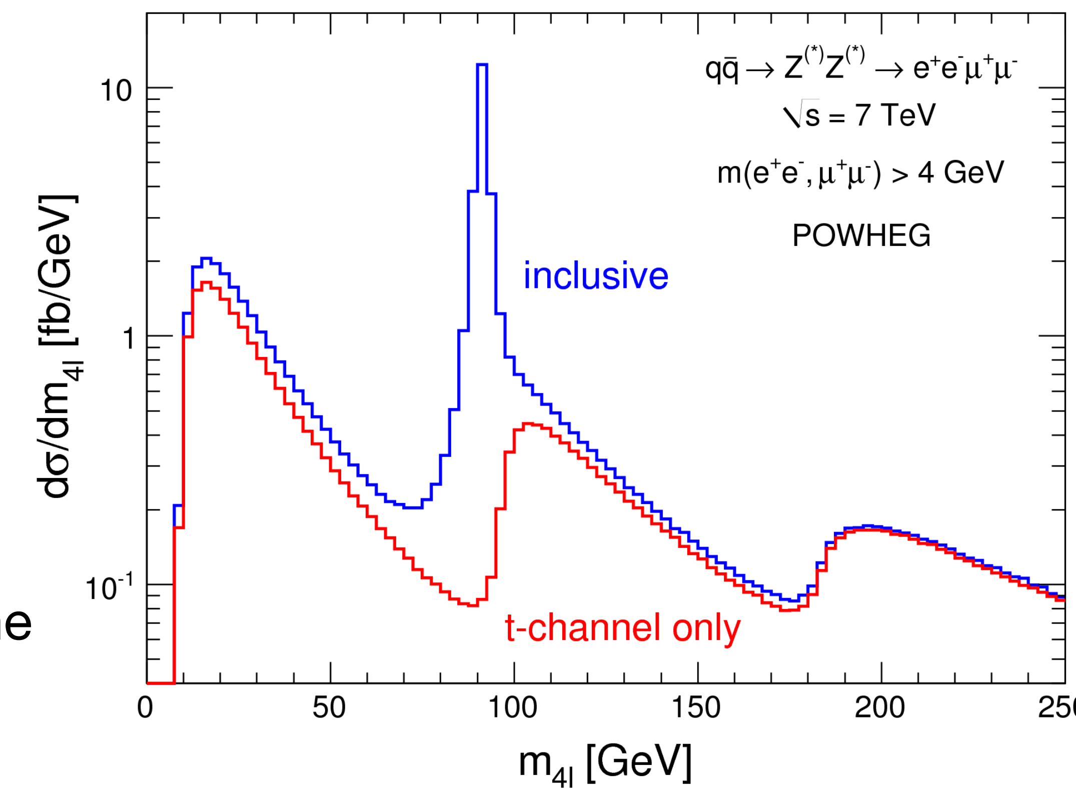
* CDF collects 50K Z→ μμ events

* Also no pseudorapidity binning, harder to probe localised effects

* Power of the LHC: 20M J/ψ→ μμ and ~2M Z→ μμ (2011)

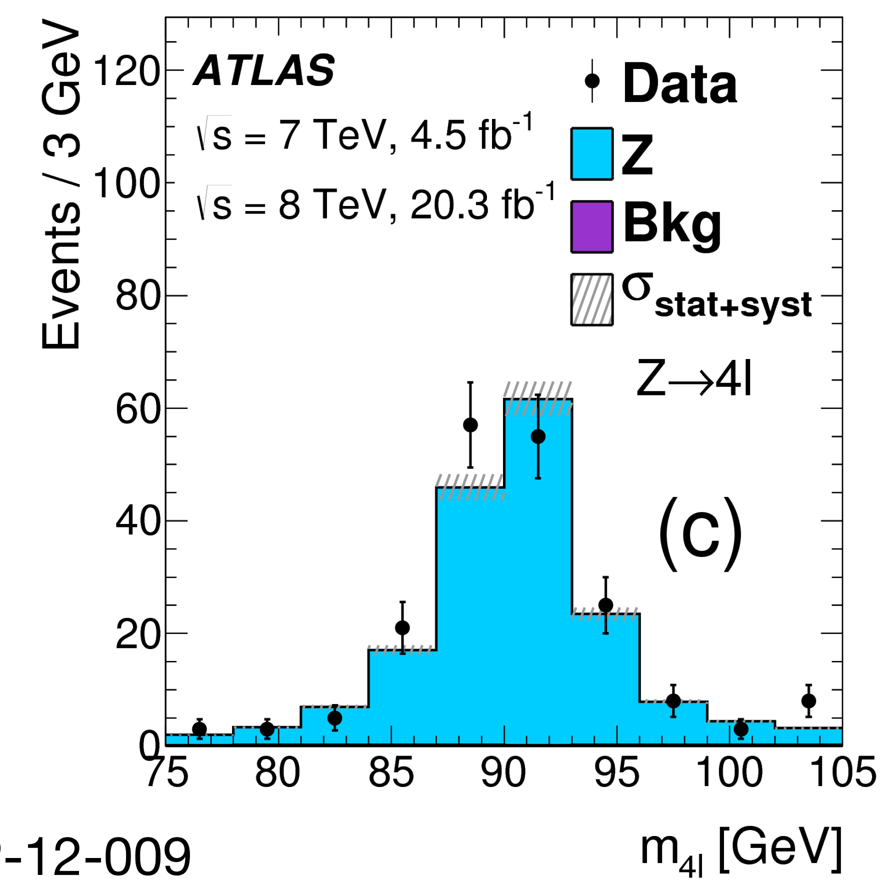
$Z \to llll$





- Measurement of the 4lep production cross section at the Z resonance provides a test of the SM and a cross-check of the detector response to the 4lep state from Higgs decays.
- Rare decay, no measurement before the LHC
- Cross section measured:
  - $\sigma_{Z\to 4\ell} = 107 \pm 9\ (\mathrm{stat}) \pm 4\ (\mathrm{syst}) \pm 3\ (\mathrm{lumi})$ fb
  - SM (NLO, 8 TeV): $\sigma_{Z\to 4\ell} = 104.8 \pm 2.5$ fb
- Branching ratio subtract expected non-resonant contribs, normalize to Z→ μμin same dataset:
- consistent with SM expectations (Powheg):(3.30±0.01) x 10^{-6}

$$\Gamma_{Z\to 4\ell}/\Gamma_Z = (3.20 \pm 0.25\ (\mathrm{stat}) \pm 0.13\ (\mathrm{syst})) \times 10^{-6}$$

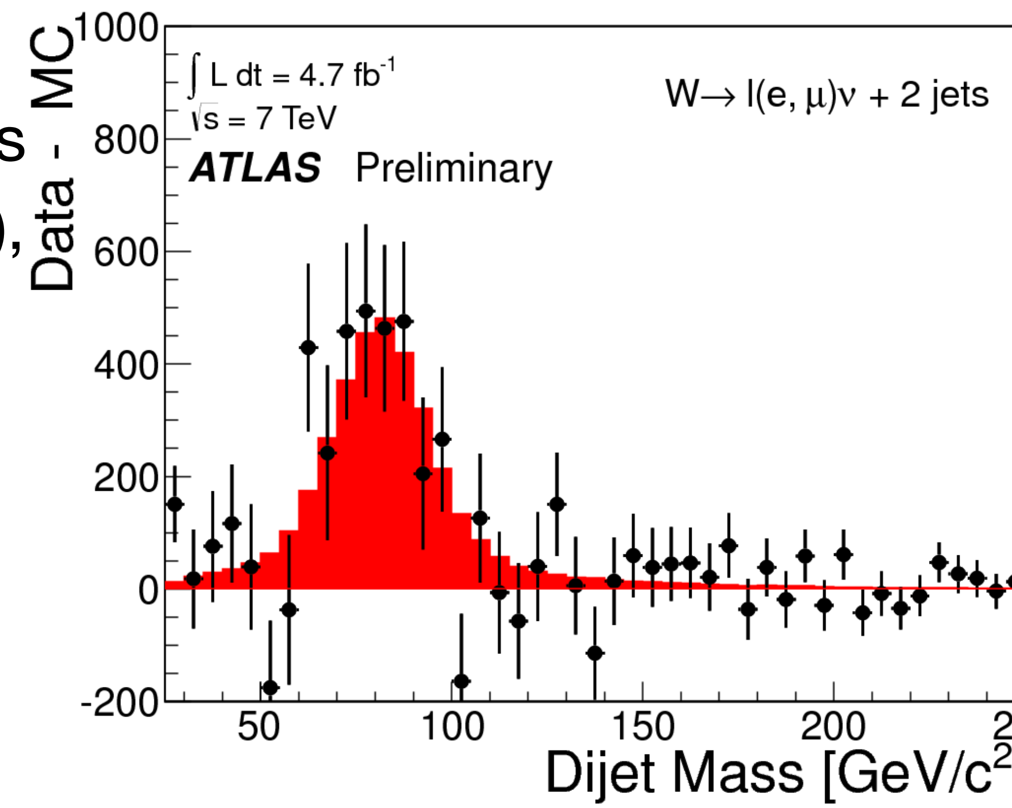


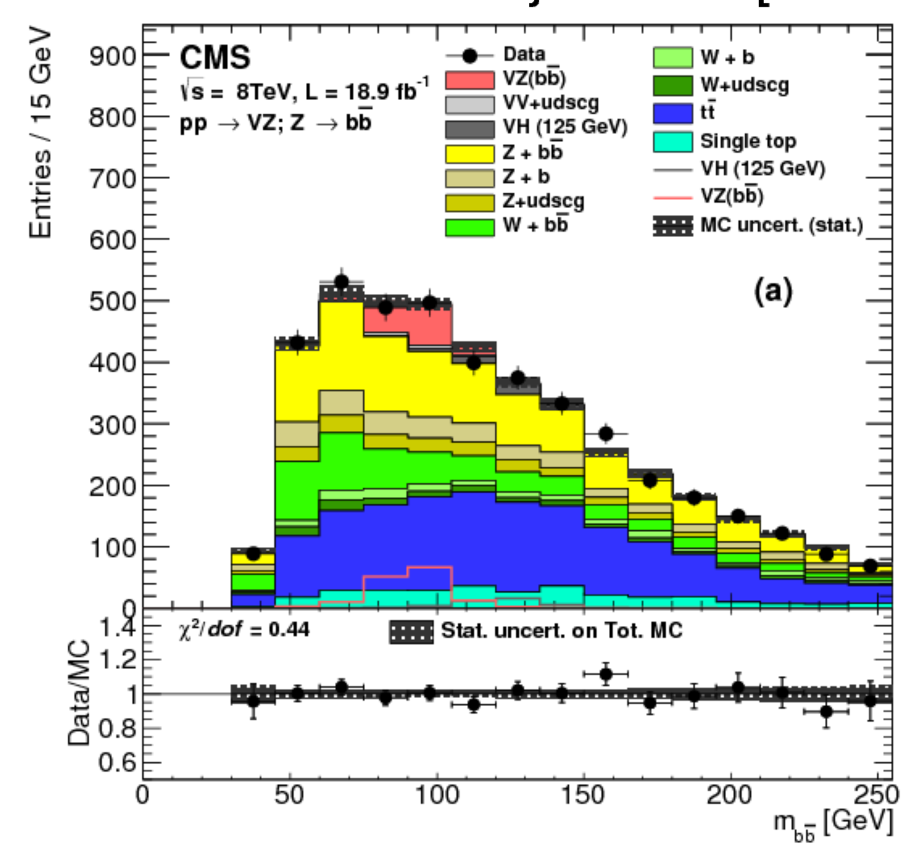
ATLAS: arXiv:1403.5657 [hep-ex]; ATLAS-CONF-2013-055
CMS: JHEP 12 (2012) 034, arXiv:1210.3844 [hep-ex]; CMS PAS SMP-12-009

WW/WZ WITH JET FINAL STATES

- Advantage to fully leptonic: Larger BR, direct reconstruction of boson pT but larger backgrounds
  - Disadvantage: larger background (mainly W+jets), Larger systematics due to jet energy scale/ resolution
- WW+WZ: limits on $\Delta\kappa_\gamma$ and λ (HISZ parametrisation)
  - $0.038 < \lambda < 0.030$, $0.11 < \Delta\kappa_\gamma < 0.14$.
  - more stringent with respect to fully leptonic final state analysis
- WW+WZ with bb final states
  - important background for VH, H->bb productions,
  - three categories of events presented:

    $W\to l\nu$, $Z\to ll$, $Z\to\nu\nu$, cross sections measured in all three
  - BDT analysis based on classification in $p_T V$, events sorted by expected S/B, 4.3σ observation



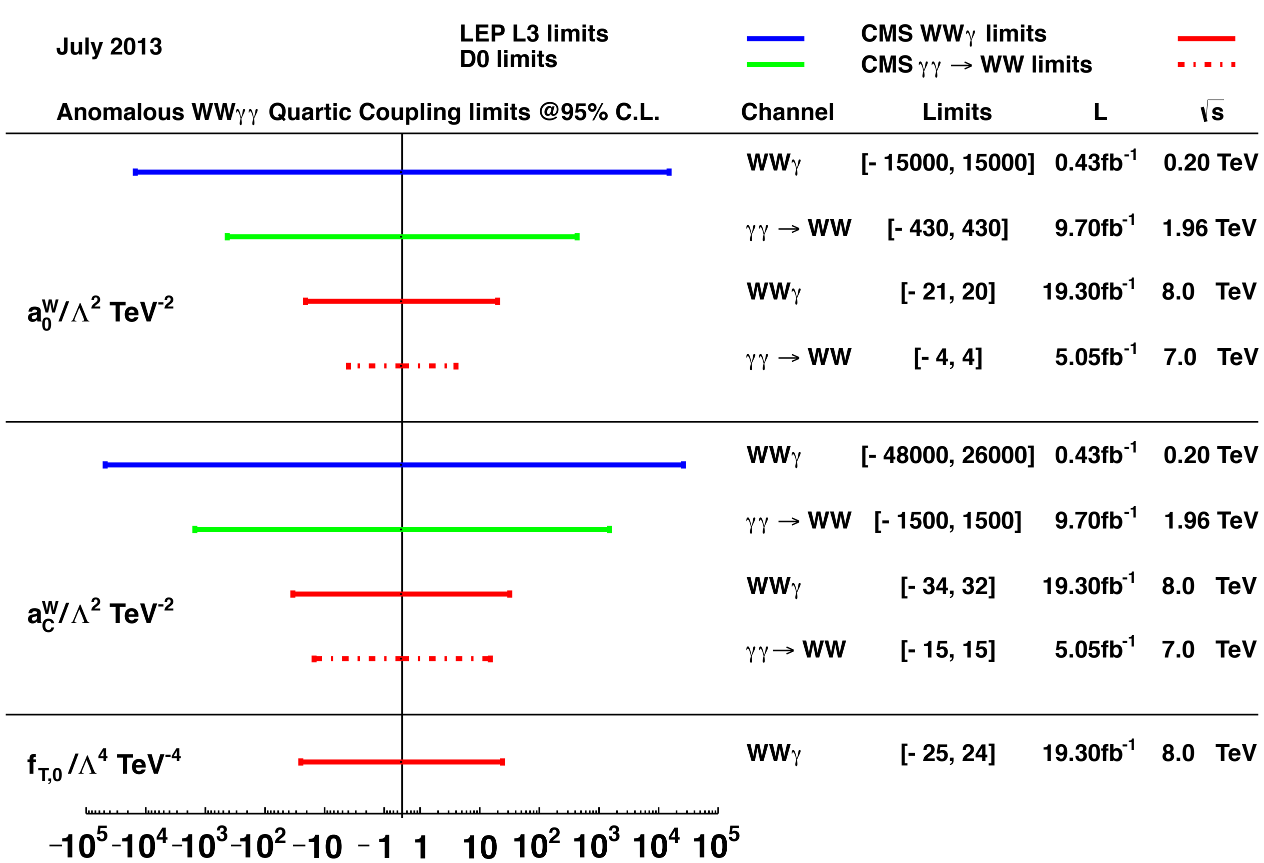


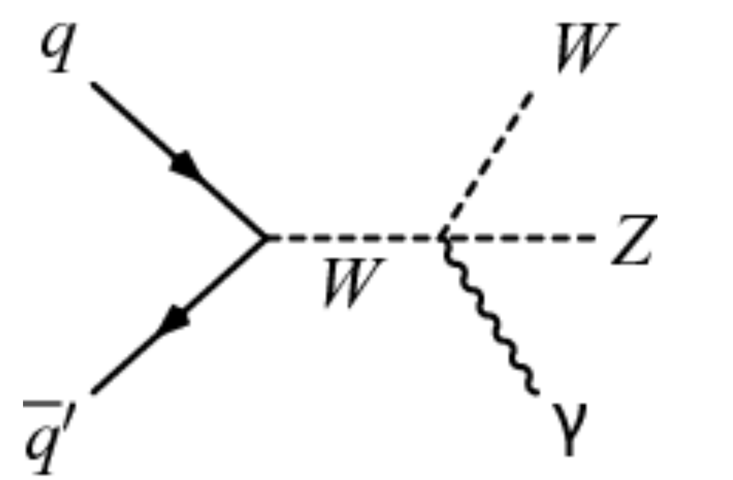
AQGC

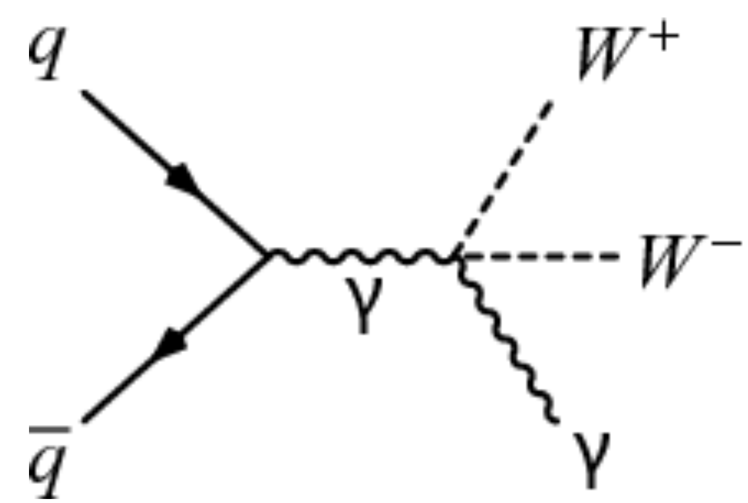
Exploit unique final states to access pure quartic contributions

- Exclusive WW production
- WWγ and WZγ, with one massive boson decay into jets
- New measurements in last year

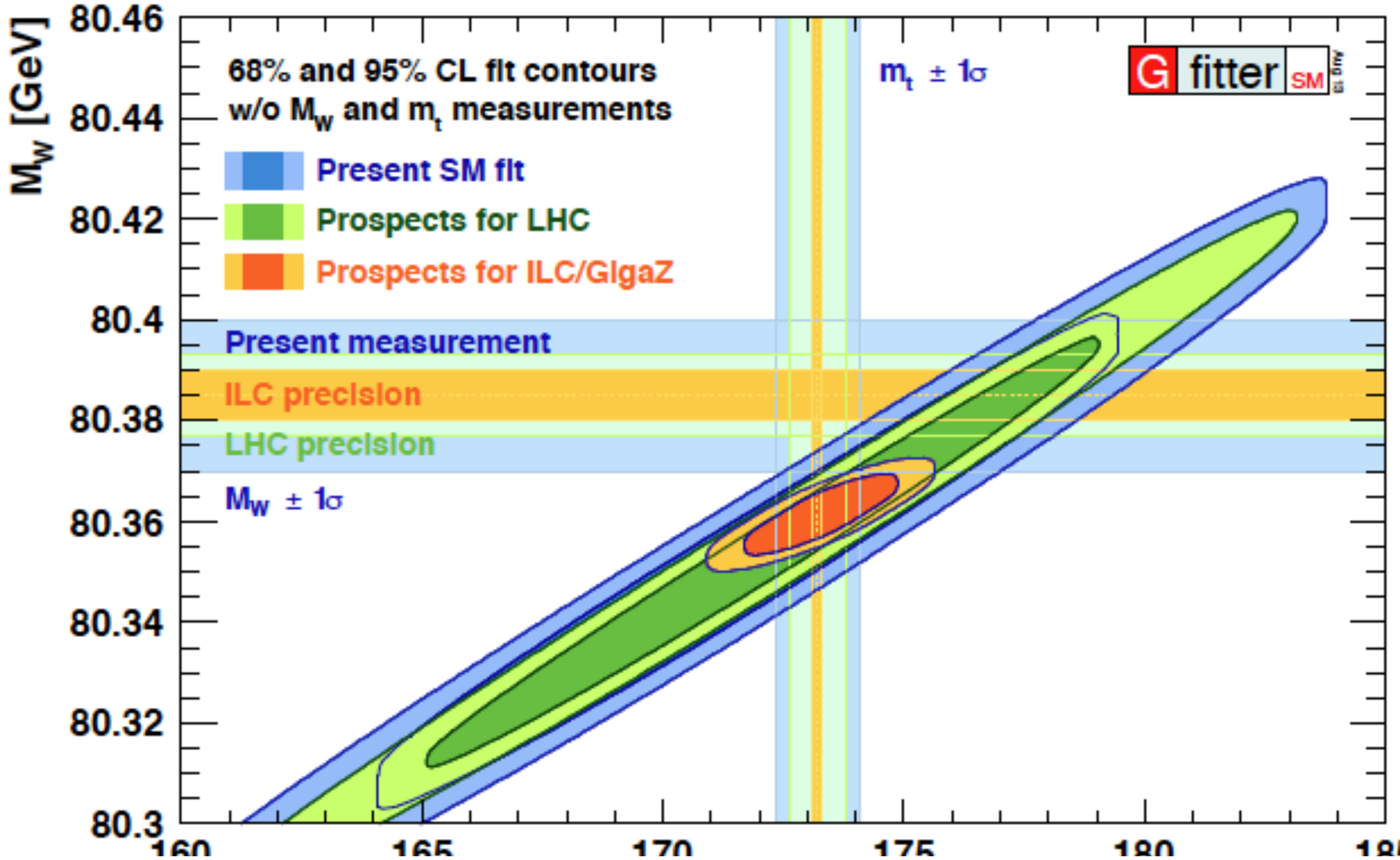
- ***New measurements in the last year***
  - Probing charged quartic gauge coupling
  - WWγγ, WWZγ
  - Significant improvement over Tevatron and LEP







EXPECTED PRECISION



ΔM_W [MeV]	LHC		
$\sqrt{s}$ [TeV]	8	14	14
$\mathcal{L}[\mathrm{fb}^{-1}]$	20	300	3000
PDF	10	5	3
QED rad.	4	3	2
$p_T(W)$ model	2	1	1
other systematics	10	5	3
W statistics	1	0.2	0
Total	15	8	5

	LHC	LHC	ILC/GigaZ	ILC	ILC	ILC	TLEP	SM prediction
$\sqrt{s}$ [TeV]	14	14	0.091	0.161	0.161	0.250	0.161	-
$\mathcal{L}[\mathrm{fb}^{-1}]$	300	3000		100	480	500	3000×4	-
ΔM_W [MeV]	8	5	-	4.1-4.5	2.3-2.9	2.8	< 1.2	4.2(3.0)
$\Delta \sin^2\theta^{\ell}_{\rm eff}$ $[10^{-5}]$	36	21	1.3	-	-	-	0.3	3.0(2.6)

Table 1-12. *Target accuracies for the measurement of M_W and $\sin^2\theta^{\ell}_{eff}$ at the LHC, ILC and TLEP, also including estimated future theoretical uncertainties due to missing higher-order corrections, and theory uncertainties of their SM predictions. The uncertainties on the SM predictions are provided for $\Delta m_t = 0.5(0.1)$ GeV (see Table 1-3 for details). At present the measured values for M_W and $\sin^2\theta^{\ell}_{\rm eff}$ are: $M_W = 80.385 \pm 0.015$ GeV [112] and $\sin^2\theta^{\ell}_{\rm eff} = (23153 \pm 16) \times 10^{-5}$ [3] compared to their current SM predictions of Section 1.2.1: $M_W = 80.360 \pm 0.008$ GeV and $\sin^2\theta^{\ell}_{\rm eff} = (23127 \pm 7.3) \times 10^{-5}$.*