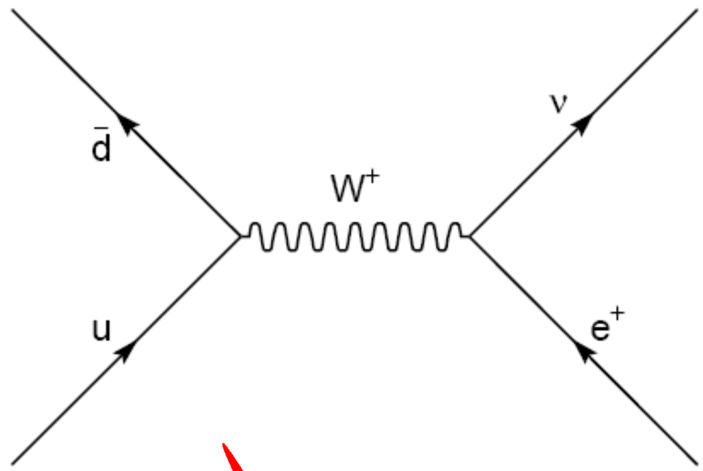
W MASS

can improve at LHC ?

(acknowledgements: Jeff Berryhill [ICHEP 2015])

W mass measurement at hadron colliders

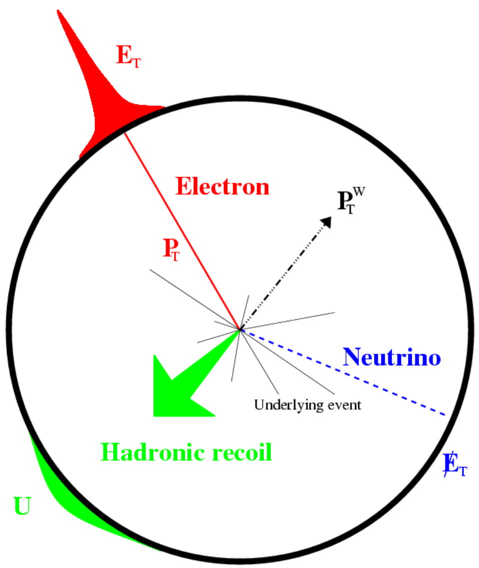
- Production from quark-antiquark annihilation
- Leptonic W decays (e o μ) + neutrino
- Fit to transverse mass distribution M_W^T



$$M_W^T = \sqrt{(E_T^{lepton} + E_T^{\nu})^2 - (\mathbf{p}_T^{lepton} + \mathbf{p}_T^{\nu})^2}$$

$$(E_T^i)^2 = (p_T^i)^2 + m_i^2$$

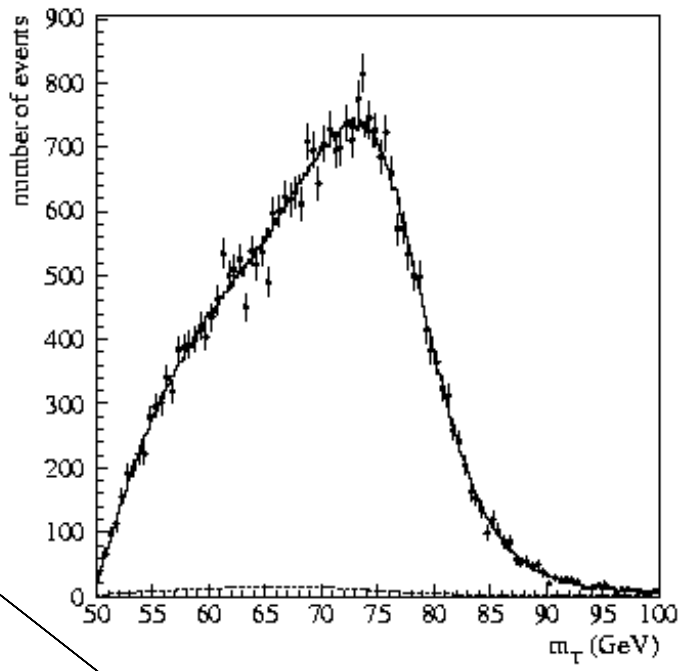
$$M_W^T = \sqrt{2 p_T^{lepton} p_T^{\upsilon} (1 - \cos\varphi)}$$



Precision measurement of W mass at hadron colliders

$$M_W^T = \sqrt{2 p_T^{lepton} p_T^{\upsilon} (1 - \cos\varphi)}$$

- Fit to transverse mass distribution M_W^T
- Jacobian peak

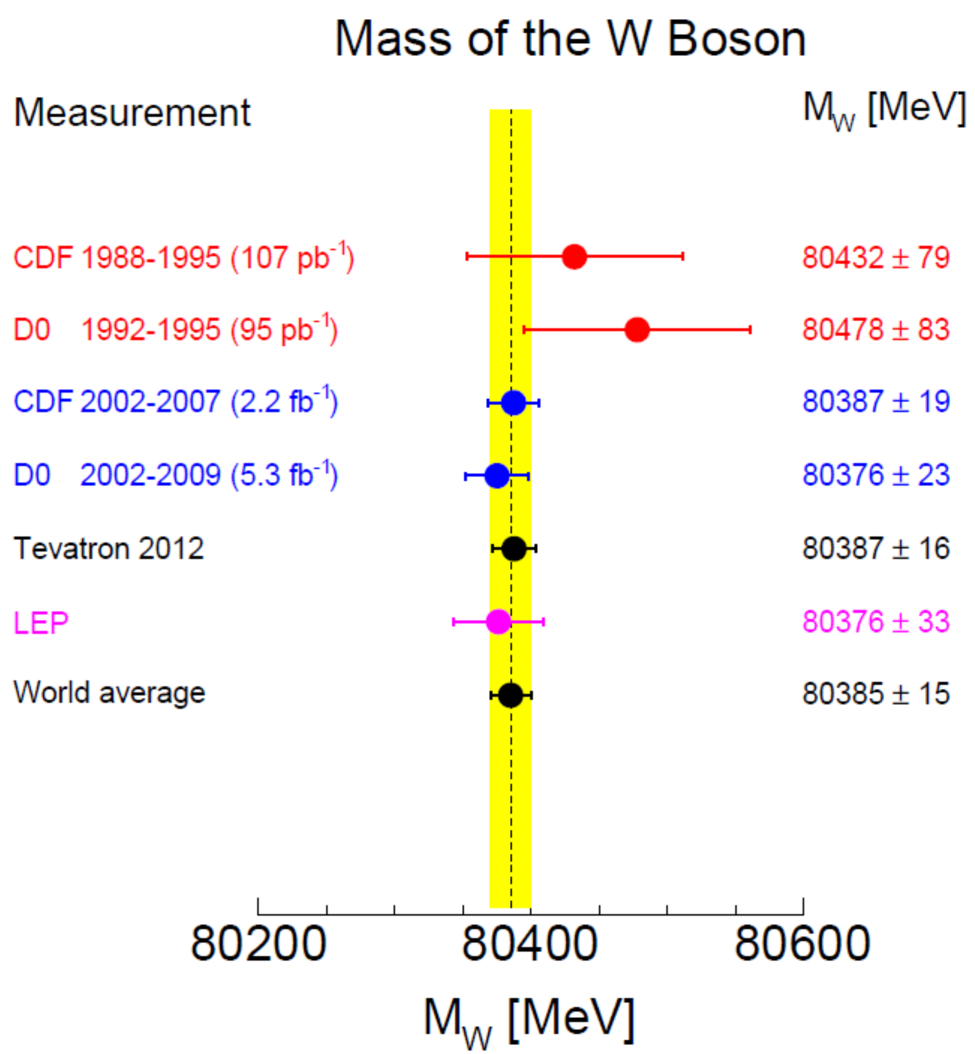


$$\frac{d\sigma}{dM_W^T} = \frac{d\sigma}{dcos\theta}\frac{dcos\theta}{dM_W^T} = \frac{d\sigma}{dcos\theta}\left(\frac{M_W^T}{2m_W}\right)(m_W^2 - (M_W^T)^2)^{-\frac{1}{2}}$$

Status of W mass

PRL 108 (2012) 151803 PRD 89 (2014) 072003

- CDF and DØ currently have world's most precise measurements based on 20% and 50% of their data → 1.1M and 1.7M Ws, resp.
- MT is the most sensitive single variable, lepton PT and MET used also
- Precision lepton response (0.01%) and recoil models (1%) built up from Z dileptons, Z mass reproduced to 6X LEP precision
- **MW precision:**
    - **CDF 19 MeV,**
    - **DØ 23 MeV,**
    - **LEP2 33 MeV**
    - **2012 world average: 15 MeV**

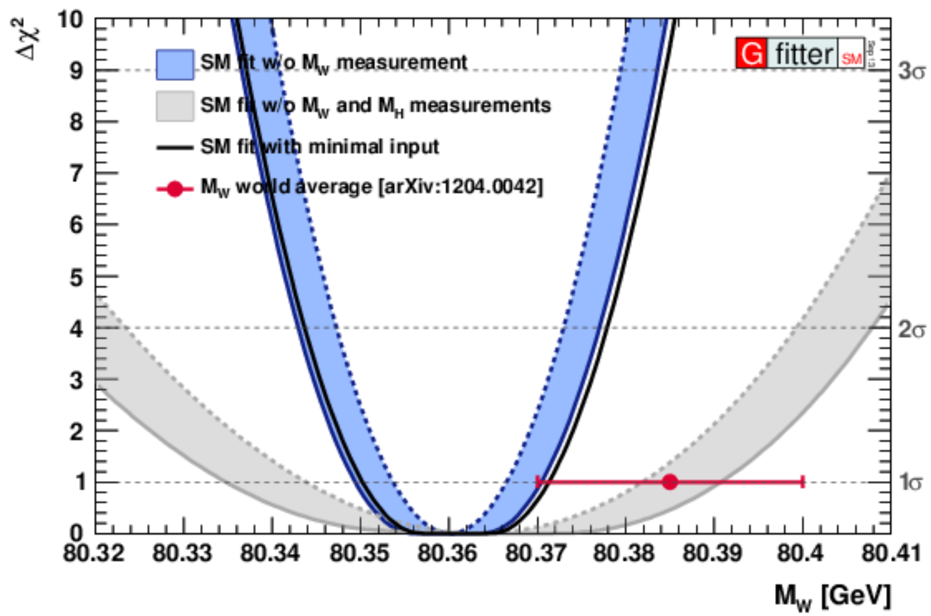


Prospects for Tevatron W mass

arxiv:1310.6708

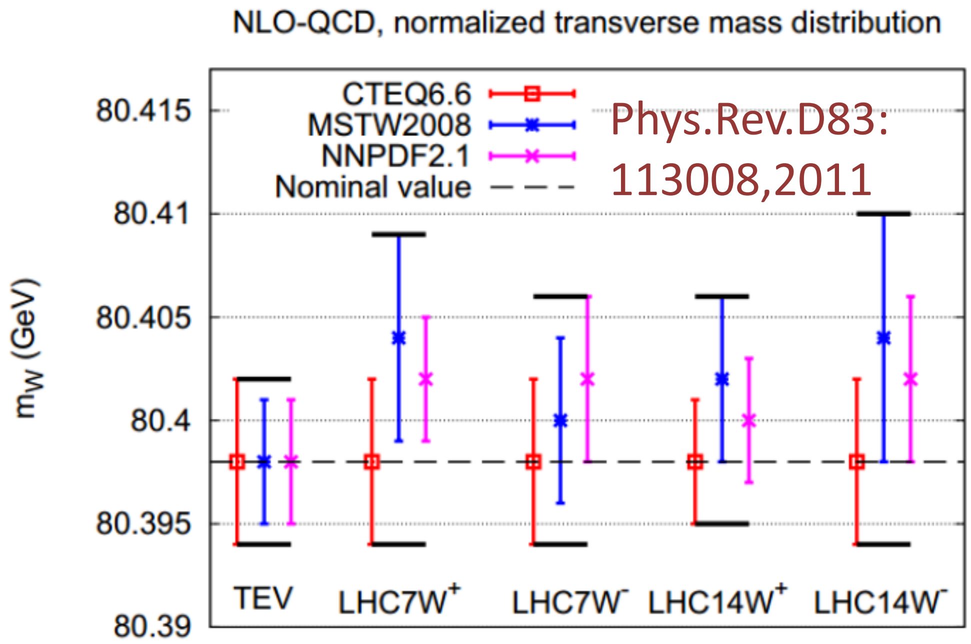
ΔM_W [MeV]	CDF	D0	combined	projected combined
$\mathcal{L}[\text{fb}^{-1}]$	2.2	4.3 (+1.1)	7.6	20
PDF	10	11	10	5
QED rad.	4	7	4	3
$p_T(W)$ model	5	2	2	2
other systematics	10	18	9	4
W statistics	12	13	9	5
Total	19	26 (23)	16	9

- Largest single uncertainties are **stat. and PDF syst.**
- **2X PDF improvement** and incremental improvement elsewhere results in **9 MeV projected final Tevatron precision**
- <10 MeV precision is well motivated to **further confront indirect precision (11 MeV)**



Prospects for LHC W mass

- The LHC has excellent detectors and semi-infinite statistics and thus has a good *a priori* prospect for a <10-MeV measurement
- Biggest three obstacles to surmount:
    - PDFs: sea quarks play a much stronger role than the Tevatron. **Need at least 2X better PDFs.**
    - Momentum scale
    - Recoil model/MET

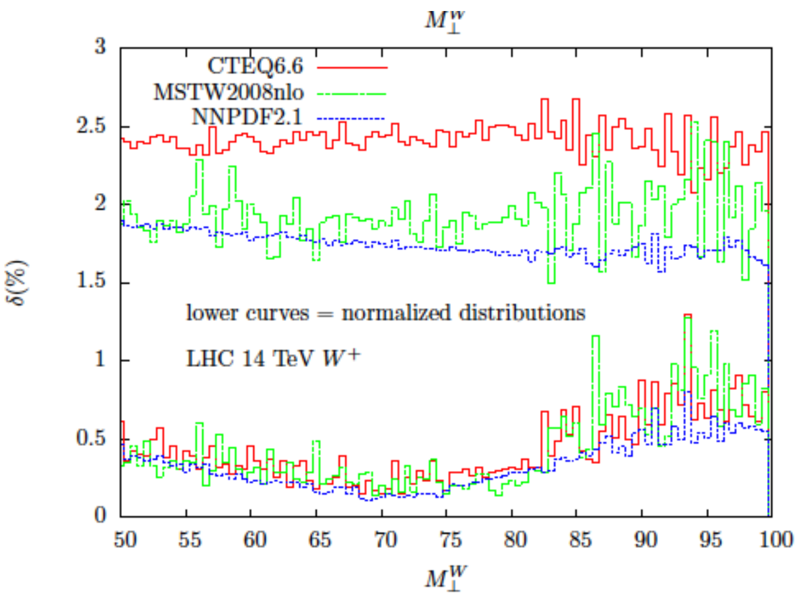


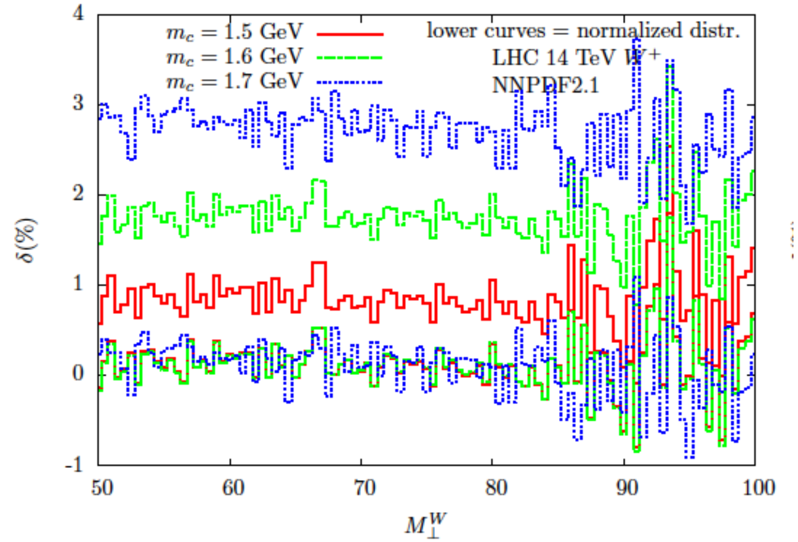
ΔM_W [MeV]	LHC		
$\sqrt{s}$ [TeV]	8	14	14
$\mathcal{L}[\text{fb}^{-1}]$	20	300	3000
PDF	10	5	3
QED rad.	4	3	2
$p_T(W)$ model	2	1	1
other systematics	10	5	3
W statistics	1	0.2	0
Total	15	8	5

arxiv:1310.6708

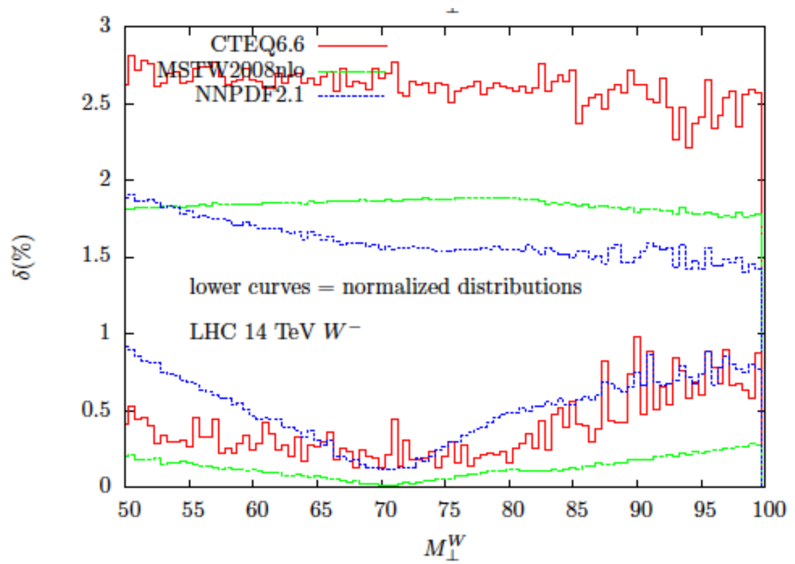
arXiv:1104.2056

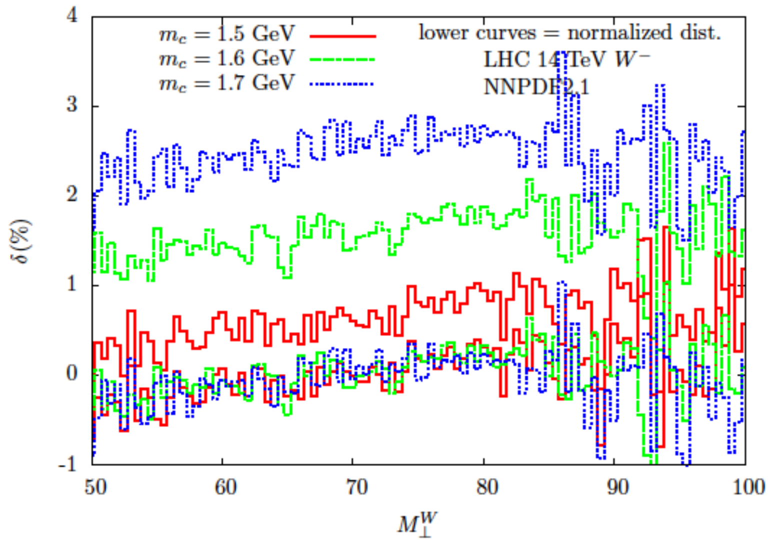
Note on W mass at LHC and PDF





deviation with respect m_c=2 GeV





ASYMMETRIES AND SIN$^2\Theta_W$

can improve at LHC ?

Z couplings and the electroweak mixing angle

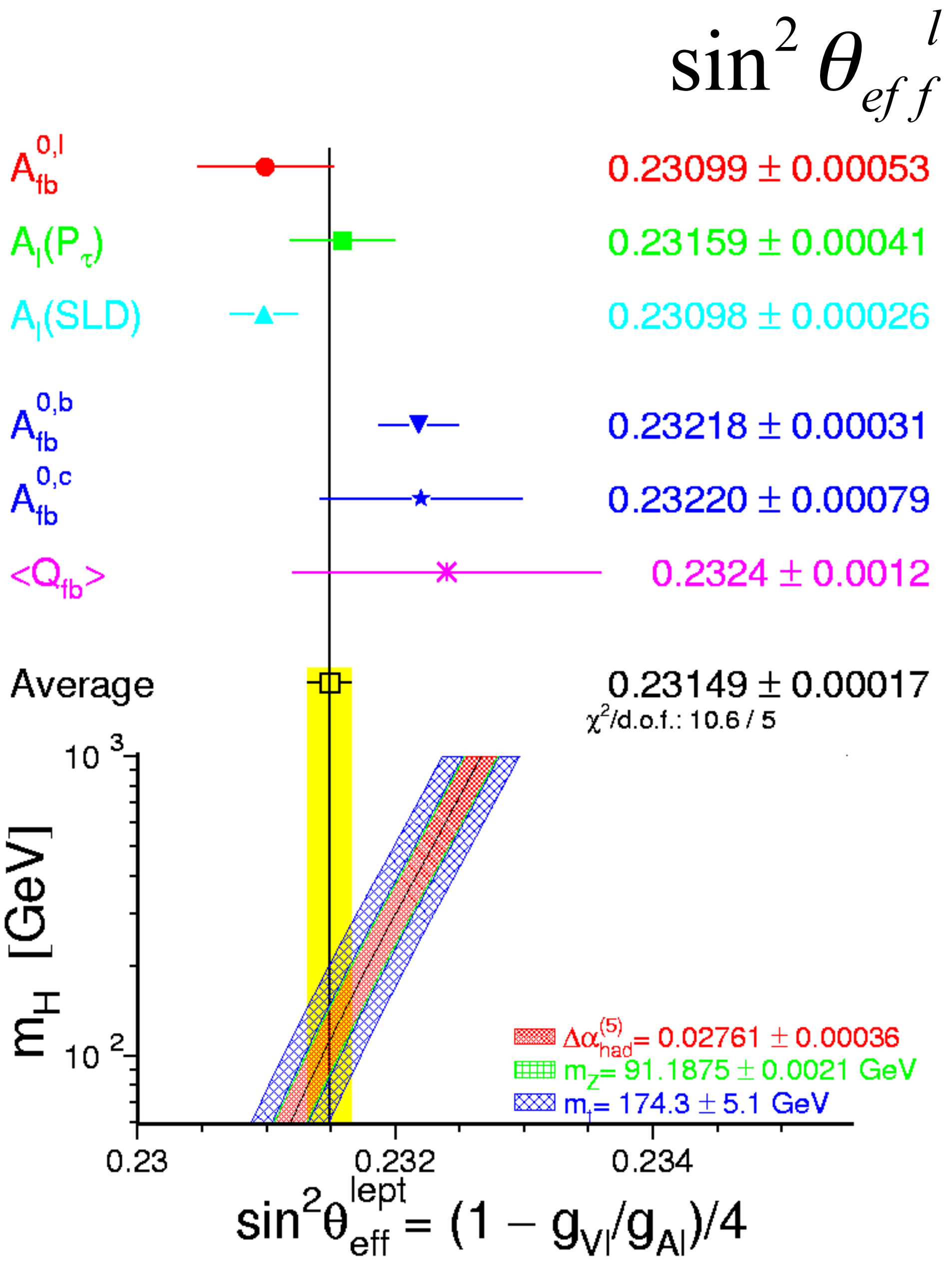
$$A_{FB} = \frac{\sigma_F - \sigma_B}{\sigma_{tot}} = \frac{3}{4} A_e A_f$$

$$A_{LR} = \frac{\sigma_l - \sigma_r}{\sigma_{tot}} = A_e$$

$$A_f = \frac{2 g_{Vf} g_{Af}}{(g_{Vf})^2 + (g_{Af})^2}$$

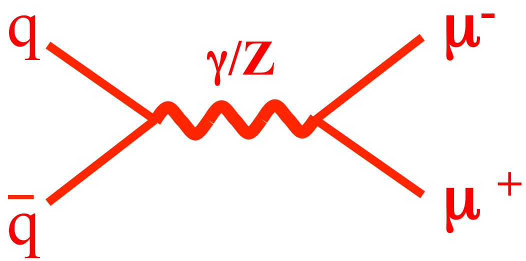
$$\sin^2 \theta_{eff}^{\,l} \equiv \frac{1}{4}\left(1 - \frac{g_{Vl}}{g_{Al}}\right)$$

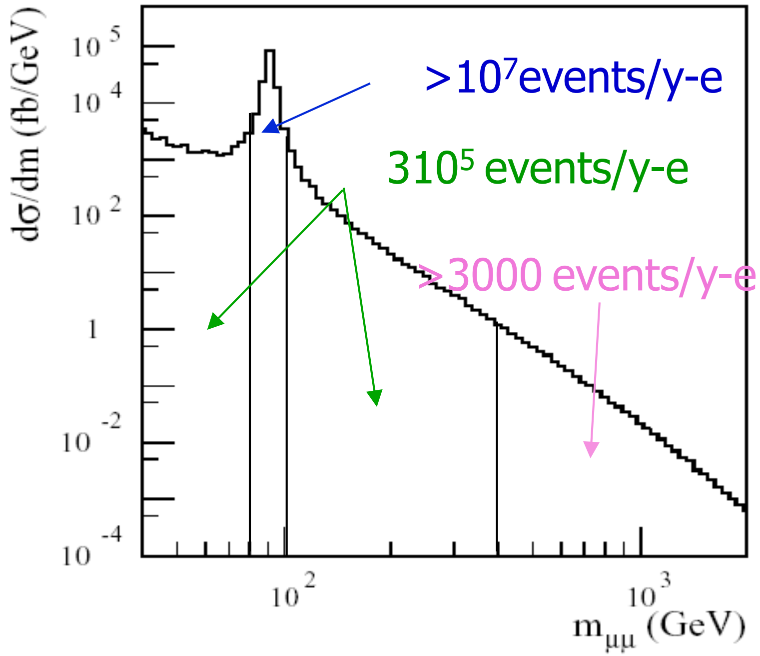
- Obtained 10^{-4} precision, but consistency between A_{LR} (from SLC) and A_{FB}(b) at 3 σ level

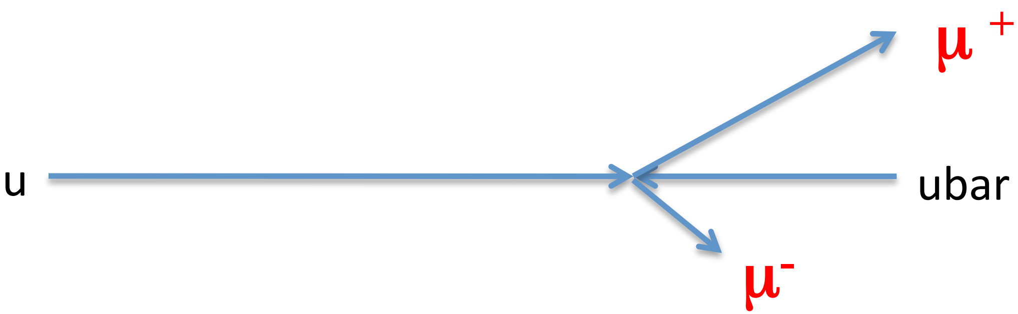


Asymmetry from Drell-Yan events at LHC

- Signature is clear and background is low, however →
- forward-backward asymmetry: need to know quark direction
- at LO easy at Tevatron (p – pbar)
- at LHC study DY cross section as a function of invariant mass and
- assume that at high rapidity direction gives information on direction of valence quark

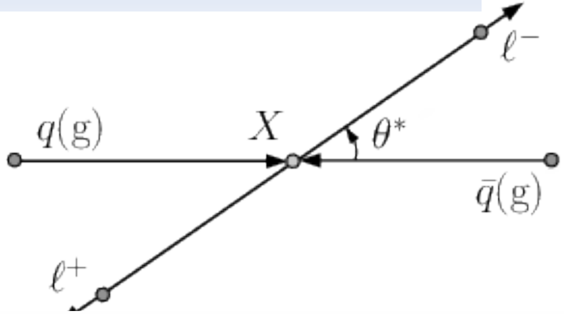






Weak mixing angle at hadron colliders

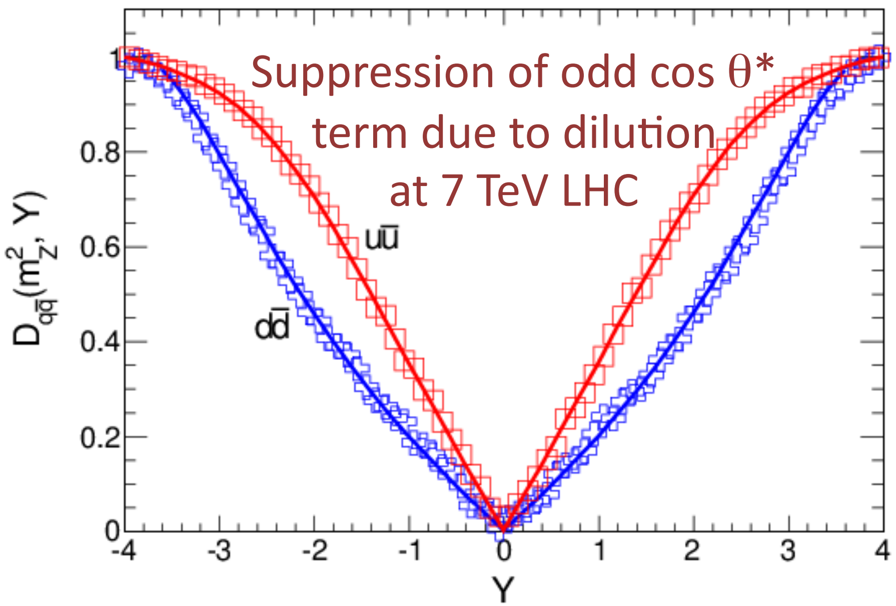
- In the dilepton CM, lepton angle with respect to axis of quark momentum is sensitive to interference effects: vector with axial-vector Z couplings, Z with photon, or Z with new physics



$$\hat{\sigma}_{q\bar{q}}(\hat{s}, \cos\theta^*; \theta_W) \propto \frac{3(\rho_V^{q\bar{q}\to\gamma})^2(\rho_V^{\gamma\to\ell\ell})^2}{2\hat{s}} \times (1+\cos^2\theta^*) + \frac{3}{2}\frac{\hat{s}}{(\hat{s}-m_Z^2)^2 + m_Z^2\Gamma_Z^2}$$
$$\times [((\rho_V^{q\bar{q}\to Z})^2 + (\rho_A^{q\bar{q}\to Z})^2)((\rho_V^{Z\to\ell\ell})^2 + (\rho_A^{Z\to\ell\ell})^2)(1+\cos^2\theta^*) + 8\rho_V^{q\bar{q}\to Z}\rho_A^{q\bar{q}\to Z}\rho_V^{Z\to\ell\ell}\rho_A^{Z\to\ell\ell}\cos\theta^*]$$
$$+ \frac{3(\hat{s}-m_Z^2)\rho_V^{q\bar{q}\to\gamma}\rho_V^{\gamma\to\ell\ell}}{(\hat{s}-m_Z^2)^2 + m_Z^2\Gamma_Z^2} \times [\rho_V^{q\bar{q}\to Z}\rho_V^{Z\to\ell\ell}(1+\cos^2\theta^*) + 2\rho_A^{q\bar{q}\to Z}\rho_A^{Z\to\ell\ell}\cos\theta^*].$$

V-A int. ~ $\sin^2\theta_{eff}$ -1/4

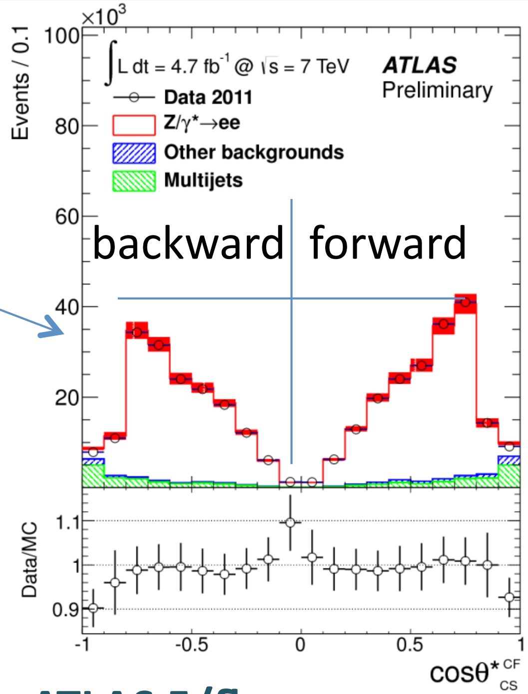
- This relation is (un)**diluted** in ($p\bar{p}$) pp collisions, where reconstructed cos θ* axis is (strongly) weakly correlated with real quark axis.

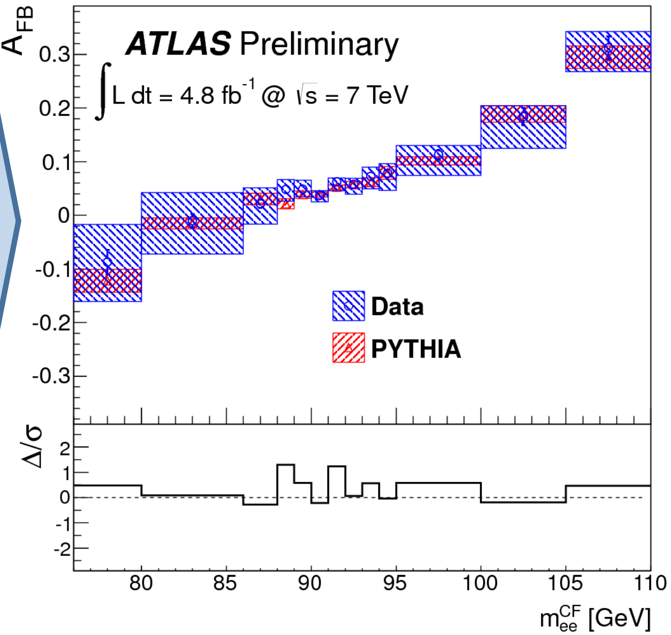


Weak mixing angle at LHC

ATLAS-CONF-2013-043

- Select central dilepton pairs, **and also central-forward electrons** with full 7 TeV dataset
- Raw AFB = Count forward/ backward abundance in CS frame
- AFB in good agreement with PYTHIA * PHOZPR NNLO K-factor (MSTWNNLO2008)
- 1.8σ lower angle than LEP +SLD average



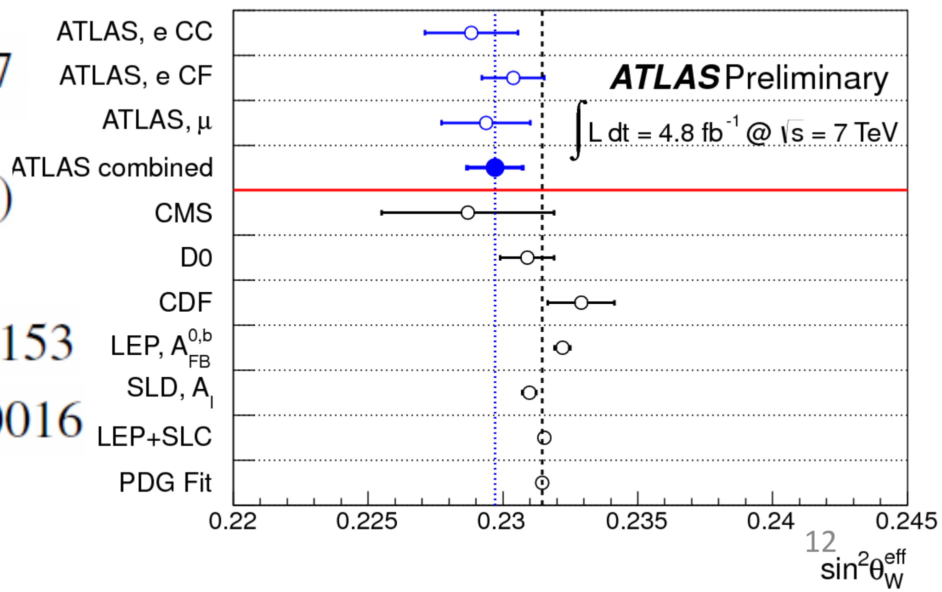


ATLAS 5/fb

$$\sin^2\theta_W^{eff} = 0.2297 \pm 0.0004(\text{stat.}) \pm 0.0009(\text{syst.})$$

LEP + SLD

$$\sin^2\theta_W^{eff} = 0.23153 \pm 0.00016$$

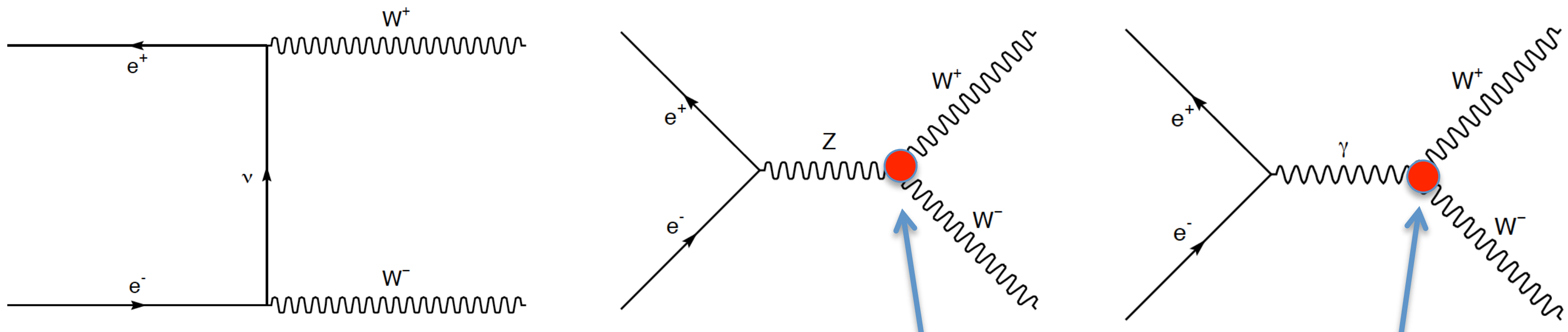


WW, ZZ, WZ, Wγ

DIBOSON PRODUCTION AND TRIPLE GAUGE COUPLINGS

WW Production at LEP2

Three diagrams contribute at Born level (CC03 diagrams) :



Dominant diagram at production threshold, alone it gives a cross section which violates unitarity

Triple Gauge Couplings

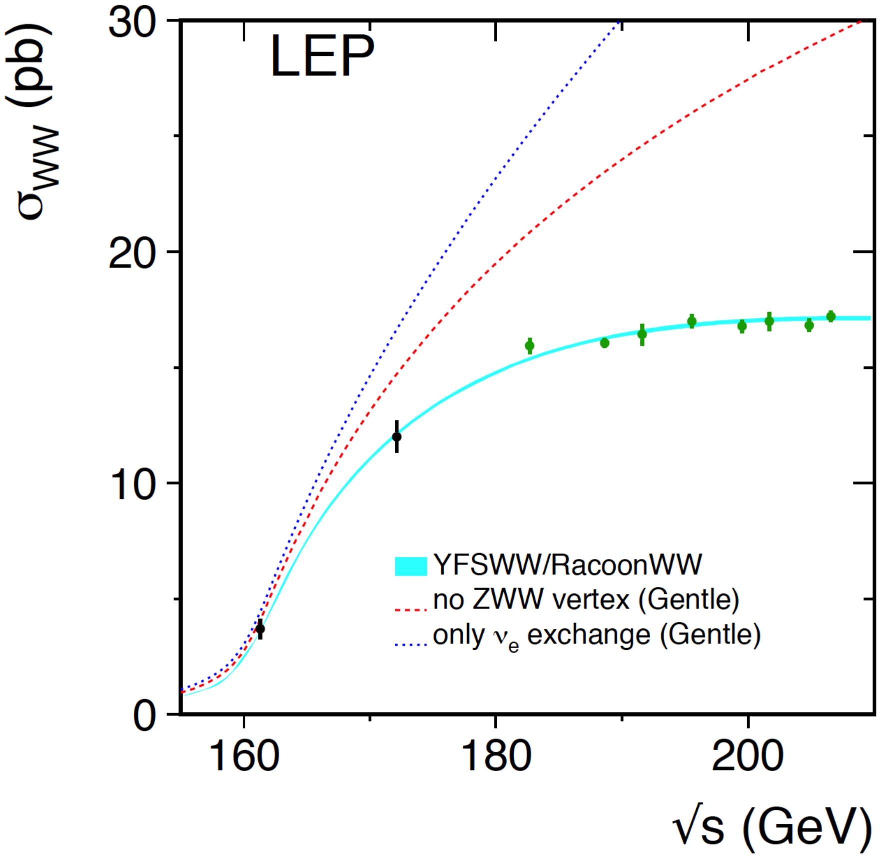
Total WW Cross Section

Strong evidence of Triple Gauge Couplings

- Precision reached by LEP experiments a challenge to theoretical predictions
  - Predictions with non-leading $O(\alpha)$ radiative corrections were needed !

$$R_{\text{with } O(\alpha)} = \frac{\sigma(\text{LEP})}{\sigma(\text{Theory: YFSWW})} = 99.32 \pm 0.89$$

$$R_{\text{without } O(\alpha)} = \frac{\sigma(\text{LEP})}{\sigma(\text{Theory: KORALW})} = 97.42 \pm 0.87$$



Probing Triple Gauge Couplings

- Triple gauge boson vertices (WWγ , WWZ) : probing the non-Abelian structure of the Standard Model. Search for anomalous couplings.
- The most general Lorentz invariant Lagrangian involves 14 couplings (7 for WWγ and 7 for WWZ)
- Assuming electromagnetic gauge invariance, C and P conservation, leaves 5 parameters

$$\left\{ g_1^z, \kappa_Z, \kappa_\gamma, \lambda_Z, \lambda_\gamma \right\}$$

W anomalous magnetic moment $$\mu_W = \frac{e}{2m_W}(1 + k_\gamma + \lambda_\lambda)$$

W anomalous electric quadrupole moment $$Q_w = -\frac{e}{m_W^2}(\kappa_\gamma - \lambda_\gamma)$$

Triple Gauge Couplings

Precise LEP1 measurements motivated SU(2)xU(1) constraints

TGC contributes via loops

$$\Delta\kappa_Z = -\Delta\kappa_\gamma \tan^2\theta_W + \Delta g_Z^1$$

$$\lambda_Z = \lambda_\gamma$$

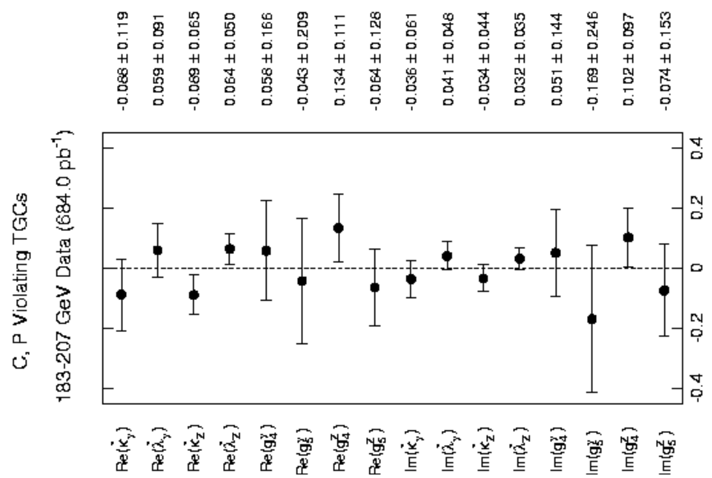
Δ is deviation from SM

Within Standard Model

Typical analyses (and LEP combinations) in terms of three couplings.

$$\left\{\Delta g_Z^1, \Delta\kappa_\gamma, \lambda_\gamma\right\} \equiv \left\{0,0,0\right\}$$

However more general constraints of C, P and CP violating couplings were published: all 14 couplings were probed !!



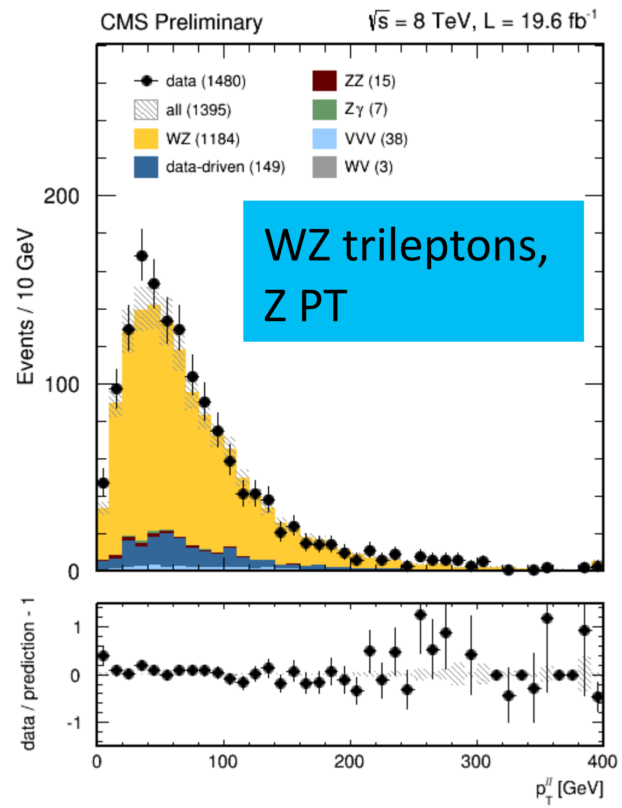
PLB 614 (2005) 7

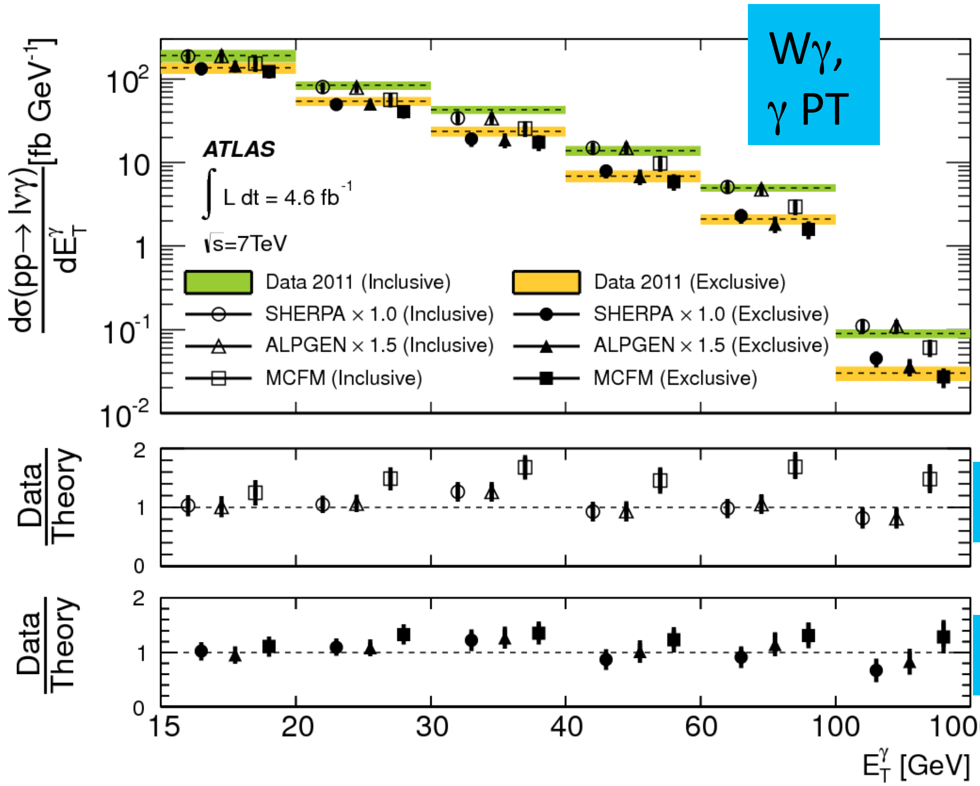
WZ and Wγ Production

[PRD 87, 112003 (2013)]

[CMS-PAS-SMP-12-006]

- LHC has thousands of high purity trilepton WZ candidates, tens of thousands of Wγ
- Photon and lepton fakes are the predominant background
- No evidence of new physics in high PT tails





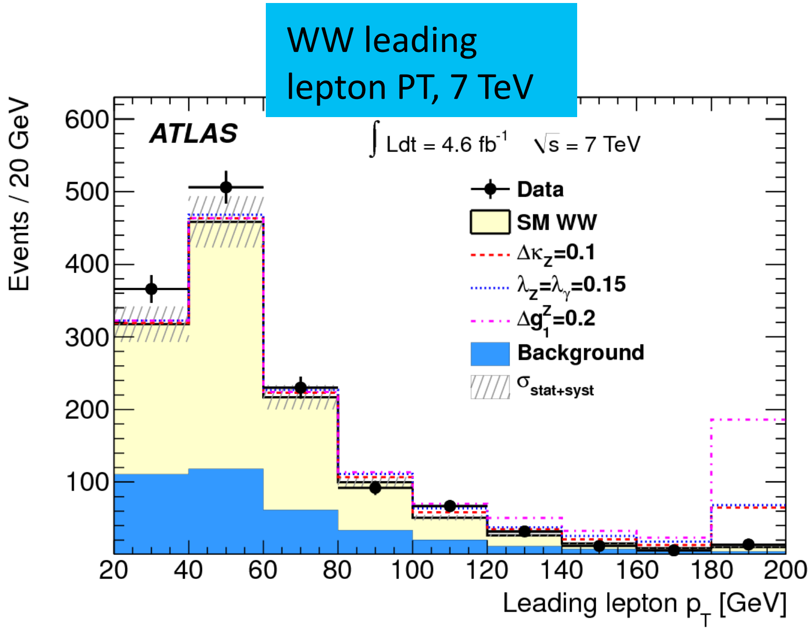
inclusive

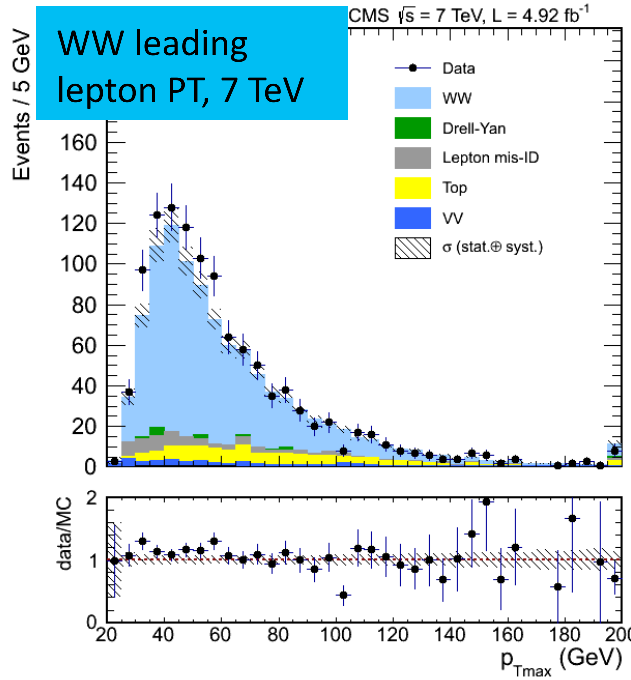
exclusive 0-jet

WW Production (7 TeV)

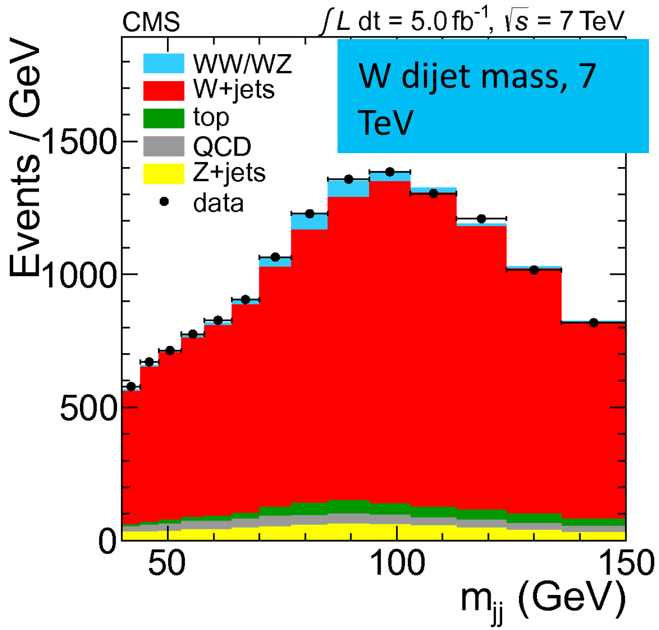
PRD 87 (2013) 112001
EPJC 73 (2013) 2610
EPJC 73 (2013) 2283
ATLAS-CONF-2012-157

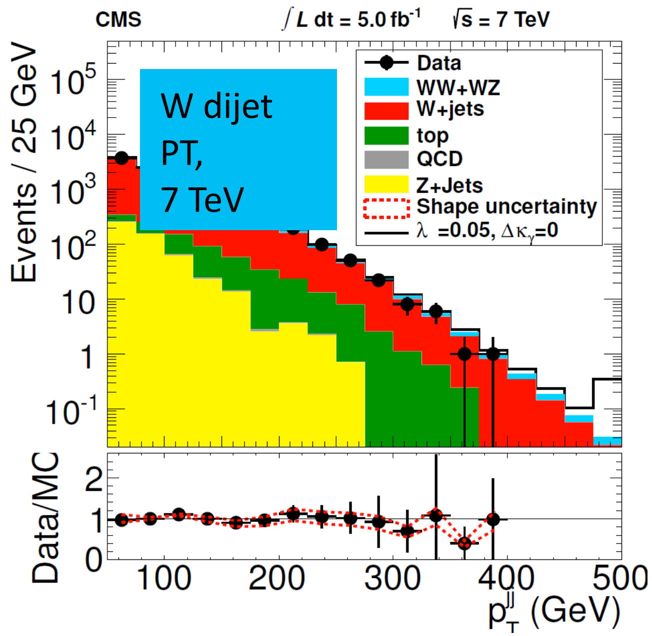
- Thousands of candidates in dilepton channel
- Leading lepton PT shows no anomalous contribution





- Significant diboson signal in semileptonic channel
- Higher BR and low background at high PT gives superior TGC constraint



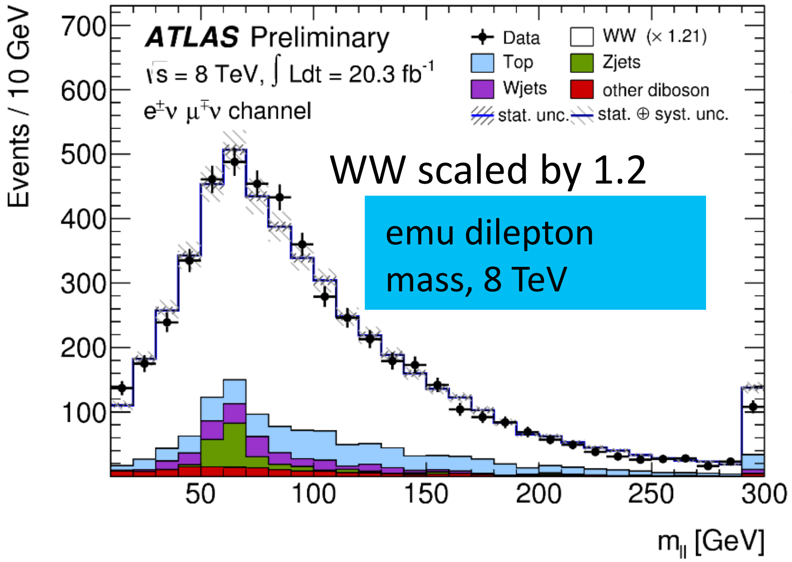


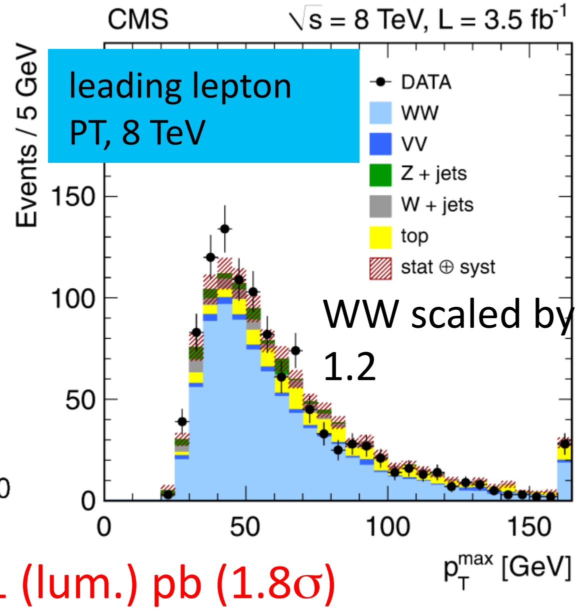
WW Production (8 TeV)

PLB 721 (2013) 190
ATLAS-CONF-2014-033

NEW for ICHEP14

- **Kinematic shapes agree with prediction, but cross section excess observed at 20% level in CMS and ATLAS**
- ~5000 emu ATLAS candidates with 20/fb!
- Systematics from jet veto acceptance, background methods
- Not yet reporting: CMS lvlv 20/fb, WW→lvjj 20/fb
- Theory calculation being actively studied (jet vetoes, NNLO)





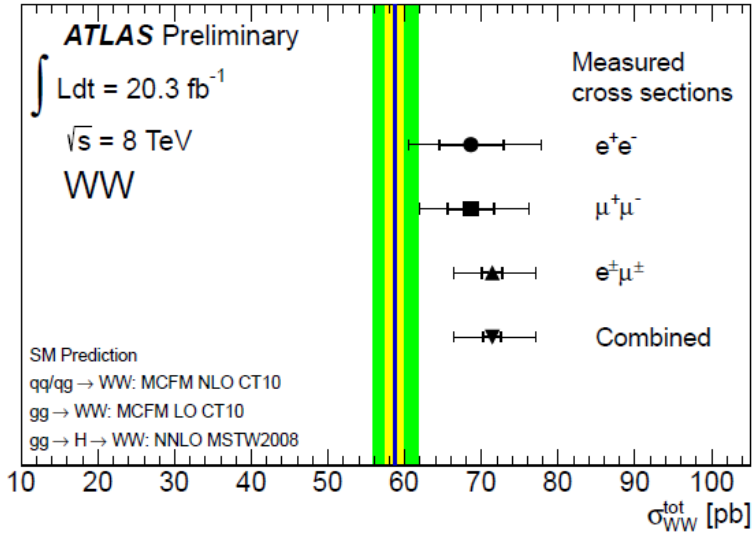
CMS 69.9±2.8 (stat.)±5.6 (syst.)±3.1 (lum.) pb (1.8σ)

ATLAS 71.4±1.2 (stat.)±5.0 (syst.)±2.2 (lum.) pb (2.1σ)

MCFM 58.7±3.0 (syst.) pb

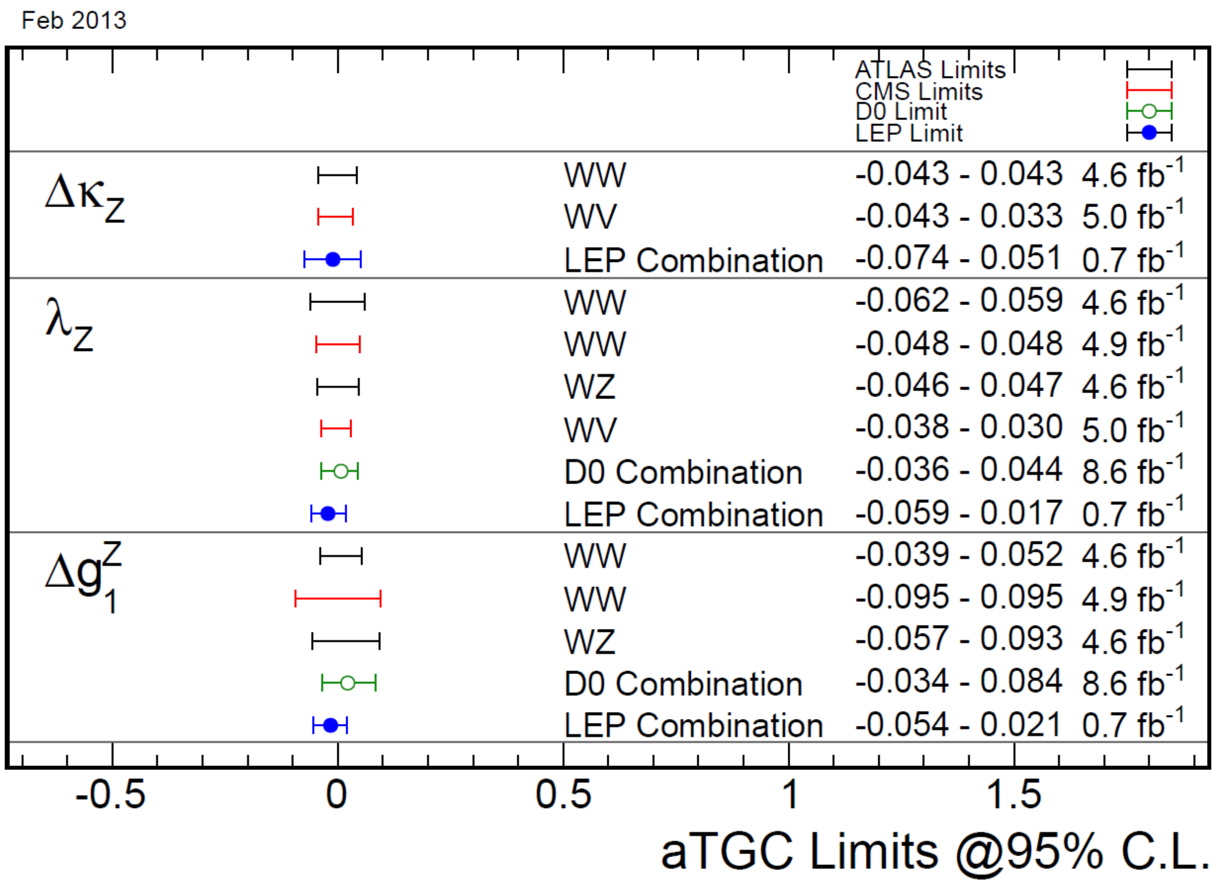
=qq,qg 53.2 MCFM NLO
+gg 1.4 MCFM LO
+HWW 4.1 NNLO+NNLL

Higher order/other≈ +3-4pb?



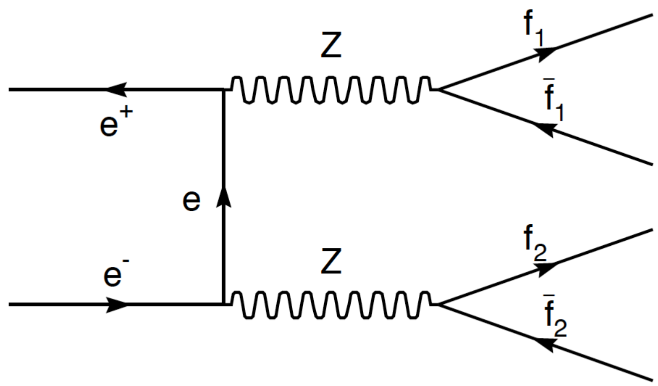
Charged aTGCs: World Summary

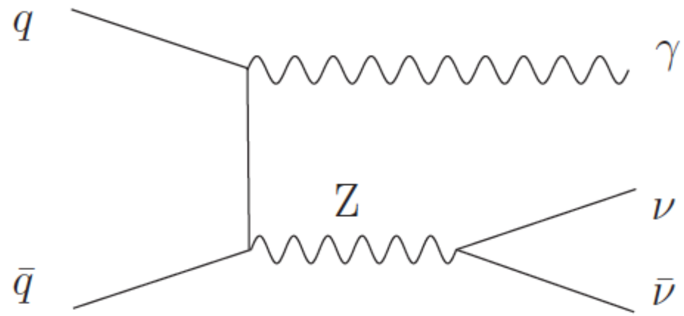
- Best single LHC 7 TeV measurements equal LEP2 or Tevatron combinations
- Semileptonic WW gives the best information on κ and λ, leptonic WW and WZ better for g.
- LHC 8 TeV will provide 2-3X better constraints, reaching LEP2 precision also for g

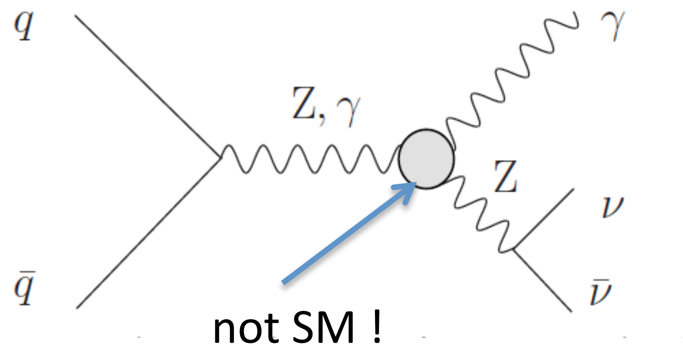


Anomalous Neutral couplings

- ZZZ, γZZ and γγZ trilinear couplings are not present in the Standard Model: ZZ and Zγ production does not take place through s-channel
- Anomalous couplings can be defined through effective lagrangians, two CP-conserving and two CP-violating couplings are defined
- The parametrization depends on the final state (*f* couplings for ZZ, *h* couplings for γZ)







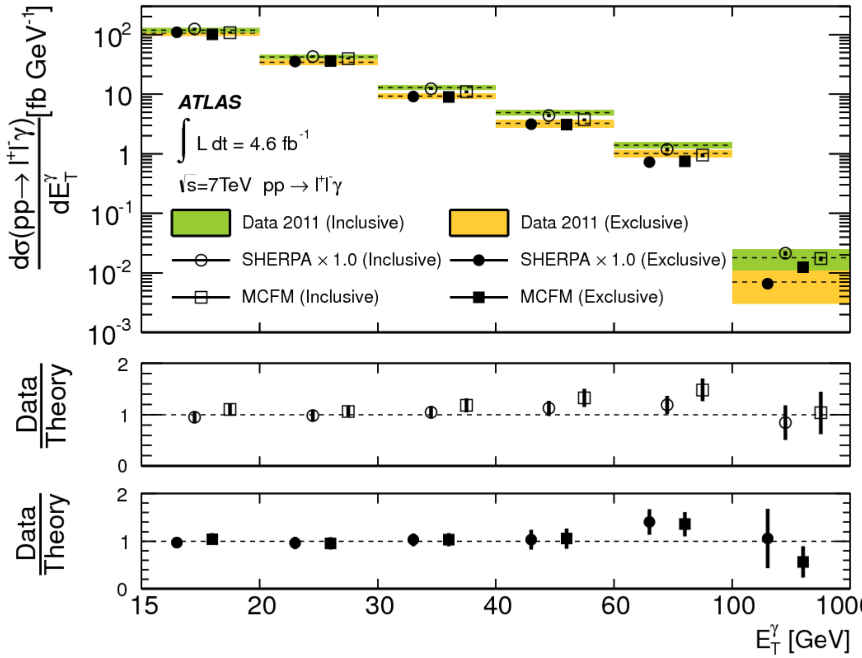
Zγ Production

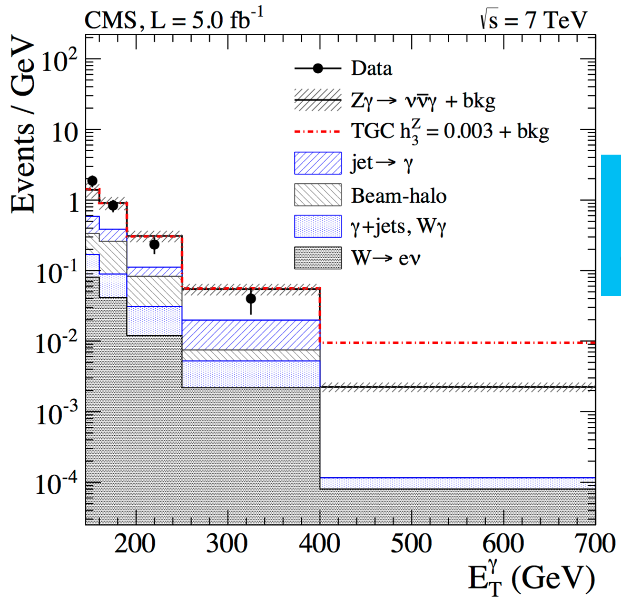
JHEP 10 (2013) 164

PRD 89 (2014) 092005 PRD 87 (2013) 112003

Zγ → llγ
γ PT

- Thousands of dilepton-photon events at 7 TeV agree with SM
- MET-photon channel: Higher BR and low background at high PT gives superior (dim 8) TGC constraint



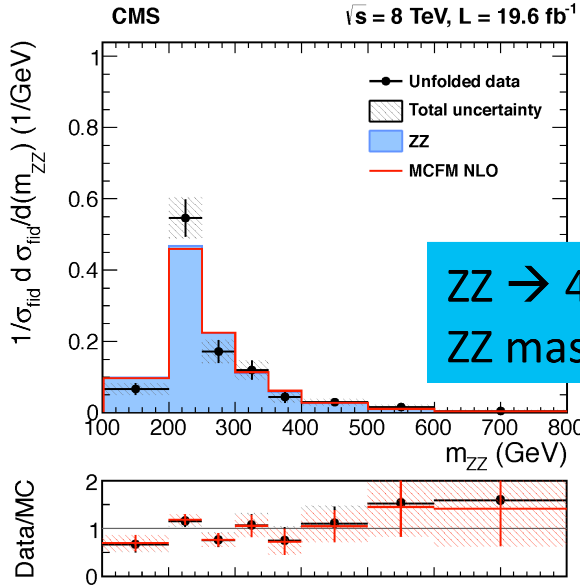


Zγ →MET+γ
γ PT

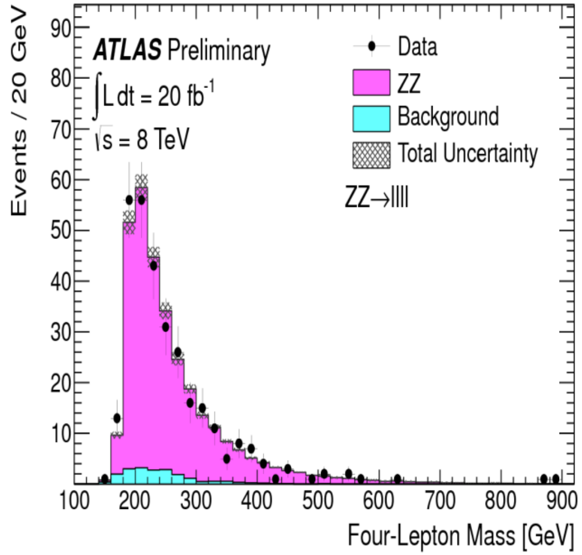
ZZ Production

ATLAS-CONF-2013-020
CMS-PAS-SMP-12-016 arxiv:1406.0113

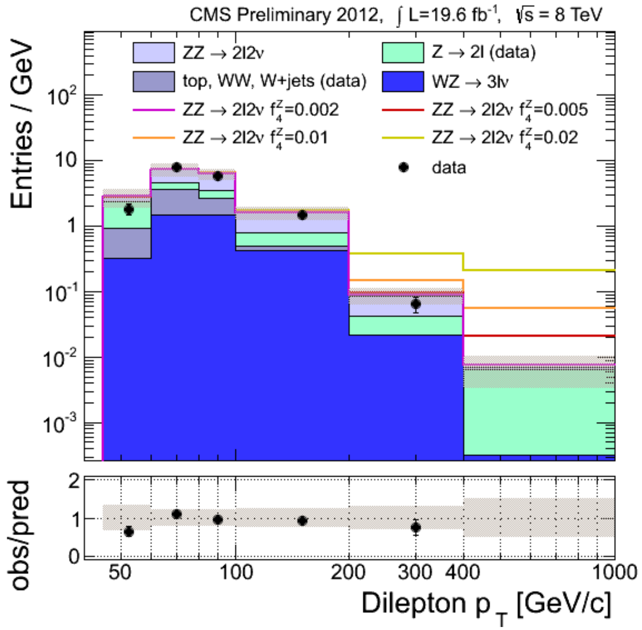
- ~300 ZZ to 4-lepton candidates observed at 8 TeV/experiment with SM rate and shapes
- ~200 ZZ to 2l2v candidates observed at 8 TeV, give best (dim 8) TGC constraint



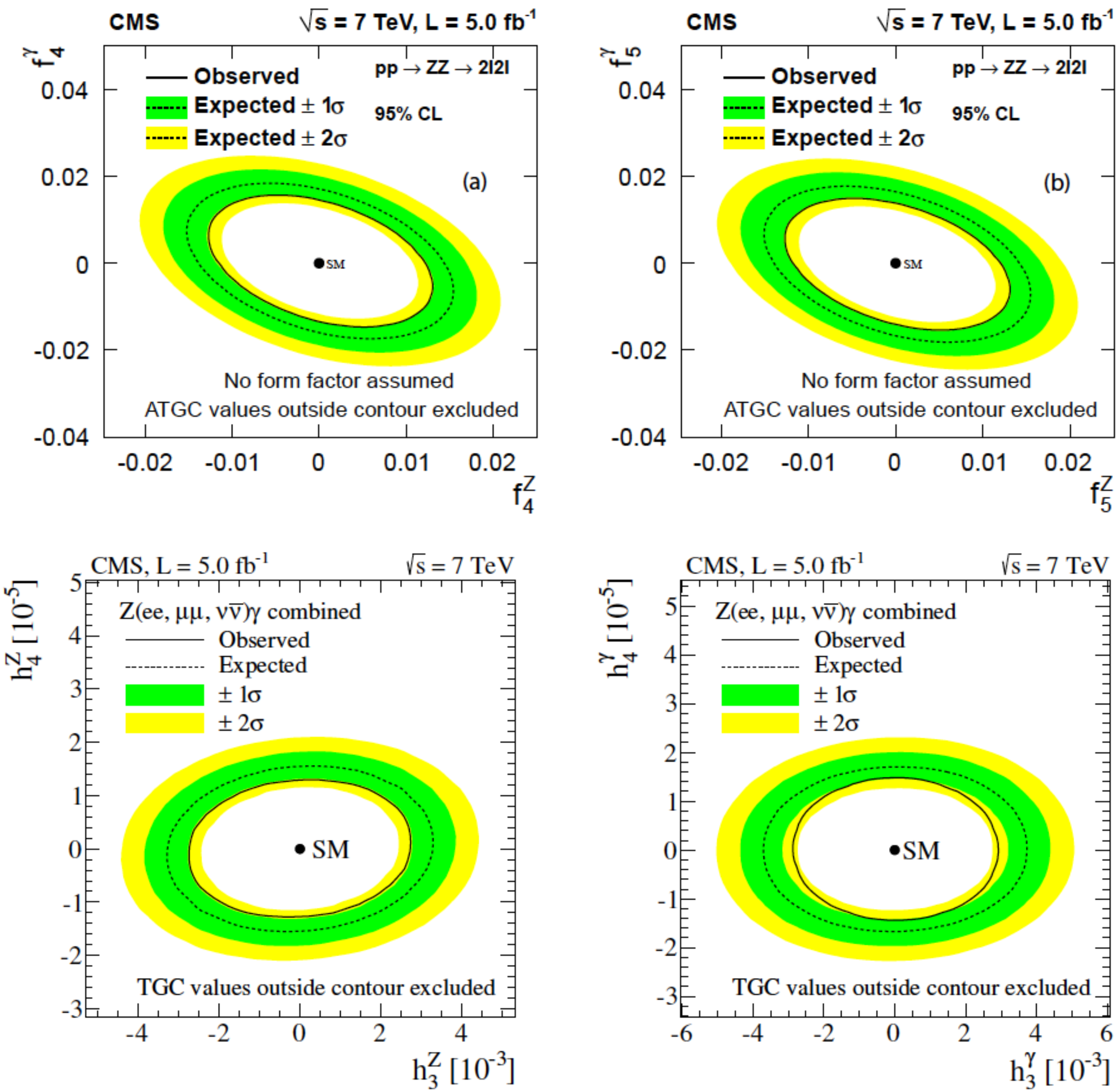
ZZ → 4l
ZZ mass



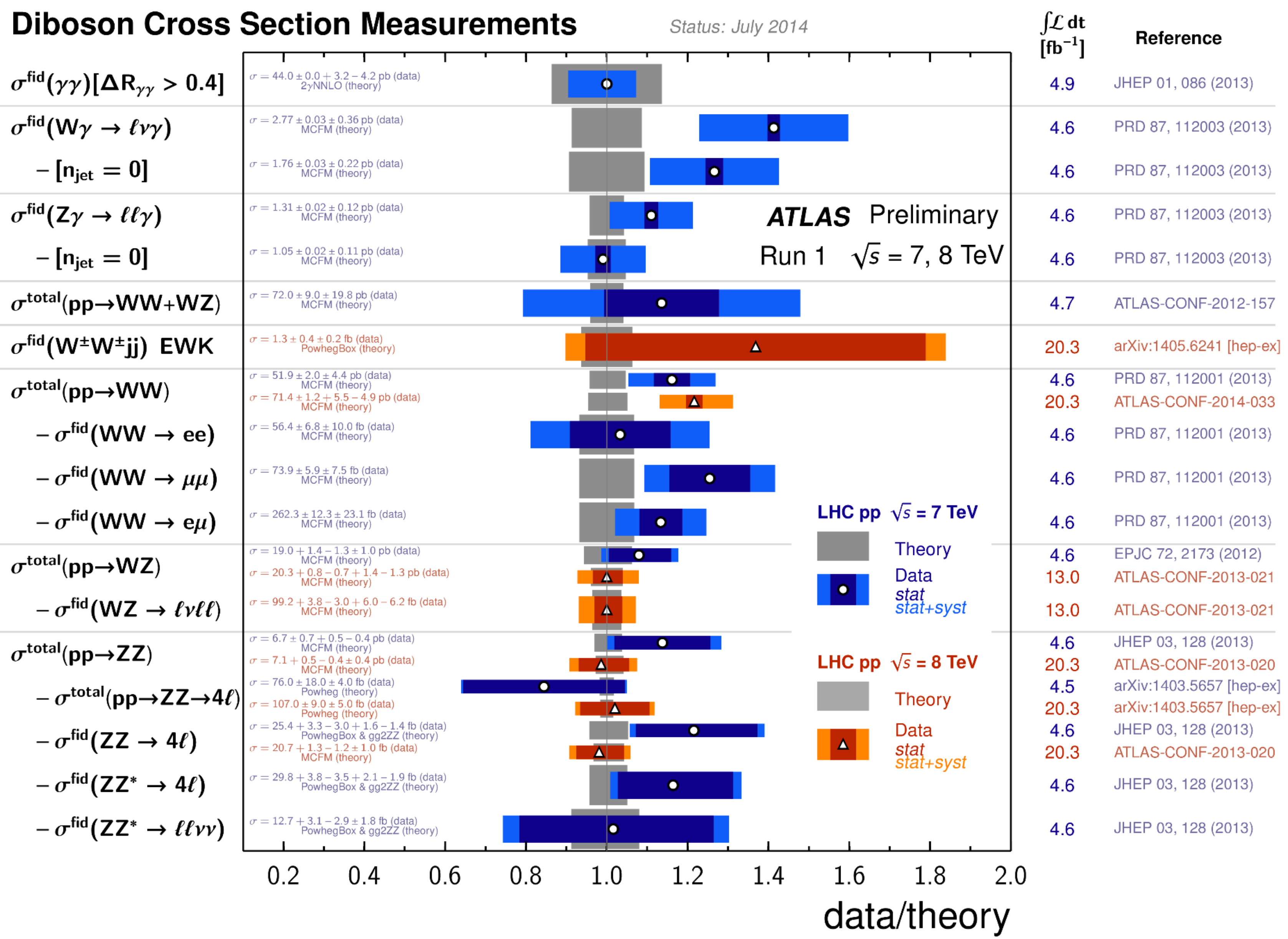
ZZ → 2l2v
Z PT

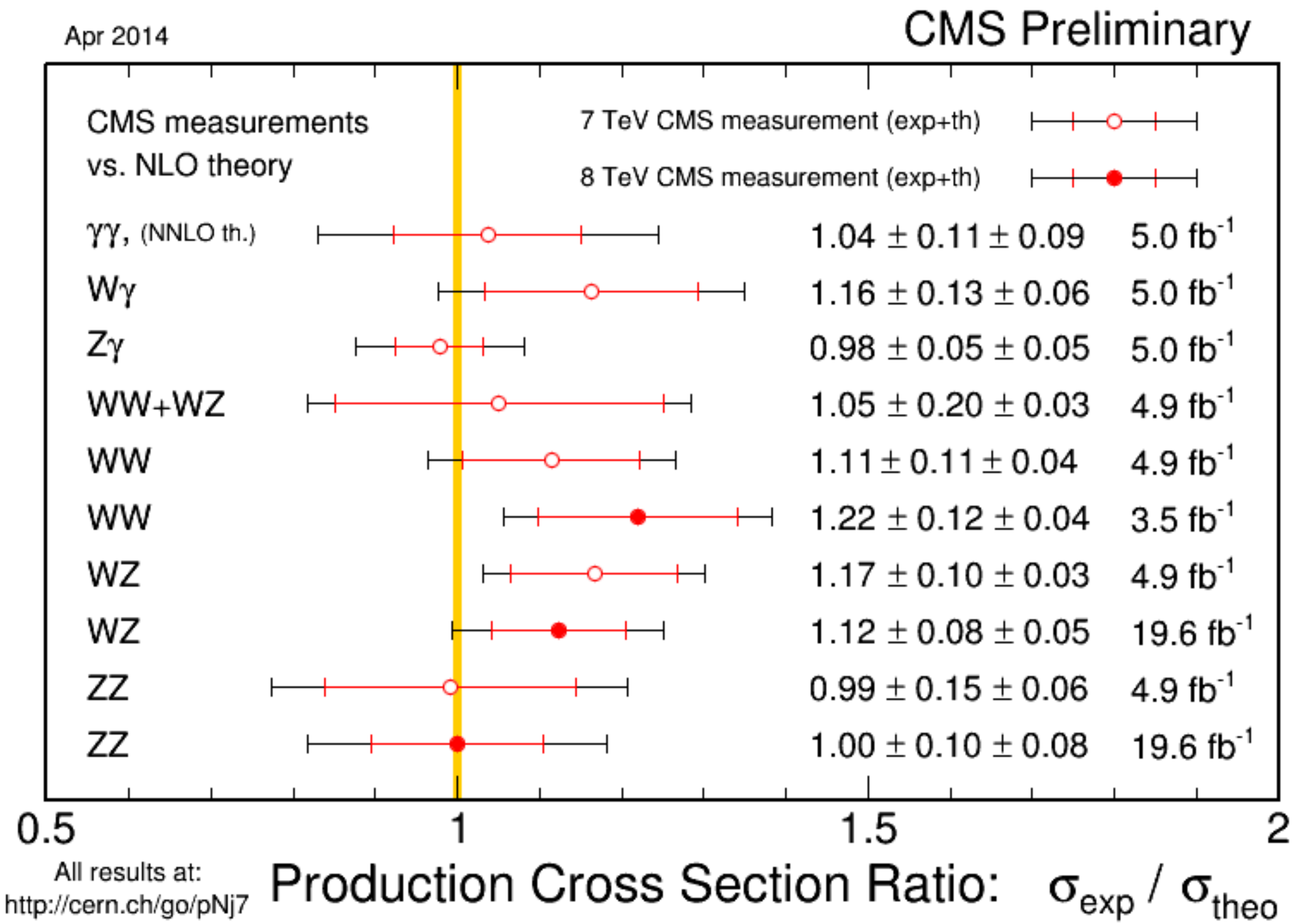


Limits on neutral couplings



ATLAS Diboson Summary





Apr 2014
CMS Preliminary
CMS measurements
vs. NLO theory
7 TeV CMS measurement (exp+th)
8 TeV CMS measurement (exp+th)
γγ, (NNLO th.)
1.04 ± 0.11 ± 0.09
5.0 fb-1
Wγ
1.16 ± 0.13 ± 0.06
5.0 fb-1
Zγ
0.98 ± 0.05 ± 0.05
5.0 fb-1
WW+WZ
1.05 ± 0.20 ± 0.03
4.9 fb-1
WW
1.11 ± 0.11 ± 0.04
4.9 fb-1
WW
1.22 ± 0.12 ± 0.04
3.5 fb-1
WZ
1.17 ± 0.10 ± 0.03
4.9 fb-1
WZ
1.12 ± 0.08 ± 0.05
19.6 fb-1
ZZ
0.99 ± 0.15 ± 0.06
4.9 fb-1
ZZ
1.00 ± 0.10 ± 0.08
19.6 fb-1
0.5
1
1.5
2
All results at:
http://cern.ch/go/pNj7
Production Cross Section Ratio: σexp / σtheo