Electroweak Physics

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EPS HEP 2013, Stockholm, 18-25 July 2013

Global electroweak fit

May 13 version of Gfitter standard model fit includes, in addition to the latest theory calculations, the LEP/SLD precision legacy, …, various updates:

- latest top quark combination from Tevatron,
- latest world average W boson mass,
- measurements of the "Higgs boson mass" from the LHC,
- latest precision calculations.

Parameter	Input value	Free in fit	Fit Result	Fit without M_H measurements	Fit without exp. input in line
M_H [GeV]$^{\circ}$	125.7 ± 0.4	yes	125.7 ± 0.4	94.1^{+25}_{-22}	94.1^{+25}_{-22}
M_W [GeV]	80.385 ± 0.015	–	$80.367^{+0.006}_{-0.007}$	$80.380^{+0.011}_{-0.012}$	80.360 ± 0.011
Γ_W [GeV]	2.085 ± 0.042	–	2.091 ± 0.001	2.092 ± 0.001	2.091 ± 0.001
M_Z [GeV]	91.1875 ± 0.0021	yes	91.1878 ± 0.0021	91.1874 ± 0.0021	91.1983 ± 0.0115
Γ_Z [GeV]	2.4952 ± 0.0023	–	2.4953 ± 0.0014	2.4957 ± 0.0015	2.4949 ± 0.0017
$\sigma^0_{\rm had}$ [nb]	41.540 ± 0.037	–	41.480 ± 0.014	41.479 ± 0.014	41.472 ± 0.015
R^0_ℓ	20.767 ± 0.025	–	20.739 ± 0.017	20.741 ± 0.017	20.713 ± 0.026
$A^{0,\ell}_{\rm FB}$	0.0171 ± 0.0010	–	$0.01627^{+0.0001}_{-0.0002}$	0.01637 ± 0.0002	0.01624 ± 0.0002
A_ℓ $^{(\star)}$	0.1499 ± 0.0018	–	$0.1473^{+0.0006}_{-0.0008}$	$0.1477^{+0.0009}_{-0.0008}$	–
$\sin^2\theta^\ell_{\rm eff}(Q_{\rm FB})$	0.2324 ± 0.0012	–	$0.23148^{+0.00011}_{-0.00007}$	$0.23143^{+0.00010}_{-0.00012}$	0.23150 ± 0.00009
A_c	0.670 ± 0.027	–	$0.6681^{+0.00021}_{-0.00042}$	$0.6682^{+0.00042}_{-0.00035}$	0.6680 ± 0.00031
A_b	0.923 ± 0.020	–	$0.93464^{+0.00005}_{-0.00007}$	$0.93468^{+0.00008}_{-0.00007}$	0.93463 ± 0.00006
$A^{0,c}_{\rm FB}$	0.0707 ± 0.0035	–	$0.0739^{+0.0003}_{-0.0005}$	$0.0740^{+0.0005}_{-0.0004}$	0.0738 ± 0.0004
$A^{0,b}_{\rm FB}$	0.0992 ± 0.0016	–	$0.1032^{+0.0004}_{-0.0006}$	$0.1036^{+0.0007}_{-0.0006}$	0.1034 ± 0.0003
R^0_c	0.1721 ± 0.0030	–	$0.17222^{+0.00006}_{-0.00005}$	0.17223 ± 0.00006	0.17223 ± 0.00006
R^0_b	0.21629 ± 0.00066	–	0.21491 ± 0.00005	0.21492 ± 0.00005	0.21490 ± 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	173.49 ± 0.82	173.17 ± 0.86	$175.83^{+2.74}_{-2.42}$
$\Delta\alpha^{(5)}_{\rm had}(M_Z^2)$ $^{(\dagger\triangle)}$	2756 ± 10	yes	2755 ± 11	2757 ± 11	2716^{+49}_{-43}
$\alpha_s(M_Z^2)$	–	yes	$0.1188^{+0.0028}_{-0.0027}$	$0.1190^{+0.0028}_{-0.0027}$	0.1188 ± 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	-1.4	4.7	–

$^{(\circ)}$Average of ATLAS ($M_H = 126.0 \pm 0.4\,({\rm stat}) \pm 0.4\,({\rm sys})$) and CMS ($M_H = 125.3 \pm 0.4\,({\rm stat}) \pm 0.5\,({\rm sys})$) measurements assuming no correlation of the systematic uncertainties. $^{(\star)}$Average of LEP ($A_\ell = 0.1465 \pm 0.0033$) and SLD ($A_\ell = 0.1513 \pm 0.0021$) measurements, used as two measurements in the fit. The fit w/o the LEP (SLD) measurement gives $A_\ell = 0.1474^{+0.0005}_{-0.0009}$ ($A_\ell = 0.1467^{+0.0006}_{-0.0004}$). $^{(\dagger)}$In units of 10^{-5}. $^{(\triangle)}$Rescaled due to α_s dependency.

Also note:

ZFITTER
Comput. Phys. Commun. 133, 229 (2001)
Comput. Phys. Commun. 174, 728 (2006)

TOPAZ0
Comput. Phys. Commun. 117, 278 (1999)

Global electroweak fit

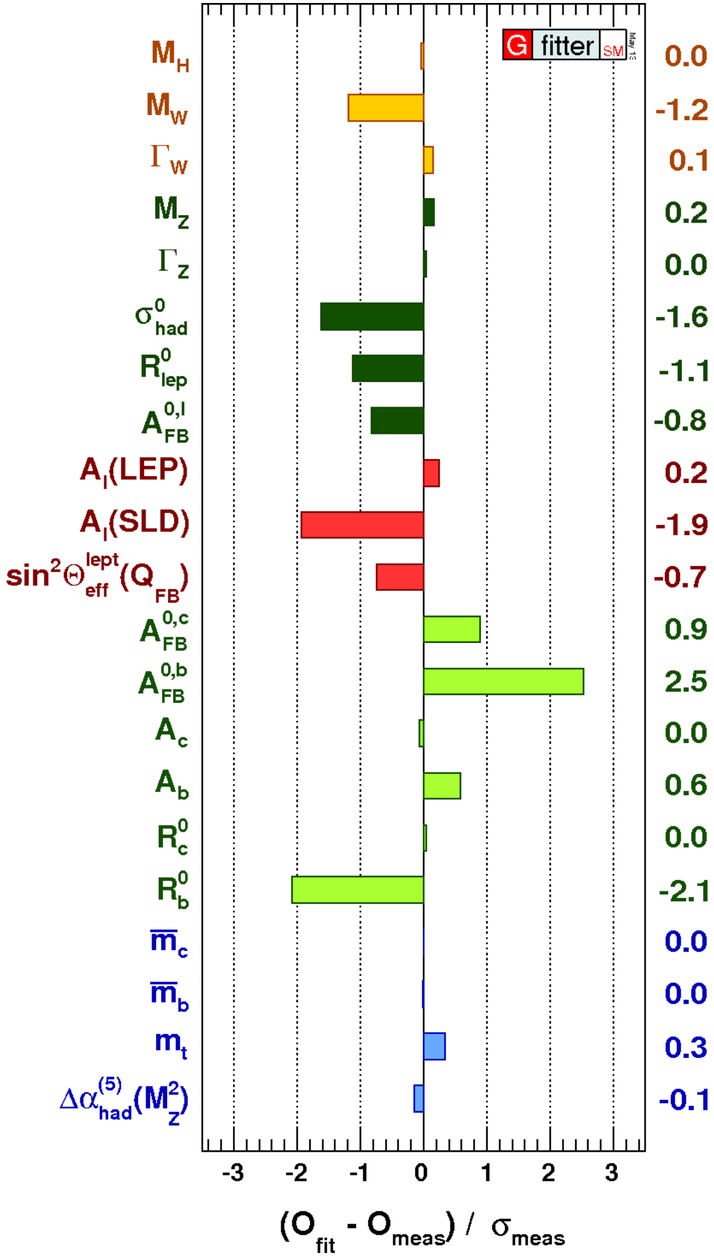
Complete fit:
χ^2_{min} = 20.7 for 14 degrees of freedom.

Pull values for the different observables are shown on the right.

- no value exceeds 2.5 sigma
- largest individual contribution to χ^2 from FB asymmetry of bottom quarks.

Overall good agreement between precision data and standard model.

As is well known, some tension between A_l(SLD) and $A_{FB}^{0,b}$ from LEP.

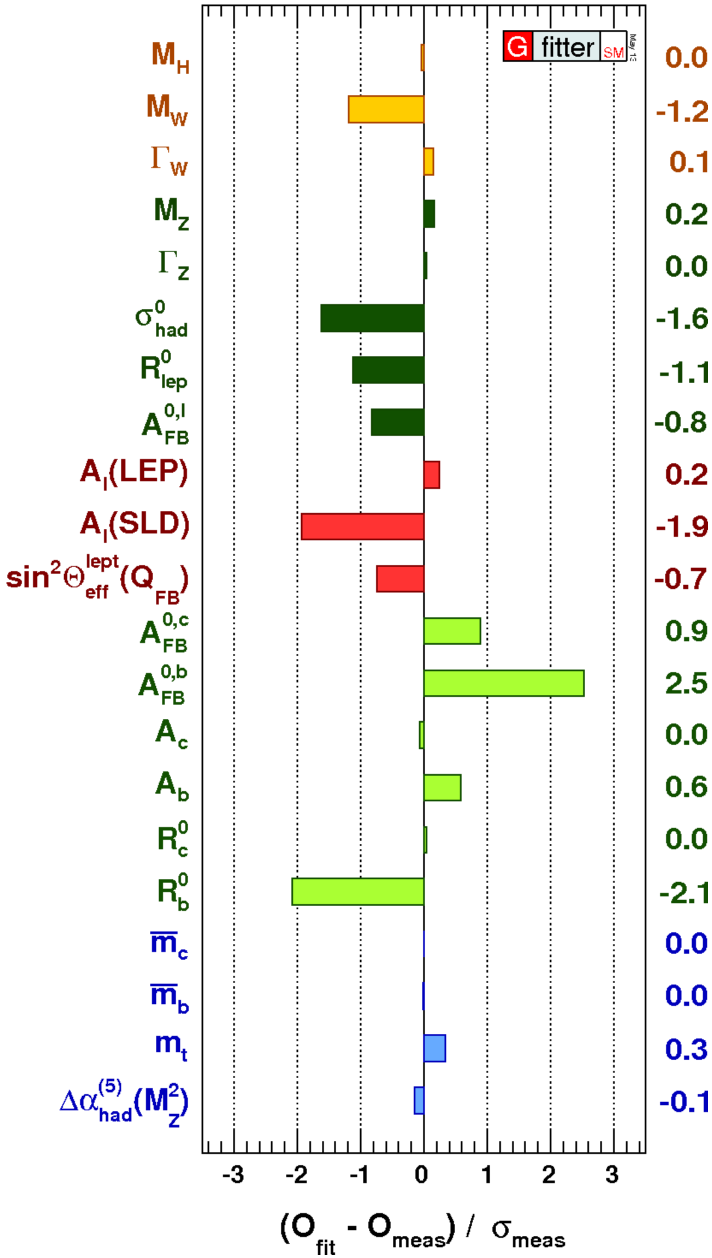


Global electroweak fit

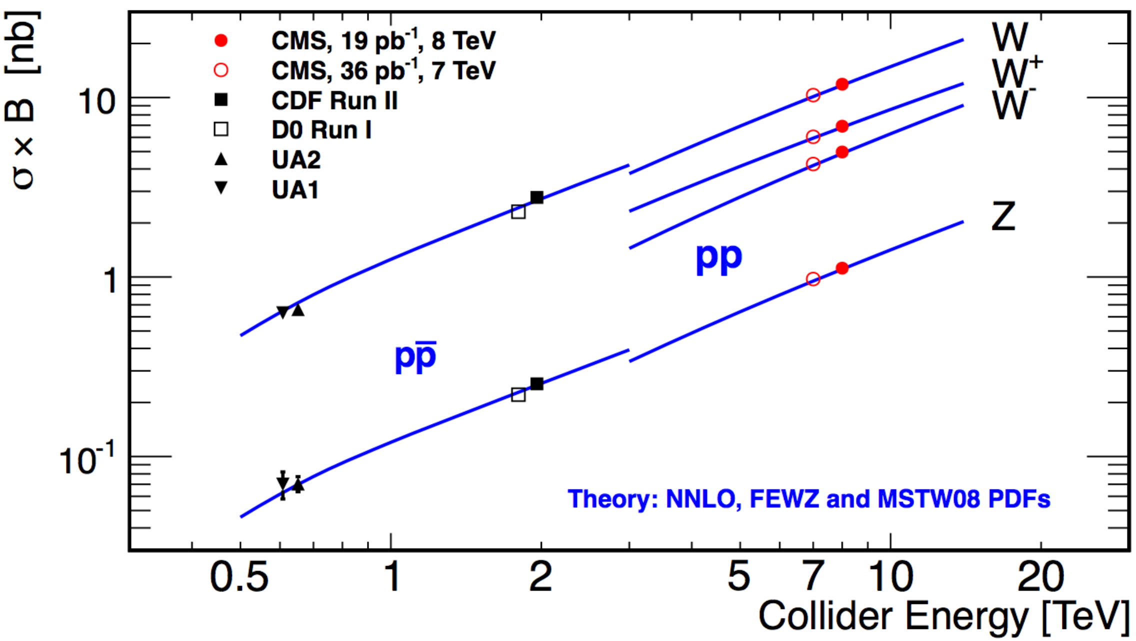
“So, how do we make progress now ?”

Electroweak physics is bustling with activity right now:

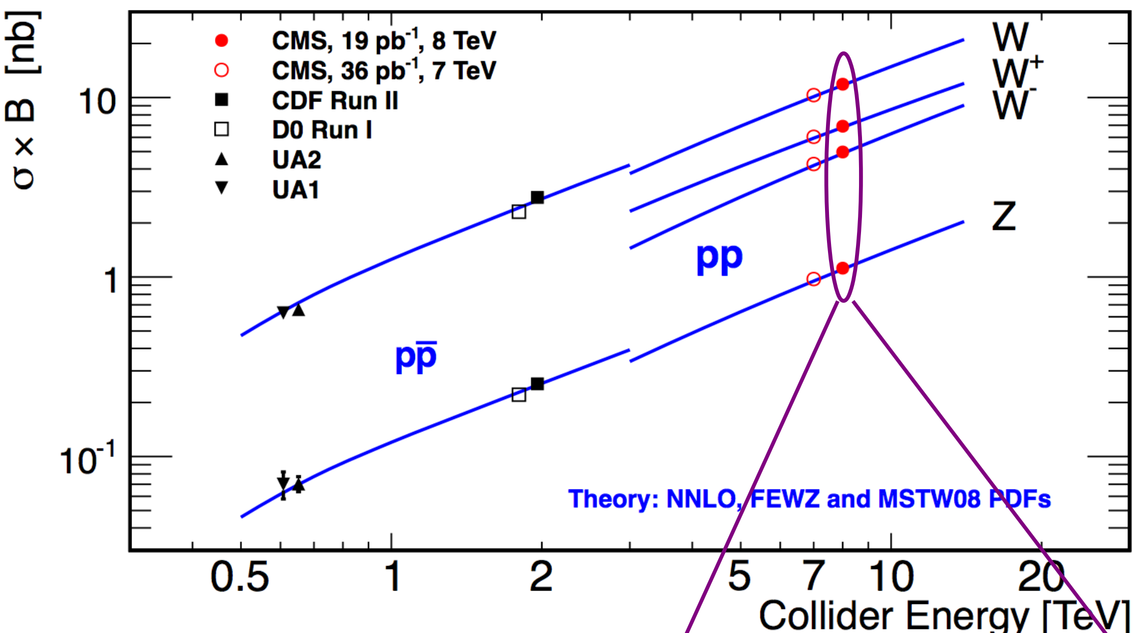
- further improve precision on parameters
  - W boson mass
  - potentially FB asymmetry (weak mixing angle)
- study in detail production of W and Z bosons at hadron colliders (differential cross sections, etc)
  - confront to the precise theory predictions (EWK+QCD) discussed, e.g., in previous talk
  - constrain PDFs
- study EWK interactions at the TEV scale to look for new physics (anomalous couplings etc)
- ...



Inclusive W and Z cross sections

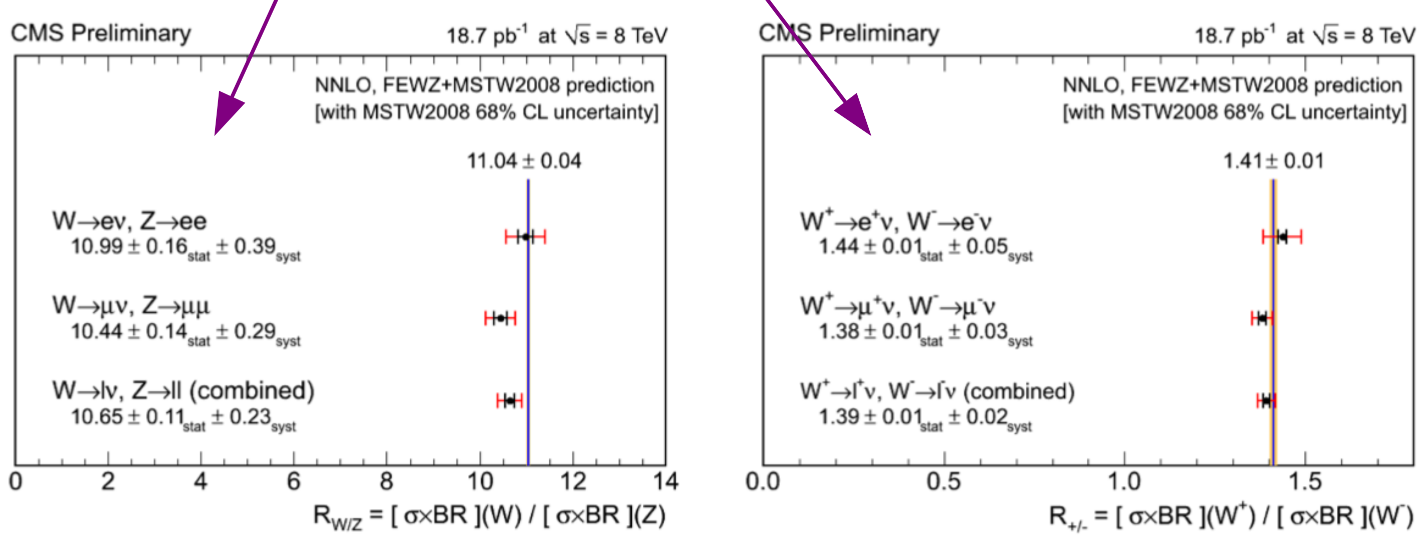


Inclusive W and Z cross sections



CMS PAS SMP-12-011

Results based on 18.7 ± 0.9 pb^{-1} of low-pileup data collected at the start of the 8 TeV run.



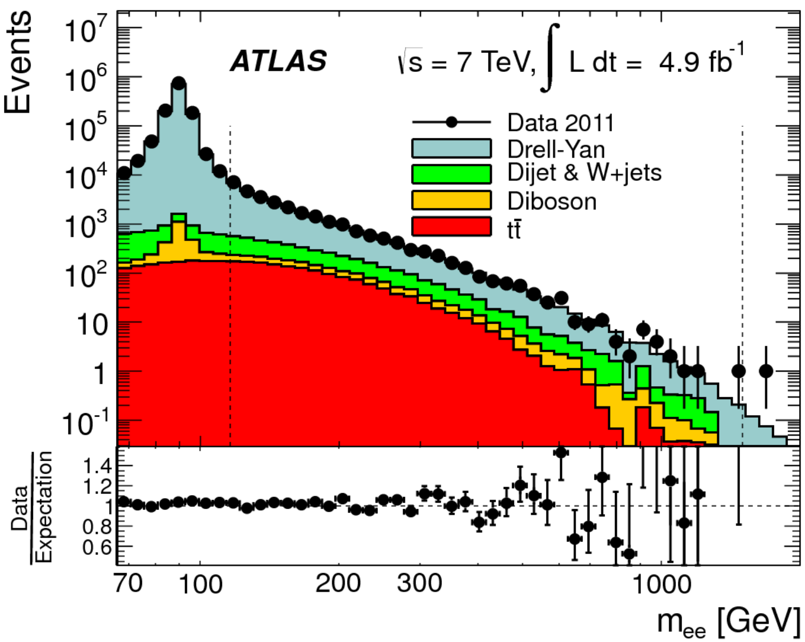
High-mass Drell-Yan (DY) cross section

arXiv:1305.4192

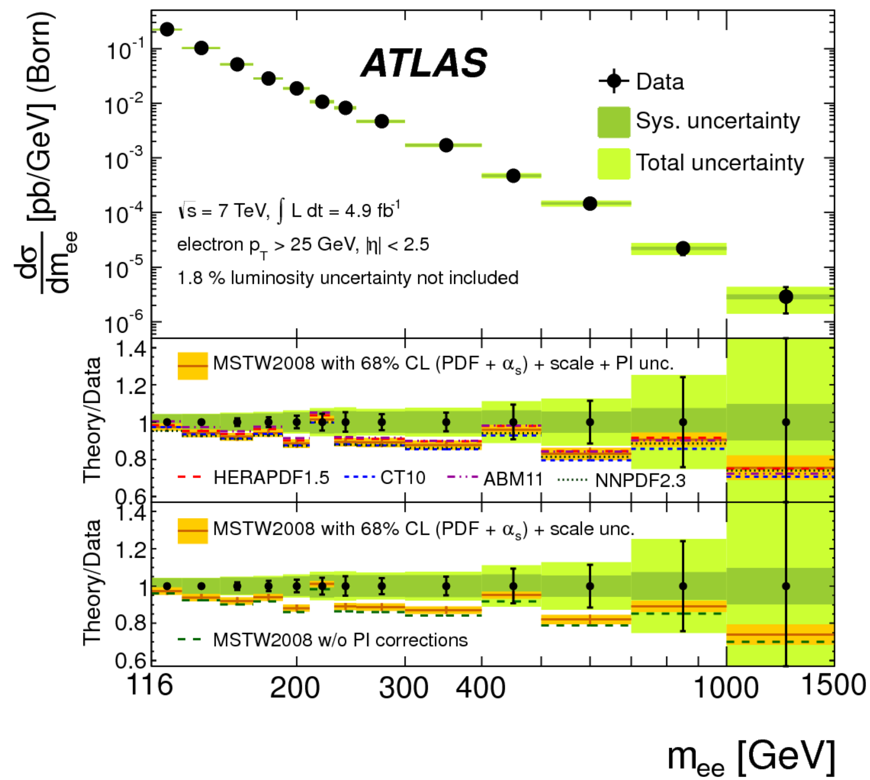
In addition to inclusive W and Z cross sections, have differential cross sections; including in the region far away from the Z pole.

Cross section measured for electrons with p_T > 25 GeV and |η| < 2.5

Data/MC comparison at reconstructed level



Cross section unfolded to "Born level":



Predictions based on NNLO QCD calculations including NLO EW corrections; shown for different NLO PDF sets. Photon-induced component is also included. Its effect is not small compared to differences between PDF sets.

Similar results from CMS: CMS PAS SMP-13-003

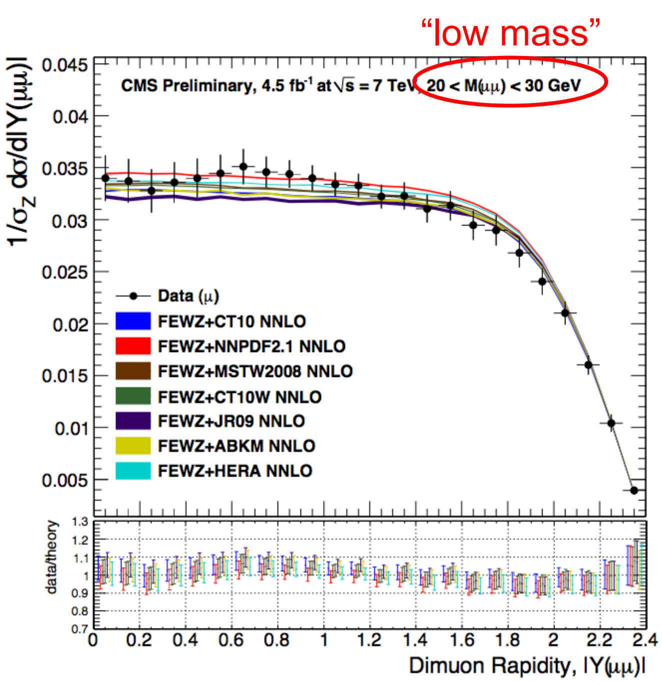
Double-differential DY cross section

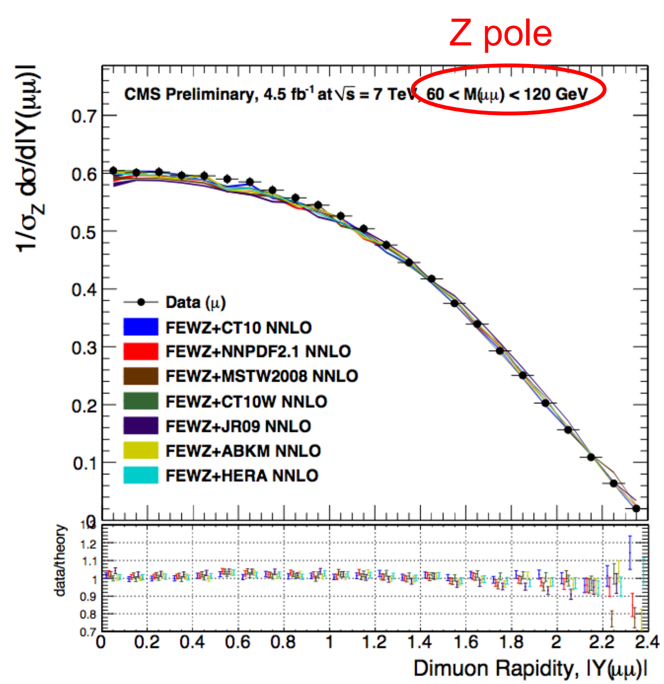
Also available: double-differential (in mass and rapidity) cross section.

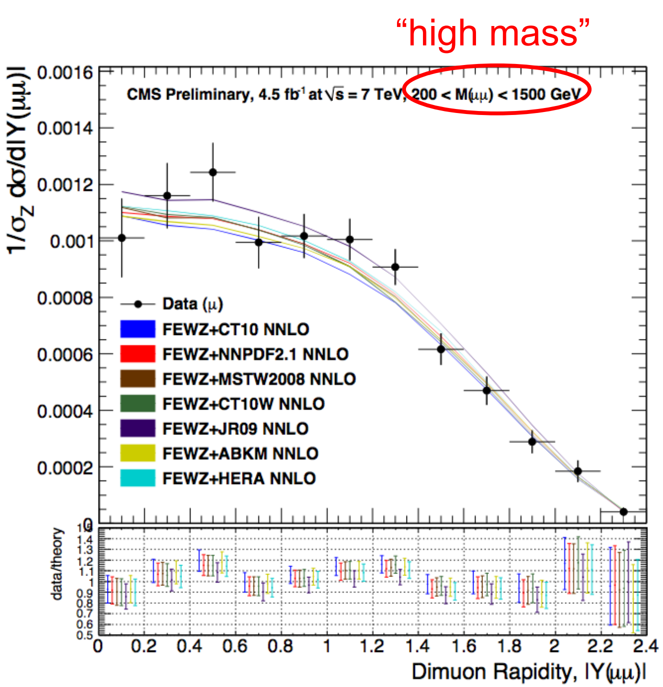
Shown here: rapidity-dependence of cross section for a few example bins in mass.

The rapidity distribution is sensitive to PDFs.

NNLO effects are particularly important at low mass.





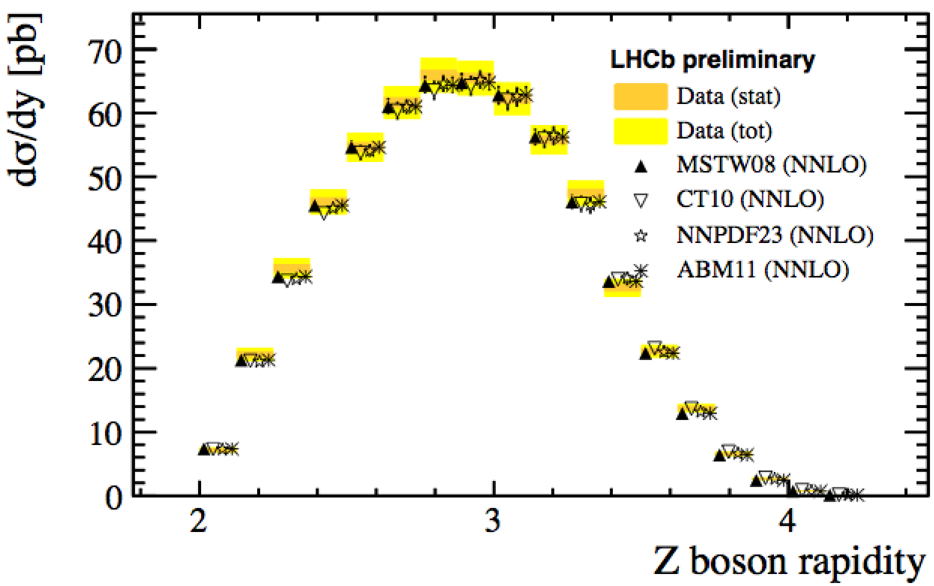


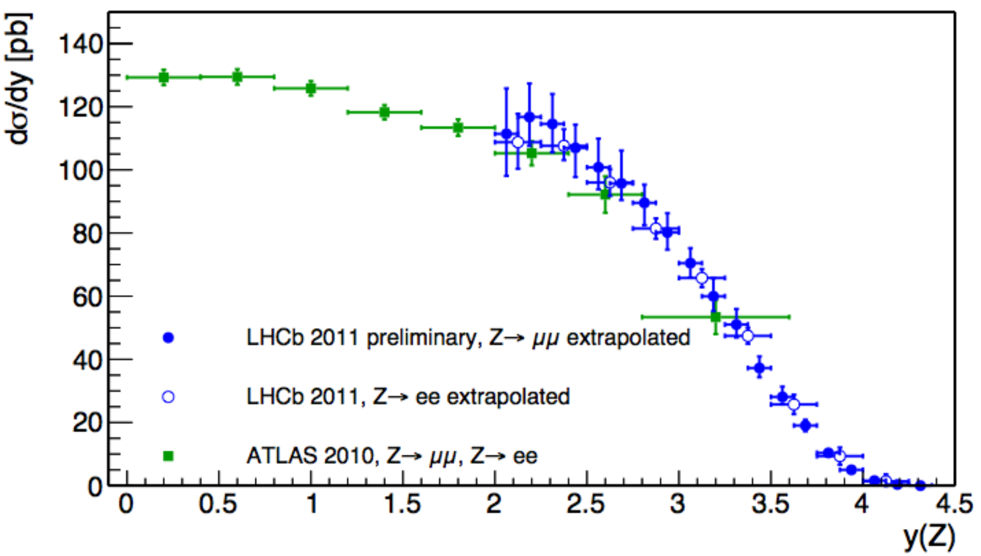
CMS PAS SMP-13-003

Very forward results from LHCb

LHCb-CONF-2013-007

The very forward acceptance of the LHCb detector allows the extension of DY rapidity studies (among other things) in the forward region.





Differential cross-section within the LHCb fiducial volume:

$p_T(\mu) > 20$ GeV, $2.0 <$ rapidity$(\mu) < 4.5$

$60 < m(\mu\mu) < 120$ GeV ("Z pole")

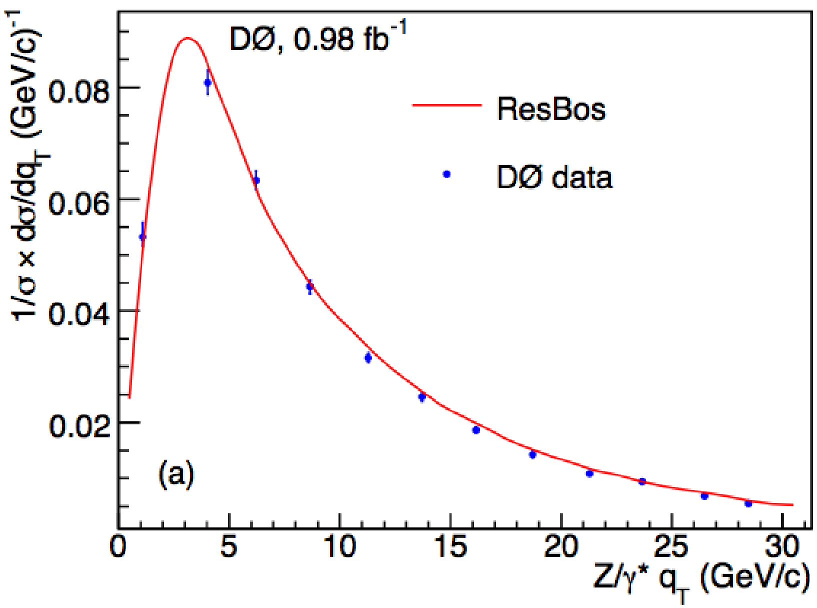
LHCb result extrapolated to ATLAS fiducial volume:

$p_T(l) > 20$ GeV

$66 < m(ll) < 116$ GeV

W and Z transverse momentum spectra

Phys. Rev. Lett. 100, 102002 (2008)



One region of particular interest in terms of boson p_T is the region at low p_T
(bulk of the sample in measurements like W mass).

Fixed-order QCD calculations diverge;
need resummation.

The measurement above (only 1 fb^{-1} of data) is already limited by systematic uncertainties due to the poor resolution on $p_T(Z)$.

New variable pioneered by DØ:

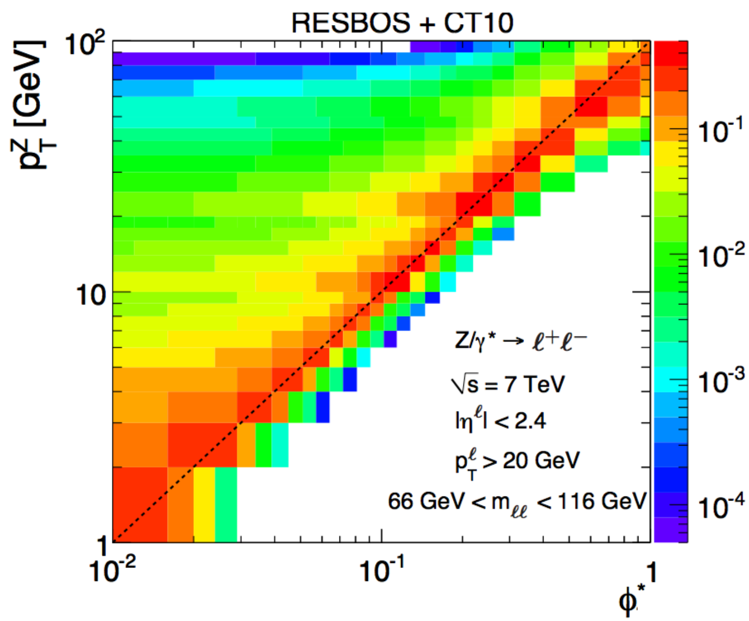
$$\phi^* \equiv \tan(\phi_{acop}/2) \cdot \sin(\theta^*_\eta)$$

Based on the (precise) measurements of *track directions*.

M. Vesterinen and T.R. Wyatt, NIM A602, 432.

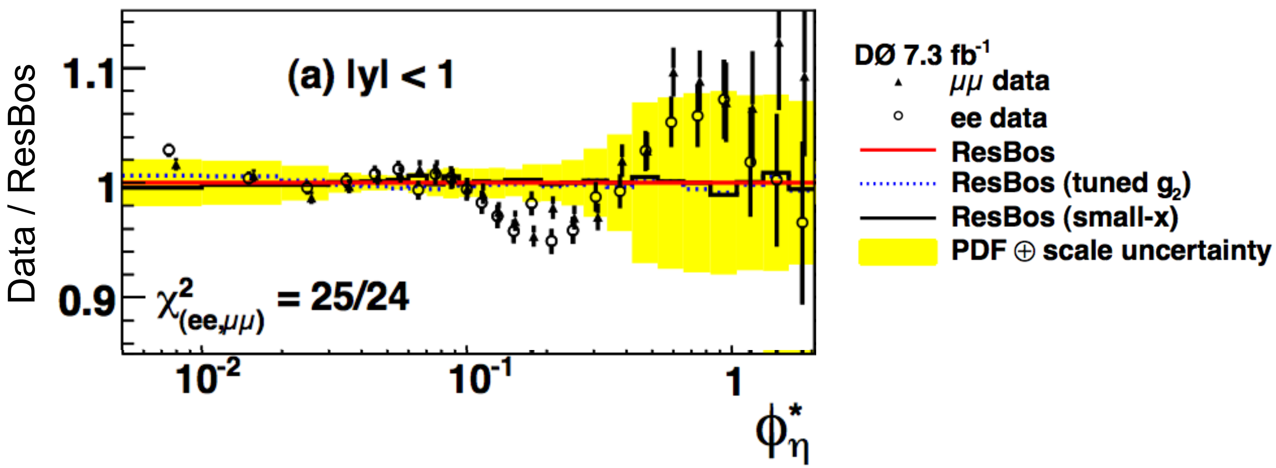
A. Banfi *et al.*, EPJ C71, 1600.

This new variable ϕ^* probes the same physics as $p_T(Z)$,
as illustrated in this scatter plot from ATLAS.



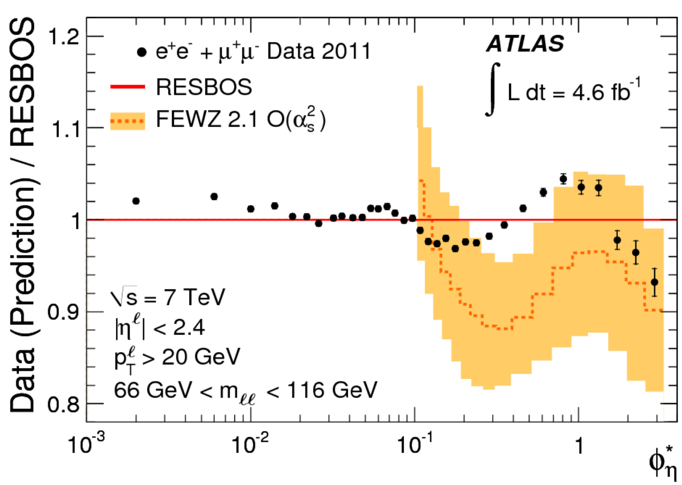
Z transverse momentum: ϕ^*

DØ (Phys. Rev. Lett. 106, 122001)

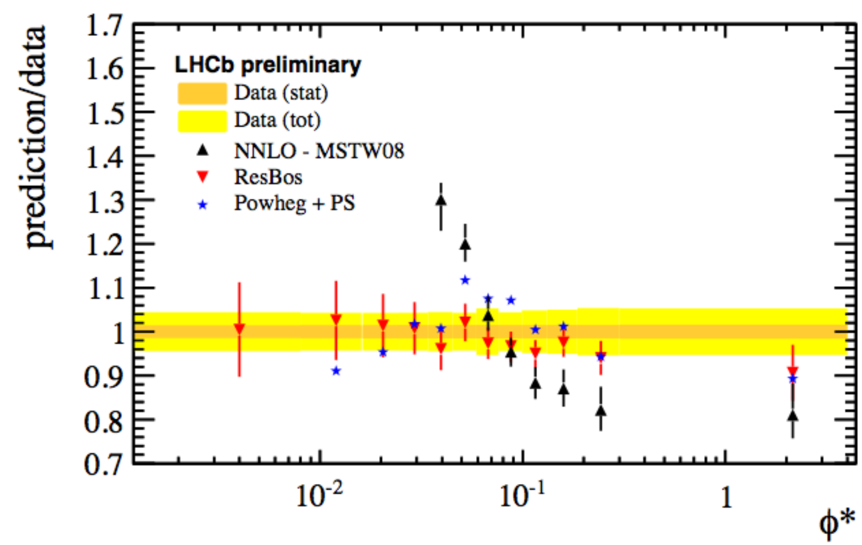


Available measurements more precise than the current best predictions.

ATLAS (Phys. Lett. B720, 32)



LHCb (LHCb-CONF-2013-007)

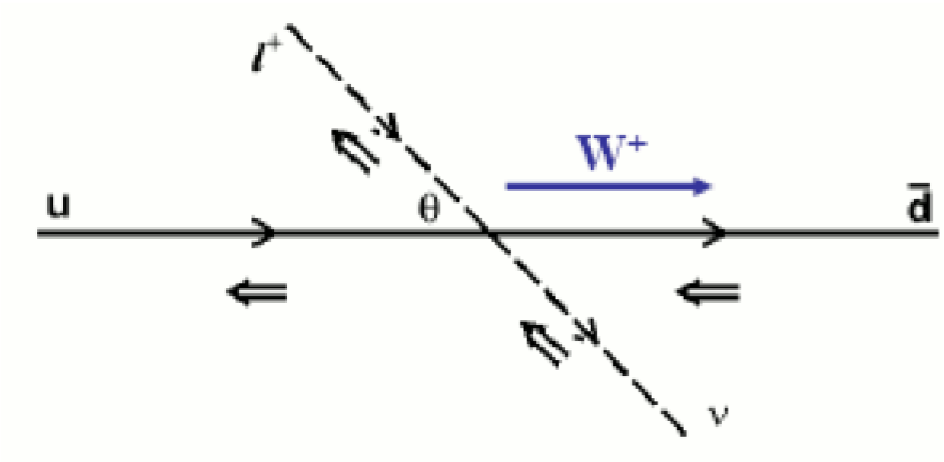


W charge asymmetry

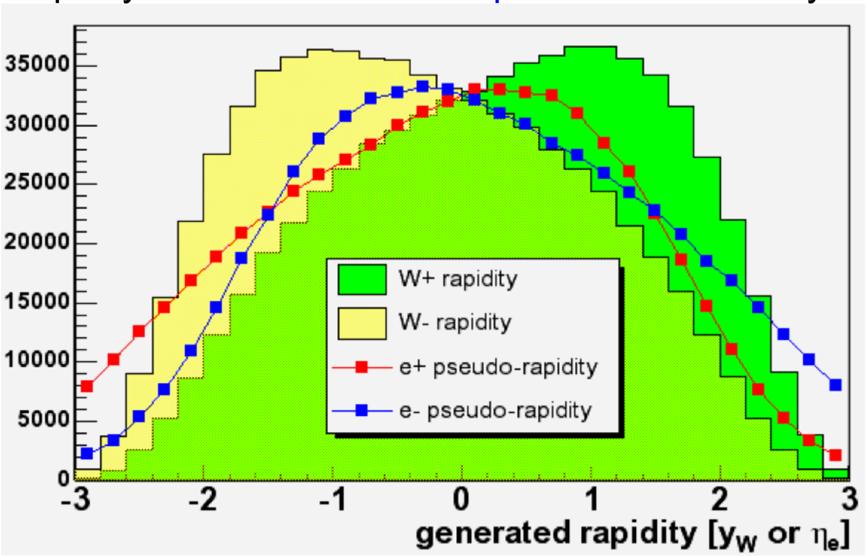
Tevatron ($p\bar{p}$ at "lower energy"): W boson mostly produced by valence quarks.

u quarks tend to carry more momentum than d quarks.

=> W^+ preferentially boosted in proton direction



Asymmetry also present, albeit diluted, in the rapidity distributions of the leptons from W decay.



Define asymmetry:
Often measured as function of lepton rapidity.

$$\mathcal{A}(\eta) = \frac{\frac{d\sigma}{d\eta}(W^+ \to \ell^+\nu) - \frac{d\sigma}{d\eta}(W^- \to \ell^-\bar{\nu})}{\frac{d\sigma}{d\eta}(W^+ \to \ell^+\nu) + \frac{d\sigma}{d\eta}(W^- \to \ell^-\bar{\nu})}$$

This measurement is also critical at the LHC.
Measurements at Tevatron and LHC probe different aspects of PDFs (flavour, Bjorken x).

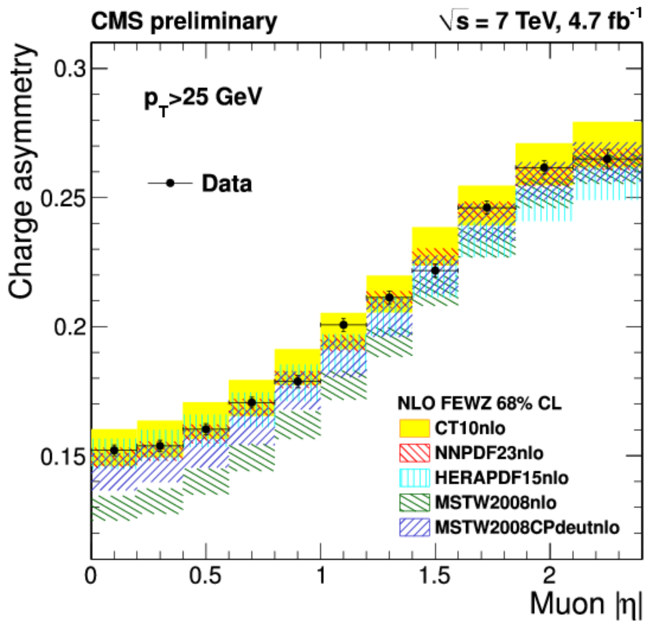
W charge asymmetry

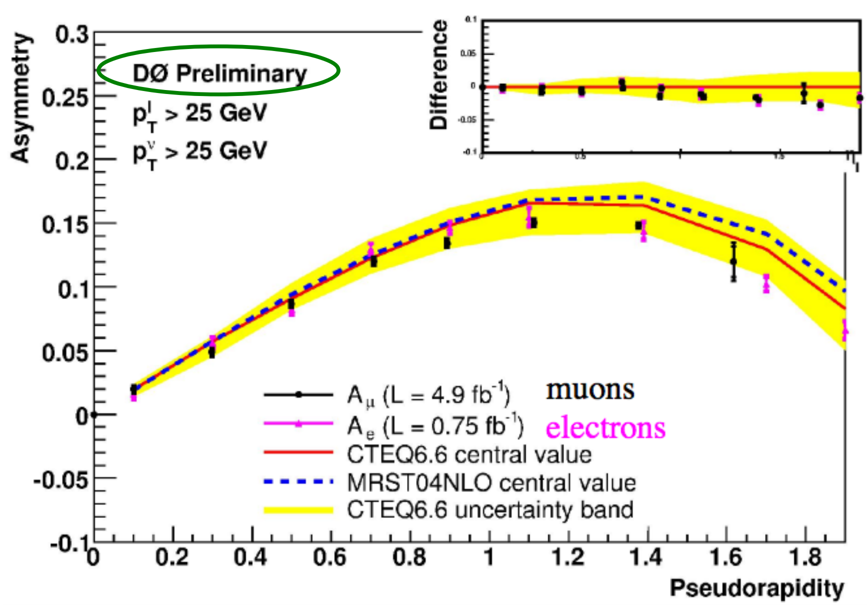
This slide shows a subset of the available measurements; more are expected.

Comparison of uncertainties in measurements and in predictions based on current PDF sets illustrates the large potential for improvements in PDFs.

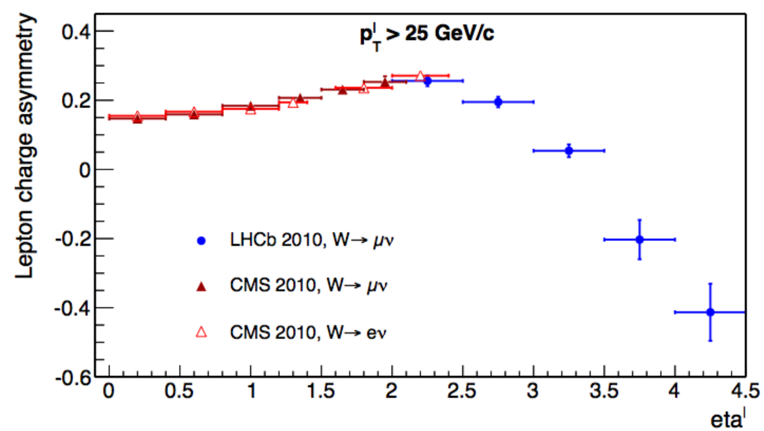
Also note CDF measurement of asymmetry as a function of **W boson** rapidity:
PRL 102, 181801.

CMS PAS SMP-12-021





LHCb-CONF-2013-005

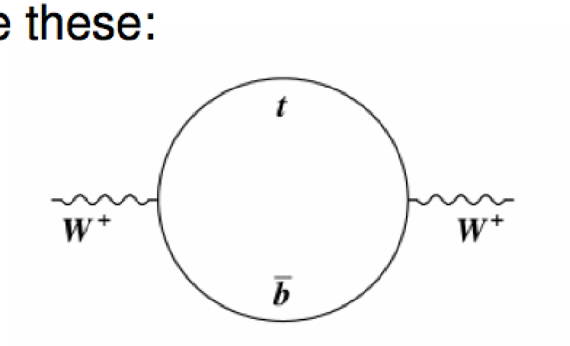


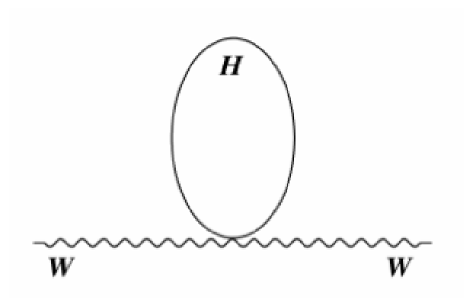
W boson mass: motivation

Today's measurements are precise enough to test the electroweak theory at the **loop level**.
At higher orders (including loop diagrams), the mass of the W boson can be expressed as:

$$M_W = \sqrt{\frac{\pi\alpha}{\sqrt{2}G_F}} \frac{1}{\sin\theta_W \sqrt{1-\Delta r}}$$

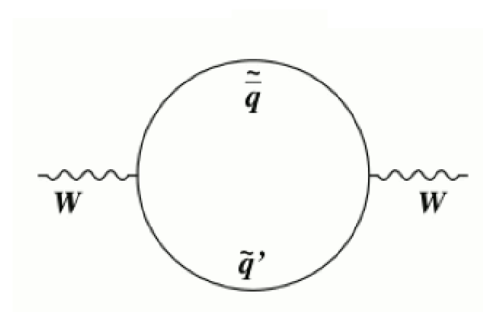
Radiative corrections (Δ r) depend on M_t as ~M_t^2 and on M_H as ~log M_H. They include diagrams like these:



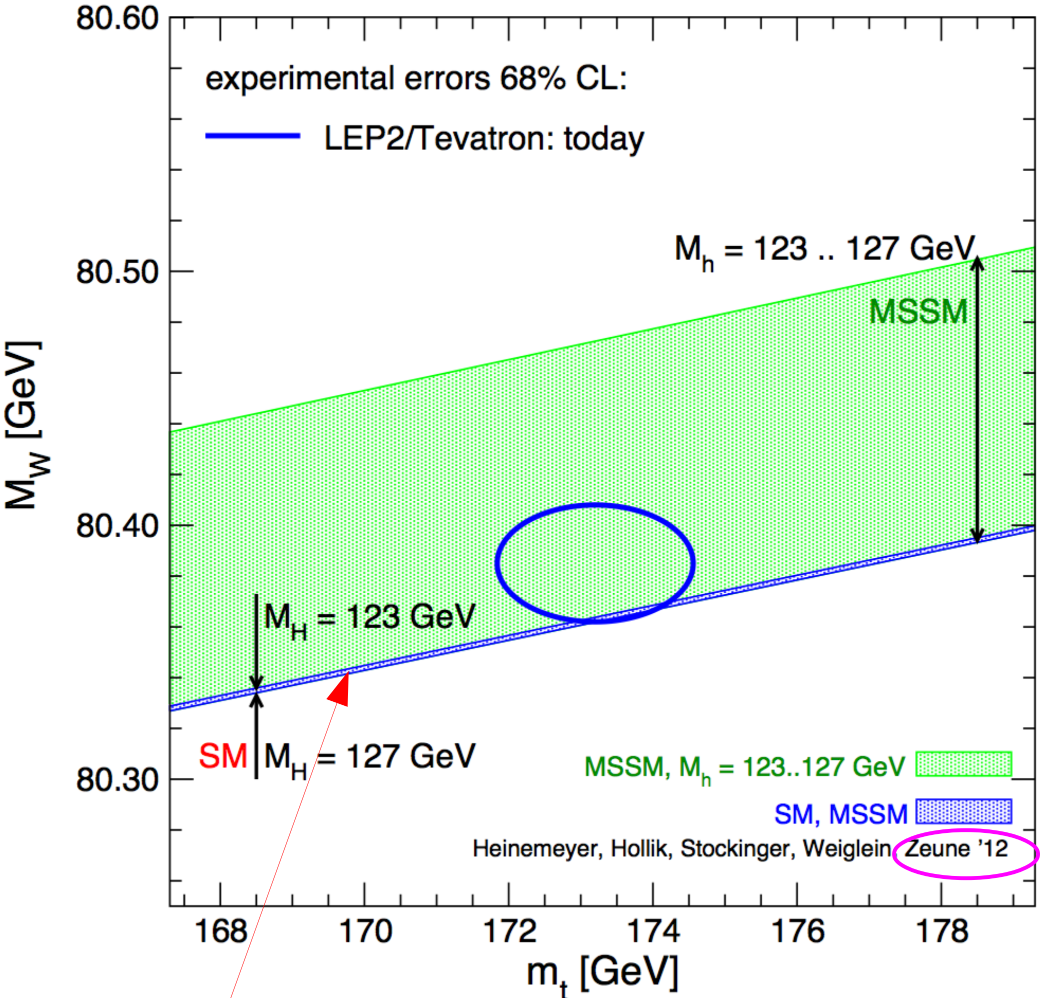


Precise measurements of M_W and M_t constrain SM Higgs mass.

Additional contributions to Δr arise in various extensions to the Standard Model, *e.g.* in SUSY:

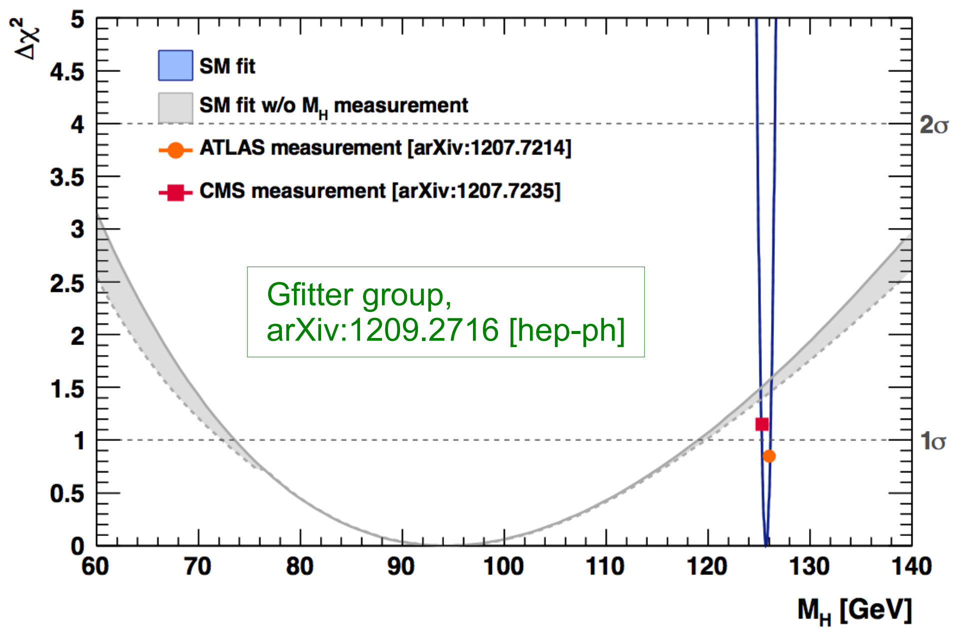


W boson mass



In the context of the standard model,
the mass of the new boson
discovered by ATLAS+CMS
is inside this blue band.

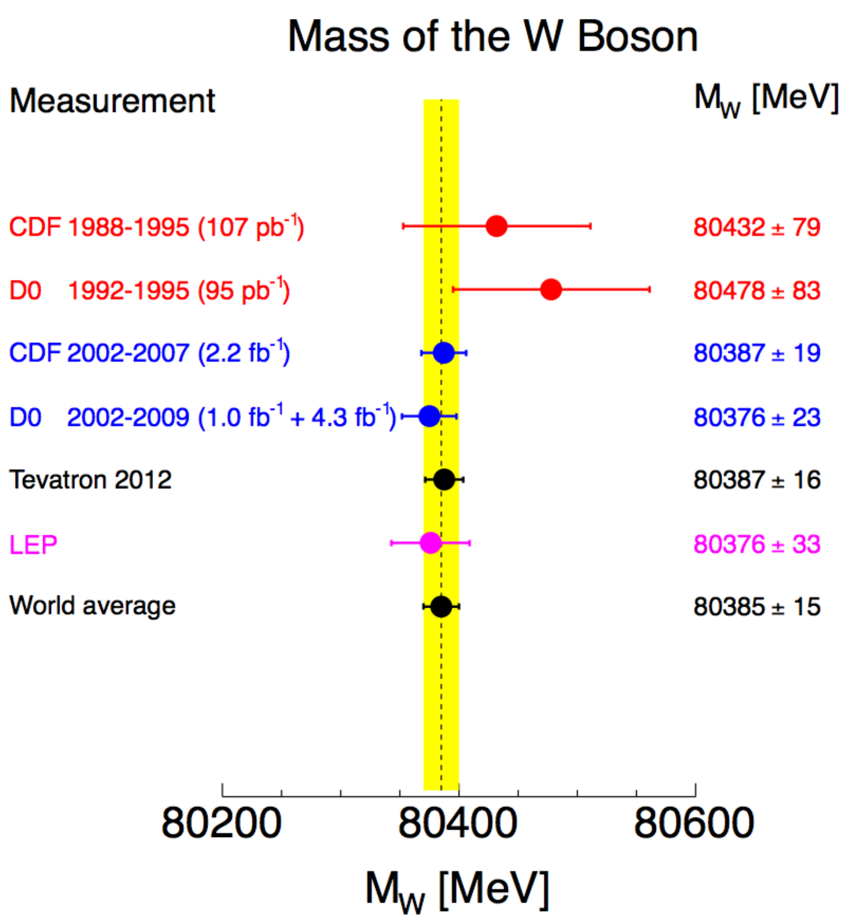
Comparison of indirect constraints on the Standard Model Higgs boson and the direct measurements of the mass of the new boson discovered by ATLAS and CMS:



Consistent at the 1.3 σ level.

W boson mass

Current state of the art:



Projections:

DØ: analyse full data set
significantly extend eta coverage
=> 15 MeV uncertainty
(not including improvements in PDFs)

CDF: analyse full dataset
=> 10 MeV uncertainty
(including improvements in PDFs;
which are expected from
measurements of W charge asymmetry)

LHC: 10 MeV to 5 MeV, ultimately

Current measurements of boson p_T, rapidity spectra
W charge asymmetry,
W+c jet (c.f. QCD plenary on Wednesday), ...
are critical steps toward this goal.

The next "quantum leap" in precision could come from a machine like e.g. TLEP (0.5 MeV uncertainty).

$\sin^2\theta_{eff}$

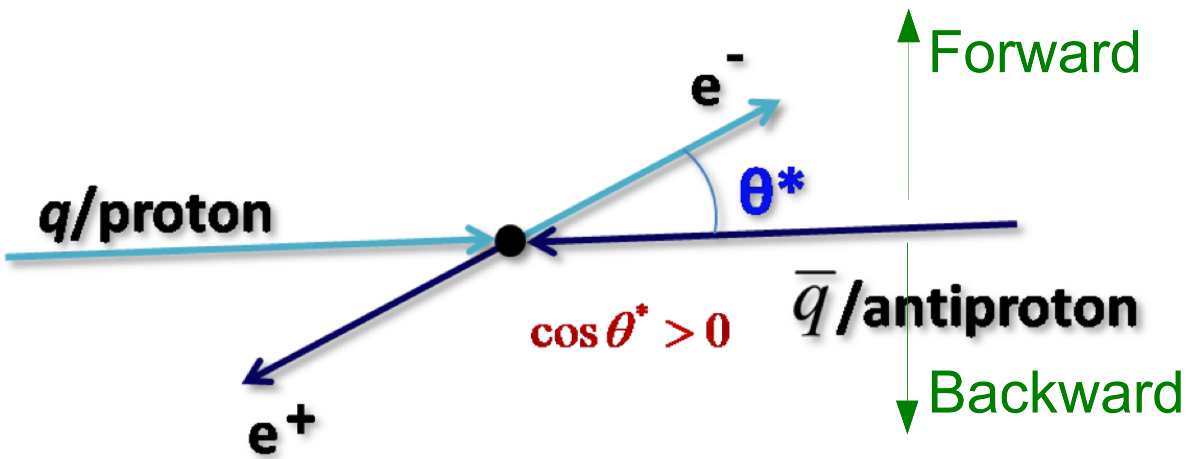
In the process $q\bar{q} \to Z/\gamma^* \to e^+e^-$

fermion-γ^* coupling contains only vector component

fermion-Z coupling contains both vector and axial-vector components

Vector coupling: $g_v^f = I_3^f - 2Q_f \sin^2\theta_W$

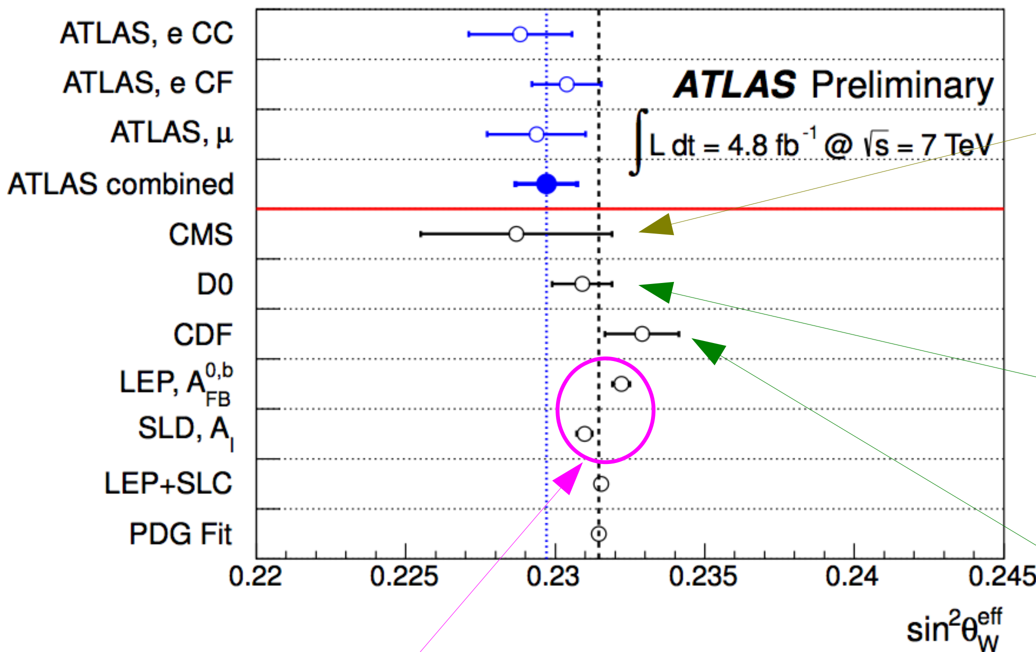
Axial-vector coupling: $g_a^f = I_3^f$



Define
Forward-Backward asymmetry:

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

$\sin^2 \theta_{eff}$



First measurement at the LHC (1.1 fb^{-1}):
Phys. Rev. D84 112002 (2011)

see also: Phys. Lett. B718, 752 (2013)

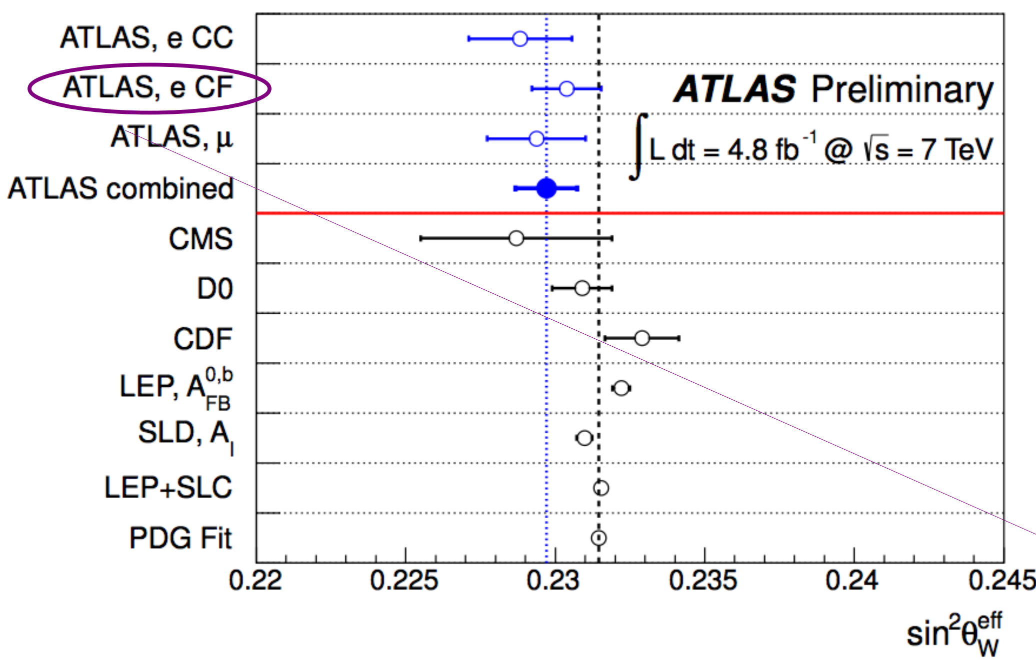
5.0 fb^{-1}
Phys. Rev.D 84, 012007 (2011)

2.1 fb^{-1} (using boosted Z bosons)
arXiv:1307.0770 (2013)

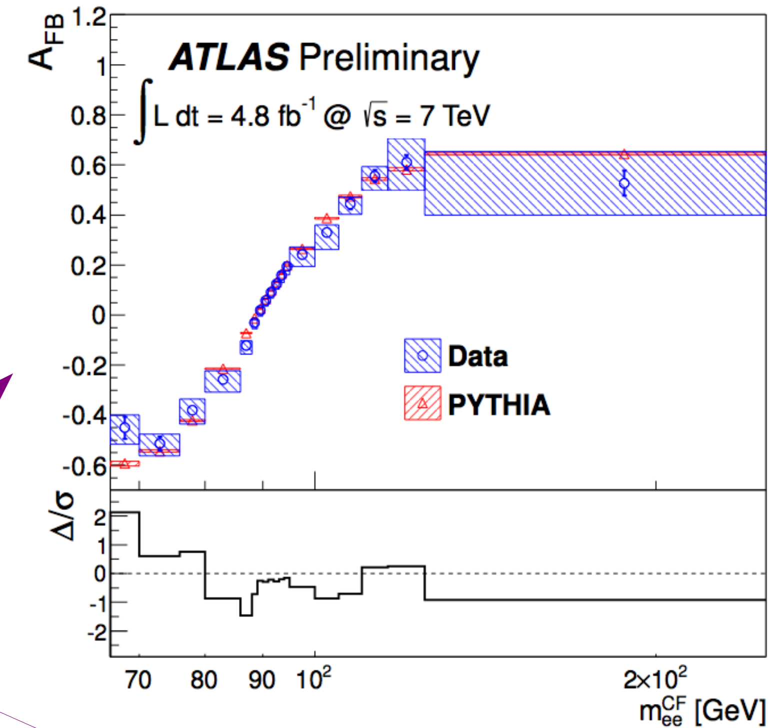
The tension mentioned
during discussion of global EWK fit.

$\sin^2 \theta_{eff}$

ATLAS-CONF-2013-043



fully unfolded to Born level



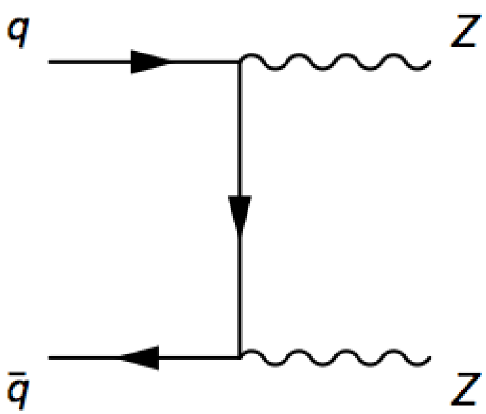
Large potential for reduced syst. uncertainties with more data and MC.

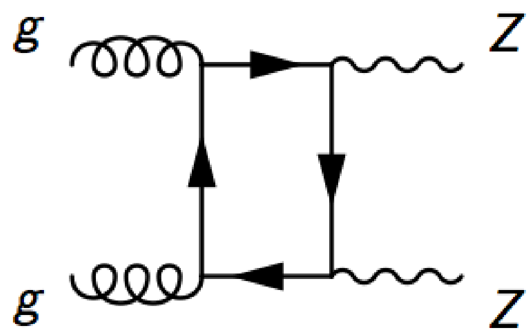
Disentangling PDF effects will be the key.

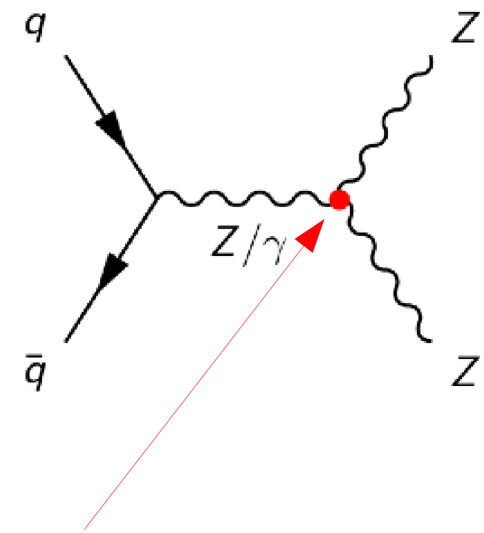
Uncertainty source	CC electrons (10^{-4})	CF electrons (10^{-4})	Muons (10^{-4})	Combined (10^{-4})
PDF	9	5	9	7
MC statistics	9	5	9	4
Electron energy scale	4	6	–	4
Electron energy smearing	4	5	–	3
Muon energy scale	–	–	5	2
Higher-order corrections	3	1	3	2
Other sources	1	1	2	2

Dibosons: example of ZZ

Examples of leading order Feynman diagrams for ZZ production through $q\bar{q}$ and gg initial state:







In the Standard model:

- This coupling is forbidden.
  => no contribution at tree level

- At one loop level:
  effective coupling at 10^{-4} level

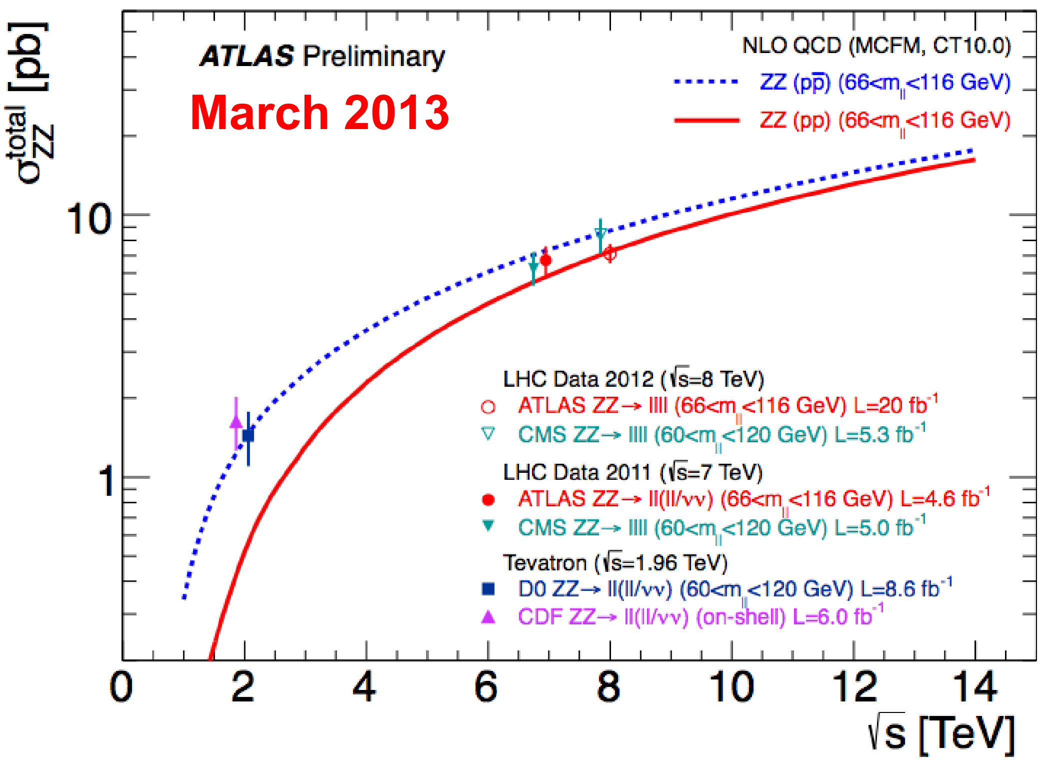
In various extensions to SM:
expect couplings in 10^{-4} to 10^{-3} range

Experimental limits on anomalous ZZγ coupling are typically parameterised in terms of the parameters f_4^{γ} (CP-violating) and f_5^{γ} (CP-conserving).

Similarly for ZZZ coupling.

ZZ production cross sections

ATLAS-CONF-2013-020



Three updates since this plot.

CMS prel. (8 TeV, 19.6 fb^{-1}):
CMS PAS SMP-13-005

$$\sigma(\mathrm{pp} \to \mathrm{ZZ}) = 7.7^{+0.5}_{-0.5}\,(\mathrm{stat.})^{+0.5}_{-0.4}\,(\mathrm{syst.}) \pm 0.4\,(\mathrm{theo.}) \pm 0.3\,(\mathrm{lum.})\ \mathrm{pb}$$

in agreement with prediction (MCFM):
7.7 ± 0.6 pb

CDF prel. (9.7 fb^{-1}): $\sigma(p\bar{p} \to ZZ) = 1.04^{+0.20}_{-0.24}(\mathrm{stat.})^{+0.15}_{-0.08}(\mathrm{syst.}) = 1.04^{+0.32}_{-0.25}$ pb

DØ (9.6-9.8 fb^{-1}):
arXiv:1304.5422

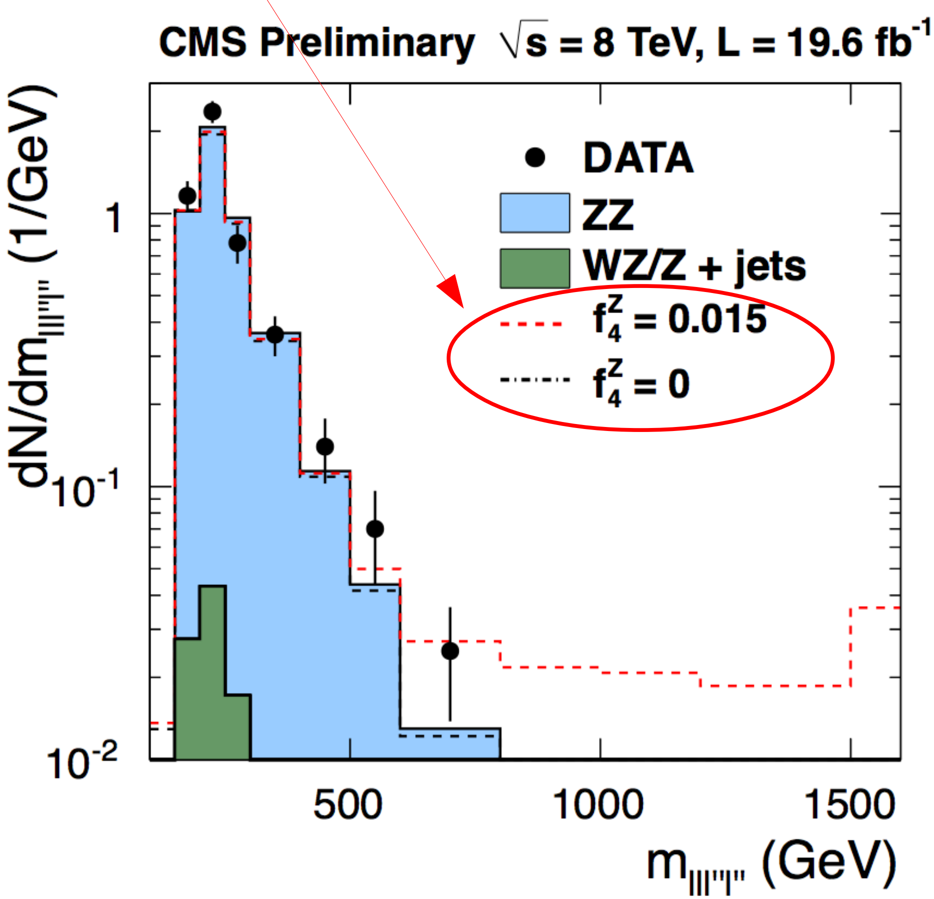
$$1.32^{+0.29}_{-0.25}\,(\mathrm{stat}) \pm 0.12\,(\mathrm{syst}) \pm 0.04\,(\mathrm{lumi})\ \mathrm{pb}$$

in agreement with prediction (MCFM):
1.4 ± 0.1 pb

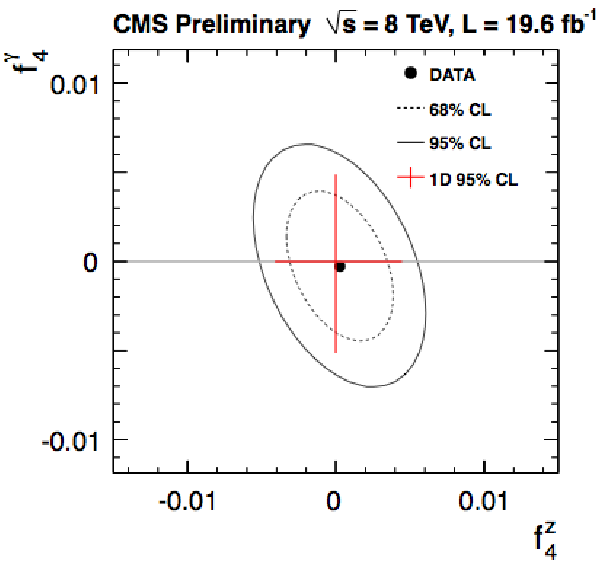
ZZ: constraints on anomalous TGC

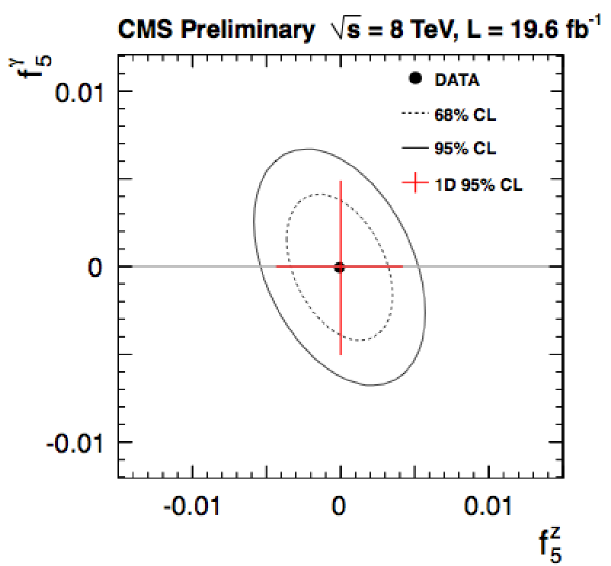
Use kinematic distributions to set limits on anomalous TGC.

Shown here is an example from the new CMS search in the four-lepton channel.

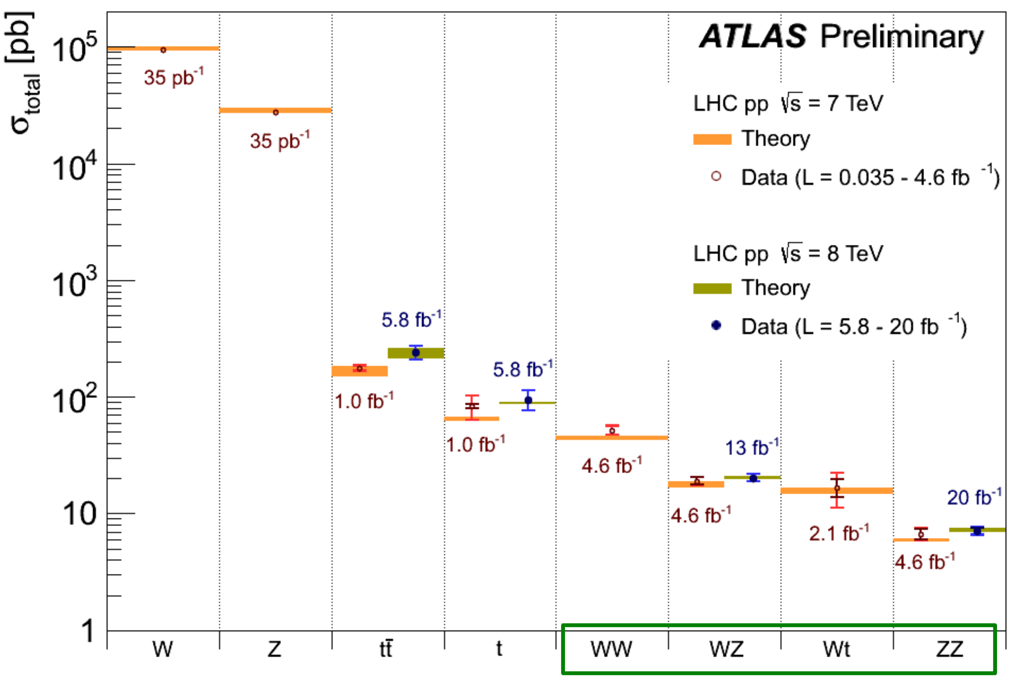


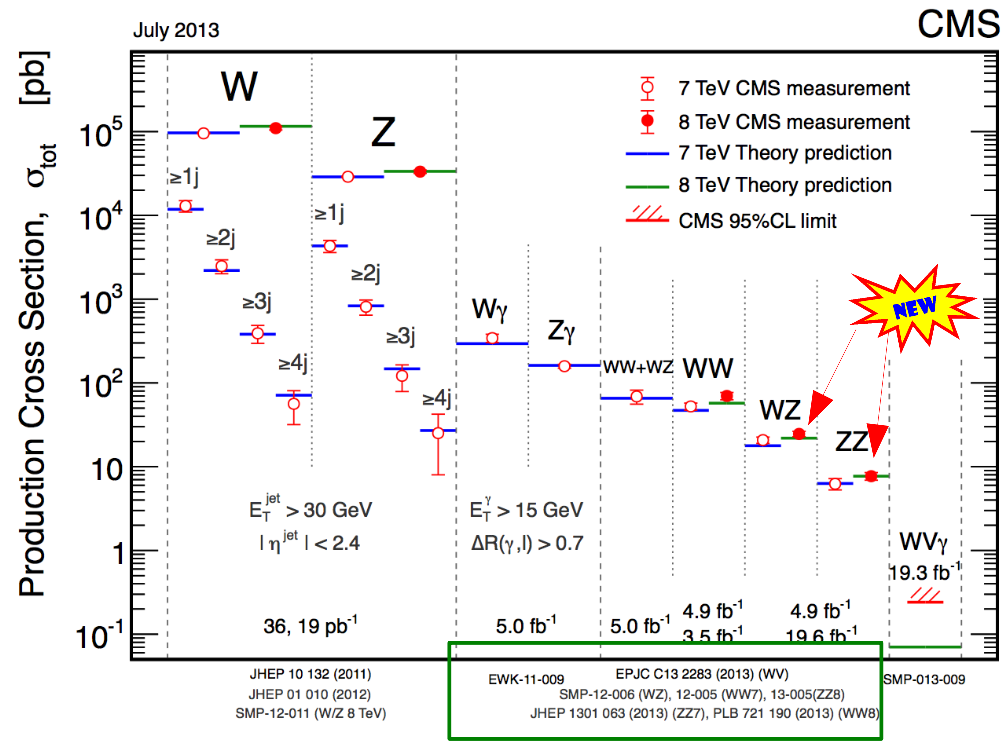
NEW





Other diboson modes

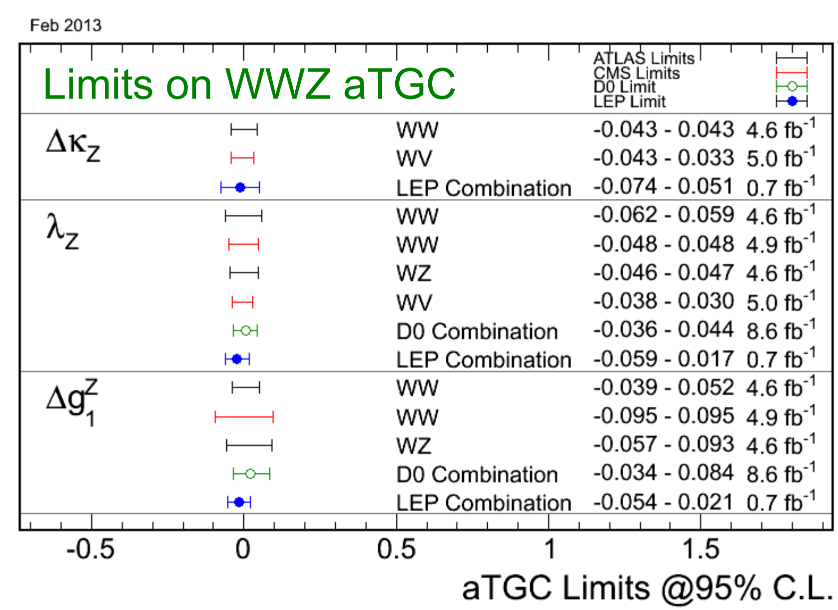




ZZ was chosen as an example.

Extensive studies of other di-boson final states are available.

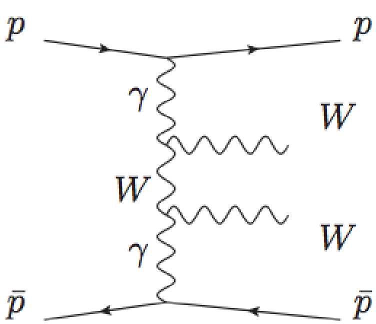
These studies report production cross sections and limits on aTGC.



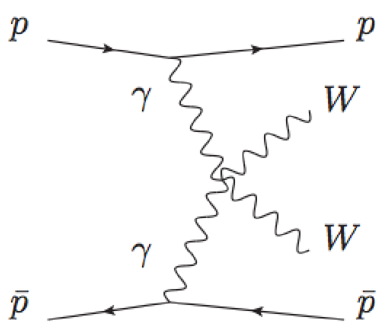
Quartic Gauge Couplings (QGC)

QGCs have been probed, at the Tevatron and the LHC, using two approaches:

photon-initiated processes

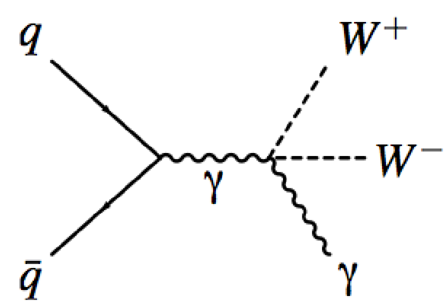


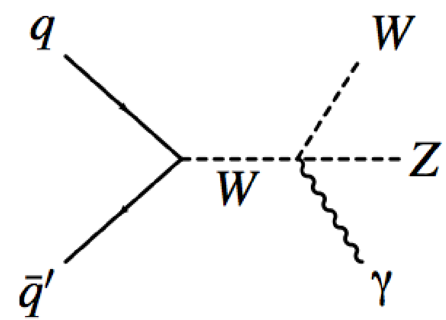
TGC



QGC

triple boson production





examples of QGC diagrams

Limits on anomalous QGC couplings are often reported in terms of parameters of effective Lagrangians:

$$\mathcal{L}_6^0 = \frac{-e^2}{8}\frac{a_0^W}{\Lambda^2}F_{\mu\nu}F^{\mu\nu}W^{+\alpha}W^-_\alpha$$

(e.g.: would receive contributions due to exchange of a heavy neutral scalar)

$$\mathcal{L}_6^C = \frac{-e^2}{16}\frac{a_C^W}{\Lambda^2}F_{\mu\alpha}F^{\mu\beta}(W^{+\alpha}W^-_\beta + W^{-\alpha}W^+_\beta)$$

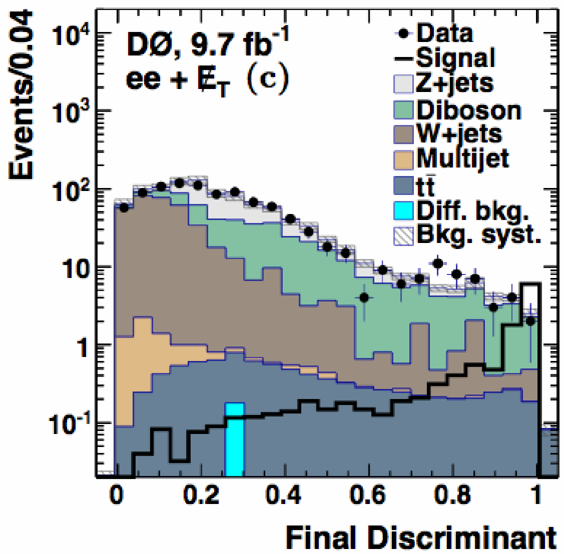
Latest CMS search for triple bosons also includes limits on operators of higher dimension (8).

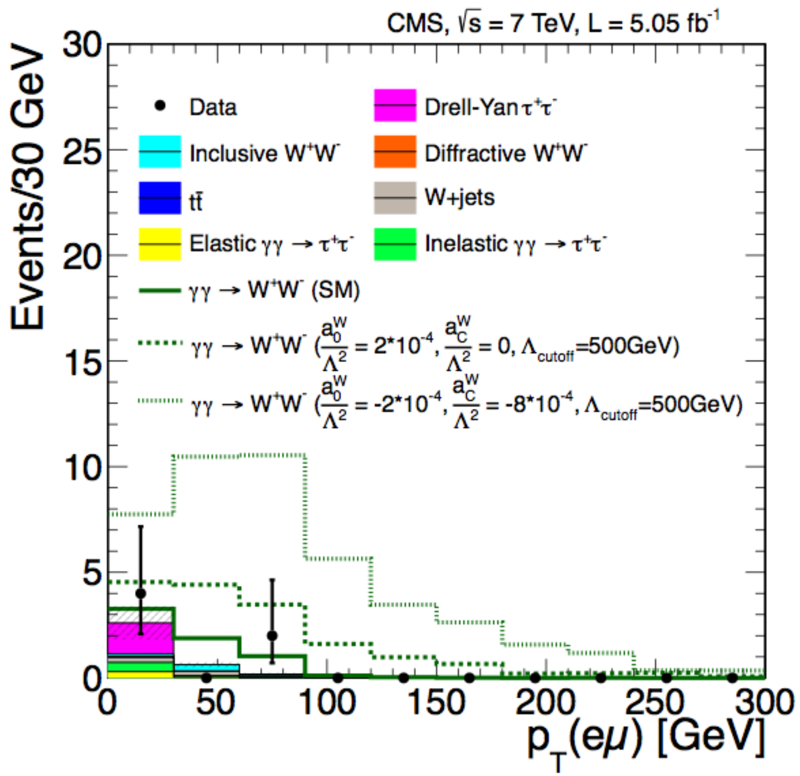
aQGC: photon-initiated processes

DØ: arXiv:1305.1258 (accepted by Phys. Rev. D)

After cut on final discriminant (BDT), expect 0.1 events from SM.

Plot on right shows final discriminant, and expected aQGC signal for $a_0^W/\Lambda^2 = 5\times10^{-4}\,\mathrm{GeV}^{-2}$ (no FF)





CMS: arXiv:1305.5596

Close to SM sensitivity (prediction: 4.0 +/- 0.7 fb):

$$\sigma(pp \to p^{(*)}W^+W^-p^{(*)} \to p^{(*)}\mu^\pm e^\mp p^{(*)}) < 10.6\,\mathrm{fb}$$

or interpreted as cross section (1 σ significance):

$$\sigma(pp \to p^{(*)}W^+W^-p^{(*)} \to p^{(*)}\mu^\pm e^\mp p^{(*)}) = 2.2^{+3.3}_{-2.0}\,\mathrm{fb}$$

Use kinematic distributions (like in plot on left) to search for aQGC.

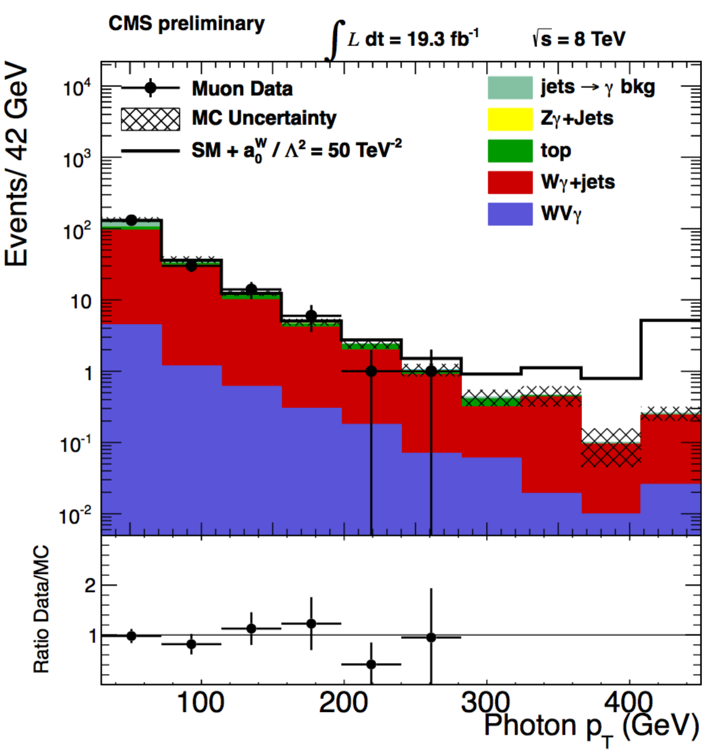
aQGC: triple boson production

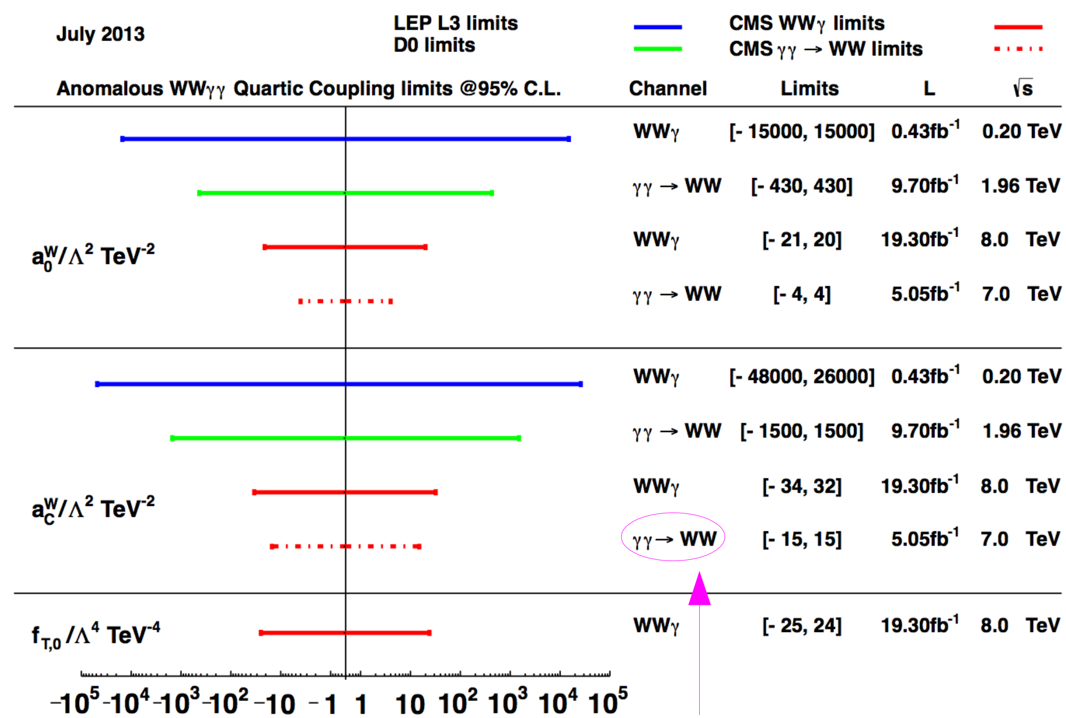
CMS search in final state WVγ

W → l ν

V: W → jet jet   or Z → jet jet

Summary of limits on anomalous WWγγ coupling:





CMS PAS SMP-13-009

NEW

"γγ → WW" corresponds to results on previous slide

Conclusions

We have a precise and predictive model of the electroweak interactions.
We have a wealth of precision measurements that over-constrain the parameters of this model.
Good consistency between model and data.

The precision of several of these measurements is dominated by hadron colliders (Tevatron and LHC): mass of the Top quark, mass of the (candidate) Higgs boson, mass of the W boson.
Excellent potential for competitive measurements of weak mixing angle.

Wealth of precision data (differential cross sections, ...) from Tevatron and LHC (ATLAS, CMS and LHCb in the very forward region) on vector boson production:

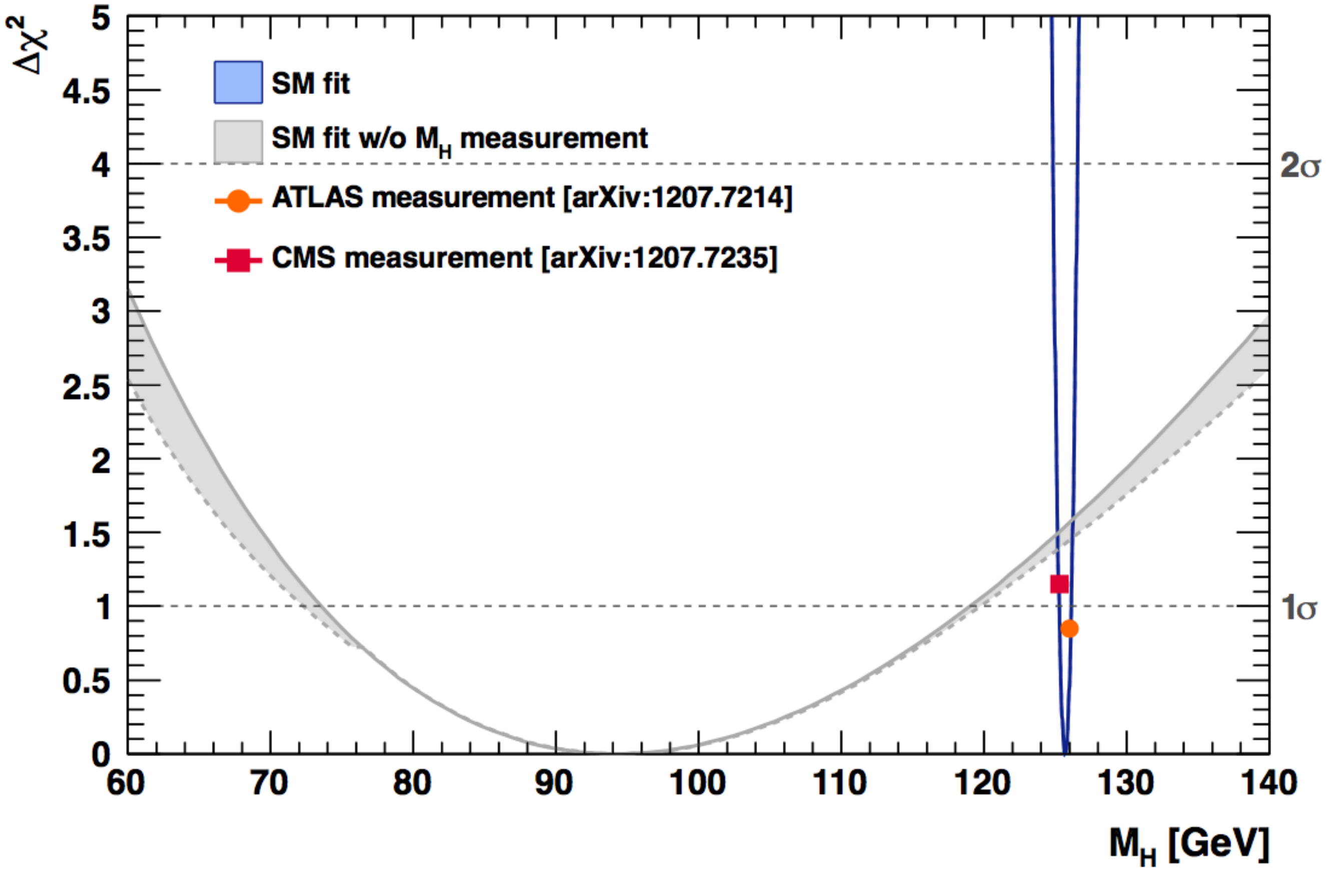
- Allow to test the EWK and QCD aspects of production processes, as well as their interplay. At the same time, impressive and continuous progress on the theoretical predictions.
- New constraints on PDFs, ...
- These are critical input to precision measurements of W boson mass, weak mixing angle, among many others.

Probing the electroweak interaction at the TeV scale: constraints on anomalous couplings, …
No evidence for new physics yet; looking forward to even higher energies.

Cannot overemphasise the importance of progress in theory / MC generators, etc and the communication between experimentalists and theorists.

Backup Slides

Constraints on the Higgs boson mass



Indirect constraint on Higgs mass:

$M_H = 94\ ^{+25}_{-22}$ GeV

Consistent (1.3 σ) with direct measurements the mass of the new boson discovered at CERN.

Gfitter group, arXiv:1209.2716 [hep-ph]

Alternatively, this test can be "turned around": use electroweak fit, including measurement of Higgs boson mass, to predict the W boson mass:

$$\begin{aligned} M_W &= 80.3593 \pm 0.0056_{m_t} \pm 0.0026_{M_Z} \pm 0.0018_{\Delta\alpha_{\rm had}} \\ &\qquad \pm 0.0017_{\alpha_S} \pm 0.0002_{M_H} \pm 0.0040_{\rm theo} \\ &= 80.359 \pm 0.011_{\rm tot} \end{aligned}$$

Direct measurement:
M_W = 80.385 ± 0.015

PDF uncertainties

In principle:
transverse observables (*e.g.* m_T) are insensitive to the uncertainties in the (longitudinal) parton distribution functions (PDFs)

In practice:
the uncertainties are to some extent reintroduced via the limited η coverage of experiments,
which are not invariant under longitudinal boosts

How to reduce the impact of the PDF uncertainties in measurements of the W boson mass ?

- Reduce the uncertainties in the PDFs

  e.g. via measurements of the W charge asymmetry
  at the Tevatron and the LHC (complementarity of the two colliders)

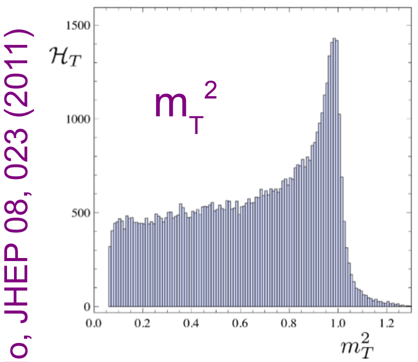
- Reduce the impact of the PDF uncertainties on W boson mass

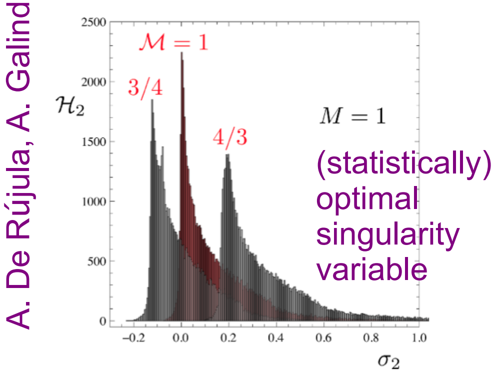
  by extending the η coverage as much as possible
  (challenging: understanding lepton energy scale and pile-up and
  backgrounds in the forward detectors)

- Possibly reduce the impact of the PDF uncertainties on W boson mass

  by exploring even more robust observables
  ("single out events with small longitudinal momentum") to replace/complement m_T

A. De Rújula, A. Galindo, JHEP 08, 023 (2011)





These three approaches are not mutually exclusive, *i.e.* they can be pursued at the same time and gains should "add up".

Global electroweak fit

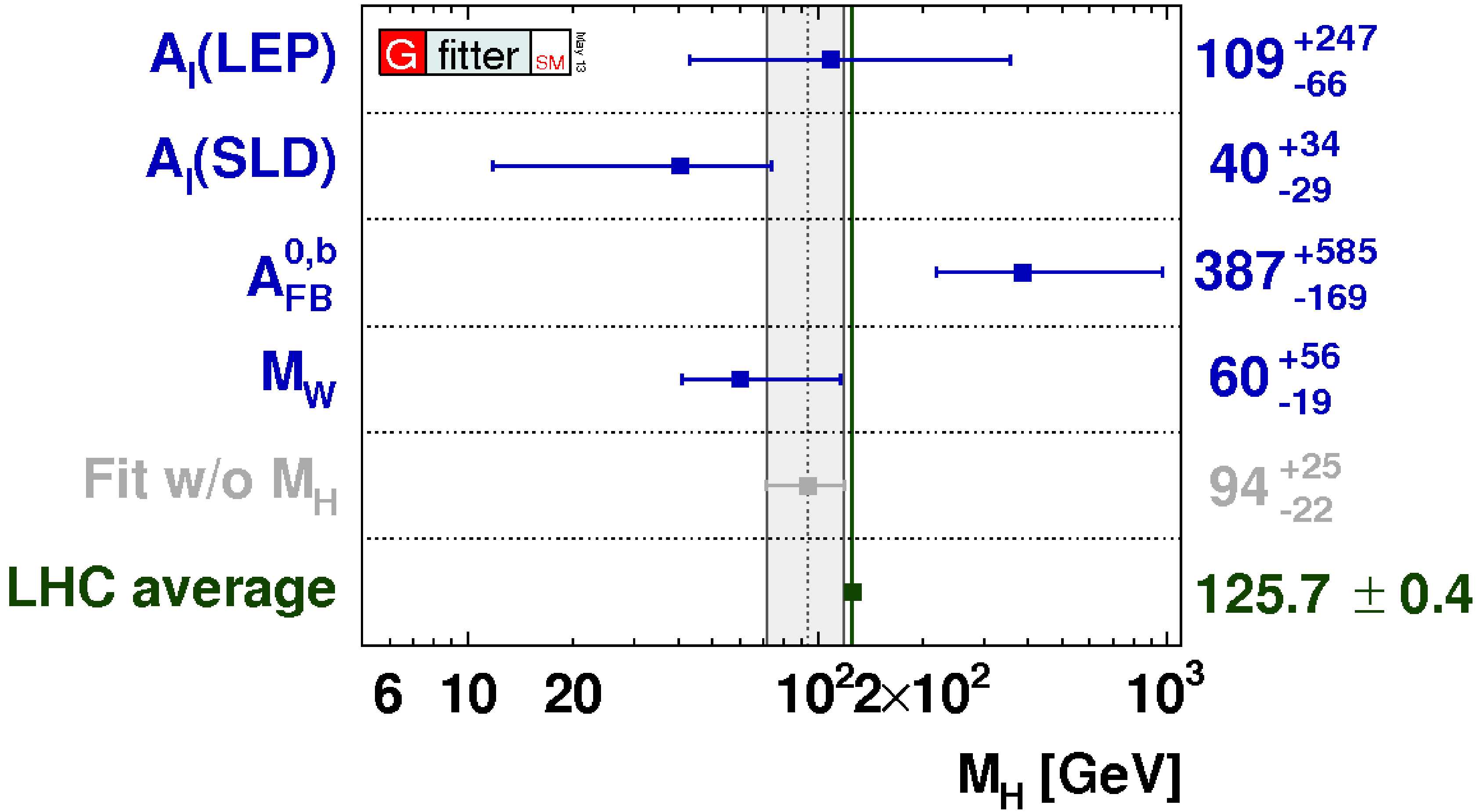


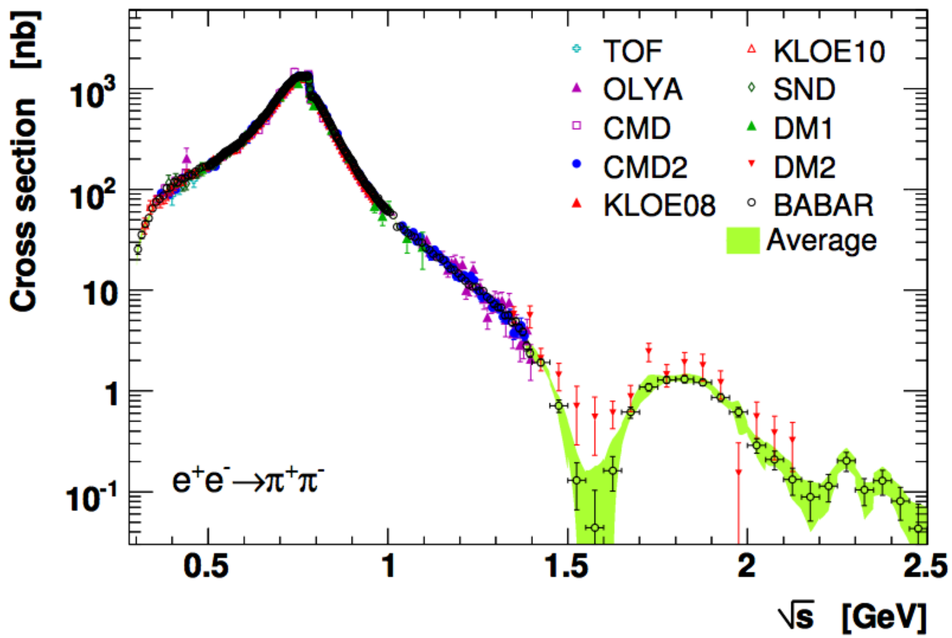
Figure 2: Left: pull comparison of the fit results with the direct measurements in units of the experimental uncertainty. Right: determination of M_H excluding the direct M_H measurements and all the sensitive observables from the fit, except the one given. Note that the fit results shown are not independent.

Hadronic contributions to $\alpha(M_Z^2)$

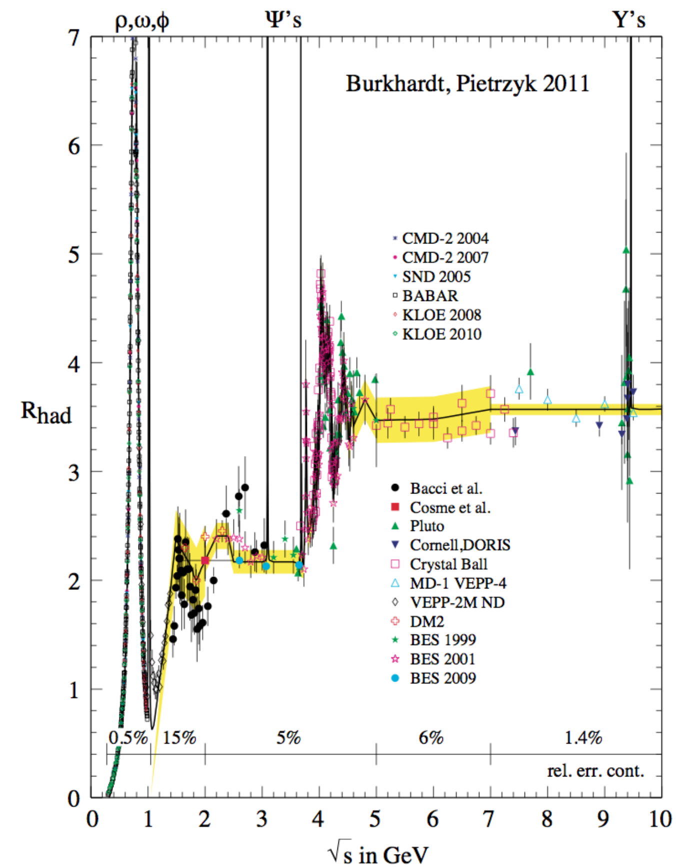
Electroweak fit requires the knowledge of the electromagnetic coupling strength at the Z mass scale to an accuracy of 1% or better.

Hadronic contribution for quarks with masses smaller than M_Z cannot be obtained from perturbative QCD alone (low energy scale).

Constrain photon vacuum polarisation function using measured total cross section for e^+e^- annihilation to hadrons above the two-pion threshold.



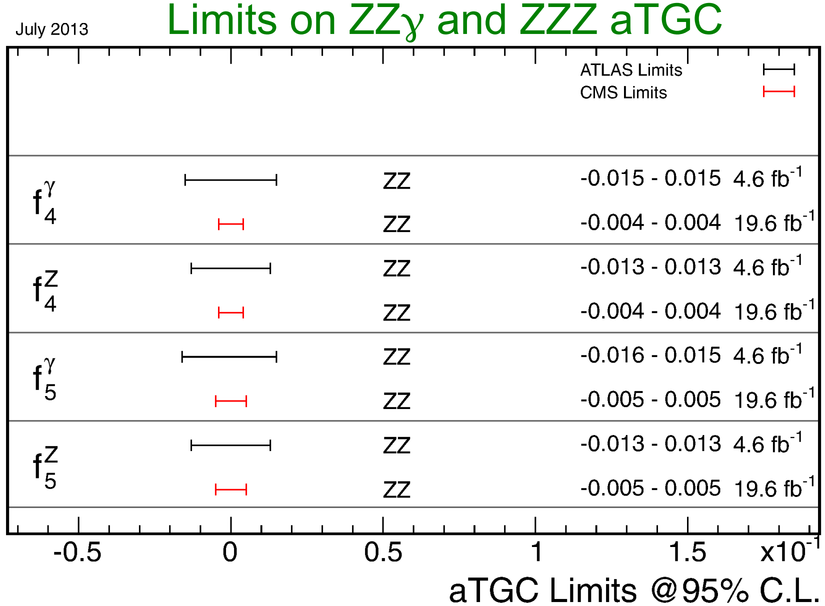
Davier *et al.*, Eur. Phys. J. C71, 1515 (2011)



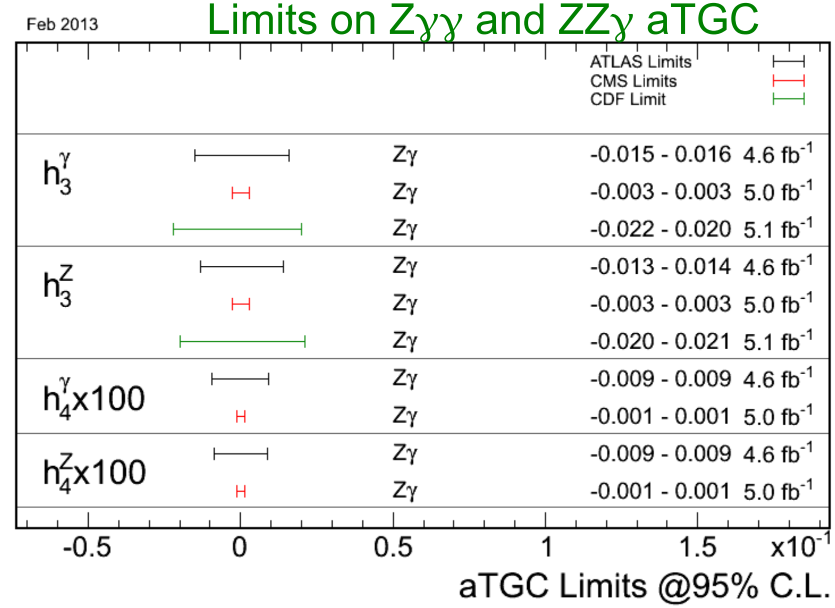
Burkhardt and Pietrzyk, Phys. Rev. D 84, 037502 (2011)

aTGC: diboson modes

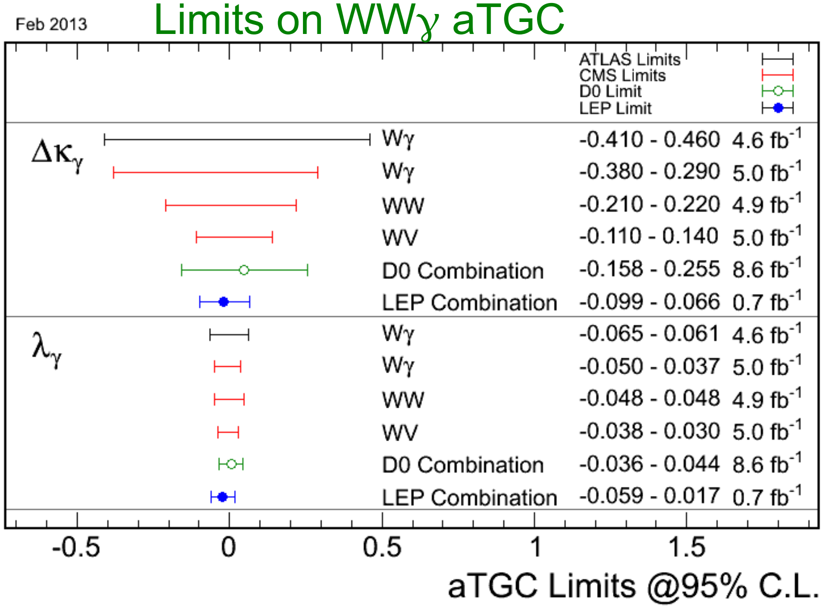
Limits on ZZγ and ZZZ aTGC



Limits on Zγγ and ZZγ aTGC



Limits on WWγ aTGC



Limits on WWZ aTGC