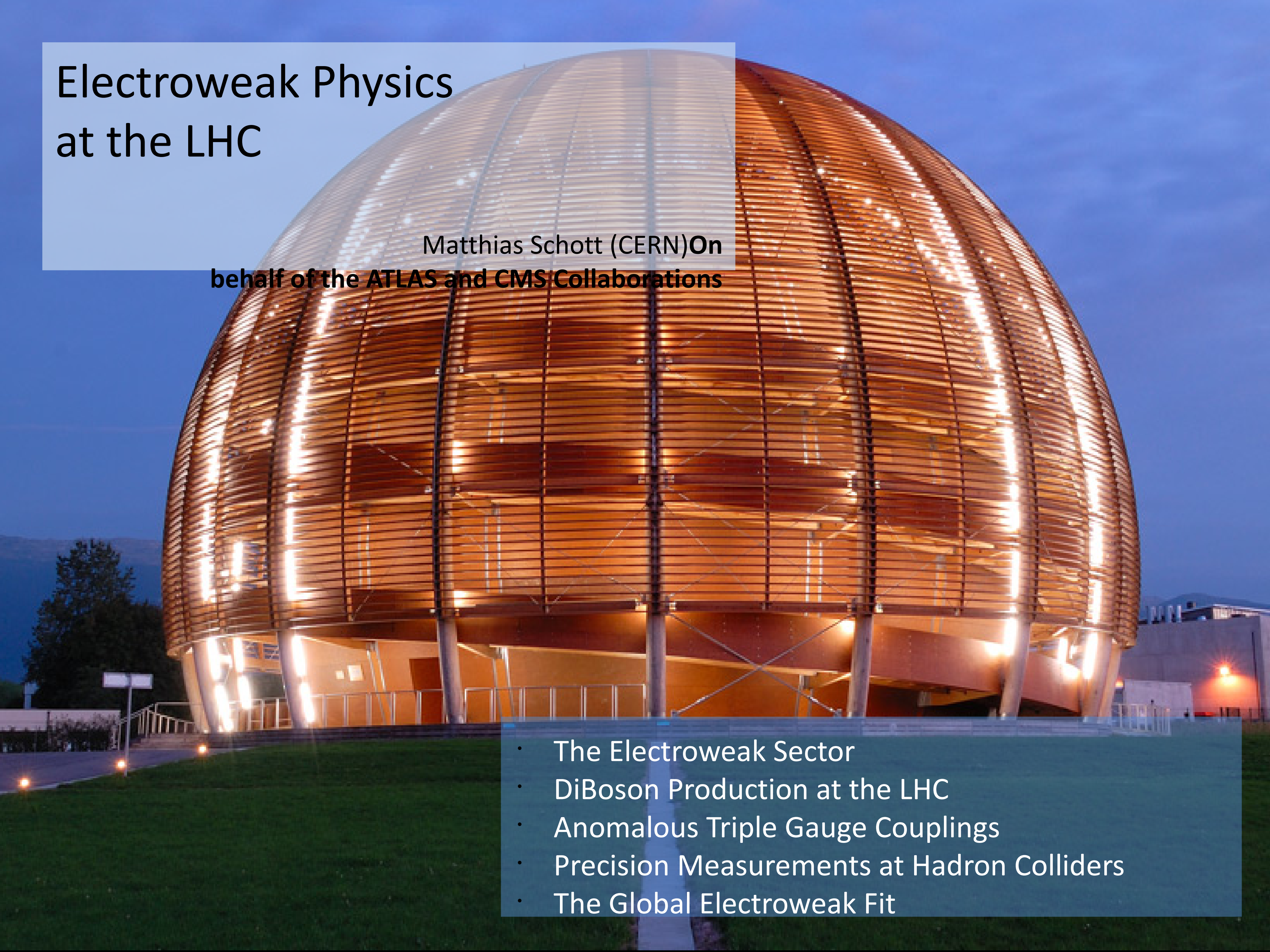
Electroweak Physics at the LHC

Matthias Schott (CERN)**On behalf of the ATLAS and CMS Collaborations**



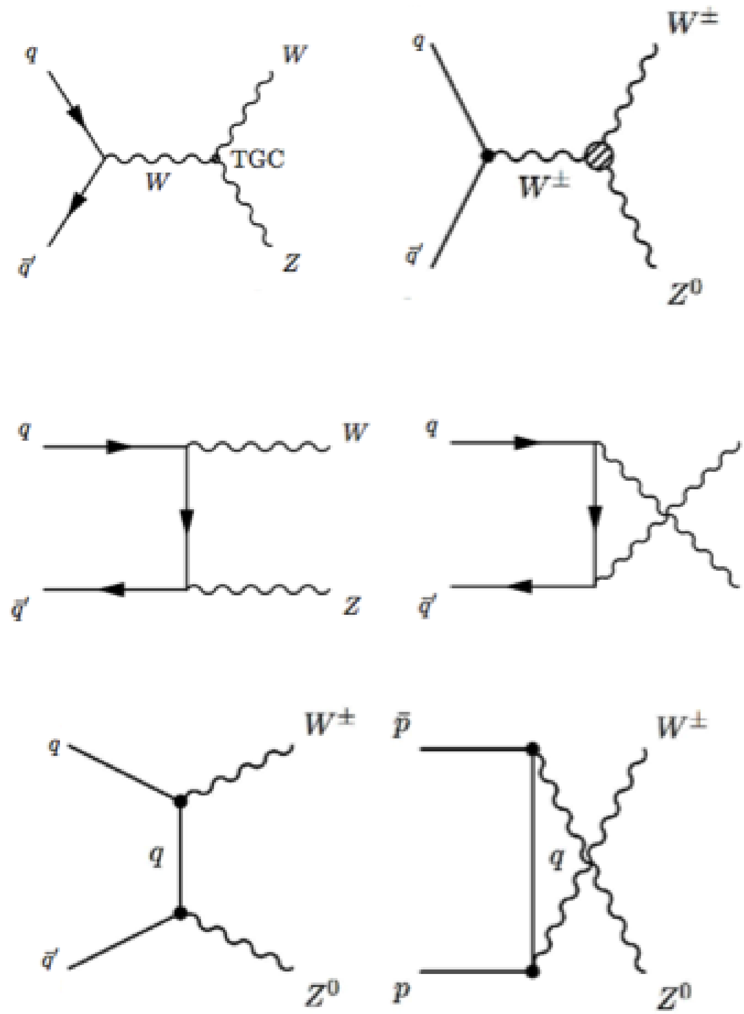
- The Electroweak Sector
- DiBoson Production at the LHC
- Anomalous Triple Gauge Couplings
- Precision Measurements at Hadron Colliders
- The Global Electroweak Fit

The Electroweak Sector of the SM

Glashow, Weinberg and Salam

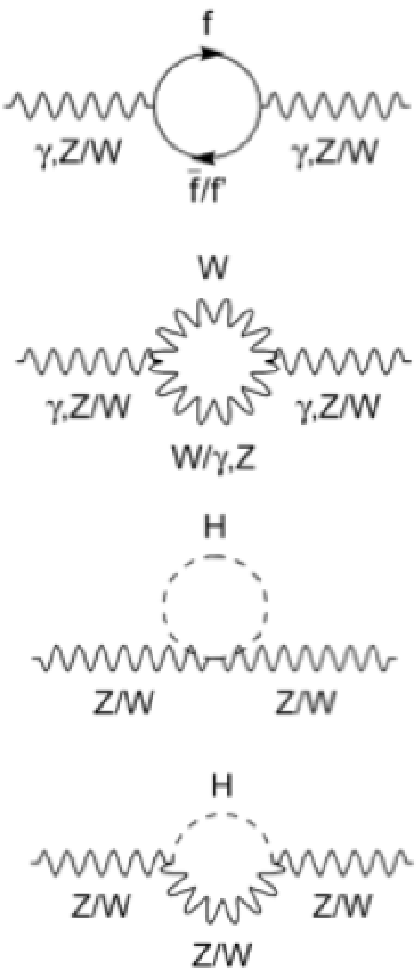
- Unification of electromagnetic U(1) and weak force SU(2)
- Triple gauge couplings
  - Five Observables: $m_W, m_Z, \alpha_{em}, G_F, sin^2\theta_W$
  - $sin^2\theta_W = 1 - \frac{m_W^2}{m_Z^2}$
  - $m_W^2 = \frac{m_Z^2}{2} \cdot (1 + \sqrt{\frac{\sqrt{8}\pi\alpha_{em}}{G_F m_Z^2}})$

- Higgs mechanism to allow for heavy gauge boson (W,Z) masses



Radiative Corrections

- Loop corrections have to be considered
  - Modifications to vertices and propagators by electroweak form-factors
- Predictions of observables depend on further parameters (e.g. mt, mH)
  - Loop corrections ~1%
  - Precision observables measured to much better
- Electroweak Fits
  - Test consistency of SM
  - **Need precision measurements**



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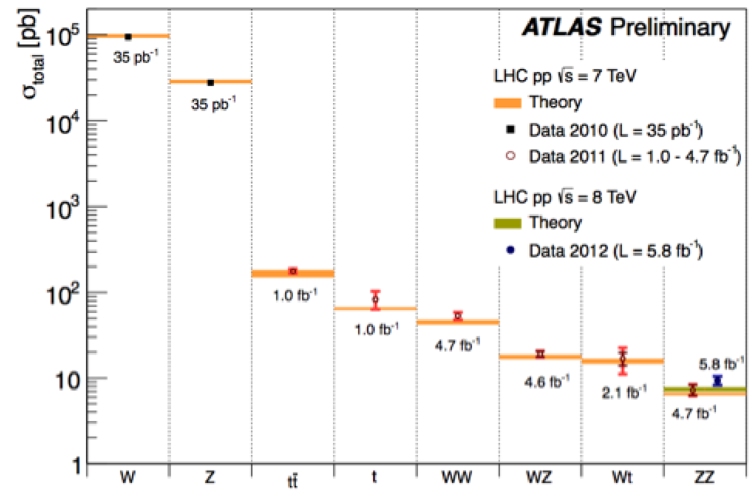
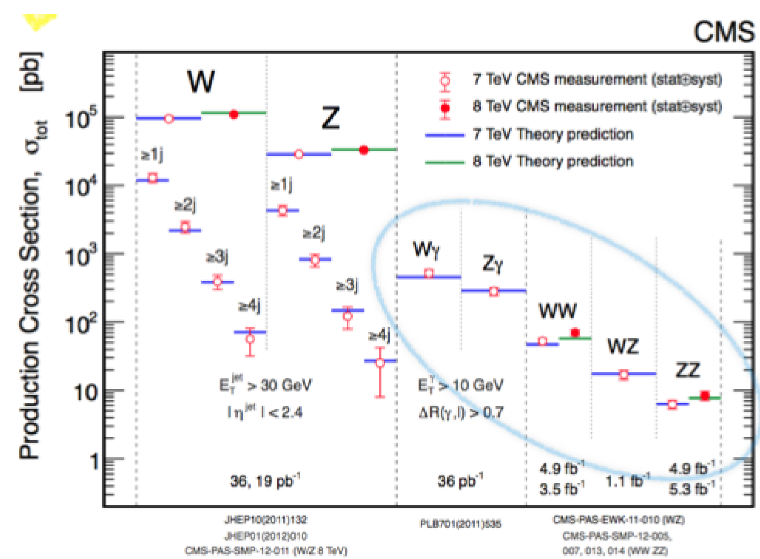
Testing QCD and Electroweak Predictions

- ATLAS References: arxiv:1205.2531, ATLAS-CONF-2012-025, PLB 709 (2012), ATLAS-CONF-2012-027, ATLAS-CONF-2012-026
- CMS References: PLB 701 (2011), CMS-PAS-SMP-12-005, CMS-PAS-EWK-11-010

Summary of Results

- ATLAS and CMS have measured the production cross-section of Wγ, Zγ, WW, WZ and ZZ at √s= 7/8 TeV
  - All measured results compatible with SM-expectations
  - Note: TGC (i.e. s-channel) contributes only ≈10% on inclusive cross-sections
- **Note: Focus in this talk on √s=7 TeV results**



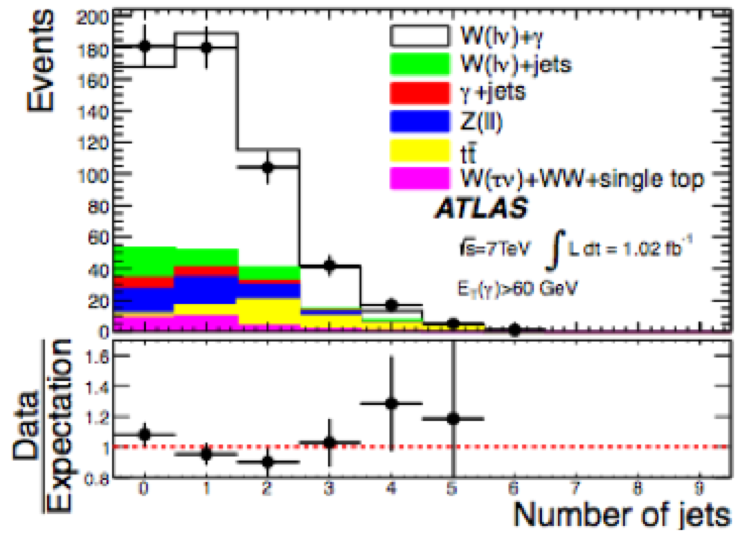


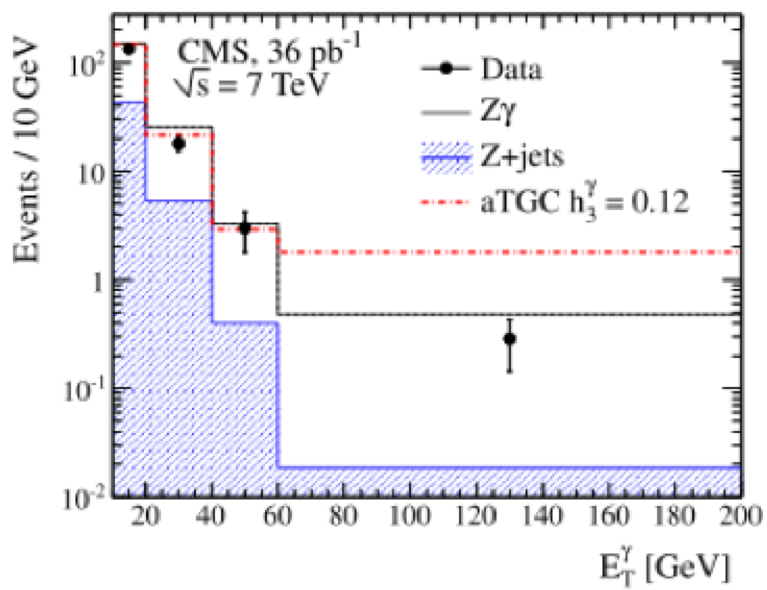
Wγ/Zγ Production: Selection

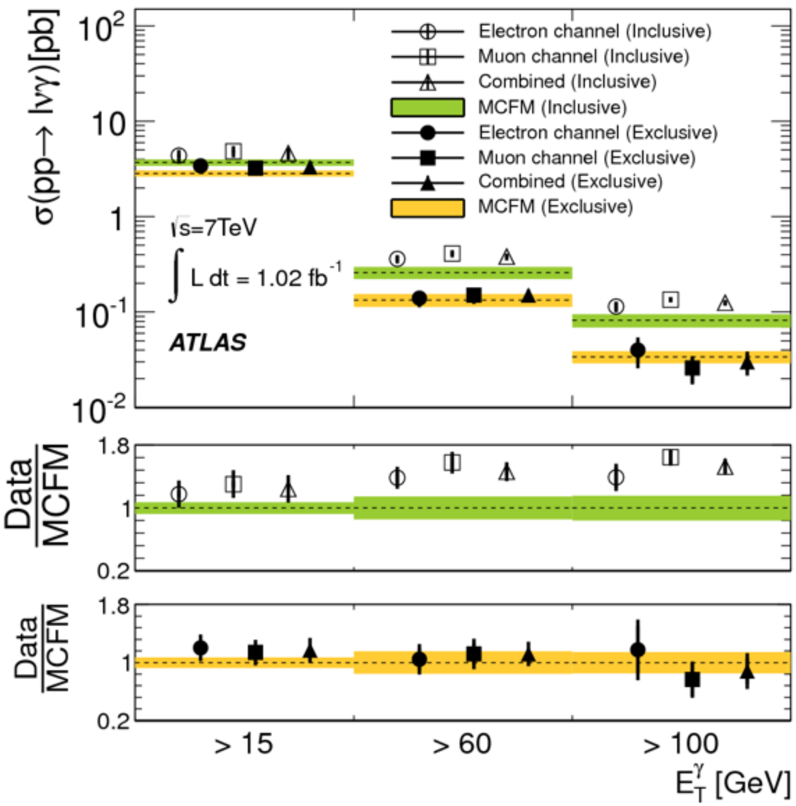
Signal Selection: ATLAS (CMS)

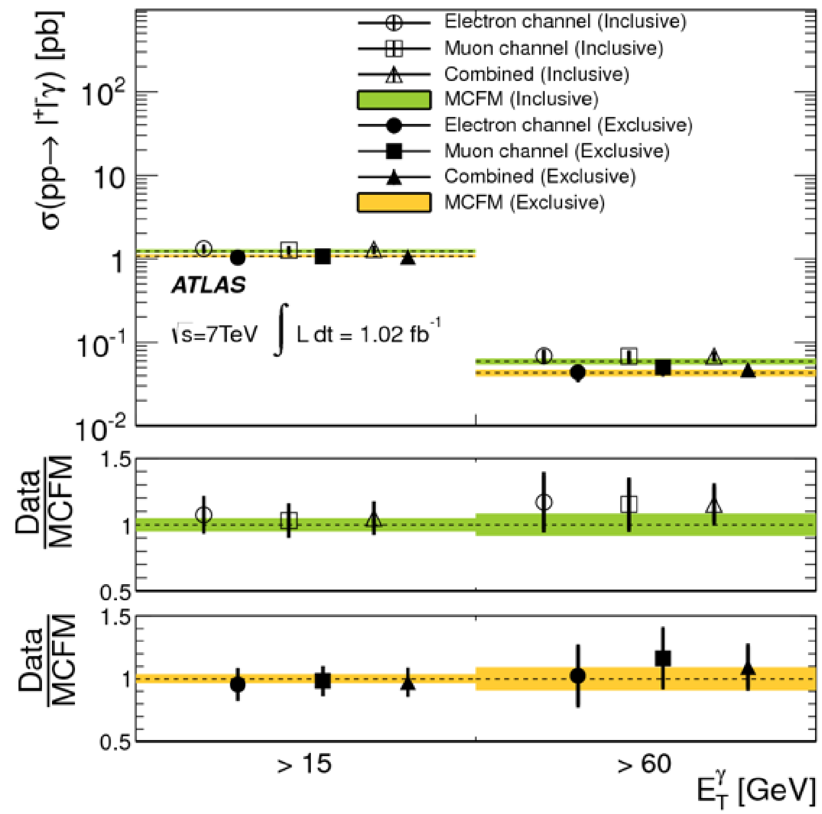
- Standard W-Boson Selection
  - one lepton, pT>25(20)GeV, ETMiss>25(25) GeV, mT>40(0)GeV
- Standard Z-Boson:
  - two leptons, pT>25(20)GeV, mll>40(50)GeV
- γ: ET>15(10)GeV, ΔR(l,γ)>0.7(0.7)

- Major backgrounds: W+jets, Z+jets
  - one jet faking photon signal
  - data-driven estimates









- **Results from CMS**
  - σ×BR(W →lν) = 56.3 ± 5.0(stat) ± 5.0(syst) ± 2.3(lumi) pb
  - σ×BR(Z →ll) = 9.4 ± 1.0(stat) ± 0.6(syst) ± 0.4(lumi) pb
- **Standard Model Expectation**
  - σ×BR(W →lν) = 49.4 ± 3.8 pb
  - σ×BR(Z →ll) = 9.6 ± 0.4 pb

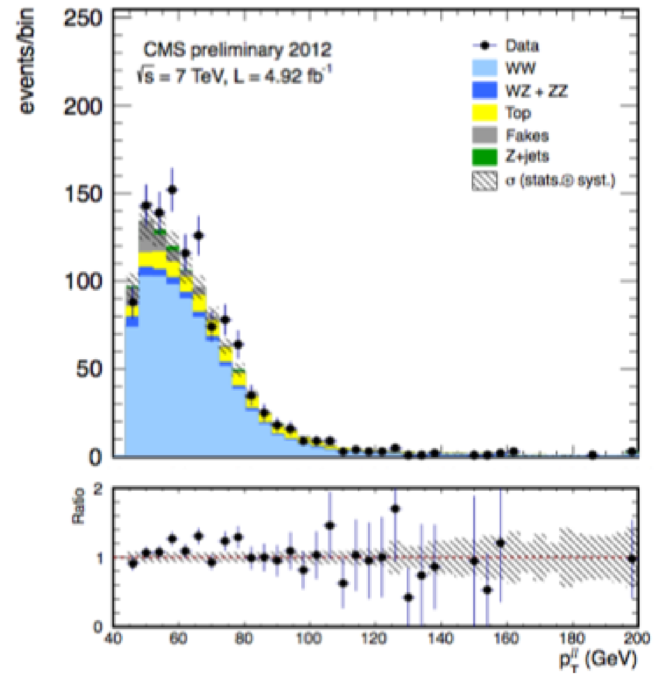
WW Production: Selection

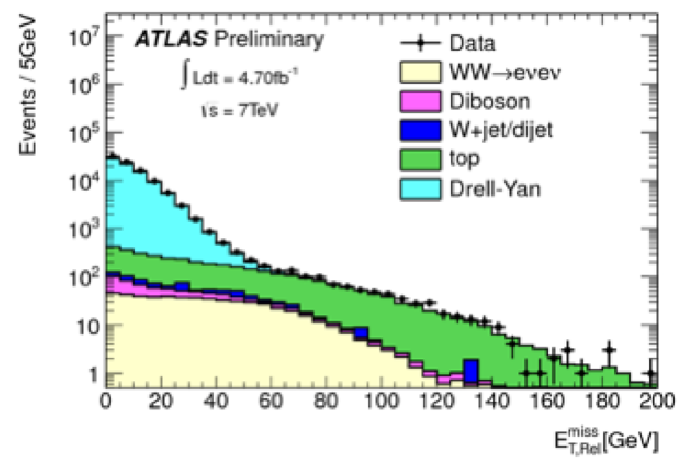
Signal Selection: ATLAS as example

- leptons: pT > 20 GeV
  (ee, μμ, eμ)
- ETMiss,Rel > 45, 45, 25 GeV
  mll > 15, 15, 10 GeV
- |mll−mZ| > 15, 15, 0 GeV
- no jets with pT > 25

- Important for H → WW studies

- Major Backgrounds
  - Top
  - W+Jets
  - Drell-Yan
  - Other DiBosons



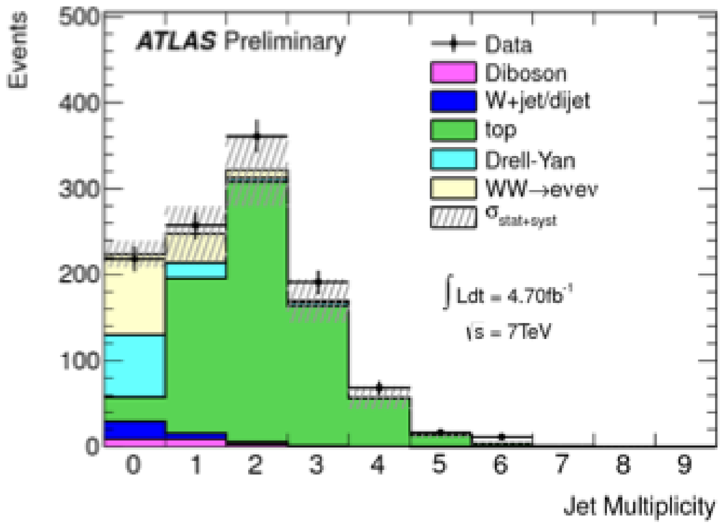


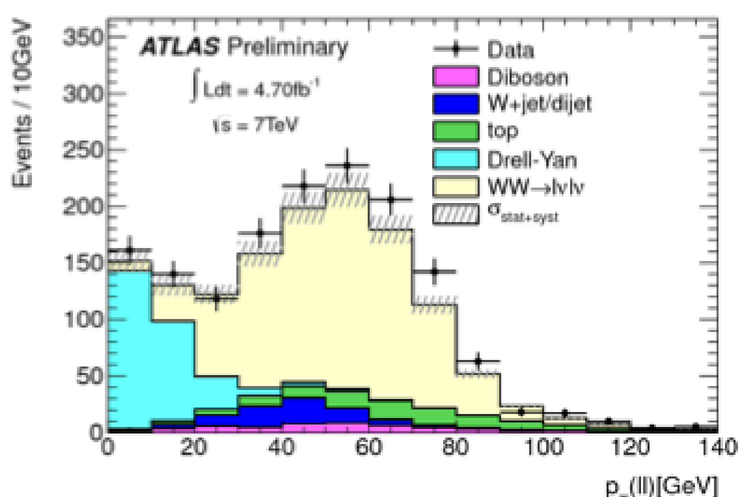
WW Production: Background and Results

- Drell-Yan Background
  - drastically reduced by pT(ll) cut
- W+jets Background
  - Estimated with fake-factor methods
- Top-Quark Background
  - Reduced by jet-veto requirement
    - **significant theo. Unc.!**
  - Use b-tagged control region
- SM-Higgs?
  - accounts only for ≈ 3% of the cross-section

Results for $\sigma(pp \to WW)$

- CMS: $52.4 \pm 2.0(stat) \pm 4.5(syst) \pm 1.2(lumi)pb$
- ATLAS: $51.9 \pm 2.0(stat) \pm 3.9(syst) \pm 0.9(lumi)pb$
- Theory: $44.7 \pm 2.0\dot{p}b$





Signal Selection: ATLAS (CMS)

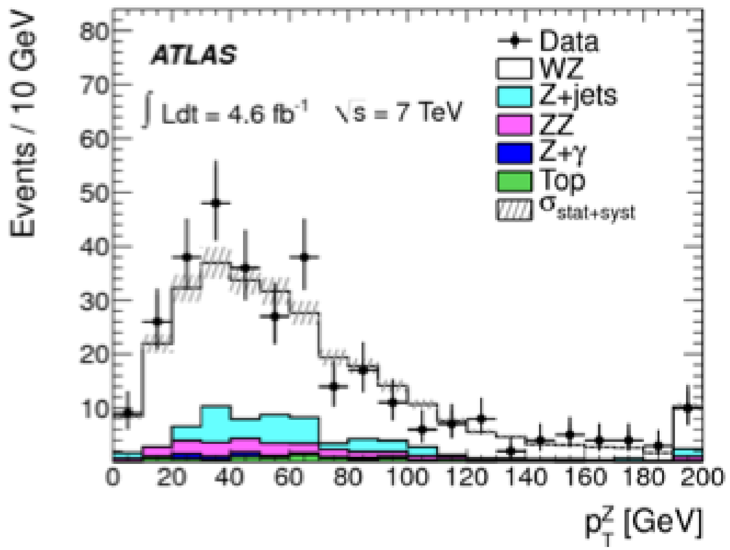
- Standard Z-Boson: 2 leptons, …
- W-Boson “Tag”
  - 3rd lepton (pT>20), ETMiss >20(30) GeV, mT>20(0)GeV

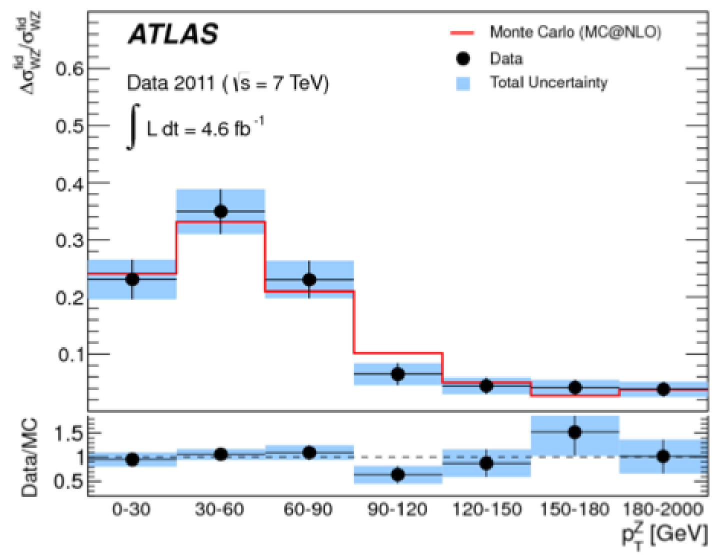
- Small background contribution from Top, ZZ and Z+Jets

Results

- CMS: 17.0±2.4(stat)±1.1(syst)±1.0(lumi)pb
- ATLAS: 19.0±1.4(stat)±0.9(syst)±0.4(lumi)pb
- **Theory: 17.6 ± 1.1pb**

- ATLAS: provide unfolded pT(Z) and mWZ distributions
  - …other channels will follow





ZZ Production

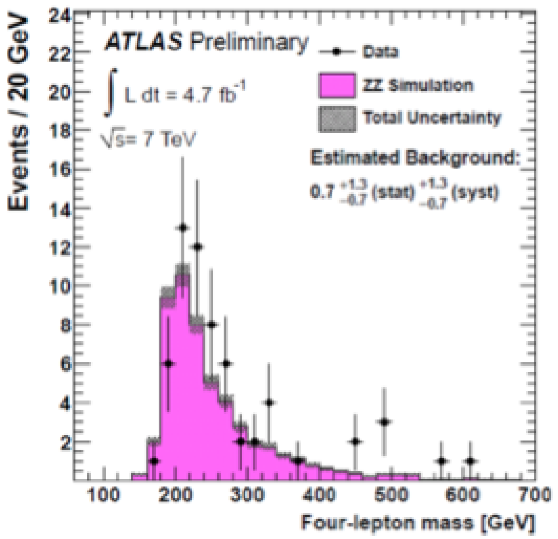
- Important for H → ZZ* studies
- Very clean process with little backgrounds

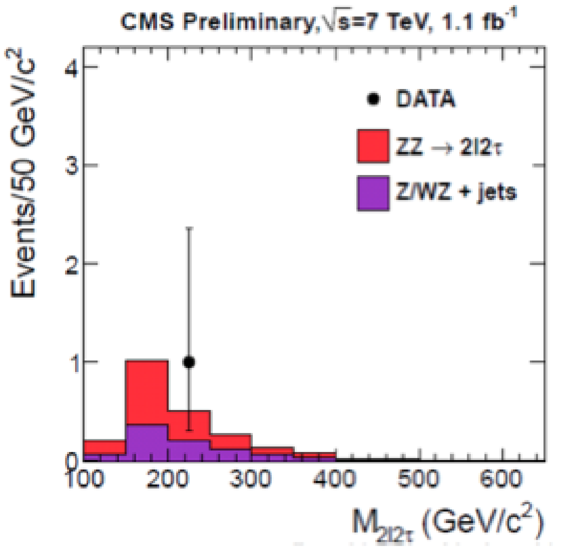
Signal Selection: ATLAS / CMS

- 4 leptons: pT > 7GeV
- leading-lepton: pT > 25/20GeV for e,μ
  - best-Z cand.: pT >20/10GeV
- two-opposite same flavor pairs with 66(60)GeV<mll<116(120)GeV
- CMS: Z→ττ as 2nd candidate allowed

Results

- CMS: 3.8±1.5(stat)±0.2(syst)±0.2(lumi)pb
- ATLAS: 8.5±2.7(stat)±0.4(syst)±0.3(lumi)pb
- Theory: 6.5 ± 0.3pb

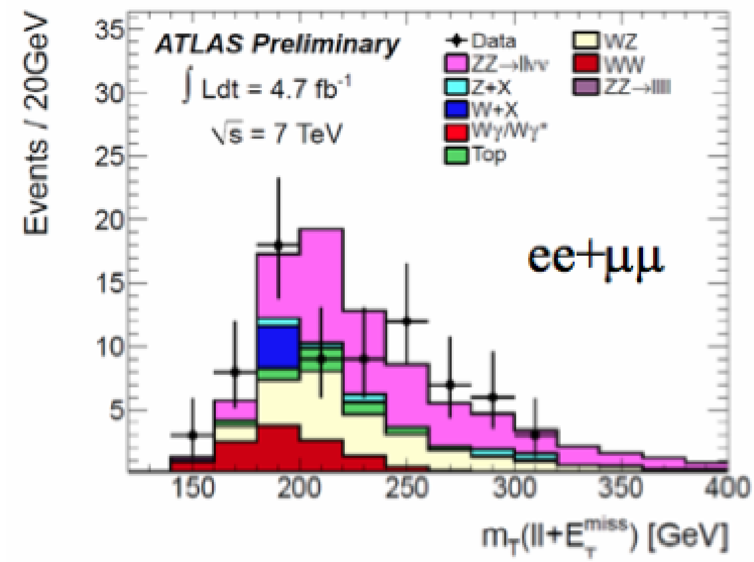




New Results: ZZ → llνν

Signal Selection: ATLAS

- 2 same flavor leptons: pT >20GeV
- |mll −mZ|<15GeV
- Axial-ETMiss >80GeV
- No jets with pT > 25GeV
- |ETMiss −pZT|/pZT >0.6



Observed	78
Expected ZZ	42.3 ± 0.8 ± 1.8
Background estimations:	
$W^{\pm}Z$ (MC)	22.7 ± 0.8 ± 3.5
$W^{\pm}+\gamma$ (MC)	0.29 ± 0.12 ± 0.01
$t\bar{t}$, $W^{\pm}t$, W^+W^- and $Z \to \tau\tau$ (data-driven)	14.7 ± 4.1 ± 0.6
Z+jets (data-driven)	1.7 ± 0.5 ± 0.8
$W^{\pm}$+jets (data-driven)	1.3 ± 0.4 ± 0.3
Total Background	40.7 ± 4.3 ± 3.7

- ATLAS

  σZZ=5.4±1.3(stat) ±1.4(sys)pb
- Theory:

  σZZ = 6.5 ± 0.3pb

Preliminary Conclusion

No surprises in the DiBoson Production at the LHC!

Just a new background: Higgs…

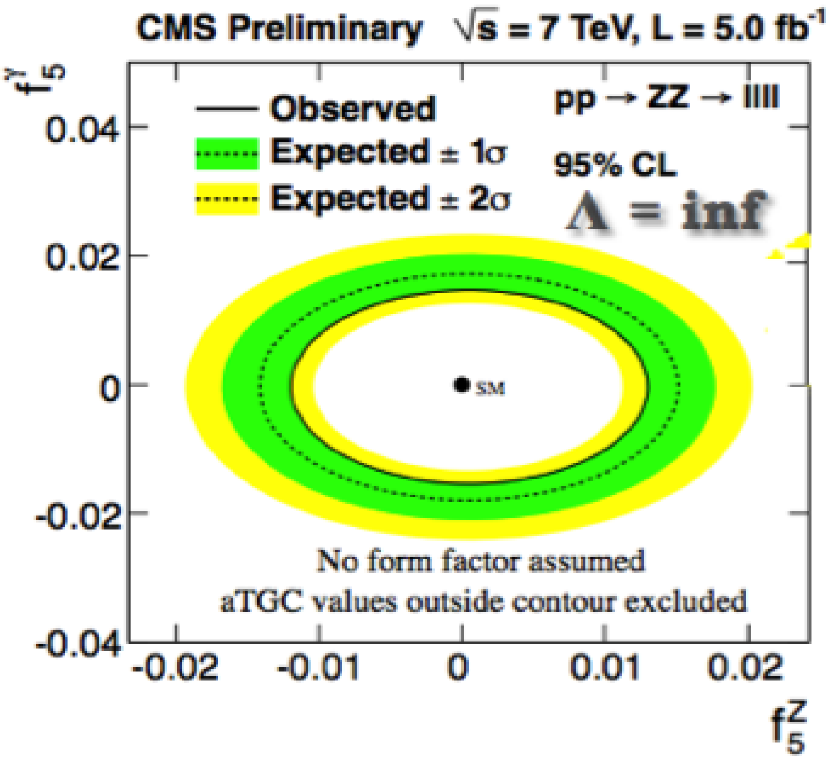
Content

Results and Limits on Anomalous Triple Gauge Couplings

- ATLAS References: arxiv:1205.2531, ATLAS-CONF-2012-025, PLB 709 (2012), ATLAS-CONF-2012-027, ATLAS-CONF-2012-026
- CMS References: PLB 701 (2011), CMS-PAS-SMP-12-005, CMS-PAS-EWK-11-010

Triple Gauge Couplings (ZZZ and ZZγ)

- non-SM processes can affect TGCs in s-channel
- aTGCs modify total production rate as well as event kinematics



- Possible vertices using an effective Lagrangian

$$\mathcal{L}_{VZZ} = -\frac{e}{M_Z^2}\left[f_4^V(\partial_\mu V^{\mu\beta})Z_\alpha(\partial^\alpha Z_\beta) + f_5^V(\partial^\sigma V_{\sigma\mu})\tilde{Z}^{\mu\beta}Z_\beta\right]$$

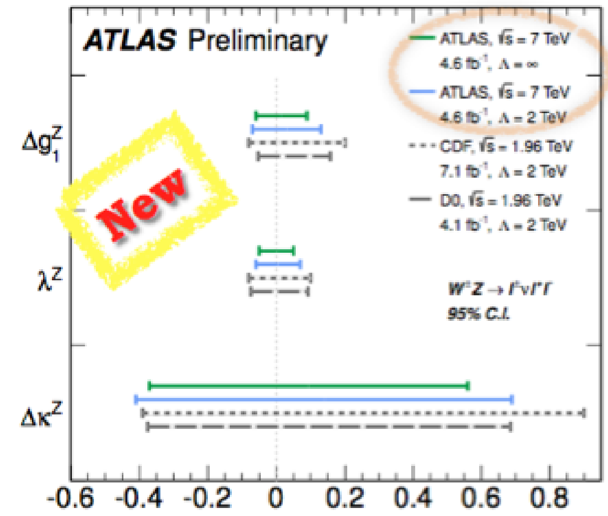
- Suppression factor depending on scale Λ ensures unitarity
- For (ZZZ) and (ZZγ) couplings
  - in SM (f4Z, f4γ, f5Z, f5γ) = (0, 0, 0, 0)SM
- ATLAS: Limits based on total ZZ cross-section
- CMS: Limit from ZZ invariant mass → most power limit to date

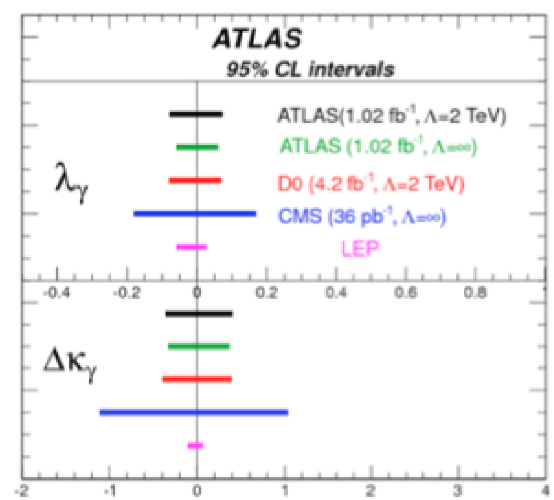
Triple Gauge Couplings (WWZ, WWγ)

- Possible vertices using an effective Lagrangian

$$\frac{\mathcal{L}_{WWV}}{g_{WWV}} = i\left[g_1^V(W^\dagger_{\mu\nu}W^\mu V^\nu - W_{\mu\nu}W^{\dagger\mu}V^\nu) + \kappa^V W^\dagger_\mu W_\nu V^{\mu\nu} + \frac{\lambda^V}{m_W^2} W^\dagger_{\rho\mu} W^\mu_\nu V^{\nu\rho}\right]$$

- For (WWZ) and (WWγ) couplings
  - in SM for WWZ (g1Z,kZ,λ) = (1,1,0)SM
- Limits on g1Z,kZ,λ via pT(Z) distribution
- Limits on λγ, Δκλ via pT(γ) distribution





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Discussion on measurements of mW and sin2θW

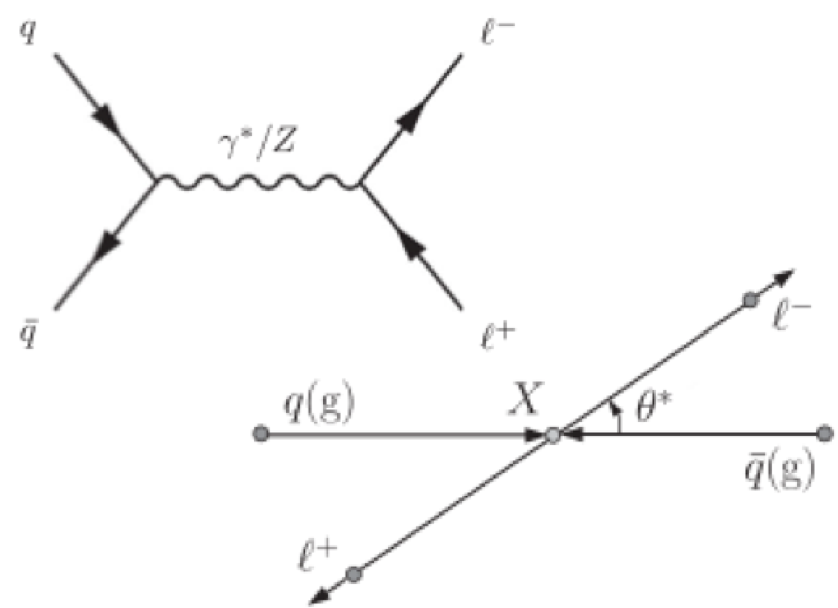
- mW References: P.R.Lett. 108, 151803/151803 (2012)
- sin2θW References: Phys. Rev. D 85 (2012) 032002
- Supporting Measurements: Phys. Rev. D85 (2012) 072004, JHEP 06 (2012) 058, ATLAS-CONF-2011-129, arXiv:1206.2598
- mtop: Tomorrow’s Talk(?0 References: arXiv:1209:2319, arXiv:1203.575

Forward Backward Asymmetry

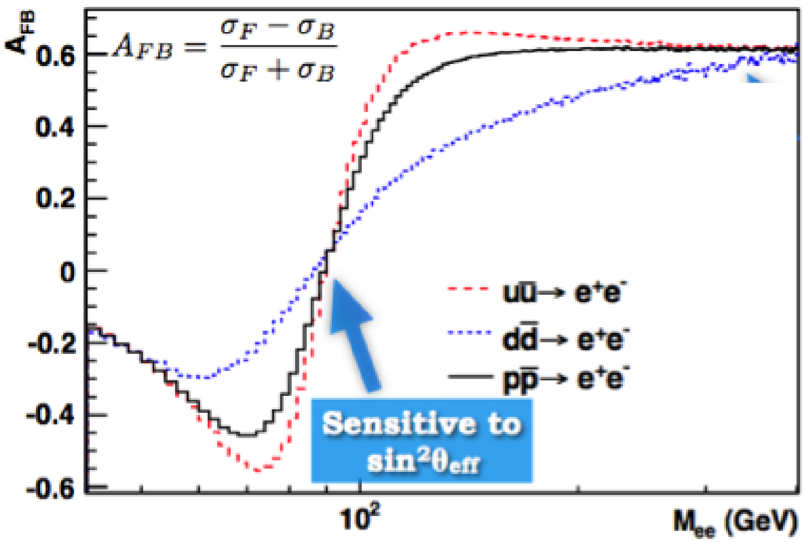
- AFB=(σF-σB)/(σF+σB) determines sin2θW
- In the SM, sin2θW is the only free parameter that fixes the relative couplings of all fermions to γ/Z
  - test universality of fermion/gauge-boson interactions
- Previous Measurements: LEP, NuTeV, Tevatron
- @LHC: symmetric pp collision
  - unkown quark direction
  - → deduced only on a statistical basis using the boost direction

Basic Idea

- interference of the axial-vector and vector couplings
- → asymmetry in the distribution of the polar angle of the lepton with respect to the direction of the constituent quark



- CMS: multivariate analysis with unbinned maximum likelihood fit based on Yll, mll, θ*



Results

- CMS: $sin^2_{eff} = 0.2287 \pm 0.0020(stat) \pm 0.0025(sys)$
- WA: $sin^2_{eff} = 0.23153 \pm 0.00016$

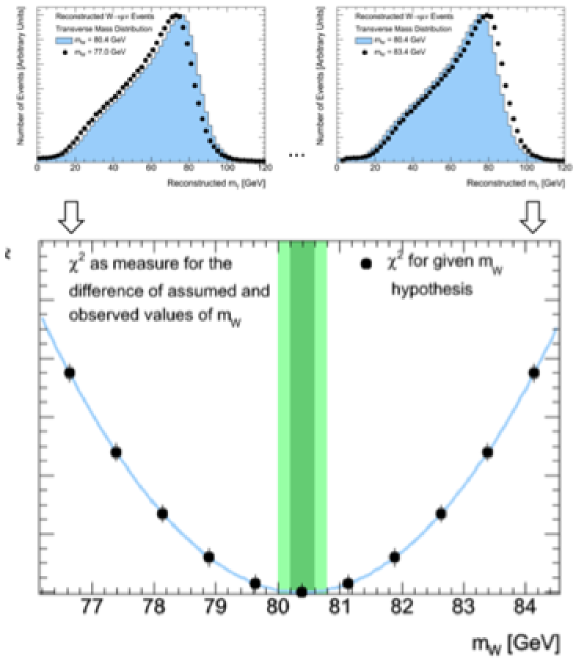
source	correction	uncertainty
PDF	-	$\pm$0.0013
FSR	-	$\pm$0.0011
LO model (EWK)	-	$\pm$0.0002
LO model (QCD)	+0.0012	$\pm$0.0012
resolution and alignment	+0.0007	$\pm$0.0013
efficiency and acceptance	-	$\pm$0.0003
background	-	$\pm$0.0001
total	+0.0019	$\pm$0.0025

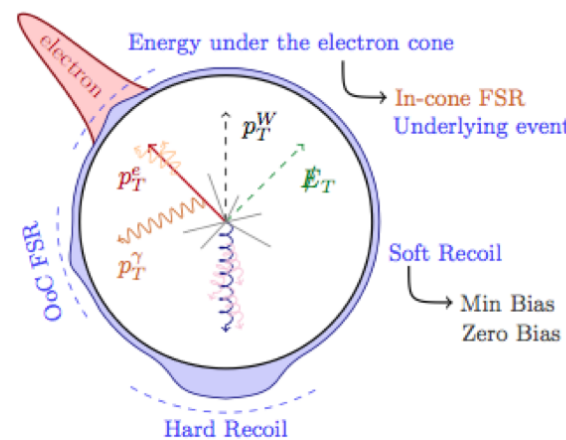
- Outlook
  - Expect improvements on PDF
  - Detector modeling

Measurement of the W-Boson mass

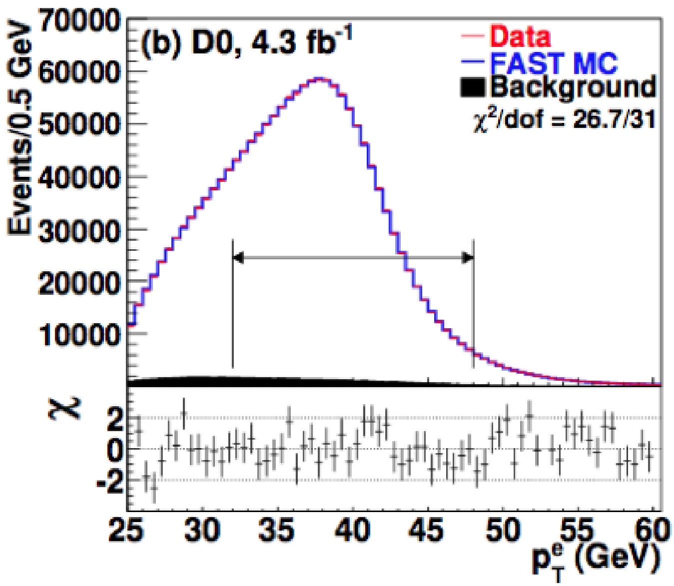
- Measurement technique at hadron colliders
  - Only leptonic decay channel can be used
  - neutrino leaves detector unseen

- Template Fit method with three observables to assess mW
  - lepton pT , transverse mass mT, ETmiss
  - → Need excellent understanding of detector and MC simulation



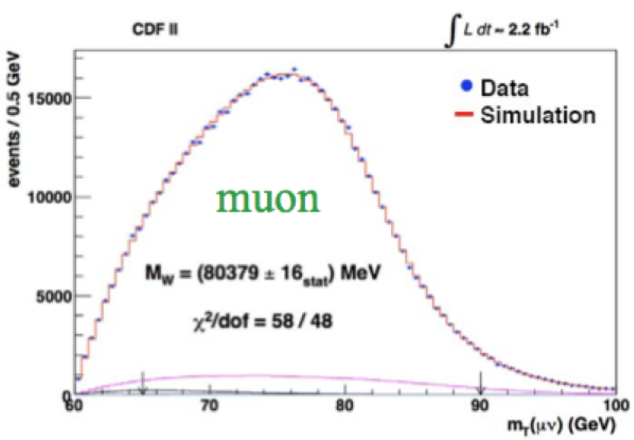


- General Approach
  - based on three observables
  - combination after fitting
  - most sensitive variable: mT



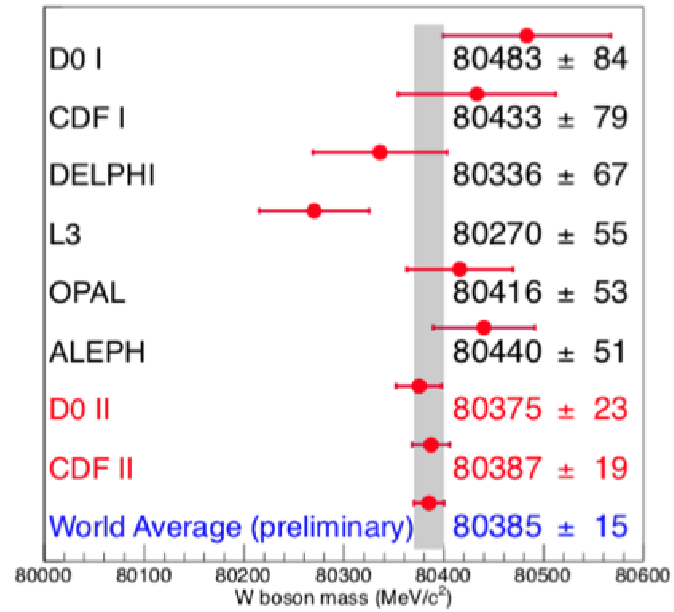
- D0-Experiment
  - only using electron channel

- CDF-Experiment
  - using electron and muon channel



Results from Tevatron (2/2)

- Best measurement from CDF: ΔmW =19
- World average: ΔmW = 15
- Dominating Uncertainties
  - PDF's
  - Recoil energy scale and resolution
  - lepton energy scale and resolution
- Outlook at Tevatron
  - Twice statistics available
  - include leptons (η>1)



Transverse Momentum

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

mW at the LHC - Challenges

- Target Precision @LHC: 7 MeV
- 2011 dataset: Stat. precision of 4 MeV

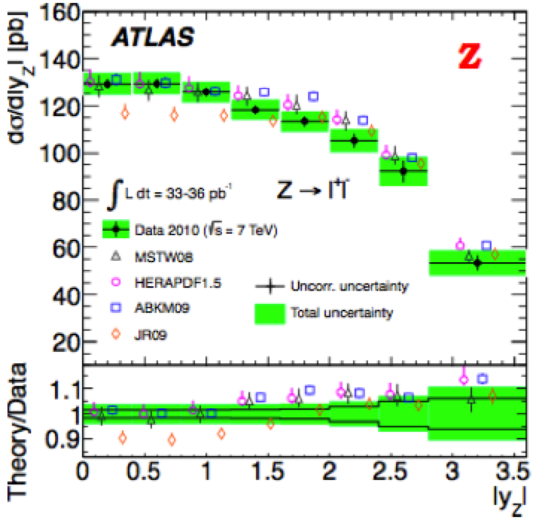
Detector Effects

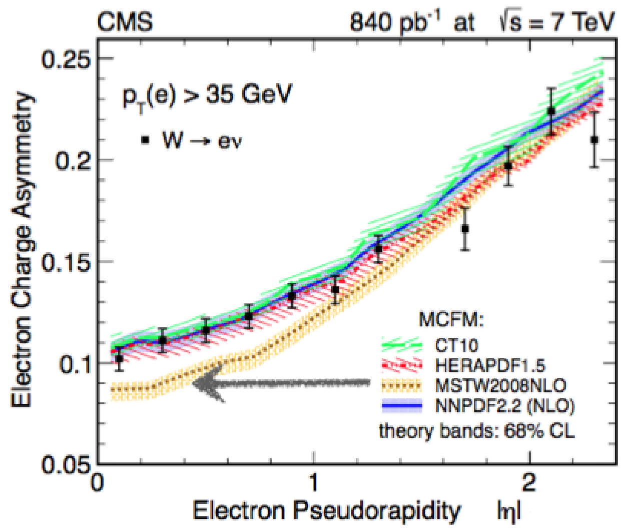
- High Pile-Up
  - → worse ETmiss resolution
- Energy Scale and Momentum Resolution

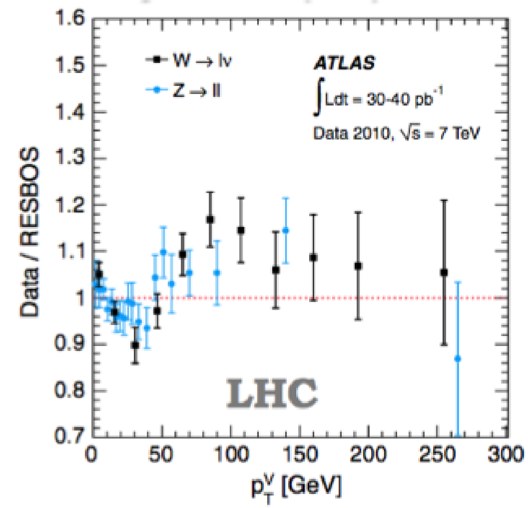
Understanding the Proton and QCD

- Determine PDFs @ LHC
  - η, mll-differential W/Drell-Yan production cross-sections
  - W/Z+c/b quarks
  - …
- Measurement of W/Z Boson transverse momenta
  - pQCD
  - Resummation, …

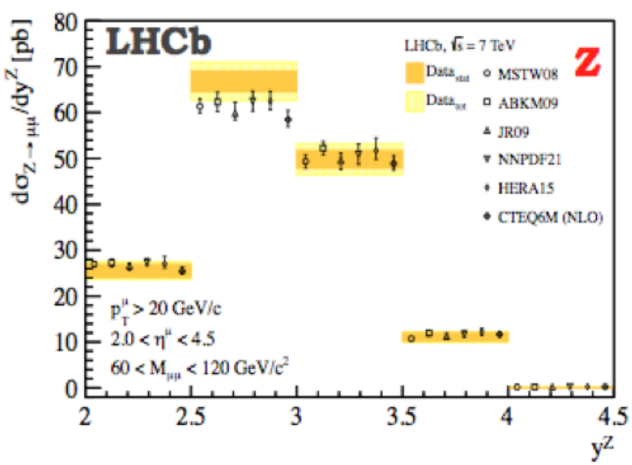
mW - Supporting Measurements

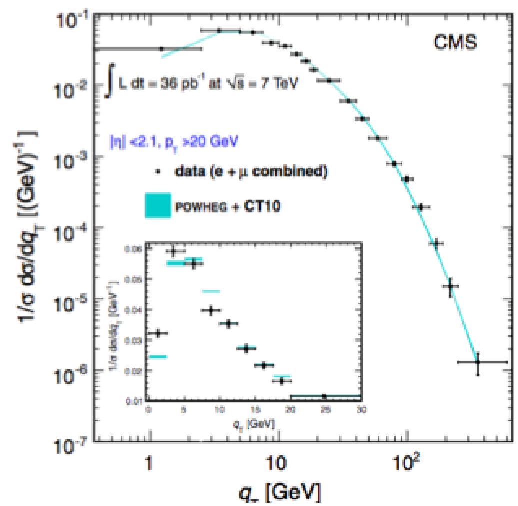






- Crucial: Differential Distributions
- Significant improvements expected
- Might need some dedicated collider runs!





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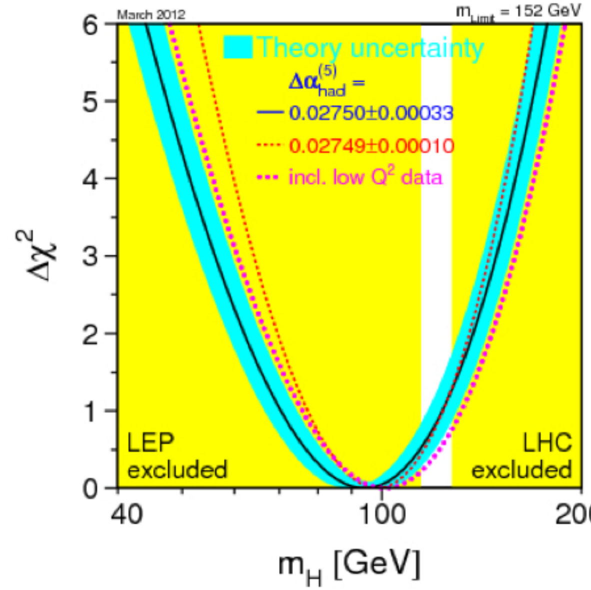
Global electroweak fit results assuming a SM Higgs Boson with m=125.7±0.4GeV

- Gfitter-Group: http://arxiv.org/abs/1209.2716
- CKM-Fitter Package: http://arxiv.org/pdf/1209.1101

Gfitter-Package

- State of the art implementation of SM predictions of EW precision observables
  - Based on huge amount of pioneering work by many people
  - Radiative corrections are important
    - Logarithmic dependence on *MH* through virtual corrections

- In particular:
  - *MW* : full two-loop + leading beyond-two-loop corrections
    [M. Awramik et al., Phys. Rev D69, 053006 (2004) and refs.]
    (Theoretical uncertainties: Δ*MW* = 4–6 GeV)
  - *sin2θleff*: full two-loop + leading beyond-two-loop corrections
    [M. Awramik et al., JHEP 11, 048 (2006) and refs.]
    (Theoretical uncertainties: Δsin2θ *l*eff=4.7▯10–5)
  - Partial and total widths of *Z* and *W*: based on parameterized formulae
    [Hagiwara et al. (http://arxiv.org/abs/arXiv:1104.1769)]
  - Radiator Functions using 3NLO calc. of massless QCD Adler function
    [P.A. Baikov et al., Phys. Rev. Lett. 101 (2008) 012022]



SM-Higgs?

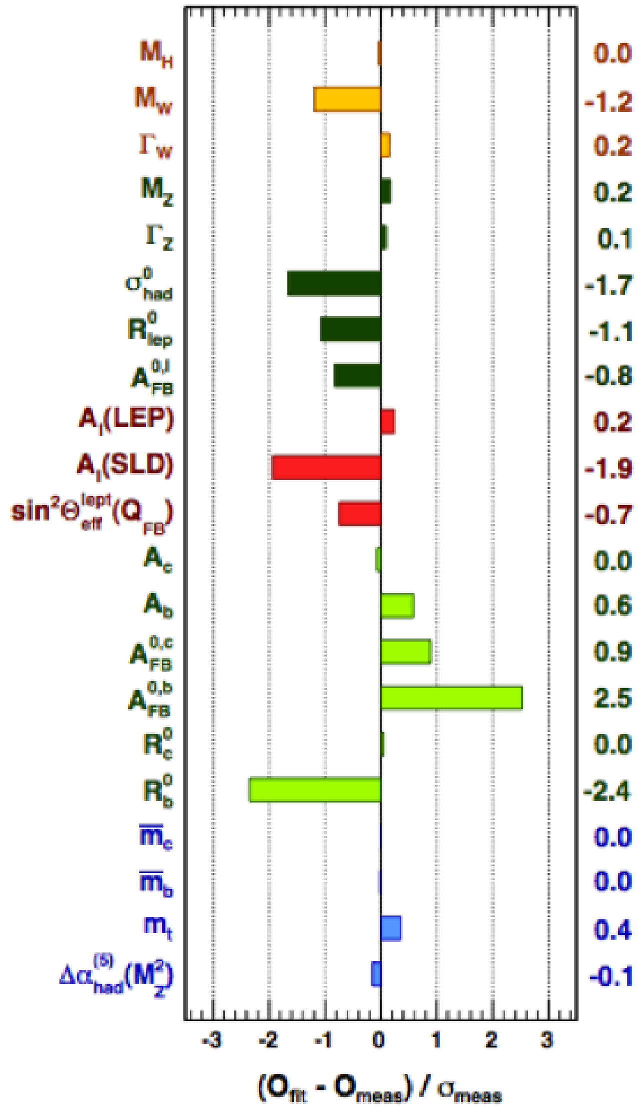
- Use (uncorrelated) weighted average of ATLAS and CMS measurements:
- mH =125.7± 0.4GeV

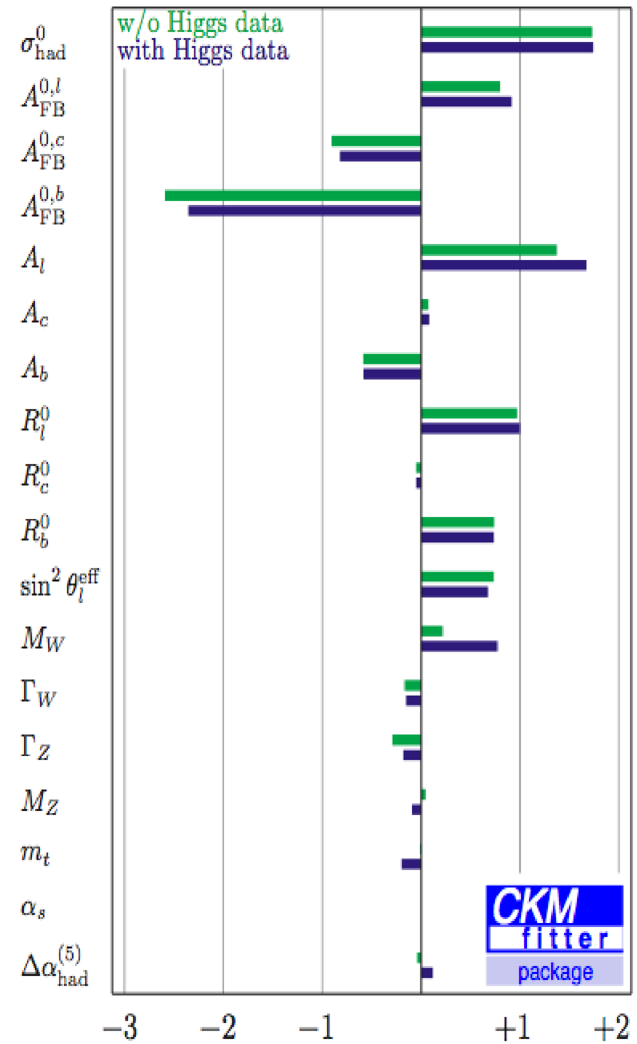
Fit-Results (1/2)

Parameter	Input value	Free in fit	Fit result incl. M_H	Fit result not incl. M_H	Fit result incl. M_H but not exp. input in row
M_H [GeV]$^{(\circ)}$	125.7 ± 0.4	yes	125.7 ± 0.4	94^{+25}_{-22}	94^{+25}_{-22}
M_W [GeV]	80.385 ± 0.015	–	80.367 ± 0.007	80.380 ± 0.012	80.359 ± 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 ± 0.0116
Γ_Z [GeV]	2.4952 ± 0.0023	–	2.4954 ± 0.0014	2.4958 ± 0.0015	2.4951 ± 0.0017
$\sigma^0_{\rm had}$ [nb]	41.540 ± 0.037	–	41.479 ± 0.014	41.478 ± 0.014	41.470 ± 0.015
R^0_ℓ	20.767 ± 0.025	–	20.740 ± 0.017	20.743 ± 0.018	20.716 ± 0.026
$A^{0,\ell}_{\rm FB}$	0.0171 ± 0.0010	–	0.01627 ± 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	$0.1468 \pm 0.0005^{(\dagger)}$
$\sin^2\theta^\ell_{\rm eff}(Q_{\rm FB})$	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	–	$0.6680^{+0.00025}_{-0.00038}$	$0.6682^{+0.00042}_{-0.00035}$	0.6680 ± 0.00031
A_b	0.923 ± 0.020	–	$0.93464^{+0.00004}_{-0.00007}$	0.93468 ± 0.00008	0.93463 ± 0.00006
$A^{0,c}_{\rm FB}$	0.0707 ± 0.0035	–	$0.0739^{+0.0003}_{-0.0005}$	0.0740 ± 0.0005	0.0738 ± 0.0004
$A^{0,b}_{\rm FB}$	0.0992 ± 0.0016	–	$0.1032^{+0.0004}_{-0.0006}$	0.1036 ± 0.0007	0.1034 ± 0.0004
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	–	0.21474 ± 0.00003	0.21475 ± 0.00003	0.21473 ± 0.00003
$\overline{m}_c$ [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]	173.18 ± 0.94	yes	173.52 ± 0.88	173.14 ± 0.93	$175.8^{+2.7}_{-2.4}$
$\Delta\alpha^{(5)}_{\rm had}(M_Z^2)$ $^{(\dagger\triangle)}$	2757 ± 10	yes	2755 ± 11	2757 ± 11	2716^{+49}_{-43}
$\alpha_s(M_Z^2)$	–	yes	0.1191 ± 0.0028	0.1192 ± 0.0028	0.1191 ± 0.0028
$\delta_{\rm th} M_W$ [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	–

- Assume new particle is SM-Higgs
  - Fit results are insensitive to the combination procedure for ATLAS and CMS results

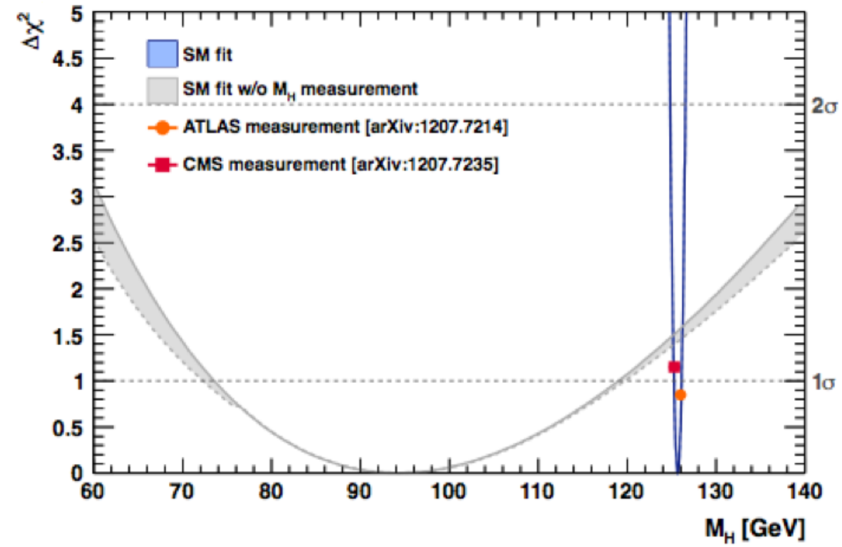
- Global minimum value for the test statistics
  - χ^2_{min} = 21.8 (14 d.o.f)
  - naive p-value Prob(21.8, 14) = 0.08

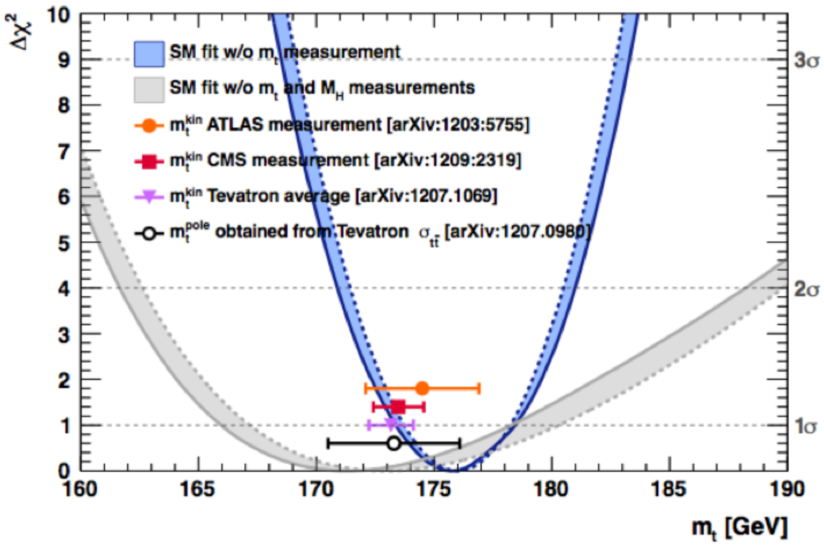


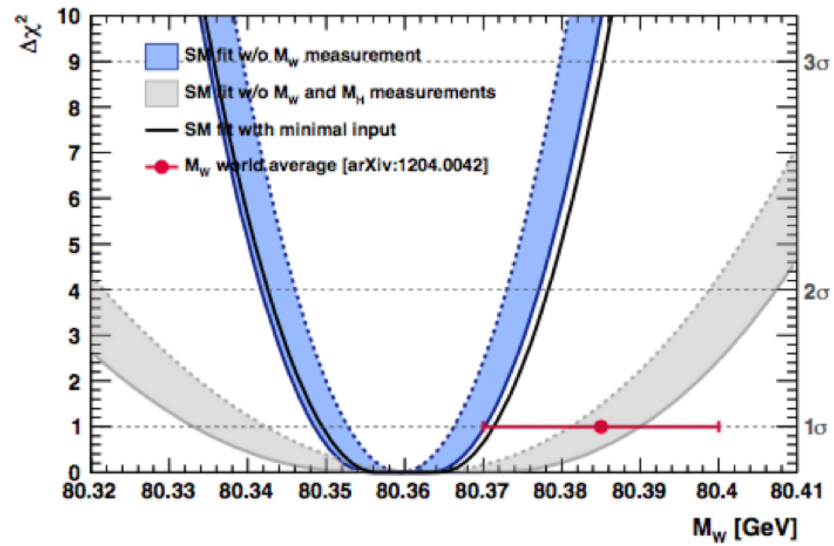


Indirect Determinations

- Perform fit for each parameter or observable without using the corresponding constraint
  - mH = 94 (+25,−22) GeV
  - mW =80.359 ± 0.011 GeV
  - mt = 175.8 (+2.7,-2.4) GeV







Electroweak Physics at the LHC

Summary and Conclusion

Matthias Schott (CERN)

- LHC on good path towards precision physics with W and Z
  - High precision measurements of Diboson-production just about to come with the 2012 data-set
- Agreement with theory across orders of magnitude is impressive
- Tevatron will be better on mW and mt for a long(?) time
- EW Fit in a fair agreement with a SM-Higgs with mH = 126GeV

- **Future precision measurements help disentangle new physics ?**