Precision QCD and Electroweak Physics at the LHC

- **Introduction:** why precision QCD/Electroweak measurements ?
- Production of W/Z bosons, inclusive and differential
- **Survey:** what we know about the Electroweak parameters
- Precision measurements at LHC and Electroweak parameters
- Electroweak measurements and constraints on EWK Lagrangian
- Diboson measurements: cross-sections, kinematics, aTGCs…
- Beyond Dibosons: Tribosons, VBF/VBS processes, aQGCs…
- Summary and Open Issues

- Many topics left out (jet/photon physics, α_S measurements, top production especially single top, QCD/EWK studies with 126 GeV Higgs, etc.)

Kevin Einsweiler – Lawrence Berkeley Lab – June 4 2013

Why make precision QCD measurements ?

- Deep understanding of QCD to at least NLO level for given processes is the foundation of any quantitative measurement program looking for deviations from SM (as opposed to bump-hunting based on assumptions of smoothness, etc.)
- Many SM deviations look similar to those arising from higher-order QCD effects.
- Technology is very challenging, and evolving very rapidly under pressure of new LHC results, better computational tools, greater computing resources, etc.
- Transition from LO + PS to NLO + PS and multi-leg + PS MCs has been critical for Run1 analyses. Next step is NLO multi-leg + PS, which should mature during Run2.
- Huge thanks to our many dedicated colleagues who have spent decades working in this area, and without whom we would never have reached our current understanding of LHC data !!!

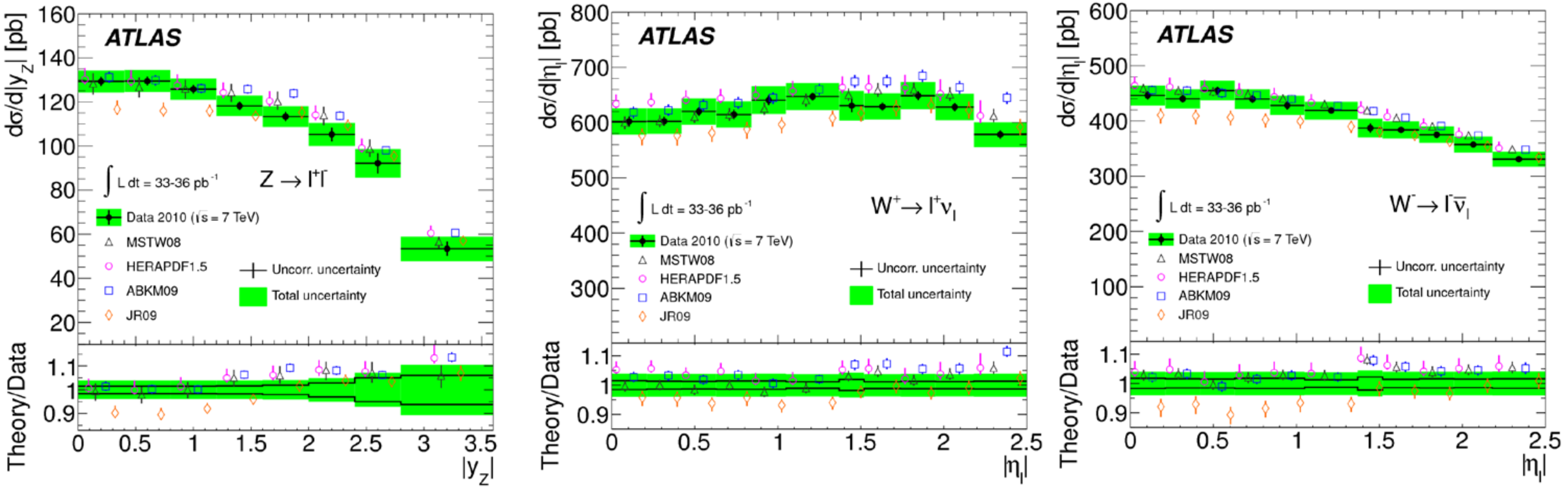
Program is vast, covering:

- Photons (including inclusive γ, γ+jets, inclusive $\gamma\gamma$, γ+HF, etc.)
- Jets (including inclusive and multijets, jet sub-structure, HF production in jets, etc.)
- W/Z production (including inclusive W and Z, W and Z+jets, ratio of W+jets/Z+jets, W and Z plus HF, etc.)
- Also combination analyses focusing on PDF fitting or α_S measurements.
- Use sophisticated unfolding techniques to provide detector-independent results.
- Focus on few examples today (this discussion would easily justify an entire talk)…

Inclusive W and Z Measurements I

Incl W/Z hep-ex 1109.5141
s density hep-ex 1203.4051

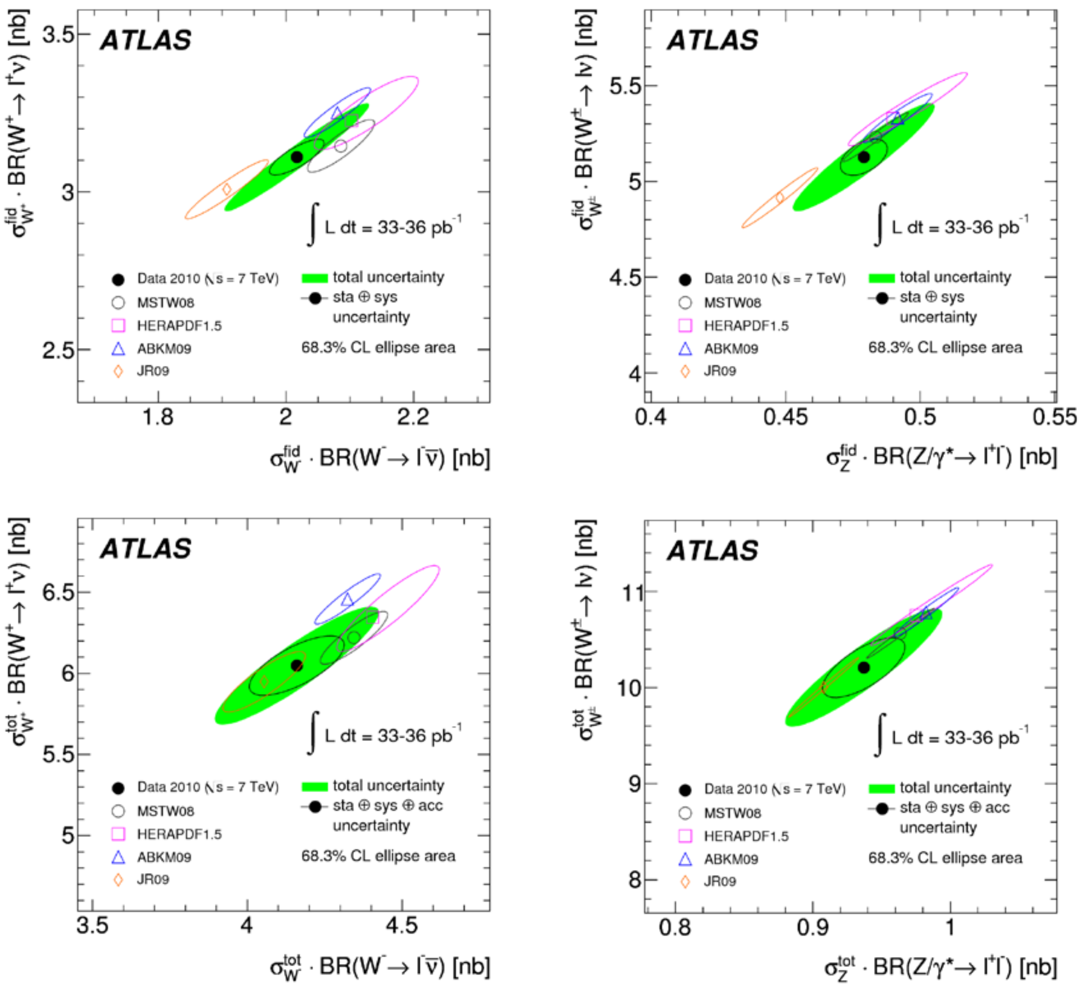
- One of small set of processes with full NNLO QCD calculations.
- Note critical element is availability of calculations for cross-sections in fiducial regions in lepton P_T and η with NNLO precision (FEWZ and DYNNLO) – however NOT event generators.
- Show some highlights from 7 TeV 2010 analysis from ATLAS, including differential and fiducial cross-sections, and recent 8 TeV 2012 analysis from CMS.
- Show unfolded differential distributions for Z (left), W^+ (center), and W^- (right), for ATLAS analysis, compared to NNLO predictions using a wide range of PDFs. Differences are largely due to PDFs themselves.



2010 analysis has 3.4% lumi uncertainty, in 2011 it is 1.8%, with 100 times more data !

Inclusive W and Z Measurements II

- Compare to cross-sections extrapolated to full phase-space, as well as measurements in a fiducial region (limited P_T and η). The latter provide more precise comparisons to theory, and better separate experimental and theory uncertainties. Already with 35 pb^{-1} analysis, significant information available.



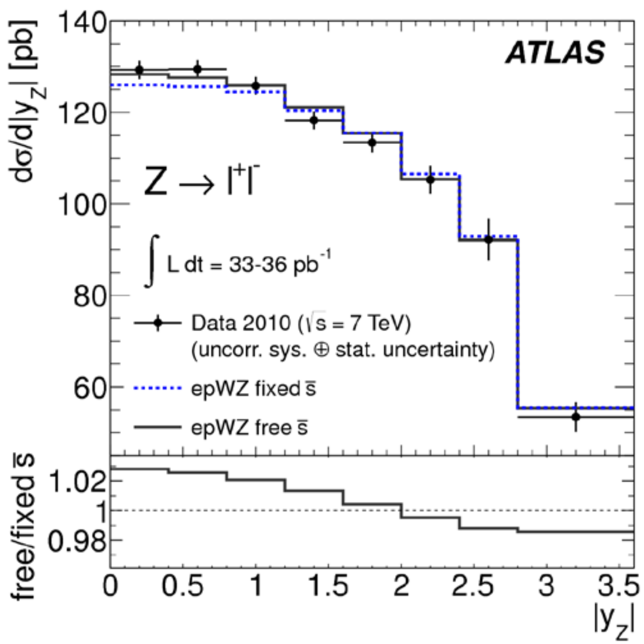
Fiducial cross-sections (upper) provide better discriminating power for PDF comparisons. Will improve with more data.

Systematic uncertainties (excluding luminosity) on fiducial cross-sections are:

1.9% (W->e)
1.6% (W->μ)
2.8% (Z->ee)
0.9% (Z->$\mu\mu$)

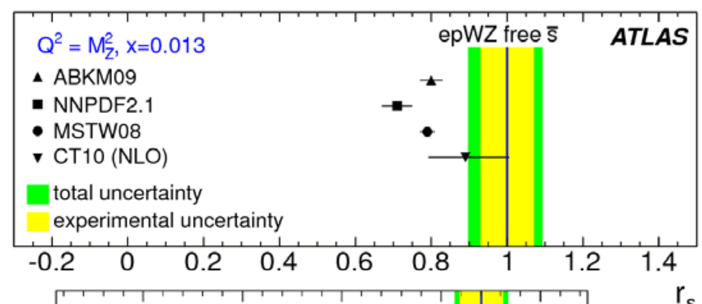
Inclusive W and Z Measurements III

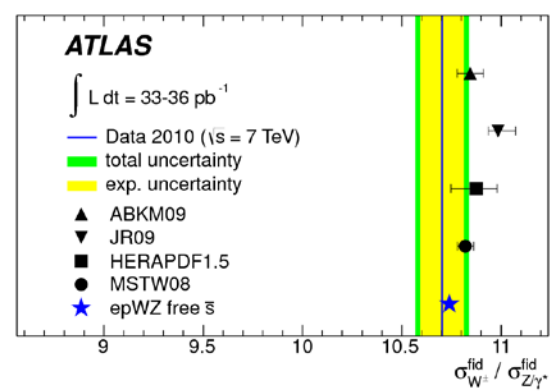
- Separate analysis of ATLAS inclusive W/Z data was performed by PDF fitting team in ATLAS, exploring the implication of these results.
- Starting point was to use HERA PDF fitting software, start from the HERA data used in the HERA PDFs, and then add only ATLAS data from Inclusive W/Z analysis.
- HERA fits are not very sensitive to s density, so this is a very clean way to test the impact of the ATLAS measurements, with a minimum amount of confusion from combining results from many experiments with different uncertainty sources.
- Interesting result: in the region of x roughly 0.01, find that the usual assumption that the ratio of the average of the strange and anti-strange density to the down density (r_s) is not 0.5, but very close to 1.



Fit to Z differential is shown on left showing large improvement from floating r_s.

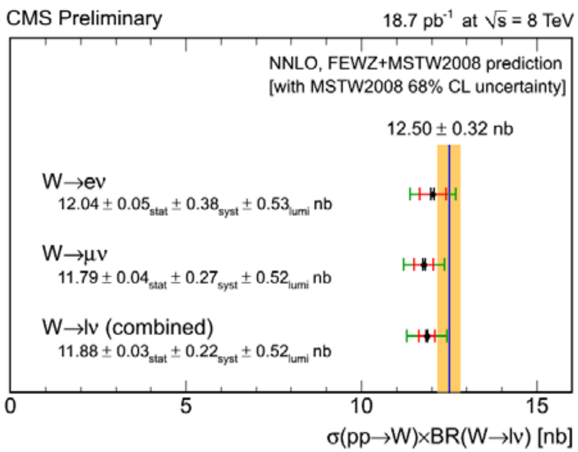
Agreement for usual PDFs with ATLAS data is not good. New PDF ("epWZ") provides nice improvement !

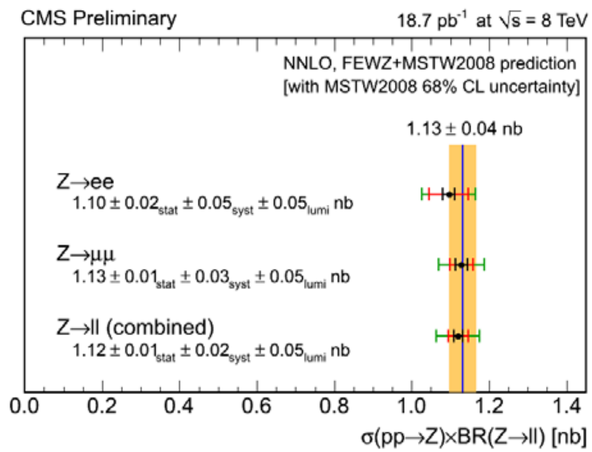




Inclusive W and Z Measurements IV

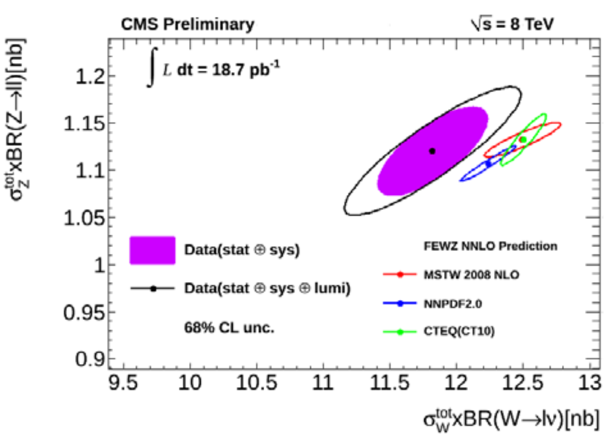
- First analysis of 8 TeV 2012 data by CMS, using special separated beam run to reduce pileup, and concentrating on total cross-sections only. Total lumi 19 pb^{-1}.

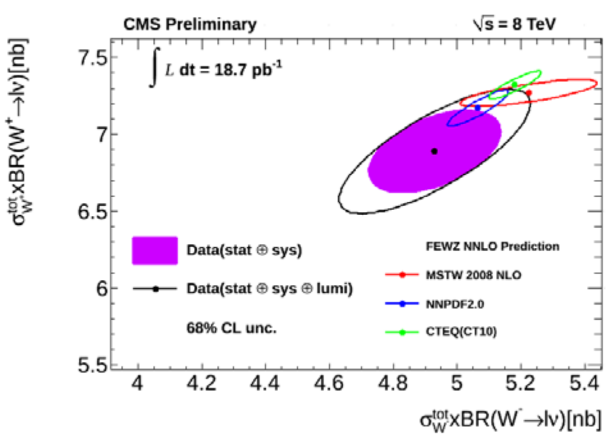




Incl W/Z CMS-SMP-12-011

Generally consistent with NNLO predictions.



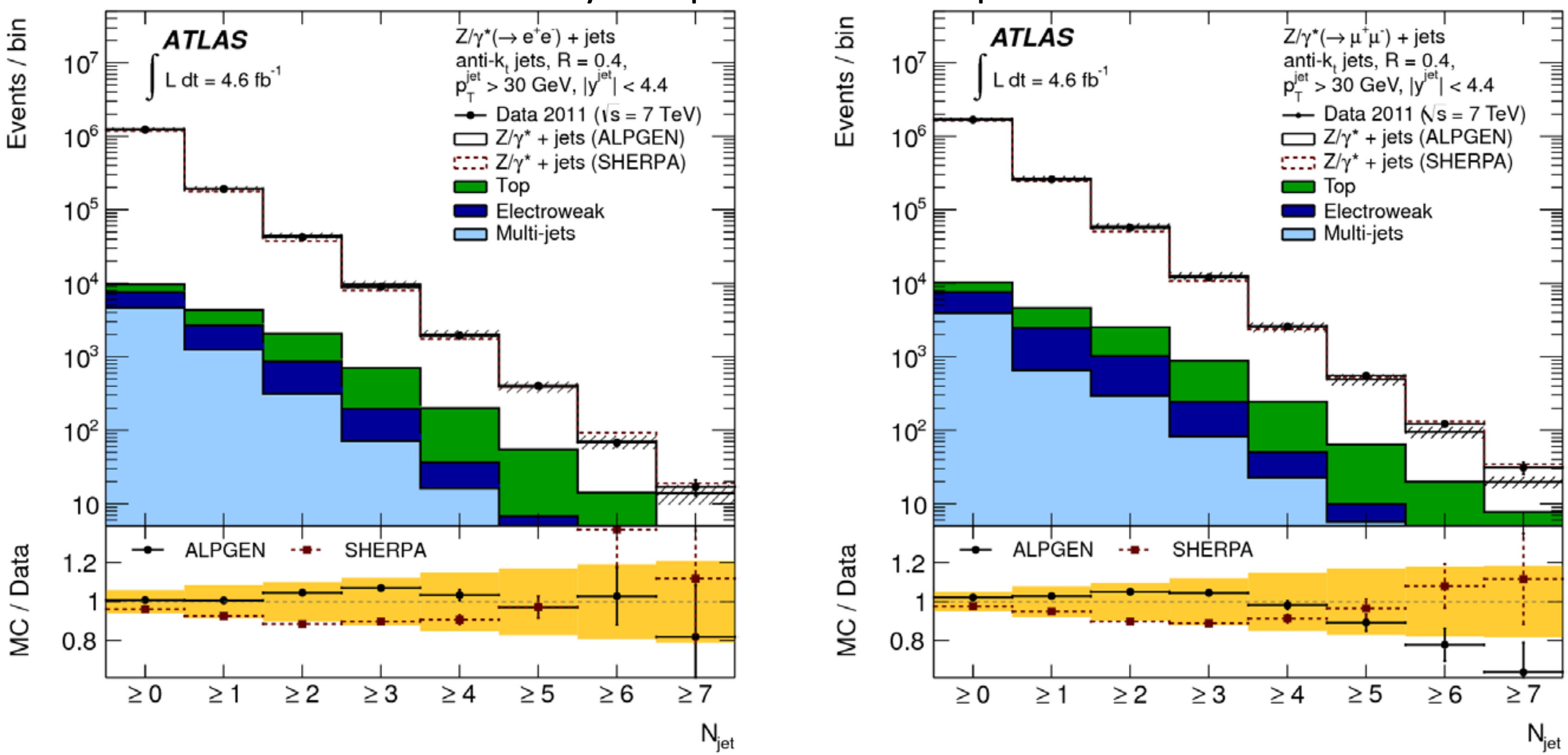


Comparison of W and Z in 2D plot highlights disagreement with current PDFs, but only about a 2σ effect.

Measurements of Z+Jets (7 TeV 5fb^{-1}) I

Z+Jets hep-ex 1304.7098

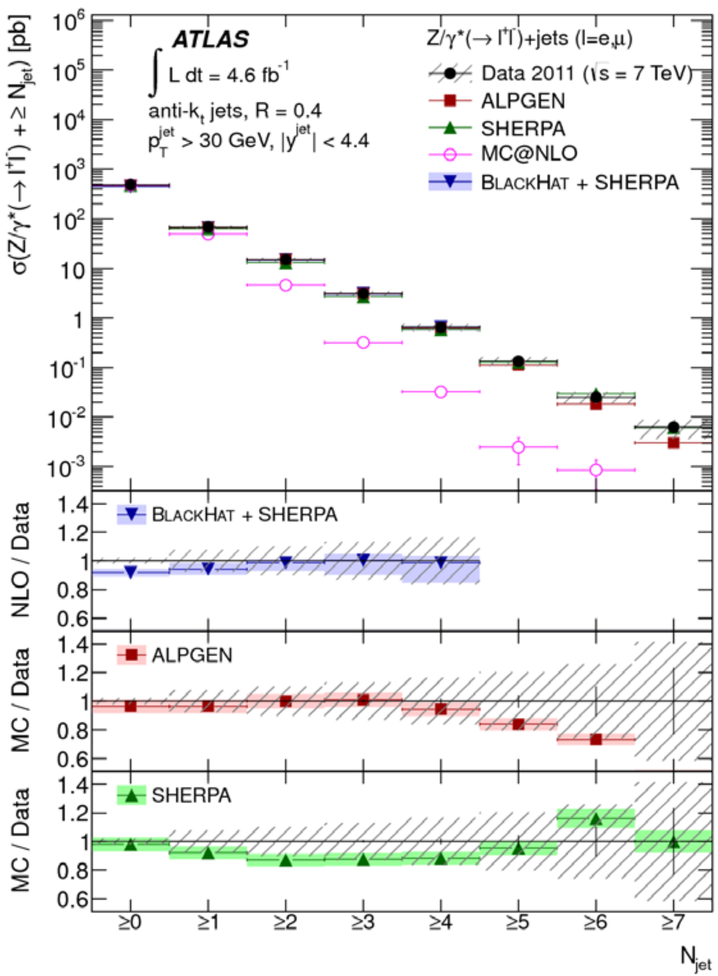
- One of the cleanest laboratories for studying jet production, since clean Z trigger and selection allows unbiased, low background, studies of the jets in the event.
- Have full suite of NLO ME + PS (here use MC@NLO), Multi-leg LO + PS (here use Alpgen and Sherpa with np up to 5), plus the Blackhat+Sherpa NLO fixed-order parton-level calculations (available for up to 4-jets at the time of this analysis). Most complete set of calculations available for any process at the LHC…
- ATLAS has evaluated a very comprehensive and precise JES for the full 2011 data.

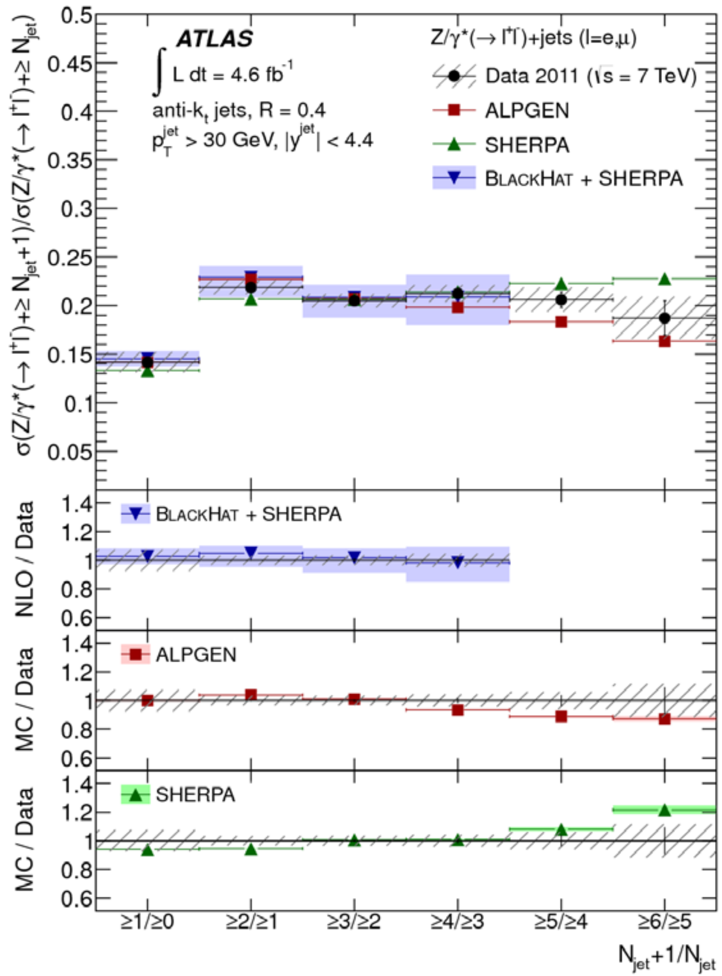


Measurements of Z+Jets (7 TeV 5fb^{-1}) II

Z+Jets hep-ex 1304.7098

- Compare unfolded distributions to suite of MC predictions. Note Blackhat+Sherpa predictions have non-perturbative corrections (UE+hadronization), computed with Alpgen+Herwig/Pythia, applied. Left is jet multiplicity, right is ratio of n+1/n jets.
- Comparison is for absolute cross-sections. Note Alpgen/Sherpa n>5 uses PS.

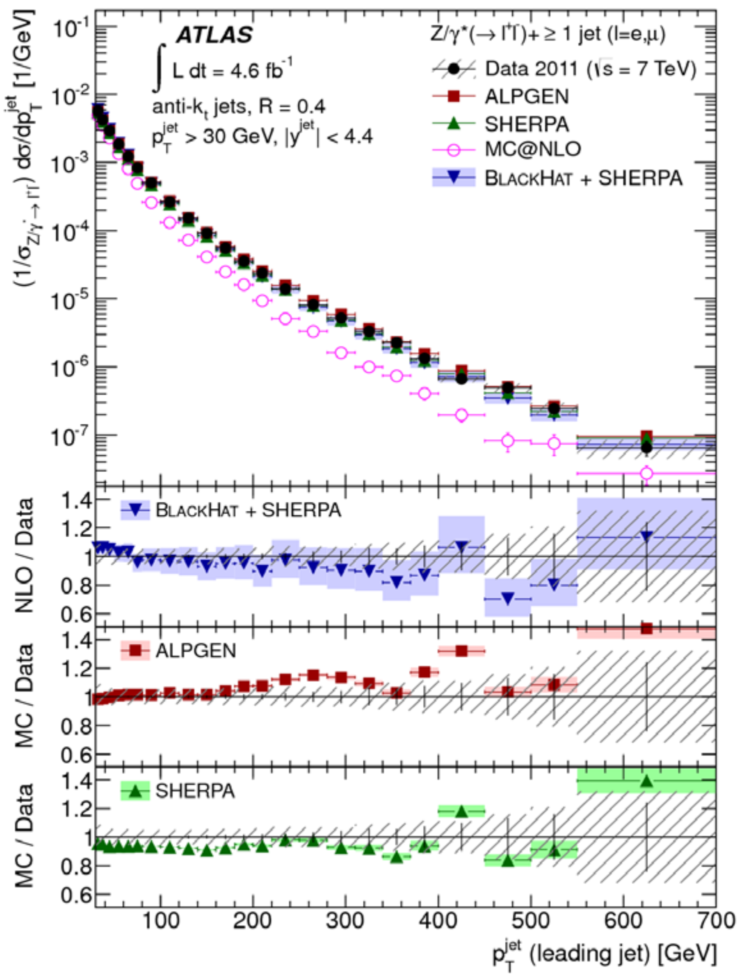


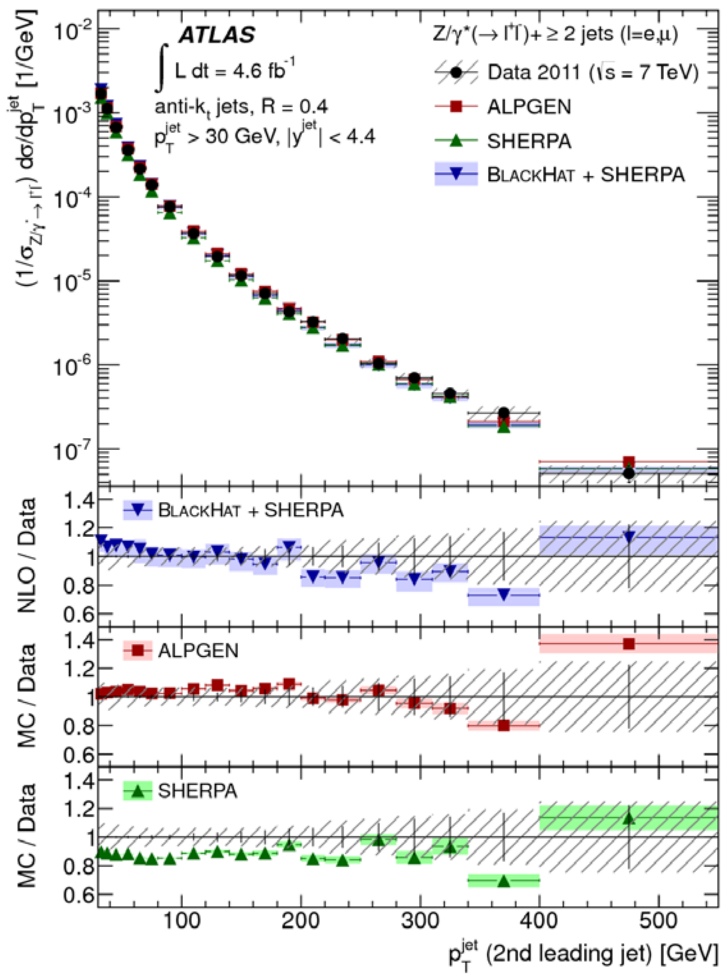


Measurements of Z+Jets (7 TeV 5fb^{-1}) III

Z+Jets hep-ex 1304.7098

- Compare σ_{tot}(Z)-normalized P_T distributions to suite of MC predictions. As in previous plots, MC@NLO does not describe data well (first jet is LO, other jets come from PS). Overall, multi-leg LO generators do surprisingly well. Left is P_T (leading jet), right is P_T(second leading jet).

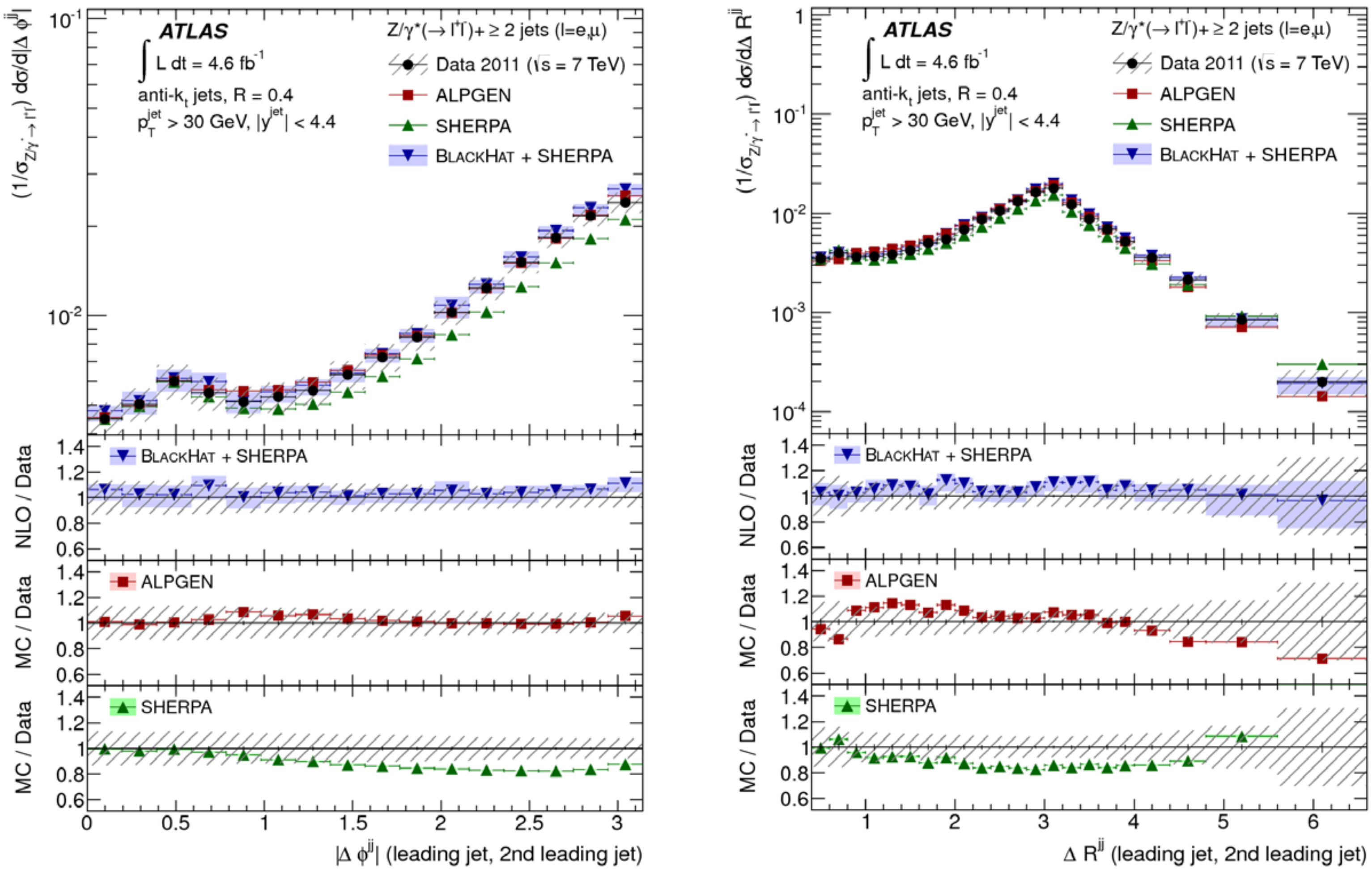




Measurements of Z+Jets (7 TeV 5fb^{-1}) IV

Z+Jets hep-ex 1304.7098

- Compare σ_{tot}(Z)- normalized $\Delta\phi$ and ΔR distributions to suite of MC predictions. Alpgen, but not Sherpa, does surprisingly well. Left is $\Delta\phi$ (two leading jets), right is ΔR(two leading jets). Blackhat+Sherpa does very well overall (typically within about 10%) => need for NLO multi-leg ! This analysis is a high-precision QCD test.



Why make precision EWK measurements ?

- Closest we can get to model-independent tests for deviations from SM.
- Complementary to targeted search programs in areas like SUSY, Exotics, BSM Higgs, etc. Potentially able to catch the unexpected, though deducing the cause of any anomaly seen can be a long process…
- If you have a model for something (SUSY, Exotics, etc.), its best to proceed with a targeted search, making use of control regions, validation regions, and signal regions, minimizing uncertainties for backgrounds under signals, maximizing impact of limited statistics. Will always achieve better sensitivity than by looking at more global observables averaged over larger phase space regions…
- For the moment, "only" one new result from LHC search program. Still have much to learn from higher luminosity design-energy program (Run2…), but many attractive options, like "natural SUSY" becoming less natural => need model-independence !
- LHC is an EWK-scale microscope, able to provide unprecedented statistics for well-known particles and processes, and to shed intense light on all aspects of gauge boson self-interactions => "validate" EWK Lagrangian in great detail…

Note: scope here is "probing EWK Lagrangian", not "all physics with gauge bosons"…

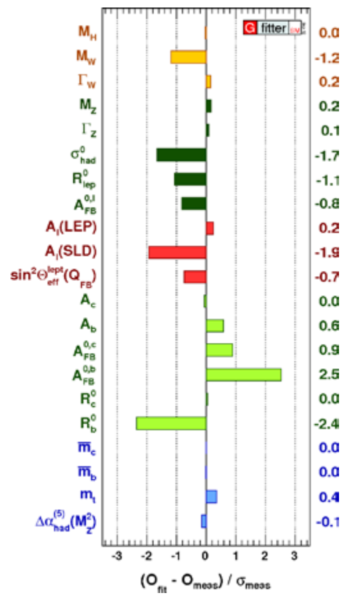
Electroweak Parameters today

	Measurement with Total Error	Systematic Error	Standard Model fit	Pull
$\Delta\alpha^{(5)}_{\mathrm{had}}(m^2_{\mathrm{Z}})$ [82]	0.02758 ± 0.00035	0.00034	0.02768	−0.3
a) LEP-I				
line-shape and				
lepton asymmetries:				
m_{Z} [GeV]	91.1875 ± 0.0021	$^{(a)}0.0017$	91.1874	0.0
Γ_{Z} [GeV]	2.4952 ± 0.0023	$^{(a)}0.0012$	2.4959	−0.3
σ^0_{had} [nb]	41.540 ± 0.037	$^{(b)}0.028$	41.478	1.7
R^0_ℓ	20.767 ± 0.025	$^{(b)}0.007$	20.742	1.0
$A^{0,\ell}_{\mathrm{FB}}$	0.0171 ± 0.0010	$^{(b)}0.0003$	0.0164	0.7
+ correlation matrix [1]				
τ polarisation:				
$\mathcal{A}_\ell$ ($\mathcal{P}_\tau$)	0.1465 ± 0.0033	0.0016	0.1481	−0.5
$\mathrm{q\overline{q}}$ charge asymmetry:				
$\sin^2\theta^{\mathrm{lept}}_{\mathrm{eff}}(Q^{\mathrm{had}}_{\mathrm{FB}})$	0.2324 ± 0.0012	0.0010	0.23139	0.8
b) SLD				
$\mathcal{A}_\ell$ (SLD)	0.1513 ± 0.0021	0.0010	0.1481	1.6
c) LEP-I/SLD Heavy Flavour				
R^0_{b}	0.21629 ± 0.00066	0.00050	0.21579	0.8
R^0_{c}	0.1721 ± 0.0030	0.0019	0.1723	−0.1
$A^{0,\mathrm{b}}_{\mathrm{FB}}$	0.0992 ± 0.0016	0.0007	0.1038	−2.9
$A^{0,\mathrm{c}}_{\mathrm{FB}}$	0.0707 ± 0.0035	0.0017	0.0742	−1.0
$\mathcal{A}_{\mathrm{b}}$	0.923 ± 0.020	0.013	0.935	−0.6
$\mathcal{A}_{\mathrm{c}}$	0.670 ± 0.027	0.015	0.668	0.1
+ correlation matrix [1]				
d) LEP-II and Tevatron				
m_{W} [GeV] (LEP-II, Tevatron)	80.399 ± 0.023		80.379	0.9
Γ_{W} [GeV] (LEP-II, Tevatron)	2.085 ± 0.042		2.092	0.2
m_{t} [GeV] (Tevatron [43])	173.3 ± 1.1	0.9	173.4	−0.1

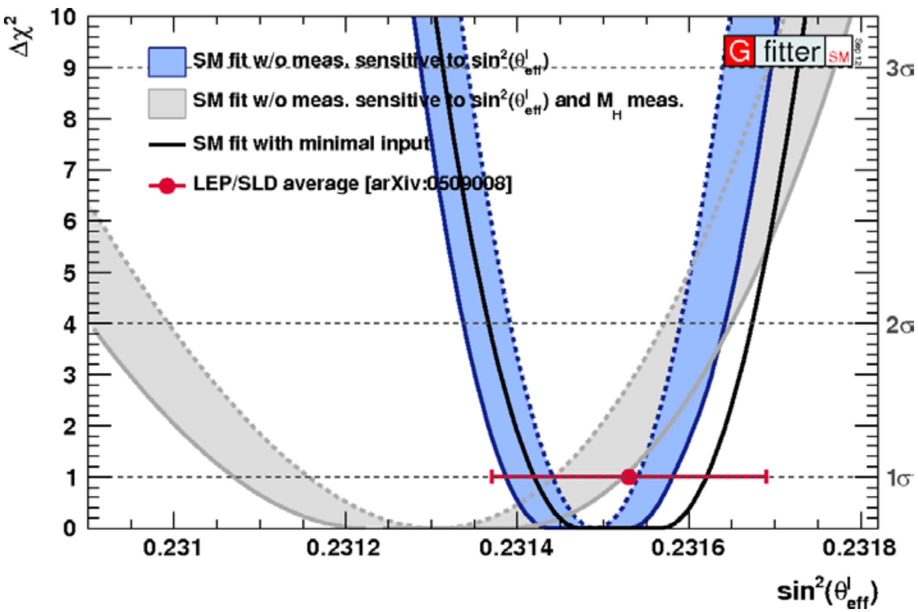
$\sin^2(\theta_{\mathrm{eff}}) = 0.23153 \pm 0.00016$
ArXiv hep-ex 1012.2367

- Much of what we know comes from LEP/SLD
- Table from 2010 summary, so no LHC input
- Tevatron contributions include most precise m(W), Γ(W), and m(Top) values. For W parameters, combined LEP/Tevatron results have roughly half uncertainty of LEP alone.
- LHC contributions emerging in m(Top), and will overtake the Tevatron with Run1 data.
- No LHC results on m(W) or Γ(W) yet, but analyses underway with 2011 data – however, very demanding, time required !
- First interesting A_{fb} measurements for $\sin^2(\theta_{\mathrm{eff}})$ for leptons.
- Of course with precise measurements of m(H) now available, assuming it is the SM Higgs, everything has changed…

Detailed Picture: latest Gfitter results I



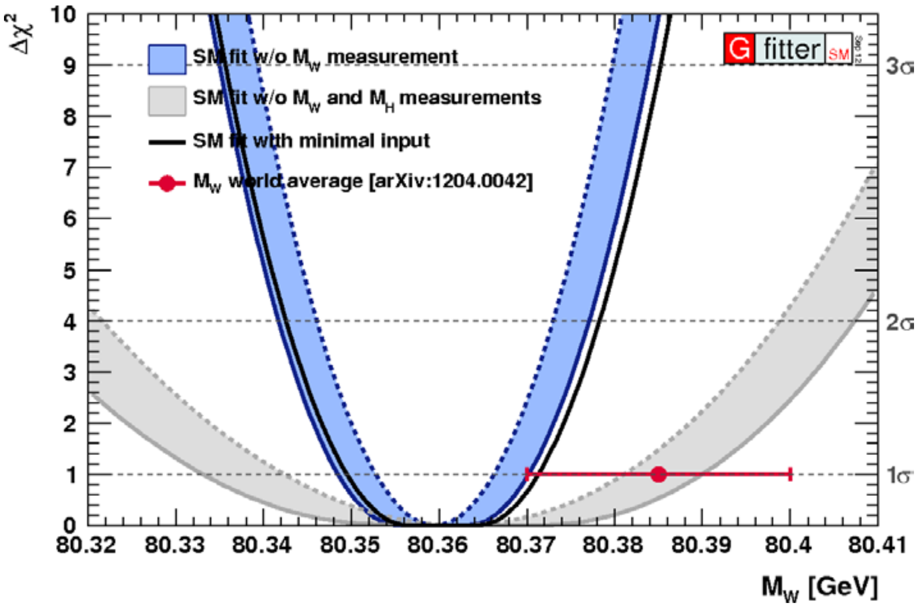
- Compare full SM fit values for each parameter with the world average measured values and plot pulls.
- Two of largest differences are for A_l (SLD) in red (about -2σ) and A_{fb}(b) (LEP) in green (about $+2.5\sigma$).



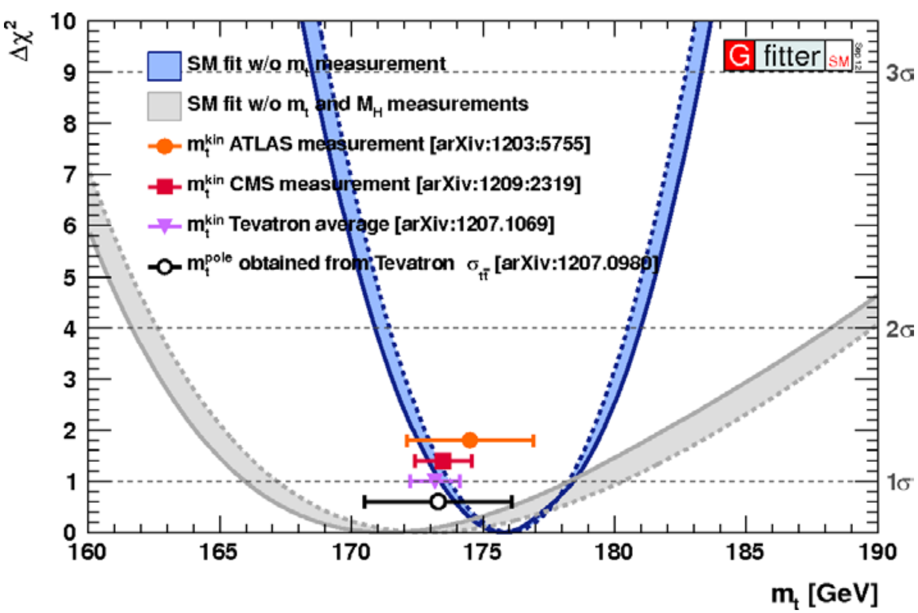
- Compare full SM fit (without $\sin^2(\theta_{eff})$) and world average $\sin^2(\theta_{eff})$ value. Agreement is very good.
- Note however that two best individual measurements are far from world avg !
- SLD $\sin^2(\theta_{eff}) = 0.23221 \pm 0.00029$
  LEP $\sin^2(\theta_{eff}) = 0.23098 \pm 0.00026$

ArXiv hep-ph 1209.2716

Detailed Picture: latest Gfitter results II

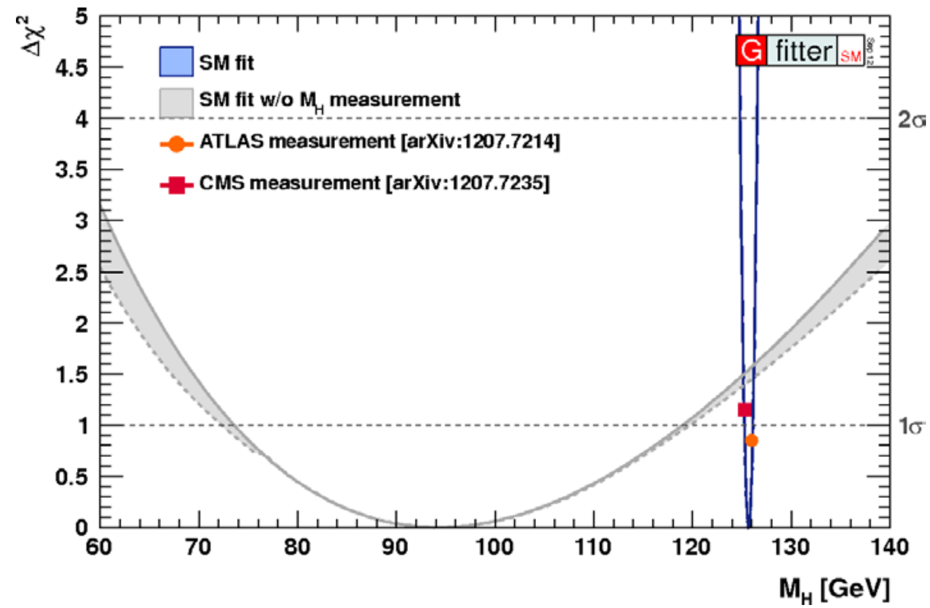


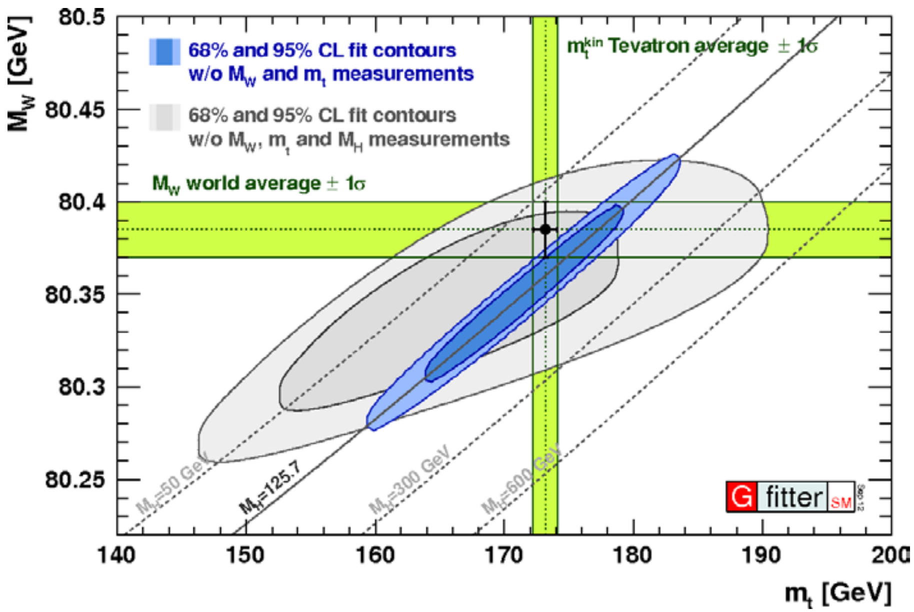
- Compare full SM fit (without m(W)) and world average m(W) value. Agreement is within about 1.6σ including m(H) in SM fit.
- Astonishing result at experimental and theoretical level !



- Compare full SM fit (without m(Top)) and individual best m(Top) measurements. Agreement is very good.

Detailed Picture: latest Gfitter results III





- Compare full SM fit (without m(H)) and world average m(H) value from Sept 2012. Agreement is excellent !
- Note from EWK parameter fitting point of view, m(H) experimental precision already far exceeds what is needed.
- Compare full SM fit (without m(W), m(Top) = blue ellipse) and individual best m(W) and m(Top) measurements (data point).
- Width of ellipse projected along m(W) axis has many small contributions, but the 4 MeV theory uncertainty (HO corrections) is dominant.
- Agreement is excellent. Projected errors on ellipse are about ± 10 MeV in m(W) direction and ± 2 GeV in m(Top), setting scale for experimental improvements.

Detailed Picture: latest Gfitter results IV

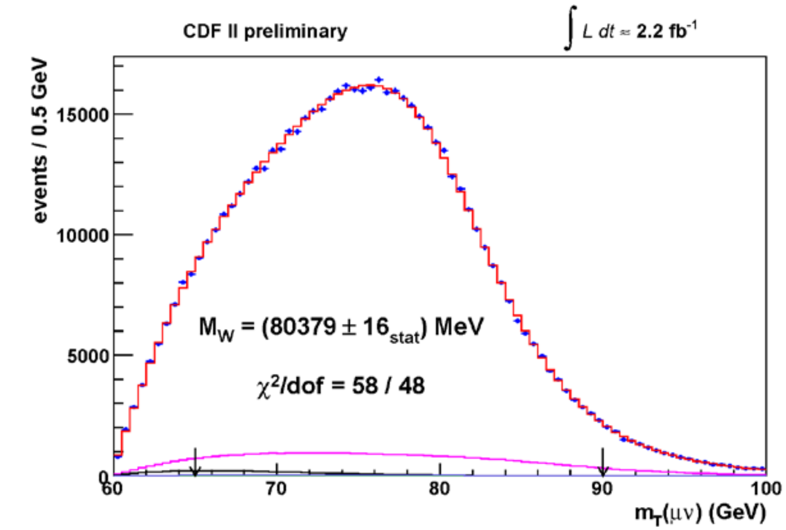
Parameter	Input value	Free in fit	Fit result incl. M_H	Fit result not incl. M_H	Fit result incl. M_H but not exp. input in row
M_H [GeV]$^{(\circ)}$	125.7 ± 0.4	yes	125.7 ± 0.4	94^{+25}_{-22}	94^{+25}_{-22}
M_W [GeV]	80.385 ± 0.015	–	80.367 ± 0.007	80.380 ± 0.012	80.359 ± 0.011
Γ_W [GeV]	2.085 ± 0.042	–	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	$175.8^{+2.7}_{-2.4}$
$\Delta\alpha^{(5)}_{\rm had}(M_Z^2)$ $^{(\triangle\triangledown)}$	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	–
$\delta_{\rm th}\sin^2\theta^\ell_{\rm eff}$ $^{(\triangle)}$	$[-4.7, 4.7]_{\rm theo}$	yes	-1.4	4.7	–

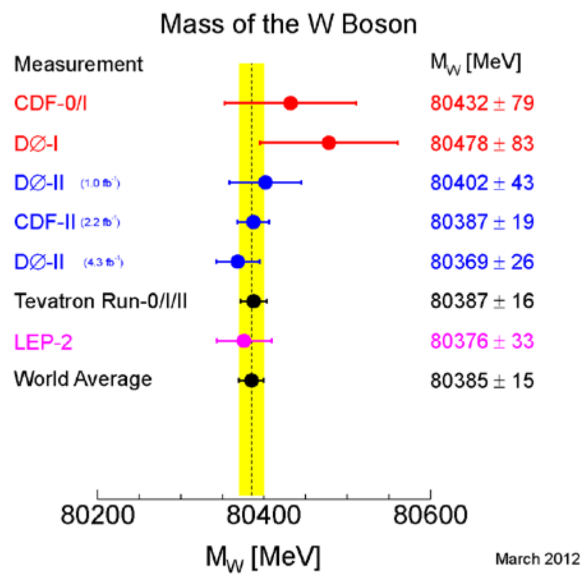
$^{(\circ)}$Average of ATLAS ($M_H = 126.0 \pm 0.4$ (stat) ± 0.4 (sys)) and CMS ($M_H = 125.3 \pm 0.4$ (stat) ± 0.5 (sys)) measurements assuming no correlation of the systematic uncertainties (see discussion in Sect. 2). $^{(\star)}$Average of LEP ($A_\ell = 0.1465 \pm 0.0033$) and SLD ($A_\ell = 0.1513 \pm 0.0021$) measurements, used as two measurements in the fit. $^{(\dagger)}$The fit w/o the LEP (SLD) measurement gives $A_\ell = 0.1474^{+0.0005}_{-0.0009}$ ($A_\ell = 0.1467^{+0.0006}_{-0.0004}$).
$^{(\triangle)}$In units of 10^{-5}. $^{(\triangledown)}$Rescaled due to α_S dependency.

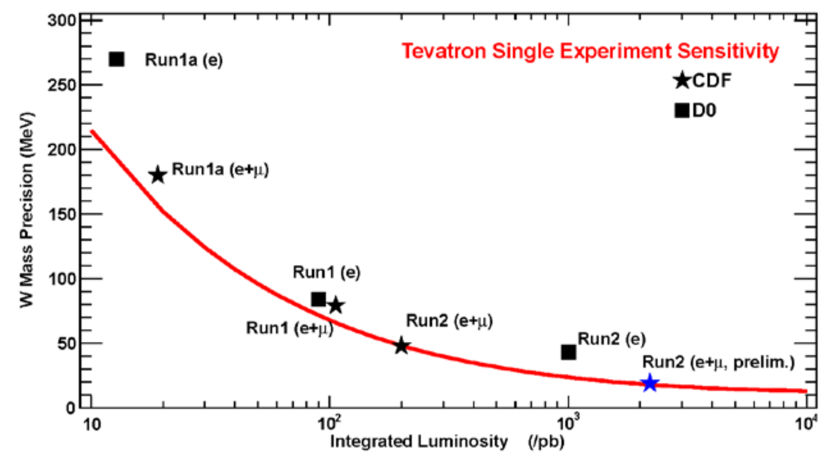
- For those who want all the numbers, here are the detailed input values, fit results with and without the m(H) input, and fit prediction without given input.
- Right-most column is the fitted value of the given parameter, ignoring the actual measured valued in the left-most column
  => compute "pulls"…

Hadron Collider Contributions: m(W) I

Systematic (MeV)	Electrons	Muons	Common
Lepton Energy Scale	10	7	5
Lepton Energy Resolution	4	1	0
Recoil Energy Scale	5	5	5
Recoil Energy Resolution	7	7	7
$u_{\|\|}$ Efficiency	0	0	0
Lepton Removal	3	2	2
Backgrounds	4	3	0
$p_T(W)$ Model (g_2, g_3, α_s)	3	3	3
Parton Distributions	10	10	10
QED Radiation	4	4	4
Total	18	16	15







CDF hep-ex 1203.0275
D0 hep-ex 1203.0293
Comb hep-ex 1204.0042

- Tevatron best single result is CDF $m_T(\mu)$ fit.
- Tevatron combined results dominate world average.
- Expected full 10 fb^{-1} Tevatron result < 10 MeV ?

Hadron Collider Contributions: m(W) II

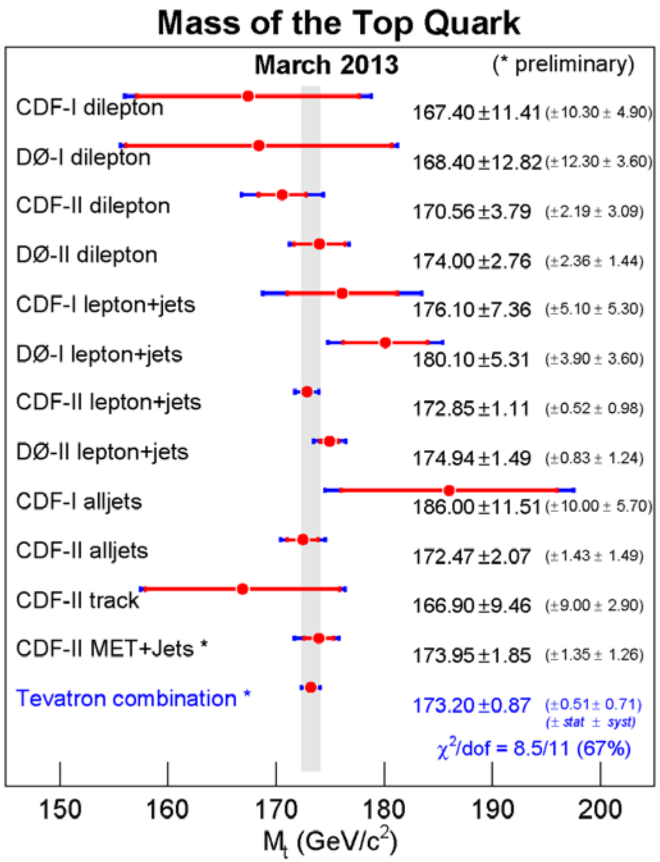
Challenges for measuring m(W) at LHC:

- Detector level: resolution in m_T broader than in $P_T(l)$ already in 2011 data due to pileup. Almost certainly have to use $P_T(l)$ fits, which are much more sensitive to $P_T(W)$ distribution. Therefore require more stringent control of theory.
- Lower x production and lack of valence anti-quarks at pp machine lead to increased sensitivity to less well-known parts of PDFs (s-quark > 10% at 7/8 TeV).
- Need greater investment in in-situ measurements (e.g. PDF fitting) to control some of the uncertainties. Probably need in-situ PDF fitting to take advantage of increased statistics for A_{fb} measurement as well (see later). W^+ and W^- production have different kinematics (y and P_T) due to PDFs => must measure separately !
- Significantly more material in tracking volumes compared to Tevatron, so will need to invest more effort in establishing solid lepton E scales.

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

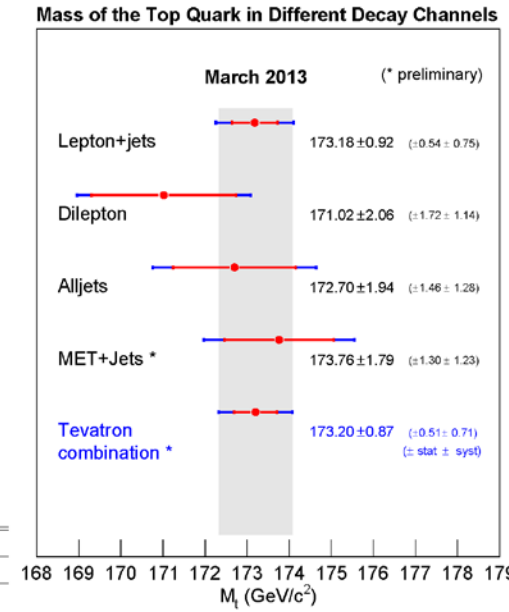
- Table shows CDF $P_T(l)$ fit uncertainties – more sensitive to lepton scale, PDFs, and especially $P_T(W)$ modeling.
- Explore issues in a "prototype" analysis for 2011. Possible to achieve uncertainties in range 20-30 MeV (stat < 1 MeV)? Ultimate goal of order 5 MeV ?

Hadron Collider Contributions: m(Top) I



Tevatron combines 12 measurements (left) in 4 basic categories (right).

Lepton+Jets measurement dominates the combination, with lowest uncertainty.



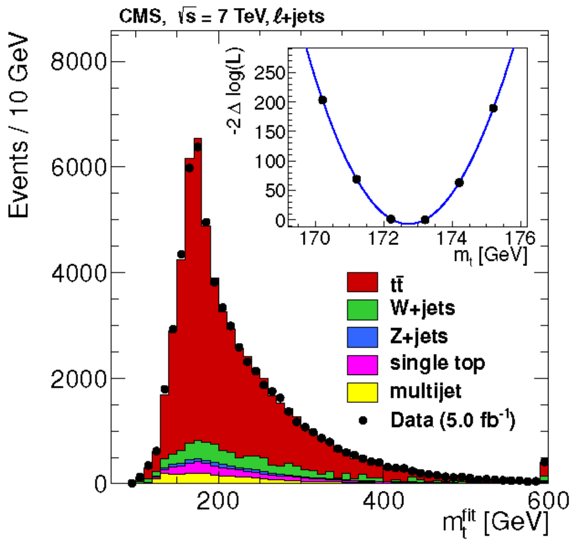
	Tevatron combined values (GeV/c^2)
M_t	173.20
In situ light-jet calibration (iJES)	0.36
Response to $b/q/g$ jets (aJES)	0.09
Model for b jets (bJES)	0.11
Out-of-cone correction (cJES)	0.01
Light-jet response (2) (dJES)	0.15
Light-jet response (1) (rJES)	0.16
Lepton modeling (LepPt)	0.05
Signal modeling (Signal)	0.52
Jet modeling (DetMod)	0.08
Offset (UN/MI)	0.00
Background from theory (BGMC)	0.06
Background based on data (BGData)	0.13
Calibration method (Method)	0.06
Multiple interactions model (MHI)	0.07
Systematic uncertainty (syst)	0.71
Statistical uncertainty (stat)	0.51
Total uncertainty	0.87

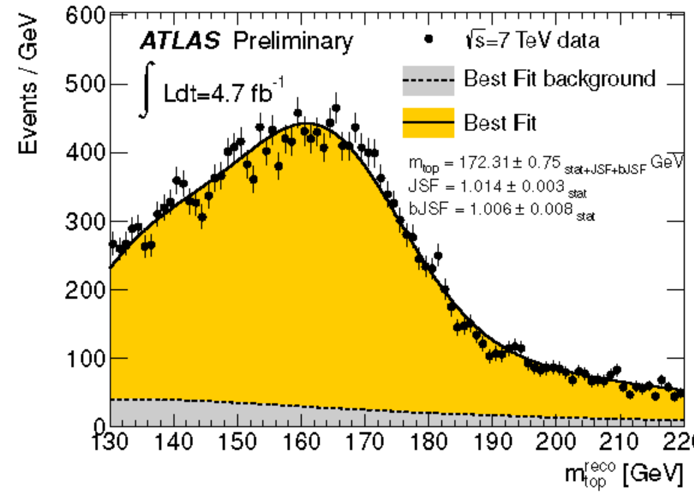
Breakdown of uncertainties shows systematics dominate, with Top modeling and light-jet JES as largest.

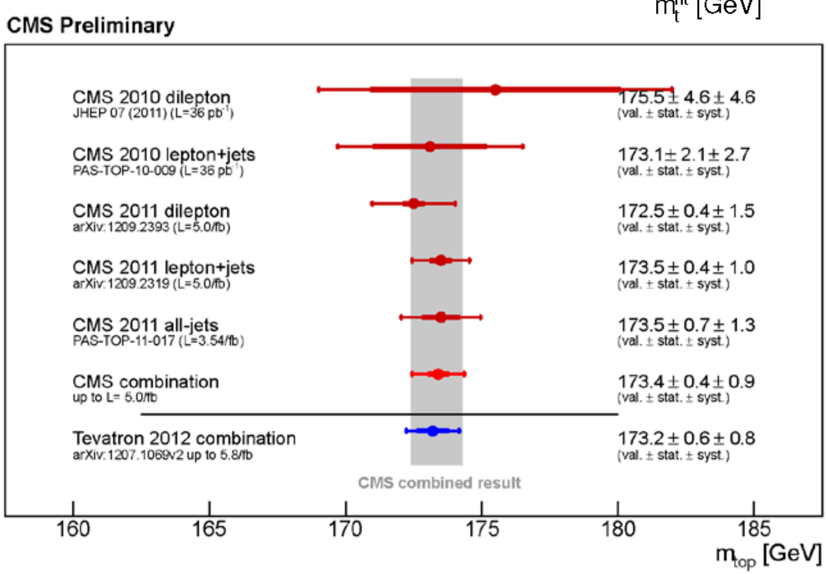
CDF hep-ex 1203.0275
D0 hep-ex 1203.0293
Comb hep-ex 1305.3929

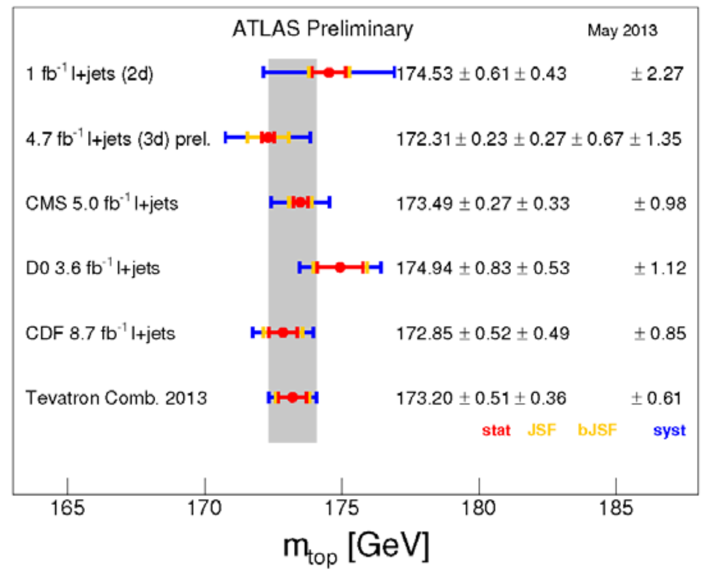
- Tevatron combination best overall: 173.18 ± 0.87 GeV
- CMS (prelim) combination gives 173.36 ± 0.99 GeV
- ATLAS has new (prelim) 3D result 173.31 ± 1.54 GeV

Hadron Collider Contributions: m(Top) II









CMS hep-ex 1209.2319
Comb CMS-TOP-11-018
ATLAS ATLAS-CONF-2013-046

ATLAS figure (lower right) makes comparison for lepton+jets channel of pure syst, removing “stat-like” contribution from other fit parameters => CDF is best at 0.85 GeV

Hadron Collider Contributions: m(Top) III

	2d-analysis		3d-analysis		
	m_{top} [GeV]	JSF	m_{top} [GeV]	JSF	bJSF
Measured value	172.80	1.014	172.31	1.014	1.006
Data statistics	0.23	0.003	0.23	0.003	0.008
Jet energy scale factor (stat. comp.)	0.27	n/a	0.27	n/a	n/a
bJet energy scale factor (stat. comp.)	n/a	n/a	0.67	n/a	n/a
Method calibration	0.13	0.002	0.13	0.002	0.003
Signal MC generator	0.36	0.005	0.19	0.005	0.002
Hadronisation	1.30	0.008	0.27	0.008	0.013
Underlying event	0.02	0.001	0.12	0.001	0.002
Colour reconnection	0.03	0.001	0.32	0.001	0.004
ISR and FSR (signal only)	0.96	0.017	0.45	0.017	0.006
Proton PDF	0.09	0.000	0.17	0.000	0.001
single top normalisation	0.00	0.000	0.00	0.000	0.000
W+jets background	0.02	0.000	0.03	0.000	0.000
QCD multijet background	0.04	0.000	0.10	0.000	0.001
Jet energy scale	0.60	0.005	0.79	0.004	0.007
b-jet energy scale	0.92	0.000	0.08	0.000	0.002
Jet energy resolution	0.22	0.006	0.22	0.006	0.000
Jet reconstruction efficiency	0.03	0.000	0.05	0.000	0.000
b-tagging efficiency and mistag rate	0.17	0.001	0.81	0.001	0.011
Lepton energy scale	0.03	0.000	0.04	0.000	0.000
Missing transverse momentum	0.01	0.000	0.03	0.000	0.000
Pile-up	0.03	0.000	0.03	0.000	0.001
Total systematic uncertainty	2.02	0.021	1.35	0.021	0.020
Total uncertainty	2.05	0.021	1.55	0.021	0.022

	μ+jets		e+jets		ℓ+jets	
	$\delta^{\mu}_{m_t}$ (GeV)	$\delta^{\mu}_{\mathrm{JES}}$	$\delta^{e}_{m_t}$ (GeV)	$\delta^{e}_{\mathrm{JES}}$	$\delta^{\ell}_{m_t}$ (GeV)	$\delta^{\ell}_{\mathrm{JES}}$
Fit calibration	0.08	0.001	0.09	0.001	0.06	0.001
b-JES	0.60	0.000	0.62	0.000	0.61	0.000
p_T- and η-dependent JES	0.30	0.001	0.28	0.001	0.28	0.001
Lepton energy scale	0.03	0.000	0.04	0.000	0.02	0.000
Missing transverse momentum	0.05	0.000	0.07	0.000	0.06	0.000
Jet energy resolution	0.22	0.004	0.24	0.004	0.23	0.004
b tagging	0.11	0.001	0.15	0.001	0.12	0.001
Pileup	0.07	0.002	0.08	0.001	0.07	0.001
Non-$t\bar{t}$ background	0.10	0.001	0.16	0.000	0.13	0.001
Parton distribution functions	0.07	0.001	0.07	0.001	0.07	0.001
Renormalization and factorization scales	0.23	0.004	0.41	0.005	0.24	0.004
ME-PS matching threshold	0.17	0.000	0.15	0.001	0.18	0.001
Underlying event	0.26	0.002	0.24	0.001	0.15	0.002
Color reconnection effects	0.66	0.004	0.39	0.003	0.54	0.004
Total	1.06	0.008	1.00	0.007	0.98	0.008

CMS: Dominant syst from b-JES and color reconnection effects. Total “non-stat” syst is 0.98 GeV.

ATLAS: Dominant syst from overall JES and b-tagging. Total “non-stat” syst is 1.35 GeV. New 3D technique needs more statistics !

Two experiments have working group to harmonize definitions of syst uncertainties as part of combination effort.

CMS hep-ex 1209.2319
Comb CMS-TOP-11-018
ATLAS ATLAS-CONF-2013-046

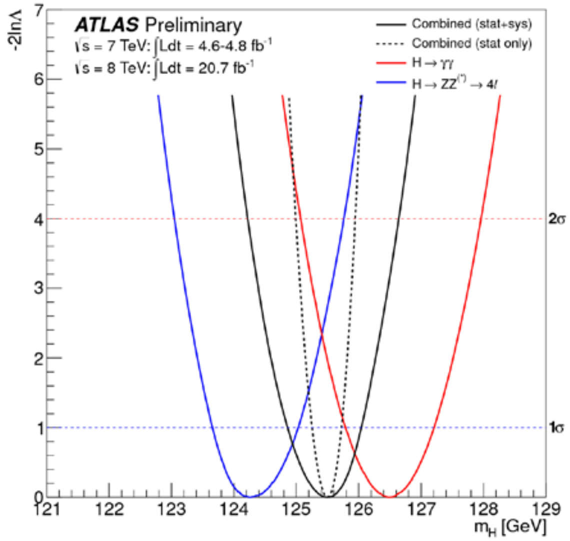
- Tevatron combination best overall: 173.18 ± 0.87 GeV
- CMS (prelim) combination gives 173.36 ± 0.99 GeV
- ATLAS has new (prelim) 3D result 173.31 ± 1.54 GeV

Hadron Collider Contributions: m(Top) IV

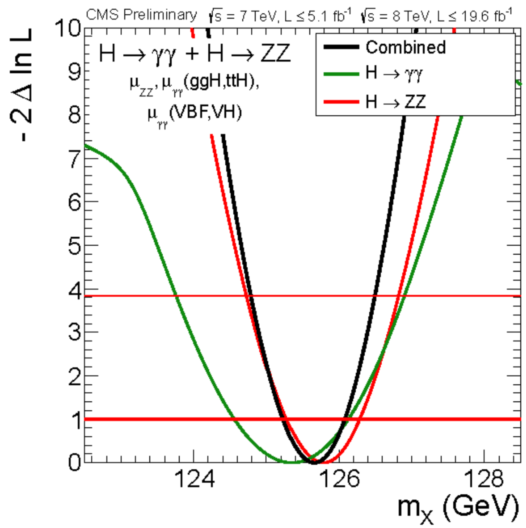
Challenges for measuring m(Top) at LHC:

- All measurements based on MC-based templates, today use generators like LO ME + PS like MadGraph+Pythia (CMS) or NLO ME + PS Powheg+Pythia (ATLAS).
- Many systematics arise from details of MC modeling (ISR/FSR, color reconnection, hadronization). The "mass" is an MC parameter, NOT equal to pole mass !
- These will be difficult to reduce in a simple way – need as many in-situ constraints based on related measurements as possible to constrain MC modeling parameters.
- Basic experimental uncertainties to do with Jet and b-Jet scales are fit as part of the method, and hence have large statistical components at the present time.
- Other experimental uncertainties related to b-tagging, etc. will be improved with time and more sophisticated methods based on larger data samples.
- Might be possible to reach 0.5 - 0.7 GeV level for LHC combination for Run1 – still busy learning and improving understanding of detectors, data, and models…
- Recall in m(Top) versus m(W) plot, projected uncertainty is +/- 2 GeV => improve !
- Ultimate improvements will only come from very concerted effort to understand Top physics in all details at the NNLO and NNLL level.
- Note: need to address fundamental problem of how to relate what we are measuring to a parameter like pole mass – otherwise sub-GeV precision is useless !

Hadron Collider Contributions: m(H)



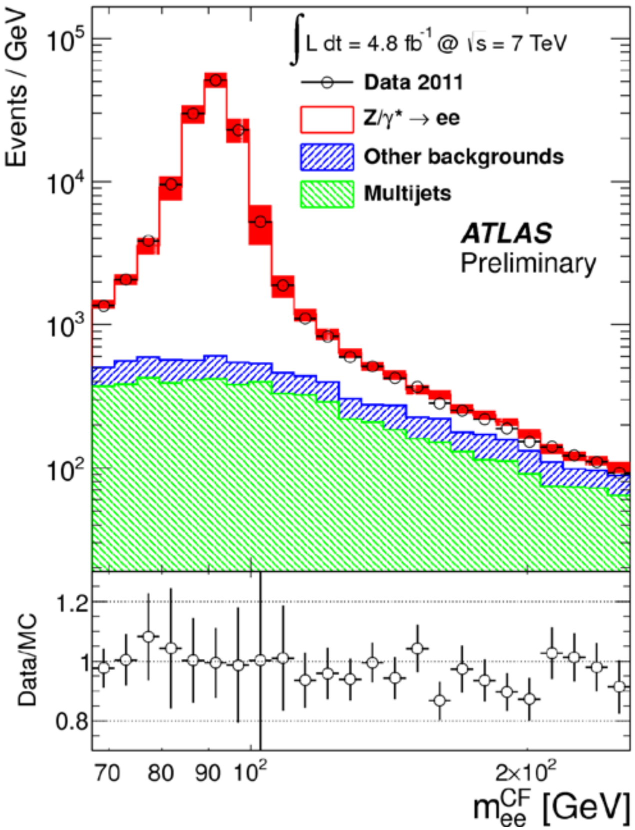
- ATLAS: Combining the H->γγ and H->4-lepton final states gives M(H) = 125.5 ± 0.6 GeV.
- We can expect the total error to shrink slightly for the final Run1 result.



- CMS: Combining the H->γγ and H->4-lepton final states gives M(H) = 125.7 ± 0.4 GeV.
- Final Run1 result will improve somewhat with a combination – might reach 300 MeV overall uncertainty ?
- Recent analysis (hep-ph 1305.6397) suggests that no presently available theory sensitive to precisions below 150 MeV => we are almost there !

ATLAS ATLAS-CONF-2013-014
CMS CMS-HIG-13-005

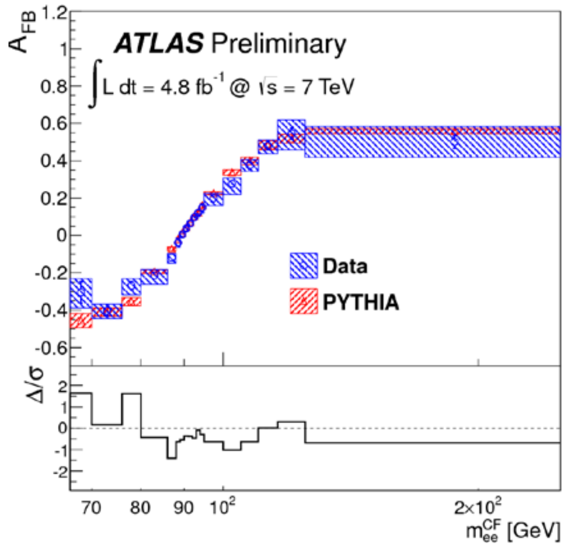
Hadron Collider Contributions: A_{fb} I

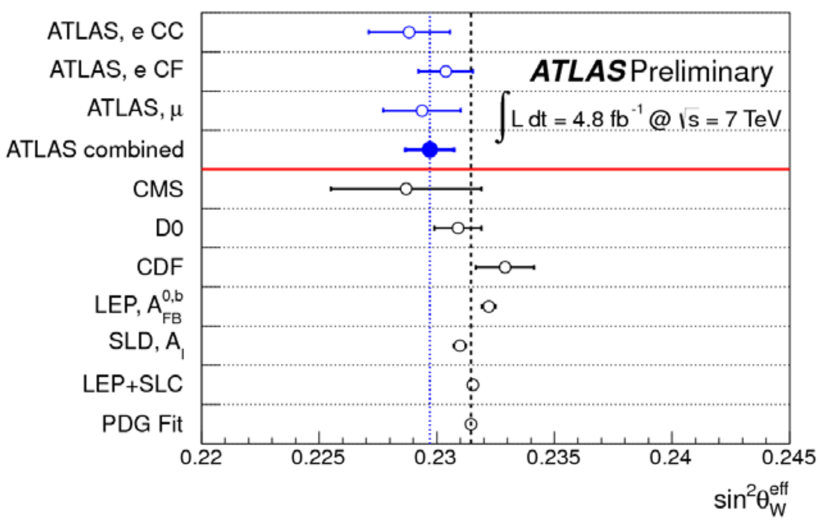


- A_{fb} defined using “forward” and “backward” asymmetry defined using the sign of $\cos\theta_{CS}$ (Collins-Soper angle), which is defined relative to the quark direction.
- Analysis significantly more difficult at pp machine because of large “dilution” arises because quark direction cannot be determined experimentally (assume quark direction given by y(Z)). Di-leptons produced at larger rapidity have reduced dilution.
- Recent ATLAS analysis with 5 fb^{-1} 7 TeV data sample (CMS analysis $\mu\mu$ 1fb^{-1}), using muons to $|\eta| < 2.4$, central electrons to $|\eta| < 2.5$, forward electrons from $2.5 < |\eta| < 4.9$. Combine CC, CF electron samples, and CC muons.
- Although there is no tracking for the forward electrons, so hadronic backgrounds are higher, advantage of reduced dilution makes the CF electron measurement most powerful.

ATLAS ATLAS-CONF-2013-043

Hadron Collider Contributions: A_{fb} II





ATLAS ATLAS-CONF-2013-043

- Upper plot is Afb for CF electrons only, unfolded to Born level, including all detector corrections, NO dilution corrections => significant asymmetry.

- Make three independent determinations of $\sin^2(\theta_{eff})$, for CC and CF electrons, CC muons using templates from Pythia6 and scanning $\sin^2(\theta_{eff})$.

- Results are consistent, and CF electrons have smallest uncertainty, despite reduced statistics and larger background.

- Combined result (within factor 3-4 of LEP/SLD):

  $\sin^2(\theta_{eff}) = 0.2297 \pm 0.0004\ (\text{stat}) \pm 0.0009\ (\text{syst})$
  $= 0.2297 \pm 0.0010\ (\text{total})$

- Dominant uncertainty is from PDFs. Extraction done using Pythia6 LO MC as it gives full control of EWK parameters. Achieving order 5 reduction in systematics needs work on theory side…

Constraints on the EWK Lagrangian I

- In SM, delicate cancellations required in di-boson and tri-boson production processes to control potential divergences at high energy…
- Accurately measure total and fiducial cross-sections and differential distributions for $W\gamma$, $Z\gamma$, WW, WZ, and ZZ production to test underlying theory.
- Have NLO calculations for all di-boson cross-sections available in MCFM, and several NLO ME+PS generators – critical for precision measurements.

Traditional approach: parametrize deviations from SM values for TGC and QGC as anomalous (aTGC and aQGC) couplings. Basic assumption is Lorentz invariance…

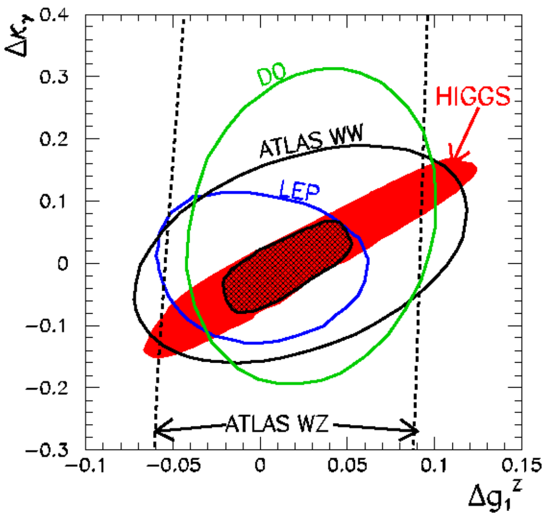
- For $W\gamma$ final state, 2 parameters for $WW\gamma$ vertex: $\Delta\kappa_\gamma$, λ_γ.
- For WW final state, 5 parameters for $WW\gamma$ and WWZ vertices: $\Delta\kappa_\gamma$, λ_γ, $\Delta\kappa_Z$, λ_Z, Δg_1^Z
- For WZ final state, 3 parameters for WWZ vertices: $\Delta\kappa_Z$, λ_Z, Δg_1^Z
- For $Z\gamma$ final state, 4 parameters for $ZZ\gamma$ and $Z\gamma\gamma$ vertices: h_3^γ, h_4^γ, h_3^Z, h_4^Z
- For ZZ final state, 4 parameters for $ZZ\gamma$ and ZZZ vertices: f_4^γ, f_5^γ, f_4^Z, f_5^Z

Alternative approach: use EFT (effective field theory) approaches, expanding deviations from the SM Lagrangian in dim 6 operators (e.g. hep-ph 1205.4231).

- Assuming scale of new physics in EFT much larger than today's energies, only dim 6 operators contribute. Assuming (or not) C and P conservation, have 3 (5) operators that contribute to gauge boson self-interactions => much reduced parameter set.
- EFT framework not used in any di-boson analysis to my knowledge…

Constraints on the EWK Lagrangian II

- Additional advantage with EFT approach is greater predictive power:
- Example calculation (hep-ph 1304.1151), uses an EFT to relate limits on Higgs couplings to anomalous TGCs:



- In this case, Higgs coupling data from LHC is used to restrict the allowed range for anomalous couplings that have been studied by LEP, D0, and ATLAS/CMS.
- In this case, even the limited Higgs coupling data available today provides more stringent limits.
- Important message: allows combining constraints from different sets of measurements.

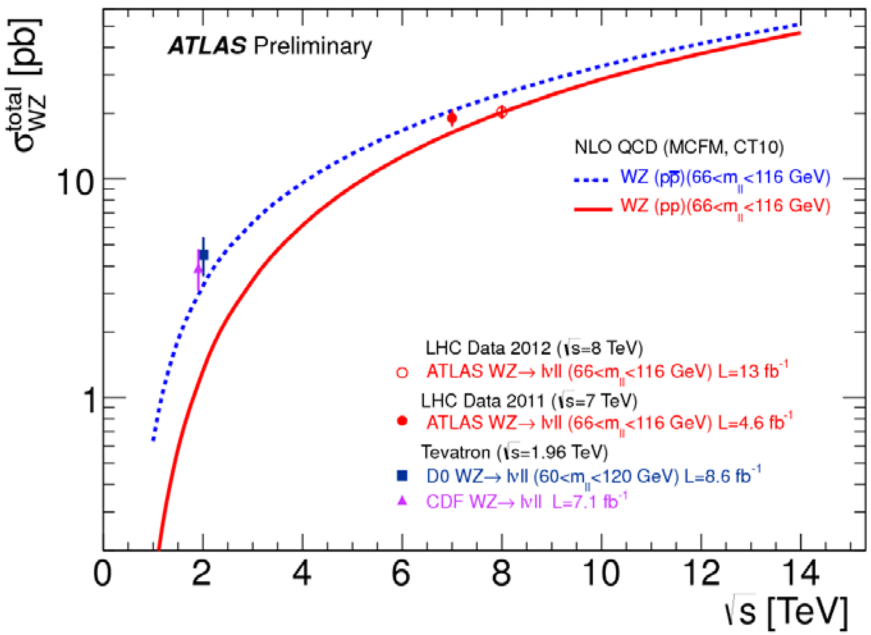
Definitely an area in need of further development to help link all the coupling measurements made for the Higgs, and in di-boson and tri-boson final states, now being made with full Run1 data into a more coherent picture of allowed deviations from EWK Lagrangian.

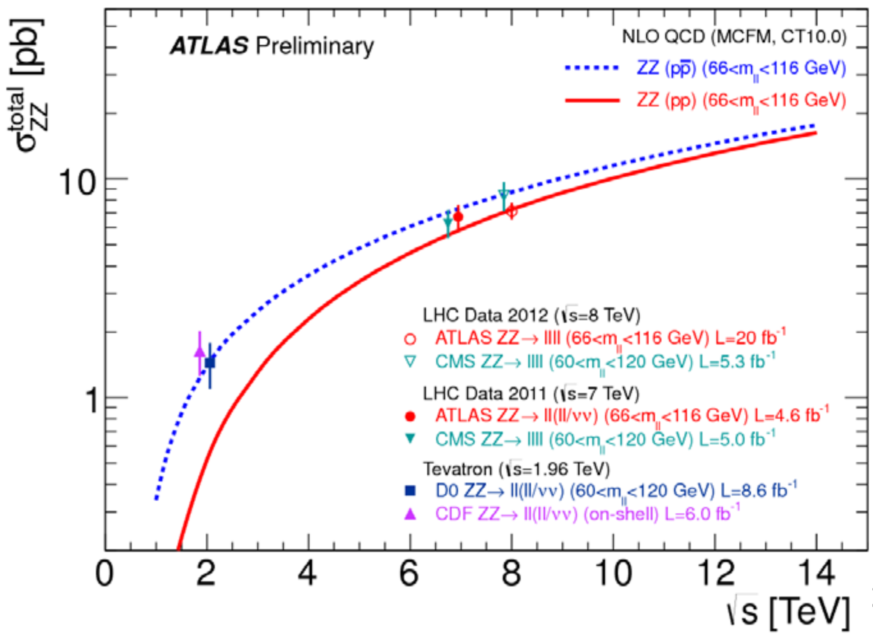
WW CMS-SMP-12-013
ZZ CMS-SMP-12-014

Diboson Studies at the LHC I

WZ ATLAS-CONF-2013-021
ZZ ATLAS-CONF-2013-020

- Both ATLAS and CMS extensively studied di-boson production using the full 2011 data sample of 5 fb^{-1}. Cover $\gamma\gamma$, W/Z+γ, WW, WZ, and ZZ, and include limits on aTGCs. As $\gamma\gamma$ does not directly probe the gauge self-couplings, do not discuss it further.
- Also have preliminary cross-section results for most di-boson final states at 8 TeV. CMS has measured the WW and ZZ cross-sections with 5 fb^{-1}, ATLAS has measured the WZ cross-section with 13 fb^{-1} and the ZZ cross-section with 20 fb^{-1}.
- At 7 TeV, general trend for cross-sections to be high by (1-2σ). WW highest (10-15%).
- Among the 8 TeV results, all agree within about 1σ with SM expectations (typically MCFM within a fiducial region), except for CMS WW which is about 2σ high. Most likely just NNLO QCD corrections missing, but there is sensitivity to EWK effects too !





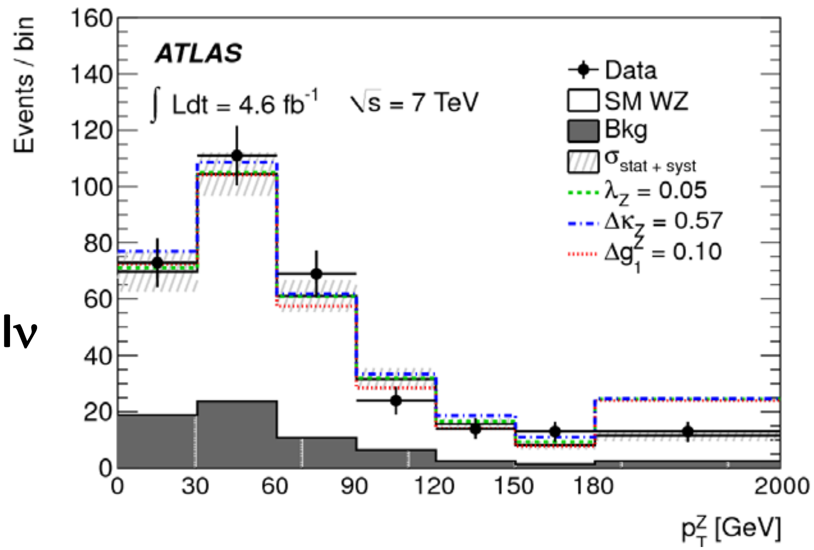
ATLAS:
WW hep-ex 1210.2979
WZ hep-ex 1208.1390

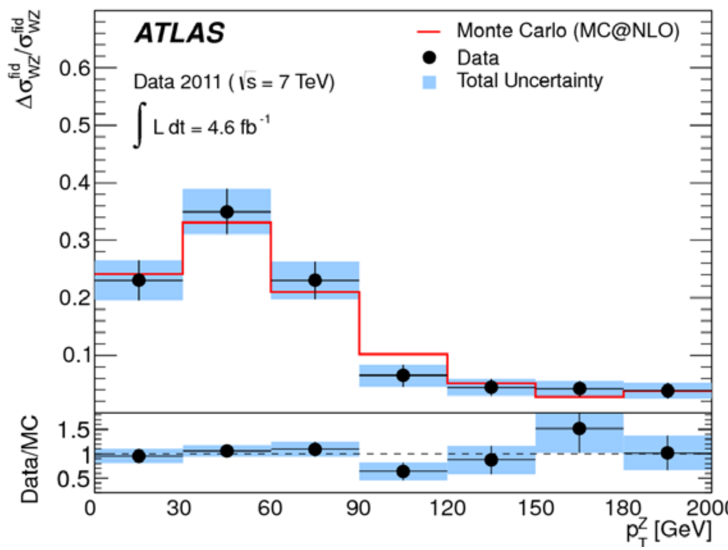
Diboson Studies at the LHC II

ATLAS
W/Zγ hep-ex 1302.1283
ZZ hep-ex 1211.6096

- Deviations due to "new physics" tend to affect kinematic tails more than integral σ.
- ATLAS has done systematic unfolding of relevant distributions in all diboson modes.

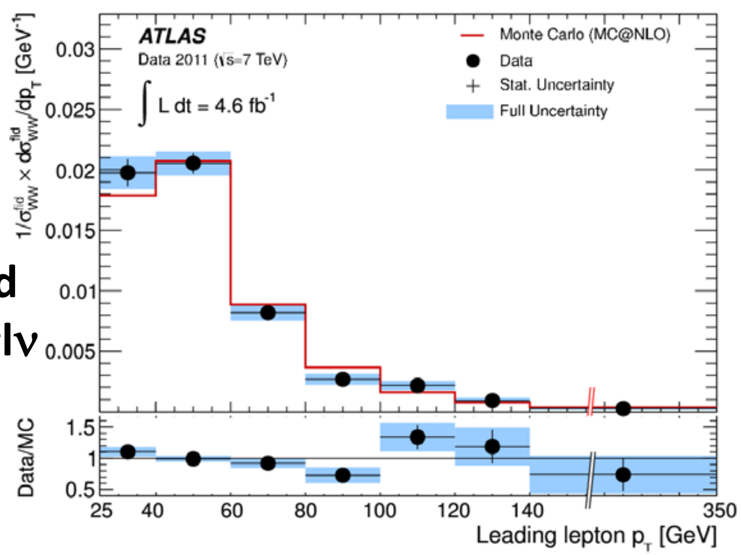
raw
WZ->lllν
$P_T(Z)$

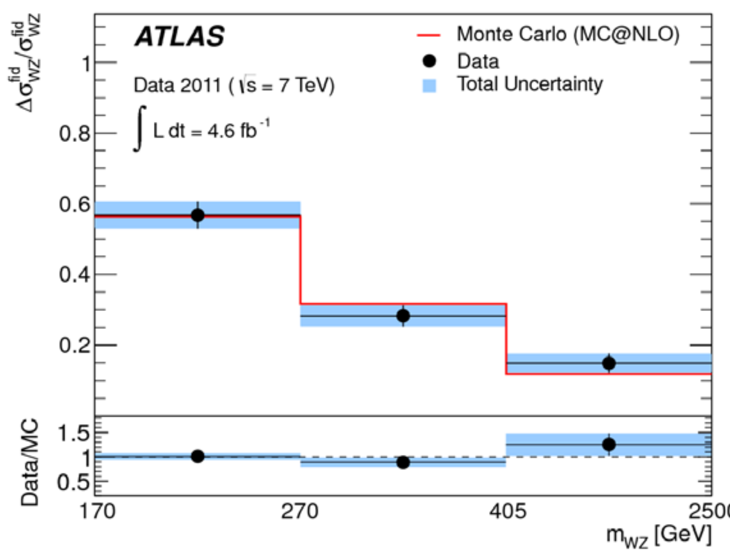




unfolded
WZ->lllν
$P_T(Z)$

unfolded
WW->lνlν
$P_T(l)$





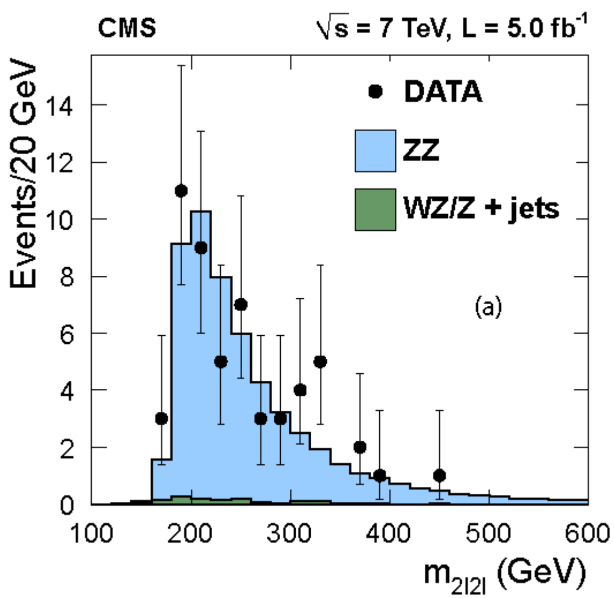
unfolded
WZ->lllν
m(WZ)

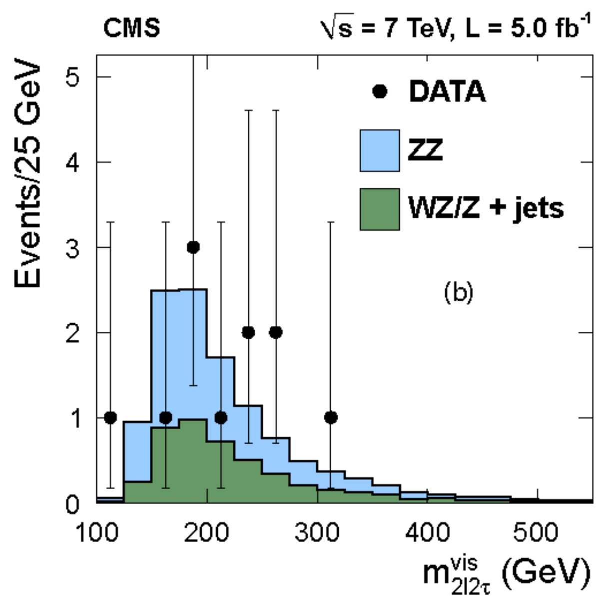
CMS:
WW SMP-12-005
WW/WZ hep-ex 1210.7544

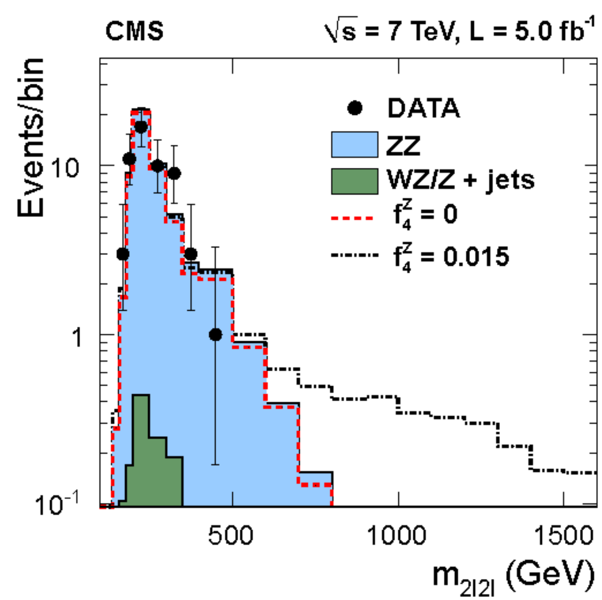
Diboson Studies at the LHC III

CMS
W/Zγ EWK-11-009
SMP-12-020
ZZ hep-ex 1211.4890

- Deviations due to "new physics" tend to affect kinematic tails more than integral σ.
- ZZ statistics still very limited, but backgrounds are low for 4l. No excess at high mass.
- CMS also includes $2l2\tau$ channel.
- Right plot shows impact of aTGC not equal to zero (f_4^Z=0.015).



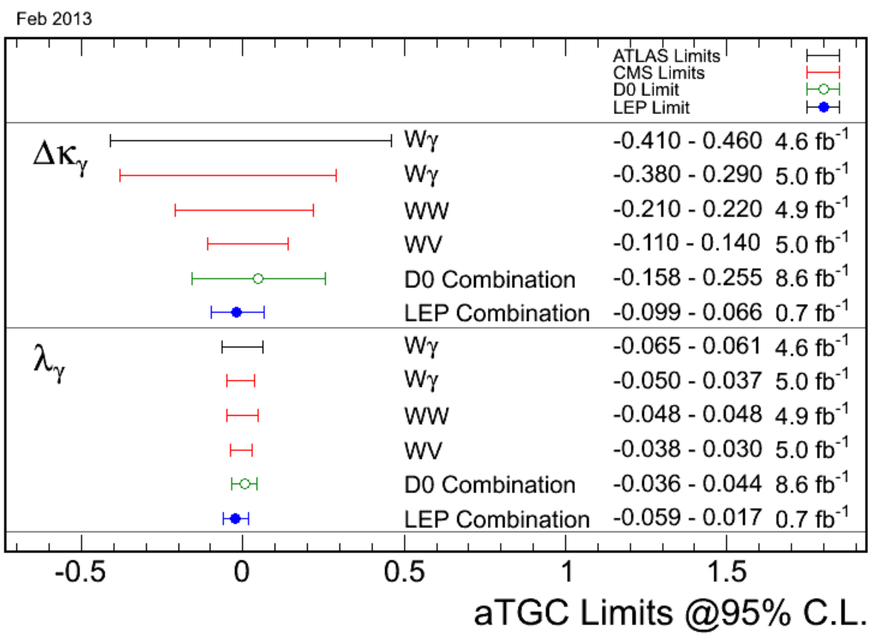


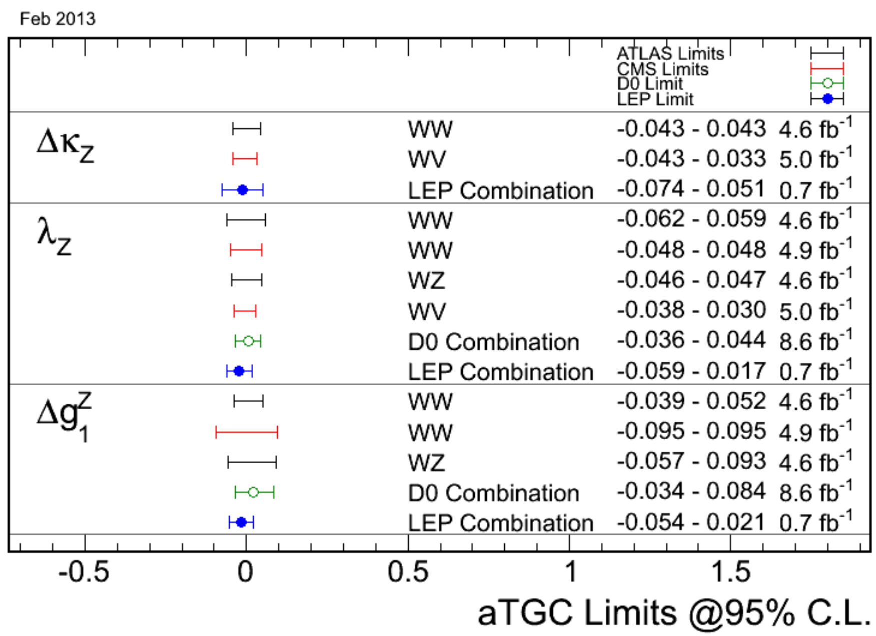


Diboson Studies at the LHC IV

- No deviations seen in differential kinematic distributions for W/Z+γ, WW, WZ, or ZZ.
- Set limits on 5 anomalous **charged couplings** accessible in W+γ, WW, WZ channels.
- For W+γ, likelihood fit to events with $E_T(\gamma)$ > 100 GeV.
- For WW, ATLAS shown with LEP convention, likelihood fit to binned P_T(leading lepton)
- For WV, this is CMS WW/WZ -> lνjj, use HISZ convention (λ, $\Delta\kappa_Z$), fit to PT(dijet)
- For WZ, ATLAS shown with LEP convention ($\Delta\kappa_Z$ missing in table), fit to binned P_T(Z)

- Basic message: no deviations from SM, LHC limits already close or equal to LEP limits. Note all limits set assuming no form-factors (Λ -> infinity).



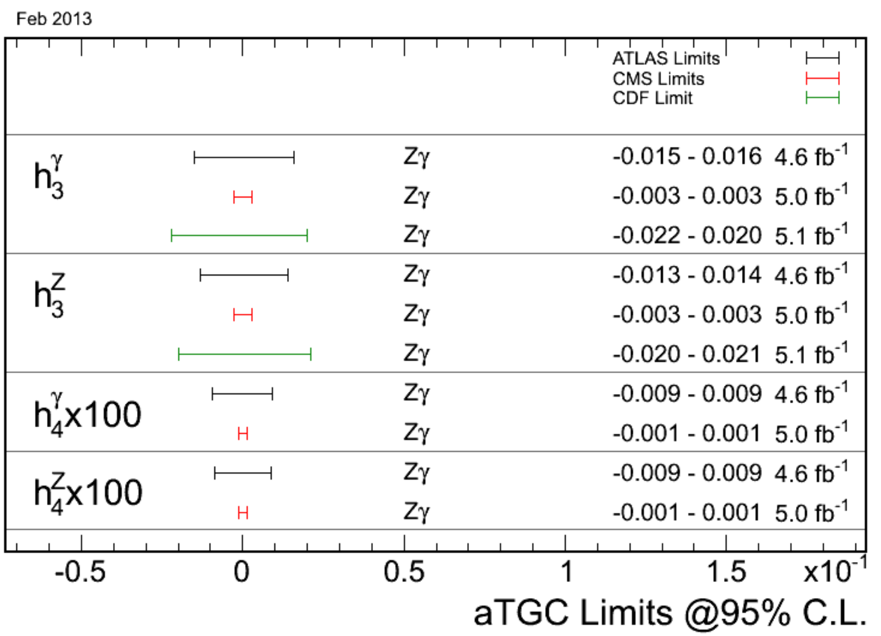


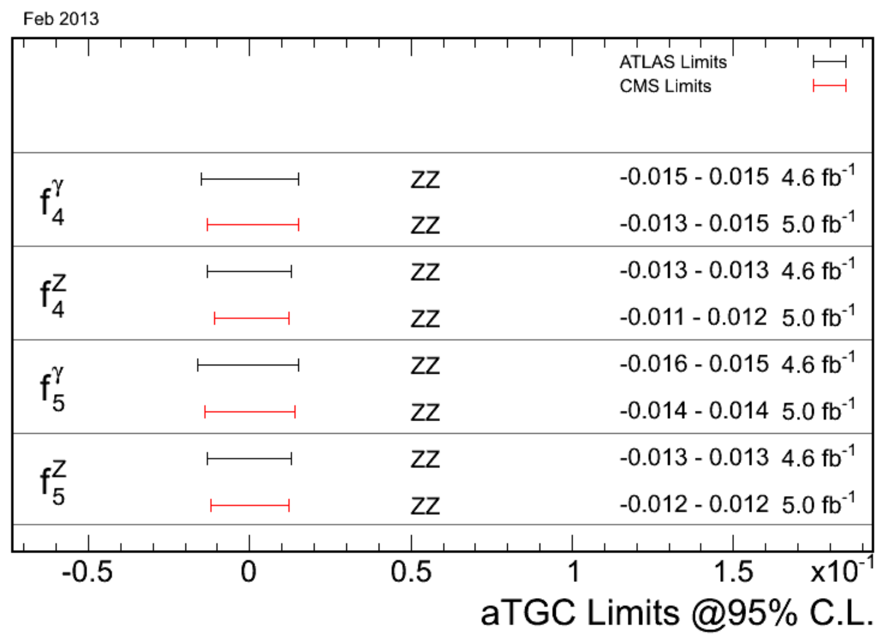
Summary plots courtesy of CMS

Diboson Studies at the LHC V

- No deviations seen in differential kinematic distributions for W/Z+γ, WW, WZ, or ZZ.
- Set limits on 8 anomalous **neutral couplings** accessible in Z+γ, ZZ channels.
- For Z+γ, ATLAS uses likelihood fit to events with $E_T(\gamma)$ > 100 GeV. For the $\nu\nu\gamma$ final state, CMS raises the $E_T(\gamma)$ cut to 400 GeV, achieving almost a factor 10 better limits.
- For ZZ, extract both CP-conserving (h) and CP-violating (f) couplings, likelihood fit to binned $P_T(Z)$

- Basic message: no deviations from SM, LHC limits already far stricter than LEP limits. Note all limits set assuming no form-factors (Λ -> infinity).





Summary plots courtesy of CMS

Diboson Studies at the LHC VI

- Recent progress in calculating di-boson cross-sections at NNLO in α_S and in calculating EWK corrections at NLO (α^3).

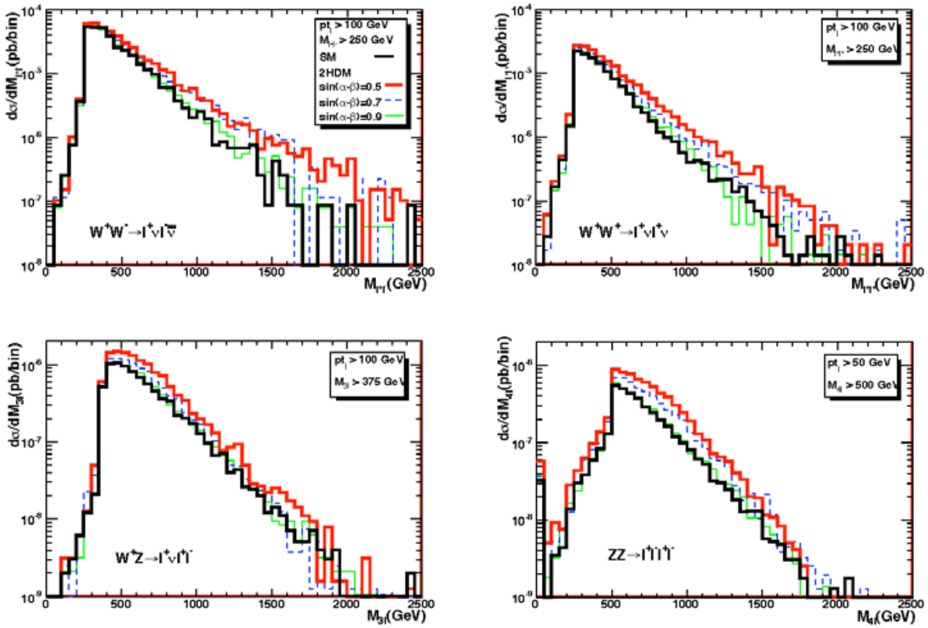
- For EWK corrections, initial calculation for WW (hep-ph 1208.3147) and for the complete set of di-boson final states including $\gamma\gamma$, WZ, and ZZ (hep-ph 1305.5402).
- Typically total cross-section is reduced by about 5%. However, the differential cross-section for WW at large P_T(W) or m(WW) can decrease by 10-30% for the dominant qq -> WW process. Similar results are found for WZ and ZZ. These results can have a significant impact on next generation analyses which will probe the tails of P_T/mass distributions with moderate statistics.

- For QCD corrections, some first results from an approximate NNLO calculation for WZ (hep-ph 1305.6531) indicate fairly significant enhancements at large P_T (500-1000 GeV and K-factors of 1.5 or 2 relative to the NLO calculation).
- These large corrections arise because new channels open up (qq channel is LO, qg opens at NLO, and gg opens at NNLO).

- Clearly, precision di-boson physics will require all of these corrections to be fully computed - sensitive searches for aTGC risk to find false anomalies without these corrections in the theory predictions. Needed for Run2/Run3 period with 300 fb^{-1}.

Diboson Studies at the LHC VII

- One problem with looking for deviations from SM in areas like di-boson production or aTGC/aQGC, is that it is not clear what scale of deviation is really interesting.

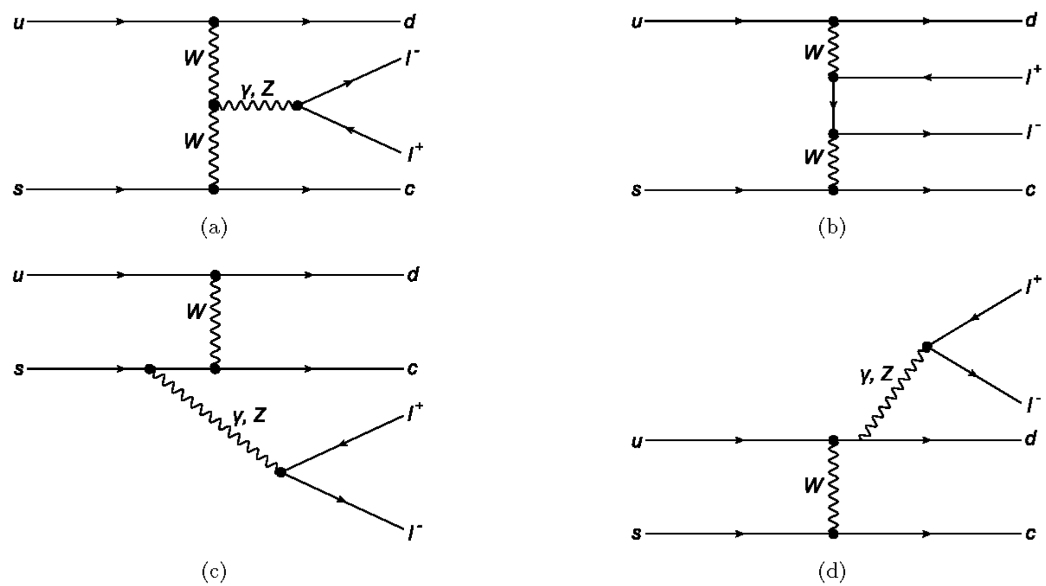


- A (naïve) example (hep-ph 1303.6335), is a model with a 2-HDM with h as the 125 GeV object of today, and H being very heavy (about 2 TeV).
- As expected, there are enhancements visible in VBF-like di-boson final states => some sensitivity to very heavy 2HDM models (this assumes order 300 fb^{-1} at 14 TeV), particularly in WW.

- Various SUSY models with light stops (hep-ph 1303.5696) or sleptons (hep-ph 1304.7011) would “predict” or be consistent with, modest excesses in the SM WW cross-section. However, would still expect targeted searches to be more sensitive…
- A recent calculation of loop effects on di-boson production due to a simple UED model (hep-ph 1305.0621) indicates that aTGC for a scale in the range of 1-3 TeV would be roughly $\Delta\kappa$ = a few 10^{-3} to a few 10^{-4}. This is almost certainly beyond the reach of LHC…

Beyond Dibosons at LHC: QGC and VBF/VBS I

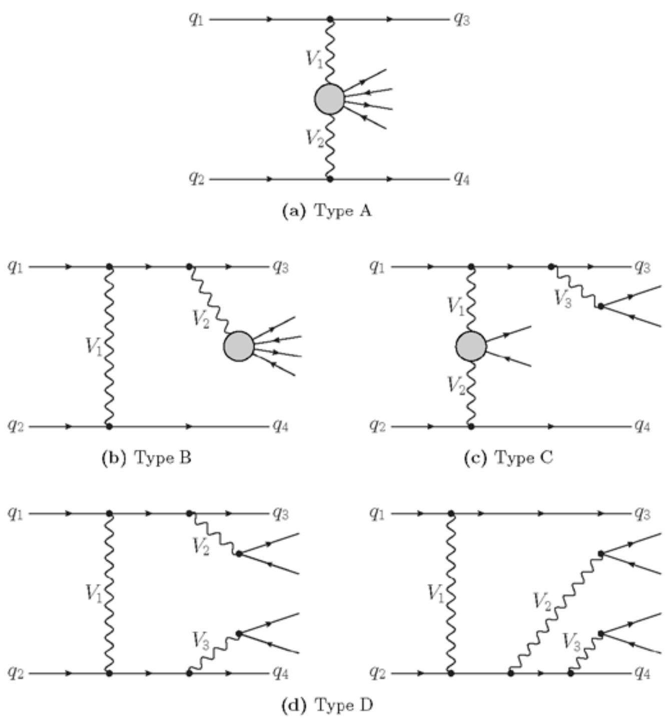
- With increasing luminosity, become sensitive to tri-boson final states.
- From Run1 data sample, $W\gamma\gamma$ and $Z\gamma\gamma$ signals are feasible, $WW\gamma$ and $WZ\gamma$ now short on statistics, but will emerge in Run2. Many diagrams, including QGC, TGCs, etc.
- Begin setting limits on anomalous QGCs (quartic self-interactions), limited sensitivity.
- In addition, becoming sensitive to VBF processes. For now, investigate VBF production of W and Z. For QCD bkgd, have NLO ME+PS for n-jet up to 2, and NLO ME for n-jet up to 4-5. Precise experimental measurements over wide range => background "known".
- After coping with very large QCD backgrounds from V+2-jets, then have multiple EWK (α^4) diagrams contributing (below). Available at NLO in Powheg (NLO ME + PS):



- Only diagram (a) involves TGC – need to work to isolate anomalous contributions.

Beyond Dibosons at LHC: QGC and VBF/VBS II

- The next step in VBF studies is investigating VBF production of di-bosons.
- This is the definitive means to study potential imperfect cancellations in vector boson self-couplings, looking at TeV scales, etc…
- Have not yet started serious studies of VV+jets, and do not have corresponding NLO ME+PS calculations (except W^+W^+ + 2-jet). Run1 data will provide first measurements.
- For VBF, have to cope with very large QCD backgrounds from VV+2-jets, then have both mixed $\alpha_s^2\alpha^4$ and multiple EWK (α^6) diagrams contributing (below).



(a) Type A

(b) Type B

(c) Type C

(d) Type D

- For now, have only parton-level NLO (VBFNLO) calculations of signals and backgrounds.

- Need everything available in NLO ME+PS generator like Powheg.
- Also need many additional experimental measurements of QCD backgrounds in particular.
- Real measurements are a Run2 (and beyond) project !

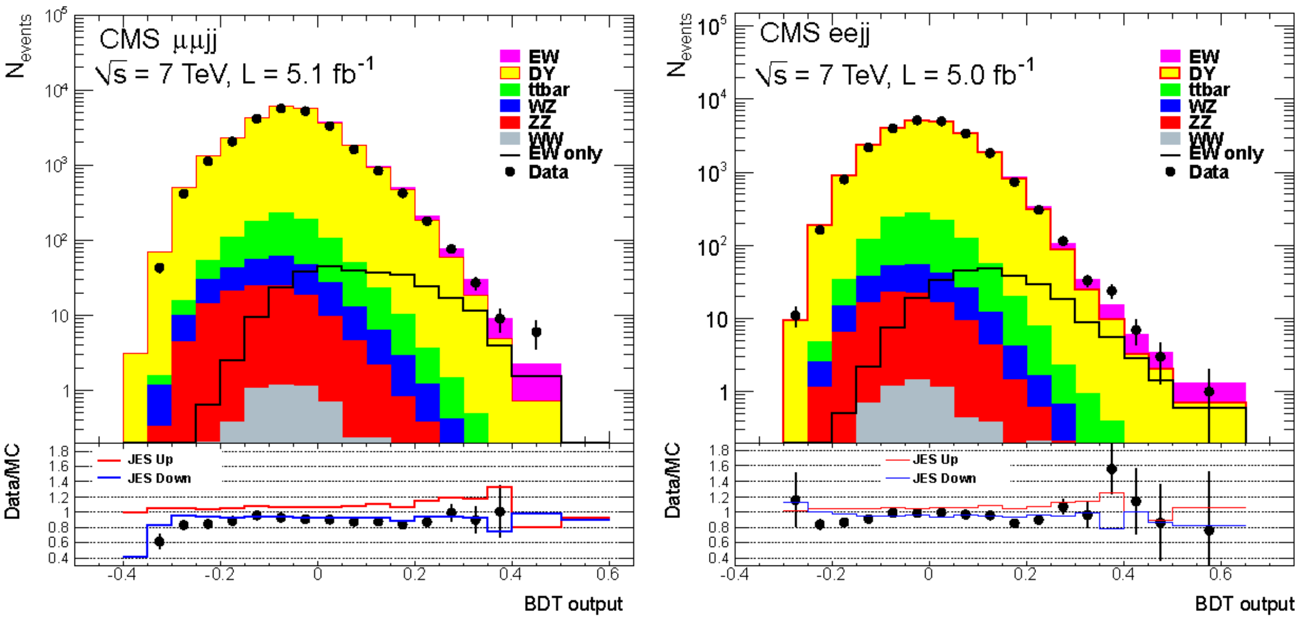
- Only diagram (a) involves QGC – need to work to isolate anomalous contributions.

Beyond Dibosons at LHC: QGC and VBF/VBS III

- What measurements are available today ? CMS have been pioneers in this area, with two ambitious, but statistically very limited, results:

Extracting EWK production of single Z in 5 fb^{-1} of 7 TeV data (hep-ex 1305.7389):

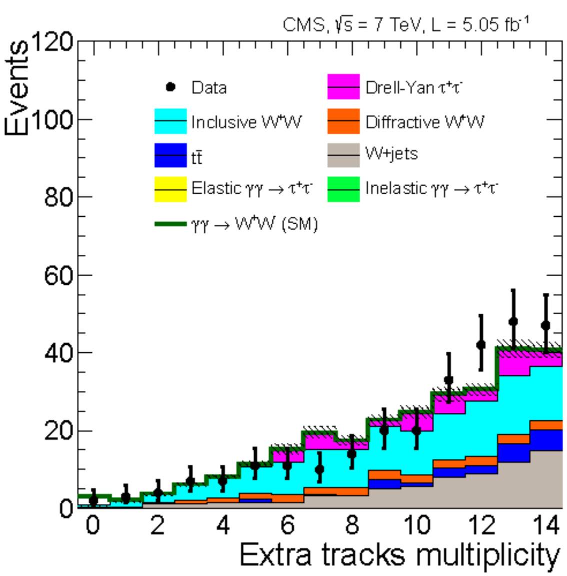
- Choose two highest P_T jets to be tag jets, and optimize jet criteria to select EWK tag jets using processes implemented in MadGraph5 – technically analysis aims to extract EWK production of single Z, since it is not obvious that VBF contribution is dominant.
- Demonstrate good modeling of dominant QCD Z+jets background in relevant variables and regions of phase space.
- Extensive use of BDT to "concentrate" EWK contributions at high discriminant values.
- Resulting "excess" is consistent with expectations for EWK Z production:

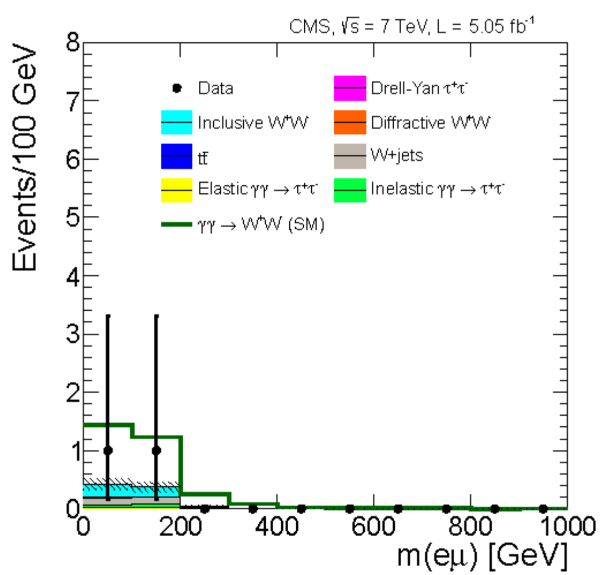


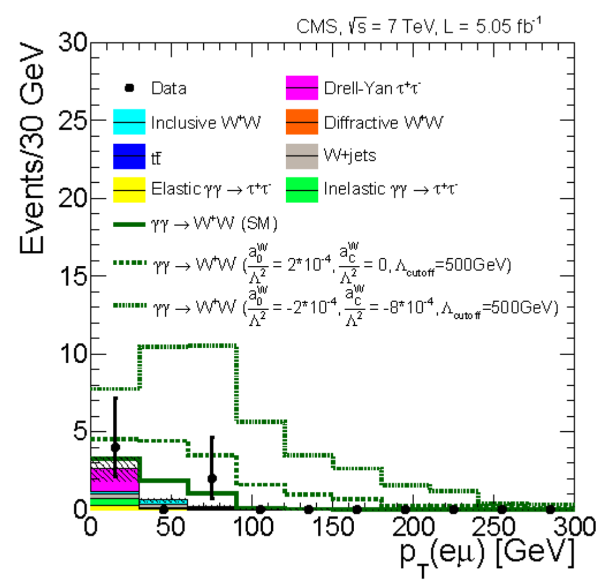
Beyond Dibosons at LHC: QGC and VBF/VBS IV

Exclusive production of WW ($\gamma\gamma$ ->WW) in 5 fb^{-1} of 7 TeV data (hep-ex 1305.5596):

- Choose only OS μe channel to reduce DY backgrounds. Require $P_T(\mu e) > 30$ GeV.
- Force exclusive production mode (VBF-like) by requiring only two leptons are associated with primary vertex for final SM signal region (no other tracks from PV).
- Set limits on aQGC by looking for events with $P_T(\mu e) > 100$ GeV.
- Lower left plot shows the distribution of estimated backgrounds in N(extra tracks), center plot shows 2 signal events after all cuts, consistent with expectations, lower right plot shows AQGC limit setting before $P_T(\mu e) > 100$ GeV cut removes all events.
- Limits on aQGC are $a_0^W/\Lambda^2 < 10^{-4}$ and $a_C^W/\Lambda^2 < 10^{-3}$ for Λ=500 GeV, 100x below LEP.







“Homework Problems” for Run2

1. Need to develop a framework, presumably based on EFT, which allows combined analysis of Higgs couplings, TGC/QGC couplings, etc. in a coherent manner to best set limits on additional contributions to the EWK Lagrangian. Need common agreement on assumptions (anomalous couplings: just require Lorentz invariance for vector boson self-couplings ? EFT: assume SU(2)xU(1) gauge theory ?)

2. Need to develop coherent NLO ME + PS calculations for all components of EWK and VBF analyses (tri-bosons, single W/Z + 2-jets, di-bosons + 2-jets, etc.). Also need NNLO QCD and NLO EWK calculations of di-boson cross-sections within fiducial regions as for single W/Z (FEWZ and DYNNLO). Similarly, need access to differential NNLO Top calculations, and more rigorous modeling for Top mass measurements in NLO ME + PS (ideally, would need NLO ME + PS multi-leg).

3. Current limits for inclusive W/Z cross-sections are less than 1% per lepton, and roughly 1.5-2% for luminosity. Need to bring di-boson measurements to same level of precision (1-3% fiducial cross-sections) for 300 fb^{-1} measurements.

4. Need to develop active program in improving SM analyses that are foundations for precision EWK, e.g. PDF fitting, higher precision object calibrations, etc. Critical ingredients for next generation m(W), m(Top), and $A_{fb}/\sin^2(\theta_{eff})$ measurements !