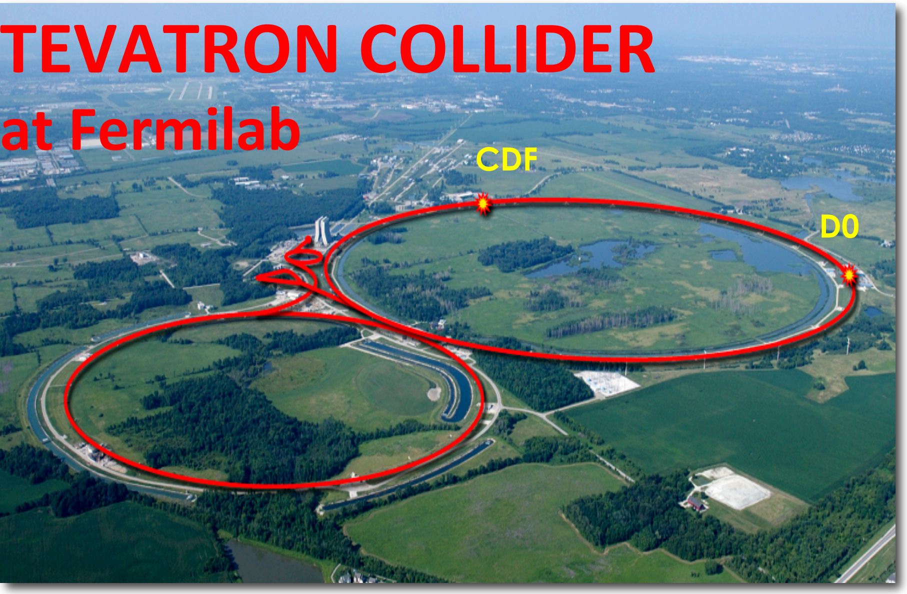
Status of Electroweak Physics

Slawek Tkaczyk

FERMILAB



Standard Model After the Higgs Discovery

- Several parameters describe the SM formulation
  - At tree level gauge sector described by three free parameters: e.g. most precisely measured: **α, M_Z, G_{Fermi}**
    - Correspond to Gauge sector parameters (g, g’, vev)
  - Additional parameters essential for radiative corrections: M_t, M_H, α_s (equivalent to: Yukawa top, λ_{Higgs})
  - Radiative corrections modify the propagators and vertices
    - Modifications to the couplings and M_W
- Radiative corrections as a test of the SM and constraints of new unknown parameters
  - Constrains on Higgs mass prior to its discovery
  - Super-seeded with the measurement M_H=125.7±0.4 GeV

Standard Model After the Higgs Discovery

- Theoretical achievements:
  - SM observables known to at least two loop calculation
  - Higher order calculation available for selected observables

- Experimental achievements:
  - Precision measurements available from LEP/SLC, Tevatron and LHC
  - Discovery of the Higgs boson and its mass determination
    - SM has no free parameters anymore

Standard Model After the Higgs Discovery

- Many SM observables can be defined and/or measured:
  - Total and partial cross sections
  - Strong and electromagnetic couplings
  - Asymmetries: forward-backward, left-right
  - Partial and total width of vector bosons
  - Hadronic and leptonic width ratios
  - Effective mixing angle
  - Masses of the fermions
  - Masses of W,Z and Higgs bosons

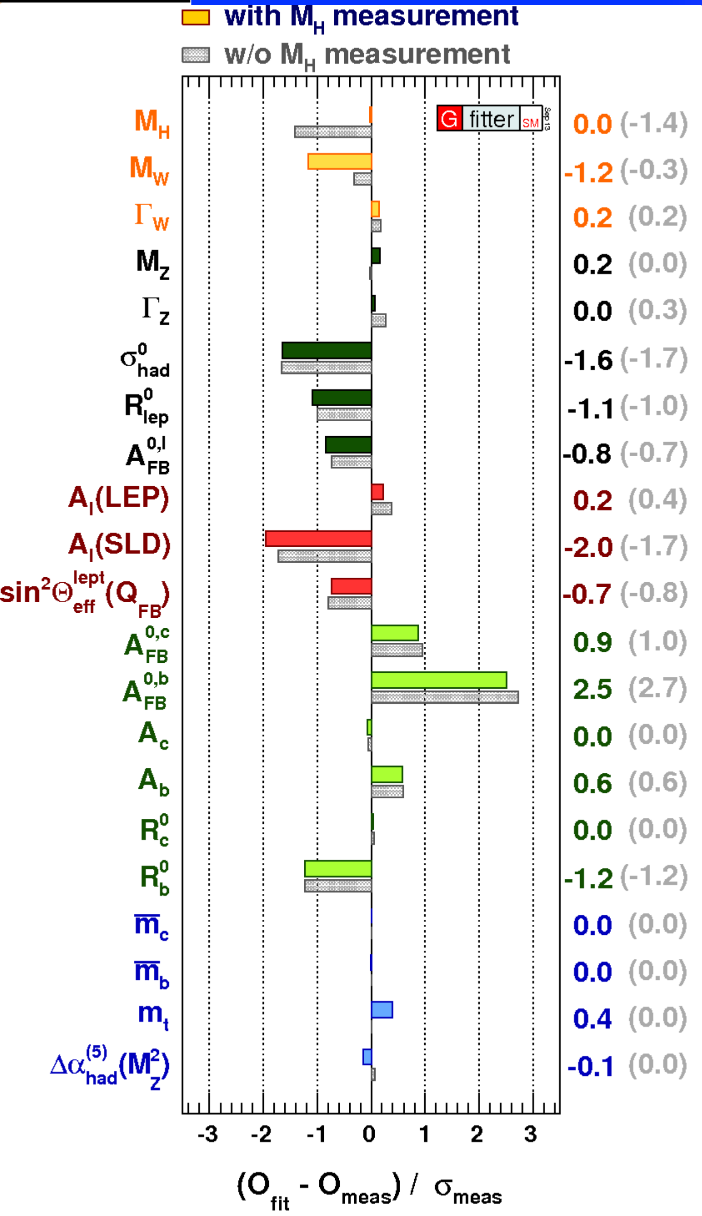
- In principle, all can be precisely computed using a fixed, complete, independent and finite set of input parameters
  - e.g.:[M_H, M_Z, $m_{f,}$ $\alpha_S(M_Z)$, $\Delta\alpha(M_Z)$, G_F]

Standard Model after the Higgs discovery

- **How to precisely test consistency of the SM after the Higgs discovery?**
        - No more missing parameters !
    - quantify the consistency within the SM observables
    - detect the differences among them leading to a hint of new physics ?
        - SM is an effective theory !

- **Professional:** run a global fit to all observables and explore the power of statistical tools to characterize the agreement or presence of new physics effects
    - e.g. M_W uncertainties: **15** MeV experimental and **11** MeV in the global fit!
- **Amateur but transparent**: choose an observable, and calculate it as a function of the selected best measured six observables;
    - analyze limitations of existing calculations, check its sensitivity to other parameters and new physics effects
    - e.g.: M_W has **8** MeV uncertainty from 1σ exp. uncertainties on M_t, α_S, α_{EM}

Standard Model After the Higgs Discovery



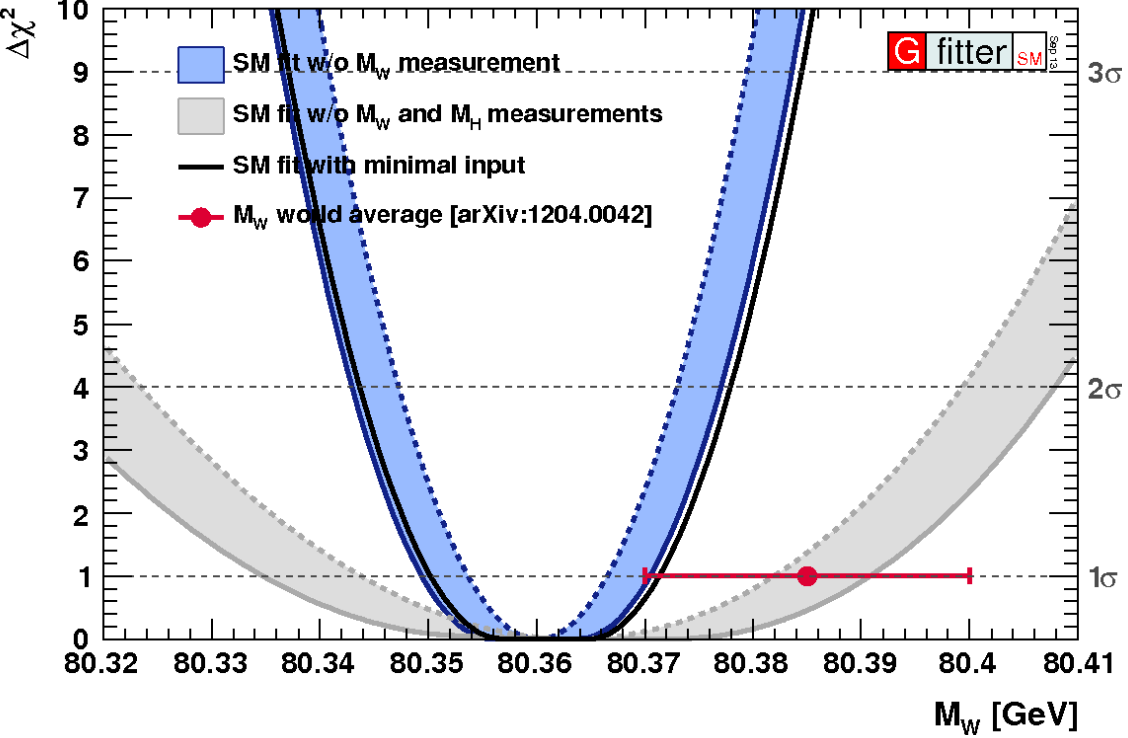
Plot inspired by Eberhardt et al. [arXiv:1209.1101]

- Relative Deviations of the EWK Precision Observables
  - Experimental values compared with fit results
  - Higgs signal strength as input
  - **Better than 3σ agreement with SM**

- Conclusion: **Higgs data have relatively small impact on the deviations for most of the precision observables**
  - Increased deviation of the M_W

http://gfitter.desy.de

Global Fit Results for M_W



- Approach:
  - Measurements of M_W are excluded from the fits
  - M_W fit w/ and w/o M_H
- SM prediction with minimal input:
  - M_Z, G_F, M_H, $\alpha_S(M_Z)$,$\alpha_{had}(M_Z)$ and fermion masses

- Indirect: (with Higgs mass in the fit)

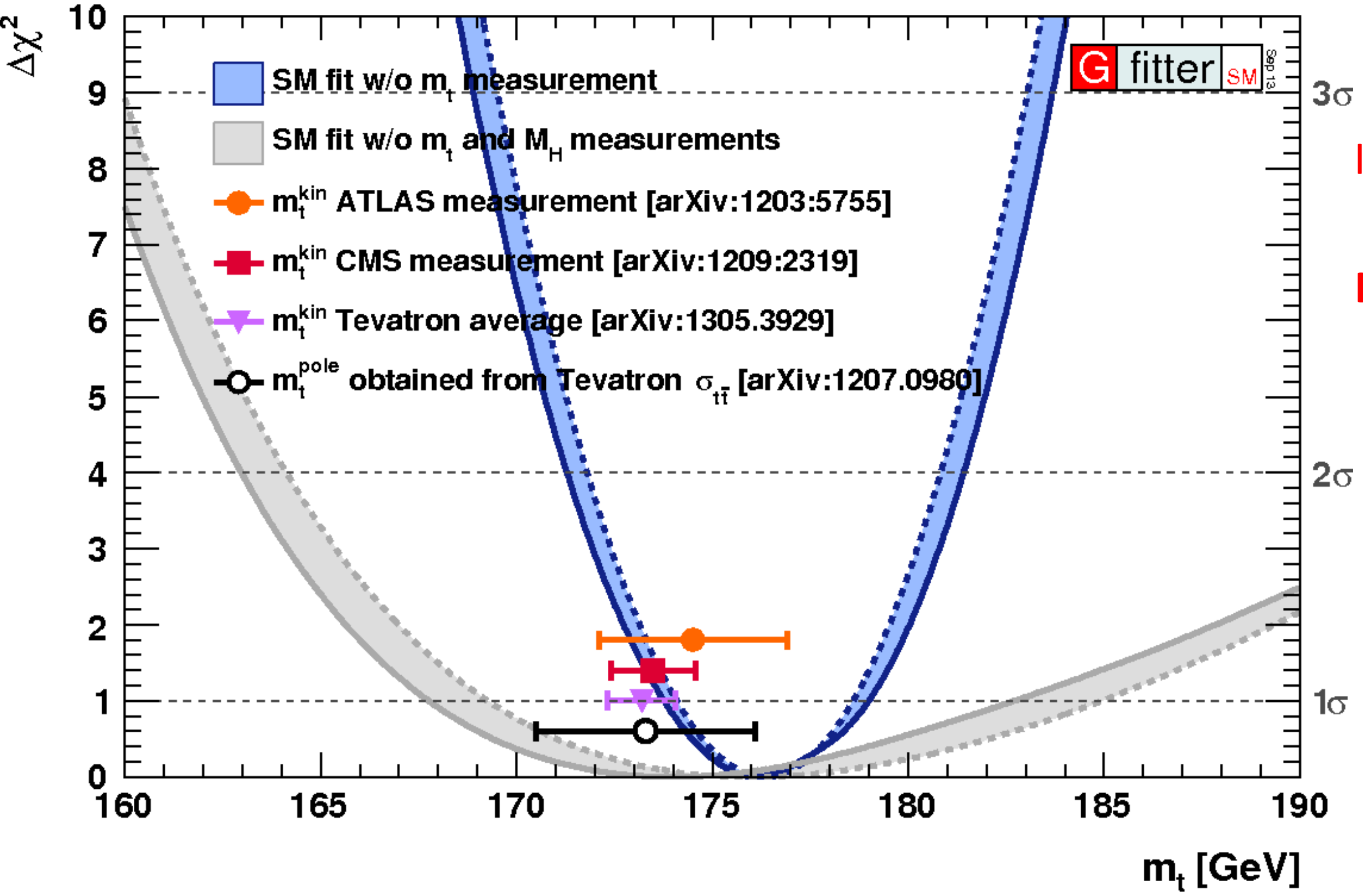
M_W=80,359±11 MeV

- World average (direct):

M_W=80,385±15 MeV

Will be discussed later on!

Global Fit Results for M_t



Indirect mass (with Higgs)

m_t=175.8 $^{+2.7}_{-2.4}$ GeV

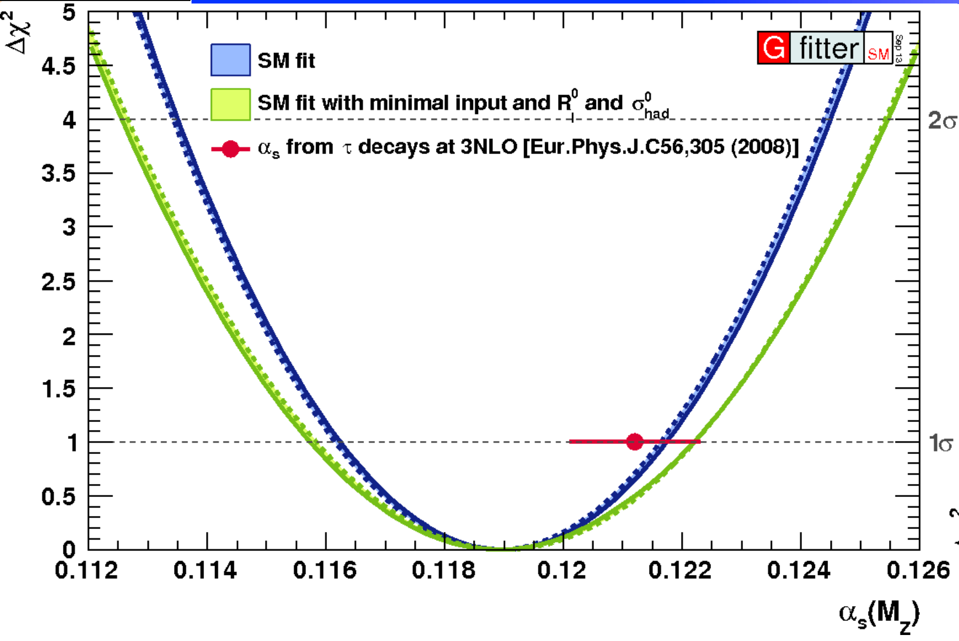
Tevatron value:
m_t=173.2±0.9 GeV

LHC value:
m_t=173.29±0.95 GeV

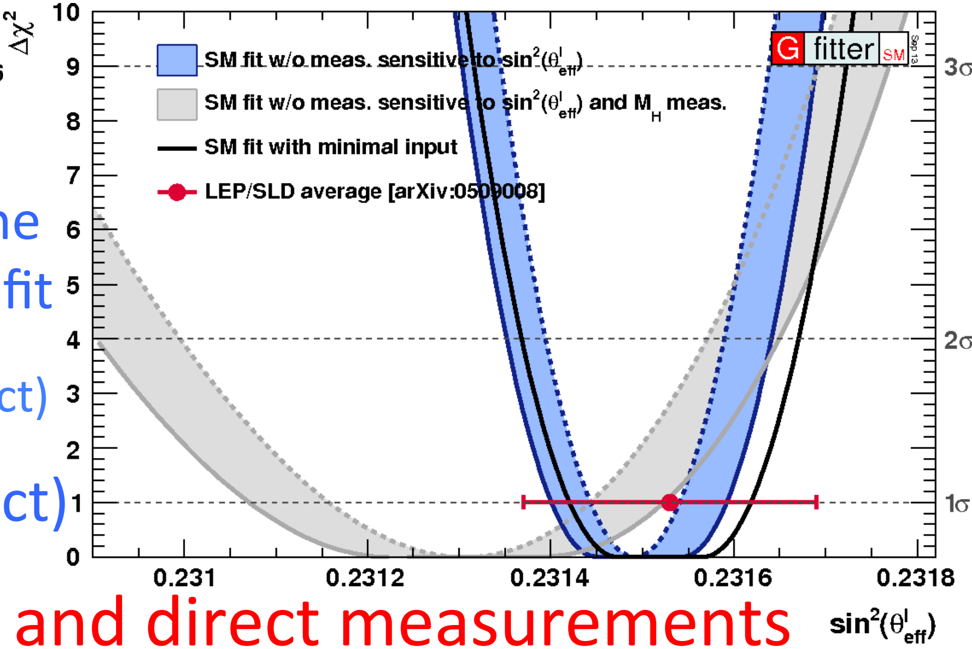
M_H measurement improved the constraint of m_t

- Consistency of the fit results and direct measurements

Sensitivity of α_s and $\sin^2(\theta^l_{eff})$



- Strong coupling at M_Z
- Green: $\alpha_s(M_Z)$ left free in the fit with σ_0(had) and R_0^{lep} used as inputs



- Precision observables sensitive to the mixing angle are excluded from the fit

$\sin^2(\theta^l_{eff}) = 0.2315 \pm 0.0001$ (indirect)

$\sin^2(\theta^l_{eff}) = 0.2324 \pm 0.0012$ (direct)

Consistency of the fit results and direct measurements

Mass of W boson

- Precise theoretical calculations of W mass in the SM:

$$M_W \xrightarrow{SM} (80.368\,\mathrm{GeV})\,(1 + 1.42\,\delta M_Z + 0.21\,\delta G_F - 0.43\,\delta\alpha$$
$$+0.013\,\delta M_t - 0.0011\,\delta\alpha_S - 0.00075\,\delta M_H$$

Almeida,Lee,Pokorski,Wells et al. arXiv:1311.6721
A.Ferroglia, G.Ossola, M.Passera and A.Sirlin,
Phys. Rev. D 65, 113002 (2002) [hep-ph/0203224]

The definition of $\delta\tau$ is $\delta\tau \equiv (\tau - \tau_{ref})/\tau_{ref}$

Parametric and theory uncertainties of SM predictions of M_W

	ΔM_T	$\Delta\alpha_{had}$	ΔM_z	Missing HO	Total
	0.9 GeV	$1.38*10^{-4}$	2.1 MeV	Missing HO [MeV](a)	**Total [MeV]**
ΔM_W[MeV]	**5.4**	**2.8**	**2.6**	**4.0**	**7.6**

m_H	125.7(4)	pole mass m_t	173.5(10)
pole mass m_c	1.67(7)	pole mass m_b	4.78(6)
pole mass M_Z	91.1535(21)	G_F	$1.1663787(6)\ \times 10^{-5}$
pole mass m_τ	1.77682(16)	$\alpha_S(M_Z)$	0.1184(7)
$\alpha(M_Z)$	1/128.96(2)	$\Delta\alpha^{(5)}_{had}$	0.0275(1)

- Uncertainty on M_W – **7.6** MeV!

- Fit result is **11** MeV – higher than 7.6MeV since the best measured observables used !

(a)Awramik et al., Phys.Rev.D69:053006,2004

Editorial Comment

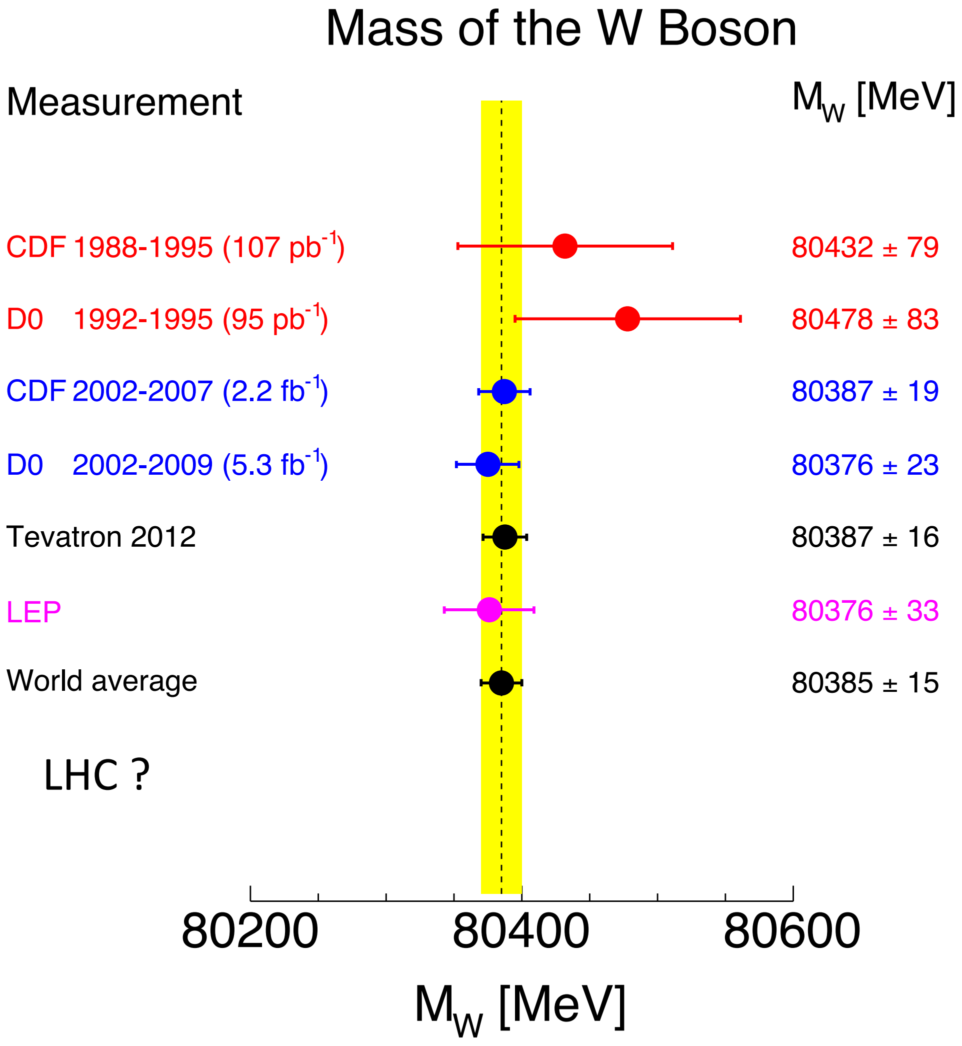
- Perform careful analysis of relations between improvements in experimental measurements, their effect on the parametric uncertainties and the impact of theoretical uncertainties

- Open question to address: what is easier to improve… reduce **4** MeV HO correction… or reduce experimental uncertainties ?

Measurements of W Mass

- Observables transversal to the beam direction
  - – Lepton P_T – dependent on W boson P_T – non-pert. QCD effects important
  - – W boson transverse mass M_T – dependent on resolution effects
  - – Missing E_T – strong dependence on resolution effects – recoil
- M_W obtained from the template fit technique
  - – Different observables
  - – Templates for each value of M_W based on the theoretical model
    - Dependence on NLO EW and QCD corrections, PDF's
  - – Minimization of log likelihood ratio as a function of M_W

Measurements of W Boson Mass



Phys. Rev. D 88, 052018 (2013) (arXiv:1307.7627)

- M_T most sensitive variable
  - Also MET and lepton P_T
- CDF – most precise M_W measurement **19 MeV**!

- World average W mass is:

M_W = 80385 ± 15 MeV

- Tevatron Legacy results:

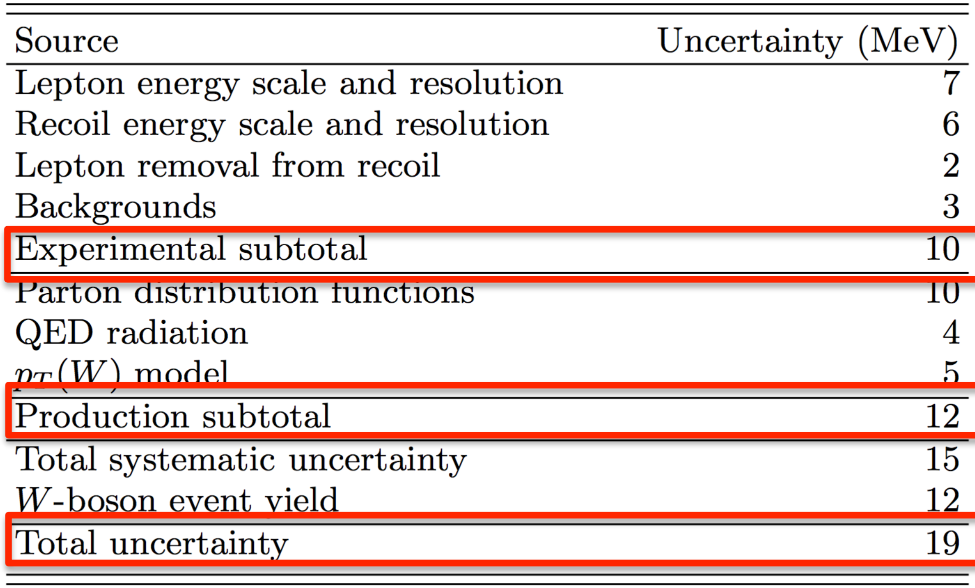
PRD 89, 072003 (2014) CDF

PRD 89, 012005 (2014) D0

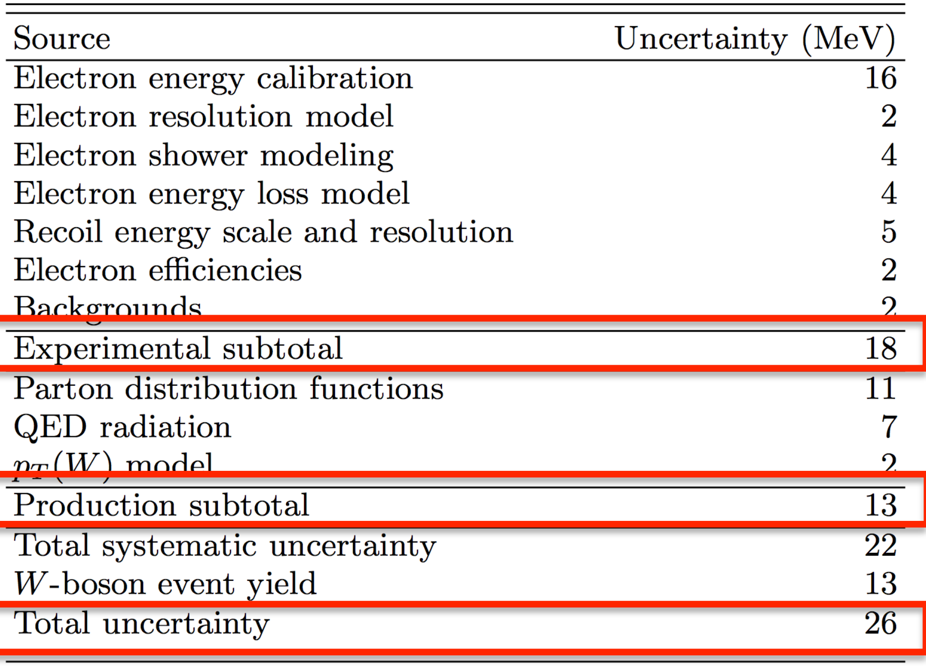
Tevatron 2012 M_W Results

CDF 2012: Phys. Rev. Lett. 108, 151803 (2012)
Phys. Rev. D 89, 072003 (2014) arXiv:1311.0894

D0 2012: Phys. Rev. Lett. 108, 151804, (2012)
Phys. Rev. D **89**, 012005 (2014), arXiv:1310.8628



Source	Uncertainty (MeV)
Lepton energy scale and resolution	7
Recoil energy scale and resolution	6
Lepton removal from recoil	2
Backgrounds	3
Experimental subtotal	10
Parton distribution functions	10
QED radiation	4
$p_T(W)$ model	5
Production subtotal	12
Total systematic uncertainty	15
W-boson event yield	12
Total uncertainty	19



Source	Uncertainty (MeV)
Electron energy calibration	16
Electron resolution model	2
Electron shower modeling	4
Electron energy loss model	4
Recoil energy scale and resolution	5
Electron efficiencies	2
Backgrounds	2
Experimental subtotal	18
Parton distribution functions	11
QED radiation	7
$p_T(W)$ model	2
Production subtotal	13
Total systematic uncertainty	22
W-boson event yield	13
Total uncertainty	26

CDF:

M_W=80,387+/-12(stat)+/-15(syst)
=80,387+/-19 MeV

D0 :

M_W= 80.375+/-0.011(stat)+/-0.020(syst) GeV
= 80.375+/-0.023 GeV

W Mass at the LHC

- Important physics measurement in the LHC program
  - Large samples of W, Z in 2011-2012 data sets
- Differences between pp (LHC) and pp-bar (Tevatron) collisions
  - Differences in W+ and W- production, PDFs

- Challenges for LHC for precision M_W determination:
  - Theoretical understanding of the $p_T(W)$
  - Improved PDFs (strangeness)
  - Pile-up effects on soft recoil

- Discussions at Snowmass'13
- A lot of work ahead !

- **TOP QUARK MASS Determination**

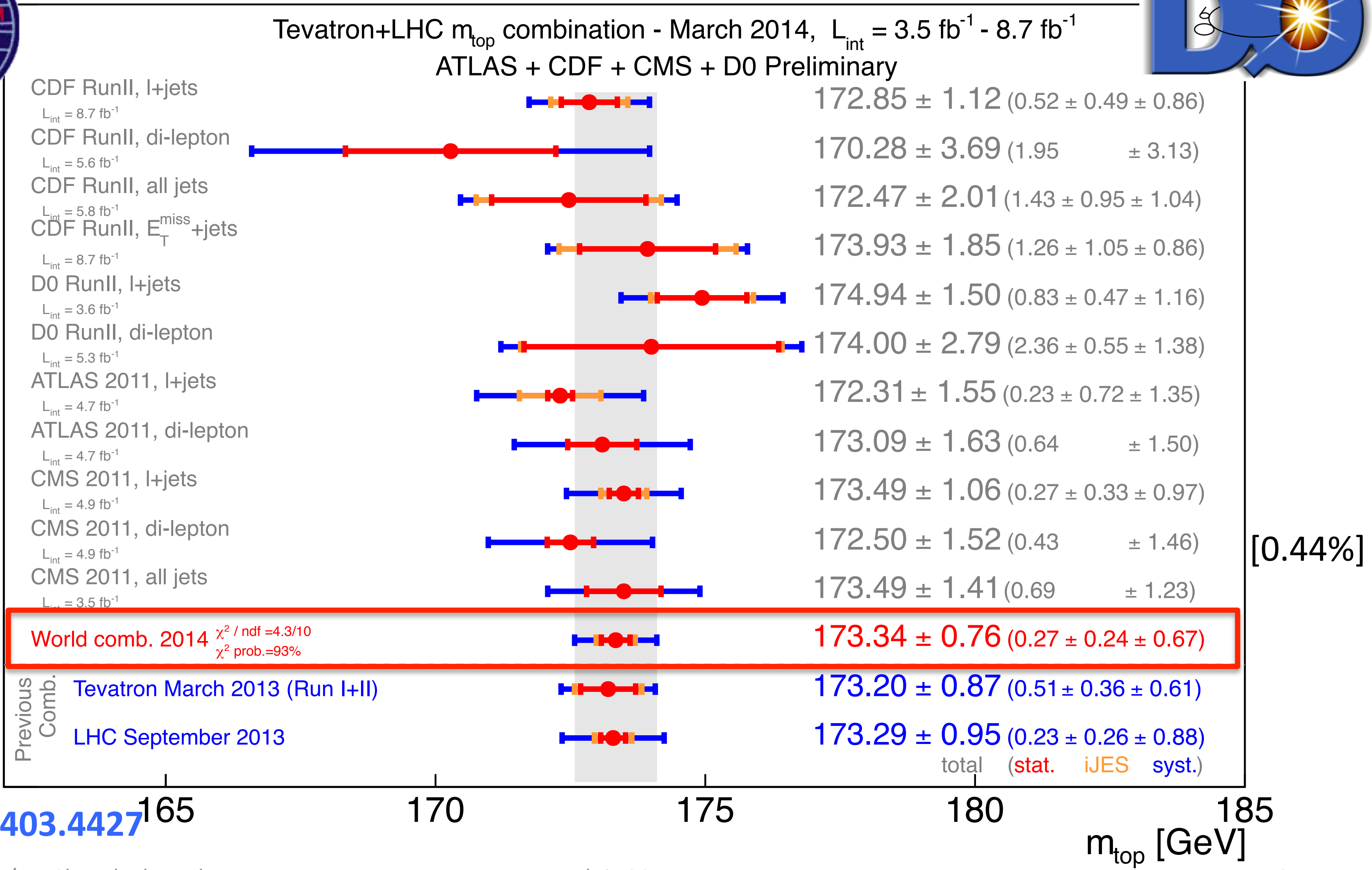
Top Quark Mass

- Important precise parameter of the SM
  - Critical input to the EWK global fits to constrain the Higgs properties, and to assess the internal consistency of the SM

- Experimental methods of measurement of the top mass
  - Templates – generated distributions with different M_t
  - Matric Element – probability based on ME using full kinematics
  - Ideogram – event likelihood evaluated from analytical expressions

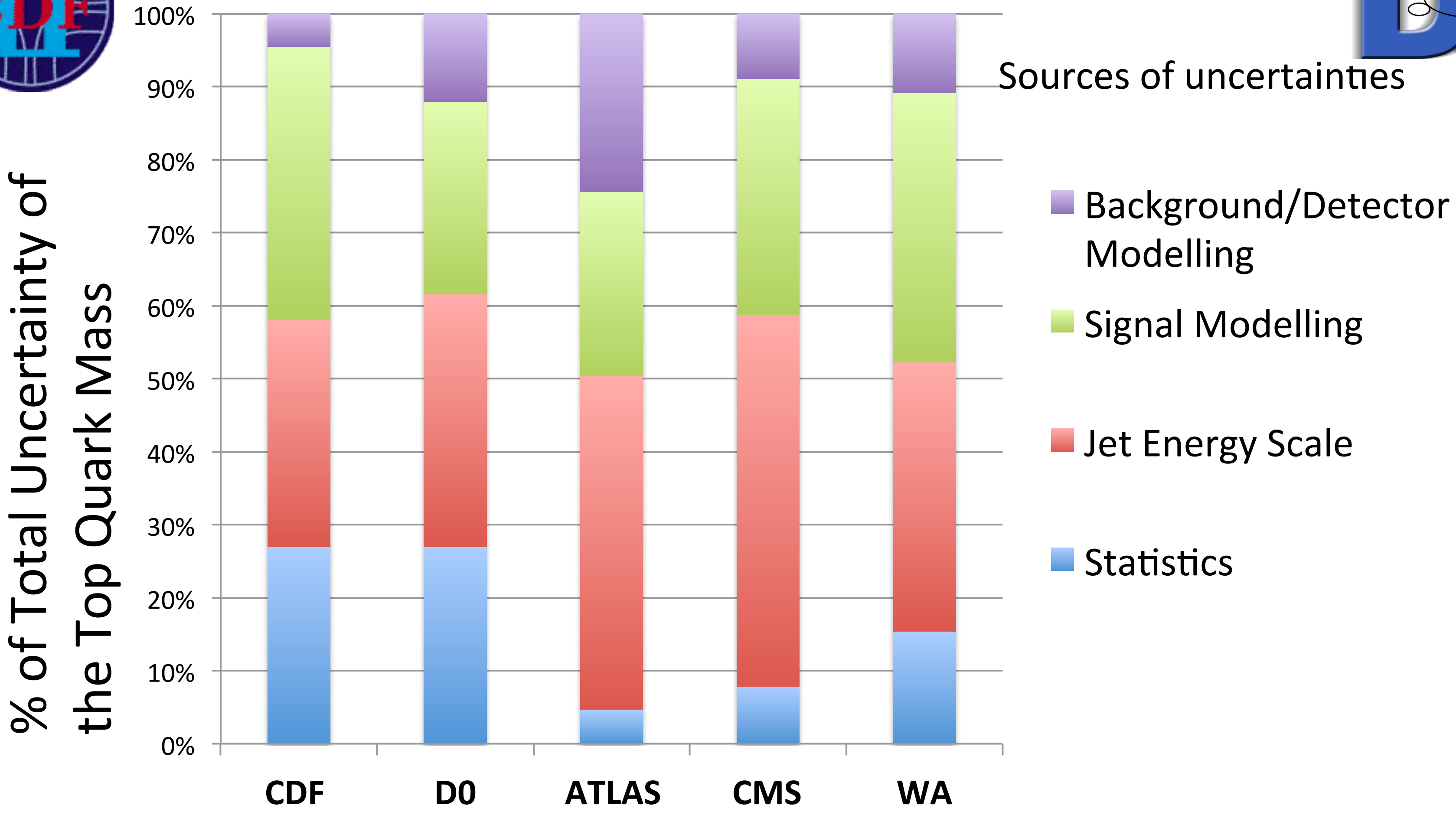
  - Use same systematic categories between experiments

Top Quark Mass Measurements



arXix: 1403.4427

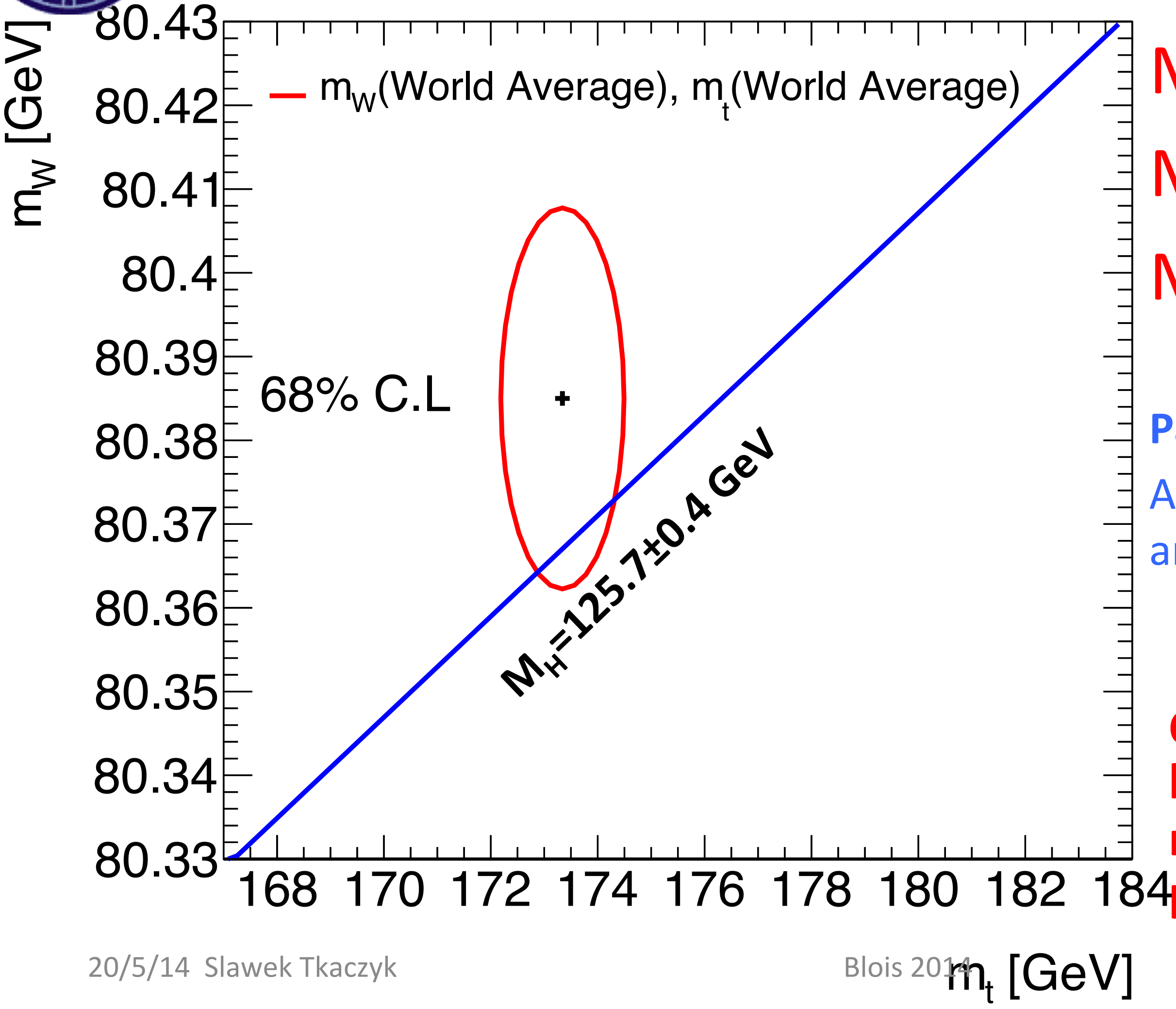
Top Quark Mass Measurements



ATLAS, CMS, CDF, D0 – arXix: 1403.4427 March 2014

M_W, M_t, M_H Combination

- World's best M_t , M_W combinations with the M_H measurement included



M^{dir}_W=80385±15 MeV

M^{dir}_t=173.34±0.76 GeV

M^{dir}_H=125.7±0.4 GeV

Parametrisation:

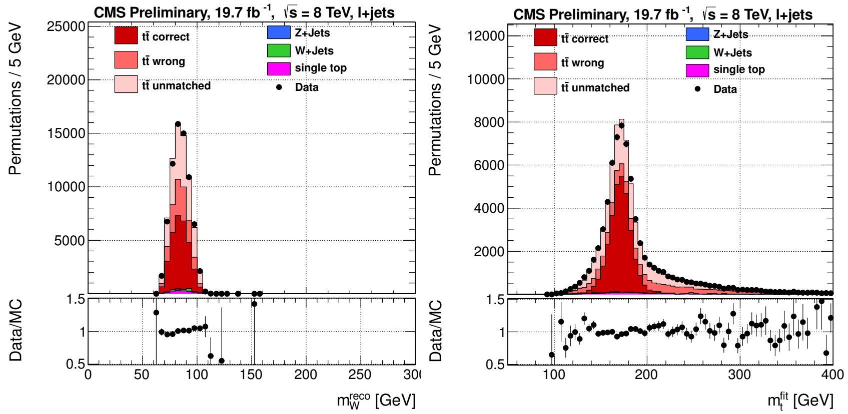
Almeida,Lee,Pokorski,Wells et al.
arXiv:1311.6721

Consistent agreement between the world average masses of M_t, M_W, in the presence of the measured M_H

Top Quark Mass Measurements

CMS and D0 updated results in lepton+jets channel

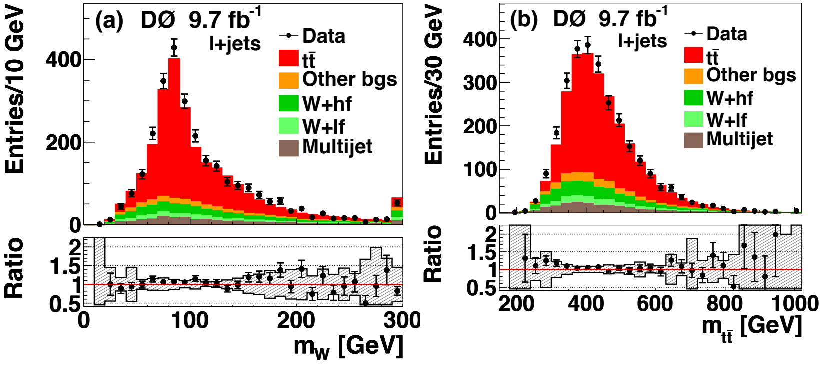
- – Top quark mass determined simultaneously with the Jet energy Scale Factor constrained by the W mass



CMS: CMS-PAS-TOP-14-001; 26 Mar 2014

M_t = 172.0±0.2 (stat.+JSF) ±0.75 (syst.) GeV

CMS combination with previous measurements:
M_t = 172.2±0.1 (stat.) ±0.7 (syst.) GeV



D0: **arXiv:/1405.1756 [hep-ex]**

M_t = 174.98±0.58 (stat.+JSF) ±0.49 (syst.) GeV
= 174.98±0.76 GeV

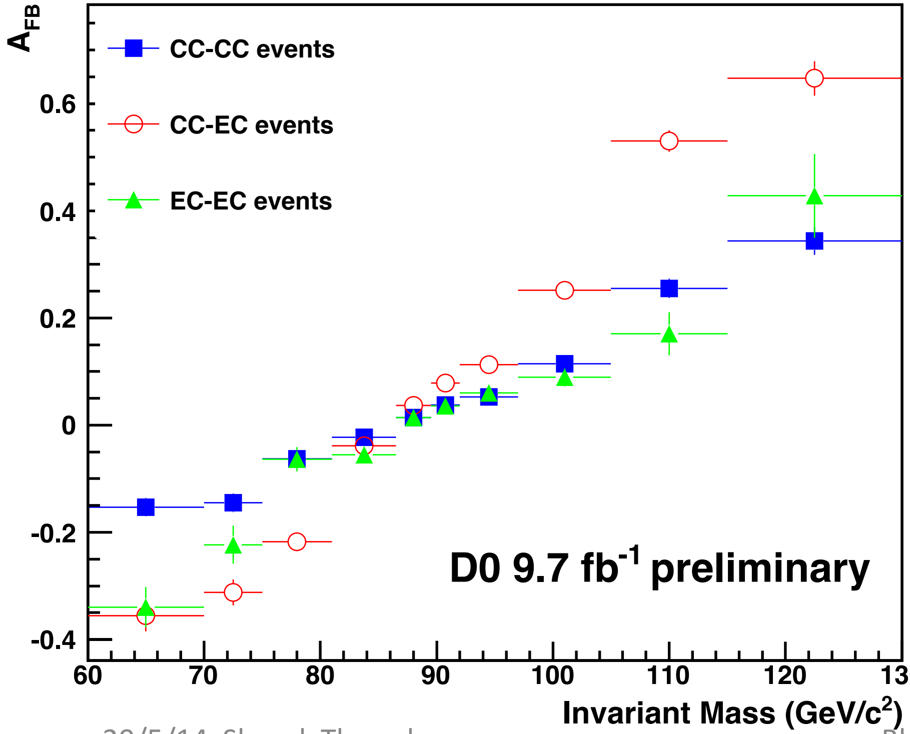
More about TOP: - today's plenary
Top+Higgs: Tue 20 May; 16:30
-Top quark physics at the Tevatron, R. Kehoe
-Top Quark mass measurements at the LHC; B. Stieger

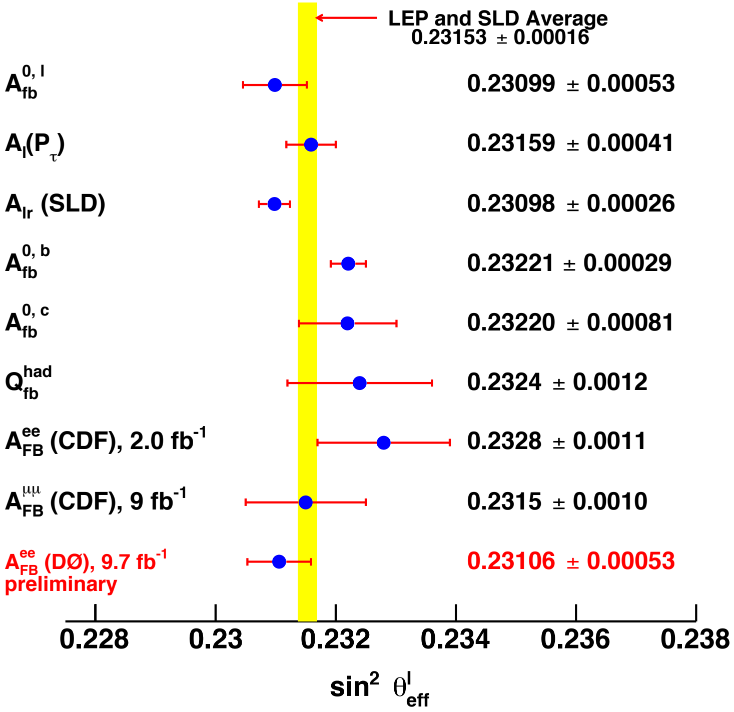
- Other EWK observables

A_{FB} and $\sin^2(\theta_W)$

- Important input to global tests of the EWK theory
  - In hadron collisions A_{FB} sensitive to the $\sin^2(\theta_W)$
- Recent measurements from Tevatron and LHC
  - Systematics dominated by the PDFs
- D0 with preliminary measurement in electron data set
  - More precise energy calibrations and increased data size

D0 Conf Note 6426-Conf (2014)



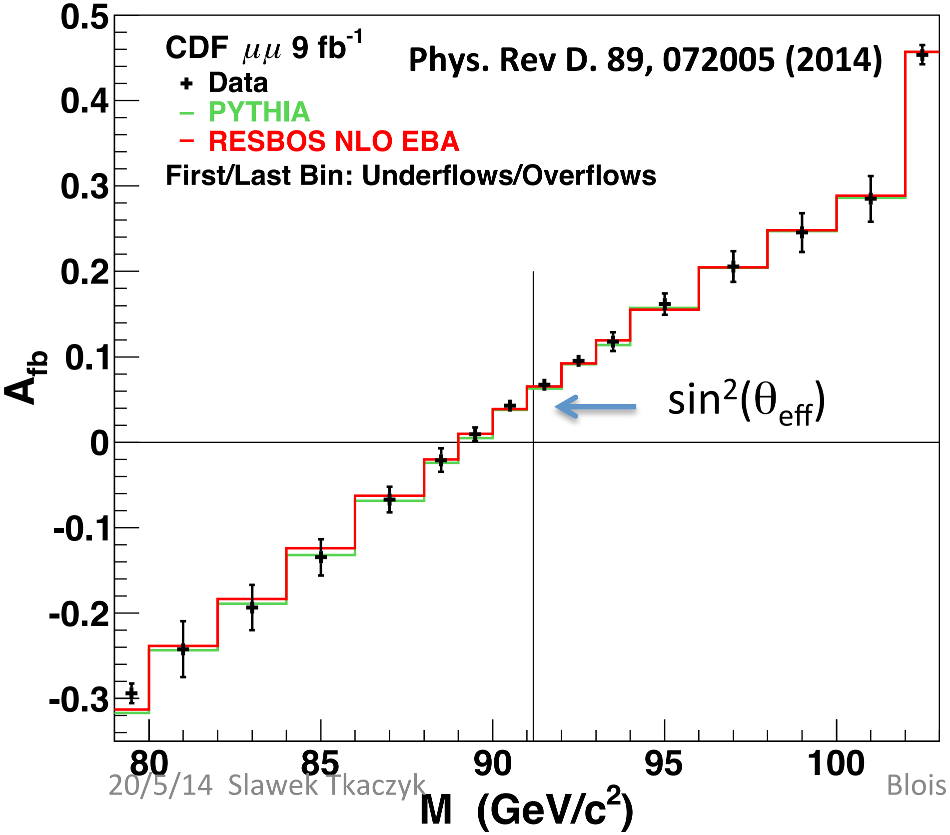


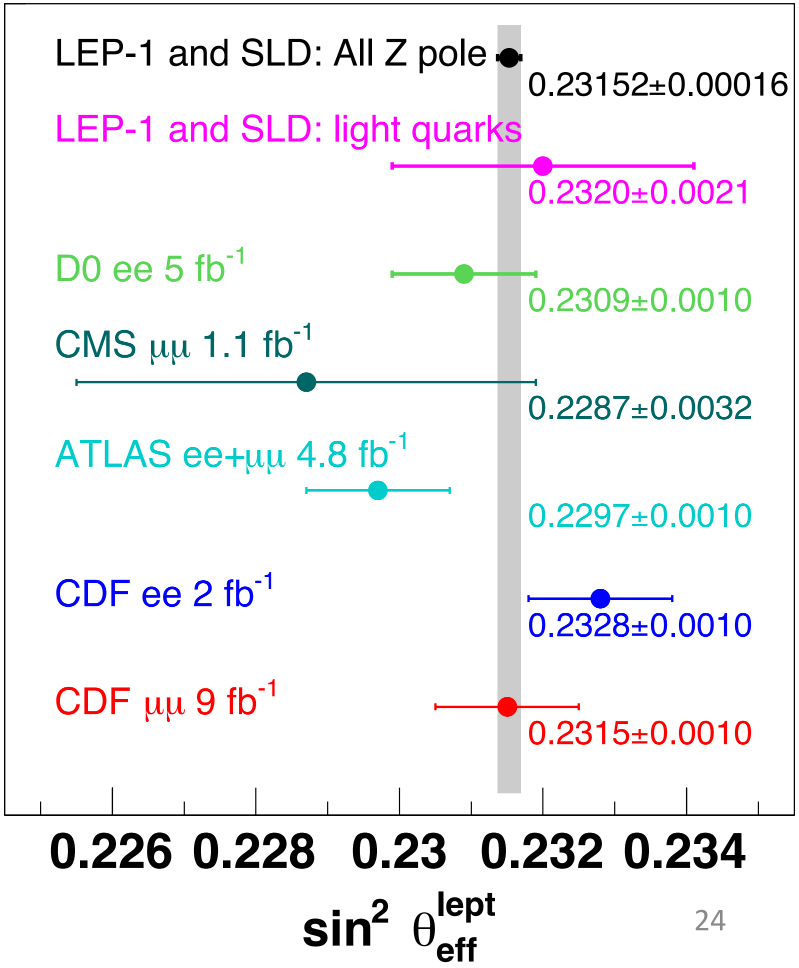
Tevatron precision close to LEP/SLC

A_{FB} and $\sin^2(\theta_W)$ in CDF

- Method: Forward-Backward asymmetry in DY muon pairs
- $\sin^2(\theta_W^{eff})$ from angular coefficient (A_4) and ResBos predictions using a template fit
  - Polar angle Born level distribution: $1+\cos^2\theta + A_4\cos\theta$; $A_{FB}=3/8A_4$

New SM measurements at the Tevatron, Arie Bodek
QCD+HF+EW Session, Wed, 21 May 14:00

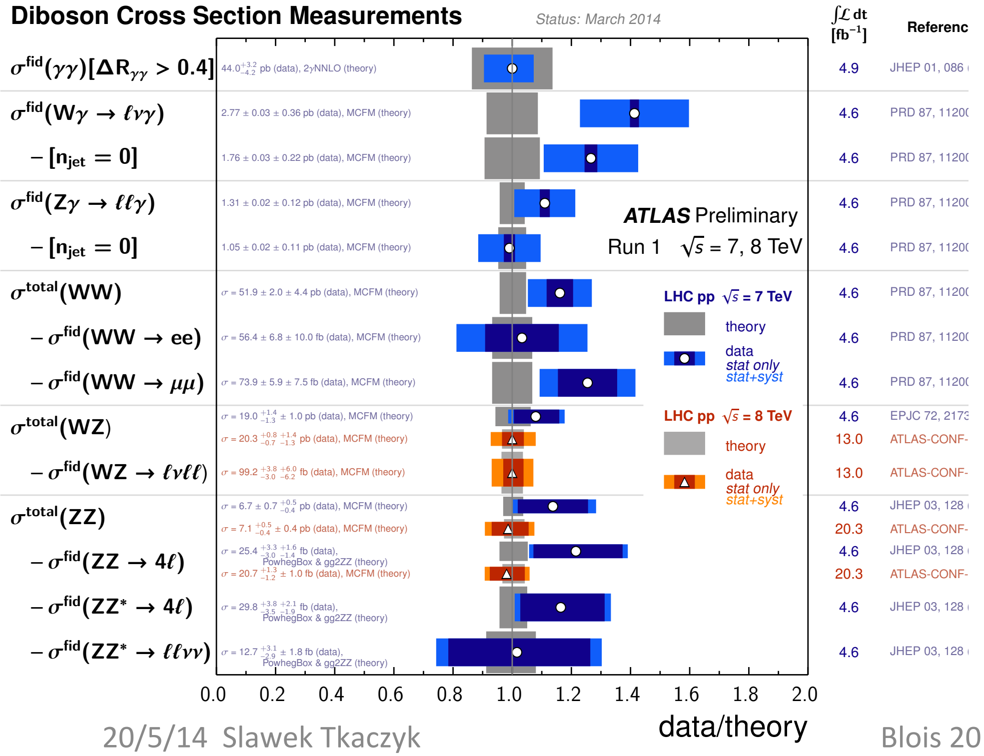


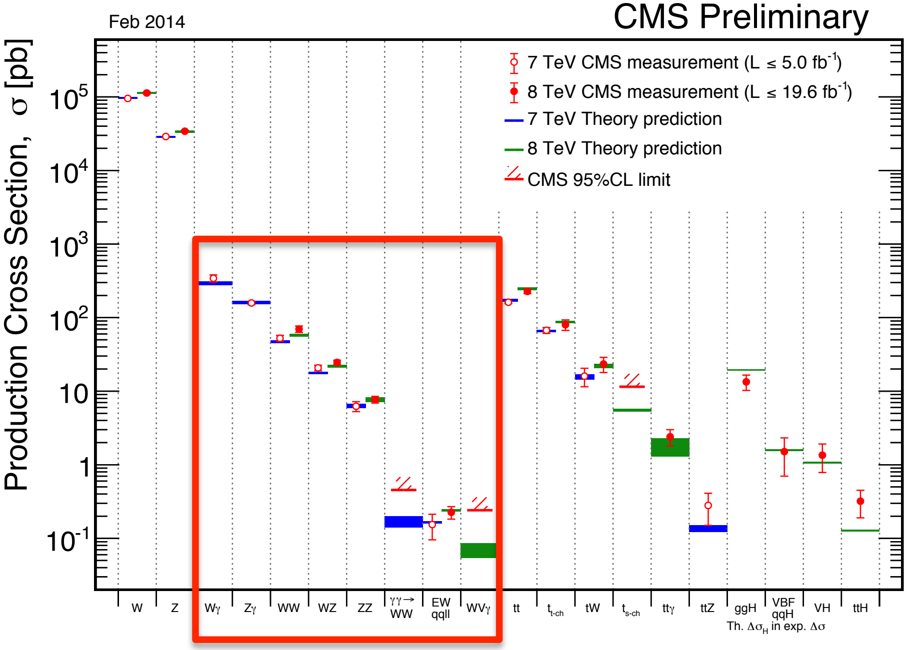


- Multi-boson production at colliders

Vector Boson Production

- Provide fundamental tests of the SM
  - Measurements of self-interactions and gauge couplings (TGC, QGC)
  - Probe of new physics
    - Direct – resonances with dibosons final states
    - Indirect – deviations from SM expectations
- Interesting final states:
  - Single boson from VV scattering – TGC
  - Di-bosons from VV scattering – multiple graphs
  - Di-bosons inclusive – also TGC
  - Tri-bosons – QGC



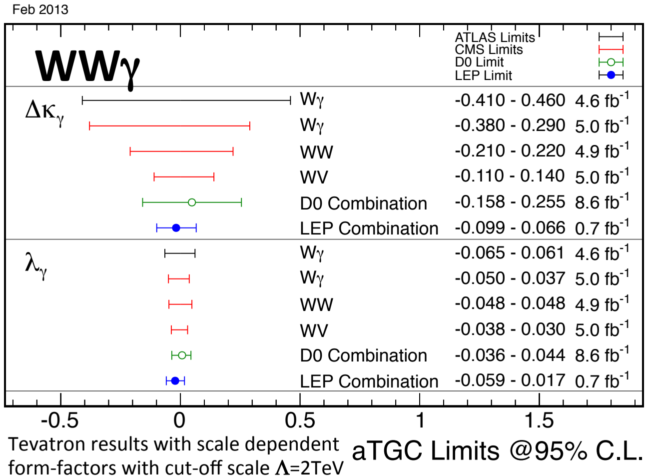


Production Consistent with the SM

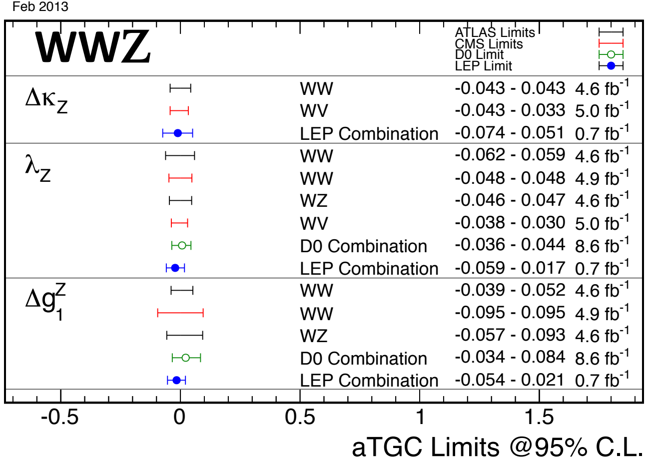
Limits on Triple GC

- Analysis of the **WWZ** and **WWγ** final states
- Limits obtained from p_T distributions

- Analysis of the **ZZZ** and **ZZγ** final states
- Form factors used with various cut-off scales
- Limits obtained from the ZZ cross sect.



Tevatron results with scale dependent form-factors with cut-off scale Λ=2TeV



Left:

Effective lagrangian method with 5 param.

SM : $(g_1^Z, K_{\gamma,Z}, \lambda_{\gamma,Z}) = (1,1,0)$

Right:

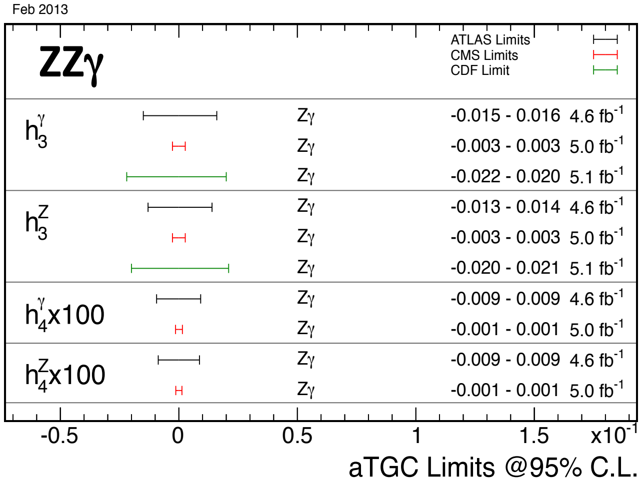
ZZ: Effective lagrangian method with 2 parameters

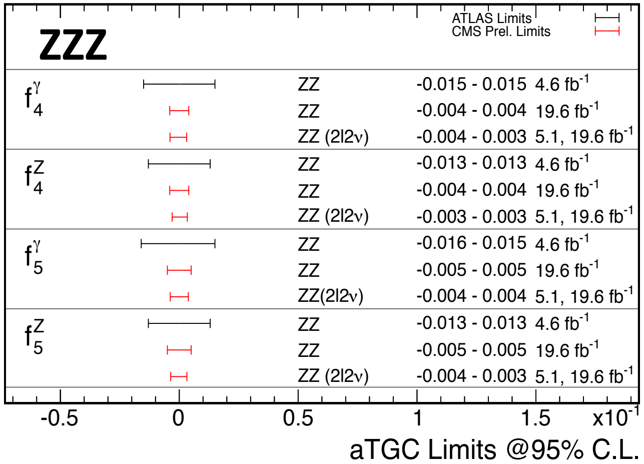
SM: $(f_4^{\gamma,Z}, f_5^{\gamma,Z}) = (0,0)$

Zγ: Vertex function approach method with 2 parameters

SM: $(h_3^{\gamma,Z}, h_4^{\gamma,Z}) = (0,0)$

Consistent with SM expectations

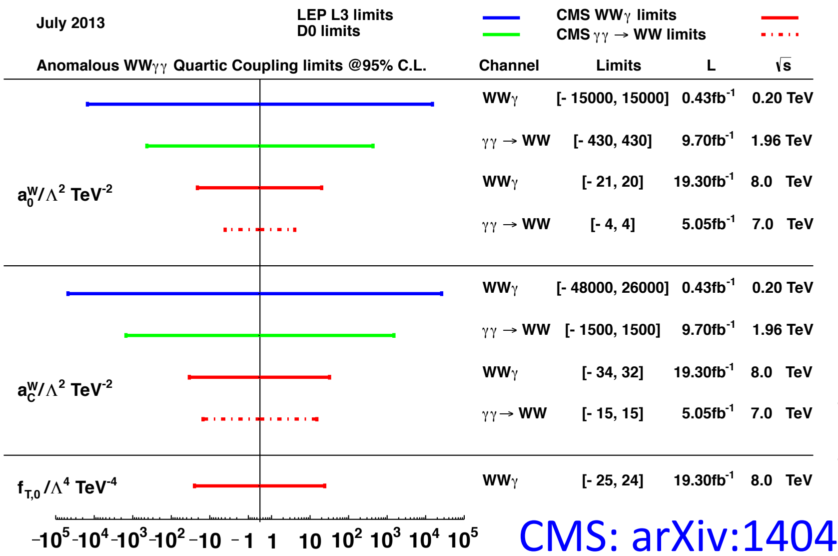




Limits on Quartic GC

- Analysis of di-bosons in the final state
  - in scattering topologies
  - with tri-boson final states
- QGC limits set on dim-6 and dim-8 EFT operators
  - dim-6: $a^W_{0,C}$,(WWγγ); $k^W_{0,C}$,(WWZγ); dim-8: $f_{T,0}$; $f_{M,i}$
- No deviations from the SM expectations

For comparison with earlier results the EFT formalism without SM Higgs



Channel	Limits	L	√s
WWγ	[- 15000, 15000]	0.43fb^{-1}	0.20 TeV
γγ → WW	[- 430, 430]	9.70fb^{-1}	1.96 TeV
WWγ	[- 21, 20]	19.30fb^{-1}	8.0 TeV
γγ → WW	[- 4, 4]	5.05fb^{-1}	7.0 TeV
WWγ	[- 48000, 26000]	0.43fb^{-1}	0.20 TeV
γγ → WW	[- 1500, 1500]	9.70fb^{-1}	1.96 TeV
WWγ	[- 34, 32]	19.30fb^{-1}	8.0 TeV
γγ→ WW	[- 15, 15]	5.05fb^{-1}	7.0 TeV
WWγ	[- 25, 24]	19.30fb^{-1}	8.0 TeV

EFT formalism with the SM Higgs

Observed Limits	Expected Limits
$-77\ (\text{TeV}^{-4}) < f_{M,0}/\Lambda^4 < 81\ (\text{TeV}^{-4})$	$-89\ (\text{TeV}^{-4}) < f_{M,0}/\Lambda^4 < 93\ (\text{TeV}^{-4})$
$-131\ (\text{TeV}^{-4}) < f_{M,1}/\Lambda^4 < 123\ (\text{TeV}^{-4})$	$-143\ (\text{TeV}^{-4}) < f_{M,1}/\Lambda^4 < 131\ (\text{TeV}^{-4})$
$-39\ (\text{TeV}^{-4}) < f_{M,2}/\Lambda^4 < 40\ (\text{TeV}^{-4})$	$-44\ (\text{TeV}^{-4}) < f_{M,2}/\Lambda^4 < 46\ (\text{TeV}^{-4})$
$-66\ (\text{TeV}^{-4}) < f_{M,3}/\Lambda^4 < 62\ (\text{TeV}^{-4})$	$-71\ (\text{TeV}^{-4}) < f_{M,3}/\Lambda^4 < 66\ (\text{TeV}^{-4})$
$-12\text{TeV}^{-2} < k^W_0/\Lambda^2 < 10\text{TeV}^{-2}$	$-12\text{TeV}^{-2} < k^W_0/\Lambda^2 < 12\text{TeV}^{-2}$
$-18\text{TeV}^{-2} < k^W_C/\Lambda^2 < 17\text{TeV}^{-2}$	$-19\text{TeV}^{-2} < k^W_C/\Lambda^2 < 18\text{TeV}^{-2}$

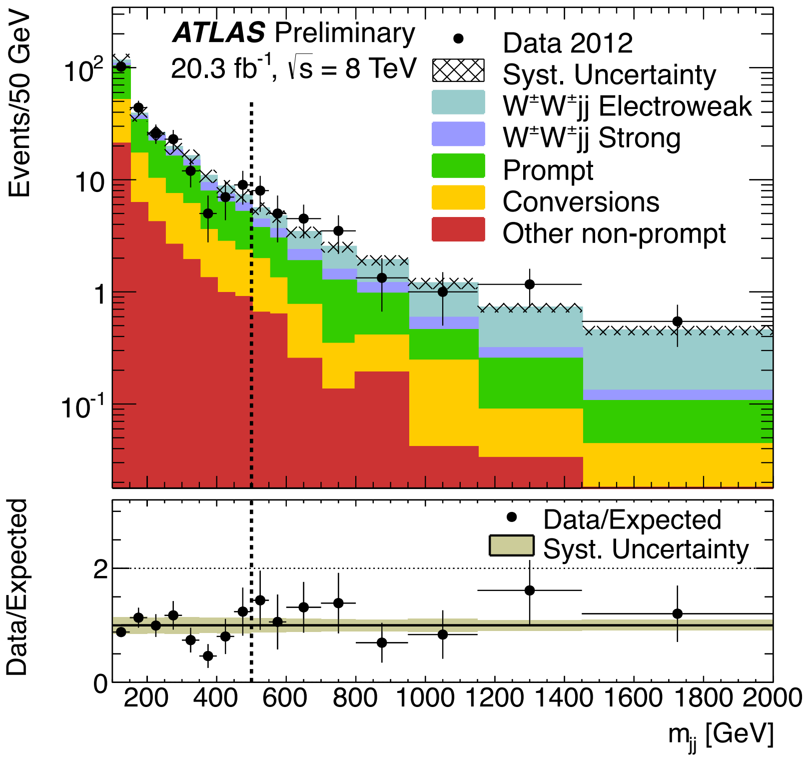
CMS: arXiv:1404.4619

First limit on dim-8 parameter $F_{T,0}/\Lambda^4$

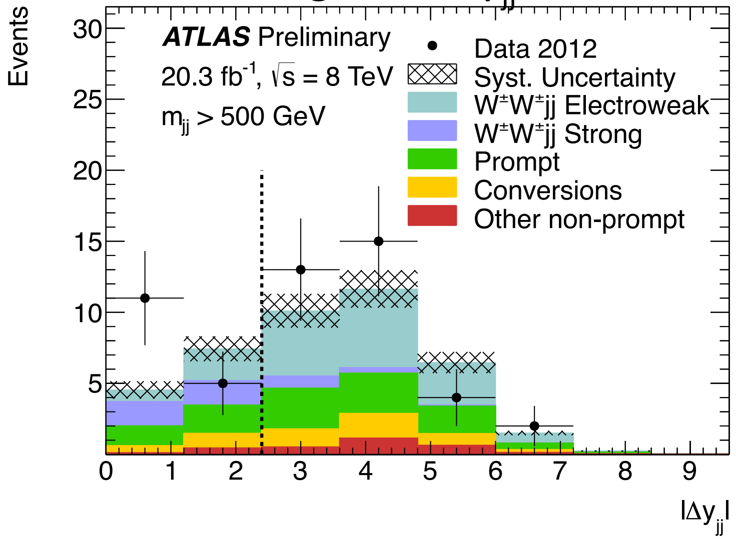
pp->W^+W^+jj->llννjj

Atlas_Conf_2014_013 (March 2014)

Inclusive m_{jj} QCD+EW region



Enriched VBS region in $\Delta y_{jj} > 2.4$



Cross section:

Incl: σ=2.1 +/- 0.5(stat(+/-0.1(sys)

VBS: σ= 1.3 +/- 0.4(stat(+/-0.2(sys)

Limits on QGC: a4 and a5

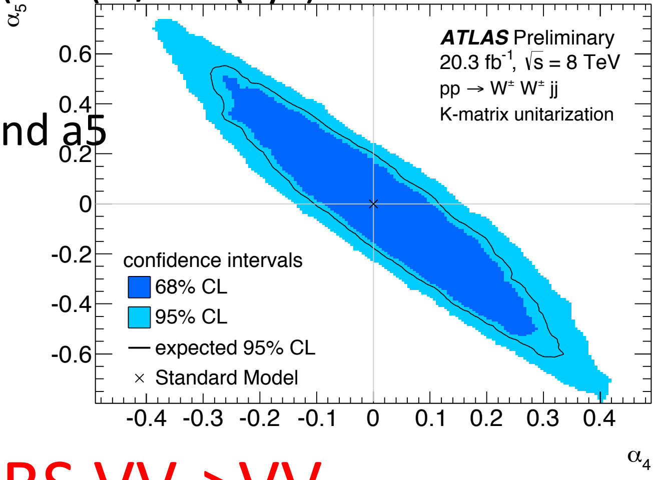
$-0.14 < a4 < 0.16$

$-0.23 < a4 < 0.24$

Expected:

$-0.10 < a4 < 0.12$

$-0.18 < a5 < 0.20$



Significance:	EWK+QCD	VBS
Observed:	4.5	3.6
Expected:	3.4	2.8

First observation of the VBS VV->VV

Multiboson Studies Summary

- LEP and Tevatron results completed!
- New LHC analyses explore the muliti-boson final states at 7, 8 (soon 13 TeV)
  - Limits set on possible deviations from the SM
  - **V**ector **B**oson **S**cattering process observed by ATLAS
  - **No evidence of anomalous couplings !**
- Is modern approach to anomalous couplings needed?
  - C. Degrande et al. Annals of Physics 335 (2013) 21–32 arXiv:1205.4231

- **Additional talks at QCD+HF+EW session on 21 May, 14:00:**
  - Electroweak tests at the LHC – Nenad Vranjes
  - Diboson Production cross section at the LHC – Hughes Louis Brun

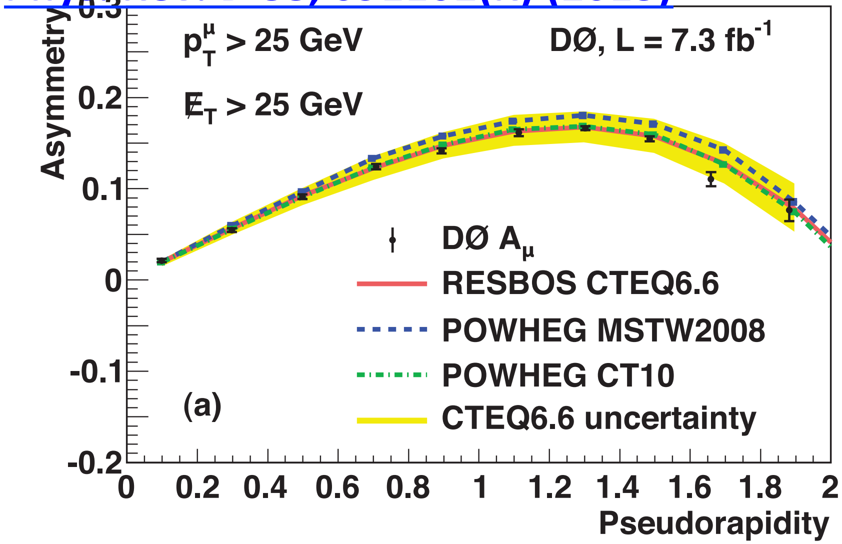
SUMMARY

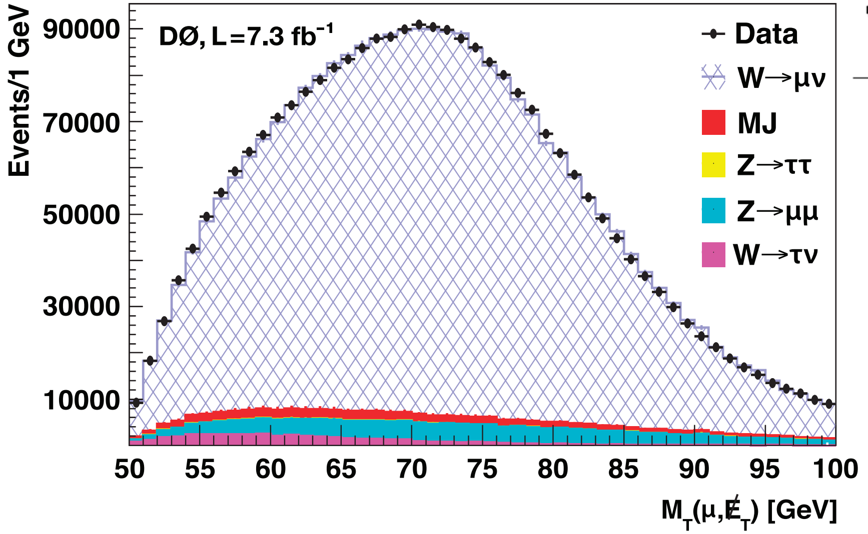
- Continue the tradition of precision SM measurements with new data and new theoretical developments
- Challenging to find Beyond Standard Model Physics using the precision EWK measurements
- More attention to searches for exotic physics effects which may be forbidden or suppressed in the SM

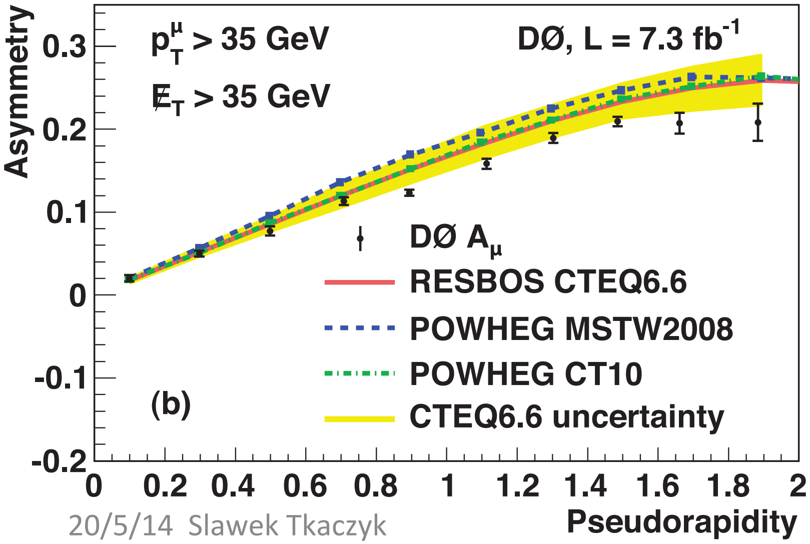
Backup SLIDES

W boson asymmetry at Tevatron

Phys. Rev. D 88, 091102(R) (2013)





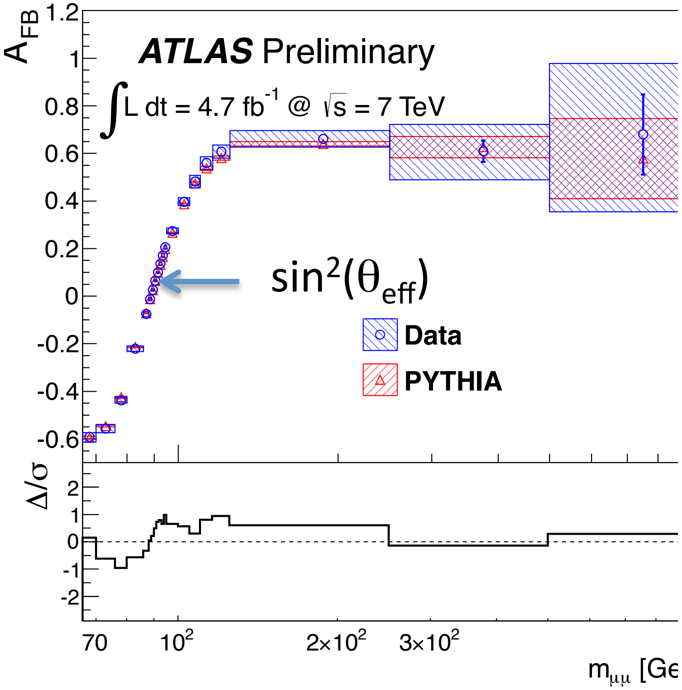


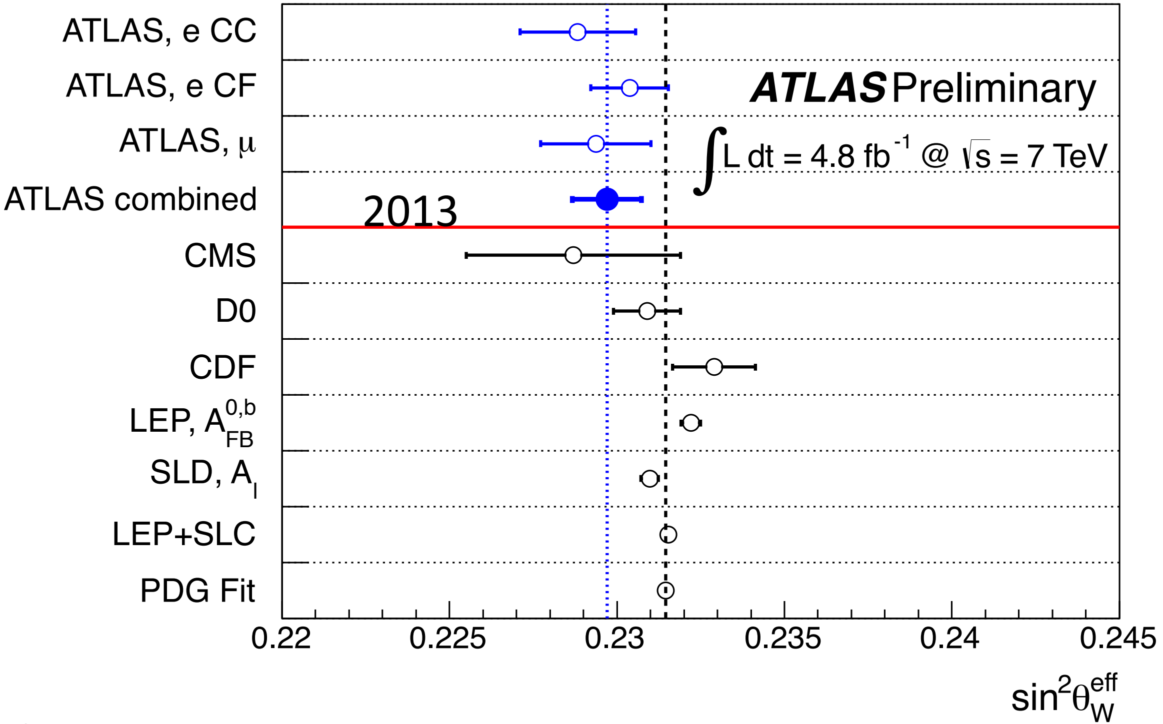
- D0 recent measurements of the muon charge asymmetry
- Shape difference from influence of V-A decay in (a)
- Tevatron results most precise

A_{FB} and $\sin^2(\theta_W)$ in ATLAS

- Method: Forward Backward asymmetry in DY lepton pairs
  - A_{FB} induced by the V-A interference
  - In pp additional dilution from unknown quark direction – $p_z(ll)$

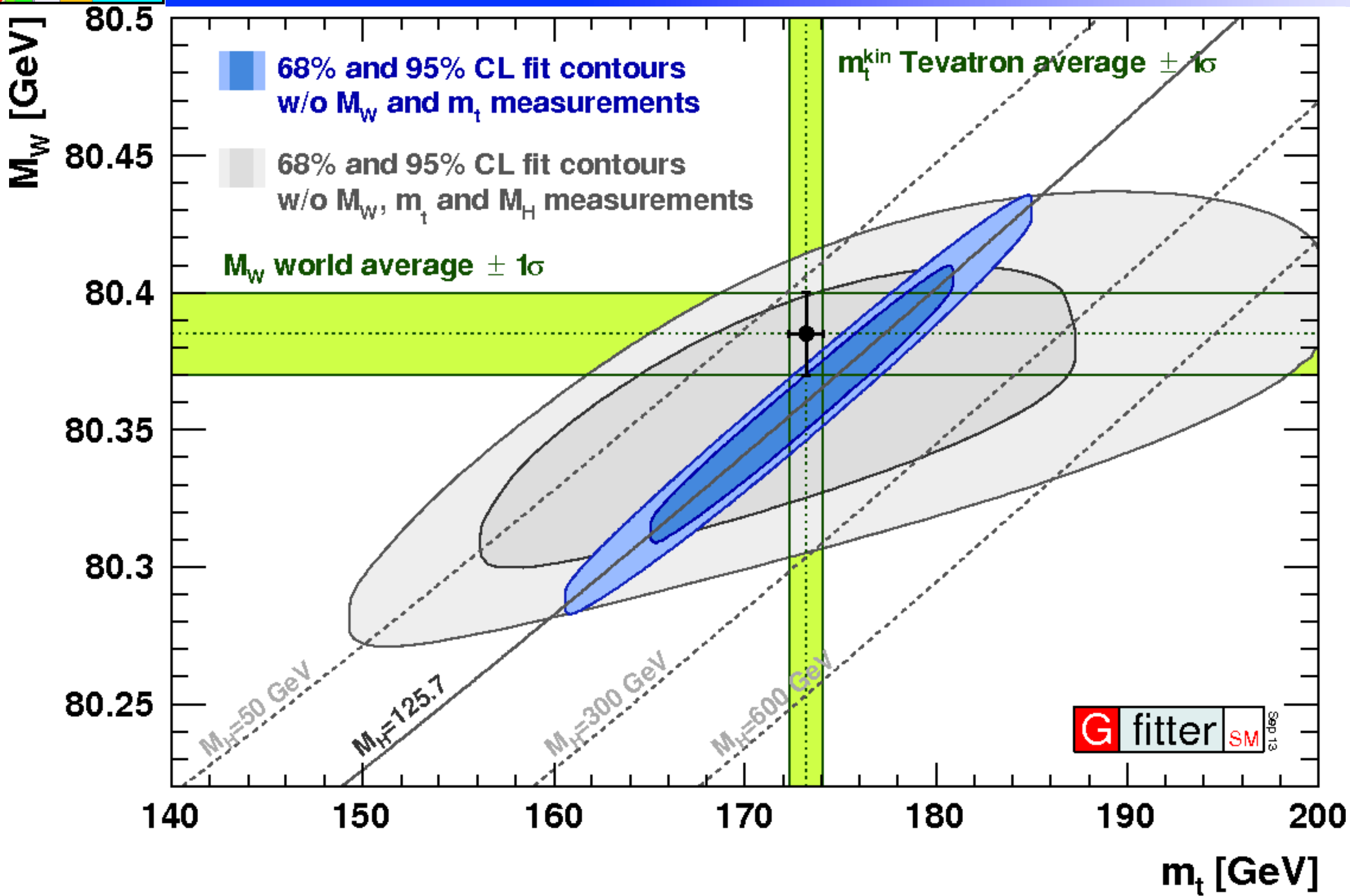
ATLAS-CONF-2013-043





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

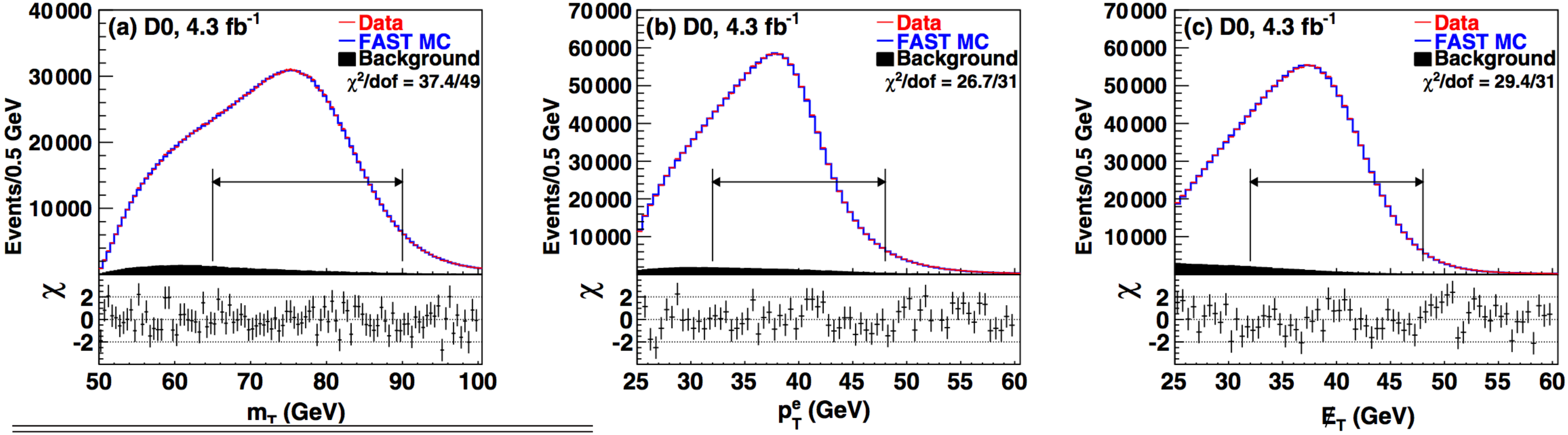
SM Contours in M_W and M_t plane

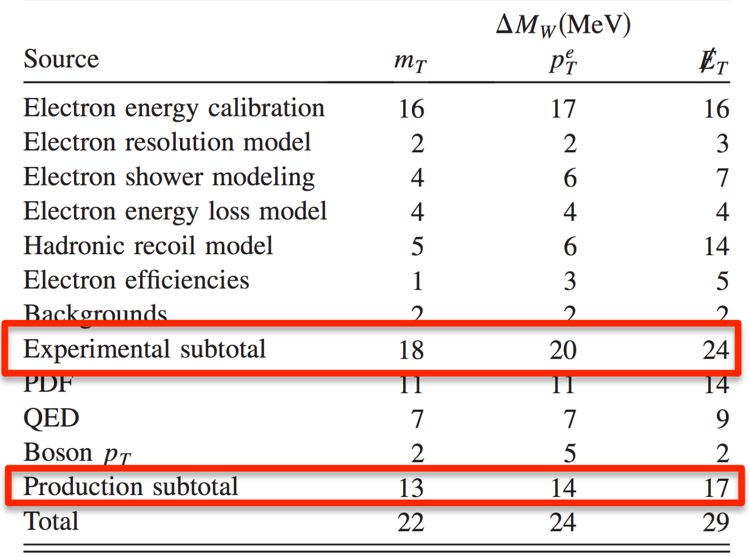


- **Consistent agreement between the world average masses of M_t, M_W, in the presence of the measured M_H**

D0 M_W 2013 Results

- 1.7mln W's with central electron |eta|<1.05



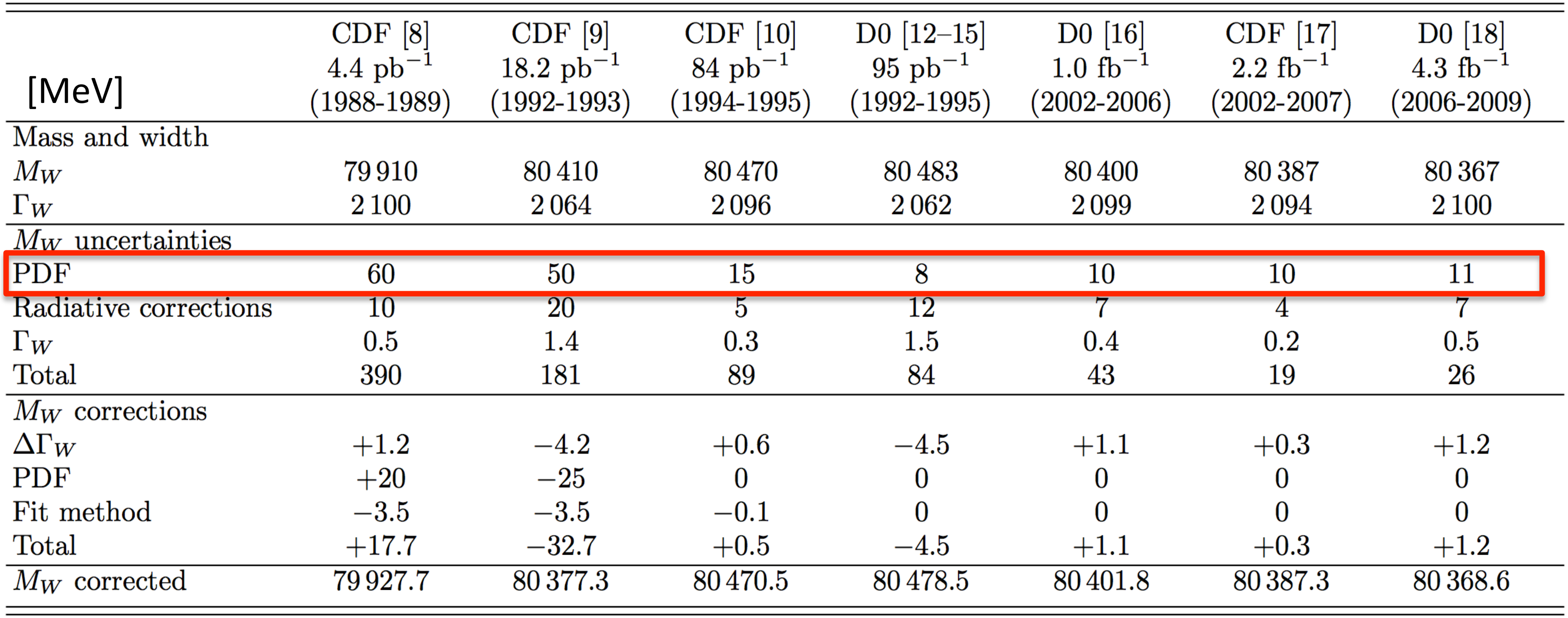


Source	ΔM_W (MeV) m_T	 p_T^e	 $\not{E}_T$
Electron energy calibration	16	17	16
Electron resolution model	2	2	3
Electron shower modeling	4	6	7
Electron energy loss model	4	4	4
Hadronic recoil model	5	6	14
Electron efficiencies	1	3	5
Backgrounds	2	2	2
Experimental subtotal	18	20	24
PDF	11	11	14
QED	7	7	9
Boson p_T	2	5	2
Production subtotal	13	14	17
Total	22	24	29

M_W= 80.367+/-0.013(stat)+/-0.022(syst) GeV
= 80.367+/-0.026 GeV

Combined with previous result:
2013 D0 combination:
M_W= 80.375+/-0.011(stat)+/-0.020(syst) GeV
= 80.375+/-0.023 GeV

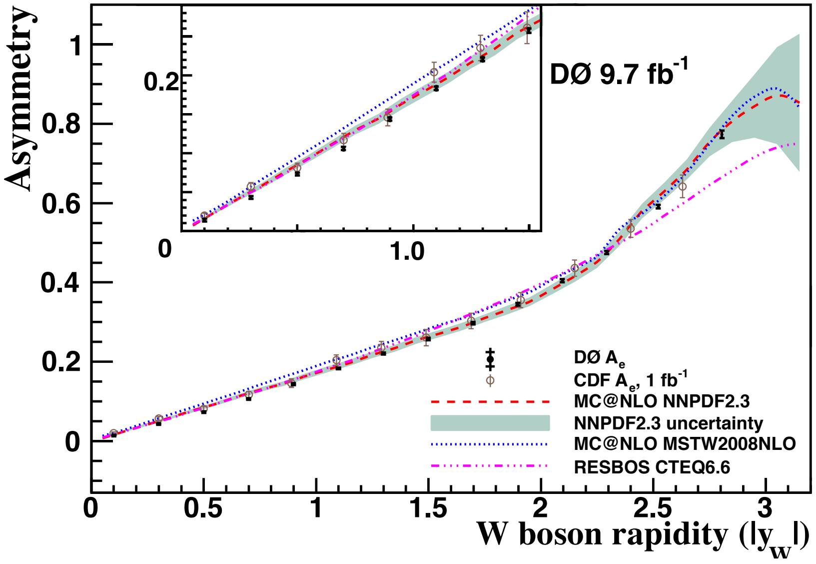
Tevatron Uncertainties in M_W combination

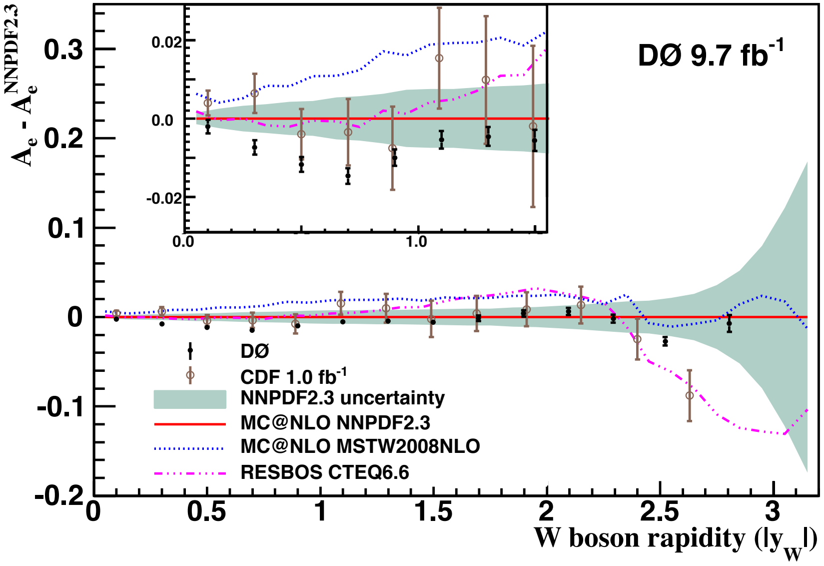


[MeV]	CDF [8] 4.4 pb^{-1} (1988-1989)	CDF [9] 18.2 pb^{-1} (1992-1993)	CDF [10] 84 pb^{-1} (1994-1995)	D0 [12–15] 95 pb^{-1} (1992-1995)	D0 [16] 1.0 fb^{-1} (2002-2006)	CDF [17] 2.2 fb^{-1} (2002-2007)	D0 [18] 4.3 fb^{-1} (2006-2009)
Mass and width							
M_W	79 910	80 410	80 470	80 483	80 400	80 387	80 367
Γ_W	2 100	2 064	2 096	2 062	2 099	2 094	2 100
M_W uncertainties							
PDF	60	50	15	8	10	10	11
Radiative corrections	10	20	5	12	7	4	7
Γ_W	0.5	1.4	0.3	1.5	0.4	0.2	0.5
Total	390	181	89	84	43	19	26
M_W corrections							
$\Delta\Gamma_W$	+1.2	−4.2	+0.6	−4.5	+1.1	+0.3	+1.2
PDF	+20	−25	0	0	0	0	0
Fit method	−3.5	−3.5	−0.1	0	0	0	0
Total	+17.7	−32.7	+0.5	−4.5	+1.1	+0.3	+1.2
M_W corrected	79 927.7	80 377.3	80 470.5	80 478.5	80 401.8	80 387.3	80 368.6

W Boson Asymmetry in at Teva

Phys. Rev. Lett. 112, 151803 (2014)





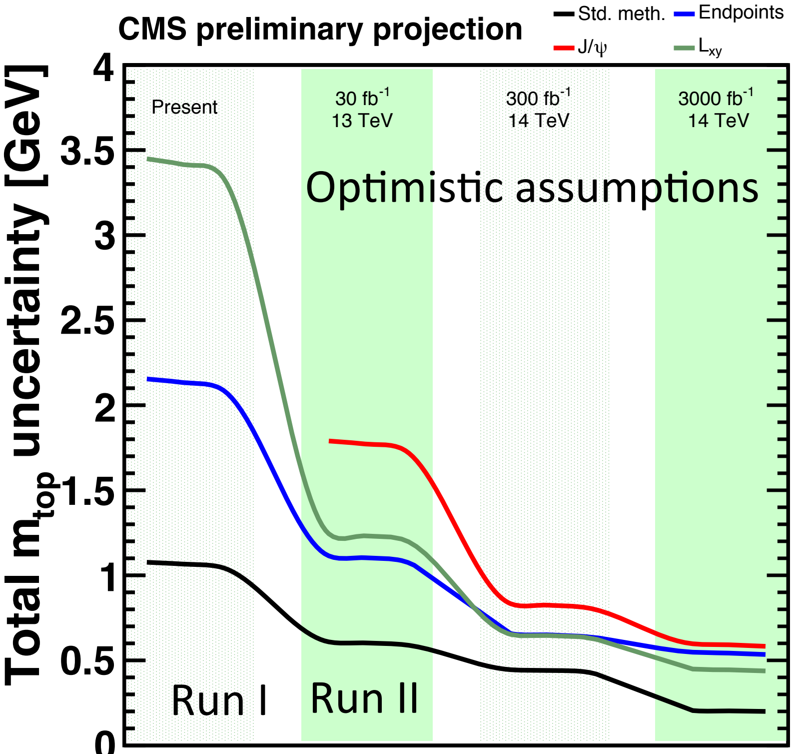
W boson asymmetry (e channel) as a function of **W boson rapidity**

- No V-A decay dilution effects
- Neutrino longitudinal momentum deduced

Overall agreement but data below the predictions for rapidities less than 1

Top Quark Mass Measurements

- Improvements in the M_t precision below 0.5GeV desired
  - Impact on understanding of SM – reduce the uncertainty on M_W
  - Decisive tests of vacuum stability in SM

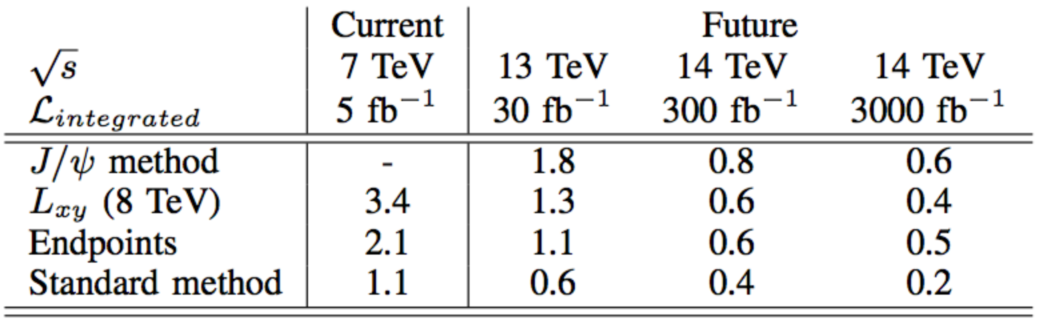


CMS: arXiv: 1404.1013

- Conventional algorithms:
  - Full reconstruction of top quark; limited by jet energy scale
- Alternative: **L_{XY}, J/Psi**, Endpoints:
  - Reduced systematics by increased statistical uncertainty
  - Limited by b-jet Energy Scale and modeling of b fragmentation
  - Suitable for HL-LHC

TABLE V

PROJECTION OF THE TOP-QUARK MASS PRECISION (IN GEV) OBTAINED WITH CURRENT METHODS, FOR VARIOUS INTEGRATED LUMINOSITIES USING THE ASSUMPTIONS EXPLAINED IN THE TEXT [4].



	Current		Future	
$\sqrt{s}$	7 TeV	13 TeV	14 TeV	14 TeV
$\mathcal{L}_{integrated}$	5 fb^{-1}	30 fb^{-1}	300 fb^{-1}	3000 fb^{-1}
J/ψ method	-	1.8	0.8	0.6
L_{xy} (8 TeV)	3.4	1.3	0.6	0.4
Endpoints	2.1	1.1	0.6	0.5
Standard method	1.1	0.6	0.4	0.2