Status of and prospects for W mass and Z mass measurements

Stefano Camarda

On behalf of the CMS and ATLAS Collaborations

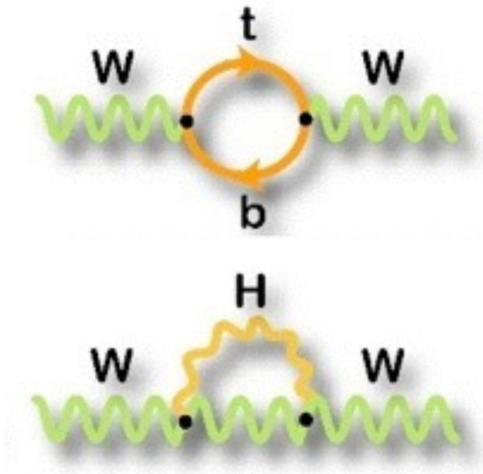
Physics at LHC and beyond
Qui-Nhon, Vietnam
10-17 August 2014

Motivation

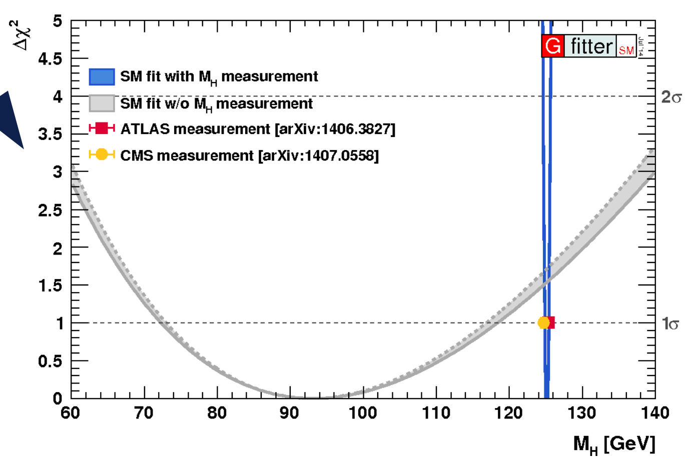
The EW sector of the SM, relates M_W to α, G_F, and $\sin^2\theta_W$

$$M_W^2 = \frac{\pi \alpha_{EM}}{\sqrt{2}\, G_F \left(1 - M_W^2/M_Z^2\right)(1 - \Delta r)}$$

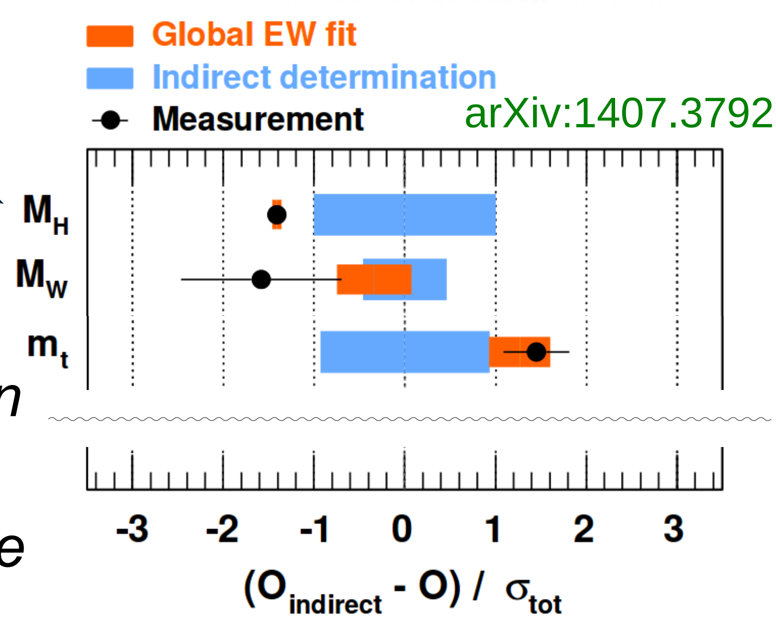
Radiative corrections Δr are dominated by Top and Higgs loops



- The relation between M_{top}, M_H and M_W provides a stringent test of the SM
- The comparison between the measured M_H and the predicted M_H is sensitive to new physics



Indirect determination of M_W (±8 MeV) is more precise than the experimental measurement → Call for $\delta M_W^{exp} < 10$ MeV

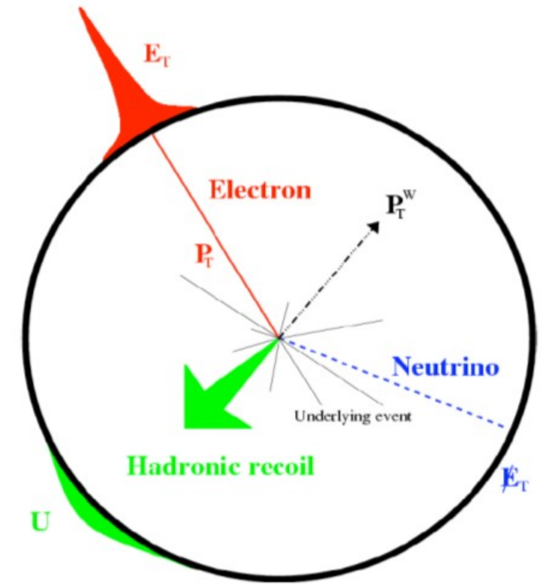


Status and prospects for W mass measurement

- Methodology for the M_W extraction
- The Tevatron experience on M_W
- Measurements of M_W and M_Z at the LHC
- Theoretical uncertainties for M_W at the LHC
- ATLAS and CMS measurements to constrain uncertainties on M_W
- Prospect for M_W and M_Z measurements at future colliders

Methodology for the W mass extraction

- Event selection: W leptonic decay
  $W \to l\,\nu$, $l = e, \mu$
- The full kinematic of the W decay cannot be reconstructed, since the longitudinal momentum of the neutrino is unknown



Traditional analyses are based on a template fit extraction from observables sensitive to M_W

Lepton transverse momentum	p_T^l
W transverse mass	$M_T = \sqrt{2 \cdot p_T^l p_T^\nu \cdot (1 - \cos\Delta\phi(l,\nu))}$
Neutrino transverse momentum (from hadronic recoil)	p_T^ν

More sophisticated analysis techniques suggest simultaneous measurements of W and Z observables TS2008-022 Eur.Phys.J. C69 (2010) 379-397

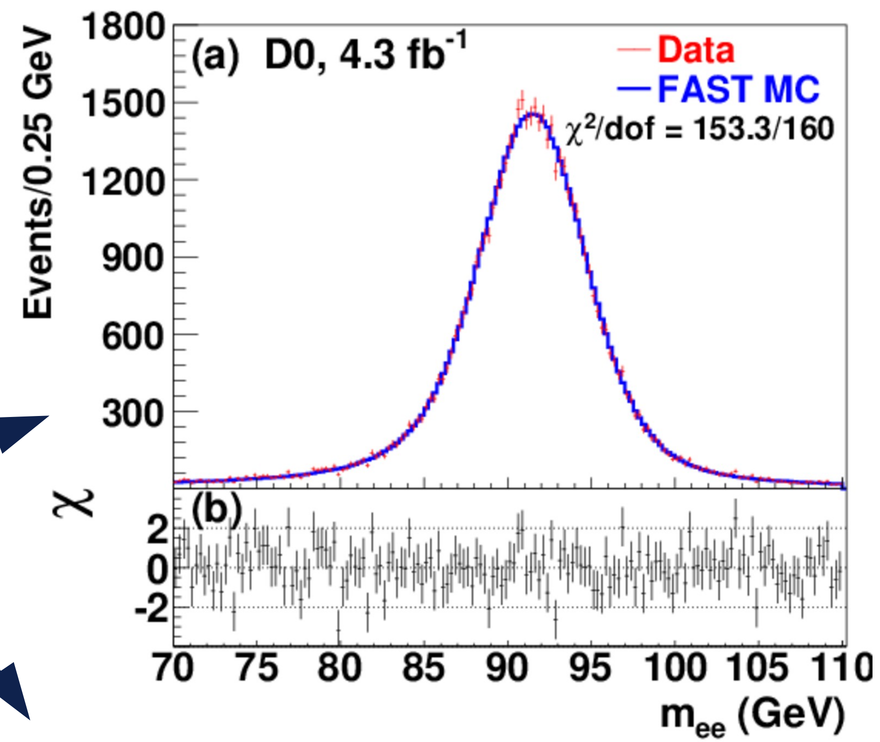
In the same spirit, a common strategy of template fits analyses is to use $Z \to ll$ events to constraint both experimental and theory systematics

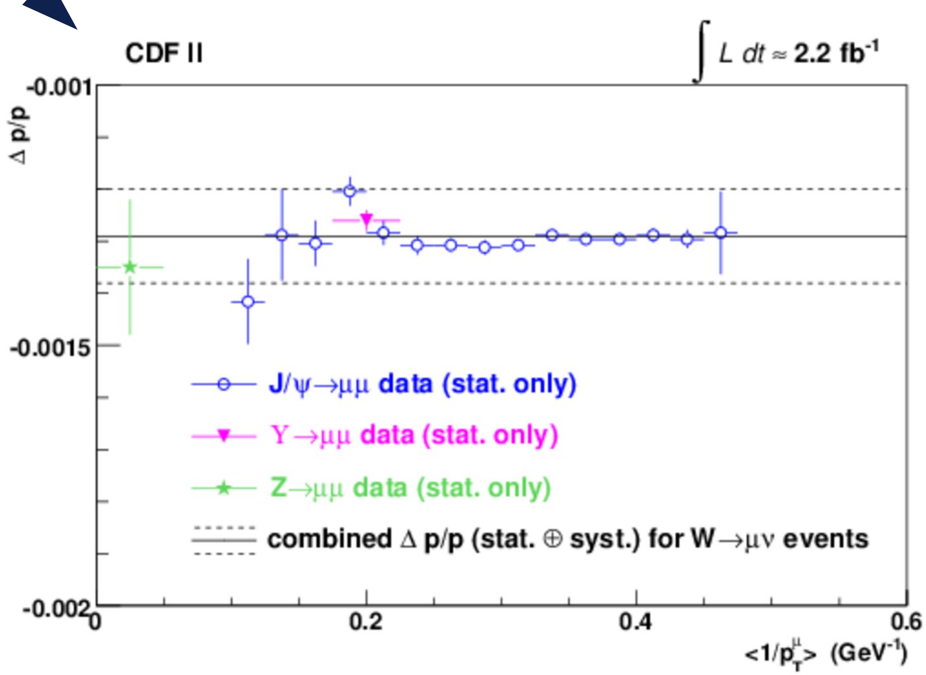
Tevatron measurements of M_W - Methodology

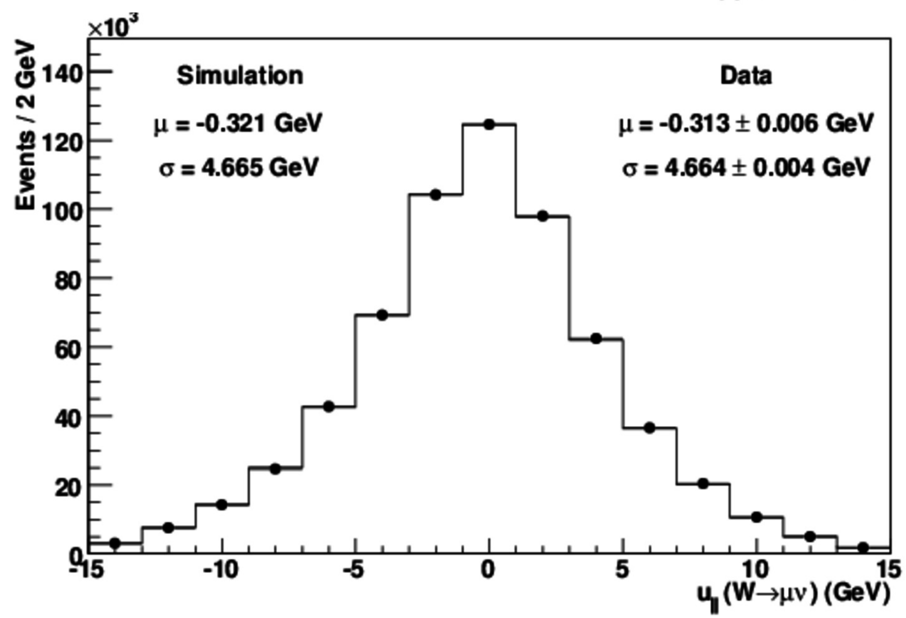
Phys. Rev. D 89, 072003 (2014)
Phys. Rev. D 89, 012005 (2014)

Detector calibrations:

- Muon momentum scale
  → Calibration of the track curvature in the drift chamber
- Electron energy scale
  → Calorimeter calibration
- Neutrino transverse momentum
  → Hadronic recoil calibration

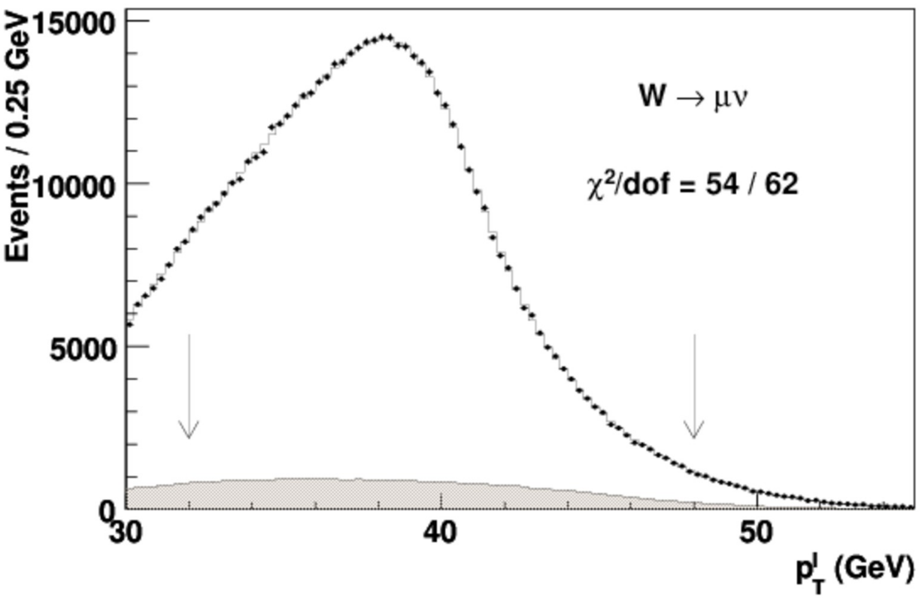






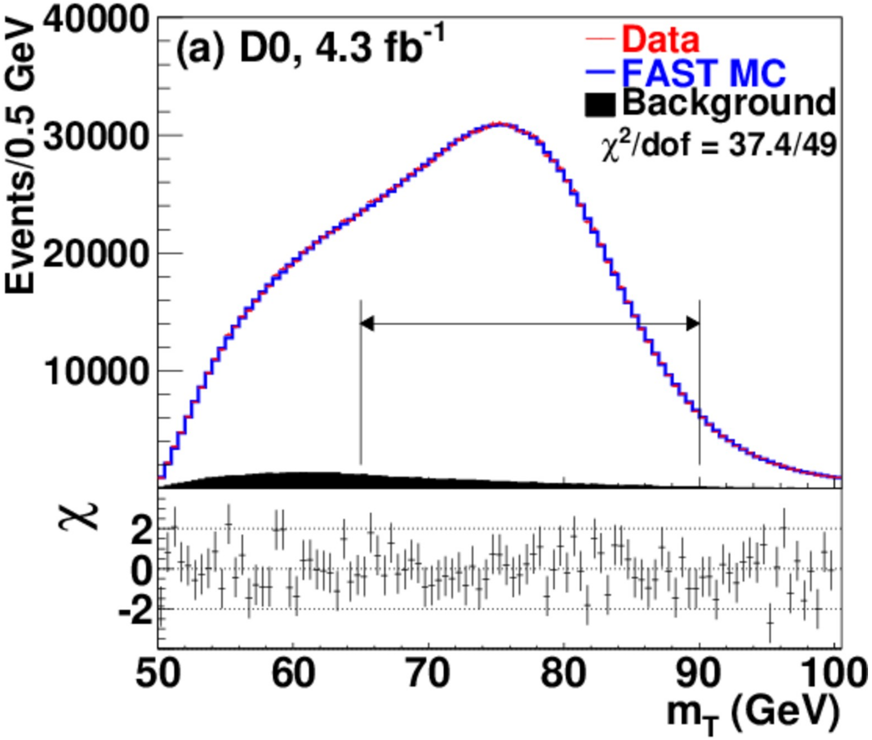
Tevatron measurements of M_W - Results

CDF



CDF p_T^μ template fit

D0



D0 M_T^e template fit

M_W extracted from p_T^l, M_T, p_T^ν in electron and muon channels
L = 2.2 fb^{-1}

$$M_W = 80.387 \pm 19 \text{ MeV}$$

Phys. Rev. D 89, 072003 (2014)

M_W extracted from p_T^l, M_T in electron channel
L = 4.3 (+1) fb^{-1}

$$M_W = 80.375 \pm 23 \text{ MeV}$$

Phys. Rev. D 89, 012005 (2014)

W mass measurement at the LHC

- The M_W measurement at the LHC follows a strategy similar to the Tevatron
- Important differences:
  - Higher pile-up environment → affect hadronic recoil calibration
  - Potentially larger theoretical uncertainties due to pp instead of $p\bar{p}$ collisions
  - W^+ and W^- production is not symmetric → Require a charge dependent analysis

Most precise observables for the M_W extraction

p_T^l	M_T
Observable does not depend on hadronic recoil, smaller experimental uncertainty	Depends on hadronic recoil measurement, expected larger experimental uncertainties
Larger theory uncertainty due to higher order QCD, p_T^W modelling, PDF, W polarisation, charm mass	M_T is quite stable wrt perturbative QCD corrections, smaller PDF uncertainties, smaller non-perturbative QCD uncertainties

↓ M_W extraction is likely to be limited by theoretical uncertainties

↓ Final balance between theory and exp uncertainties will depend on pile-up mitigation algorithms

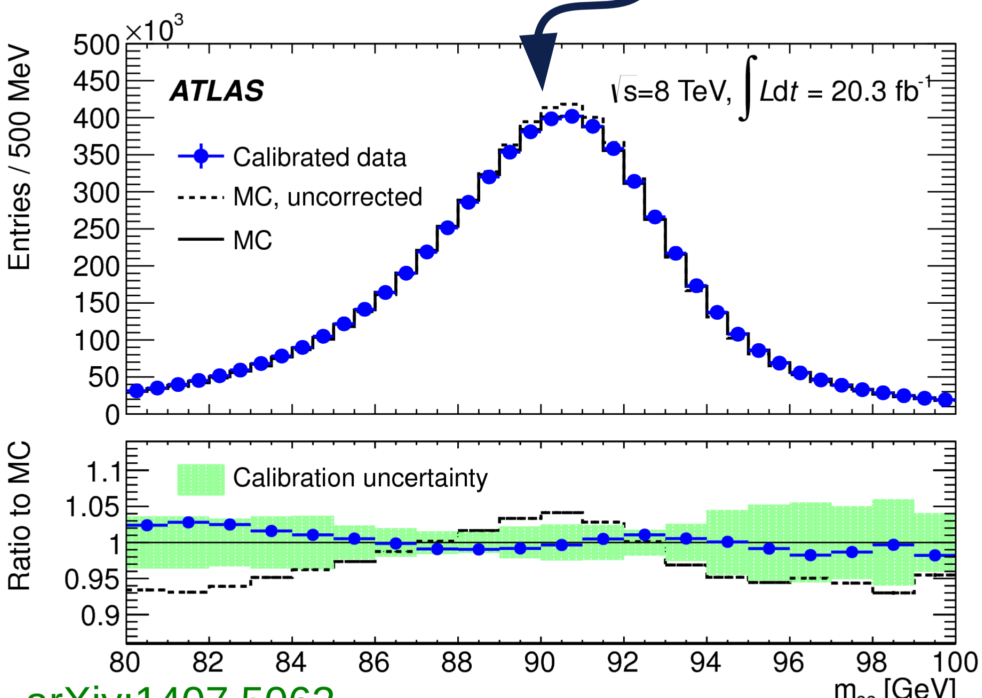
Z mass measurement at the LHC

A first step towards the measurement of M_W at the LHC is the measurement of M_Z → Test the methodology of the M_W extraction:

→ Neglect one of the two leptons, extract M_Z from p_T^l and hadronic recoil

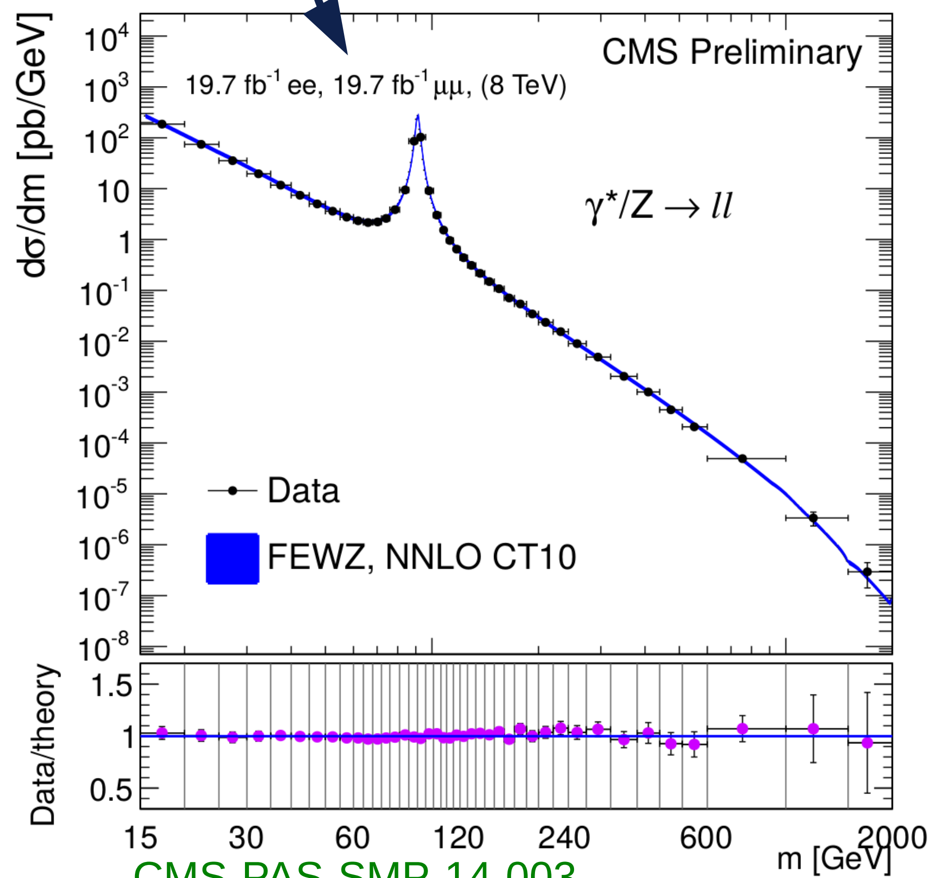
The lepton energy scale is calibrated by comparing the reconstructed M_Z to the LEP measurement of M_Z

Electron calibration from $Z \rightarrow ee$ invariant mass



arXiv:1407.5063

$Z/\gamma^* \rightarrow ll$ lineshape measurement



CMS-PAS-SMP-14-003

Theory systematics for M_W at the LHC

Why theory systematic uncertainties are crucial for the W mass measurement at the LHC?

W production at the LHC is relatively cheap
7(8) TeV, 5(20) fb^{-1} → ~15(75)x10^6
in $W \rightarrow l\nu$ ($l = e, \mu$)

- Statistics is not an issue
  → expected ~6(2) MeV statistical uncertainty on M_W

- Main experimental systematic uncertainties
  - Lepton energy scale, resolution, efficiency
  - hadronic recoil scale and resolution

Estimates depend on the analysis strategy: between 5-15 MeV

Eur.Phys.J.C57:627-651,2008   TS2008-022

Theory uncertainties at the Tevatron: 10-15 MeV
Expected similar or higher uncertainties at the LHC

Constrain M_W theory uncertainties at the LHC

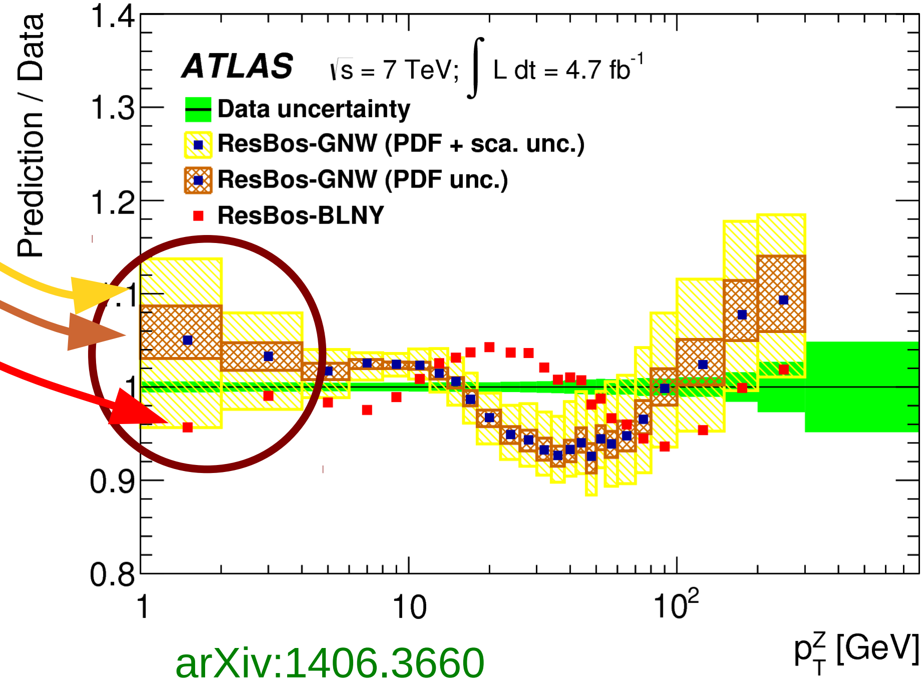
ATLAS and CMS are performing measurements of alternative W, Z observables to control the theoretical models and reduce the uncertainties on the measurement of M_W

Theory uncertainties	Measurements which can provide constraints to the theoretical models
p_T^W modelling	p_T^W, p_T^Z
PDF	W asymmetry, Z rapidity, W + charm
W polarization	Angular coefficients in W, Z production

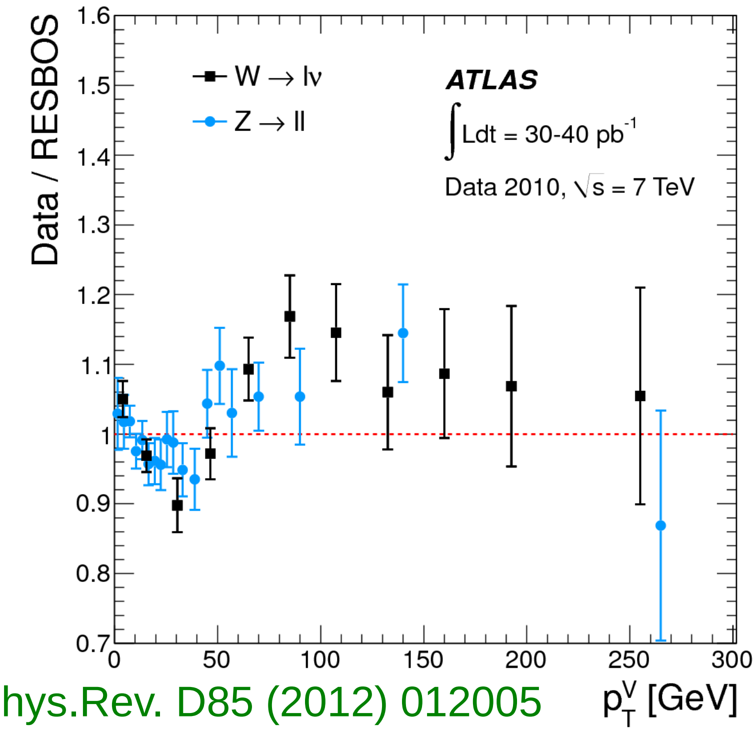
p_T^W and p_T^Z modelling

Theory uncertainties at low W, Z p_T

- Factorization, renormalization, resummation or PS scales
- PDF, low x gluon PDF
- Non perturbative QCD parameters
- Strong-interaction coupling $\alpha_s(M_Z)$
- Heavy flavour masses, HF thresholds in the PDF



arXiv:1406.3660



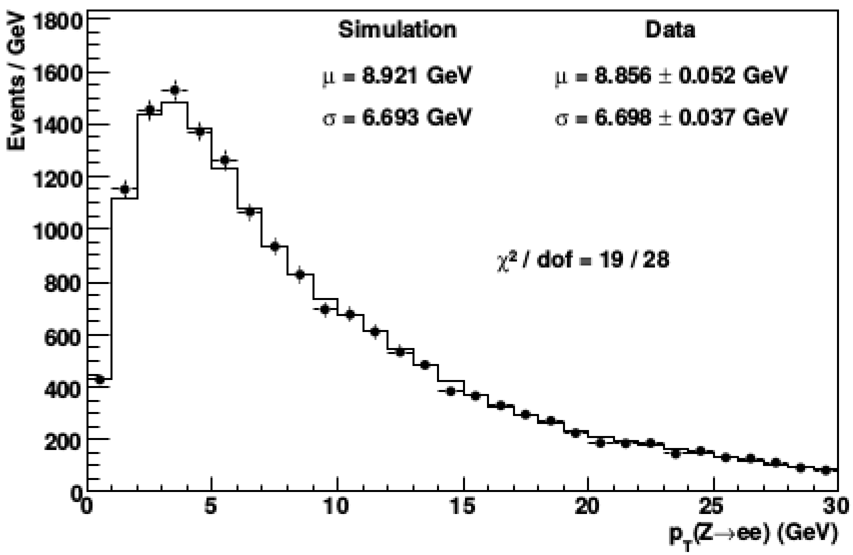
Phys.Rev. D85 (2012) 012005

- Measurement of p_T^W is less precise in the low p_T region
- However it provides an important cross check

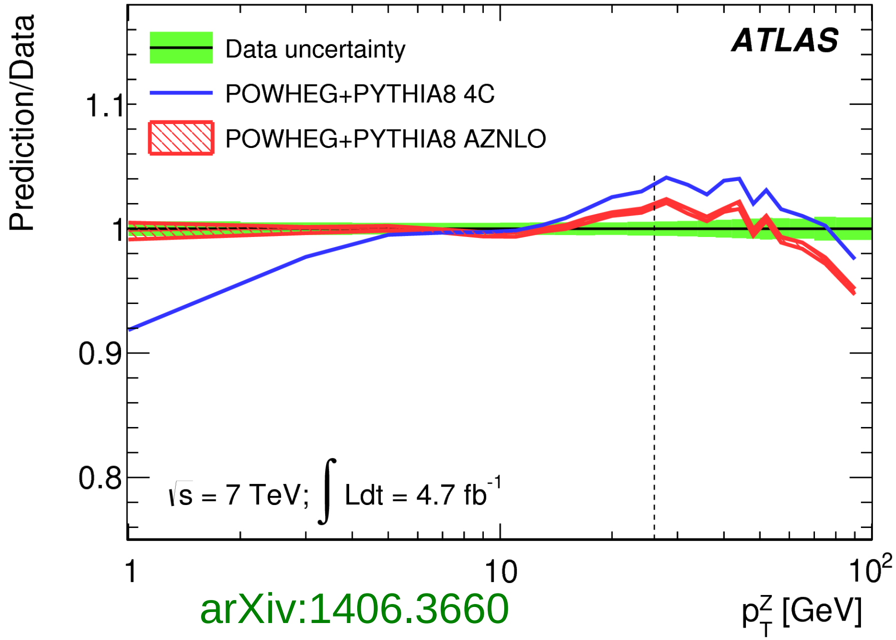
Constraining p_T^W and p_T^Z theory uncertainties

CDF W mass measurement
- RESBOS used to model $p_T^{W,Z}$
- Fit non-pQCD parameter g_2 and α_s to p_T^Z data
- Uncertainties propagated to M_W
  3, 9, 4, MeV for M_T, p_T^l, p_T^ν

$$S = \left[g_1 - g_2 \log\left(\frac{\sqrt{\hat{s}}}{2Q_0}\right) - g_1 g_3 \log(100 x_j x_k)\right] b^2$$



Phys. Rev. D 89, 072003 (2014)



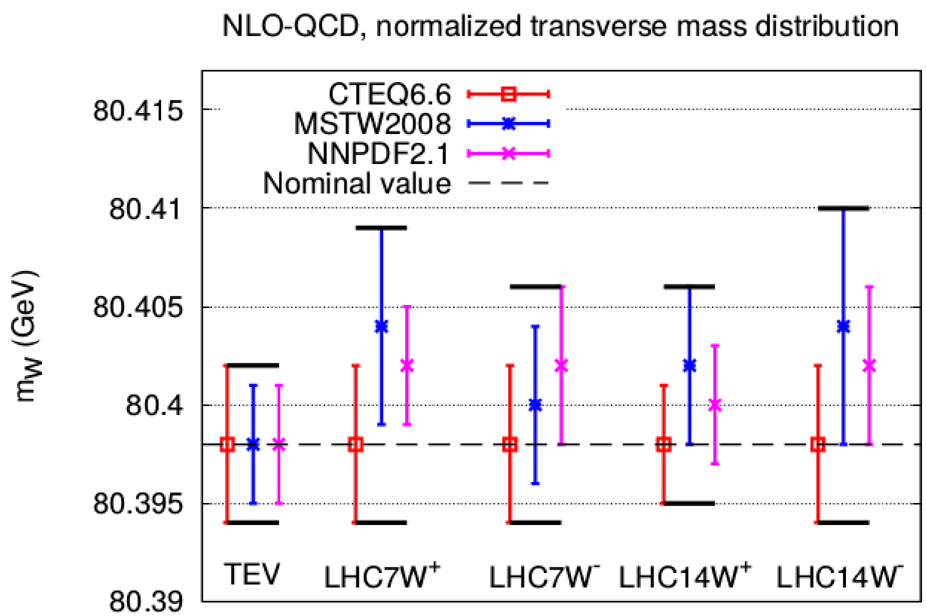
arXiv:1406.3660

ATLAS
- POWHEG+PYTHIA8 model
- Fit non-pQCD parameters primordial k_T and ISR cut-off to p_T^Z data

PDF uncertainties

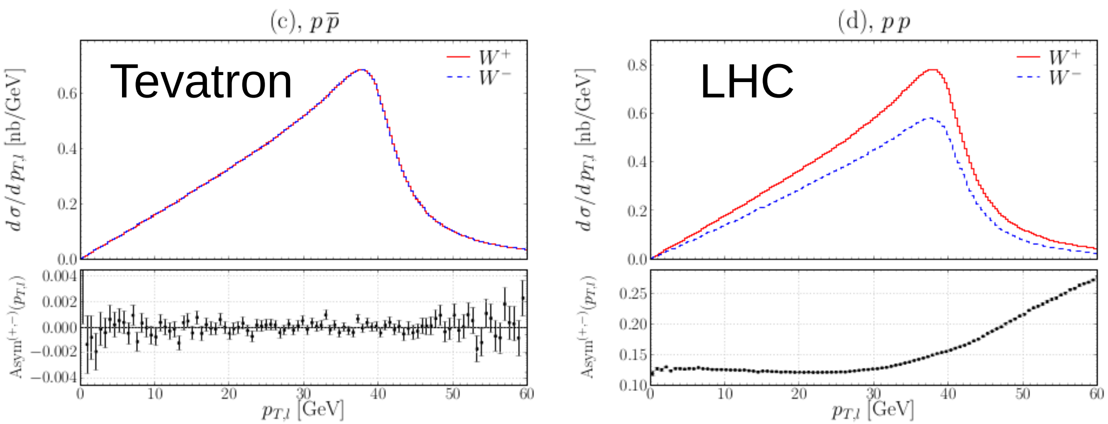
PDF uncertainties on M_W extraction from M_T (DYNNLO)

Phys.Rev.D83:113008,2011
arXiv:1309.1311



- Normalised distribution are essential to reduce PDF uncertainties
- PDF uncertainties are expected to be larger at the LHC than at the Tevatron, and different between W^+ and W^-
- Estimated small α_s and m_c uncertainties

- pp collision → no symmetry between W^+ and W^- lepton p_T due to $u_v \neq d_v$ and W polarization
  → Larger PDF uncertainties at LHC than Tevatron
- At the LHC, a charge-dependent separate analysis of W^+ and W^- helps to reduce PDF uncertainties

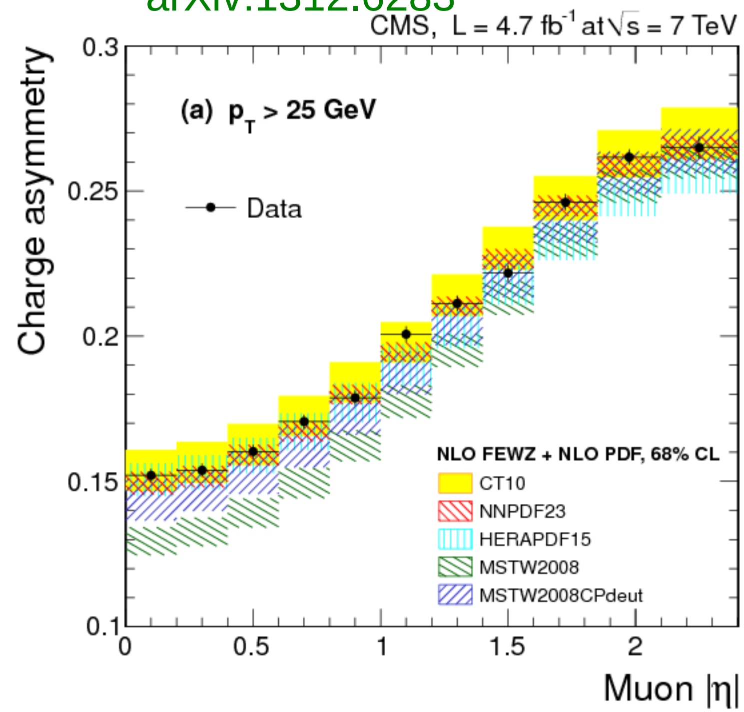


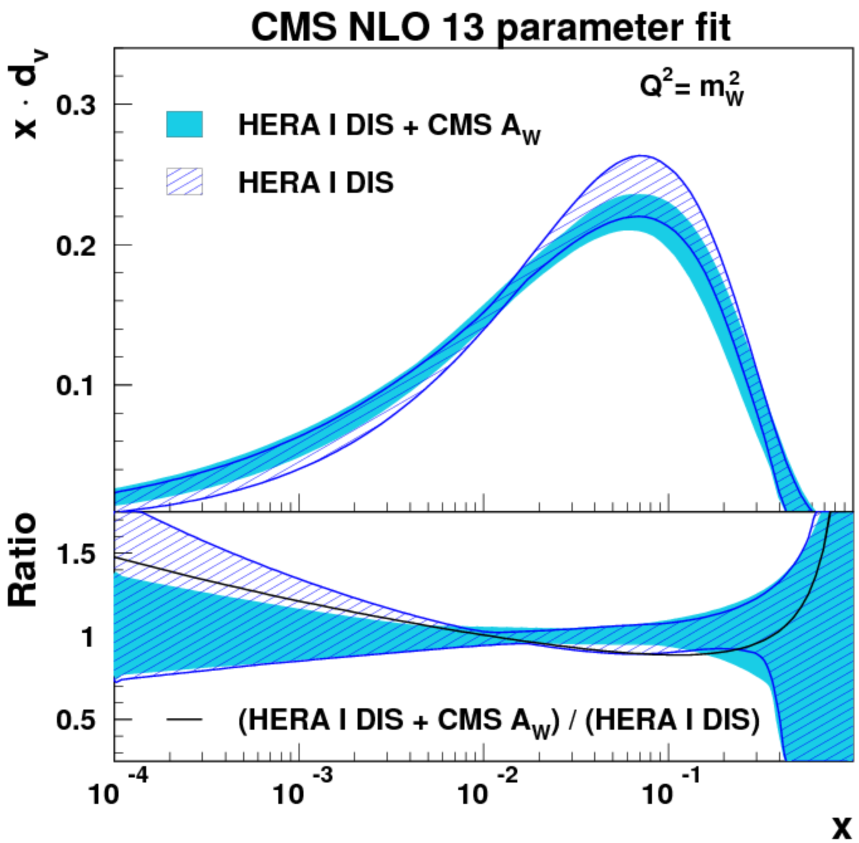
Eur.Phys.J. C69 (2010) 379-397

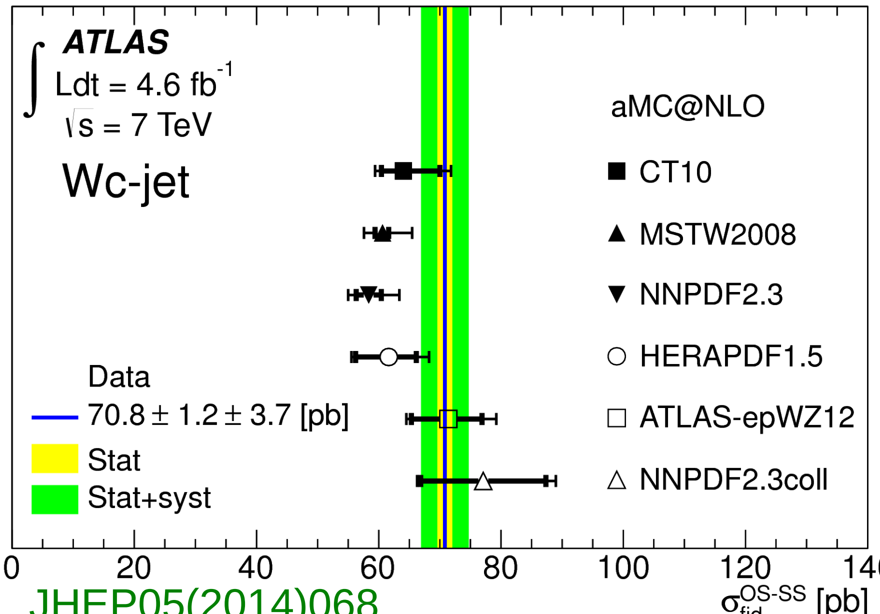
PDF uncertainties

- Crucial to reduce the valence PDF uncertainty
- The strange PDF uncertainty could be large for the M_W extraction from p_T^l
- ATLAS and CMS have provided several measurements of W, Z inclusive and W+charm, which can constrain PDF uncertainties

arXiv:1312.6283







JHEP05(2014)068

W, Z polarization

- Set of 8 observables: angular coefficients $A_i \rightarrow$ ratio of helicity cross sections
- A_i are functions of the leptons kinematic $A_i(p_T^{ll}, y^{ll}, M^{ll})$
- A_i coeffiicients can be calculated form MC sample with moments method

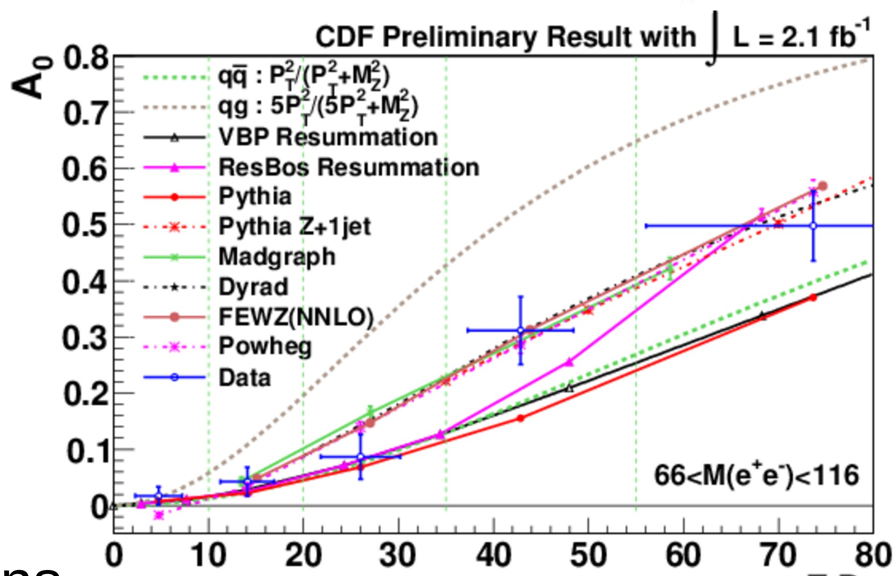
$$\langle m \rangle = \frac{\int d\sigma(p_T, y, \theta, \phi)\ m\ d\cos\theta\, d\phi}{\int d\sigma(p_T, y, \theta, \phi)\ d\cos\theta\, d\phi}$$

$$\frac{dN}{d\Omega} \propto (1+\cos^2\vartheta) + A_0\,\frac{1}{2}(1-3\cos^2\vartheta) + A_1\,\sin 2\vartheta\cos\varphi + A_2\,\frac{1}{2}\sin^2\vartheta\cos 2\varphi + A_3\,\sin\vartheta\cos\varphi + A_4\,\cos\vartheta + A_5\,\sin^2\vartheta\sin 2\varphi + A_6\,\sin 2\vartheta\sin\varphi + A_7\,\sin\vartheta\sin\varphi\,.$$

LO terms

Phys.Rev. D50 (1994) 5692
Nucl.Phys. 387 (1992) 3

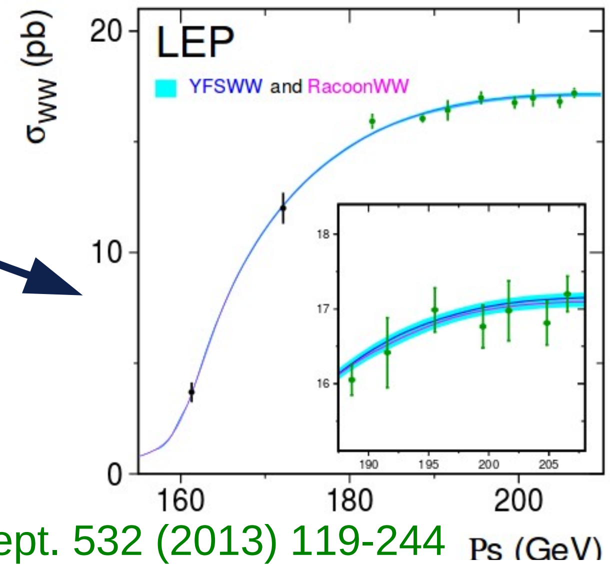
- A_i can be measured precisely for Z, the W measurement is more challenging
  - Related to boson polarization, V-A coupling
  - Provide insight into QCD and EW dynamics
  - Stringent test of predictions and MC generators
- A_0-A_4 coefficients measured at CDF
- Precise measurements at the LHC of A_0-A_7 can discriminate between different predictions



Phys. Rev. Lett. 106, 241801 (2011)

Prospects for M_W at ILC and TLEP

M_W can be measured at e^+e^- colliders through an energy scan of the WW production threshold



Phys.Rept. 532 (2013) 119-244

Near threshold, the WW cross section is proportional to the non-relativistic W velocity

$$\sigma(WW) \propto \beta_W$$

arXiv:1306.6352

ILC Giga-Z program

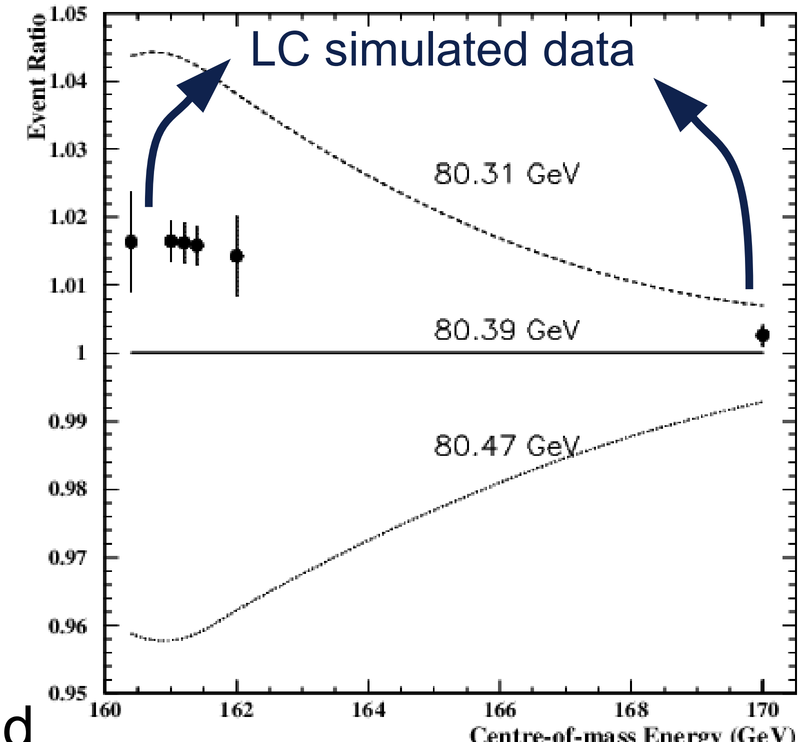
- Energy scan 160 to 170 GeV
- δM_W = 6-7 MeV

JHEP 1401 (2014) 164

TLEP OkuW program

- δM_W = 0.5 MeV

  → dominated by statistical uncertainty



LC-PHSM-2001-009

Dominant theory uncertainties

- Initial state QED corrections
- Parametrization of cross section near threshold

Prospects for M_Z at TLEP

- TeraZ program: 7 x 10^{11} visible Z in one year of data taking at 91 GeV

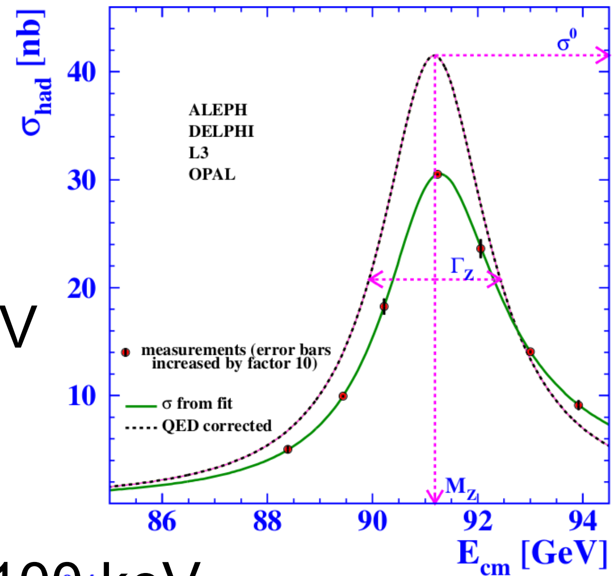
M_Z extracted from Z lineshape

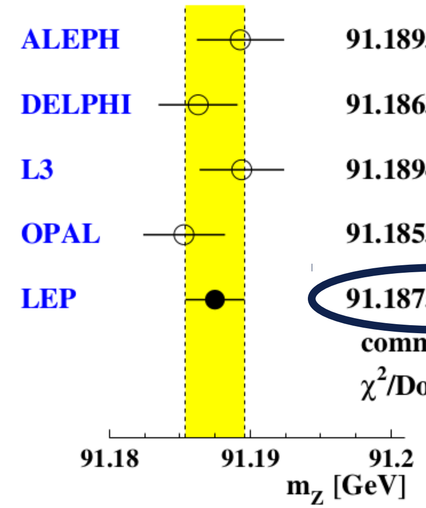
- Statistical uncertainty: 5 keV
- Systematic uncertainty: 100 keV → dominated by beam energy calibration

Dominant theory uncertainties

- Initial state QED corrections ≤ 100 keV
- Additional lepton pairs ≤ 300 keV
- Lineshape parametrization ≤ 100 keV → Need to revisit theory predictions

Phys.Rept.427:257-454,2006





Factor of 20 improvement wrt LEP M_Z measurement

JHEP 1401 (2014) 164

Quantity	Physics	Present precision	Measured from	Statistical uncertainty	Systematic uncertainty	Key	Challenge
m_Z (keV)	Input	91187500 ± 2100	Z Line shape scan	5 (6) keV	$<$ 100 keV	E_{beam} calibration	QED corrections
Γ_Z (keV)	$\Delta\rho$ (not $\Delta\alpha_{had}$)	2495200 ± 2300	Z Line shape scan	8 (10) keV	$<$ 100 keV	E_{beam} calibration	QED corrections
R_ℓ	α_s, δ_b	20.767 ± 0.025	Z Peak	0.00010 (12)	$<$ 0.001	Statistics	QED corrections
N_ν	PMNS Unitarity, ...	2.984 ± 0.008	Z Peak	0.00008 (10)	$<$ 0.004		Bhabha scat.
N_ν	... and sterile ν's	2.92 ± 0.05	$Z\gamma$, 161 GeV	0.0010 (12)	$<$ 0.001	Statistics	
R_b	δ_b	0.21629 ± 0.00066	Z Peak	0.000003 (4)	$<$ 0.000060	Statistics, small IP	Hemisphere correlations
A_{LR}	$\Delta\rho$, ϵ_3, $\Delta\alpha_{had}$	0.1514 ± 0.0022	Z peak, polarized	0.000015 (18)	$<$ 0.000015	4 bunch scheme, 2exp	Design experiment
m_W (MeV)	$\Delta\rho$, ϵ_3, ϵ_2, $\Delta\alpha_{had}$	80385 ± 15	WW threshold scan	0.3 (0.4)MeV	$<$ 0.5 MeV	E_{beam}, Statistics	QED corrections
m_{top} (MeV)	Input	173200 ± 900	$t\bar{t}$ threshold scan	10 (12) MeV	$<$ 10 MeV	Statistics	Theory interpretation

Summary

- The indirect determination of M_W from the global fit of the SM parameters calls for a target precision of 10 MeV on the measurement of M_W
- For the measurement of the W mass at the LHC it is necessary to control and reduce many sources of experimental and theoretical uncertainties
- A first step towards the measurement of M_W is the lepton calibration, and the validation of the analysis techniques through the measurement of M_Z
- ATLAS and CMS have an extensive program of W, Z measurements which can help constraining many of the theoretical uncertainties
- Prospects at future e^+e^- colliders ILC (TLEP) for approximately a factor of 2 (20) improvement on δM_W and δM_Z

BACKUP

W mass uncertainties at CDF

m_T fit uncertainties			
Source	$W \to \mu\nu$	$W \to e\nu$	Common
Lepton energy scale	7	10	5
Lepton energy resolution	1	4	0
Lepton efficiency	0	0	0
Lepton tower removal	2	3	2
Recoil scale	5	5	5
Recoil resolution	7	7	7
Backgrounds	3	4	0
PDFs	10	10	10
W boson p_T	3	3	3
Photon radiation	4	4	4
Statistical	16	19	0
Total	23	26	15

p_T^ν fit uncertainties			
Source	$W \to \mu\nu$	$W \to e\nu$	Correlation
Lepton energy scale	7	10	5
Lepton energy resolution	1	7	0
Lepton efficiency	2	3	0
Lepton tower removal	4	6	4
Recoil scale	2	2	2
Recoil resolution	11	11	11
Backgrounds	6	4	0
PDFs	11	11	11
W boson p_T	4	4	4
Photon radiation	4	4	4
Statistical	22	25	0
Total	30	33	18

p_T^ℓ fit uncertainties			
Source	$W \to \mu\nu$	$W \to e\nu$	Common
Lepton energy scale	7	10	5
Lepton energy resolution	1	4	0
Lepton efficiency	1	2	0
Lepton tower removal	0	0	0
Recoil scale	6	6	6
Recoil resolution	5	5	5
Backgrounds	5	3	0
PDFs	9	9	9
W boson p_T	9	9	9
Photon radiation	4	4	4
Statistical	18	21	0
Total	25	28	16

Phys. Rev. D 89, 072003 (2014)

Uncertainties are given in MeV

W mass uncertainties at D0

Phys. Rev. D 89, 012005 (2014)

Source	Section	m_T	p_T^e	$\not{E}_T$
Experimental				
Electron Energy Scale	VII C 4	16	17	16
Electron Energy Resolution	VII C 5	2	2	3
Electron Shower Model	V C	4	6	7
Electron Energy Loss	V D	4	4	4
Recoil Model	VII D 3	5	6	14
Electron Efficiencies	VII B 10	1	3	5
Backgrounds	VIII	2	2	2
$\sum$(Experimental)		18	20	24
W Production and Decay Model				
PDF	VI C	11	11	14
QED	VI B	7	7	9
Boson p_T	VI A	2	5	2
$\sum$(Model)		13	14	17
Systematic Uncertainty (Experimental and Model)		22	24	29
W Boson Statistics	IX	13	14	15
Total Uncertainty		26	28	33

Uncertainties are given in MeV

PDF uncertainties on M_T

	CTEQ6.6		MSTW2008		NNPDF2.1		
	$m_W \pm \delta_{\rm pdf}$	$\langle\chi^2\rangle$	$m_W \pm \delta_{\rm pdf}$	$\langle\chi^2\rangle$	$m_W \pm \delta_{\rm pdf}$	$\langle\chi^2\rangle$	$\delta_{\rm pdf}^{\rm tot}$
Tevatron, $W^\pm$	80.398 ± 0.004	1.42	80.398 ± 0.003	1.42	80.398 ± 0.003	1.30	4
LHC 7 TeV W^+	80.398 ± 0.004	1.22	80.404 ± 0.005	1.55	80.402 ± 0.003	1.35	8
LHC 7 TeV W^-	80.398 ± 0.004	1.22	80.400 ± 0.004	1.19	80.402 ± 0.004	1.78	6
LHC 14 TeV W^+	80.398 ± 0.003	1.34	80.402 ± 0.004	1.48	80.400 ± 0.003	1.41	6
LHC 14 TeV W^-	80.398 ± 0.004	1.44	80.404 ± 0.006	1.38	80.402 ± 0.004	1.57	8

Phys.Rev.D83:113008,2011

	Tevatron	LHC7W+	LHC7W-	LHC14W+	LHC14W-
$\alpha_s(m_Z) = 0.118$	80.398	80.400	80.398	80.402	80.400
$\alpha_s(m_Z) = 0.119$ (ref)	80.398	80.402	80.402	80.400	80.402
$\alpha_s(m_Z) = 0.120$	80.398	80.400	80.398	80.402	80.402

Table 7: Central value of the fit of m_W obtained with NNPDF2.1, using PDF sets that differ by the $\alpha_s(m_Z)$ value, for different colliders and energies. The fit has been done on normalized distributions and using normalized templates, and the distributions have been generated at NLO-QCD with DYNNLO.

m_W (GeV)	Tevatron	LHC7W+	LHC7W-	LHC14W+	LHC14W-
$m_c = 1.414$ (ref)	80.398	80.402	80.402	80.400	80.402
$m_c = 1.5$	80.398	80.400	80.398	80.398	80.399
$m_c = 1.6$	80.398	80.400	80.400	80.398	80.399
$m_c = 1.7$	80.396	80.400	80.400	80.396	80.398

Table 8: Central value of the fit of m_W obtained with NNPDF2.1 sets with different values of m_c for different colliders and energies. We include the default value in NNPDF2.1, $m_c^2 = 2$ GeV^2 as well.