W / Z Boson Production and Mass

Oliver Stelzer-Chilton

TRIUMF

On behalf of

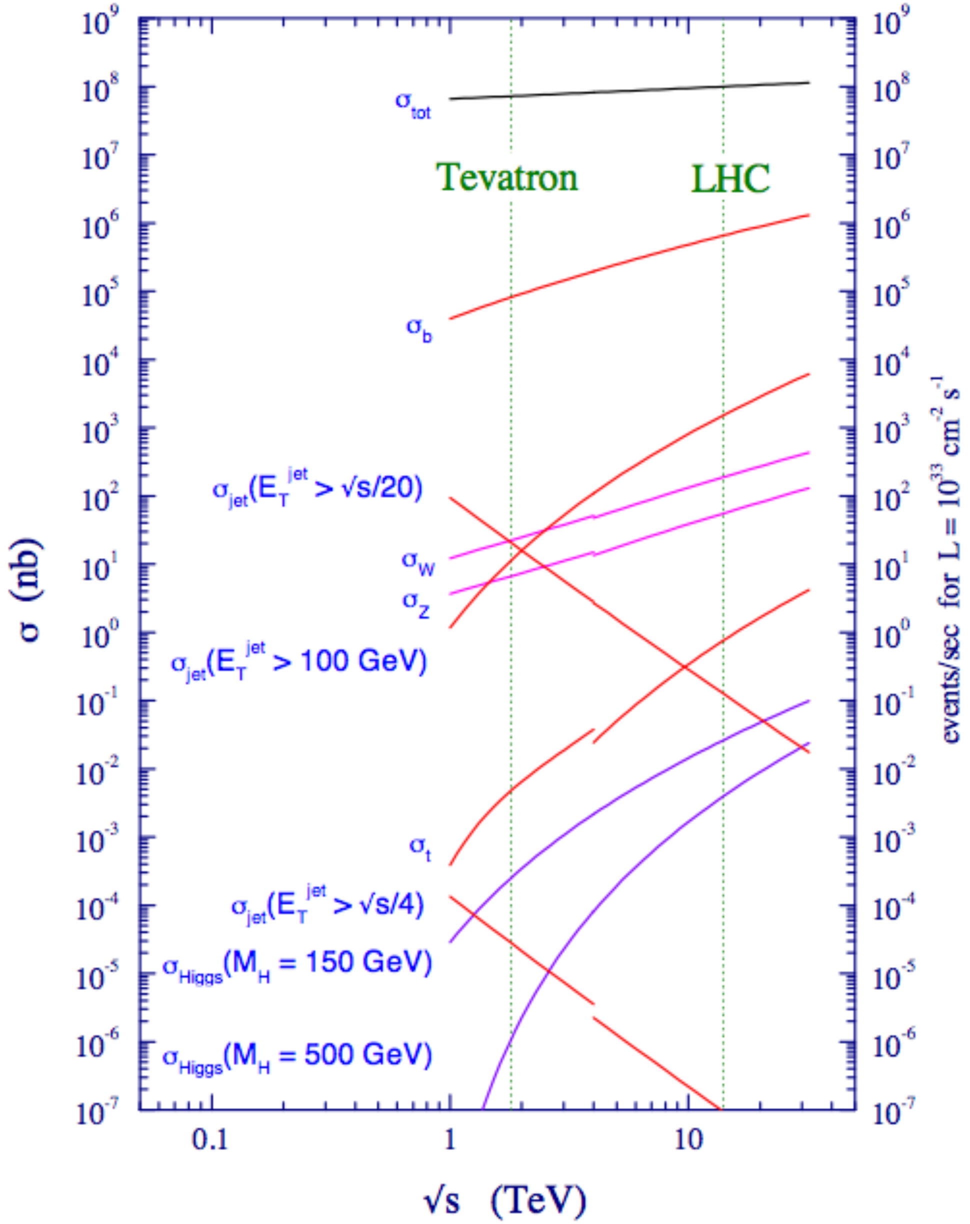
ATLAS, CMS, LHCb, CDF and D0

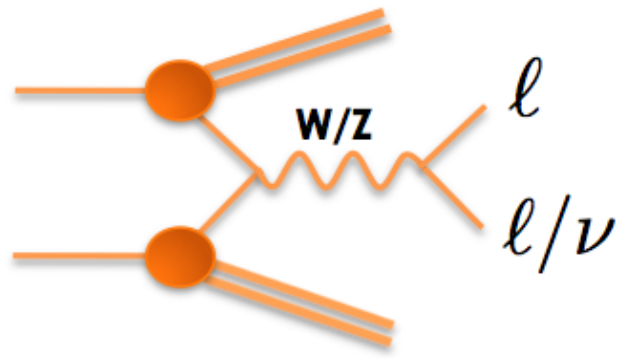
Hadron Collider Physics Symposium 2012

November 12 - 16, 2012

Kyoto, Japan

W/Z Production





Theoretically well established picture
Well identifiable final states
Corrections: QCD, EWK

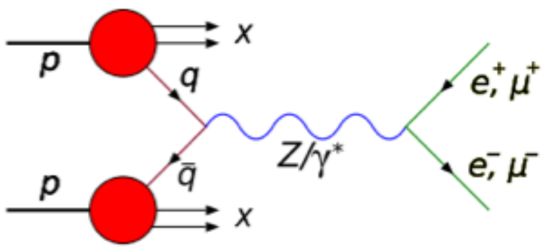
Very Important Processes

- Performance measurements
- Proton PDFs
- Backgrounds for searches
- SM tests at TeV scale

W/Z Production

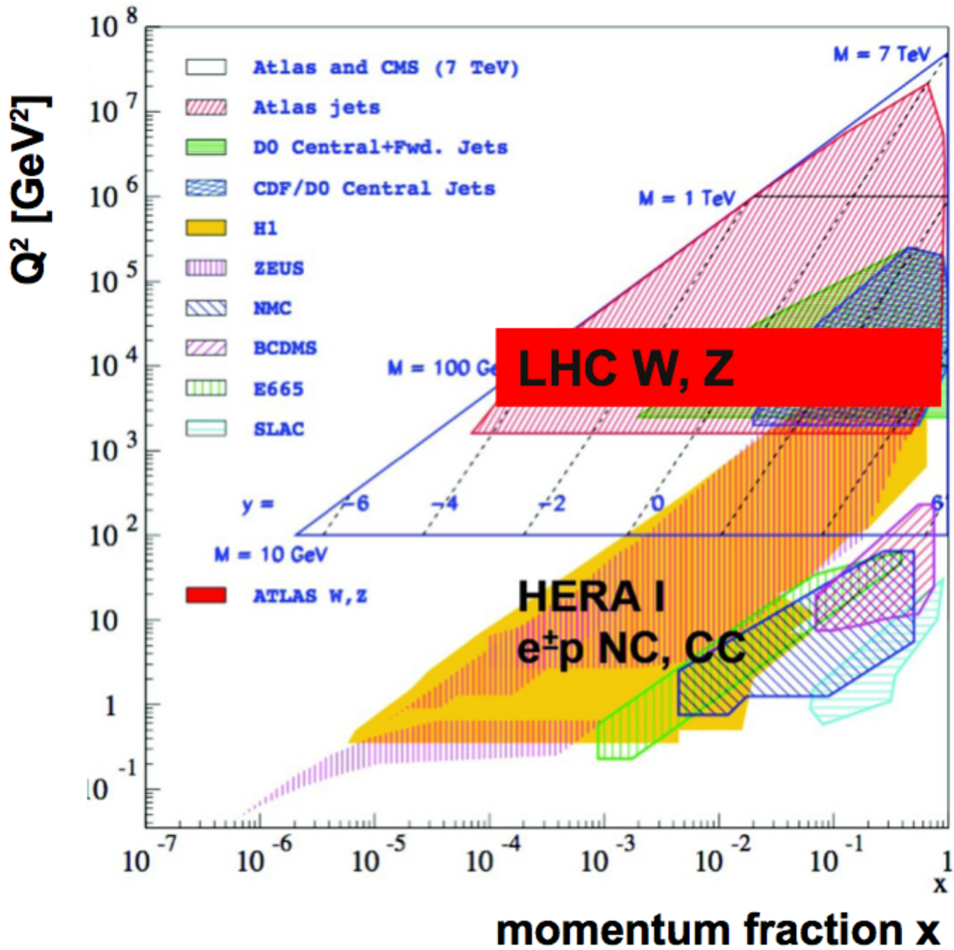
Any cross section at the LHC is a convolution of partonic cross section and parton distribution functions (PDFs)

$$\sigma_{PP} = \hat{\sigma}_{qq}(\alpha(Q^2), Q^2) \otimes \sum_q \int dx_1 dx_2 f_q(x_1, Q^2) f_q(x_2, Q^2)$$



Kinematic phase space given by

$$x_{1,2} = \frac{M_{W,Z}}{\sqrt{s}} e^{\pm y}$$



0.001<x<0.1

$M_{W,Z}$ = 80.4, 91.2 GeV

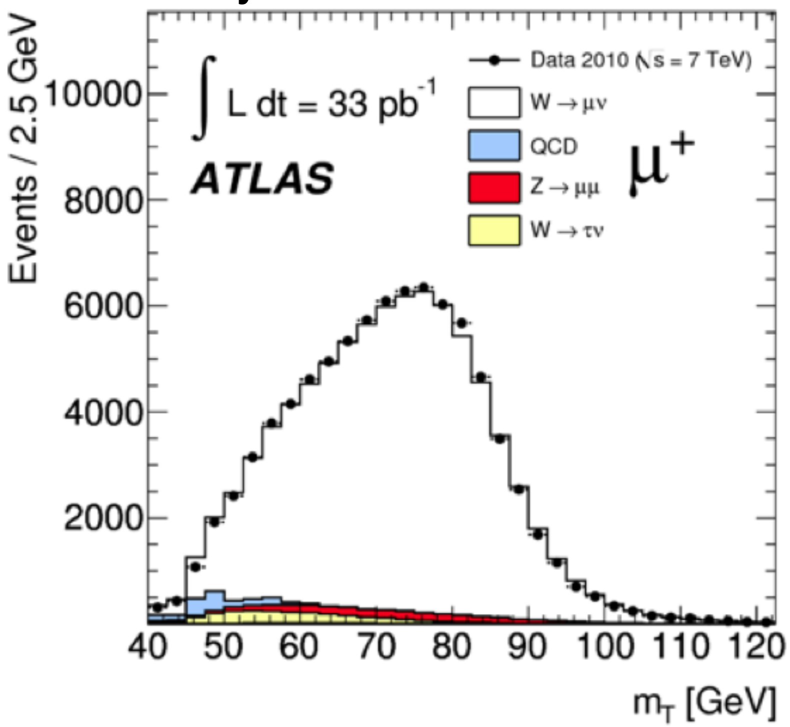
Boson rapidity |y| < 2.5

W/Z Production Cross Sections

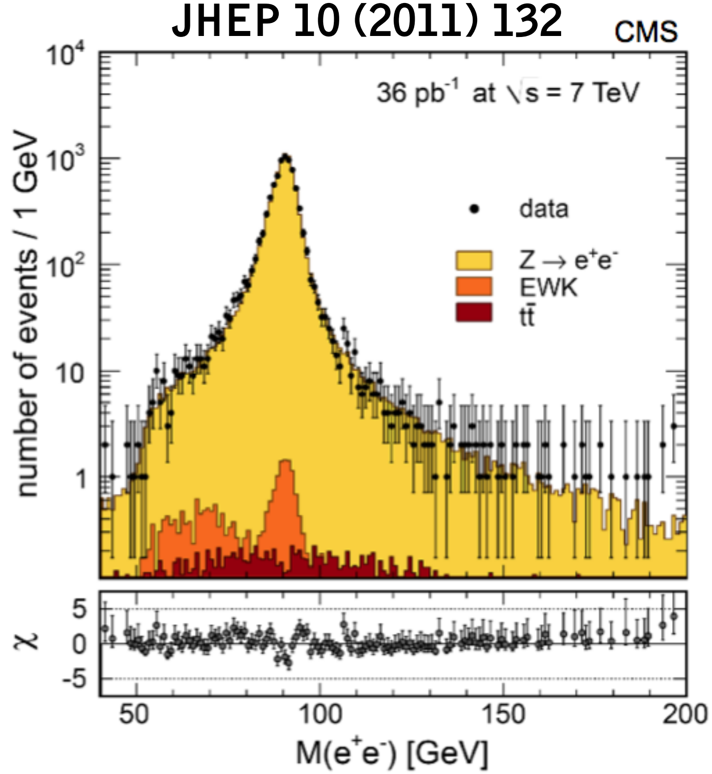
see talk by Gian Di Giovann

ATLAS and CMS published precision measurements with 2010 data

Phys. Rev. D85 (2012) 072004



JHEP 10 (2011) 132



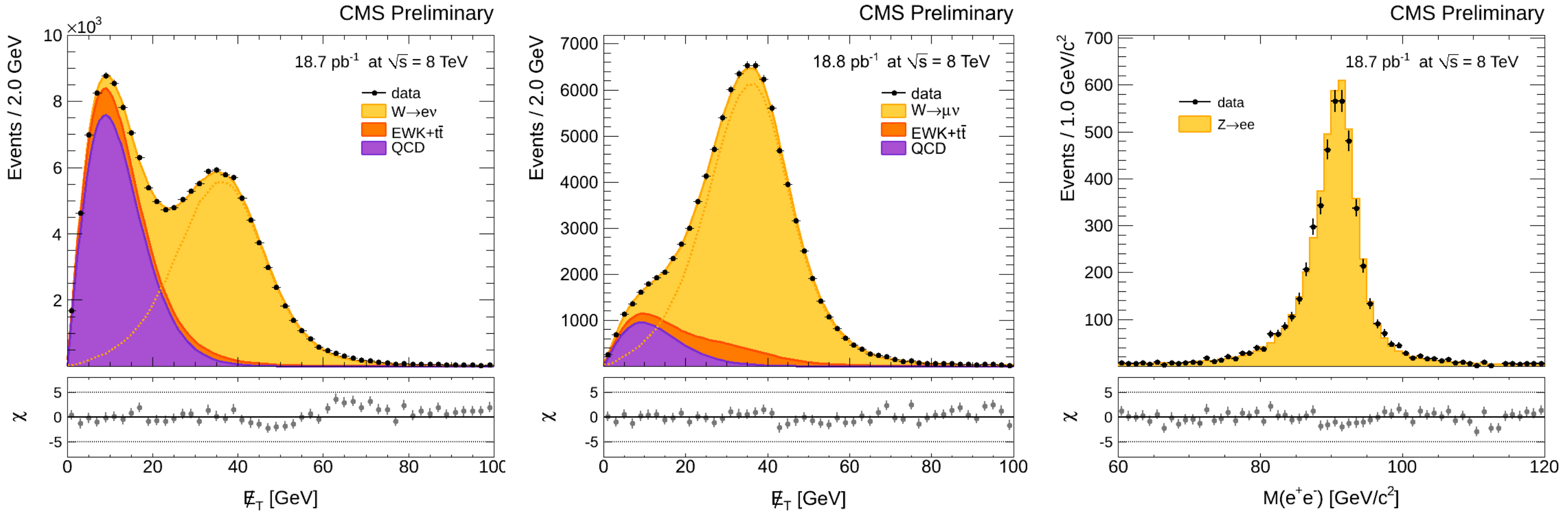
Much larger dataset now available, but:

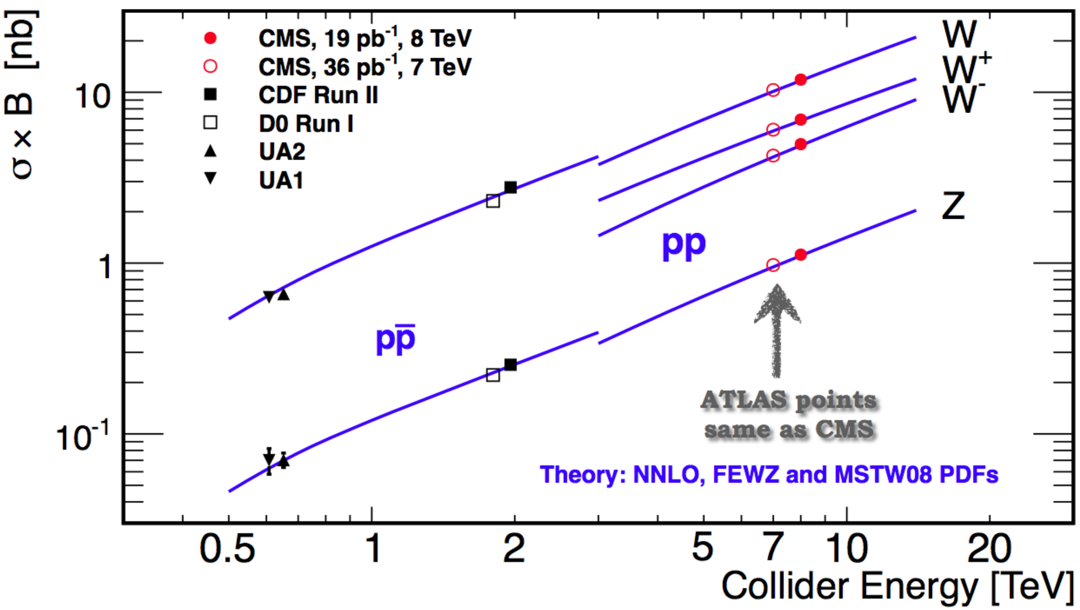
LHC luminosity is increasing $2x10^{31}$ in 2010 to $7x10^{33}$ 2012

Average number of inelastic pp interaction (pileup) increased from 2 to 20

Precise measurement of inclusive cross section requires low pileup and low P_T trigger thresholds

W/Z Production Cross Sections



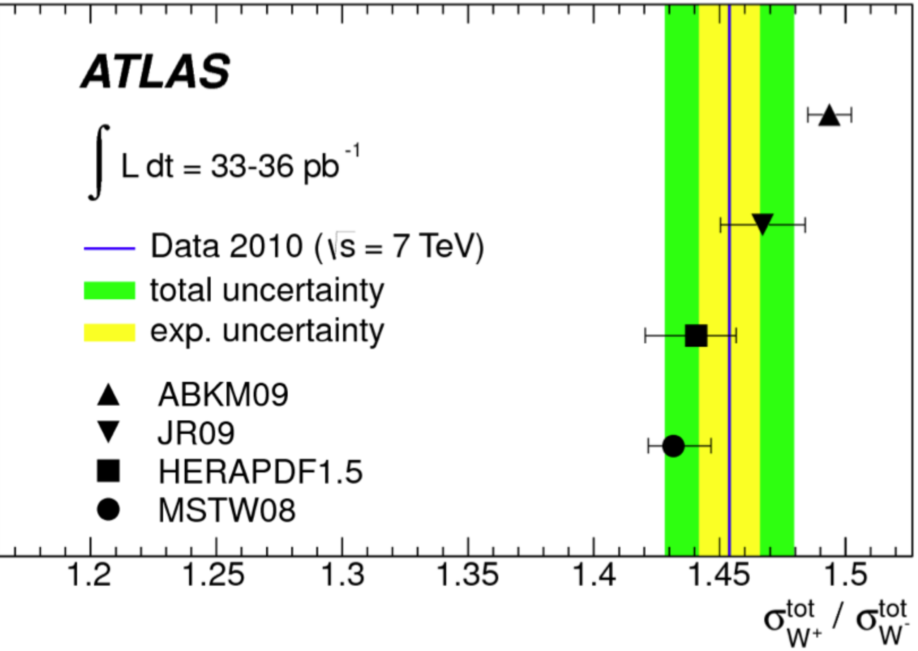


CMS-PAS-12-011

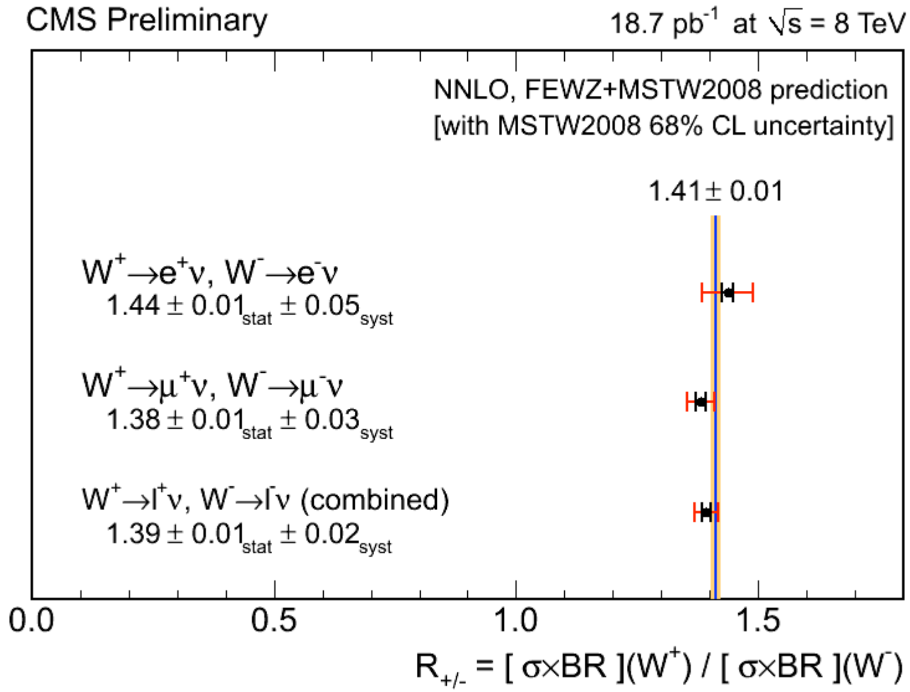
8 TeV!

Ratio of W+ and W- Cross Sections

Phys.Rev. D85 (2012) 072004



CMS-PAS-SMP-12-011



Benefits from experimental and theoretical systematics cancellation

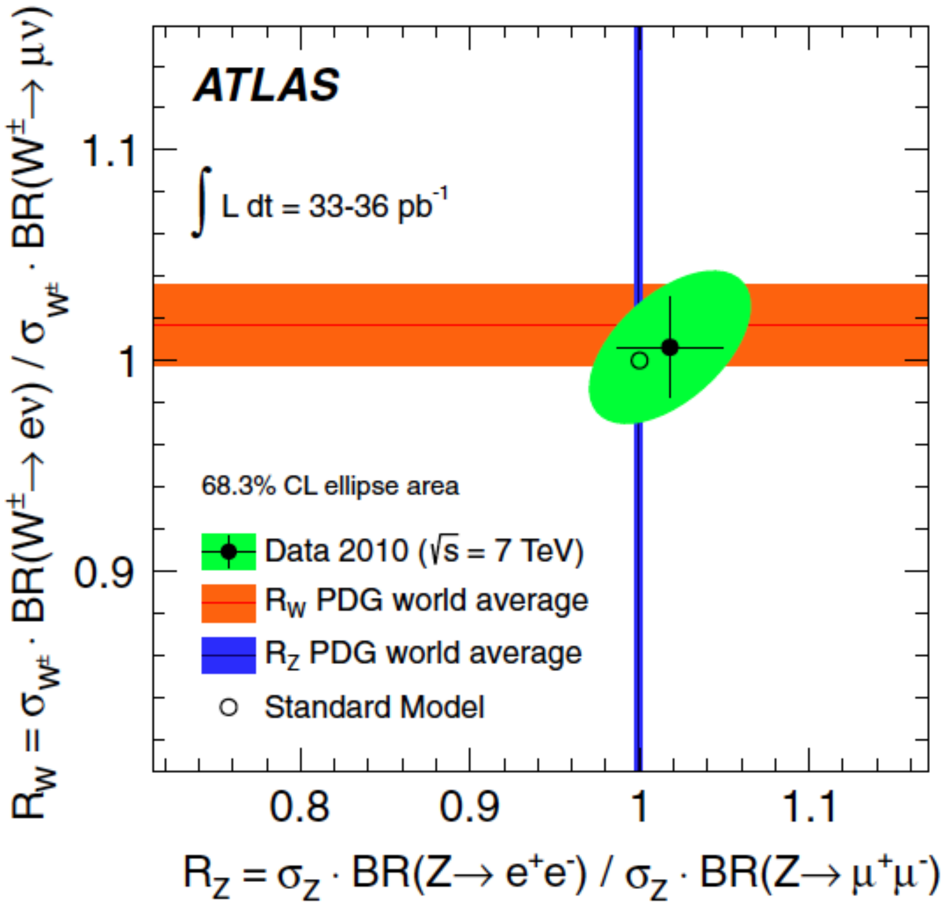
ATLAS	**7 TeV**	**1.454 +/- 0.006 (stat.) +/- 0.012 (syst.) +/- 0.022 (acc.)**
CMS	7 TeV	1.421 +/- 0.006 (stat.) +/- 0.014 (syst.) +/- 0.029 (th.)
CMS	8 TeV	1.39 +/- 0.01 (stat.) +/- 0.02 (syst.)

Lepton Universality

Phys.Rev. D85 (2012) 072004

Result already close to world average

World average
R_W=1.017 +/- 0.019
R_Z=0.9991+/-0.0024



$$R_W = \frac{\sigma_W^e}{\sigma_W^\mu} = \frac{Br(W \to e\nu)}{Br(W \to \mu\nu)} = 1.006 \pm 0.004\,(\mathrm{sta}) \pm 0.006\,(\mathrm{unc}) \pm 0.023\,(\mathrm{cor}) = 1.006 \pm 0.024$$

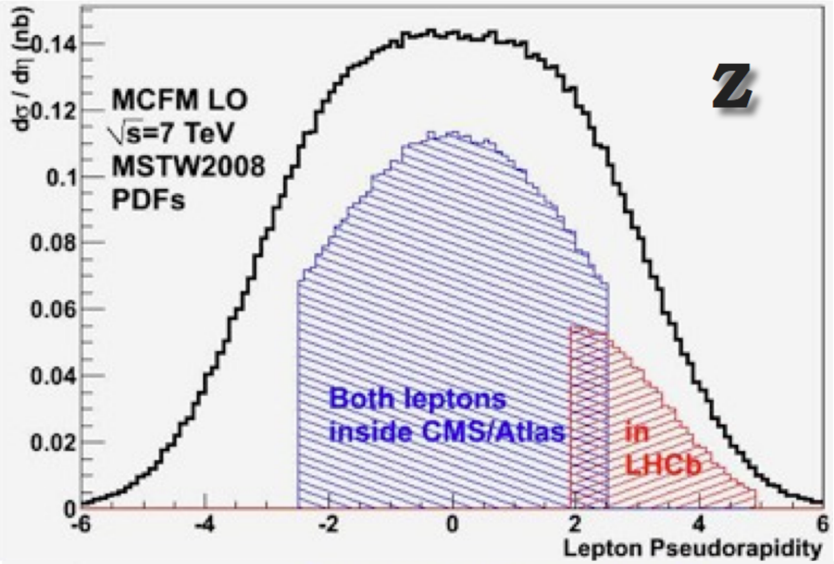
$$R_Z = \frac{\sigma_Z^e}{\sigma_Z^\mu} = \frac{Br(Z \to ee)}{Br(Z \to \mu\mu)} = 1.018 \pm 0.014\,(\mathrm{sta}) \pm 0.016\,(\mathrm{unc}) \pm 0.028\,(\mathrm{cor}) = 1.018 \pm 0.031$$

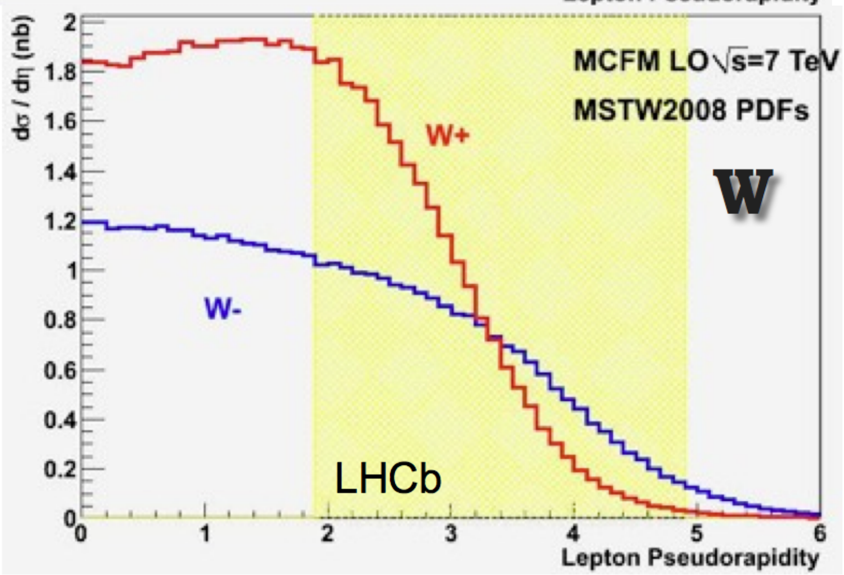
W and Z from LHCb

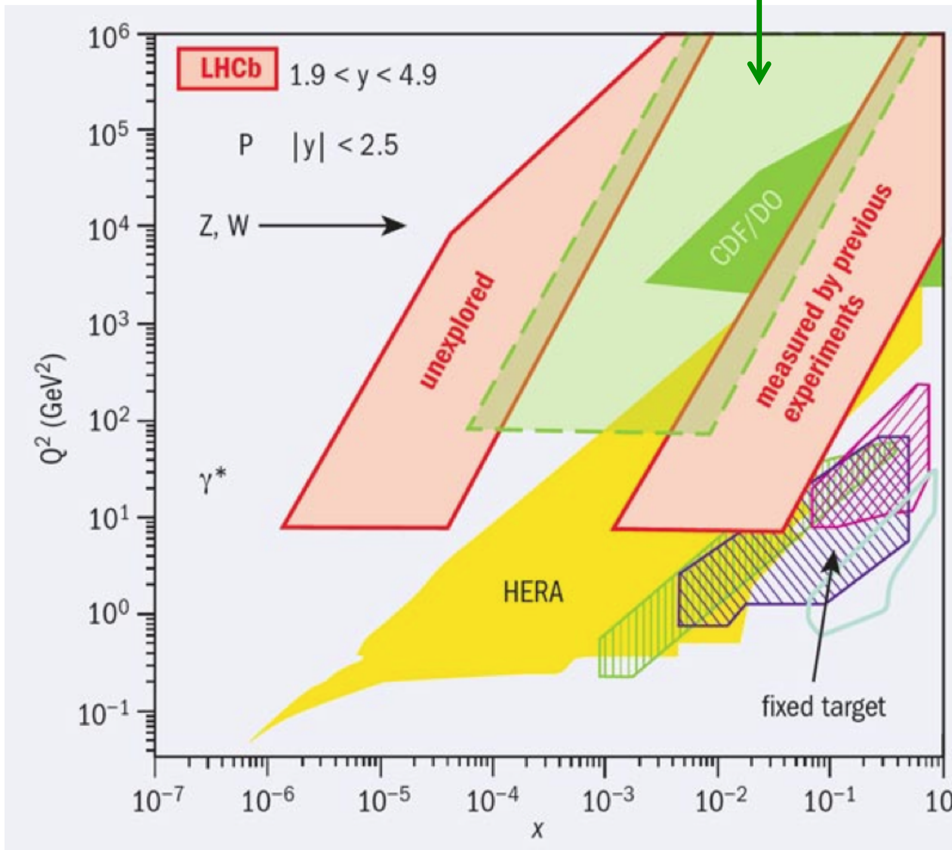
see talk by Kurt Rinnert

LHCb: Measurements extended up to $|\eta| = 4.9$

ATLAS & CMS



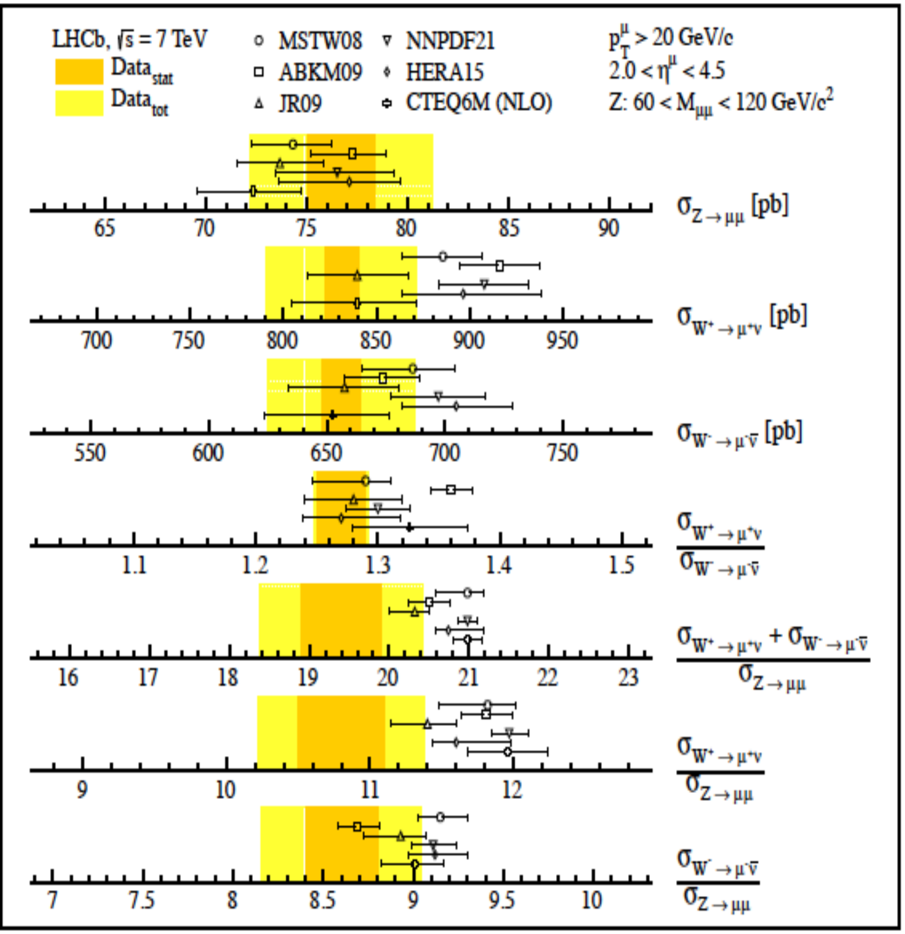




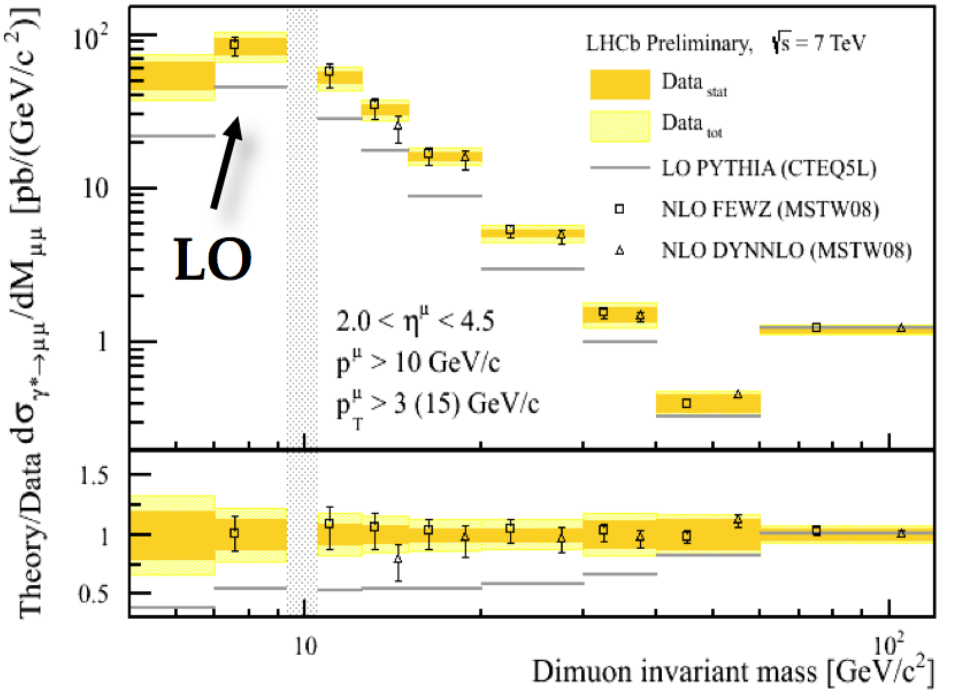
Important for PDF constrains

W and Z from LHCb

JHEP 06 (2012) 058



LHCb-CONF-2012-013

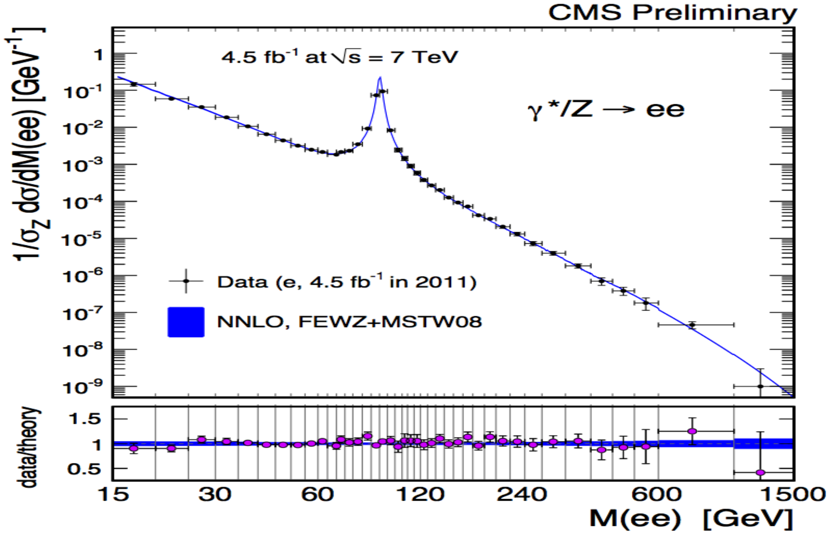


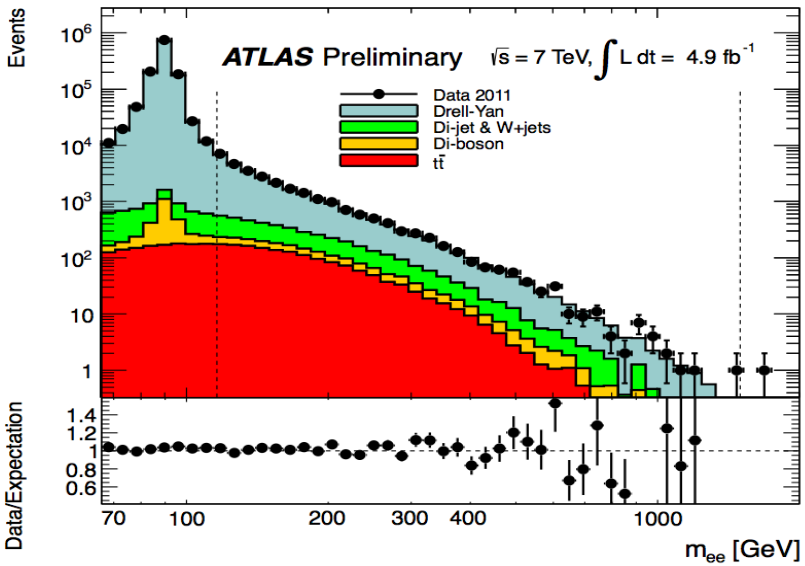
Differential Distributions

DY Differential Cross Section

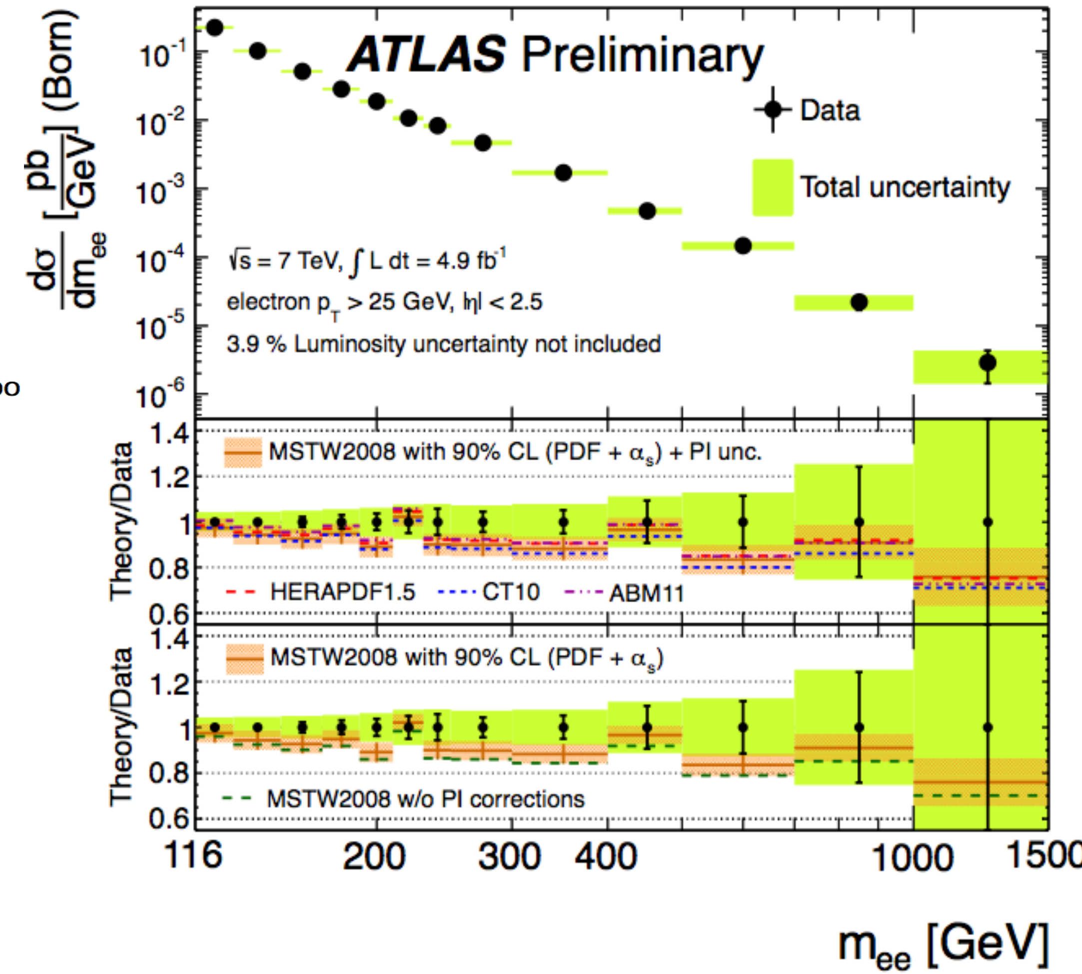
see talk by Gian Di Giovanni

CMS-PAS-EWK-11-007





NEW!



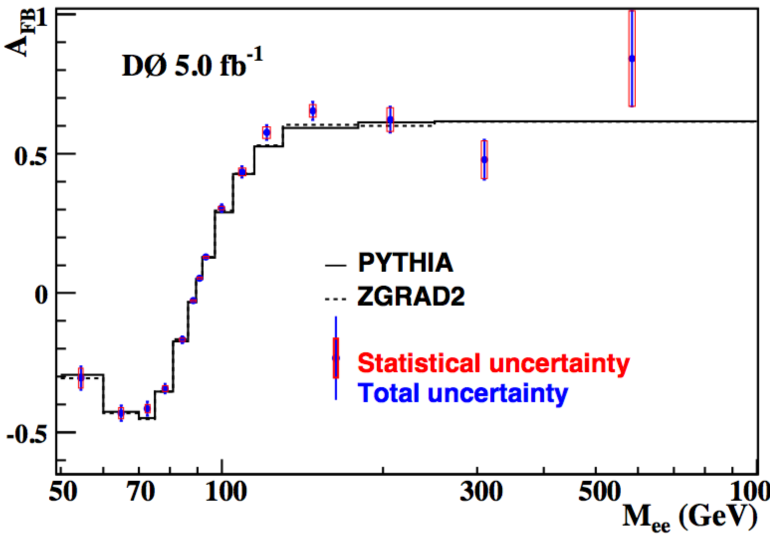
Invariant mass distributions in good agreement with theory prediction

Forward Backward Asymmetry

$$\frac{d\sigma}{d\cos\theta^*} \sim \frac{3}{8}(1 + \cos^2\theta^*) + A_{FB}\cos\theta^*$$

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

PRD 84, 012007 (2011)



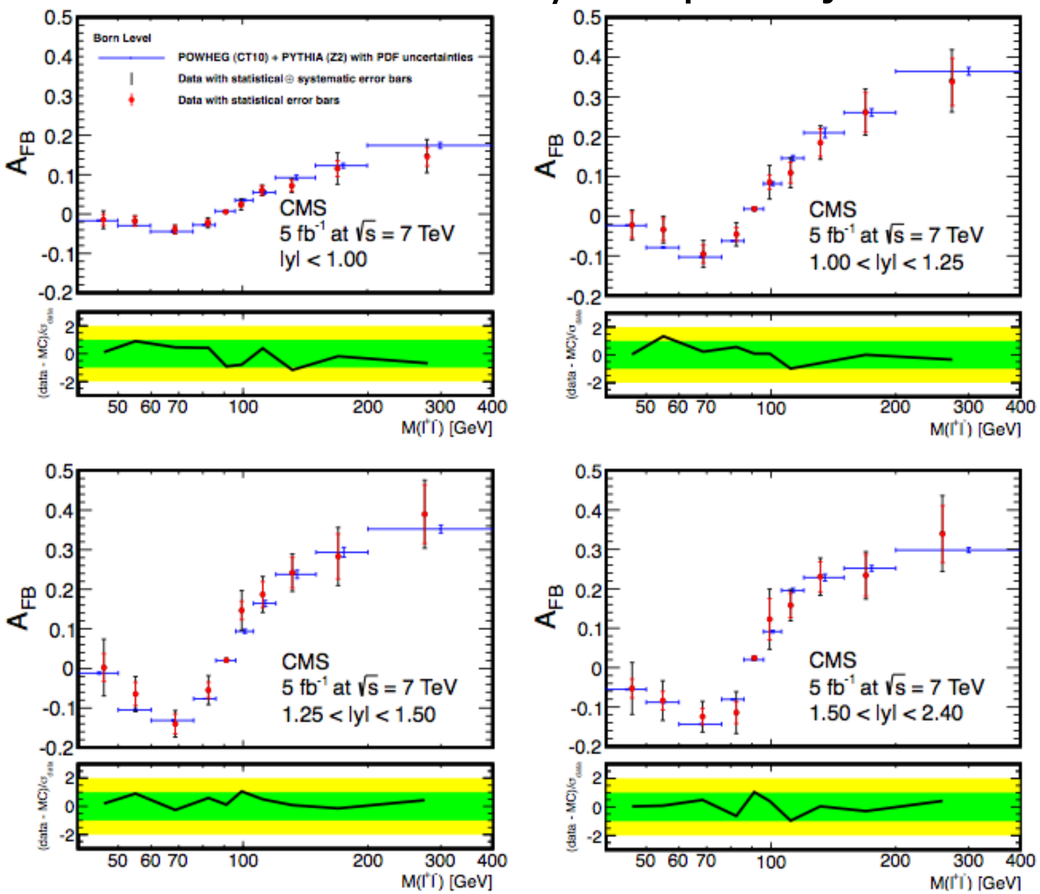
Most precise measurements of $g_a^{u(d)}$ $g_v^{u(d)}$

CMS:

Asymmetry measured as a function of mass and rapidity

Measurement in both dilepton channels and combination

arXiv:1207.3973, accepted by PLB

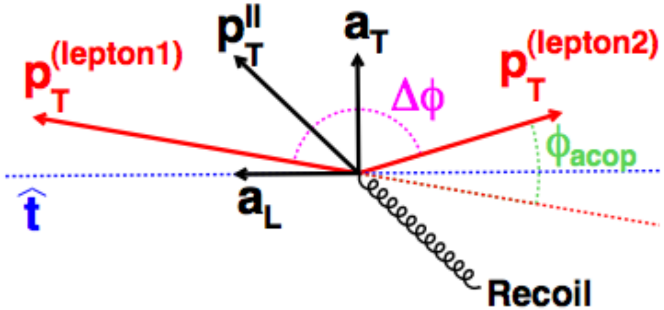


Z/γ* Transverse Momentum

see talk by Simone Marzani

ϕ^*_η depends exclusively on the angles of the two leptons which are better measured than their momenta

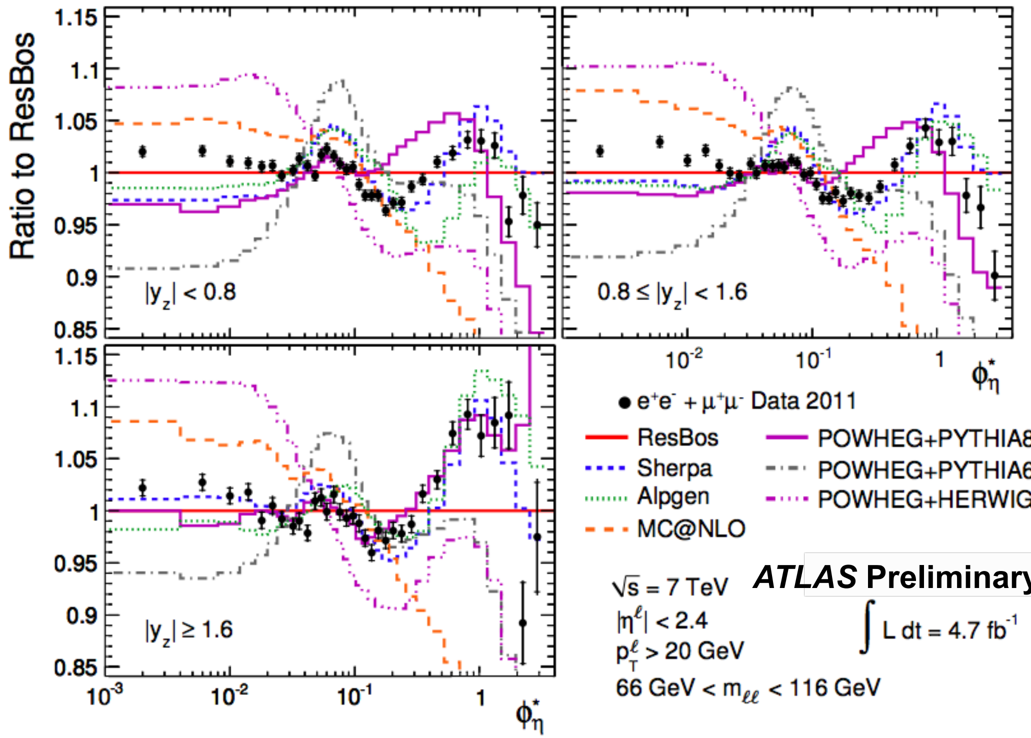
New!



$$\phi^*_\eta = \tan\left(\phi_{acop}/2\right)\sin(\theta^*_\eta)$$

$$\cos(\theta^*_\eta) = \tanh\left[\left(\eta^- - \eta^+\right)/2\right]$$

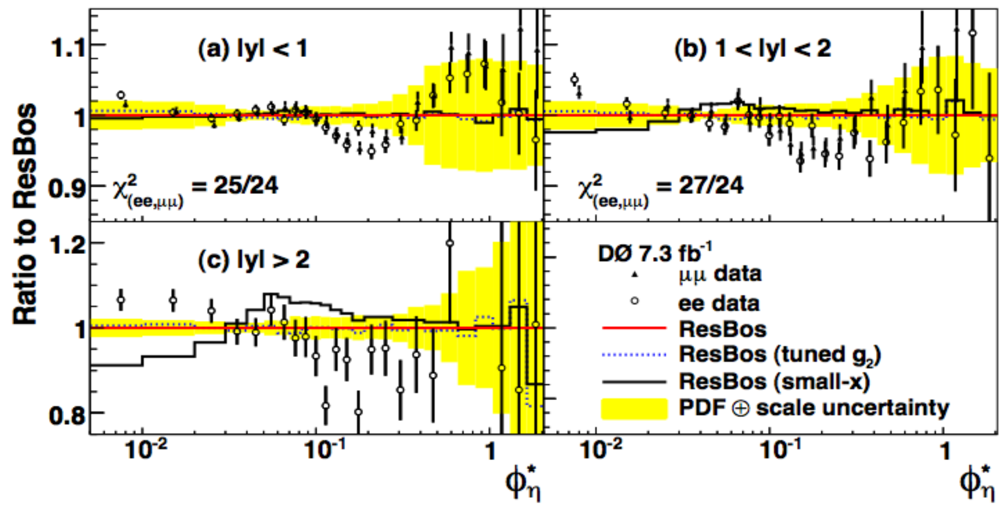
Good description of ATLAS data by RESBOS at the ~4% level



Technique used by D0

Phys. Rev. Lett. 106 (2011)

Similar residual shape mismatch to RESBOS prediction

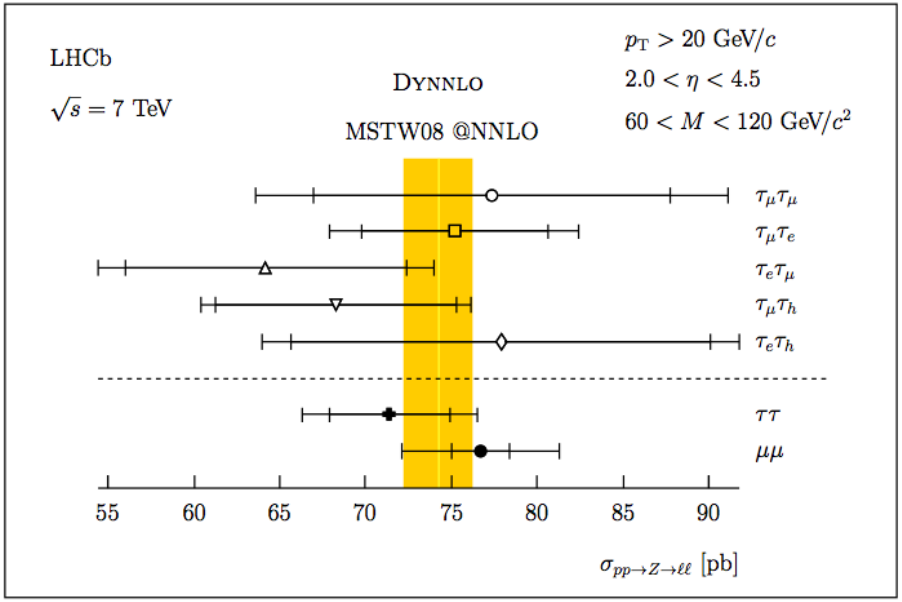


LHCb Z Cross section using Taus

see talk by Kurt Rinnert

NEW! LHCb result using $1 fb^{-1}$ of data

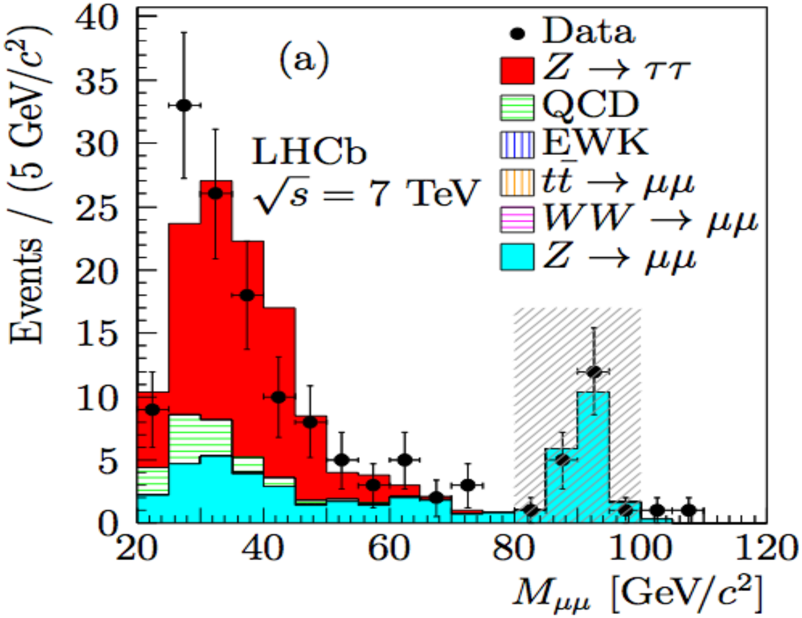
arXiv:1210.6289v1

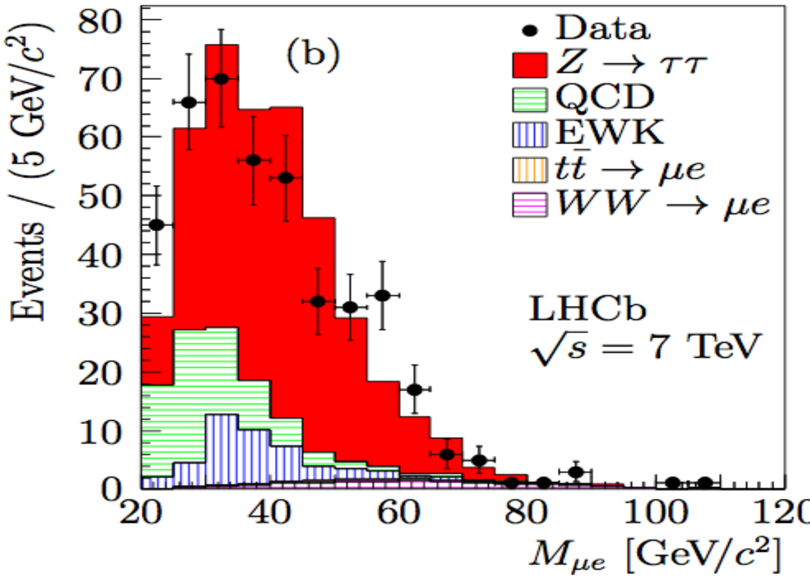


Cross sections in individual channels and combined in good agreement with SM

Lepton universality

$$\frac{\sigma_{pp\to Z\to\tau\tau}}{\sigma_{pp\to Z\to\mu\mu}} = 0.93 \pm 0.09$$



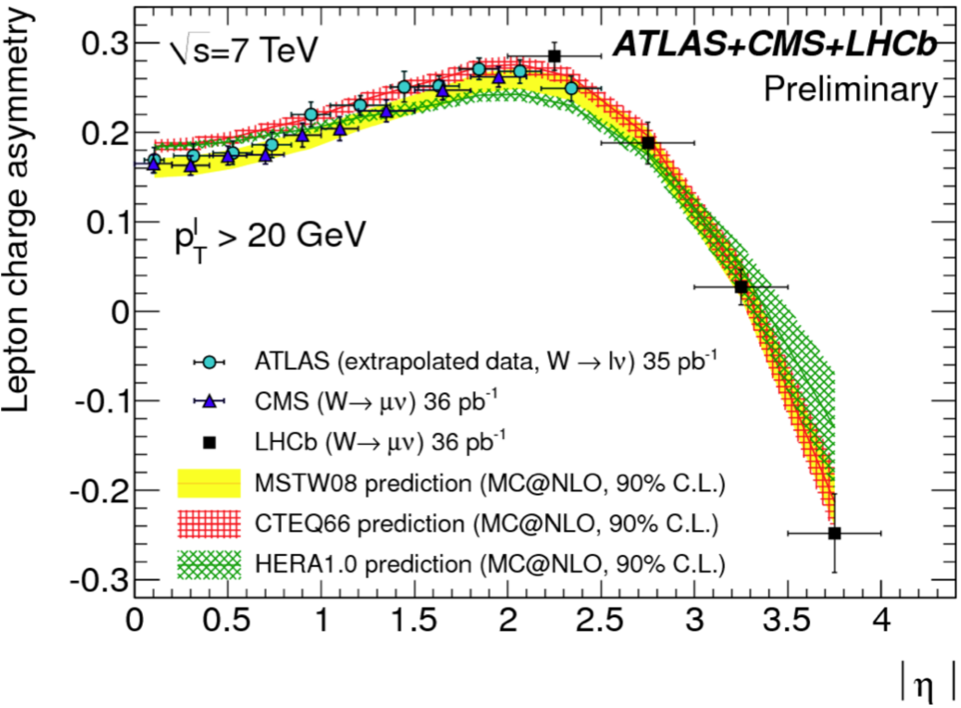


W Charge Asymmetry

Charge Asymmetry, in pp access of *u*- over *d*- quarks

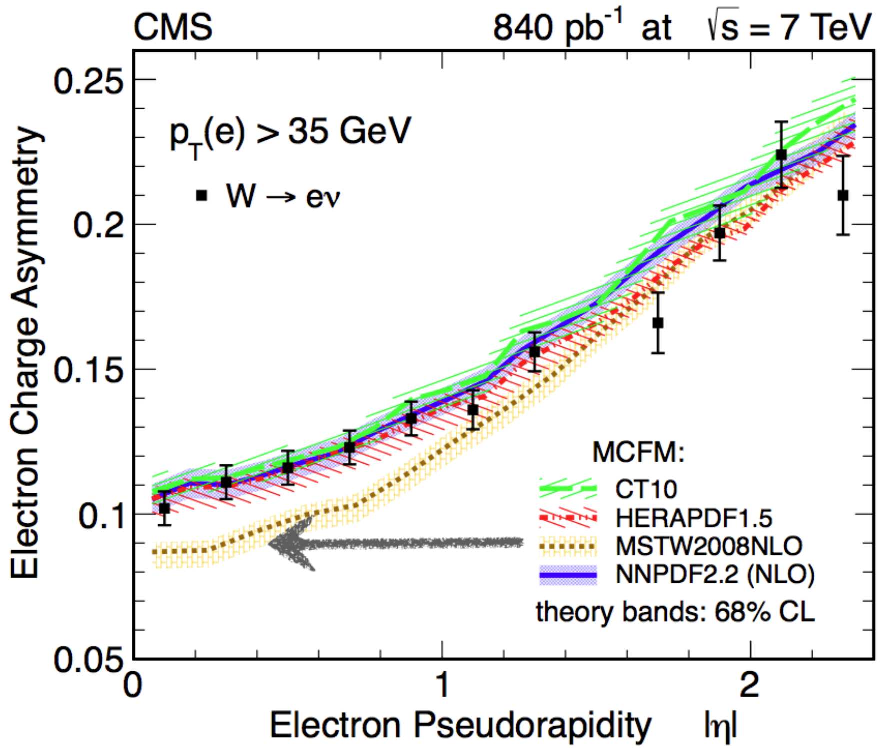
$$A(\eta_\ell) = \frac{d\sigma_{W^+}(\eta_\ell) - d\sigma_{W^-}(\eta_\ell)}{d\sigma_{W^+}(\eta_\ell) + d\sigma_{W^-}(\eta_\ell)}$$

ATLAS-CONF-2011-129



combination from all LHC experiments

arXiv:1206.2598



CMS measurement
in electron channel

Discrimination between PDF at low $|\eta|$

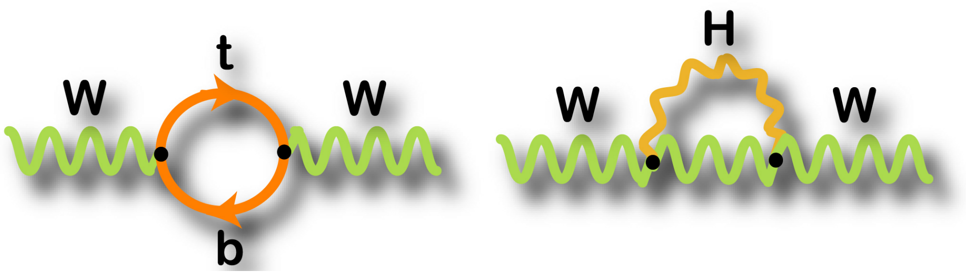
W Boson Mass

W Boson Mass Measurement

- Derive W mass from precisely measured electroweak quantities

$$m_W^2 = \frac{\pi \alpha_{em}}{\sqrt{2} G_F \sin^2\theta_W (1 - \Delta r)} \quad \sin\theta_W^2 = 1 - \frac{m_W^2}{m_Z^2}$$

- Radiative corrections Δr dominated by top quark and Higgs loop
  ⇒allows indirect constraint on Higgs mass

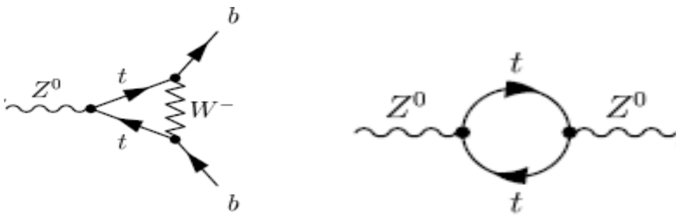


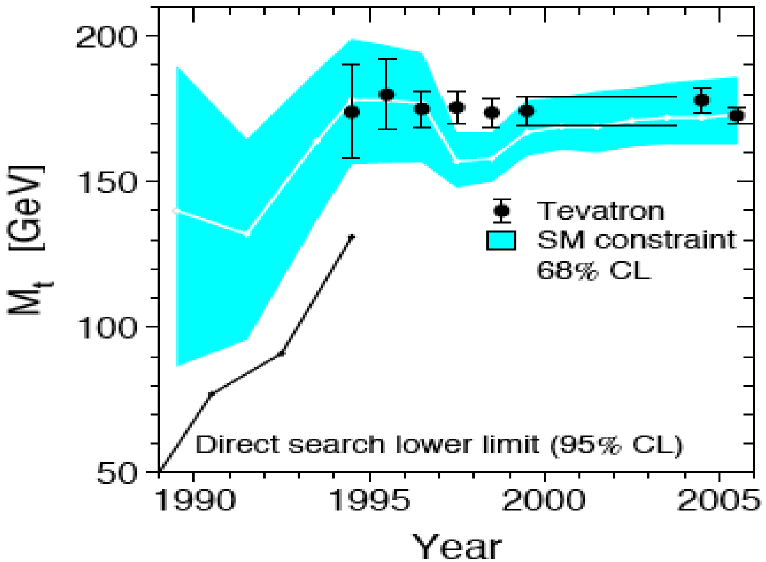
Successes from the (recent) Past

Predicting the top

From precision measurements from LEP and SLC on the Z boson pole

top quark loops in Z^0

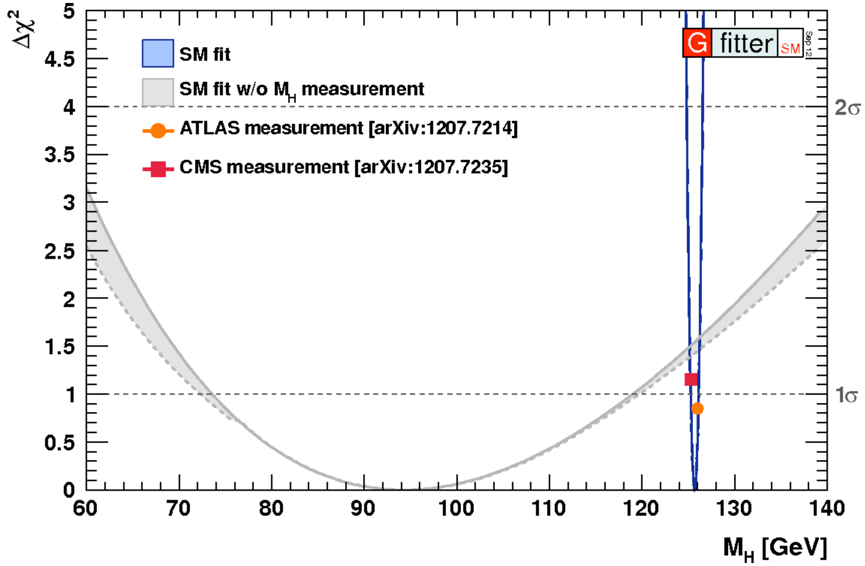




Precision measurements on Z pole constraint top mass before its discovery

Predicting the Higgs

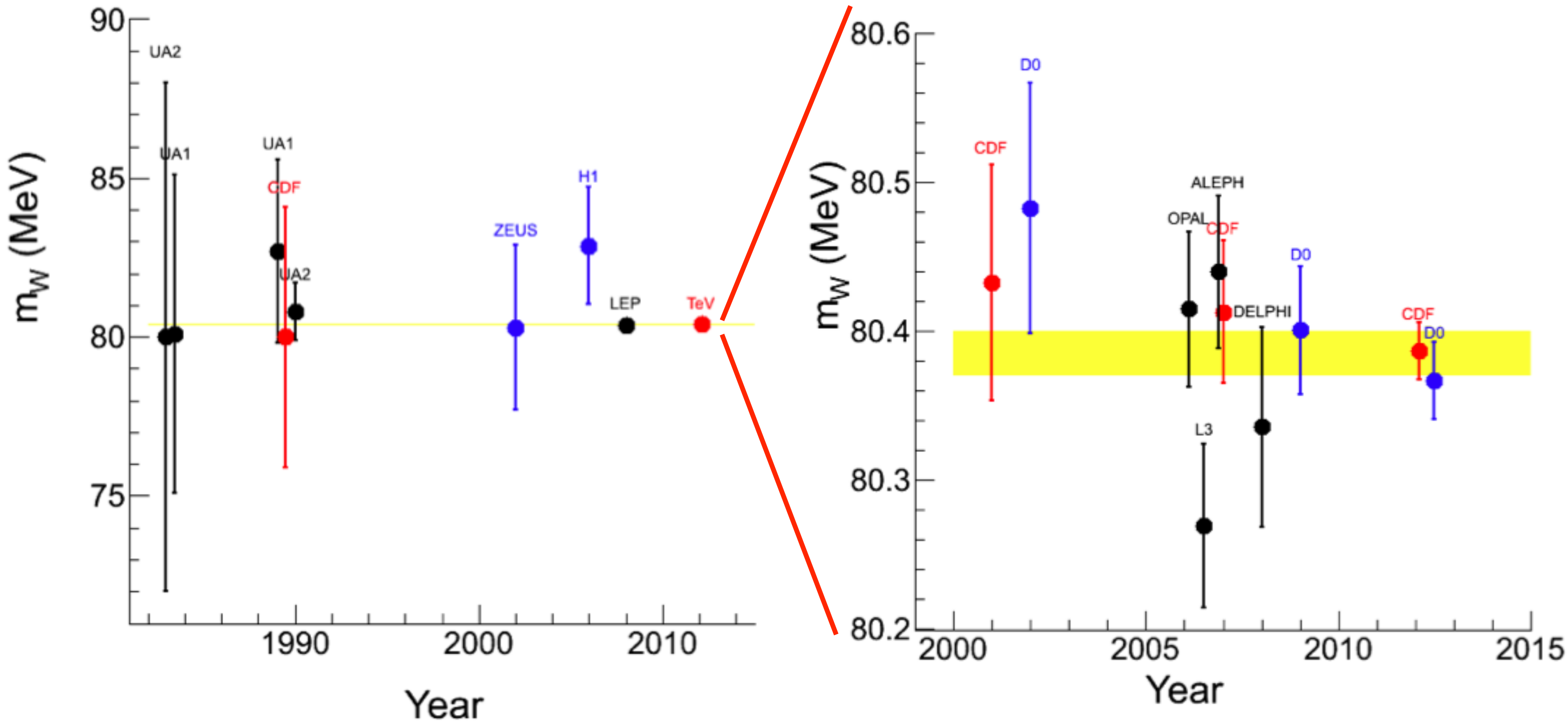
Precision measurements from LEP, SLC and Tevatron



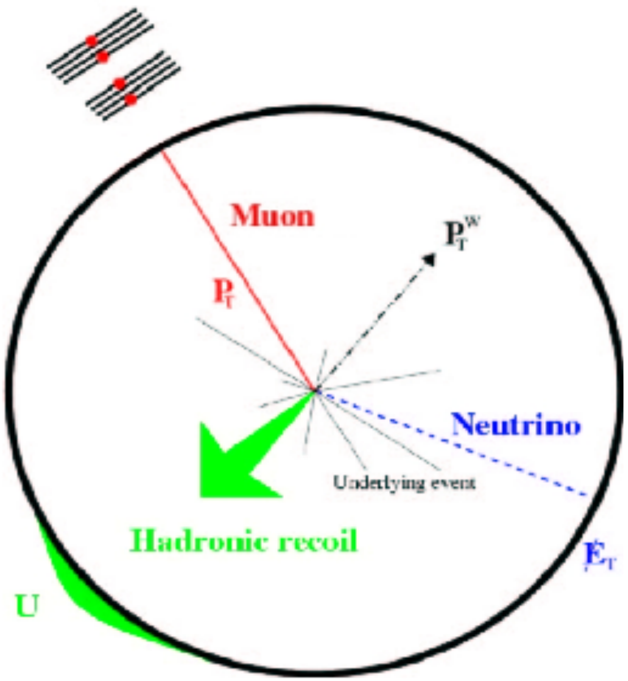
Good agreement of the electroweak constraint with the "Higgs like" discovery

History of M_W Measurements

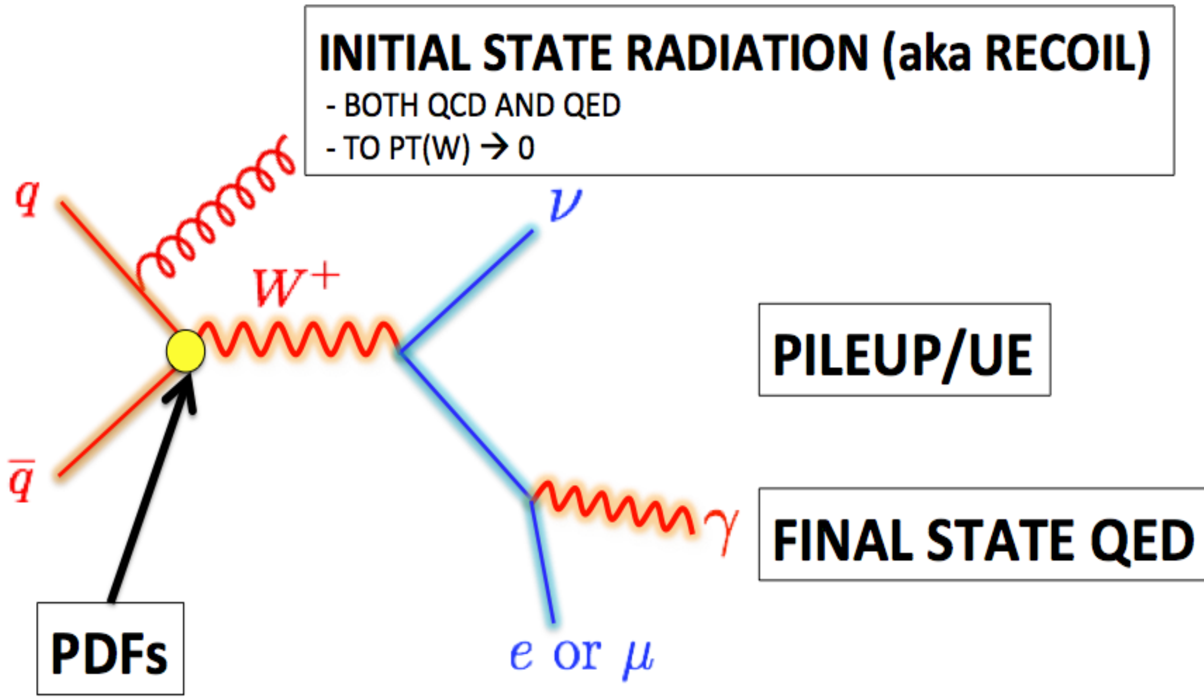
Carried out at several colliders



World average currently dominated by Tevatron (CDF precision 19 MeV)



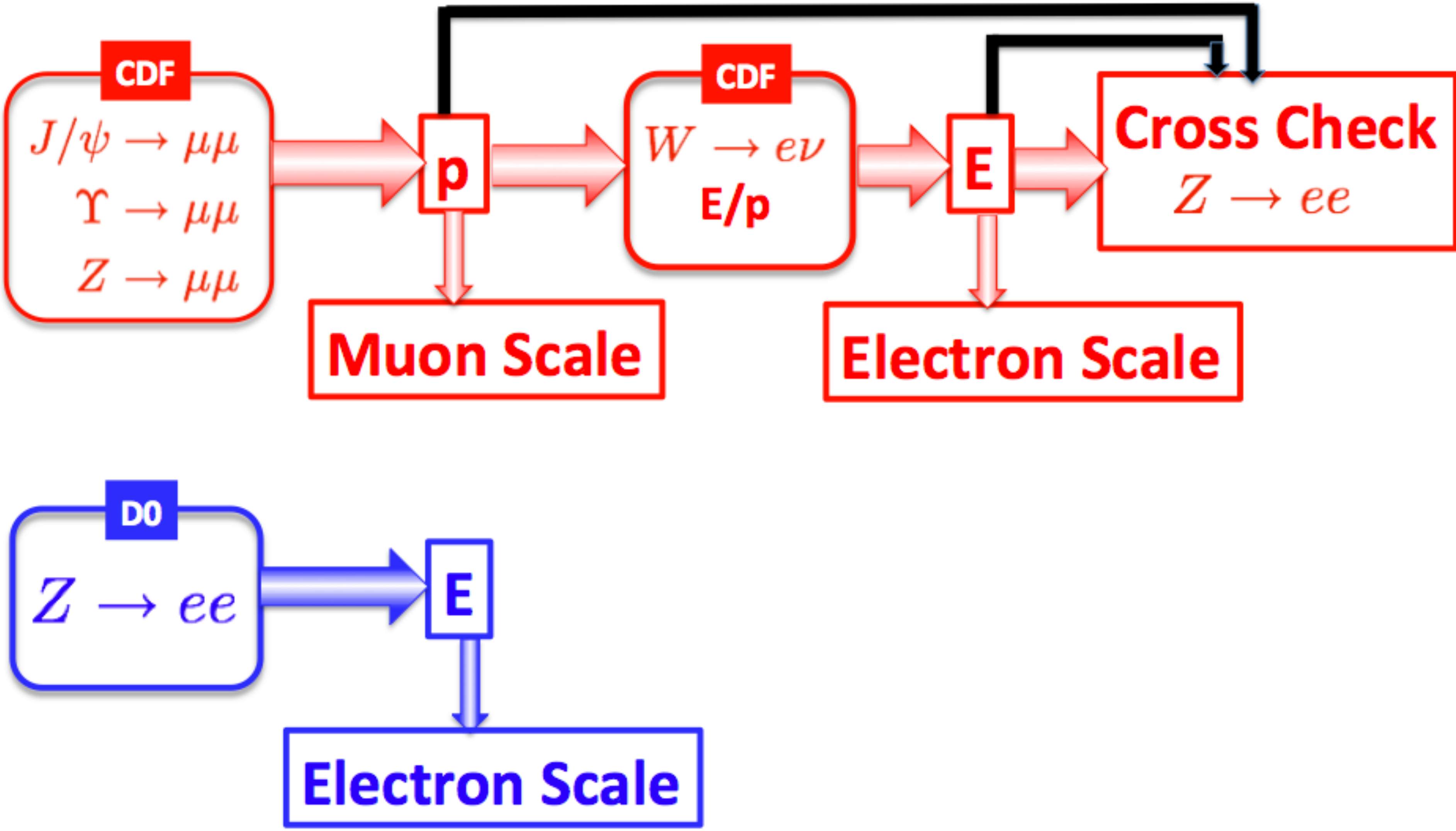
precise charged lepton measurement is the key (achieved ~0.01%)



Recoil measurement allows inference of neutrino E_T (restricted to u<15 GeV)

Use $Z \rightarrow \mu\mu$ and $Z \rightarrow ee$ events to derive recoil model

Lepton Energy Scale



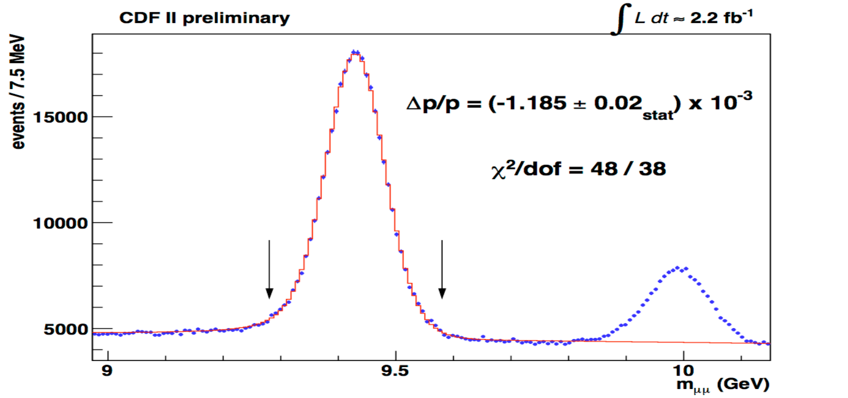
CDF Momentum Scale

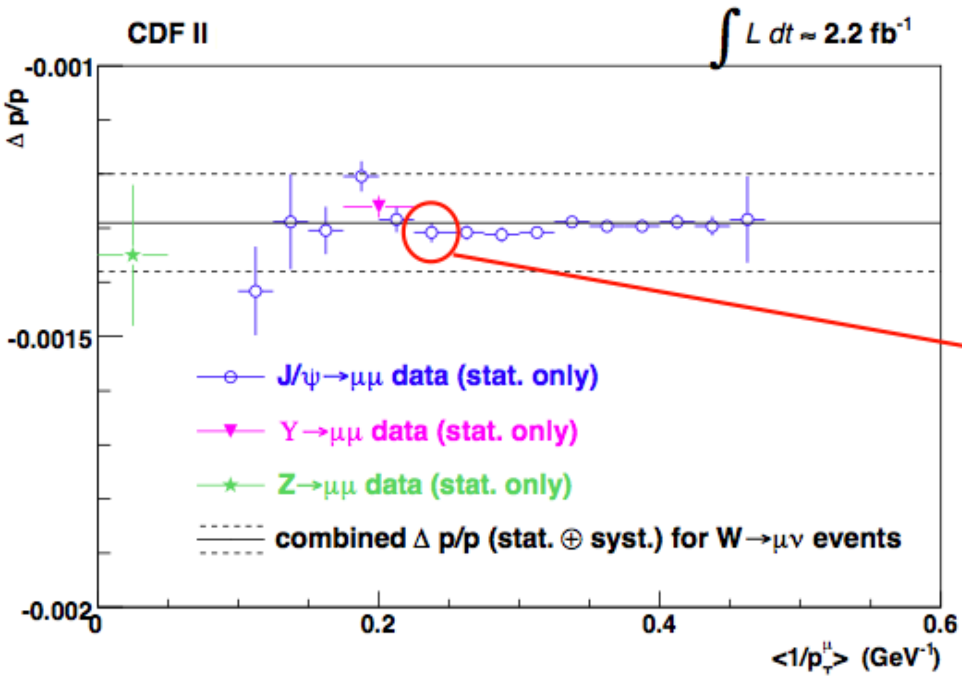
"Back bone" of CDF analysis is track p_T measurement in drift chamber (COT)

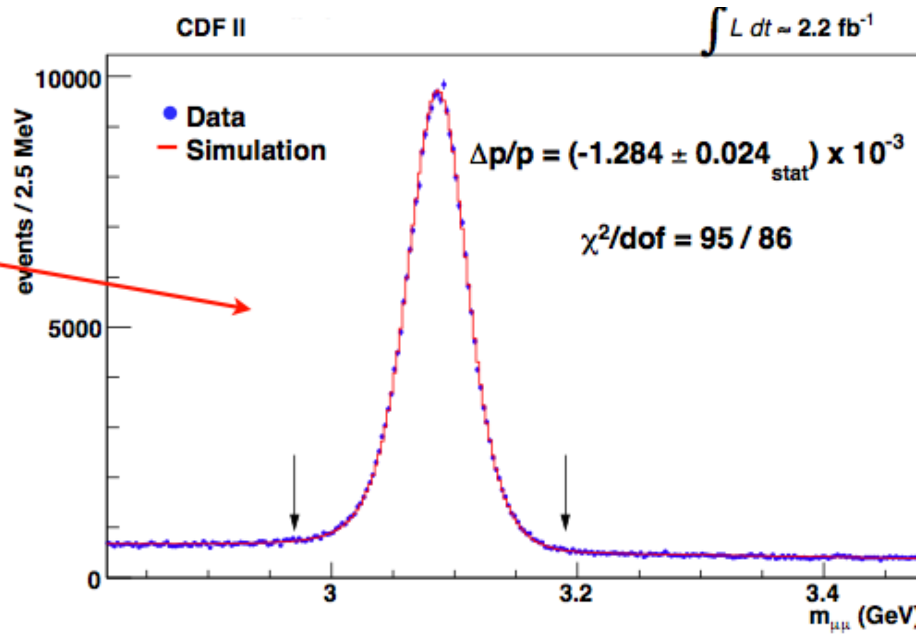
Calibrate momentum scale using samples of dimuon resonances (J/ψ, Υ, Z)

Span a large range of p_T

Final scale error of 9×10^{-5}

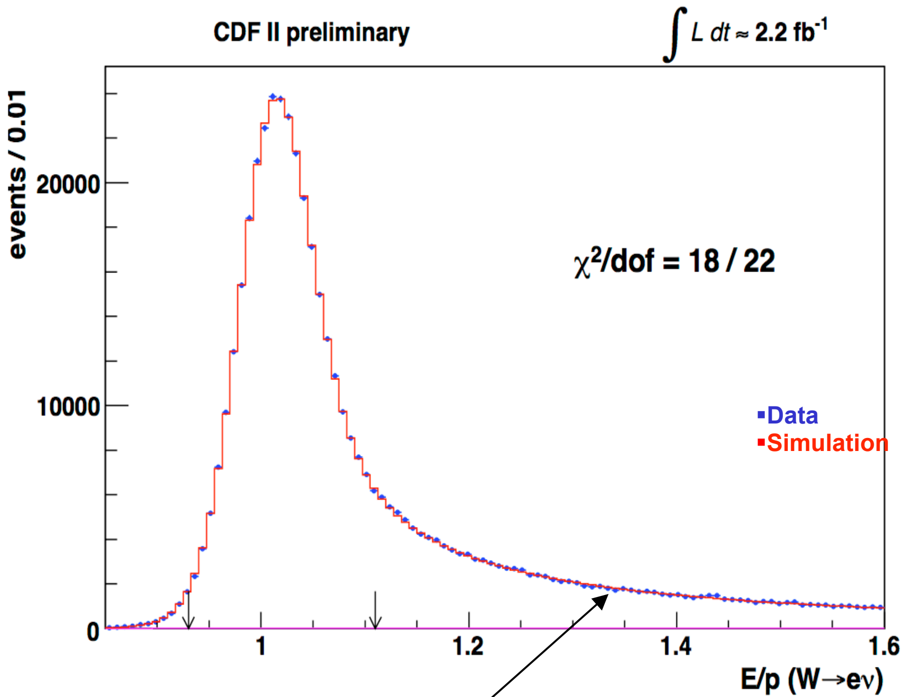




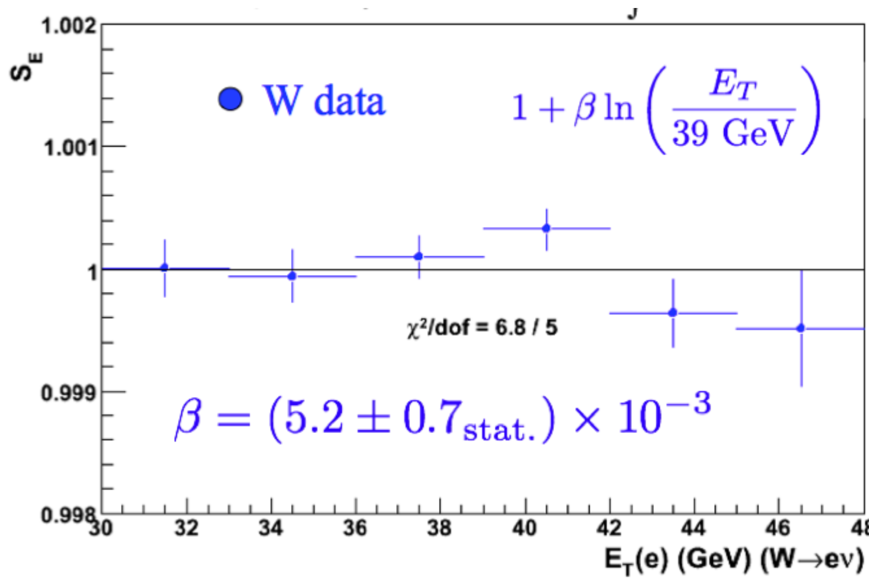


CDF Energy Scale

Transfer momentum calibration to calorimeter using E/p distribution of electrons from W decay by fitting peak of E/p



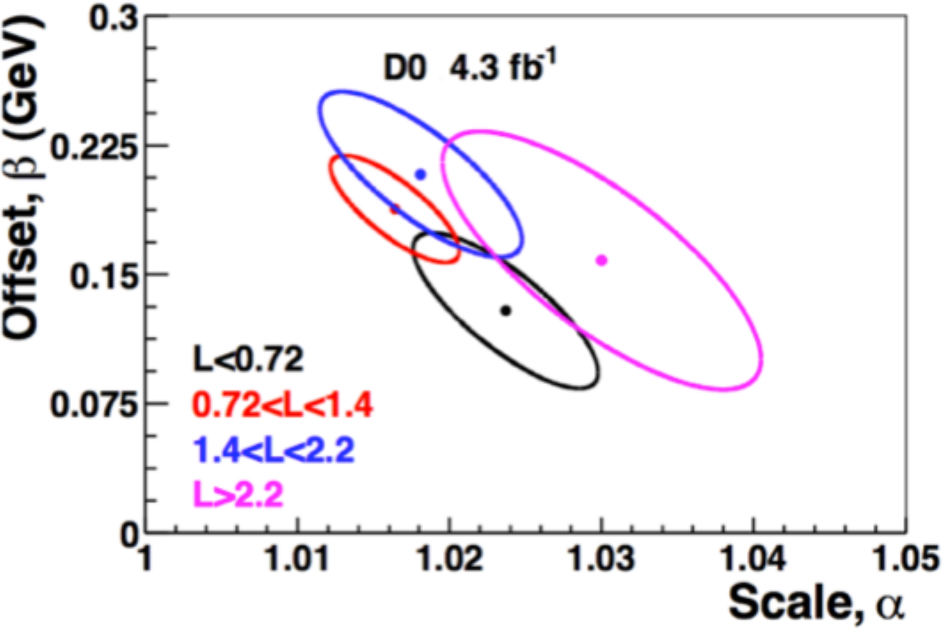
Excellent description of E/p tail
Constraints overall material

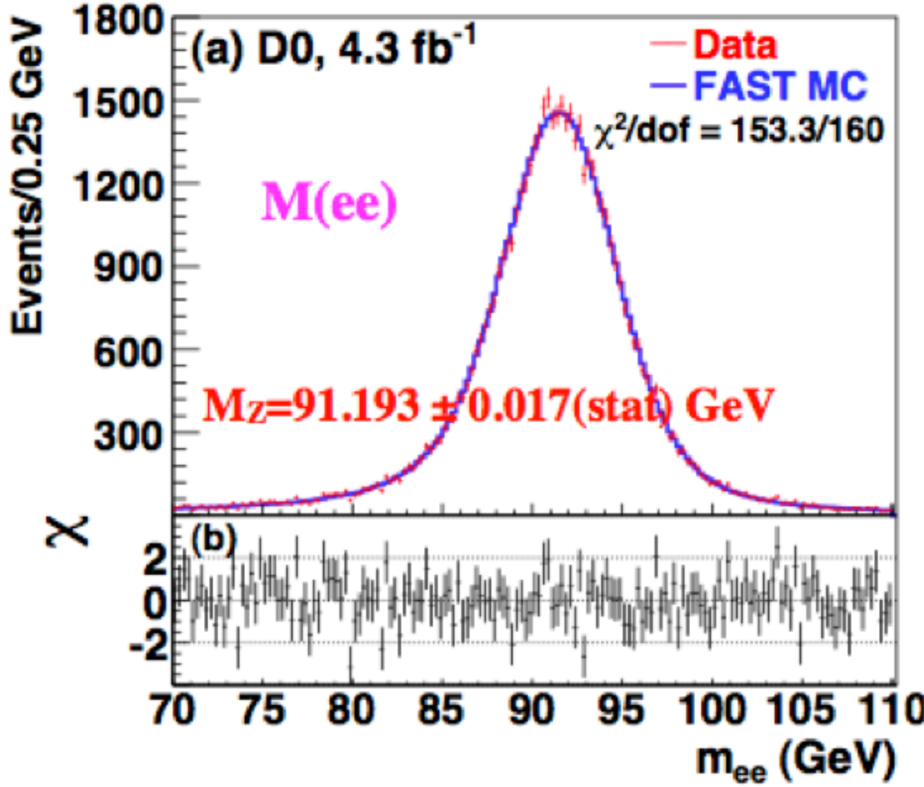


E/p also used to constrain calorimeter non-linearity

D0 Energy Scale

$$E_{measured} = \alpha \times E_{TRUE} + \beta$$





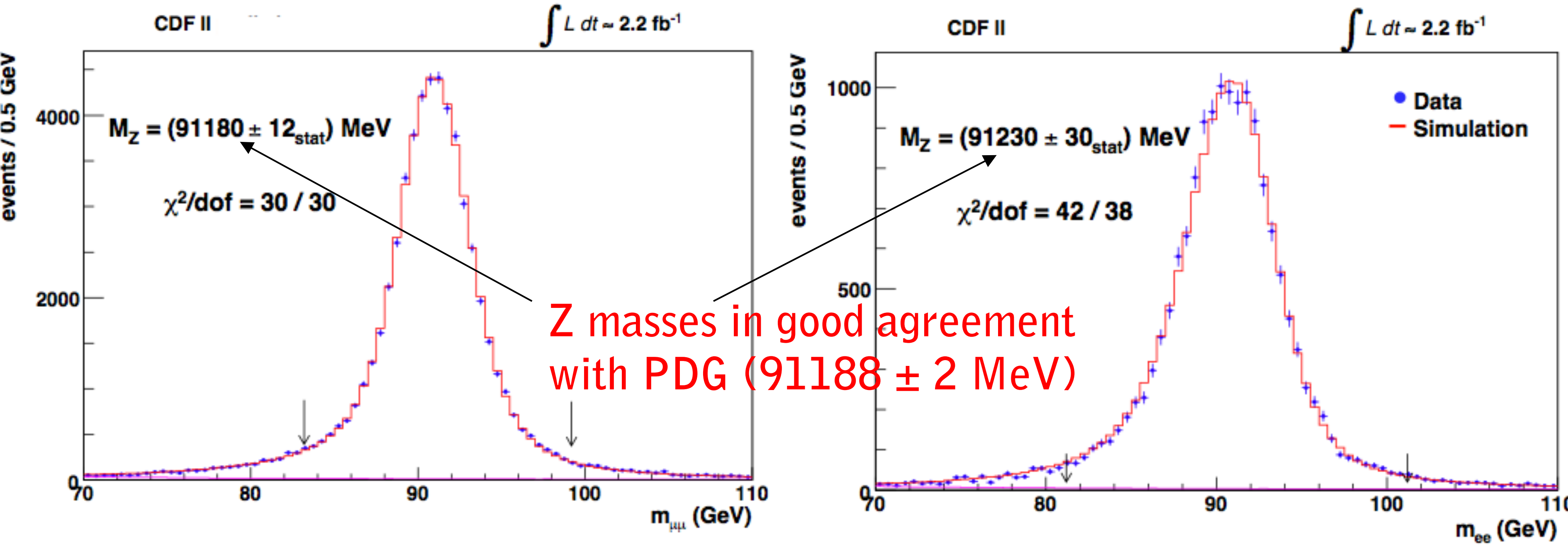
Measured in luminosity and energy bins

Consistent with PDG by construction

D0 is measuring M_W/M_Z

CDF Z Boson Masses

- Perform blinded measurement of Z mass using derived scales from independent samples
- Comparison to PDG value is a powerful cross-check of the calibration
- After unblinding, M_Z added as further calibration to both p- and E-scales

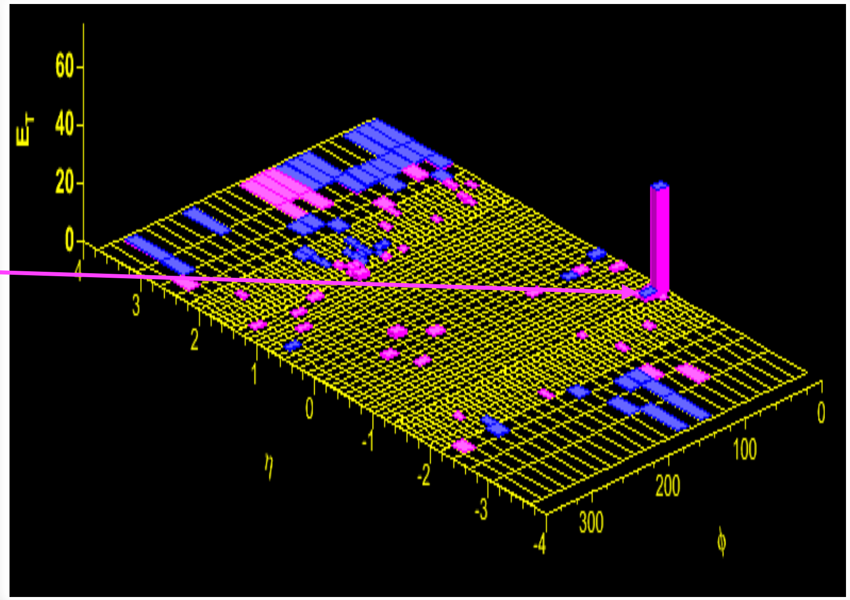


Include Z→ll masses for final momentum scale and energy scale

Hadronic Recoil

Recoil definition:
→ Energy vector sum over all calorimeter towers, excluding:

- lepton towers



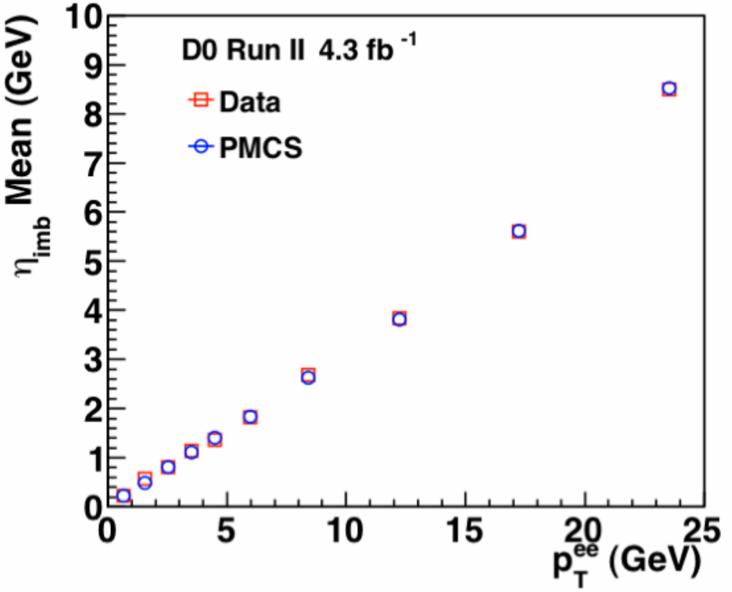
- Measured recoil:
  - hard recoil from initial state **QCD** in W/Z event
  - underlying event/spectator interaction energy

- Calibrate detector response and resolution using Z and minimum-bias data

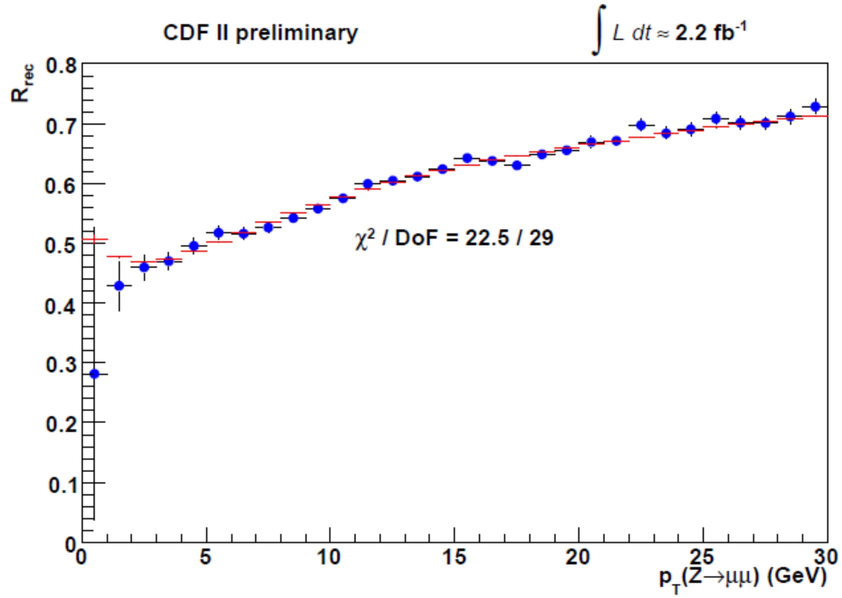
- Validate using measured recoil in W events

Recoil Response

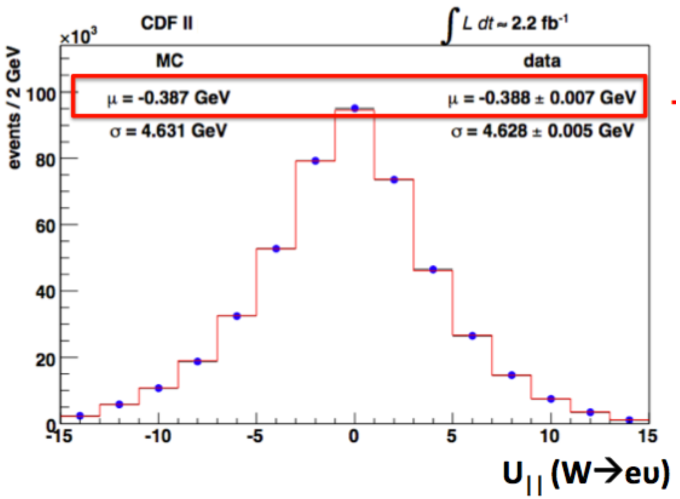
Similar calibration samples and procedures between D0 and CDF



Typically only detect 50-70% of "true" QCD readiation



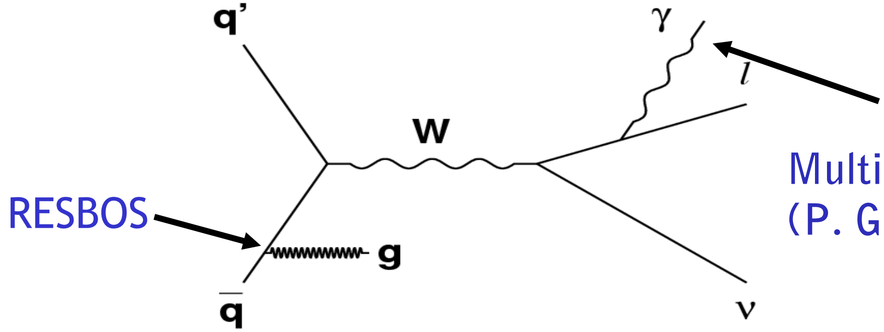
Validate model in W events



$$m_T \sim 2p_T^l + U_{||}$$

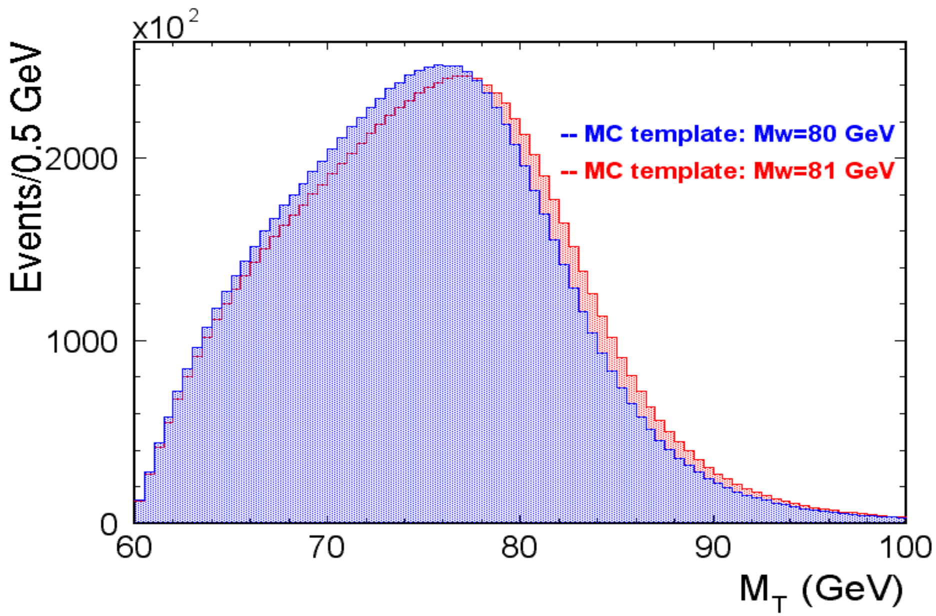
← Component of hadronic recoil along charged lepton direction

Generator-level input for W&Z simulation provided by RESBOS [Balazs *et.al.* PRD56, 5558 (1997)]



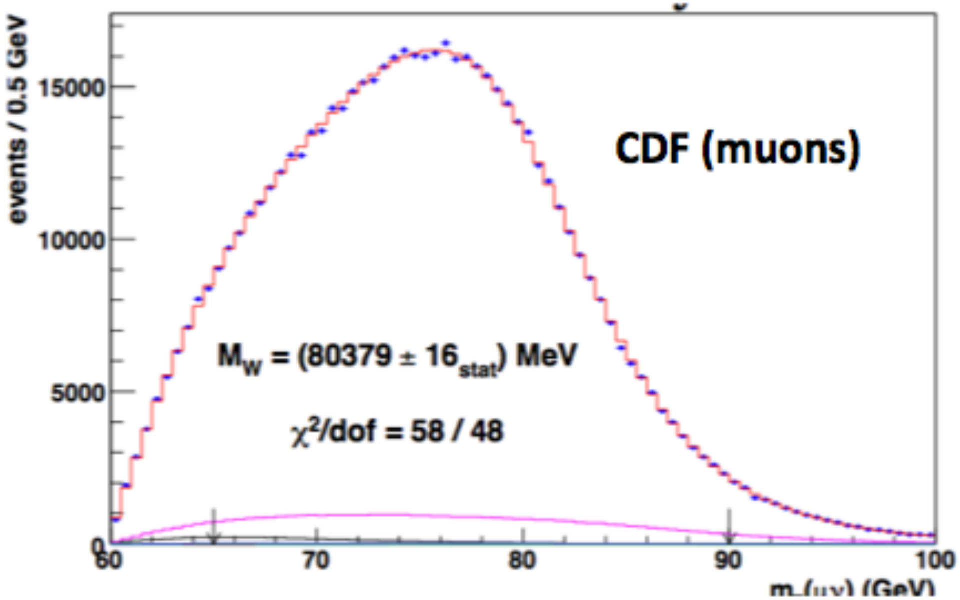
Multiple radiative photons from PHOTOS (P. Golonka et.al., Eur. J. Phys. C 45, 97 (2006)

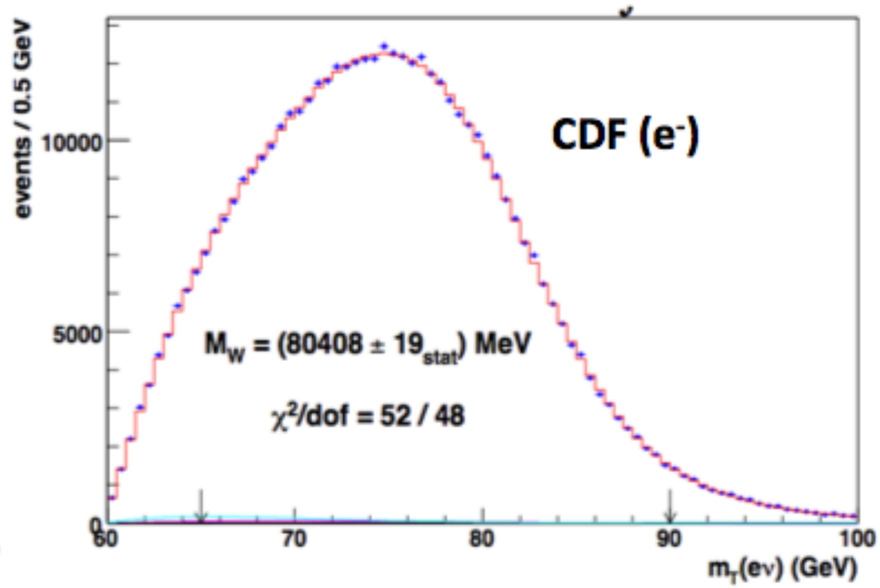
Custom fast simulation makes smooth, high statistics templates

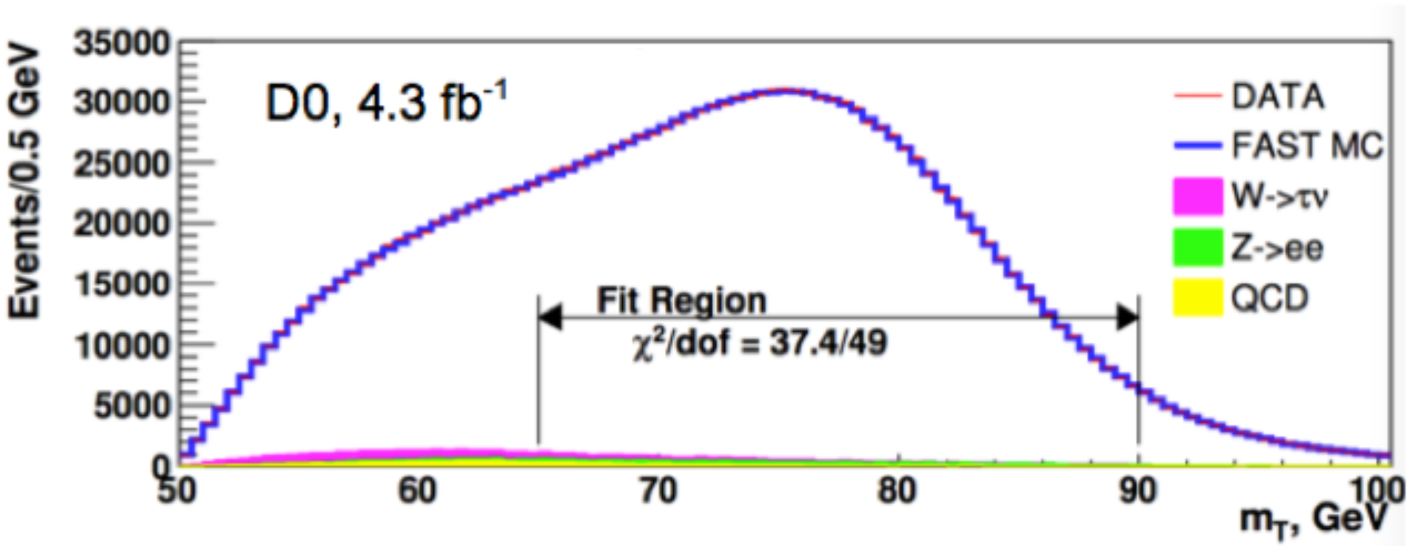


Extract the W mass from fit to: m_T, p_T and E_T^{miss} distributions in muon and electron decay channel

Transverse mass fits







90% of M_W information is in transverse mass

Uncertainties

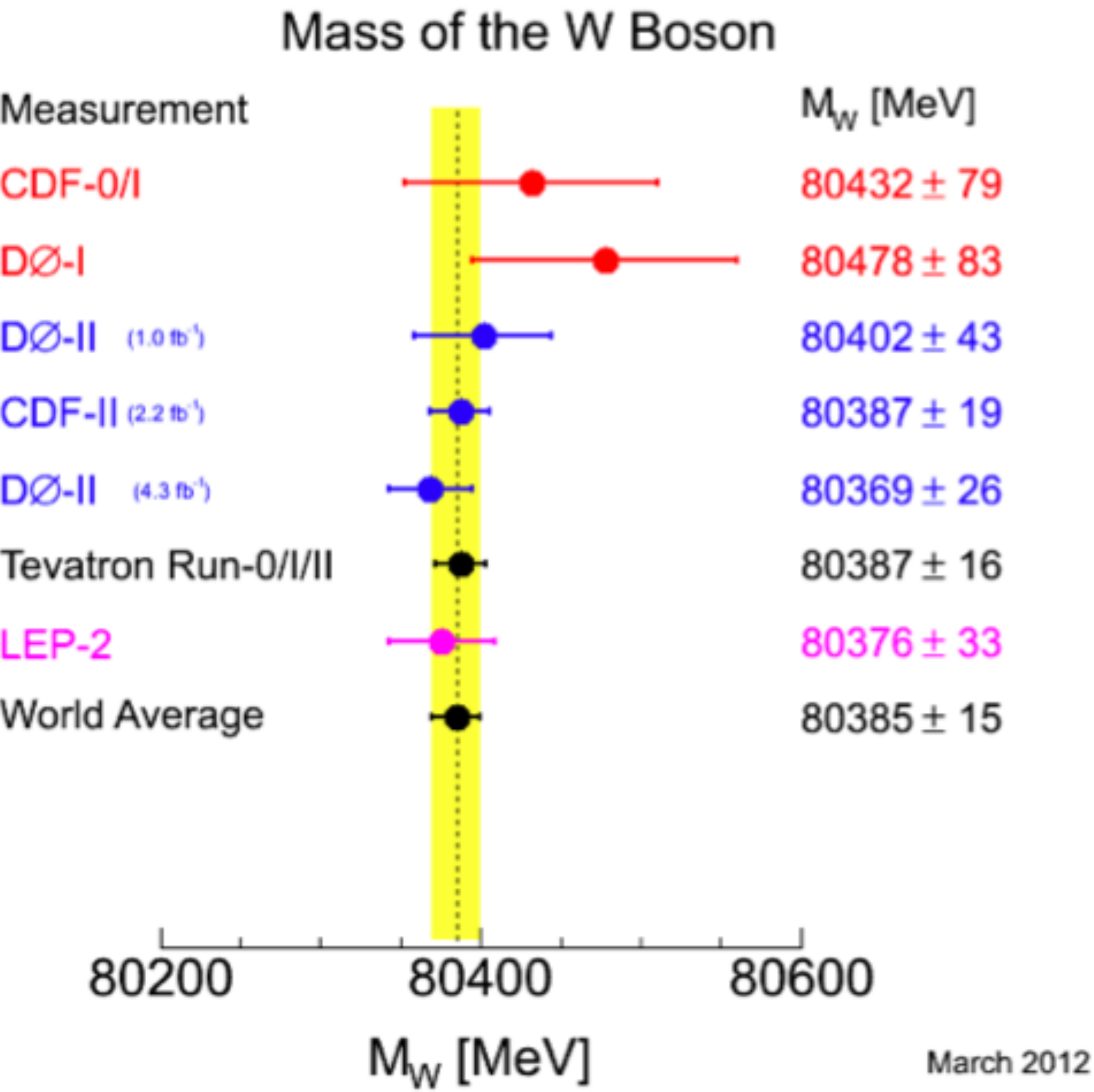
Uncertainty	D0	CDF
Lepton energy scale/resn/modelling	17	7
Hadronic recoil energy scale and resolution	5	6
Backgrounds	2	3
Parton distributions	11	10
QED radiation	7	4
$p_T(W)$ model	2	5
Total systematic uncertainty	22	15
W-boson statistics	13	12
Total uncertainty	26 MeV	19 MeV

Largely stat. in origin → **10 MeV**

Largely theory in origin → **12 MeV**

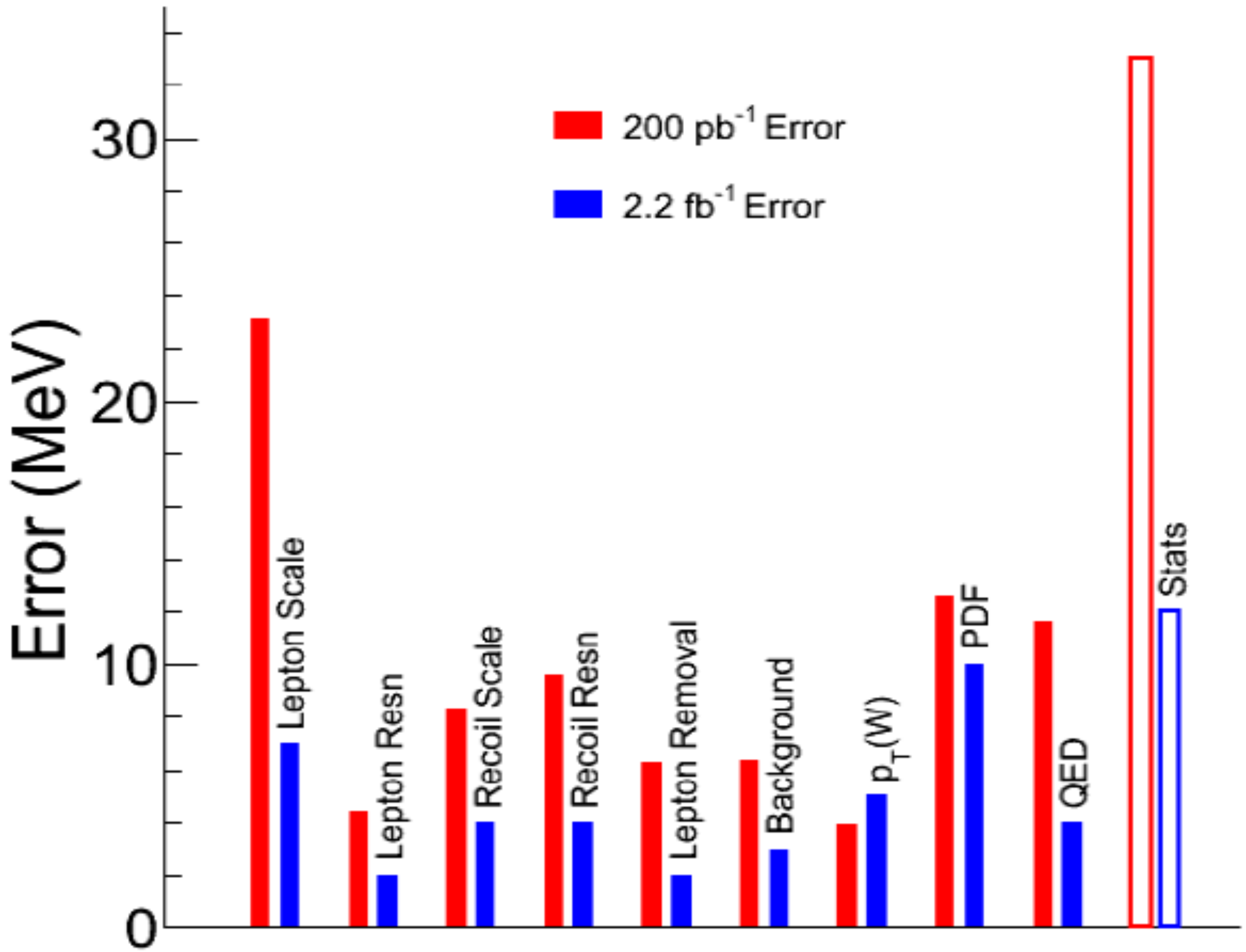
90% of M_W information is in transverse mass

World Average



Tevatron Run-II has halved the Mw uncertainty

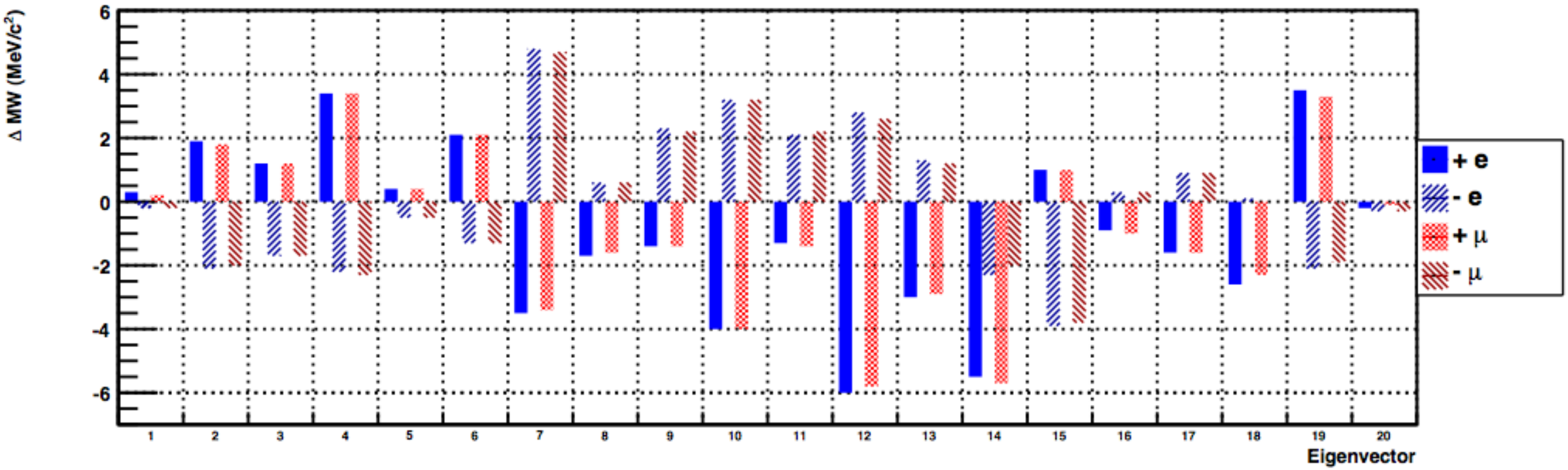
Going Below 15 MeV at the Tevatron



90% of M_W information is in transverse mass

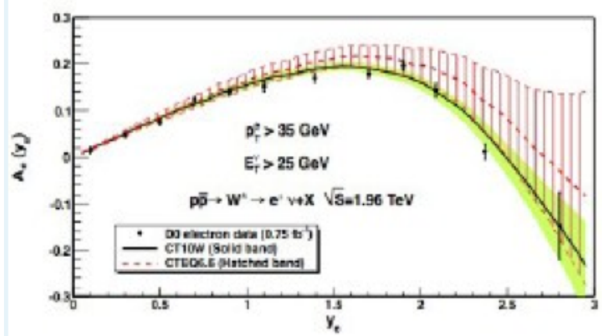
Going Below 15 MeV at the Tevatron

Limited lepton acceptance produces dependence on PDFs
Will likely be the limiting factor in reducing uncertainty
Evaluated with CTEQ and MSTW eigenvectors



Tevatron and LHC measurements that can further constrain PDFs:

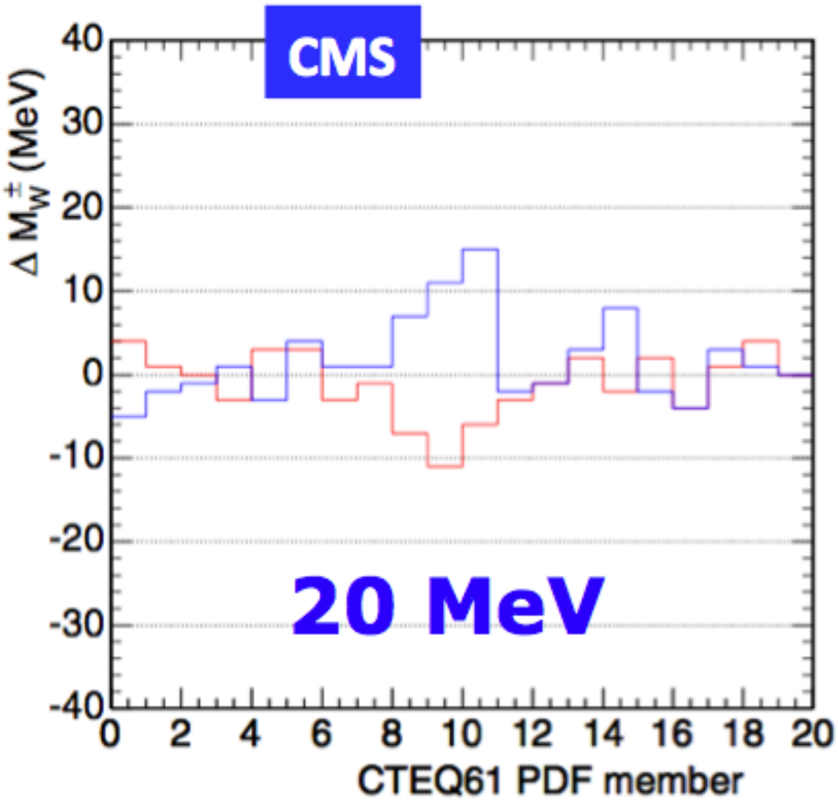
- Z boson rapidity distribution
- W → lν lepton rapidity distribution
- W boson charge asymmetry



PDF's

At LHC (unlike TeV) significant contribution from "cs" production.

Affects:
- acceptance via rapidity and kinematic cuts
- contribution to $p_T(W)$ (m_C mass)



Constraints from W and Z data will reduce this

But assumptions of s vs s-bar
Naive expectation: s = u = d
But: strange mass is larger

Reduction to: <10 MeV ?

Conclusions

Large Hadron Collider program well underway towards precision physics with W and Z bosons

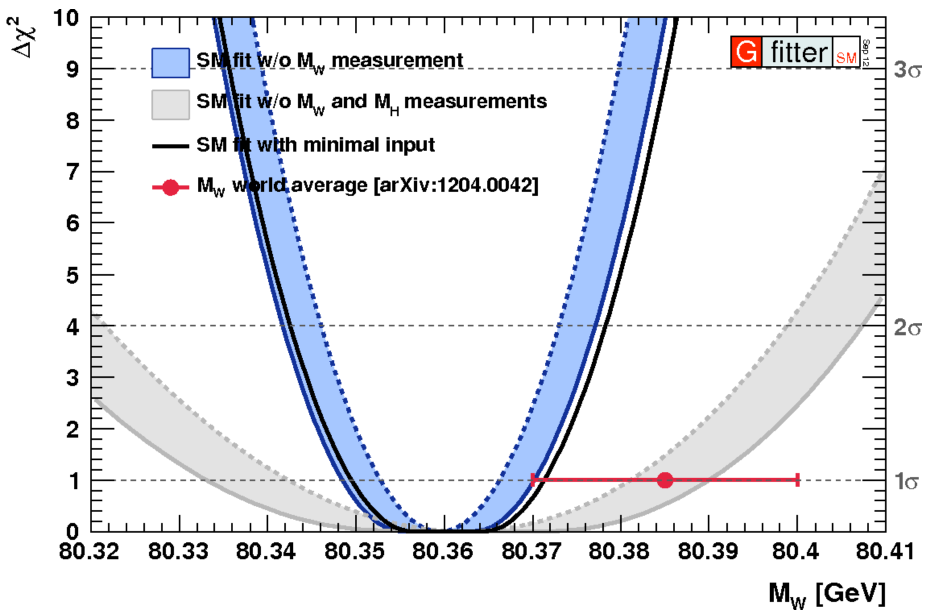
Constraints on PDF's and large backgrounds for new physics

Tevatron leading precision measurements of W boson mass

EW precision measurements in a good agreement with a "Higgs like" boson with mass of ~125 GeV

Little room for new physics

Need better measurements of m_W, m_{top}, α_{EM}, α_S, HO corrections

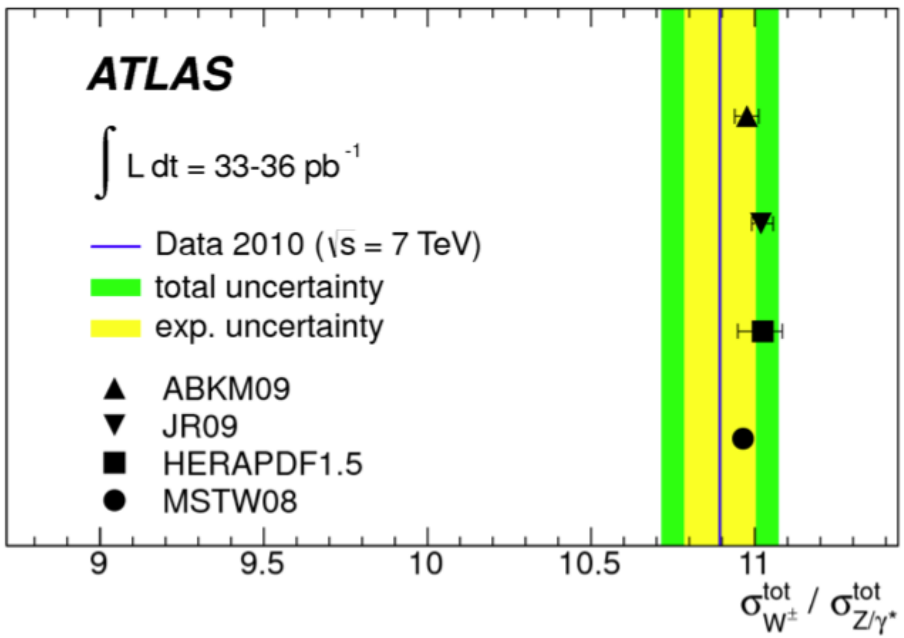


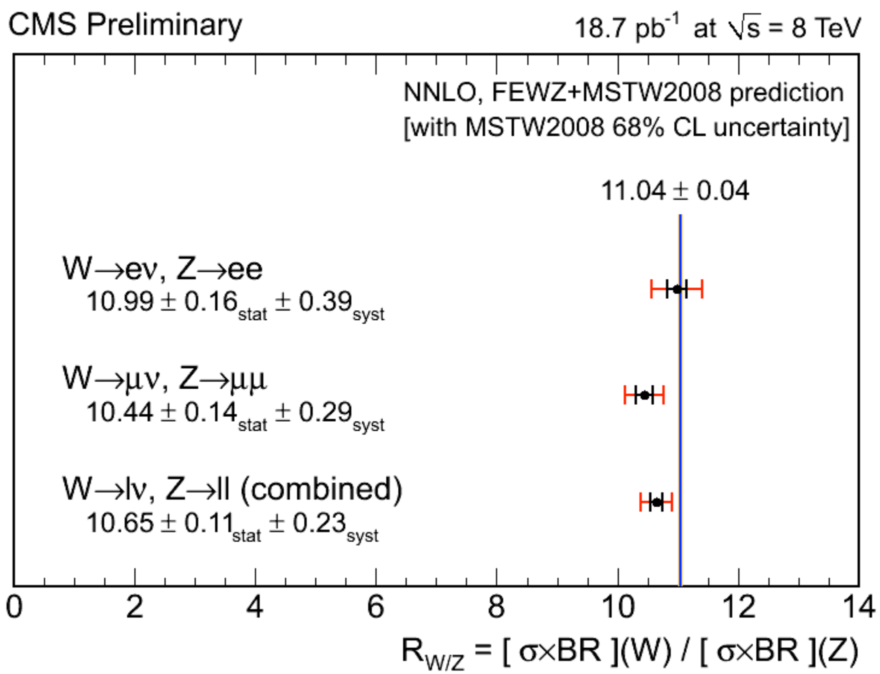
Extras

Ratio of W and Z Cross Sections

Phys.Rev. D85 (2012) 072004

CMS-PAS-SMP-12-011



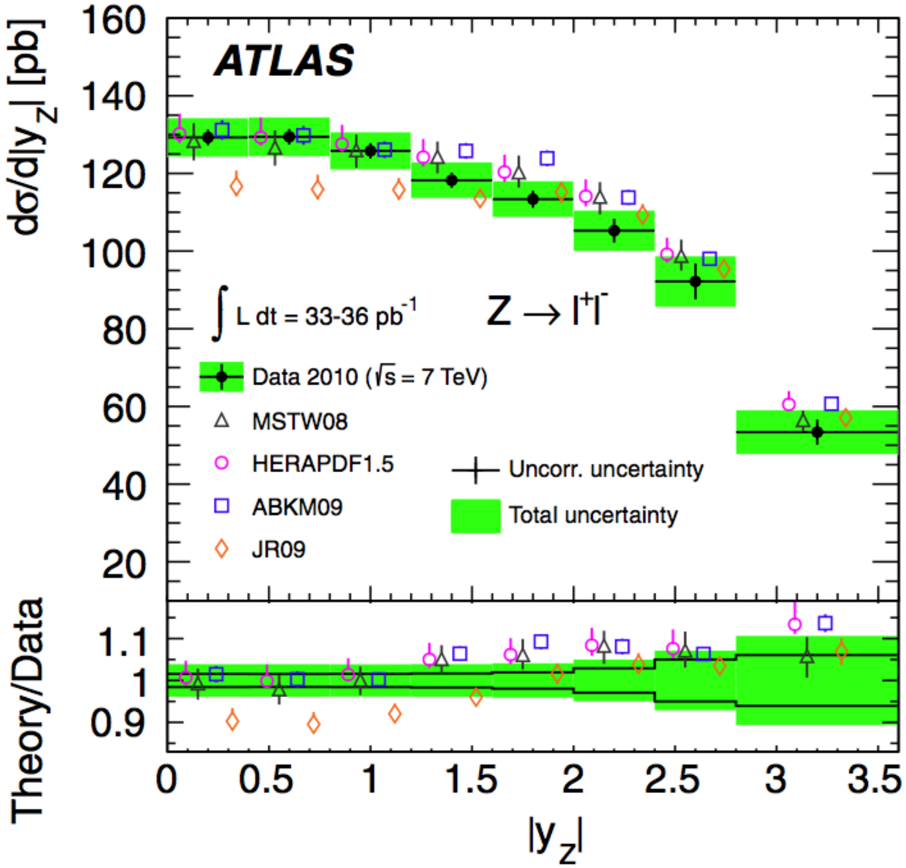


Benefits from experimental and theoretical systematics cancellation

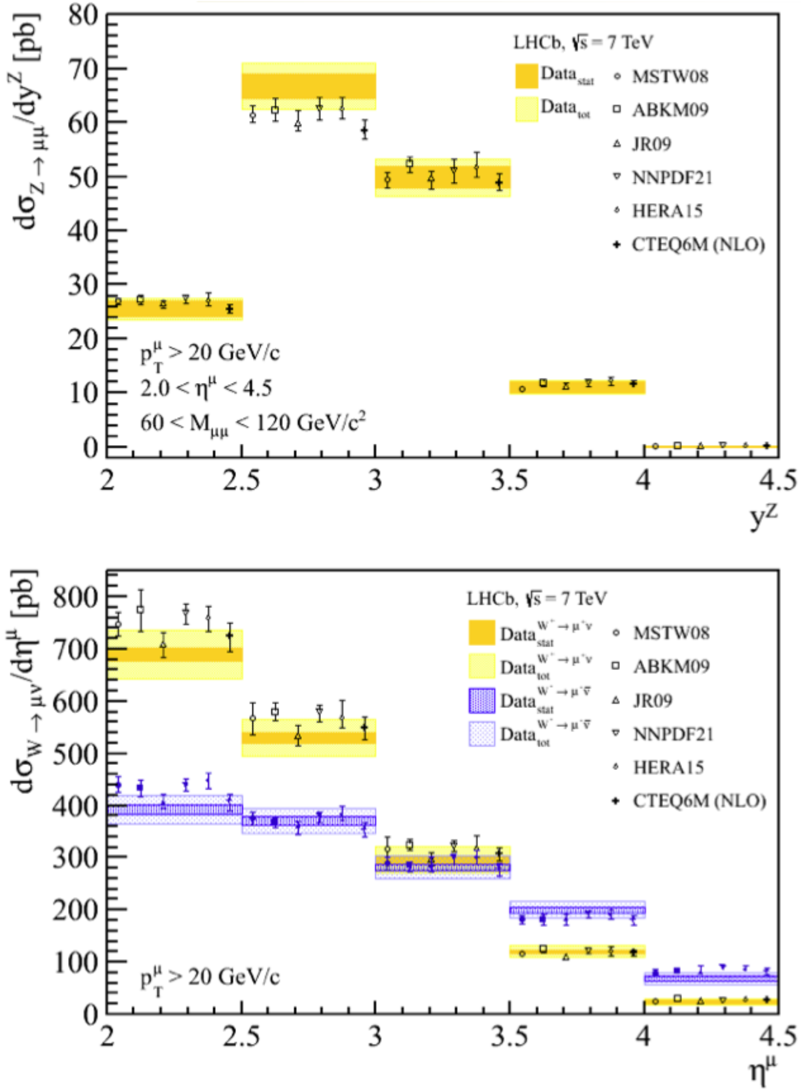
ATLAS	**7 TeV**	**10.893 +/- 0.079 (stat.) +/- 0.110 (syst.) +/- 0.116 (acc)**
CMS	7 TeV	10.54 +/- 0.07 (stat.) +/-0.08 (syst.) +/- 0.16 (th.)
CMS	8 TeV	10.65 +/- 0.11 (stat.) +/- 0.23 (syst.)

Differential Distributions

Phys.Rev. D85 (2012) 072004



LHCb-CONF-2012-011(ee)
JHEP06 (2012) 058 (mumu)

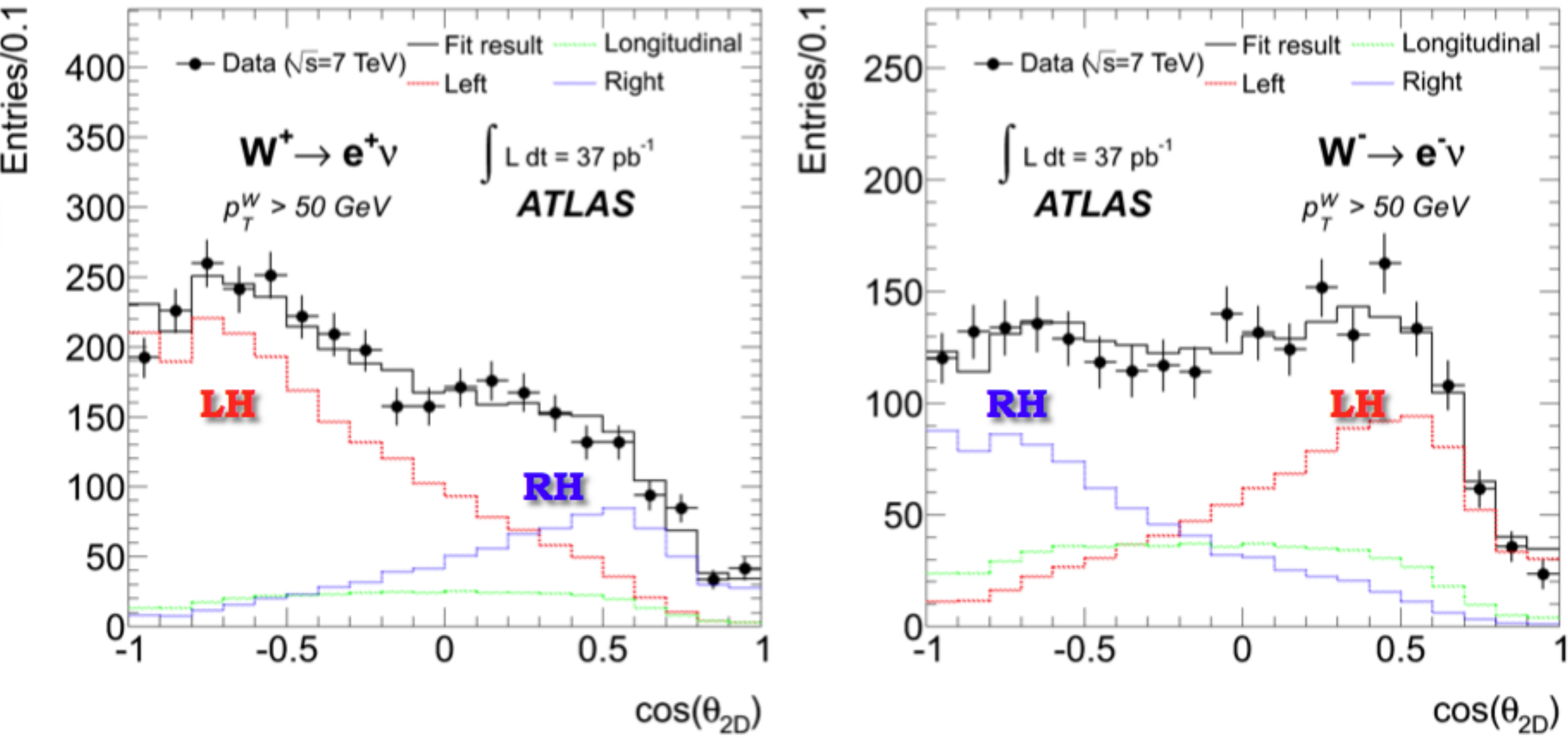


NNLO predictions generally describe the data
Differences due to PDFs are observed

W Polarization

The left-handed, right-handed and longitudinal polarization fractions are measured using both muon and electron decays

$$\cos\theta_{2D} = \frac{\vec{p}_{T}^{\,\ell*} \cdot \vec{p}_{T}^{\,W}}{|\vec{p}_{T}^{\,\ell*}|\,|\vec{p}_{T}^{\,W}|}$$

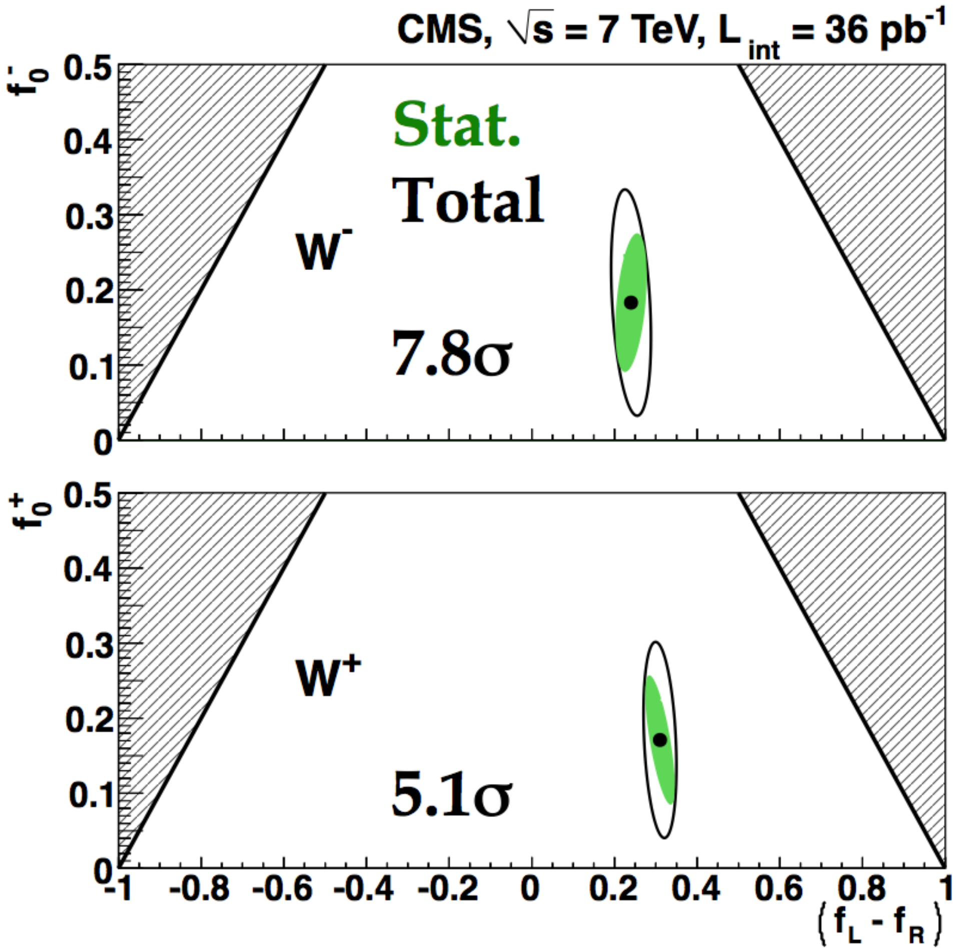


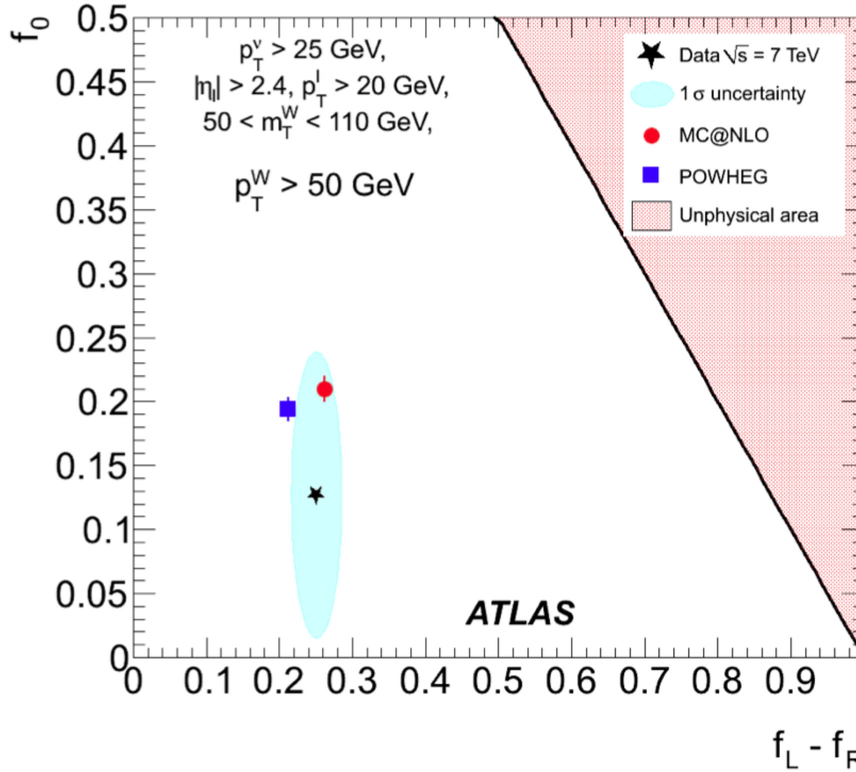
W Polarization

$$W^+ : \sigma(\theta^*) \propto f_L \frac{(1-\cos\theta^*)^2}{4} + f_o \frac{\sin^2\theta^*}{2} + f_R \frac{(1+\cos\theta^*)^2}{4}$$

Phys.Rev.Lett. 107 (2011) 021802

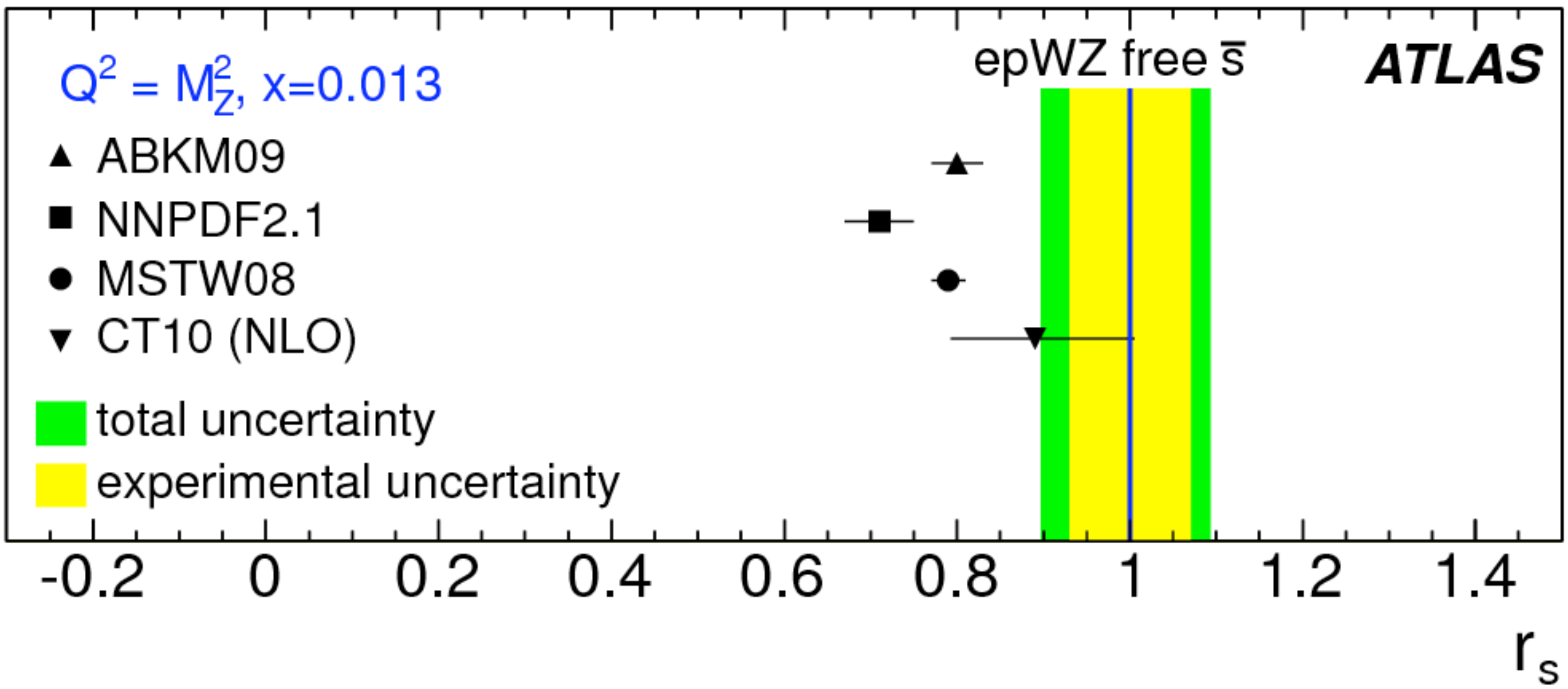
Eur.Phys.J. C72 (2012) 2001



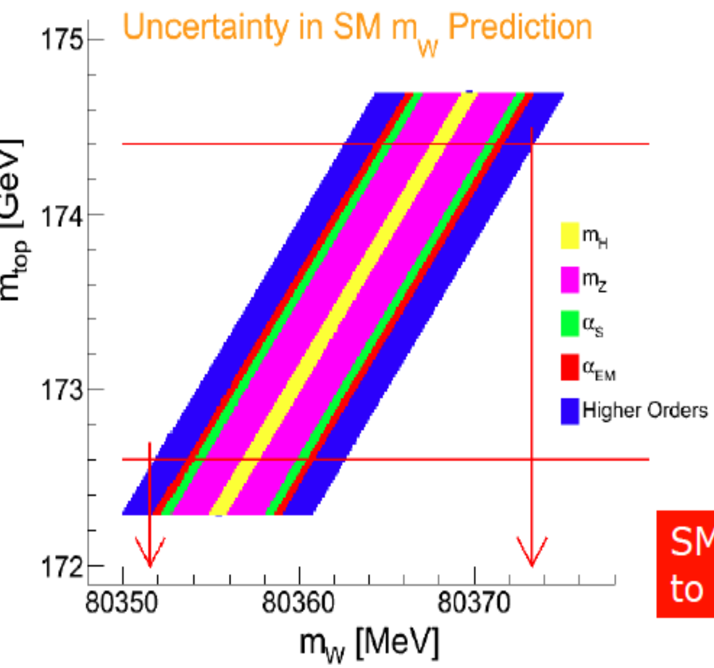


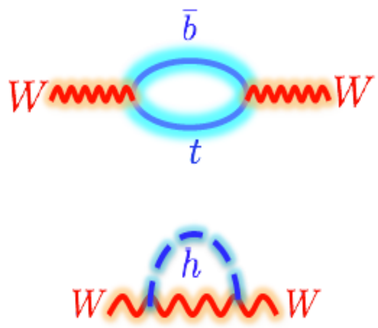
W at high-P in pp are left-handed, as expected by SM

Enhanced Strange Contribution

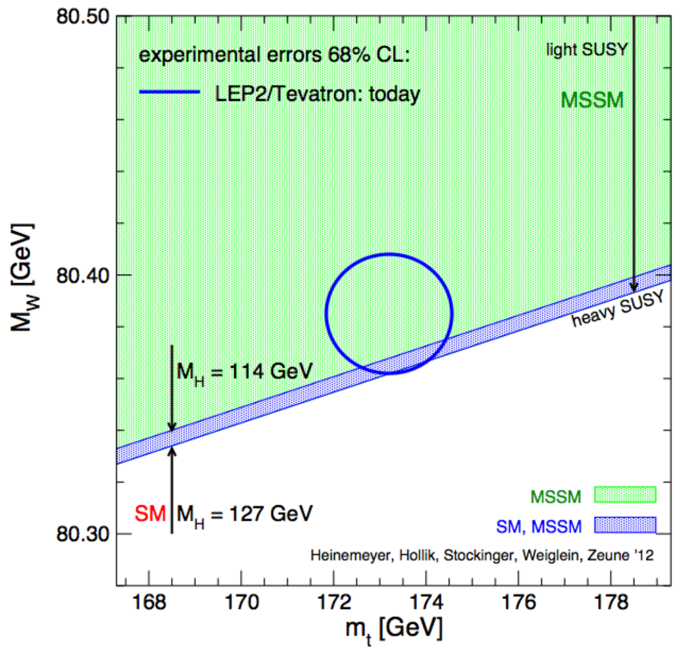


Limitations and NP Contributions to M_W





SM prediction of Mw is good to only 10 MeV



Sven Heinemeyer et al JHEP08 052 (2006)