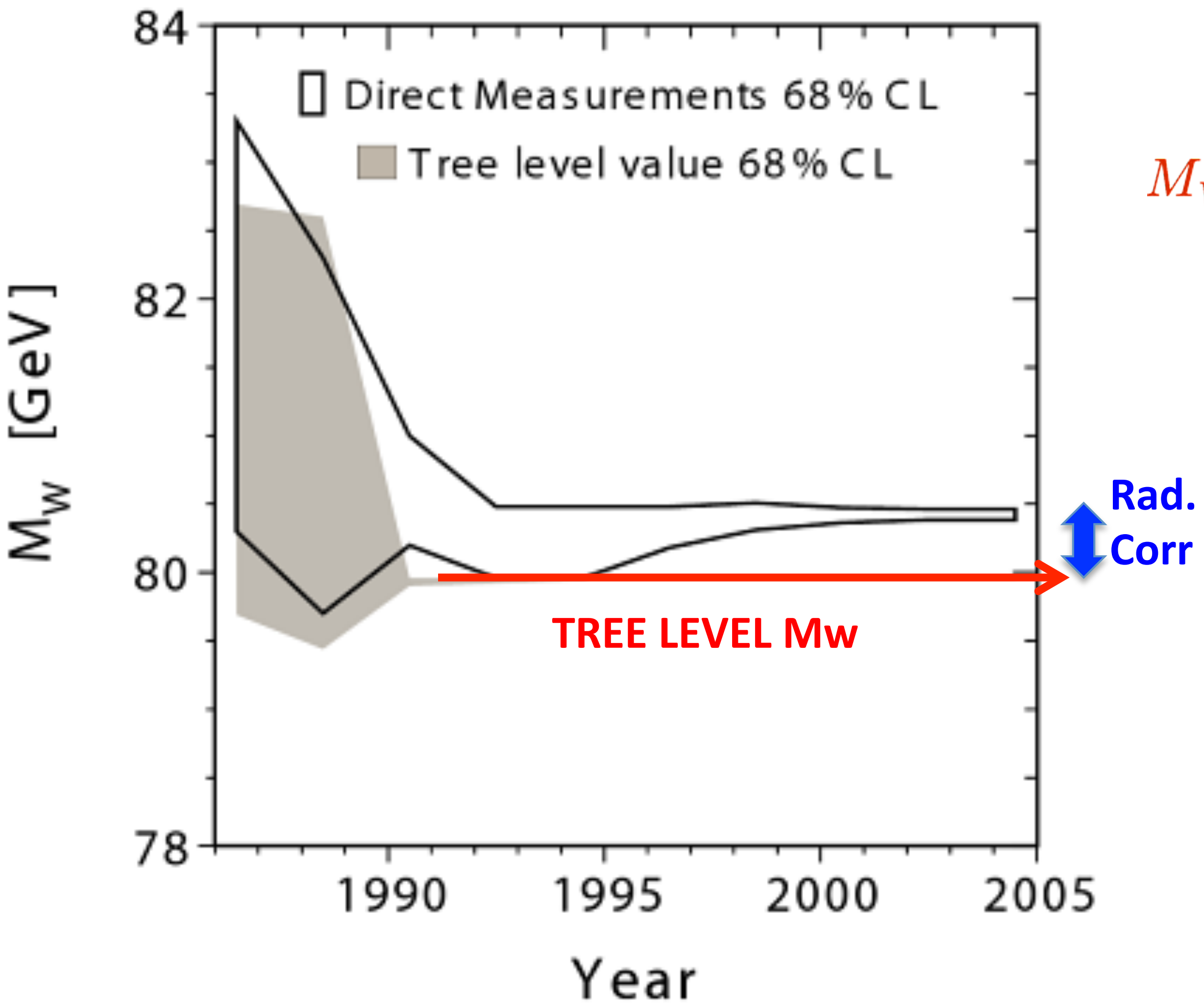
Measurement Of W Boson Mass and Width

Mark Lancaster
University College London

Motivation



TREE LEVEL SM

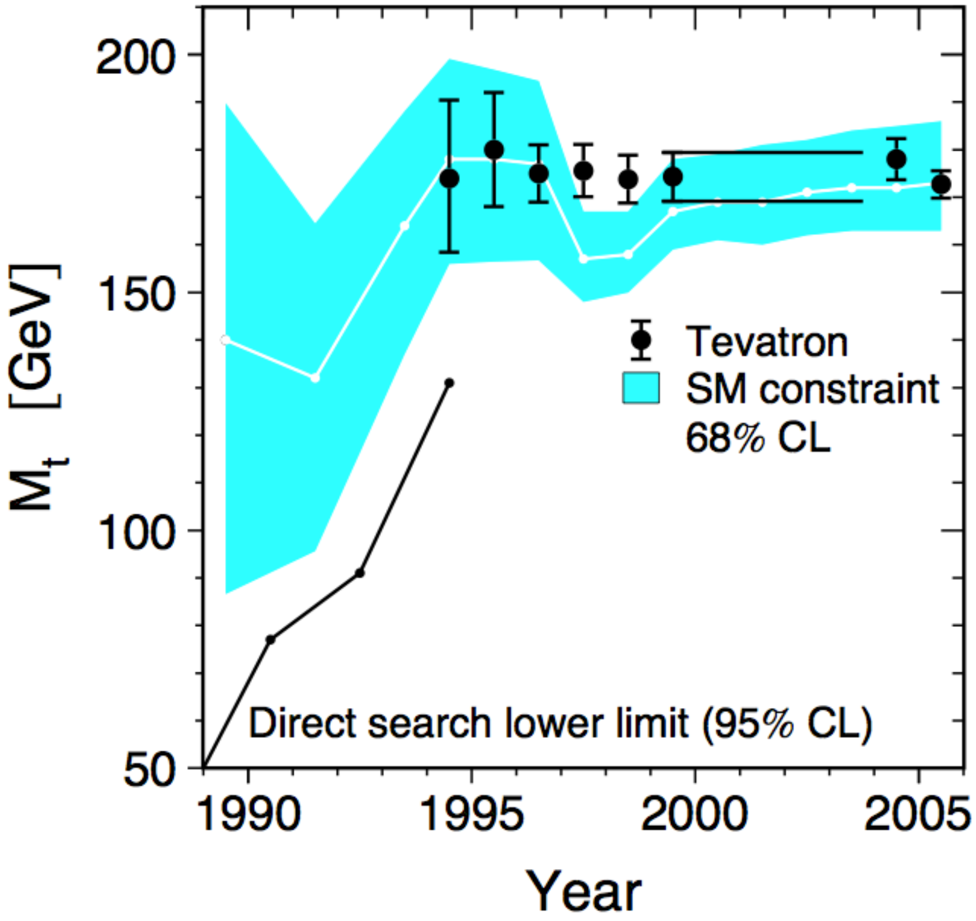
$$M_W^2\left(1-\frac{M_W^2}{M_Z^2}\right)=\frac{\pi\alpha_{EM}}{\sqrt{2}G_F}$$

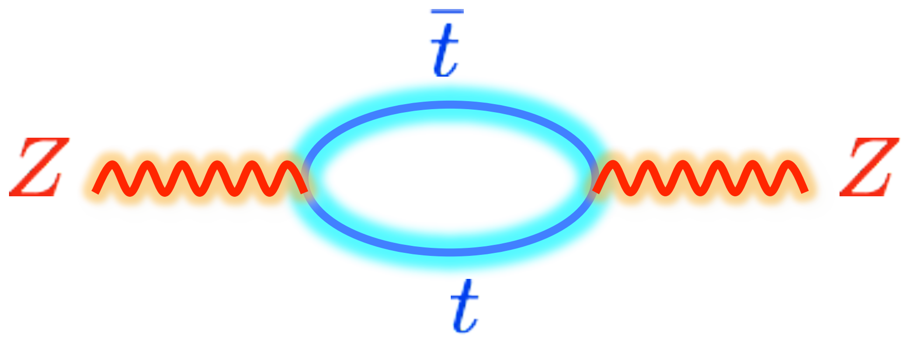
LOOP LEVEL SM

~ 500 MeV.

Requires 0.5% precision to probe

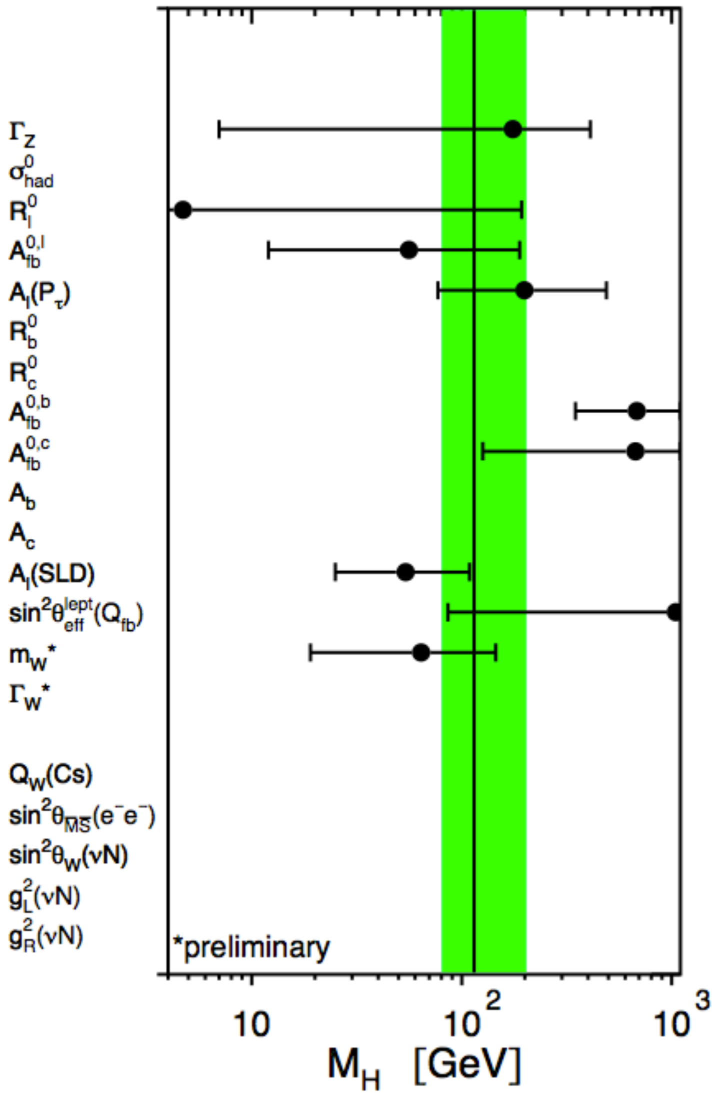
This has been successful in the past





B oscillations and
loop corrections to Z mass

At the start of Tevatron Run-II



$$A^b_{\rm FB}, A_l(SLD), m_W$$

had similar weights in constraining m_H

$$m_H = 129^{+74}_{-29}\ \text{GeV}$$

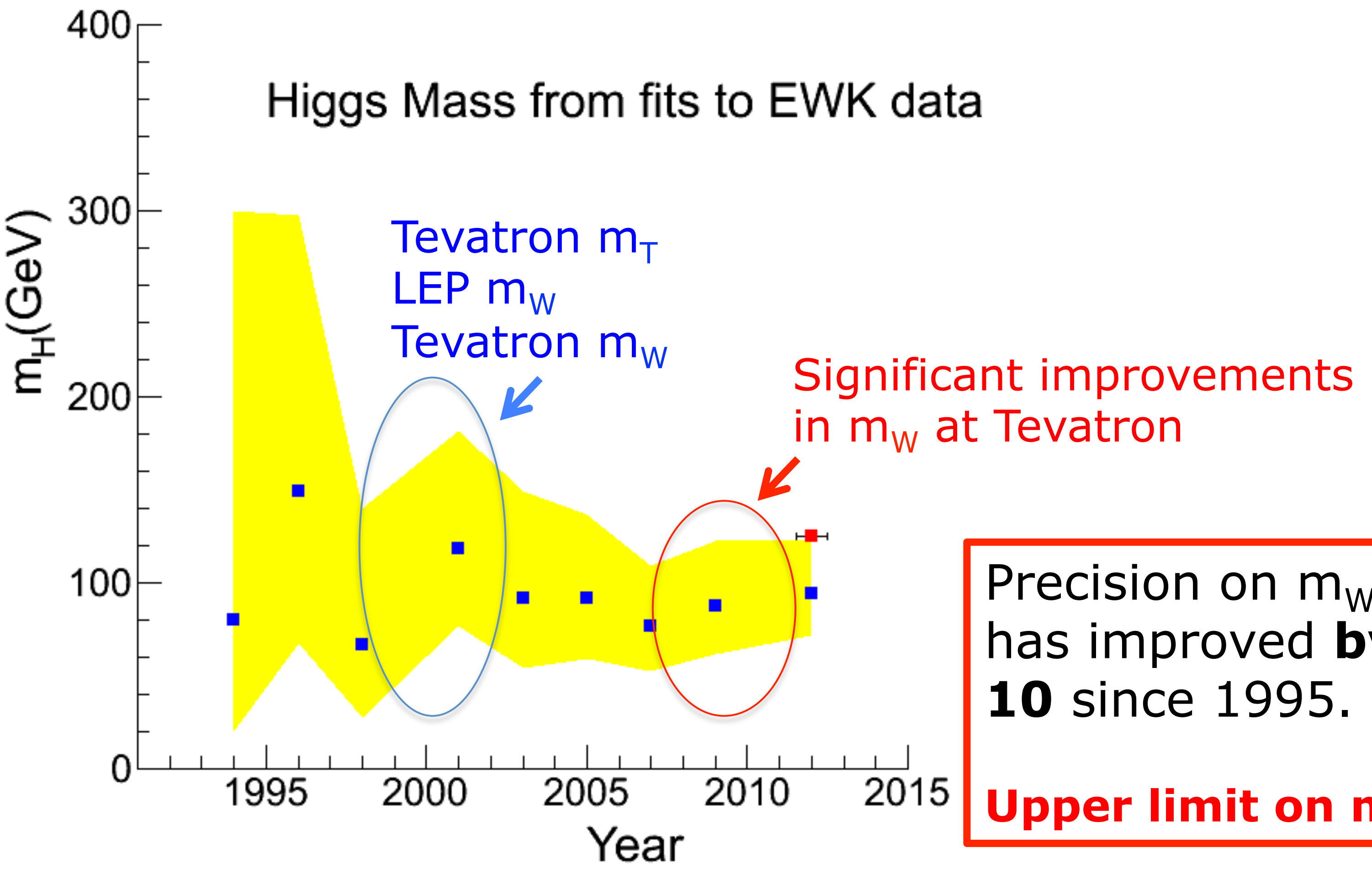
$$m_H < 285\ \text{GeV}\ (95\% CL)$$

$$\Delta m_W \sim 30\ \text{MeV}$$

$$\Delta m_{top} \sim 4\ \text{GeV}$$

Probing Internal Consistency of SM

SM Physics Only

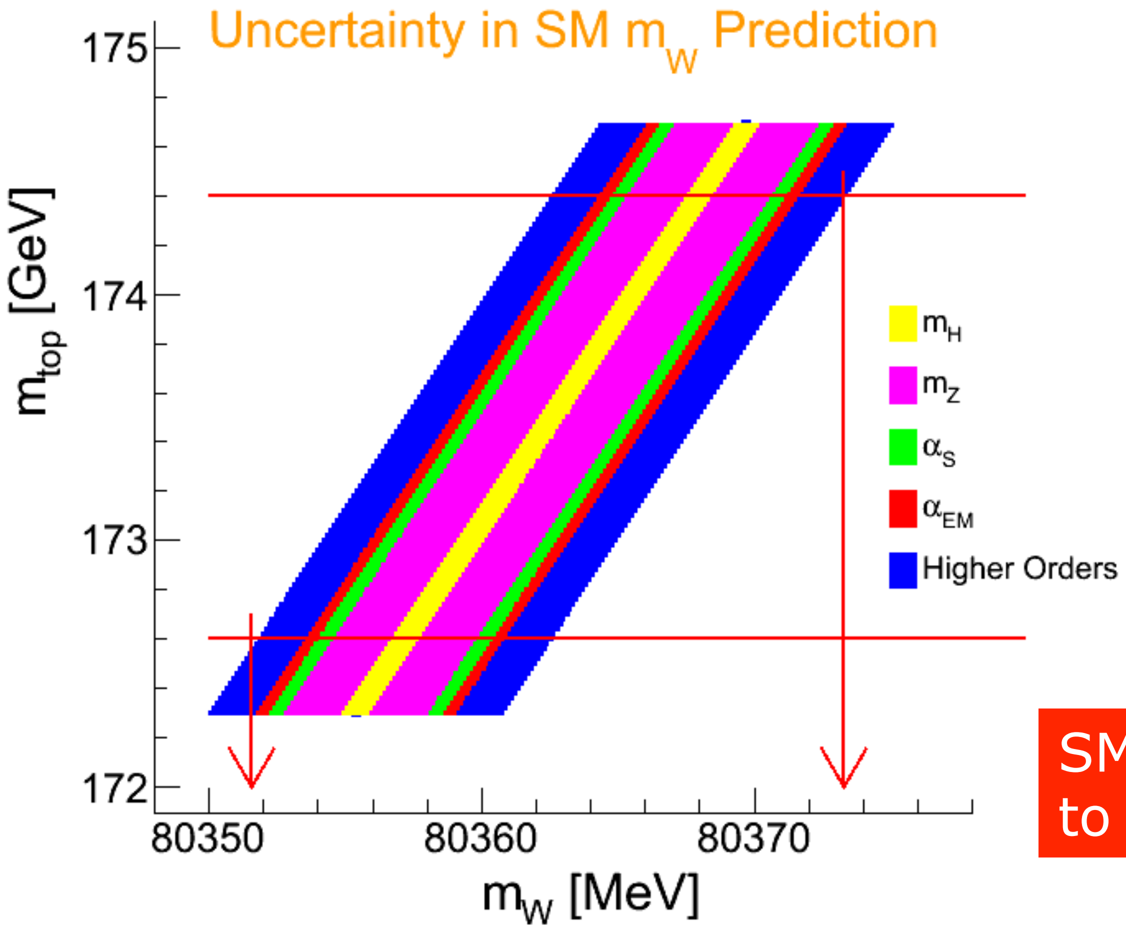


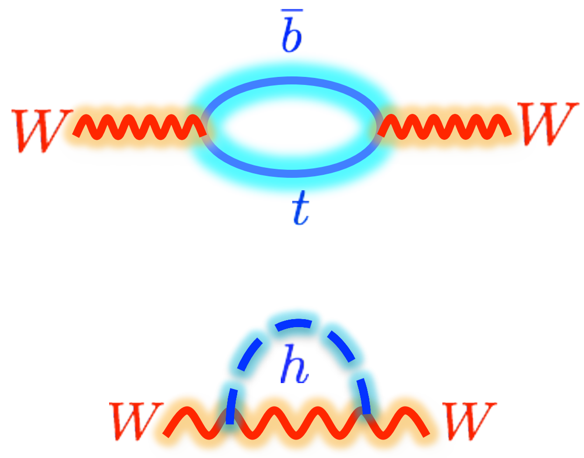
Precision on m_W and m_T has improved **by factor of 10** since 1995.

Upper limit on m_H = 152 GeV

W and Top Mass

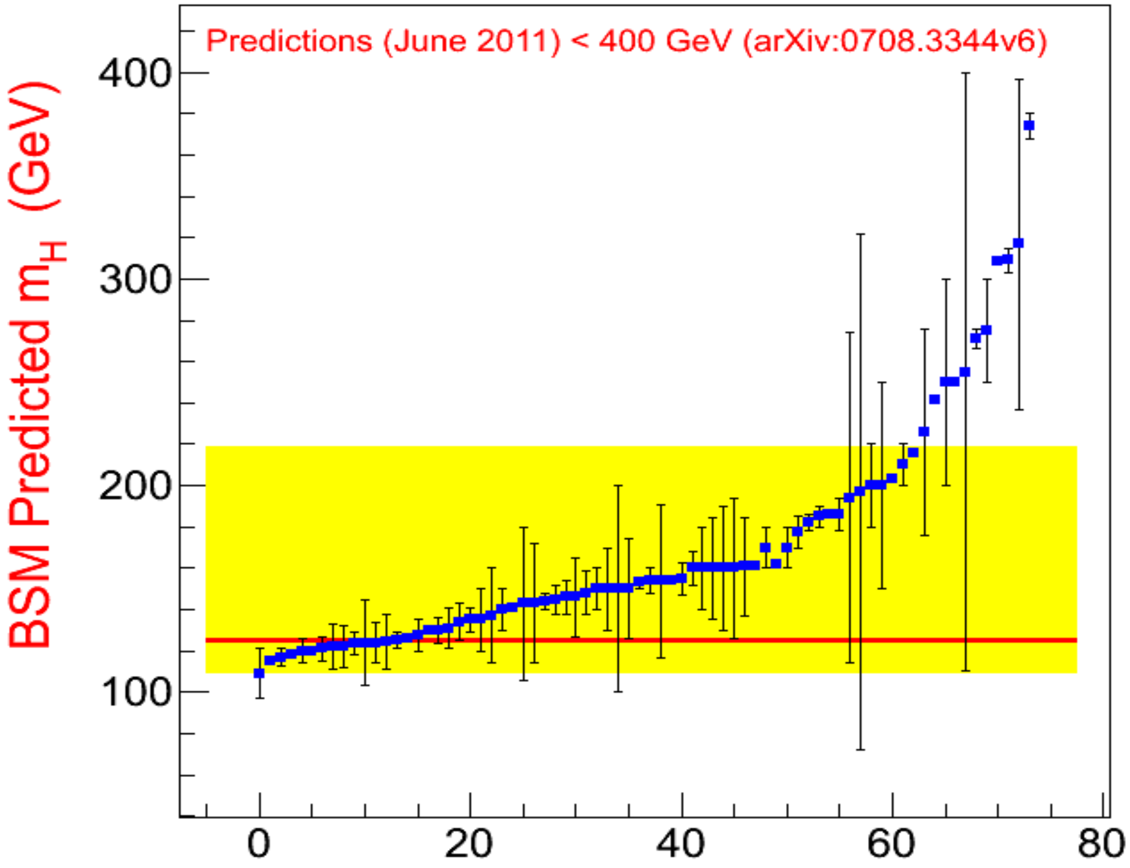
Reducing Mw uncertainty still remains the determining factor in improving the internal consistency check of the SM





SM prediction of Mw is good to only 10 MeV

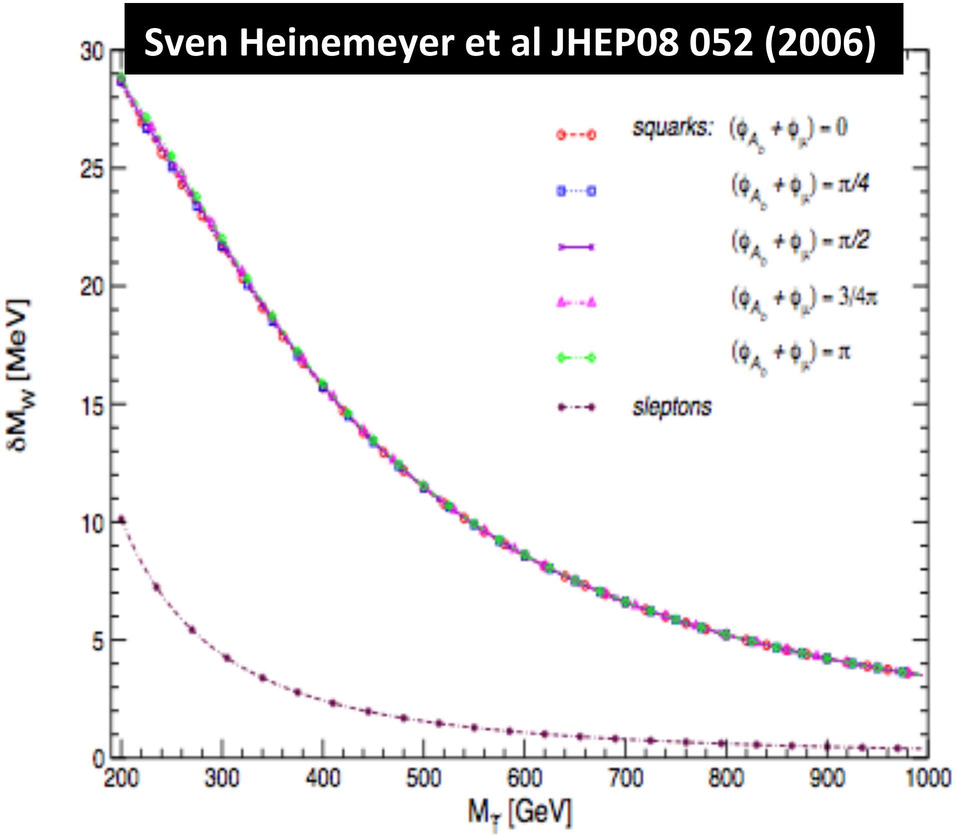
Beyond the SM



BSM Models

Most predicted larger mass than that of the Higgs-like object at the LHC !

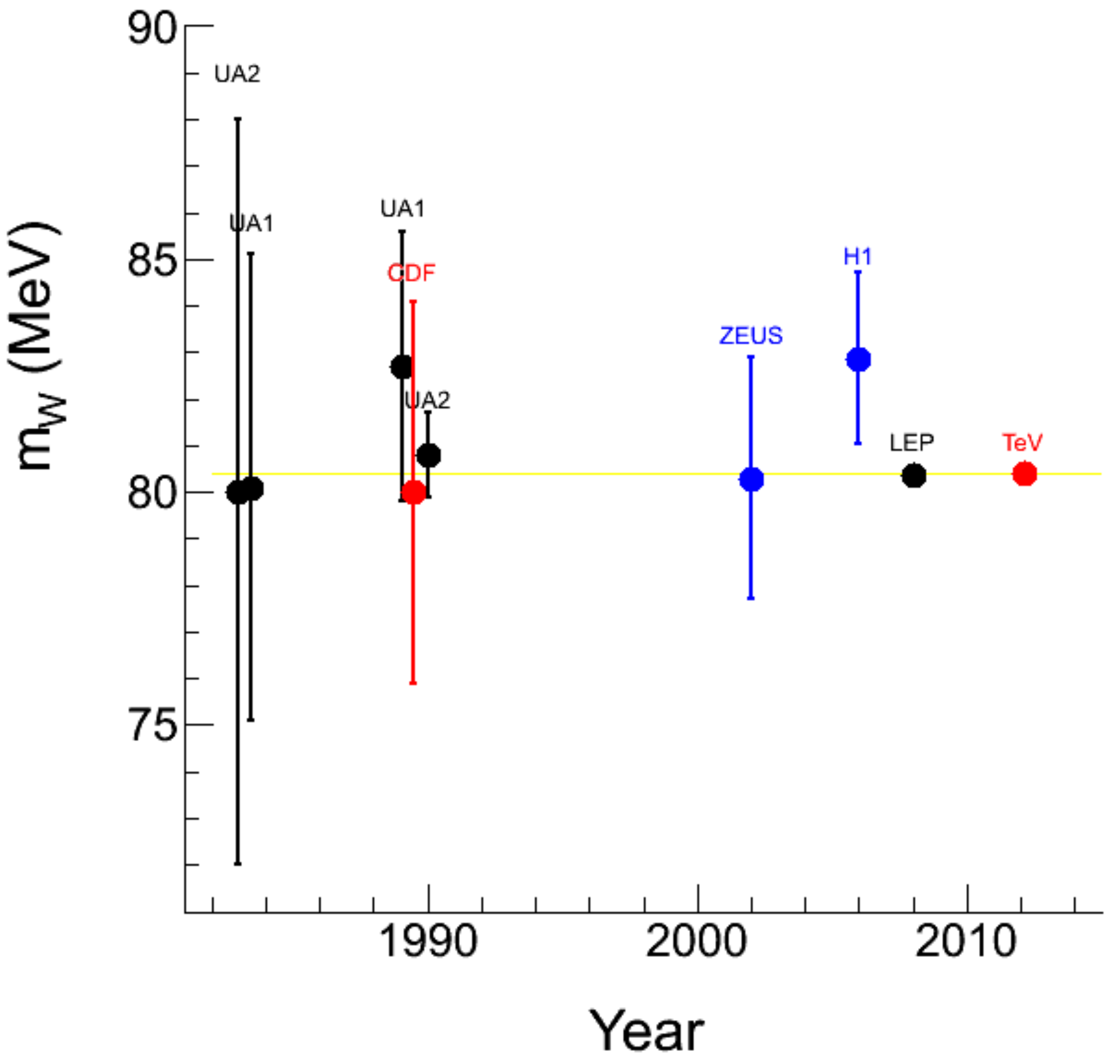
What about BSM contribution ?



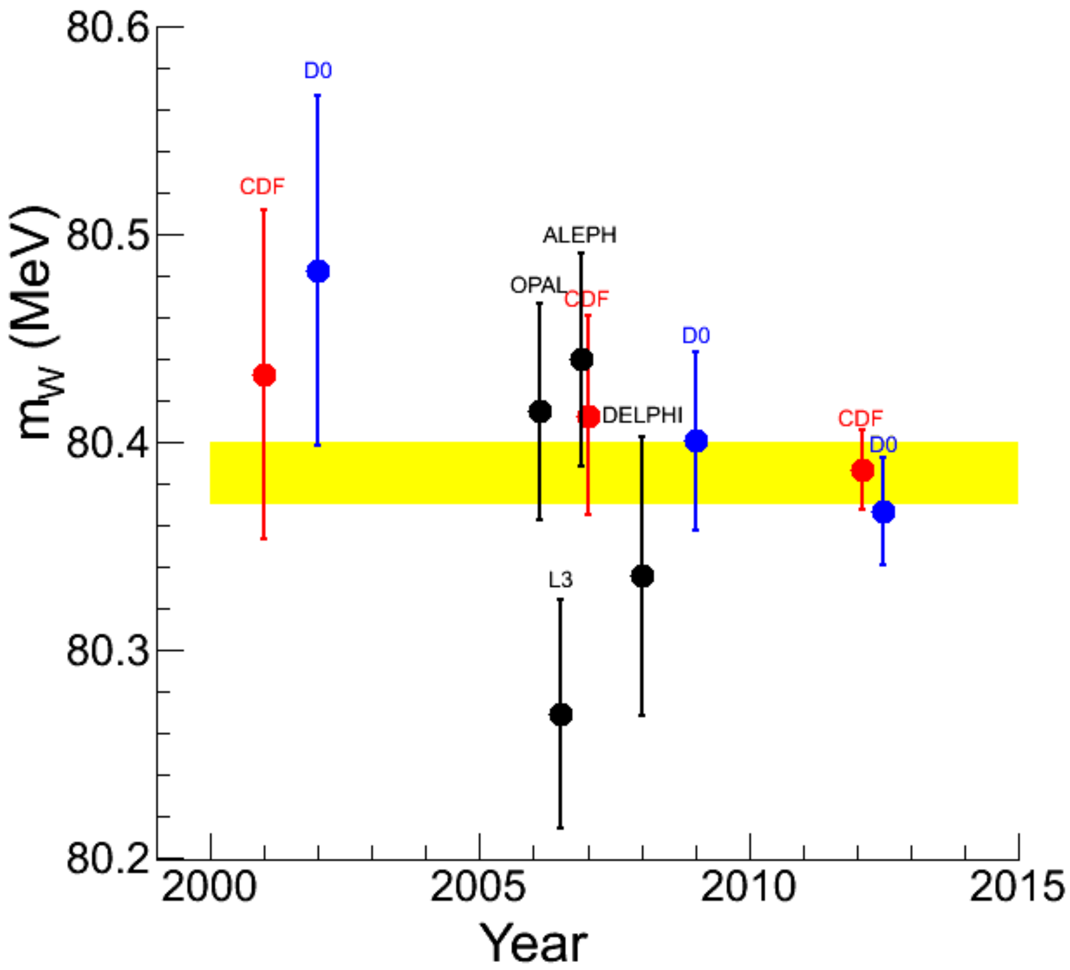
"Old" SUSY drove up Mw up by O(20 MeV) but with a large O(20 MeV) variance from e.g. unknown mass scale, complex phase in stop mass matrix

Likely given current constraints **that BSM contribution to Mw is less than** the present precision on the SM Mw prediction………

Mw over the ages



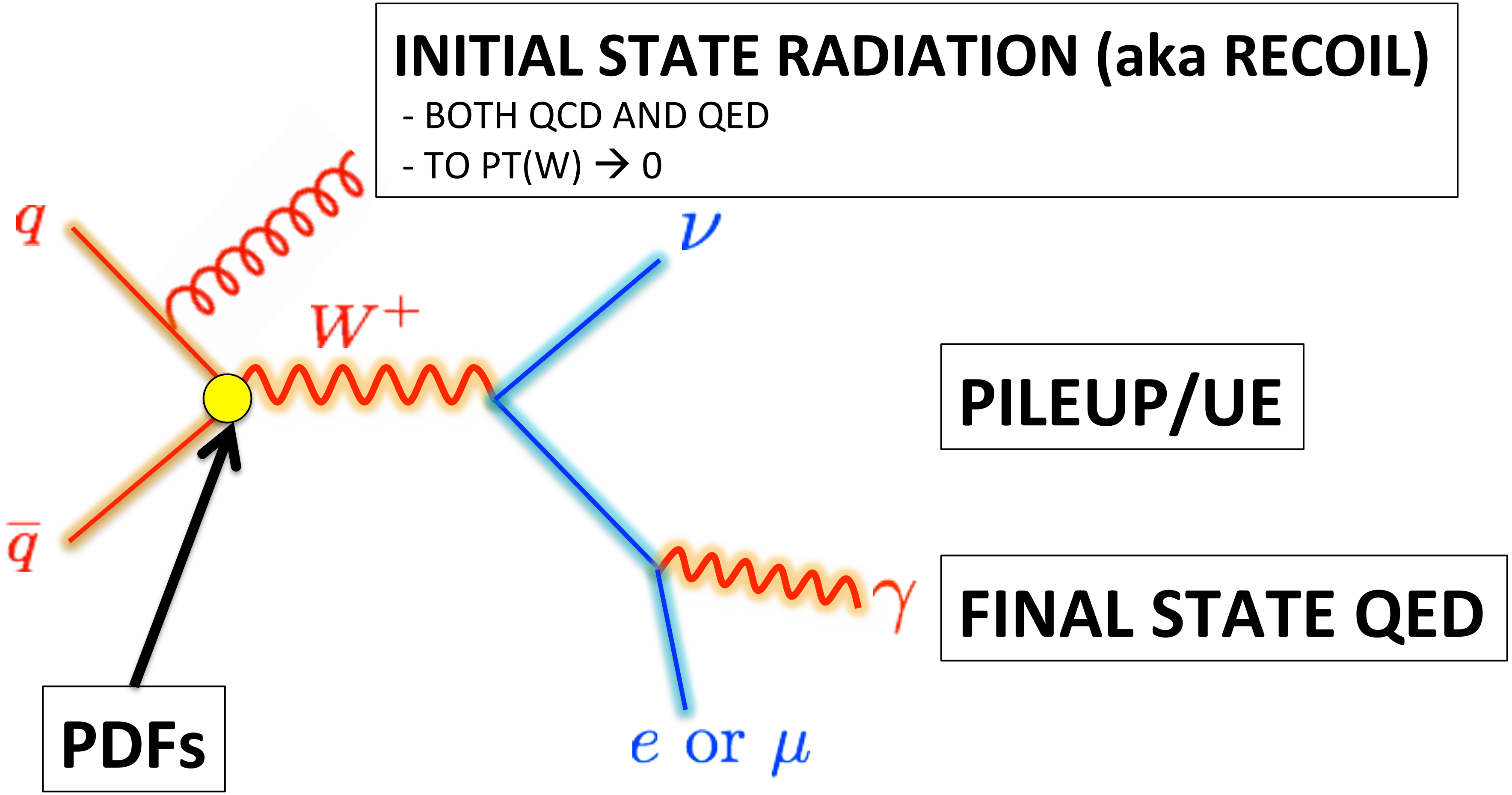
Many of the techniques that went into high precision Tevatron measurements were pioneered in the 1990 UA2 measurement



World average is dominated by Tevatron.

CDF precision is 19 MeV.

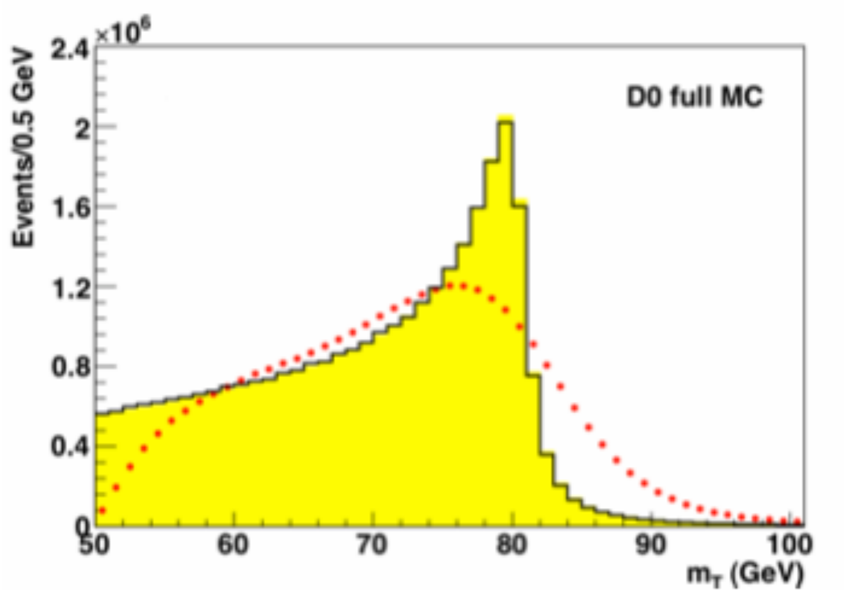
W Mass



Need to model each of these effects to a precision of ~ 5 MeV

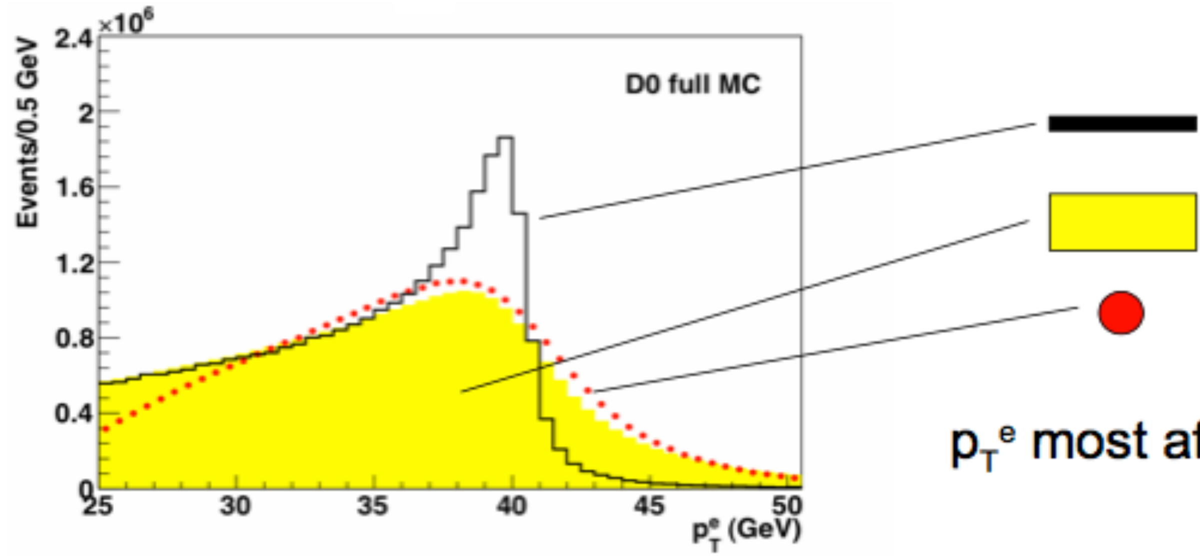
And understand response of detector to a similar level

W Mass



Transverse quantities used and transverse mass is most incisive

$$M_T = \sqrt{2 p_T^e \not{E}_T (1 - \cos \Delta\phi)}$$



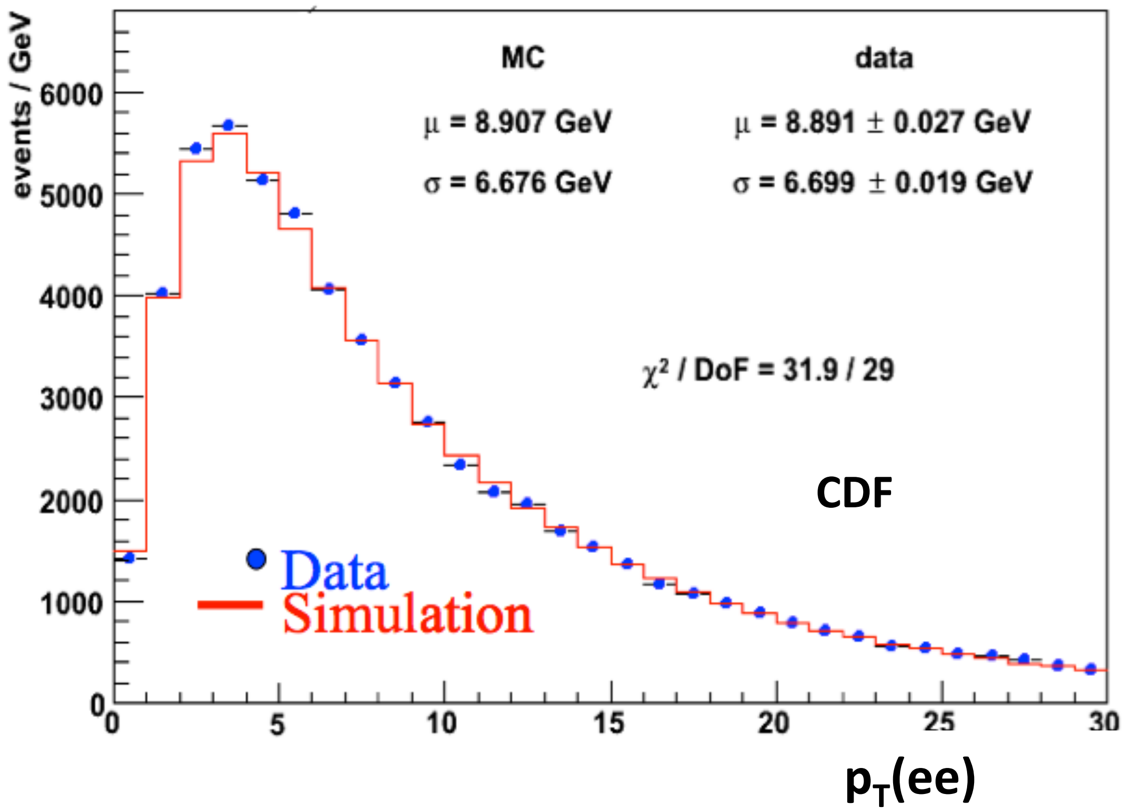
p_T^e most affected by p_T(W)

W p_T

Use RESBOS : NLO resum. + non-ptb ad-hoc parameterisation at low p_T

The W mass uses data at $p_T(W) < 30$ GeV to reduce the # jets.

Easier to simulate/parameterise "soft" events.



Tune RESBOS / BNLY g_2 parameter from Z events

Assume W / Z pT ratio is accurately defined

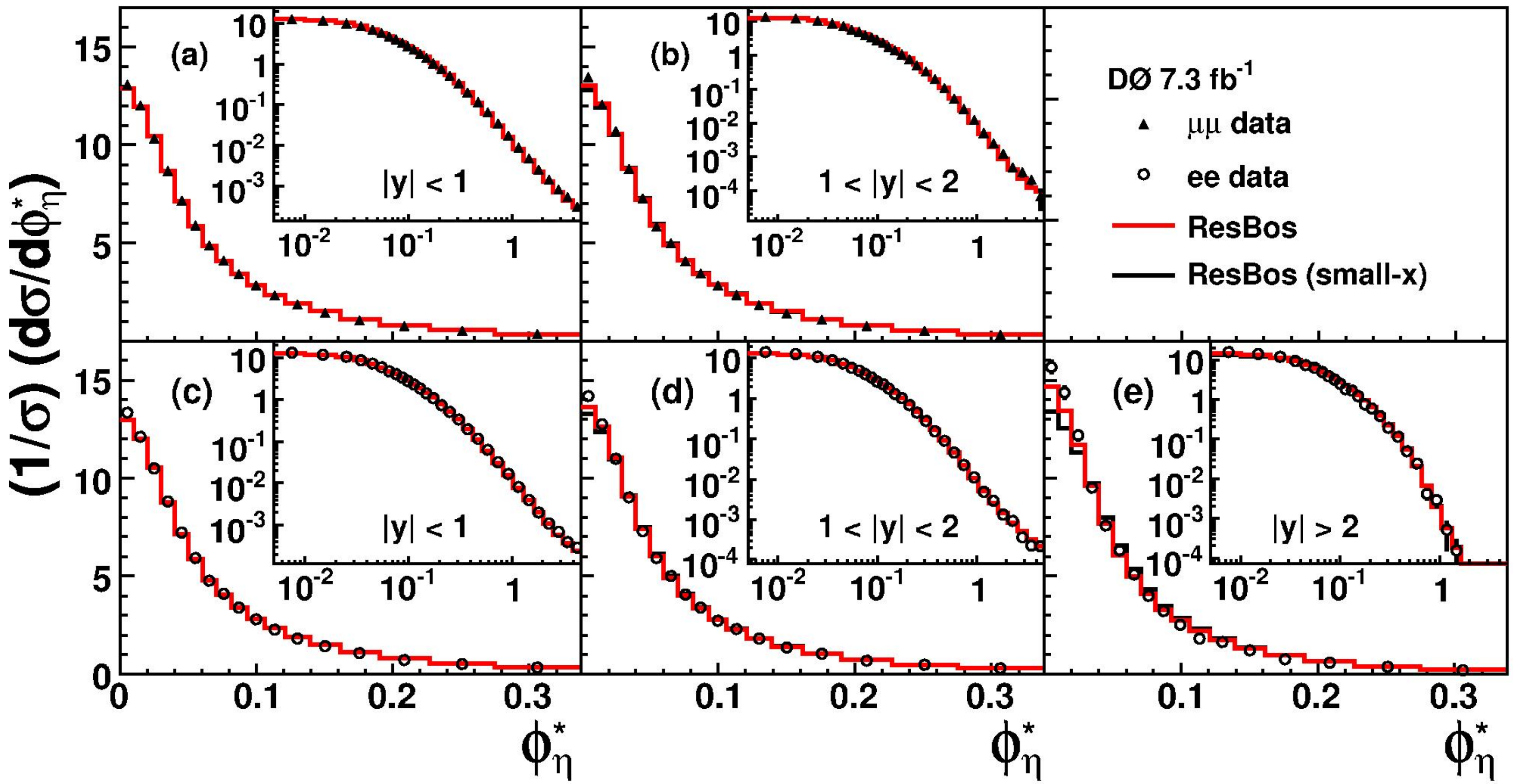
CDF ΔM_W = 5 MeV 2.2 fb^{-1}

D0 ΔM_W = 2 MeV 4.3 fb^{-1}

Z pT : D0 (ϕ*) vs RESBOS

D0 analysis using bespoke variable φ* to minimise detector effects

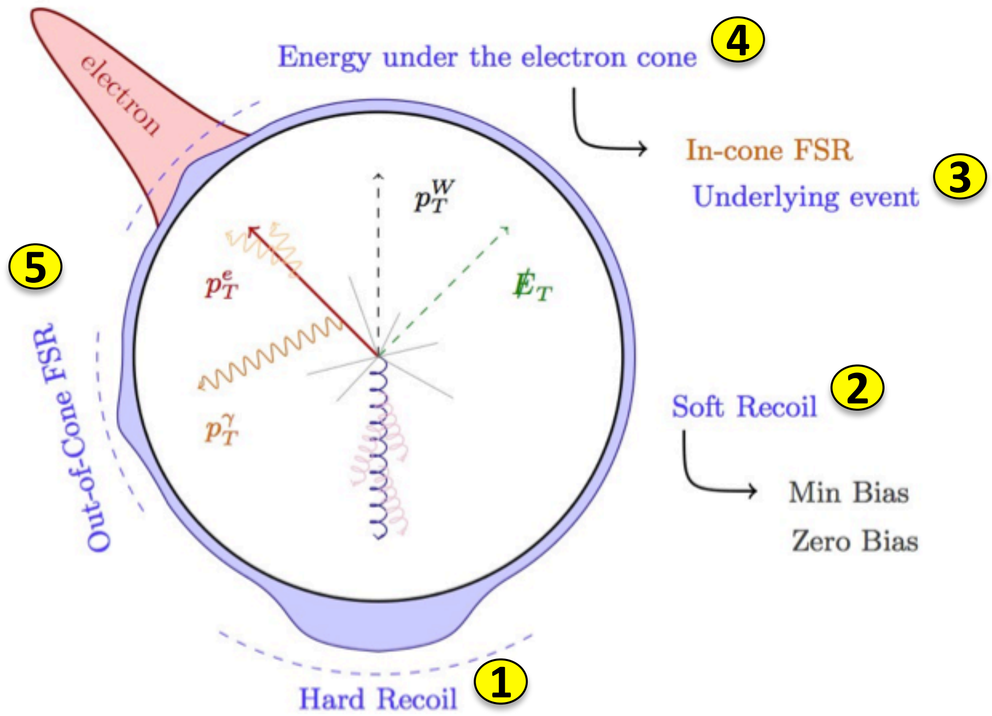
Shows RESBOS to provide very good description of data in Mw region.

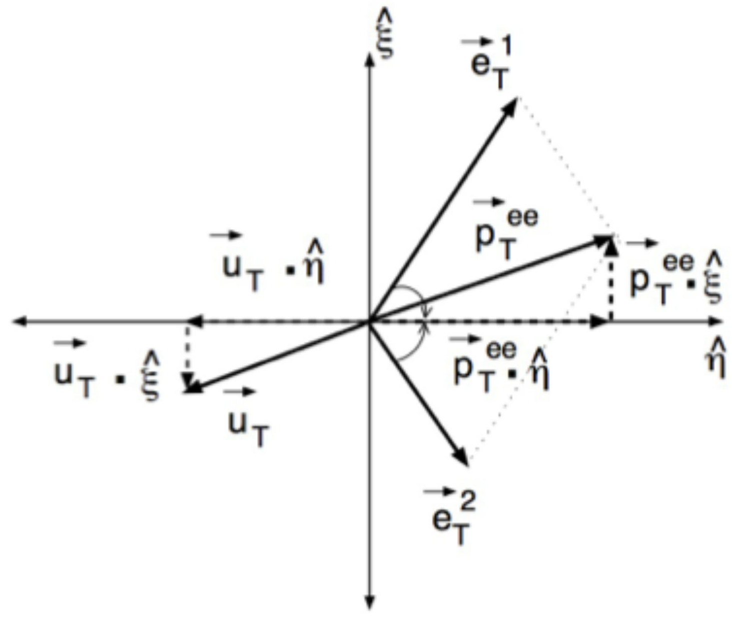


Detector Response to QCD ISR / UE

Parametric model tuned to Z + zero/min-bias events (lumi dependence)

Model separately 5 contributions from.

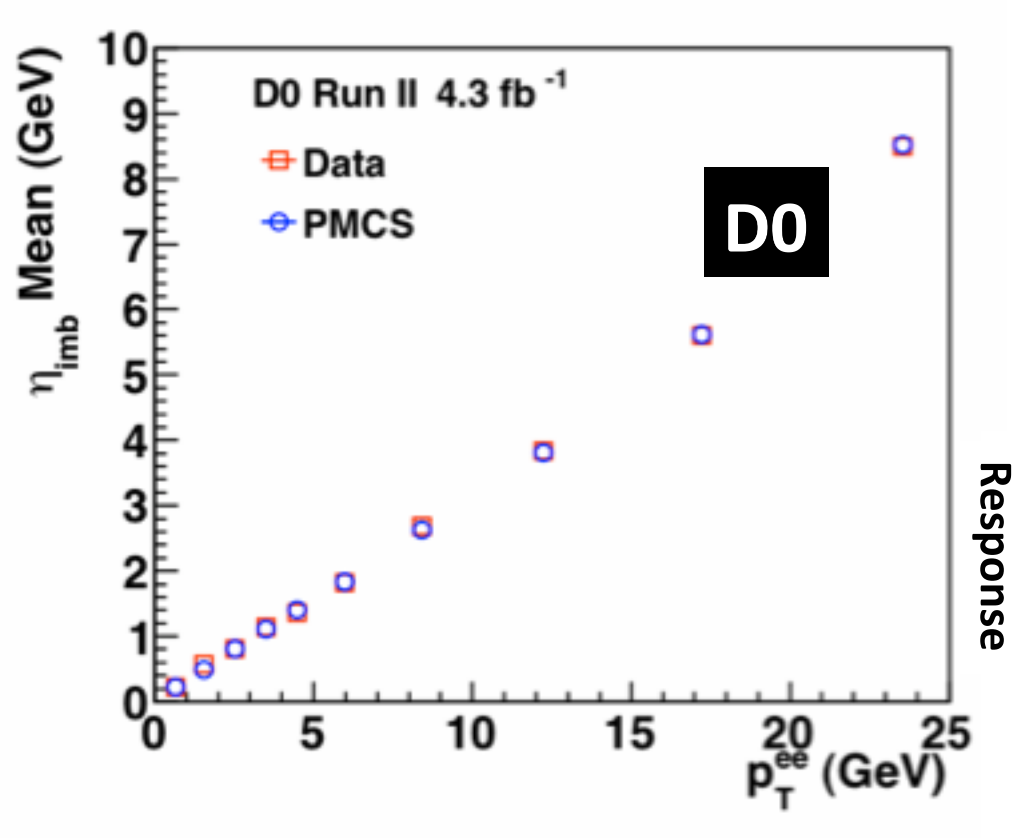




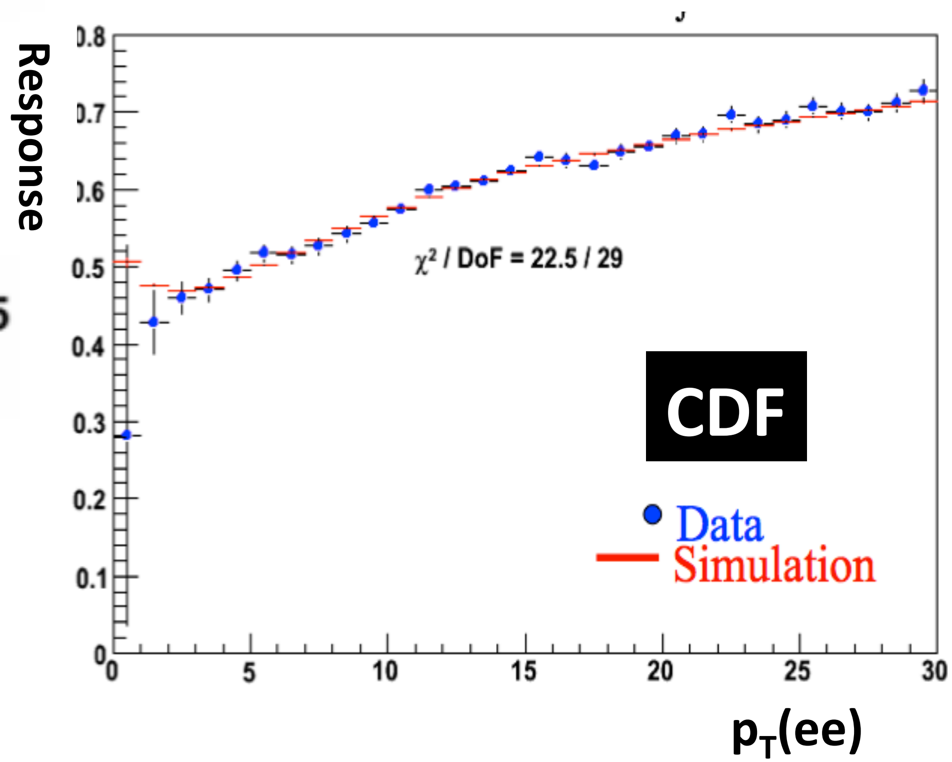
Separate contributions by considering recoil in the "UA2" directions.

Integrity of this model determines how well we model MET.

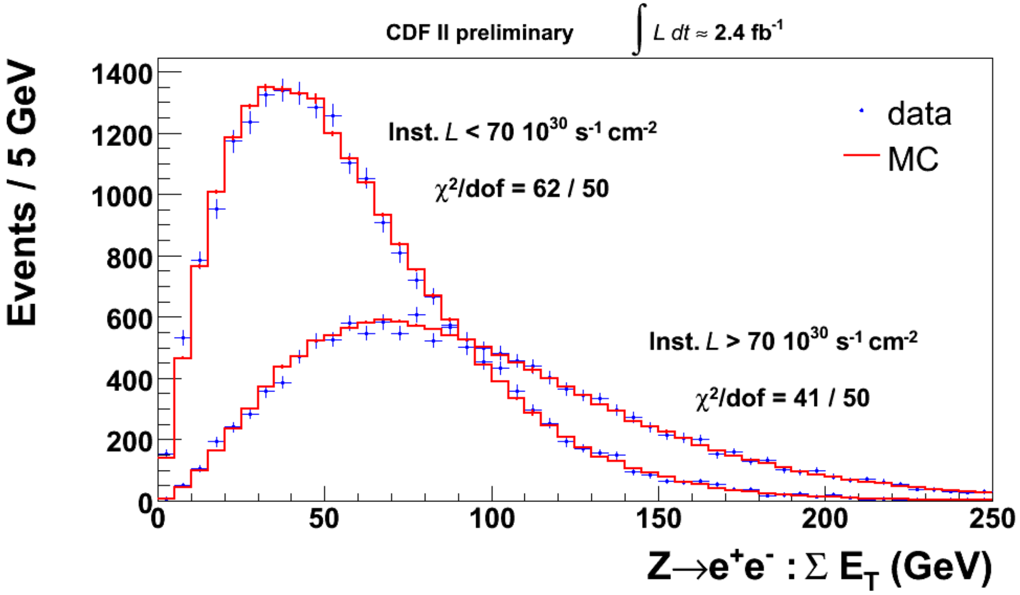
Recoil Response



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

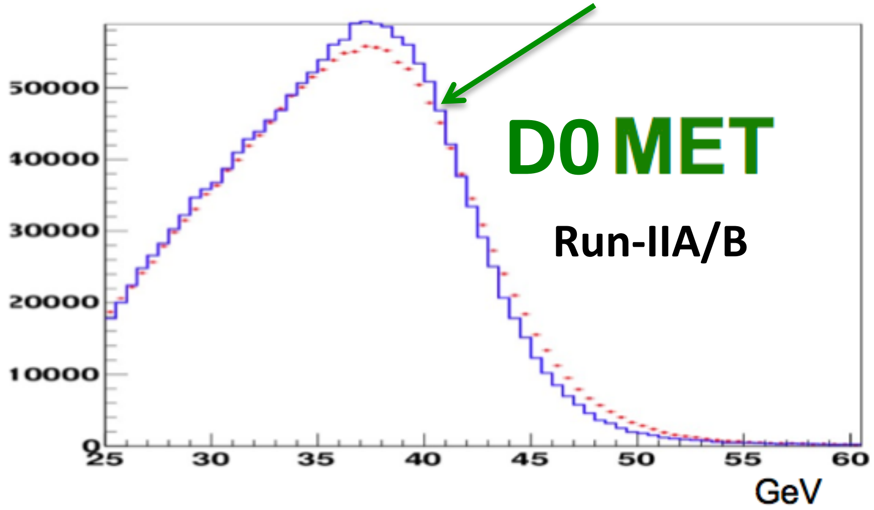


Pileup / Lumi dependence



Described well enough by having model with explicit luminosity or ΣE_T dependence

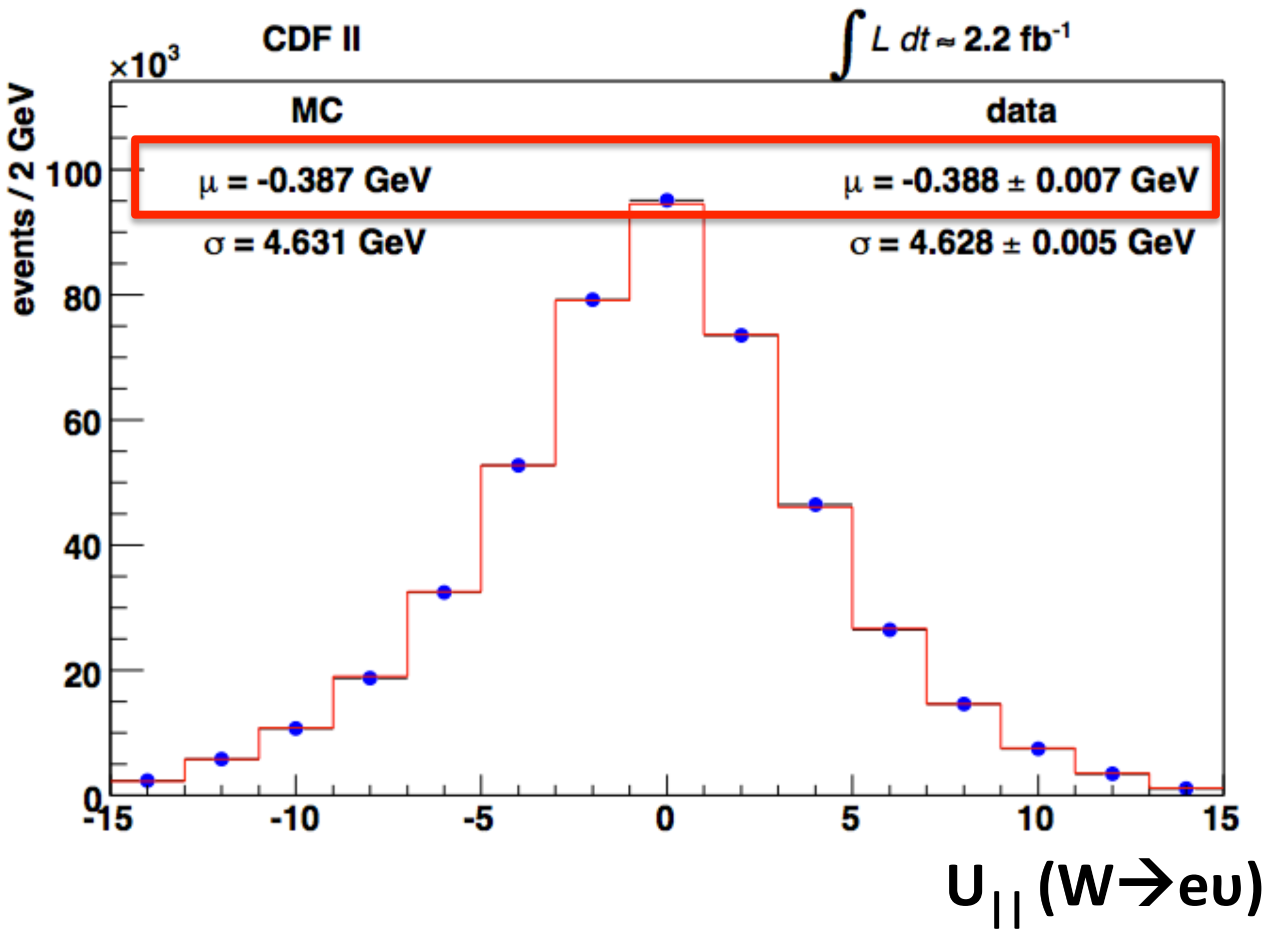
O(100) MeV on m_W



Recoil Response

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

← Component of hadronic recoil along charged lepton direction

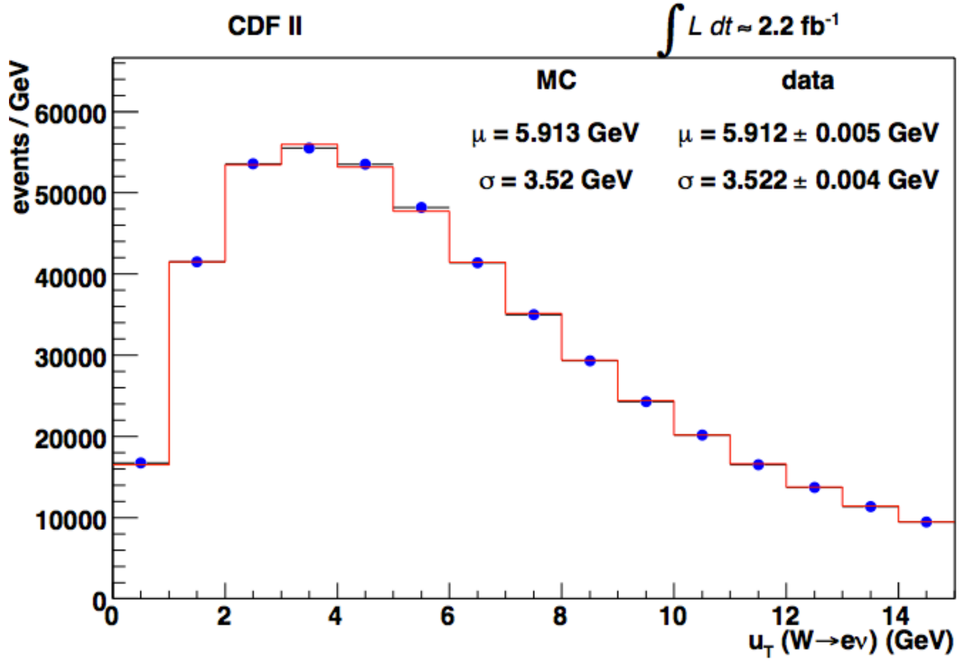


This is good to 1 MeV !

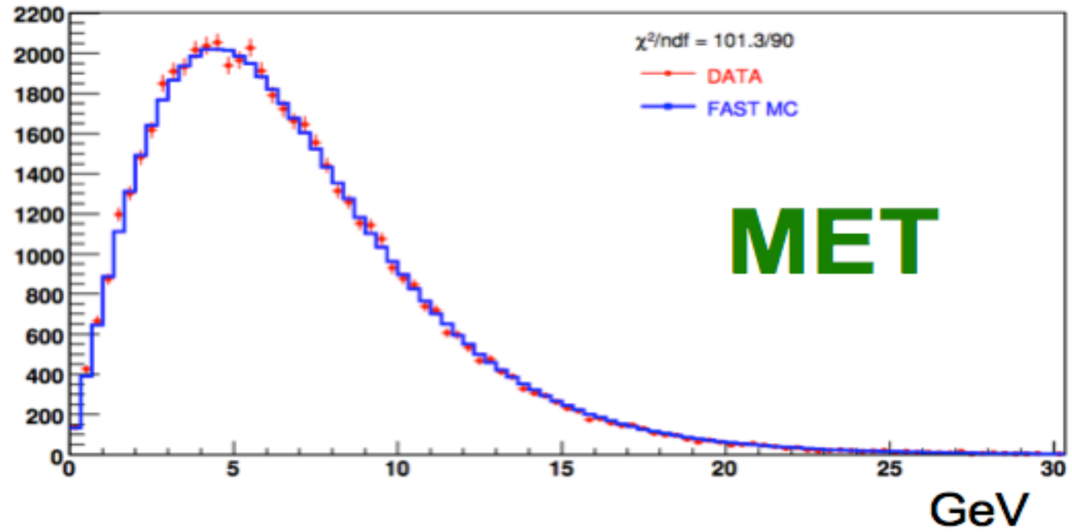
"How well do you describe MET ?"

RMS on recoil is ~ 4 GeV compares to ~ 10 GeV at LHC

Recoil Response



W p_T (from recoil)



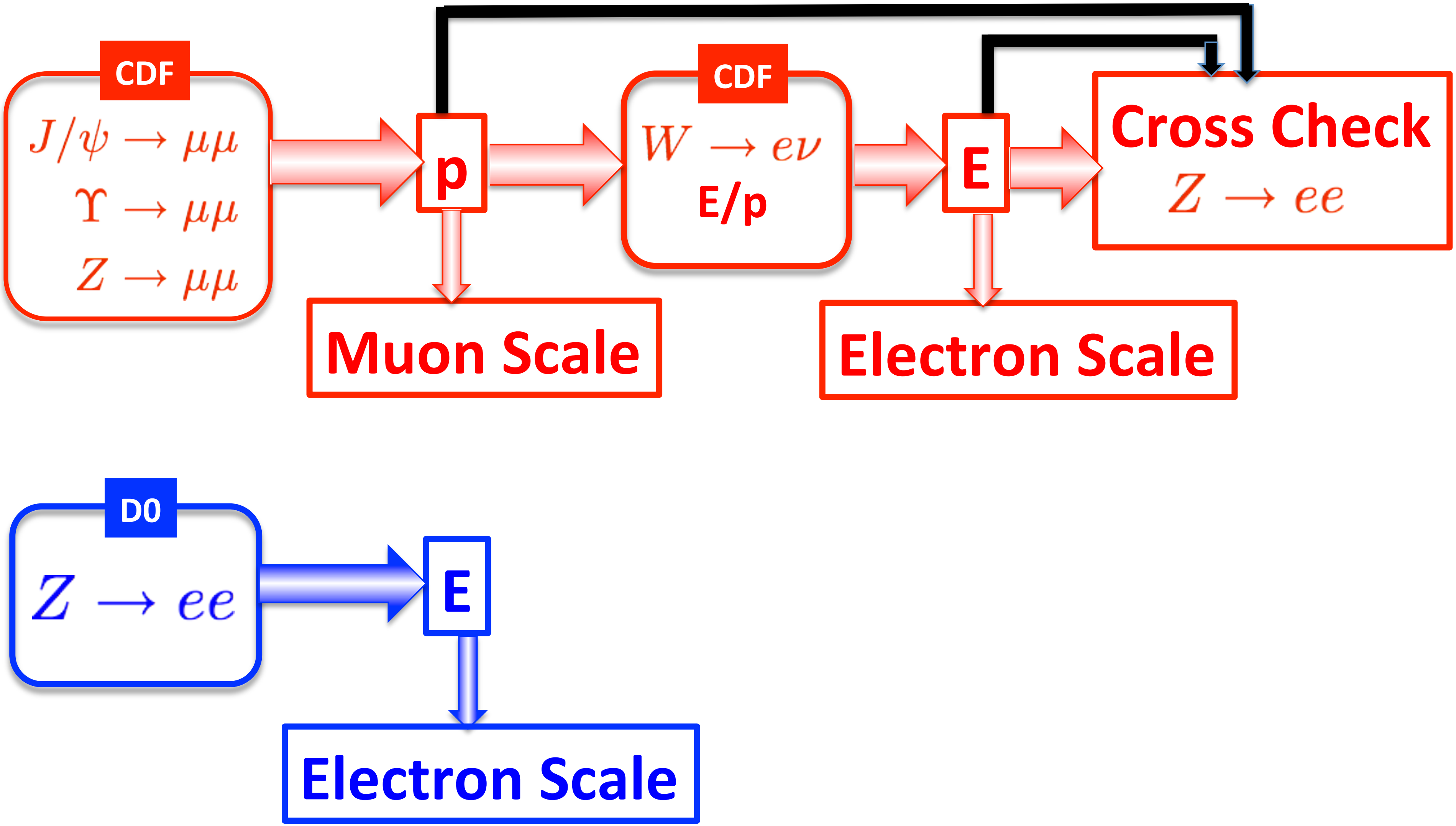
CDF

ΔM_W = 6 MeV

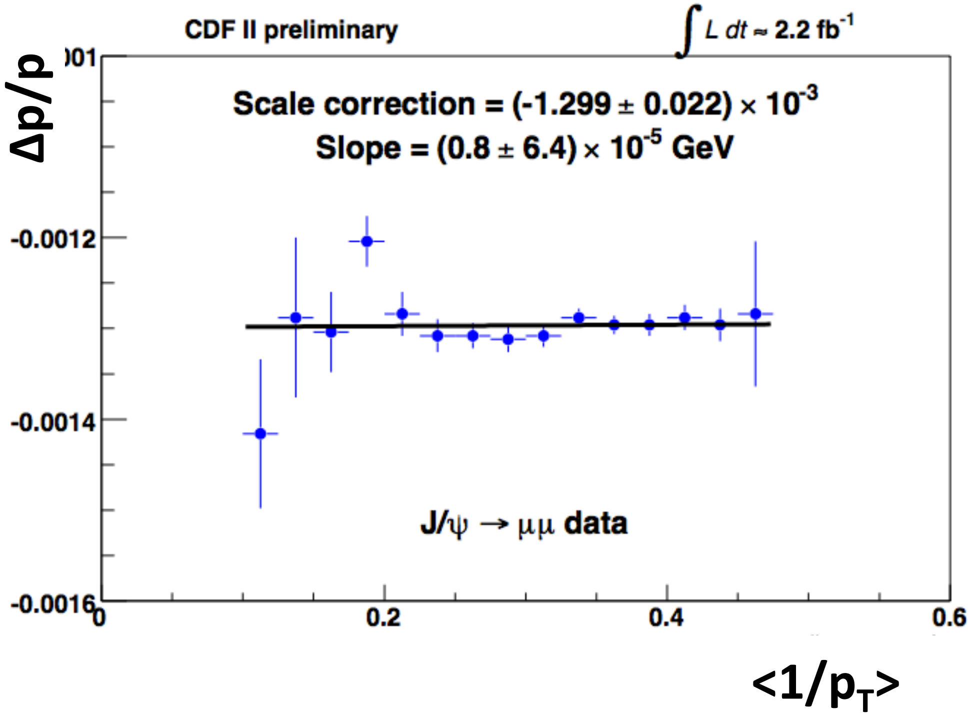
D0

ΔM_W = 5 MeV

Lepton Energy Scale

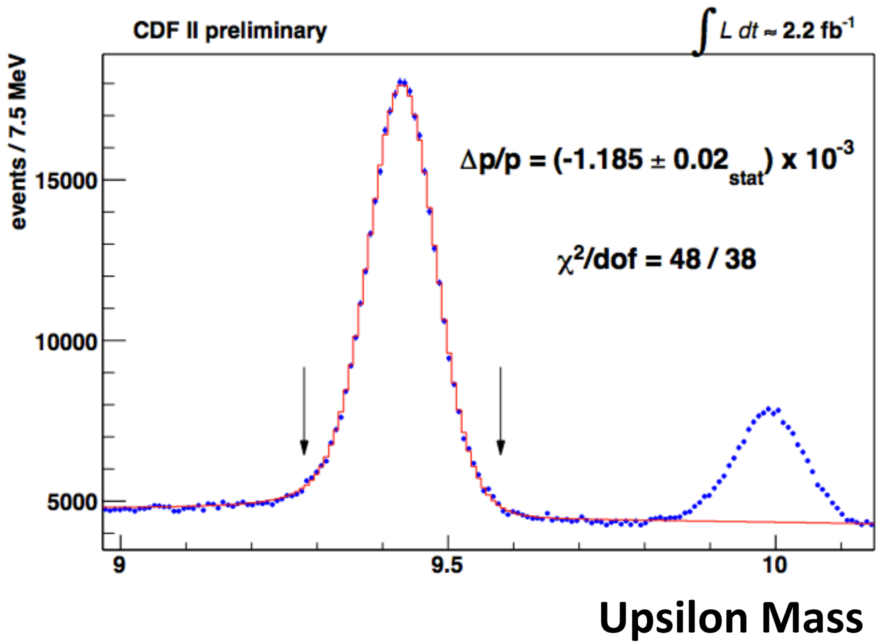


CDF p-scale



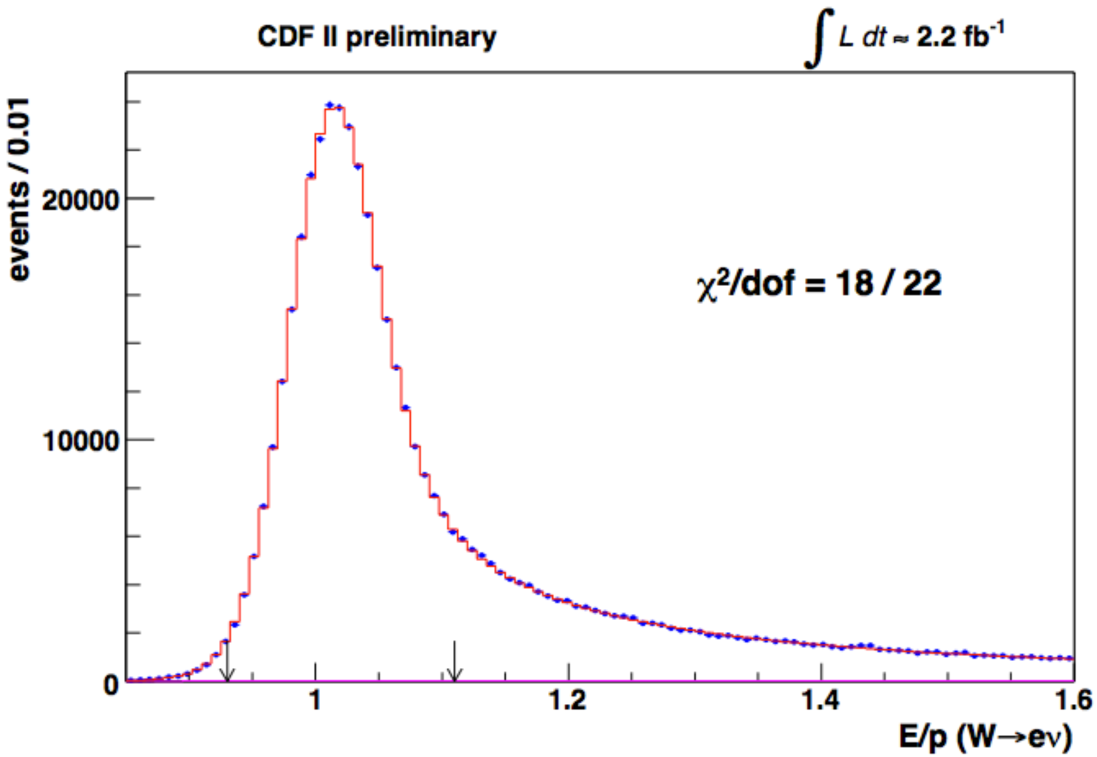
CDF MUONS

ΔM_W = 7 MeV



With this p-scale measured $Z \rightarrow \mu\mu$ mass is: 7 ± 12 MeV below PDG

CDF E-scale

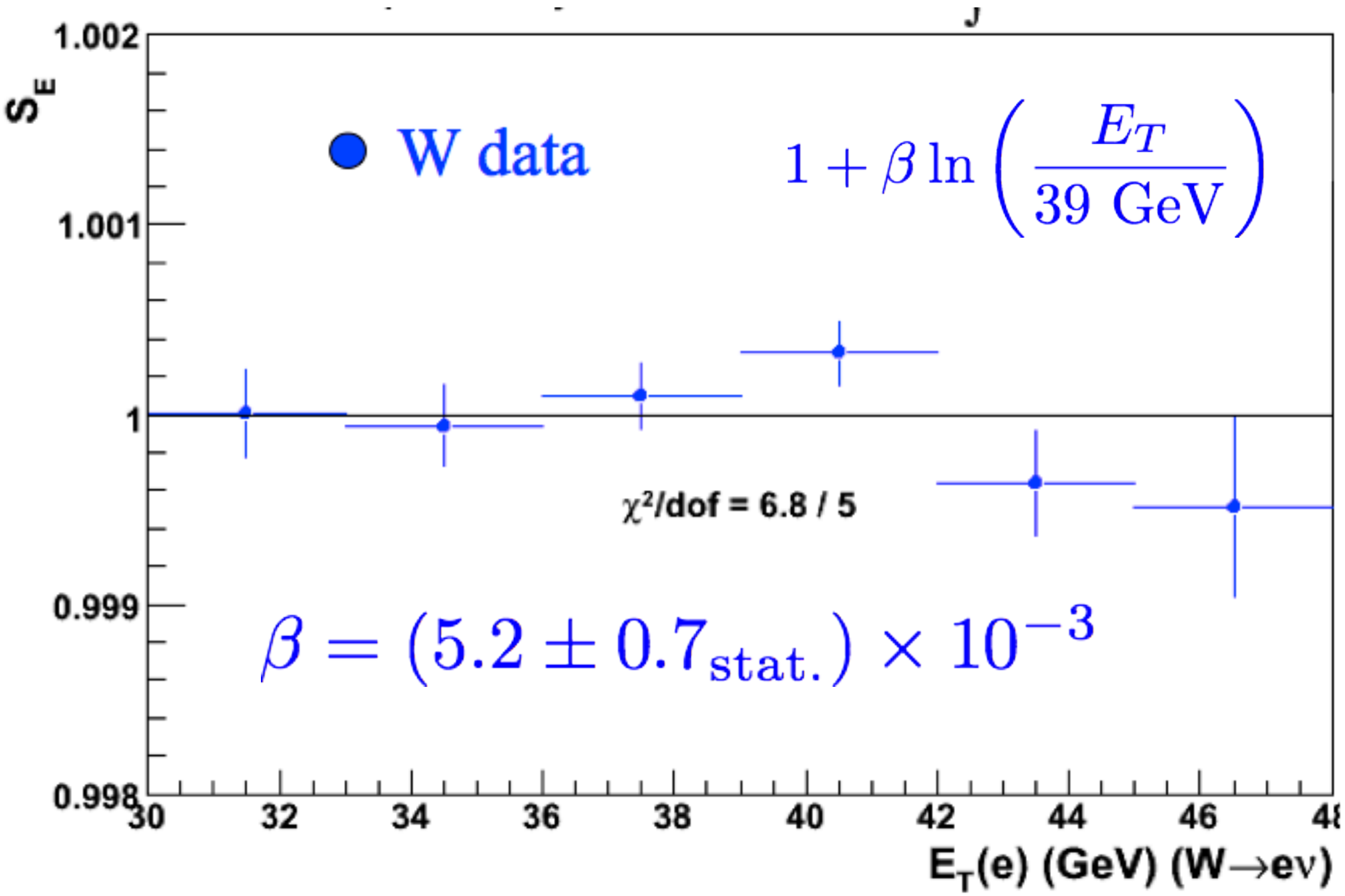


Tail of distribution used to constrain detector material X_0

With this E-scale measured Z→ee mass is: 43 ± 30 (stat.) MeV above PDG

CDF E-scale

E/p also used to constrain E-scale non-linearity



CDF ELECTRONS

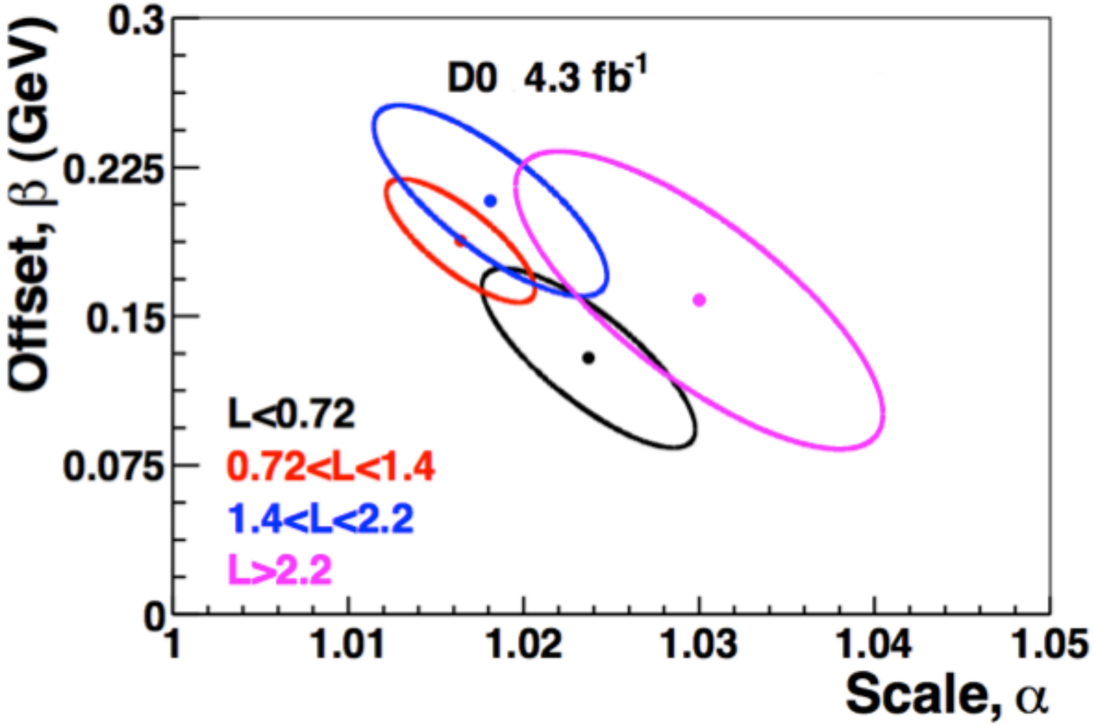
ΔM_W = 10 MeV

Includes uncertainty from:

- *p-scale*
- *material*
- *QED radiation*
- *non-linearity*
- *resolution*
- *backgrounds*

D0 E-scale

$$E_{\mathrm{MEAS}} = \alpha\,(E_{\mathrm{TRUE}} - 43\ \mathrm{GeV}) + \beta + 43\ \mathrm{GeV}$$

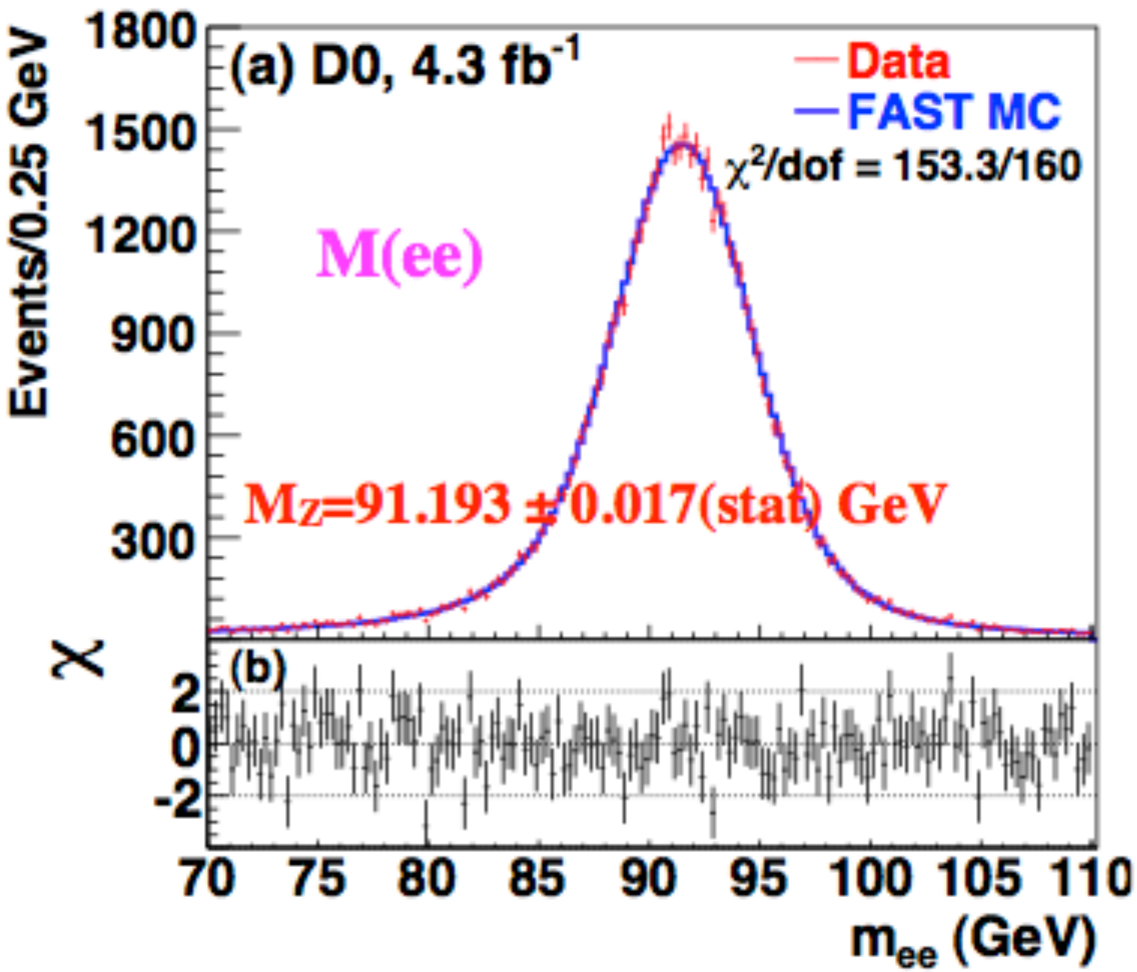


Model

- ΔE from dead material
- UE due to pileup and recoil

In luminosity and energy bins

D0 E-scale



Consistent with PDG by construction.

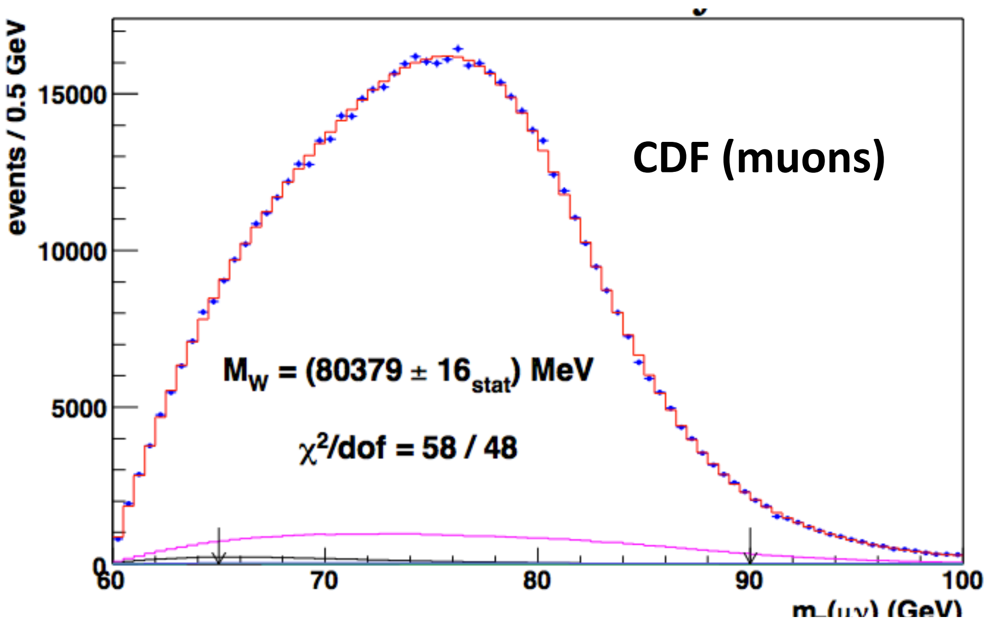
D0 measuring Mw/Mz

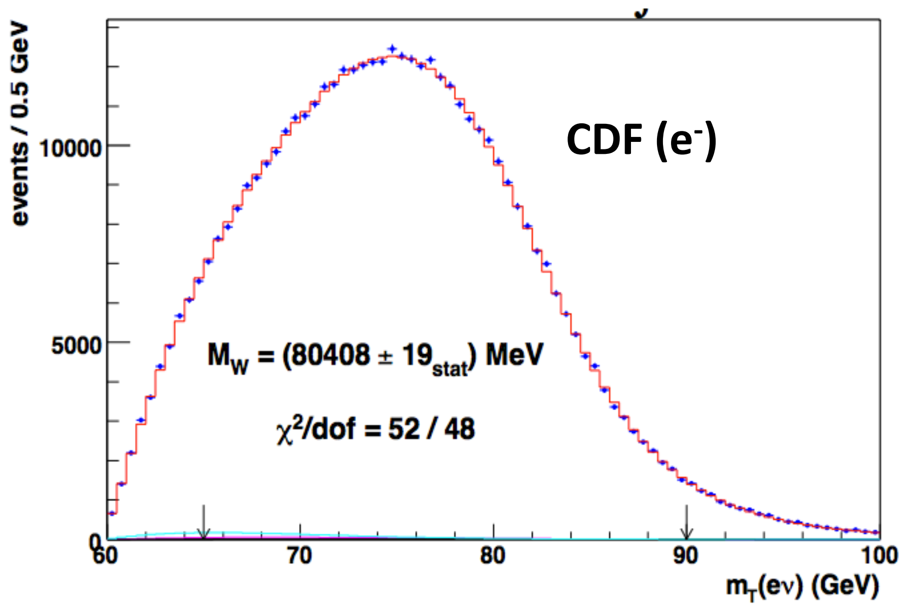
D0 ELECTRONS

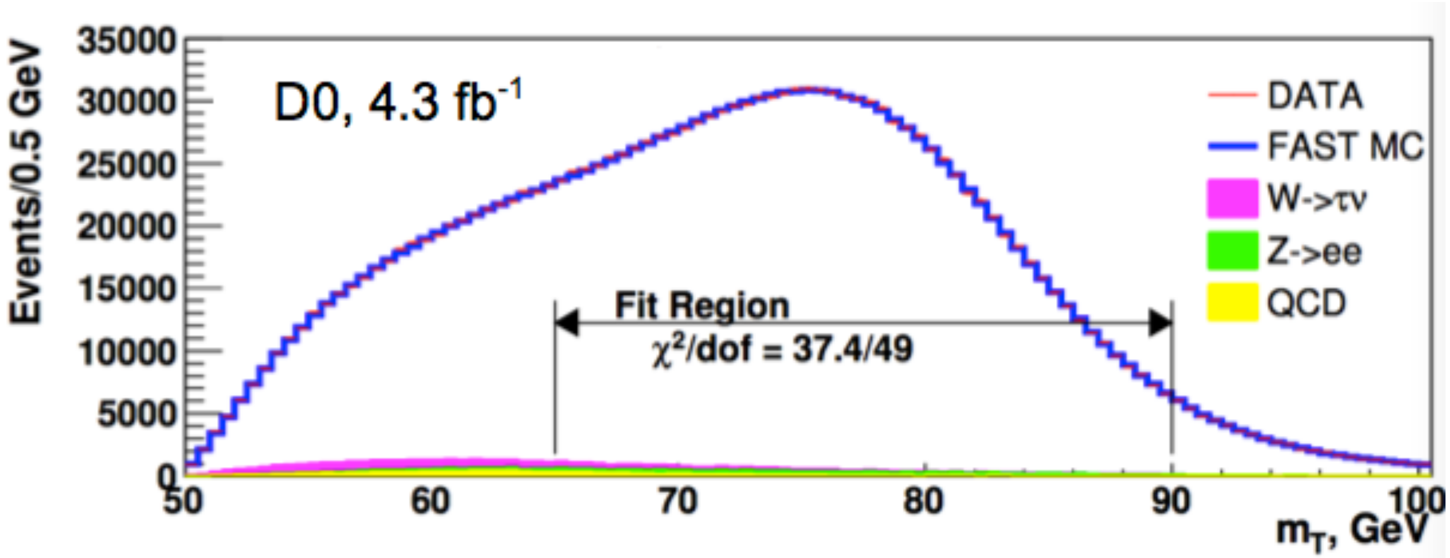
ΔM_W = 17 MeV

Nearly all statistical

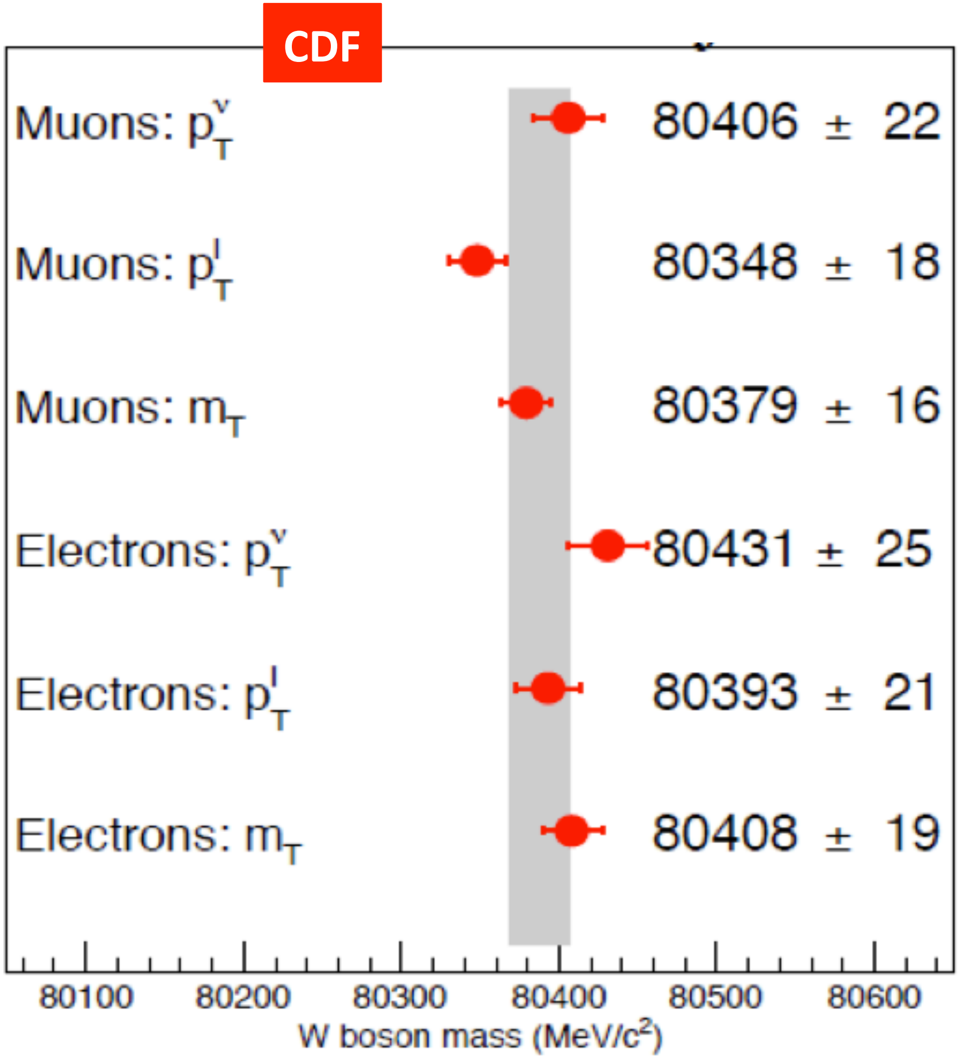
Transverse Mass Fits







Mass Fits



Possible to do many cross-checks with different fits

D0 only use m_T, p_T
CDF use m_T, p_T and MET

90% of M_W information is in m_T.

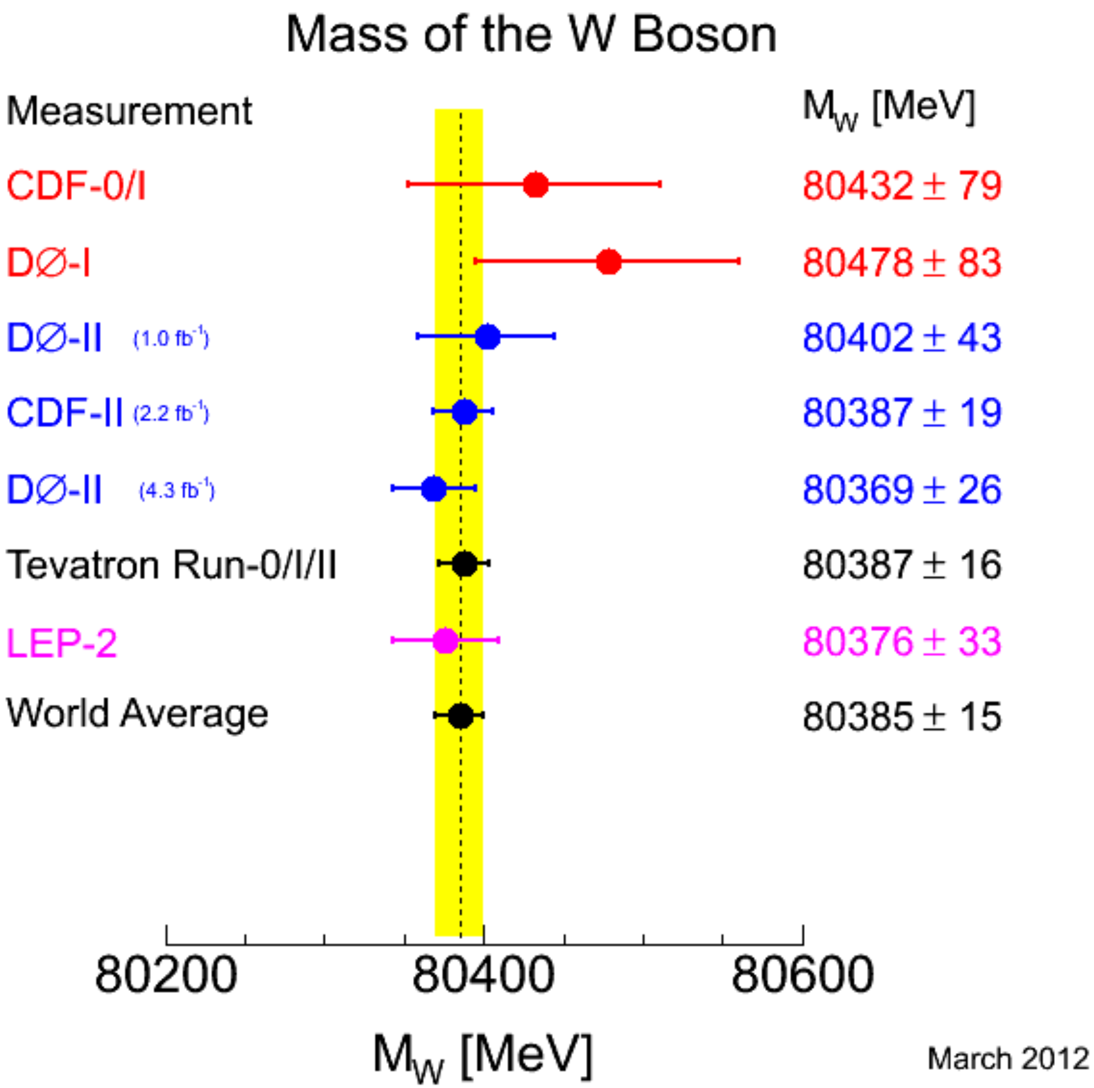
Uncertainties

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**

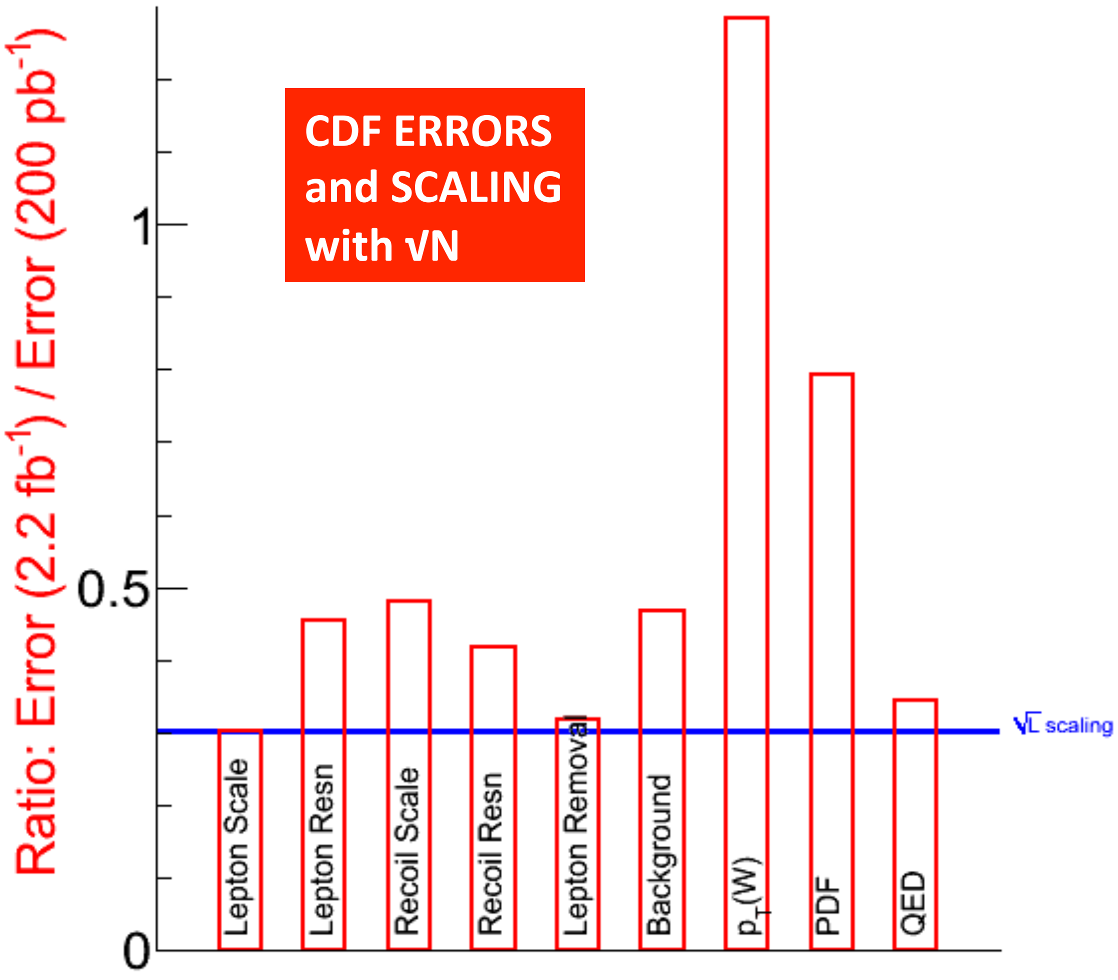
Largely theory in origin → **12 MeV**

World Average



Tevatron Run-II has halved the Mw uncertainty

Going Below 15 MeV @ Tevatron



Can expect some errors to scale with stats.

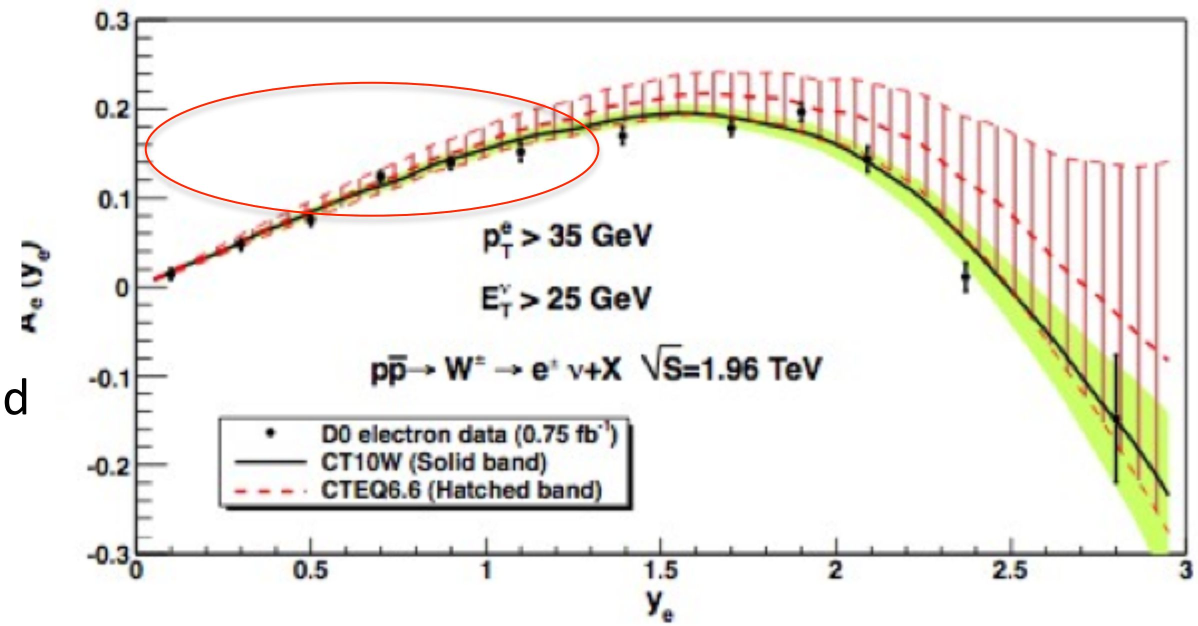
BUT

QED, PDFs, PT(W) will need more work/ideas.

Going Below 15 MeV

PDFs

- include new data in fits (e.g. SEAQUEST)
- extend rapidity range of Mw measurement
- use m_T variant with reduced PDF uncertainty



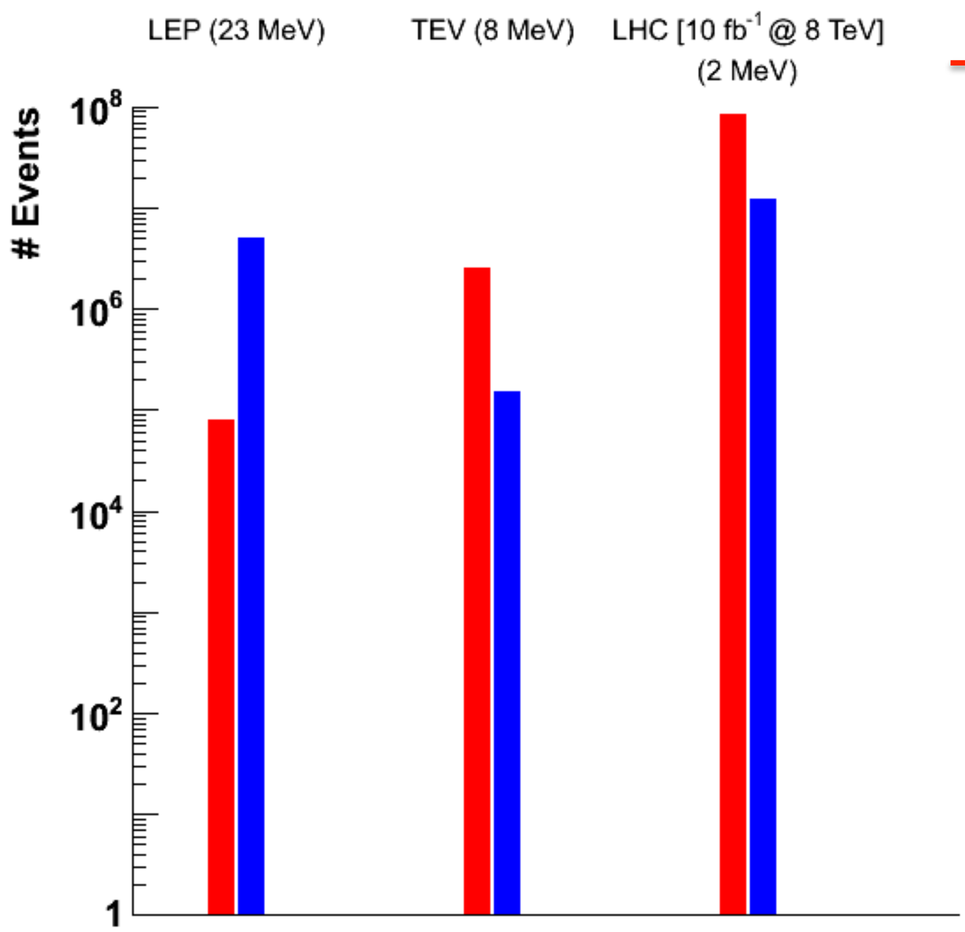
QED

- investigate new NLO QCD+QED MCs e.g. POWHEG'

LHC ….

Mw at LHC

Statistics galore but the systematic environment is far more challenging

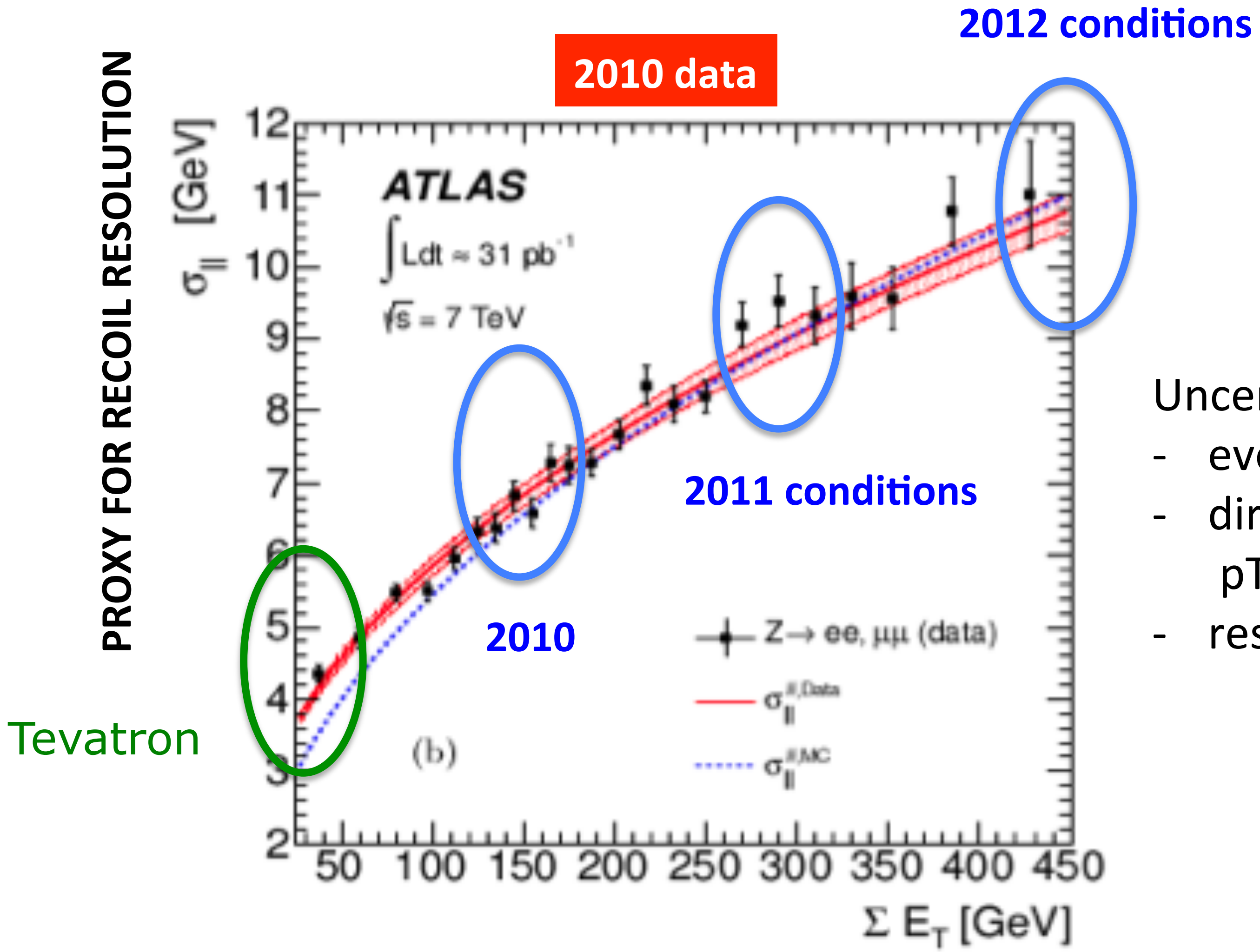


statistical uncertainties

3 key issues

- Pileup
- PDFs
- Influence of higher order (QED+QCD) corrections

PileUp



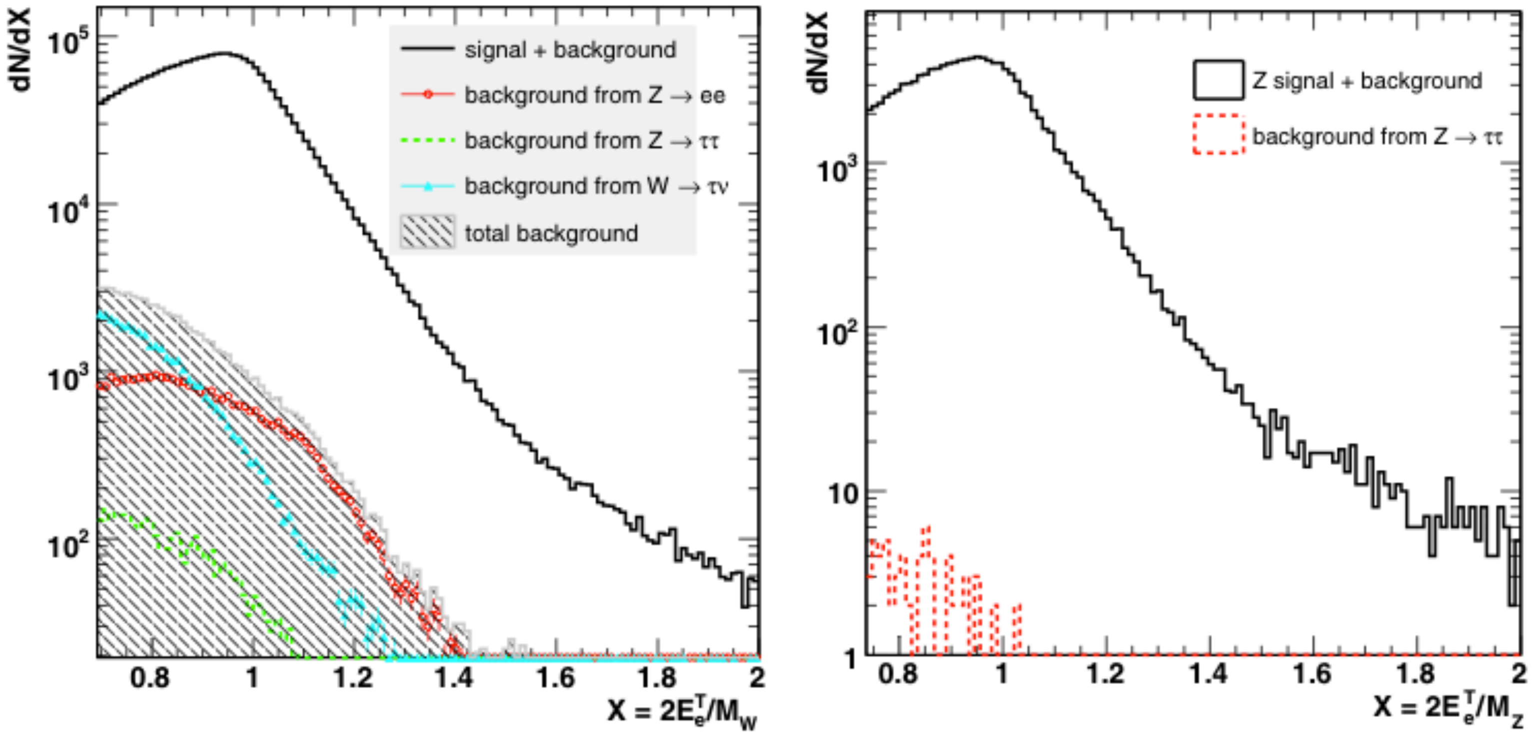
Uncertainty effects

- event selection efficiency
- direct determination of pT(W) [pT(lep) fit]
- resolution of m_T

Resolution on recoil (& hence m_T) is factor of two worse vs Tevatron
Precision modelling is much more difficult – more jets/activity.

Different Techniques

Considered since Z statistics so high (and resolution poorer).



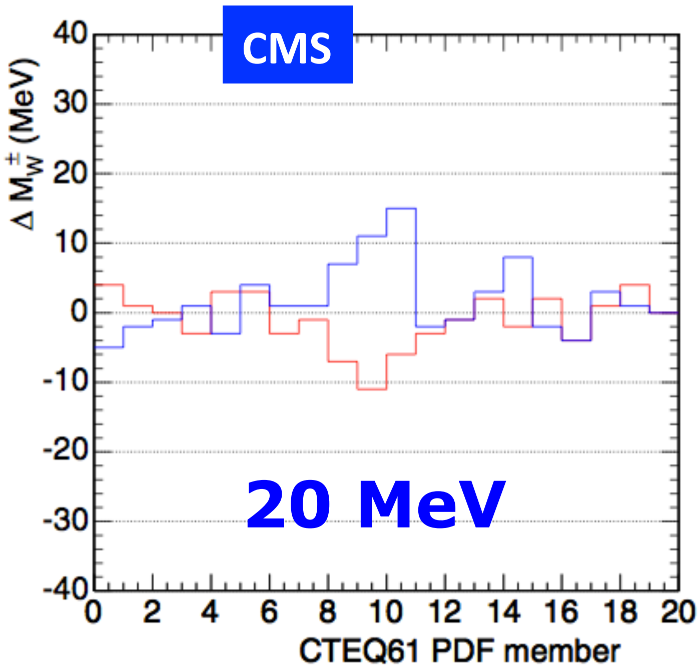
Use scaling variable: x = Obs/M_V and correct for "small" W/Z differences using MC : potentially allows precise measurement using p_T(lepton)

Much work on developing more robust QED x QCD HO understanding.

PDFs

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

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

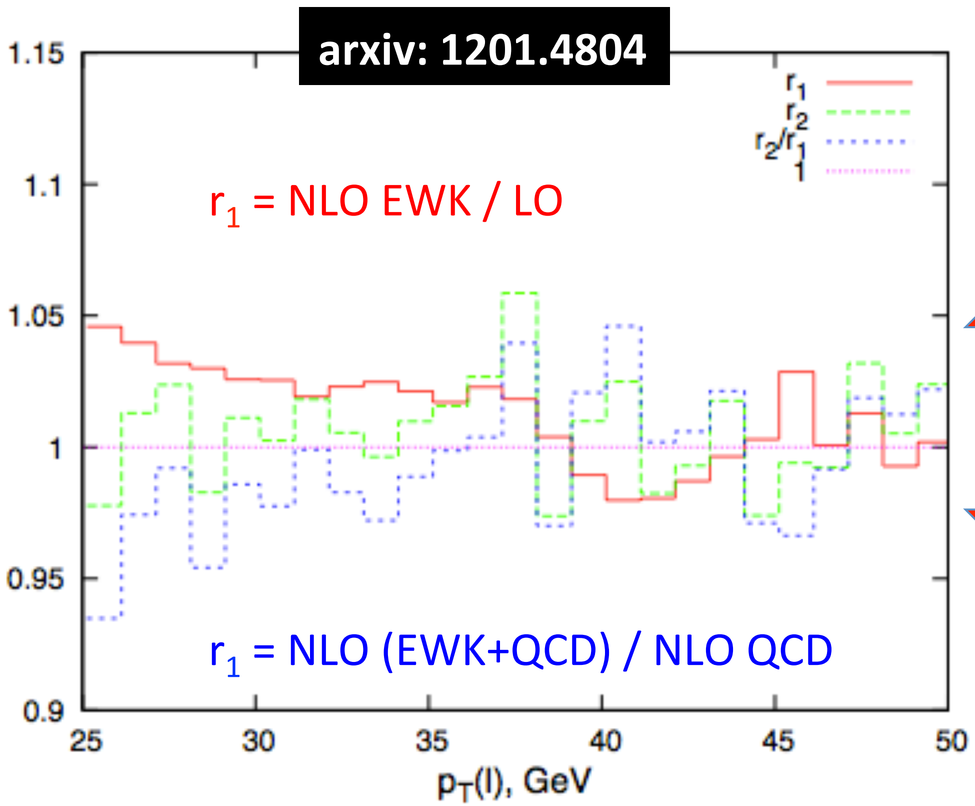


Constraints from precise measurements of Z rapidity will reduce this.

But assumptions of s vs s-bar

Reduction to: 3-10 MeV ?

Combining QCD + QED HO Corrections



Need to be careful to model experimental lepton selection

QCD + EW don't always add linearly e.g. muon p_T.

10%

Mw measurement requires 0.01%...

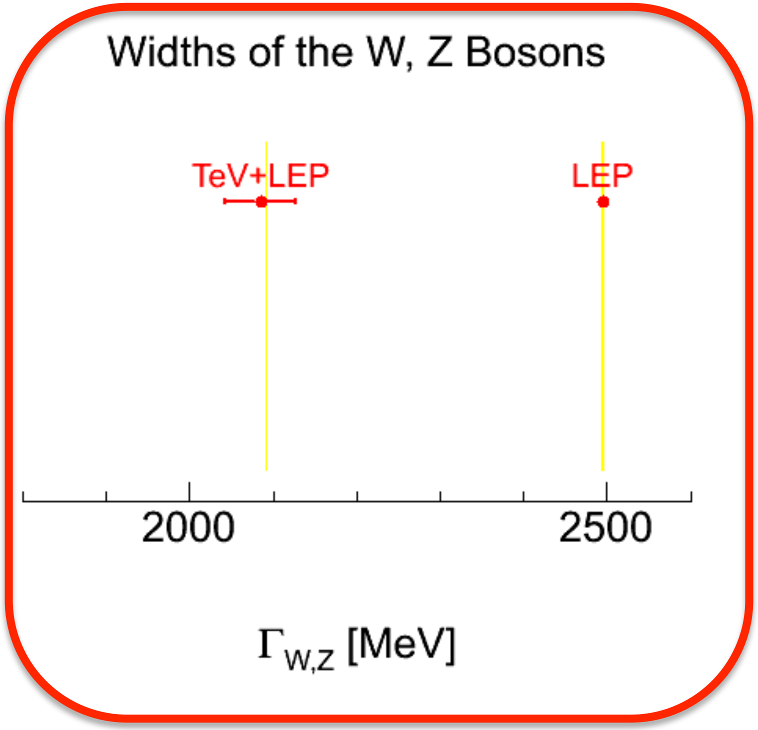
Current LHC predictions of Mw uncertainty vary from 7 – 20 MeV.
Likely will end up with similar uncertainty to 10 fb^{-1} Tevatron (i.e.~10 MeV).

W Width

Internal consistency check of SM

$$\Gamma_W = \frac{G_F M_W^3}{6\pi\sqrt{2}}(1+\delta_{RC})$$

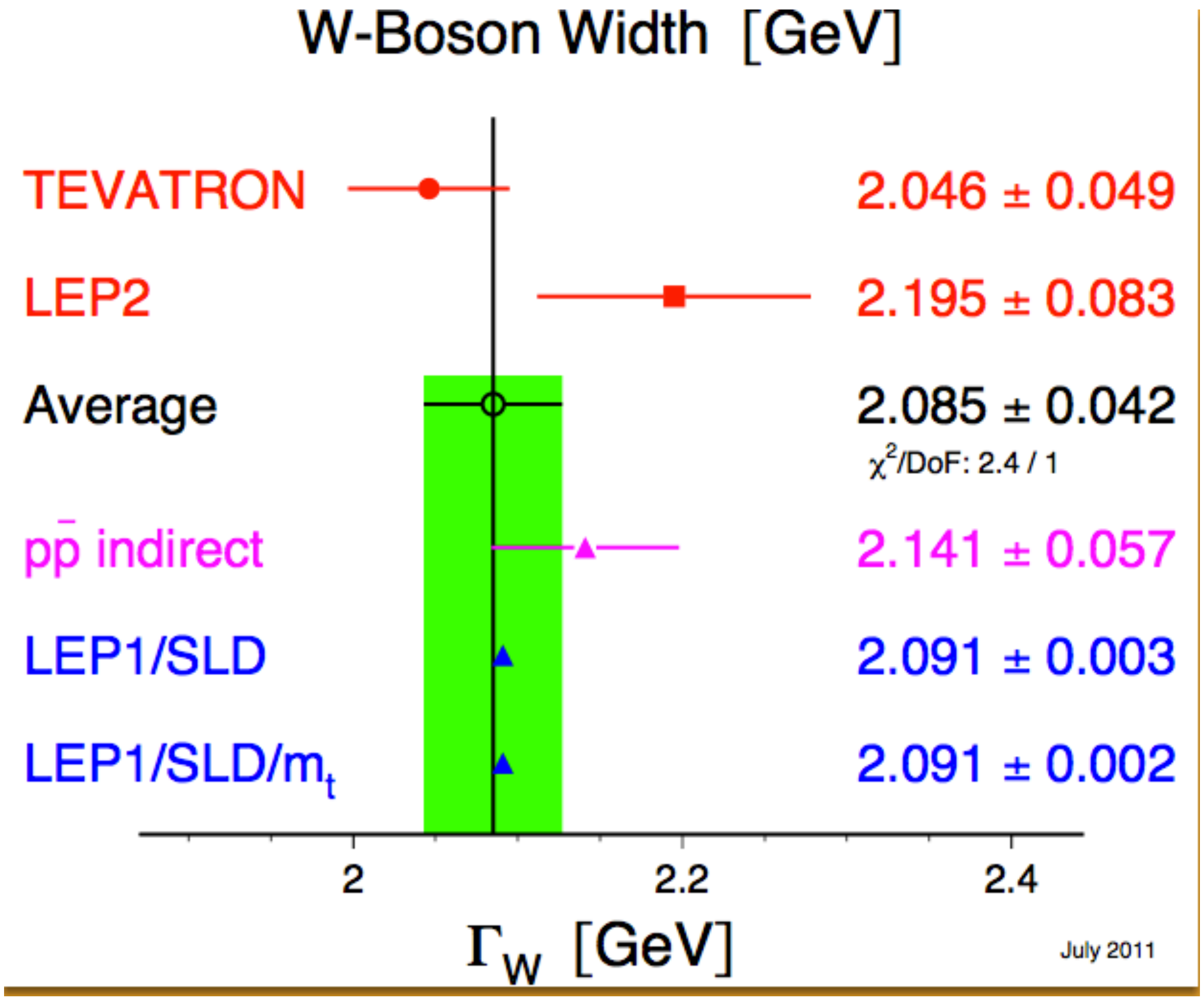
Measured Mw (has loops)



Additional sensitivity to new physics beyond Mw is tiny unless measure to O (1 MeV)

Z width uncertainty is x20 better.

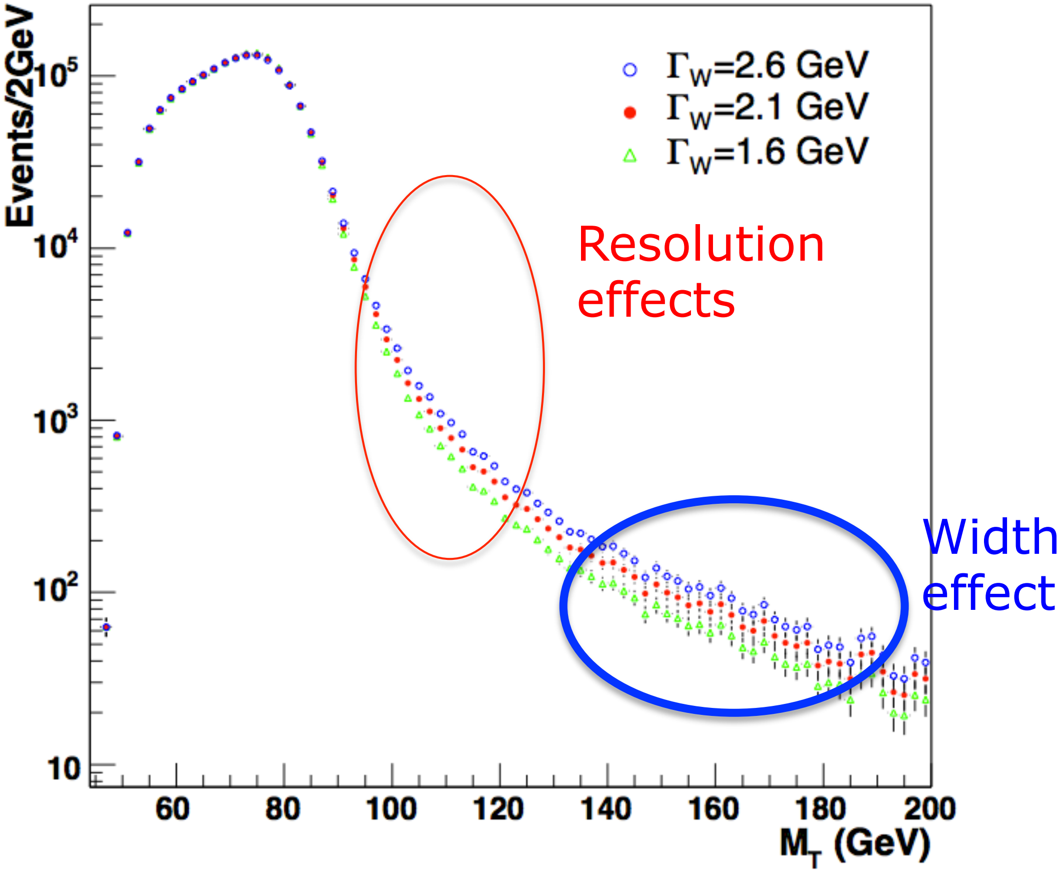
W Width



W-Boson Width [GeV]
TEVATRON
2.046 ± 0.049
LEP2
2.195 ± 0.083
Average
2.085 ± 0.042
χ²/DoF: 2.4 / 1
pp̄ indirect
2.141 ± 0.057
LEP1/SLD
2.091 ± 0.003
LEP1/SLD/m_t
2.091 ± 0.002
2
2.2
2.4
Γ_W [GeV]
July 2011

W Width

BUT relative to Mw it is a straightforward measurement ie 2 years work vs 5 years.



It is a counting experiment and the LHC has lots of statistics

Getting to O (10 MeV) (modulo box HO EWK corrections) should be far easier than getting to 10 MeV in Mw.

Conclusions

Significant recent improvements in Mw from Tevatron

almost x1000 better than SpS

$$M_W(\text{meas}) = 80385 \pm 15 \text{ MeV}$$

$$M_W(\text{SM}) = 80362 \pm 10 \text{ MeV} \quad (m_H = 125 \pm 1 \text{ GeV})$$

Like the Higgs branching ratios there is SM consistency
and **little room for BSM physics**.

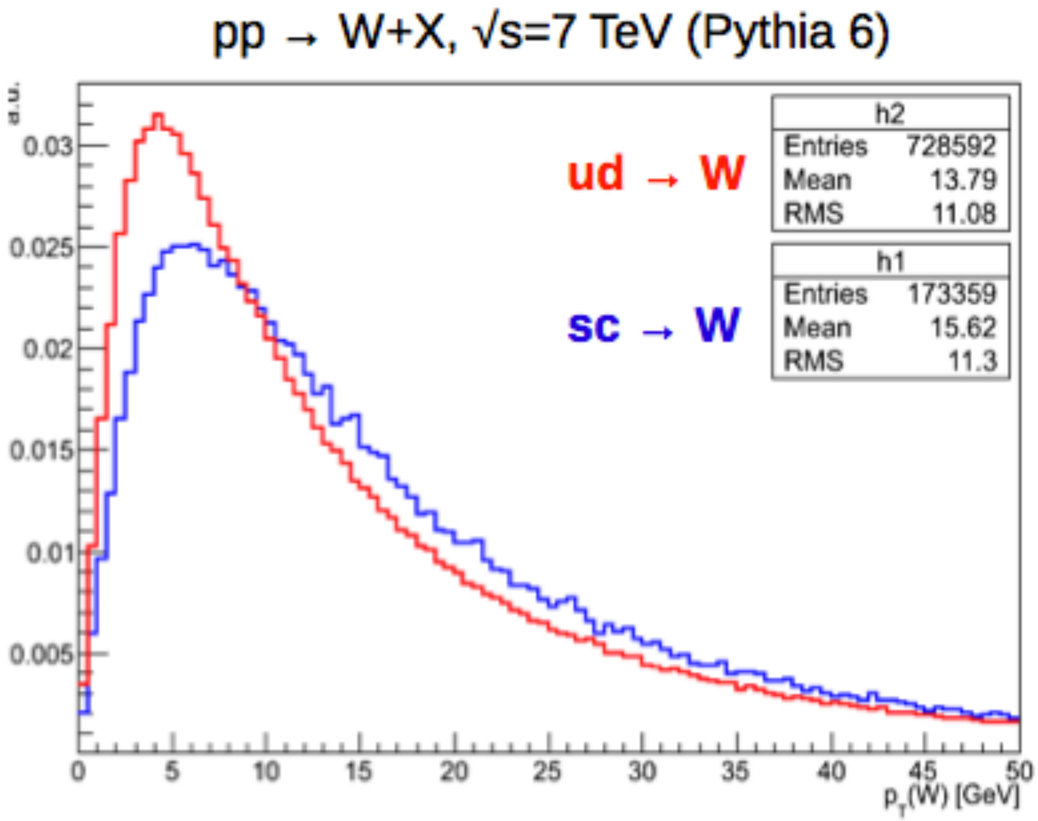
Tevatron and the LHC may both get to O(10 MeV) uncertainty in M_W

Given new physics is likely < O(10 MeV) in M_W and the SM uncertainty then further insight requires: better measurements of m_{top}, α_{EM}, α_S, M_Z and improved HO calculations …… ILC !!!

Otherwise we are close to the end of the road…..

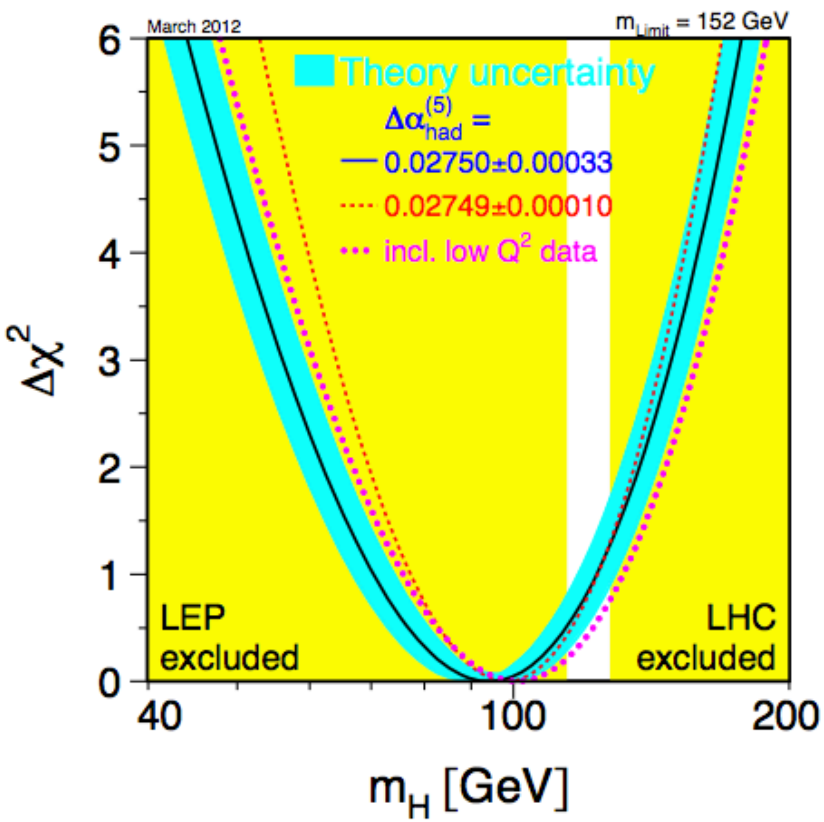
Backup

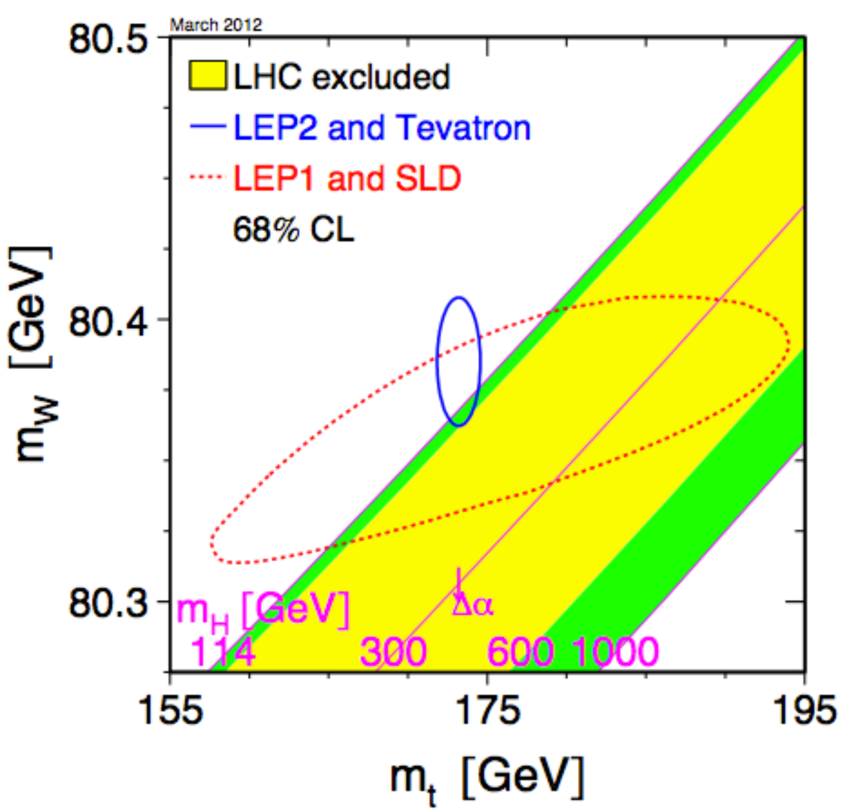
PDF : W p_T @ LHC



pp → W+X, √s=7 TeV (Pythia 6)
a.u.
ud → W
sc → W
h2
Entries 728592
Mean 13.79
RMS 11.08
h1
Entries 173359
Mean 15.62
RMS 11.3
p_T(W) [GeV]

Pre-"Higgs" Higgs Constraint





As of March 2012:

$m_H = 94^{+29}_{-24}$ GeV

$m_H < 152$ GeV @95% CL