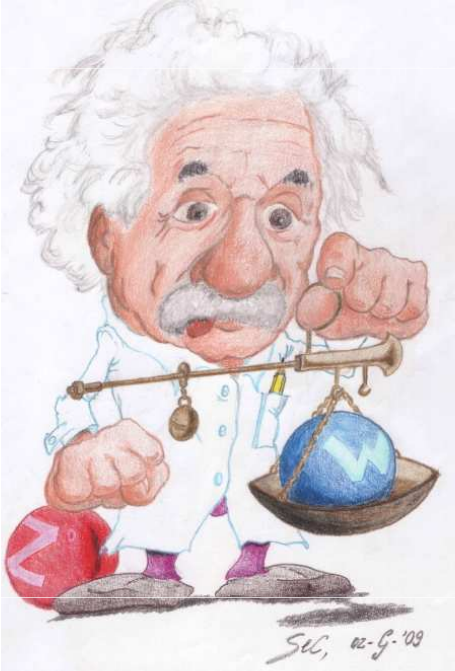
XXIIInd Rencontres de Blois

Measurement of the W boson mass at the Fermilab Tevatron



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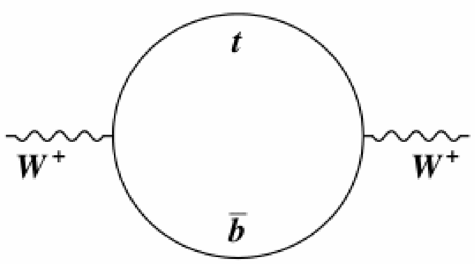
on behalf of the CDF and DØ Collaborations

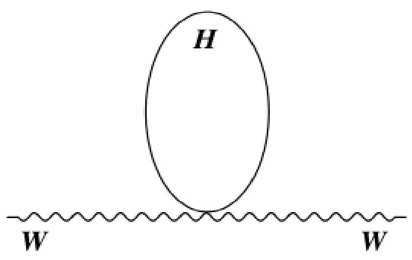
Motivation

W mass is a key parameter in the Standard Model. This model does not predict the value of the W mass, but it predicts this relation between the W mass and other experimental observables:

$$M_W = \sqrt{\frac{\pi\alpha}{\sqrt{2}G_F}} \frac{1}{\sin\theta_W \sqrt{1-\Delta r}}$$

Radiative corrections (Δr) depend on M_t as $\sim M_t^2$ and on M_H as $\sim \log M_H$. They include diagrams like these:





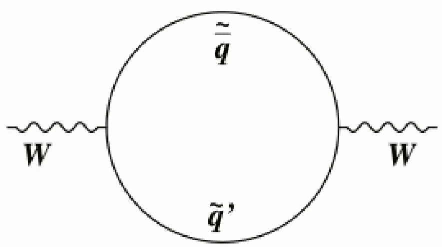
Precise measurements of M_W and M_{top} constrain SM Higgs mass.

For equal contribution to the Higgs mass uncertainty need:

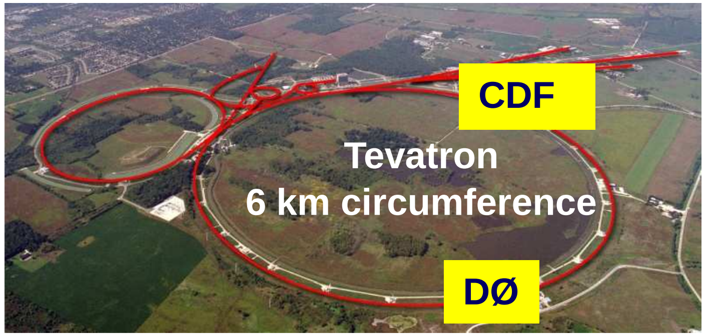
$\mathbf{\Delta M_W = 0.006\ \Delta M_{top}}$ → current Tevatron average : ΔM_{top} = 1.1 GeV

would need: ΔM_W = 7 MeV (currently have: ΔM_W = 23 MeV)

Additional contributions to Δr arise in various extensions to the Standard Model, *e.g.* in SUSY:



Tevatron



- p pbar collisions at $\sqrt{s}$ = 1.96 TeV
- up to now $\int$ Ldt >10 fb^{-1} delivered/experiment

- M_W measurement (Run IIa peak lumi ~10^{32} cm^{-2} s^{-1}):

  CDF 200 pb^{-1} **Phys. Rev. Lett. 99,151801 (2007)**

  Phys. Rev. D 77, 112001 (2008)

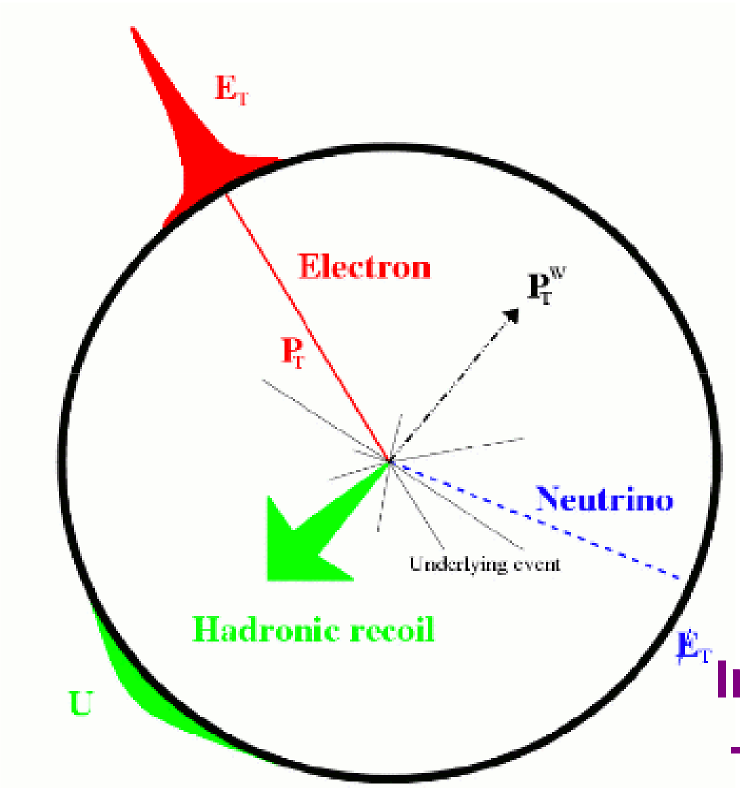
  DØ 1 fb^{-1} **Phys. Rev. Lett. 103, 141801 (2009)**

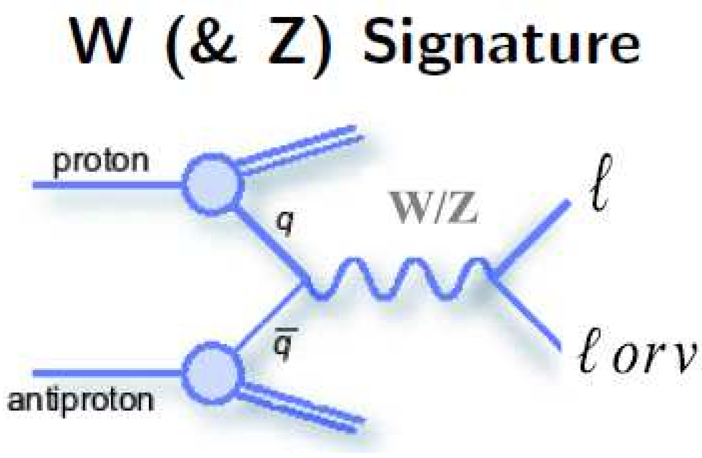
- in progress (Run IIb peak luminosity ~3 10^{32} cm^{-2} s^{-1}):

  CDF 2.4 fb^{-1}

  DØ 4.3 fb^{-1}

Signature in the detector





In a nutshell, measure two objects in the detector:

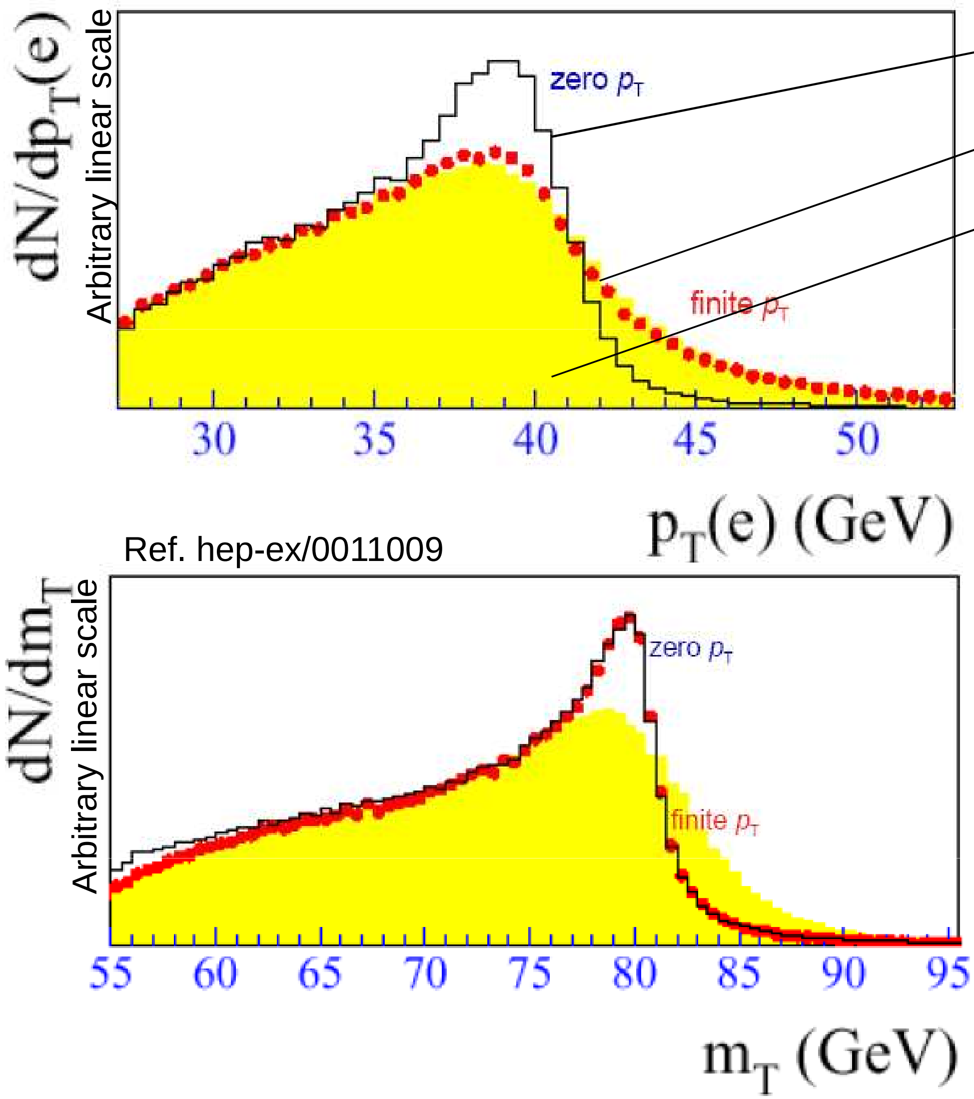
- lepton (in principle e or μ), need energy measurement with 0.2 per-mil precision

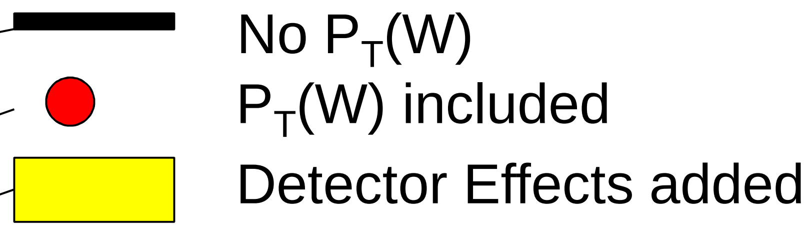
- hadronic recoil, need ~ 1% precision

Z→ee/μμ used for calibration/recoil modeling

kinematics in transverse plane

Experimental observables





$P_T(e)$ most affected by $P_T(W)$

$P_T(\nu)$ measured by $\not{E}_T$

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

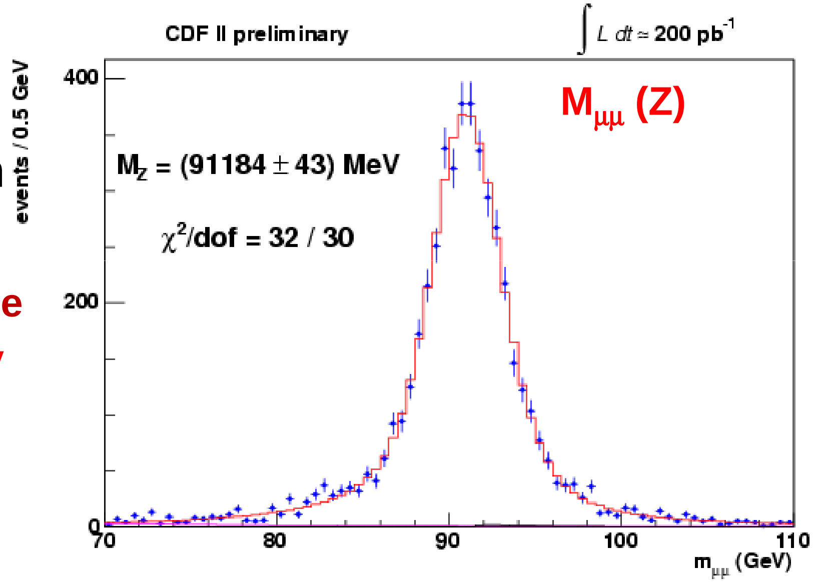
M_T most affected by measurement of missing transverse momentum

Need Monte Carlo simulation to predict shapes of these observables for given mass hypothesis. use **ResBos** [Balazs, Yuan; Phys Rev D56, 5558] + **Photos /WGRAD** for W/Z production and decay, plus **parameterised detector model**.

Momentum and Energy calibration of μ/e

Momentum scale using J/Ψ → μμ (600 K) and ϒ-> μμ data extrapolated to Z→ μμ

Tracker calibration → precise tracker simulation



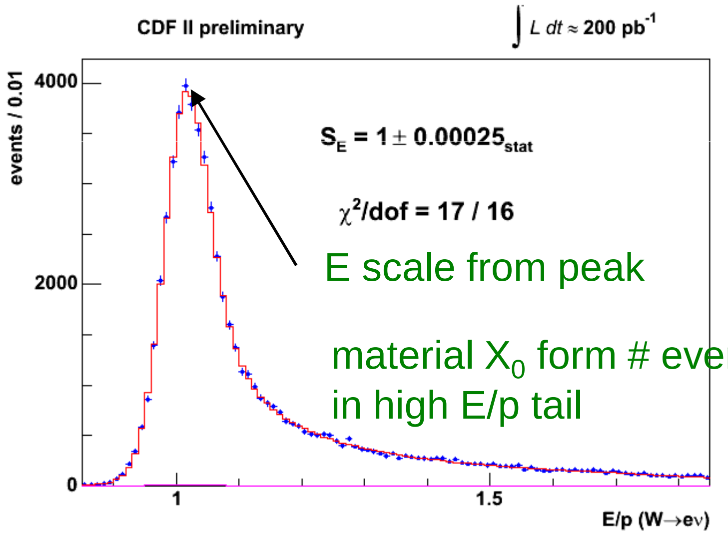
Momentum scale

ΔM_W =19 MeV

absolute M_W is measured in CDF

Material X_0 tuned to 2.5 parts in 10^4

E/p and Z_{ee} combined

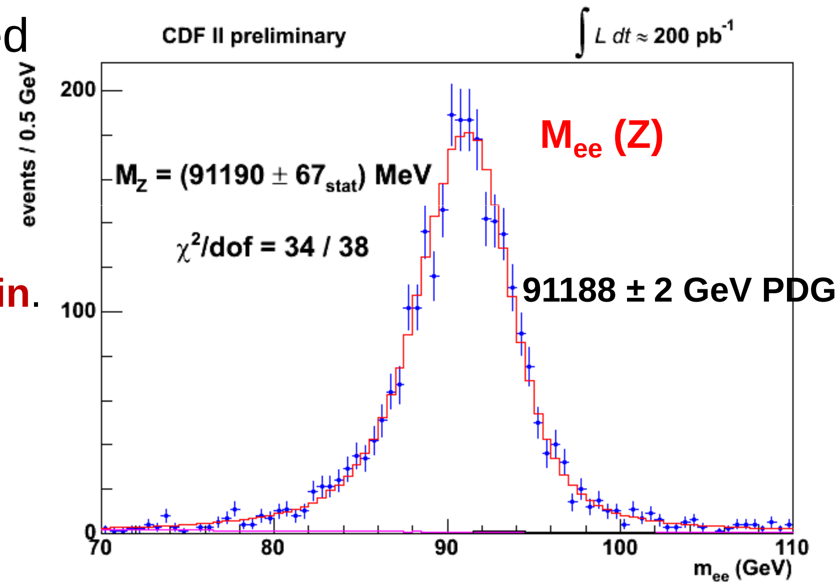


Energy scale + non-lin.

ΔM_W = 30 MeV

Resolution

ΔM_W = 9 MeV



Electrons: energy scale

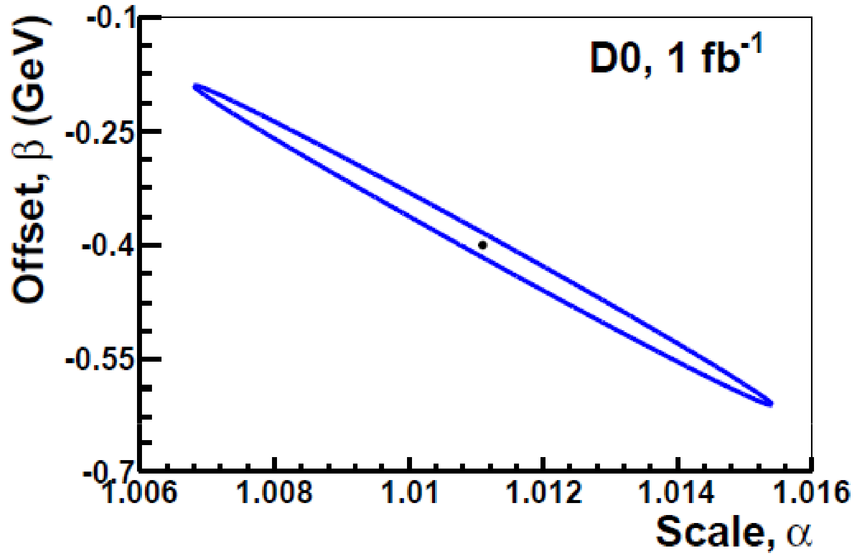
After having corrected for the effects of the uninstrumented material

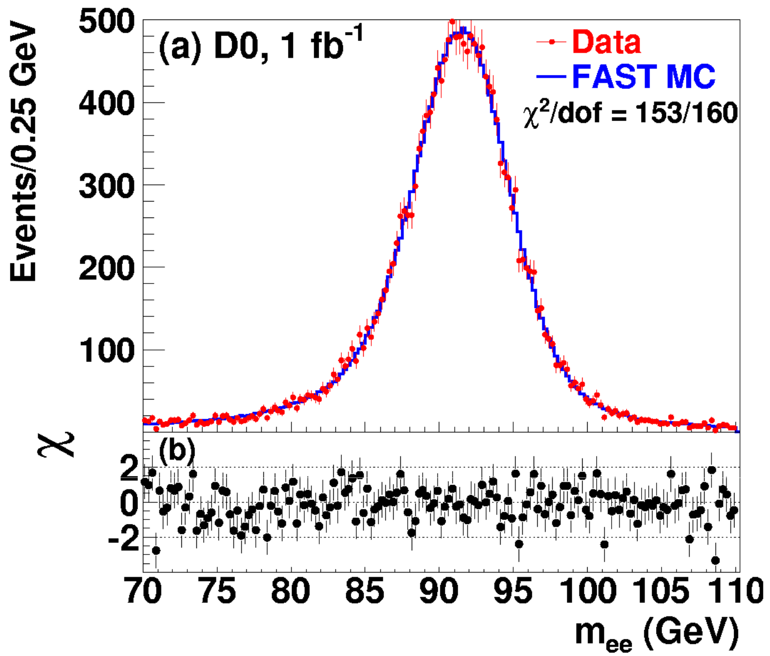
Use M_Z from LEP and energy spread of electrons in Z decay to constrain α and β.

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

M_W/M_Z is measured in DØ

m(Z) = 91.185 ± 0.033 GeV (stat)



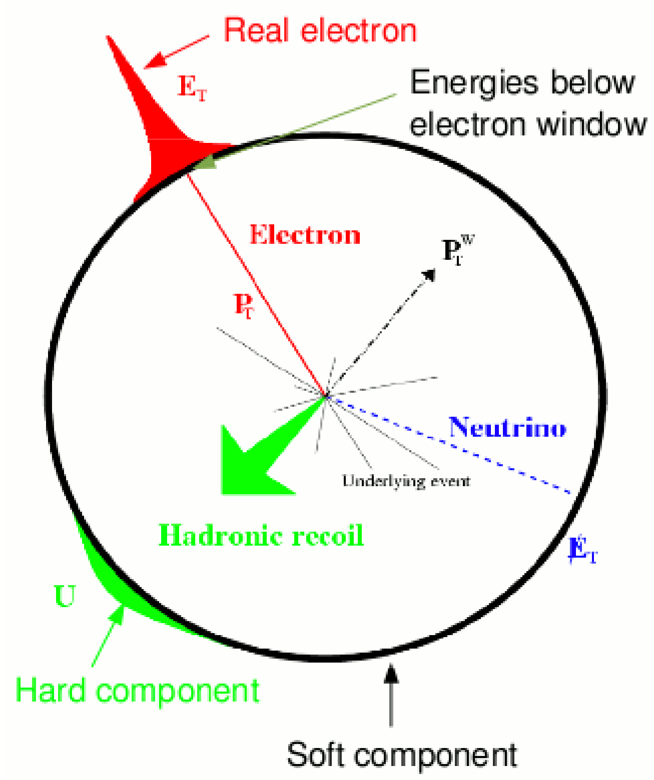


This corresponds to the dominant systematic uncertainty (by far) in the W mass measurement (but this is really just Z statistics … more data will reduce it) :

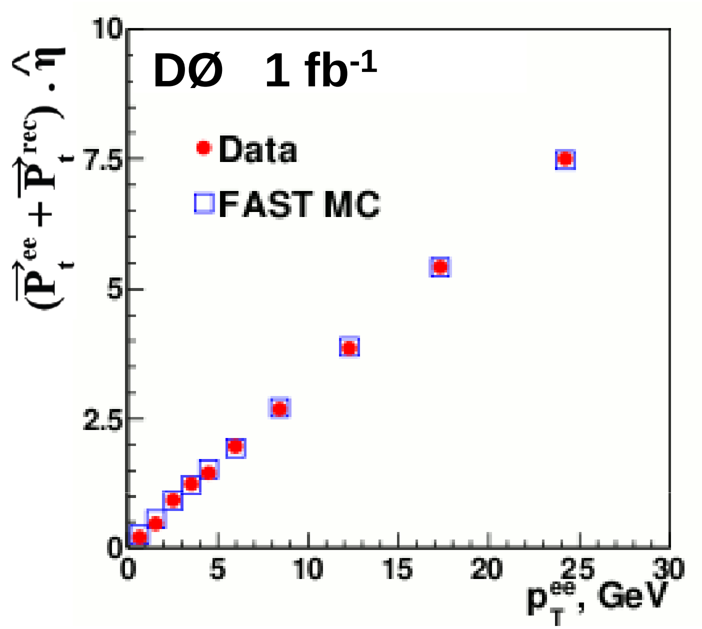
- **ΔM_W = 34 MeV, 100 % correlated between all three observables**

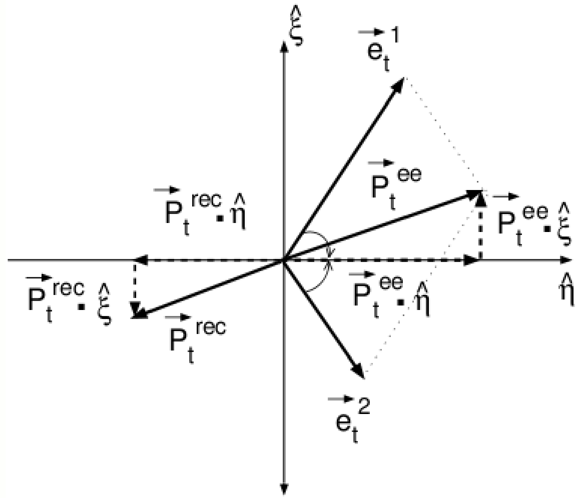
Recoil calibration

Final adjustment of free parameters in the recoil model is done *in situ* using balancing in Z → e e events and the standard UA2 observables.



UA2 observables: in transverse plane, use a coordinate system defined by the bisector of the two electron momenta.





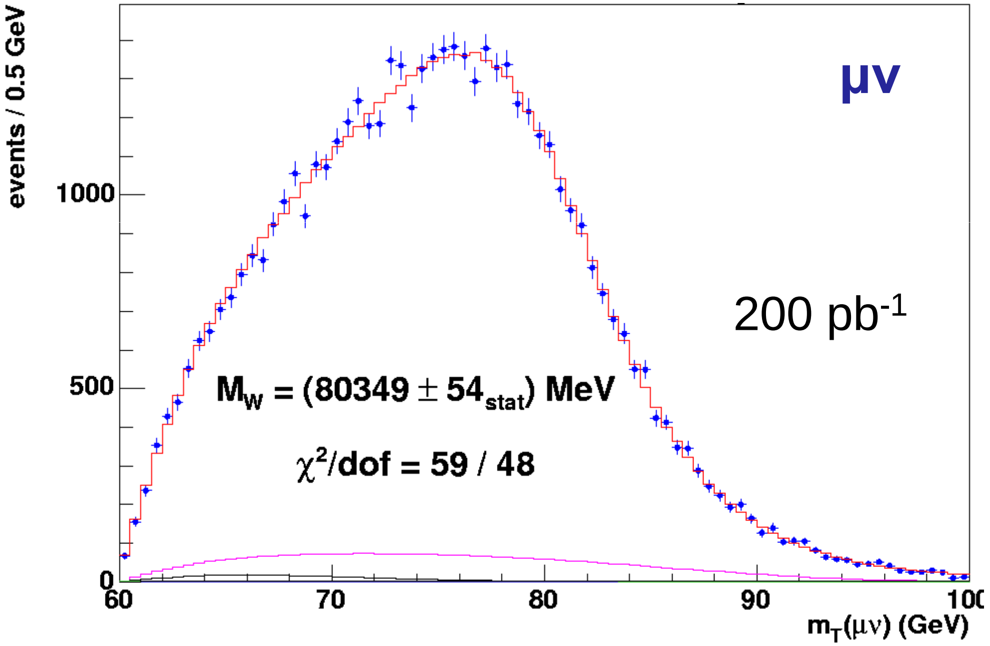
recoil: $\mathbf{u}_T = \mathbf{u}_T^{Hard} + \mathbf{u}_T^{soft} + \mathbf{u}_T^{Elec} + \mathbf{u}_T^{FSR}$

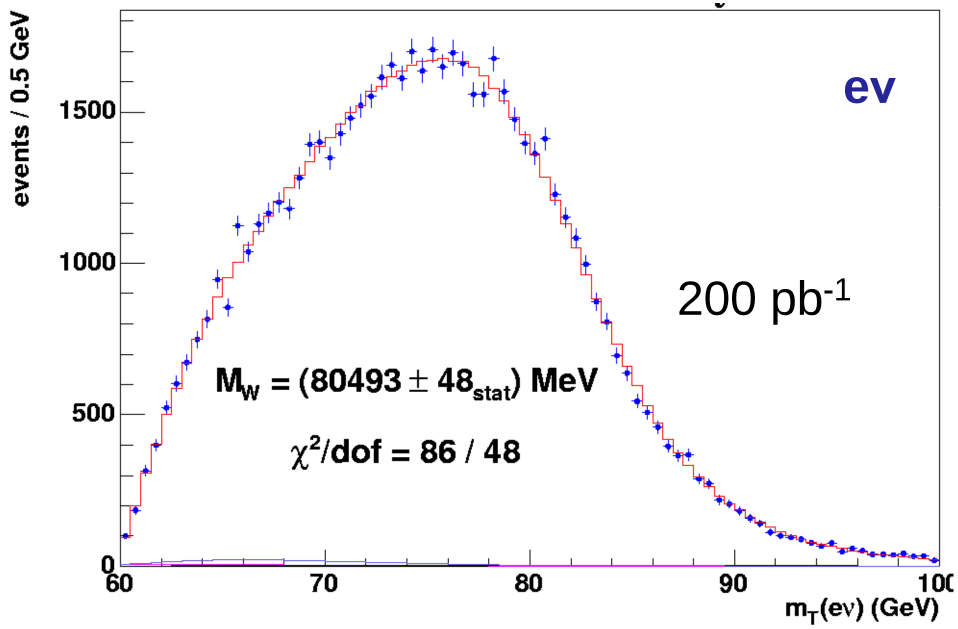
η-imbalance : $(\vec{P}_t^{ee} + \vec{P}_t^{rec}) \cdot \hat{\eta}$

ξ-imbalance : $(\vec{P}_t^{ee} + \vec{P}_t^{rec}) \cdot \hat{\xi}$

Mass Fits

Transverse mass fits $P(\chi^2) = 7\%$



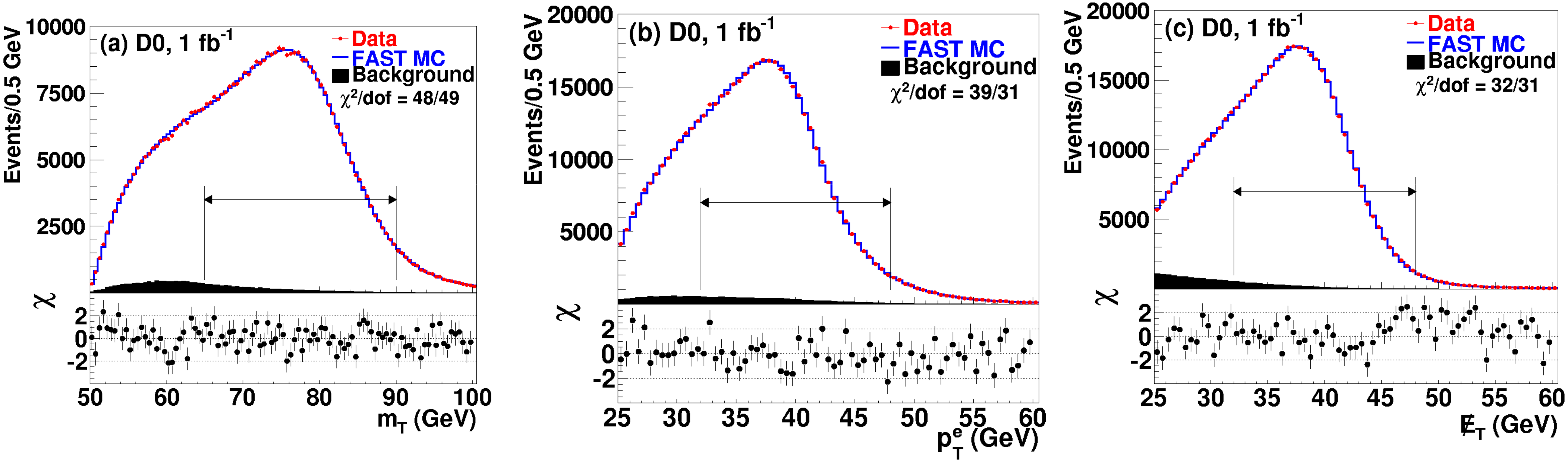


CDF combined results ($m_T(e,\mu)$, $p_T(e,\mu)$, $p_{T\nu}(e,\mu)$)

$$m_W = 80413 \pm 34_{stat} \pm 34_{syst} \text{ MeV}$$
$$= 80413 \pm 48 \text{ MeV}$$

Combination of all six fits yields $P(\chi^2) = 44\%$

Mass Fits



m(W) = 80.401 ± 0.023 GeV (stat) **m(W) = 80.400 ± 0.027 GeV (stat)** **m(W) = 80.402 ± 0.023 GeV (stat)**

DØ RunII 1fb^{-1}

80.401 ± 0.021(stat.) ± 0.038(syst.) GeV

80.401 ± 0.043 GeV

this new result is the

single most precise measurement

of the W boson mass to date

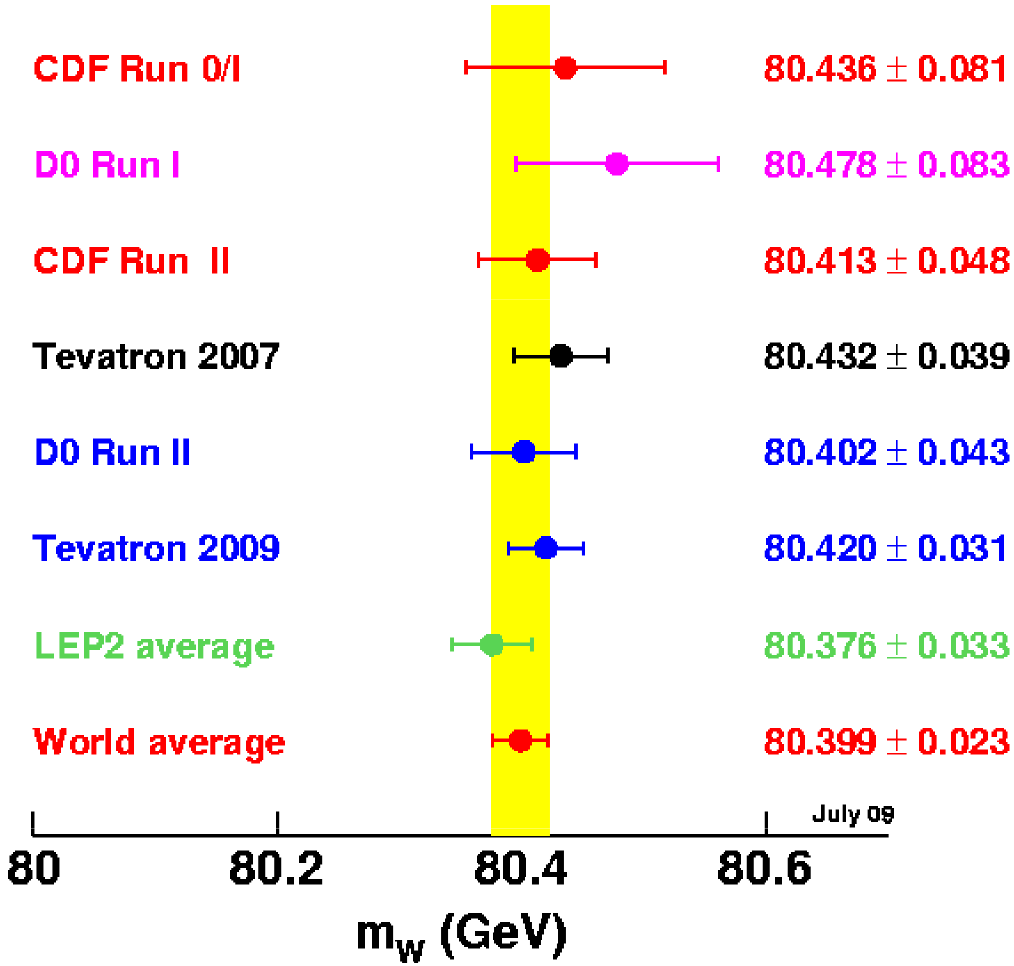
Run IIa 1 fb $^{-1}$

Summary of uncertainties

systematic uncertainties

Source	$\sigma(m_W)$ MeV m_T	$\sigma(m_W)$ MeV p_T^e	$\sigma(m_W)$ MeV $\not{E}_T$
Experimental			
Electron Energy Scale	34	34	34
Electron Energy Resolution Model	2	2	3
Electron Energy Nonlinearity	4	6	7
W and Z Electron energy loss differences (material)	4	4	4
Recoil Model	6	12	20
Electron Efficiencies	5	6	5
Backgrounds	2	5	4
Experimental Total	35	37	41
W production and decay model			
PDF	9	11	14
QED	7	7	9
Boson p_T	2	5	2
W model Total	12	14	17
Total	37	40	44
statistical	23	27	23
total	44	48	50

World average



For the first time the total uncertainty of 31 MeV from Tevatron is smaller than that of 33 MeV from LEPII

World average is now: 80.399 ± 0.023 GeV

Ref: Tevatron ElectroWeak Working Group : arXiv:0908.1374 v1 [hep-ex]
: Combination performed with B.L.U.E. method
L. Lyons et al, Nucl. Instrum. Methods in Phys. Res. A **500**, 391 (2003).
A. Valassi, Nucl.Instrum. Methods in Phys. Res. A **500**, 391 (2003).

Higgs mass constraints

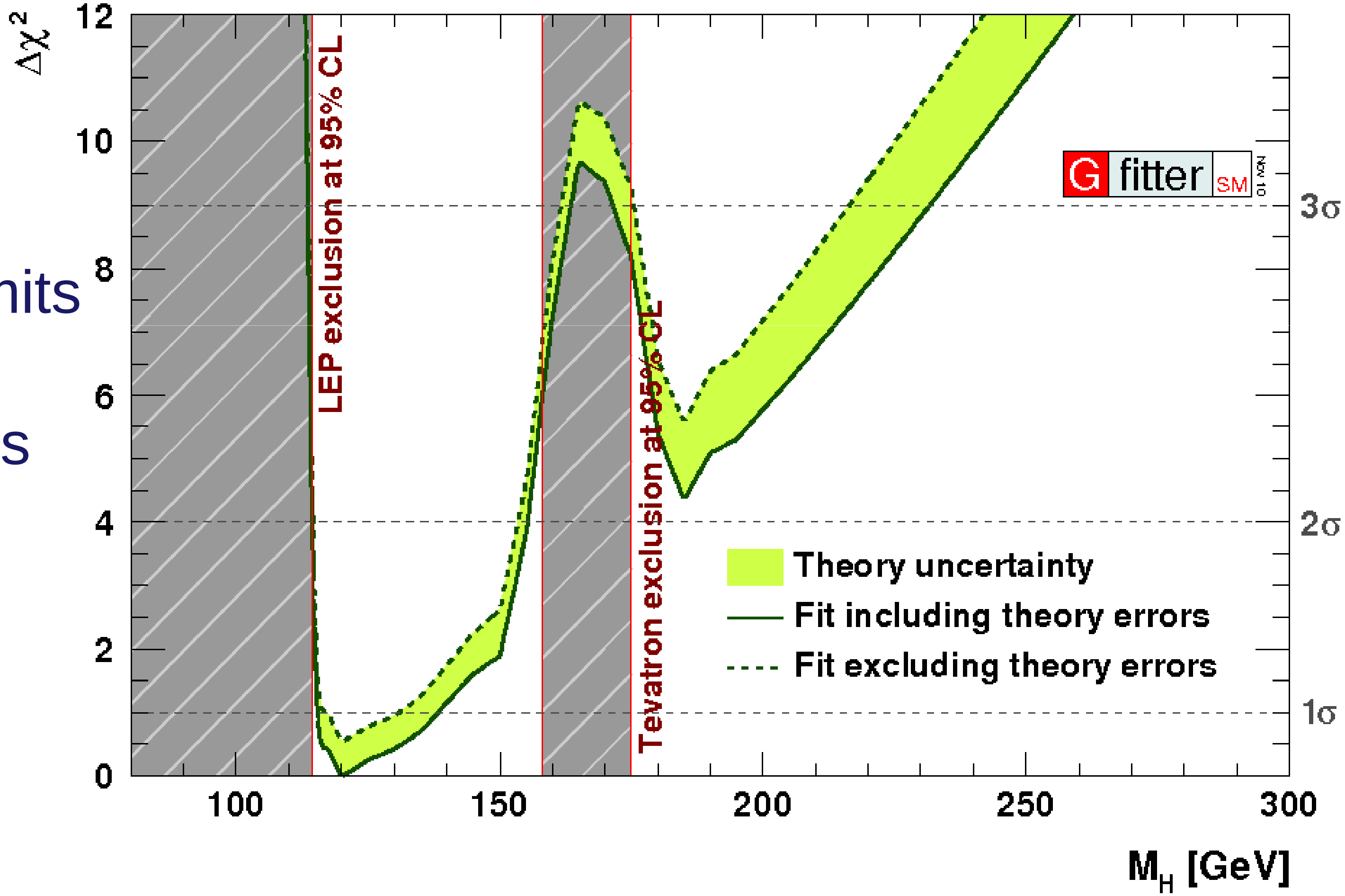
M_{top} = 173.3 ± 1.3 GeV
M_W = 80.399 ± 0.023 GeV

without LEP/Tevatron limits

MH = 84 $^{+30}_{-23}$ GeV

with LEP/Tevatron limits

MH = 120 $^{+17}_{-6}$ GeV



The 95% upper limits are 159 GeV withoutTevatron limits and 155 GeV with Tevatron limits

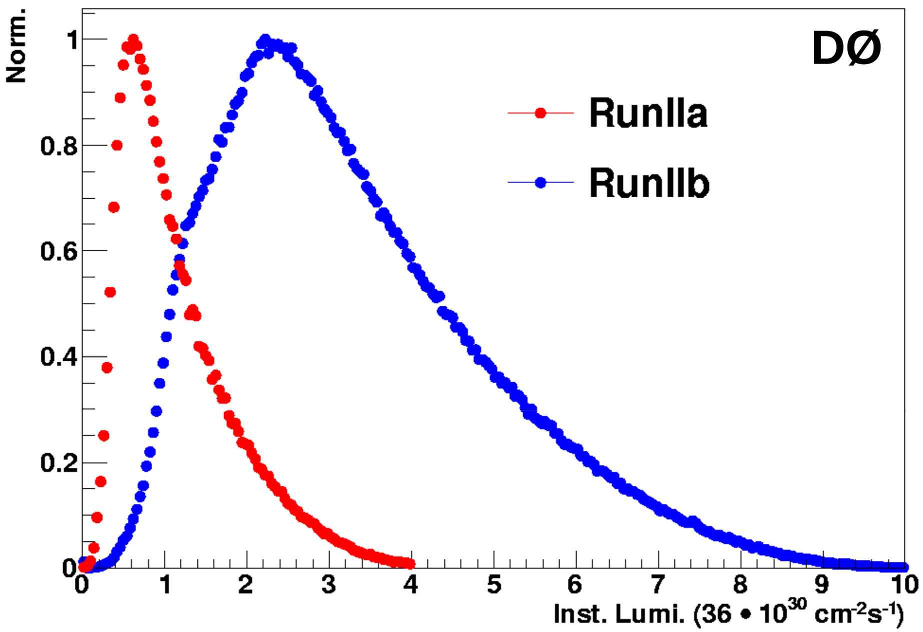
Gfitter group
arXi : 1012.1331v1 [hep-ph]
http://gfitter.desy.de/GSM

in a near future ΔM_{top} = 1 GeV and ΔM_W = 0.015 GeV

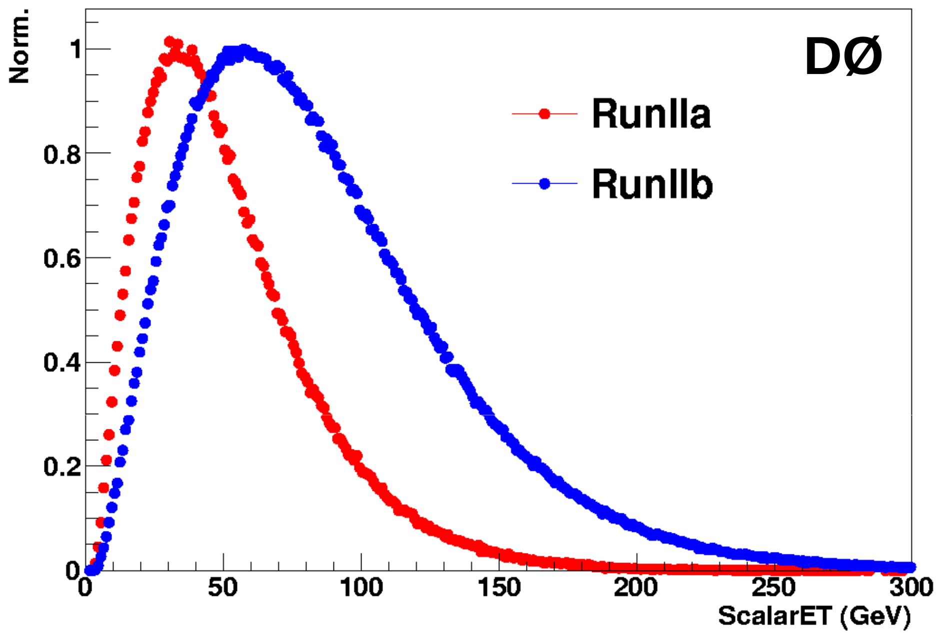
Challenges in Run IIb

Run IIb instantaneous luminosity results in much higher energy flow from additional collisions which complicates the modeling of detector effects

The impact of these additional collisions necessitates changes in all parts of the parametrized detector models both for CDF and DØ

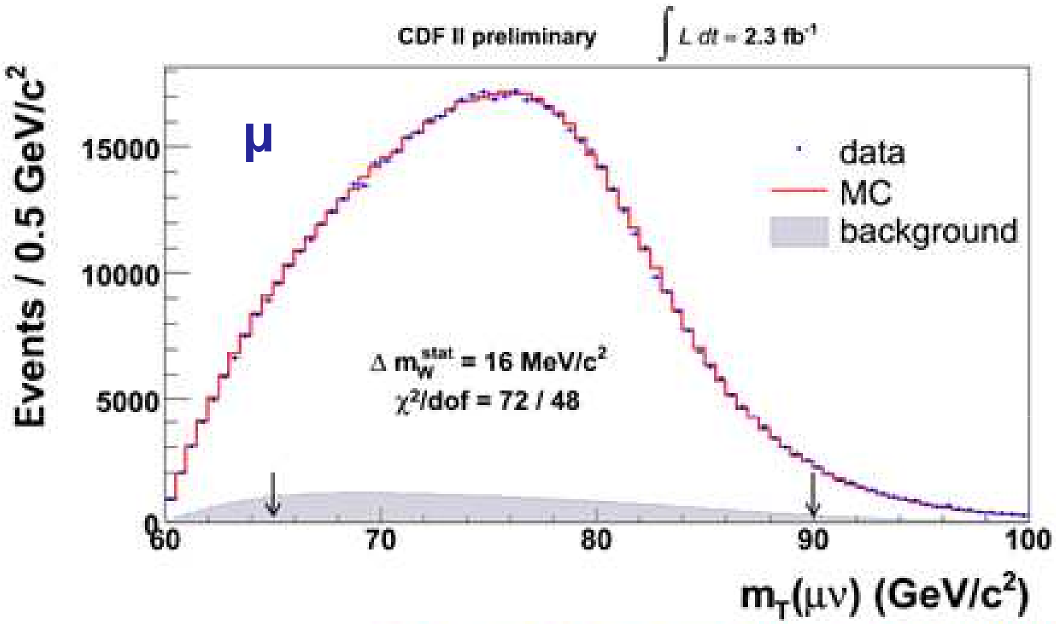


Inst. luminosity



Scalar Et : sum of the total transverse energy deposited in the DØ calorimeter (electron energy removed)

W→μν transverse mass distribution

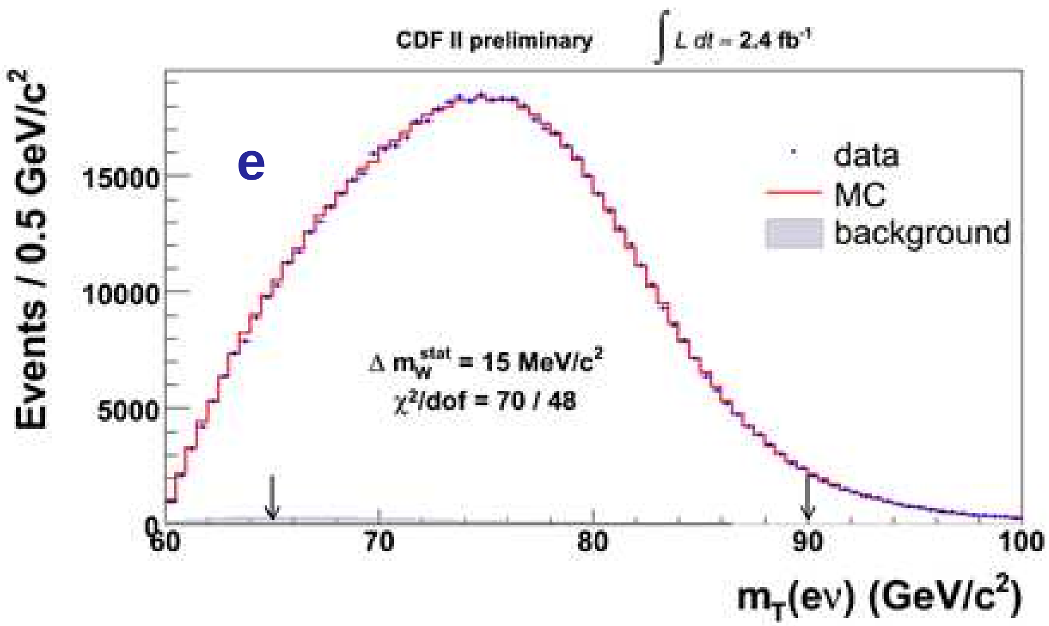


from 54 MeV to 16 meV (stat)

	Δm_W^{stat}
published (200pb^{-1})	54 MeV/c^2
expected (2.3fb^{-1})	16 MeV/c^2
fit (2.3fb^{-1})	16 MeV/c^2

fit with 2.3 fb^{-1}

W→eν transverse mass distribution



from 48 MeV to 15 meV (stat)

	Δm_W^{stat}
published (200pb^{-1})	48 MeV/c^2
expected (2.4fb^{-1})	14 MeV/c^2
fit (2.4fb^{-1})	15 MeV/c^2

fit with 2.4 fb^{-1}

DØ 4.3 fb^{-1}

55K Z→ee

1.7 M W→eν

Statistical error : 13 MeV

Electron energy scale : 15 MeV

Total error about: 25 MeV

PDF uncertainty: ~15 MeV (new estimation with RESBOS)

- close contacts with theorists :different event generators (PYTHIA, RESBOS, POWHEG) are studied
- Found including EC electrons can reduce the PDF uncertainties by half
- Including Tevatron RunII W asymmetry results in PDF constraints (CT10W set), can reduce the PDF uncertainties by ~ 20%

Work in progress

Summary

- M_W world average is **80.399 ± 0.023 GeV** **(80.420 ± 0.031 GeV from Tevatron)**

- **CDF** analysis in progress with 2.4 (μν)/2.3 (νe) fb^{-1}

- **DØ** expected Run IIb (4.3 fb-1) accuracy: ~25 MeV:
  Stat. ~13 MeV + Syst. ~22 MeV
- + Run IIa 1 fb-1, **Total Run II (5.3fb-1): ~22MeV**

- difficulties resulting from a larger instantaneous luminosity in the RunIIb make the analysis **very** challenging.

- on the road of 15 MeV uncertainty (CDF and DØ combined)
- with more statistics (10 fb^{-1} in the can already !) ⇨ 10 MeV ??

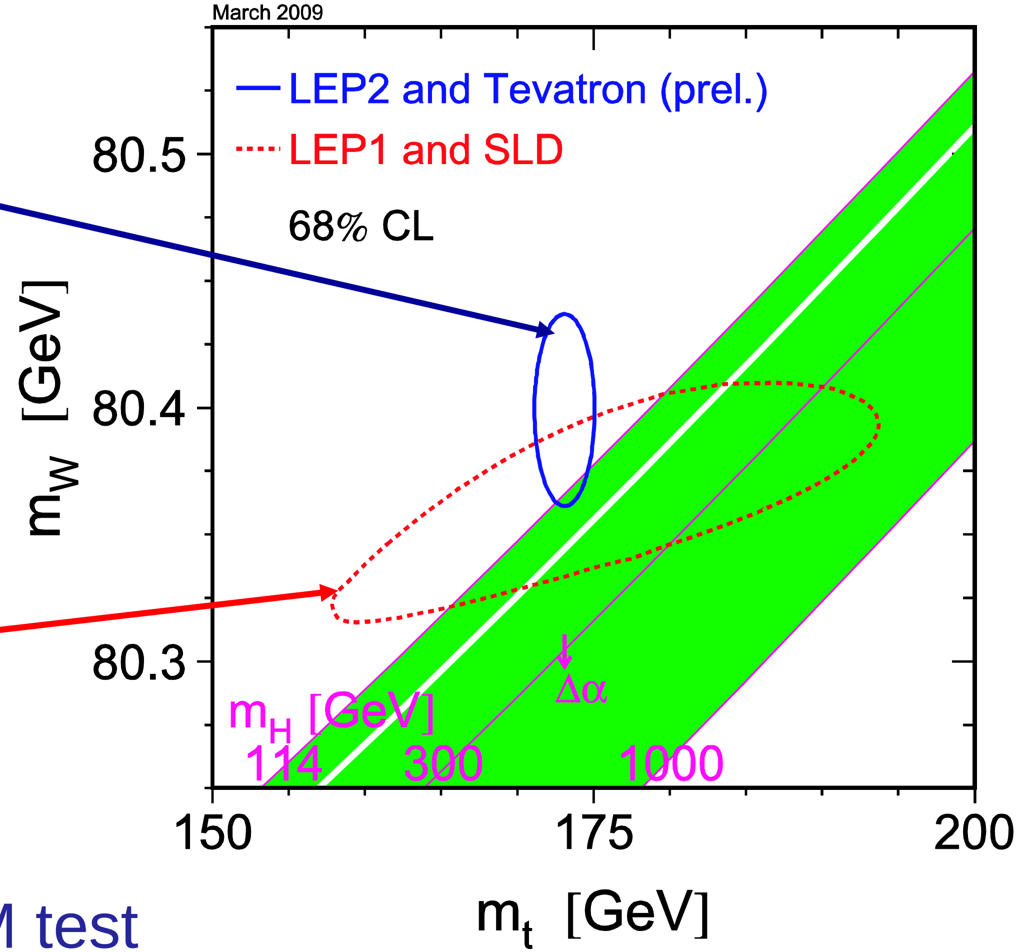
-- but theoretical errors (PDF) have to be reduced !

Backup Slides

Consistency

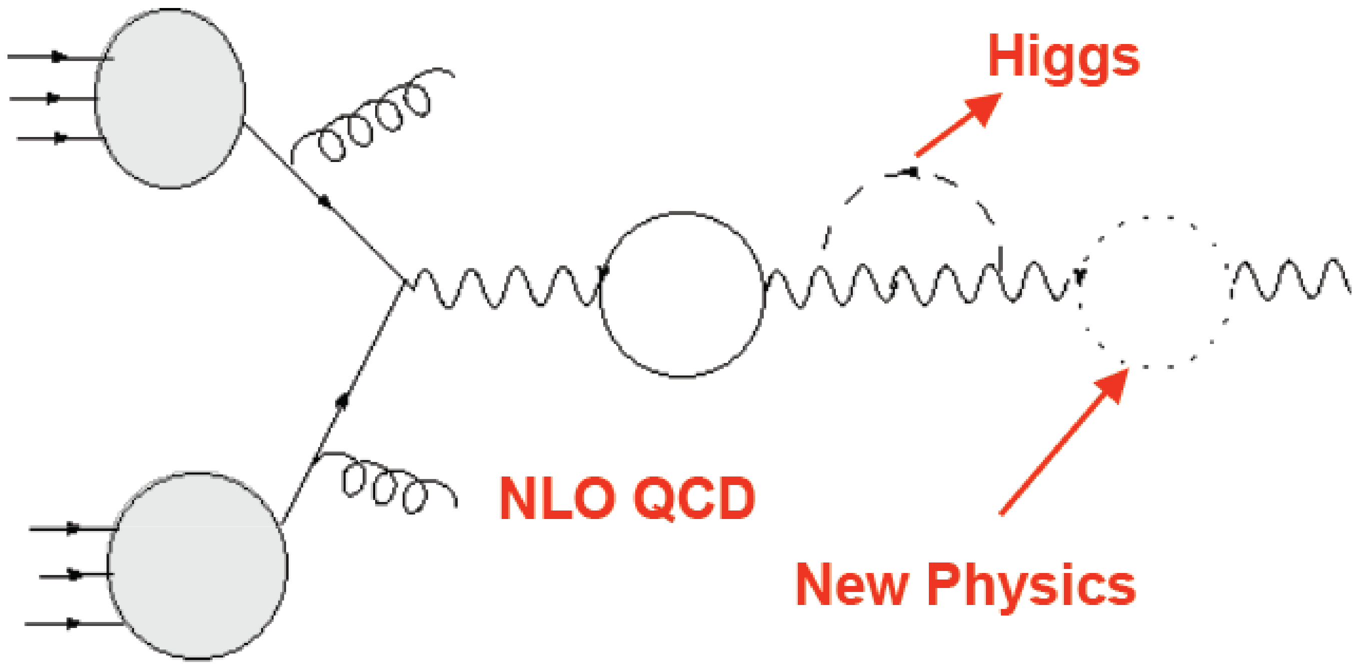
Direct measurement :
LEP and Tevatron

Indirect measurement :
Z-Pole measurements:
constrain EW radiative corrections
allow to predict M_W and M_{top}
within SM

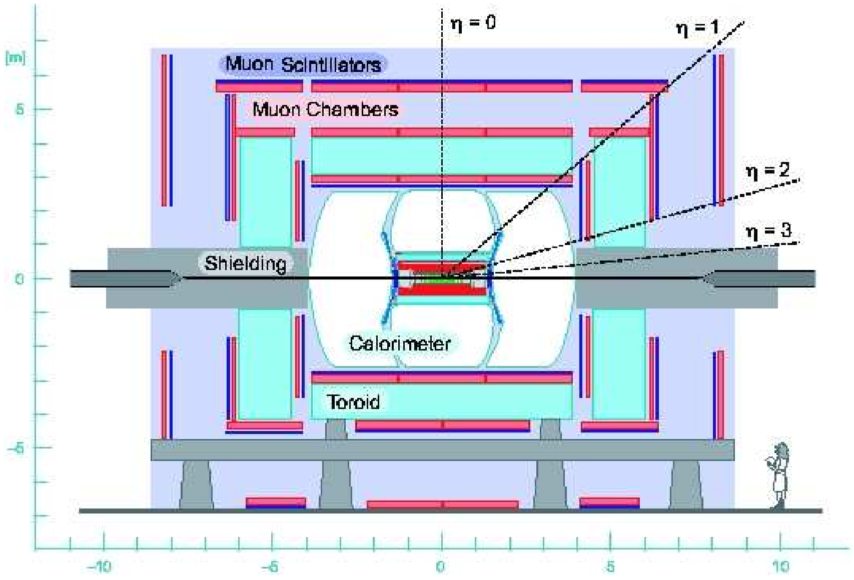


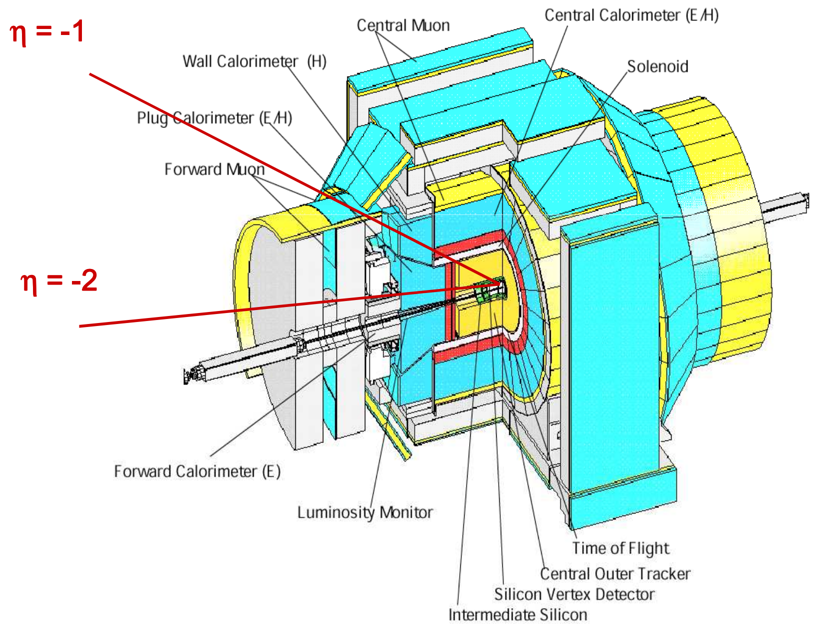
Good agreement: Successful SM test
Both data prefer light Higgs boson

Motivation



Detectors





DZero Run II upgrades
- 2T solenoid
- inner tracking
- Preshower
- extended μ coverage and shielding
- Trigger, DAQ

recorded 10 fb^{-1}
data taking efficiency ~ 85%

CDF Run II upgrades
- 1.7 T solenoid
- Inner tracking
- Forward calorimeter
- extended μ coverage
- Trigger, DAQ

Electrons: energy scale

After having corrected for the effects of the uninstrumented material:
final energy response calibration, using Z →e e, the known Z mass value from LEP, and the standard "f_z method":

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

Use energy spread of electrons in Z decay to constrain α and β.

In a nutshell: the f_Z observable allows you to split your sample of electrons from Z → e e into subsamples of different true energy; this way you can *"scan" the electron energy response as a function of energy*.

$$M_Z\,(\text{measured}) = \alpha \,.\, M_Z(\text{true}) + f_Z \,.\, \beta + X \,.\, \beta^2 + \ldots \quad \text{If } \beta \ll E(e1)+E(e2)$$

with $f_Z = (E(e1)+E(e2))(1-\cos(\gamma_{ee}))/M_Z$

γ_{ee} is the opening angle between the two electrons

M_Z(measured) vs. f_Z templates generated for range of α and β values

Result:
$\alpha = 1.0111 \pm 0.0043$
$\beta = -0.404 \pm 0.209$ GeV
correlation: -0.997

This corresponds to the dominant systematic uncertainty (by far) in the W mass measurement (but this is really just Z statistics ... more data will reduce it) :

$\Delta m(W)$ = 34 MeV, 100 % correlated between all three observables

Electrons: energy resolution

Electron energy resolution is driven by two components:
sampling fluctuations and constant term

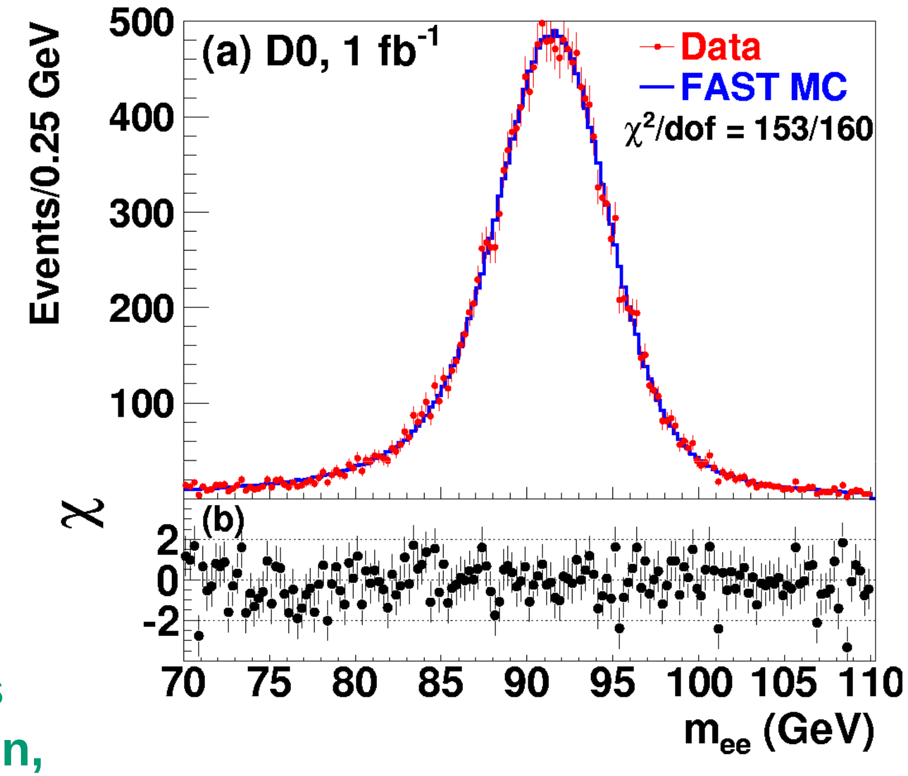
Sampling fluctuations are driven by sampling fraction of CAL modules (well known from simulation and testbeam) and by uninstrumented material.
Amount of material has been quantified with good precision (thanks to Z -> ee decay !).

Constant term is extracted from Z -> e e data (essentially fit to observed width of Z peak).

Result:

$C = (2.05 \oplus 0.10)$ %

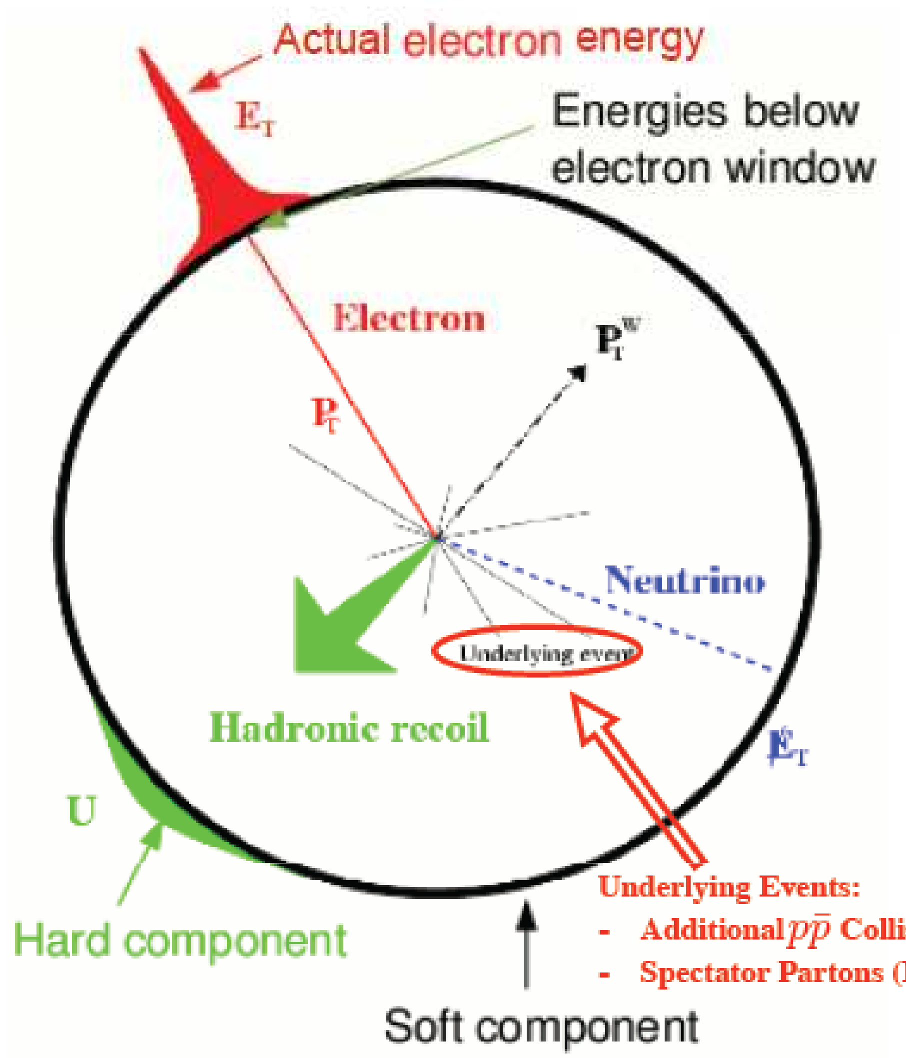
in excellent agreement with Run II design goal (2%)



m(Z) = 91.185 ± 0.033 GeV (stat)

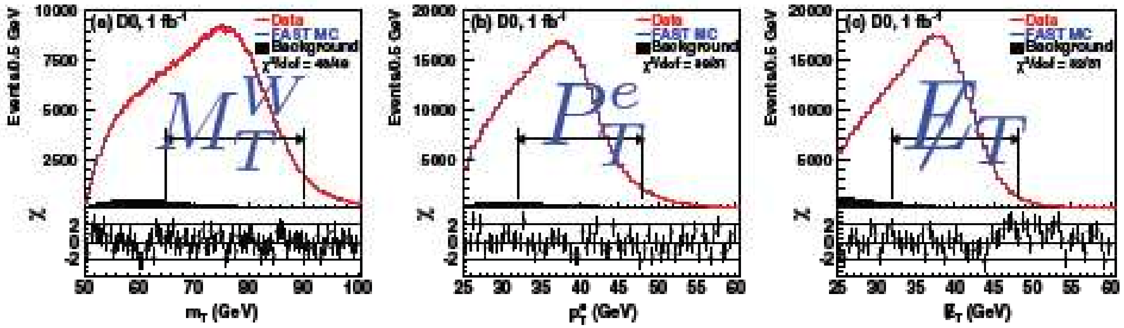
remember that Z mass value from LEP was an input to electron energy scale calibration, PDG: m(Z) = 91.1876 ± 0.0021 GeV)

A typical W -> eν event



Underlying Events:
- Additional $p\bar{p}$ Collisions (Zero-Bias)
- Spectator Partons (Mini-Bias)

Three observables:



(plots from published RunIIa 1 fb^{-1} analysis, Phys. Rev. Lett. 103, 141801 (2009).)

Developed a Fast MC model to generate templates of the 3 observables with different W mass hypotheses. Fit the templates to the Data to extract W mass.

The Fast MC model:
- **Event Generator: Resbos+Photons**
- **Parameterized Detector Model**

The Parameterized Detector Model is essential in this analysis!

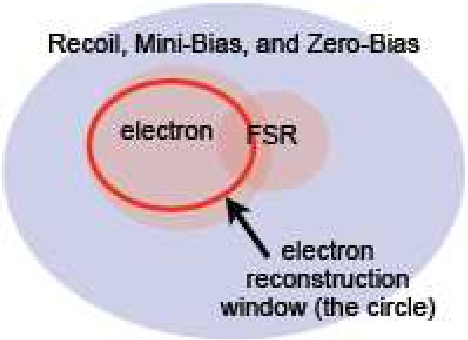
Electron Model:

$$E_{reco} = R_{EM}(E_{true}) \otimes \sigma_{EM}(E_{true}) + \Delta E_{corr}$$

Response — Resolution — (RunIIb Challenge)

Response and Resolution are calibrated using Z invariant mass of Z->ee Data

ΔE_{corr} Model: Model Update in RunIIb



1. Energy Leakage due to FSR

   Add Inst.Lumi, SET, Eta dependencies

2. Recoil, Mini-Bias and Zero-Bias Contamination inside electron window
3. Effects due to Zero-Suppression and Baseline-Subtraction

   For modeling 2. and 3., we added Inst. Lumi., SET, electron P_T and $U_{\parallel}$ dependencies in a very complicated way, based on a new Wenu FullMC production with Electron and Recoil separated.

Recoil Model:

$$\vec{u}_T = \vec{u}_T^{\,\mathrm{Hard}} + \vec{u}_T^{\,\mathrm{Soft}} + \underline{\vec{u}_T^{\,\mathrm{Elec}} + \vec{u}_T^{\,\mathrm{FSR}}}$$

Hard Recoil balancing W or Z boson

Soft Recoil: Zero-Bias and Mini-Bias

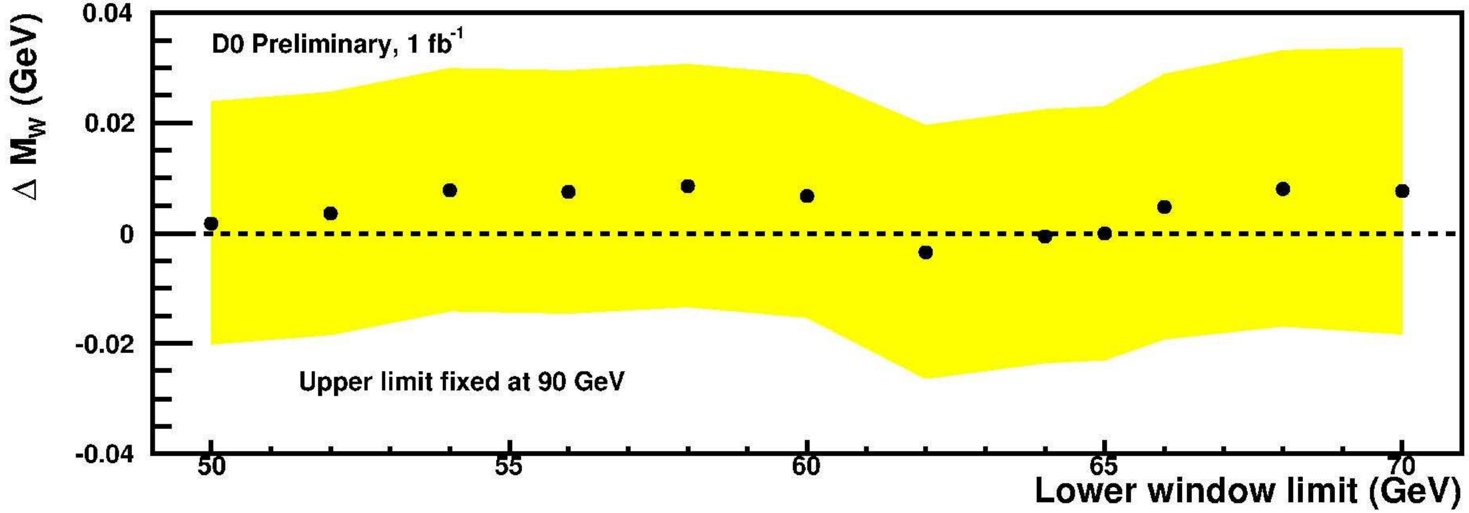
Model Update in RunIIb

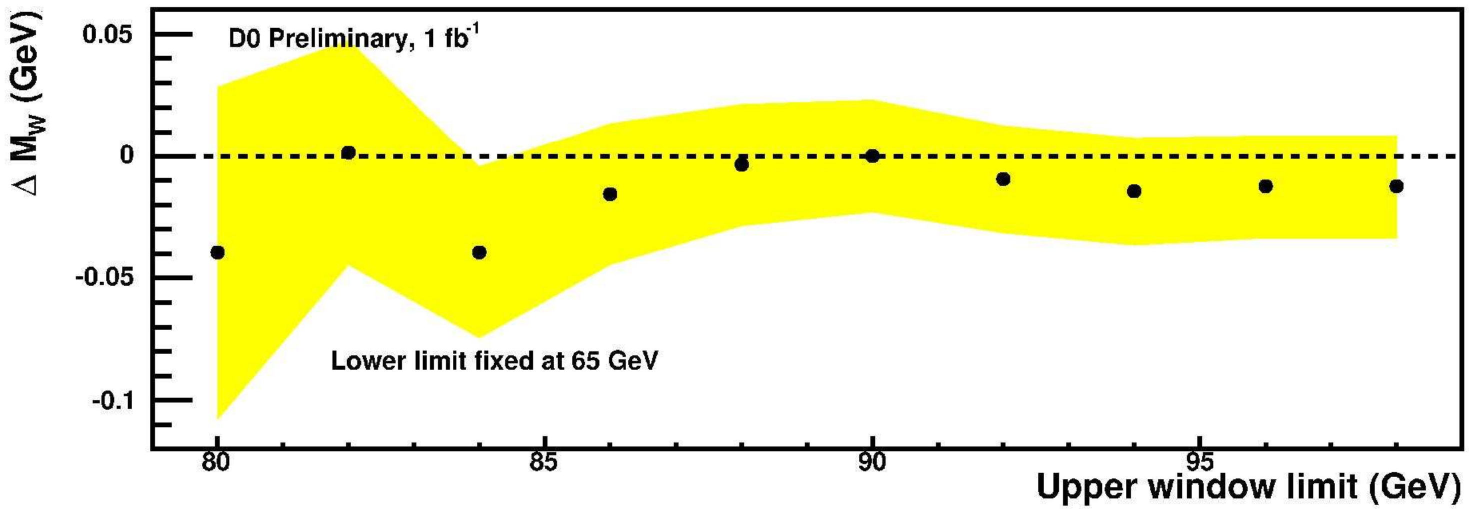
In the same framework of ΔE_{corr} Modeling

What has been added to (subtracted from) the electron has to be subtracted from (added to) the Recoil.

Stability checks

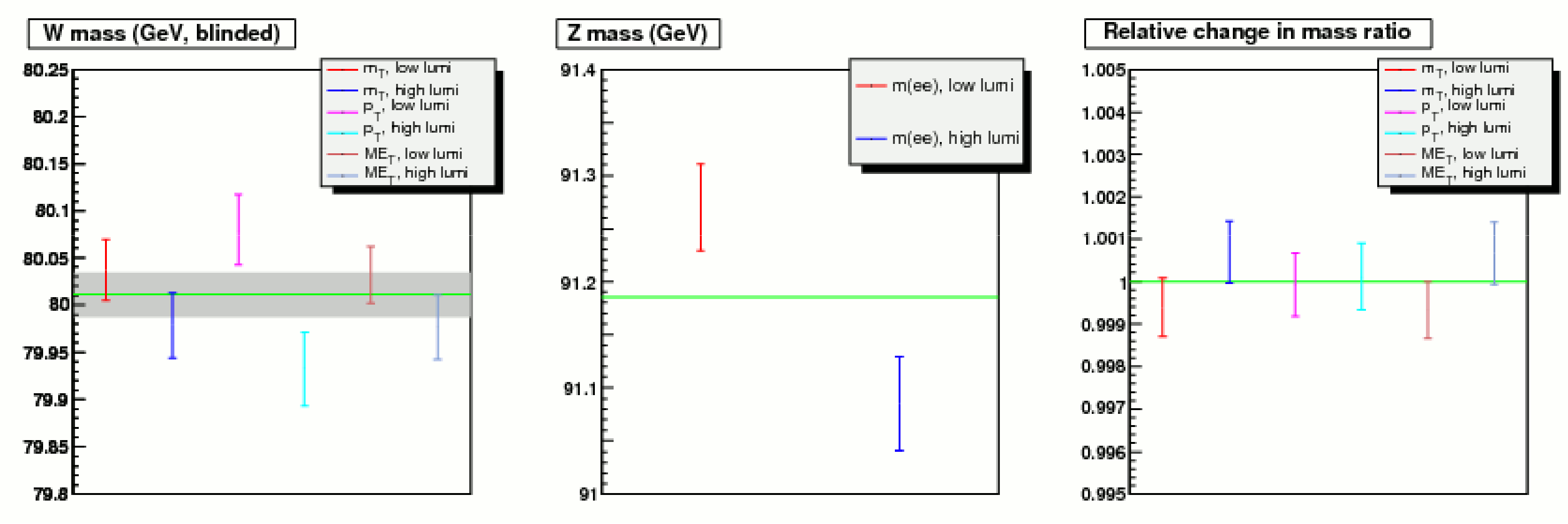
Changes in the fitted m_W when the fitting range (m_T observable) is varied.



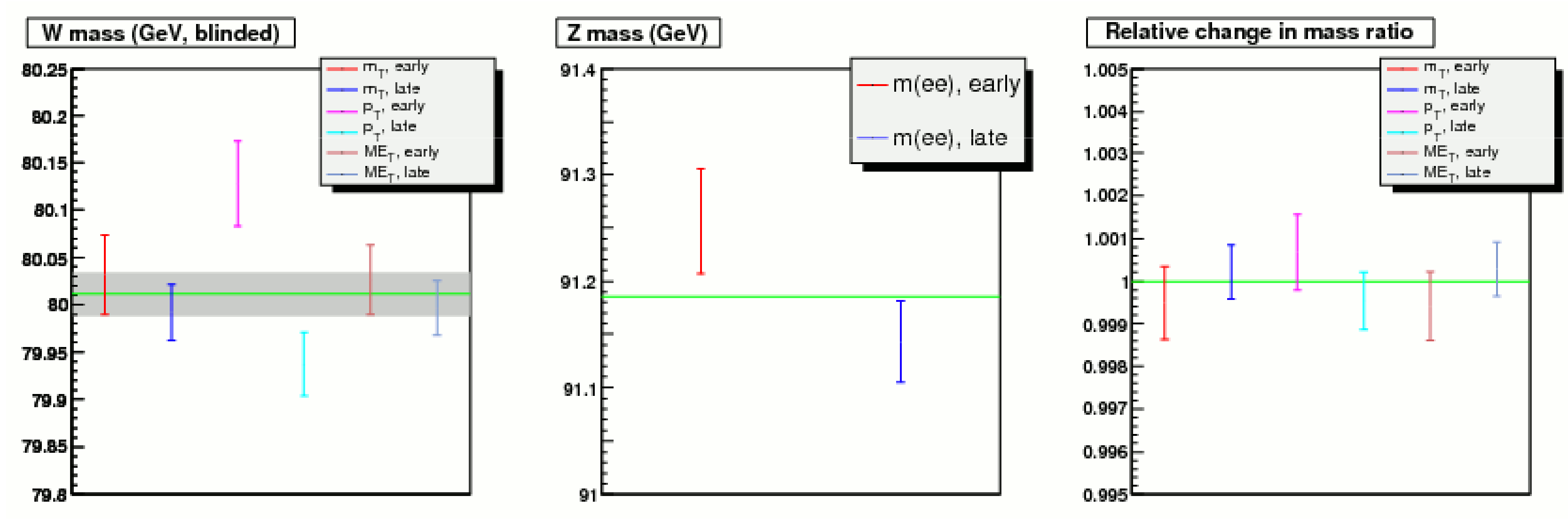


Stability checks

Instantaneous luminosity (split data into two subsets – high and low inst. luminosity)



Time (i.e. data-taking period)

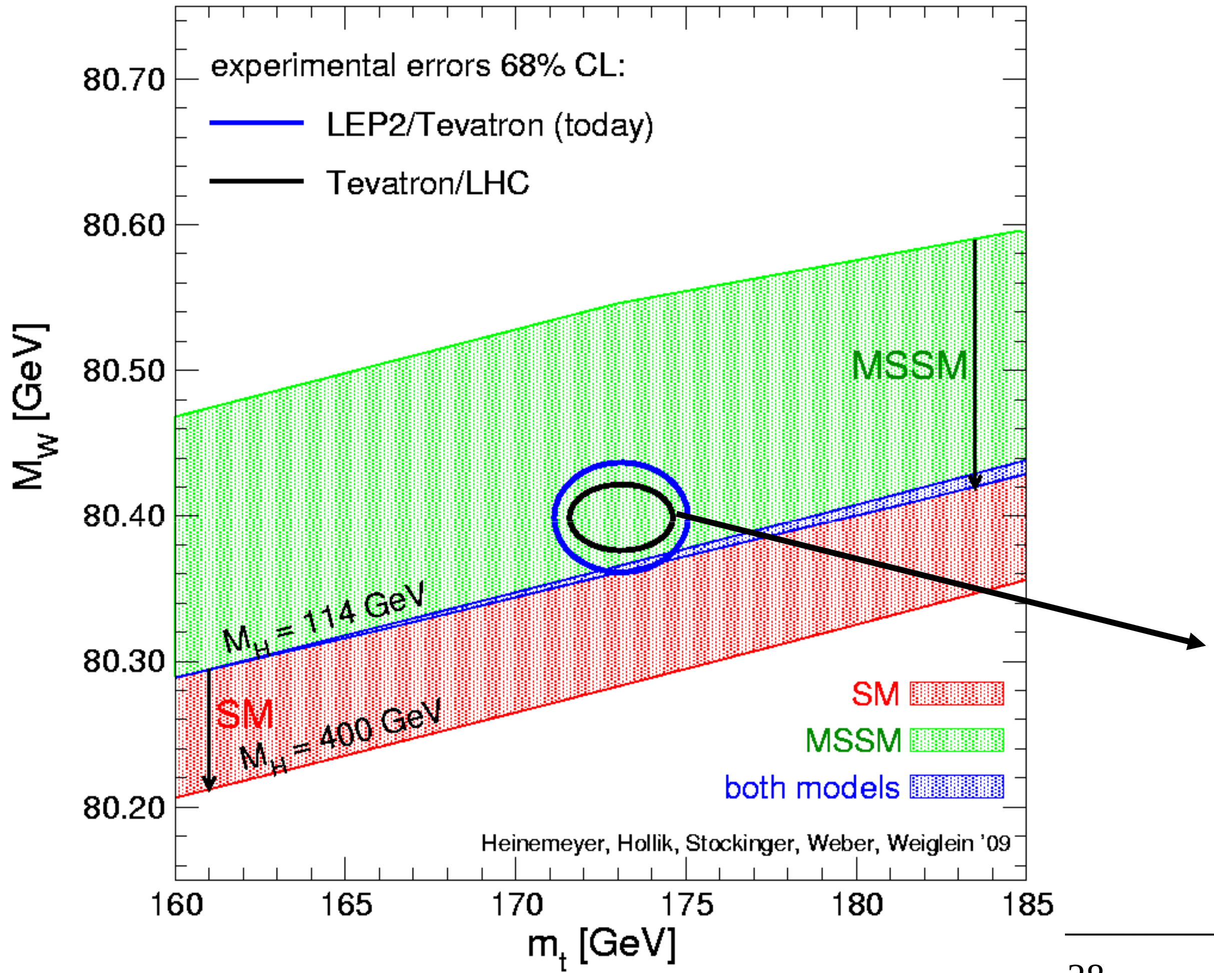


Sorry, plots still in terms of blinded mass, but it does not matter here.

Projection

Electroweak measurements prefer light Higgs, heavy SUSY

- **Some tension in both cases**
  - **Something else?**
  - **Need increased precision** **YES WE CAN !**



With > 4fb^{-1} of data being analyzed currently :

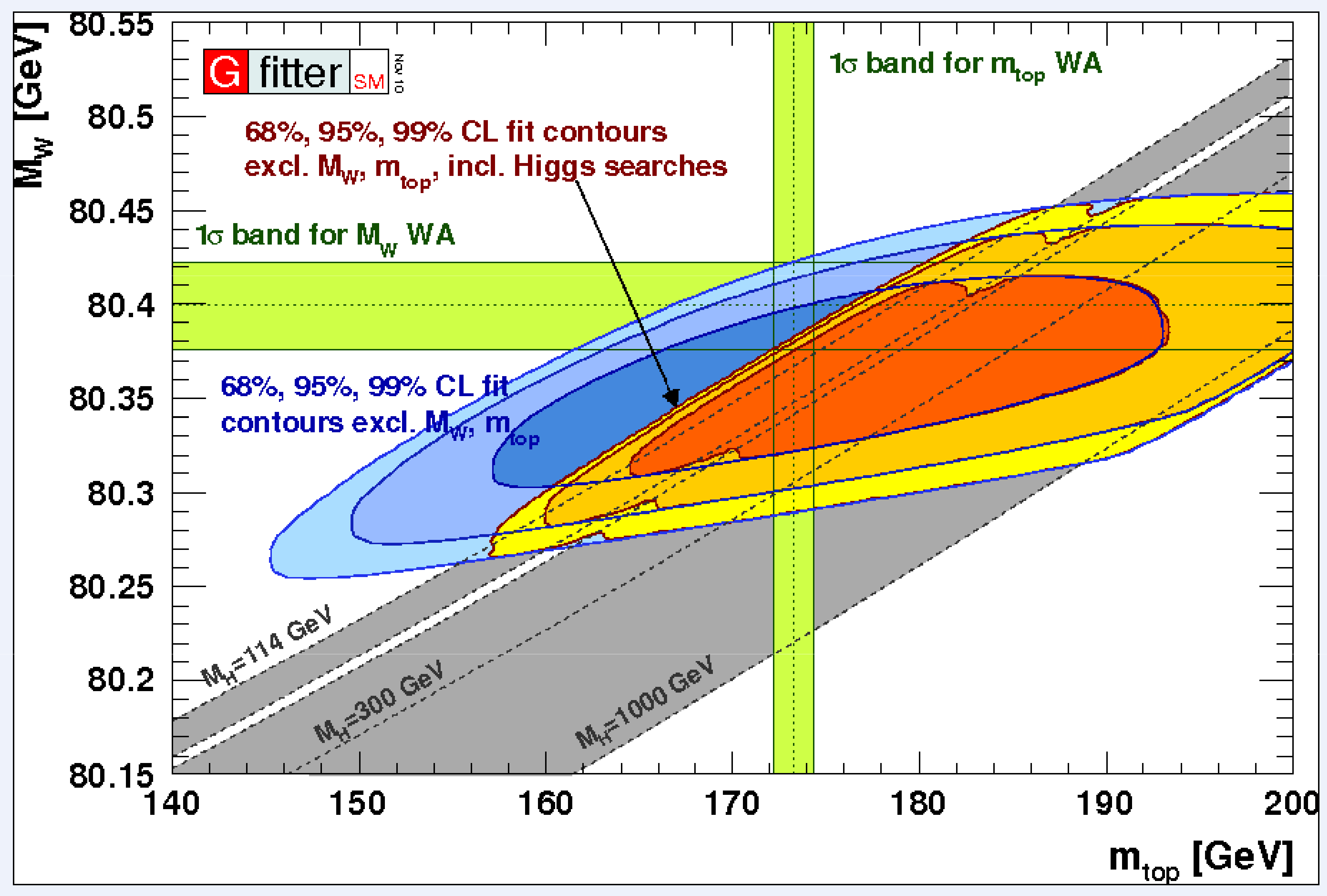
the ΔM_W per experiment is estimated ~ 25 MeV !

combined ΔM_W ~ 15 MeV possible by next year

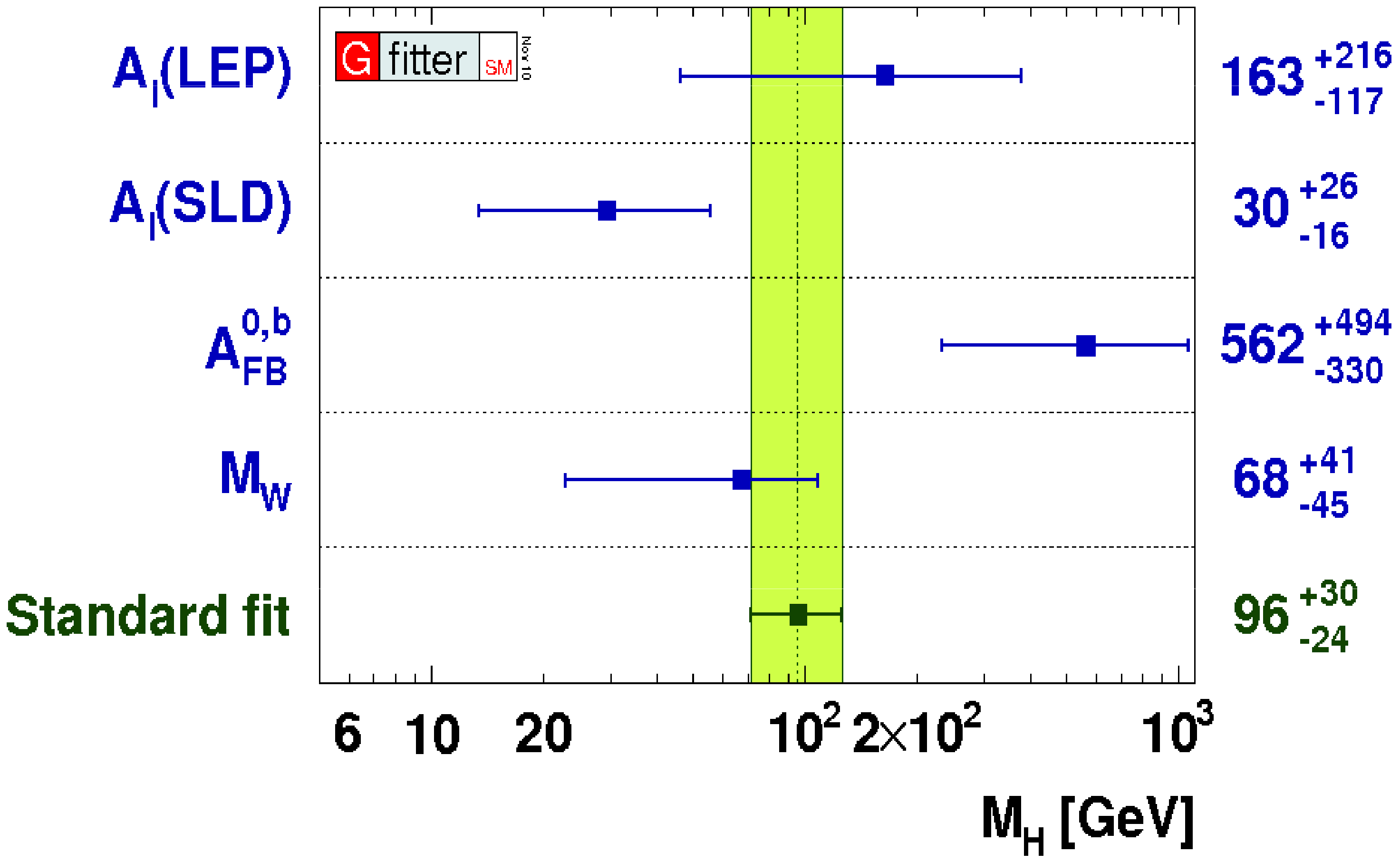
CDF/DØ combined
10 fb^{-1} 2011 (?)

ΔmW ~ 10 MeV

Δmtop ~ 1GeV



G fitter SM
Nov 10
1σ band for m_{top} WA
68%, 95%, 99% CL fit contours
excl. M_W, m_{top}, incl. Higgs searches
1σ band for M_W WA
68%, 95%, 99% CL fit
contours excl. M_W, m_{top}
M_H=114 GeV
M_H=300 GeV
M_H=1000 GeV
M_W [GeV]
80.55
80.5
80.45
80.4
80.35
80.3
80.25
80.2
80.15
140
150
160
170
180
190
200
m_{top} [GeV]



Gfitter SM
Nov 10
A_l(LEP)
A_l(SLD)
$A_{FB}^{0,b}$
M_W
Standard fit
163^{+216}_{-117}
30^{+26}_{-16}
562^{+494}_{-330}
68^{+41}_{-45}
96^{+30}_{-24}
6 10 20 10^2 2×10^2 10^3
M_H [GeV]