Séminaires du SPP
Wednesday, May 09, 2012, CEA-Saclay

New W boson mass results from the Tevatron

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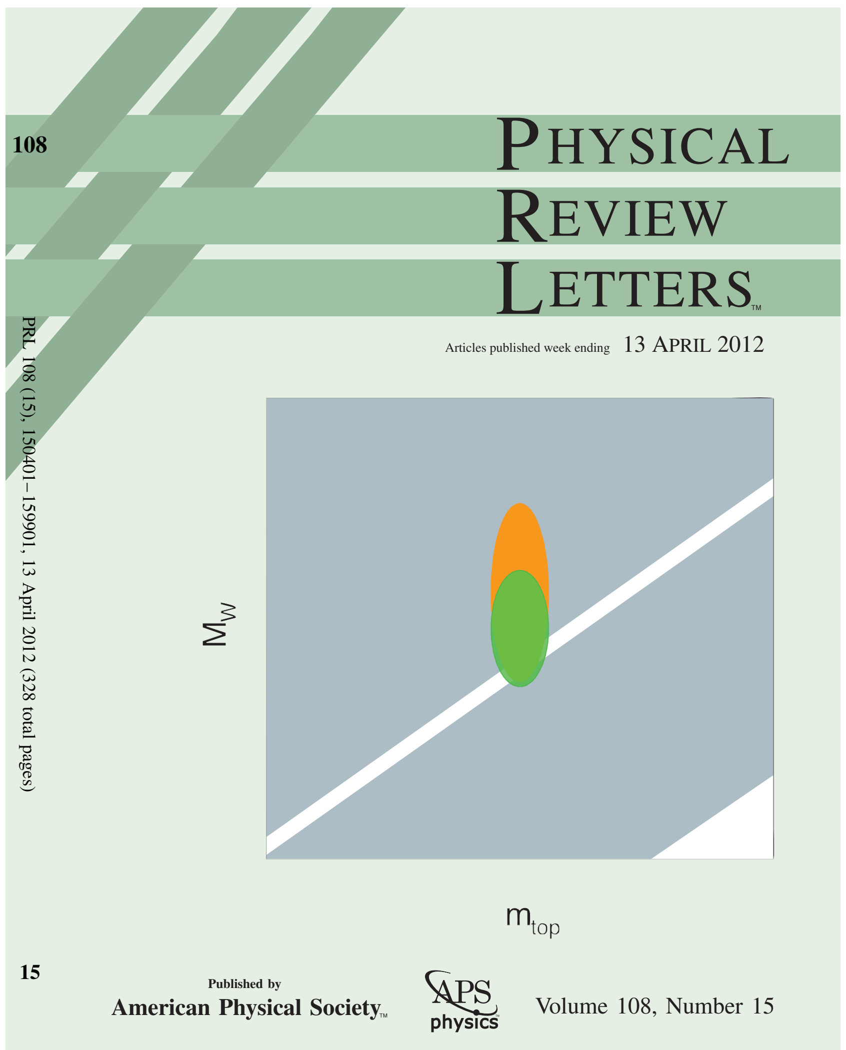
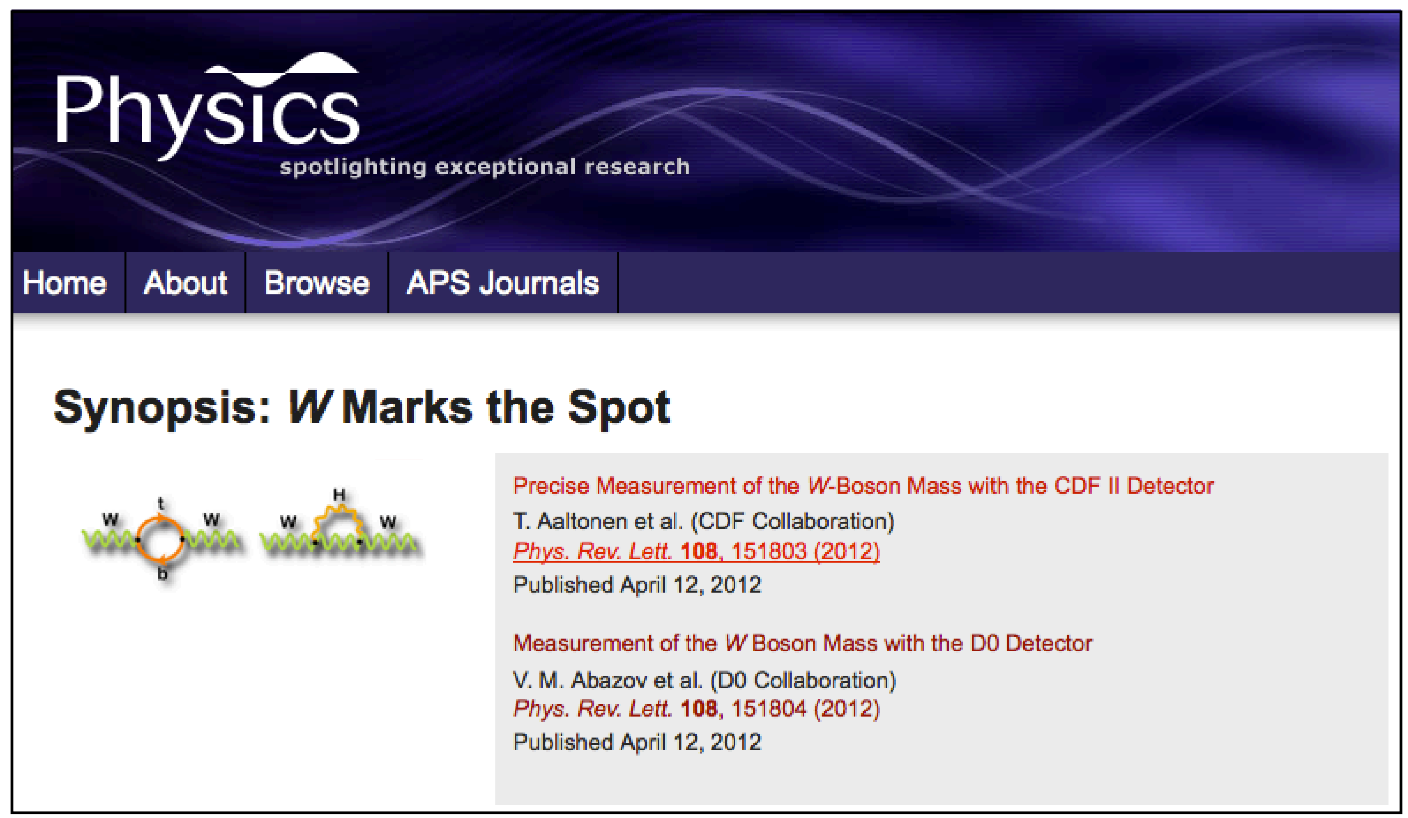
New W mass results this winter

PRL Editors' Suggestion **PRL Cover** **"Physics" Synopsis article**



D0: 5.3 fb^{-1}: Phys. Rev. Lett. 108, 151804 (2012)

CDF: 2.2 fb^{-1}: Phys. Rev. Lett. 108, 151803 (2012)



Motivation

The Standard Model (SM) predicts a relationship between the W boson mass and other parameters of electroweak theory:

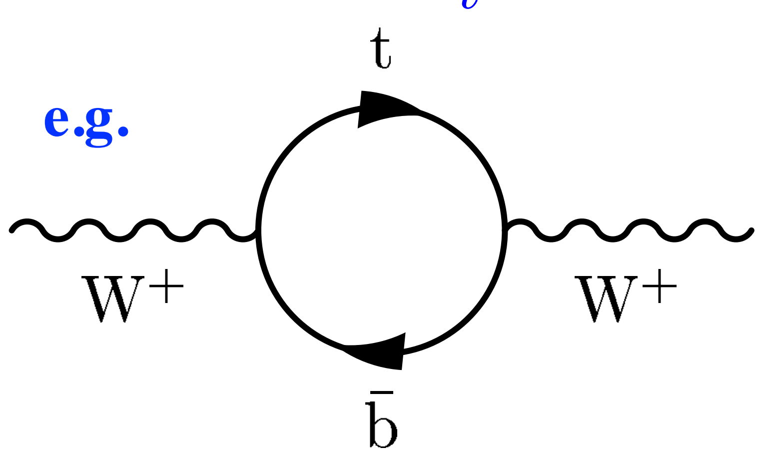
$$M_W = \sqrt{\frac{\pi\alpha}{\sqrt{2}G_F}}\frac{1}{\sin\theta_W\sqrt{1-\Delta r}}$$

Radiative corrections Δr

related to the Top quark mass as

$$\Delta r \propto M_t^2$$

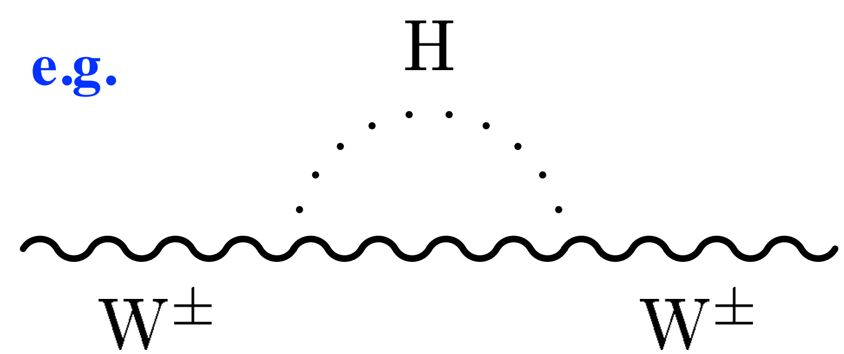
e.g.



related to the Higgs mass as

$$\Delta r \propto \ln M_H$$

e.g.



Precise knowledge of the W mass and top quark mass can indirectly constrain the mass of the hypothetical Higgs boson.

Motivation

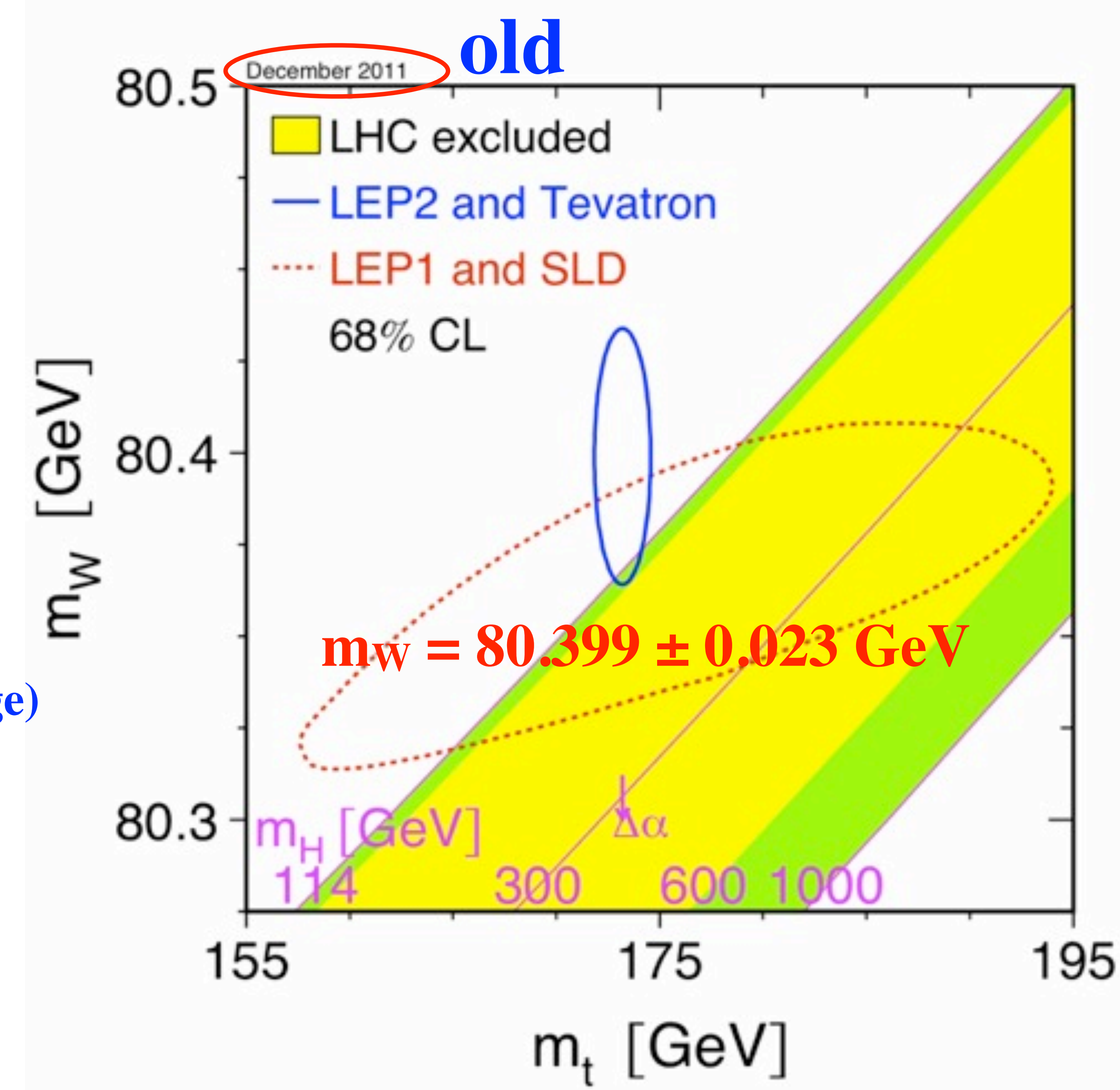
The Higgs mass is much more sensitive to the W mass than the top mass:

$\Delta m_H / \Delta m_W \sim 170\ \Delta m_H / \Delta m_t$

For equal constraint on the Higgs mass, W mass has to be measured much more precise than the top quark mass:
$\Delta m_W \sim 0.006\ \Delta m_t$

e.g. $m_t = 173.2 \pm 0.9$ GeV (world average)
equivalent to
$\Delta m_W \sim 5$ MeV !!

Previous world average:
$m_W = 80.399 \pm 0.023$ GeV



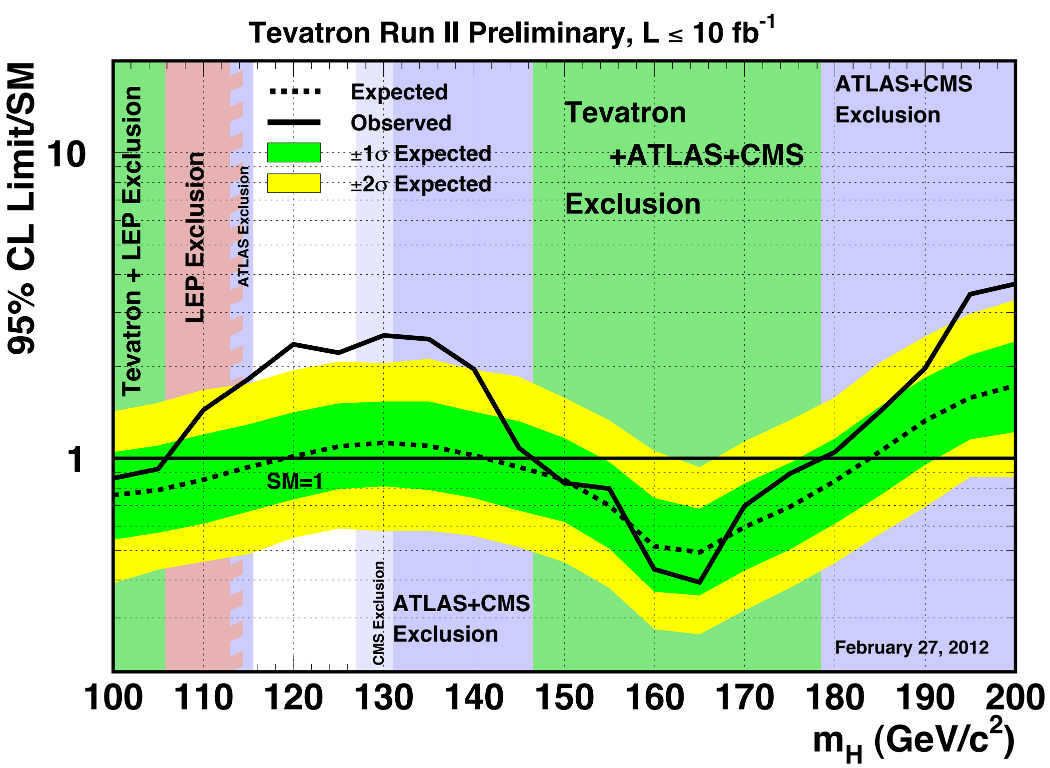
The W mass is the limiting factor in constraining the Higgs mass.

Motivation

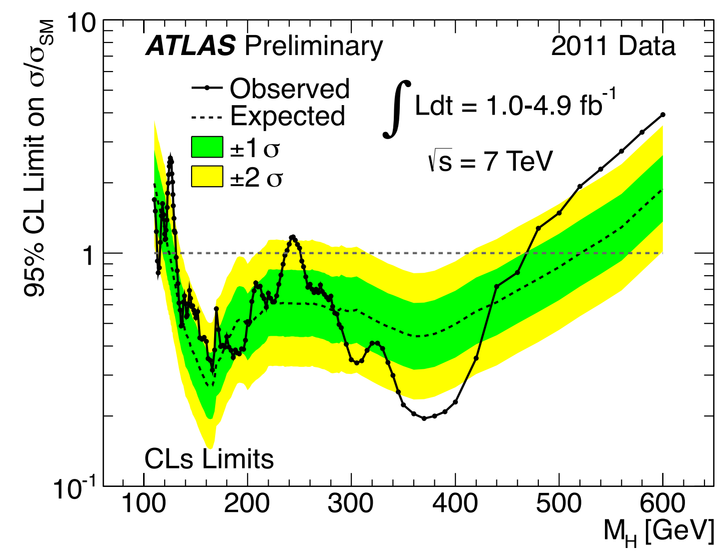
Results from direct searches of Higgs boson

Most likely mass region @ 95% C.L. : Moriond EW 2012

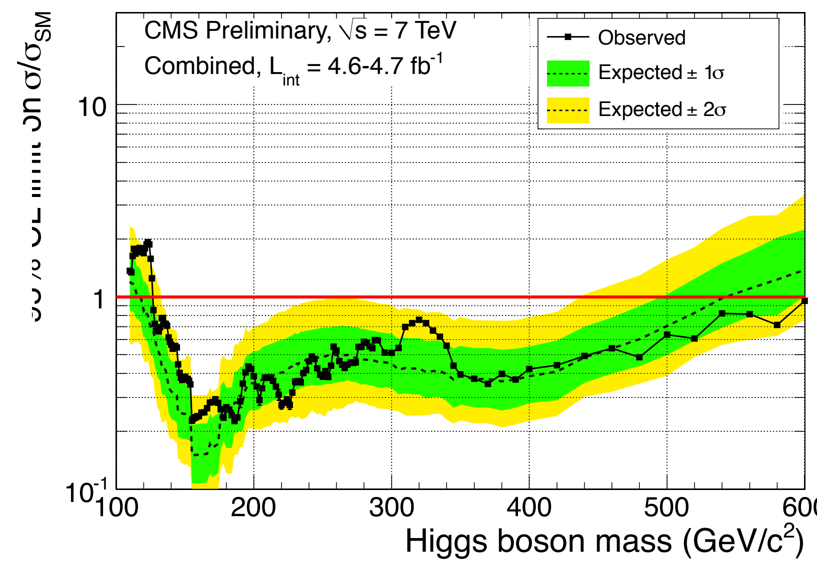
Tevatron Higgs exclusion



ATLAS:
117.5 - 118.5 GeV
or
122.5 - 129 GeV



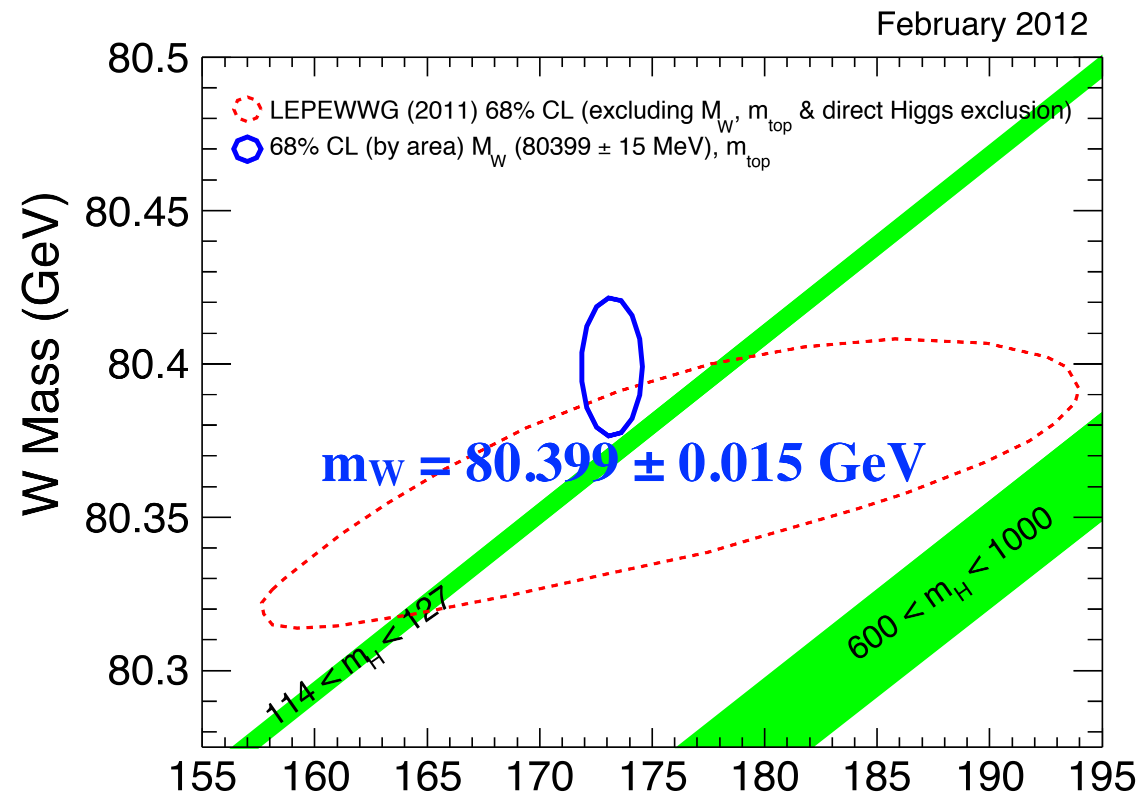
CMS:
114.4 - 127.5 GeV



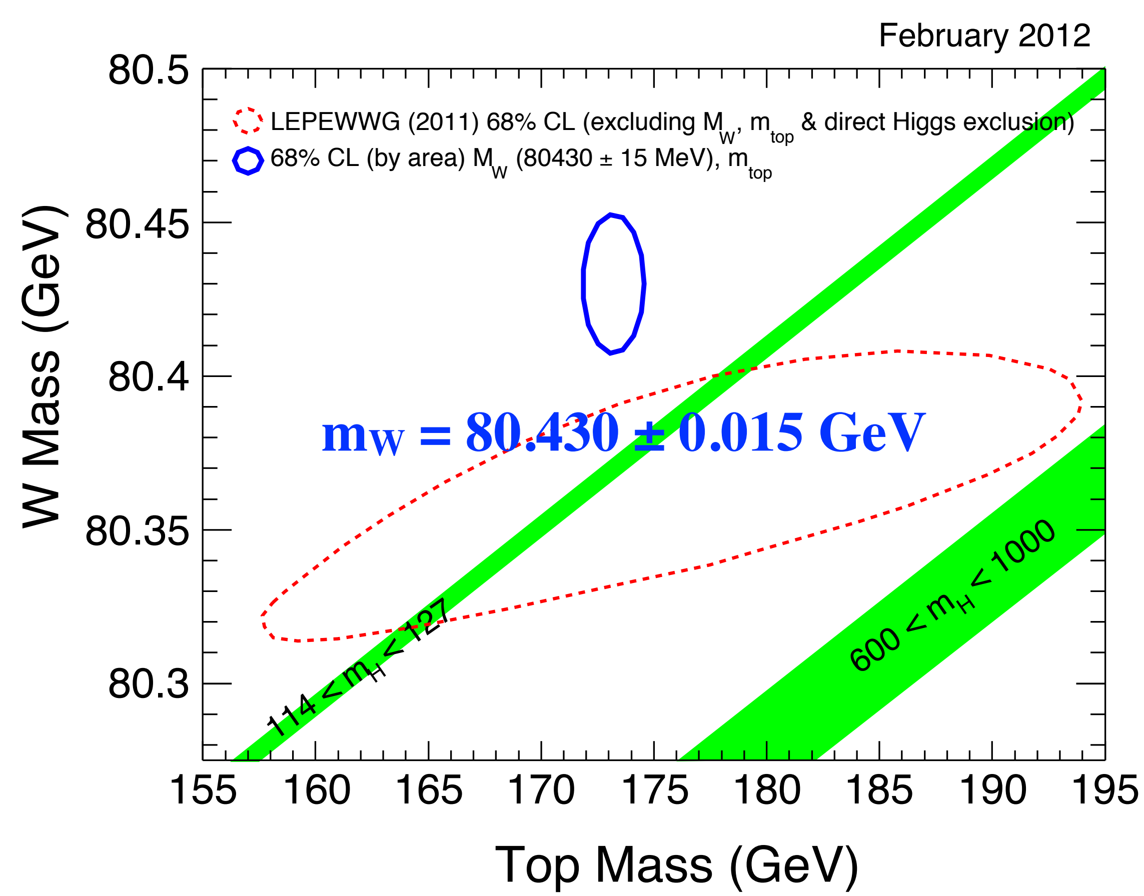
Comparison of indirect constraints and direct searches of Higgs is an important test of the SM.

Motivation

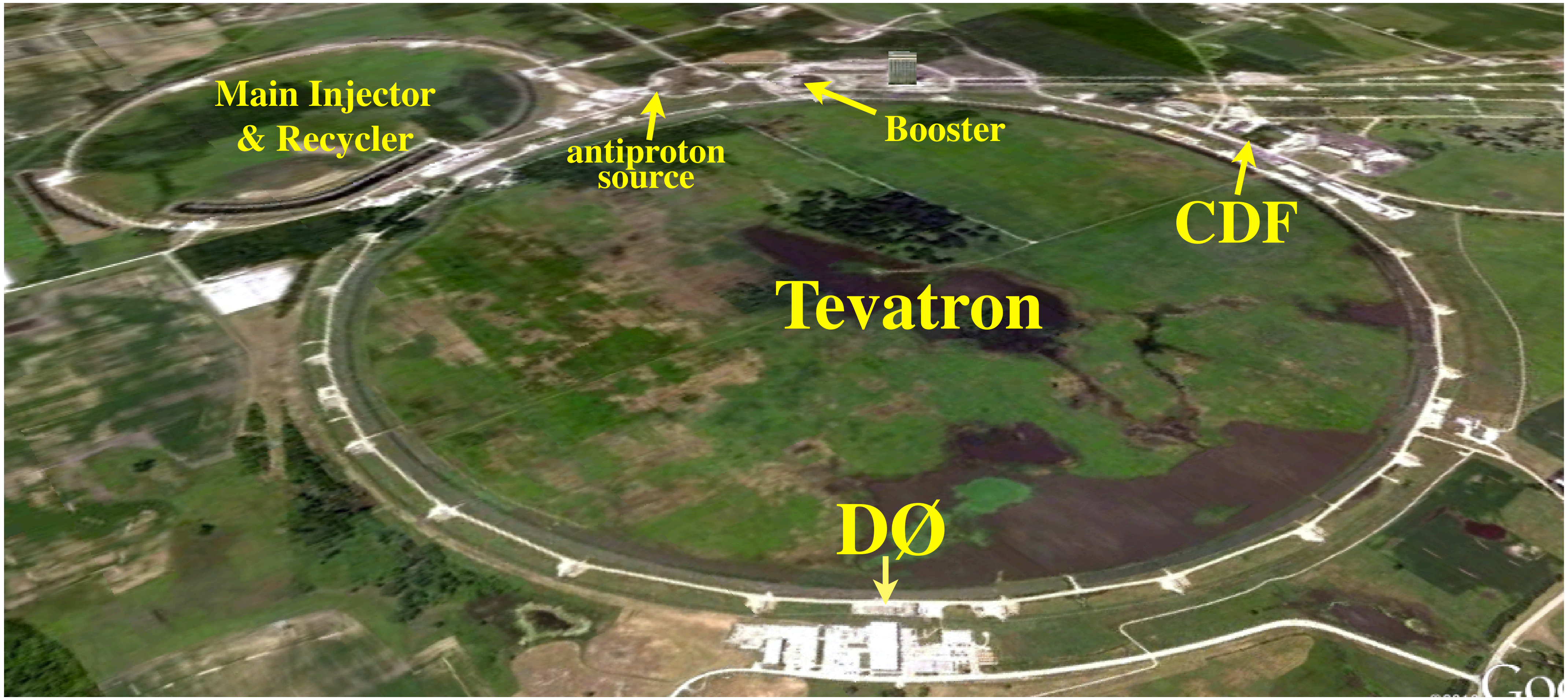
Before the results came out, we were hoping ...



and even more ...



The Tevatron



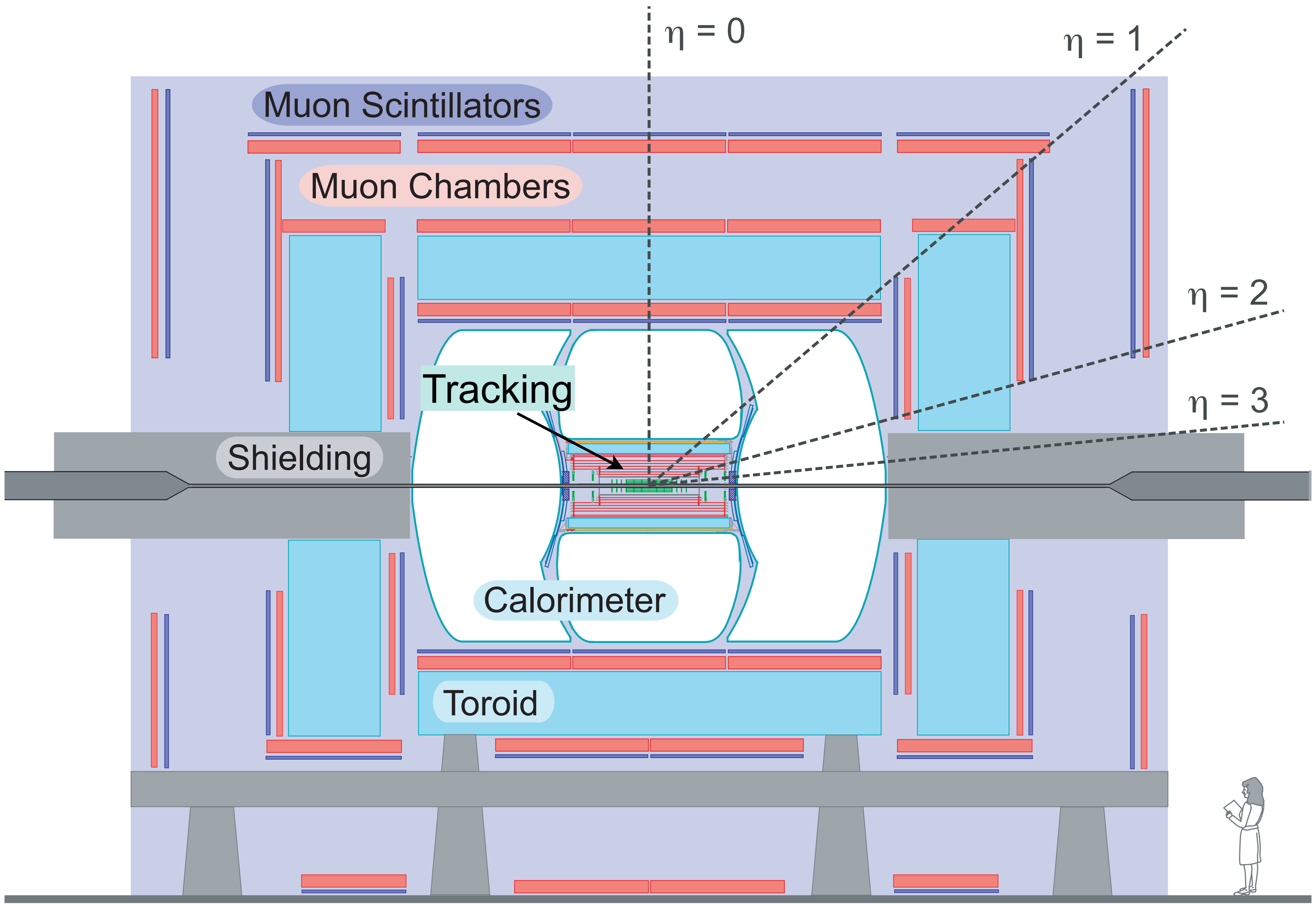
Proton-antiproton collider, at center-of-mass energy = 1.96 TeV
36 proton and antiproton bunches
396 ns between bunch crossing

The D0 detector

Tracking system provides precise spatial resolution

Liquid argon calorimeter provides stable and high precision energy measurements:

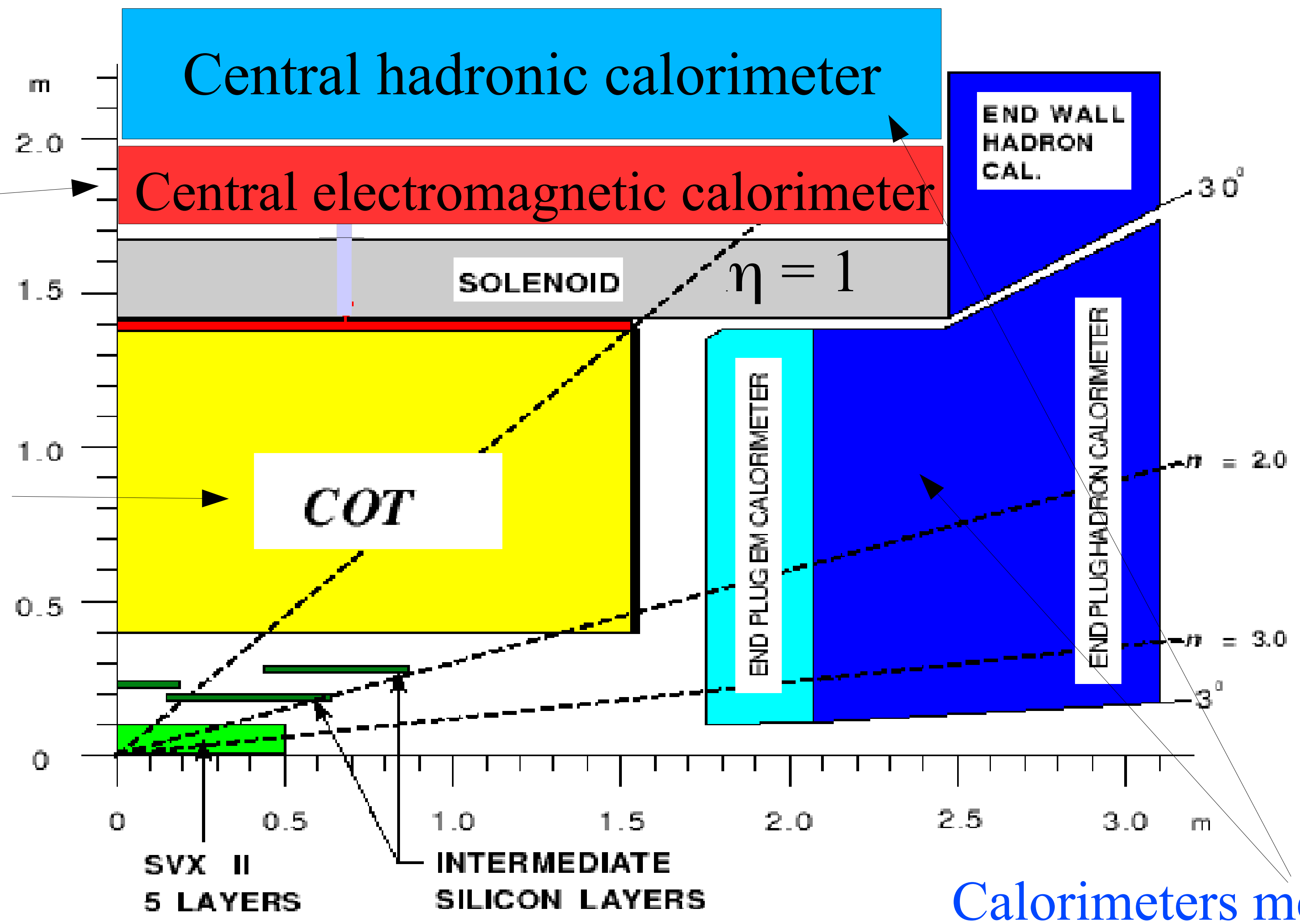
- **η coverage up to 4.2**
- **$\delta E/E \sim 4\%$ @ 45 GeV**



The CDF detector

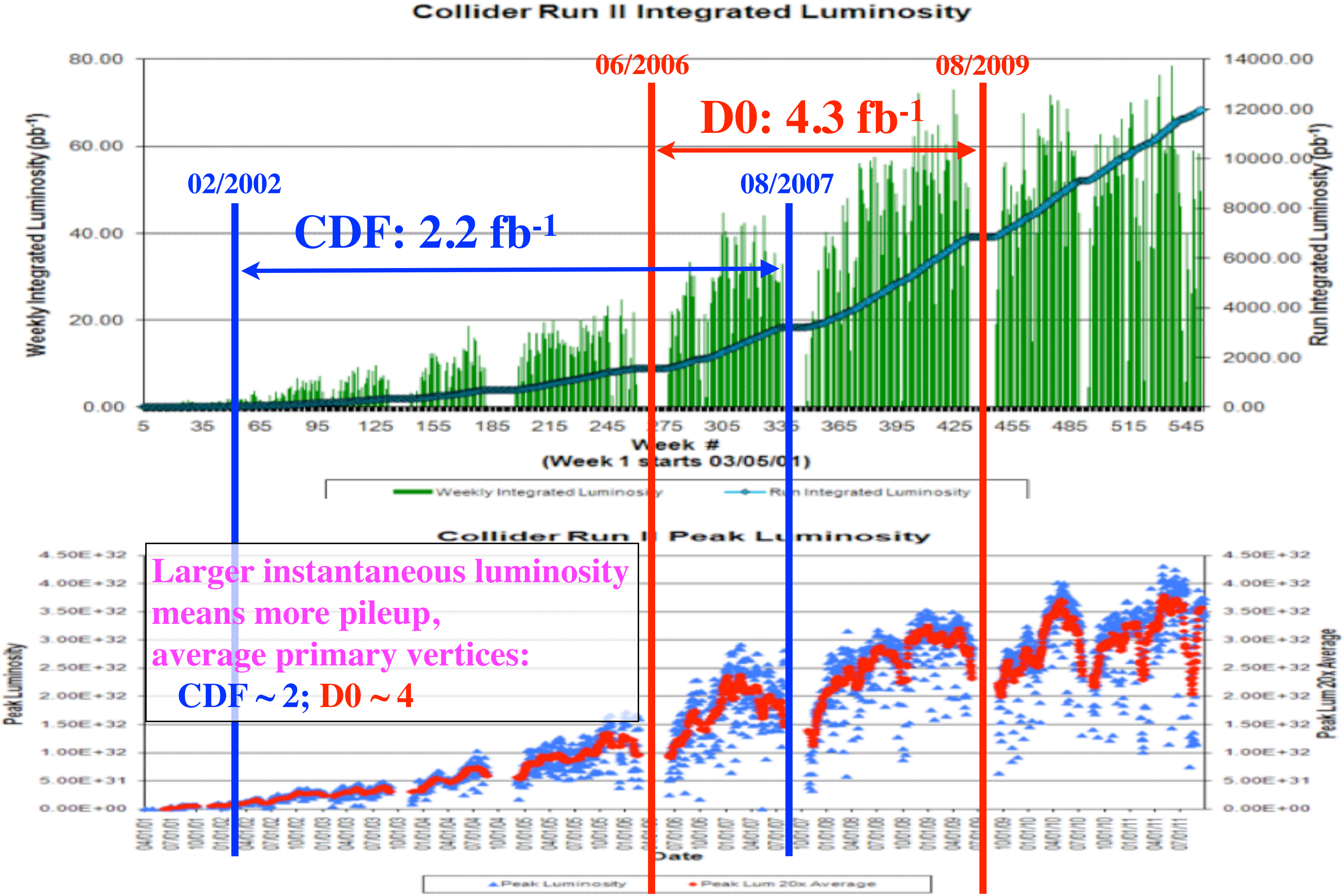
EM calorimeter
Lead-aluminum scintillator

Central drift chamber
provides accurate tracking momentum measurements
- $dP_T/P_T \sim 3.2\%$ @ 45 GeV



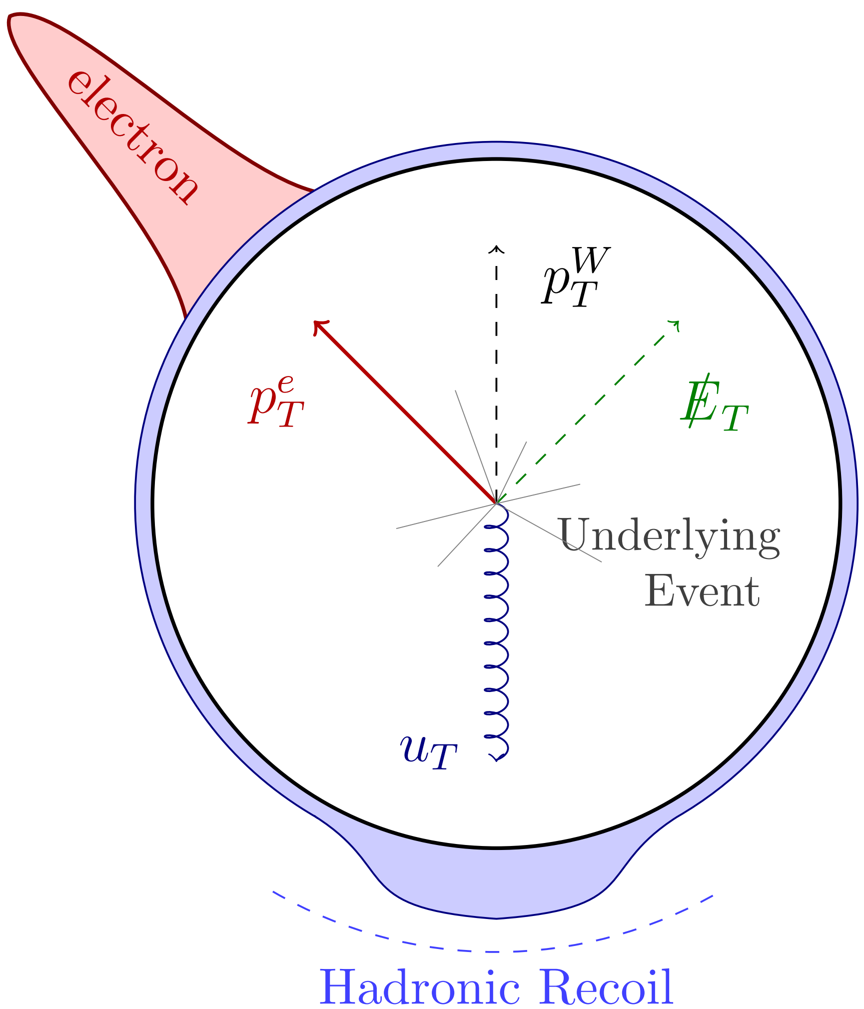
Calorimeters measure hadronic recoil particles

Integrated luminosity



Analysis strategy in a nutshell

A typical W→eν event in CDF and D0 detectors



Three observables:

$$M_T, \quad P_T^l, \quad \not{E}_T$$

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

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:

- **Theoretical Model: Resbos(CTEQ6.6)+Photos**
- **Parametrized Detector Model**

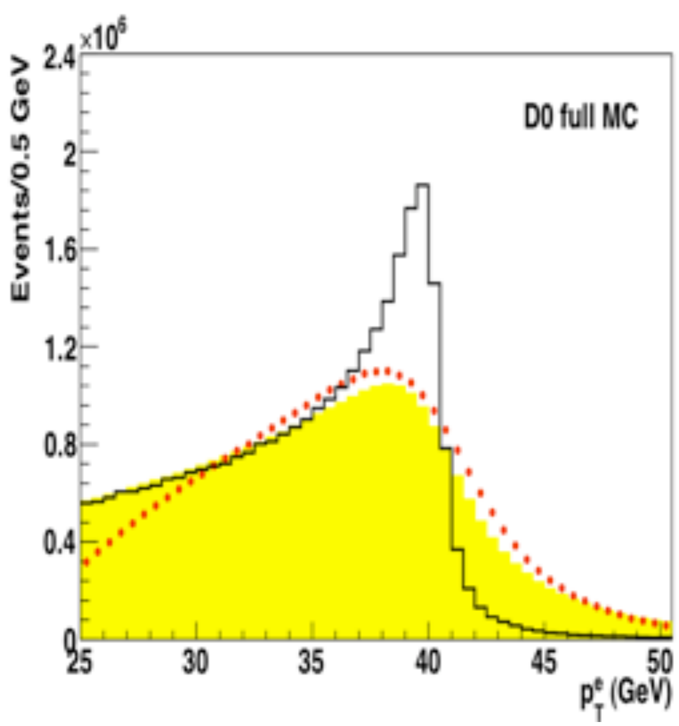
Event selection

D0 analysis: 4.3 fb^{-1}

- W→ eν events
- Central electrons: |η| < 1.05
- $p_T(e)$ > 25 GeV
- Missing E_T > 25 GeV
- Hadronic recoil: u_T < 15 GeV
- After selection:
  - 1,677,394 W→ eν candidates

CDF analysis: 2.2 fb^{-1}

- W→ eν and W→ μν events
- Central leptons: |η| < 1.0
- $p_T(l)$ > 30 GeV
- Missing E_T > 25 GeV
- Hadronic recoil: u_T < 15 GeV
- After selection:
  - 470,126 W→ eν candidates
  - 624,708 W→ μν candidates



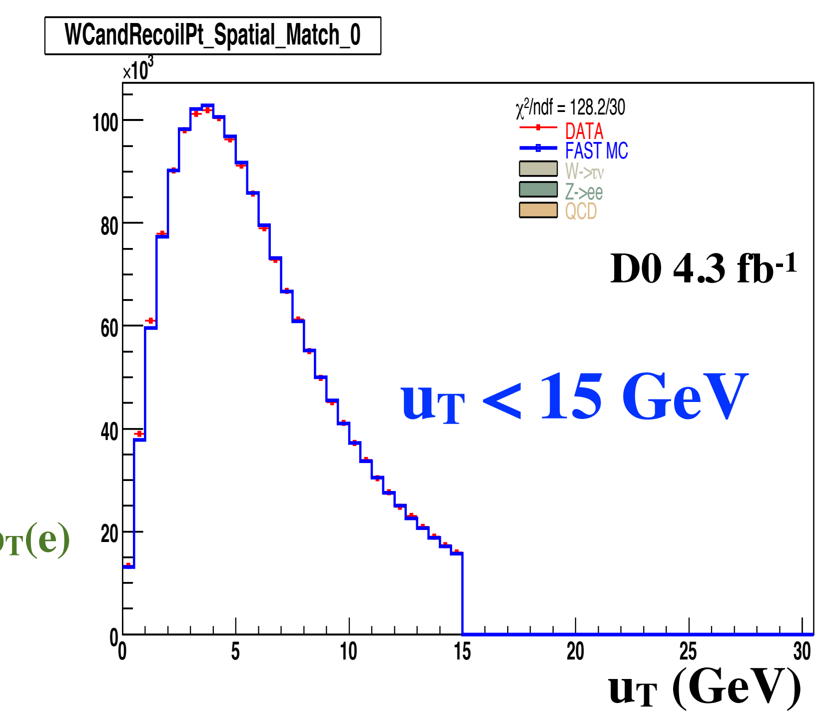
No $p_T(W)$

$p_T(W)$ included

detector effects added

Transverse boost of the W boson degrades the sharpness of the $p_T(e)$ Jacobian edge.

Requiring uT<15 GeV is helpful, however, it also transfers certain recoil modeling uncertainty into $p_T(e)$

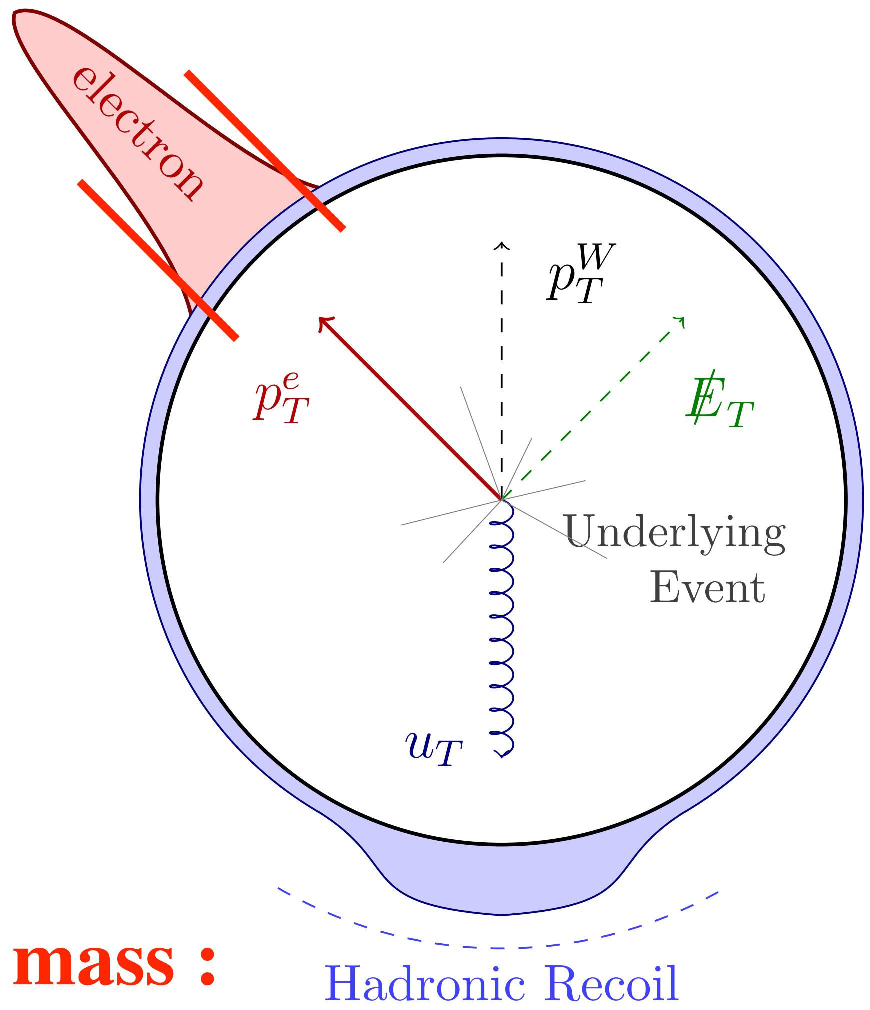


The observables

Can directly reconstruct two variables:

$\vec{P}_T^l$ **Lepton pT can be precisely measured, 0.01% precision.**

$\vec{u}_T$ **Hadronic recoil: vectorial sum of the transverse energies of all the calorimeter cells outside the lepton reconstruction window.**
- **less precise, ~1% precision,**
- **low resolution, $\Delta u_T > 3.5$ GeV**
- **hadronic energy response is only ~ 65%**



Calculate three observables to extract the W boson mass :

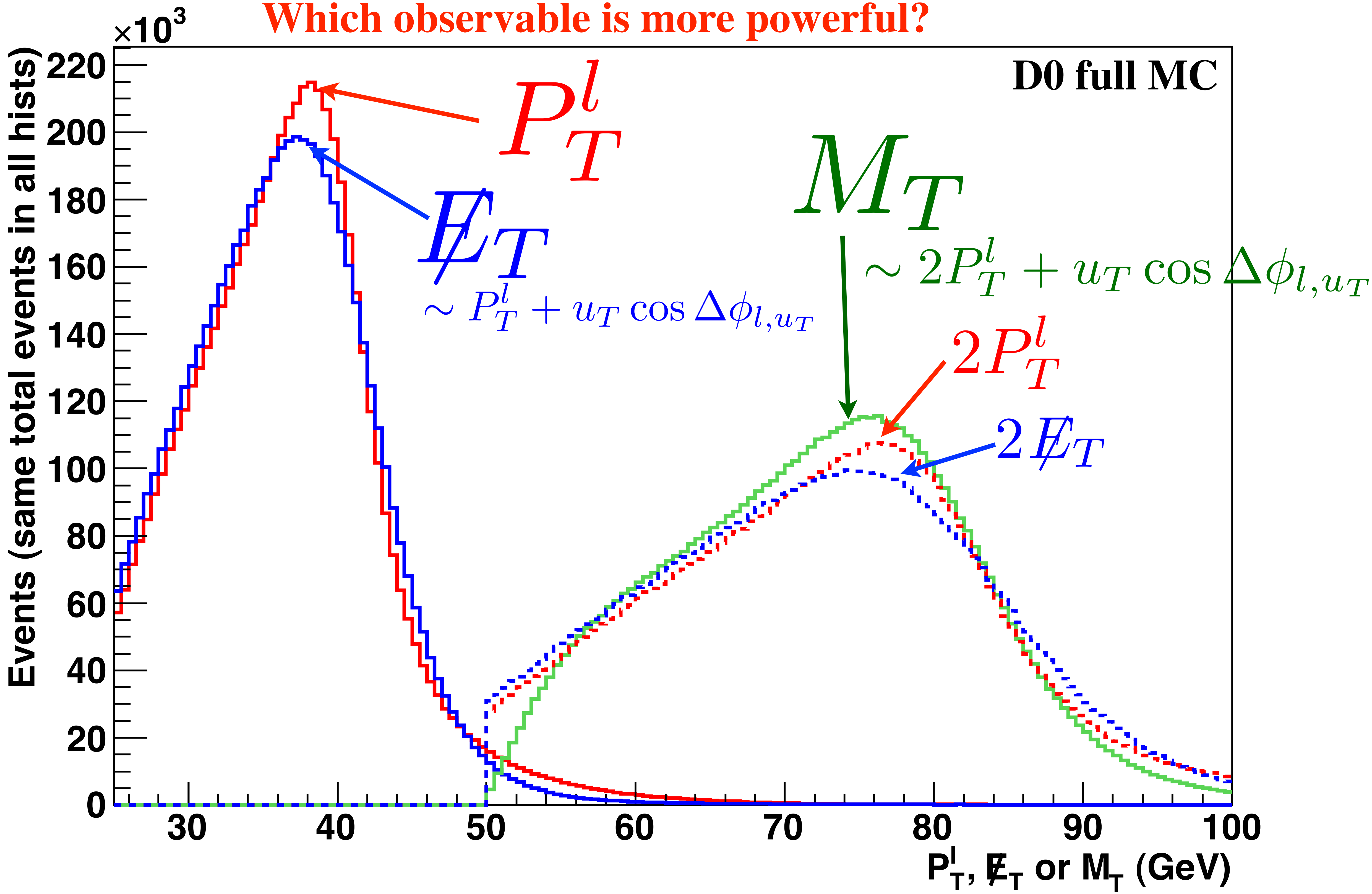
$$P_T^l \qquad \not{E}_T \qquad M_T$$

$$\not{E}_T = |\vec{P}_T^l + \vec{u}_T| \sim P_T^l + u_T \cos\Delta\phi_{(lepton-recoil)}$$

$$M_T = \sqrt{(P_T^l + \not{E}_T)^2 - (\vec{P}_T^l + \vec{\not{E}}_T)^2} \sim 2P_T^l + u_T \cos\Delta\phi_{lepton-recoil}$$

The observables

Which observable is more powerful?

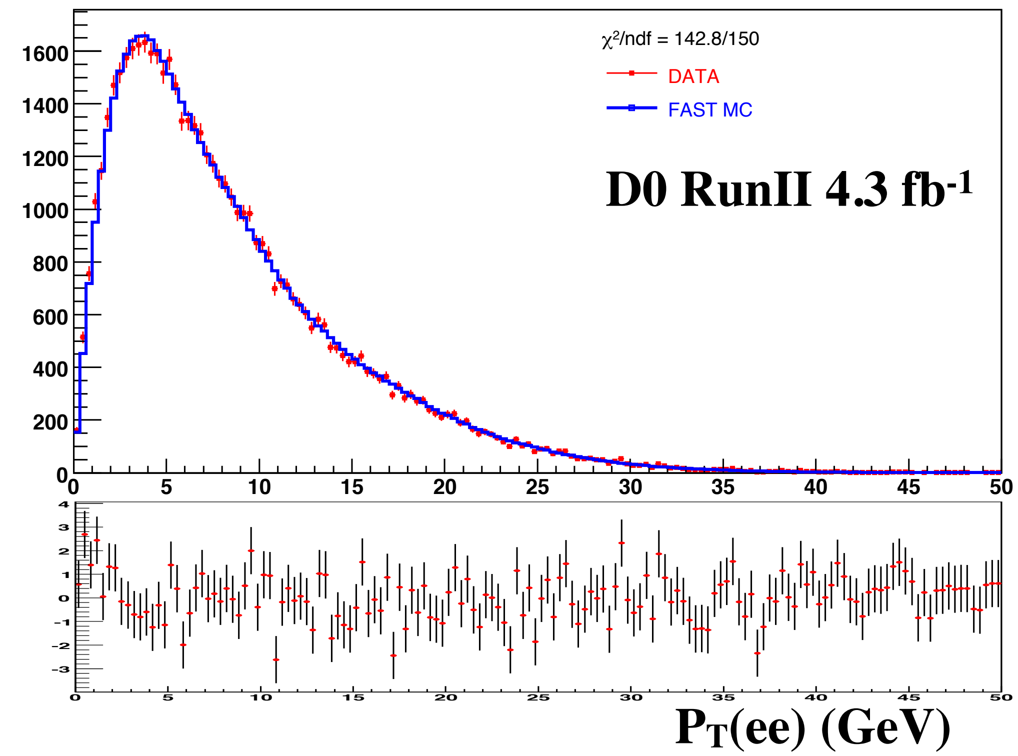


Theoretical Model

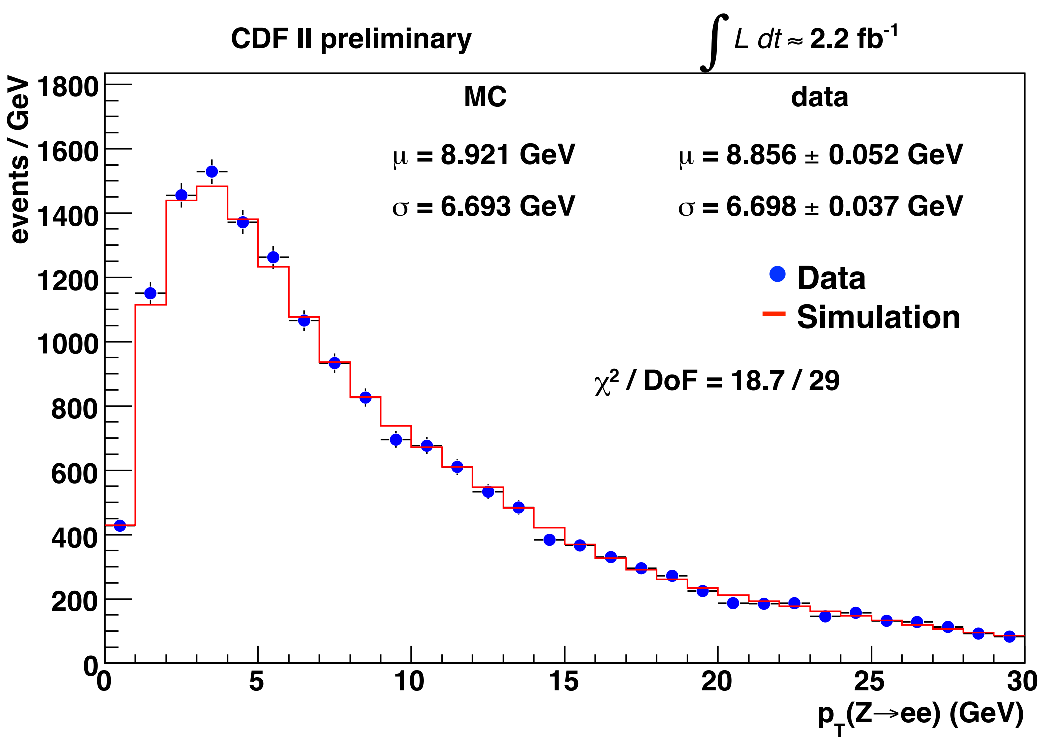
The Fast MC model (generate templates, fit to the data to extract W mass):
- **Theoretical Model: Resbos(CTEQ6.6)+Photos**
- **Parametrized Detector Model**

- **Resbos:** **Next-to-leading order event generator with next-to-next-to-leading logarithm resummation of soft gluons, gives the best boson pT description so far.** [C. Balazs and C. P. Yuan, Phys. Rev. D 56, 5558 (1997).]
- **Photos:** **generates up to two final state radiation photons.** [P. Golonka and Z. Was, Eur. Phys. J. C 45, 97 (2006).]

D0 Z pT



CDF Z pT

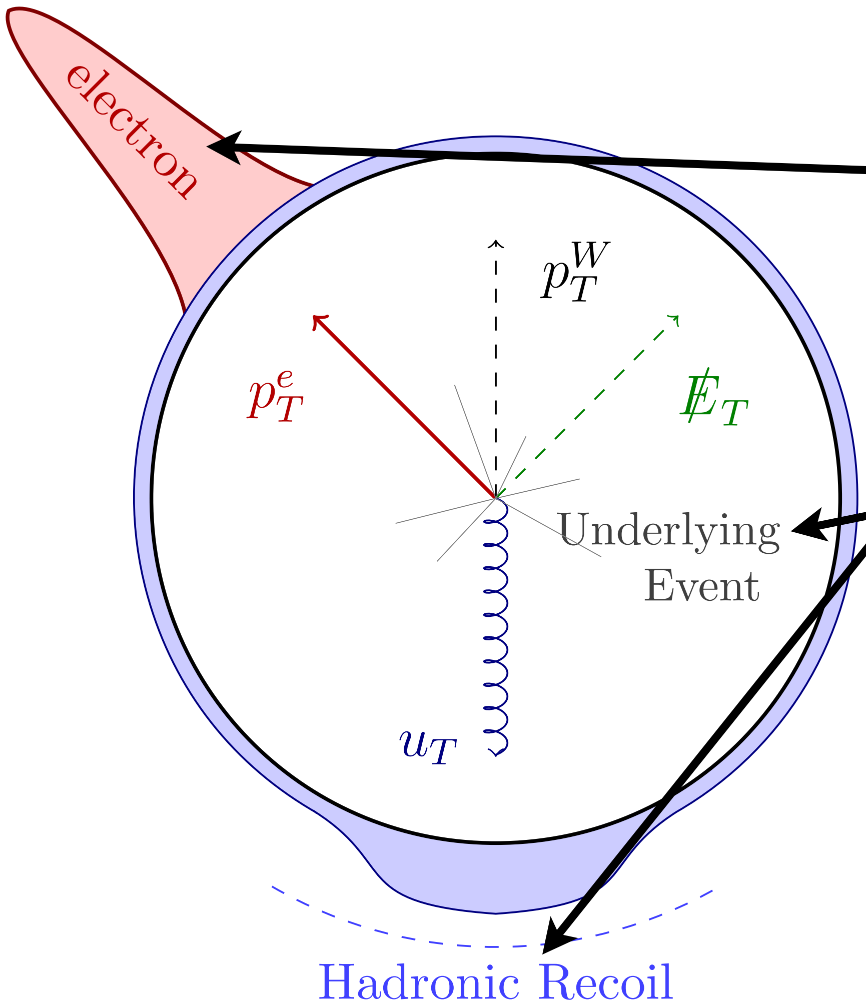


Parametrized Detector Model

The Fast MC model (generate templates, fit to the data to extract W mass):

- Event Generator: Resbos(CTEQ6.6)+Photos
- Parametrized Detector Model

The parametrized detector model has to simulate:



- Lepton energy response and smearing
- Hadronic recoil energy response and smearing
- Underlying energy:
  - additional ppbar interactions (pileup):
    - average number of primary vertices:

      CDF ~ 2 ; D0 ~ 4
  - spectator parton interactions
- Lepton selection efficiency
- Background

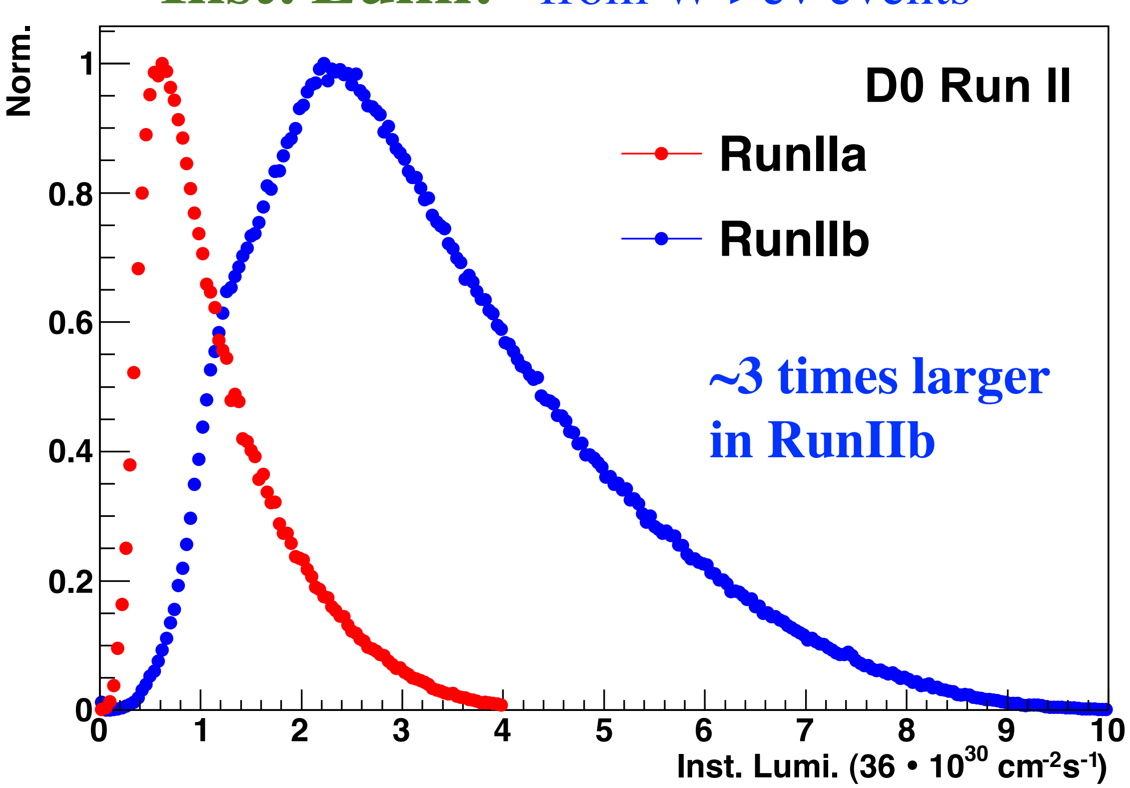
Electron energy scale at D0

Correct/model non-linear energy responses:

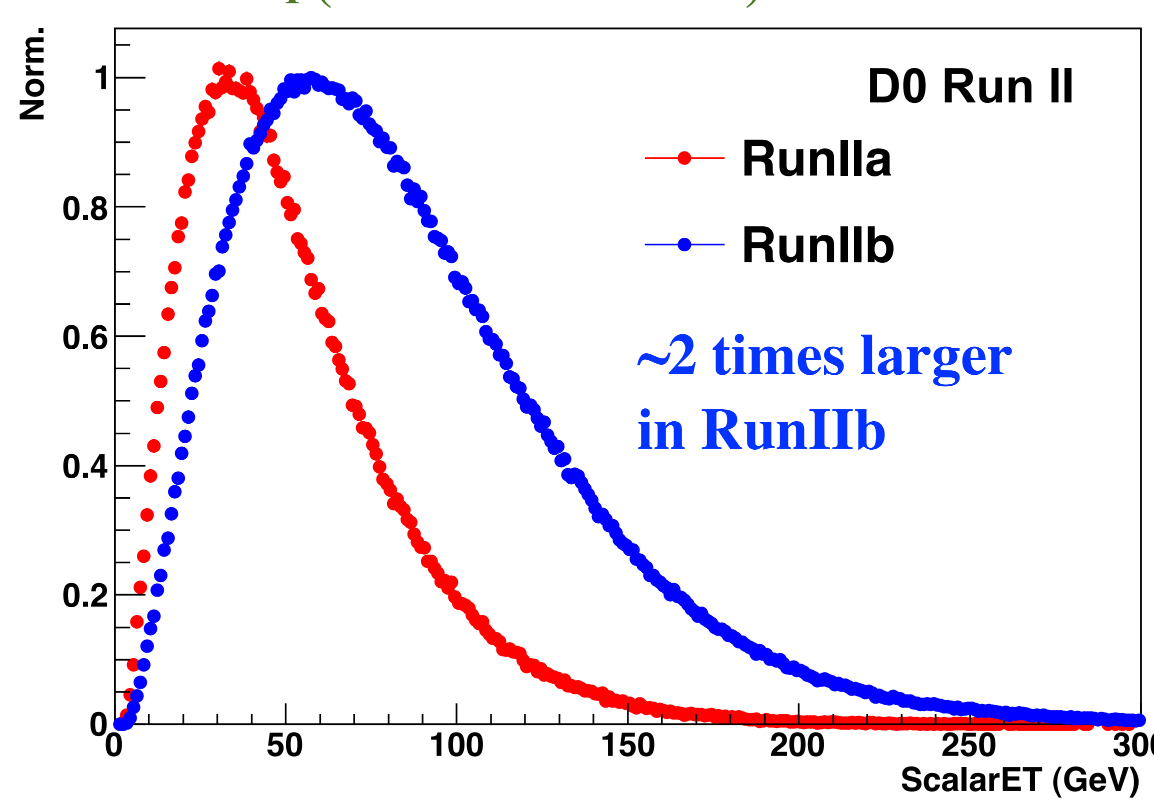
- Correction of the energy loss due to dead material,
- Correction of the response decrease due to pileup
- Modeling underlying energy contamination from pileup and hadronic recoil

Final electron energy response is tuned using Z->ee events assuming a linear response.

Inst. Lumi. from W->eν events



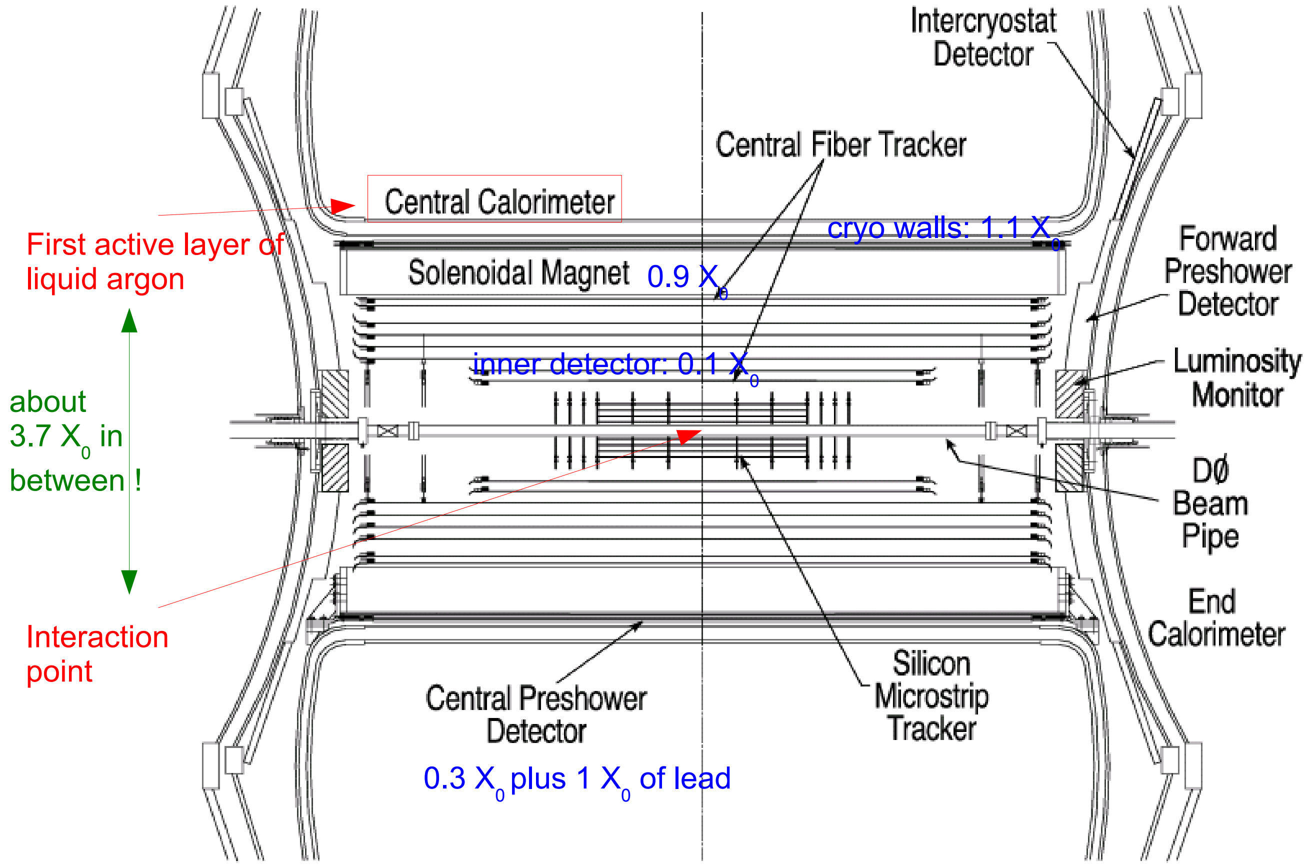
Scalar E_T (electron removed) from W->eν events



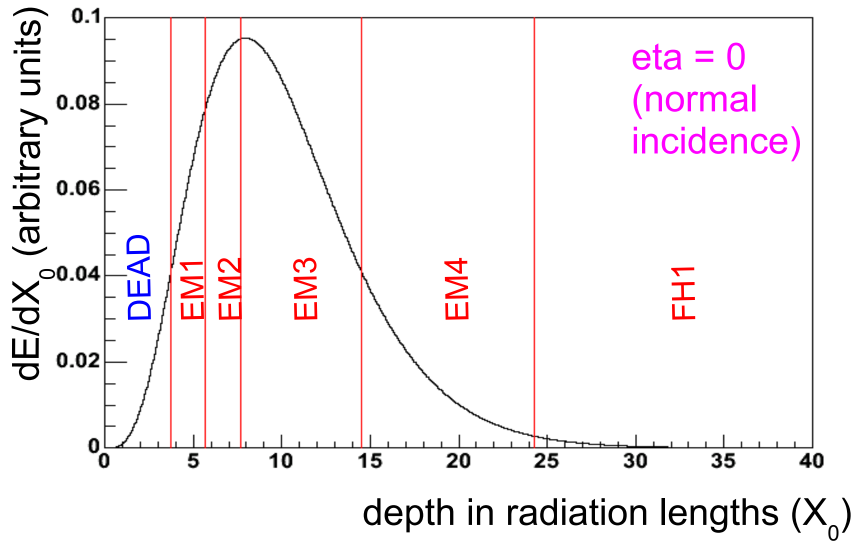
Dead material, electron energy loss

About 3.7 X_0 dead material in front of EM calorimeter

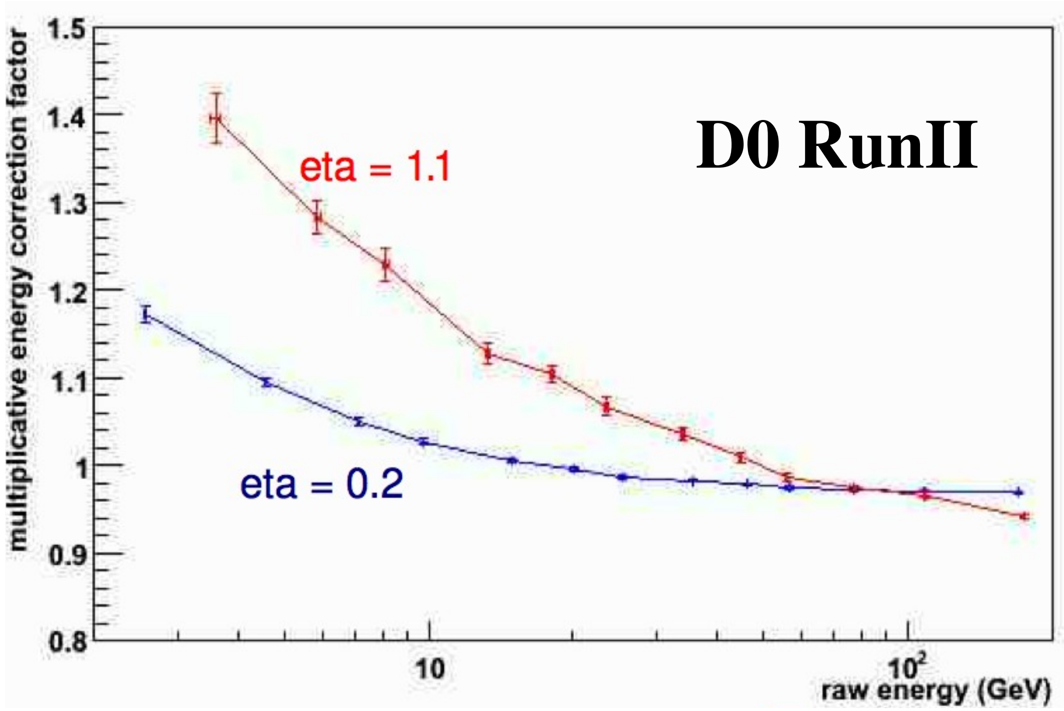
- Electrons start to loose energy before flying to the EM calorimeter
- Depends on electron energy and incidence angle (eta)



dE/dX vs. depth



E-loss correction factors

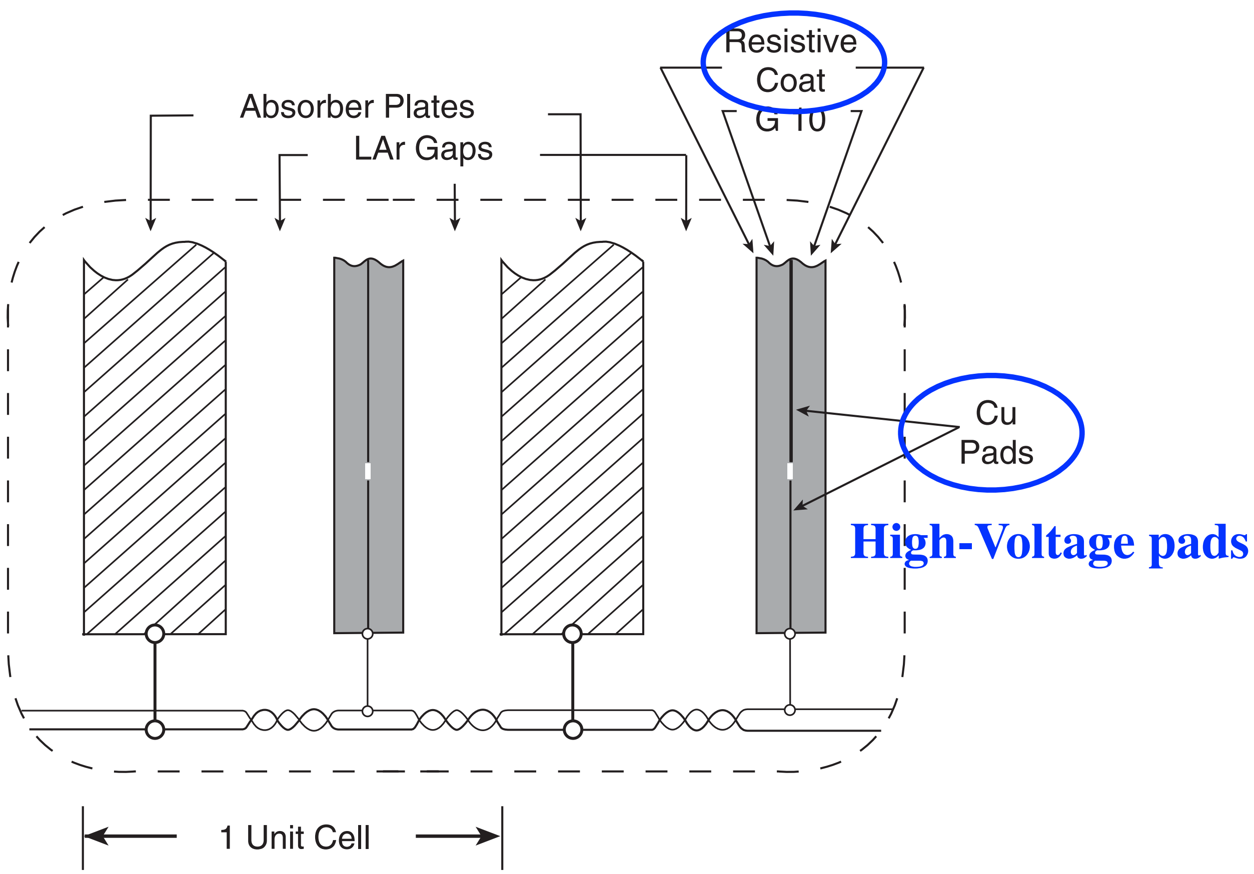


Response reduction due to pileup

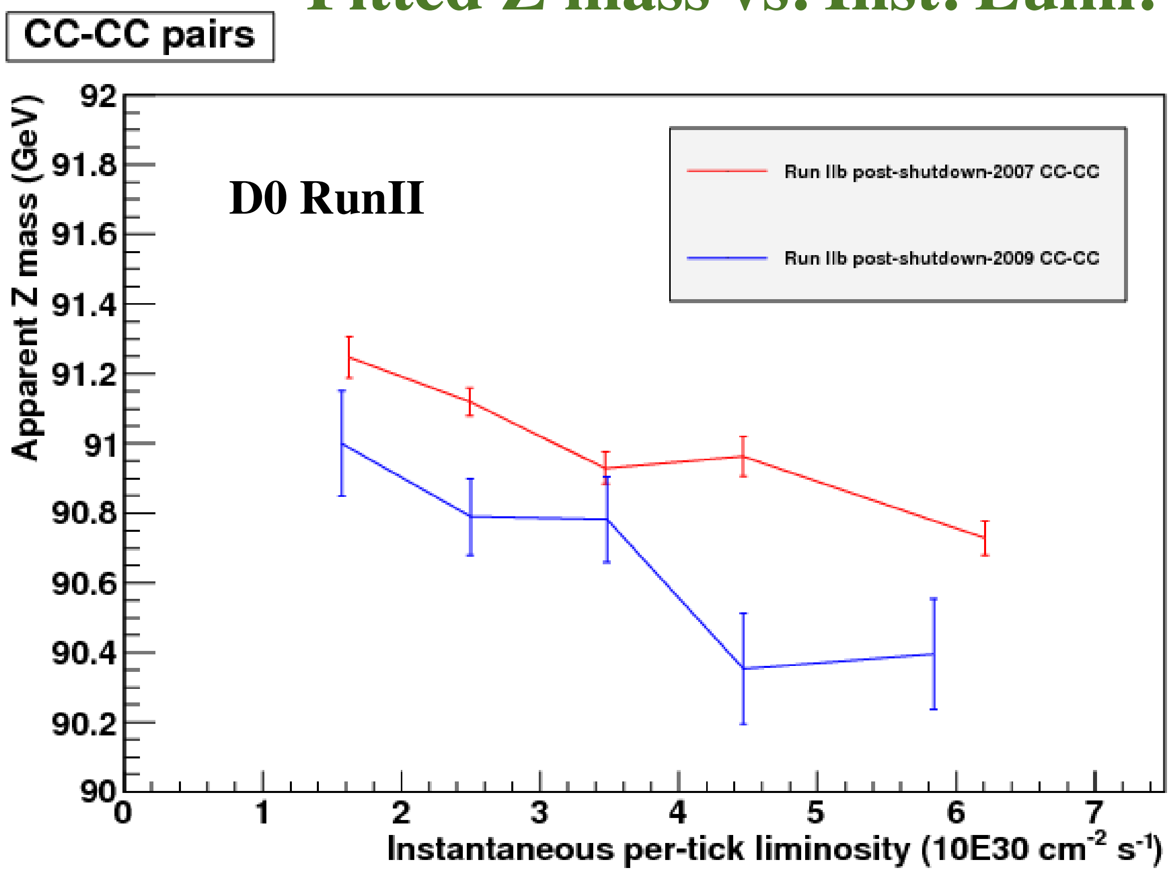
Pileup causes reduction of energy response!

- Too much pileup creates high current in the readout
- The current that flows through resistive coat of the HV pads results in HV drops, thus, reduces the energy response

Unit cell of the LAr calorimeter readout



Fitted Z mass vs. Inst. Lumi.



Energy gain due to pileup

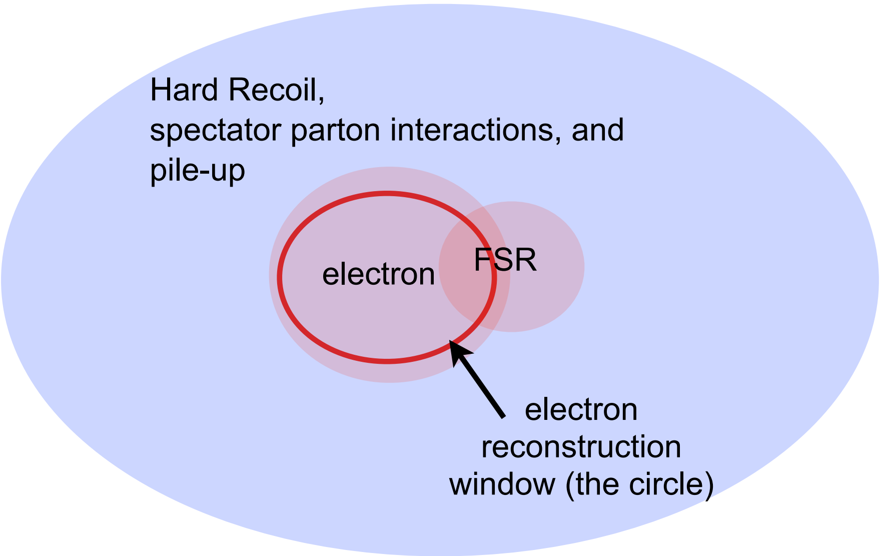
Electron Model:

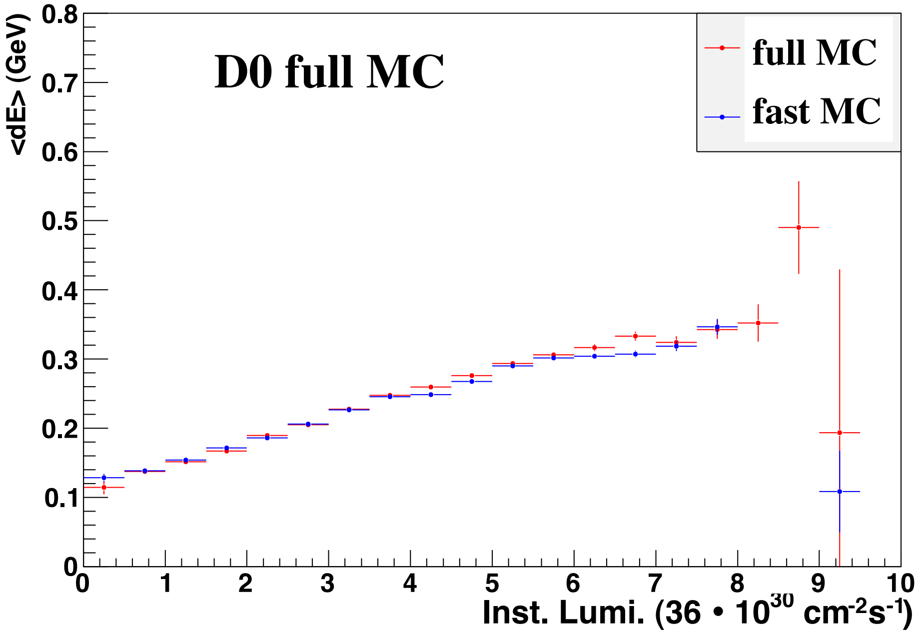
$$E_{reco} = R_{EM}(E_{true}) \otimes \sigma_{EM}(E_{true}) + \Delta E_{corr}$$

Response — Resolution — Energy contamination

ΔE_{corr} Model:

1. Energy loss due to FSR
2. Recoil, spectator partons interactions and pileup contamination inside the electron reconstruction cone
3. Effects due to electronics noise subtraction and baseline subtraction (to subtract residue energy deposition from previous bunch crossings)





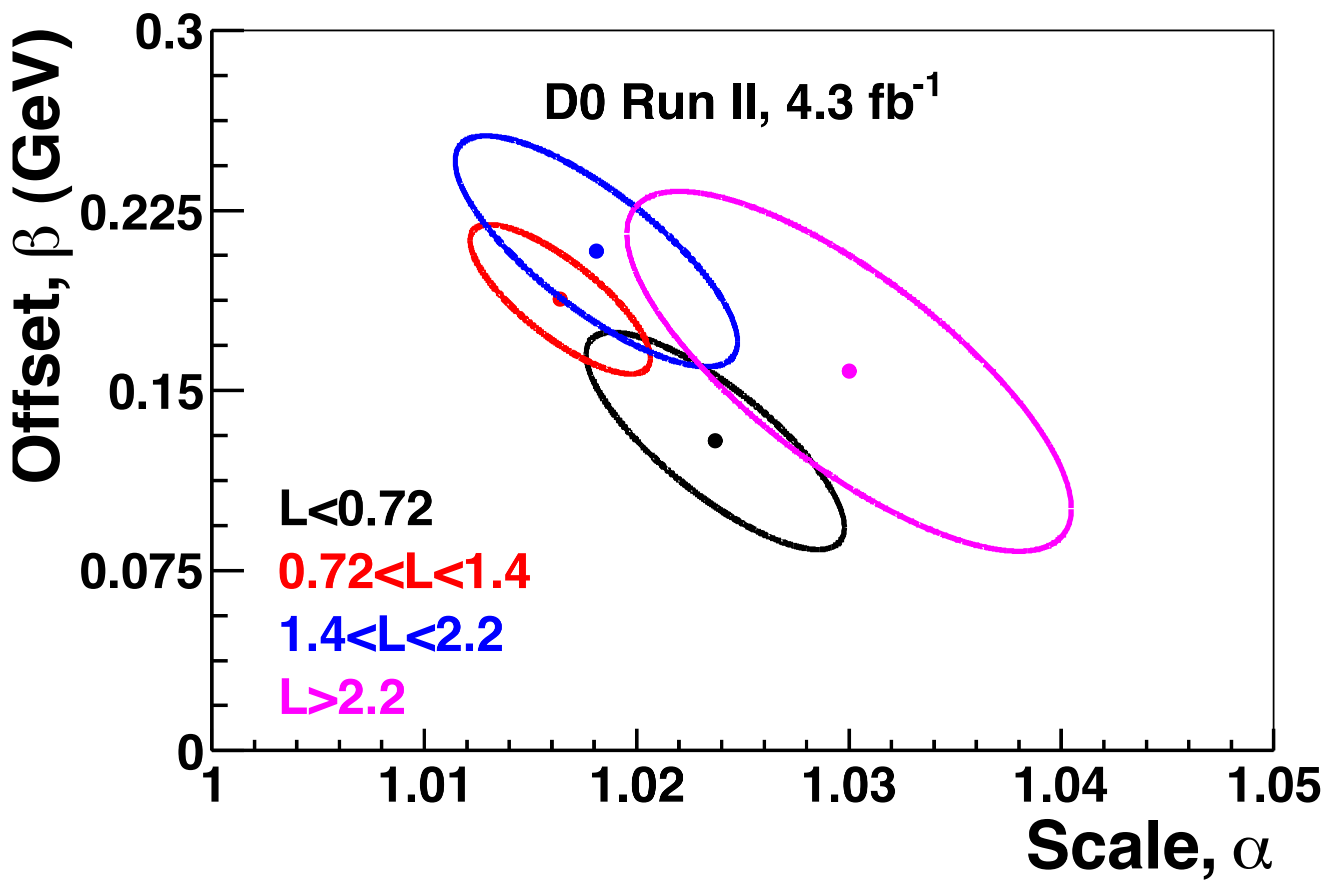
Final electron energy scale

After the correction and modeling of the non-linear energy responses, the final electron energy response is calibrated using Z->ee events assuming a linear response:

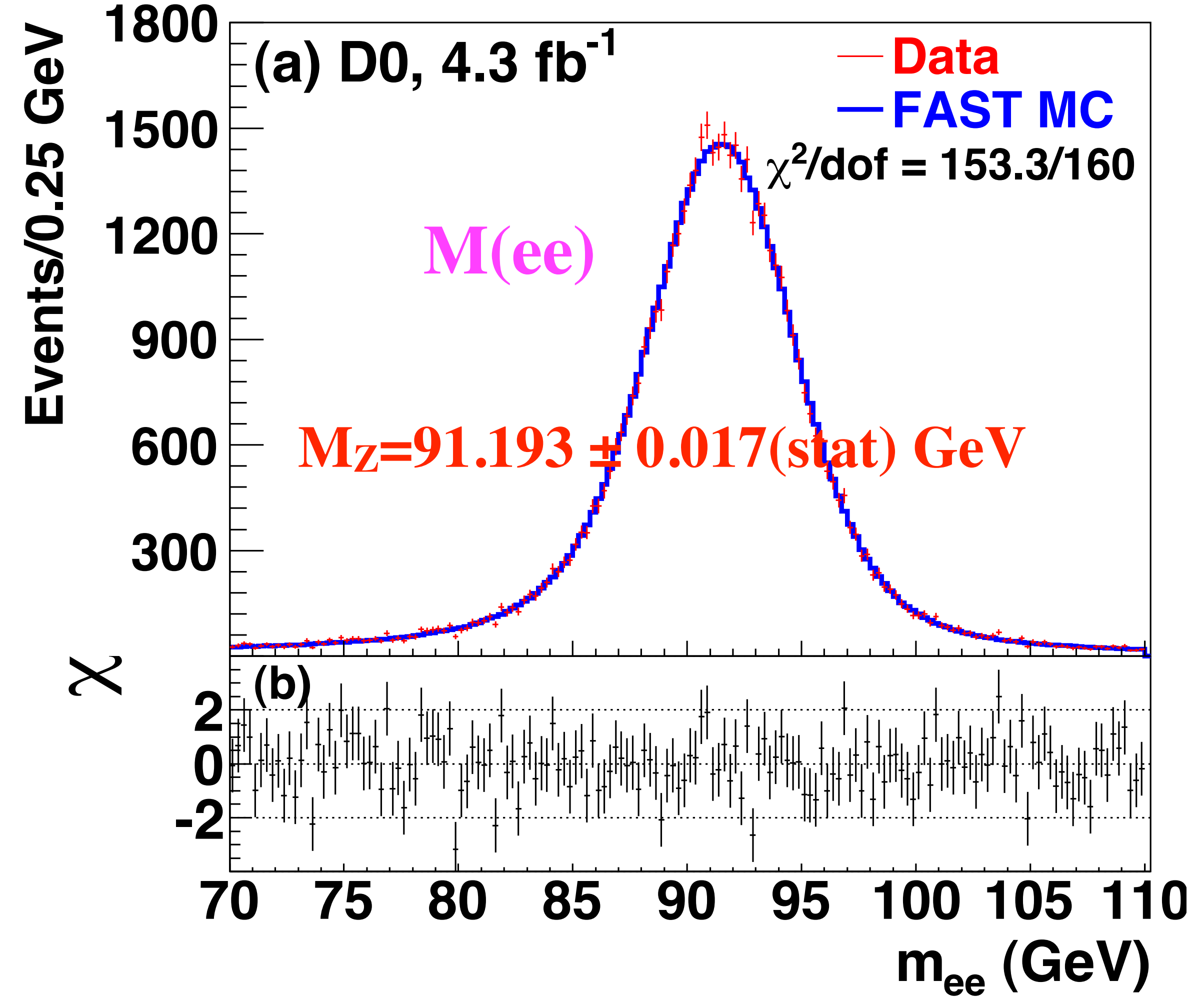
$$R_{EM}(E_{true}) = \alpha \cdot (E_{true} - \bar{E}_{true}) + \beta + \bar{E}_{true}$$

Essentially, measuring the ratio M_W/M_Z , limited by the Z->ee statistics

Scale and offset are determined in 4 inst. lumi. bins



Fit back to determine the Z mass:



Lepton energy scale at CDF

Tracker calibration (for muon channel)

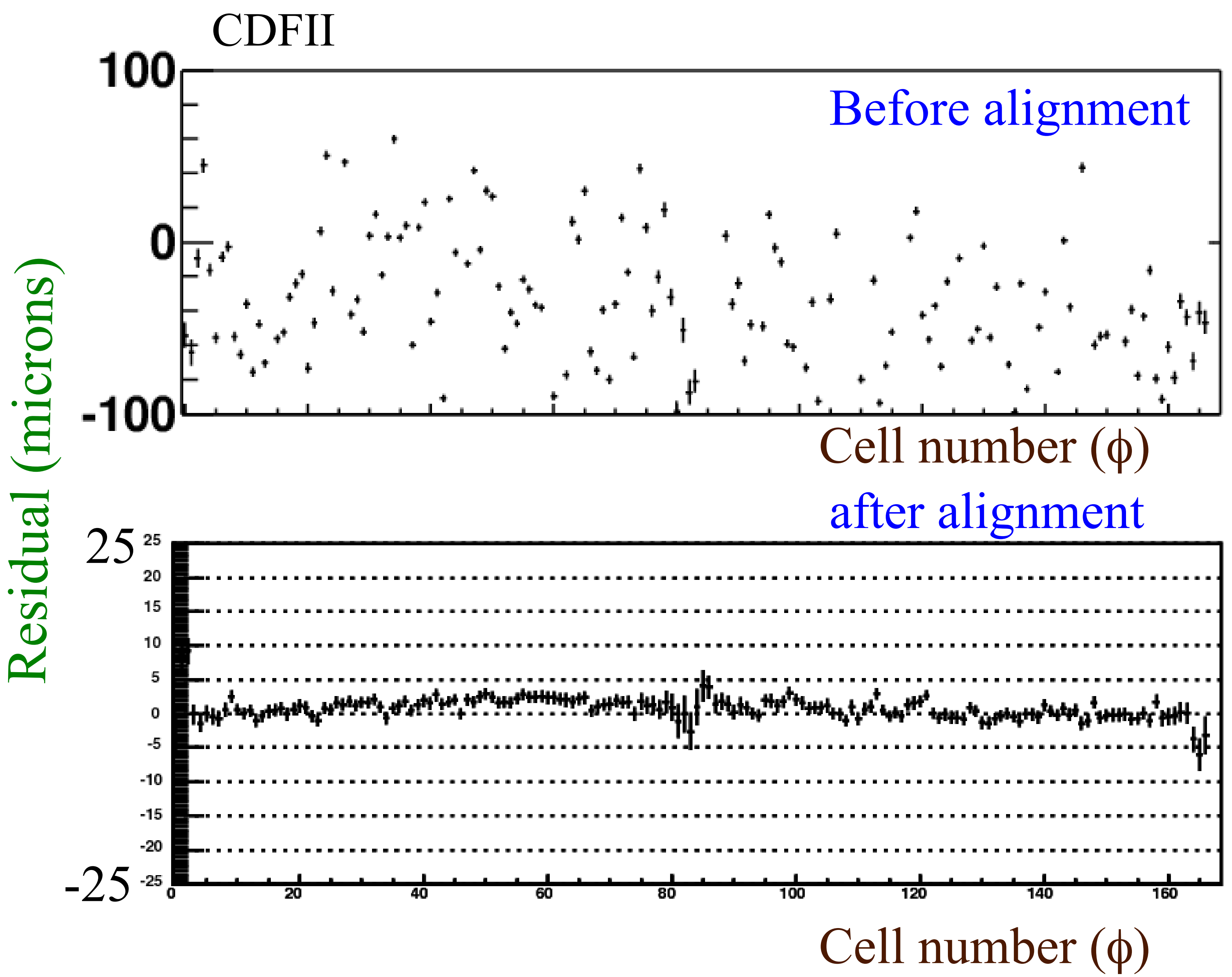
- tracker alignment using cosmic rays
- tracker momentum scale and non-linearity constrained using $J/\psi \to \mu\mu$ and $\Upsilon \to \mu\mu$ events
- confirmed using $Z \to \mu\mu$ fits

EM calorimeter calibration (for electron channel):

- Transfer tracker momentum scale to EM calorimeter energy scale using fits to the E/p spectrum using $W \to e\nu$ and $Z \to ee$ events
- confirmed using $Z \to ee$ fits

Tracker alignment

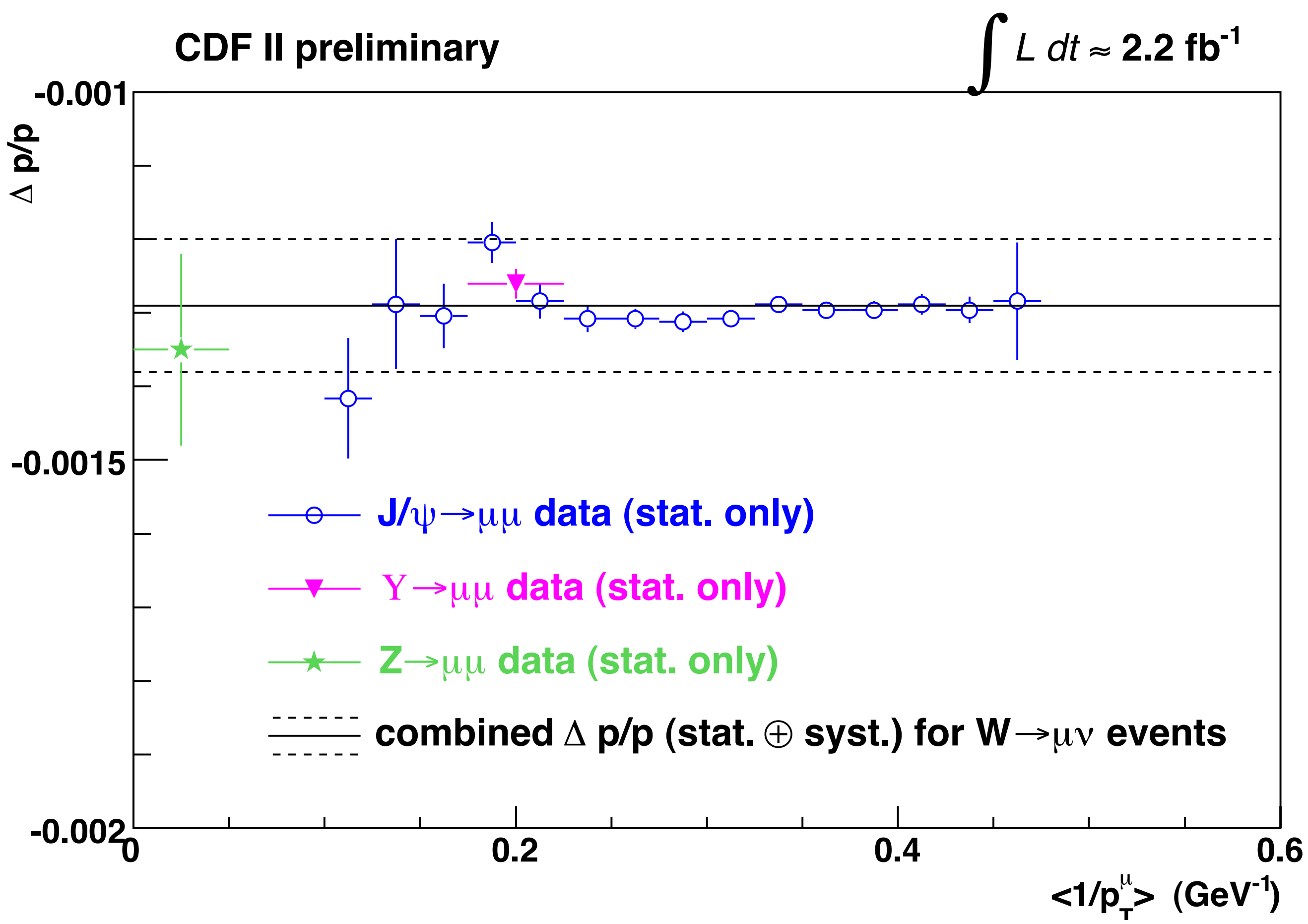
Tracking alignment using cosmic rays

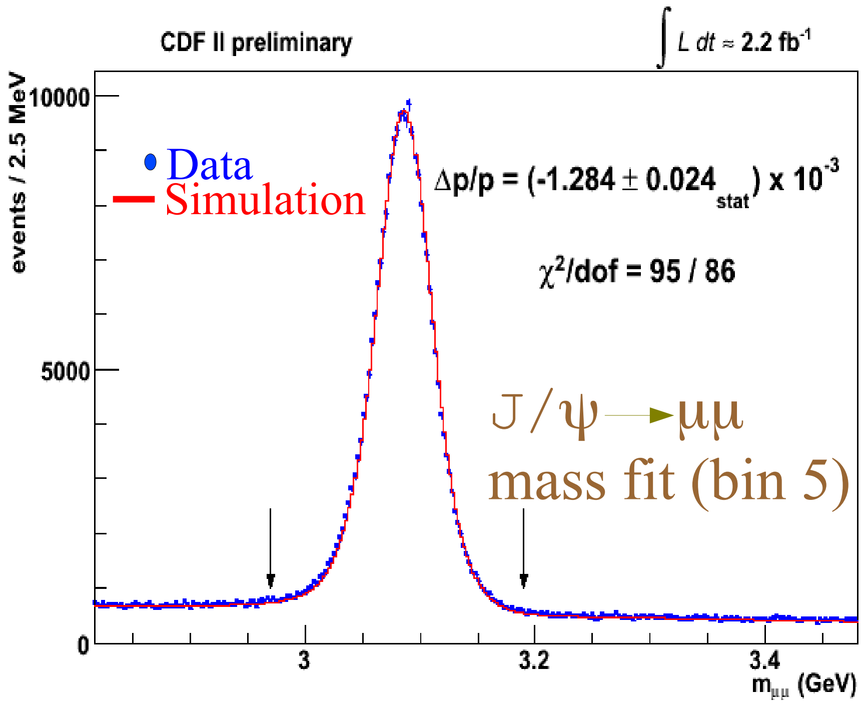


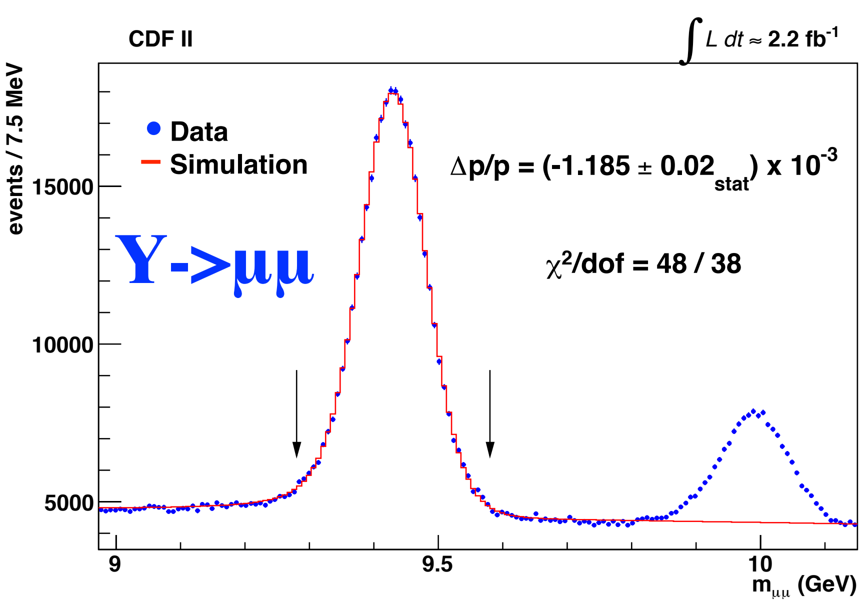
Tracking momentum scale

Tracking momentum scale is determined using J/ψ->μμ and Y->μμ events:

- **High statistics J/ψ->μμ and Y->μμ events !! (in contrast to D0)**
- **Extract momentum scale by fitting J/ψ mass in bins of $p_T(\mu)$**
- **Also using fit to Y->μμ mass**

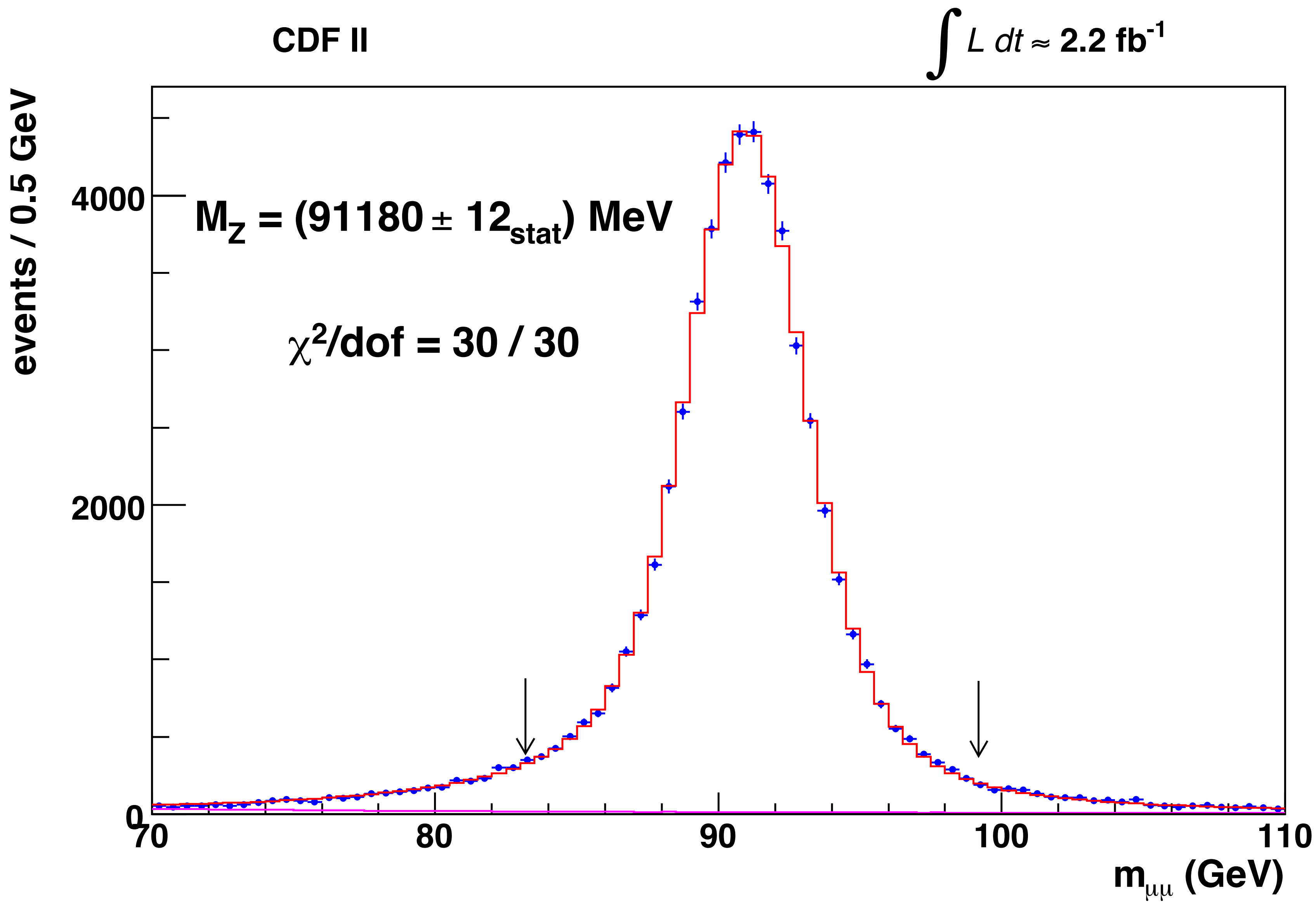






Tracking momentum scale

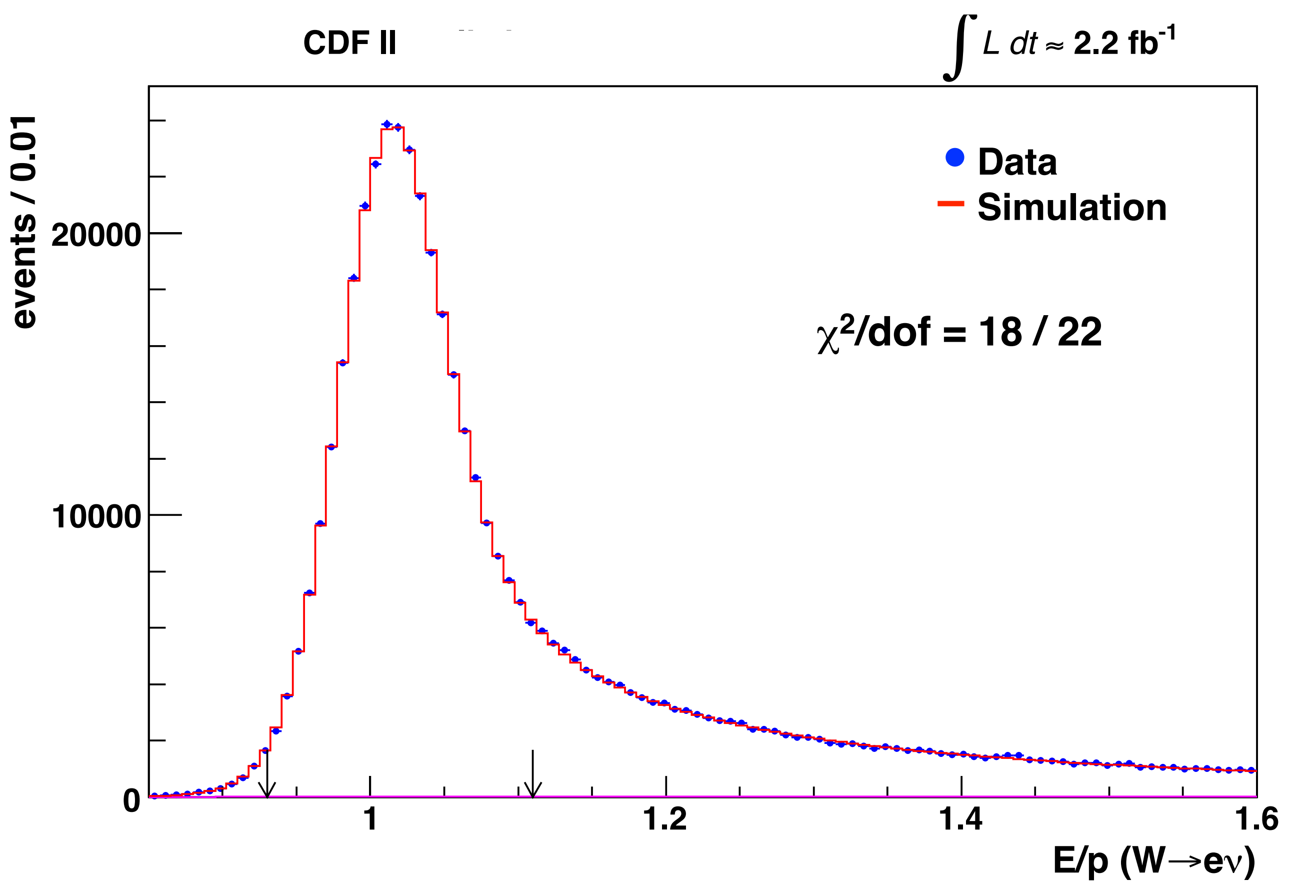
Examine the momentum scale by fitting to Z ->μμ mass

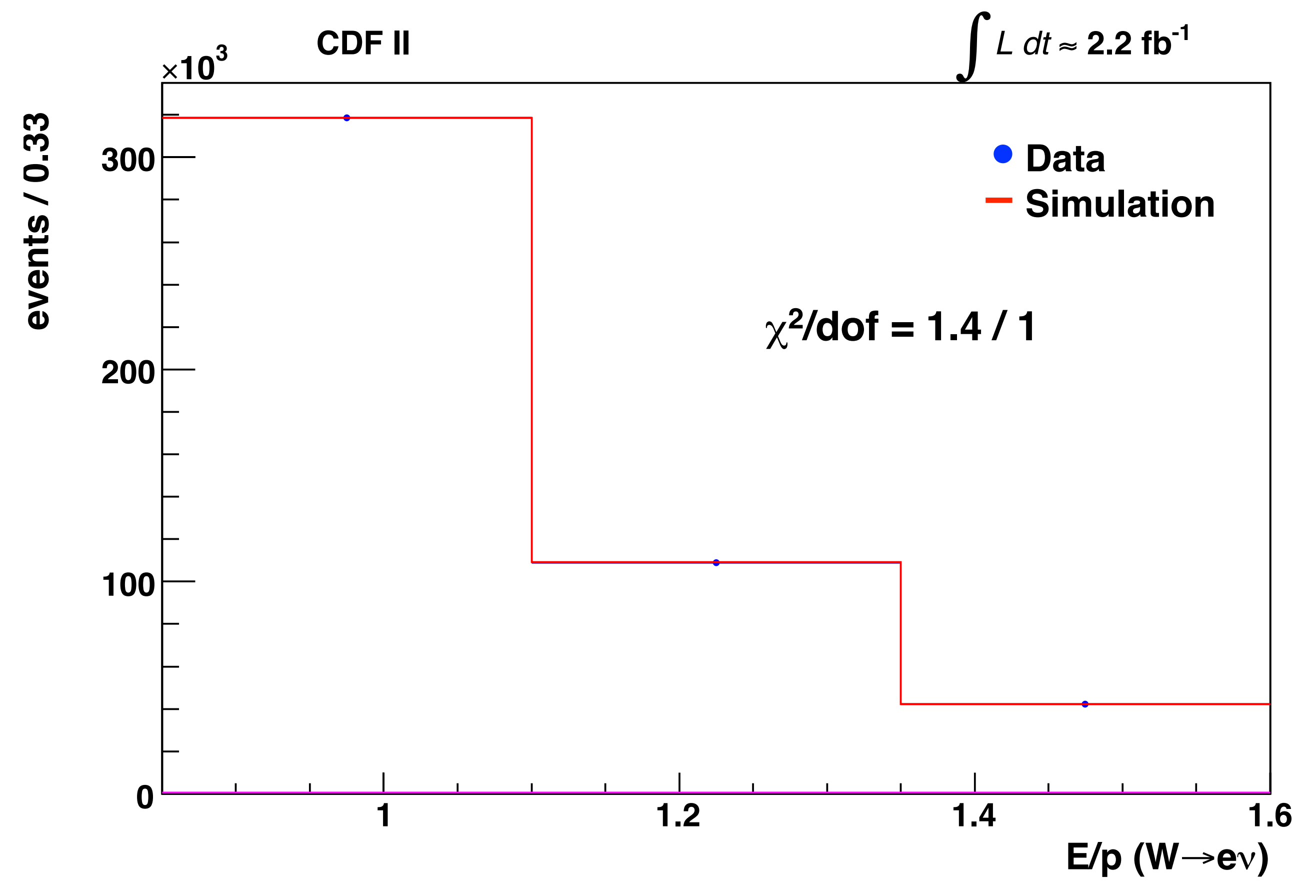


Electron energy scale

Determine electron energy scale by transferring tracking momentum scale !

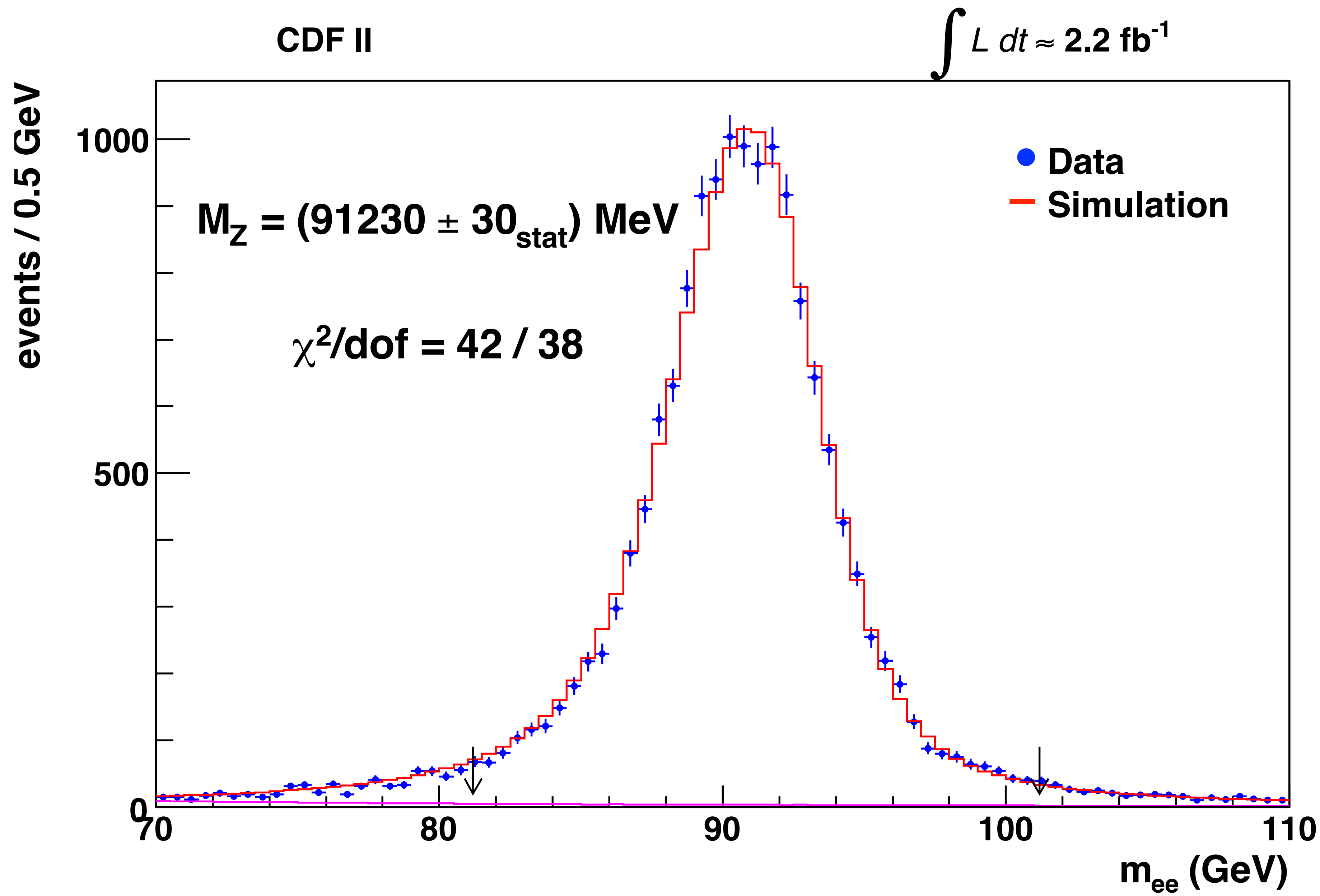
- using E(cal)/P(track) distributions of electrons in W->eν and Z->ee events
- Fit to peak to determine the energy scale
- Fit to the tail to tune the dead material





Electron energy scale

Examine the energy scale by fitting to Z ->ee mass



Hadronic recoil modeling

Recoil Model:

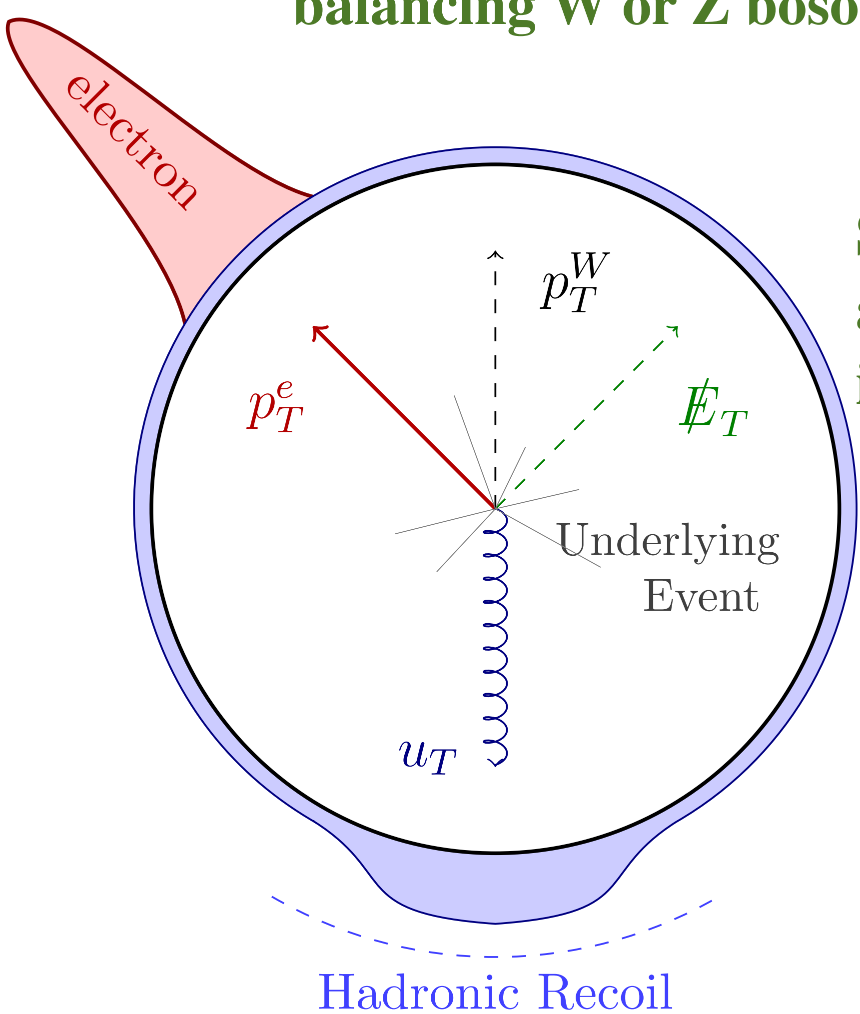
$$\vec{u}_T = \vec{u}_T^{\,\mathrm{Hard}} + \vec{u}_T^{\,\mathrm{Soft}} + \vec{u}_T^{\,\mathrm{Elec}} + \vec{u}_T^{\,\mathrm{FSR}}$$

"pure" Hard Recoil balancing W or Z boson

Soft Recoil: pileup and spectator parton interactions

Recoil energy that falls in the electron reconstruction window, as well as electron energy leakage to the recoil.

FSR photons that fly outside the electron reconstruction window.

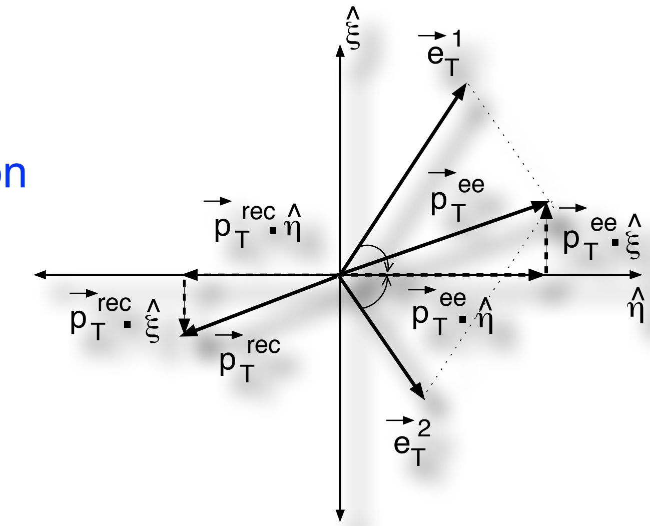


Recoil tuning at D0

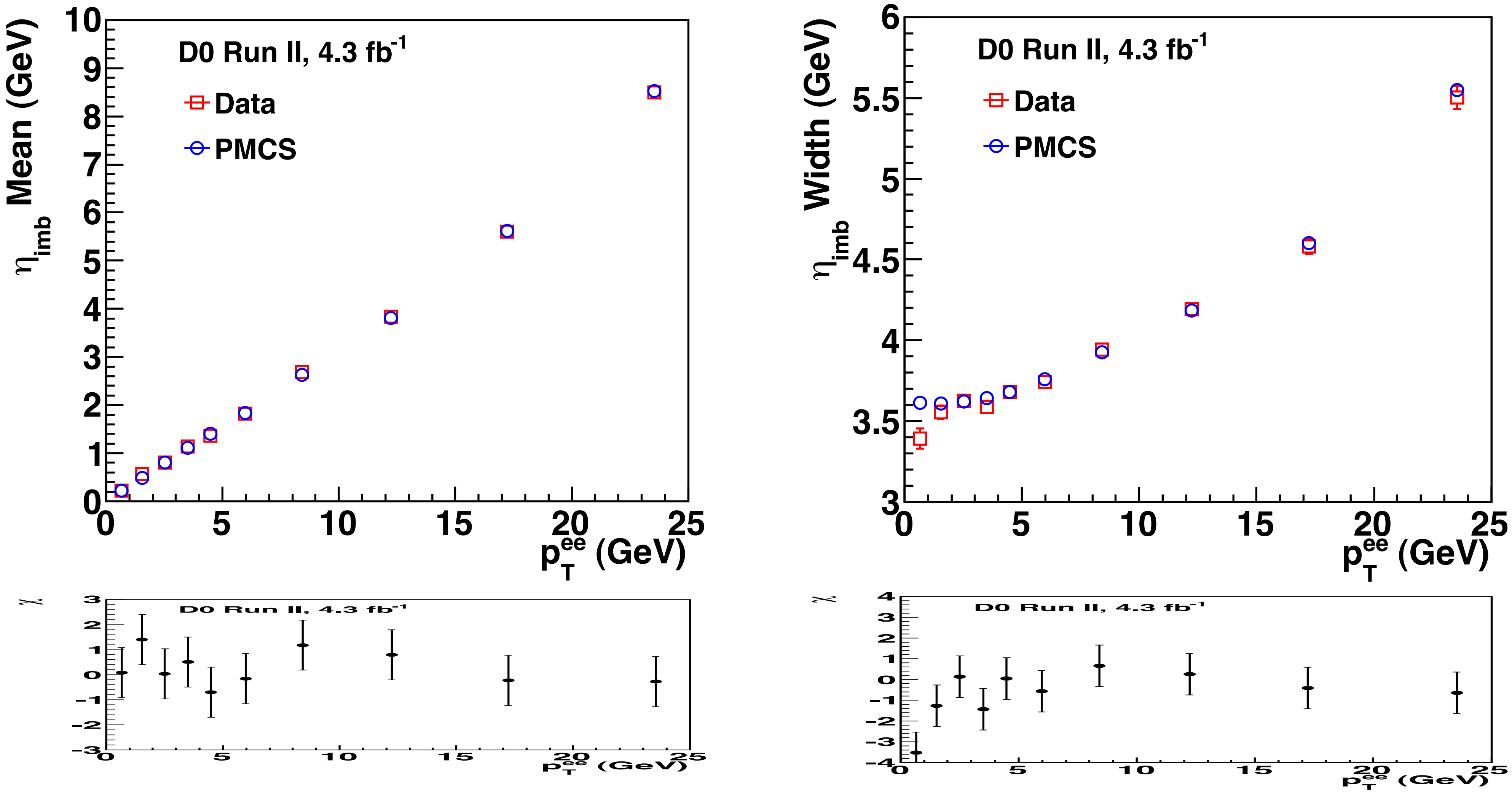
The recoil model is fine tuned using standard UA2 observables

$$\eta_{imb} = (\vec{p}_T^{\,e} + \vec{u}_T) \cdot \hat{\eta}$$

η-axis: the bisector of two electron momenta of Z->ee events



- **Use the mean of η-imbalance to tune the recoil response**
- **Use the width of η-imbalance to tune the recoil resolution**

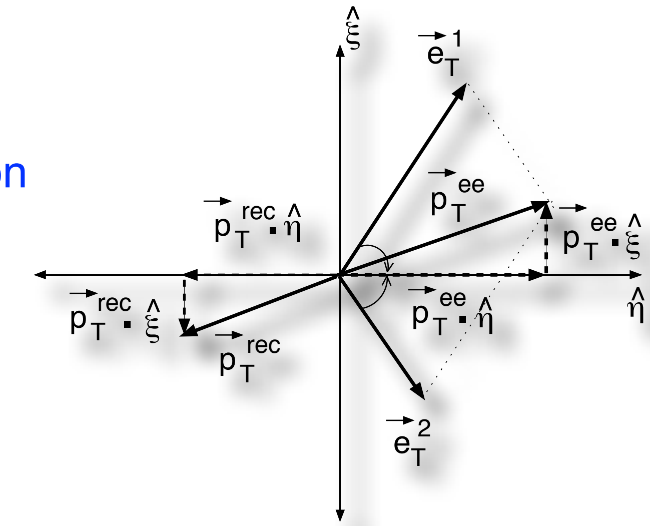


Recoil tuning at CDF

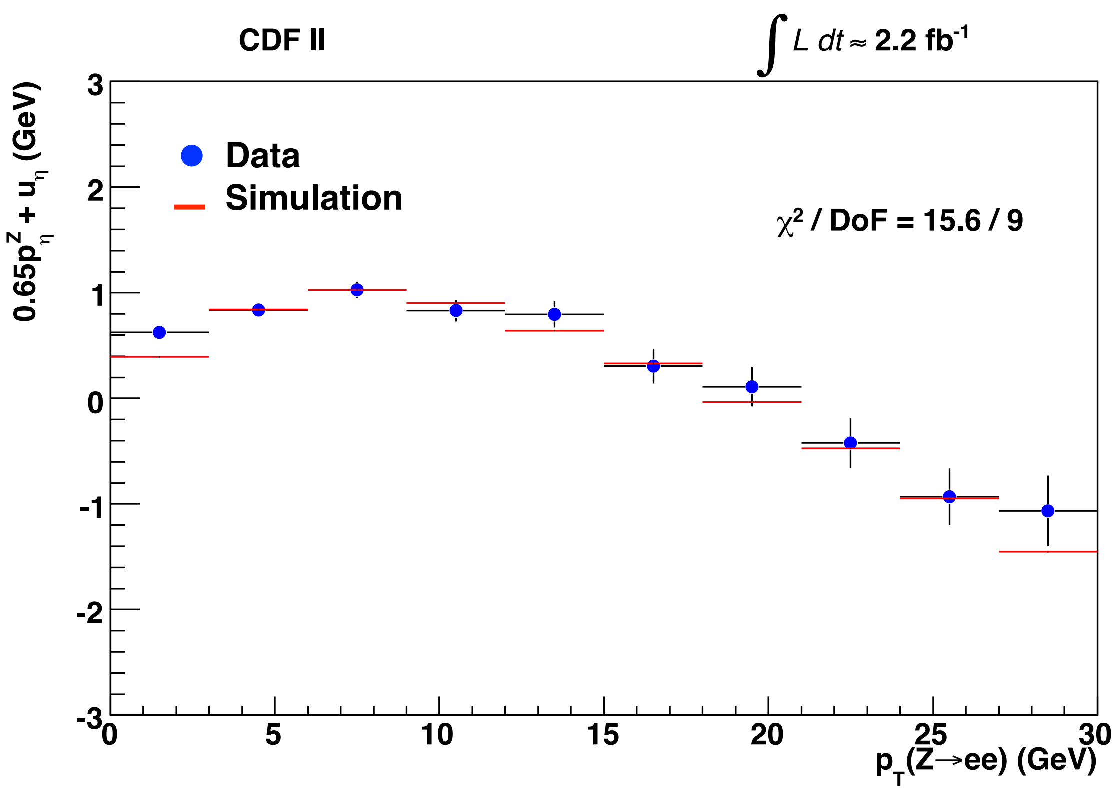
Similar to D0, just that at CDF the η-imbalance is defined as:

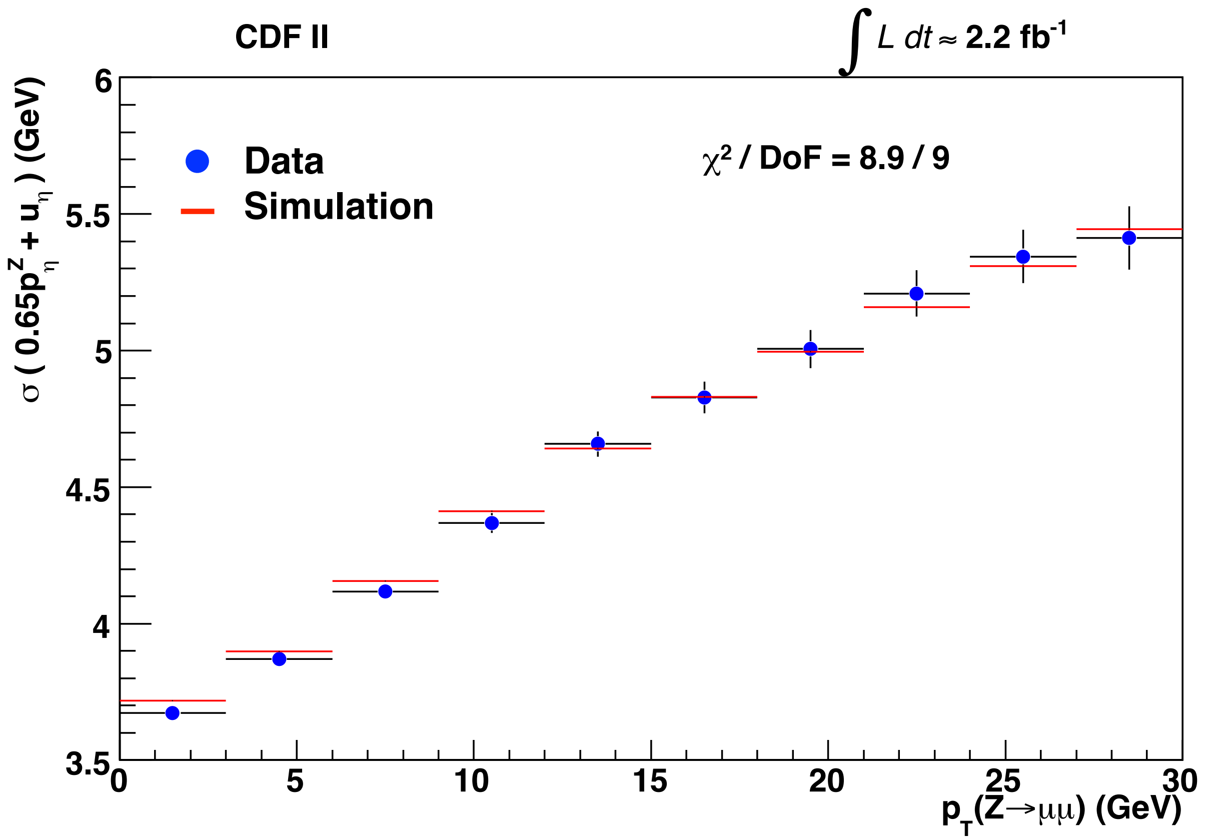
$$\eta_{imb} = (0.65 \cdot \vec{p}_T^{\,Z} + \vec{u}_T) \cdot \hat{\eta}$$

η-axis: the bisector of two electron momenta of Z->ee events



- **Use the mean of η-imbalance to tune the recoil response**
- **Use the width of η-imbalance to tune the recoil resolution**

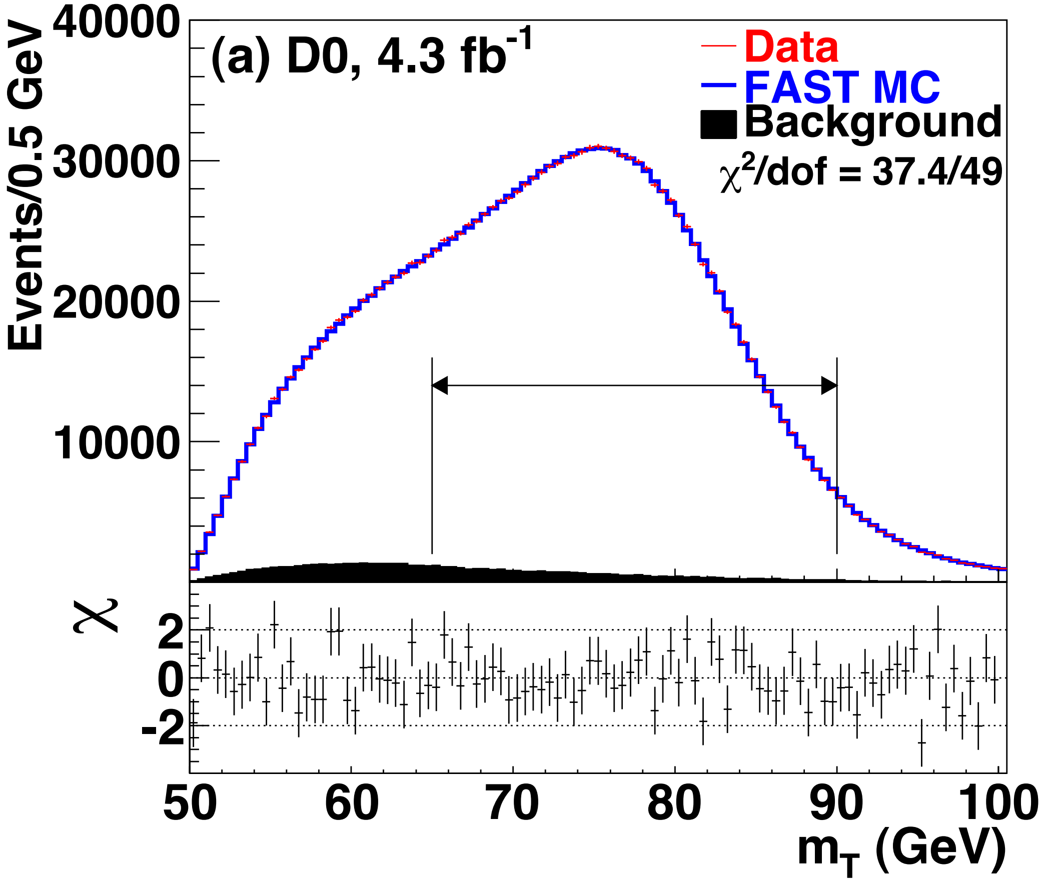


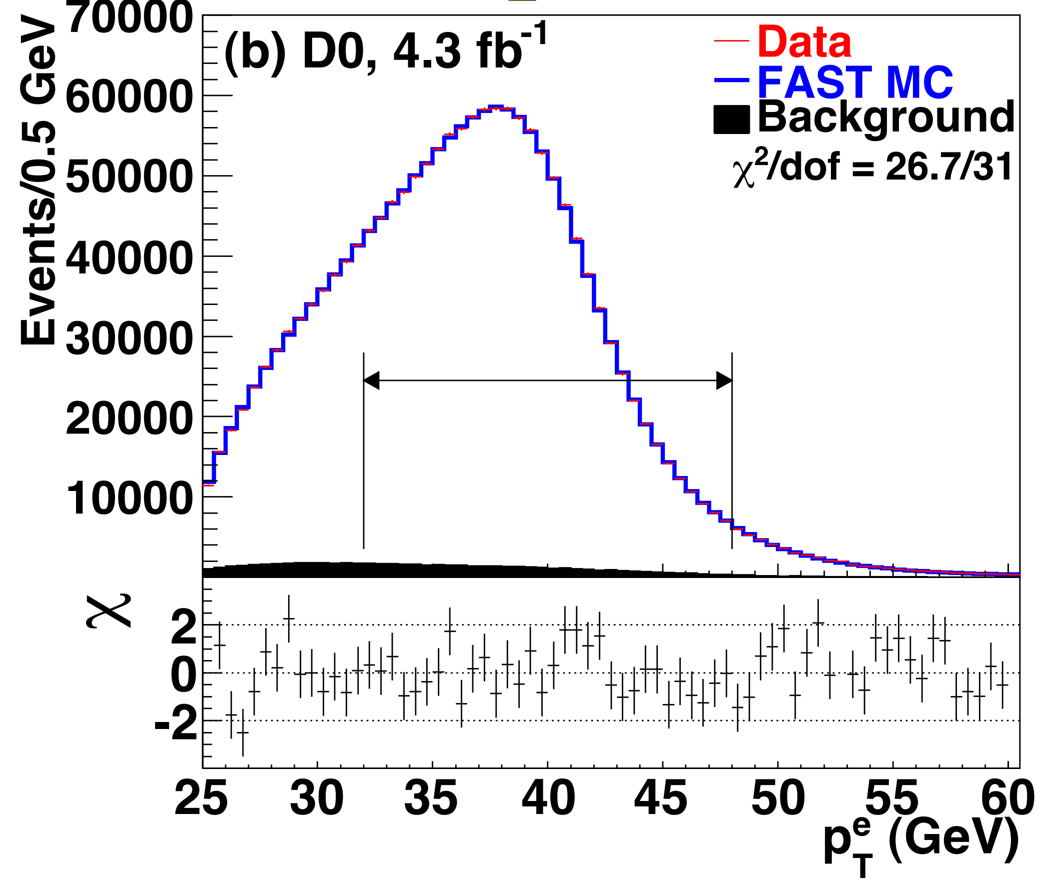


W mass: Results

Results from D0:

M_T **$p_T(e)$**



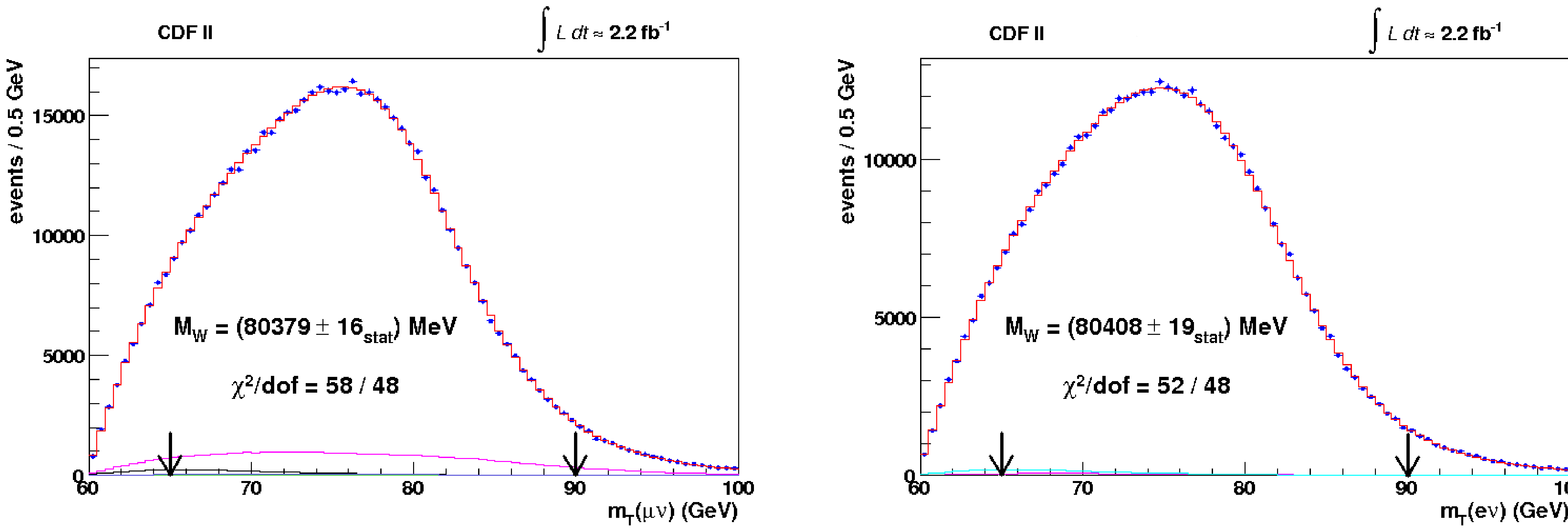


Method $(4.3\ fb^{-1})$	M_W (MeV)
$m_T(e,\nu)$	80371 ± 13(stat)
$p_T(e)$	80343 ± 14(stat)
$\not{E}_T(e,\nu)$	80355 ± 15(stat)
Combination $m_T \oplus p_T$ $(4.3\ fb^{-1})$	80367 ± 26(syst + stat)
Combination $(5.3\ fb^{-1})$	**80375 ± 23**(syst + stat)

23 MeV was the previous world average!

W mass: Results

Results from CDF:



Method $(2.2\ fb^{-1})$	M_W (MeV)	Method $(2.2\ fb^{-1})$	M_W (MeV)
$m_T(\mu,\nu)$	80379 ± 16(stat)	$m_T(e,\nu)$	80408 ± 19(stat)
$p_T(\mu)$	80348 ± 18(stat)	$p_T(e)$	80393 ± 21(stat)
$\not{E}_T(\mu,\nu)$	80406 ± 22(stat)	$\not{E}_T(e,\nu)$	80431 ± 25(stat)
Combination $(2.2\ fb^{-1})$		$\mathbf{80387 \pm 19}\ MeV$ (syst + stat)	

Most precise single experiment result!

Systematic uncertainties at D0

D0 4.3 fb^{-1}, e-channel

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	16	17	16
Electron Energy Resolution	2	2	3
Electron Energy Nonlinearity	4	6	7
W and Z Electron energy loss differences	4	4	4
Recoil Model	5	6	14
Electron Efficiencies	1	3	5
Backgrounds	2	2	2
Experimental Total	18	20	24
W production and decay model			
PDF	11	11	14
QED	7	7	9
Boson p_T	2	5	2
W model Total	13	14	17
Total Systematic Uncertainty	22	24	29

Systematic uncertainties at CDF

CDF 2.2 fb-1, e- and μ-channels

Systematic (MeV)	M_T Electrons	M_T Muons	P_T^l Electrons	P_T^l Muons	$\not{E}_T$ Electrons	$\not{E}_T$ Muons
Lepton Energy Scale	10	7	10	7	10	7
Lepton Energy Resolution	4	1	4	1	7	1
Recoil Energy Scale	5	5	6	6	2	2
Recoil Energy Resolution	7	7	5	5	11	11
$u_{\|\|}$ Efficiency	0	0	2	1	3	2
Lepton Removal	3	2	0	0	6	4
Backgrounds	4	3	3	5	4	6
$p_T(W)$ Model (g_2, g_3, α_s)	3	3	9	9	4	4
Parton Distributions	10	10	9	9	11	11
QED Radiation	4	4	4	4	4	4
Total	18	16	19	18	22	20

about the PDF uncertainties

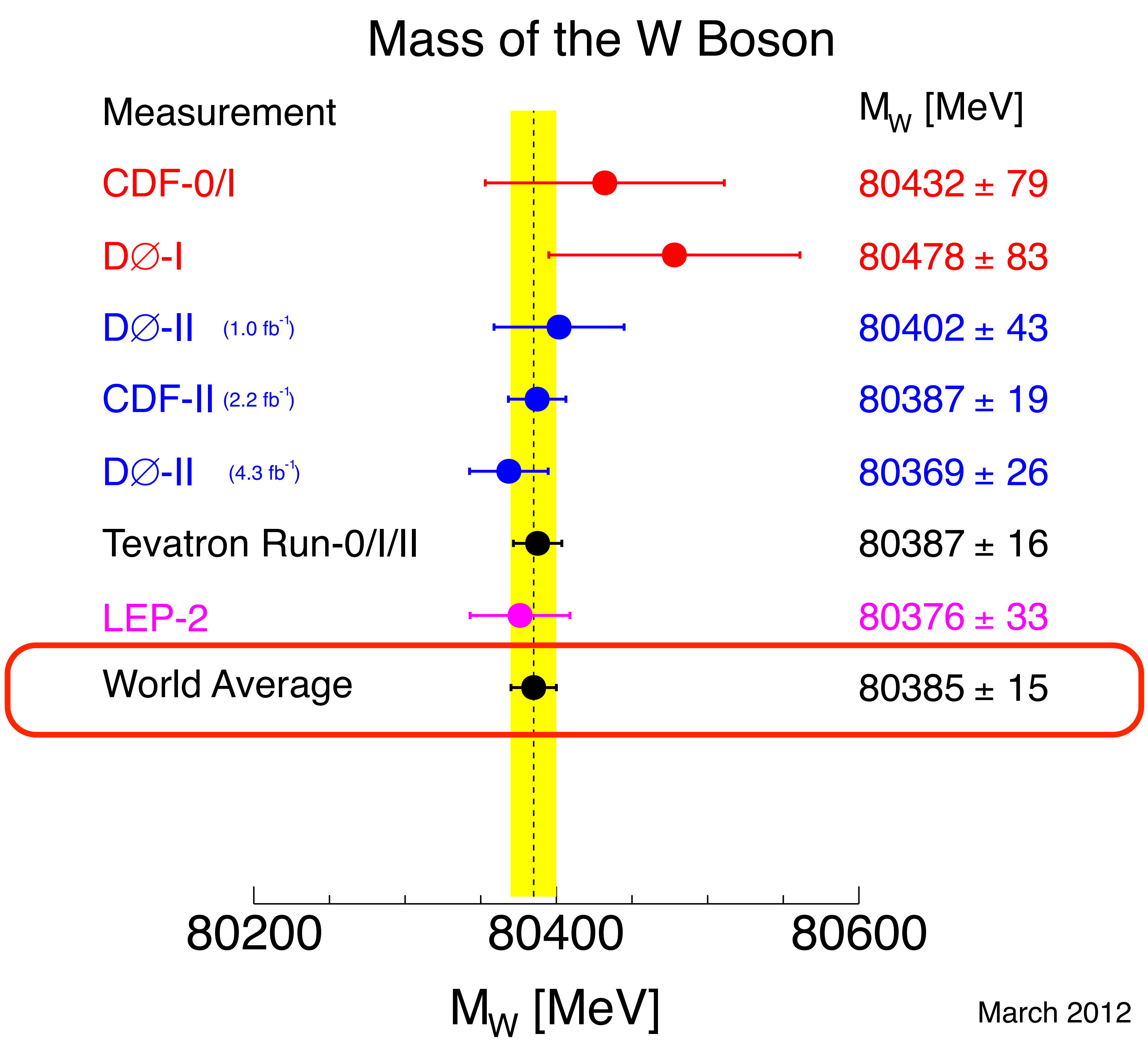
In principle, the transverse observables (e.g. mT, pT(e)) are insensitive to the uncertainties in the (longitudinal) parton distribution functions (PDF).

However, our cuts on the leptons η (|η|<1.0) is not invariant under longitudinal boosts. Changes in PDFs can modify the shapes of the transverse observables under η cuts. Therefore, PDF uncertainties are introduced.

Ways to reduce the PDF uncertainties:

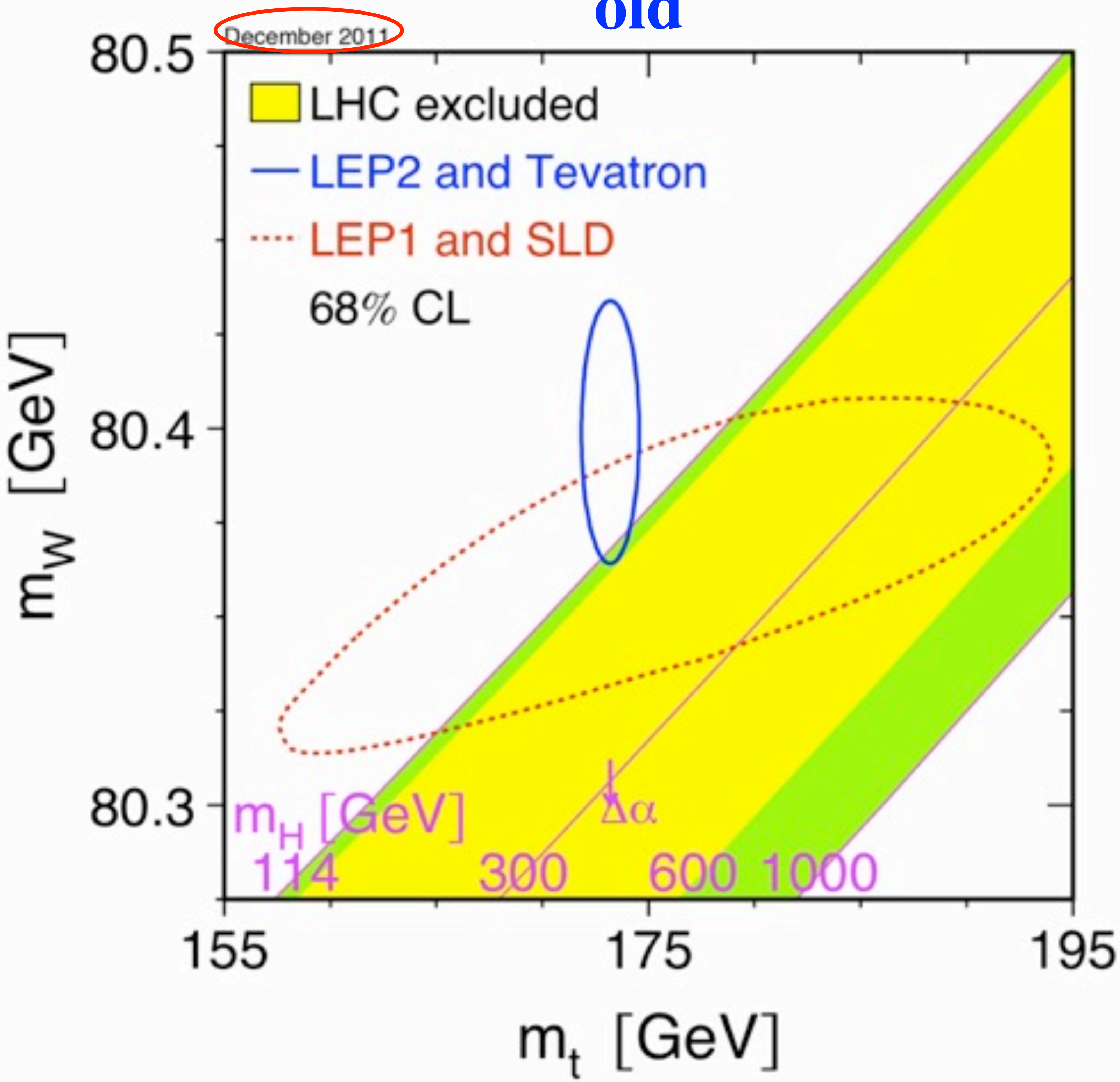
- Extending the η coverage as much as possible, including end-cap leptons:
  - Can reduce by a factor of two, need to understand the energy scale, pileup, and backgrounds for the end-cap leptons.
- Reduce the PDF uncertainties by other measurements:
  - e.g. W charge asymmetry measurements.

New world average



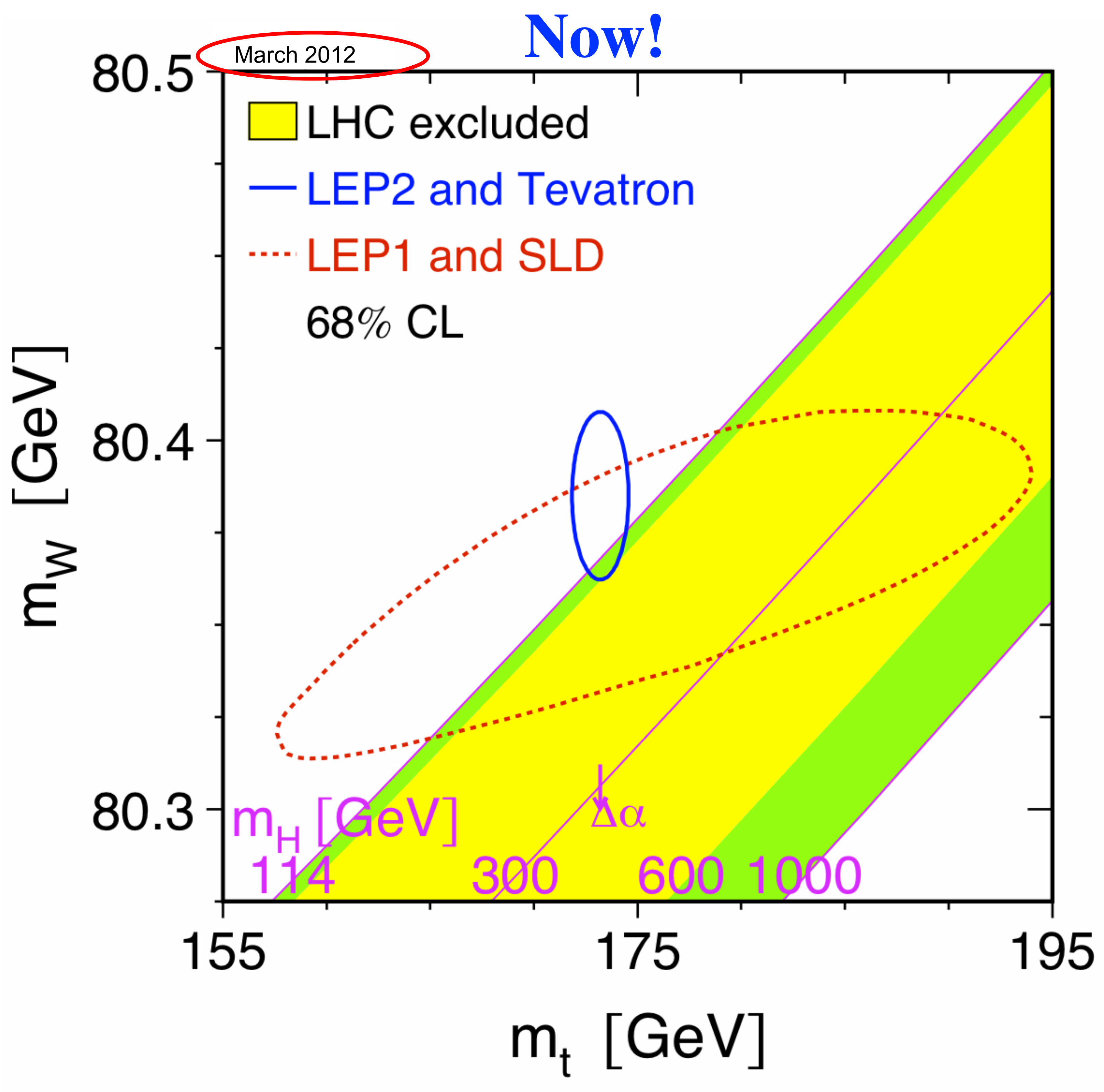
Step back...

old

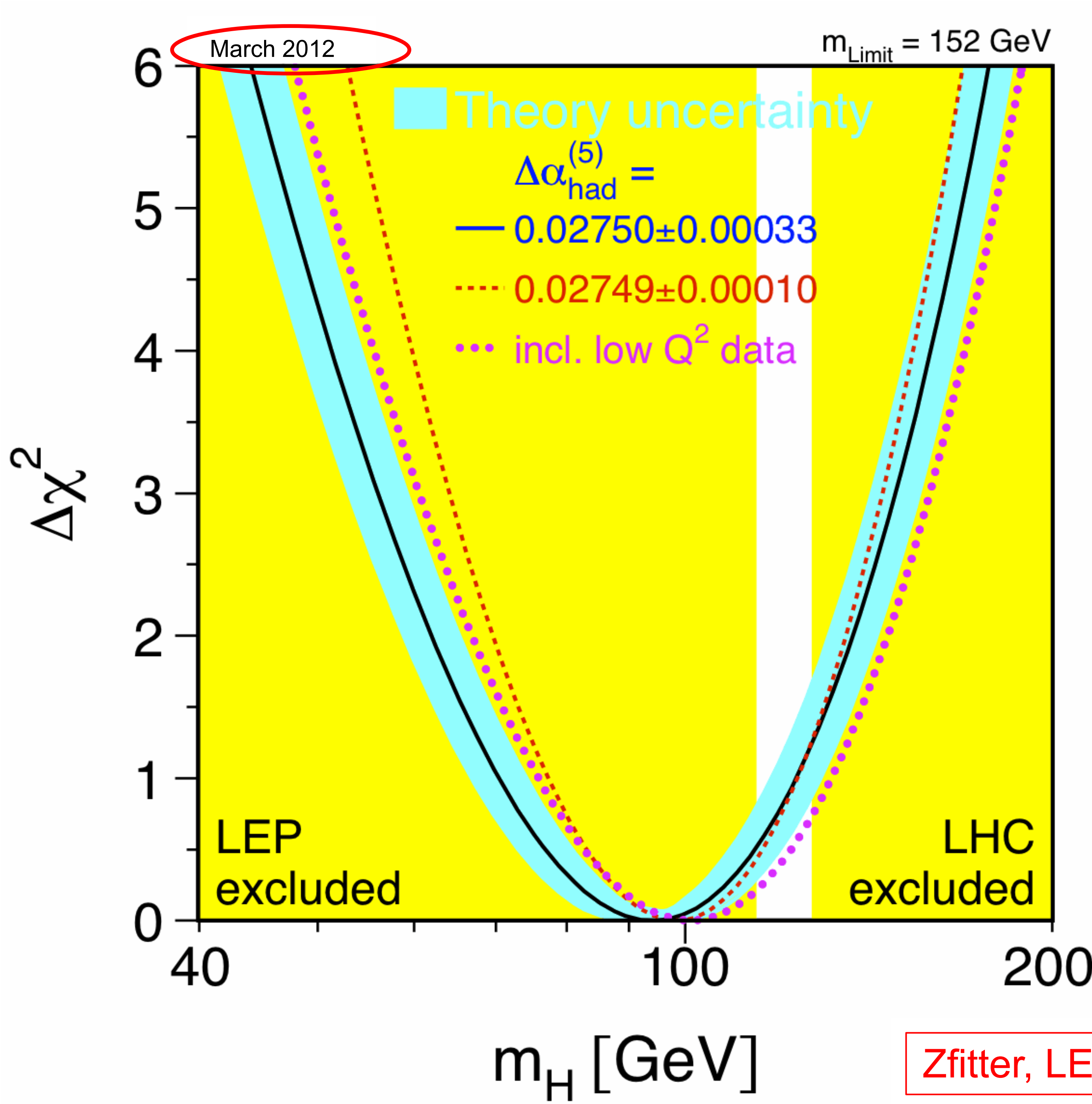


The new world average

Zfitter, LEPEWWG



W mass: Constraint on Higgs mass



Zfitter, LEPEWWG

Previous (Dec. 2011) SM Higgs fit:

$m_H = 92^{+34}_{-26}$ GeV

$m_H < 161$ GeV @ 95% C.L.

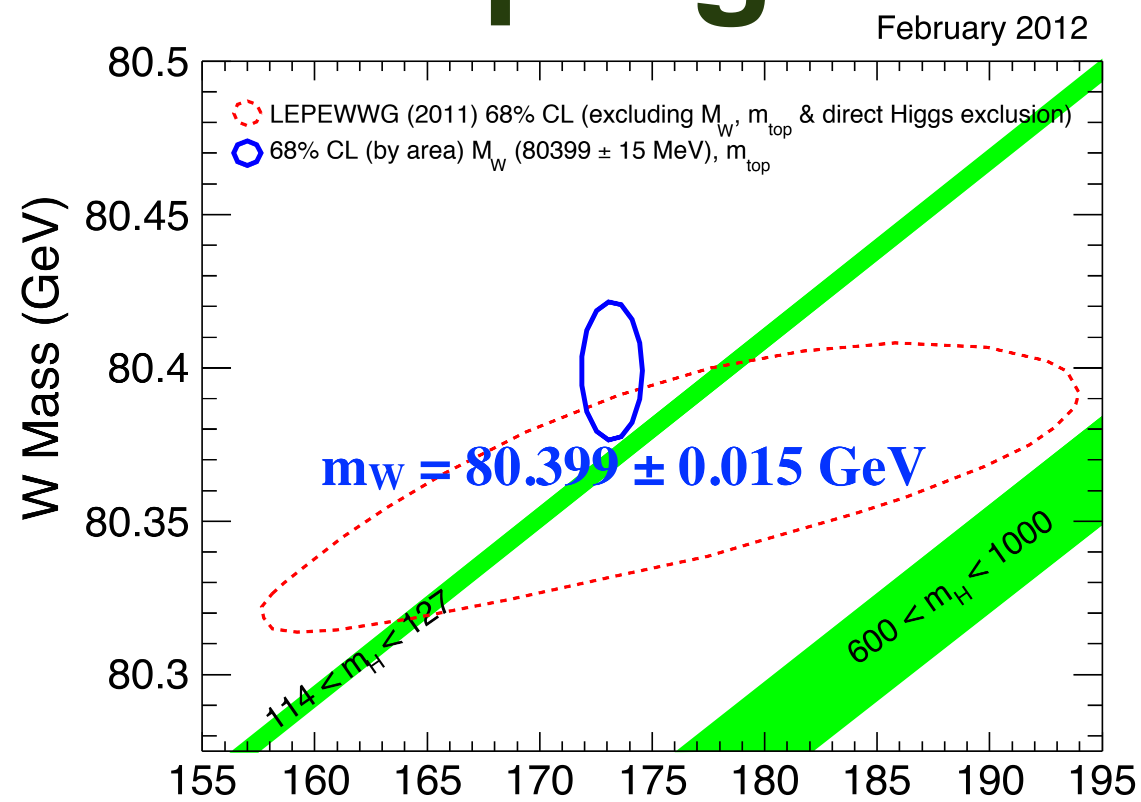
New prel. SM Higgs fit:

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

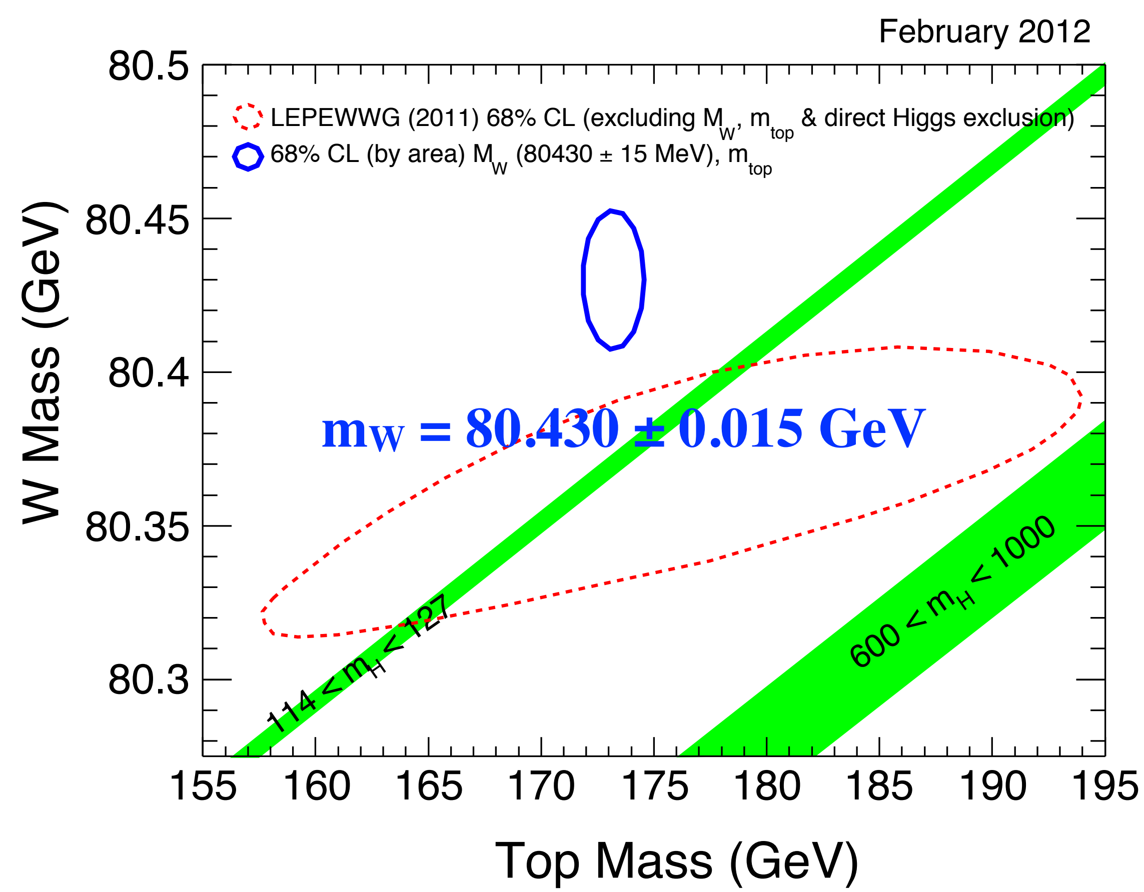
$m_H < 152$ GeV @ 95% C.L.

We were hoping

Before the results came out, we were hoping ...



and even more ...

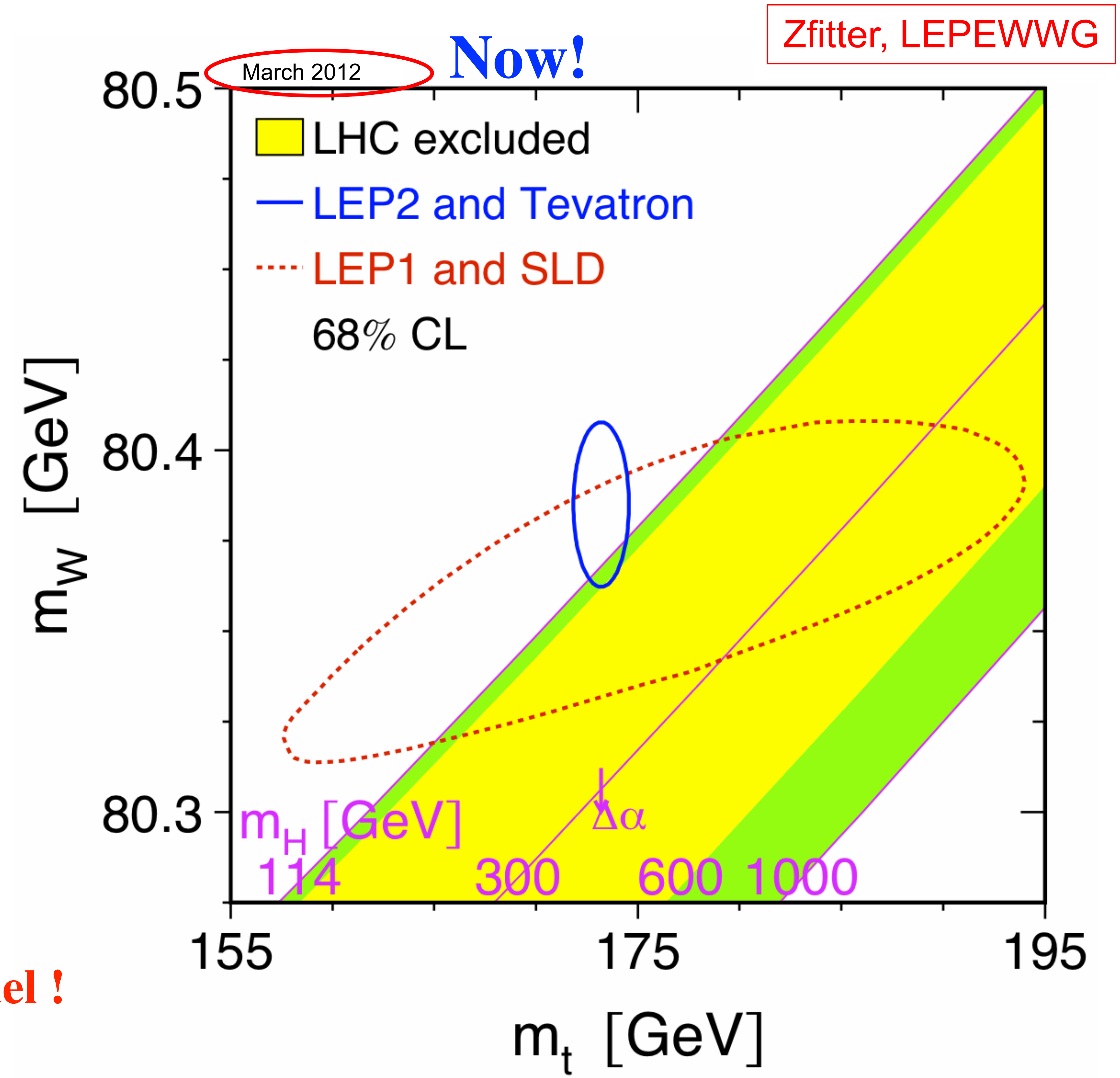


The new world average

When we knew this at first, we felt...

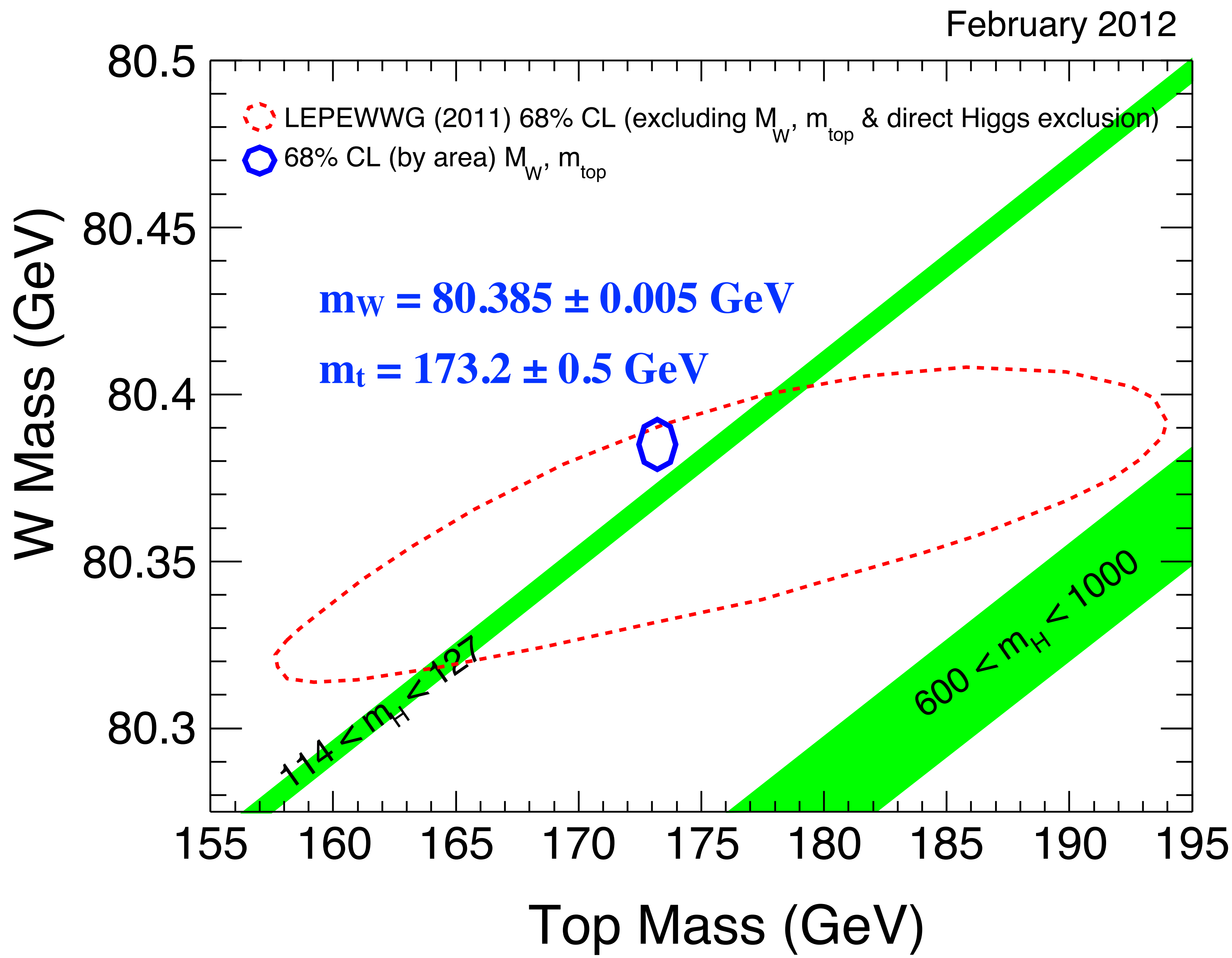
but, we quickly changed to say ...

Hooray!
Long live Standard Model !



We are again hoping

We start to dream again ...



Summary and outlook

- **New results from CDF and D0 this winter bring down the world average W boson mass uncertainty from 23 MeV to 15 MeV!**

  New world average : M_W = 80.385 ± 0.015 GeV
  Constraints on the SM Higgs boson: $M_H = 94^{+29}_{-24}$ GeV
  M_H < 152 GeV @ 95% C.L.

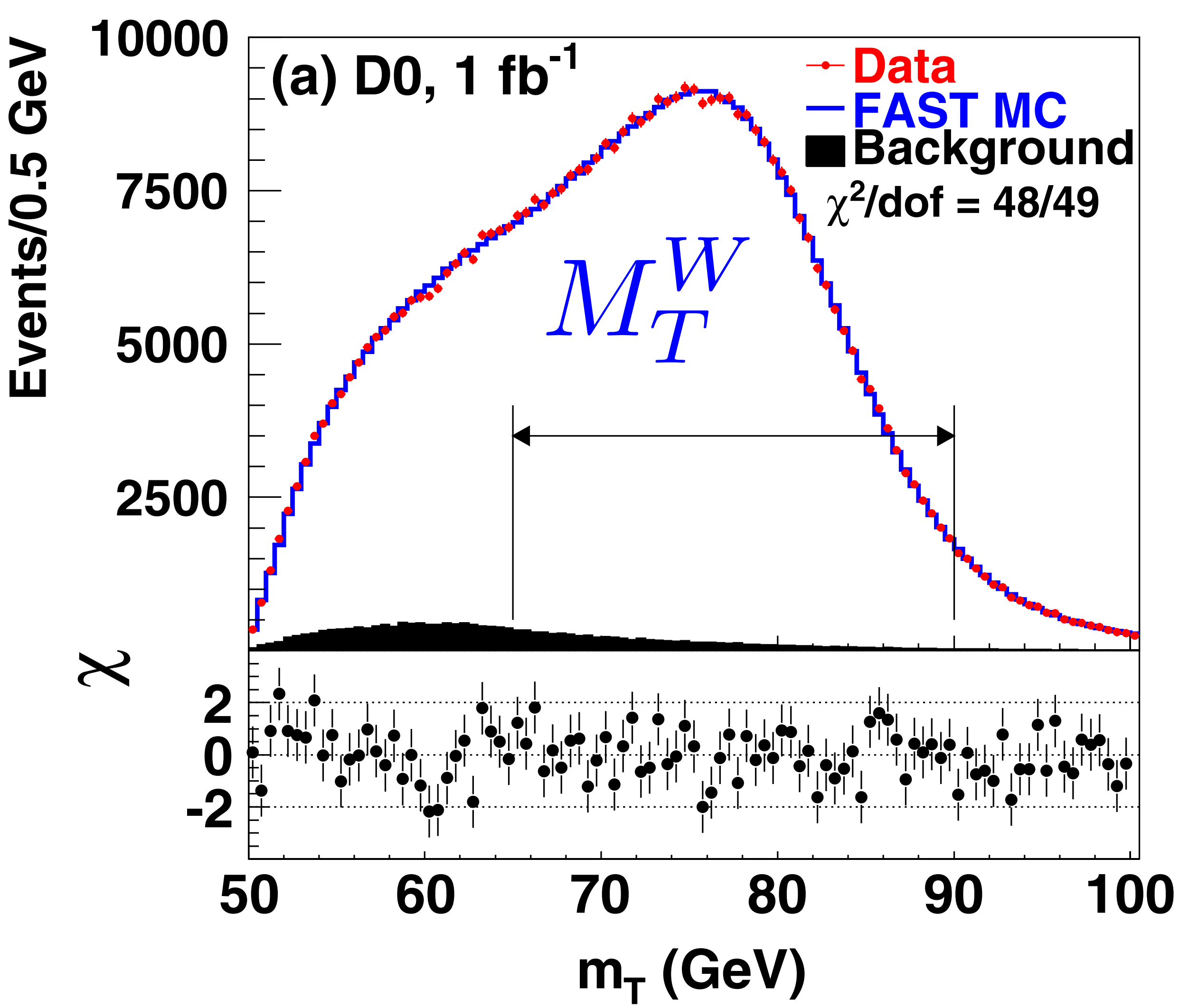
- **Improve the measurement:**
  - **PDF uncertainty: can be reduced by including end-cap electrons and by other analysis e.g. W change asymmetry measurement**
  - **With the full Tevatron data sets**
  - **There is the LHC.**

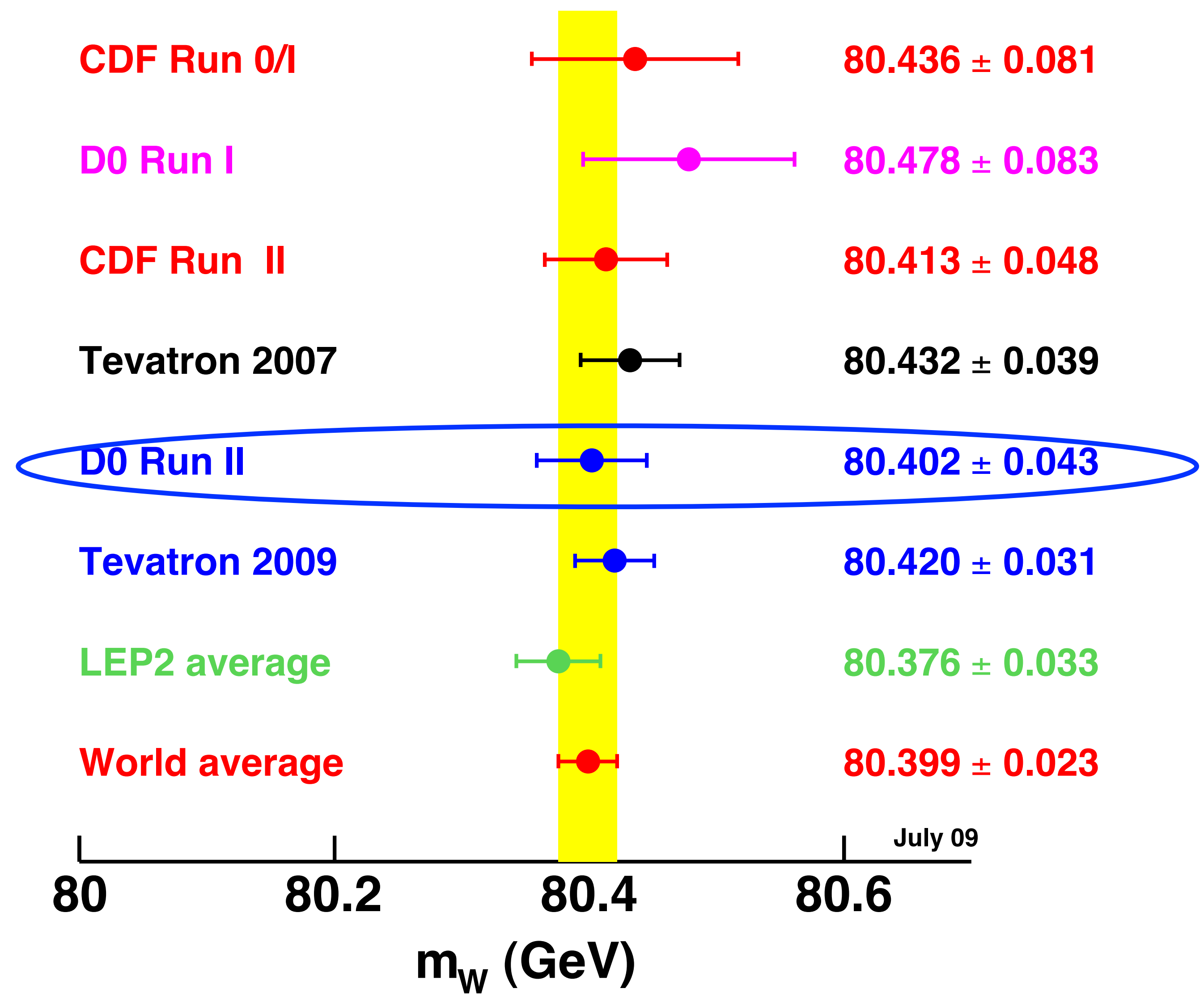
Backups

Published Results DØ RunIIa 1 fb^{-1}

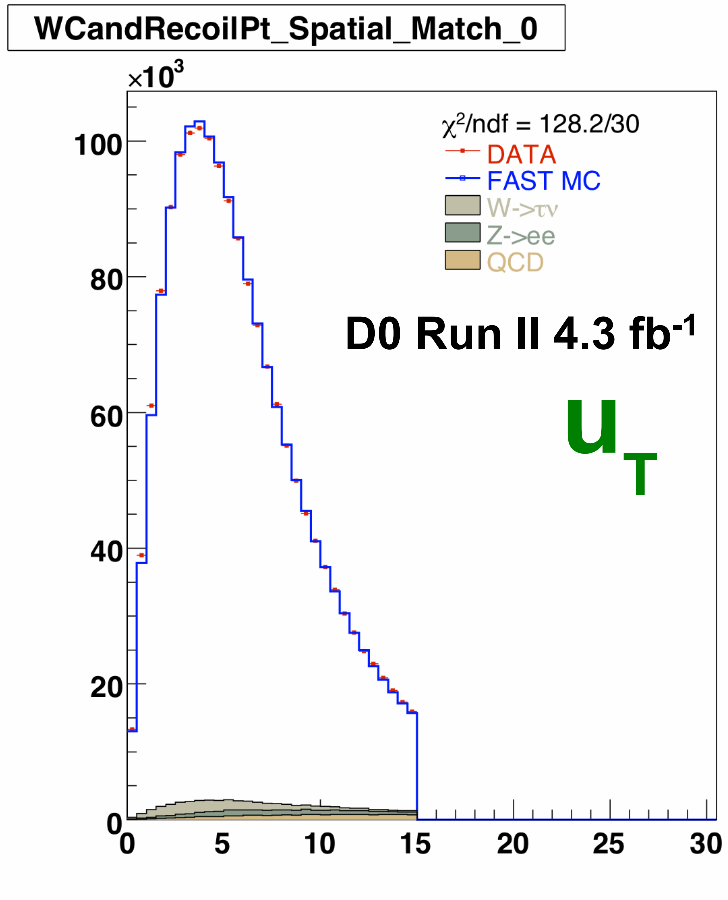
Central Calorimeter (CC) Electrons

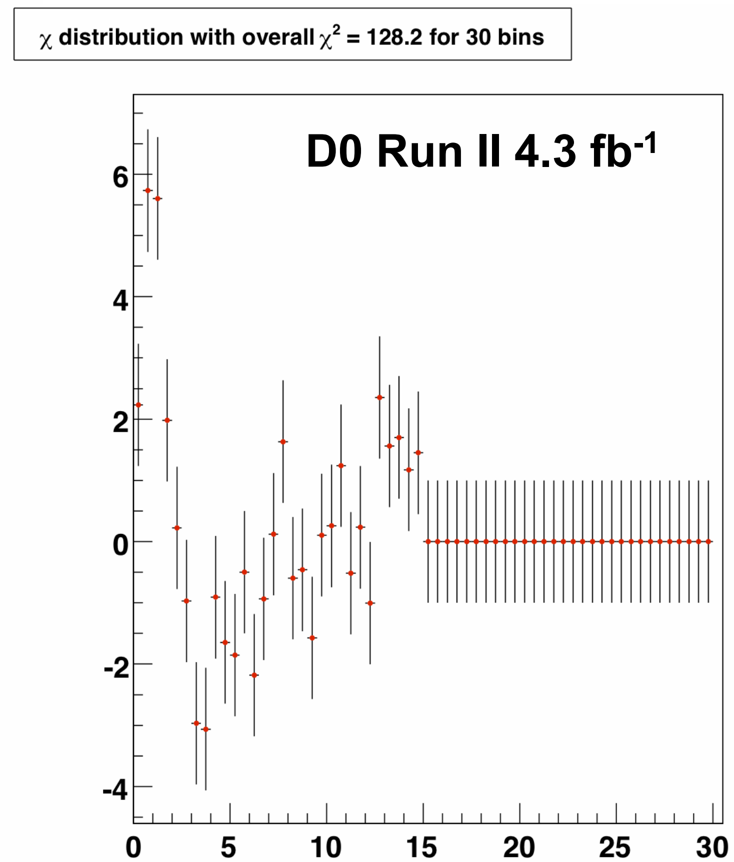
Phys. Rev. Lett. 103, 141801 (2009).



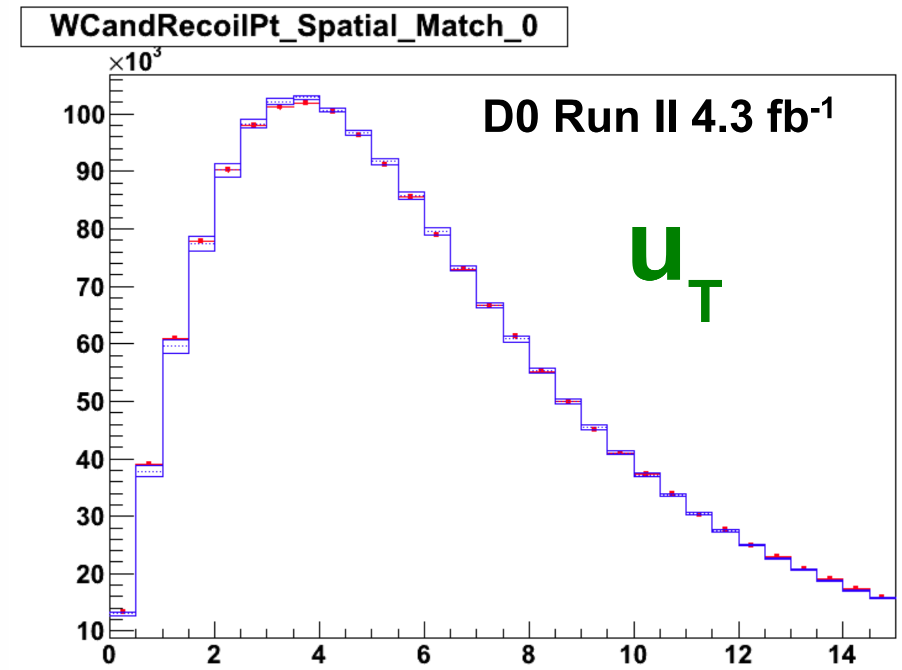


W data





Here the error bars only reflect the finite statistics of the W candidate sample.



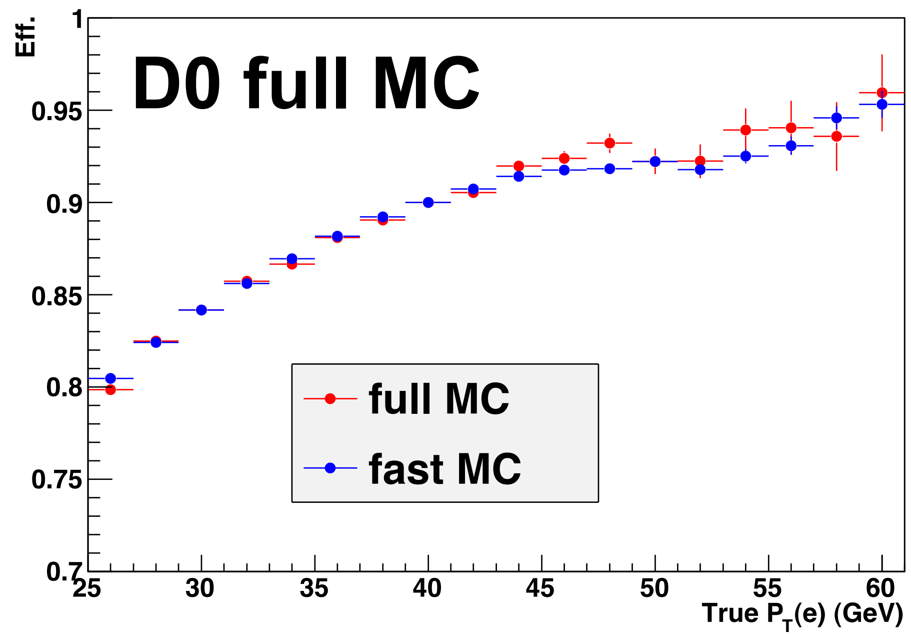
These are the same W candidates in the data. The blue band represents the uncertainties in the fast MC prediction due to the uncertainties in the recoil tune from the finite Z statistics.

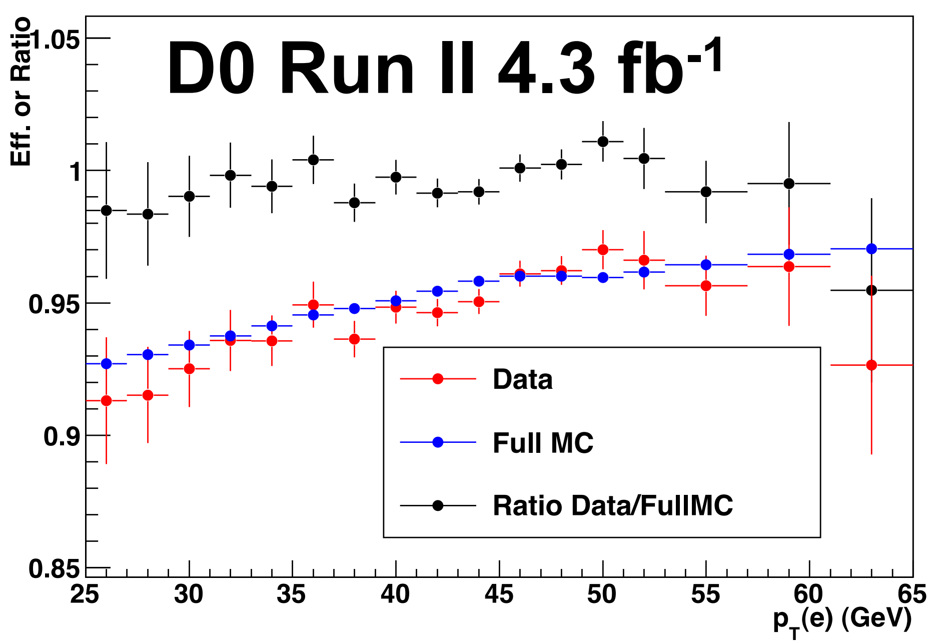
Good agreement between data and parameterised Monte Carlo.

Electron efficiency model

Efficiency modeling in the high inst. lumi. condition is challenging:
- pileup and hard recoil contaminate the electron reconstruction window,
- correlations with electron kinematics.

A two-step modeling:
- model the efficiency in a detailed simulation overlaid with pileup from collider data.
- check efficiency dependences using Z->ee events comparing data and detailed simulation.

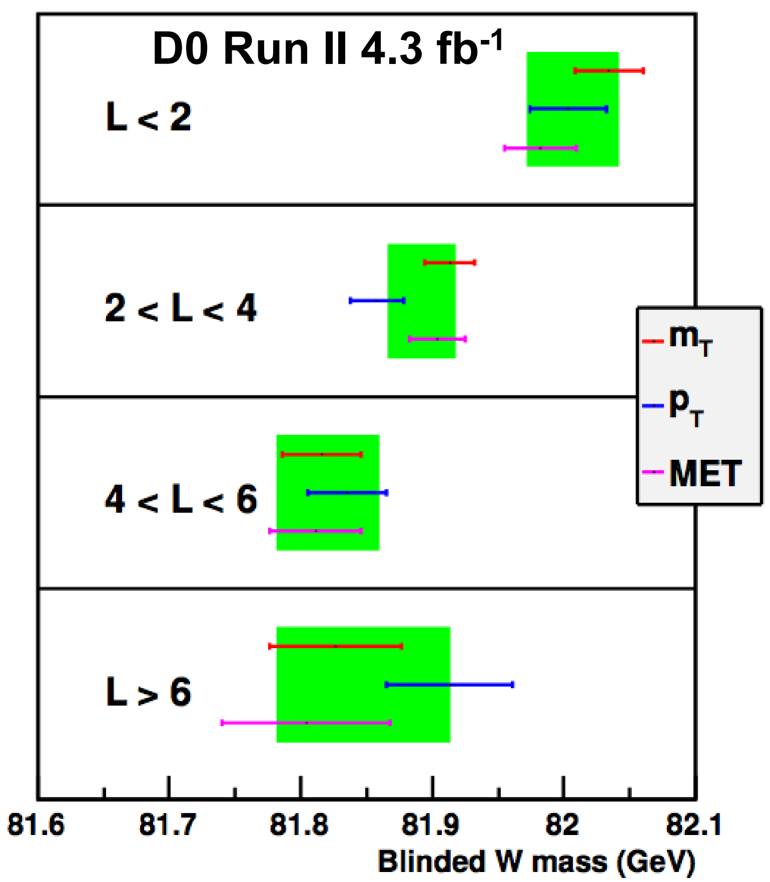




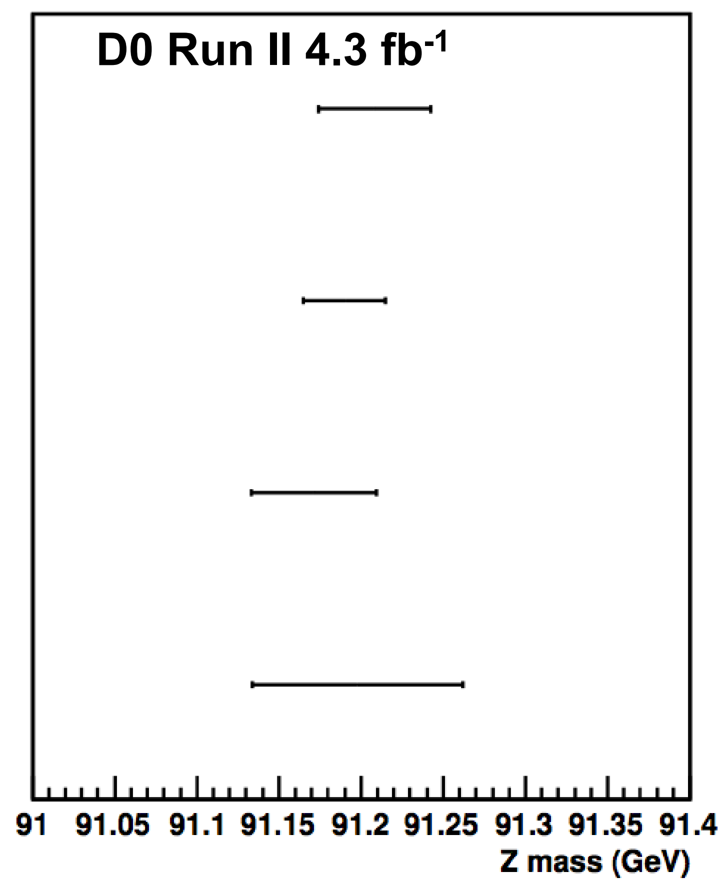
Consistency checks

Split data sample into four bins of instantaneous luminosity and measure W mass separately for each bin:

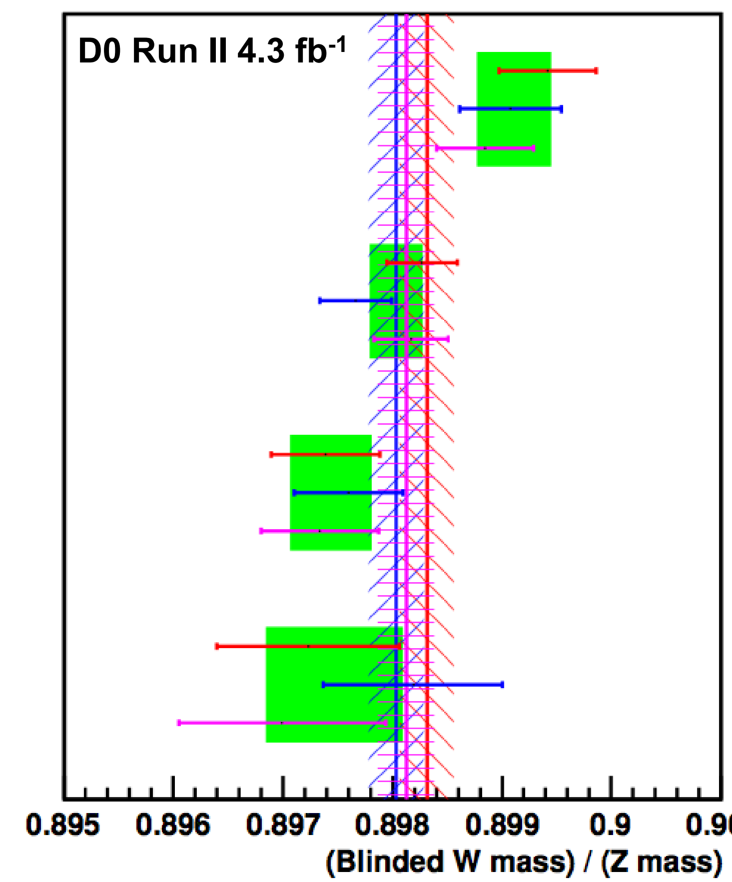
W



Z



"W/Z"



Error bars represent W statistics.

Green bands represent EM scale uncertainty (100 % correlated for m_T, p_T and MET).

Sorry, still using blinded mass in these plots.
But it does not matter here …
differences between observables and subsamples are preserved by the blinding.

Error bars represent W *and* Z statistics.

Green bands represent contribution from Z alone (100 % correlated for m_T, p_T and MET).

mass ratio is stable vs. lumi.

Backgrounds