A Precision Measurement of the *W* Boson Mass

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on behalf of the D0 Collaboration

Outline

- Motivation
- Experimental Setup: Tevatron and D0 Detector
- Measurement Strategy
- Data samples
- Simulation
- Summary and Outlook

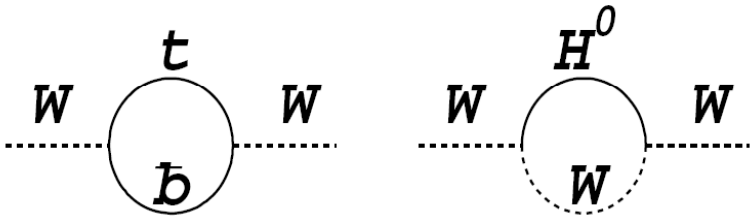
Motivation

- M_W is a key parameter in the Standard Model

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

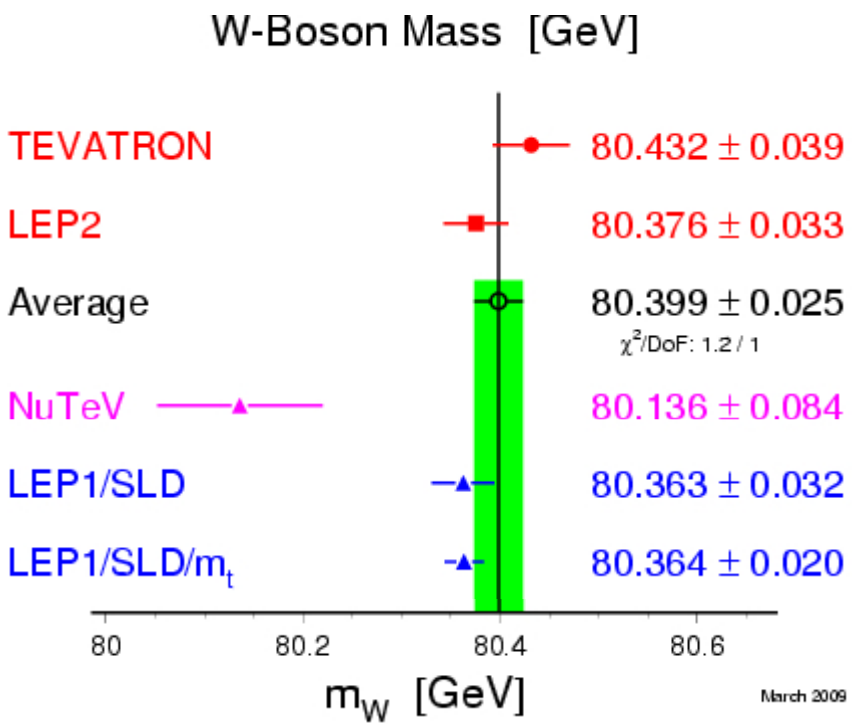
α: Electromagnetic constant
G_F: Fermi constant
θ_W: Weak mixing angle

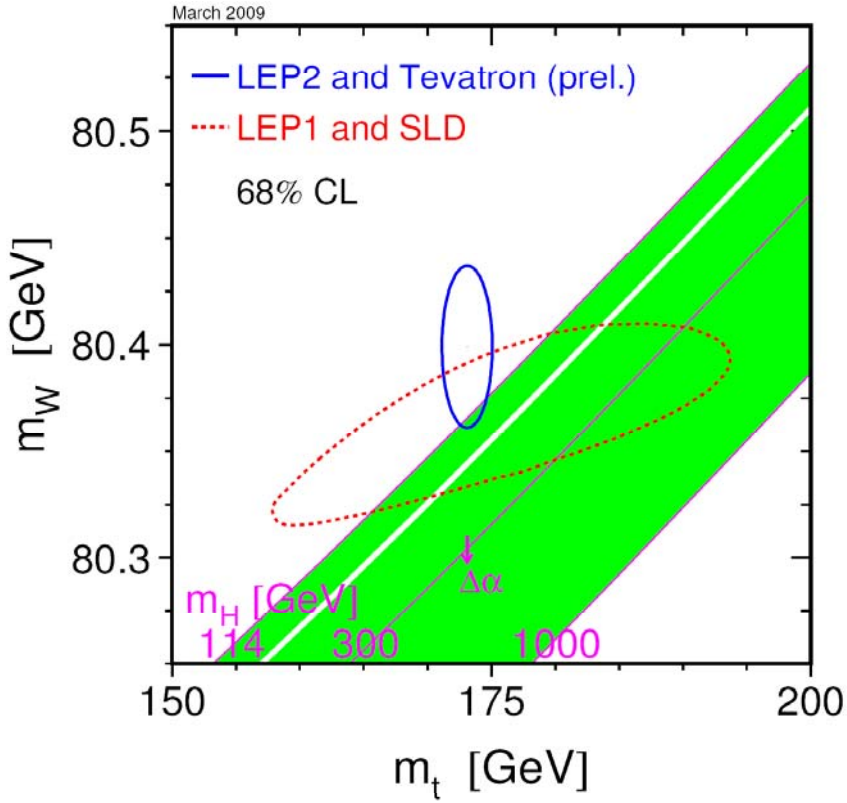
- In the Standard Model, radiative correction (Δr) depends on M_t as $\sim M_t^2$ and M_H as $\sim \log M_H$:



$\Delta r \sim M_t^2$ $\Delta r \sim \log M_H$

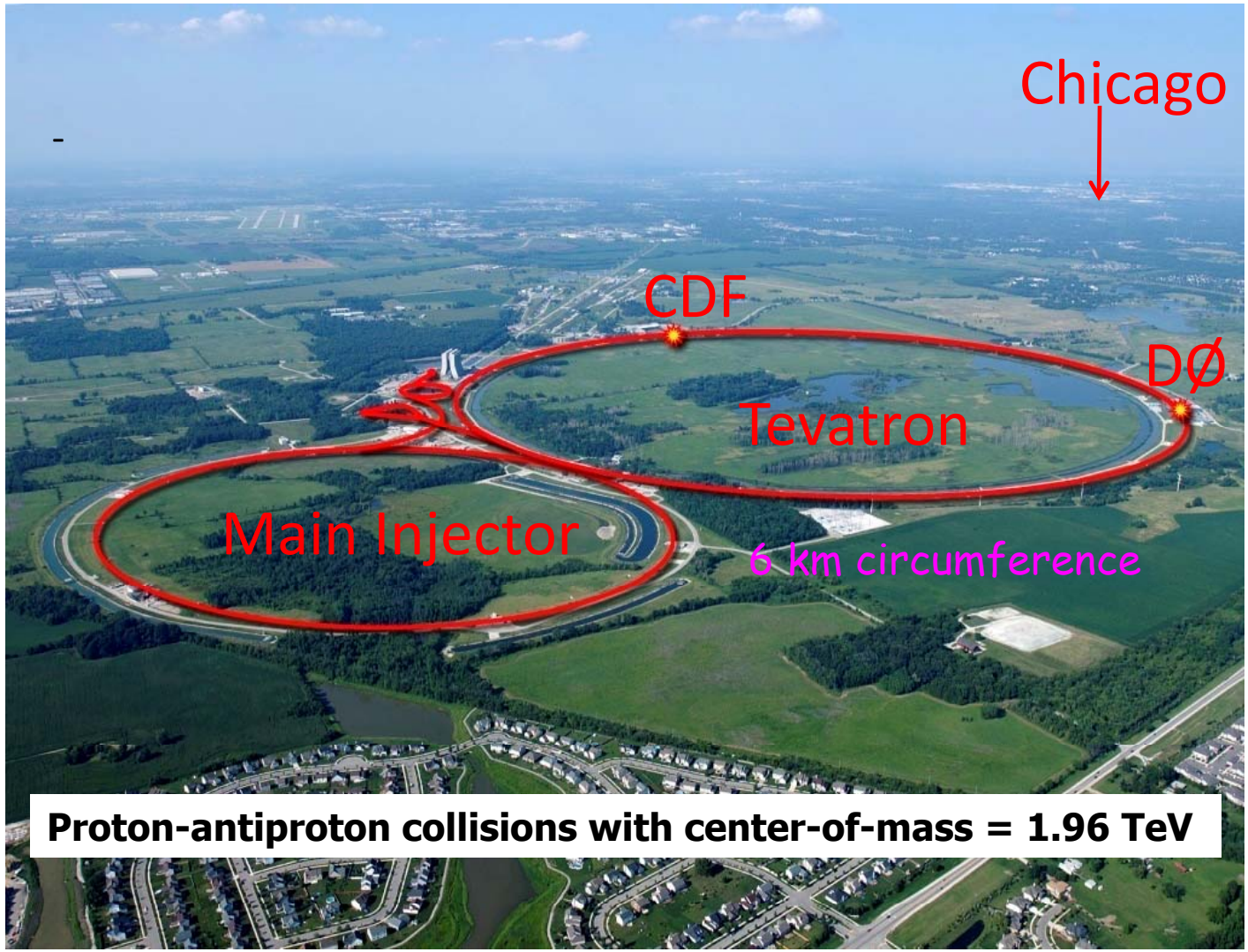
Current Precision





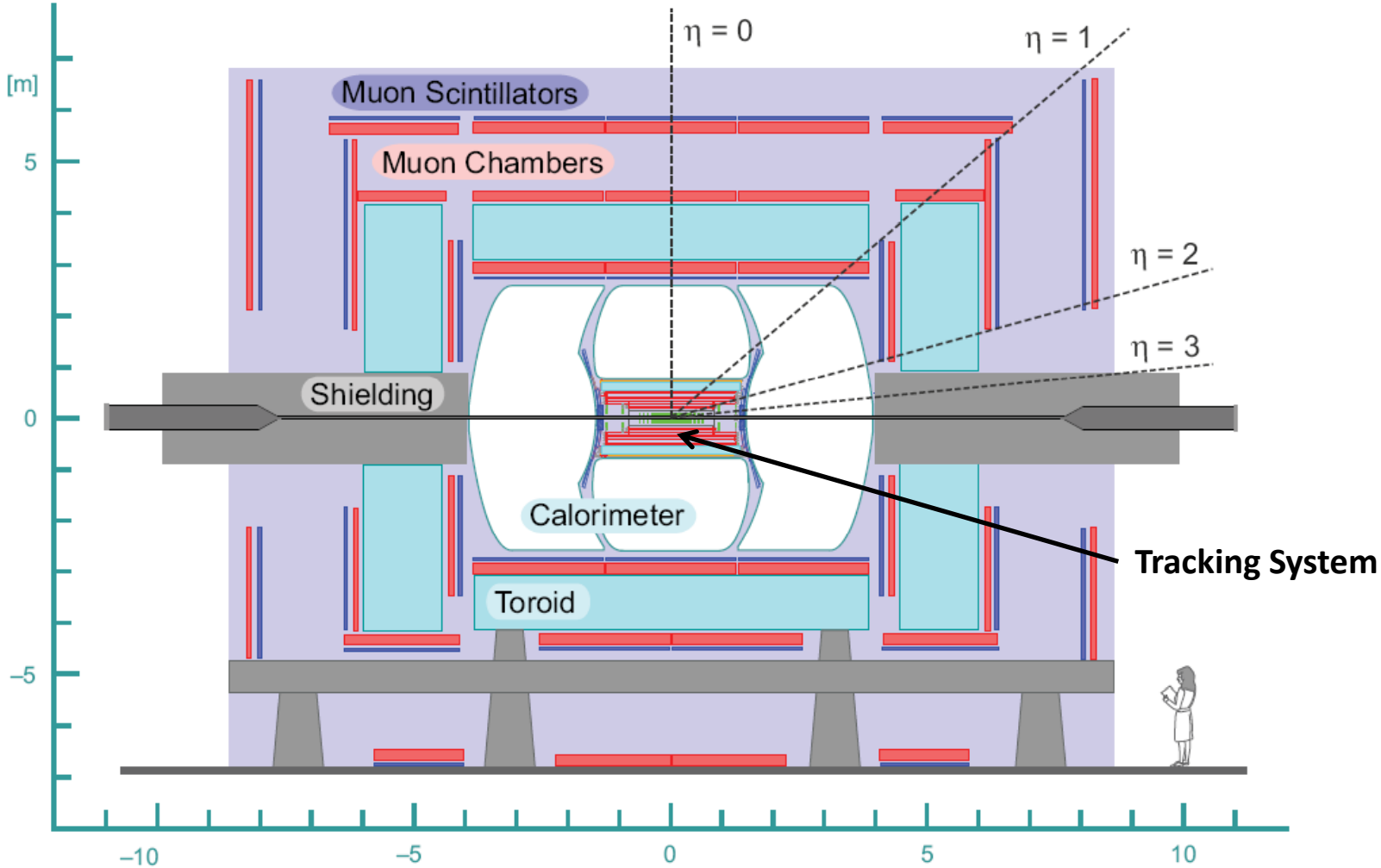
- **For equal contribution to the Higgs mass uncertainty we need:**
  $\Delta M_W \approx 0.006\ \Delta M_t$
- **Top quark mass is known with an uncertainty ~1.3 GeV, which requires $\Delta M_W \approx 8$ MeV, while currently $\Delta M_W \approx 25$ MeV. M_W is the limiting factor!**

Experimental Setup: Tevatron

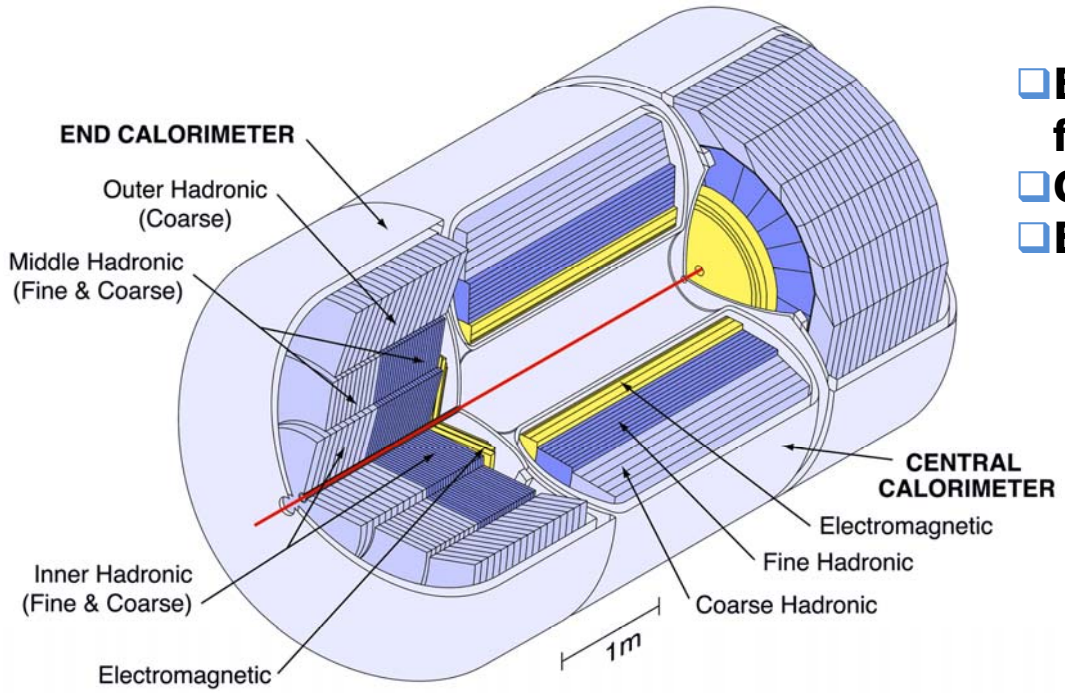


Proton-antiproton collisions with center-of-mass = 1.96 TeV

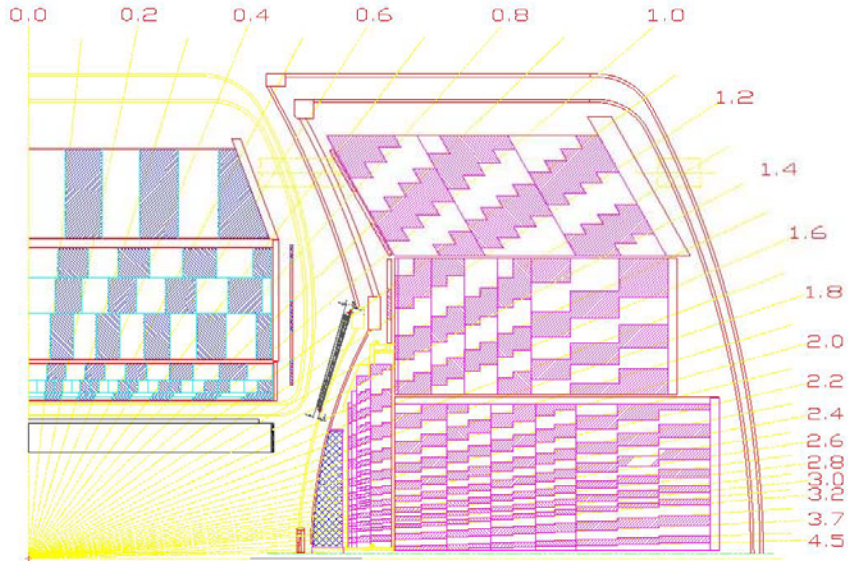
Experimental Setup: D0 Detector



Uranium / Liquid-argon Calorimeter



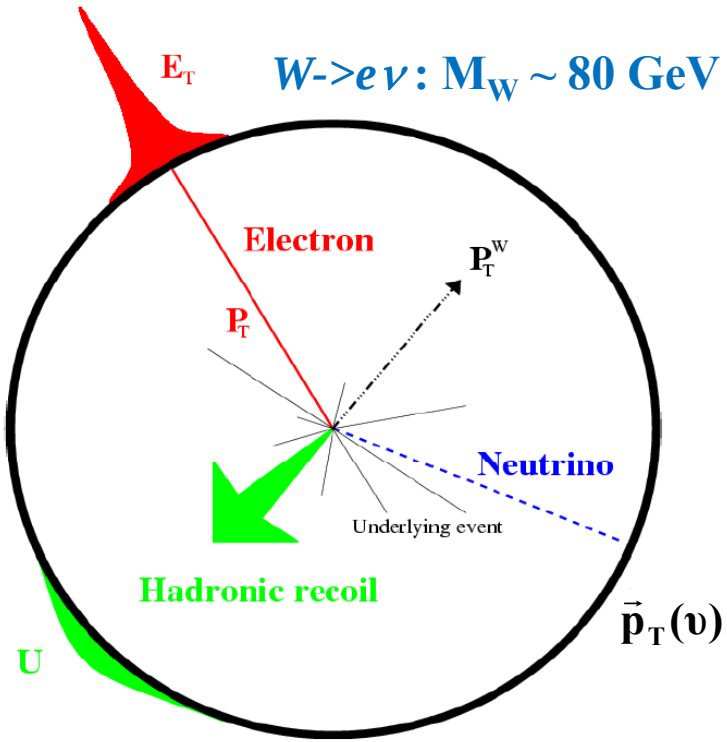
- Energy measurement and identification for electrons, photons and jets
- Central and Forward
- Electromagnetic and Hadronic

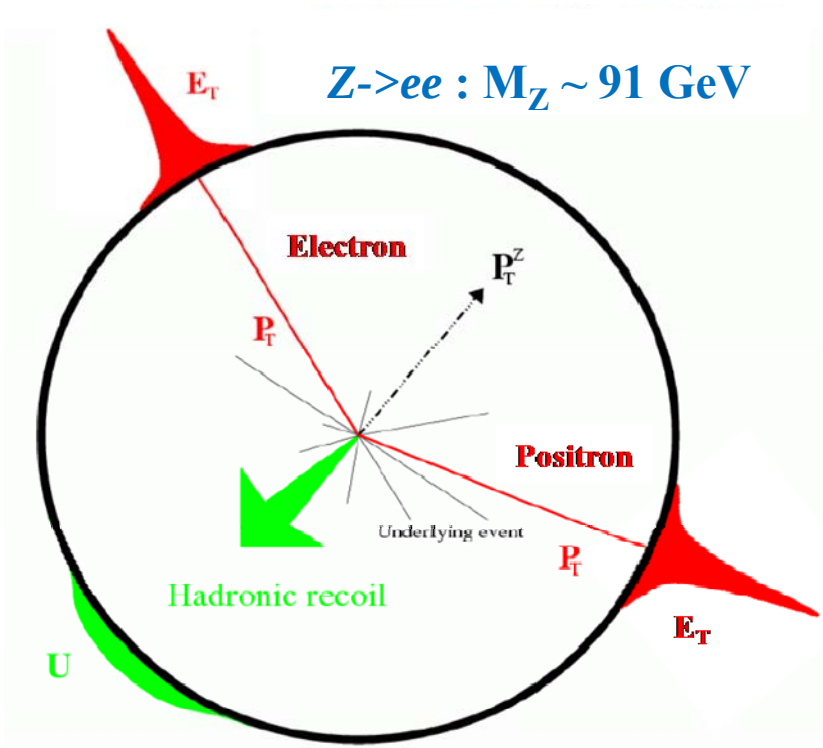


- **Full coverage** : $|\eta| < 4.2$
- **~46,000 channels**
- **Fine segmentation(towers): $\Delta\eta$ x $\Delta\varphi$ = 0.1x0.1**

(0.05x0.05 in third EM layer, near shower maximum)

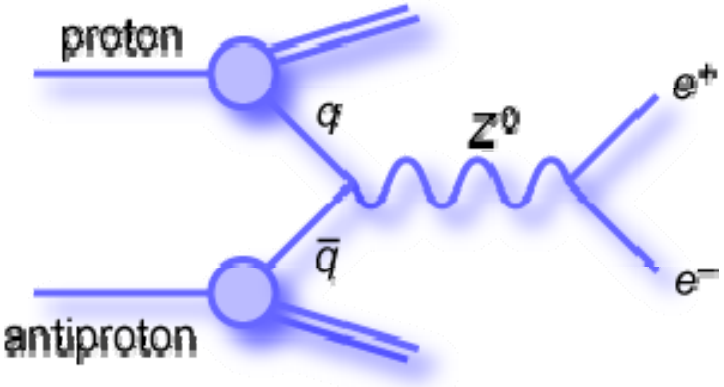
Signatures in the Detector

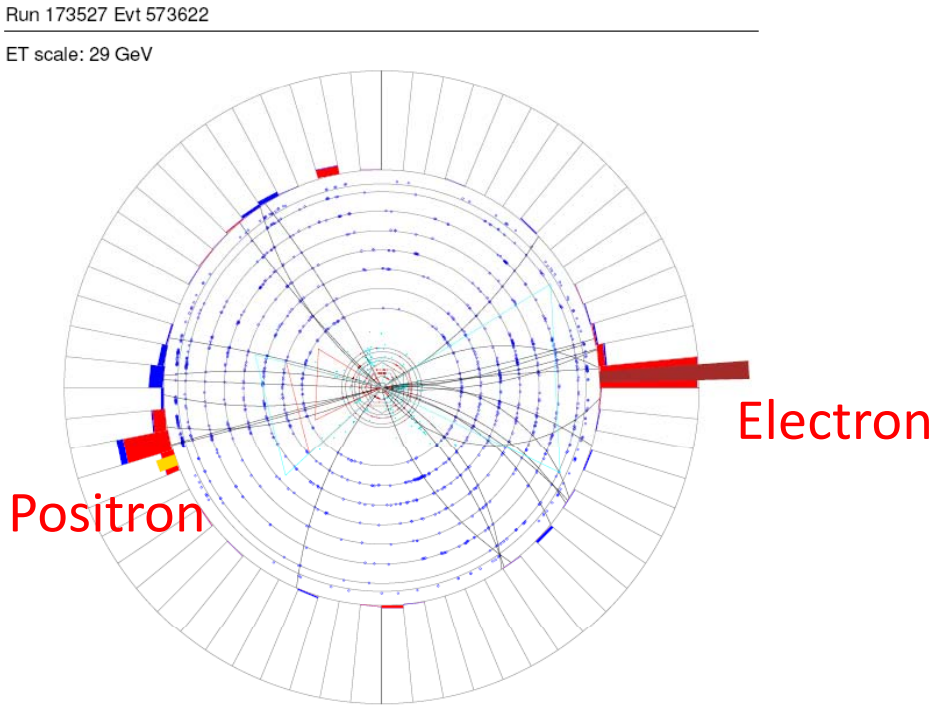




- *Z->ee* events served as the control sample for energy response, resolution, efficiency, etc.

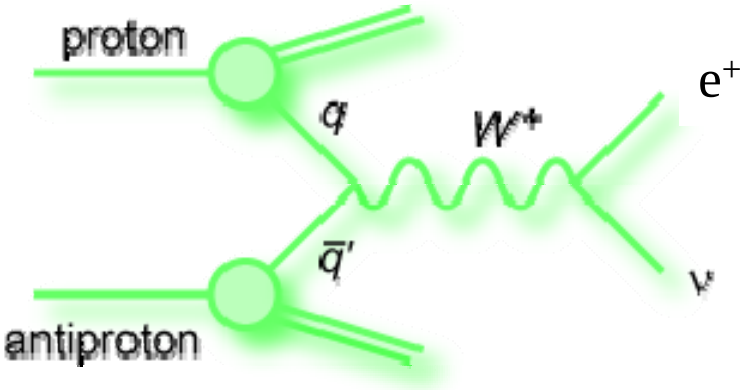
Z->ee

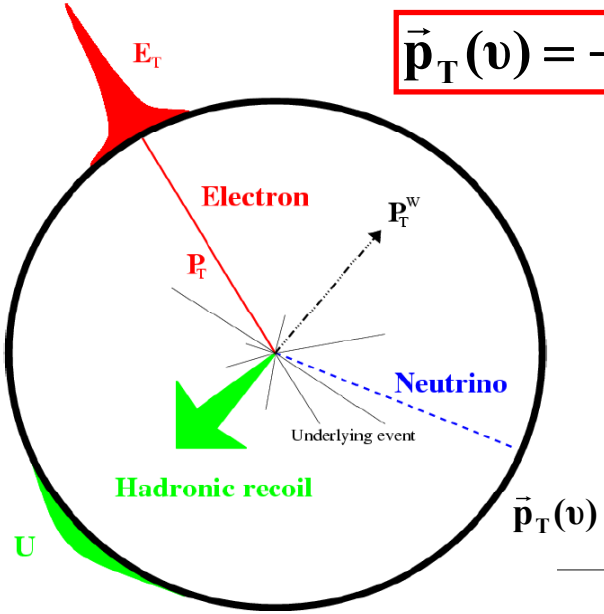




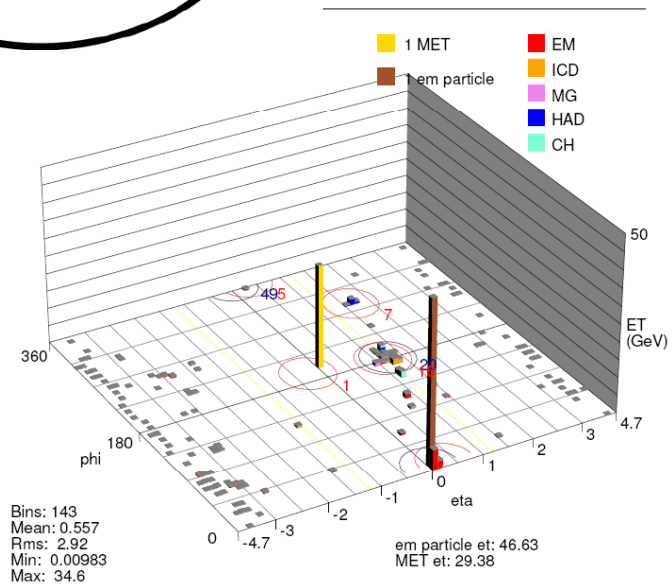
- **Electron deposits most of its energy in the calorimeter, which can be measured with 0.5 per-mil precision**
- $m_Z^2=(E_1+E_2)^2-|\vec{p}_1+\vec{p}_2|^2$ **is used to extract *Z* mass**

W->eν



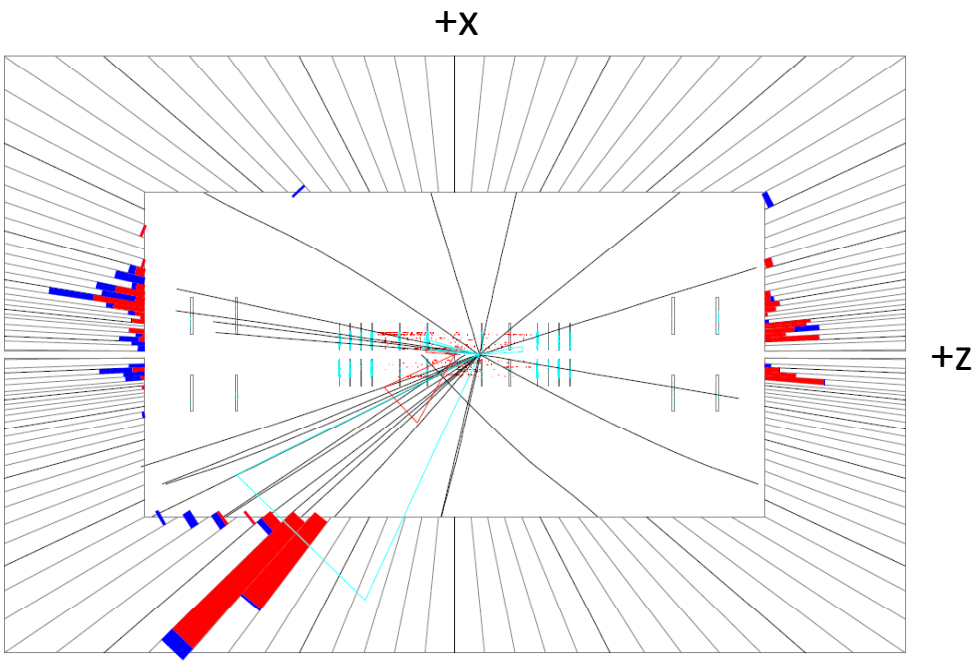


$$\vec{p}_T(\nu) = -\vec{p}_T(e) - \vec{u}_T$$



- **Neutrino escapes from detection, causing substantial missing energy**
- **$p_T(\nu)$(MET) : Missing transverse momentum**

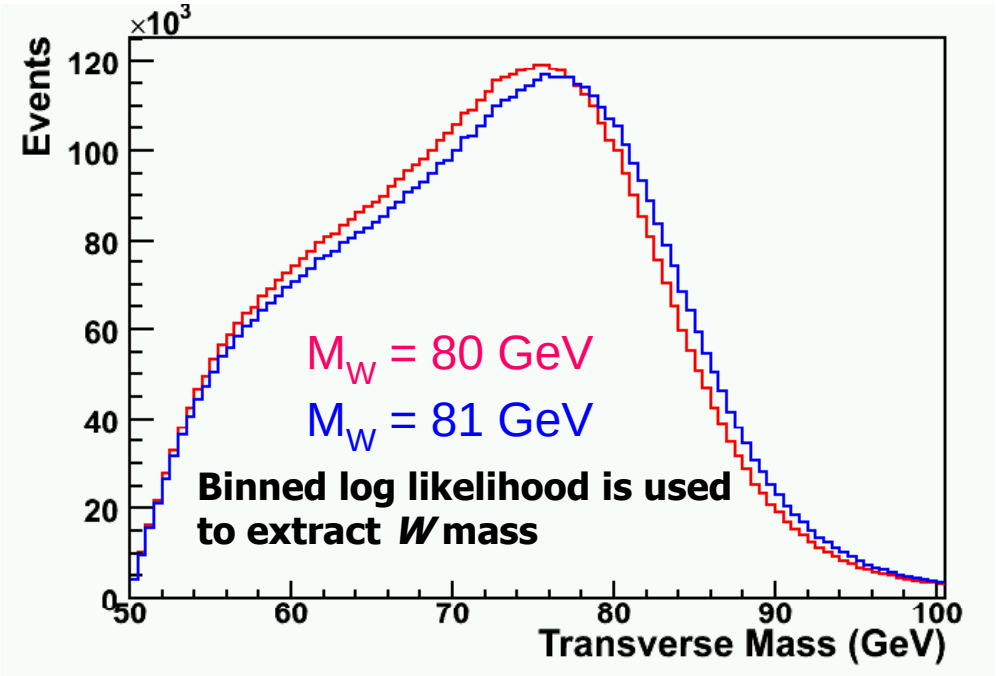
Why MET?



- **Unknown initial and final momentum sum along the beam direction($|\eta|$ <4.2)**
- $M_T = \sqrt{(E_T(e)+E_T(\upsilon))^2 - |\vec{p}_T(e)+\vec{p}_T(\upsilon)|^2}$ **: *W* transverse mass**

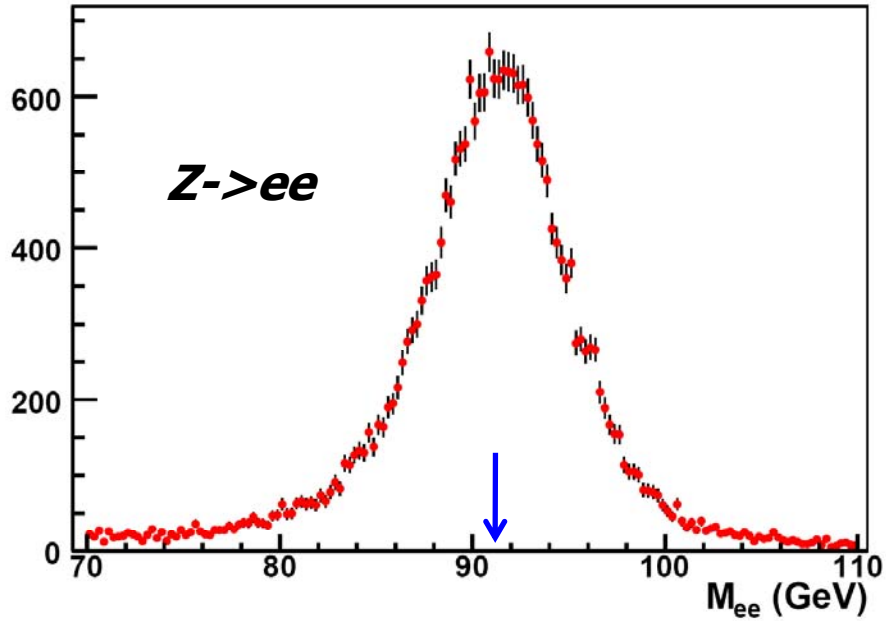
W Mass Measurement Strategy

- **Transverse Mass(M_T), transverse electron momentum (pT(e)) and missing transverse momentum(MET) are used to extract *W* mass**
- **A fast parameterized simulation(fast MC) is used to model the detector effect and offline selection, which takes the *W* mass as the input**
- **Vary the input *W* mass and compare with the data to extract the *W* mass value**
- **Do a blind analysis**

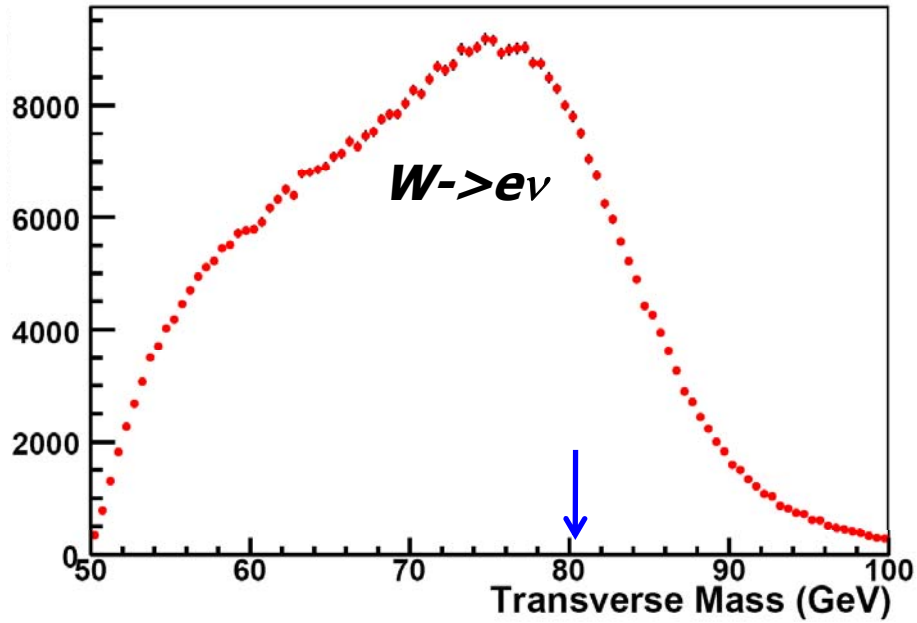


Characteristic Spectrum

$m_Z^2=(E_1+E_2)^2-|\vec{p_1}+\vec{p_2}|^2$

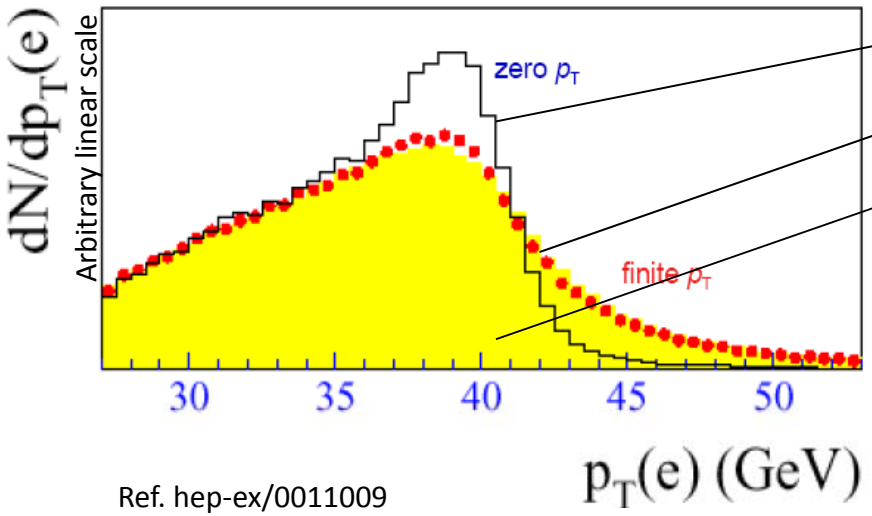


$M_T^2=(E_{Te}+E_{T\nu})^2-|\vec{p_{Te}}+\vec{p_{T\nu}}|^2$

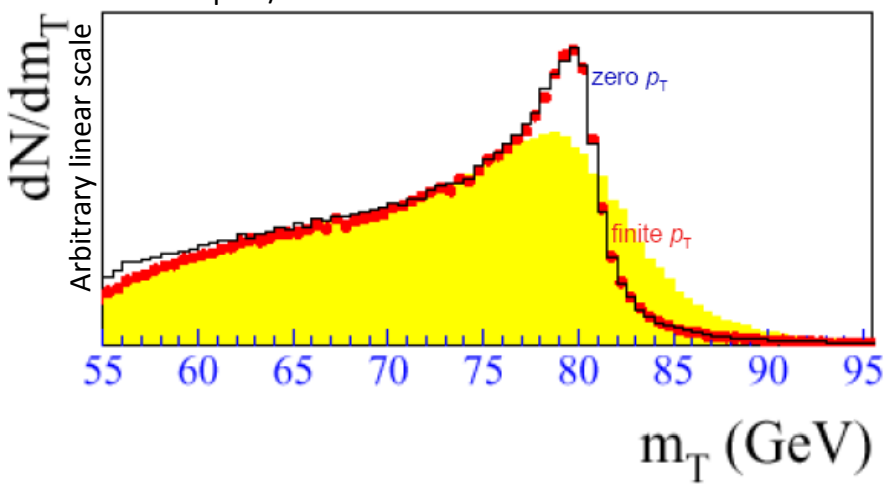


- ***Z*** **events are used to calibrate the electron energy response by forcing the measured dielectron mass peak to agree with the well-known** ***Z*** **mass(91.1876 ± 0.0021 GeV).**
- **We are essentially measuring the ratio of** ***W*** **and** ***Z*** **masses.**

Observables Sensitivities



Ref. hep-ex/0011009



No $P_T(W)$

$P_T(W)$ included

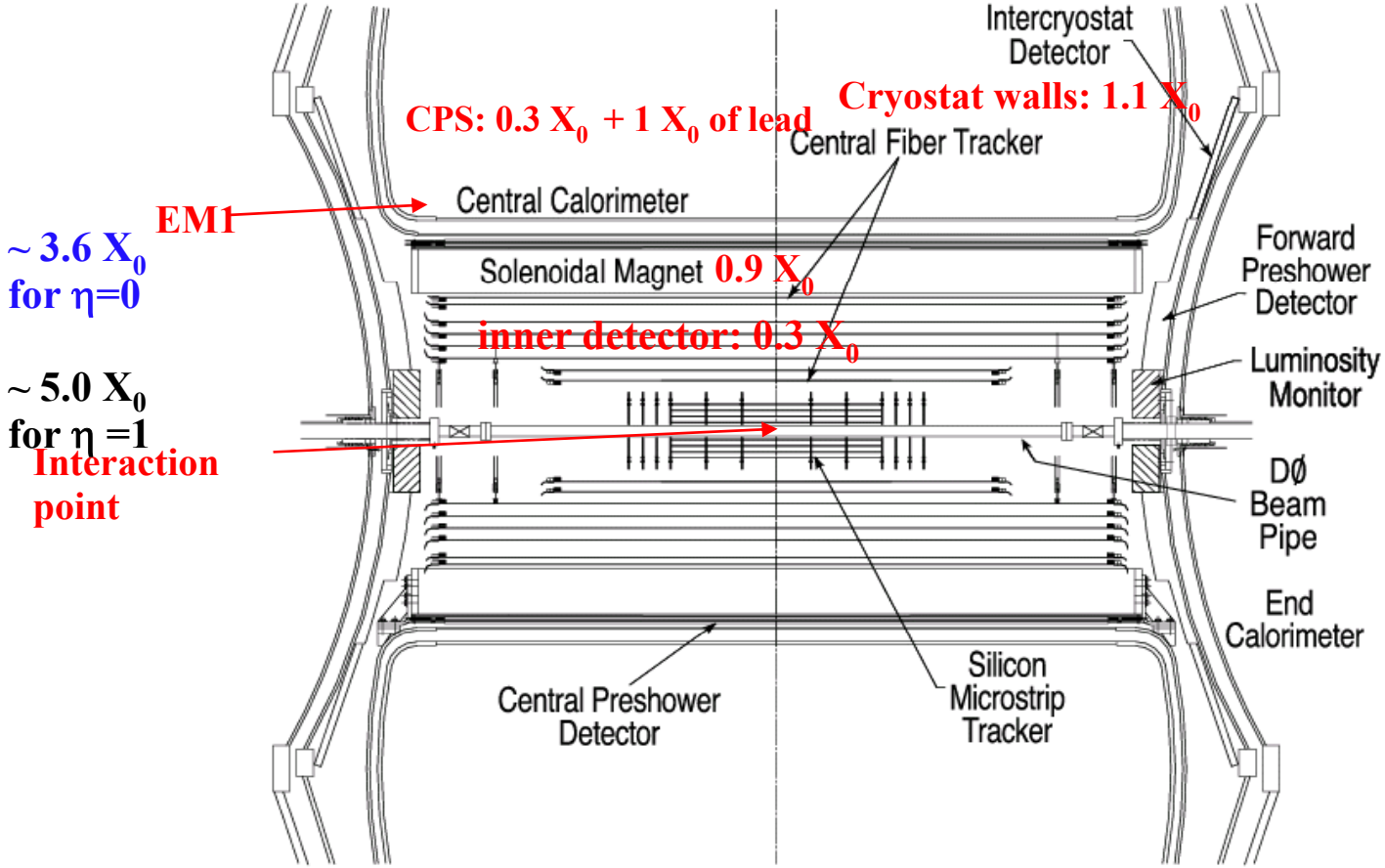
Detector Effects added

$p_T(e)$ most sensitive to $p_T(W)$

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

M_T most affected by measurement of missing transverse momentum

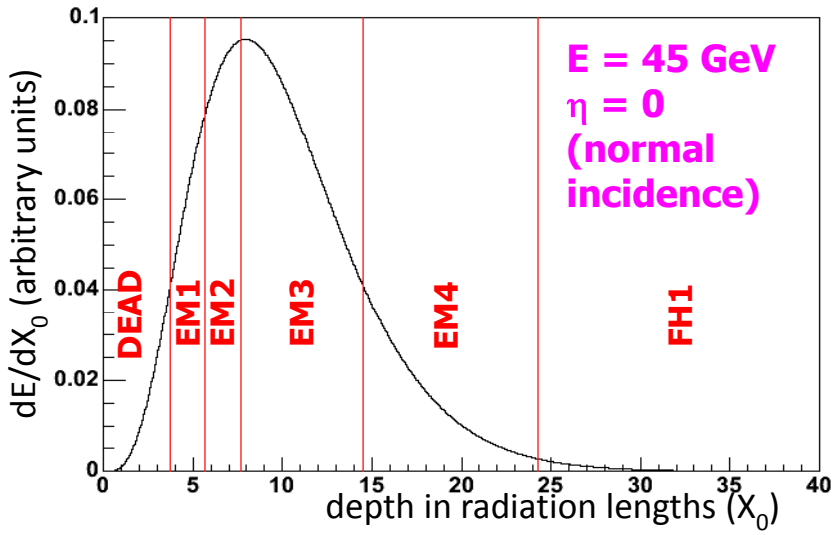
Material in front of Calorimeter



Energy loss in front of the calorimeter is estimated using detailed simulations based on Geant(full MC)

Material in front of calorimeter

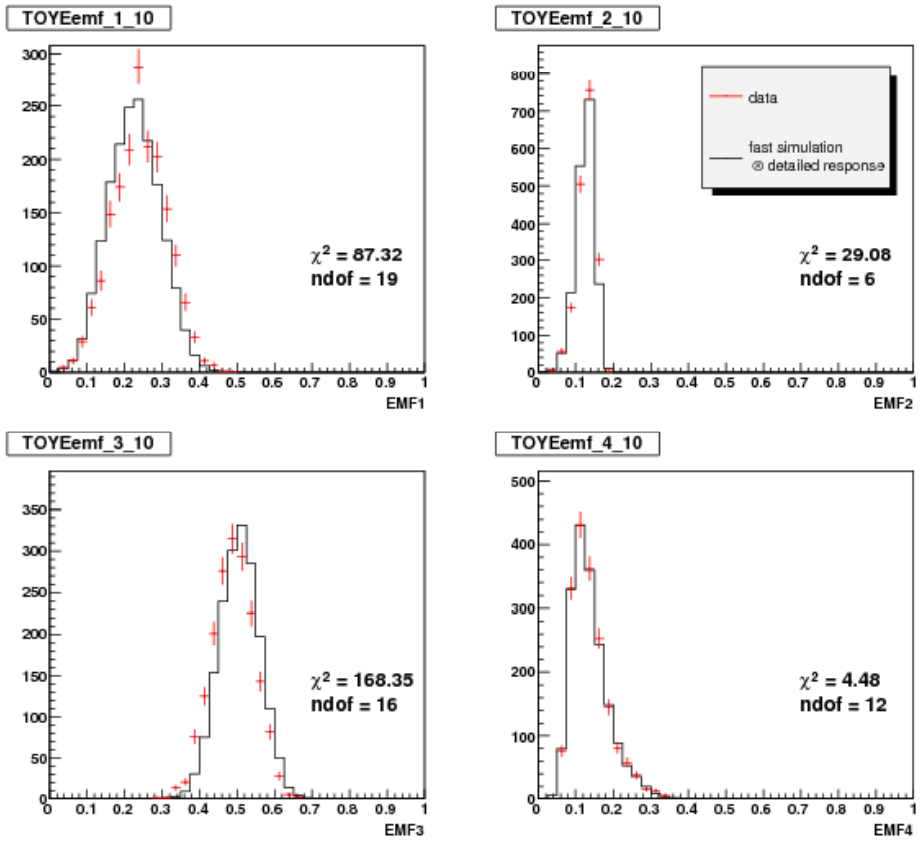
- ~3.6X0 dead material in front of the calorimeter
- Need to know number of X0 in front of calorimeter precisely
- Measurement method:
  - electron energy fraction in each layer is sensitive to the material in front of calorimeter
  - Construct a model to predict EMF distribution for different nX0
  - Compare predictions with data



Before Tuning of Model Material

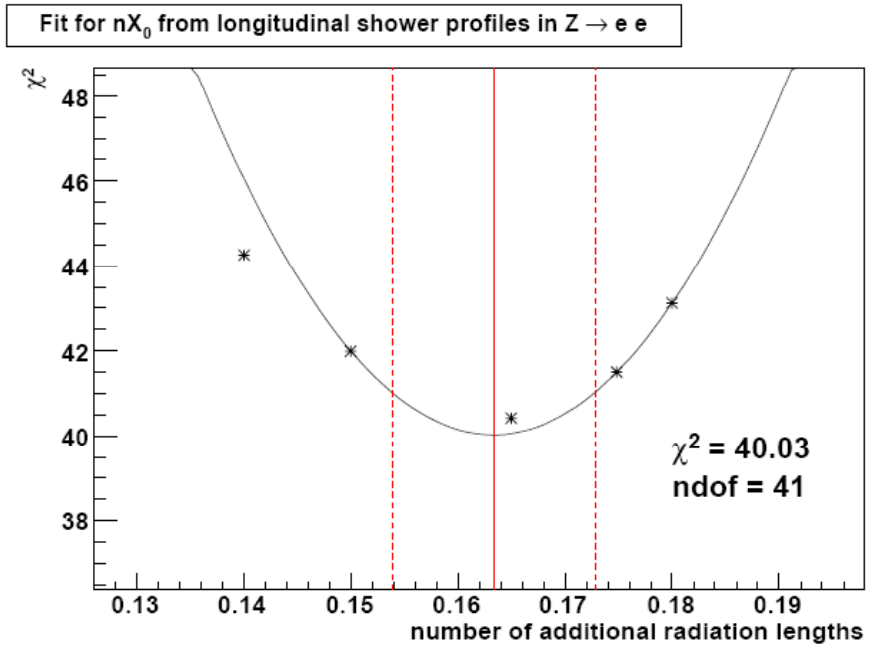
Fractional energy deposits, electrons with $|\eta| < 0.2$

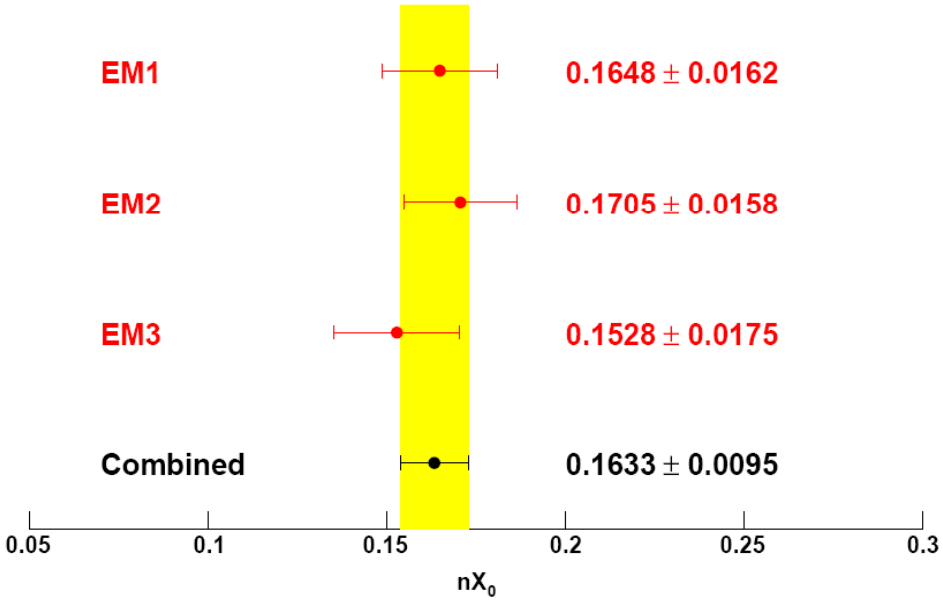
- **distributions of energy fraction deposits do not quite match between data and the simulation.**



Final Result

- **Take data/MC ratios vs 15 categories(based on two electrons' η) for EM1, EM2 and EM3 and fit each one (separately) to a constant.**
- **Add the chi-squareds from the three fits. Vary amount of extra material to minimise the global chi-squared**





Additional material by fitting for three EM layer together:

n=0.1633 +- 0.0095

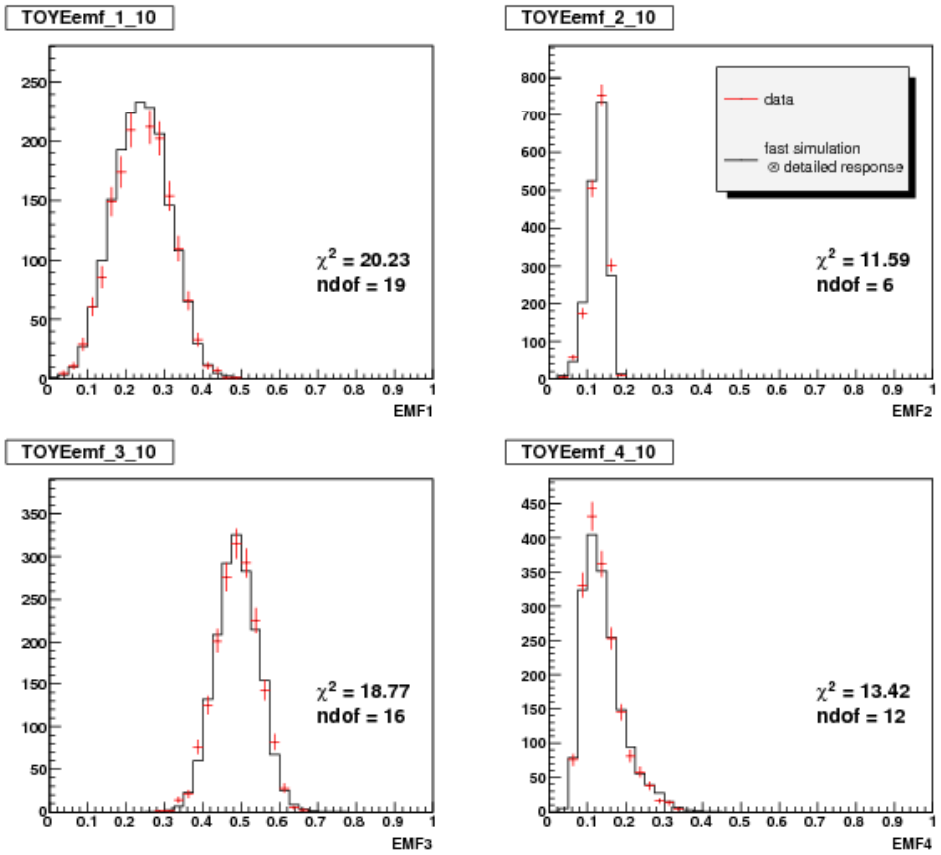
Cross check:

Fitting each of the three EM layer separately gives consistent result

Impact of Adding Missing Material

Fractional energy deposits, electrons with $|\eta| < 0.2$

After tuning of missing material



Data Samples:
$1fb^{-1}$(2002--2006)

- **Common Selection for both *Z->ee* and *W->eν*:**
  - $|Vtx_{primary}|<60$ cm
  - Single electron trigger fired
  - Electron in central calorimeter: $|\eta_{det}|<1.05$
  - Fiducial region
  - $p_T(e) > 25$ GeV, iso<0.15, emfrac>0.9, shower shape, track match
  - Recoil $p_T < 15$ GeV

- **Additional Selection for *Z->ee* (~18k):**
  - 70 GeV < Invariant Mass(e,e) < 110 GeV

- **Additional Selection for *W->eν* (~500k):**
  - 50 GeV < M_T < 200 GeV
  - MET > 25 GeV

Generator: RESBOS + PHOTOS

- **QCD process: RESBOS**

  (C. Balazs and C.-P. Yuan, Phys. Rev. D 56, 5558 (1997))

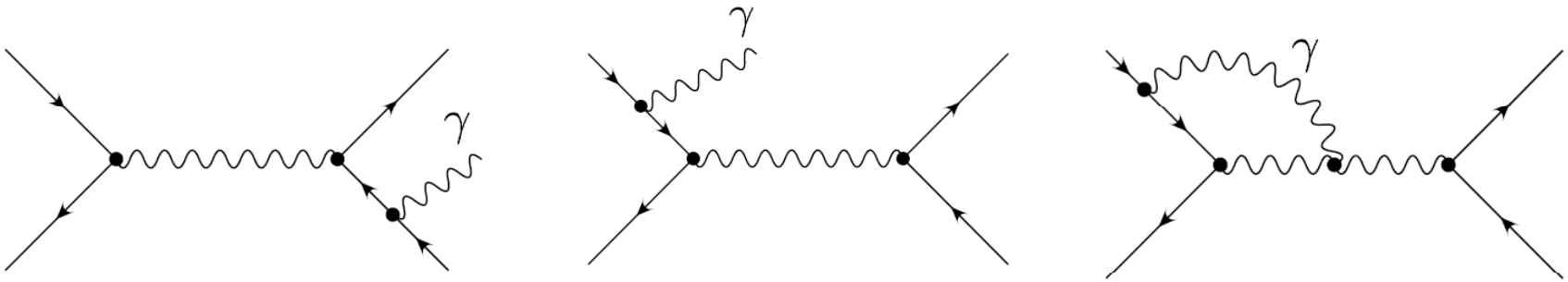
  - **Gluon resummation gives reasonable description of the transverse momentum of the vector bosons at low boson p_T**

- **Photon Radiation: PHOTOS**

  (E. Barbiero and Z. Was, Comp. Phys. Commun. 79, 291 (1994))

  - **It only simulates the final photon radiation(FSR)**
  - **Effect of full EWK correction is studied using W/ZGRAD**

    (U. Baur, S. Keller and D. Wackeroth, Phys. Rev. D 59 013002 (1999))



Selection Efficiency

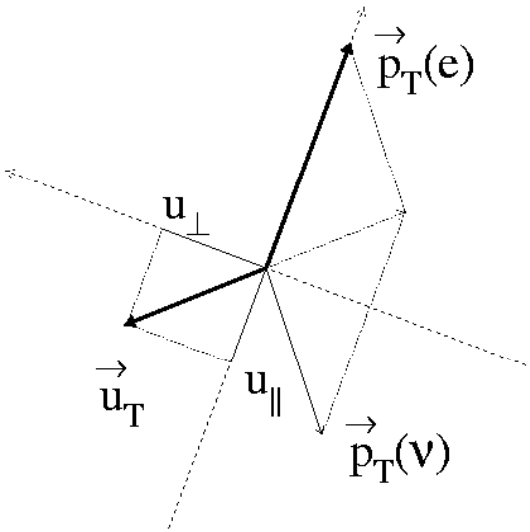
- **Electron selection is subject to multiple factors: detector geometric, electron intrinsic features and contamination from rest of the event**

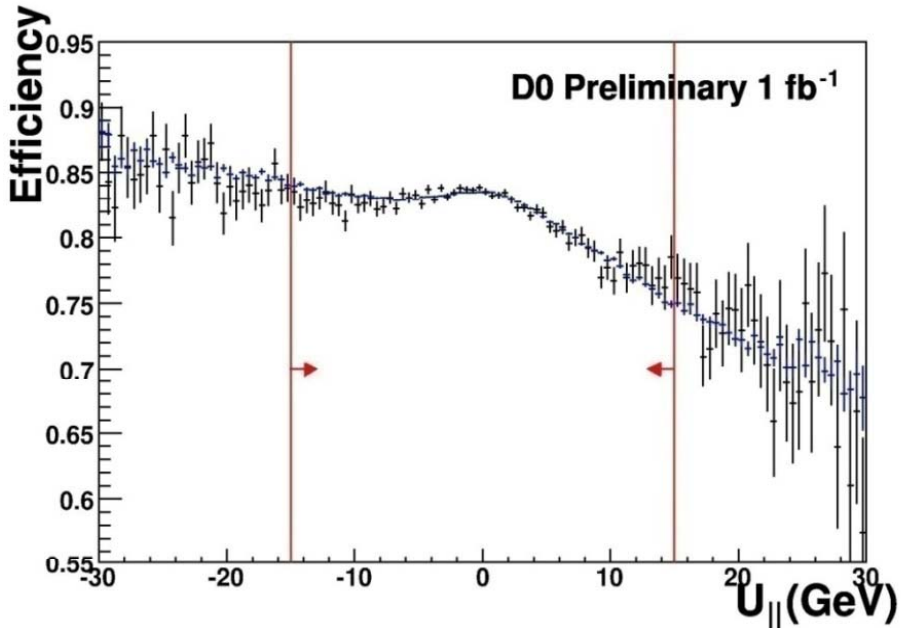
- **Study the effect from different sources using different methods.**
  - **Geometric acceptance(primary vertex and η)**
  - **Intrinsic p_T(e) dependence(internal photon radiation, etc.)**
  - **$u_{||}$ efficiency(relative direction between "e" and "recoil")**
  - **Scalar E_T efficiency(overall hadronic activity effect)**

$u_{||}$ Efficiency

- **Efficiency is measured using the tag-and-probe method on *Z->ee* events**

- **The recoil of the boson affects electron identification, especially when the recoil is close to the electron**





Electrons Energy Response

- **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 for $\beta \ll E(e1) + E(e2)$:**

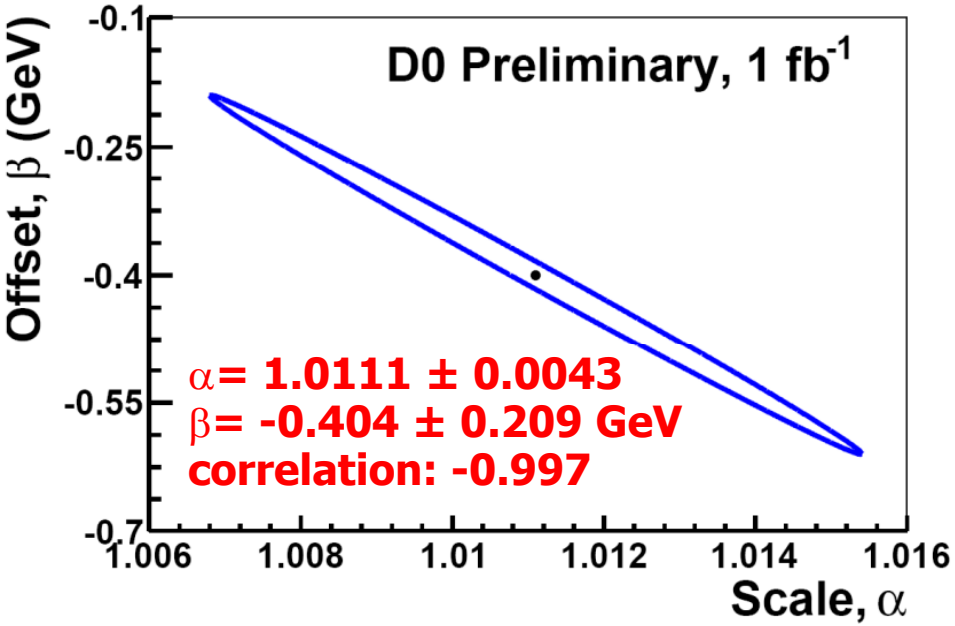
$$m(ee) = \alpha \times m_Z + f_Z \beta$$

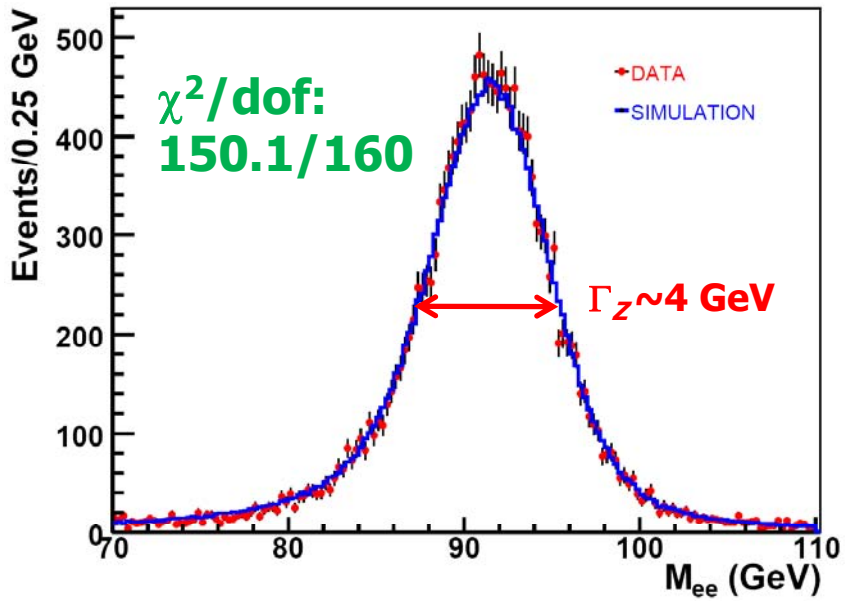
$$f_Z = (E(e1)+E(e2))(1-\cos(\gamma_{ee}))/m_{measured}$$

γ_{ee} is the opening angle between the two e's

- **Templates of m(ee) vs f_Z are generated for variant α and β values**

Electron Energy Response





- **This is so far the dominant systematic uncertainty in the W mass measurement (limited by *Z* statistics : ~18k) :**
  - **Δm(W) = 34 MeV, 100 % correlated between all three observables**

Recoil System

Recoil: everything else in the event except the electron(s).

(1) Hard component: from W/Z boson p_T

(2) Soft component:

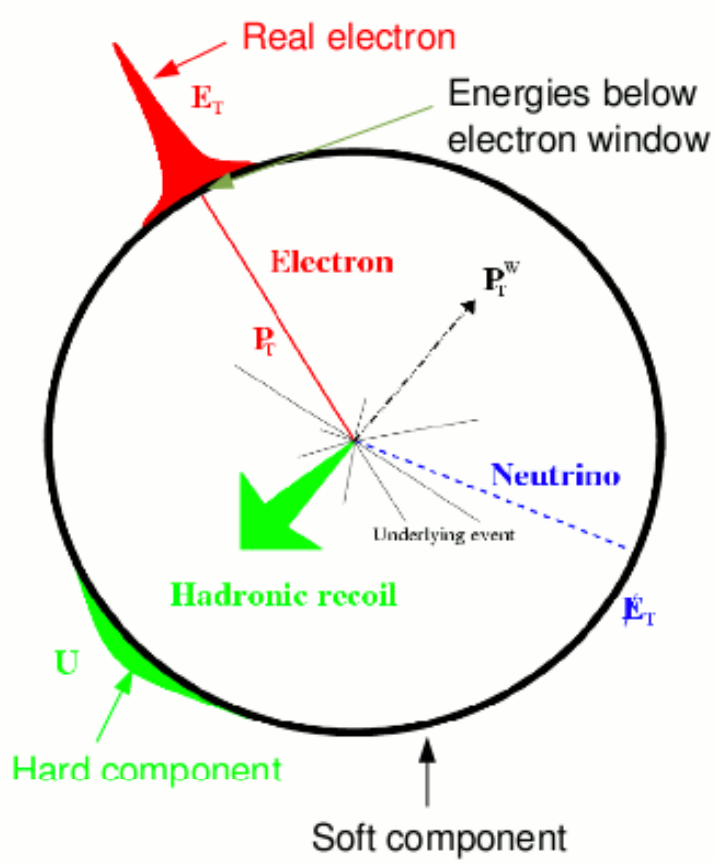
--Spectator parton interactions

--Additional ppbar interactions and electronic noise, etc.

(3) Recoil energy lost in the electron cones and electron energy leakage outside the electron cluster

(4) FSR outside the electron cones

Additional parameters are introduced and tuned to the *Z->ee* data



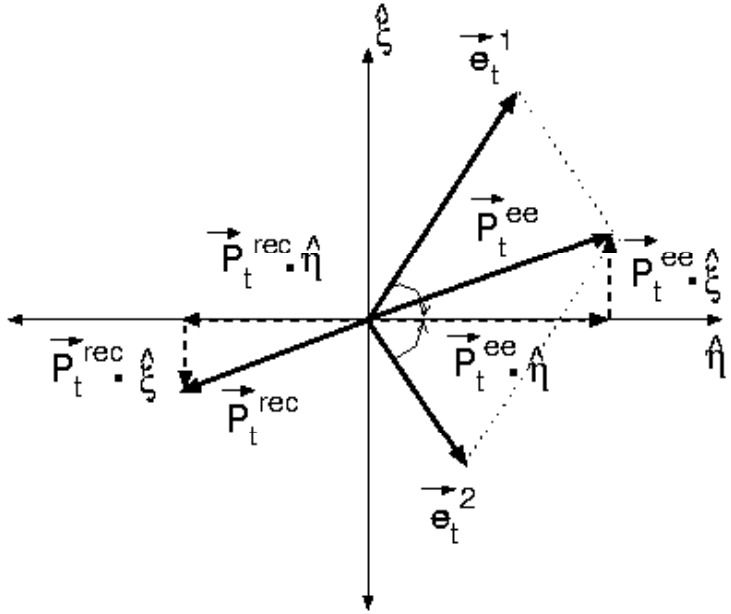
Recoil response and resolution

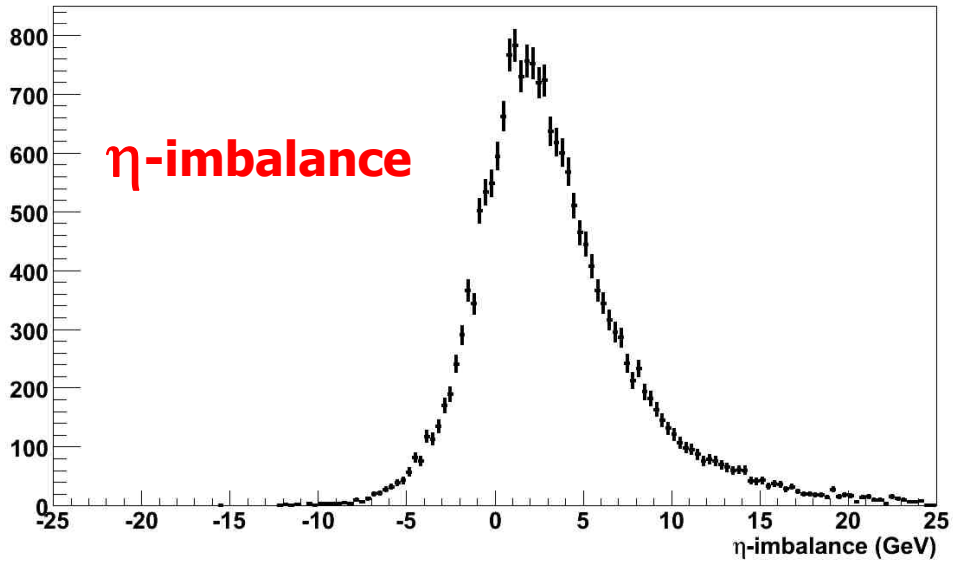
Project the u_T(recoil p_T) and Z boson p_T on η axis (bisector of the two electron directions)

Introduce a optimized variable called η-imbalance: $u_\eta + p_\eta(ee)$

Mean value of η-imbalance: sensitive to hadronic response parameters

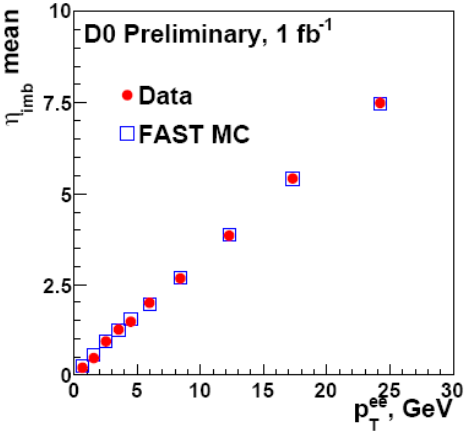
Width of η-imbalance: sensitive to hadronic resolution parameters (introduced by UA2)

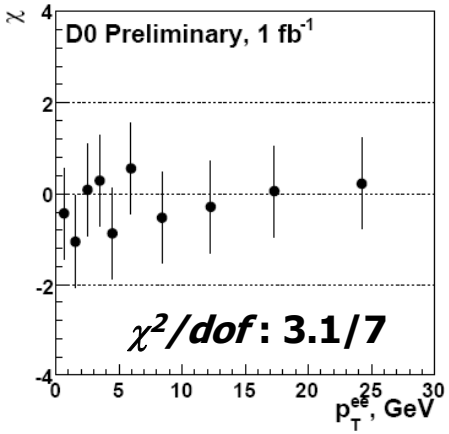


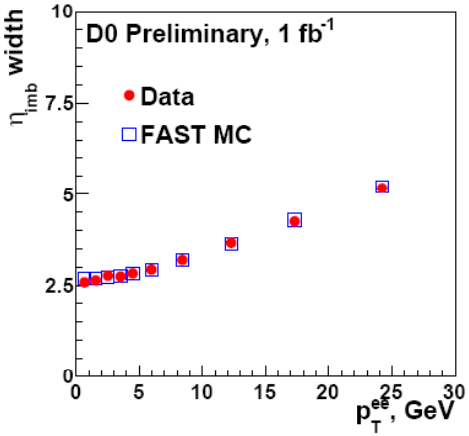


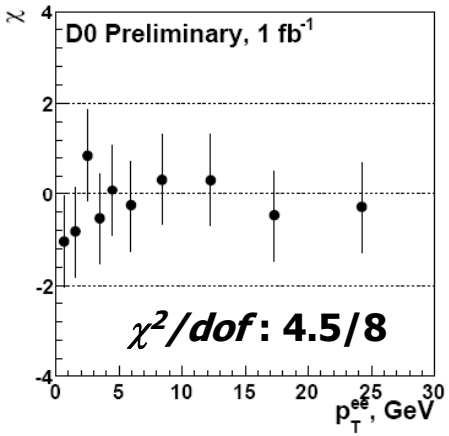
Hadronic Recoil System

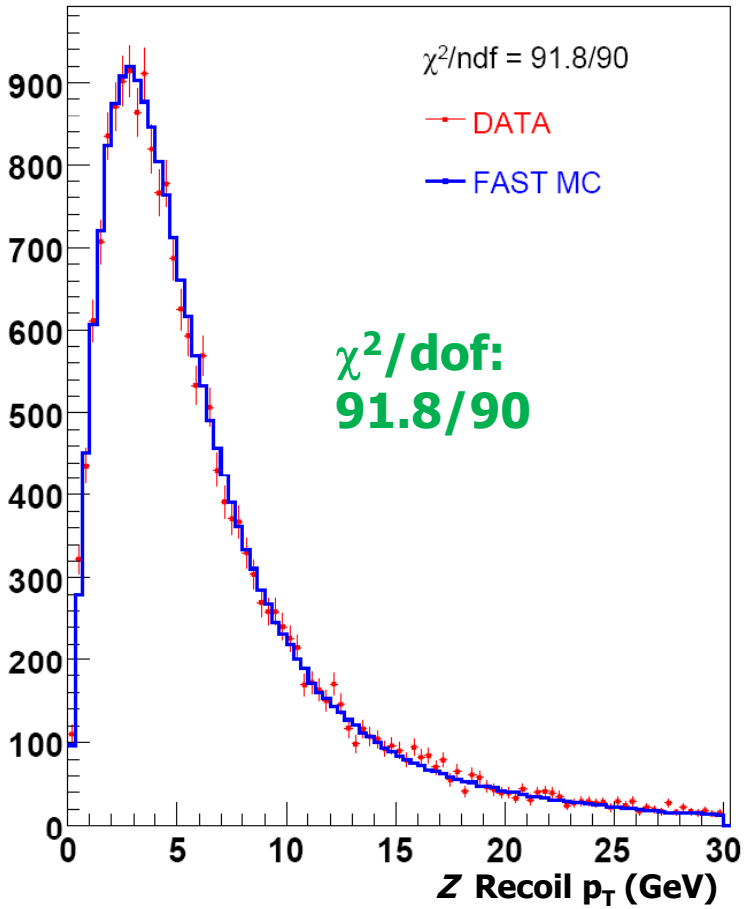
Final adjustment of free parameters in the recoil model is done *in situ* using balancing in *Z -> e e* events and the standard UA2 observables.









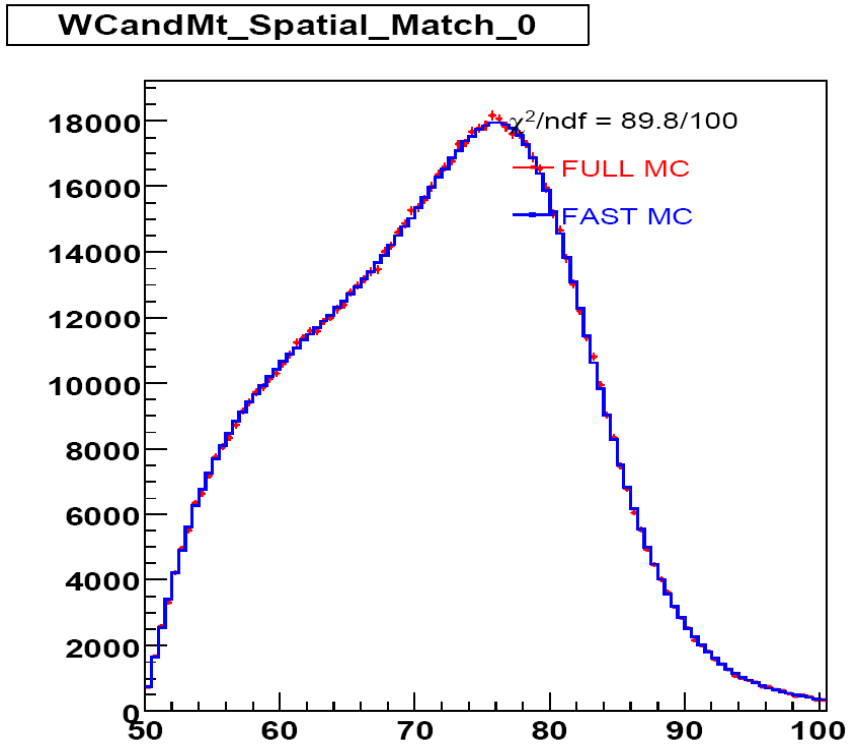


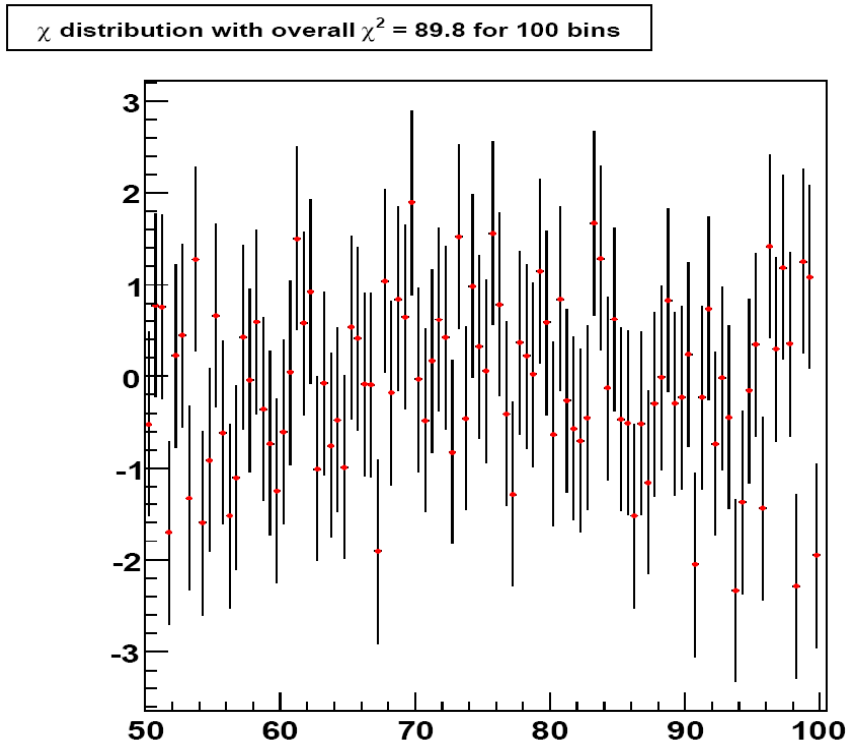
Monte Carlo Closure Test

***Z->ee* : 6 fb^{-1}**

***W->eν* : 2.3 fb^{-1}**

- **Treat full MC as data for closure test: Test methods we developed for efficiency, response, resolution etc measurements**



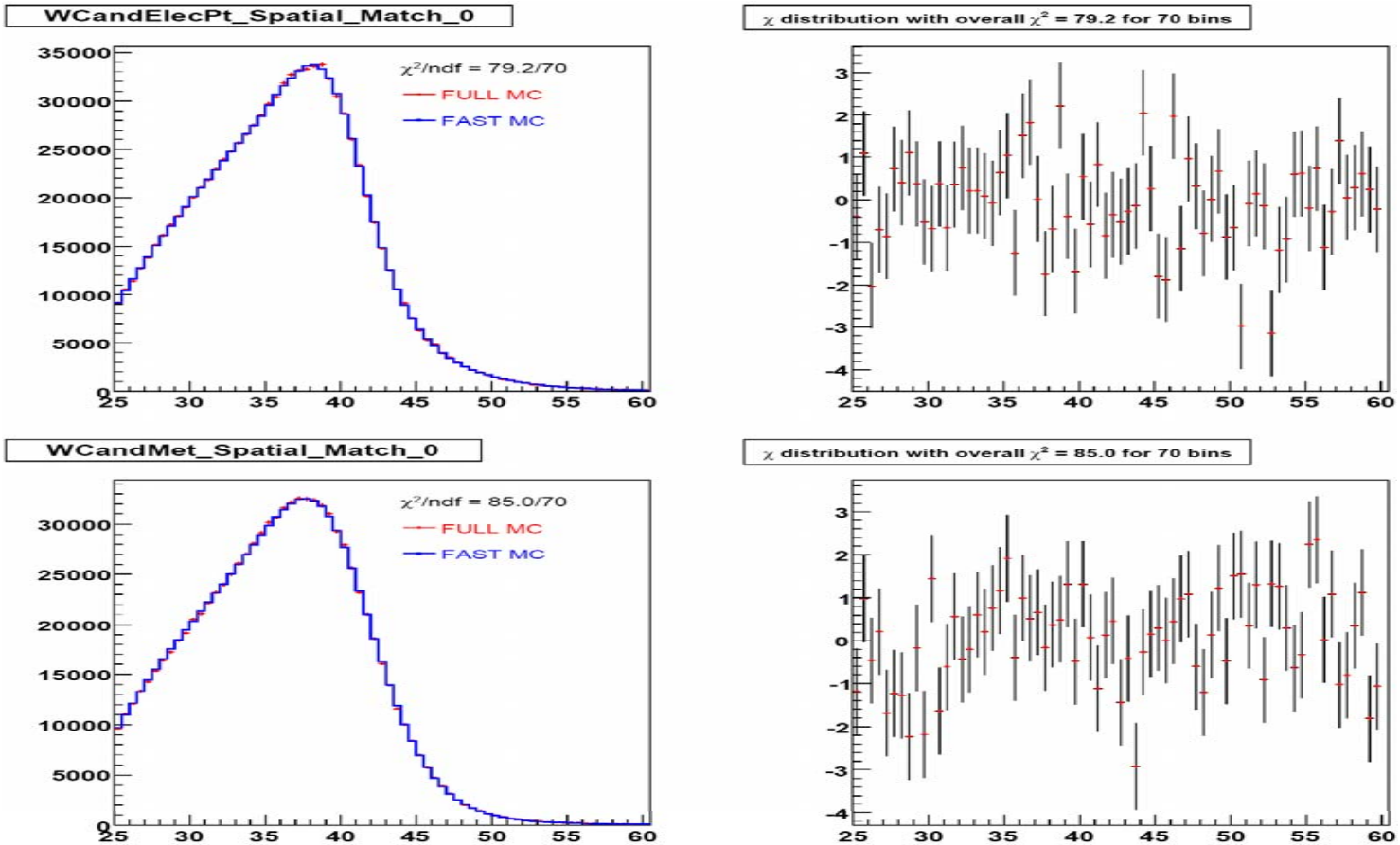


M_W (M_T): 80.441 ± 0.015 (stat) ± 0.011 (EM scale) ± 0.010 (E-loss bias)
Fit range: [65, 90] GeV
In good agreement with the input *W* mass: 80.450 GeV

Monte Carlo Closure Test

***Z->ee* : 6 fb^{-1}**

***W->eν* : 2.3 fb^{-1}**



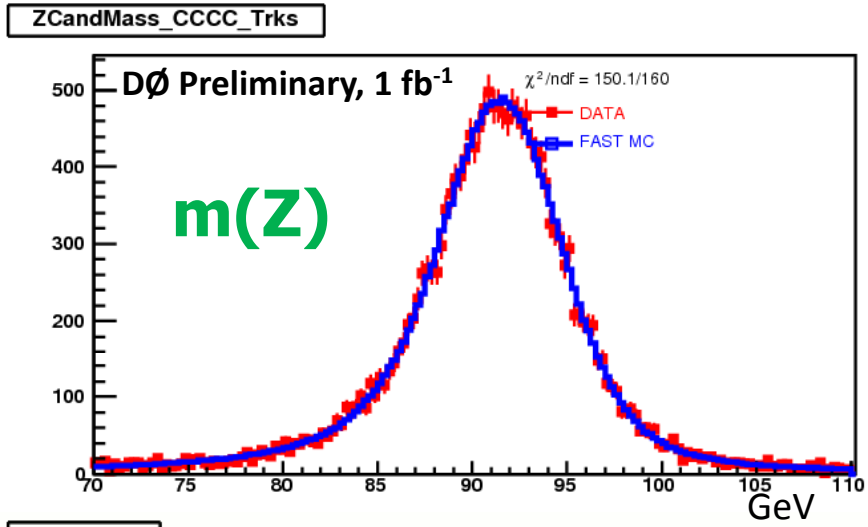
M_W (p_T(e)): 80.441 ± 0.019 (stat) ± 0.007 (EM scale) ± 0.010 (E-loss bias)

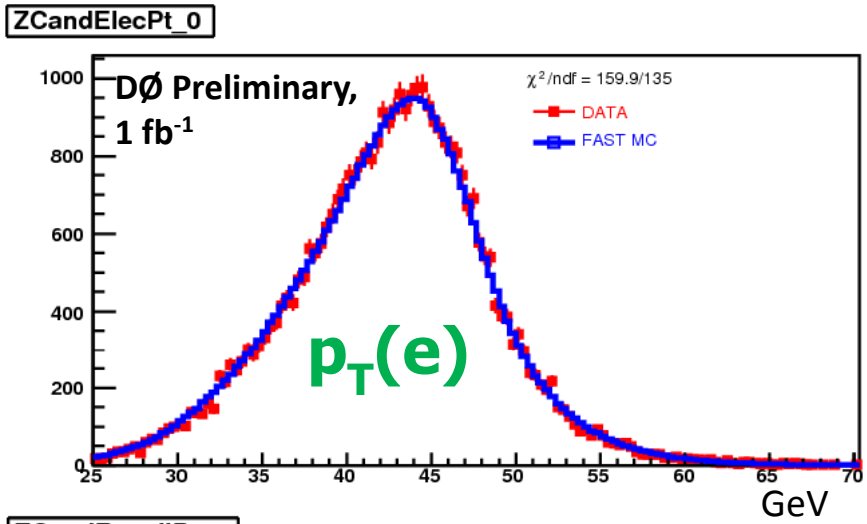
M_W (MET): 80.429 ± 0.019 (stat) ± 0.011 (EM scale) ± 0.010 (E-loss bias)

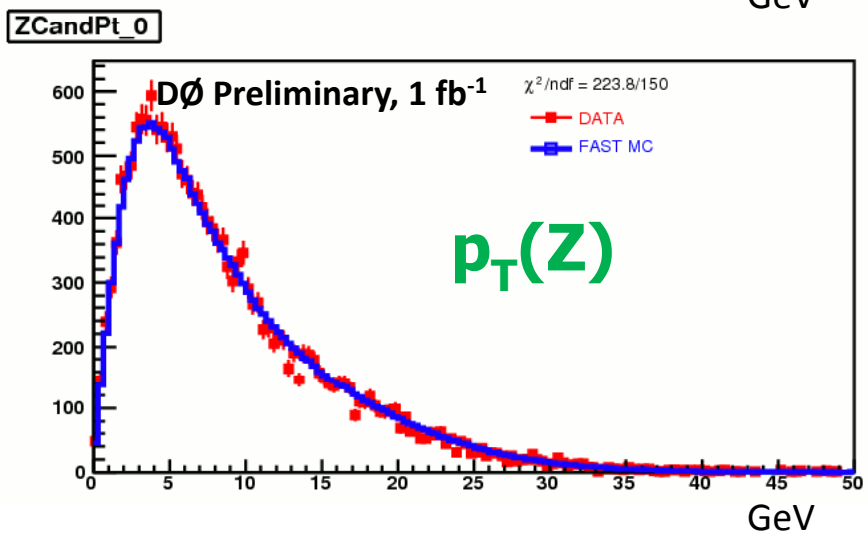
Fit ranges: [32, 48] GeV

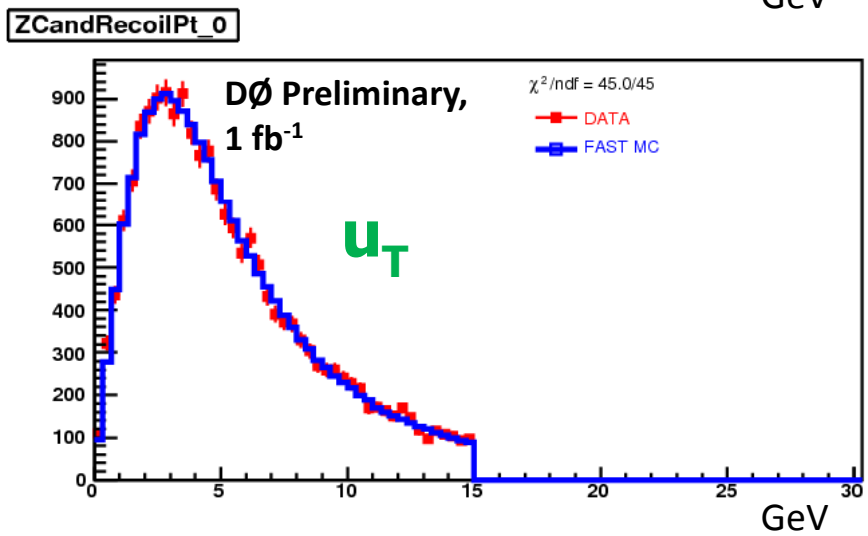
In good agreement with the input *W* mass: 80.450 GeV

Z->ee data





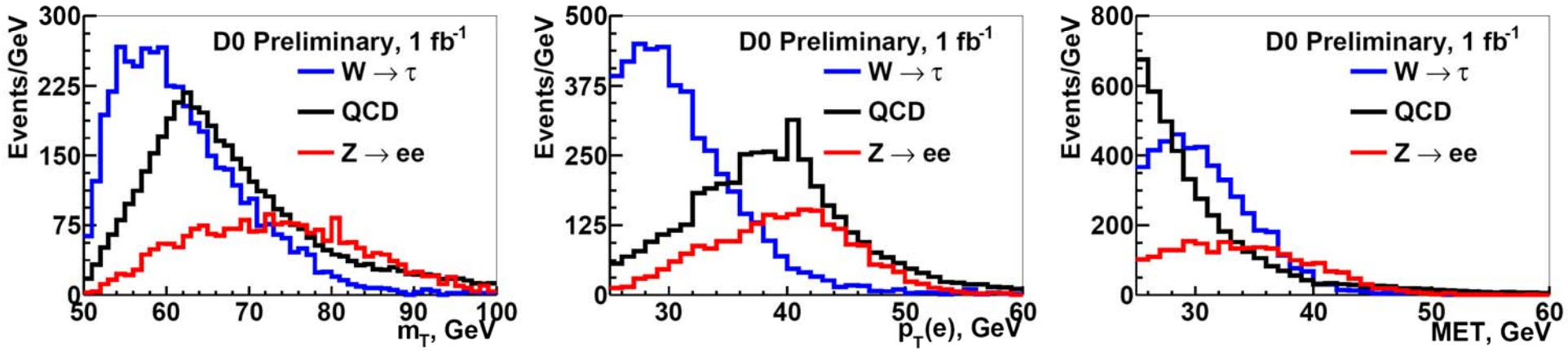




❖ **Good agreement between parameterized MC and collider data**

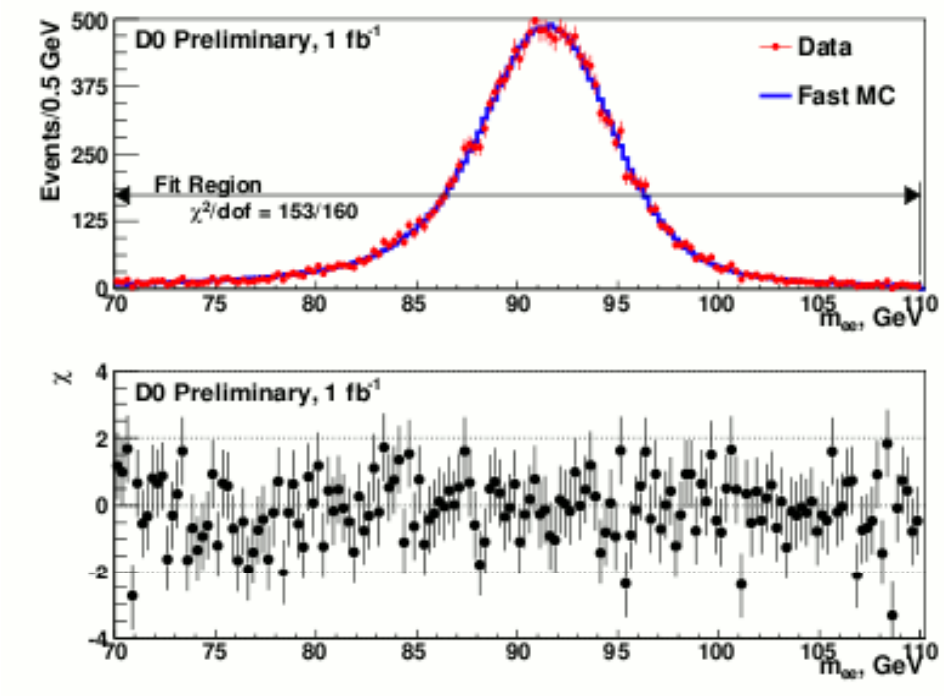
Backgrounds to W->eν

- **QCD (di-jet)((1.49±0.03)%):** one jet faked as electron
- **Z -> ee((0.80±0.01)%):** one electron lost in ICR(between central and forward calorimeter)
- **W -> τν((1.60±0.02)%)**: mostly from τ decays into "eνν"

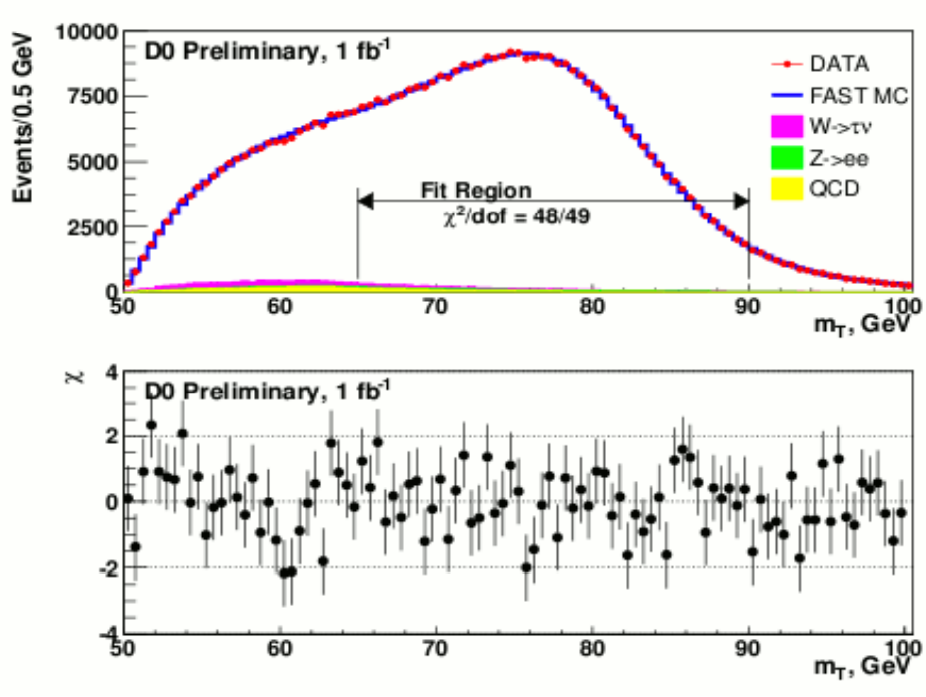


Mass fits

Z Mass



M_T



***Z->ee* : ~18k**

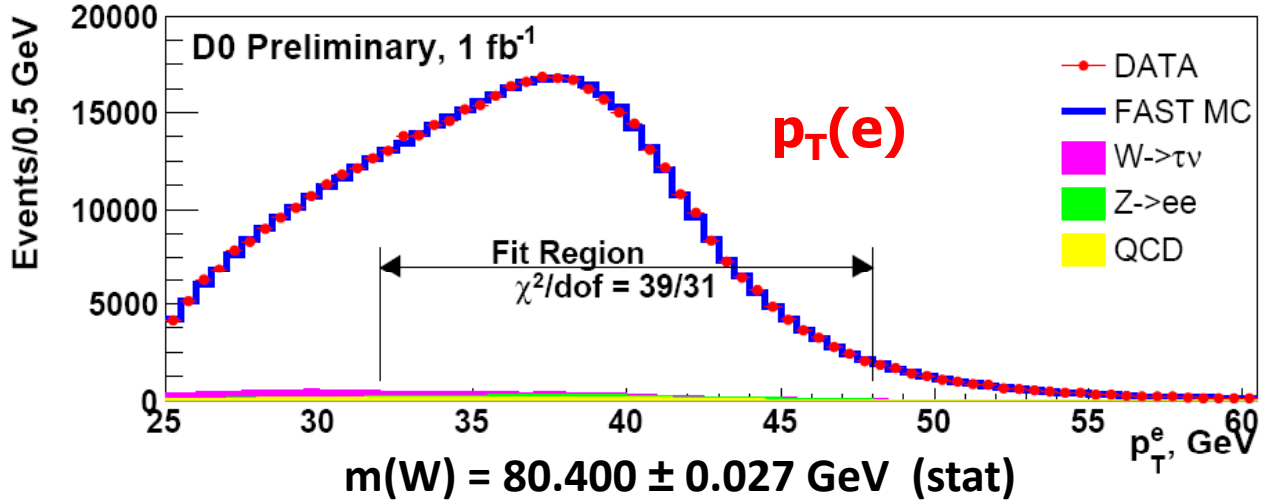
m(Z) = 91.185 ± 0.033 GeV (stat)

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

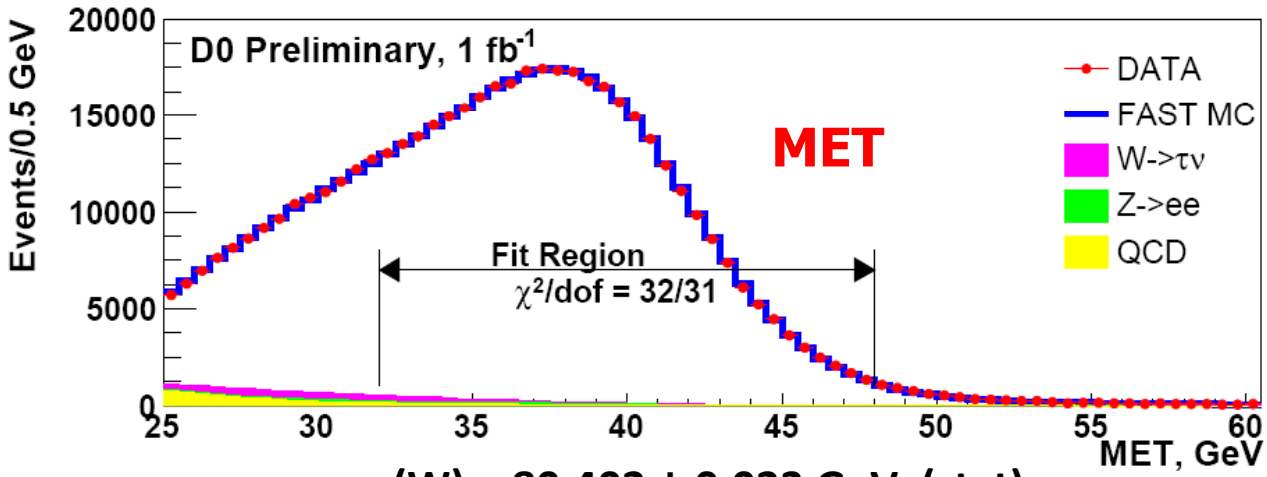
***W->eν* : ~500k**

m(W) = 80.401 ± 0.023 GeV (stat)

Mass fits



m(W) = 80.400 ± 0.027 GeV (stat)



m(W) = 80.402 ± 0.023 GeV (stat)

Summary of Uncertainties

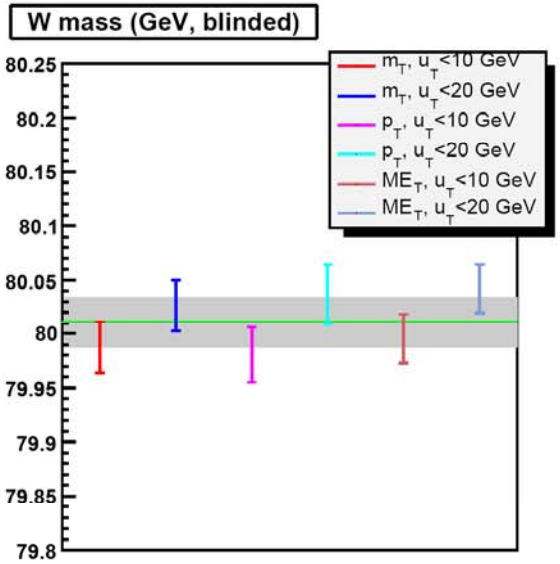
systematic uncertainties

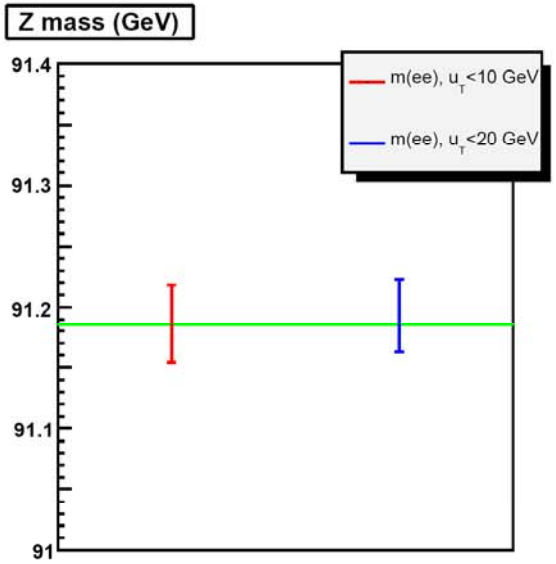
Source	$\sigma(m_W)$ MeV m_T	$\sigma(m_W)$ MeV p_T^e	$\sigma(m_W)$ MeV $\not{E}_T$
Experimental			
Electron Energy Scale	34	34	34
Electron Energy Resolution Model	2	2	3
Electron Energy Nonlinearity	4	6	7
W and Z Electron energy loss differences	4	4	4
Recoil Model	6	12	20
Electron Efficiencies	5	6	5
Backgrounds	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

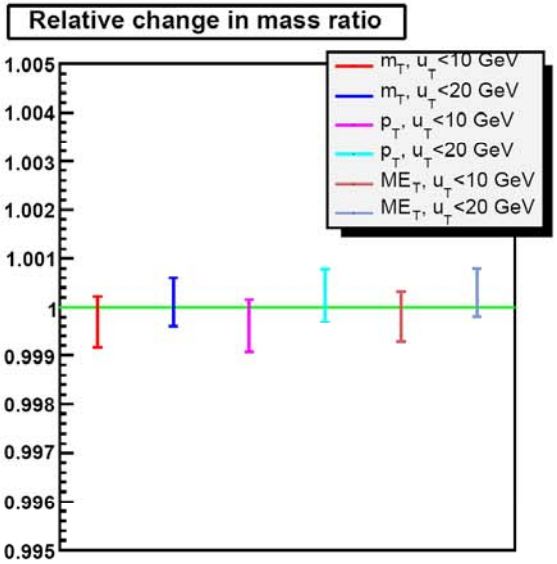
M_W : 80.401 ± 0.043 GeV (Combined)

Consistency Checks

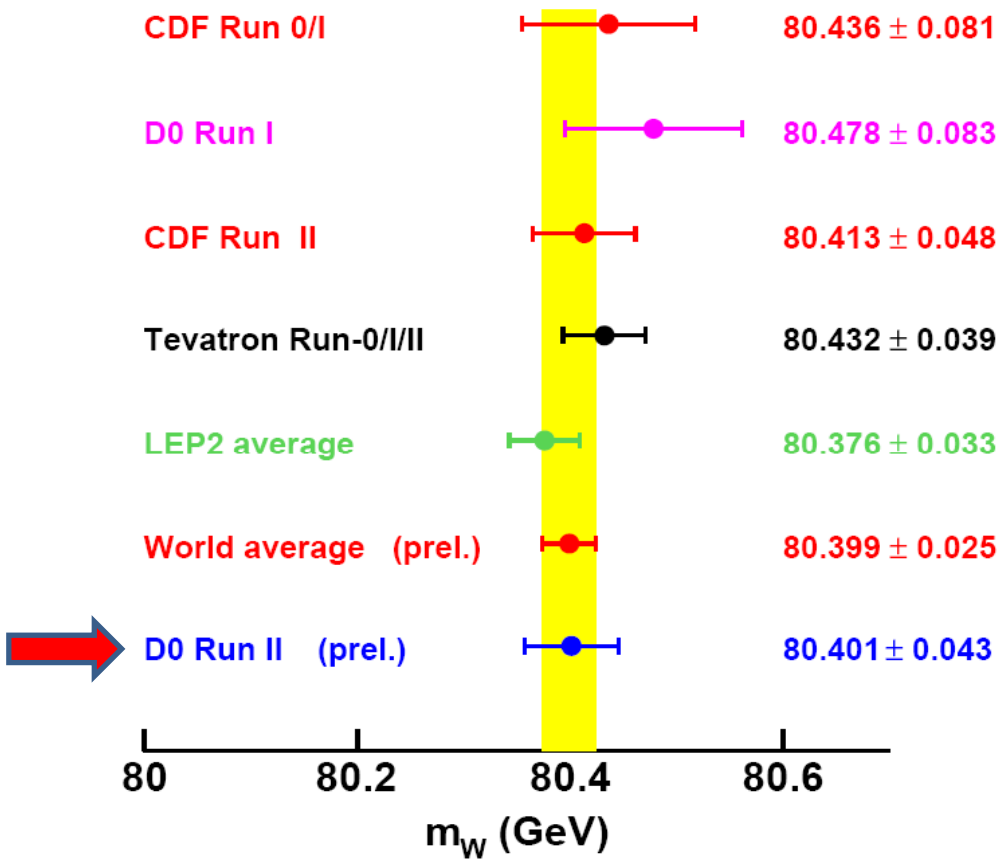
- u_T cut(shown below)
- Fit ranges
- Instantaneous luminosity
- Time
- Scalar E_T
- Phi fiducial cut
- $u_{||}$







Comparison to previous results



- D0 group measured W boson mass using 1 fb^{-1} Run II data with a precision of 0.05%, which is in good agreement with previous measurements.
- Single most precise measurement of the *W* boson mass to date
- Expect the world average to be reduced by ~10%

Summary

- D0 group measured W boson mass using 1 fb^{-1} Run II data with a precision of 0.05%:

  80.401 ± 0.023(stat) ± 0.037(syst) GeV= 80.401 ± 0.044 GeV (M_T)

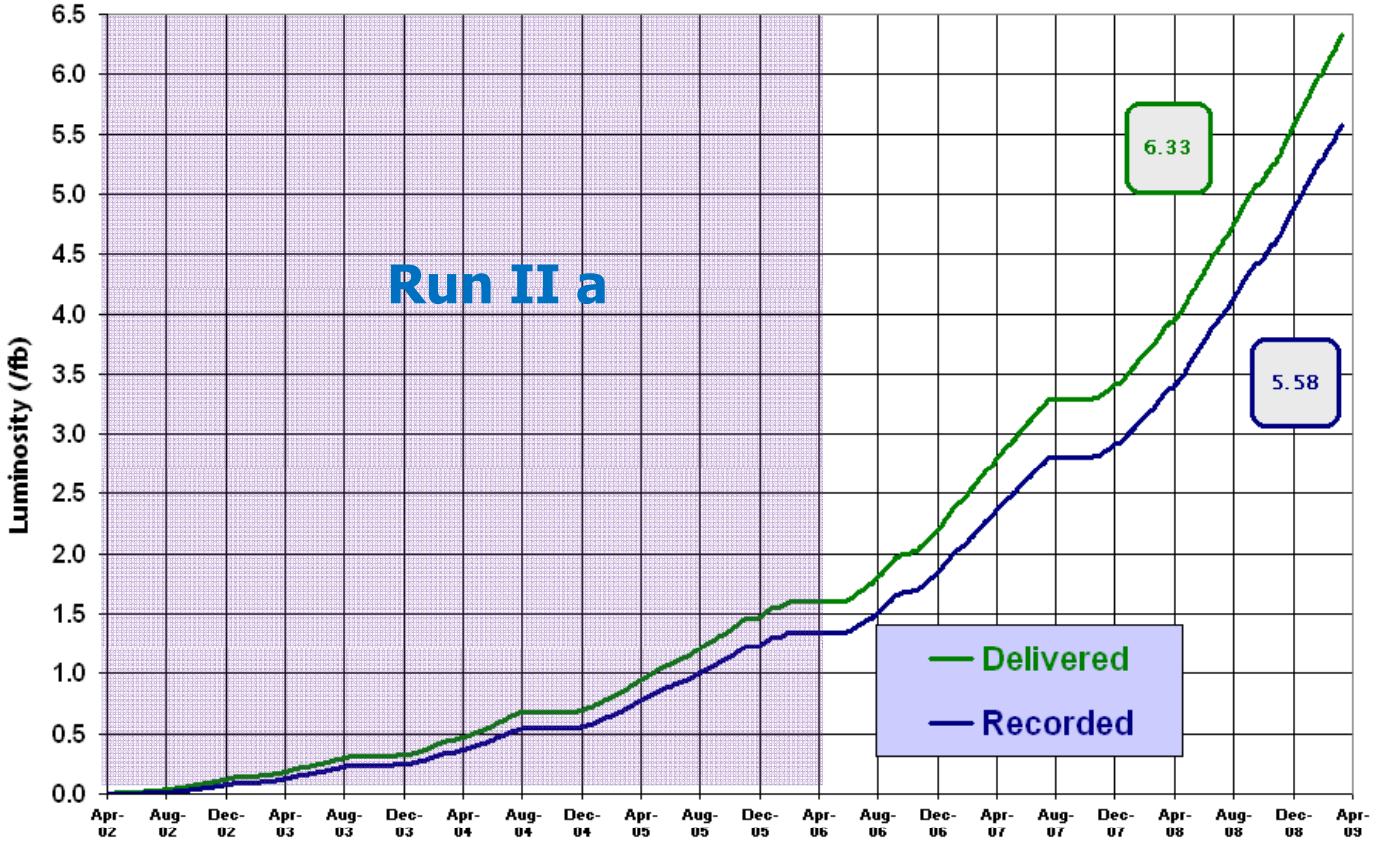
  80.400 ± 0.027(stat) ± 0.040(syst) GeV= 80.400 ± 0.048 GeV ($p_T(e)$)

  80.402 ± 0.023(stat) ± 0.044(syst) GeV= 80.402 ± 0.050 GeV (MET)
- 80.401 ± 0.043 GeV (Combined)

- Single most precise measurement of the *W* boson mass to date and in good agreement with previous measurements

- Will be submitted to Phys. Rev. Lett.

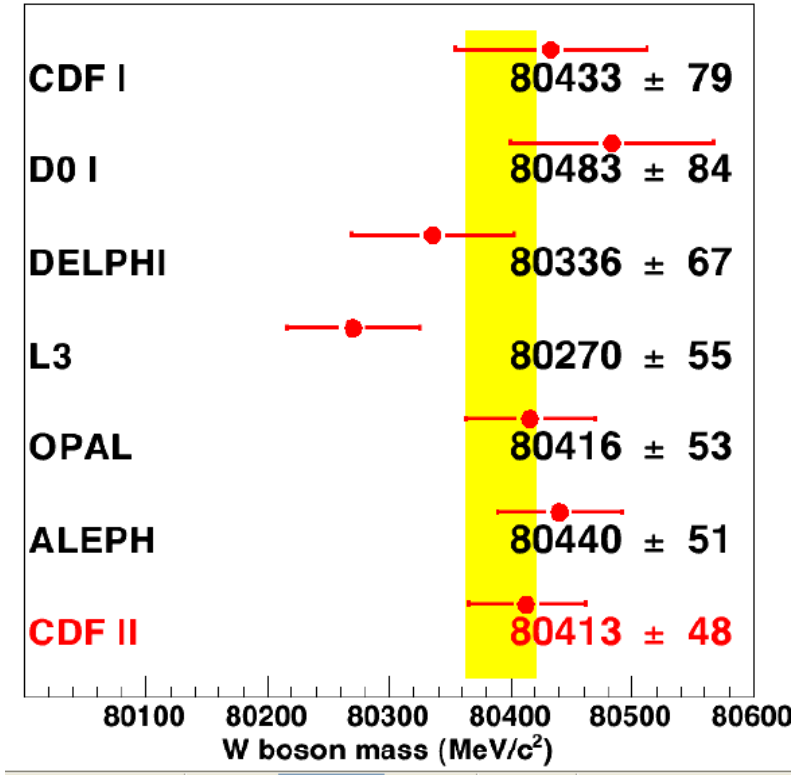
Outlook

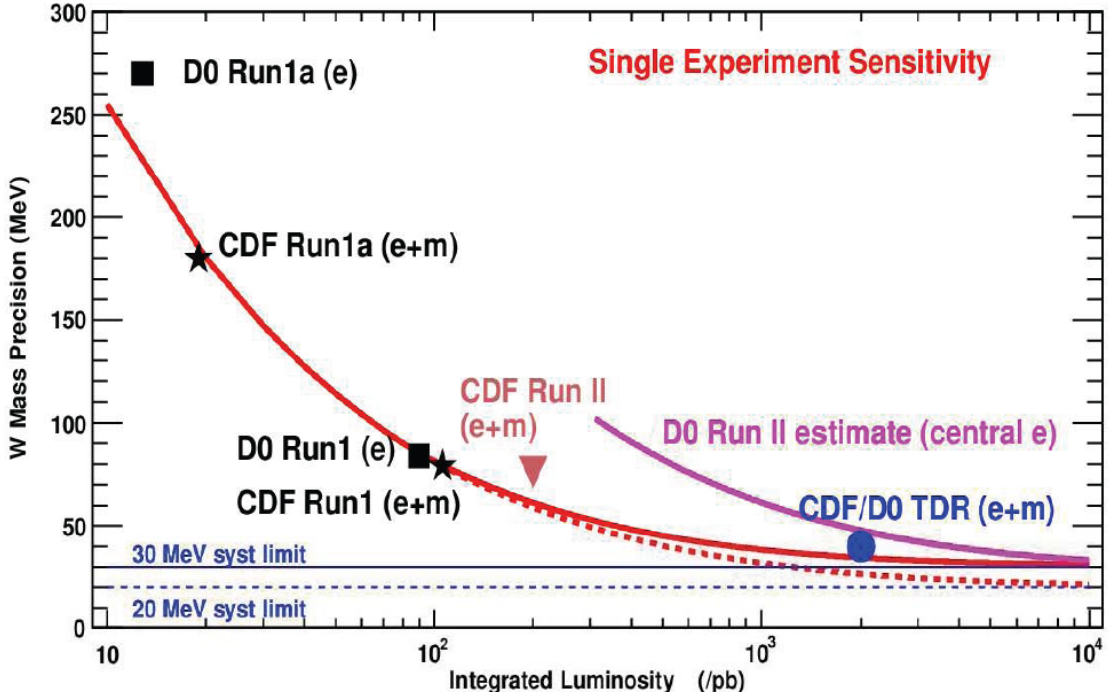


- **As just pointed out, the systematic uncertainty is mainly driven by the *Z→ee* statistics(1 fb^{-1}). With 5 fb^{-1} data, we expect to measure the *W* boson mass with an uncertainty ~ 25 MeV.**

- **Backup Slides**

Timeline of W Mass Measurement





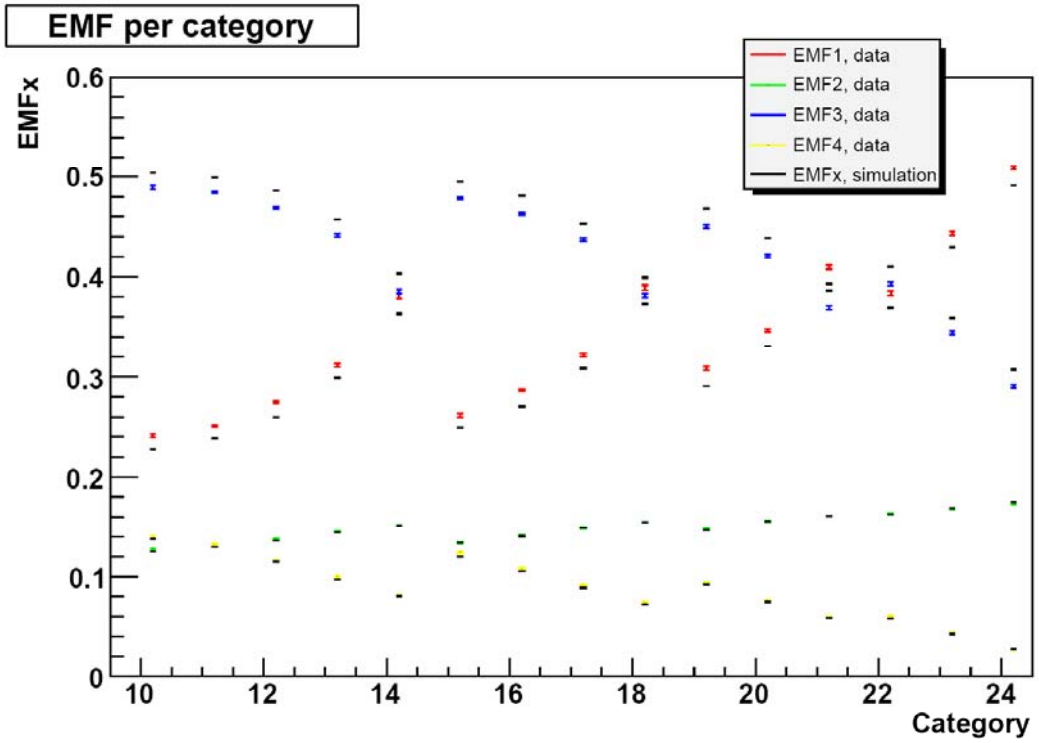
CDF Run II result used 200 pb-1 data in electron and muon channels

D0 RunII expectation was getting better thanks to the improved calibration

Calorimeter Calibration

- **Electronic calibration using pulsers**
- **Inter-phi calibration using inclusive electron sample collected with special triggers to make response uniform in phi**
- **Apply energy loss corrections for electrons due to the dead material in front of the calorimeter, corrections measured using full MC**
- **Inter-eta calibration: Z->ee data to do absolute calibration**

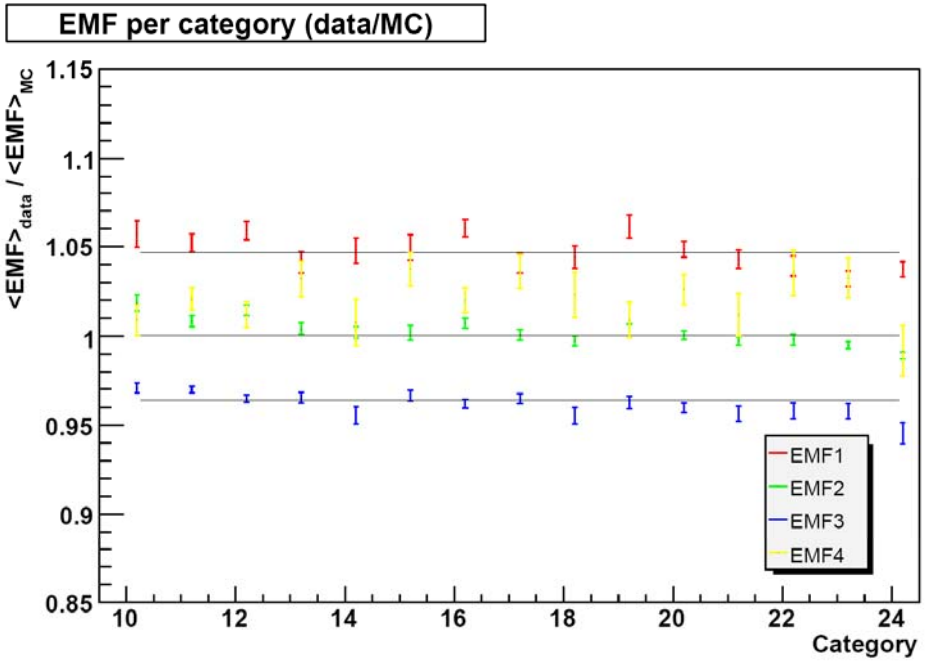
EM fraction(each of 4 layers) vs. category for data and simulation



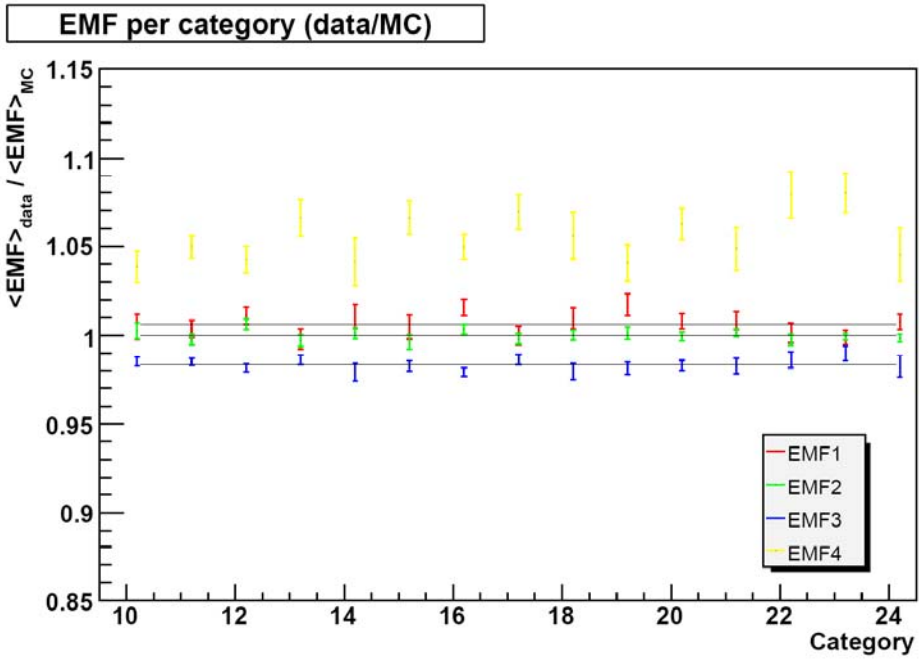
$$\text{bin 0:} \quad |\eta_{\text{phys}}| < 0.2$$
$$\text{bin 1:} \quad 0.2 \leq |\eta_{\text{phys}}| < 0.4$$
$$\text{bin 2:} \quad 0.4 \leq |\eta_{\text{phys}}| < 0.6$$
$$\text{bin 3:} \quad 0.6 \leq |\eta_{\text{phys}}| < 0.8$$
$$\text{bin 4:} \quad 0.8 \leq |\eta_{\text{phys}}|$$

Category	Combination of η_{phys} bins
10	0 - 0
11	0 - 1
12	0 - 2
13	0 - 3
14	0 - 4
15	1 - 1
16	1 - 2
17	1 - 3
18	1 - 4
19	2 - 2
20	2 - 3
21	2 - 4
22	3 - 3
23	3 - 4
24	4 - 4

Before tuning of missing material



After tuning of missing material



Electron Energy Resolution

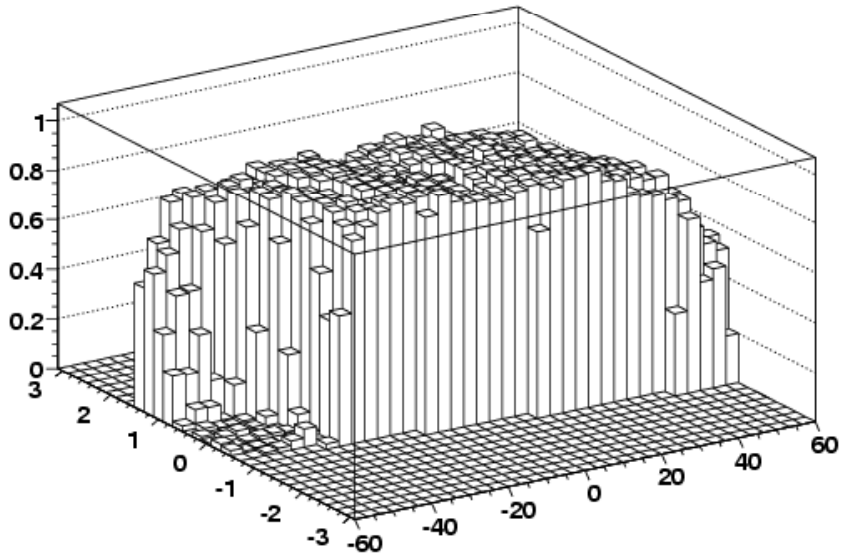
$$\frac{\sigma_{EM}(E)}{E} = \sqrt{C_{EM}^2 + \frac{S_{EM}^2}{E} + \frac{N_{EM}^2}{E^2}}$$

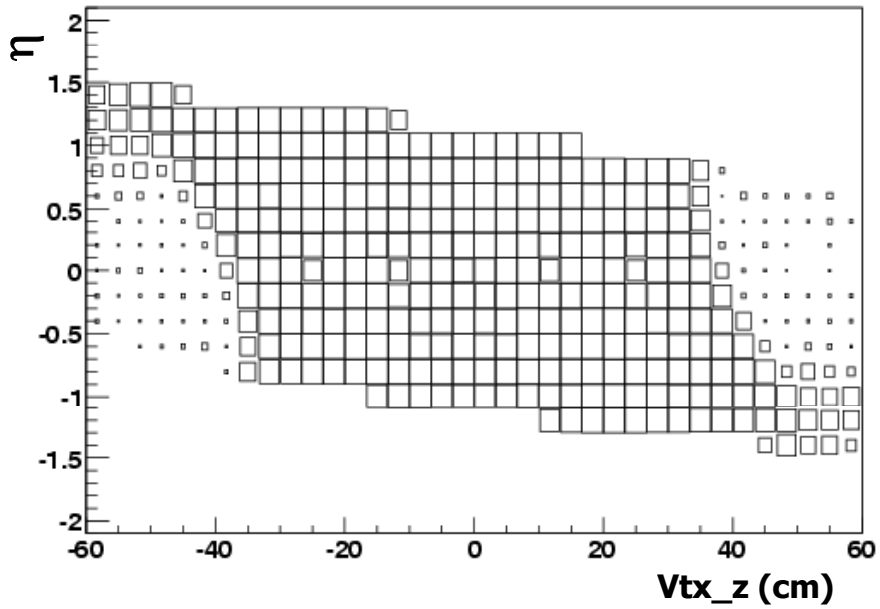
$$S_{EM} = (S_1 + \frac{S_2}{\sqrt{E}}) \times \frac{e^{S_{exp}/\sin\theta}}{e^{S_{exp}}}$$

$$S_{exp} = S_3 - S_4/E - S_5^2/E^2$$

$$S_1 = 0.164$$
$$S_2 = 1.122$$
$$S_3 = 1.35193$$
$$S_4 = 2.09564$$
$$S_5 = 6.98578$$

Geometry Acceptance

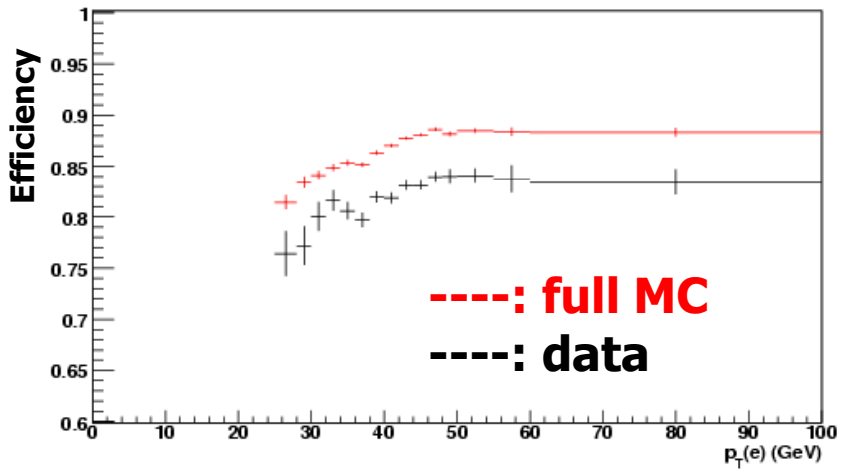


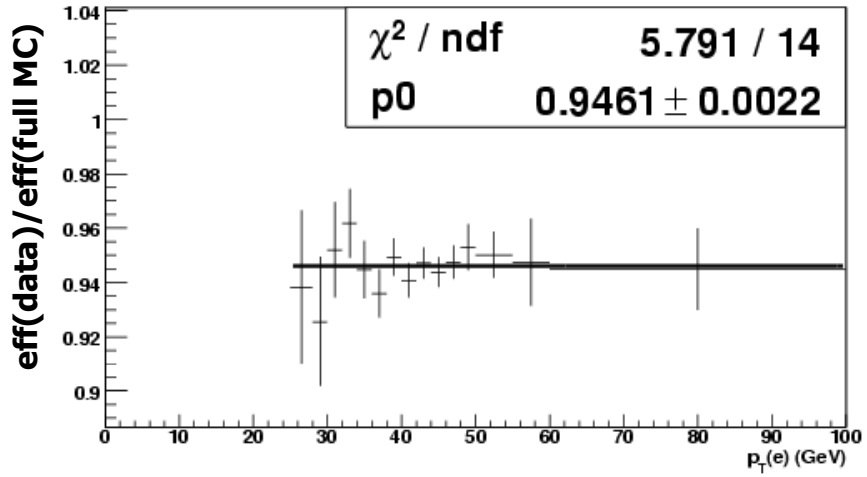


- **Efficiency vs eta and primary vertex is measured using the tag-and-probe method**

Final Efficiency Check

- The SET and pure $p_T(e)$ dependence of efficiency is studied in details using full MC(6 fb^{-1}) truth, which cannot be performed in data due to the method and limited statistics
- Use tag-and-probe method to measure $p_T(e)$ dependence in full MC and data as a final check

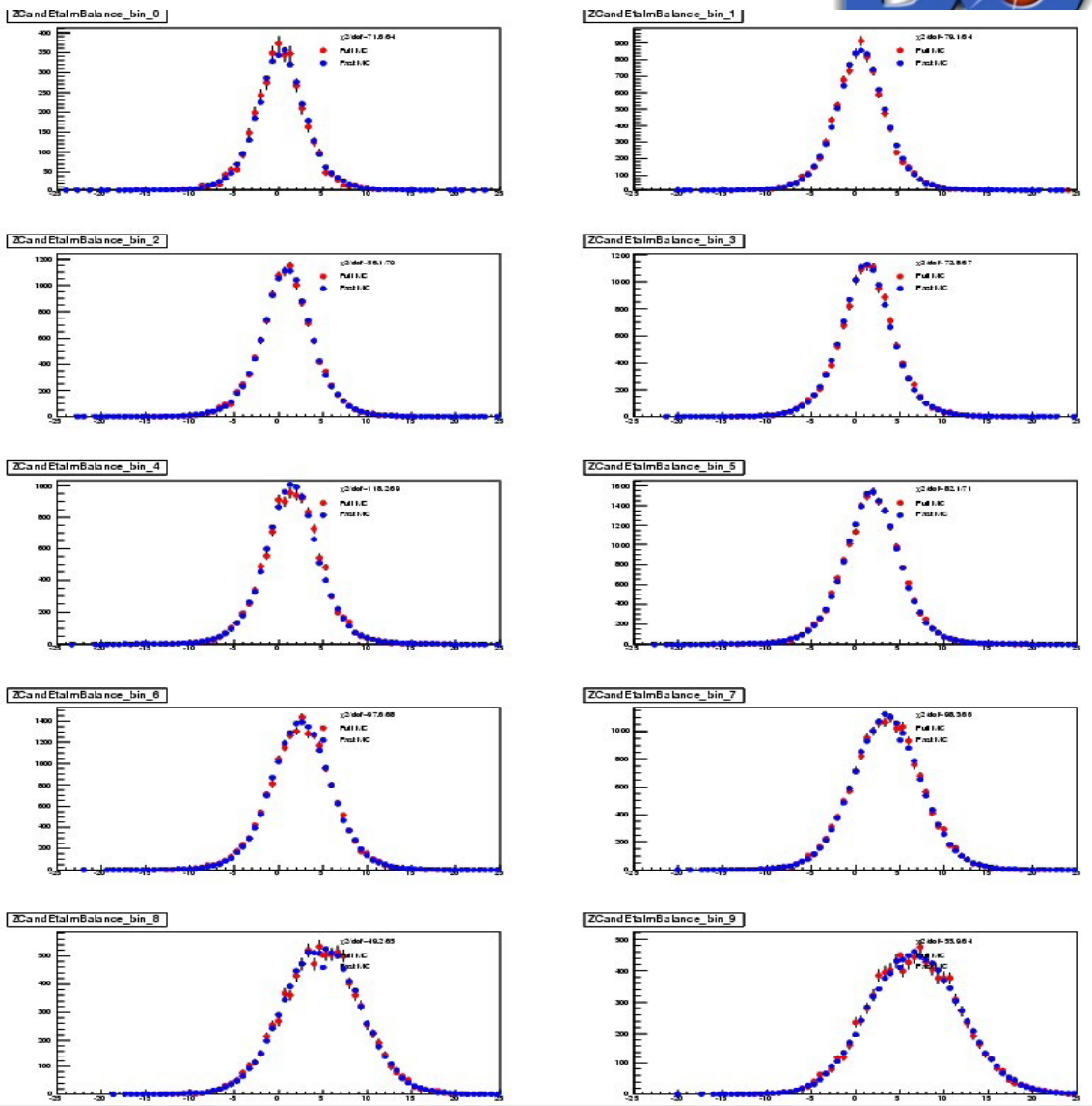




η-imbalance

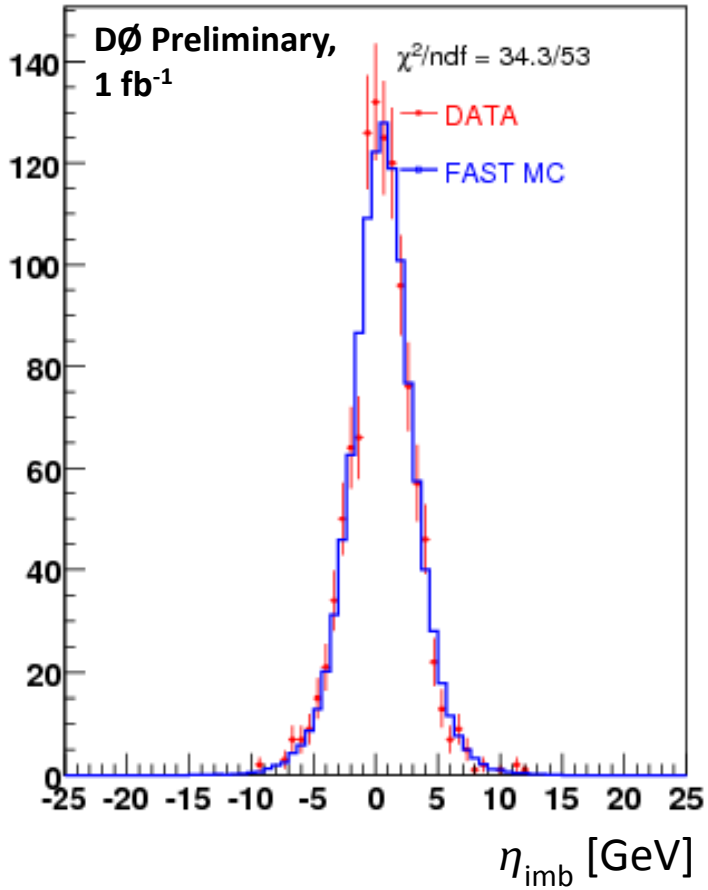
$p_T(ee)$(GeV)

0 – 1
1 - 2
2 - 3
3 - 4
4 - 5
5 - 7
7 - 10
10 - 15
15 - 20
20 - 30

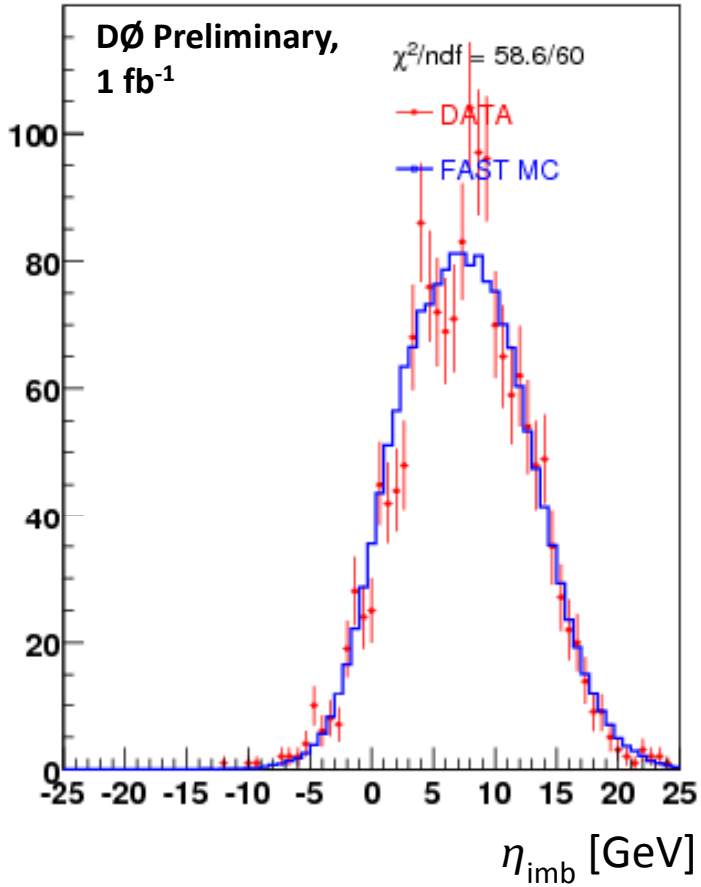


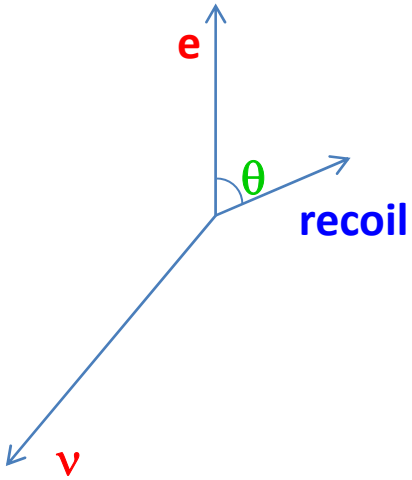
Examples: η_{imb} Distributions

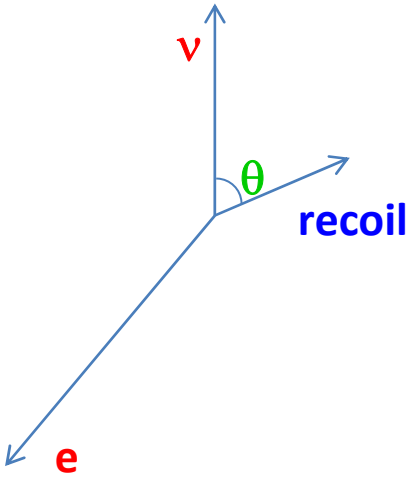
$1 < p_T(ee) < 2$ GeV

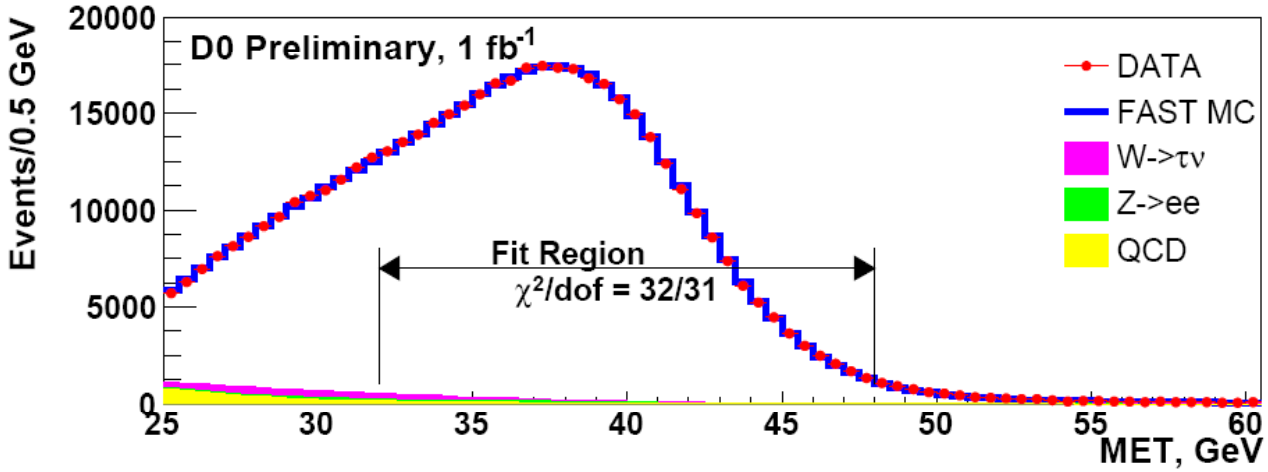


20 GeV $< p_T(ee)$



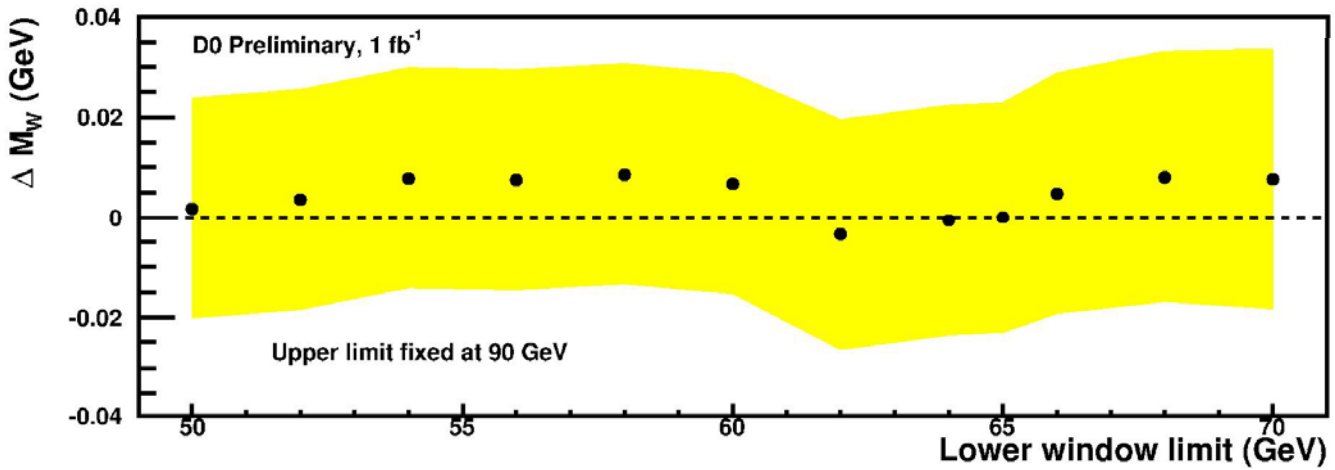

e
θ
recoil
ν

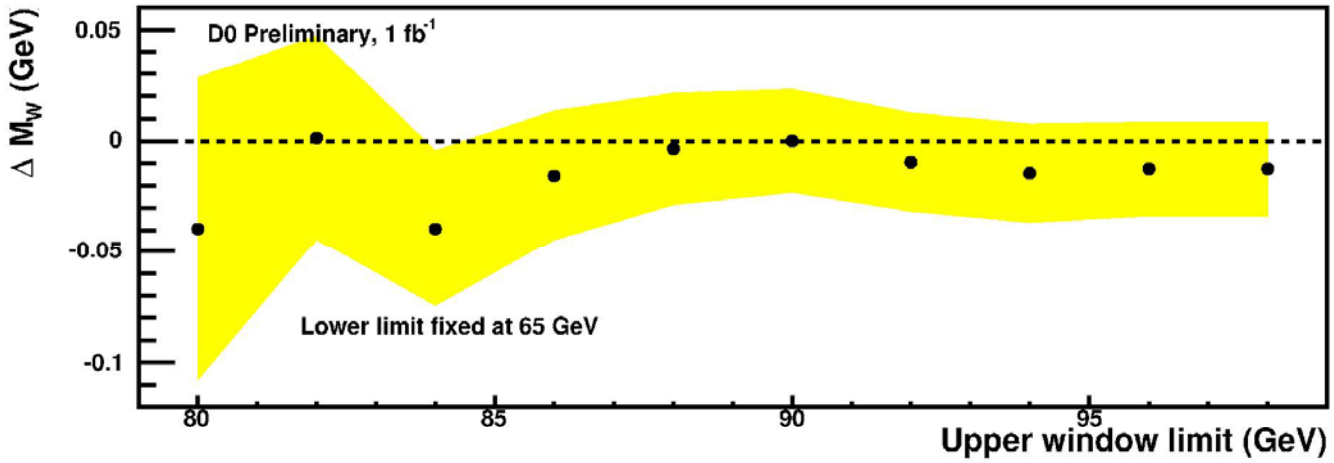

ν
θ
recoil
e


D0 Preliminary, 1 fb-1
Events/0.5 GeV
20000
15000
10000
5000
0
25
30
35
40
45
50
55
60
MET, GeV
Fit Region
χ2/dof = 32/31
DATA
FAST MC
W->τν
Z->ee
QCD

Consistency Checks

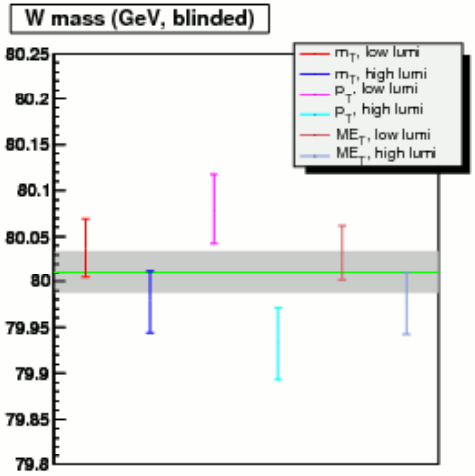
Changes in the fitted m_W when the fitting range (m_T observable) is varied.

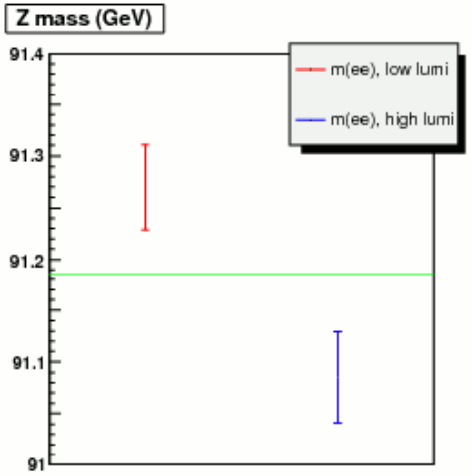


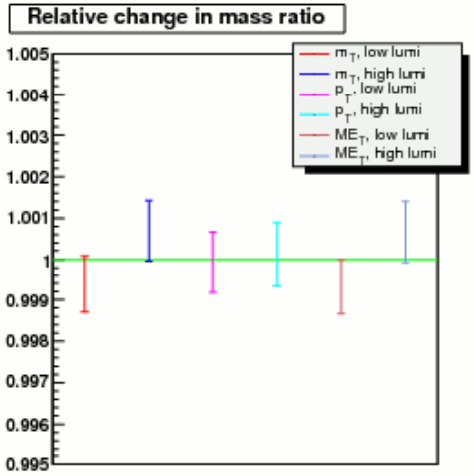


Consistency Checks

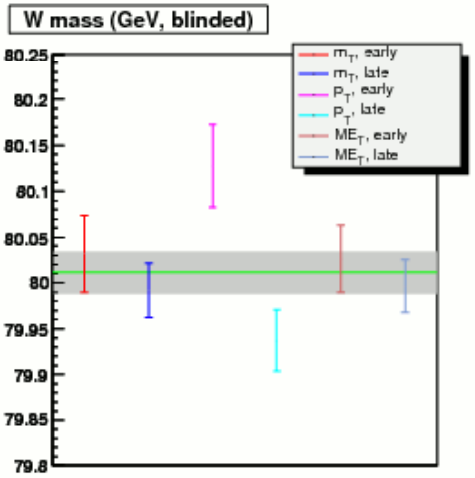
Instantaneous luminosity (split data into two subsets – high and low inst. luminosity)

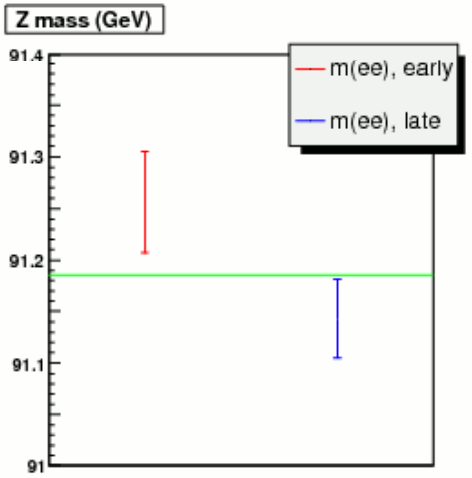


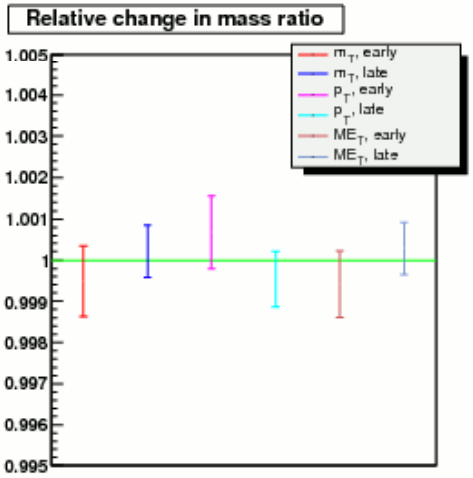




Time (i.e. data-taking period)

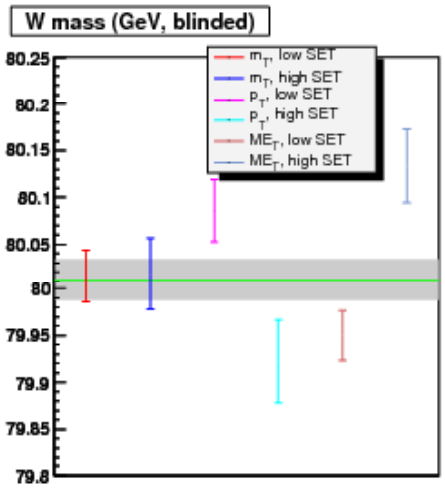


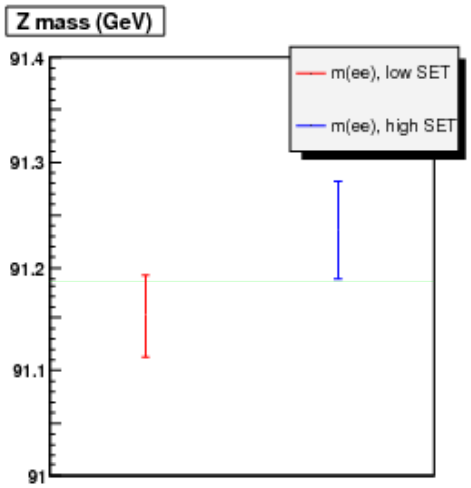


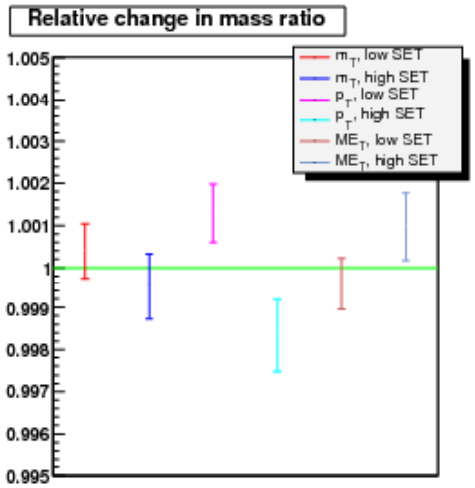
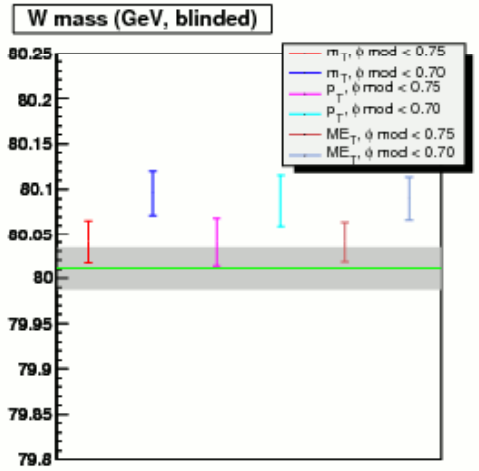
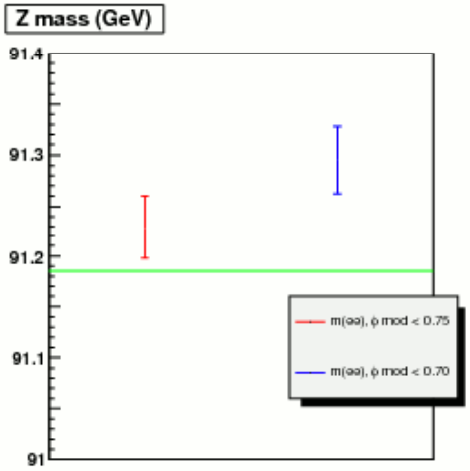
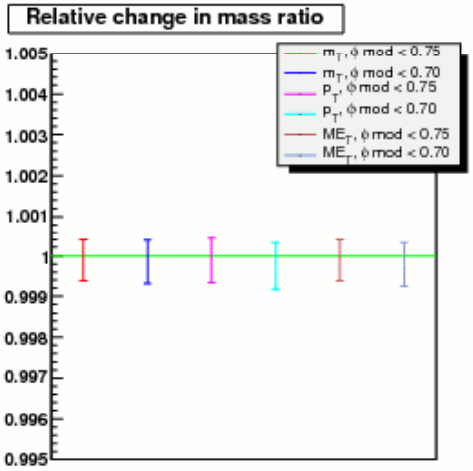


Consistency Checks

Scalar E_T ("global event activity as seen by calorimeter")







Electron distance from phi cracks