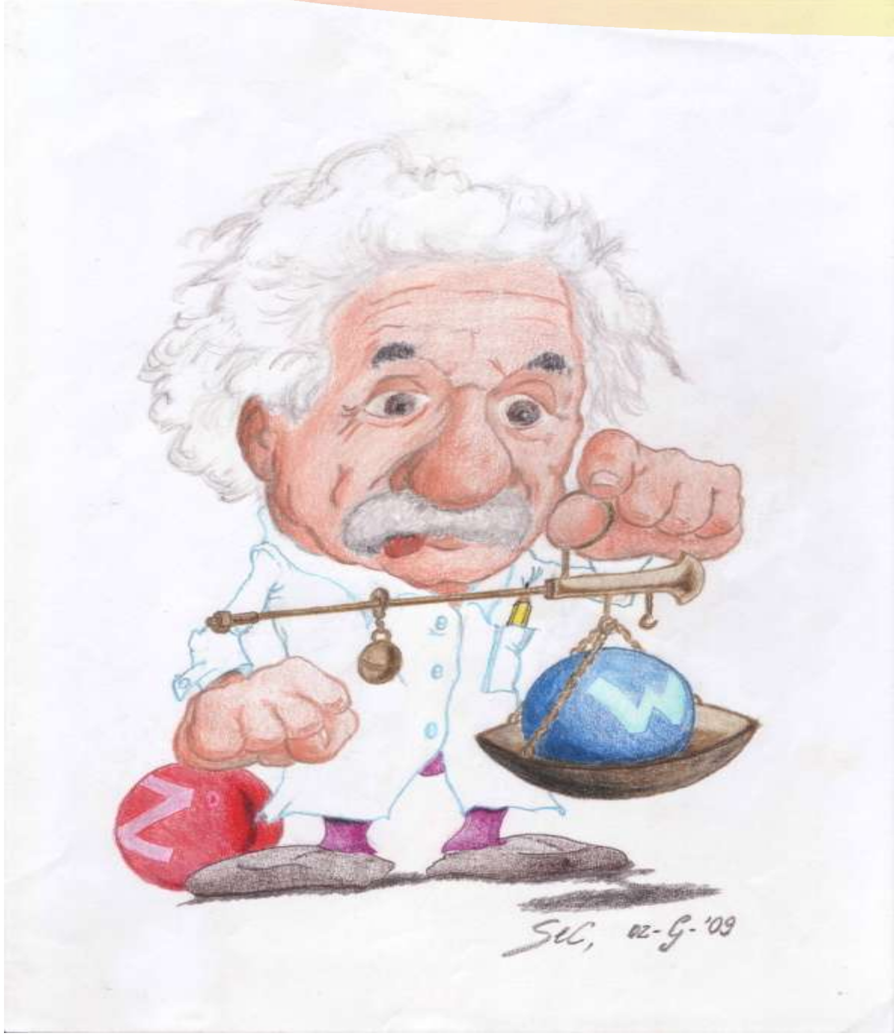
DPF 2009

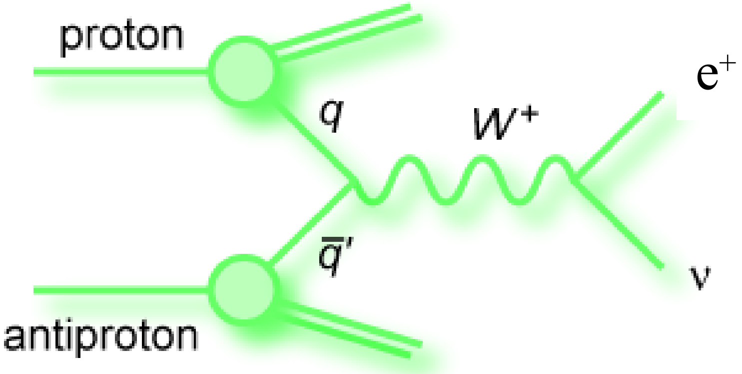
2009 Meeting of the Division of Particles and Fields of the American Physical Society (DPF 2009)

26-31 JULY 2009

Wayne State University, Detroit, MI

Measurement of the W Boson Mass with 1fb^{-1} of DØ RunII Data





Jyotsna Osta

University of Notre Dame

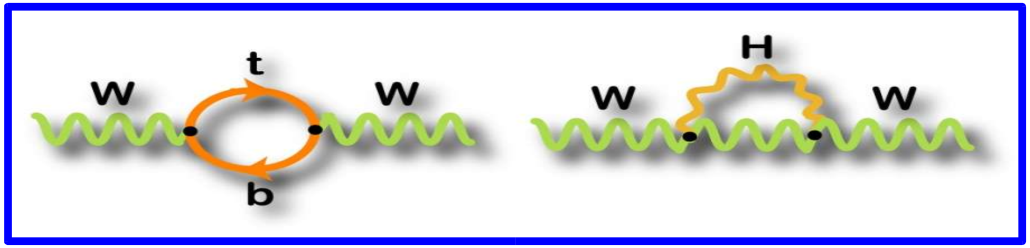
On Behalf of the DØ collaboration

Motivation for a precise measurement of M_W

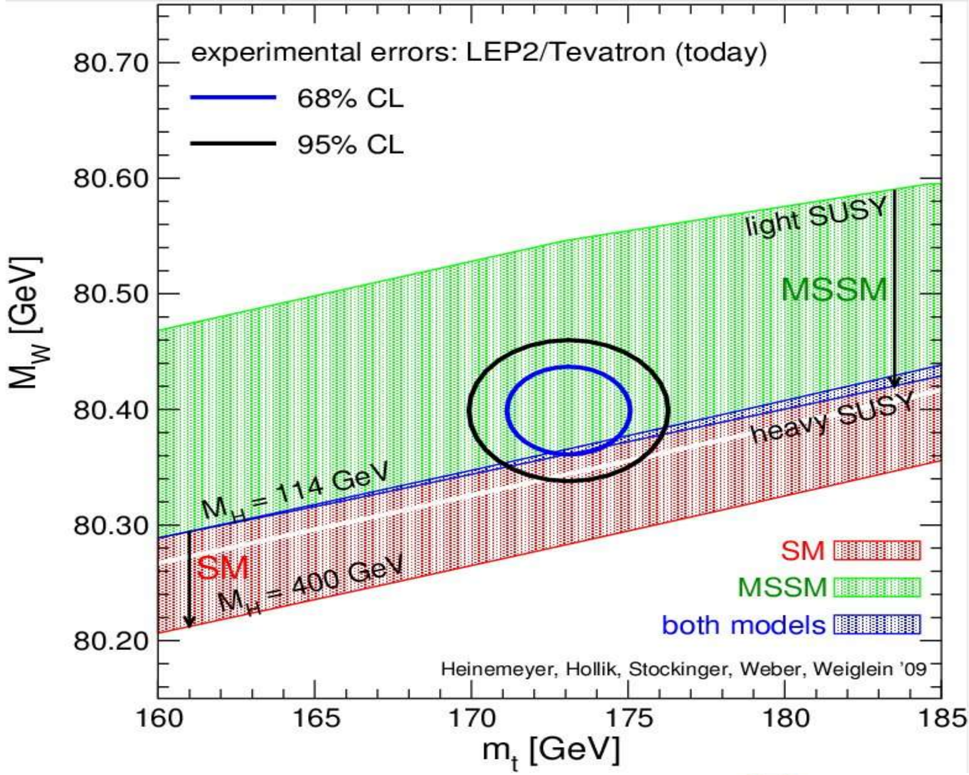
- W boson is one of the fundamental carriers of the weak nuclear force

$$\boxed{M_W = \sqrt{\frac{\pi \alpha_{EM}}{2G_F}}\,\frac{1}{\sin\theta_W \sqrt{1-\Delta r}}}$$

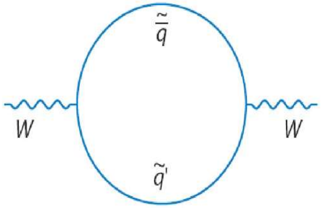
- SM prediction of W mass = 80.390 ± 0.018 GeV



$\Delta r \sim \mathbf{M}_{\mathbf{top}}^{2}$ $\Delta r \sim \log \mathbf{M}_{\mathbf{Higgs}}$



- Higher order contributions to Δr could come from new physics



- Precise measurements of $\mathbf{M}_{\mathbf{W}}$ and $\mathbf{M}_{\mathbf{top}}$ help constrain SM Higgs mass ($\mathbf{M}_{\mathbf{Higgs}}$) !
- For equal contributions on $\Delta M_{\mathrm{Higgs}}$ from M_{top} and M_W we need :
  - $\mathbf{\Delta M_w \approx 0.006\, \Delta M_{top}}$
- Currently $\mathbf{\Delta M_{top}}$ = 1.3 GeV ⇒ $\mathbf{\Delta M_w}$ = 8 MeV (0.01%) !
- Present World Average : $\mathbf{\Delta M_w}$ = 25 MeV (0.03 %)

Expectation of this analysis :
$\mathbf{\Delta M_w}$ ~ 50 MeV (0.05%)

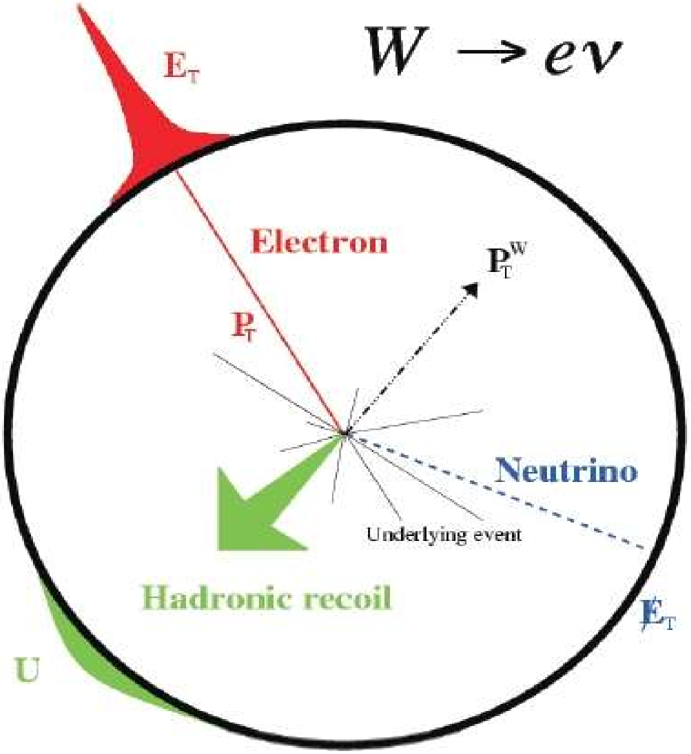
Experimental observables

- **Three important signatures -**
  - **Lepton (Electron/Muon)**
  - **Neutrino**
  - **Recoiling hadrons**

- W boson is reconstructed in plane transverse to beamline of detector
  - Cannot reconstruct the longitudinal momentum (p_z) of neutrino

- W mass is measured using three physical observables :
  - p_T^{lepton} – sensitive to motion of W boson (p_T^W)
  - m_T – sensitive to missing energy resolution
  - $p_T^{neutrino}$ ($\not{E}_T$) – sensitive to both effects but is not 100% correlated with the other 2 measurements

- For an uncertainty of $\Delta M_W = 0.05\%$
  - Precision on EM response ~ **0.05%**
  - Precision on HAD recoil ~ **1%**



$$\vec{\not{E}}_T = -(\vec{p}_T^{\,e} + \vec{p}_T^{\,Recoil})$$

$$m_T^2 = (|E_T^e| + |E_T^\nu|)^2 - (\vec{p}_T^{\,e} + \vec{p}_T^{\,\nu})^2$$

$$m_T^2 = 2E_T^e E_T^\nu (1 - \cos\varphi_{e\nu})$$

Strategy for the M_W measurement

This analysis focuses on W→ eν mode of decay only

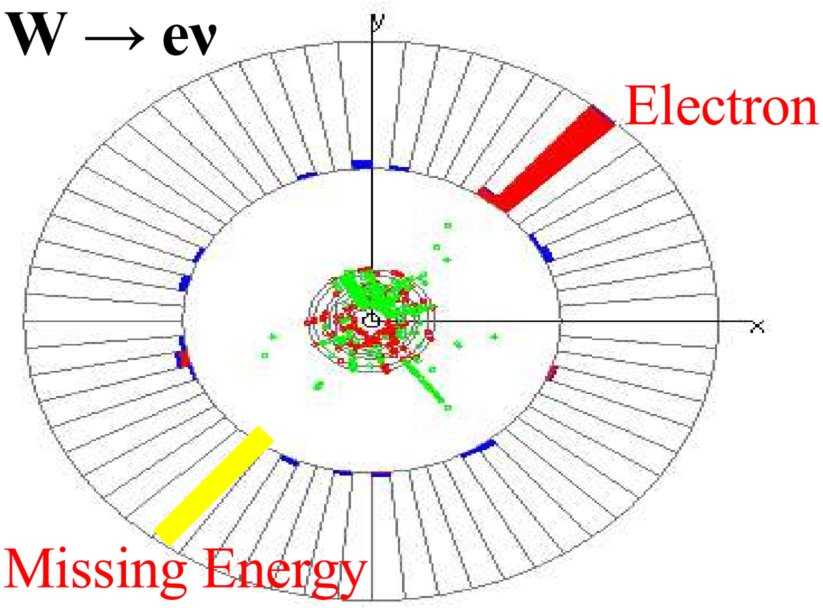
- **Compare m_T, p_T^e, $\not{E}_T$** distributions from data with corresponding templates from Monte-Carlo

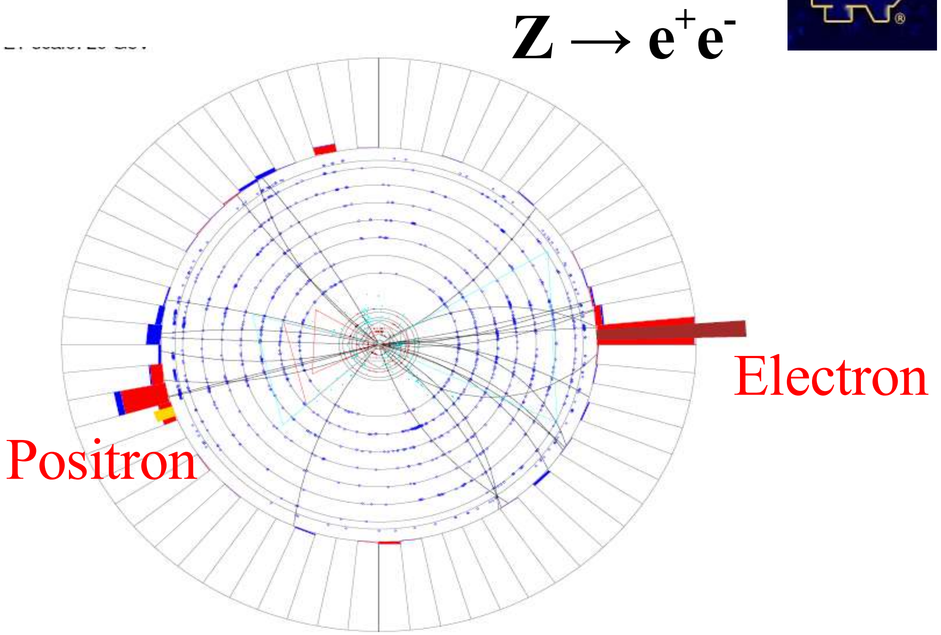
- **Develop** a fast parameterized MC simulation (PMCS)
  - models response, resolution, recoil, efficiencies using parameters tuned to **Z→ ee** data
  - uses NLO event generators for modeling production and decay of W & Z bosons
    - **RESBOS** : [C. Balazs and C.P. Yuan; Phys. Rev. D56, 5558 (1997)]
      - Gluon resummation for low boson p_T and NLO perturbative QCD calculations for high boson p_T
    - **PHOTOS** : [E. Barbiero, Z. Was and B. van Eijk; Comp Phys Comm. 79, 291 (1994)]
      - Simulates radiative corrections for ≤ 2 FSR photons

- **Perform** a Geant MC analysis first to ensure analysis tools and methods work correctly and effectively

- **On to a blinded data analysis** – M_W values were obscured by an offset, uncertainties were never hidden ! Results unblinded after analysis won approval !

Event Selections for data





Common requirements for electrons

- In fiducial region of central calorimeter ($|\eta_{det}| < 1.05$), p_T(electron) > 25 GeV
- Isolation of electron < 0.15, EMFrac > 0.9
- Shower shape requisites, cluster matched to track, require SMT hits
- p_T(Recoil) < 15 GeV

Specific requirements for W (~500K events)

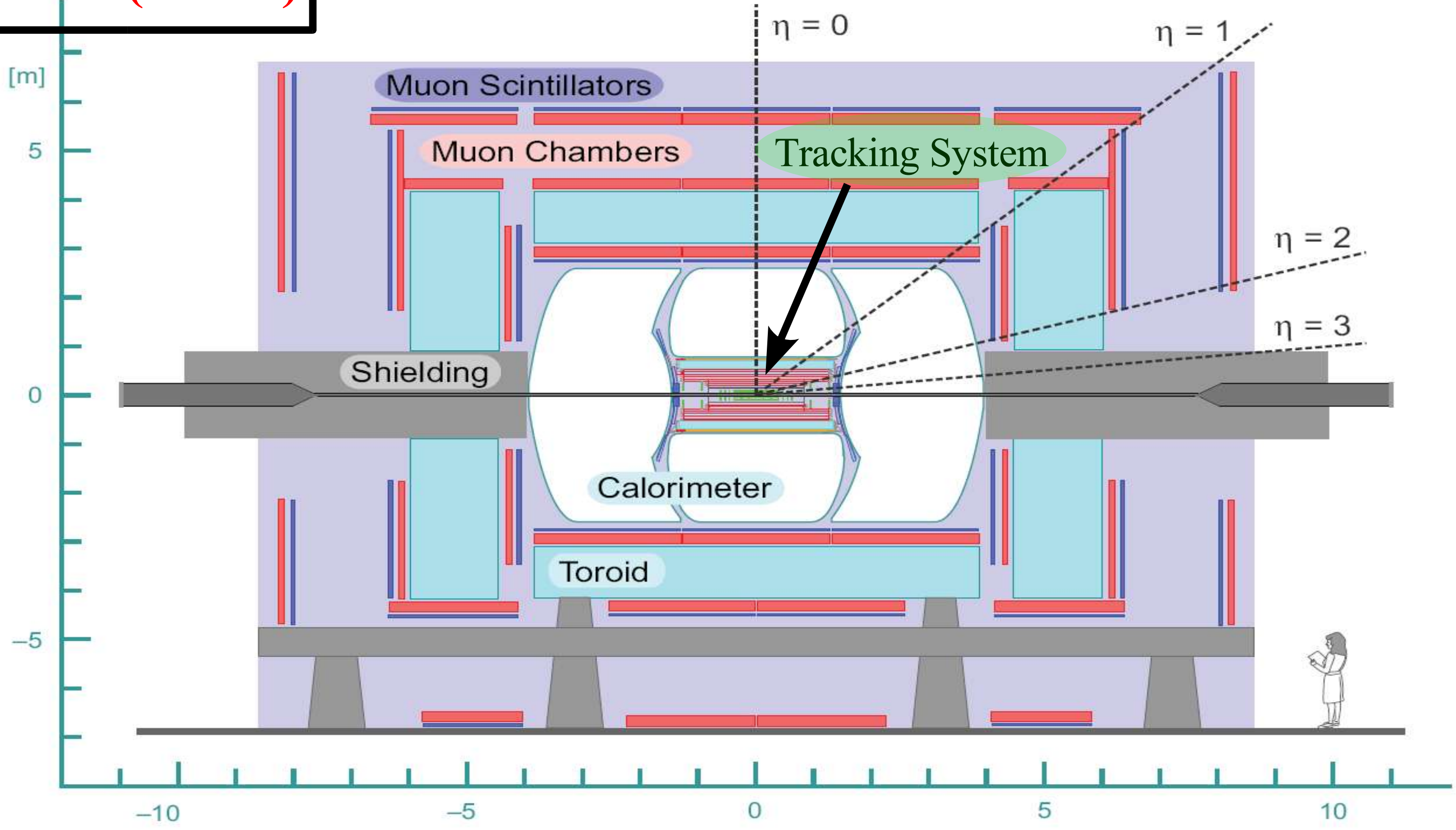
- 50 GeV < m_T < 200 GeV
- Missing Energy > 25 GeV

Specific requirements for Z (~19K events)

70 GeV < Invariant Mass(Z→ee) < 110 GeV

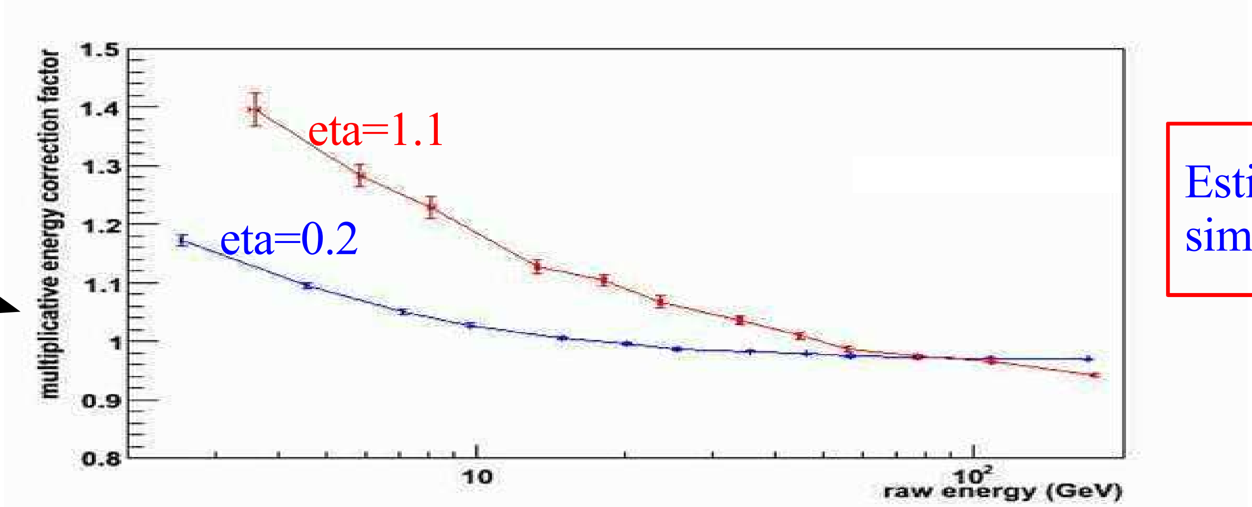
Energy Loss corrections

η = - ln(tanθ/2)



- Energy loss corrections derived as function of energy **(E)** and angle **(η)**

Corrects back to incident energy of electron



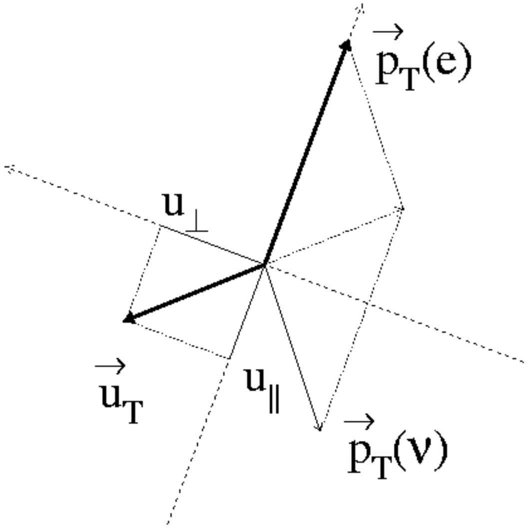
Estimated from full simulation GEANT MC

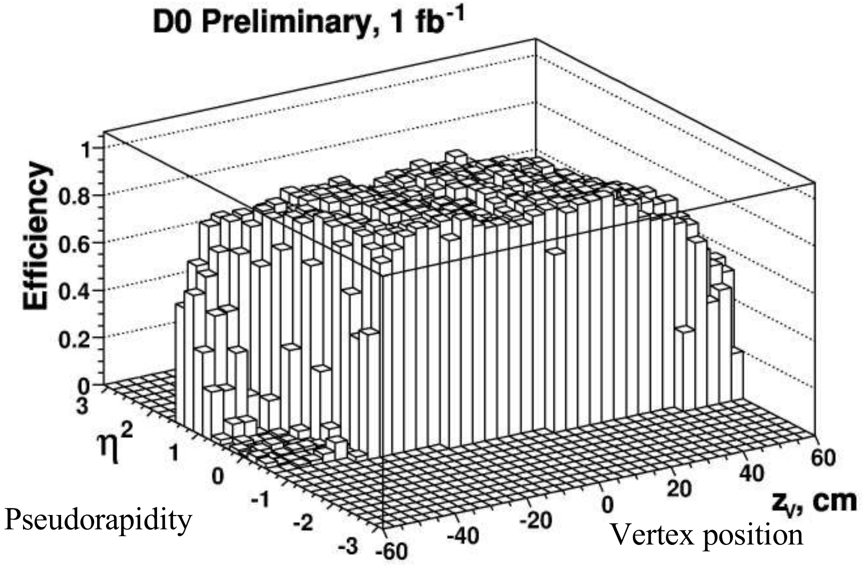
Electron energy reconstructed in CAL

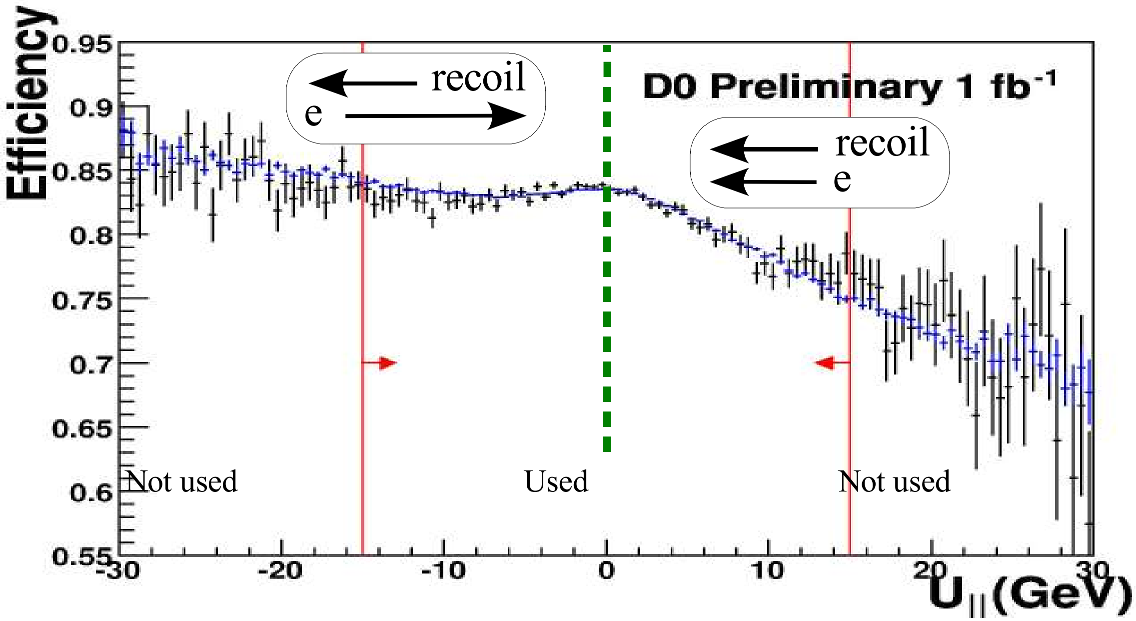
Efficiencies

PMCS models various electron selection efficiencies

- **Electron-only :** trigger, CAL-based ID, tracking
  - from Z data; tag and probe; parameterized using : η, p_T^e, z_{vtx}
- **W event topology :** spatial proximity of recoil to electron
  - from Z data; parameterized using : p_T^e, $u_{//}$
- **Additional hadronic energy in CAL at high luminosity**
  - from full MC + ZB data; parameterized using Scalar E_T, $u_{//}$







Electron Simulation – energy response and resolution

Electron energy response :

- using Z→ee events from data, known Z mass value from LEP

$$\boxed{E_{measured} = \alpha \, . \, E_{true} + \beta}$$

$\alpha \rightarrow$ scale $\quad \beta \rightarrow$ offset

- We use non-monochromaticity of the Z electrons to constrain α and β simultaneously → use f_Z method

$$M_Z(\text{measured}) = \alpha \, . \, M_Z(\text{true}) + f_Z \, . \, \beta$$

α = 1.0111 ± 0.0043
β = -0.404 ± 0.209 GeV
correlation = -0.997

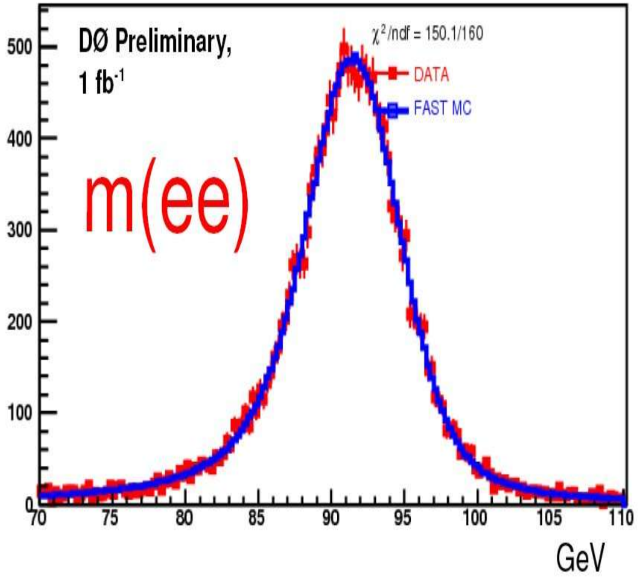
  - where f_Z is calculable from kinematics

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

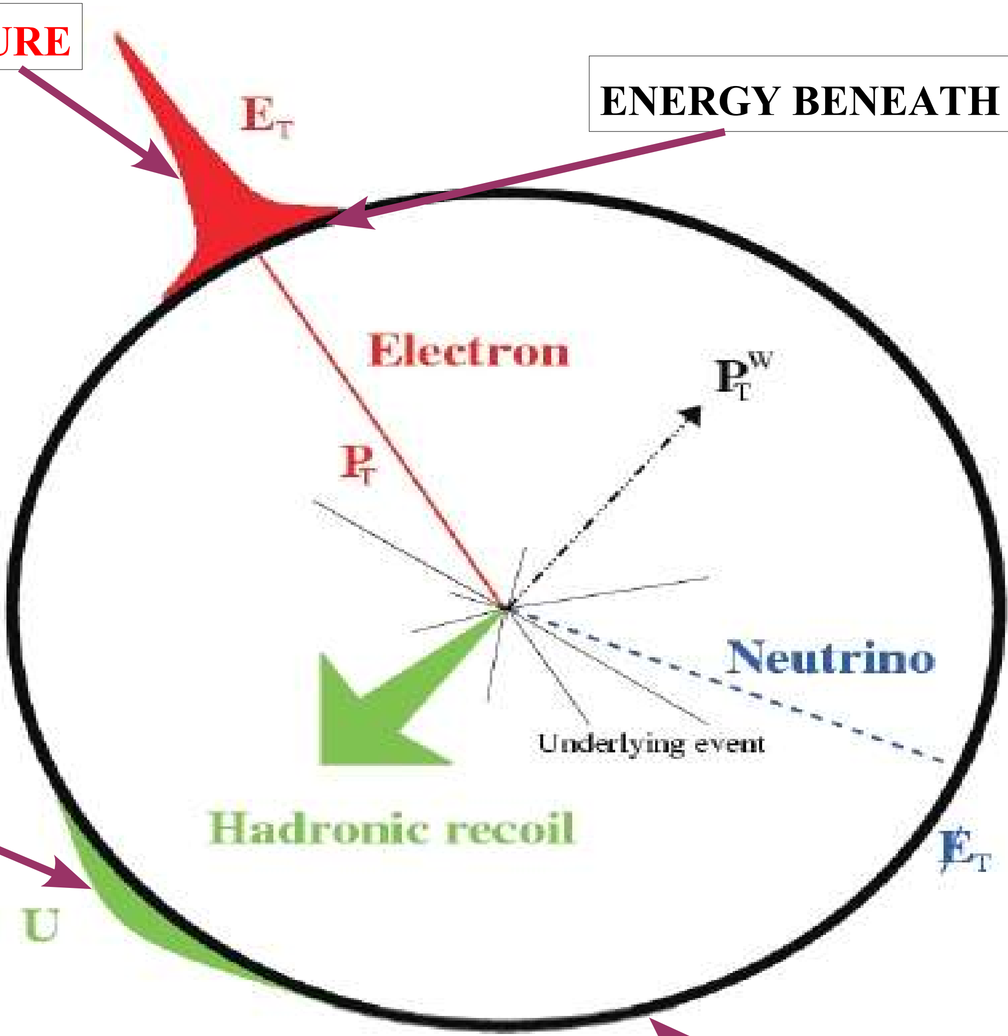
Electron energy resolution :

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

- **Sampling** term S_{EM} determined as function of energy & incidence angle
  - S_{EM} determined from full simulation (Geant) MC
- **Constant** term extracted from fit to observed width of Z→ ee peak
  - $C_{EM} = (2.05 \pm 0.10)\%$



Hadronic Recoil Simulation



ELECTRON SIGNATURE

ENERGY BENEATH ELECTRON WINDOW

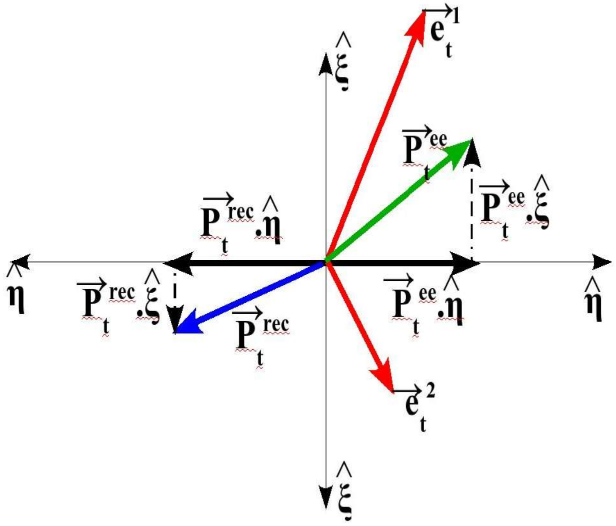
HARD COMPONENT
(Geant Z→ νν)

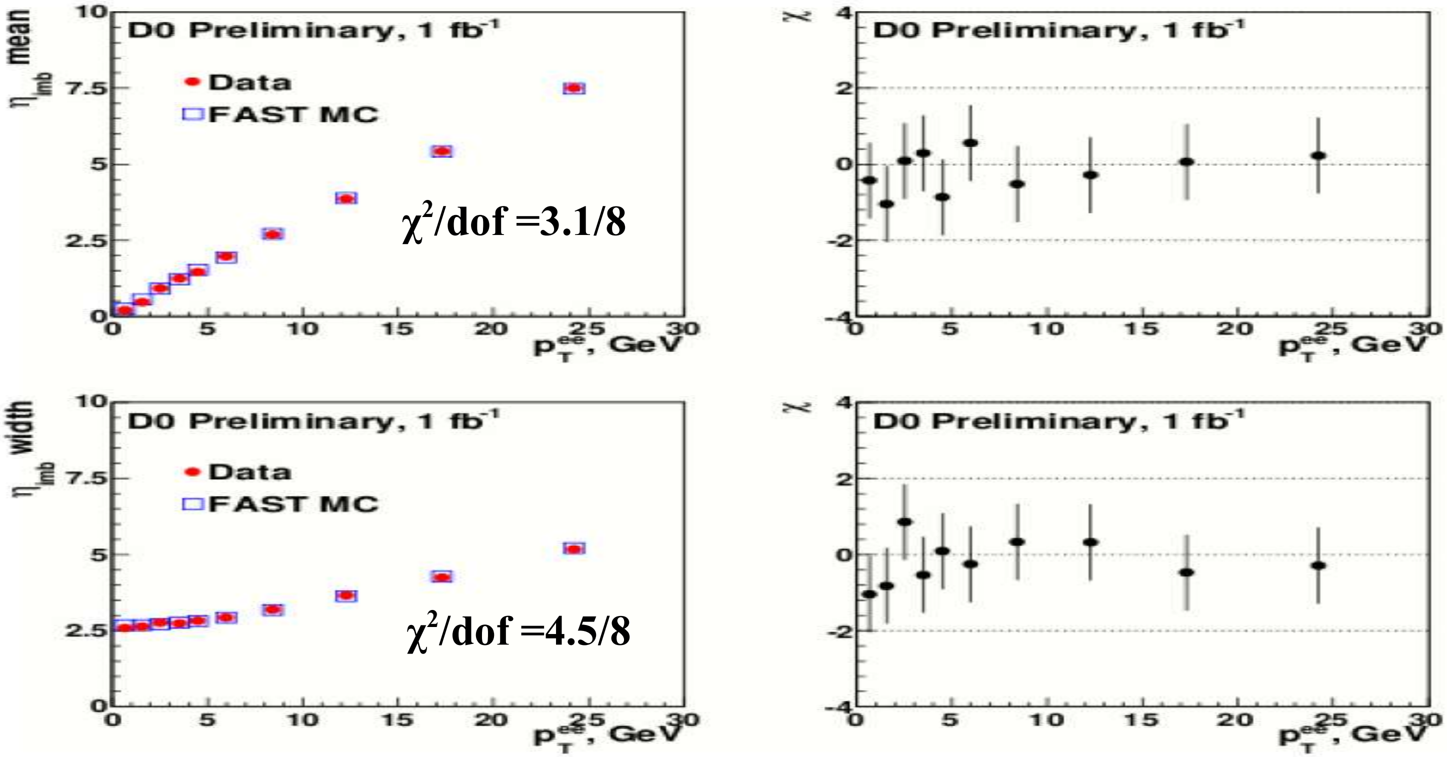
SOFT COMPONENT = SPECTATOR PARTONS + ADDITIONAL $p\bar{p}$ INTERACTIONS
(Minimum Bias data) (Zero Bias data)

Modeled recoil : $\vec{u}_T = \vec{u}_T^{HARD} + \vec{u}_T^{SOFT} + \vec{u}_T^{ELEC} + \vec{u}_T^{FSR}$

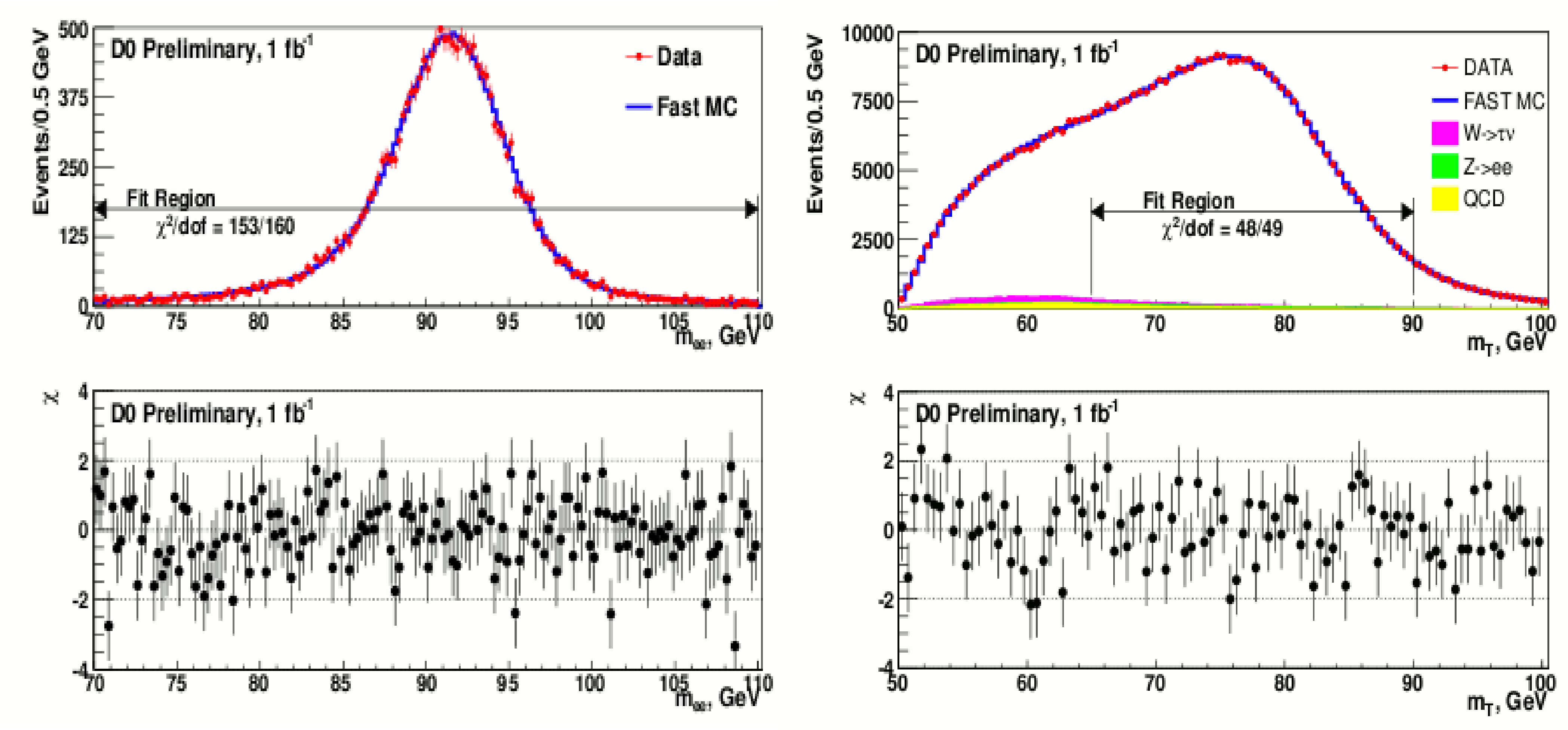
Tuning model to data

- Fine tune - to match modeled recoil to that from data
  - Addl. params. introduced to account for correl. between components
  - Using $Z \rightarrow e^+e^-$ events as a control sample
  - Define $\hat{\eta}$ and $\hat{\xi}$ axes (first used by UA2 collab)
  - **Use momentum imbalance** as diagnostic variables
    - **η-imbalance : $(\vec{P}_t^{ee} + \vec{P}_t^{rec}) \cdot \hat{\eta}$**
  - mean of η_{imb} tunes response, width of η_{imb} tunes resolution





Onto collider data - Z and W (m_T) mass fits !



M_Z = 91.185 ± 0.033 GeV (stat)

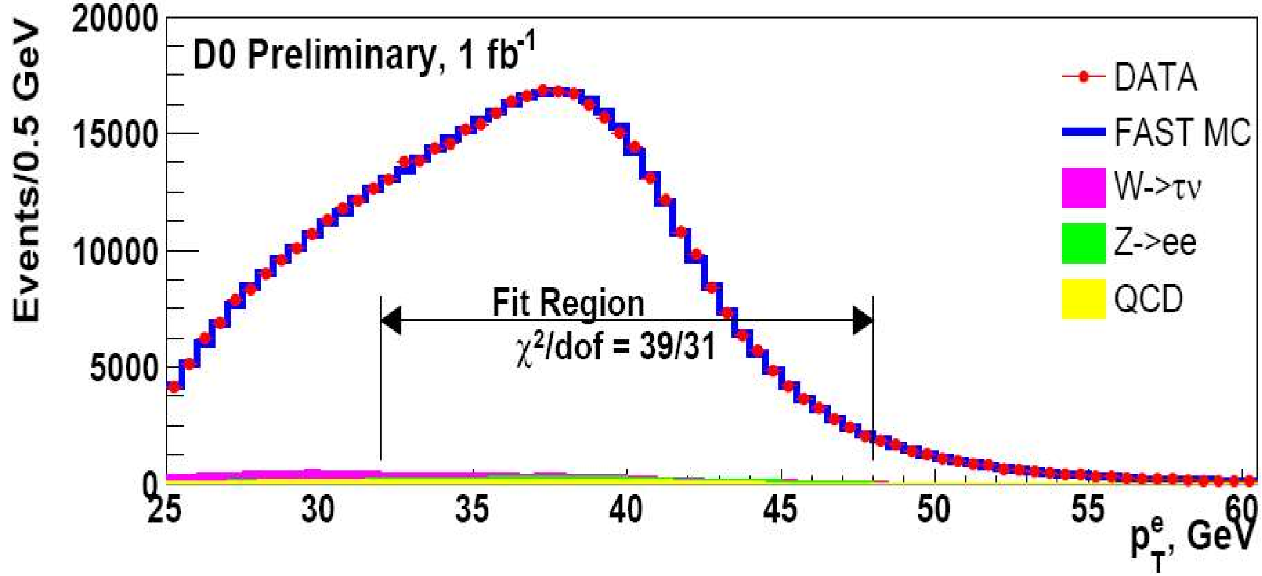
Z mass value (LEP) was an input to estimating the electron energy response and resolution

PDG MZ = 91.1876 ± 0.0021 GeV

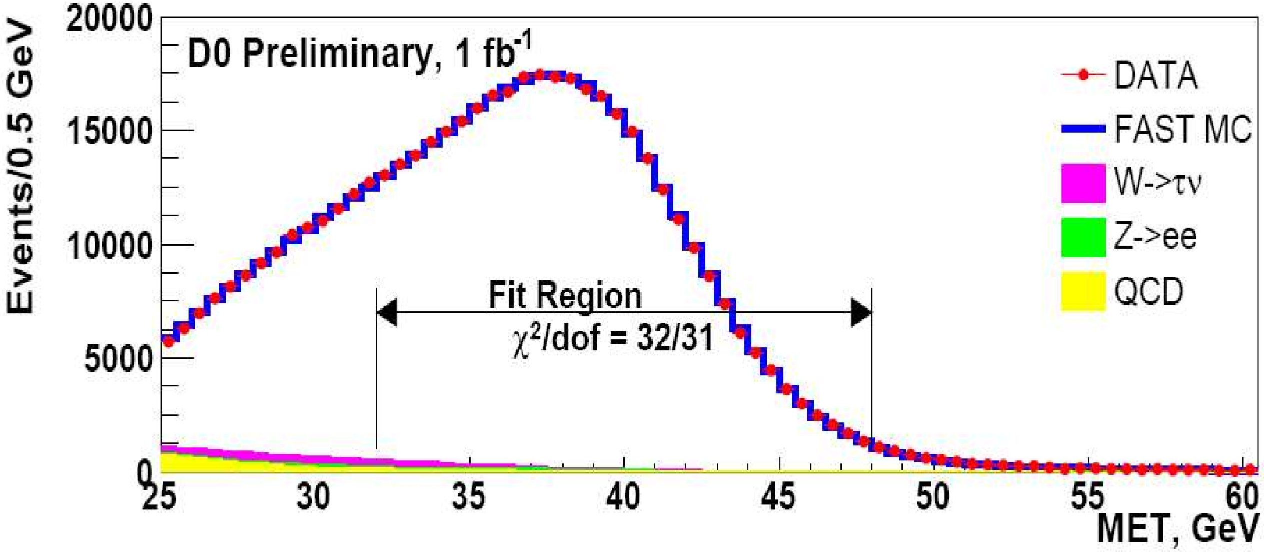
M_W = 80.401 ± 0.023 GeV (stat)

Onto collider data - W mass fits – p_T^e and $\not{E}_T$

-



M_W = 80.400 ± 0.027 GeV (stat)



M_W = 80.402 ± 0.023 GeV (stat)

Statistical and Sytematic Uncertainties on M_W

Source	$\sigma(M_W)$ MeV		
	m_T	p_T^e	$\not{E}_T$
Statistical	**23**	**27**	**23**
Systematic - Experimental			
Electron energy response	34	34	34
Electron energy resolution	2	2	3
Electron energy non-linearity	4	6	7
Electron energy loss differences	4	4	4
Recoil model	6	12	20
Efficiencies	5	6	5
Backgrounds	2	5	4
Experimental Subtotal	**35**	**37**	**41**
Systematic - W production and decay model			
PDF	10	11	11
QED	7	7	9
Boson pT	2	5	2
W model Subtotal	**12**	**14**	**17**
Systematic – Total	**37**	**40**	**44**

Preliminary W mass results from D0

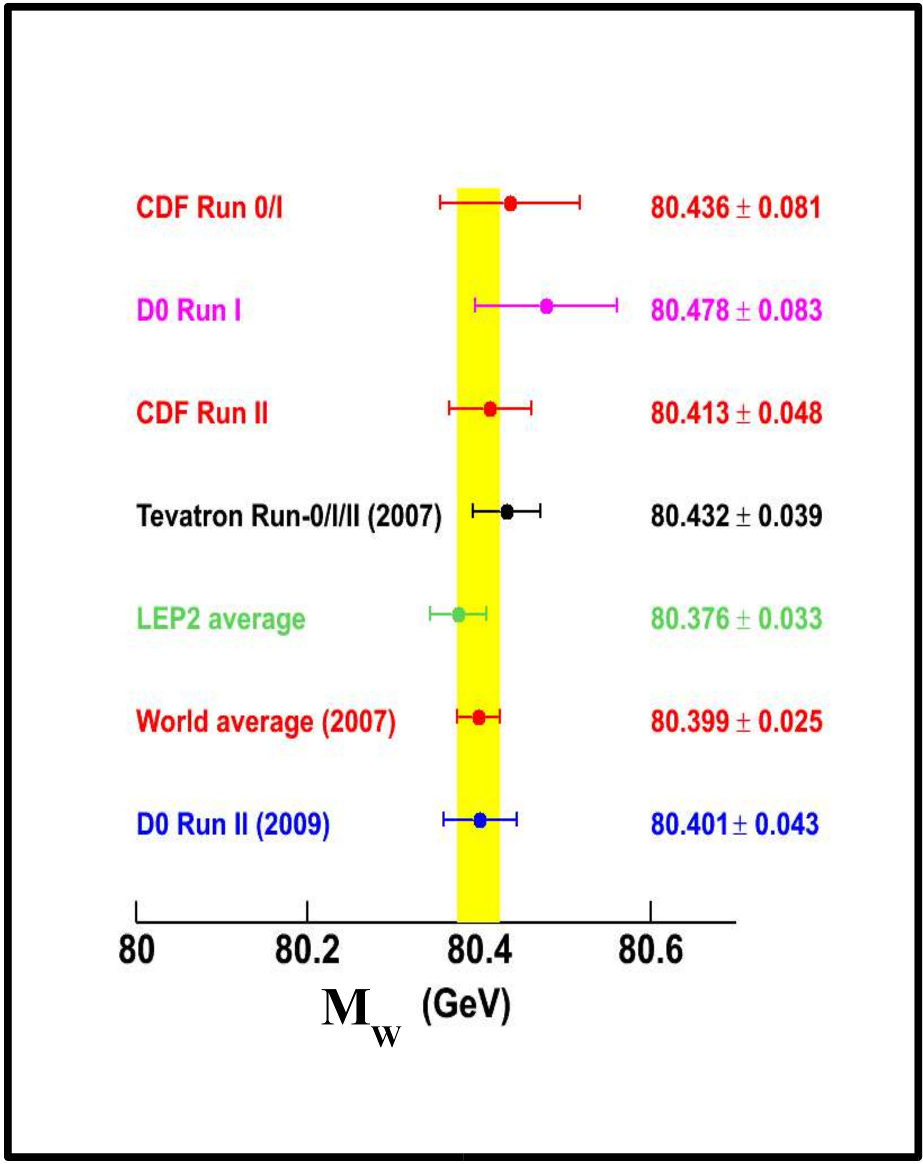
- Results in good agreement with previous measurements
- Correlation matrix from combining the 3 results :

	m_T	p_T^e	$\not{E}_T$
m_T	1	0.83	0.82
p_T^e		1	0.68
$\not{E}_T$			1

Combined DØ measurement for M_W :

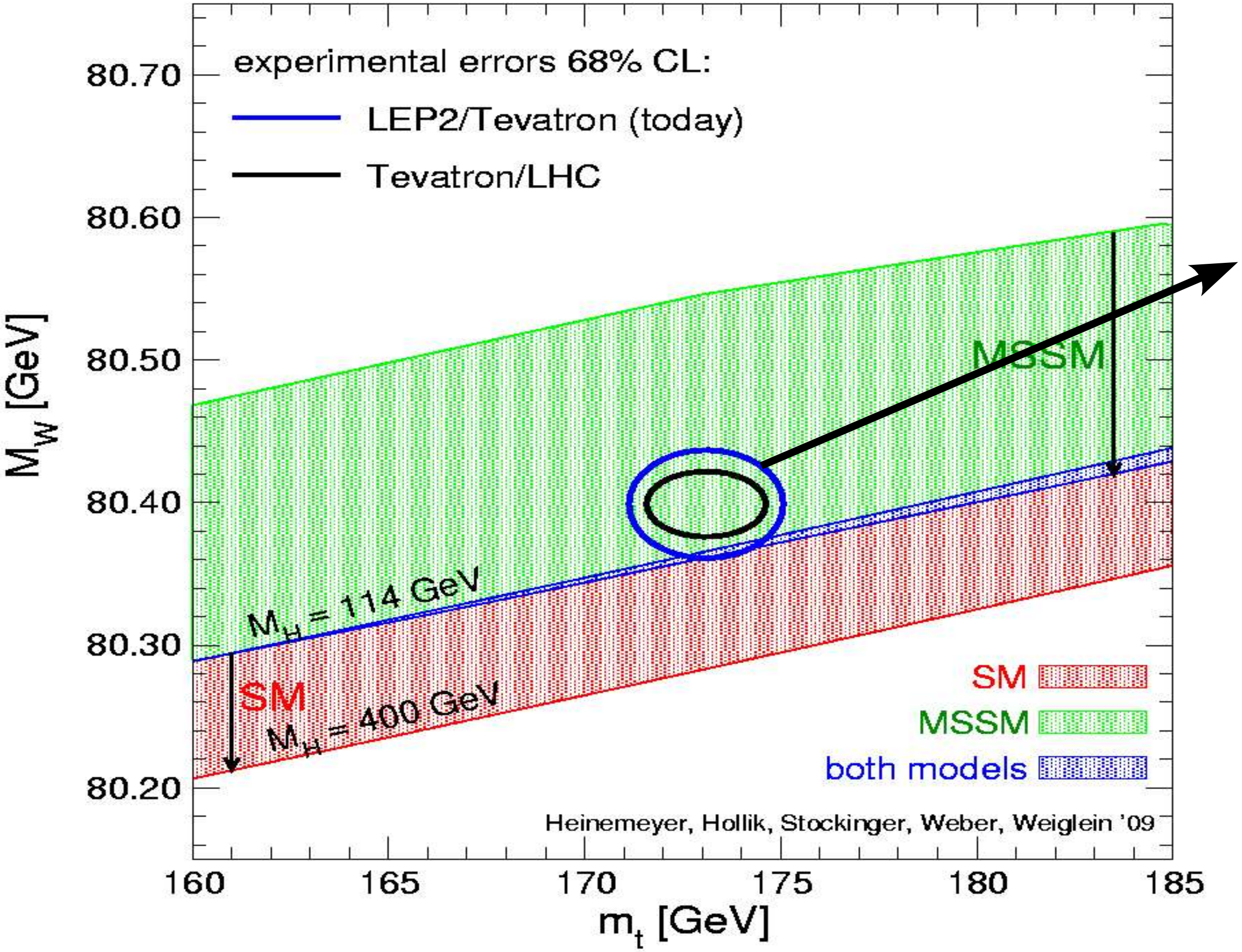
80.401 ± 0.021(stat) ± 0.038(syst) GeV

⇒ **80.401 ± 0.043 GeV**



- **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 !

Summary and Outlook



Heinemeyer, Hollik, Stockinger, Weber, Weiglein '09

By 2011 we anticipate that D0 and CDF will have recorded ~$10 fb^{-1}$ of data !

- **$\Delta M_W \sim 10$ MeV**
- **$\Delta M_{top} \sim 1$ GeV**

Very significant implications for the Higgs boson search -

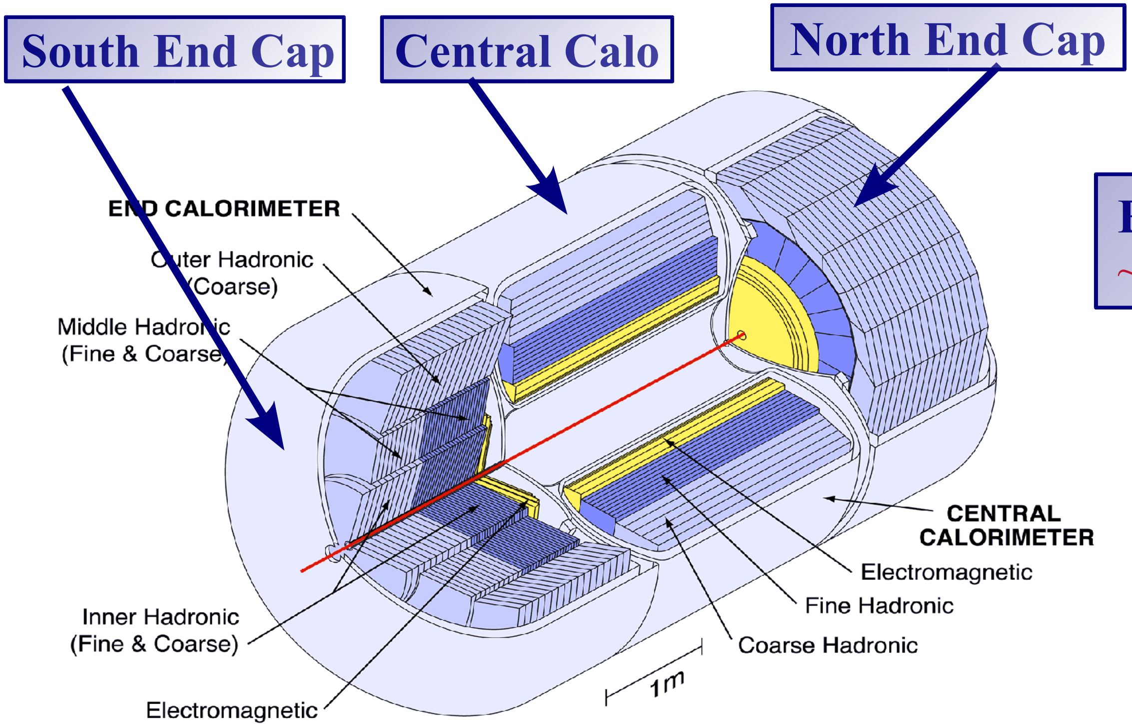
If $\Delta M_W \sim 15$ MeV and $\Delta M_{top} \sim 1$ GeV and $M_W = 80.400$ GeV then –

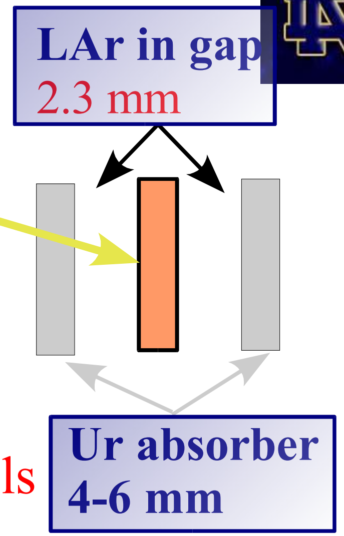
- **$M_{Higgs} < 117$ GeV @ 95% CL !**

[Ref: Peter Renton, ICHEP08]

Backup Slides

DØ RunII Calorimeter



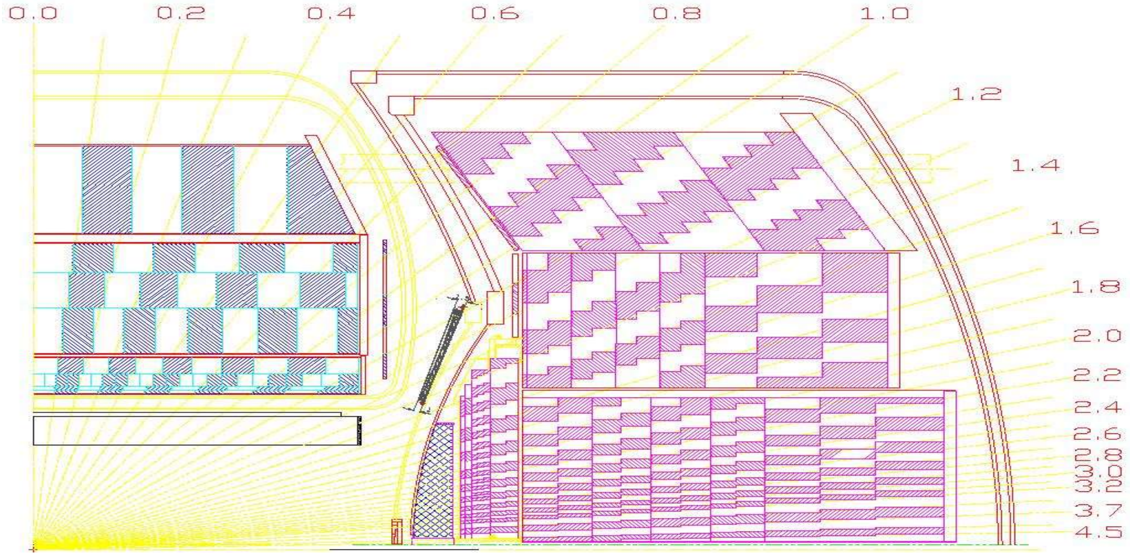


Readout Cell
Cu pad electrode

Electron drift time
~ 450 ns

- ~ 50,000 readout cells
- Fine segmentation
  - 5000 psuedoprojective towers (0.1x0.1)
  - 4 EM layers, EM3 is 0.05x0.05
  - 4/5 Hadronic (3FH + CH)

- Liquid Argon sampling
  - uniform response, radiation hard
  - Liquid Ar purity important (~0.3 ppm)
- Ur absorber (EM); Cu(FH); Steel(CH)
  - dense, compact
- Uniform, hermetic with full coverage
  - $\eta < 4.2$, $\lambda_{int} \sim 7.2$ (total)

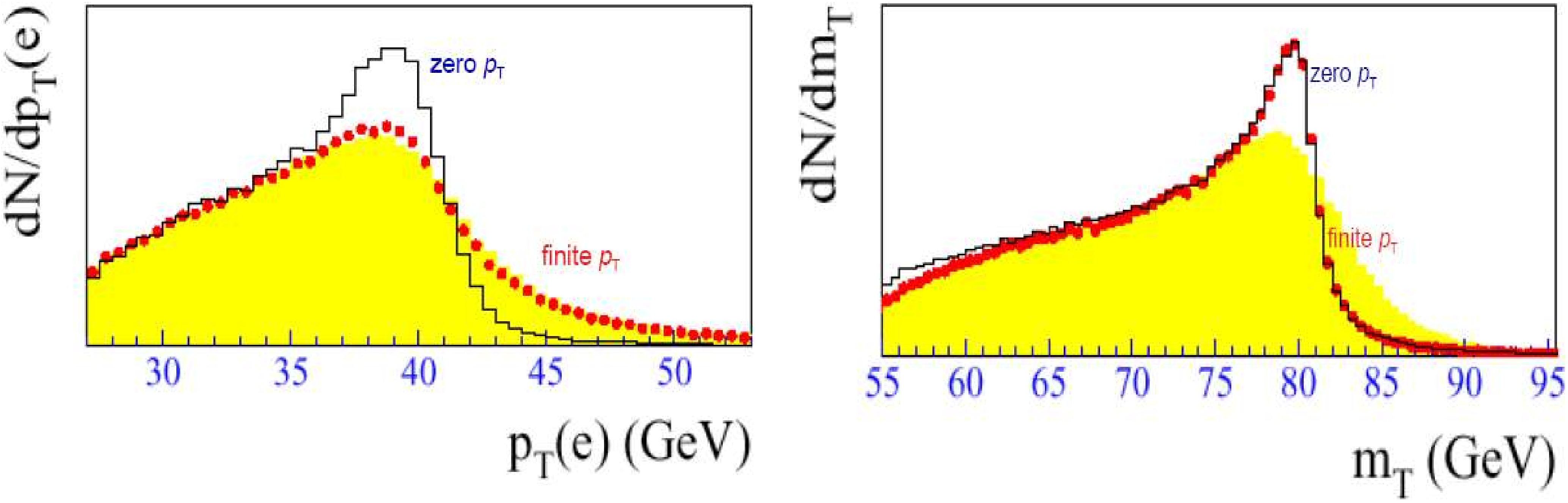


Electron p_T and Transverse mass

▬ no p_T(W)

● p_T(W) effects included

🟨 Detector effects added

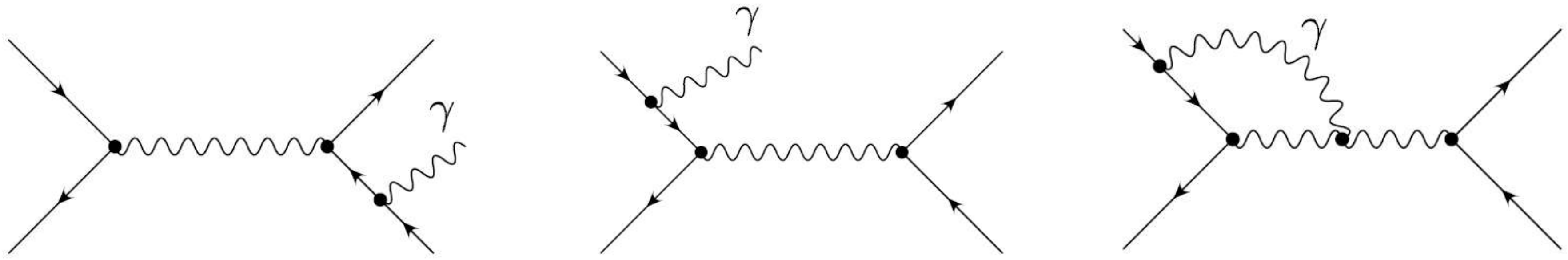


- Sensitive to p_T of W boson – p_T(W)
- Insensitive to detector response

- Impacted by detector response (recoil measurement)
- Insensitive to p_T(W)

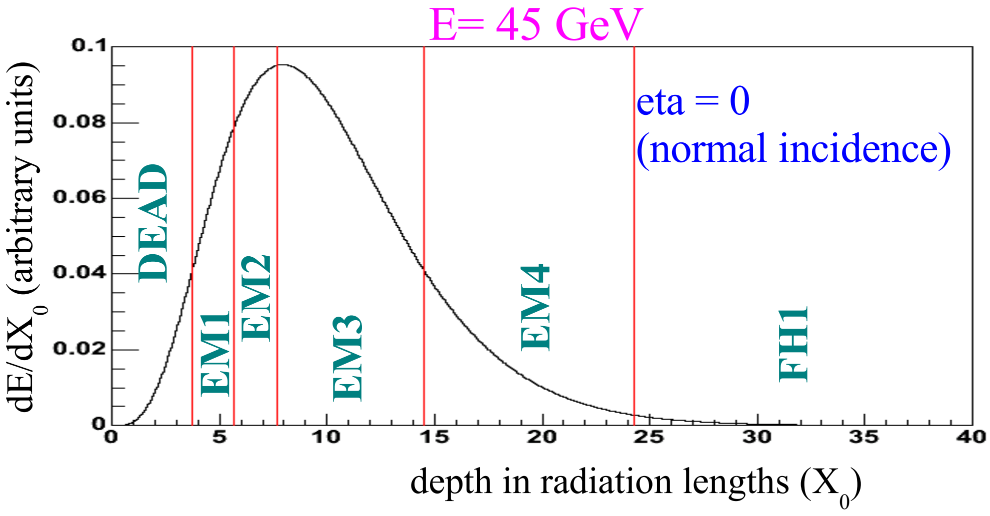
MC event generators used for analysis

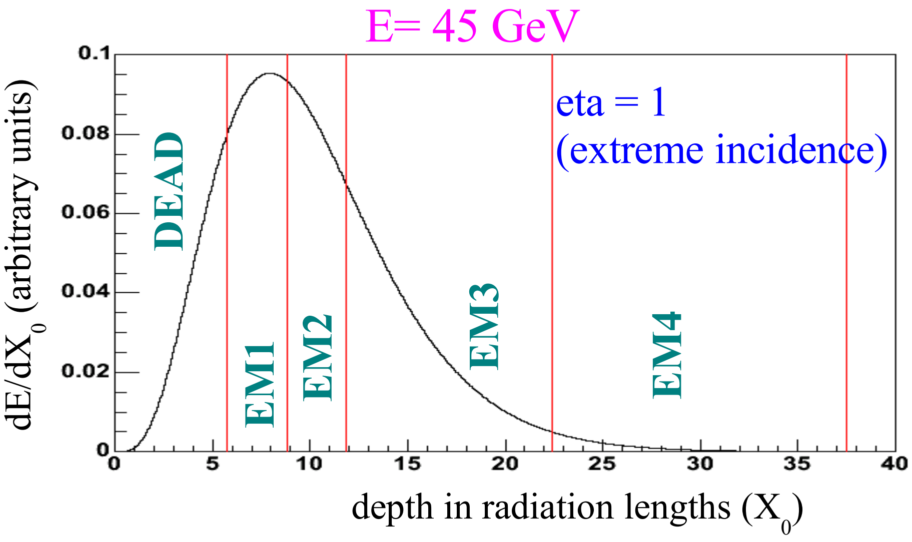
- PMCS uses NLO event generators for modeling production and decay of W & Z bosons :
  - For QCD corrections –
    - **ResBos** [C. Balazs and C.P. Yuan; Phys. Rev. D56, 5558 (1997)]
      - Gluon resummation accounts for low boson momenta
      - NLO perturbative QCD calculations at high boson momenta
  - For QED corrections –
    - **Photos** [E. Barbiero, Z. Was and B. van Eijk; Comp Phys Comm. 79, 291 (1994)]
      - Simulates single/double final-state photon radiative corrections (FSR) during the production and decay of W and Z bosons
    - Effect of full electroweak corrections studied using WGRAD/ZGRAD [Bauer, Keller and Wackeroth; Phys. Rev. D59, 013002 (1999)]



Energy response linearity

- Two average longitudinal profiles of showers at electron energy E=45 GeV for “normal” and “extreme” angles of incidence





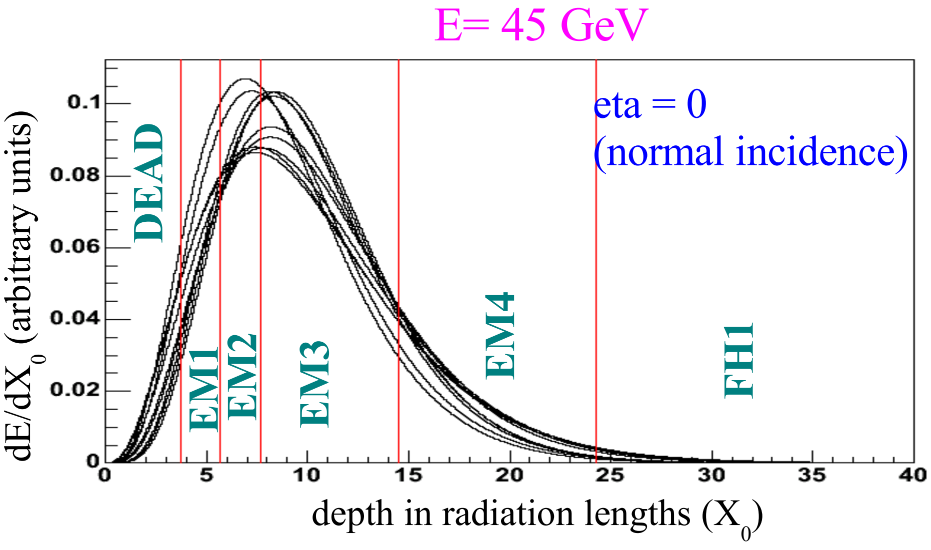
- Shower maximum is in EM1 for eta=1 !
  - Notice the fraction of energy loss in the dead material !

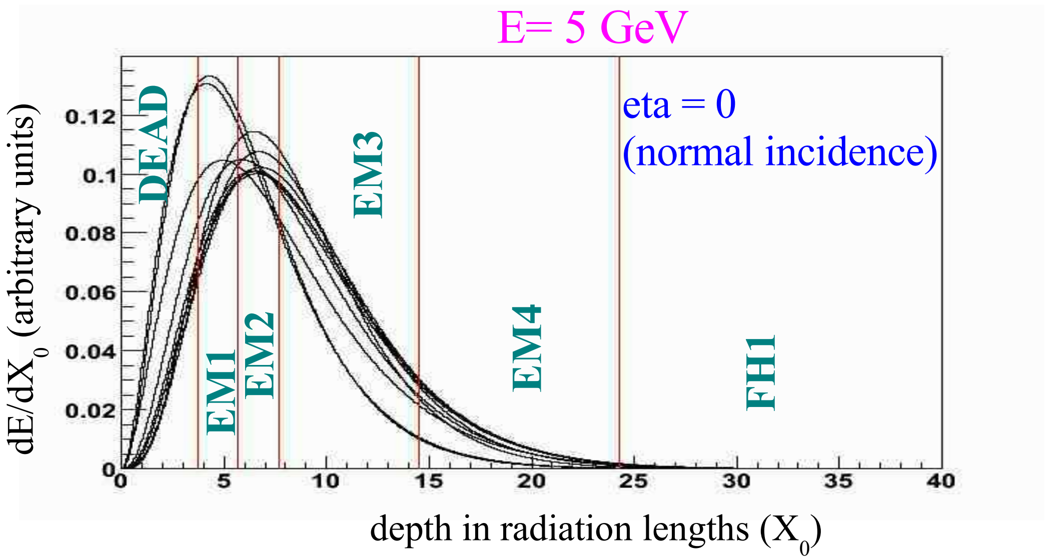
- During reconstruction high weights are applied to the early layers (especially EM1) to compensate partially for losses in dead material
  - what is the situation when there are significant losses in dead material ?

N.B. - Profiles have been made using GFLASH – a fast parameterized toy model for EM showers

Energy dependence and fluctuations

- Two longitudinal profiles showing shower-to-shower fluctuations for two different electron energies





- Fraction of energy lost in the dead material varies from shower to shower
  - position of shower maximum (in X_0) varies approximately as ln(E)

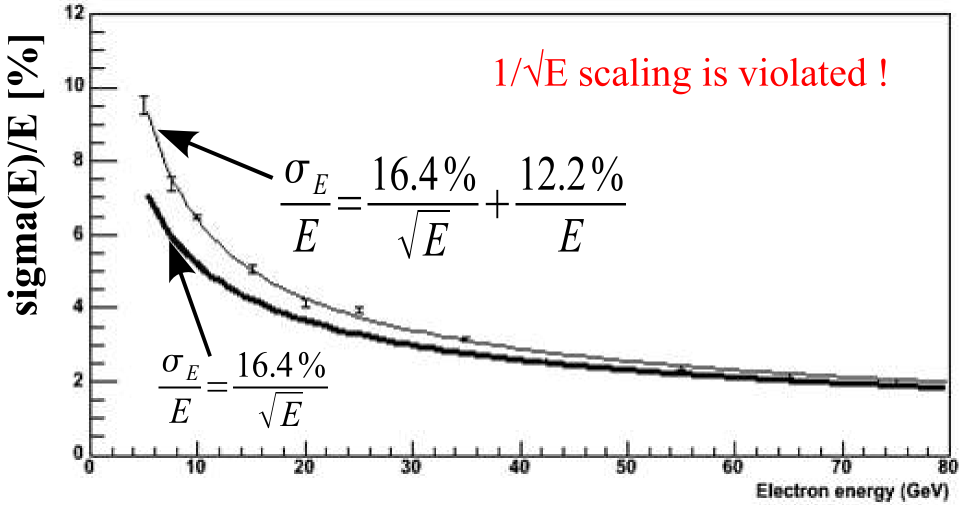
- Relative importance of shower-to-shower fluctuations also depend on energy of the incident electrons

N.B. - Profiles have been made using GFLASH – a fast parameterized toy model for EM showers

Impact on energy resolution of electrons

- GFLASH simulation of energy resolution of electrons shows deviations from that of an ideal sampling calorimeter !
- Resolution at normal incidence for different electron energies

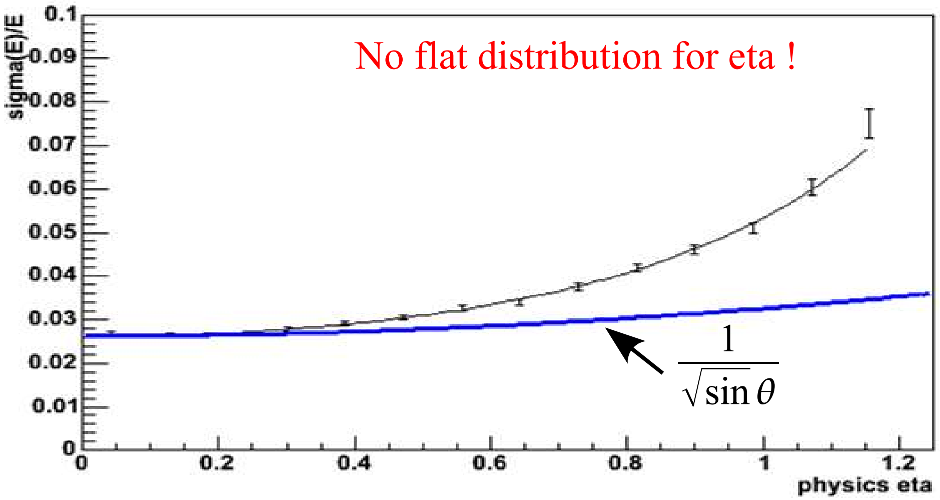
$$\frac{\sigma_{EM}}{E}=\sqrt{C^2+\frac{S^2}{E_T}+\frac{N^2}{E^2}}$$



For an ideal sampling calorimeter (no dead material) $\sigma_E/E \sim 1/\sqrt{E}$!

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

- Resolution at an energy E=45 GeV for different angles of incidence (eta)



For an ideal sampling calorimeter (no dead material) $\sigma_E/E \sim 1/\sqrt{\sin\theta}$!

Triggers used

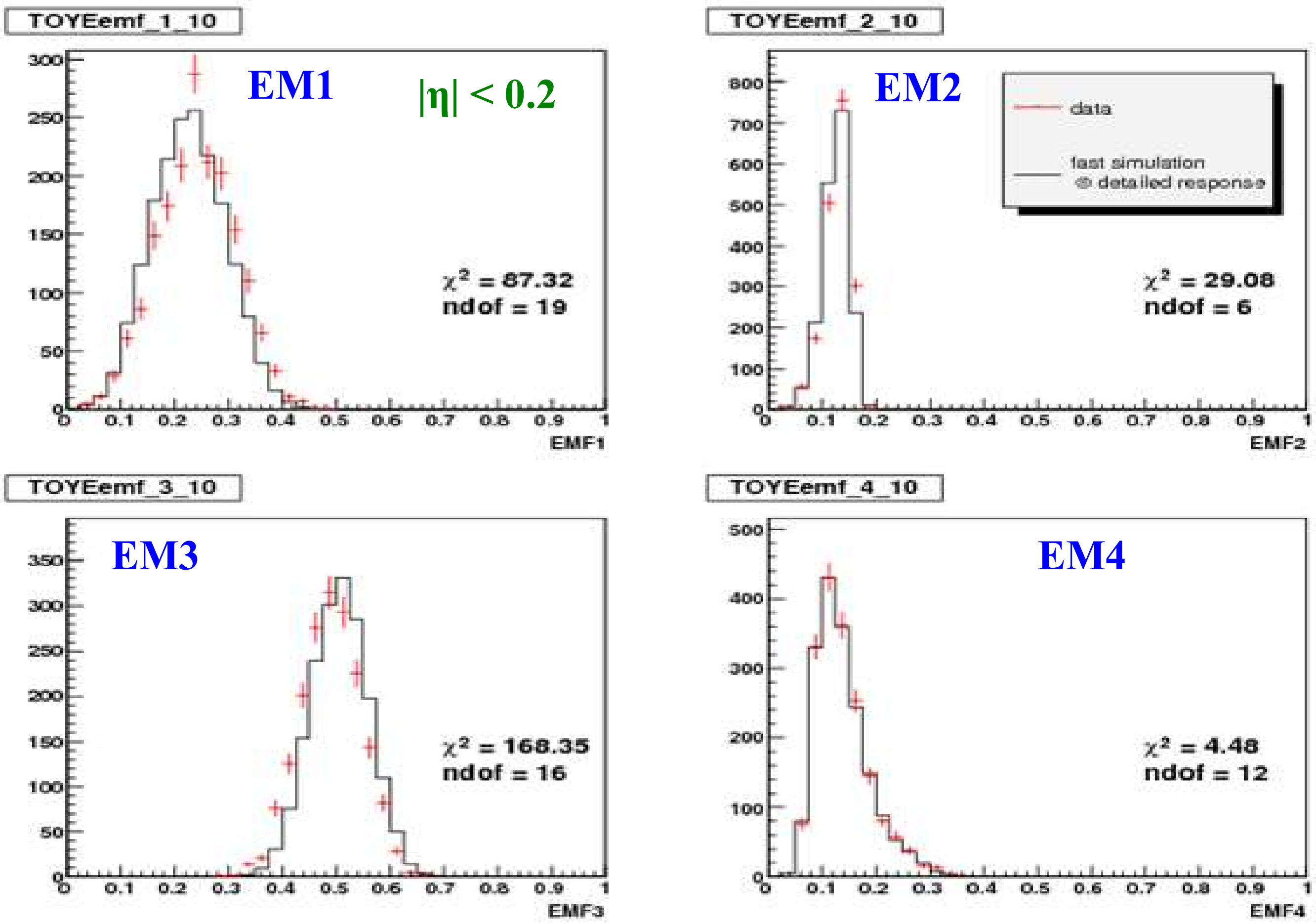
- Data used has been obtained from EM inclusive skims
  - EM + MET sample for studying Ws
  - 2EM sample for studying Zs
  - EM + Jet sample for studying jet-faking-electron probability
- Requirements for EM+MET :
  - 1 EM with pT > 20 GeV, $|\eta_{det}| < 1.2$, EmFrac > 0.9 and raw MET > 20 GeV
- Requirements for 2 EM :
  - 2 EM with pT > 20 GeV, EMFrac > 0.9 and iso < 0.2
- Requirements for EM + Jet :
  - 1 EM with pT > 20 GeV, $|\eta_{det}| < 1.2$, EmFrac > 0.9 and iso < 0.2
  - 1 Jet with pT > 20 GeV, $|\eta_{det}| < 0.8$ or $1.5 < |\eta_{det}| < 2.5$, 0.05 < EMFrac < 0.95, chFrac<0.4, hotcellratio<10 and n90>10
- Trigger lists for dataset : v8-11, v12, v13, v14
- Single electron triggers : EM_HI_SH for v8-11, E1_SHT20 for v12, E1_SHT22 for v13, E1_SHT25 for v14

Modeling the Hadronic Recoil

- Modeled recoil: $\mathbf{u_T = u_T^{HARD} + u_T^{SOFT} + u_T^{ELEC} + u_T^{FSR}}$
- $\mathbf{u_T^{HARD} = f(q_T)}$
  - Recoiling partons from the hard scatter that produced vector boson
  - Parameterized function obtained from Z→νν FULL MC. Later fine-tuned to match Z→ee
- $\mathbf{u_T^{SOFT} = \alpha_{MB} . E_T^{MB} + \alpha_{ZB} . E_T^{ZB}}$
  - Spectator partons interactions (underlying event)
    - Modeled from MB events→ same lumi profile as data. α_{MB} is for fine-tuning
  - Additional partons interactions, electronics noise, pileup
    - Modeled from ZB events→ same epoch as data. α_{ZB} is for fine-tuning
- $\mathbf{u_T^{ELEC} = - \Sigma\, \Delta u_{//} . p_T^{e}}$
  - Recoil energy present under electron window
  - Energy leakage outside the electron cluster
    - Modeled from single energy electrons in FULL MC
- $\mathbf{u_T^{FSR} = \Sigma\, p_T(\gamma)}$
  - FSR photons far away from “mother” electrons, so part of recoil
    - A detailed model of the calorimeter response to FSR photons is used for this

Uninstrumented material in the detector

- For an accurate estimate of dead material we study the fractional electron energy sampled by each layer (EM1-EM4) as a function of incident angle (η)
  - Compare DATA and GEANT MC

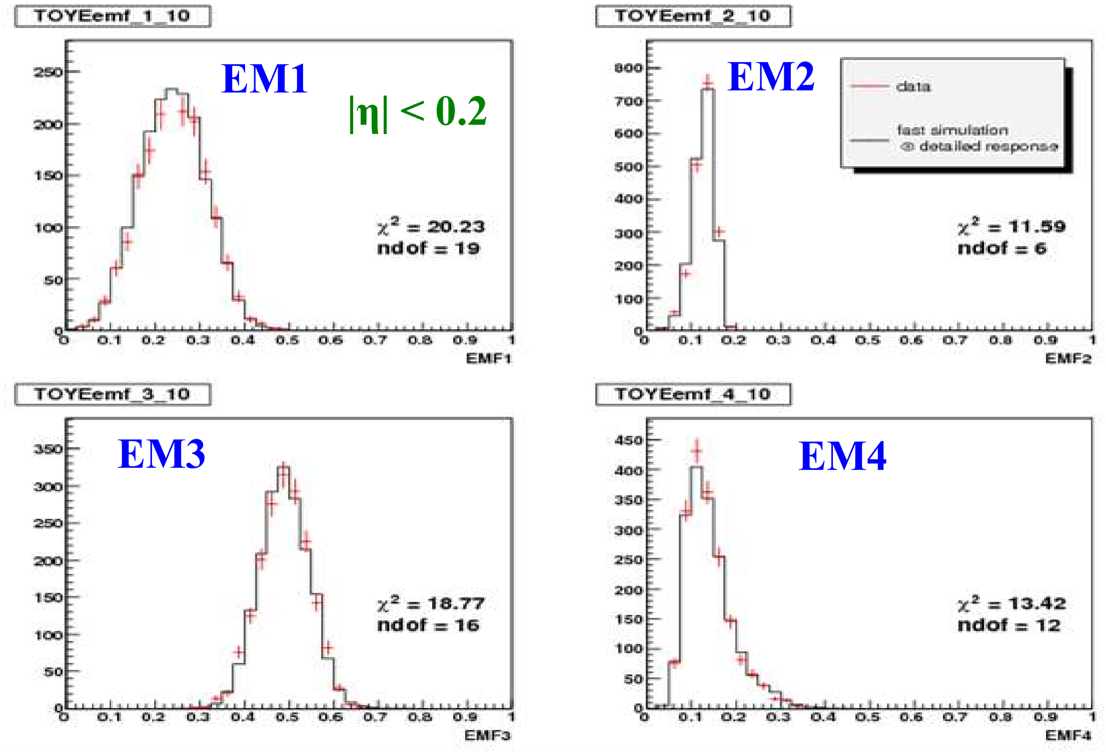


Fractional energy deposits between data and GEANT simulation do not match !

- We vary the size of dead region incrementally in GEANT simulation and compare it with collider data

Found some missing material !

- We found $0.163X_0$ of extra dead material which was missing in GEANT MC simulation

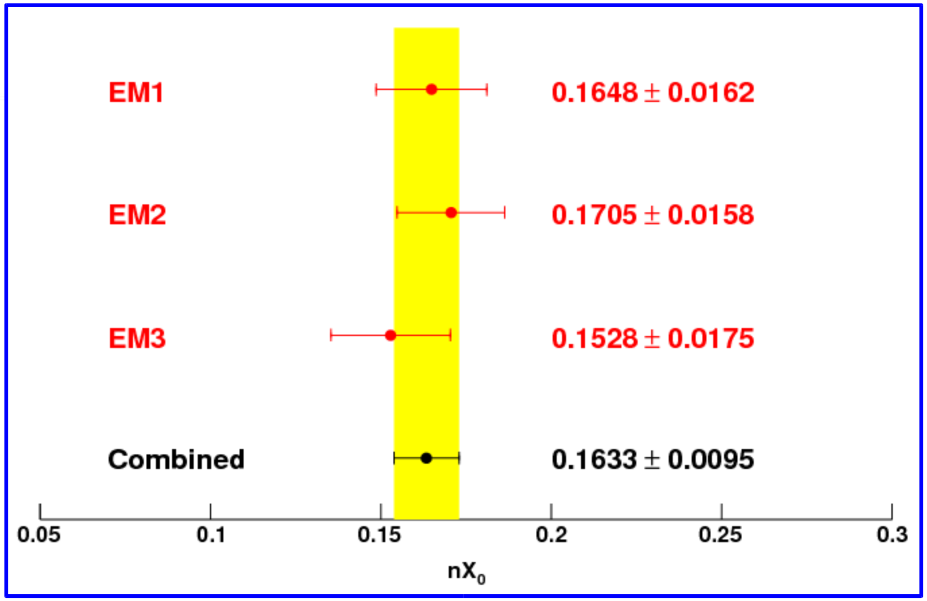


After tuning our material model :

Fractional energy deposits between data and GEANT simulation match very well !

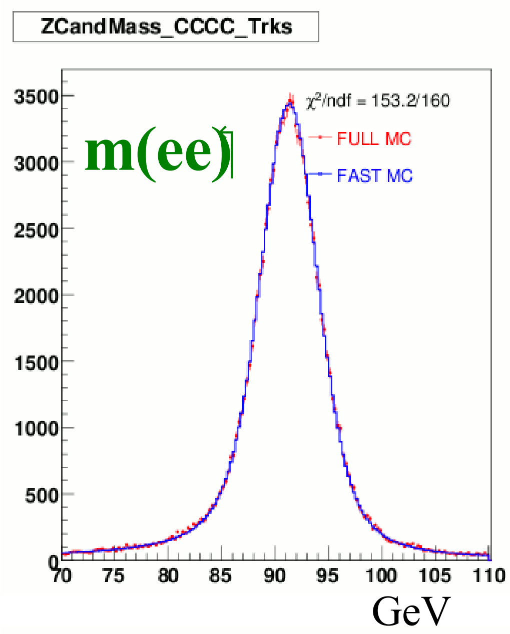
As a cross-check :

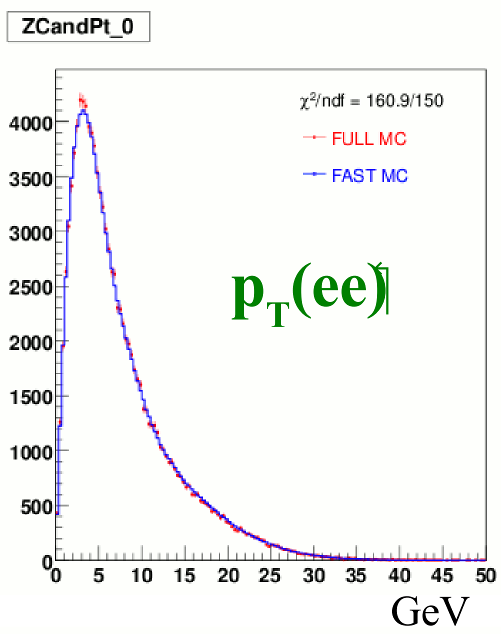
Evaluated missing nX_0 for each EM layer separately – good consistency observed !

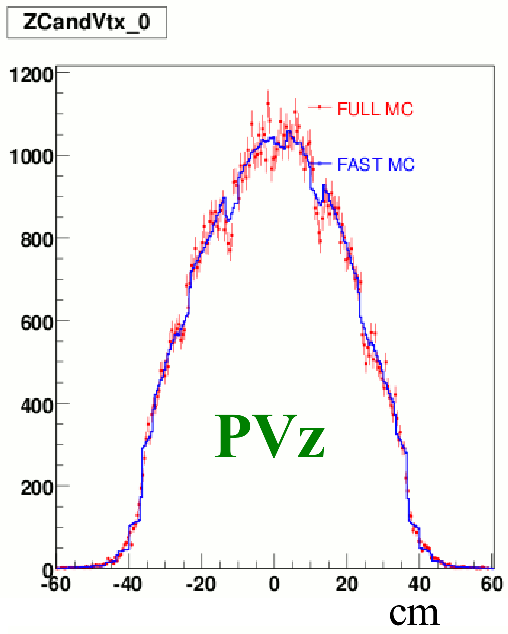


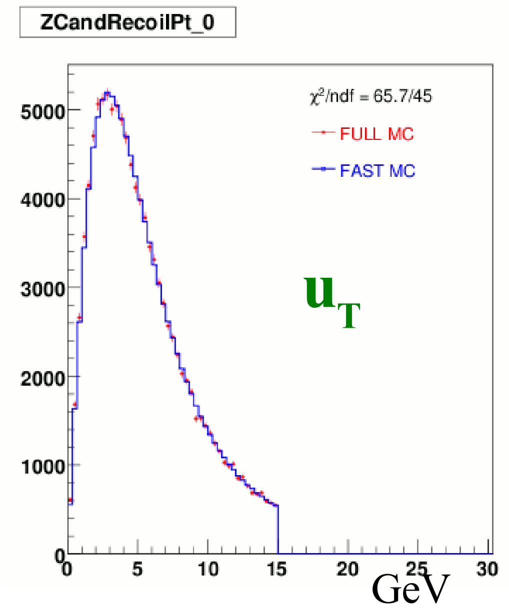
MC closure test results: Z → e e

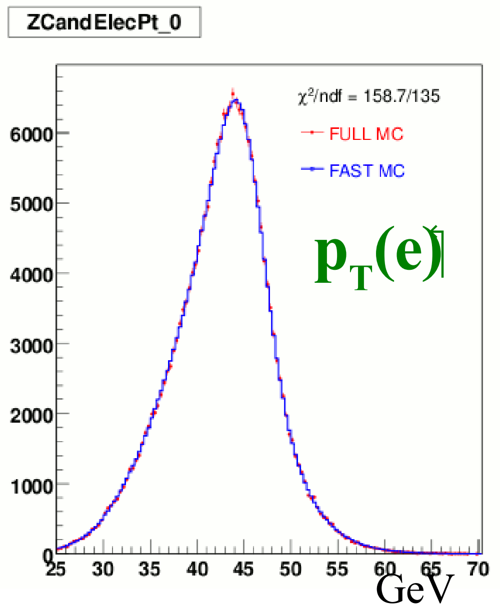
✓ Good agreement between full and parameterised MC.

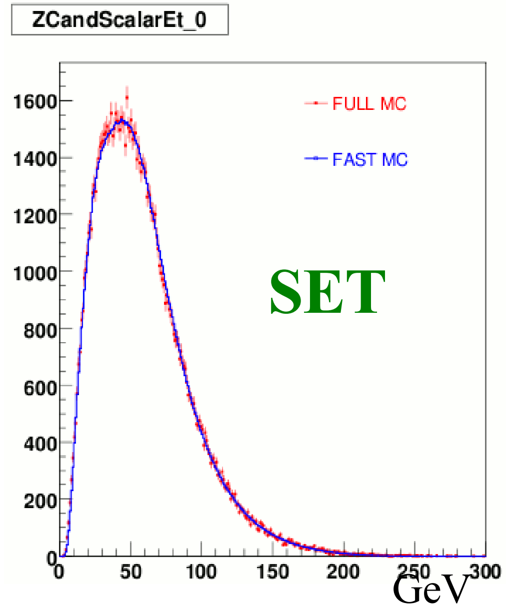




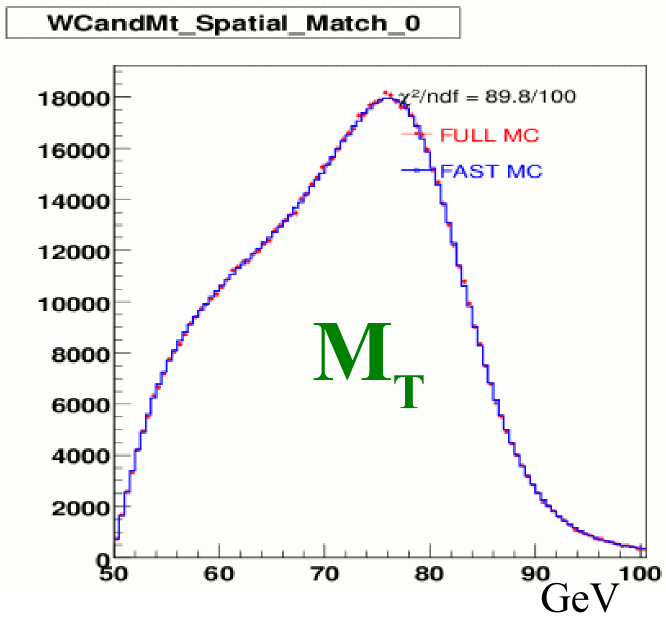


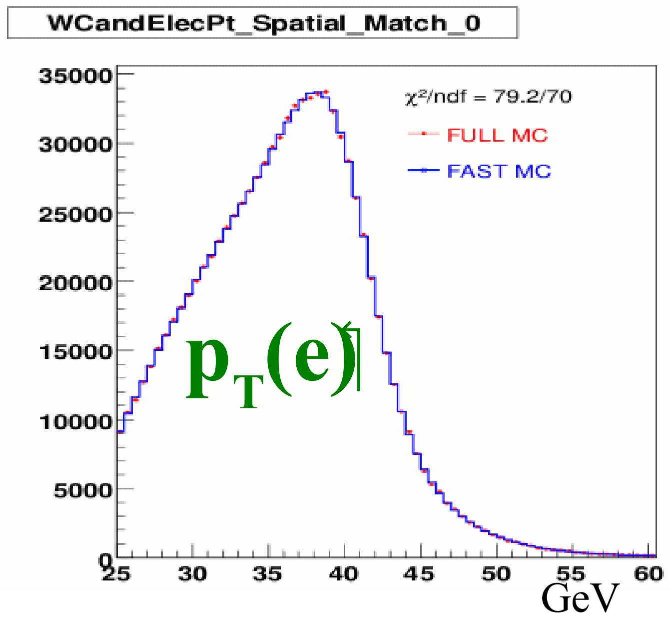


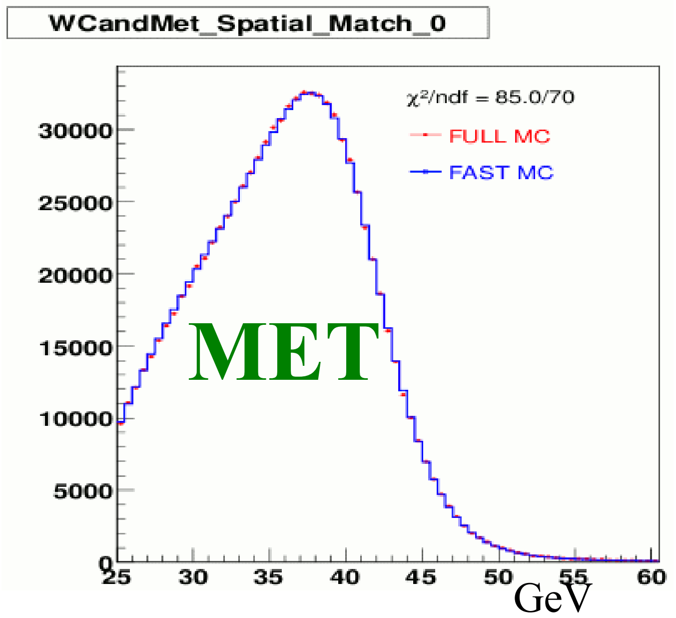


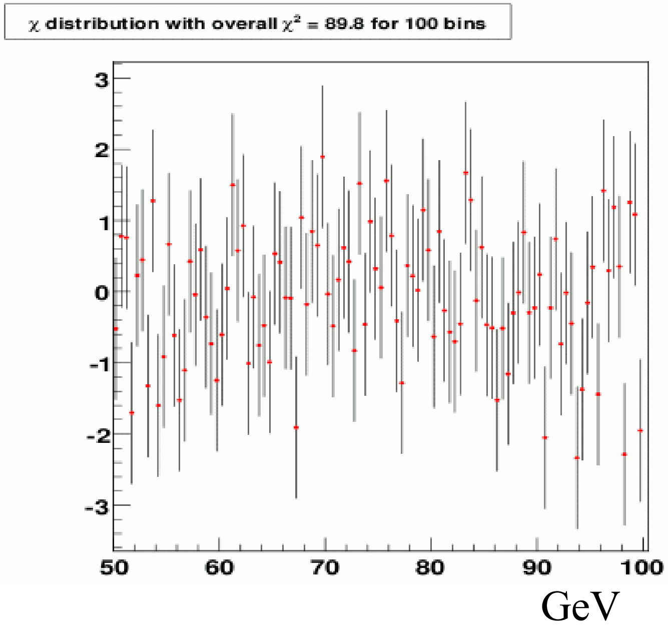


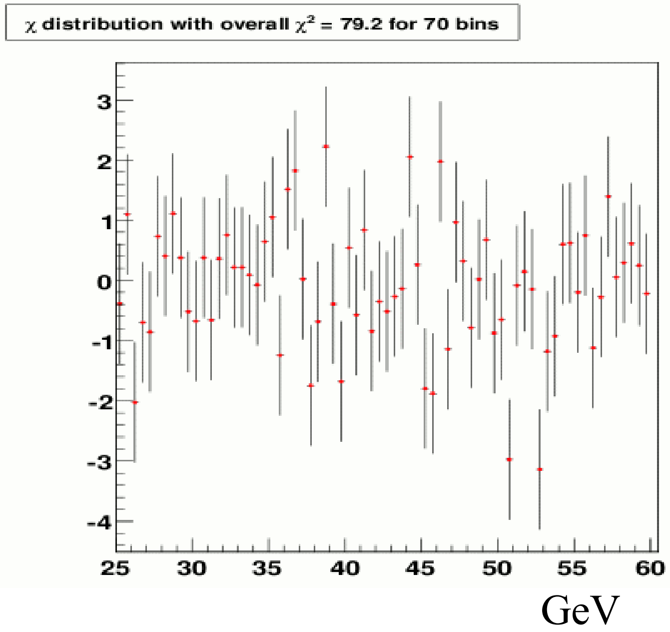
MC closure test results: W → e ν

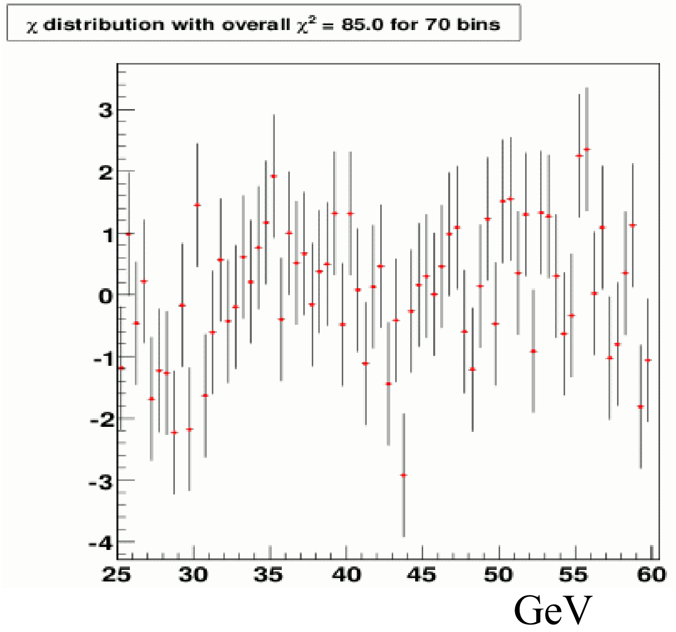




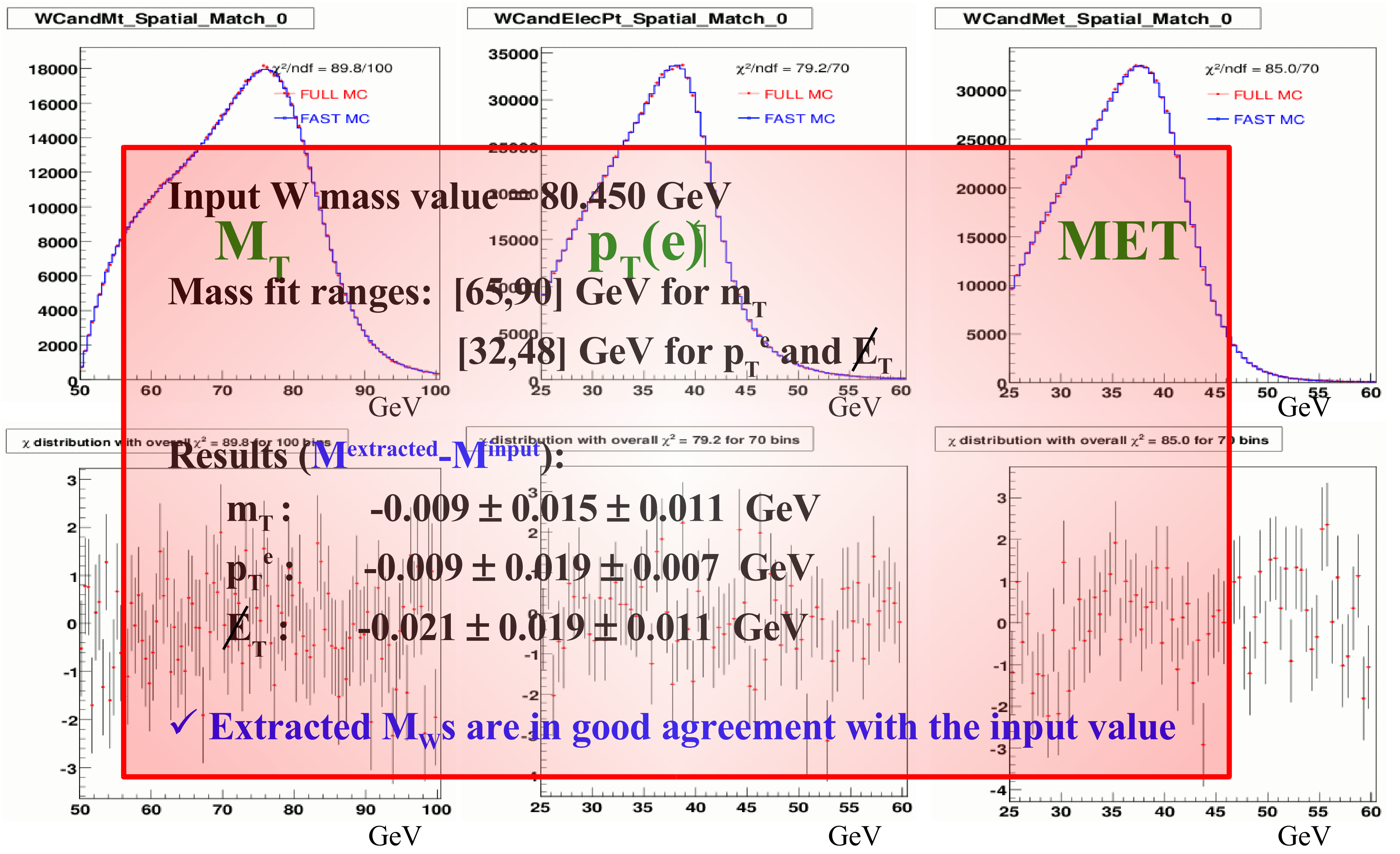








MC closure test results: $W \to e\nu$



Input W mass value = 80.450 GeV

Mass fit ranges: [65,90] GeV for m_T

[32,48] GeV for p_T^e and $\not{E}_T$

Results ($M^{extracted}$-M^{input}):

m_T : -0.009 ± 0.015 ± 0.011 GeV

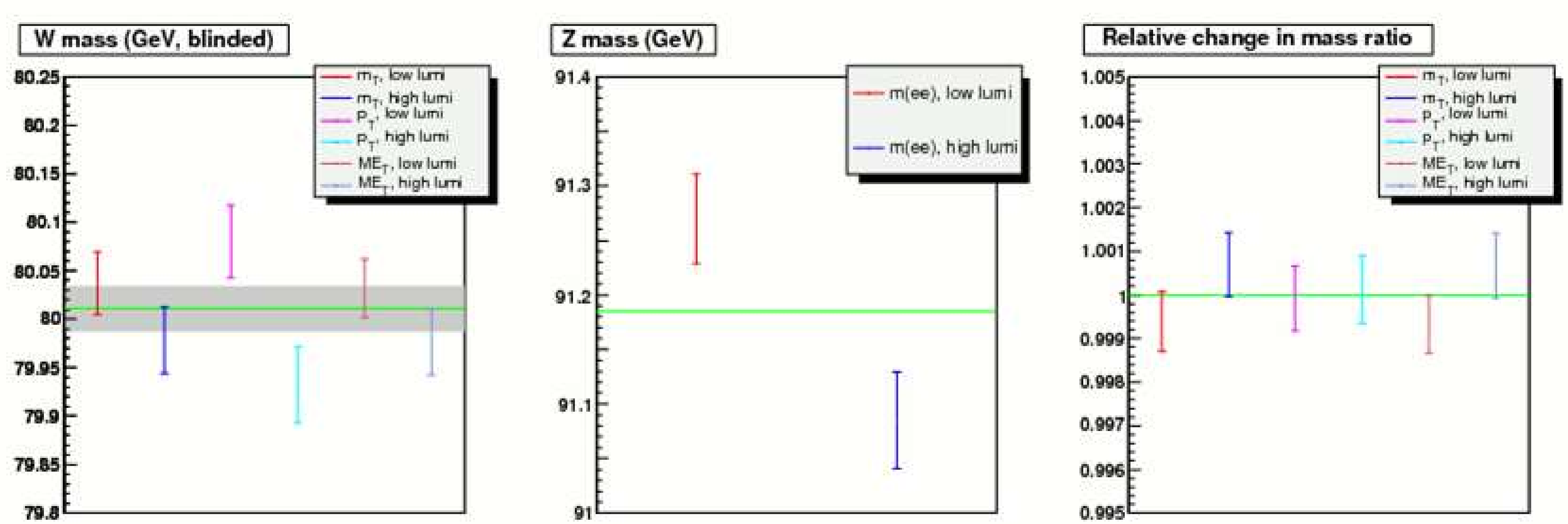
p_T^e : -0.009 ± 0.019 ± 0.007 GeV

$\not{E}_T$: -0.021 ± 0.019 ± 0.011 GeV

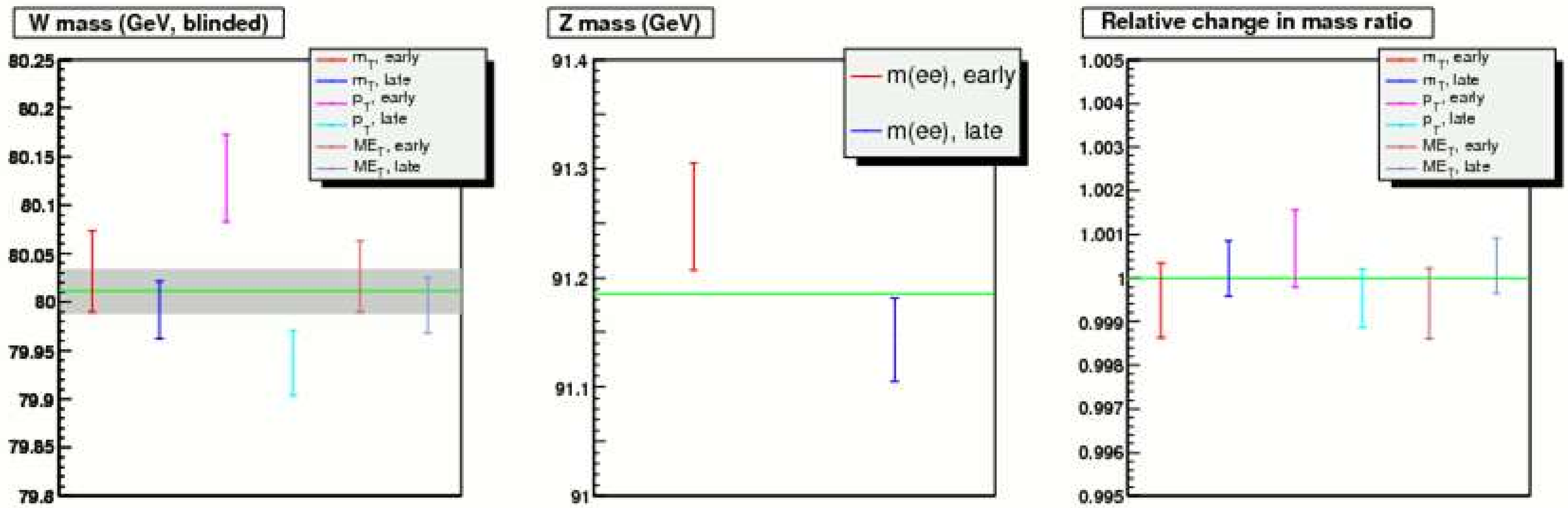
✓ Extracted M_Ws are in good agreement with the input value

Consistency Checks – I

- **Instantaneous Luminosity** (split data into 2 subsets – high and low inst. luminosities)

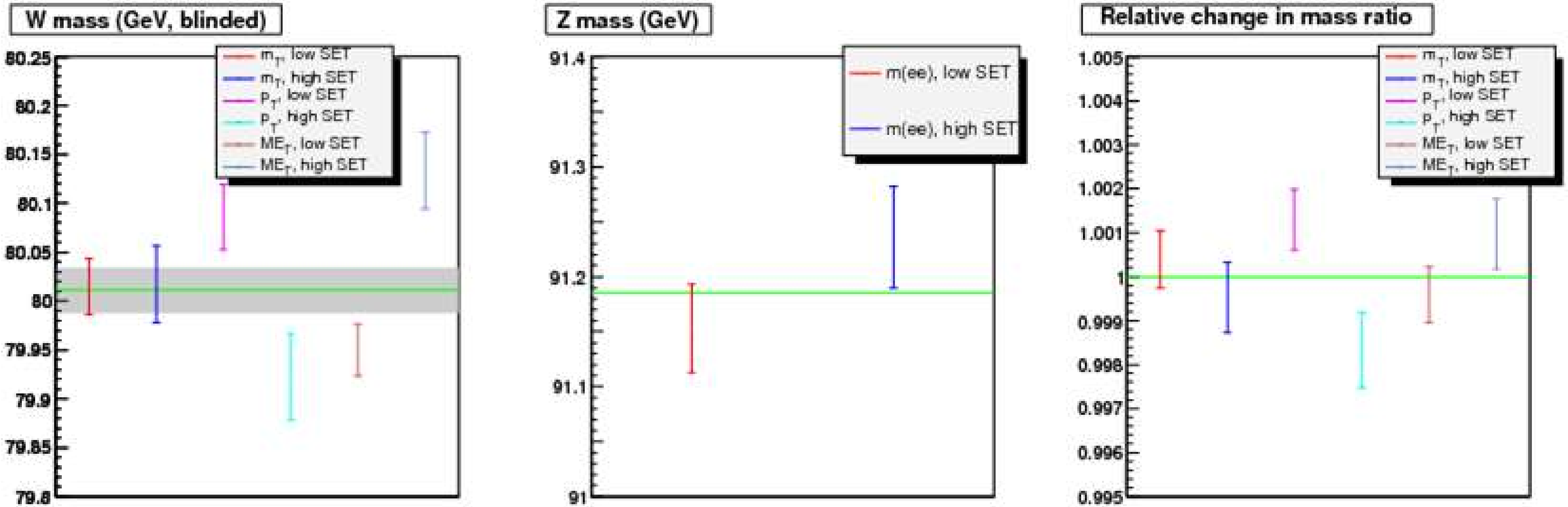


- **Time** (data taking period)

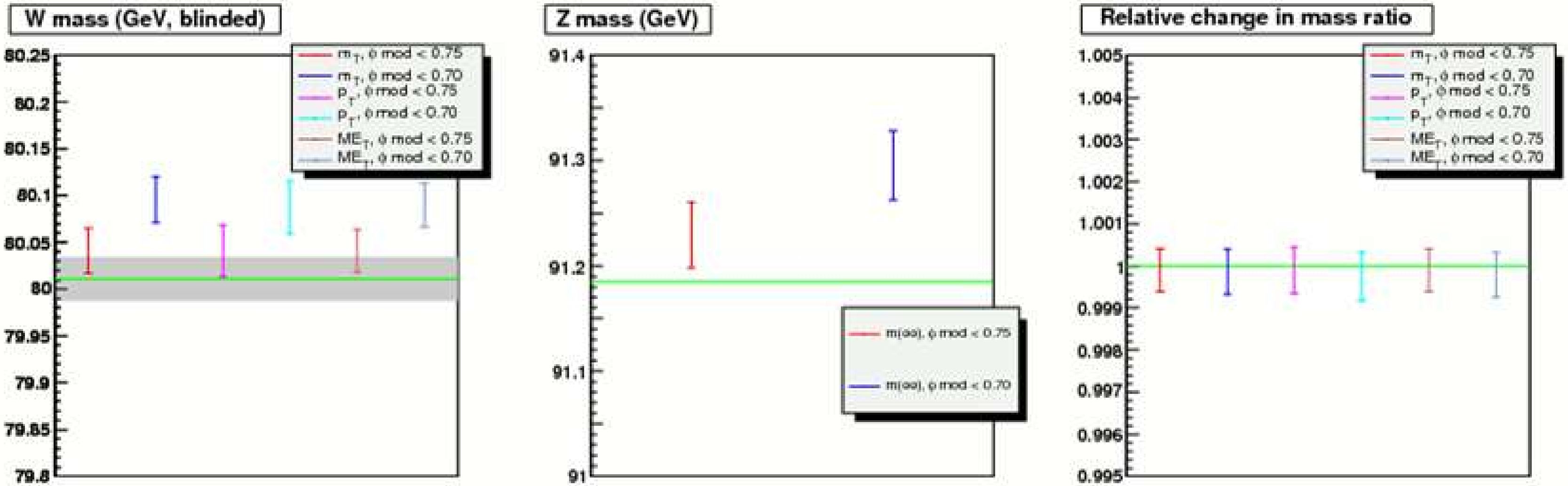


Consistency Checks – II

- **Scalar E_T** (total “visible” energy as seen in plane transverse to beam in calorimeter)

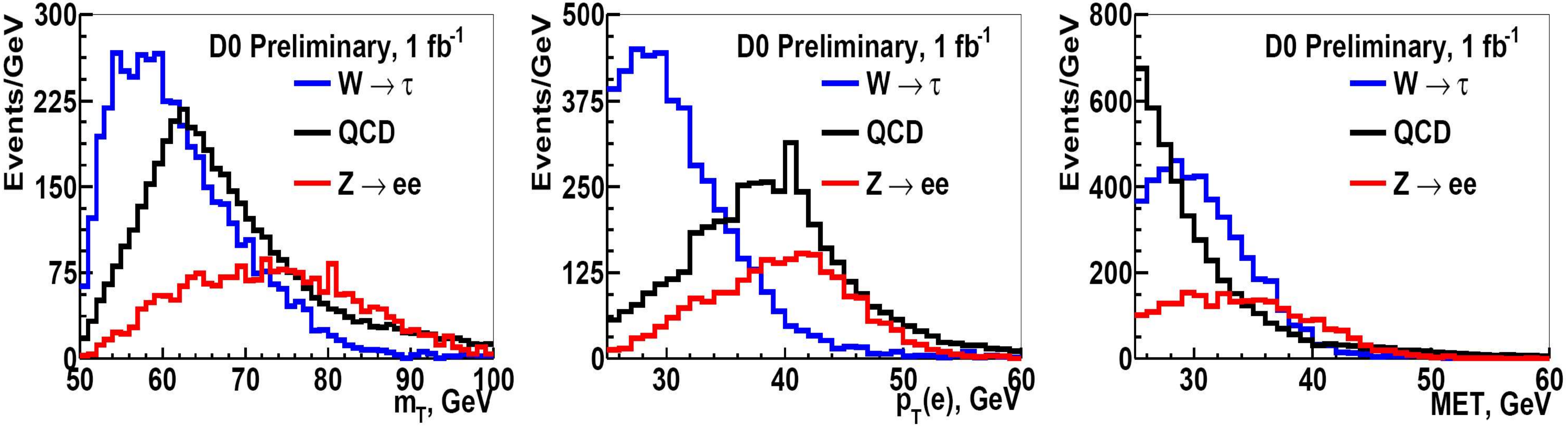


- **Electron distance from phi cracks**

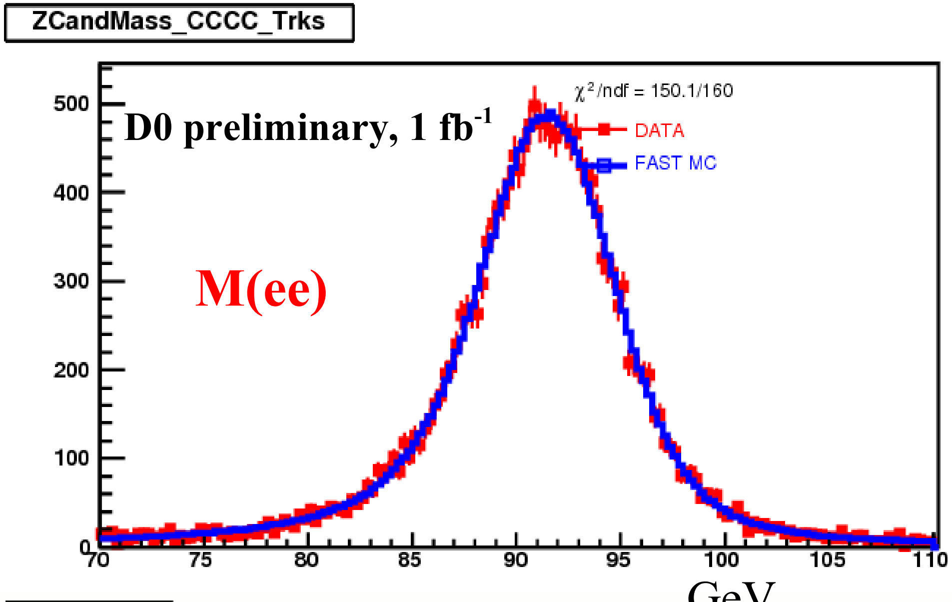


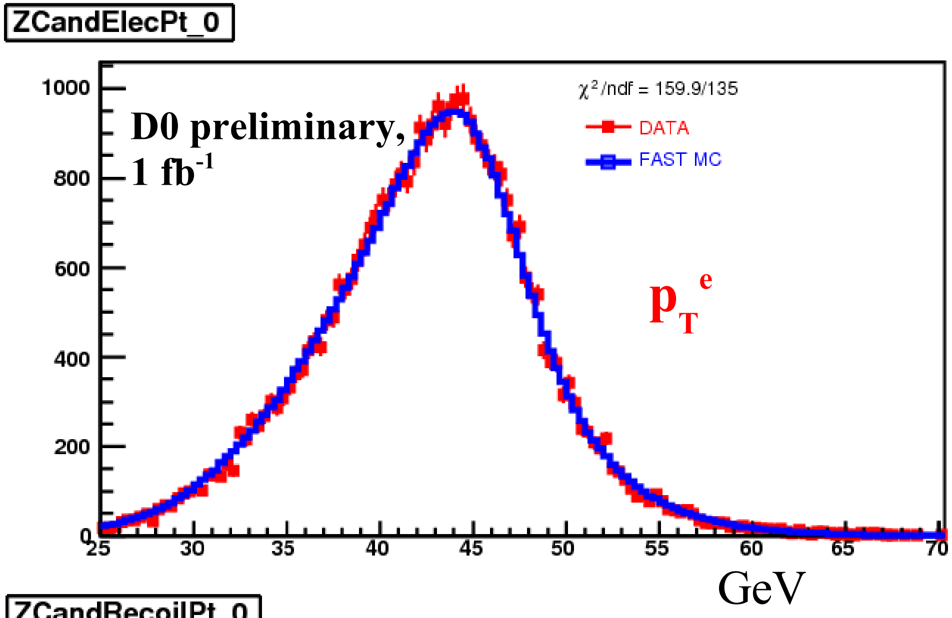
Backgrounds to W→eν

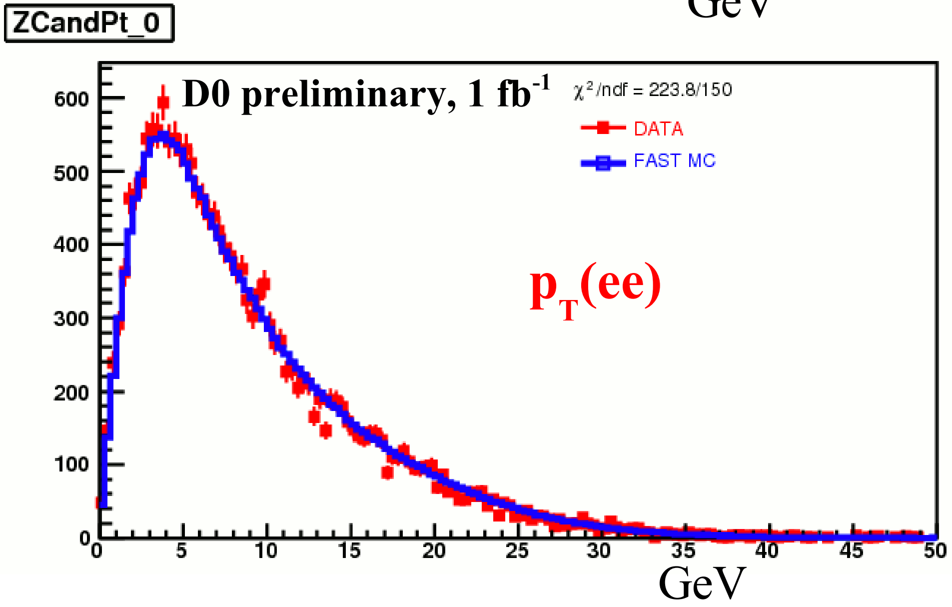
- QCD (di-jet) (1.49 ± 0.3 %) : one jet fakes as an electron
  - determined from QCD data
- Z→ee (0.80 ± 0.01 %) : one electron lost in ICR(between central and end cal)
  - determined from Z→ee data
- W→τν (1.60 ± 0.02 %) : Taus decaying into eνν
  - determined from GEANT (full) MC
- For all 3 observables: estimated backgrounds are added to simulated signal from W PMCS

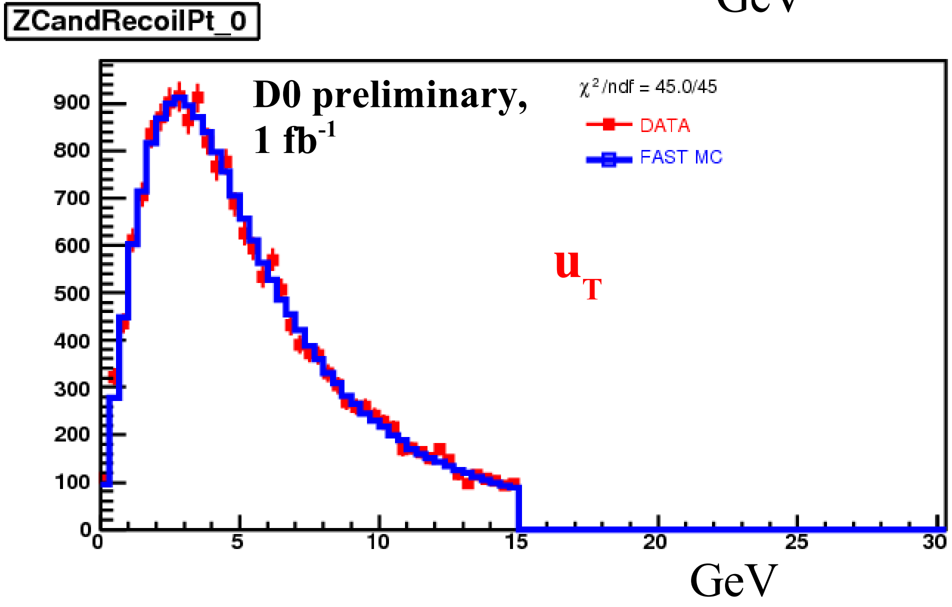


Diagnostic plots from Z→ ee data/MC comparisons



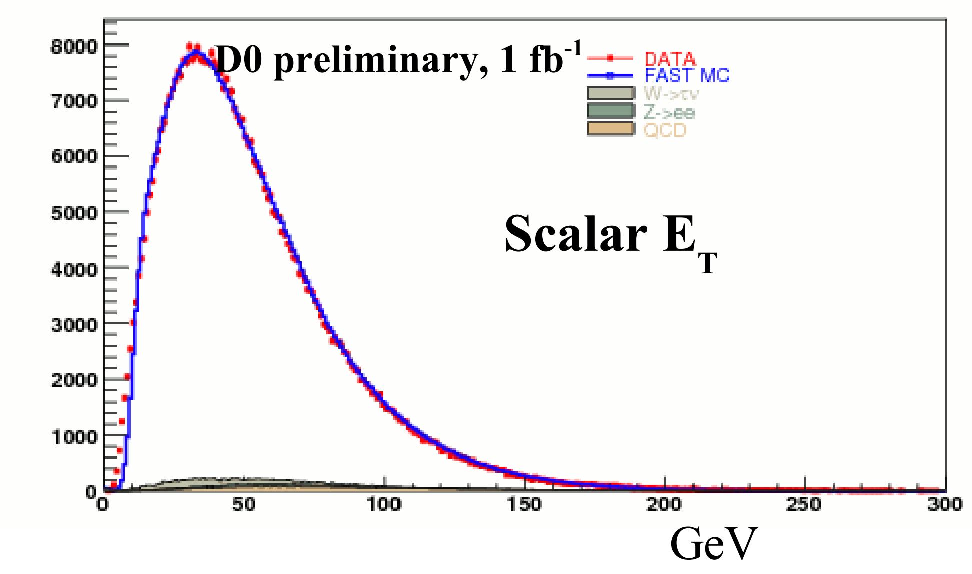


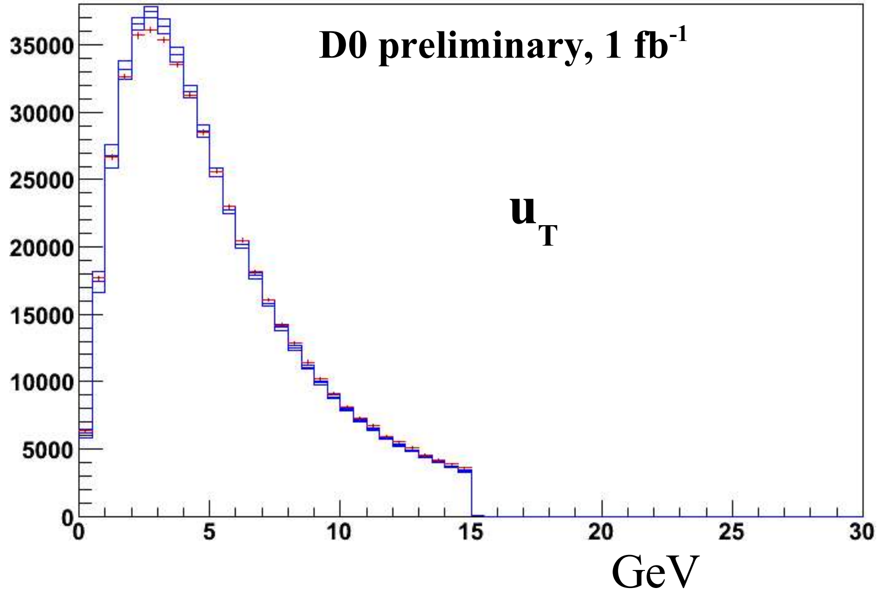


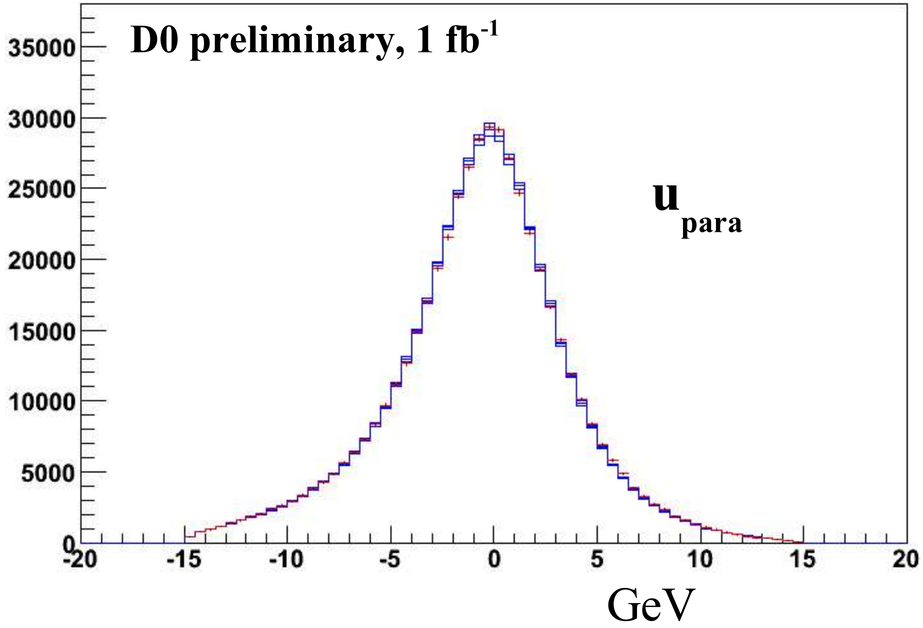


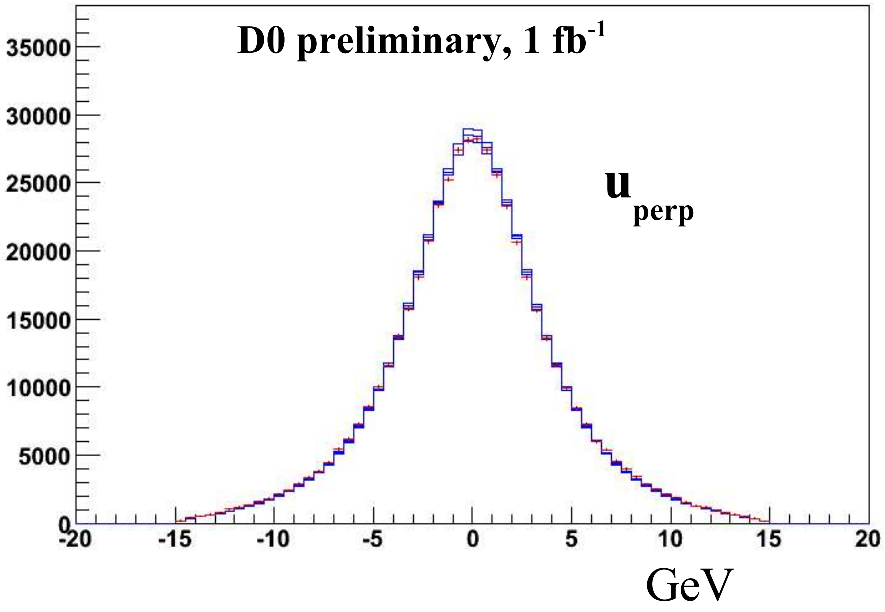
- Good agreement between PMCS and data, useful for checking that the calibrations are working fine !

Diagnostic plots from $W \rightarrow e\nu$ data









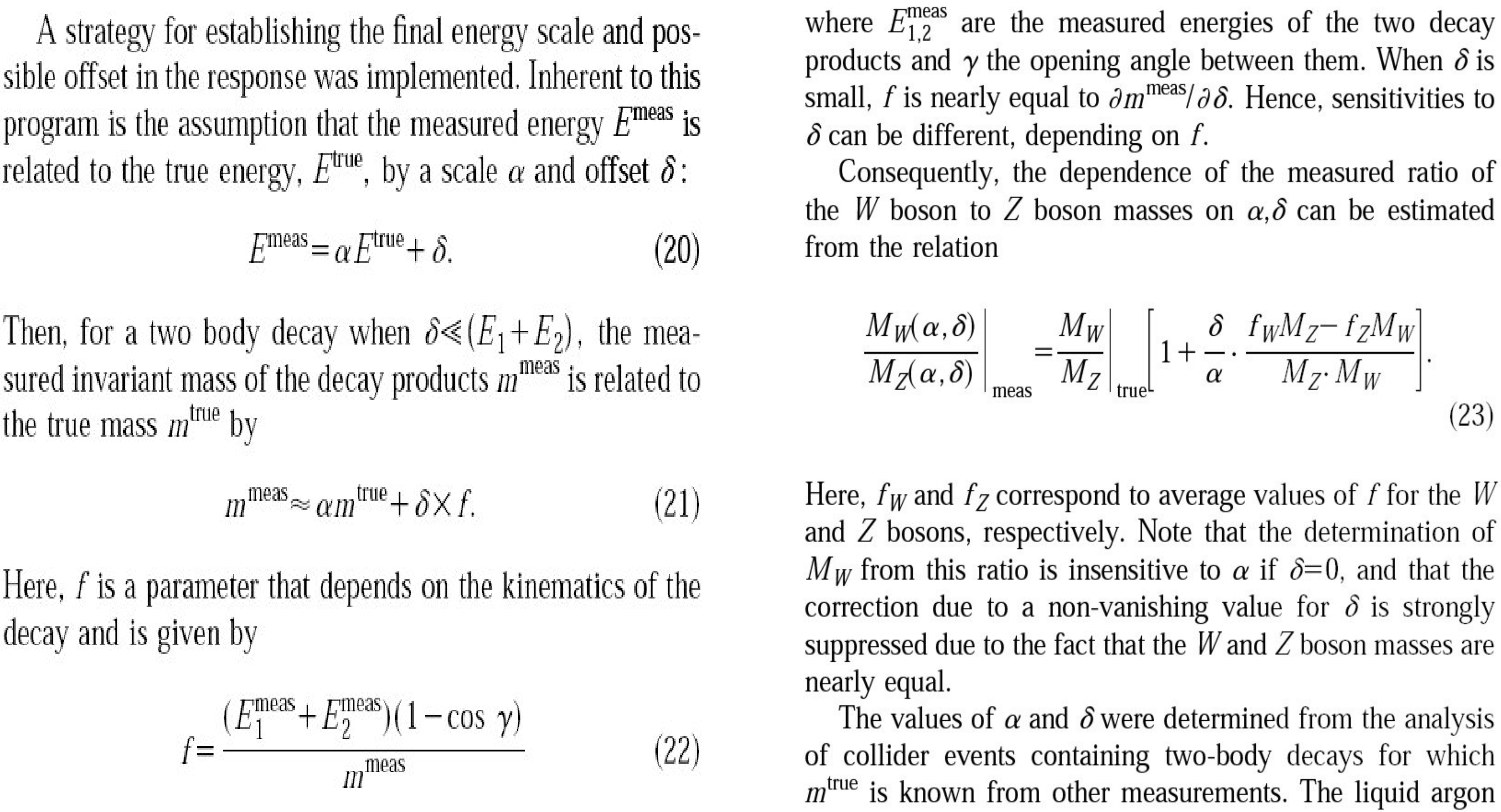
- Parameterized MC tuned to Z data describes W very well too !

Some information

- In Run I, they had single particle resolution :
    - e: $\sigma/E = 15\%/\sqrt{E} + 0.3\%$
    - π: $\sigma/E = 45\%/\sqrt{E} + 4\%$
- Resolution of calorimeter is 4% at E=45 GeV
- Pseudorapidity : $\eta = -\ln(\tan\theta/2)$ where θ is the angle between the p and beam axis ⟶
    - $\eta = \frac{1}{2}\ln[(|p| + p_L) / (|p| - p_L)]$ where p_L is the component of p along beam direction
    - When v~c: $\eta = y(\text{rapidity}) = \frac{1}{2}\ln[(E + p_L) / (E - p_L)]$
- p = rqB (q →charge of particle; r →radius of curvature)
- Momentum resolution of tracker depends on :
    - magnetic field (B)
    - number of measurements
    - Lever arm (radius of tracker)
    - single hit resolution (SHR)
    - momentum + detector granularity + mass of detector (affects negatively) feed into SHR
- $M_W = M_Z \cos\theta_W$
- α_{EM} = EM coupling at $Q=M_Zc^2$, $G_F = 1.16637(1) \times 10^{-5}\ \text{GeV}^{-2}$, $M_Z = 91.1876 \pm 0.0021\ \text{GeV}/c^2$, $\theta_W \sim 30^{\circ}$

Addtl. info on Electron Energy Scale

- Electron energy scale : E(measured) = α.E(true) + β
- For a 2-body decay assuming β <<(E1+E2) we get : M_Z(measured) = α . M_Z(true) + f_Z . β



A strategy for establishing the final energy scale and possible offset in the response was implemented. Inherent to this program is the assumption that the measured energy E^{meas} is related to the true energy, E^{true}, by a scale α and offset δ:

$$E^{\text{meas}} = \alpha E^{\text{true}} + \delta. \tag{20}$$

Then, for a two body decay when $\delta \ll (E_1 + E_2)$, the measured invariant mass of the decay products m^{meas} is related to the true mass m^{true} by

$$m^{\text{meas}} \approx \alpha m^{\text{true}} + \delta \times f. \tag{21}$$

Here, f is a parameter that depends on the kinematics of the decay and is given by

$$f = \frac{(E_1^{\text{meas}} + E_2^{\text{meas}})(1 - \cos\gamma)}{m^{\text{meas}}} \tag{22}$$

where $E_{1,2}^{\text{meas}}$ are the measured energies of the two decay products and γ the opening angle between them. When δ is small, f is nearly equal to $\partial m^{\text{meas}}/\partial\delta$. Hence, sensitivities to δ can be different, depending on f.

Consequently, the dependence of the measured ratio of the W boson to Z boson masses on α,δ can be estimated from the relation

$$\left.\frac{M_W(\alpha,\delta)}{M_Z(\alpha,\delta)}\right|_{\text{meas}} = \left.\frac{M_W}{M_Z}\right|_{\text{true}} \left[1 + \frac{\delta}{\alpha} \cdot \frac{f_W M_Z - f_Z M_W}{M_Z \cdot M_W}\right]. \tag{23}$$

Here, f_W and f_Z correspond to average values of f for the W and Z bosons, respectively. Note that the determination of M_W from this ratio is insensitive to α if $\delta=0$, and that the correction due to a non-vanishing value for δ is strongly suppressed due to the fact that the W and Z boson masses are nearly equal.

The values of α and δ were determined from the analysis of collider events containing two-body decays for which m^{true} is known from other measurements. The liquid argon