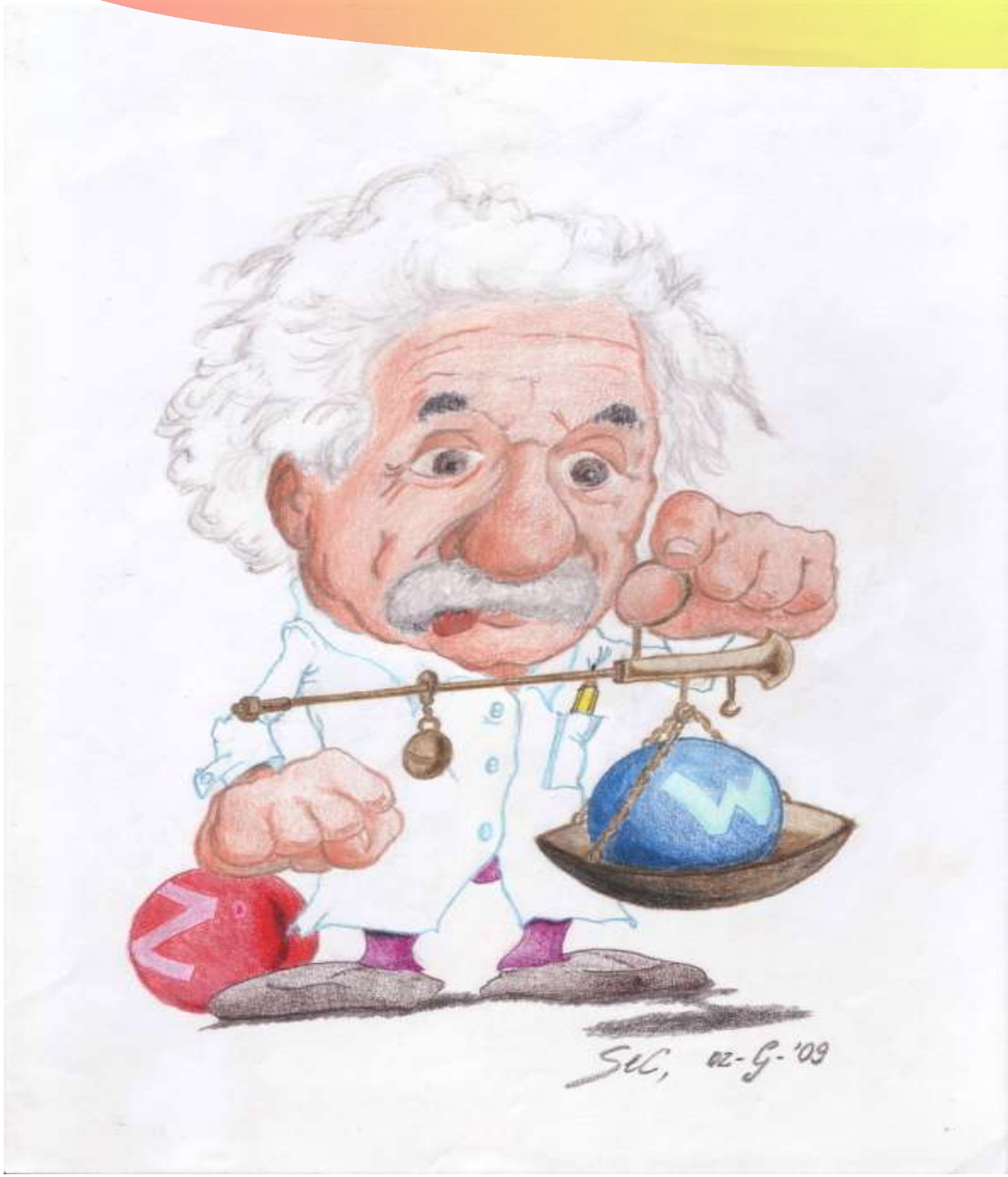
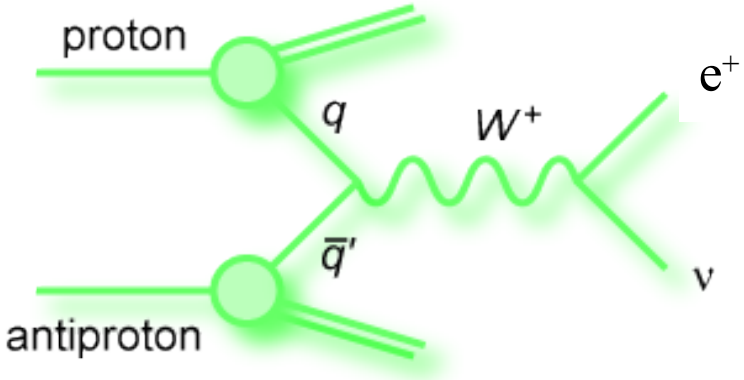
A precision measurement of the W boson mass at DØ





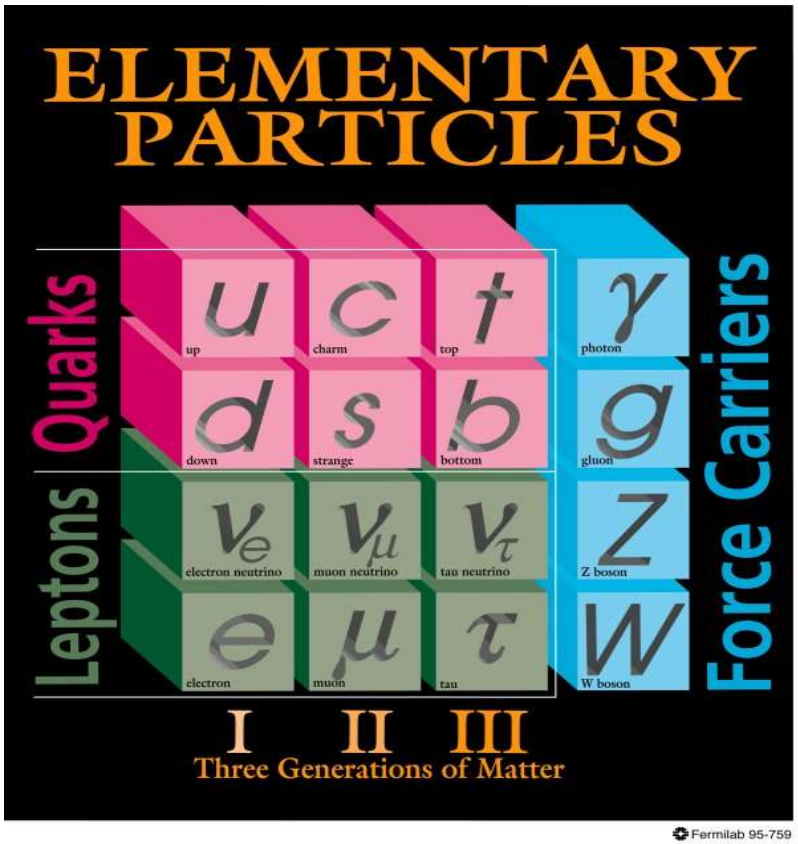
$\int L\,dt = 1\ fb^{-1}$

Jyotsna Osta

University of Notre Dame

The W boson in the Standard Model

W → carrier of weak force



Outline of talk

- Introduction
- Tevatron and the DØ Experiment
- Measurement Strategy
- Calibrating the calorimeter
- Parameterized MC Simulation of detector
  - Electron Modeling
  - Recoil Modeling
- Results
- Outlook

So let's begin ...

- **Introduction**
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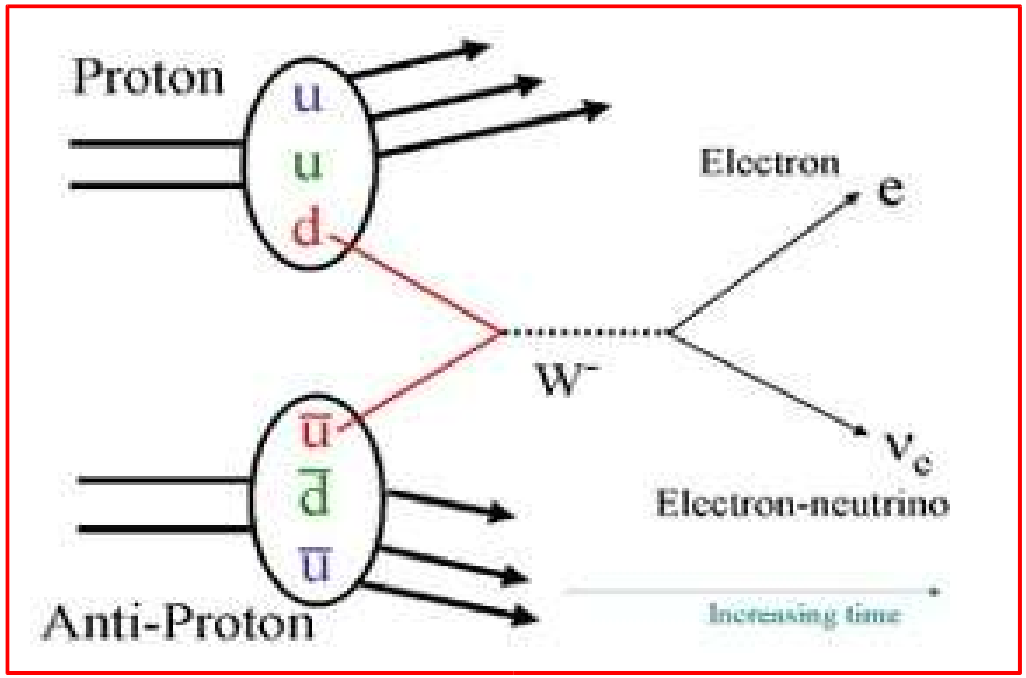
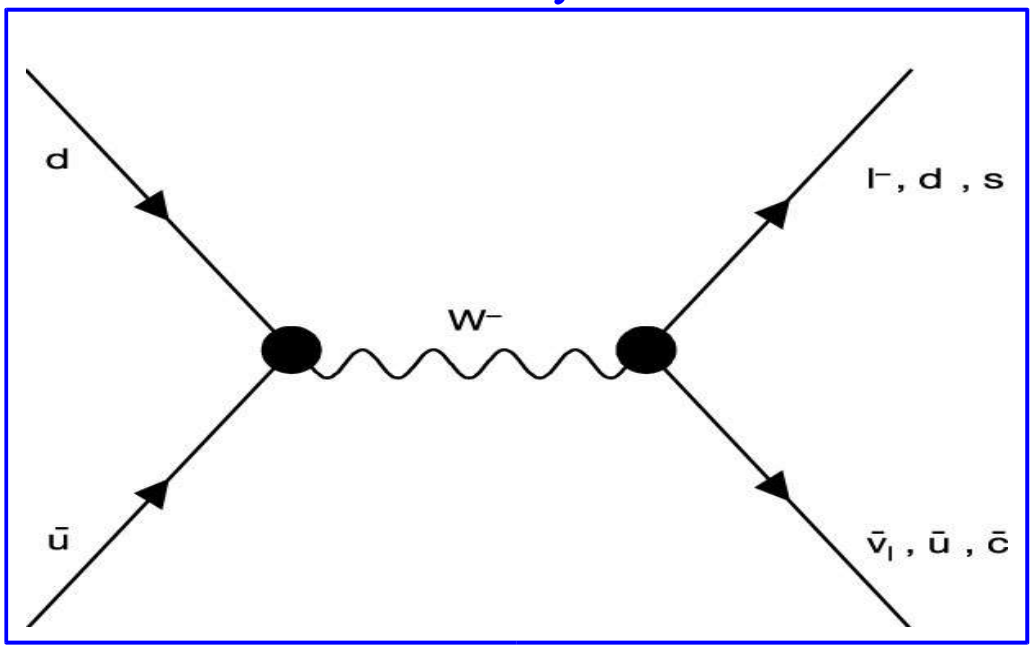
Production and decay of W bosons

W boson is made from annihilation of u and d quarks at Tevatron ($u\bar{d} \rightarrow W^+$; $\bar{u}d \rightarrow W^-$)



W has other decay modes as well ...



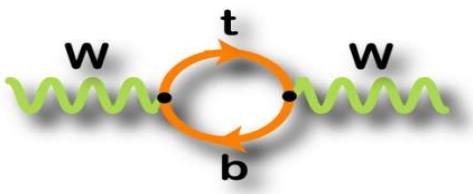
We analyze the semi-leptonic decay channel of the electron(positron) and anti-neutrino(neutrino)

W boson mass and Radiative Corrections

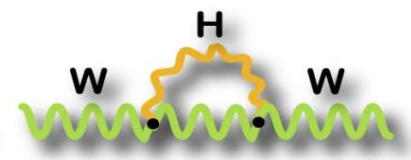
- W mass (M_W) is a relevant parameter of the SM

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

- SM prediction of W mass = 80.390 ± 0.018 GeV

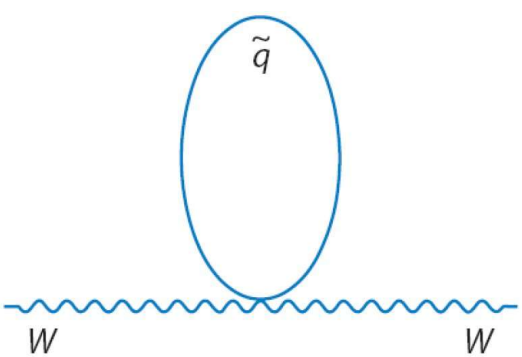


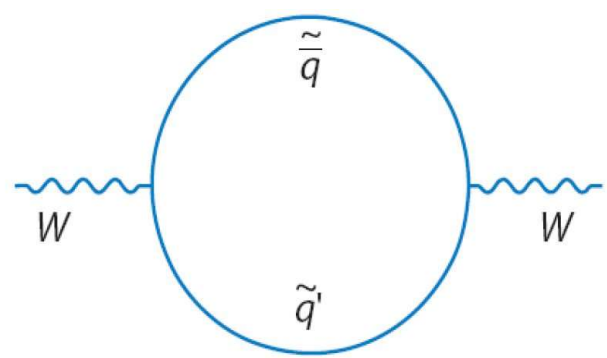
$\Delta r \sim M_{top}^2$



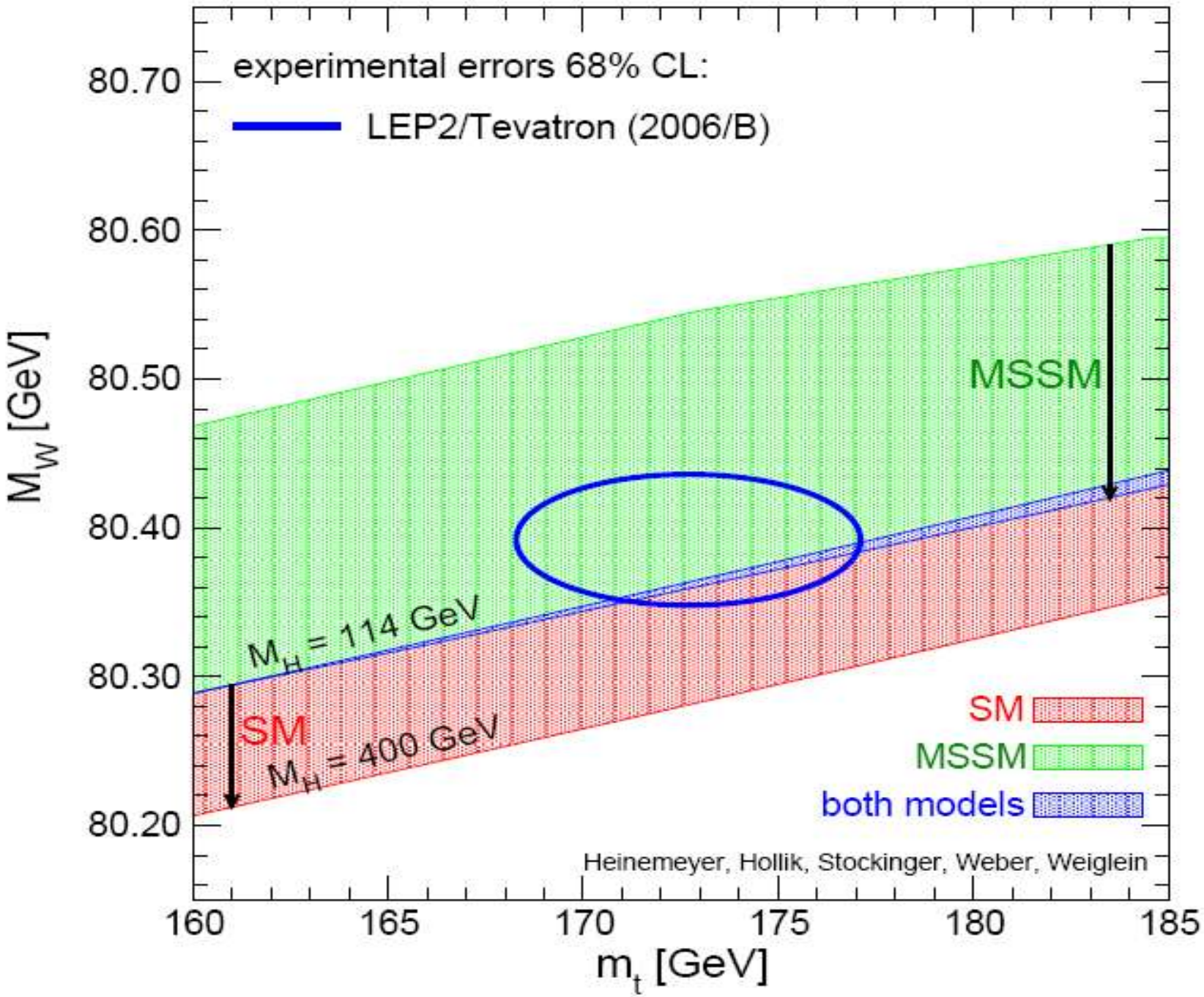
$\Delta r \sim \log M_{Higgs}$

- Other contributions to Δr could come from Supersymmetric particles

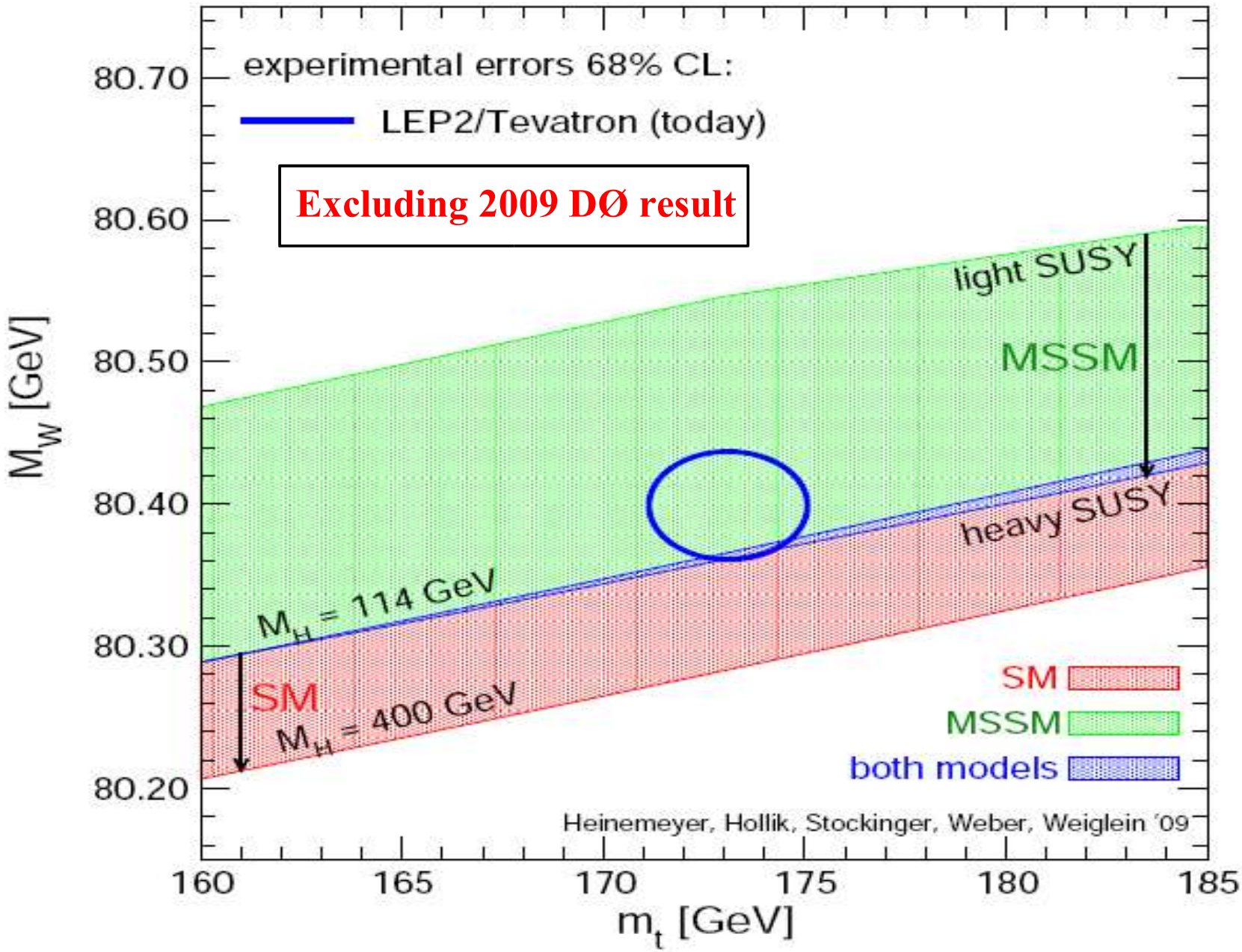




Impact on mass of Higgs - I



Impact on mass of Higgs - II



Motivation for a precise M_W measurement

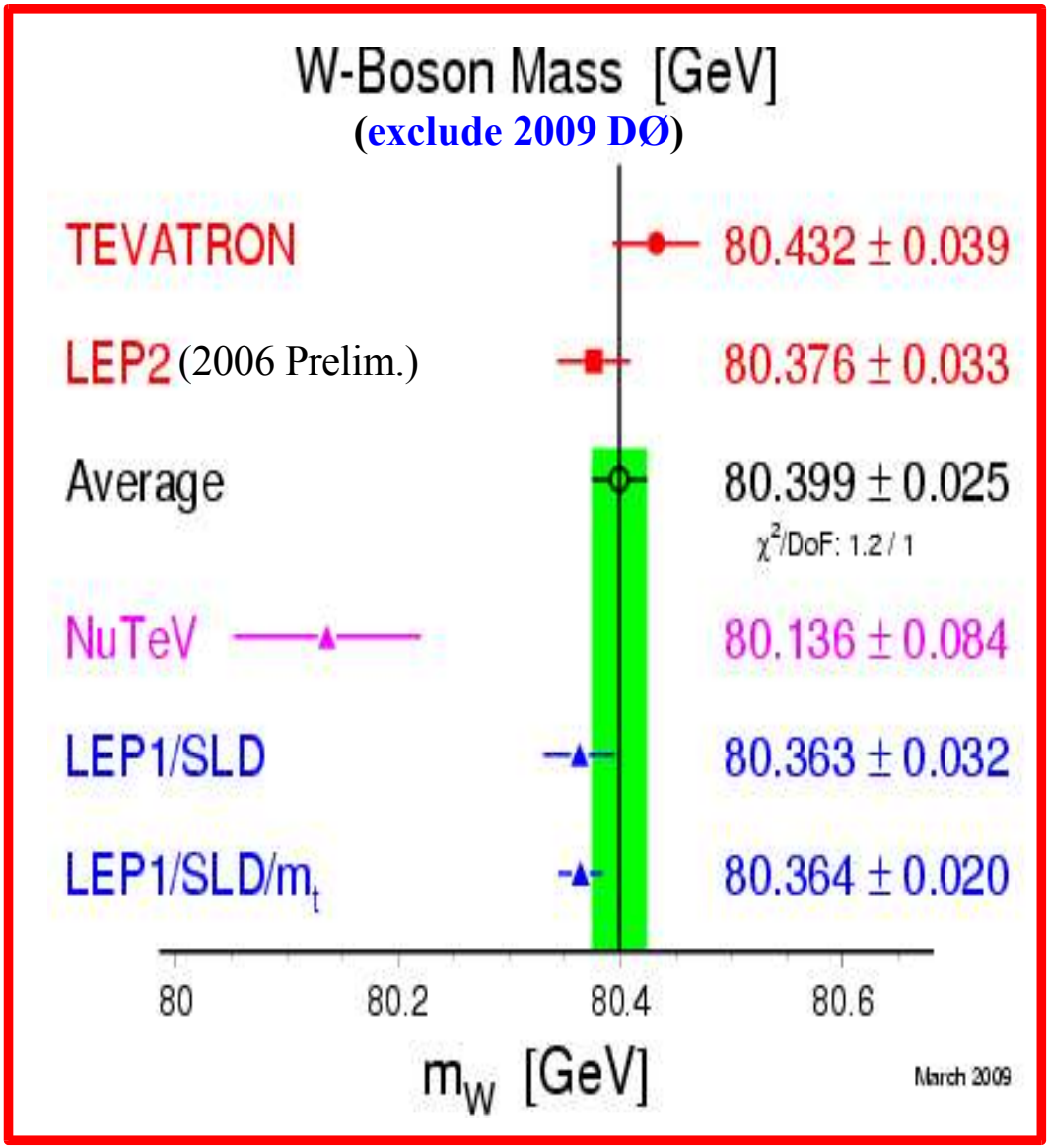
- For equal contributions on ΔM_{Higgs} from M_{top} and M_W we need :
  - $\Delta M_w = 0.006\ \Delta M_{top}$

    $\Delta M_{top} = 1.3$ GeV (Tev Average)

    $\Rightarrow \Delta M_w = 8$ MeV (0.01%) !
  - Present World Average :

    $\Delta M_w = 25$ MeV (0.03 %)
- Thus the limiting factor here is
  - ΔM_w !
- Expectation of this analysis :

  $\Delta M_w \approx 50$ MeV (0.05%)



Experimental facility

- Introduction
- **Tevatron and the DØ Experiment**
- Measurement Strategy
- Calibrating the calorimeter
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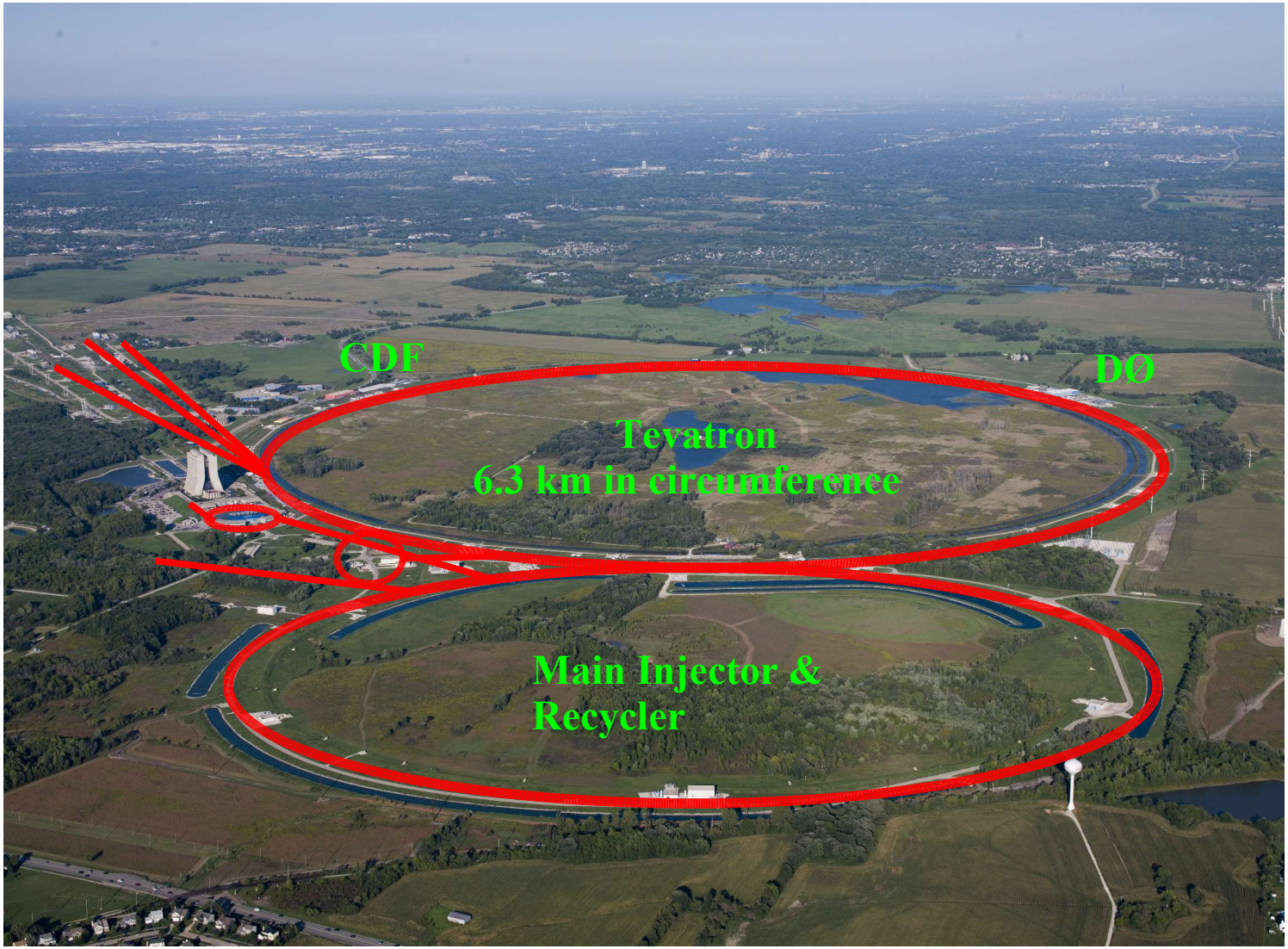
  - Recoil Modeling
- Results
- Conclusion and Outlook

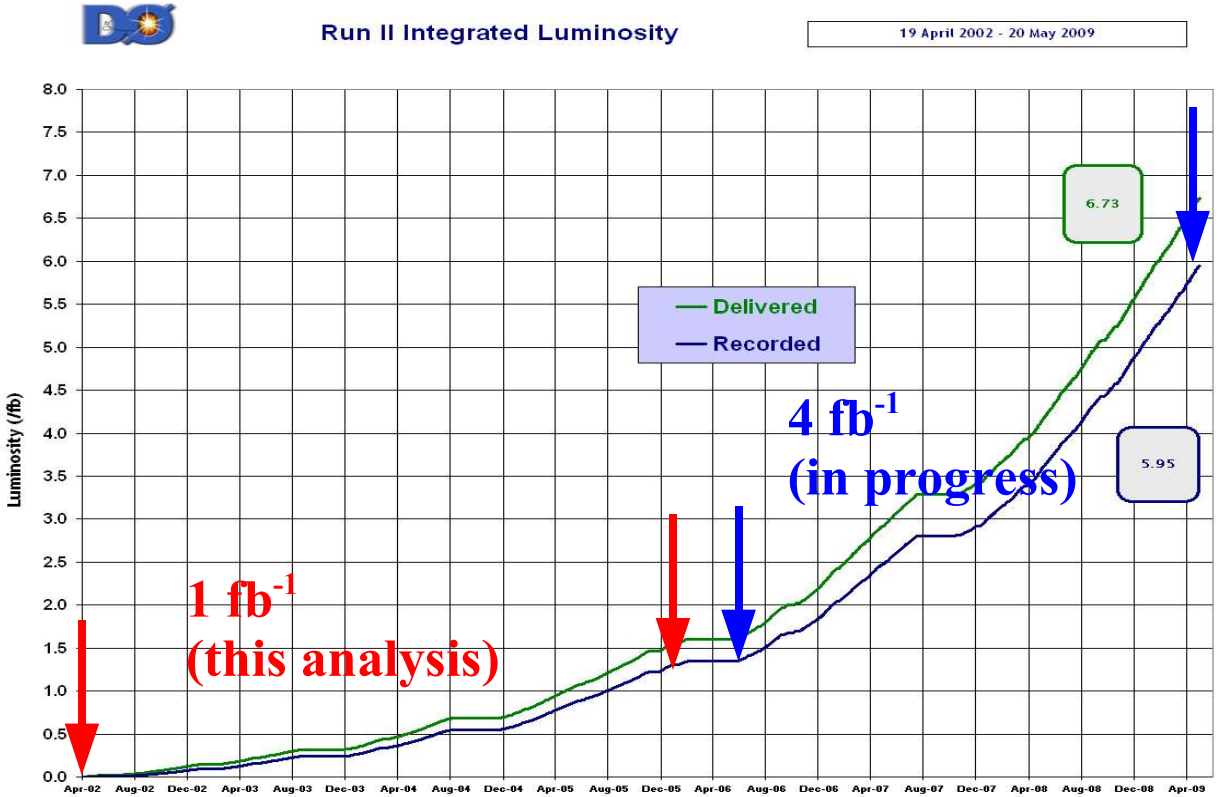
Tevatron at Fermilab

- A synchroton that collides protons and anti-protons at a center-of-mass energy =1.96 TeV !
- 36 bunches each for protons and anti-protons in each load
- 396 ns between two bunch crossings

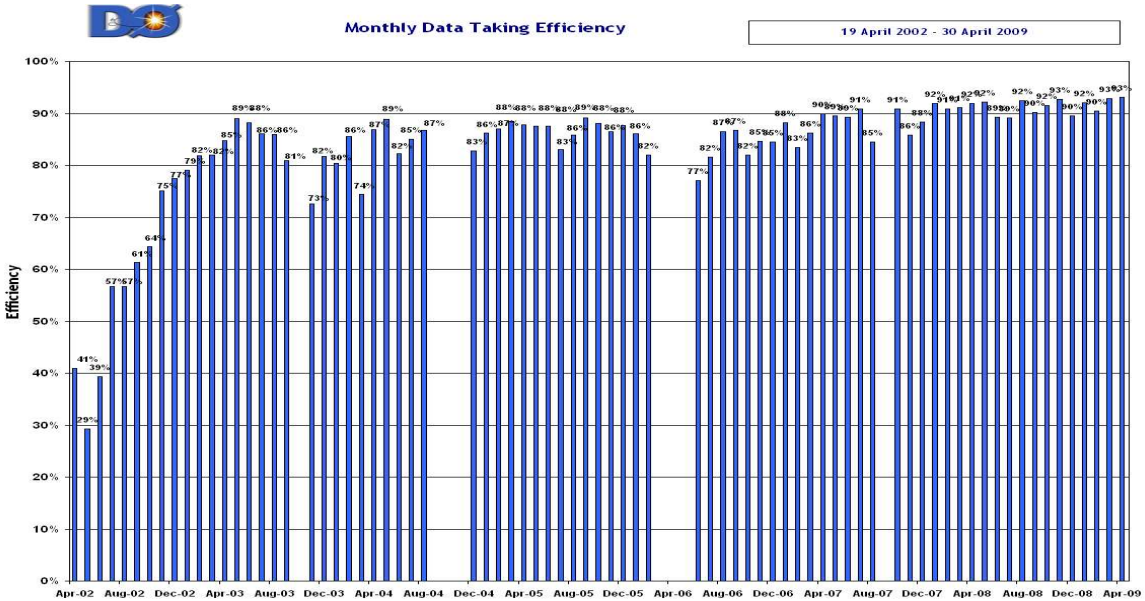


Currently the only collider that produces W and Z bosons and Top quarks directly !

Luminosity for Run IIa at DØ

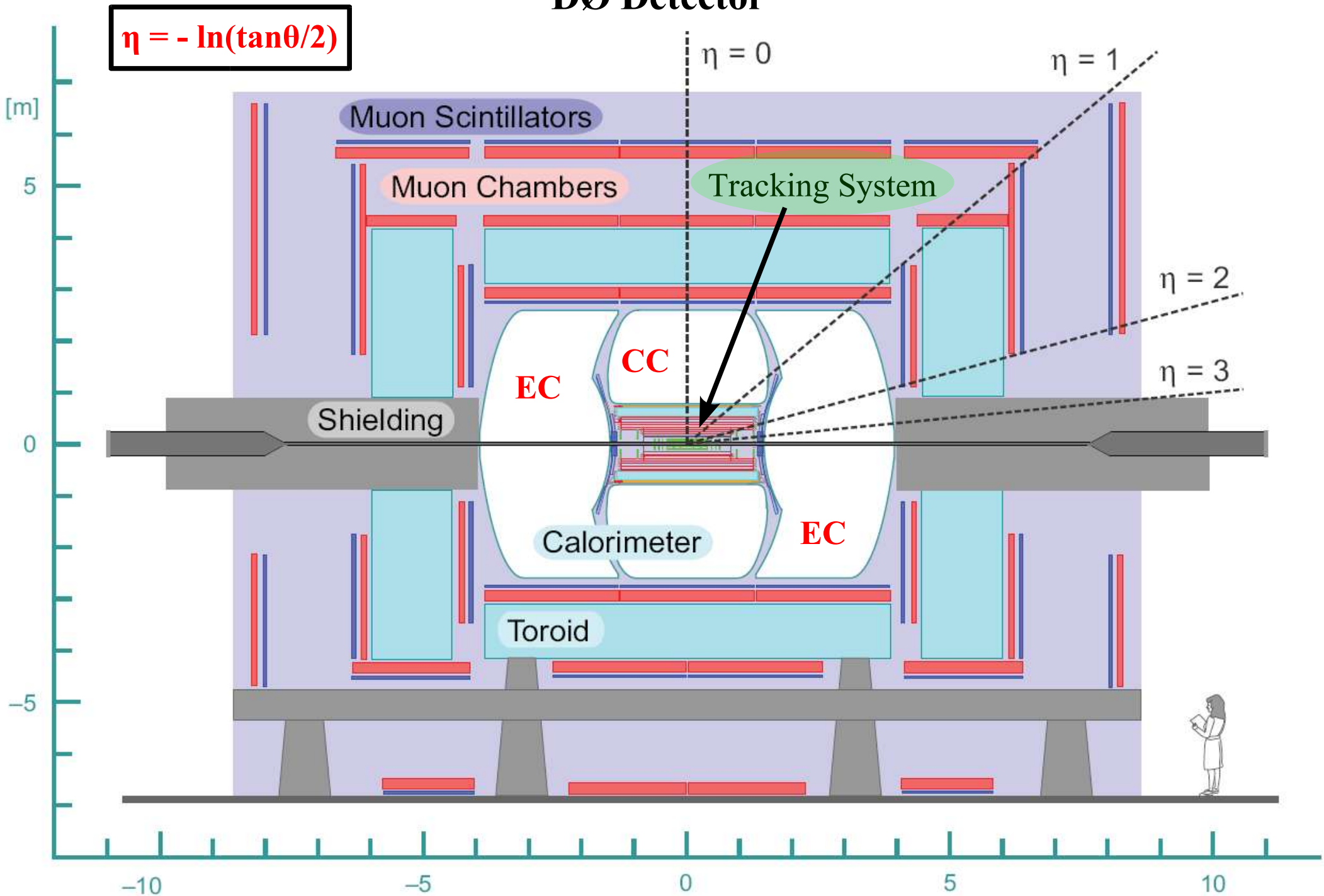


Accelerator has been running very well → delivering ~1fb^{-1} in about 5 months !
Thanks to Accelerator Division at FNAL !

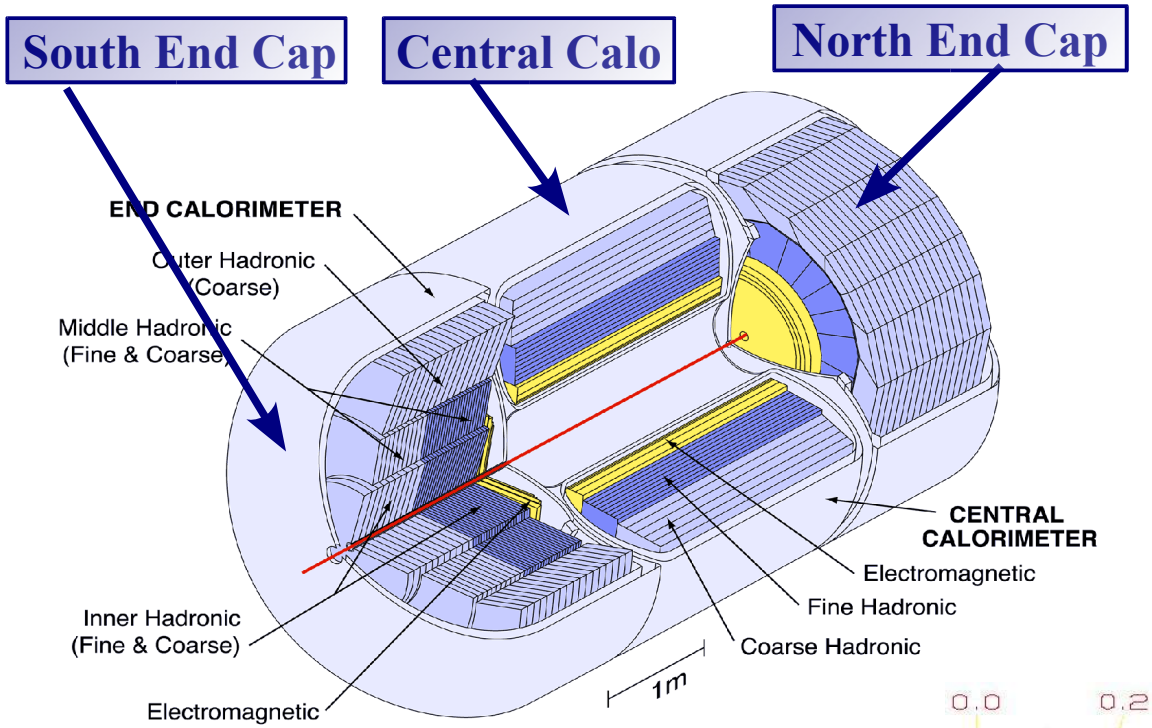


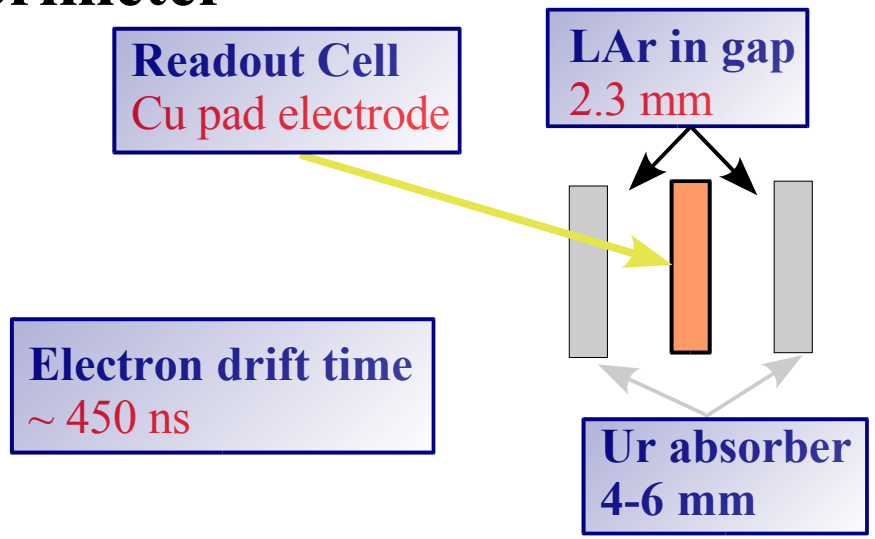
D0 has been taking data at over 90% → very efficient !
Thanks to the collaboration !

DØ Detector

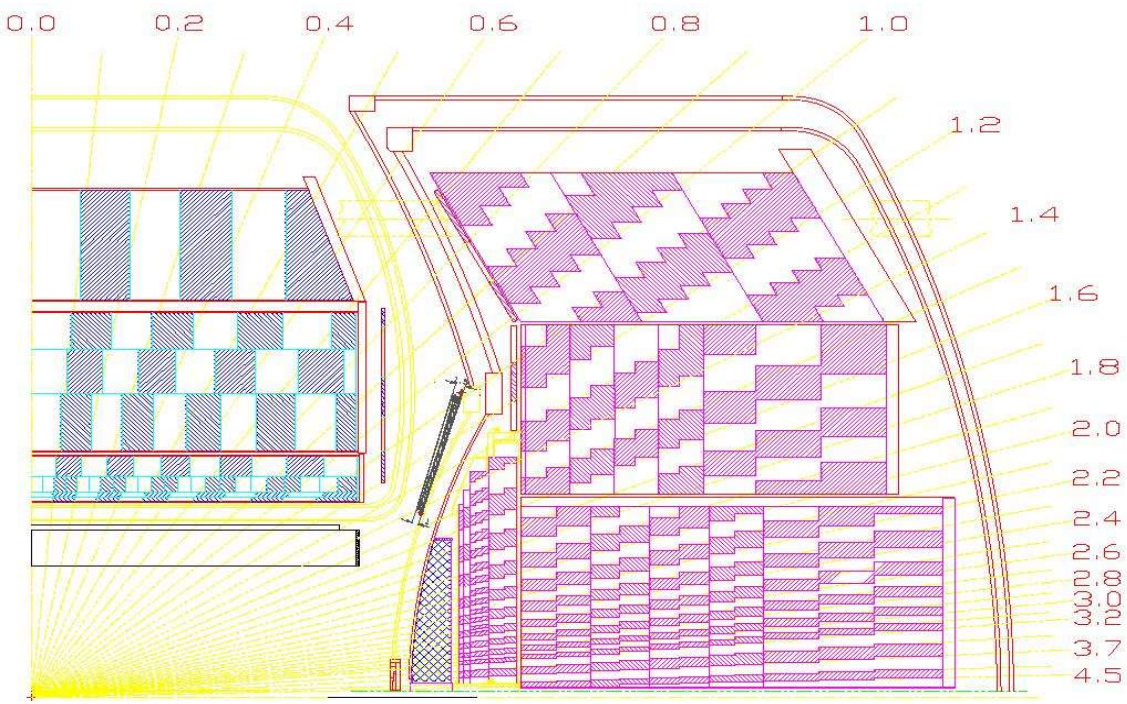

η = - ln(tanθ/2)
η = 0
η = 1
η = 2
η = 3
[m]
5
0
–5
–10
–5
0
5
10
Muon Scintillators
Muon Chambers
Tracking System
CC
EC
EC
Shielding
Calorimeter
Toroid

DØ RunII Calorimeter



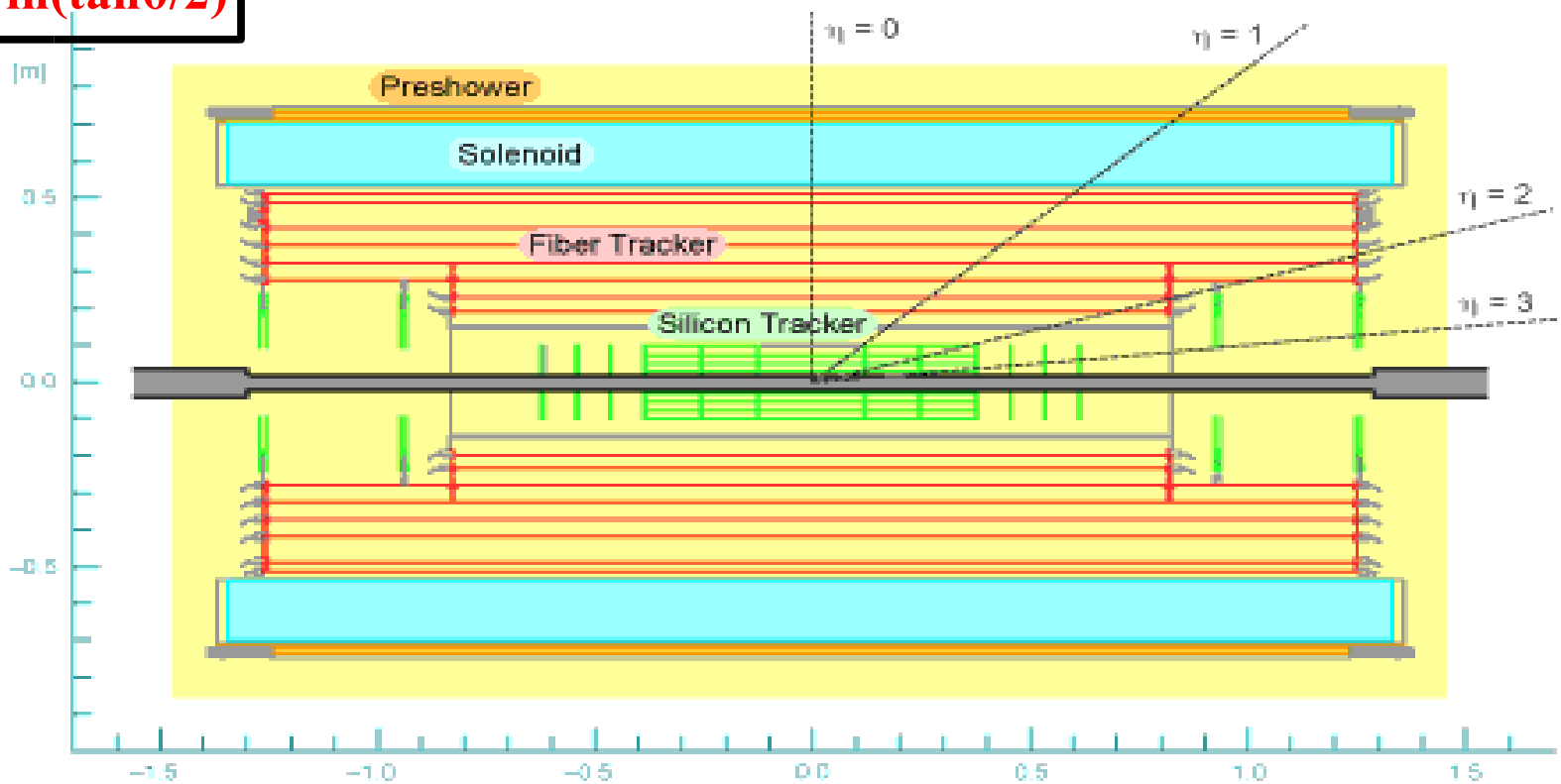


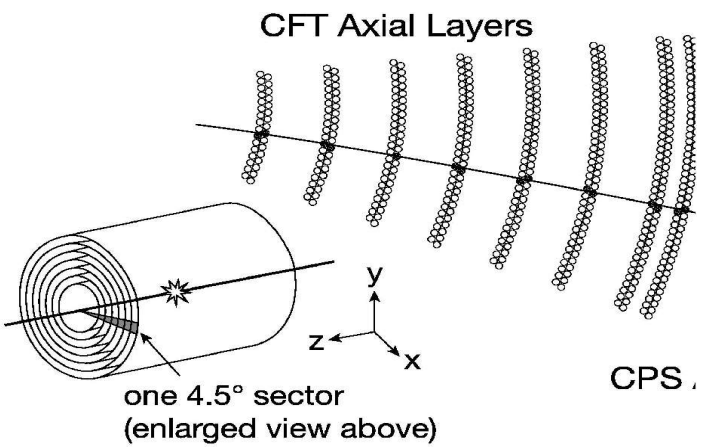
- Liquid Argon active medium
- Absorbers –
  - Uranium(EM); Copper(FH); Steel(CH)
- Almost full coverage ($\eta < 4.2$)
- ~ 46,000 readout cells
- Readout towers are 0.1x0.1 in $\Delta\eta$ x $\Delta\varphi$
  - EM3 is 0.05x0.05 in $\Delta\eta$ x $\Delta\varphi$



Central Fiber Tracker

$\eta = -\ln(\tan\theta/2)$





- 8 layers of doublet scintillating fibers
- Magnetic field (B) ~ 2 T to bend tracks
- $\Delta p_T/p_T$ ~ 3% at E=5 GeV

  ~ 8% at E=45 GeV
- I participated in the RunIIb upgrade of CFT readout hardware

Strategy for the analysis

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- Tevatron and the DØ Experiment
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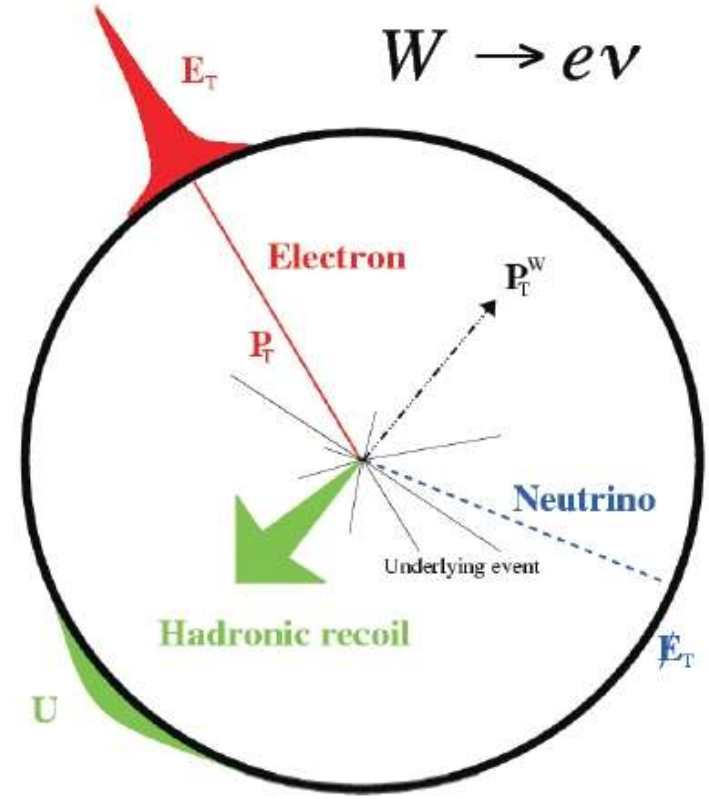
Experimental observables

- **Three important signatures -**
  - **Electron**
  - **Neutrino**
  - **Recoiling hadons**
- W mass is reconstructed in the plane transverse to the beamline of detector
  - Do not detect particles at large rapidities ($|\eta| > 4.2$)
    - they are lost down the beampipe
  - Decay product of W is neutrino (ν) which is measured as missing energy

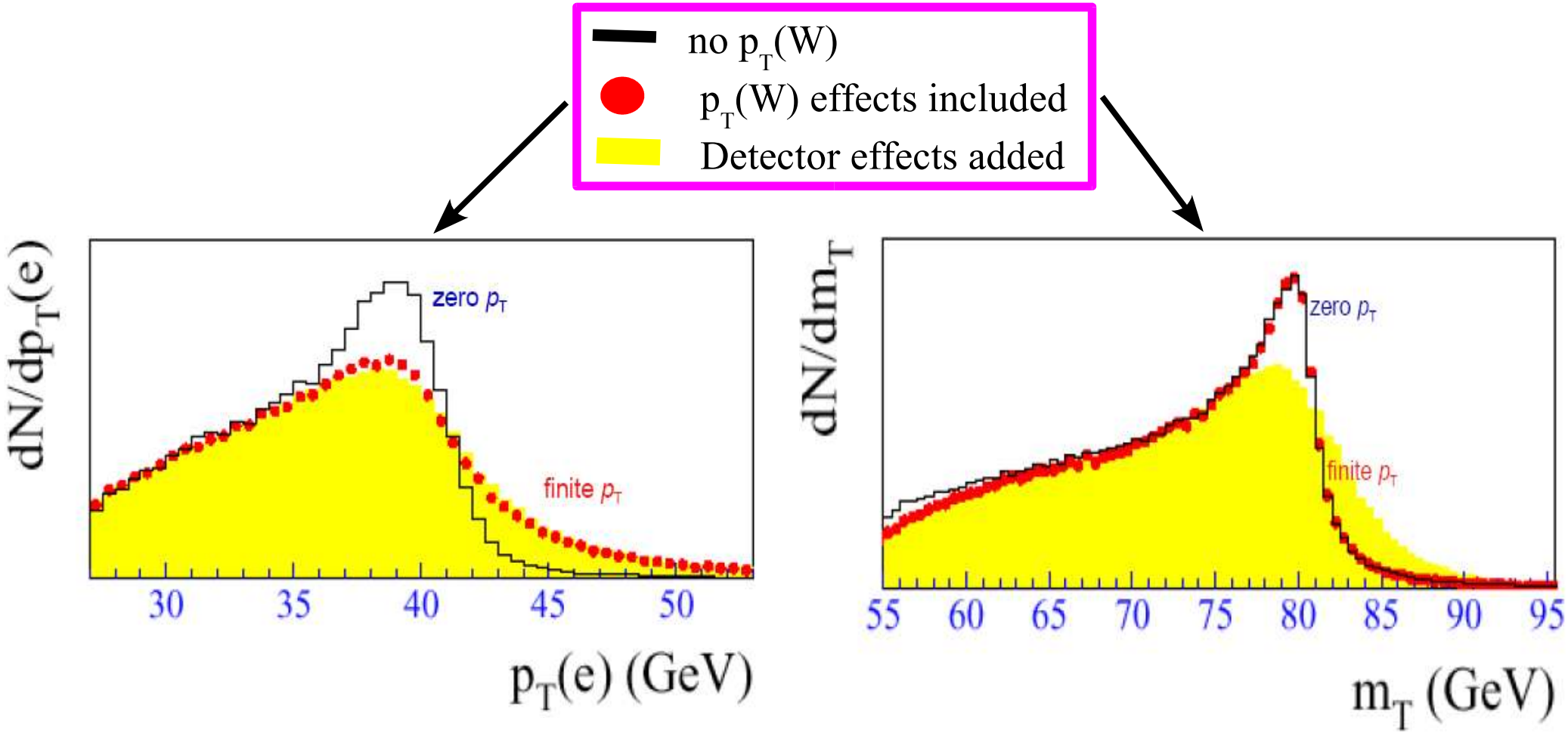


- W mass is measured by 'three' physical observables :
  - transverse momentum of electron ($\mathbf{p_T^e}$)
  - transverse momentum of neutrino ($\mathbf{E_T^\nu}$)
    - also known as missing energy ($\not{E}_T$)
  - transverse mass of W ($\mathbf{m_T}$)

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

$$m_T^2 = (|E_T^e| + |E_T^\nu|)^2 - (\vec{p}_T^{\,e} + \vec{p}_T^{\,\nu})^2$$
$$= 2E_T^e E_T^\nu (1 - \cos\varphi_{e\nu})$$

Electron p_T and Transverse mass



- 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)

Strategy for the measurement

- **Develop** a fast parameterized MC simulation (PMCS)
  - models detector effects very meticulously
  - parameters tuned to collider $Z \rightarrow ee$ data

↓

- **Generate** templates at different input M_W values using this PMCS

↓

- **Measure** the three distributions ($\mathbf{m_T}$, $\mathbf{p_T^e}$, $\not{\mathbf{E}}_\mathbf{T}$) from data

↓

- **Determine** best value of M_W
  - comparing data distributions and MC templates
  - use likelihood or χ^2 method in the fitting program

↓

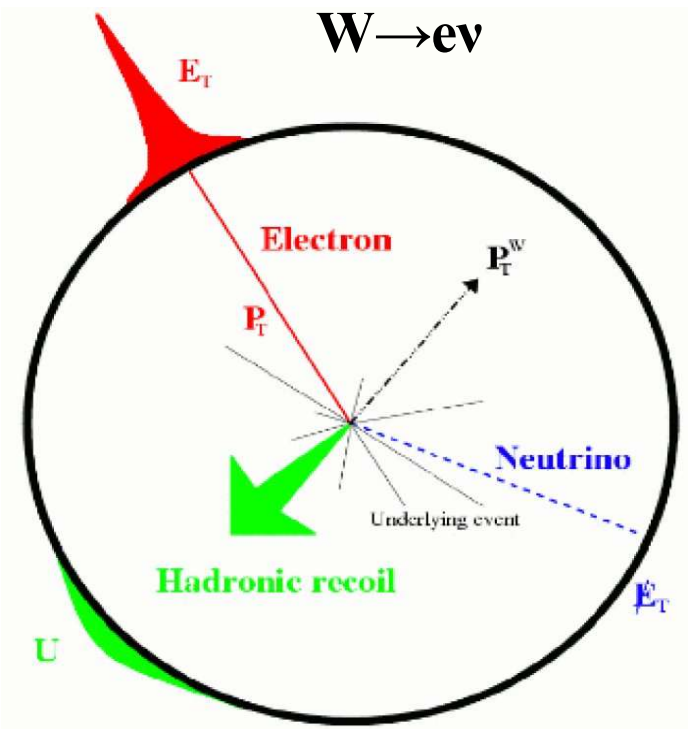
- **Perform** a Geant MC analysis to ensure analysis tools work correctly and effectively

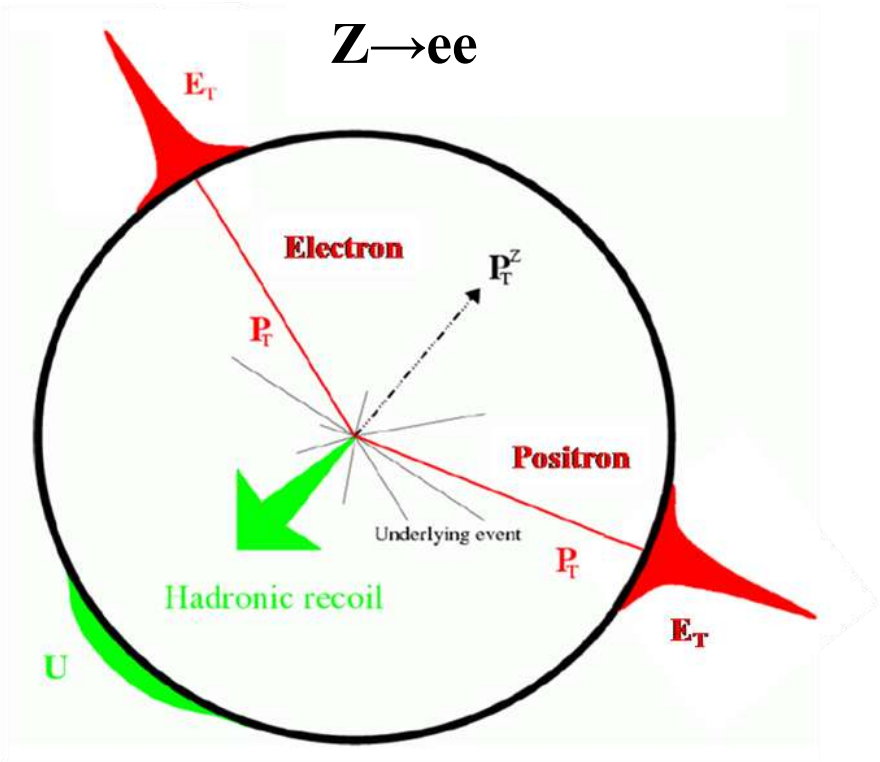
↓

- **Onto** a blinded data analysis !

Use of Z→ee as a standard candle for W

- Z→ee events provide for an excellent control sample for the W→eν events





- Topologically similar signatures, masses pretty close

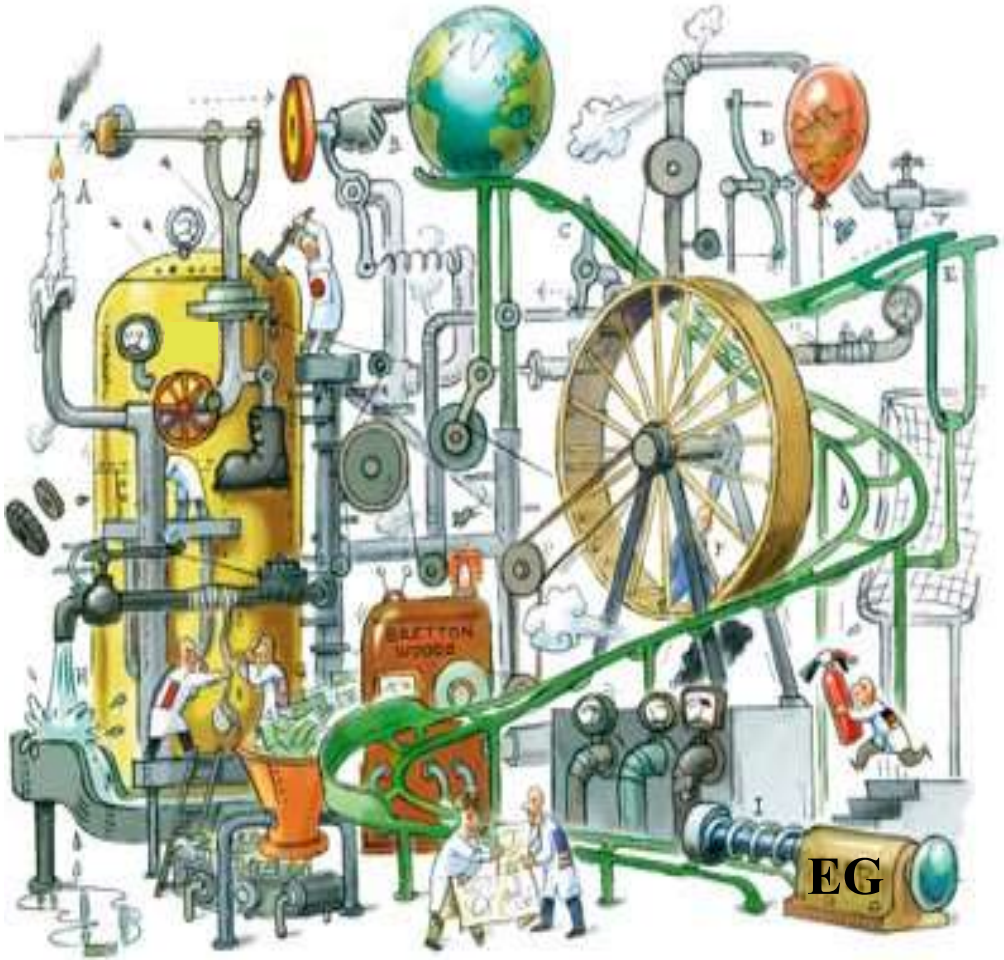
$$m_T^2 = (|E_T^e| + |E_T^\nu|)^2 - (\vec{p}_T^{\,e} + \vec{p}_T^{\,\nu})^2 \qquad m_Z^2 = (|E_1| + |E_2|)^2 - (\vec{p}_1 + \vec{p}_2)^2$$

- Z→ ee events are used for obtaining many detector-modeling parameters for PMCS
  - used for studying electron and recoil response

A few words on PMCS

PMCS for M_W analysis

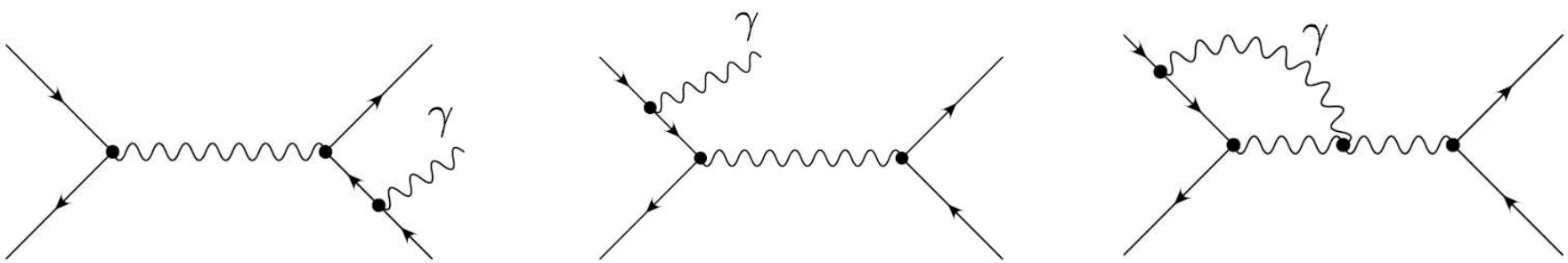
- Correct modeling of calorimeter response and resolution for electron and recoil is crucial for analysis
  - For an uncertainty of $\Delta M_W = 0.05\%$
    - Precision on EM response ~ **0.05%**
    - Precision on HAD recoil ~ **1%**
- PMCS uses NLO event generators
  - **ResBos + Photos**
  - Detector effects incorporated in the form of parameters
- $Z \rightarrow e^+e^-$ events used for calibrating electron and recoil systems
  - we effectively measure M_W/M_Z



Lots of time and effort devoted to developing this complex machinery that emulates the detector well now !

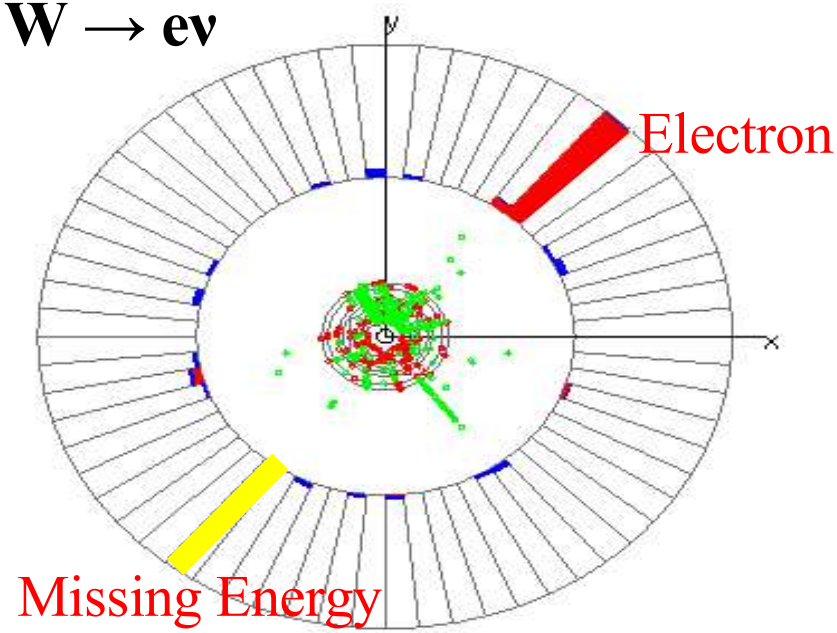
MC event generators used for analysis

- 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)]

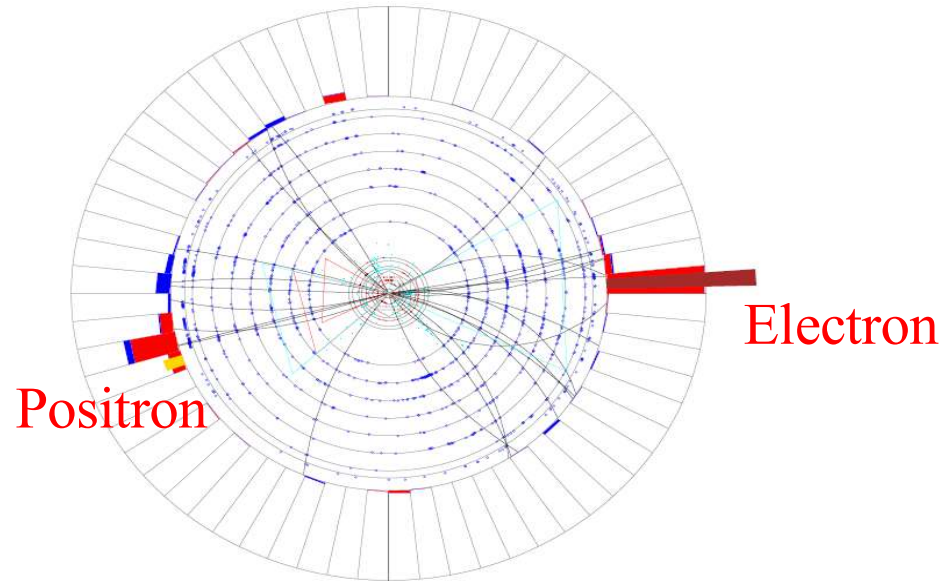


Event Selections for data

$W \rightarrow e\nu$



$Z \rightarrow e^+e^-$



Common requirements for electrons

- In fiducial region of central calorimeter ($|\eta_{det}| < 1.05$), pT(electron) > 25 GeV
- Isolation of electron < 0.15, EMFrac > 0.9
- Shower shape requisites, cluster matched to track, require SMT hits
- pT(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($Z \rightarrow ee$) < 110 GeV

Optimization for the analysis

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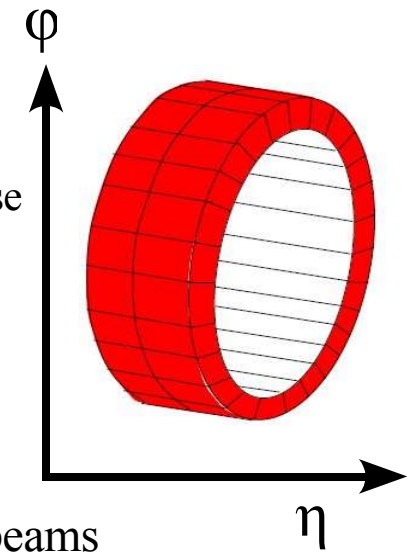
Why do we need to calibrate the calorimeter ?

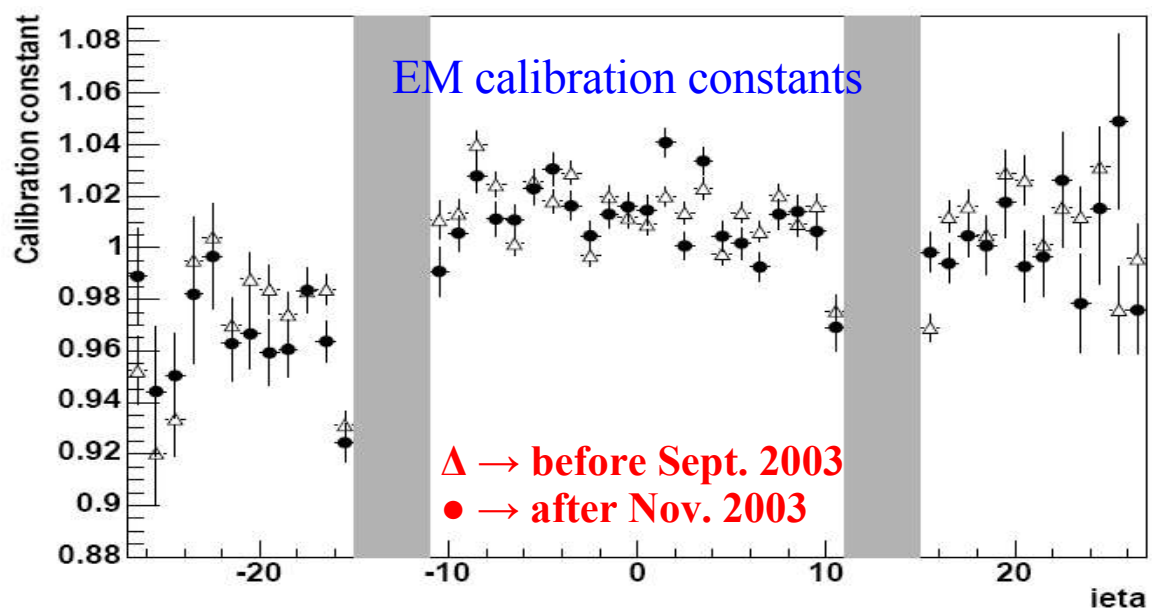
- We're doing a precise measurement –
  - We're aiming for a precision of 0.0005 on the W mass
    - This is essentially a calorimeter-based measurement
- So we need a well-understood calorimeter !
  - What does calorimeter response to the electrons look like ?
  - Is electron energy response linear ?
  - Significant energy loss before reaching the calorimeter ?
  - Smearing effect of calorimeter on electron energy ?

- In DØ's RunII we have ~ $4X_0$ of material in front of the DØ calorimeter
  - causes particles to loose a considerable fraction of their energy (15%) before they reach the detection regions.
  - A detailed understanding of the amount of dead material is crucial for getting a handle on the response and resolution of the calorimeter to the incident particles.
- ~**$0.163X_0$** of extra material was discovered during the course of M_W analysis !

Calibrating the calorimeter

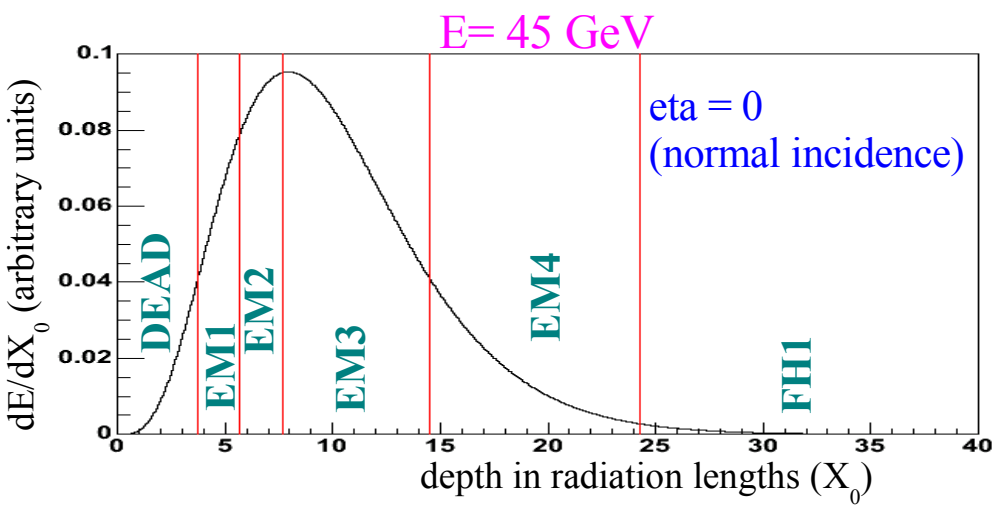


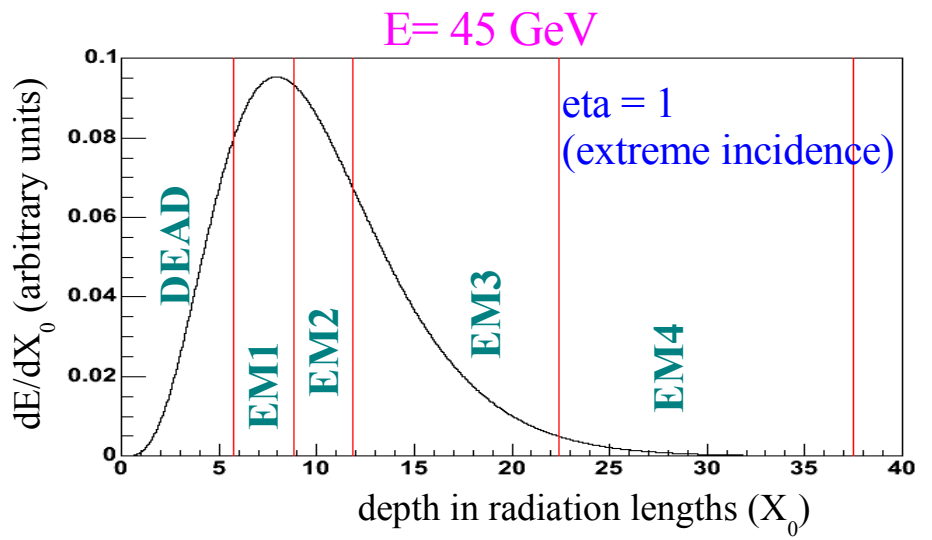
- **Electronics calibration using pulsers –**
  - Inject pulses, probe full dynamic range of readout channels, correct differences in response
- **φ-intercalibration for both EM and HAD calorimeters –**
  - Unpolarized beams at Tevatron
  - Energy flow in transverse plane should not have azimuthal dependence due to beams
  - Calibrated using inclusive EM and jet collider data
- **η-intercalibration for both EM and HAD calorimeters –**
  - EM CAL: Using Z ⟶ ee events
  - HAD CAL: Back-to-back di-jet events



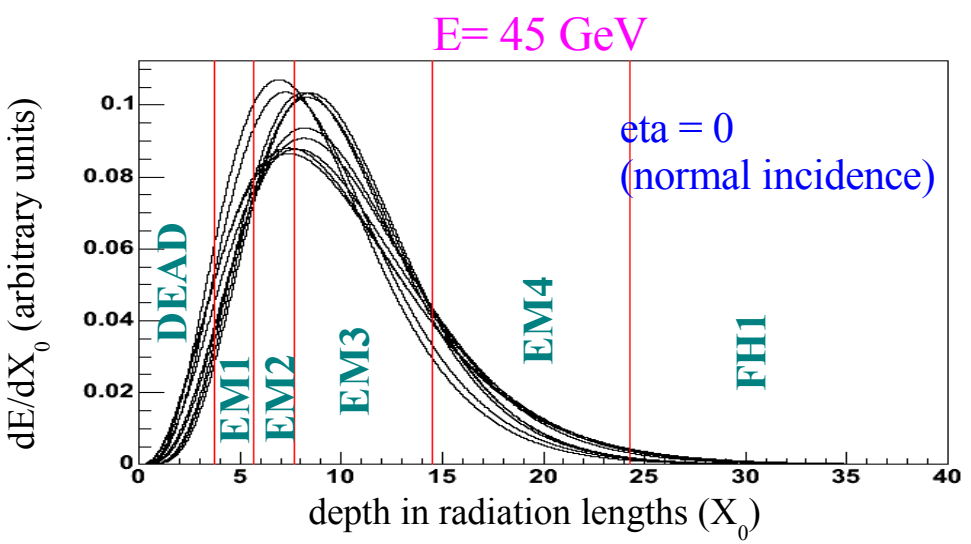
Energy response linearity and fluctuations

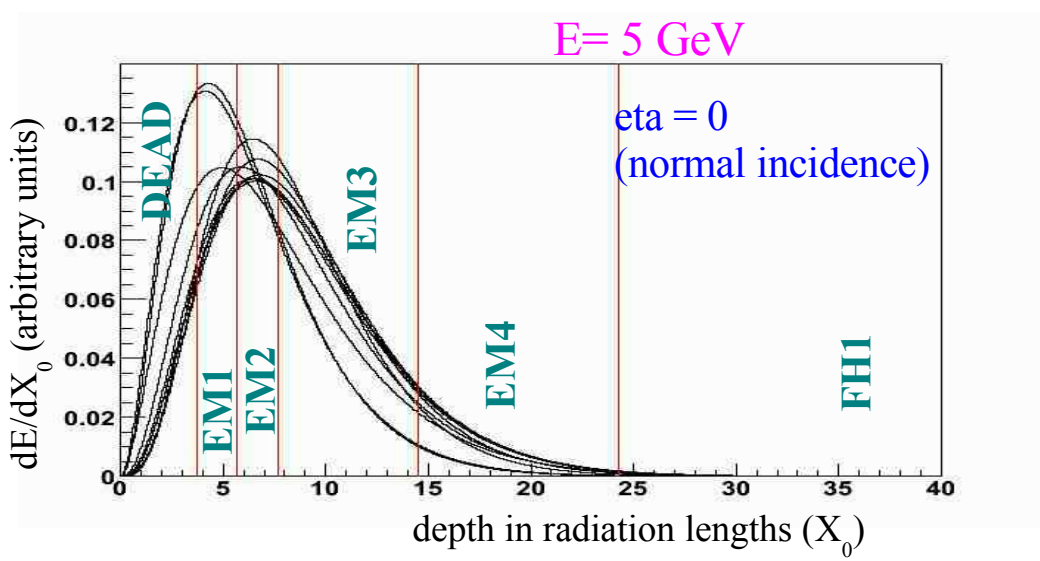
- Let's study longitudinal profiles showing shower development





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



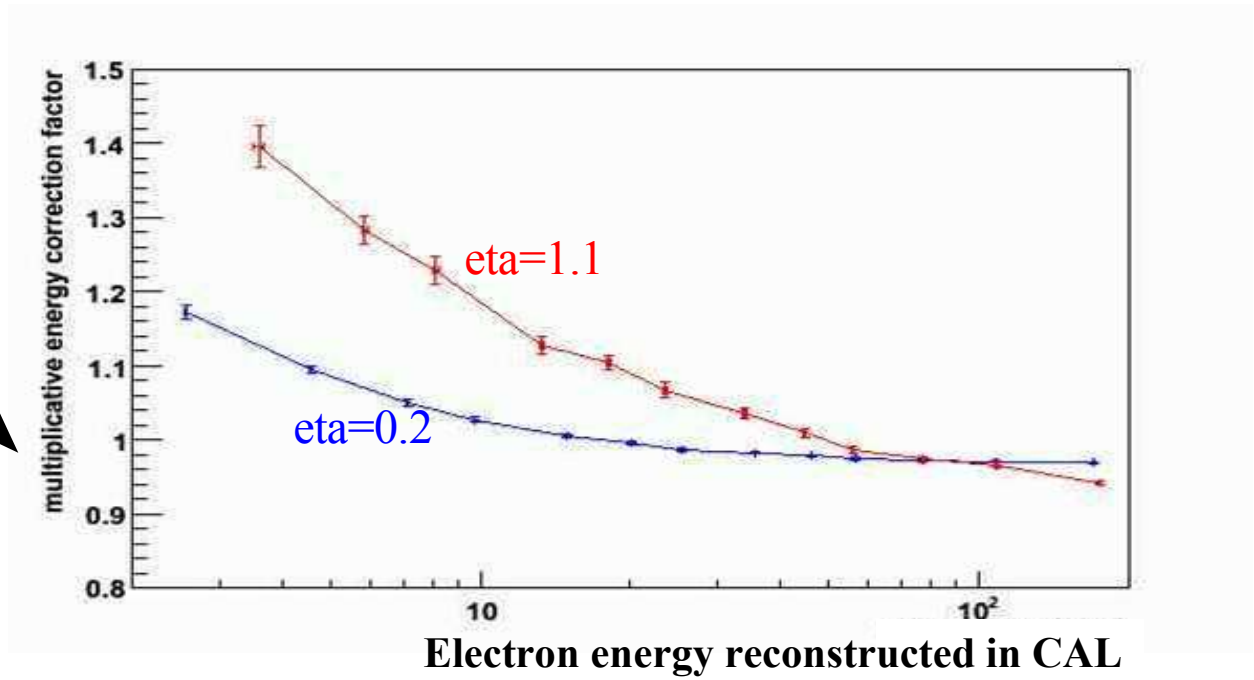


- Fraction of energy lost in dead material varies from shower to shower – depends on E !

Energy Loss corrections

- We need to apply energy loss corrections to our reconstructed electron energies (EMReco) to account for the energy lost before reaching the calorimeter
  - Reconstructed energy + Correction = Incident energy
- Energy loss corrections determined as a function of **energy** and **angle** (eta)
  - Estimated from detailed Geant-based detector simulations

Corrects back to incident energy of electron



Parameterized MC Simulation – I

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Electron Simulation – energy scale

- **Electron energy response :**
  - using Z→ee events from data, known Z mass value from LEP

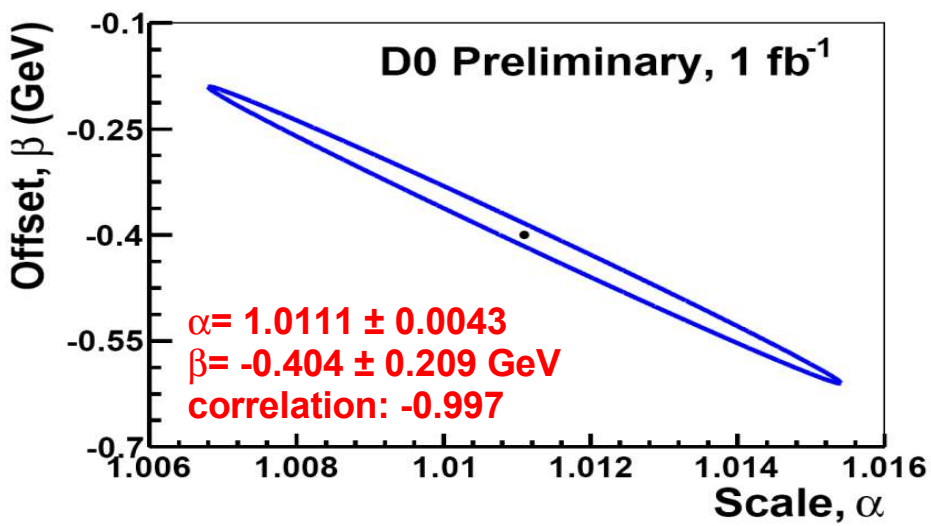
$$E_{measured} = \alpha \cdot E_{true} + \beta$$

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

$$M_Z(measured) = \alpha \cdot M_Z(true) + f_Z \cdot \beta$$

  - where f_Z is calculable from kinematics

- M_Z(measured) vs. f_Z templates were generated for a range of α and β values → extract α and β



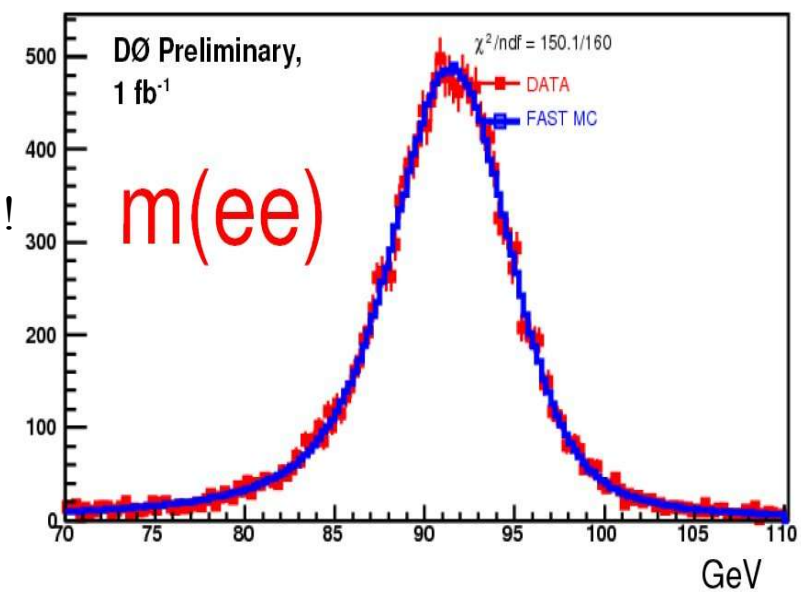
Dominant systematic

Electron Simulation – energy resolution

- **Electron energy resolution :**

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

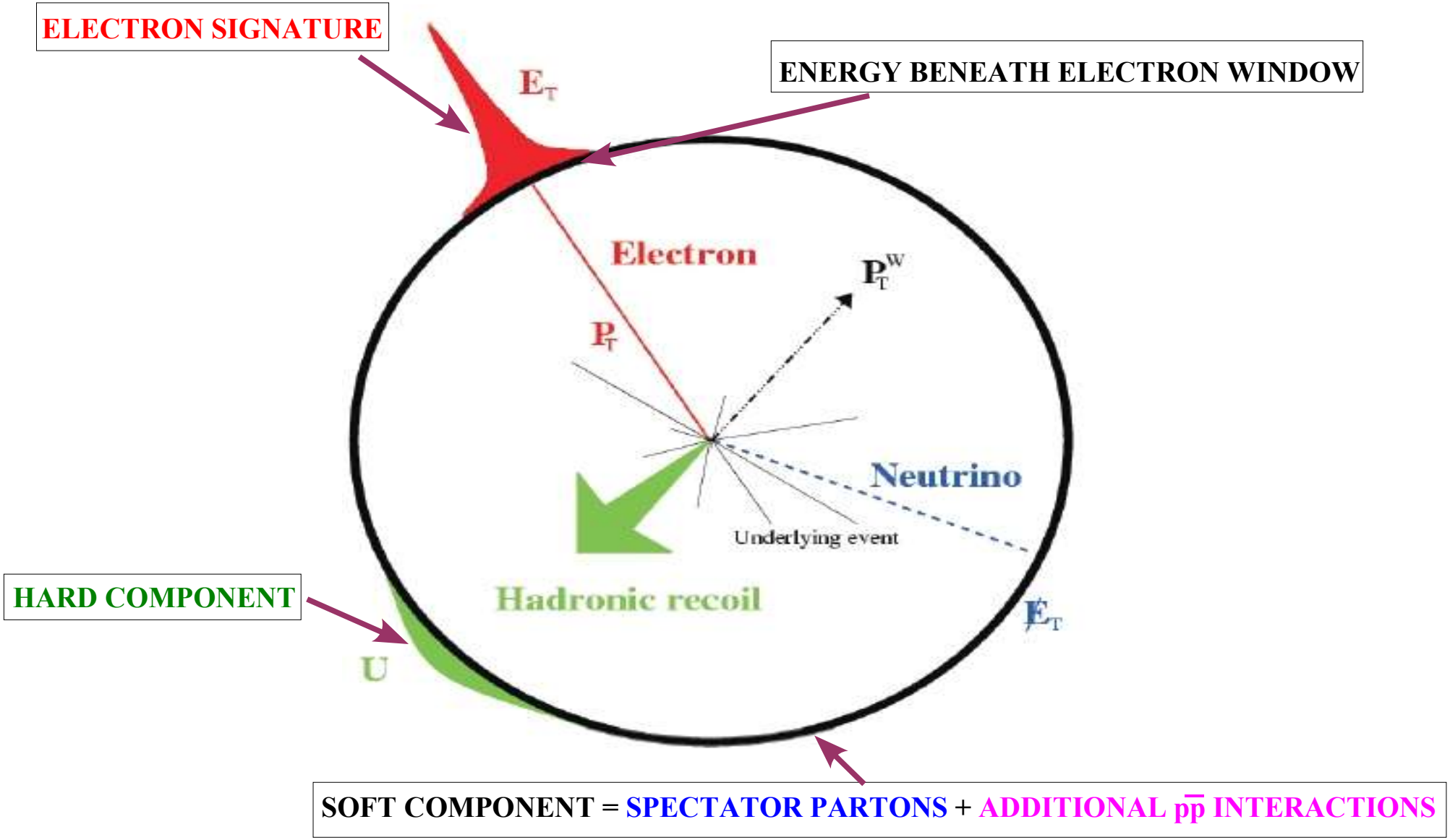
- Resolution driven by **Constant** and **Sampling** terms
- **Sampling** fluctuations arise from differences in the sampling fractions between calorimeter modules and from uninstrumented material
- **Constant** term accounts for all non-energy dependent sources of smearing
  - Extracted from fit to observed width of Z→ee peak
  - C_{EM} = (2.05 ± 0.10)%
    - In agreement with expected RunIIa design goal (2%) !



Parameterized MC Simulation – II

- Introduction
- Tevatron and the DØ Experiment
- Measurement Strategy
- Calibrating the calorimeter
- **Parameterized MC Simulation of detector**
  - Electron Modeling
  - **Recoil Modeling**
- Results
- Outlook

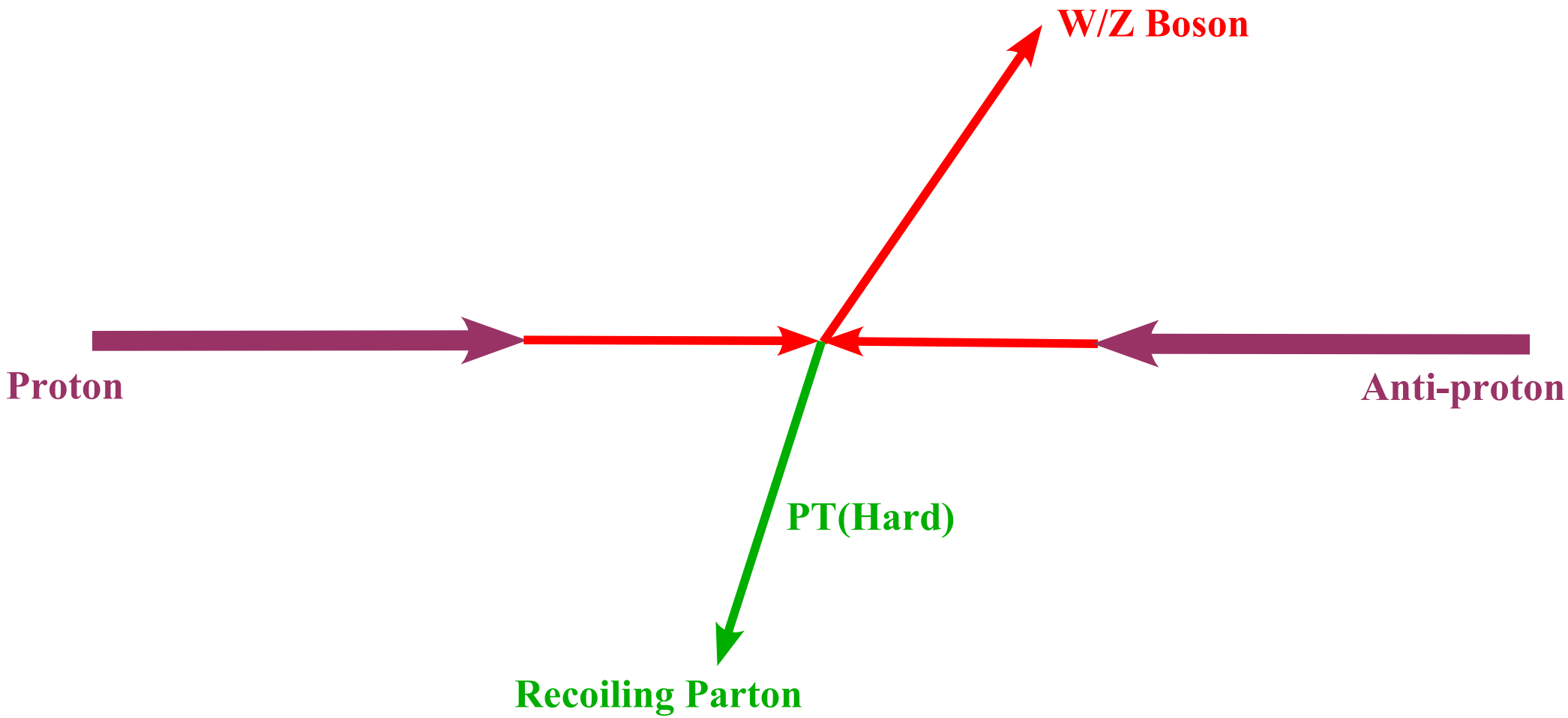
Putting the W recoil together .....



$$\text{Modeled recoil : } u_T = u_T^{HARD} + u_T^{SOFT} + u_T^{ELEC} + u_T^{FSR}$$

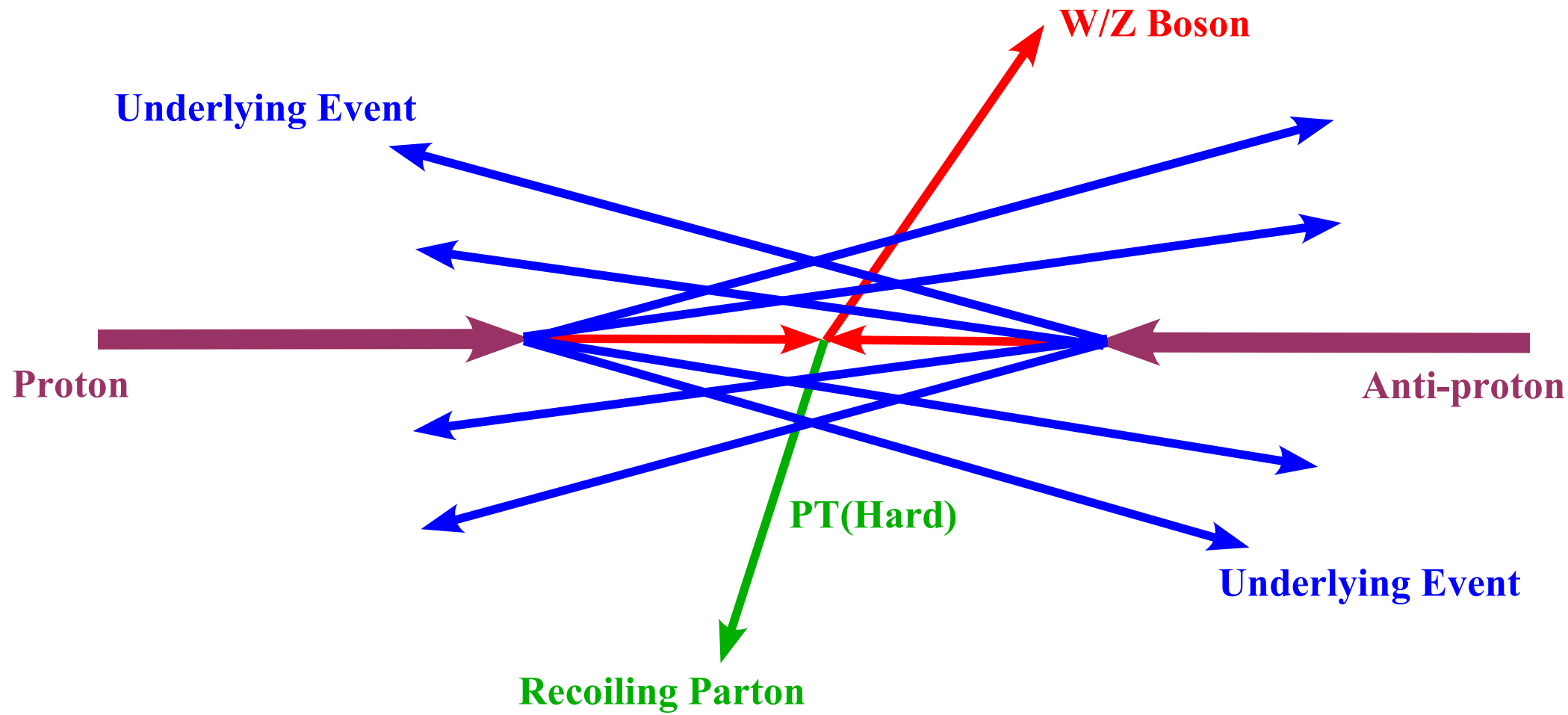
Components of Hadronic Recoil – Hard Component

Hard recoil modeled from GEANT MC Z→νν events



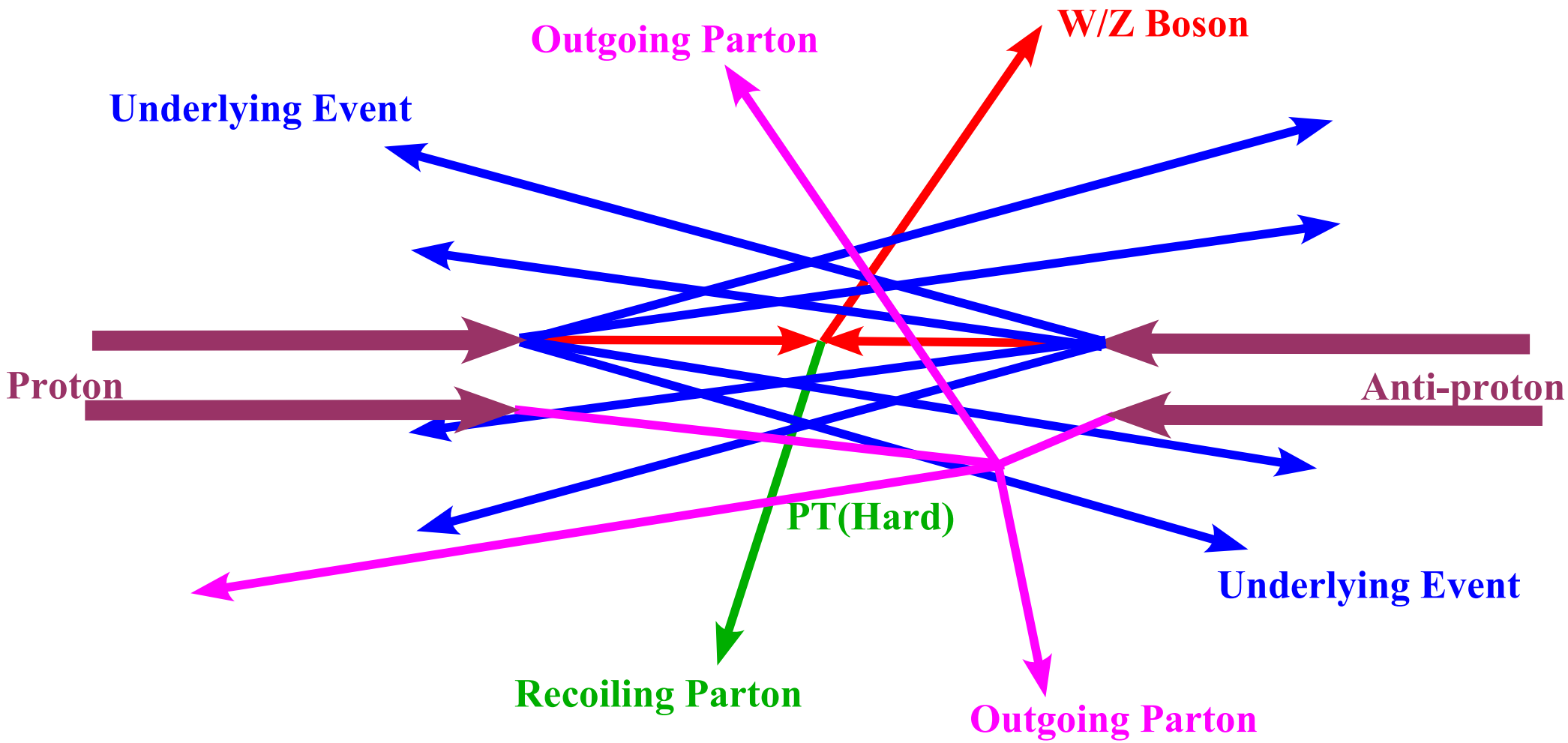
Components of Hadronic Recoil – Underlying Event

Spectator partons contribution modeled from data Minimum Bias events



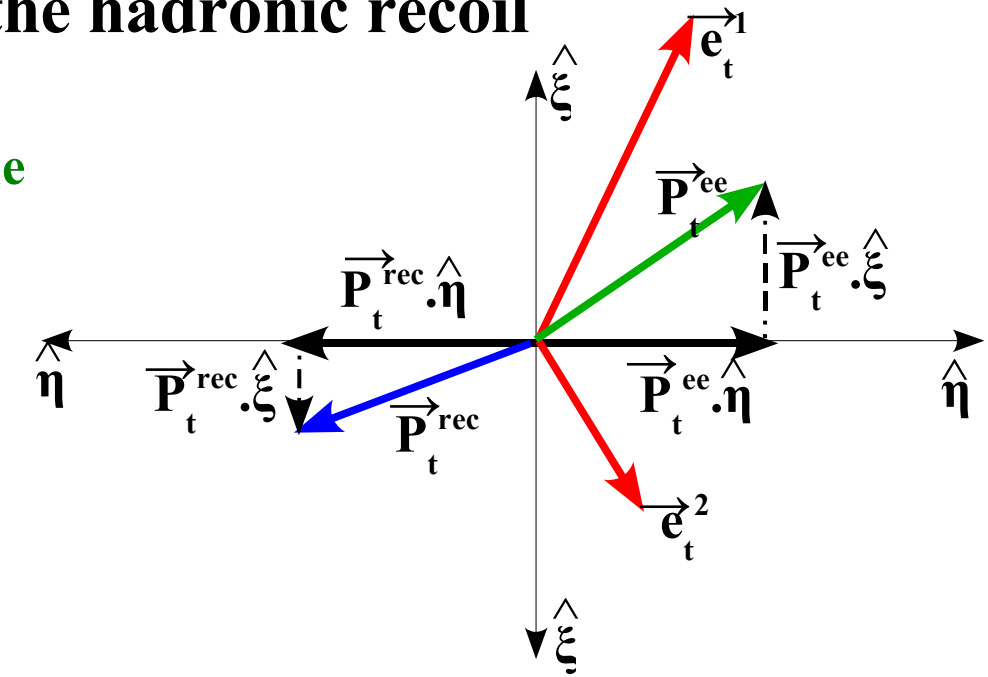
Components of Hadronic Recoil – Additional interactions

Additional $p\bar{p}$ interactions modeled from data Zero Bias events



Final adjustments for the hadronic recoil

- **Fine tune - to match the modeled recoil to the one from collider data**
  - Using $\mathbf{Z \rightarrow e^+e^-}$ events as a control sample
  - Define $\hat{\eta}$ and $\hat{\xi}$ axes (first used by UA2 collaboration)
  - **Use momentum imbalance** between electron and recoil as diagnostic observables for tuning
    - **η-imbalance :** $(\vec{P}_t^{ee} + \vec{P}_t^{rec}) \cdot \hat{\eta}$
    - **ξ-imbalance :** $(\vec{P}_t^{ee} + \vec{P}_t^{rec}) \cdot \hat{\xi}$



$\hat{\eta} \rightarrow$ inner bisector of angle between $\vec{e}_t^{\,1}$ and $\vec{e}_t^{\,2}$

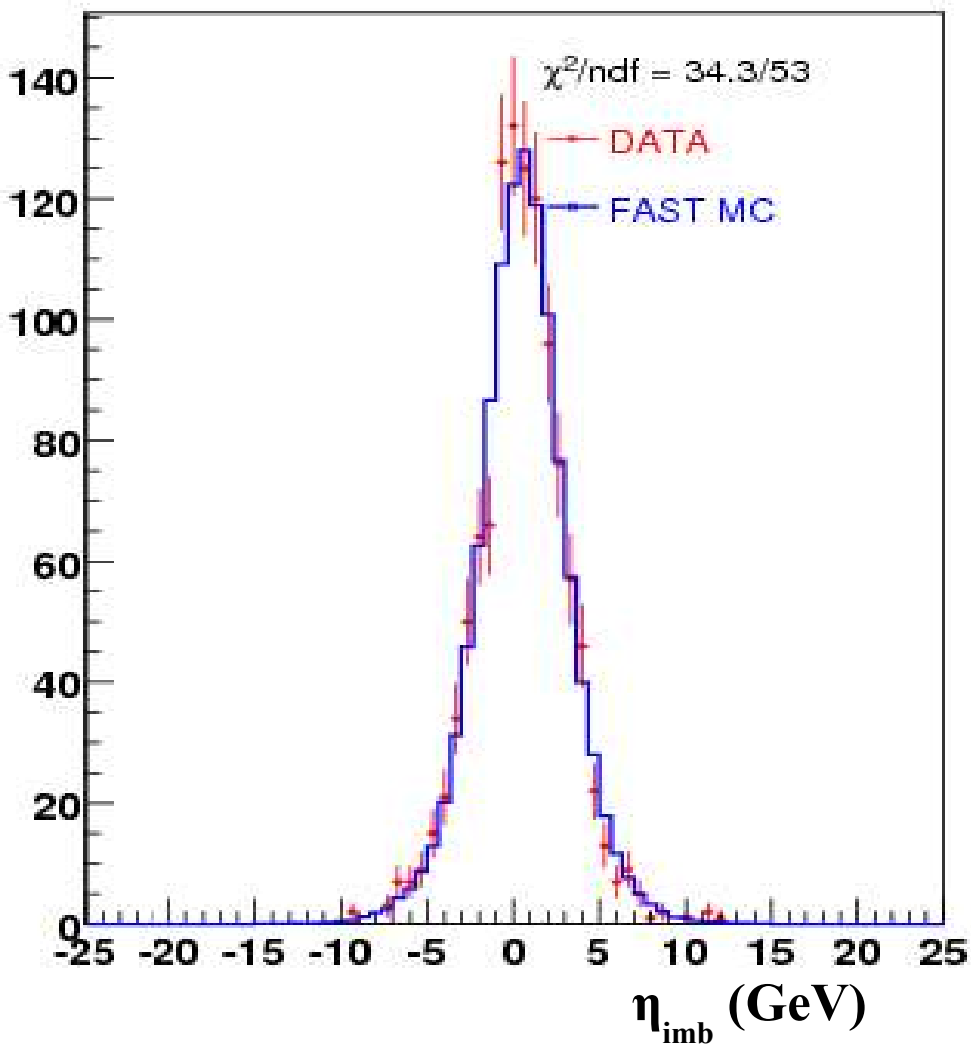
$\hat{\xi} \rightarrow$ perpendicular to $\hat{\eta}$ axis

- 6 floating parameters were used for the final adjustment of modeled recoil

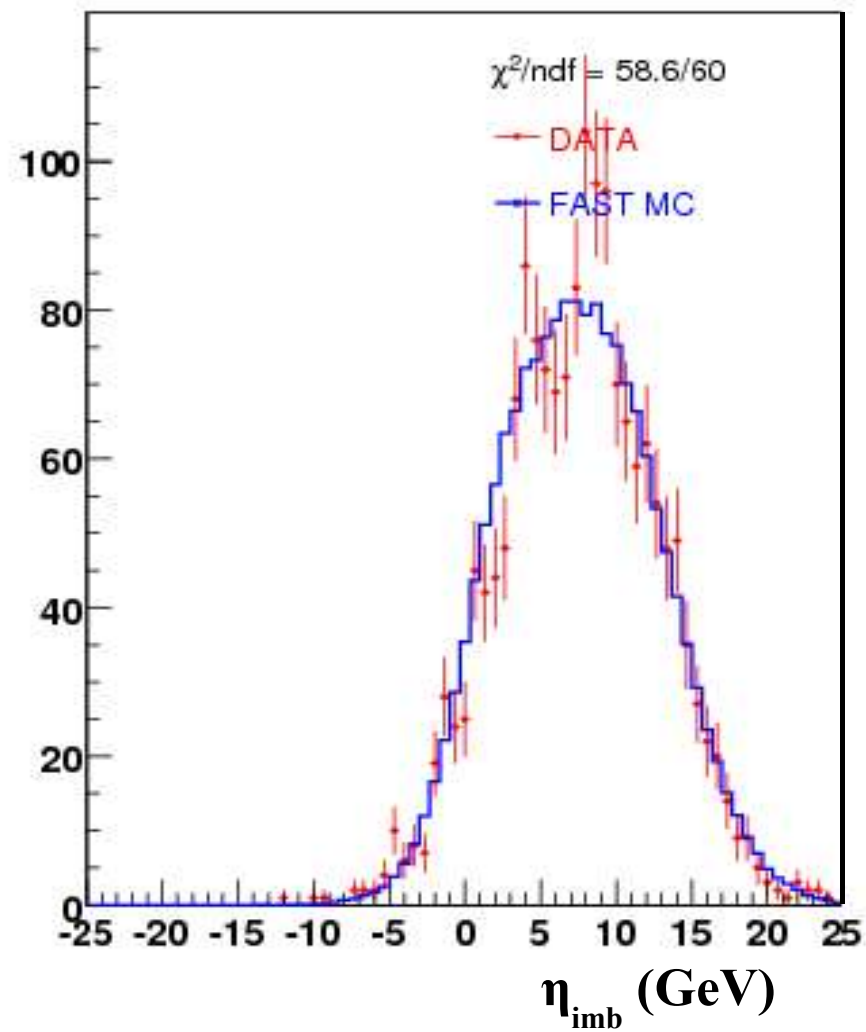
Diagnostic $\eta_{imbalance}$ Z plots after recoil tuning

- **MEAN** of η-imbalance sensitive to **recoil response**
- **RMS** of η-imbalance sensitive to **recoil resolution**

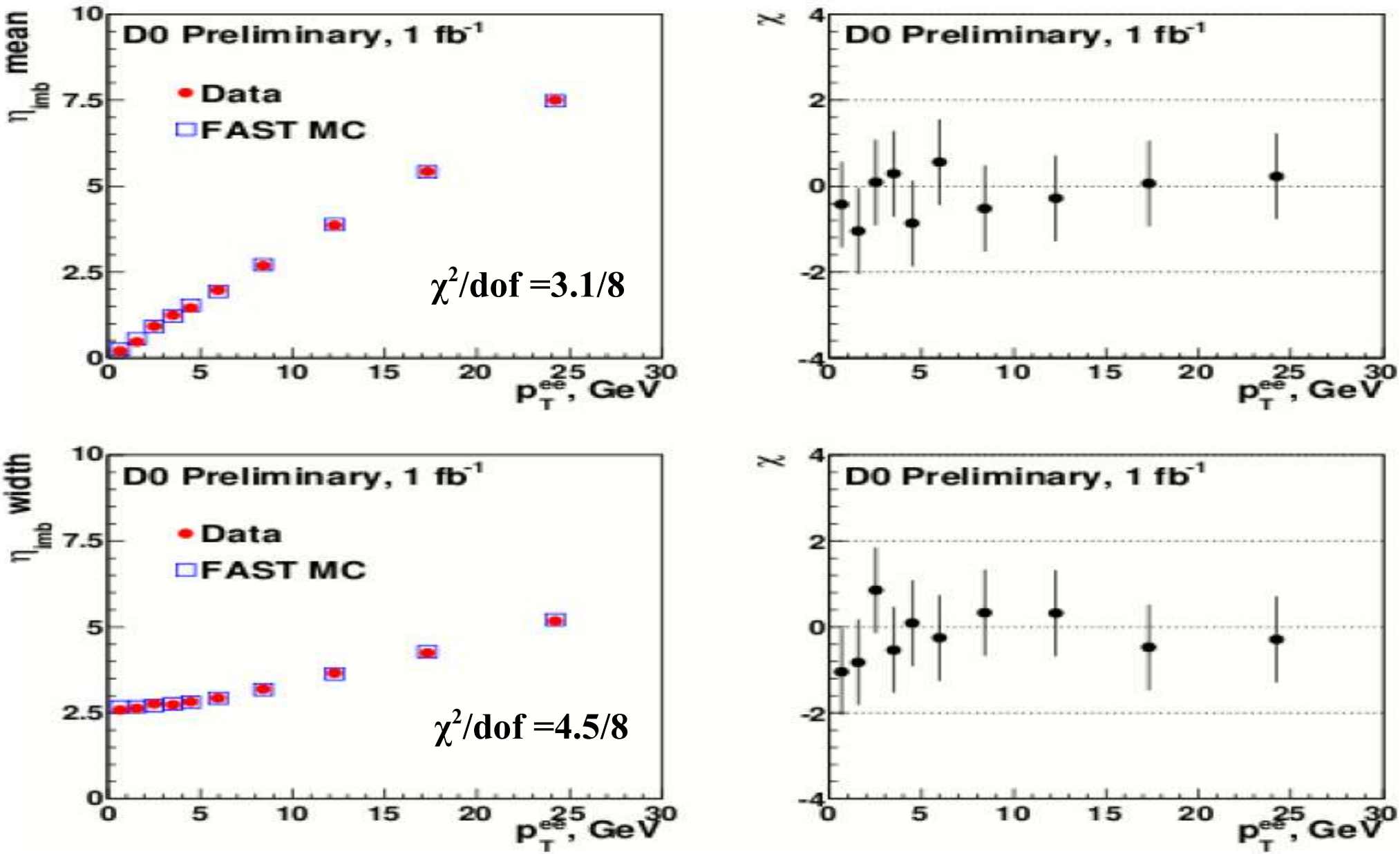
$1 < p_T^{ee} < 2$ GeV



$p_T^{ee} > 20$ GeV



MEAN and RMS of $\eta_{imbalance}$ Z plots after recoil tuning



- Indication - good agreement between modeled recoil and Z recoil from data

Results from the analysis

- Introduction
- Tevatron and the DØ Experiment
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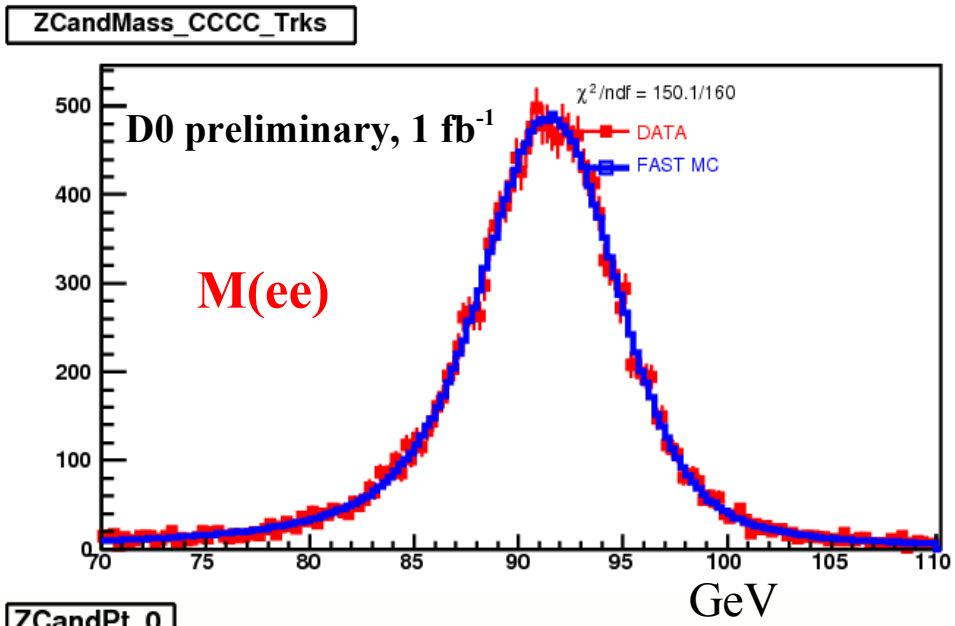
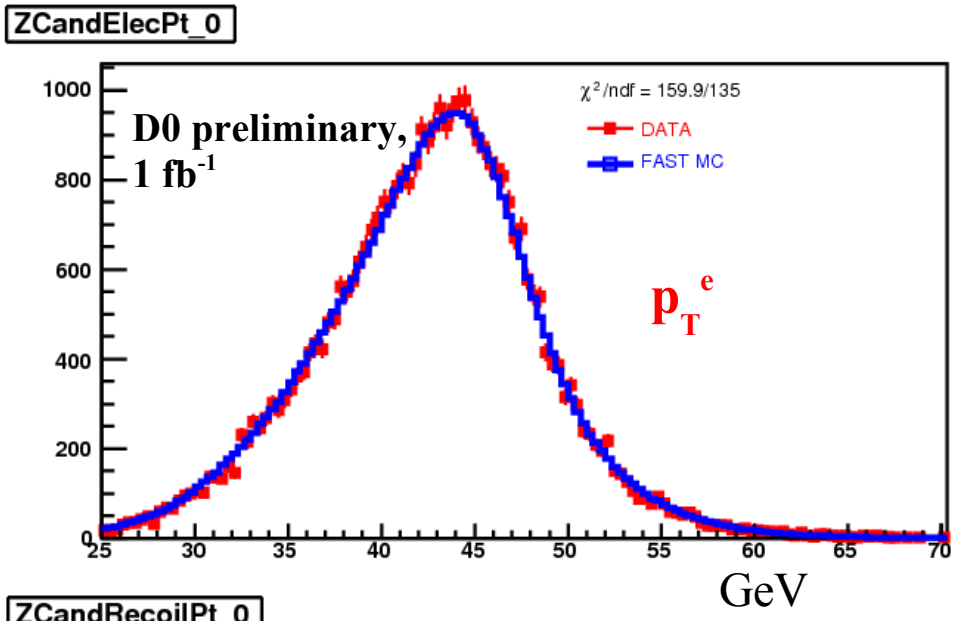
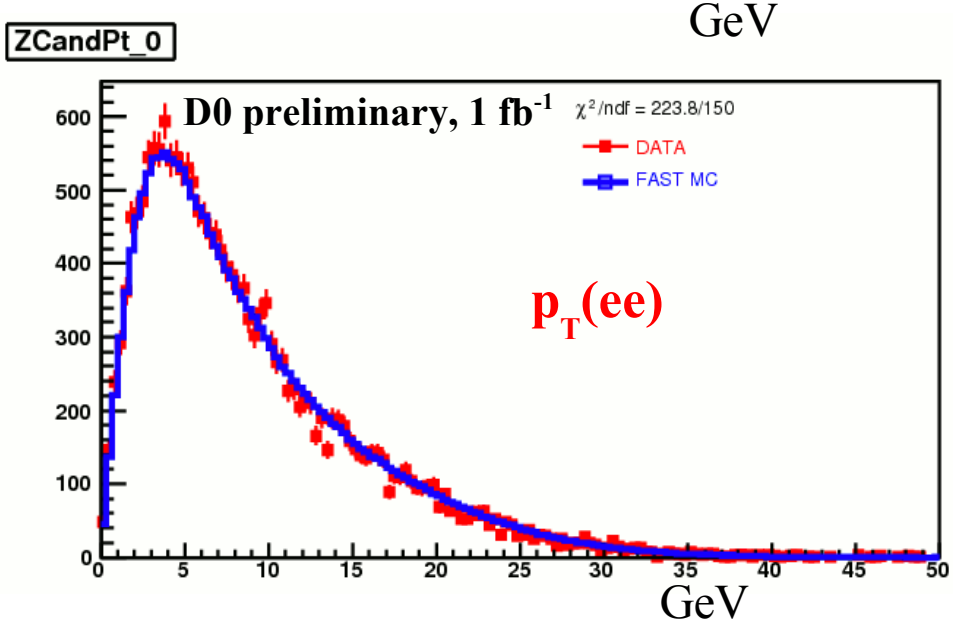
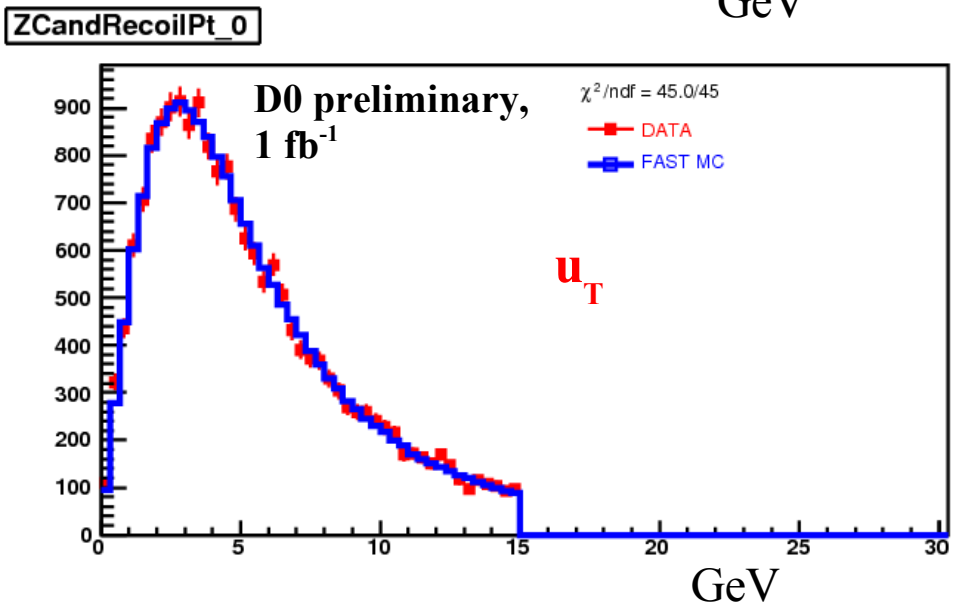
  - Recoil Modeling
- **Results**
- Outlook

Diagnostic plots from Z→ ee data/MC comparisons









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

Blind Analysis

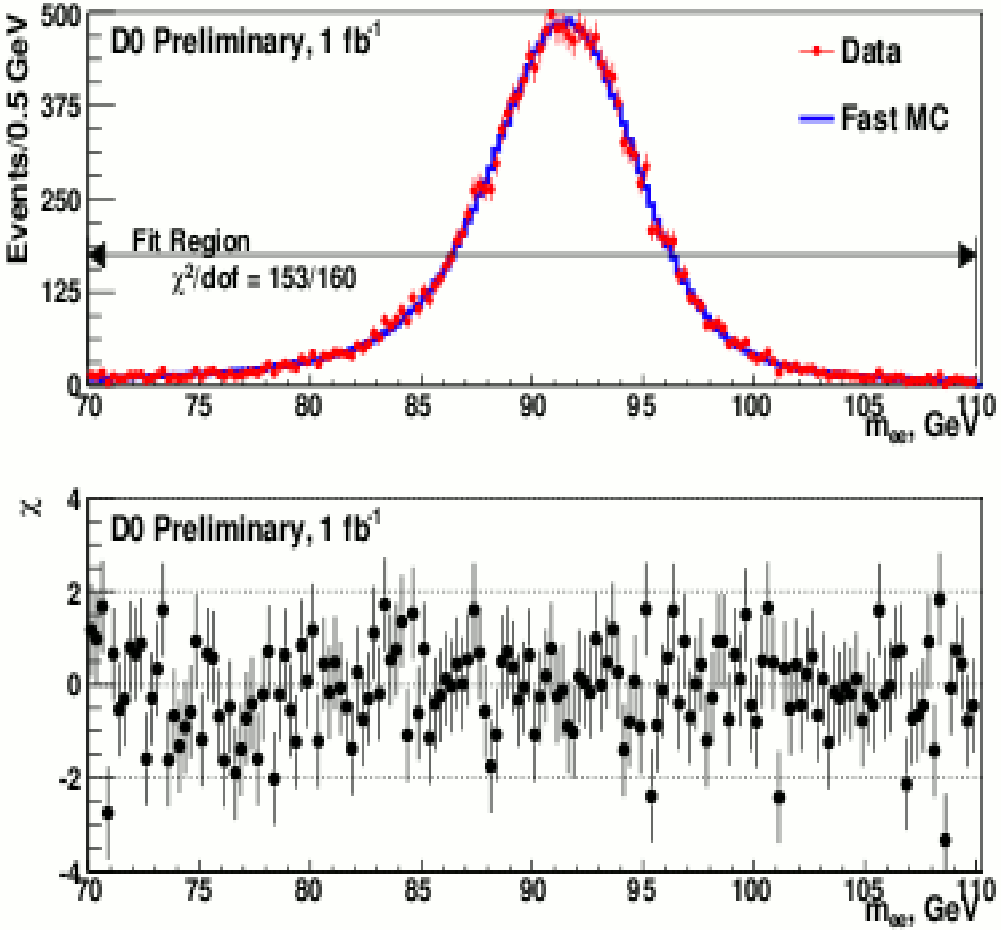
- The measurement was performed as a blind analysis
  - a standard technique to avoid bias towards a previous value or statistical pattern
  - central values were deliberately hidden from analyzers and reviewers until approval
  - no uncertainties (stat or syst) were ever obscured
  - used a hidden offset, it's same for all three observables in mass fitter

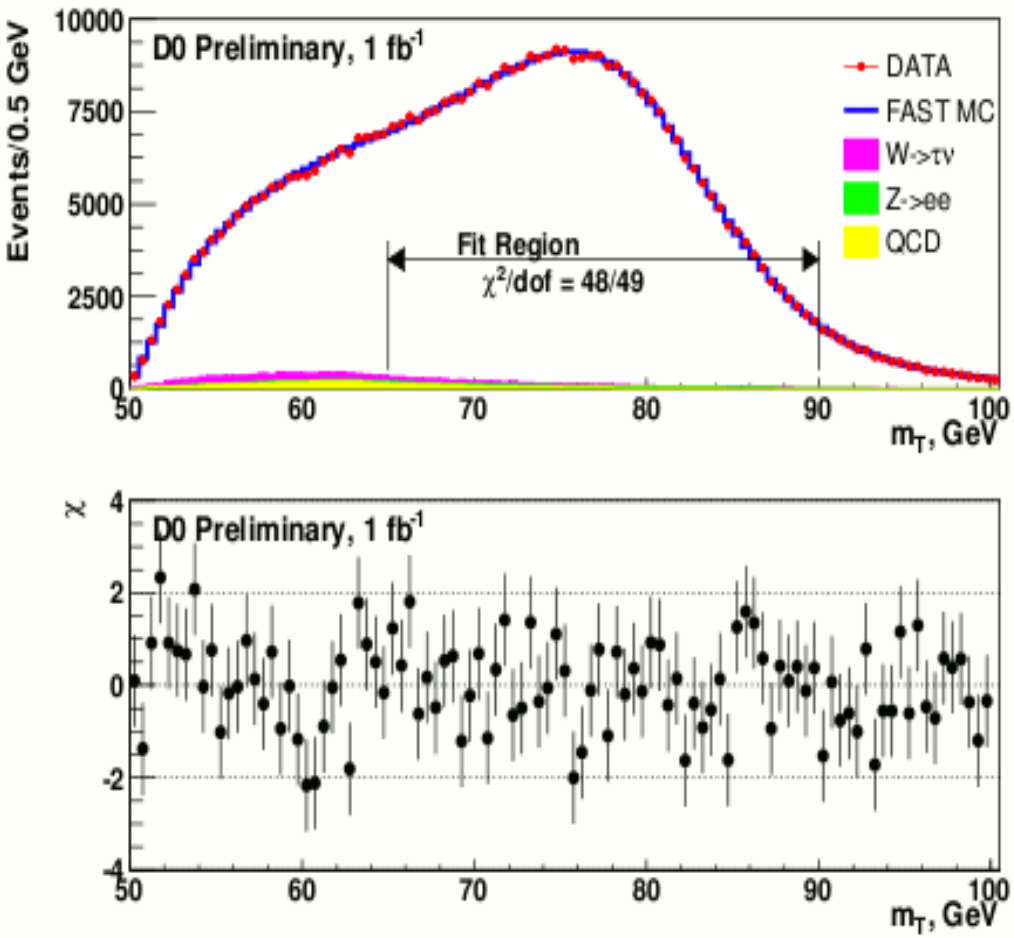
- "Unblinding" done only after collaboration approval

- Performed Monte-Carlo closure test first
  - develop & test analysis procedure & code
  - Pythia/Geant MC treated as data
  - at each step check conformity
  - perfect agreement

Doing a blind analysis does not mean doing the analysis blindly !

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



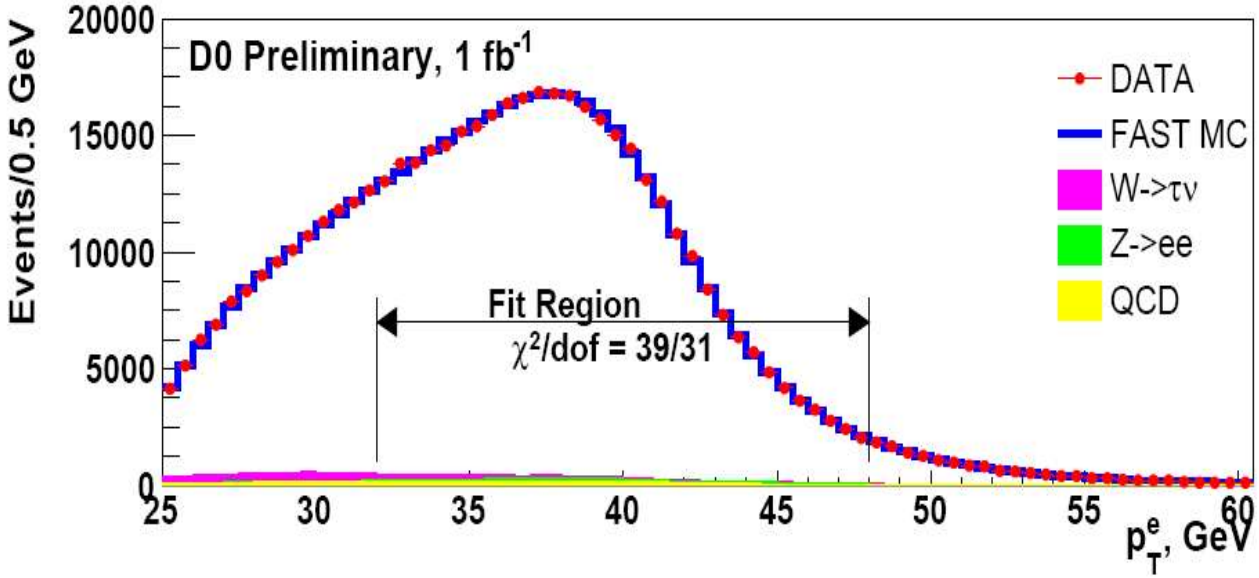


M_Z = 91.185 ± 0.033 GeV (stat)

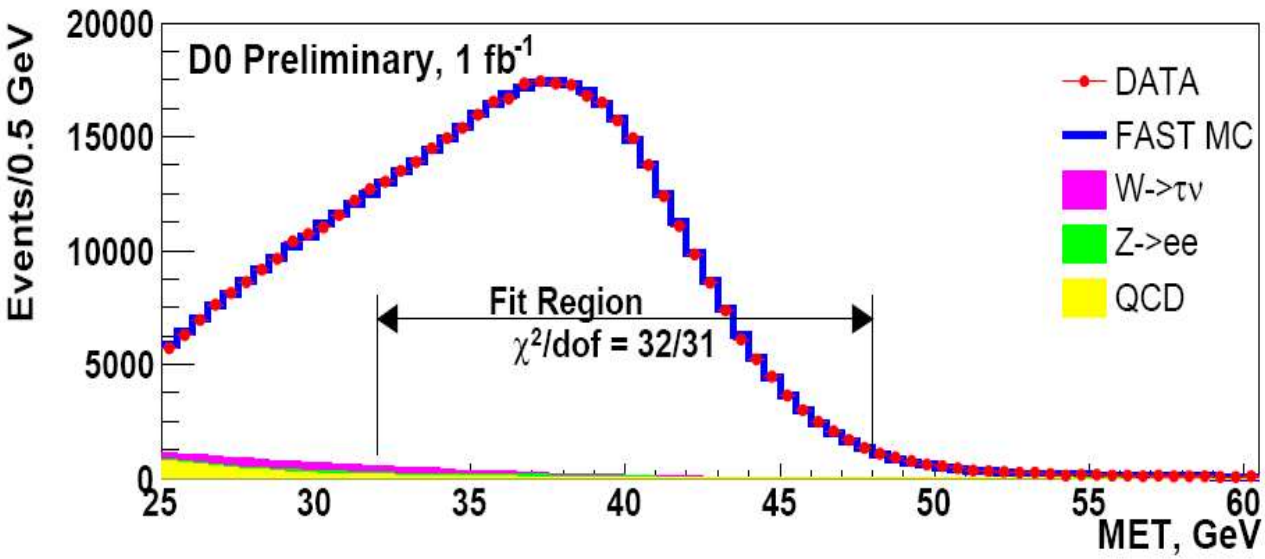
Z mass value (LEP) was an input to estimating the electron energy response and resolution
PDG MZ = 91.1876 ± 0.0021 GeV

M_W = 80.401 ± 0.023 GeV (stat)

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

- 

$M_W = 80.400 \pm 0.027$ GeV (stat)



$M_W = 80.402 \pm 0.023$ 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

- For a 1fb^{-1} collider data W→ eν sample :

For M_T : M_W = **80.401 ± 0.023(stat) ± 0.037(syst)** GeV

For p_T^e : M_W = **80.400 ± 0.027(stat) ± 0.040(syst)** GeV

For $\not{E}_T$: M_W = **80.402 ± 0.023(stat) ± 0.044(syst)** GeV

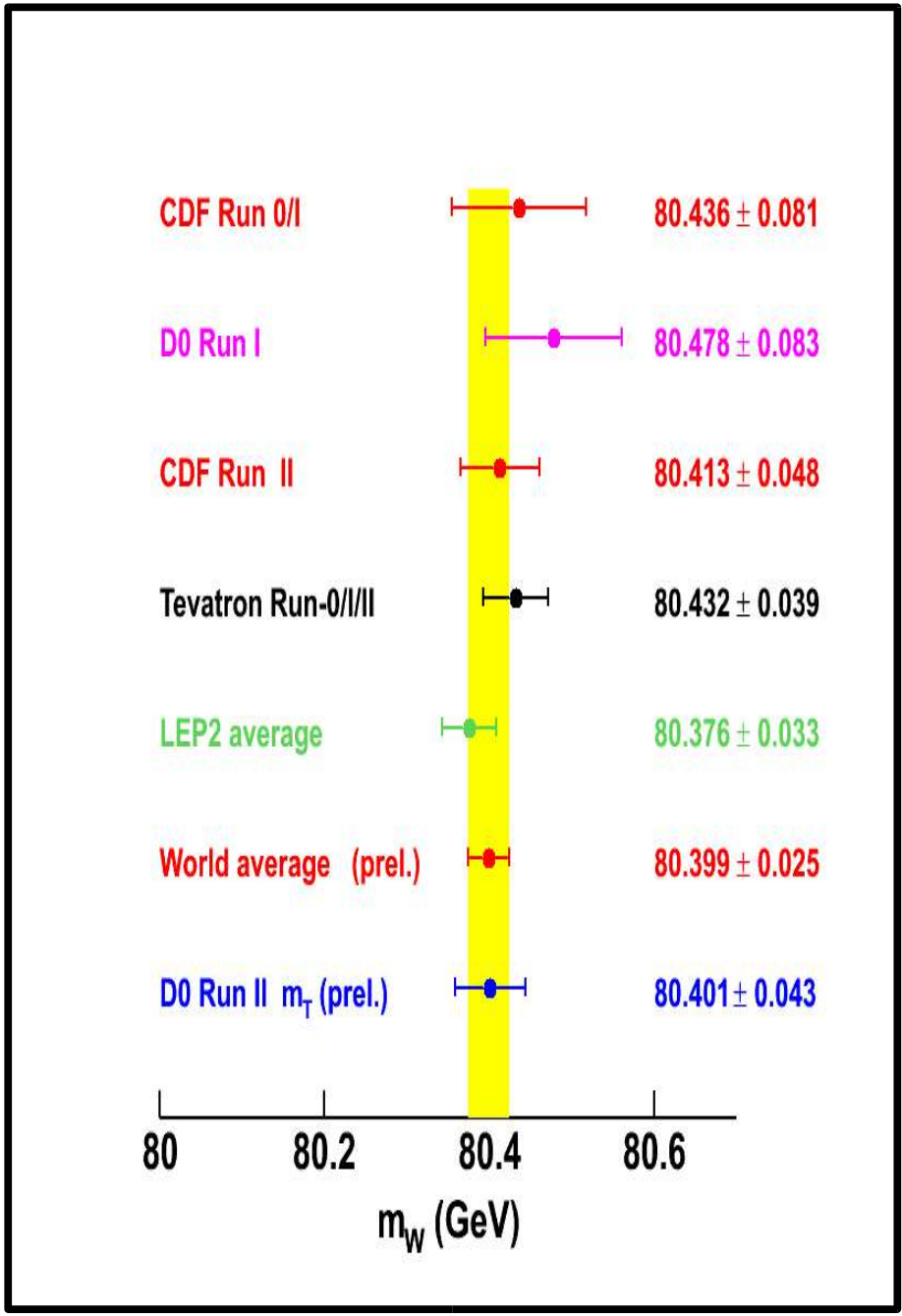
- In good agreement with previous measurements

Combined DØ measurement :

NEW

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 !



Towards the end ...

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- Tevatron and the DØ Experiment
- Measurement Strategy
- Optimizing the calorimeter
- Parameterized MC Simulation of detector
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  - Recoil Modeling
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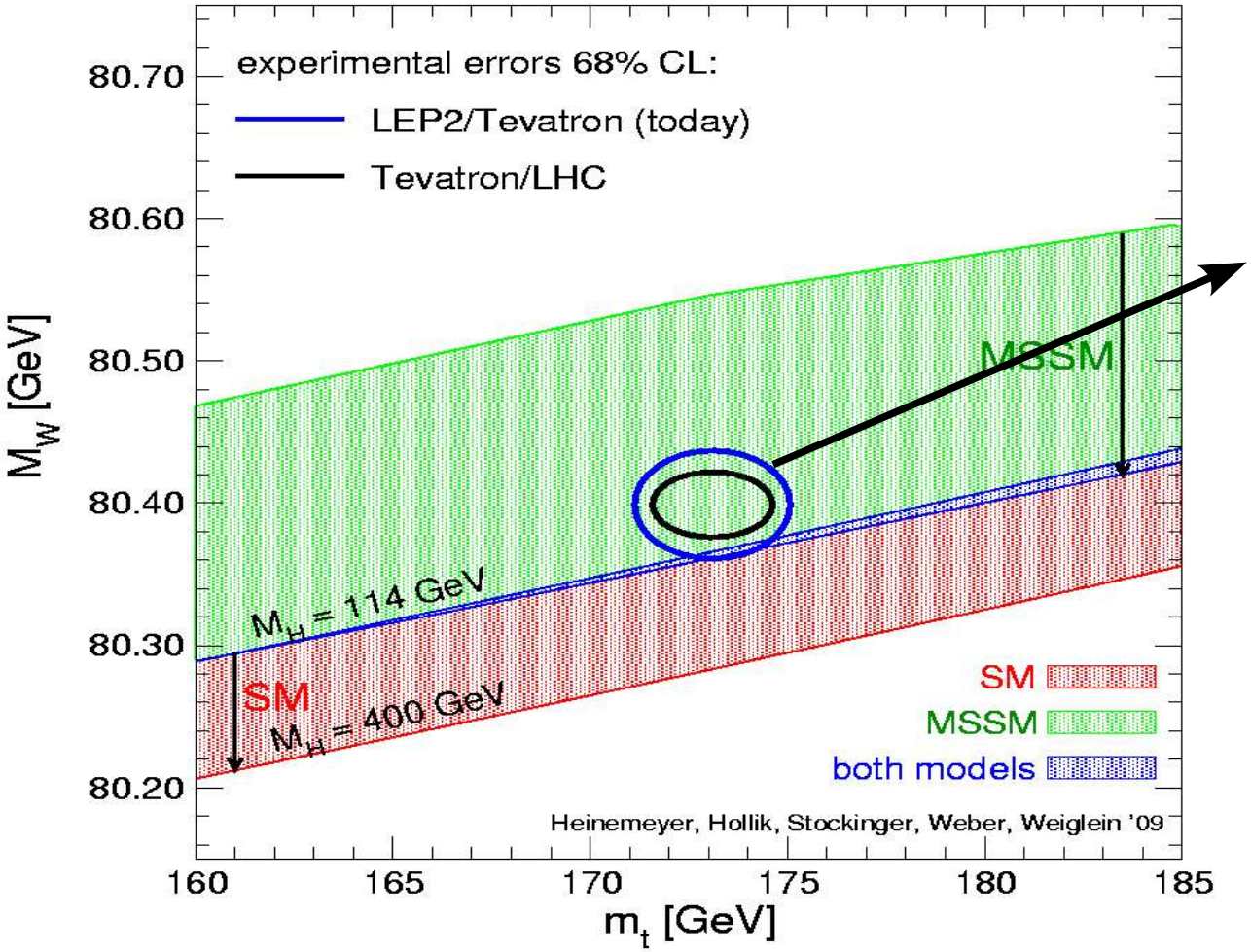
Projections for the future



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

- **ΔM_W ~ 10 MeV**
- **ΔM_{top} ~ 1 GeV**

Very significant implications for the Higgs boson search -

If ΔM_W ~ 15 MeV and ΔM_{top} ~ 1 GeV and M_W = 80.400 GeV then –

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

[Ref: Peter Renton, ICHEP08]

Backup Slides

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

Electron Simulation – energy scale

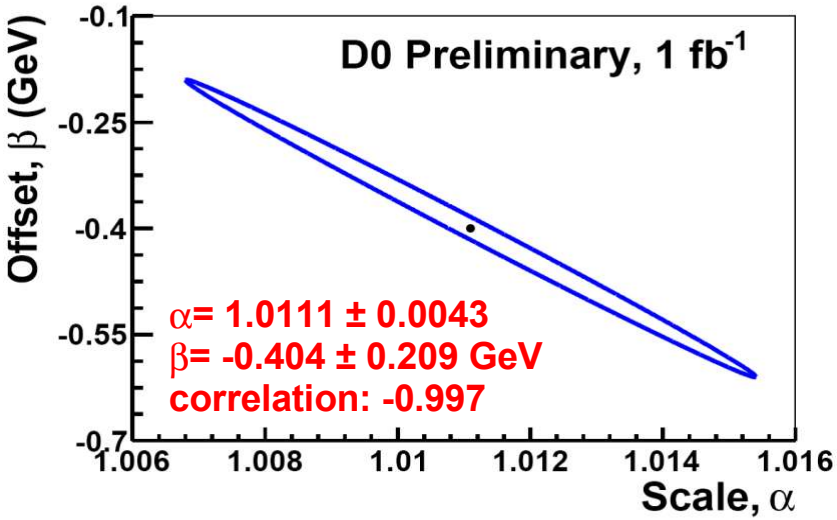
- **Electron energy response :**
  - using Z→ee events from data, known Z mass value from LEP

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

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

$$M_Z(measured) = \alpha \cdot M_Z(true) + f_Z \cdot \beta$$

  - where $f_Z = (E(e1) + E(e2))(1 - \cos\gamma_{ee})/M_Z(true)$
  - γ_{ee} → opening angle between the two detected electrons
  - M_Z is the mass of Z boson



- f_Z observable gives a handle for studying energy response as a function of incident energy
  - $\beta = \delta M_Z(measured)/\delta f_Z$
- M_{ee} vs. f_Z templates were generated for a range of α and β values → extract α and β

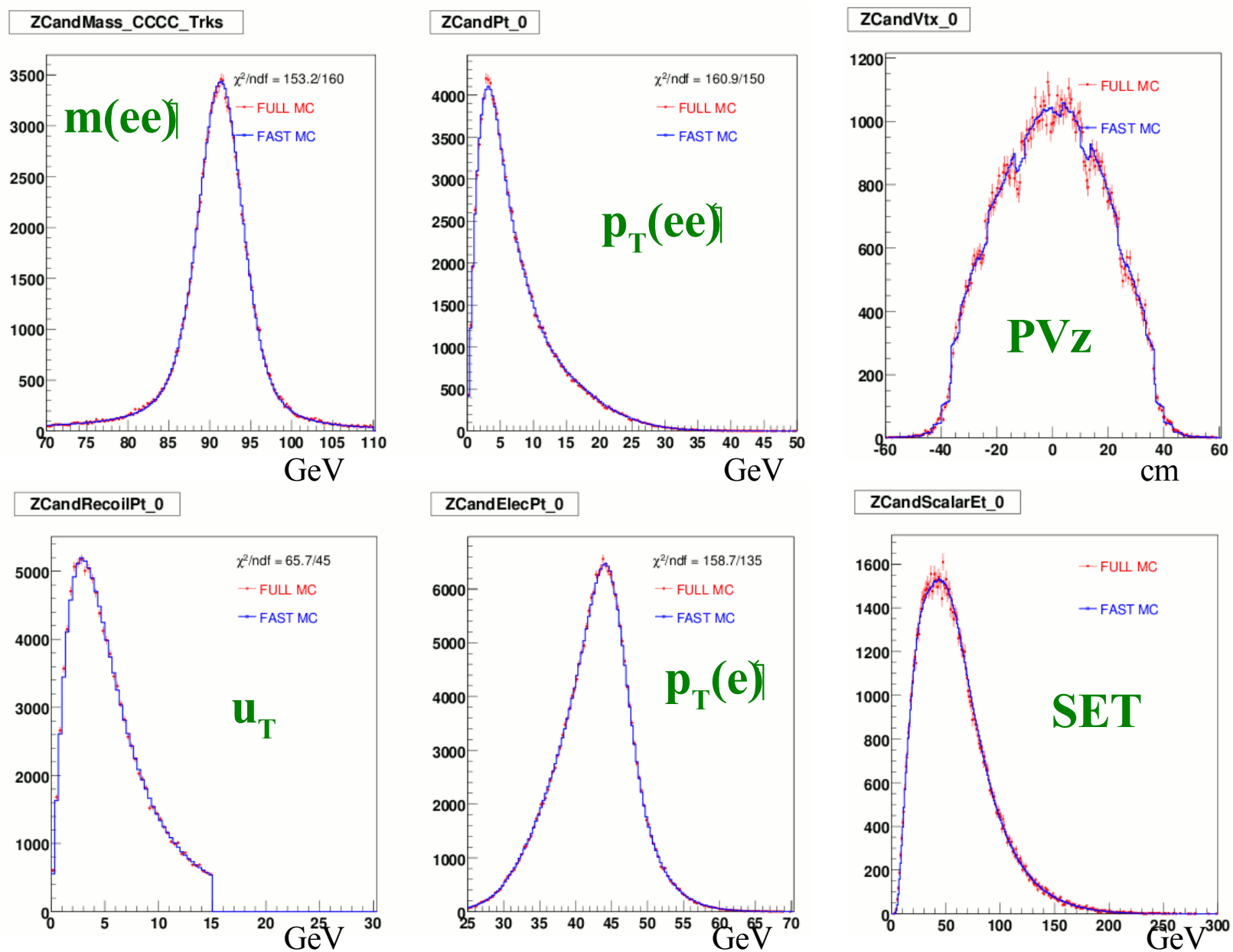
Dominant systematic

Modeling the Hadronic Recoil

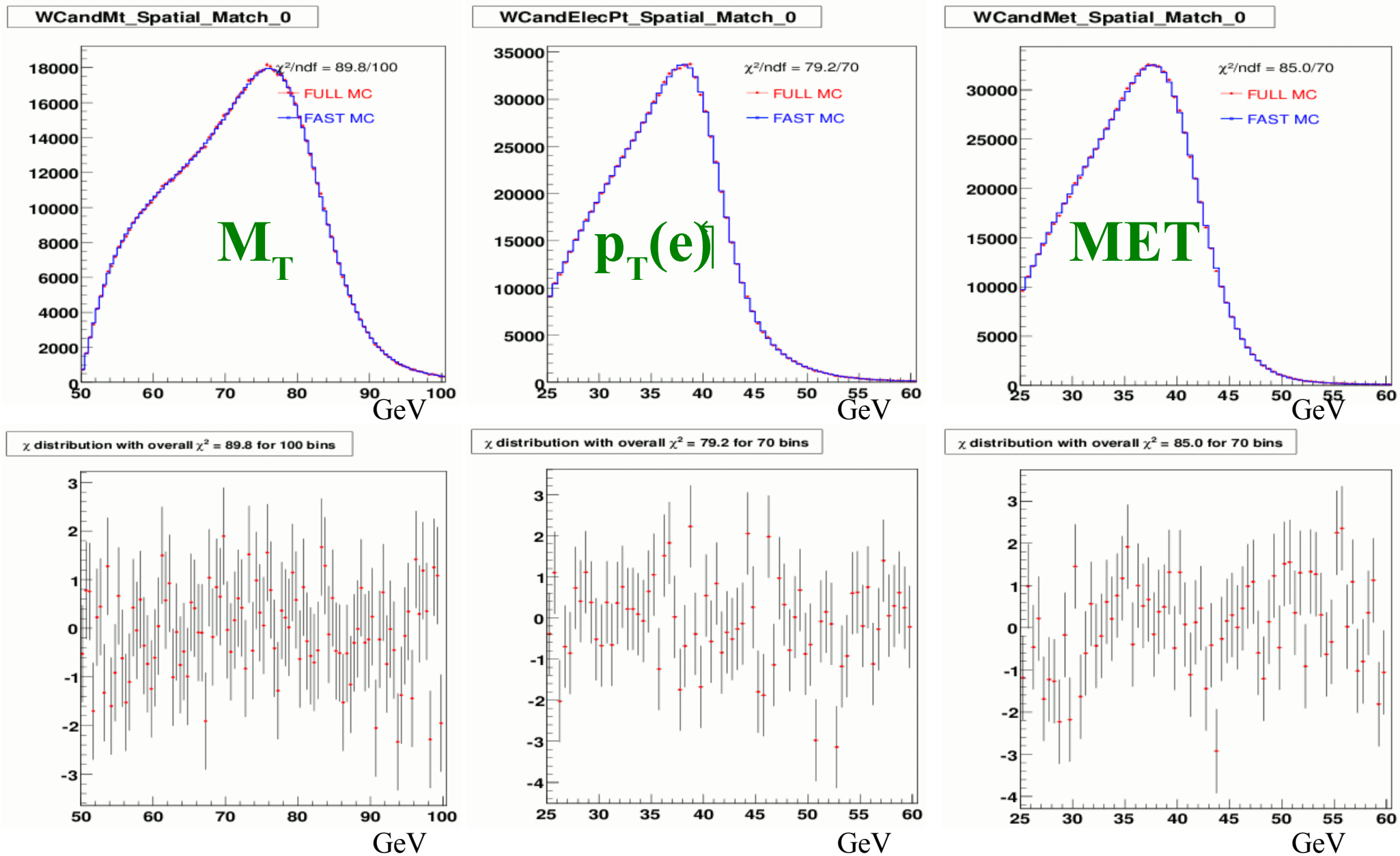
- Modeled recoil: $\mathbf{u_T = u_T^{HARD} + u_T^{SOFT} + u_T^{ELEC} + u_T^{FSR}}$
- $\mathbf{u_T^{HARD} = f(q_T)}$
  - Recoiling partons from the hard scatter that produced vector boson
  - Parameterized function obtained from Z→νν FULL MC. Later fine-tuned to match Z→ee
- $\mathbf{u_T^{SOFT} = \alpha_{MB} \cdot E_T^{MB} + \alpha_{ZB} \cdot E_T^{ZB}}$
  - 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
- $\mathbf{u_T^{ELEC} = - \Sigma\, \Delta u_{//} \cdot p_T^{e}}$
  - 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

MC closure test results: Z → e e

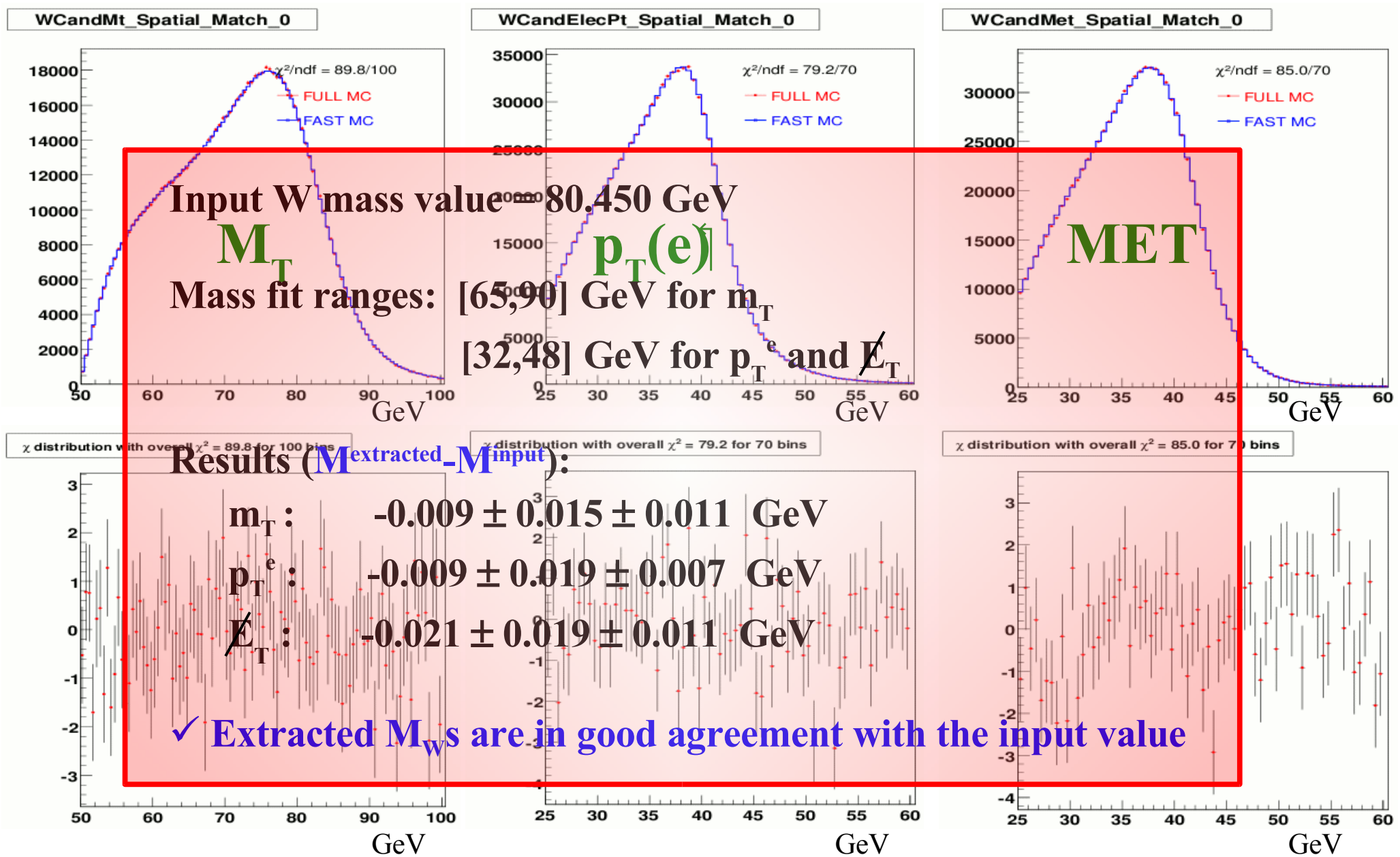
✓ Good agreement between full and parameterised MC.



MC closure test results: W → e ν



MC closure test results: $W \rightarrow e\,\nu$



Input W mass value = 80.450 GeV

M_T **$p_T(e)$** **MET**

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

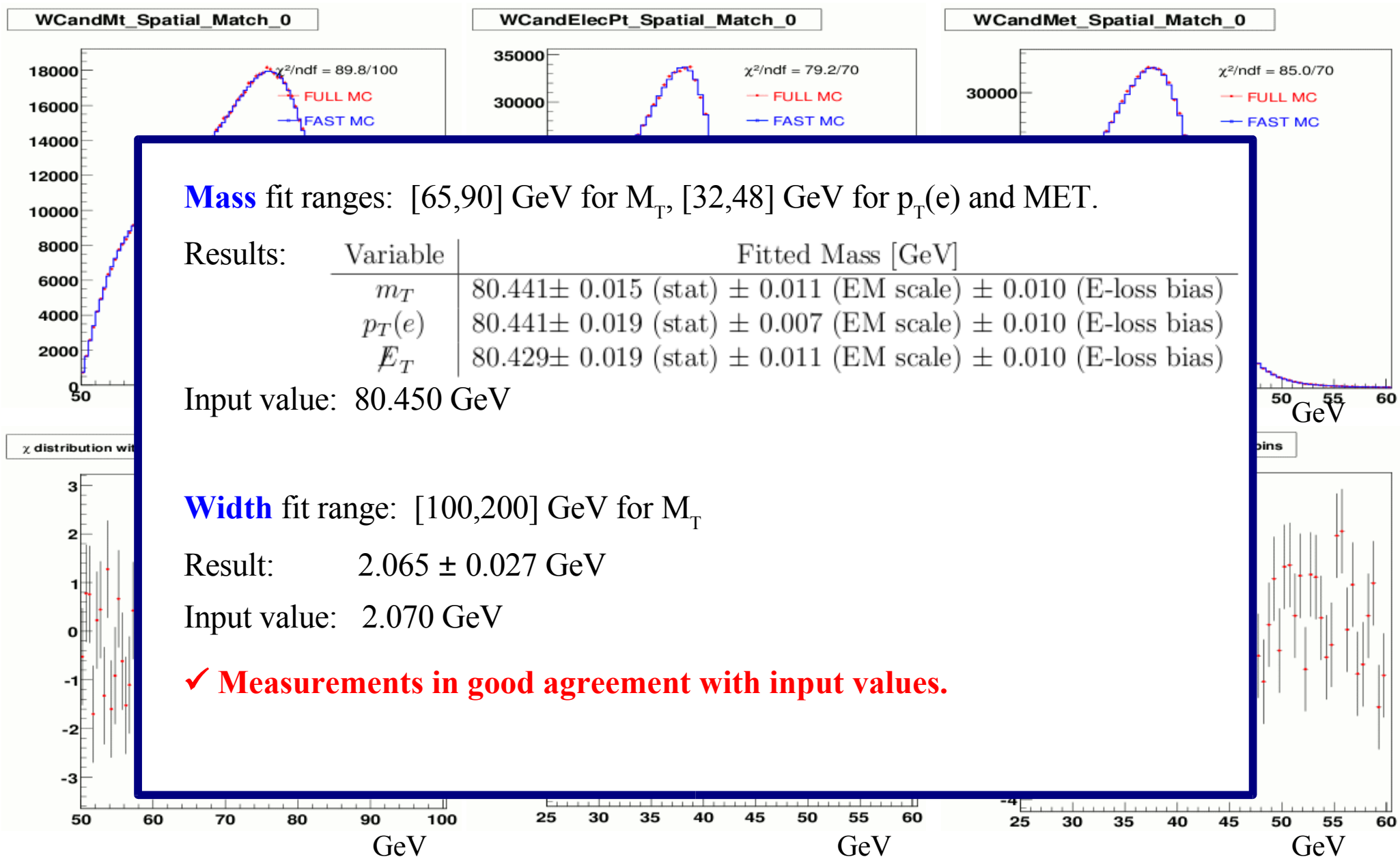
[32,48] GeV for p_T^e and $\not{E}_T$

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

m_T :	$-0.009 \pm 0.015 \pm 0.011$ GeV
p_T^e :	$-0.009 \pm 0.019 \pm 0.007$ GeV
$\not{E}_T$:	$-0.021 \pm 0.019 \pm 0.011$ GeV

✓ **Extracted M_Ws are in good agreement with the input value**

MC closure test results: W → e ν



Mass fit ranges: [65,90] GeV for M_T, [32,48] GeV for $p_T(e)$ and MET.

Results:

Variable	Fitted Mass [GeV]
m_T	80.441± 0.015 (stat) ± 0.011 (EM scale) ± 0.010 (E-loss bias)
$p_T(e)$	80.441± 0.019 (stat) ± 0.007 (EM scale) ± 0.010 (E-loss bias)
$\not{E}_T$	80.429± 0.019 (stat) ± 0.011 (EM scale) ± 0.010 (E-loss bias)

Input value: 80.450 GeV

Width fit range: [100,200] GeV for M_T

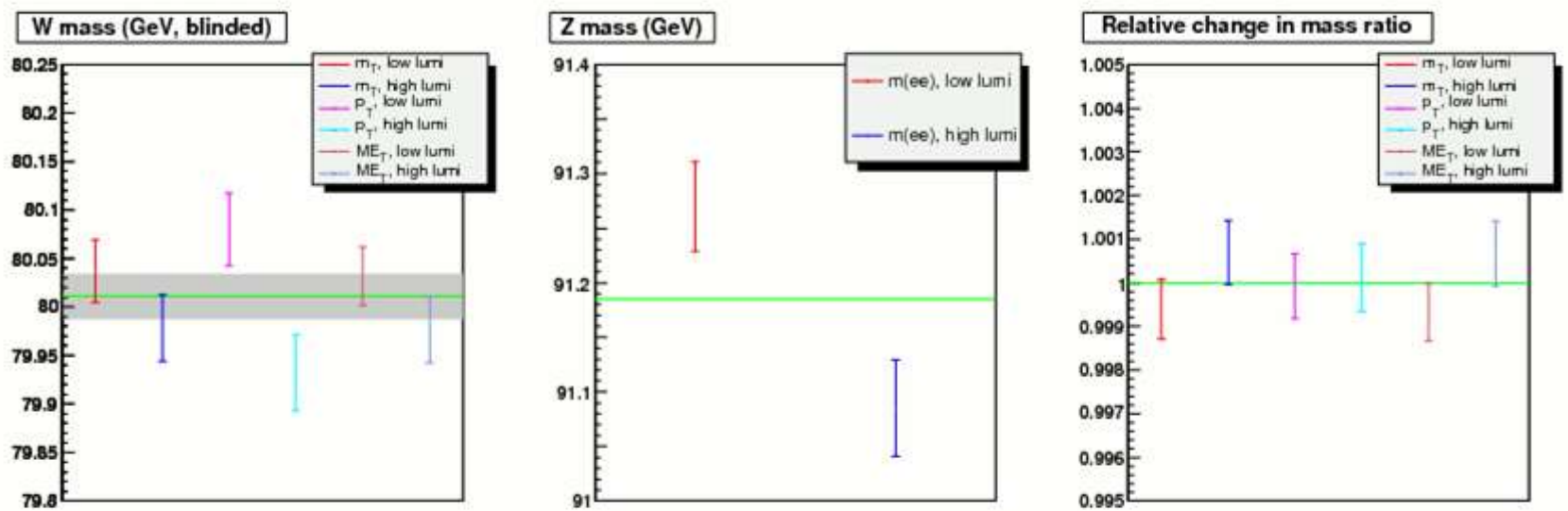
Result: 2.065 ± 0.027 GeV

Input value: 2.070 GeV

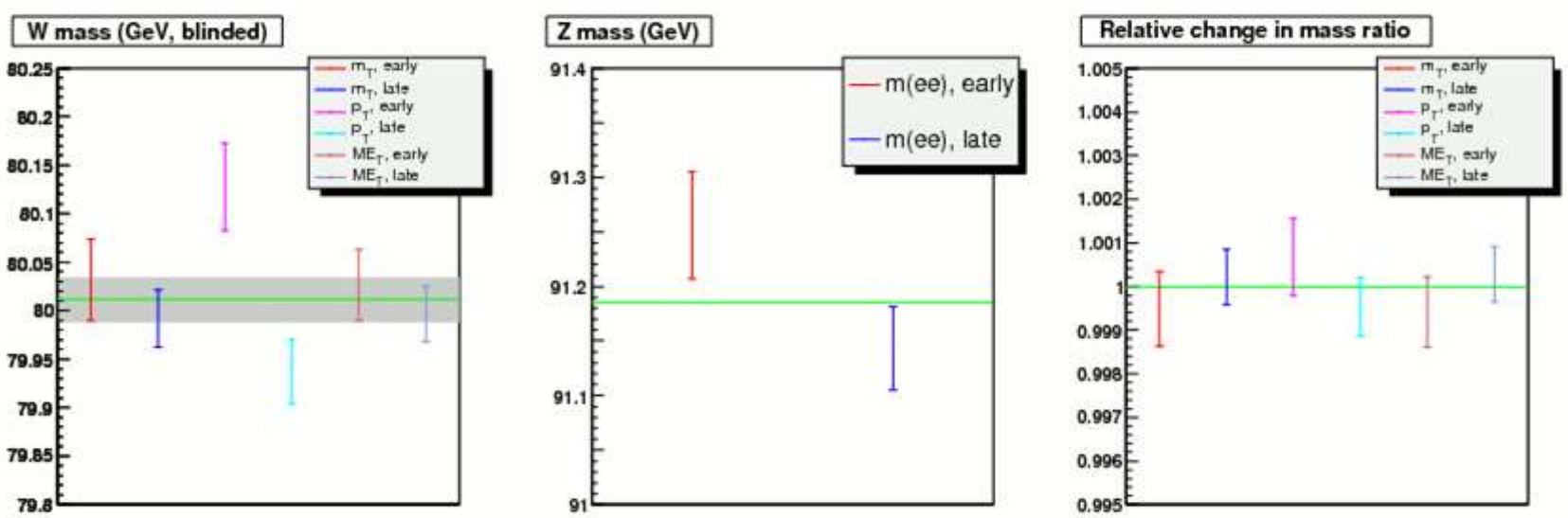
✓ **Measurements in good agreement with input values.**

Consistency Checks – I

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

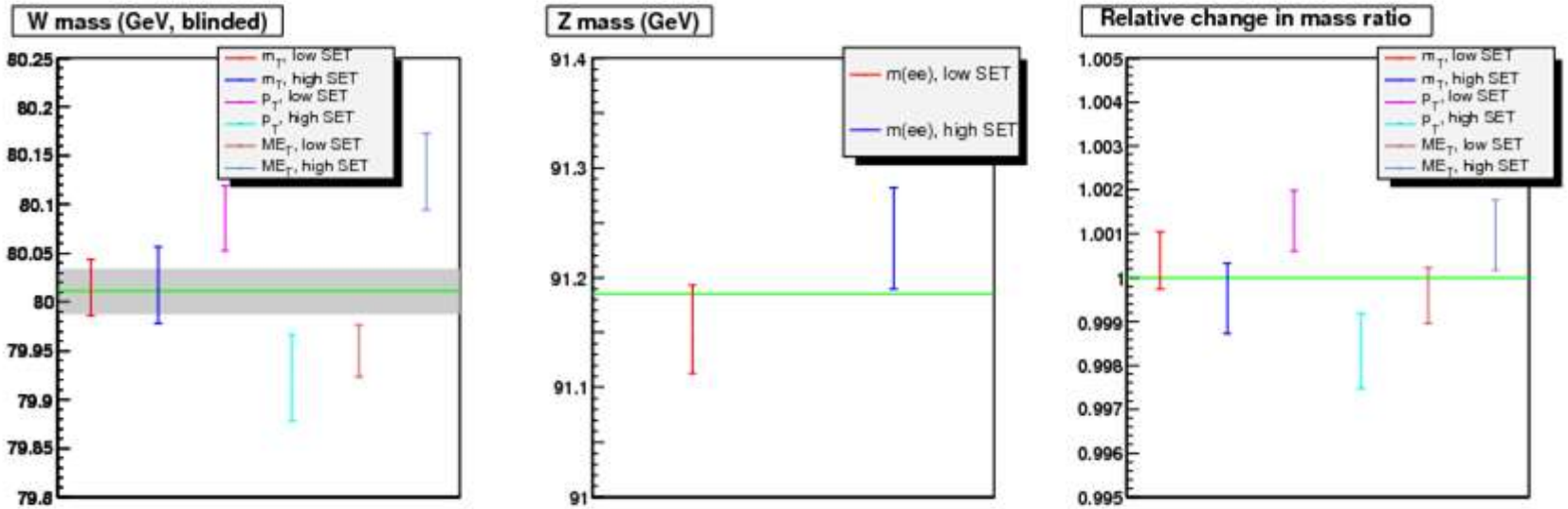


- **Time** (data taking period)

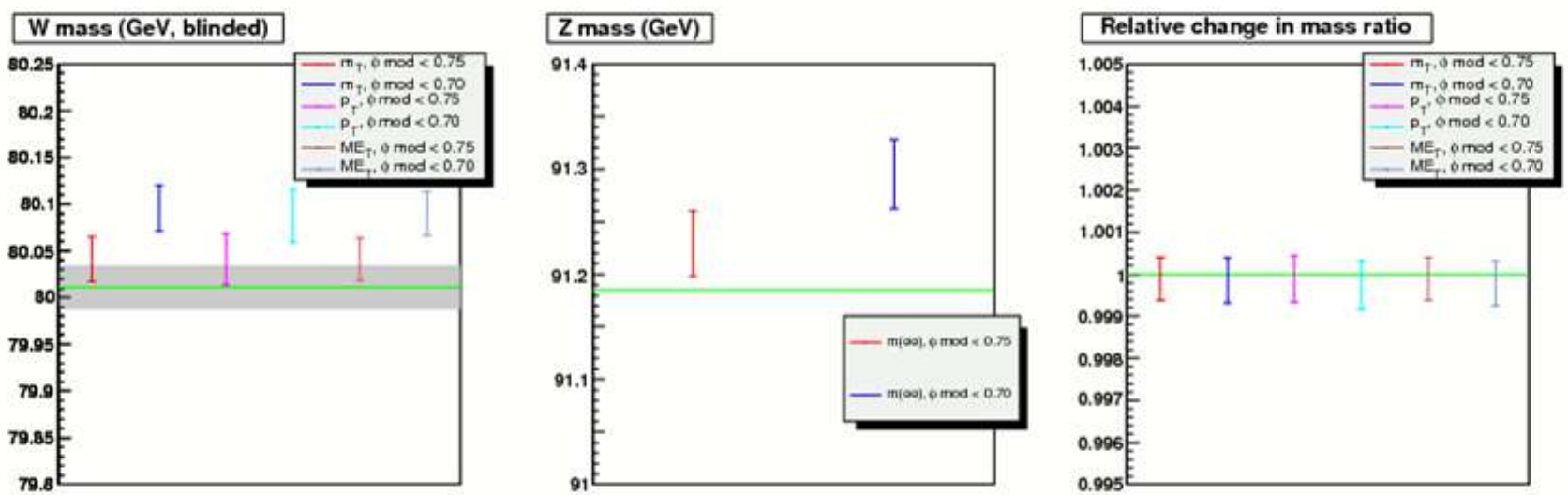


Consistency Checks – II

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

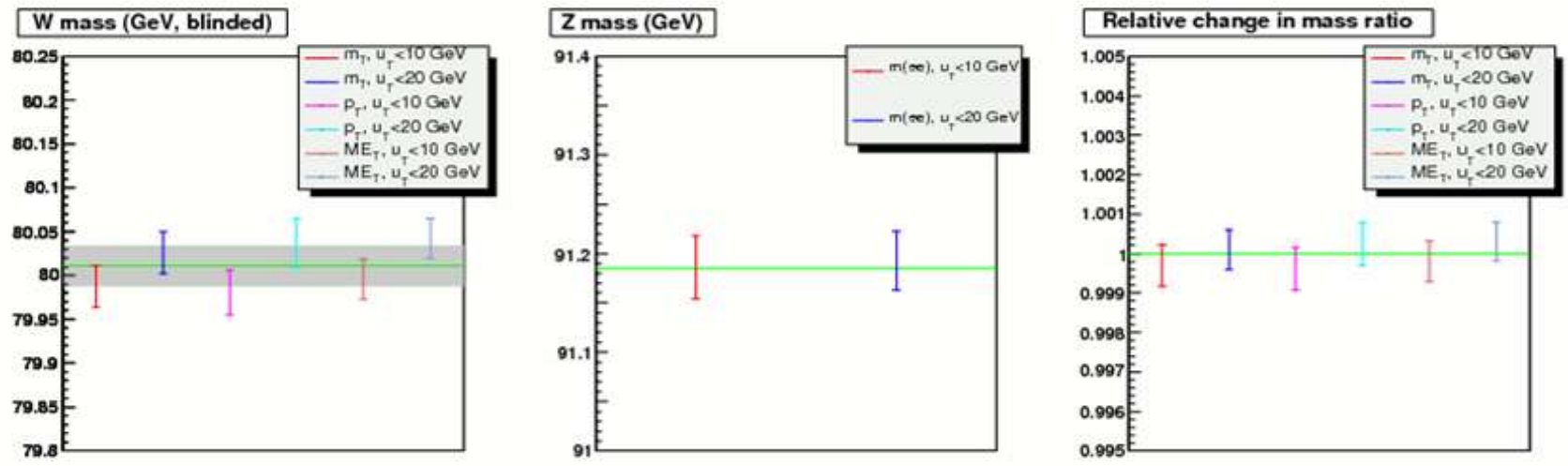


- **Electron distance from phi cracks**



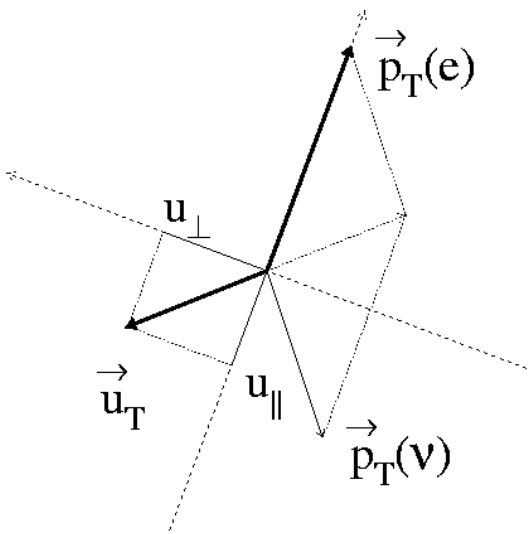
Consistency Checks – III

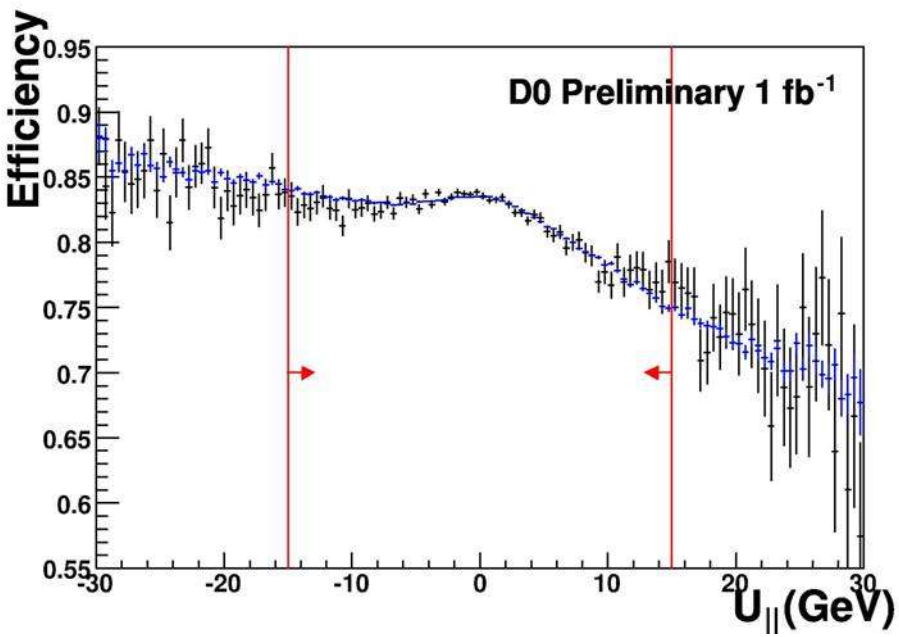
- **Cut on u_T** (length of recoil vector)



Selection Efficiencies

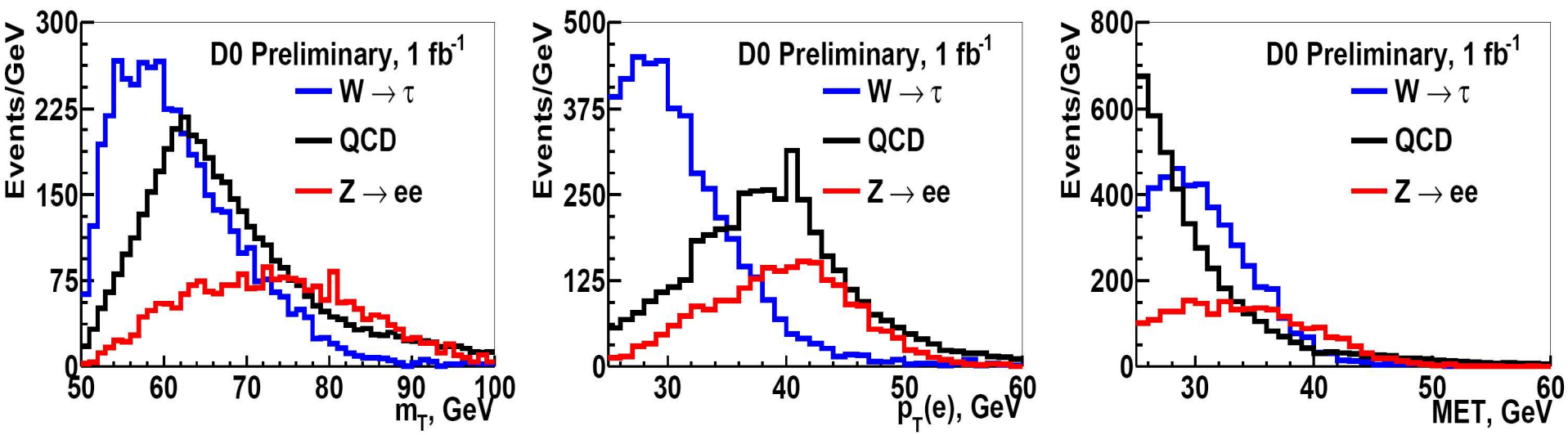
- Electron selection is subject to multiple factors: detector geometric, electron intrinsic features and contamination from rest of the event
- Study the effect from different sources using different methods
  - Geometric dependence(primary vertex and η)
  - Intrinsic $p_T(e)$ dependence(internal photon radiation, etc.)
  - $u_{||}$ efficiency(relative direction between "e" and "recoil")
  - Scalar E_T efficiency(overall hadronic activity effect)





Backgrounds to W→eν

- QCD (di-jet) (1.49 ± 0.3 %) : one jet fakes as an electron
- Z→ee (0.80 ± 0.01 %) : one electron lost in ICR(between central and end cal)
- W→τν (1.60 ± 0.02 %) : Taus decaying into eνν

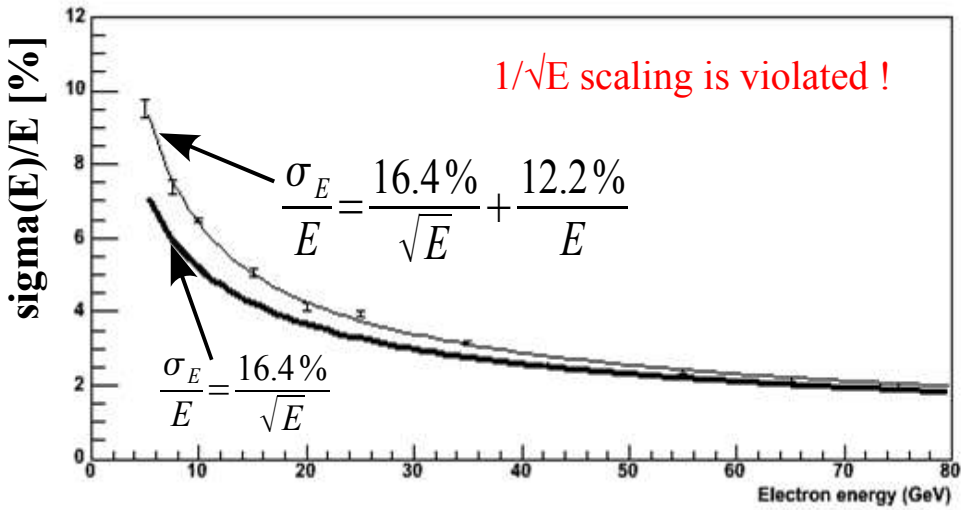


Impact on energy resolution of electrons

- GFLASH simulation of energy resolution of electrons shows deviations from that of an ideal sampling calorimeter !

- Resolution at normal incidence for different electron energies

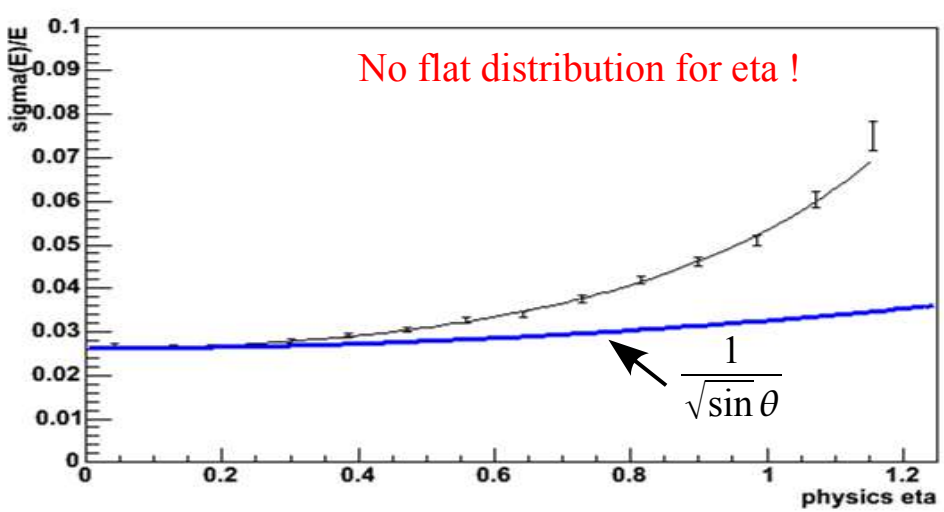
$$\frac{\sigma_{EM}}{E} = \sqrt{C^2 + \frac{S^2}{E_T} + \frac{N^2}{E^2}}$$



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

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

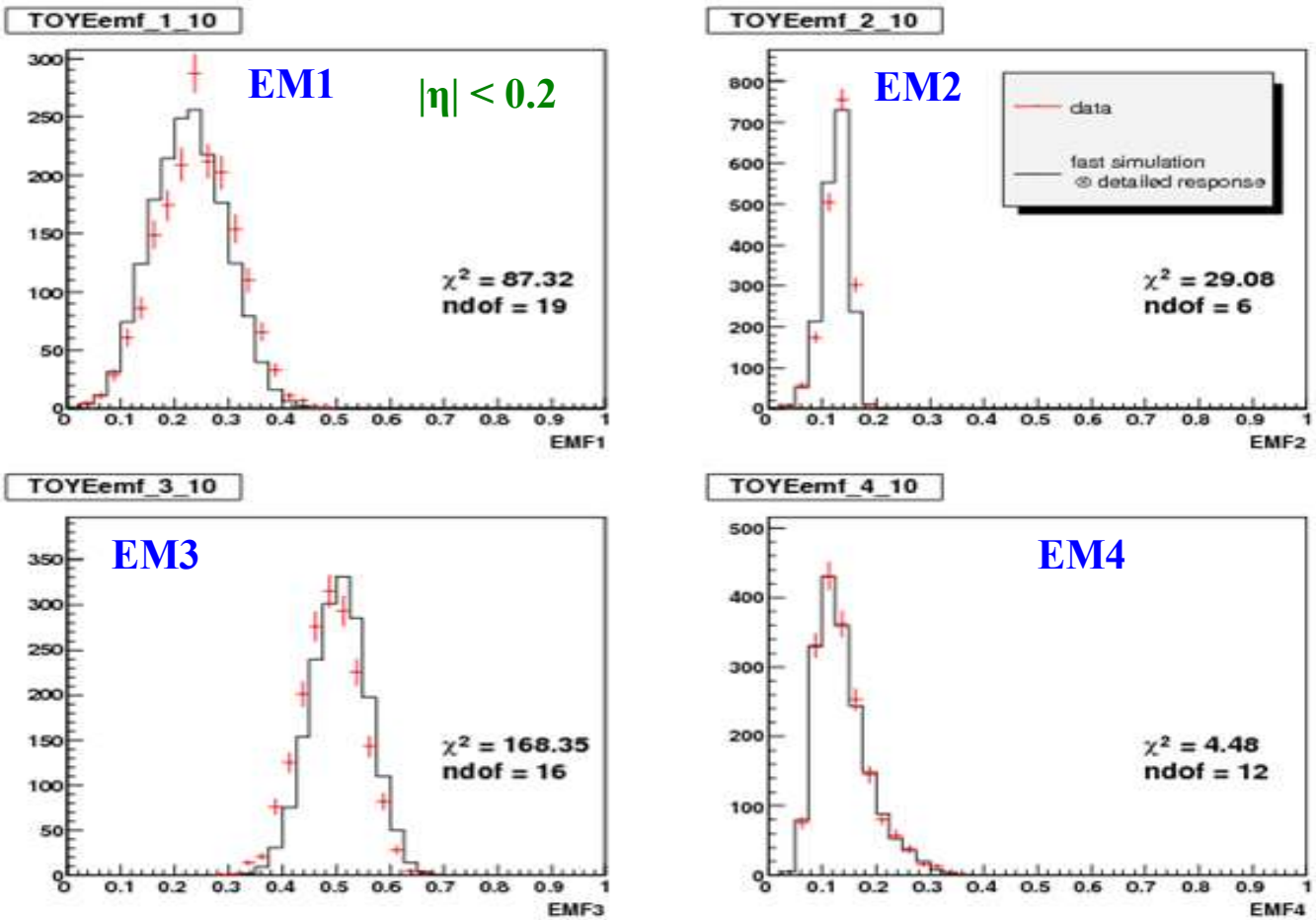
- Resolution at an energy E=45 GeV for different angles of incidence (eta)



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

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

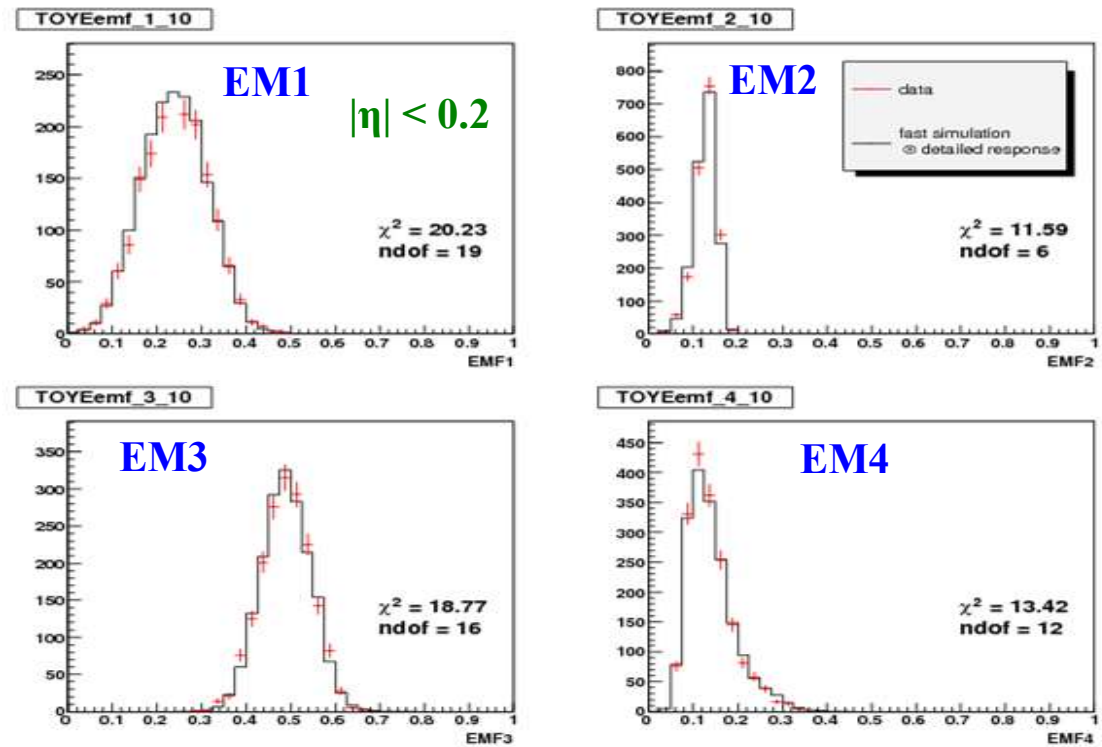


Fractional energy deposits between data and GEANT simulation do not match !

- 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

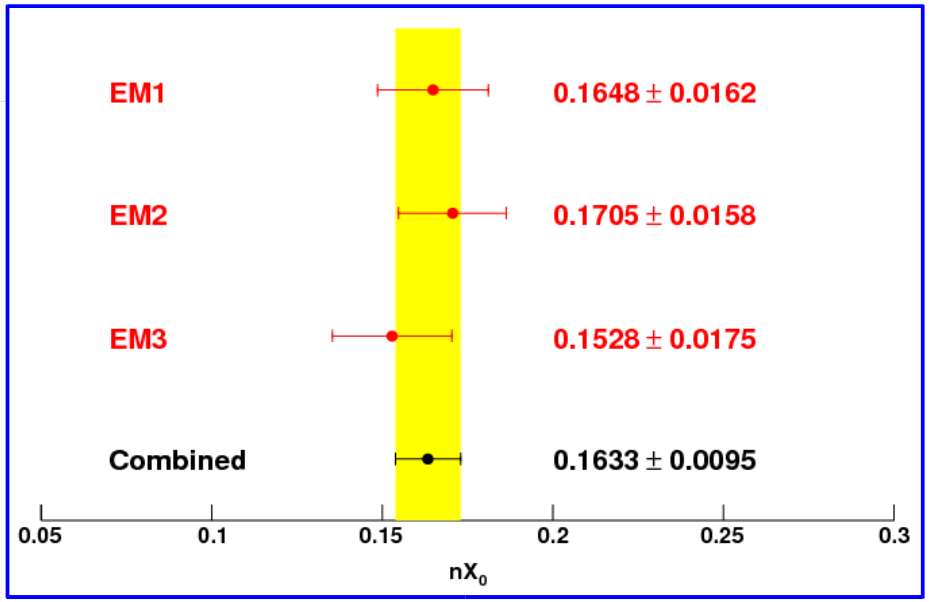


After tuning our material model :

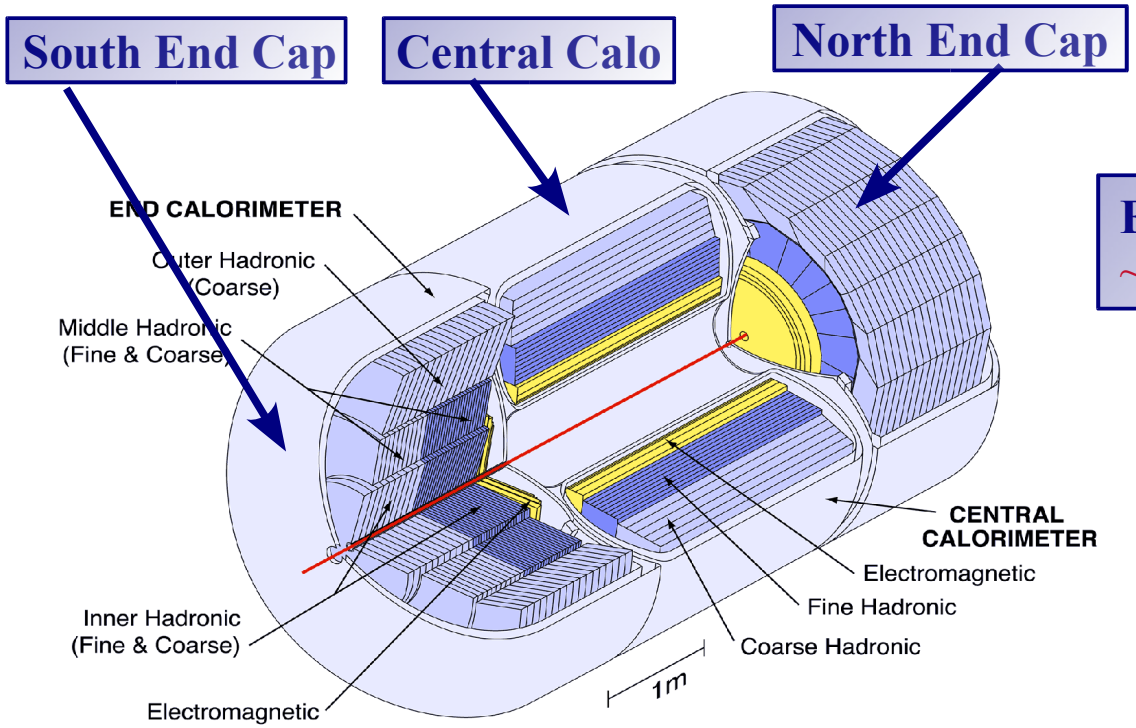
Fractional energy deposits between data and GEANT simulation match very well !

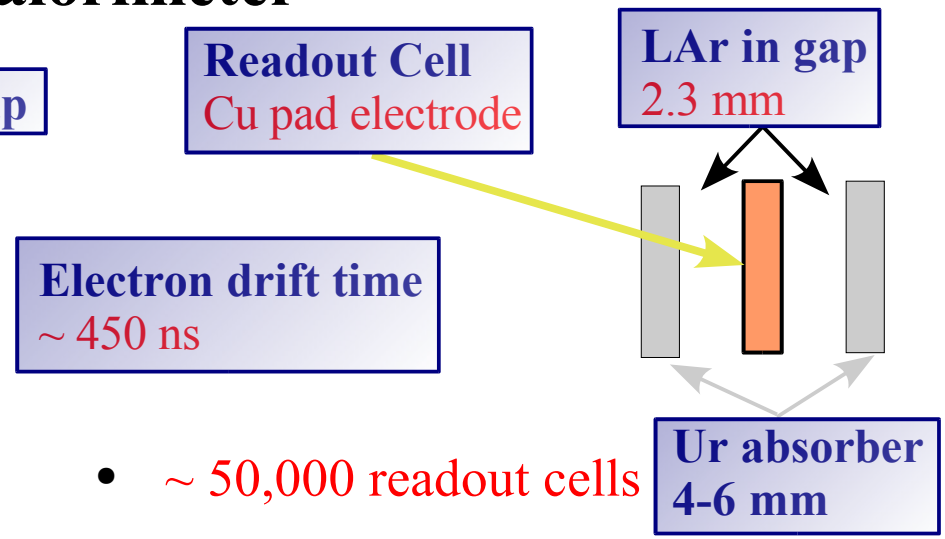
As a cross-check :

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



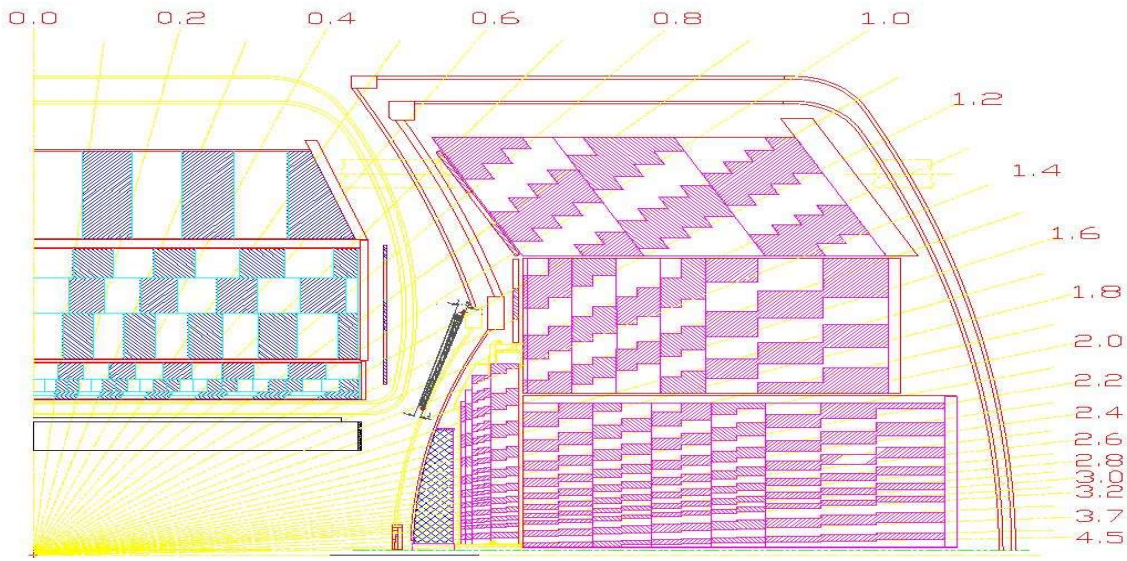
DØ RunII Calorimeter





- ~ 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)

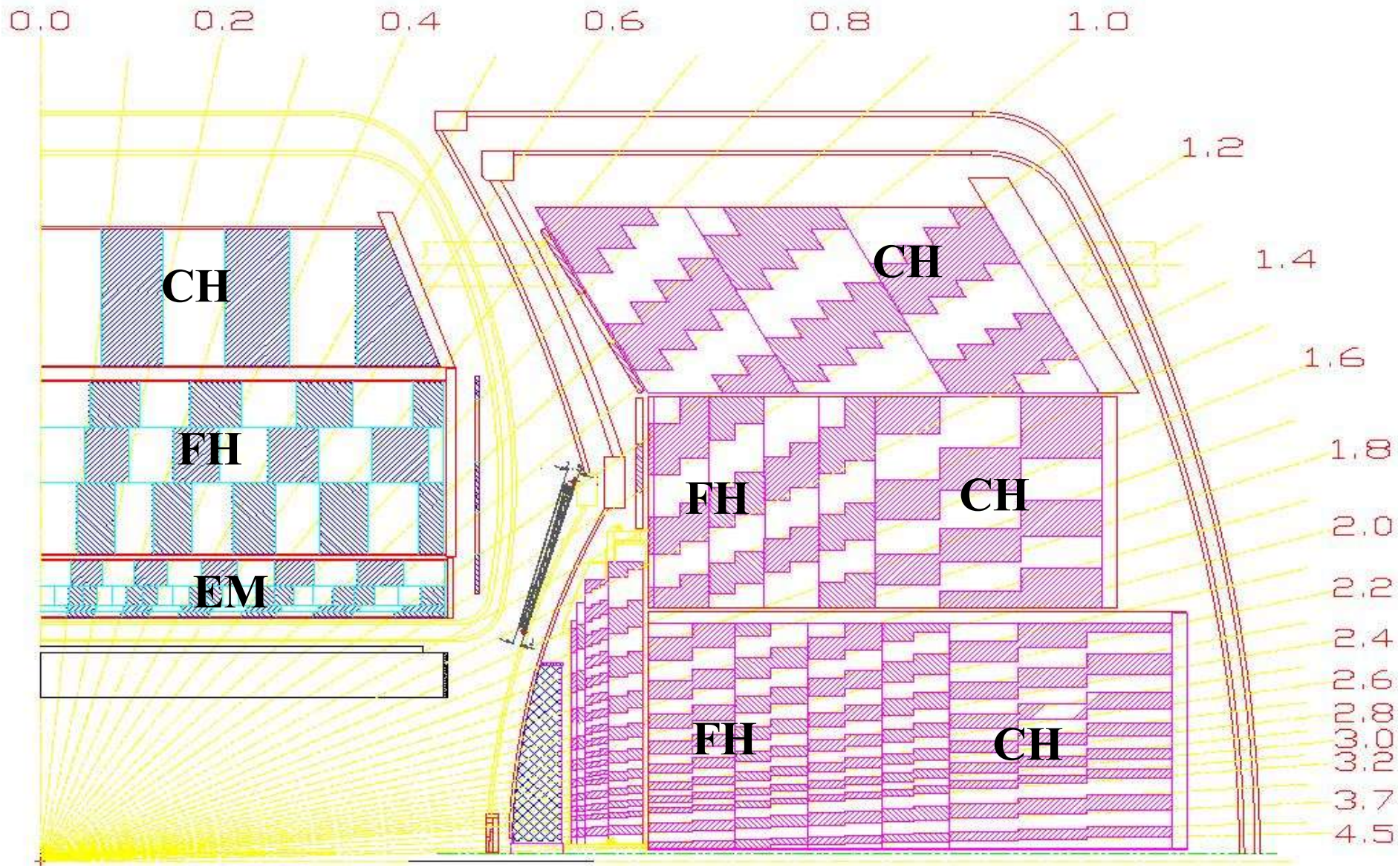
- Liquid Argon sampling
  - uniform response, radiation hard
  - Liquid Ar purity important (~0.3 ppm)
- Ur absorber (EM); Cu(FH); Steel(CH)
  - dense, compact
- Uniform, hermetic with full coverage
  - $\eta < 4.2$, $\lambda_{int} \sim 7.2$ (total)



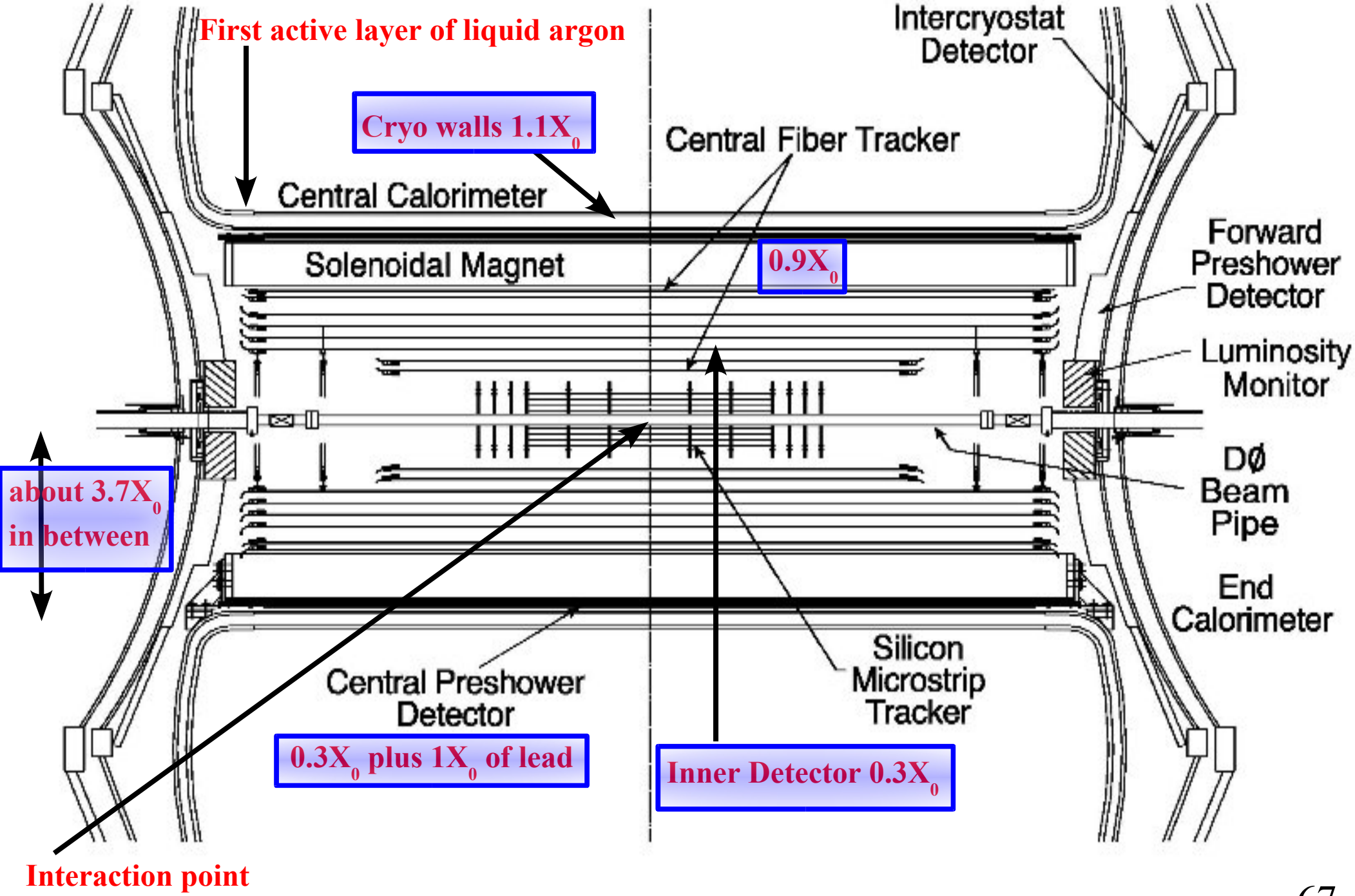
DØ RunIIa Calorimeter

46,000 readout cells
4 EM layers, 3 FH layers, CH

Electron: $|\eta| < 1.1$
Recoil: sum over all cells ($|\eta| < 4.2$)

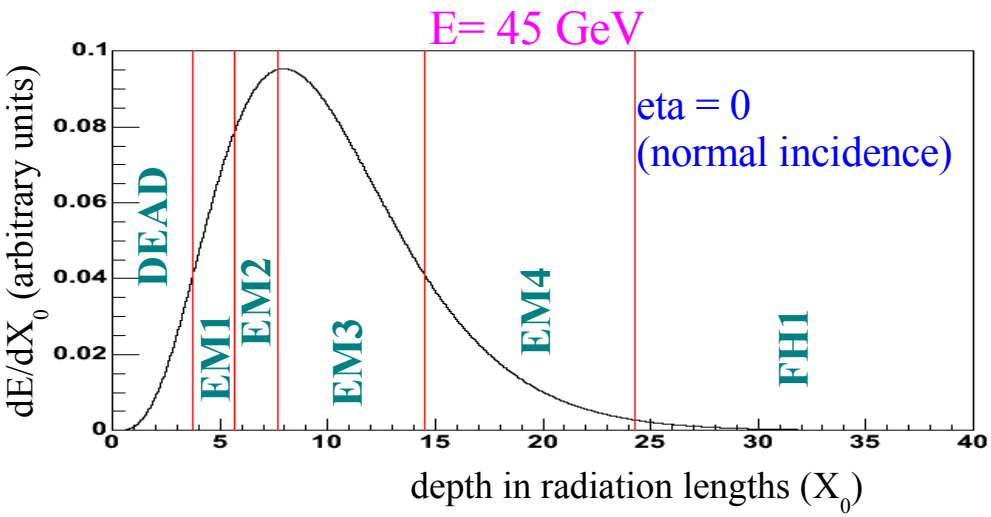


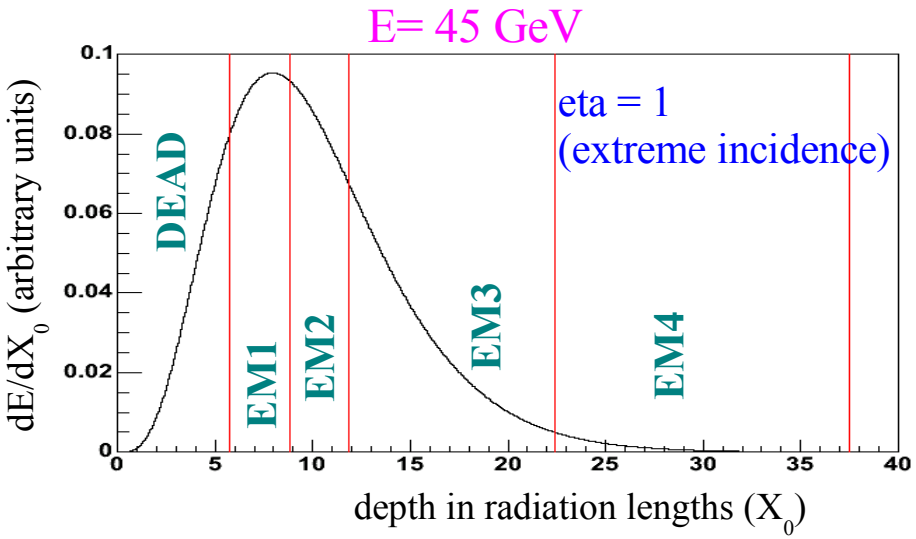
Material infront of Calorimeter



Energy response linearity

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





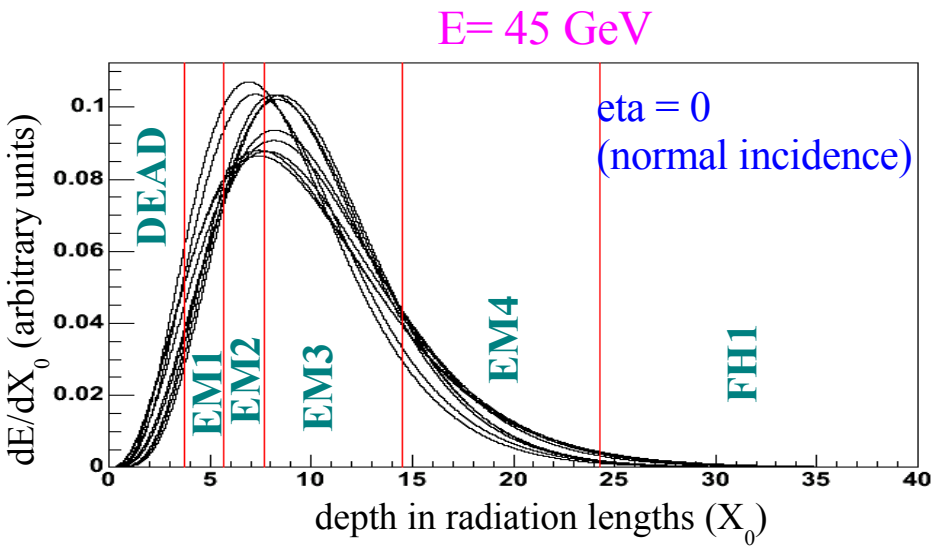
- Shower maximum is in EM1 for eta=1 !
  - Notice the fraction of energy loss in the dead material !

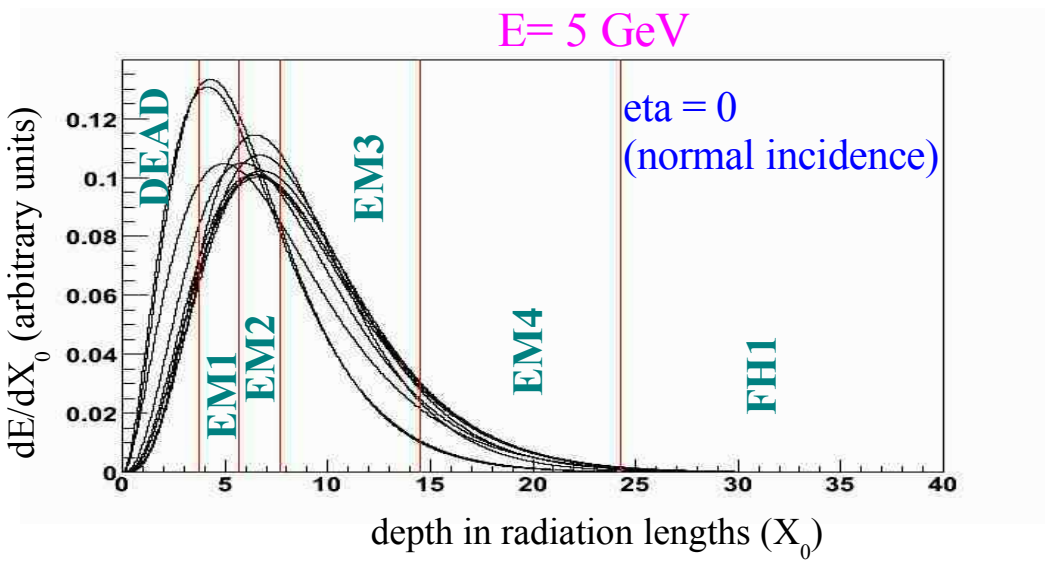
- During reconstruction high weights are applied to the early layers (especially EM1) to compensate partially for losses in dead material
  - what is the situation when there are significant losses in dead material ?

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



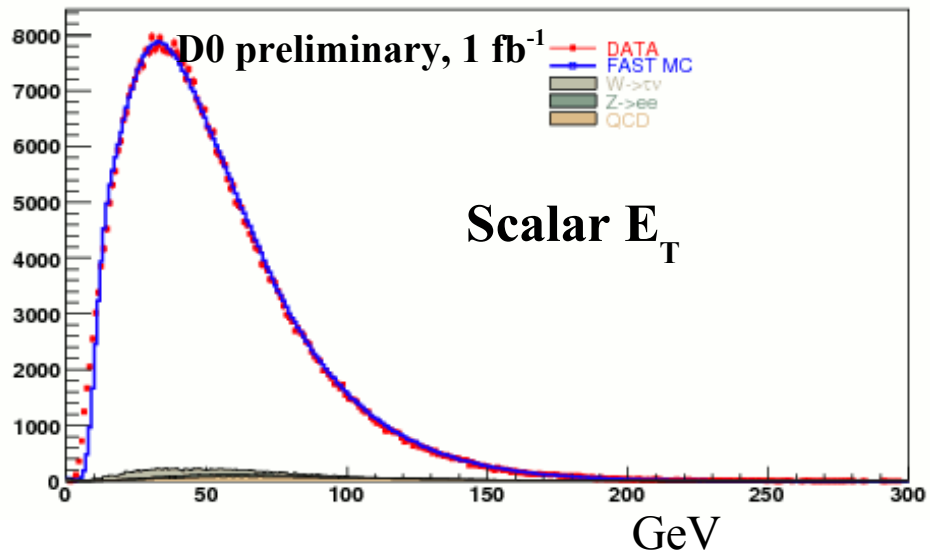


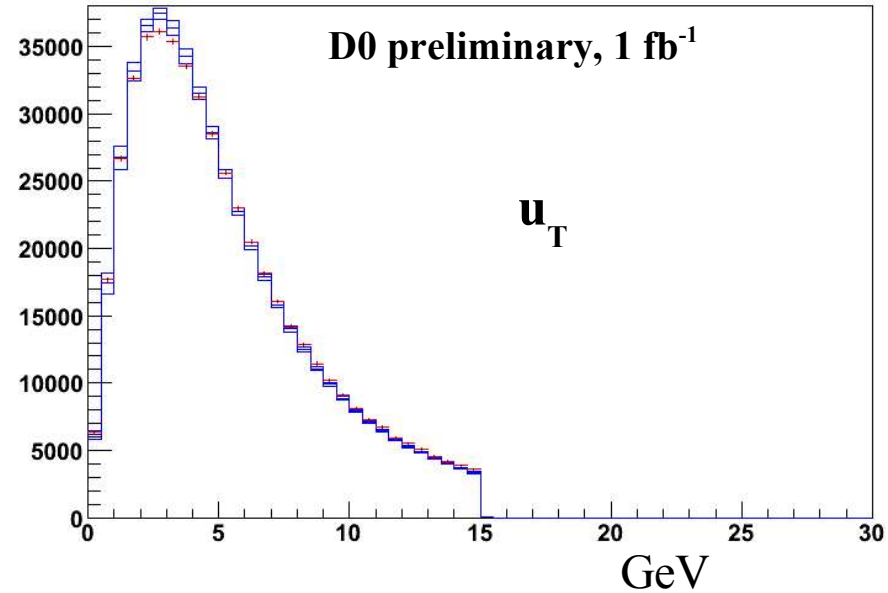
- Fraction of energy lost in the dead material varies from shower to shower
  - position of shower maximum (in X_0) varies approximately as ln(E)

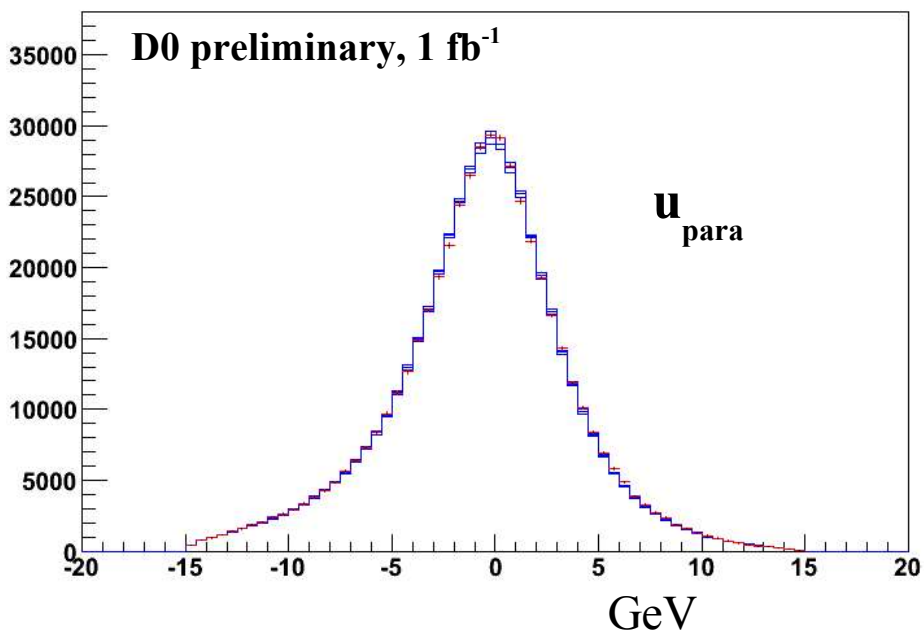
- Relative importance of shower-to-shower fluctuations also depend on energy of the incident electrons

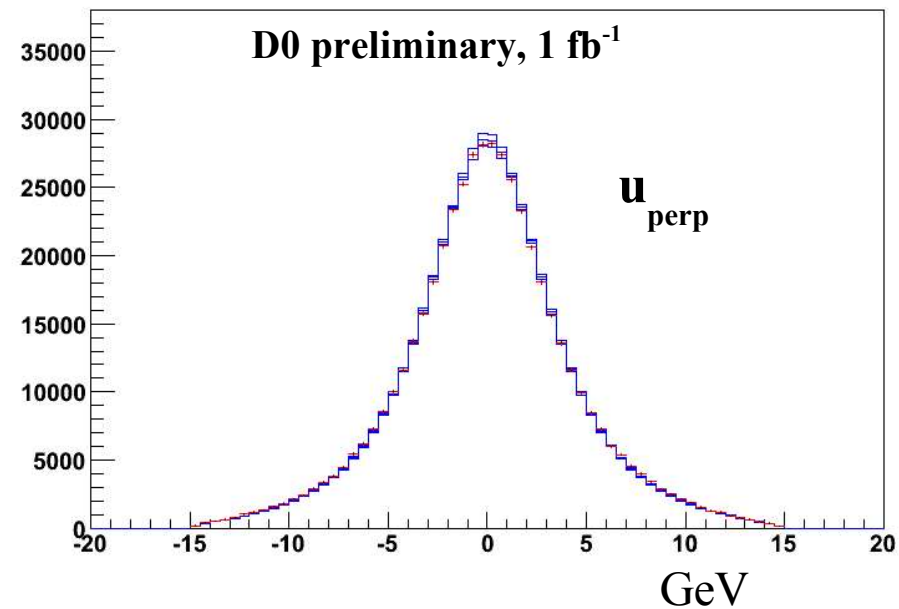
N.B. - Profiles have been made using GFLASH – a fast parameterized toy model for EM showers

Diagnostic plots from W→ eν 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 $\longrightarrow$
  - $\eta = \frac{1}{2} \ln [(|p| + p_L) / (|p| - p_L)]$ 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 $\rightarrow$charge of particle; r $\rightarrow$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 $Q=M_Zc^2$, $G_F = 1.16637(1) \times 10^{-5}\ \text{GeV}^{-2}$, $M_Z = 91.1876 \pm 0.0021\ \text{GeV}/c^2$, $\theta_W \sim 30^\circ$
-

Some information

- Why use η and ξ axes ?
  - avoids bias from electron energy resolution
  - since positive η is in direction of P_t^{ee}, bias in P_t^{rec} is manifested as bias in η-imbalance
- Both $\mathbf{u}_T^{HARD}$ and $\mathbf{u}_T^{SOFT}$ are fine-tuned with the help of 6 floating parameters

$$S_{EM} = \left(S_1 + \frac{S_2}{\sqrt{E}}\right) \times \left(\frac{e^{\frac{S_{\exp}}{\sin\theta}}}{e^{S_{\exp}}}\right) \qquad S_{\exp} = S_3 - \frac{S_4}{E} - \frac{S_5^2}{E^2}$$

-

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