W Boson Mass and Width Measurements with DØ Detector

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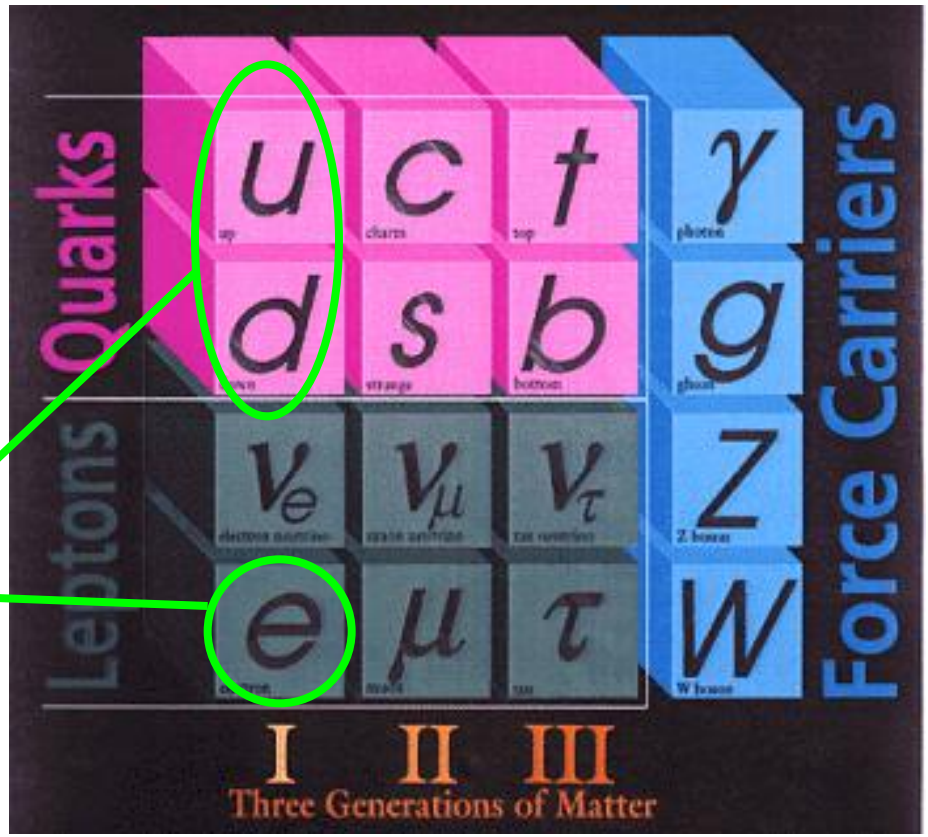
W Boson in the Standard Model

- Standard Model is a relativistic quantum field theory based on SU(3) × SU(2) × U(1) gauge group
- SM contains: spin-1/2 fermions, spin-1 bosons, spin-0 boson



Higgs Boson

Bound states → structures in the Universe

W, Z weak gauge bosons

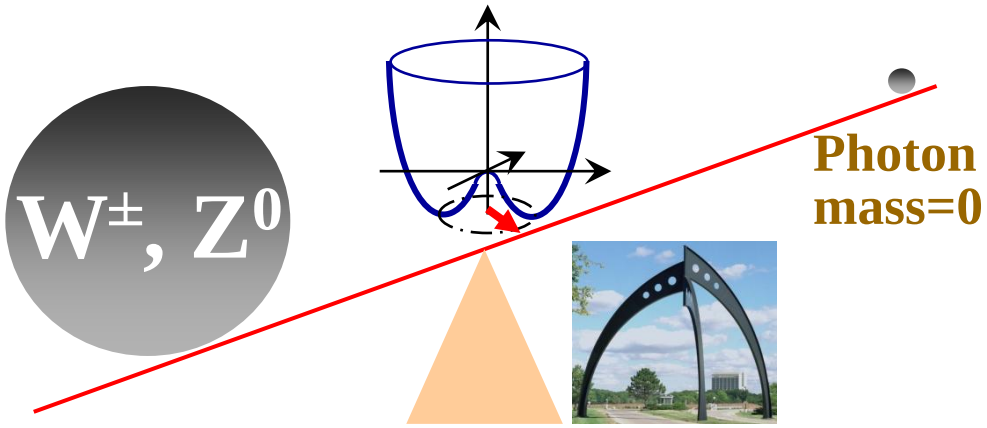
A Little Bit of History

- W and Z bosons discovered in 1983 by UA1 and UA2 Collaborations at CERN
- W boson first observed in November-December 1982 run
- 5 $W \rightarrow e\nu$ events at UA1 and 4 $W \rightarrow e\nu$ events at UA2
- For comparison: currently CDF and DØ are measuring W boson mass with 4-5 million $W \rightarrow e\nu$ events
- Why ~30 years later we are still interested in W and Z ?

Electroweak Symmetry Breaking

- W and Z bosons are interesting objects to study:
  mass, width, production and decay properties

- Even more interesting to find out how exactly these objects came to be



- What is the mechanism by which W and Z bosons acquired their mass ?

- Precise measurements of M(W) tell us about Electroweak Symmetry Breaking

M(W) Motivation

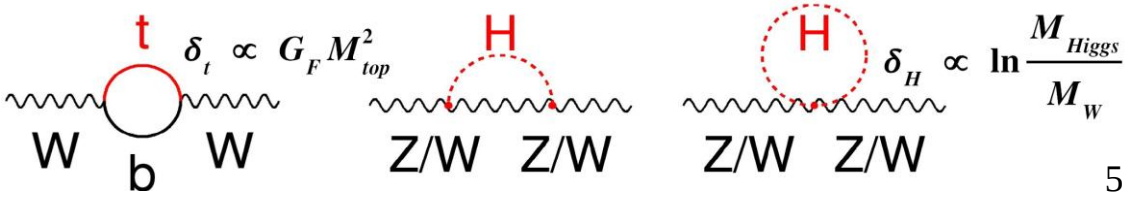
- W boson mass is an important Standard Model parameter related to $\mathbf{G_F}$, $\boldsymbol{\alpha_{EM}}$, and $\mathbf{M_z}$ via

$$M_W^{\,2} = \frac{\pi\alpha_{EM}(0)}{\sqrt{2}G_F\,(1 - M_W^{\,2}/M_Z^{\,2})(1-\Delta r)}$$

tree level

- Δr term represents (large!) higher-order corrections to M_W

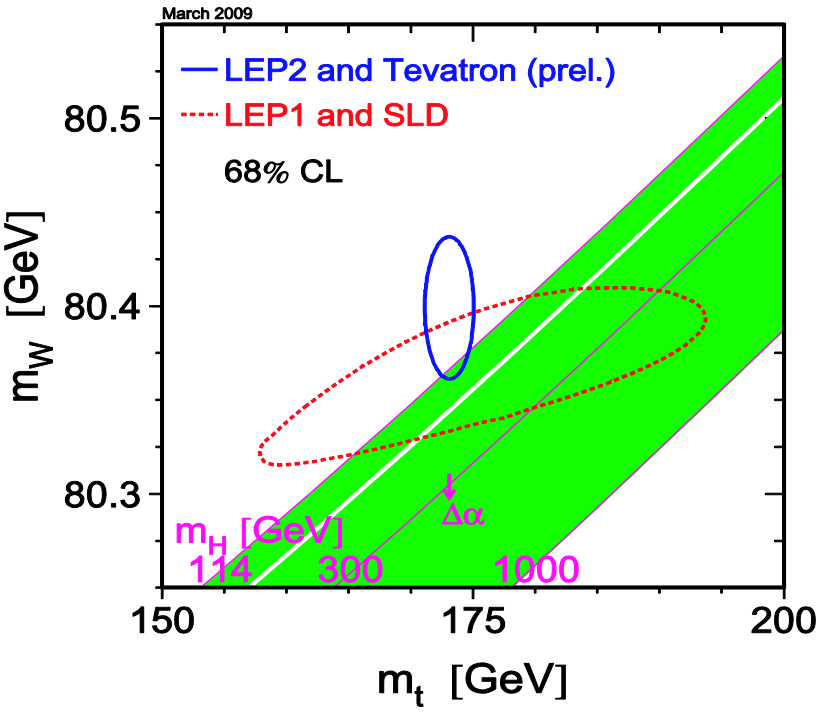
Δr = $\alpha_{EM}(0 \rightarrow M_Z)$ Running of α_{EM} + Radiative Corrections



Constraining Standard Model

- Since M_W, M_{top}, and M_{Higgs} are all related via radiative corrections, we can constrain M_{Higgs} with precision measurements of M_W and M_{top}

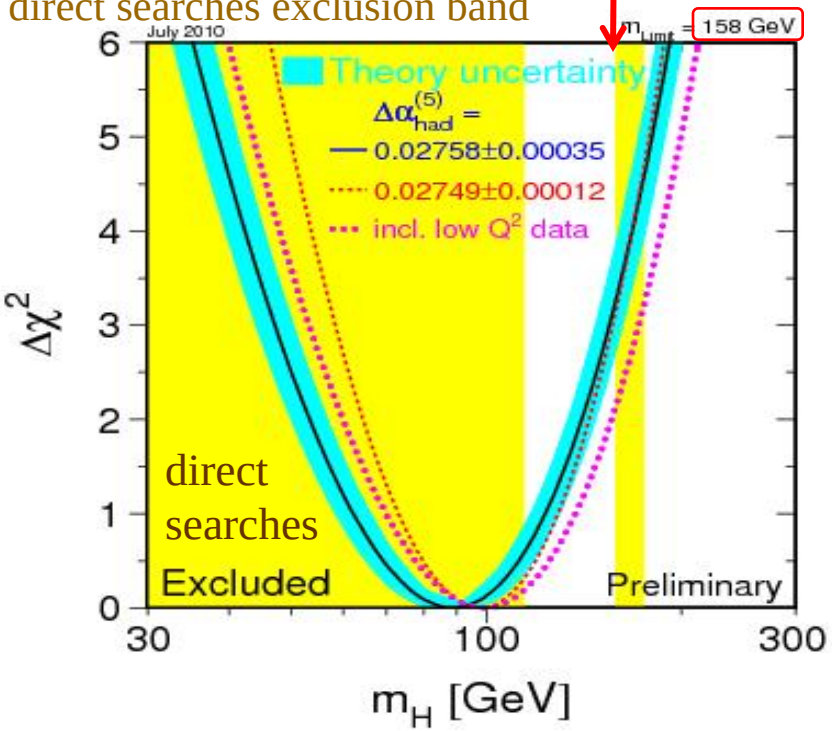
- Measurements of M_W and M_{top} overlaid with theory predictions for the Higgs boson



Higgs limit from EW fits

coincides with
low edge of Tevatron
direct searches exclusion band

158GeV @95%CL



DØ Collaboration

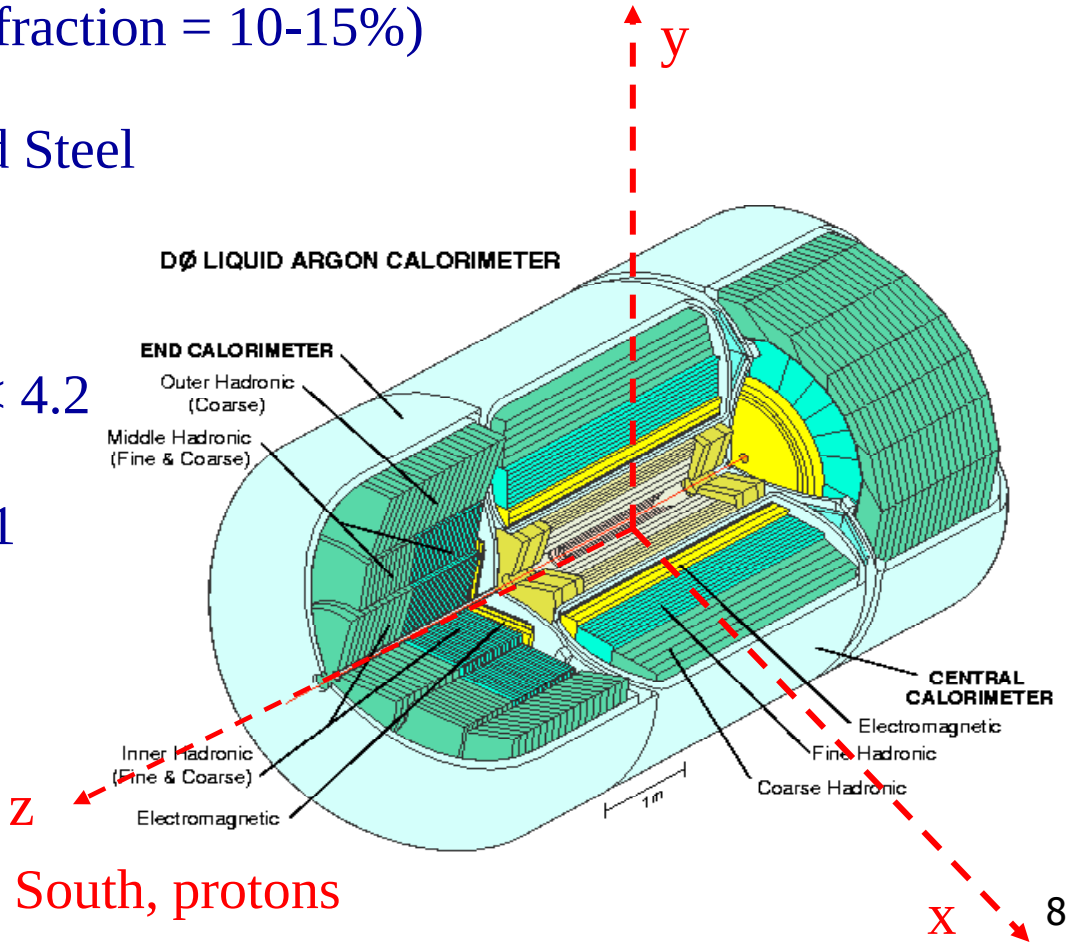
- 487 physicists from 86 institutions from 20 countries
- Institutions from Ukraine and Spain joined in 2010 and 2011 respectively

DØ Calorimeter

- Three modules: Central Calorimeter (CC), two End-Cap Calorimeters (EC)
- Each module consists of Electromagnetic section (EM) and Hadronic section
- Sampling Calorimeter (sampling fraction = 10-15%)
- Absorber = (mostly) Uranium and Steel
- Active Material = Liquid Argon
- Hermetic with full coverage :$|\eta| < 4.2$
- Segmentation : $\Delta\eta \times \Delta\varphi = 0.1 \times 0.1$ (0.05×0.05 in the 3rd EM layer, near shower maximum)

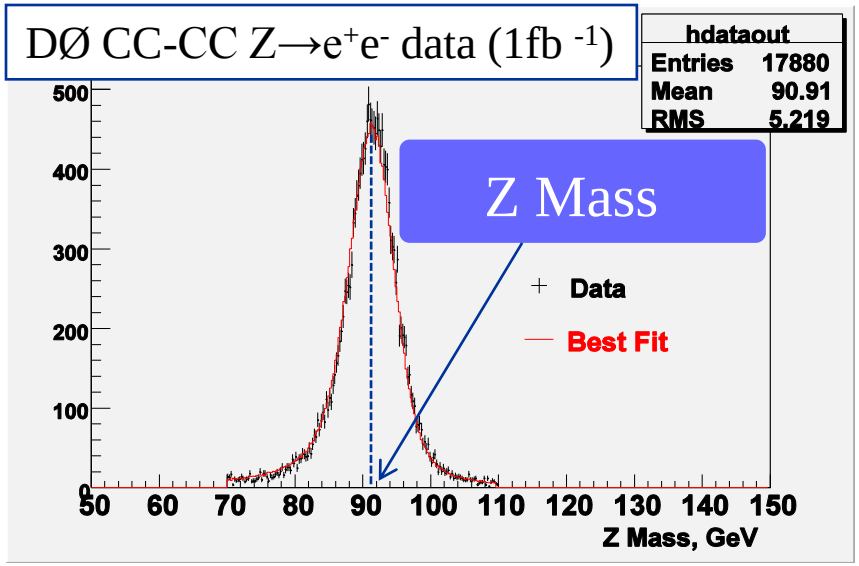
~55000 readout channels

50 dead channels



Measuring M(W)

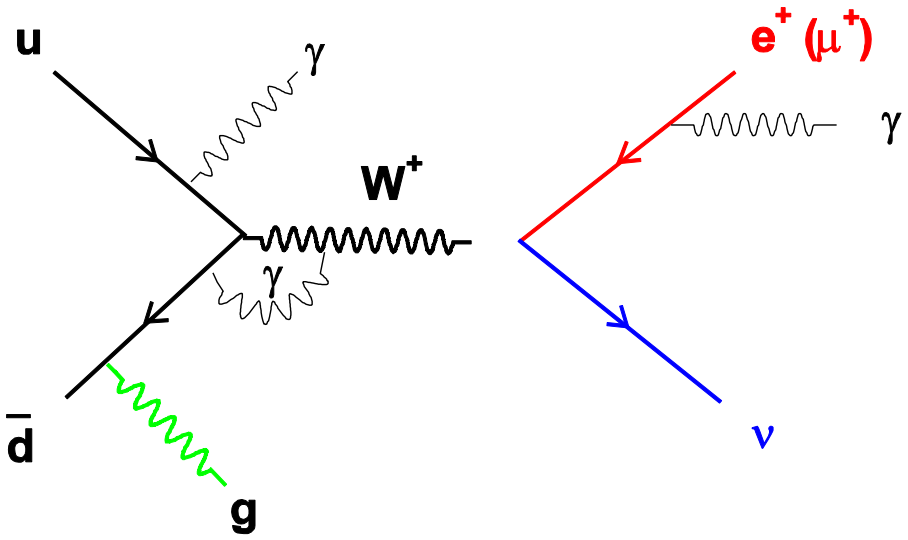
- How do we measure mass of a particle ?
- Direct mass reconstruction
  - calculate invariant mass using 4-vectors of its decay products
  - fit the data with characteristic lineshape to extract mass
  - example: M(Z) from Z→e+e- decay



- (DØ uses W→eν decay mode for M(W) measurement)
- Cannot reconstruct M(W) directly (missing neutrino p_z)
- Extract it from observables that are sensitive to M(W) , e.g. "transverse "mass

$$M_T = \sqrt{2 p_T^e \, p_T^\nu \, (1 - \cos \phi_{e\nu})}$$

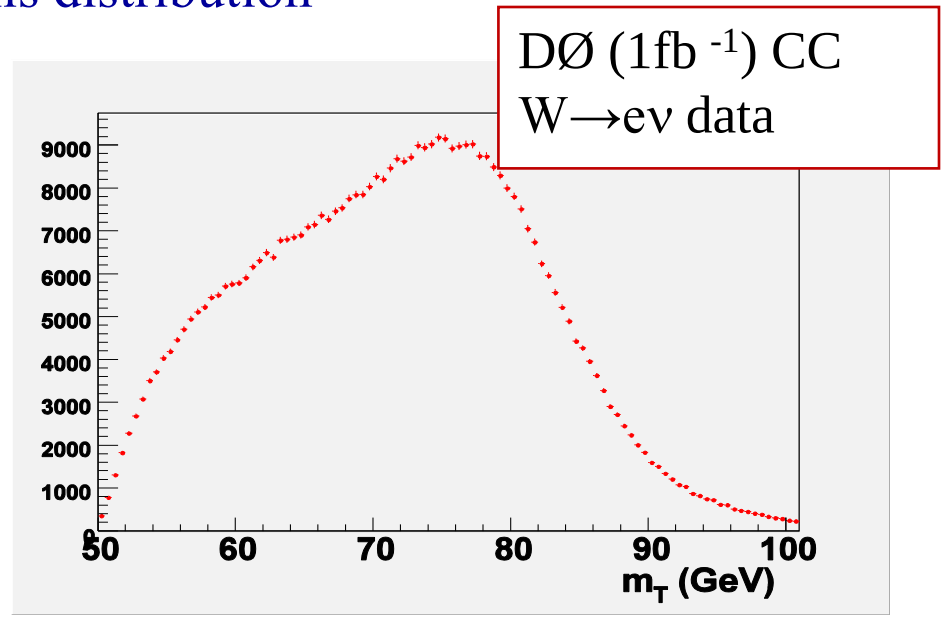
W→eν Event: Theory View



$$M_T = \sqrt{2 p_T^e \, p_T^\nu \, (1 - \cos \phi_{e\nu})}$$

Measuring M(W) (Cont'd)

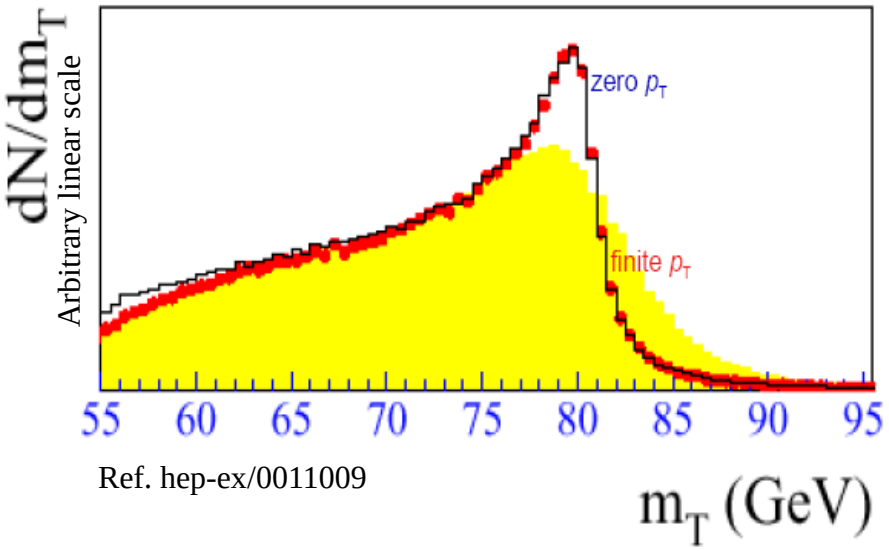
- M(W) number is "hidden" in this distribution



- How do we extract it ?

- Which effects are responsible for this shape?
  - W boson natural width
  - motion of the W boson before its decay
  - detector effects

What Affects Observable Shapes



Ref. hep-ex/0011009

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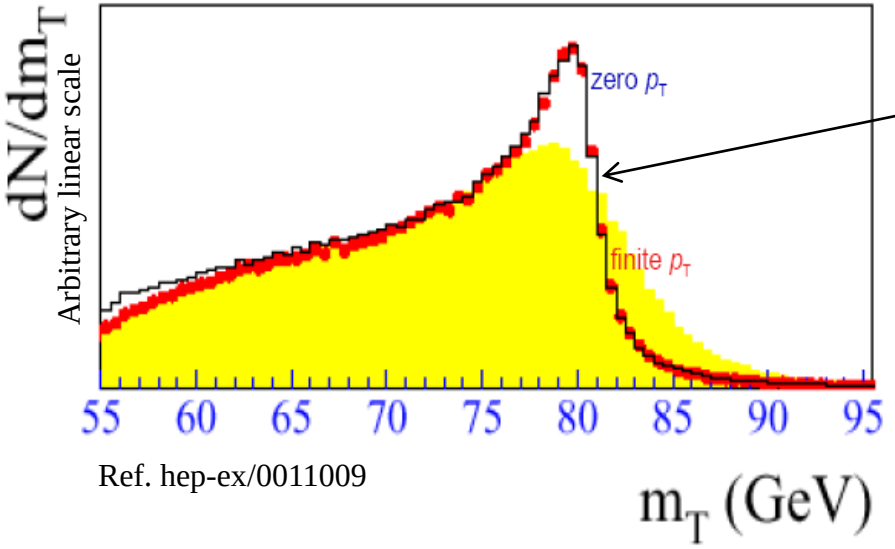

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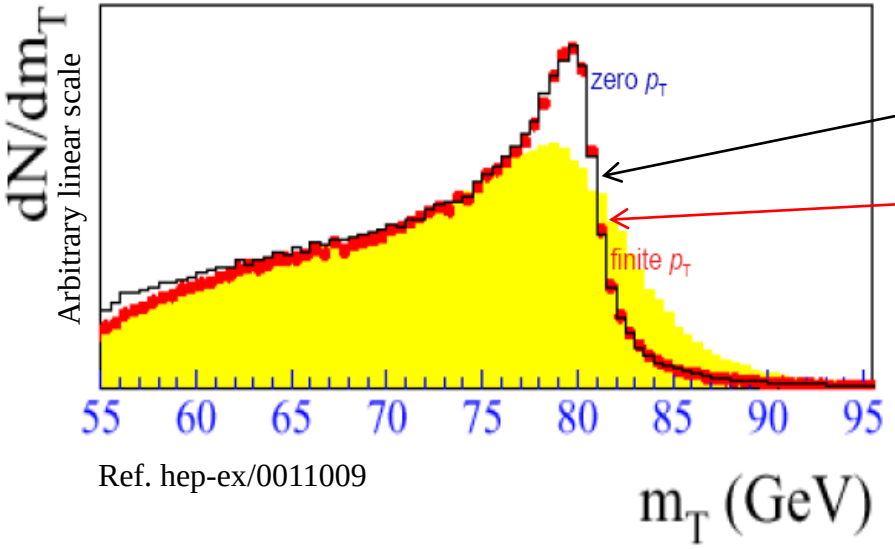
W boson at rest ($P_T(W)=0$), no detector effects

What Affects Observable Shapes



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W boson at rest ($P_T(W)=0$), no detector effects

$P_T(W)\neq 0$ included, still no detector effects

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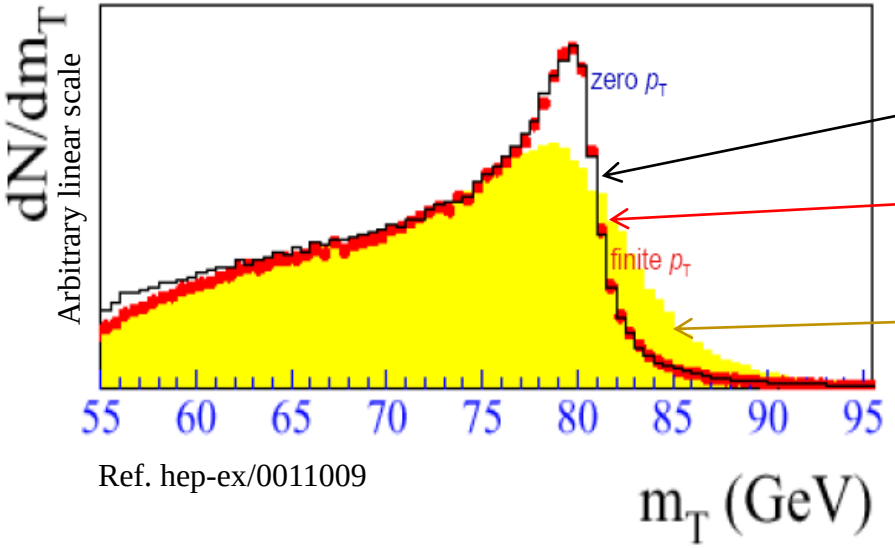

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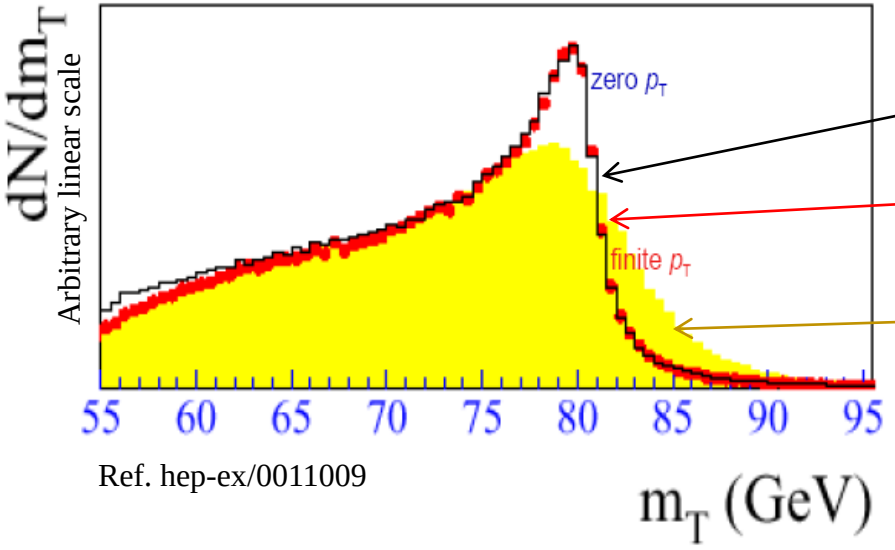
$P_T(W)\neq 0$ included, still no detector effects

detector effects added

What Affects Observable Shapes



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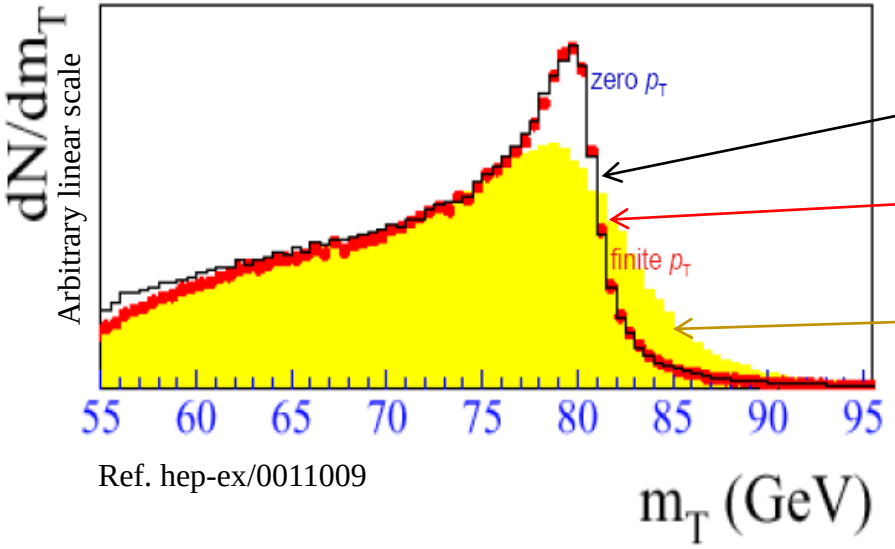
W boson at rest ($P_T(W)=0$), no detector effects

$P_T(W)\neq 0$ included, still no detector effects

detector effects added

What about other observables e.g. electron p_T ($p_T(e)$) ?

What Affects Observable Shapes



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W boson at rest ($P_T(W)=0$), no detector effects

$P_T(W)\neq 0$ included, still no detector effects

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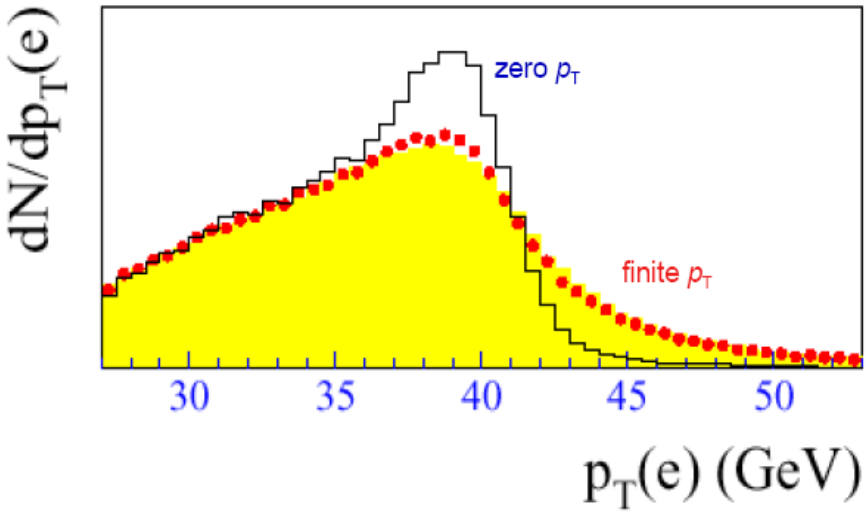


compare m_T (top plot)

and

$p_T(e)$ (bottom plot)

m_T mostly affected by detector effects

$p_T(e)$ mostly affected by $p_T(W)$ effects

$\Rightarrow$ m_T and $p_T(e)$ have complementary systematics

Measuring M(W) (Cont'd)

- Cannot reconstruct M(W) directly (missing neutrino p_z)
- Extract it from observables that are sensitive to M(W) , e.g. "transverse "mass

$$M_T = \sqrt{2 p_T^e \, p_T^\nu (1 - \cos\phi_{e\nu})}$$

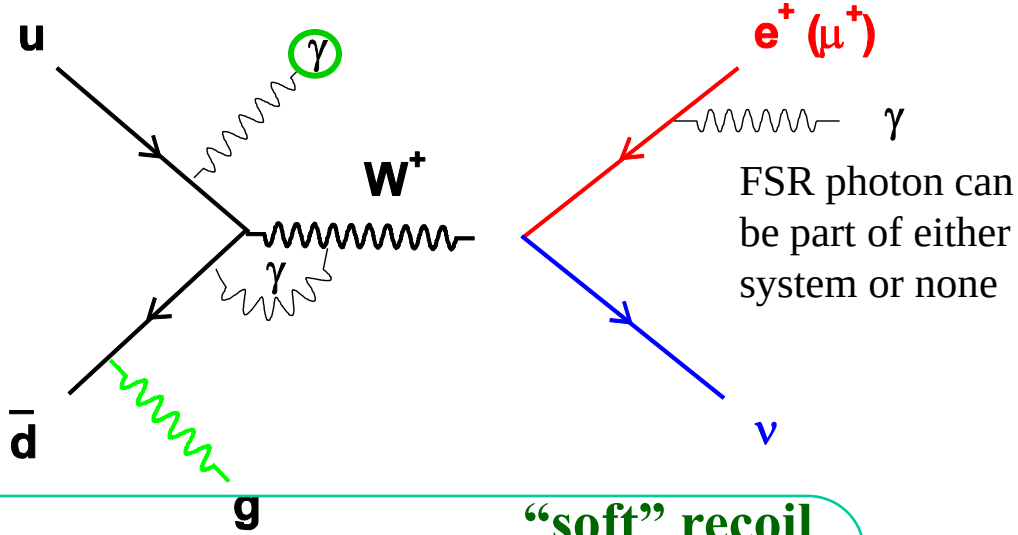
- Due to complicated detector effects analytical computation impossible
- Determine M(W) via template fit
- Need Fast Monte Carlo model of detector effects
- Also need a good model of P_T(W)

- Use three observables:

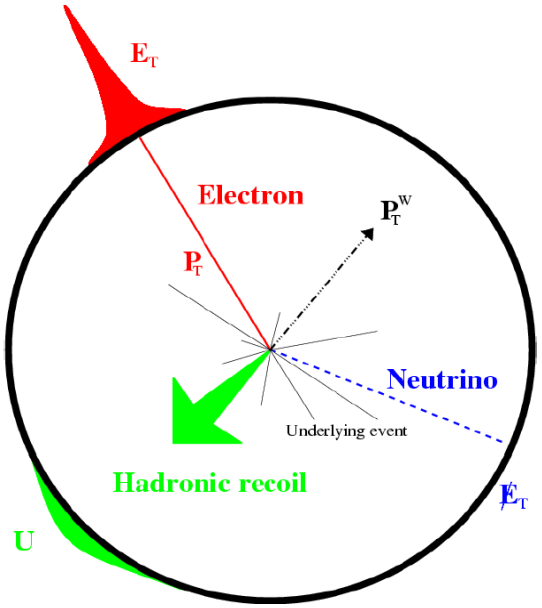
$M_T = \sqrt{2 p_T^e \, p_T^\nu (1 - \cos\phi_{e\nu})}$ $\quad p_T^e \quad p_T^\nu \left(\not{E}_T = \left| \vec{p}_T^{\,e} + \vec{p}_T^{\,recoil} \right| \right)$

W→eν Event: Theory and Analysis View

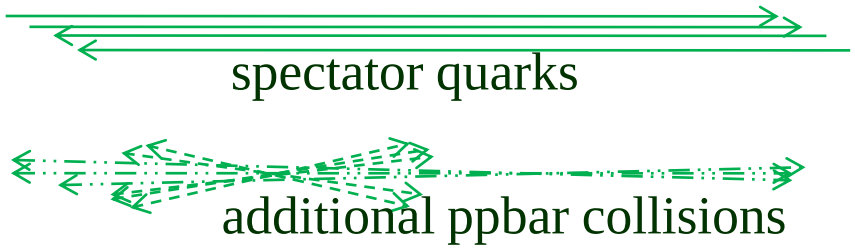
"hard" recoil = recoil against W



FSR photon can be part of either system or none



"soft" recoil



$$\vec{\not{E}}_T = -\vec{p}_T^{\,e} - \vec{p}_T^{\,recoil}$$

In the analysis we think of the W→eν (and Z→ee) events as

Electron system + **Recoil**

Electron Energy Scale

- W mass precision is controlled by electron energy scale precision
- Fractional uncertainty of energy scale translates into fractional uncertainty on the W mass
- Total fractional uncertainty with $1fb^{-1}$ was $\Delta M_W/M_W \approx 0.5\times10^{-3}$

Required detector response precision: **electron** $\sim 0.5 \times 10^{-3}$; **hadronic recoil** **~ 1%**

- Good calibration of electron showers in the calorimeter is crucial
- Use Z→ee data sample for calibration, set energy scale with Z mass measured by LEP with very high precision

measurement of W/Z mass ratio ⇒ many systematic effects cancel

Stages of Electron Energy Calibration

- Cell-level
  - pulser calibration *(ADC → collected charge)*
  - sampling fractions *(collected charge → total deposited energy)*
- Cluster – level
  - energy loss corrections
  - inter-φ calibration
  - η equalization and absolute scale
  - layer inter-calibration
- Final M_W calibration

Final Calibration

- After data calibration is performed , Fast MC fine-tune calibration is done
- Linear response model : E_measured(e) = **α** × E_true(e) + **β**

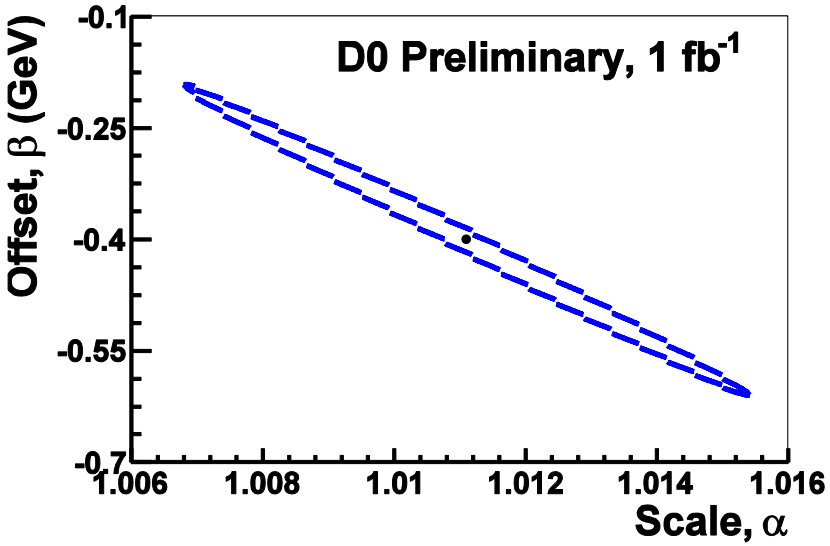
  α → scale **β** → offset
- Use Z → ee electrons to constrain **α** and **β** (precision limited by statistics)
- Two observables to fit the data
  - Z → ee invariant mass
  - f_Z variable "scans" the response as a function of energy

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

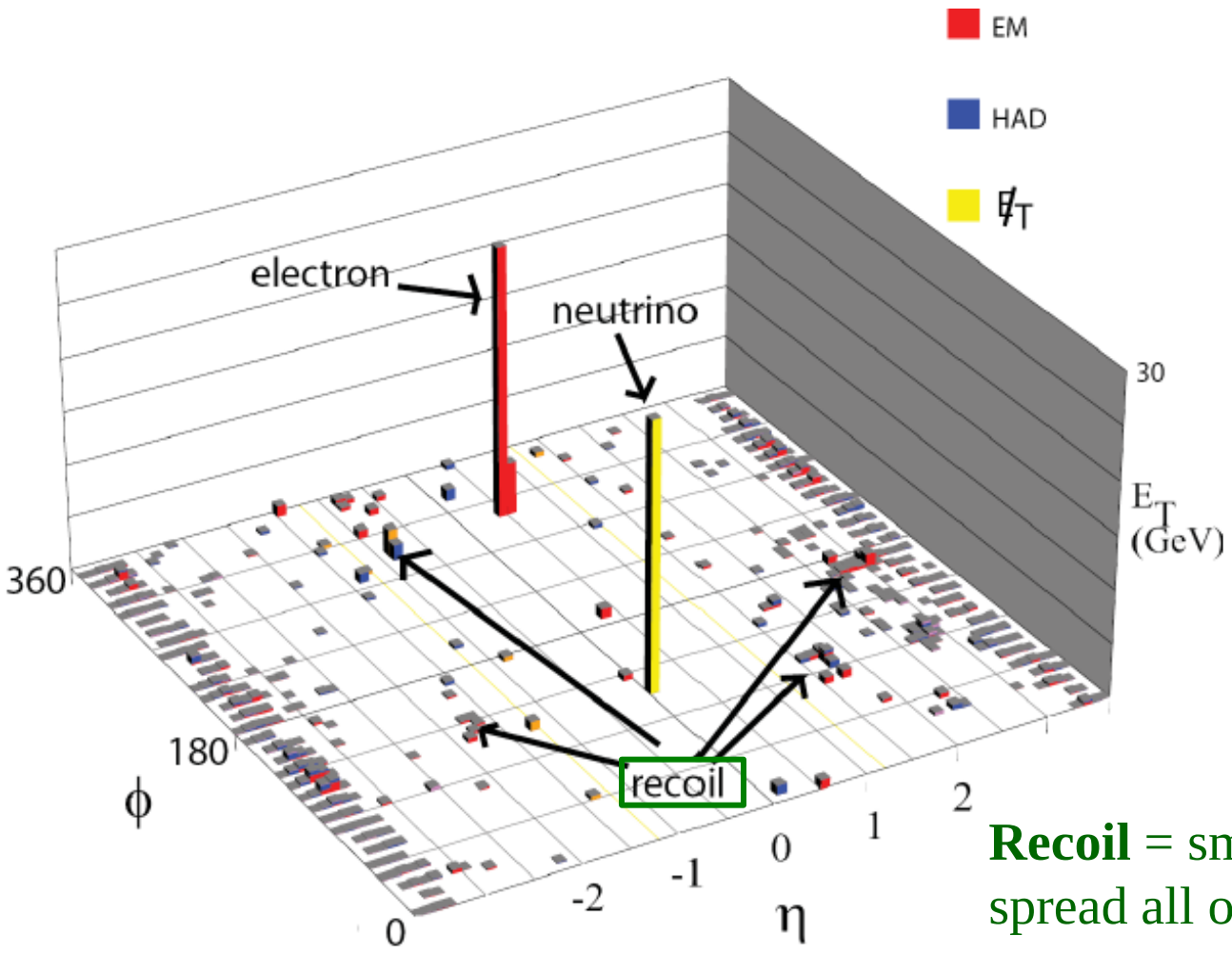
$\alpha = 1.0111 \pm 0.0043$
$\beta = -0.404 \pm 0.209$ GeV
correlation = -0.997

⇒ dominant systematic error,

100 % correlated between three observables



Event Display of W→eν Candidate at DØ

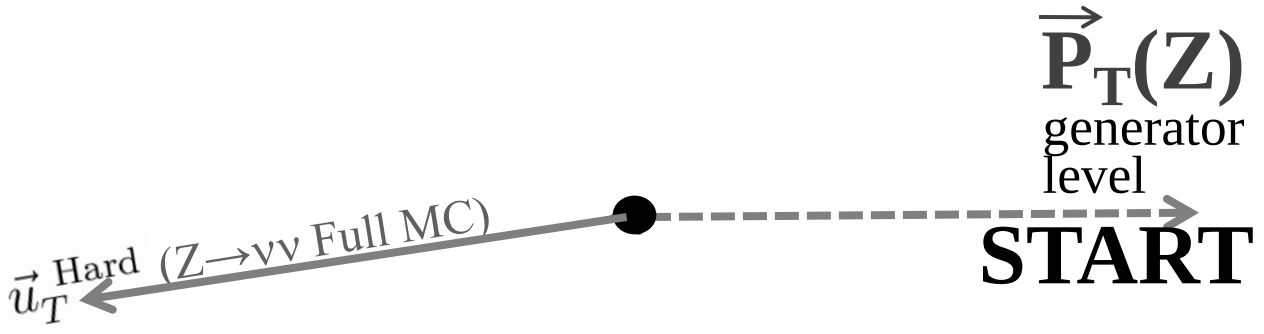


Recoil = small energy deposits spread all over the detector

⇒ sensitivity to small effects, challenges for modeling

Recoil (U_T) Model

P_T(W) vs. P_T(Z) difference due to physics is small compared to recoil resolution effects – use same model, tune to Z data.



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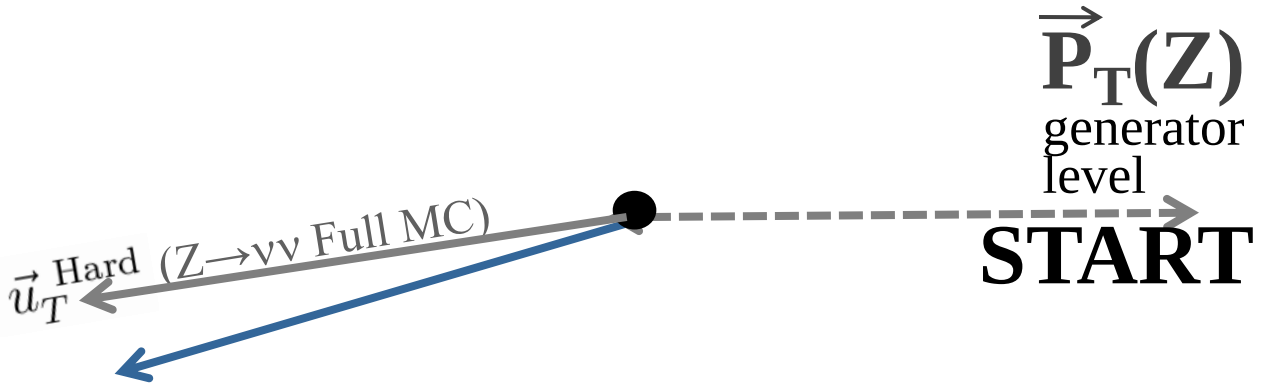

$$\Delta\phi \times \text{RelPhiA} + \text{RelPhiB}/\sqrt{q_T}$$

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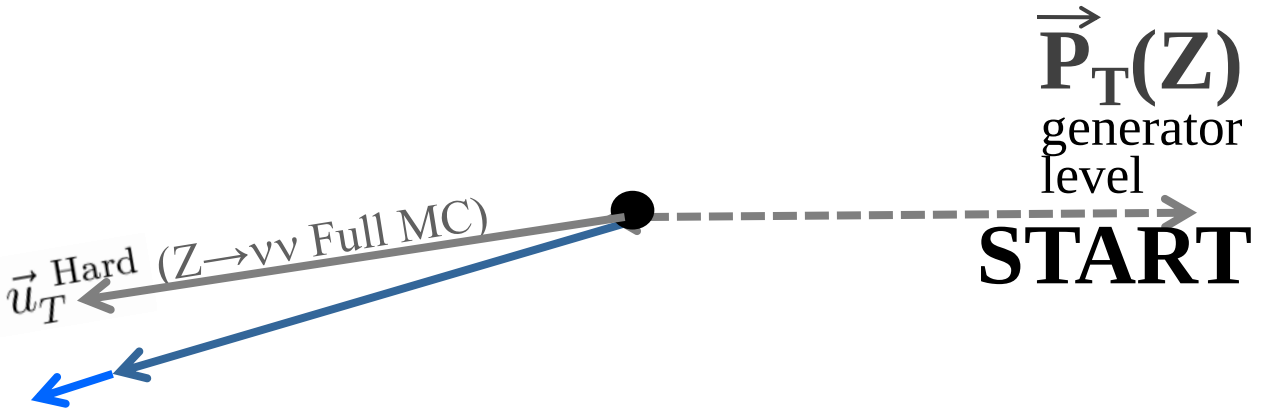

$$\Delta\phi \times \boxed{\text{RelPhiA} + \text{RelPhiB}/\sqrt{q_T}}$$

$$\left|\vec{u}_T^{\,Hard}\right| \times \boxed{\texttt{RelScale} + \texttt{RelOffset} \cdot \exp\frac{-q_T}{\tau_{\texttt{HAD}}}}$$

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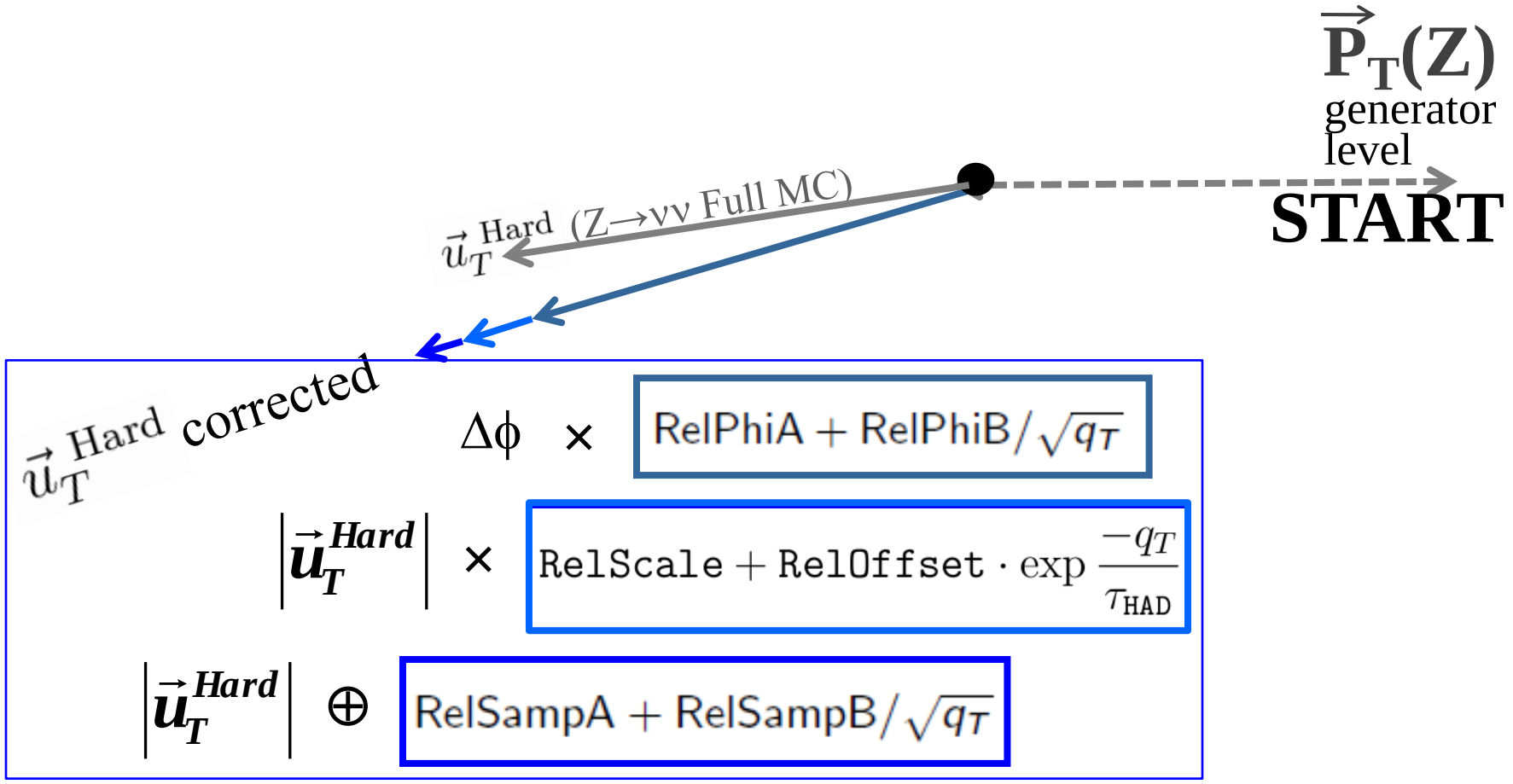

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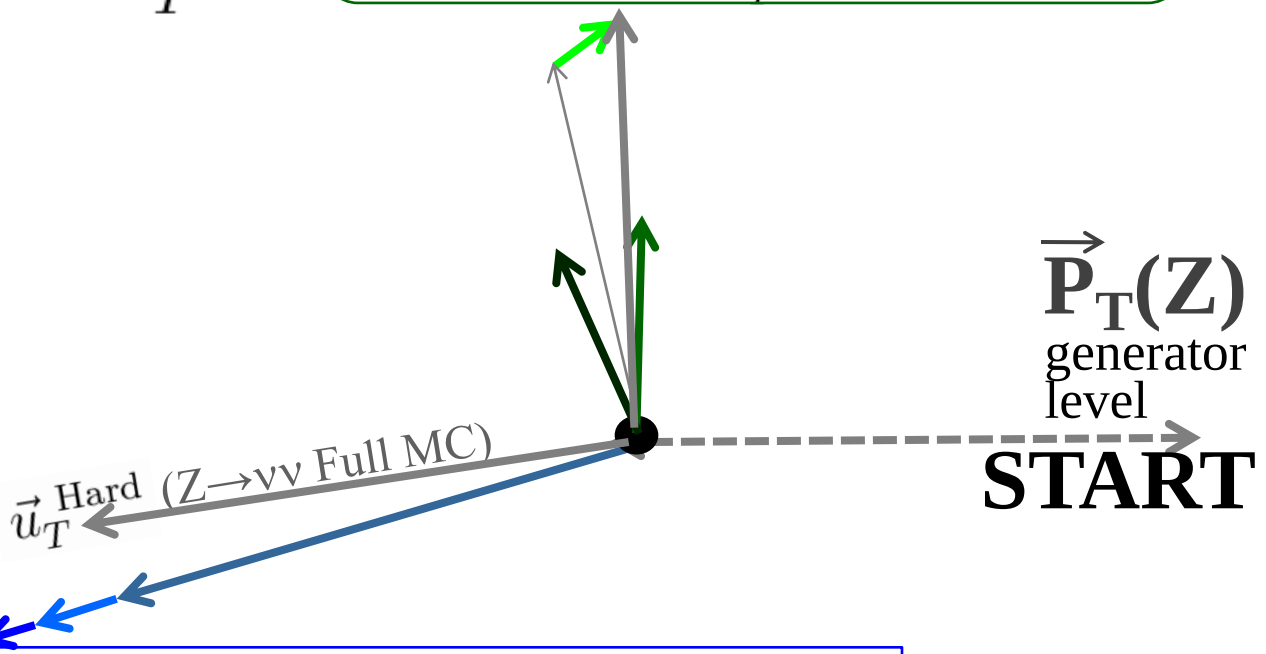

$\vec{u}_T^{\,\text{Hard}}$ corrected

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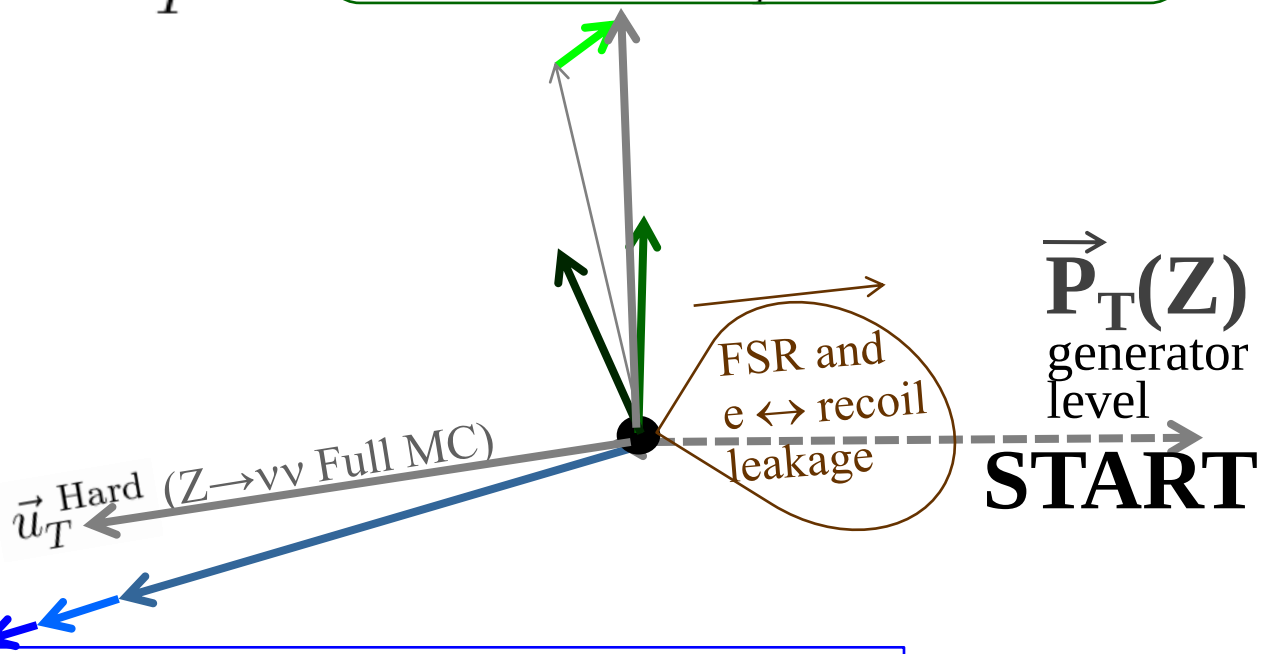

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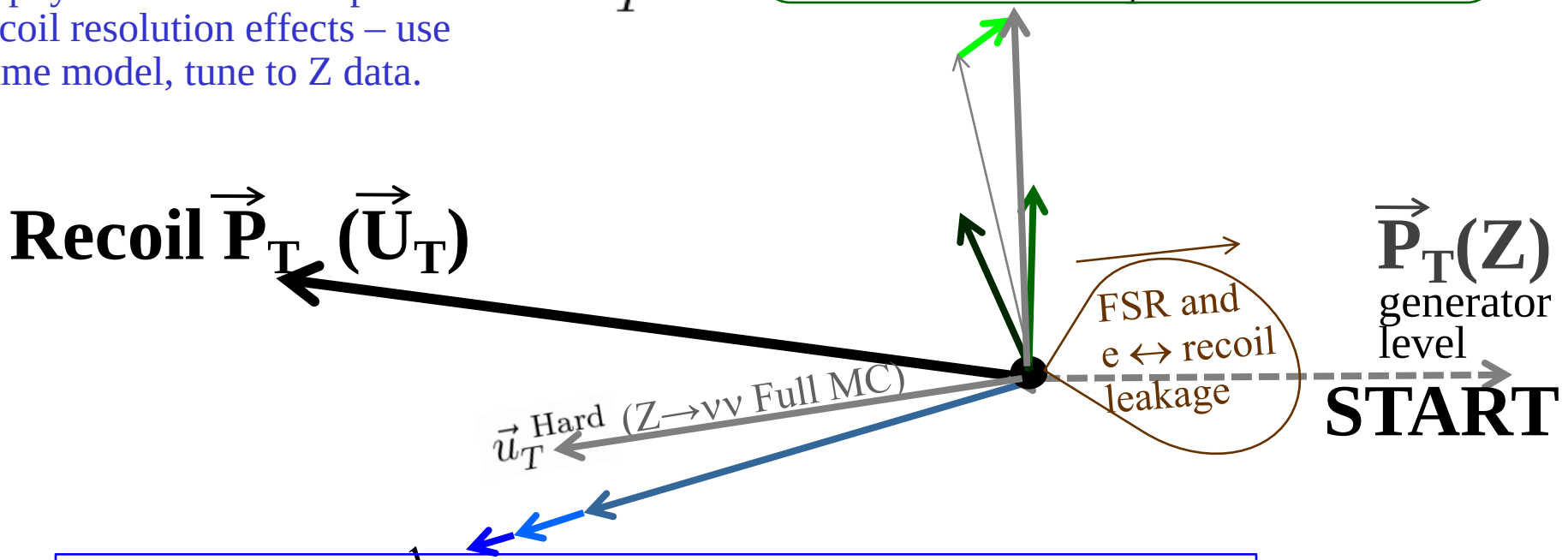

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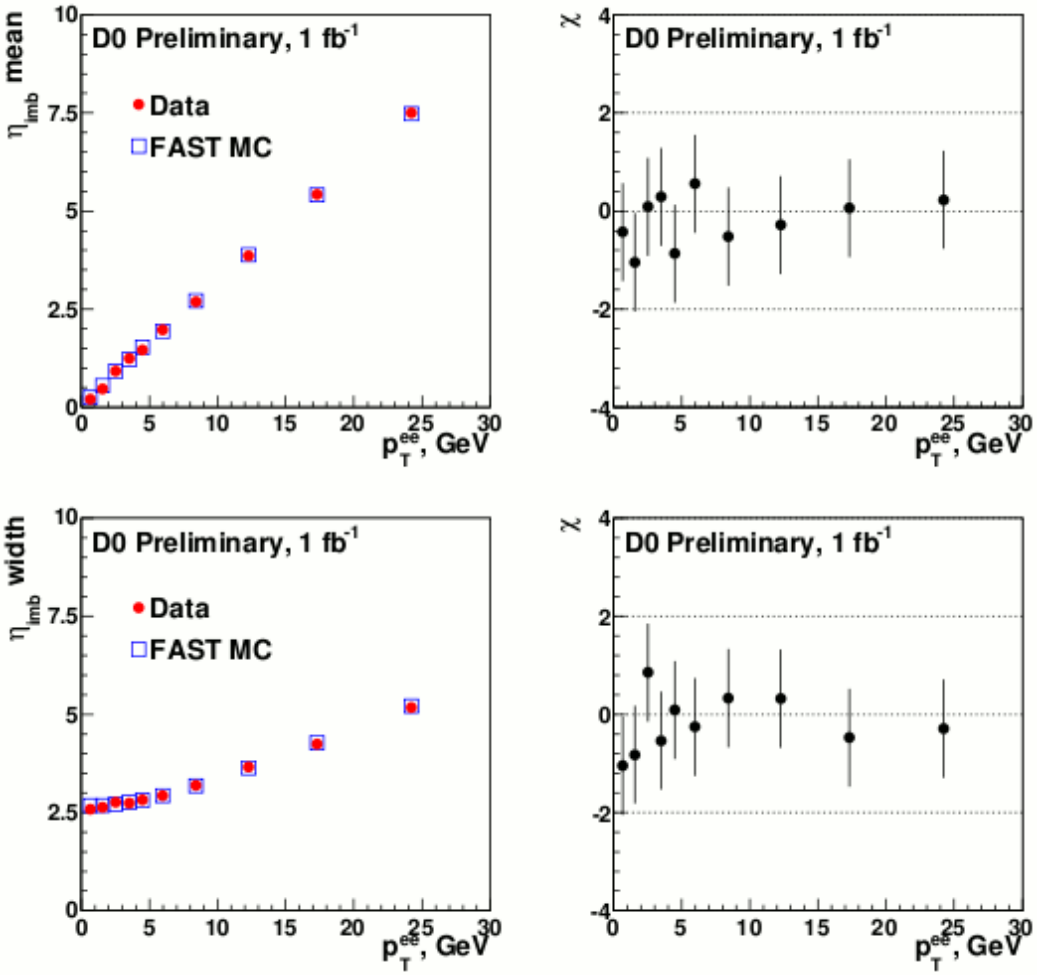
Parameterize small corrections and tune to Z → ee data

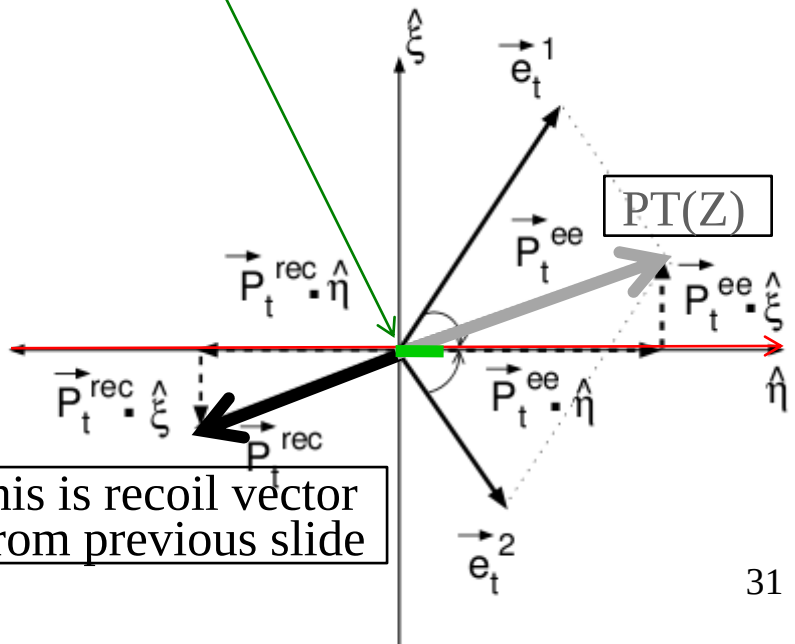
Recoil Calibration

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



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

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



M(W) Measurement Strategy

Generator-Level W→eν Input

Fast Monte Carlo Detector Model

electron

recoil

background modeling

repeat with many M(W) hypotheses

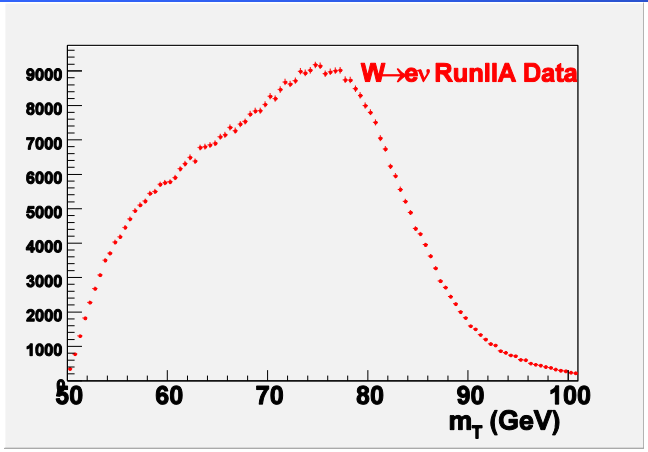
modeled M_T , P_T^e , MET

FIT

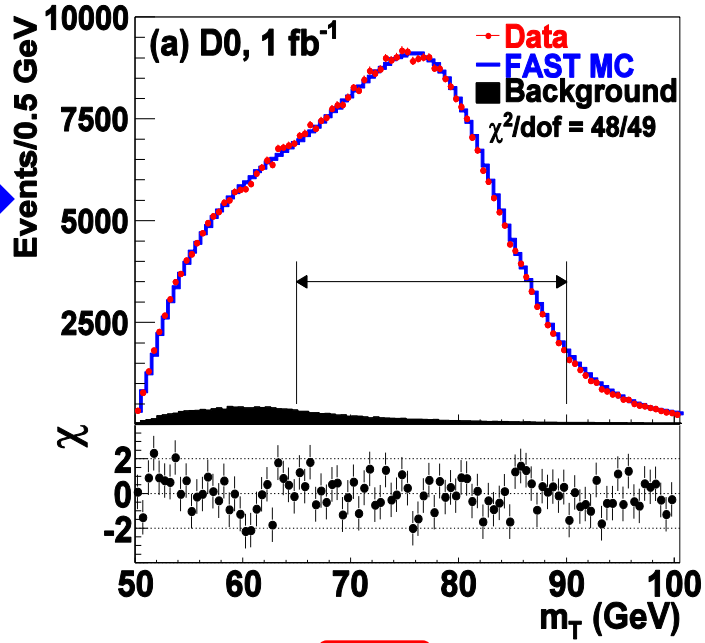
- <u>blinded</u> measured M(W) value
- evaluate uncertainty
- collaboration approval
- un-blinding ⇒ result

understand, calibrate detector

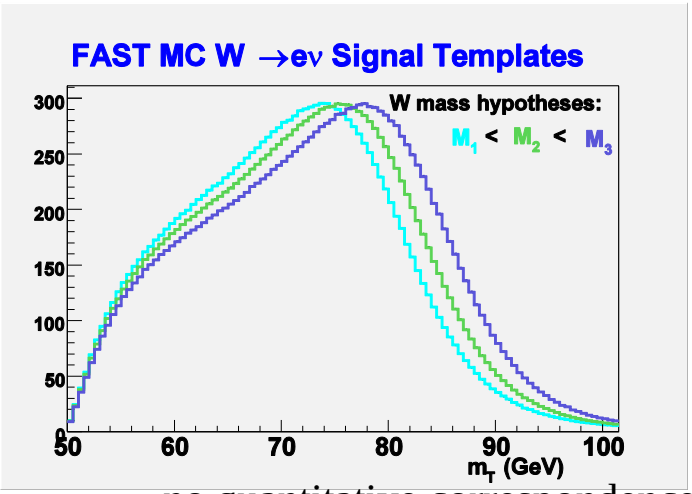
Template Fit



best fit

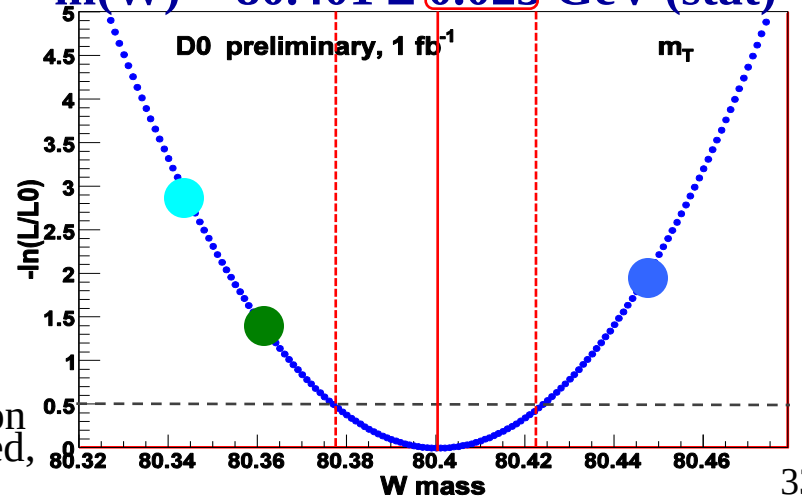


template fit



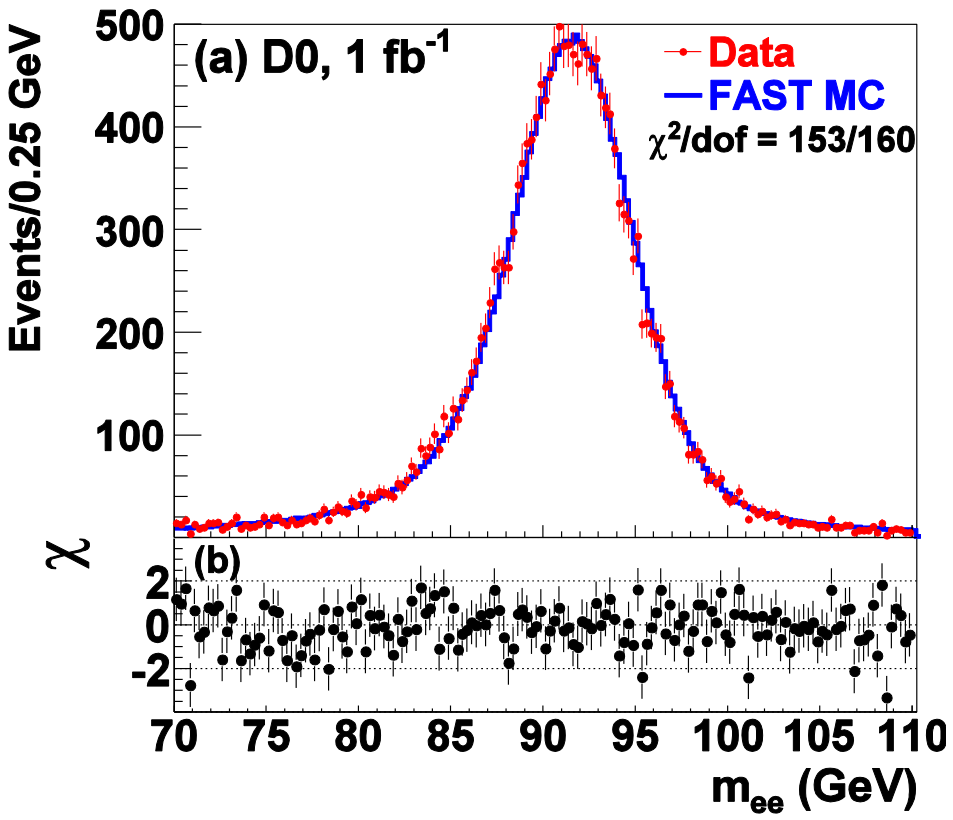
+ background model

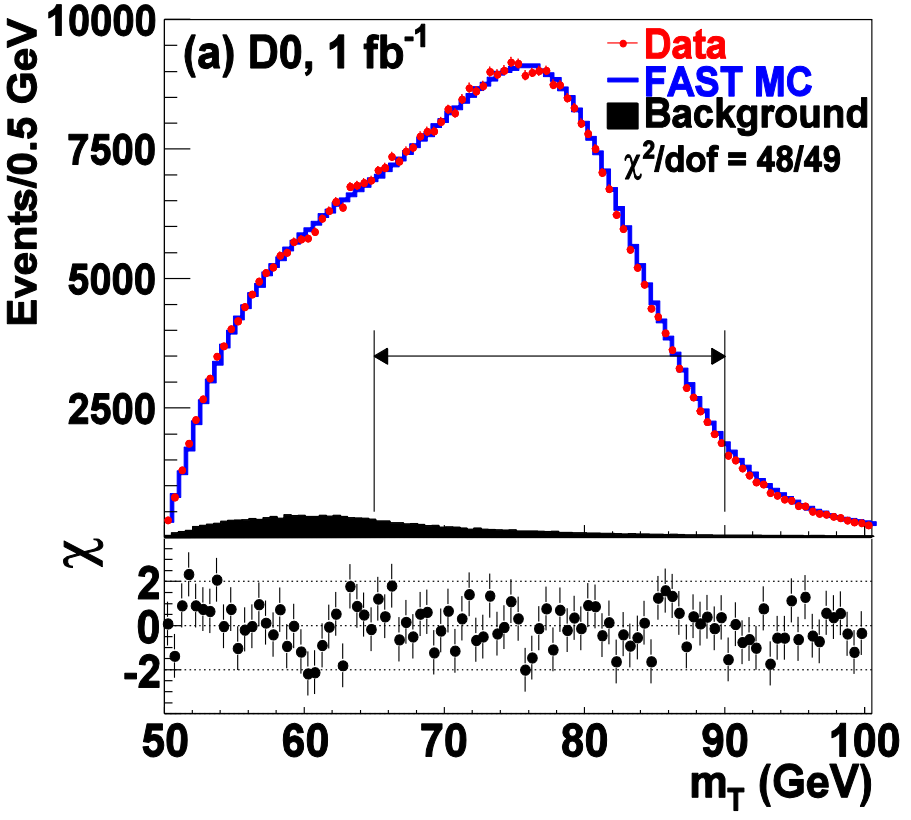
m(W) = 80.401 ± 0.023 GeV (stat)



no quantitative correspondence between three curves on the left plot and filled circles on the right plot is implied, this is a qualitative illustration

Mass fits: M(Z), M_T(W)



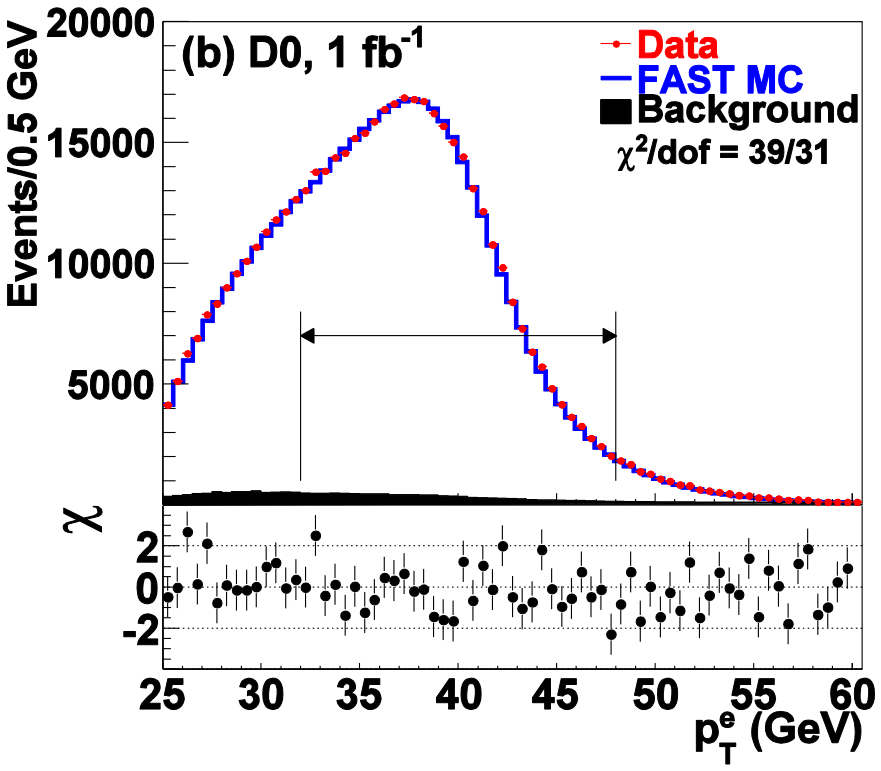


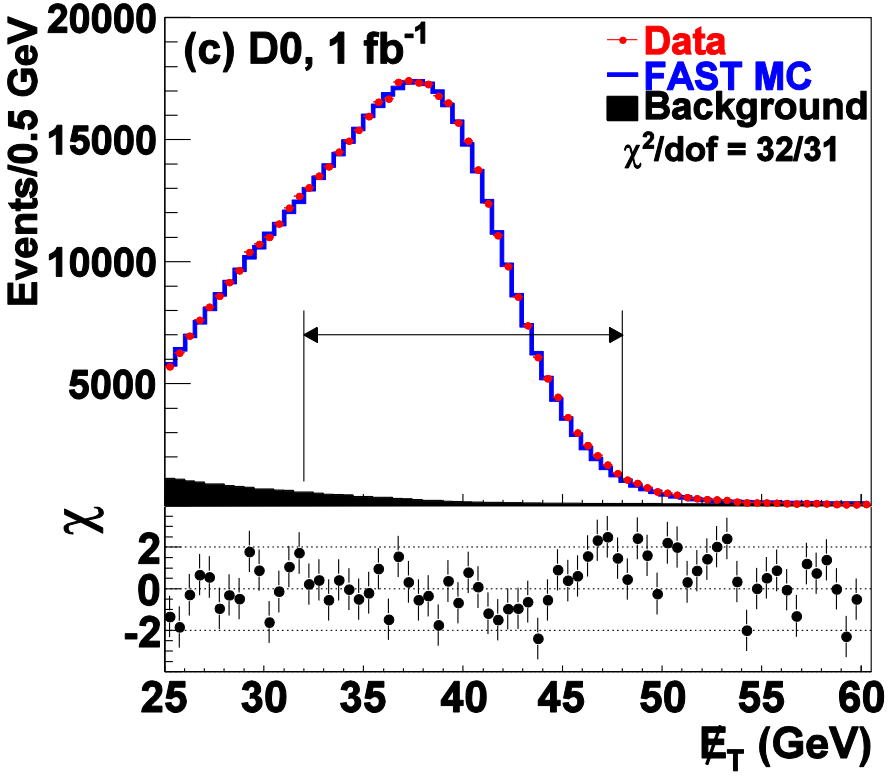
m(Z) = 91.185 ± 0.033 GeV (stat)

m(W) = 80.401 ± 0.023 GeV (stat)

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

Mass fits: $P_T(e)$, MET

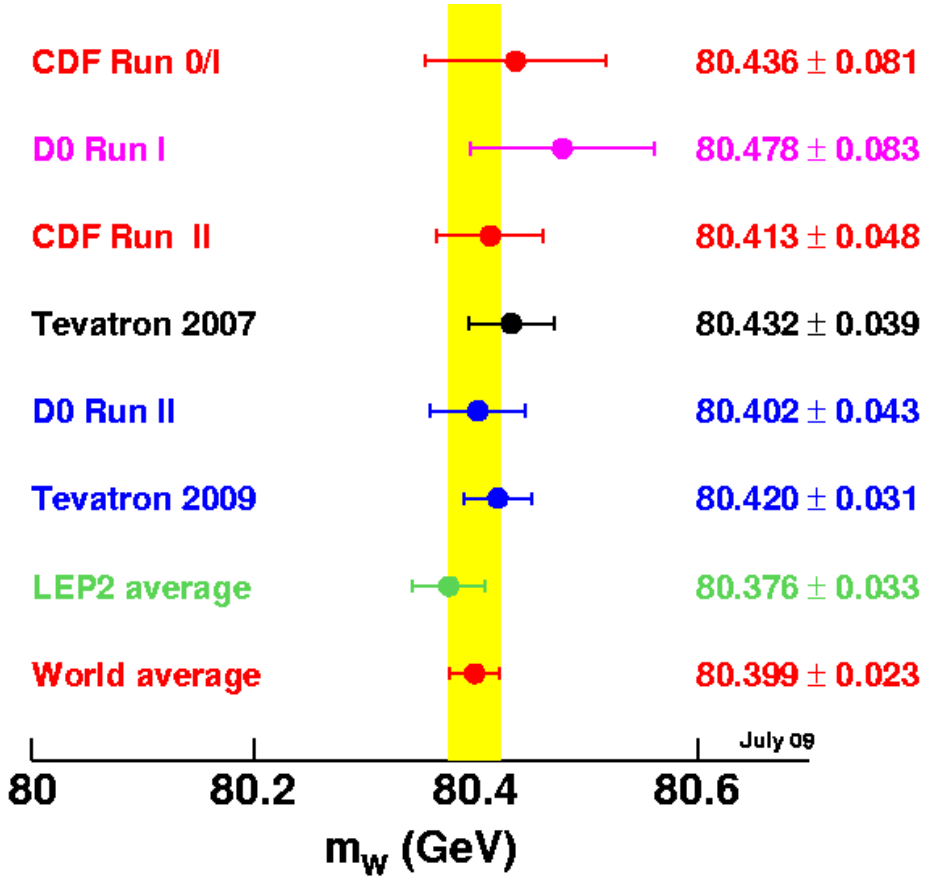




m(W) = 80.400 ± 0.027 GeV (stat)

m(W) = 80.402 ± 0.023 GeV (stat)

DØ 1fb^{-1} W Mass Result



TEVEWWG/WZ 2009/01
FERMILAB-TM-2439-E

DØ RunII 1fb^{-1} PRL 103, 141801 (2009)

single most precise measurement of the W boson mass to date

80.401 ± 0.021(stat.) ± 0.038(syst.) GeV
80.401 ± 0.043 GeV

total uncertainty of 31 MeV from Tevatron is smaller than that of 33 MeV from LEPII

World average is now:
80.399 ± 0.023 GeV

CDF RunII 0.2 fb^{-1}
80.413 ± 0.034 (stat.) ± 0.034 (syst.) GeV
80.413 ± 0.048 GeV

M(W) Uncertainties, MeV (DØ)

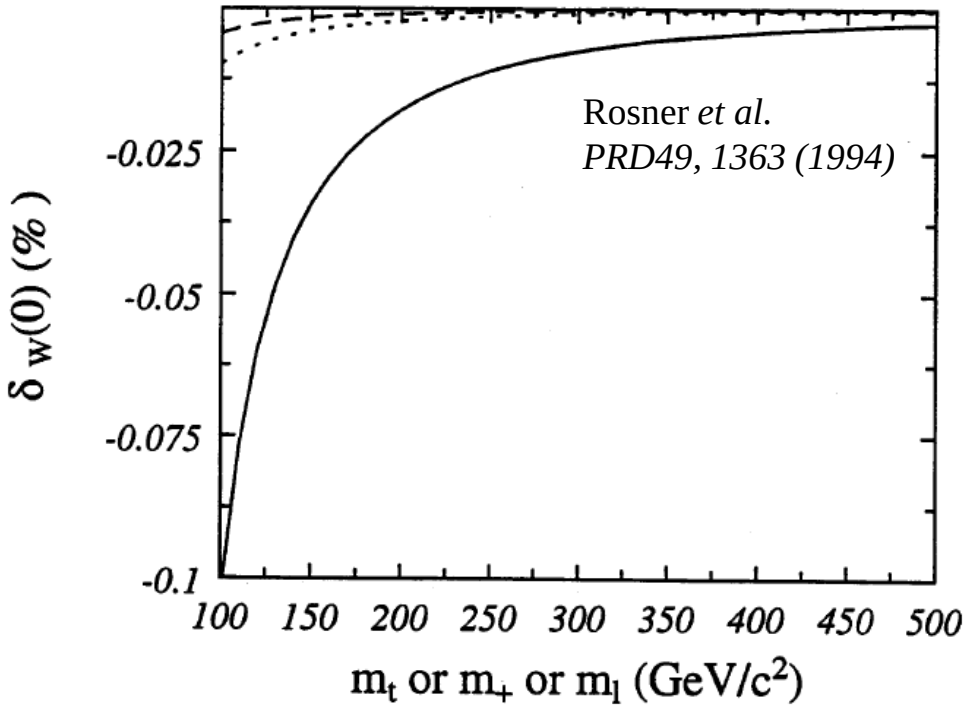
Source	m_T	p_T^e	$\not{E}_T$
Statistical	**23**	**27**	**23**
Systematic - Experimental			
Electron energy response	34	34	34
Electron energy resolution	2	2	3
Electron energy non-linearity	4	6	7
Electron energy loss differences	4	4	4
Recoil model	6	12	20
Efficiencies	5	6	5
Backgrounds	2	5	4
Experimental 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**	**17**	**17**
Systematic -- Total	**37**	**40**	**44**

in the near future expect reduction of experimental errors and increased importance of theoretical errors

1 fb^{-1} W Boson Width Analysis

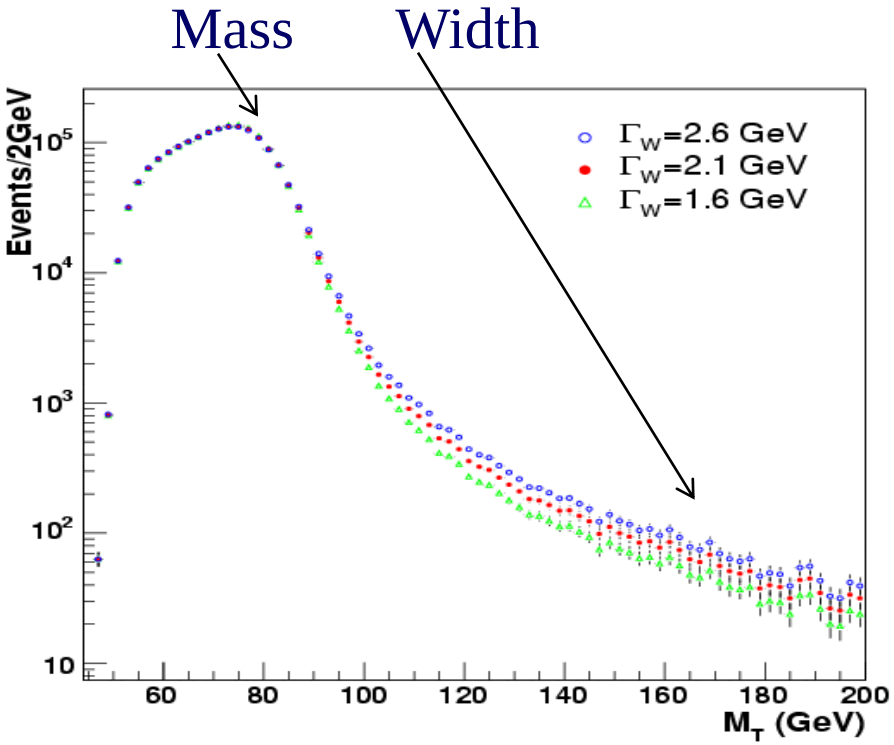
Γ(W)

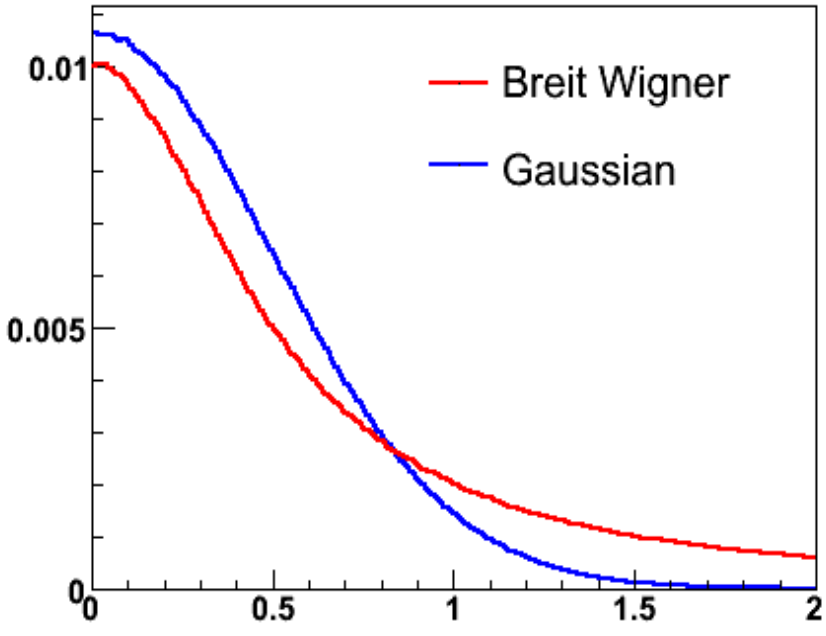
Due to insensitivity to “oblique” corrections,
W boson width is expected to agree with the SM
prediction almost regardless of new physics



Γ(W) (Cont'd)

Exploit high tail of M_T(W) distribution





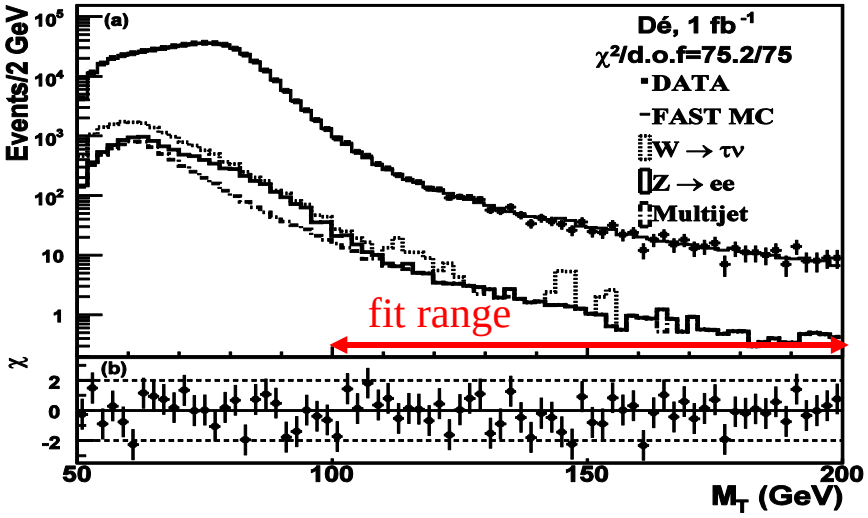
Width, to LO, is proportional to the fraction of events at high M_T

Breit-Wigner falls off slower than Gaussian resolution

Γ(W) Results

DØ Γ_W = 2.028 ± 0.038 (stat) ± 0.061 (syst) GeV = 2.028 ± 0.072 GeV

PRL 103 231802(2009)



Source	$\Delta\Gamma_W$ (MeV)
Electron energy scale	33
Electron resolution model	10
Recoil model	41
Electron efficiencies	19
Backgrounds	6
PDF	20
Electroweak radiative corrections	7
Boson p_T	1
M_W	5
Total Systematic	61

Standard Model $\Gamma_W = 2.093 \pm 0.002$ GeV

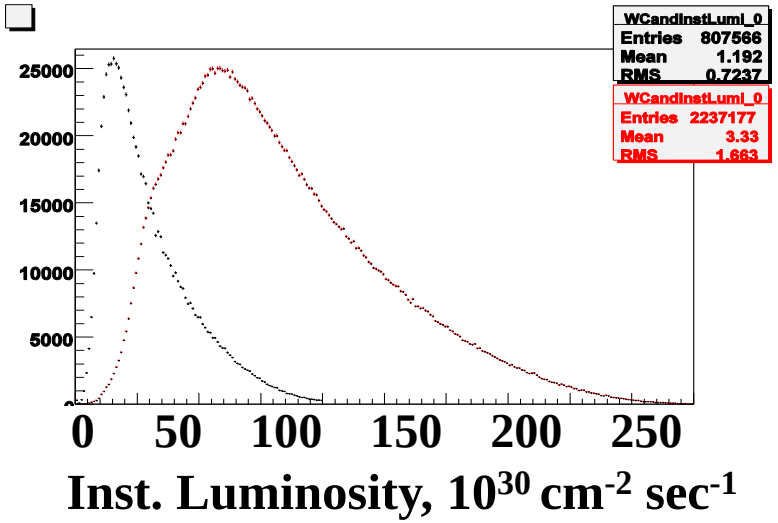
Tevatron $\Gamma_W = 2.046 \pm 0.049$ GeV

LEP $\Gamma_W = 2.196 \pm 0.083$ GeV

4 fb^{-1} W Mass Analysis

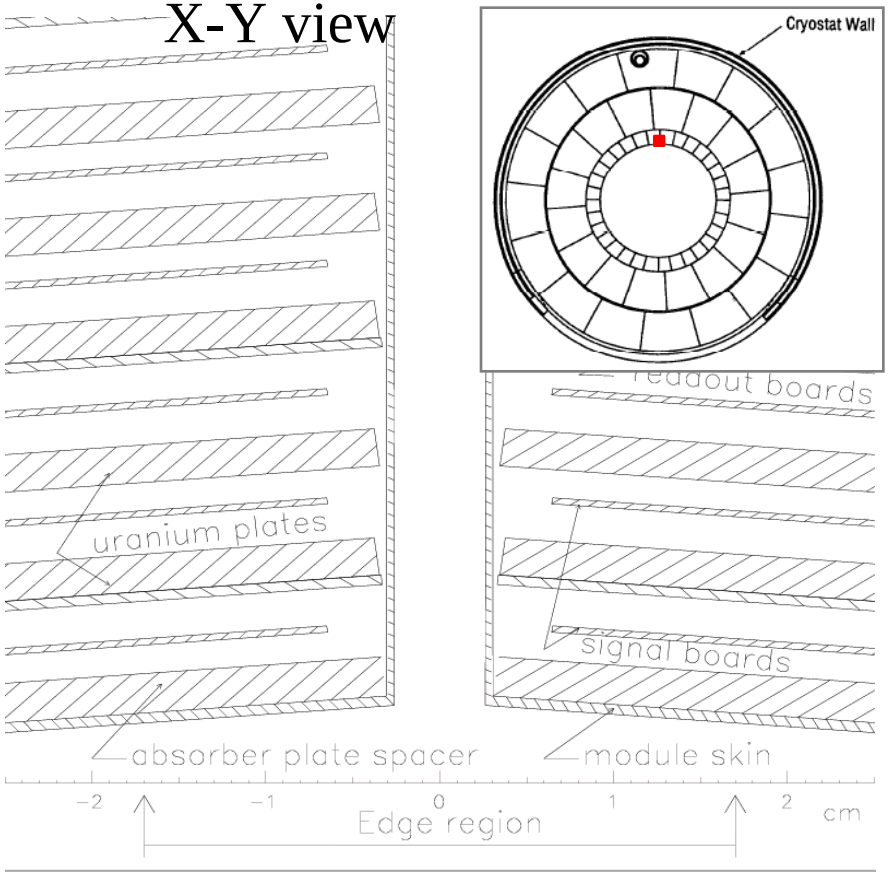
Specific Features of 4 fb^{-1} Analysis

- Dominant systematic error is expected to scale with the number of events
- Theoretical errors become more important / require more careful treatment
- Collisions at significantly higher instantaneous luminosities
  $\Rightarrow$ W$\rightarrow$eν events get more obscured by additional proton-antiproton interactions
- A number of systematic effects not seen with smaller statistics become relevant
  $\Rightarrow$ need to build more sophisticated models
  - Example: modeling detector performance near calorimeter module boundaries



Detector Regions near φ-Module Boundaries

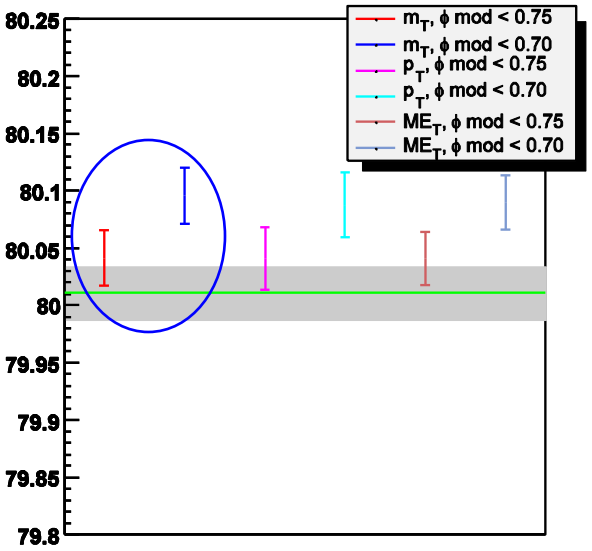
- Perfect azimuthal symmetry of physics interactions gets spoiled by the detector effects
- Near φ-module boundaries electron showers are different
  - different shape (less uranium traversed)
  - sampled differently (less liquid argon / less ionization charge)
  - interactions with support material
- Degradation of both electron energy response and the resolution



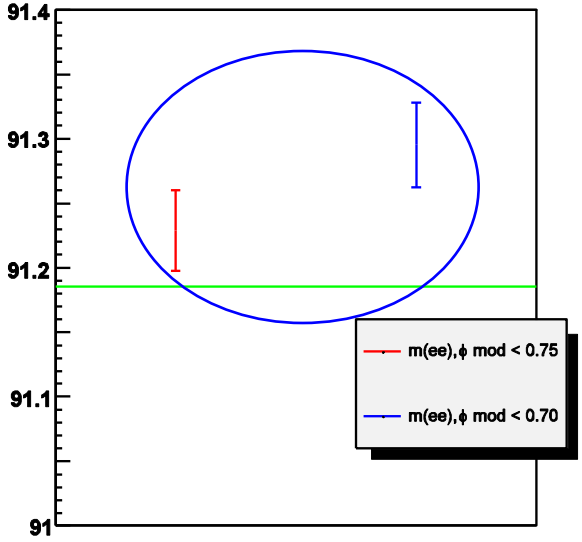
Central calorimeter is not uniform in the azimuthal angle (32 φ-modules)

Effect on measured W and Z mass (1fb^{-1})

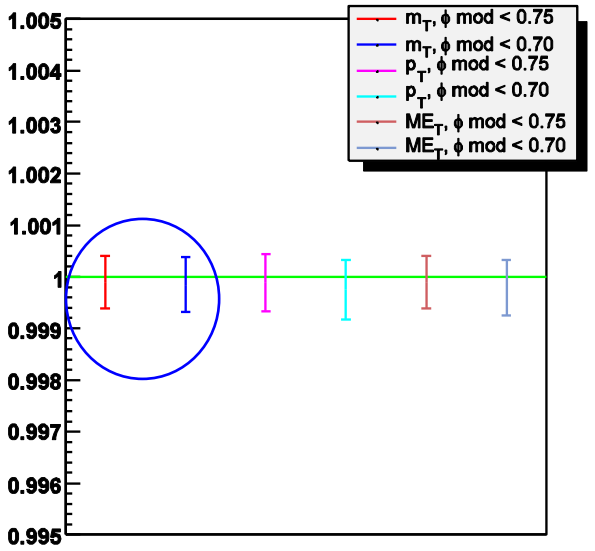
blinded W mass



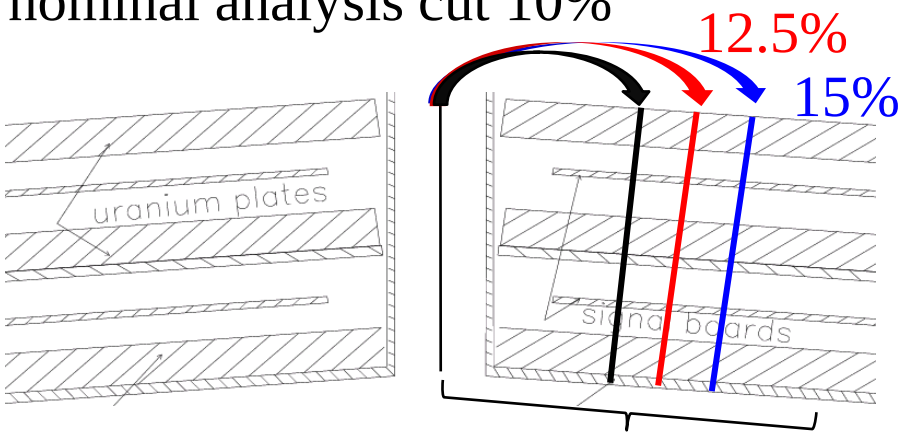
Z mass



relative change in W/Z mass ratio



nominal analysis cut 10%

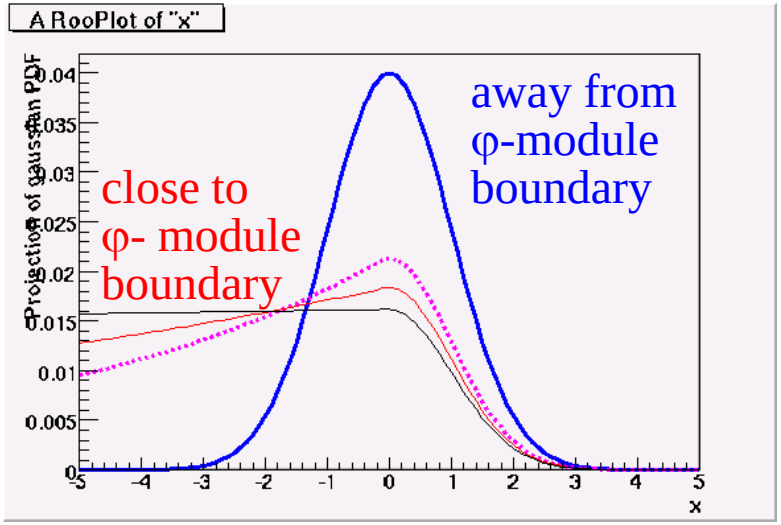


The effect cancels in the W/Z ratio;
but we need to do better than that
⇒refine electron model in Fast MC

Electron Energy Response and Resolution near φ-Module Boundaries

Fast MC Model

Electron Energy Resolution



Electron Energy Response

α → scale, **β** → offset

away from φ-module boundary

$$E = \alpha \times E_true(e) + \beta - \textbf{extra offset}$$

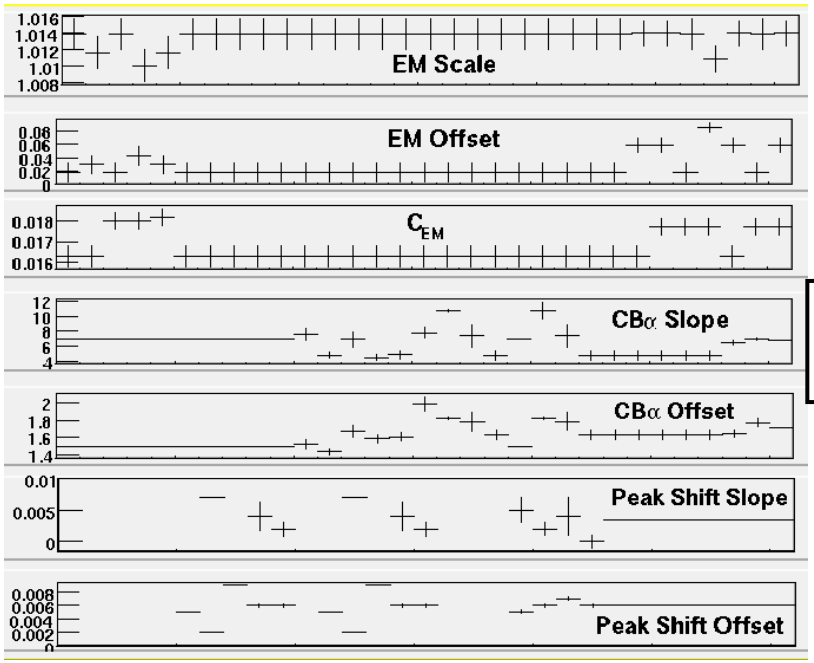
close to φ -module boundary

Observables for tuning Fast MC:
Z → ee mass in 15 bins (categories)
of "distance to the edge of the module"

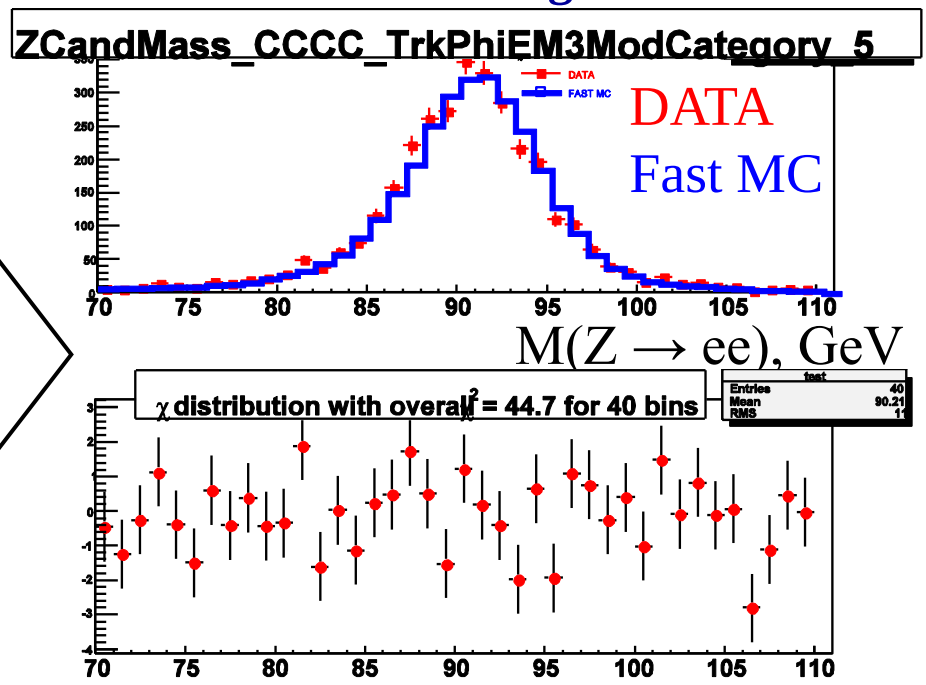
Parameters are correlated with other Fast MC electron model ingredients:
overall scale and offset, constant term of the resolution ⇒ **iterations**

Tuning the Model

model evolution with iterations

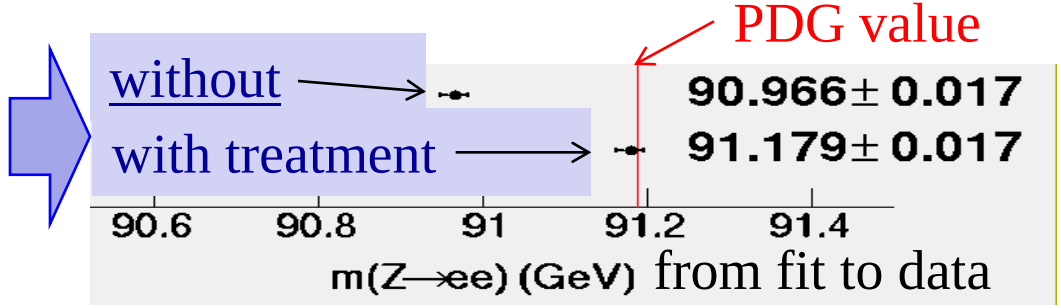


electrons closest to the edge of the module



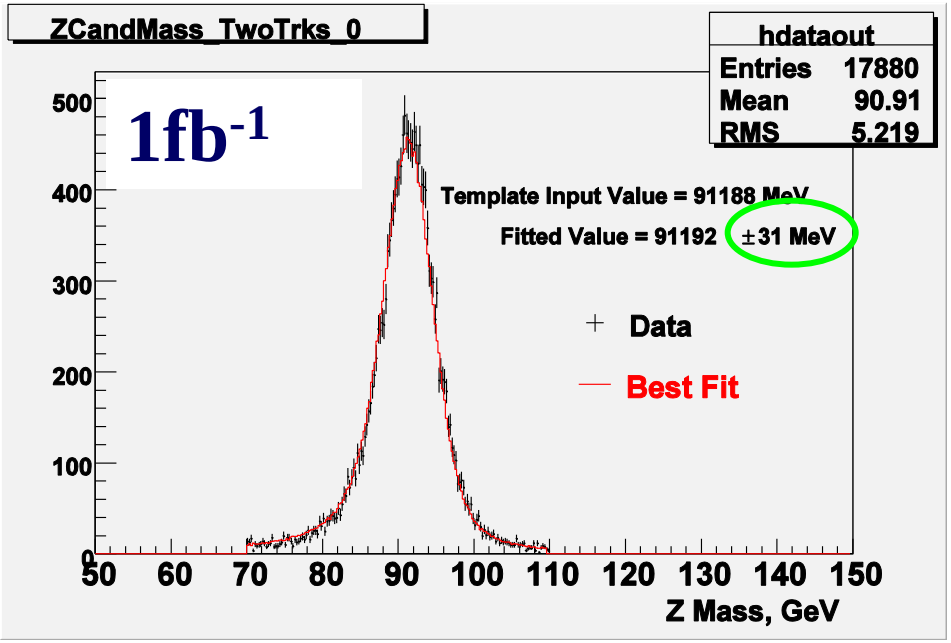
What happens if we do not model the degradation near module boundaries ?

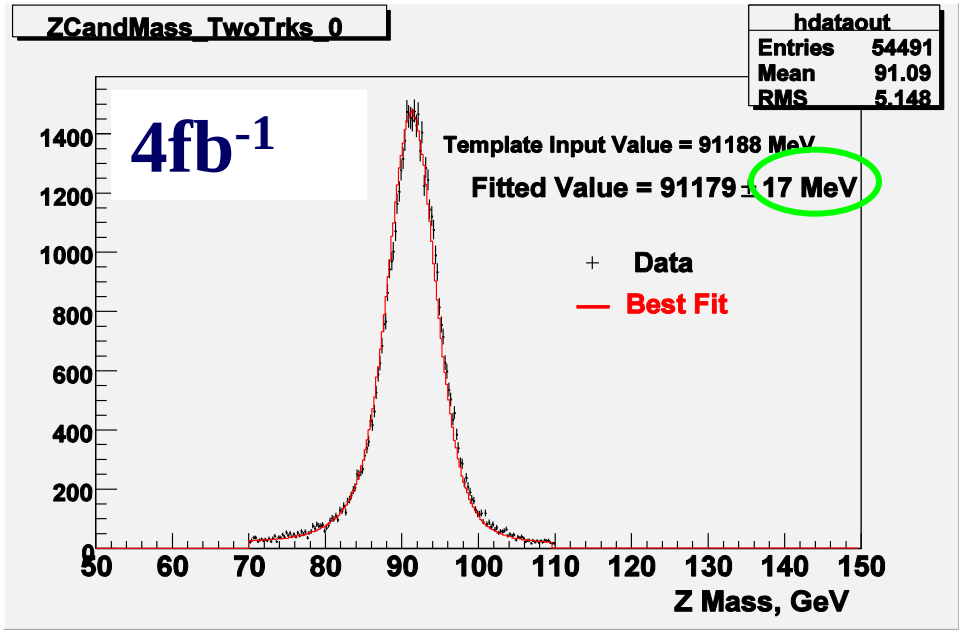
Data-Fast MC fitting prefers lower input mass in Fast MC



Dominant Uncertainty and 4fb^{-1} Prospects

dominant M_W uncertainty:
electron energy scale uncertainty ≈ statistical uncertainty from Z mass fit





M_W uncertainty from electron energy scale (M_T, standard template-based propagation)

34.0 ± 0.9 MeV 15.3 ± 0.4 MeV

⇒ Expect total ΔM_W of ≈25 (22) MeV with 4fb^{-1} (4+1 fb^{-1} combined)

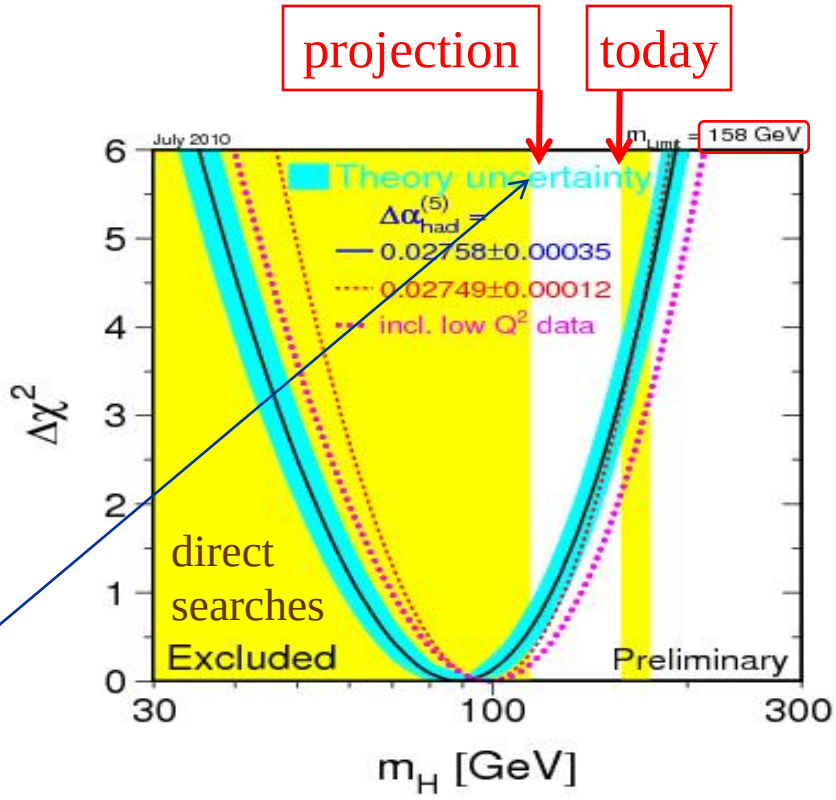
M(W) Prospects with all Tevatron Data

- Electroweak fits favor light Higgs
- Currently
  - most probable Higgs mass value = 89 GeV
  - excluded above 158 GeV @95% CL
- Under the following example scenario

ΔM_W : 23 MeV → 15 MeV
central values (M_W, M_{top}) do not move
ΔM_{top} : 1 GeV

- Higgs:
  - most probable value = 71 GeV
  - excluded above 117GeV @95% CL (114.4 from current direct searches)

Higgs limit from EW fits



Pete Renton, ICHEP2008

can be achieved at the Tevatron with the full dataset !!!

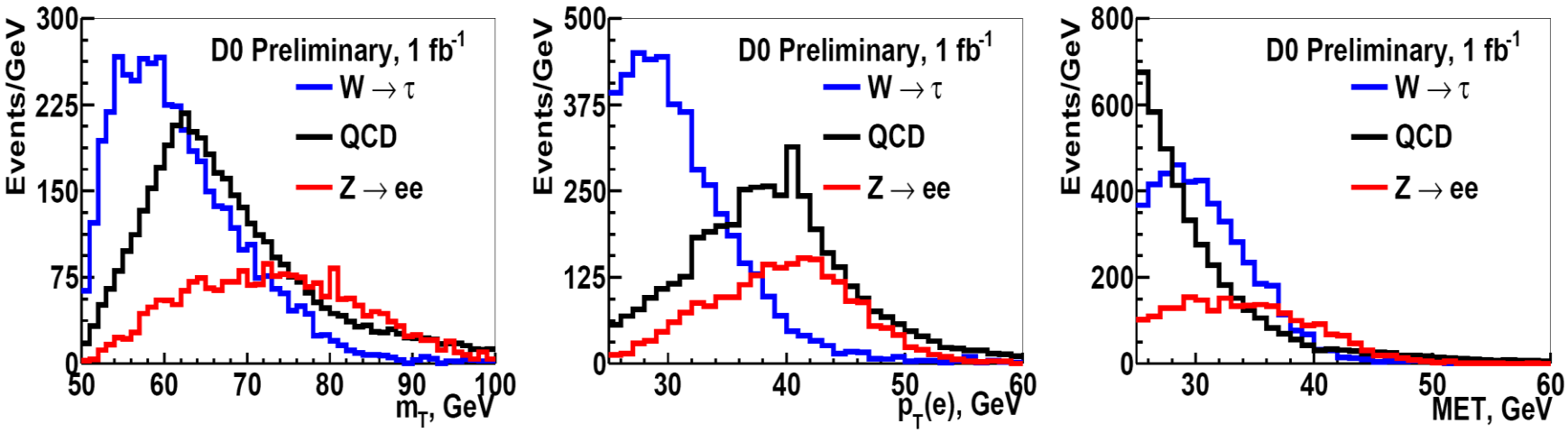
Summary

- W mass measurement is crucial for constraining the Standard Model
- W mass and width measurements with $1fb^{-1}$ of Tevatron RunII data by DØ are the most precise measurements from a single experiment
- CDF-DØ combined W mass result is more precise than that from LEPII
- W mass prospects and potential physics implications with the full Tevatron dataset are very exciting !
- More data are being analyzed
- Expecting significant improvements in precision soon
- Stay tuned for new results

BACKUP SLIDES

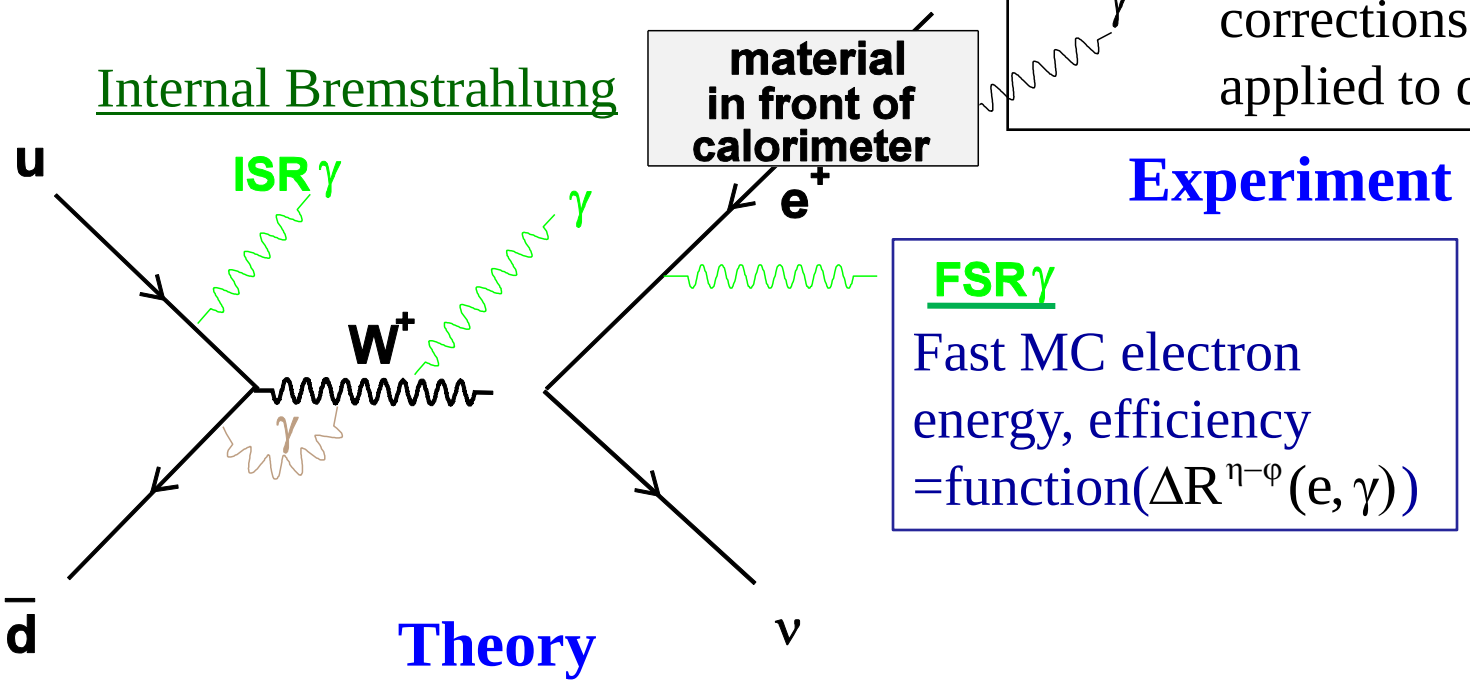
Backgrounds to W→eν

- 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 cap)
  - 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 Fast MC simulated signal**



Photons

Tool	Process	QCD	EW
RESBOS	W,Z	NLO	-
WGRAD	W	LO	complete $\mathcal{O}(\alpha)$, Matrix Element, ≤ 1 photon
ZGRAD	Z	LO	complete $\mathcal{O}(\alpha)$, Matrix Element, ≤ 1 photon
PHOTOS			QED FSR, ≤ 2 photons



Leading EW effects: 1st and 2nd FSR photons -- modeled with PHOTOS.

Effect of full EW corrections: compare W/ZGRAD in full EW mode with FSR-only mode

Quality of FSR model: compare PHOTOS with W/ZGRAD in FSR-only mode

Electron Energy Resolution

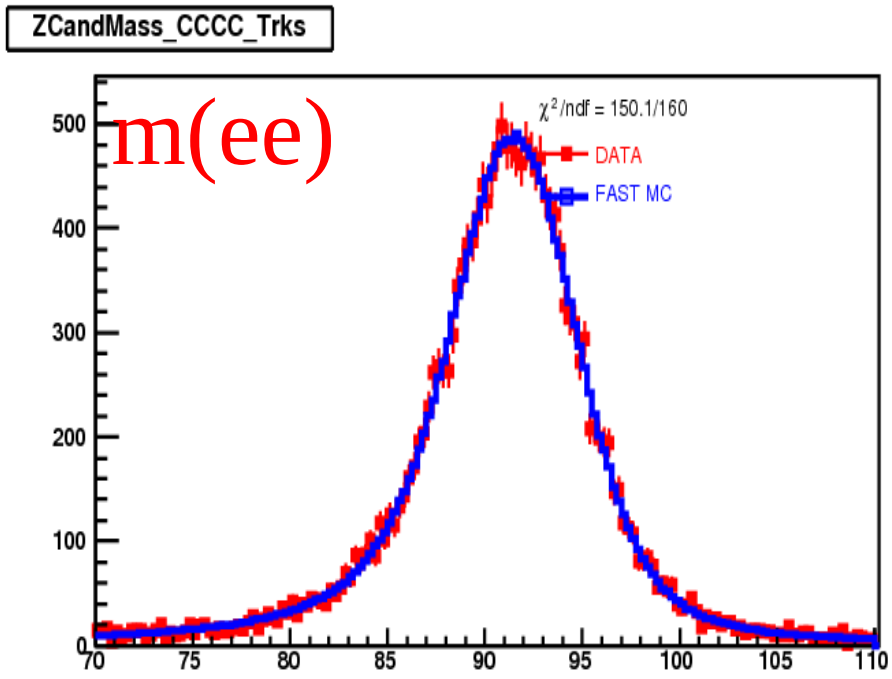
Electron energy resolution is driven by two components:
sampling fluctuations and constant term

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

Sampling fluctuations are driven by sampling fraction of CAL modules (well known from simulation and test-beam) and by un-instrumented material. Amount of material has been quantified with good precision.

Constant term is extracted from Z → ee data (fit to observed width of the Z peak).

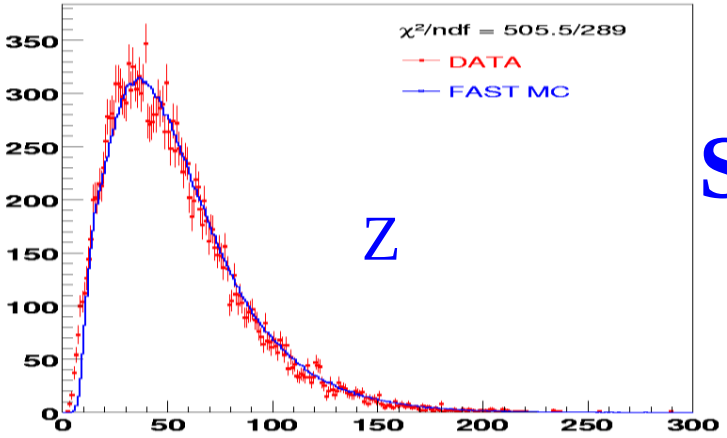
Result: C = (2.05 ± 0.10) %
in excellent agreement
with Run II design goal (2%)



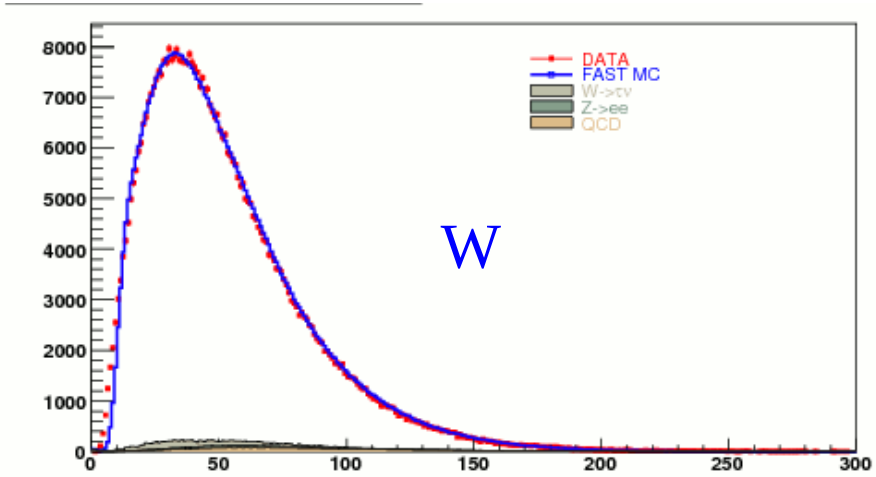
Z→e e and W → e ν

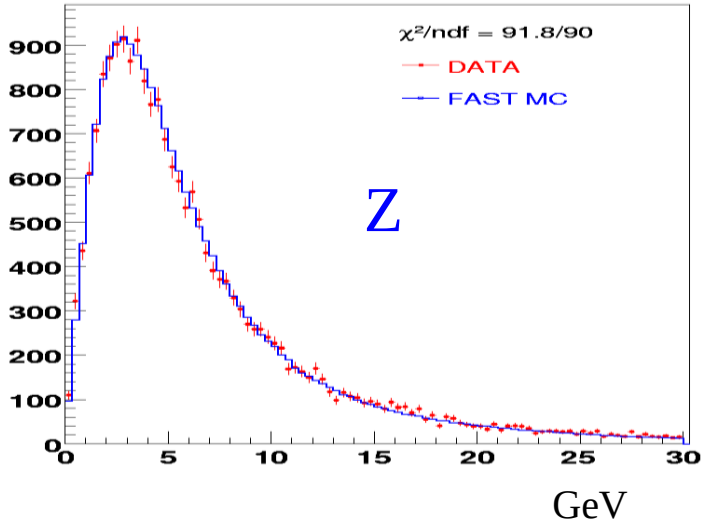
Data in red

Fast MC in blue

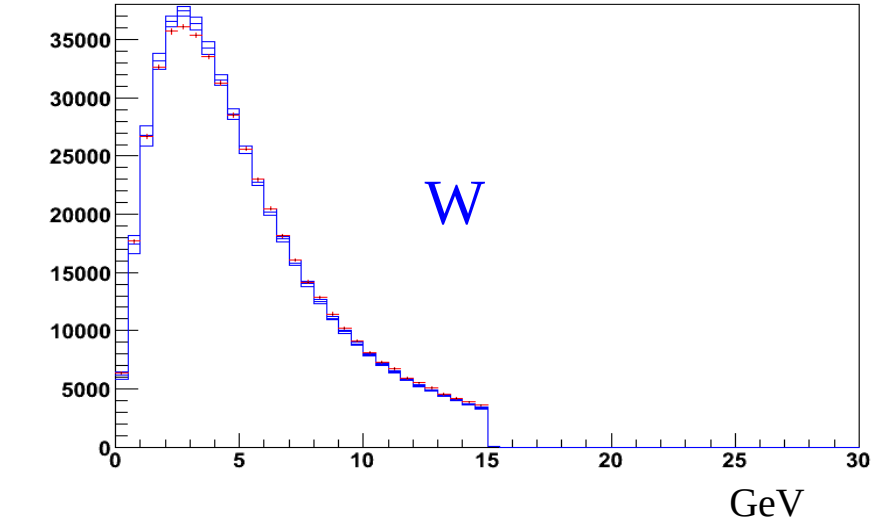


SET





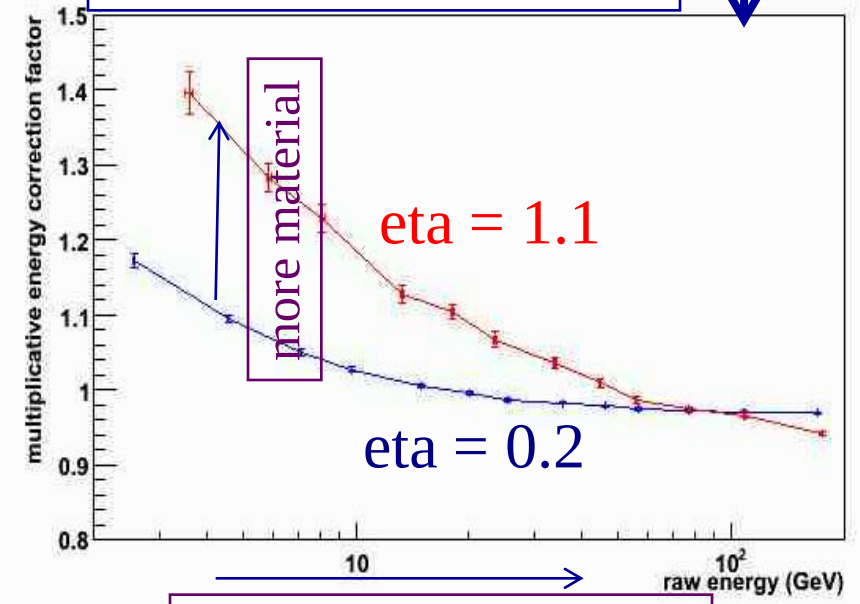
u_T



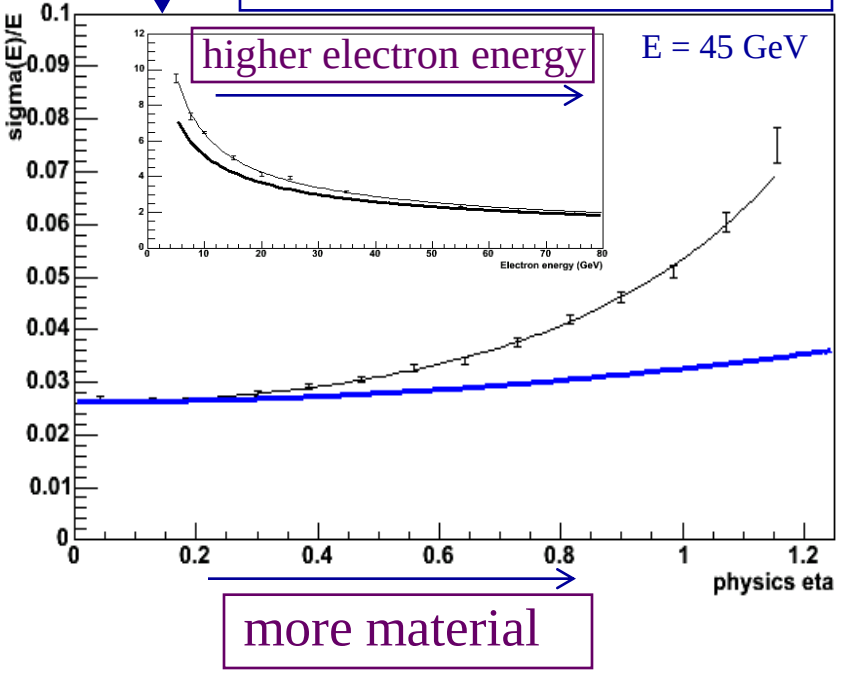
Electron Response and Resolution

- Dead material in front of the calorimeter complicates shower sampling
- ⇒ Degradation of both the **response** and the **resolution**

detailed GEANT simulation



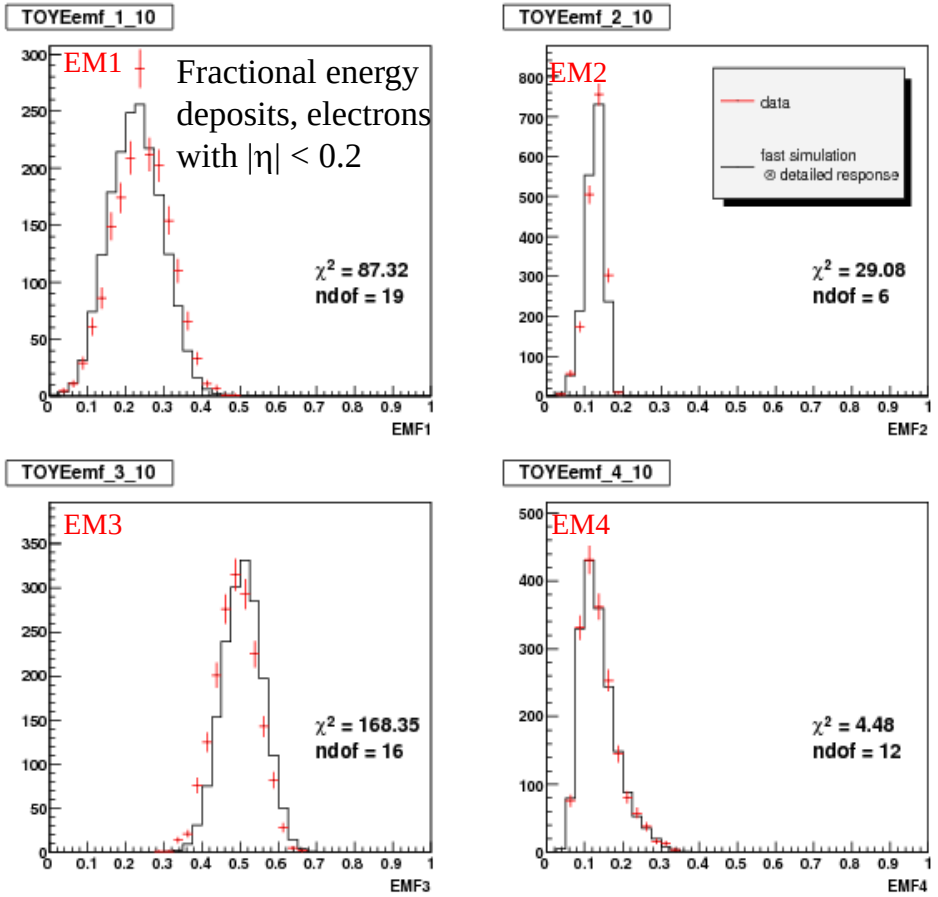
detailed GEANT simulation



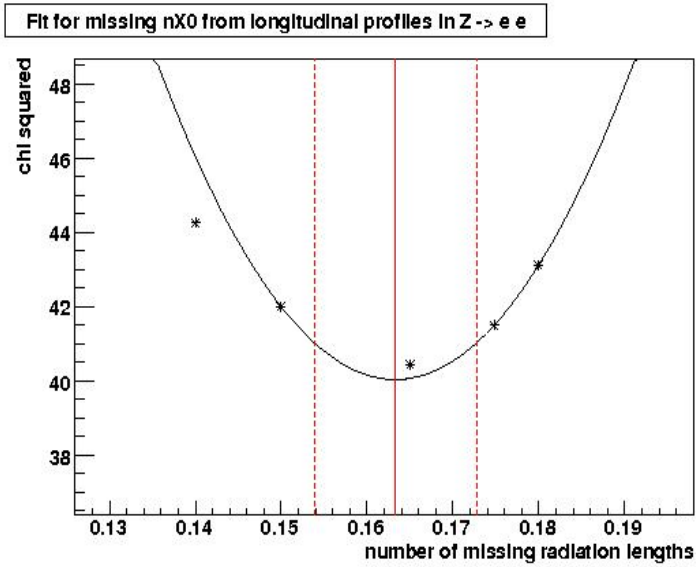
- The magnitude of the effect of the dead material depends on electron energy

Before tuning of material model

Before tuning of material model:
distributions of fractional energy deposits
do not quite match between data and the simulation.



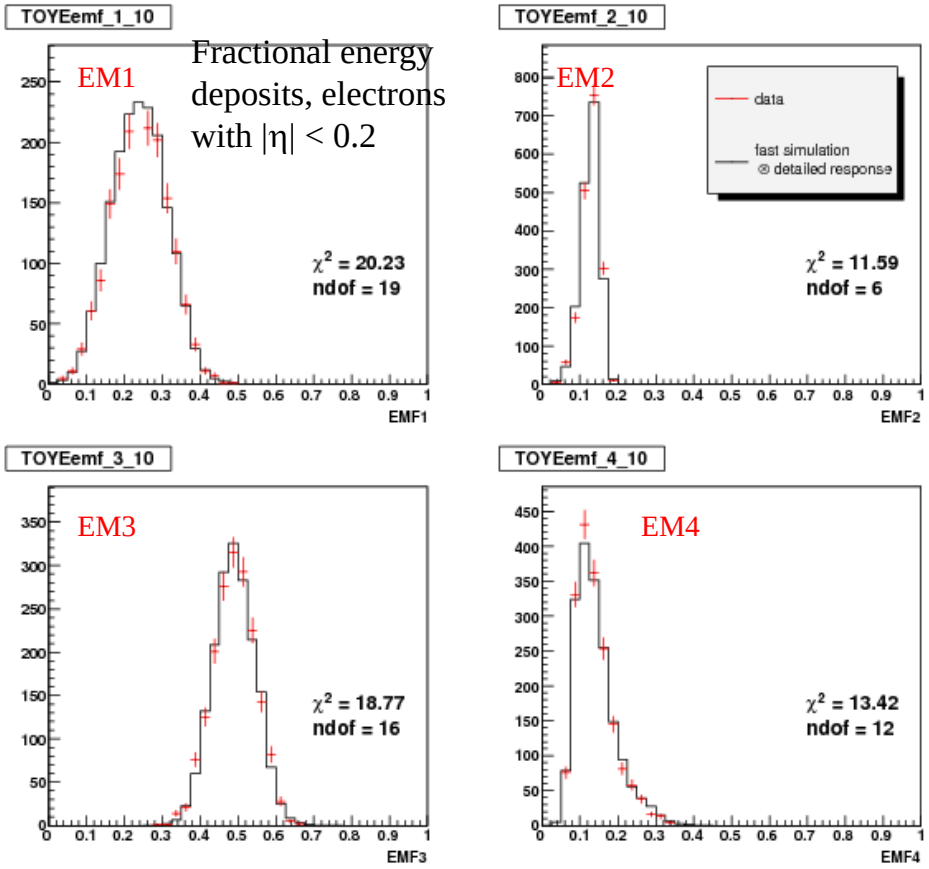
FIT



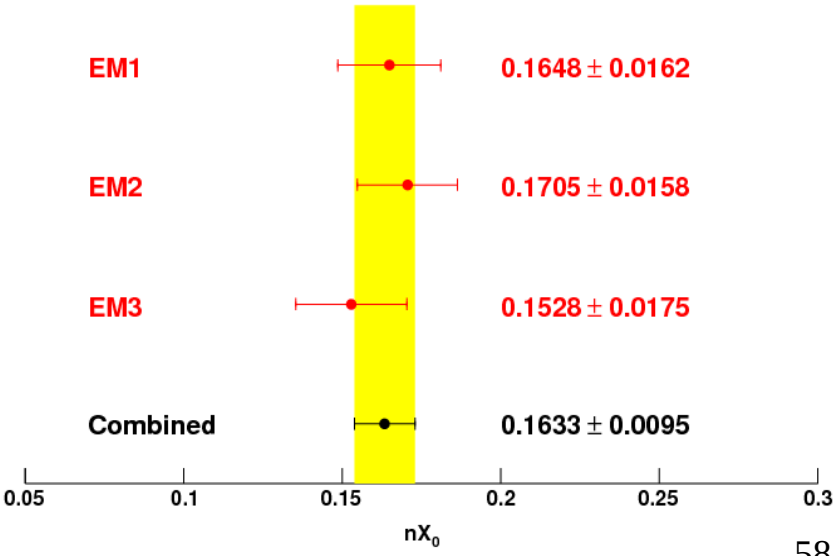
Amount of extra material to within less than $0.01X_0$!

After Tuning of Material Model

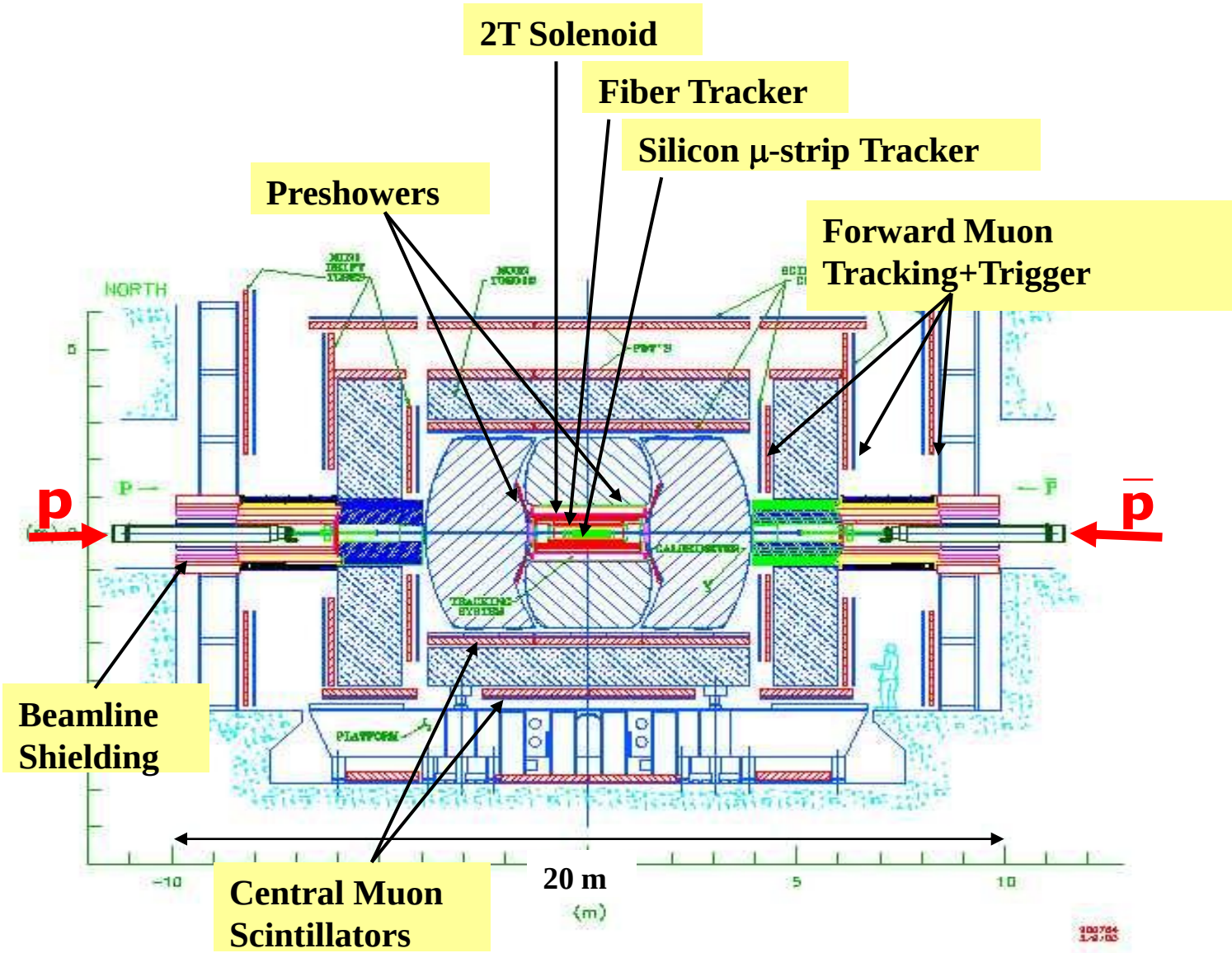
After tuning of material model:
distributions of fractional energy deposits are very well described by the simulation.



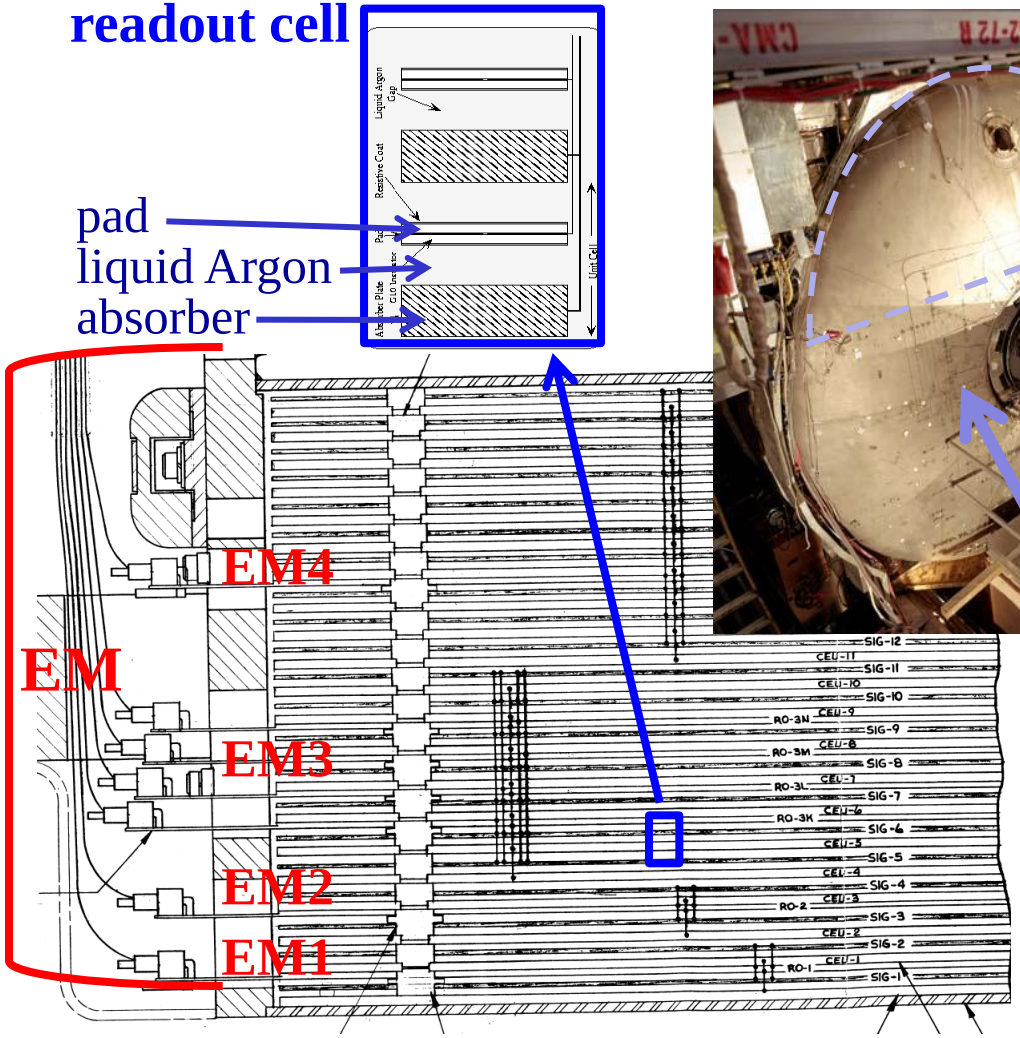
As a cross-check:
Repeat fit for nX_0,
separately for each EM layer.
Good consistency is found.

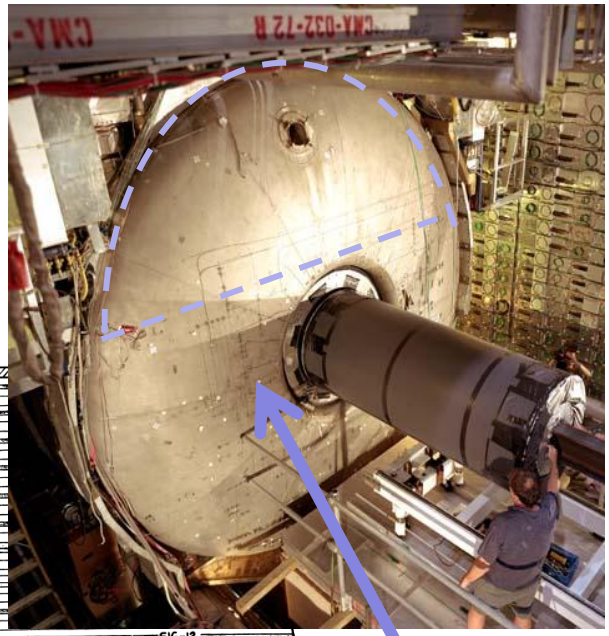


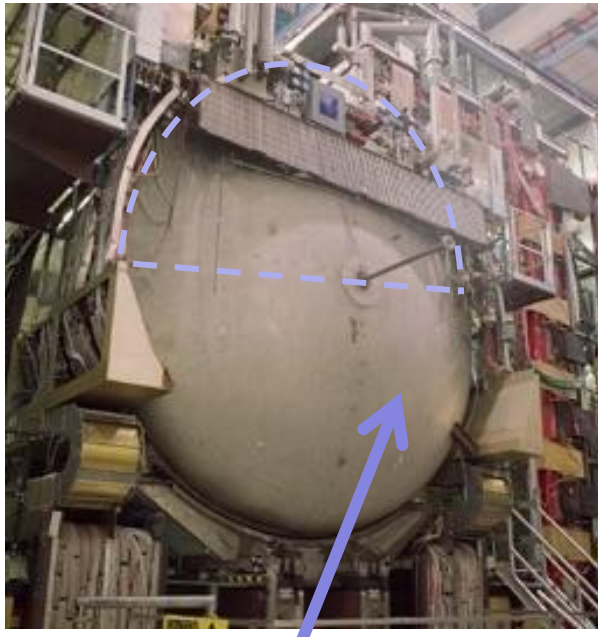
DØ Detector (r-z View)

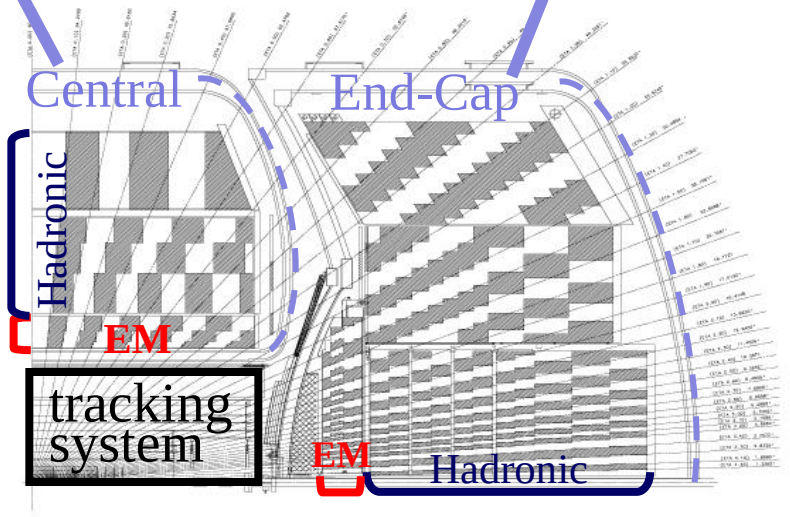


DØ Calorimeter: Modules, Layers, and Cells

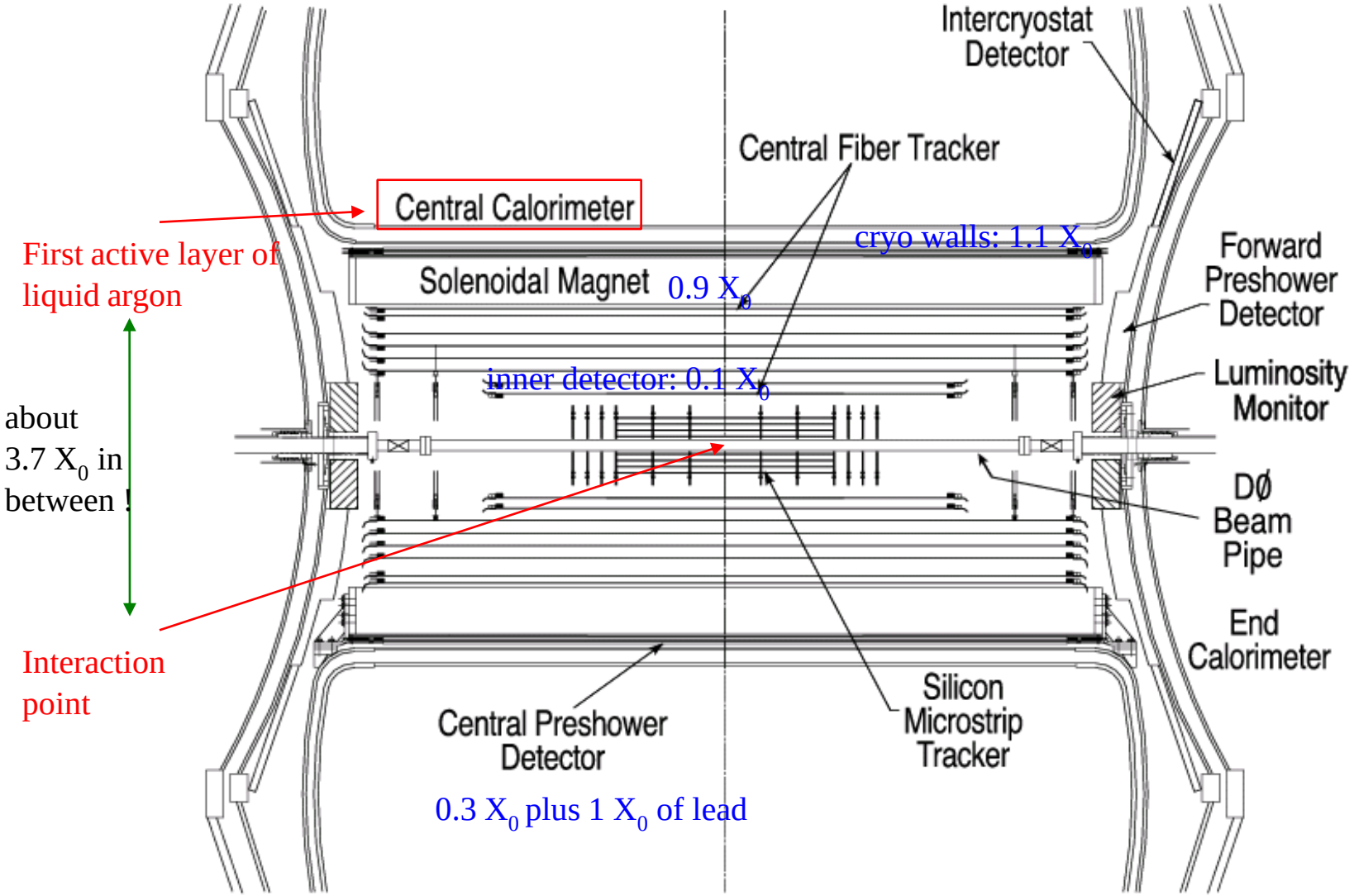


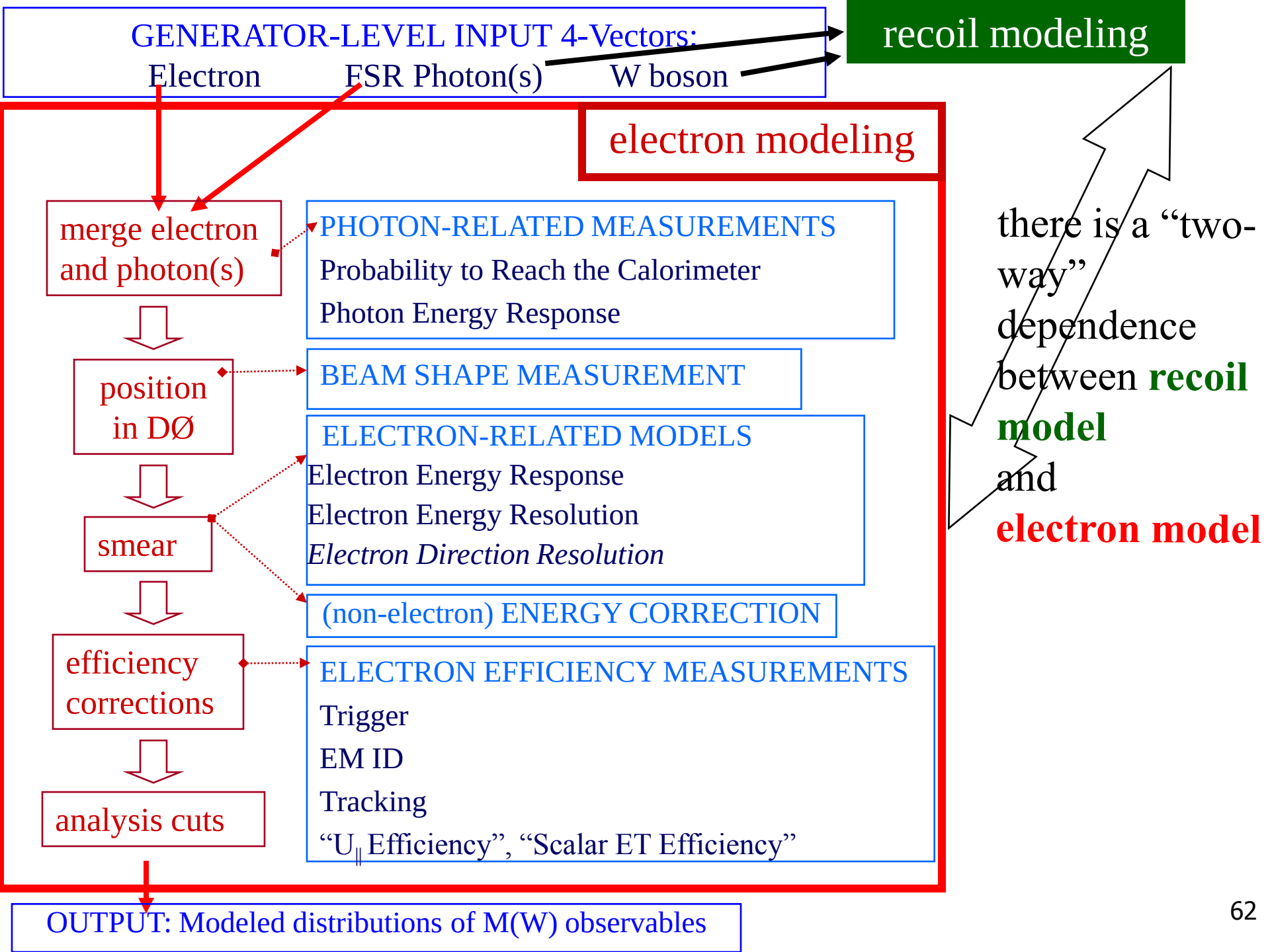




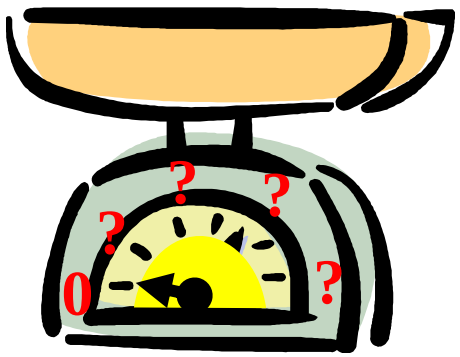


Material in front of the Calorimeter



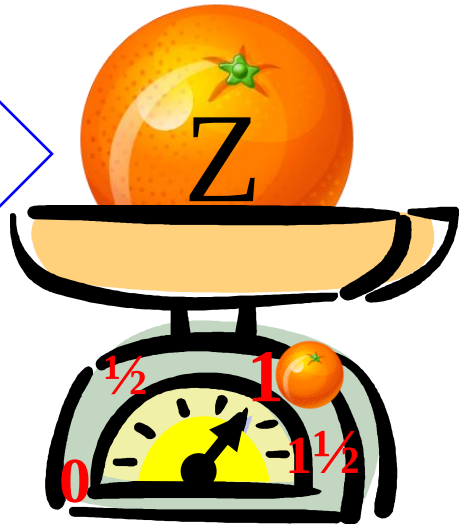

GENERATOR-LEVEL INPUT 4-Vectors:
Electron
ESR Photon(s)
W boson
recoil modeling
electron modeling
merge electron and photon(s)
PHOTON-RELATED MEASUREMENTS
Probability to Reach the Calorimeter
Photon Energy Response
position in DØ
BEAM SHAPE MEASUREMENT
smear
ELECTRON-RELATED MODELS
Electron Energy Response
Electron Energy Resolution
Electron Direction Resolution
(non-electron) ENERGY CORRECTION
efficiency corrections
ELECTRON EFFICIENCY MEASUREMENTS
Trigger
EM ID
Tracking
"U∥ Efficiency", "Scalar ET Efficiency"
analysis cuts
OUTPUT: Modeled distributions of M(W) observables
there is a "two-way" dependence between recoil model and electron model

Measuring W mass relative to Z mass



we start with un-calibrated device

calibrate with Z



measurement

find out where W is on *our* scale(s)

we measure this number ≈ 8/9 × Z

LEP tells us Z is 90188±2MeV

W mass result

Calibrations Steps in Detail

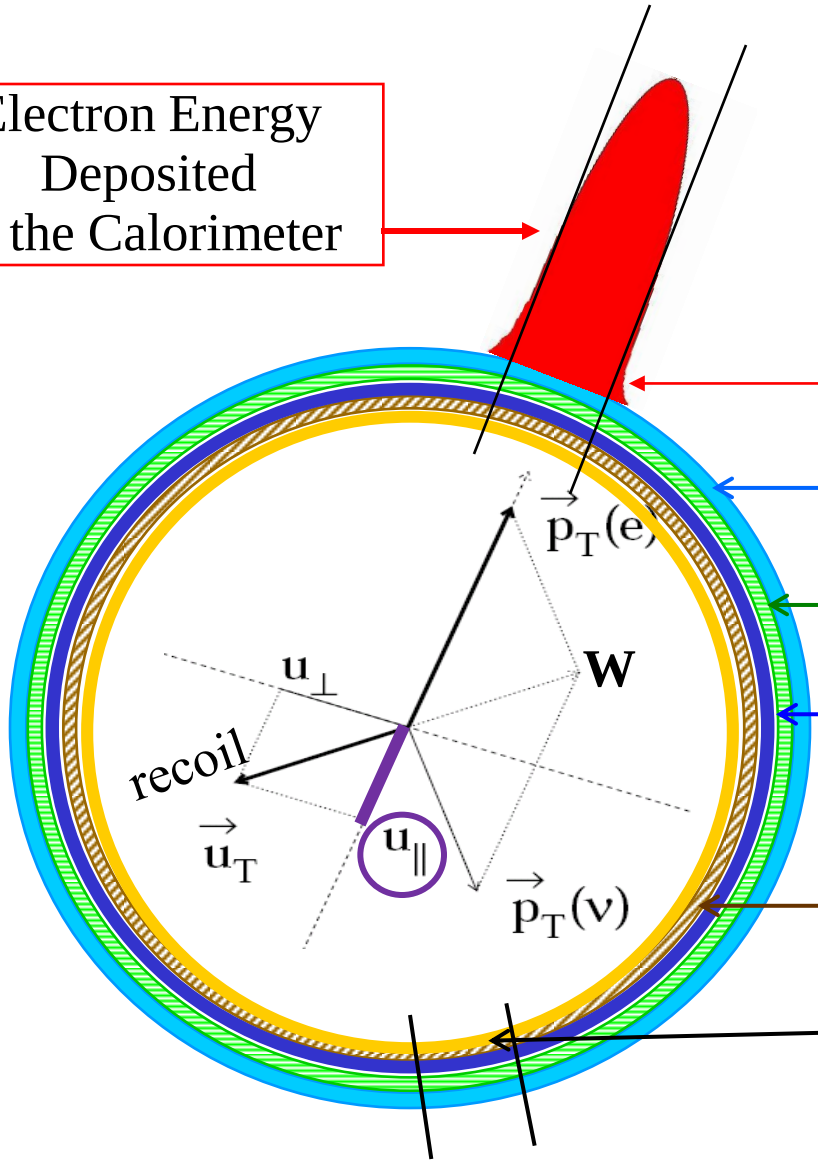
- Let N=number of pedestal-subtracted ADC counts in (iphi, ieta, ilayer) channel, which survived zero-suppression

- What happens to N before it becomes a part of a well-calibrated EM cluster ?

  × 1/(gain (iphi, ieta, ilayer) + non-linearity correction (iphi, ieta, ilayer, N))
  × Charge-to-Energy units factor
  ×1/Sampling Fraction
  × Layer Weight (ilayer) optimized for resolution
  × E-loss (EM cluster phys.eta, energy) developed in RunIIA W mass analysis
  × C(iphi, ieta, ilayer) from phi-intercalibration
  × C(ieta, ilayer) from eta equalization
  × C set absolute scale with M_Z from LEP
  × C(ilayer) from layer-intercalibration

- Remaining fine-tune calibration is performed with Fast MC

Modeling Electron Energy



Electron Energy Deposited in the Calorimeter

electron energy leakage outside the cone

initial state radiation

spectator quark remnants

additional proton-antiproton interactions

calorimeter noise

effect of zero-suppression in the calorimeter readout (when estimating "extra energy")

W Boson Mass and Top Quark Mass

- Higgs boson mass is sensitive to M(W) and M(top)
- For equal contribution to the Higgs mass uncertainty need: $\Delta M_W \approx 0.006\ \Delta M_{top}$
- Current world average $\Delta M_{top} = 1.06$ GeV
- $\Rightarrow$ Would need: $\Delta M_W = 6$ MeV (currently have: $\Delta M_W = 23$ MeV)

Effect of Corrections on M(W)

tree level 80.939

α	*electron g-2*	0.68 pp10^9
G_F	*muon life-time*	9 pp10^6
M_z	*LEP 1 lineshape*	23 pp10^6

- 42 σ

+ 19 σ

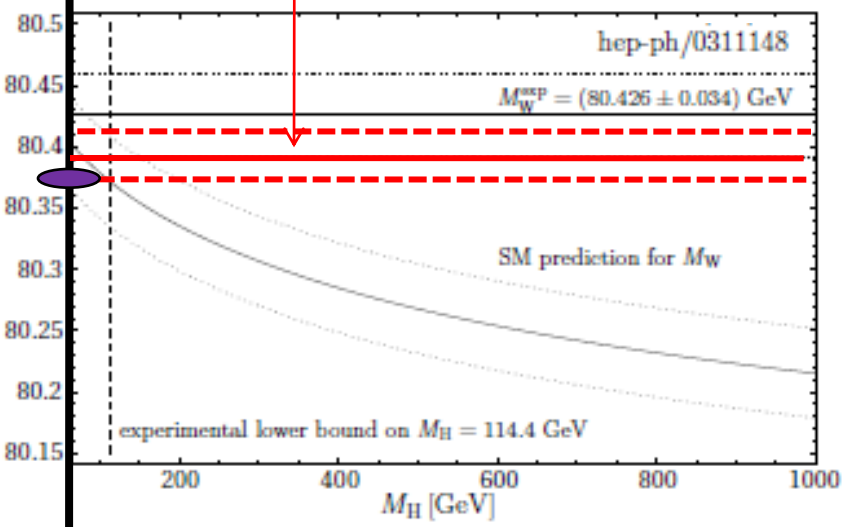
+ radiative corrections (M_H=100GeV)

80.380

+ running α_{EM} correction 79.964

W Mass, GeV

current world average (experiment) 80.399 ± 0.023



Higgs Mass, GeV