W Mass and Width Measurements at the Tevatron

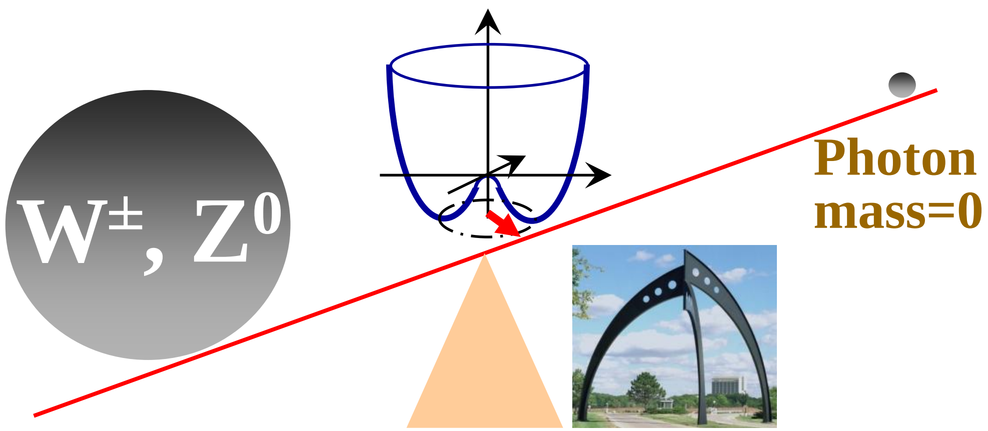
Alex Melnitchouk
University of Mississippi

on behalf of the CDF and DØ Collaborations

XXIV Rencontres de Physique de la Vallée d'Aoste,
La Thuille, Italy, March 4, 2010

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

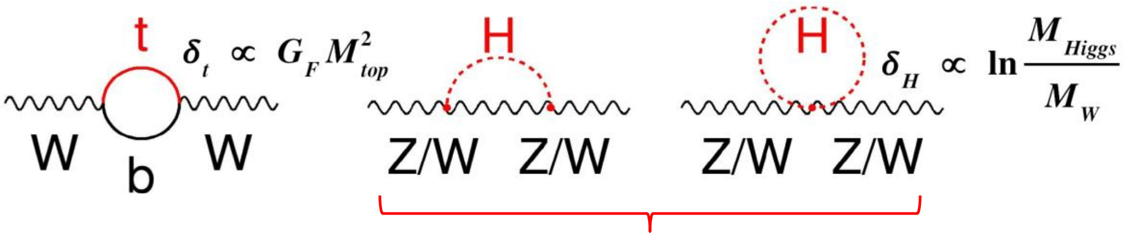
- W boson mass is an important Standard Model parameter related to **G_F , α_{EM}**, and **M_z** via

tree level

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

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

$$\Delta r = \underset{\text{Running of } \alpha_{EM}}{\alpha_{EM}(0 \rightarrow M_Z)} + \text{Radiative Corrections}$$



Sensitivity to Higgs Mass

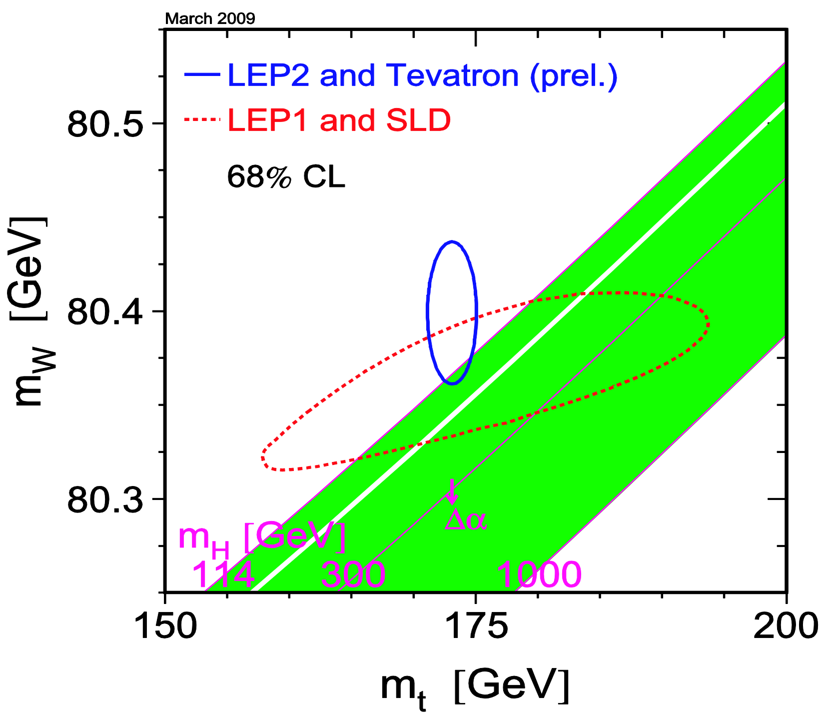
Constraining Standard Model

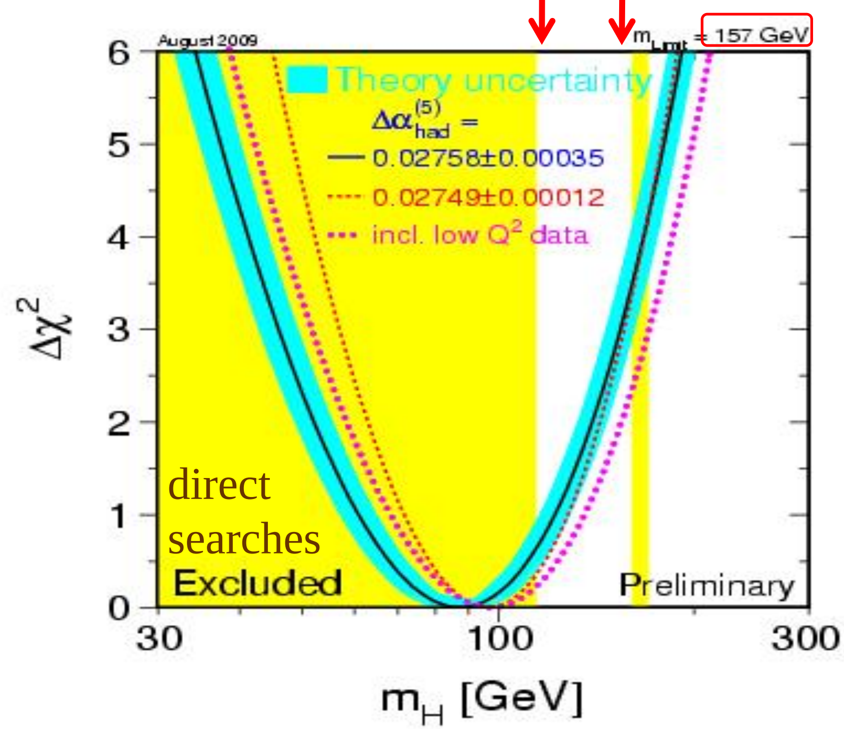
- Precision measurements provide sensitivity to new physics at much higher energy scales than the mass of the particles on which the measurements are performed
- Measurements of the M_W and M_{top} constrain the mass of the Higgs boson

Higgs limit from EW fits

may be possible with full Tevatron dataset

Current 157GeV @95%CL



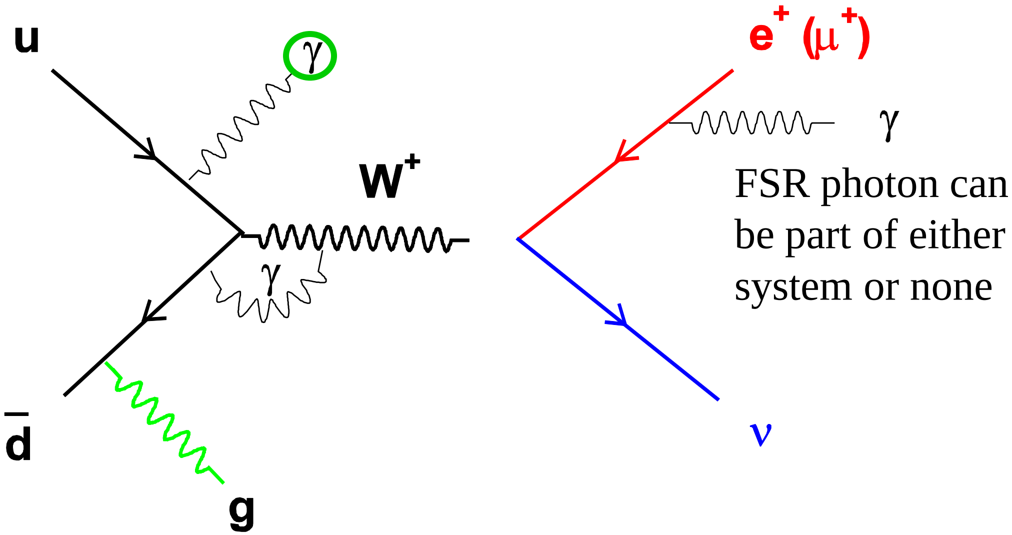


W Boson Mass and Top Quark Mass

- 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 Tevatron average ΔM_{top} = 1.3 GeV
- ⇒ Would need: ΔM_W = 8 MeV (currently have: ΔM_W = 23 MeV)

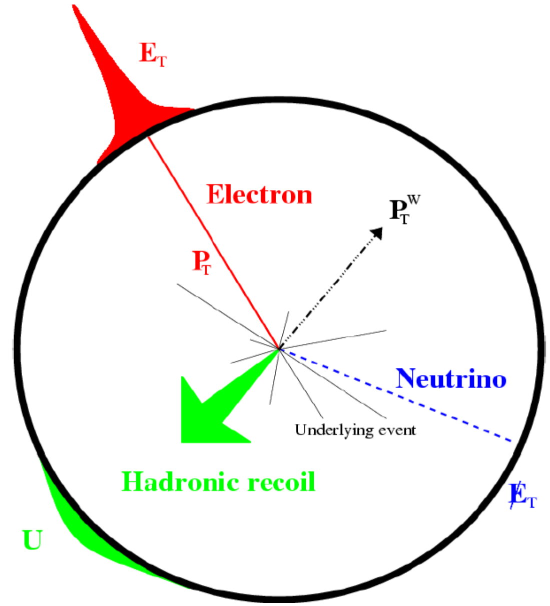
W→eν Event: Theory and AnalysisView

hard component = recoil against W



spectator quarks

additional ppbar collisions



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

Analysis: describe W→eν event in terms of **recoil** and **electron** systems

to achieve

$\Delta M_W/M_W \approx 0.5\times10^{-3}$

Required detector	**electron**	$\sim 0.3\times10^{-3}$
response precision:	**hadronic recoil**	**~ 1%**

Measuring M(W)

- Cannot reconstruct M(W) directly (missing neutrino p_z)
- Extract it from observables that are sensitive to M(W)

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

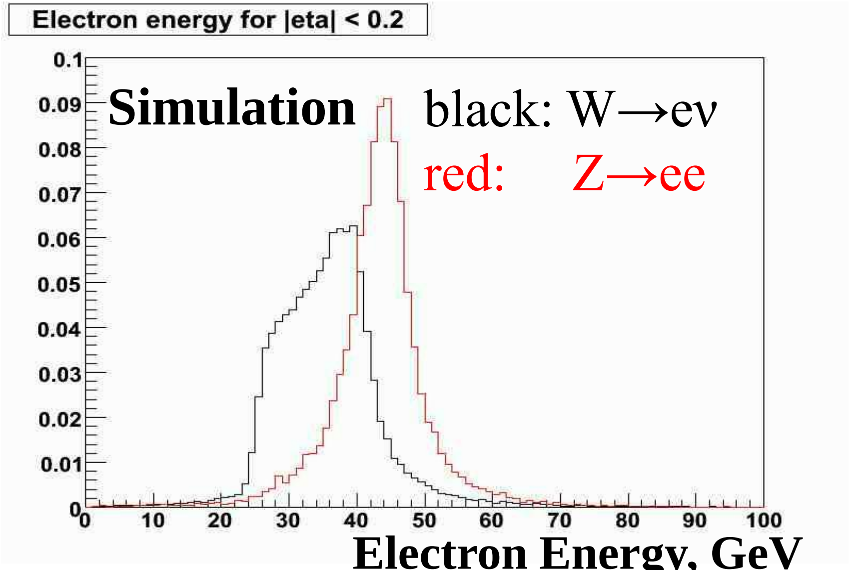
  - due to complicated detector effects analytical computation impossible
  - determine M(W) via template fit (need Fast Monte Carlo model of detector effects)
- The observables are transverse, not Lorentz-invariant: sensitive to transverse motion of W boson
  - need good model of W boson production

Electron Energy Calibration (DØ)

- M(W) precision is controlled by electron energy scale precision
- Understanding electron showers in the calorimeter is very important
- Knowing the amount of un-instrumented material is the key
- Use $Z \rightarrow ee$ data sample for calibration to precisely measured M(Z) by LEP

measurement of W/Z mass ratio
$\Rightarrow$ many systematic effects cancel

- Need proper description of energy dependence as well
- Achieved via
  - dedicated version of GEANT simulation
  - calibration of longitudinal shower profile
  - accurate tuning of material model



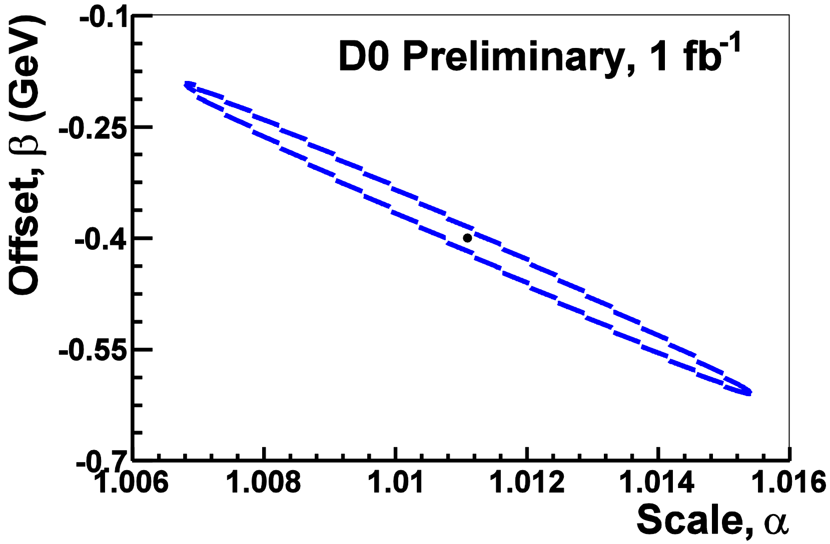
Final M(W) Calibration (DØ)

- Linear response model : E_measured(e) = $\alpha \times$ E_true(e) + β
  $\alpha \rightarrow$ scale $\beta \rightarrow$ offset
- Use $Z \rightarrow ee$ electrons to constrain α and β (precision limited by statistics)
- Calibrate to M_Z ($\pm$ 2 MeV from LEP)
- Two observables to fit the data
  - $Z \rightarrow ee$ invariant mass
  - f_Z variable "scans" the response as a function of energy

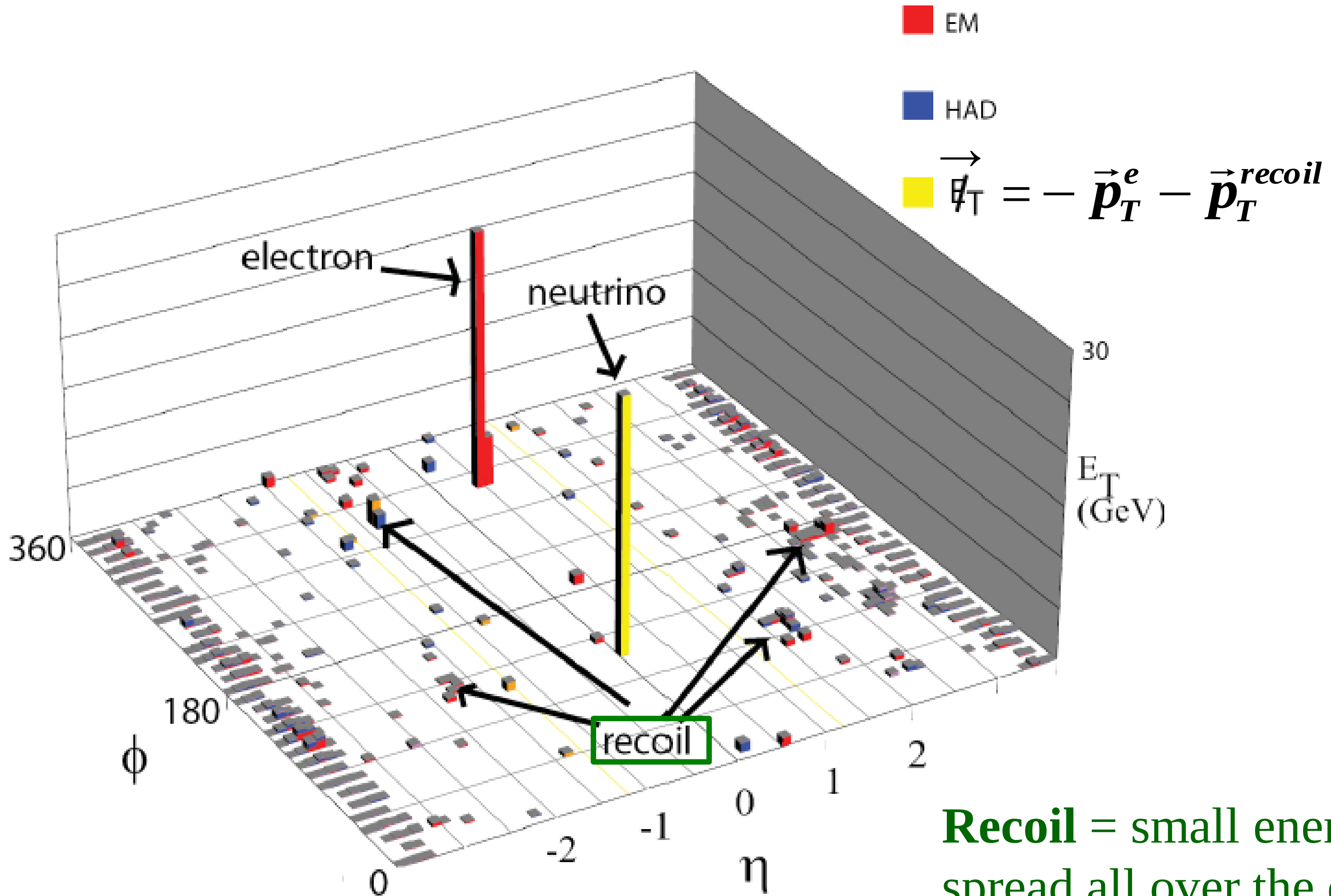
$f_Z = (E(e1)+E(e2))(1-\cos(\gamma_{ee}))/m_Z$

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

$\Rightarrow$ dominant systematic error, 100 % correlated between three observables



Event Display of DØ W→eν Candidate Event



Recoil = small energy deposits spread all over the detector
⇒ sensitivity to small effects, challenges for modeling

Recoil Model (DØ)

Recoil in Fast MC: $\vec{u}_T = \vec{u}_T^{\,\mathrm{Hard}} + \vec{u}_T^{\,\mathrm{Soft}} + \vec{u}_T^{\,\mathrm{Elec}} + \vec{u}_T^{\,\mathrm{FSR}}$

recoil energy "lost" in electron cone(s)

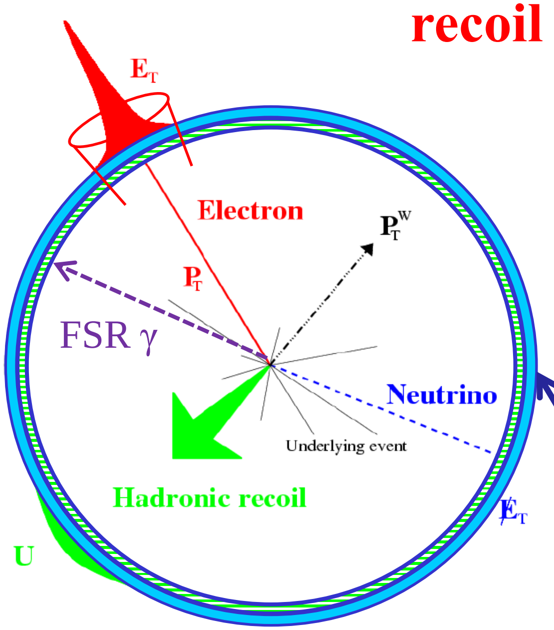
estimate from W→ eν data

$$\vec{u}_T^{\,\mathrm{Elec}} = -\sum \Delta u_{\parallel} \cdot \hat{p}_T(e)$$

FSR photon outside electron cone

full MC derived model

$$\vec{u}_T^{\,\mathrm{FSR}} = \sum_{\gamma} \vec{p}_T(\gamma)$$



balances P_T of the vector boson:

Z→νν full MC model $q_T \rightarrow (\Delta q_T, \Delta\phi)$

$$\vec{u}_T^{\,\mathrm{Hard}} = \vec{f}(\vec{q}_T)$$

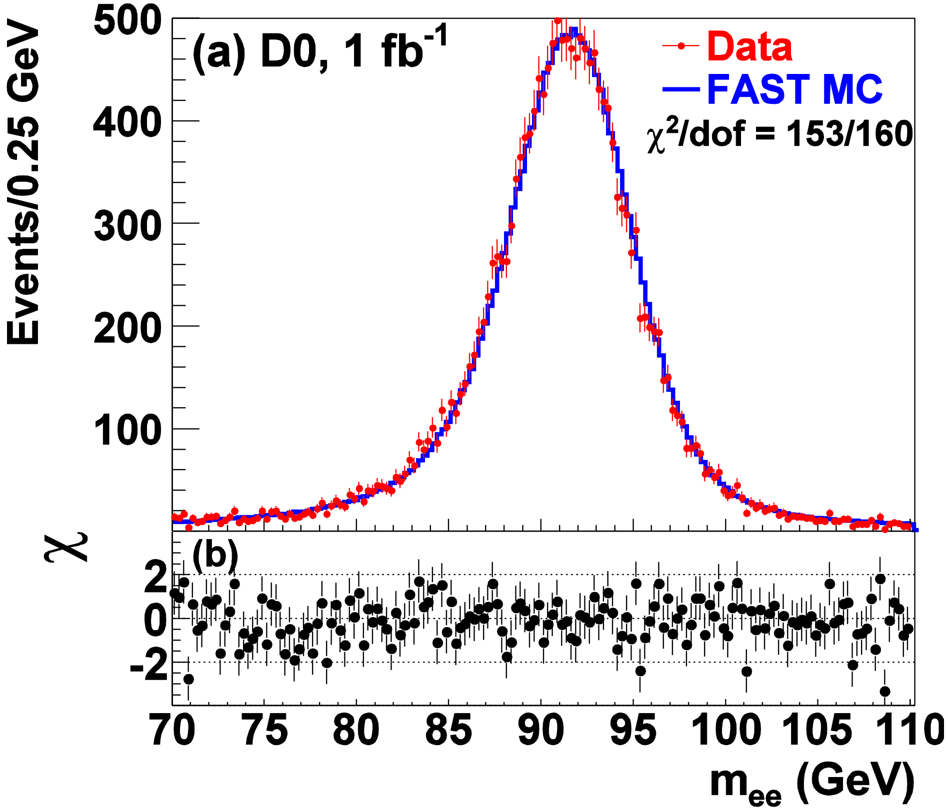
not correlated with the vector boson, two sub-components:

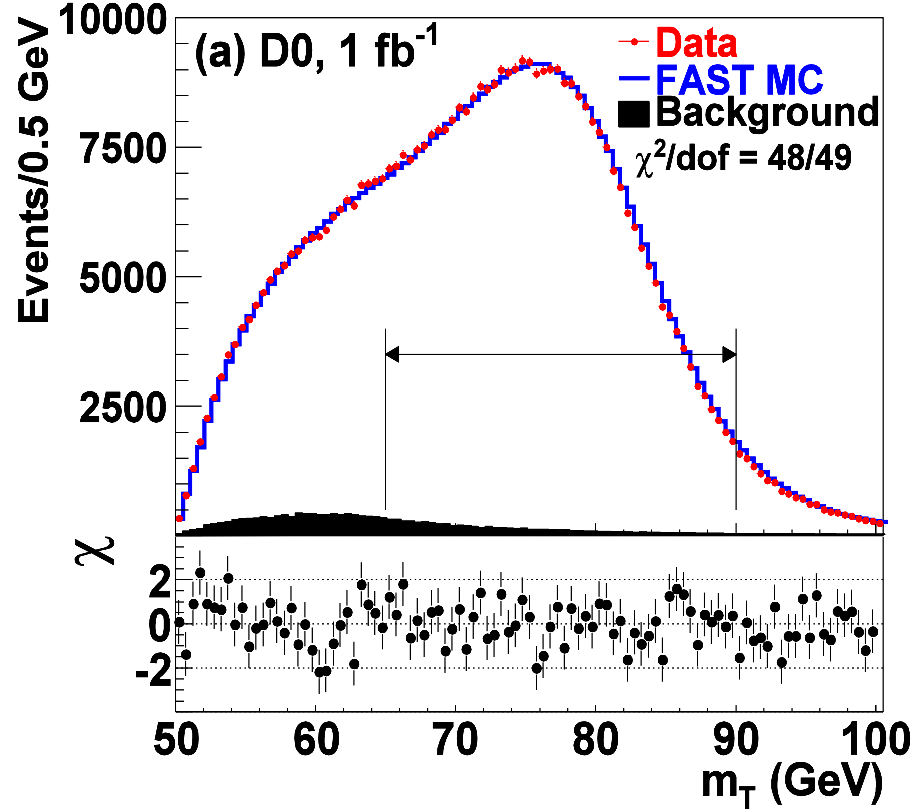
-- spectator partons

-- additional interactions

$$\vec{u}_T^{\,\mathrm{Soft}} = \alpha_{\mathrm{MB}} \cdot \vec{E}_T^{\,\mathrm{MB}} + \alpha_{\mathrm{ZB}} \cdot \vec{E}_T^{\,\mathrm{ZB}}$$

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



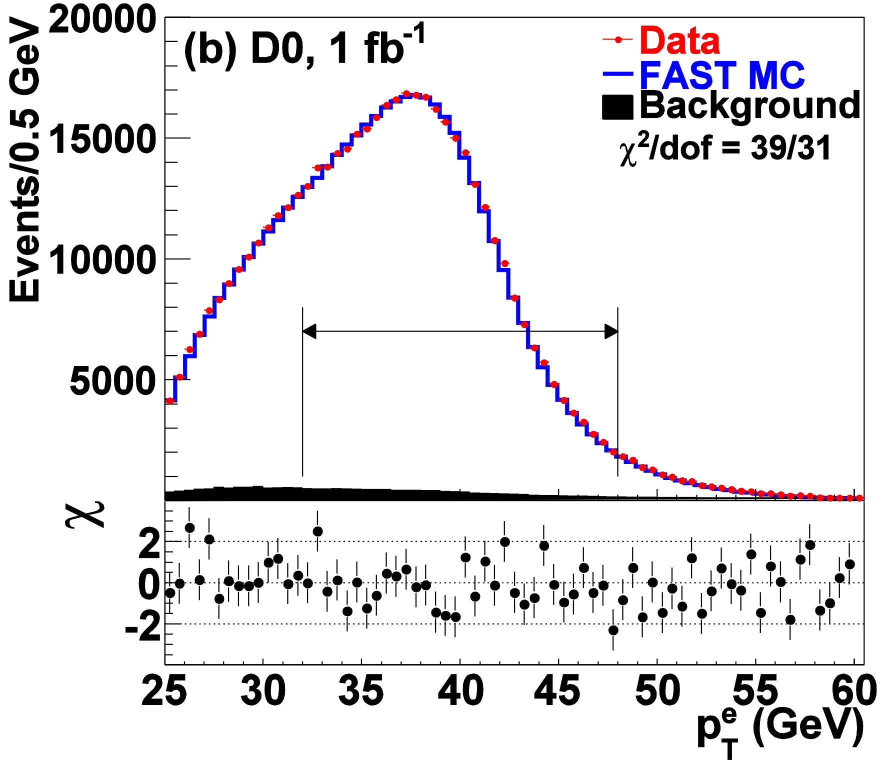


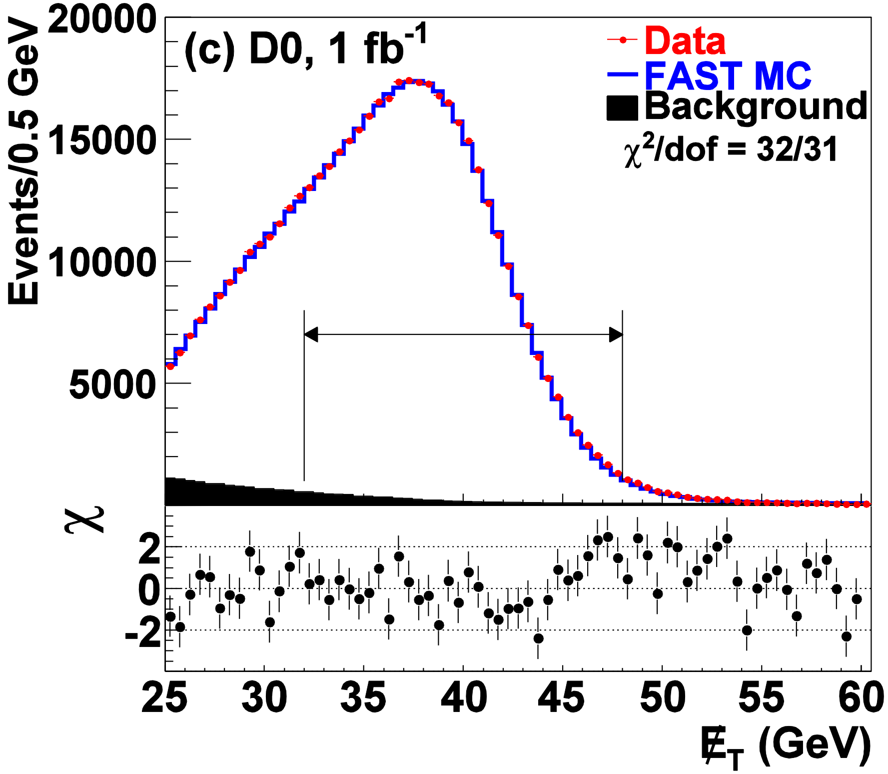
m(Z) = 91.185 ± 0.033 GeV (stat)

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)**

M(W) Uncertainties, MeV (DØ)

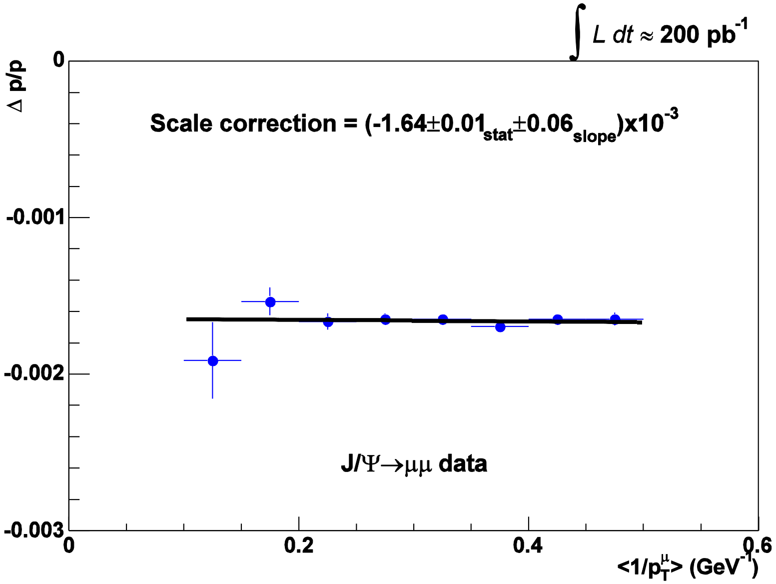
Source	m_T	p_T^e	$\not{E}_T$
Statistical	**23**	**27**	**23**
Systematic - Experimental			
Electron energy response	34	34	34
Electron energy resolution	2	2	3
Electron energy non-linearity	4	6	7
Electron energy loss differences	4	4	4
Recoil model	6	12	20
Efficiencies	5	6	5
Backgrounds	2	5	4
Experimental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

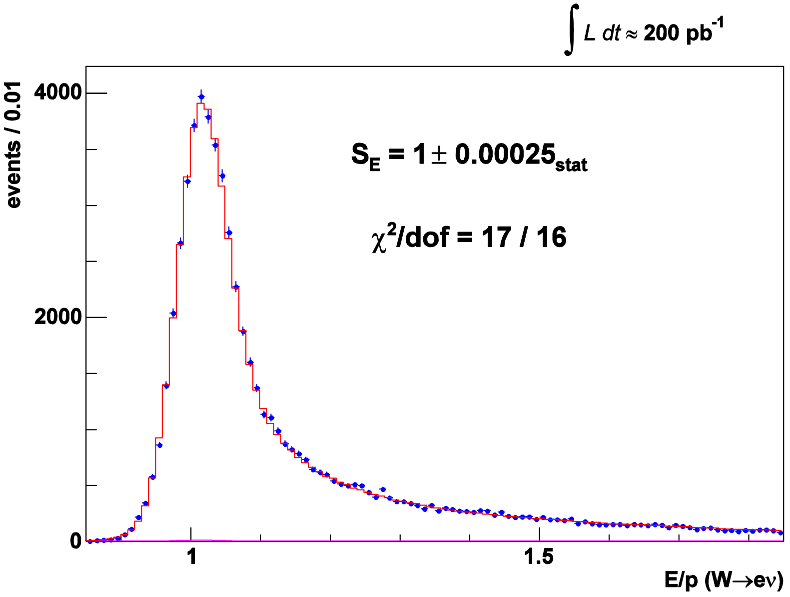
Lepton Energy Calibration (CDF)

precise tracker calibration

measure J/ψ mass
in bins of muon momentum



transferred to calorimeter
using E/p in W→eν sample



adjust energy loss model

0.02% calibration precision
main uncertainties:

- QED corrections
- magnetic field non-uniformity

M(W) Uncertainties (CDF)

			L = 200 pb^{-1}			L = 200 pb^{-1}			L = 200 pb^{-1}
m_T Uncertainty [MeV]	Electrons	Muons	Common	Electrons	Muons	Common	Electrons	Muons	Common
Lepton Scale	30	17	17	30	17	17	30	17	17
Lepton Resolution	9	3	0	9	3	0	9	5	0
Recoil Scale	9	9	9	17	17	17	15	15	15
Recoil Resolution	7	7	7	3	3	3	30	30	30
$u_{\parallel}$ Efficiency	3	1	0	5	6	0	16	13	0
Lepton Removal	8	5	5	0	0	0	16	10	10
Backgrounds	8	9	0	9	19	0	7	11	0
$p_T(W)$	3	3	3	9	9	9	5	5	5
PDF	11	11	11	20	20	20	13	13	13
QED	11	12	11	13	13	13	9	10	9
Total Systematic	39	27	26	45	40	35	54	46	42
Statistical	48	54	0	58	66	0	57	66	0
Total	62	60	26	73	77	35	79	80	42

$M_T(W)$ **$P_T(e,\mu)$** **MET**

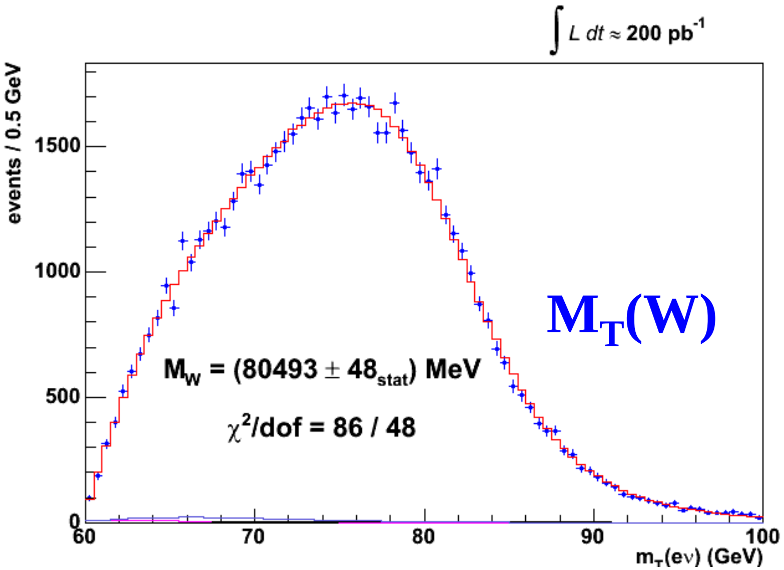
Individual measurements dominated by **statistical uncertainties**

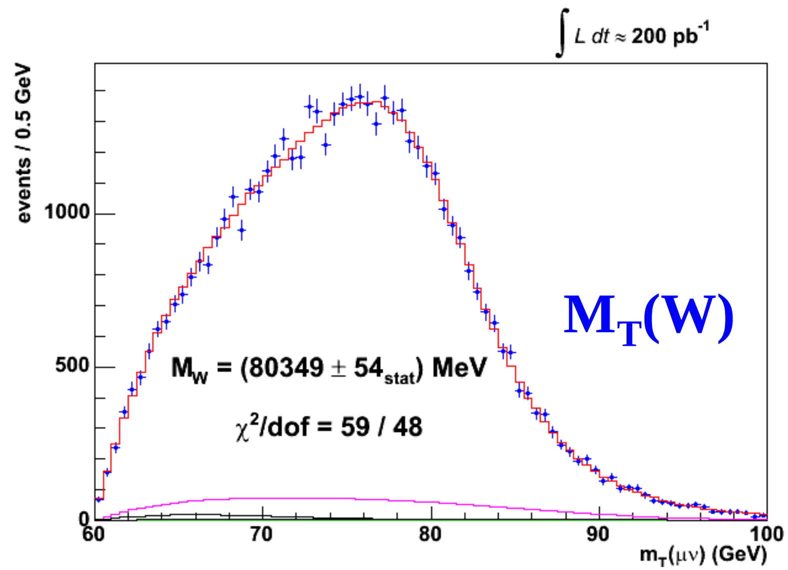
Largest **systematic uncertainties** (M_T example)

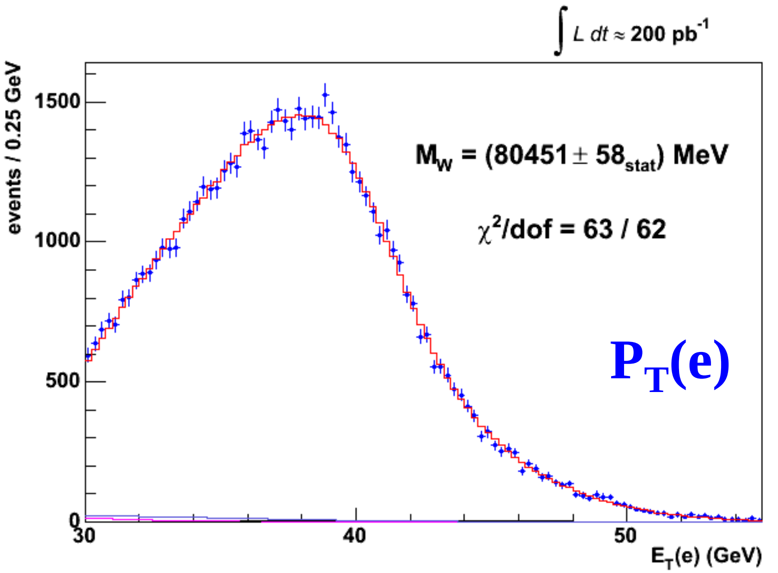
Experiment: Lepton Scale
Theory: PDF and QED

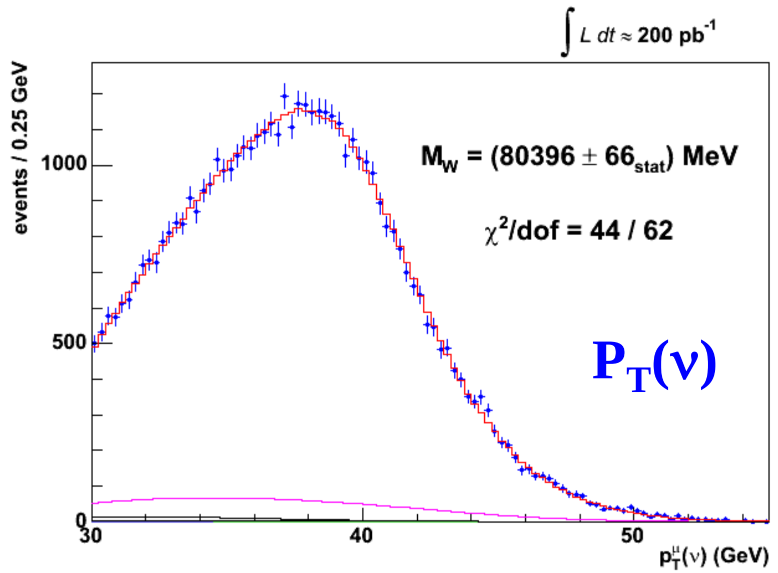
CDF M(W) Analysis

Electron Channel | Muon Channel

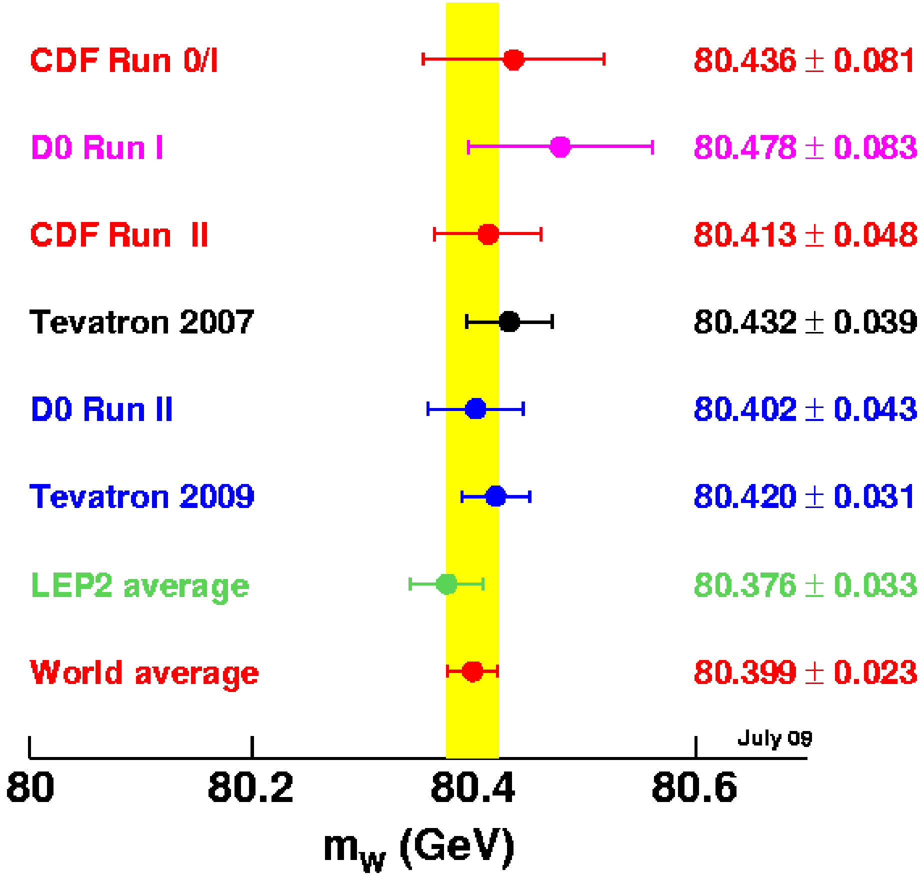








Results



Tevatron ElectroWeak Working Group
http://tevewwg.fnal.gov
Combination performed with B.L.U.E. method
L. Lyons et al, NIM in Phys. Res. A **500**, 391 (2003)
A. Valassi, NIM in Phys. Res. A **500**, 391 (2003)

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

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

80.401 ± 0.043 GeV

this new result is the **single most precise measurement** of the W boson mass to date

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

World average is now
80.399 ± 0.023 GeV

CDF RunII 0.2 fb^{-1} PRL 99, 151801 (2007)
PRD 77, 112001 (2008)

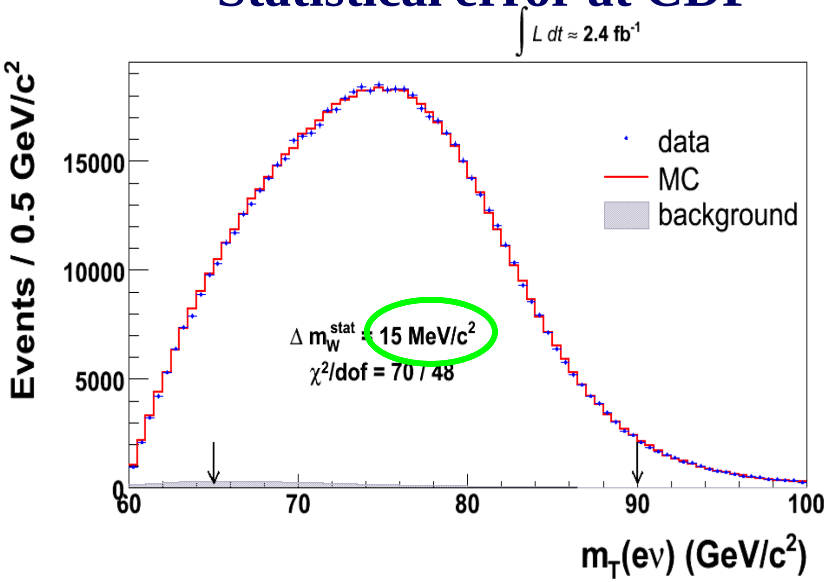
80.413 ± 0.034 (stat.) ± 0.034 (syst.) GeV

80.413 ± 0.048 GeV

Current M(W) Effort at the Tevatron

- More data are being analyzed at CDF and DØ
- Main new challenges
  - "busier" events (recorded at higher instantaneous luminosities)
  - need for more careful treatment of systematic effects that used to be swamped by statistical fluctuations
- With the data currently analyzed dominant errors are reduced by a factor of 2-3 compared to published analyses

Statistical error at CDF



Electron scale error at DØ

$M_T(W)$	34.0 ± 0.9 MeV
PT(e)	33.5 ± 0.5 MeV
MET	33.6 ± 0.7 MeV

⇓

MT(W)	15.3 ± 0.4 MeV
PT(e)	16.2 ± 0.2 MeV
MET	16.6 ± 0.2 MeV

M(W) Prospects with all Tevatron Data

- Electroweak fits favor light Higgs

- Currently
  - most probable Higgs mass value = 87 GeV
  - excluded above 157 GeV @95% CL

- Under the following example scenario

  ΔM_W : 23 MeV $\rightarrow$ 15 MeV

  central values (M_W, M_{top}) do not move

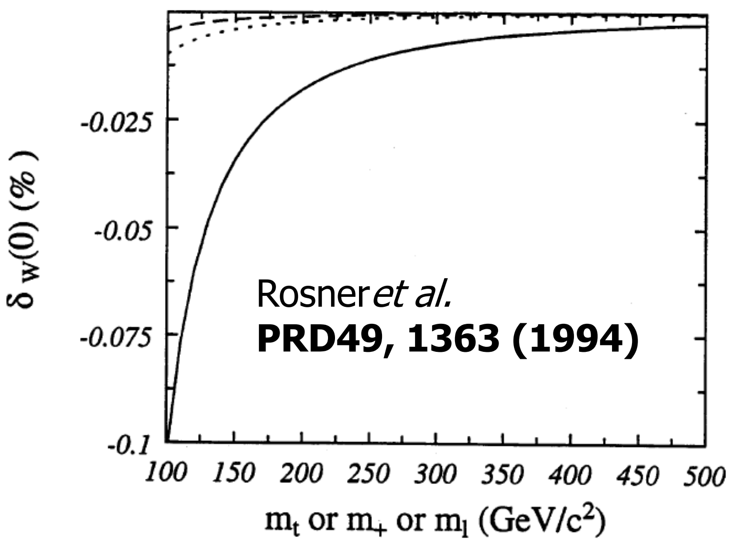
  ΔM_{top} : 1.3 GeV $\rightarrow$ 1 GeV

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

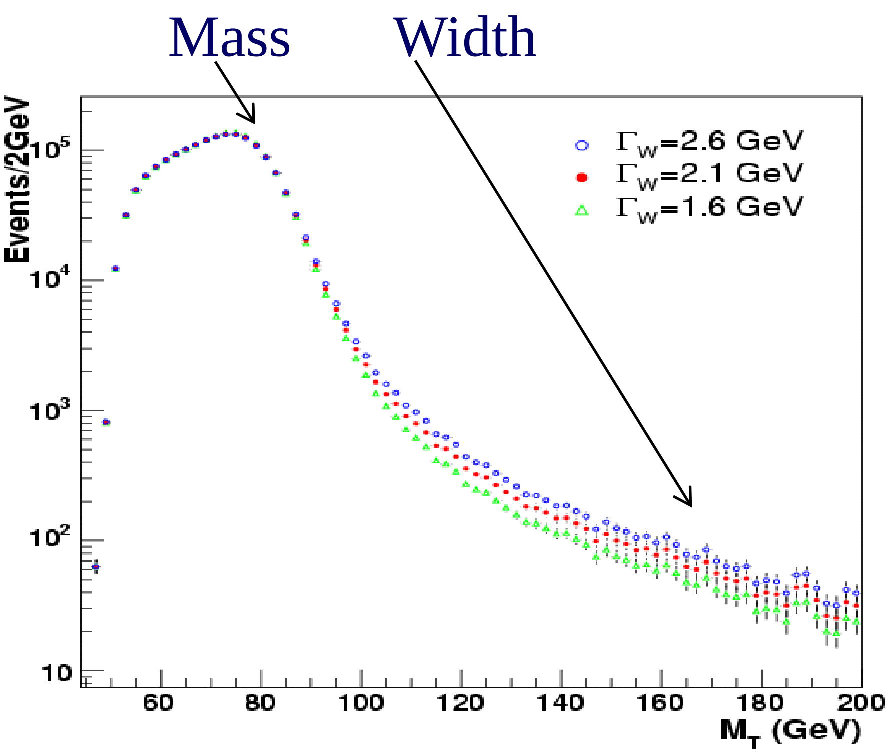
- Higgs:
  - most probable value = 71 GeV
  - excluded above 117GeV @95% CL (114.4 from current direct searches)

$\Gamma(W)$

Due to insensitivity to "oblique" corrections, expected to agree with SM prediction almost regardless of new physics



Exploit high tail of $M_T(W)$ distribution

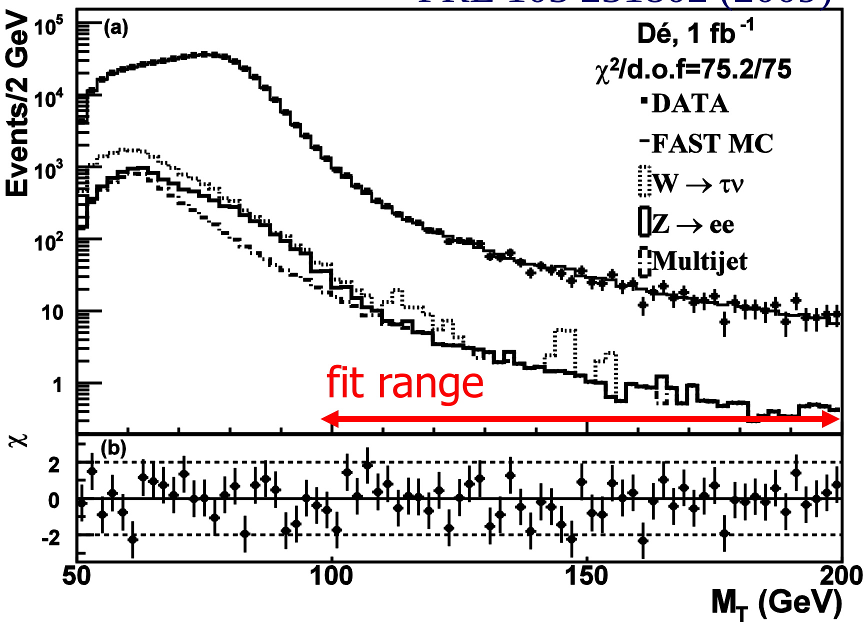


Width, to LO, is proportional to the fraction of events at high M_T

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

CDF RunII 350 pb^{-1} 2.032 ± 0.073 GeV

PRL 100 071801 (2008)

Tevatron combined value without DØ Run II:
Γ_W = 2.050 ± 0.058 GeV
Expect ~ 10 MeV improvement from including it

Standard Model prediction
and LEP result

(SM Γ_W = 2.093 ± 0.002 GeV)
(LEP Γ_W = 2.196 ± 0.083 GeV)

Summary

- W Mass measurement is crucial for constraining the Standard Model
- DØ recently published the most precise measurements of the W boson mass and width from a single experiment
- Comparable results published earlier by CDF
- Considering M(W) prospects and its physics implications with the full Tevatron dataset as well as direct Higgs searches
  → we are in exciting time and place !
- More data are being analyzed, expecting significant improvements in precision soon
- Stay tuned for new results

BACKUP SLIDES

Main Differences between CDF and DØ M(W) Analyses

	CDF	DØ
Luminosity	0.2 fb^{-1}	1.0 fb^{-1}
Events	63964 $W \rightarrow e\nu$ 51128 $W \rightarrow \mu\nu$	499830 $W \rightarrow e\nu$
W Decay Channels	electron, muon	electron
Lepton Energy Scale	tracker	$Z \rightarrow ee$ calorimeter data
Interpretation	absolute M(W)	M(W)/M(Z) ratio
MC Closure Test		full analysis performed first on Monte Carlo
Beyond M(W)	$M(W^+)$ and $M(W^-)$ comparison (intriguing!)	

Effect of Corrections on M(W)

tree level 80.939

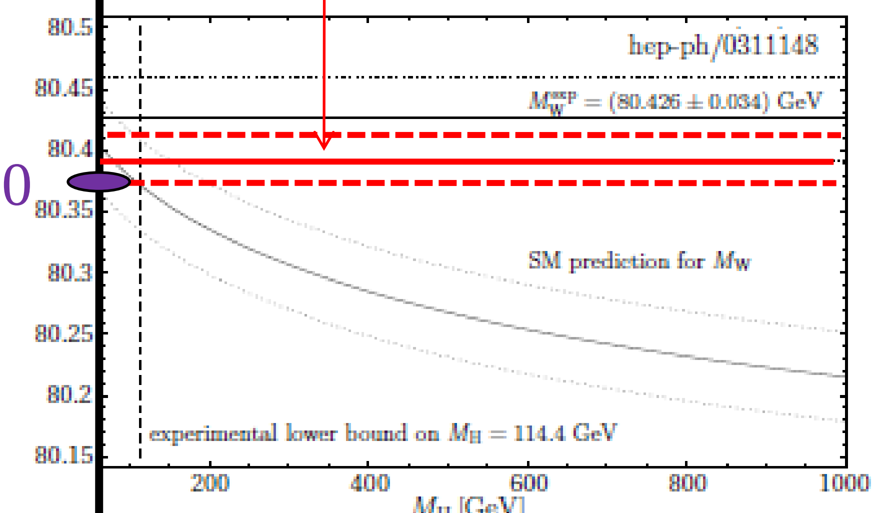
α	*electron g-2*	0.68 pp10^9
G_F	*muon life-time*	9 pp10^6
M_Z	*LEP 1 lineshape*	23 pp10^6

W Mass, GeV

current world average (experiment)
80.399 ± 0.023

+ radiative corrections
(M_H=100GeV)

80.380



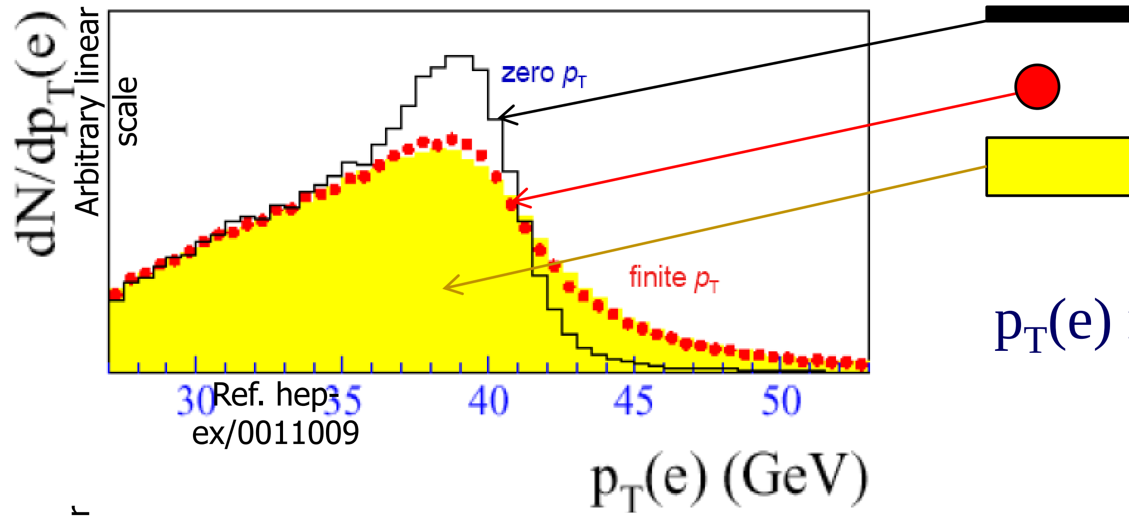
- 42 σ

+ 19 σ

Higgs Mass, GeV

+ running α_{EM} correction 79.964

What Affects Observable Shapes

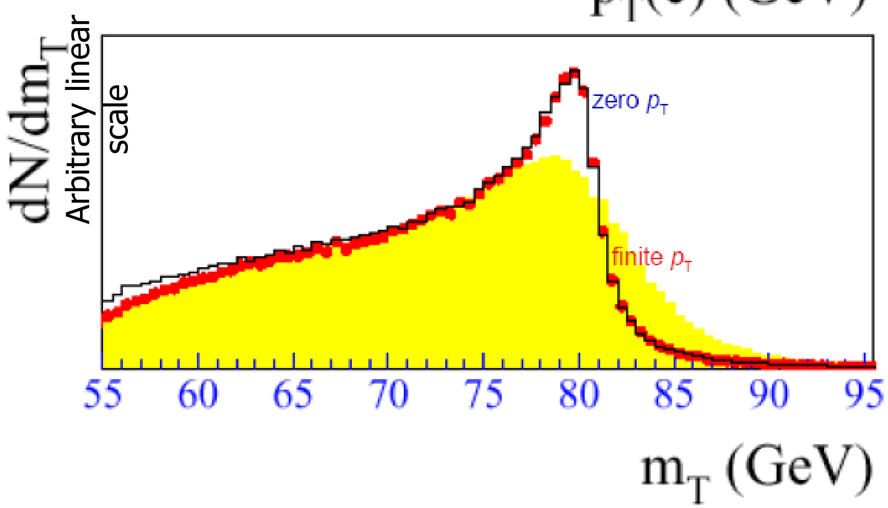


$P_T(W)=0$, no detector effects

$P_T(W)$ included

detector effects added

$p_T(e)$ most affected by $p_T(W)$

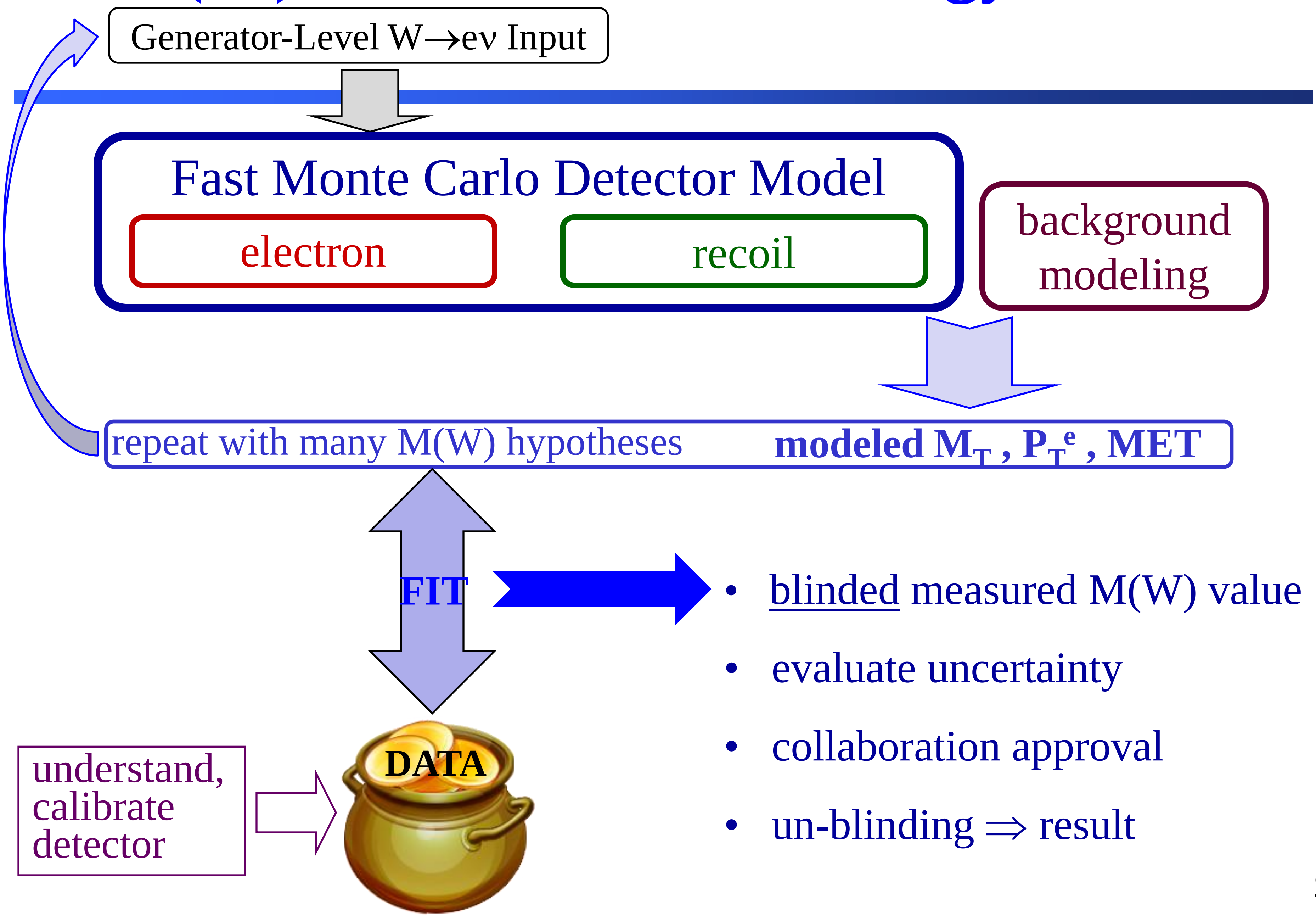


$$M_T = \sqrt{2E_T^l \not{E}_T(1-\cos\Delta\phi)}$$

M_T most affected by measurement of missing transverse momentum

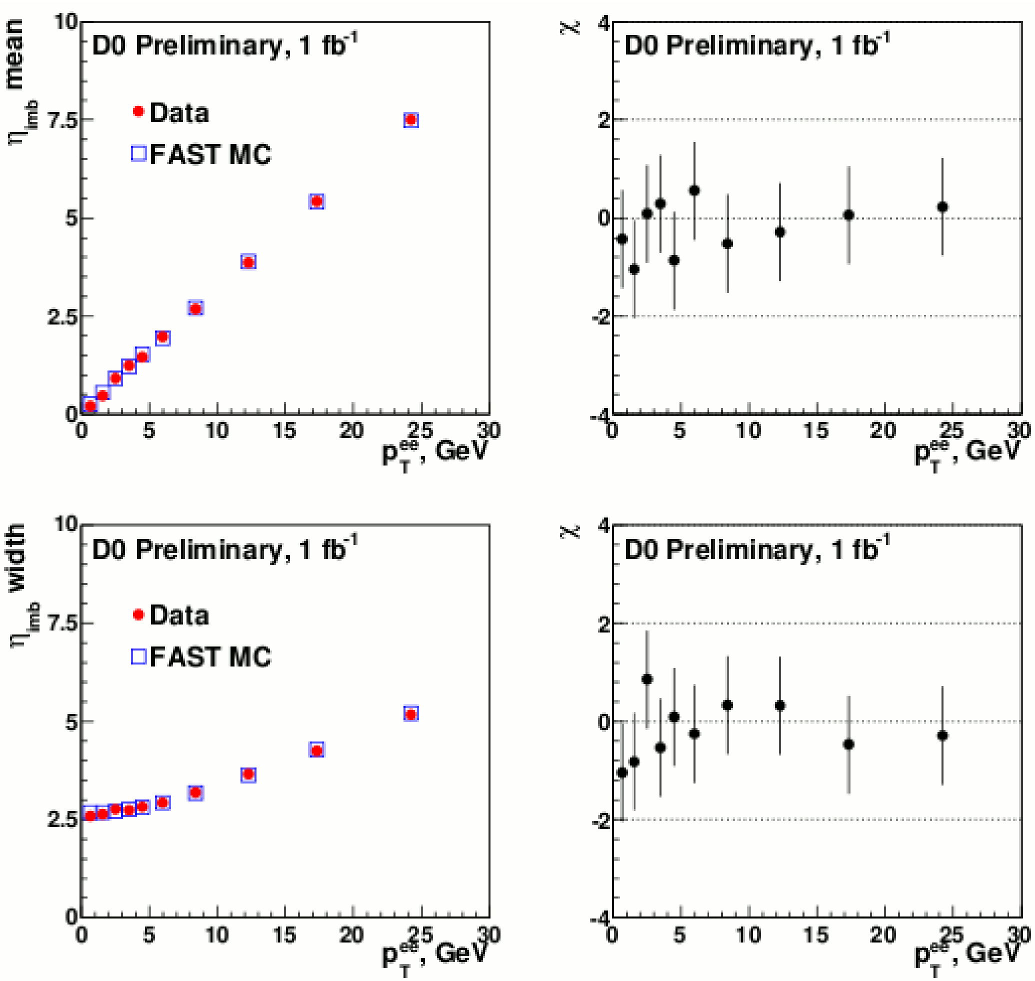
For W/Z production and decay both CDF and DØ use **ResBos (**Balazs, Yuan; Phys Rev D56, 5558,1997);
For photons CDF:**WGRAD** (Baur, Keller, Wackeroth PRD59, 013002 (1998)) ,
DØ: **Photos** (Barbiero, Was, Comp Phys Com 79, 291 (1994))

M(W) Measurement Strategy



Recoil Calibration

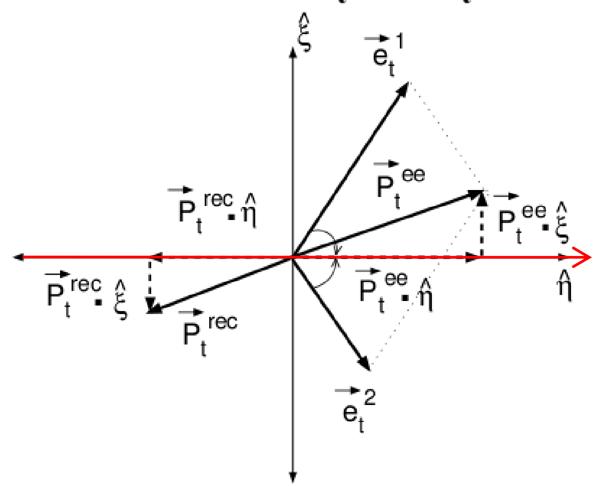
Final adjustment of free parameters in the recoil model is done *in situ* using balancing in $Z \to ee$ events and the standard **UA2 observables:**



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

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

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



Stages of Electron Energy Calibration

- Cell-level
  - pulser calibration *(ADC → collected charge)*
  - sampling fractions *(collected charge → total deposited energy)*

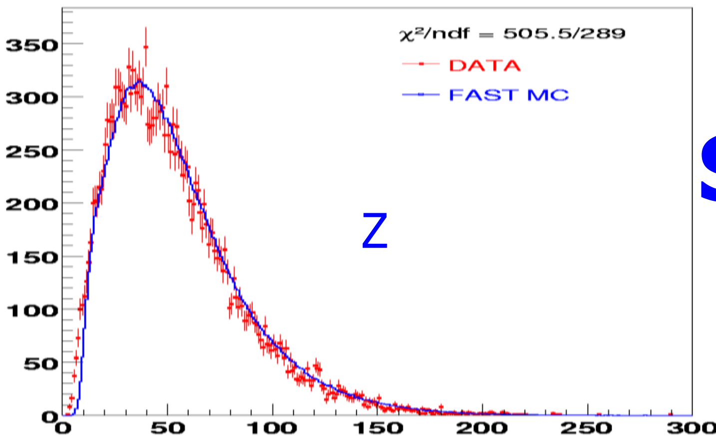
- Cluster – level
  - energy loss corrections
  - inter-φ calibration
  - η equalization and absolute scale
  - layer inter-calibration

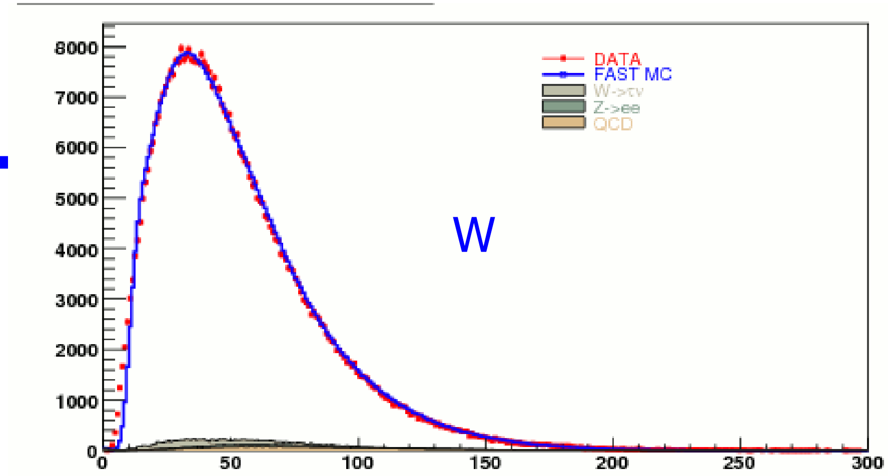
- Final M_W calibration

$Z \rightarrow e\,e$ and $W \rightarrow e\,\nu$

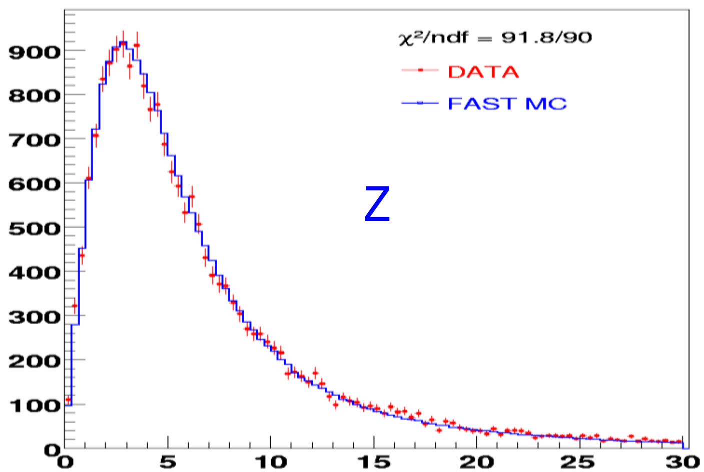
Data in red
MC in blue

SET

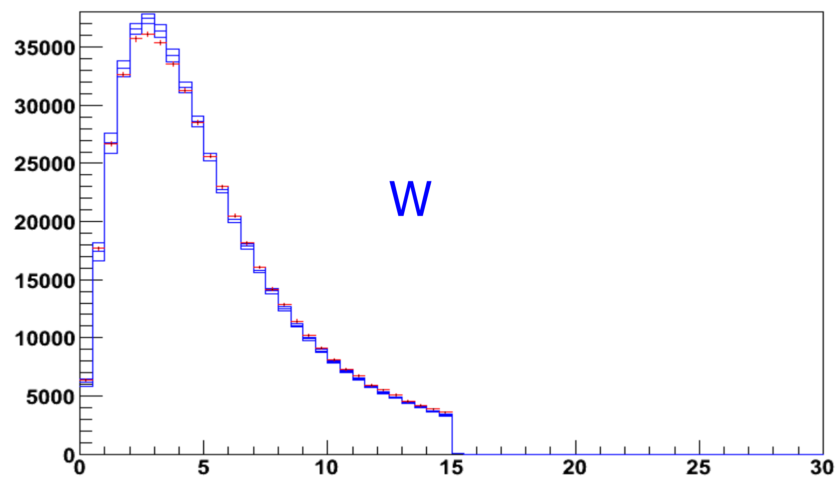




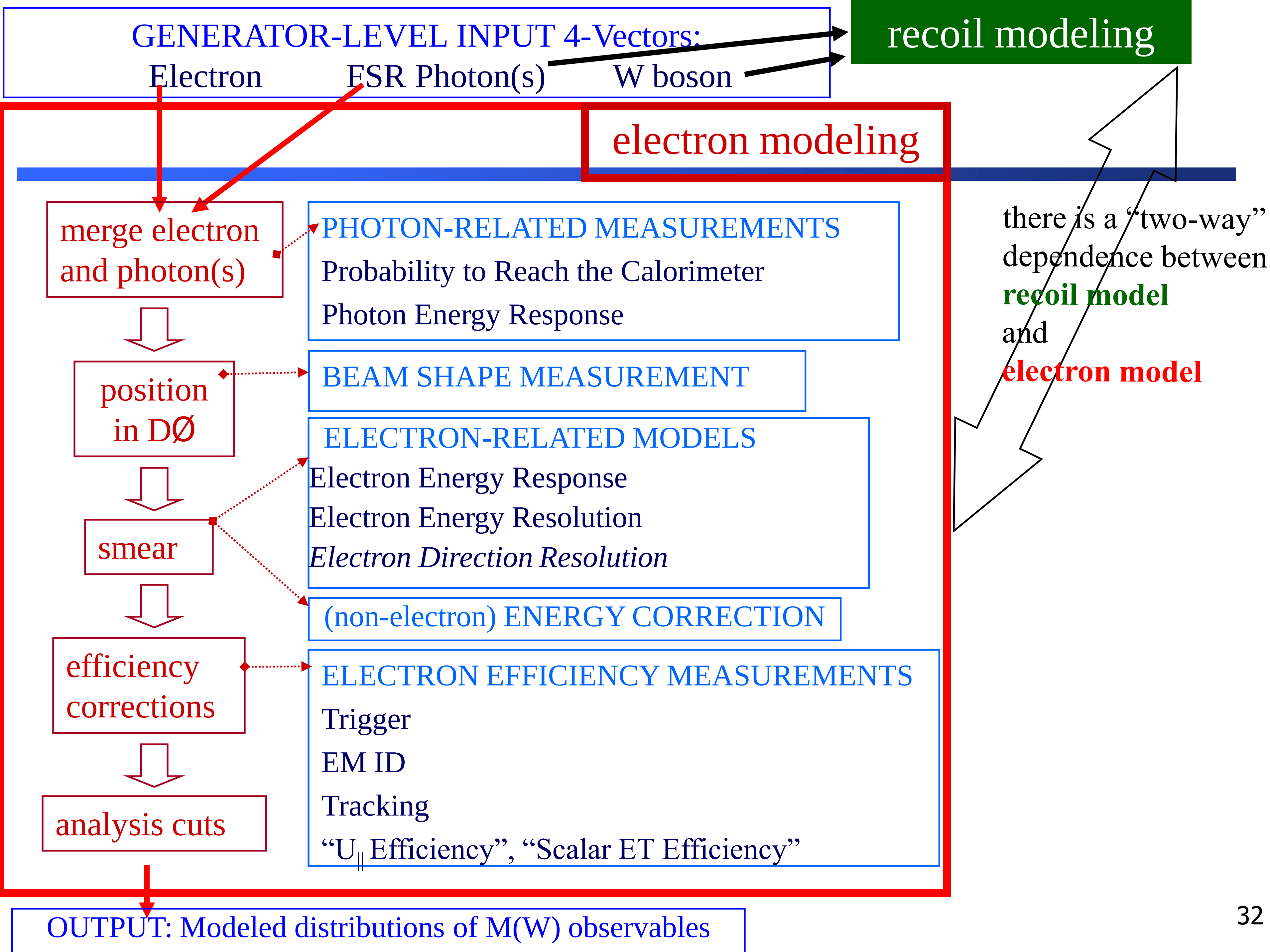
u_T



GeV



GeV


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

Electron Energy Resolution

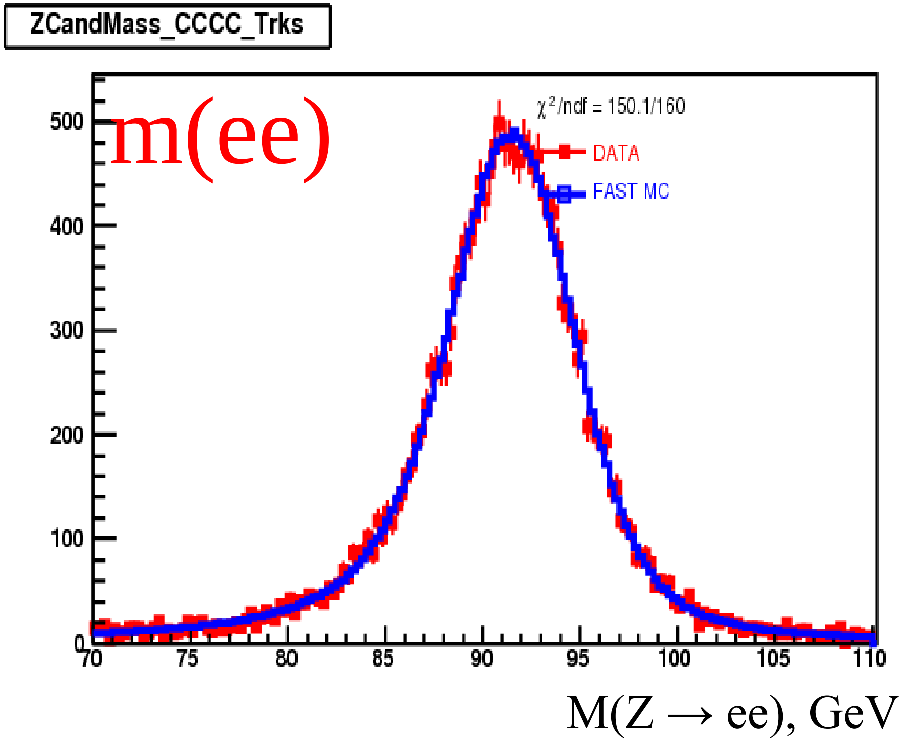
Electron energy resolution is driven by two components: sampling fluctuations and constant term

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

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.

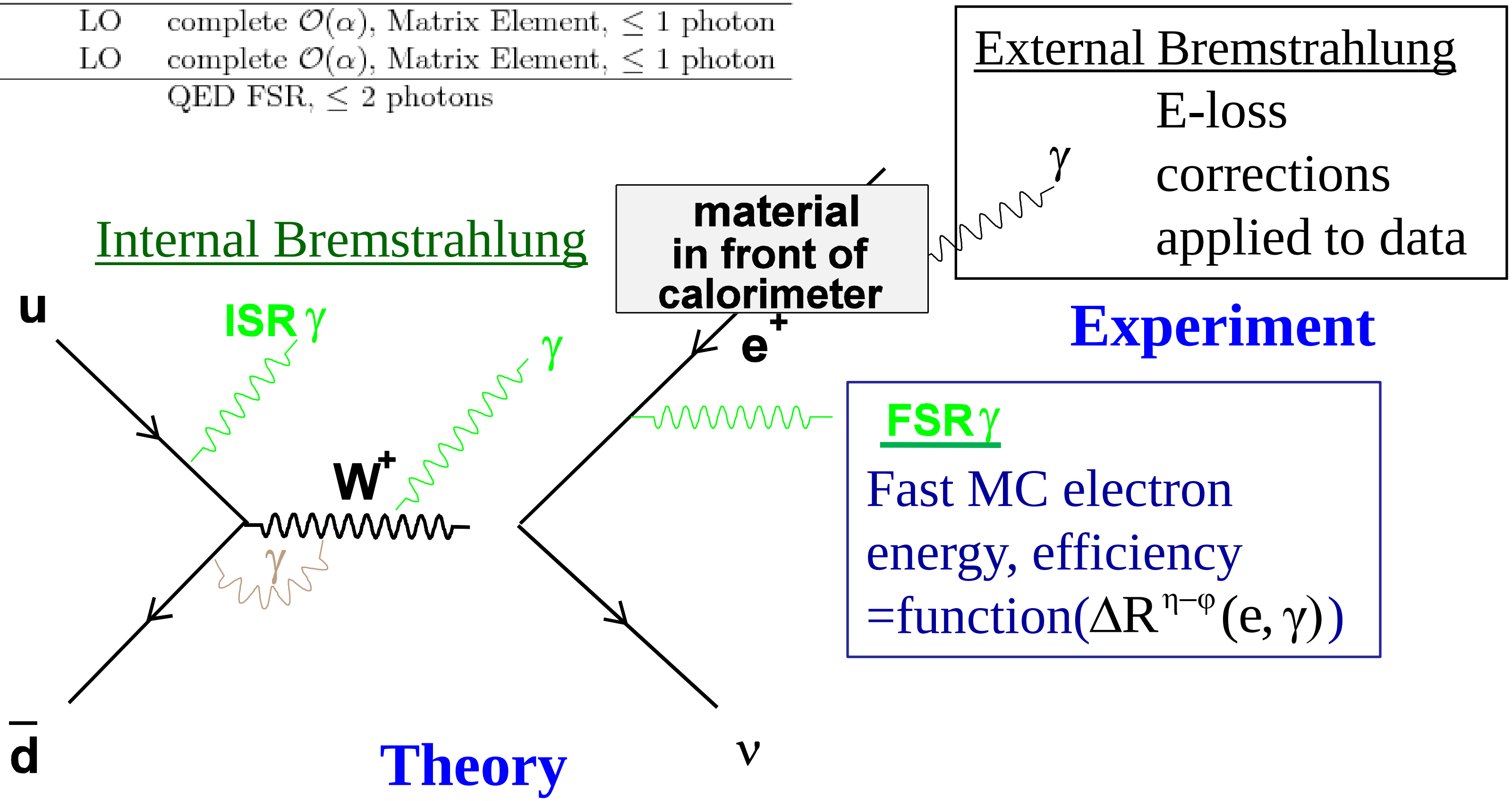
Constant term is extracted from Z → ee data (fit to observed width of the Z peak).

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



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.

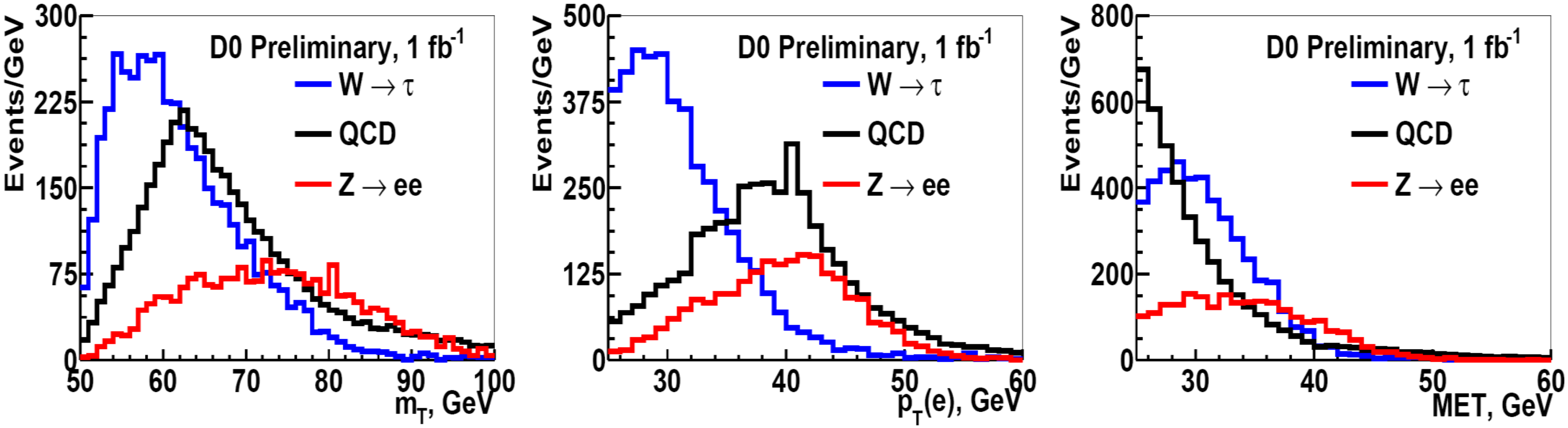
Effect of full EW corrections: compare W/ZGRAD in full EW mode with FSR-only mode

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

Backgrounds to W→eν

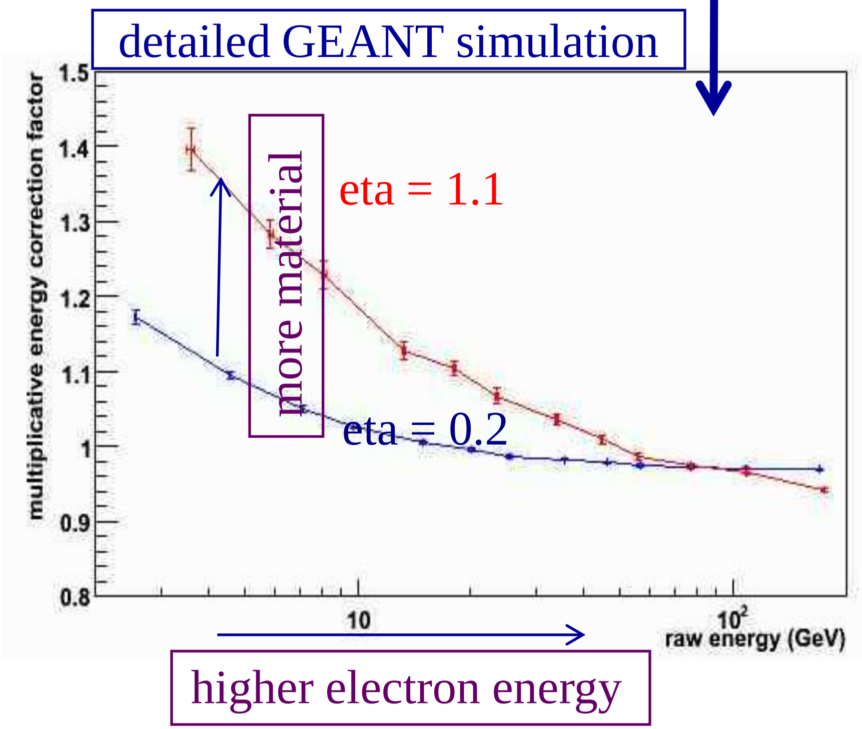
- QCD (di-jet) (1.49 ± 0.3 %) : one jet fakes as an electron
  - determined from QCD data
- Z→ee (0.80 ± 0.01 %) : one electron lost in ICR(between central and end cap)
  - determined from Z→ee data
- W→τν (1.60 ± 0.02 %) : Taus decaying into eνν
  - determined from GEANT (full) MC

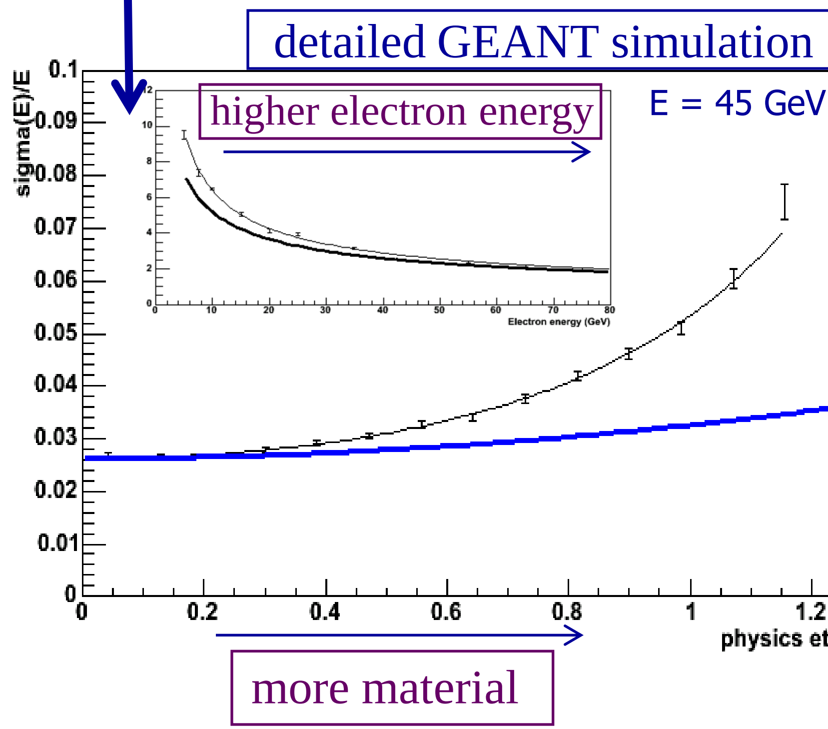
- **For all 3 observables: estimated backgrounds are added to Fast MC simulated signal**



Electron Response and Resolution

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

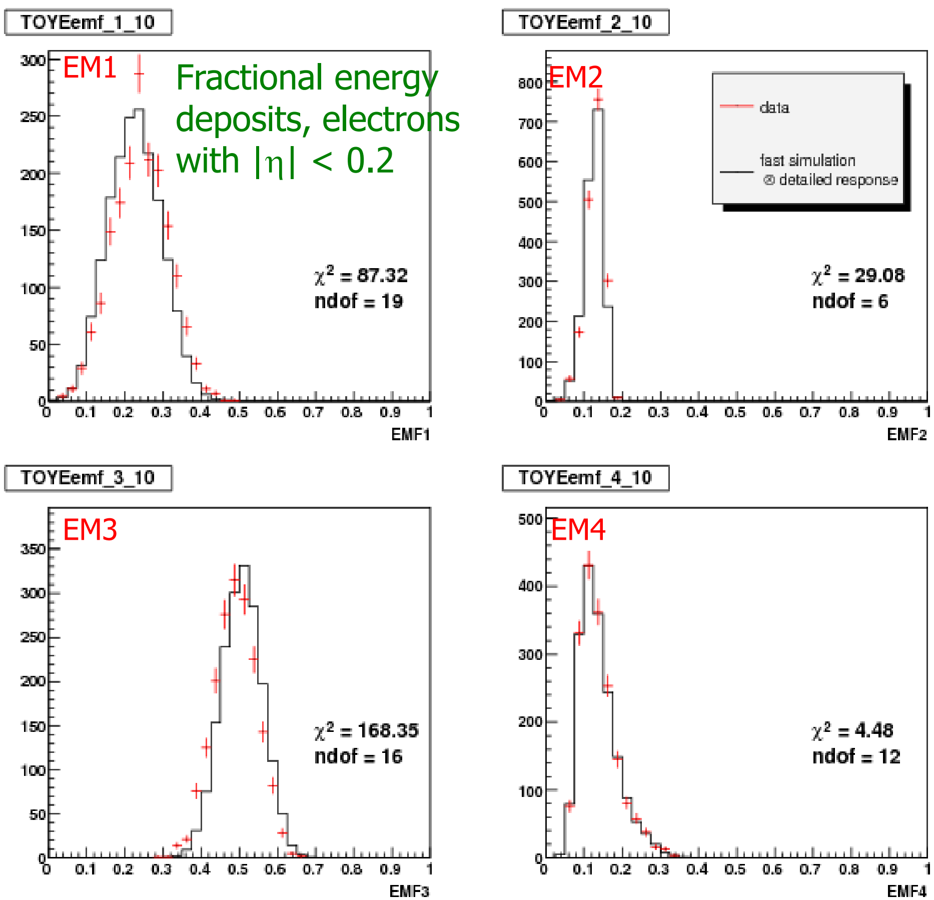




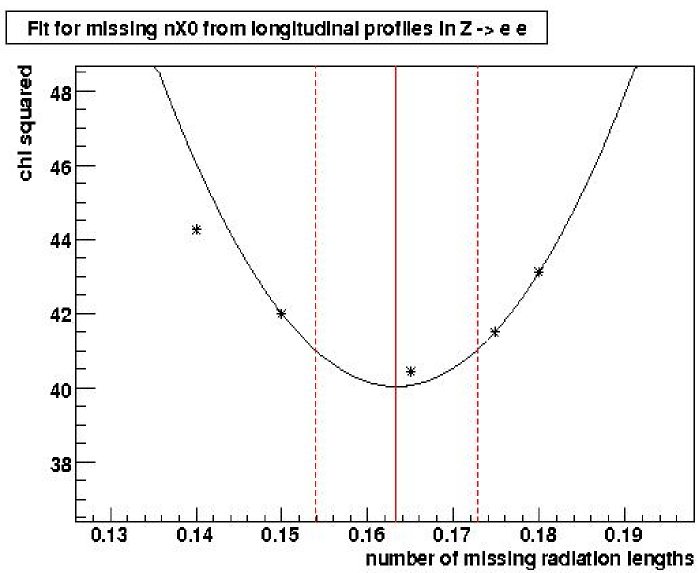
- The magnitude of the effect of the dead material depends on electron energy

Before tuning of material model

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



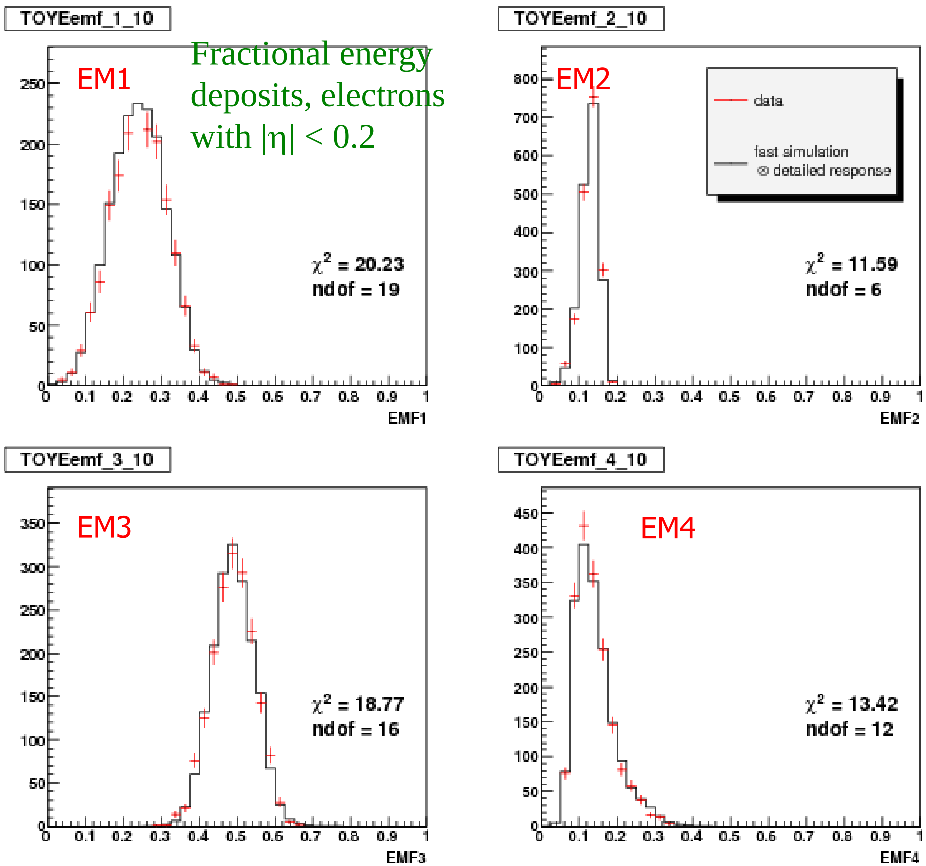
FIT



Amount of fudge 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.