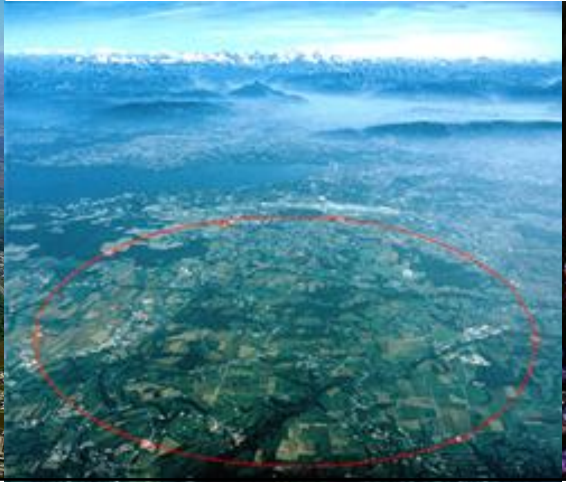
  

W Mass Results at Tevatron and LHC

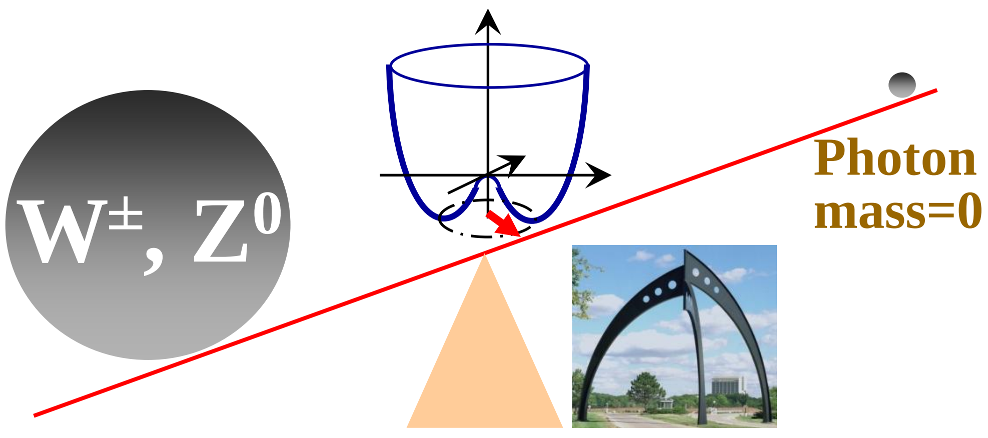
Alex Melnitchouk on behalf of ATLAS, CDF, CMS, DØ, and LHCb Collaborations
University of Mississippi

HCP2011, Paris, France, November 15, 2011

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

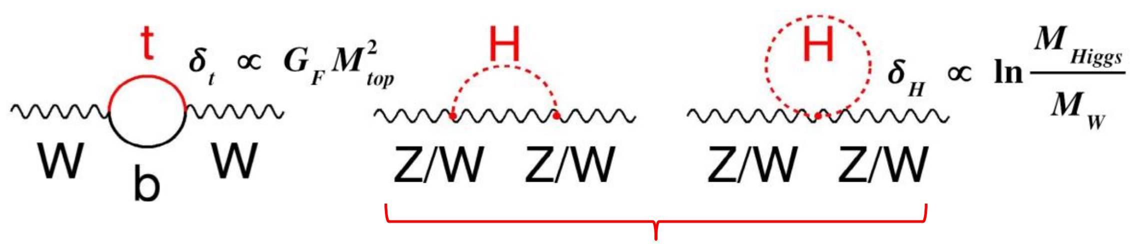
tree level

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

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

$$\alpha_{EM}(0 \rightarrow M_Z)$$

Δr = Running of α_{EM} + Radiative Corrections

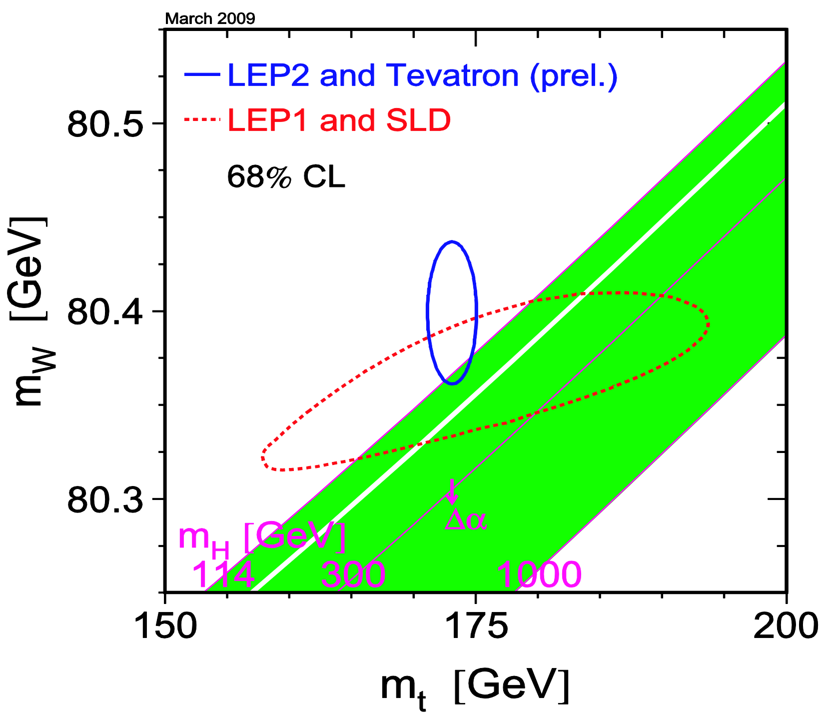


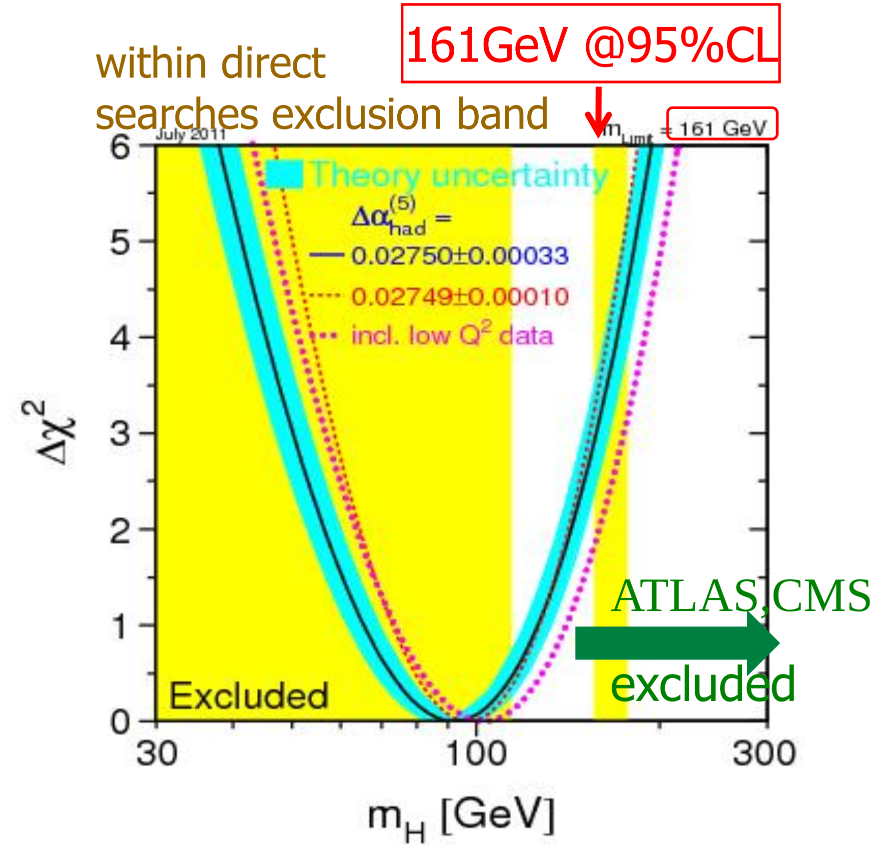
Sensitivity to Higgs Mass

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





Measuring M(W)

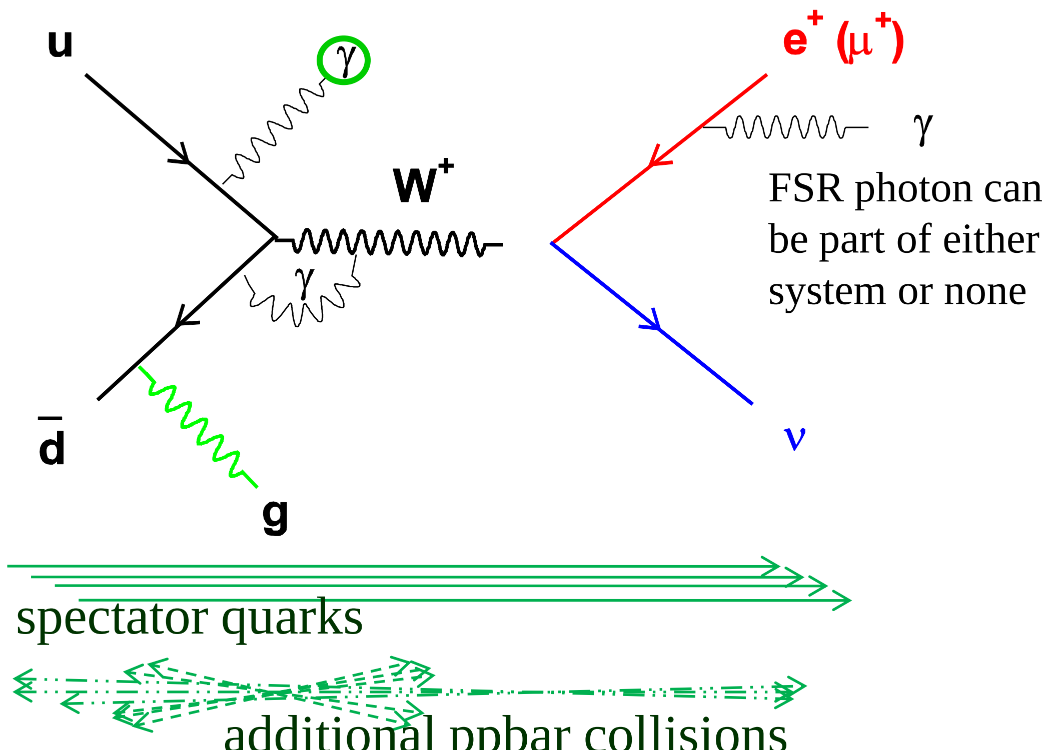
- Cannot reconstruct M(W) directly (missing neutrino p_z)
- Extract it from observables that are sensitive to M(W)

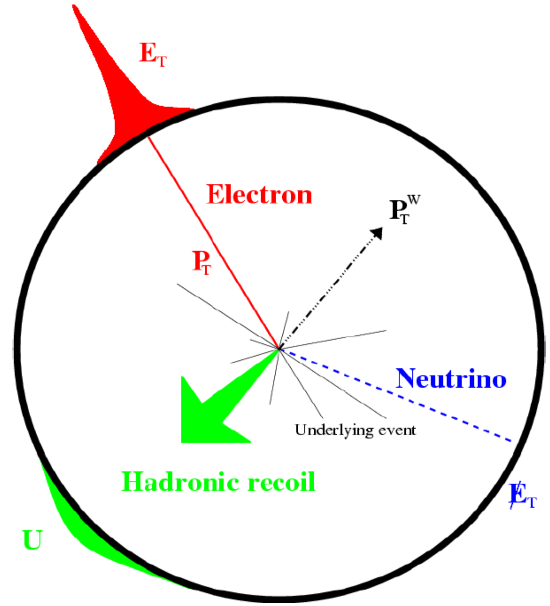
$$M_T = \sqrt{2 p_T^e \, p_T^\nu (1 - \cos\phi_{e\nu})} \qquad p_T^e \qquad p_T^\nu \left(\not{E}_T = \left| \vec{\boldsymbol{p}}_T^{\boldsymbol{e}} + \vec{\boldsymbol{p}}_T^{\boldsymbol{recoil}} \right| \right)$$

  - 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 Lorentz-invariant only longitudinally: sensitive to transverse motion of W boson
  - need good model of W boson production

W→eν Event: Theory and AnalysisView

hard component = recoil against W





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

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

to achieve

$\Delta M_W / M_W \approx 0.5 \times 10^{-3}$

Required detector response precision:	**electron**	$\sim 0.3 \times 10^{-3}$
	hadronic recoil	**~ 1%**

Lepton Energy Calibration

CDF

- Good tracker resolution
- Linearity
- Good calibration even based on first-principles
- Transfer precise tracker calibration to calorimeter
- Muon and electron channels

Lepton Energy Calibration

CDF

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- Linearity
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- Transfer precise tracker calibration to calorimeter
- Muon and electron channels

DØ

- Tracker volume is small
- Very good calorimeter
- First-principles understanding of EM showers
- Final calibration: LEP M(Z)
- Electron channel only

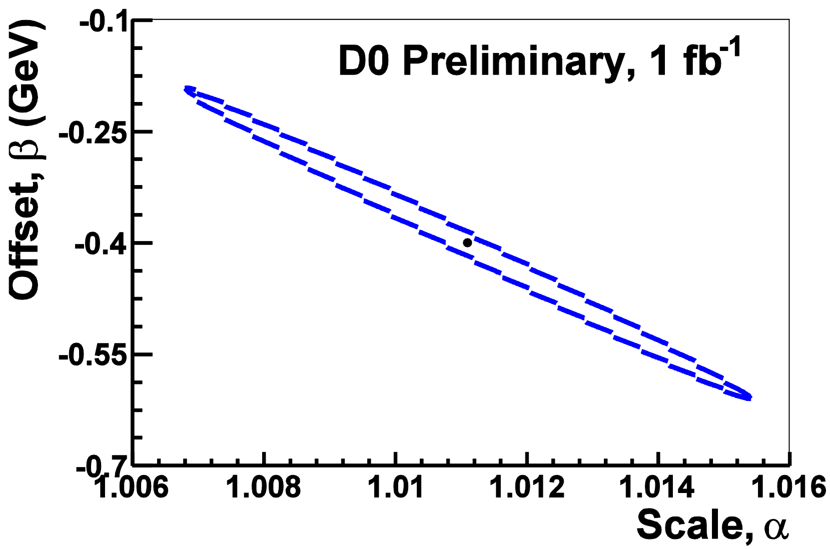
Final M(W) Calibration (DØ)

- 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

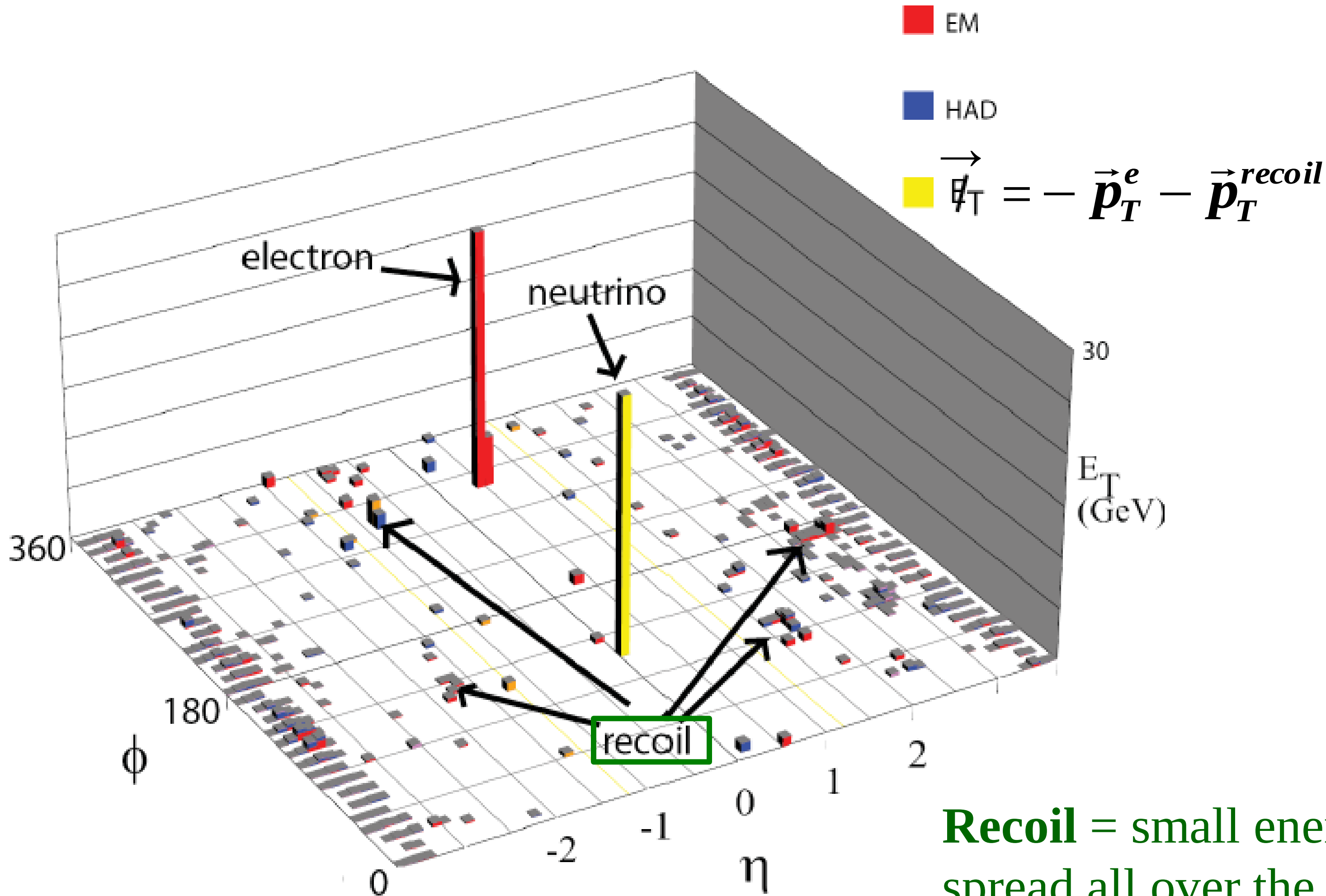
$f_Z = (E(e1)+E(e2))(1-\cos(\gamma_{ee}))/m_Z$

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)

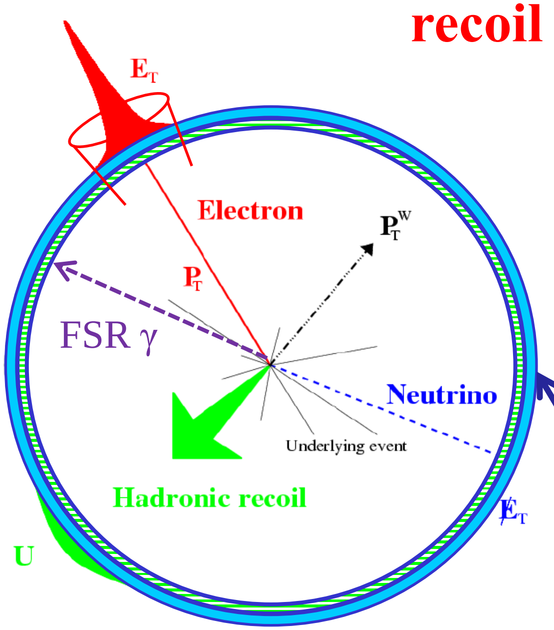
estimate from W→ eν data

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

FSR photon outside electron cone

full MC derived model

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



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

-- spectator partons

-- additional interactions

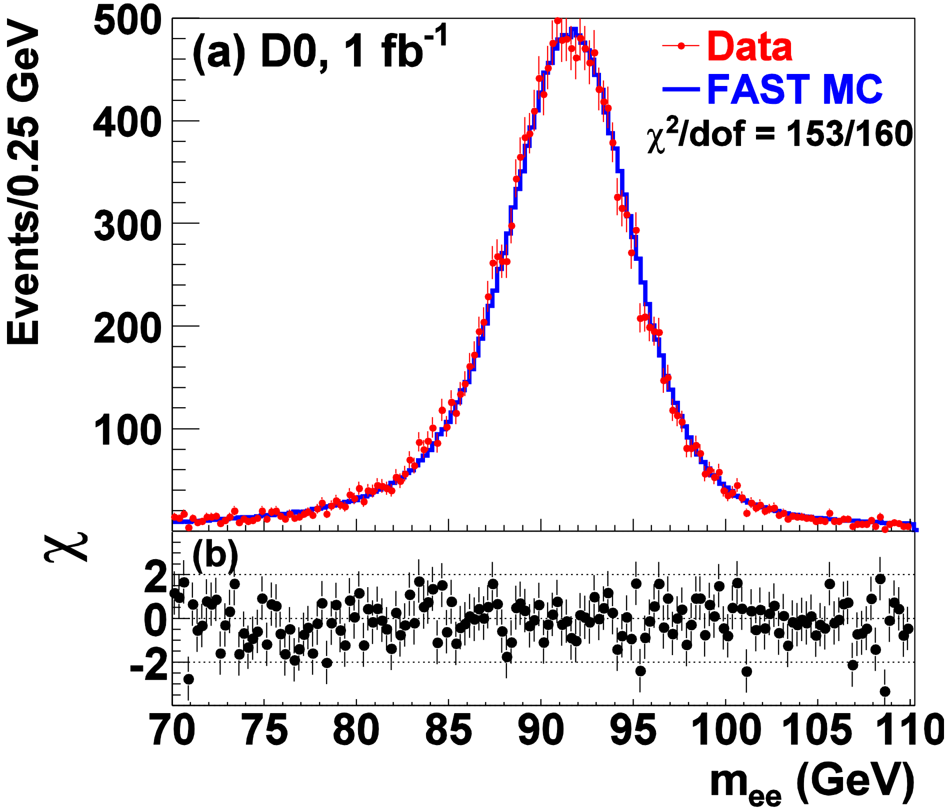
$$\vec{u}_T^{\,\mathrm{Soft}} = \alpha_{\mathrm{MB}} \cdot \vec{E}_T^{\,\mathrm{MB}} + \alpha_{\mathrm{ZB}} \cdot \vec{E}_T^{\,\mathrm{ZB}}$$

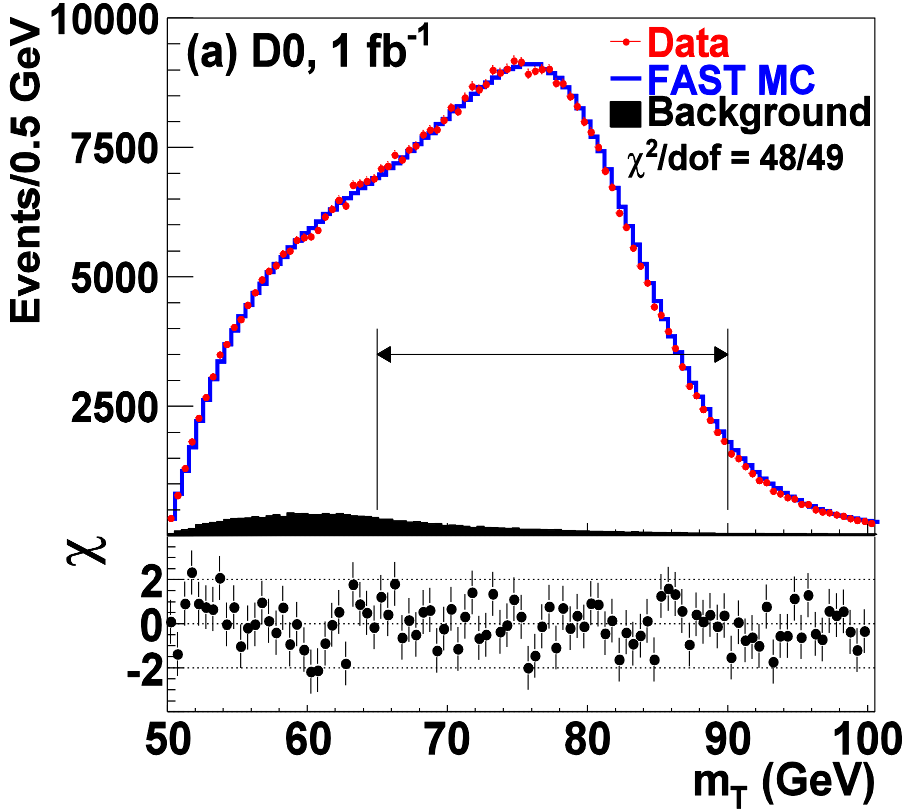
balances P_T of the vector boson:

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

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

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



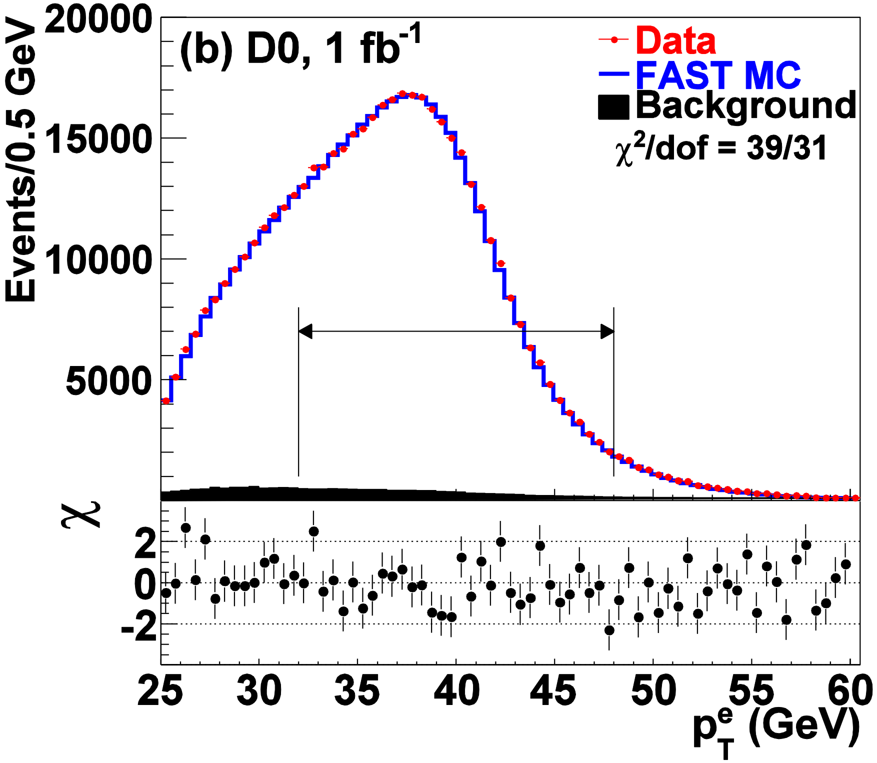


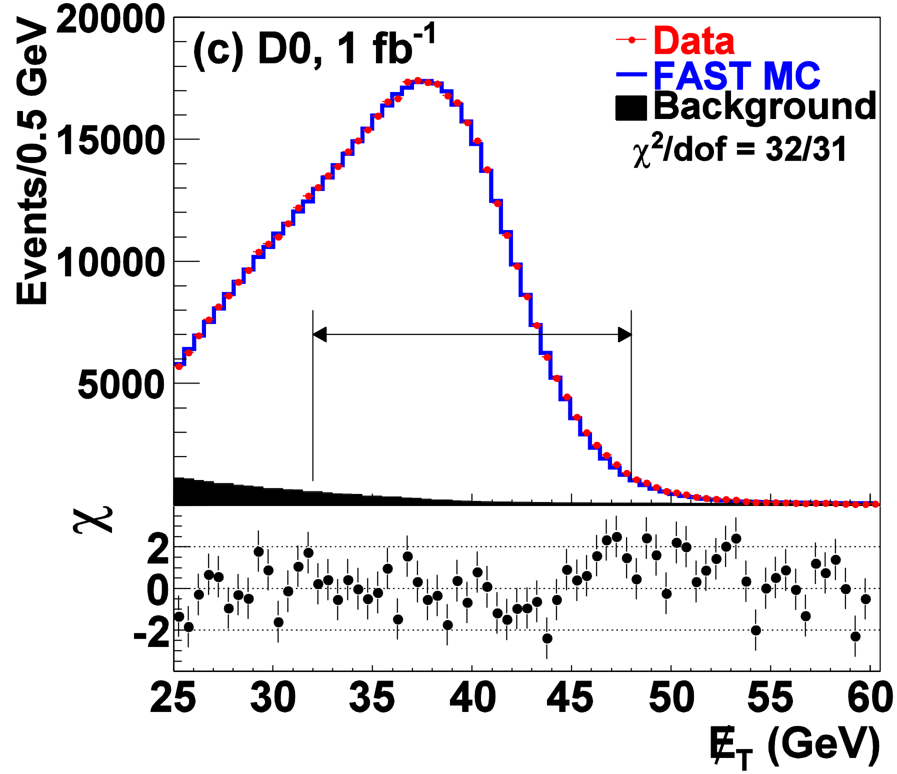
m(Z) = 91.185 ± 0.033 GeV (stat)

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)

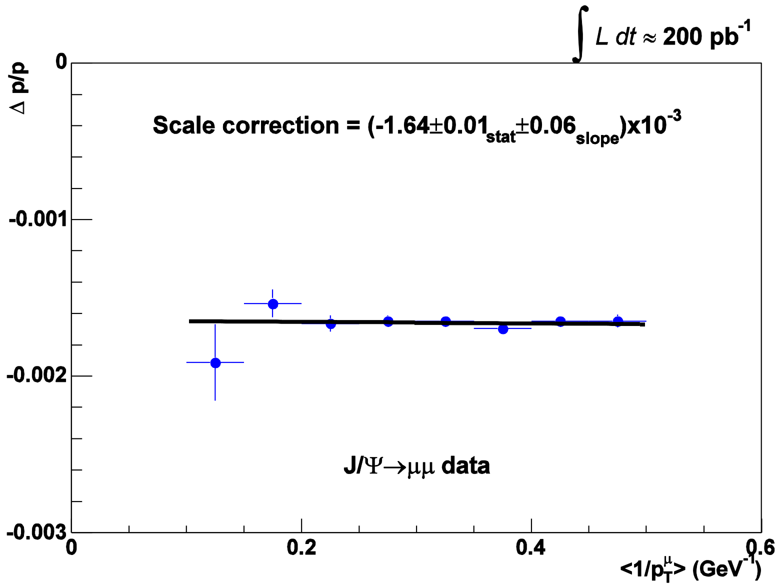
Source	m_T	p_T^e	$\not{E}_T$
Statistical	**23**	**27**	**23**
Systematic - Experimental			
Electron energy response	34	34	34
Electron energy resolution	2	2	3
Electron energy non-linearity	4	6	7
Electron energy loss differences	4	4	4
Recoil model	6	12	20
Efficiencies	5	6	5
Backgrounds	2	5	4
Experimental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

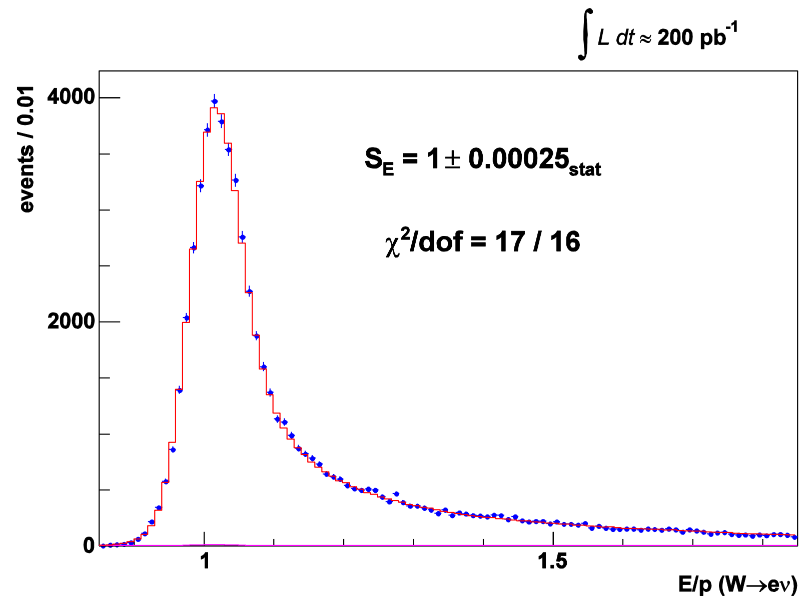
Lepton Energy Calibration (CDF)

precise tracker calibration

measure J/ψ mass
in bins of muon momentum



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



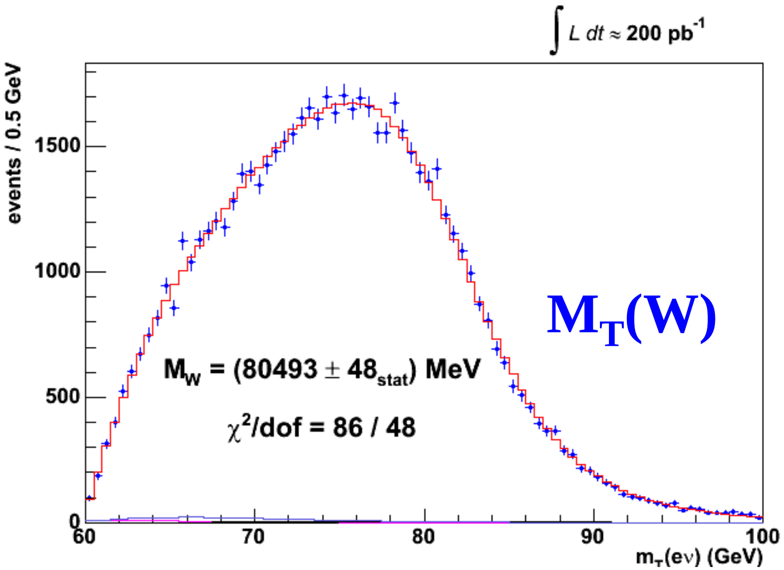
adjust energy loss model

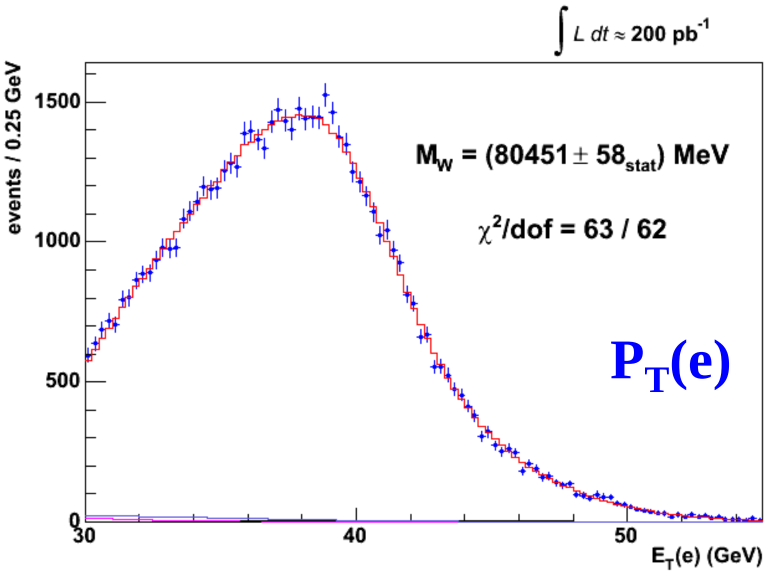
0.02% calibration precision
main uncertainties:

- QED corrections
- magnetic field non-uniformity

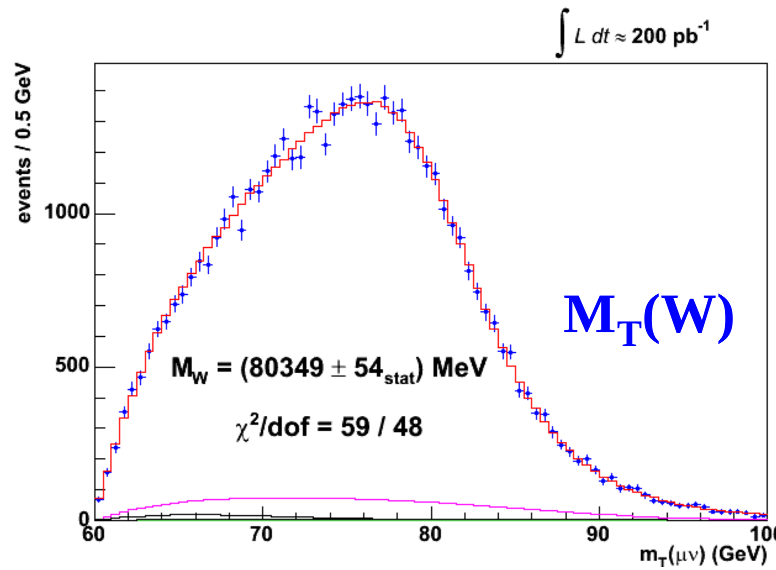
CDF M(W) Analysis

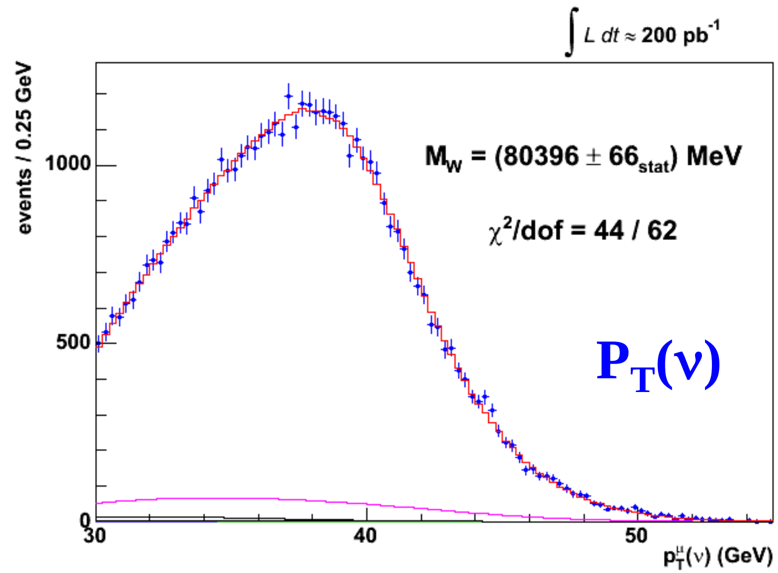
Electron Channel



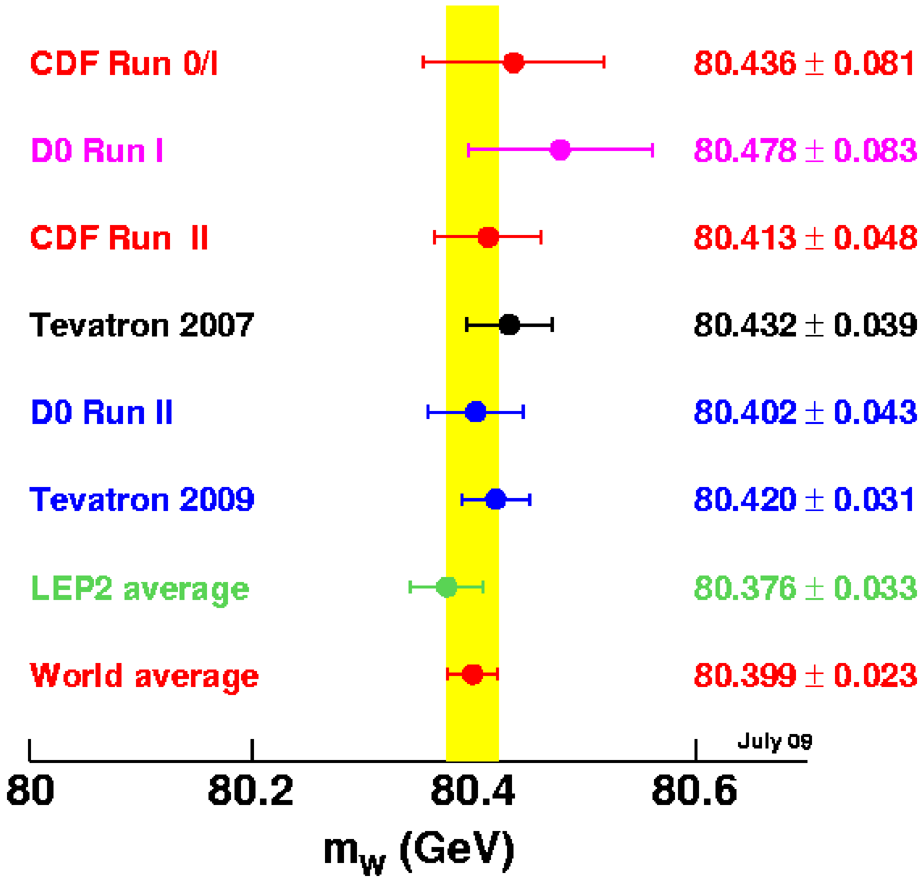


Muon Channel





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)

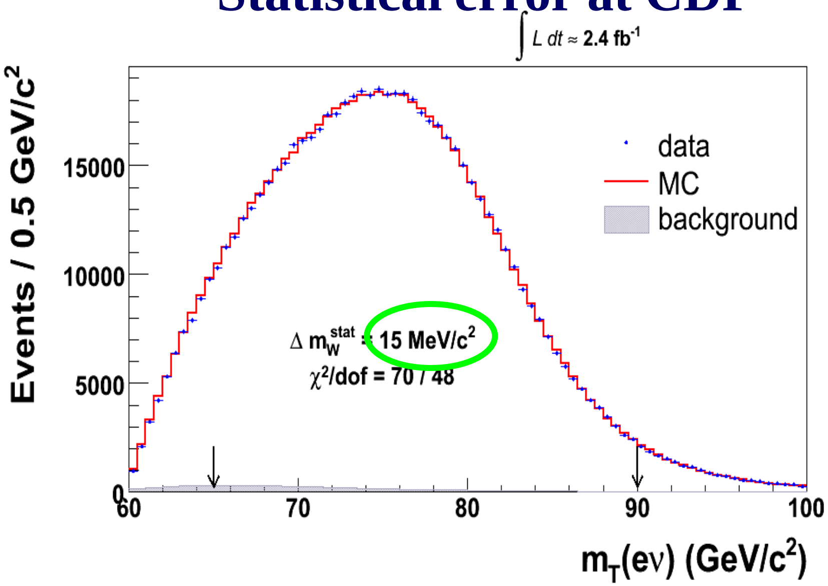
80.413 ± 0.034 (stat.) ± 0.034 (syst.) GeV

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



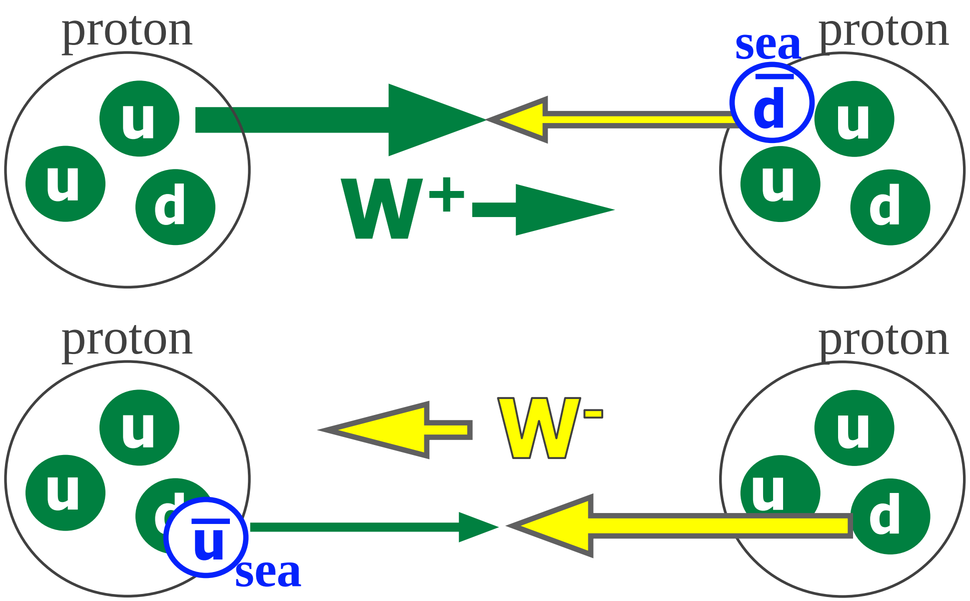
Electron scale error at DØ

≈34 MeV

↓

≈16 MeV

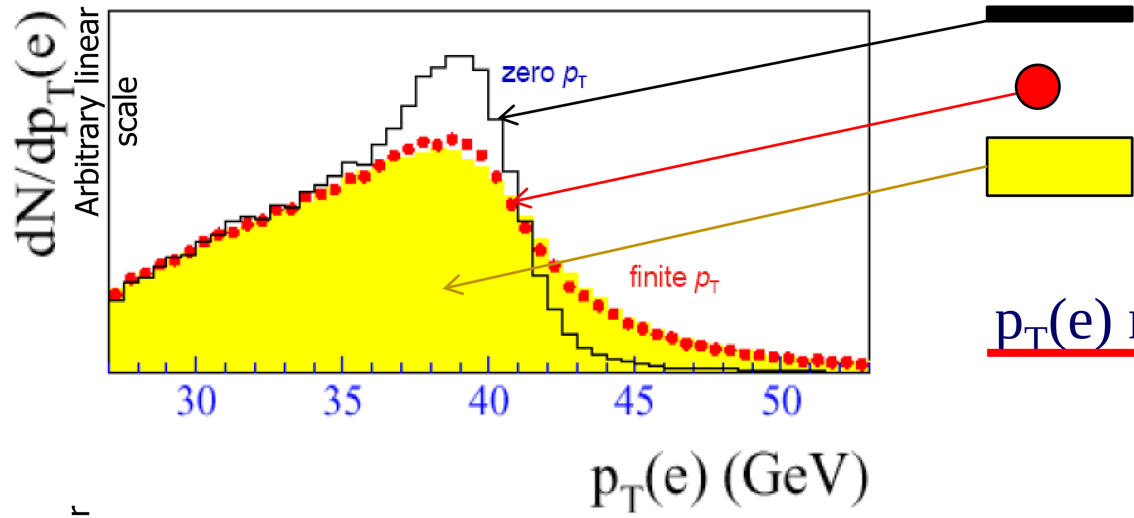
W Production at LHC



- W bosons are produced with valence quarks and see quarks
- $N(u_V) > N(d_V)$
  $\Rightarrow$ Total $N(W+) > N(W-)$
  $\sigma(W+)/\sigma(W-)$ ratio = 1.43 ± 0.05
  CMS-EWK-10-006

- $P_T(W+)$ and $P_T(W-)$ spectra are different
- c-quark and s-quark contribute significantly

Importance of knowing $P_T(W)$

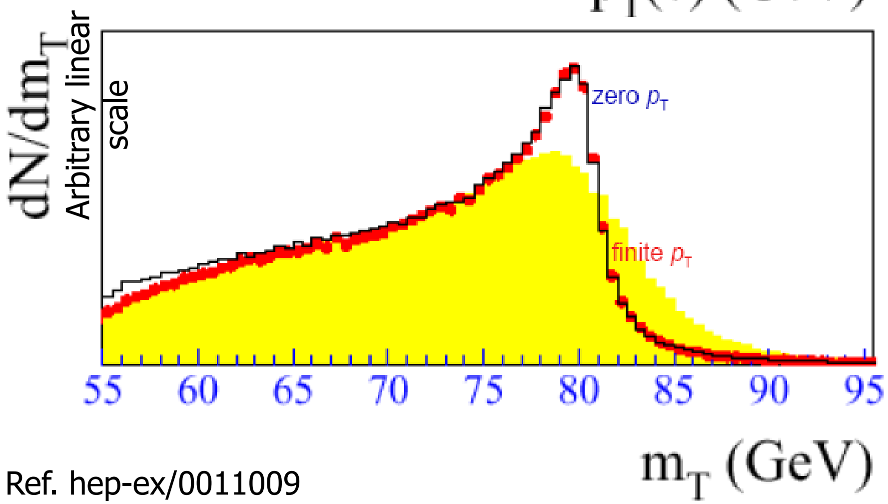


$P_T(W)=0$, no detector effects

$P_T(W)$ included

detector effects added

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



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

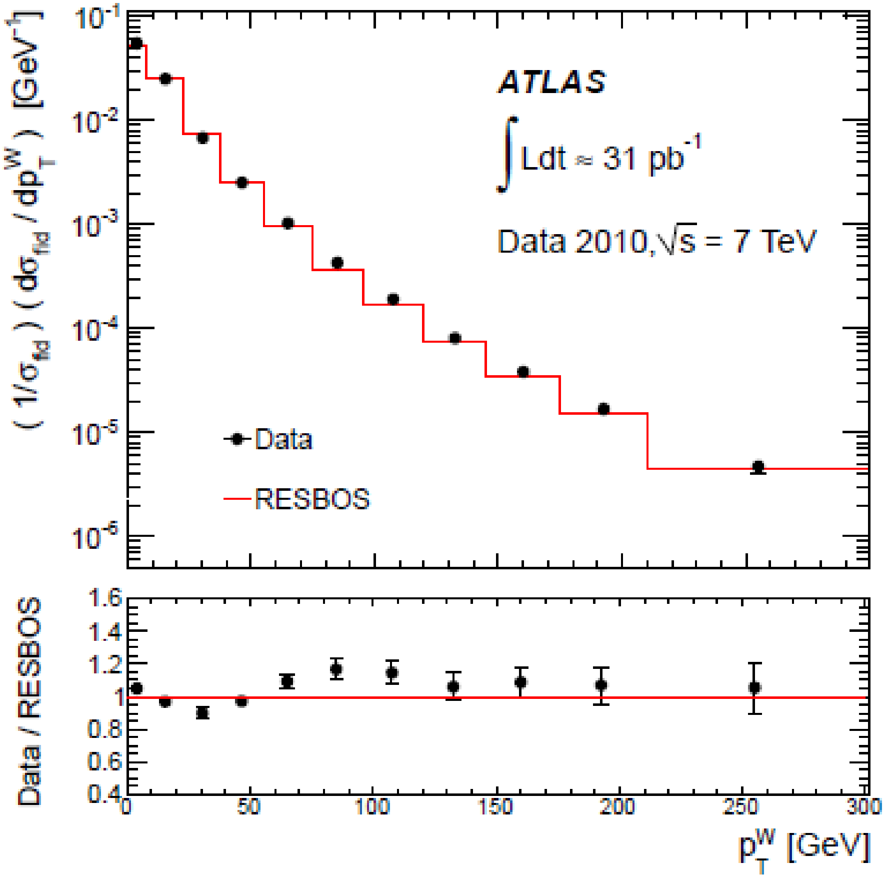
M_T most affected by measurement of missing transverse momentum

Ref. hep-ex/0011009

P_T(W) Measurement (ATLAS)

- Impressive result with $31 pb^{-1}$

arXiv:1108.6308v1



P_T(W) Measurement (ATLAS)

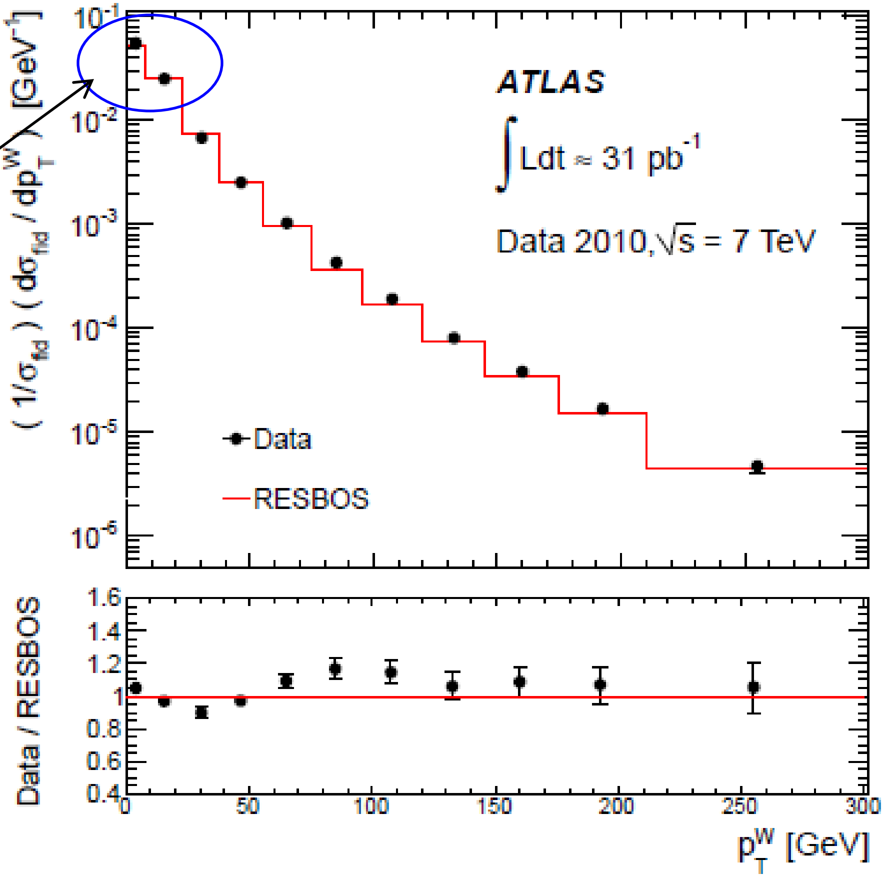
arXiv:1108.6308v1

- Impressive result with $31pb^{-1}$

- W mass measurement is mostly interested in low end
  - lower hadronic energy
  - better theory description

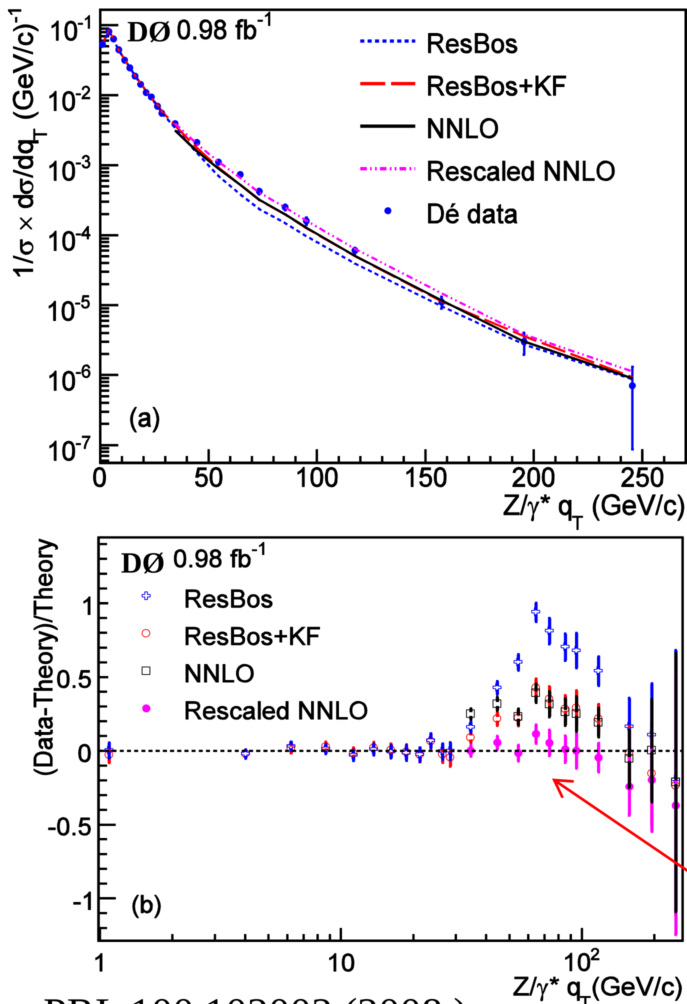
- Serious step towards precision needed for W mass input

plan to split in $P_T(W+)$ and $P_T(W-)$ and use together with $P_T(Z)$ measurement as feedback to W mass measurement



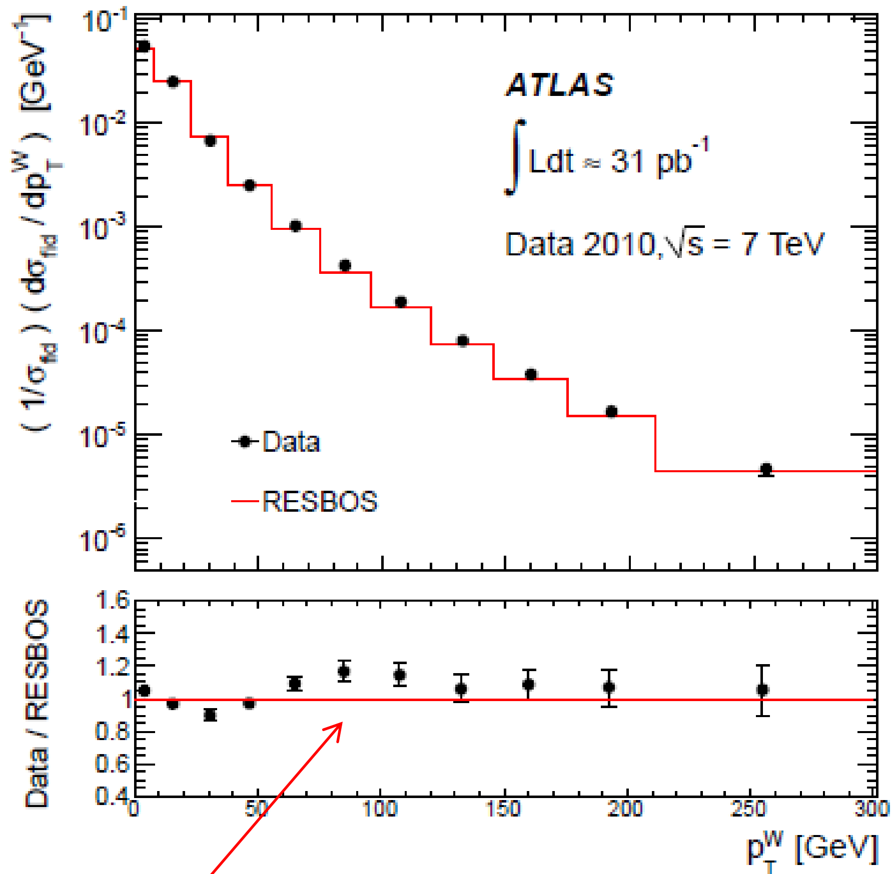
$P_T(W)$ Measurement (ATLAS)

$P_T(Z)$ from DØ, $1fb^{-1}$



PRL 100 102002 (2008)

arXiv:1108.6308v1



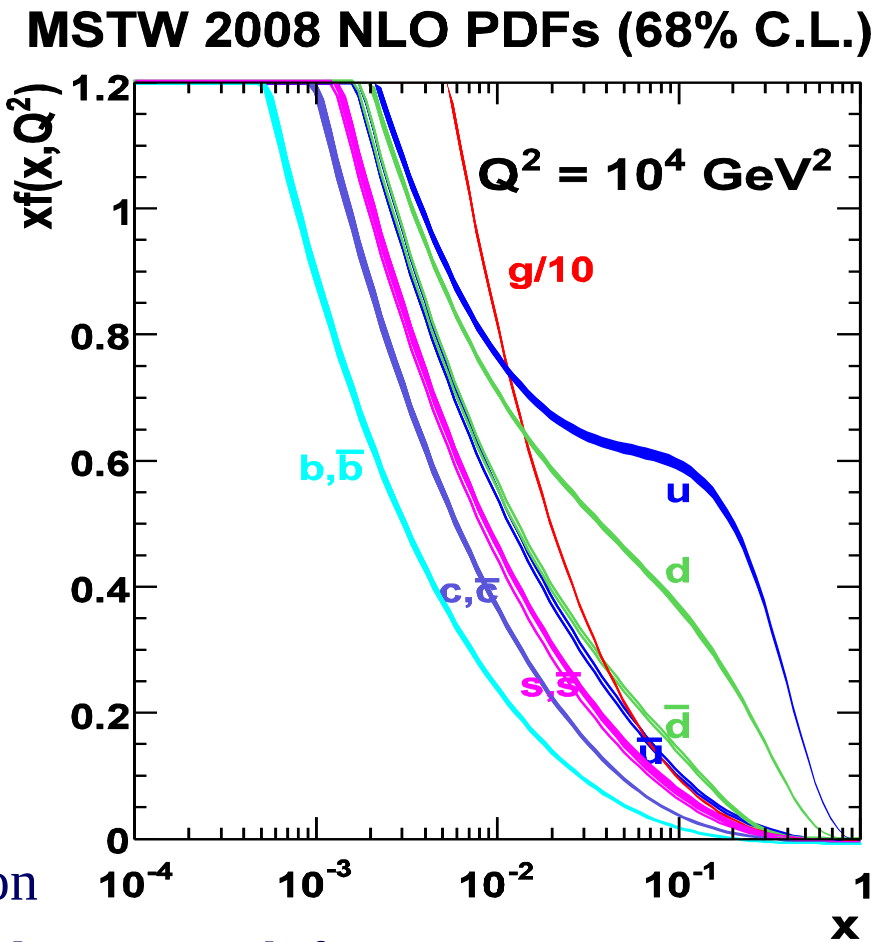
same problem ?

W Production Asymmetry, PDFs

- Both at the Tevatron and the LHC W bosons are produced via

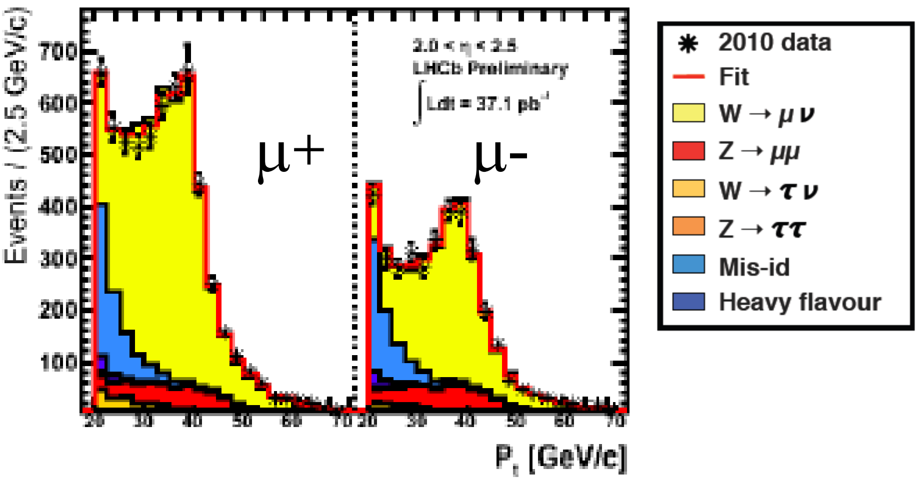
$$u\bar{d} \rightarrow W^{+}$$

$$d\bar{u} \rightarrow W^{-}$$

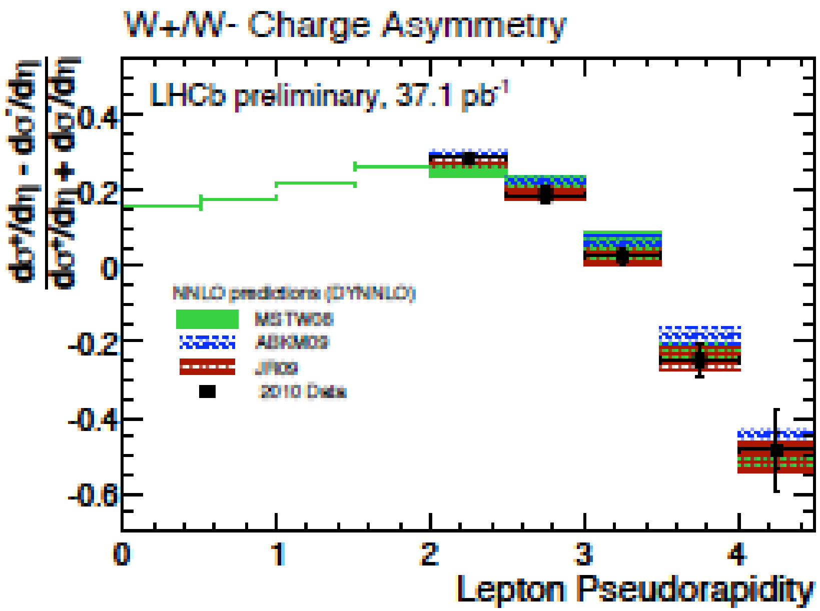


- Tevatron:
  valence quark from proton
  and valence anti-quark from anti-proton
- LHC: a valence quark from proton and a sea quark from proton
- W production asymmetry is governed by the PDFs
  $\Rightarrow$ constrain the PDFs with asymmetry measurements

Lepton Asymmetry from LHCb



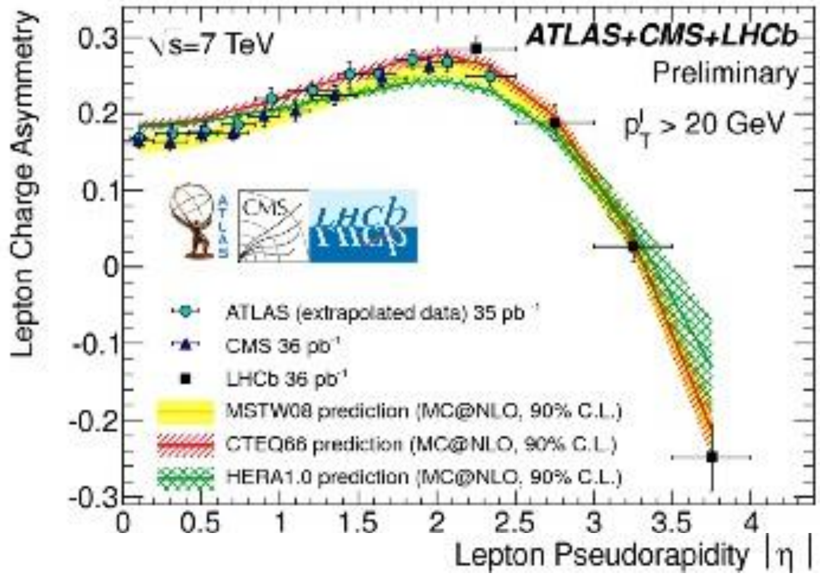
LHCb-CONF-2011-039v2



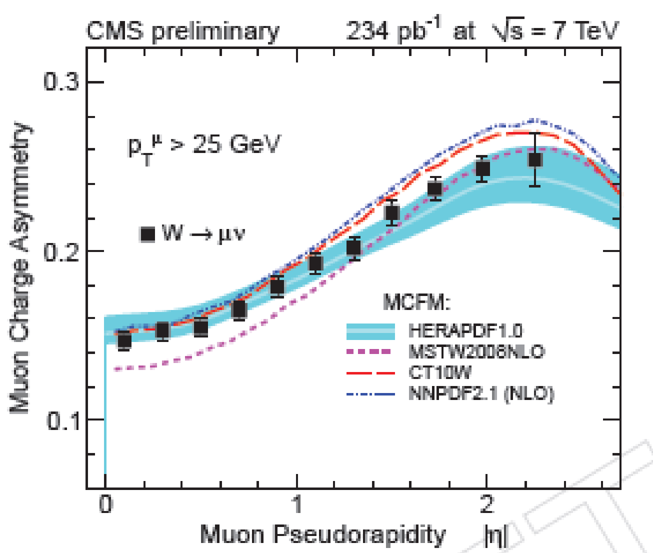
$$x_1 = M_W e^{y} / \sqrt{s}, x_2 = M_W e^{-y} / \sqrt{s}.$$

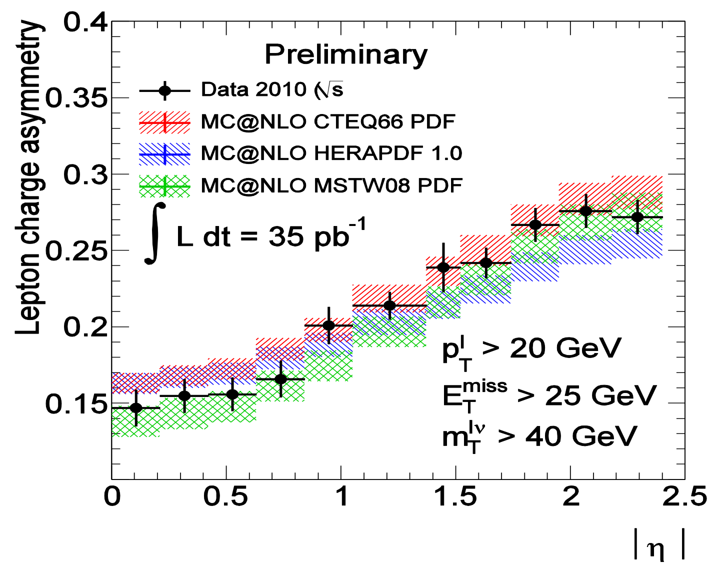
probing smaller x region than other experiments

Lepton Charge Asymmetry at LHC



ATLAS-CONF-2011-129
LHCb-CONF-2011-039
CMS-EWK-10-006 (arXiv:1103.3407)





M(W) Prospects with all Tevatron Data

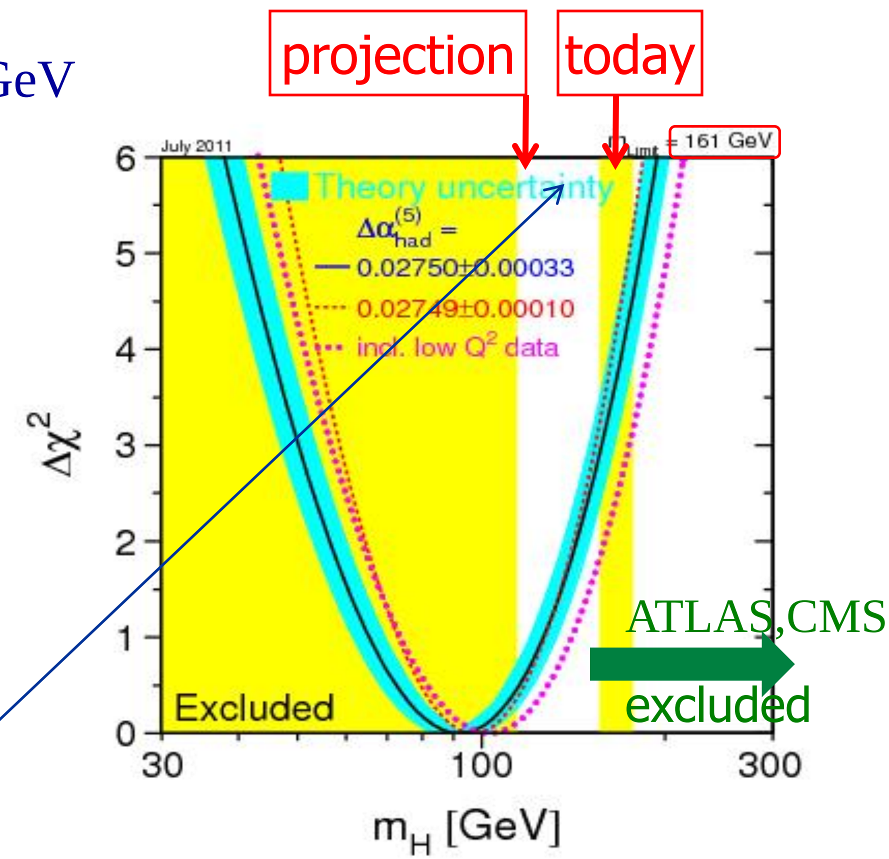
- Electroweak fits favor light Higgs
- Currently
  - most probable Higgs mass value = 92 GeV
  - excluded above 161GeV @95% CL

- Under the following example scenario*

  ΔM_W : 23 MeV $\rightarrow$ 15 MeV
  central values (M_W, M_{top}) do not move
  ΔM_{top} : 1 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
- DØ made most precise measurement of the W boson mass from a single experiment
- Comparable results from CDF
- World average is now 23 MeV
- More Tevatron data are being analyzed, expecting significant improvements in precision soon
- With full Tevatron dataset expect 10-15 MeV precision
- Comparable ultimate precision expected from LHC

BACKUP SLIDES

Effect of Corrections on M(W)

tree level 80.939

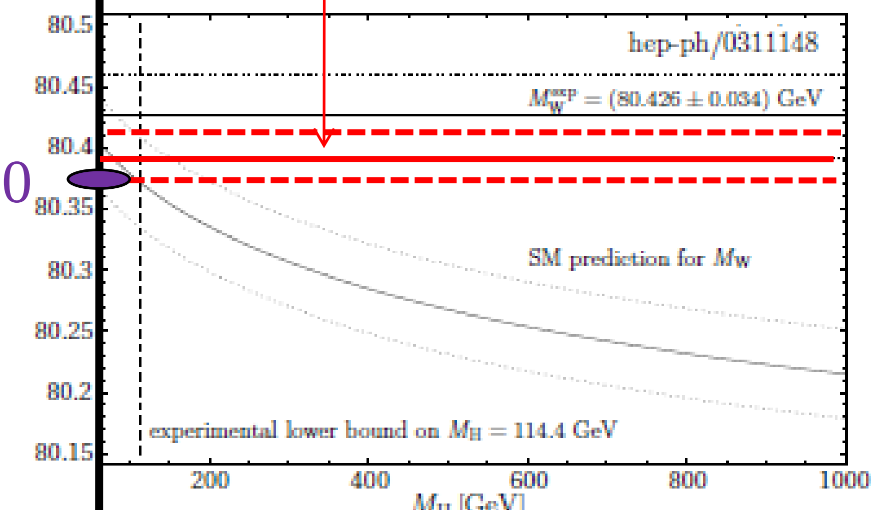
α	*electron g-2*	0.68 pp10^9
G_F	*muon life-time*	9 pp10^6
M_Z	*LEP 1 lineshape*	23 pp10^6

W Mass, GeV

current world average (experiment) 80.399 ± 0.023

+ radiative corrections (M_H=100GeV)

80.380



- 42 σ

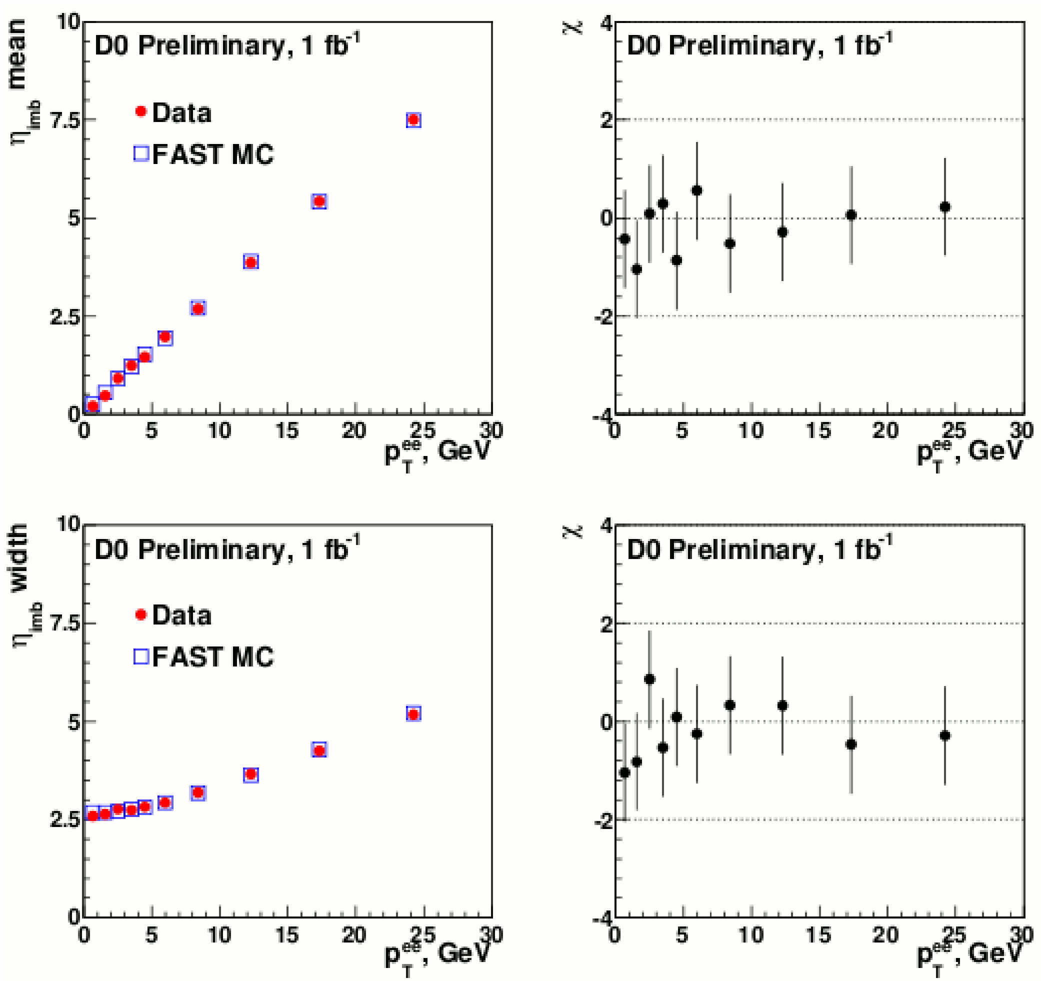
+ 19 σ

Higgs Mass, GeV

+ running α_{EM} correction 79.964

Recoil Calibration

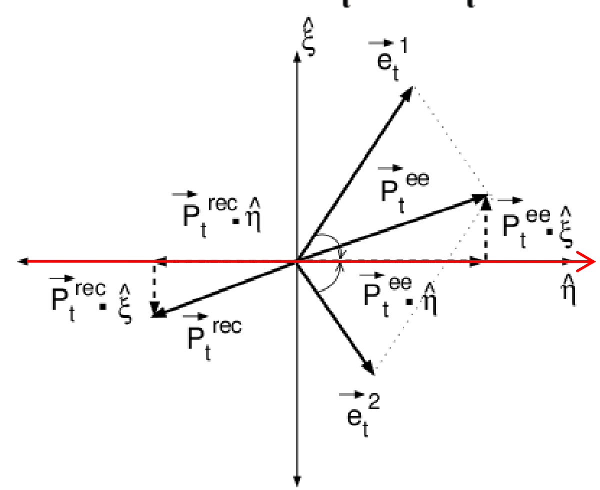
Final adjustment of free parameters in the recoil model is done *in situ* using balancing in $Z \rightarrow ee$ events and the standard **UA2 observables:**



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

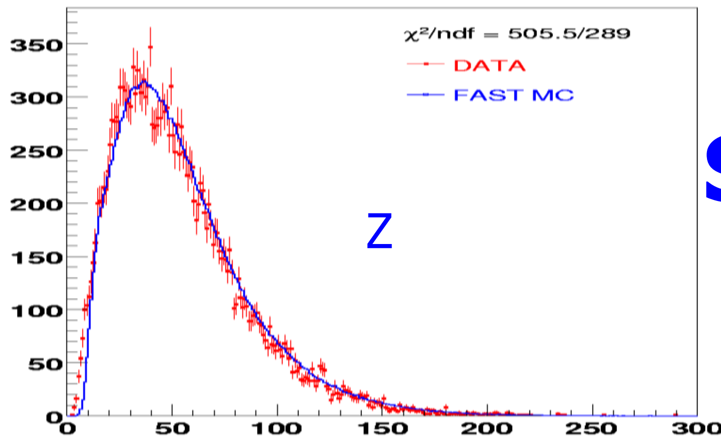
η-imbalance : $(\vec{\mathbf{P}}_t^{\,ee} + \vec{\mathbf{P}}_t^{\,rec}) \cdot \hat{\eta}$

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

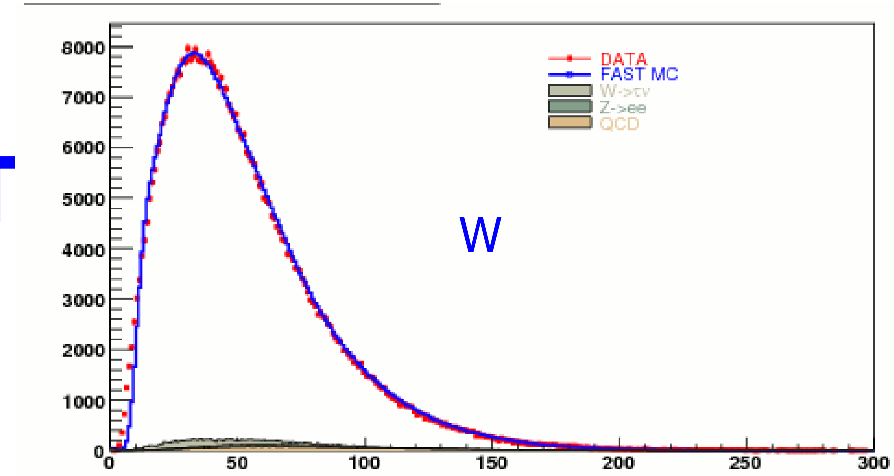


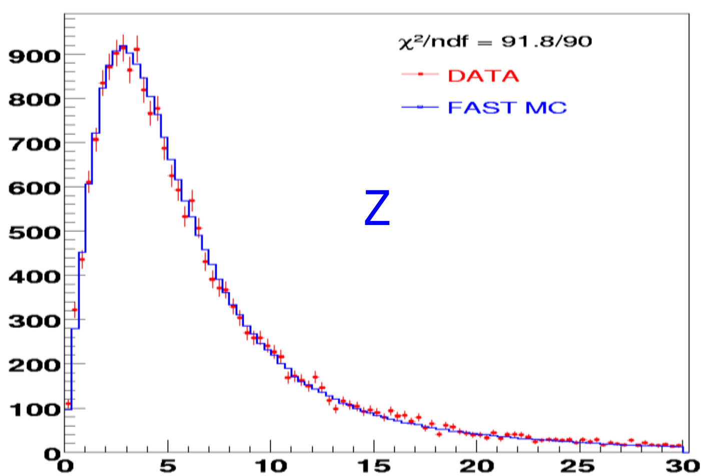
$Z \rightarrow e\,e$ and $W \rightarrow e\,\nu$

Data in red
MC in blue

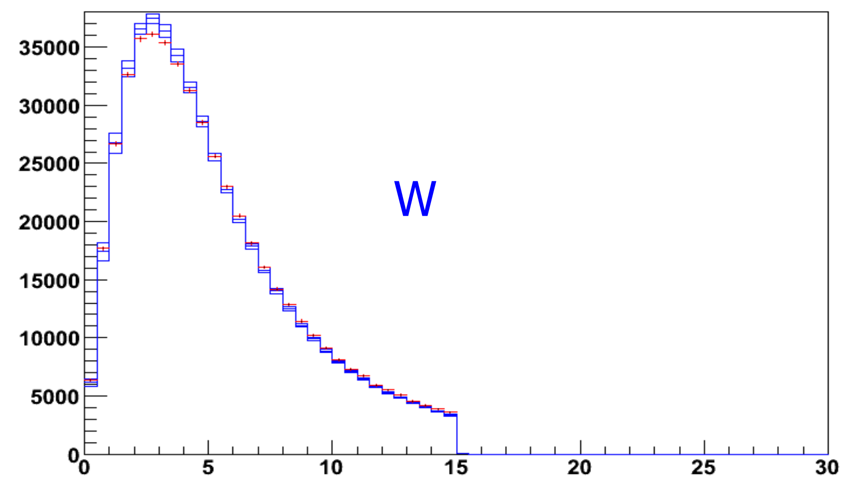


SET





u_T



GeV GeV

Electron Energy Resolution

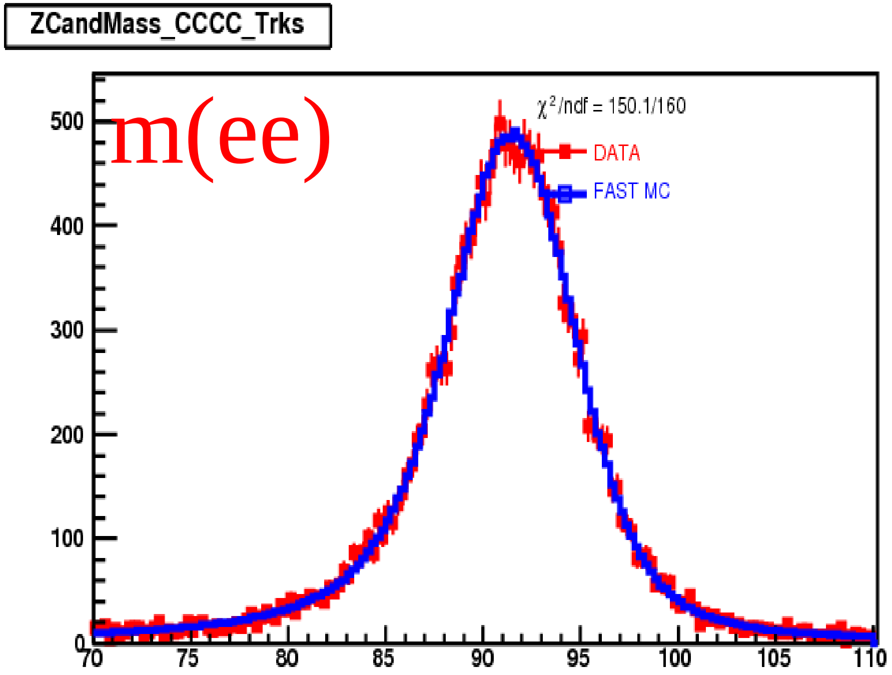
Electron energy resolution is driven by two components:
sampling fluctuations and constant term

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

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).

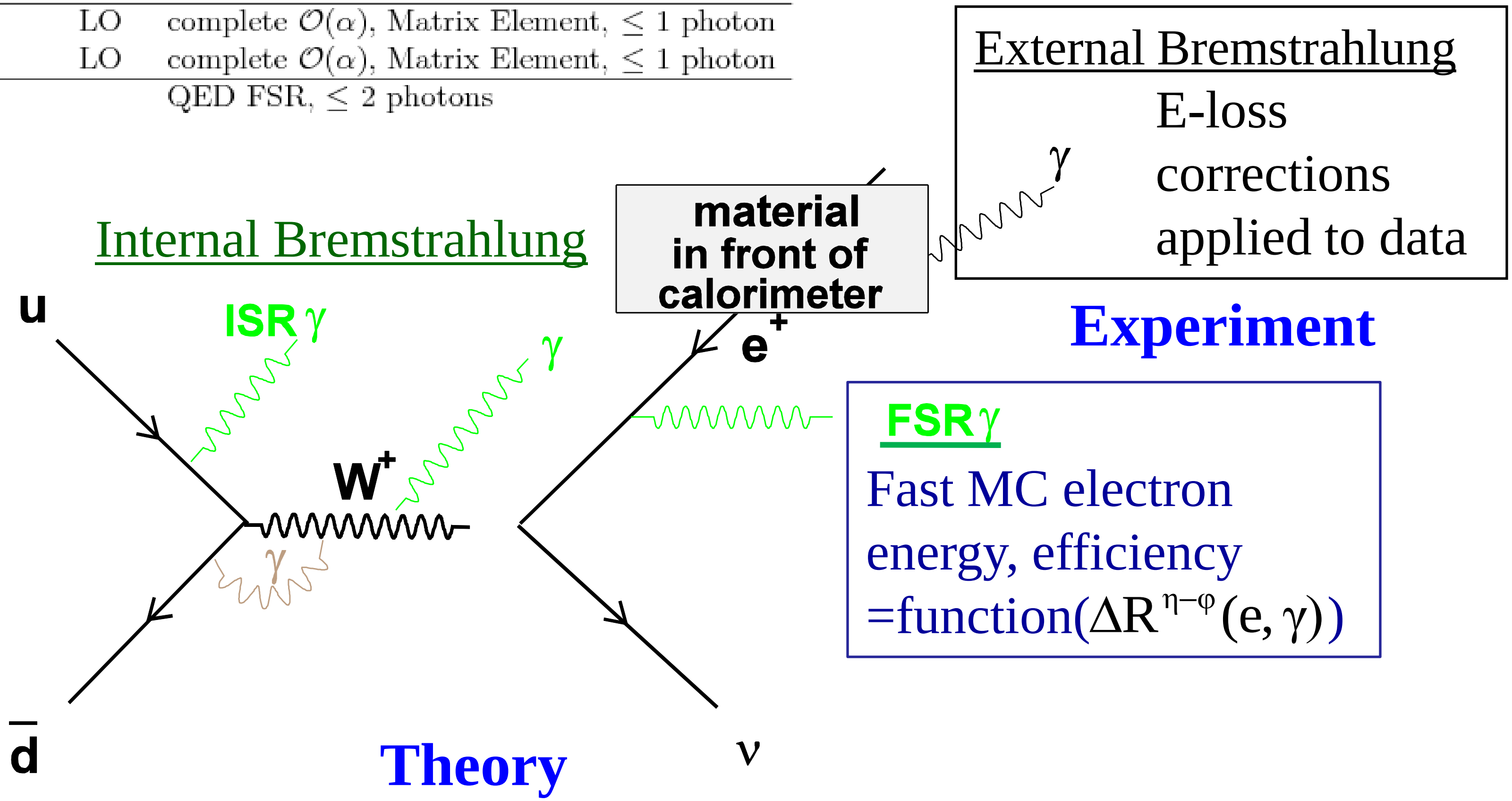
Result: C = (2.05 ± 0.10) %
in excellent agreement
with Run II design goal (2%)



M(Z → ee), GeV

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.

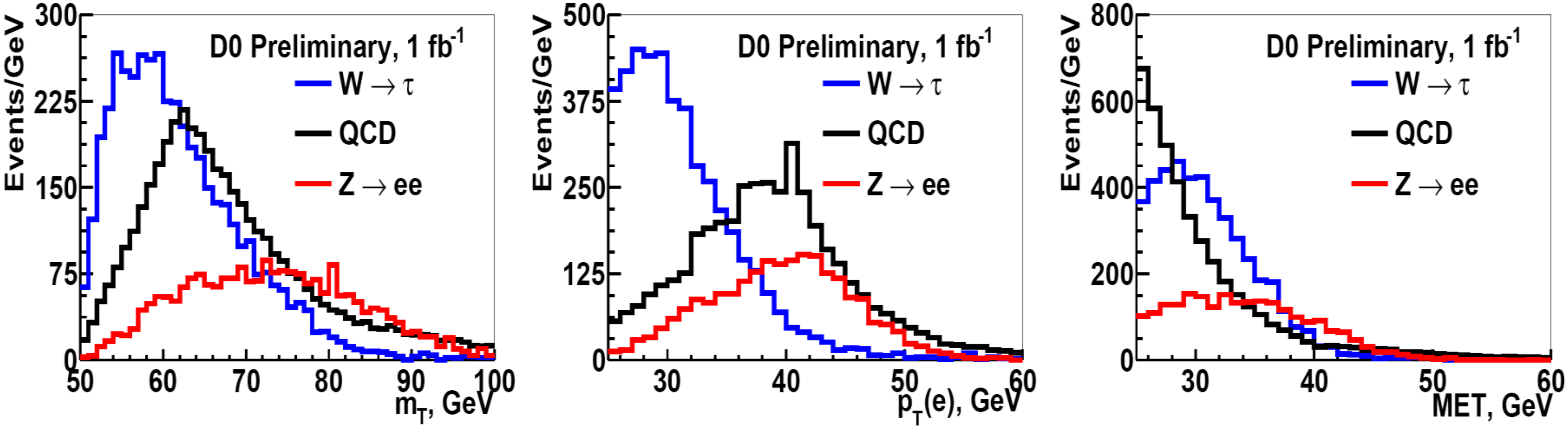
Effect of full EW corrections: compare W/ZGRAD in full EW mode with FSR-only mode

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**



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
- $\Rightarrow$ Would need: ΔM_W = 8 MeV (currently have: ΔM_W = 23 MeV)

Lepton Charge Asymmetry

W rapidity cannot be reconstructed on event-by-event basis
due to non-measurable longitudinal neutrino momentum

W charge asymmetry

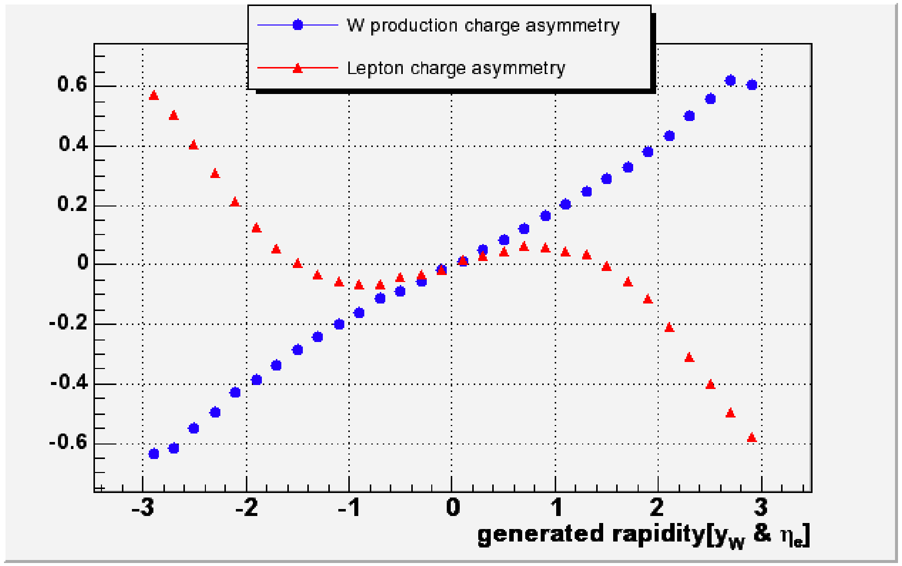
$$A(y_W) = \frac{d\sigma(W^+)/dy_W - d\sigma(W^-)/dy_W}{d\sigma(W^+)/dy_W + d\sigma(W^-)/dy_W}$$

$$y_W = \frac{1}{2}\ln\left(\frac{E+p_z}{E-p_z}\right)$$

lepton charge asymmetry

$$A(\eta_l) = \frac{d\sigma_+/d\eta_l - d\sigma_-/d\eta_l}{d\sigma_+/d\eta_l + d\sigma_-/d\eta_l} \sim \frac{d(x)}{u(x)} = A(y_W) \otimes (V\text{-}A)$$

$$x_{u,d} = \frac{M_W}{\sqrt{s}} e^{\pm y_W}$$



E.L. Berger, F. Halzen, C.S. Kim and S. Willenbrock; Phys. Rev. D40 (1989) 83