W boson mass measurements from DØ and possible combination with LHC

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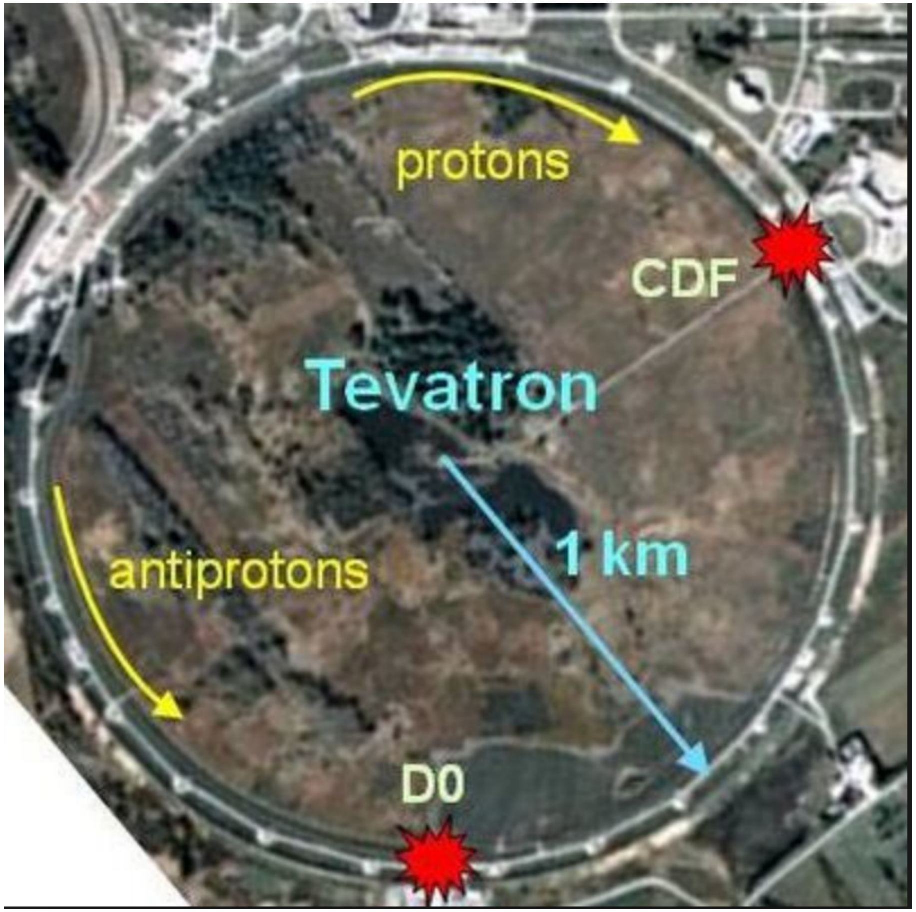
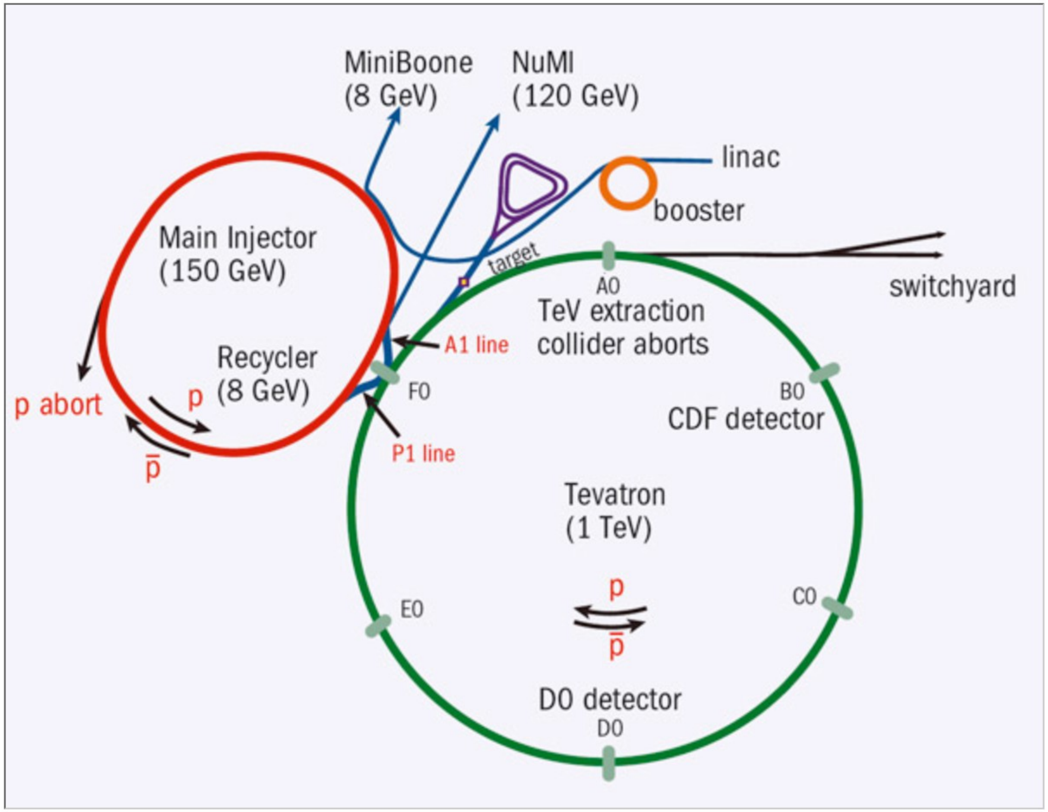
LHC precision EW working group, March 25th, 2018

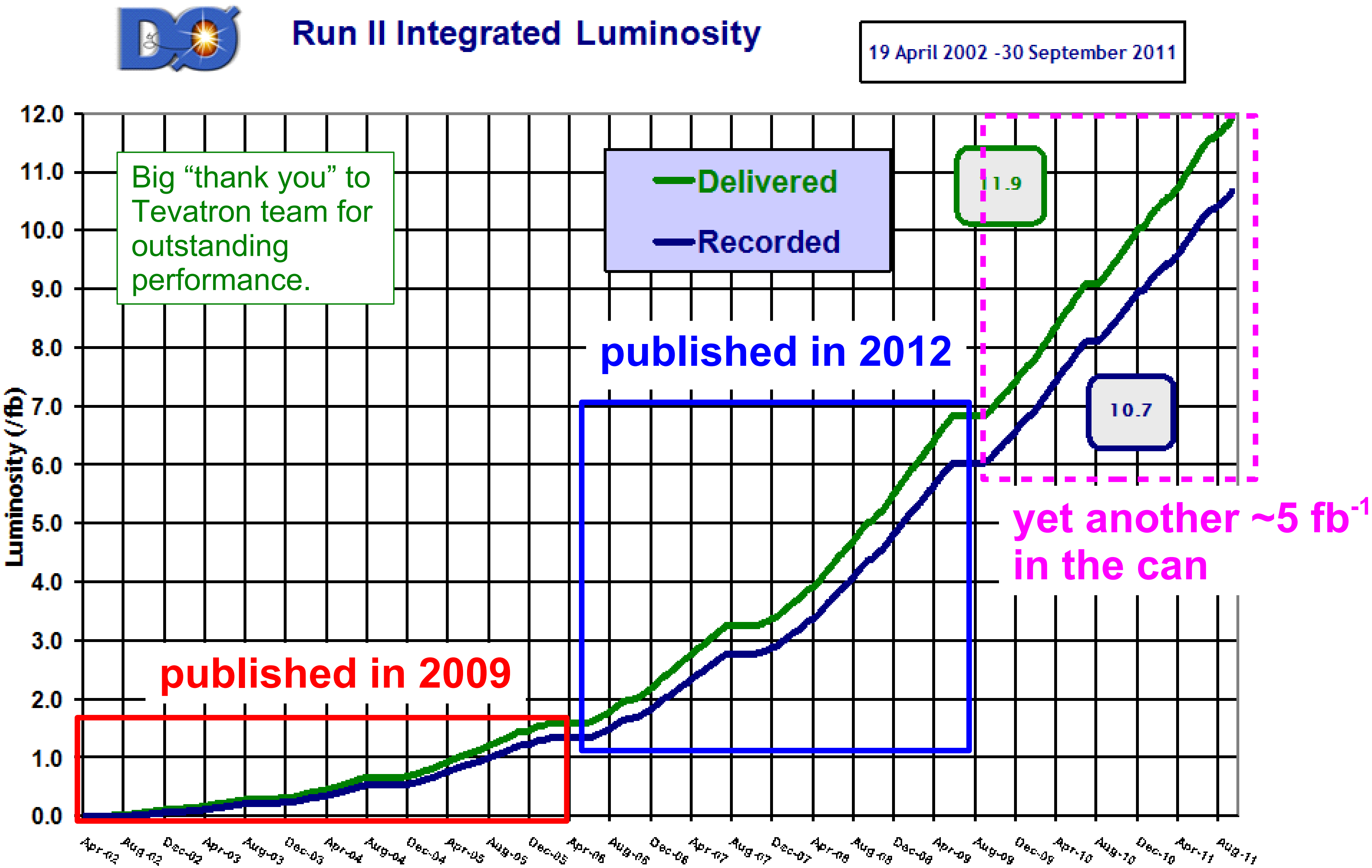
Tevatron collider





In proton-antiproton collisions at this energy, W bosons are predominantly produced in interactions between two valence quarks.

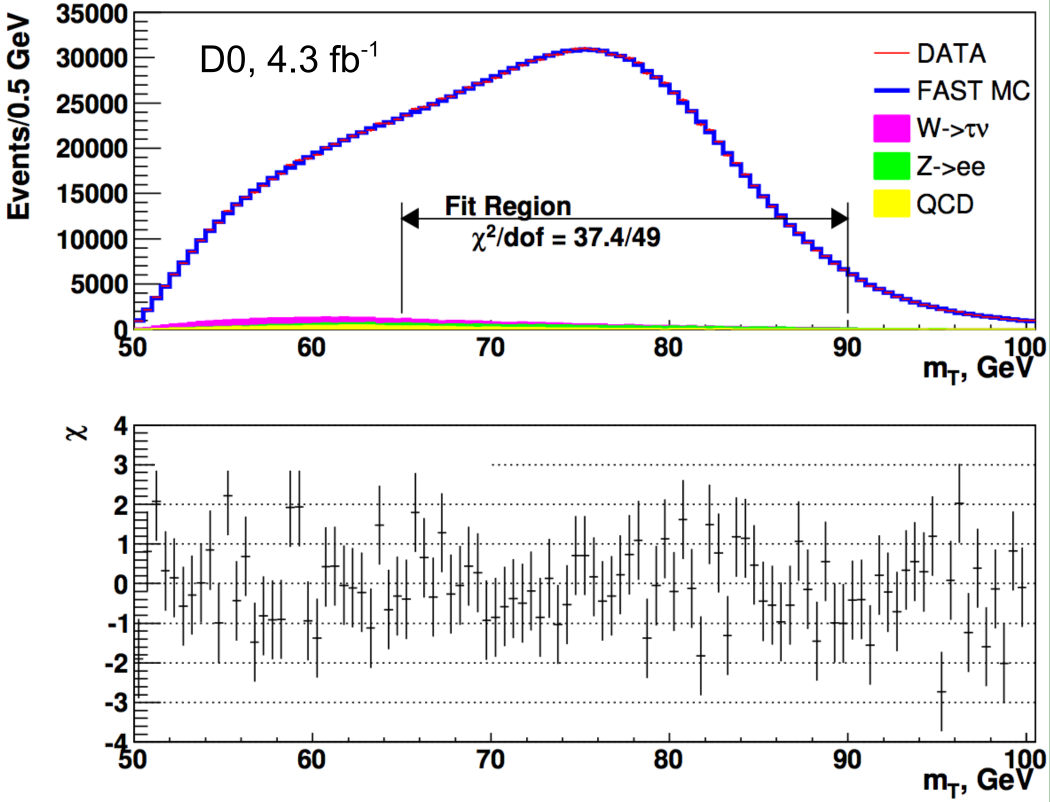
Data periods and analysis iterations



1.68M events
central electrons ($|\eta|<1.05$)

W data

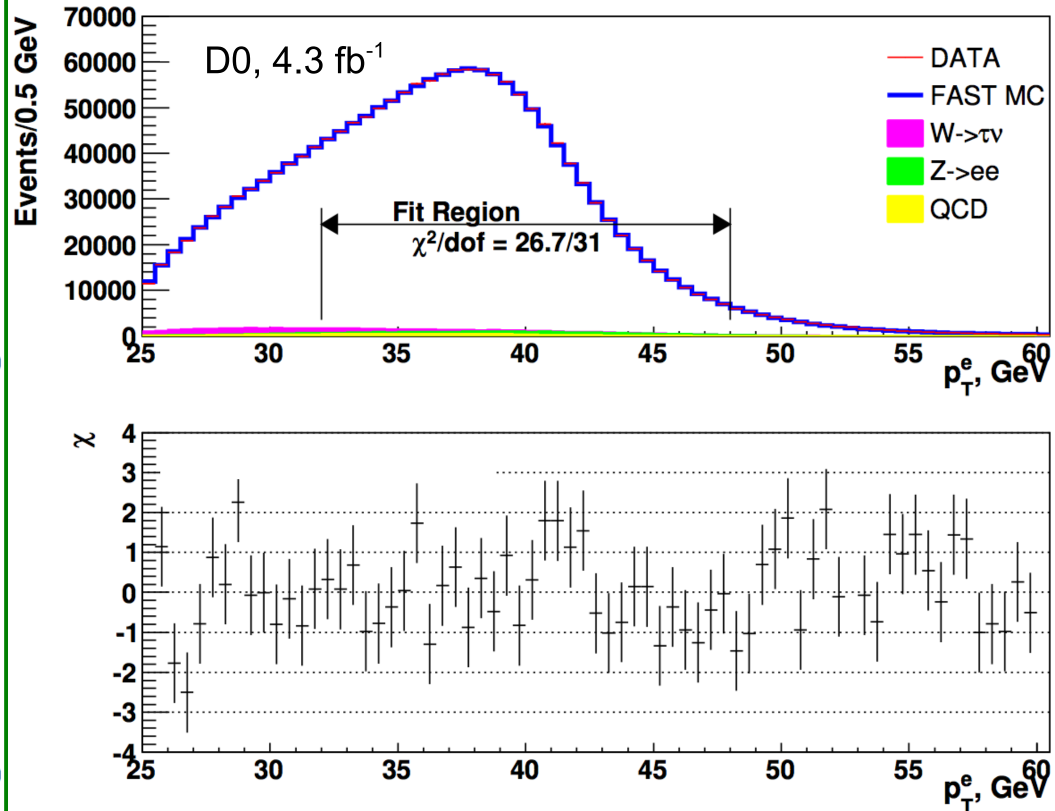
m_T



Fit results:

m(W) =
80371 ± 13 MeV (stat)

$p_T(e)$



m(W) =
80343 ± 14 MeV (stat)

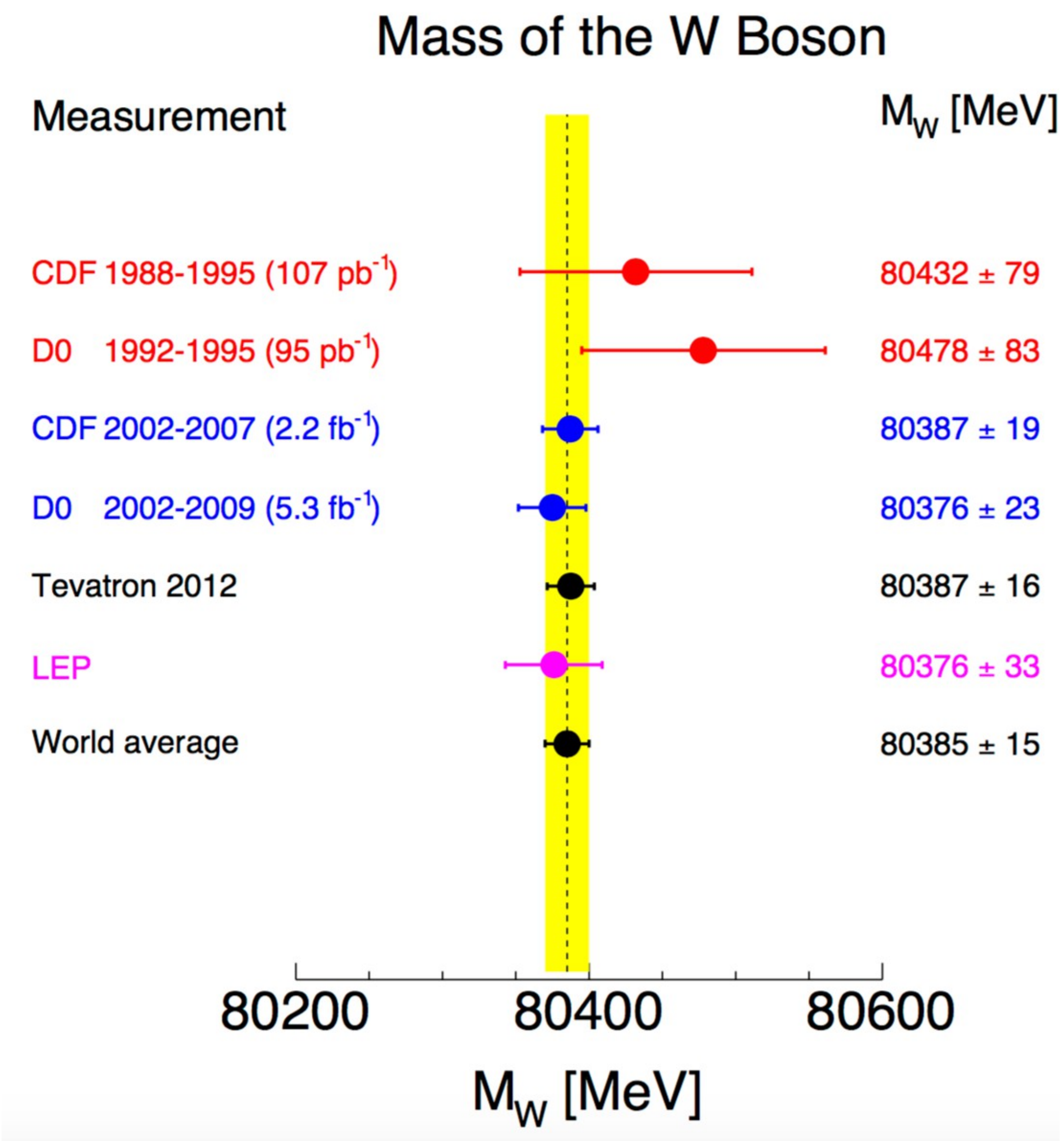
Systematic uncertainties, CDF and D0

Comparison of systematic uncertainties in the $m_T(\ell,\nu)$ measurement

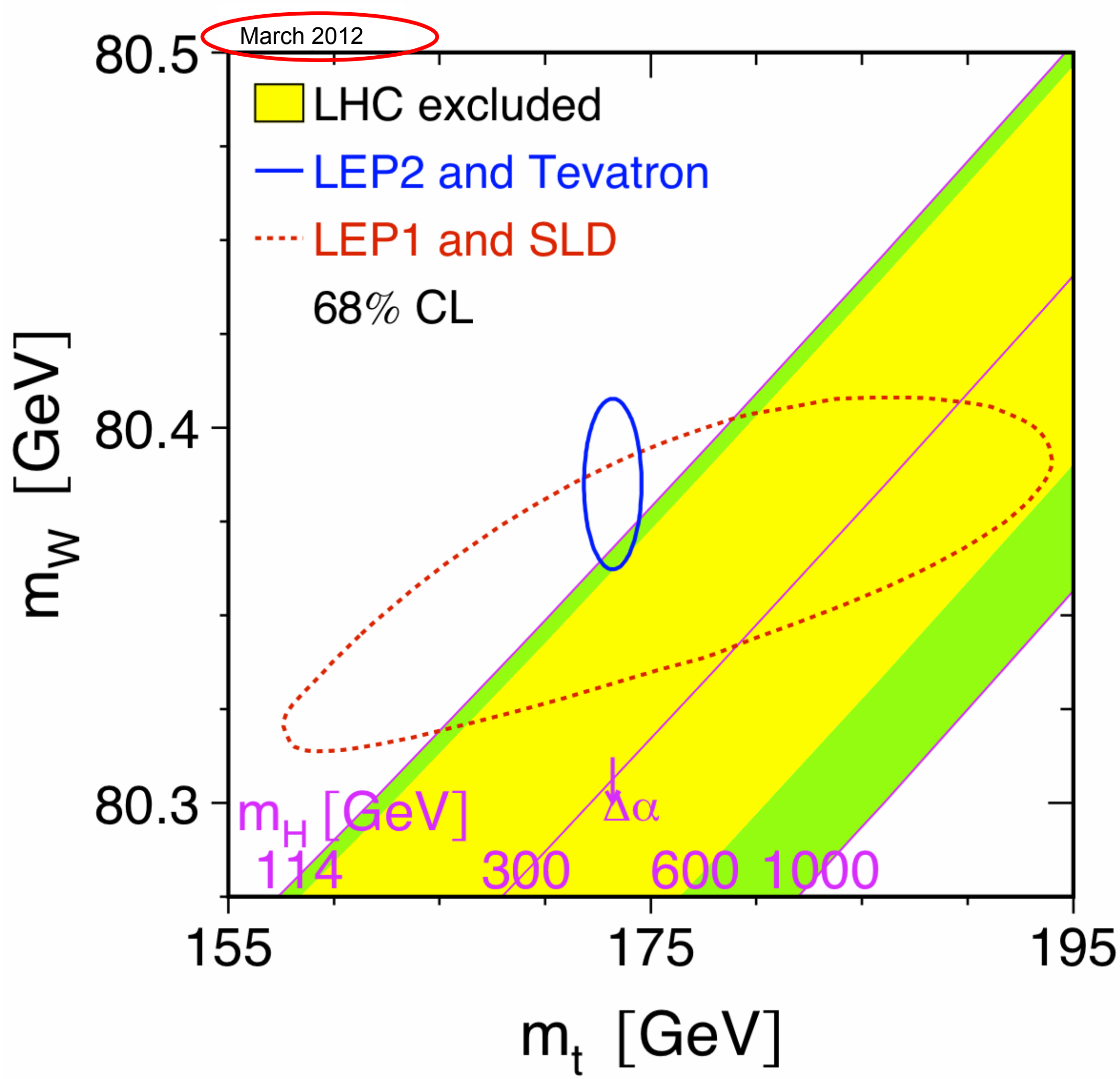
(values in MeV)

Source	CDF $m_T(\mu,\nu)$	CDF $m_T(e,\nu)$	DØ $m_T(e,\nu)$
Experimental – Statistical power of the calibration sample.			
Lepton Energy Scale	7	10	16
Lepton Energy Resolution	1	4	2
Lepton Energy Non-Linearity			4
Lepton Energy Loss			4
Recoil Energy Scale	5	5	
Recoil Energy Resolution	7	7	
Lepton Removal	2	3	
Recoil Model			5
Efficiency Model			1
Background	3	4	2
W production and decay model – Not statistically driven.			
PDF	10	10	11
QED	4	4	7
Boson p_T	3	3	2

Comparison with previous results; averages (march 2012)



March 2012: summary graph



Combination with CDF (and LEP)

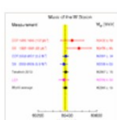
PHYSICAL REVIEW D
covering particles, fields, gravitation, and cosmology

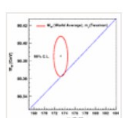
Combination of CDF and D0 W-Boson mass measurements

T. Aaltonen *et al.* (CDF Collaboration, D0 Collaboration)
Phys. Rev. D **88**, 052018 – Published 23 September 2013

ABSTRACT

We summarize and combine direct measurements of the mass of the W boson in $\sqrt{s} = 1.96$ TeV proton-antiproton collision data collected by CDF and D0 experiments at the Fermilab Tevatron Collider. Earlier measurements from CDF and D0 are combined with the two latest, more precise measurements: a CDF measurement in the electron and muon channels using data corresponding to $2.2\ \mathrm{fb}^{-1}$ of integrated luminosity, and a D0 measurement in the electron channel using data corresponding to $4.3\ \mathrm{fb}^{-1}$ of integrated luminosity. The resulting Tevatron average for the mass of the W boson is $M_W = 80387 \pm 16$ MeV. Including measurements obtained in electron-positron collisions at LEP yields the most precise value of $M_W = 80385 \pm 15$ MeV.





Received 29 July 2013

DOI: https://doi.org/10.1103/PhysRevD.88.052018

Issue
Vol. 88, Iss. 5 — 1 September 2013

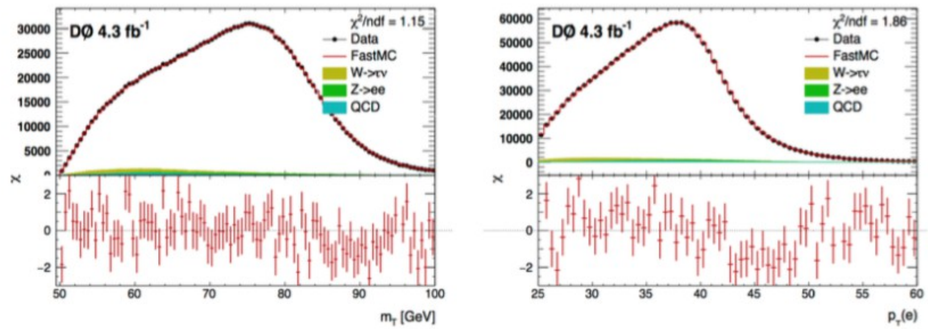
Combination with LHC

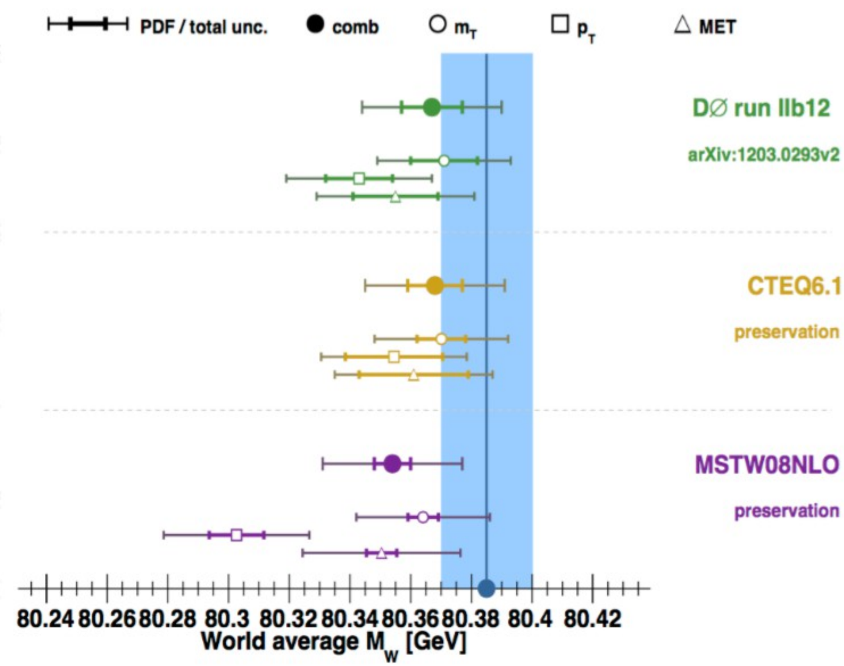
Dzero is looking forward to a combination with LHC.

Our code still runs (cf. next slide), and it will be needed for the study of correlations.

Preservation of the D0 W mass measurement to incorporate future PDF and physics models

- Effort from 2015 to preserve previous D0 W mass measurement
  - Ldt = 4.3 fb^{-1}
  - M_W = 80.375 ± 0.023 GeV
  - Based on CTEQ6.1 PDF Set
  - Further material: https://cds.cern.ch/record/2159233
- Setup allows to rederive published W boson mass with new PDF-sets/models
  - Rederivation with MSTW08NLO as example
  - Relies on the availibility of ResBos-Grids for newer PDF-Sets
- Relevant for combination
  - We can easily provide the mW values for each eigenvector of a given PDF-Sets





Slide from Matthias Schott

Backup Slides

Model of W production and decay

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

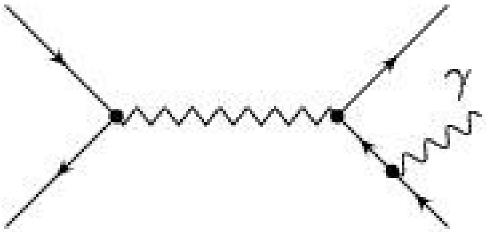
Our main generator is "**ResBos+Photos**". The NLO QCD in **ResBos** allows us to get a reasonable description of the p_T of the vector bosons. The two leading EWK effects are the first FSR photon and the second FSR photon. **Photos** gives us a reasonable model for both.

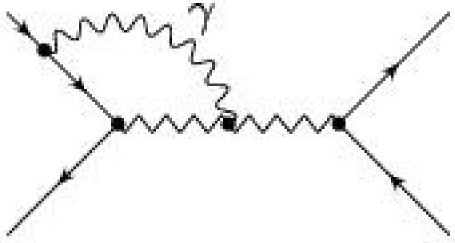
We use **W/ZGRAD** to get a feeling for the effect of the full EWK corrections.

The final "QED" uncertainty we quote is 7/7/9 MeV (m_T,p_T,MET).

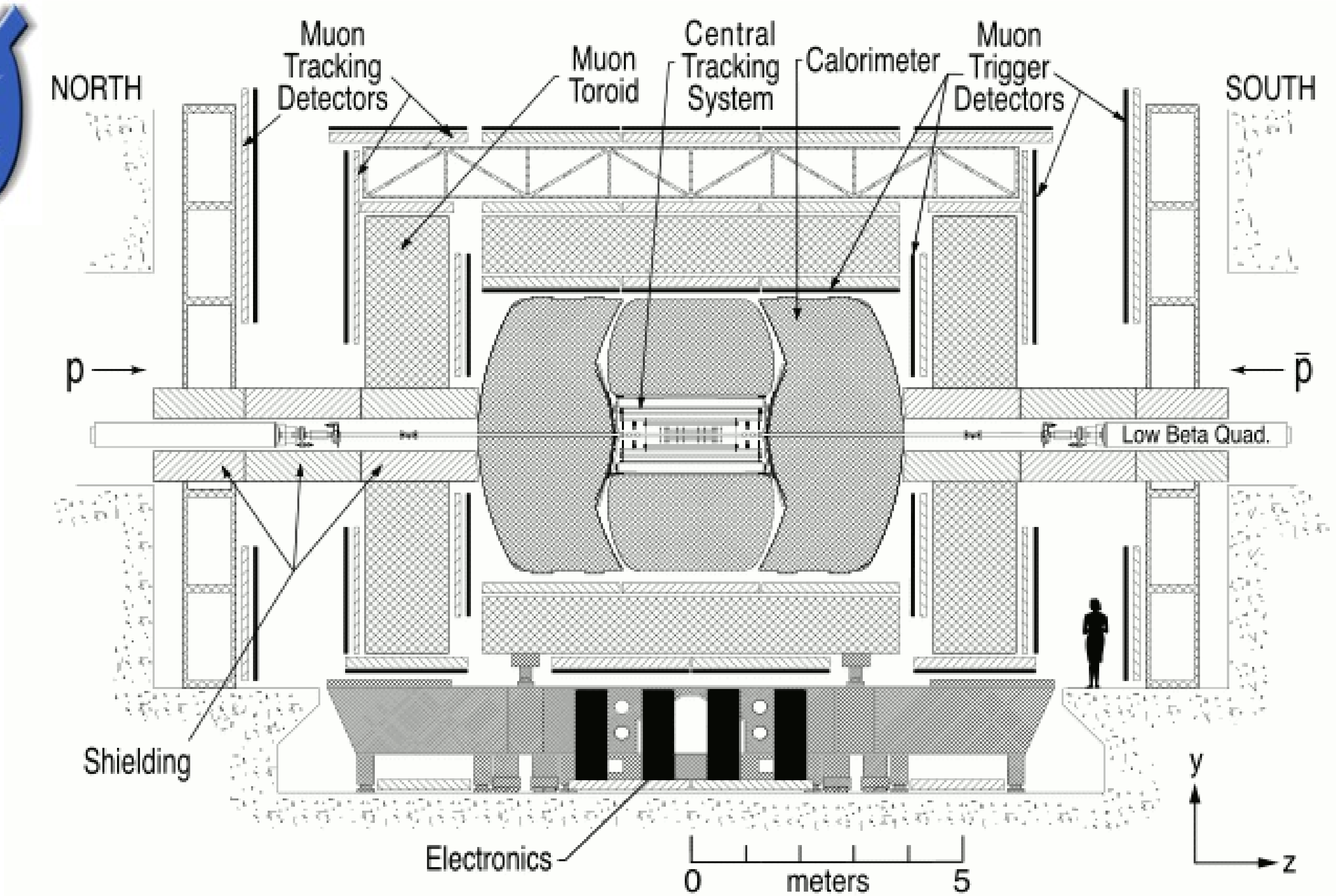
This is the sum of different effects; the two main ones are:

- Effect of full EWK corrections, from comparison of W/ZGRAD in "FSR only" and in "full EWK" modes (5/5/5 MeV).
- Very simple estimate of "quality of FSR model", from comparison of W/ZGRAD in FSR-only mode vs **Photos** (5/5/5 MeV).

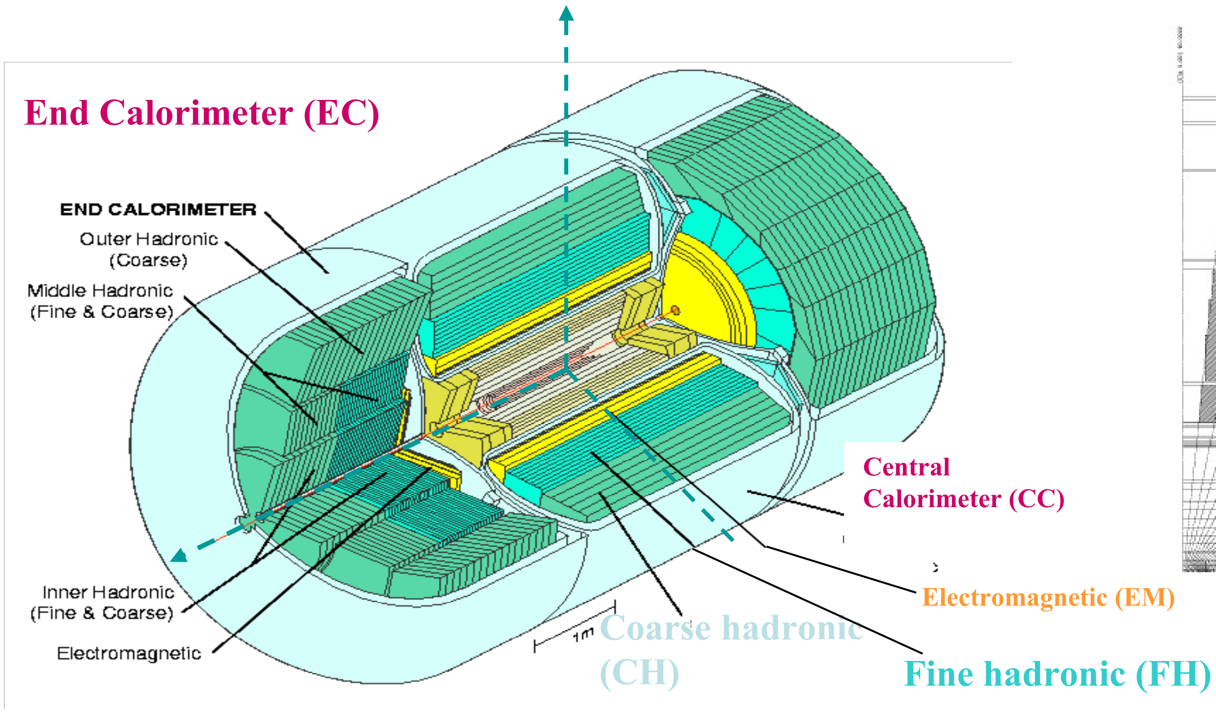


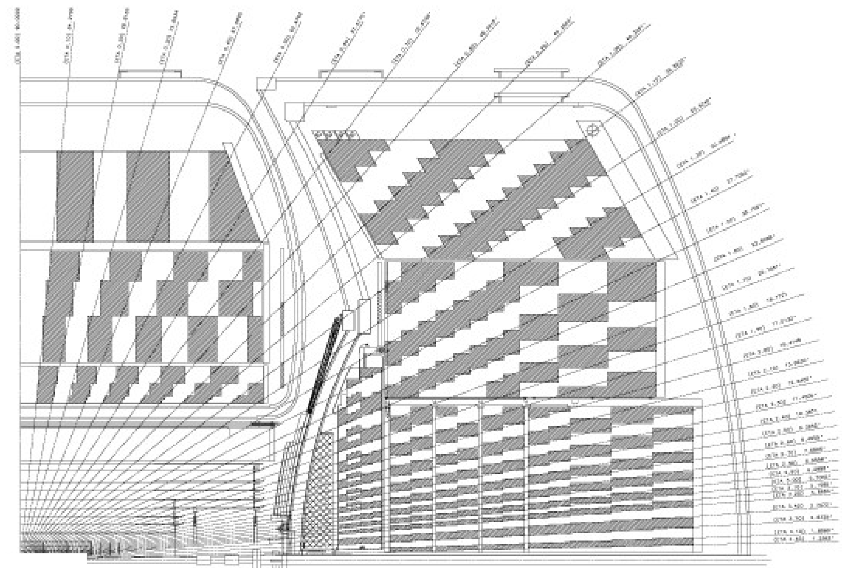


The upgraded DØ detector



Overview of the calorimeter





46000 cells

50 dead channels

- Liquid argon active medium and (mostly) uranium absorber
- Hermetic with full coverage : $|\eta| < 4$
- Segmentation (towers): $\Delta\eta \times \Delta\phi = 0.1 \times 0.1$

  (0.05x0.05 in third EM layer, near shower maximum)

Final electron energy scale calibration

AFTER calorimeter calibration, simulation of effect of inst. luminosity, corrections for dead material, modeling of underlying energy flow:

final electron energy response calibration, using $Z \rightarrow e\,e$, the known Z mass value from LEP and the standard "f_z method":

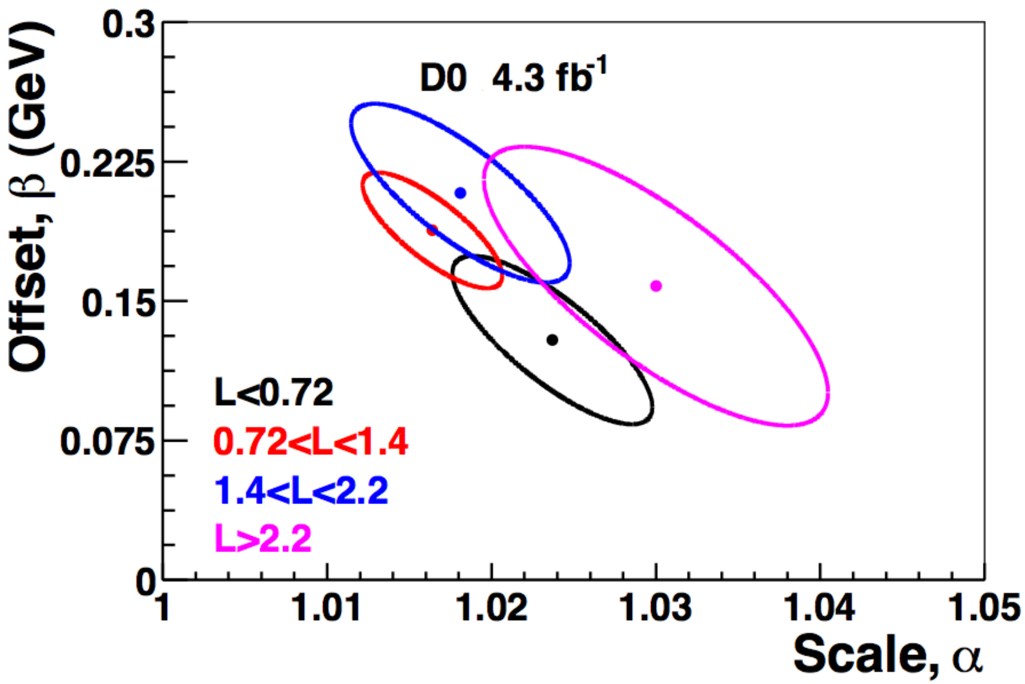
$$E_{measured} = scale * (E_{true} - 43\text{ GeV}) + offset + 43\text{ GeV}$$

We are effectively measuring m_W/m_Z.

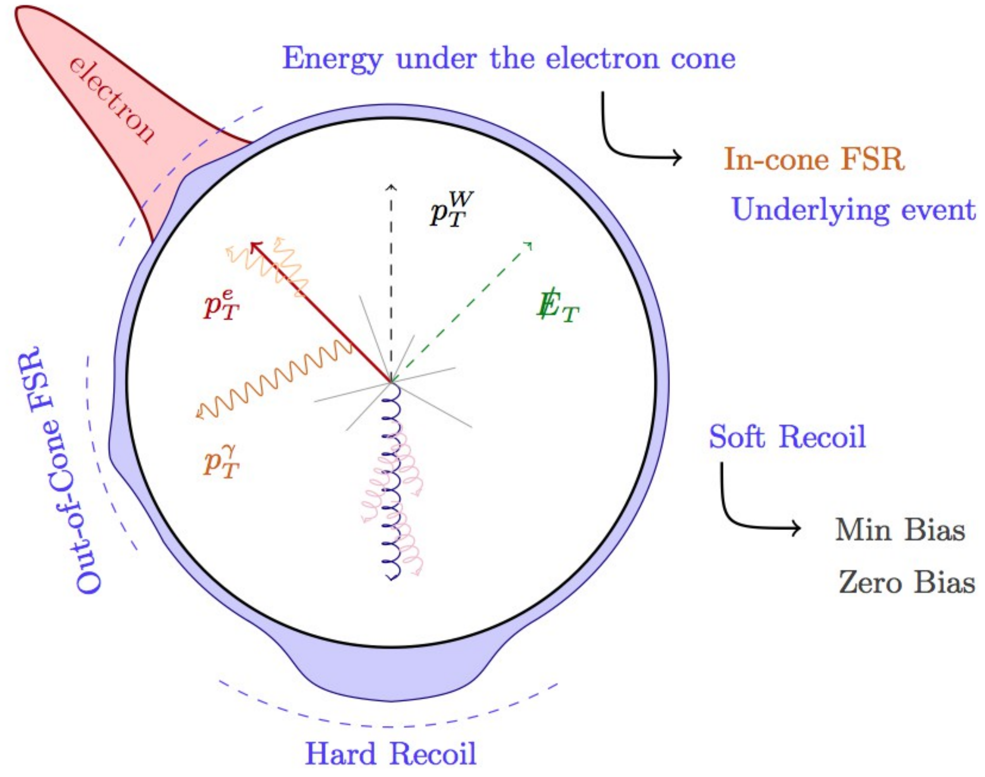
Use energy spread of electrons in Z decay (e.g. due to Z boost) to constrain scale *and* offset .

In a nutshell: the f_z observable allows you to split your sample of electrons from $Z \rightarrow e\,e$ into subsamples of different true energy; this way you can "scan" the electron energy response as a function of energy.

In Run IIb we do this separately for four bins of instantaneous luminosity (plot on the right).



Recoil model



$$\vec{u}_T = \vec{u}_T^{\,\mathrm{HARD}} + \vec{u}_T^{\,\mathrm{SOFT}} + \vec{u}_T^{\,\mathrm{ELEC}} + \vec{u}_T^{\,\mathrm{FSR}}$$

- $\vec{u}_T^{\,\mathrm{HARD}}$ models the hard hadronic energy from the W recoil.
- $\vec{u}_T^{\,\mathrm{SOFT}}$ models the soft hadronic activity from zero bias and minimum bias activity.
- $\vec{u}_T^{\,\mathrm{ELEC}} = -\sum_e \Delta u_{\|} \cdot \hat{p}_T(e) + \vec{p}_T^{\,\mathrm{LEAK}}$ models the recoil energy that was reconstructed under the electron cone, as well as any energy form the electron that leaked outside the cone.
- $\vec{u}_T^{\,\mathrm{FSR}}$ models the out–of–cone FSR that is reconstructed as hadronic recoil.

Recoil model

Have five tunable parameters in the recoil model that allow us to adjust the response to the hard recoil as well as the resolution (separately for hard and soft components):

$$\vec{u}_{T,smear}^{soft} = \sqrt{\alpha_{MB}}\,\vec{u}_T^{MB} + \vec{u}_T^{ZB}$$

model of spectator partons (based on soft collisions in collider data)

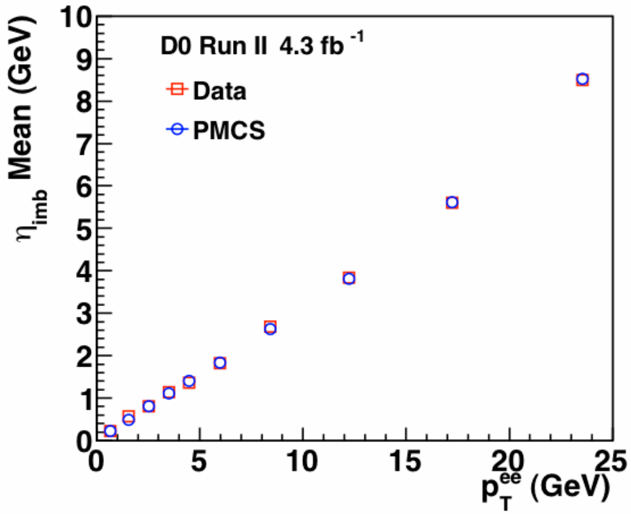
model of pileup/noise (from collider data, random trigger)

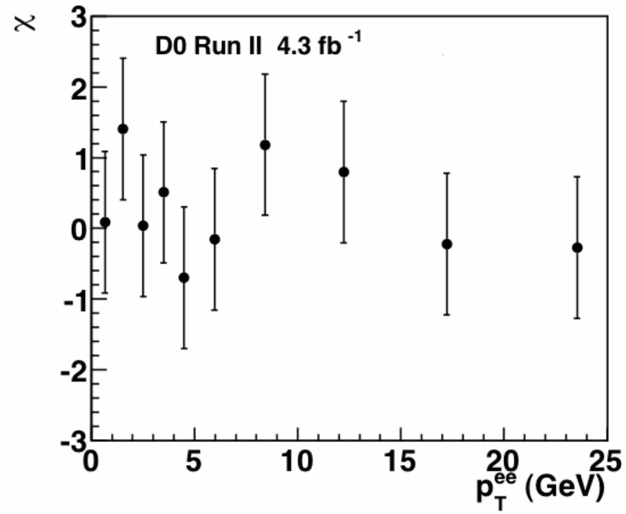
$$u_{T,smear}^{\parallel,hard} = \left(\mathrm{R}_A + \mathrm{R}_B \cdot e^{-p_T^Z/\tau_{HAD}}\right) p_T^Z \langle \frac{u_T}{p_T^Z} \rangle^{\parallel} + \mathrm{S}_A \left(u_T^{\parallel} - p_T^Z \langle \frac{u_T}{p_T^Z} \rangle^{\parallel} \right)$$

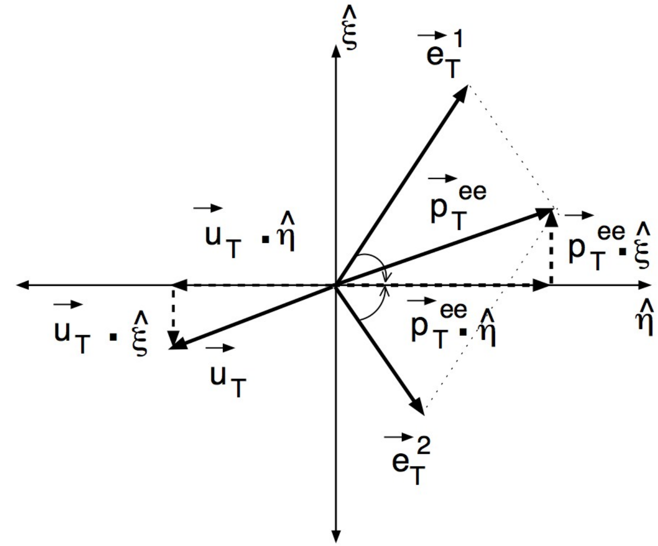
model of hard recoil response (from detailed first-principles simulation)

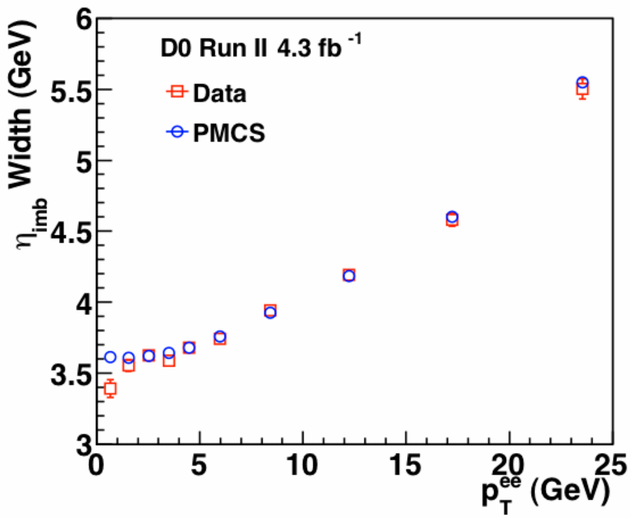
Recoil calibration

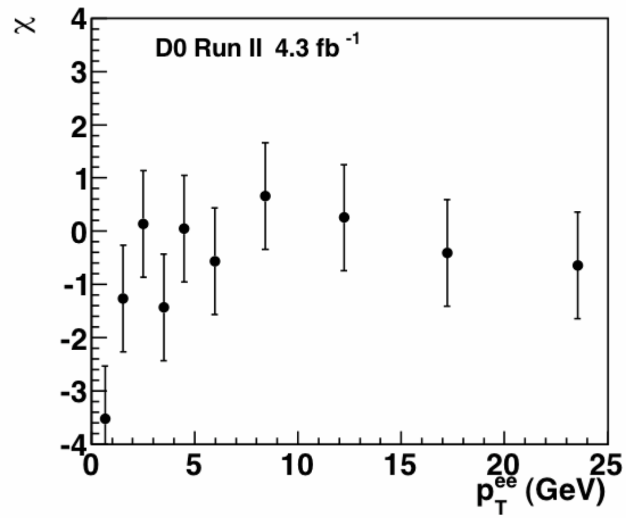
Final adjustment of free parameters in the recoil model is done *in situ* using balancing in Z → e e events and the standard UA2 observables.











Electron energy resolution

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

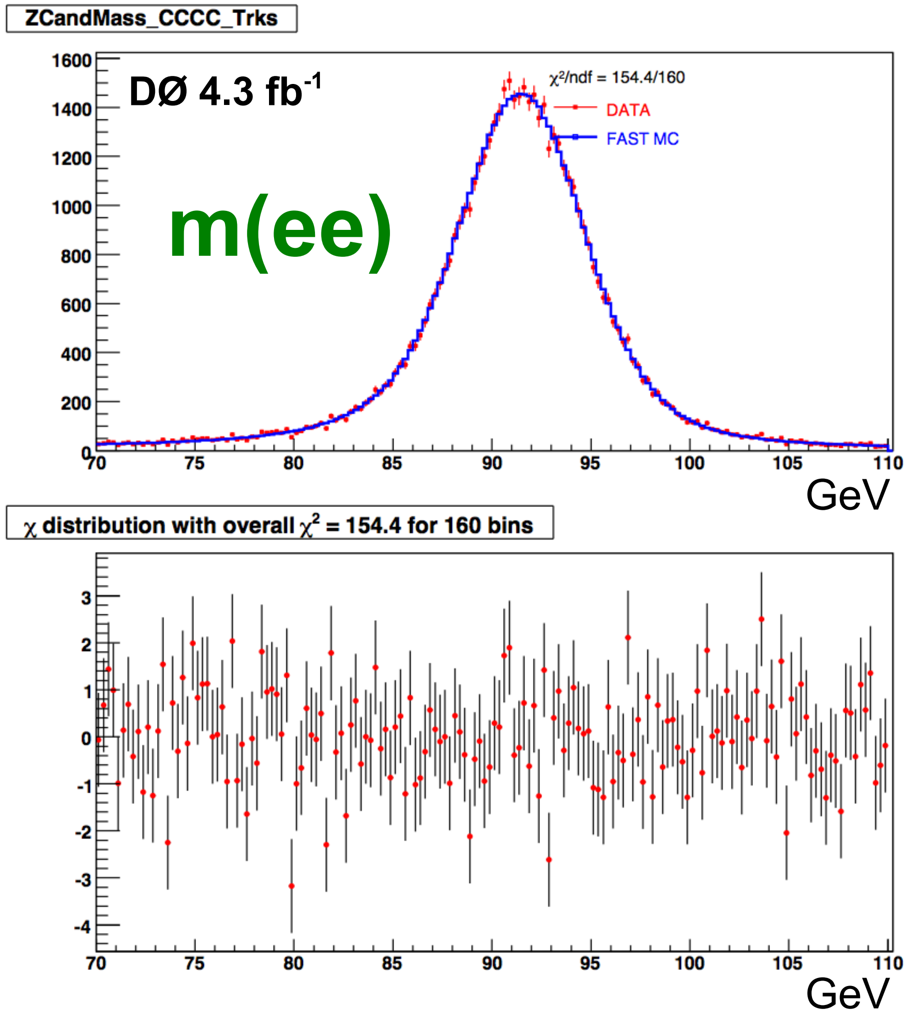
Sampling fluctuations are driven by sampling fraction of CAL modules (well known from simulation and testbeam) and by uninstrumented material. As discussed before, amount of material has been quantified with good precision.

Constant term is extracted from $Z \rightarrow e\,e$ data (essentially fit to observed width of Z peak).

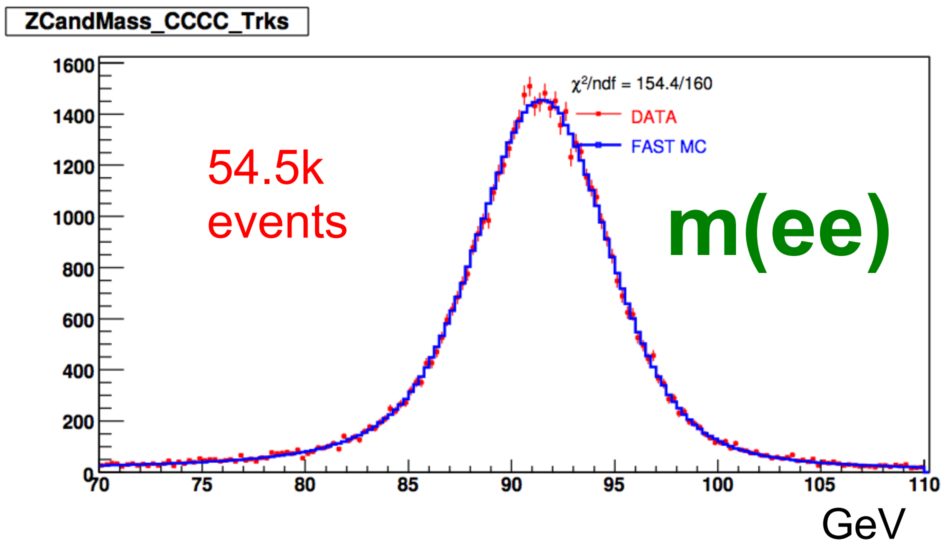
Result:

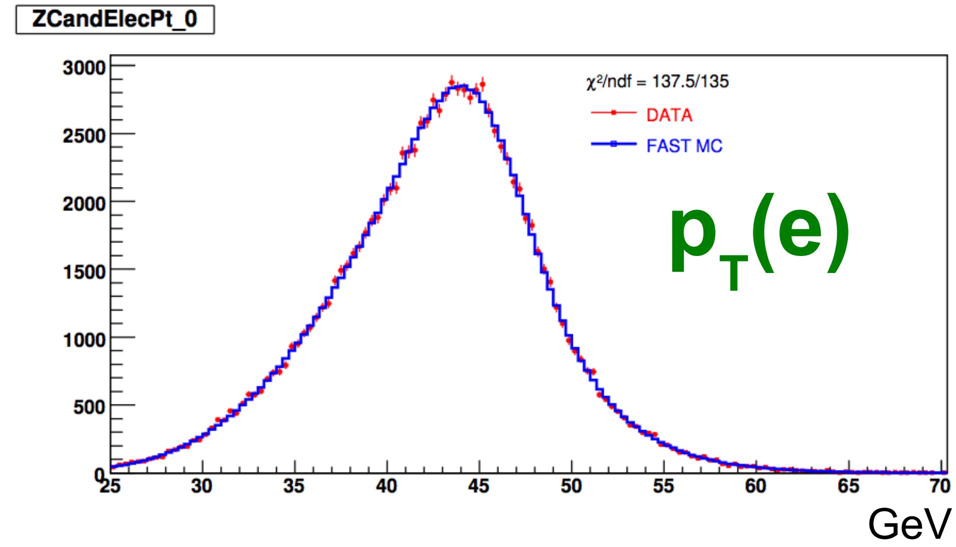
$C = (2.00 \pm 0.07)\ \%$

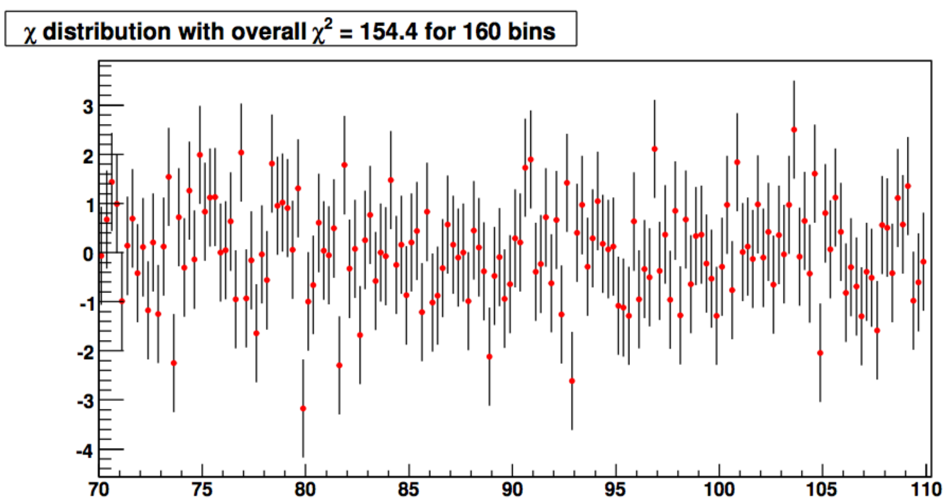
in excellent agreement with Run II design goal (2%)

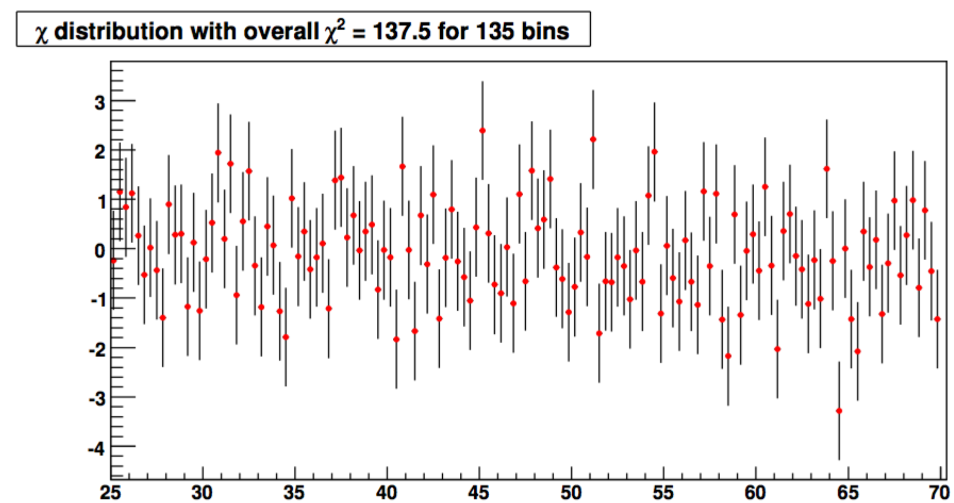


Z data





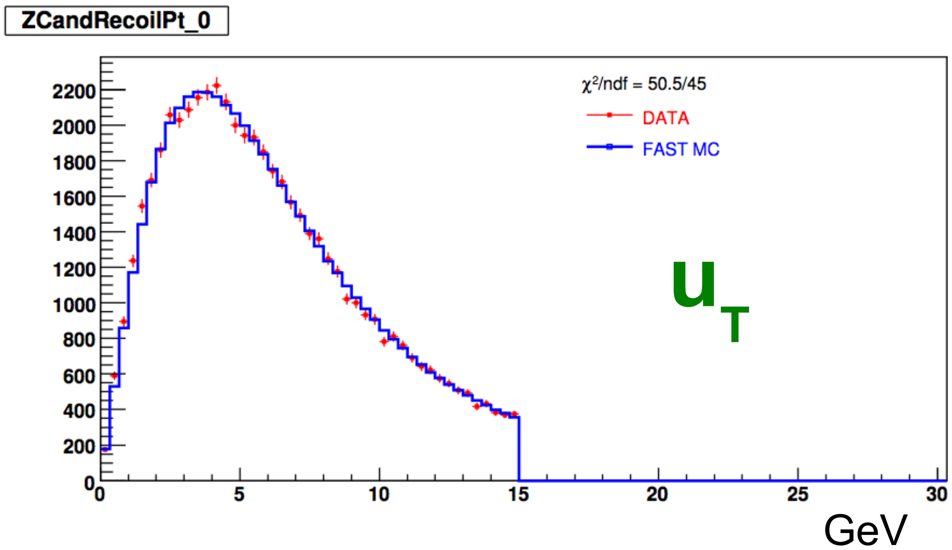


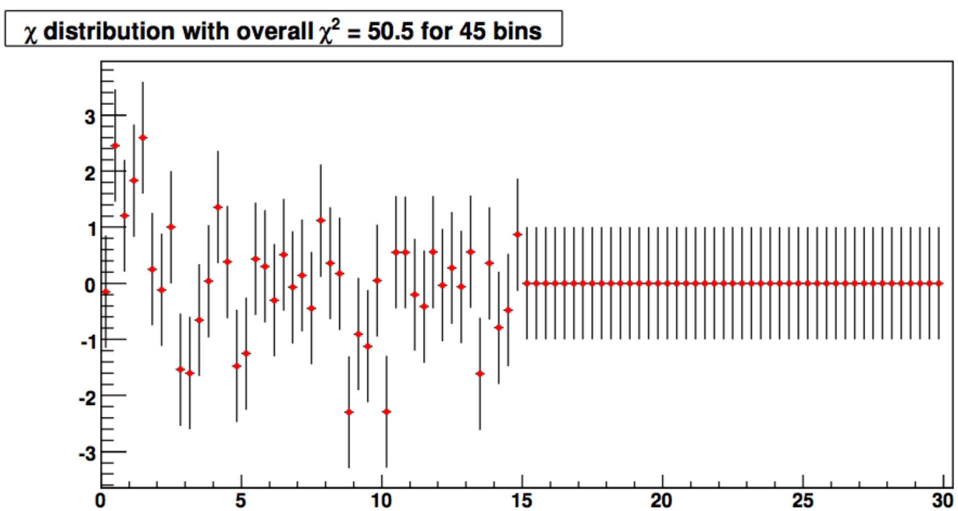


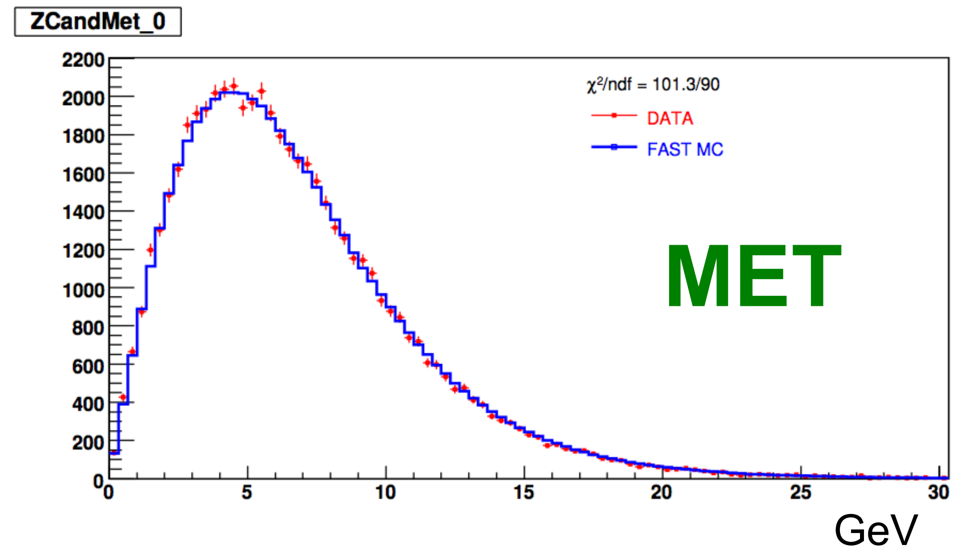
m(Z) = 91.193 ± 0.017 (stat) GeV

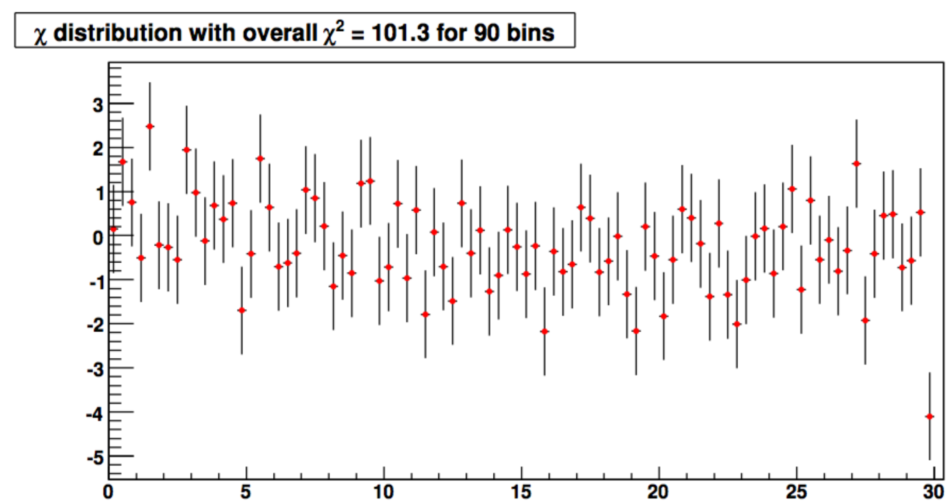
Good agreement between data and parameterised Monte Carlo.

Z data



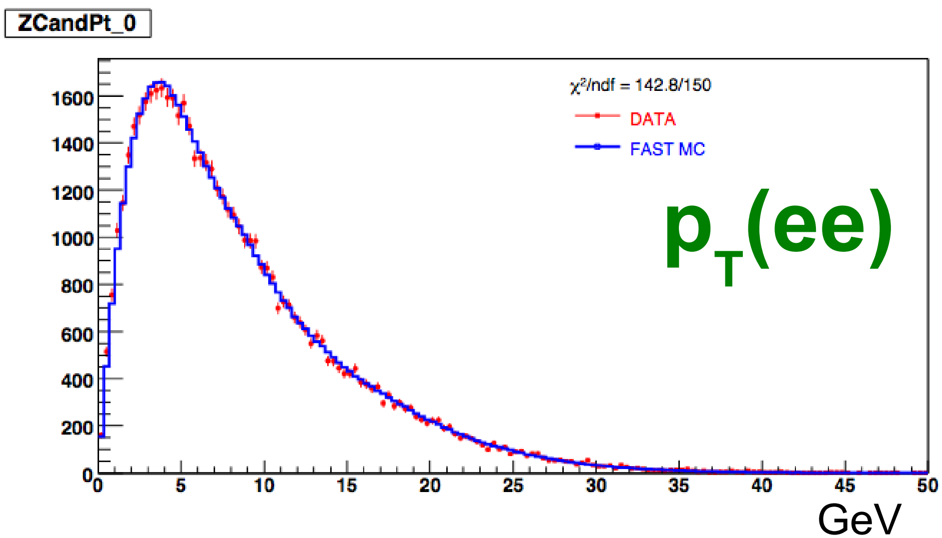


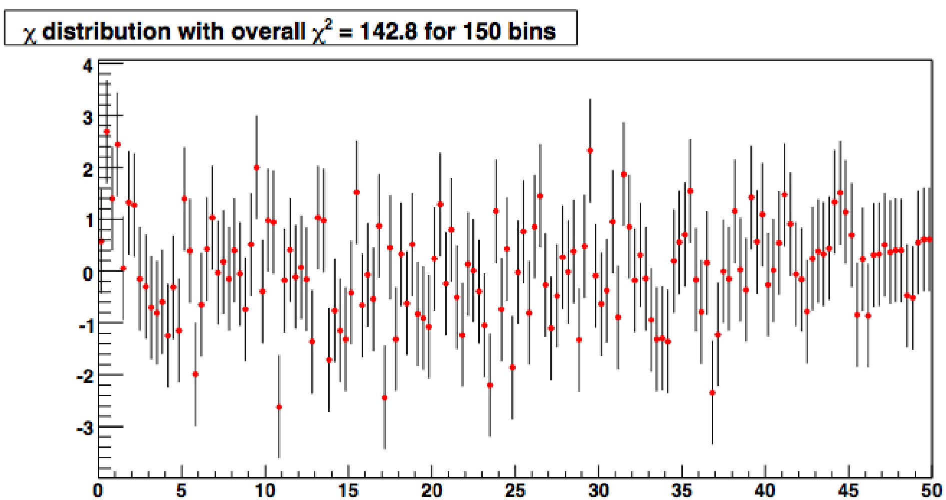


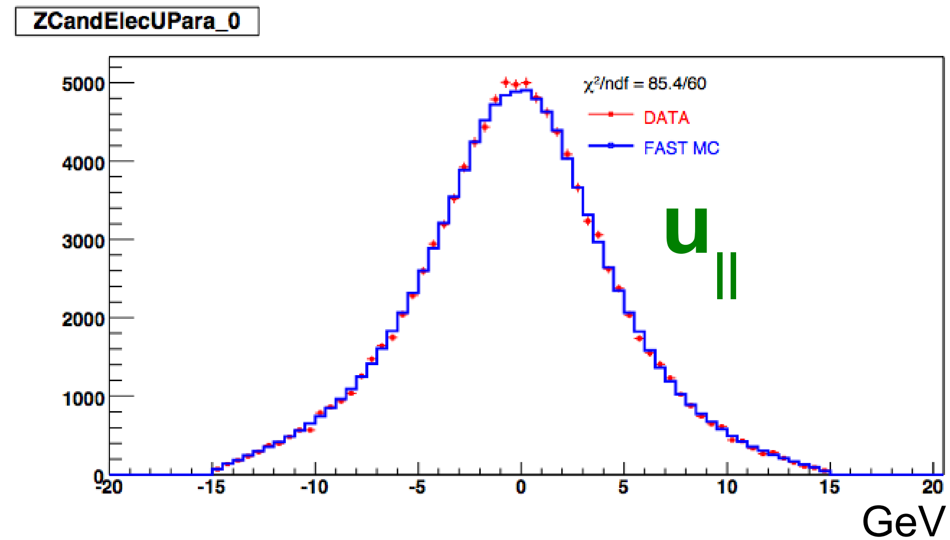


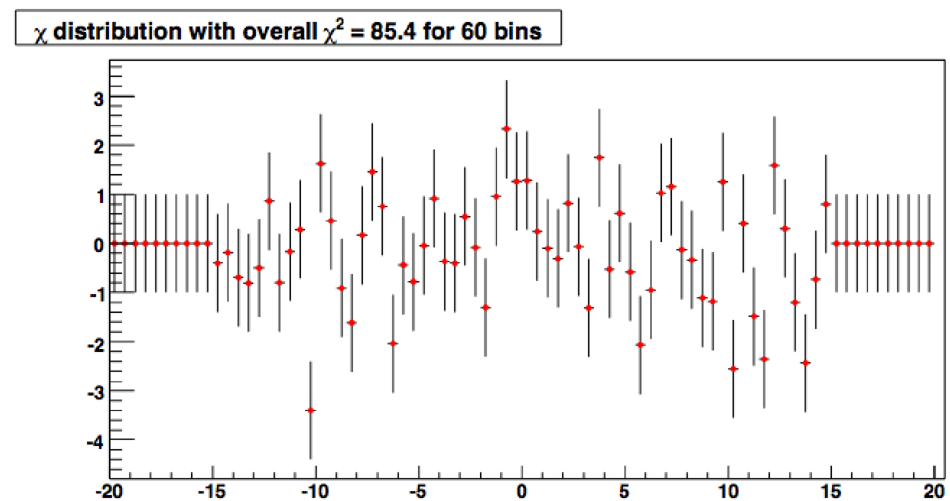
Good agreement between data and parameterised Monte Carlo.

Z data





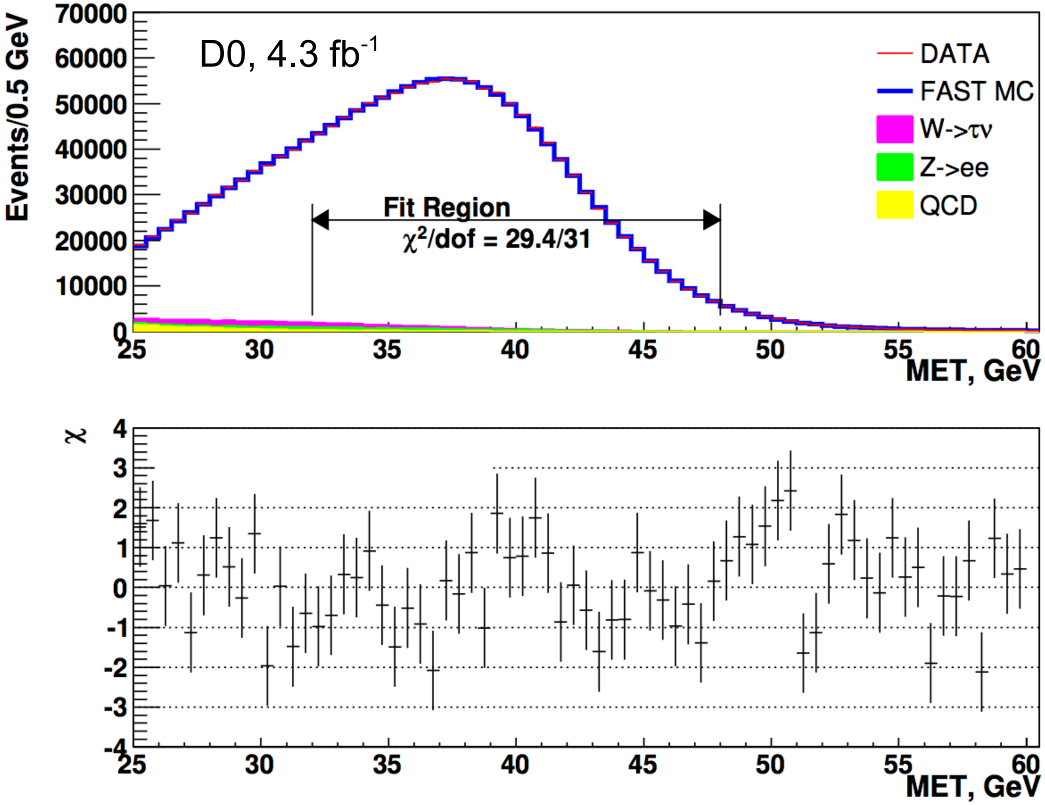




Good agreement between data and parameterised Monte Carlo.

W data

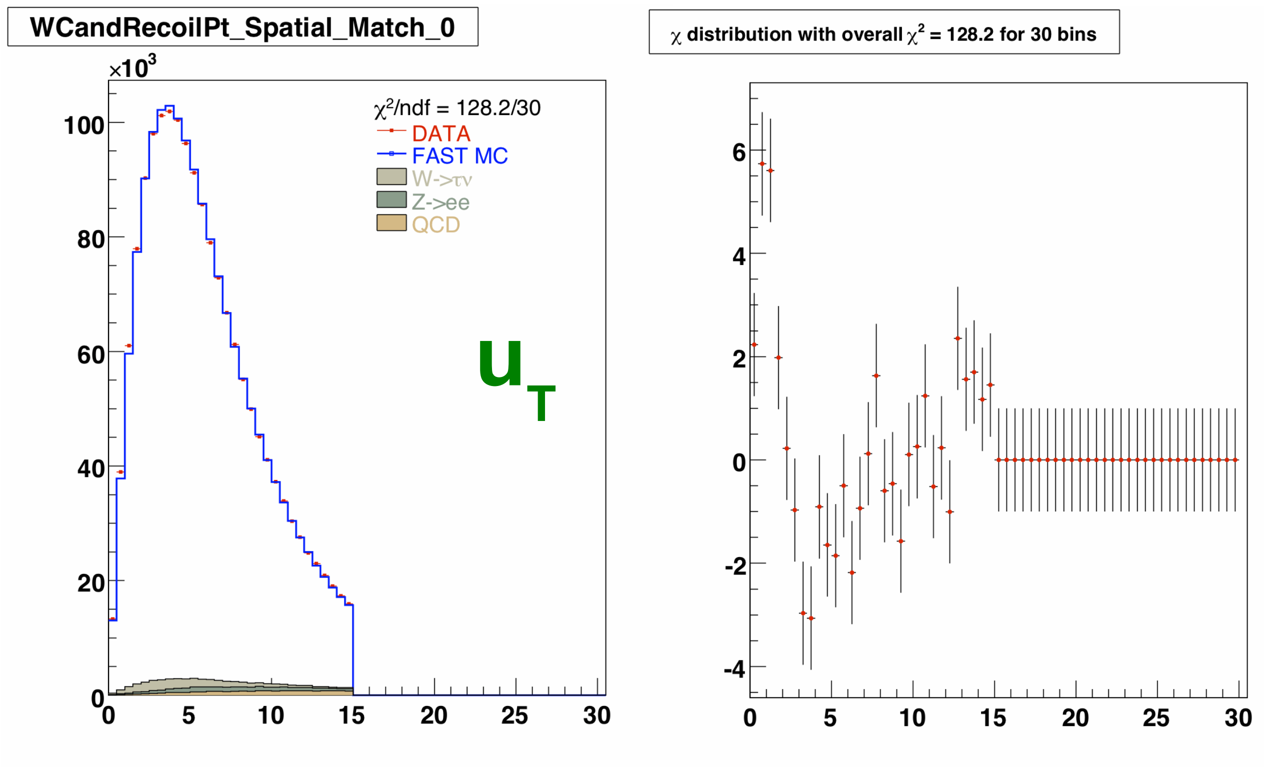
MET



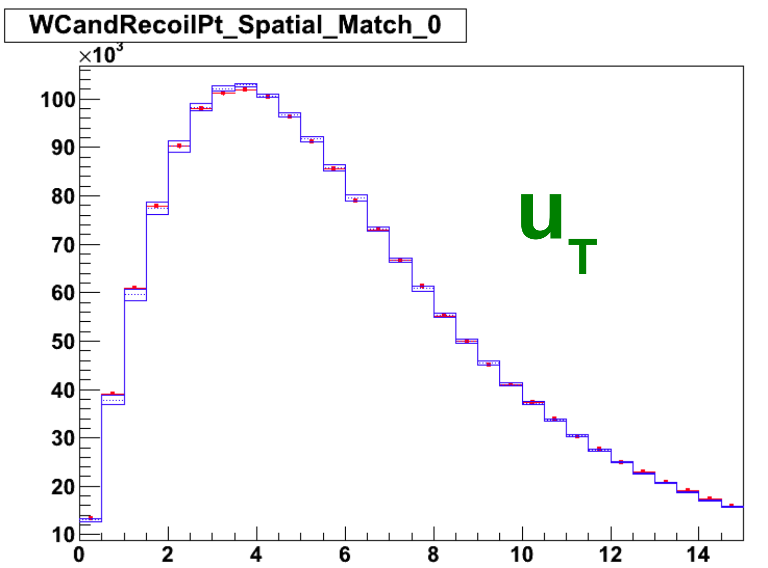
Fit results:

m(W) =
80355 ± 15 MeV (stat)

W data



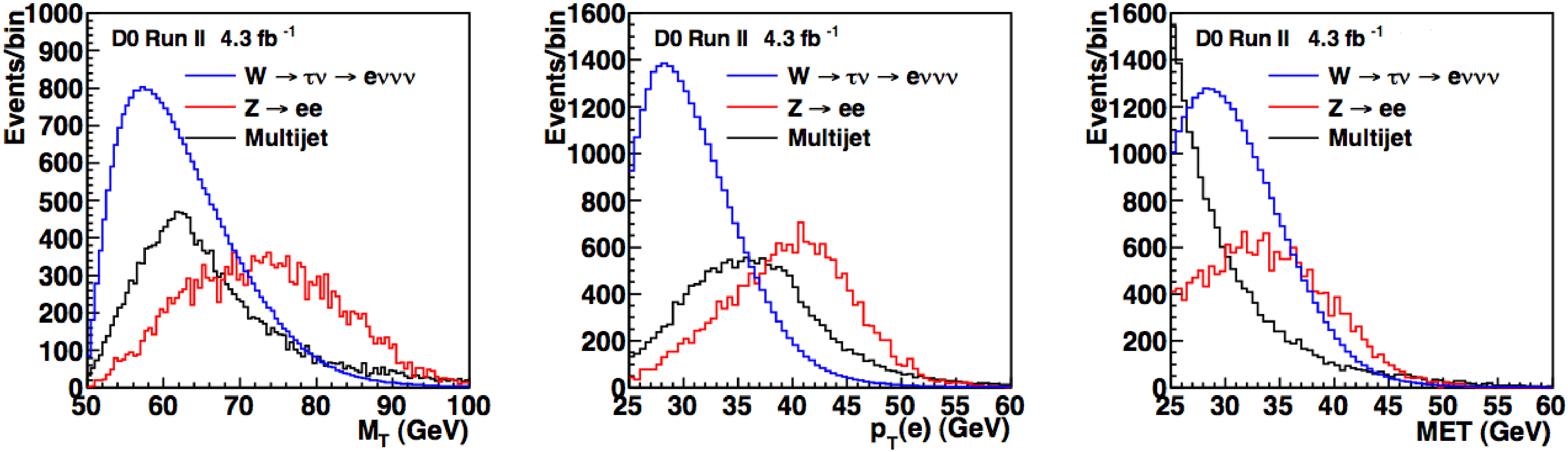
Here the error bars only reflect the finite statistics of the W candidate sample.



These are the same W candidates in the data. The blue band represents the uncertainties in the fast MC prediction due to the uncertainties in the recoil tune from the finite Z statistics.

Good agreement between data and parameterised Monte Carlo.

Backgrounds



Summary of uncertainties

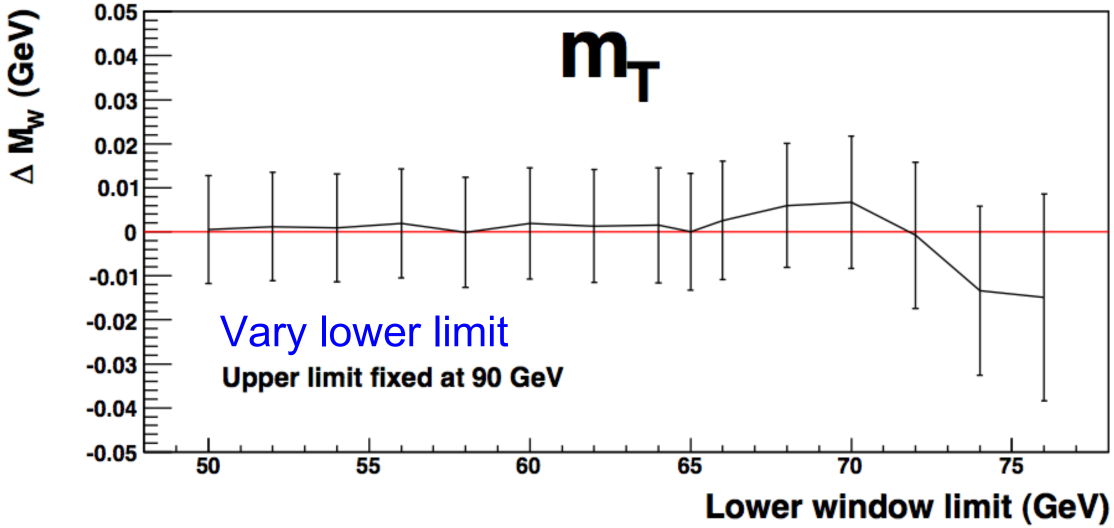
systematic uncertainties

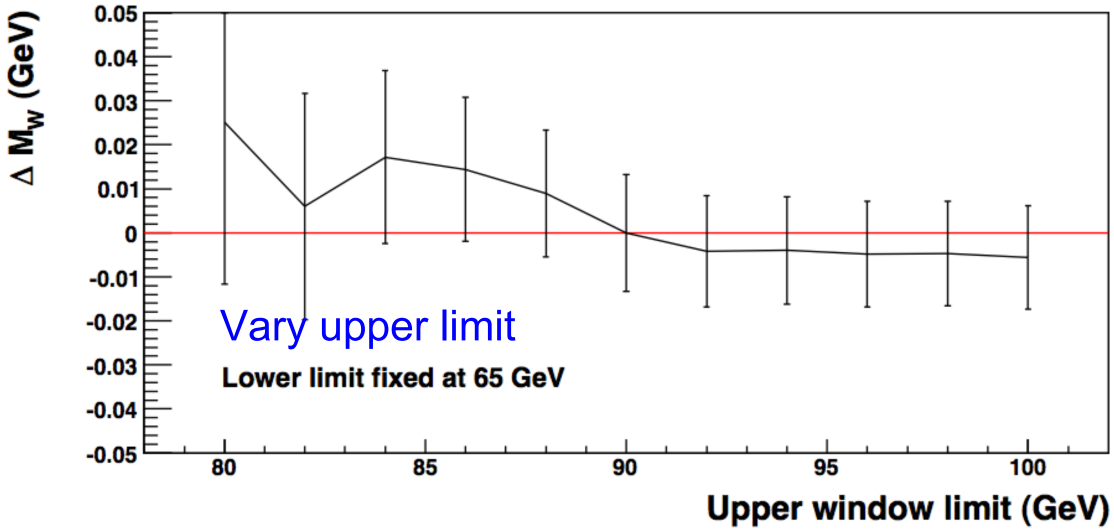
Source	$\sigma(m_W)$ MeV m_T	$\sigma(m_W)$ MeV $p_T(e)$	$\sigma(m_W)$ MeV $\not{E}_T$
Experimental			
Electron Energy Scale	16	17	16
Electron Energy Resolution	2	2	3
Electron Energy Nonlinearity	4	6	7
W and Z Electron energy loss differences	4	4	4
Recoil Model	5	6	14
Electron Efficiencies	1	3	5
Backgrounds	2	2	2
Experimental Total	18	20	24
W production and decay model			
PDF	11	11	14
QED	7	7	9
Boson p_T	2	5	2
W model Total	13	14	17
Total	22	24	29
statistical	13	14	15
total	26	28	33

Keep in mind that this analysis uses *only* Run IIb data, *i.e.* it is intended to be combined with our Run IIa result.
23 MeV uncertainty for the combination with Run IIa.

Consistency checks

Vary the range used in the m_T fit:

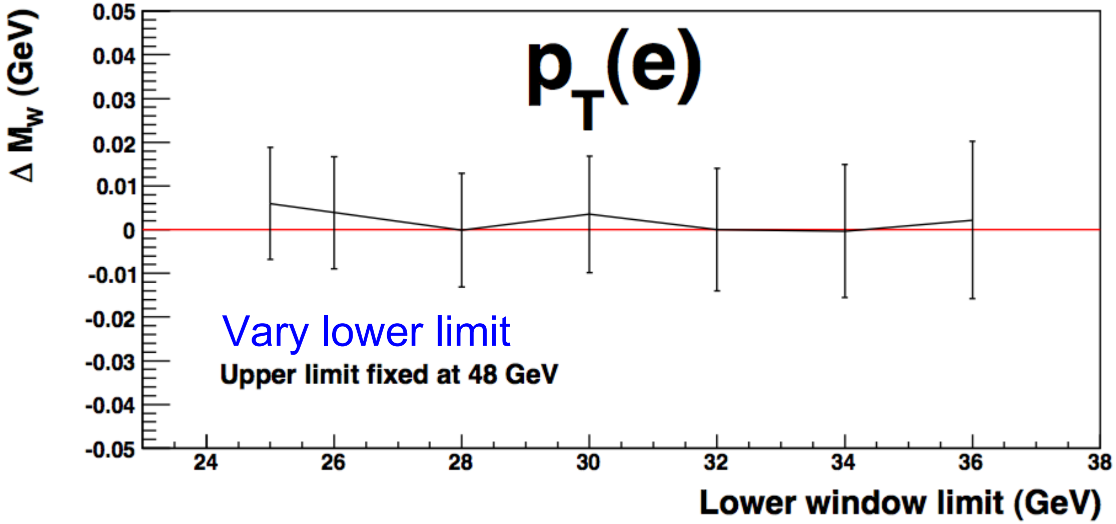


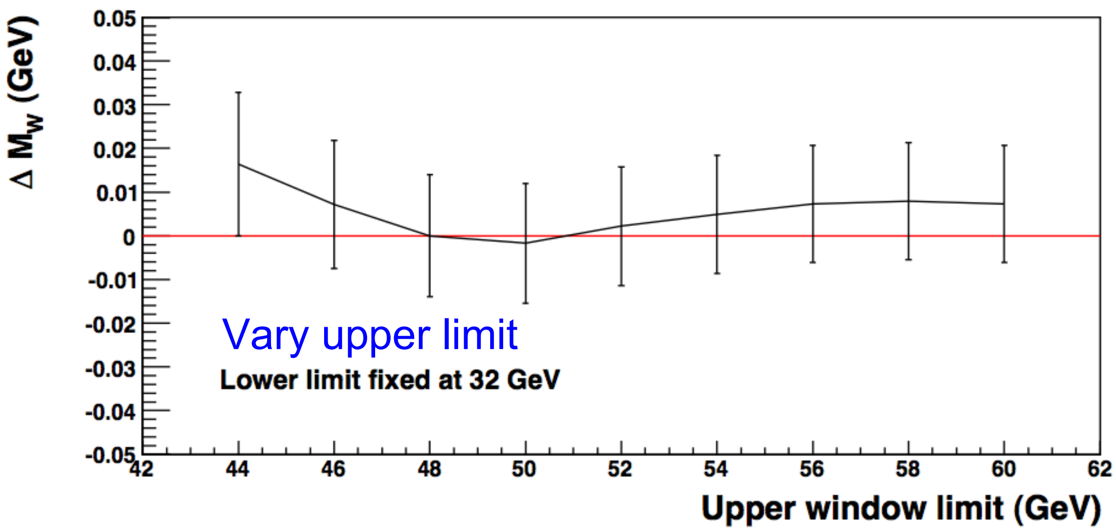


Measurement is stable

Consistency checks

Vary the range used in the $p_T(e)$ fit:

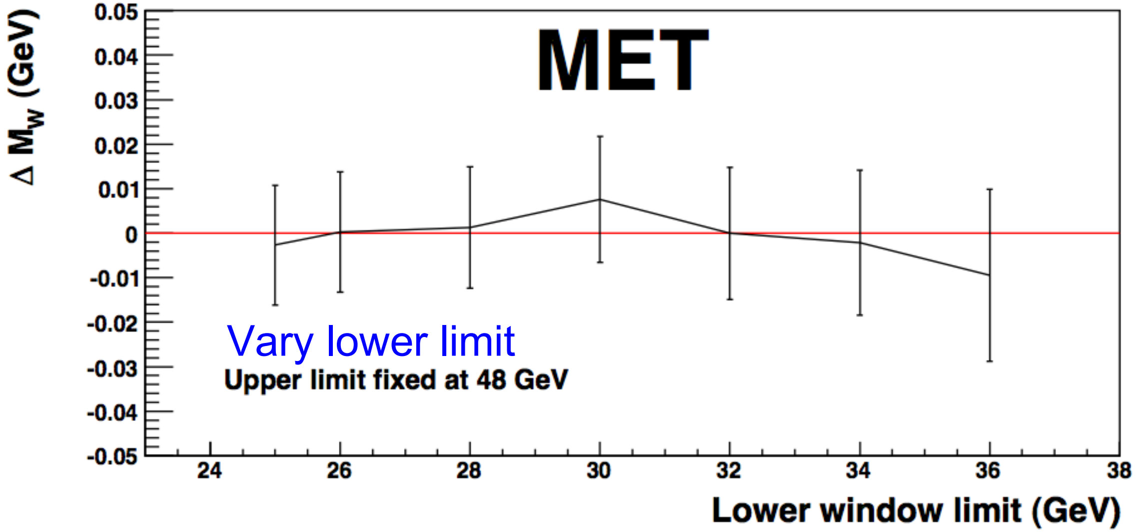


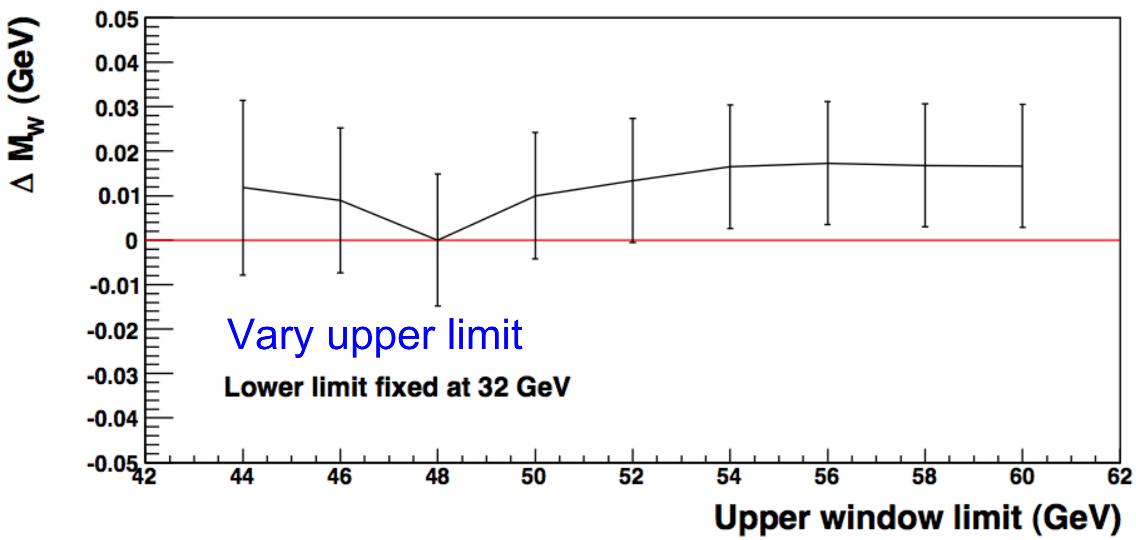


Measurement is stable

Consistency checks

Vary the range used in the MET fit:



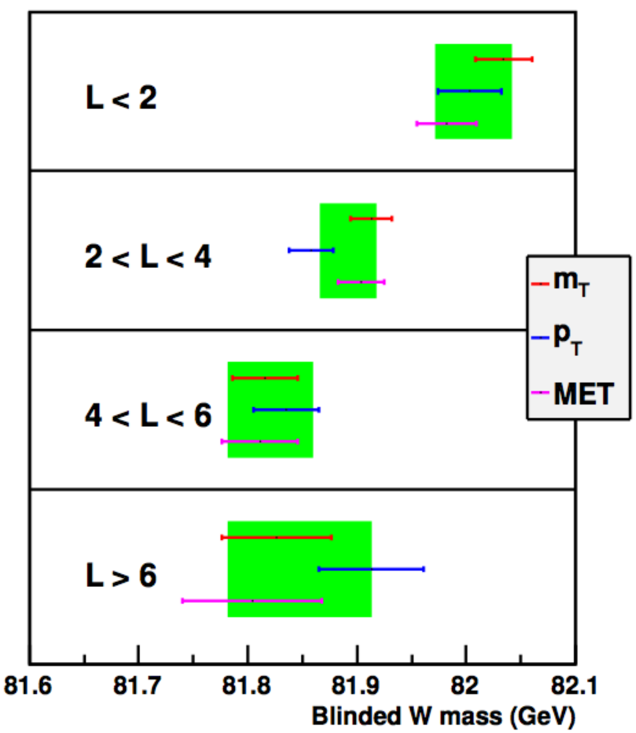


Measurement is stable

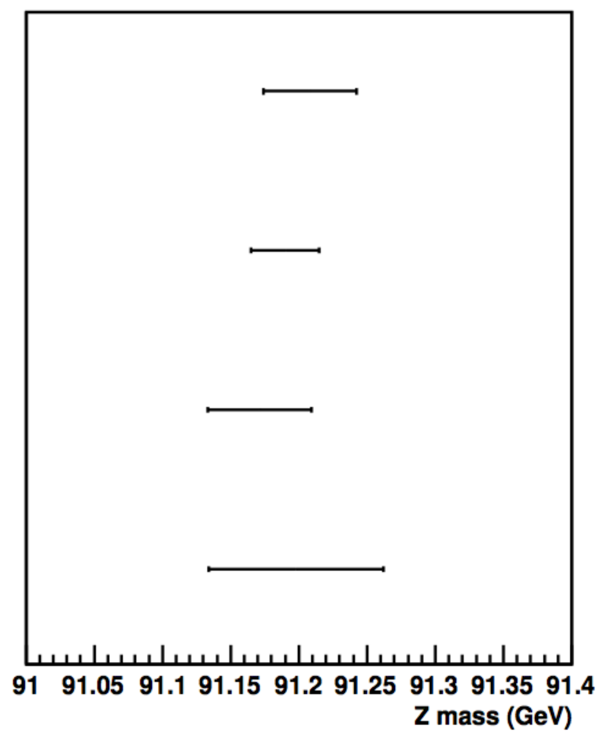
Consistency checks

Split data sample into four bins of instantaneous luminosity and measure W mass separately for each bin:

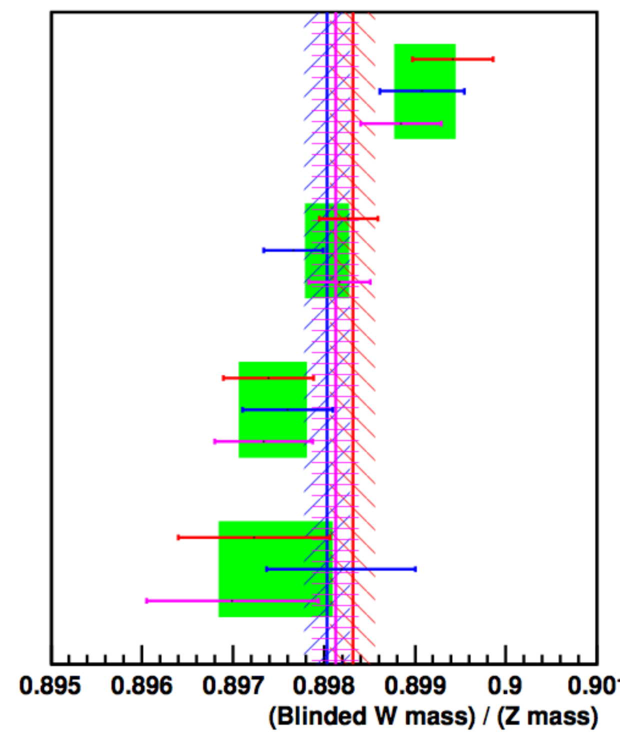
W



Z



"W/Z"



Error bars represent W statistics.

Green bands represent EM scale uncertainty (100 % correlated for m_T, p_T and MET).

Sorry, still using blinded mass in these plots.
But it does not matter here …
differences between observables and subsamples are preserved by the blinding.

Error bars represent W *and* Z statistics.

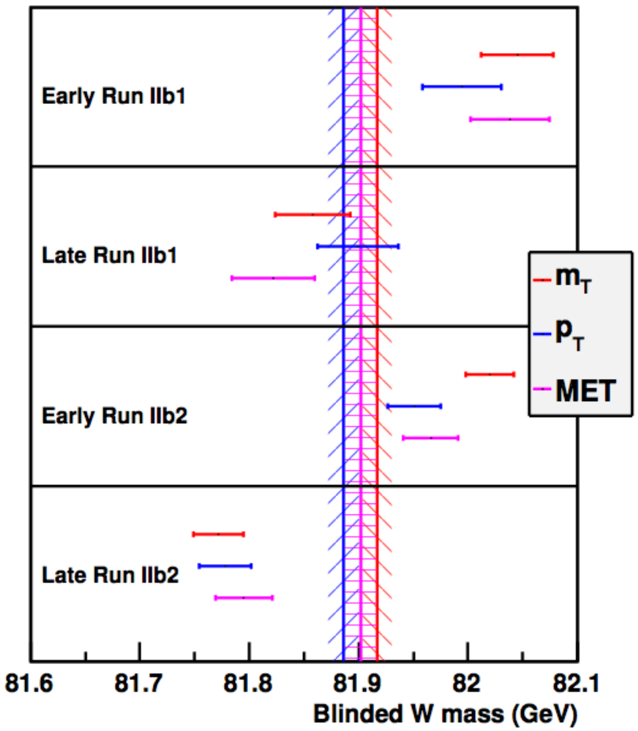
Green bands represent contribution from Z alone (100 % correlated for m_T, p_T and MET).

Mass ratio is stable with lumi.

Consistency checks

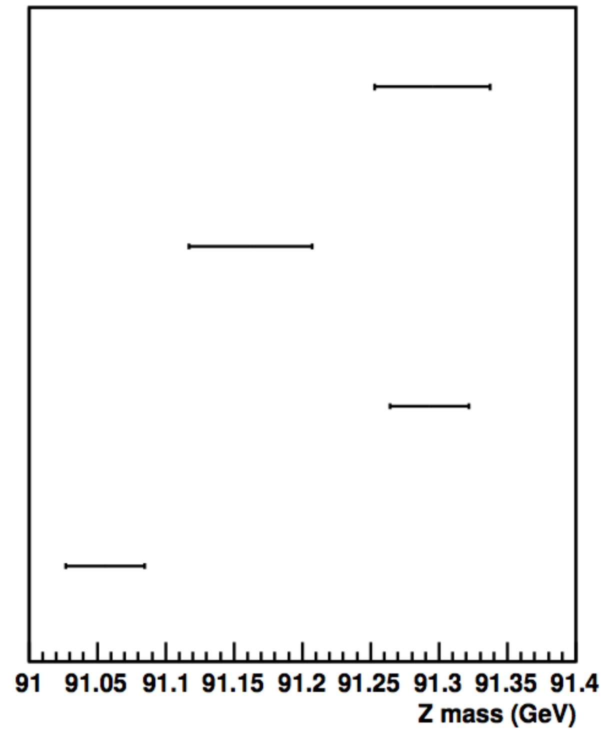
Split data sample into four data taking periods and measure W mass separately for each period:

W

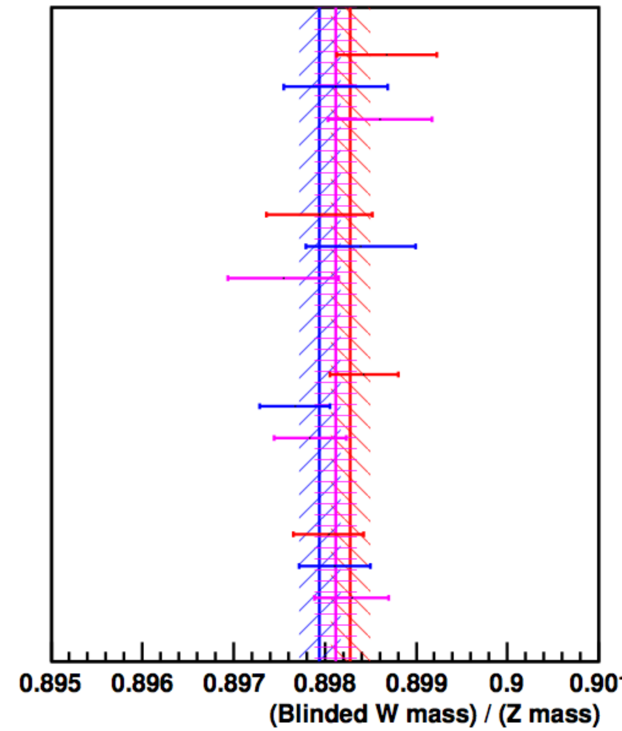


Error bars represent W statistics.

Z



"W/Z"



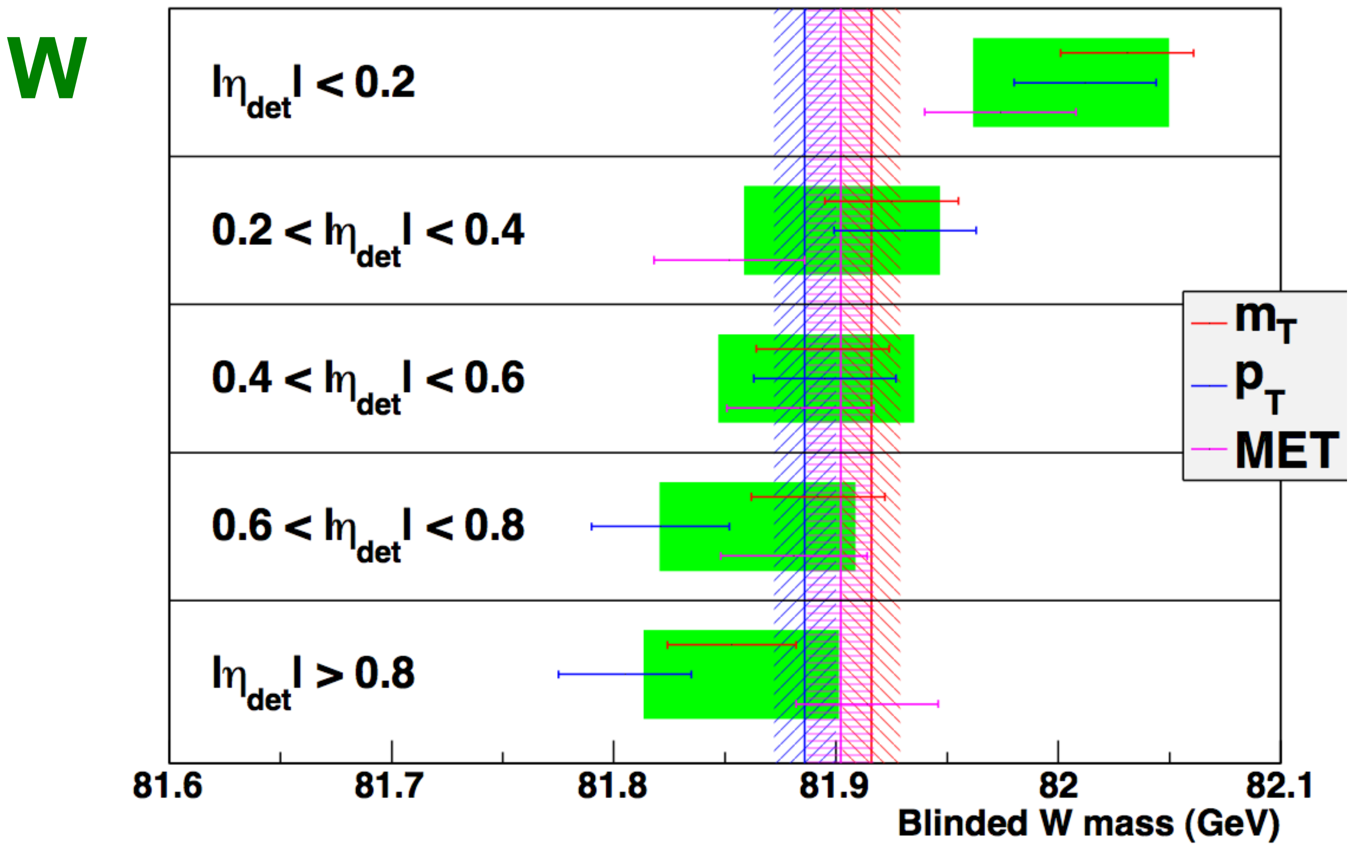
Error bars represent W *and* Z statistics.

Mass ratio is stable over time.

These are just a few examples. Many more cross-checks have been performed.

Consistency checks

Split data sample into five bins of detector eta and measure W mass separately for each bin:



Error bars represent W statistics.

Green bands represent the part of the EM scale uncertainty that is uncorrelated from one eta bin to another (100 % correlated for m_T, p_T and MET).

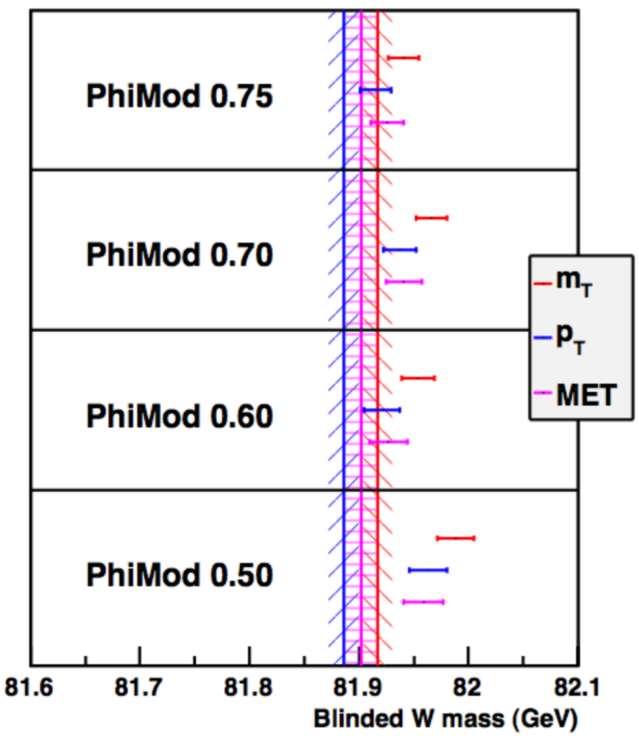
Sorry, still using blinded mass in these plots.
But it does not matter here …
differences between observables and subsamples are preserved by the blinding.

Mass is stable with eta.

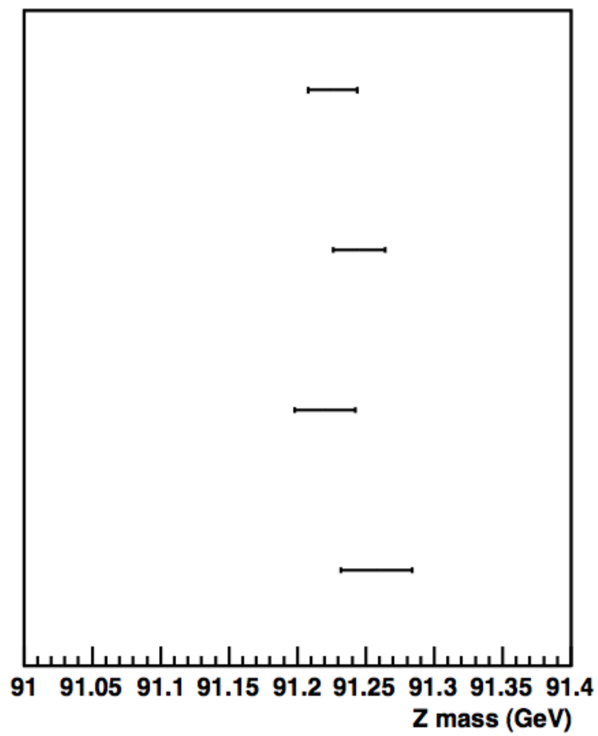
Consistency checks

Vary phi fiducial cut. In default analysis, keep 80 % of acceptance. Here we test four tighter requirements.

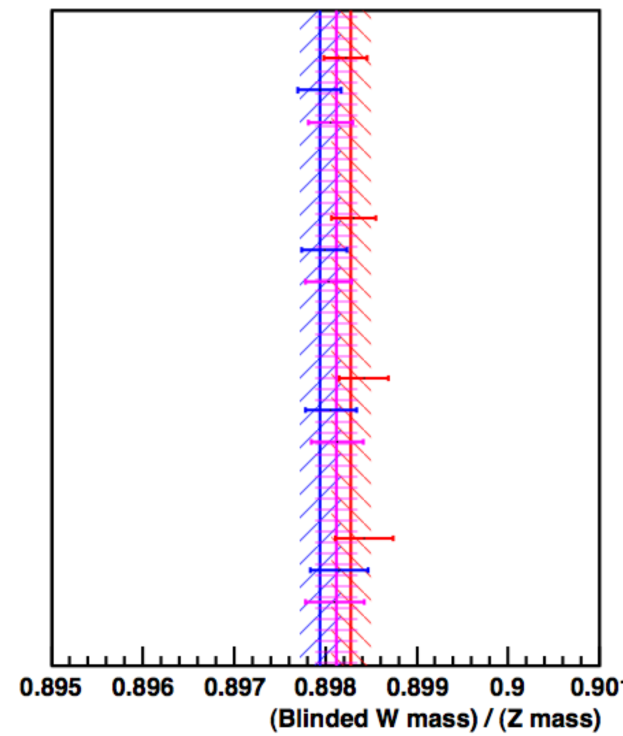
W



Z



"W/Z"



Error bars represent W statistics.

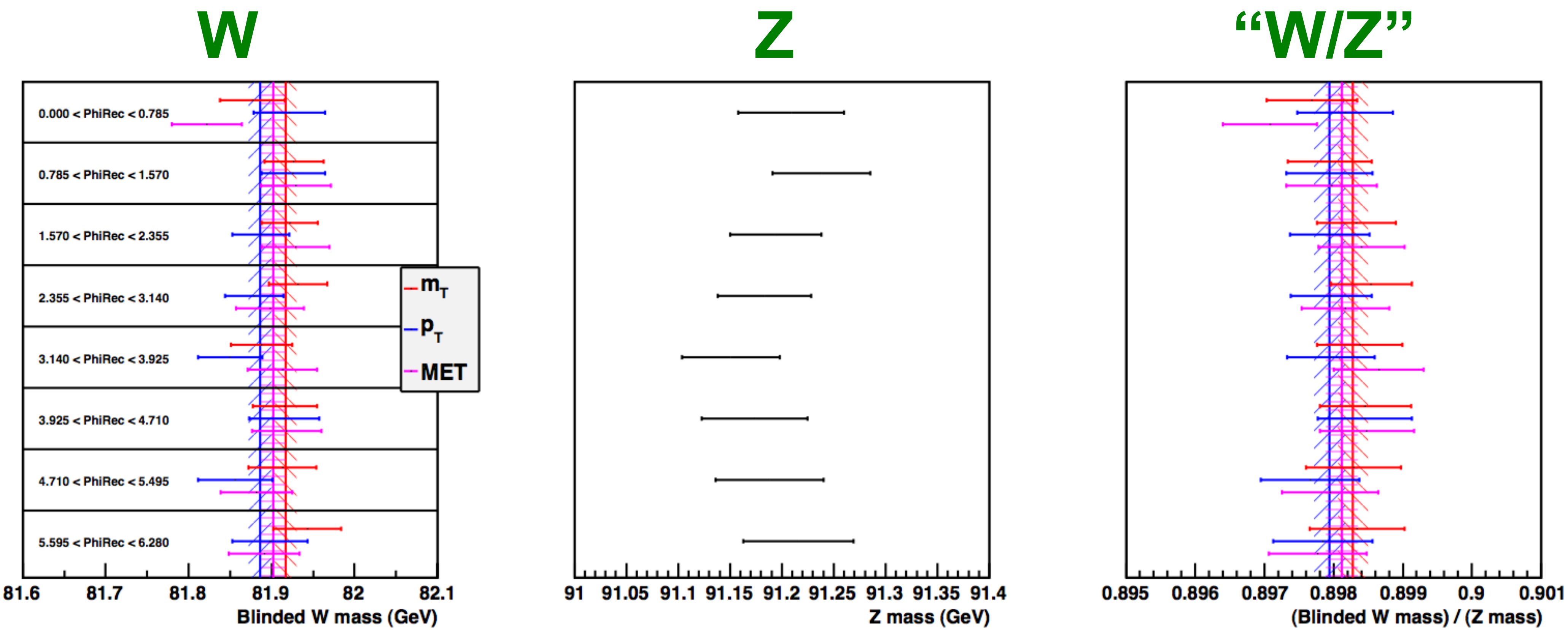
Error bars represent W *and* Z statistics.

Sorry, still using blinded mass in these plots.
But it does not matter here …
differences between observables and subsamples are preserved by the blinding.

Mass ratio is stable with fiducial requirement

Consistency checks

Split data sample into eight bins according to the direction in phi of the measured recoil vector, and measure W boson mass separately in each bin.



Error bars represent W statistics.

Error bars represent W *and* Z statistics.

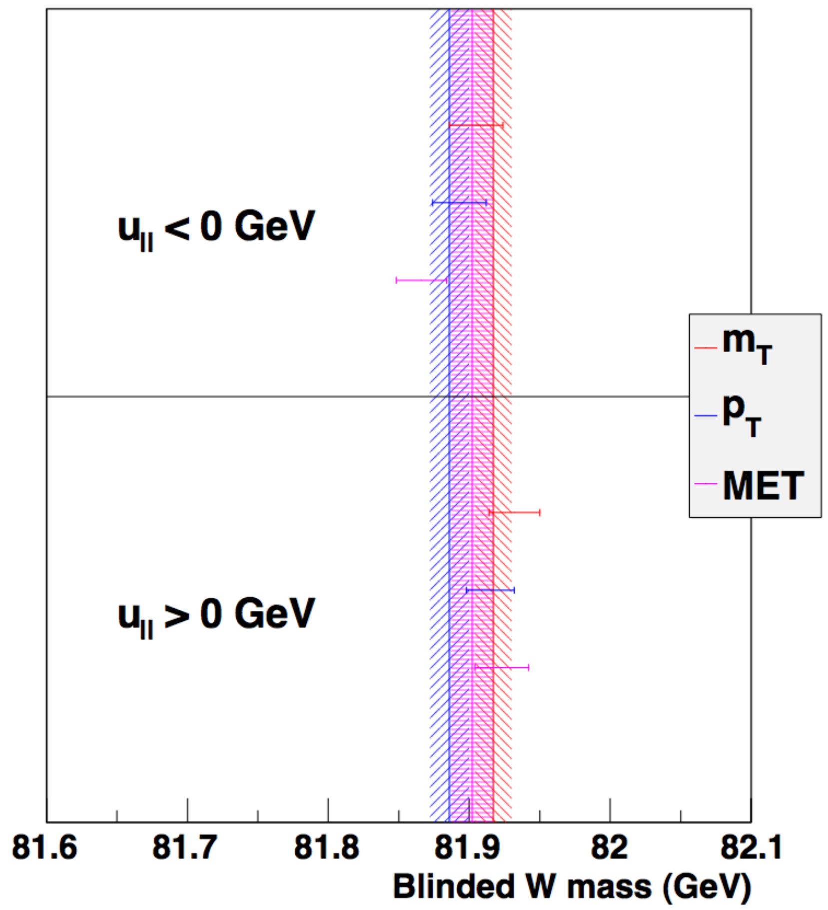
Sorry, still using blinded mass in these plots.
But it does not matter here …
differences between observables and subsamples are preserved by the blinding.

Mass ratio is stable with recoil phi.

Consistency checks

Split data sample into two bins of $u_{||}$ and measure W mass separately for each bin:

W



Error bars represent W statistics.

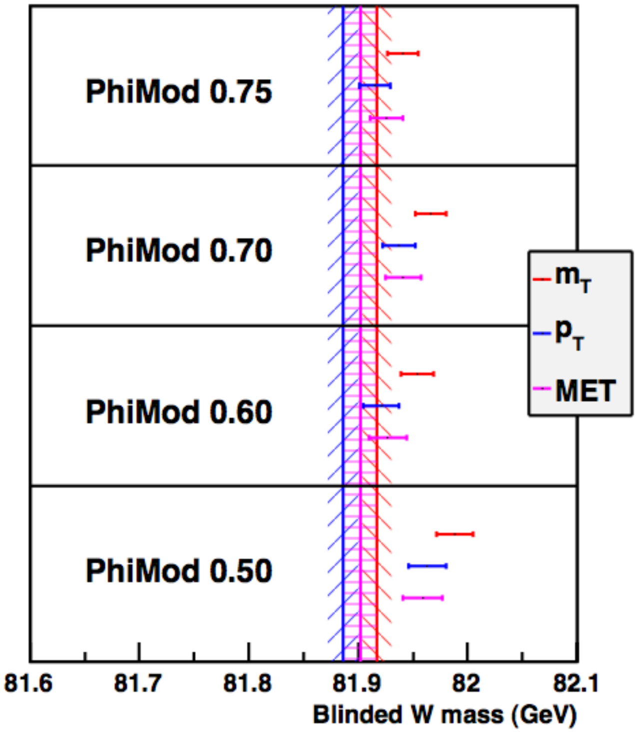
Sorry, still using blinded mass in these plots.
But it does not matter here …
differences between observables and subsamples are preserved by the blinding.

Mass is stable with $u_{||}$.

Consistency checks

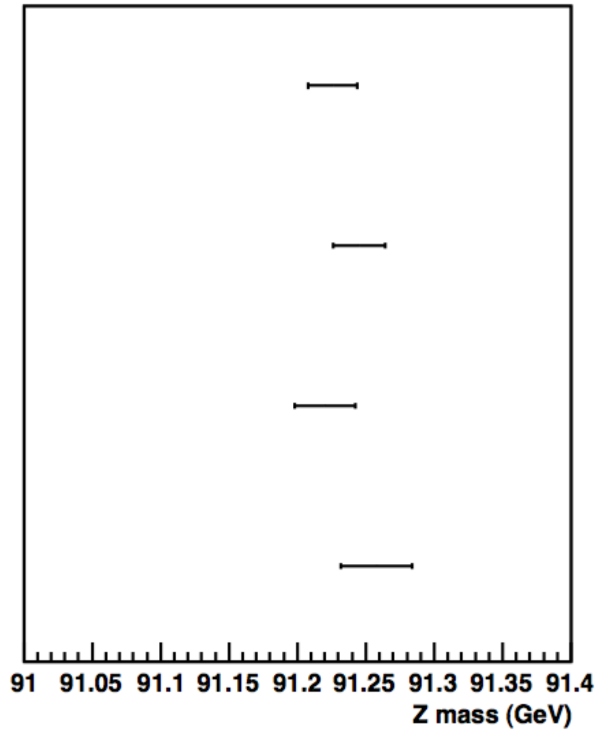
Vary phi fiducial cut. In default analysis, keep 80 % of acceptance. Here we test four tighter requirements.

W

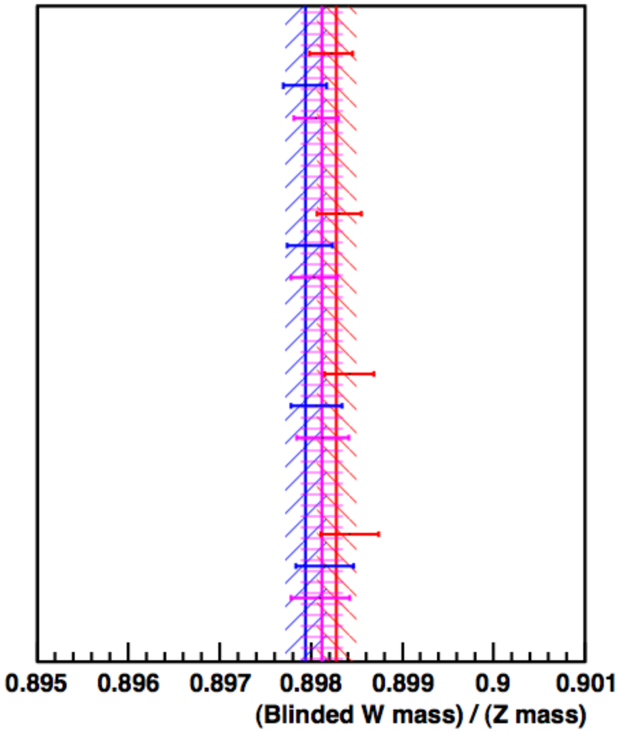


Error bars represent W statistics.

Z



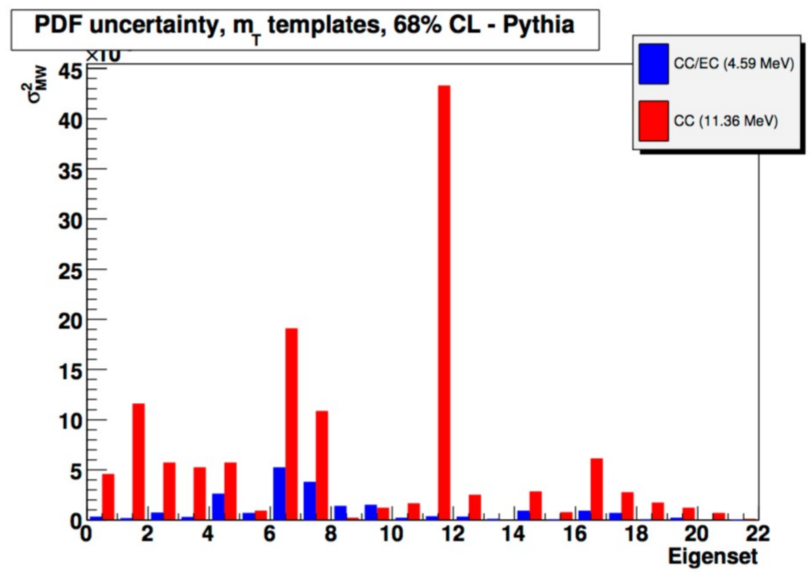
"W/Z"



Error bars represent W *and* Z statistics.

Sorry, still using blinded mass in these plots.
But it does not matter here …
differences between observables and subsamples are preserved by the blinding.

Mass ratio is stable with fiducial requirement



CTEQ6.1

FIG. 1. Comparison of the PDF uncertainty for the CC only and CC/EC cases. Variance in MeV^2.