W/Z physics at Dzero

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Outline/“philosophy” of this talk

Will not show an extensive overview of W/Z physics results from D0.
Such “catalogs of results” can be found elsewhere and are not necessarily useful for this workshop.

Will show the following material:

- Precision measurement of W boson mass,
- Try to give some “behind the scenes” details to illustrate how its precision is achieved.
- Projections for precision of future Tevatron measurements.
- Insist a little bit on the “parameterised detector model” that is used, because similar models are used in almost all D0 electroweak analyses.
- Measurements of W charge asymmetry.
- New measurement of Z transverse momentum spectrum.

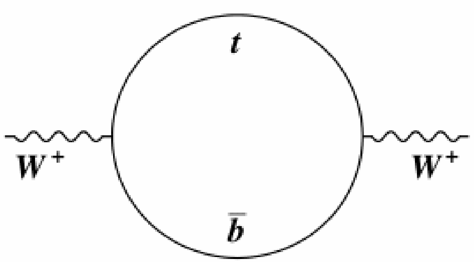
Have some back-up slides on other results (W boson width, weak mixing angle, Z couplings, ...).
We can always discuss these over a cup of coffee.

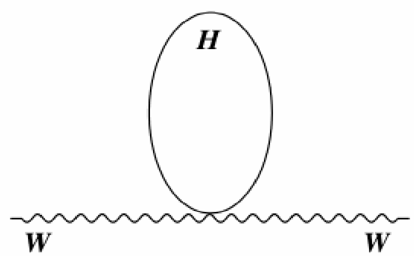
W mass: motivation

W mass is a key parameter in the Standard Model. This model does not predict the value of the W mass, but it predicts this relation between the W mass and other experimental observables:

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

Radiative corrections (Δ r) depend on M_t as ~M_t^2 and on M_H as ~log M_H. They include diagrams like these:



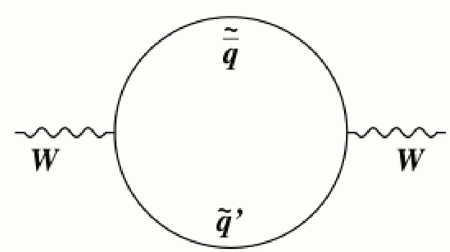


Precise measurements of M_W and M_t constrain SM Higgs mass.

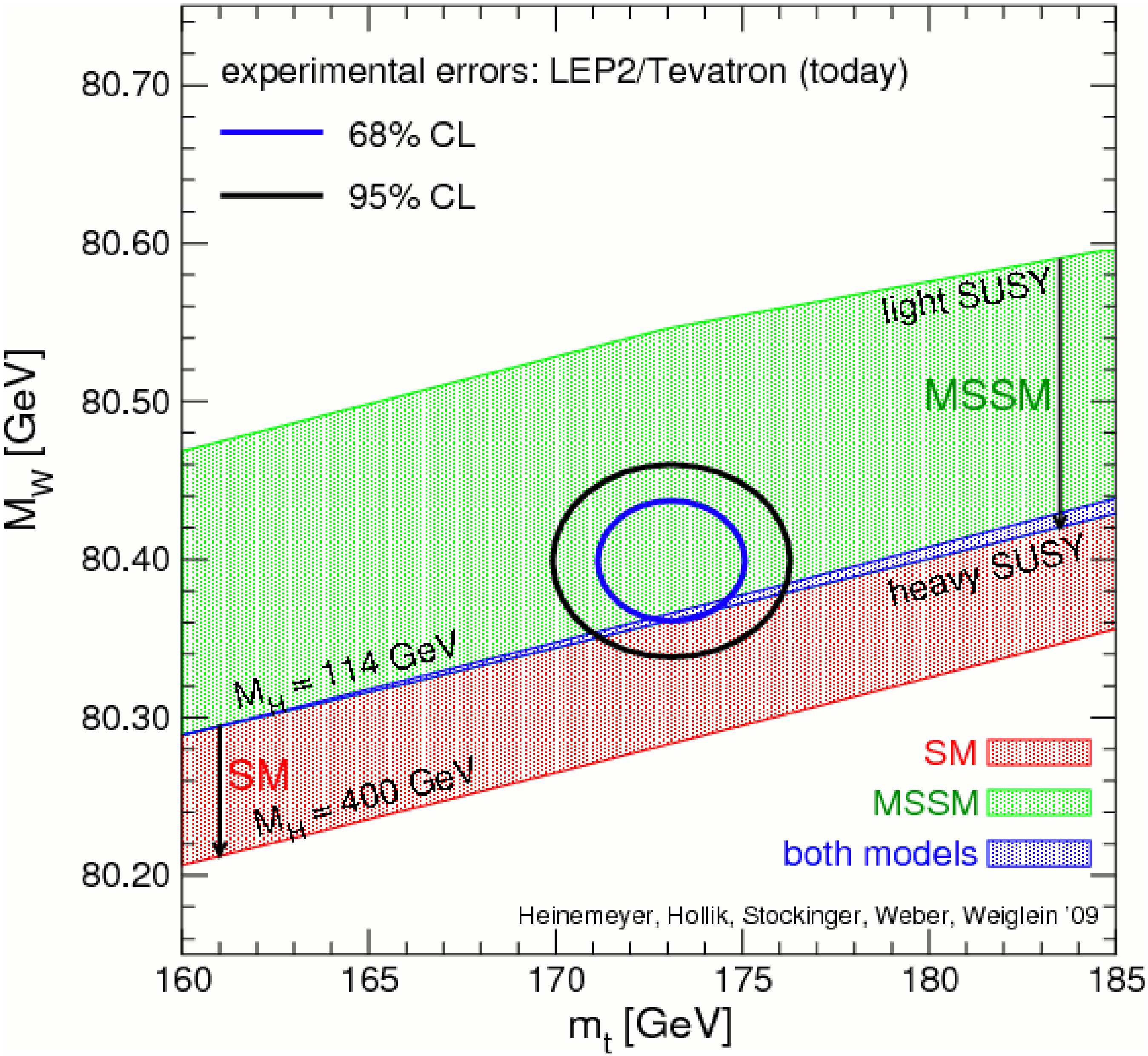
For equal contribution to the Higgs mass uncertainty need:
$\Delta M_W \approx 0.006 \ \Delta M_t$.

The limiting factor here will be ΔM_W, not ΔM_t !

Additional contributions to Δr arise in various extensions to the Standard Model, *e.g.* in SUSY:



W mass: motivation



For equal contribution to the Higgs mass uncertainty need:

$$\Delta M_W \approx 0.006 \ \Delta M_t .$$

Current Tevatron average:

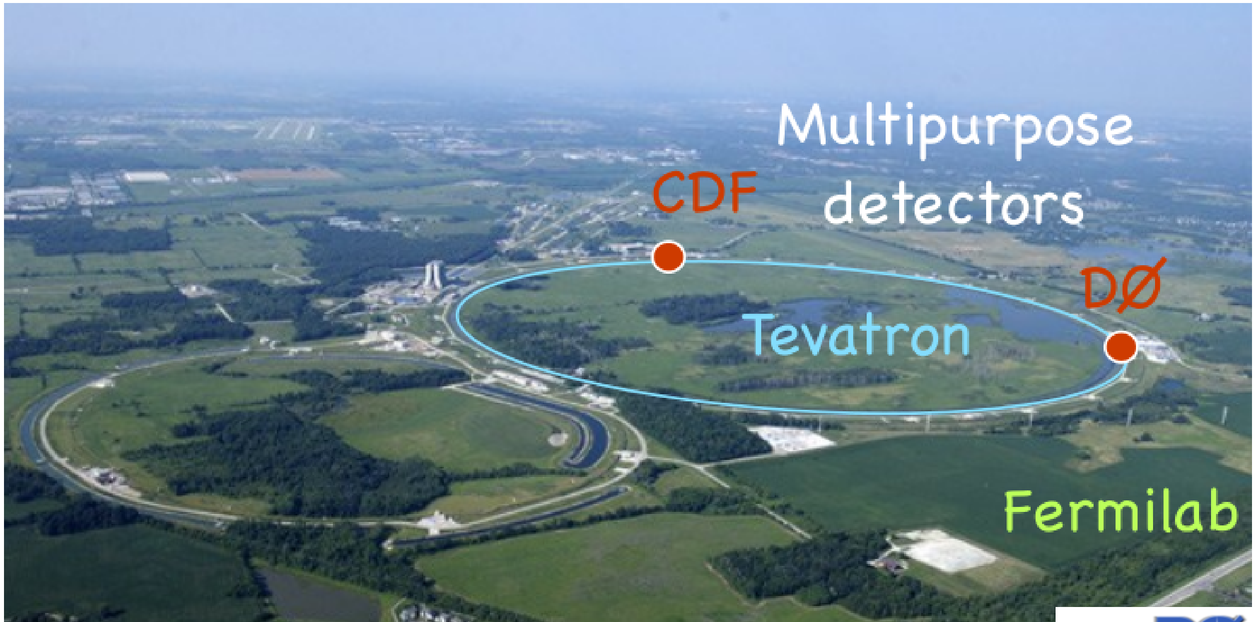
$$\Delta M_t = 1.1 \text{ GeV}$$

$\Rightarrow$ would need: $\Delta M_W =$ 7 MeV

Currently have: $\Delta M_W = 23$ MeV

At this point, i.e. after all the precise top mass measurements from the Tevatron, the limiting factor here is ΔM_W, not ΔM_t .

The Tevatron



Proton-antiproton collisions with centre-of-mass = 1.96 TeV

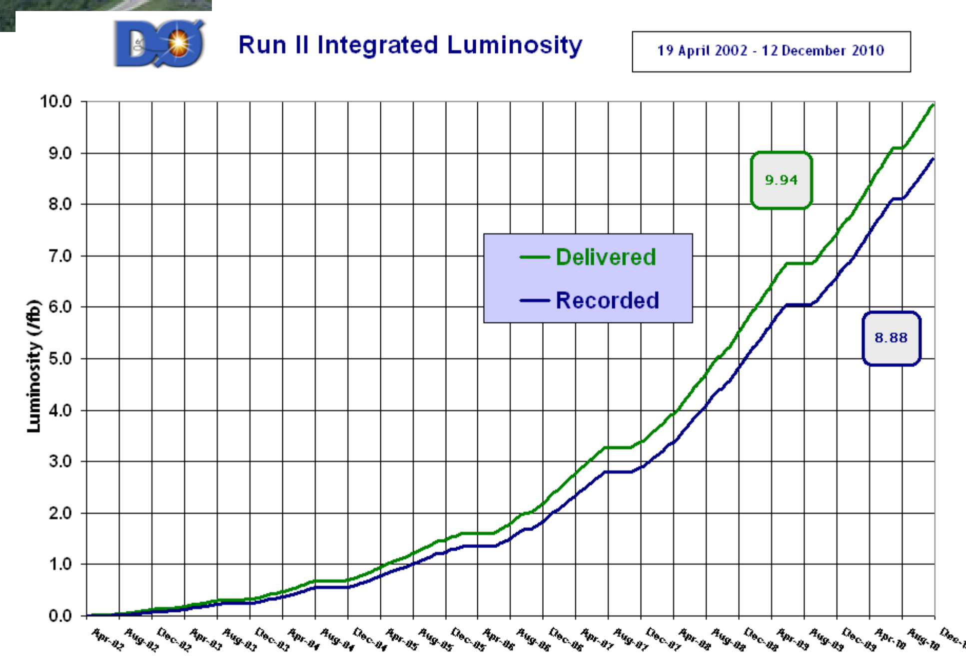
36 p and pbar bunches
396 ns between bunch crossing

Since a few years the Tevatron performance is truly excellent.

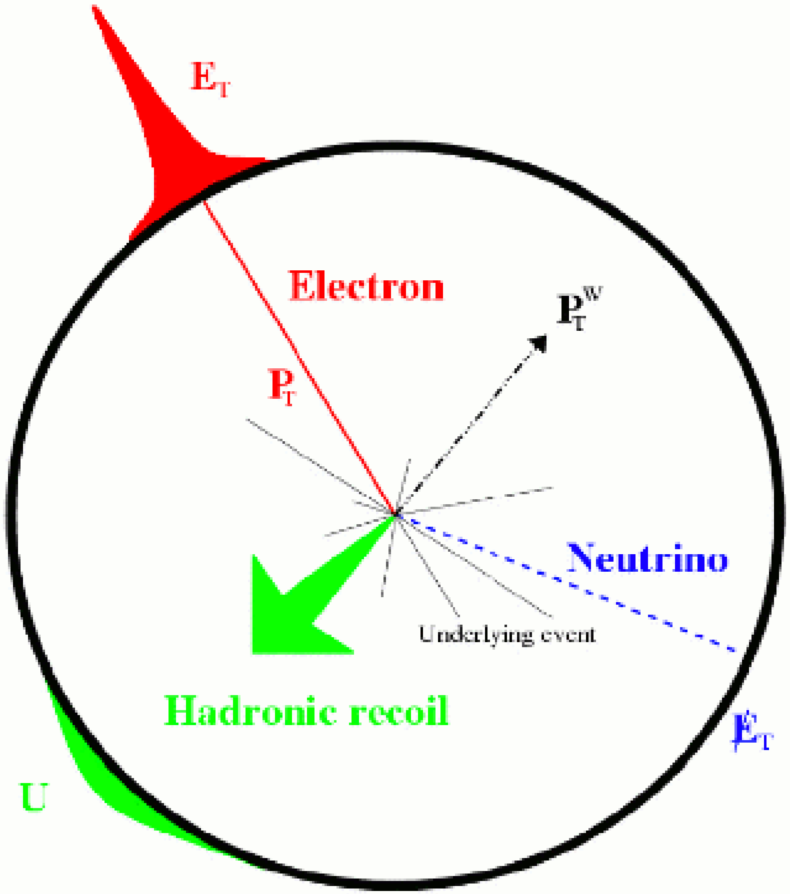
Peak initial instantaneous luminosity:
400 * 10^{30} cm^{-2} s^{-1}

Still the world's most powerful "boson factory".

Both experiments are collecting data efficiently.

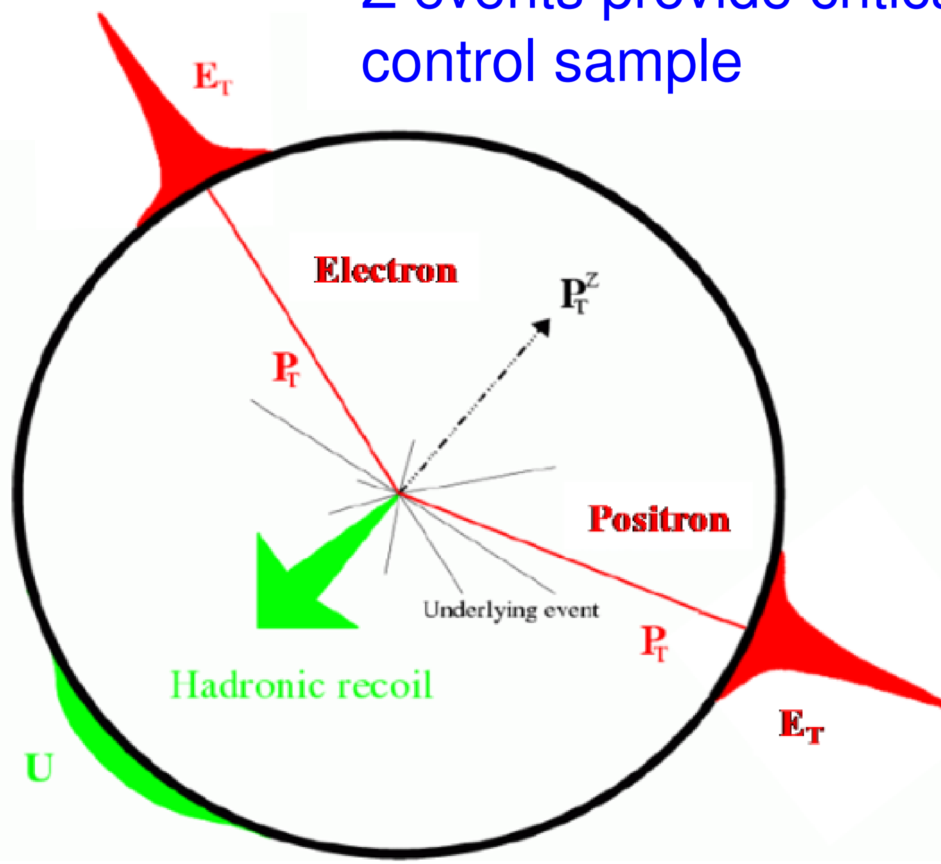


Signature in the detector



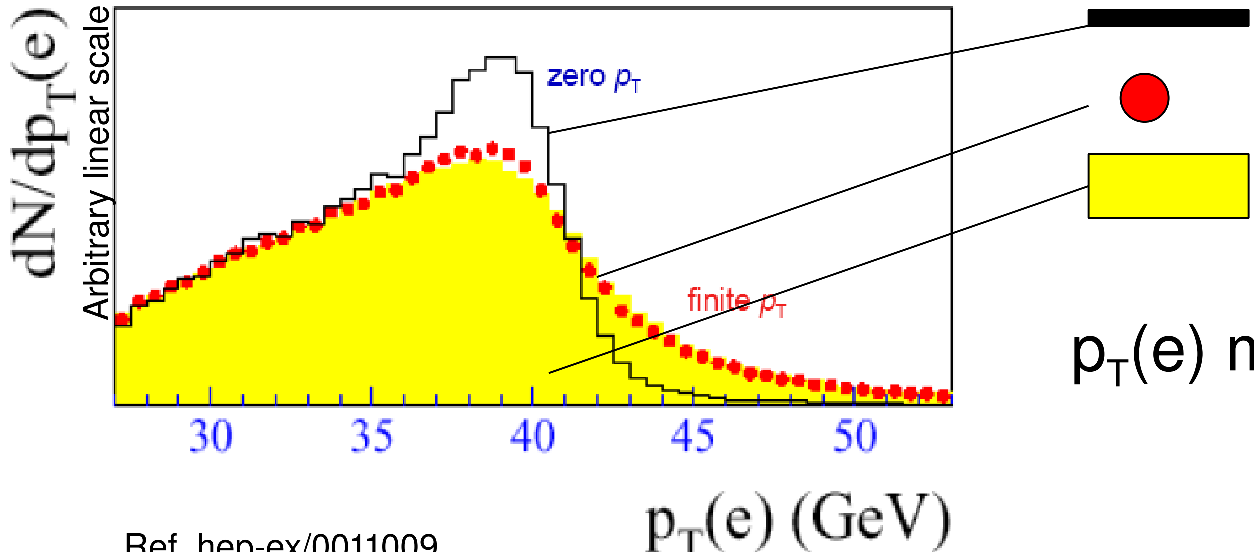
Isolated, high p_T leptons,
missing transverse momentum in W's

Z events provide critical control sample



In a nutshell, measure two objects in the detector:
- Lepton (in principle e or μ; e in our analysis), need energy measurement with 0.2 per-mil precision (!!)
- Hadronic recoil, need ~ 1% precision

Experimental observables



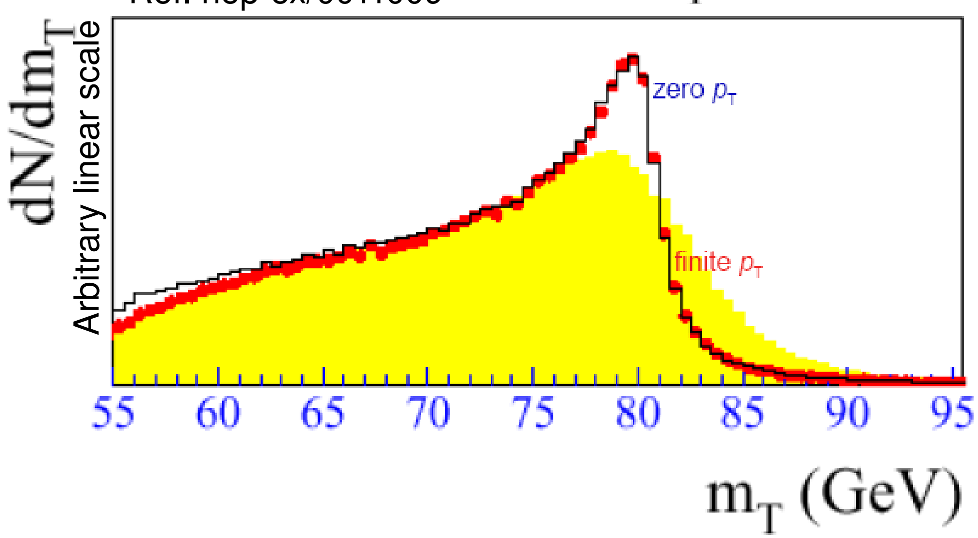
No $P_T(W)$

$P_T(W)$ included

Detector Effects added

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

Ref. hep-ex/0011009

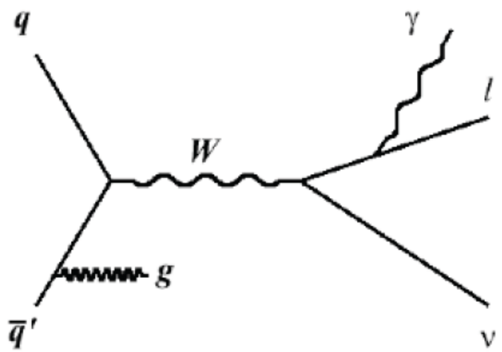


$$M_T = \sqrt{2E_T^l \not{E}_T (1 - \cos\Delta\phi)}$$

M_T most affected by measurement of missing transverse momentum

Measurement strategy

W mass is extracted from transverse mass, transverse momentum and transverse missing momentum:
Need Monte Carlo simulation to predict shapes of these observables for given mass hypothesis



NLO event generator : DØ uses **ResBos** [Balazs, Yuan; Phys ReV D56, 5558] + **Photos** {Barbiero, Was; Comp Phys Com 79, 291] for W/Z production and decay

+

Parameterised detector model

↓

W mass templates

+

backgrounds

Validated in "MC closure test"

Detector calibration
- calorimeter energy scale
- recoil

data

binned likelihood fit

↓

W mass

"First principles" vs. "parameterised" simulations

We all like "first principles" simulations, *i.e.* simulations where everything is based on a formal theory that predicts everything.

Examples:
- A gauge theory used to simulate some $e^+ e^- \to X$ collision.
- A simulation based on the known laws of the interactions between high-energy particles and matter, as well as a model of the DØ detector geometry is used to predict the electron energy response in DØ.

But what to do when the "first principles" cannot be made precise/complete enough ?

Examples:
- Tricky mathematical issues in QCD description of $p^+ p^{+/-} \to X$.
- Response to hadrons not simulated quite right in detector simulation.
- ...

Here "parameterised" simulations can be very powerful, because they have simple "knobs" that we can turn to adjust things.

Examples:
- Non-perturbative form factors to be determined from collider data.
- Simple parameterisation of hadron energy response, to be fit to control sample from collider data.

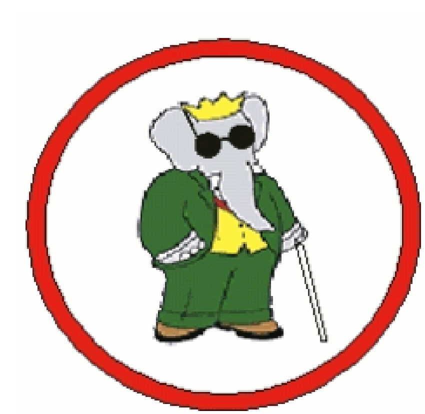
In practice, the trick is to combine the two approaches. In the DØ m(W) measurement we have a parameterised simulation with many parameterisations derived from first-principles simulations.

First DØ Run II measurement of the W boson mass

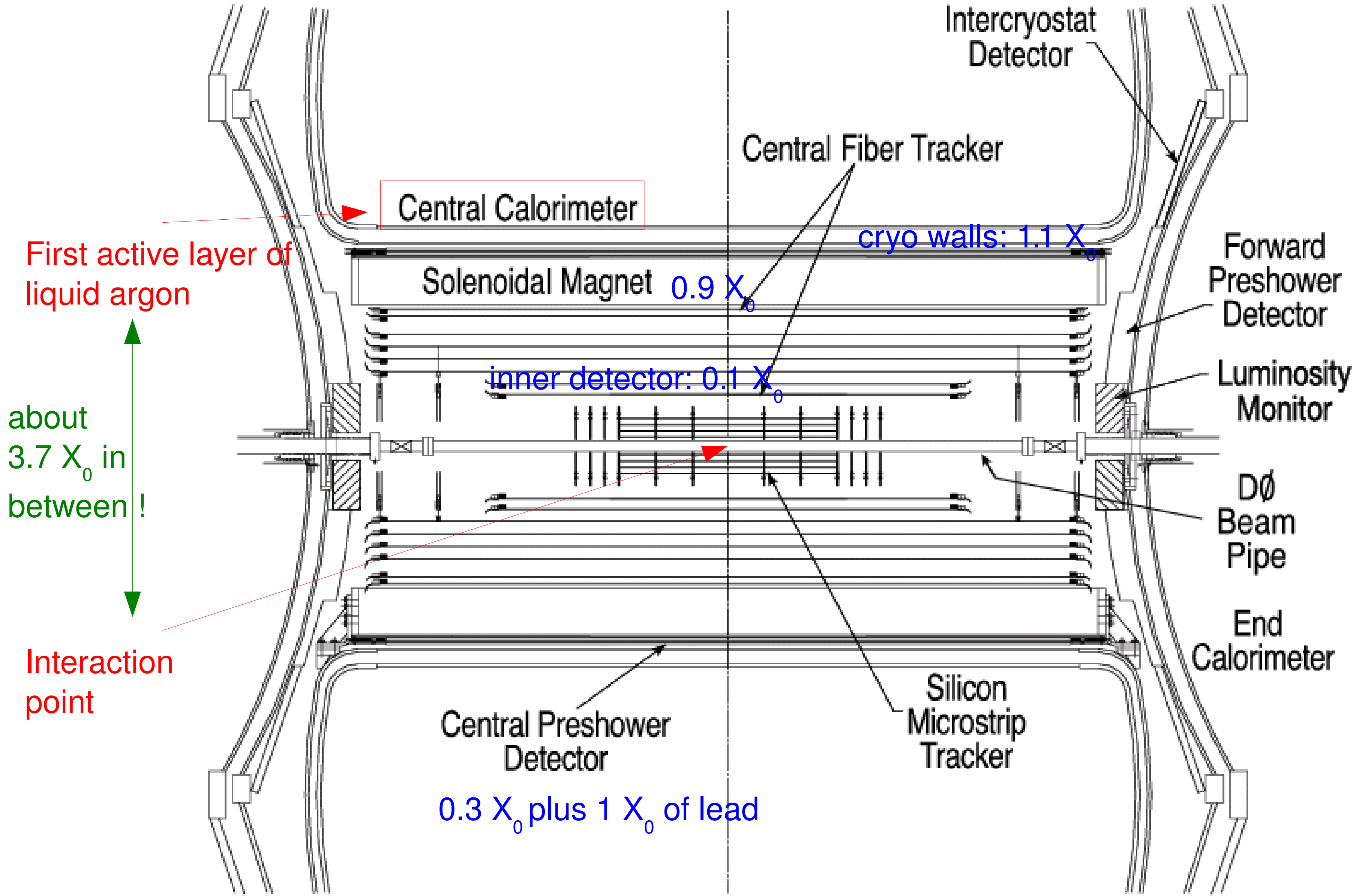
1 fb^{-1} of data
using central electrons ($|\eta|<1.05$)

~ 500k W events
~ 19k Z events

"blind" analysis : central value hidden but not the uncertainties
Standard blinding technique "à la BaBar"
Unblinding has been done only after collaboration approval



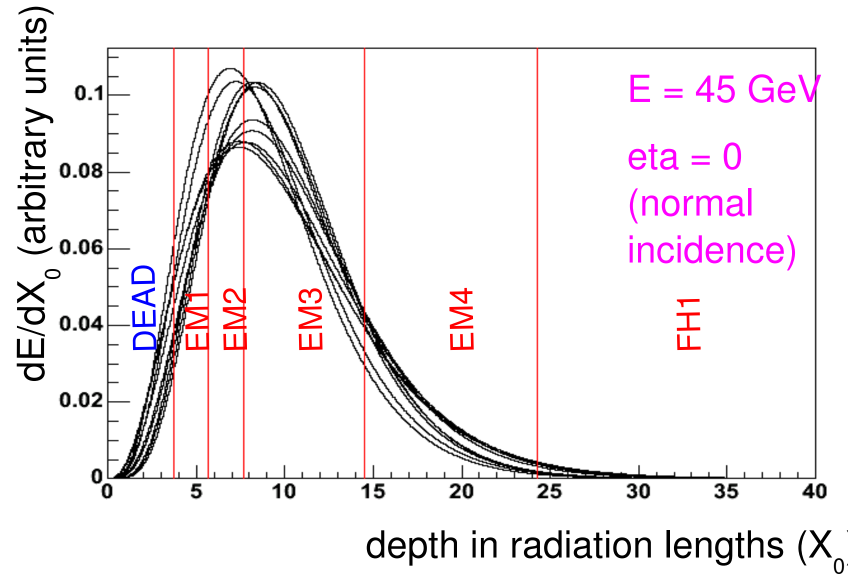
Keep in mind: the CAL is not alone !



Energy-dependence and fluctuations

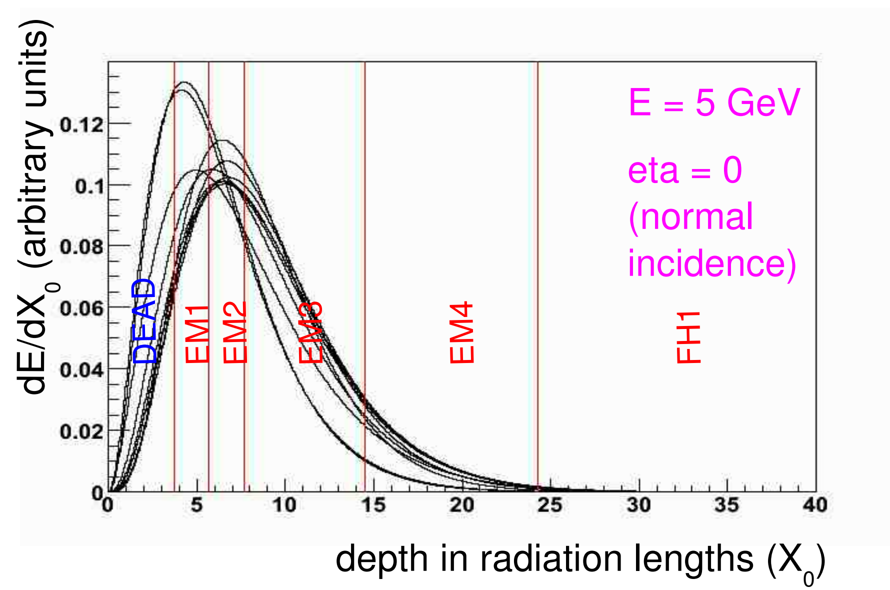
The plots on the previous slide show the *average* shower profile at E = 45 GeV.
The plot on the right is basically the same, except that it includes typical *shower fluctuations*.

=> The fraction of energy lost in the dead material varies from shower to shower.



The bottom plot illustrates the situation at a different, lower, energy. The position of the shower maximum (in terms of X_0) varies approximately like ln(E).

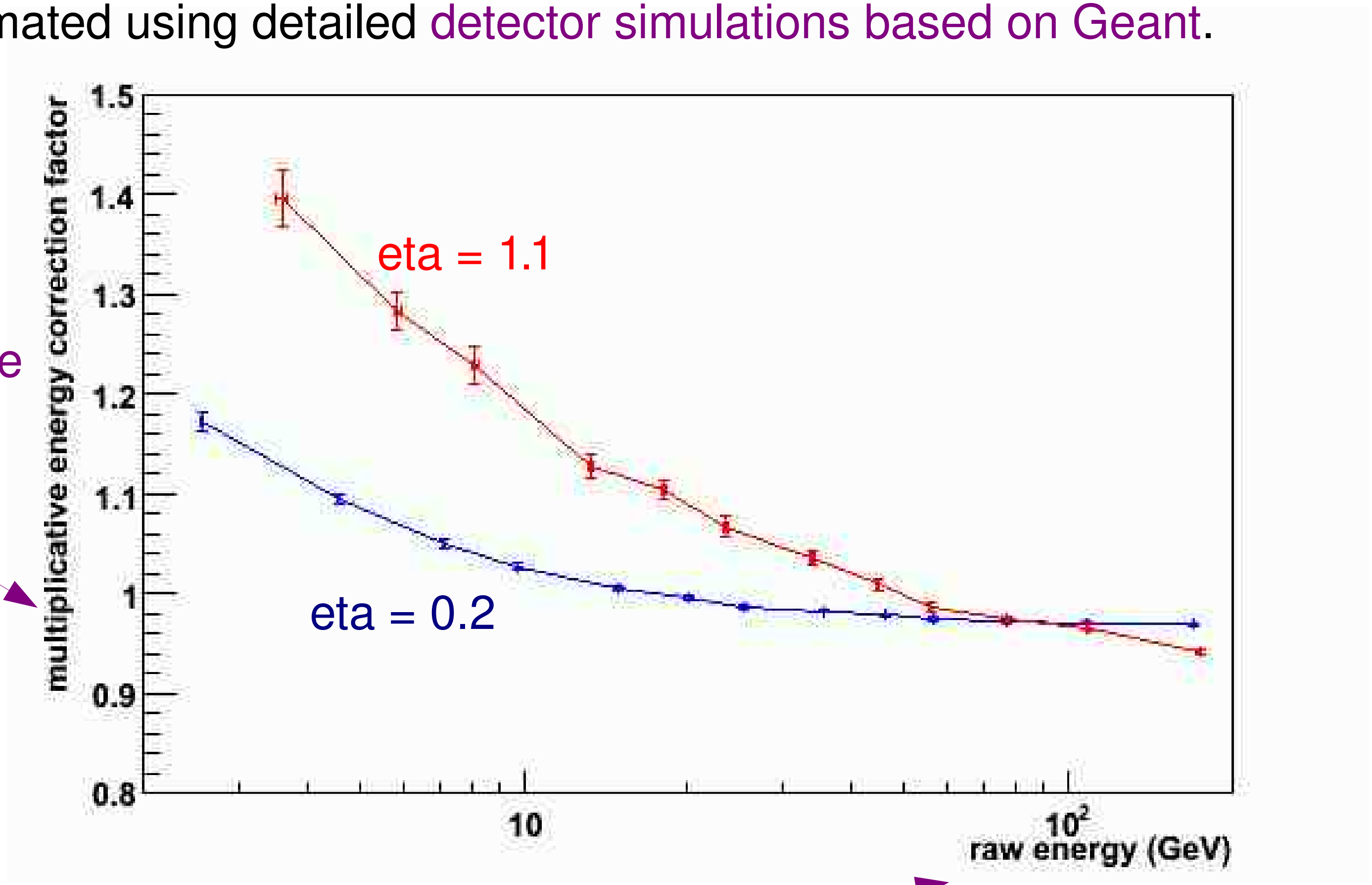
=> The average fraction of energy lost in dead material, as well as the relative importance of shower-by-shower fluctuations depend on the energy of the incident electron.



Average response ...

So we need to apply an energy-loss correction to our reconstructed electron energies to account for the energy lost in front of the calorimeter. This correction, as a function of energy and angle (eta) is estimated using detailed detector simulations based on Geant.

This is the energy correction factor that gets us back to the energy of the incident electron.



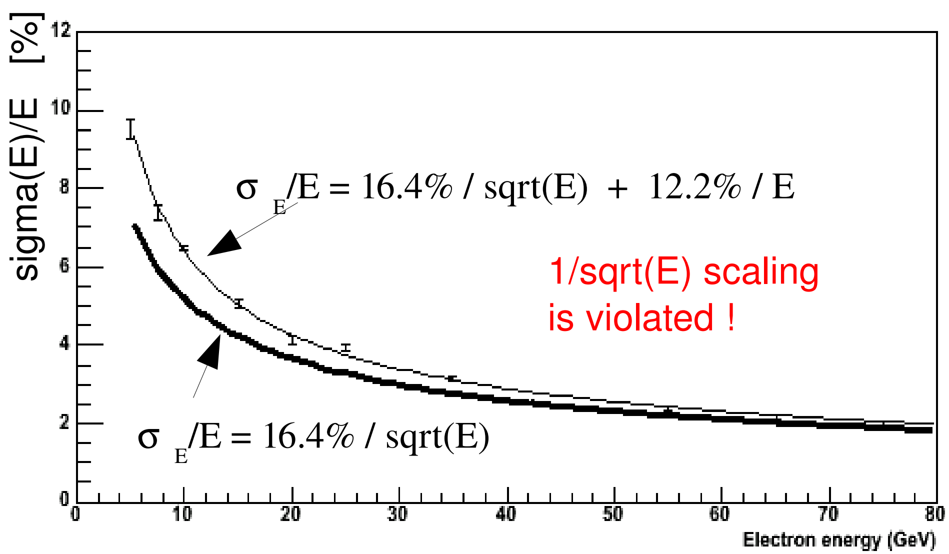
This is the energy as reconstructed in the CAL.

Knowing the amount of dead material is the key to energy response linearity:
Measure amount of dead material *in situ* using electrons from Z → e e.

... and fluctuations around the average

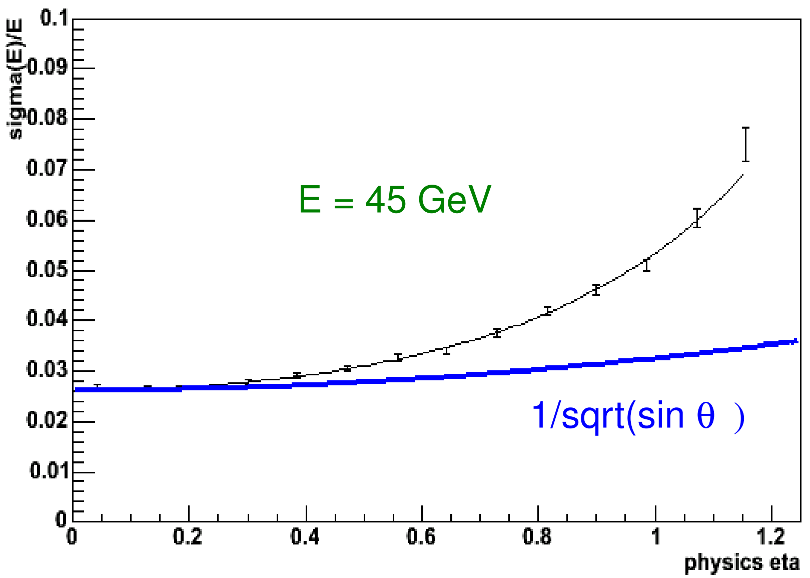
Here we show the impact on the energy resolution for electrons. This is again from a detailled detector simulation based on Geant.

Resolution at normal incidence, as a function of electron energy:



for an ideal sampling calorimeter (no dead material) one would expect this to scale as 1/sqrt(E)

Resolution at E = 45 GeV, as a function of the angle of incidence (eta):

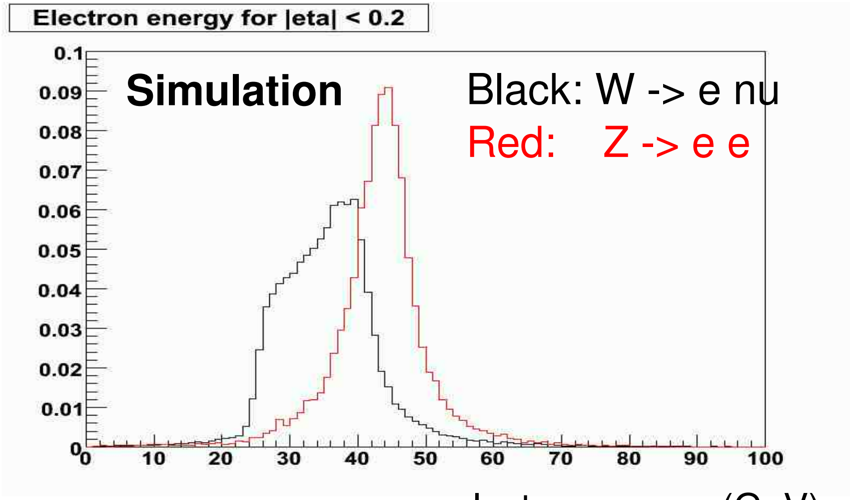


for an ideal sampling calorimeter (no dead material) one would expect this to be almost flat

How to split our (already small) $Z \rightarrow e\,e$ sample ??

So we need to understand both average response and the resolution as a function of both energy and angle of incidence.

$Z \rightarrow e\,e$ data gives us access to a line in energy/angle space. Consider CC/CC events. At a given angle, the distribution of energies provided by Nature is rather narrow.



electron energy (GeV)

How to proceed:

=> Bin electrons in angle (5 bins).

=> Two electrons per Z.

=> 15 distinct combinations of bins - "categories" (no E ordering).

bin 0 : $0 \le |\eta| < 0.2$
bin 1 : $0.2 \le |\eta| < 0.4$
bin 2 : $0.4 \le |\eta| < 0.6$
bin 3 : $0.6 \le |\eta| < 0.8$
bin 4 : $0.8 \le |\eta|$

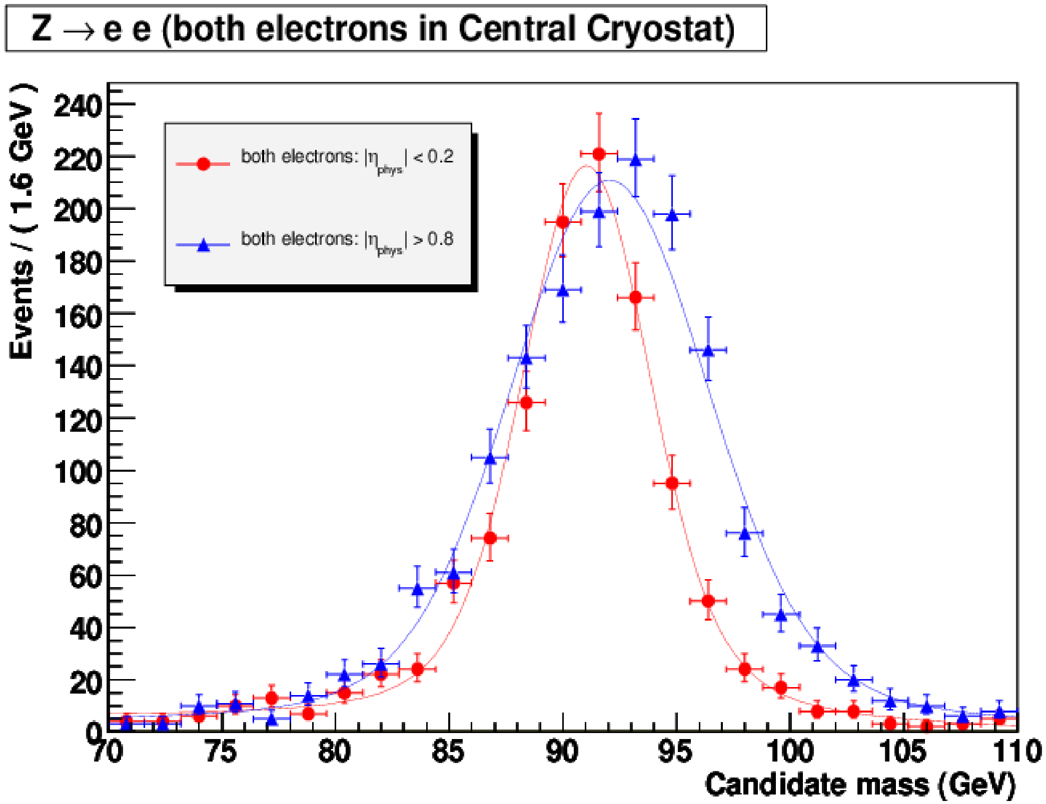
Category	Bins of Each Electron
10	0 – 0
11	0 – 1
12	0 – 2
13	0 – 3
14	0 – 4
15	1 – 1
16	1 – 2
17	1 – 3
18	1 – 4
19	2 – 2
20	2 – 3
21	2 – 4
22	3 – 3
23	3 – 4
24	4 – 4

Split CC/CC $Z \rightarrow e\,e$ sample into the 15 categories and study measured Z mass and mass resolution per category.

Once the information from Z has been harvested, we still need to propagate that down to the lower energies of the W. Need to understand scaling laws.

Simple plots (after splitting)

Let's start with a few simple plots that are based on the idea of splitting the sample according to eta of the two electrons. Here are the Z mass peaks (early version of data reconstruction) for "both electrons very central" and "both electrons very forward", i.e. "both electrons at close to normal incidence" and "both electrons at highly non-normal incidence"



We note:

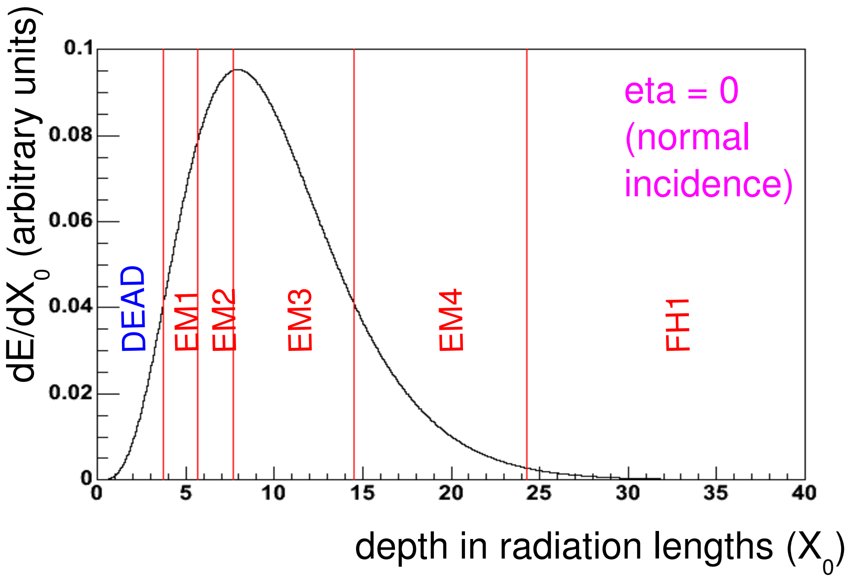
- different resolutions (material !),
- the peaks are not in the same place.

Why aren't the peaks in the same place ? Could be a problem in the MC-based E-loss corrections. But could also be a problem with gain calibrations in different regions of the CAL. This plot alone is not going to tell us, we need more information, new observables.

Need more information: additional observables

Let's go back to one of the plots that we have discussed on an earlier slide.
It clearly suggests that we should try to **exploit the longitudinal segmentation of the EM CAL** to get a handle on dead material:

Imagine we vary the size of the "DEAD" region a little bit
=> the individual layers (EM1 etc) would sample different parts of the shower and therefore see different fractions of the shower energy !!

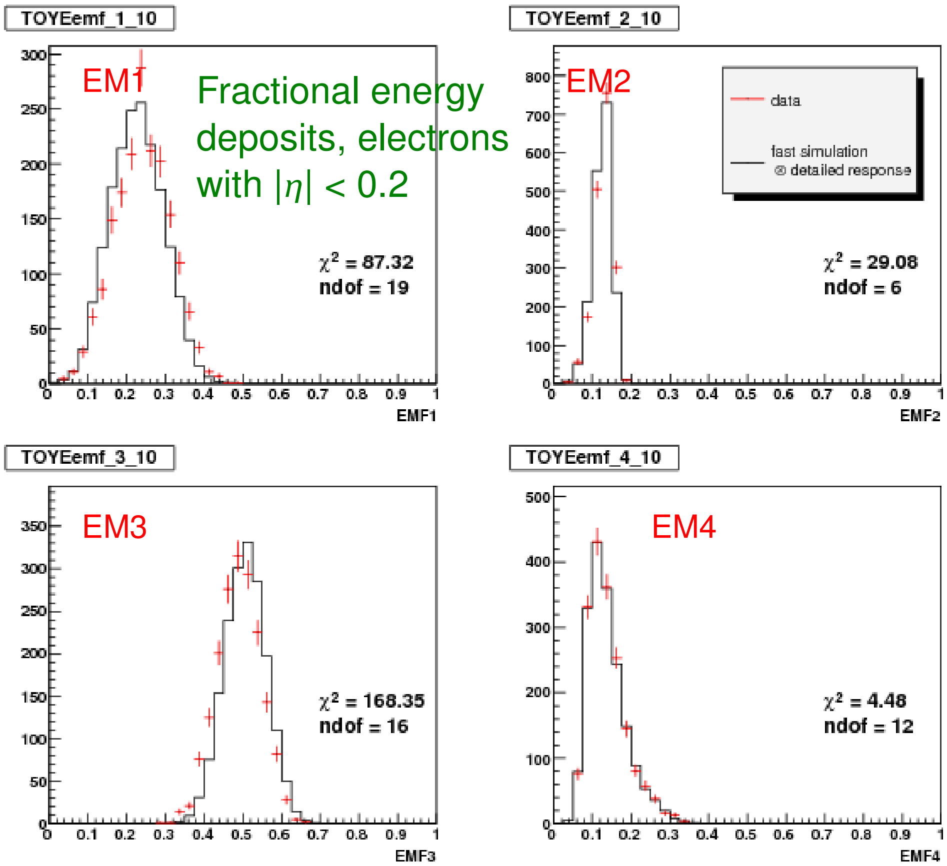


Using the longitudinal segmentation to get a handle on material is a standard technique, it is discussed in the textbooks (e.g. Wigmans).

Back to Dzero. Let's compare data (old reconstruction) and full Monte Carlo (nominal geometry) in terms of the four fractional EM energy deposits. We do this separately in each of the 15 eta categories.

Before tuning of material model

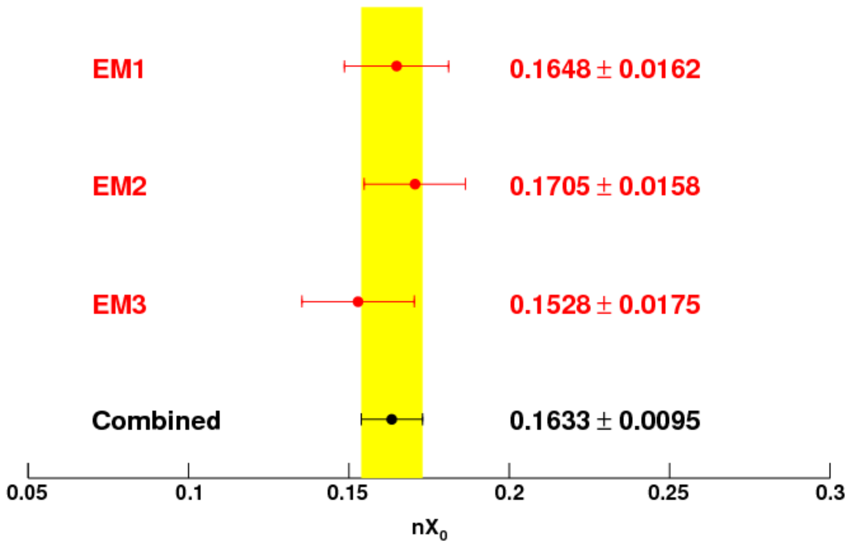
Before tuning of material model:
distributions of fractional energy deposits
do not quite match between data and the simulation.

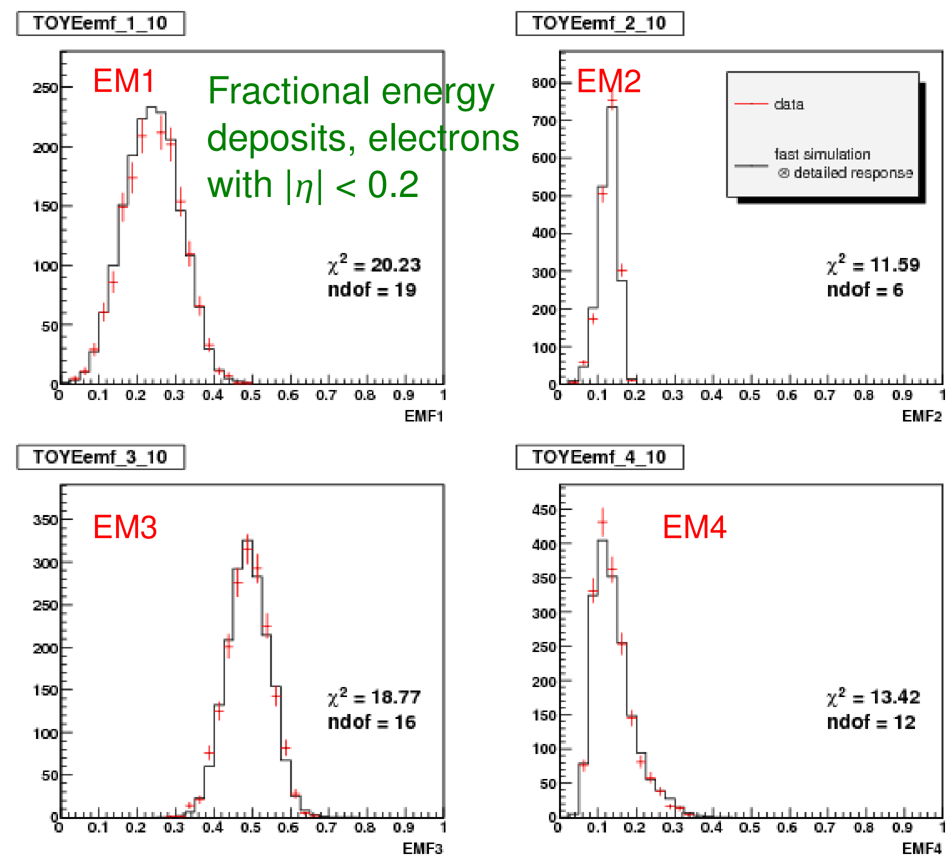


After tuning of material model

"Turn the plots from the previous slide into a fit for the amount of missing material".

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

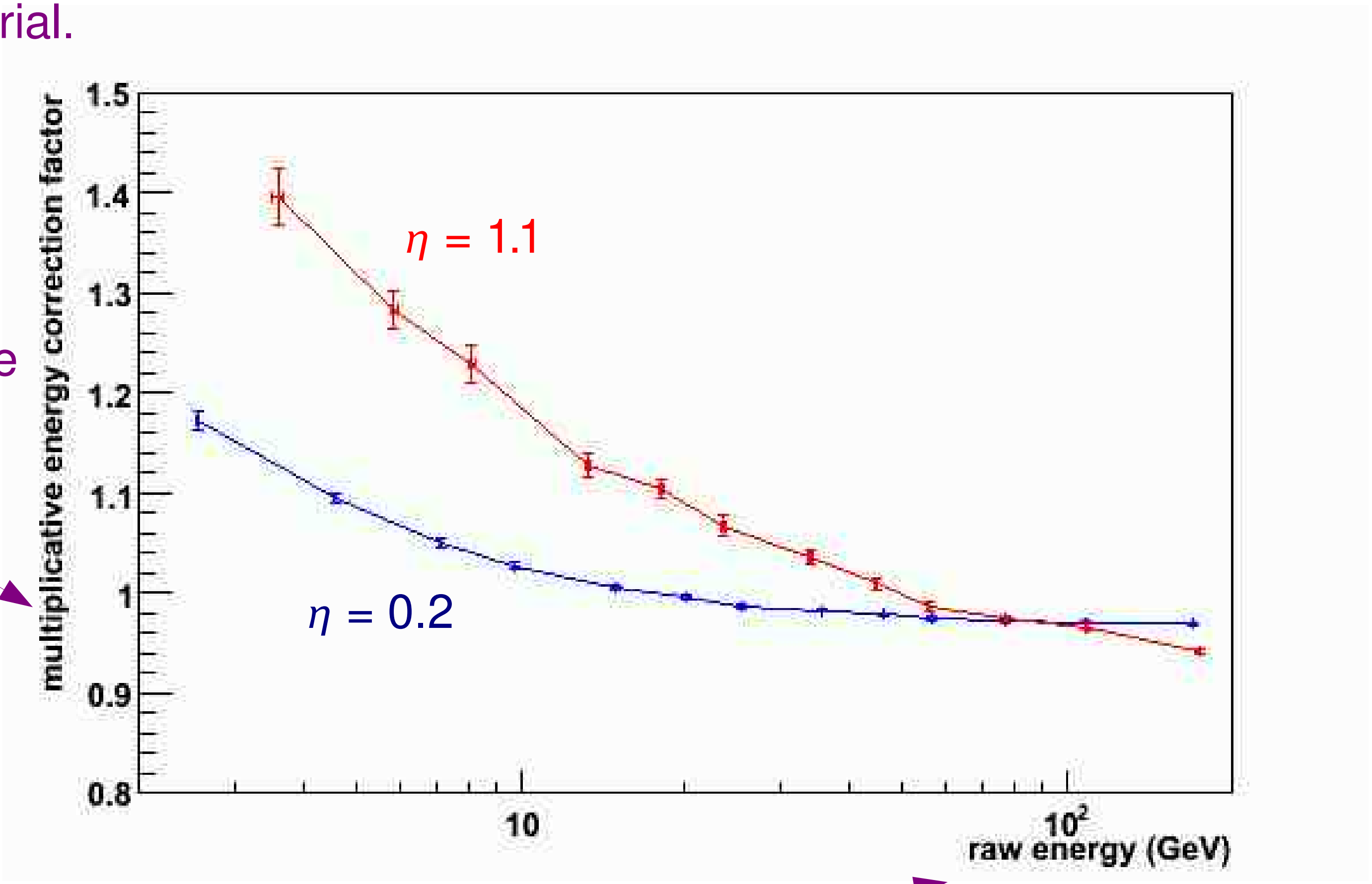




Correction to the raw energy

An energy-loss correction is applied to our reconstructed electron energies to account for the energy lost in front of the calorimeter. This correction, as a function of energy and angle (η) is estimated using detailed detector simulations based on Geant including the fitted amount of missing material.

This is the energy correction factor that gets us back to the energy of the incident electron.



This is the energy as reconstructed in the CAL.

This energy correction is applied on the data and not parameterised in our fast MC.

Electrons: energy scale

After having corrected for the effects of the uninstrumented material:
final energy response calibration, using $Z \rightarrow e\, e$, the known Z mass value from LEP, and the standard "f_z method":

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

Use energy spread of electrons in Z decay to constrain α and β .

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*.

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

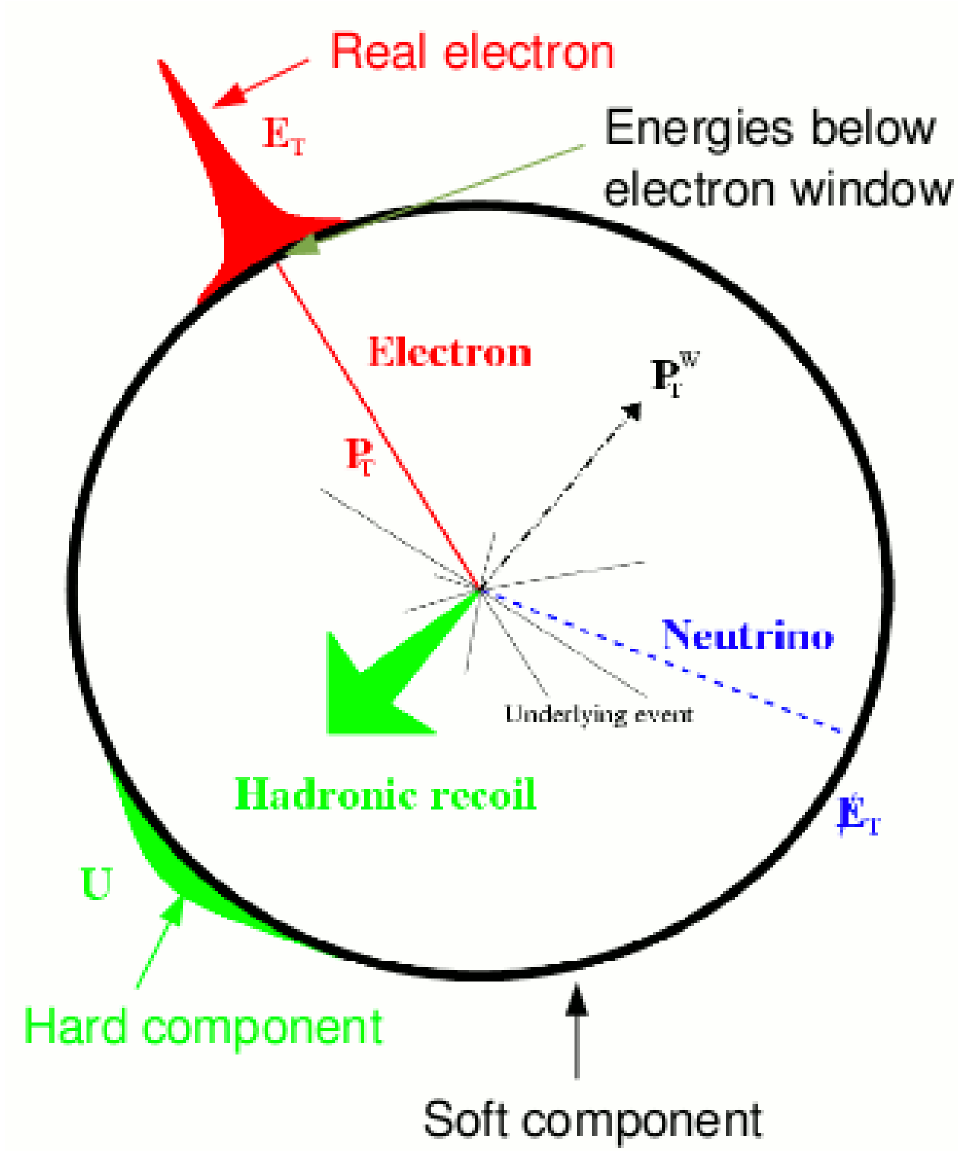
γ_{ee} is the opening angle between the two electrons

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

This corresponds to the dominant systematic uncertainty (by far) in the W mass measurement (but this is really just Z statistics ... more data will reduce it) :

Δ m(W) = 34 MeV, 100 % correlated between all three observables

Switching gears: recoil model



Recoil model

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

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

Hard component that balances the vector boson in transverse plane.
Ansatz from full Z → ν ν MC; plus free parameters for fine tuning,
e.g. multiplicative scale adjustment as function of q_T:

$$\mathtt{RelResp} = \mathtt{RelScale} + \mathtt{RelOffset} \cdot \exp \frac{-q_T}{\tau_{\mathtt{HAD}}}$$

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

Soft component,
not correlated with vector boson.

Two sub-components; - additional ppbar interactions and detector noise: from ZB events, plus parameter for fine tuning
- spectator partons: from MB events, plus parameter for fine tuning

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

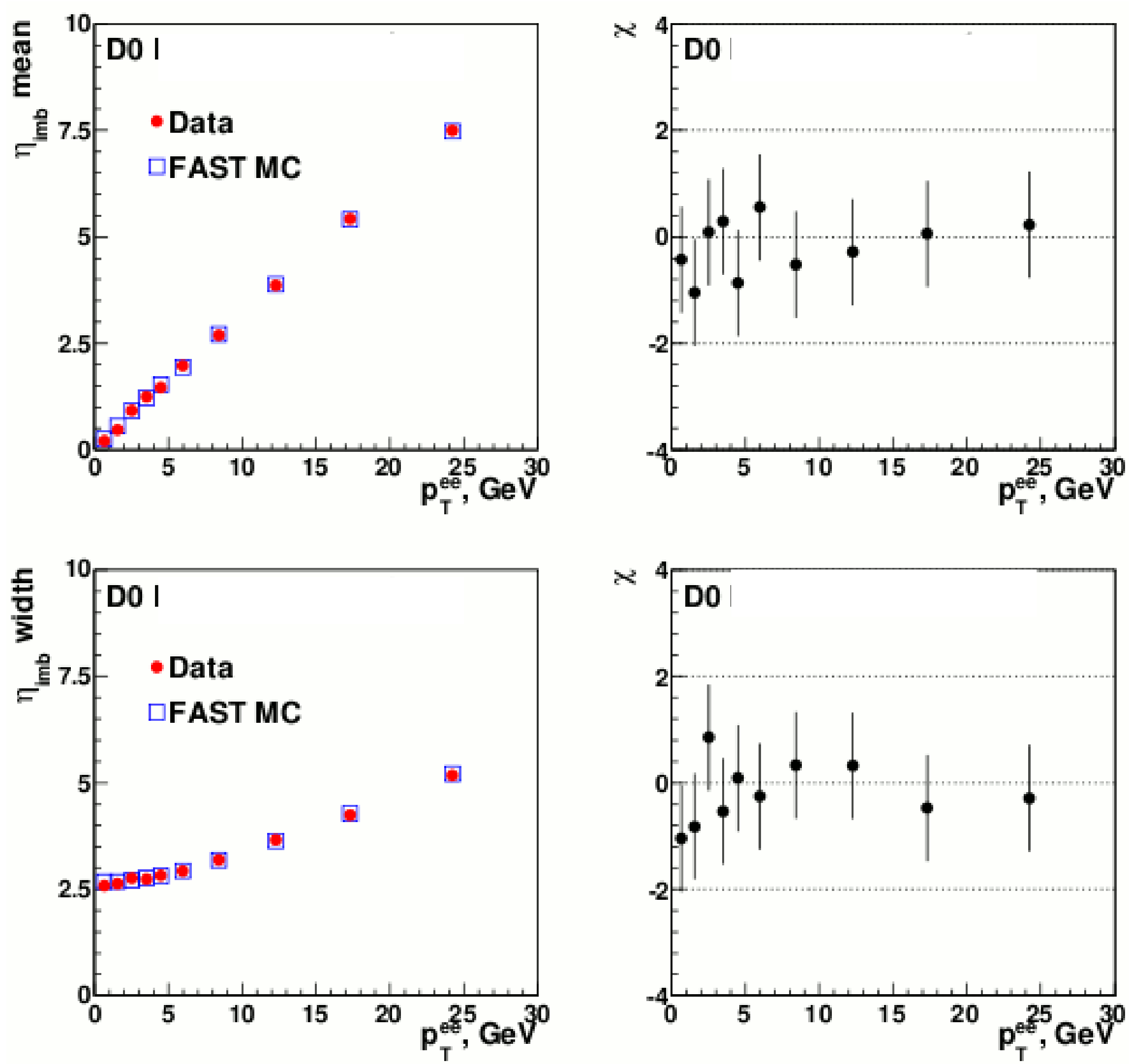
Recoil energy “lost” into the **electron cones**.
Electron energy leakage outside cluster.

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

FSR photons (internal bremsstrahlung) outside cone;
includes detailed response model.

Recoil calibration

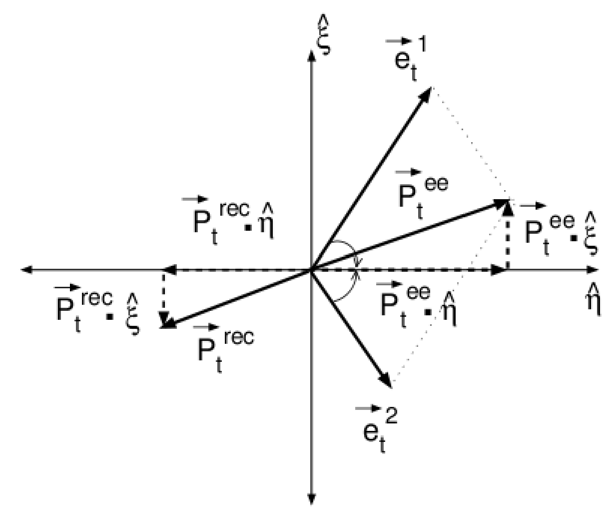
Final adjustment of free parameters in the recoil model is done *in situ* using balancing in Z → e e events and the standard UA2 observables.



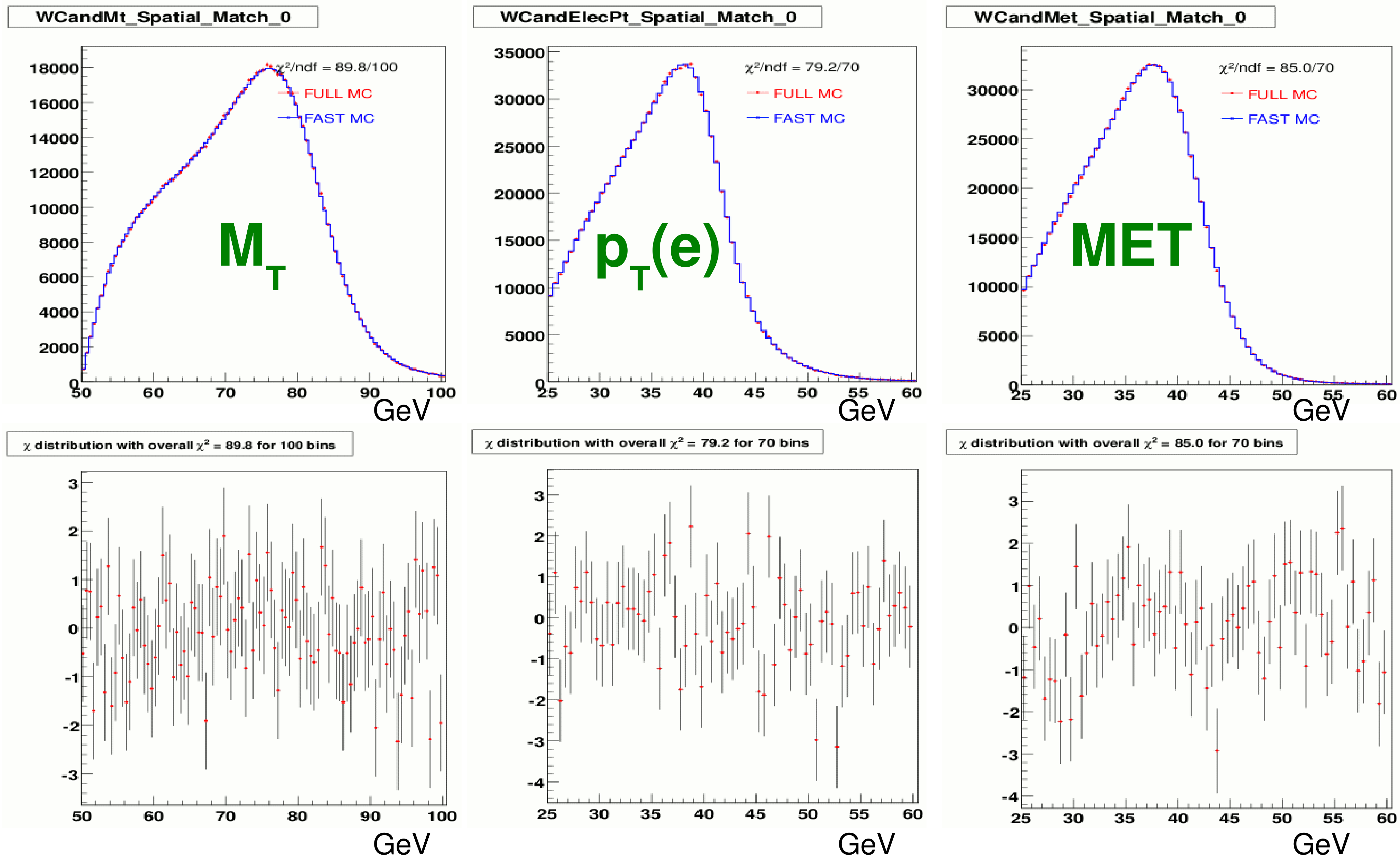
UA2 observables:
In transverse plane, use a coordinate system defined by the bisector of the two electron momenta.

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

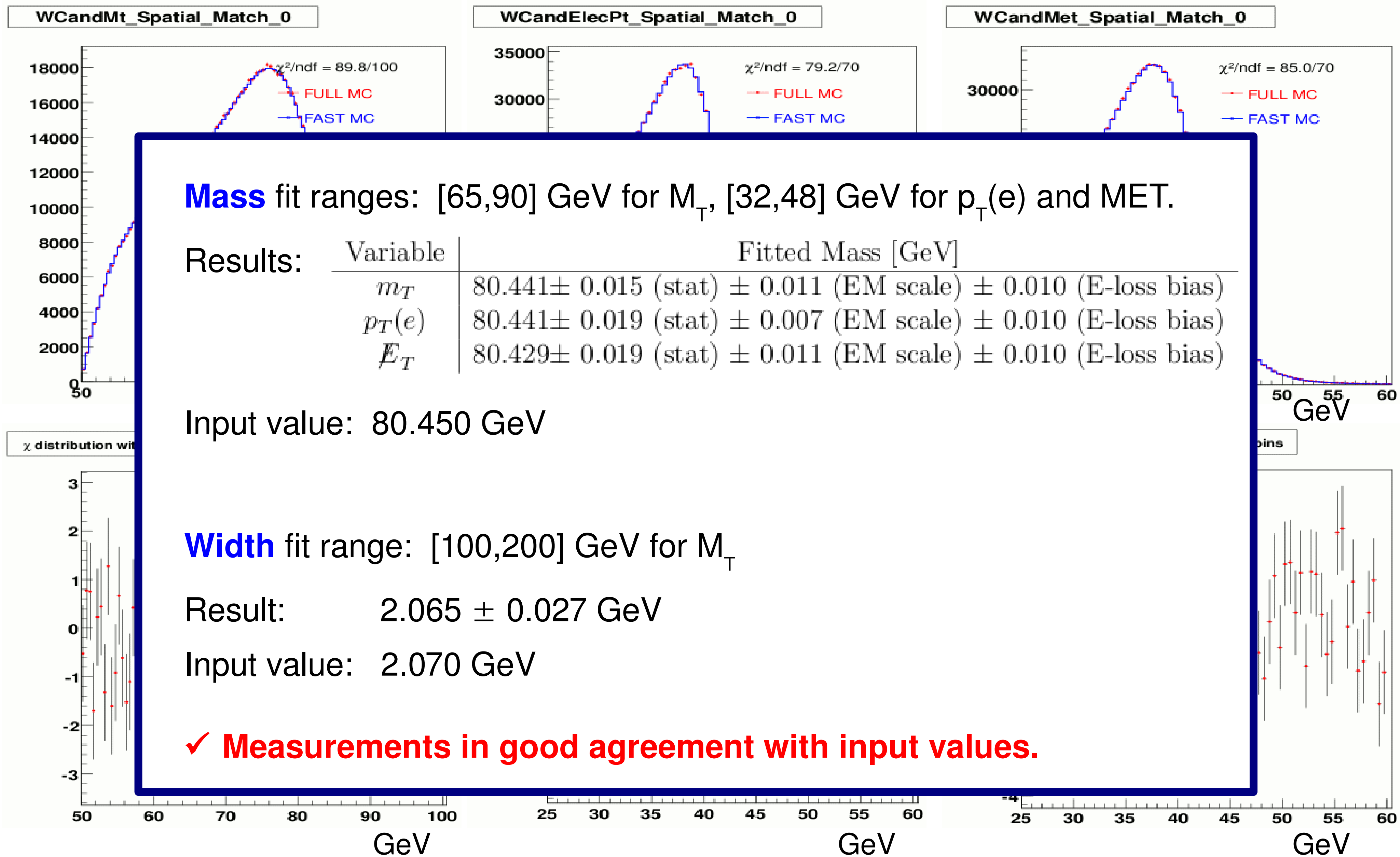
ξ-imbalance : $(\vec{P}_t^{ee} + \vec{P}_t^{rec}) \cdot \hat{\xi}$



MC closure test: $W \to e\,\nu$



MC closure test: W $\rightarrow$ e ν



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

Results:

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

Input value: 80.450 GeV

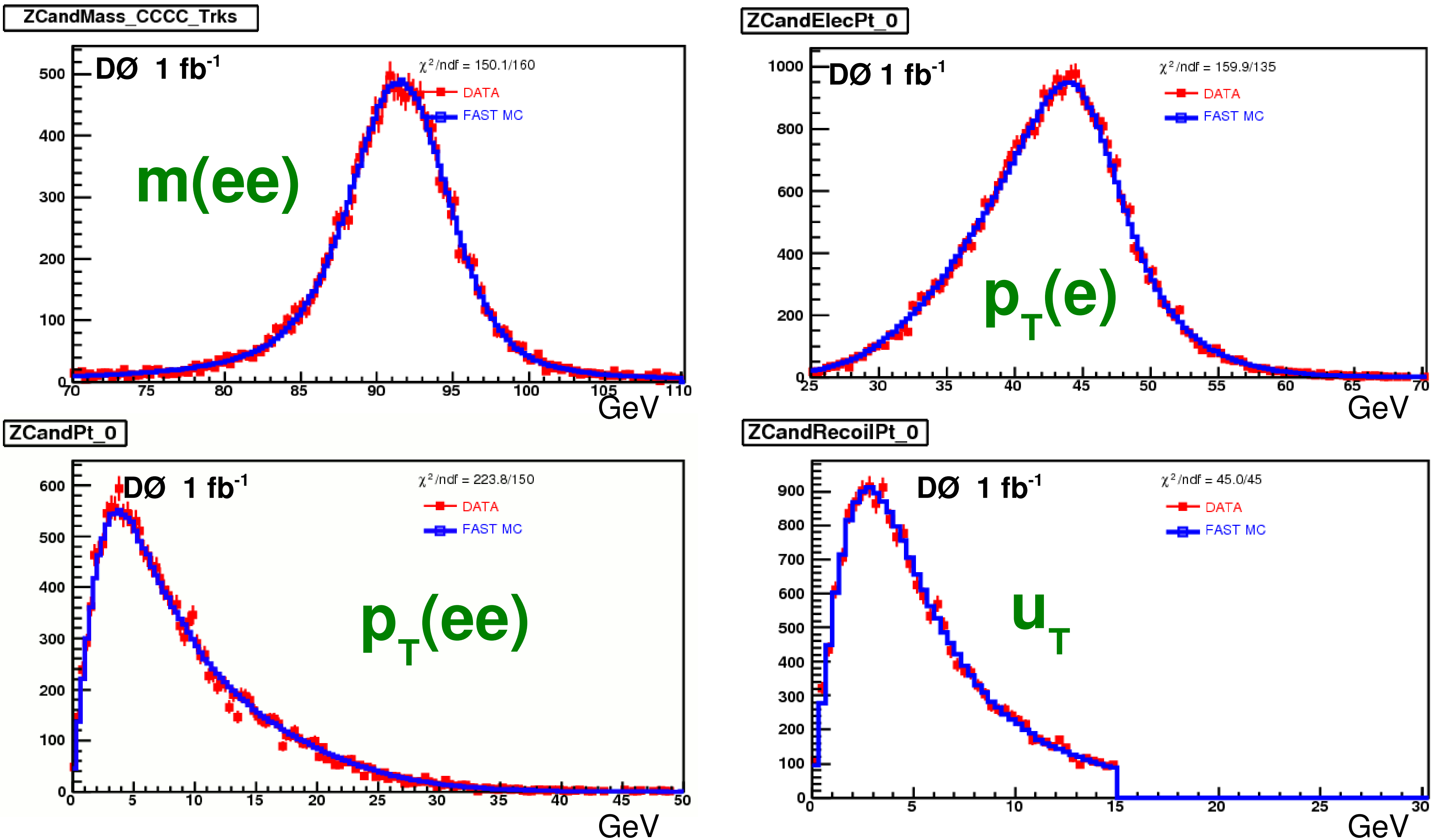
Width fit range: [100,200] GeV for M_T

Result: 2.065 ± 0.027 GeV

Input value: 2.070 GeV

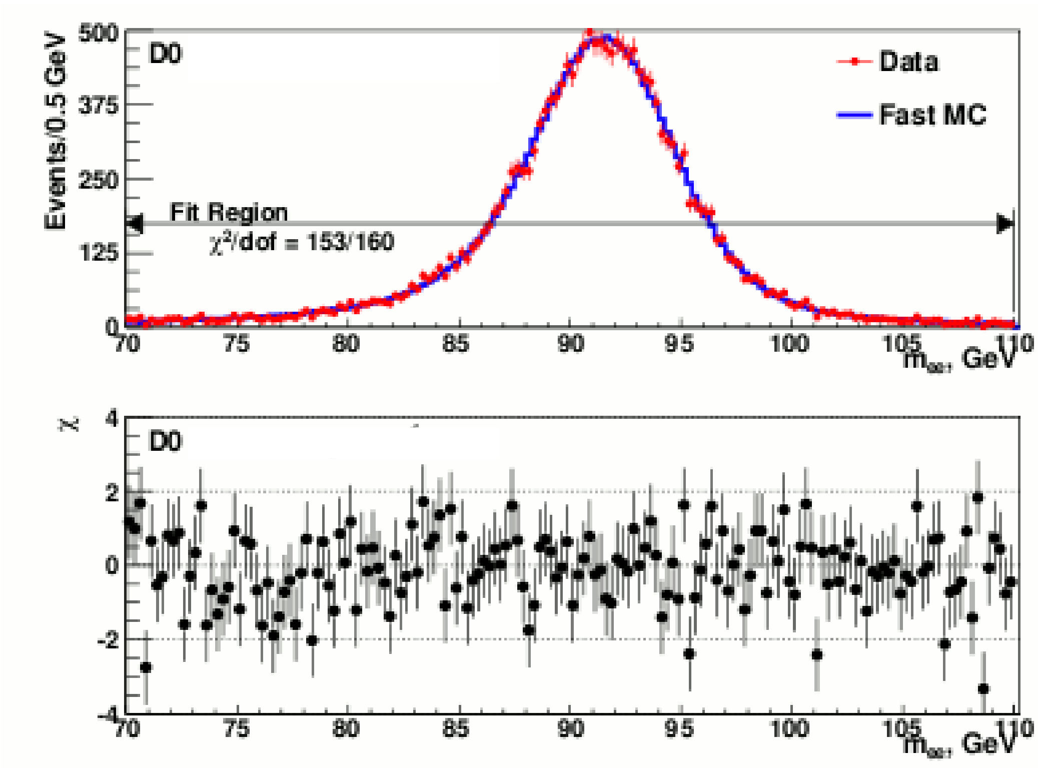
✓ **Measurements in good agreement with input values.**

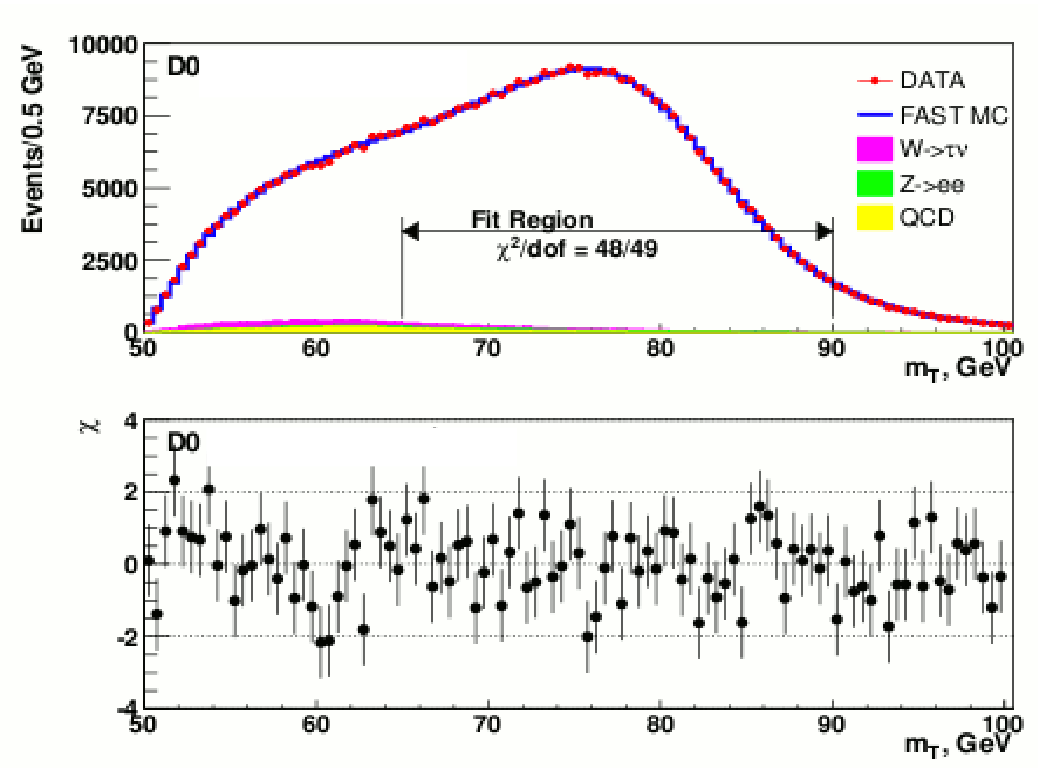
Results: $Z \to e\ e$ data



✓ **Good agreement between parameterised MC and collider data.**

Mass fits





m(Z) = 91.185 ± 0.033 GeV (stat)

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

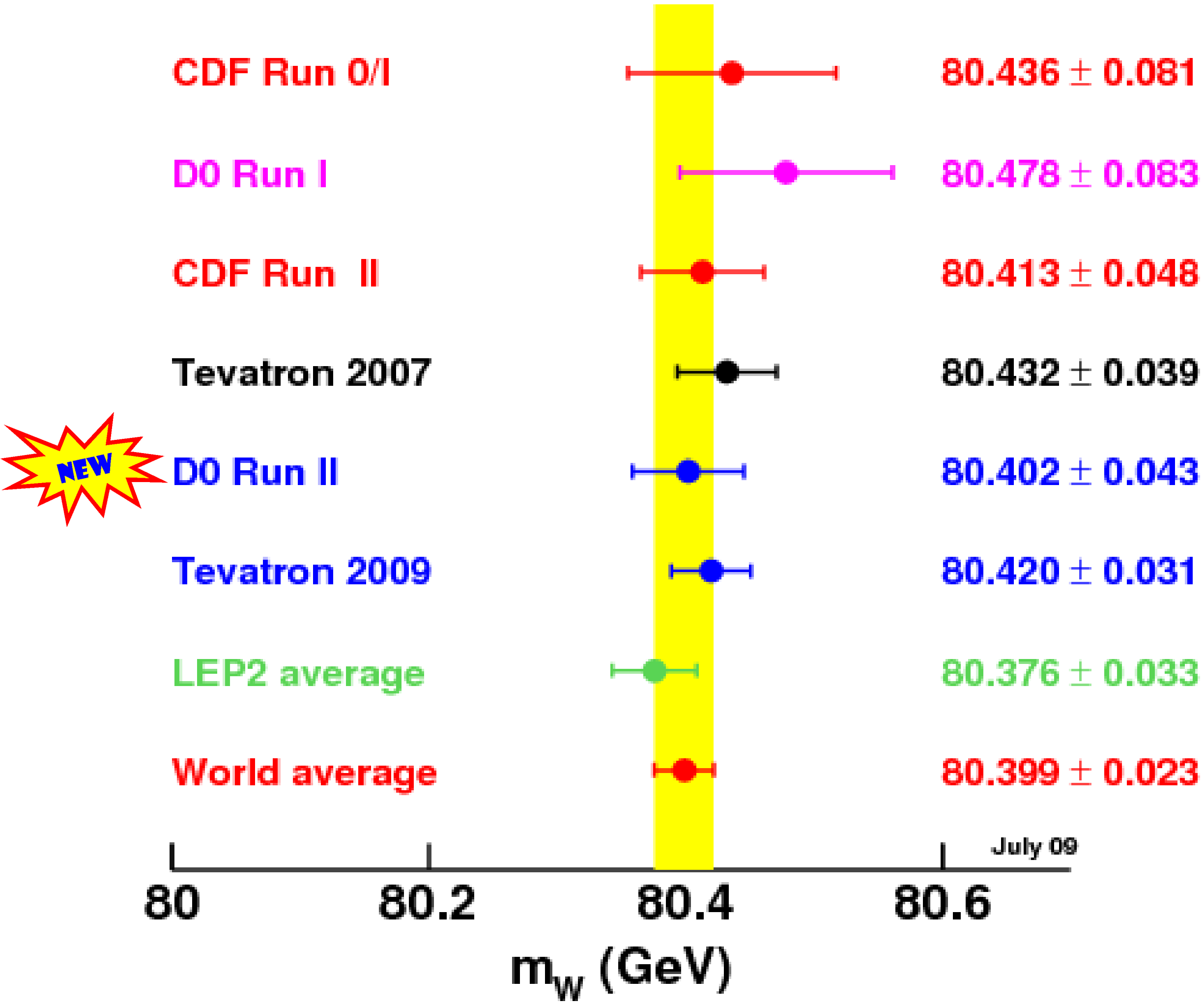
m(W) = 80.401 ± 0.023 GeV (stat)

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	34	34	34
Electron Energy Resolution Model	2	2	3
Electron Energy Nonlinearity	4	6	7
W and Z Electron energy loss differences (material)	4	4	4
Recoil Model	6	12	20
Electron Efficiencies	5	6	5
Backgrounds	2	5	4
Experimental Total	35	37	41
W production and decay model			
PDF	9	11	14
QED	7	7	9
Boson p_T	2	5	2
W model Total	12	14	17
Total	37	40	44
statistical	23	27	23
total	44	48	50

Comparison to previous results



The new result from DØ is the single most precise measurement of the W boson mass to date.

The new result is in good agreement with previous measurements.

W mass: projections

With 1 fb^{-1} uncertainties are mainly statistical (including 'systematics' from limited data control samples). Let's extrapolate:

source of uncertainties	1 fb-1	6 fb-1	10 fb-1
Statistics	23	10	8
Systematics			
Electron energy scale	34	14	11
Electron resolution	2	2	2
Electron energy offset	4	3	2
Electron energy loss	4	3	2
Recoil model	6	3	2
Electron efficiencies	5	3	3
Backgrounds	2	2	2
Total Exp. systematics	35	16	13
Theory			
PDF	9	6	4
QED (ISR-FSR)	7	4	3
Boson Pt	2	2	2
Total Theory	12	8	5
Total syst+theory	37	18	14
(if theory unchanged)		20	17
Grand total	44	21	16 (20)

At end of Run II, expect total uncertainty on W mass of 16 MeV from DØ alone.

Expect similar performance from CDF, and combined error of 12 MeV.

This legacy measurement will be in the textbooks for decades to come.

Could be an important contribution to getting the standard model into trouble in the near future:

with δm_W = 15 MeV, δm_t = 1 GeV and m_W = 80.400 GeV :

$$m_H = 71^{+24}_{-19}\ \text{GeV} \quad < 117\ \text{GeV @ 95\% cl}$$

(P. Renton, ICHEP 2008)

W charge asymmetry

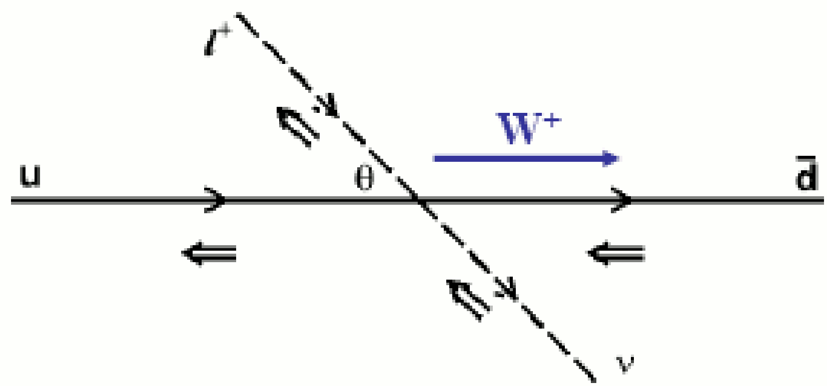
W$^{\pm}$ rapidity measurement constrains
PDF of u and d quarks.

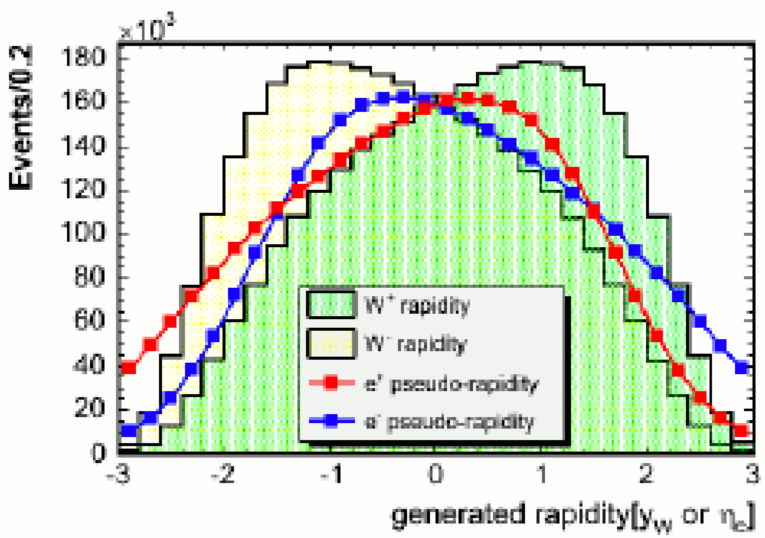
$$x_{1,2} = \frac{M_W}{\sqrt{s}} e^{\pm y}$$

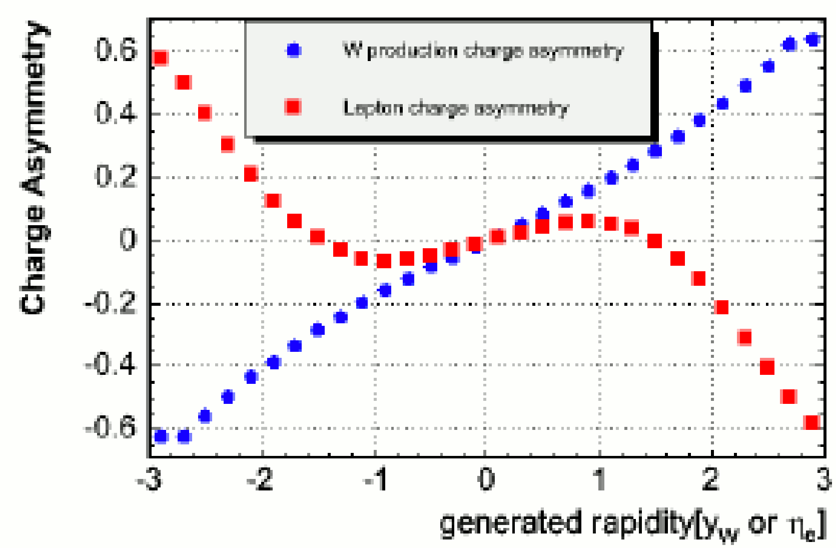
Different u, d momentum:
W$^{\pm}$ produced asymmetrically.

→ charge asymmetry of l, ν from W decay

But V-A interaction: **reduces** the observable **asymmetry** in the lepton rapidity distributions.

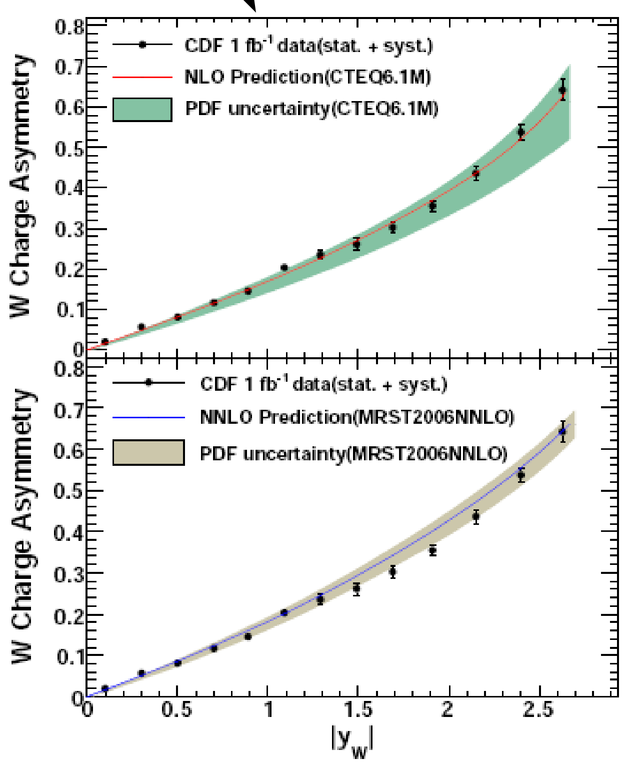


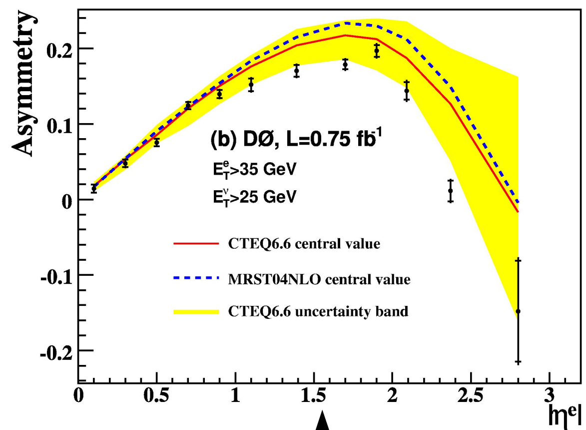


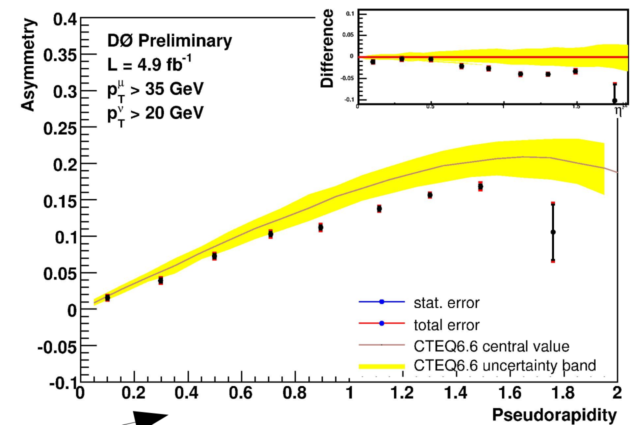


Ongoing work: inclusion in PDF sets

CTEQ6.1 and CTEQ6.6 are in excellent agreement with the CDF measurement of the **W boson** charge asymmetry ...

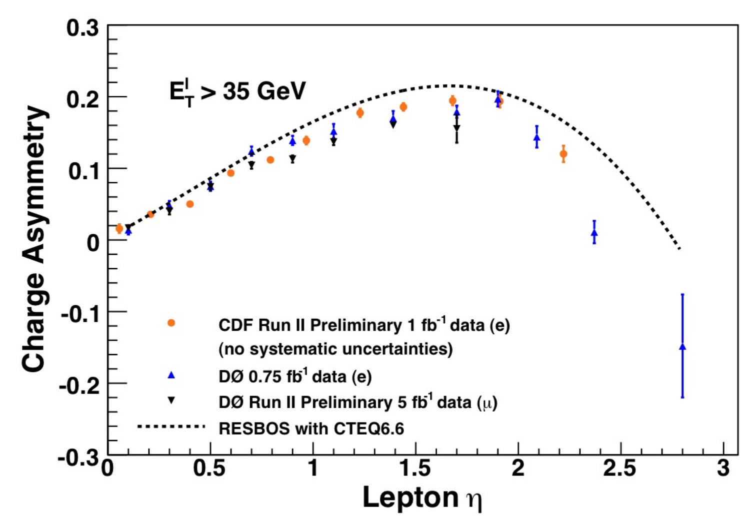






... they do not agree with the D0 **lepton** charge asymmetries (neither with the electrons nor with the muons) ...

... but when you plot the CDF data in terms of **lepton** charge asymmetry then they do not really disagree with the D0 data !



New experimental constraints on “$p_T(Z)$”

Measure $d\sigma/dp_T$ for inclusive Z boson production (455k $Z \to ee$/ 511k $Z \to \mu\mu$ decays) in 7.3 fb^{-1} of DØ data.

Investigate possibility of small-x broadening of Z p_T distribution at low p_T.

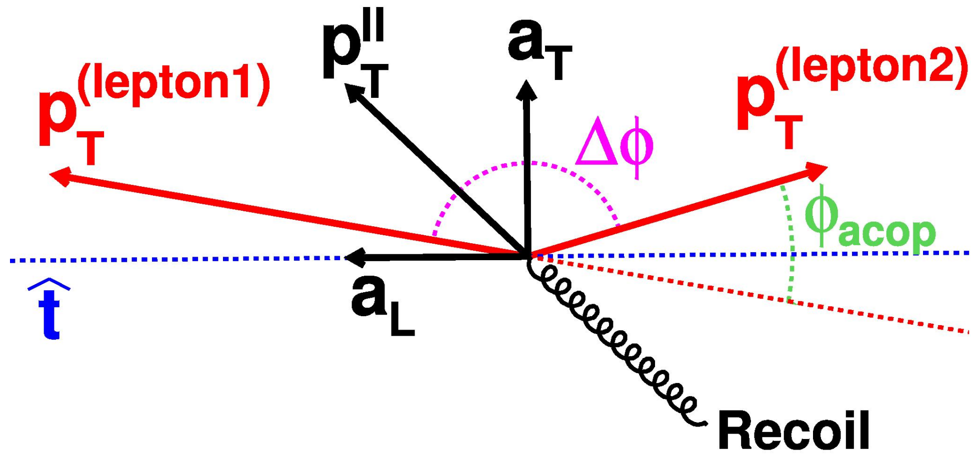
Minimise detector resolution effects: use novel technique requiring only measurements of lepton **directions**.

Define:

$\phi_{acop} = \pi - \Delta\phi_{ll}$

$\cos\theta^*_\eta = \tanh((\eta^- - \eta^+)/2))$

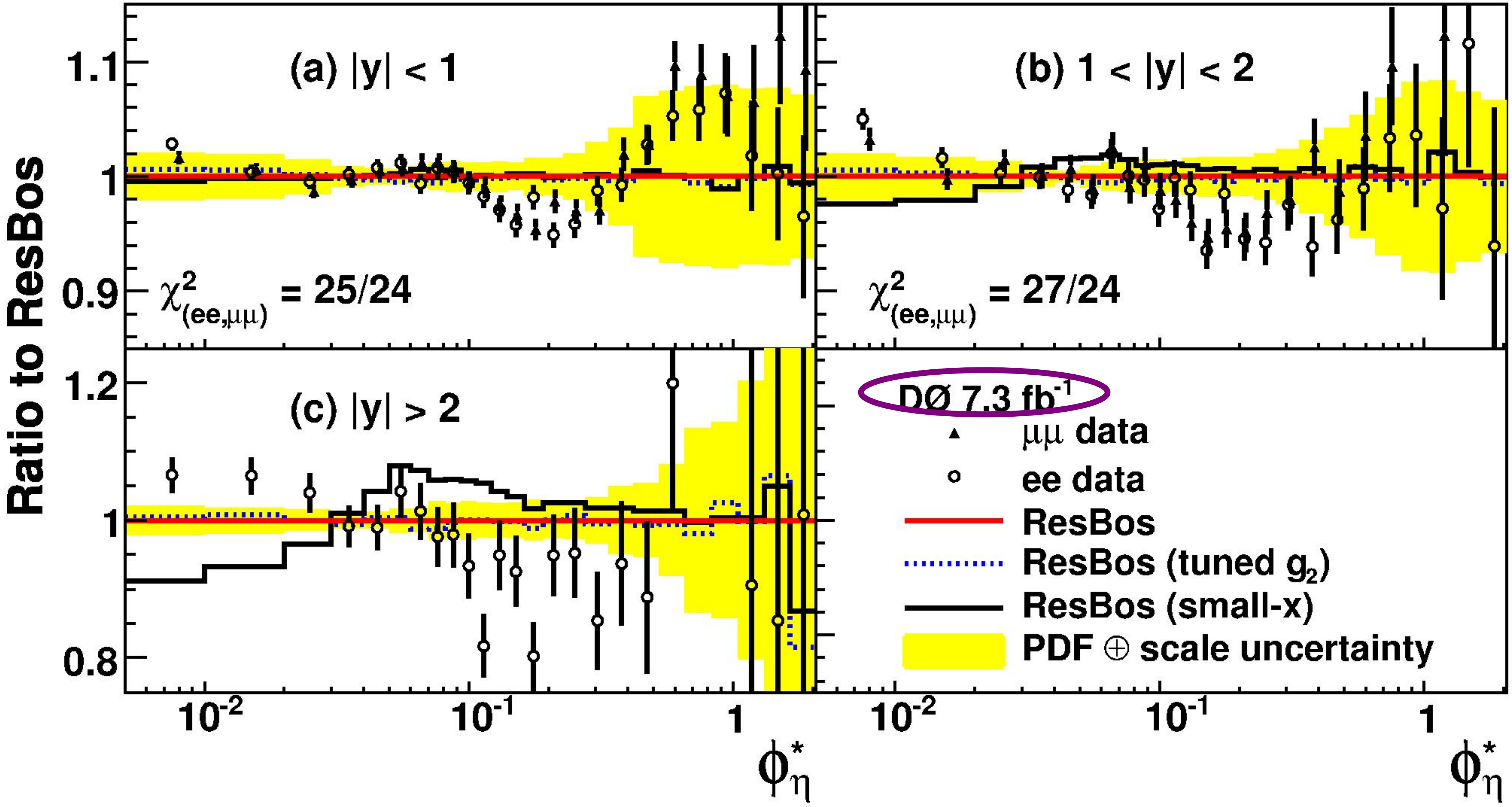
$\phi^*_\eta = \tan(\phi_{acop}/2)\sin(\theta^*_\eta)$



Perform measurement of $d\sigma/d\Phi^*_\eta$ in bins of Z boson rapidity y.

New experimental constraints on “$p_T(Z)$”

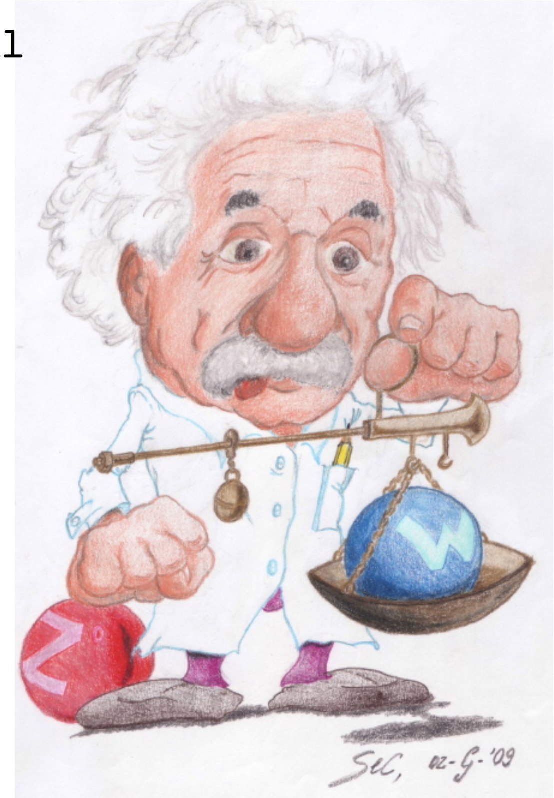
Comparison of the unfolded data to (three flavours of) ResBos:



Theory-experiment collaboration

Of course, this precision measurement requires an efficient collaboration between theorists and experimentalists. We are very active in this area, in the framework of the "Milano series of W mass workshops". More information from the WS website is pasted below.

URL: `http://wwwteor.mi.infn.it/~vicini/wmass.html`



W mass workshop

Department of Physics, University of Milano, March 17-18, 2009

W mass workshop

Second meeting, Fermilab, October 4-5 2010

Organizers:
John Campbell (Fermilab)
Ashutosh Kotwal (Duke)
Jan Stark (Grenoble)
Alessandro Vicini (Milano)
Doreen Wackeroth (SUNY at Buffalo)

In view of a 25 MeV measurement of the W mass, it becomes increasingly important to control the theoretical predictions and to fully understand the present theoretical uncertainties. A lot of progress has been made in both the QCD and the EW sector. However, the predictions including QCD and EW radiative corrections are not available in one event generator: therefore the need for developing recipes which allow to combine the different sets of radiative corrections. The uncertainties intrinsic for these recipes should be quantified in a systematic way.

Summary and outlook

We have presented the first Run II measurement of the W boson mass from the DØ Collaboration. It is based on central electrons in 1 fb^{-1} of data:

$$\begin{aligned} m_W &= 80.401 \pm 0.023(\mathrm{stat}) \pm 0.037(\mathrm{syst})\ \mathrm{GeV} = 80.401 \pm 0.044\ \ \mathrm{GeV}\ \ (\mathrm{m_T}) \\ &\ 80.400 \pm 0.027(\mathrm{stat}) \pm 0.040(\mathrm{syst})\ \mathrm{GeV} = 80.400 \pm 0.048\ \ \mathrm{GeV}\ \ (p_T^e), \\ &\ 80.402 \pm 0.023(\mathrm{stat}) \pm 0.044(\mathrm{syst})\ \mathrm{GeV} = 80.402 \pm 0.050\ \ \mathrm{GeV}\ \ (\not\!\!E_T). \end{aligned}$$

A combination of the results from the three observables gives:

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

This is the most precise single measurement of the W boson mass to date.

Tried to give a feeling for the methods that have been developed – calibrations, simulations, ...

Showed projected precision that we expect from the much larger datasets that we are currently analysing. Depending on the central value that we will obtain, the standard model could get into serious trouble in the next years.

Discussed some of the other measurements that we do in order to further constrain the details of the model of W/Z production and decay. They are interesting measurements in their own right, and they help reduce systematic uncertainties in W mass measurements.

This is an extremely exciting period at the Tevatron and at the LHC.

Backup slides

Comments on analysis strategy

Before analysing the collider data, we perform a **Monte Carlo closure test**. This means we treat simulated events from a detailed Pythia/Geant simulations as collider data and perform a full W mass/width analysis. Goal: develop and test analysis procedures and code with known input values. At each analysis step, check that predictions from parameterised MC match MC truth.

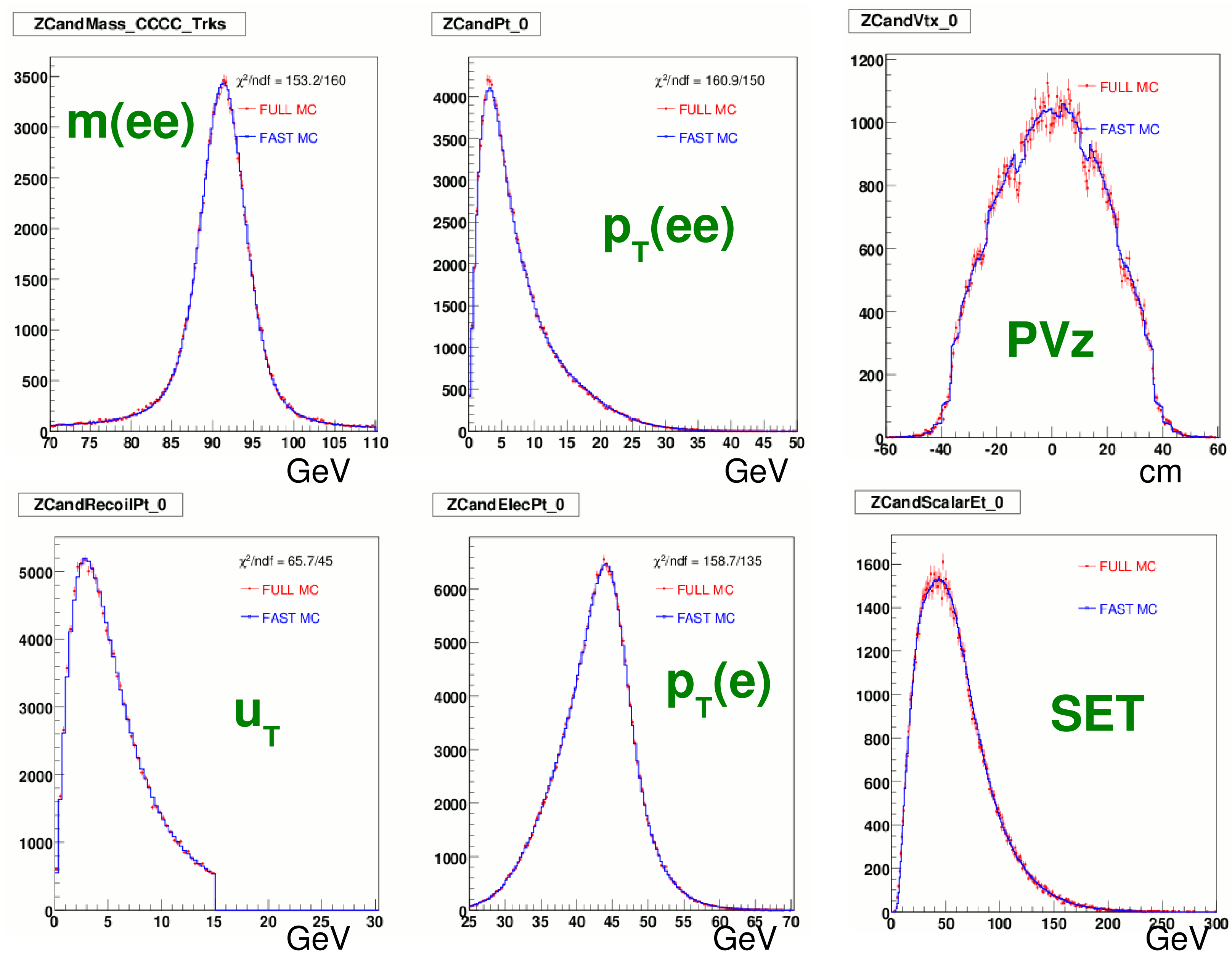
We perform our measurements as a **blind analysis**. This means that the central values (but not the uncertainties) are deliberately hidden from the analysers and reviewers until the analysis is considered complete. The blinding technique we used is a standard technique that is routinely used by other collaborations, *e.g.* BaBar:

> Simply change your mass fitting program in such a way that it reports the fitted mass, offset by some hidden offset.
> The offset is the same for all three observables (=> allow comparisons),
> no uncertainties, neither statistical nor systematic are ever obscured by the blinding.

"Unblinding" has been done only after collaboration approval.

MC closure test: $Z \to e\ e$

✓ Good agreement between full and parameterised MC.



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

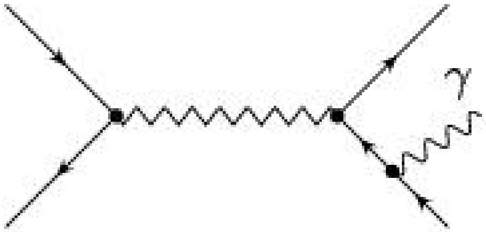
Our main generator is "**ResBos+Photos**". The NLO QCD in **ResBos** allows us to get a reasonable description of the p_T of the vector bosons. The two leading EWK effects are the first FSR photon and the second FSR photon. **Photos** gives us a reasonable model for both.

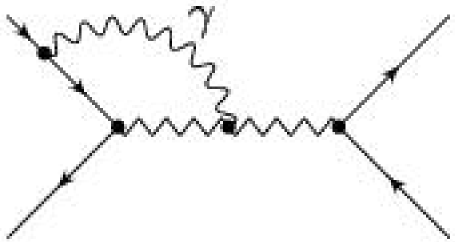
We use **W/ZGRAD** to get a feeling for the effect of the full EWK corrections.

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

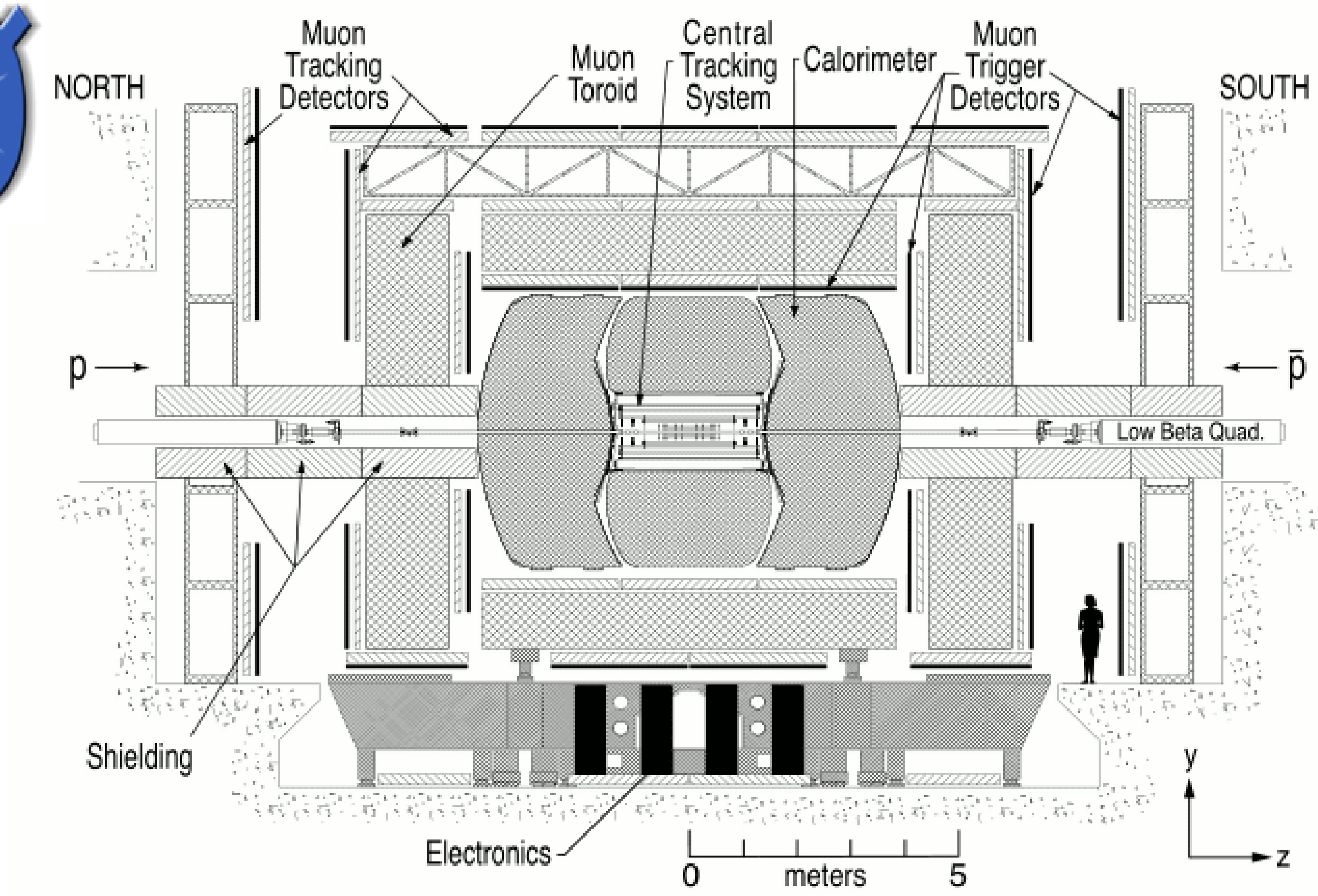
This is the sum of different effects; the two main ones are:

- 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).

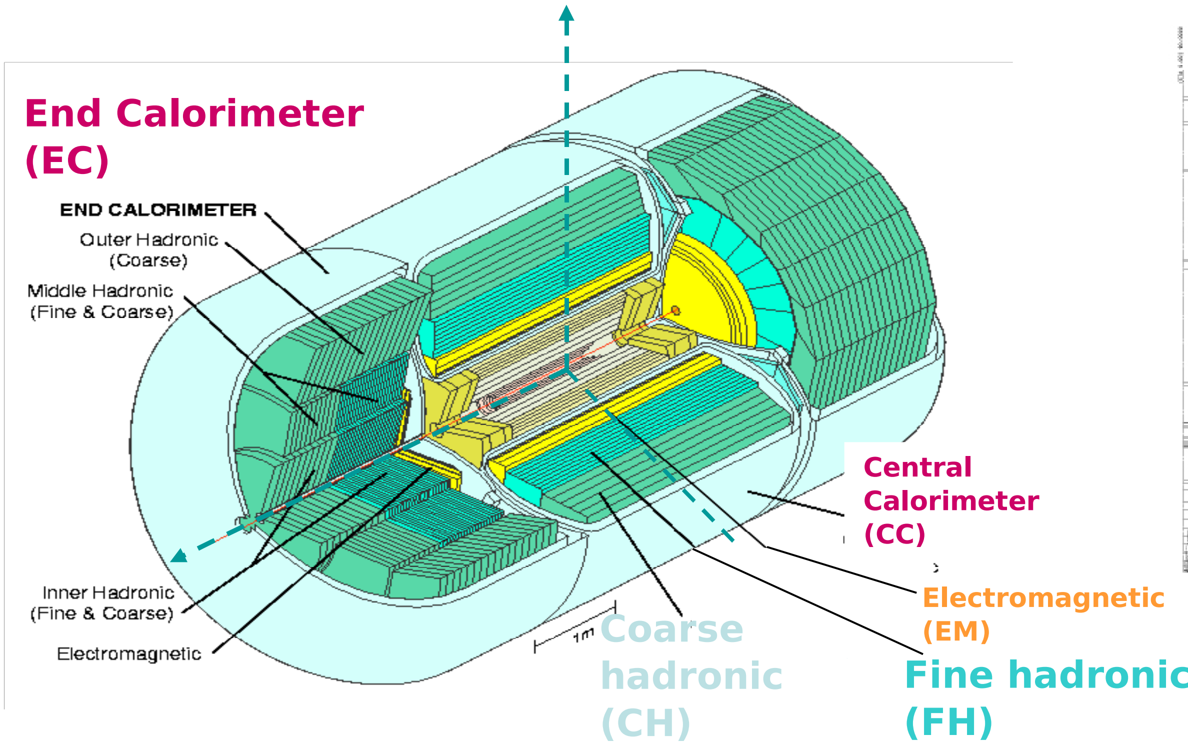


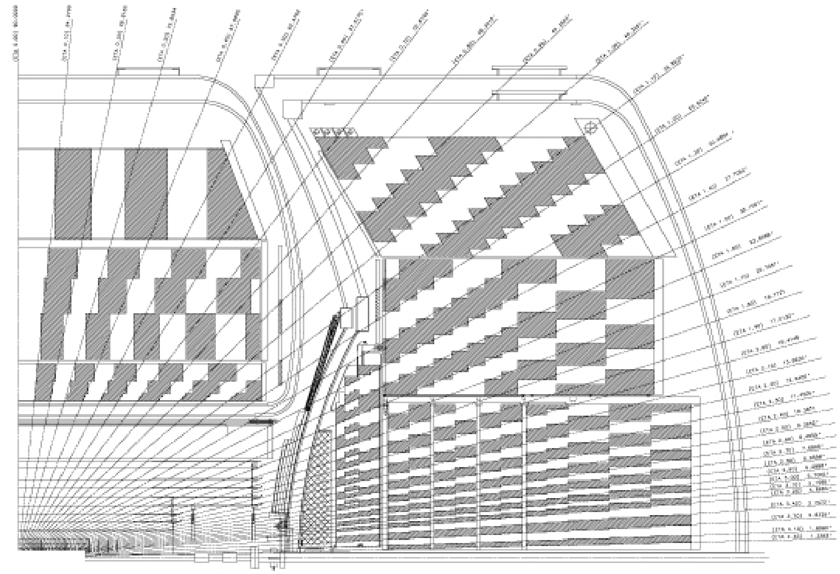


The upgraded Dzero detector



Overview of the calorimeter





46000 cells

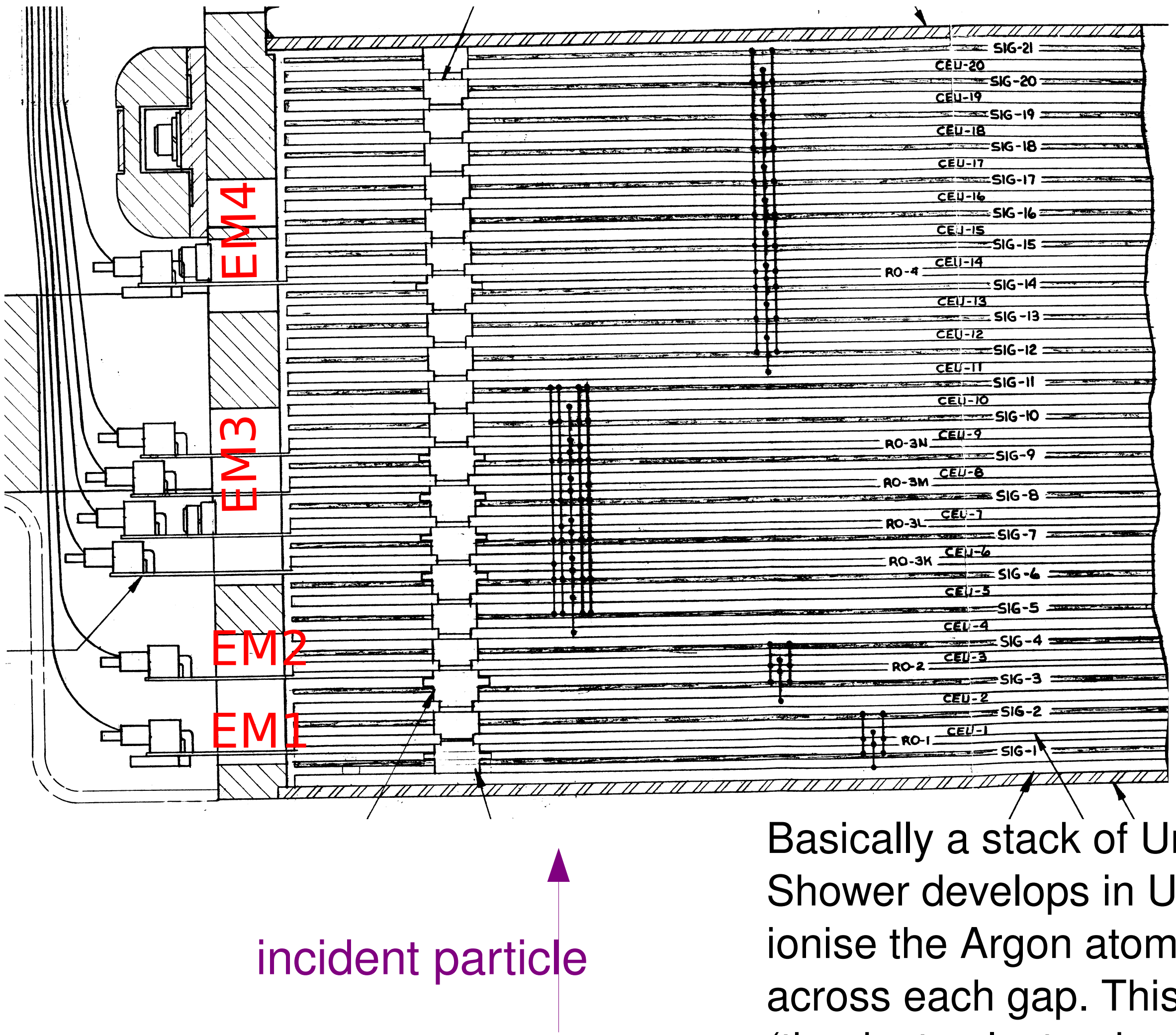
50 dead channels

- Liquid argon active medium and (mostly) uranium absorber
- Hermetic with full coverage :$|\eta| < 4.2$
- Segmentation (towers): $\Delta\eta \times \Delta\varphi = 0.1\text{x}0.1$

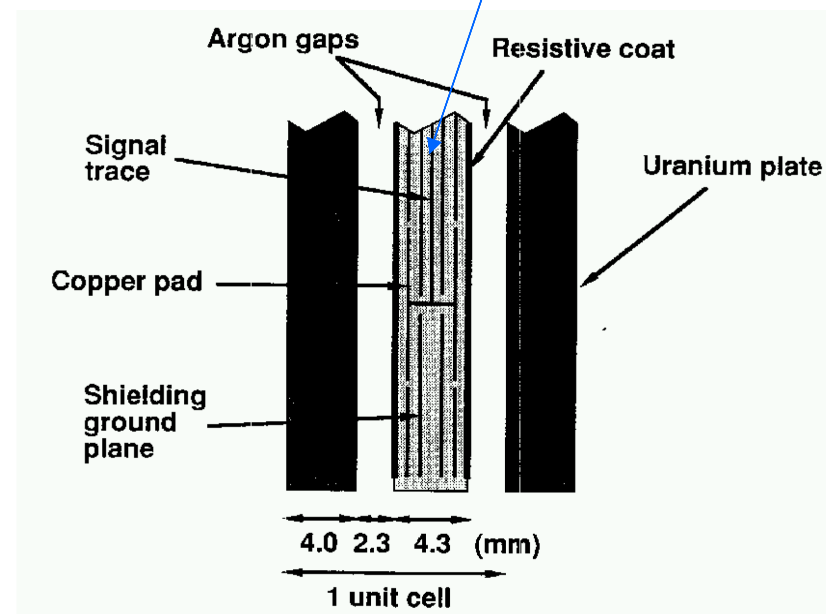
  (0.05x0.05 in third EM layer, near shower maximum)

This is a U/LAr sampling calorimeter

More detailled view of one CC-EM module :



One "*di-gap*" : *signal board*

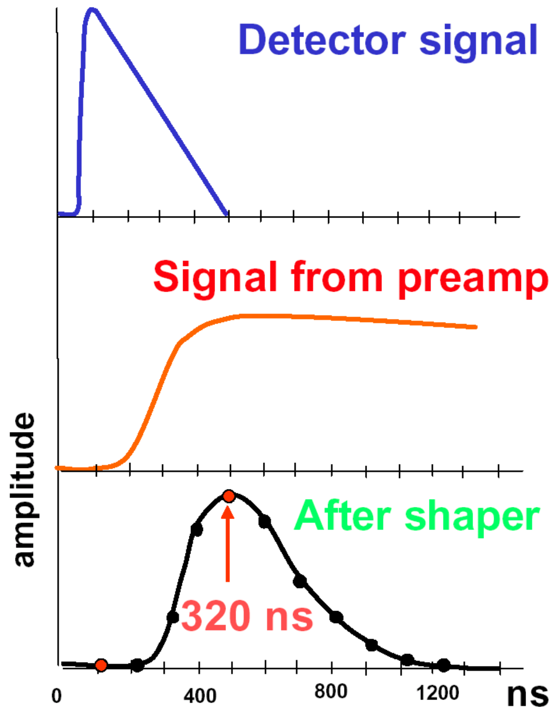


sampling fraction: 15 %

Basically a stack of Uranium plates with liquid Argon in between. Shower develops in U and LAr (mainly U); charged shower particles ionise the Argon atoms => current in Argon because of HV applied across each gap. This current is measurable (thanks to electronic charge amplifiers with very large gain).

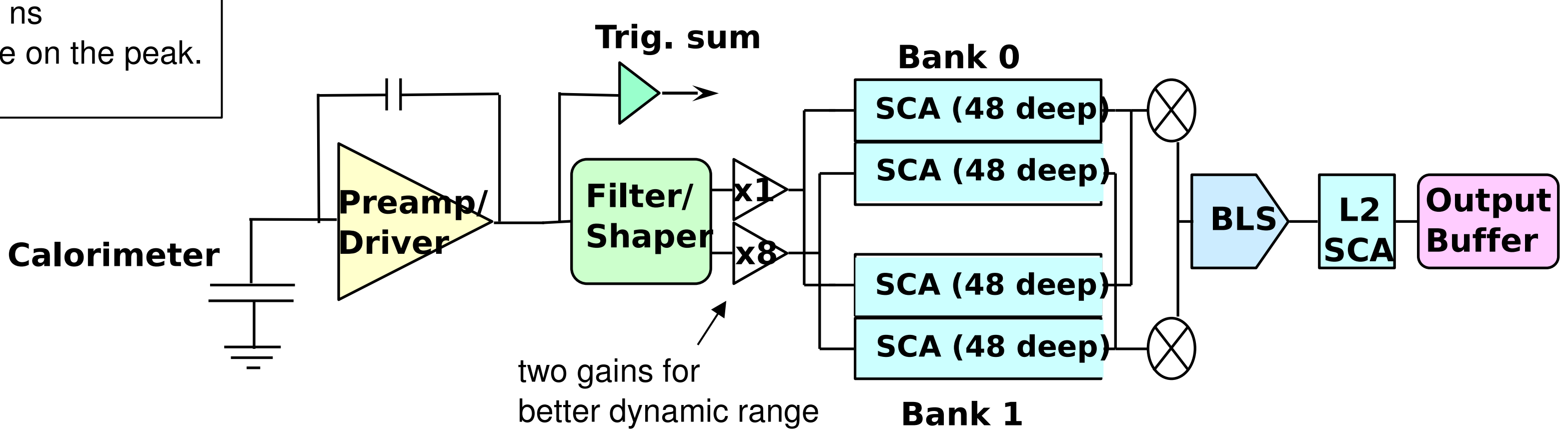
EM1, EM2, EM3 and EM4 are read out separately; each one of these layers regroups a number of digaps.

Basics of the readout



Have ability to sample and record the shaped signal also at (320 ± 120) ns to make sure we are on the peak.

- Detector signal ~ 450 ns long
  (bunch crossing time: 396 ns)
- Charge preamplifiers
- BLS (baseline subtraction) boards
  - short shaping of ~2/3 of integrated signal
  - signal sampled and stored every 132 ns in analog buffers (SCA) waiting for L1 trigger
  - samples retrieved on L1 accept, then baseline subtraction to remove pile-up and low frequency noise
  - signal retrieved after L2 accept
- Digitisation

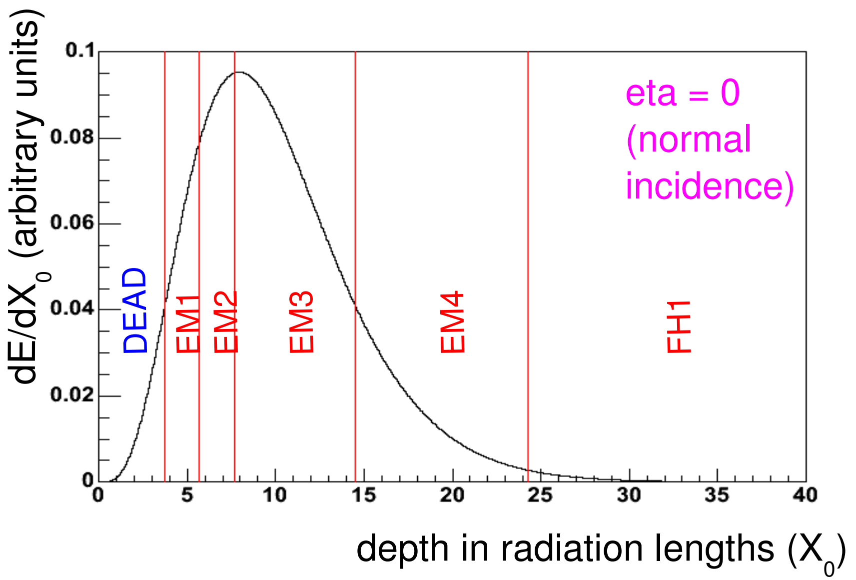


Samples and weights

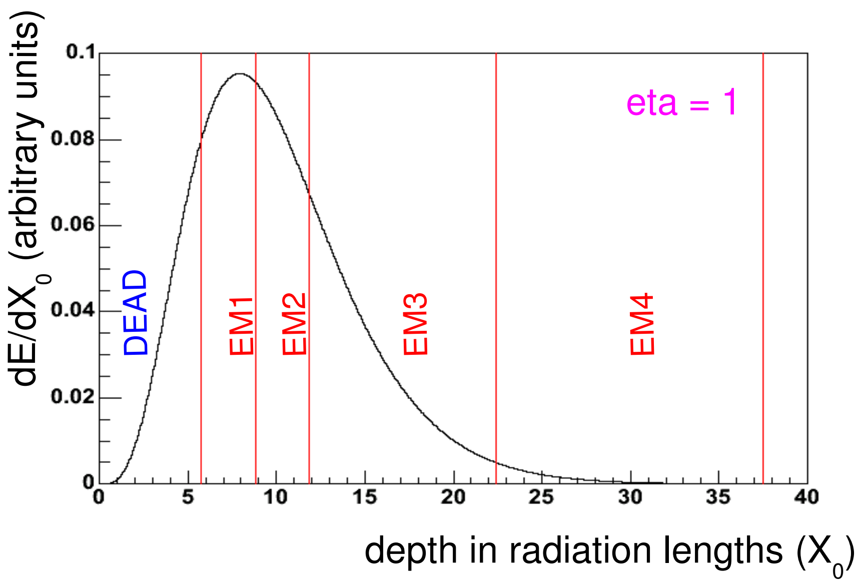
The plot on the right shows the average longitudinal profile of a shower with E = 45 GeV. Assuming normal incidence, the position of the active parts of the CC are also indicated.

In the reconstruction, we apply artificially high weights to the early layers (especially EM1) in an attempt to partially compensate the losses in the dead material:

Layer	depth (X_0)	weight (a.u.)	weight/X_0
EM1	2.0	31.199	15.6
EM2	2.0	9.399	4.7
EM3	6.8	25.716	3.8
EM4	9.1	28.033	3.1
FH1	$\approx$ 40	24.885	$\approx$ 0.6



The lower plot illustrates the situation for the same average shower, but this time under a more extreme angle of incidence (physics eta = 1). The shower maximum is now in EM1 !

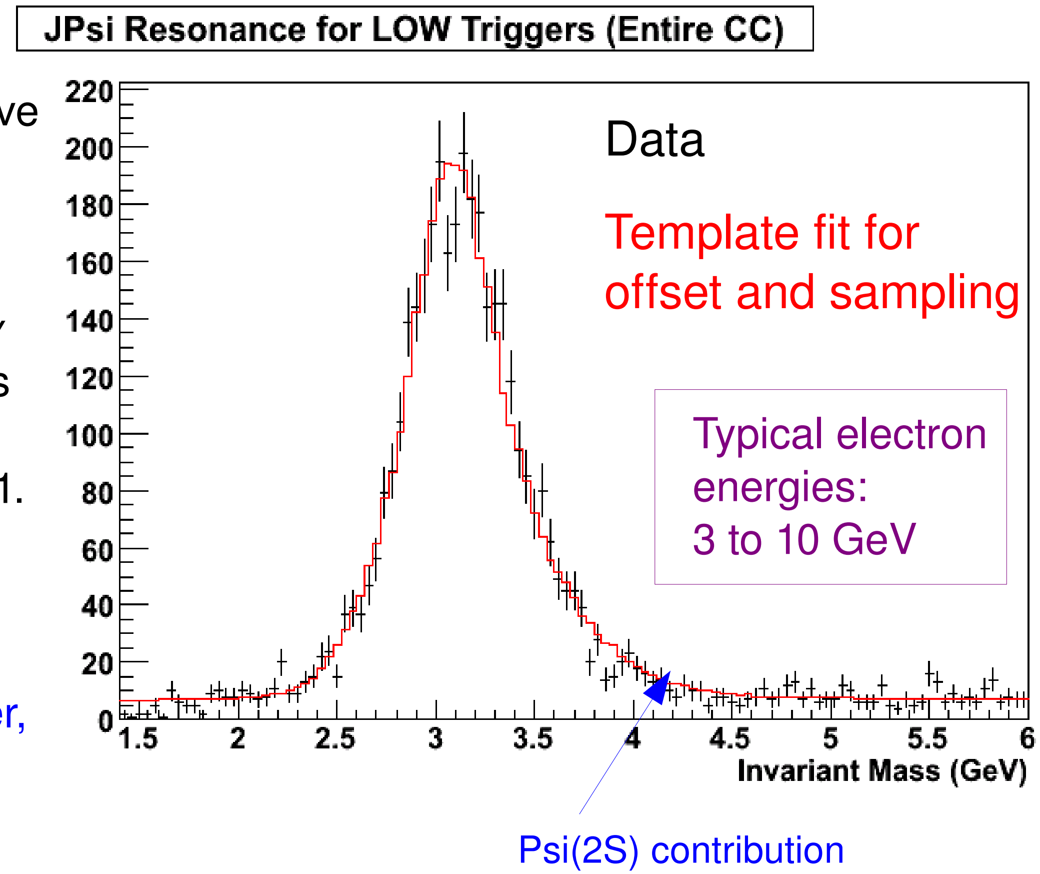


$J/\Psi \rightarrow e^+ e^-$

Fortunately, when I said "*extrapolation*" down to the W, that was not the whole story. We also have another di-electron resonance that sits **lower** in energy than the W: the J/Ψ.

At a hadron collider, such a sample is *extremely* hard to obtain. One of the keys to our success is D0's excellent *Central Track Trigger*. It allows us to trigger on isolated tracks already at Level 1. We typically require two tracks of p_T > 3 GeV.

It took us many many person-months to obtain this sample: design/implementation of the trigger, understanding efficiencies, etc, etc.

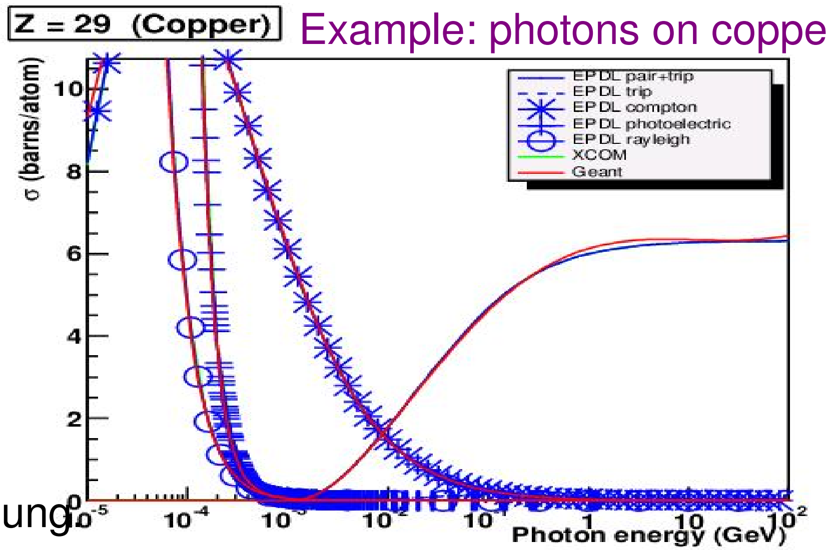


In contrast to the Z, the energy resolution at J/Ψ energies is practically insensitive to issues with gain calibration (the constant term in the energy resolution is irrelevant). The J/Ψ is a nice probe for sampling fluctuations and scale issues related to dead material.

Cross-sections: QED is easy, right ?

But in practice these calculations involve time-consuming Hartree-Fock calculations, partial wave expansions, etc, etc.

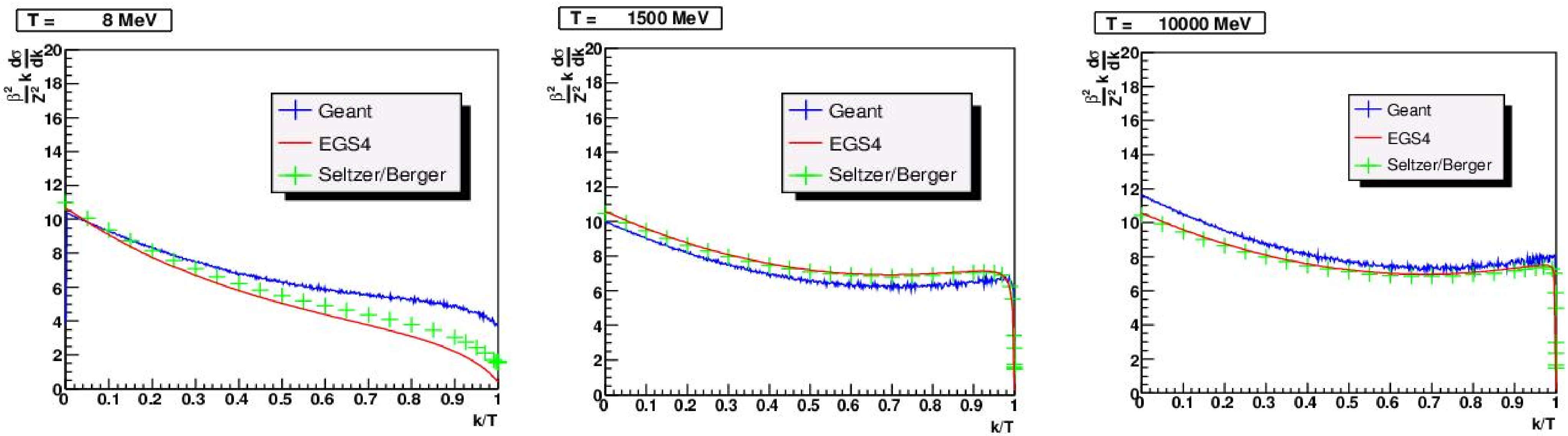
Example: photons on copper



In addition, popular simulation programs (like Geant or EGS) often use simplified models or simple parameterisations of cross sections in order to avoid large look-up tables and to implement fast random number techniques.

A detailed comparison of Geant and EGS to state-of-the-art cross section calculations is striking, especially for Bremsstrahlung.

Example: Bremsstrahlung in by electrons in uranium



T = kinetic energy of incident electron k = energy of the radiated photon

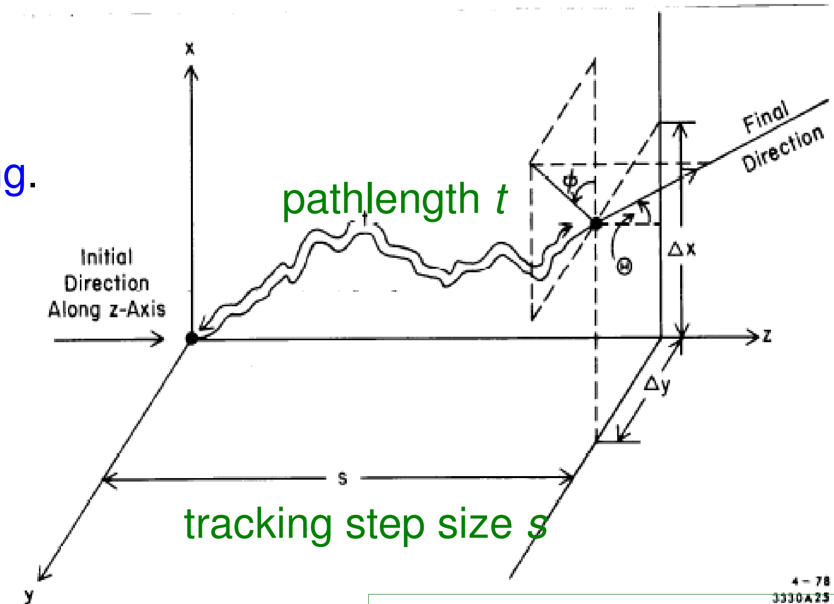
Pathlength correction in e-tracking

In a nutshell:

- There are various parameters in Geant particle tracking. These include things like the "maximum fractional energy loss in one step" and the "shortest step size Geant is willing to take".

- We use Geant in AUTO mode, *i.e.* Geant choses the values of the parameters for us.

- Mulitiple scattering is simulated using Molière theory. That theory provides predictions (PDFs) for things like the scattering angles defined in the plot on the right. It also provides the *pathlength correction* (predict *t* for a given *s*).



The tracking algorithm "thinks" in terms of *s*, but for dE/dx it calculates *t*.

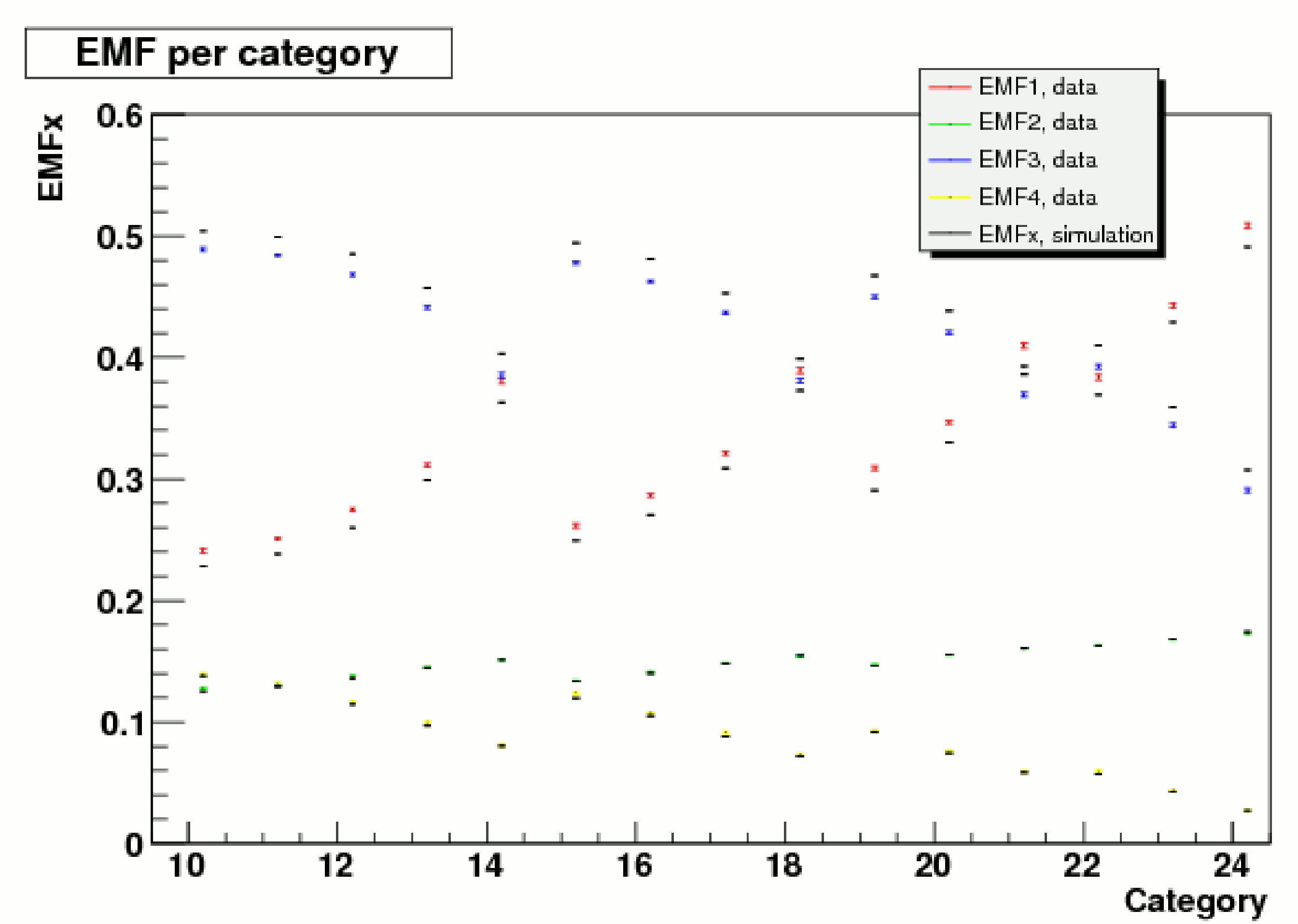
- The formula for the pathlength correction is only valid for small steps *s* (a precise definition for "small" is provided by the theory).

- As it turns out, already at high energies (1 MeV level), the upper limit on *s* from Molière theory is **inconsistent** with the lower limit on *s* chosen by Geant (to conserve CPU).

- Geant choses to not say anything, take the large step anyway, and not apply the pathlegth correction. At 400 keV the correction should be of the order of 3; it rises for lower energies.

EM fractions in Z $\rightarrow e^+ e^-$ events

Use electrons from Z -> e e, plot mean fractional energy deposit in each one of the EM layers. Separate the events into the standard categories in physics eta. The plot below shows each of the four EM fractions for each of the 15 categories.



Data:

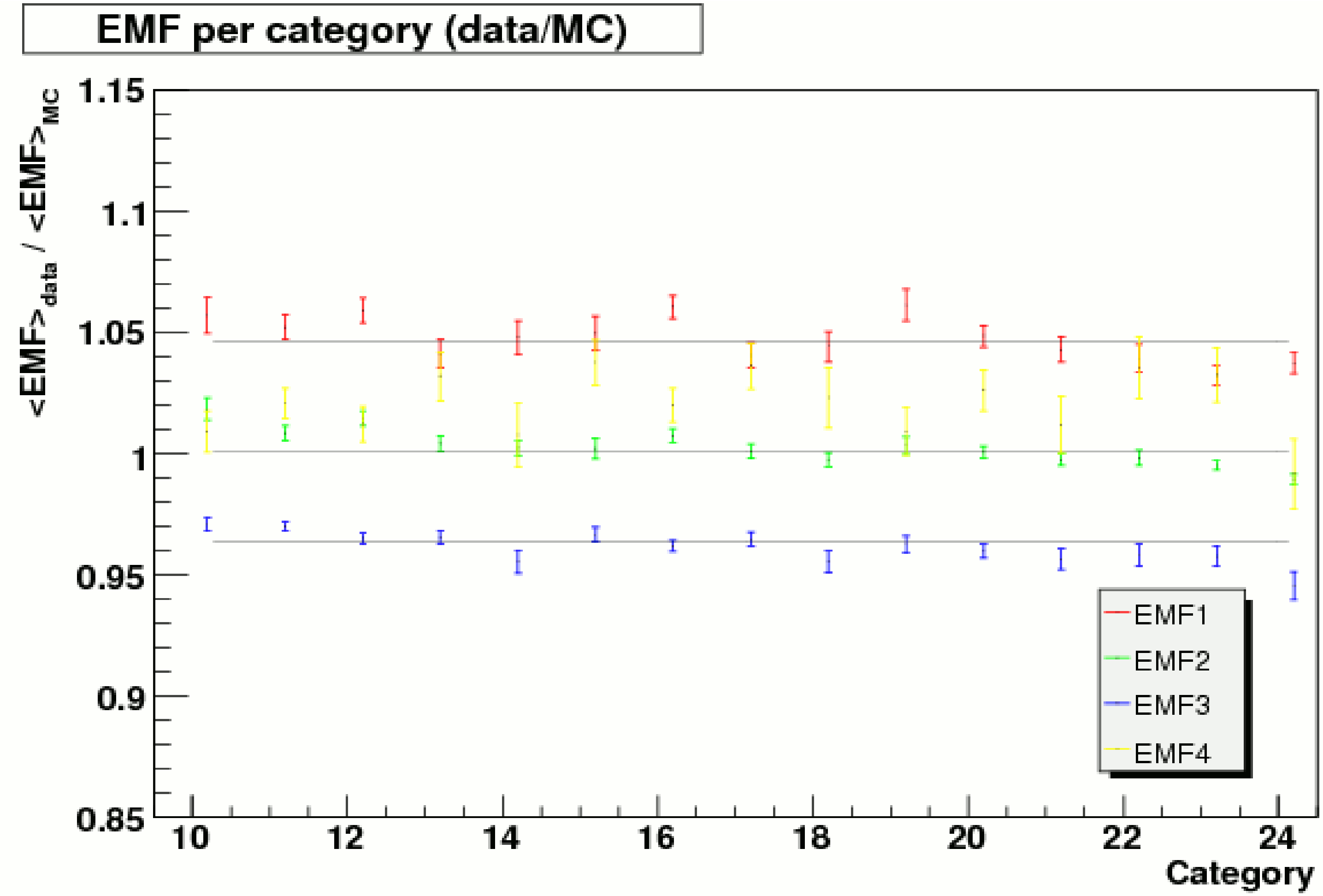
EM1
EM2
EM3
EM4

Monte Carlo (no fudge material):

black

This is a busy plot that can be tricky to read. Let's look at the data/MC ratios instead (on the next slide).

EM fractions in $Z \rightarrow e^+ e^-$ events

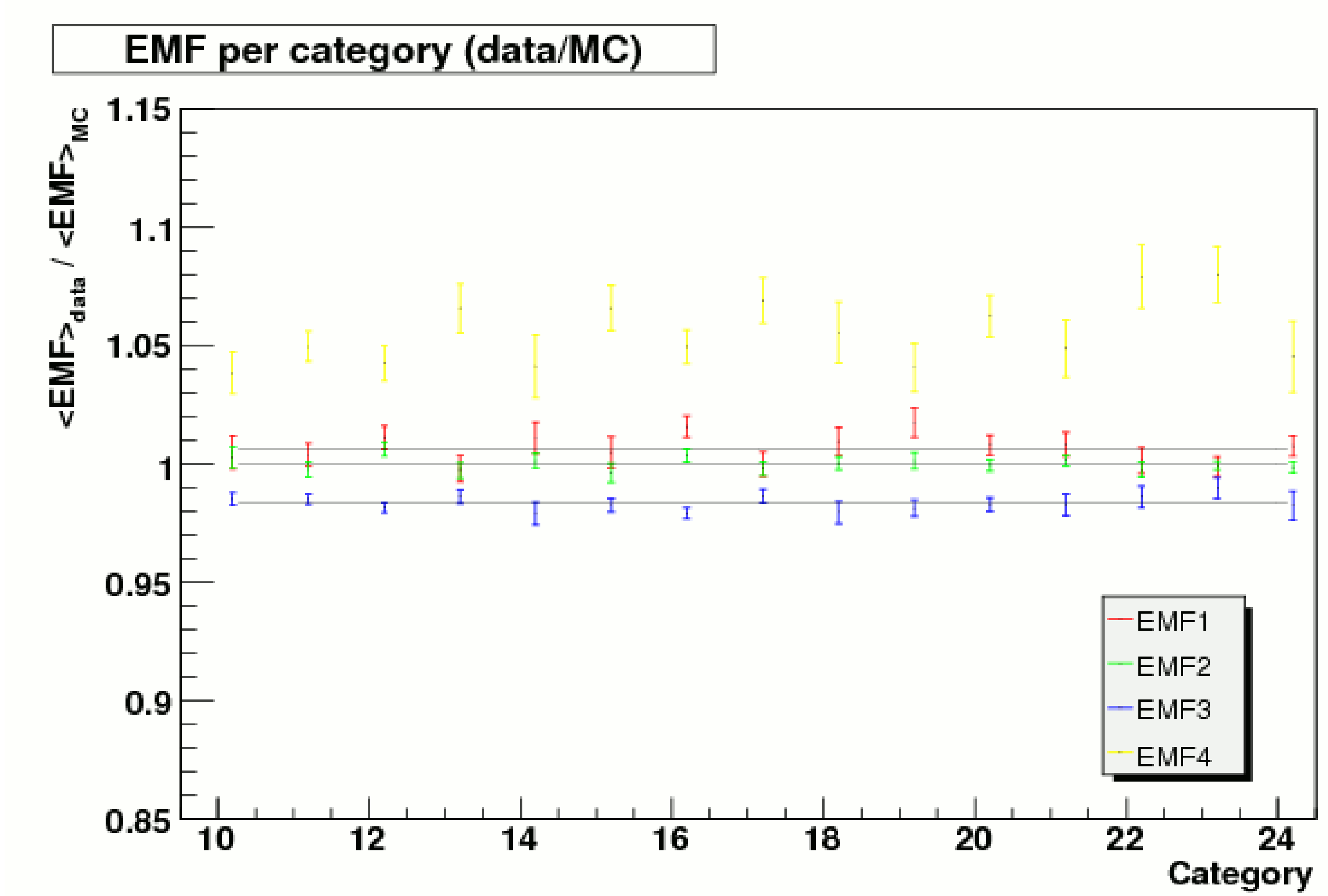


Data / Monte Carlo (MC without fudge material):

EM1
EM2
EM3
EM4

Clear trends are visible, especially for EM1 and EM3.
Also, the excursions away from unity are pretty large. Part of the mean per-layer excursion could be explained by the layers not being properly calibrated with respect to each other, but deviations of O(5 %) are not really expected.

EM fractions in $Z \rightarrow e^+ e^-$ events



Data / Monte Carlo (MC with 0.16 X_0 fudging):

EM1
EM2
EM3
EM4

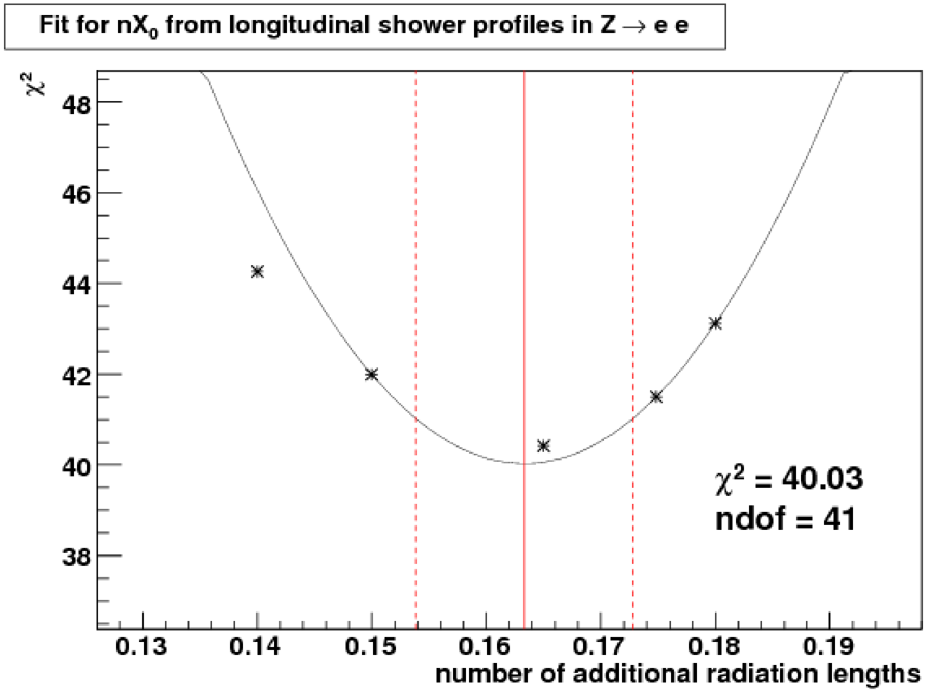
Certainly less trendy than with the nominal detector geometry.

The layers that receive the bulk of the energy (EM1, EM2 and EM3) are also much closer to unity.

Fit for amount of missing material

"Turn the plots from the previous slides into a fit for the amount of missing material":
Take data/MC ratios per η category for EM1, EM2 and EM3 and fit each one (separately) to a constant. Add the chi-squareds from the three fits. Vary amount of extra material to minimise the global chi-squared.

This implies that we leave the absolute energy scale of each layer free to float. This is because this fit is the first time that we have a handle on the intercalibration of the layers.



Amount of fudge material to within less than $0.01X_0$!
With comparatively small systematics from background (underlying event) subtraction and modelling of cut efficiencies.

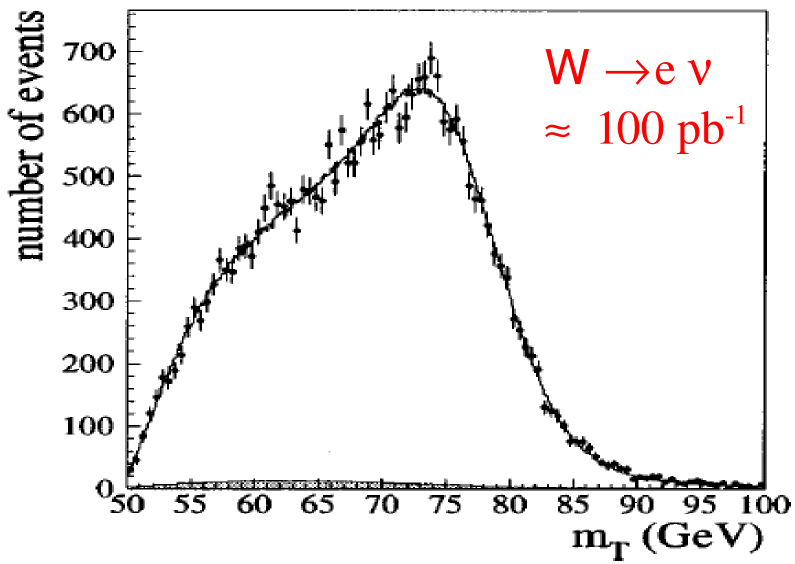
Dzero Run I

DØ Collaboration, PRD 58, 092003 (1998)

Observable: “transverse mass”

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

Relatively robust against uncertainties in physics model.



Model detector effects using parameters “from data” (and a lot of hypotheses).

Generate M_T templates for different M_T points -> likelihood fit.

Understanding the detector behaviour, based mainly on $Z \rightarrow e\,e$ and $\Psi \rightarrow e\,e$ calibration samples, is crucial.

Uncertainties

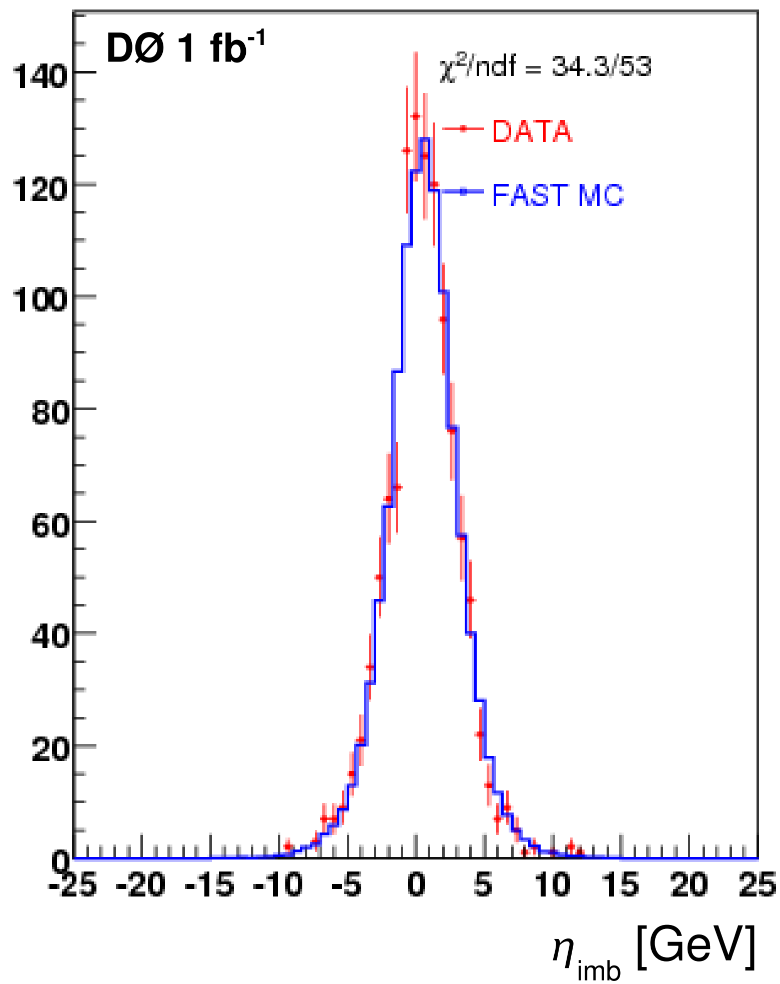
Stat.	m_T fit (MeV)	$p_T(e)$ fit (MeV)	$p_T(\nu)$ fit (MeV)
W sample	70	85	105
Z sample	65	65	65
Total	95	105	125

“Detector understanding”	m_T fit (MeV)	$p_T(e)$ fit (MeV)	$p_T(\nu)$ fit (MeV)
Calorimeter linearity	20	20	20
Calorimeter uniformity	10	10	10
Electron resolution	25	15	30
Electron angle calibration	30	30	30
Electron removal	15	15	20
Selection bias	5	10	20
Recoil resolution	25	10	90
Recoil response	20	15	45
Total	60	50	115

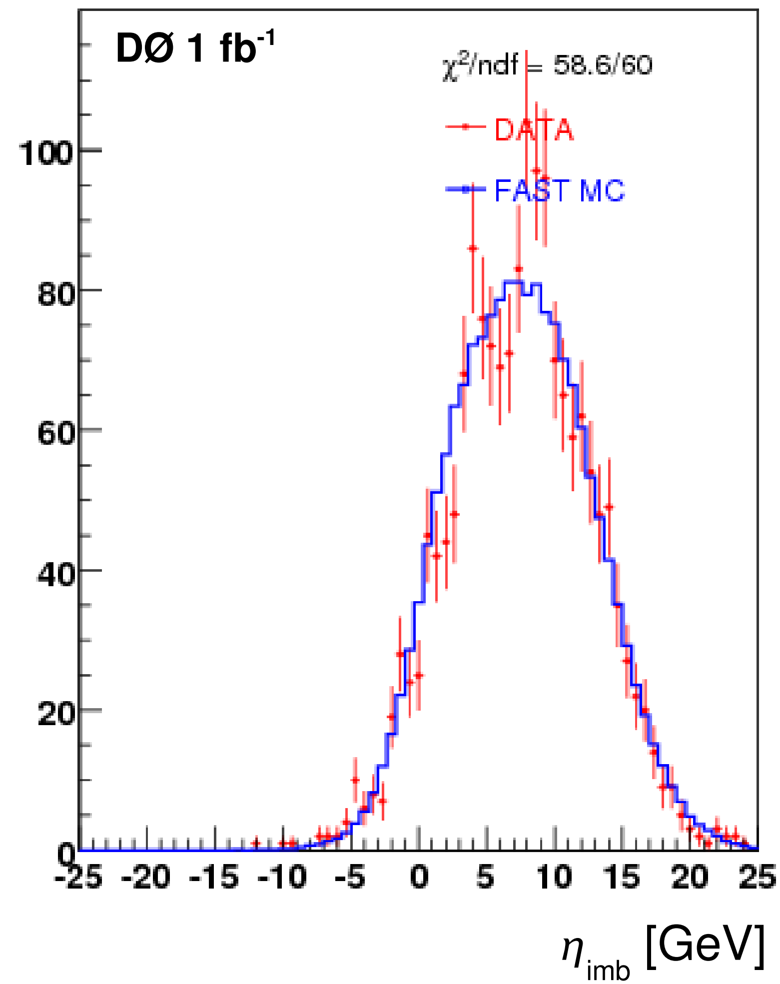
“Production and decay model”	m_T fit (MeV)	$p_T(e)$ fit (MeV)	$p_T(\nu)$ fit (MeV)
$p_T(W)$ spectrum	10	50	25
Parton distribution functions	20	50	30
Parton luminosity β	10	10	10
Radiative decays	15	15	15
W width	10	10	10
Total	30	75	45

Examples: η_{imb} distributions

1 < p_T(ee) < 2 GeV



20 GeV < p_T(ee)



Electrons: energy resolution

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

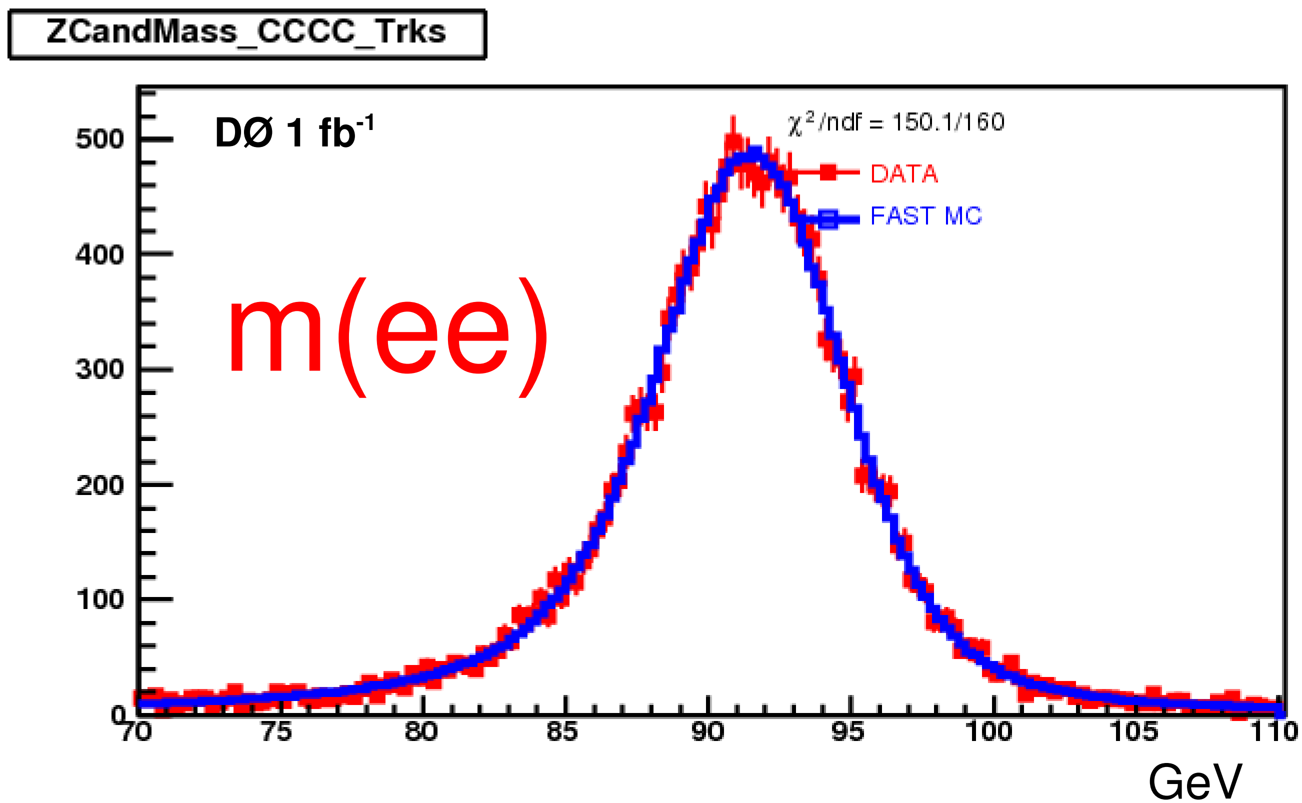
Sampling fluctuations are driven by sampling fraction of CAL modules (well known from simulation and testbeam) and by uninstrumented material. As discussed before, amount of material has been quantified with good precision.

Constant term is extracted from Z -> e e data (essentially fit to observed width of Z peak).

Result:

C = (2.05 ± 0.10) %

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



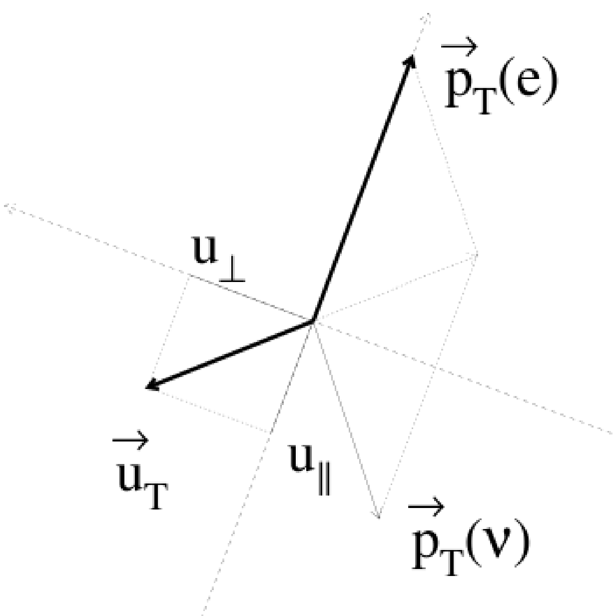
Electron reco efficiency model

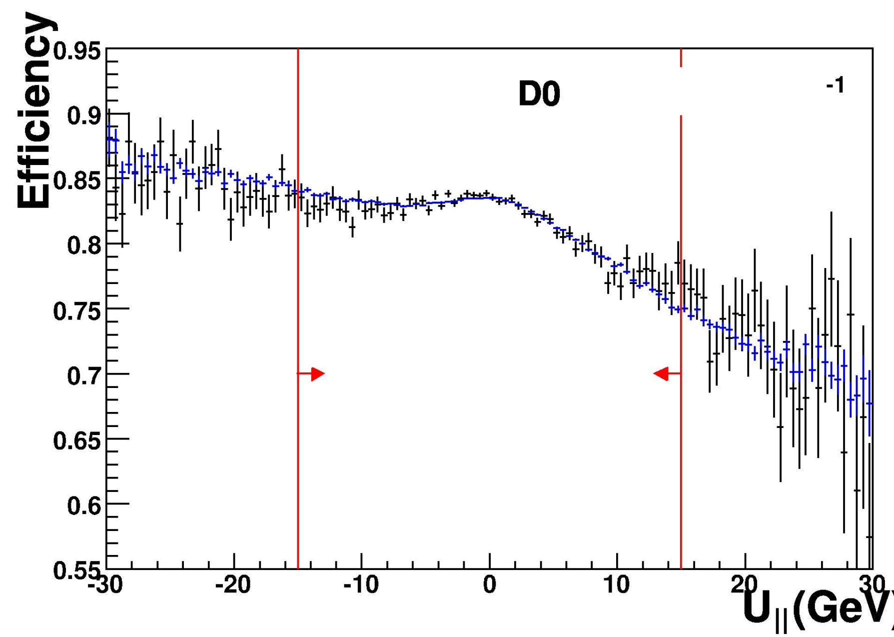
Efficiency model also takes into account relative orientation of electron and “rest of the event” (hadronic activity). For example:

- Efficiency corrections vs. $p_T(e)$ and scalar E_T.

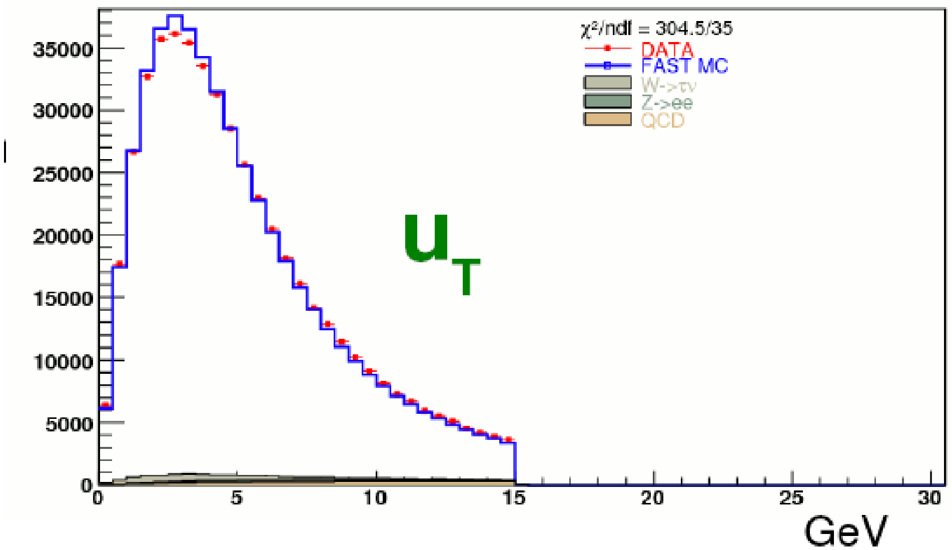
- Efficiency corrections vs. $u_{||}$.

Much of this level of detail is only necessary for a measurement of the W width, not the mass.





$W \rightarrow e\,\nu$ data   WARNING !

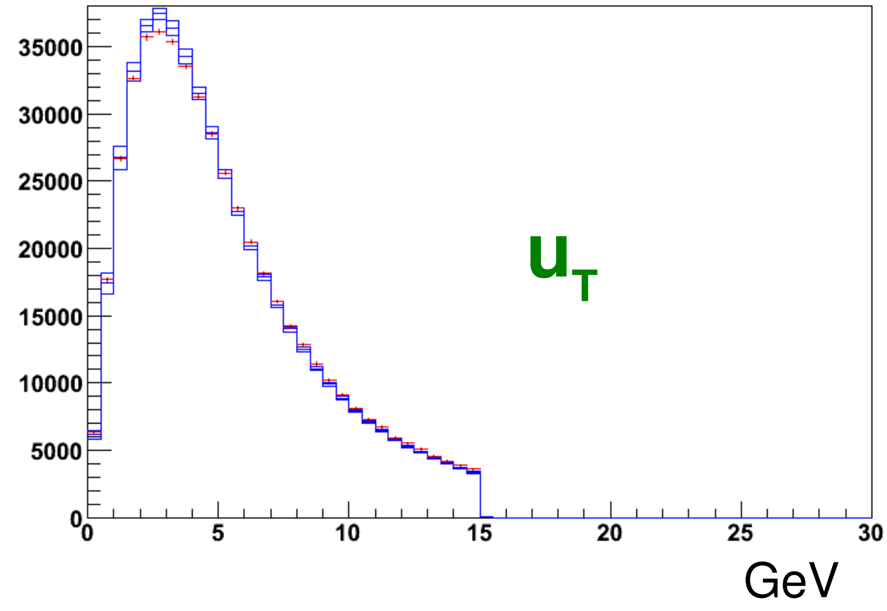


Data-MC apparently not in good agreement !

Error bars only reflect limited W statistics they do not reflect the much more limited **Z statistics** that have been used to calibrate the recoil model !

The blue band in the bottom plot reflects one sigma excursions in the recoil parameters.

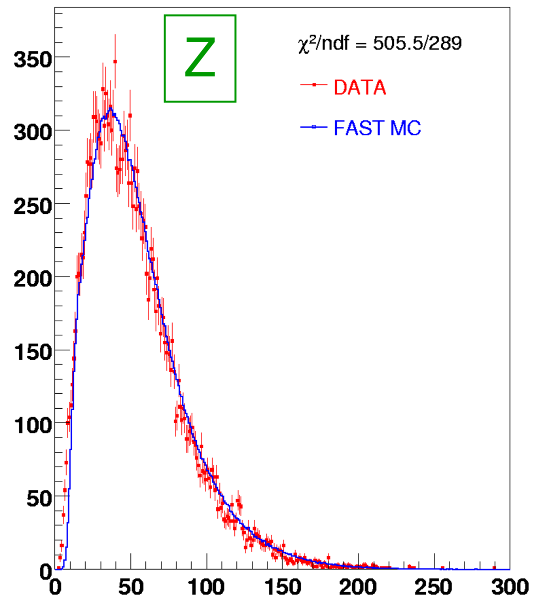
→ agreement is not so bad !



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

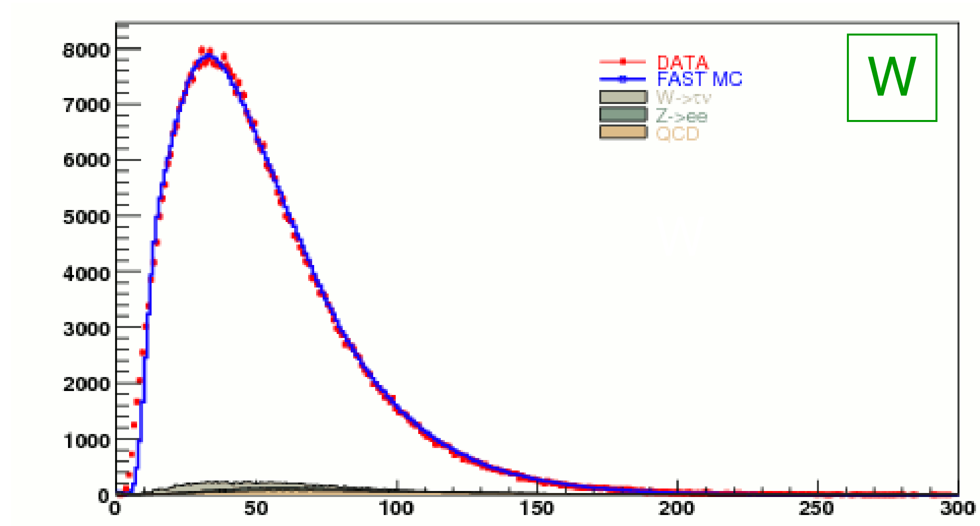
Data in red

MC in blue

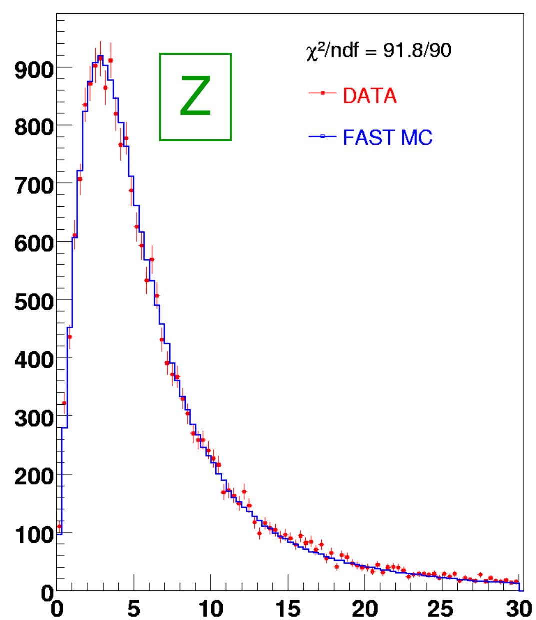


GeV

SET

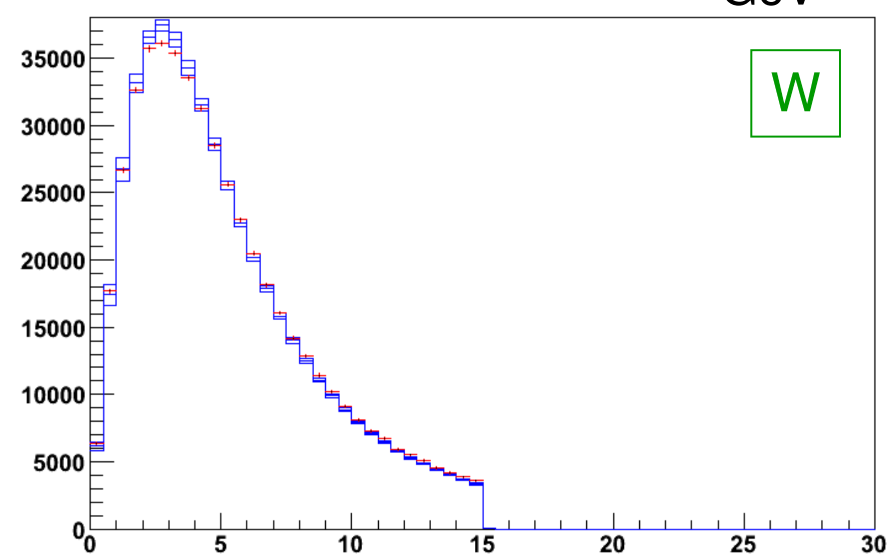


GeV



GeV

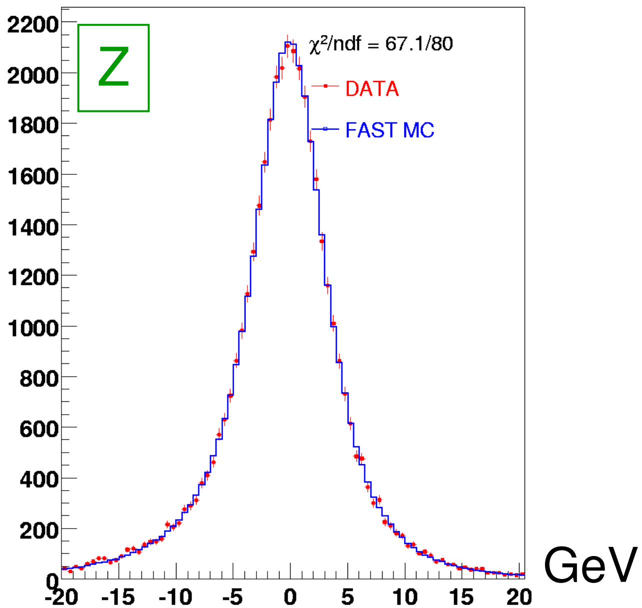
u_T

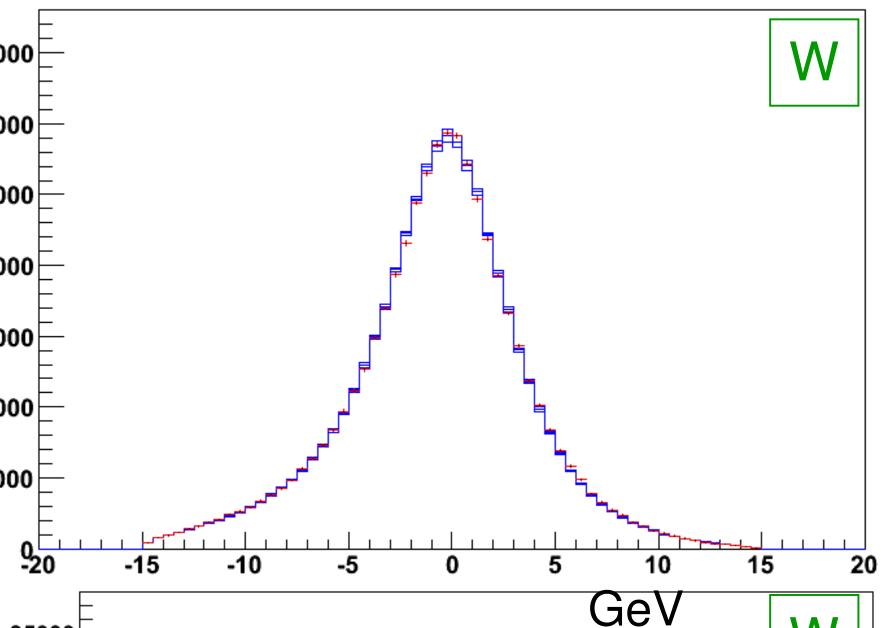


GeV

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

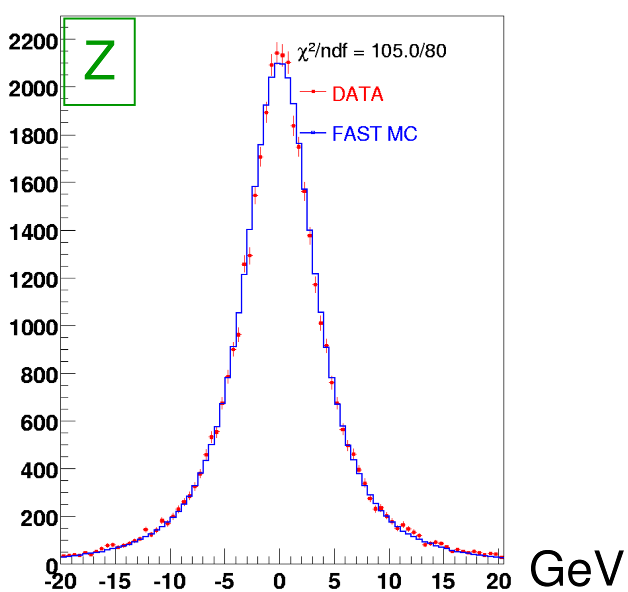
Data in red
MC in blue

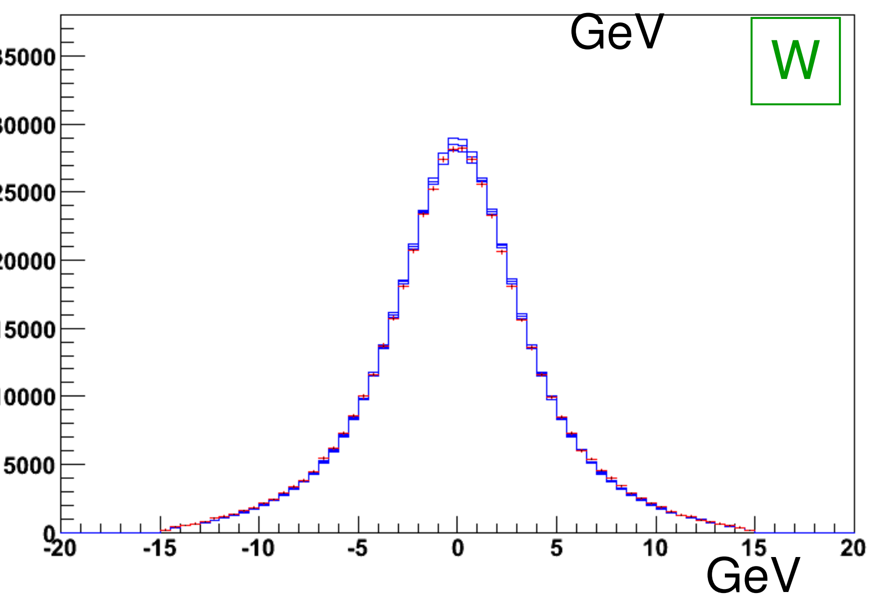




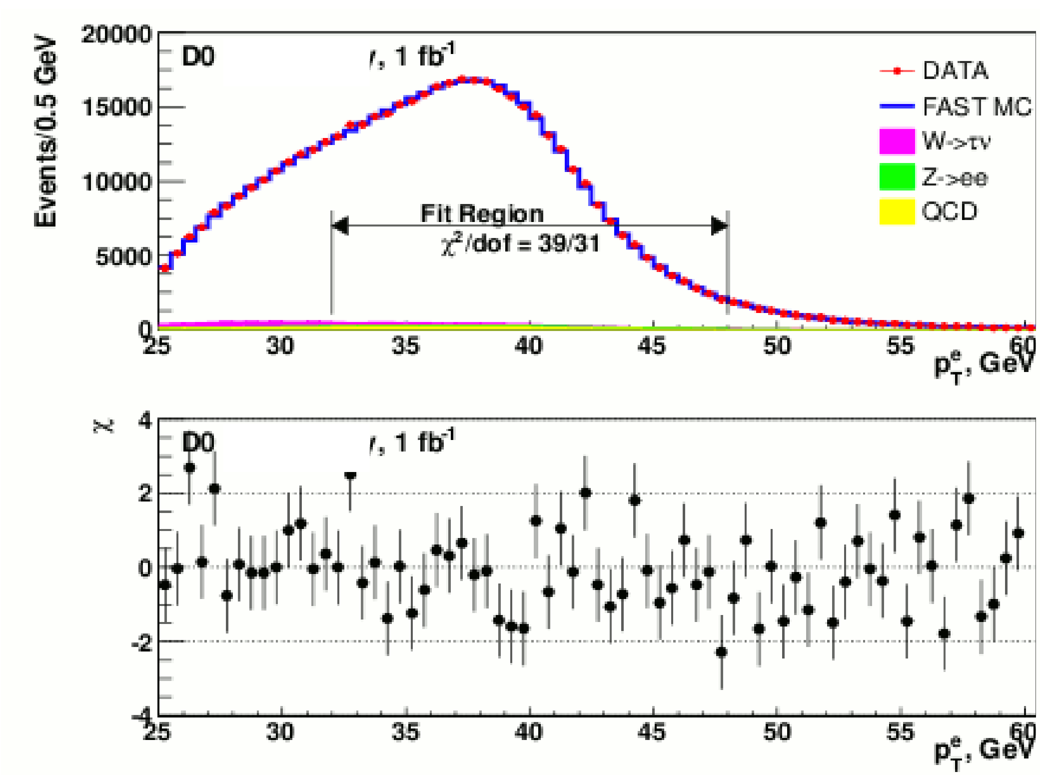
u_{para}

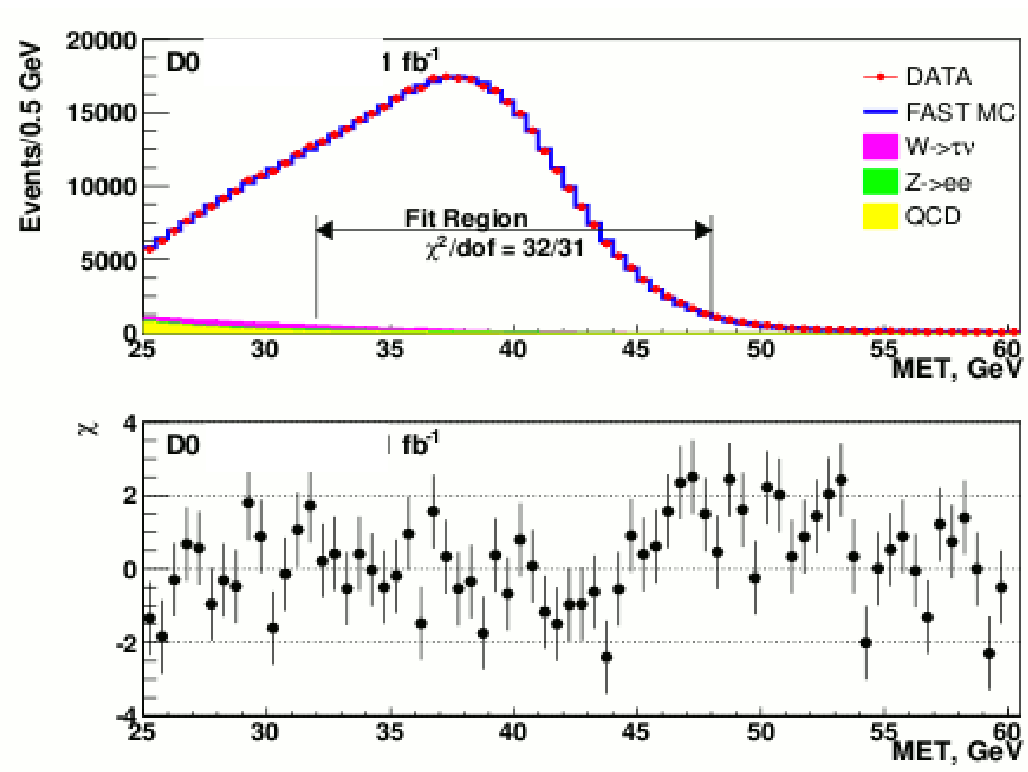
u_{perp}





Mass fits



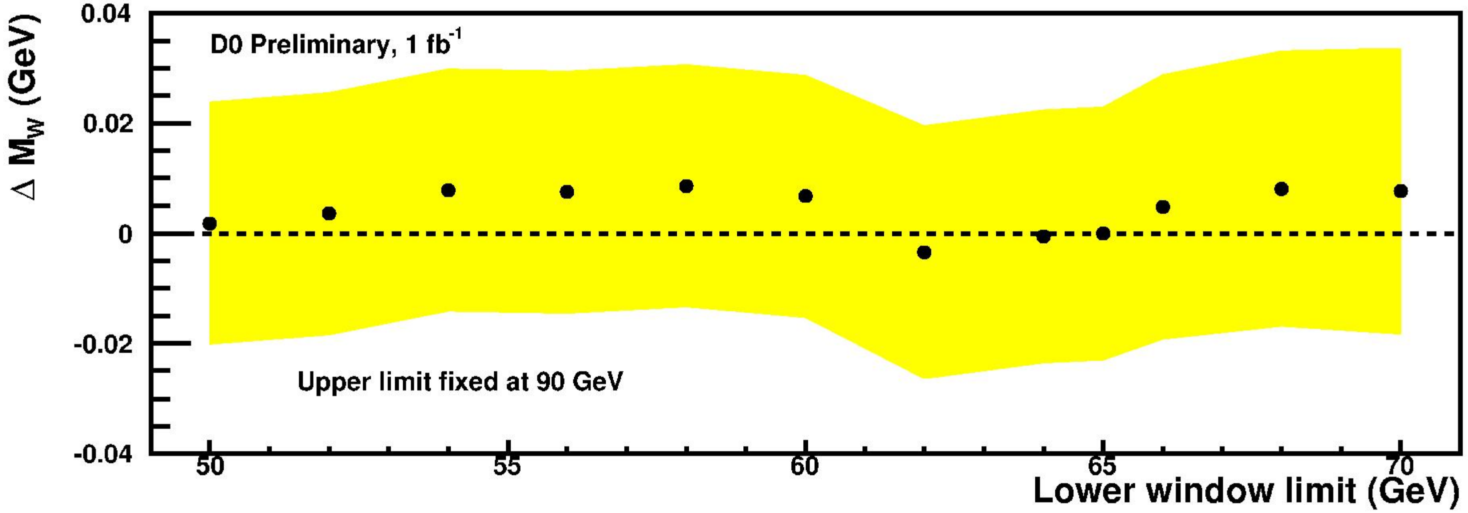


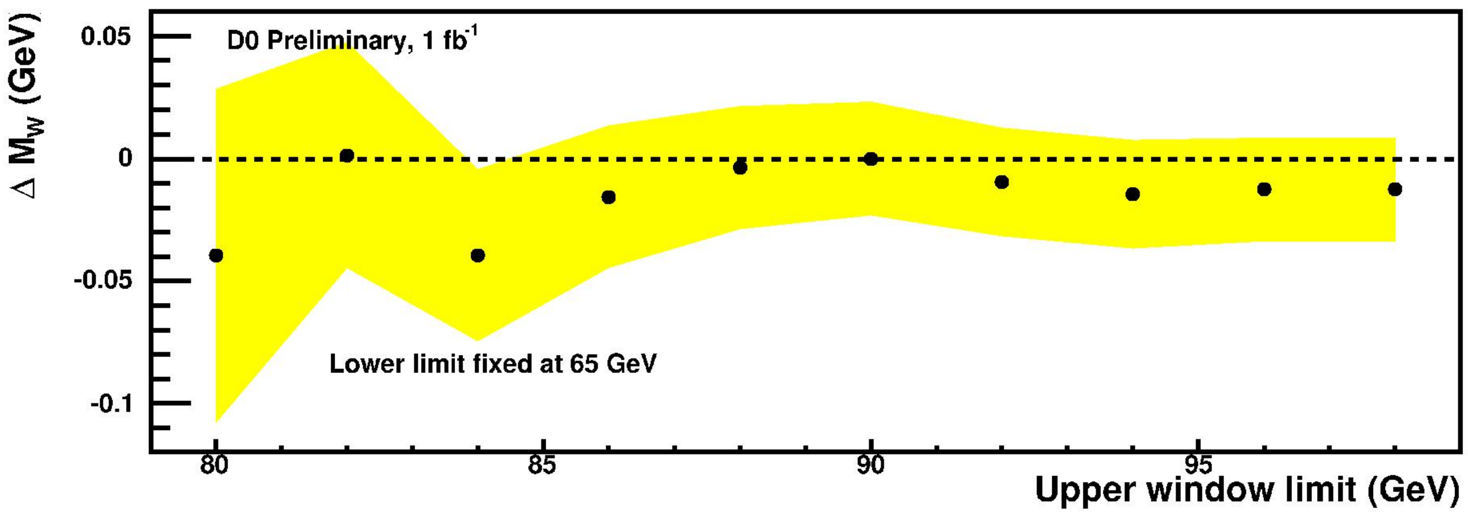
m(W) = 80.400 ± 0.027 GeV (stat)

m(W) = 80.402 ± 0.023 GeV (stat)

Stability checks

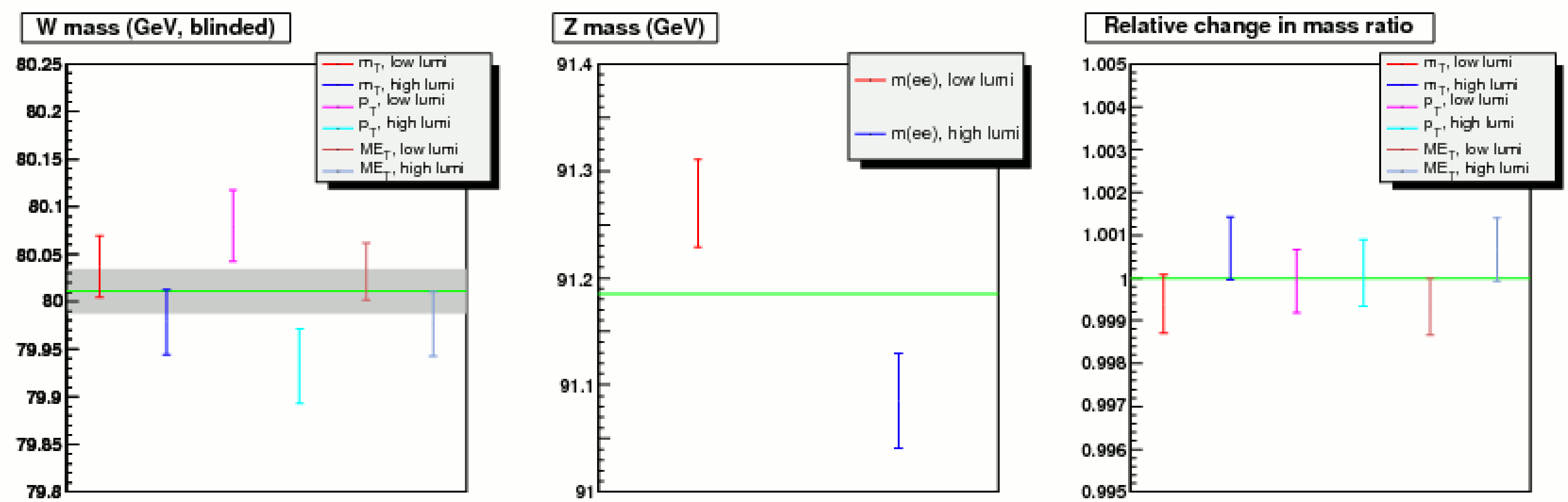
Changes in the fitted m_W when the fitting range (m_T observable) is varied.



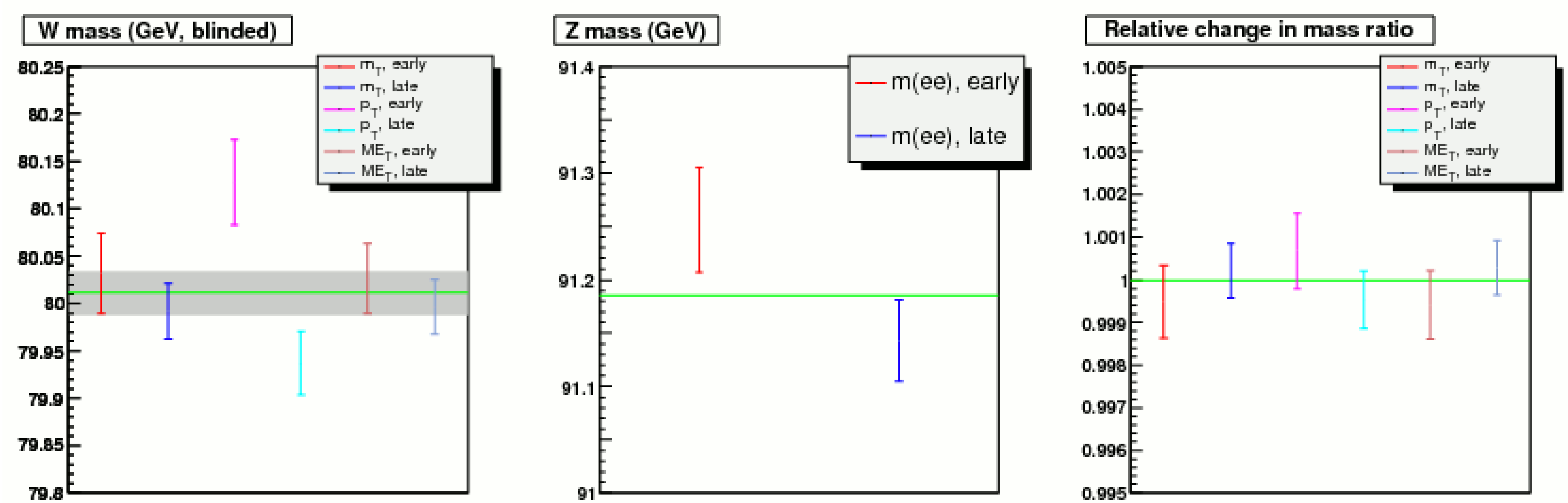


Stability checks

Instantaneous luminosity (split data into two subsets – high and low inst. luminosity)



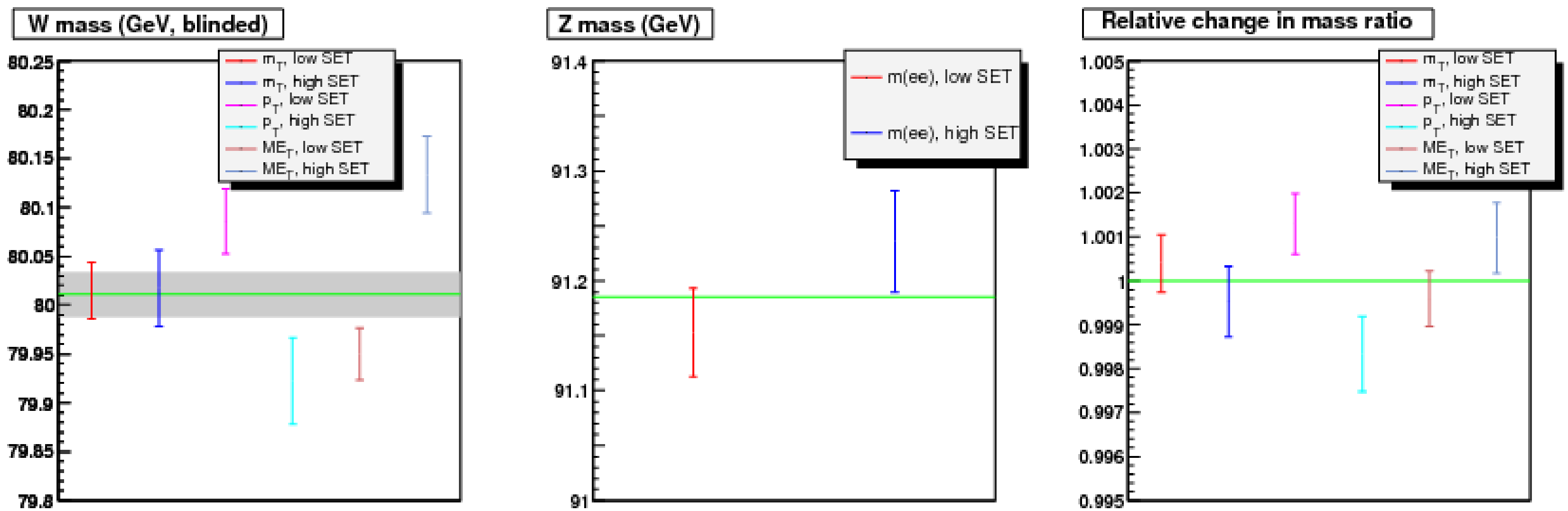
Time (i.e. data-taking period)



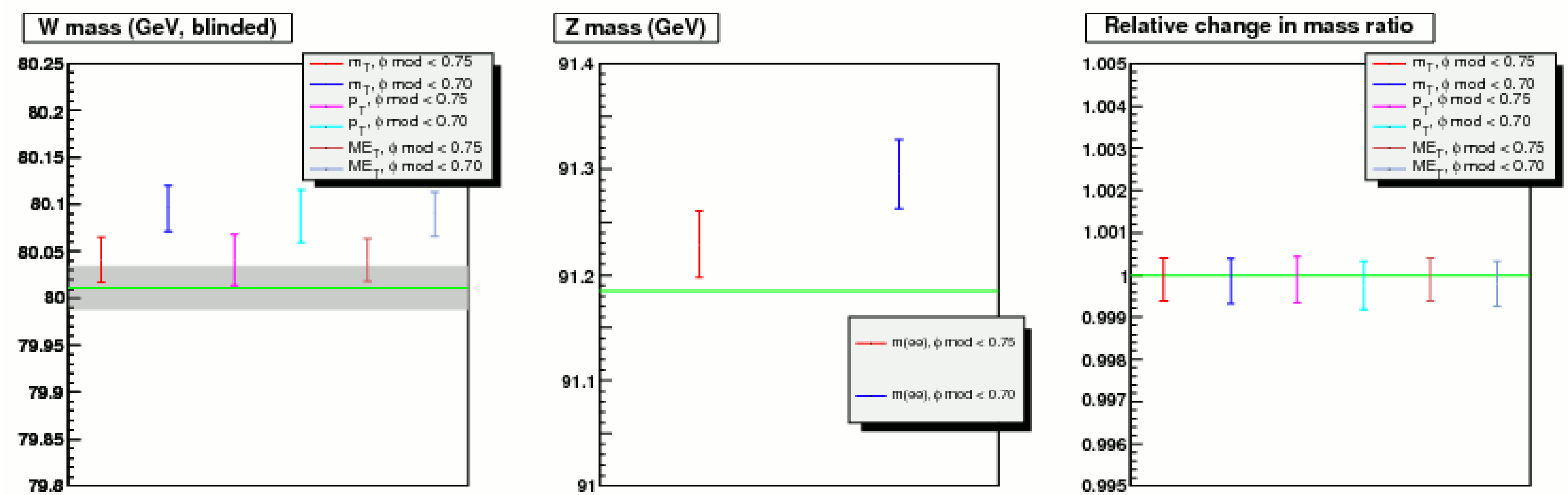
Sorry, plots still in terms of blinded mass, but it does not matter here.

Stability checks

Scalar E_T ("global event activity as seen by calorimeter")



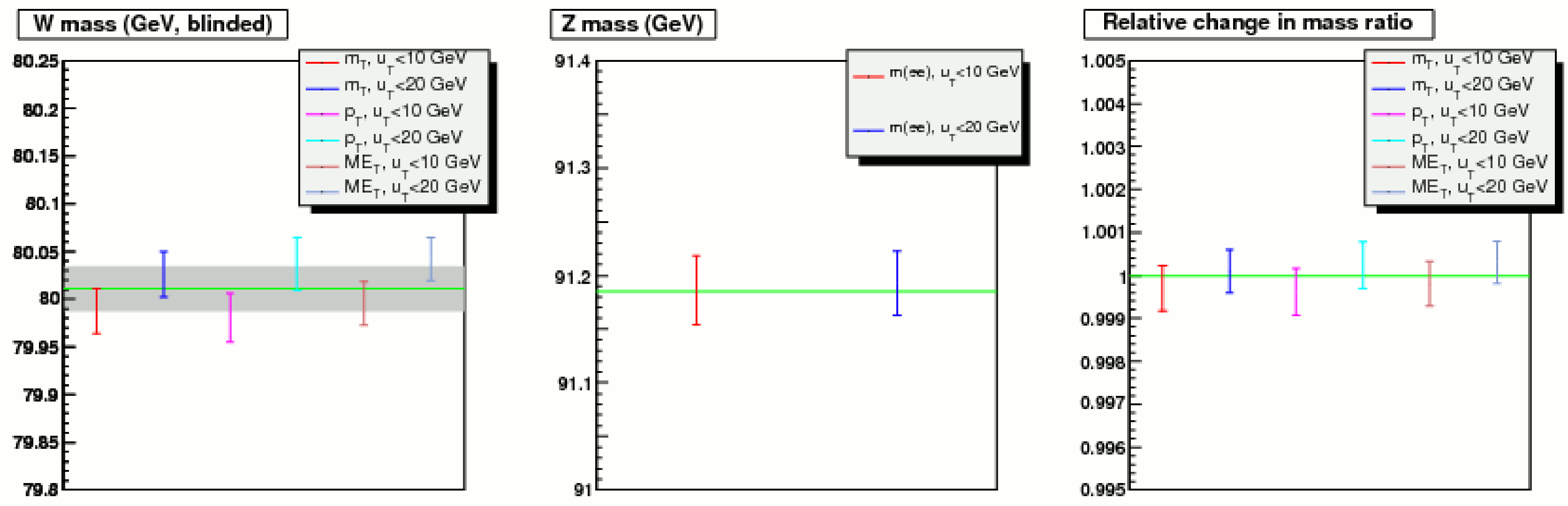
Electron distance from phi cracks



Sorry, plots still in terms of blinded mass, but it does not matter here.

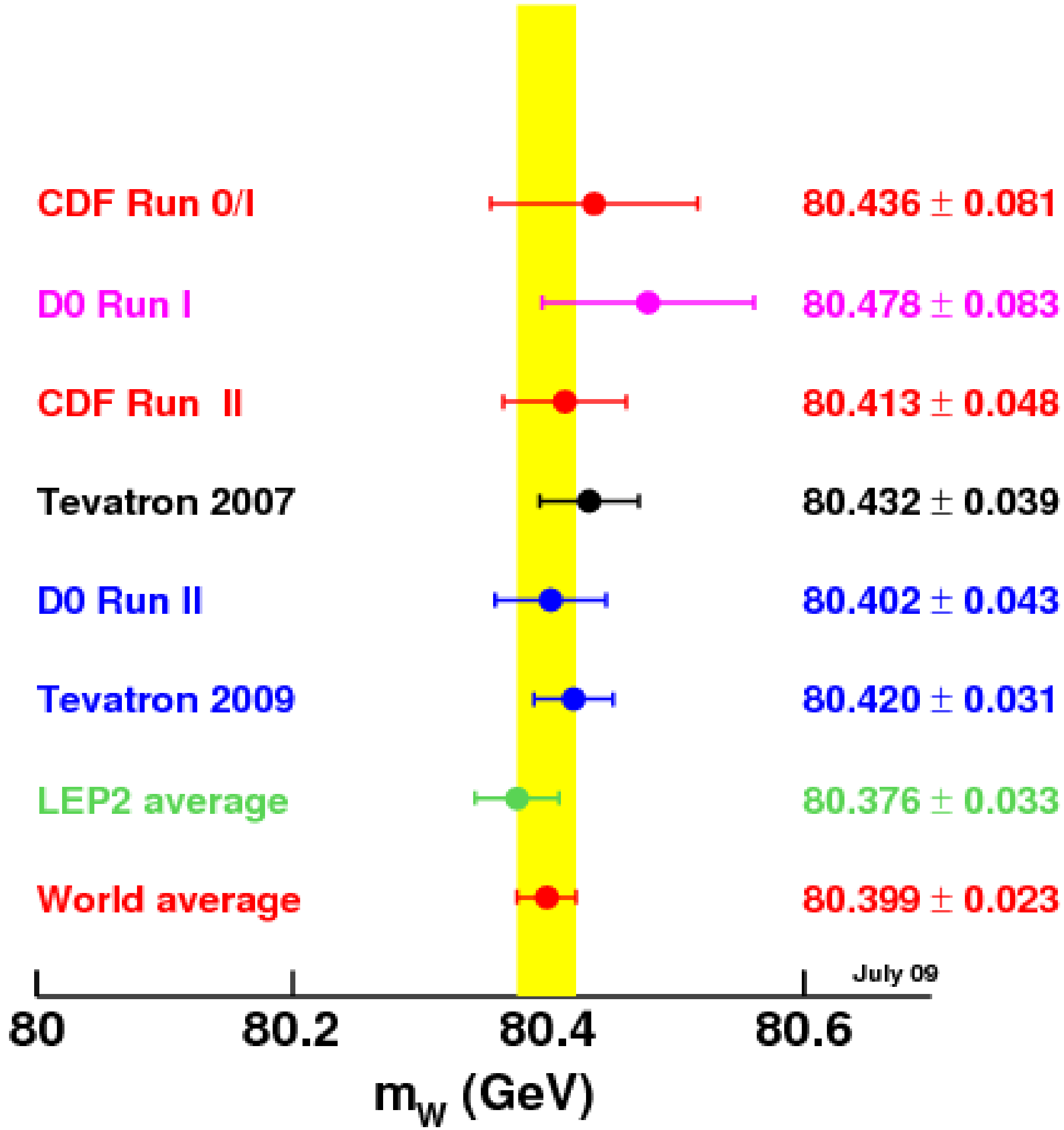
Stability checks

Cut on u_T (“length of recoil vector”)



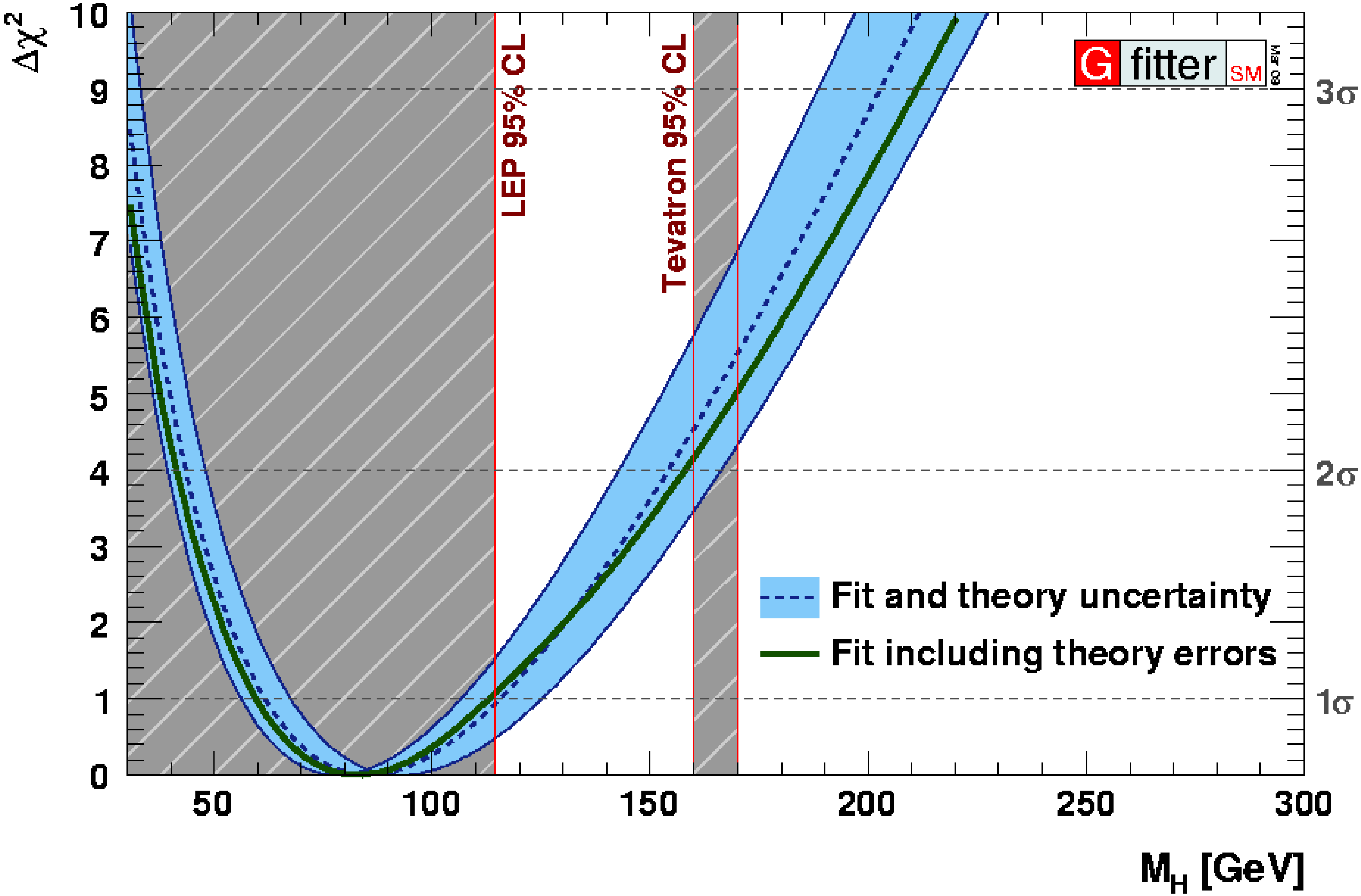
Sorry, plots still in terms of blinded mass, but it does not matter here.

The new world average



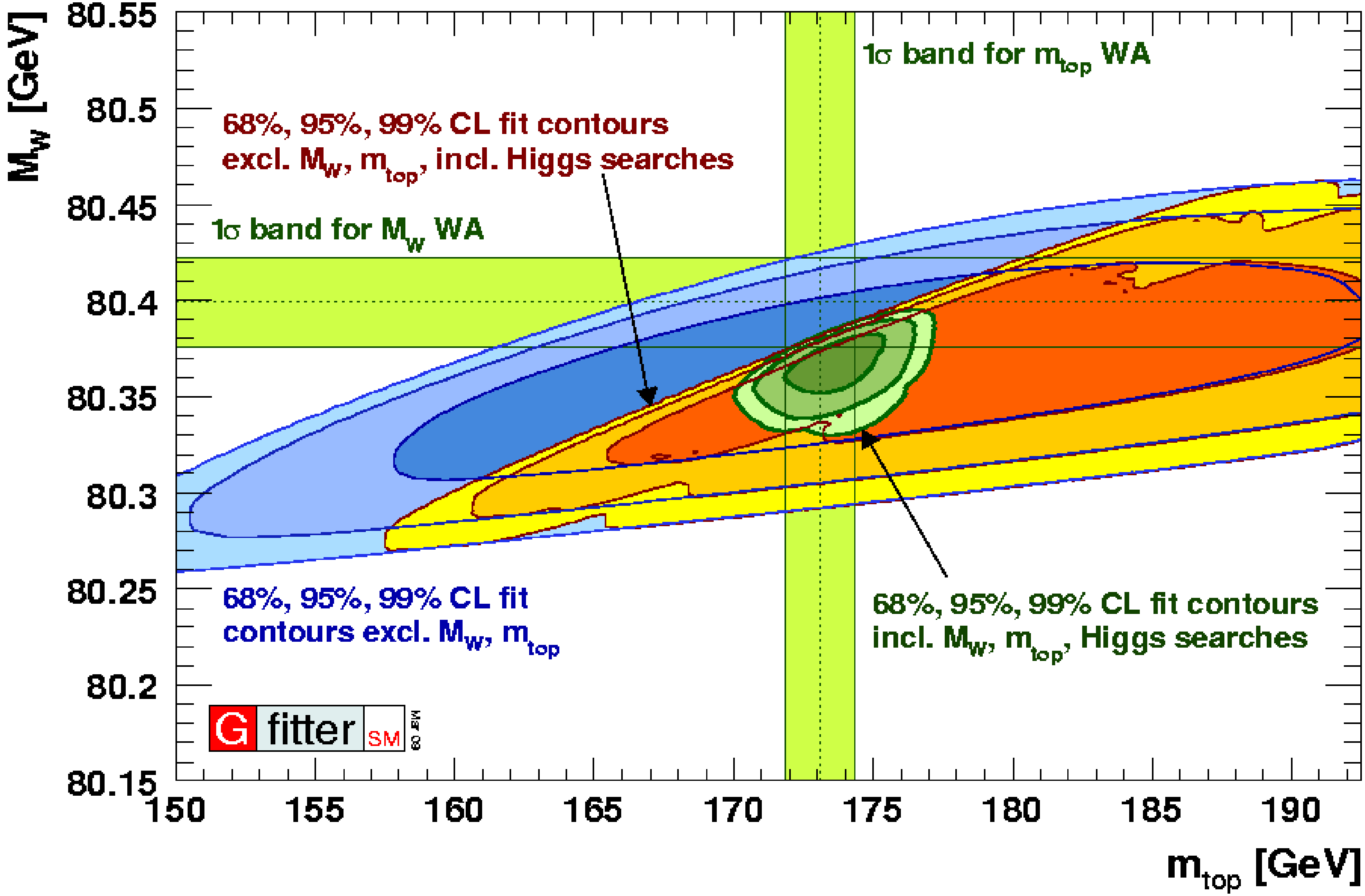
Latest constraints on Higgs mass

For detailed description of this update, please see web page of Gfitter group.



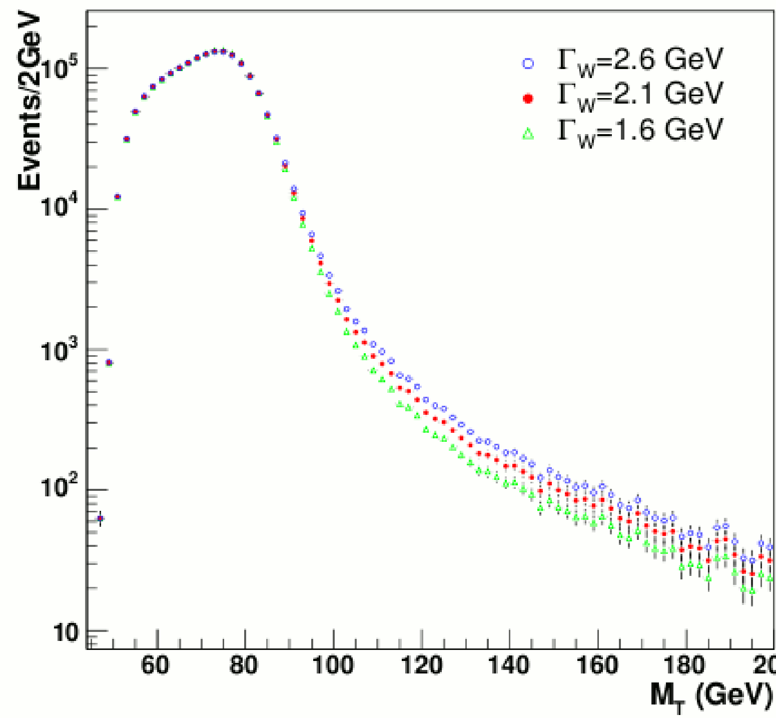
Latests constraints on Higgs mass

For detailed description of this update, please see web page of Gfitter group.

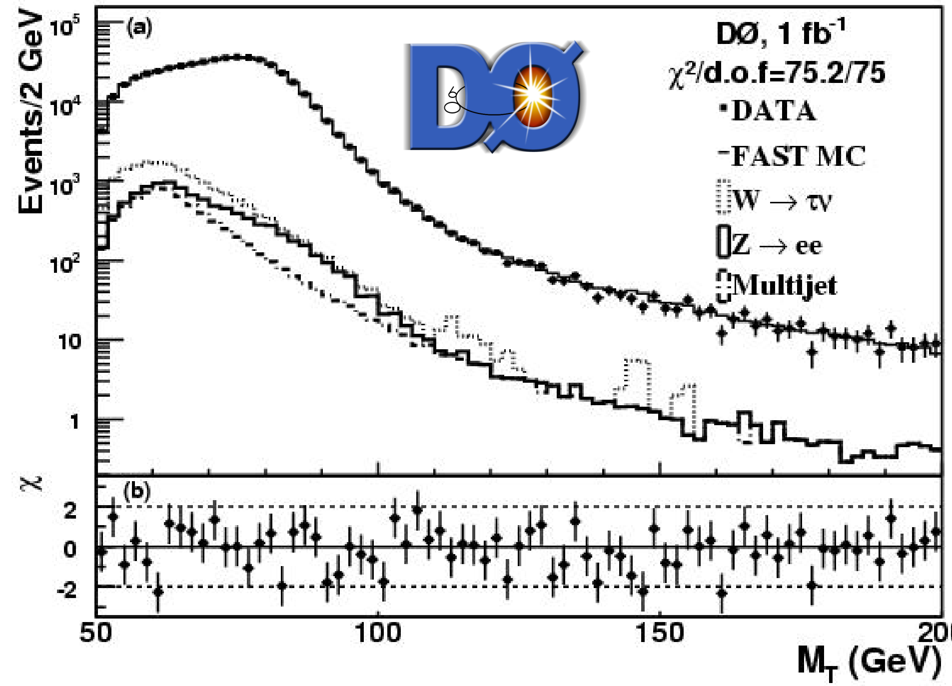


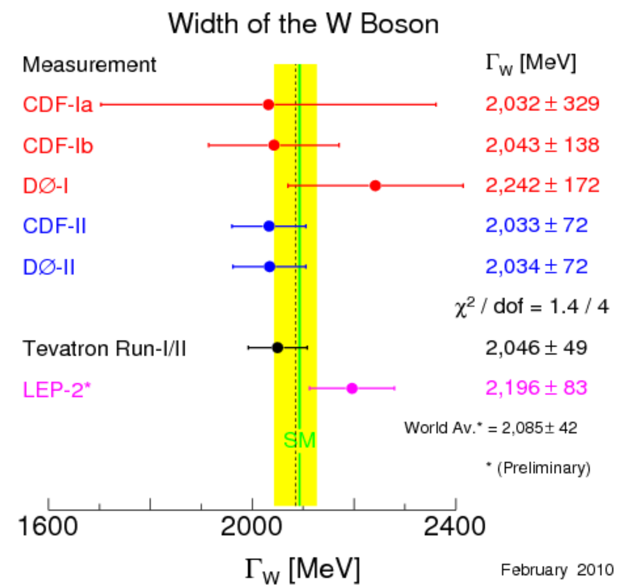
W boson width

Let's look in more detail into the tail of the M_T distribution. Shown below are MC simulations for different values of the W width (note wide horizontal scale and log vertical scale):



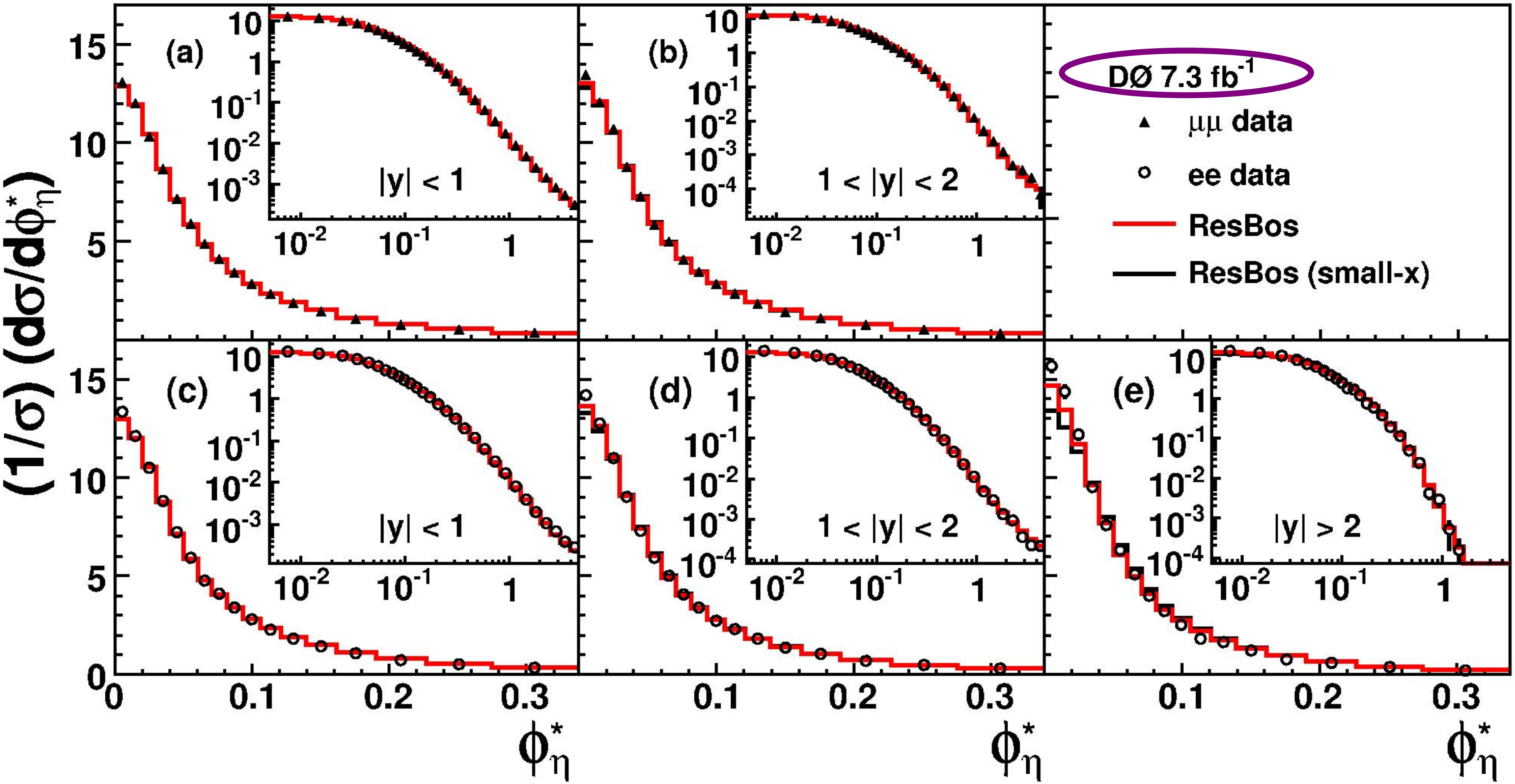
In the tail the effect of the natural width is not swamped by detector resolution.



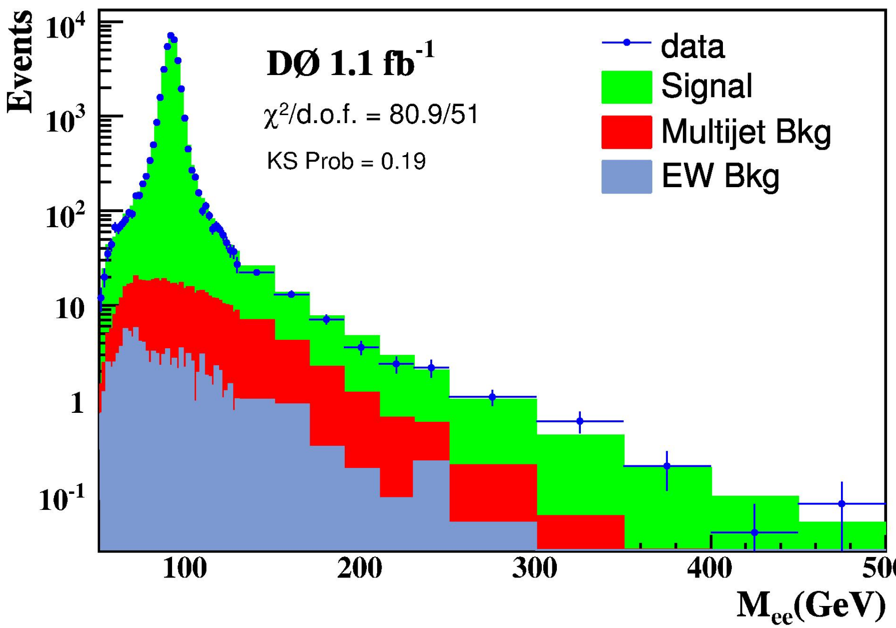


New experimental constraints on "$p_T(Z)$"

Unfolded data (ee and $\mu\mu$ channels shown separately) in three bins of Z rapidity:



Z -> e$^+$ e$^-$: Forward-backward asym.



$$\sin^2\theta_W^{\mathrm{eff}} = 0.2326 \pm 0.0018\ (\mathrm{stat.}) \pm 0.0006\ (\mathrm{syst.})$$