Monte Carlo modelling issues for W measurements

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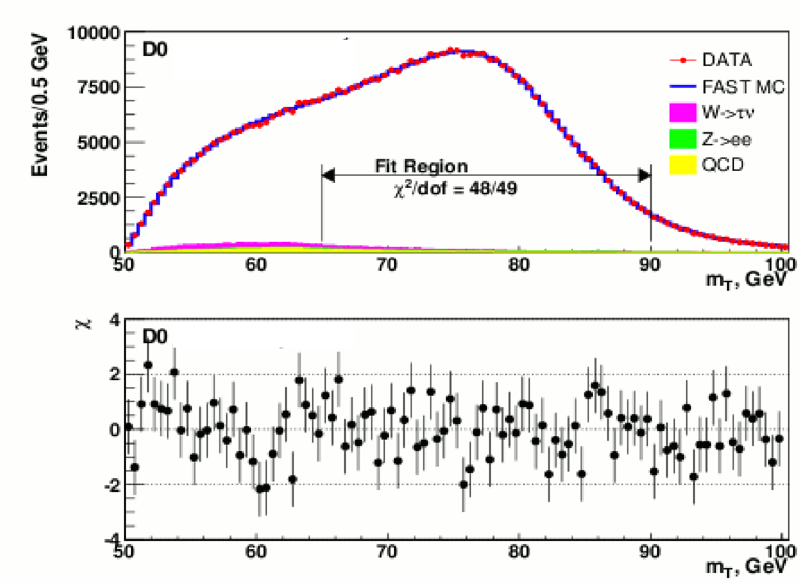
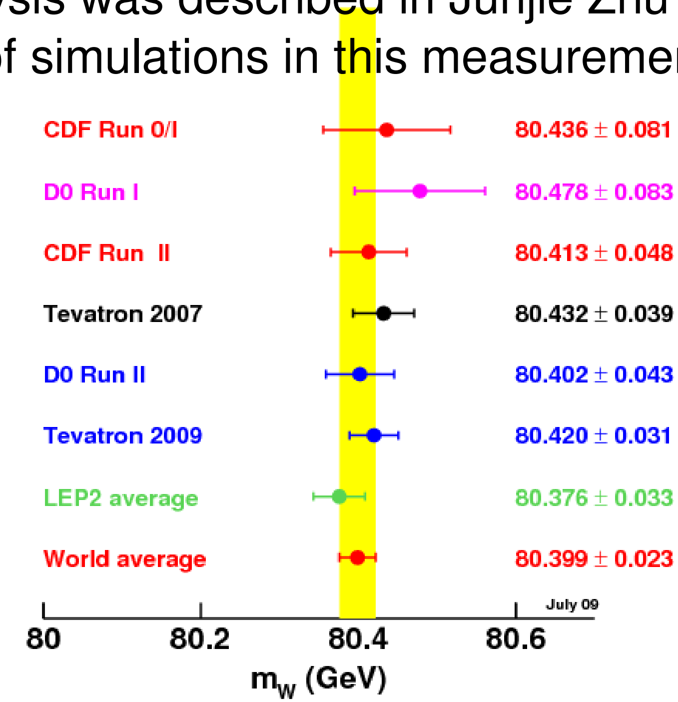
Context

Most of the comments in this talk are based on experience from the DØ 1 fb^{-1} measurement of the W boson mass. A complete overview of this analysis was described in Junjie Zhu's talk earlier today. Here we provide more details on the use of simulations in this measurement.





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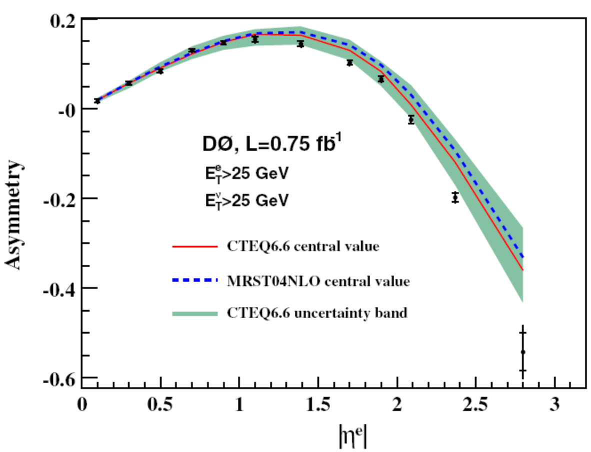
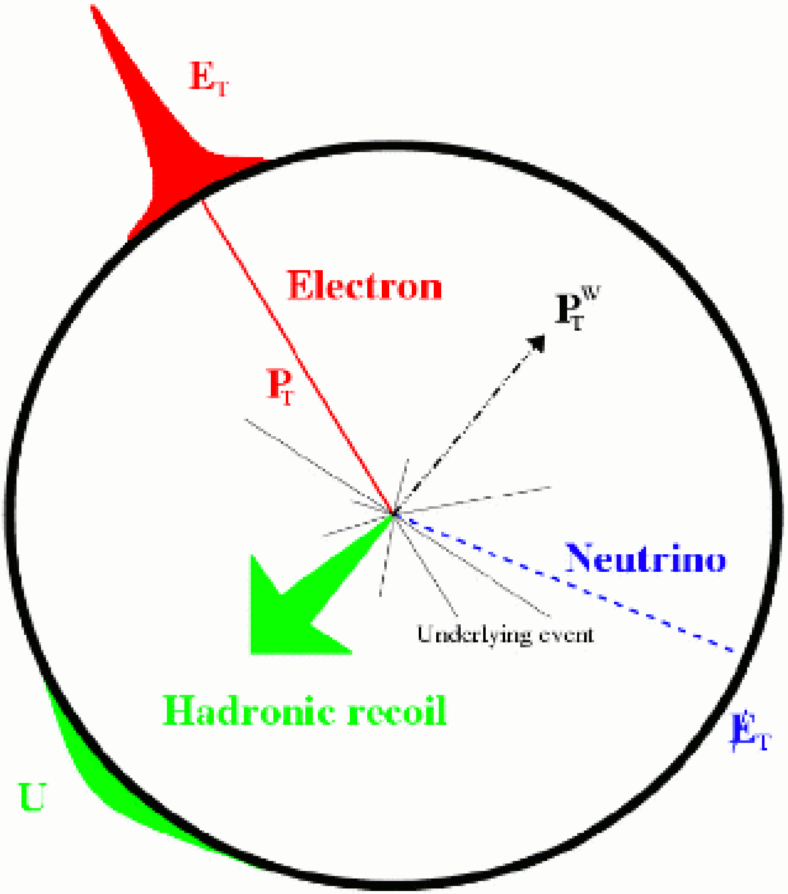


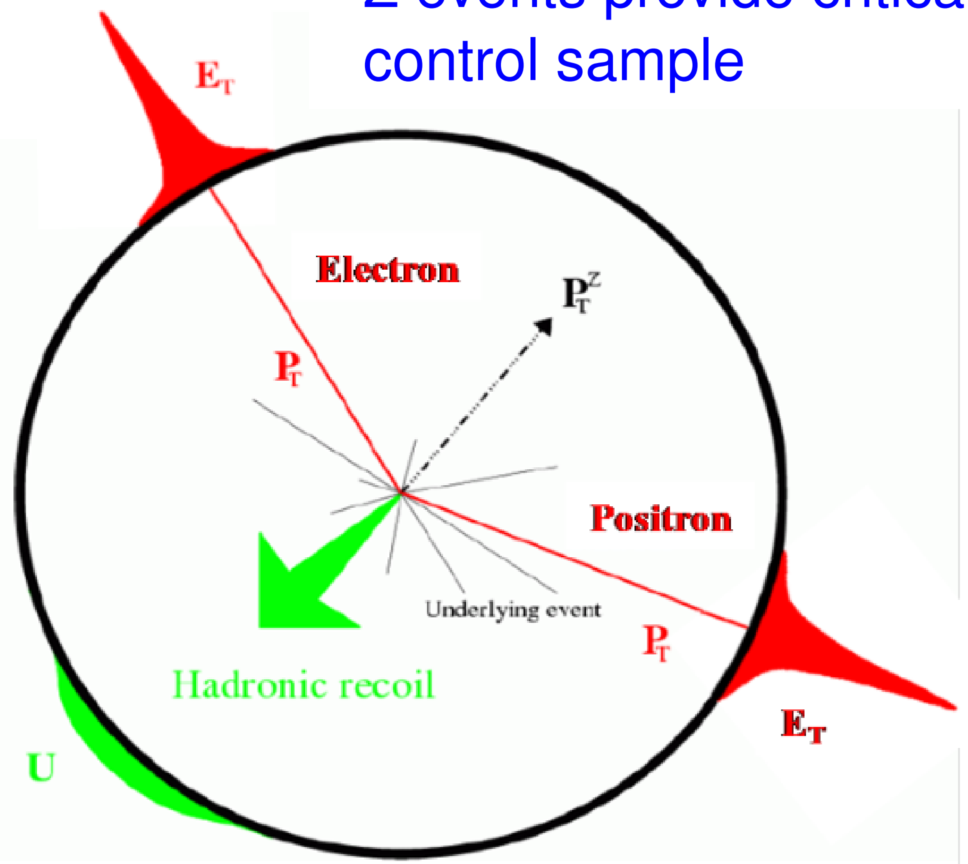
But many of the techniques and strategies discussed here also apply to many other W and Z measurements ...

Reminder: signature in the detector, requirements on precision

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



Z events provide critical control sample

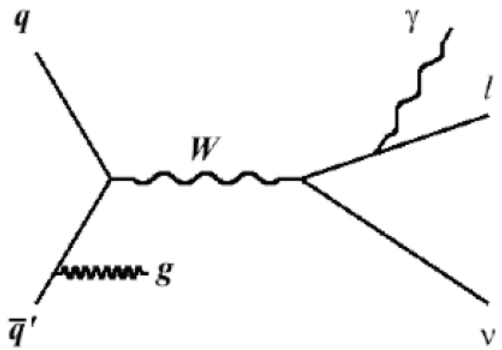


In a nutshell, measure two objects in the detector:
- Lepton (in principle e or μ; e in our analysis),
  need energy measurement with 0.2 per-mil precision (!!)
- Hadronic recoil, need ~ 1% precision

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 $e^+ e^- \rightarrow X$ 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 $p^+ p^{+/-} \rightarrow X$.
- 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.

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

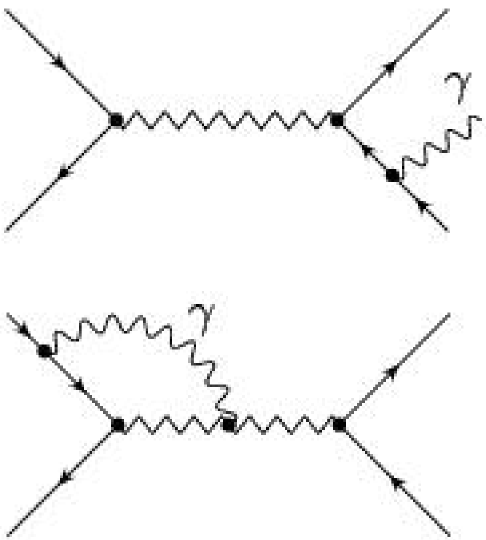
Our main generator is "**ResBos+Photos**". The NLO QCD in **ResBos** allows us to get a reasonable description of the p_T of the vector bosons. The two leading EWK effects are the first FSR photon and the second FSR photon. **Photos** gives us a reasonable model for both.

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).



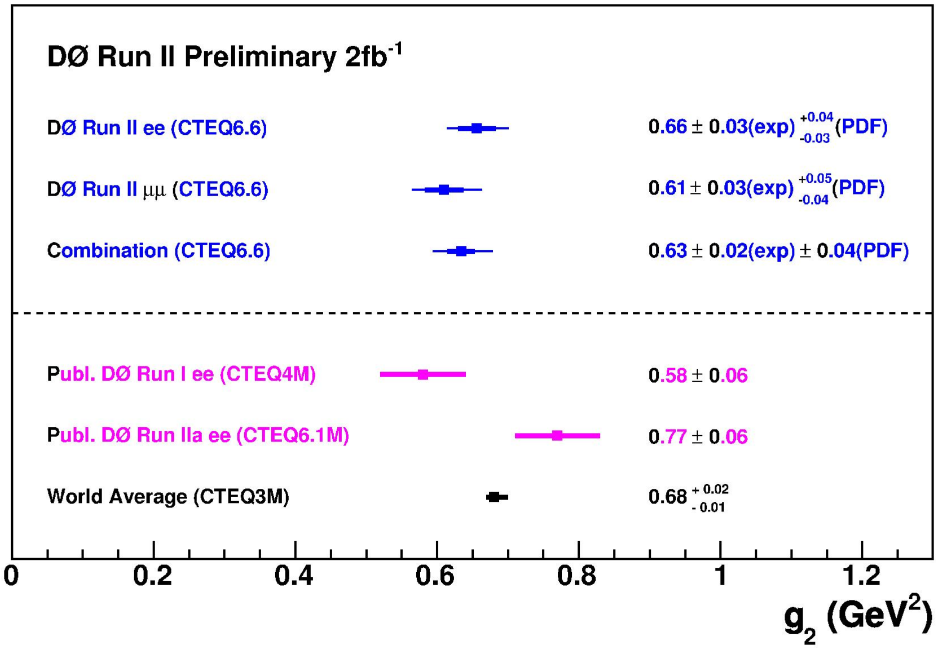
Model of W production and decay

As we have seen in Junjie's talk, at DØ we really measure the ratio of the masses of the W and the Z.
So our comparisons of two generators (or two setups of one generator) typically look like the one below.
Here we study the effect of a variation of the δs cut in W/ZGRAD. The cut is shown in the first two columns of the table. The fitted m_W moves around (columns 3-5), but so does the fitted Z mass (column 6), and the mass ratios (columns 7-9) turn out to be stable within toy MC statistics in this case.

δs	$E_\gamma cut$ (MeV)	ΔM_W (M_T) (MeV)	ΔM_W (P_T) (MeV)	ΔM_W (MET) (MeV)	ΔM_Z (Z Mass) (MeV)	$\Delta(\frac{M_W}{M_Z})$ (M_T) ($\times 10^{-5}$)	$\Delta(\frac{M_W}{M_Z})$ ($p_T(e)$) ($\times 10^{-5}$)	$\Delta(\frac{M_W}{M_Z})$ (MET) ($\times 10^{-5}$)
0.00025	10	-25 $\pm$ 3	-23 $\pm$ 4	-22 $\pm$ 4	-34 $\pm$ 2	5.5	7.7	8.8
0.0005	20	-29	-29	-27	-30	-2.8	-2.8	-0.6
0.0006	24	-24	-27	-24	-32	4.6	1.3	4.6
0.0007	28	-24	-29	-19	-32	4.6	-0.85	10.0
0.0008	32	-21	-23	-20	-33	8.9	6.7	10.0
0.001	40	-20	-20	-20	-27	4.2	4.2	4.2
0.003	120	-17	-22	-14	-21	1.7	-3.8	5.0
0.005	200	-10	-13	-12	-15	3.5	0.25	1.3
0.01	400	0	0	0	0	0	0	0
0.015	600	5	8	6	11	-5.2	-1.9	-4.1
0.02	800	18	20	15	26	-5.4	-3.2	-8.7

Table 4: Mass shift of W and Z due to δs variation.

On the non-perturbative form factor in ResBos



For the time being DØ discuss the form factor in terms of "g_2".

The present public results of our measurements of g_2 are shown on the left.

The one thing that I would like to point out is the (not unexpected) interplay between PDFs and g_2.

It would be good to have simultaneous parameterisations of the PDFs and the form factor (and I assume that Nadolsky and Yuan will discuss this in more detail in their talks).

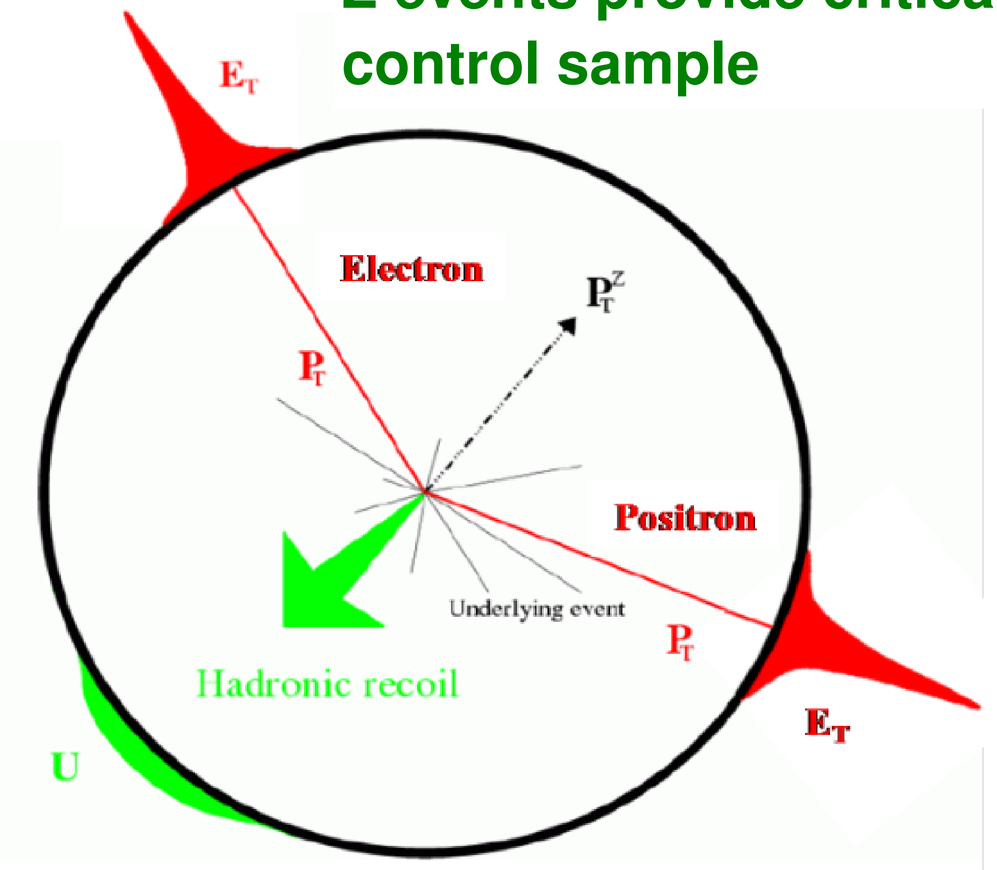
New, greatly improved DØ results are in the pipeline. Among other things, they will present **unfolded** DØ data in a way that is useful for such combined fits.

Changing gears: detector simulation

The detector simulation used in the DØ m(W) measurement is a parameterised simulation,
i.e. it has paramterised models for things like,
- electron identification efficiencies,
- electron energy resolution,
- recoil resolution,
- energy flow from the recoil into electron cone and vice versa,
- ...

Most parameter values are derived from data control samples. The single most important control sample is **$Z \rightarrow e\, e$** (because the Z mass is well known and the e e final state can be reconstructed with excellent resolution).

Z events provide critical control sample

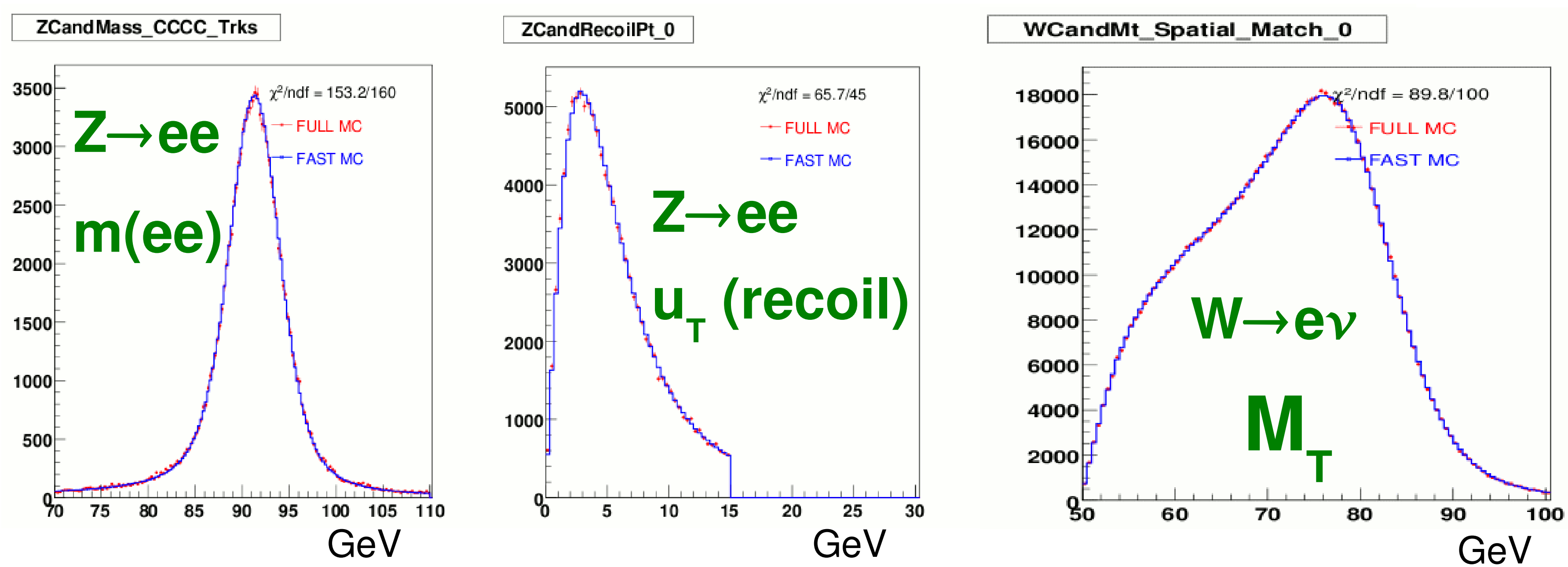


But: some parameterisations are derived from detailed first principles simulations,
e.g. electron E-loss corrections, sampling term in electron energy resolution, detailed model of electron identification efficiency [Z data are used to derive a small correction], photon energy response (for FSR), ...

MC closure test

Standard worry with parameterised detector simulations: "*you fit some ad-hoc parameterisation to some data and of course they will match; but how do you know that the parameterisation and fit procedures make any sense ?*". Useful tool: MC closure test !!

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 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.



✓ **Good agreement between full and parameterised MC.**

MC closure test

Standard worry with parameterised detector simulations: "*you fit some ad-hoc parameterisation to some data and of course they will match; but how do you know that the parameterisation and fit p*

Before a … ns we treat sim … erform a full W … known in … MC match M

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

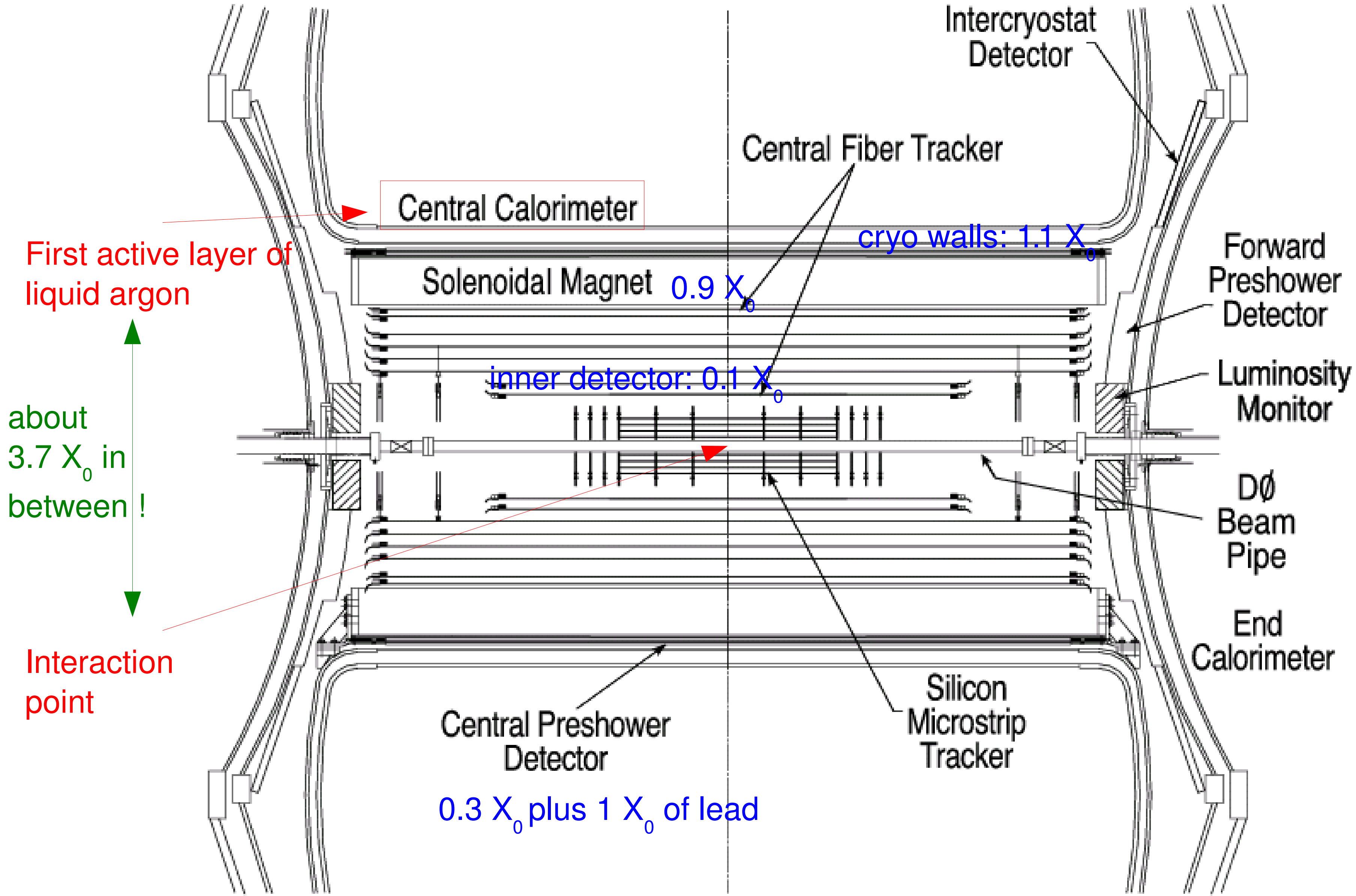
Input value: 2.070 GeV

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

GeV GeV GeV

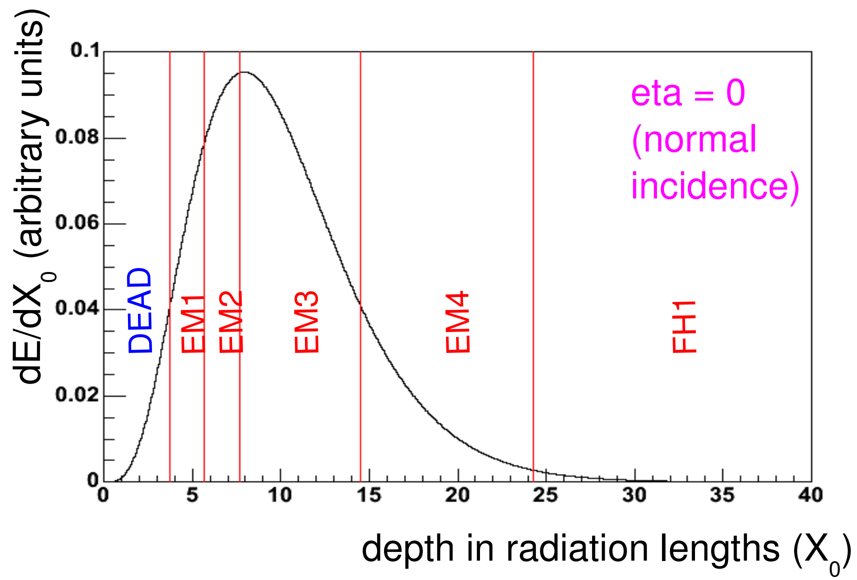
✓ **Good agreement between full and parameterised MC.**

Keep in mind: the CAL is not alone !



Samples and weights

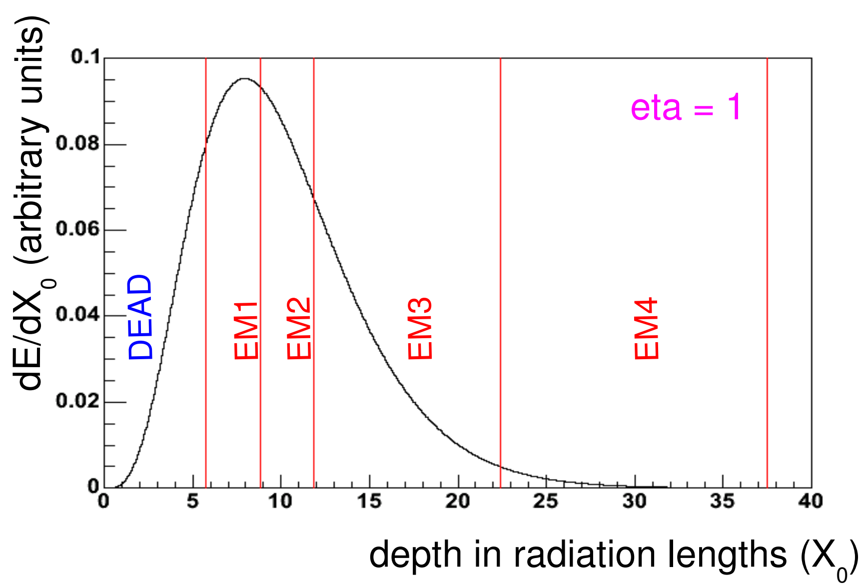
The plot on the right shows the average longitudinal profile of a shower with E = 45 GeV. Assuming normal incidence, the position of the active parts of the CC are also indicated.



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

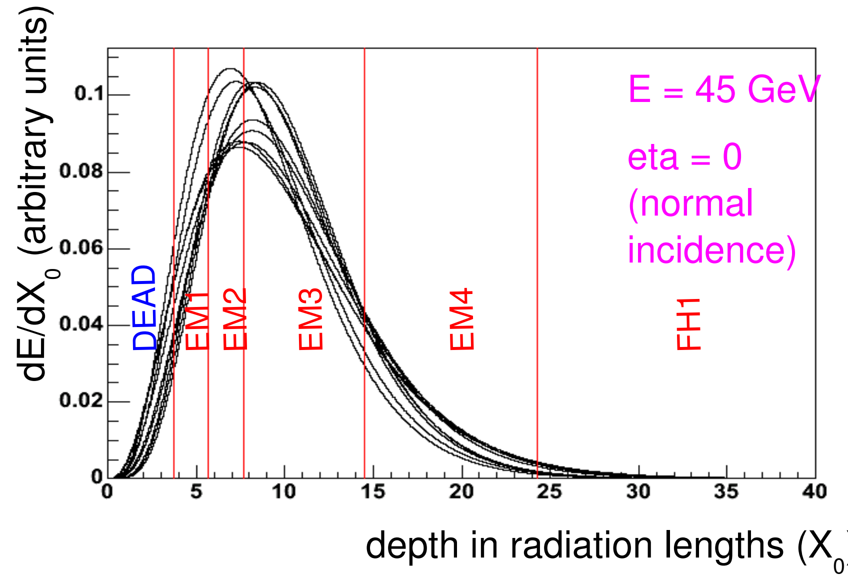
The lower plot illustrates the situation for the same average shower, but this time under a more extreme angle of incidence (physics eta = 1). The shower maximum is now in EM1 !



Energy-dependence and fluctuations

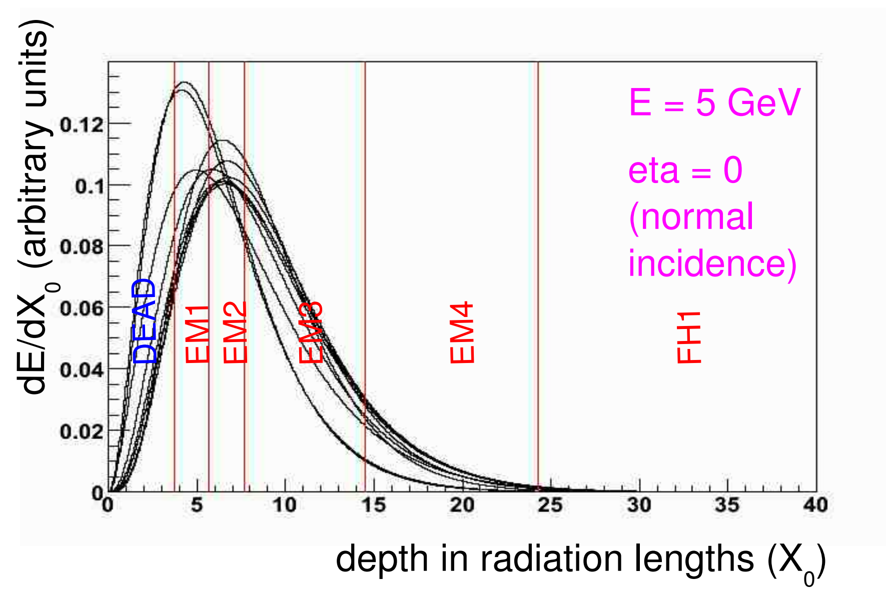
The plots on the previous slide show the *average* shower profile at E = 45 GeV.
The plot on the right is basically the same, except that it includes typical *shower fluctuations*.

=> 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).

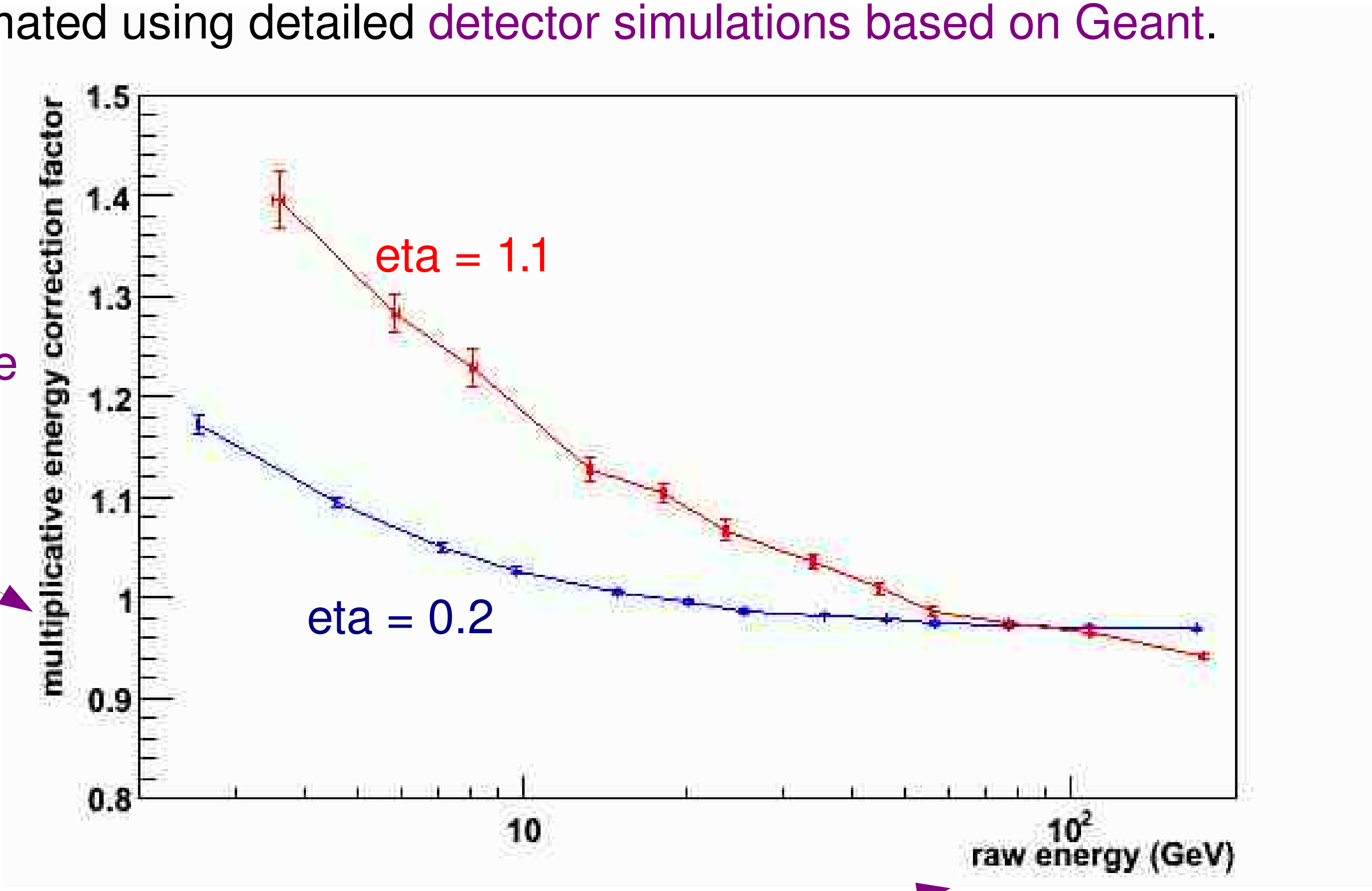
=> The average fraction of energy lost in dead material, as well as the relative importance of shower-by-shower fluctuations depend on the energy of the incident electron.



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.



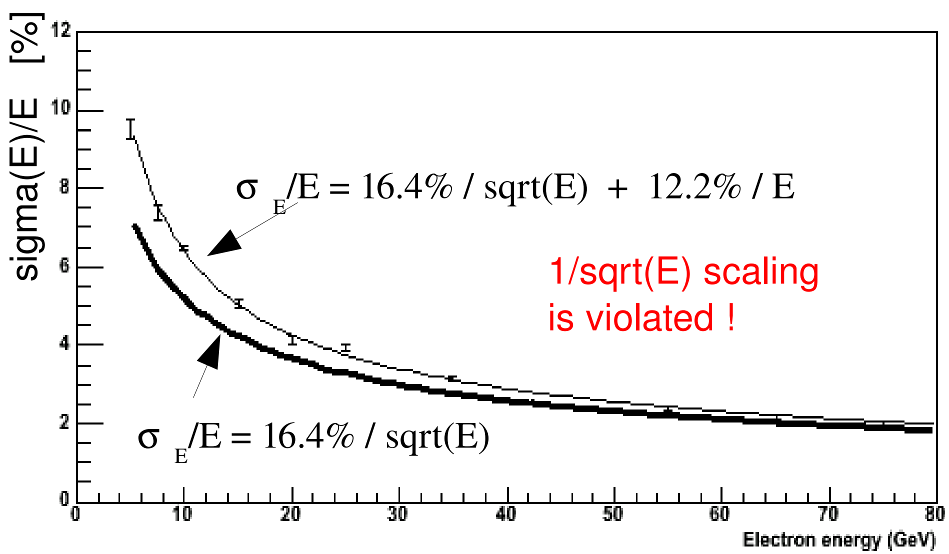
This is the energy as reconstructed in the CAL.

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

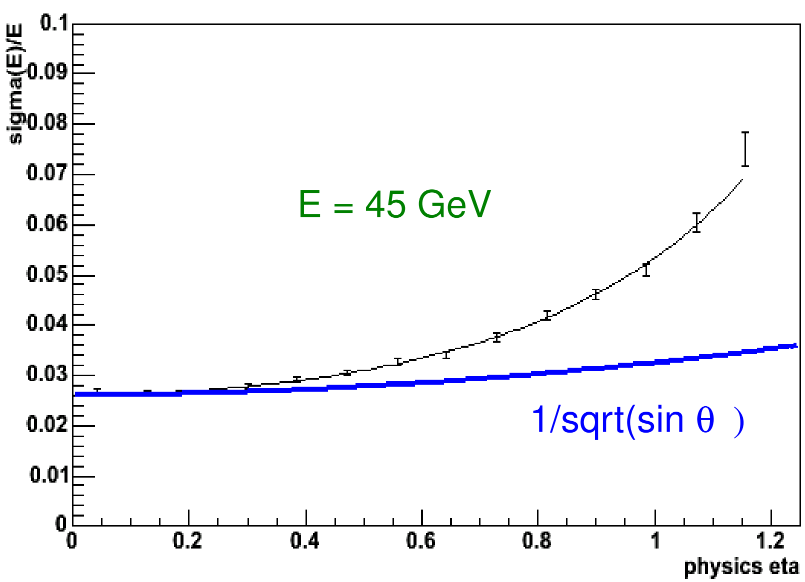
Here we show the impact on the energy resolution for electrons. This is again from a detailed detector simulation based on Geant.

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):

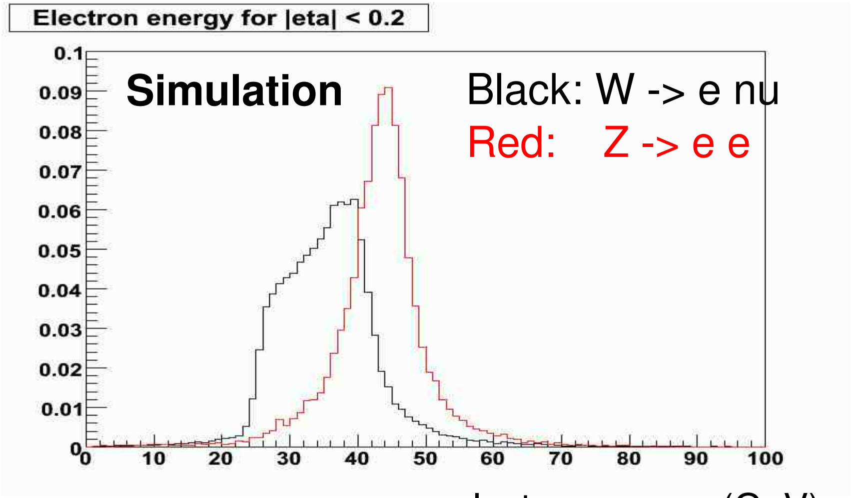


for an ideal sampling calorimeter (no dead material) one would expect this to be almost flat

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 : $0.8 \le |\eta|$

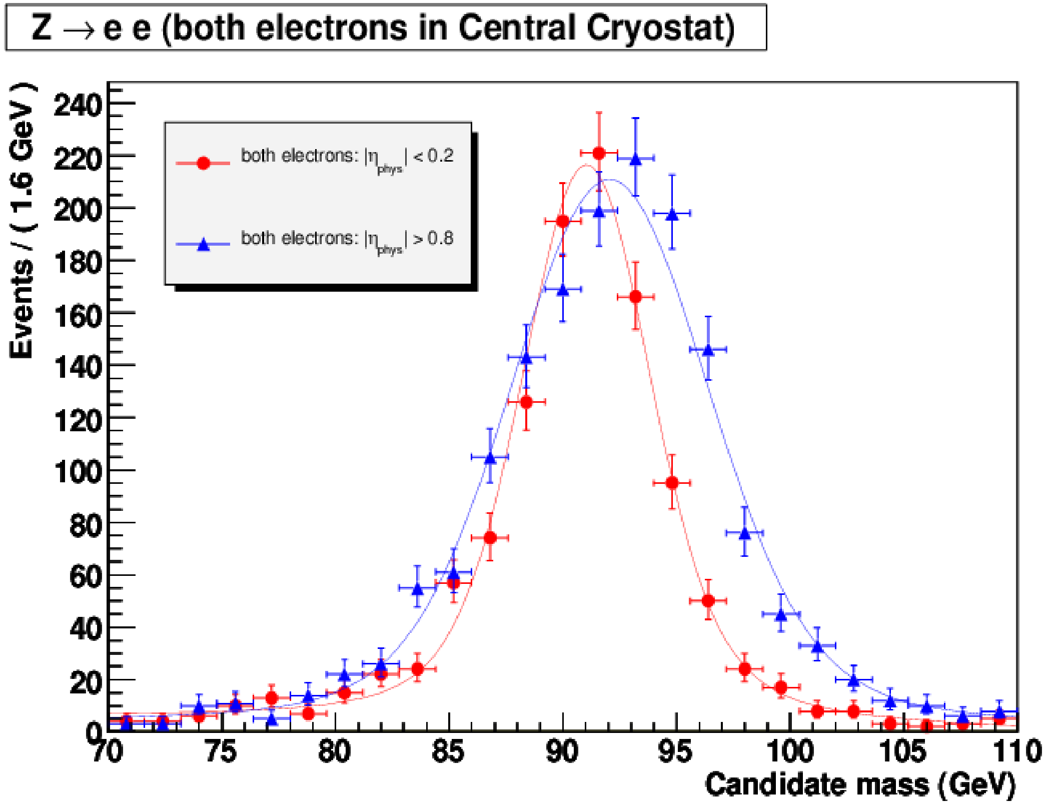
Category	Bins of Each Electron
10	0 – 0
11	0 – 1
12	0 – 2
13	0 – 3
14	0 – 4
15	1 – 1
16	1 – 2
17	1 – 3
18	1 – 4
19	2 – 2
20	2 – 3
21	2 – 4
22	3 – 3
23	3 – 4
24	4 – 4

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:

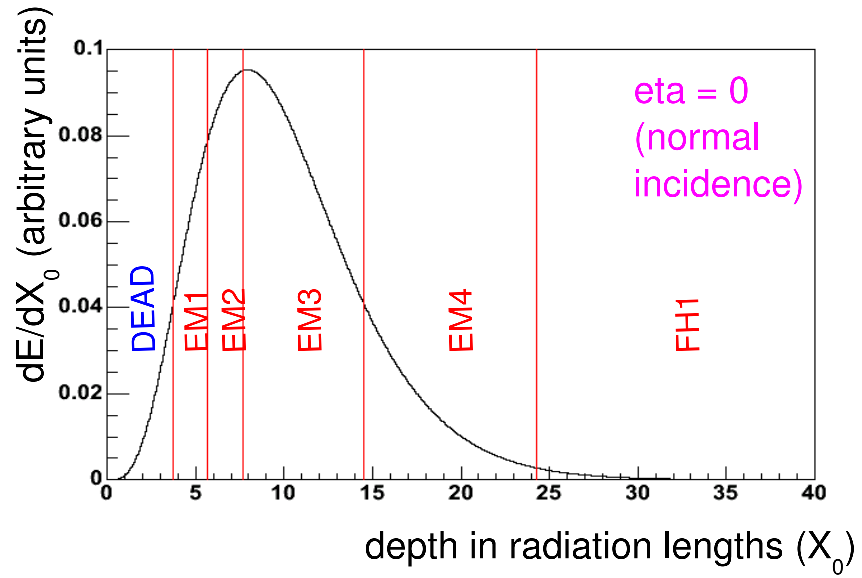
- different resolutions (material !),
- the peaks are not in the same place.

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 !!

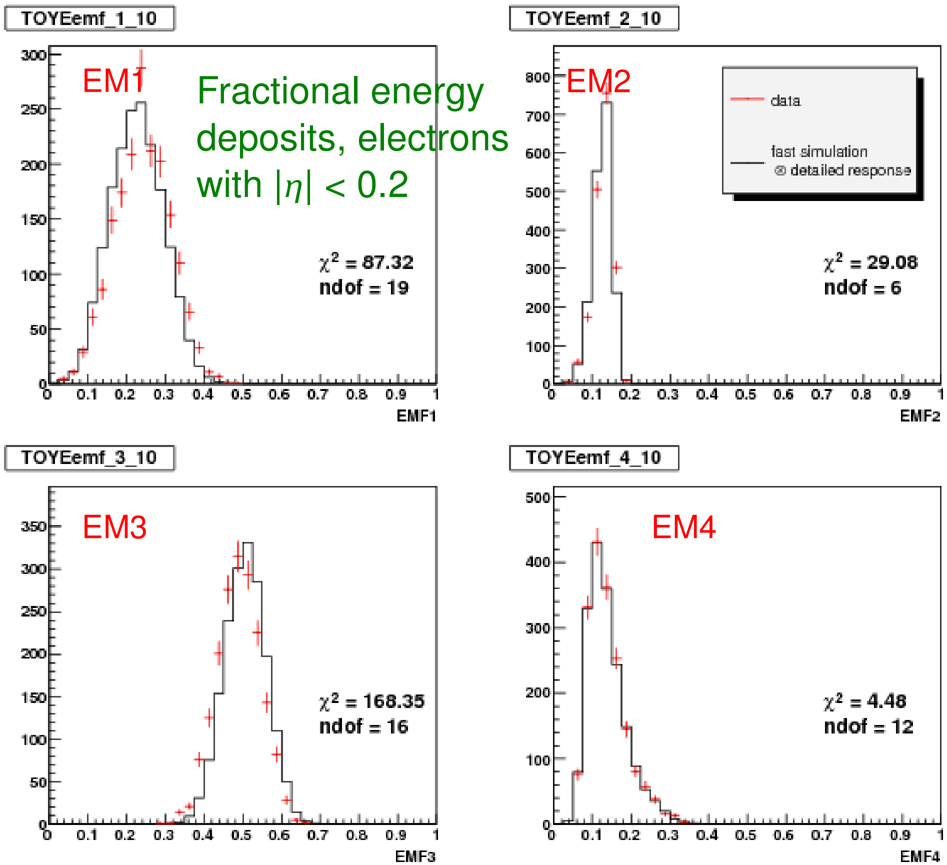


Using the longitudinal segmentation to get a handle on material is a standard technique, it is discussed in the textbooks (e.g. Wigmans).

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.

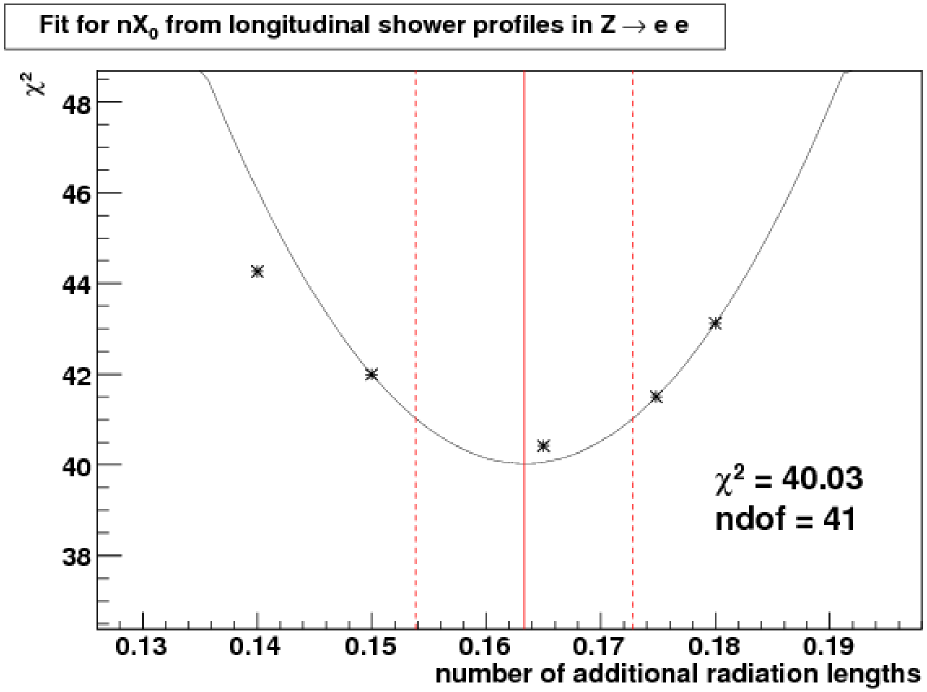


Fit for amount of missing material

"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.

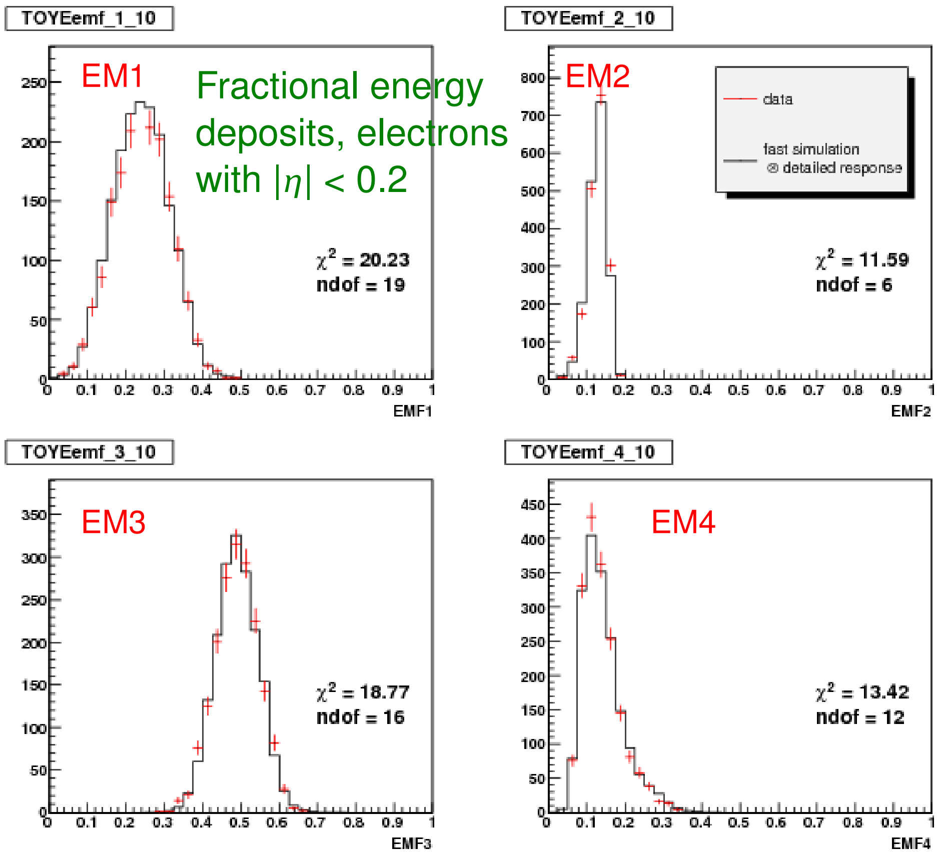


Amount of fudge material to within less than $0.01X_0$!

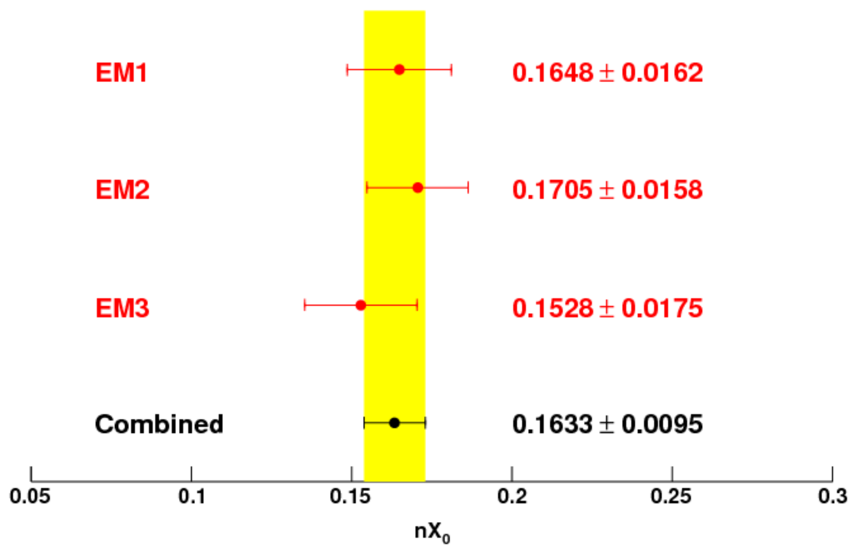
With comparatively small systematics from background (underlying event) subtraction and modelling of cut efficiencies.

After tuning of material model

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



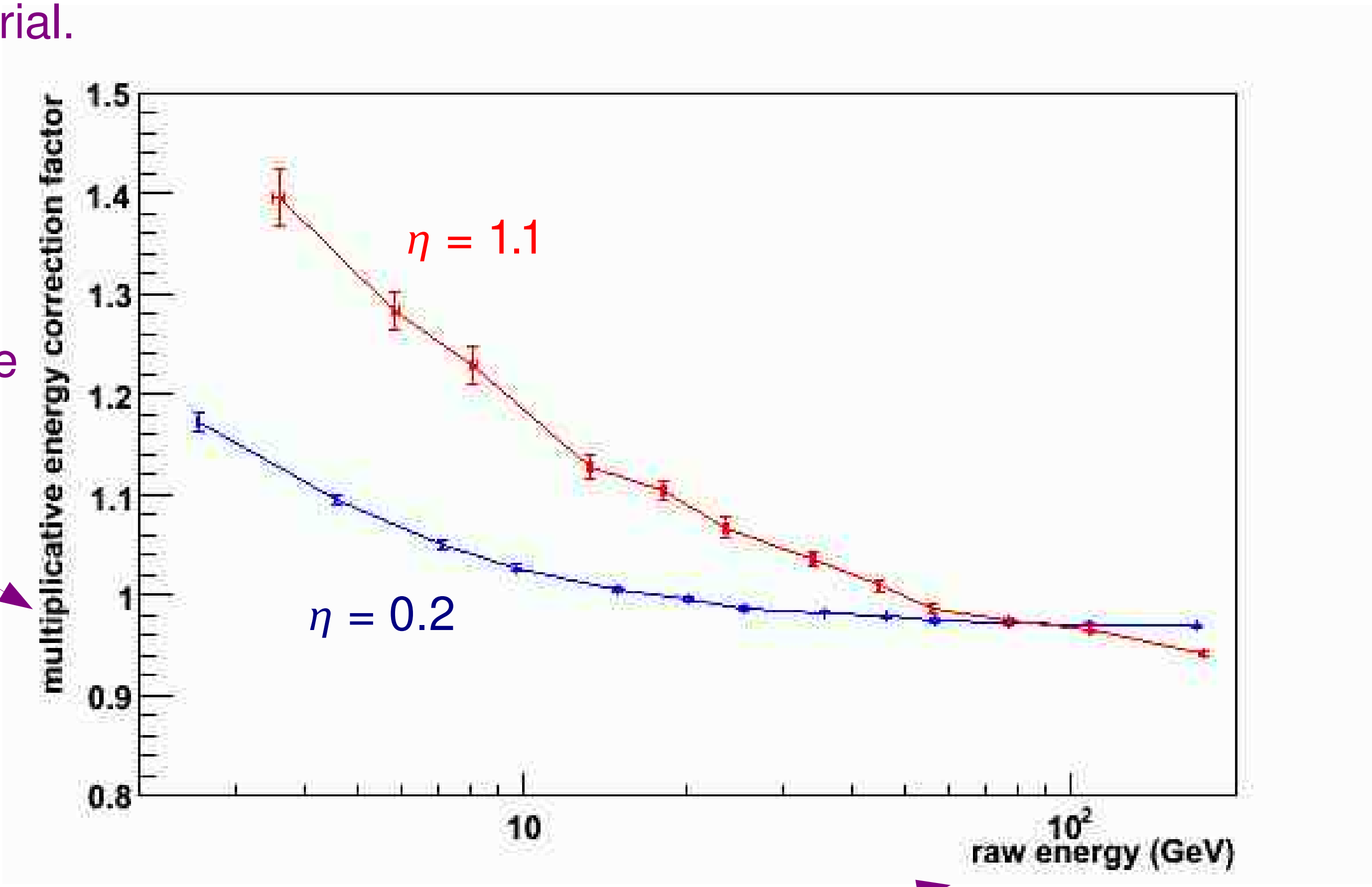
As a cross-check:
Repeat fit for nX_0, separately for each EM layer. Good consistency is found.



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 $Z \to e\,e$, 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 $Z \to e\,e$ 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:
α = 1.0111 ± 0.0043
β = -0.404 ± 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

Electrons: energy resolution

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

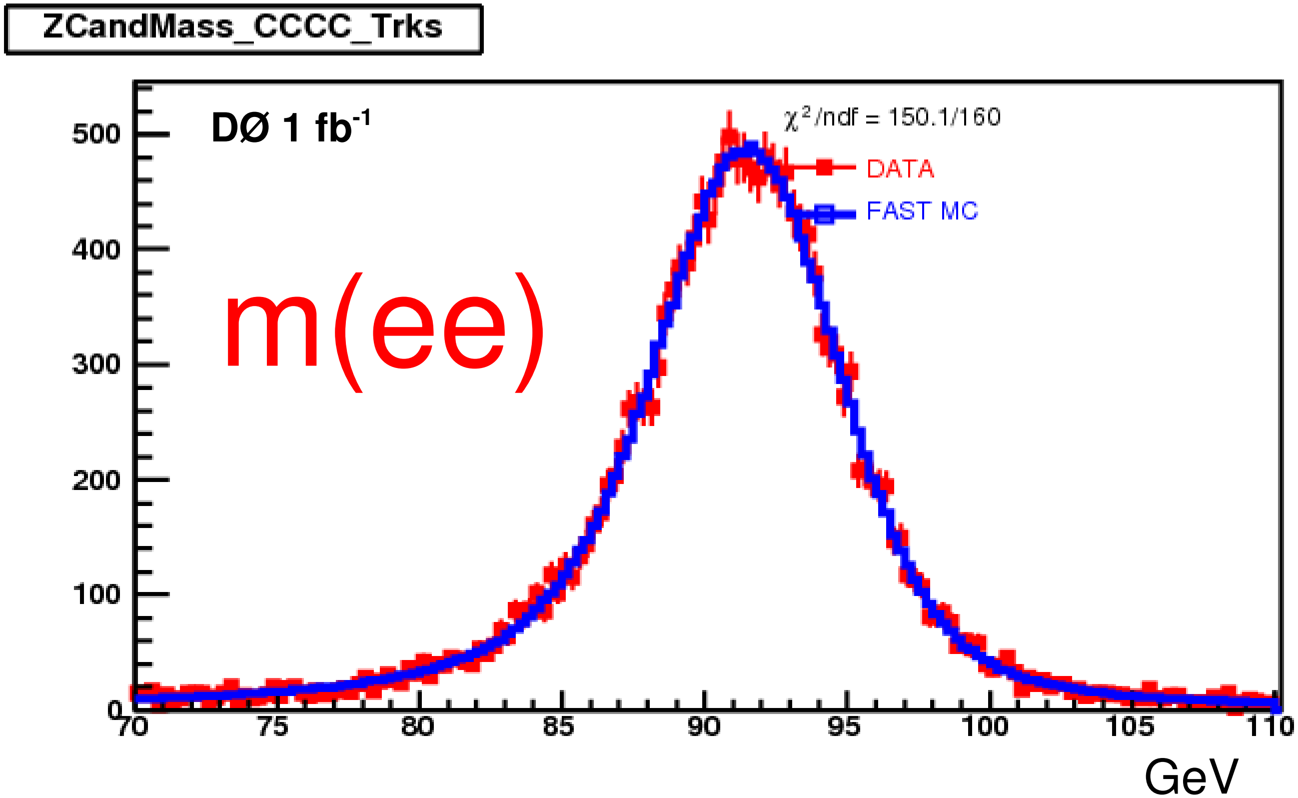
Sampling fluctuations are driven by sampling fraction of CAL modules (well known from simulation and testbeam) and by uninstrumented material. As discussed before, amount of material has been quantified with good precision.

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

Result:

C = (2.05 $\pm$ 0.10) %

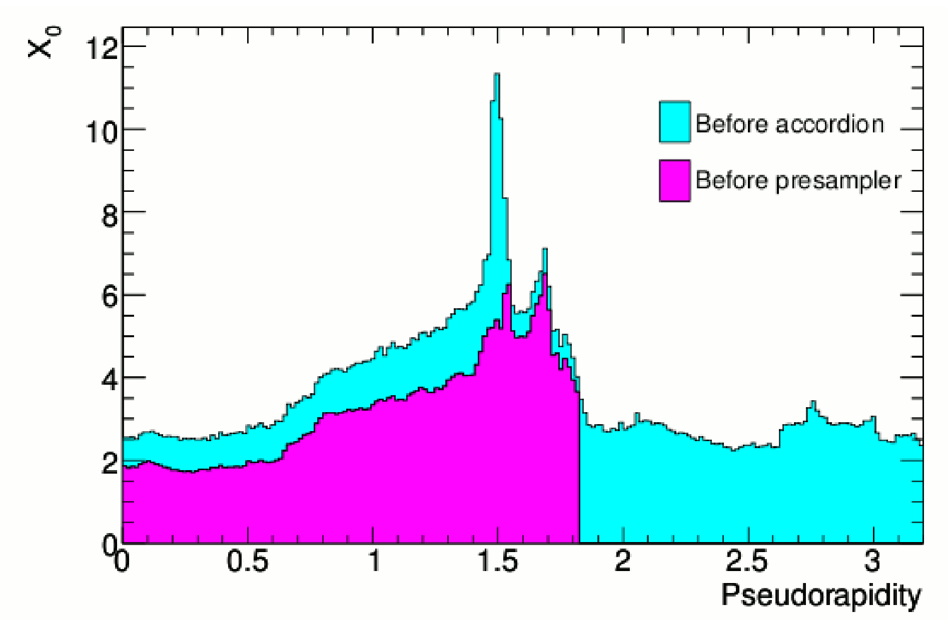
in excellent agreement with Run II design goal (2%)



More discussion: dead material

Large amounts of dead material are not uncommon in modern experiments; here is one example.

From ATLAS detector paper:



Amount of passive material in front of the EM calorimeters.

From ATLAS CSC book:

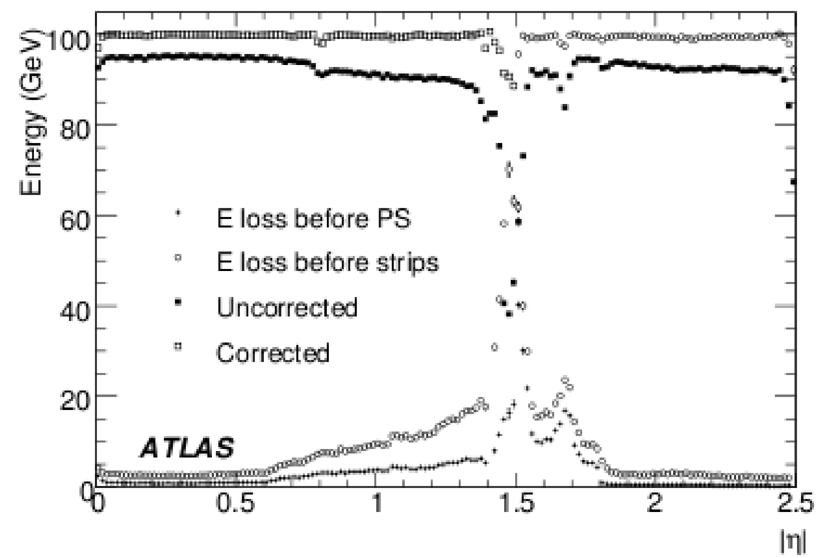


Figure 1: Average energy loss vs. $|\eta|$ for $E =$ 100 GeV electrons before the presampler/strips (crosses/open circles), and reconstructed energies before/after (solid/open boxes) corrections.

EM shower simulation: the basics

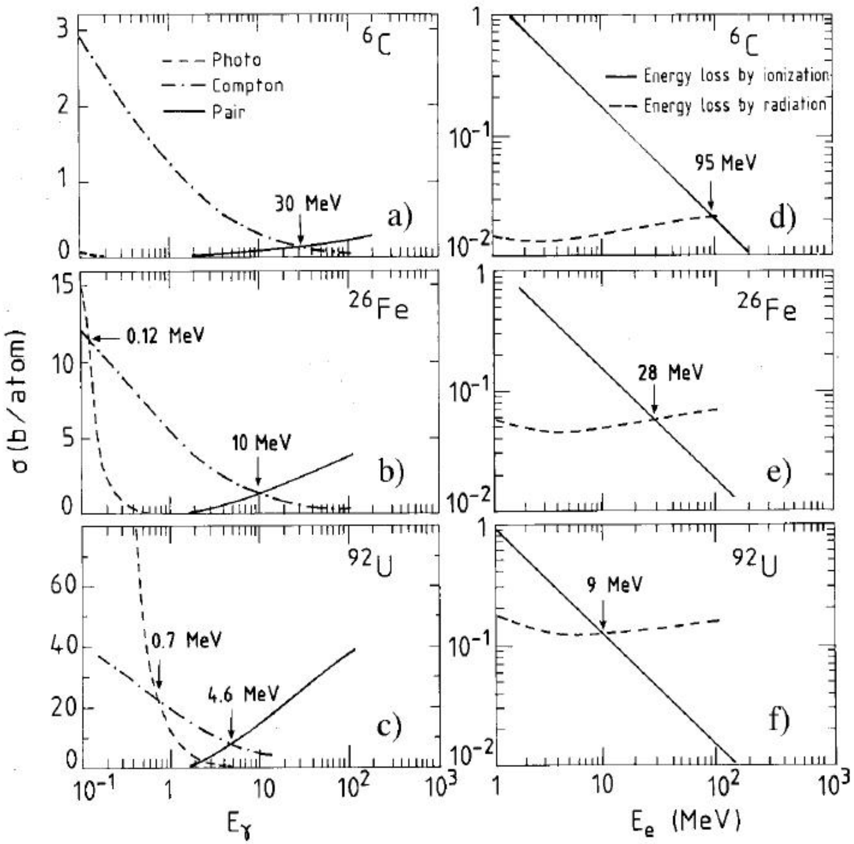


FIG. 2.1. Cross sections for the processes through which the particles composing electromagnetic showers lose their energy, in various absorber materials. To the left are shown the cross sections for pair production, Compton scattering and photoelectric effect in carbon (*a*), iron (*b*) and uranium (*c*). To the right, the fractional energy losses by radiation and ionization are given as a function of the electron energy in carbon (*d*), iron (*e*) and uranium (*f*).

Figures from the textbook by Wigmans (and references therein).

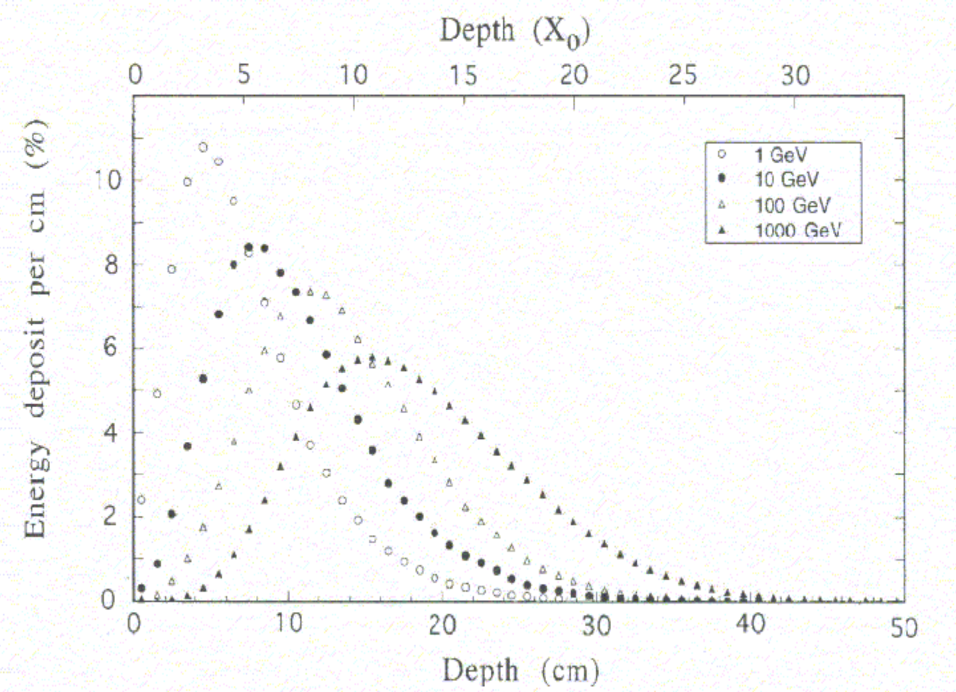


Figure 4: The energy deposit as a function of depth, for 1, 10, 100 and 1000 GeV electron showers developing in a block of copper. In order to compare the energy deposit profiles, the integrals of these curves have been normalised to the same value. The vertical scale gives the energy deposit per cm of copper, as a percentage of the energy of the showering particle. Results of EGS4 [8] calculations. This figure has been taken from Ref. [9].

Bremsstrahlung and pair production drive the overall shower development.
Ionisation (including δ-rays), Compton scattering and the photoelectric effect are important for the details of the way in which the energy of low-energy e/γ is deposited locally (effects at U/LAr boundary).

Bremsstrahlung

In principle, the calculation of Bremsstrahlung cross sections may sound easy: it is just plain QED.
But in practice these calculations involve time-consuming Hartree-Fock calculations,
partial wave expansions, etc, etc.

The state of the art is described in this paper (as well as references therein):

S.M. Seltzer and M. J. Berger,
"Bremsstrahlung spectra from electron interactions with screened atomic nuclei and orbital electrons",
NIM **B**12, 95-134 (1985).

The authors provide a comprehensive set of cross sections, differential in photon energy, for electrons with kinetic energies from T = 1 keV to T = 10 GeV incident on neutral atoms with atomic nums Z = 1 to 100.

Bremsstrahlung in the nuclear field:

For $T < 2$ MeV:

Full numerical partial-wave analysis for a few elements and energies (limited by computing at the time)

For $T > 50$ MeV:

Analytical calculations, including screening and Coulomb corrections

In between:

"Smooth interpolation" in $(\beta^2/Z^2)k*d\sigma/dk$

Bremsstrahlung in the field of the atomic electrons:

Effects of atomic binding and screening are taken into account (includes full Hartree-Fock calculations), give or take a few small approximations, justified in the paper.

Uncertaities on total cross section, estimated by the authors:

$T < 2$ MeV: 5 – 10 %

2 MeV $< T <$ 50 MeV:

decreasing from 10 % at 2 MeV to 3 % at 50 MeV

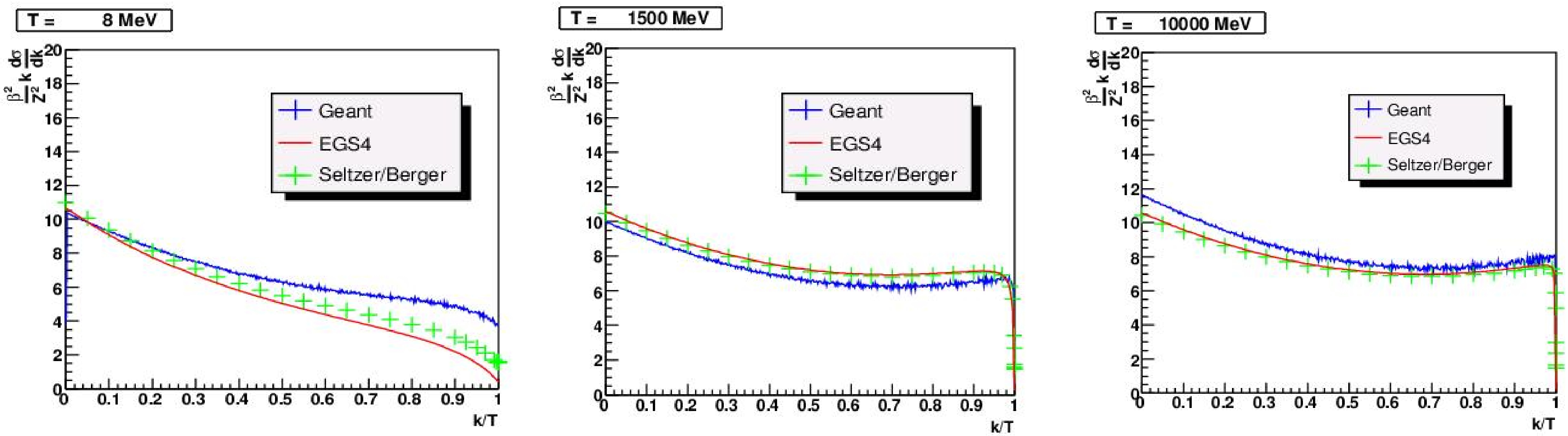
$T > 50$ MeV: 3 %

Within these uncertainties, the predictions are consistent with the limited experimental data that are available.

Bremsstrahlung

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.

Example: Bremsstrahlung by electrons in uranium



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

Geant uses a simple fit to a subset (six elements and a limited number of k/T values) of the numbers published by*Seltzer and Berger. Uranium (shown above), is one of the elements included in the fit; agreement is much worse for some elements that are not included.

Seltzer and Berger have published a large ASCII file with all their results. Have plugged this complete look-up table into Geant. For energies above T = 10 GeV, the analytical high-energy formulae are used .

Photon interactions

Two extensive collections of cross sections for the interactions of photons with matter are accessible to the community.

- XCOM: Photon Cross Sections Database
  Provided by the National Institute of Standards and Technology

  http://physics.nist.gov

- EPDL97: The Evaluated Photon Data Library
  Lawrence Livermore National Laboratory

  http://www-nds.iaea.org/epdl97

These databases provide, among other things, cross sections for pair production, coherent (Rayleigh) and incoherent (Compton) scattering, as well as the photoelectric effect, for $1 \leq Z \leq 100$ and $1\ \text{keV} \leq T \leq 100\ \text{GeV}$.

Have compared the cross sections in these two databases with the parameterisations that are implemented in Geant.

As we will see on the next slide, the two databases are in remarkable agreement with each other.
This is not surprising given that there is a large overlap between the list of authors of these two databases, and given that, in many cases, they use numbers from the same papers.

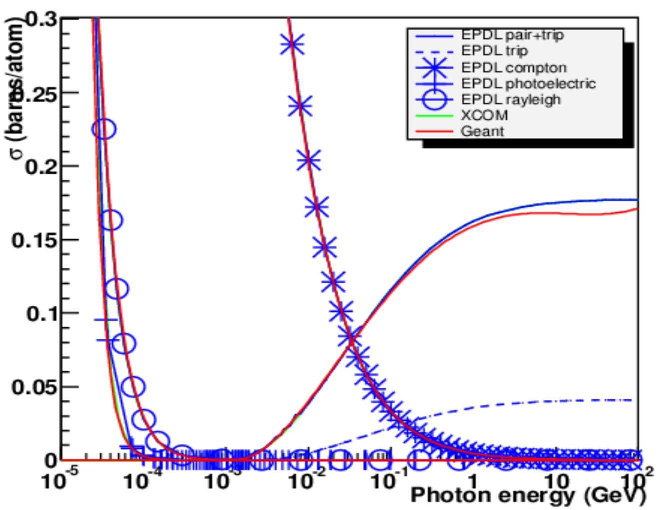
Geant also agrees remarkably well with these databases. This is again not surprising. Geant uses again simple parameterisations, but the shapes of the photon cross sections are much easier to parameterise than Bremsstrahlung, and again the numbers from the same papers have been used as inputs to the fits.

A small exception is pair production at low Z where the fits do not work too well, as we will see on the next slide.

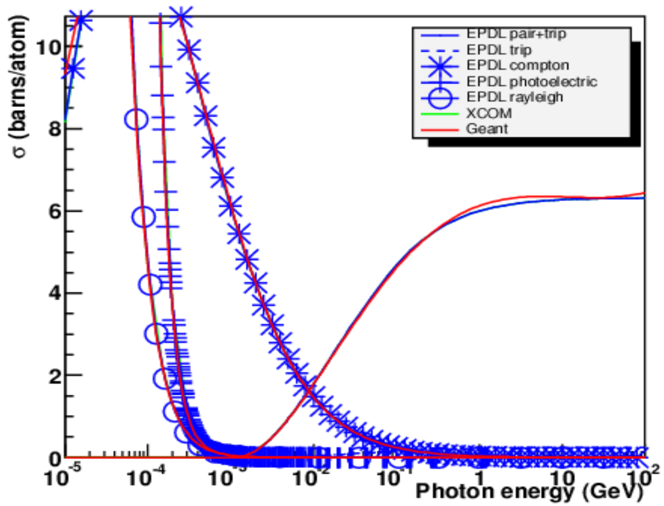
Photon interactions

Comparision for three example elements:

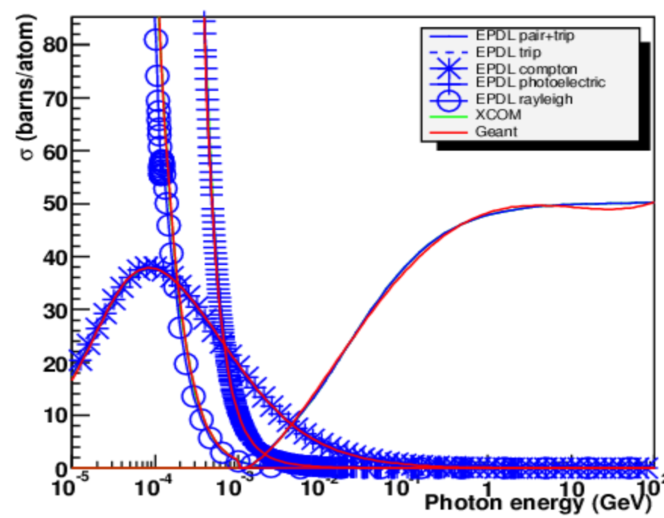
Z = 4 (Beryllium)



Z = 29 (Copper)



Z = 92 (Uranium)



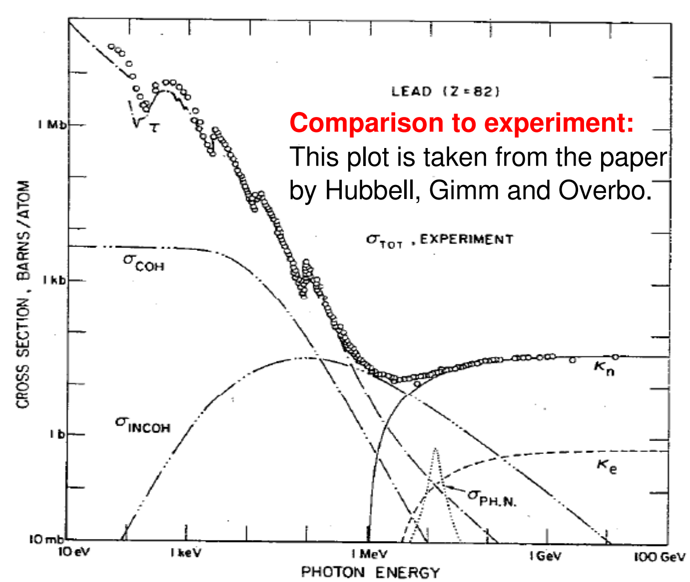
Most parameterisations of photon cross sections in Geant are not too bad. One small exception is pair production.

For pair production, both databases use the results from this paper:

J.H. Hubbell, H.A. Gimm and I. Overbo,
"*Pair, Triplet, and total atomic cross sections (and mass attenuation coefficients) for 1 MeV – 100 GeV photons in elements Z = 1 to 100*",
J. Phys. Chem. Ref. Data **9**, 1023 (1980).

The results in this paper have also been used to establish the parameterisation for Geant.

Have extracted the results from Hubbell *et al.* from the XCOM database and have plugged a complete look-up table into Geant.



Comparison to experiment:
This plot is taken from the paper by Hubbell, Gimm and Overbo.

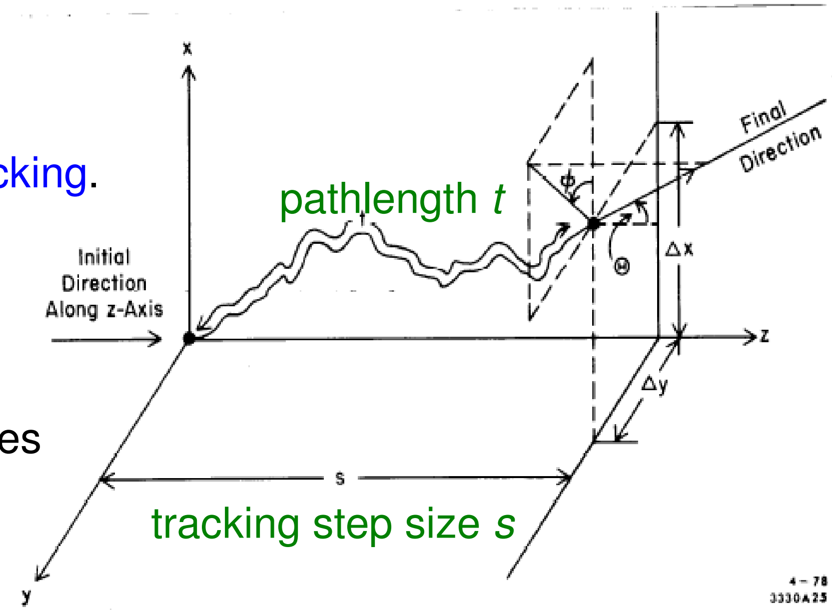
Particle “tracking”

In a nutshell:

- There are various parameters in Geant (3) particle tracking. These include things like the “maximum fractional energy loss in one step” and the “shortest step size Geant is willing to take”.

- Most users use Geant in AUTO mode, *i.e.* Geant choses the values of the parameters for them.

- 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).

- *One* of the nasty things that can happen in AUTO mode is that, 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). This leads to dramatic (factor 3-4) overestimates of the range of sub-MeV electrons ... [which is pretty bad when you simulate a sampling calorimeter].

(Important) technical comments

Some technical comments/pleas, without any specific order:

- **We need "knobs to turn":**

  It is good that we have ever more precise calculations and event generators that get close to reproducing the data ! But in most cases they will not match *exactly* => want adjustable parameters.

  Of course, the parameters need to make some physics sense ... of you tune them to Z data they should work well for W data.

- **We all need alternatives to compare:**

  It is good that there are multiple experiments per collider (*e.g.* CDF and DØ); we can compare their analyses and results.

  We have learned very valuable lessons from comparing Geant and EGS.

  It would be good if there were multiple generators that are good at EWK and QCD and that, out-of-the-box, give a good description of vector boson data (including boson p_T) ...

- **We need public codes (including event generators):**

  Could not have done the Geant <-> EGS validation/comparison without the source code.

  Even if they contain bells, whistles and switches that we do not have to / want to play with, being able to run ourselves at least allows us to check a few obvious things like numerical stability.

  Also, we need to generate *huge* samples.

Conclusion

Precise simulations, both in terms of event generators and detector simulations, are the key ingredient for precise W and Z measurements at the Tevatron.
This statement is true in general, and even more true for the m(W) measurement.

For event generators, soft QCD and getting the boson p_T distribution right is crucial.
For far, have ~one generator that ~works in the real world.

For detector simulations, the trick is to effectively combine parameterised and detailed first principles simulations.
There is a trend to give more and more weight to the first principles calculations (they were a minor aspect in the Run IIa analyses, and they have become crucial in the first DØ Run IIb analysis). This trend is expected to continue in the future.

In this talk we have discussed in some detail the specific example of the precise simulation of the electron energy response (and resolution). This response needs to be known with extraordinary precision for m(W) measurements.

Last but not least, the technical pleas on the previous slide are important for continuing progress.

Backup slides

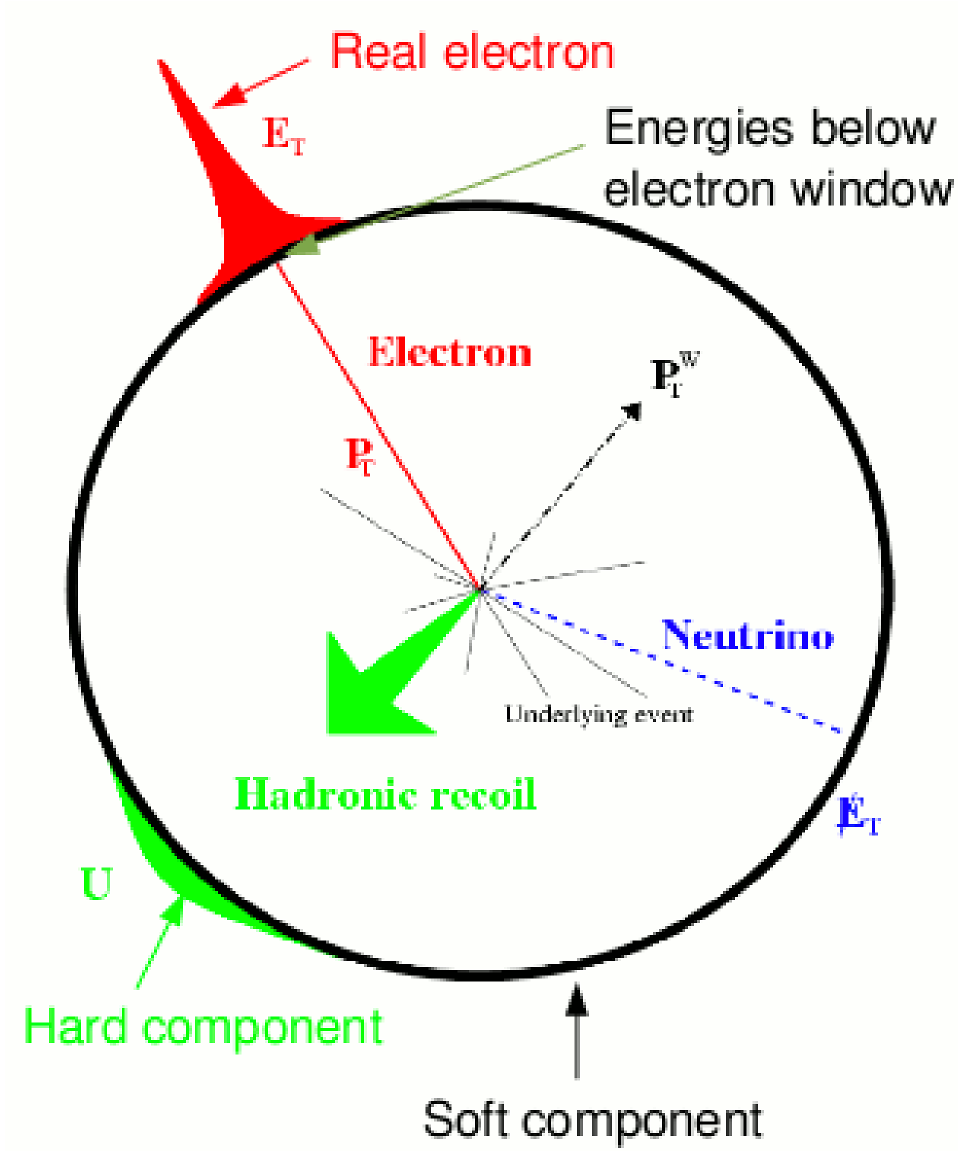
First DØ Run II measurement of the W boson mass

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

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

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

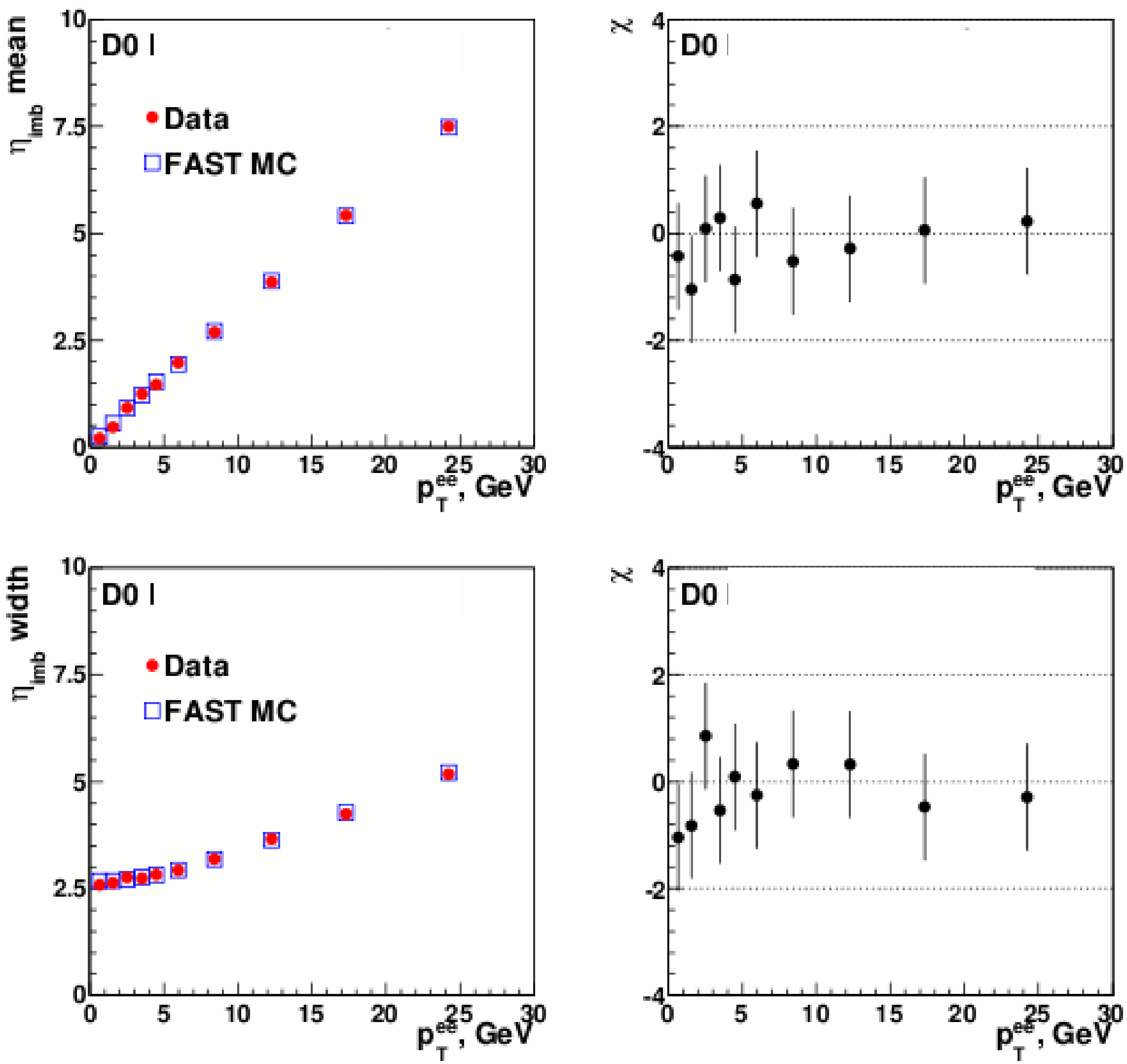
Recoil energy "lost" into the **electron cones**.
Electron energy leakage outside cluster.

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

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

Recoil calibration

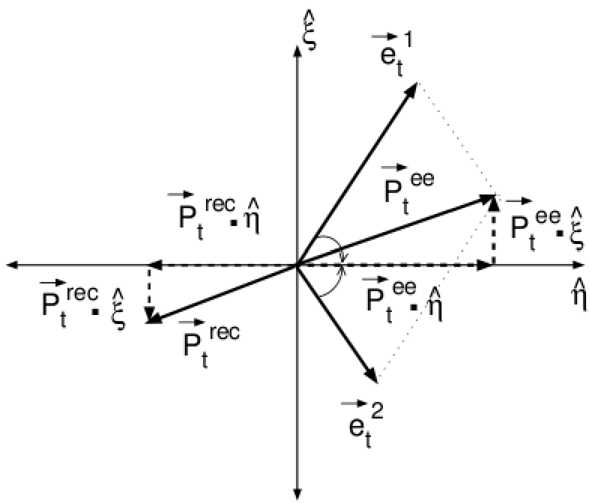
Final adjustment of free parameters in the recoil model is done *in situ* using balancing in $Z \rightarrow e\,e$ events and the standard UA2 observables.



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

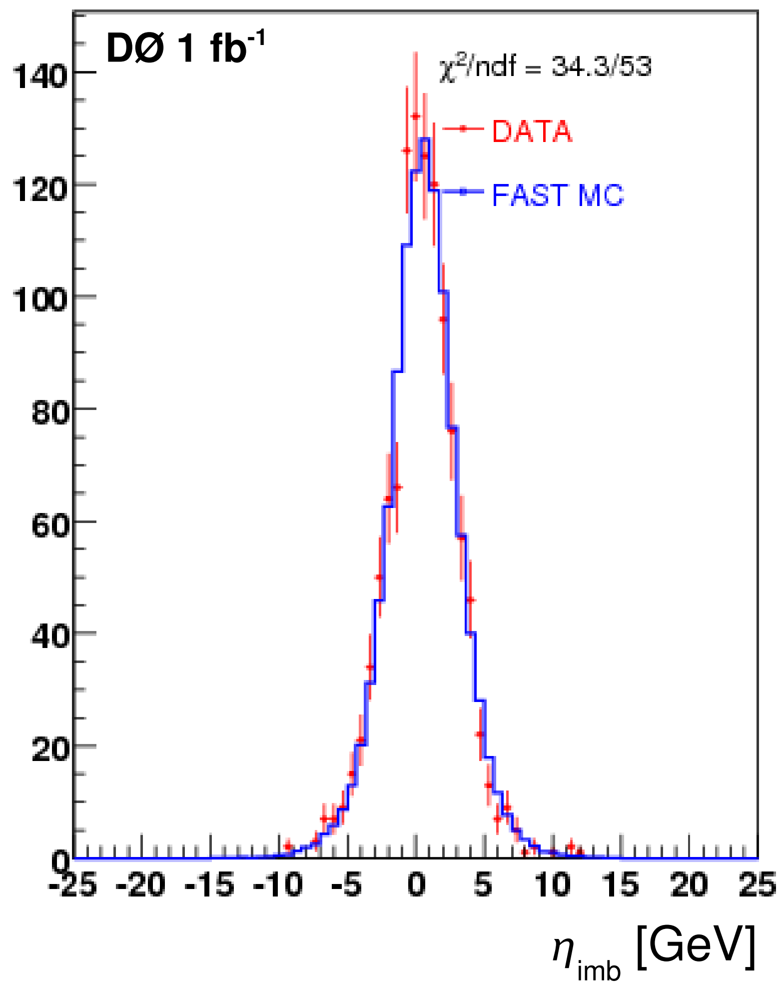
$$\eta\text{-imbalance} : (\vec{P}_t^{\,ee} + \vec{P}_t^{\,rec}) \cdot \hat{\eta}$$

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

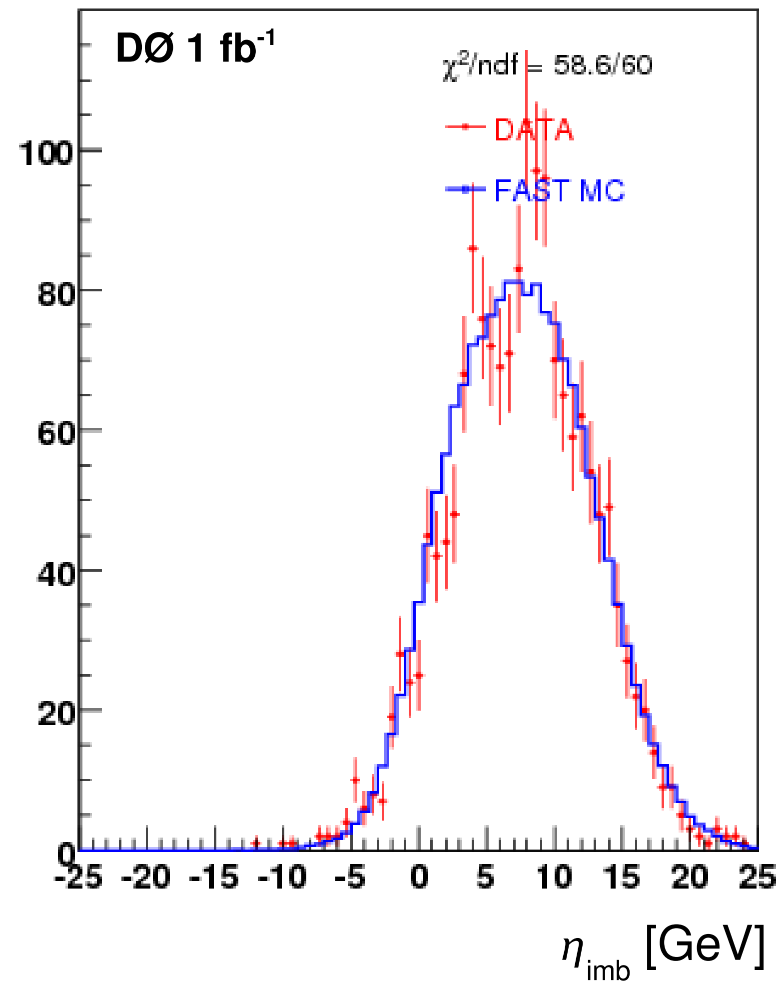


Examples: η_{imb} distributions

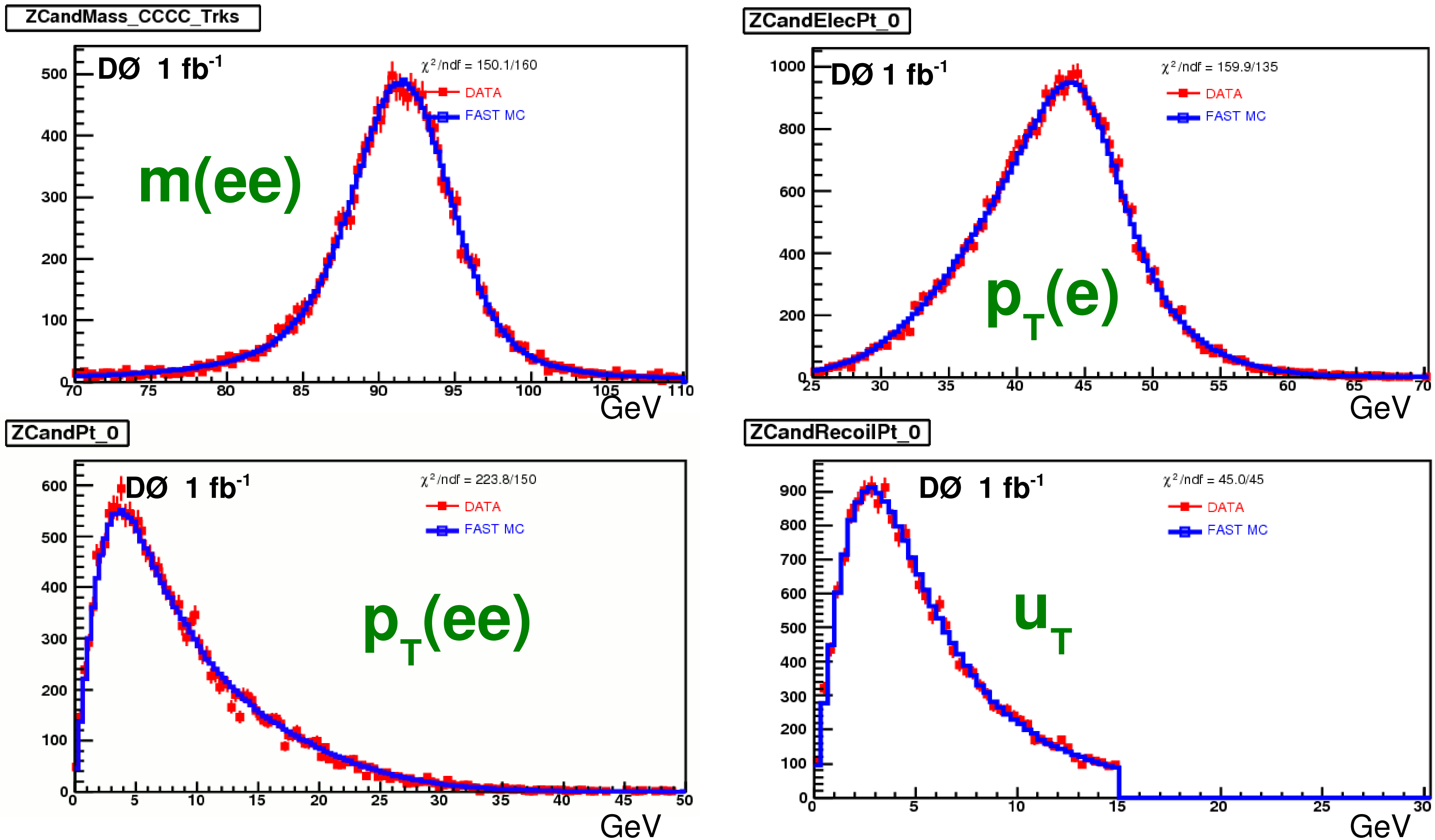
1 < p_T(ee) < 2 GeV



20 GeV < p_T(ee)



Results: Z → e e data

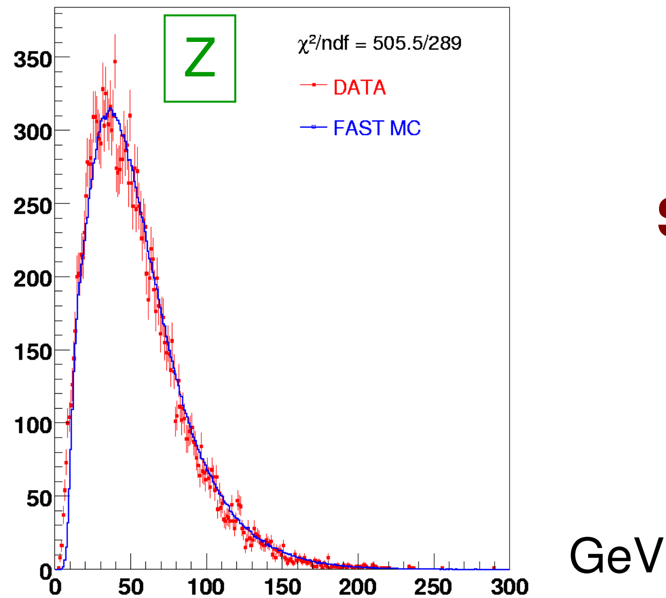


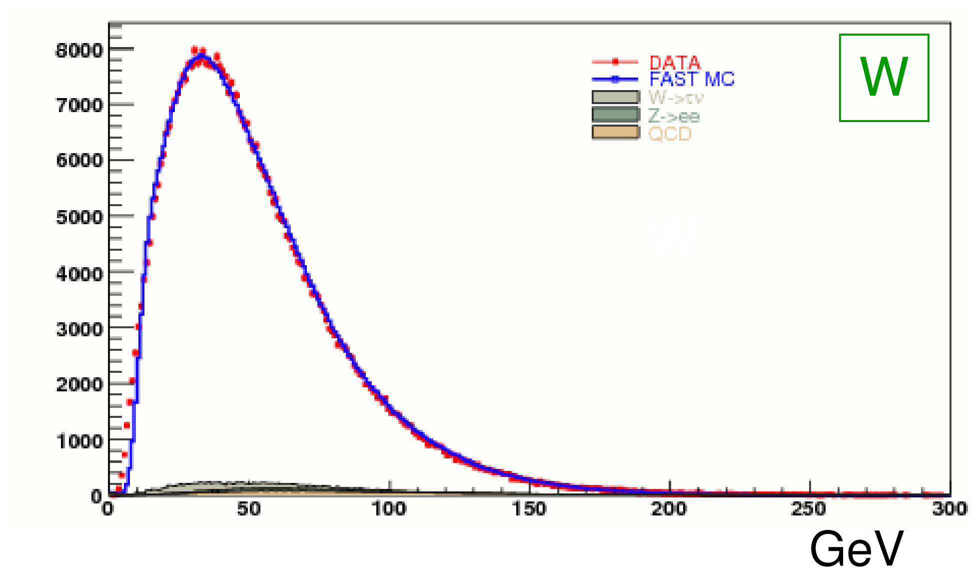
✓ **Good agreement between parameterised MC and collider data.**

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

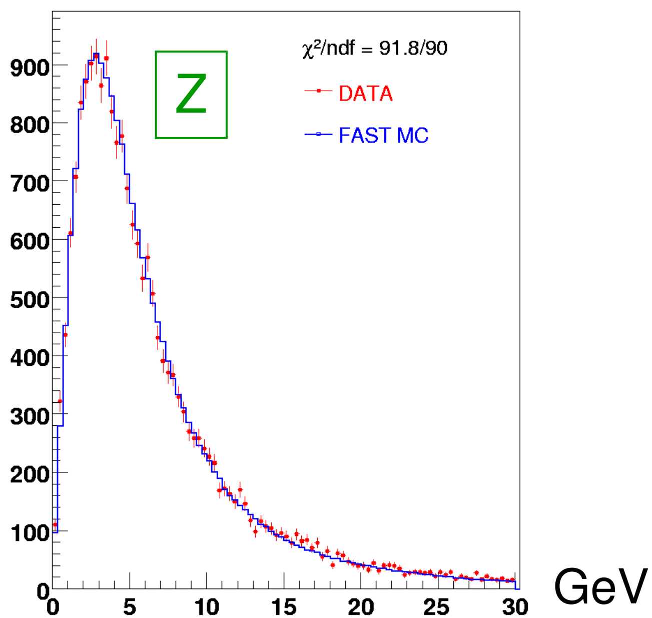
Data in red
MC in blue

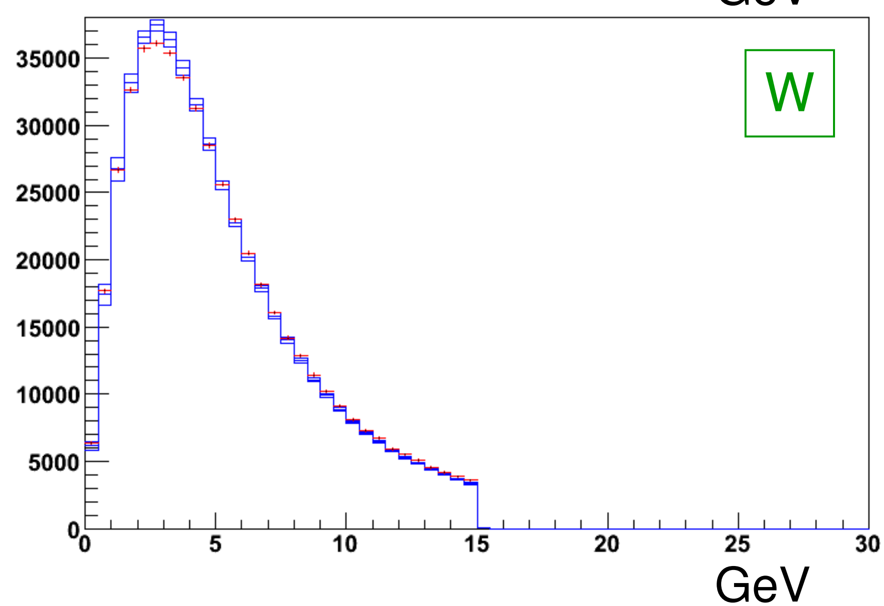
SET





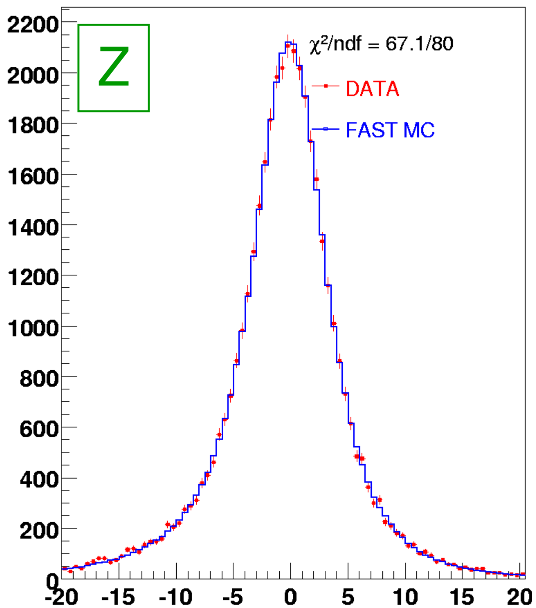
u_T





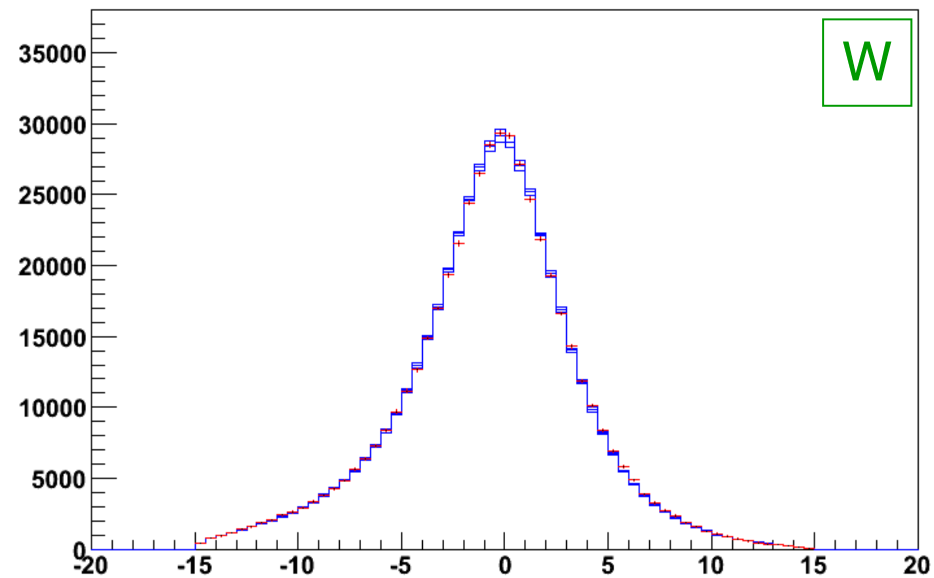
$Z \rightarrow e\,e$ and $W \rightarrow e\,\nu$

Data in red
MC in blue

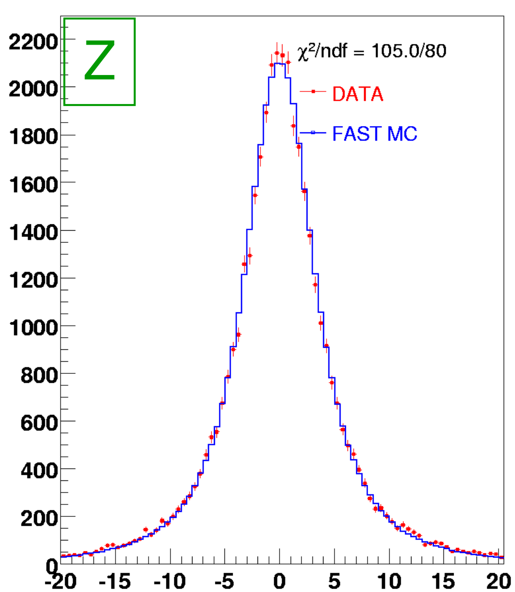


GeV

u_{para}

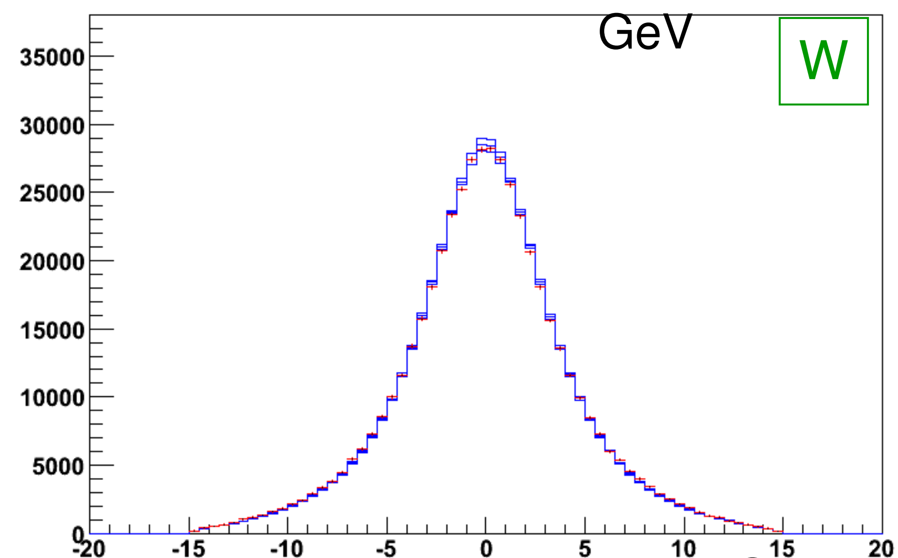


GeV



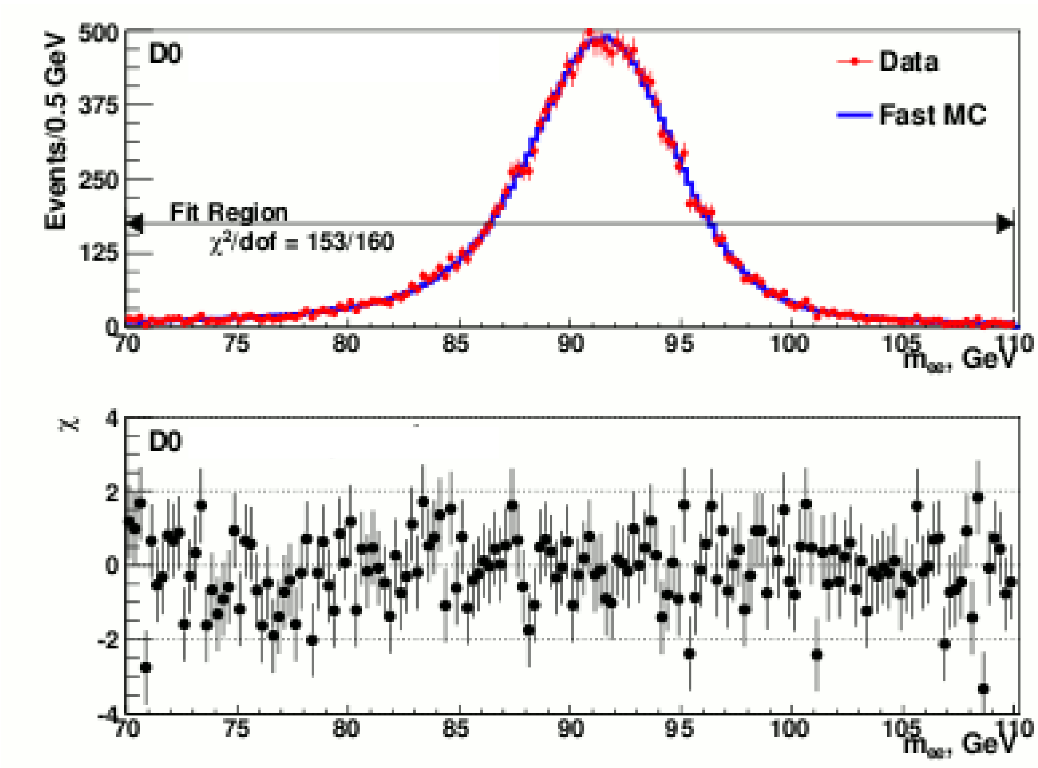
GeV

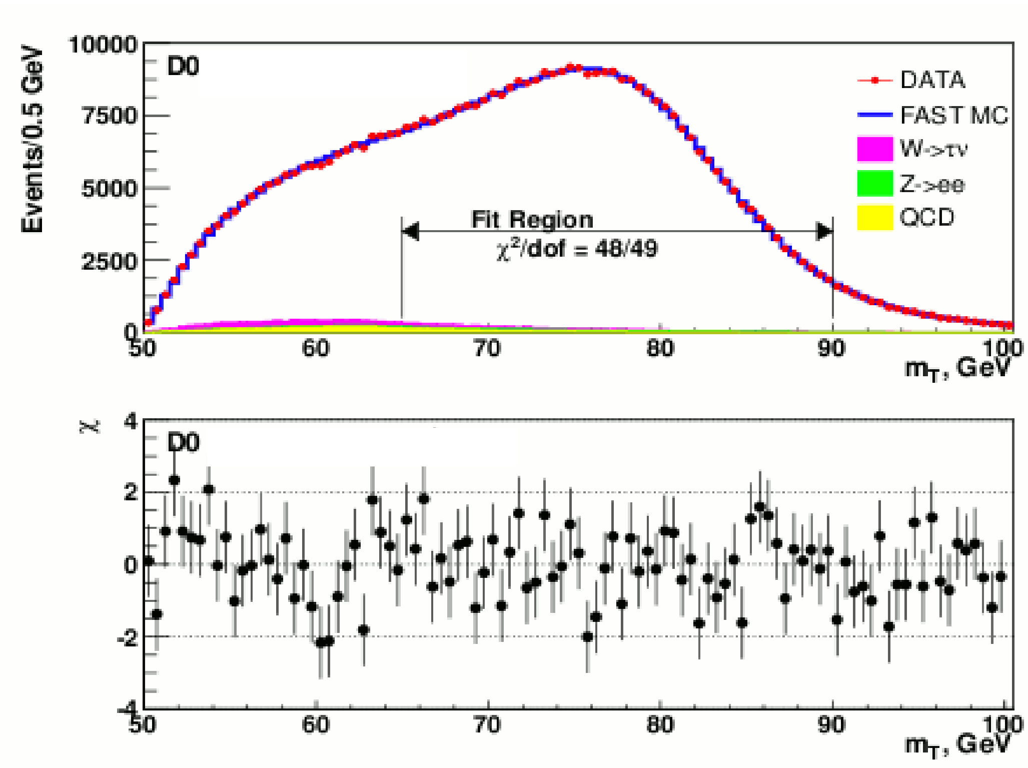
u_{perp}



GeV

Mass fits



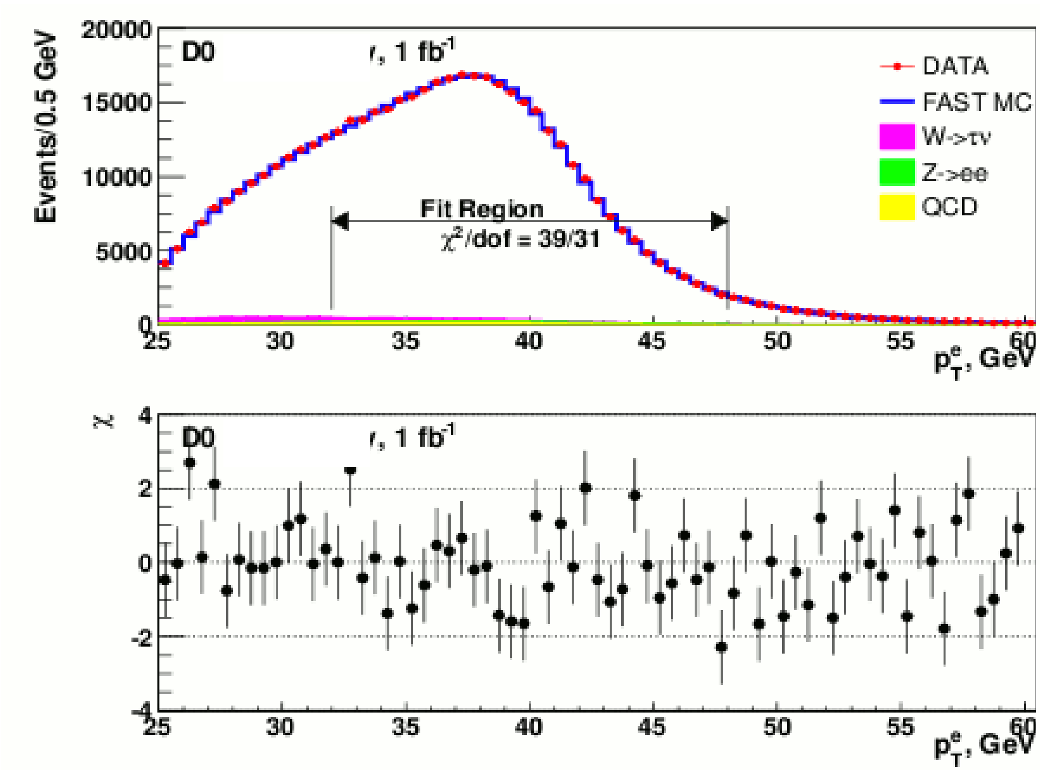


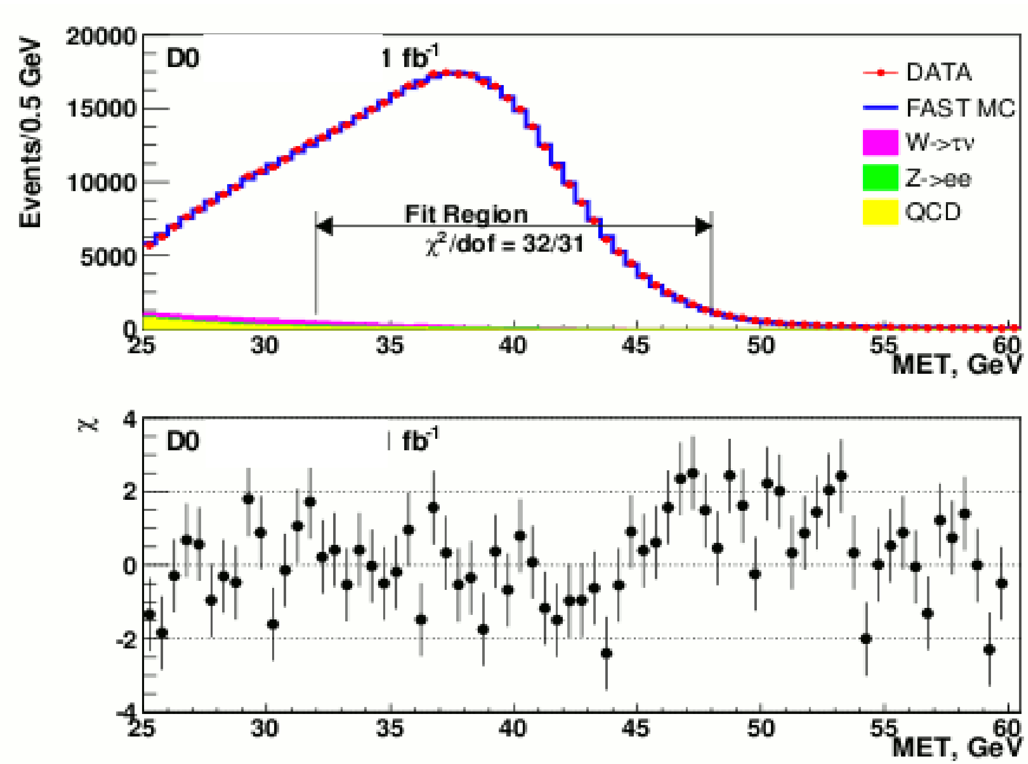
m(Z) = 91.185 ± 0.033 GeV (stat)

(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)

Mass fits





m(W) = 80.400 ± 0.027 GeV (stat)

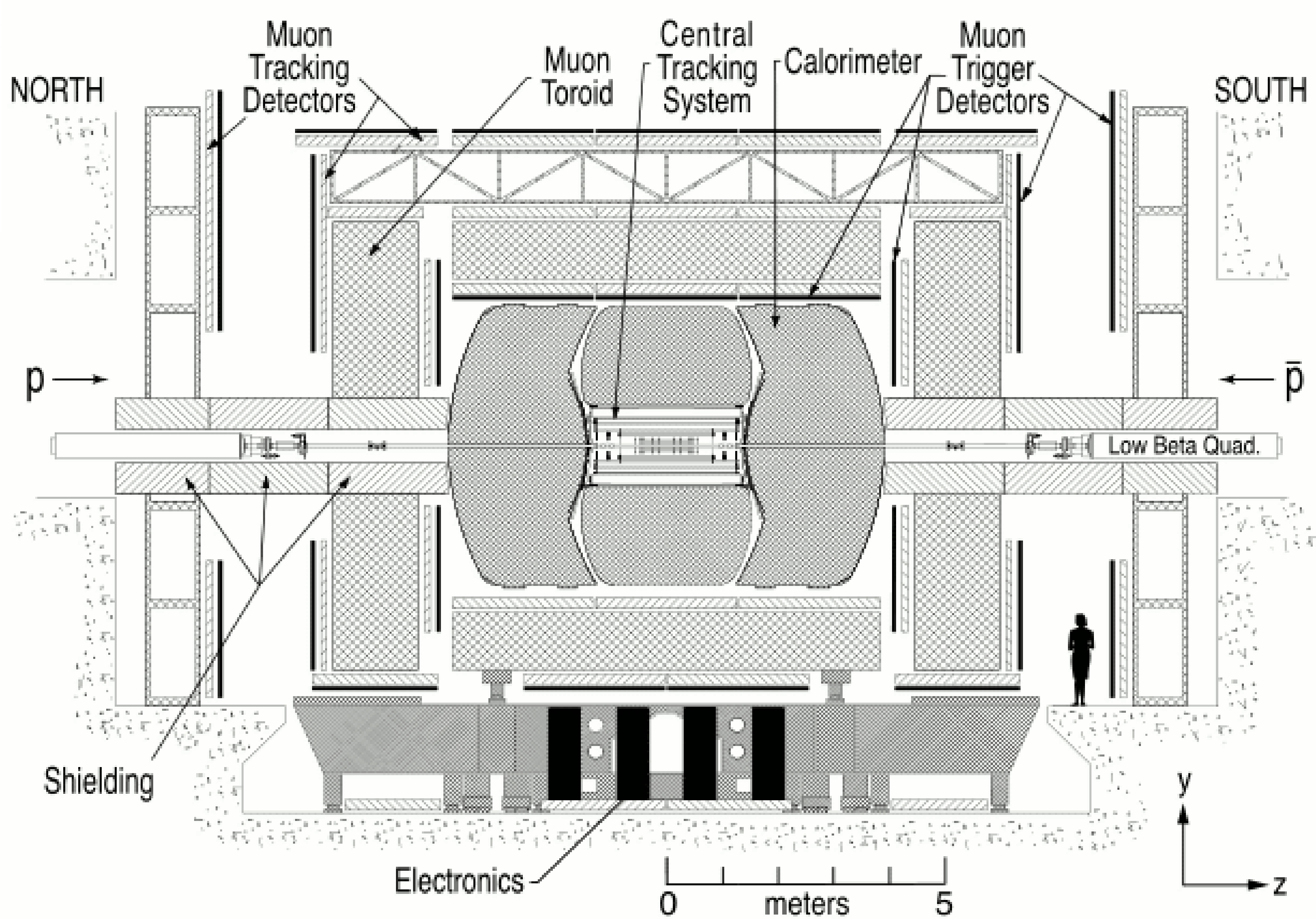
m(W) = 80.402 ± 0.023 GeV (stat)

Summary of uncertainties

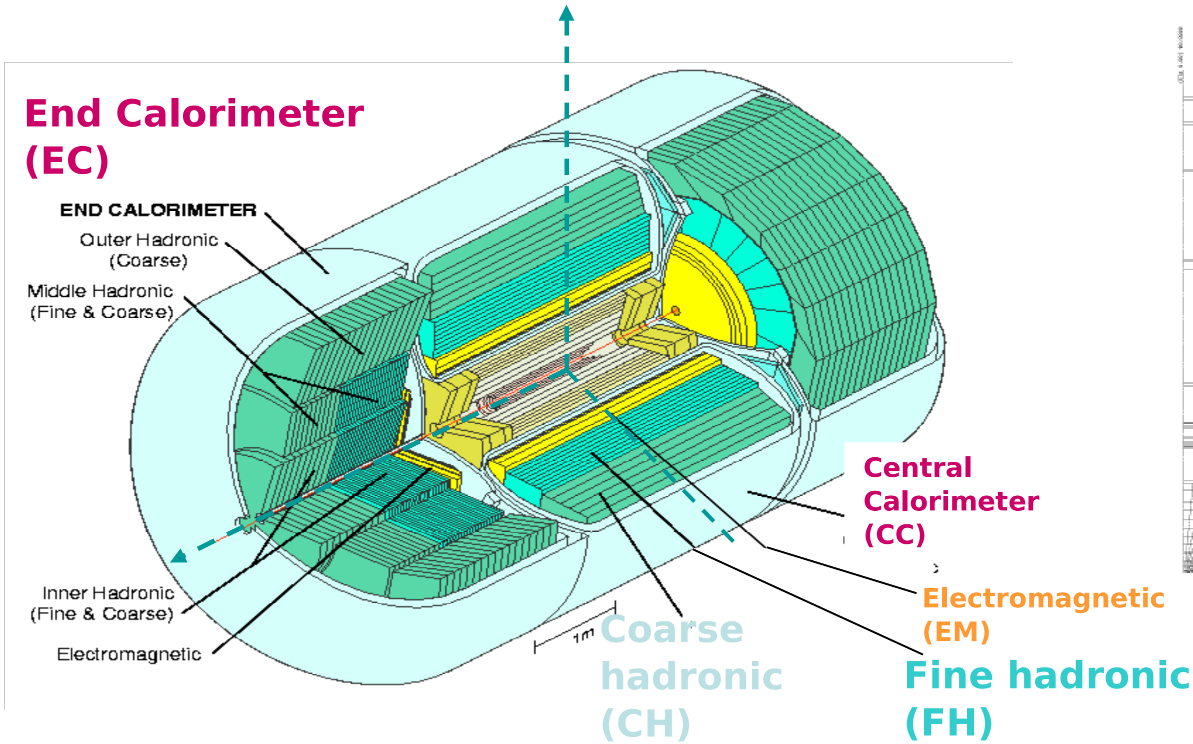
systematic uncertainties

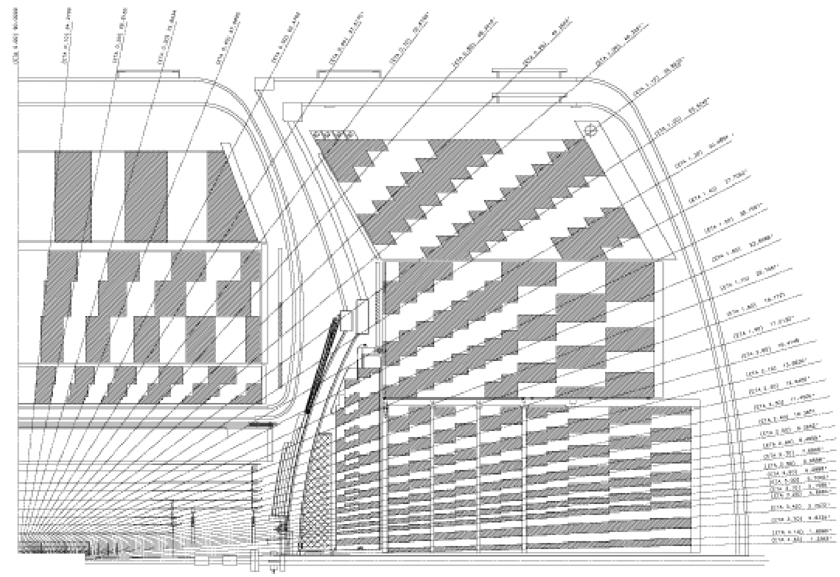
Source	$\sigma(m_W)$ MeV m_T	$\sigma(m_W)$ MeV p_T^e	$\sigma(m_W)$ MeV $\not\!\!E_T$
Experimental			
Electron Energy Scale	34	34	34
Electron Energy Resolution Model	2	2	3
Electron Energy Nonlinearity	4	6	7
W and Z Electron energy loss differences (material)	4	4	4
Recoil Model	6	12	20
Electron Efficiencies	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

The upgraded Dzero detector



Overview of the calorimeter





46000 cells

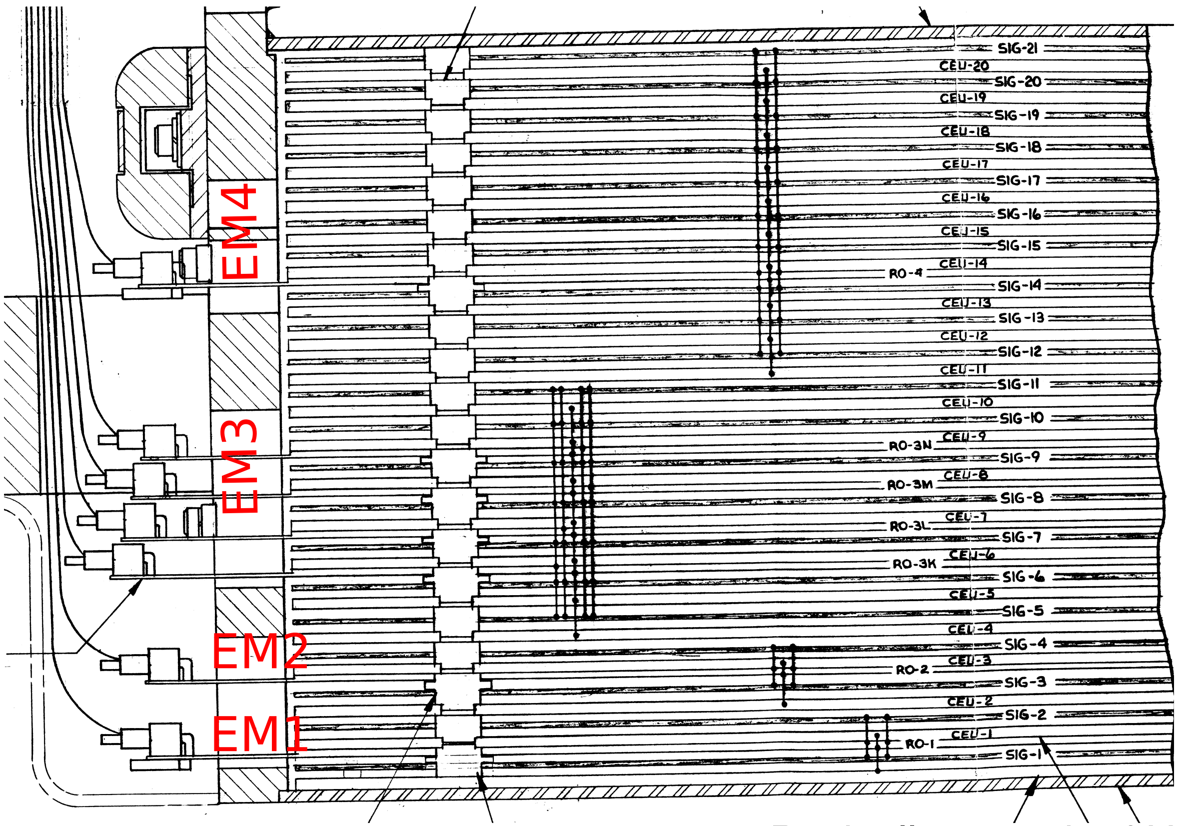
50 dead channels

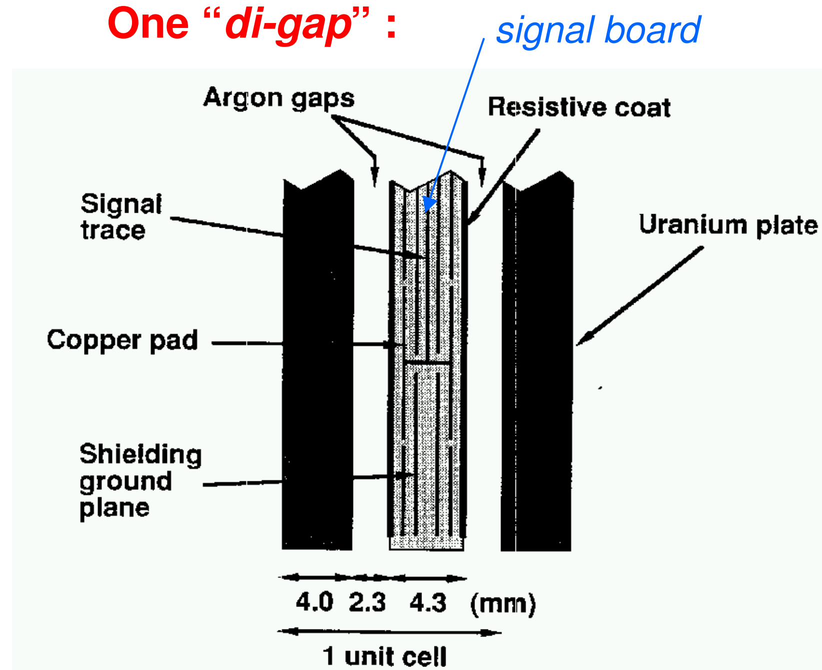
- Liquid argon active medium and (mostly) uranium absorber
- Hermetic with full coverage :$|\eta| < 4.2$
- Segmentation (towers): $\Delta\eta \times \Delta\varphi = 0.1\text{x}0.1$

  (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 :





incident particle

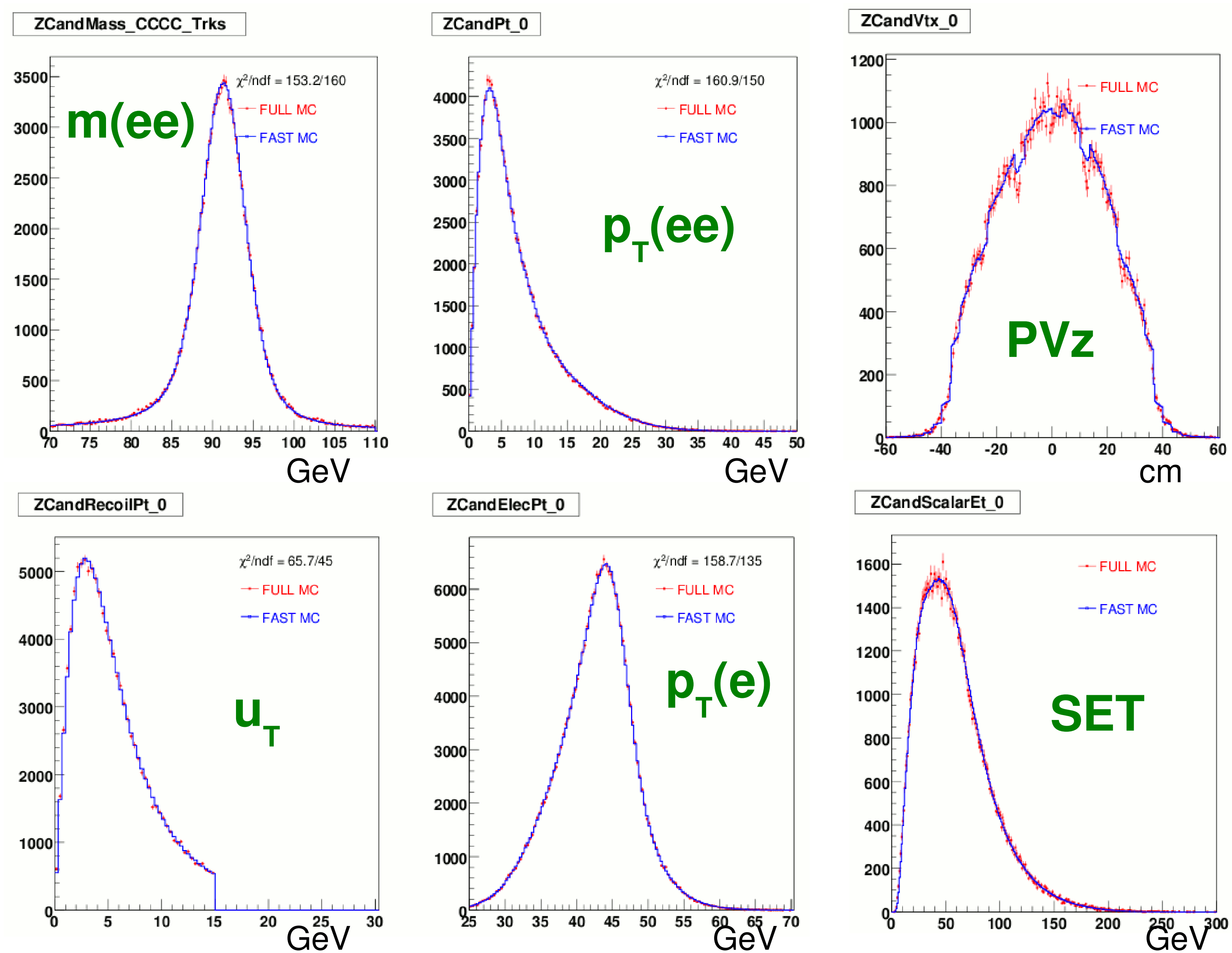
Basically a stack of Uranium plates with liquid Argon in between. Shower develops in U and LAr (mainly U); charged shower particles ionise the Argon atoms => current in Argon because of HV applied across each gap. This current is measurable
(thanks to electronic charge amplifiers with very large gain).

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

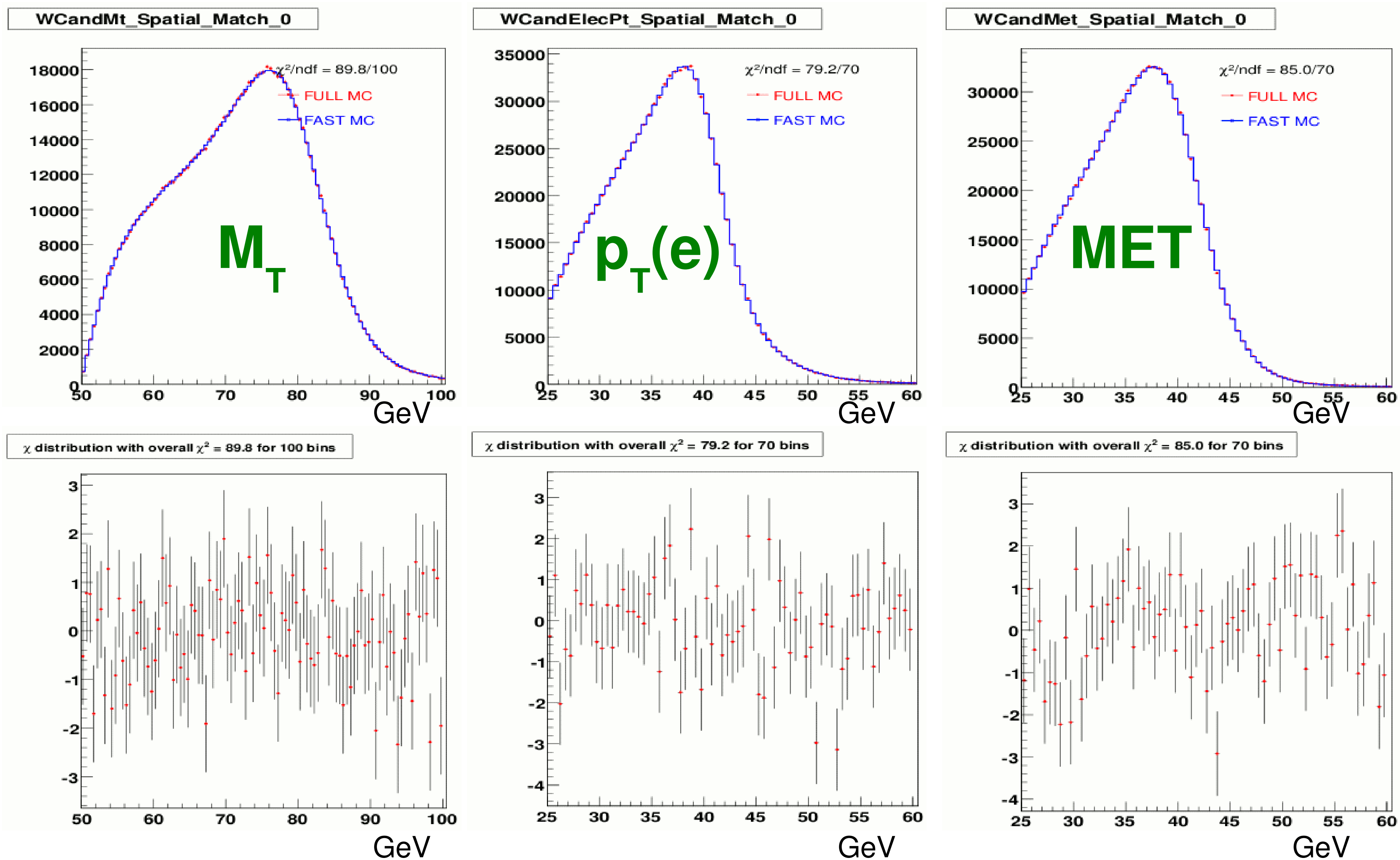
sampling fraction: 15 %

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

✓ Good agreement between full and parameterised MC.



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

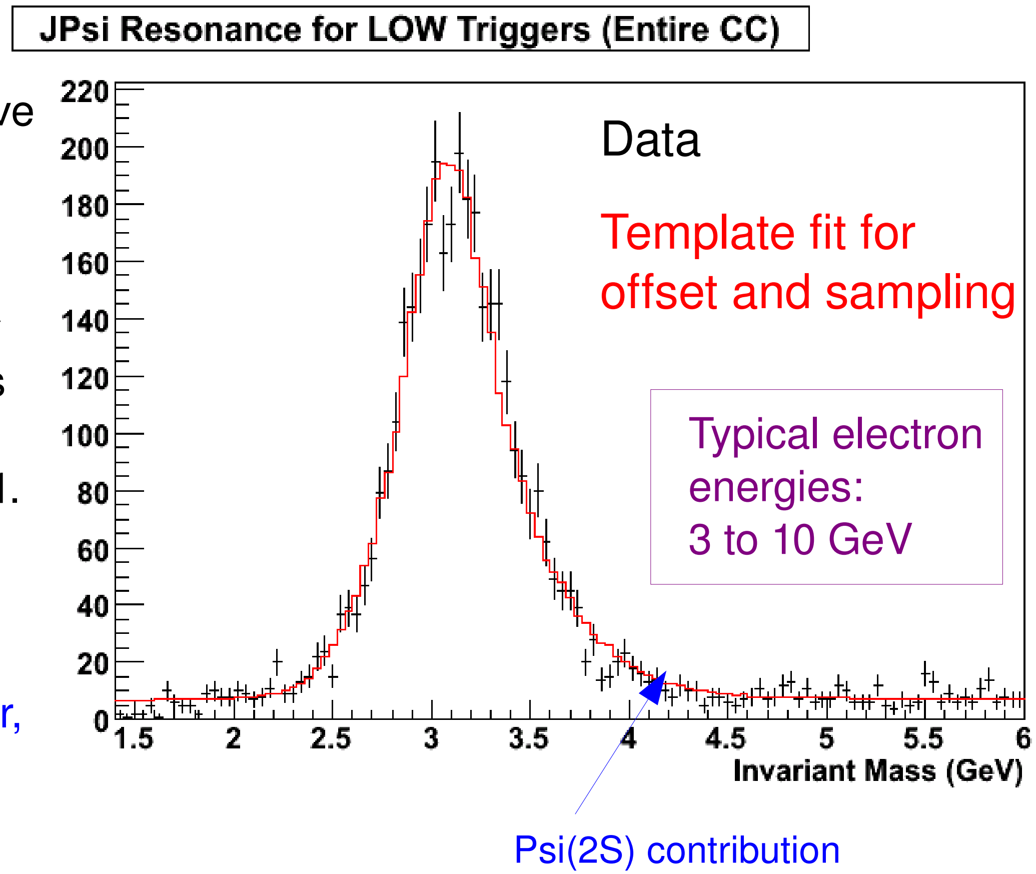


$J/\Psi \rightarrow e^+ e^-$

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.

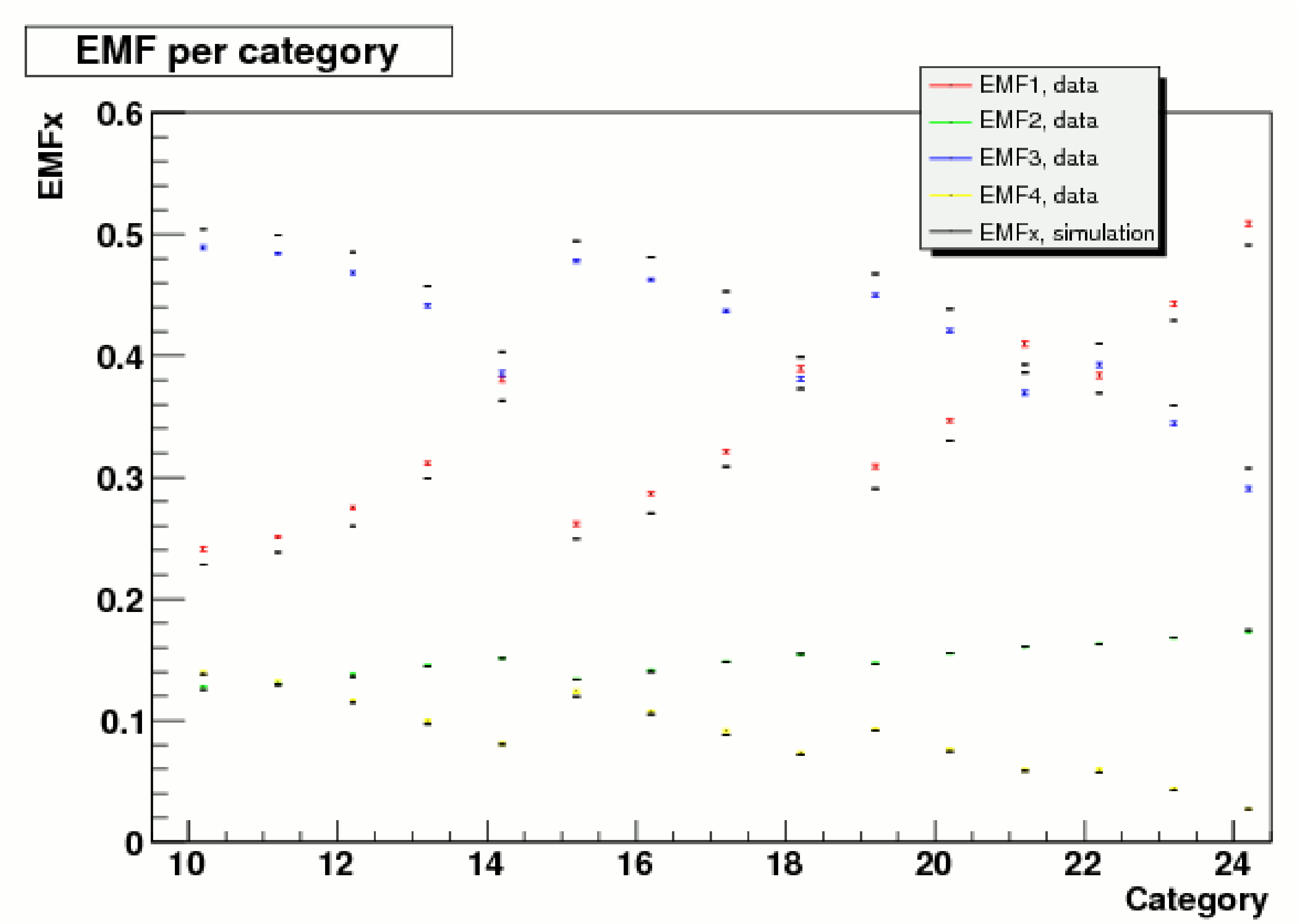
It took us many many person-months to obtain this sample: design/implementation of the trigger, understanding efficiencies, etc, etc.



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.

EM fractions in Z → $e^+ e^-$ 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:

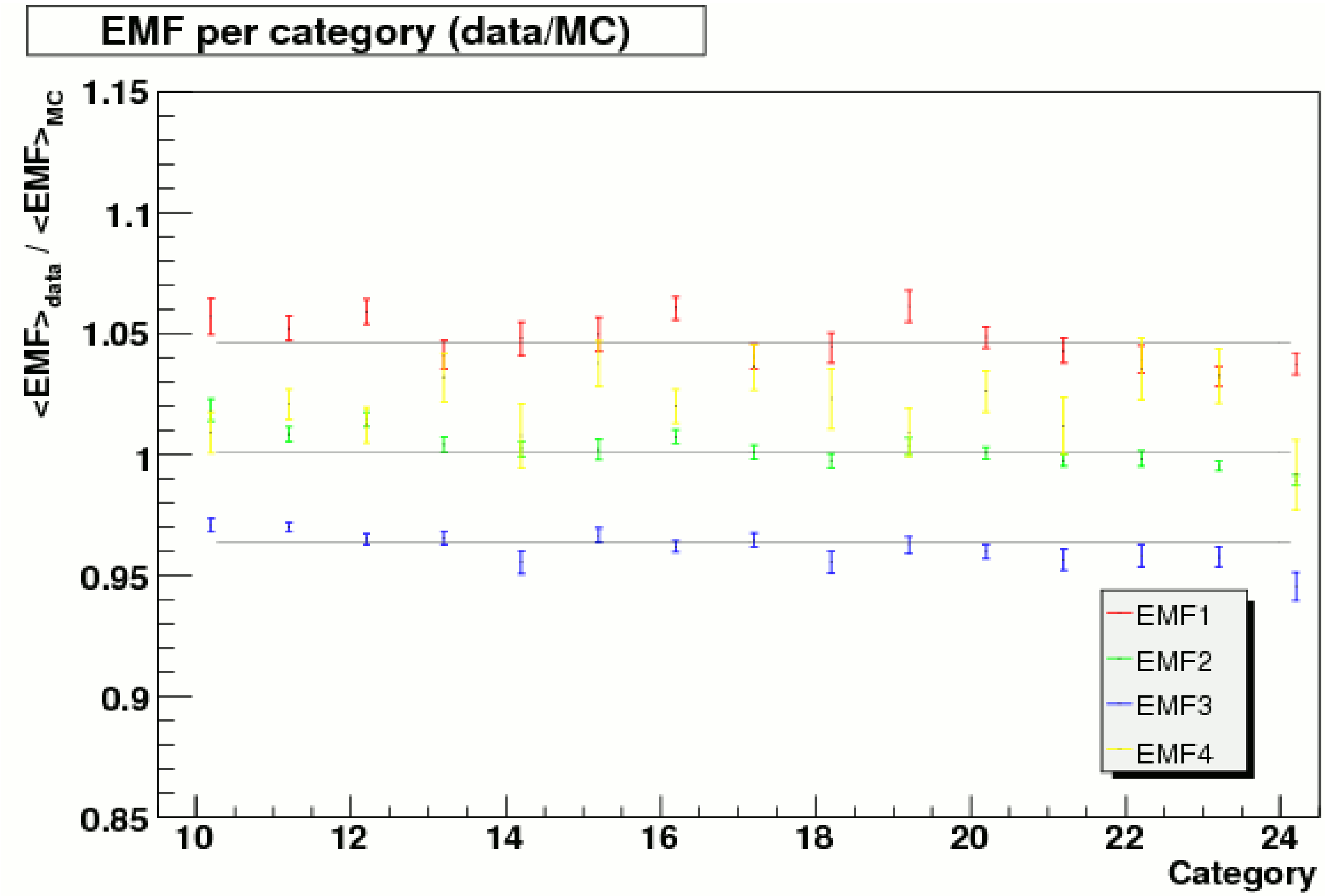
EM1
EM2
EM3
EM4

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

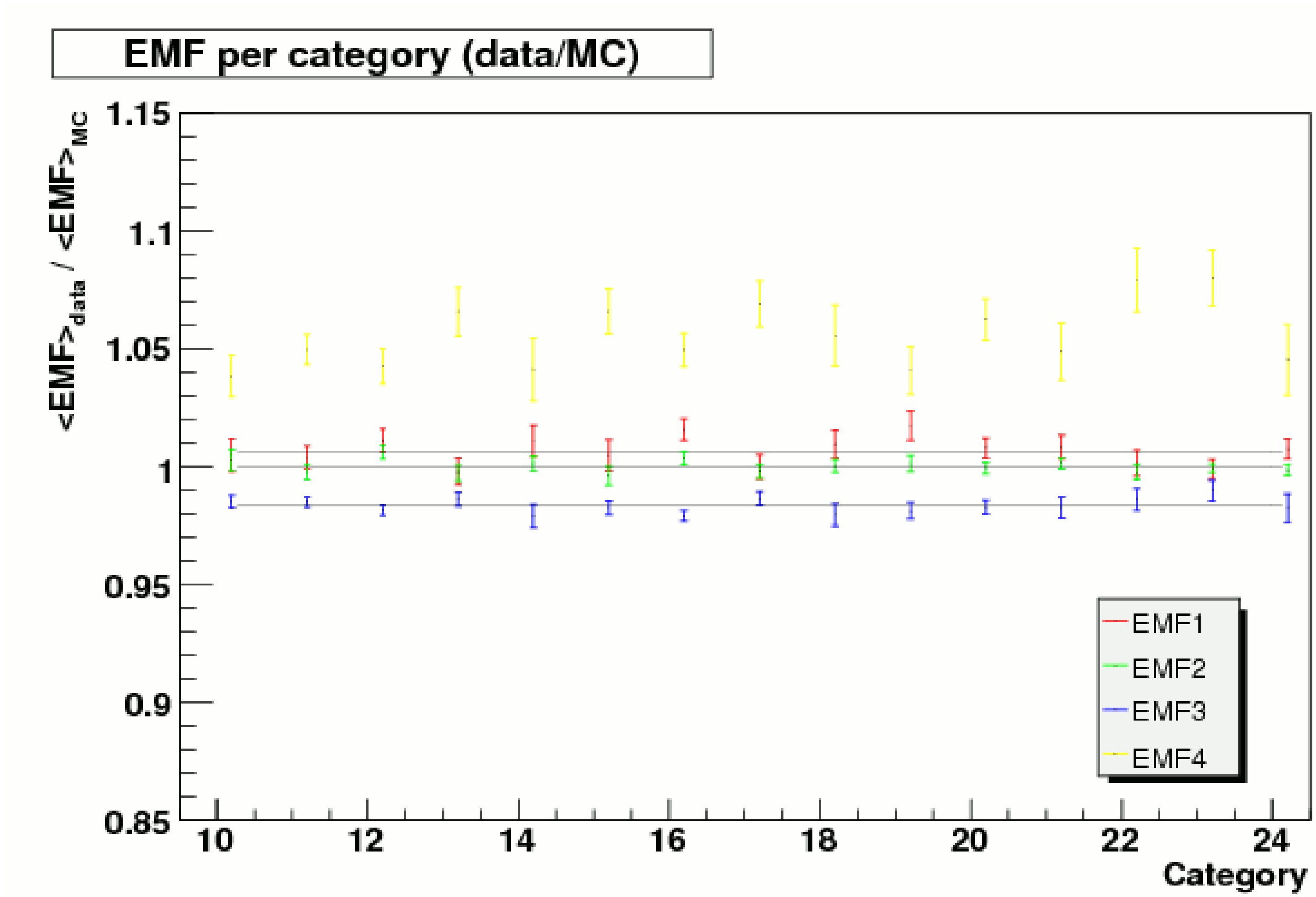


Data / Monte Carlo (MC without fudge material):

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.