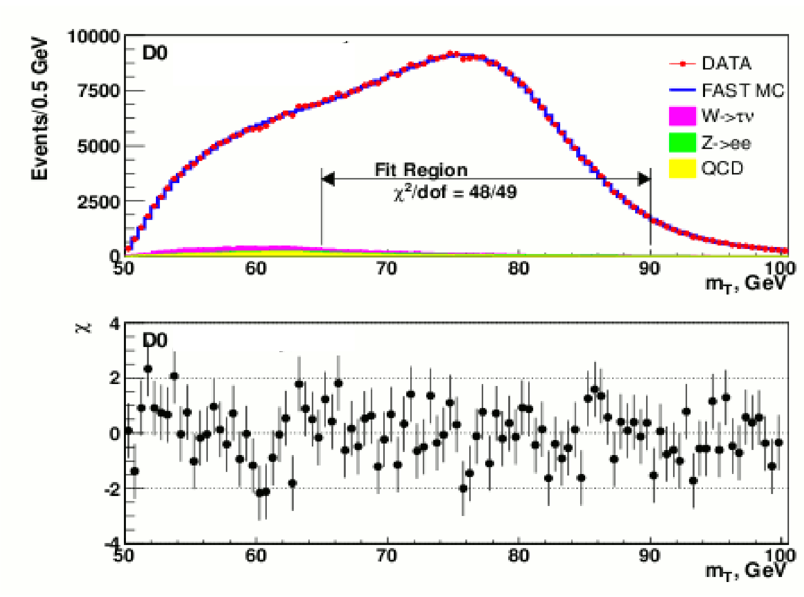
Simple comments on QCD-related aspects of the W boson production and decay model in the DØ Run II measurement of the W boson mass

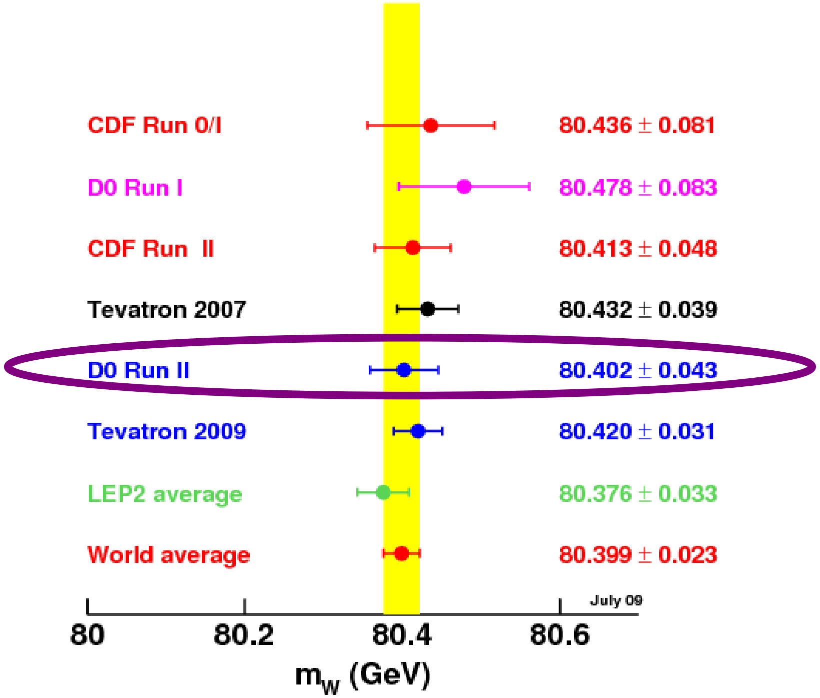
Jan Stark
Laboratoire de Physique Subatomique et de Cosmologie
Grenoble, France

W mass workshop,
Second meeting, Fermilab, October 4-5, 2010

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 can be found in our PRL, various other talks (*e.g.* the "Wine & Cheese" seminar talk), or in our upcoming PRD.
Here we just comment on a few details related to QCD in the model of W boson production that we use in this measurement.



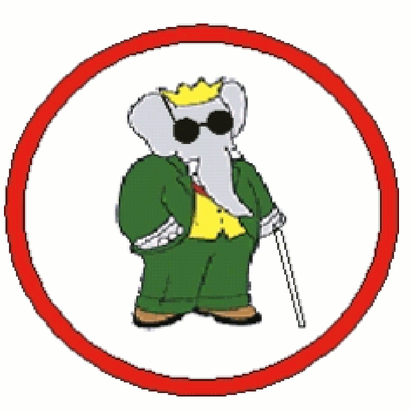


First DØ Run II measurement of the W boson mass

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

~ 500k W events
~ 19k Z events

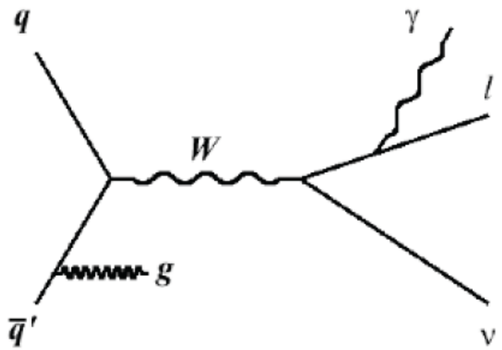
"blind" analysis : central value hidden but not the uncertainties
Standard blinding technique "à la BaBar"
Unblinding has been done only after collaboration approval



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

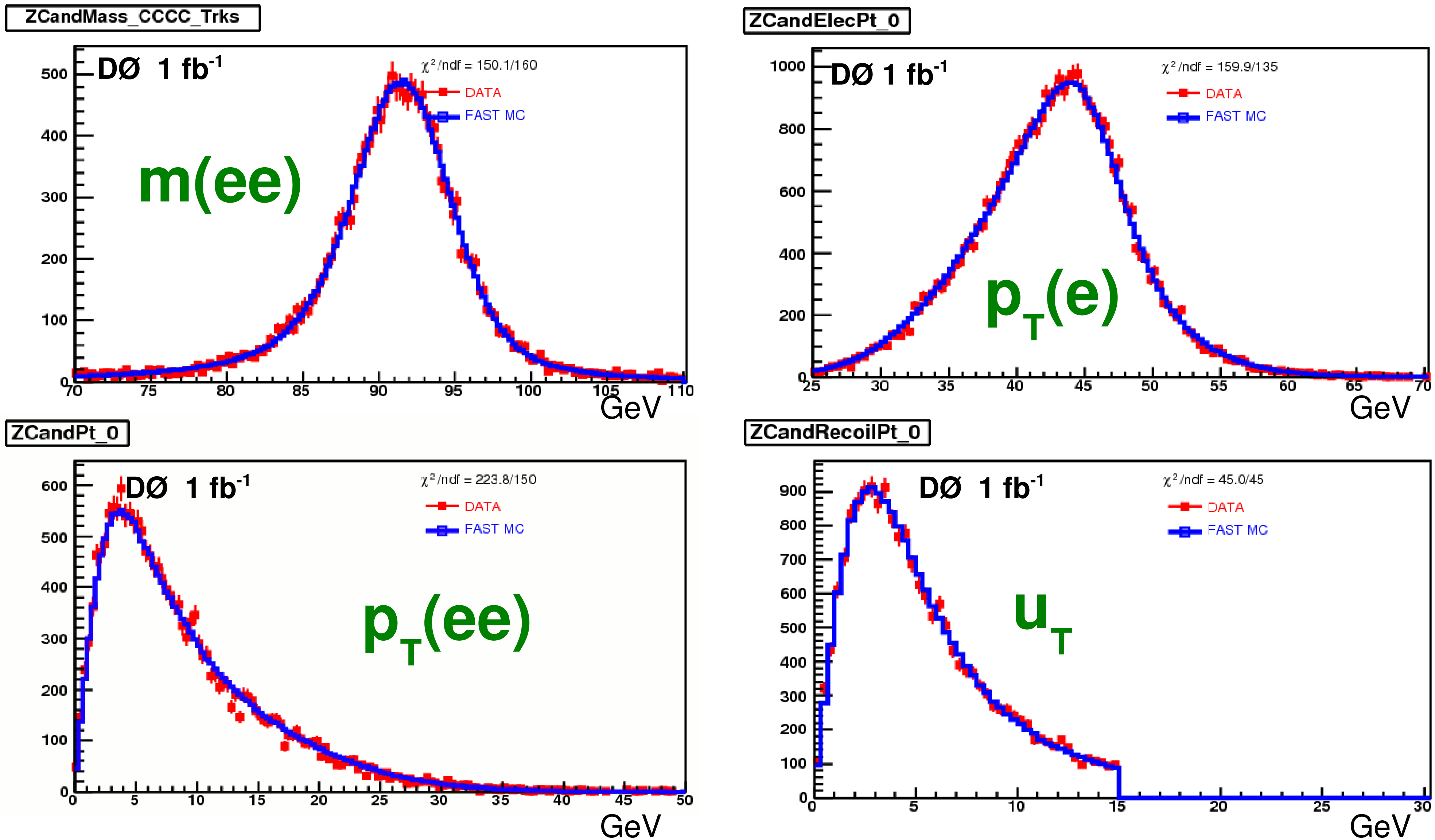
data

binned likelihood fit

↓

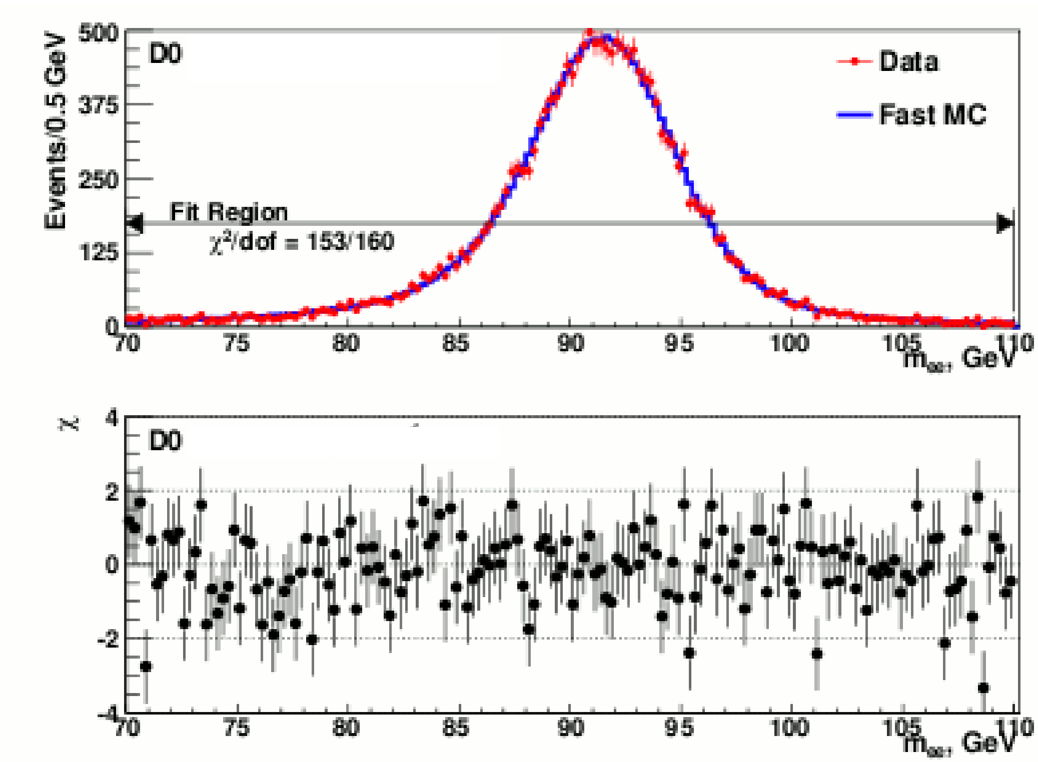
W mass

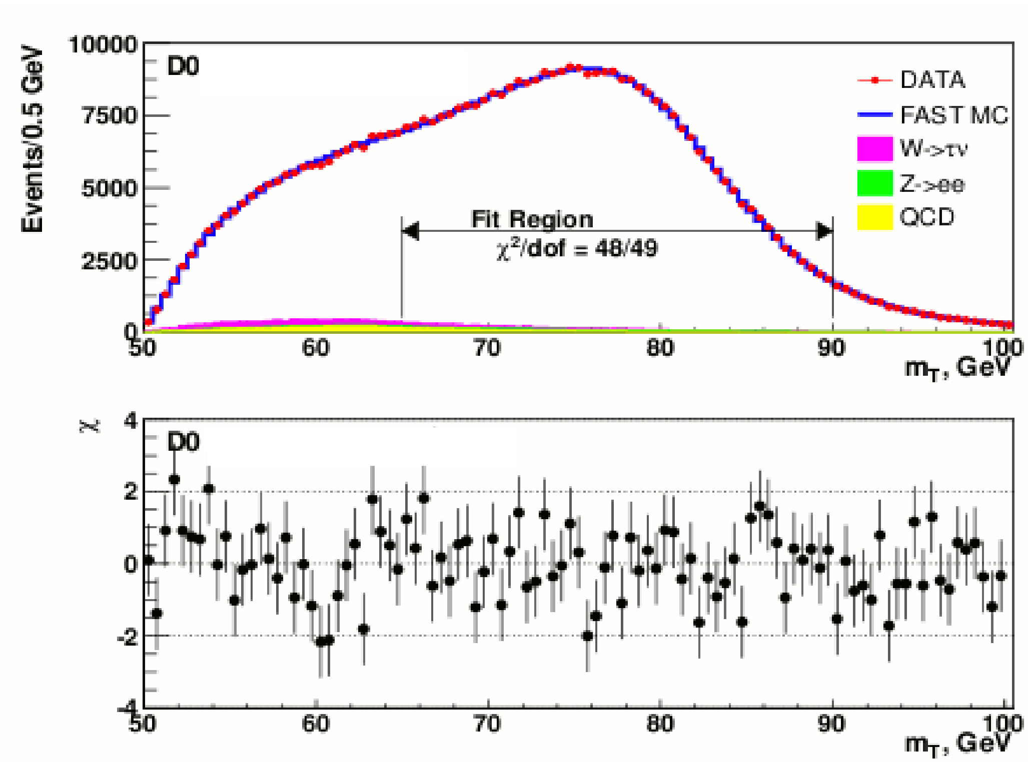
Results: Z → e e data



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

Mass fits



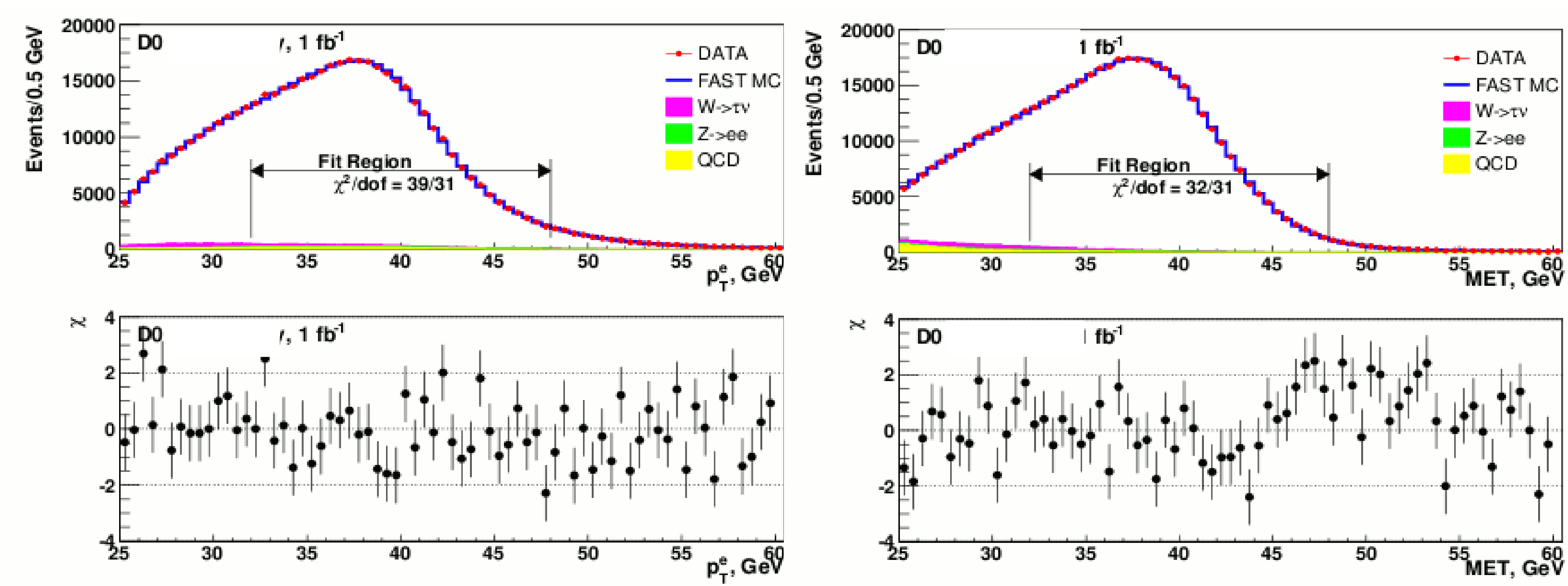


m(Z) = 91.185 ± 0.033 GeV (stat)

(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)

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

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

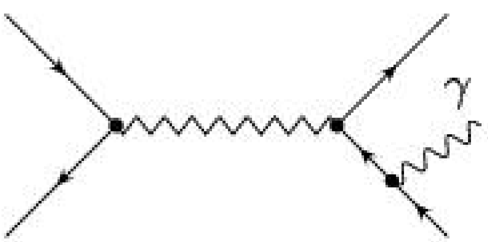
Our main generator is "**ResBos+Photos**". The NLO QCD in **ResBos** allows us to get a reasonable description of the p_T of the vector bosons. The two leading EWK effects are the first FSR photon and the second FSR photon. **Photos** gives us a reasonable model for both.

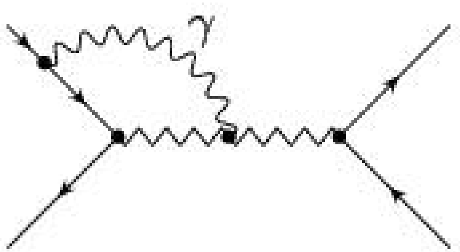
We use **W/ZGRAD** to get a feeling for the effect of the full EWK corrections.

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:

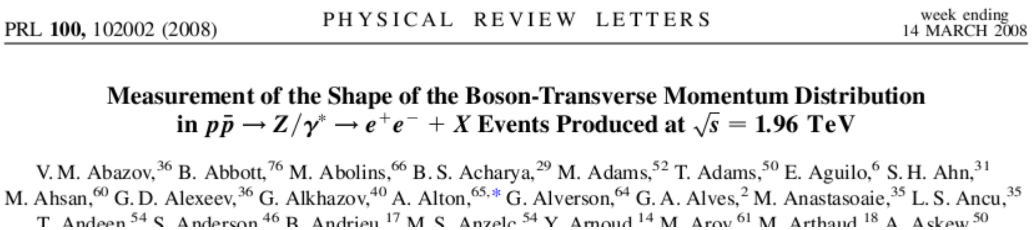
- Effect of full EWK corrections, from comparison of W/ZGRAD in "FSR only" and in "full EWK" modes (5/5/5 MeV).
- Very simple estimate of "quality of FSR model", from comparison of W/ZGRAD in FSR-only mode vs **Photos** (5/5/5 MeV).





Experimental constraints on boson production model

Natural question:
How can we (Tevatron) help
- check the agreement of the (QCD part of) the model of W boson production,
- help constrain/improve the (QCD part of) this model ?


PRL **100,** 102002 (2008) PHYSICAL REVIEW LETTERS week ending 14 MARCH 2008

Measurement of the Shape of the Boson-Transverse Momentum Distribution in $p\bar{p} \rightarrow Z/\gamma^* \rightarrow e^+e^- + X$ Events Produced at $\sqrt{s} = 1.96$ TeV

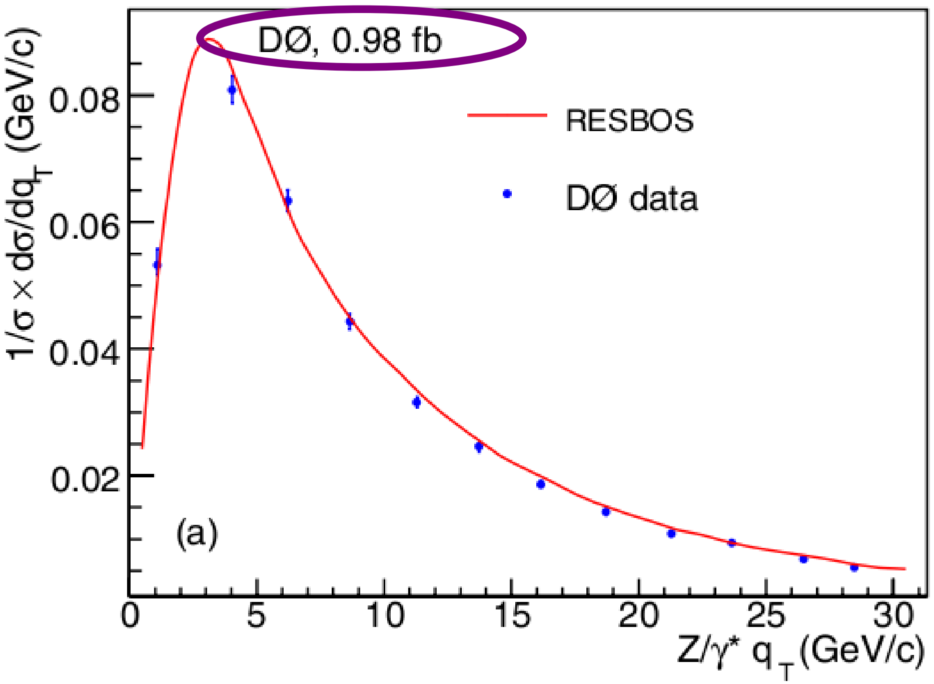
V. M. Abazov,[36] B. Abbott,[76] M. Abolins,[66] B. S. Acharya,[29] M. Adams,[52] T. Adams,[50] E. Aguilo,[6] S. H. Ahn,[31] M. Ahsan,[60] G. D. Alexeev,[36] G. Alkhazov,[40] A. Alton,[65,*] G. Alverson,[64] G. A. Alves,[2] M. Anastasoaie,[35] L. S. Ancu,[35]

One thing that is critical to get right is the $p_T(W)$ distribution. In the data, $p_T(W)$ and W rapidity are measured poorly.

But: we do have a much better measurement of $p_T(Z)$ and Z rapidity.

=> Confront vector boson production model to Z data.

Shown on the right is an example of $p_T(Z)$ in DØ data, integrated over a large range in Z rapidity, and unfolded.

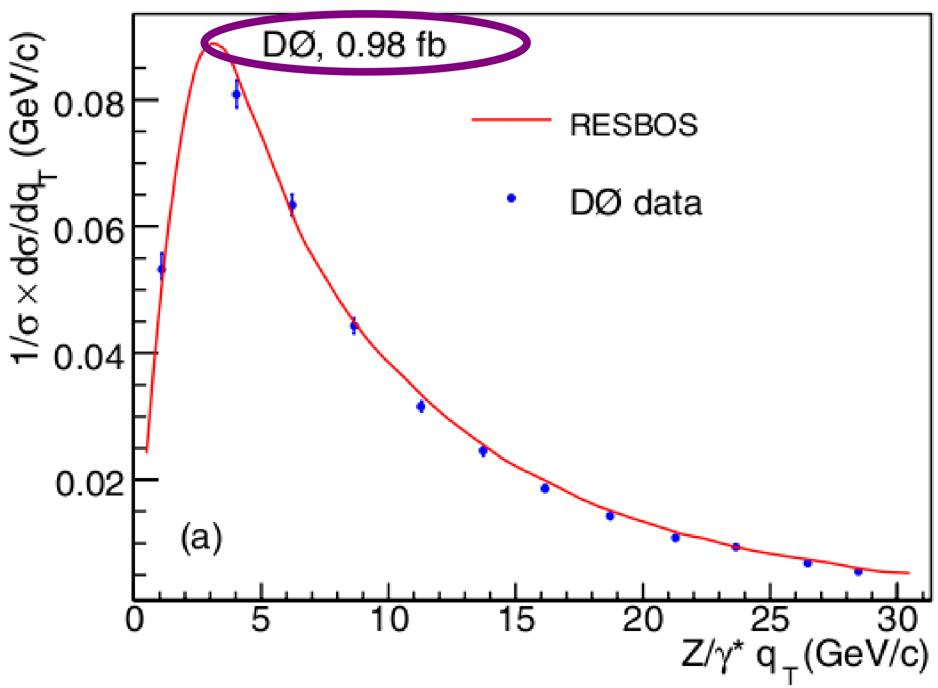


Experimental constraints on boson production model

TABLE I. The normalized differential cross section for Z events produced in bins of q_T. The first uncertainty is statistical, and the second is systematic.

$\langle q_T \rangle$ (GeV/c)	$1/\sigma \times d\sigma/dq_T$ (GeV/c)$^{-1}$
1.1	$(5.32 \pm 0.13 \pm 0.24) \times 10^{-2}$
4.0	$(8.08 \pm 0.12 \pm 0.19) \times 10^{-2}$
6.2	$(6.33 \pm 0.11 \pm 0.14) \times 10^{-2}$
8.7	$(4.43 \pm 0.09 \pm 0.11) \times 10^{-2}$
11.3	$(3.15 \pm 0.08 \pm 0.08) \times 10^{-2}$
13.7	$(2.46 \pm 0.07 \pm 0.06) \times 10^{-2}$
16.2	$(1.86 \pm 0.06 \pm 0.05) \times 10^{-2}$
18.7	$(1.42 \pm 0.05 \pm 0.05) \times 10^{-2}$
21.3	$(1.09 \pm 0.04 \pm 0.03) \times 10^{-2}$
23.7	$(9.40 \pm 0.40 \pm 0.20) \times 10^{-3}$
26.4	$(6.90 \pm 0.30 \pm 0.20) \times 10^{-3}$
28.5	$(5.50 \pm 0.30 \pm 0.10) \times 10^{-3}$
34.6	$(3.90 \pm 0.10 \pm 0.10) \times 10^{-3}$
44.6	$(2.10 \pm 0.07 \pm 0.06) \times 10^{-3}$
54.6	$(1.10 \pm 0.05 \pm 0.03) \times 10^{-3}$
64.6	$(7.30 \pm 0.40 \pm 0.20) \times 10^{-4}$
73.4	$(4.20 \pm 0.30 \pm 0.20) \times 10^{-4}$
85.4	$(2.50 \pm 0.20 \pm 0.10) \times 10^{-4}$
95.1	$(1.60 \pm 0.17 \pm 0.08) \times 10^{-4}$
117.5	$(6.00 \pm 0.50 \pm 0.30) \times 10^{-5}$
157.5	$(1.10 \pm 0.20 \pm 0.07) \times 10^{-5}$
195.5	$(3.00 \pm 1.00 \pm 0.30) \times 10^{-6}$
245.5	$(7.10 \pm 6.10 \pm 0.60) \times 10^{-7}$

This is very nice, but issue for the future:
This paper is based on only ~12 % if the present DØ dataset.
And yet, in the most important domain ($p_T(Z) < 20$ GeV)
it is already pretty much limited by systematic uncertainties.
A large part of these systematics is related to the
poor experimental resolution on $p_T(Z)$.
Also, the choice of binning is also mostly driven by
the poor resolution and not by physics considerations.



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

NEW

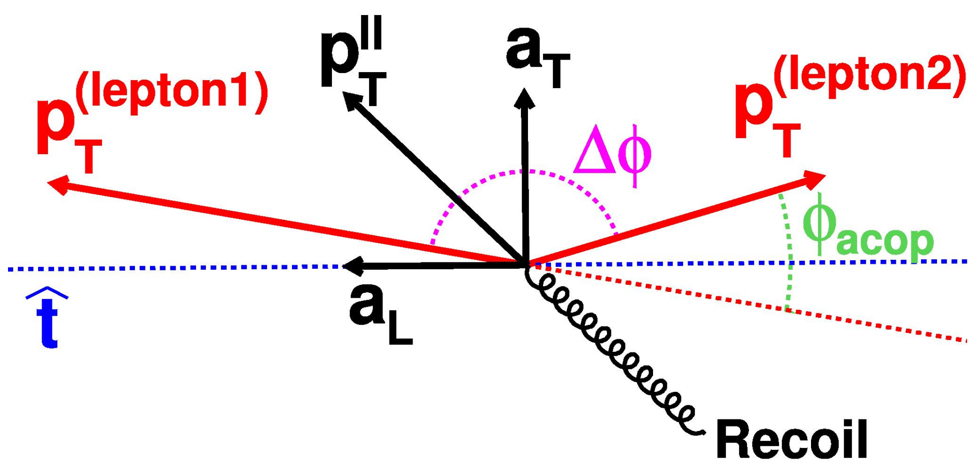
Just submitted to Phys. Rev. Lett.:

Fermilab-Pub-10-403-E

Precise study of the Z/γ^* boson transverse momentum distribution in $p\bar{p}$ collisions using a novel technique

(Dated: October 1, 2010)

Using 7.3 fb^{-1} of $p\bar{p}$ collisions collected by the D0 detector at the Fermilab Tevatron, we measure the distribution of the variable ϕ^*_η, which probes the same physical effects as the Z/γ^* boson transverse momentum, but is less susceptible to the effects of experimental resolution and efficiency. A QCD prediction is found to describe the general features of the ϕ^*_η distribution, but is unable to describe its detailed shape or dependence on boson rapidity. A prediction that includes a broadening of transverse momentum for small values of the parton momentum fraction is strongly disfavored.



The next-generation DØ measurement (7.3 fb^{-1}) has just been completed.

It avoids the resolution issues with $p_T(Z)$ by using an alternative observable that is sensitive to the same physics, but much less sensitive to lepton p_T resolution:

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

ϕ_{acop} and θ_η^* only depend on lepton *directions*

=> ϕ_η^* is measured much more precisely than any quantity that depends on lepton momenta.

Note: $\phi_\eta^* \approx a_T / m(ll)$

Detailed discussion of observables alternative to $p_T(Z)$:

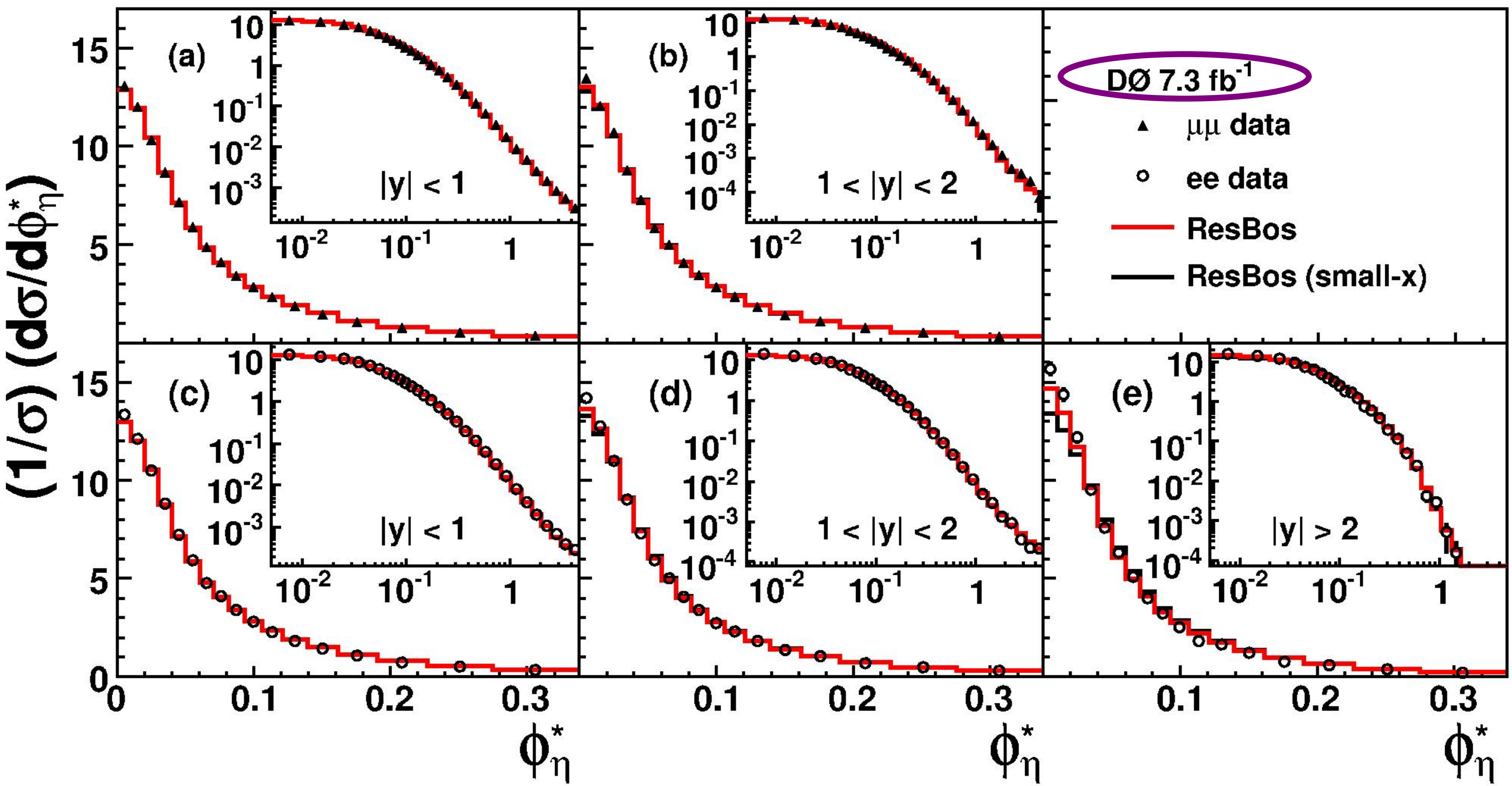
M. Vesterinen and T.R. Wyatt, Nucl. Instrum. Methods Phys. Res. A 602, 432 (2009).

A. Banfi et al., arXiv:1009.1580, submitted to Eur. Phys. J. C (2010).

Comment from JS:
One tricky experimental aspect that all of these observables remain sensitive to is any phi structure in the lepton acceptance of the detector (*e.g.* phi cracks).

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

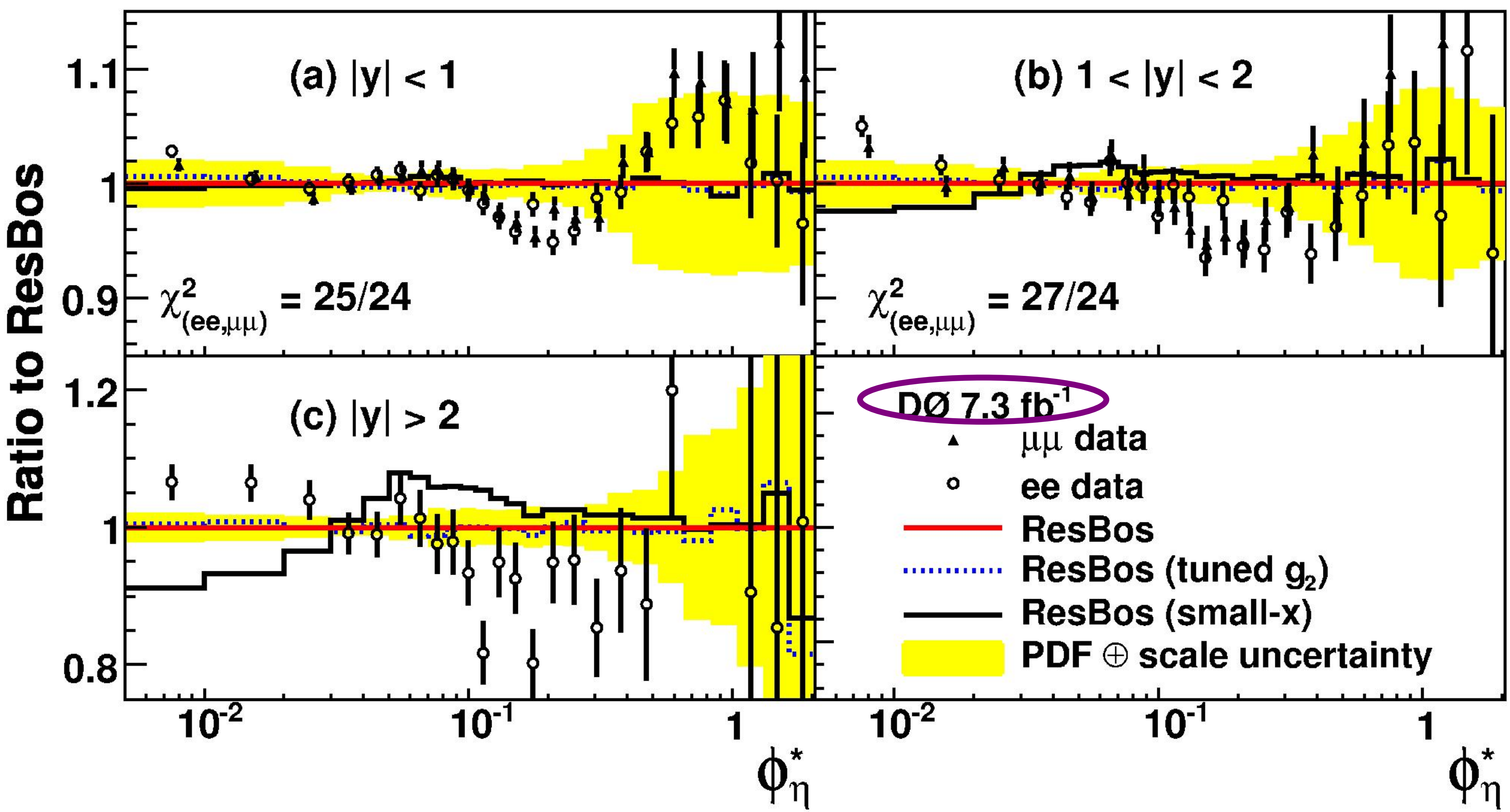
Unfolded data (ee and $\mu\mu$ channels shown separately) in three bins of Z rapidity:



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

NEW

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



Comments/questions on $p_T(V)$

- We hope that this new-generation set of unfolded precision data will help accelerate further development of theoretical tools.

- We are not aware of any additional hassles on the theory side introduced by the use of $\phi\eta^*$ instead of $p_T(Z)$. Are we missing anything ?

- Overall agreement between data and ResBos is good, but the large data statistics clearly reveal issues in the details.

  Which physics ingredients in missing from the current calculations are expected to be the main culprits ?

  Which future developments to we expect to address these ?

- A general comment: of course, in all of this we absolutely need theory to get "from the Z to the W".

  How well do we know the Z/W differences ? What are the limiting factors ?
  What is needed to improve the predictions ?

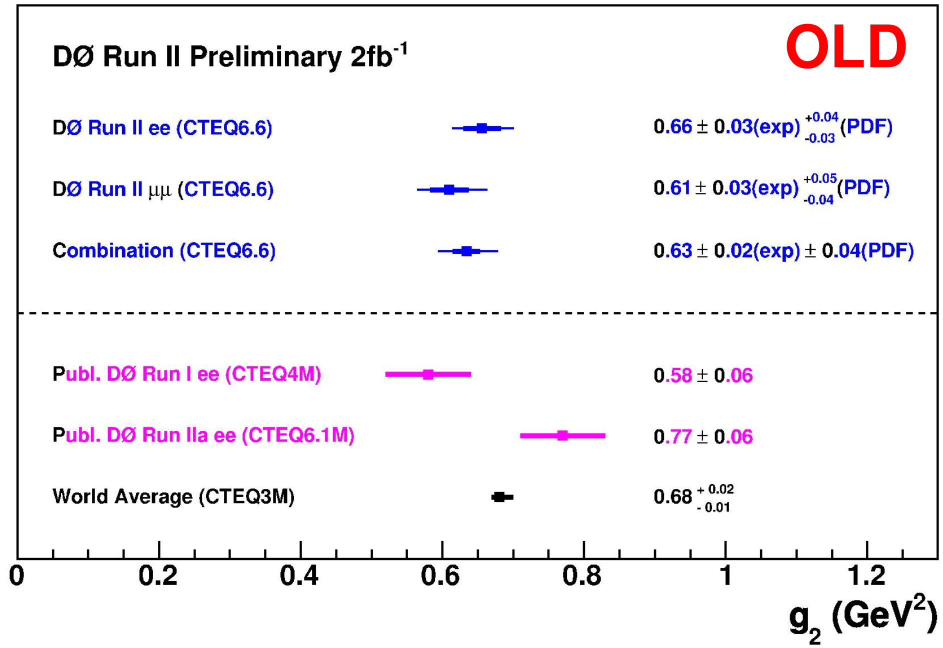
- This measurement is pretty precise ... Say one wanted to use (a smoothed version of) this measurement of the Z plus some "W/Z ratio" from theory to describe the W. How exactly would you construct this "W/Z ratio" ? What are the pitfalls is this approach ?

- Comment on PDF uncertainties on the next slide.

On the correlation between "boson p_T model" and PDF uncertainties

You have noticed the sizable PDF uncertainties in the ResBos prediction on slide 14.

This is a feature that already manifested itself in this old plot on the right which dates from the time when DØ discussed the non-perturbative form factor in terms of "g_2": large PDF uncertainties in fits for g_2.



This interplay interplay between PDFs and $g_{2,}$ or more generally, between the PDFs and the boson p_T model (including form factors etc.) is not unexpected.
It would be good to have simultaneous parameterisations of the PDFs and the form factor.

The new D0 measurement provides unfolded data that should be useful for such combined fits.

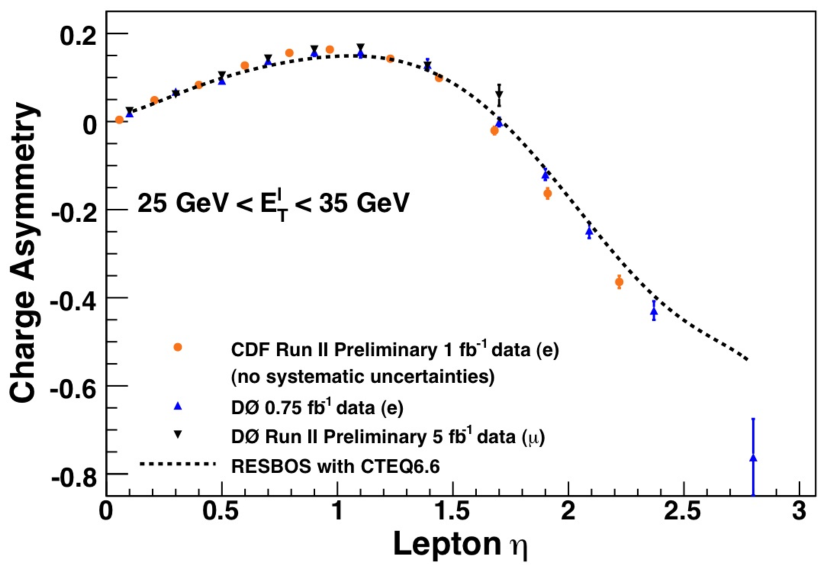
Two other items on PDF uncertainties

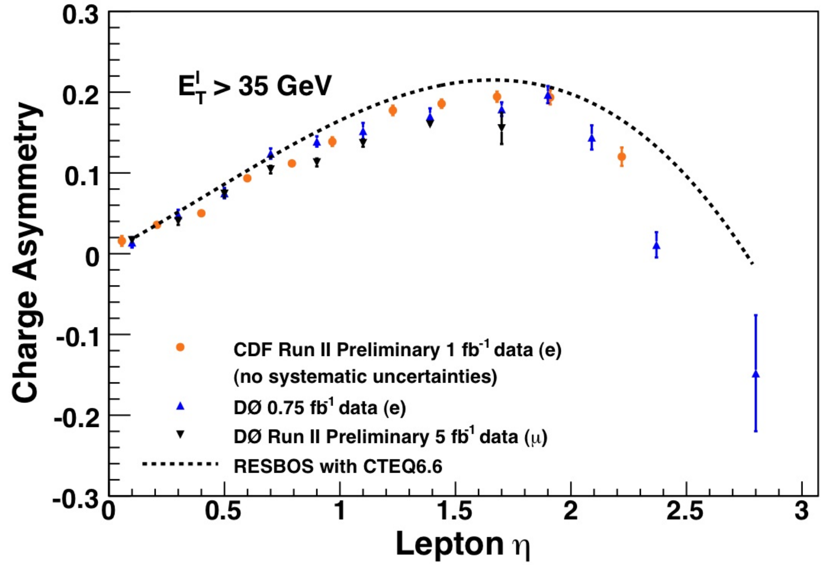
- There is this long-standing feature that both CDF and DØ use Pythia to propagate PDF uncertainties (*e.g.* CTEQ variation sets) to the measured W mass.

  In the past, attempts to use ResBos for this exercise have lead to much larger values of the uncertainties, and these where attributed to non-physical features in the ResBos gridfiles for the variation sets. Such non-physical features can, *e.g.* be caused by statistical limitations in the generation of the gridfiles.

  We would like to settle this discussion once and for all (using new, better gridfiles and new reweighting tools in ResBos that reduce the amount of toy statistics that is needed in the error propagation) and also compare to other generators (DYNNLO, ...). Dan and Rafael may have more on this.

- So the PDF uncertainties will be a limiting factor in our m(W) measurements very soon. One way to help reduce them is to included new Tevatron measurements of the W/lepton charge asymmetry into the PDF fits. These measurements and the tensions some of them include in global PDF fits could be the topic of a workshop of its own.

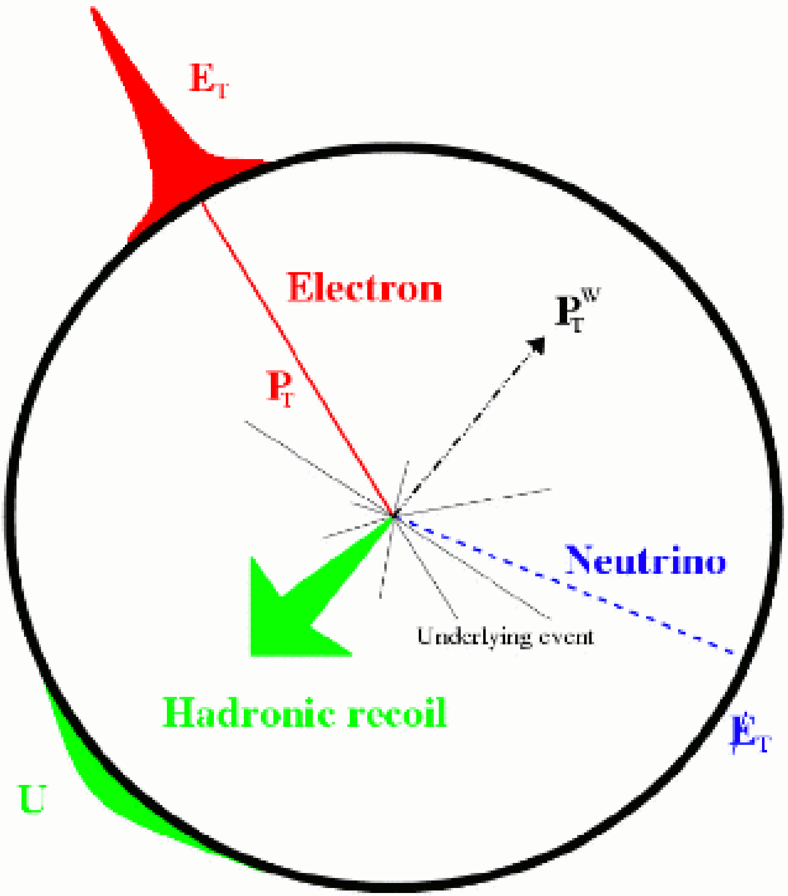




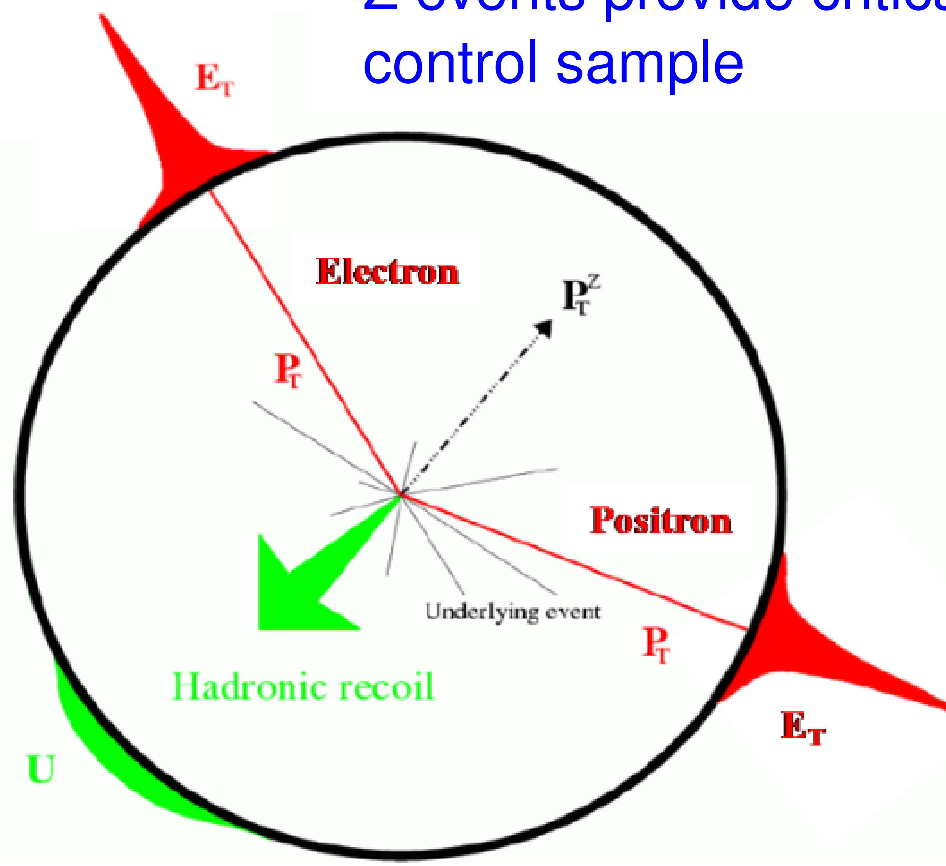
Backup slides

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

Model of W production and decay

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.

(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) ...

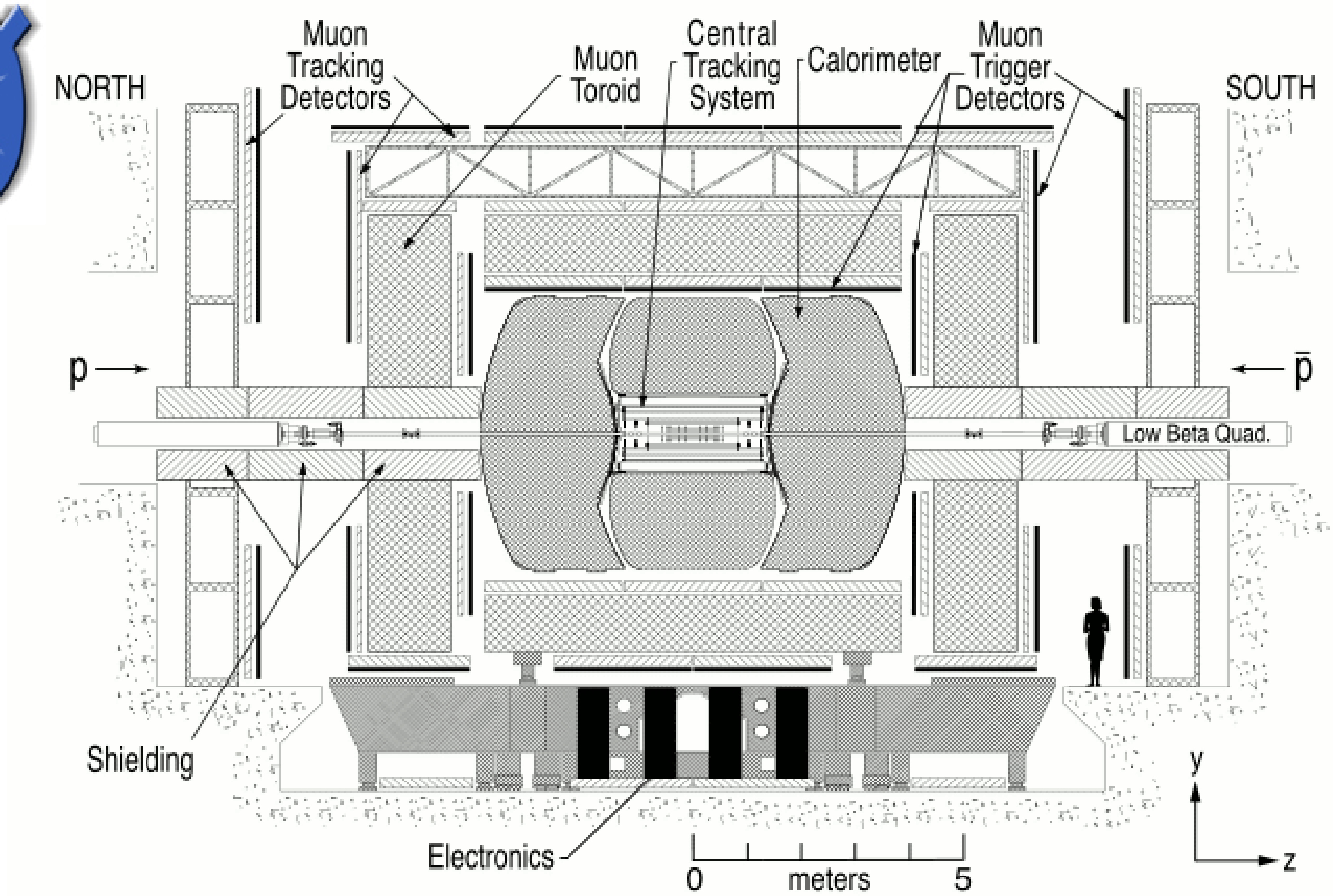
- **We need public codes (including event generators):**

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

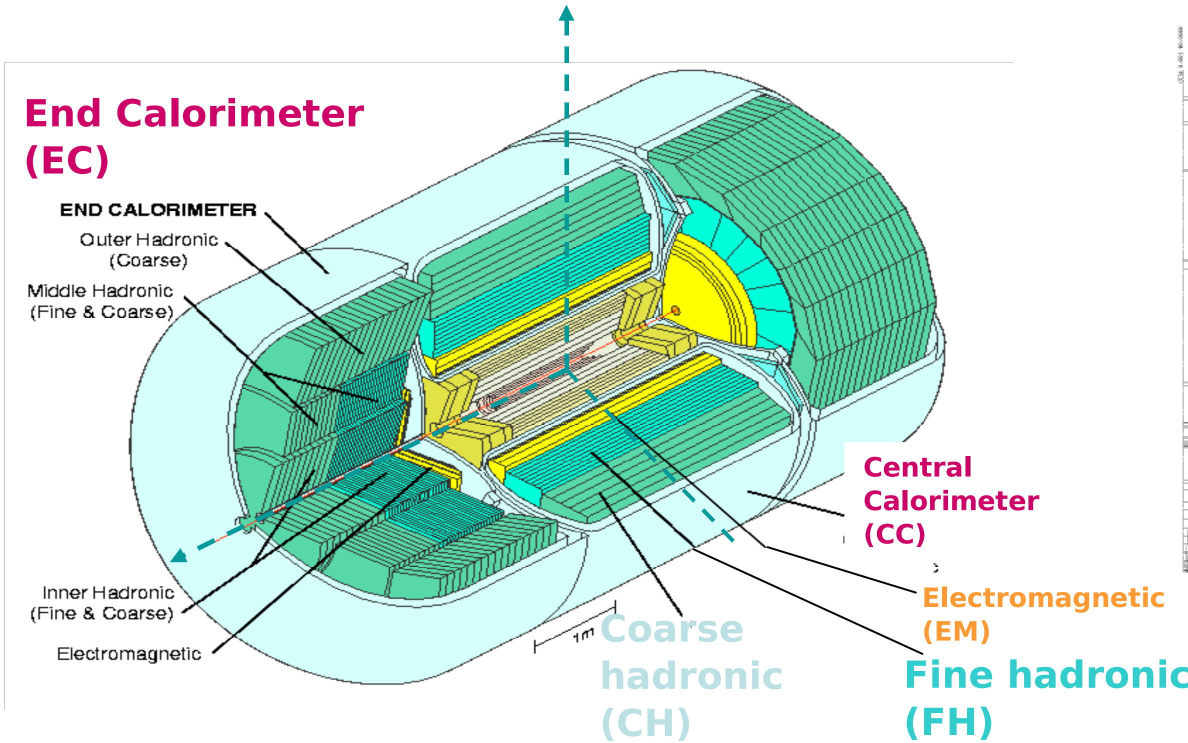
  Even if they contain bells, whistles and switches that we do not have to / want to play with, being able to run ourselves at least allows us to check a few obvious things like numerical stability.

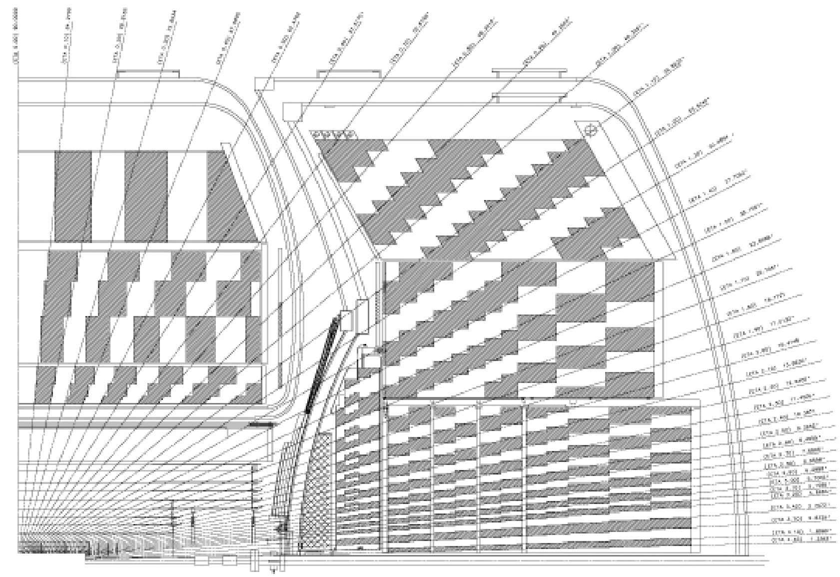
  Also, we need to generate *huge* samples.

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): $\Delta\eta \times \Delta\varphi = 0.1 \times 0.1$

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