Measurement of the W boson mass at the Tevatron

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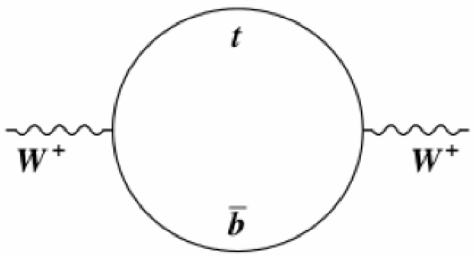
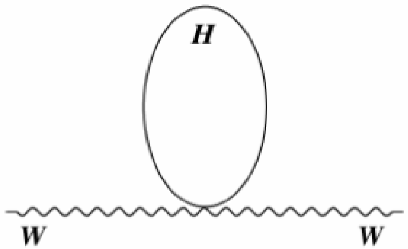
Motivation

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:

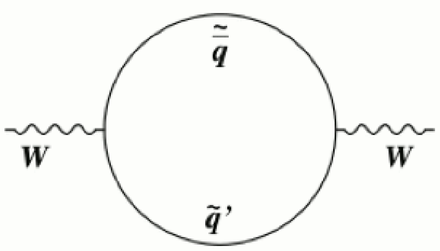




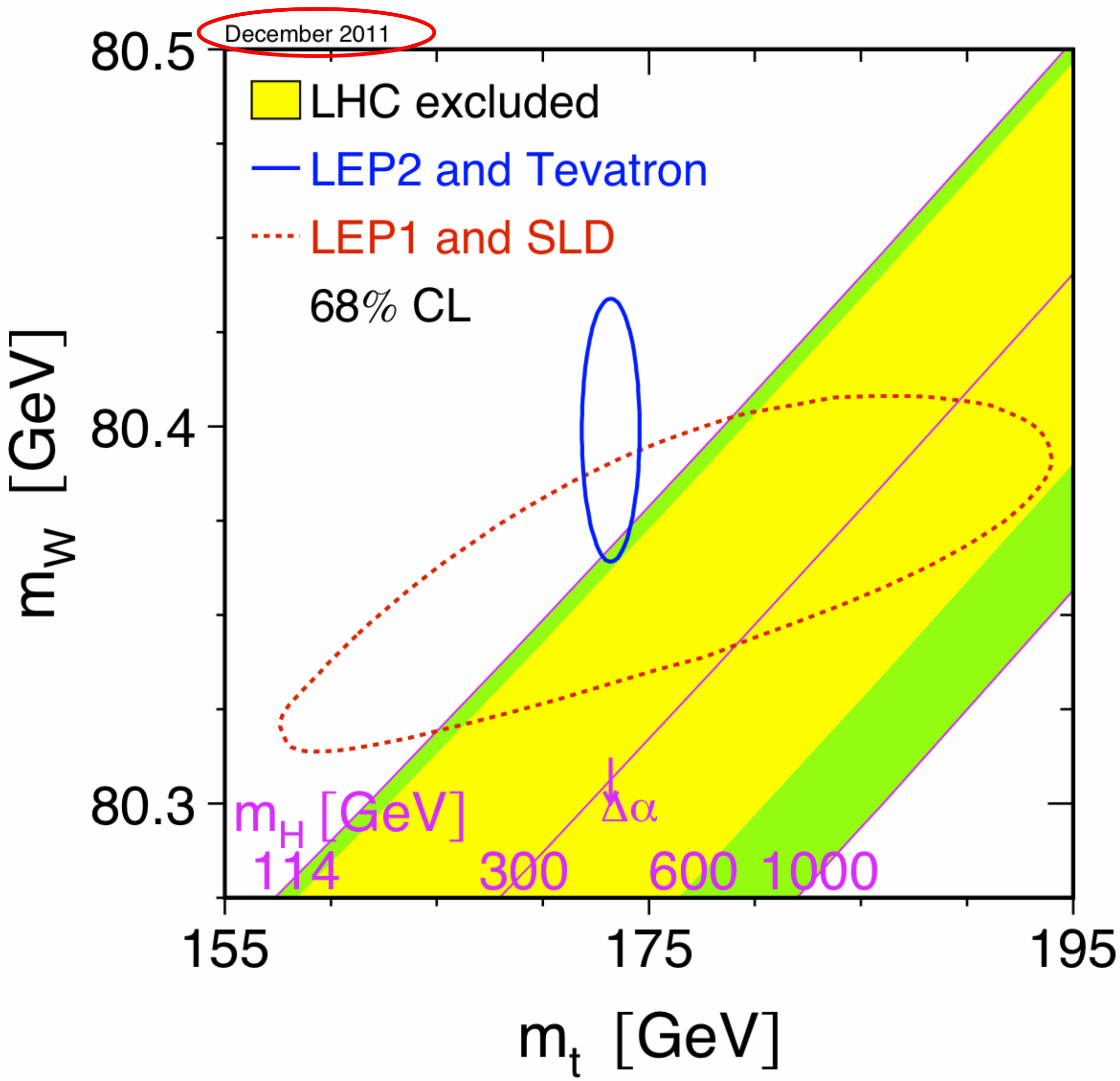
Precise measurements of M_W and M_t constrain SM Higgs mass.

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

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



Motivation



For equal contribution to the Higgs mass uncertainty need:

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

Current Tevatron average:

$\Delta M_t = 0.9$ GeV (arXiv:1107.5255)

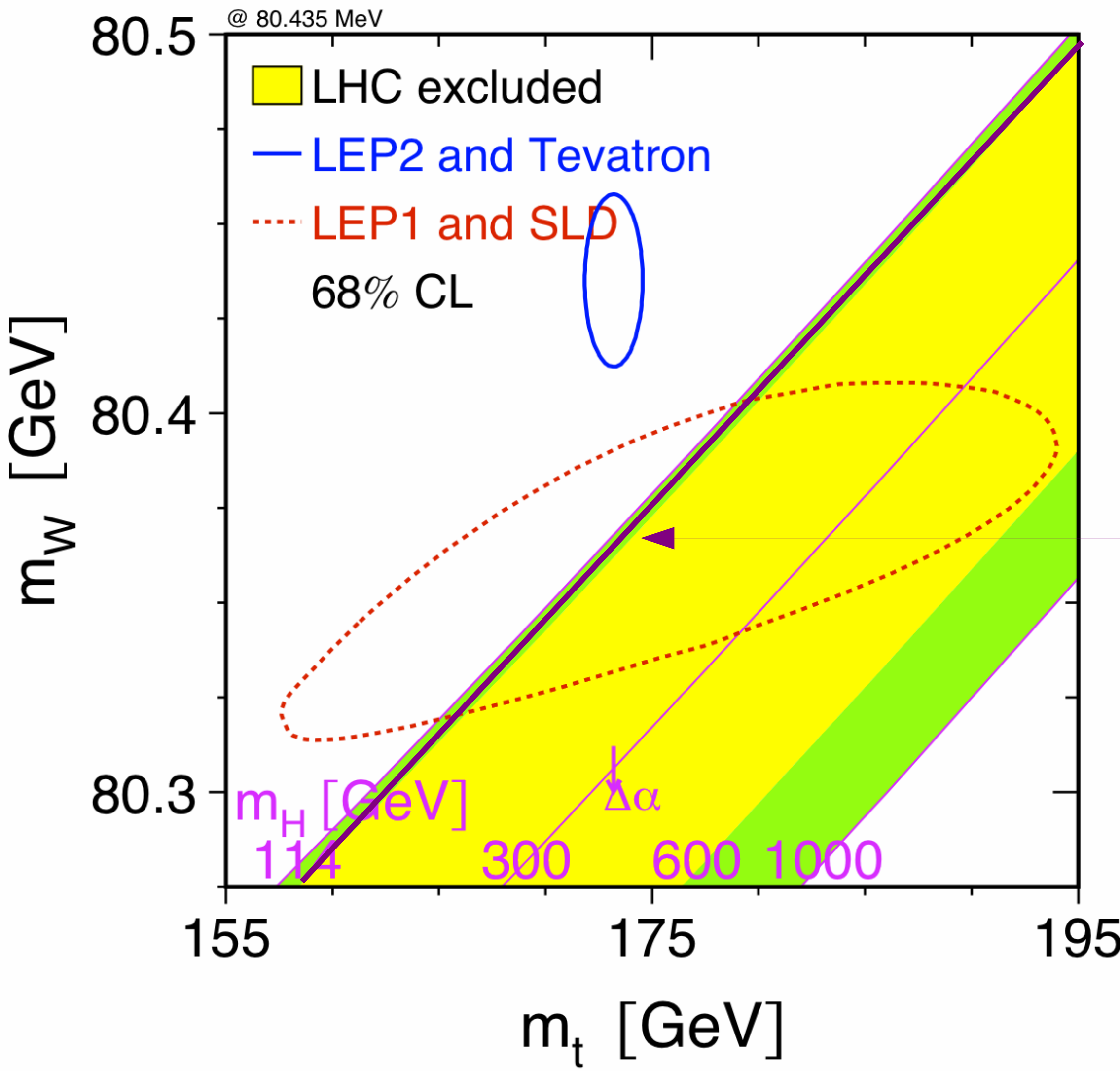
$\Rightarrow$ would need: ΔM_W = 5 MeV

Currently have: ΔM_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 .

A possible scenario for December 2012

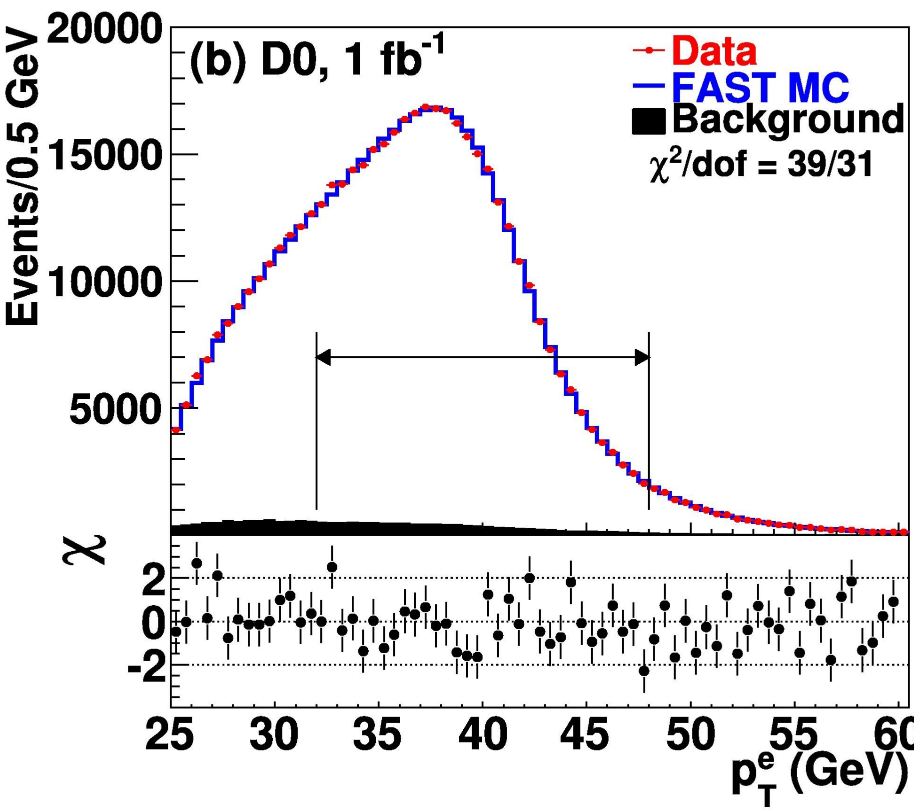
Hypothetical

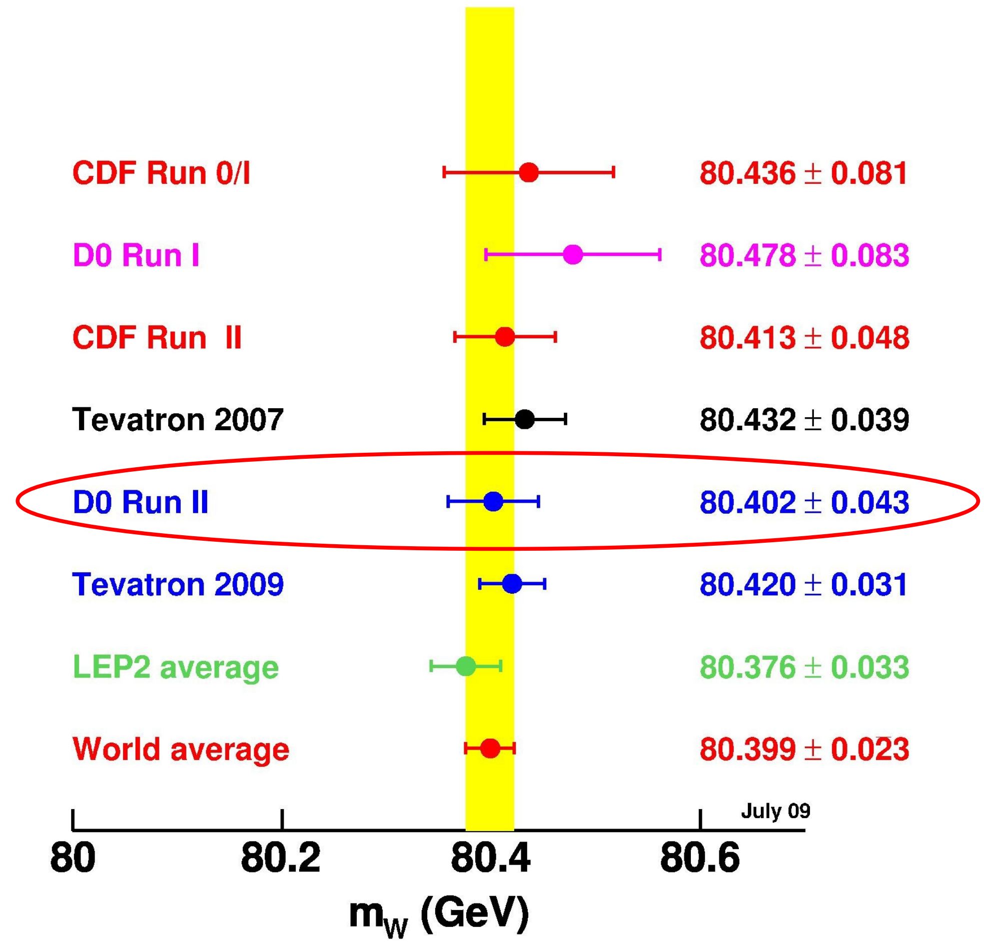


Direct observation at LHC and/or Tevatron

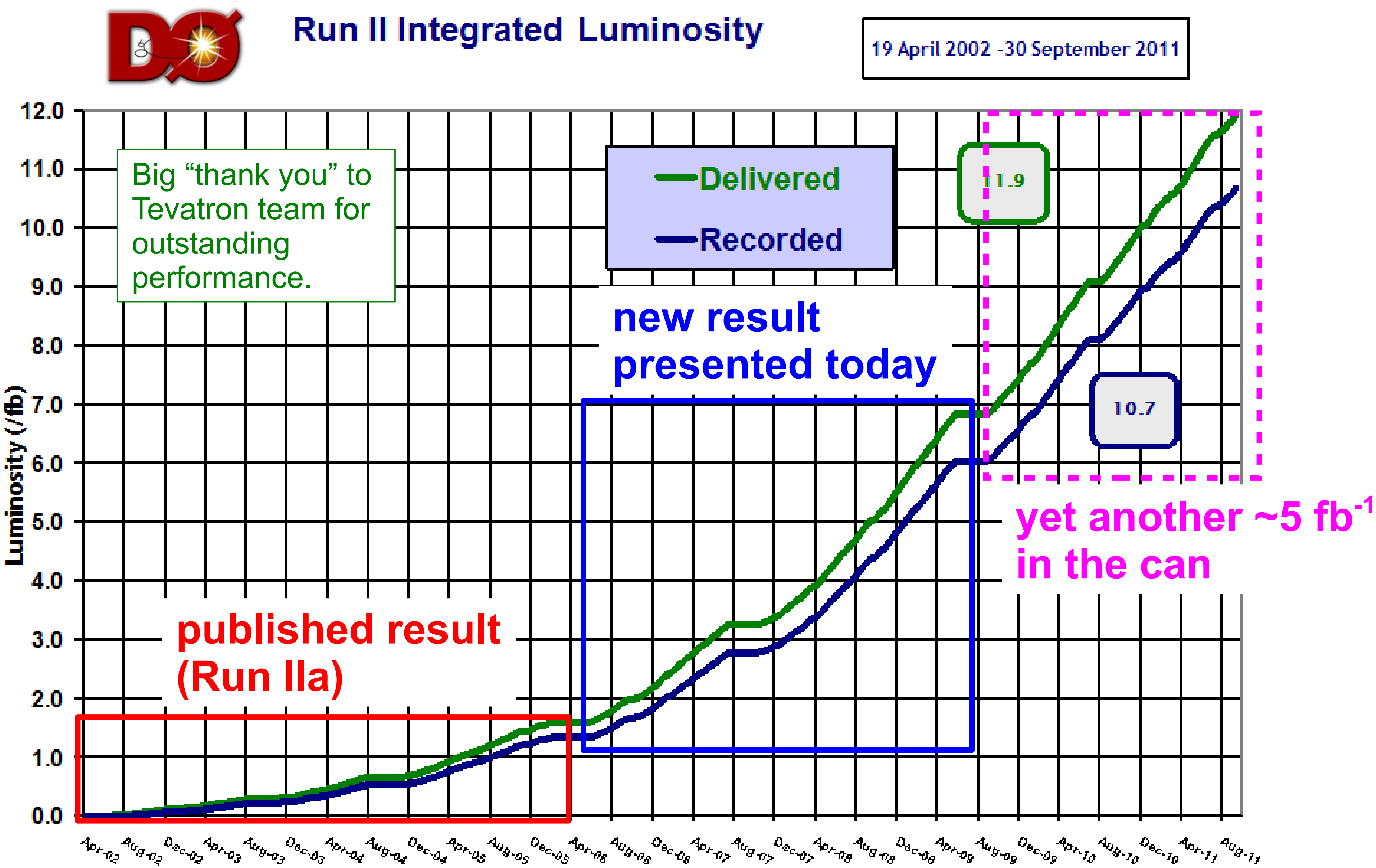
Published results

Phys. Rev. Lett. **103**, 141801 (2009)



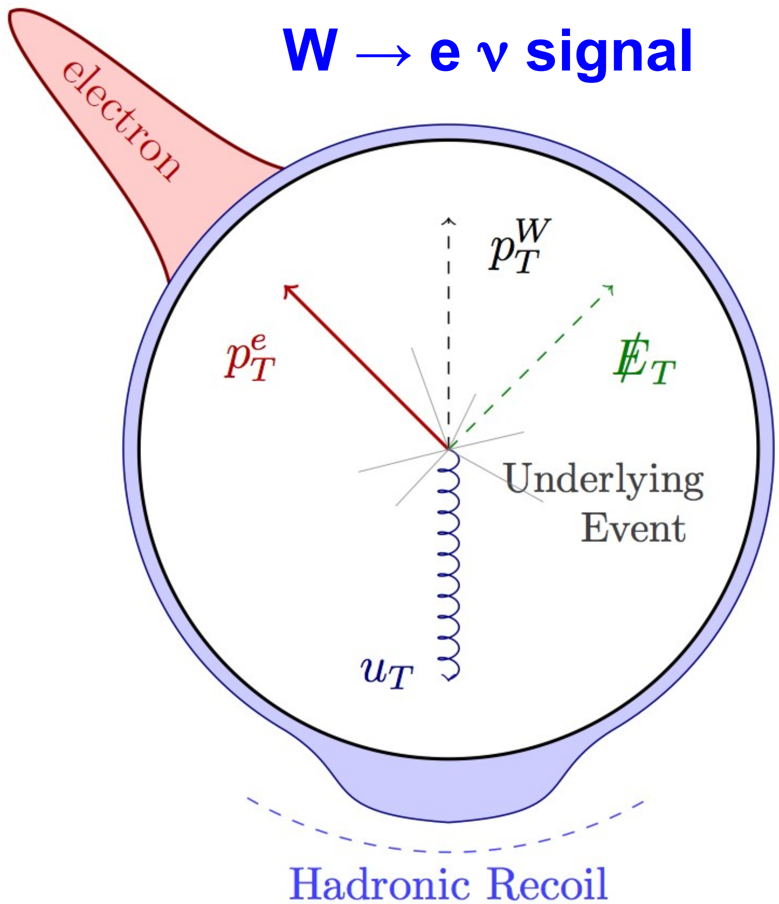


Data periods and analysis iterations

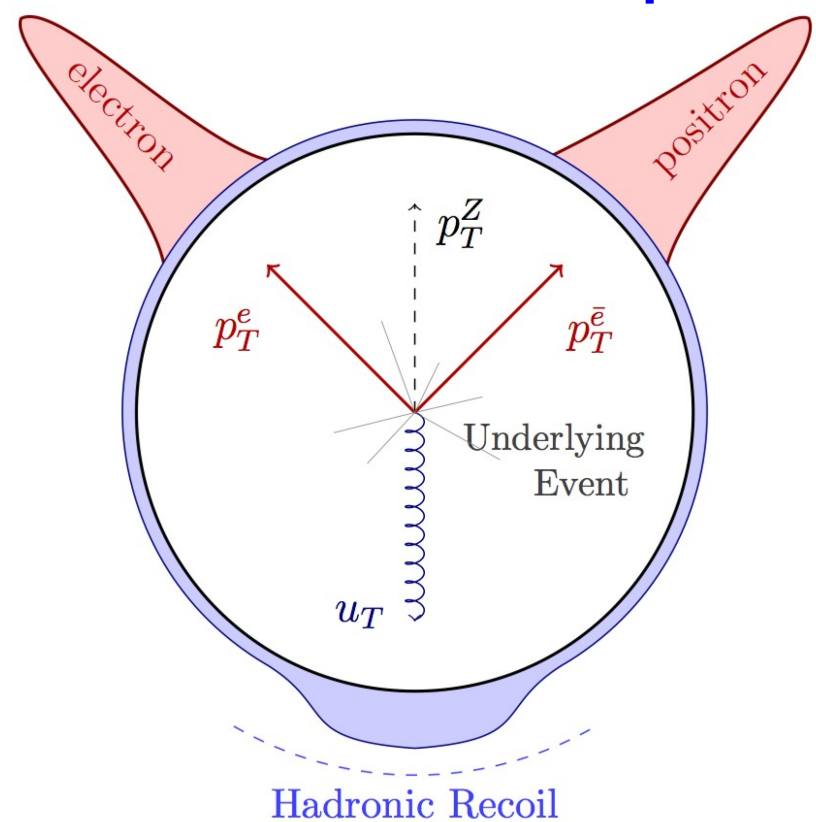


W mass: measurement method

W → e ν signal



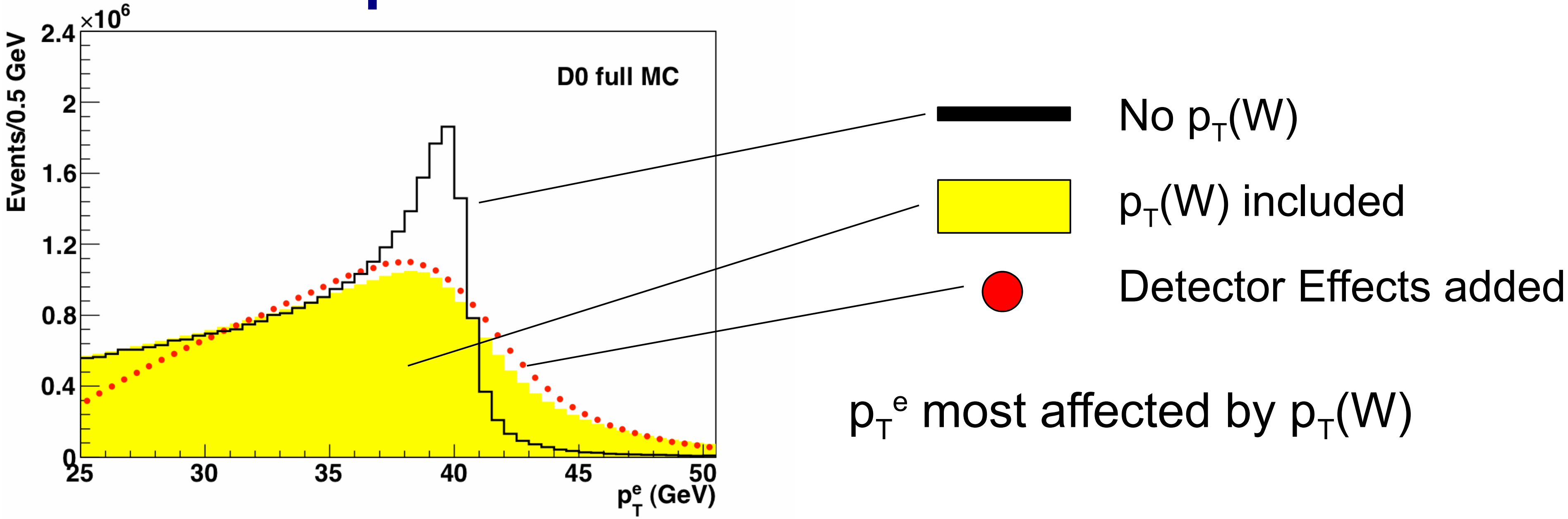
Z → e e events provide critical control sample



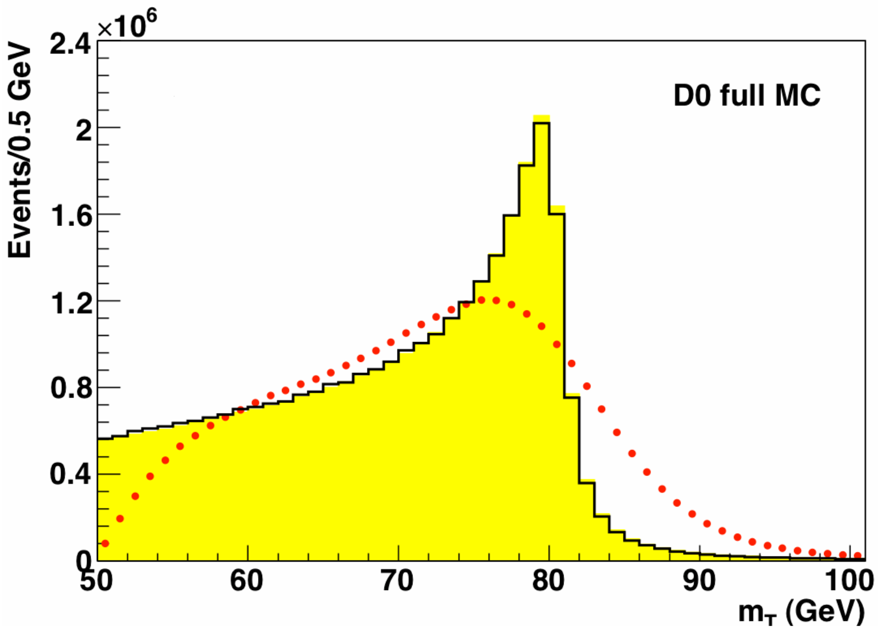
In a nutshell: measure two objects in the detector:

- Lepton (in our case an electron), need energy measurement with 0.1 per-mil precision (!!)
- Hadronic recoil, need ~1 % precision

Experimental observables



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



$$m_T = \sqrt{2\, p_T^e\, \not{E}_T (1 - \cos \Delta \phi)}$$

m_T most affected by measurement of recoil transverse momentum

Event selection

Event selection

- CAL only trigger (single EM)
- vertex $z < 60\,cm$

Electron selection

- $p_T > 25GeV$
- HMatrix7 < 12, emf > 0.9 and iso < 0.15
- $\eta_{\text{det}} < 1.05$ in the calorimeter fiducial region
- In the calorimeter ϕ fiducial region, as determined from the track
- Spatial track match, track with $p_T > 10GeV$ and at least one SMT hit

$Z \to ee$ selection

- At least two good electrons
- Hadronic recoil transverse momentum $u_T < 15\,GeV$
- Invariant mass $70 < m_{ee} < 110\,GeV$

$W \to e\nu$ selection

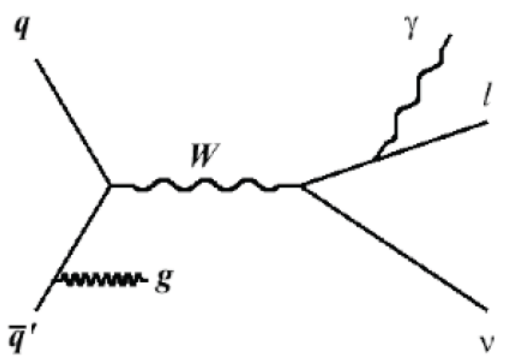
- At least one good electron
- Hadronic recoil transverse momentum $u_T < 15\,GeV$
- Transverse mass $50 < m_T < 200\,GeV$
- $\not{E}_T > 25GeV$

Number of candidates after selection: 54,512 (Z → e e)
1,677,394 (W → e nu)

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 with non-perturbative form factor which resums large logarithmic terms from emission of multiple soft gluons:
DØ uses **ResBos** + **Photos** 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

Blind analysis:
true value of mass hidden from the analysers until the analysis was completed

↓

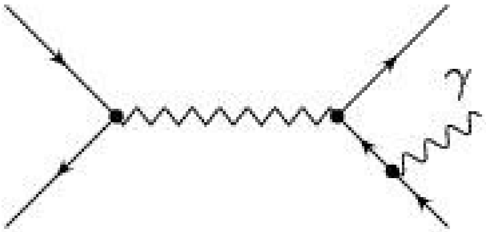
W mass

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.

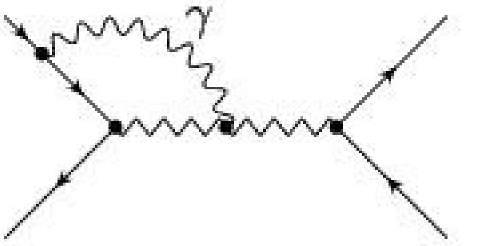
We use **W/ZGRAD** to get a feeling for the effect of the full EWK corrections.



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

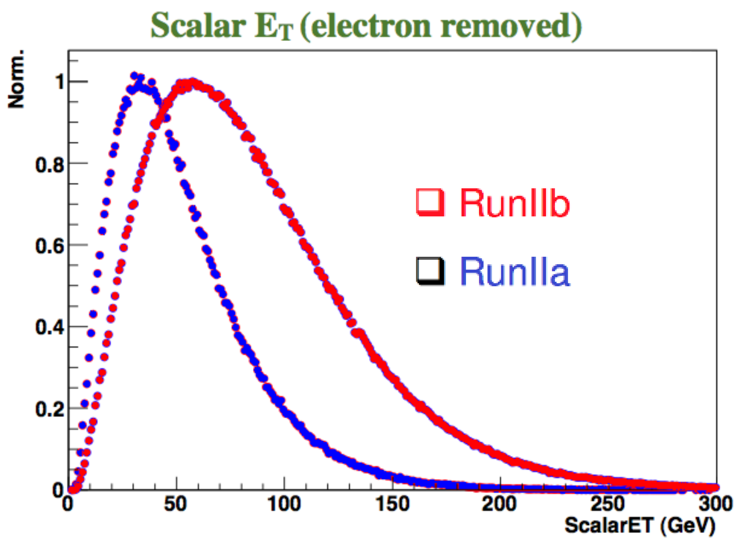
This is the sum of different effects; the two main ones are:

- 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).



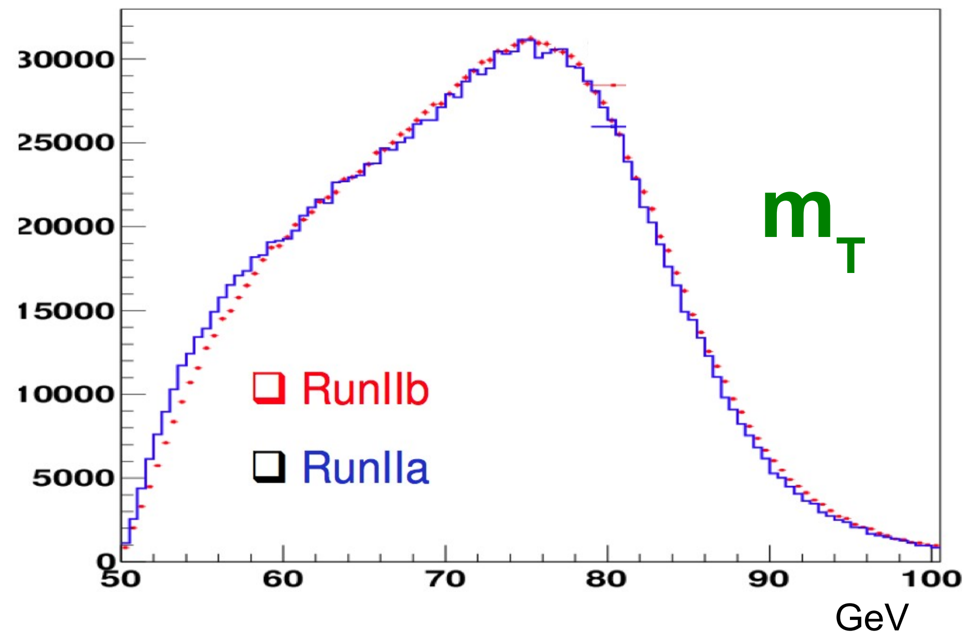
Run IIb-specific challenges

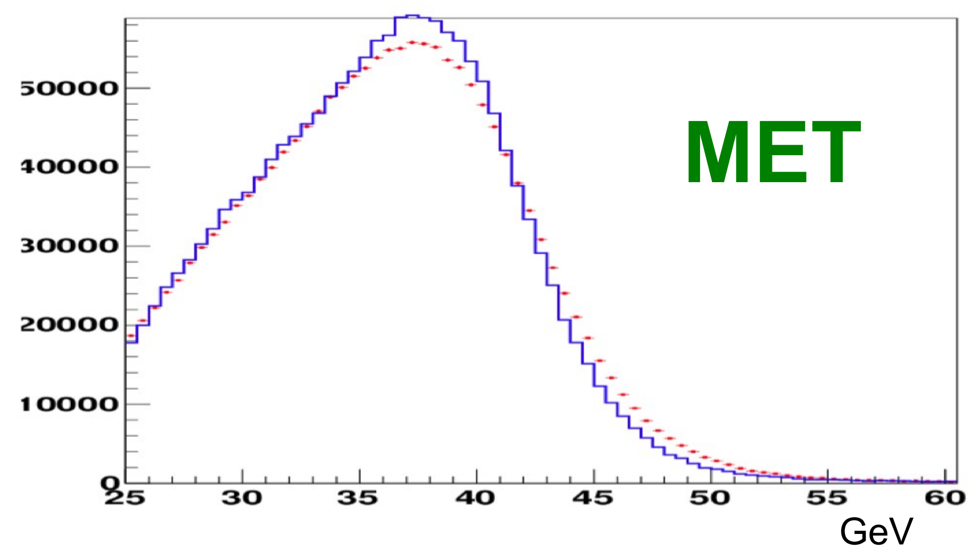
Higher lumi, hence "way more activity in the detector":



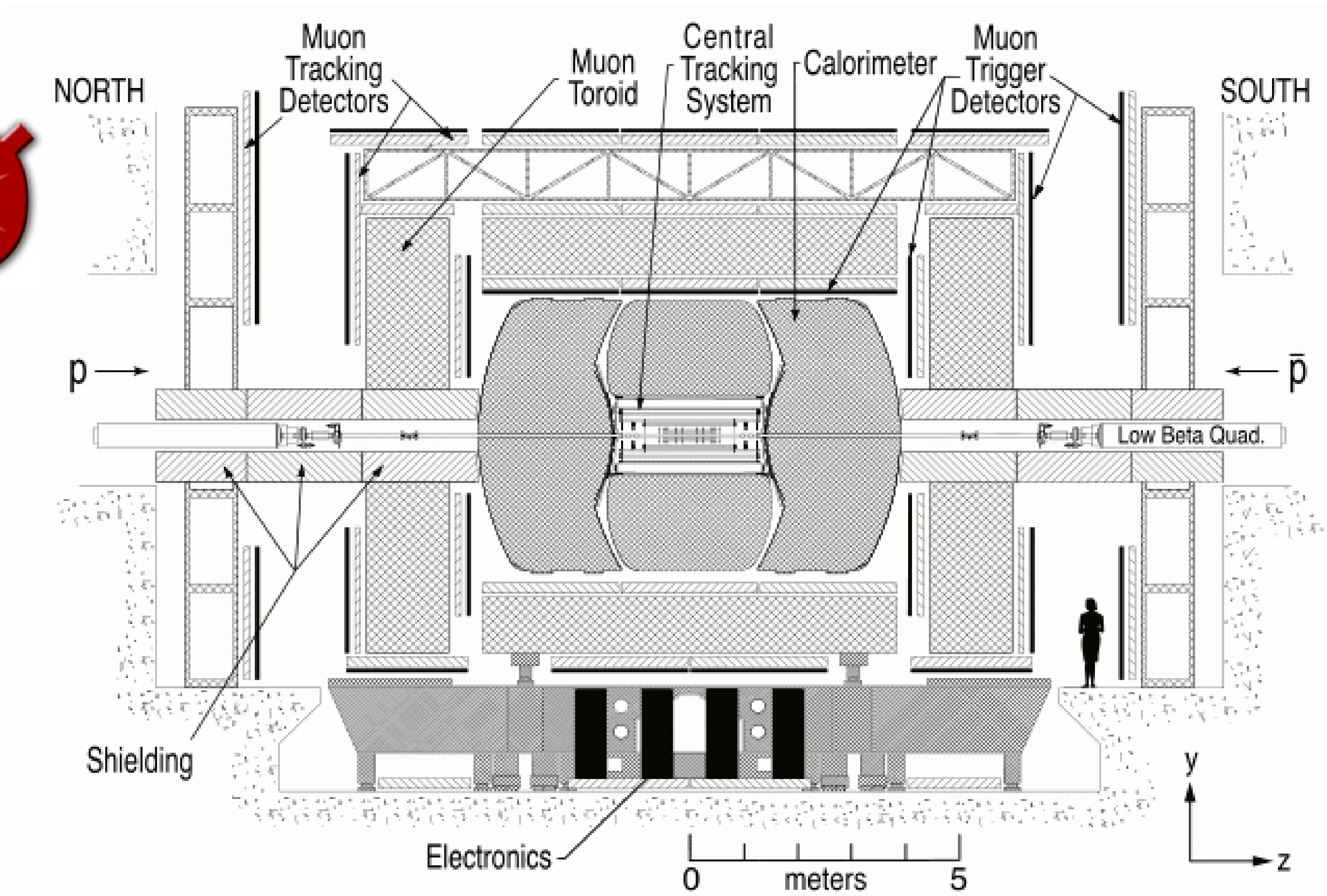
Does have quite an impact on the observables of interest (as shown on the right).

This is why we had to do significant additional R&D (w.r.t. to Run IIa analysis). No additional R&D is expected for the final 5 fb^{-1} (similar lumi spectrum as in current analysis).

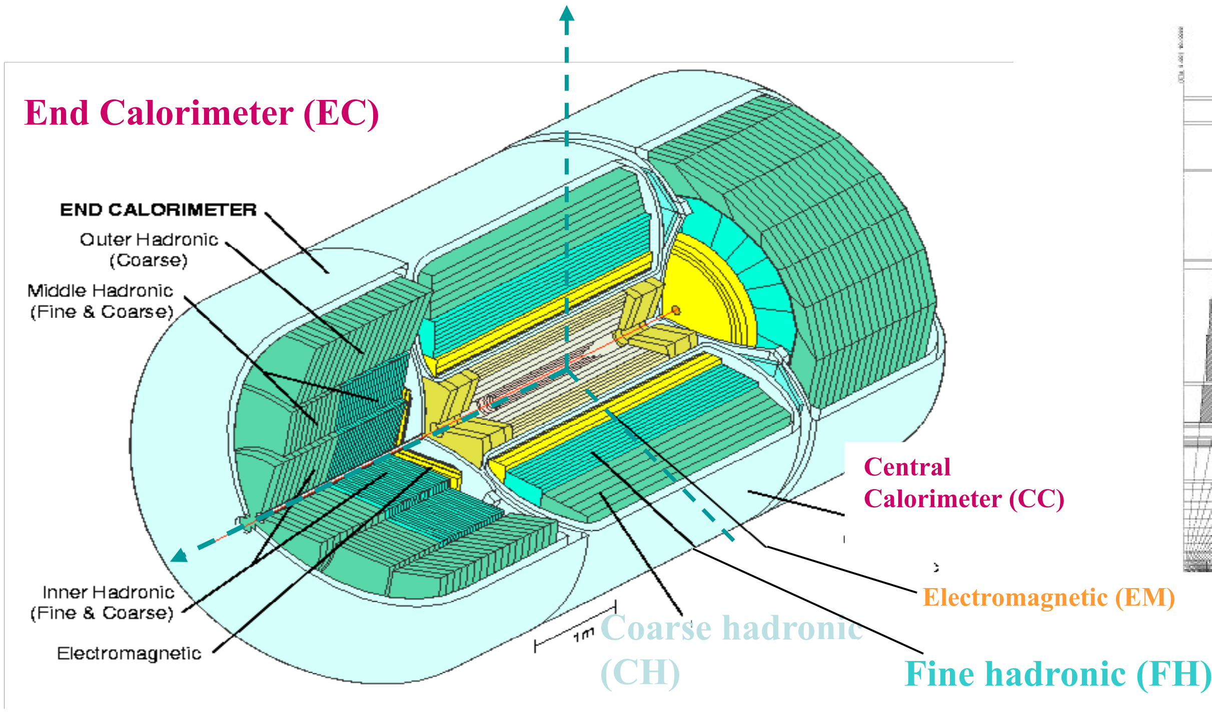


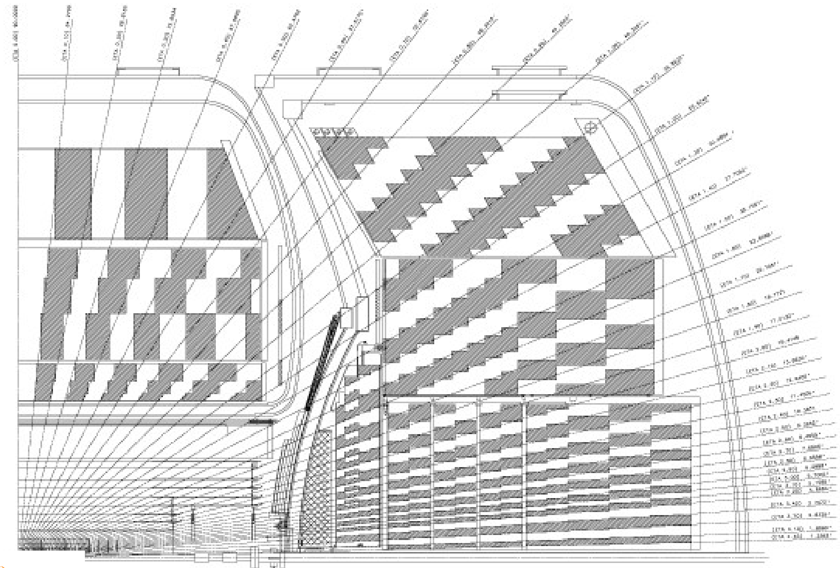


The upgraded DØ detector



Overview of the calorimeter





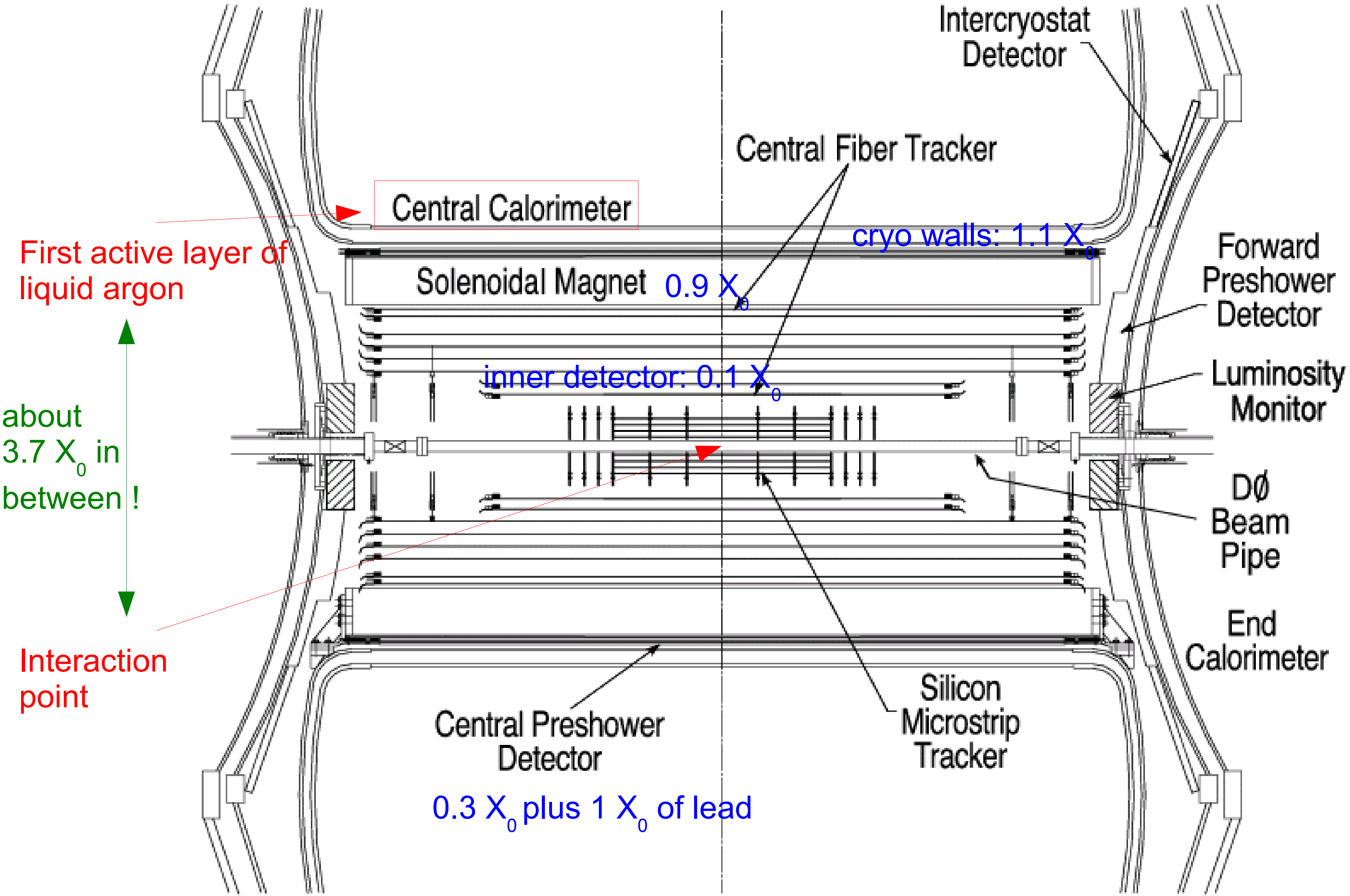
46000 cells

50 dead channels

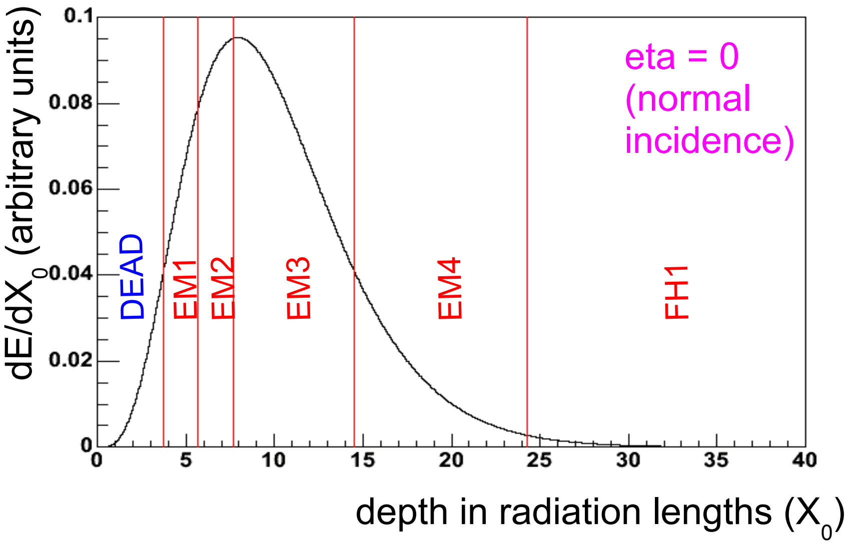
- Liquid argon active medium and (mostly) uranium absorber
- Hermetic with full coverage : $|\eta| < 4$
- Segmentation (towers): $\Delta\eta \times \Delta\phi = 0.1 \times 0.1$

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

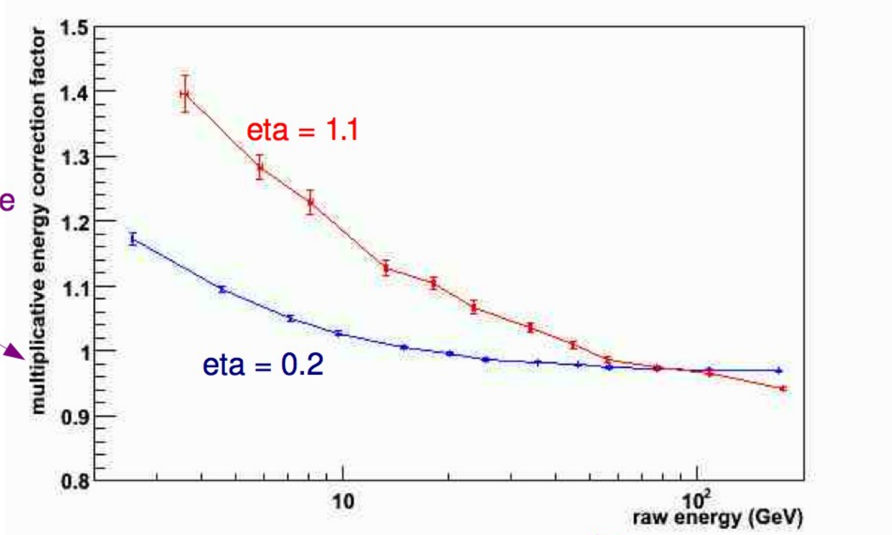
Keep in mind: the CAL is not alone !



Electron energy loss



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.

Calorimeter: “aging”, high inst. lumi.

Unit cell of the calorimeter readout:

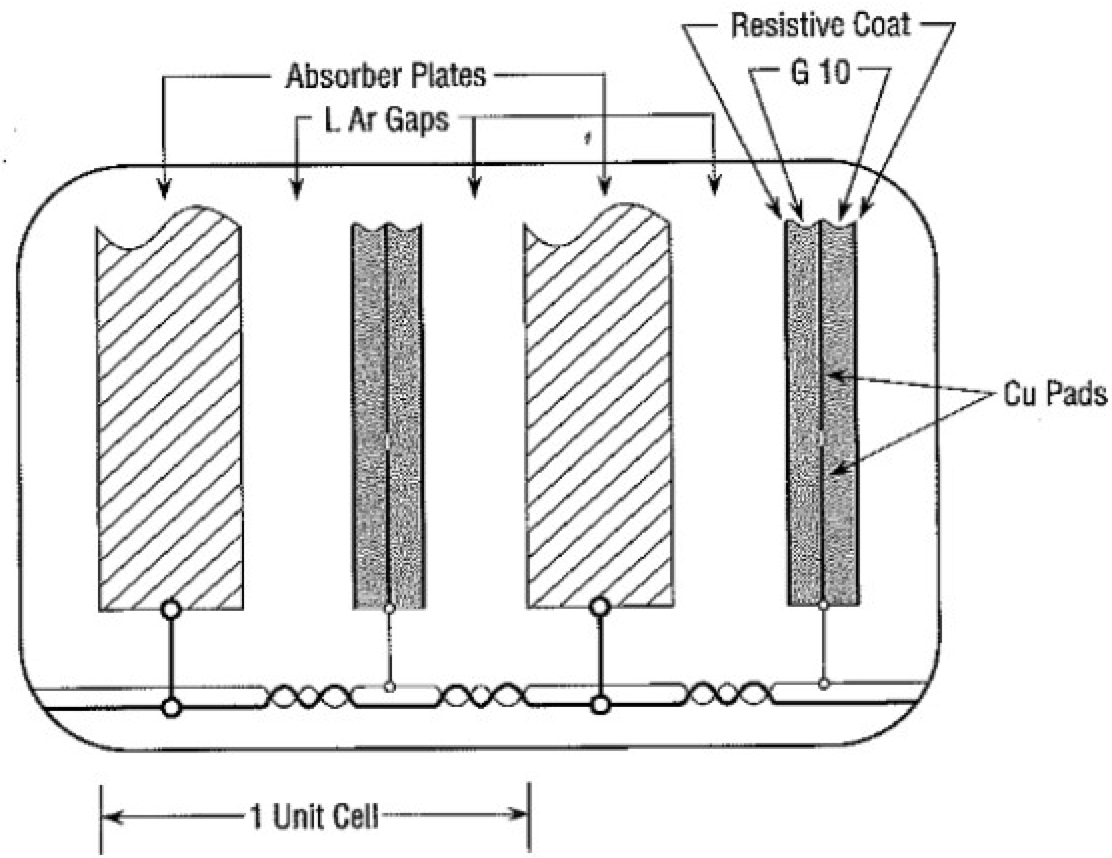


Fig. 27. Schematic view of the liquid argon gap and signal board unit cell.

Liquid Argon calorimeter:

- no intrinsic amplification
- very stable device
  - argon is pure
  - geometry is stable
  - readout electronics is monitored regularly; found to be very stable

=> do not expect significant changes in energy response or performance due to “aging” or high instantaneous luminosity

Figure taken from Run I NIM paper.

Calorimeter: stability of effective HV

Unit cell of the calorimeter readout:

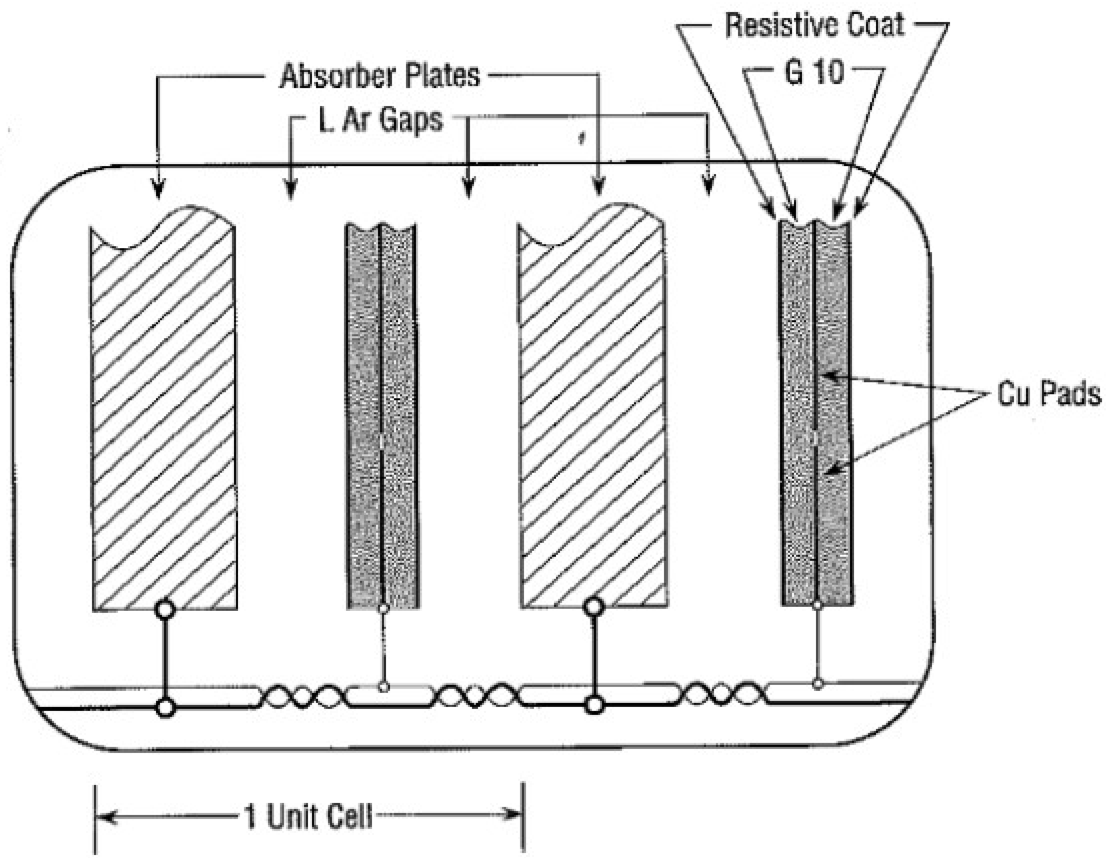


Fig. 27. Schematic view of the liquid argon gap and signal board unit cell.

Figure taken from Run I NIM paper.

One caveat:

The current that flows trough the Argon gaps also needs to flow through cables and such, and – more importantly – through the resistive coat !

The resistive coat has very high surface resistivity:

~ 200 MΩ/☐

Any significant current will lead to a voltage drop across the resistive coat

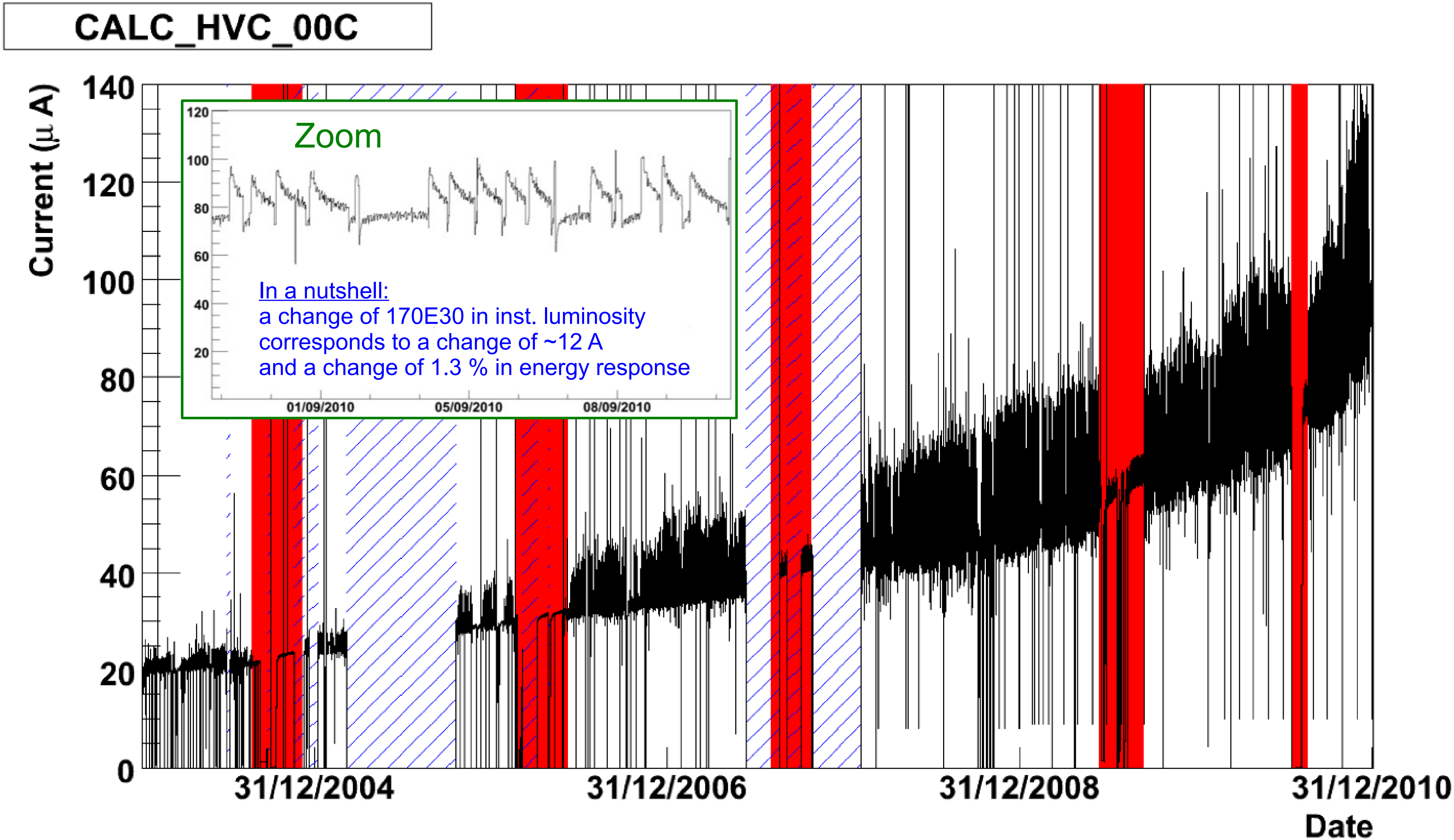
=> reduced electric field

=> reduced drift velocity

=> (slightly) reduced energy response

Calorimeter: currents

This example channel is connected to di-gaps in CC-EM4 readout sections.



Bottom line

Continuous rise in “dark currents” taken into account by regular recalibrations of calorimeter gain using control samples in collider data:

- inclusive EM events (phi intercalibration)
- $Z \rightarrow e\ e$

Have detailed first-principles model (adjusted to $Z \rightarrow e\ e$ data) to describe effect of instantaneous luminosity, separately per readout cell.

Final electron energy scale calibration

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

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

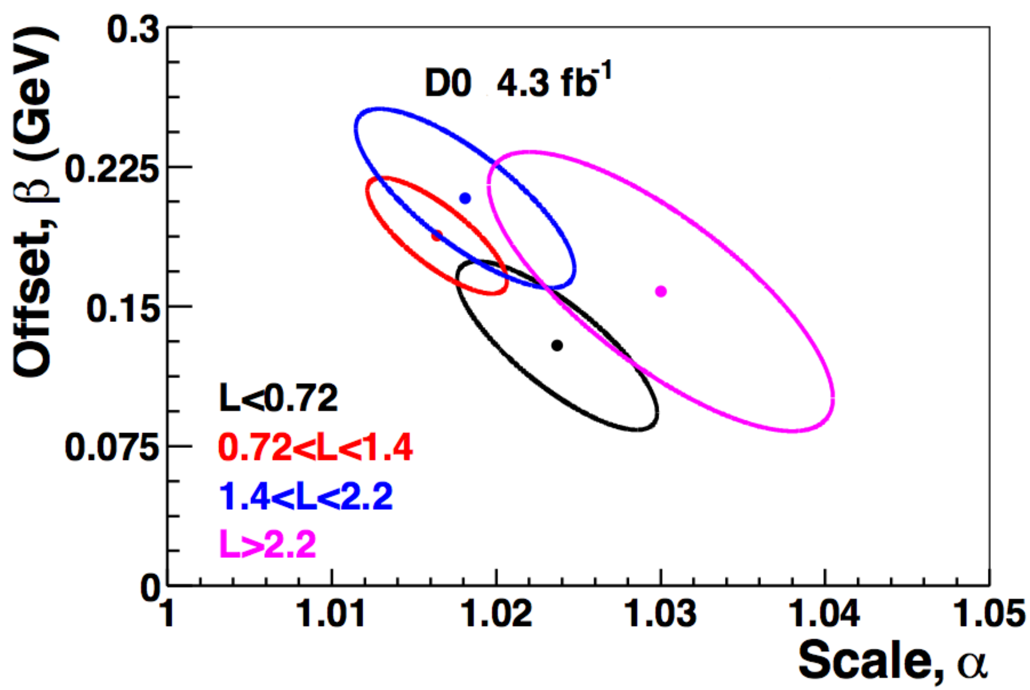
$$E_{measured} = \text{scale} * (E_{true} - 43\text{ GeV}) + \text{offset} + 43\text{ GeV}$$

We are effectively measuring m_W/m_Z.

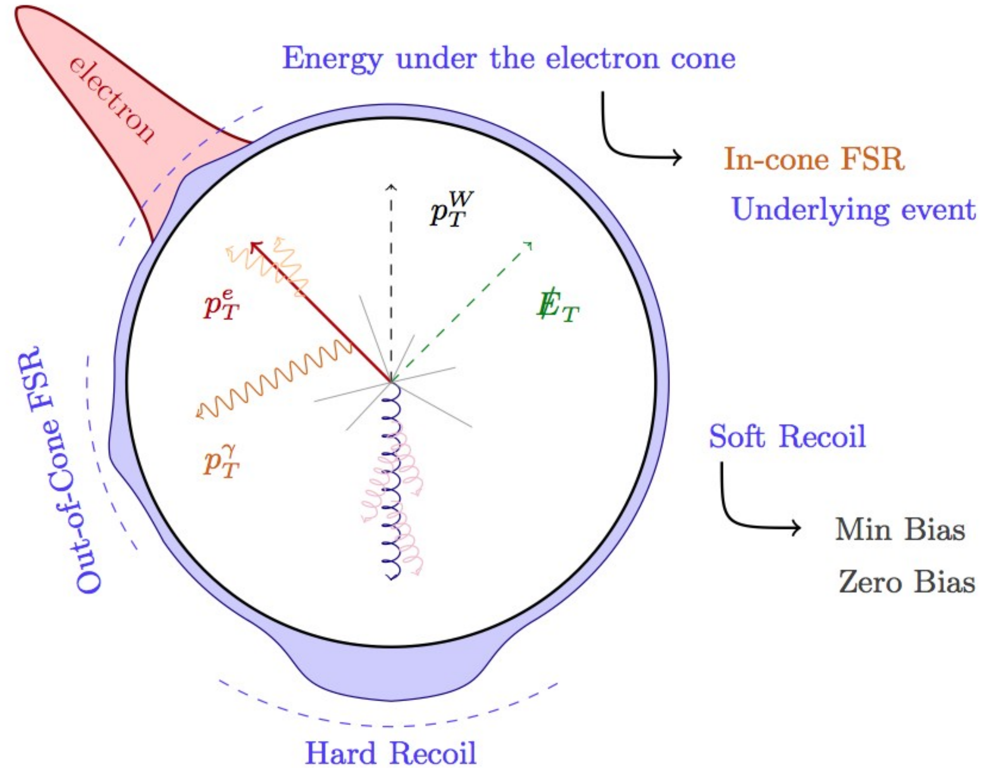
Use energy spread of electrons in Z decay (e.g. due to Z boost) to constrain scale *and* offset .

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

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



Recoil model



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

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

Recoil model

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

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

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

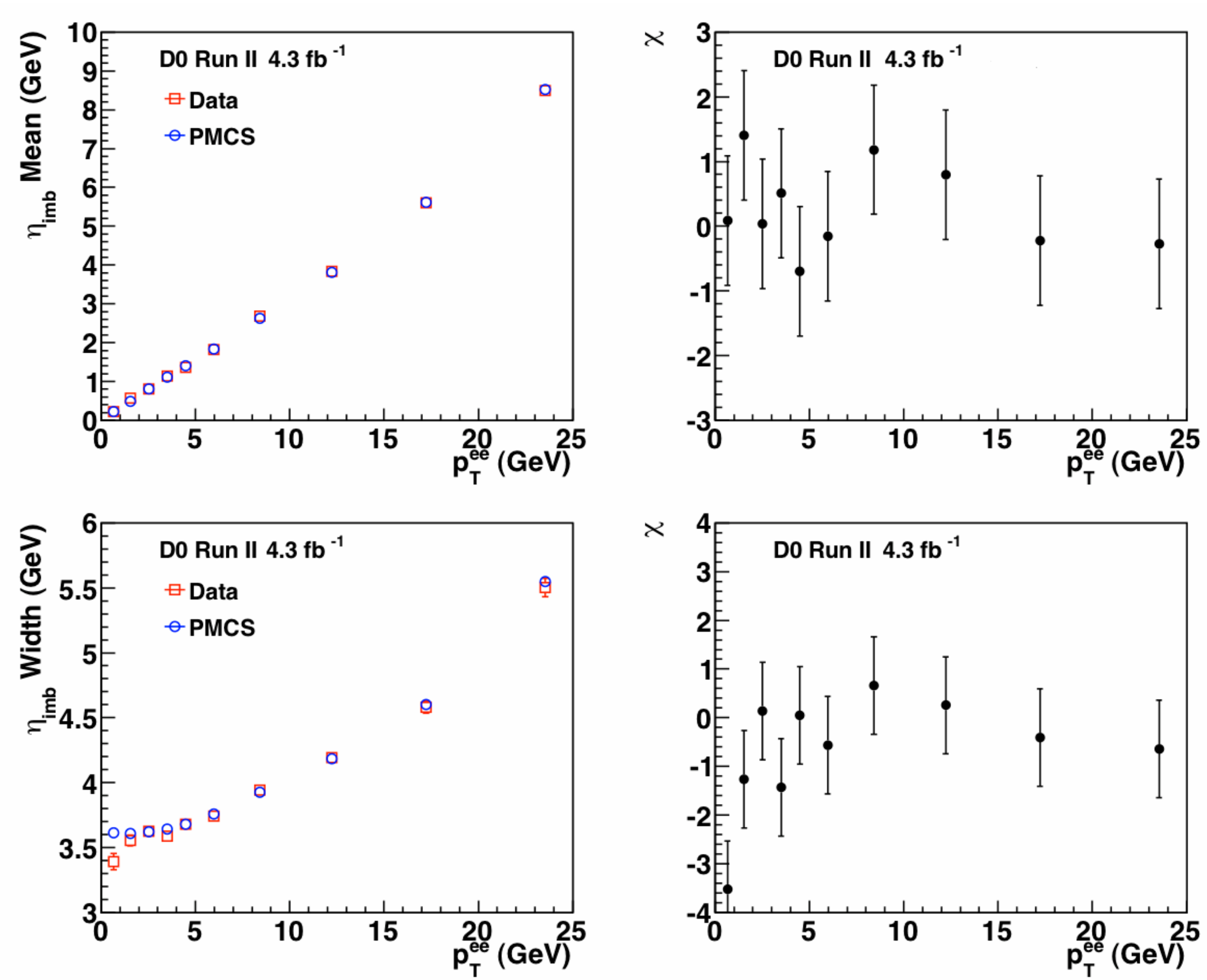
model of pileup/noise (from collider data, random trigger)

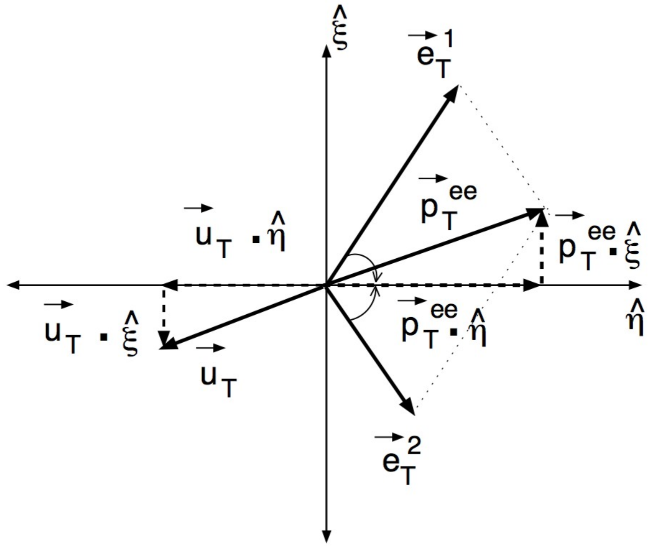
$$u_{T,smear}^{\parallel,hard} = \left(\mathrm{R}_A + \mathrm{R}_B \cdot e^{-p_T^Z/\tau_{HAD}}\right) p_T^Z \langle \frac{u_T}{p_T^Z} \rangle^{\parallel} + \mathrm{S}_A \left(u_T^{\parallel} - p_T^Z \langle \frac{u_T}{p_T^Z} \rangle^{\parallel} \right)$$

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

Recoil calibration

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





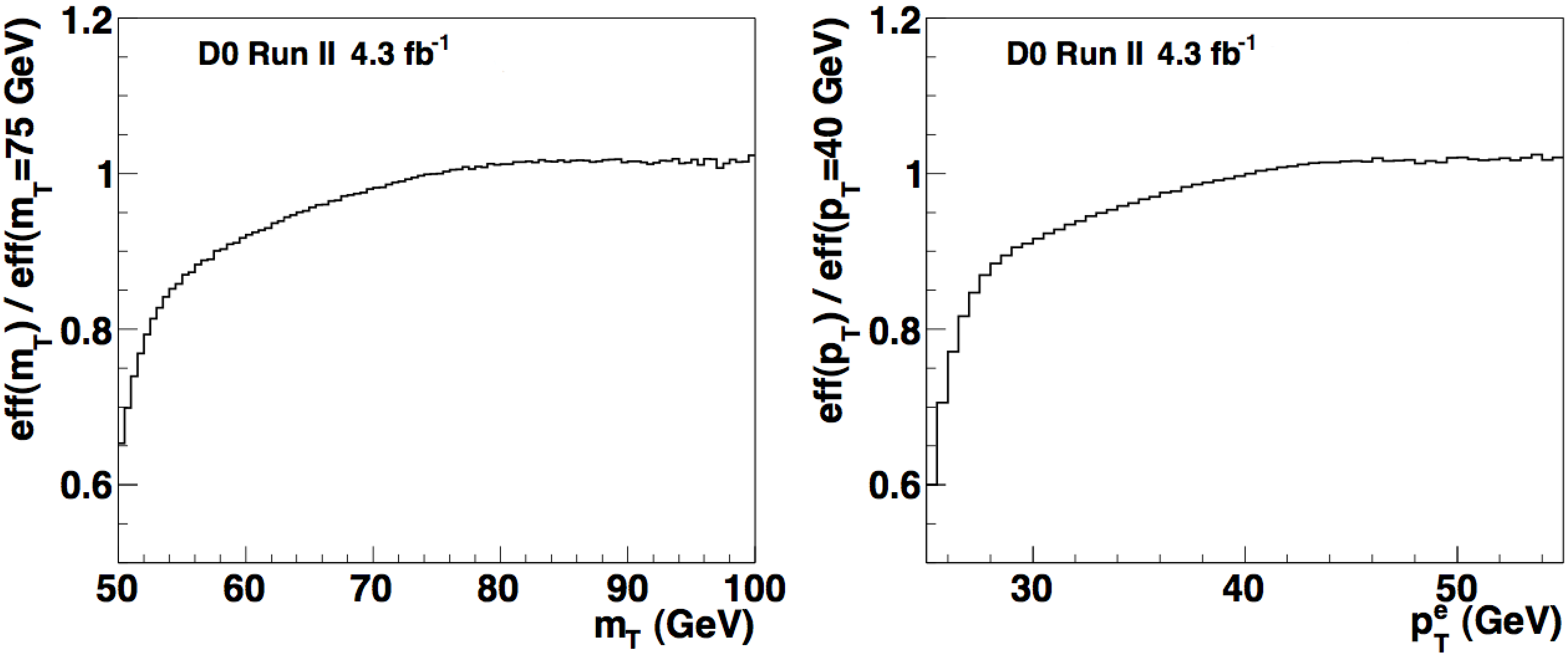
Electron efficiency model

Detailed model of electron reconstruction/identification efficiency in the busy Run IIb environment:

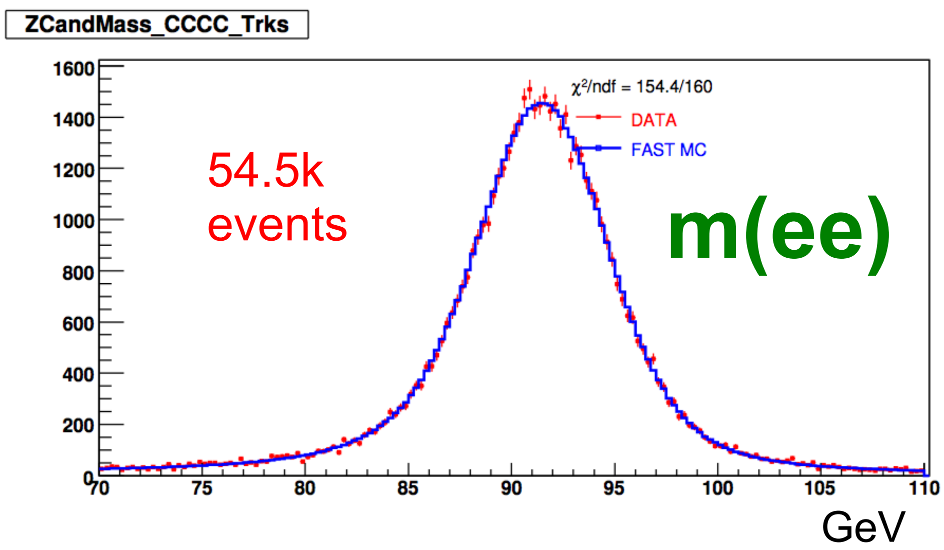
- dependence on electron kinematics (p_T, rapidity)
- effect of the hard recoil
- effect of pileup

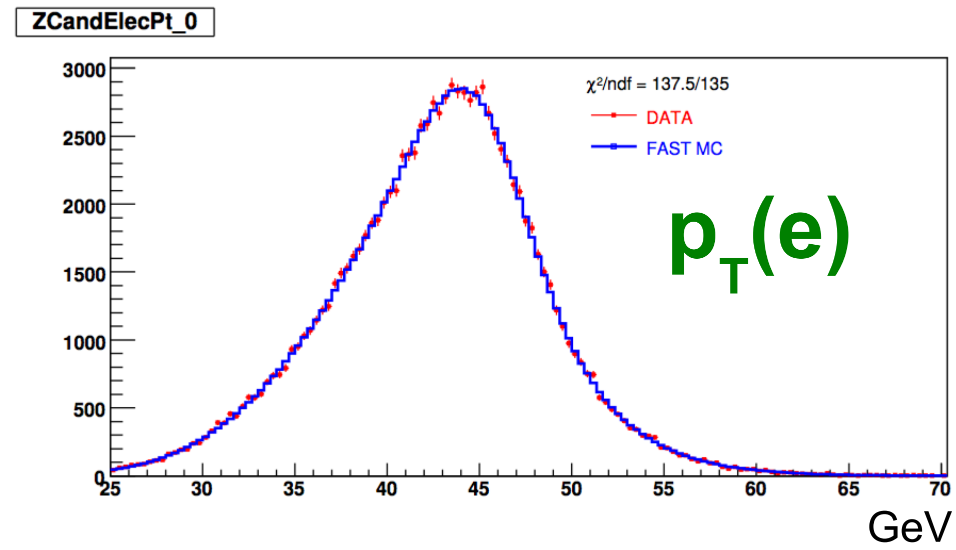
Two critical control samples:

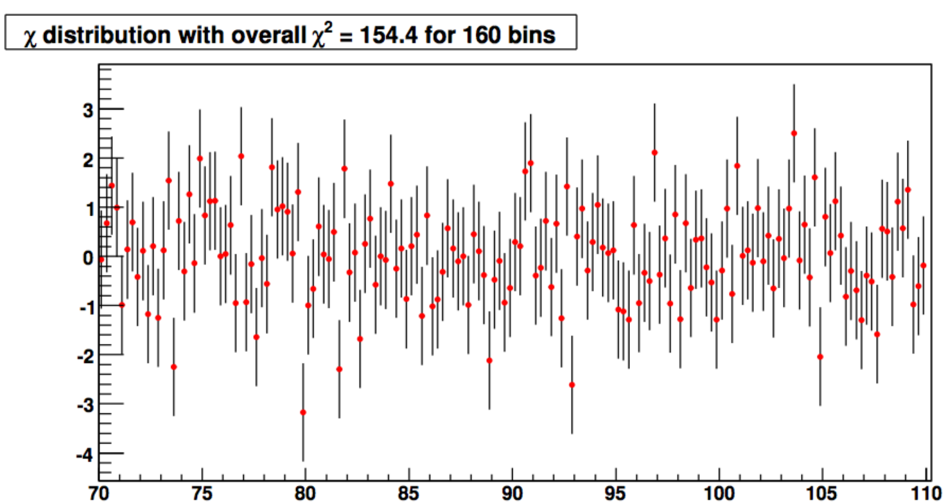
- W and Z events from detailed simulation, with "overlay" of collider data (trigger on random bunch crossing)
- Z $\rightarrow$ e e (can be selected with minimal electron requirements)

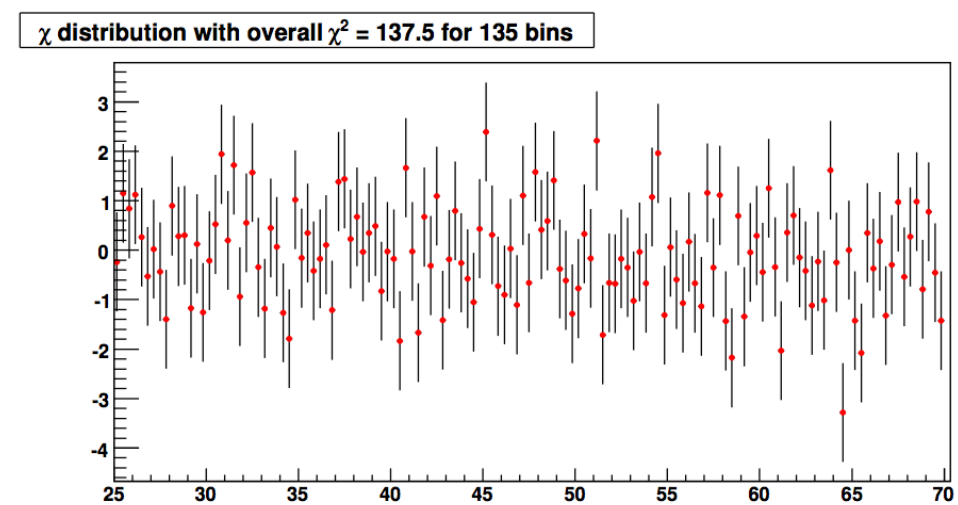


Z data





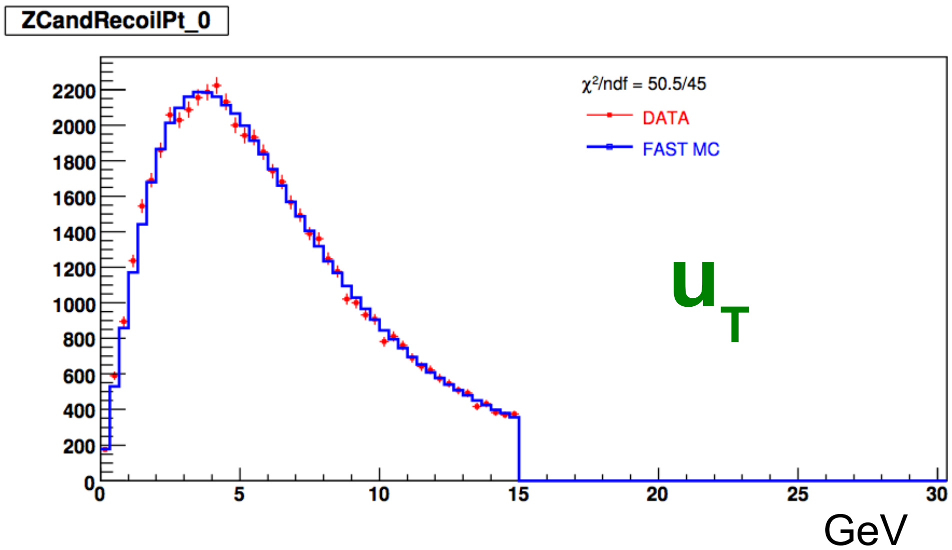


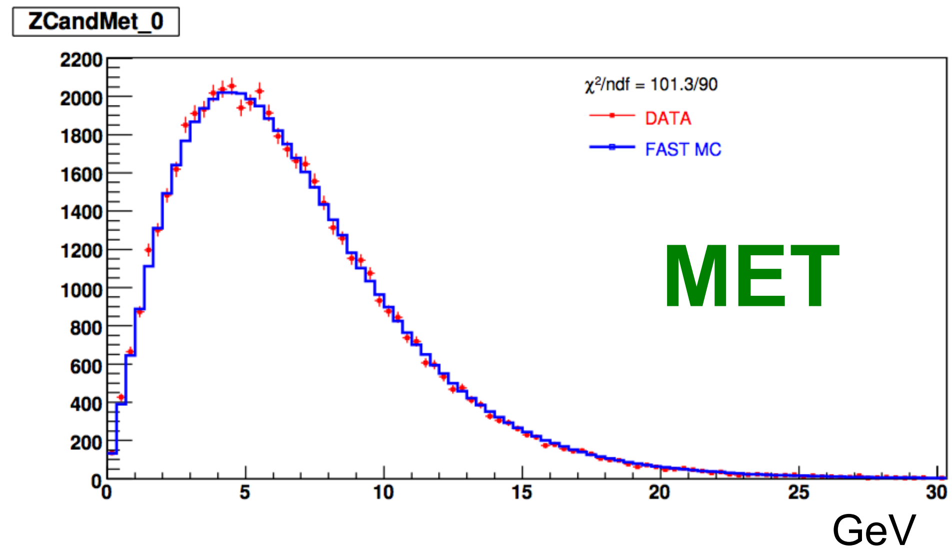


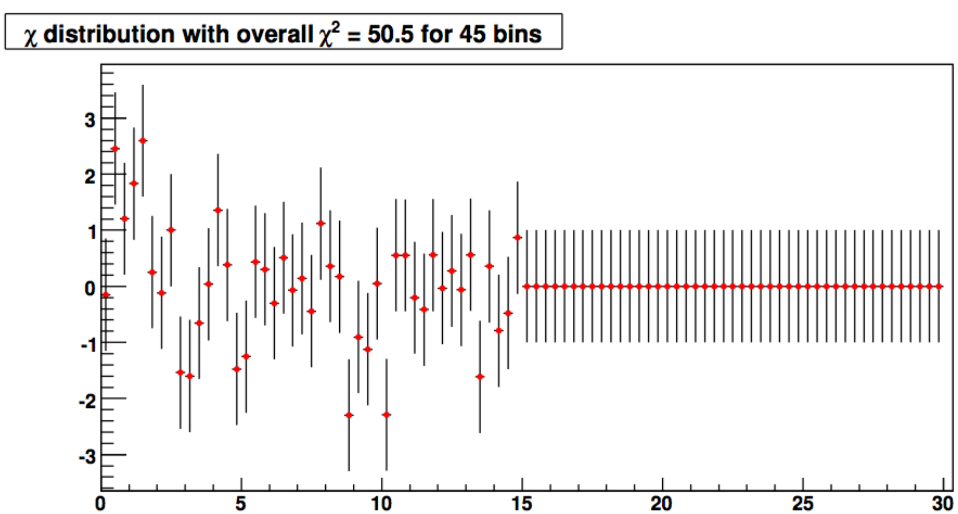
$m(Z) = 91.193 \pm 0.017$ (stat) GeV

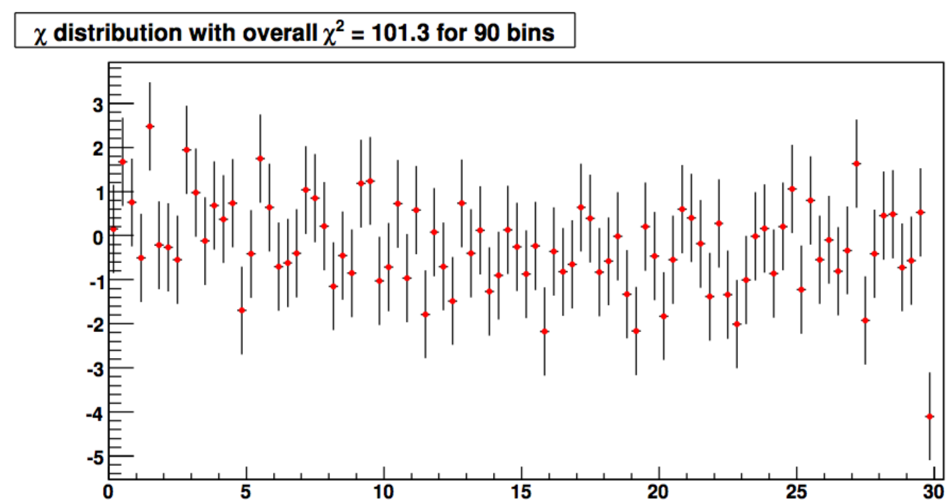
Good agreement between data and parameterised Monte Carlo.

Z data







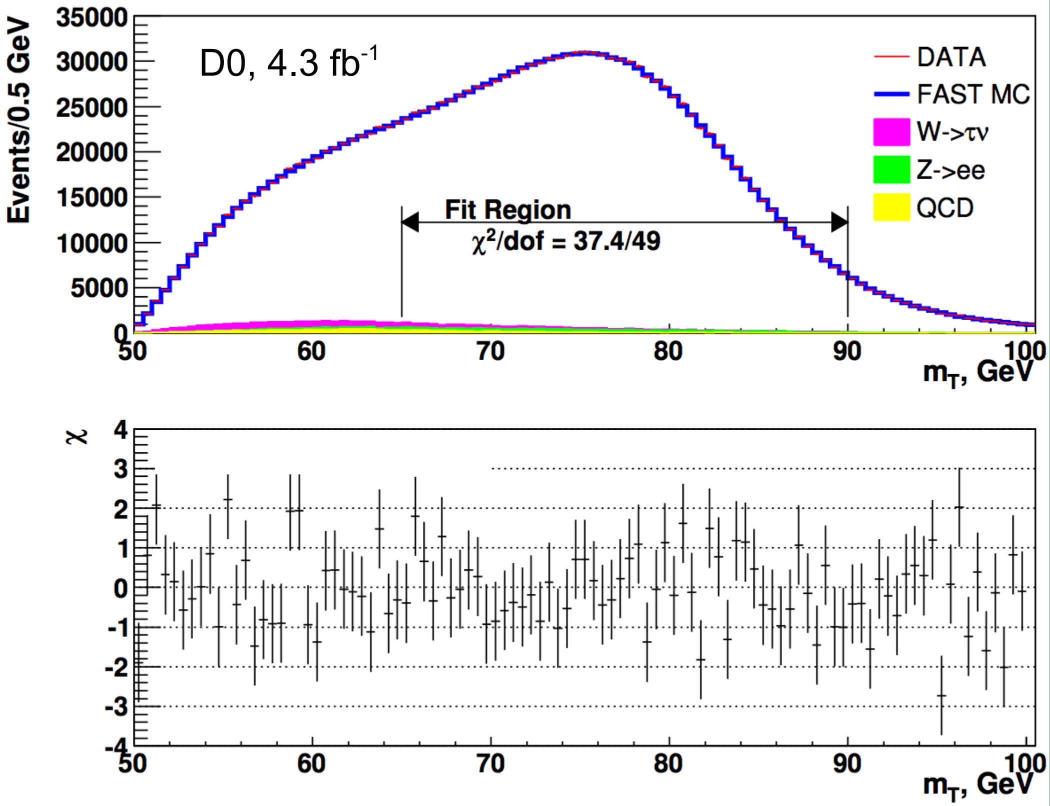


Good agreement between data and parameterised Monte Carlo.

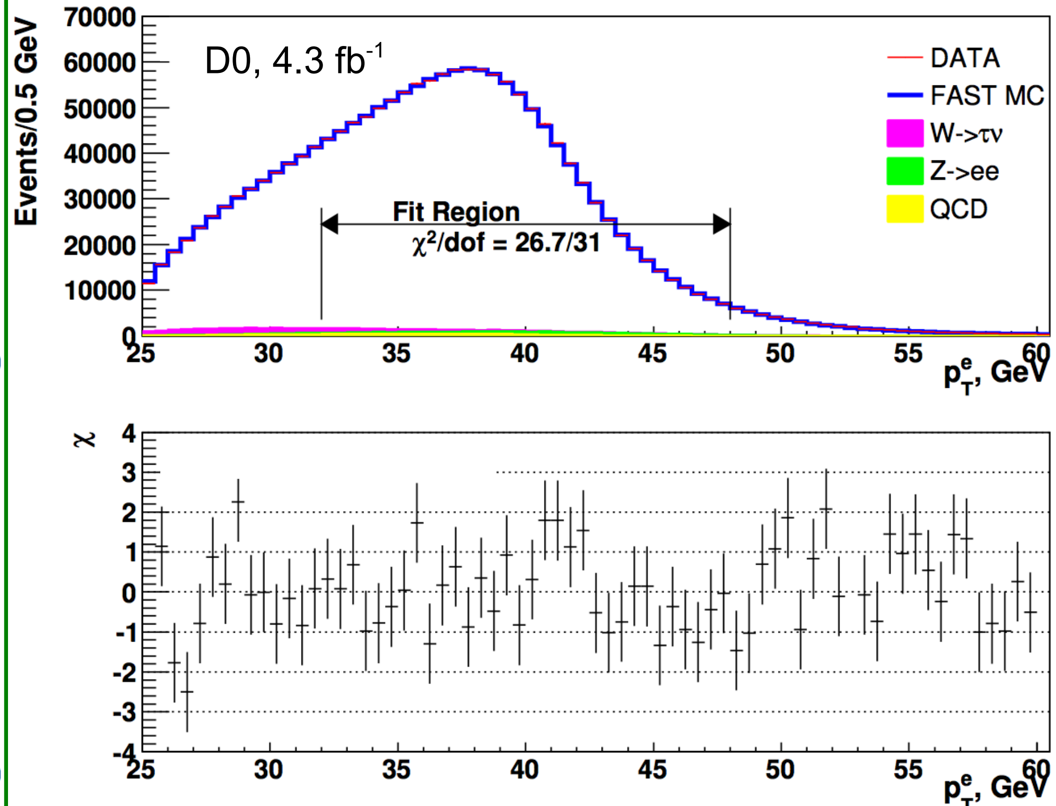
1.68M events
central electrons ($|\eta|<1.05$)

W data

m_T



$p_T(e)$



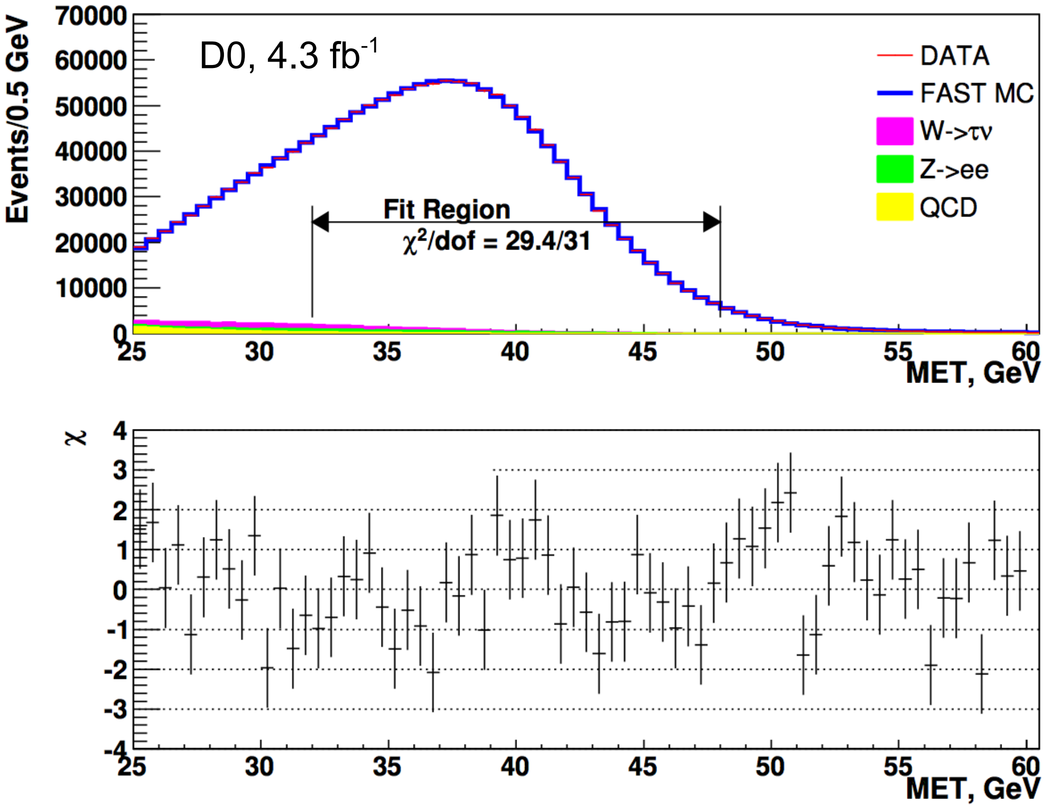
Fit results:

m(W) =
80371 ± 13 MeV (stat)

m(W) =
80343 ± 14 MeV (stat)

W data

MET



Fit results:

m(W) =
80355 ± 15 MeV (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	16	17	16
Electron Energy Resolution	2	2	3
Electron Energy Nonlinearity	4	6	7
W and Z Electron energy loss differences	4	4	4
Recoil Model	5	6	14
Electron Efficiencies	1	3	5
Backgrounds	2	2	2
Experimental Total	18	20	24
W production and decay model			
PDF	11	11	14
QED	7	7	9
Boson p_T	2	5	2
W model Total	13	14	17
Total	22	24	29
statistical	13	14	15
total	26	28	33

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

Combination of the three observables

We take the results from the three observables (with their correlations) and combine them:

m_T: 80.371 ± 0.013 (stat) ± 0.022 (syst)

p_T^e: 80.343 ± 0.014 (stat) ± 0.024 (syst)

MET: 80.355 ± 0.015 (stat) ± 0.029 (syst)

$$\rho = \begin{pmatrix} \rho_{m_T m_T} & \rho_{m_T p_T^e} & \rho_{m_T \not{E}_T} \\ \rho_{m_T p_T^e} & \rho_{p_T^e p_T^e} & \rho_{p_T^e \not{E}_T} \\ \rho_{m_T \not{E}_T} & \rho_{p_T^e \not{E}_T} & \rho_{\not{E}_T \not{E}_T} \end{pmatrix} = \begin{pmatrix} 1.0 & 0.89 & 0.86 \\ 0.89 & 1.0 & 0.75 \\ 0.86 & 0.75 & 1.0 \end{pmatrix}$$

When considering only the uncertainties which are allowed to decrease in the combination (i.e. *not* QED and PDF), we find that the MET measurement has negligible weight. We therefore only retain p_T^e and m_T for the combination.

The combined result is:

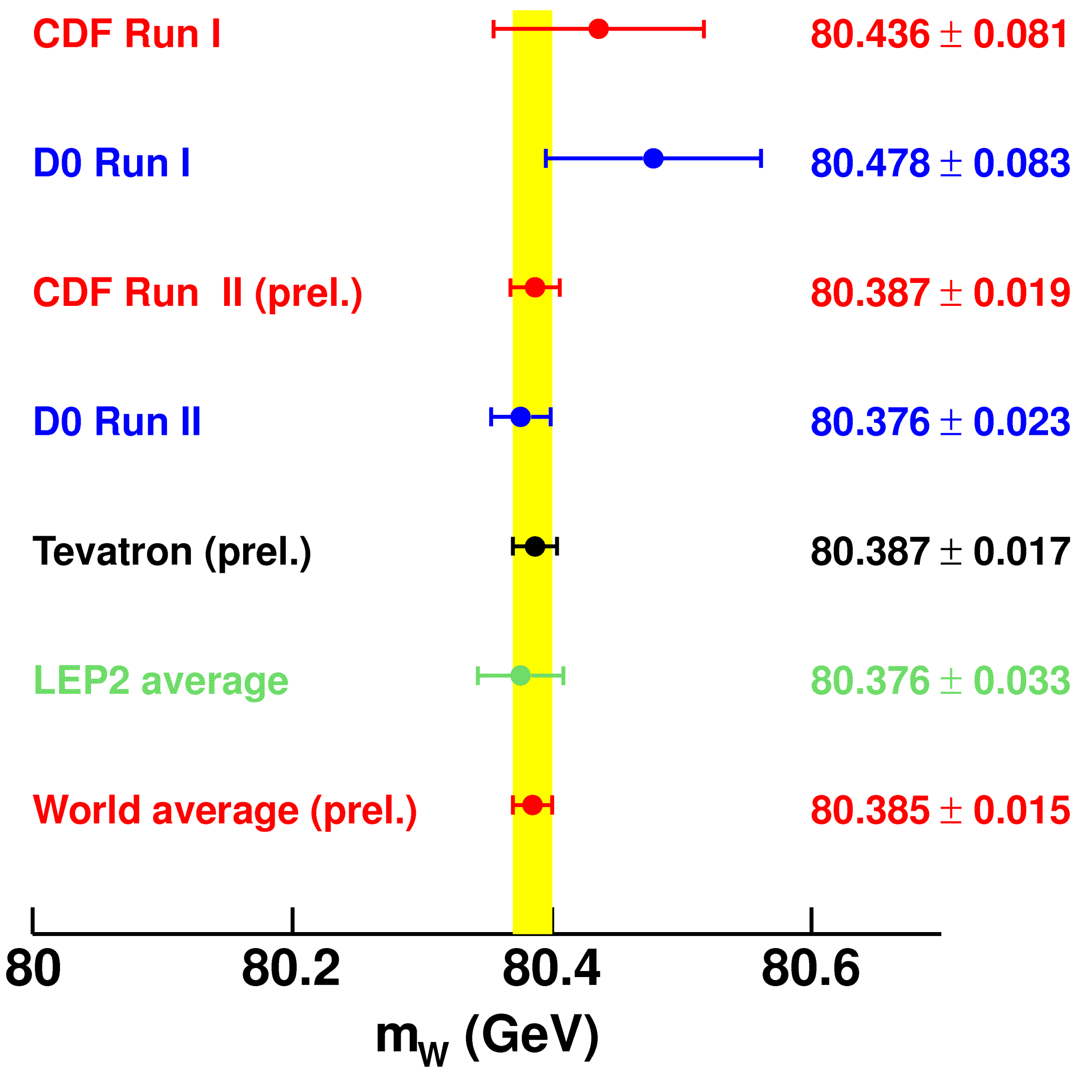
$$\begin{aligned} M_W &= 80.367 \pm 0.013\ (\mathrm{stat}) \pm 0.022\ (\mathrm{syst})\ \mathrm{GeV} \\ &= 80.367 \pm 0.026\ \mathrm{GeV}. \end{aligned}$$

The probability to observe a larger spread between the three measurements than in the data is 5 %.

We further combine with our earlier Run II result (1 fb^{-1}) to obtain the new D0 Run II result:

$$\begin{aligned} M_W &= 80.375 \pm 0.011\ (\mathrm{stat}) \pm 0.020\ (\mathrm{syst})\ \mathrm{GeV} \\ &= 80.375 \pm 0.023\ \mathrm{GeV}. \end{aligned}$$

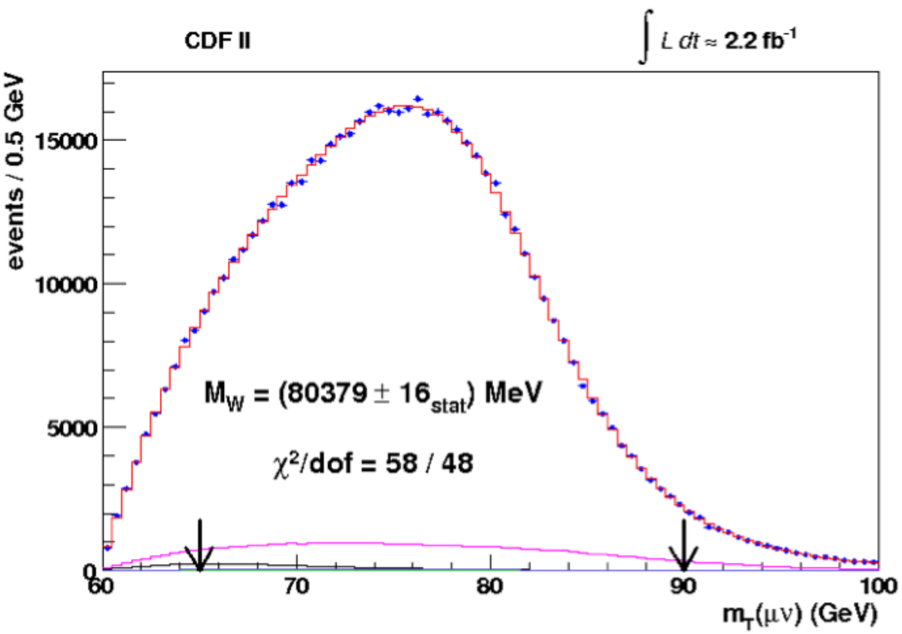
Comparison with previous results; New averages

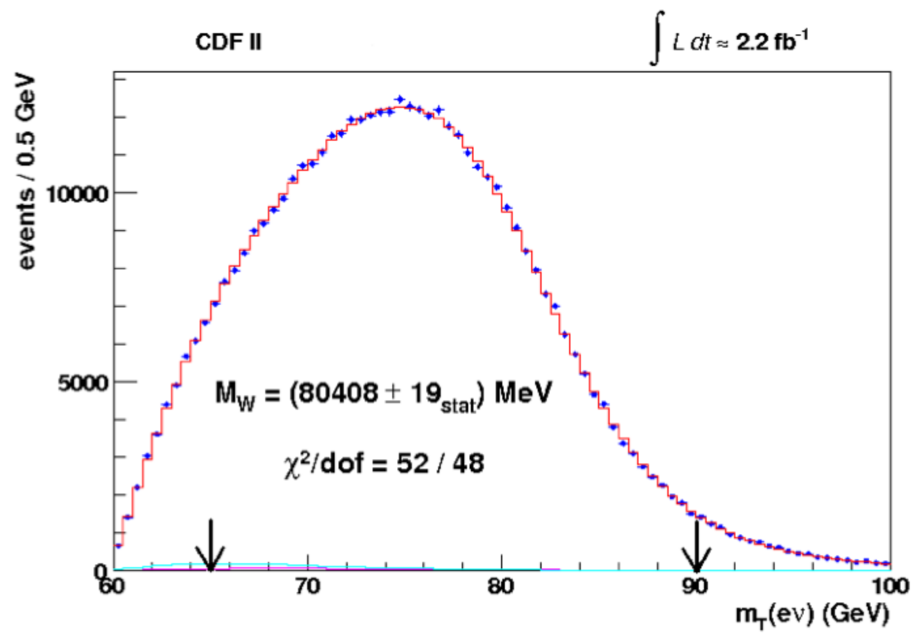


Our new result, as presented on the previous slides assumes a W width of 2100.4 MeV.

For the purpose of the combinations shown here the width hypothesis has been adjusted to the Standard Model value 2093.2 ± 2.2 MeV.

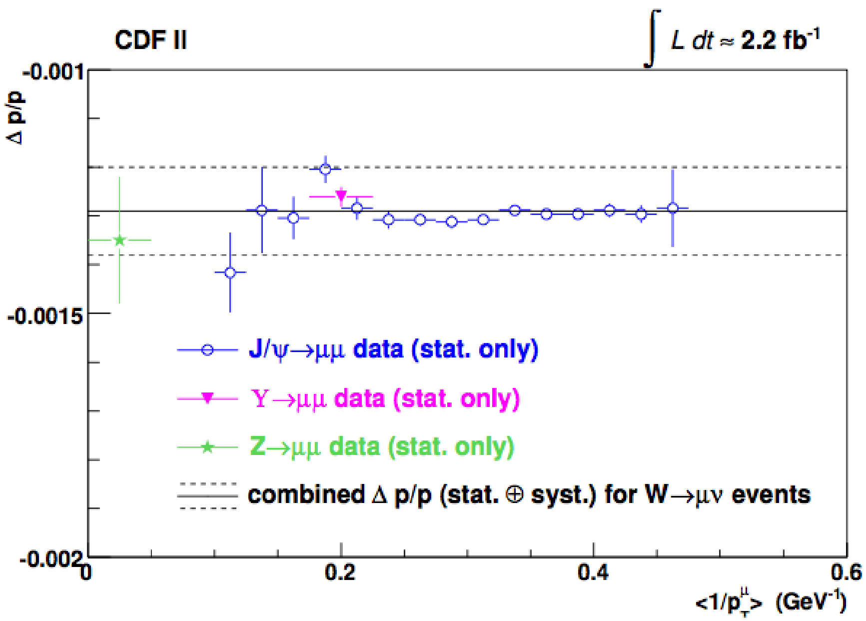
New CDF result

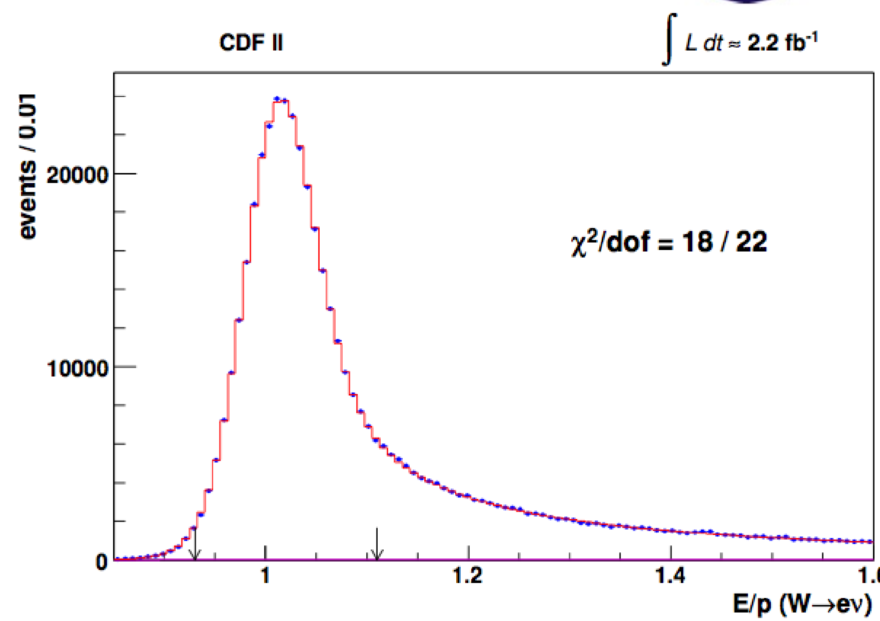


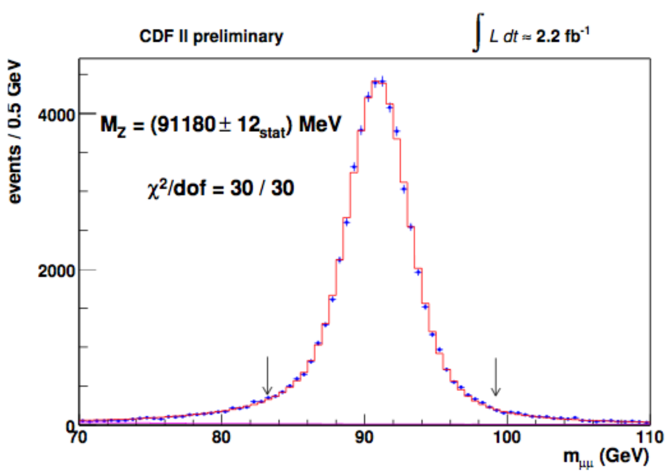


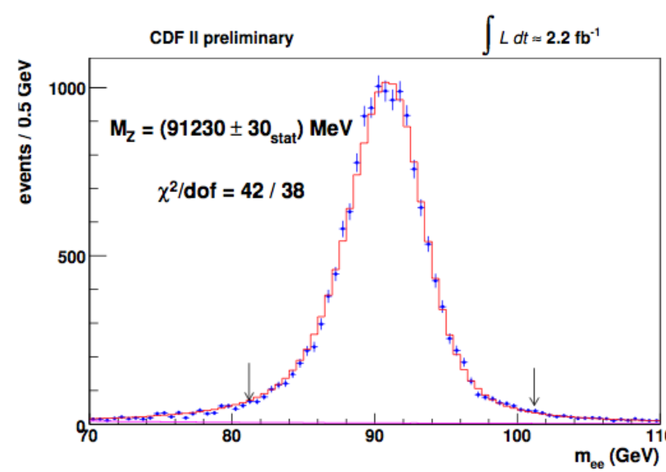
Method $(2.2\,fb^{-1})$	M_W (MeV)	Method $(2.2\,fb^{-1})$	M_W (MeV)
$m_T(\mu,\nu)$	80379 ± 16(stat)	$m_T(e,\nu)$	80408 ± 19(stat)
$p_T(\mu)$	80348 ± 18(stat)	$p_T(e)$	80393 ± 21(stat)
$\not{E}_T(\mu,\nu)$	80406 ± 22(stat)	$\not{E}_T(e,\nu)$	80431 ± 25(stat)
Combination $(2.2\,fb^{-1})$		**$80387 \pm 19\ MeV$ (syst + stat)**	

CDF: lepton energy scale









$M_Z(\mu\mu) = 91180 \pm 12(\text{stat}) \pm 10(\text{syst})\ MeV$ $M_Z(ee) = 91230 \pm 30(\text{stat}) \pm 14(\text{syst})\ MeV$

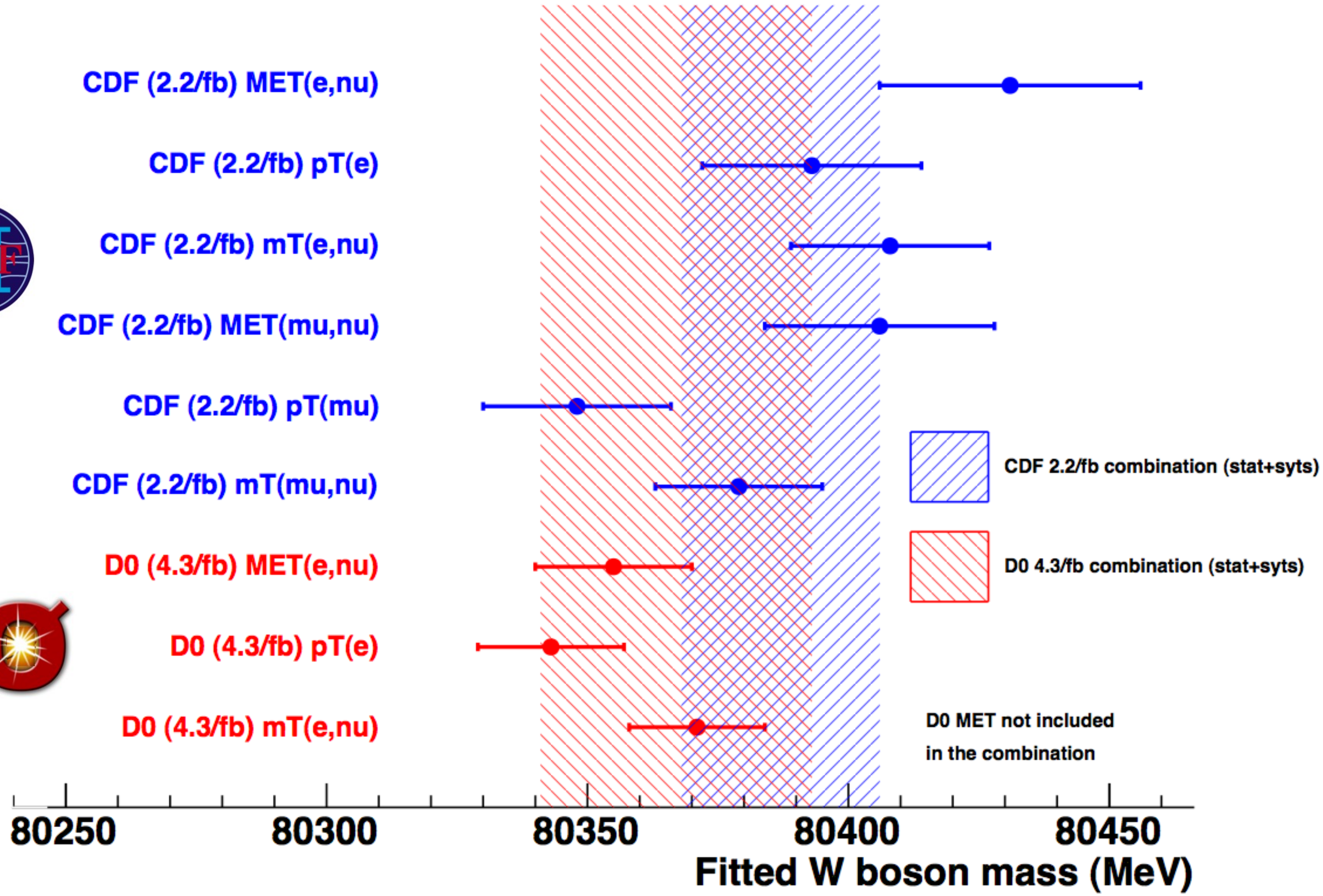
CDF vs. DØ: systematics

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

(values in MeV)

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

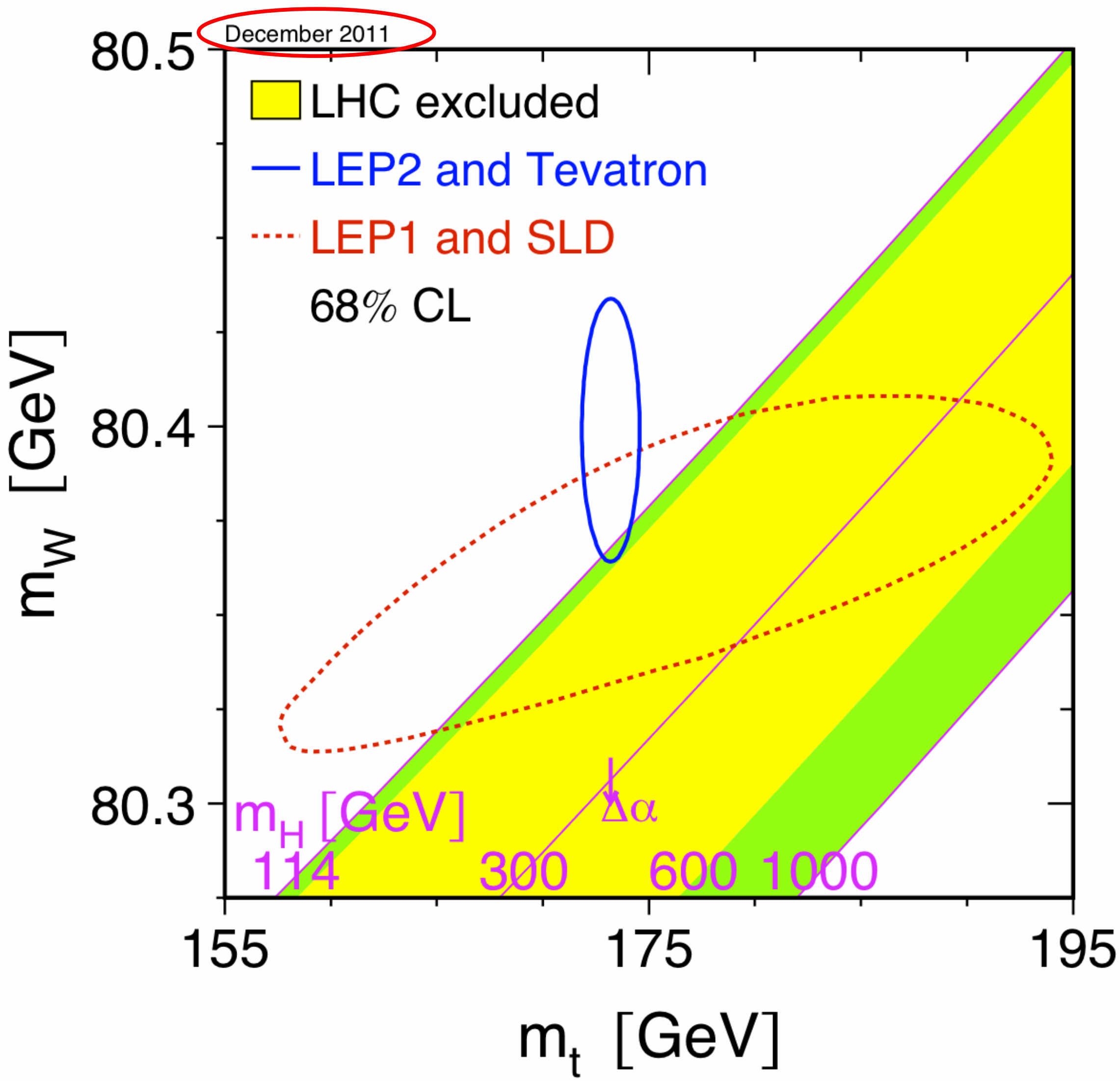
CDF vs. DØ: results



Very consistent results obtained with completely different calibration strategies!

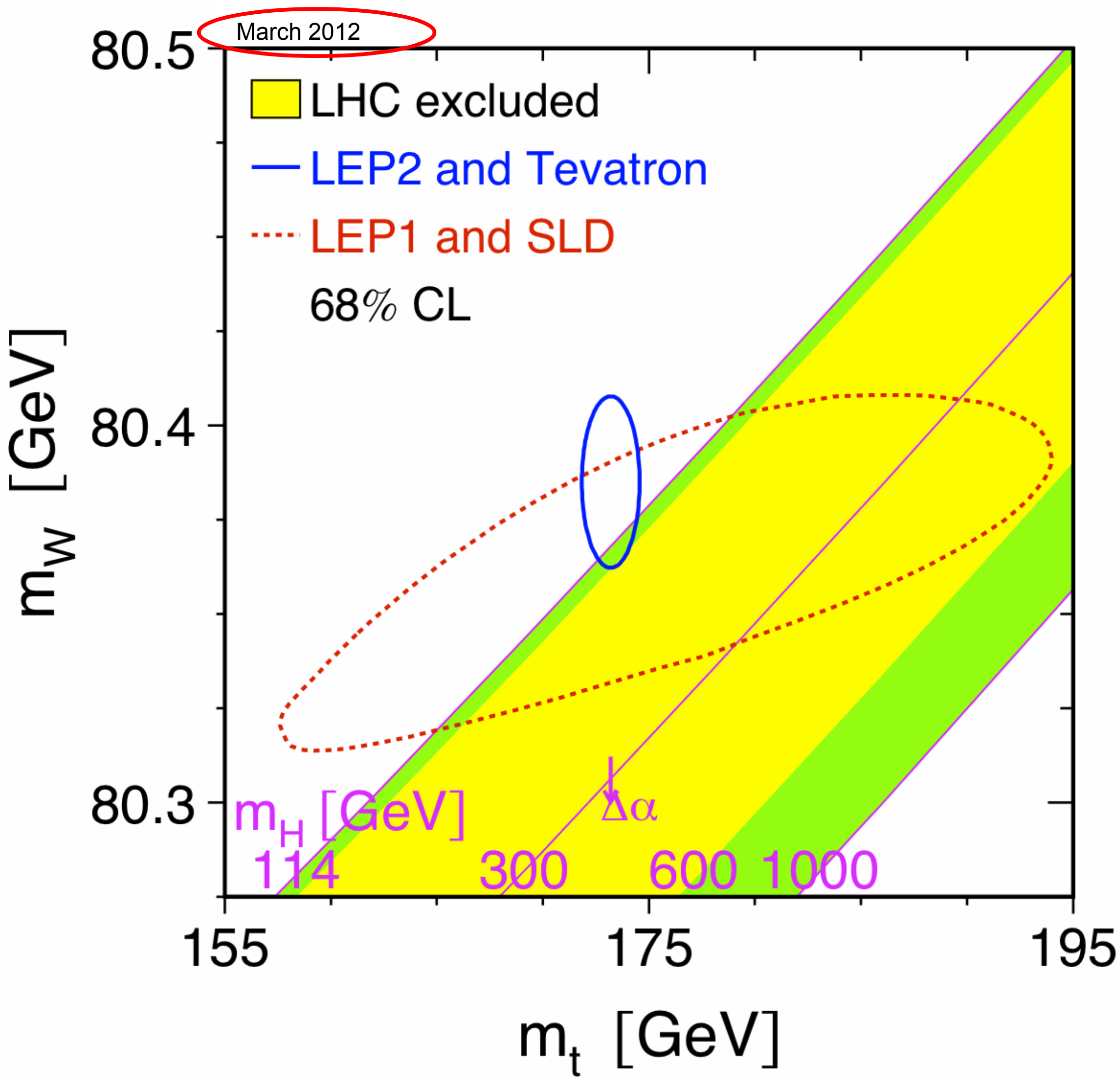
(uncertainties from individual measurements are only statistical)

New summary graph



This is from December 2011
(same as on slide 3).

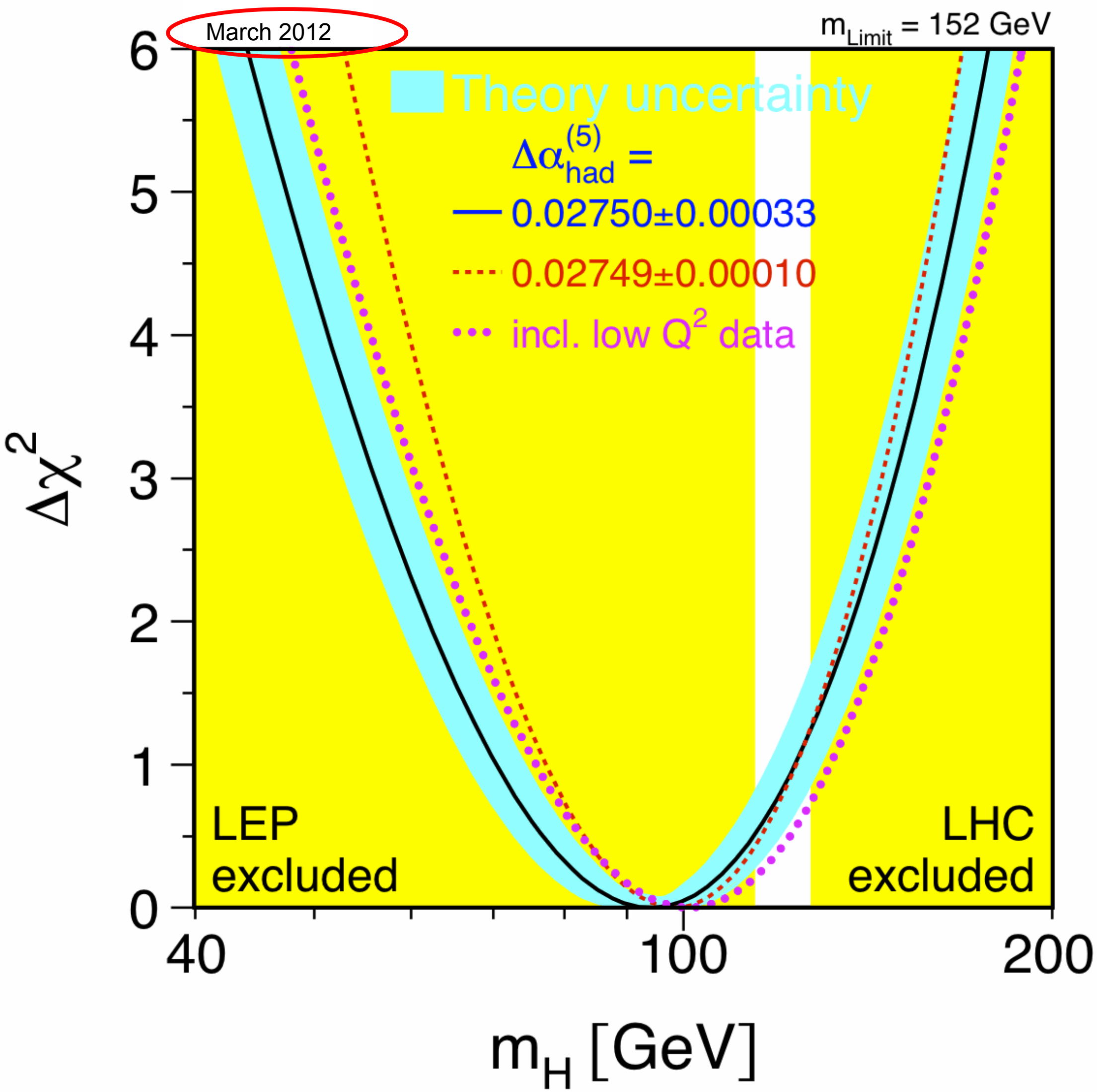
New summary graph



And this is what it looks like now !

Constraints on the Higgs boson mass

Zfitter, LEPEWWG



Previous SM Higgs fit:

$m_H = 92^{+34}_{-26}$ GeV

$m_H < 161$ @ 95% C.L.

New preliminary SM Higgs fit:

$m_H = 94^{+29}_{-24}$ GeV

$m_H < 152$ @ 95% C.L.

Towards the future

The bigger picture:

- "In our first Run II measurement (1 fb^{-1}), we have learned how to use our Run II detector to achieve the necessary precision on electron and recoil energy measurements".

  Uninstrumented material, …

- "In the the Run II measurement presented today (4.3 fb^{-1}), we have learned how to deal with the effect of high instantaneous luminosity and therefore to exploit large Run II datasets".

- We still have roughly another factor two more data in the can.

  Dominant experimental systematic uncertainty (electron energy scale) is expected to scale with statistics.

  To be able to *fully* benefit from this sample, we will have to beat down the uncertainties in the model of W production and decay.

  QED uncertainty and PDF uncertainty !

Fortunately, our theory friends are also very active !

As an example, two very recent publications that should help with the QED uncertainty:

- Implementation of electroweak corrections in the POWHEG BOX: single W production arXiv:1202.0465
- Combining NLO QCD and Electroweak Radiative Corrections to W-boson Production at Hadron Colliders in the POWHEG Framework arXiv:1201.4804

PDF uncertainties

In principle:
transverse observables (*e.g.* m_T) are insensitive to the uncertainties in the (longitudinal) parton distribution functions (PDFs)

In practice:
the uncertainties are to some extent reintroduced via the limited η coverage of experiments,
which are not invariant under longitudinal boosts

How to reduce the impact of the PDF uncertainties in measurements of the W boson mass ?

- Reduce the uncertainties in the PDFs

  e.g. via measurements of the W charge asymmetry
  at the Tevatron and the LHC (complementarity of the two colliders)

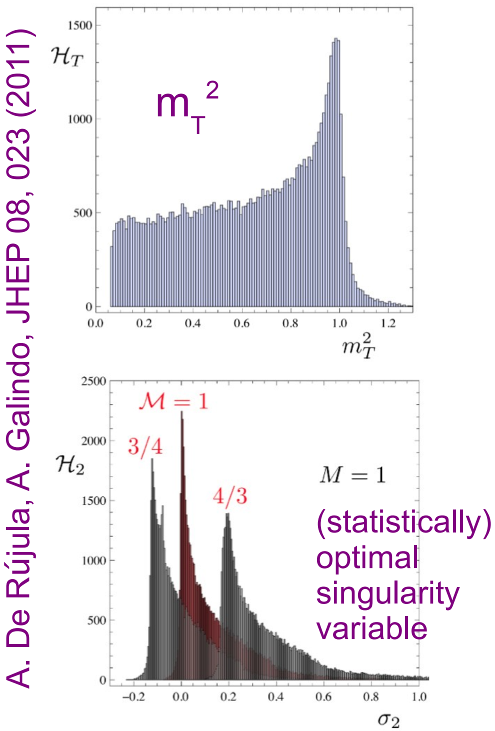
- Reduce the impact of the PDF uncertainties on W boson mass

  by extending the η coverage as much as possible
  (challenging: understanding lepton energy scale and pile-up and
  backgrounds in the forward detectors)

- Possibly reduce the impact of the PDF uncertainties on W boson mass

  by exploring even more robust observables
  ("single out events with small longitudinal momentum") to replace/complement m_T

A. De Rújula, A. Galindo, JHEP 08, 023 (2011)



These three approaches are not mutually exclusive, *i.e.* they can be pursued at the same time and gains should "add up".

Future PDF sets

Our theory friends are also active on improvements to PDF sets.

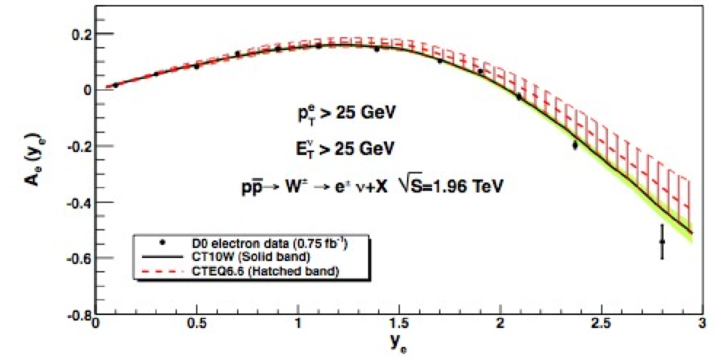
An example:

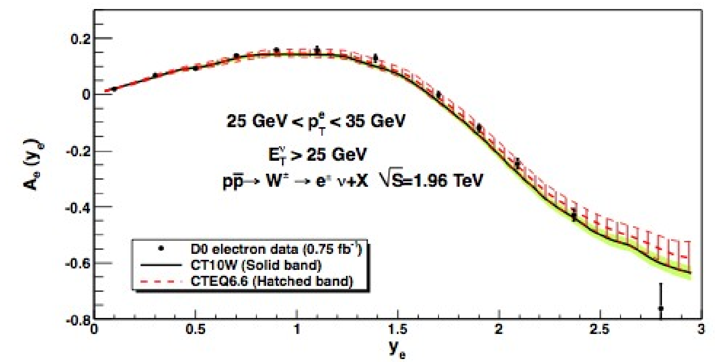
MSUHEP-100707, SMU-HEP-10-10, arXiv:1007.2241[hep-ph]

New parton distributions for collider physics

Hung-Liang Lai,[1,2] Marco Guzzi,[3] Joey Huston,[1] Zhao Li,[1] Pavel M. Nadolsky,[3] Jon Pumplin,[1] and C.-P. Yuan[1]

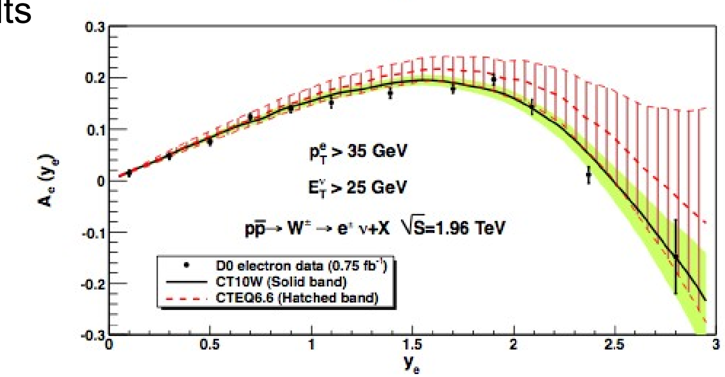
[1]*Department of Physics and Astronomy, Michigan State University, East Lansing, MI 48824-1116, U.S.A.*
[2]*Taipei Municipal University of Education, Taipei, Taiwan*
[3]*Department of Physics, Southern Methodist University, Dallas, TX 75275-0175, U.S.A.*





The PDF set "CT10W" is an important step towards including new results on W (lepton) charge asymmetry from the Tevatron into PDF sets. Critical to further constrain the u/d ratio !

Not quite "production quality" yet, but this is going into the right direction.



Conclusions

New measurement of the W boson mass based on 4.3 fb^{-1} of DØ Run II data:

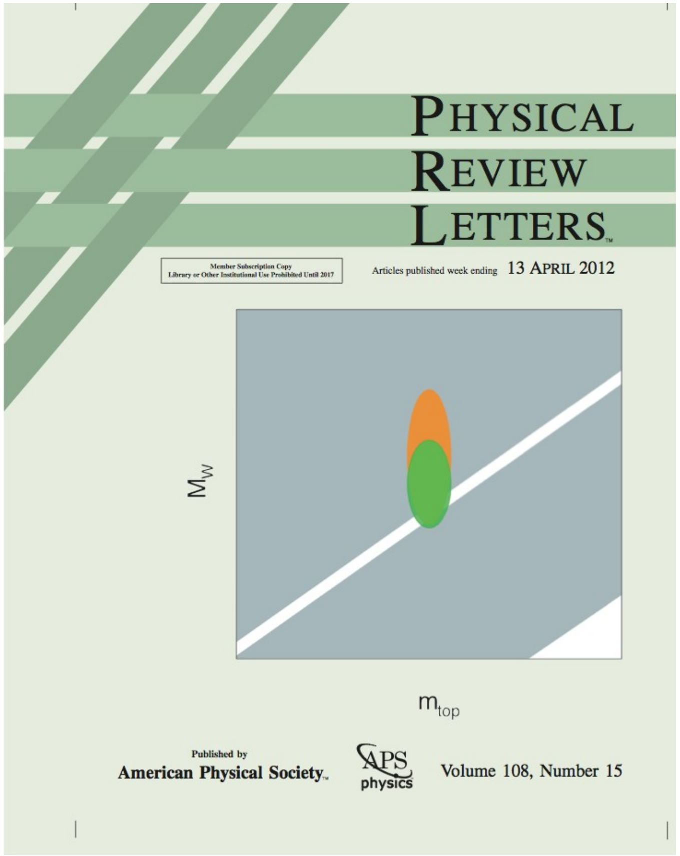
$$\begin{aligned} M_W &= 80.367 \pm 0.013\ (\text{stat}) \pm 0.022\ (\text{syst})\ \text{GeV} \\ &= 80.367 \pm 0.026\ \text{GeV}. \end{aligned}$$

Combined with earlier DØ Run II measurement (1 fb^{-1}), we obtain:

$$\begin{aligned} M_W &= 80.375 \pm 0.011\ (\text{stat}) \pm 0.020\ (\text{syst})\ \text{GeV} \\ &= 80.375 \pm 0.023\ \text{GeV}. \end{aligned}$$

Together with the new CDF result, this leads to a new preliminary Tevatron average with an uncertainty of 17 MeV (factor of 2 improvement over LEP), and a new preliminary world average with an uncertainty of 15 MeV.

The new results from CDF and DØ have been published back-to-back in PRL and highlighted on the PRL cover.



Exciting new indirect constraints on the mass of the hypothetical Higgs boson.

Still much more data to come. Working to reduce sensitivity of measurement to PDF uncertainties.
Working with our theory colleagues to reduce uncertainties in model of W production and decay.
=> looking forward to even smaller uncertainties in the future.

Backup Slides

Global electroweak fit

Aug 11 version of Gfitter standard model fit includes, in addition to the latest theory calculations, the LEP/SLD precision legacy, …, various updates that have been shown in July at EPS-HEP in Grenoble:

- latest top quark combination from Tevatron,
- new $\Delta\alpha_{had}(M_Z^2)$ using *e.g.* all available BaBar results,
- latest Higgs limits from Tevatron,
- first Higgs limits from LHC !

Parameter	Input value	Free in fit	Results from global EW fits: *Standard fit*	*Complete fit*	*Complete fit w/o exp. input in line*
M_Z [GeV]	91.1875 ± 0.0021	yes	91.1874 ± 0.0021	91.1877 ± 0.0021	$91.1983^{+0.0133}_{-0.0155}$
Γ_Z [GeV]	2.4952 ± 0.0023	–	2.4959 ± 0.0015	2.4955 ± 0.0014	$2.4951^{+0.0017}_{-0.0016}$
$\sigma^0_{\rm had}$ [nb]	41.540 ± 0.037	–	41.478 ± 0.014	41.478 ± 0.014	41.469 ± 0.015
R^0_ℓ	20.767 ± 0.025	–	20.743 ± 0.018	20.741 ± 0.018	$20.718^{+0.027}_{-0.026}$
$A^{0,\ell}_{\rm FB}$	0.0171 ± 0.0010	–	0.01641 ± 0.0002	$0.01620^{+0.0002}_{-0.0001}$	0.01606 ± 0.0001
A_ℓ $^{(\star)}$	0.1499 ± 0.0018	–	0.1479 ± 0.0010	$0.1472^{+0.0009}_{-0.0006}$	–
A_c	0.670 ± 0.027	–	$0.6683^{+0.00044}_{-0.00043}$	$0.6680^{+0.00040}_{-0.00028}$	$0.6679^{+0.00042}_{-0.00025}$
A_b	0.923 ± 0.020	–	$0.93470^{+0.00009}_{-0.00008}$	$0.93463^{+0.00008}_{-0.00005}$	$0.93463^{+0.00007}_{-0.00005}$
$A^{0,c}_{\rm FB}$	0.0707 ± 0.0035	–	0.0741 ± 0.0005	$0.0737^{+0.0005}_{-0.0004}$	0.0738 ± 0.0004
$A^{0,b}_{\rm FB}$	0.0992 ± 0.0016	–	0.1037 ± 0.0007	$0.1035^{+0.0003}_{-0.0004}$	$0.1038^{+0.0003}_{-0.0005}$
R^0_c	0.1721 ± 0.0030	–	0.17226 ± 0.00006	0.17226 ± 0.00006	0.17226 ± 0.00006
R^0_b	0.21629 ± 0.00066	–	$0.21578^{+0.00005}_{-0.00008}$	$0.21577^{+0.00005}_{-0.00008}$	$0.21577^{+0.00005}_{-0.00007}$
$\sin^2\theta^\ell_{\rm eff}(Q_{\rm FB})$	0.2324 ± 0.0012	–	0.23141 ± 0.00012	$0.23150^{+0.00008}_{-0.00011}$	$0.23152^{+0.00006}_{-0.00013}$
M_H [GeV] $^{(\circ)}$	Likelihood ratios	yes	$95^{+30[+74]}_{-24[-43]}$	$125^{+8[+21]}_{-10[-11]}$	$95^{+30[+74]}_{-24[-43]}$
M_W [GeV]	80.399 ± 0.023	–	$80.382^{+0.014}_{-0.015}$	$80.368^{+0.007}_{-0.010}$	$80.360^{+0.012}_{-0.011}$
Γ_W [GeV]	2.085 ± 0.042	–	2.093 ± 0.001	2.092 ± 0.001	$2.091^{+0.002}_{-0.001}$
$\overline{m}_c$ [GeV]	$1.27^{+0.07}_{-0.11}$	yes	$1.27^{+0.07}_{-0.11}$	$1.27^{+0.07}_{-0.11}$	–
$\overline{m}_b$ [GeV]	$4.20^{+0.17}_{-0.07}$	yes	$4.20^{+0.16}_{-0.07}$	$4.20^{+0.16}_{-0.07}$	–
m_t [GeV]	173.2 ± 0.9	yes	173.3 ± 0.9	173.5 ± 0.9	$177.2^{+2.9}_{-3.1}$ $^{(\triangledown)}$
$\Delta\alpha^{(5)}_{\rm had}(M_Z^2)$ $^{(\dagger\triangle)}$	2749 ± 10	yes	2750 ± 10	2748 ± 10	2716^{+60}_{-45}
$\alpha_s(M_Z^2)$	–	yes	0.1192 ± 0.0028	0.1193 ± 0.0028	0.1193 ± 0.0028
$\delta_{\rm th} M_W$ [MeV]	$[-4, 4]_{\rm theo}$	yes	4	4	–
$\delta_{\rm th} \sin^2\theta^\ell_{\rm eff}$ $^{(\dagger)}$	$[-4.7, 4.7]_{\rm theo}$	yes	4.7	4.7	–

$^{(\star)}$Average of LEP ($A_\ell = 0.1465 \pm 0.0033$) and SLD ($A_\ell = 0.1513 \pm 0.0021$) measurements. The fit w/o the LEP (SLD) measurement but with the direct Higgs searches gives $A_\ell = 0.1471^{+0.0010}_{-0.0008}$ ($A_\ell = 0.1467^{+0.0007}_{-0.0004}$). $^{(\circ)}$In brackets the 2σ. $^{(\dagger)}$In units of 10^{-5}. $^{(\triangle)}$Rescaled due to α_s dependency. $^{(\triangledown)}$Ignoring a second less significant minimum, *cf.* fig. ?? and the result of eq. (??).

Global electroweak fit

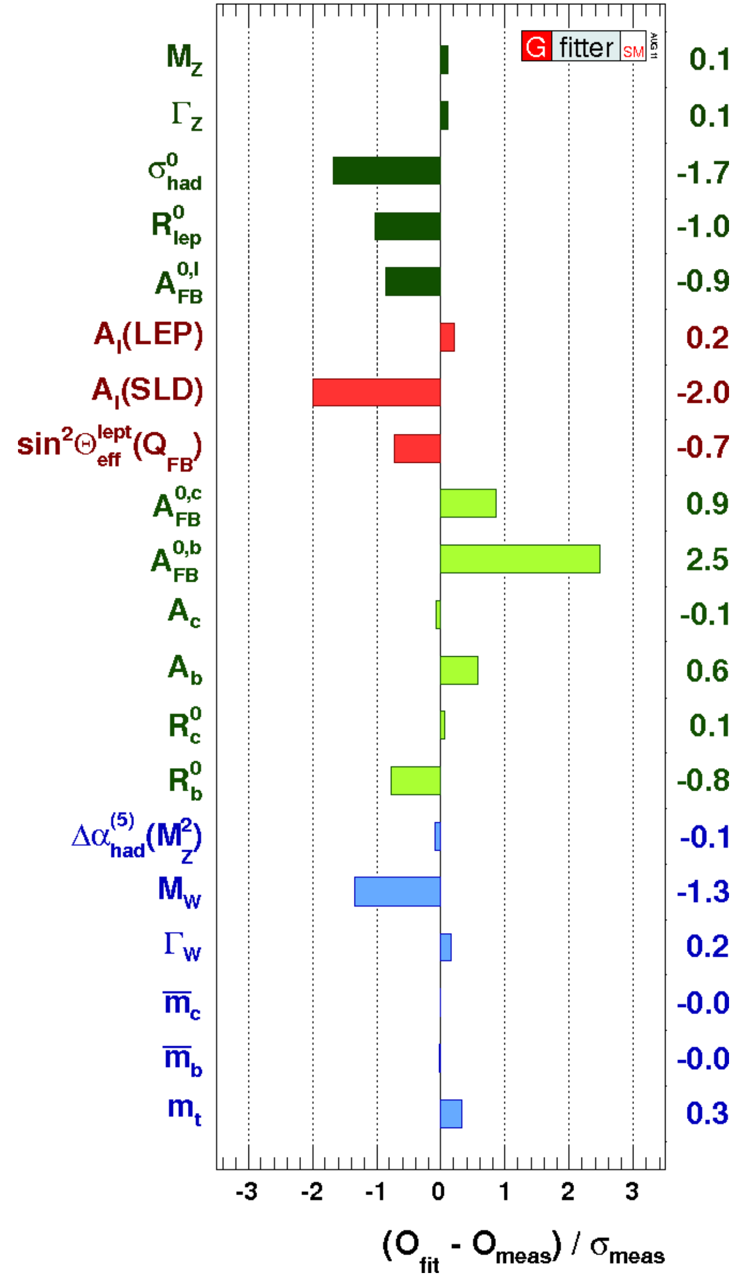
Complete fit:
χ^2_{min} = 17.9 for 14 degrees of freedom.

Pull values for the different observables are shown on the right.

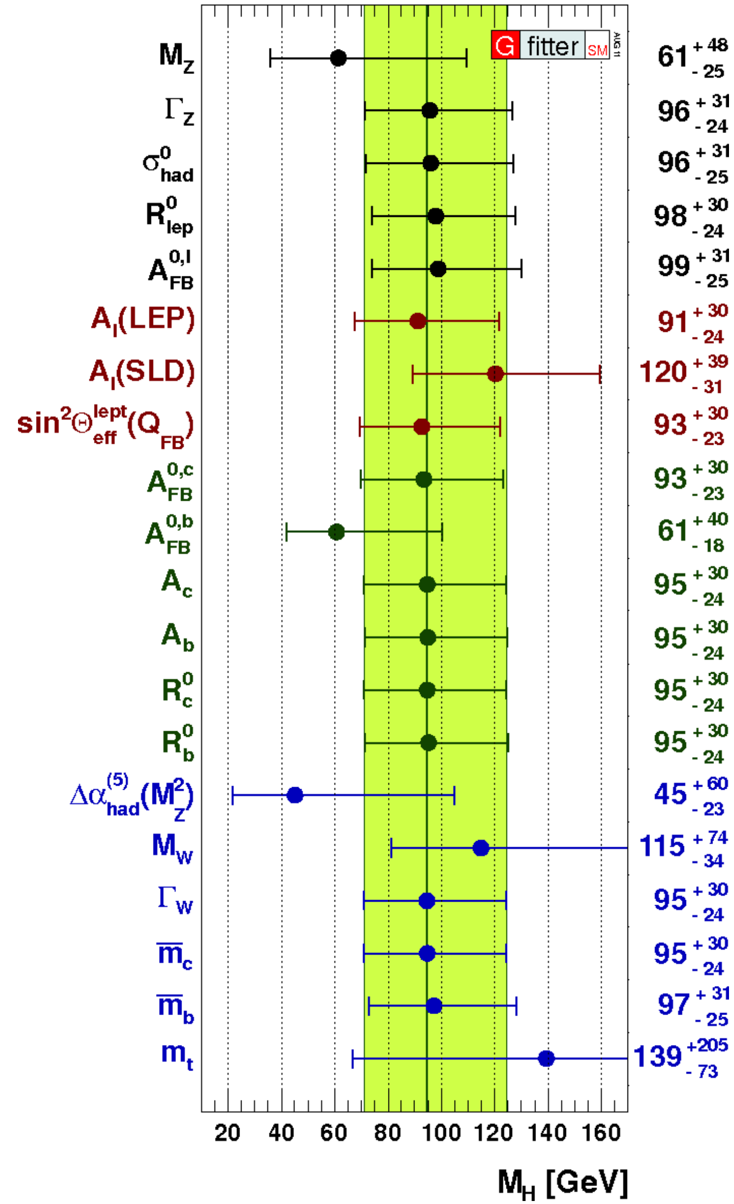
- no value exceeds 3 sigma
- largest individual contribution to χ^2 from FB asymmetry of bottom quarks.

Overall good agreement between precision data and standard model.

As is well known, some tension between A_l(SLD) and $A_{FB}^{0,b}$ from LEP.



Global electroweak fit

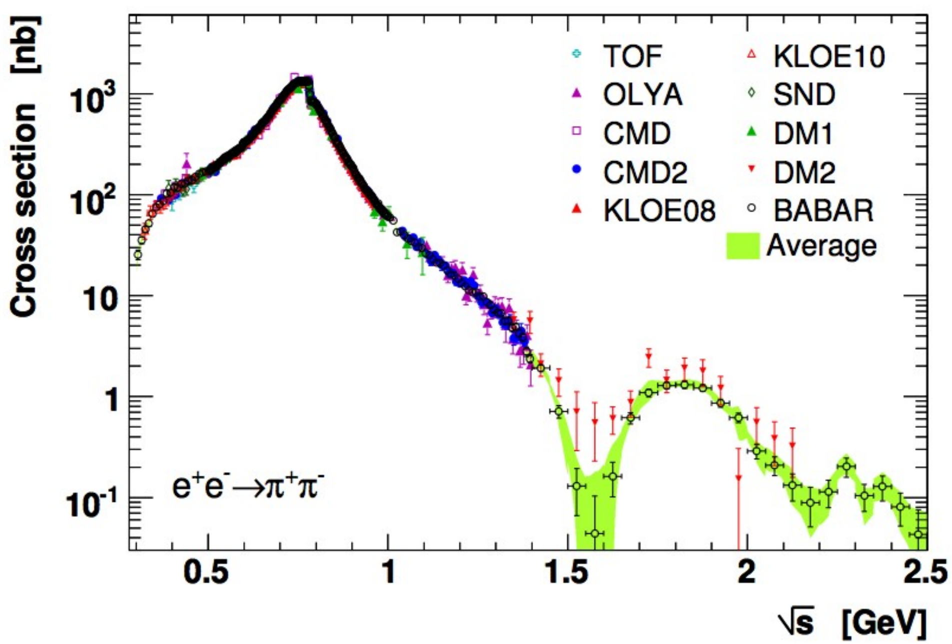


Hadronic contributions to $\alpha(M_Z^2)$

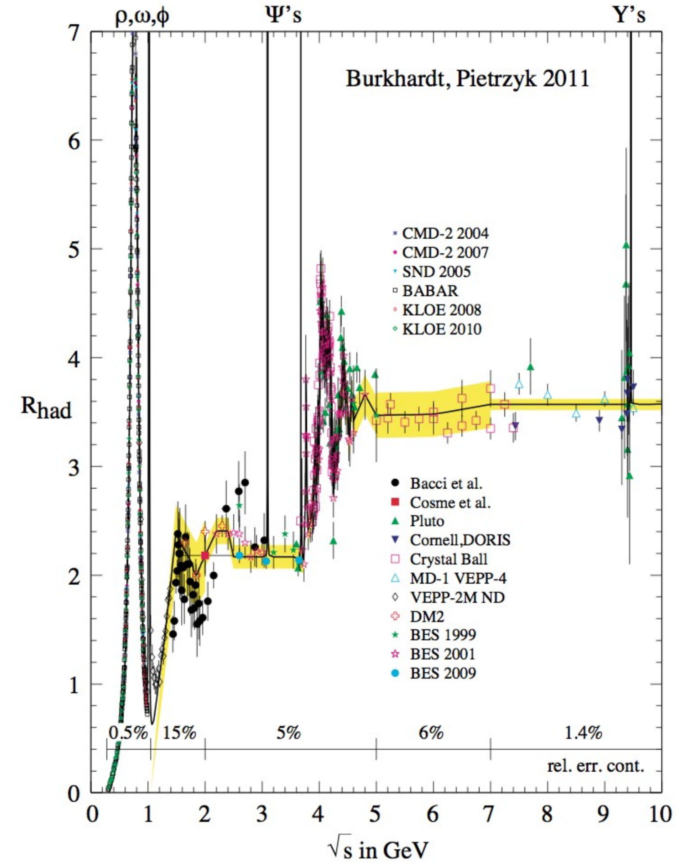
Electroweak fit requires the knowledge of the electromagnetic coupling strength at the Z mass scale to an accuracy of 1% or better.

Hadronic contribution for quarks with masses smaller than M_Z cannot be obtained from perturbative QCD alone (low energy scale).

Constrain photon vacuum polarisation function using measured total cross section for e^+e^- annihilation to hadrons above the two-pion threshold.

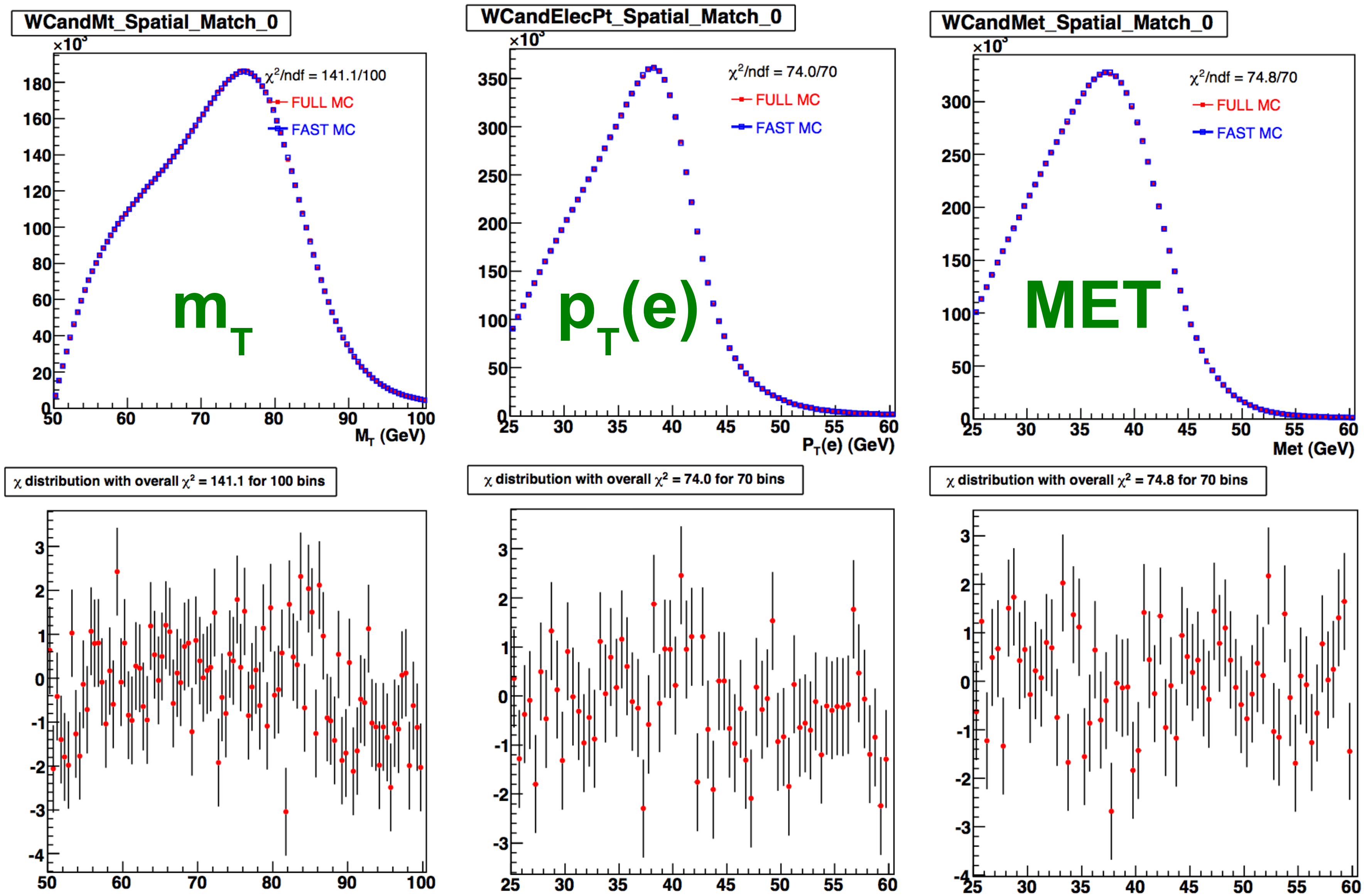


Davier *et al.*, Eur. Phys. J. C71, 1515 (2011)



Burkhardt and Pietrzyk, Phys. Rev. D 84, 037502 (2011)

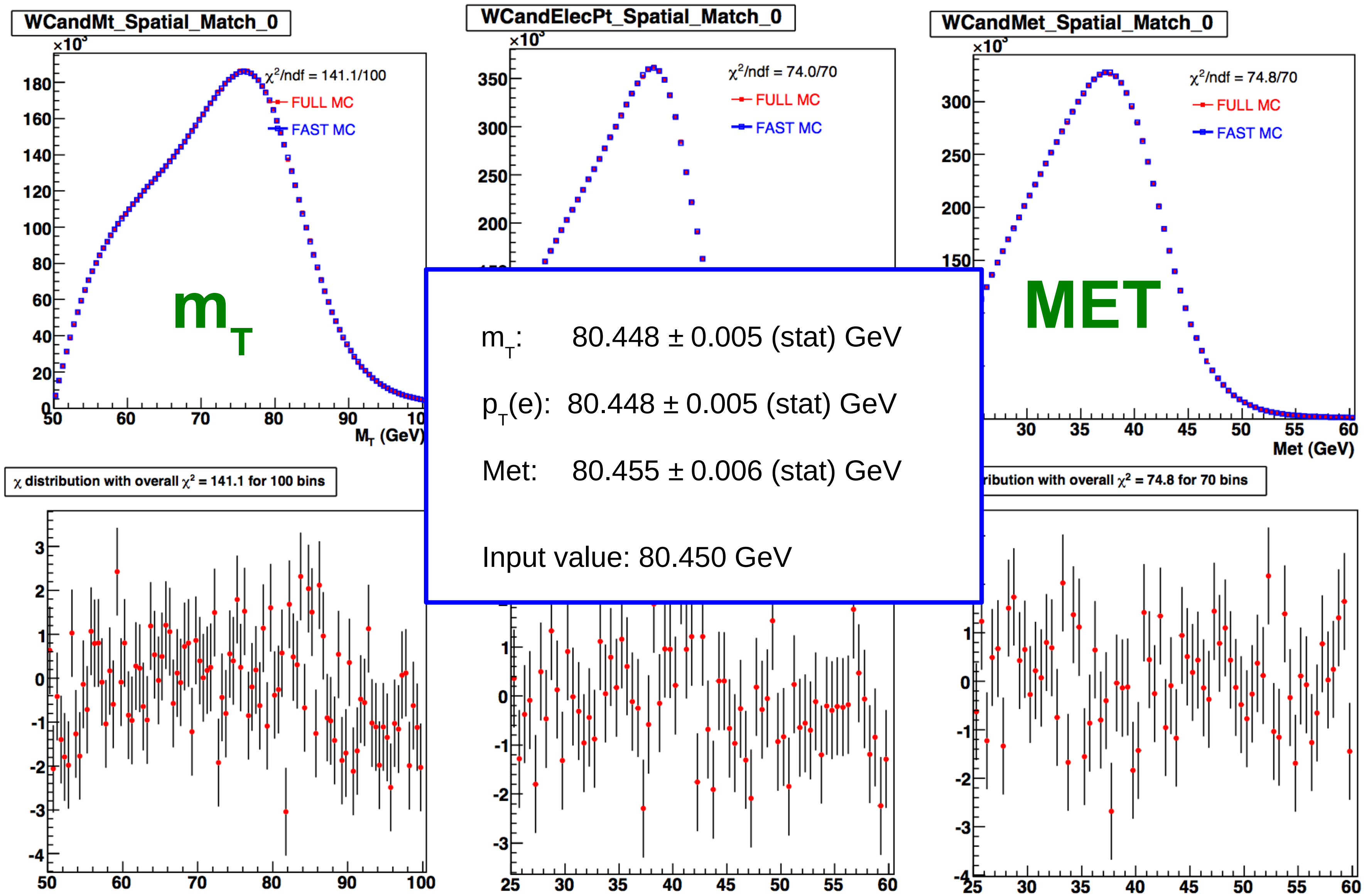
MC closure test



Full MC $W \rightarrow e\nu$ 62M events simulated, 9.8M events after selection

Very good agreement between fast and full MC.
Fitted W mass within one sigma of generated mass for all three observables.

MC closure test



m_T: 80.448 ± 0.005 (stat) GeV

$p_T(e)$: 80.448 ± 0.005 (stat) GeV

Met: 80.455 ± 0.006 (stat) GeV

Input value: 80.450 GeV

Full MC W → e ν 62M events simulated, 9.8M events after selection

Very good agreement between fast and full MC.
Fitted W mass within one sigma of generated mass for all three observables.

Definition of f_Z

To determine α and β we use the following strategy. Suppose $R_{EM}(E_0) = \alpha' E_0 + \beta'$, then:

$$M(Z) = \sqrt{2E(e_1)E(e_2)(1-\cos\omega)} \Rightarrow M(Z) \simeq \alpha' \times M_{true}(Z) + f_Z\beta' + \mathcal{O}(\beta'^2)$$

where

$$f_Z(true) = \frac{(E_0(e_1) + E_0(e_2))(1-\cos\omega)}{M_{true}(Z)}$$

Inspired by this observation, we fit templates of $m_{ee} \times f_Z$ for varying α and β against our Z sample.

Electron energy resolution

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

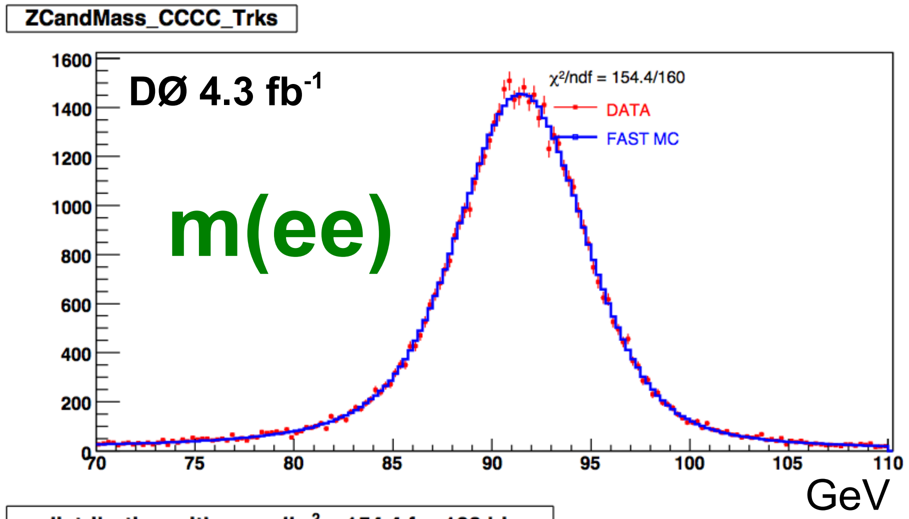
Sampling fluctuations are driven by sampling fraction of CAL modules (well known from simulation and testbeam) and by uninstrumented material. As discussed before, amount of material has been quantified with good precision.

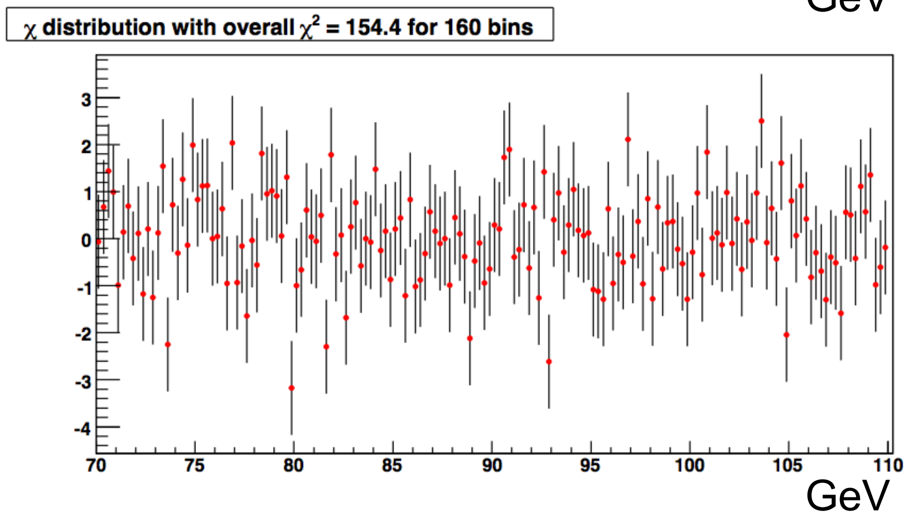
Constant term is extracted from $Z \rightarrow e\,e$ data (essentially fit to observed width of Z peak).

Result:

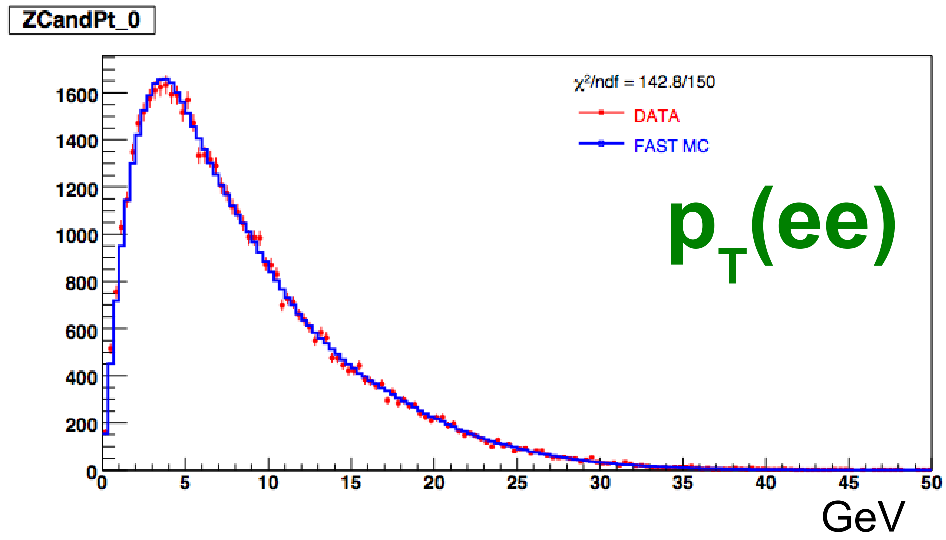
$C = (2.00 \pm 0.07)\ \%$

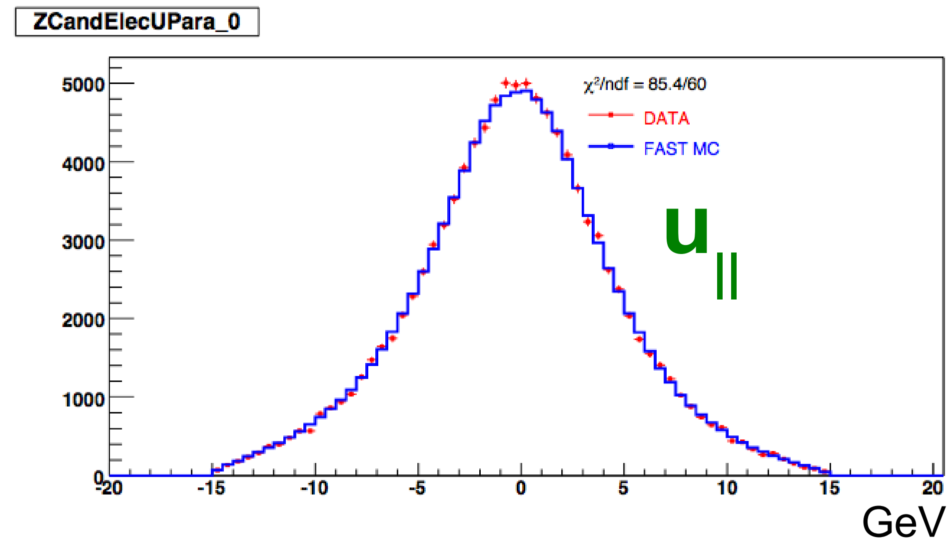
in excellent agreement with Run II design goal (2%)

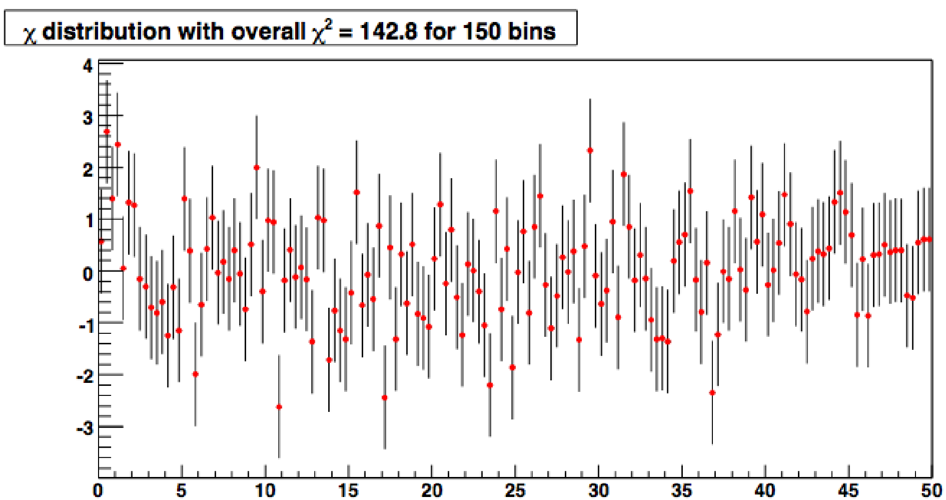


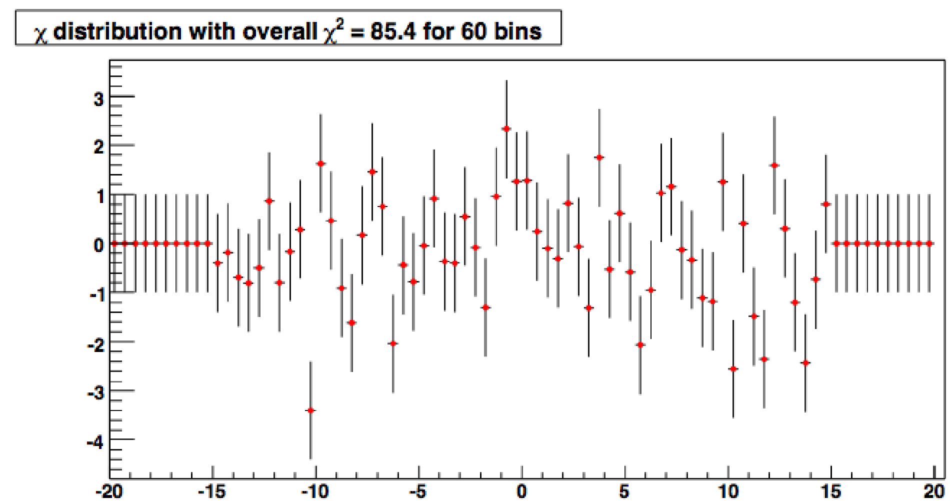


Z data



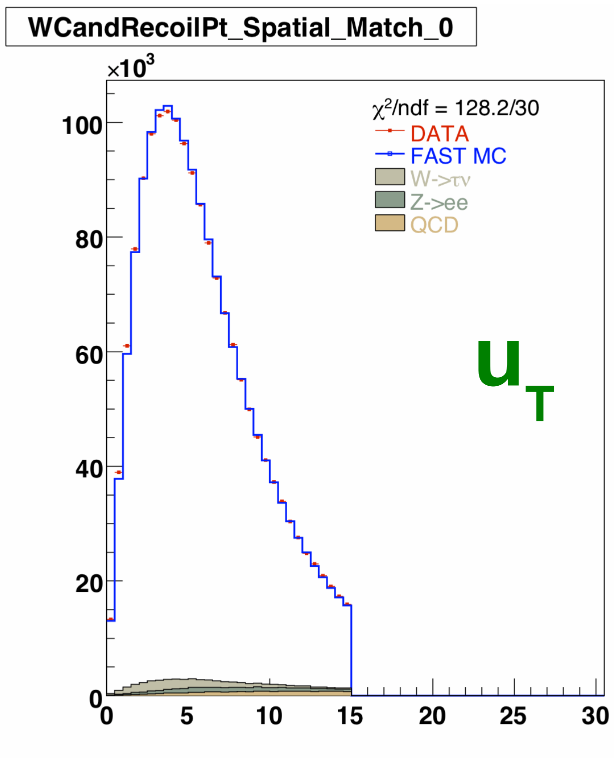


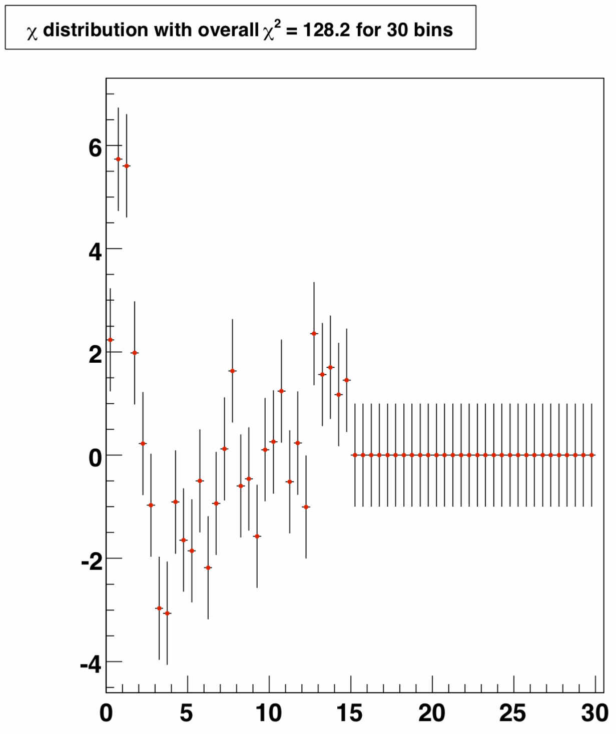




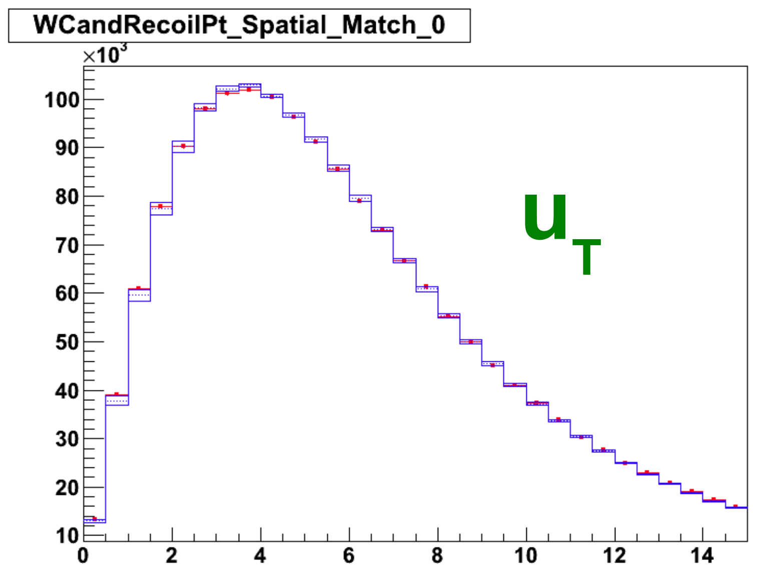
Good agreement between data and parameterised Monte Carlo.

W data





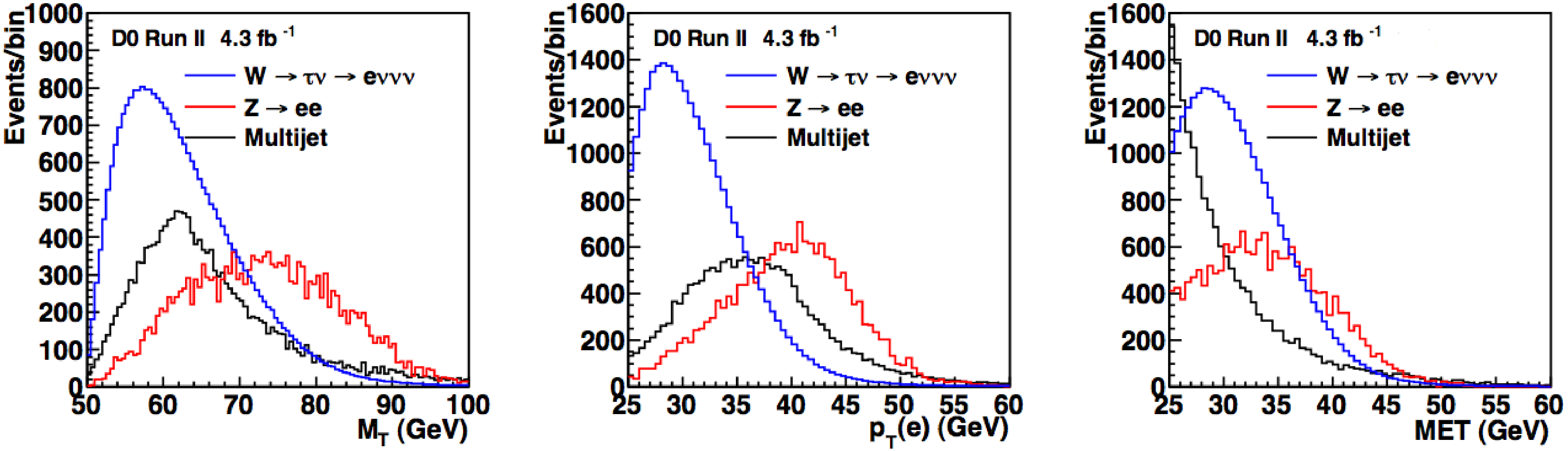
Here the error bars only reflect the finite statistics of the W candidate sample.



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

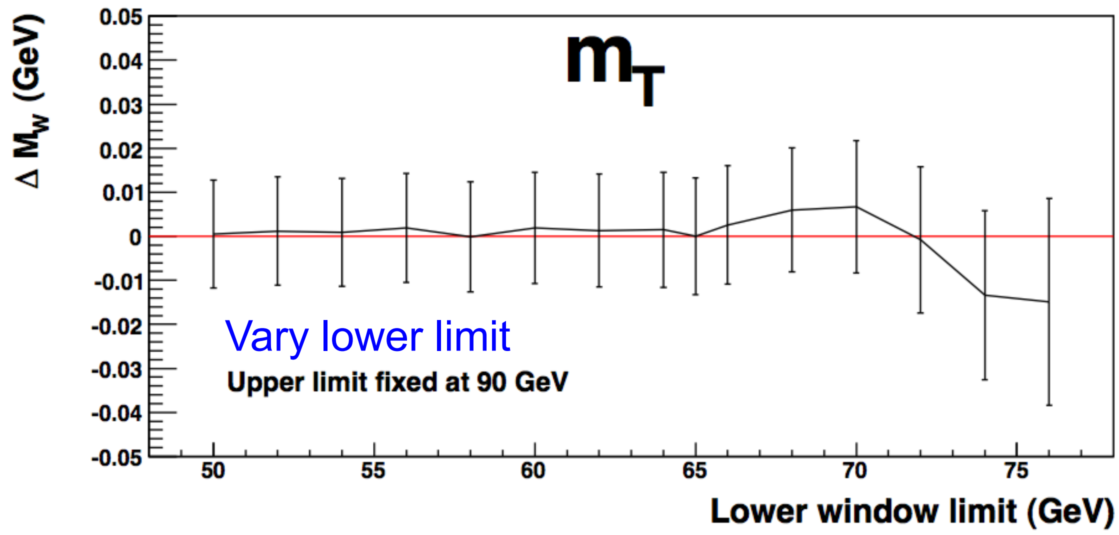
Good agreement between data and parameterised Monte Carlo.

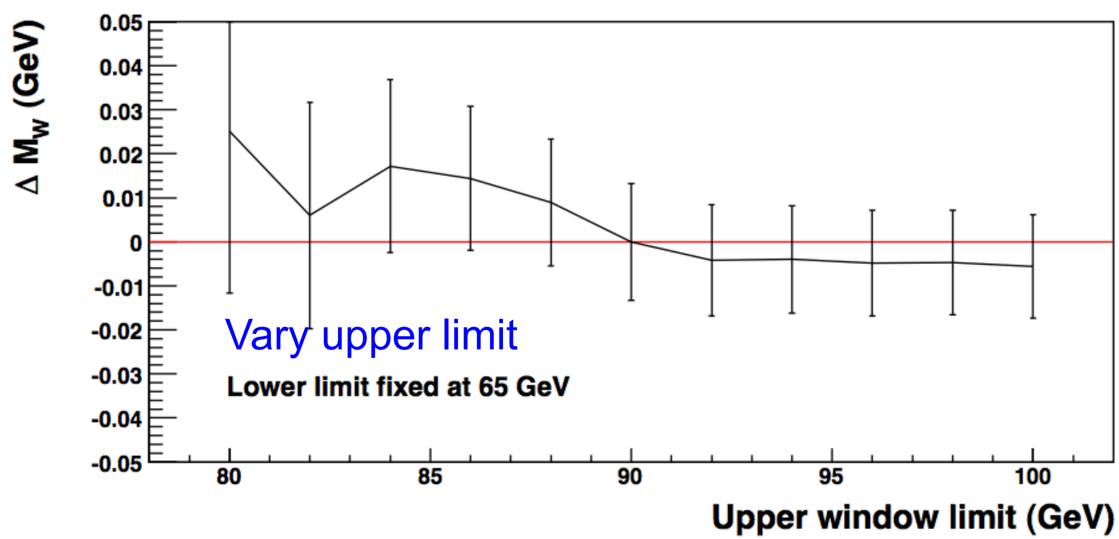
Backgrounds



Consistency checks

Vary the range used in the m_T fit:

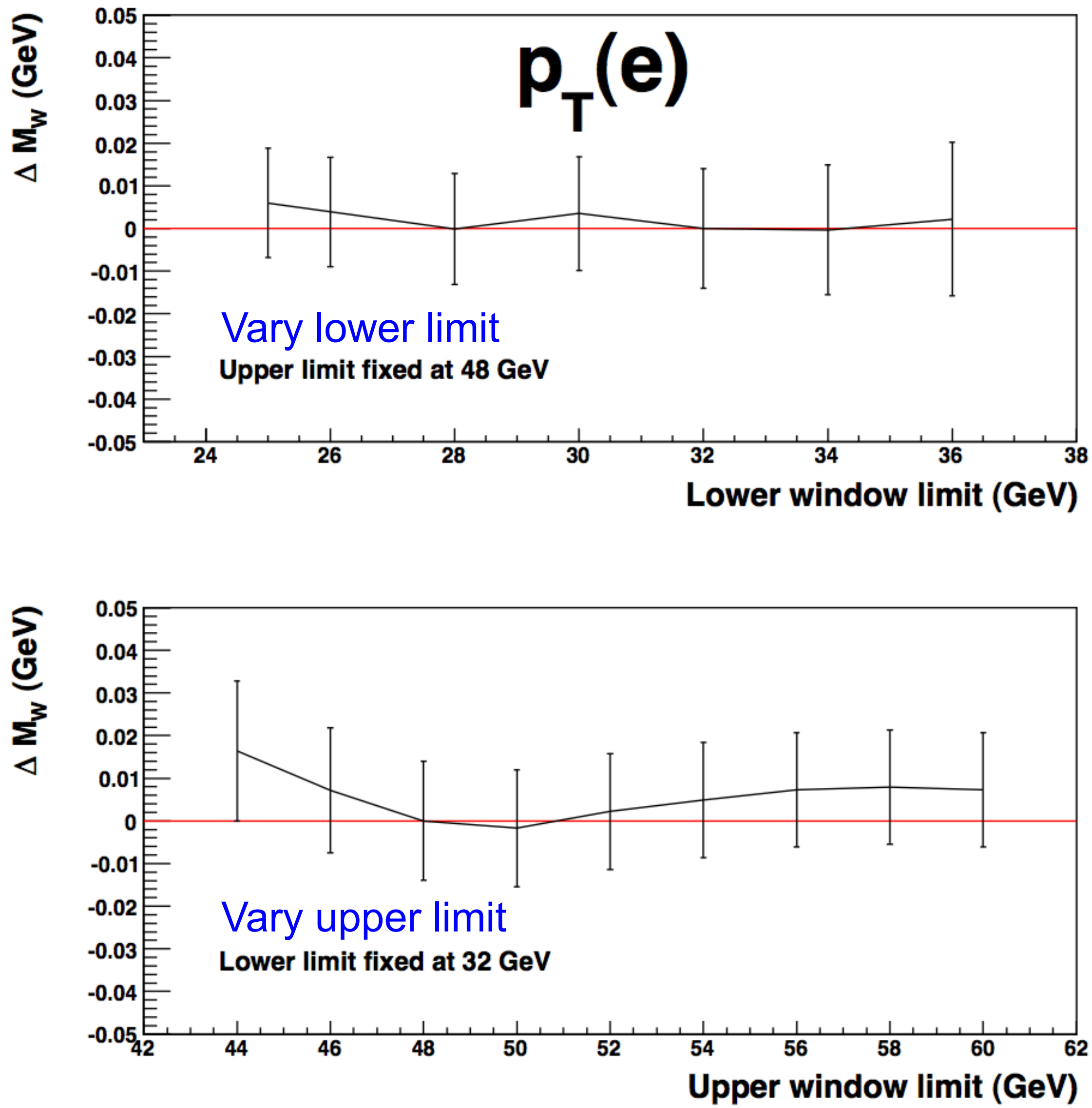




Measurement is stable

Consistency checks

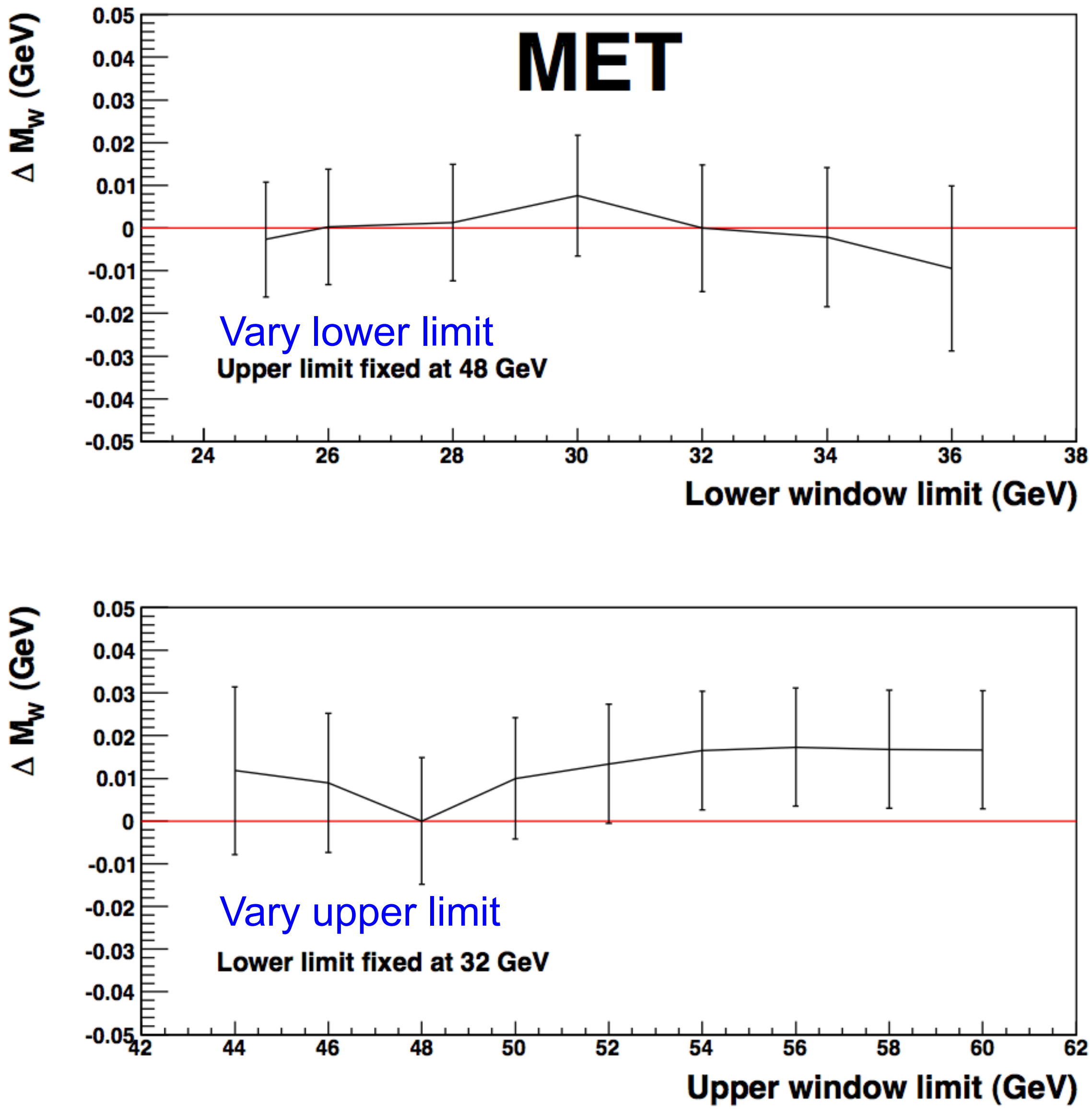
Vary the range used in the $p_T(e)$ fit:



Measurement is stable

Consistency checks

Vary the range used in the MET fit:

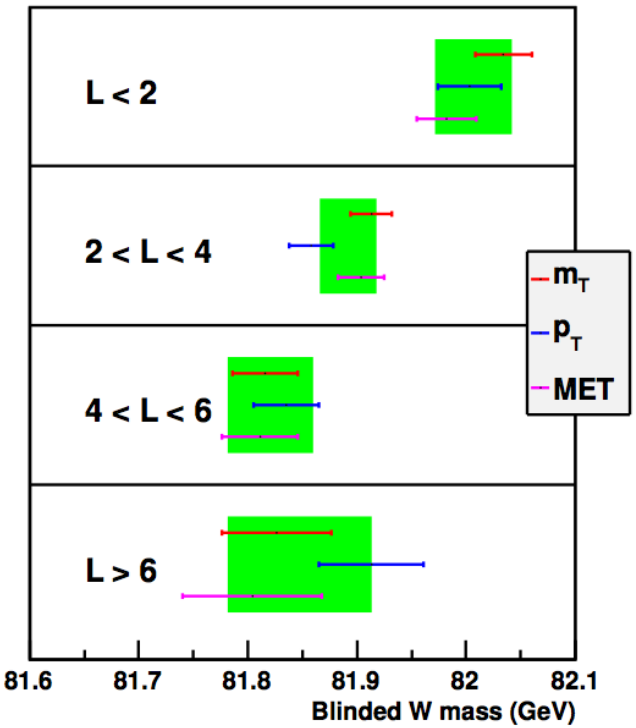


Measurement is stable

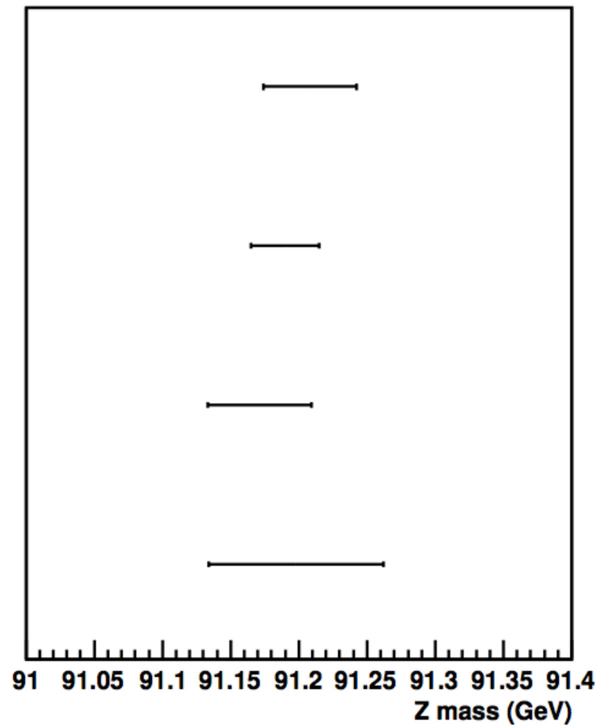
Consistency checks

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

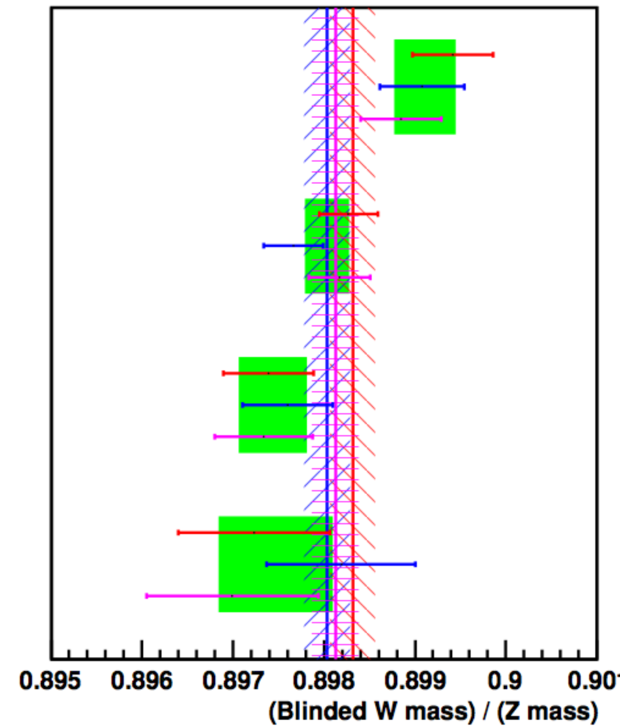
W



Z



“W/Z”



Error bars represent W statistics.

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

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

Error bars represent W *and* Z statistics.

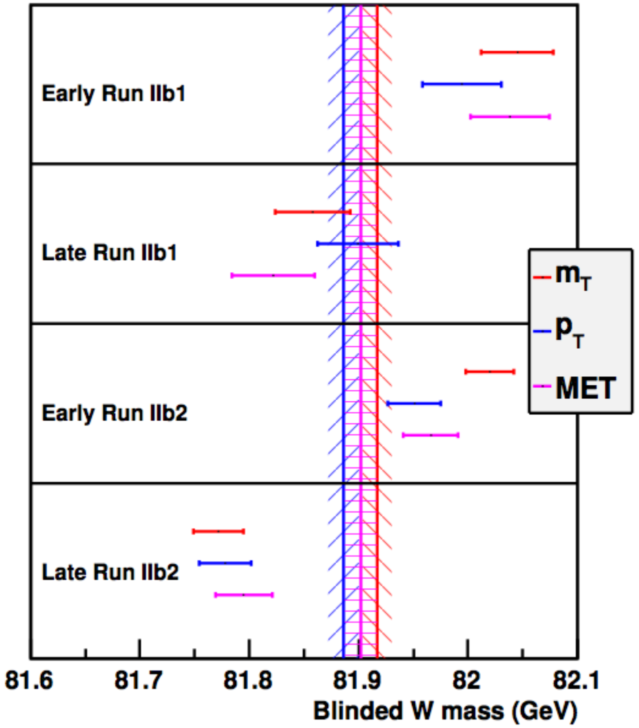
Green bands represent contribution from Z alone (100 % correlated for m_T, p_T and MET).

Mass ratio is stable with lumi.

Consistency checks

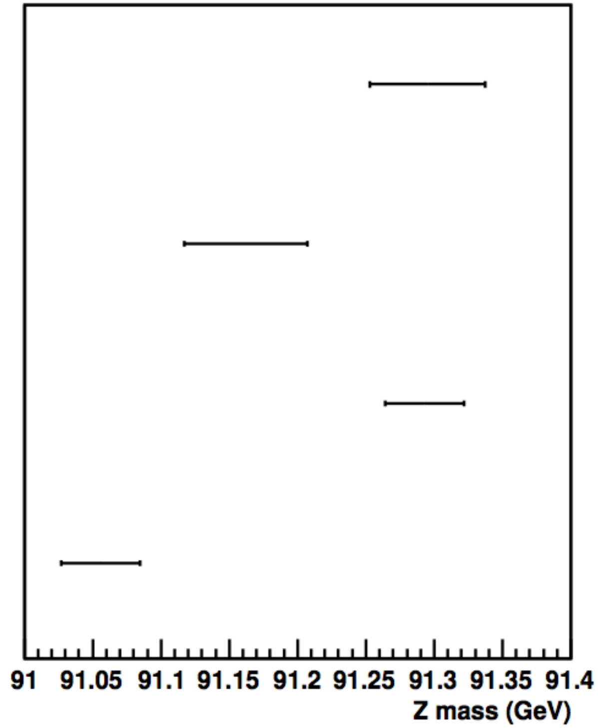
Split data sample into four data taking periods and measure W mass separately for each period:

W

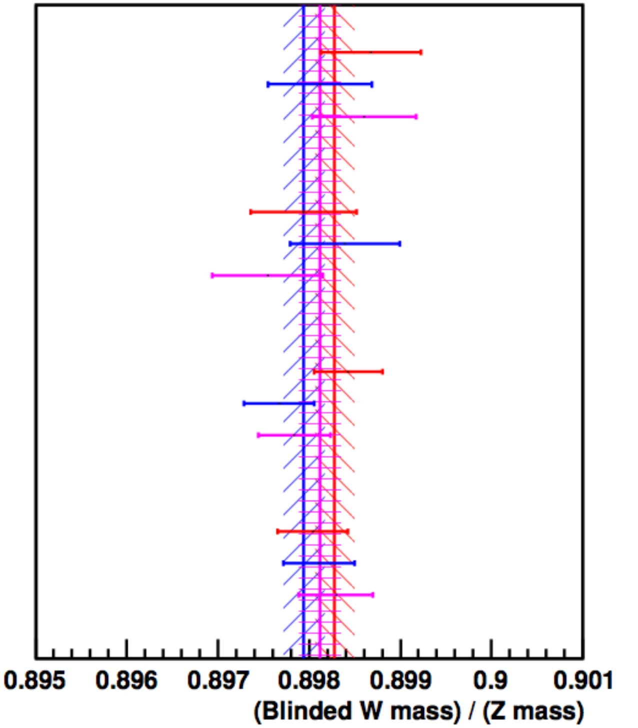


Error bars represent W statistics.

Z



"W/Z"



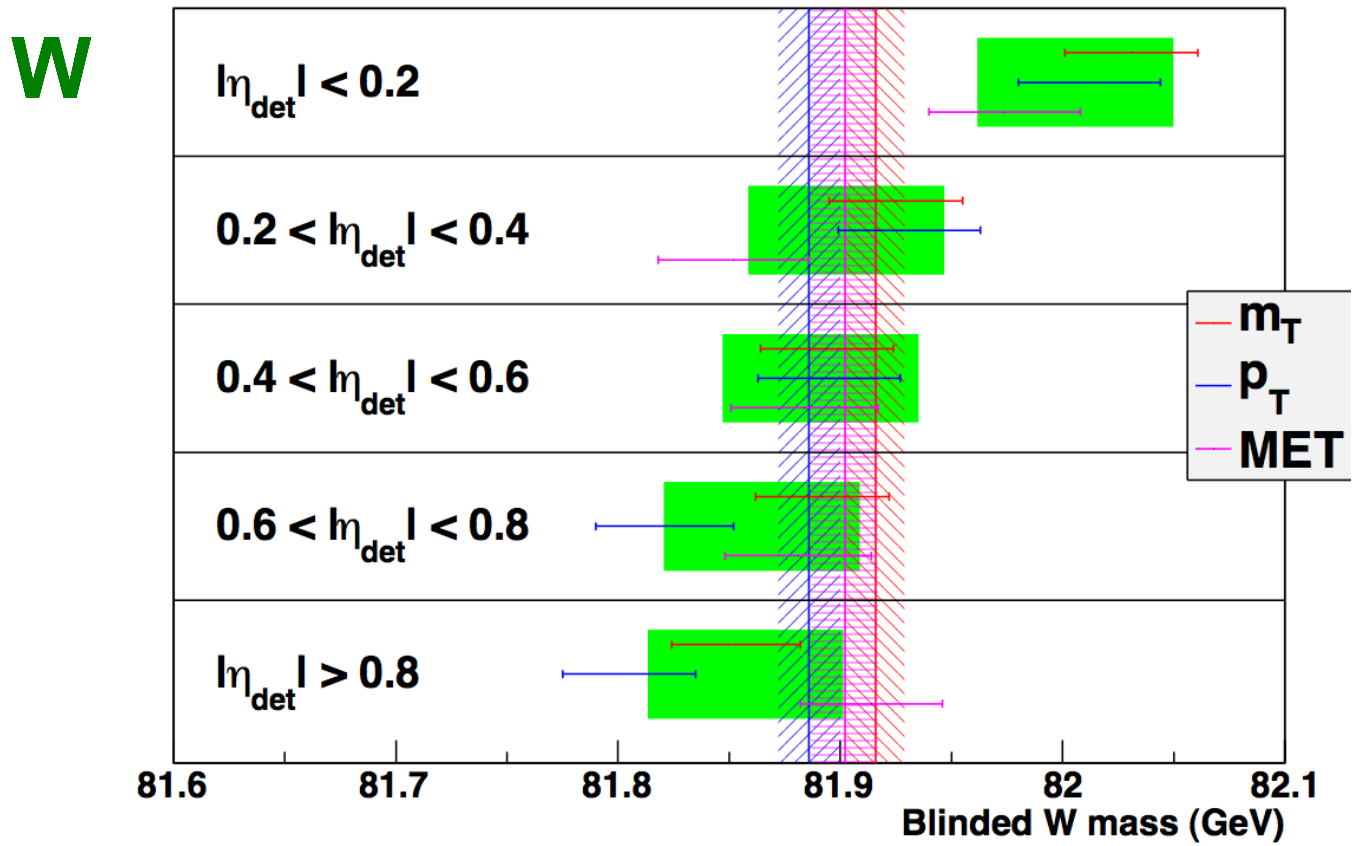
Error bars represent W *and* Z statistics.

Mass ratio is stable over time.

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

Consistency checks

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



Error bars represent W statistics.

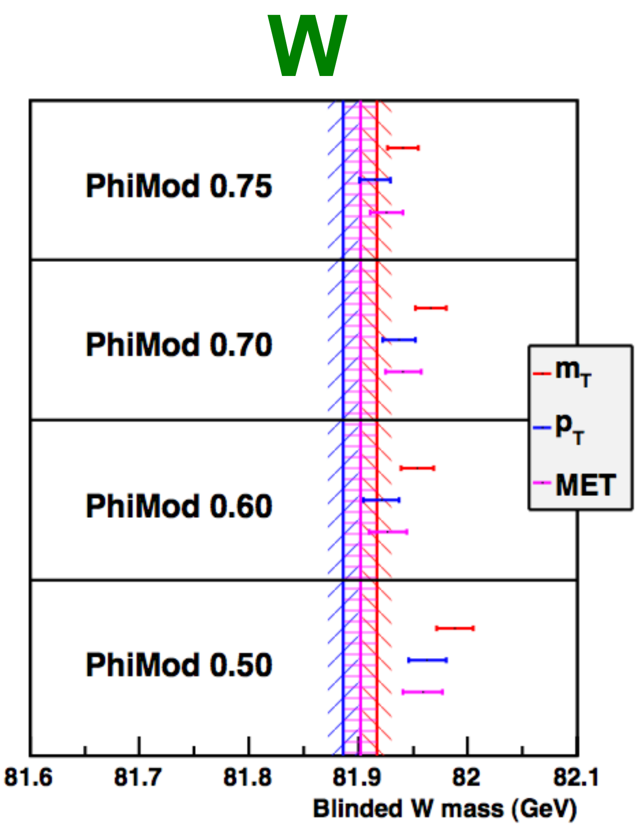
Green bands represent the part of the EM scale uncertainty that is uncorrelated from one eta bin to another (100 % correlated for m_T, p_T and MET).

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

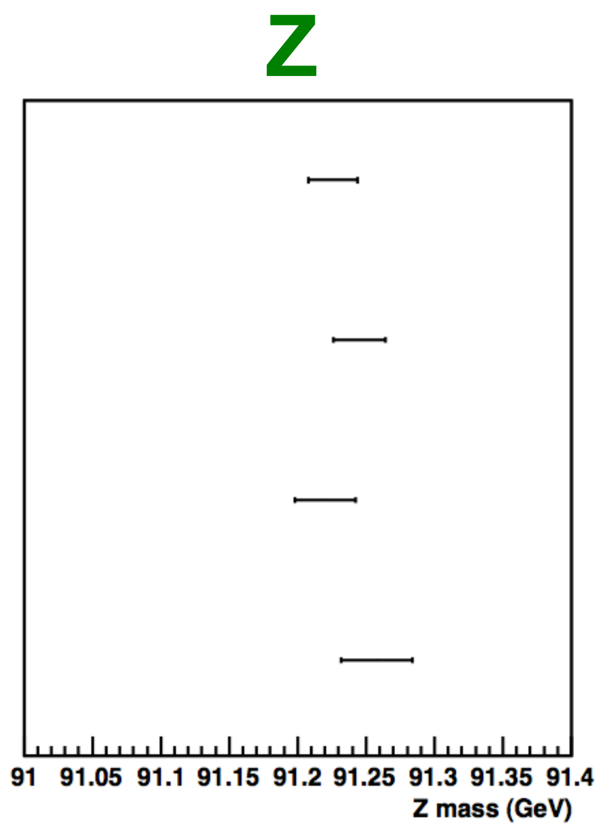
Mass is stable with eta.

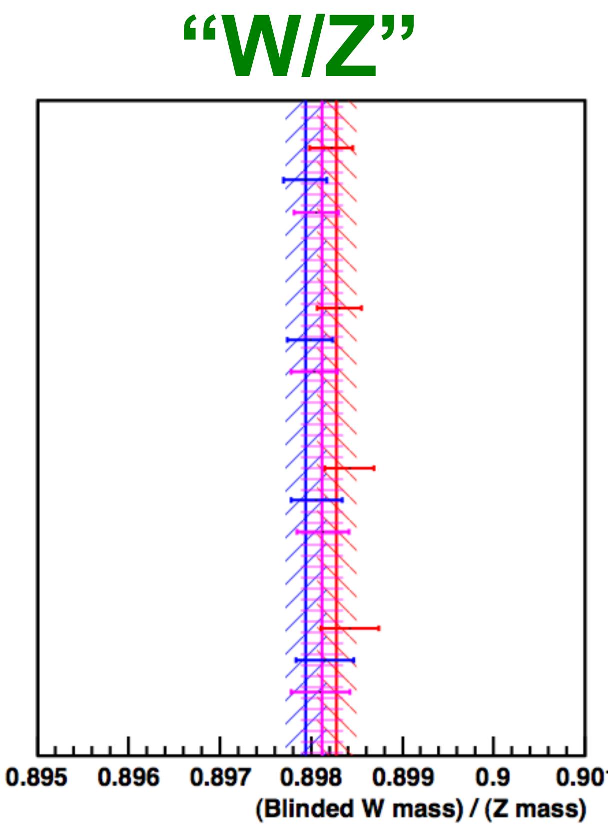
Consistency checks

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



Error bars represent W statistics.





Error bars represent
W *and* Z statistics.

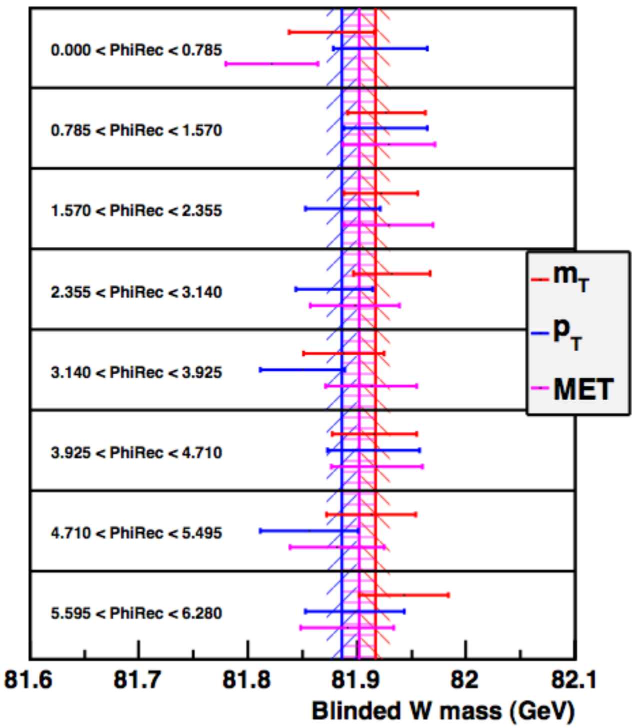
Sorry, still using blinded mass in these plots.
But it does not matter here …
differences between observables and subsamples
are preserved by the blinding.

Mass ratio is stable with fiducial requirement

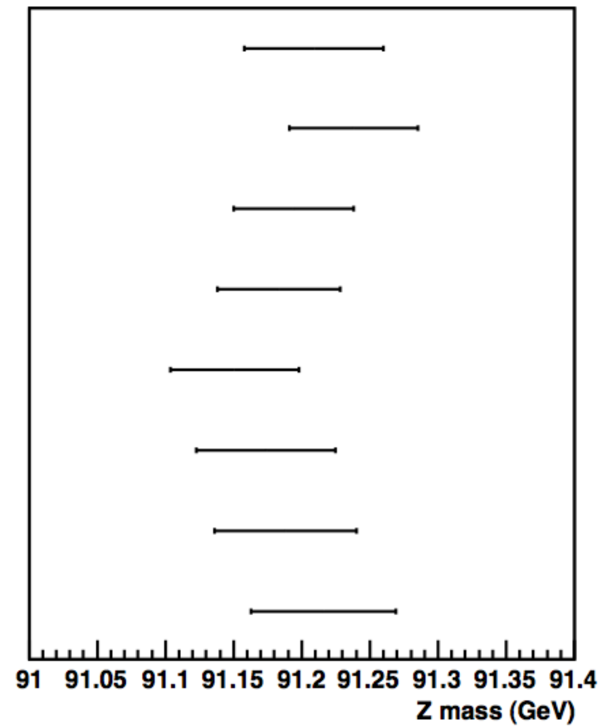
Consistency checks

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

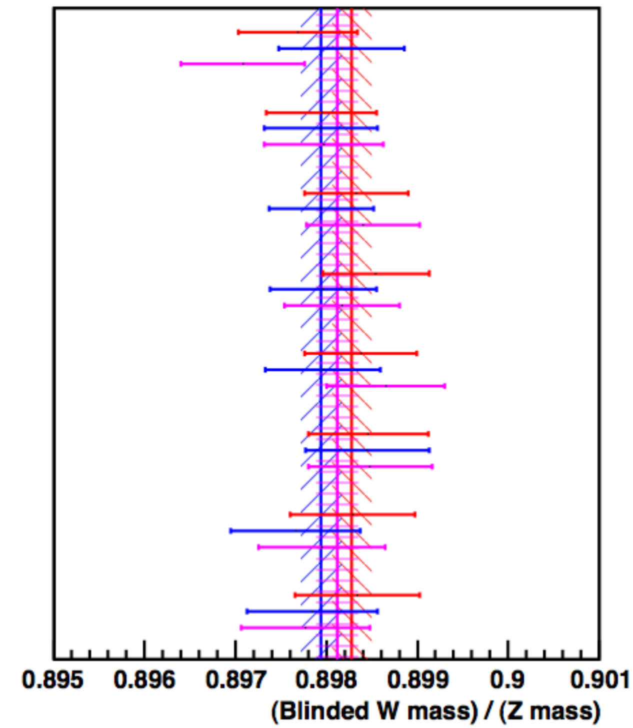
W



Z



"W/Z"



Error bars represent W statistics.

Error bars represent W *and* Z statistics.

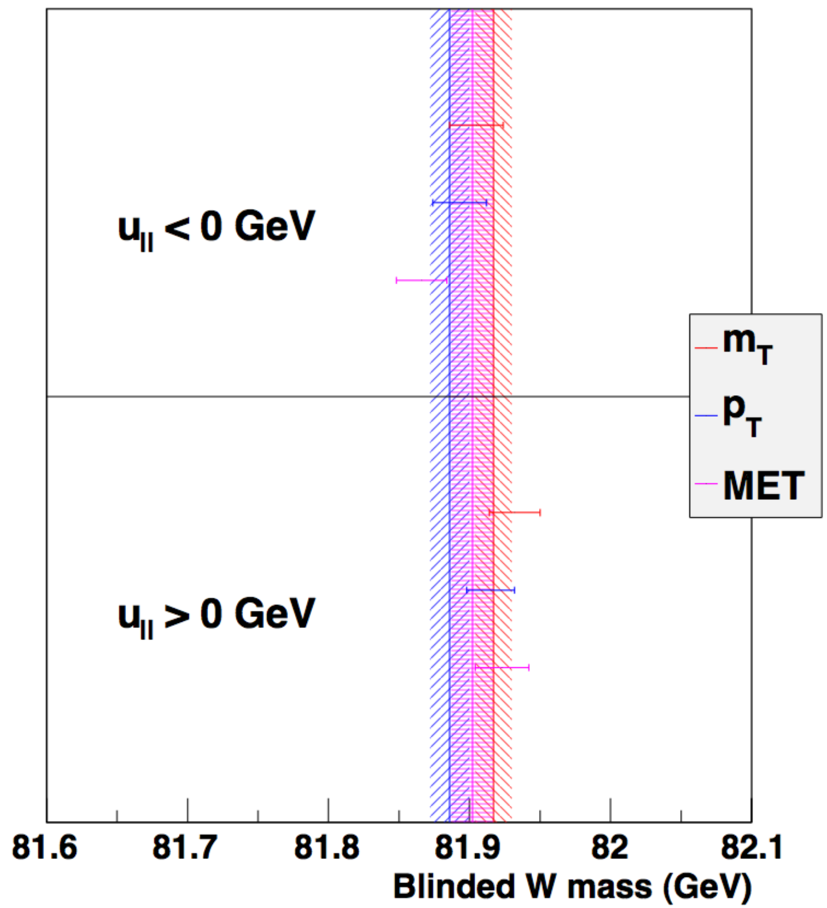
Sorry, still using blinded mass in these plots.
But it does not matter here …
differences between observables and subsamples are preserved by the blinding.

Mass ratio is stable with recoil phi.

Consistency checks

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

W



Error bars represent W statistics.

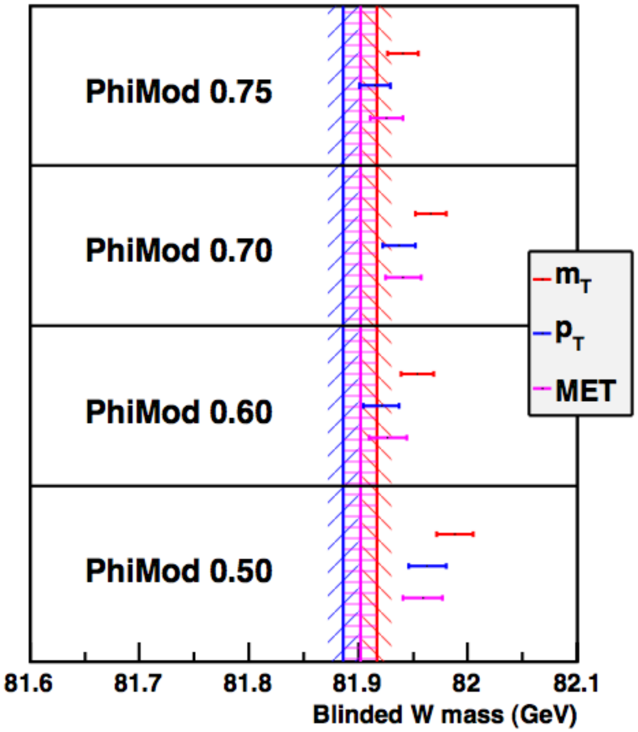
Sorry, still using blinded mass in these plots.
But it does not matter here …
differences between observables and subsamples are preserved by the blinding.

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

Consistency checks

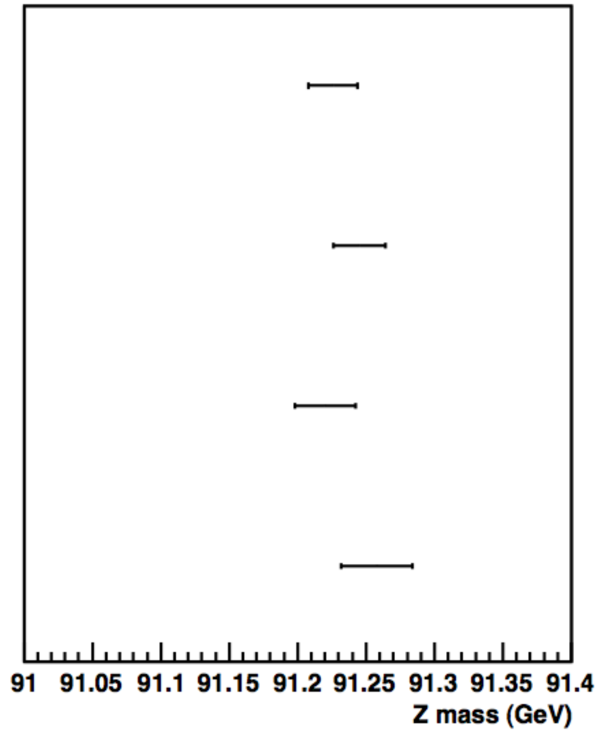
Vary phi fiducial cut. In default analysis, keep 80 % of acceptance. Here we test four tighter requirements.

W

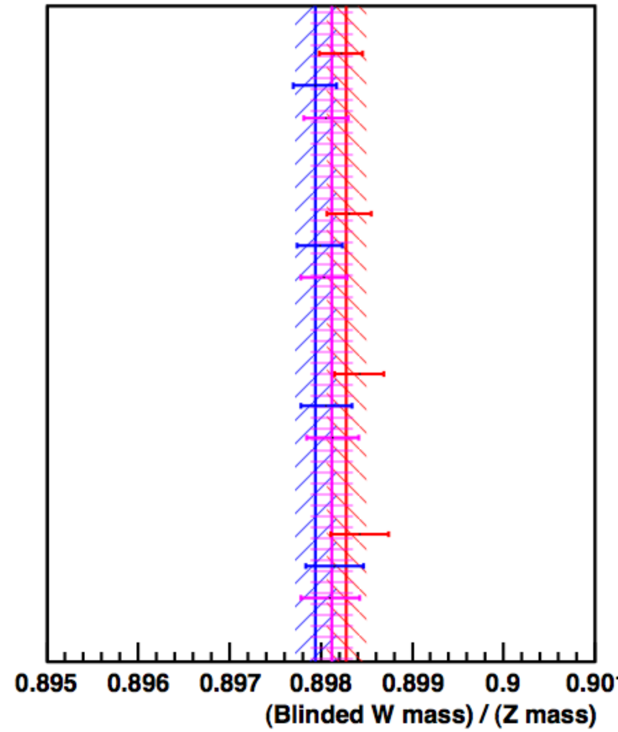


Error bars represent W statistics.

Z



"W/Z"

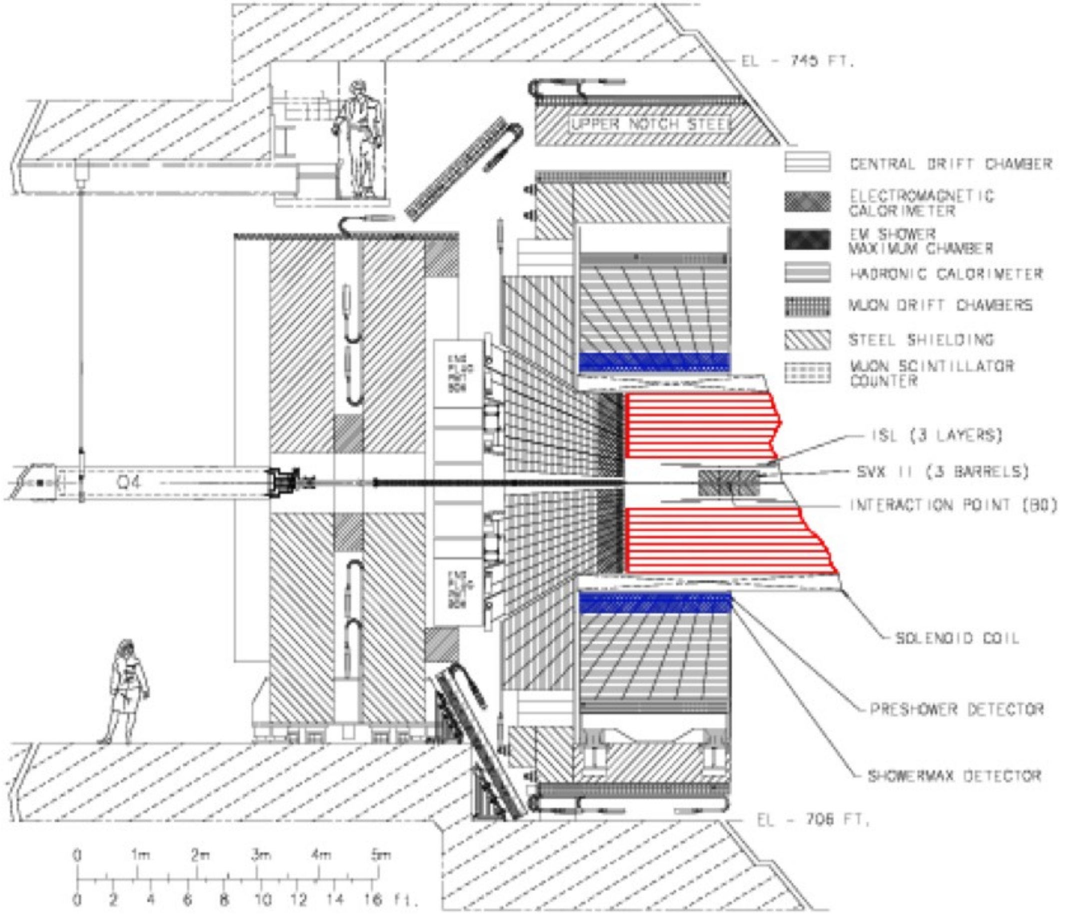


Error bars represent
W *and* Z statistics.

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

Mass ratio is stable with fiducial requirement

CDF detector



General purpose detector. For this analysis, the important subdetectors are:

- Central Drift Chamber immersed in a 1.4T solenoid. Provides accurate lepton momentum measurement and position measurement.
- Electromagnetic Calorimeter. Lead-aluminium-scintillator calorimeter. Provides shower energy measurement as well as position measurement via wire chamber embedded at the EM shower maximum.

Central tracker single muon resolution: 3.2% (for $p_T = 45\,GeV$)