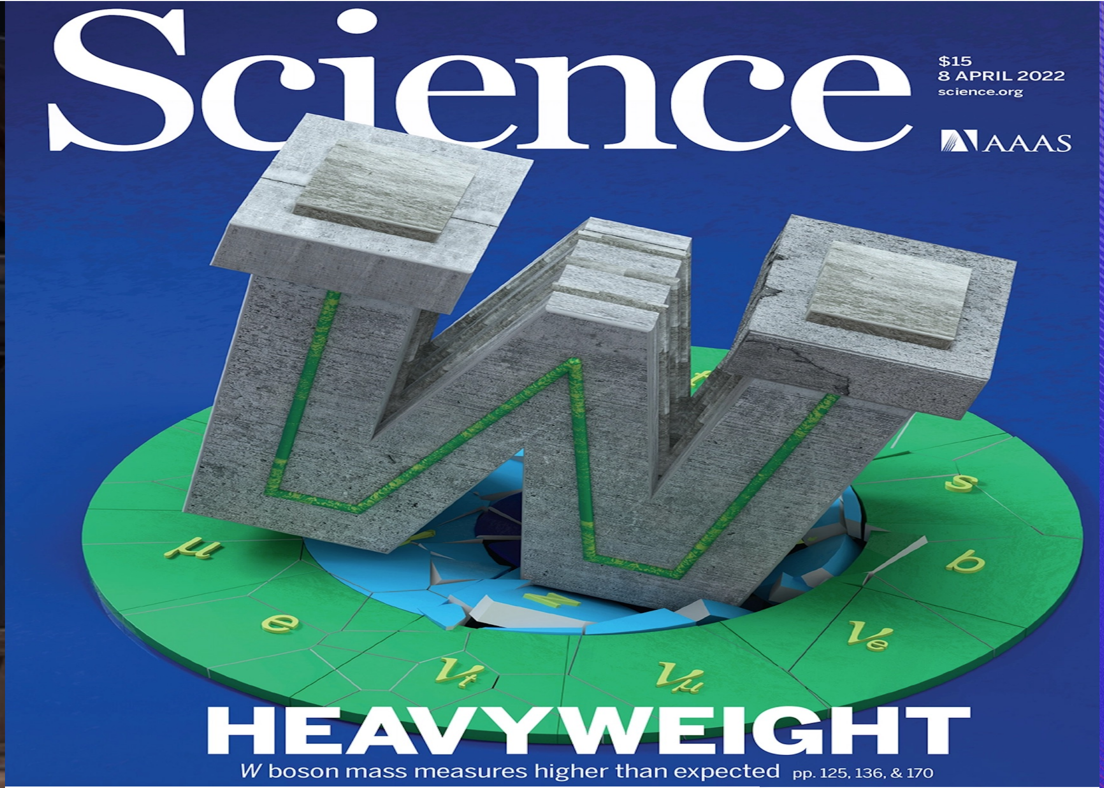
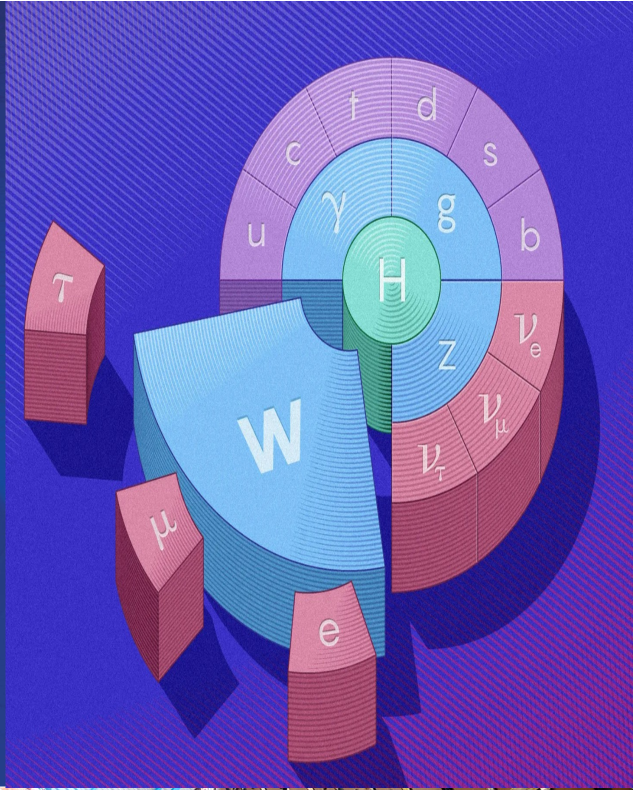
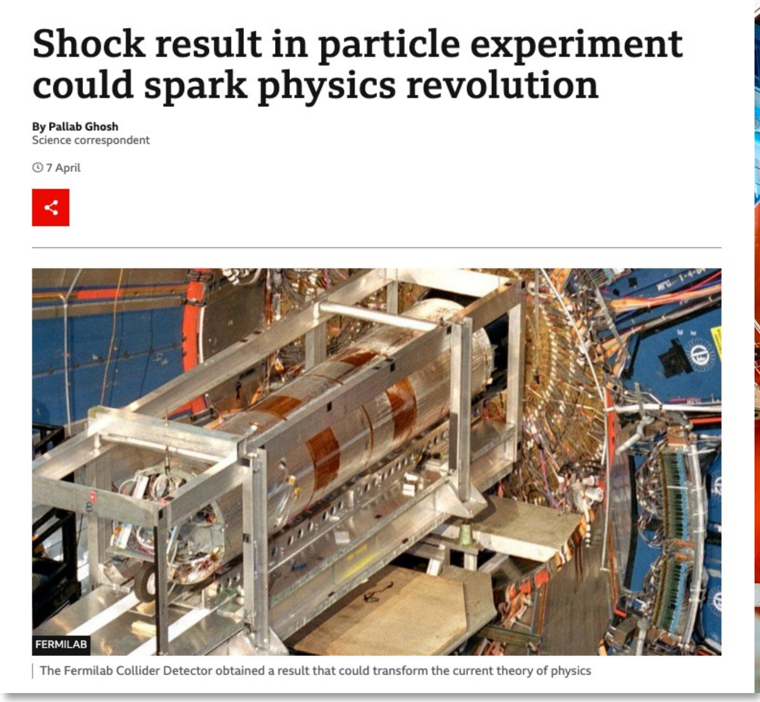




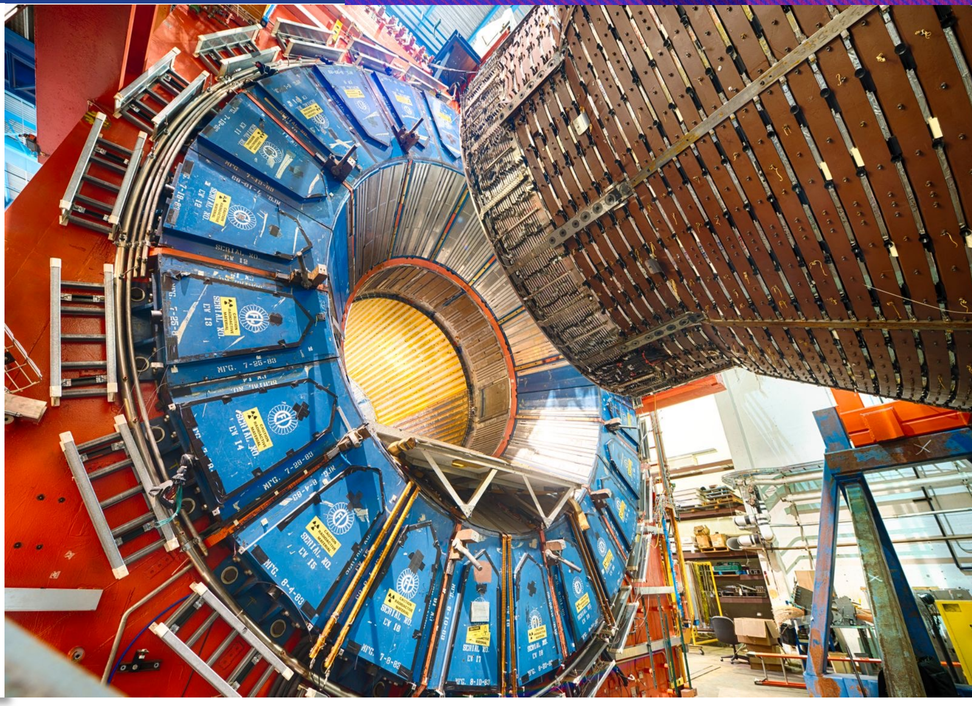


Shock result in particle experiment could spark physics revolution

By Pallab Ghosh
Science correspondent

7 April

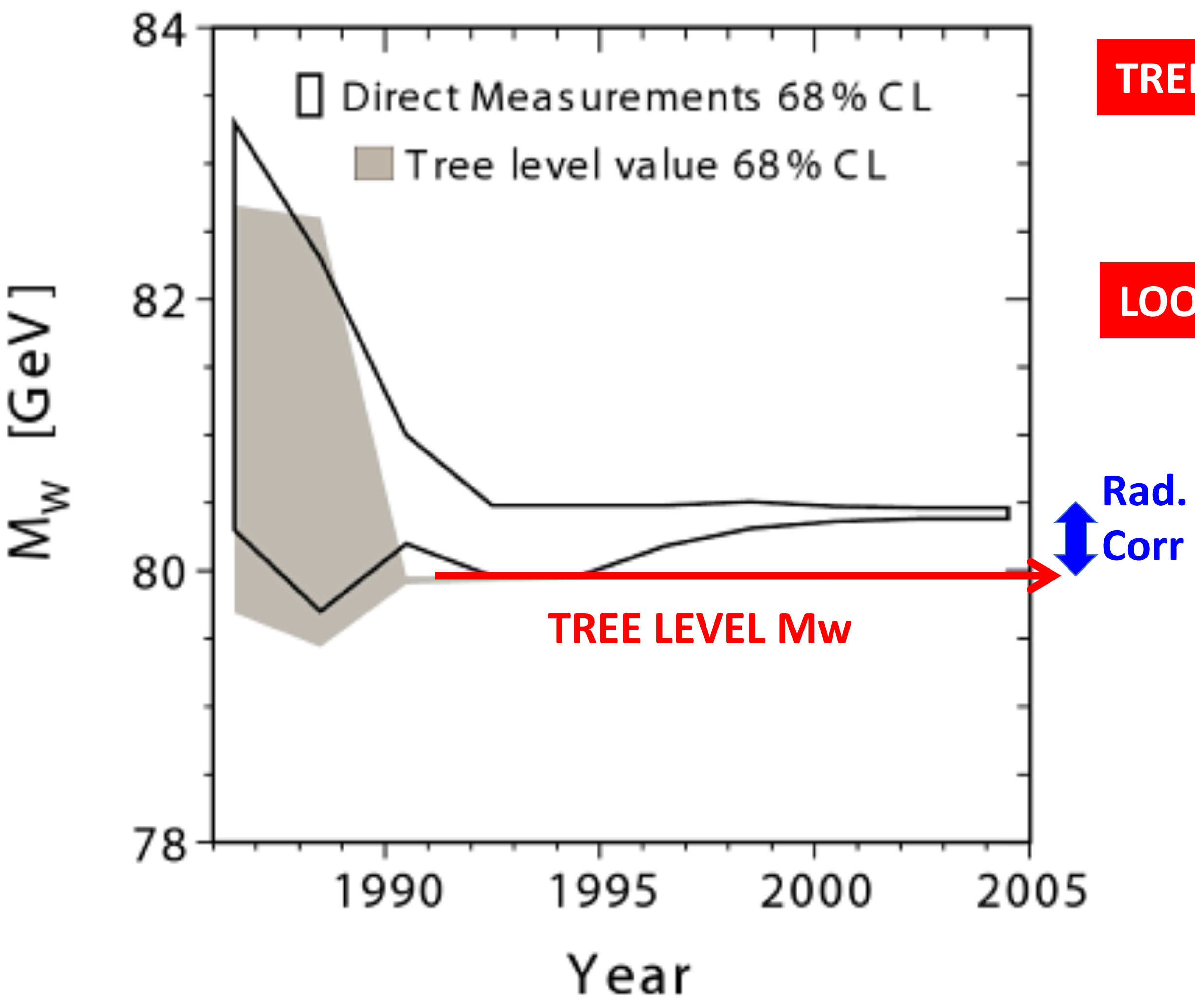
The Fermilab Collider Detector obtained a result that could transform the current theory of physics



(CDF) W Mass : Experimental Review

Mark Lancaster : University of Manchester

W Mass in SM



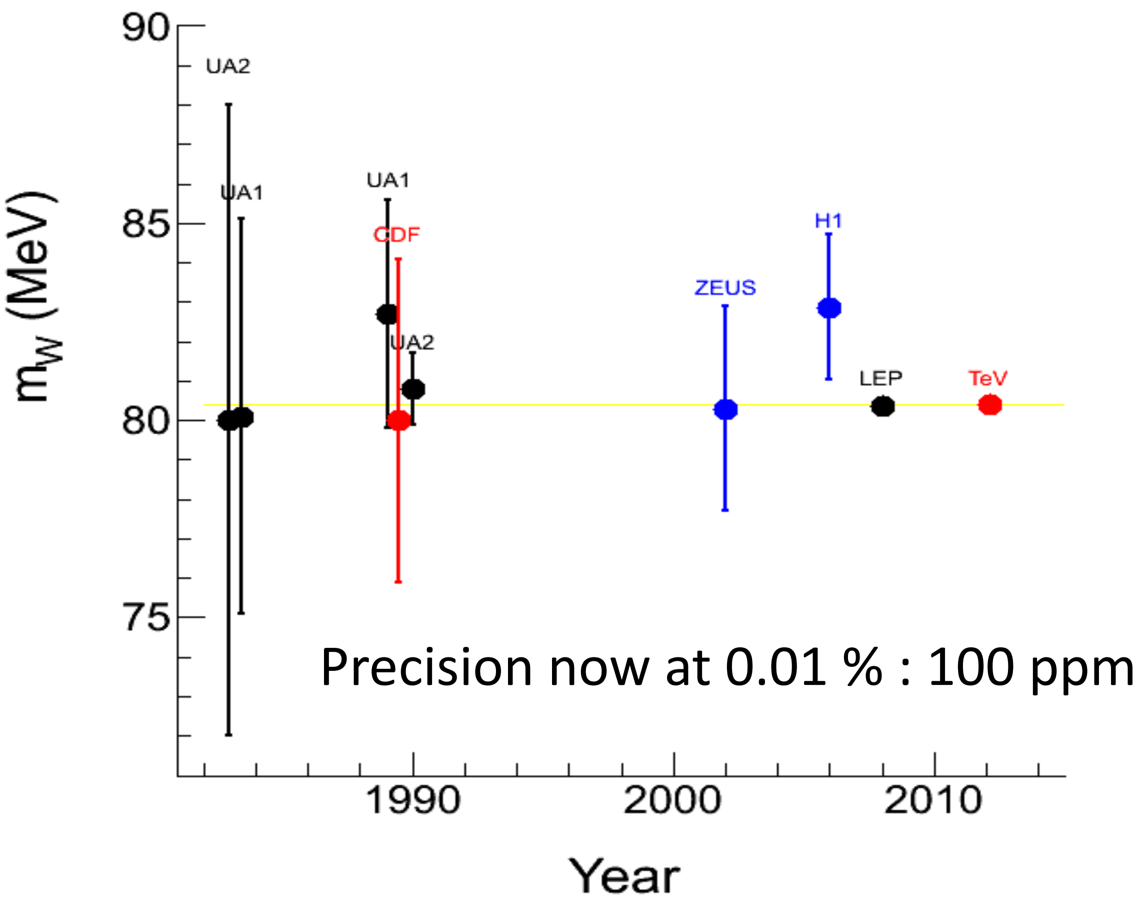
TREE LEVEL SM

$$M_W^2\left(1-\frac{M_W^2}{M_Z^2}\right)=\frac{\pi\alpha_{EM}}{\sqrt{2}G_F}$$

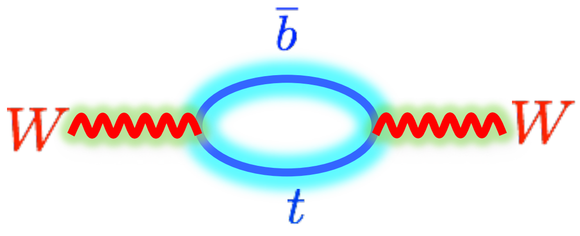
LOOP LEVEL SM

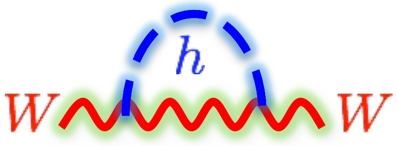
~ 500 MeV (0.6%)

Mass depends on M_{top}, M_H,…..

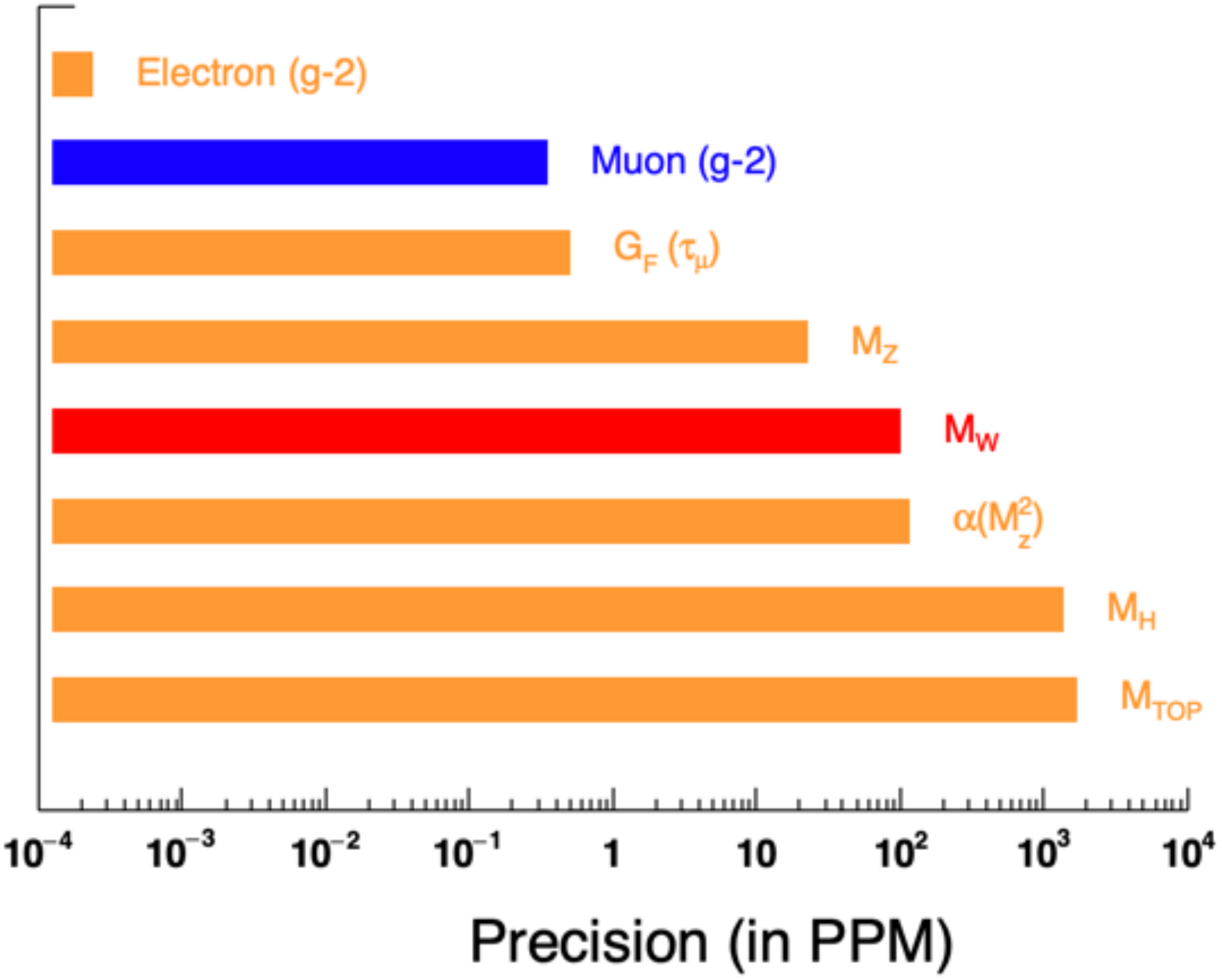


Precision now at 0.01 % : 100 ppm

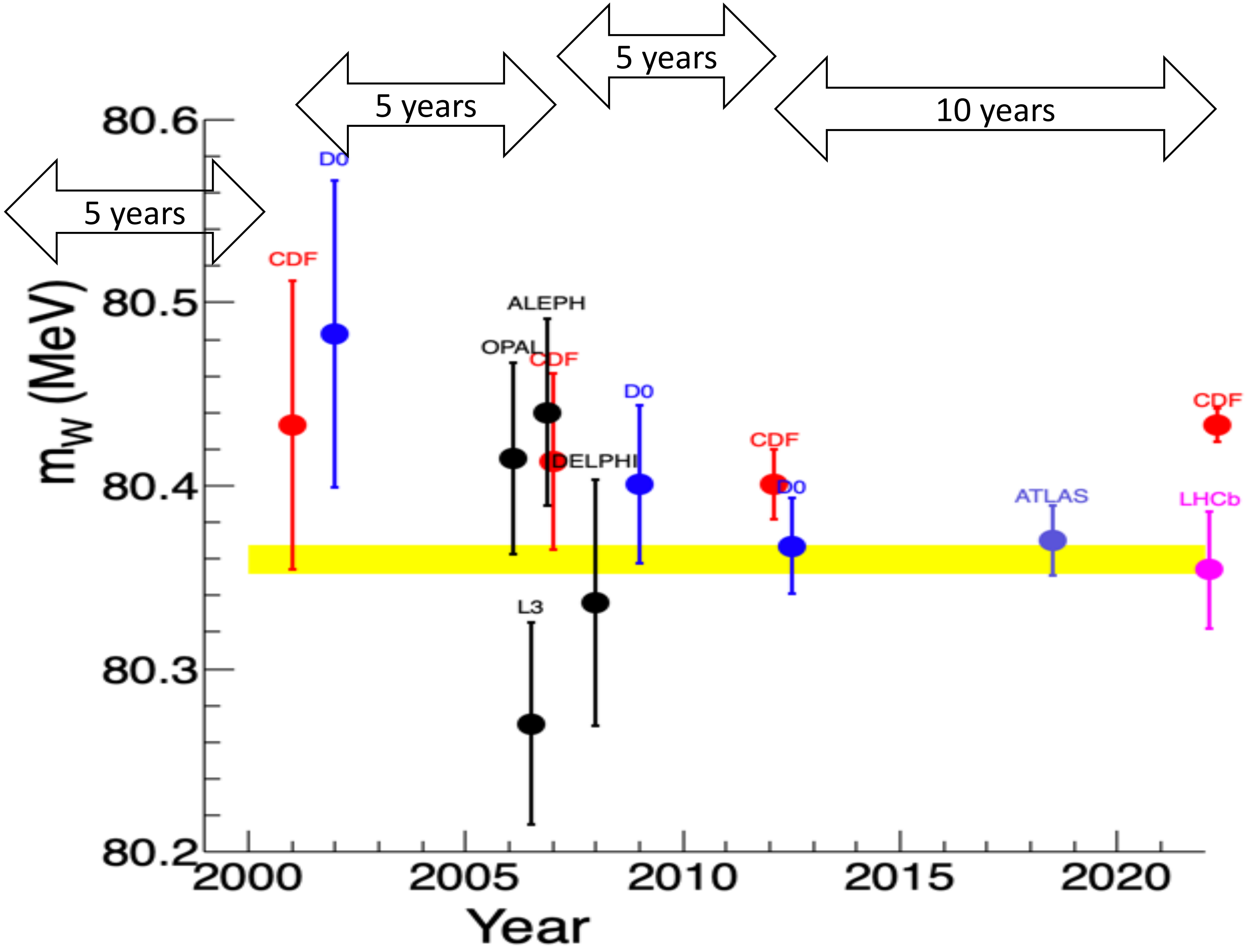




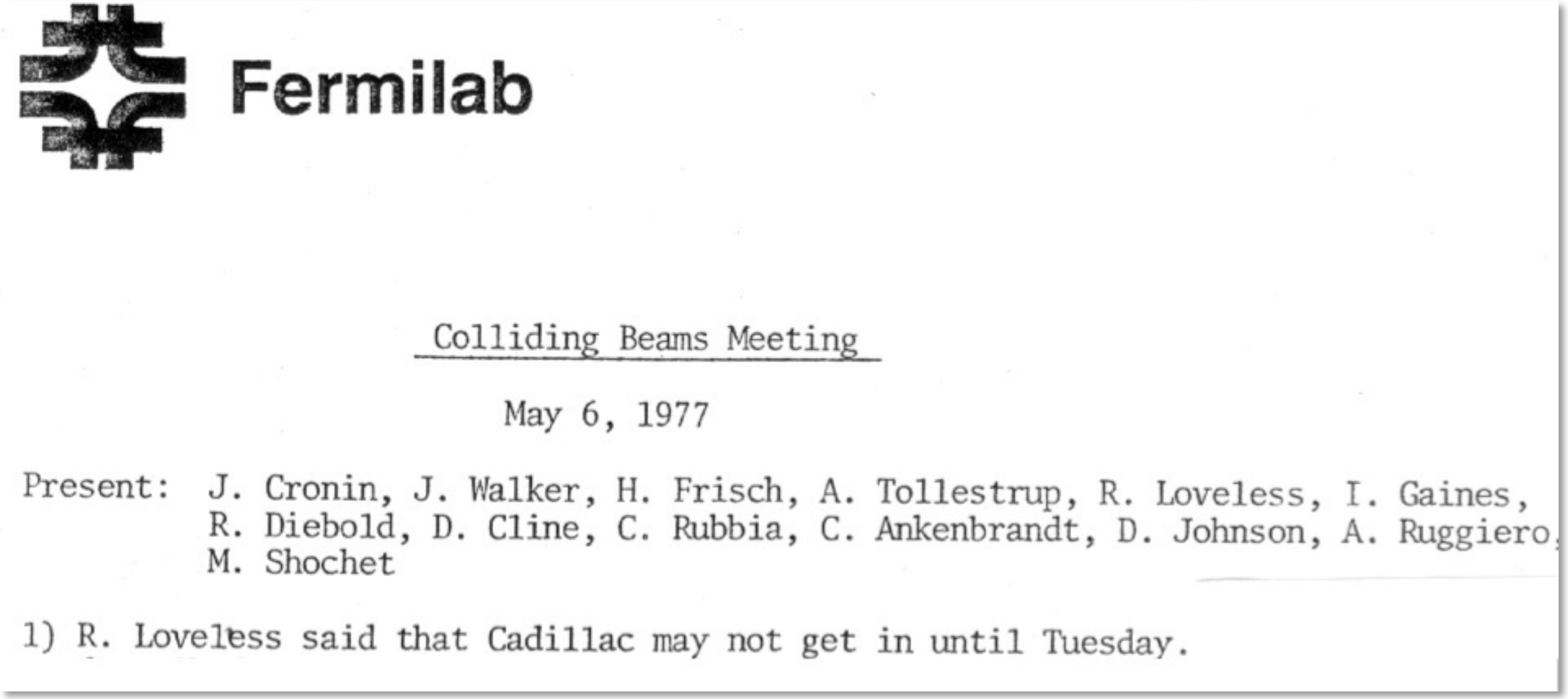
Precision


Electron (g-2)
Muon (g-2)
G_F (τ_μ)
M_Z
M_W
$\alpha(M_Z^2)$
M_H
M_{TOP}
10^{-4}
10^{-3}
10^{-2}
10^{-1}
1
10
10^2
10^3
10^4
Precision (in PPM)

Most recent results



Most recent results



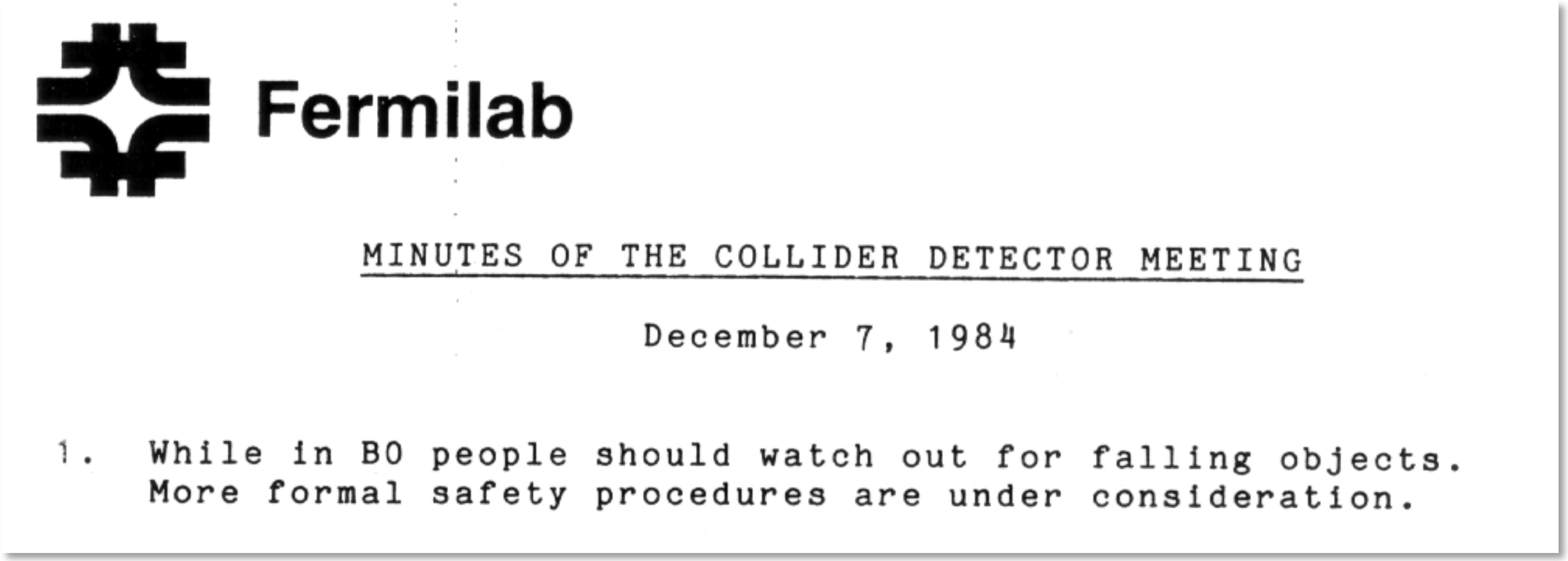
Fermilab

Colliding Beams Meeting

May 6, 1977

Present: J. Cronin, J. Walker, H. Frisch, A. Tollestrup, R. Loveless, I. Gaines,
R. Diebold, D. Cline, C. Rubbia, C. Ankenbrandt, D. Johnson, A. Ruggiero,
M. Shochet

1) R. Loveless said that Cadillac may not get in until Tuesday.

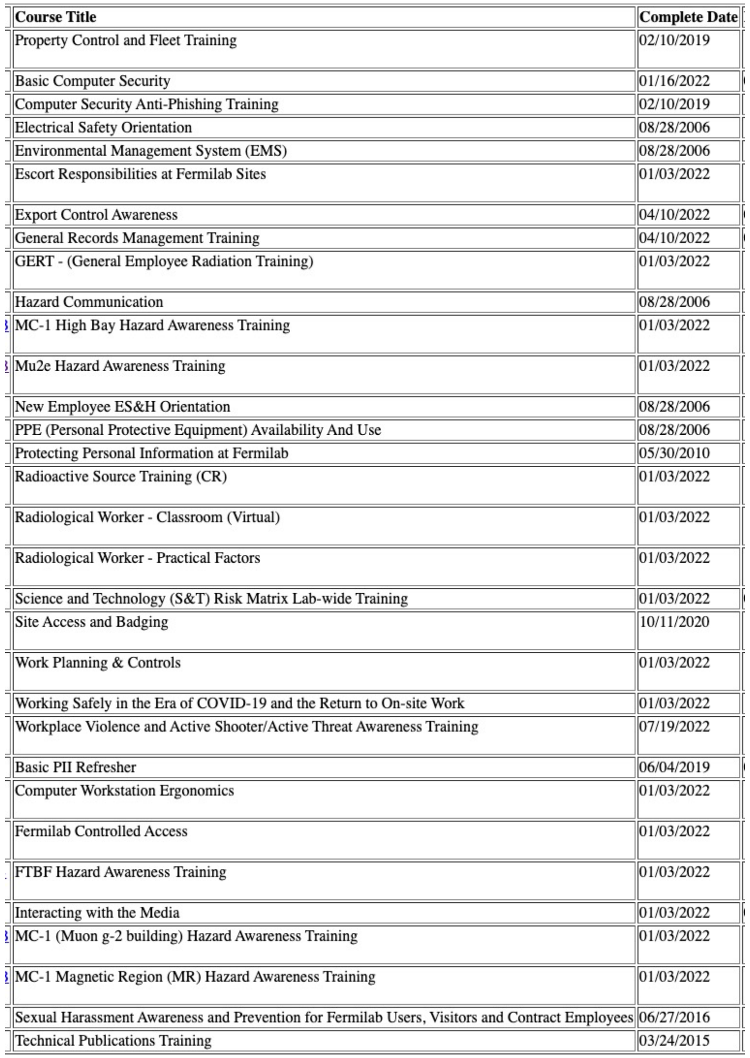


Fermilab

MINUTES OF THE COLLIDER DETECTOR MEETING

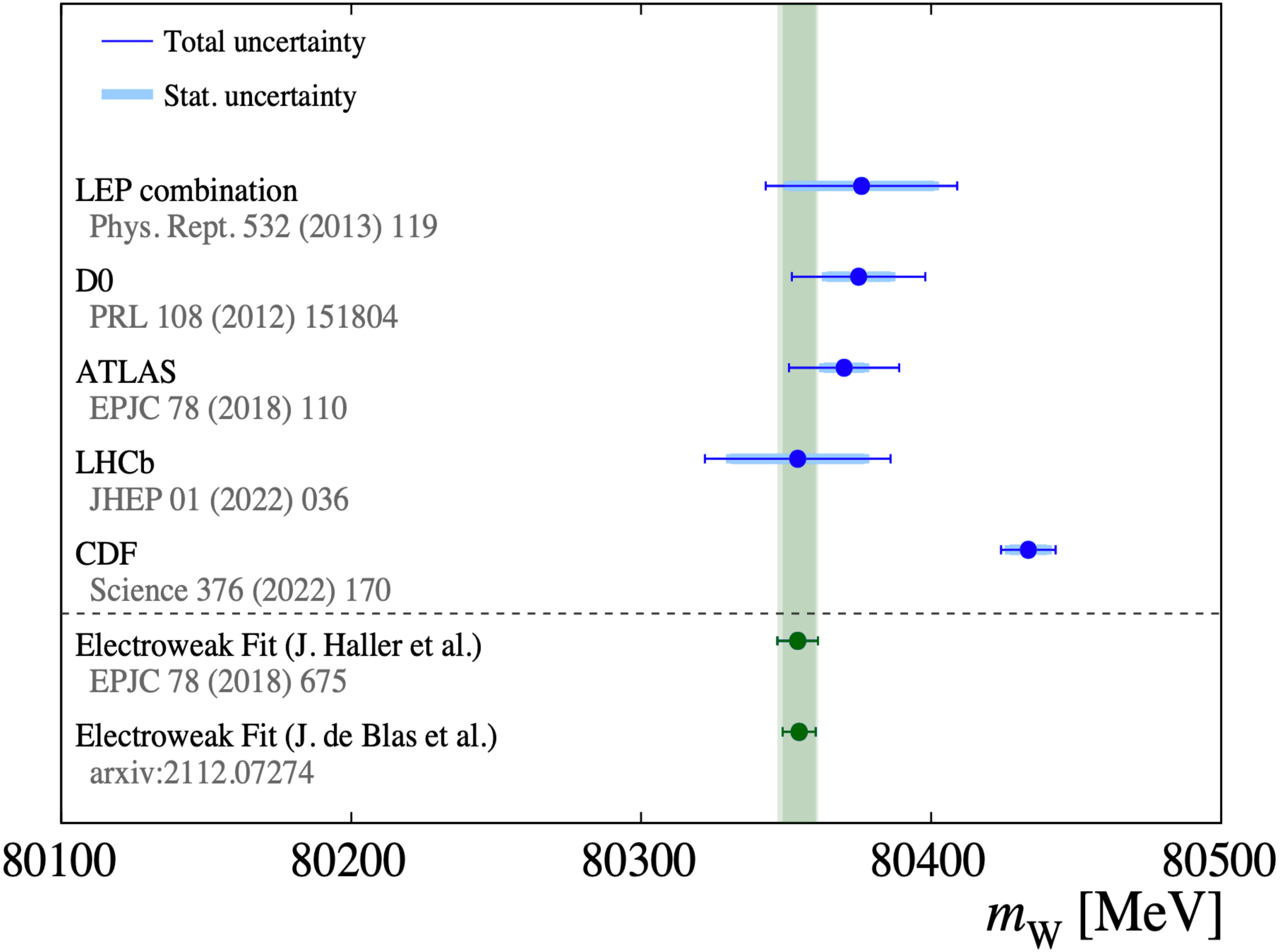
December 7, 1984

1. While in BO people should watch out for falling objects. More formal safety procedures are under consideration.

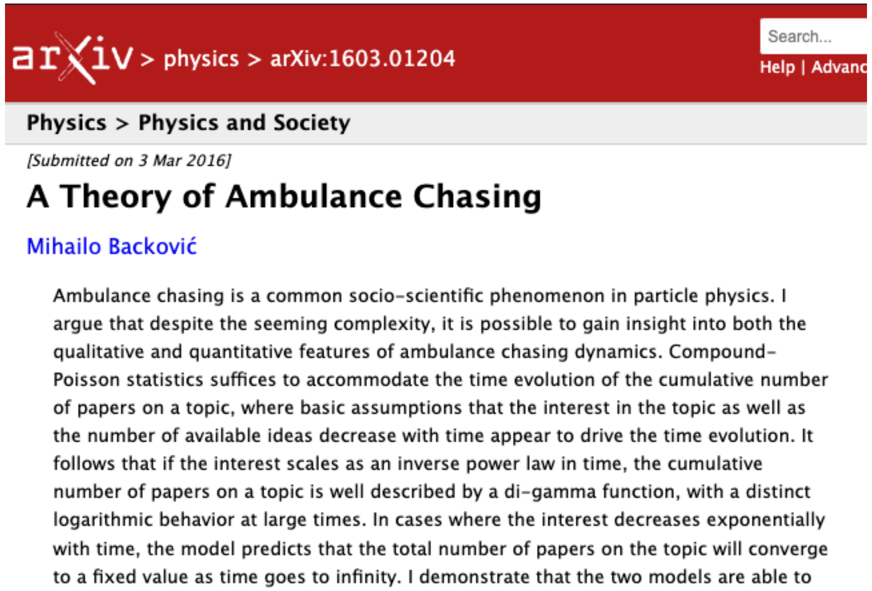


Course Title	Complete Date
Property Control and Fleet Training	02/10/2019
Basic Computer Security	01/16/2022
Computer Security Anti-Phishing Training	02/10/2019
Electrical Safety Orientation	08/28/2006
Environmental Management System (EMS)	08/28/2006
Escort Responsibilities at Fermilab Sites	01/03/2022
Export Control Awareness	04/10/2022
General Records Management Training	04/10/2022
GERT - (General Employee Radiation Training)	01/03/2022
Hazard Communication	08/28/2006
MC-1 High Bay Hazard Awareness Training	01/03/2022
Mu2e Hazard Awareness Training	01/03/2022
New Employee ES&H Orientation	08/28/2006
PPE (Personal Protective Equipment) Availability And Use	08/28/2006
Protecting Personal Information at Fermilab	05/30/2010
Radioactive Source Training (CR)	01/03/2022
Radiological Worker - Classroom (Virtual)	01/03/2022
Radiological Worker - Practical Factors	01/03/2022
Science and Technology (S&T) Risk Matrix Lab-wide Training	01/03/2022
Site Access and Badging	10/11/2020
Work Planning & Controls	01/03/2022
Working Safely in the Era of COVID-19 and the Return to On-site Work	01/03/2022
Workplace Violence and Active Shooter/Active Threat Awareness Training	07/19/2022
Basic PII Refresher	06/04/2019
Computer Workstation Ergonomics	01/03/2022
Fermilab Controlled Access	01/03/2022
FTBF Hazard Awareness Training	01/03/2022
Interacting with the Media	01/03/2022
MC-1 (Muon g-2 building) Hazard Awareness Training	01/03/2022
MC-1 Magnetic Region (MR) Hazard Awareness Training	01/03/2022
Sexual Harassment Awareness and Prevention for Fermilab Users, Visitors and Contract Employees	06/27/2016
Technical Publications Training	03/24/2015

Most recent results



Ambulances



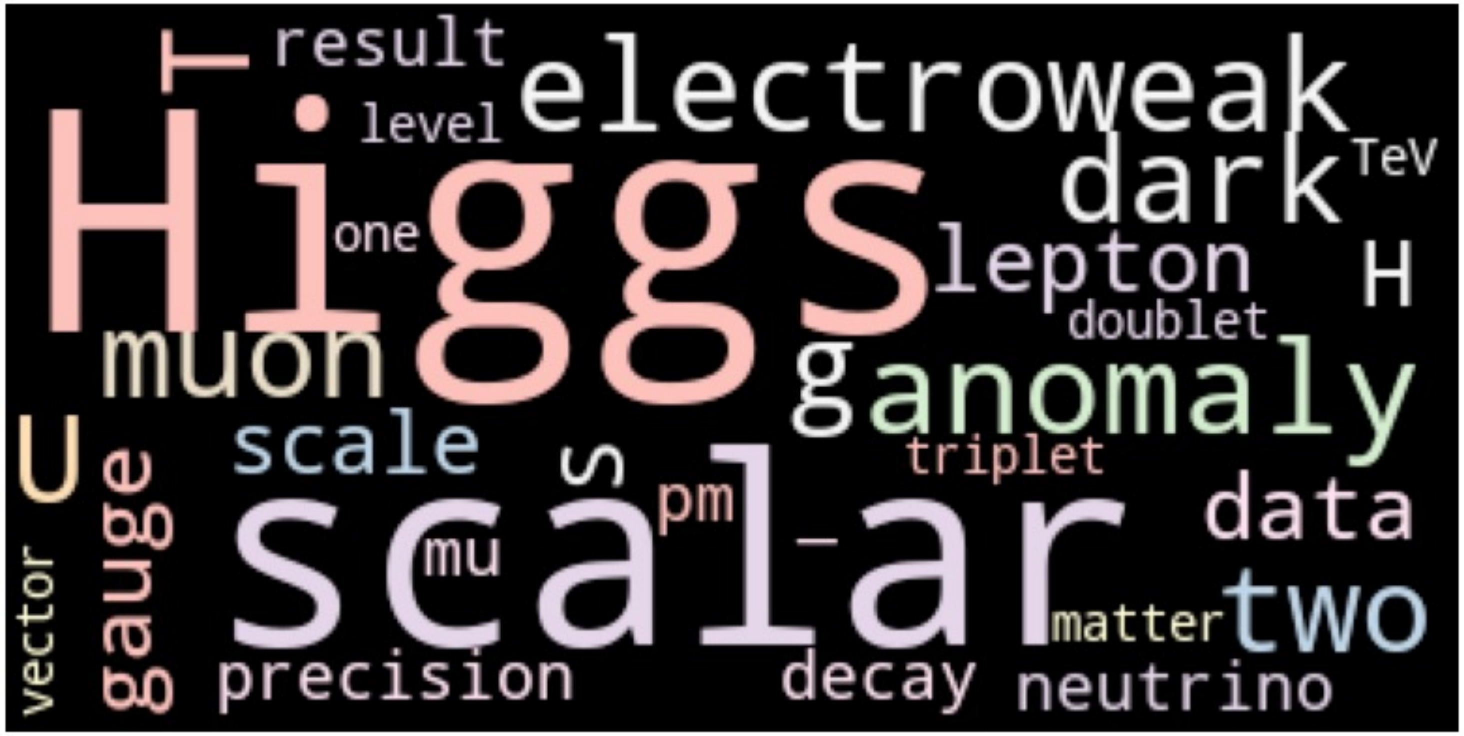
Physics > Physics and Society

[Submitted on 3 Mar 2016]

A Theory of Ambulance Chasing

Mihailo Backović

Ambulance chasing is a common socio-scientific phenomenon in particle physics. I argue that despite the seeming complexity, it is possible to gain insight into both the qualitative and quantitative features of ambulance chasing dynamics. Compound-Poisson statistics suffices to accommodate the time evolution of the cumulative number of papers on a topic, where basic assumptions that the interest in the topic as well as the number of available ideas decrease with time appear to drive the time evolution. It follows that if the interest scales as an inverse power law in time, the cumulative number of papers on a topic is well described by a di-gamma function, with a distinct logarithmic behavior at large times. In cases where the interest decreases exponentially with time, the model predicts that the total number of papers on the topic will converge to a fixed value as time goes to infinity. I demonstrate that the two models are able to

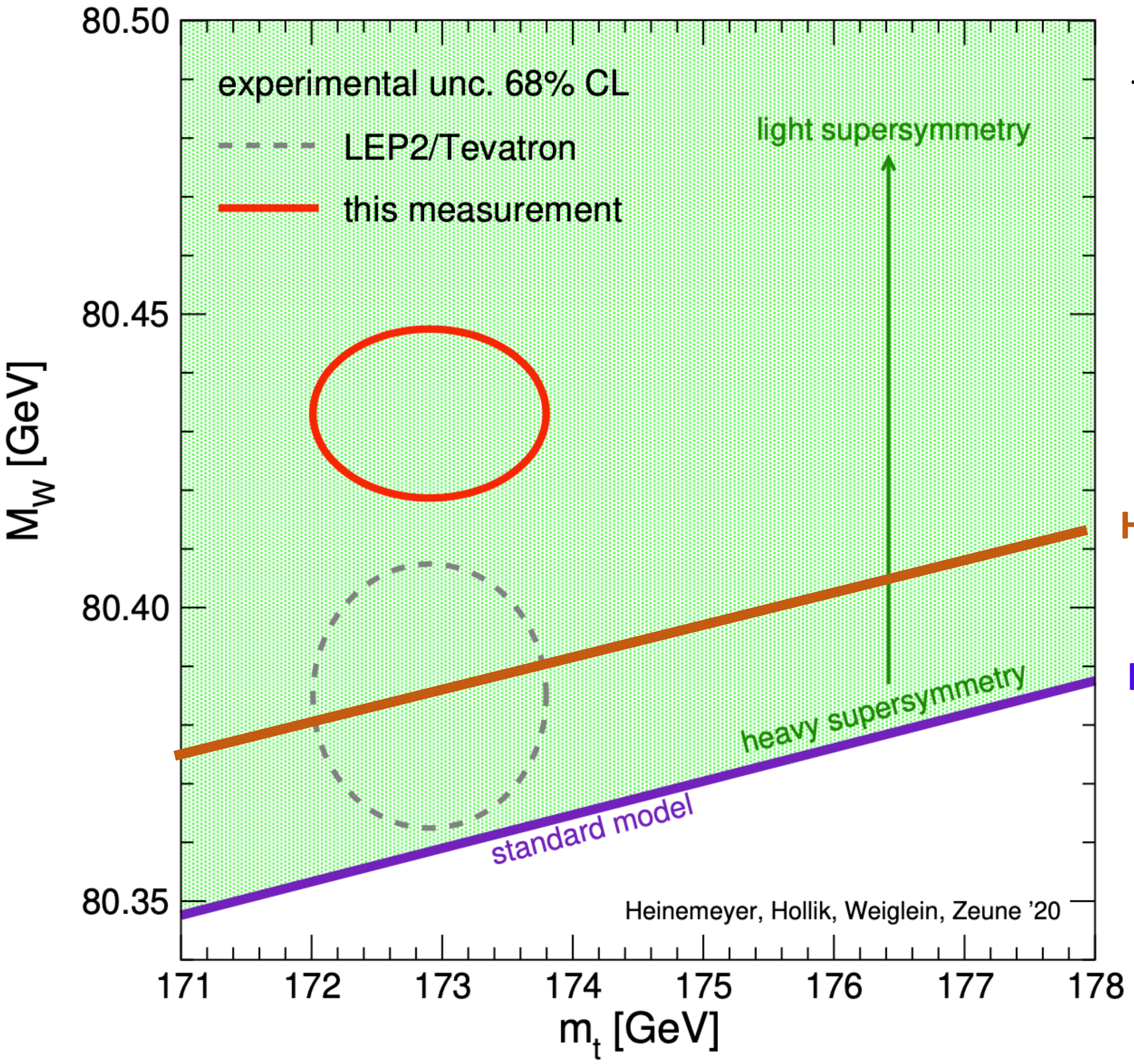


~ 100 papers since April with theories of why Mw should be above the SM.

About 20% of these also try and explain the high (g-2) at the same time

Many of these BSM ideas date back 20 years : e.g. Higgs triplets

Why the excitement ?

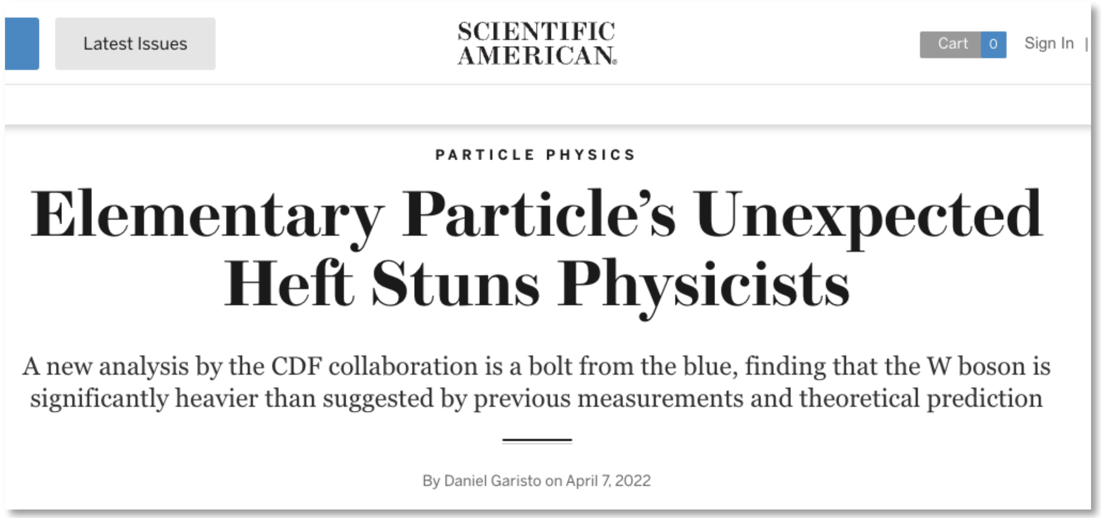


Top mass and W mass strongly related in SM

Before the CDF result. SM looked OK at the 1.5σ level

Higgs Mass = 90 GeV

Higgs Mass = 125 GeV



PARTICLE PHYSICS

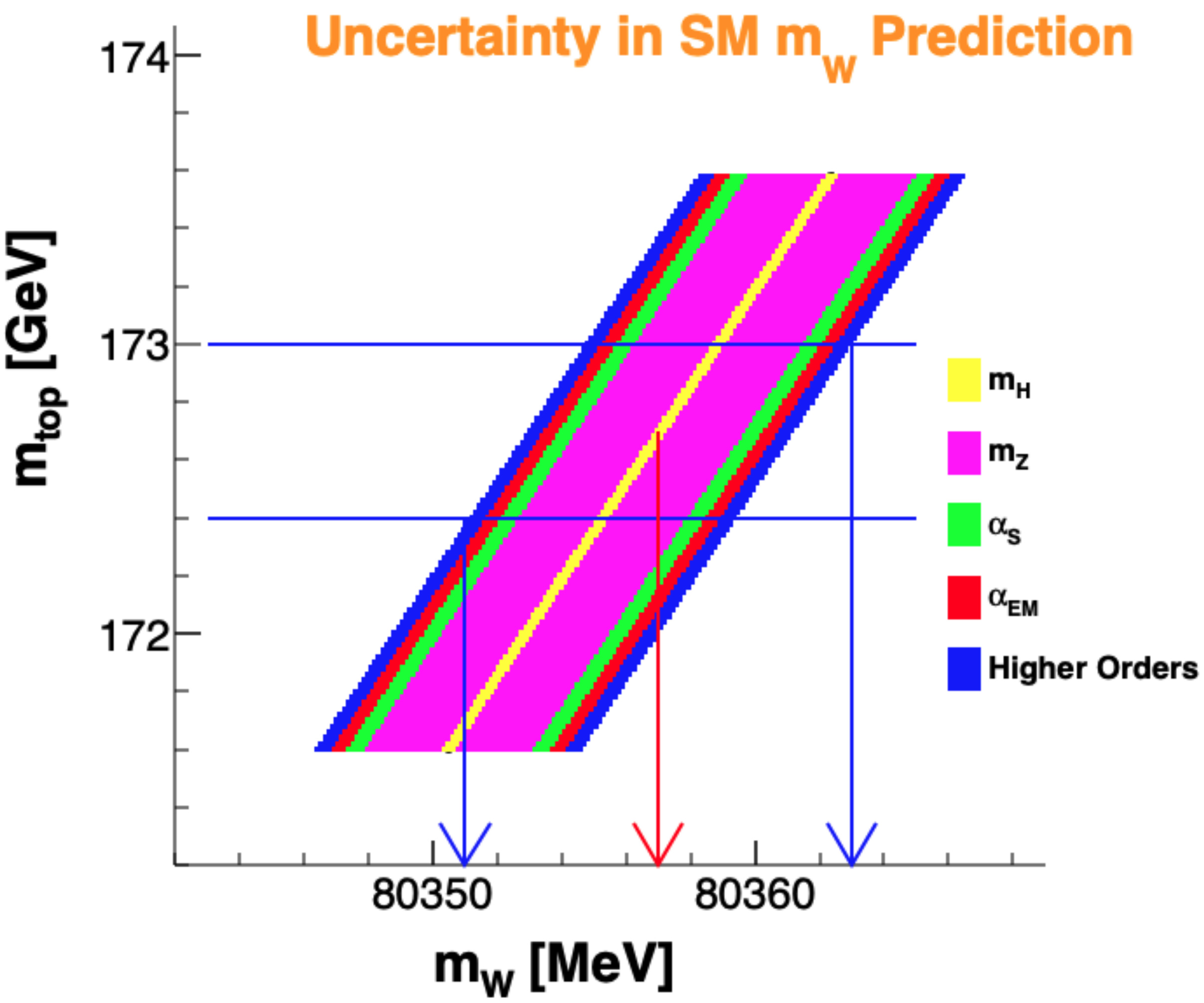
Elementary Particle's Unexpected Heft Stuns Physicists

A new analysis by the CDF collaboration is a bolt from the blue, finding that the W boson is significantly heavier than suggested by previous measurements and theoretical prediction

By Daniel Garisto on April 7, 2022

W Mass in the SM

Predicted Mw has uncertainty 6-8 MeV : half from theory, half from exp. measurements
Top mass and Z mass uncertainty are now the dominant drivers in SM Mw uncertainty
Our friend : $\Delta\alpha_{had}$ is also important. This is basically (g-2) HVP ….



Could this be wrong ?

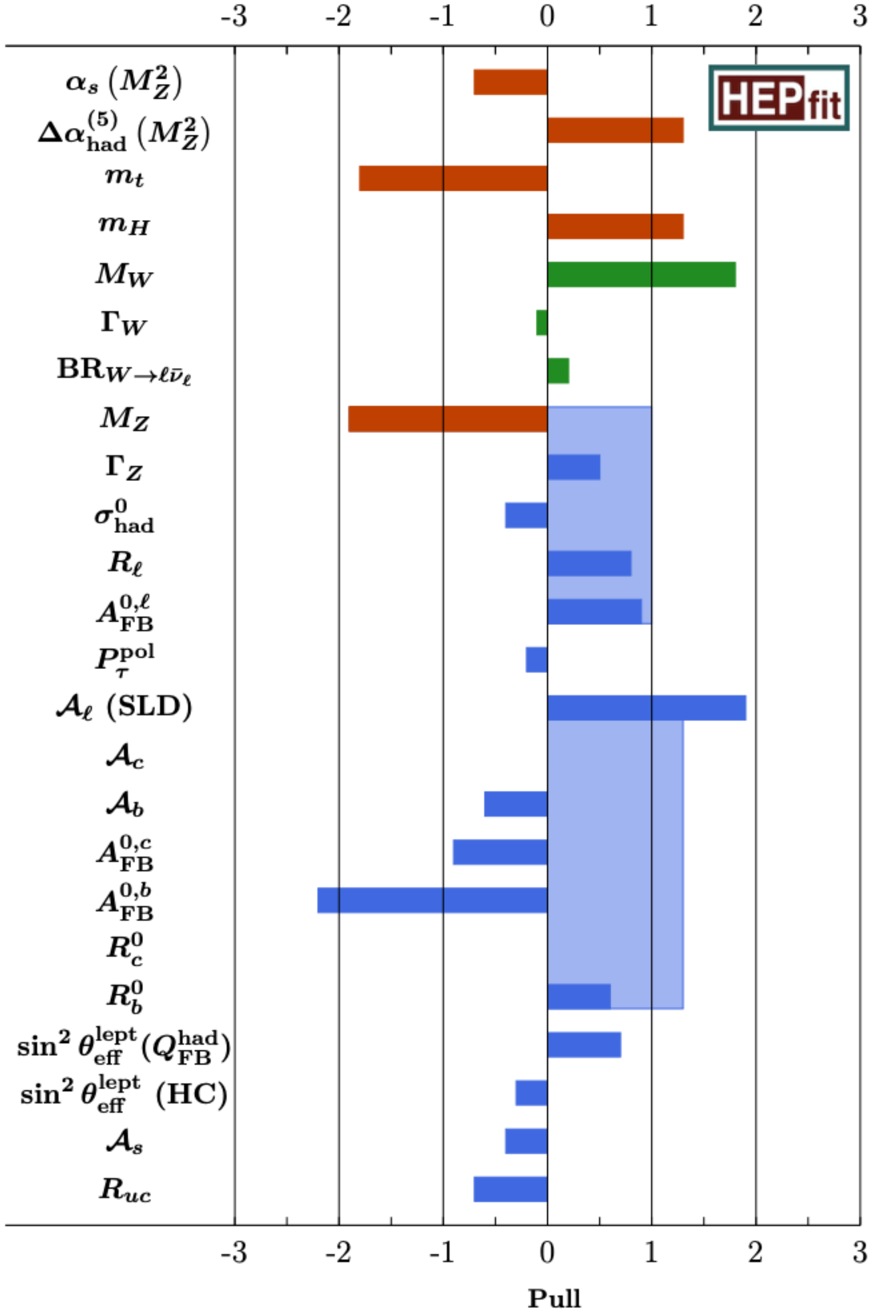
The inputs are:

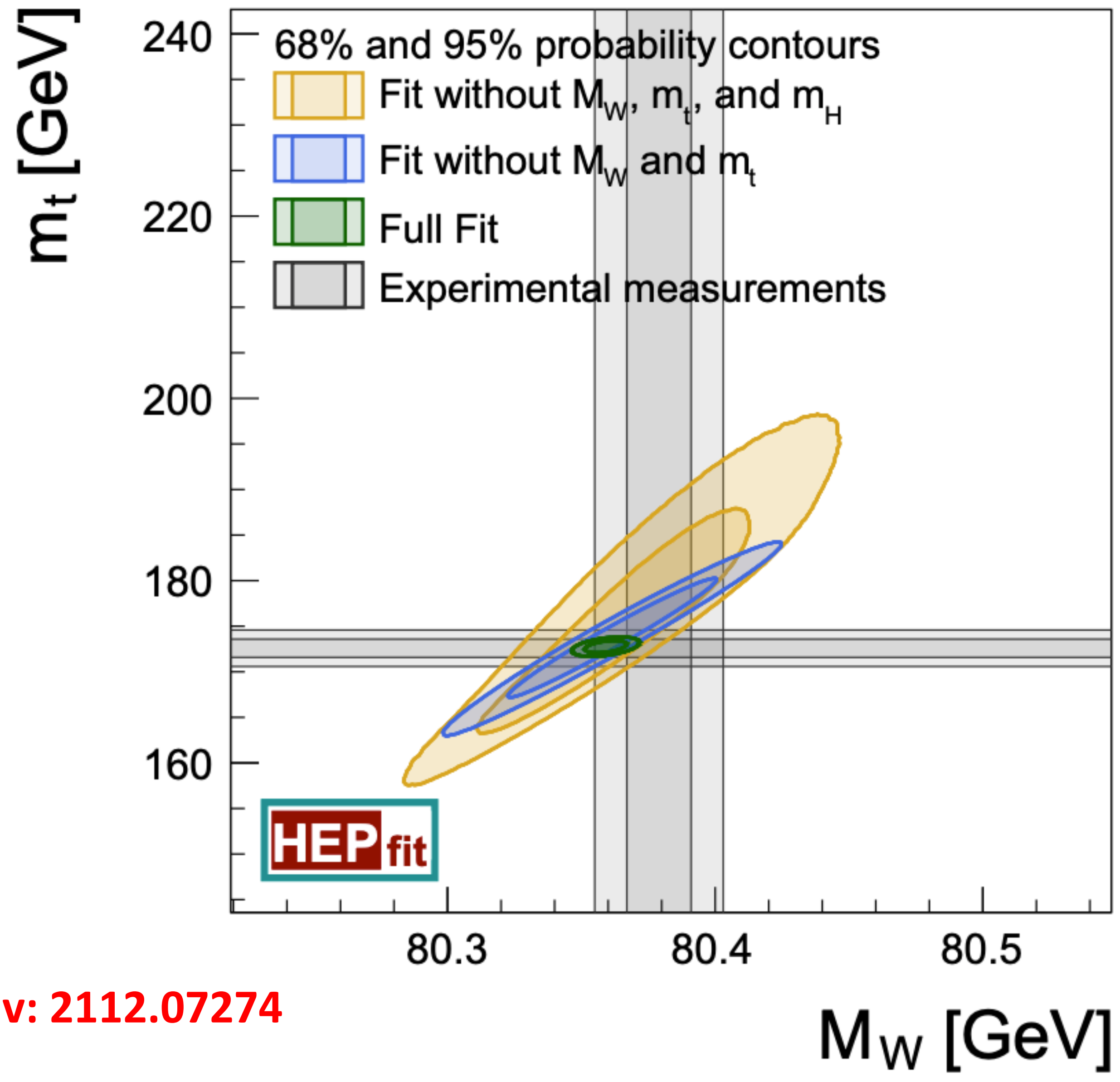
G_F, $\alpha(0)_{EM}$, α_s, $\Delta\alpha_{had}$, M_Z, M_t, M_H, M_b

G_F → MuLan (τ_μ)
$\alpha(0)_{EM}$ → $(g\text{-}2)_e$
$\Delta\alpha_{had}$ → e^+e^-, lattice

$\Delta\alpha_{had}$ comes from analysis of same e^+e^- data (or lattice calculation) as that determining (g-2) HVP.

SM Electroweak Fits / Constraints





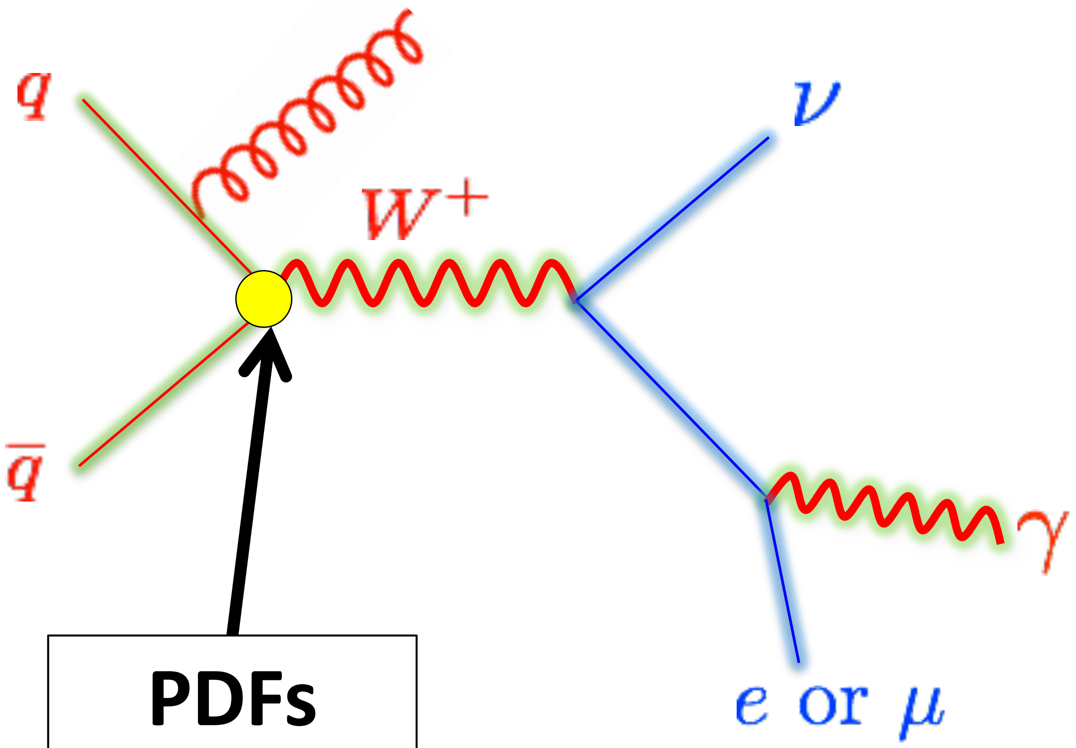
arXiv: 2112.07274

N.B. peculiarly in break with tradition this uses BMW lattice QCD result to constrain: $\Delta\alpha_{had}$ and not the e^+e^- cross section data

Measurement Details

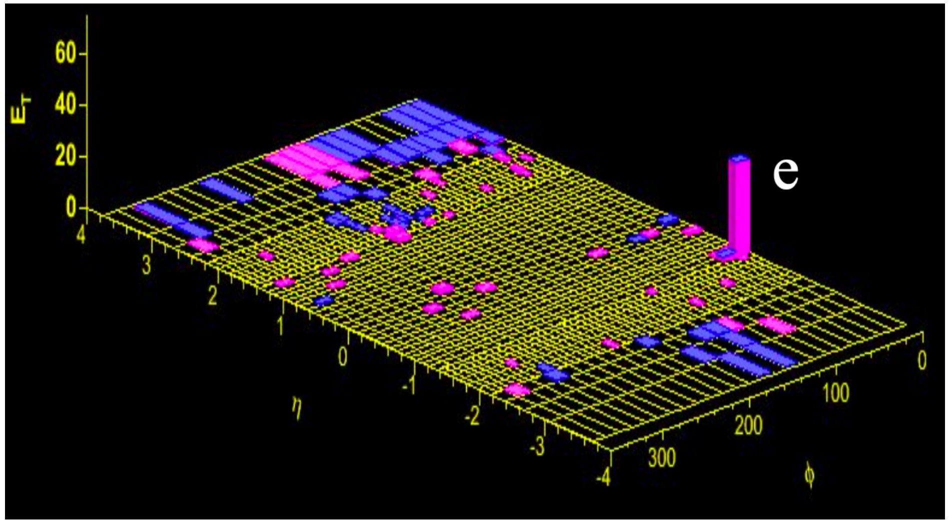
INITIAL STATE RADIATION (aka RECOIL)

- BOTH QCD AND QED
- TO NON PERTURBATIVE REGION IE PT(W) → 0



PDFs

Parton Distribution Functions

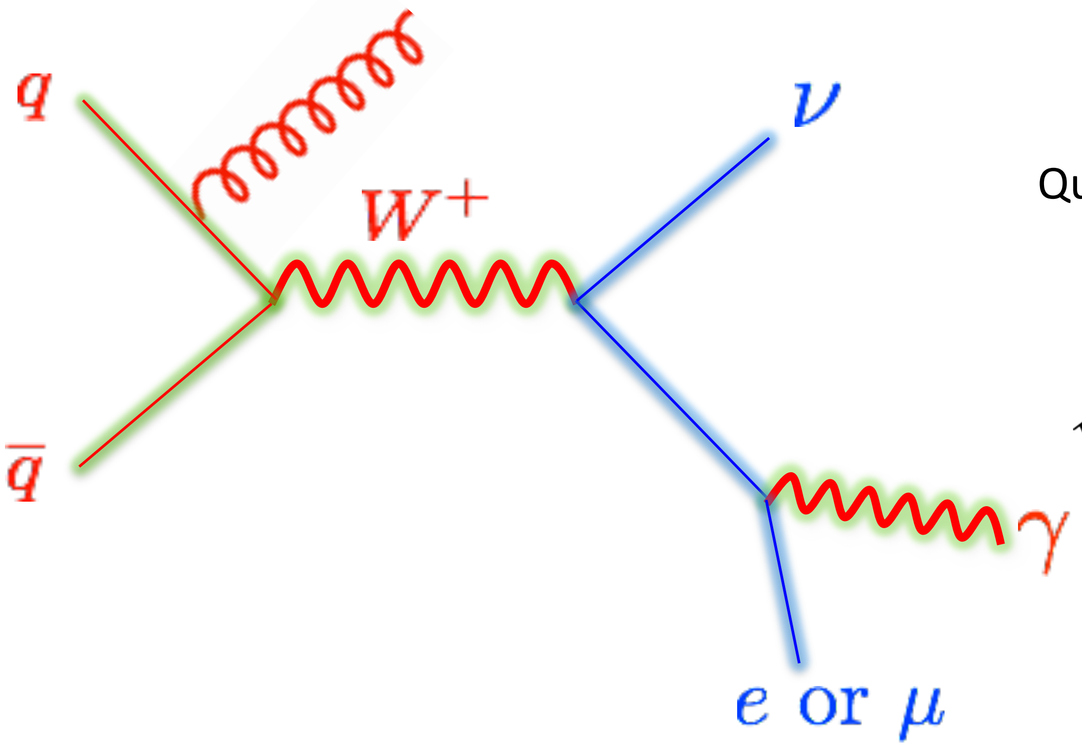


PILEUP/Underlying Event

FINAL STATE QED

MOMENTUM-SCALE
ENERGY-SCALE

Measurement Details



Quarks producing W carry momentum fraction x of parent proton

$$M_W^2 = s x_1 x_2$$

$$\sqrt{s} = 2E_p$$

$$\eta = -\ln\left(\tan\frac{\theta}{2}\right)$$

x values at LHC are much lower and so uncertainties (and shifts) from parton distribution functions are different

Only measure 2-vectors in plane transverse to beam since there is no measured momentum constraint along the colliding beam direction.

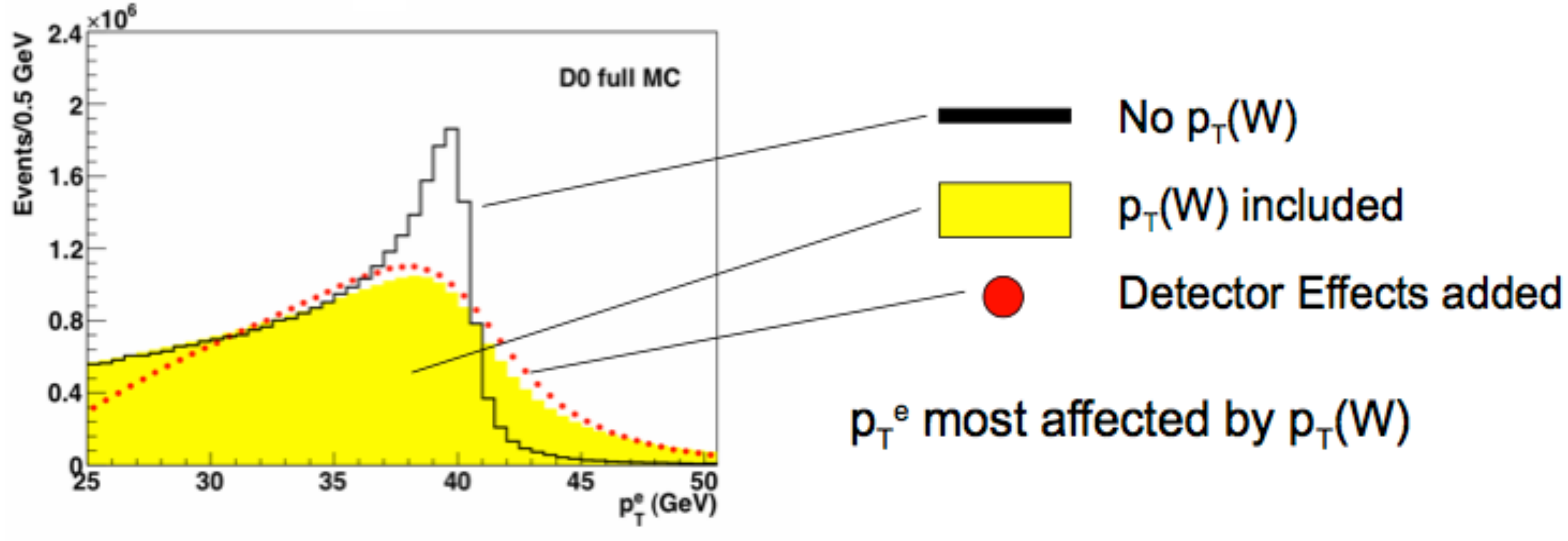
Initial beams have no transverse momentum so p_T is conserved i.e. $\vec{p_T}^{\,l} + \vec{p_T}^{\,\nu} + \vec{p_T}^{\,ISR} + \vec{p_T}^{\,FSR} = 0$

$$\vec{p_T}^{\,\nu} = -\left(\vec{p_T}^{\,l} + \vec{U}\right)$$

We get the W mass by comparing the transverse quantities $p_T{}^{\nu}, p_T{}^{l}, m_T$ with simulation

$$m_T = \sqrt{2 p_T{}^{\nu} p_T{}^{l} (1 - \cos\Delta\phi_{l\nu})} \longleftarrow \textbf{Transverse mass}$$

Transverse Quantities

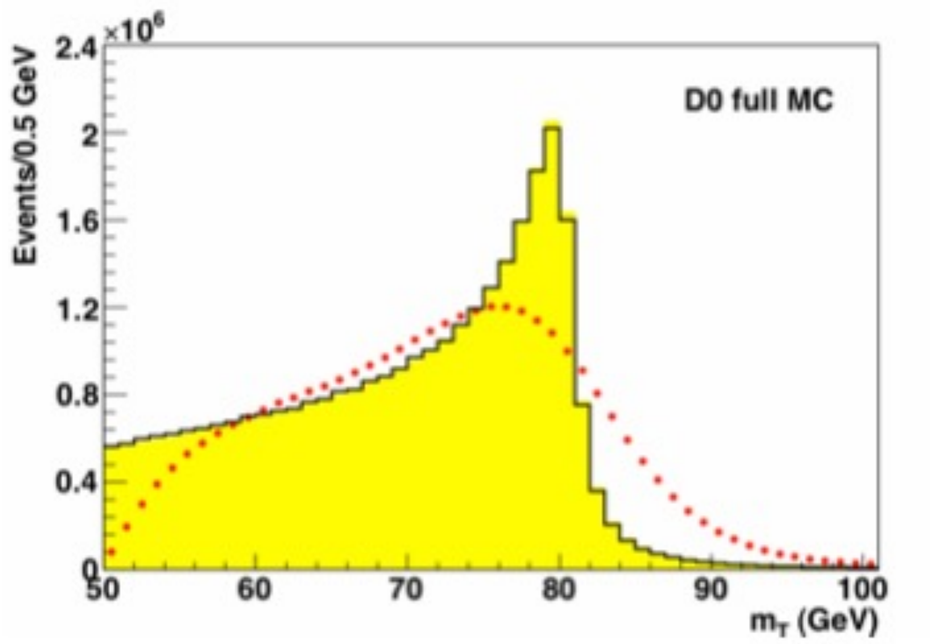


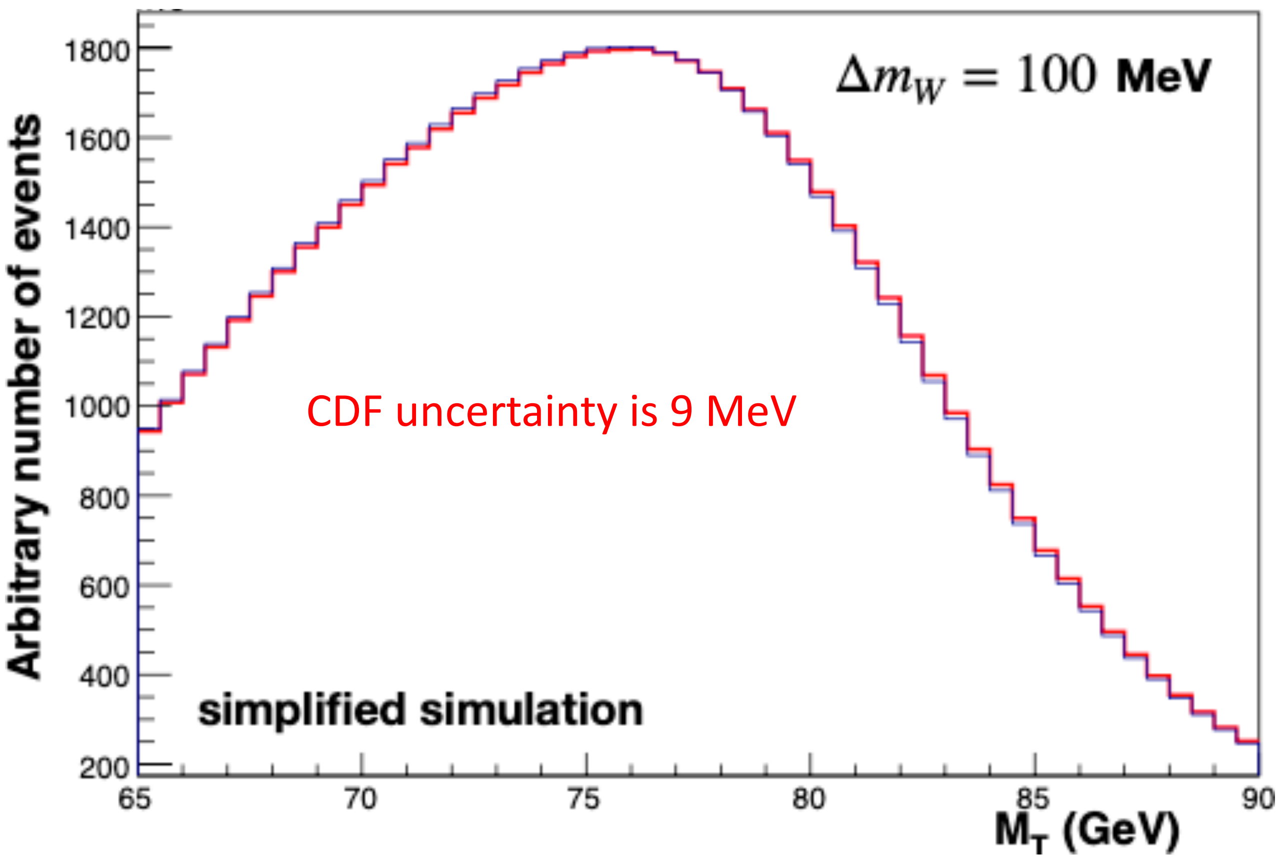
▬ No $p_T(W)$

🟨 $p_T(W)$ included

● Detector Effects added

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

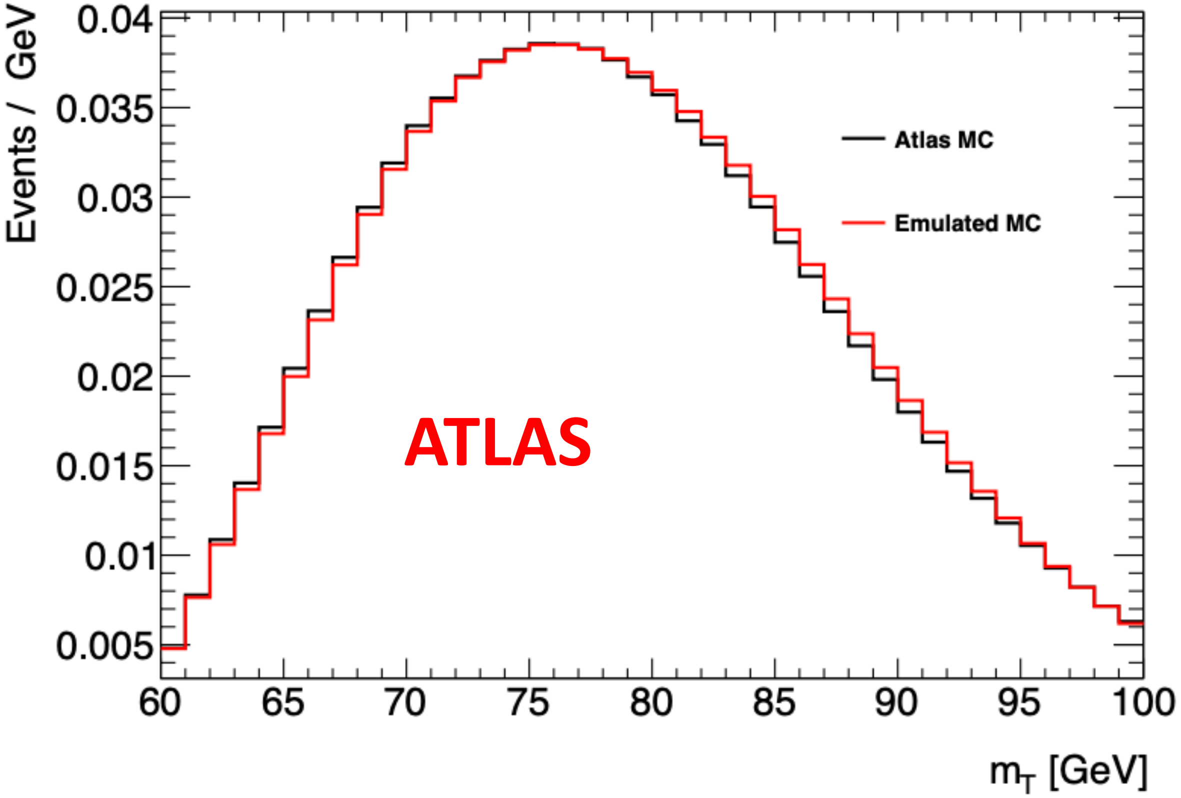


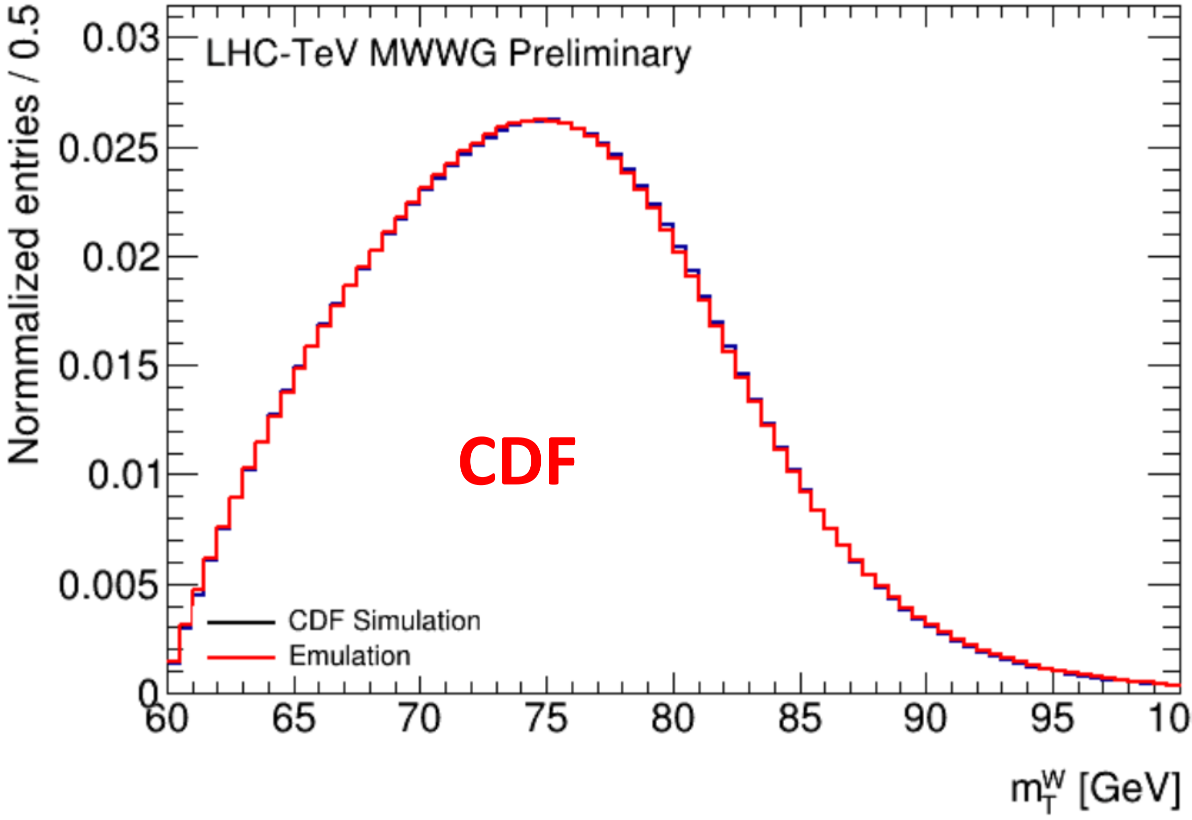


CDF uncertainty is 9 MeV

Transverse Quantities

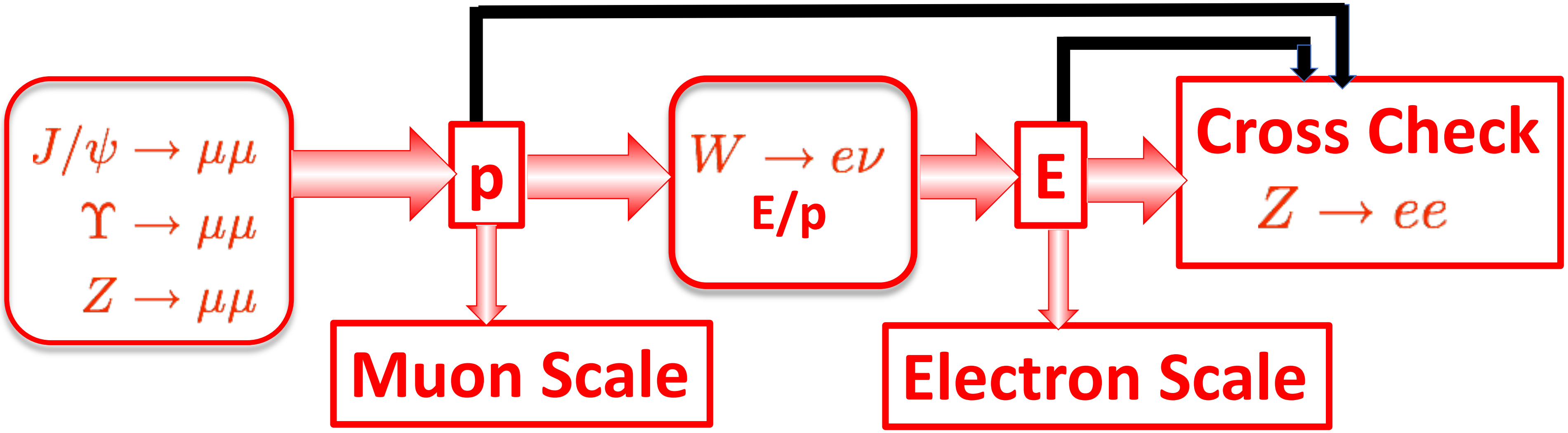
Additional (x5) min bias pile-up interactions mean transverse mass resolution significantly worse at LHC vs Tevatron





To achieve the same statistical precision as CDF/D0 requires x10 the data at LHC.

Setting the energy and momentum scale



$J/\psi \to \mu\mu$

$\Upsilon \to \mu\mu$

$Z \to \mu\mu$

p

Muon Scale

$W \to e\nu$

E/p

E

Electron Scale

Cross Check

$Z \to ee$

ATLAS is the same except it does not use J/Ψ or Υ data at low momentum to constrain non-linearity in the momentum scale instead it uses the vast Z statistics to look at Z mass in different momentum bins. W data is ~ 5 GeV lower in momentum than Z data.

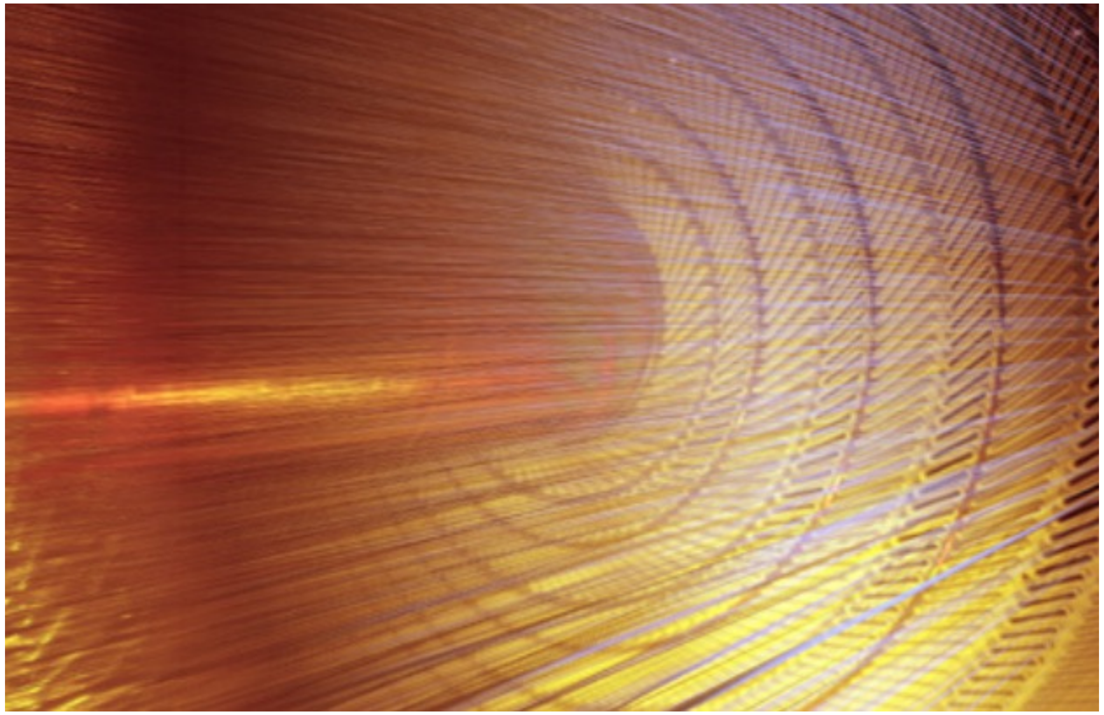
LHCb only uses muons and does it the same as CDF.

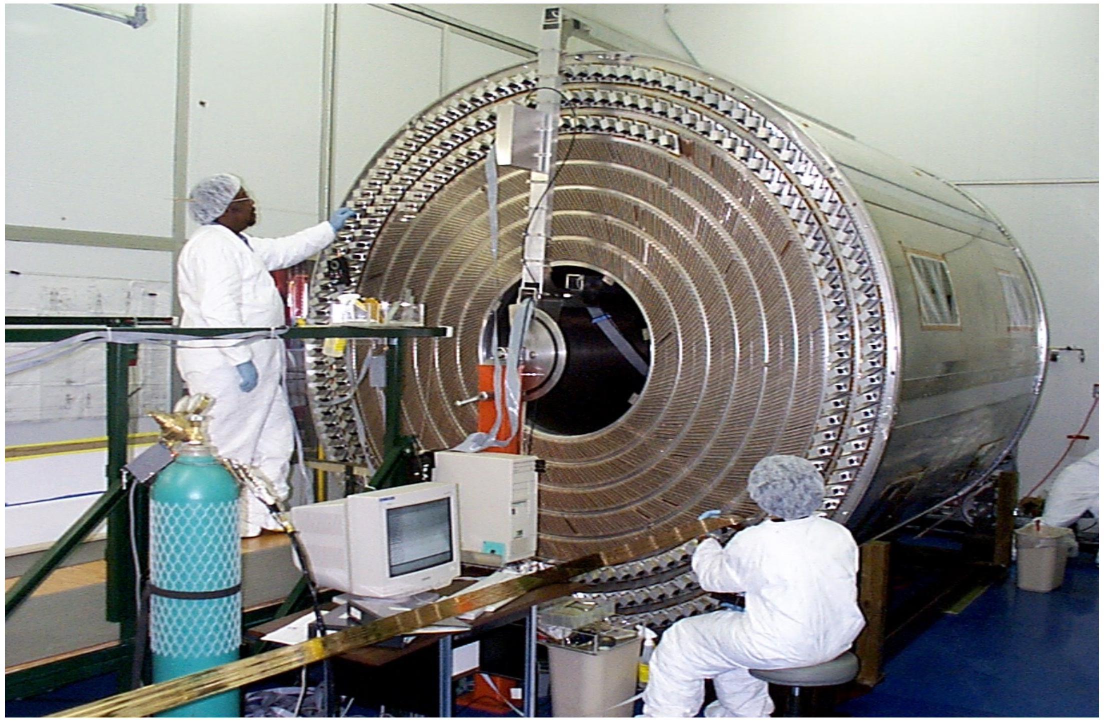
D0 only uses electrons and sets scale only with Z→ ee (no E/p cross-check, no J/Ψ or Υ).

ATLAS and LHCb have better detectors than CDF: better resolution, less leakage.

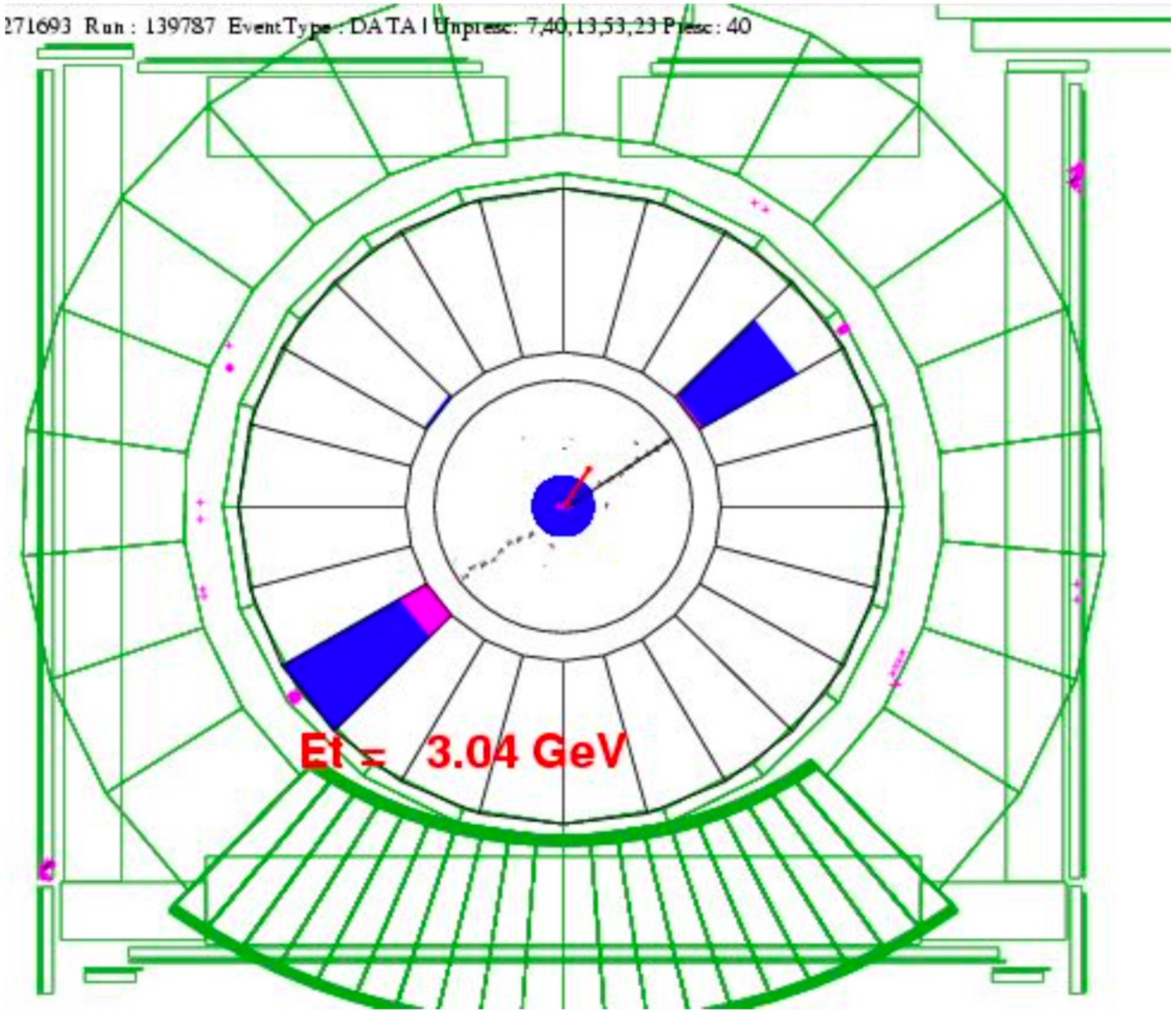
Arguably CDF has the most internal consistency checks in the scale determination

CDF: Momentum Scale



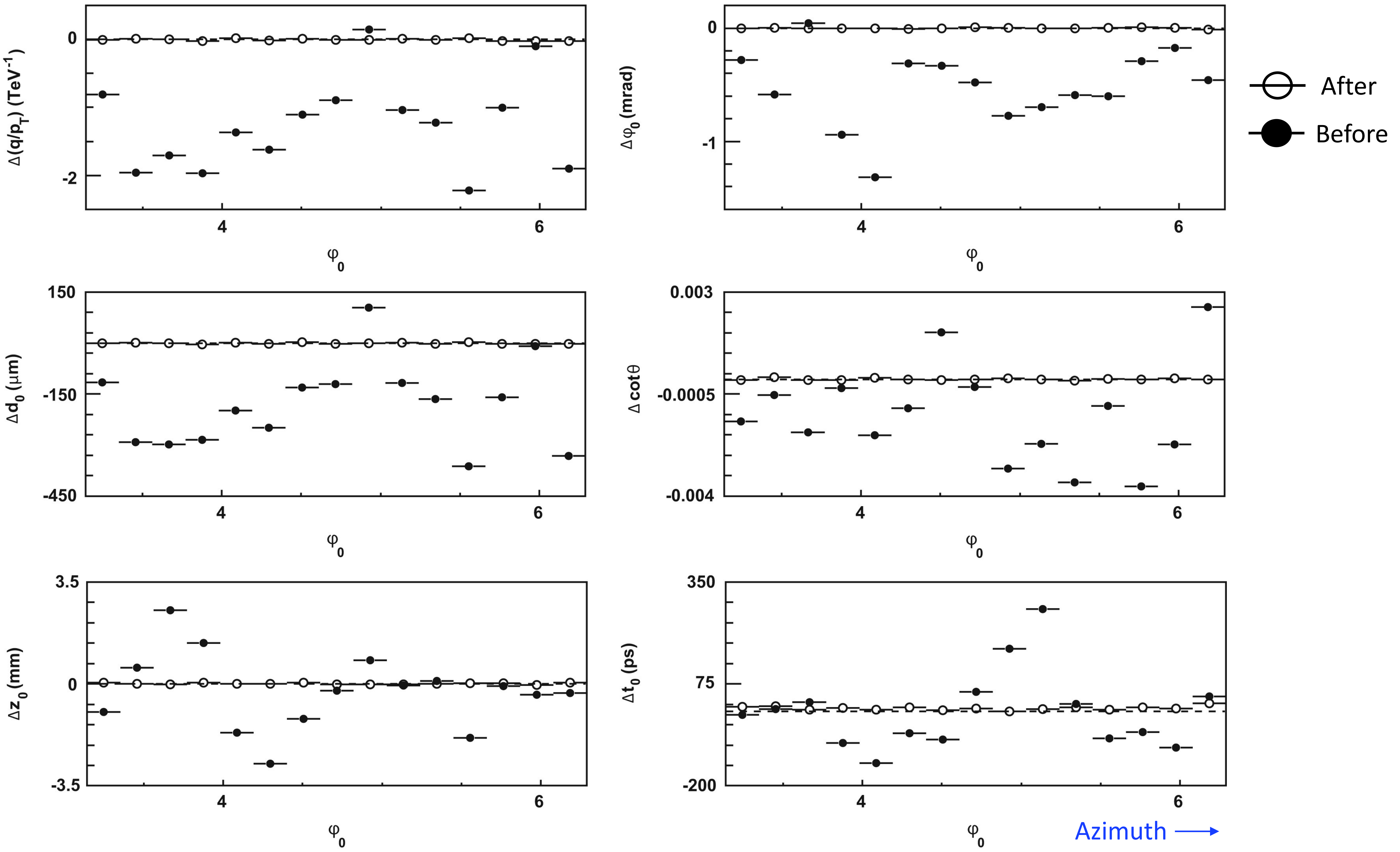


Years of work to calibrate and align the drift chamber and remove biases due to gravity, twists, bends ….



0.5M cosmics

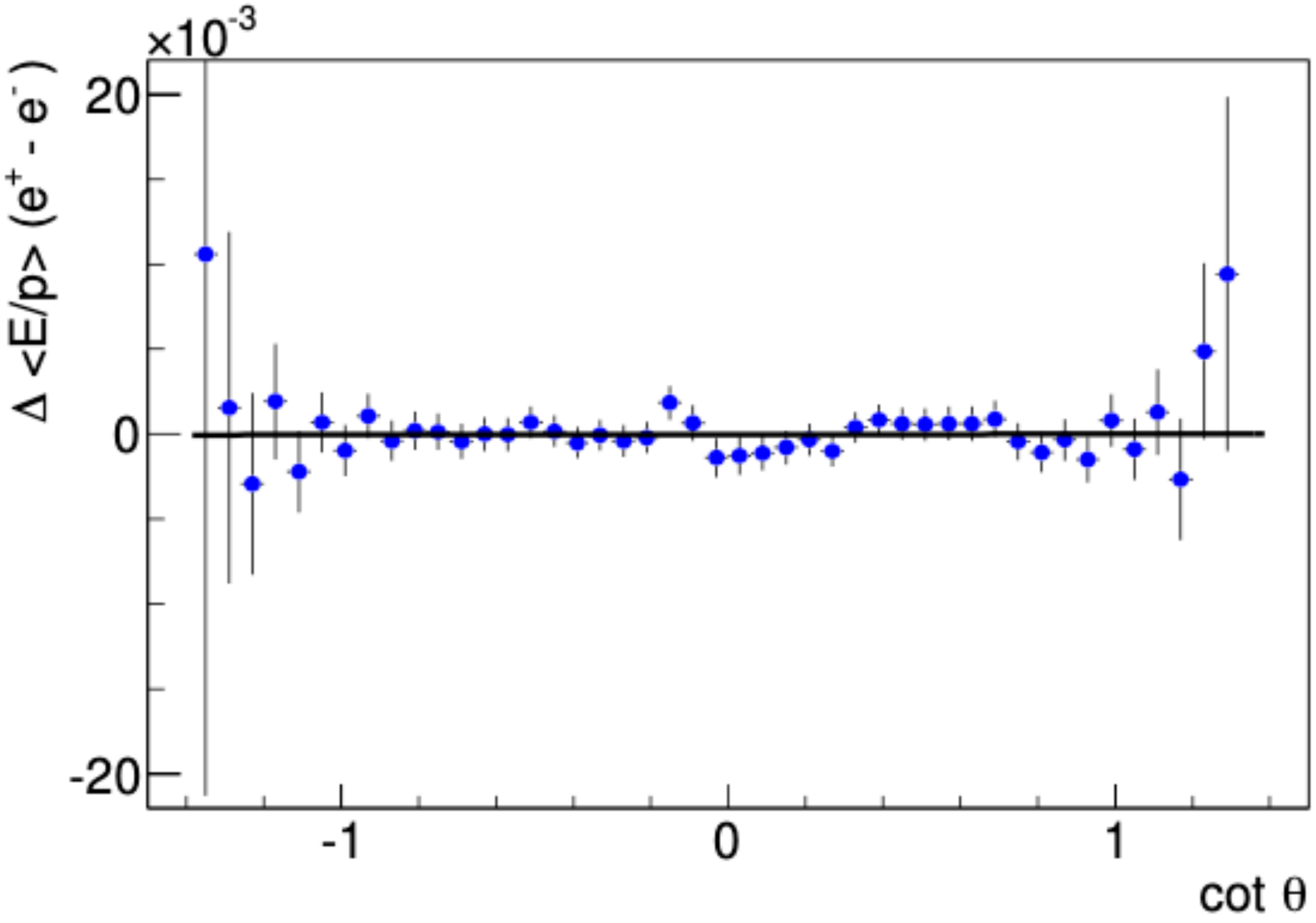
CDF: Momentum Scale

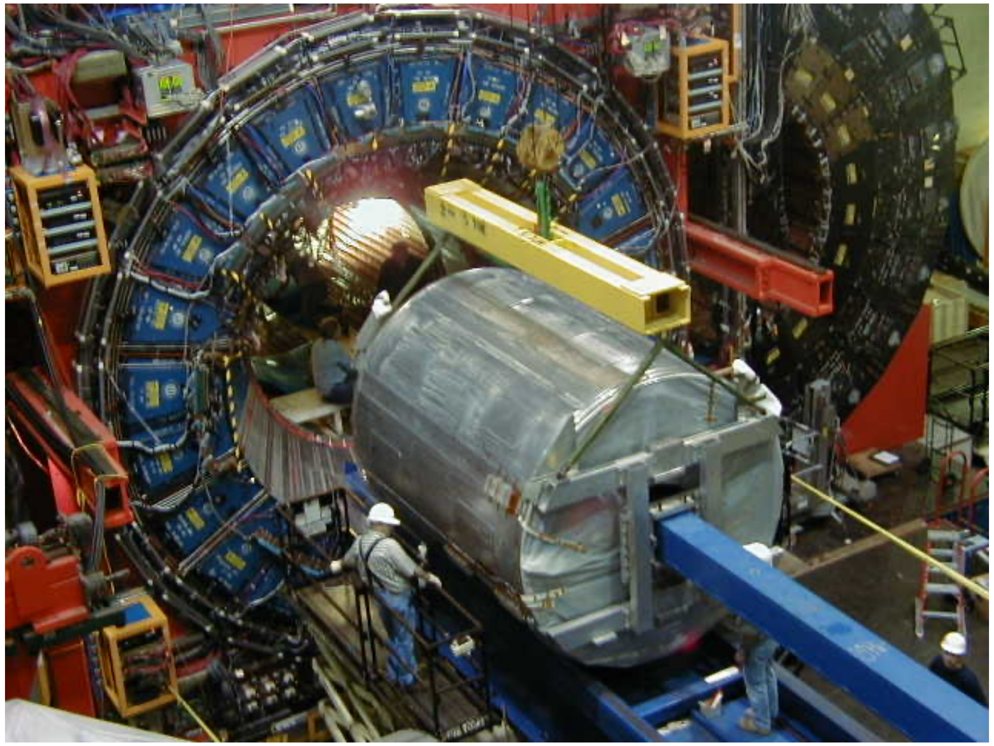


Azimuth →

CDF: Momentum Scale

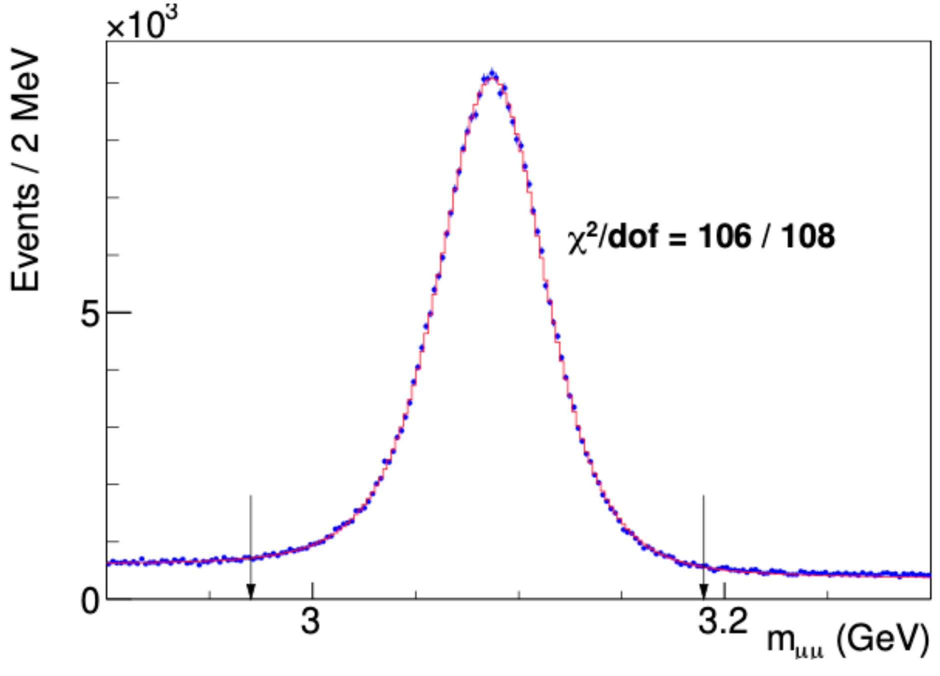
After corrections no evidence of “false curvatures”

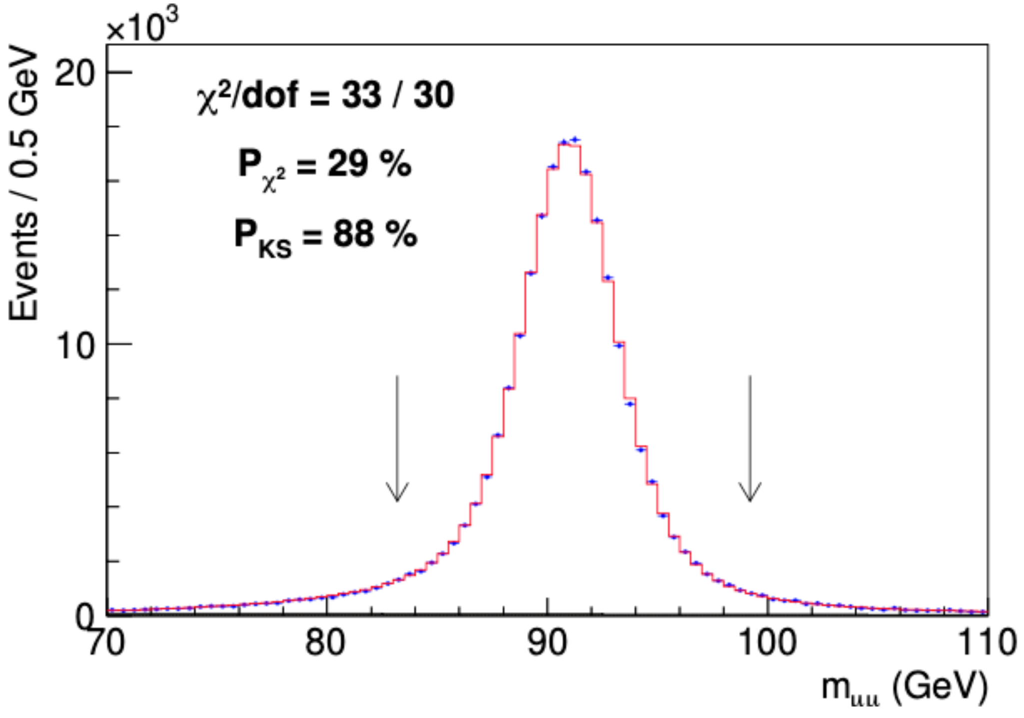




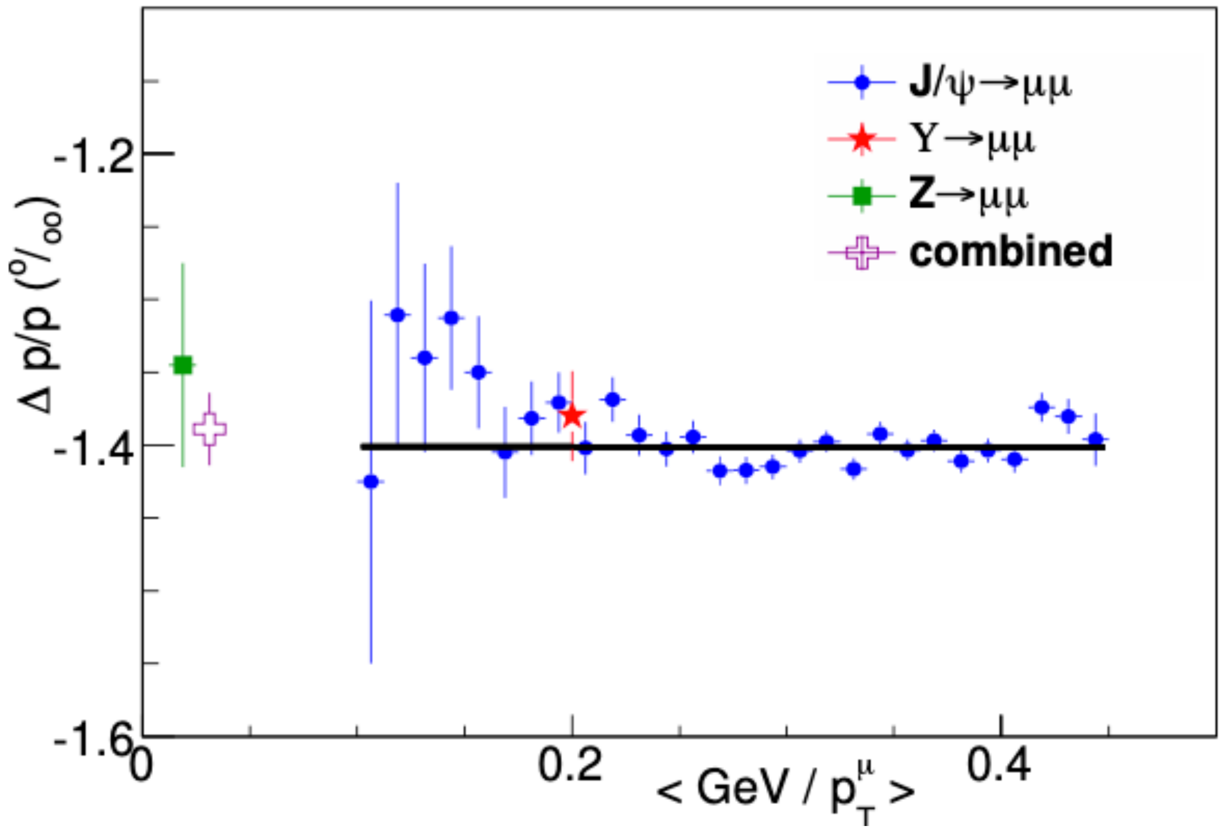
Azimuth ⟶

CDF: Momentum Scale



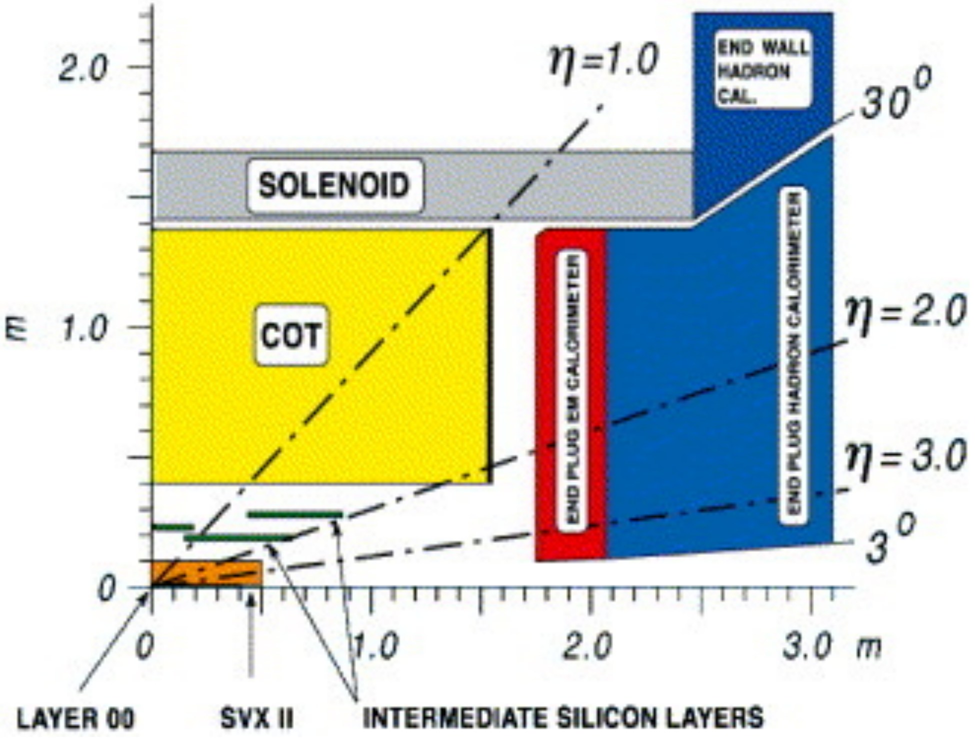


Z mass result was blinded until p-scale (and E-scale) analyses completed

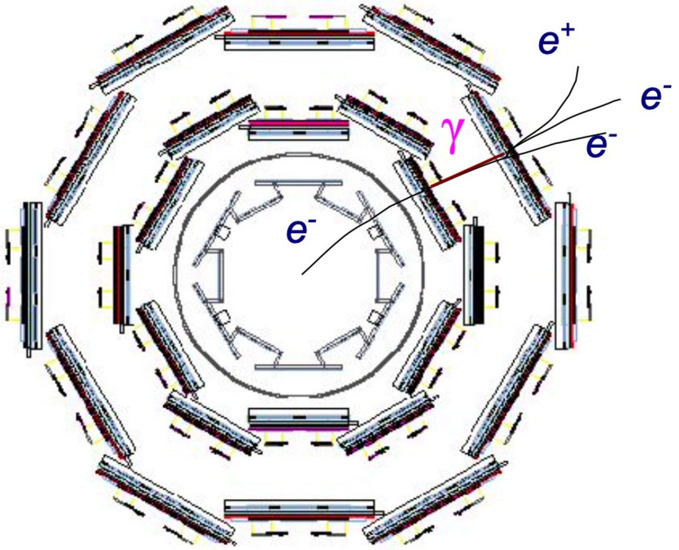


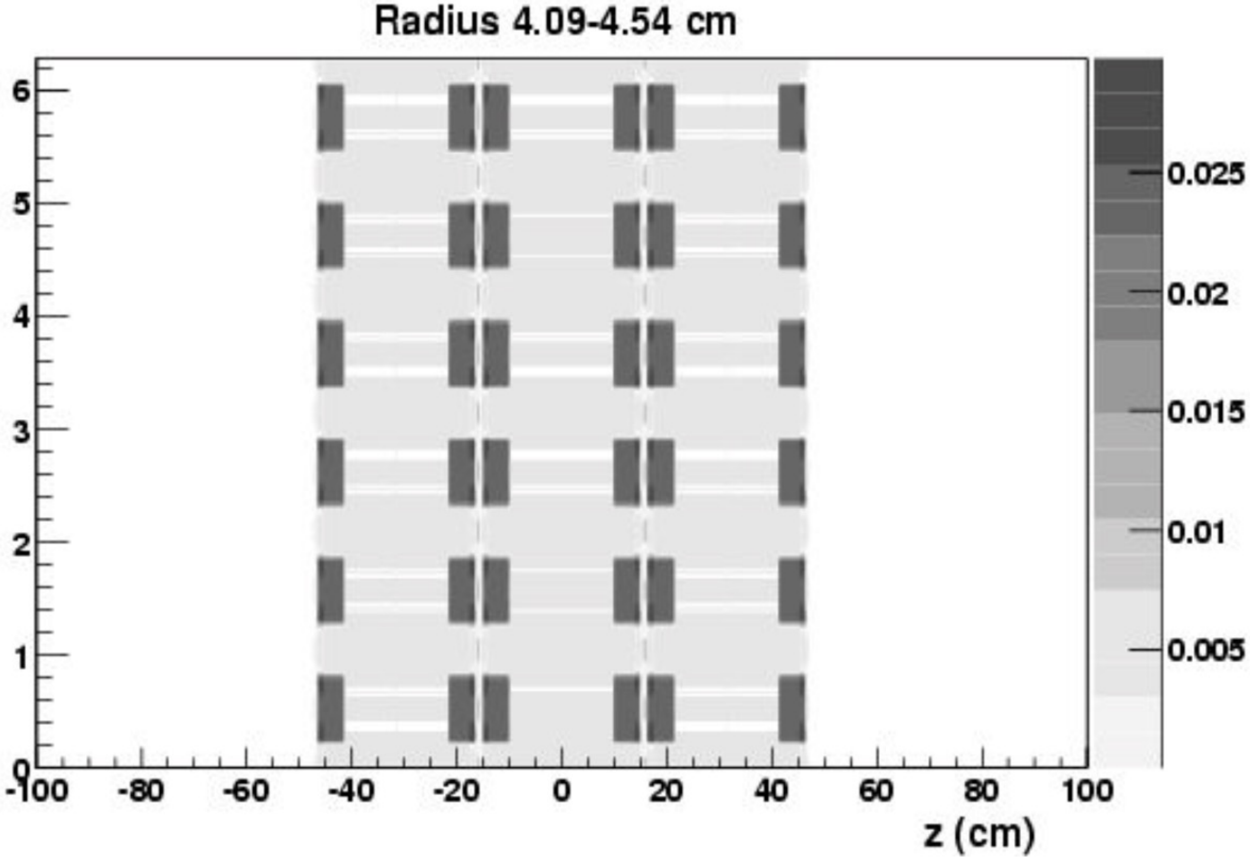
$M_Z - M_Z$ (LEP) = 4.5 ± 6.4 (stat) ± 2.3 (mom) ± 3.1 (QED) ± 1 (alignment) MeV

CDF: Energy Scale

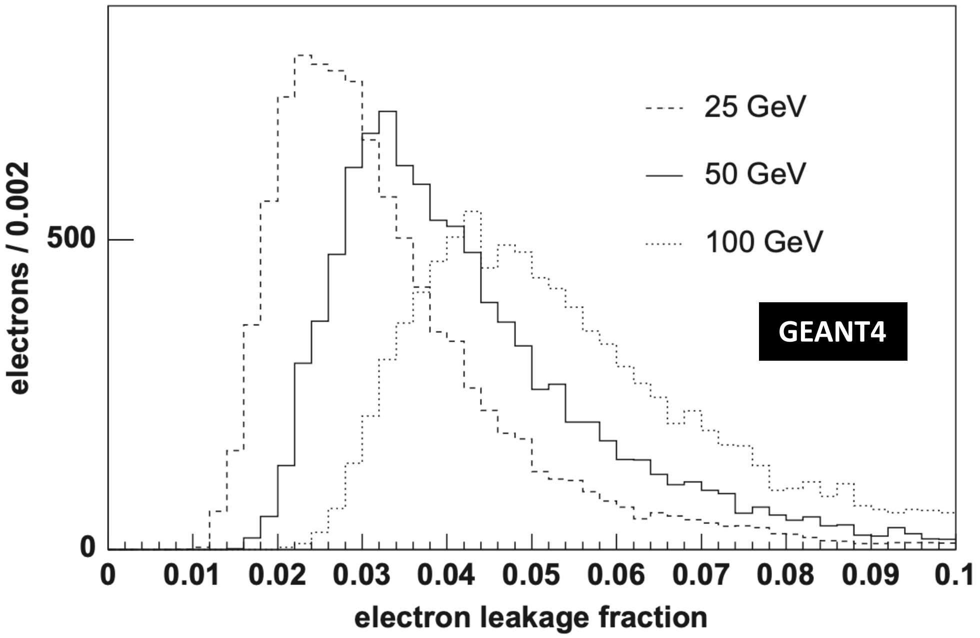


Done via E/p which requires detailed model of mass and Z of all passive material prior to calorimeter

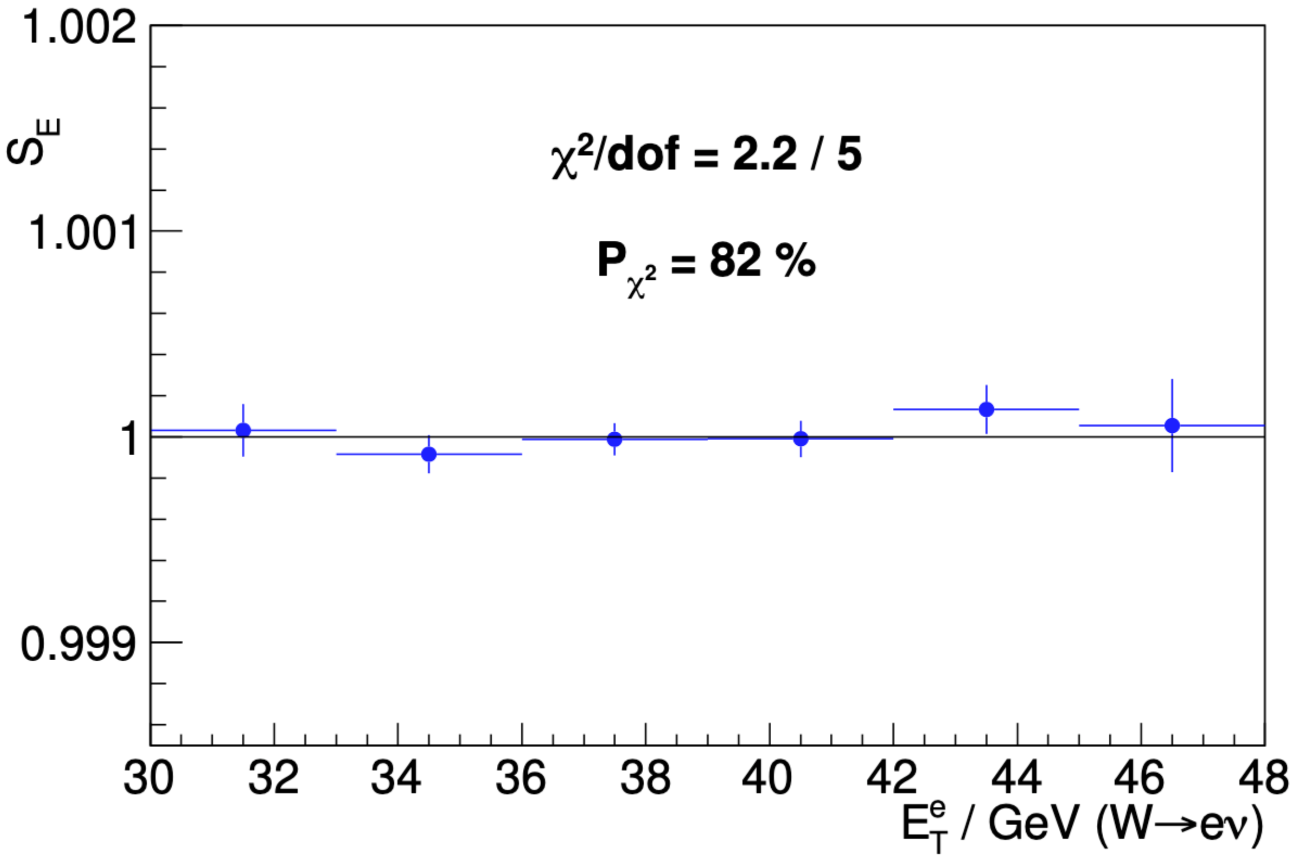


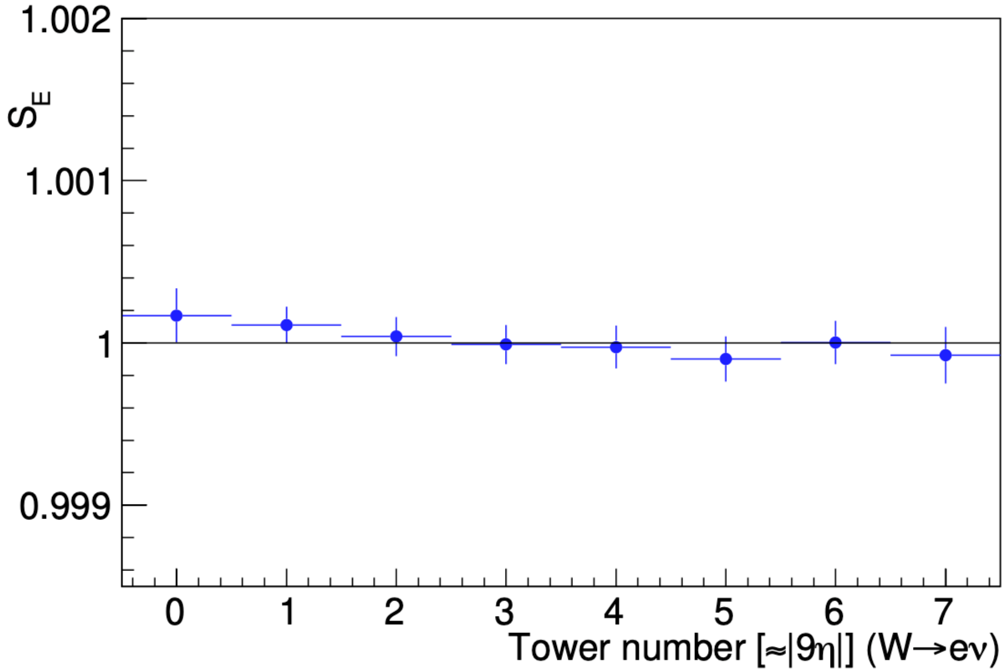


CDF: Energy Scale



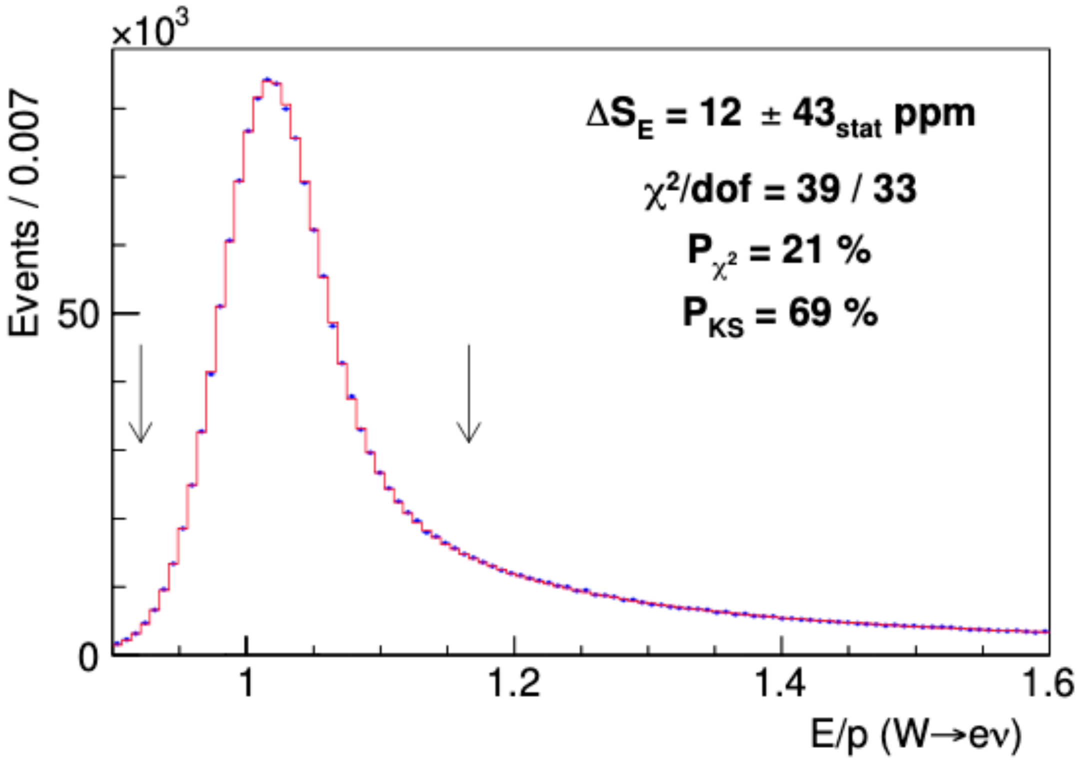
Also need to model
- shower leakage
- QED effects (incl LPM suppression)
- detector response

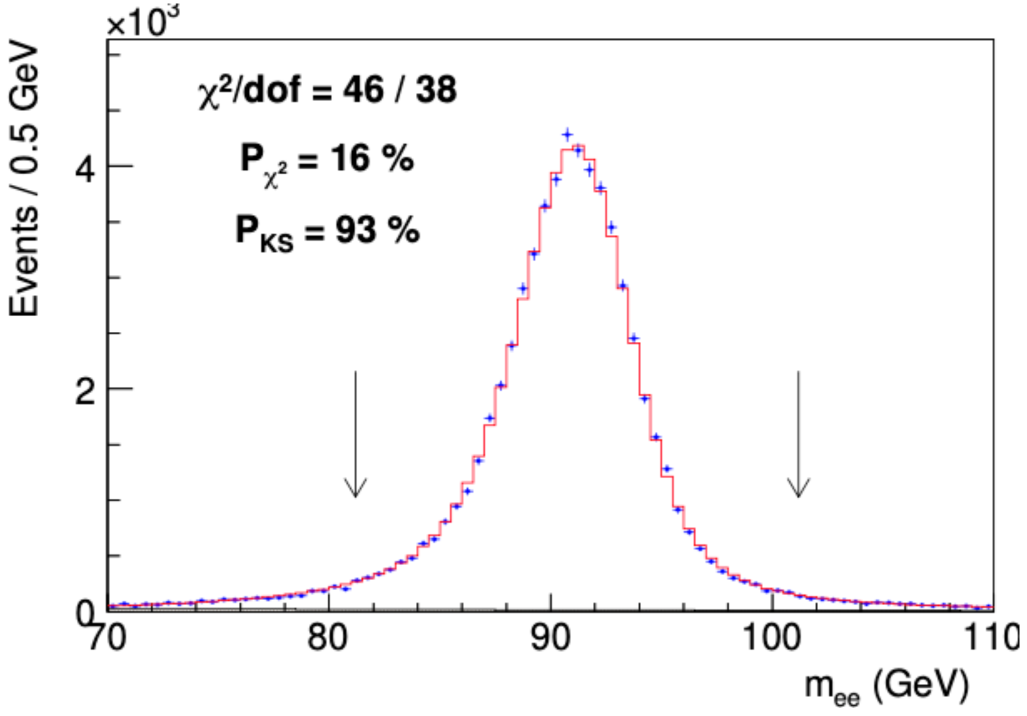




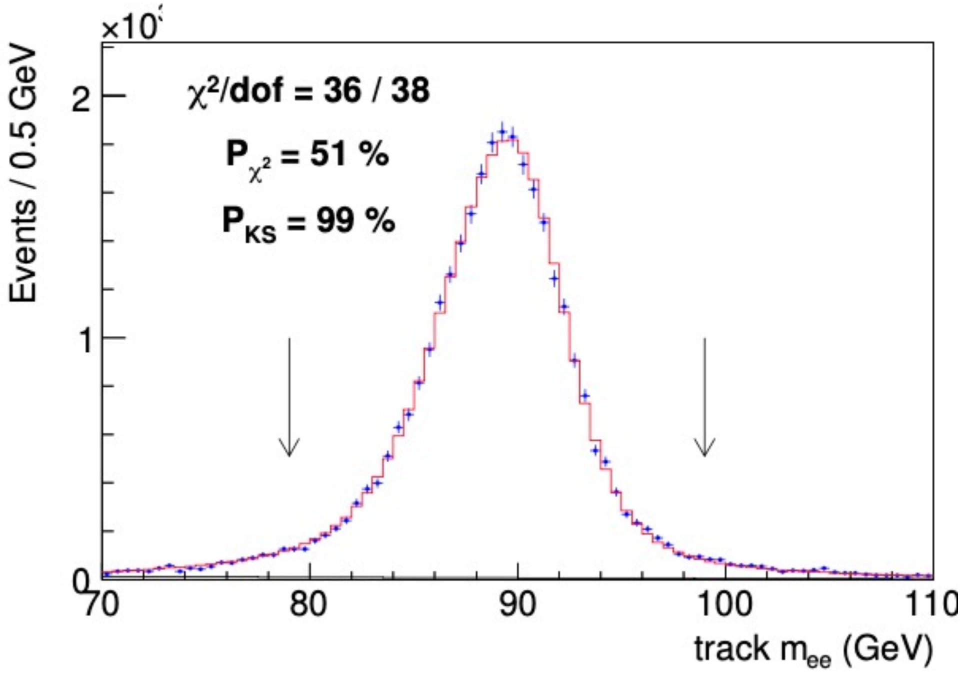
CDF: Energy Scale

$M_Z - M_Z\,(\mathrm{LEP}) = 6.8 \pm 13.8\,(\mathrm{stat}) \pm 7.6\,(\mathrm{sys})\ \mathrm{MeV}$





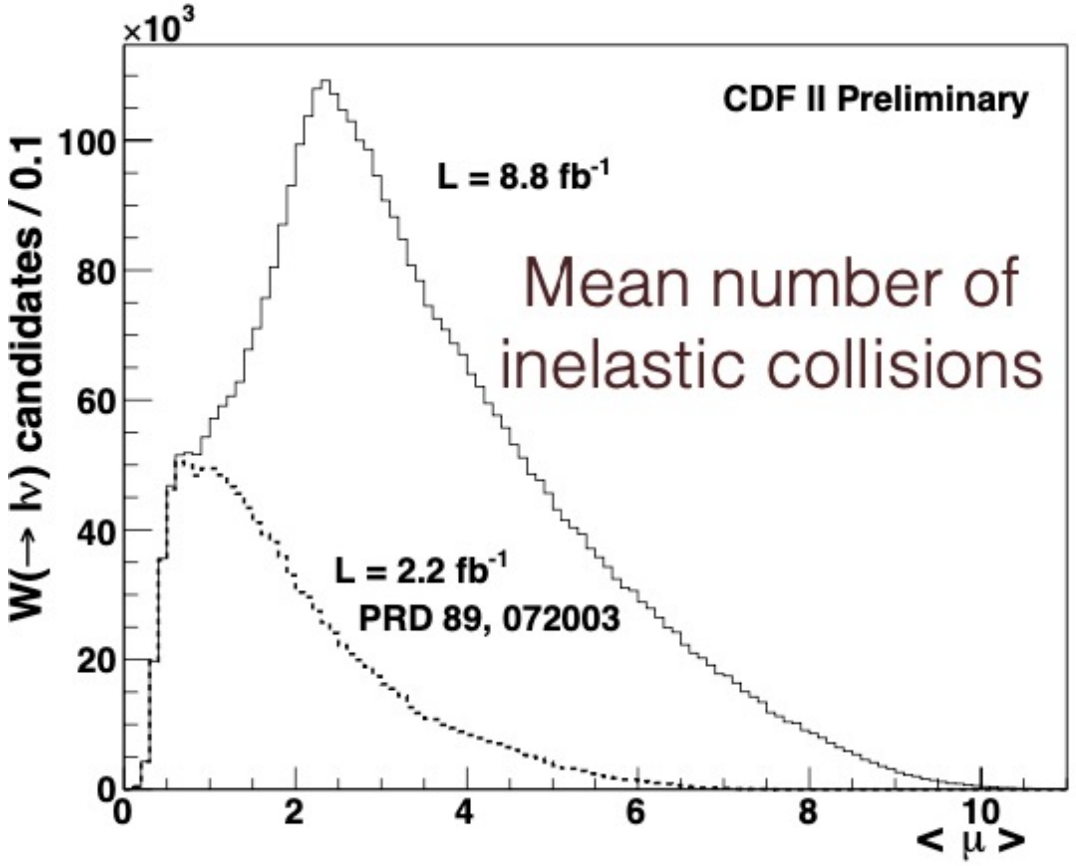
Z mass from electron-E

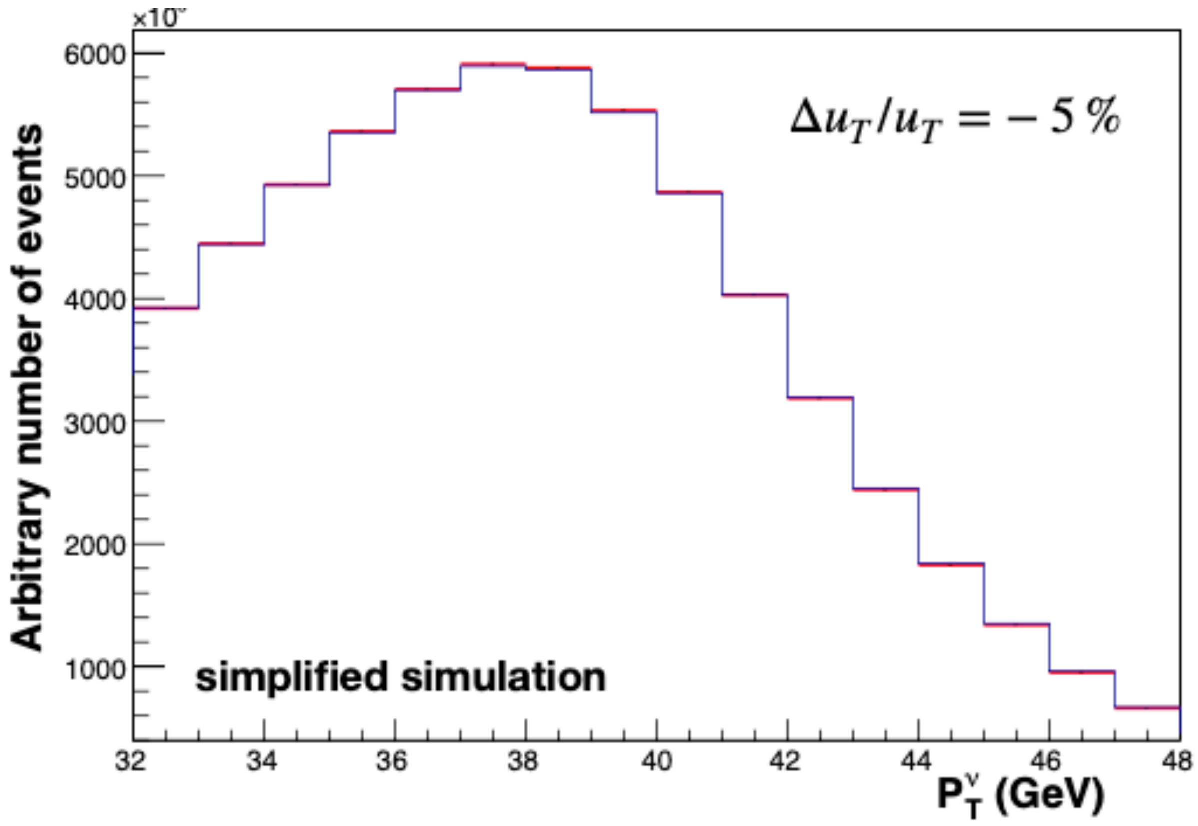


Z mass from electron-p (for E/p < 1.1)

CDF: Recoil/ Underlying Event Scale

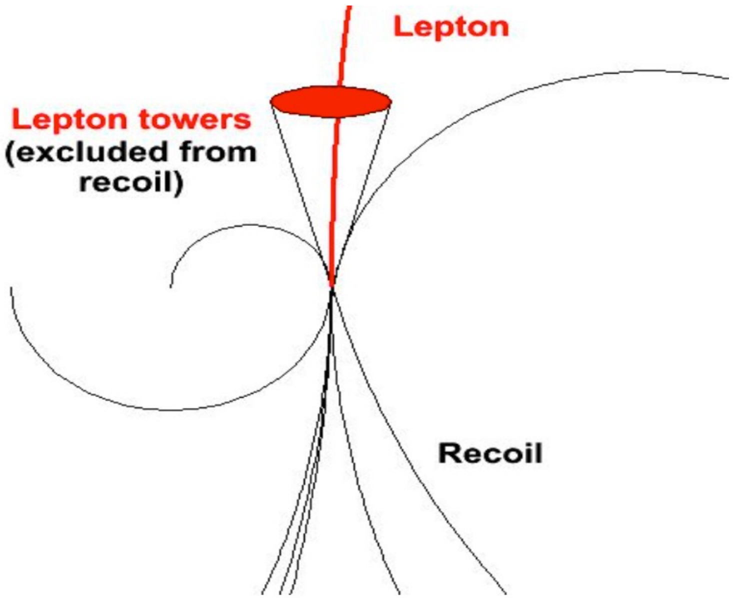
Unlike momentum and energy scale calibration that needs to be good to 0.01% the calibration of the non electron/muon part of the event i.e. initial state QCD radiation, underlying event energy (from additional interactions) only needs to be good to 0.5% or so



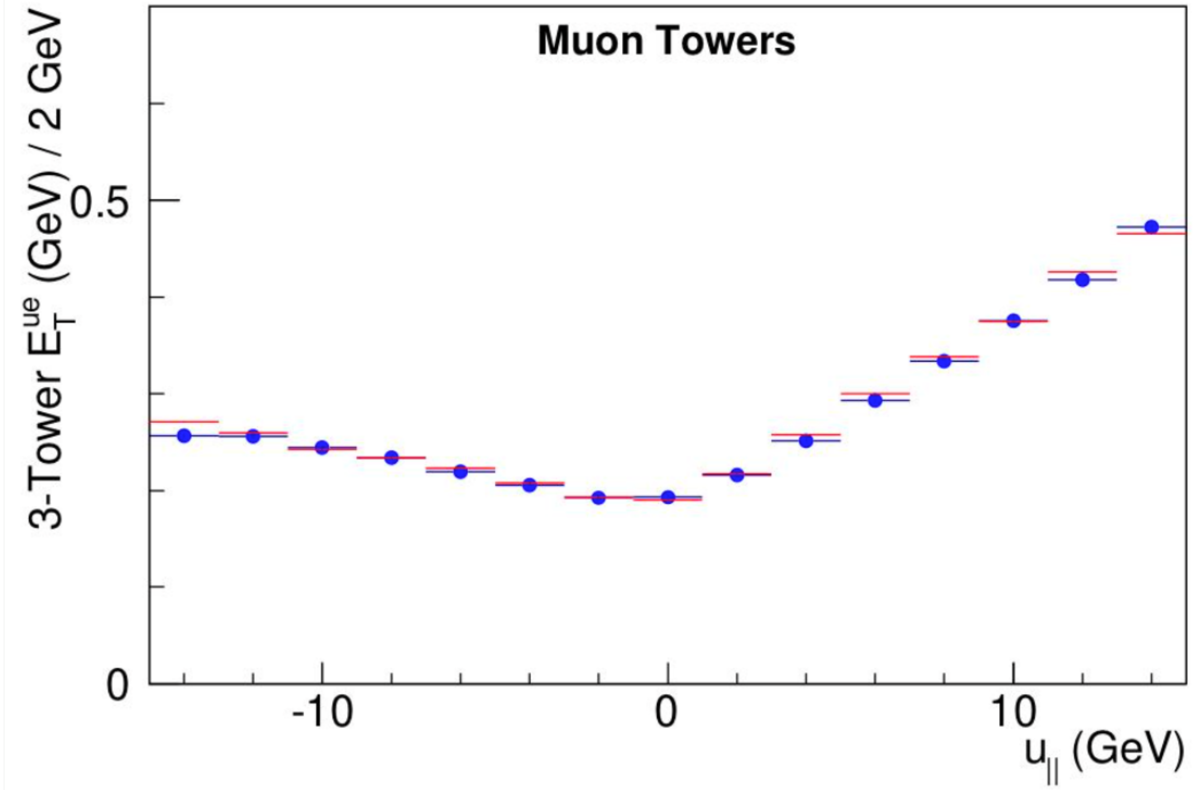


At ATLAS/CMS the mean number of inelastic collisions was ~ x5 that of CDF/D0

CDF: Recoil/ Underlying Event Scale



Calorimeter towers with lepton are removed from recoil sum and correction for underlying energy removed is made.

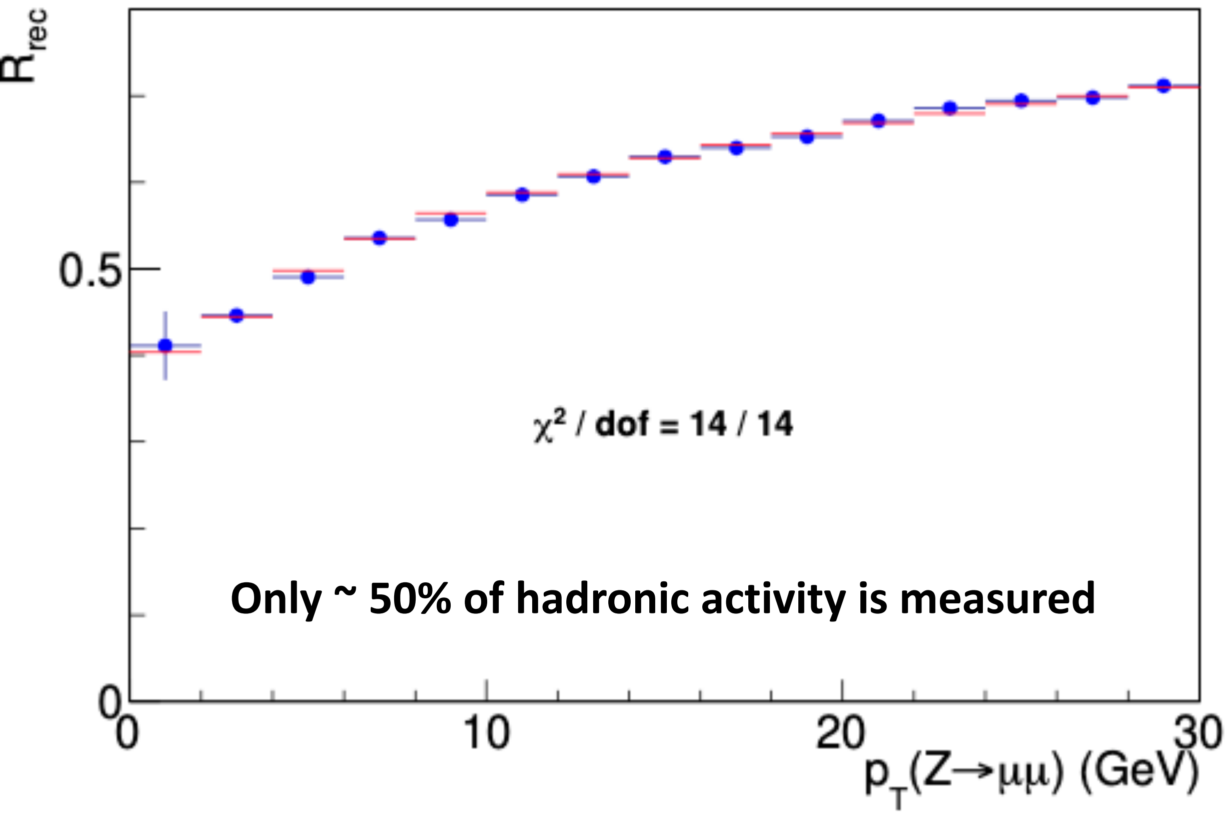


Calorimeter alignment is important

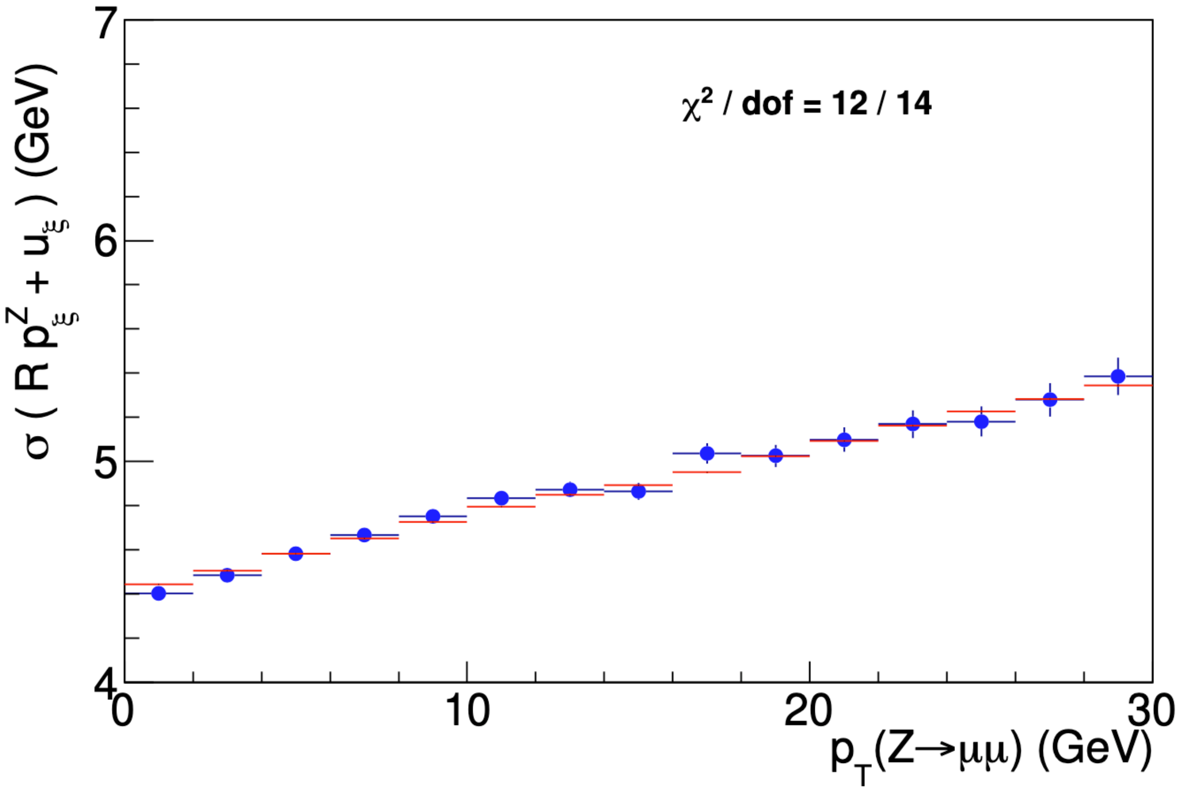
QCD ISR, underlying event is calibrated on Z events (as a function of p_T of the Z)

The model to do this ad-hoc: D0, ATLAS, LHCb do the same.

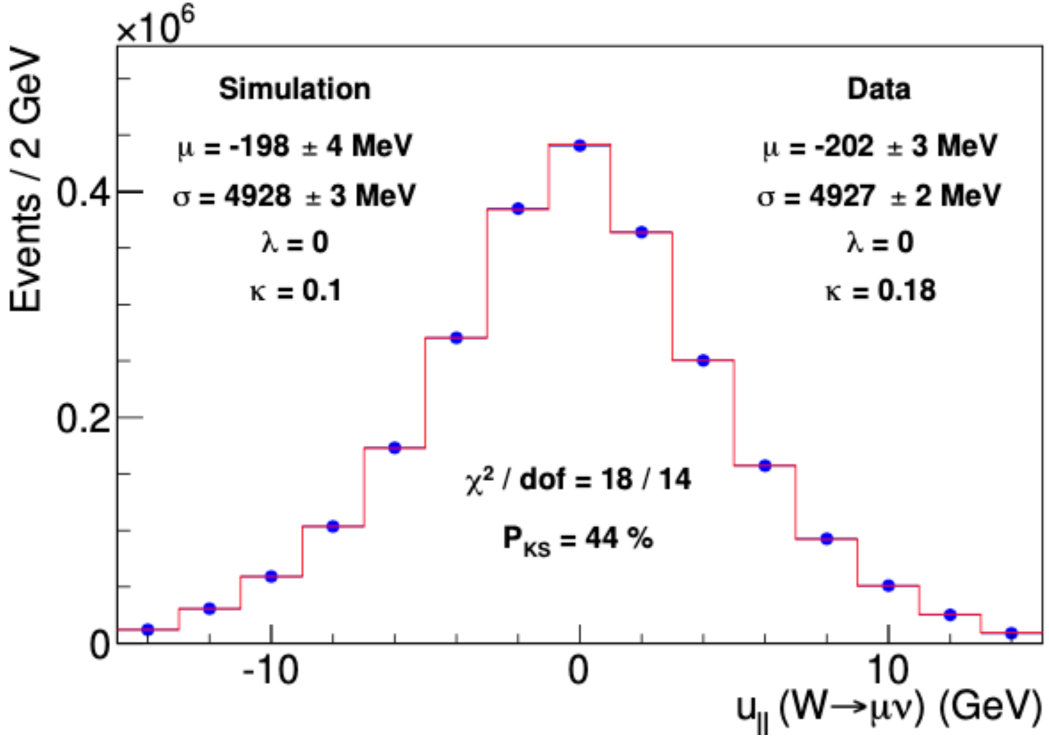
CDF: Recoil / Underlying Event Scale

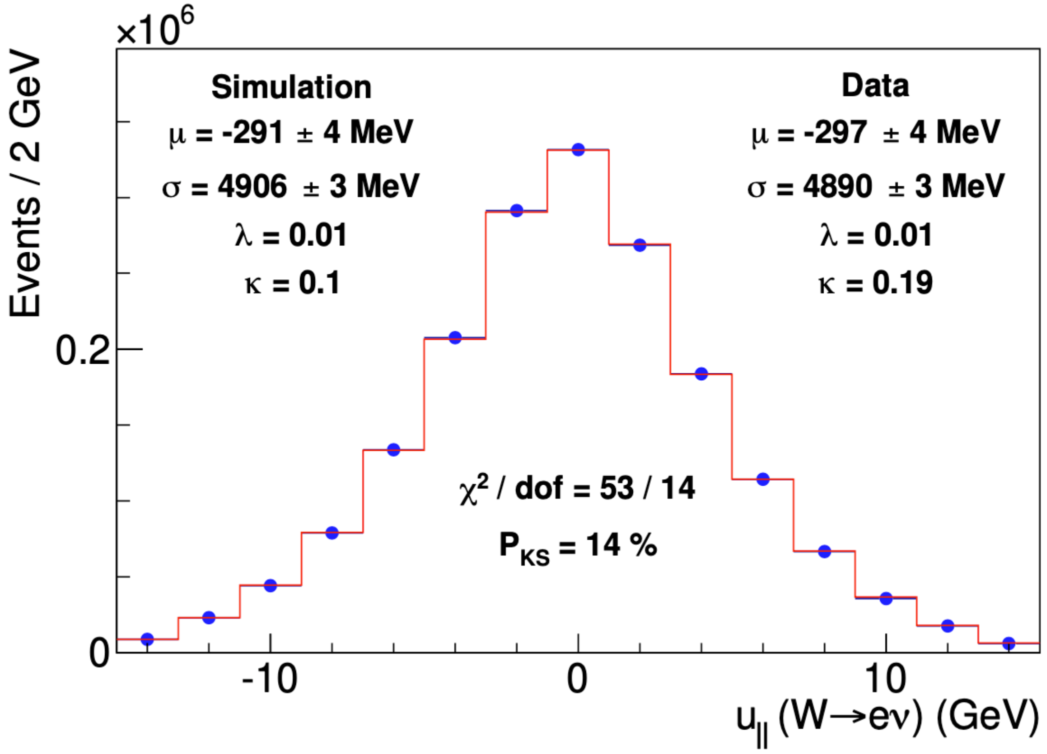


Only ~ 50% of hadronic activity is measured

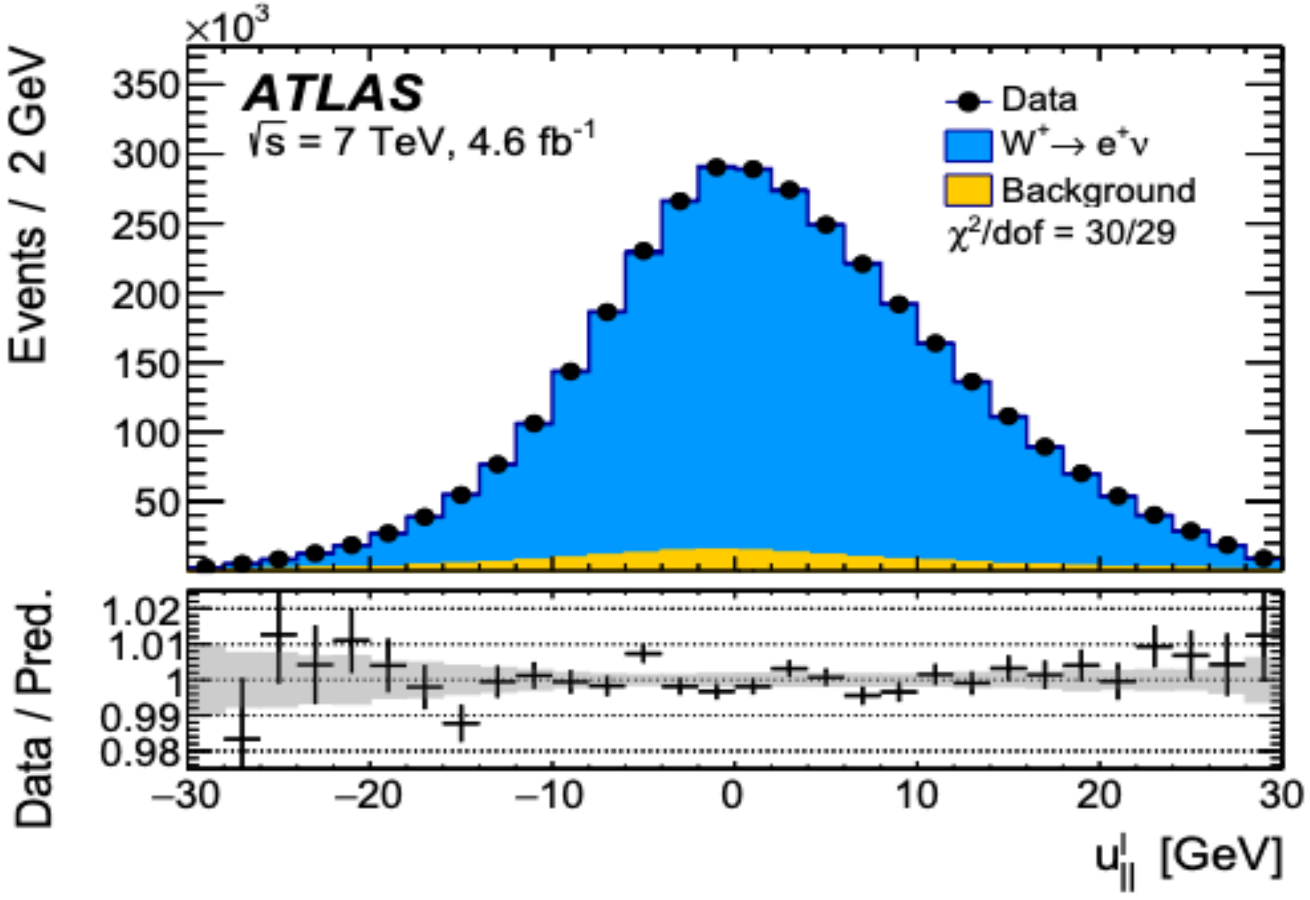


CDF: Recoil / Underlying Event Scale

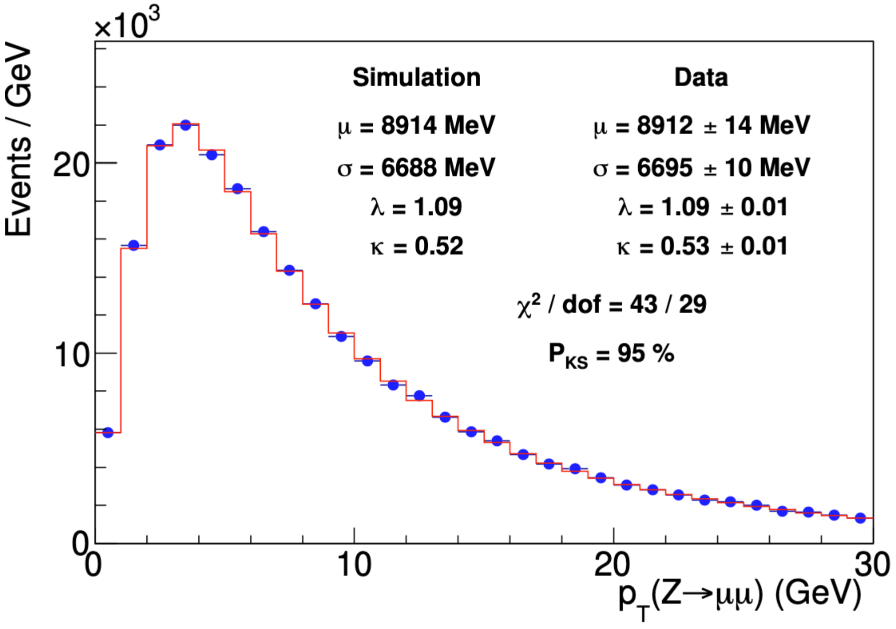


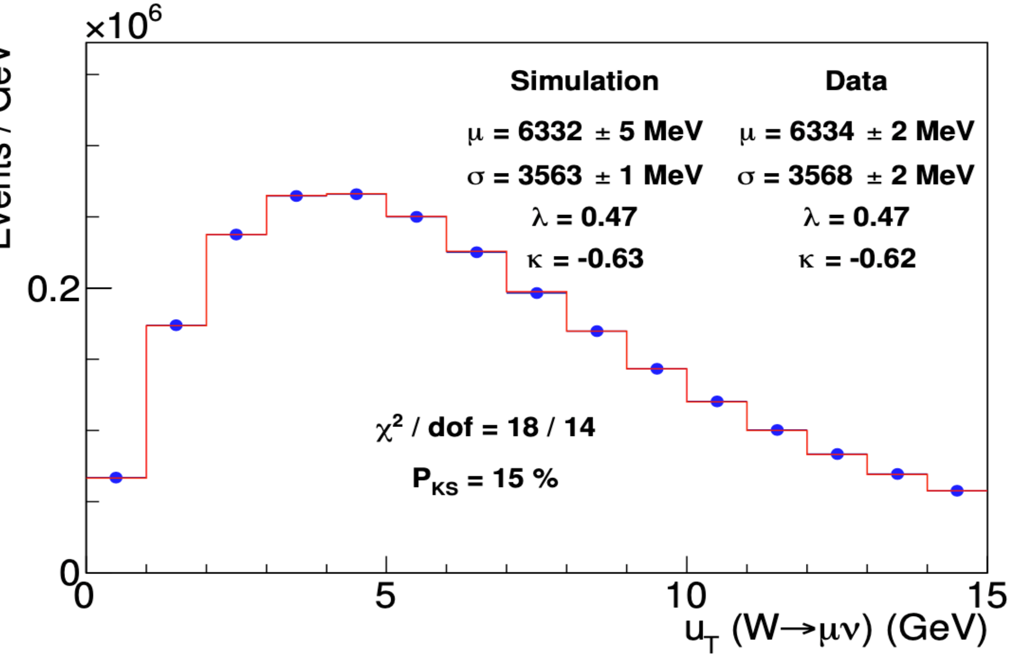


$$m_T \approx 2p_T^l + u_{||}$$



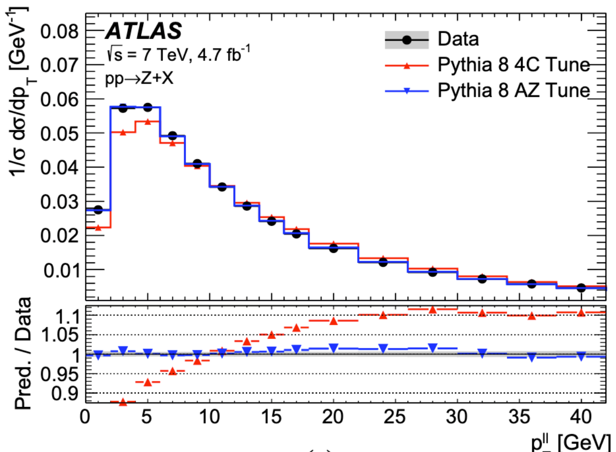
CDF: Recoil / Underlying Event Scale



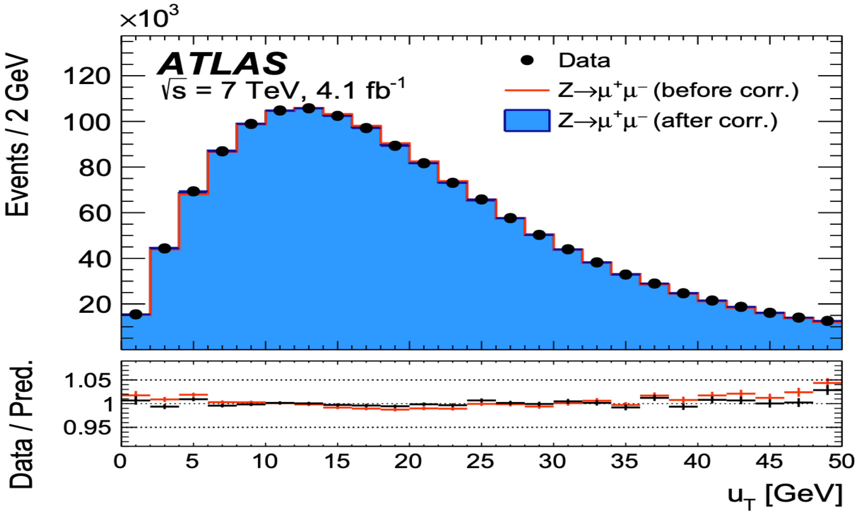


p_T of the W (and Z) boson has significant contribution from low-momentum radiation only modelled via an ad-hoc non-perturbative contribution and a QCD NNLL resummation.

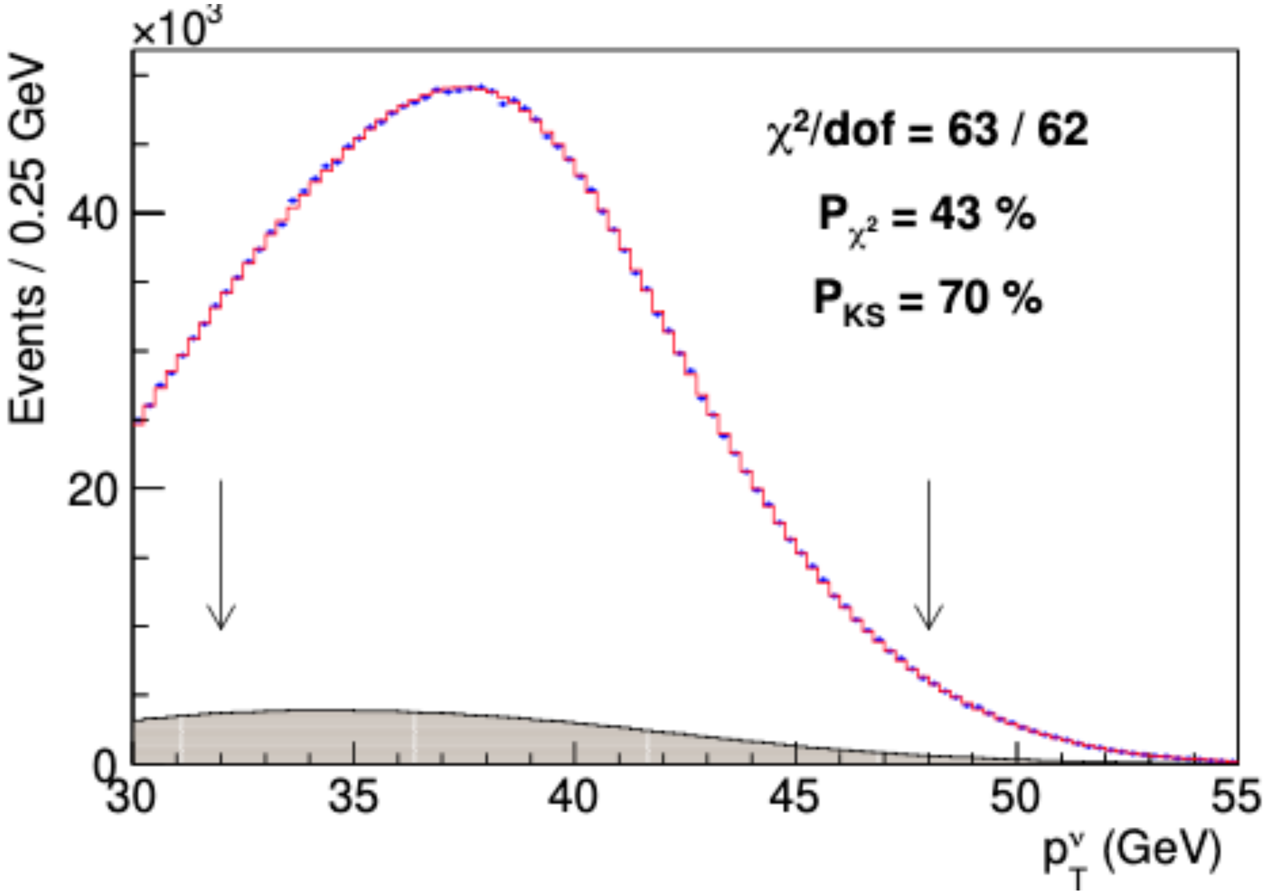
CDF/D0: PYTHIA/RESBOS,
ATLAS: PYTHIA/DYNNLO/POWHEG/MiNNLO$_{PS}$
LHCb: PYTHIA/POWHEG/DYTurbo



(a)



CDF: Recoil / Underlying Event Scale

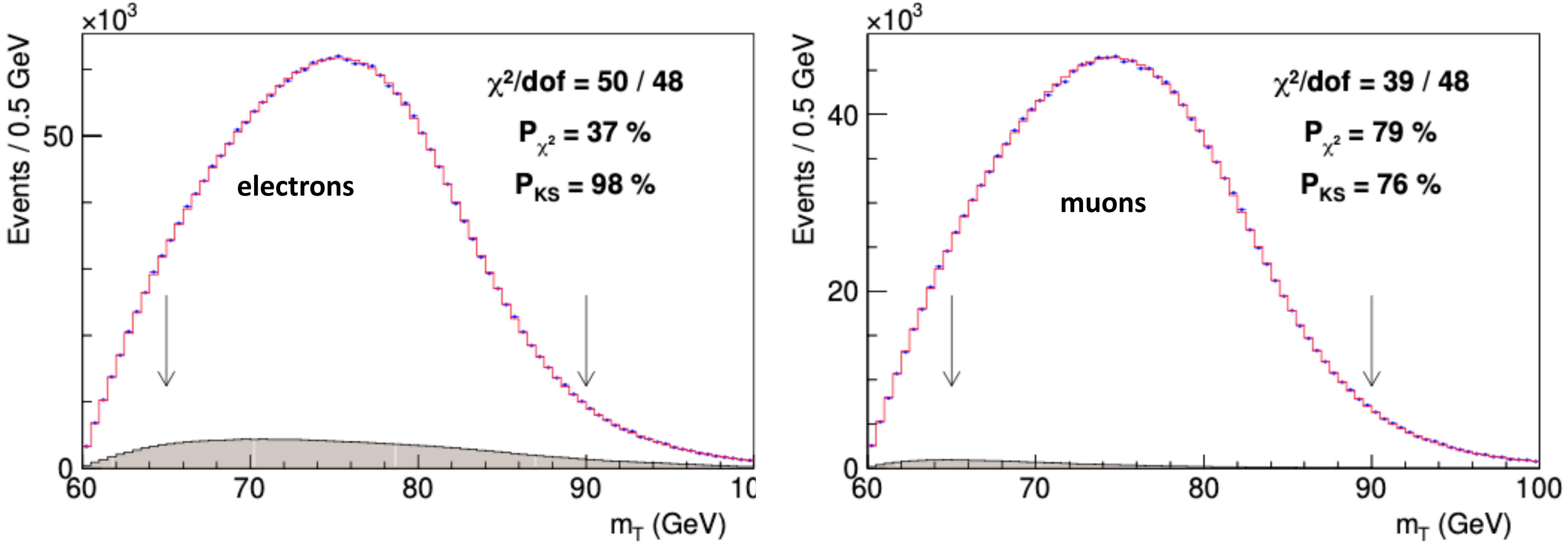


Mw = 80428 ± 14 MeV

Determination from transverse mass and lepton p_T is more precise : 10 MeV and 12 MeV and very correlated

CDF: Transverse Mass Fits

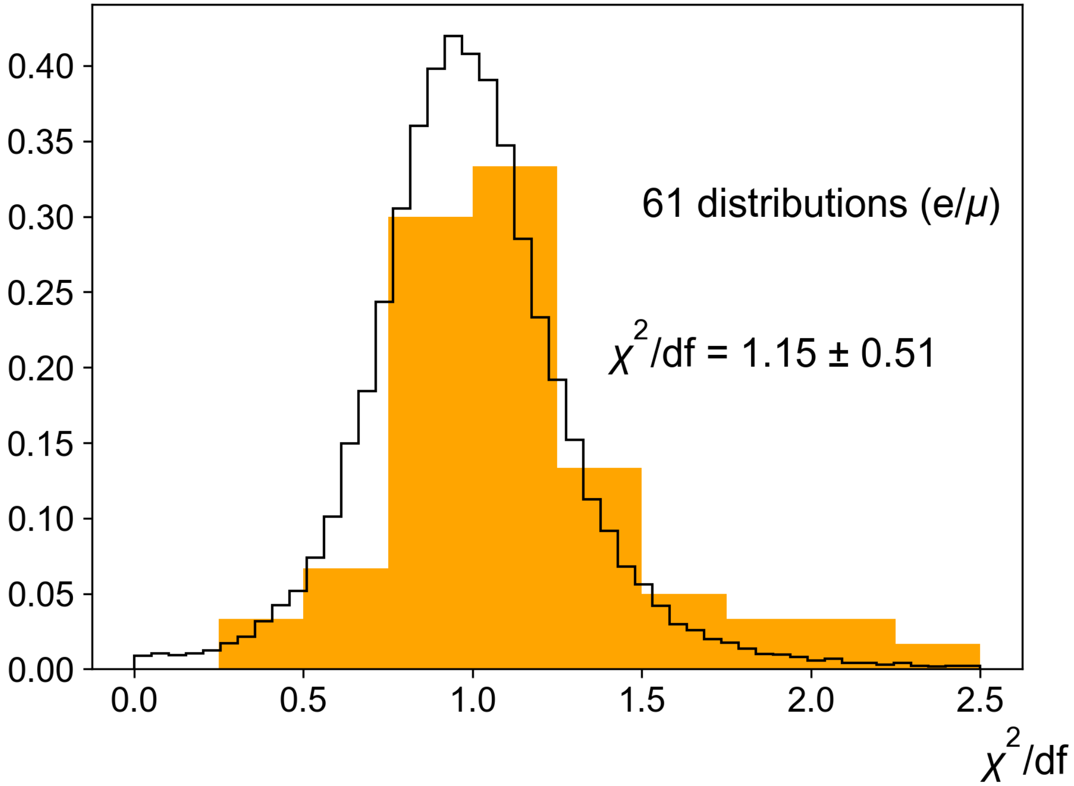
These fits were done with a blinded Mw offset.



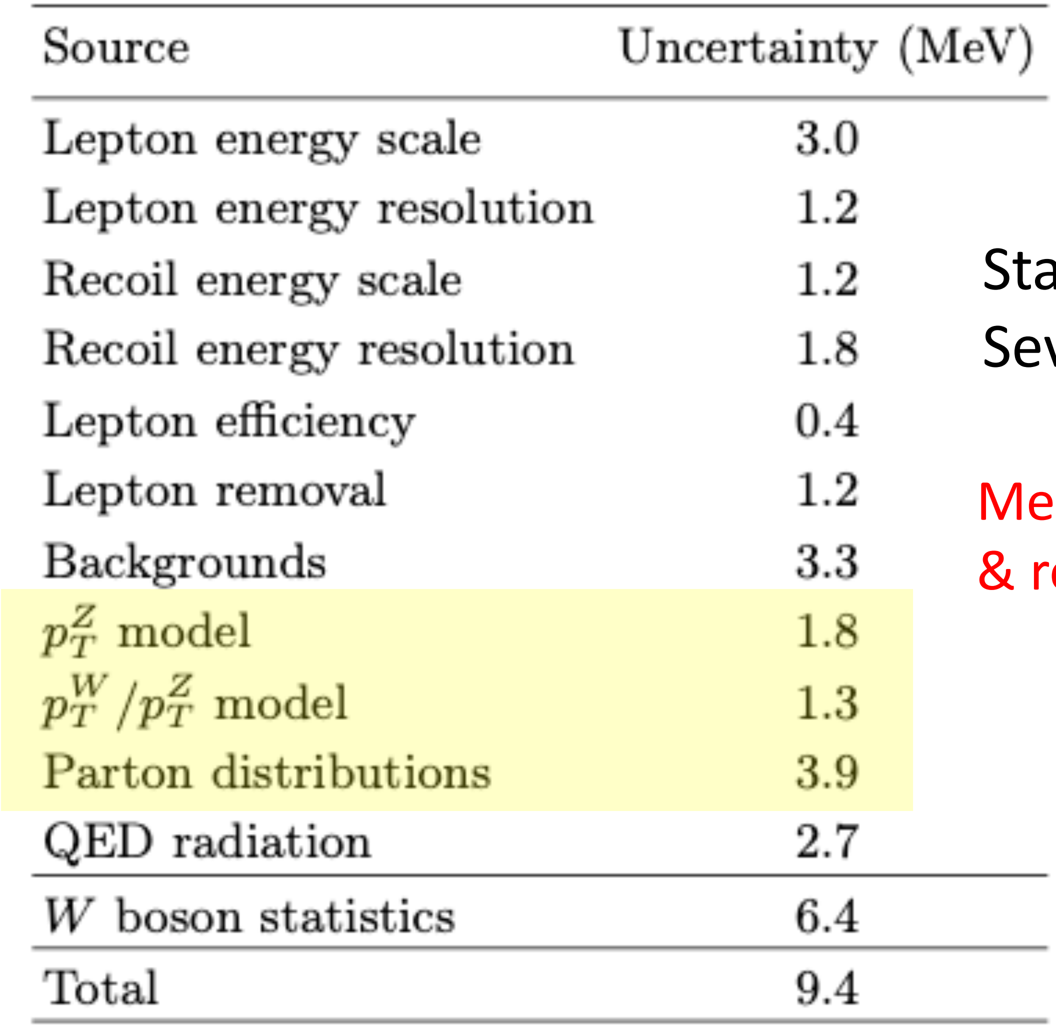
Difference in Mw between muons and electrons : 13.3 ± 15.1 MeV

CDF: Transverse Mass Fits

	Muons	Electrons	
Positive-Negative Lepton	-7.8 ± 22.4 MeV	14.7 ± 22.6 MeV	
Second 4/fb - First 4/fb of data	5.2 ± 22.4 MeV	63.2 ± 31.0 MeV	
8/fb – published 2/fb of data	50.4 ± 24.6 MeV	5.1 ± 28.3 MeV	



CDF Systematics



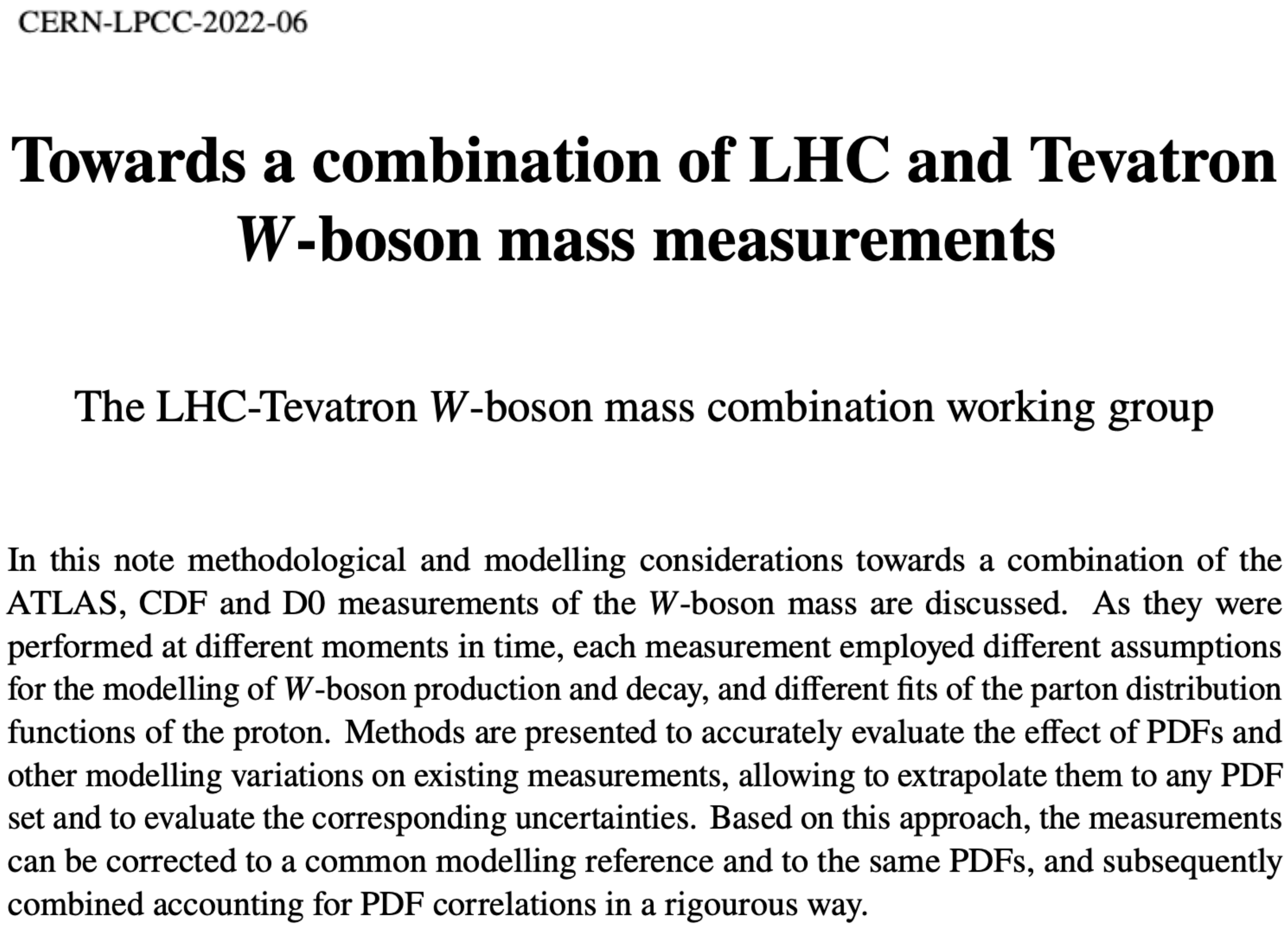
Source	Uncertainty (MeV)
Lepton energy scale	3.0
Lepton energy resolution	1.2
Recoil energy scale	1.2
Recoil energy resolution	1.8
Lepton efficiency	0.4
Lepton removal	1.2
Backgrounds	3.3
p_T^Z model	1.8
p_T^W/p_T^Z model	1.3
Parton distributions	3.9
QED radiation	2.7
W boson statistics	6.4
Total	9.4

Statistical and systematic uncertainty ~ same.
Several of systematics are driven by available Z stats

Methodology particularly in setting the energy, momentum & recoil scales is basically the same for CDF, D0, ATLAS, LHCb

What is mildly different is choice of parton distributions and the modelling of the transverse momentum of the W and Z and W decay (polarization) : QCD.

This **changes the central value** and means the values from different experiments can't simply be compared (combined) but must be corrected to the same underlying PDF and QCD model.



CERN-LPCC-2022-06

Towards a combination of LHC and Tevatron *W*-boson mass measurements

The LHC-Tevatron *W*-boson mass combination working group

In this note methodological and modelling considerations towards a combination of the ATLAS, CDF and D0 measurements of the *W*-boson mass are discussed. As they were performed at different moments in time, each measurement employed different assumptions for the modelling of *W*-boson production and decay, and different fits of the parton distribution functions of the proton. Methods are presented to accurately evaluate the effect of PDFs and other modelling variations on existing measurements, allowing to extrapolate them to any PDF set and to evaluate the corresponding uncertainties. Based on this approach, the measurements can be corrected to a common modelling reference and to the same PDFs, and subsequently combined accounting for PDF correlations in a rigourous way.

ATLAS is 15 ± 19 MeV above the SM
LHCb is 0 ± 32 MeV above the SM
D0 is 22 ± 24 MeV above the SM
CDF is 79 ± 11 MeV above the SM

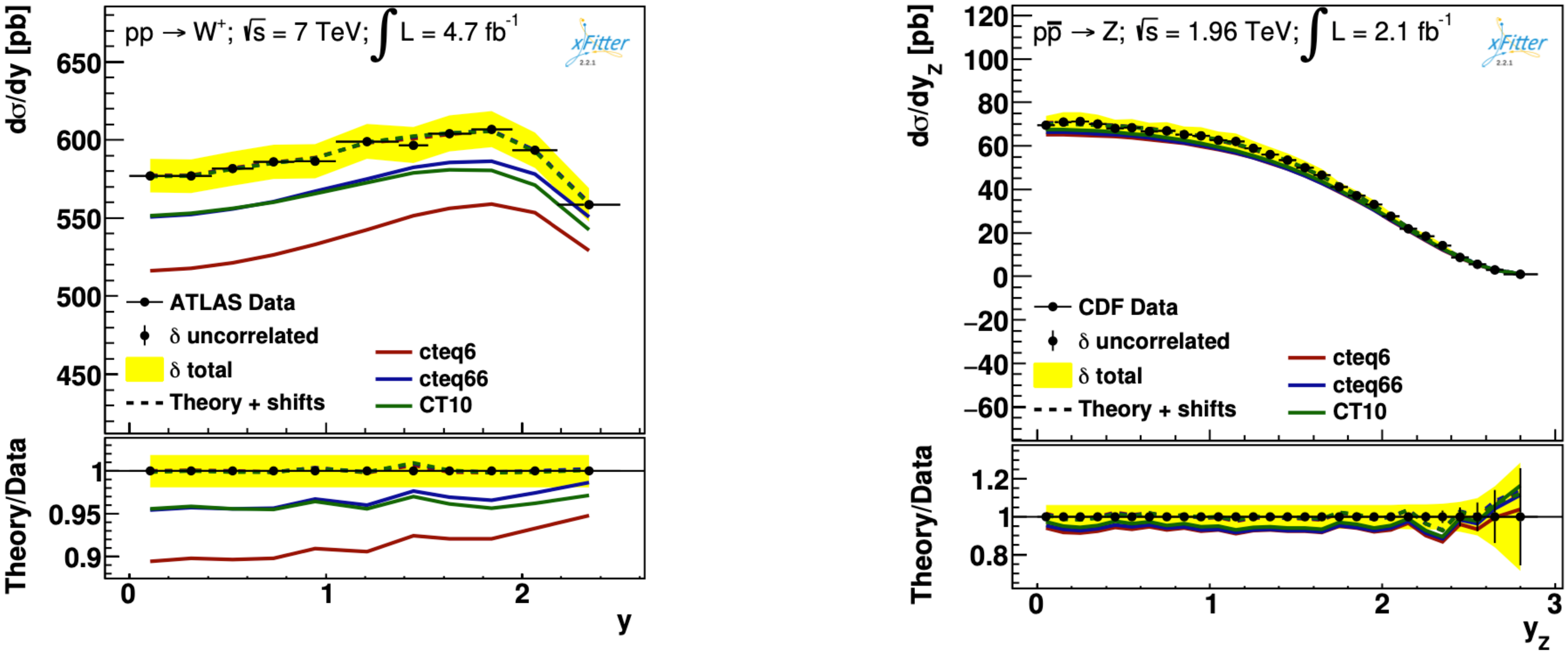
Preliminary findings were presented at ICHEP.

PDFs

Two issues:

- each experiment has used a different parton distribution function
- no single parton distribution function describes all data used in the PDF fits

"The ATLAS 7 TeV precision W/Z data are not included in CT18, due to their tension with other data sets in the global fit"



Tevatron: only 5% of events involve c/s quarks and same number of W^+ and W^-

LHC: 25% of events involves c/s quarks and x1.4 W^+ vs W^-

CDF data much better described by current PDFs than ATLAS.

Shifts when change PDFs up to 10 MeV

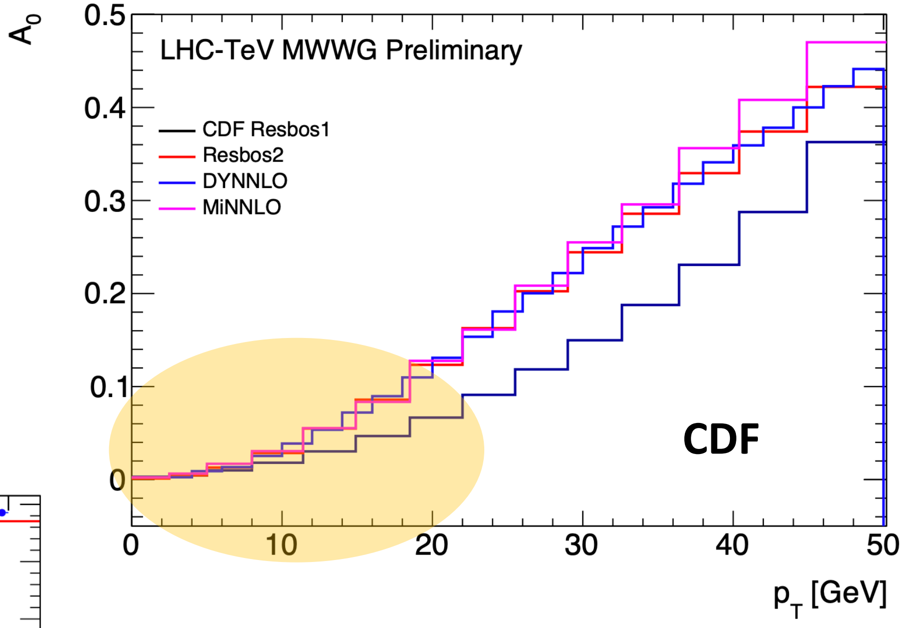
Higher Order QCD Effects on Lepton Angular Distribution

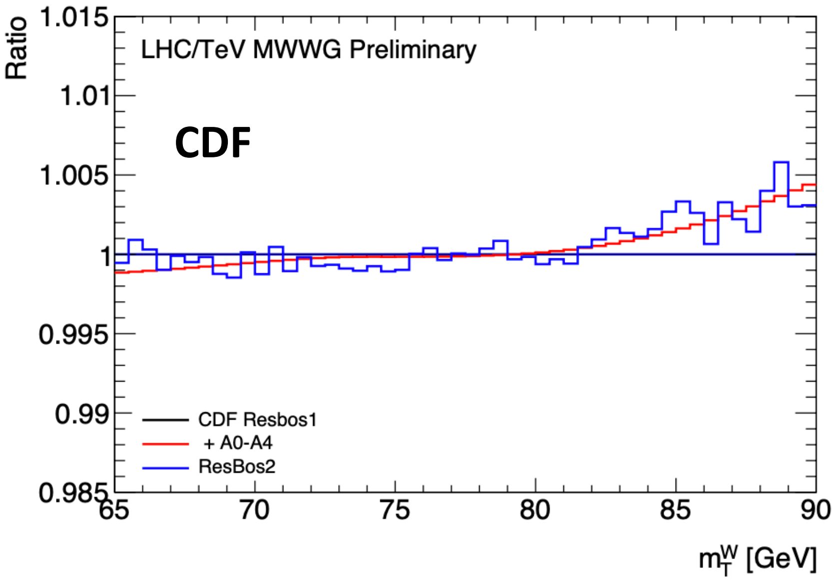
$$\frac{d\sigma}{dp_T^Z\,dy^Z\,dm^Z\,d\cos\theta\,d\phi}=\frac{3}{16\pi}\frac{d\sigma^{U+L}}{dp_T^Z\,dy^Z\,dm^Z}\Big\{(1+\cos^2\theta)+\frac{1}{2}A_0(1-3\cos^2\theta)+A_1\ \sin 2\theta\ \cos\phi$$
$$+\frac{1}{2}A_2\ \sin^2\theta\ \cos 2\phi+A_3\ \sin\theta\ \cos\phi+A_4\ \cos\theta$$
$$+A_5\ \sin^2\theta\ \sin 2\phi+A_6\ \sin 2\theta\ \sin\phi+A_7\ \sin\theta\ \sin\phi\Big\}.$$

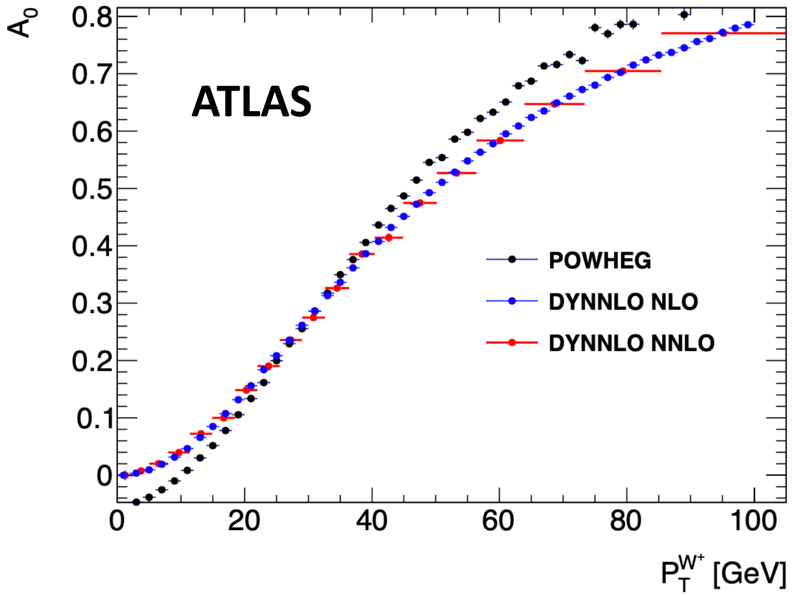
At leading order all but A4(=2) is zero. $A_{5,6,7}$ are zero until NNLO and are negligible afterwards.

CDF/D0 used NLO predictions for these A parameters.

There are now NNLO (and resumed) predictions for these which are being studied.

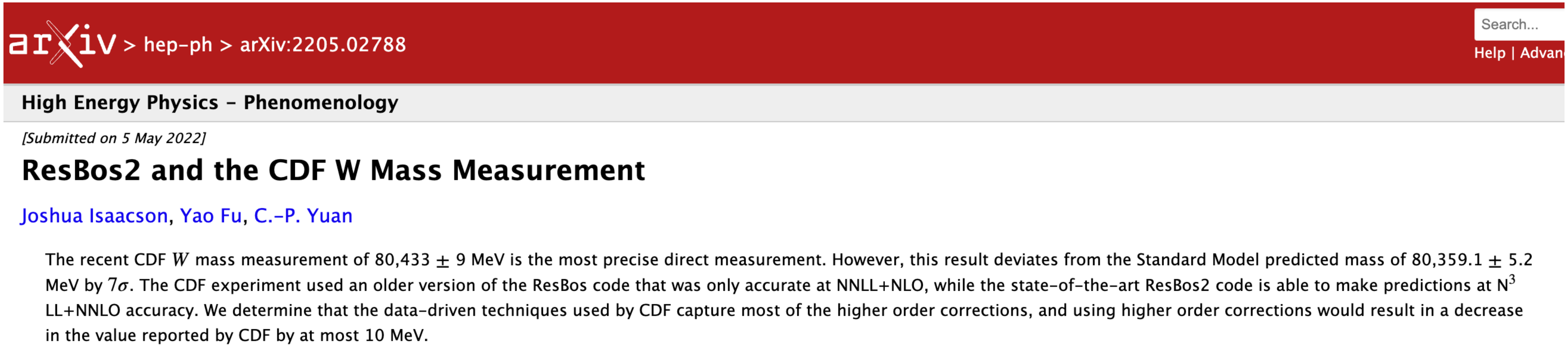






Can lead to shifts up to 10 MeV

A view from (QCD) theorists …



High Energy Physics – Phenomenology

[Submitted on 5 May 2022]

ResBos2 and the CDF W Mass Measurement

Joshua Isaacson, Yao Fu, C.-P. Yuan

The recent CDF W mass measurement of 80,433 ± 9 MeV is the most precise direct measurement. However, this result deviates from the Standard Model predicted mass of 80,359.1 ± 5.2 MeV by 7σ. The CDF experiment used an older version of the ResBos code that was only accurate at NNLL+NLO, while the state-of-the-art ResBos2 code is able to make predictions at N^{3}LL+NNLO accuracy. We determine that the data-driven techniques used by CDF capture most of the higher order corrections, and using higher order corrections would result in a decrease in the value reported by CDF by at most 10 MeV.

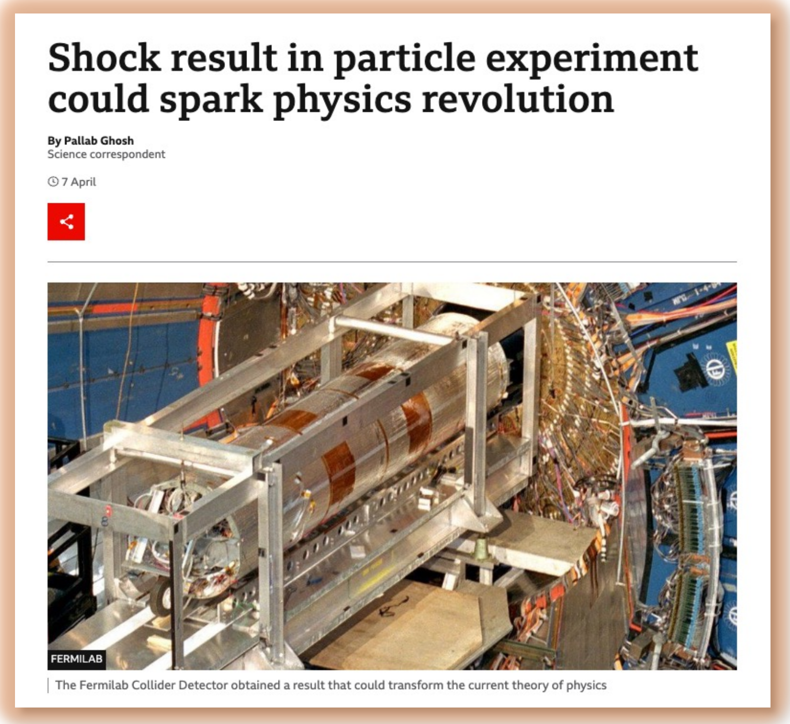
In conclusion, two of the major criticisms leveled against the theory calculations involved in the ResBos program cannot explain the deviation from the SM that is reported by CDF. We found that the data-driven techniques used by the CDF experiment help to reduce the effects of higher order corrections. **The estimated shift due to including these corrections is at most 10 MeV**, and may reduce the disagreement from 7σ to 6σ. The PDF uncertainty is found to be consistent with the numbers quoted by CDF. ….. we have addressed the most important questions related to the theory calculations…..

Muon g-2 and Mw

Muons: 'Strong' evidence found for a new force of nature

By Pallab Ghosh
Science correspondent

7 April



Shock result in particle experiment could spark physics revolution

By Pallab Ghosh
Science correspondent

7 April

FERMILAB

The Fermilab Collider Detector obtained a result that could transform the current theory of physics

The muon g-2 and W-mass anomalies explained and the electroweak vacuum stabilised by extending the minimal Type-II seesaw
http://arxiv.org/abs/2206.11771v1

Leptoquark-vectorlike quark model for mW (CDF), (g-2)_μ, R_K anomalies and neutrino mass: http://arxiv.org/abs/2205.03917v2

A leptoquark and vector-like quark extended model for the simultaneous explanation of the W boson mass and muon g-2 anomalies:
http://arxiv.org/abs/2205.02088v1

CDF W boson mass and muon g-2 in type-X two-Higgs-doublet model with a Higgs-phobic light pseudoscalar: http://arxiv.org/abs/2205.01701v2

Compatibility of muon g-2, W mass anomaly in type-X 2HDM : http://arxiv.org/abs/2205.01437v1

Muon and electron g-2 anomalies in a flavor conserving 2HDM with an oblique view on the CDF M_W value : http://arxiv.org/abs/2205.01115v1

The CDF W-mass, muon g-2, and dark matter in a U(1)_{L_μ-L_τ} model with vector-like leptons: http://arxiv.org/abs/2204.13027v1

Implications of CDF W-mass and (g-2)_μ on U(1)_{L_μ-L_τ} model : http://arxiv.org/abs/2204.09585v1

**Combined explanation of W-mass, muon g-2, R_K* and R_D* anomalies in a singlet-triplet scalar leptoquark model:
http://arxiv.org/abs/2204.09031v1**

The 2HD+a model for a combined explanation of the possible excesses in the CDF Mw measurement and (g-2) with Dark Matter :
http://arxiv.org/abs/2204.08406v1

A model explaining the new CDF II W boson mass linking to muon g-2 and dark matter: http://arxiv.org/abs/2204.07411v1

W boson mass and muon (g-2) in a lepton portal dark matter model: http://arxiv.org/abs/2204.07022v2

A joint explanation of W-mass and muon g-2 in 2HDM: http://arxiv.org/abs/2204.06505v2

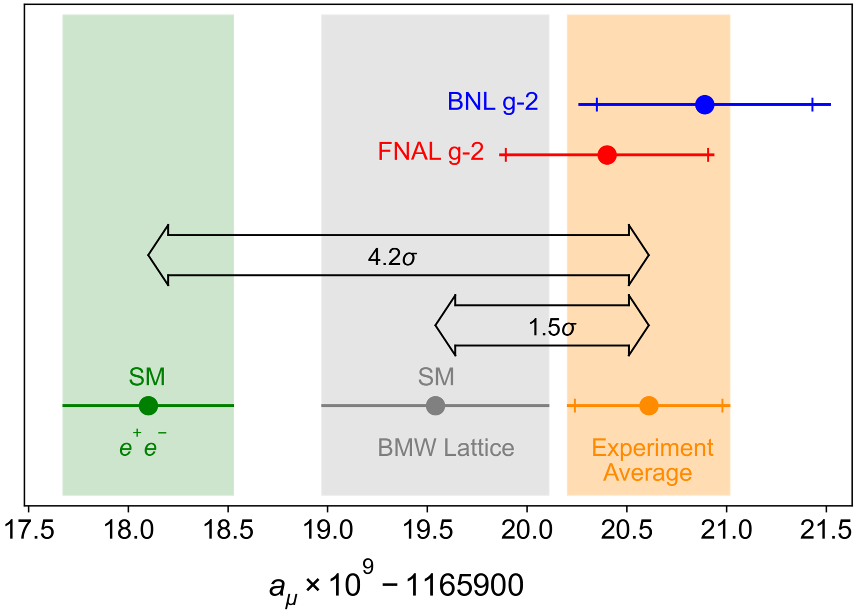
Correlating W-Boson Mass Shift with Muon {g-2} in the 2HDM: http://arxiv.org/abs/2204.05303v2

NMSSM neutralino dark matter for W-boson mass and muon g-2 and the promising prospect of direct detection : http://arxiv.org/abs/2204.04356v2

Explaining The Muon g-2 Anomaly and New CDF II W-Boson Mass in the Framework of (Extra)Ordinary Gauge Mediation
http://arxiv.org/abs/2204.04286v3

Low energy SUSY confronted with new measurements of W-boson mass and muon g-2: http://arxiv.org/abs/2204.04202v3

The W boson Mass and Muon g-2: Hadronic Uncertainties or New Physics? : http://arxiv.org/abs/2204.03996v2



W Mass & g-2

$\Delta\alpha_{had}$ that goes in EWK fits is also what determines the SM prediction for (g-2)

$$a_l^{\mathrm{had,\,LO\,VP}} = \frac{\alpha^2}{3\pi^2}\int_{s_{th}}^{\infty}\frac{\mathrm{d}s}{s}R(s)K_l(s)\,,$$

g-2

$$\Delta\alpha_{\mathrm{had}}^{(5)}(M_Z^2) = -\frac{\alpha M_Z^2}{3\pi}\,\mathrm{P}\int_{s_{th}}^{\infty}\mathrm{d}s\frac{R(s)}{s(s-M_Z^2)}\,,$$

EWK FIT

R(s) are measured e^+e^- ⟶ hadrons cross sections

If you change the SM prediction for (g-2) e.g. by using a lattice calculation and not measured e^+e^- cross sections then you also change your EWK fit predictions e.g. of Mw.

W Mass & g-2

SM predicted Mw = 80355 ± 6 MeV and Higgs predicted = 95 ± 20 GeV
CDF measured Mw = 80433 ± 9 MeV and Higgs measured = 125.2 ± 0.1 GeV

You can remove the SM tension in (g-2) by changing the SM prediction ie blindly increasing the measured e^+e^- cross sections (ie moving in direction of BMW lattice calculation).

If you do this then the SM predicted Mw reduces to about 80340 and so does the predicted Higgs to about 60 GeV.
So you remove BSM from (g-2) and need BSM to explain why the measured W (even without CDF) and Higgs masses are so much higher than the SM predictions….

Conversely to predict a high Mw in the SM you need to reduce the measured e^+e^- cross sections but then your SM (g-2) value goes lower and the (g-2) tension increases ….

Tricky to accommodate both a high measured g-2 and a high measured Mw **without SM inconsistencies** which can potentially be removed instead with BSM.

Measurement Conclusions

We need a precise measurement from CMS….

Experimental techniques used by CDF, D0, ATLAS, LHCb are all very similar

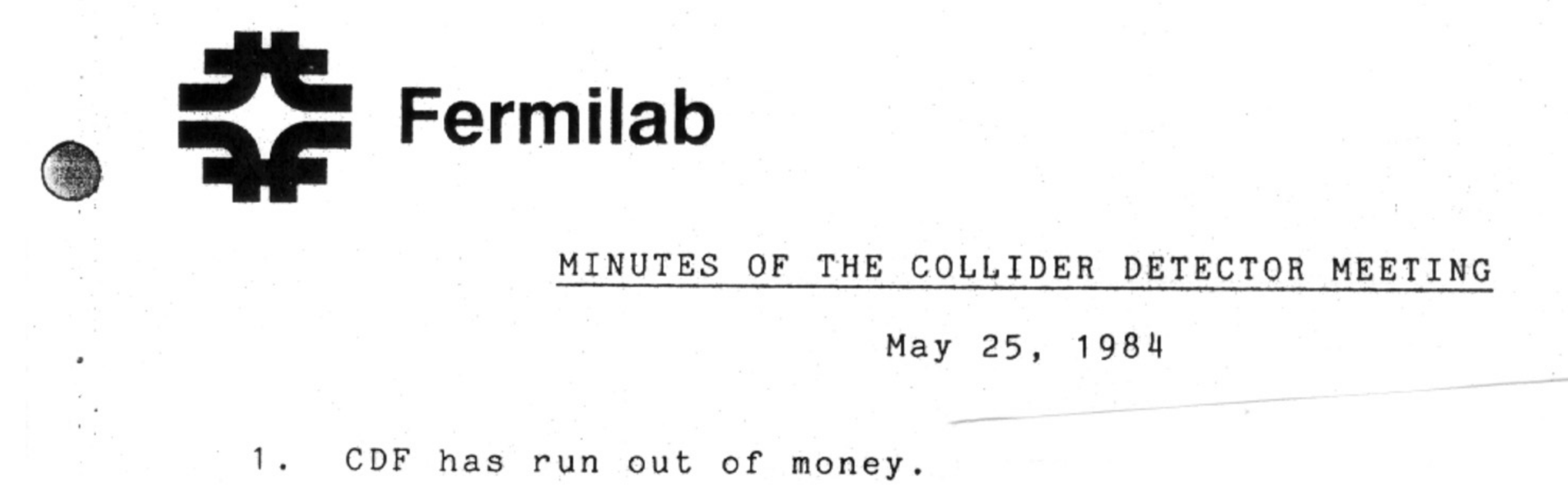
However, each experiment has a different model for PDFs, p_T(W), angular coefficients and QED radiation.

These are all “theoretical” and so one can “easily” reweight a given measurement to another model.

This needs to be done before any meaningful comparison with SM can be made
i.e. a common model has to be agreed by all experiments…..and then the published values shifted. This is not something the PDG can do.

There are effects at the 10 MeV level in these models.

However, assuming a combination with uncertainty 10 MeV then a combined Mw > 80400 MeV looks tricky for the SM and then we have Muon g-2 ….

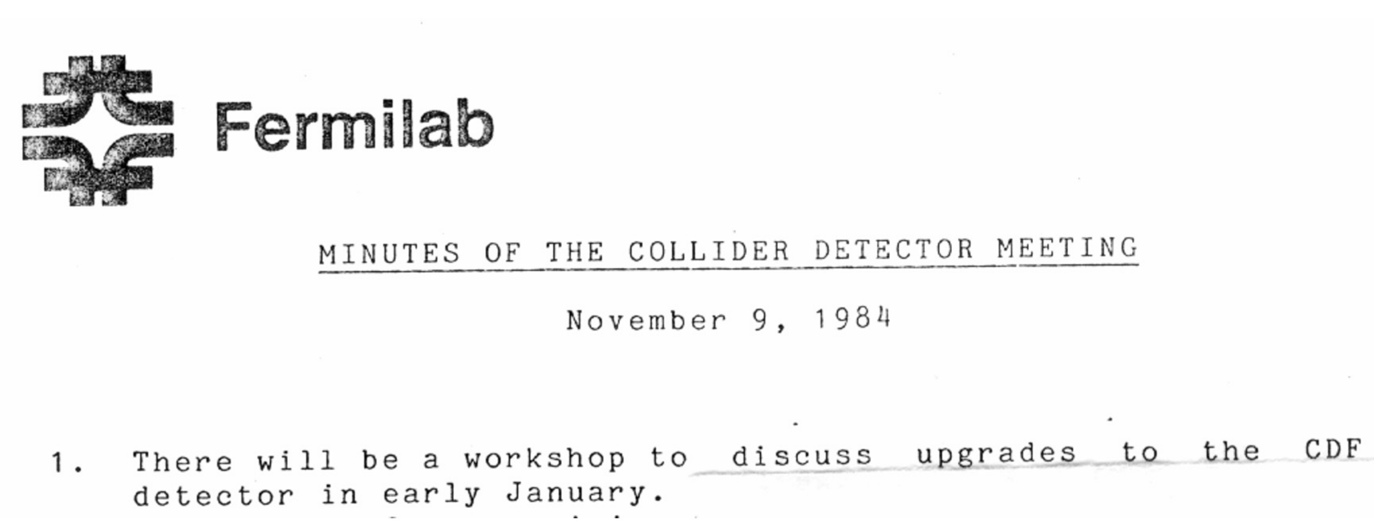


Fermilab

MINUTES OF THE COLLIDER DETECTOR MEETING

May 25, 1984

1. CDF has run out of money.



Fermilab

MINUTES OF THE COLLIDER DETECTOR MEETING

November 9, 1984

1. There will be a workshop to discuss upgrades to the CDF detector in early January.