# Precision Electroweak Measurements at Colliders

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Séminaire au LAPP Annecy,
21 octobre 2011

# Context

This seminar is based on a presentation that I gave at the Lepton-Photon conference in Bombay late this summer:

XXV International Symposium on
Lepton and Photon Interactions at High Energies,
Mumbai, 22 – 27 August 2011

# 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 at EPS-HEP in July 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] | $91.1875 \pm 0.0021$ | yes | $91.1874 \pm 0.0021$ | $91.1877 \pm 0.0021$ | $91.1983^{+0.0133}_{-0.0155}$ |
| $\Gamma_Z$ [GeV] | $2.4952 \pm 0.0023$ | – | $2.4959 \pm 0.0015$ | $2.4955 \pm 0.0014$ | $2.4951^{+0.0017}_{-0.0016}$ |
| $\sigma^0_{\rm had}$ [nb] | $41.540 \pm 0.037$ | – | $41.478 \pm 0.014$ | $41.478 \pm 0.014$ | $41.469 \pm 0.015$ |
| $R^0_\ell$ | $20.767 \pm 0.025$ | – | $20.743 \pm 0.018$ | $20.741 \pm 0.018$ | $20.718^{+0.027}_{-0.026}$ |
| $A^{0,\ell}_{\rm FB}$ | $0.0171 \pm 0.0010$ | – | $0.01641 \pm 0.0002$ | $0.01620^{+0.0002}_{-0.0001}$ | $0.01606 \pm 0.0001$ |
| $A_\ell$ $^{(\star)}$ | $0.1499 \pm 0.0018$ | – | $0.1479 \pm 0.0010$ | $0.1472^{+0.0009}_{-0.0006}$ | – |
| $A_c$ | $0.670 \pm 0.027$ | – | $0.6683^{+0.00044}_{-0.00043}$ | $0.6680^{+0.00040}_{-0.00028}$ | $0.6679^{+0.00042}_{-0.00025}$ |
| $A_b$ | $0.923 \pm 0.020$ | – | $0.93470^{+0.00009}_{-0.00008}$ | $0.93463^{+0.00008}_{-0.00005}$ | $0.93463^{+0.00007}_{-0.00005}$ |
| $A^{0,c}_{\rm FB}$ | $0.0707 \pm 0.0035$ | – | $0.0741 \pm 0.0005$ | $0.0737^{+0.0005}_{-0.0004}$ | $0.0738 \pm 0.0004$ |
| $A^{0,b}_{\rm FB}$ | $0.0992 \pm 0.0016$ | – | $0.1037 \pm 0.0007$ | $0.1035^{+0.0003}_{-0.0004}$ | $0.1038^{+0.0003}_{-0.0005}$ |
| $R^0_c$ | $0.1721 \pm 0.0030$ | – | $0.17226 \pm 0.00006$ | $0.17226 \pm 0.00006$ | $0.17226 \pm 0.00006$ |
| $R^0_b$ | $0.21629 \pm 0.00066$ | – | $0.21578^{+0.00005}_{-0.00008}$ | $0.21577^{+0.00005}_{-0.00008}$ | $0.21577^{+0.00005}_{-0.00007}$ |
| $\sin^2\theta^\ell_{\rm eff}(Q_{\rm FB})$ | $0.2324 \pm 0.0012$ | – | $0.23141 \pm 0.00012$ | $0.23150^{+0.00008}_{-0.00011}$ | $0.23152^{+0.00006}_{-0.00013}$ |
| $M_H$ [GeV] $^{(\circ)}$ | Likelihood ratios | yes | $95^{+30[+74]}_{-24[-43]}$ | $125^{+8[+21]}_{-10[-11]}$ | $95^{+30[+74]}_{-24[-43]}$ |
| $M_W$ [GeV] | $80.399 \pm 0.023$ | – | $80.382^{+0.014}_{-0.015}$ | $80.368^{+0.007}_{-0.010}$ | $80.360^{+0.012}_{-0.011}$ |
| $\Gamma_W$ [GeV] | $2.085 \pm 0.042$ | – | $2.093 \pm 0.001$ | $2.092 \pm 0.001$ | $2.091^{+0.002}_{-0.001}$ |
| $\overline{m}_c$ [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] | $173.2 \pm 0.9$ | yes | $173.3 \pm 0.9$ | $173.5 \pm 0.9$ | $177.2^{+2.9}_{-3.1}{}^{(\bigtriangledown)}$ |
| $\Delta\alpha^{(5)}_{\rm had}(M_Z^2)$ $^{(\dagger\triangle)}$ | $2749 \pm 10$ | yes | $2750 \pm 10$ | $2748 \pm 10$ | $2716^{+60}_{-45}$ |
| $\alpha_s(M_Z^2)$ | – | yes | $0.1192 \pm 0.0028$ | $0.1193 \pm 0.0028$ | $0.1193 \pm 0.0028$ |
| $\delta_{\rm th} M_W$ [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 | – |

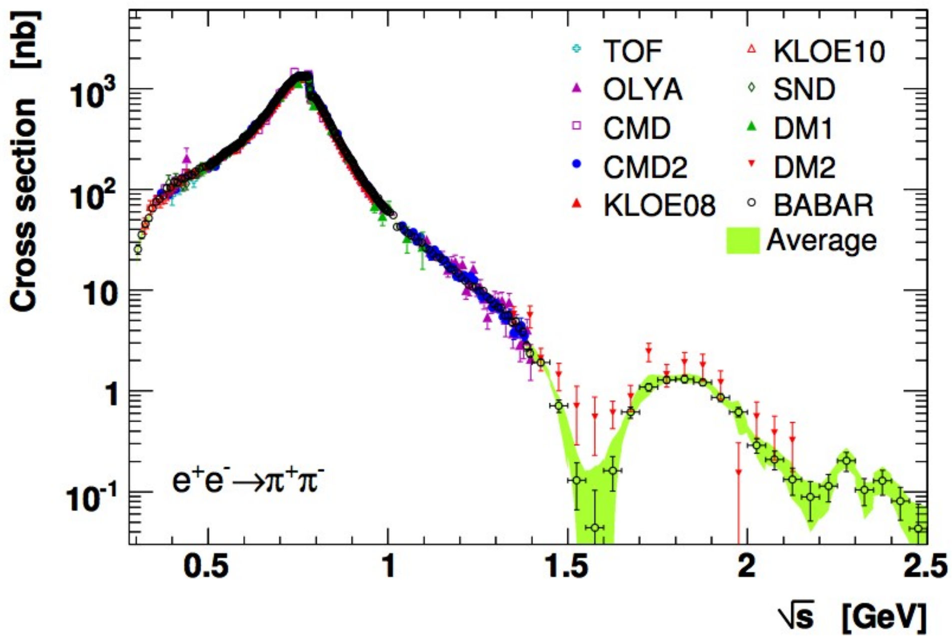
$^{(\star)}$Average of LEP ($A_\ell = 0.1465 \pm 0.0033$) and SLD ($A_\ell = 0.1513 \pm 0.0021$) measurements. The fit w/o the LEP (SLD) measurement but with the direct Higgs searches gives $A_\ell = 0.1471^{+0.0010}_{-0.0008}$ ($A_\ell = 0.1467^{+0.0007}_{-0.0004}$). $^{(\circ)}$In brackets the $2\sigma$.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

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

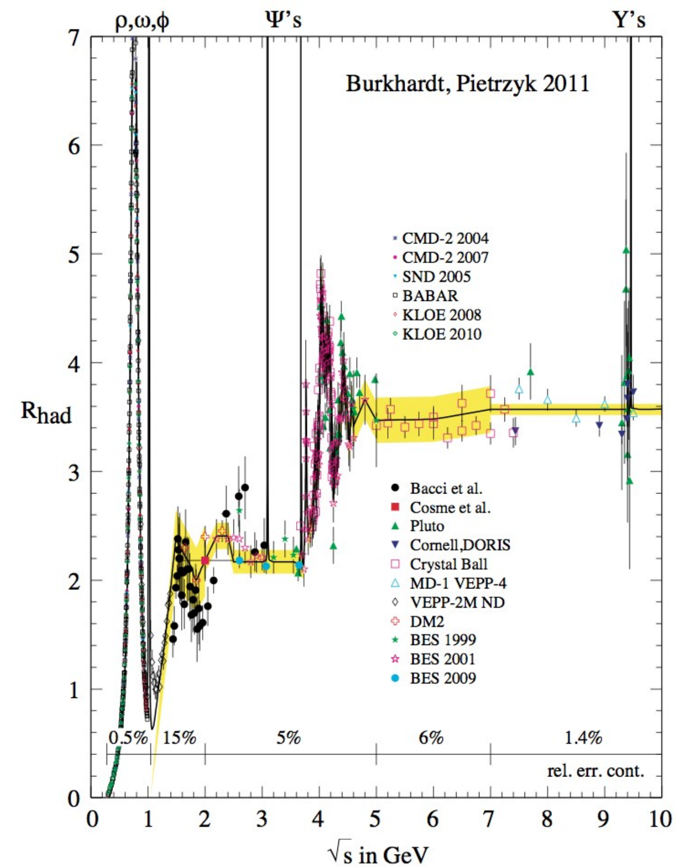
Electroweak fit requires the knowledge of the electromagnetic coupling strength at the Z mass scale to an accuracy of 1% or better.

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)

# Global electroweak fit

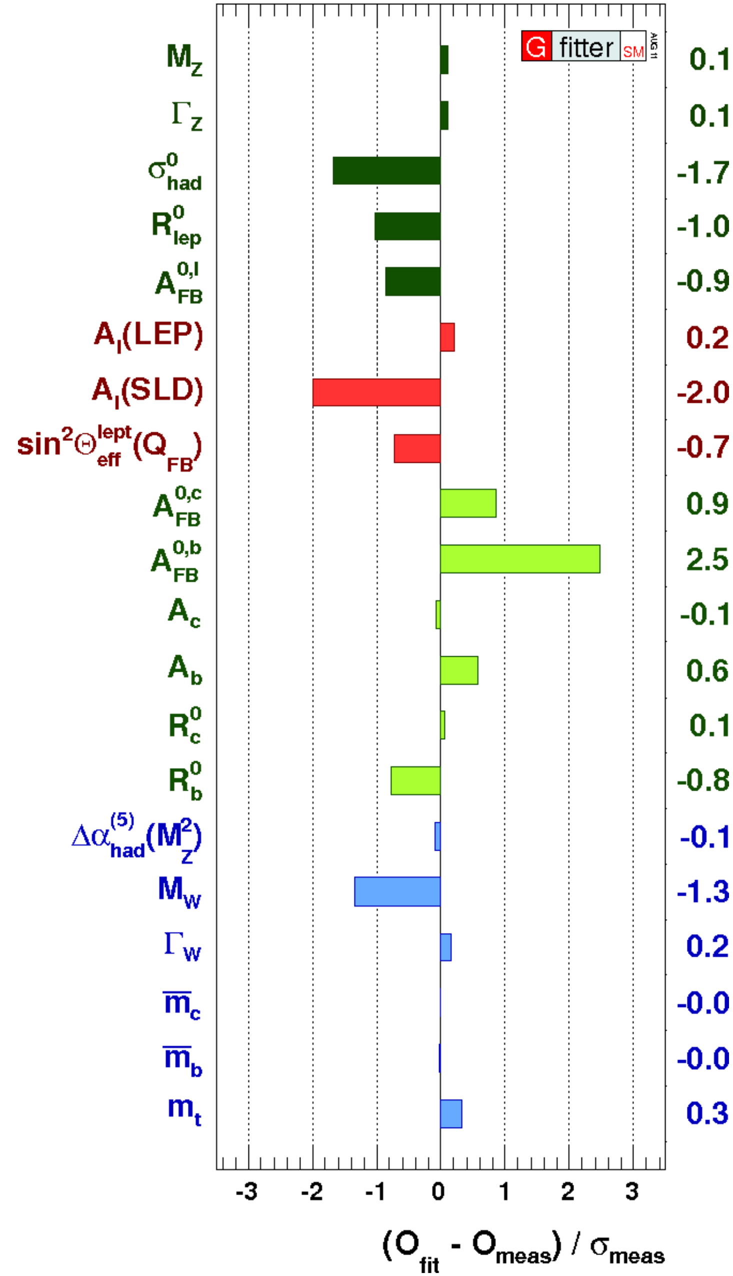
Complete fit:
$\chi^2_{min}$ = 17.9 for 14 degrees of freedom.

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

- no value exceeds 3 sigma
- largest individual contribution to $\chi^2$ 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.

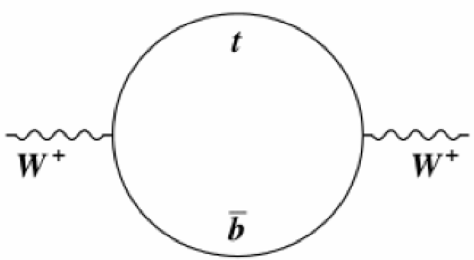


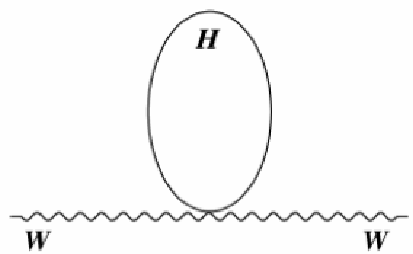
# W boson mass

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 ($\Delta$ r) depend on $M_t$ as $\sim M_t^2$ and on $M_H$ as $\sim \log M_H$. They include diagrams like these:



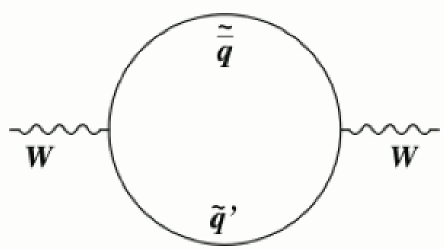




Precise measurements of $M_W$ and $M_t$ constrain SM Higgs mass.

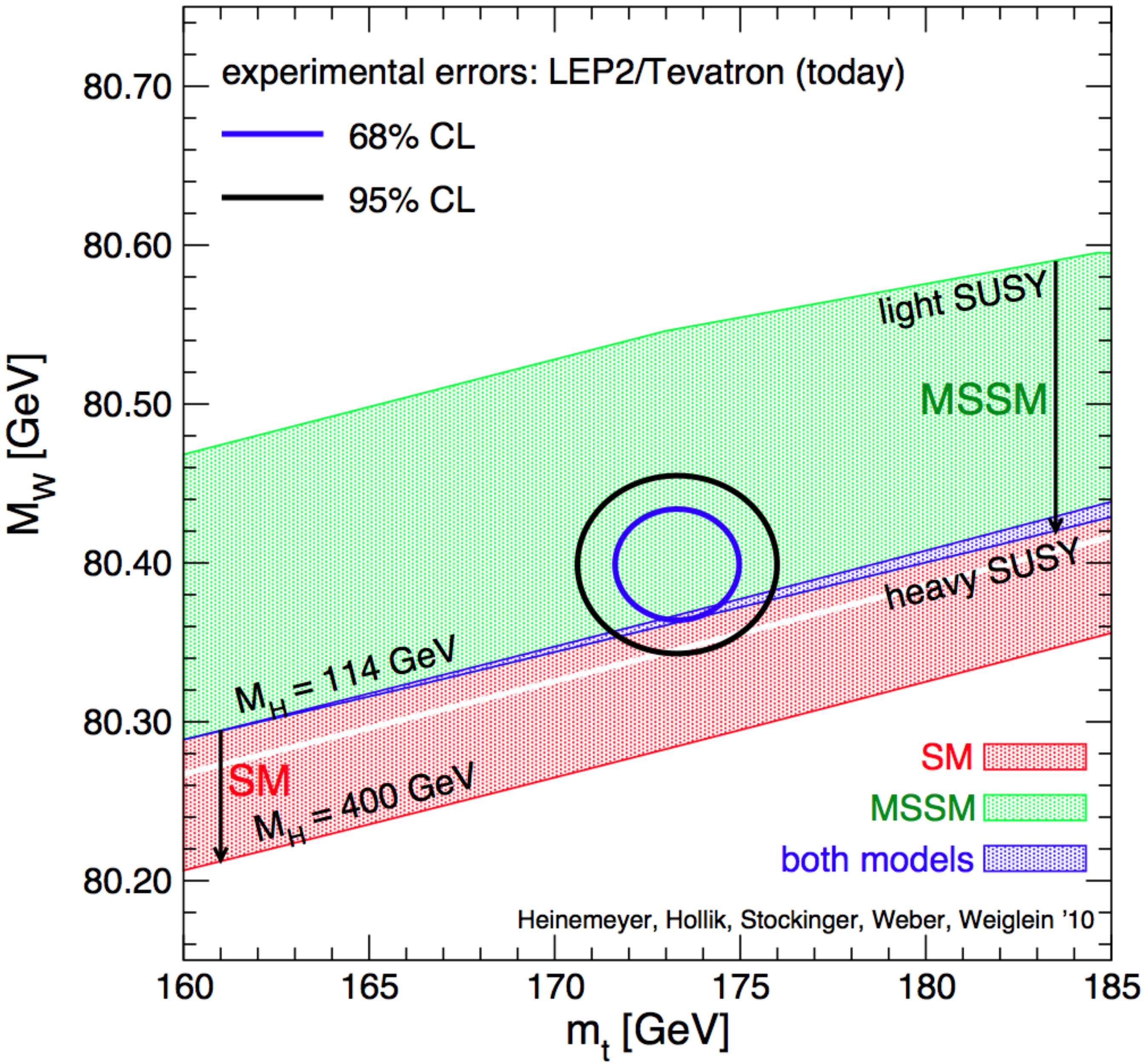
For equal contribution to the Higgs mass uncertainty need:
$\Delta M_W \approx 0.006 \; \Delta M_t$ .

The limiting factor here will be $\Delta M_W$, not $\Delta M_t$ !

Additional contributions to $\Delta$r arise in various extensions to the Standard Model,
*e.g.* in SUSY:



# W boson mass




For equal contribution to the Higgs mass uncertainty need:

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

Current Tevatron average:

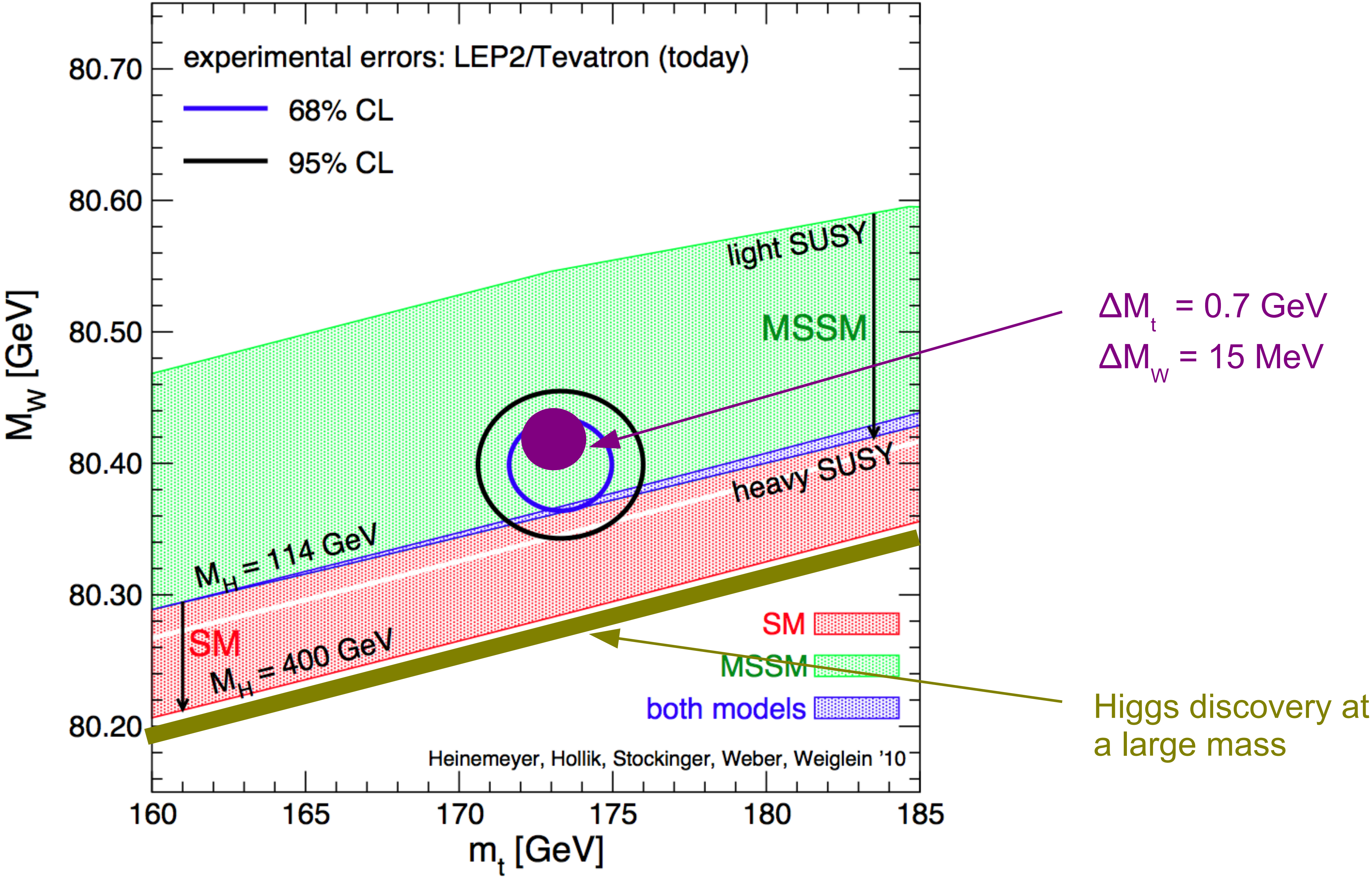
$\Delta M_t = 0.9$ GeV

$\Rightarrow$ would need: $\Delta M_W$ = 5 MeV

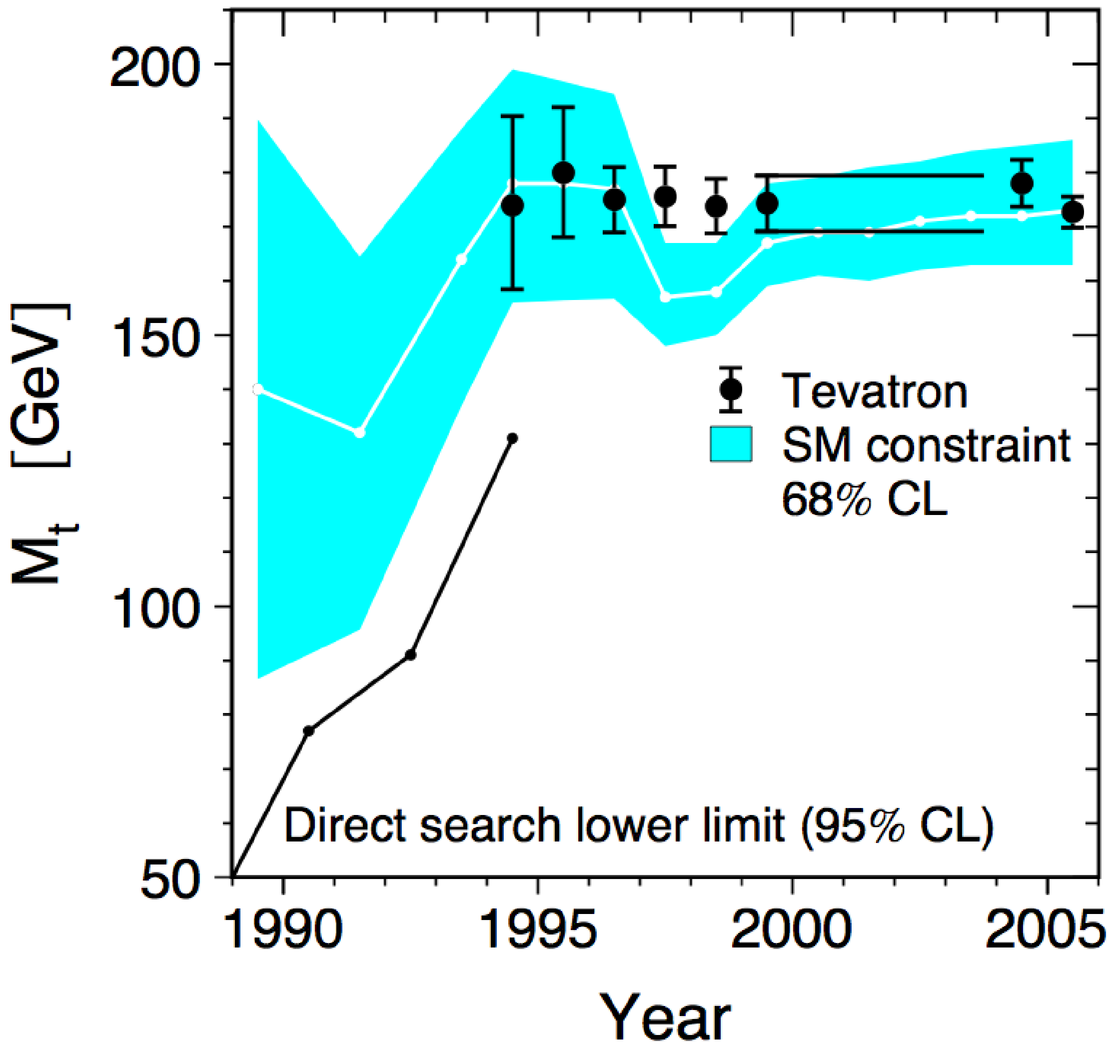
Currently have: $\Delta M_W$ = 23 MeV

At this point, *i.e.* after all the precise top mass measurements from the Tevatron, the limiting factor here is $\Delta M_W$, not $\Delta M_t$ .

# A possible scenario for Lepton Photon 2013



# Flashback

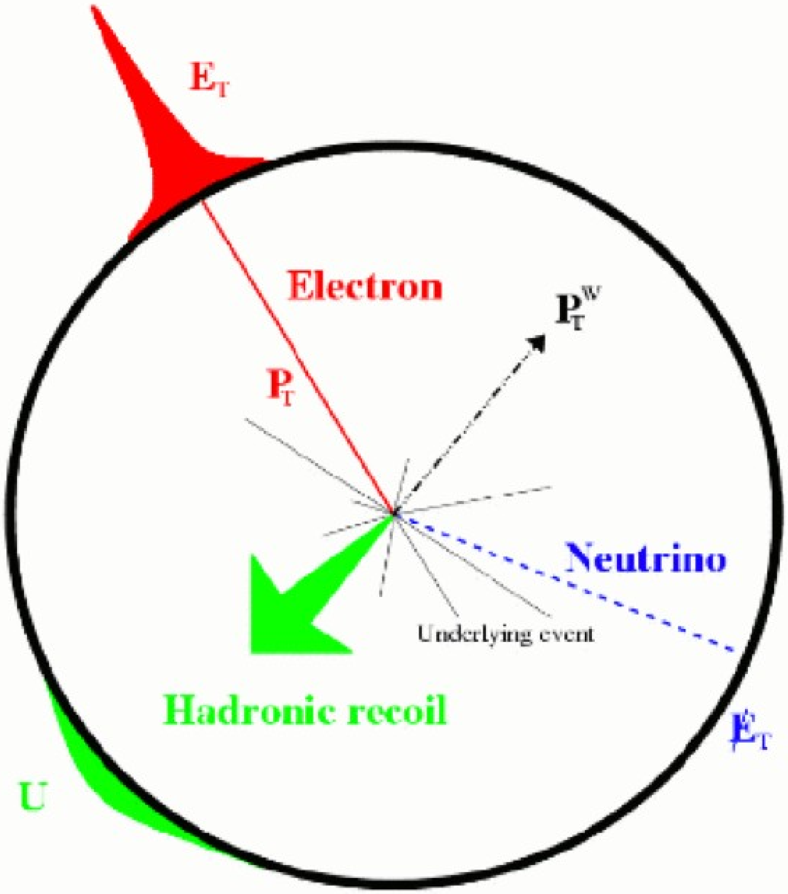



The mass of the top quark had been, quite accurately, predicted by EWK fits before the top was finally discovered in direct searches.

We are now in the middle of a comparable two-pronged hunt for the (hypothetical) Higgs boson. We should see pretty soon how this new hunt will end ...

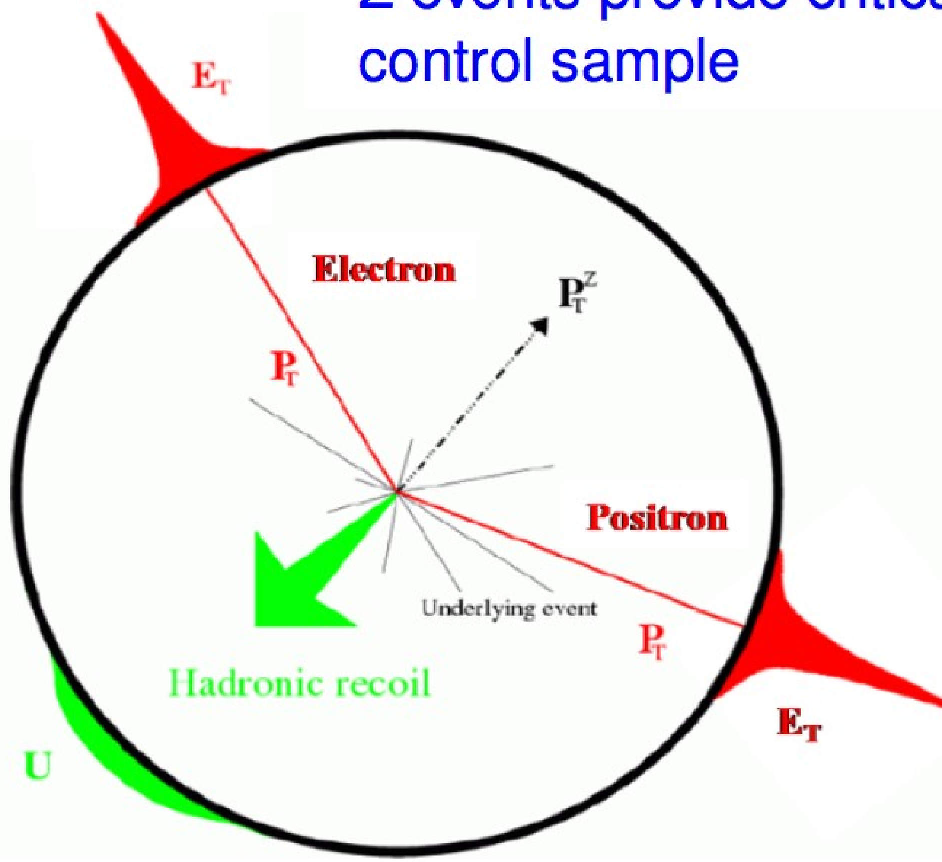
Plot from: “Precision electroweak measurements on the Z pole”, Physics Reports 427, 257-454 (2006).

# W mass: measurement method



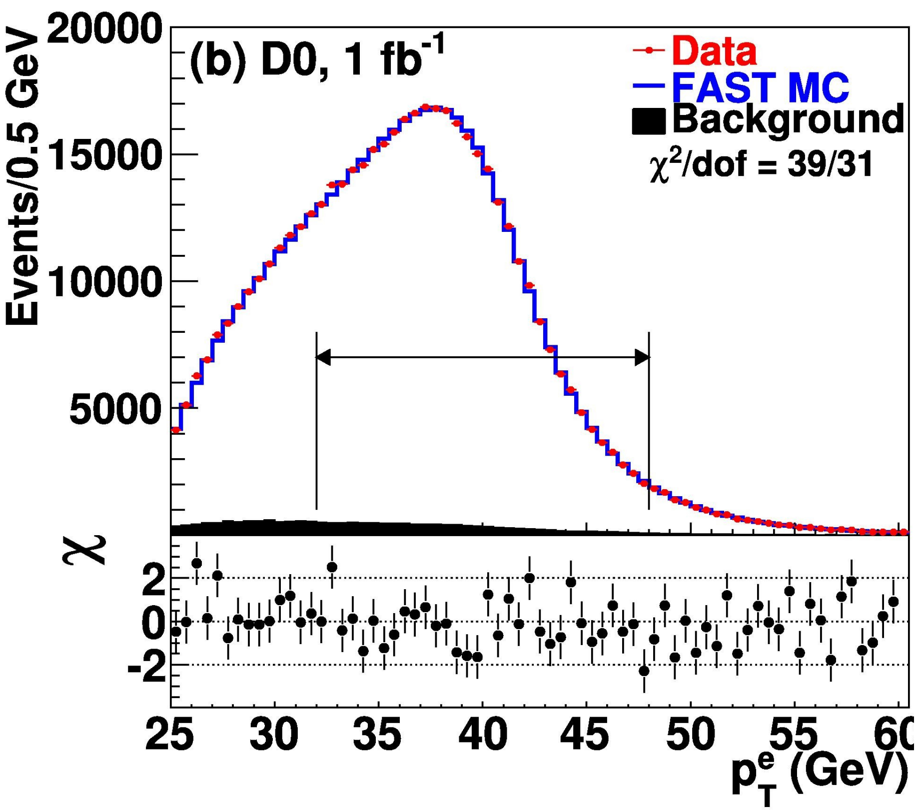

Isolated, high $p_T$ leptons,
missing transverse momentum in W's

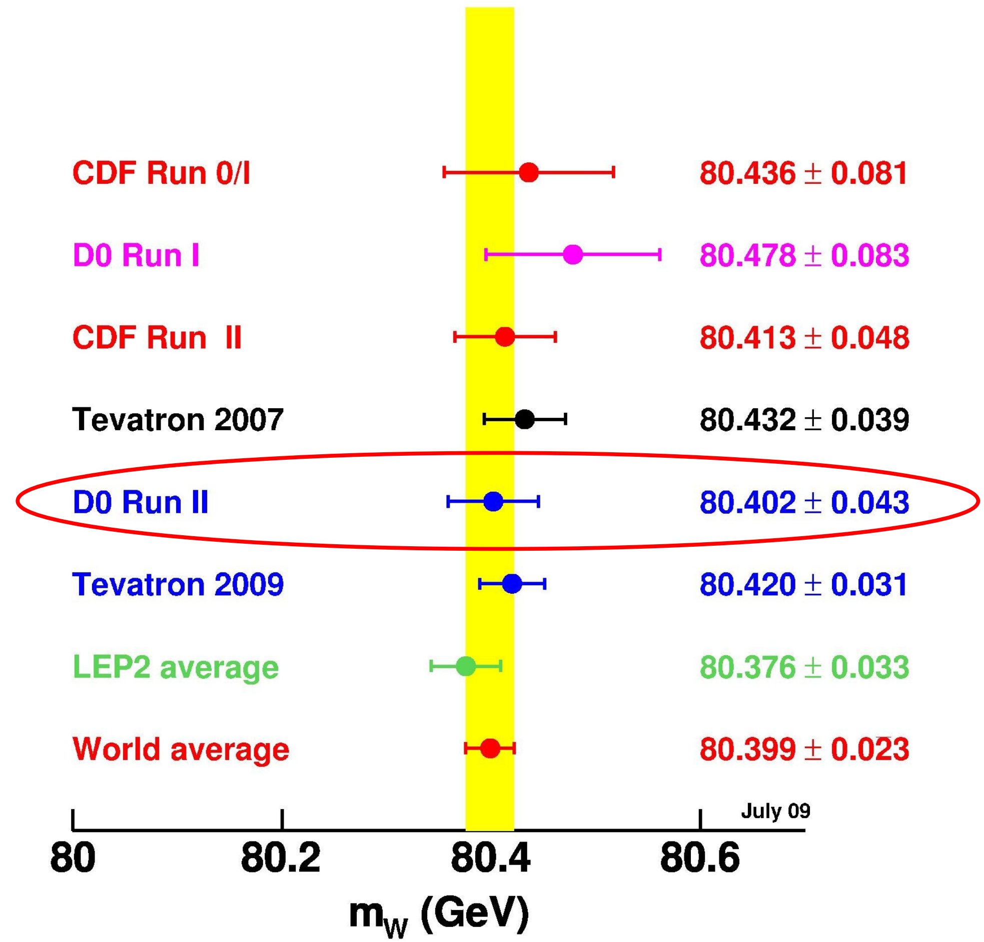
Z events provide critical control sample




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

# W mass: results



# W mass: DØ projections

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

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

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

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

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

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

with $\delta m_W$ = 15 MeV, $\delta m_t$ = 1 GeV and $m_W$ = 80.400 GeV :

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

(P. Renton, ICHEP 2008)

# W mass at the LHC

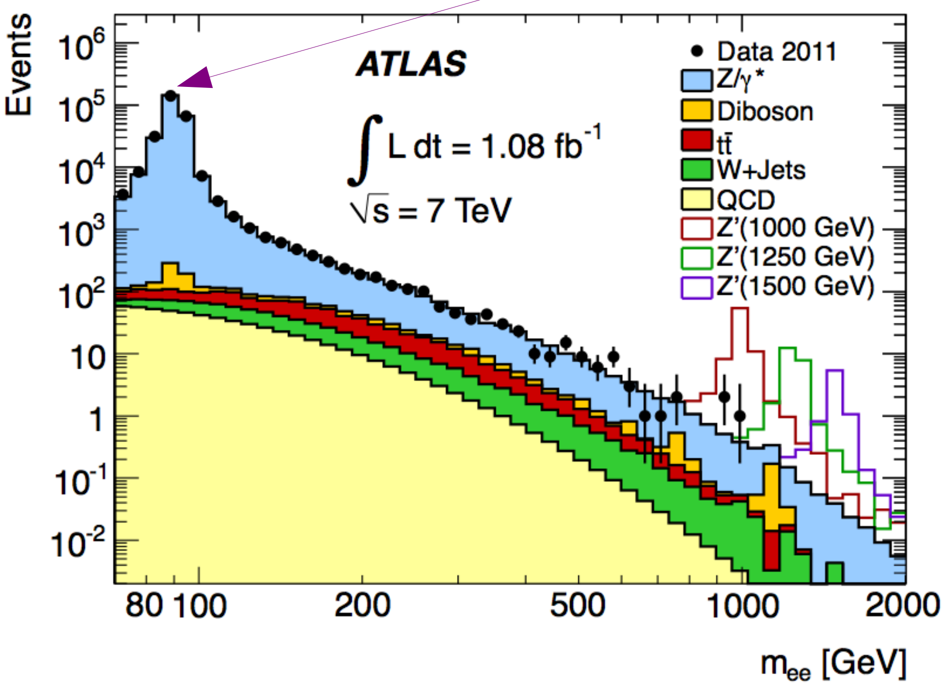
Similar level of precision can be achieved at LHC once the detectors are sufficiently well understood.

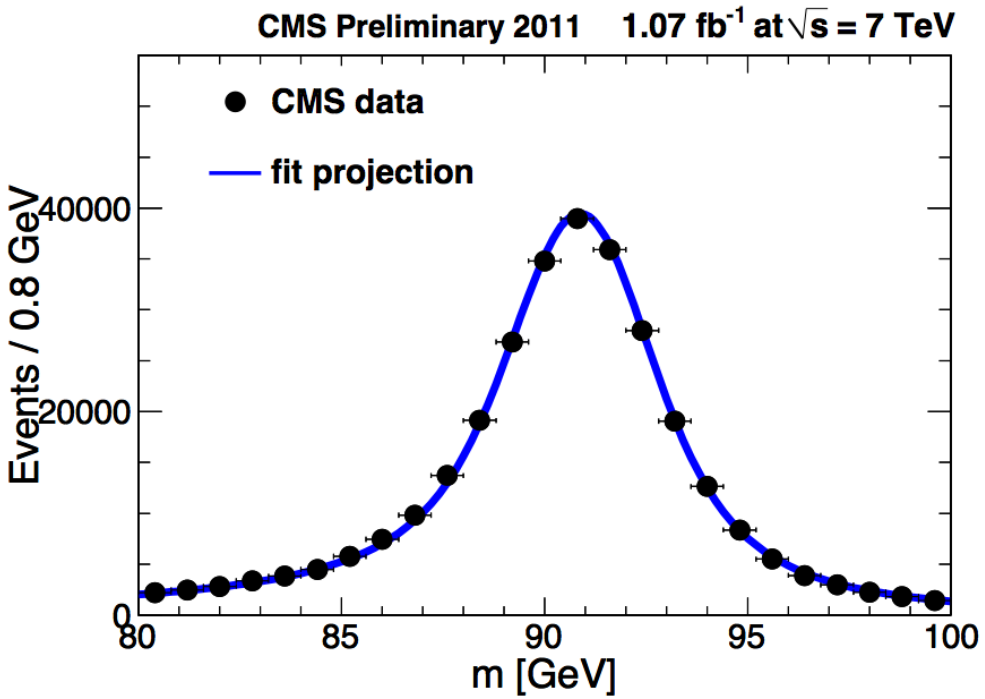
There are challenges that new (or more pronounced) than at Tevatron …

- pileup, …
- parton density functions (more on this later)

… but also a lot of powerful calibration events.

>100k Z → e e events in just this bin !



# $p_T$ distribution of Z bosons

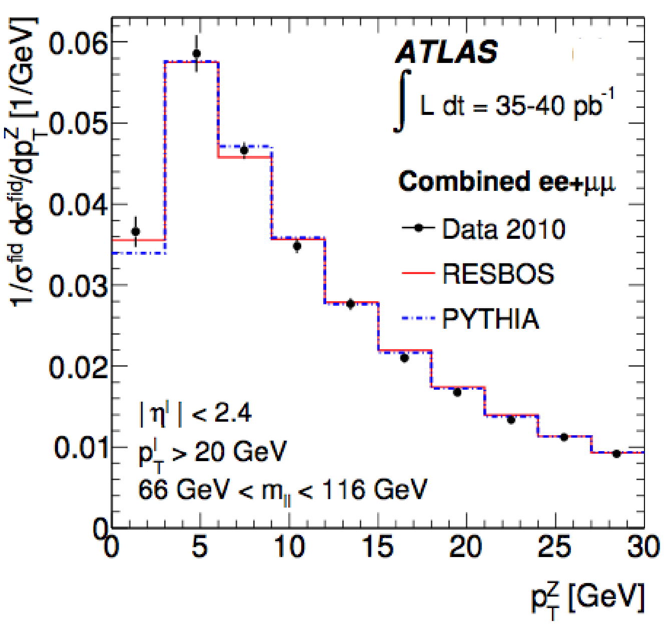
Precise description of the kinematics of W boson production and decay is a critical ingredient for precision measurements of W boson mass.

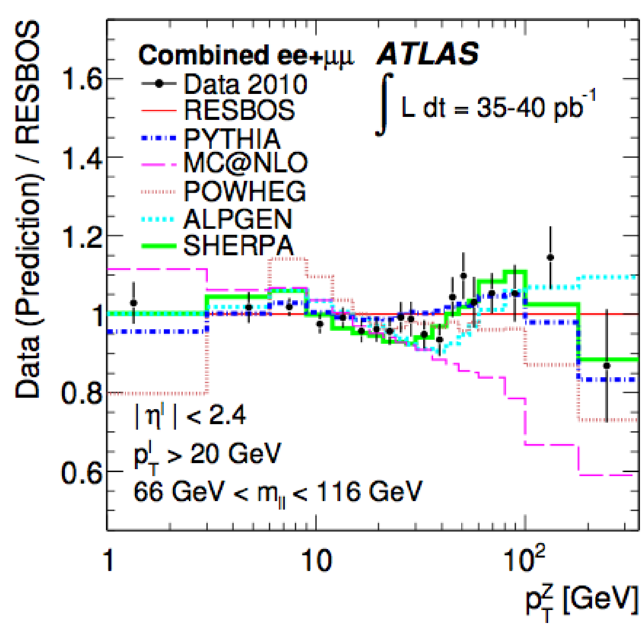
An important part is the distribution of the transverse momentum of the W bosons ($p_T^W$).

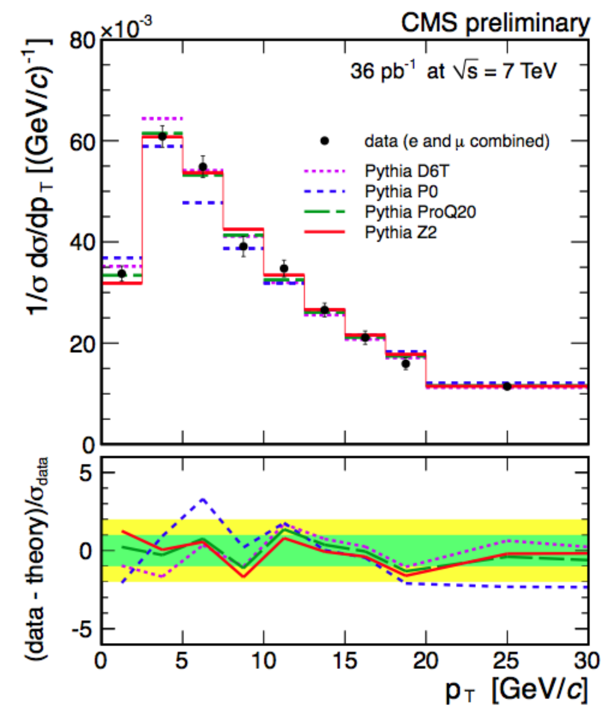
Cannot reconstruct $p_T^W$ easily (neutrino in final state). To check models of $p_T^W$, confront models to $p_T^Z$, which can be measured precisely in data (production mechanisms for W and Z are similar).

First measurements from ATLAS and CMS are available. The plots below compare shape of unfolded data distributions to various predictions.

Of particular relevance for W boson mass: lower part ($\lesssim$30 GeV) of the distribution (W mass measurements typically veto events with large hadronic recoil).



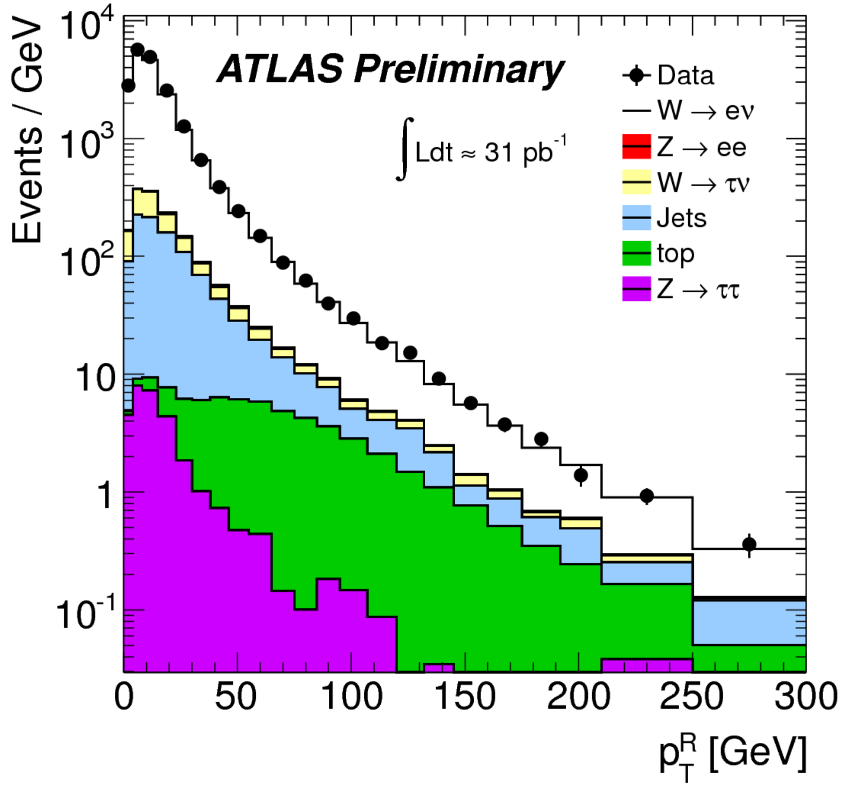



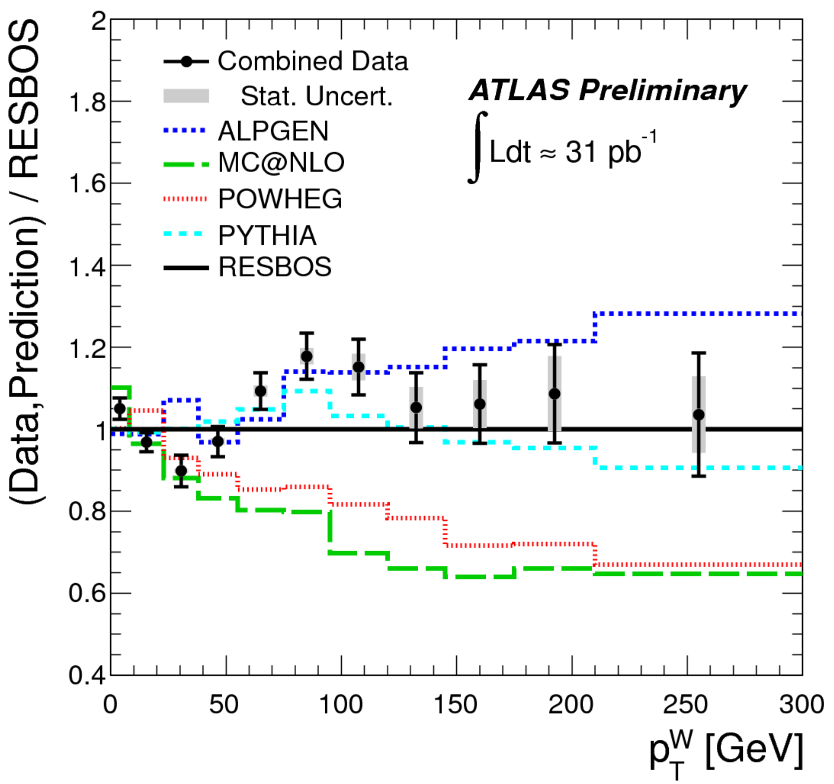
# $p_T$ distribution of W bosons

First direct measurement of the W boson transverse momentum spectrum by ATLAS.

W boson transverse momentum ($p_T^W$) is inferred from the energy deposition in the calorimeter from the recoil to the W.

Detector and FSR effects removed by "unfolding"
(invert a response matrix that parameterises the probabilistic mapping from recoil $p_T^R$ to W boson $p_T^W$).



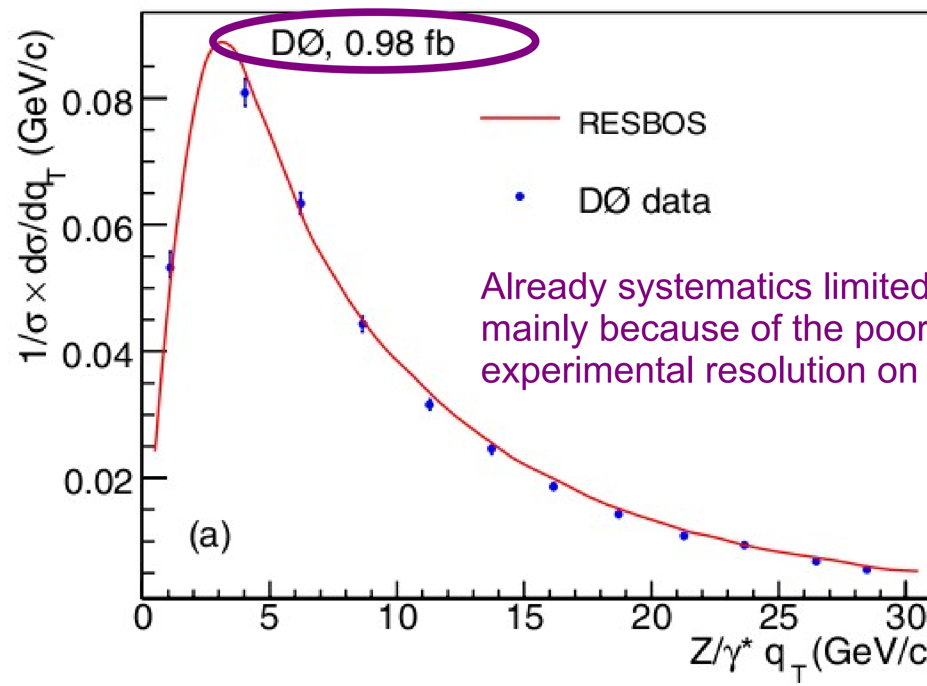
# $p_T$ distribution of Z bosons

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

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]
T. Andeen,[54] S. Anderson,[46] B. Andrieu,[17] M. S. Anzelc,[54] Y. Arnoud,[14] M. Arov,[61] M. Arthaud,[18] A. Askew,[50]




Already systematics limited, mainly because of the poor experimental resolution on $p_T(Z)$.

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

Phys. Rev. Lett. **106**, 122001 (2011)

Fermilab-Pub-10-403-E

**Precise study of the $Z/\gamma^*$ 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 $\phi^*_\eta$, which probes the same physical effects as the $Z/\gamma^*$ 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 $\phi^*_\eta$ 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.

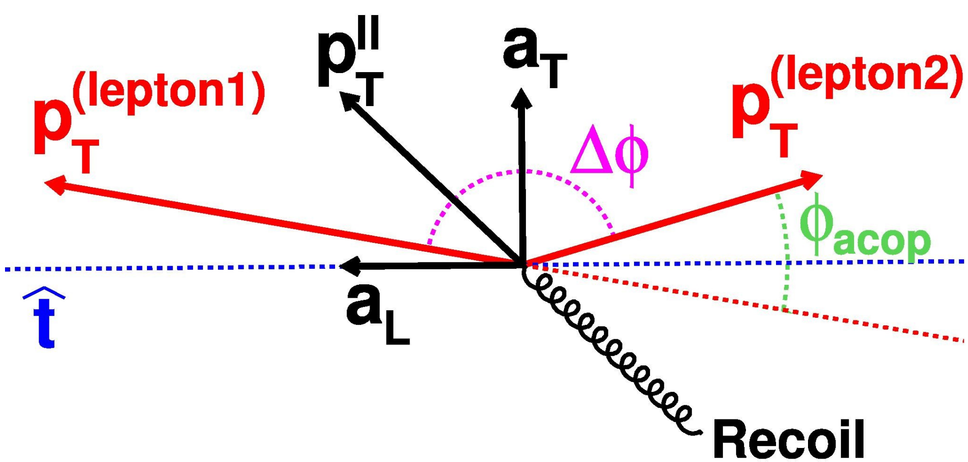
The next-generation DØ measurement (7.3 fb$^{-1}$) has just been published.
It avoids the resolution issues with $p_T(Z)$ by using an alternative observable that is sensitive to the same physics, but much less sensitive to lepton $p_T$ resolution:

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

$\phi_{acop}$ and $\theta_\eta^*$ only depend on lepton *directions*

=> $\phi_\eta^*$ 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 $p_T(Z)$:

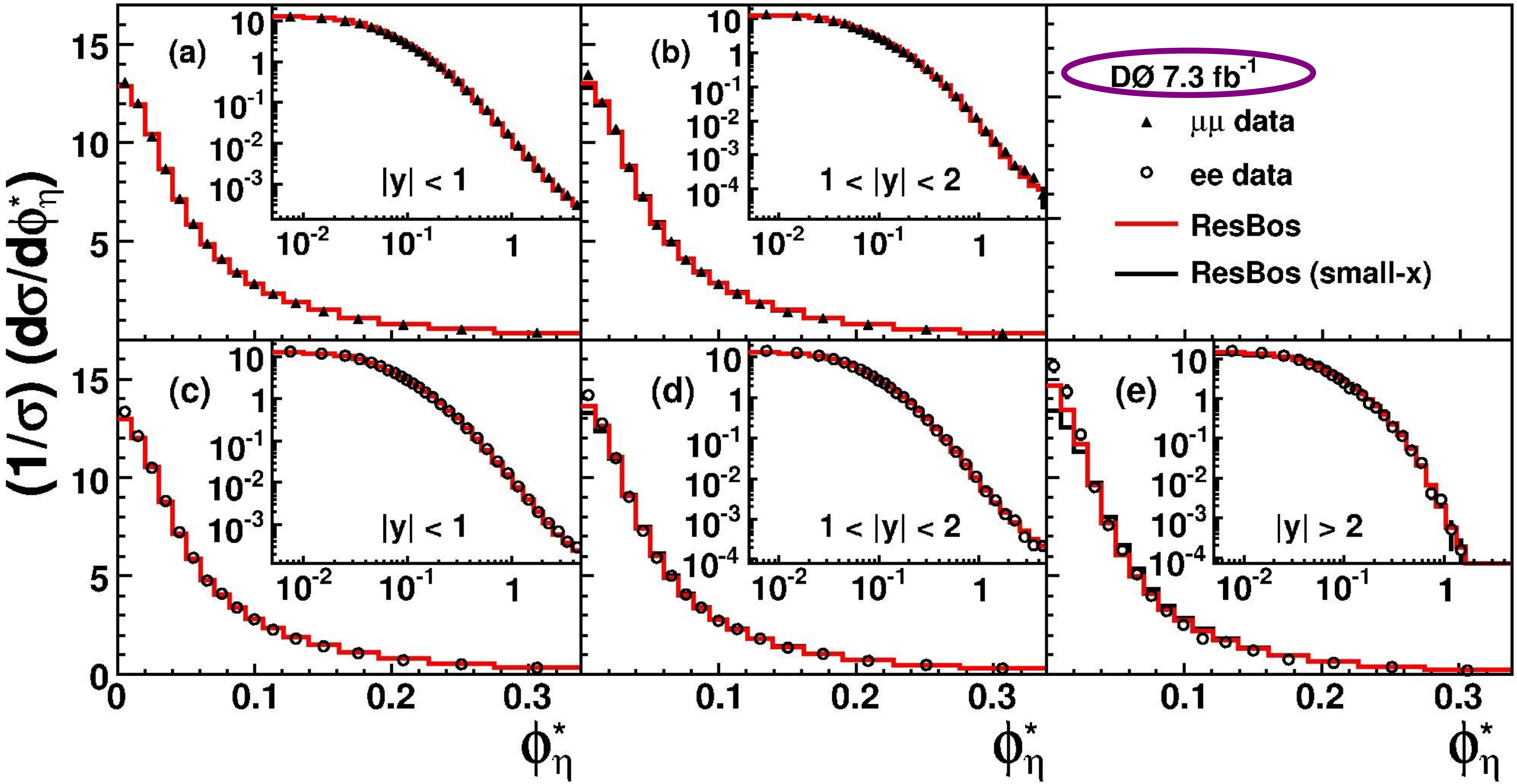
M. Vesterinen and T.R. Wyatt, Nucl. Instrum. Methods Phys. Res. A 602, 432 (2009).

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

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

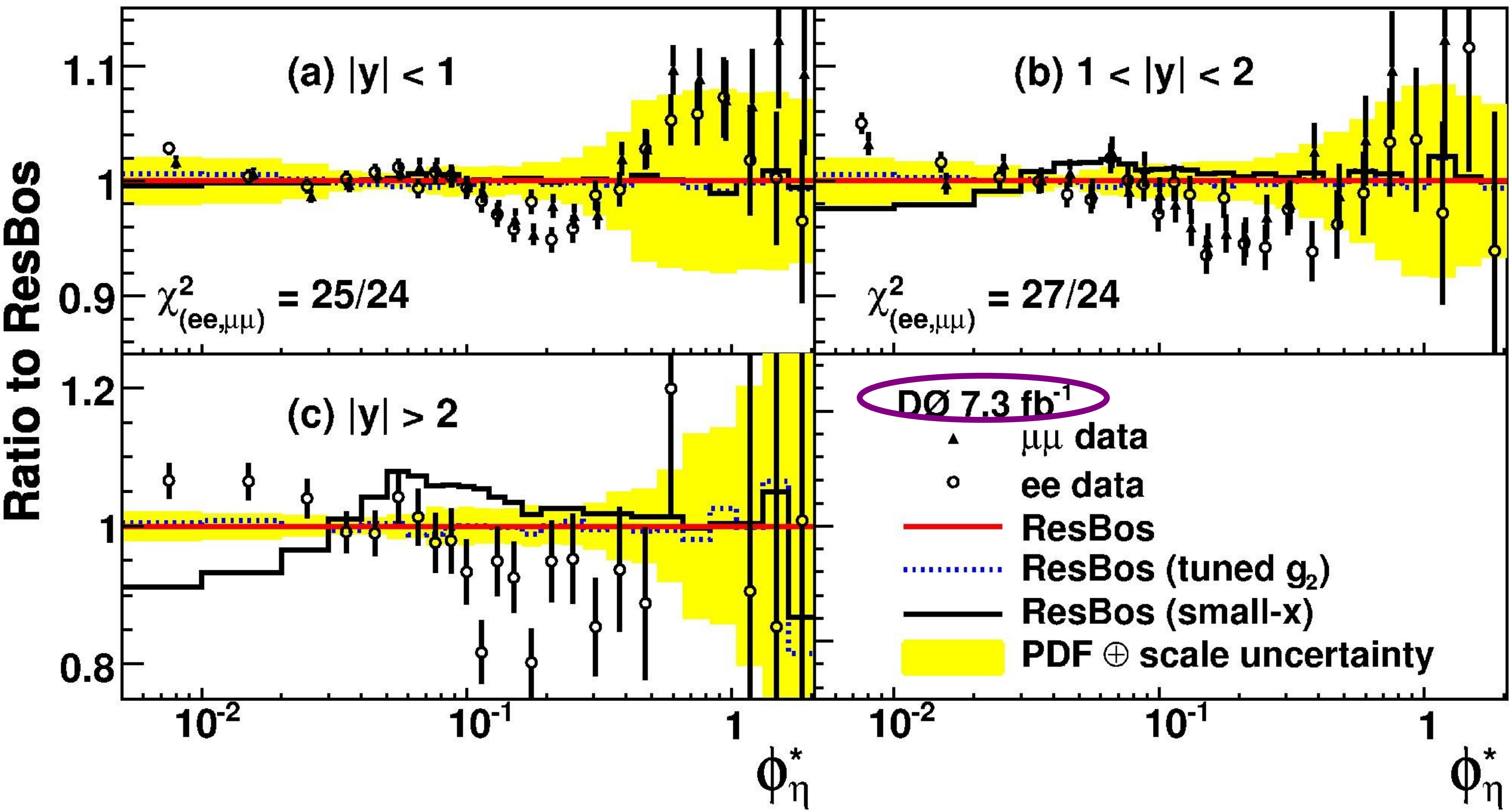
**Unfolded data (ee and μμ channels shown separately) in three bins of Z rapidity:**

(455k Z → ee/ 511k Z →μμ decays)



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

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



# 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)

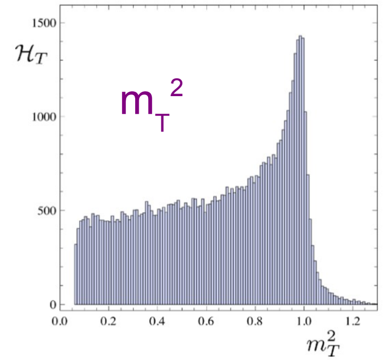
- Reduce the impact of the PDF uncertainties on W boson mass

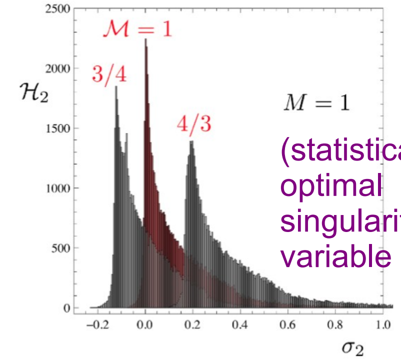
  by extending the η coverage as much as possible
  (challenging: understanding lepton energy scale and pile-up and
  backgrounds in the forward detectors)

- 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)




(statistically) optimal singularity variable

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

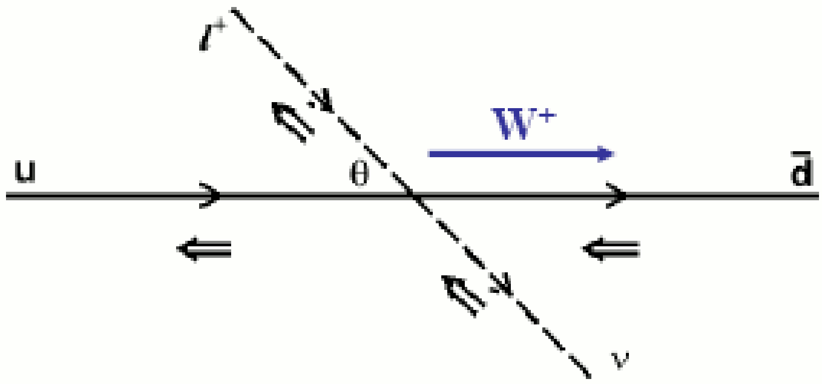
# W charge asymmetry

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

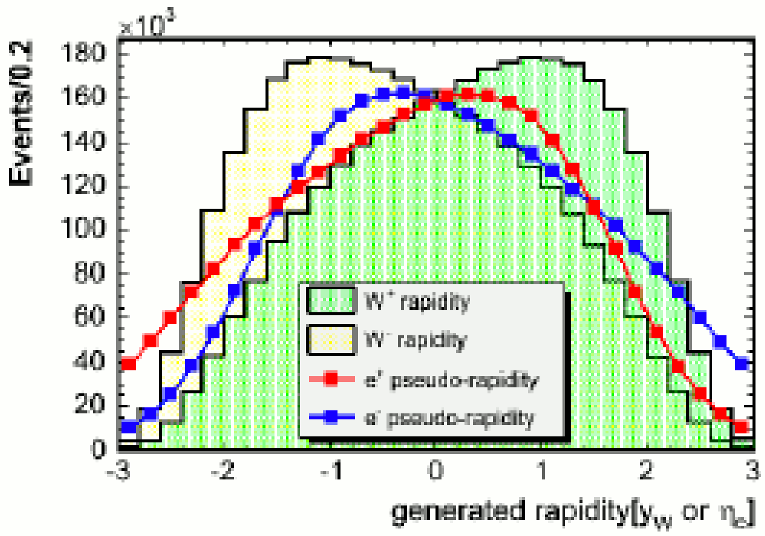
$$\boxed{x_{1,2} = \frac{M_W}{\sqrt{s}} e^{\pm y}}$$

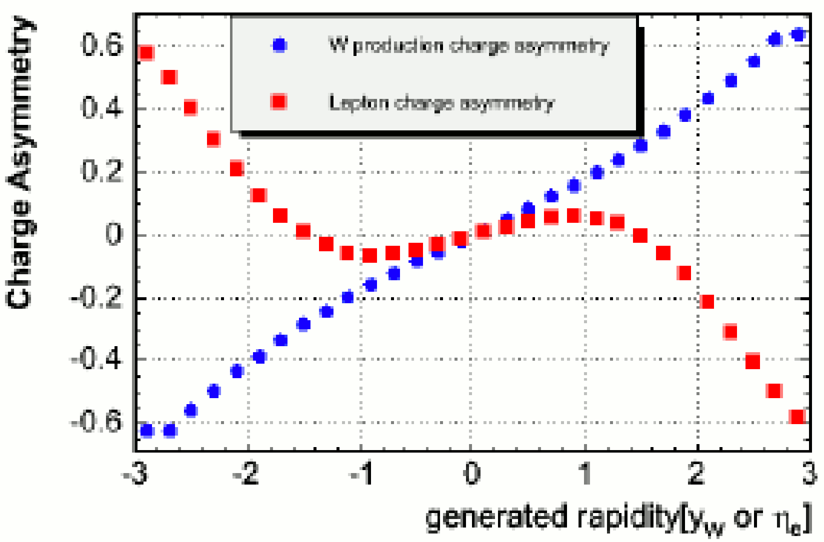
Different u, d momentum:
**$W^{\pm}$ produced asymmetrically**.

→ charge asymmetry of l, ν from W decay

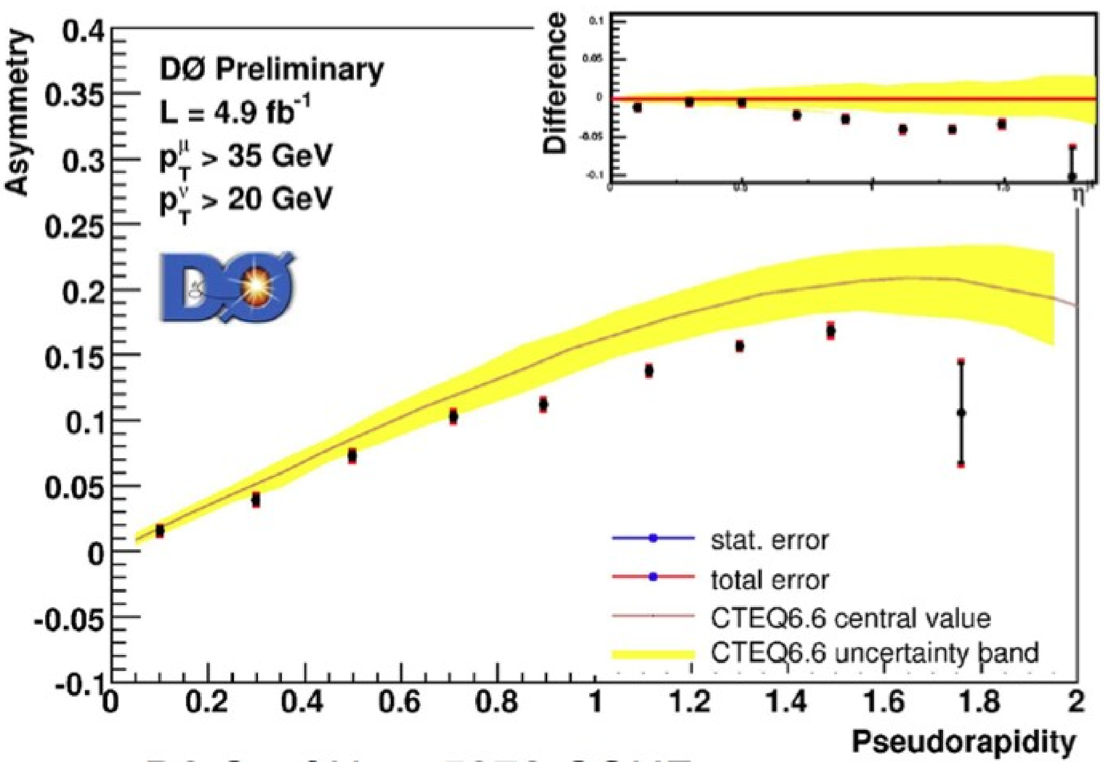



But V-A interaction: **reduces** the observable **asymmetry** in the lepton rapidity distributions.



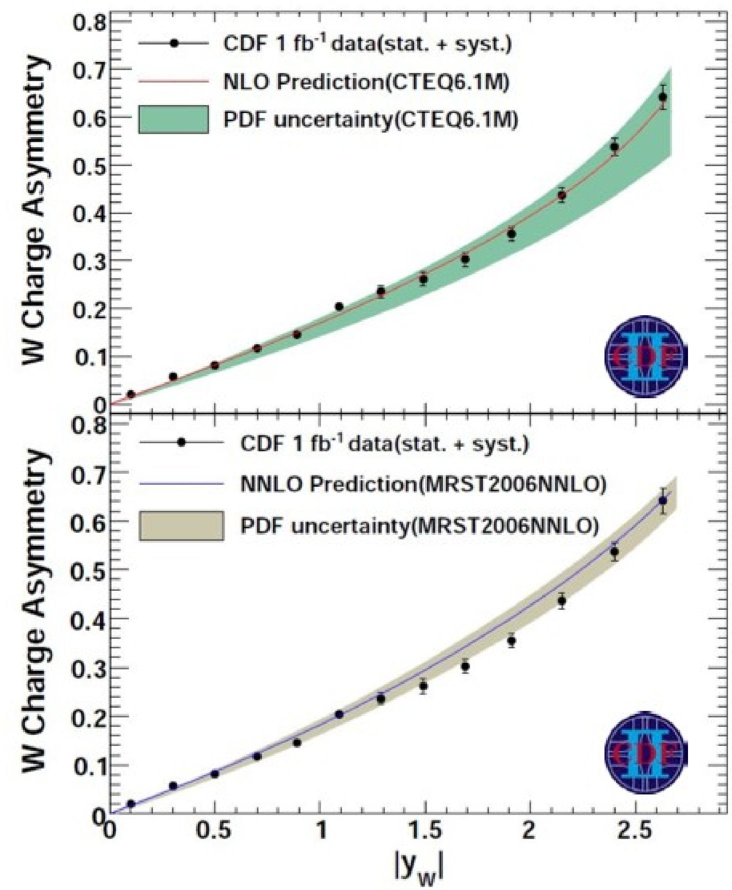



# W charge asymmetry

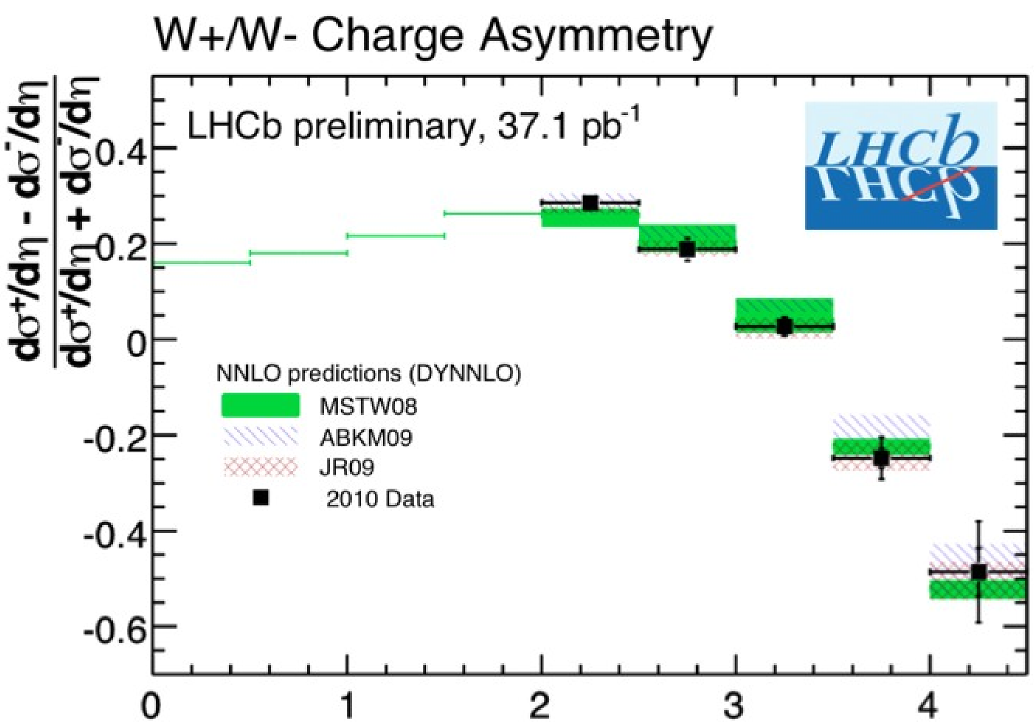



D0 Conf Note 5976-CONF

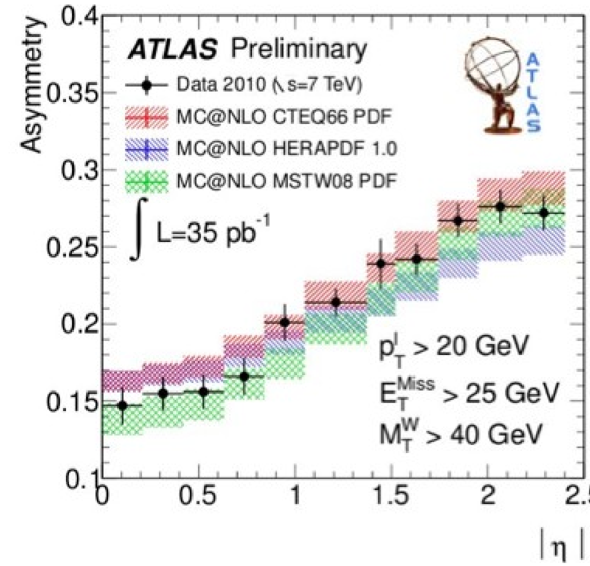
PRL 102:181801



# W charge asymmetry




LHCb-CONF-2011-039

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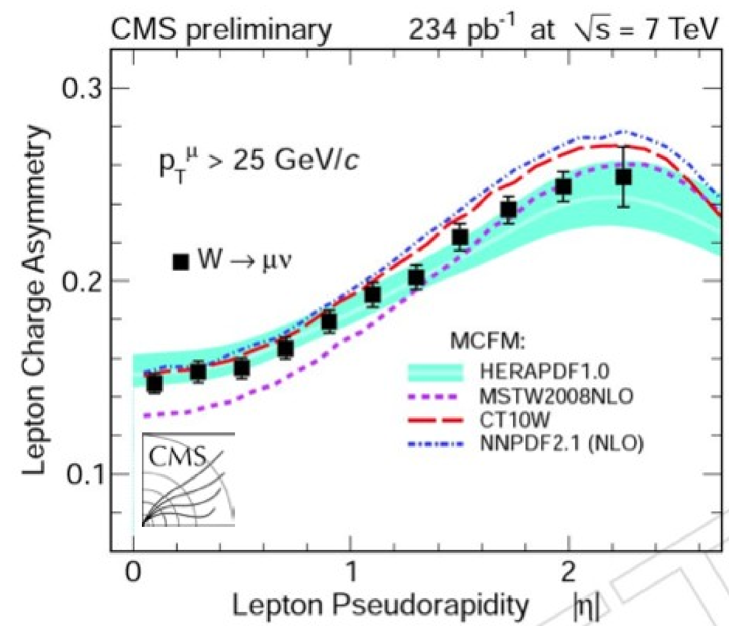



CMS-EWK-11-005

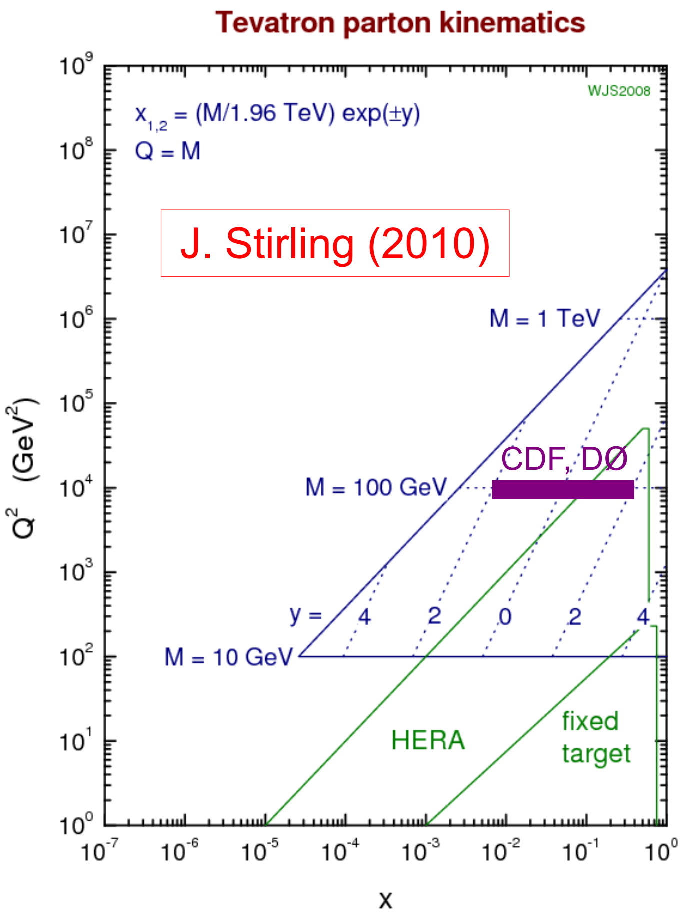
# Tevatron vs. LHC

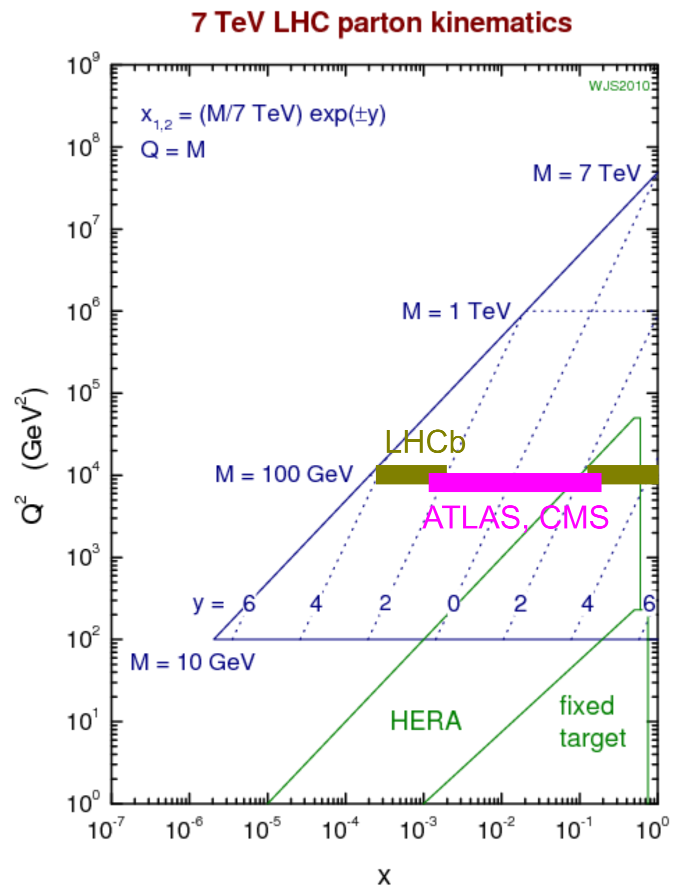
**W or Z production (first order):**

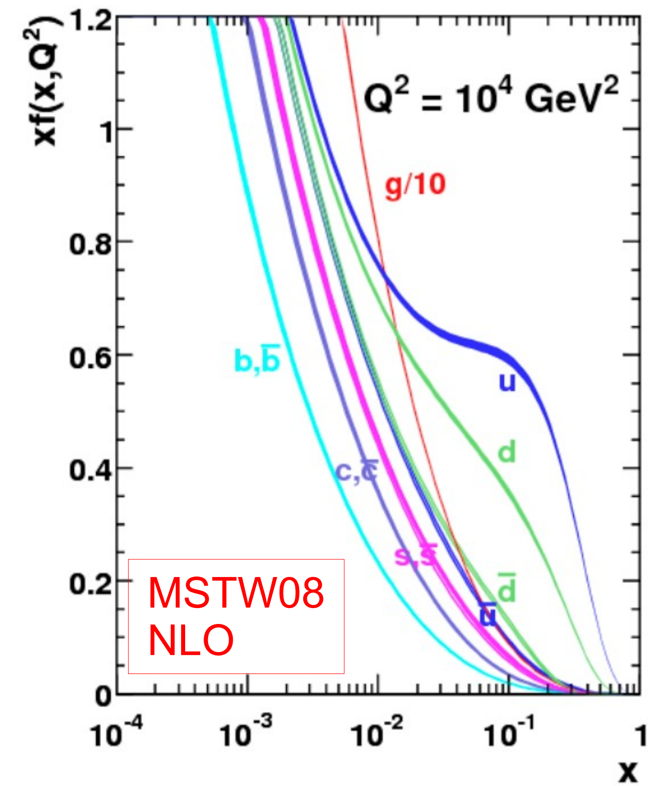
Tevatron: collision of valence quark (u,d) from proton and valence anti-quark from anti-proton

LHC: collision of valence quark (u,d) from proton and sea anti-quark from proton
typically $10^{-4} < x < 10^{-1}$, *i.e.* sea-sea contributions are also important

$$u+\bar{d}\,(\bar{s})\rightarrow W^{+}$$
$$d+\bar{u}\,(\bar{c})\rightarrow W^{-}$$

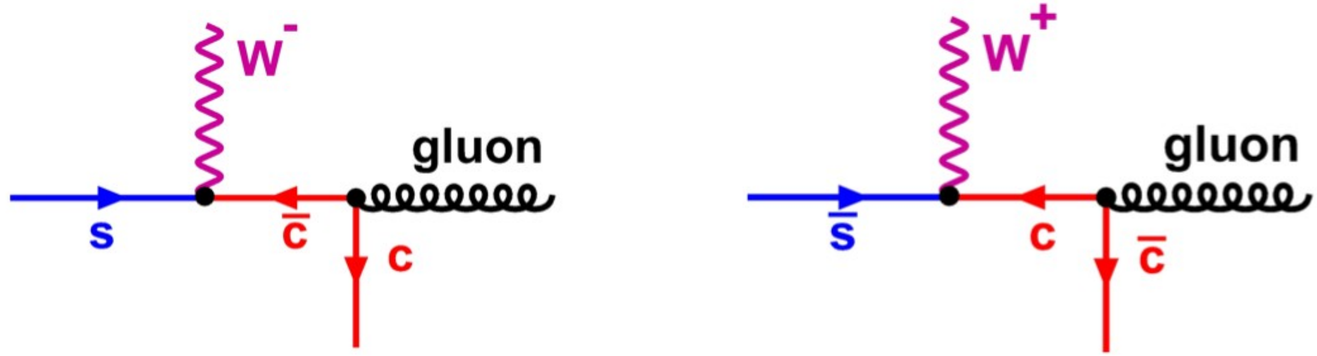


# W + c at CMS

At LHC: $p\,p \rightarrow W + c + X$ largely dominated by $\bar{s}\,g \rightarrow W^+\,\bar{c}$ and $s\,g \rightarrow W^-\,c$ :




**Probes s and $\bar{s}$ content of the proton.**

(For a measurement of the W boson mass, the process $p\,p \rightarrow W + c + X$ is also interesting by itself because it introduces a difference between the hadronic recoil in W events and in the Z events used for calibration [there is no Z equivalent of the diagrams above]).

**Select W + ≥1 jet events in the muon channel:**

Transverse mass: $m_T > 50$ GeV

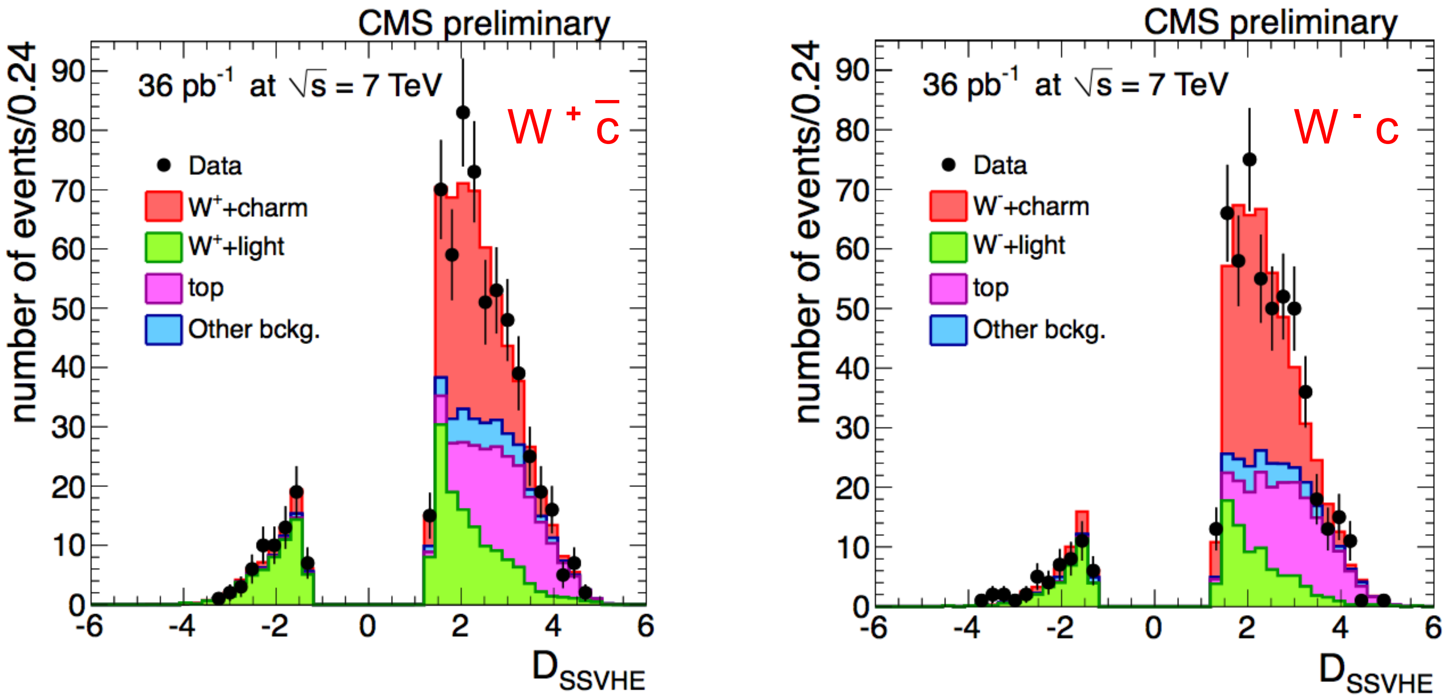
Jet $E_T > 20$ GeV

**Require secondary vertex** with ≥2 associated tracks and significantly displaced from primary vertex

b-tagging discriminant $D_{SSVHE}$ built from distance between primary and secondary vertex

# W + c at CMS

b-tagging discriminant $D_{SSVHE}$ built from distance between primary and secondary vertex




Fit of four templates to the $D_{SSVHE}$ distribution observed in data.

**For leading jet with $E_T$ > 20 GeV and $|\eta|$ < 2.1 :**

$$R_c^{\pm} \equiv \sigma(W^+\bar{c})/\sigma(W^-c)$$

$$R_c^{\pm} = 0.92 \pm 0.19\ (stat.) \pm 0.04\ (syst.)$$

$$R_c \equiv \sigma(W+c)/\sigma(W+jets)$$

$$R_c = 0.143 \pm 0.015\ (stat.) \pm 0.024\ (syst.)$$

Results in agreement with NLO predictions.

# Z/γ* forward-backward asymmetry

- **In the process:** $q\bar{q} \rightarrow Z/\gamma^* \rightarrow e^+e^-$
- **fermion-γ* coupling contains only vector component**
- **fermion-Z coupling contains both vector and axial-vector components**

**Vector coupling:** $g_v^f = I_3^f - 2Q_f \sin^2\theta_W$

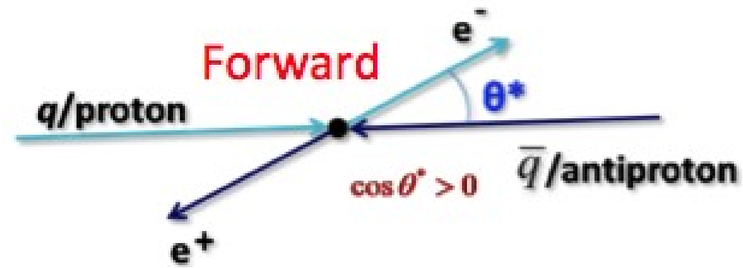
**Axial-vector coupling:** $g_a^f = I_3^f$

**effective weak mixing angle**

- **Give rise to non-zero Forward-Backward Asymmetry ($A_{FB}$) in the final states**

$$\frac{d\sigma(q\bar{q} \rightarrow e^+e^-)}{d\cos\theta^*} = A(1-\cos^2\theta^*) + B\cos\theta^*$$

**functions of vector and axial-vector couplings.**




**$A_{FB}$ is related to :**

$$A_{FB} = \frac{\sigma_F - \sigma_B}{\sigma_F + \sigma_B} = \frac{3}{8}\cdot\frac{B}{A} = f(\boxed{g_v^f, g_a^f, sin^2\theta_w}, \ldots)$$

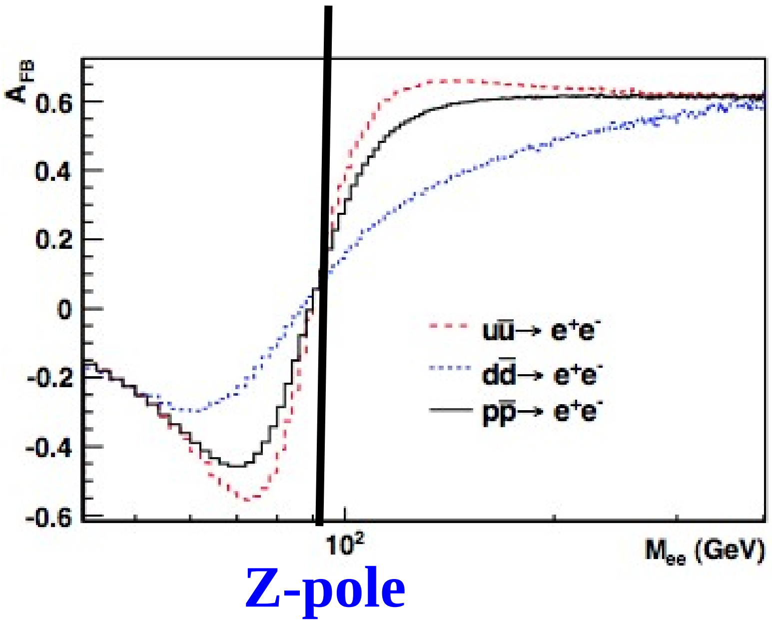
**Forward:** $\cos\theta^* > 0$ **Backward:** $\cos\theta^* < 0$

# Z/γ* forward-backward asymmetry

**Tevatron**

- **At Tevatron, Z/γ* is mostly produced by light valence quark pair, u-ubar or d-dbar**
- **From the observable $A_{FB}$, we can:**
- **Precisely measure $\sin^2\theta_w$ based on Z to light quark couplings**
- **Directly probe the coupling of Z/γ* to light quarks**

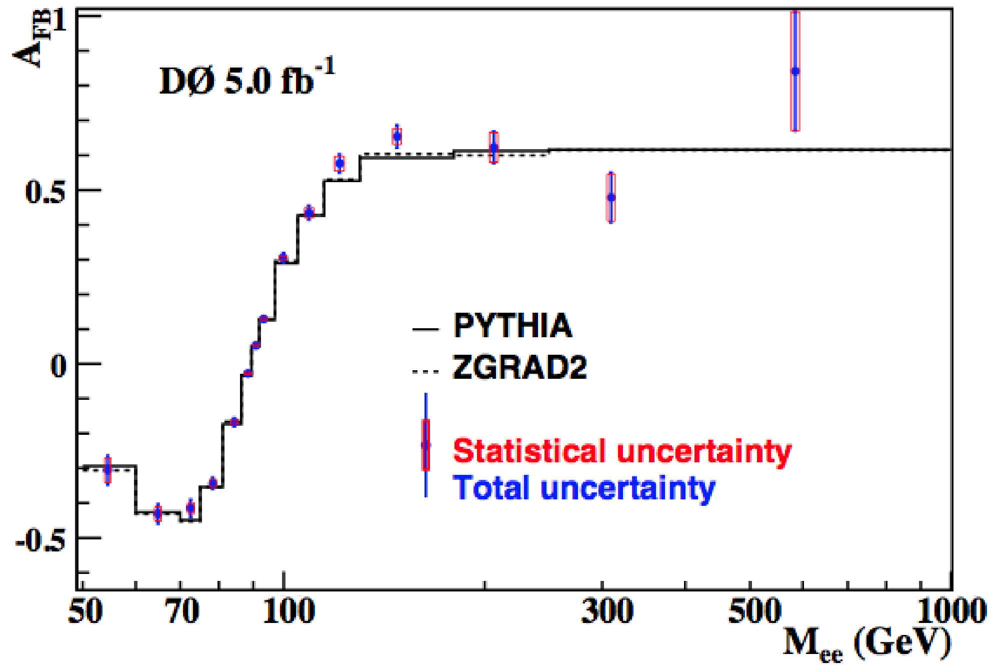
- **Investigate possible new phenomena, e.g. new neutral gauge boson Z'**
- **Around Z-pole, $A_{FB}$ is dominated by interference of vector and axial-vector couplings of Z to quarks**
- **Far away above Z-pole, $A_{FB}$ is dominated by Z/γ* interference, which is sensitive to new physics.**

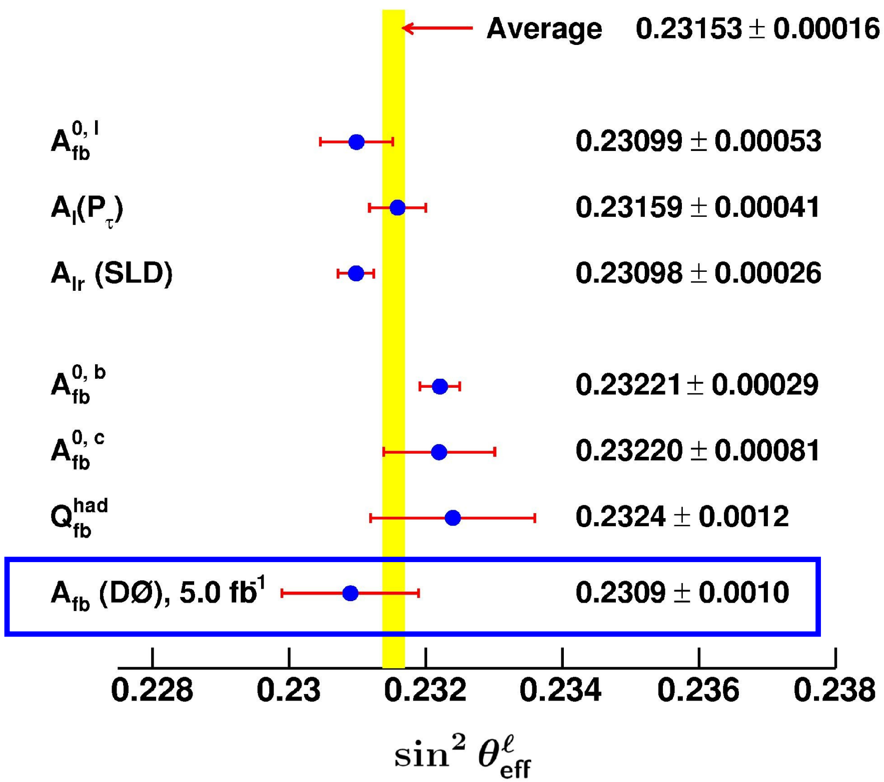


# Z/γ* forward-backward asymmetry

- **Unfolded AFB agrees well with theoretical prediction**
- **No evidence for new physics at high mass**
- **Extracted $\sin^2\theta^l_{eff}$**

**= 0.2309 ± 0.0008 (stat.) ± 0.0006 (syst.)**

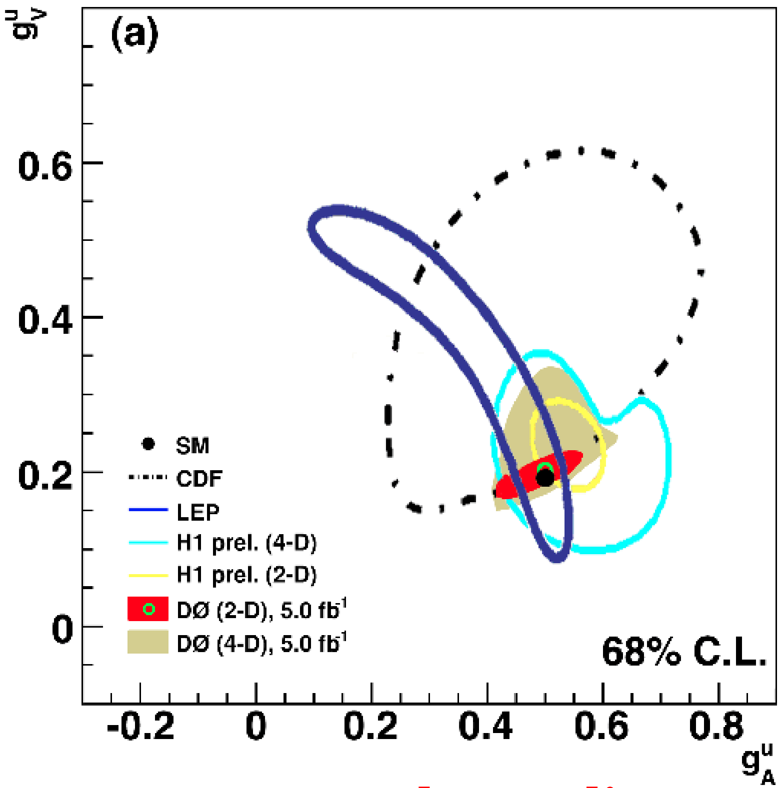


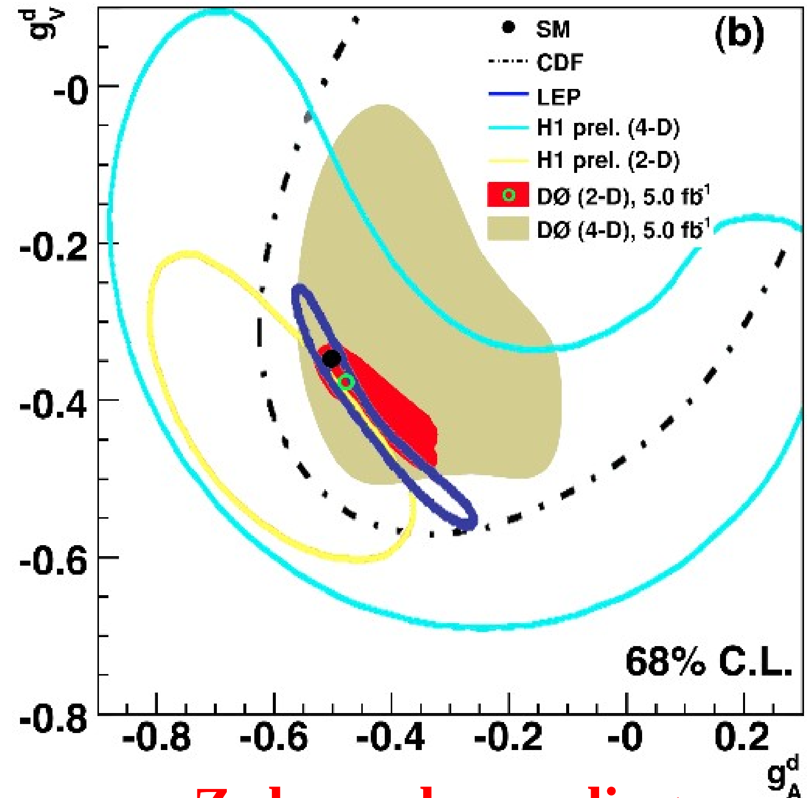

- **Statistical uncertainty is still dominant**
- **PDF uncertainty (0.00048) is dominant in systematic uncertainty**
- **Most precise measurement based on Z to light quark couplings**

***Published: Phys. Rev. D 84, 012007 (2011)***

# $Z/\gamma^*$ forward-backward asymmetry




**Z-u quark couplings**



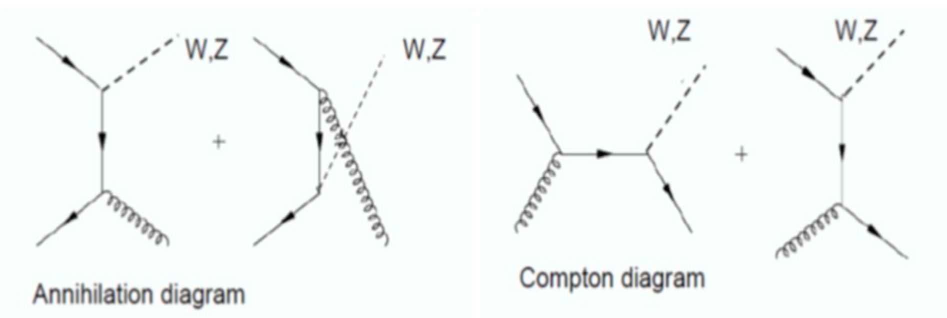

**Z-d quark couplings**

**Most precise direct measurement of couplings of Z to light quarks u and d.**

***Published: Phys. Rev. D 84, 012007 (2011)***

# "Z/γ* forward-backward asymmetry"

LO annihilation ($q\bar{q} \to \gamma^*/Z\, g$) and Compton ($qg \to \gamma^*/Z\, q$) diagrams for production of Z bosons at *finite transverse momentum*:




General expression for angular distribution of final state electron in the Collins-Soper frame:

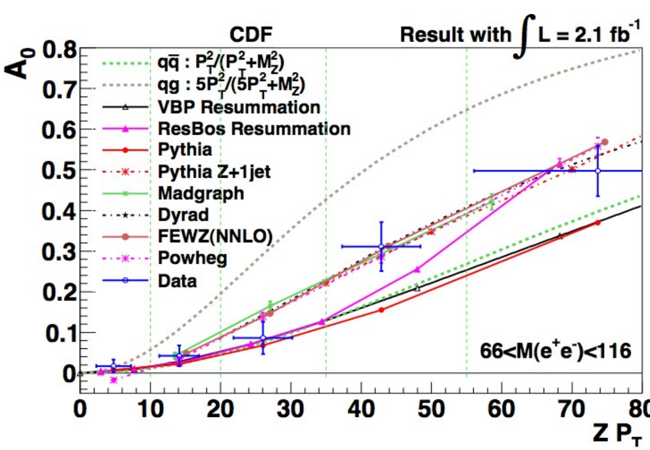
$$
\begin{aligned}
\frac{d\sigma}{d\cos\theta d\phi} \;\propto\; & (1+\cos^2\theta) \\
+\; & \frac{1}{2}A_0(1-3\cos^2\theta) + A_1 \sin 2\theta \cos\phi \\
+\; & \frac{1}{2}A_2 \sin^2\theta \cos 2\phi + A_3 \sin\theta \cos\phi \\
+\; & A_4 \cos\theta + A_5 \sin^2\theta \sin 2\phi \\
+\; & A_6 \sin 2\theta \sin\phi + A_7 \sin\theta \sin\phi .
\end{aligned}
$$

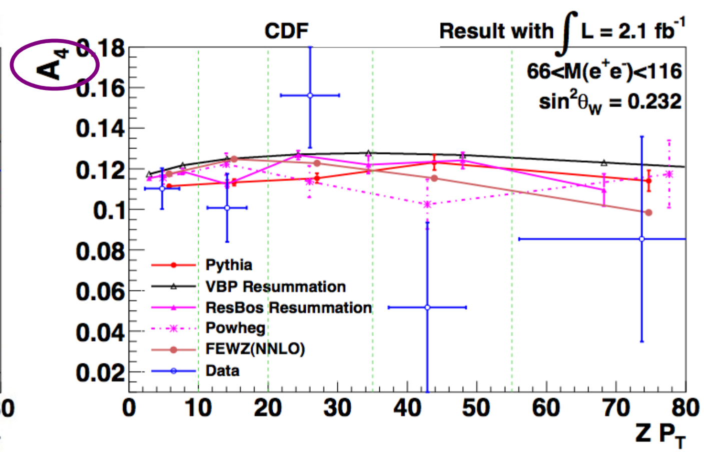
$A_i$ are functions of mass, rapidity and $p_T$ of the dilepton system.

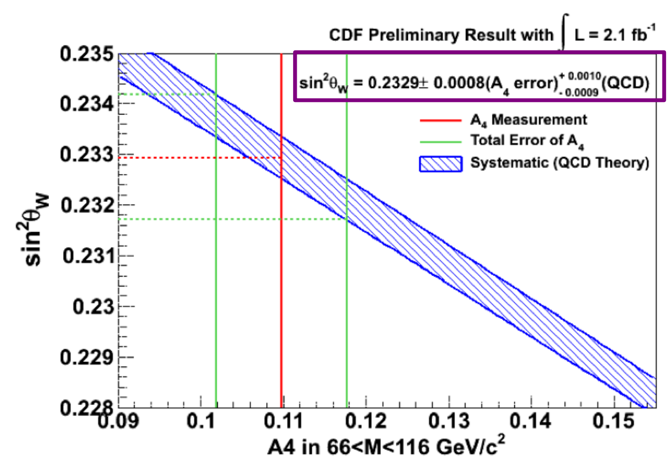
Detailed measurements of the $A_i$ are available from CDF.

A lot of physics can be extracted from these measurements (determination of spin of the gluon, test of Lam-Tung relation, relative importance of annihilation and Compton diagrams, …).

We discuss this measurement here because the weak mixing angle can be extracted from $A_4$.

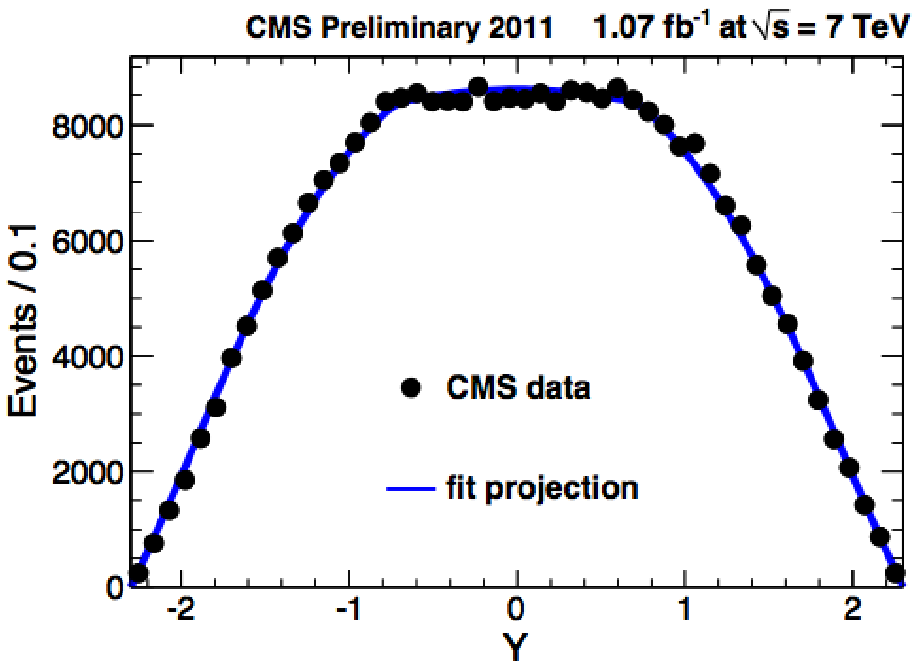


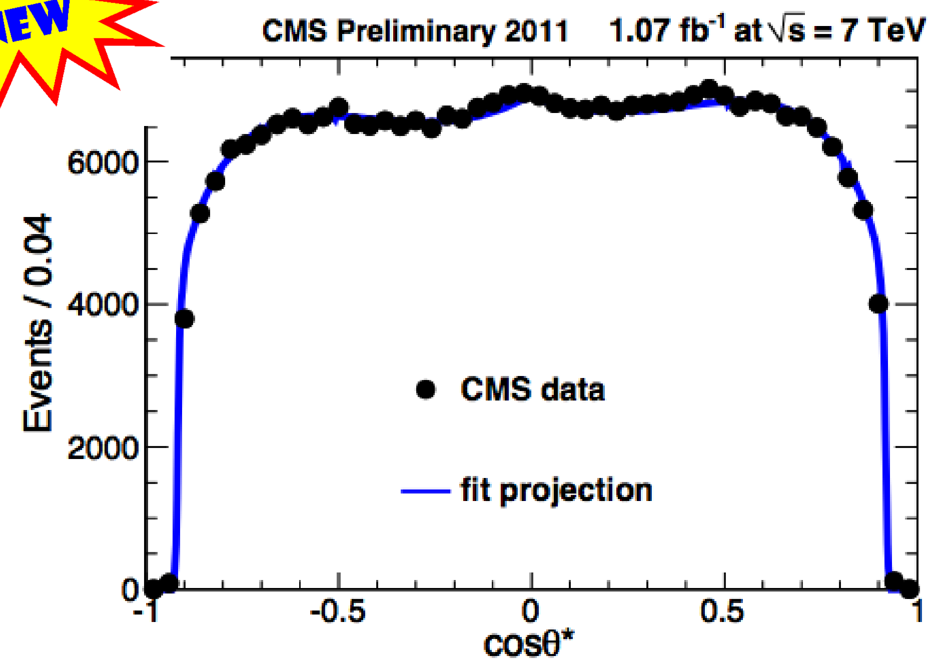



# Z/γ* forward-backward asymmetry

A first measurement of the effective weak mixing angle at the LHC is available from CMS.








The effective weak mixing angle is extracted from the di-muon data using an unbinned extended maximum-likelihood fit.

In this fit, each event is characterised by three observables: di-lepton rapidity, di-lepton invariant mass squared, cos $\theta^*_{CS}$

Result: $\sin^2\theta_{\mathrm{eff}} = 0.2287 \pm 0.0020(\mathrm{stat.}) \pm 0.0025(\mathrm{syst.})$

| source | correction | uncertainty |
|---|---|---|
| PDF | – | ±0.0013 |
| FSR | – | ±0.0011 |
| LO model (EWK) | – | ±0.0002 |
| LO model (QCD) | +0.0012 | ±0.0012 |
| resolution and alignment | +0.0007 | ±0.0013 |
| efficiency and acceptance | – | ±0.0003 |
| background | – | ±0.0001 |
| total | +0.0019 | ±0.0025 |

# Conclusions

Global EWK fit: good agreement between standard model (SM) and precision measurements.

Can use SM EWK fit to predict mass of the hypothetical Higgs boson.

Limiting factor here is the experimental precision on the W boson mass m(W).

Current central value of m(W) prefers non-standard Higgs boson.

If experimental uncertainty on m(W) can be reduced to 15 MeV and the central value remains the same, the standard Higgs would be excluded at 95 % CL.

15 MeV precision is within reach at the Tevatron.

Similar level of precision can be achieved at LHC once the detectors are sufficiently well understood.

Wealth of “supporting” precision measurements of W/Z production and decay properties are available from Tevatron and the LHC.

In many cases, the two colliders are complementary (e.g. constrain different aspects of PDFs, …).

These measurements are needed for m(W), and they are rich in physics by themselves.

As is well known, some tension in the global EWK fit between precision SLD and LEP data.

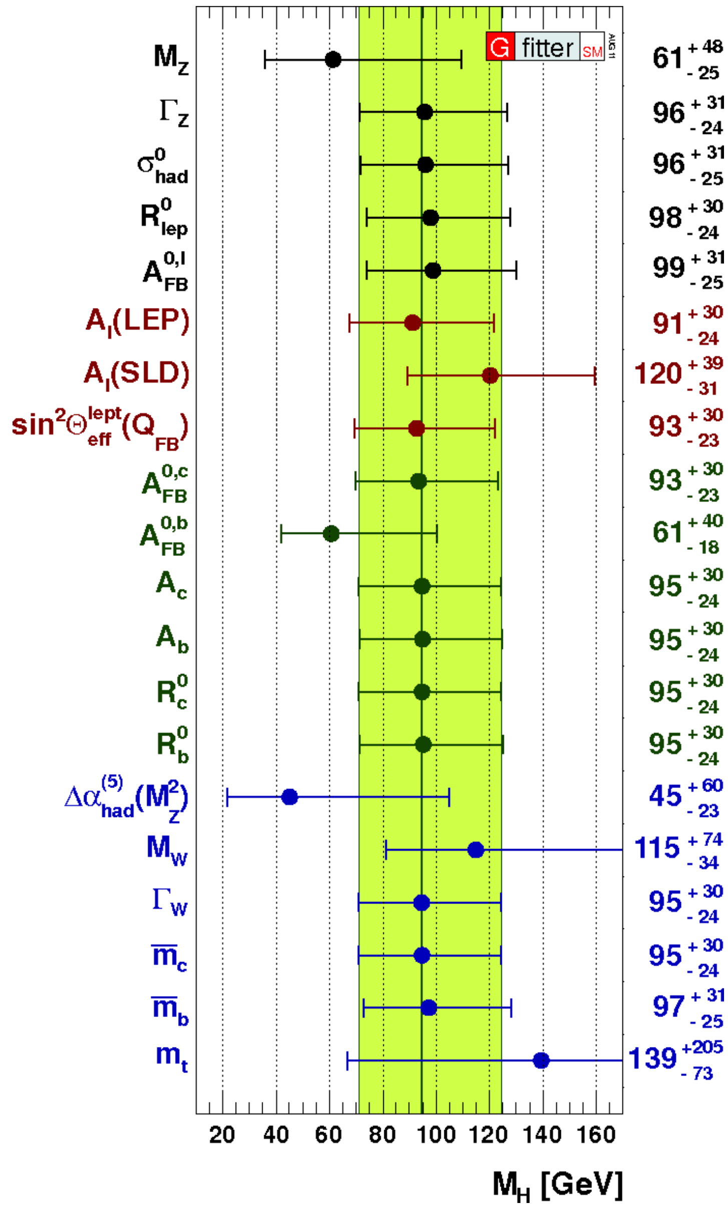
Tevatron and LHC measurements of weak mixing angle could become precise enough to shed some light on this.

Tevatron is still the reference for precision EWK physics in hadron collisions,
but LHC experiments reaching impressive precision at truly amazing speed.

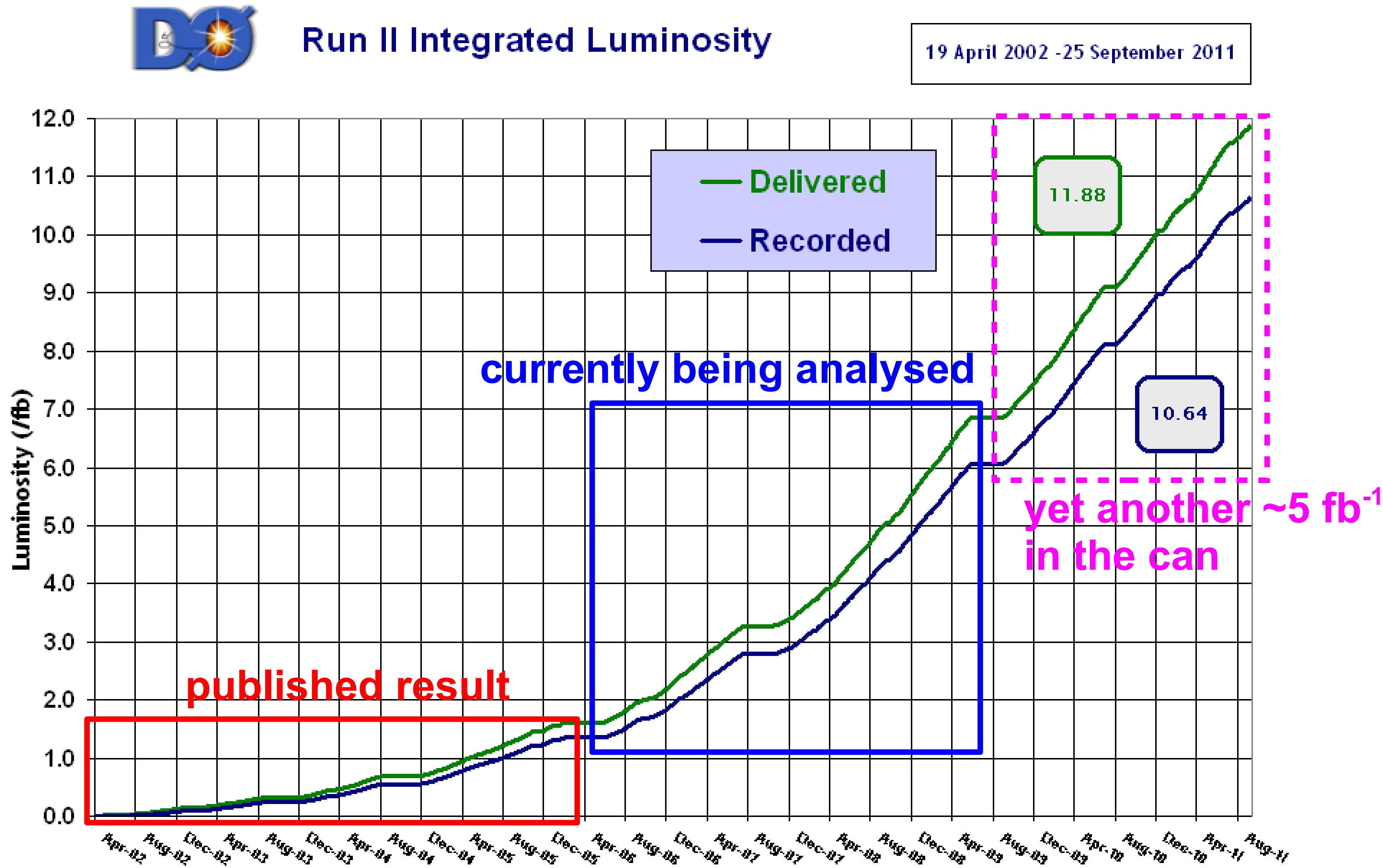
Progress in theory / MC generators continues to be essential for precision measurements.

# Backup slides

# Gfitter – removing one input at the time



# D0 data periods and m(W) analyses



# D0 projections

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

published Run IIa analysis

expected after analysis of full Run IIb dataset

expected after current Run IIb analysis

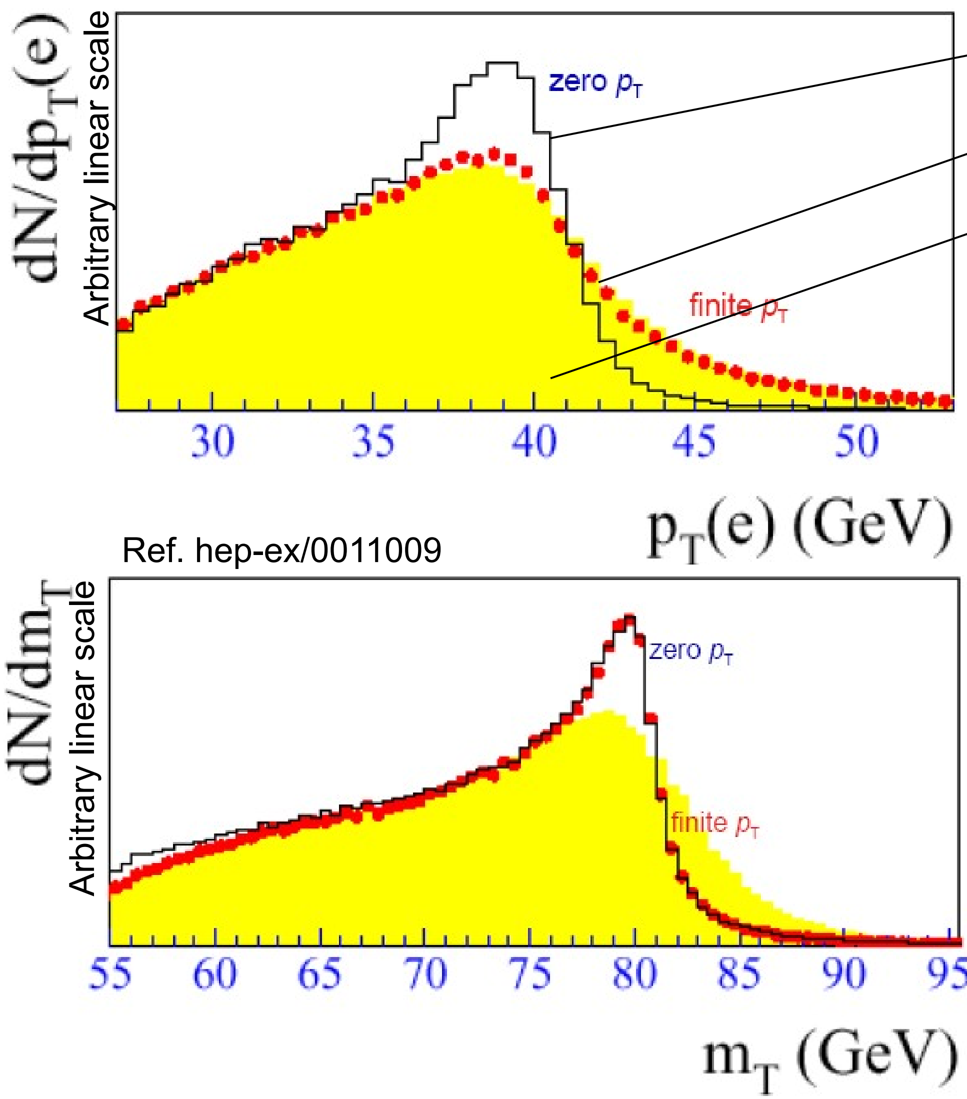
| source of uncertainties | 1 fb-1 | 6 fb-1 | 10 fb-1 |
|---|---|---|---|
| Statistics | 23 | 10 | 8 |
| Systematics | | | |
| Electron energy scale | 34 | 14 | 11 |
| Electron resolution | 2 | 2 | 2 |
| Electron energy offset | 4 | 3 | 2 |
| Electron energy loss | 4 | 3 | 2 |
| Recoil model | 6 | 3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

Here we are benefiting from the fact that our experimental systematics are mainly due to limited Z statistics (and whence become smaller with more data)

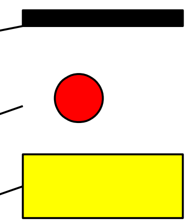
Assumes:
- reduction in PDF uncertainties (e.g. W charge asymmetry)
- reduction of sensitivity to PDF uncertainties (include EC electrons !)

Assumes more work on our treatment of FSR and EWK corrections and the assessment of associated uncertainties

# Experimental observables




Ref. hep-ex/0011009



No $P_T(W)$

$P_T(W)$ included

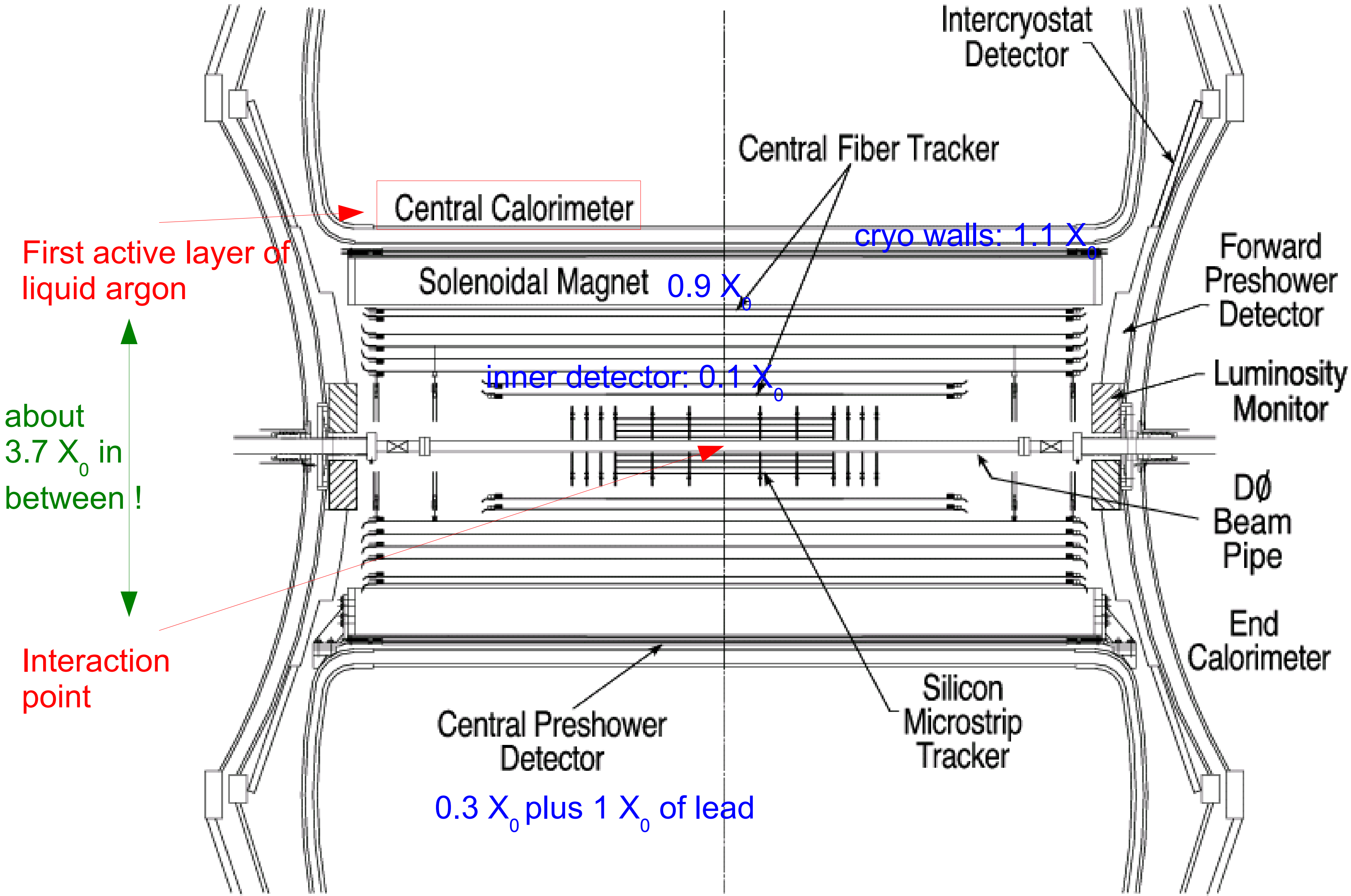
Detector Effects added

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

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

$M_T$ most affected by measurement of missing transverse momentum

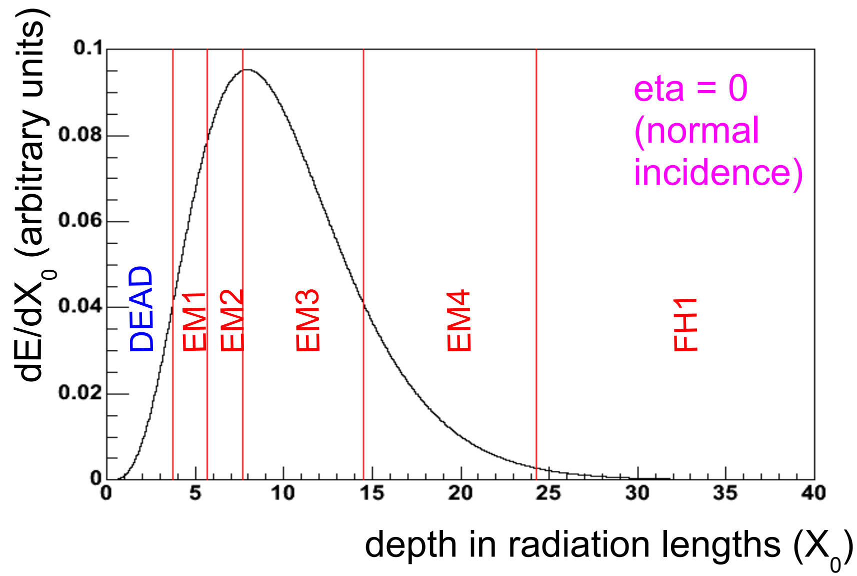
# Keep in mind: the CAL is not alone !



# Need more information: additional observables

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

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

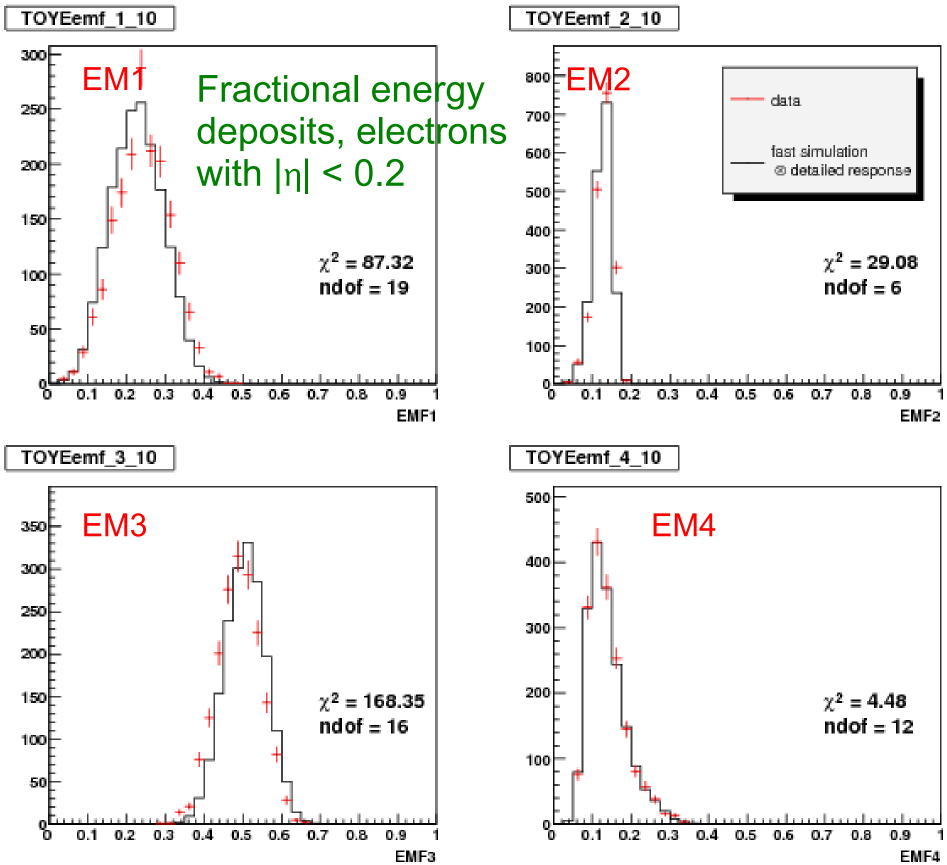



Using the longitudinal segmentation to get a handle on material is a standard technique, it is discussed in the textbooks (e.g. Wigmans).

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

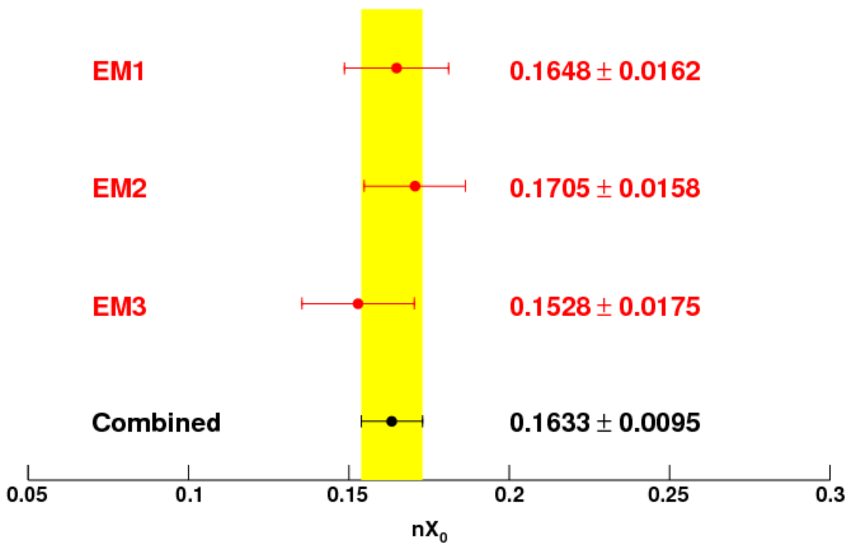
# Before tuning of material model

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

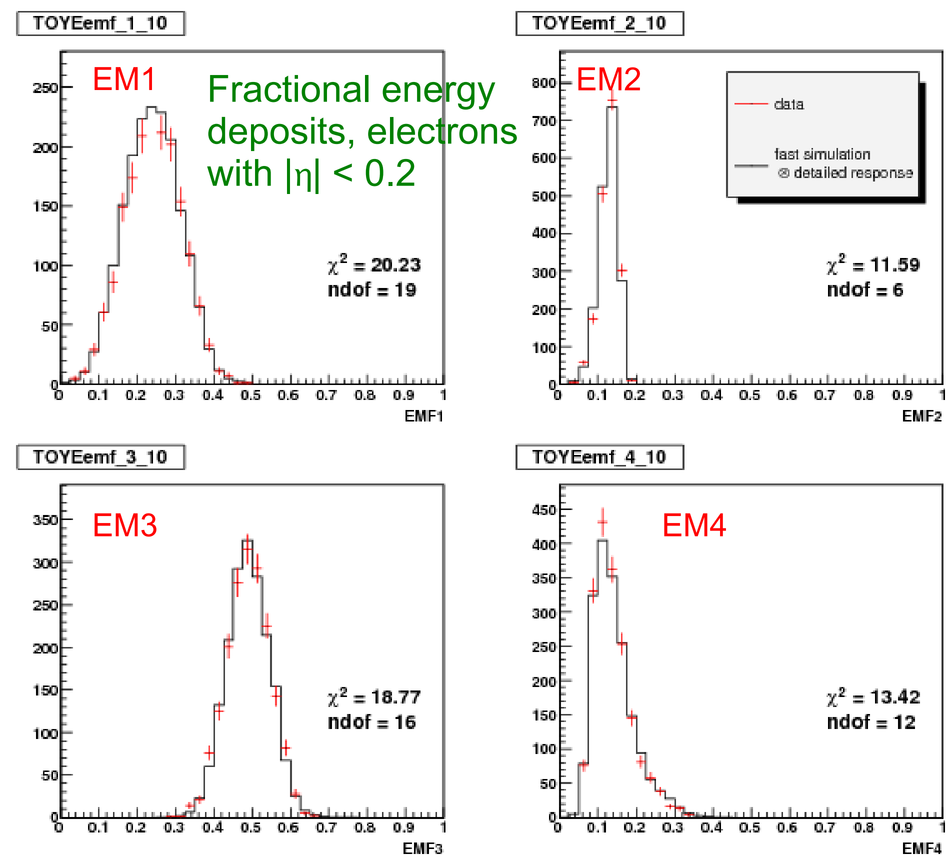


# After tuning of material model

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




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



# Recoil model

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

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

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

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

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

**Soft component,**
**not correlated with vector boson.**

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

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

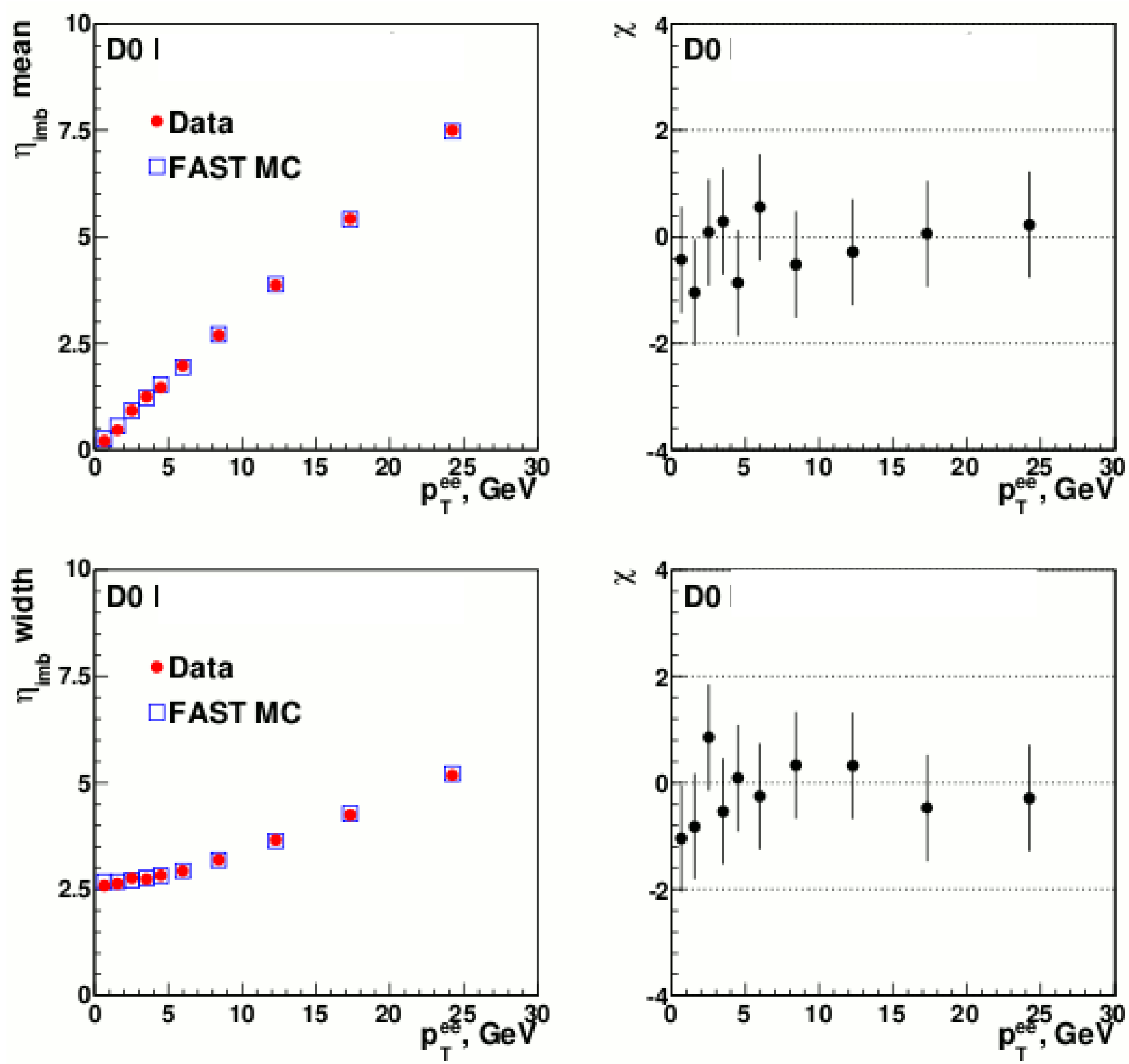
Recoil energy "lost" into the **electron cones**.
Electron energy leakage outside cluster.

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

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

# Recoil calibration

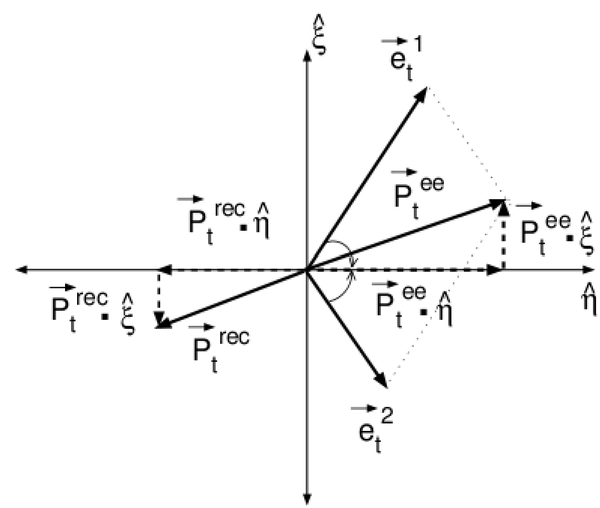
Final adjustment of free parameters in the recoil model is done *in situ* using balancing in Z → e e events and the standard UA2 observables.



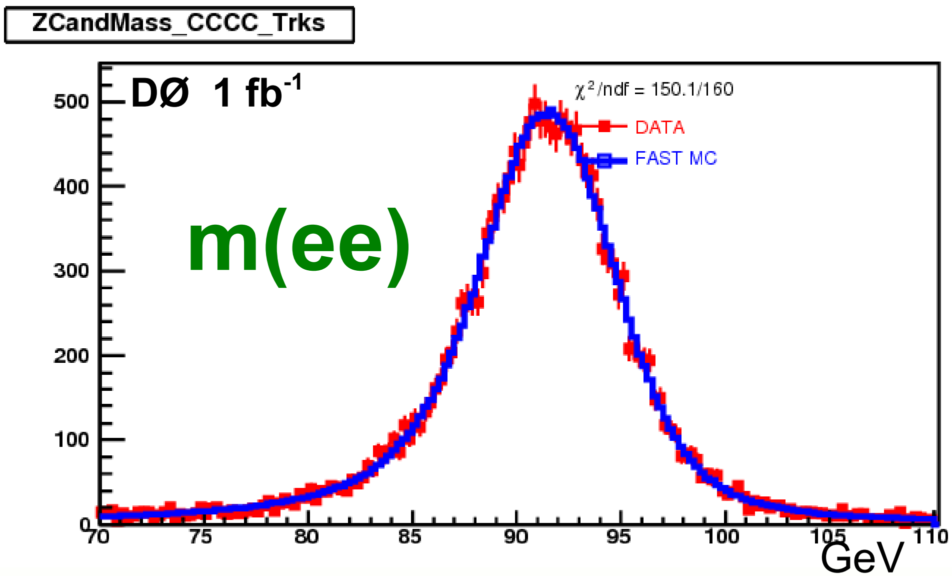

UA2 observables:
In transverse plane, use a coordinate system defined by the bisector of the two electron momenta.

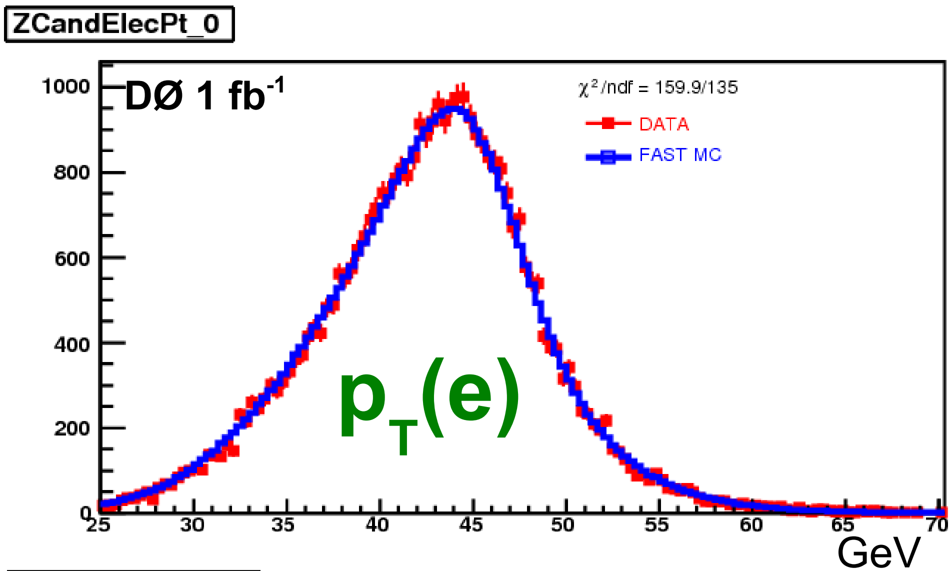
$$\eta\text{-imbalance}: (\vec{P}_t^{ee} + \vec{P}_t^{rec}) \cdot \hat{\eta}$$

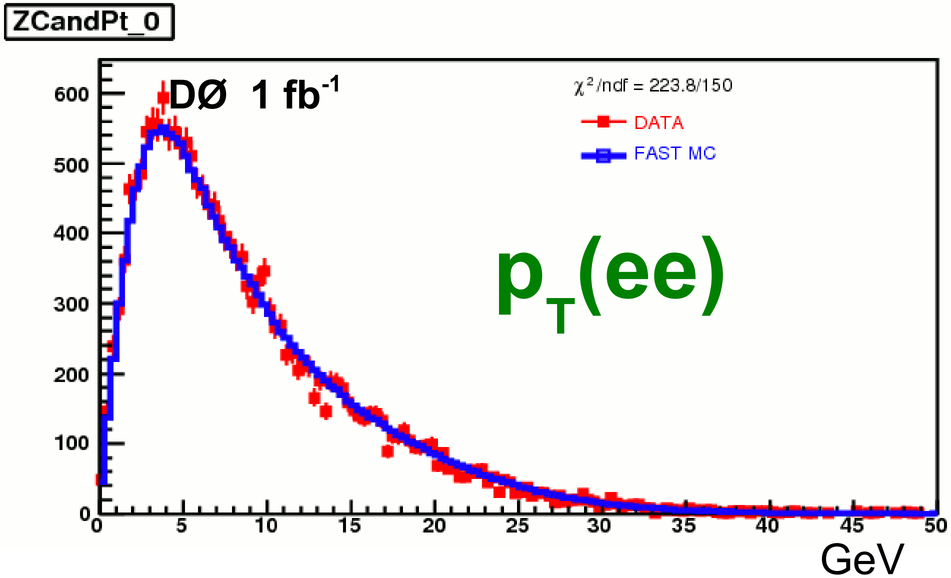
$$\xi\text{-imbalance}: (\vec{P}_t^{ee} + \vec{P}_t^{rec}) \cdot \hat{\xi}$$

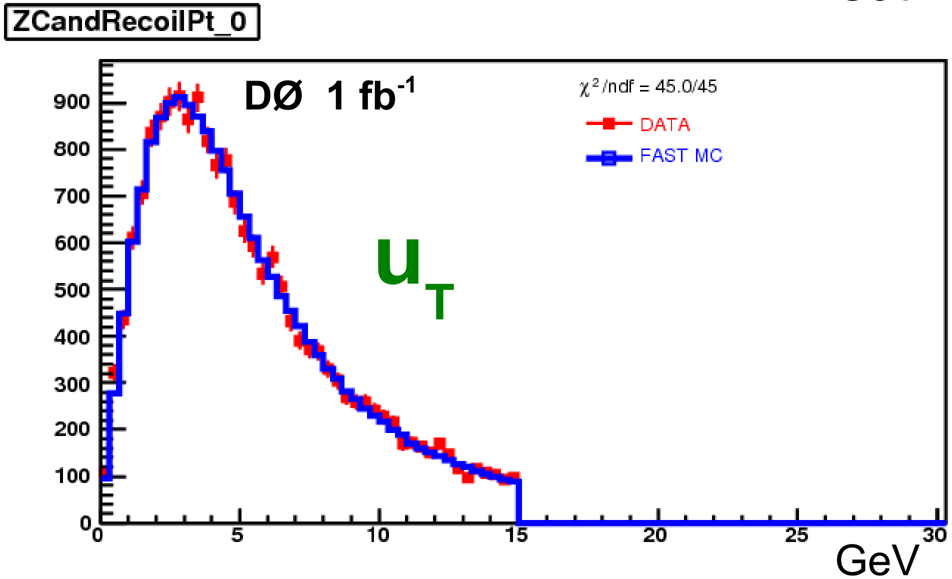


# Results: $Z \rightarrow e\,e$ data



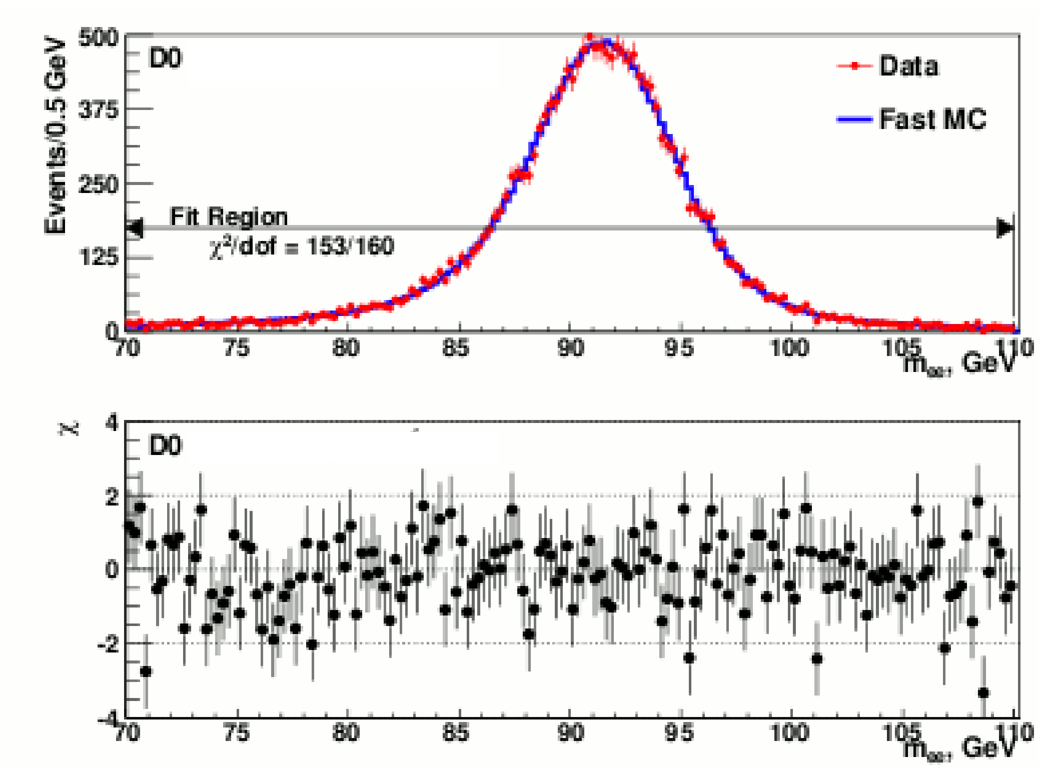



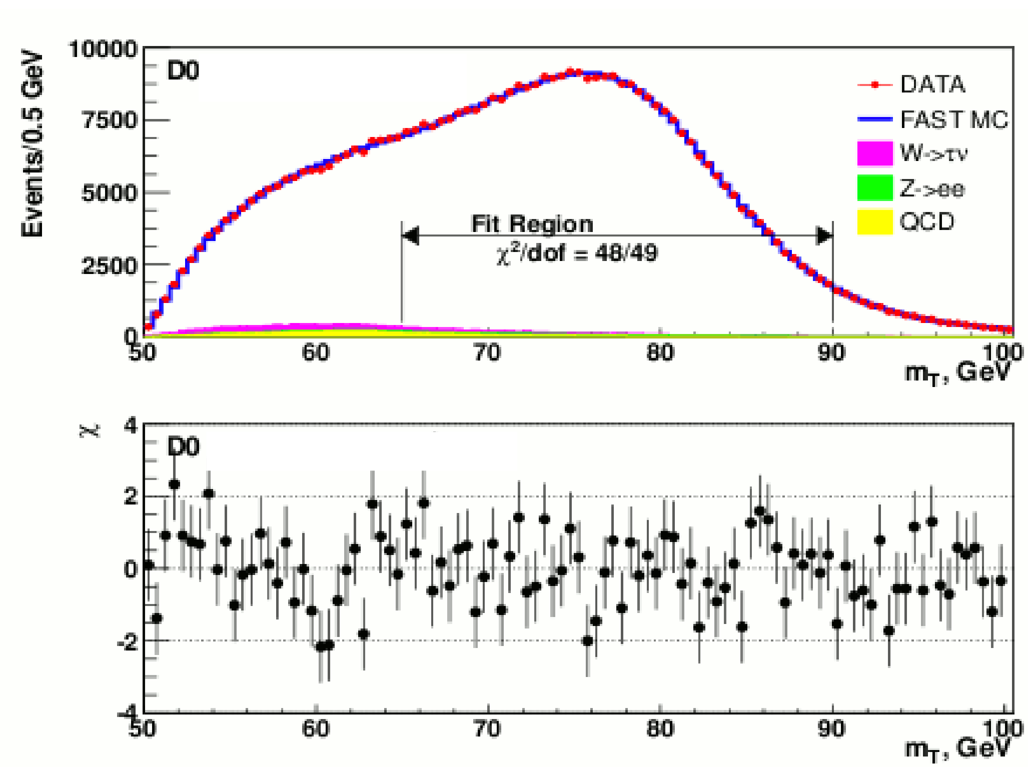




✓ **Good agreement between parameterised MC and collider data.**

# Mass fits



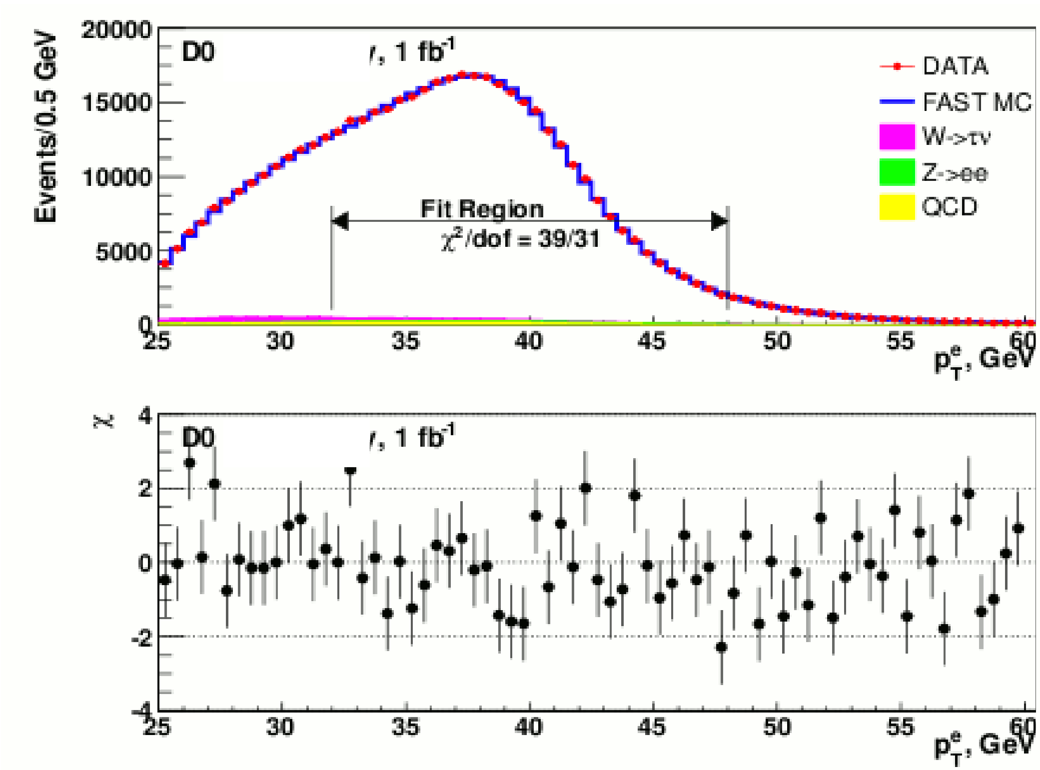



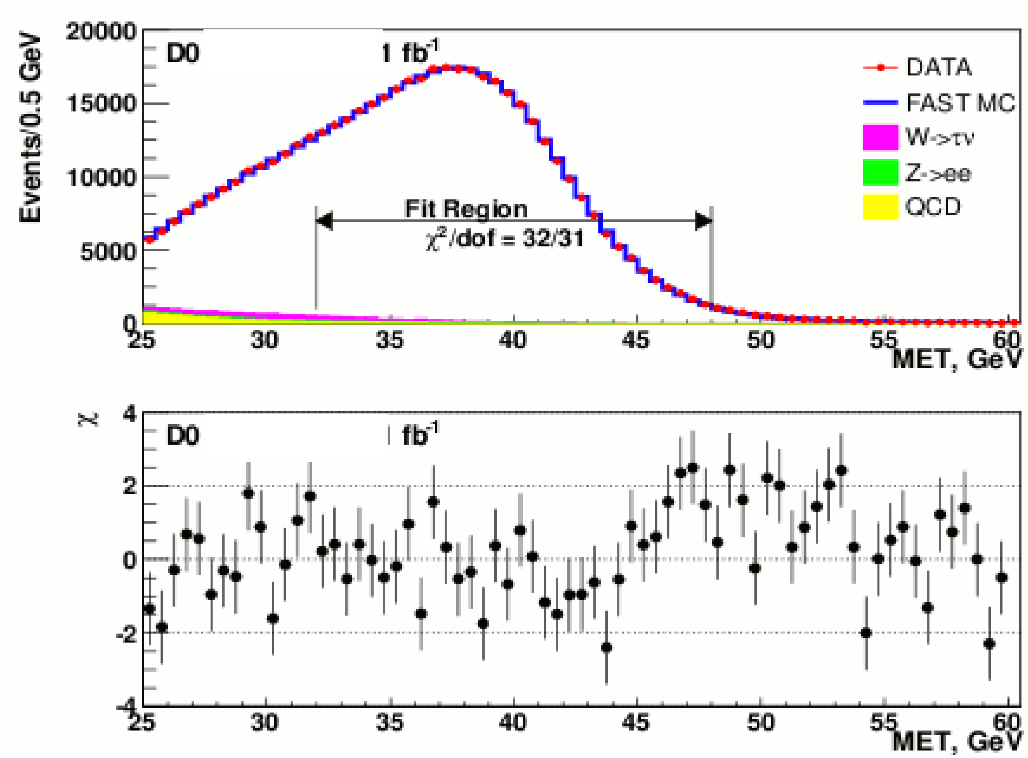

**m(Z) = 91.185 ± 0.033 GeV (stat)**

(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)**