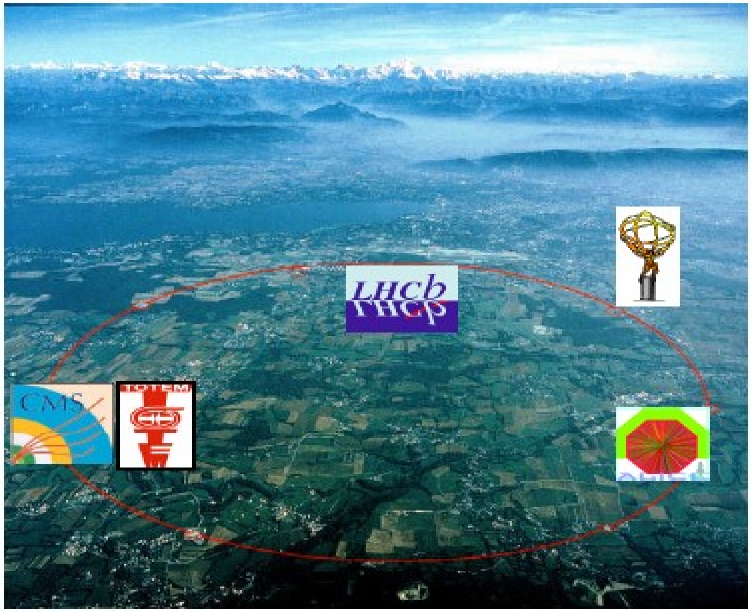
Physics Program

of the experiments at

Large Hadron Collider

Precision measurements with W and Z bosons



E. Richter-Was

14 November 2012

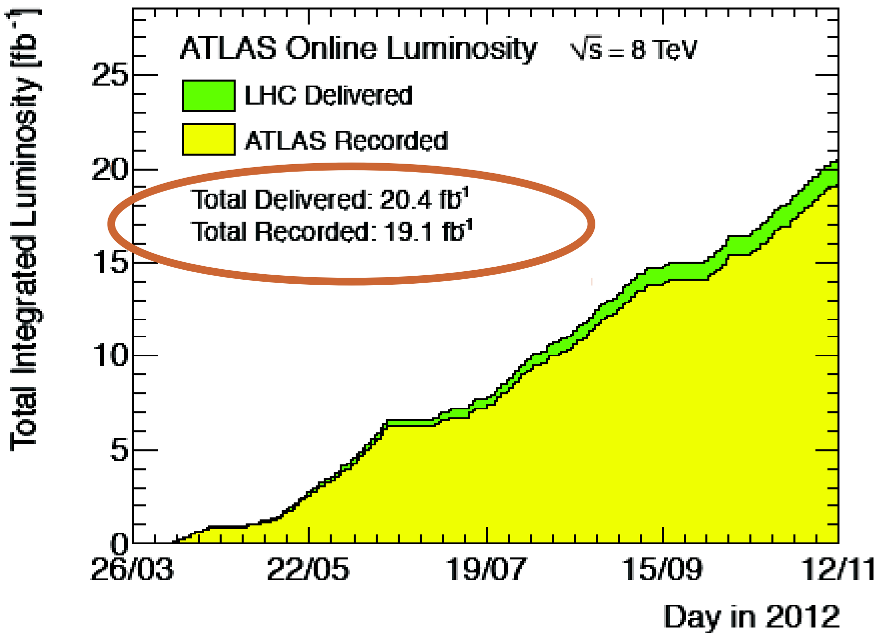
Latest news

12-18 November:

http://www.icepp.s.u-tokyo.ac.jp/hcp2012/

Hadron Collider Physics conference in Japan

Still count for another ~3fb^{-1} to come during ~20 days of pp physics left to go in 2012



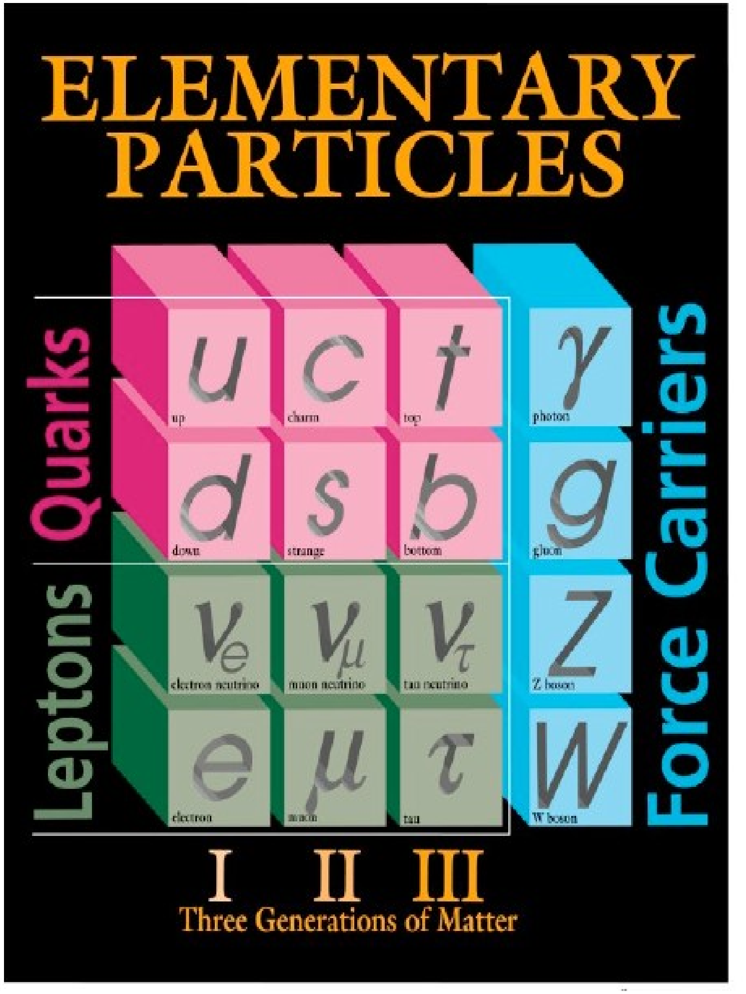
The Standard Model

Describes know particle and interactions

Does not (verifiably) describe

→ Spontaneous symmetry breaking U(1)xSU(2)

->Fermion masses



The Standard Model

Describes know particle and interactions

Does not (verifiably) describe

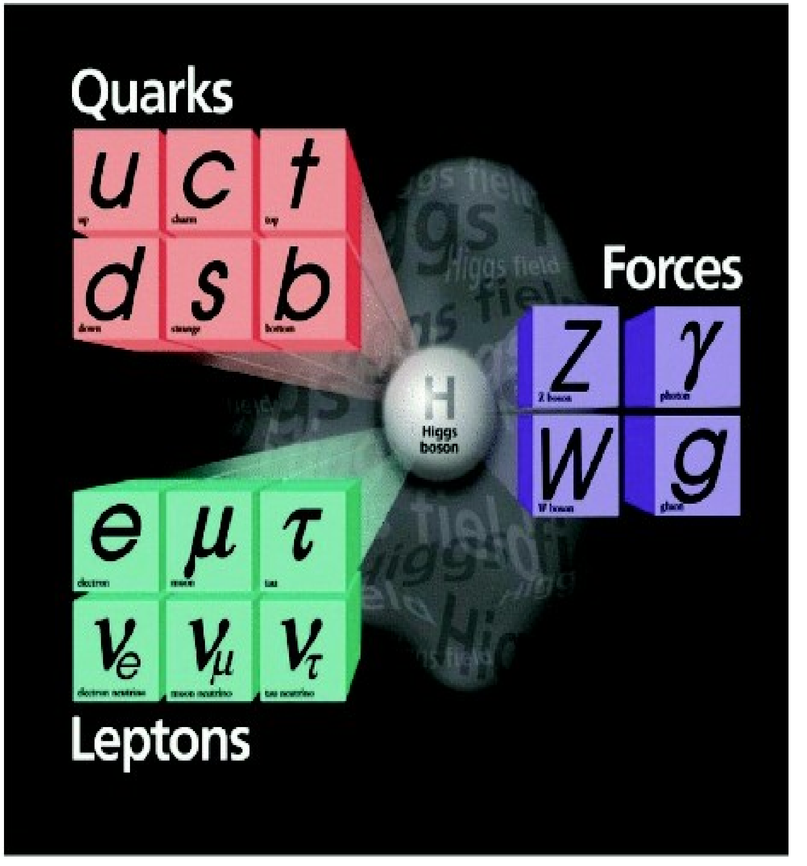
→ Spontaneous symmetry breaking U(1)xSU(2)

→ Fermion masses

Simple elegant solution: **Higgs mechanism**

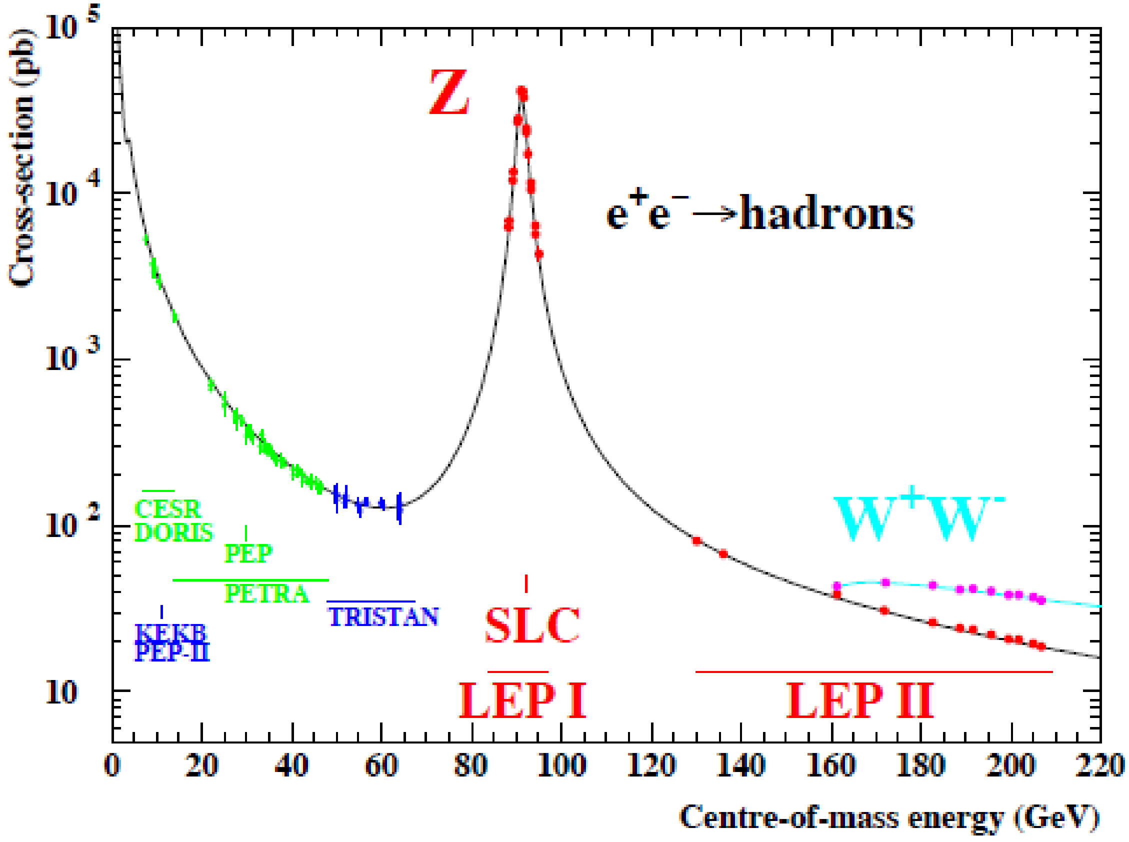
→ Explains EWSB (and fermion masses)

→ Physical manifestation is Higgs boson



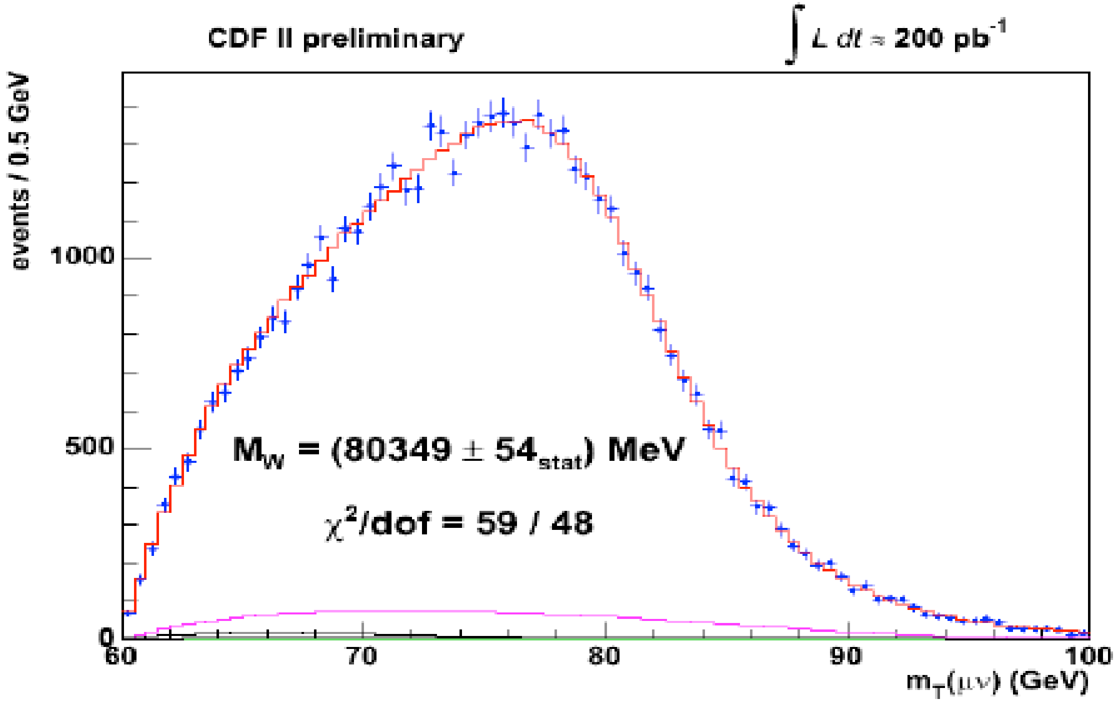
Precision measurements

Z-boson line shape



Precision measurement

W boson mass



What does the W mass tells us

- Electroweak sector of the standard model (SM) is constrained by

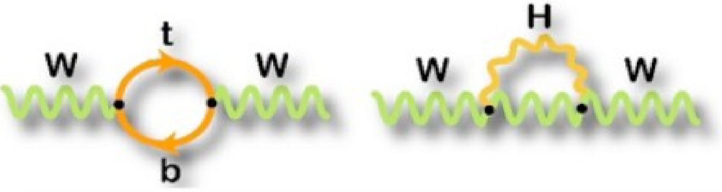
$$G_F = 1.16637(1) \times 10^{-5}\ \mathrm{GeV}^{-2} \qquad \alpha_{EM}(Q^2 = M_Z^2) = 1/127.918(18)$$

$$m_Z = 91.1876(21)\ \mathrm{GeV}/c^2$$

- These inputs give a prediction of m_W

$$m_W^2 = \frac{\pi \alpha_{em}}{\sqrt{2} G_F \sin^2\theta_W (1 - \Delta r)} \qquad \sin\theta_W^2 = 1 - \frac{m_W^2}{m_Z^2}$$

- Radiative corrections Δr dominated by top and Higgs loops



- Precision measurements of m_W and m_{top} constrain SM Higgs mass

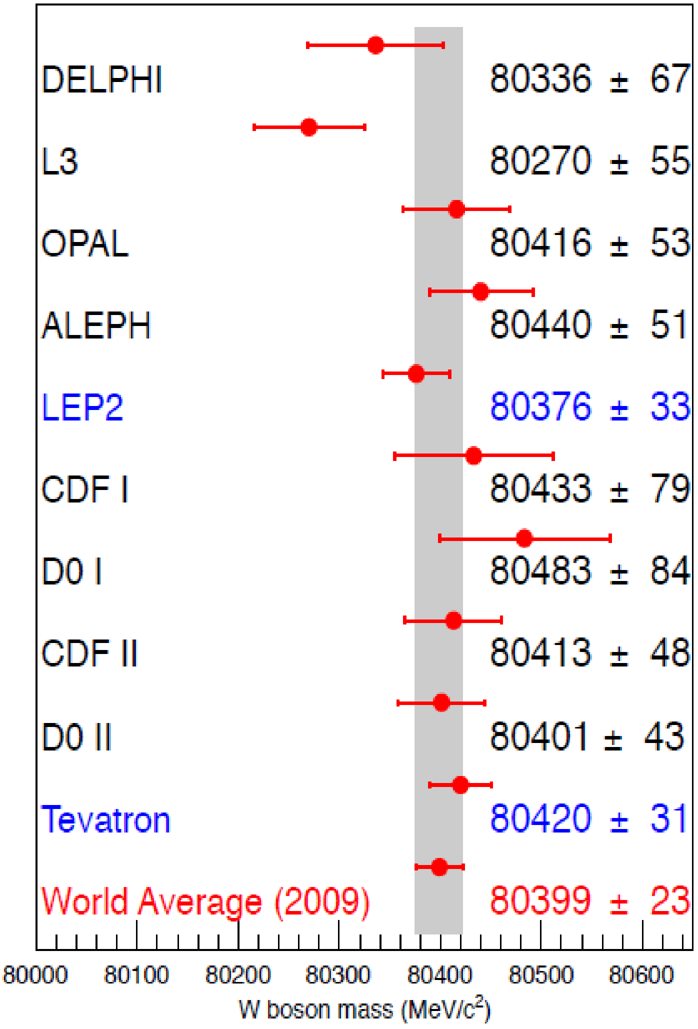
  Where should the Higgs be?

Measurements of mW

- State-of-the-art (Jan 2012)
  - DØ M_W=80401±43 MeV [1 fb^{-1}, *e*]
    *PRL **103**:141801 (2009)*
  - CDF M_W=80413±48 MeV [200 pb^{-1}, *e*+*μ*]
    *PRL **99**:151801 (2007)*
    *PRD **77**:112001 (2008)*
  - Combining with LEP ΔM_W = 23 MeV

- *Achieved:* exceed precision of e^+e^- machine measurements with hadron collider

- *Goal:* match precision of all previous measurements with single CDF measurement

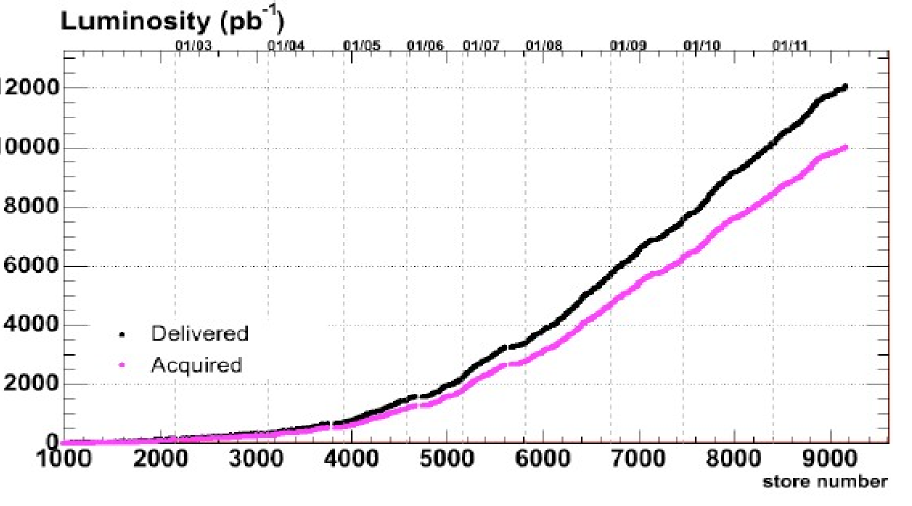


The Tevatron at Fermilab

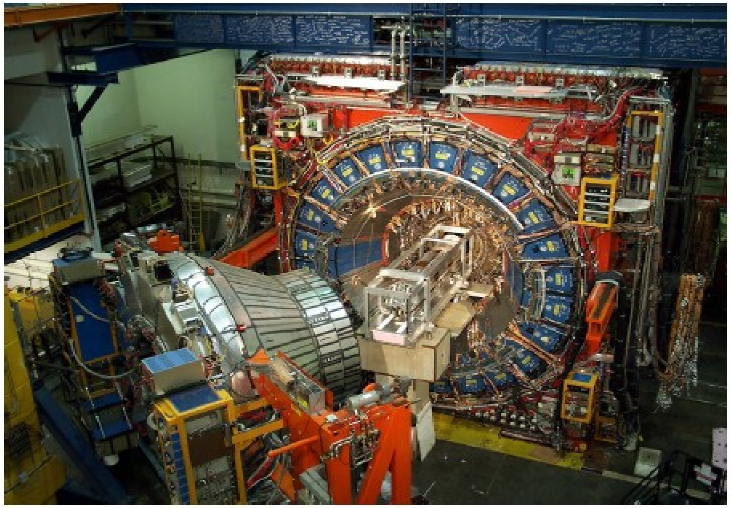
- 1.96 TeV ppbar collider
  - Highest energy (p-pbar) collider in the world
  - Typical inst. lumi.: 3×10^{32} $cm^{-2}s^{-1}$
    - 2011 LHC: ~3×10^{33} $cm^{-2}s^{-1}$
  - Bunch spacing: 396 ns
    - 2011 LHC: 50 ns

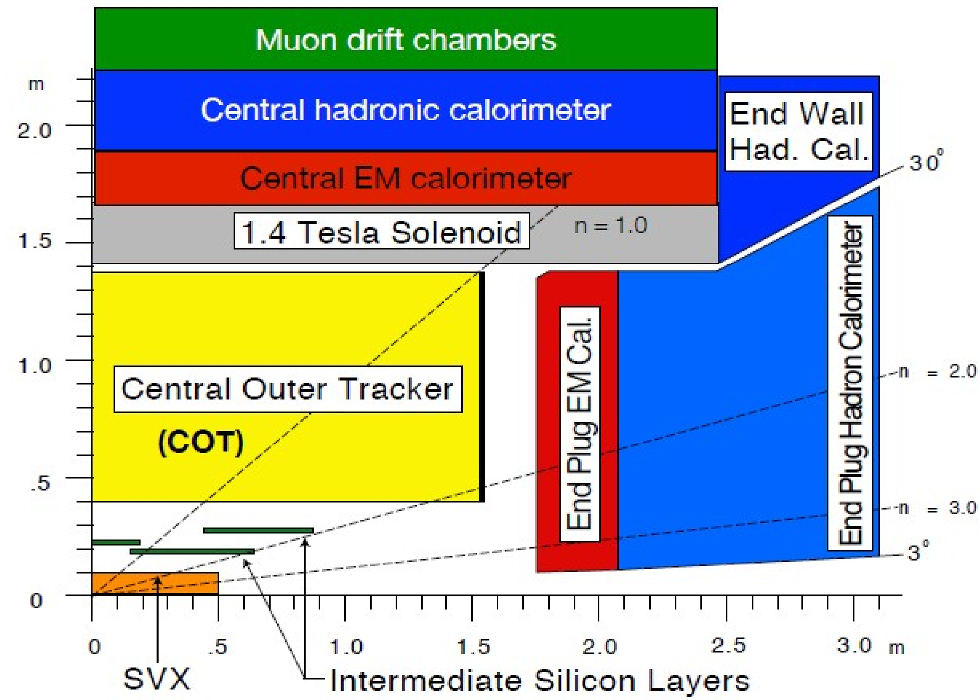
- Ceased operations Sep 30, 2011
  - ~12 fb^{-1} delivered to CDF and DØ

- Analysis presented utilizes 2.2 fb^{-1}

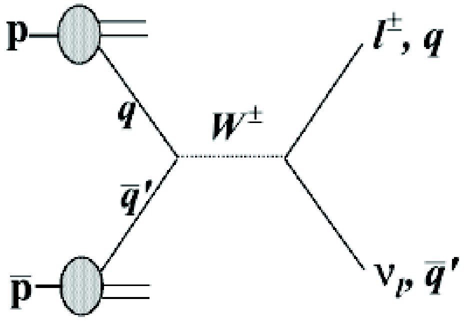


CDF(II) (2001-2011)

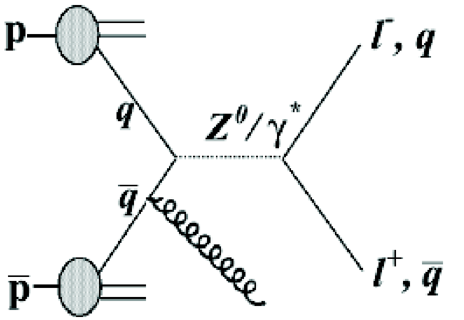




W and Z at Tevatron



$\sigma(p\bar{p} \to W^{\pm} \to l\nu) \sim 2700$ pb

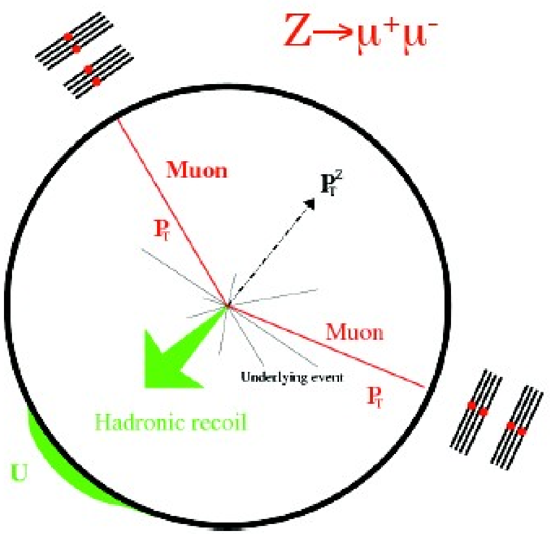


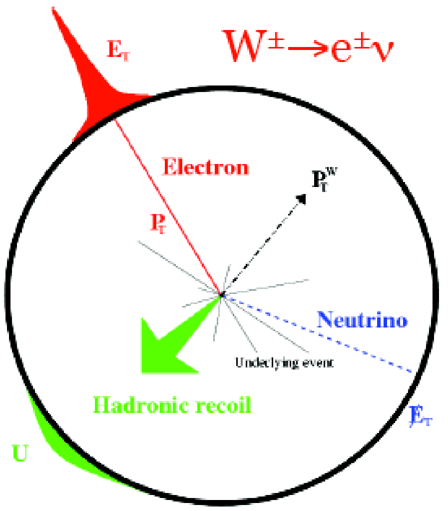
$\sigma(p\bar{p} \to Z^0 \to l^+l^-) \sim 250$ pb

- Probe QCD and EW interactions
  - Hard and soft gluon emission
  - Sensitive to parton distribution
- Leptonic decay used for precision measurements
  - Extract Electro-weak (EW) parameters: $\sin^2\Theta_W$ and m_W
- In $1fb^{-1}$/experiment: $W \to l\nu$ 10^6 events, $Z \to ee$ 10^5 events
  - High statistics samples and low background

Detecting W and Z

- $Z \rightarrow l^+l^-$
  - **Signature:** pair of charged leptons with opposite sign charge
    - Leptons are high p_T and isolated
  - Peak in l^+l^- invariant mass



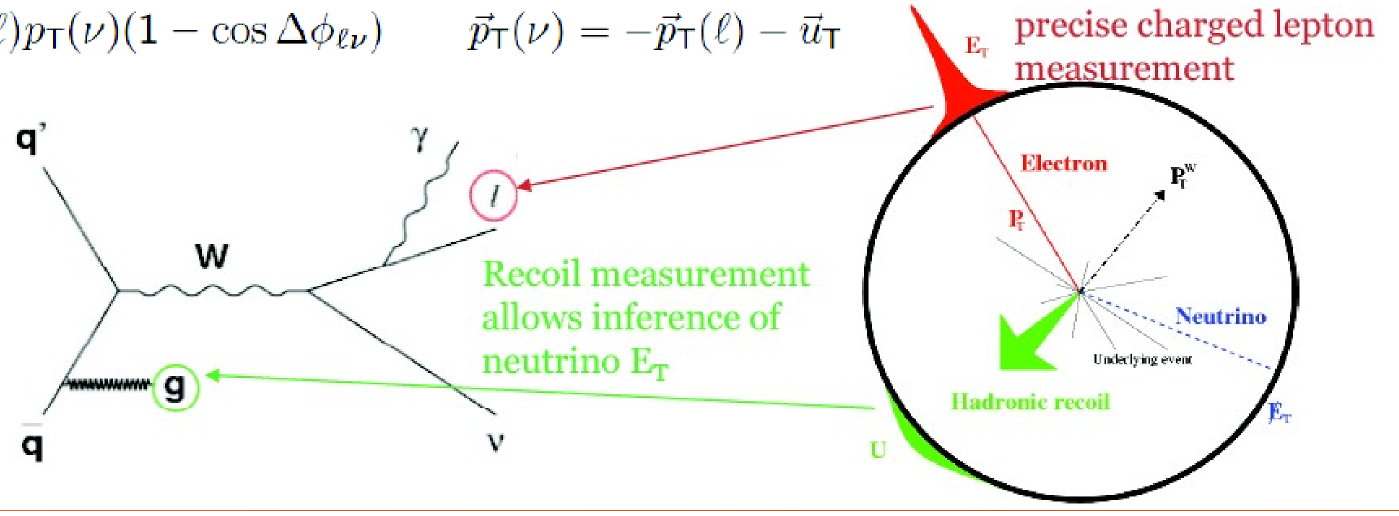


- $W \rightarrow l^{\pm}\nu^{\pm}$
  - **Signature:** single charged lepton and missing transverse energy (MET)
    - Leptons are high p_T and isolated
    - MET from neutrino
      - $p_T\nu$ is inferred
  - Peak in transverse invariant mass

W mass measurement strategy

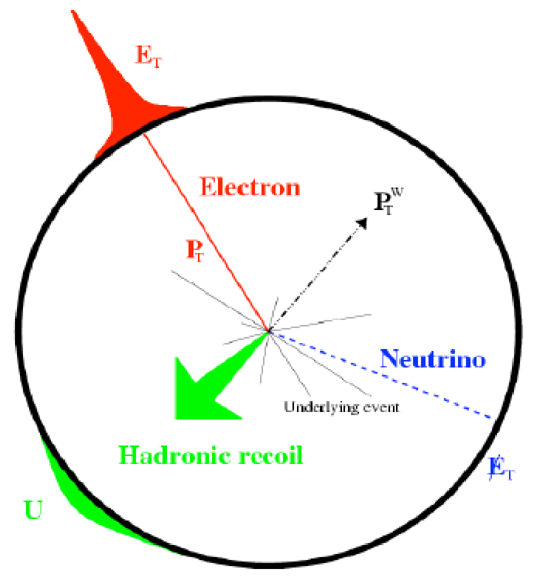
- At hadrons colliders, rely on transverse variables: m_T, p_T^l , MET (inferred neutrino p_T)
  - Requires precise measure of charged lepton p_T and hadronic recoil
  - Requires detailed knowledge of the detectors

$$m_T^2 = 2p_T(\ell)p_T(\nu)(1-\cos\Delta\phi_{\ell\nu}) \qquad \vec{p}_T(\nu) = -\vec{p}_T(\ell) - \vec{u}_T$$

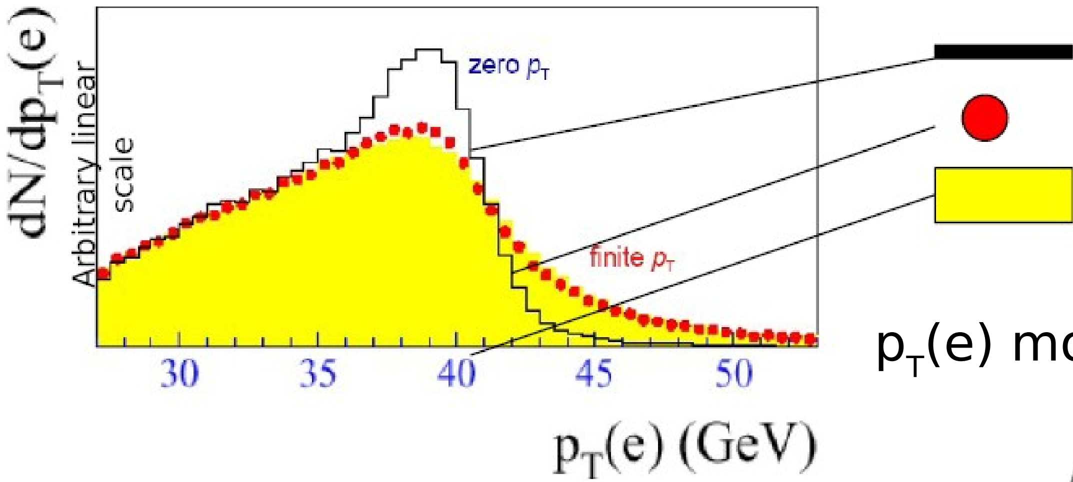


Precision

- Start with **clean**, **low-background** events
  - *i.e.*, no taus, no hadronic decays
- Lepton p_T carries most information
  - Precision achieved: *0.01%*
- Hadronic recoil affects inference of neutrino energy
  - Calibrate to ~0.5%
  - Reduce impact by requiring $p_T(W) << M_W$
- Need:
  - Accurate **theoretical model**
    - Including boson p_T model and QED radiation
  - Tunable **fast simulation**
    - Parameterized detector description for study of systematic effects
  - Large data samples of well-measured states
    - Various dimuon resonances
    - *Z* boson



Experimental observables

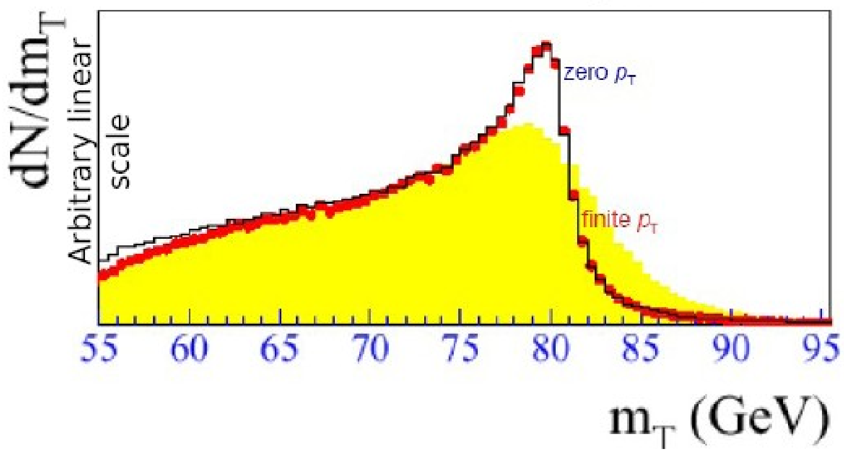


No $P_T(W)$

$P_T(W)$ included

Detector Effects added

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

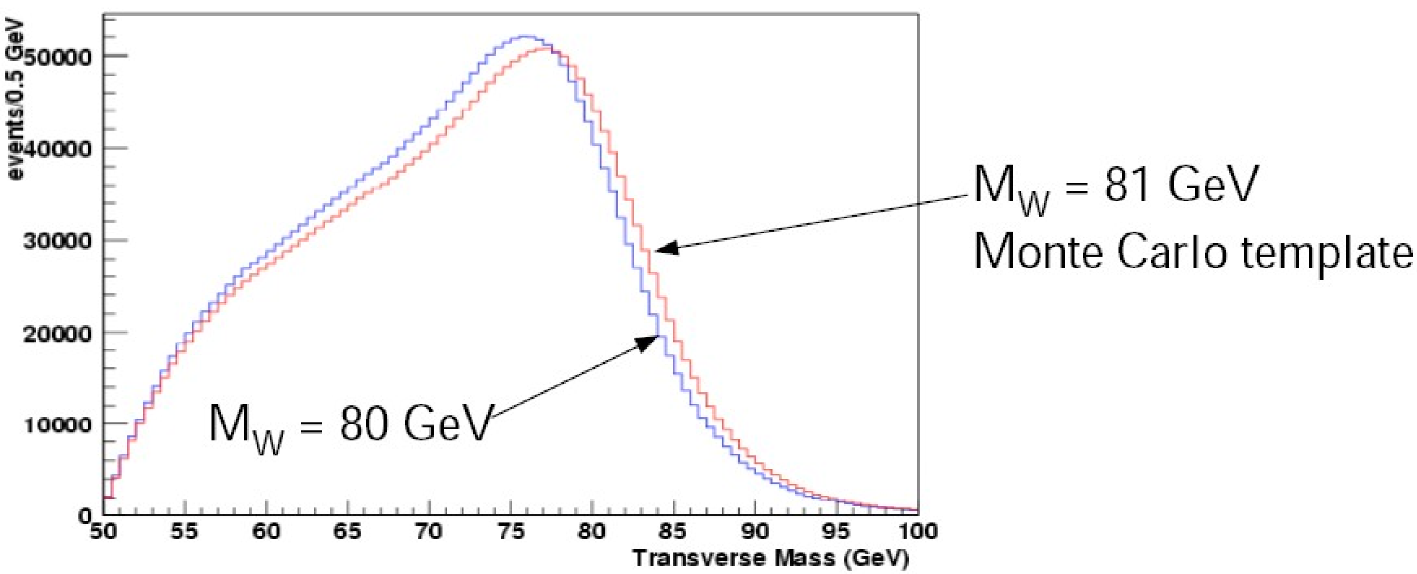


$$m_T = \sqrt{2 p_T^l p_T^\nu (1 - \cos \Delta\phi)}$$

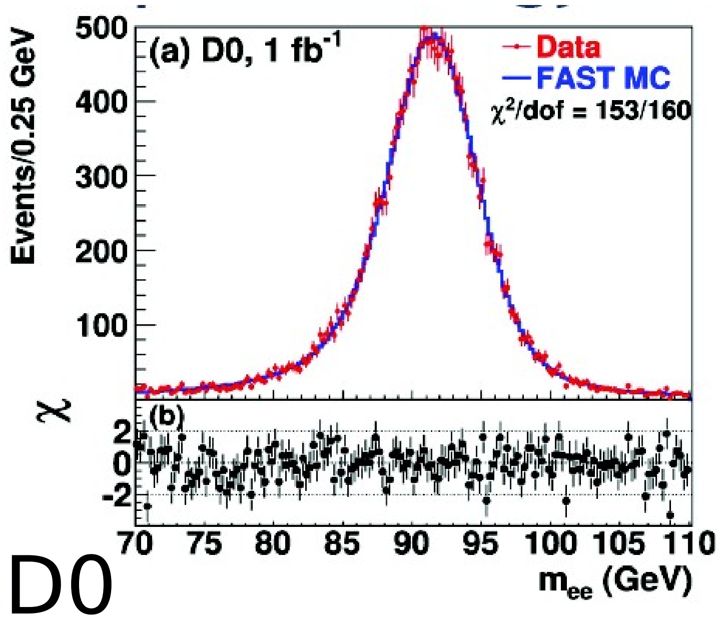
m_T most affected by measurement of MET

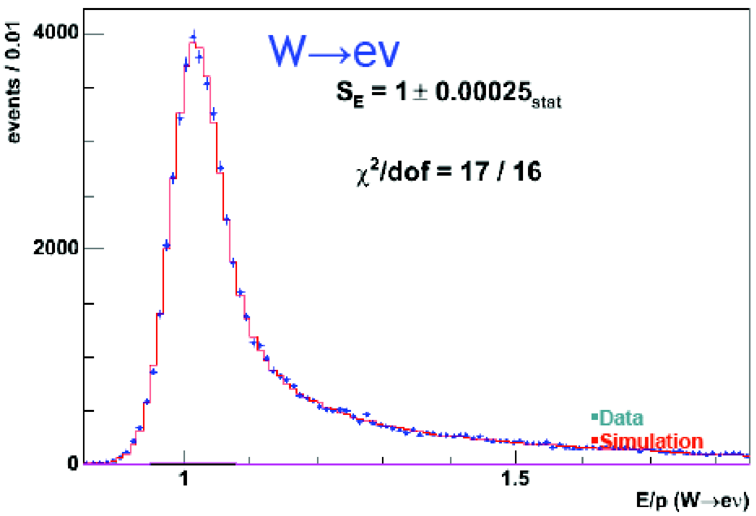
Template fitting

- Custom fast Monte Carlo makes smooth high-statistics templates. Perform binned maximum likelihood fits to the data
  - And provides analysis control over key ingredient of the simulation



Lepton energy/momentum scale

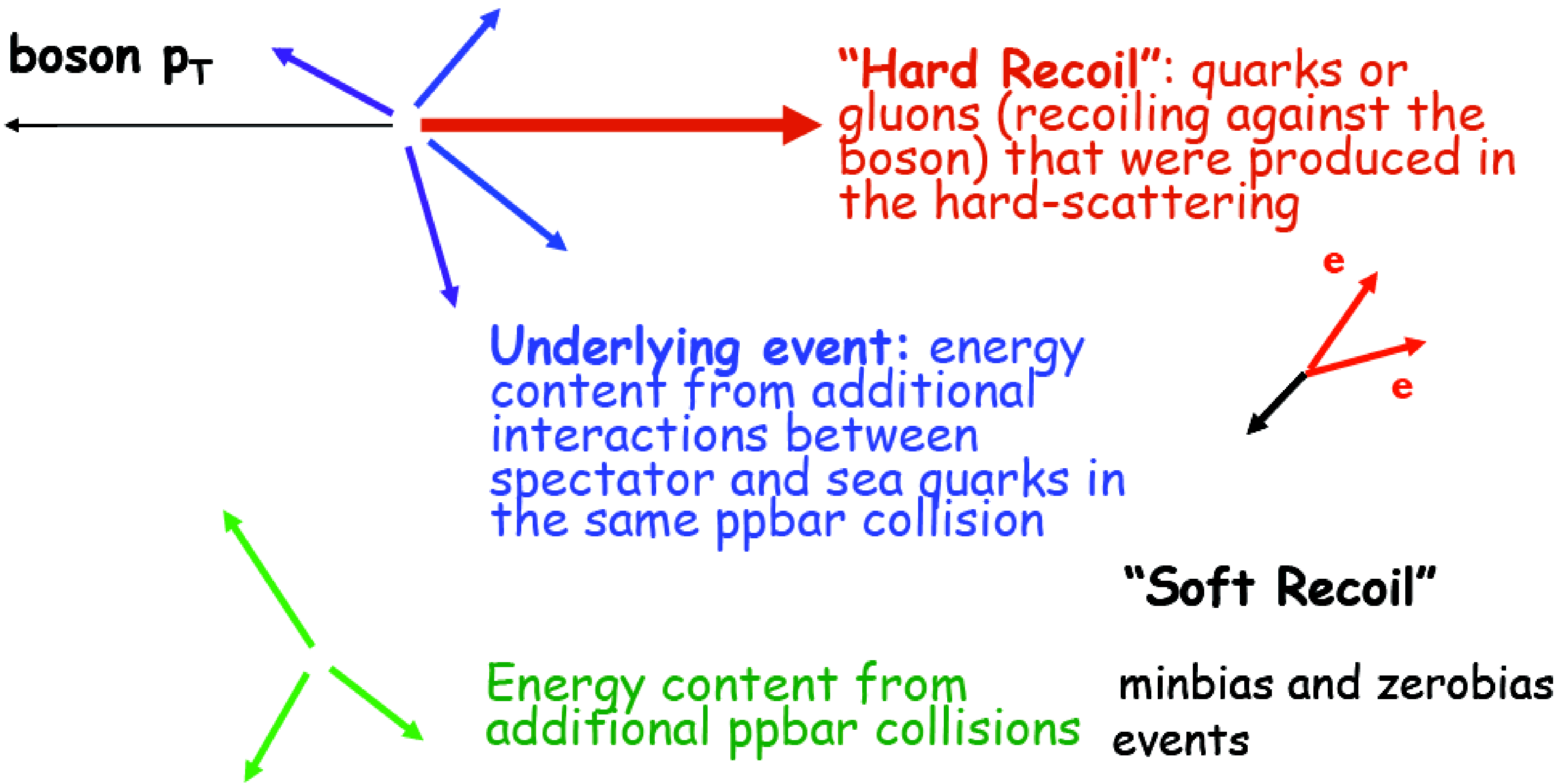




- D0
  - Calibrate calorimeter using precisely M_Z from LEP
  - Detailed corrections for uninstrumented regions
- CDF
  - Calibrate lepton momentum scale using Y, J/Ψ, m_Z
  - Calibrate calorimeter against precision tracker (E/p), M_Z

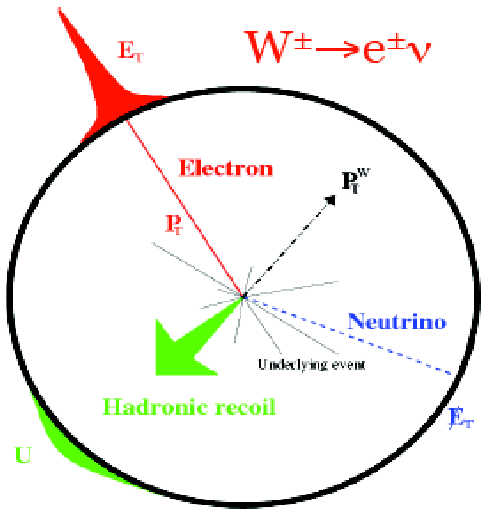
Dominant systematic uncertainty (D0: 34 MeV, CDF: 17/30 MeV e/μ)

Recoil model

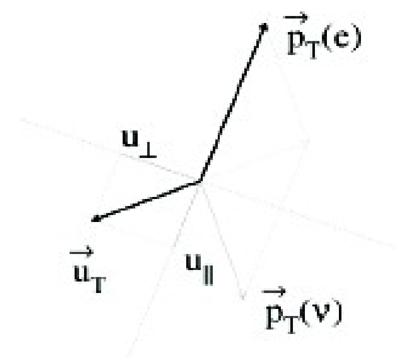


Final adjustment of free parameters in the recoil model is done **in situ** using $Z \to ee$ events

Recoil model

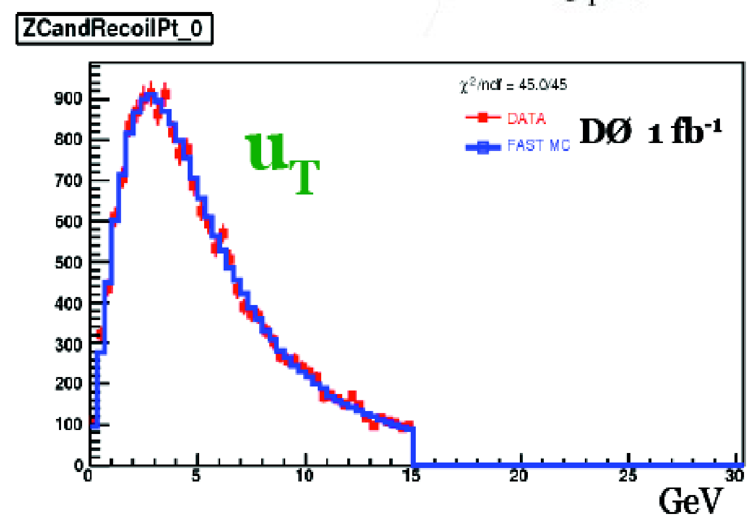


- **Recoil due to:**
  - QCD radiation “recoil” against W
  - Underlying event
  - Overlapping min bias



- Use Z→ ee (D0 and CDF) + Z→ μμ (CDF) balancing to calibrate recoil energy scale and to model resolution

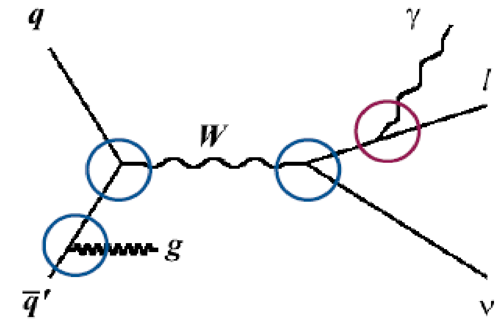
Systematic uncertainty on M_W :
Do: 6 MeV m_{TW}, 12 MeV p_T
CDF: 9 MeV m_{TW}, 17 MeV p_T



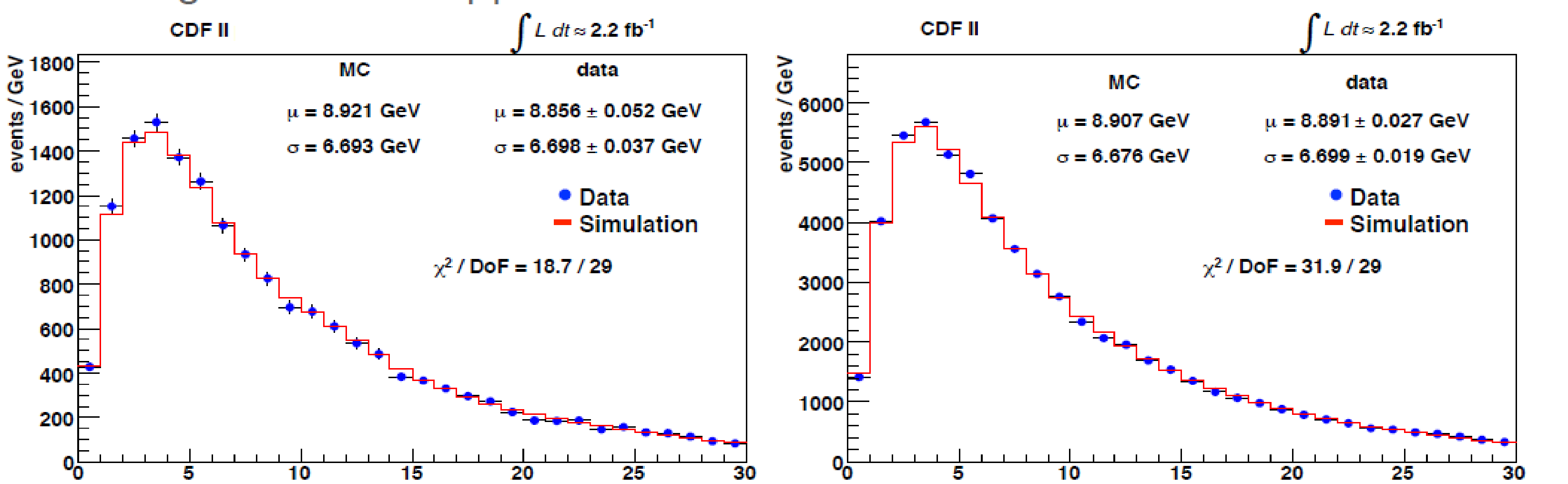
Events generation and boson pT

- Generator level simulation from **RESBOS**[1]
  - QCD effects, tunable parameters for non-perturbative regime (low-p_T)
- QED radiation simulated by **PHOTOS**[2]
  - FSR multiphoton simulation
- Fit parameters in boson p_T shape
  - Low p_T sensitive to g_2
  - Intermediate-high p_T sensitive to α_s
- Tuning with Z data applied to Ws

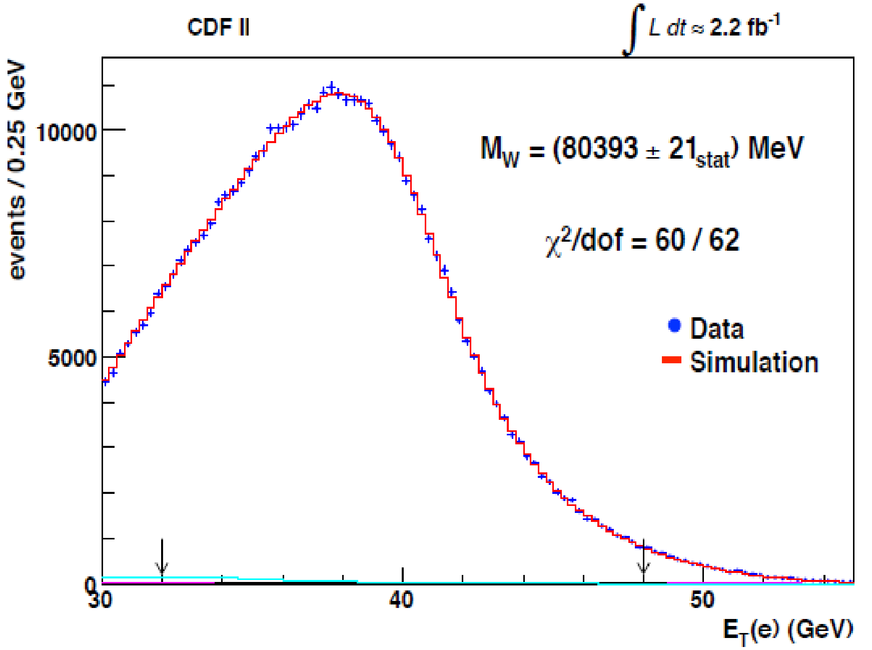
} $\Delta M_W = 5$ MeV

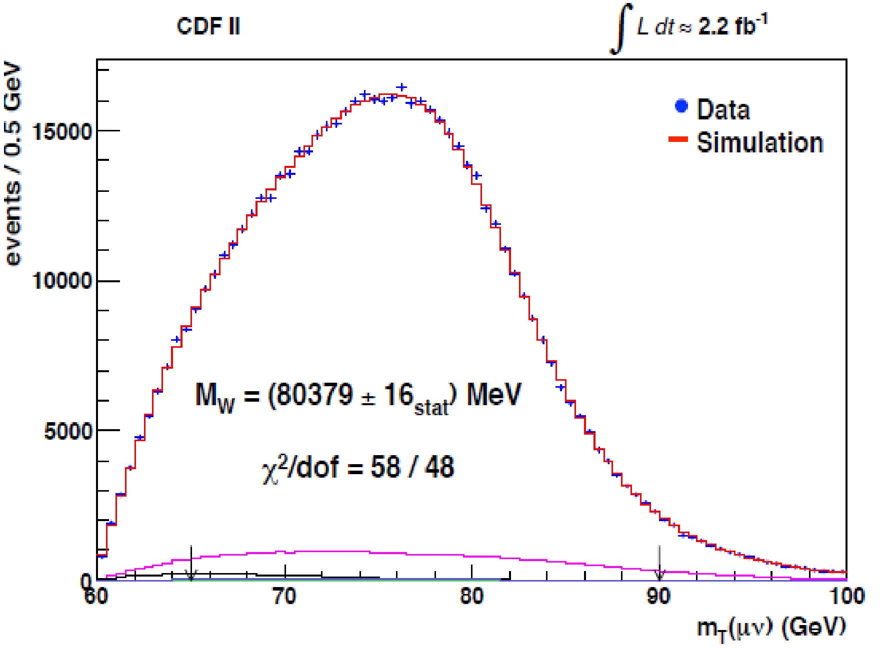


[1]C Balazs and C-P Yuan, PRD **55**, 5558 (1997)
[2]P. Golonka and Z. Was, Eur. J. Phys. C **45**, 97 (2006)



Mass fit



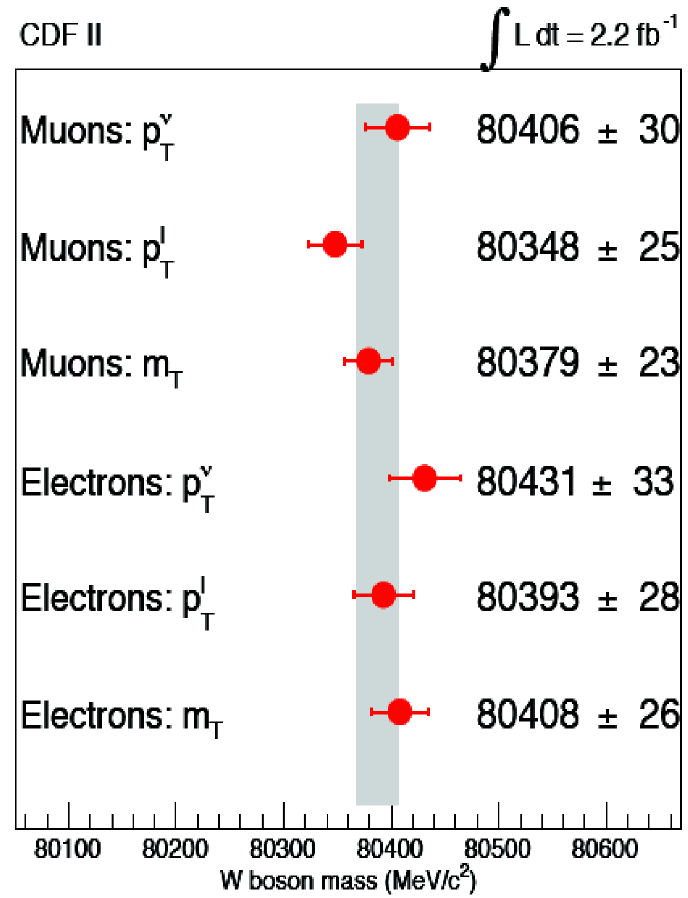


p_T^l: electrons

m_T: muons

W mass results (all fits)

Fit	Fit result (MeV)	χ^2/dof
$W \to e\nu\ (m_T)$	$80408 \pm 19_{stat} \pm 18_{syst}$	52/48
$W \to e\nu\ (p_T^l)$	$80393 \pm 21_{stat} \pm 19_{syst}$	60/62
$W \to e\nu\ (p_T^\nu)$	$80431 \pm 25_{stat} \pm 22_{syst}$	71/62
$W \to \mu\nu\ (m_T)$	$80379 \pm 16_{stat} \pm 16_{syst}$	58/48
$W \to \mu\nu\ (p_T^l)$	$80348 \pm 18_{stat} \pm 18_{syst}$	54/62
$W \to \mu\nu\ (p_T^\nu)$	$80406 \pm 22_{stat} \pm 20_{syst}$	79/62



Combined results

- All electron fits combined

  $M_W = 80406 \pm 25$ **MeV,** $\chi^2/\mathrm{dof} = 1.4/2$ (49%)

- All muon fits combined

  $M_W = 80374 \pm 22$ **MeV,** $\chi^2/\mathrm{dof} = 4/2$ (12%)

- All fits combined

  $M_W = 80387 \pm 19$ **MeV,** $\chi^2/\mathrm{dof} = 6.6/5$ (25%)

Source	Uncertainty 2.2 fb^{-1} (MeV)
Lepton energy scale	7
Lepton energy resolution	2
Recoil energy scale	4
Recoil energy resolution	4
Lepton removal	2
Backgrounds	3
p_T (W) model	5
PDFs	10
QED radiation	4
Total systematics	*15*
W statistics	12
Total	***19***

$$M_W = 80387 \pm 12_{stat} \pm 15_{syst}\ \mathrm{MeV}/c^2$$

Combined uncertainties

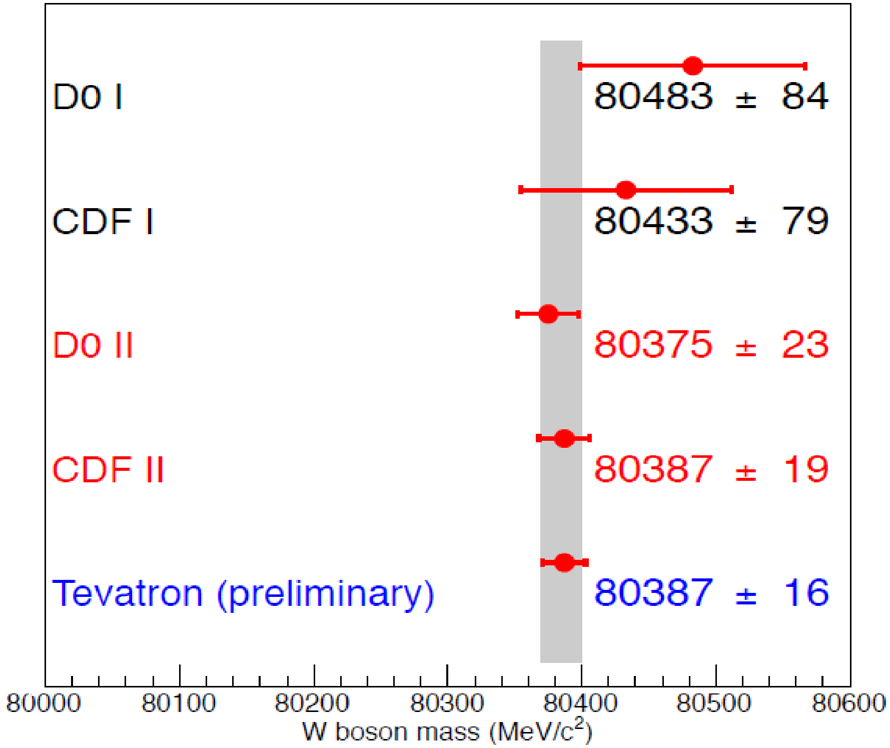
Statistics limited by control data

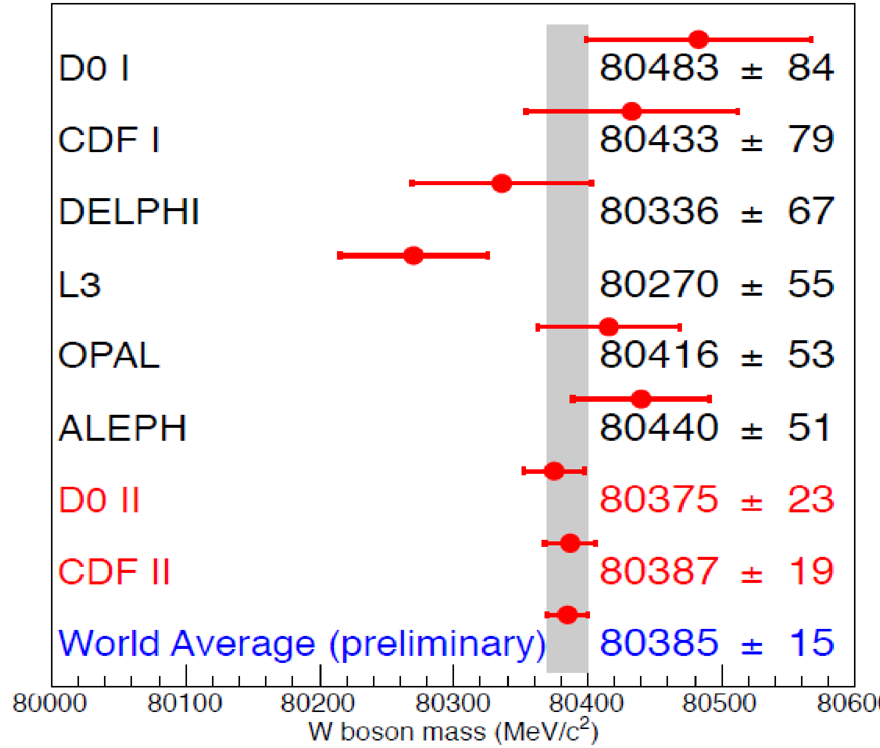
Theory based (external inputs)

Source	Uncertainty 2.2 fb^{-1} (MeV)	Uncertainty 0.2 fb^{-1} (MeV)
Lepton energy scale	7	23
Lepton energy resolution	2	4
Recoil energy scale	4	8
Recoil energy resolution	4	10
Lepton removal	2	6
Backgrounds	3	6
p_T (W) model	5	4
PDFs	10	11
QED radiation	4	10
Total systematics	*15*	*34*
W statistics	12	34
Total	***19***	***48***

$$M_W = 80387 \pm 12_{stat} \pm 15_{syst}\ \mathrm{MeV}/c^2$$

Tevatron and world combinations

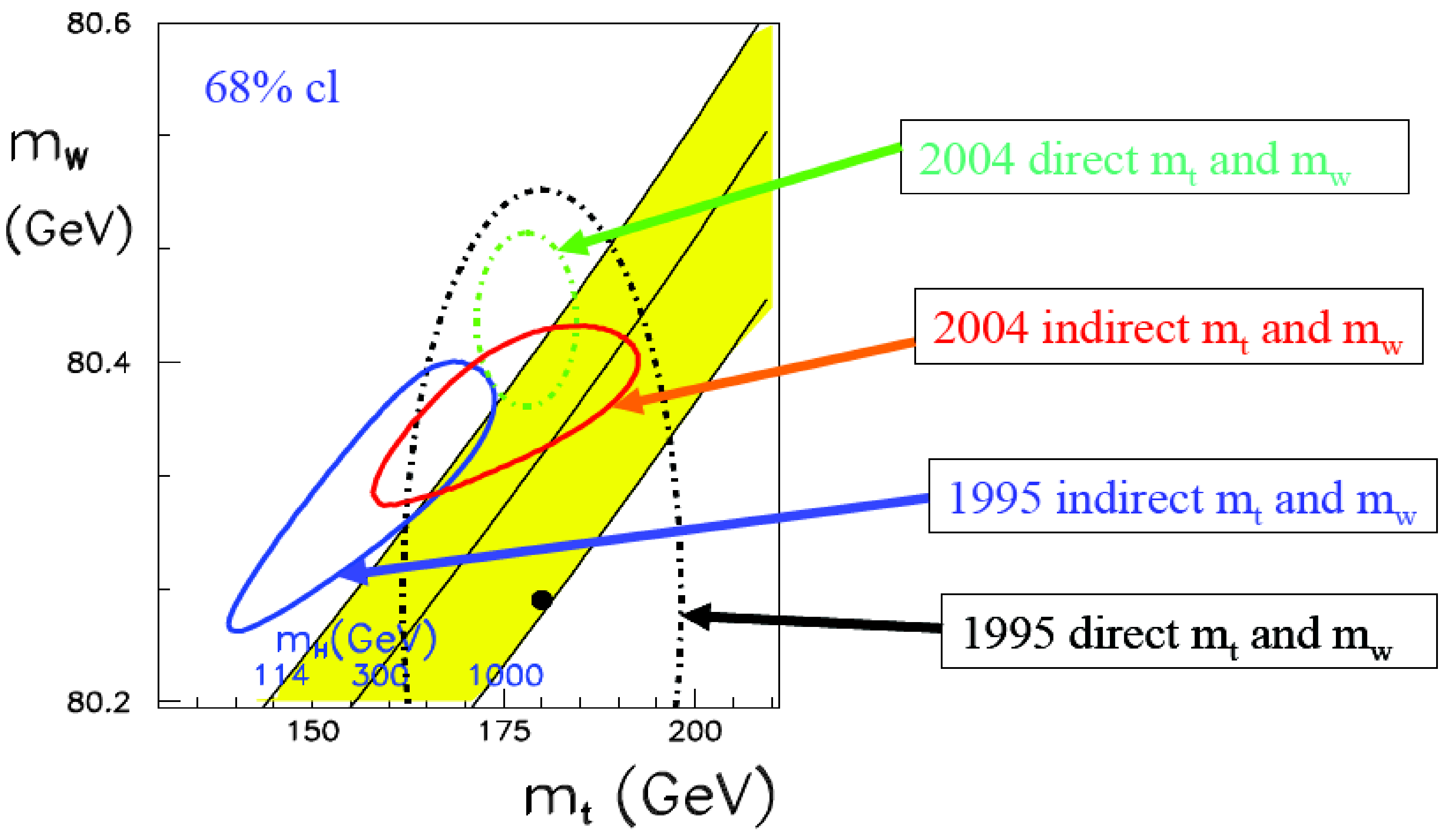




nb: 2009 world average
M_W = 80399±23 MeV

New CDF measurement significantly exceeds precision of all previous measurements of M_W combined!

Sidetrack down memory lane



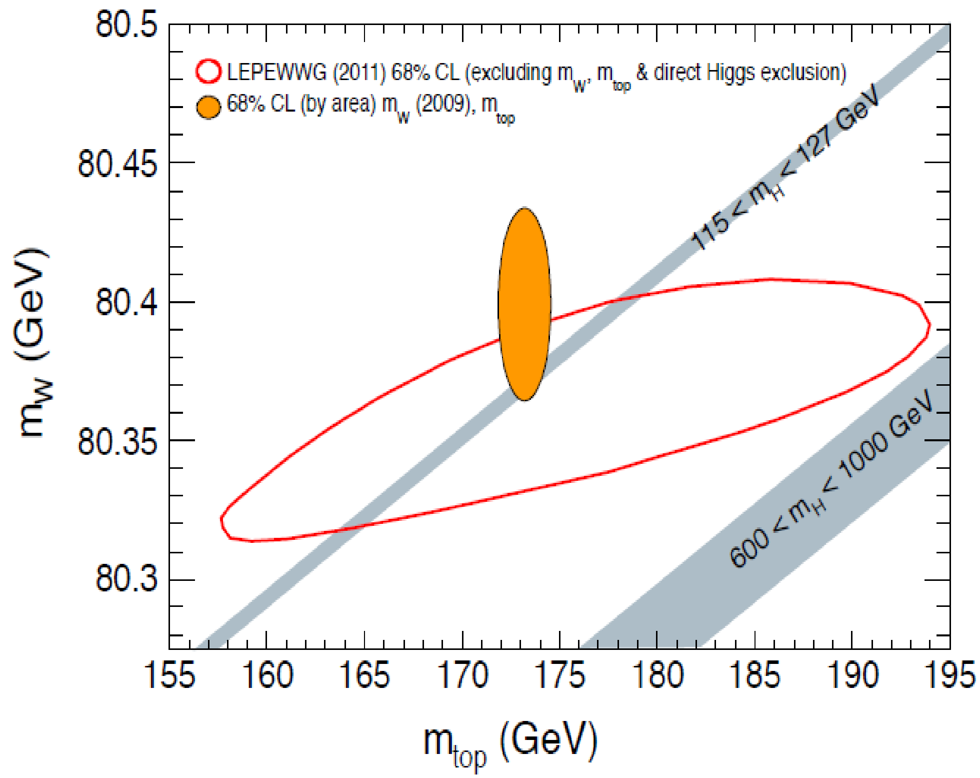
Standard Model fit

2011

With M_W = 80399±23 MeV

$M_H = 92^{+34}_{-26}$ GeV
M_H < 161 GeV @95% CL

LEPEWWG/ZFitter



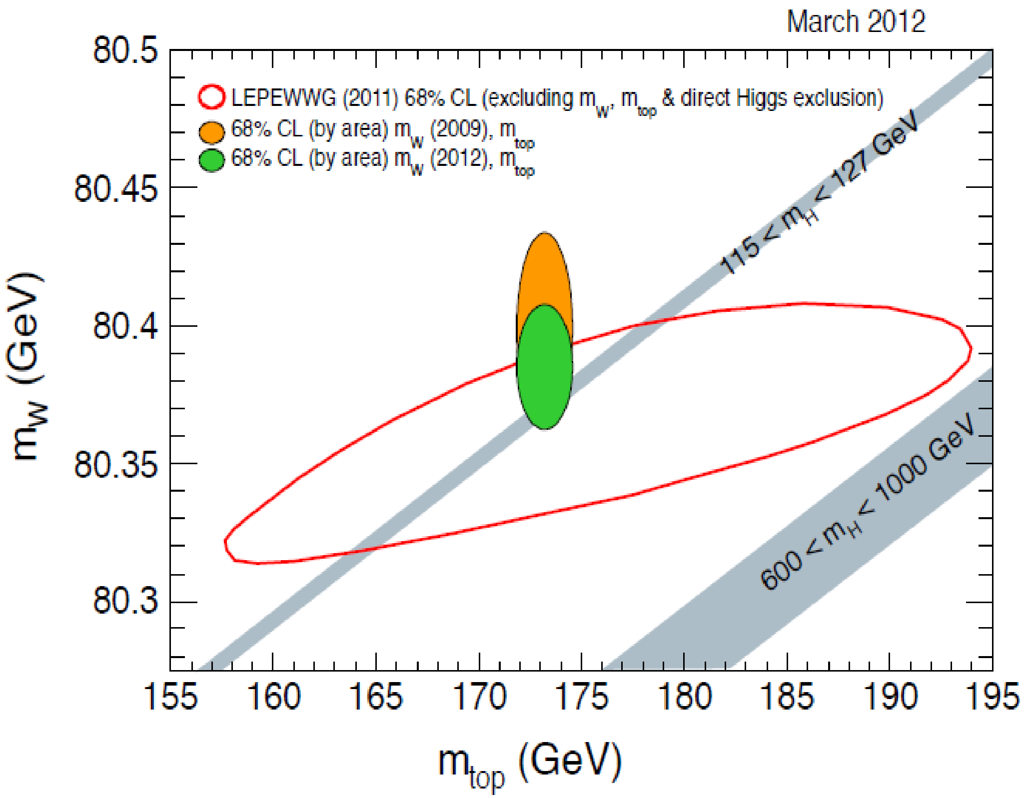
Standard Model fit

With M_W = 80385±15 MeV

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

M_H < 152 GeV @95% CL

LEPEWWG/ZFitter



almost x1000 better than SpS

$$M_W(\text{meas}) = 80385 \pm 15 \text{ MeV}$$

$$M_W(\text{SM}) = 80362 \pm 10 \text{ MeV} \quad (m_H = 125 \pm 1 \text{ GeV})$$

Testing Standard Model

After 4th July Day…

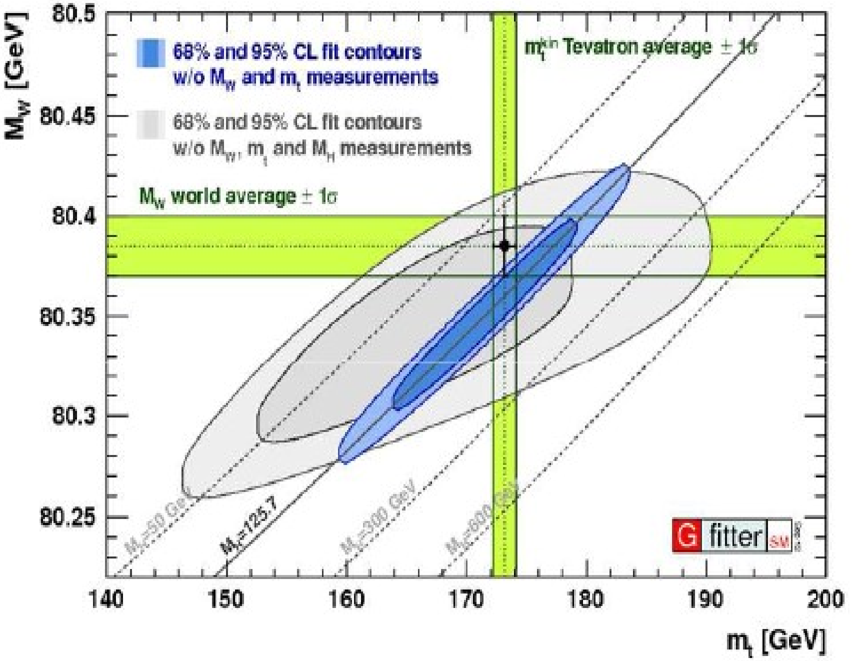
If we use the measured mass of the Higgs-like boson (125.7±0.5 GeV) to constrain the W boson mass based on SM, we get:

$m_W = 80.360 \pm 0.011$ GeV

Comparing with the current world average directly measured value:

$m_W = 80.385 \pm 0.015$ GeV

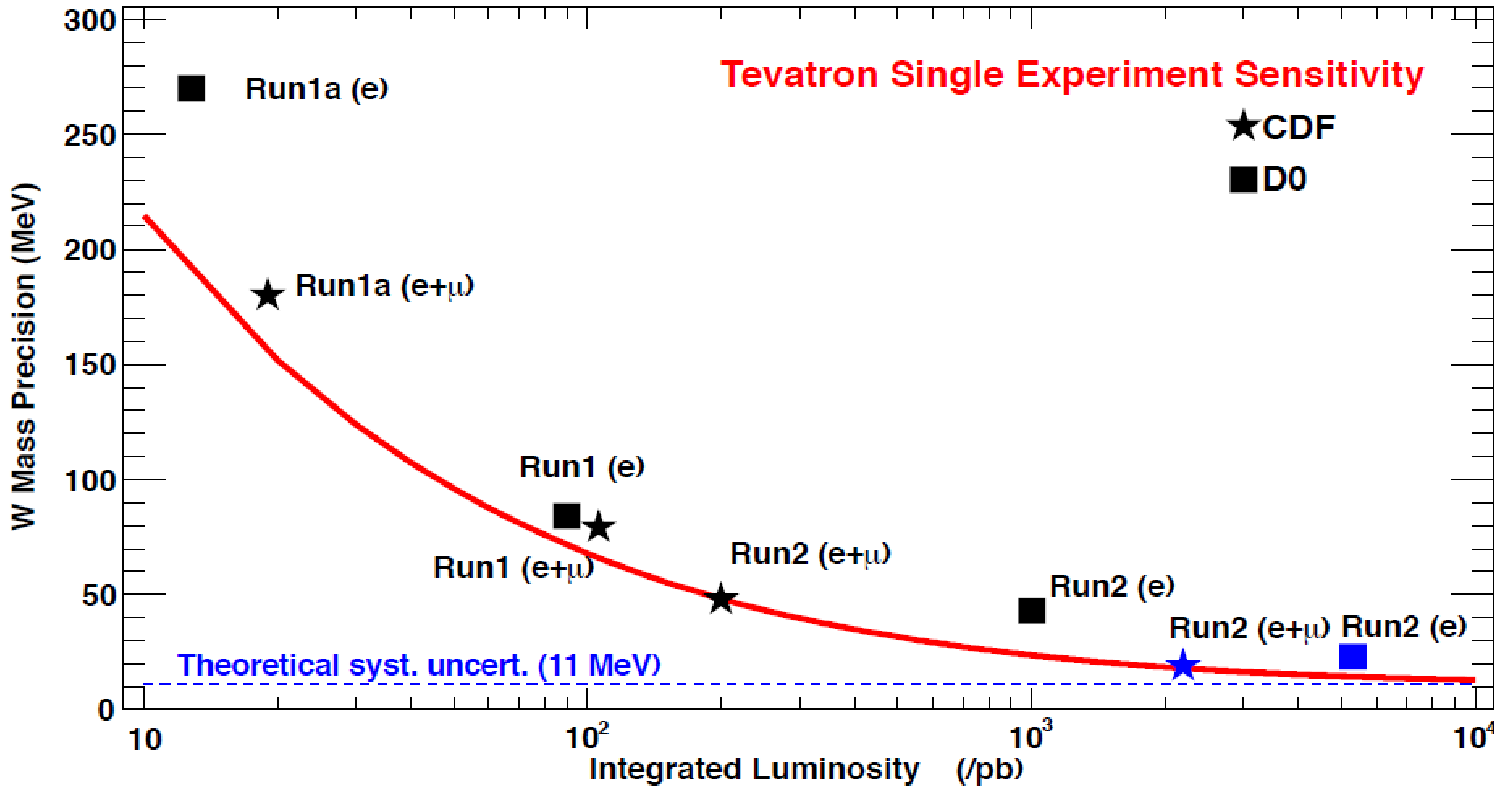
This is a way to precisely test the SM, and the observed Higgs-like boson.



Gfitter, arXiv:1209.2716

But we need to improve the precision on the W mass measurement.

Uncertainty projection



- Projection assumes PDF+QED errors (11 MeV) fixed
  - Become limiting uncertainty for measurements with full Tevatron dataset

Systematics

10 MeV full stat

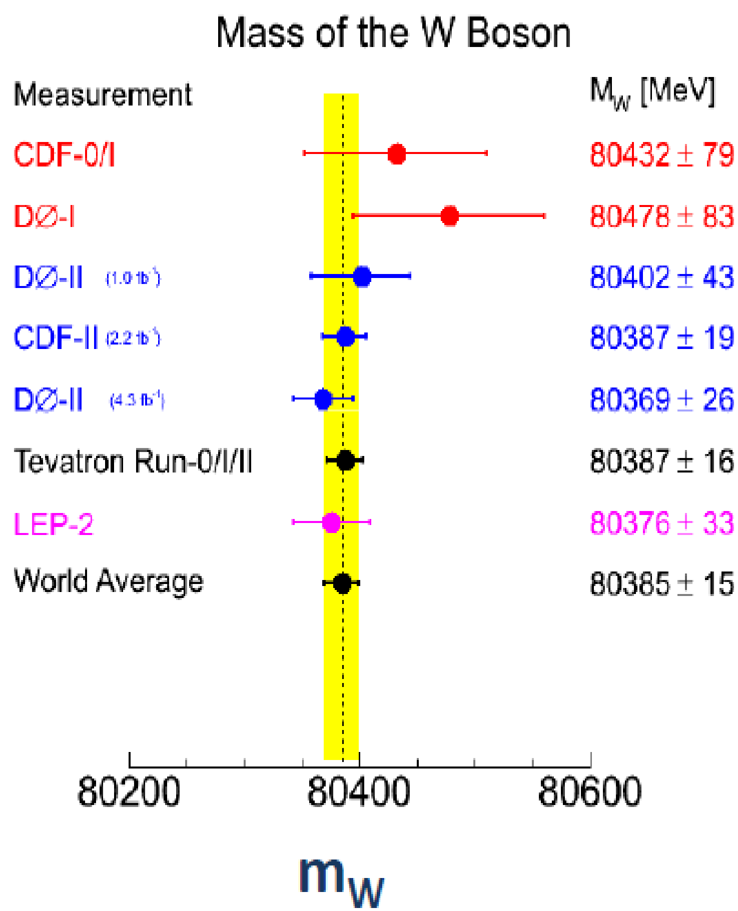
CDF and DØ in progress toward full stat : 10 fb-1

5 MeV
CC-EC
Full stat

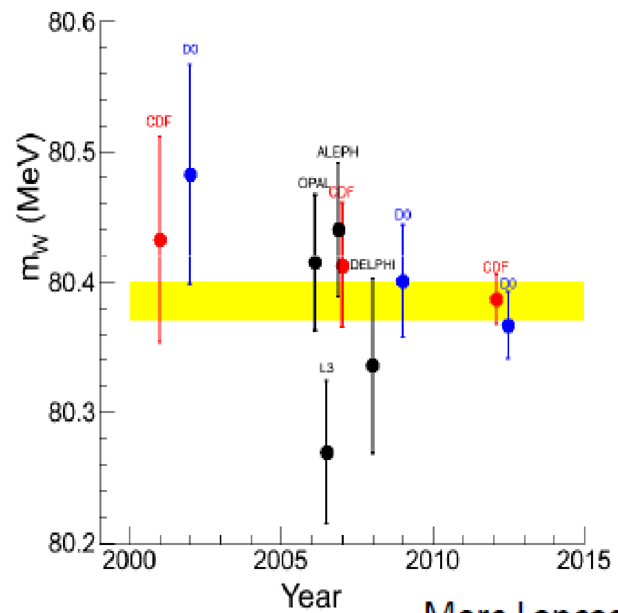
Uncertainty	D0	CDF
Lepton energy scale/resn/modelling	17	7
Hadronic recoil energy scale and resolution	5	6
Backgrounds	2	3
Parton distributions	11	10
QED radiation	7	4
$p_T(W)$ model	2	5
Total systematic uncertainty	22	15
W-boson statistics	13	12
Total uncertainty	26 MeV	19 MeV

CDF 2.3 fb^{-1} m_W = 80 387 ± 19 MeV e/μ : m_T, p_T^l, p_T^ν combined
DØ 4.3 fb^{-1} m_W = 80 367 ± 26 MeV e : m_T, p_T^l combined
DØ 5.3 fb^{-1} m_W = 80 375 ± 23 MeV combined with 1 fb^{-1}

World combination



A lot of progress at Tevatron !!



Marc Lancaster

Conclusions on m_W measurement

- CDF has performed the most precise measurement of the *W* boson mass
  - M_W = 80387±19 MeV [*Phys. Rev. Lett.* **105**, 158103]
  - More precise than all previous measurements combined
  - Improves world average uncertainty from 23 MeV to 16 MeV

- New combinations (including DØ [*Phys. Rev. Lett.* **105**, 158104])
  - ***Tevatron:*** M_W = 80387±16 MeV (TeVEWWG, preliminary)
  - ***World:*** M_W = 80385±15 MeV (TeVEWWG, preliminary)

- Results in SM fits of M_H < 152 GeV @ 95% CL
  - Previously M_H < 161 GeV @ 95% CL
  - M_W still is the limiting factor in M_H prediction

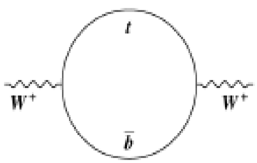
- Full Tevatron dataset (~10 fb^{-1}) on hand
  - ΔM_W < 15 MeV per experiment achievable

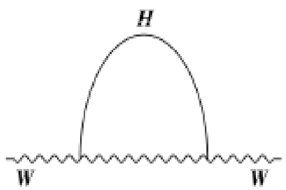
Is this precision good enough?

W mass is a key parameter in the Standard Model (SM). The model does not predict the value of the W mass but its relation with other experimental values

$$m_W = \sqrt{\frac{\pi\alpha}{\sqrt{2}G_F}}\frac{1}{\sin\theta_W\sqrt{1-\Delta r}}$$

radiative corrections (Δr) depend on $m_t \sim m_t^2$ and on $m_H \sim \log(m_H)$. They include diagrams like these:





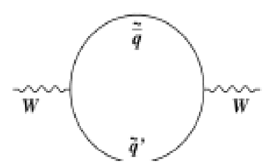
Precise measurement of the m_W and m_t constrains SM Higgs mass

For equal contribution on the Higgs mass uncertainty need: $\Delta m_W \sim 0.006\ \Delta m_t$

$m_t = 173.2 \pm 0.9$ GeV (world average) → $\Delta m_W \sim 5$ MeV

actual world accuracy is: $\Delta m_W = 15$ MeV →the limiting factor here is m_W and not m_t

Additional contributions to Δr arise in various extension of the SM e.g in SUSY

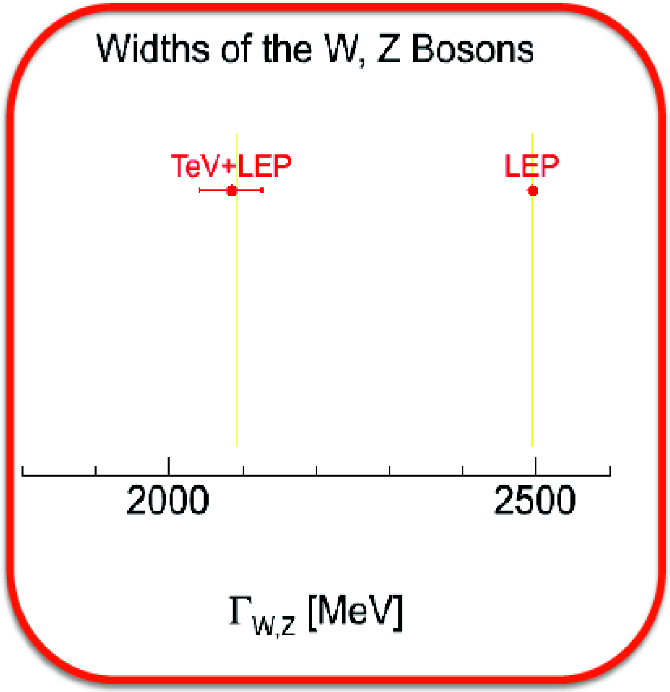


W width

Internal consistency check of SM

$$\Gamma_W = \frac{G_F M_W^3}{6\pi\sqrt{2}}(1+\delta_{RC})$$

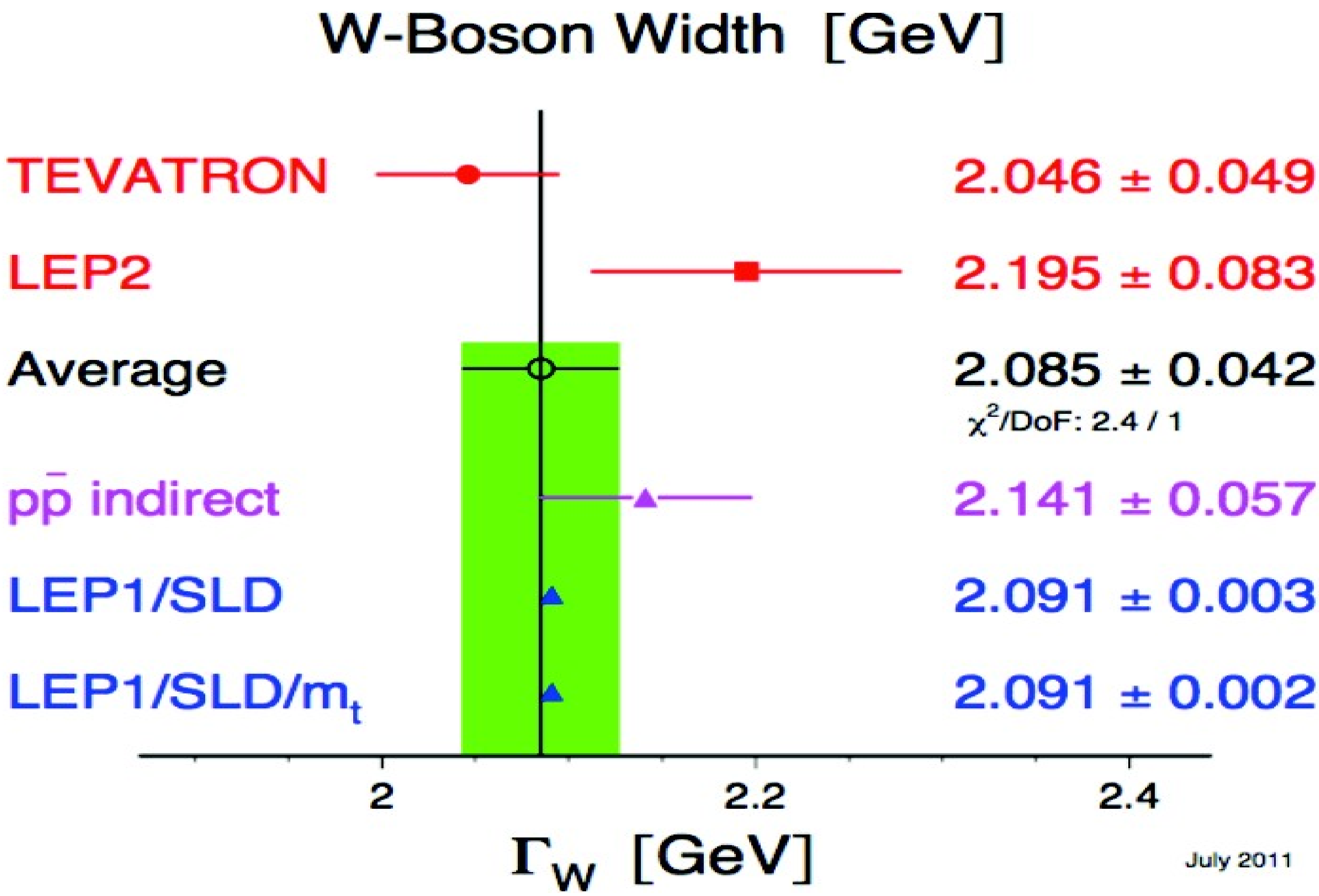
Measured Mw (has loops)



Additional sensitivity to new physics beyond Mw is tiny unless measure to O (1 MeV)

Z width uncertainty is x20 better.

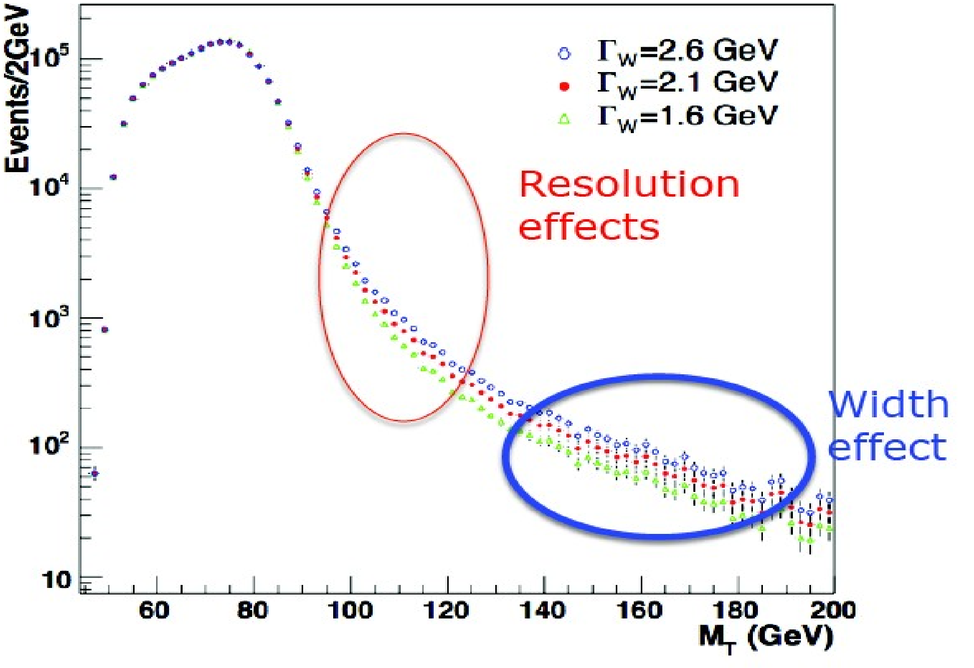
W width


W-Boson Width [GeV]
TEVATRON
2.046 ± 0.049
LEP2
2.195 ± 0.083
Average
2.085 ± 0.042
χ²/DoF: 2.4 / 1
pp̄ indirect
2.141 ± 0.057
LEP1/SLD
2.091 ± 0.003
LEP1/SLD/m_t
2.091 ± 0.002
2
2.2
2.4
Γ_W [GeV]
July 2011

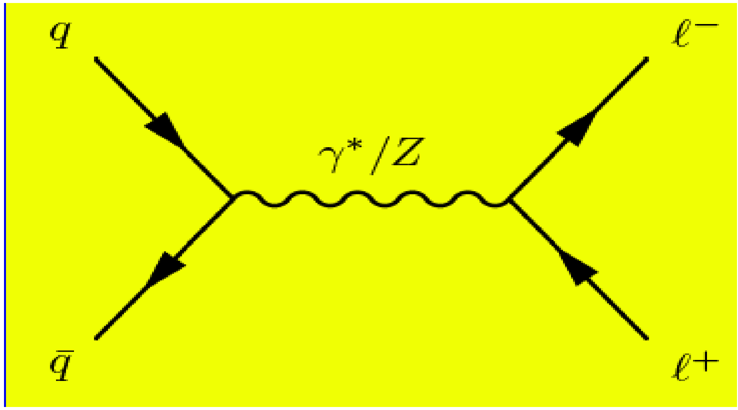
W width

Relatively to m_W it is a straightforward measurement (i.e. 2 years instead of 5 years)

It is a counting experiment and LHC has a lot of statistics



DY forward-backward asymmetry



- Direct access to vector and axial couplings

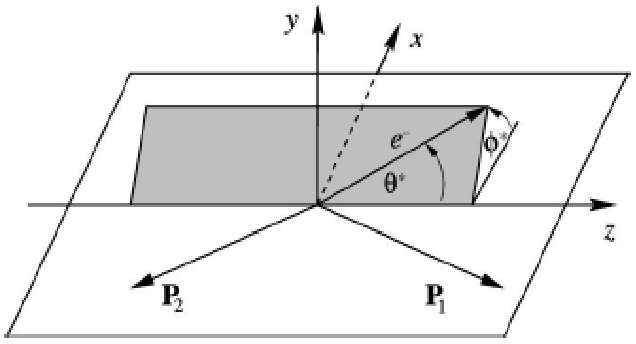
$g_v^f = I_3^f - 2q_f \sin^2\theta_W$ both γ^*-f and Z-f couplings

$g_a^f = I_3^f$ Z-f only coupling

$$\frac{d\sigma}{d\cos\theta^*} \sim \frac{3}{8}(1+\cos^2\theta^*) + A_{FB}\cos\theta^*$$

$$A_{FB} = \frac{\sigma_F - \sigma_B}{\sigma_F + \sigma_B}$$

- $\cos\theta^* > (<)\ 0 \rightarrow$ **forward** (backward) events
- θ^* is the angle of the negative lepton relative the quark momentum in the dilepton centre-of-mass frame
- Minimize the effect of unknown p_T of incoming quark by measuring θ^* in the **Collins-Soper** frame



Coulings

$W^{\pm}$  $= i\,e\,\gamma_\mu(1-\gamma_5)\,\frac{1}{2\sqrt{2}\sin\theta_W}$

Z  $= i\,e\,\gamma_\mu(v_f - a_f\gamma_5)$

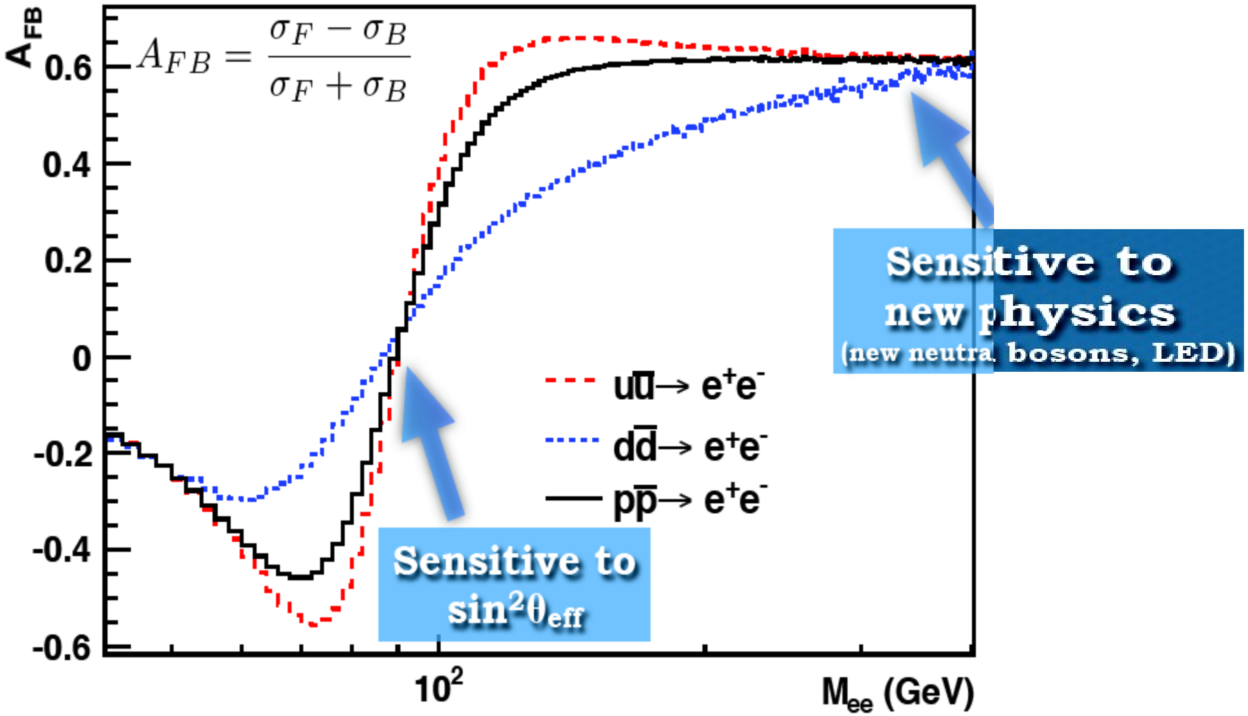
$$v_f = \frac{I_3^f - 2Q_f\sin^2\theta_W}{2\sin\theta_W\cos\theta_W},$$

γ  $= -i\,e\,Q_f\,\gamma_\mu$

$$a_f = \frac{I_3^f}{2\sin\theta_W\cos\theta_W}$$

DY forward-backward asymmetry

- Asymmetries at the Z pole dominated by lepton couplings $\longrightarrow$ sensitivity to $\sin^2\theta^l_{eff}$
- Deviations from SM may indicate presence of new particles (Z' at high masses)



DY forward-backward asymmetry

$q\bar{q} \rightarrow Z \rightarrow e^+e^-$ PRD 84, 012007 (2011)

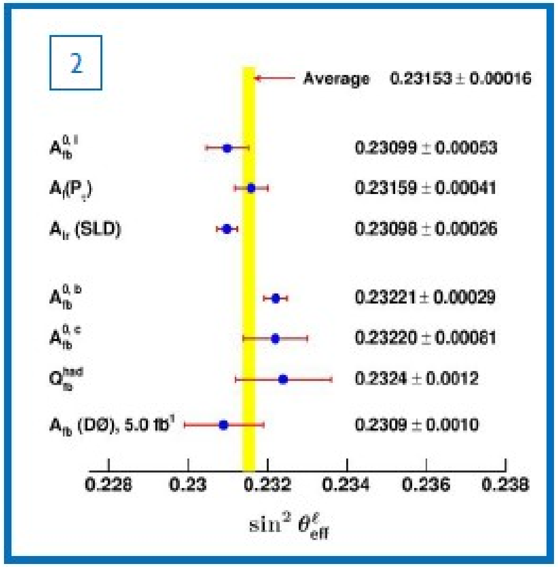
1) AFB unfolded agrees with theoretical predictions

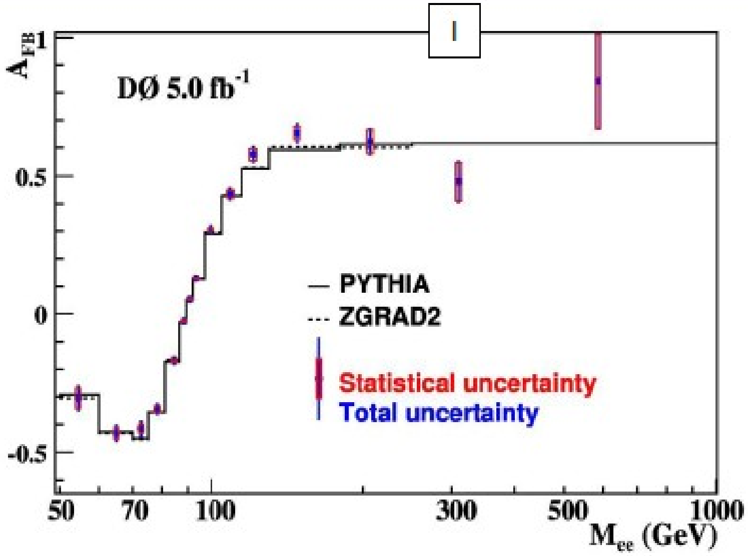
2) From AFB background subtracted and Mee in [70,130] GeV using simulated templates A_{FB} templates it is found

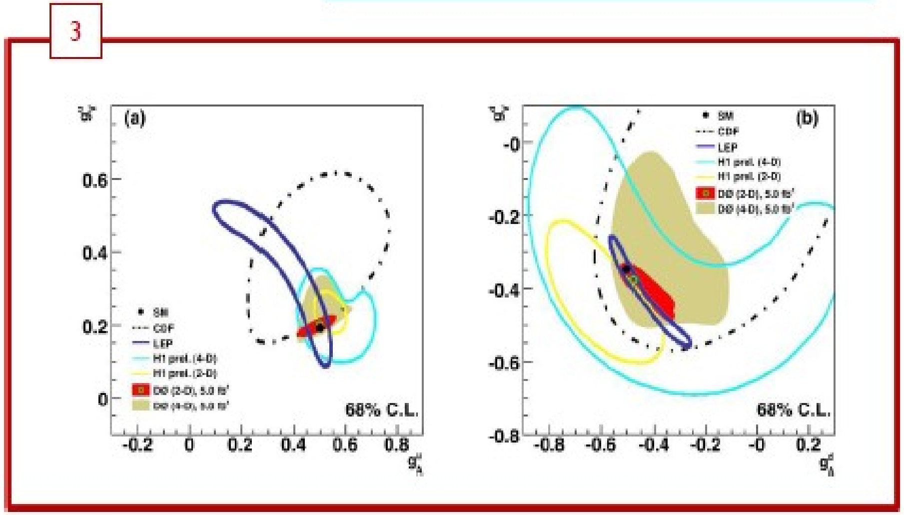
$$\sin^2\theta^l_{eff} = 0.2309 \pm 0.0008(stat.) \pm 0.006(syst.)$$

3) Fix sin to SM world average (0.23153)

→ Most precise measurements of $g_a^{u(d)}$ $g_v^{u(d)}$

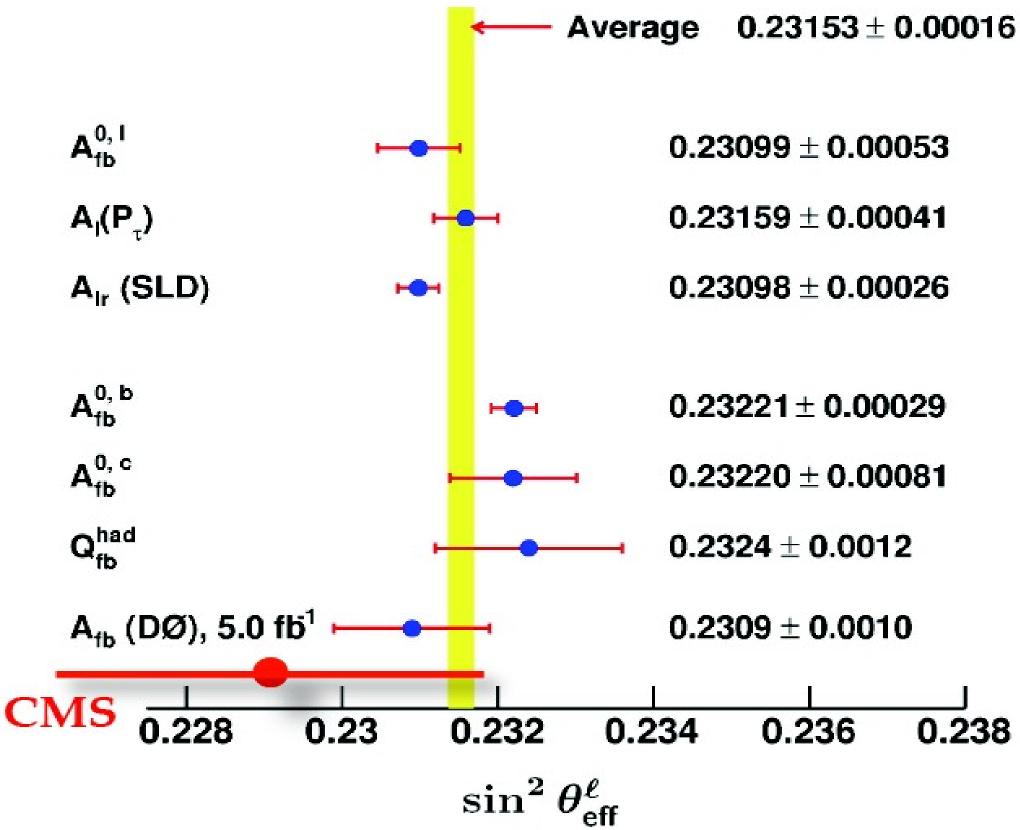






Effective weak mixing angle

Phys.Rev.D84, 012007 (2011)



In the vicinity of the Z pole, A_{FB} is sensitive to the effective weak mixing angle

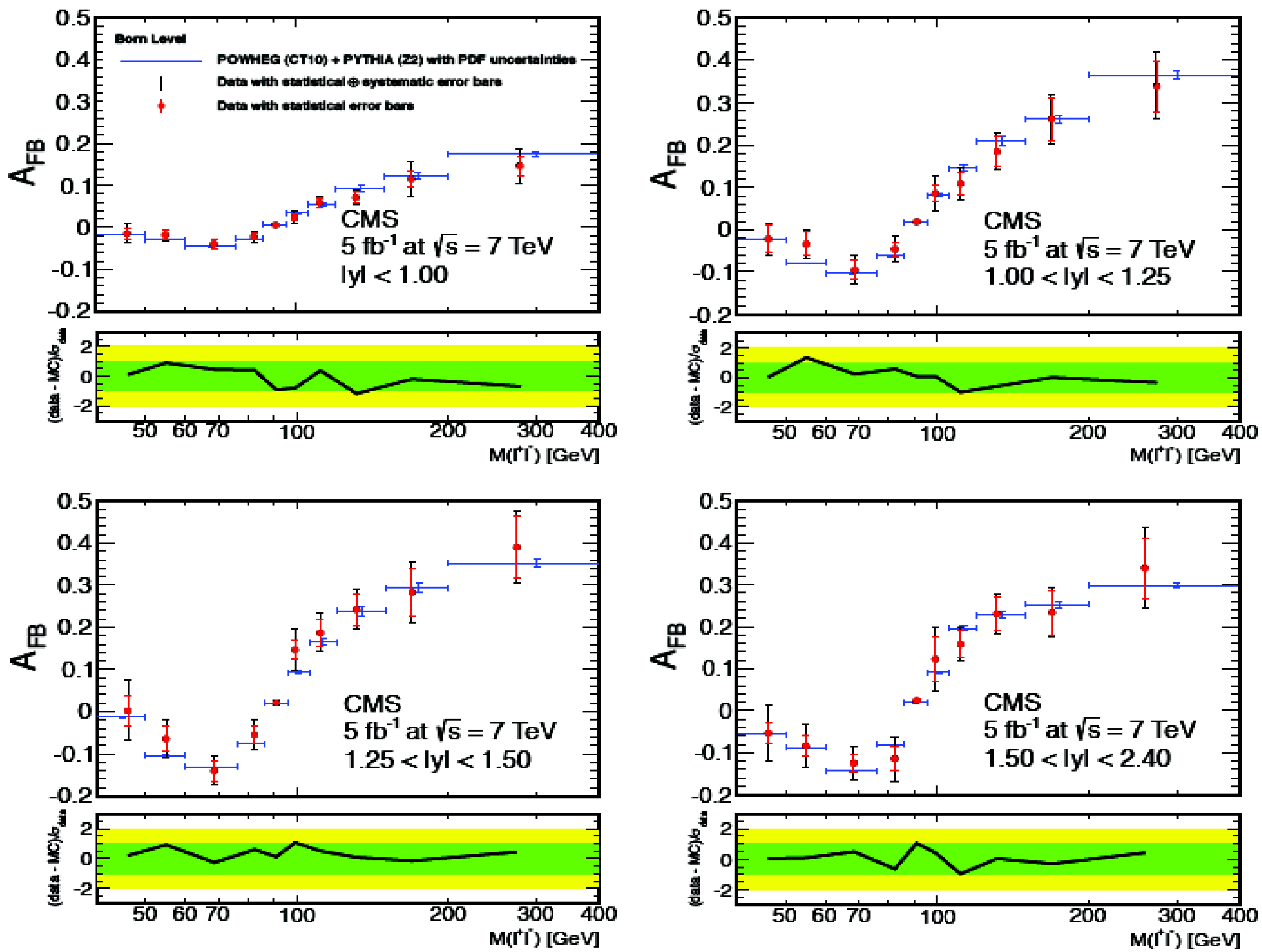
Phys.Rev.D84 (2011) 112002

First measurement at LHC by CMS

0.229 +/-0.020+/-0.025 using 1 fb^{-1} of data

DY forward-backward asymmetry

arXiv:12-7.3973, submitted to PLB

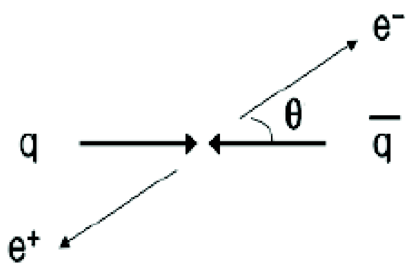


No evidence for new physics at high masses

Collins-Soper frame

- Collins-Soper frame : the center of mass frame of dilepton

$$q\bar{q} \rightarrow Z/\gamma* \rightarrow \ell^+\ell^-$$



in lepton plane

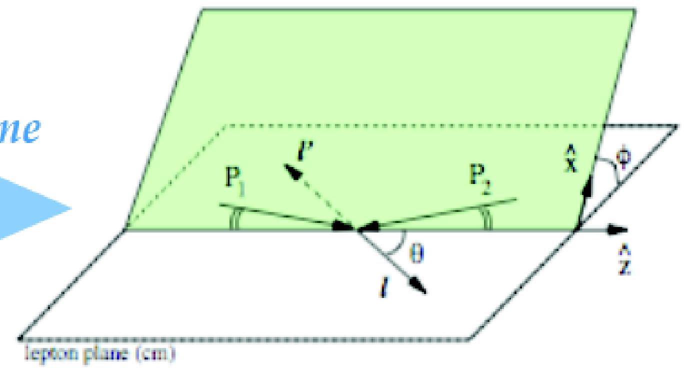


FIG. 1: The Collins-Soper frame.

- Differential cross section of cosθ and ϕ

$$\frac{\mathbf{d}\sigma}{\mathbf{dP_T^2 dy d}\cos\theta \mathbf{d}\phi} \propto (1+\cos^2\theta)$$ → **LO term**

$$+\ \frac{1}{2}A_0(1-3\cos^2\theta)$$ → *cos²θ : higher order term*

$$+\ A_1\sin 2\theta\cos\phi + \frac{1}{2}A_2\sin^2\theta\cos 2\phi + A_3\sin\theta\cos\phi$$ → *(θ, ϕ) terms*

$$+\ A_4\cos\theta$$ → **LO term : determine A_{fb}**

$$+\ A_5\sin^2\theta\sin 2\phi + A_6\sin 2\theta\sin\phi + A_7\sin\theta\sin\phi$$ → ***very small terms***

******All higher order terms are zero at Pt=0***

Z/g* Angular Coefficients

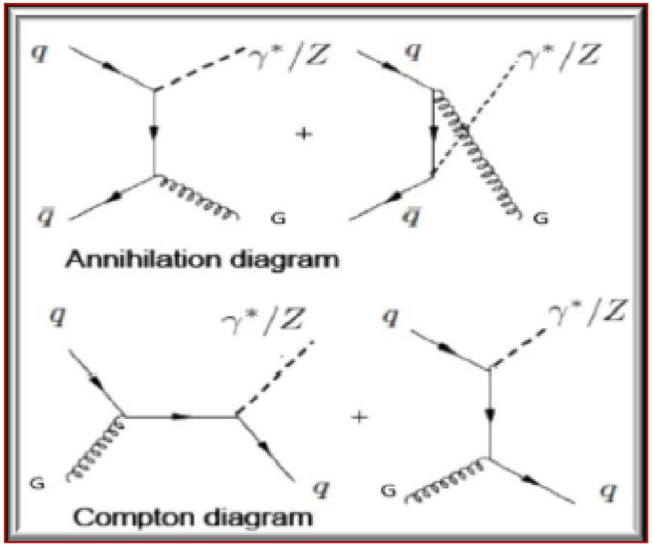
- First measurement of the $p\bar{p} \rightarrow Z/\gamma^* + X \rightarrow e^+e^- + X$ angular distributions with 2.1 fb^{-1}
- Angular distributions of the lepton decay in the Collins-Soper frame are:

$$\frac{d\sigma}{d\cos\theta} \propto (1+cos^2\theta) + \frac{1}{2}A_0(1-3cos^2\theta) + A_4\cos\theta$$

PRL 106, 241801

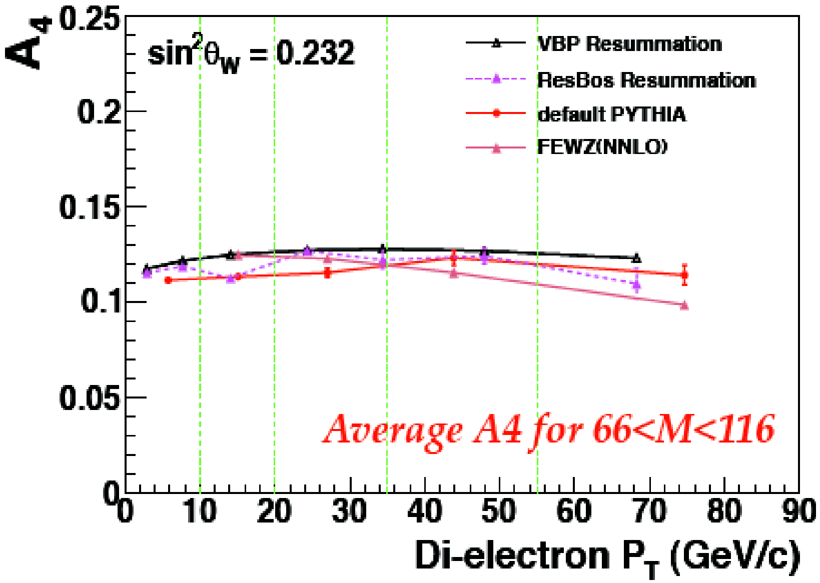
$$\frac{d\sigma}{d\varphi} \propto 1 + \frac{3\pi}{16}A_3\cos\varphi + \frac{1}{4}A_2\cos 2\varphi$$

- **Perturbative QCD makes definite predictions on $A_{0,2,3,4}$ depending on the dilepton p_T**
- **At order α_s the Z/γ^* boson can be produced via annihilation or Compton scattering**
- **Probe the contribution of different productions mechanisms contributions**

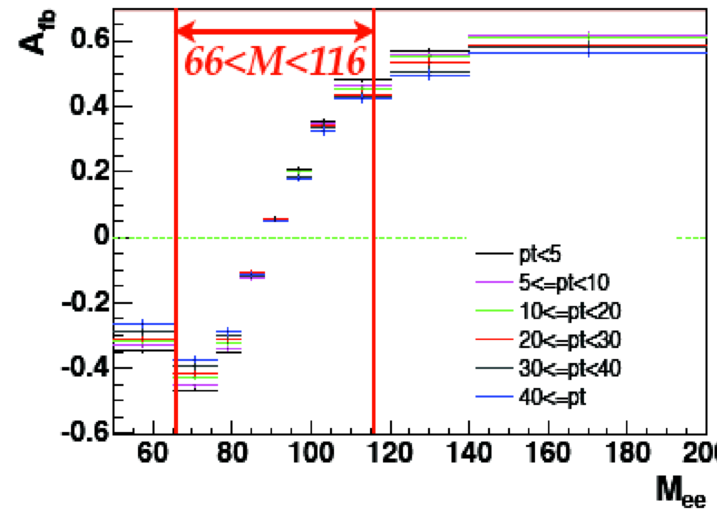


A_4 vs A_{FB}

- A_4 has a direct relation with A_{fb}



$$A_4 = \frac{8}{3} A_{fb}(M_{\ell\ell}, P_T, y)$$

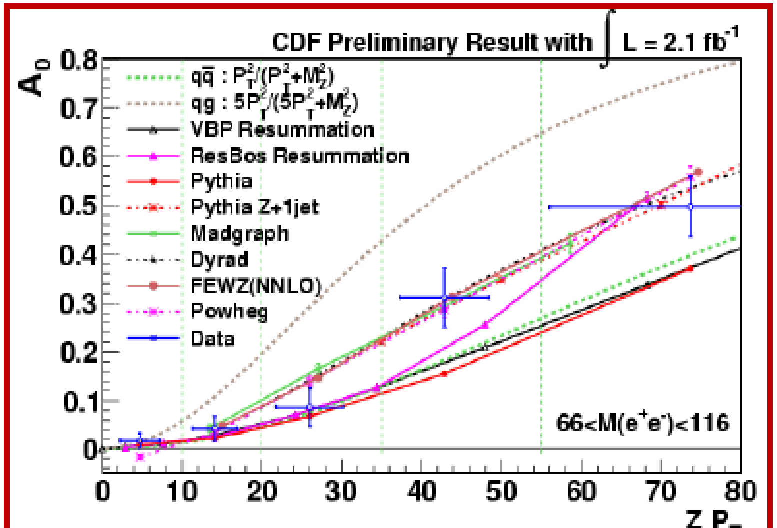


- A_4 is sensitive to weak mixing angle, $\sin^2\theta_W$
- A_{fb} has the mass, P_T, and y dependence
  - P_T and y dependence is much smaller than the mass dependence
  - A_{fb} in mass gives more sensitivity to extract the physics quantities
    - Physics quantities : $\sin^2\theta_W$, quark couplings

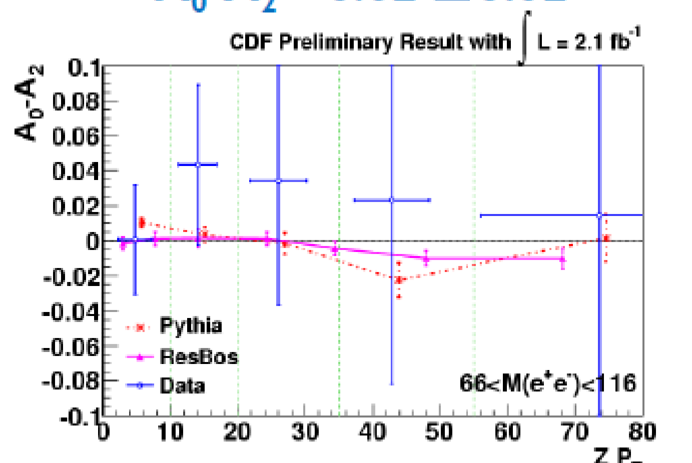
Z/γ* Angular Coefficients ($A_{0,2}$)

- At order α_s, both A_0 and A_2 should be the same for Z and γ*, but they have distinct Z p_T dependencies for annihilation or Compton scattering
- The $A_{0,2}$ trends as a function of Z p_T reveals the two Z production processes contributions, e.g. in Z +1 Jet PYTHIA simulation a significant Compton scattering contribution is expected (~30%)

- **Lam-Tung** relation predicts **A_0=A_2 at LO** and nearly the same at all orders
- Lam-Tung relation is **valid for spin-1 gluons**, but it is broken for scalar gluons
- First measurement of the Lam-Tung relation at large dilepton mass and high transverse dilepton p_T
- **Fundamental test of the vector nature of gluons**

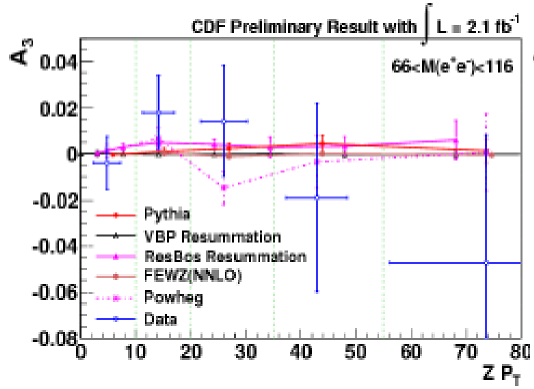


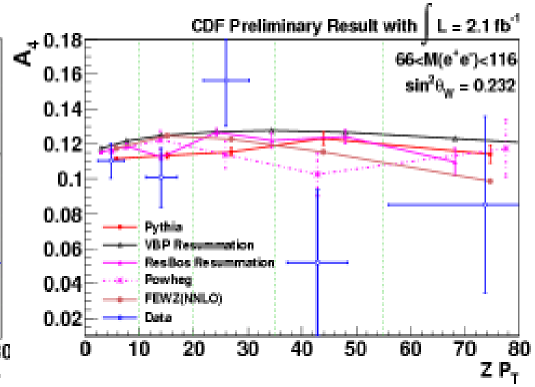
A_0-A_2 = 0.02 ± 0.02

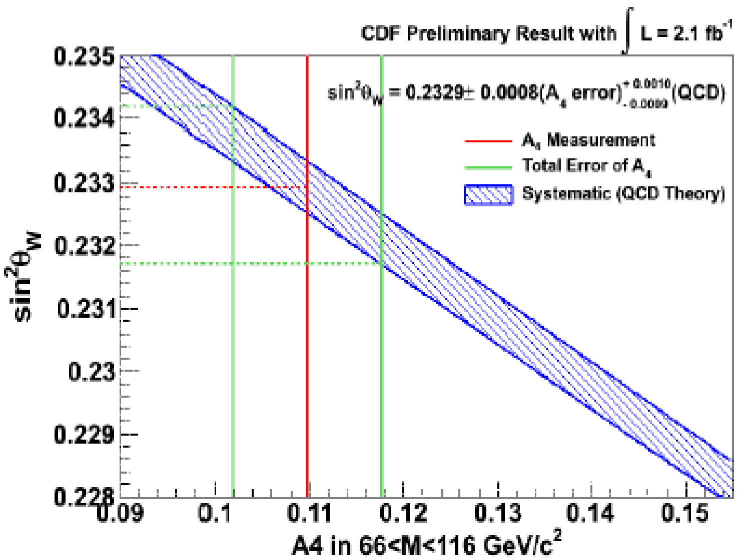


Z/γ* Angular Coefficients ($A_{3,4}$)

- A_3 and A_4 should be **nearly flat in Z p_T**
- A_3 and A_4 are found to **agree with the expectations** of all models







- A_4 is related to A_{FB} via

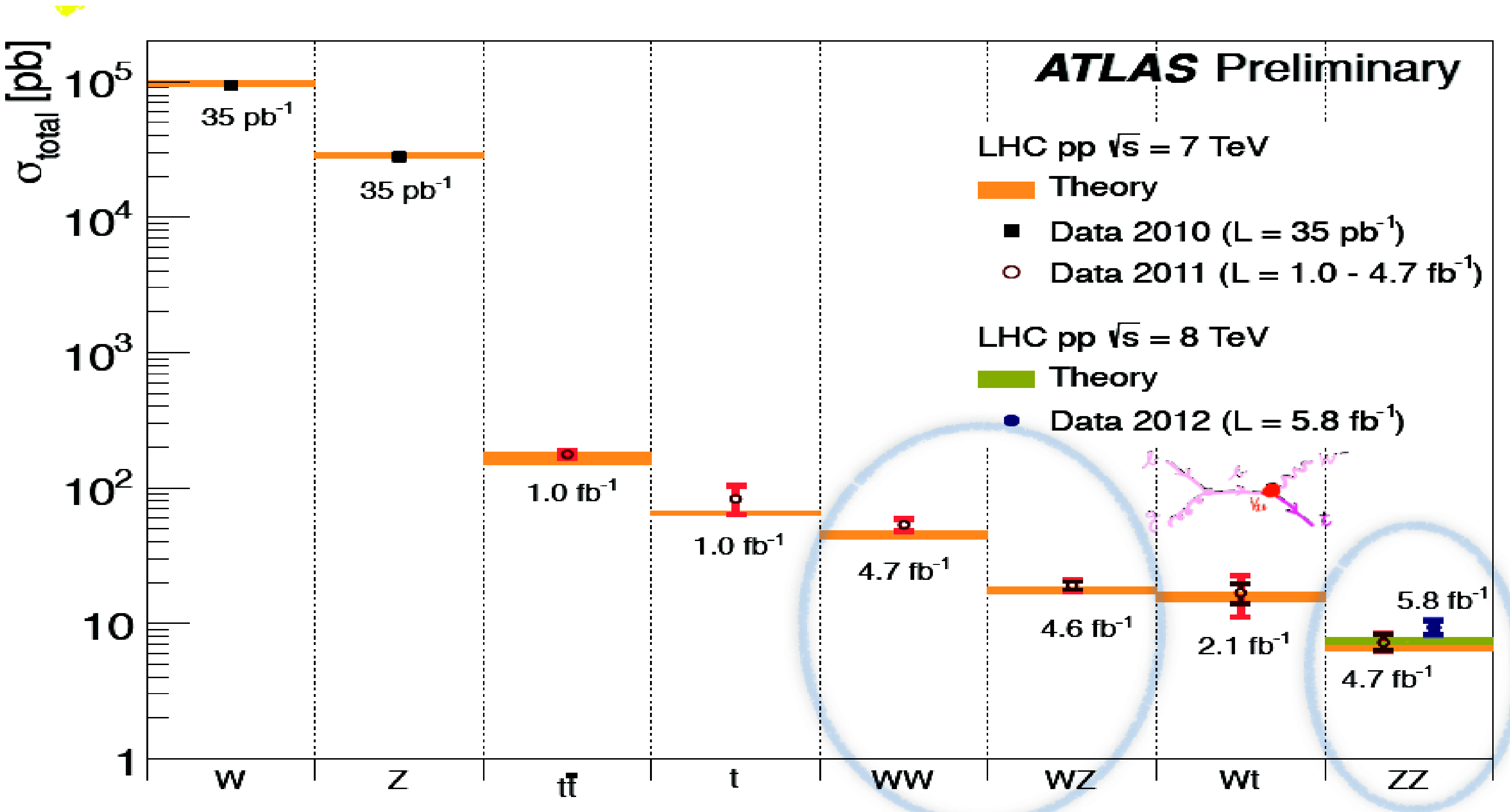
$$A_{FB} = \frac{3}{8} A_4$$

- Possible to extract the weak mixing angle $\sin^2\theta_W$
- The extracted $\sin^2\theta_W$ is

0.2329 ± 0.008 (from A4) $^{+0.0010}_{-0.0009}$ (QCD theory)

The Standard Model at LHC

- SM measurements are the foundations of all searches (summer 2012)



The Standard Model at LHC

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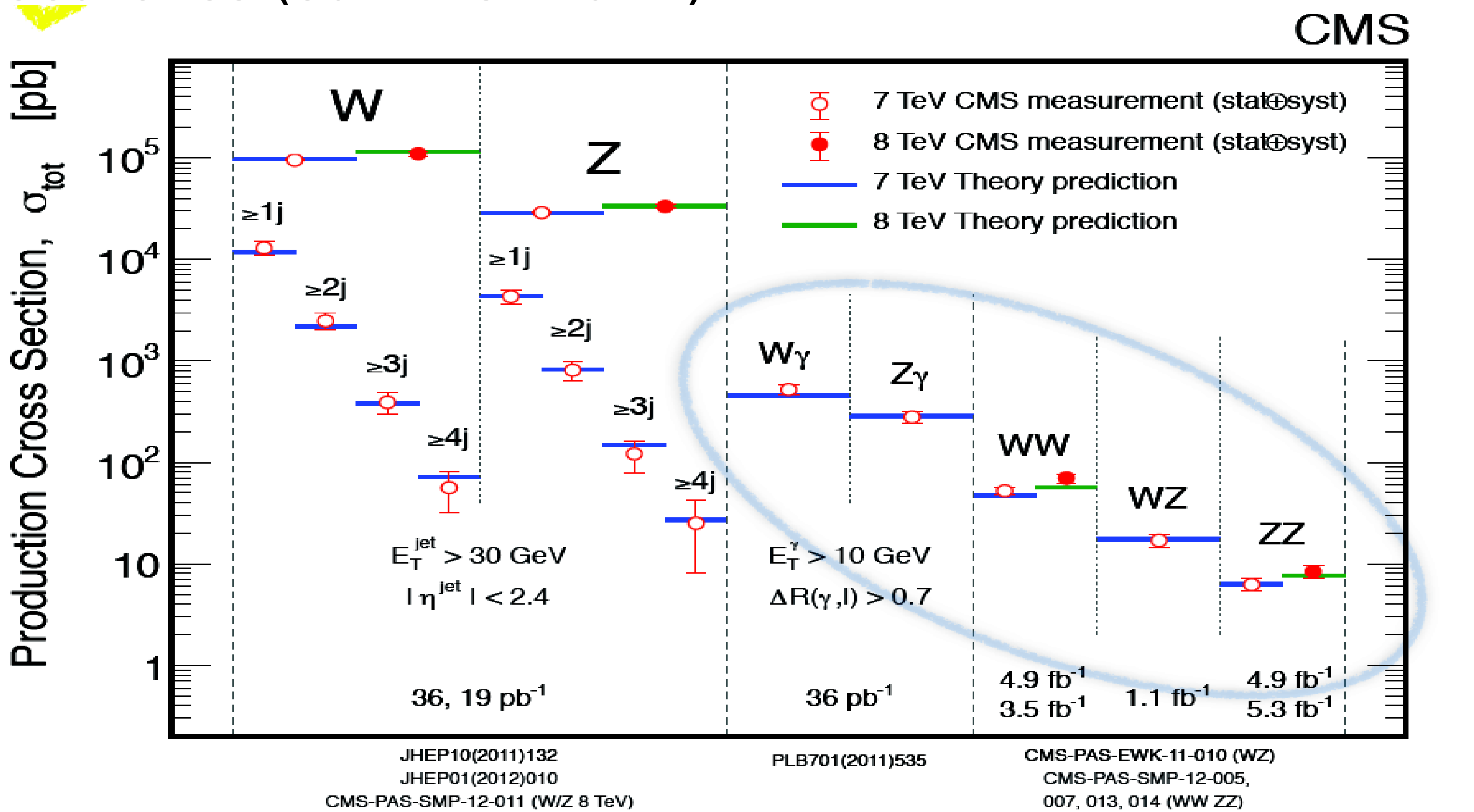

Next topics

- 21.11 – Top: xsection, mass
- 28.11 – Dibosons and anomalous couplings
- 5.12, 12.12 - **Higgs**
- 19.12 – **SUSY**
- 9.1 – other searches for New Physics
- 16.1 - B-physics programme
- 23.1 – heavy ion programme