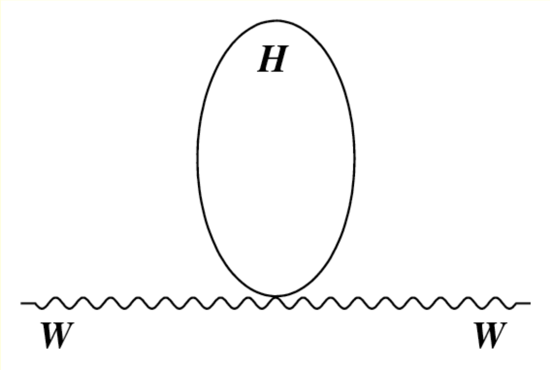
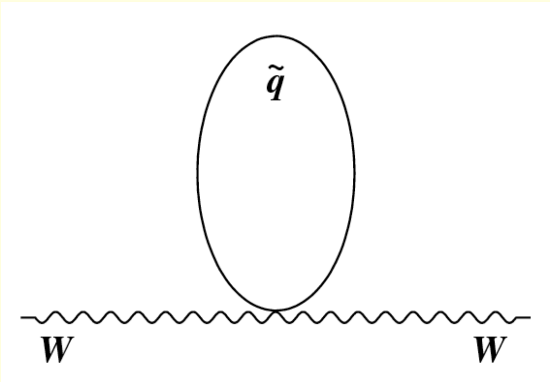
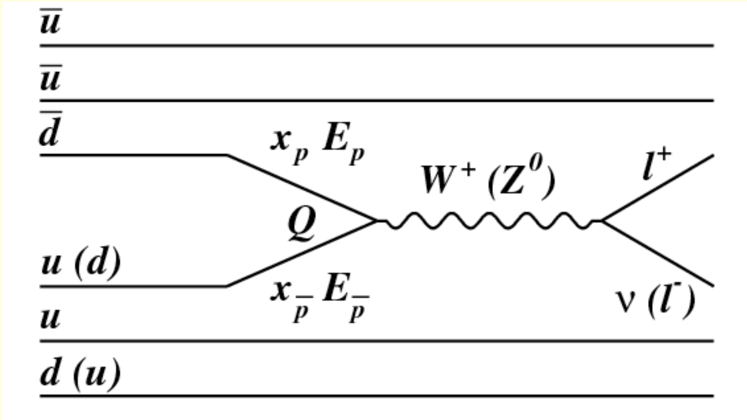
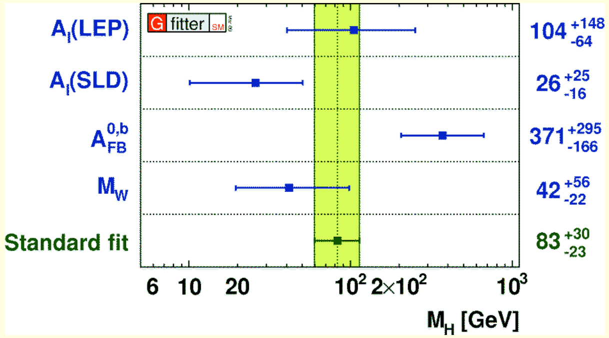
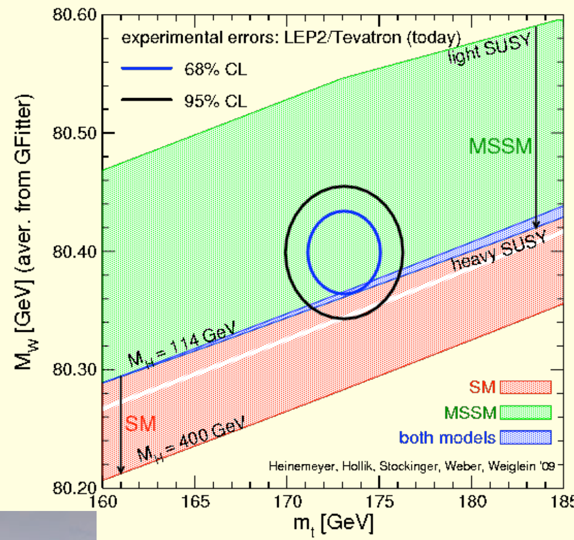
W and Z Physics









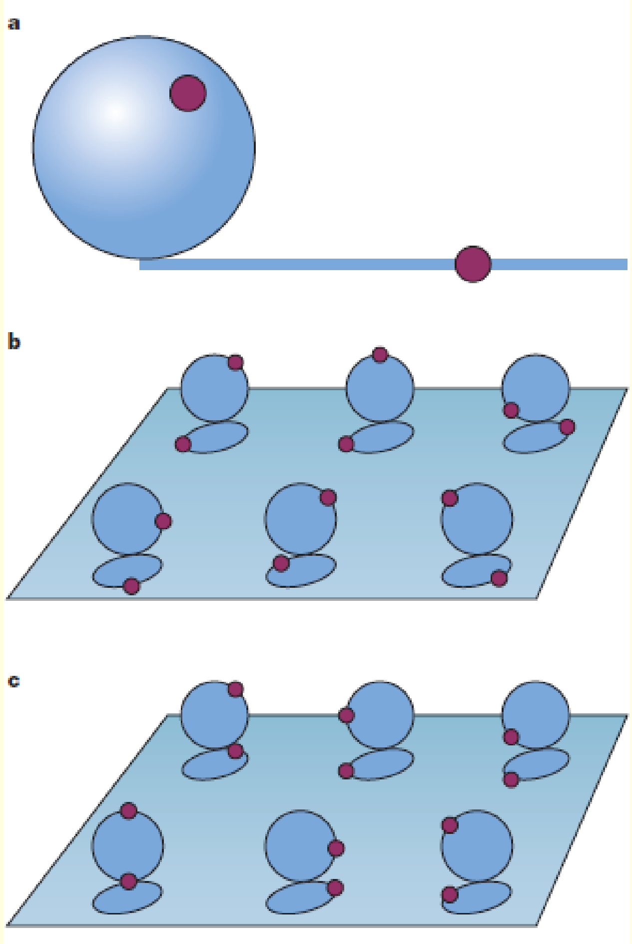


Chris Hays

Oxford University

The Electroweak Symmetry

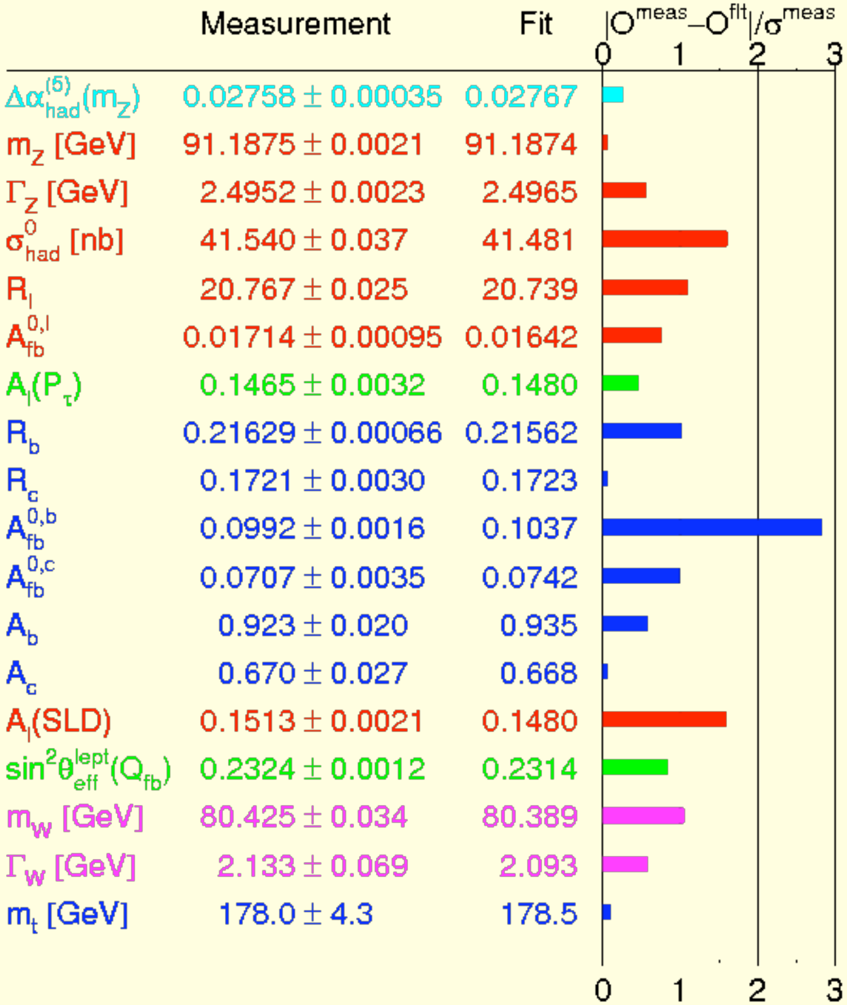
- Fundamental Lagrangian has $SU(2)_L \times U(1)_Y$ symmetry
- Vacuum charged under SU(2), U(1)
  - *Fixes relative directions*
  - *Residual $U(1)_{EM}$ symmetry*
- 3 parameters define Electroweak interactions
  - *Strength [g: SU(2), g': U(1)]*
  - *Mass scale of broken symmetry (vacuum energy v)*
- Enormously predictive theory
  - *Confirmed (W & Z discoveries) and highly tested*
  - *Missing piece: details of symmetry breaking*



F. Wilczek, Nature 433, 239 (2005)

Electroweak Tests

- Many parameters measured to high precision



Tree-level relations:

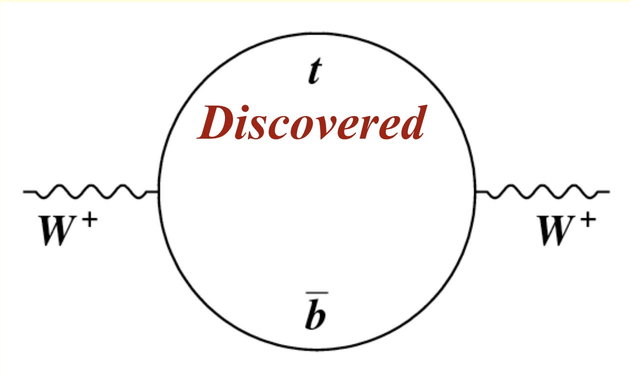
$$\alpha_{EM} = g^2 g'^2 / 4\pi[g^2 + g'^2]$$
$$m_Z = [g^2 + g'^2]^{1/2}\, v / 2$$

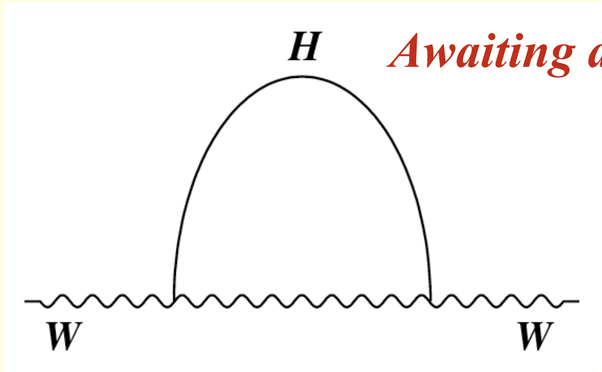
LEP & SLD Collaborations,
Physics Reports 427, 257 (2006)

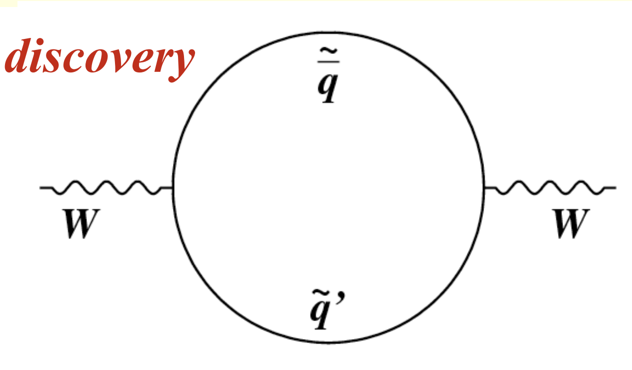
$$\sin^2\theta = g'^2 / [g^2 + g'^2]$$
$$m_W = gv / 2$$

Loop-Level Probes

- High precision provides sensitivity to unobserved particles
  - *Probed through loop corrections*
  - *Sensitivity currently limited by precision on W boson mass*







$$m_W^2 = \frac{\pi\alpha_{EM}}{\sqrt{2}G_F\,(1 - m_W^2/m_Z^2)(1 - \Delta r)}$$

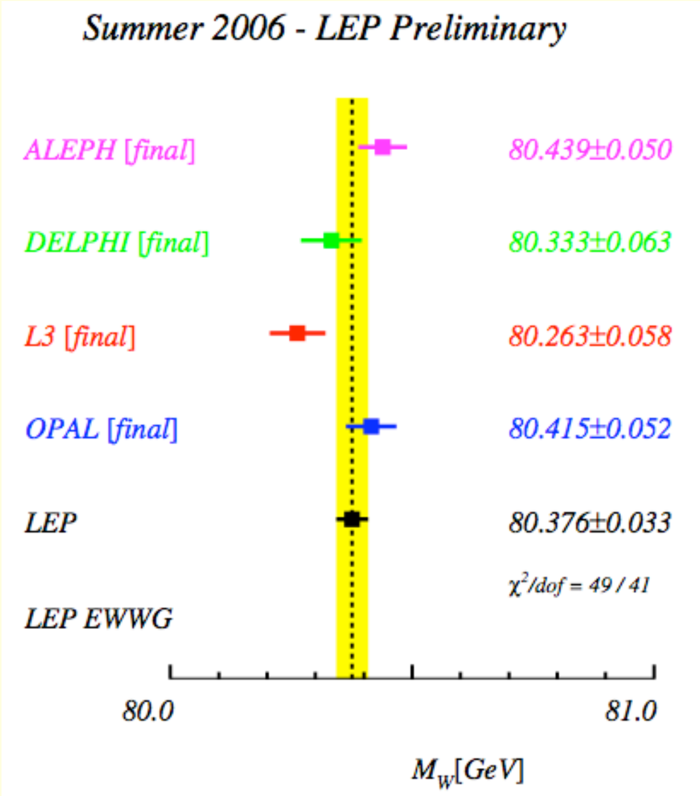
Parameter Shift	m_W Shift (MeV$/c^2$)
$\Delta \ln m_H = +0.693$	-41.3
$\Delta m_t = +1.3$ GeV$/c^2$	7.9
$\Delta\alpha_{EM}(Q = m_Z c^2) = +0.00035$	-6.2
$\Delta m_Z = +2.1$ MeV$/c^2$	2.6

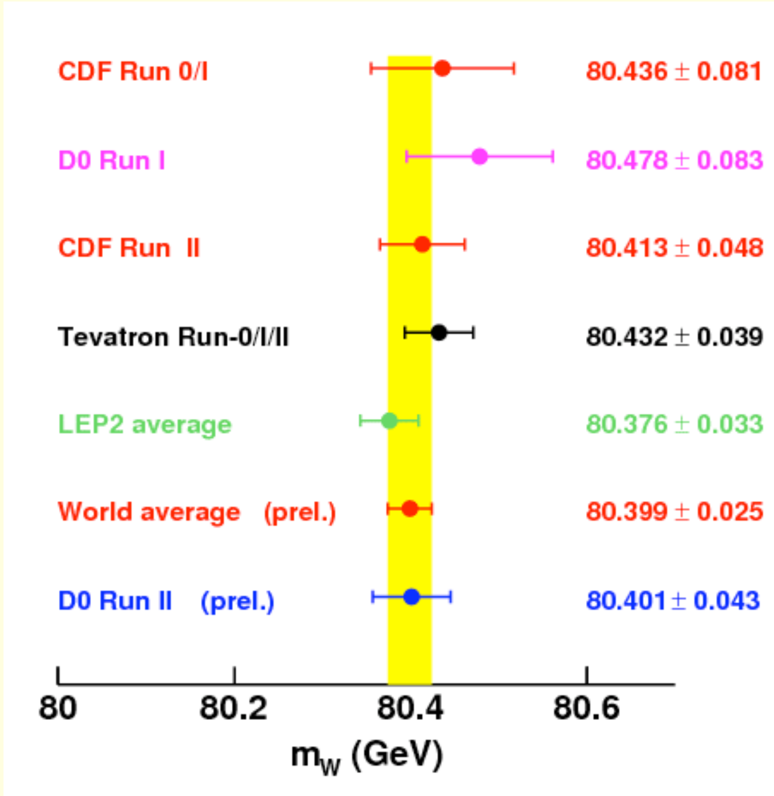
Tree level: $\boldsymbol{m_W}$ **= 79.964 ± 0.005 GeV**

Measurement: $\boldsymbol{m_W}$ **= 80.399 ± 0.023 GeV**

W Boson Mass Measurements

- Published measurements give combined precision of 25 MeV
  - *Preliminary DØ result is world's most precise single measurement*

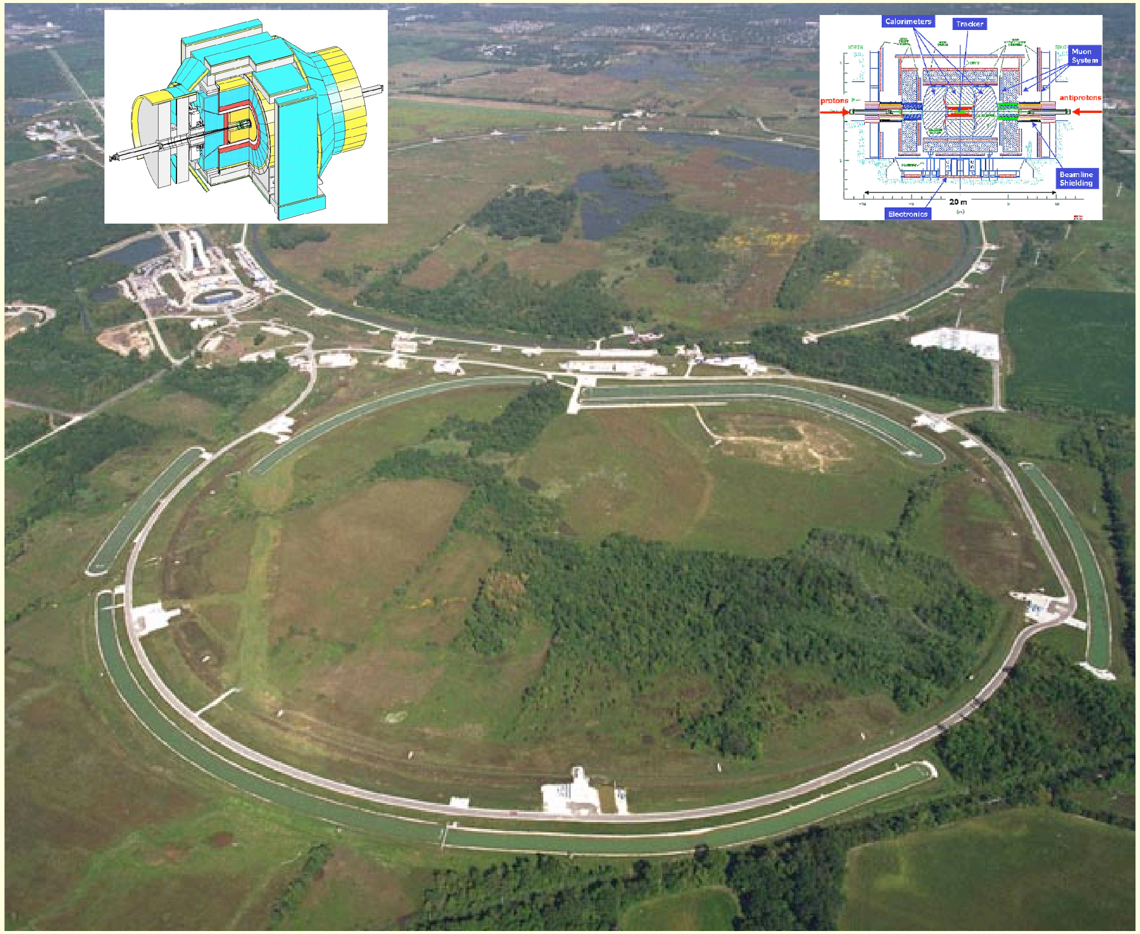


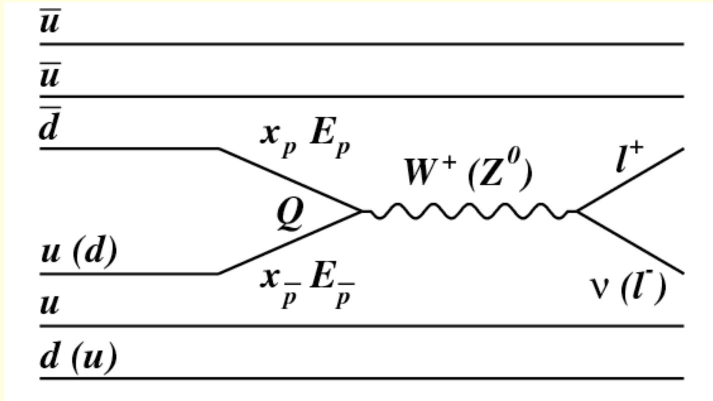


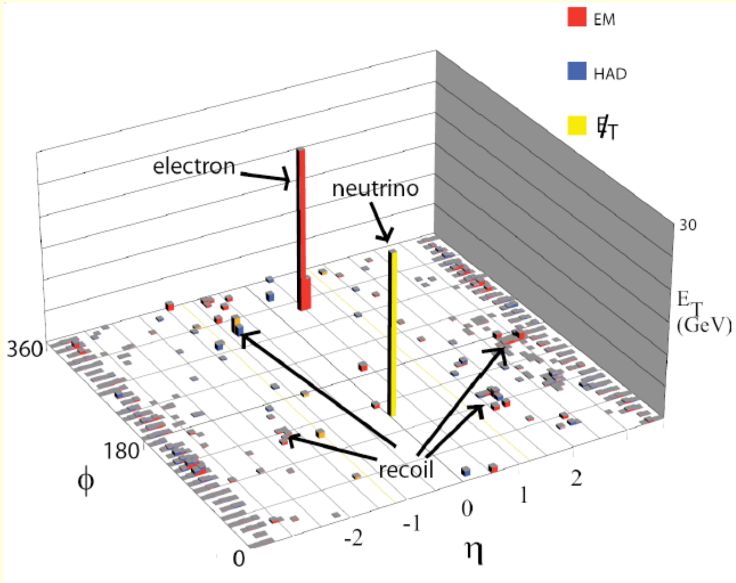
- Future hadron-collider measurements promise <10 MeV precision

W & *Z* Production at Hadron Colliders

- Initial momentum in beam direction unknown
  - *Focus on transverse quantities*

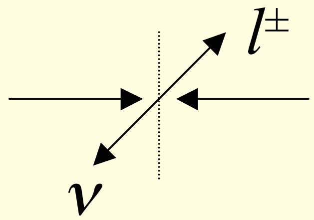






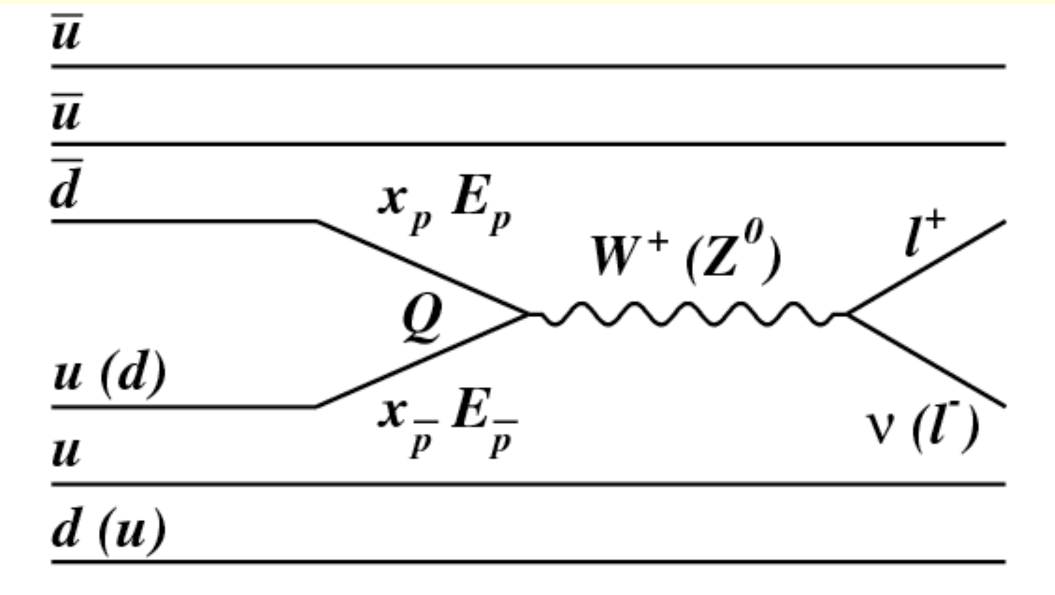
Measuring m_W at a Hadron Collider

- Experimental inputs:
  - *In situ calibration of detector response to $l^{\pm}$ and ν*
    - Only transverse momenta used in mass fit



$$m_T^{\,2} = 2p^l_T\, p^{\nu}_T\,(1 - \cos\Delta\phi)$$

- Theoretical inputs:
  - *Details of W production and decay*

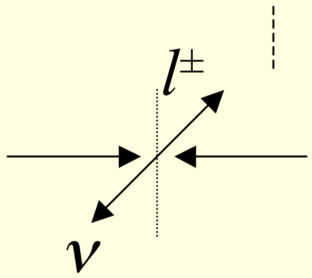


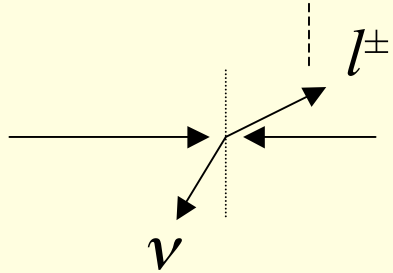
Source	Uncertainty (MeV)
Lepton Scale	23.1
Lepton Resolution	4.4
Lepton Efficiency	1.7
Lepton Tower Removal	6.3
Recoil Energy Scale	8.3
Recoil Energy Resolution	9.6
Backgrounds	6.4
PDFs	12.6
W Boson p_T	3.9
Photon Radiation	11.6

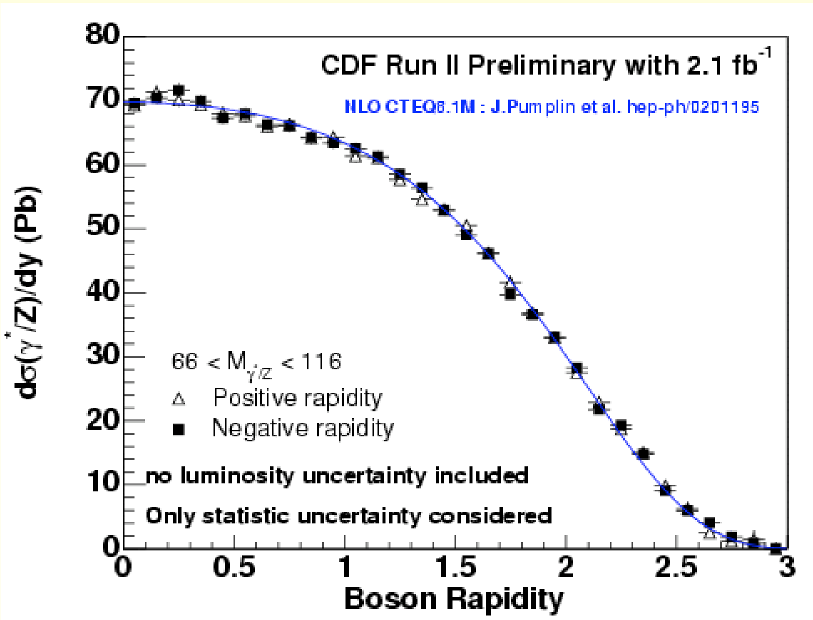
CDF Collaboration,
PRL 99, 151801 (2007),
PRD 77, 112001 (2008)

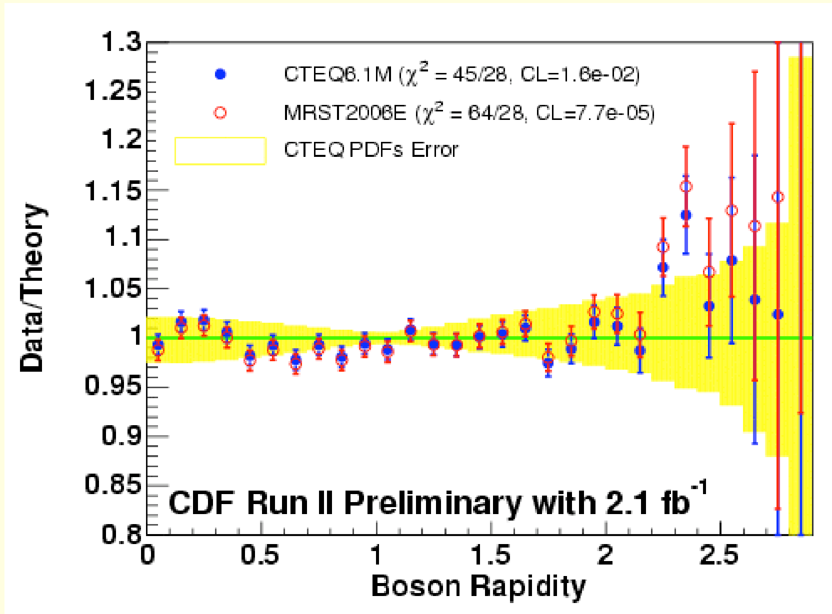
W Boson Production

- Parton distribution functions
  - *Affect observed m_T distribution*
  - *Intersection of theory and experiment*
    - Wide set of data used to fit for function parameters at given Q^2
    - Higher Q^2 obtained using DGLAP equations
  - *New Tevatron data improving PDF accuracy*





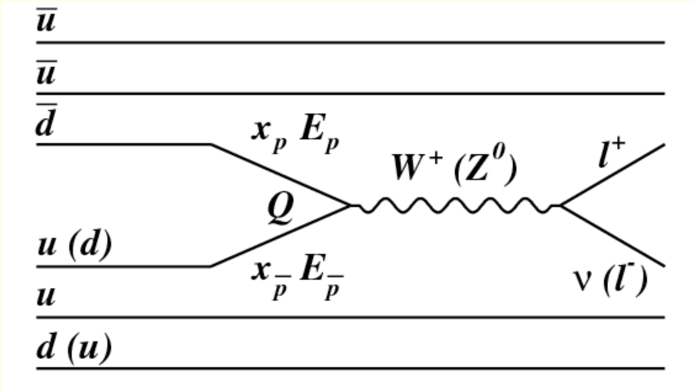


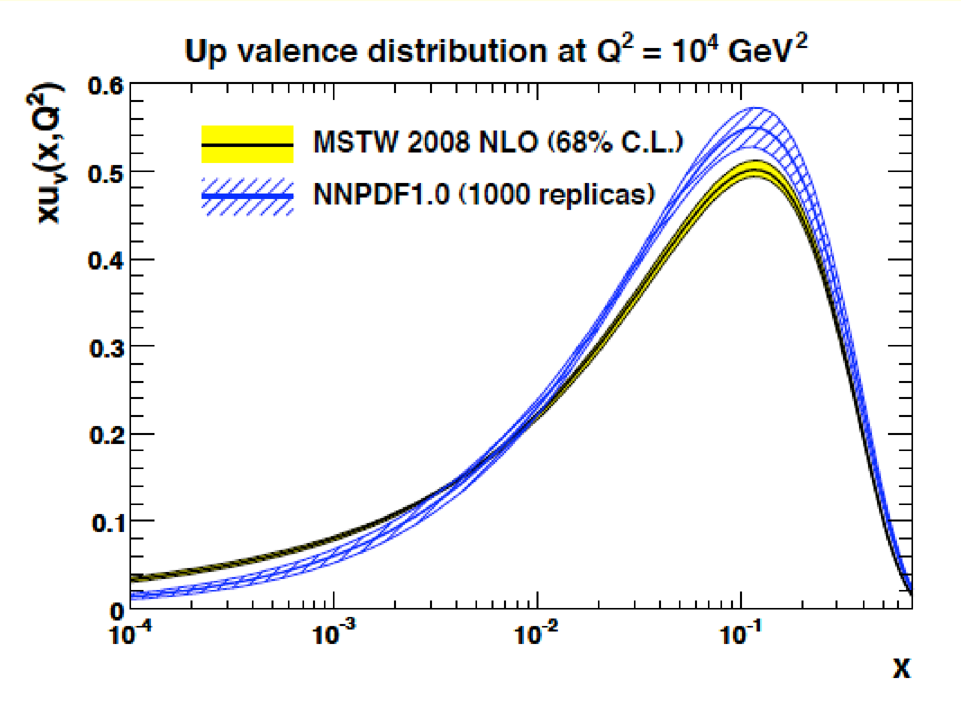


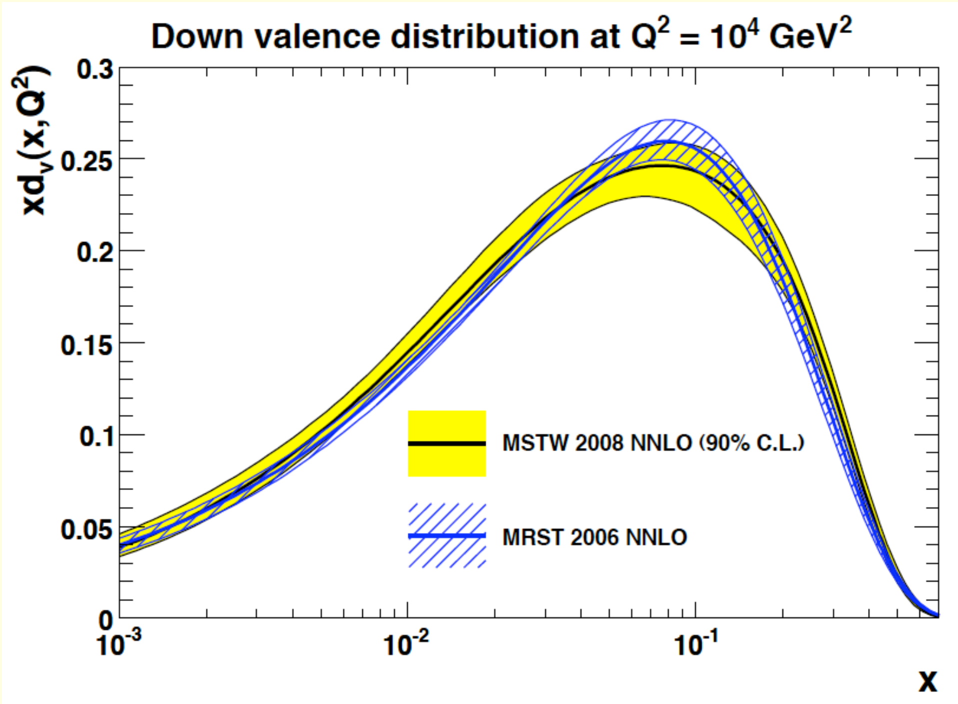
W Boson Production

- Parton distribution functions
  - *W boson charge asymmetry*

$$A(y_W) = \frac{d\sigma_+/dy_W - d\sigma_-/dy_W}{d\sigma_+/dy_W + d\sigma_-/dy_W} \approx \frac{u(x1)d(x2) - d(x1)u(x2)}{u(x1)d(x2) + d(x1)u(x2)}$$







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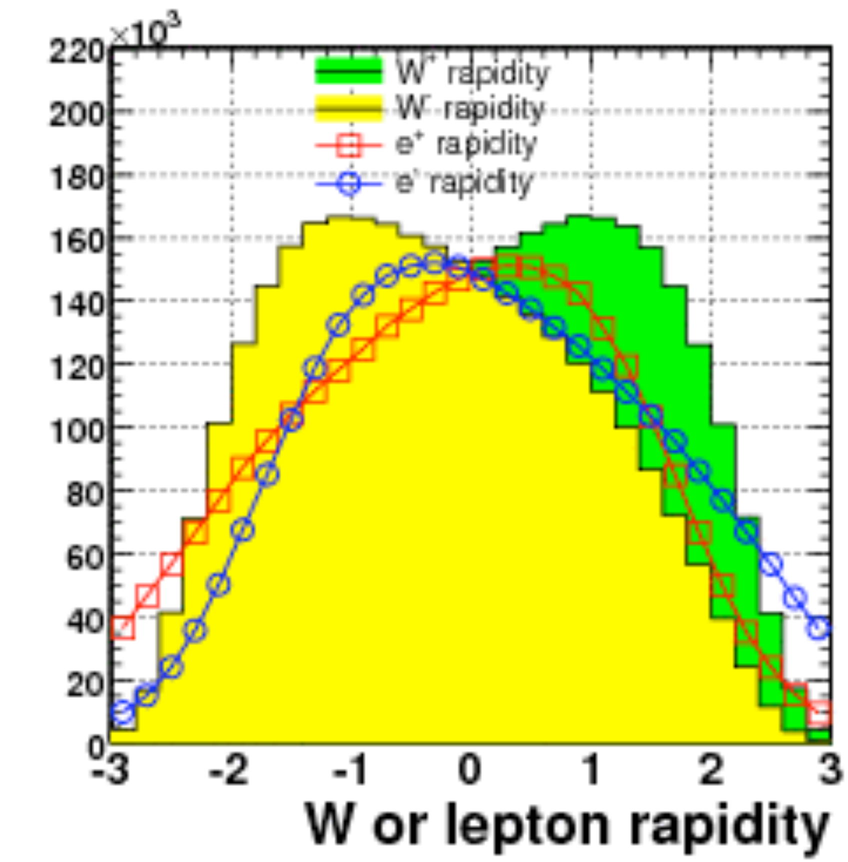

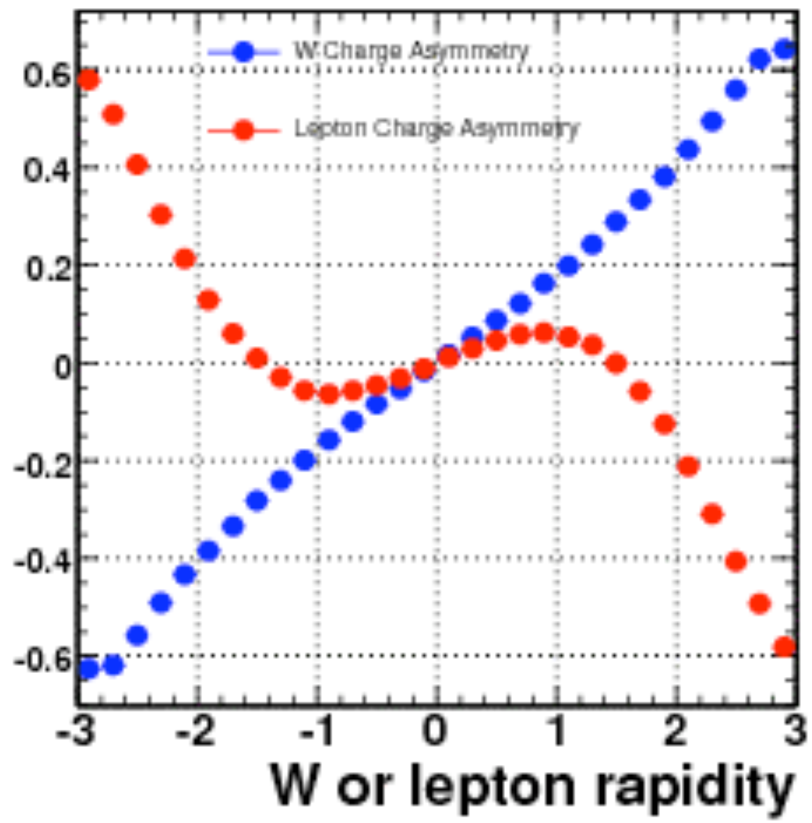

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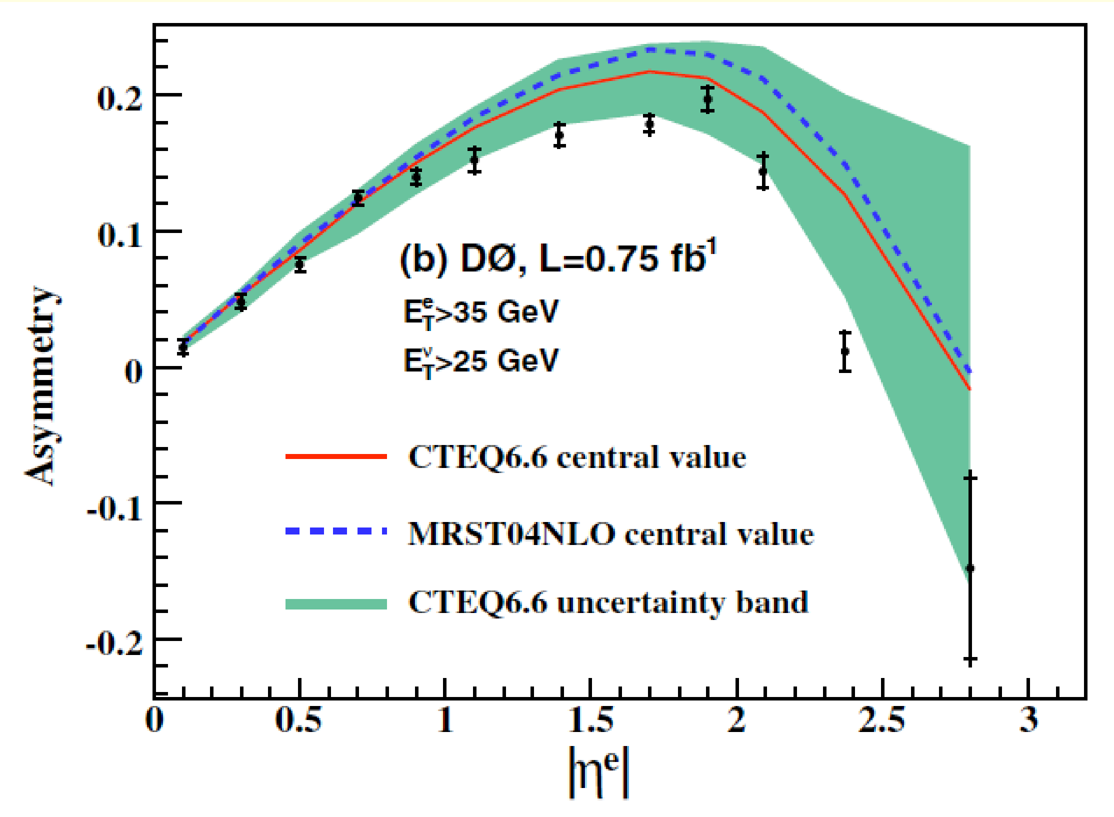
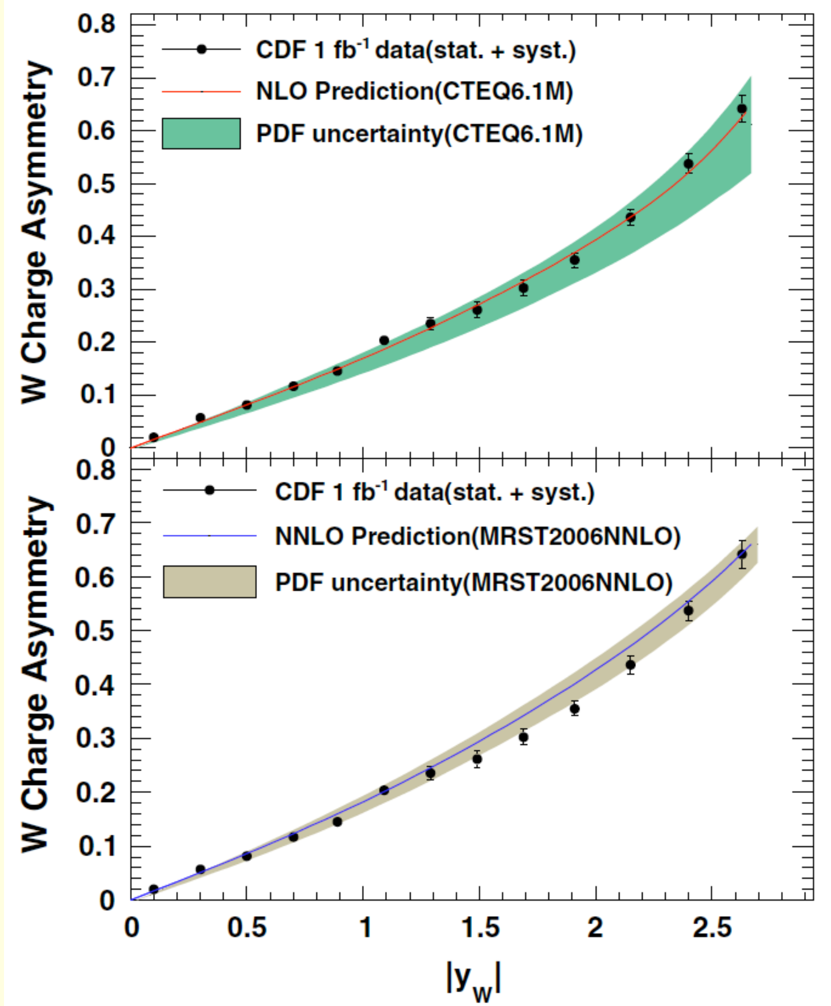


DØ Collaboration,
PRL 101, 211801 (2008)



CDF Collaboration,
PRL 102, 181801 (2009)

Measuring m_W at a Hadron Collider

- Experimental inputs:
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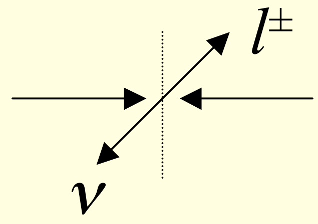

$$m_T^{\,2} = 2p^l_T\, p^\nu_T\, (1 - \cos\Delta\phi)$$

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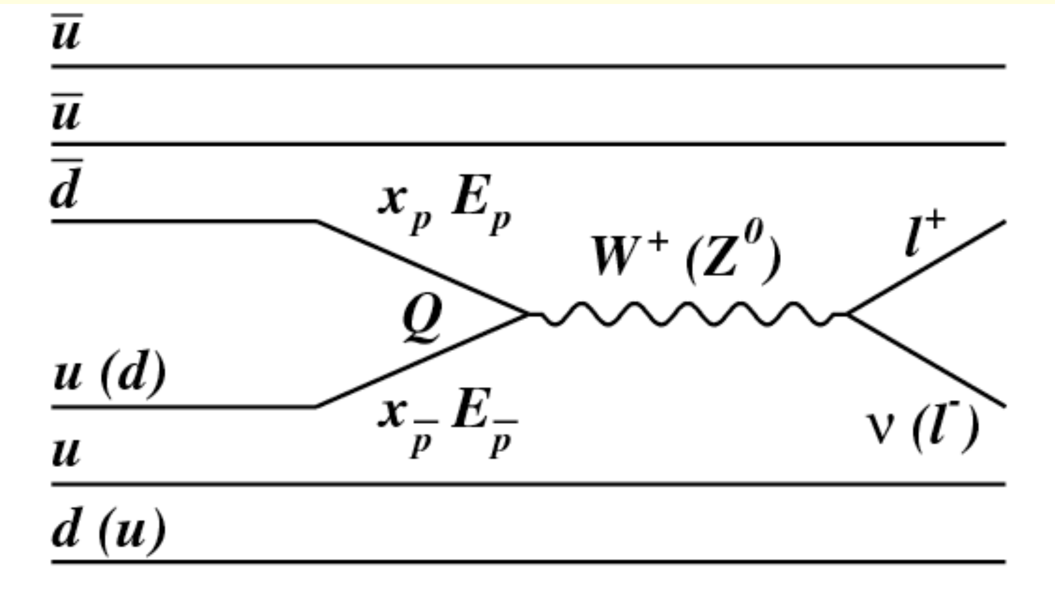

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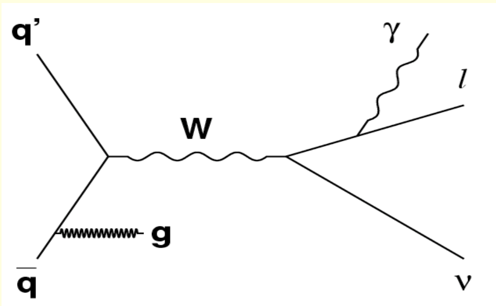
CDF Collaboration,
PRL 99, 151801 (2007),
PRD 77, 112001 (2008)

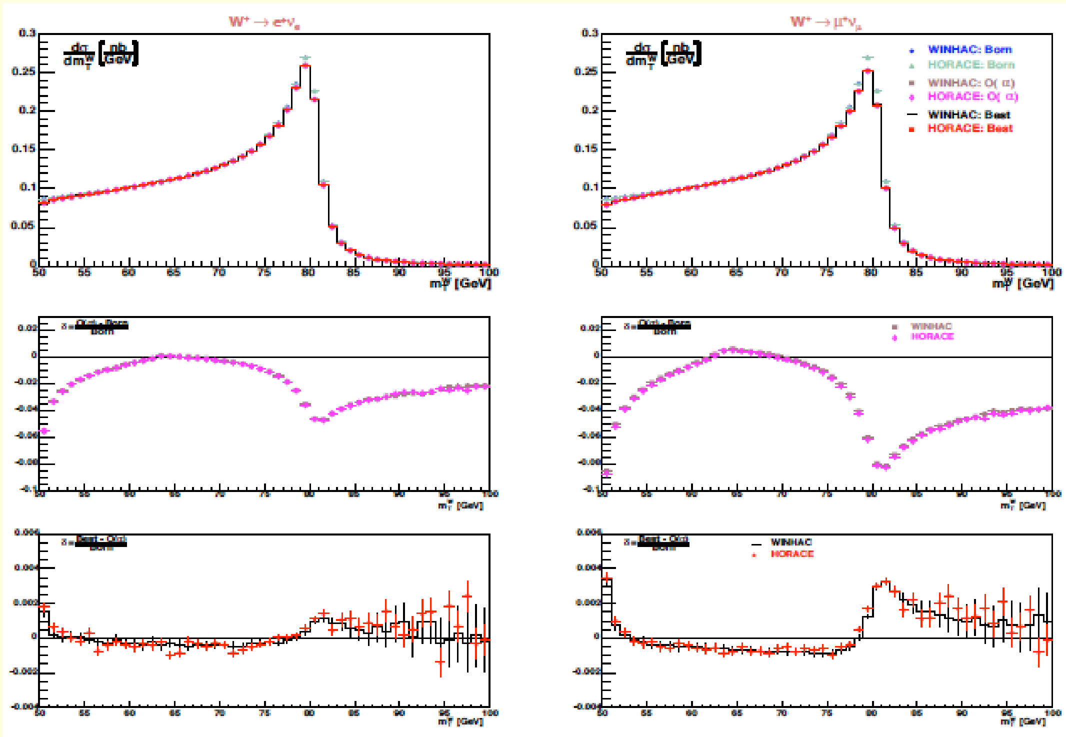
W Boson Decay

- m_W measurement sensitive to γ radiation from final-state $l^{\pm}$
  - *Including O(a) radiation has ~150 MeV effect at CDF*
  - *Uncertainty primarily due to higher orders*
  - *New generators include higher orders using exponentiation techniques*
    - Promise to significantly reduce QED uncertainties



HORACE
C.M. Carloni Calame *et al.*
PRD 69, 037301 (2004)

WINHAC
W. Placzek and S. Jadach
EPJ C 29, 325 (2003)



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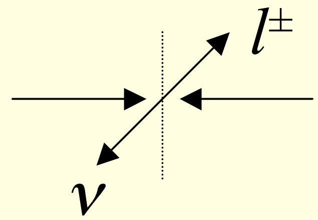

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CDF Collaboration,
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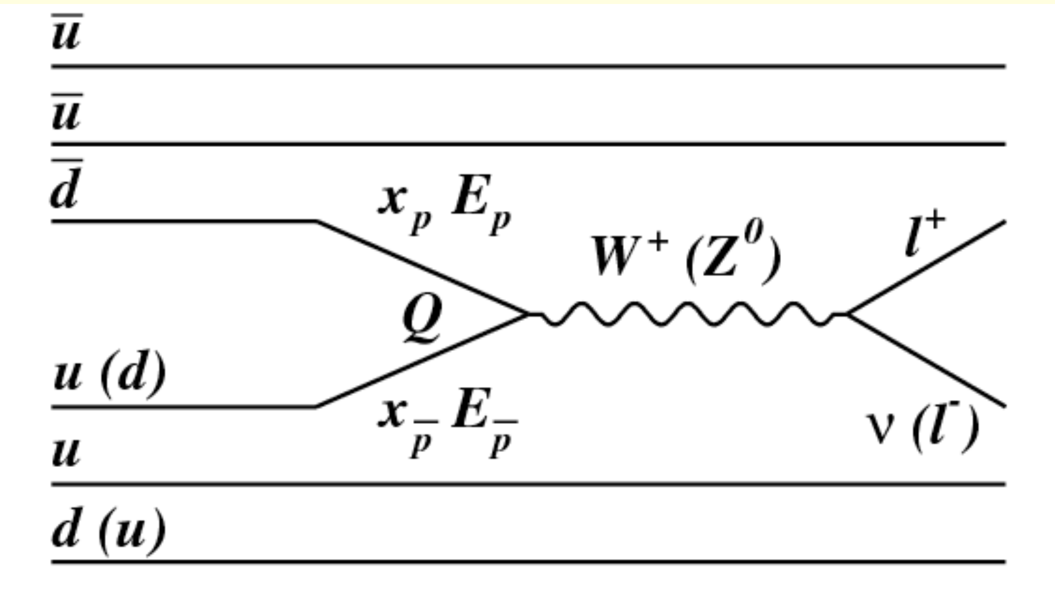
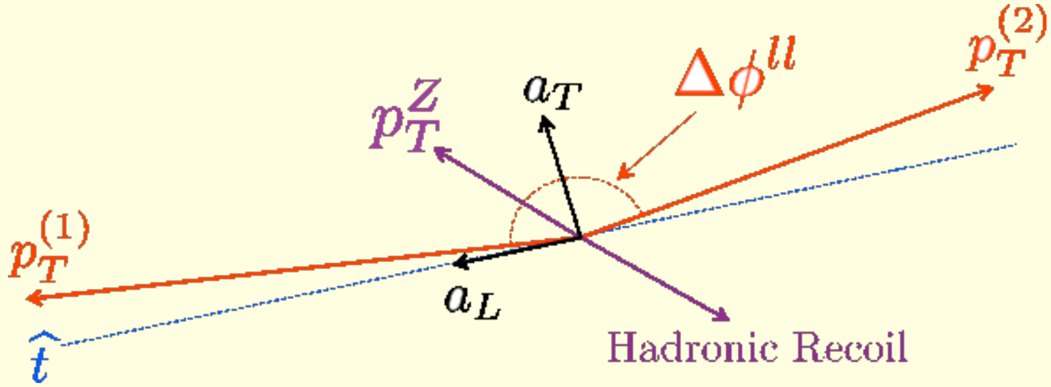
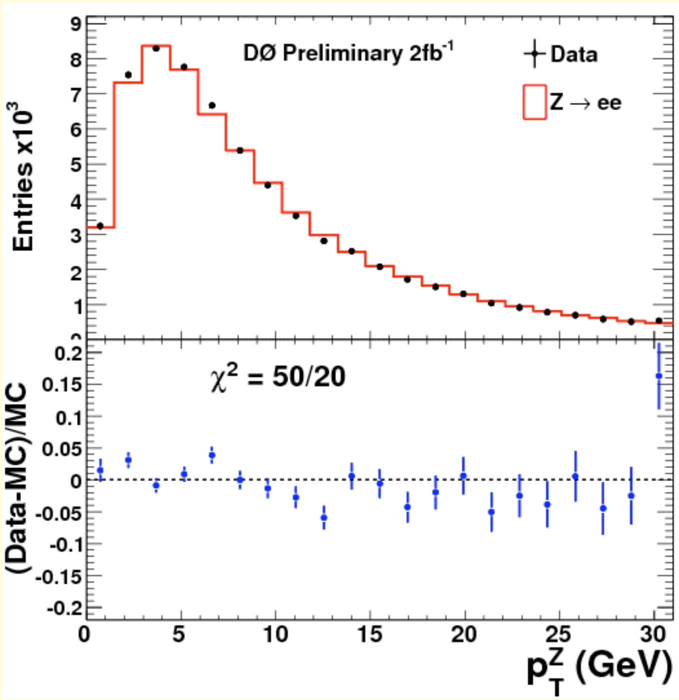
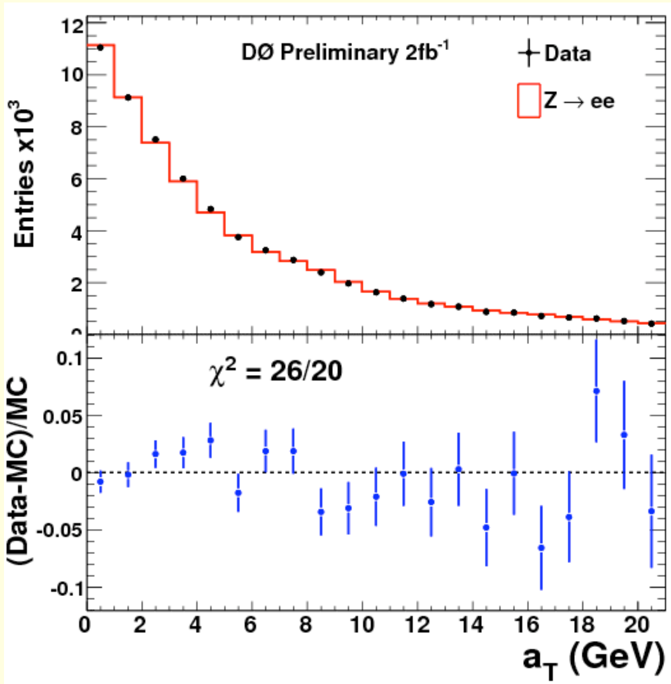


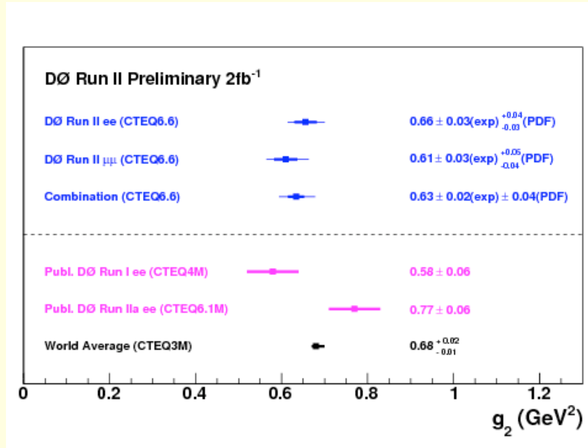
Z Boson Production

- Boson transverse momentum
  - *Dominant production in non-perturbative regime*
  - *Parameters motivated by theory, measured with Z boson data*
  - *Experimentally more precise to measure projected boson p_T*









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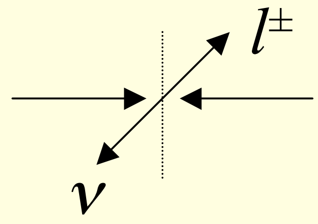

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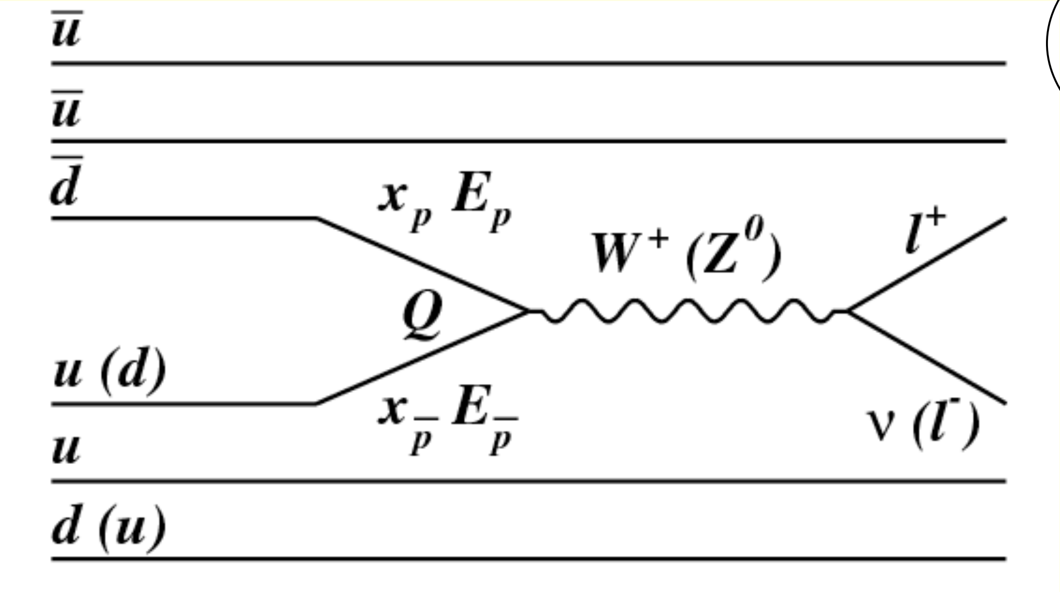

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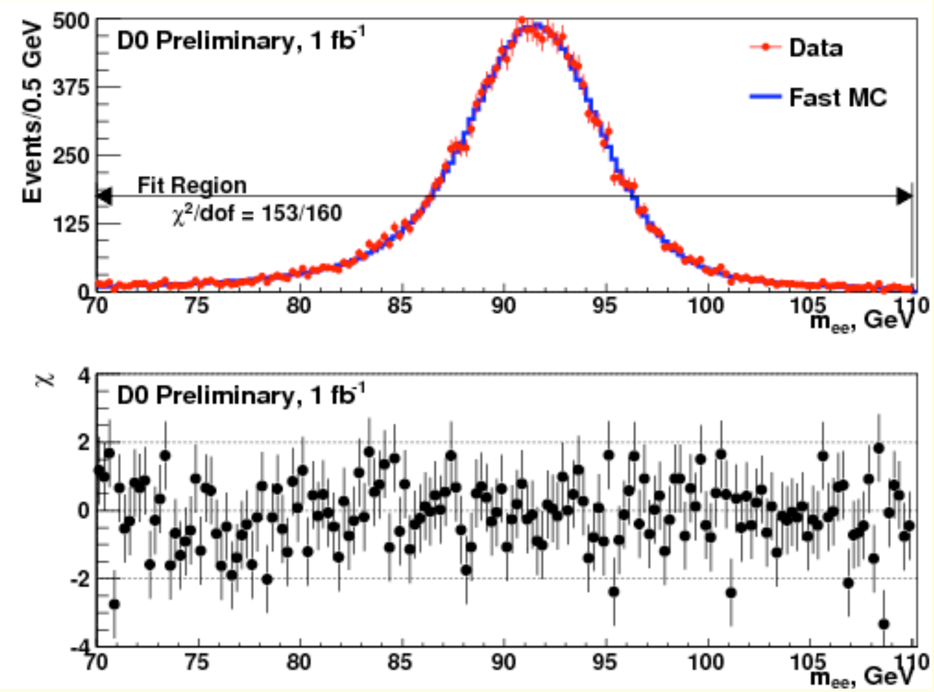
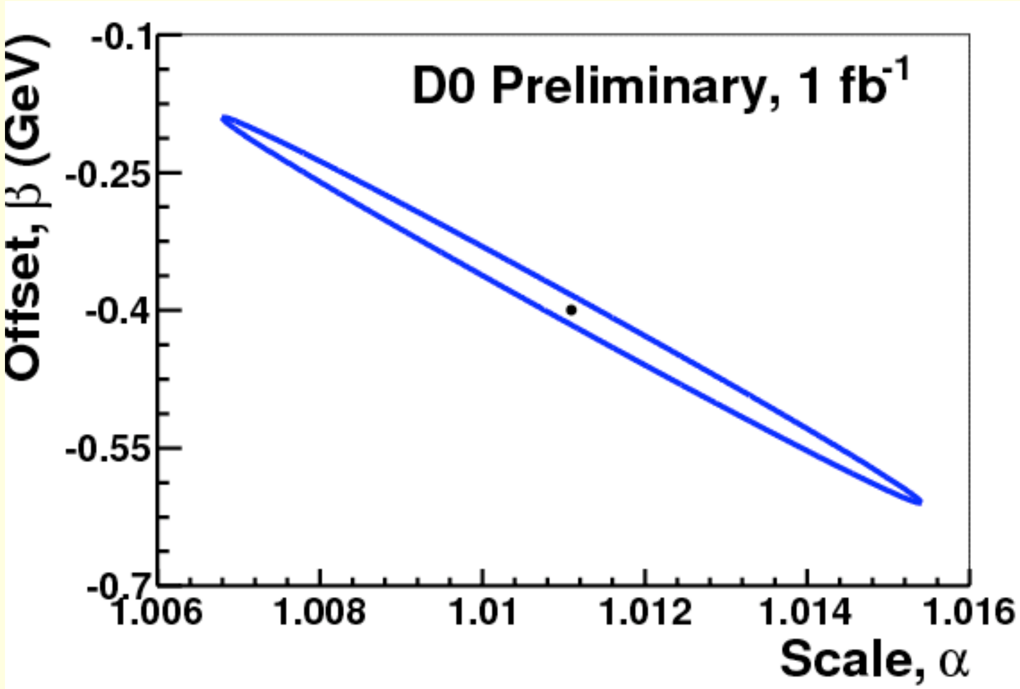
CDF Collaboration,
PRL 99, 151801 (2007),
PRD 77, 112001 (2008)

DØ m_W Measurement

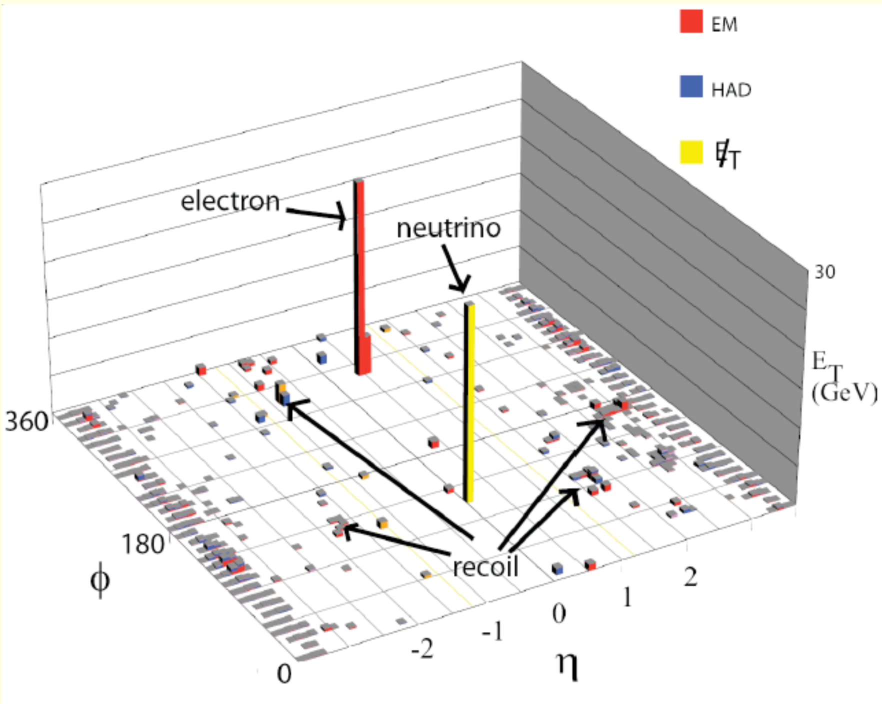
- Experimental inputs:
  - *In situ calibration of detector response to $l^{\pm}$*
    - Use sample of **18,725** fully reconstructed $Z \rightarrow ee$ events
    - Response includes scale and offset: $R = \alpha E + \beta$
    - Energy scale calibration is dominant systematic uncertainty on m_W
      - Scales with statistics

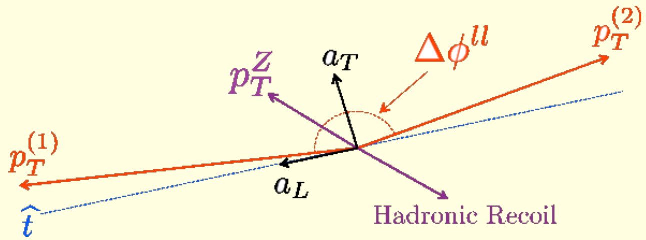


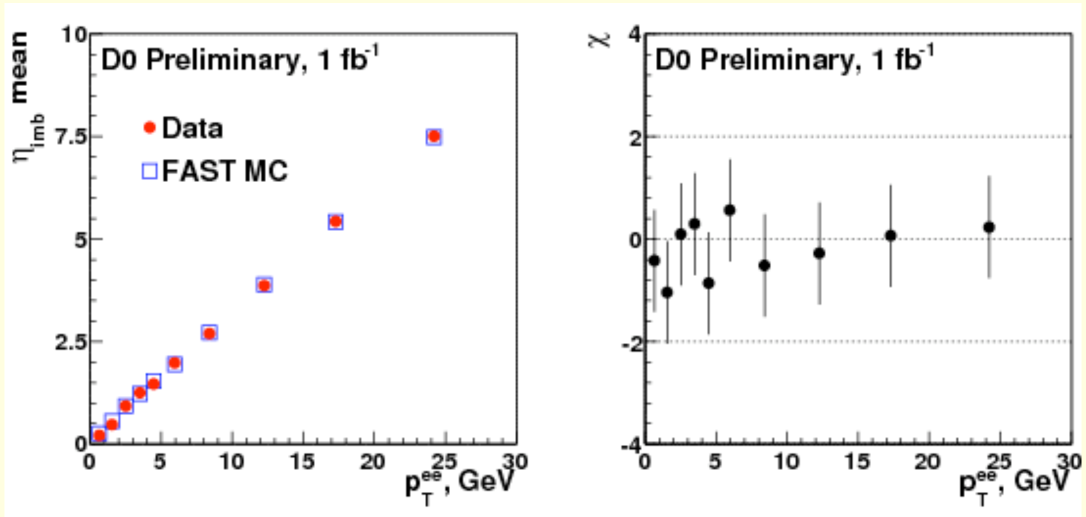


DØ m_W Measurement

- Experimental inputs:
  - *In situ calibration of detector response to ν*
    - Develop model using GEANT and randomly collected events (zero bias)
    - Tune parameters with $Z \rightarrow ee$ events
    - Response to hadrons (< 1) results in measured momentum imbalance
      - Well modeled by fast simulation

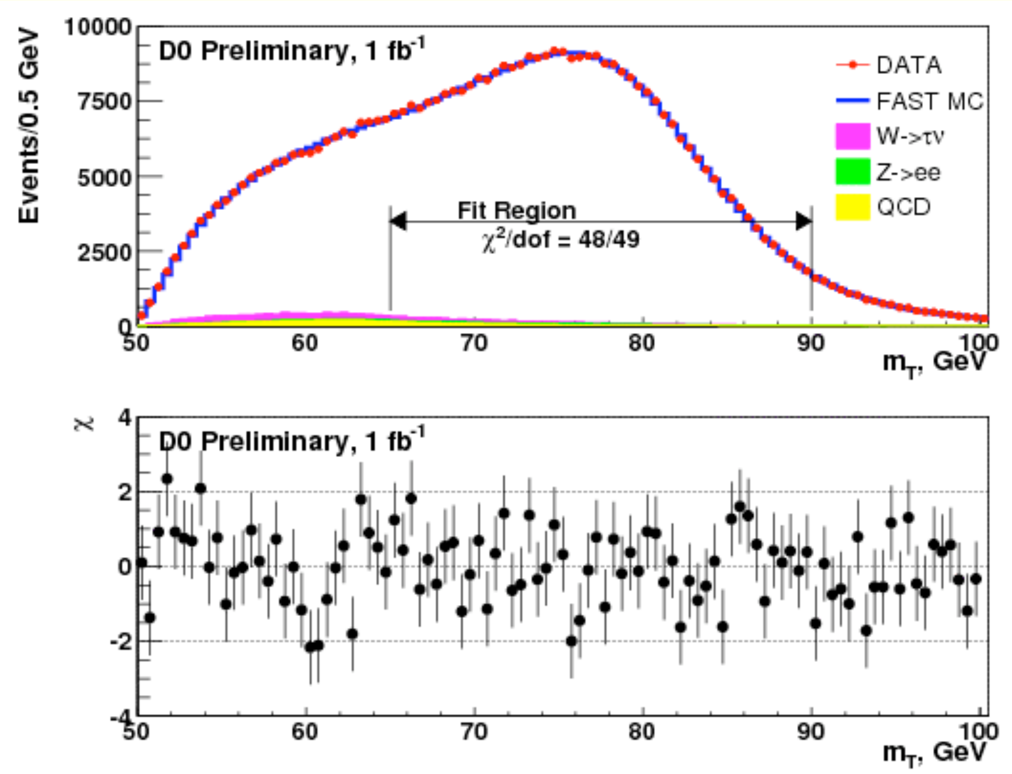






DØ m_W Measurement

- *W* boson mass fits
  - *Template fits to m_T, $p_T^{l\pm}$, p_T^{ν} distributions*
    - m_T most accurate, others provide important cross-check and additional precision

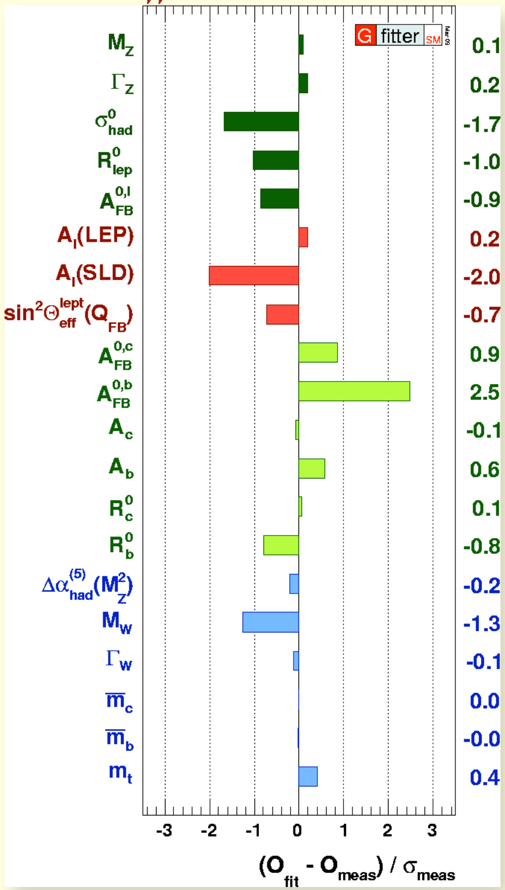


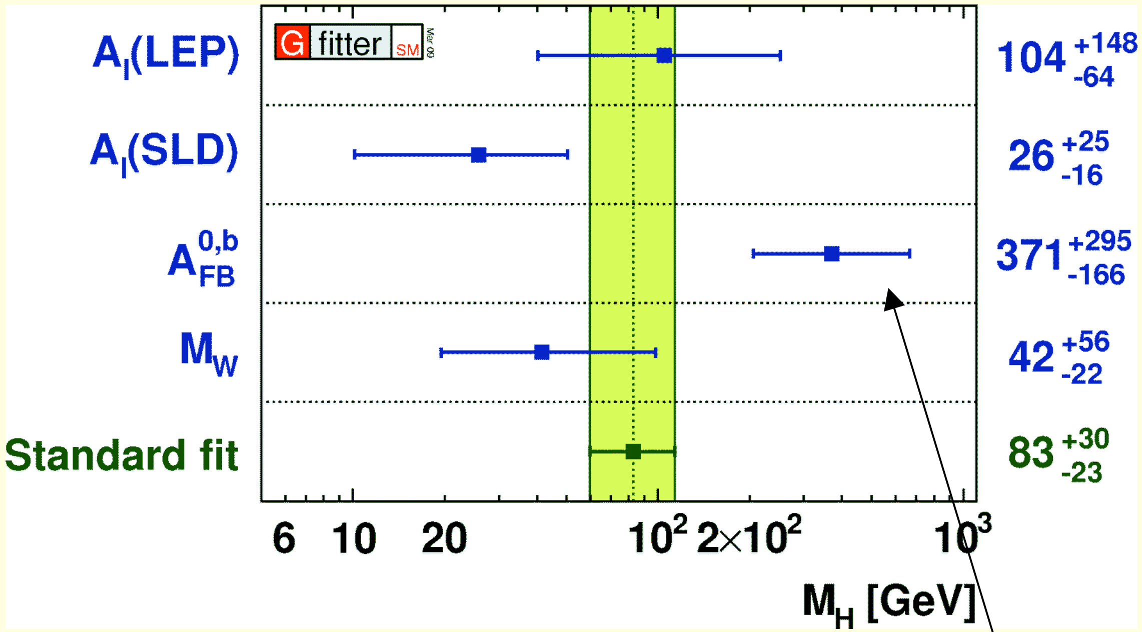
Source	m_T	$p_T(e)$	Missing E_T
Electron energy response	**34**	**34**	**34**
Electron energy resolution	2	2	3
Electron energy non-linearity	4	6	7
Electron energy loss differences for W and Z	4	4	4
Electron efficiencies	5	6	5
Recoil model	6	12	20
Backgrounds	2	5	4
Subtotal Experimental	**35**	**37**	**41**
PDF CTEQ6.1M	**9**	**11**	**11**
QED	7	7	9
Boson p_T	2	5	2
Subtotal Theory (W/Z production & decay)	**12**	**14**	**17**
Total Systematics	**37**	**40**	**44**
Total Statistics	**23**	**27**	**23**
TOTAL	**44**	**48**	**50**

$$m_W = 80.401 \pm 0.021_{stat} \pm 0.038_{sys}\ \text{GeV}$$
$$= 80.401 \pm 0.043\ \text{GeV}$$

World-Average m_W

- Tevatron average not yet available
- Gfitter group has calculated its own world-average m_W
  - *m_W = 80.399 ± 0.023 GeV (~10% reduction in uncertainty)*



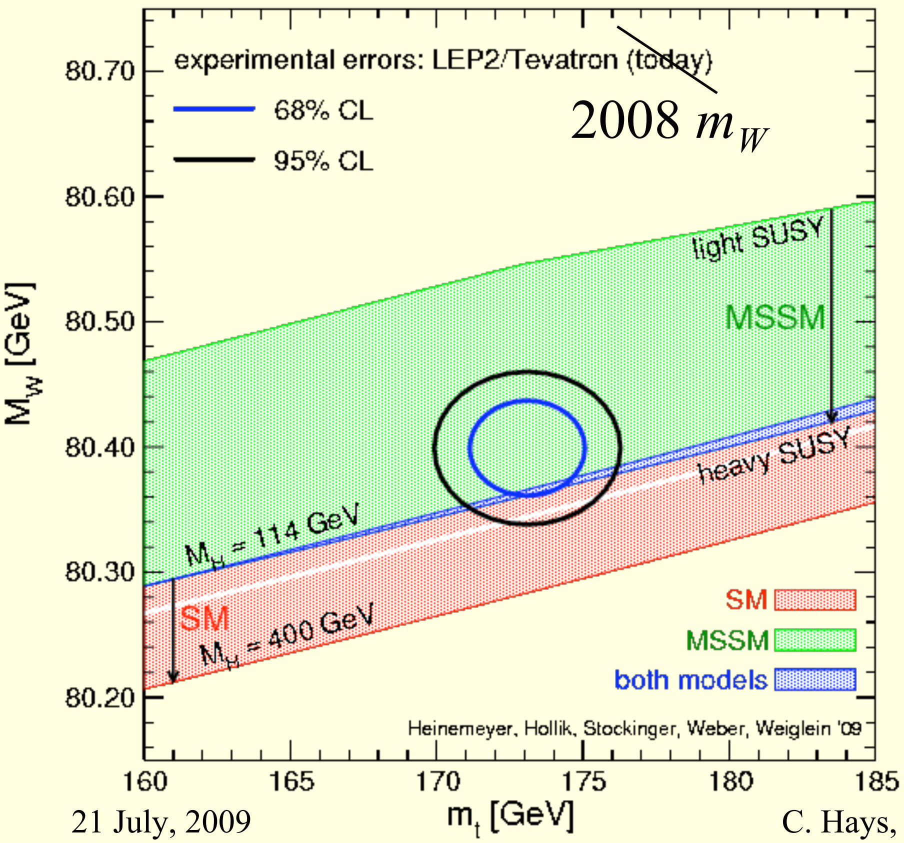


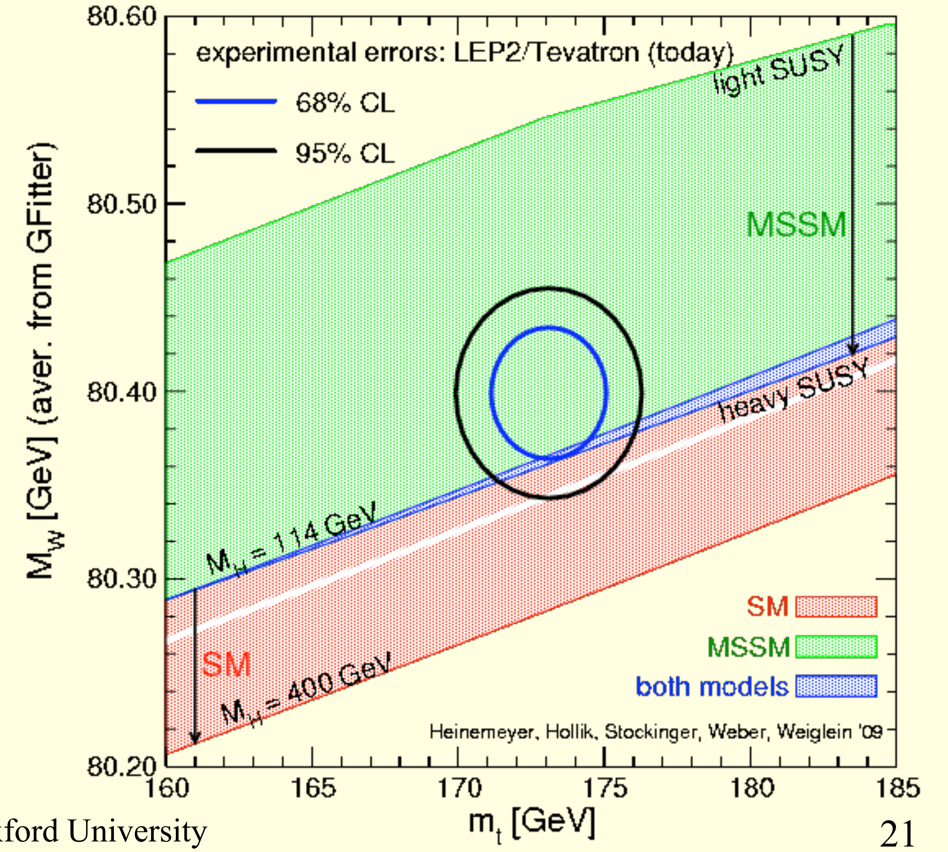
1.4% probability to find such a deviant outlier

Gfitter Group,
EPJC 60, 543 (2009)

Constraints from m_W

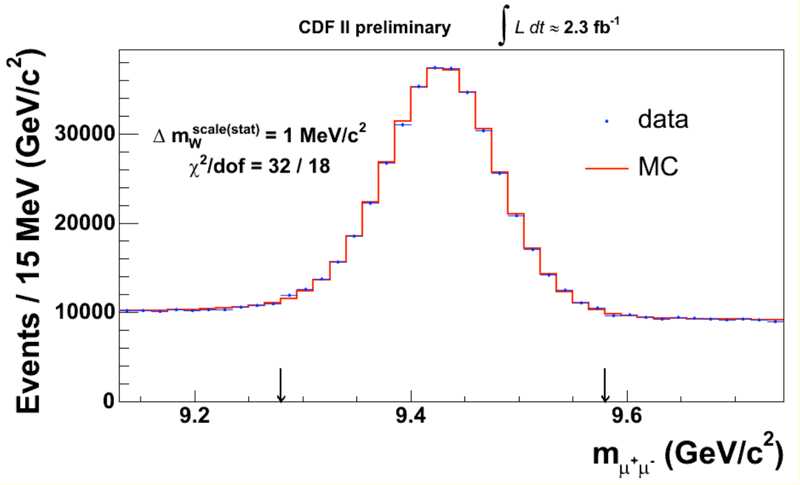
- Electroweak measurements prefer light Higgs, heavy SUSY
  - *Some tension in both cases*
    - *Something else?*
    - *Need increased precision*

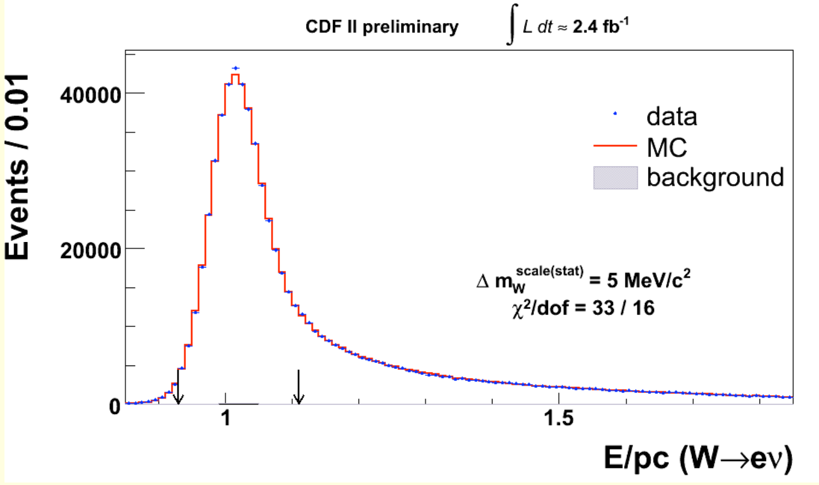




Future m_W Measurements

- Expect $\delta m_W < 25$ MeV from next Tevatron measurement
  - *CDF: 2.3 fb^{-1}, DØ: 5 fb^{-1}*
  - *CDF momentum scale calibration includes $J/\psi \to \mu\mu$, $Y \to \mu\mu$, electron E/p*





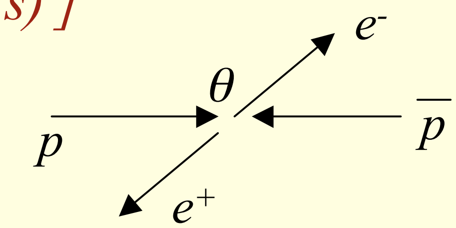
- Expect $\delta m_W \sim 7$ MeV from ATLAS p_T fit with 10 fb^{-1}
  - *45 million W boson events*
  - *4.5 million Z boson events*

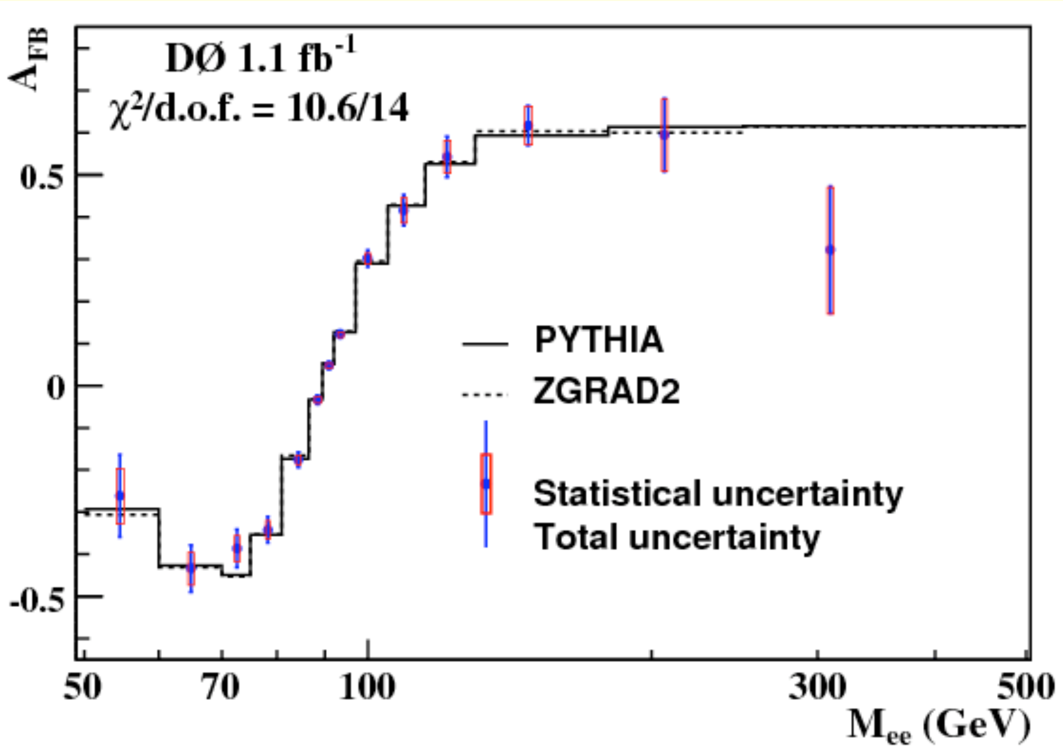
source	effect	δm_W (MeV)
Theoretical model	Γ_W	0.5
	y_W	1
	p_{tW}	3
	QED radiation	<1
Lepton measurement	linearity and scale	4
	resolution	1
	efficiency	3 (e); <1 (μ)
Backgrounds	$W \to \tau\nu$	0.4
	$Z \to l\,(l)$	0.2
	$Z \to \tau\tau$	0.1
	Jet events	0.5
Pile-up and UE		<1 (e); ~0 (μ)
Beam crossing angle		<0.1
total		~7

One channel (e) and one study (p_T)

Measurement of $\sin^2\theta_W$

- Chiral weak coupling produces angular asymmetry in Drell-Yan
  - $d\sigma / d\cos\theta \propto 1 + \cos^2\theta + A_{FB} \cos\theta$ $[A_{FB} = f(v_f, a_f, s)]$
  - *Vector & axial couplings:*
    - $\mathbf{v_f} = I^3_L - 2e \sin^2\theta_W$; $\mathbf{a_f} = I^3_L$
  - *Measurement provides sensitivity to* $\sin^2\theta_W$





$\sin^2\theta_W = 0.2326 \pm 0.0018_{stat} \pm 0.0006_{sys}$

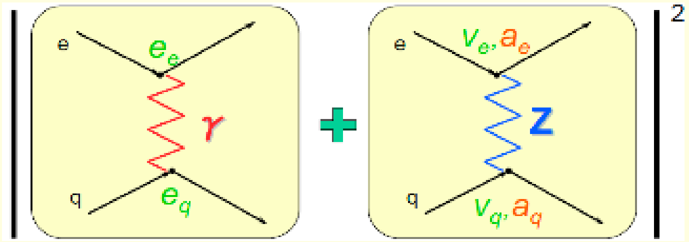
c.f. SM prediction:

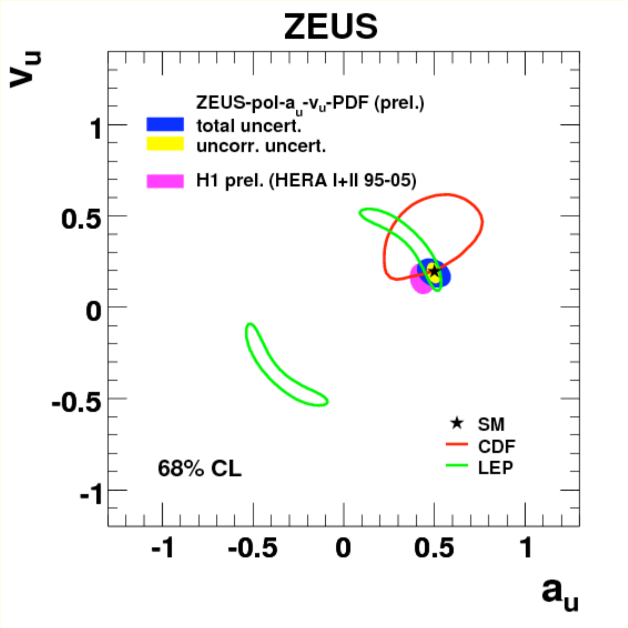
$\sin^2\theta_W = 0.23149 \pm 0.00013$

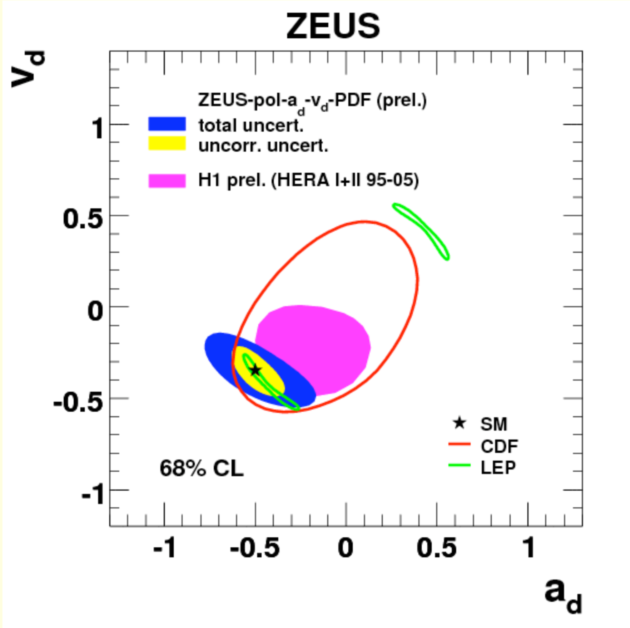
DØ Collaboration,
PRL 101, 191801 (2008)

Quark Couplings to Neutral Current

- Ambiguity in LEP measurement of quark electroweak couplings
  - *HERA and Tevatron data resolving ambiguity*
  - *Up and down quark couplings to neutral current*
    - Vector coupling:
      - $\mathbf{v_q} = I^3_L - 2e \sin^2\theta_W =$ **0.203 (u), -0.351 (d)**
    - Axial coupling:
      - $\mathbf{a_q} = I^3_L =$ **1/2 (u), -1/2 (d)**







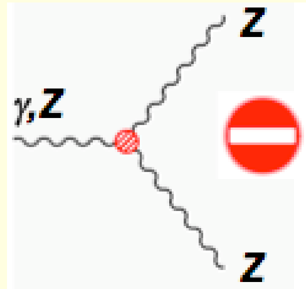
Fit to v_q, a_q using NC data from HERA

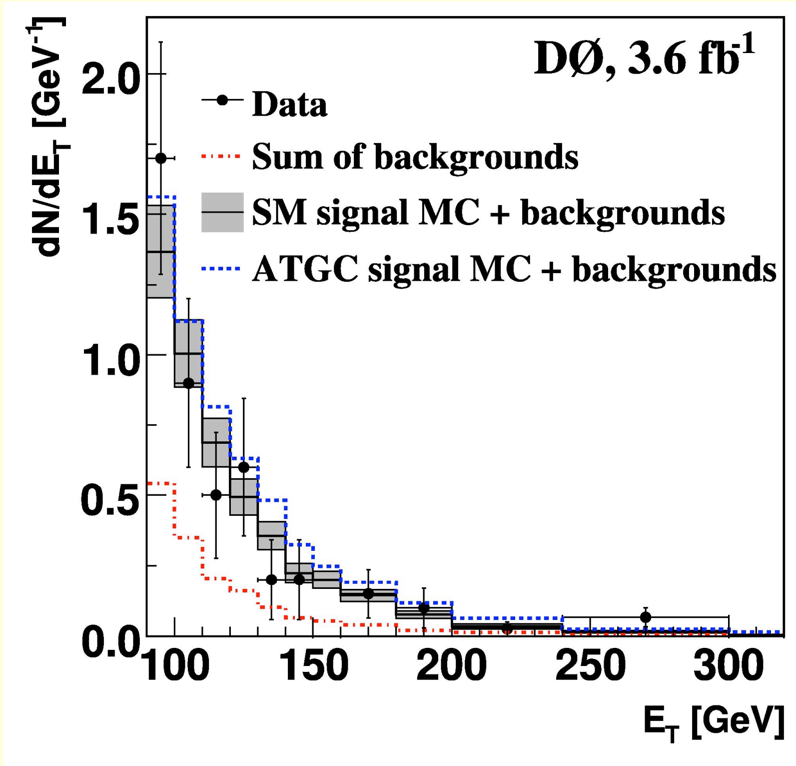
Factor of two more data available for analysis

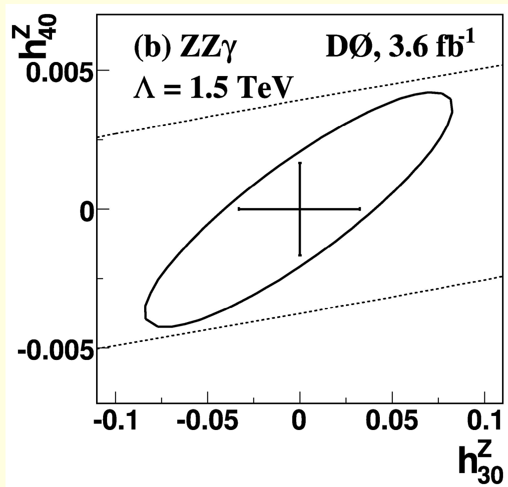
H1 Collaboration, PLB 632, 35 (2006)

Triple-Gauge Couplings

- Non-abelian electroweak structure tested in detail
  - *Tevatron results complementary to LEP*
    - Sensitive to deviations at higher Q^2
    - Separately probe WWZ and $WW\gamma$ vertices
  - *Continue to add final states to probe triple-gauge couplings*
    - $W\gamma \rightarrow l\nu\gamma$
    - $Z\gamma \rightarrow ll\gamma$
    - $\boldsymbol{Z\gamma \rightarrow \nu\nu\gamma}$
    - $WW \rightarrow ll\nu\nu$
    - $WW \rightarrow l\nu qq$
    - $WZ \rightarrow l\nu qq$
    - $WZ \rightarrow lll\nu$
    - $WZ \rightarrow qq\nu\nu$
    - $ZZ \rightarrow qq\nu\nu$
    - $ZZ \rightarrow llll$
    - $ZZ \rightarrow ll\nu\nu$
    - $ZZ \rightarrow llqq$







DØ Collaboration, PRL 102, 201802 (2009)

Triple-Gauge Couplings

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  - *Tevatron results complementary to LEP*
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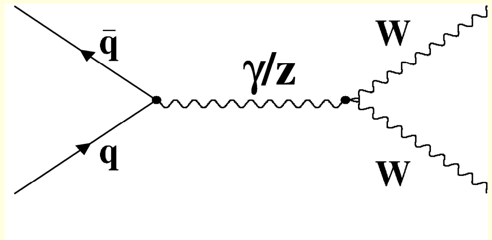
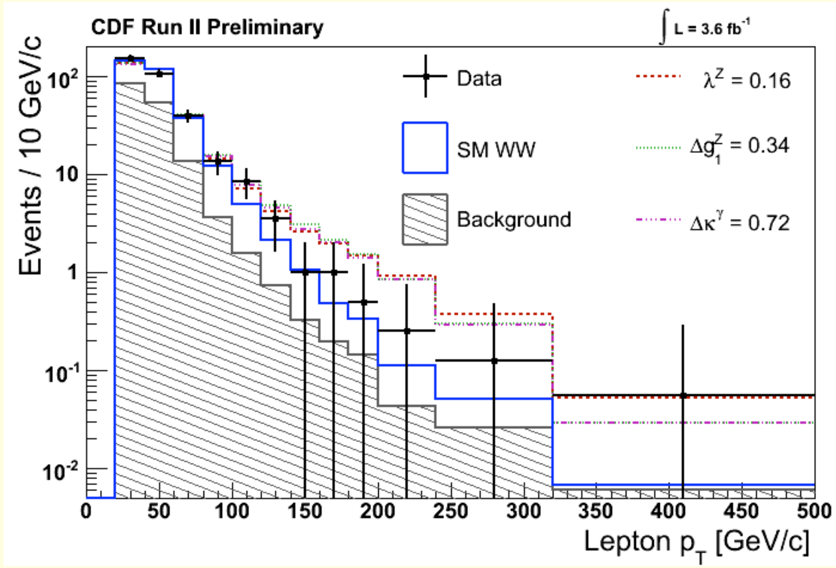


  - *Continue to add final states to probe triple-gauge couplings*
    - $W\gamma \rightarrow l\nu\gamma$
    - $Z\gamma \rightarrow ll\gamma$
    - $Z\gamma \rightarrow \nu\nu\gamma$
    - ***$WW \rightarrow l l \nu\nu$***
    - $WW \rightarrow l\nu qq$
    - $WZ \rightarrow l\nu qq$
    - $WZ \rightarrow lll\nu$
    - $WZ \rightarrow qq\nu\nu$
    - $ZZ \rightarrow qq\nu\nu$
    - $ZZ \rightarrow llll$
    - $ZZ \rightarrow ll\nu\nu$
    - $ZZ \rightarrow llqq$



$$\sigma(p\bar{p} \rightarrow WW) = 12.1 \pm 0.9(\text{stat})\ ^{+1.6}_{-1.4}(\text{syst})\ \ [\text{pb}]$$

CDF Preliminary Results at 3.6fb^{-1}

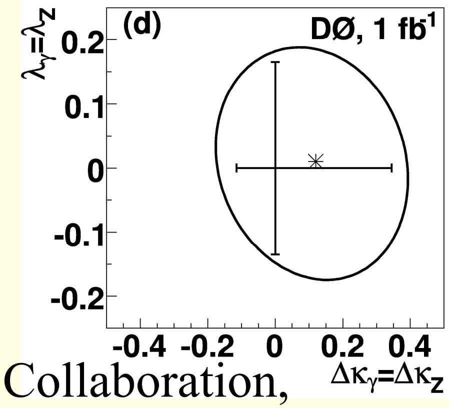
Λ	λ^Z	Δg_1^Z	$\Delta\kappa^\gamma$
2.0TeV	(-0.14,0.15)	(-0.22,0.30)	(-0.57,0.65)
1.5TeV	(-0.16,0.16)	(-0.24,0.34)	(-0.63,0.72)

CDF Expected Limits at 3.6fb^{-1}

Λ	λ^Z	Δg_1^Z	$\Delta\kappa^\gamma$
2.0TeV	-0.05 - 0.06	-0.08 - 0.15	-0.20 - 0.27
1.5TeV	-0.05 - 0.07	-0.09 - 0.17	-0.23 - 0.31

Probability of Observed Limits

Λ	λ^Z	Δg_1^Z	$\Delta\kappa^\gamma$
2.0TeV	7.1%	7.3%	7.2%
1.5TeV	7.6%	7.4%	7.3%



DØ Collaboration, arXiv:0904.0673 (2009)

Triple-Gauge Couplings

- Non-abelian electroweak structure tested in detail
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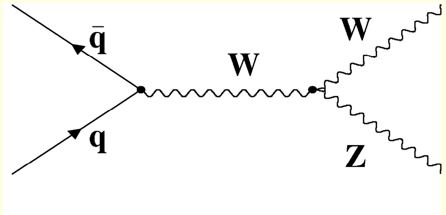
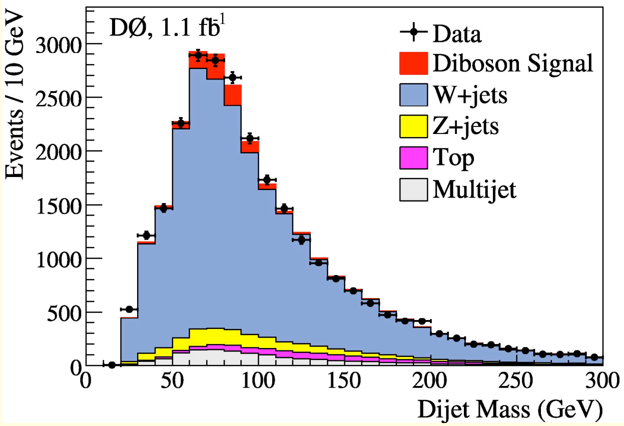
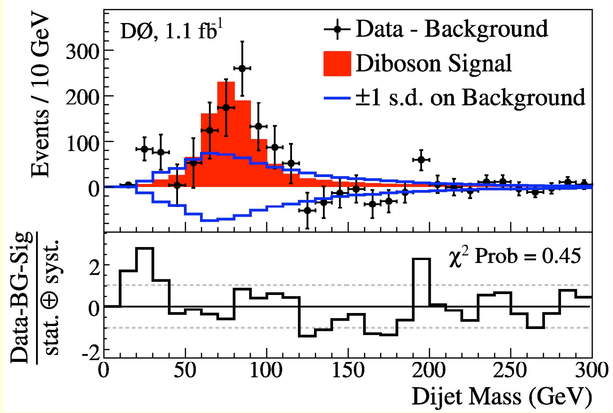
    - Sensitive to deviations at higher Q^2
    - Separately probe *WWZ* and *WWγ* vertices



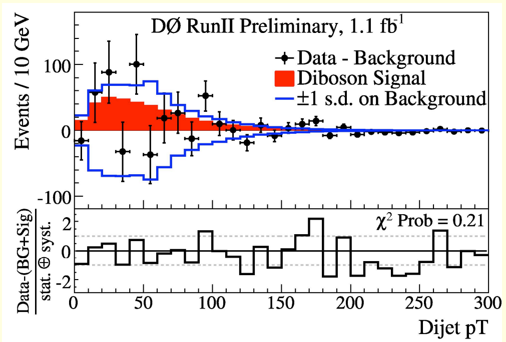
  - *Continue to add final states to probe triple-gauge couplings*
    - $W\gamma \rightarrow l\nu\gamma$
    - $Z\gamma \rightarrow ll\gamma$
    - $Z\gamma \rightarrow \nu\nu\gamma$
    - $WW \rightarrow ll\nu\nu$
    - ***$WW \rightarrow l\nu qq$***
    - ***$WZ \rightarrow l\nu qq$***
    - $WZ \rightarrow lll\nu$
    - $WZ \rightarrow qq\nu\nu$
    - $ZZ \rightarrow qq\nu\nu$
    - $ZZ \rightarrow llll$
    - $ZZ \rightarrow ll\nu\nu$
    - $ZZ \rightarrow llqq$

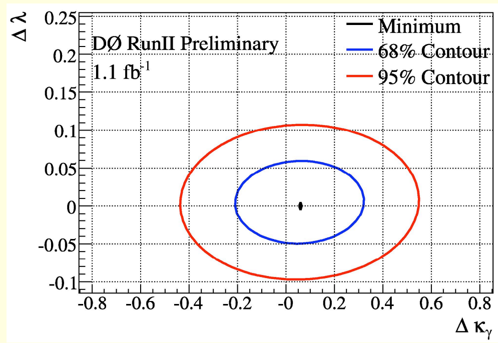




4.4σ evidence

DØ Collaboration, PRL 102, 161801 (2009)





Triple-Gauge Couplings

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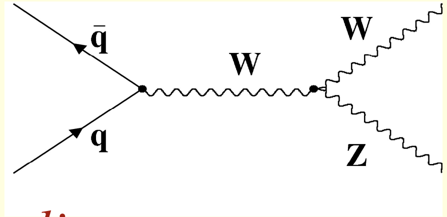
    - Separately probe WWZ and $WW\gamma$ vertices



  - *Continue to add final states to probe triple-gauge couplings*
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    - $WW \rightarrow l\nu qq$
    - $WZ \rightarrow l\nu qq$
    - $WZ \rightarrow lll\nu$
    - $\boldsymbol{WZ \rightarrow qq\nu\nu}$
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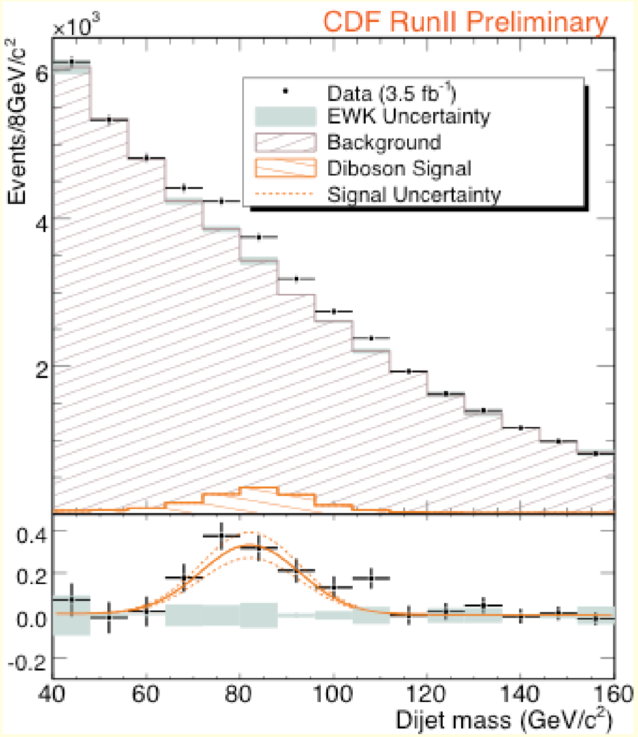
    - $ZZ \rightarrow llll$
    - $ZZ \rightarrow ll\nu\nu$
    - $ZZ \rightarrow llqq$



Floating Parameter	Fitted Value +/- Uncertainty
QCD slope	0.724±0.047
JES	0.985±0.019
# EWK background	36,140±1,230
# QCD background	7,249±1,130
# Diboson signal	1,516±239

	Systematic	% uncert.
Extraction	EWK shape	7.7
	Resolution	5.6
	Total extraction	9.5
Acceptance	JES	8.0
	JER	0.7
	$\not\!\!E_T$ resolution model	1.0
	Trigger inefficiency	2.2
	ISR/FSR	2.5
	PDF	2.0
	Total acceptance	9.0
	Luminosity	5.9
	Total	14.4

5.3σ observation

Triple-Gauge Couplings

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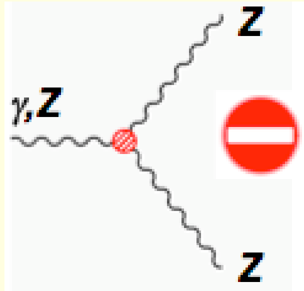
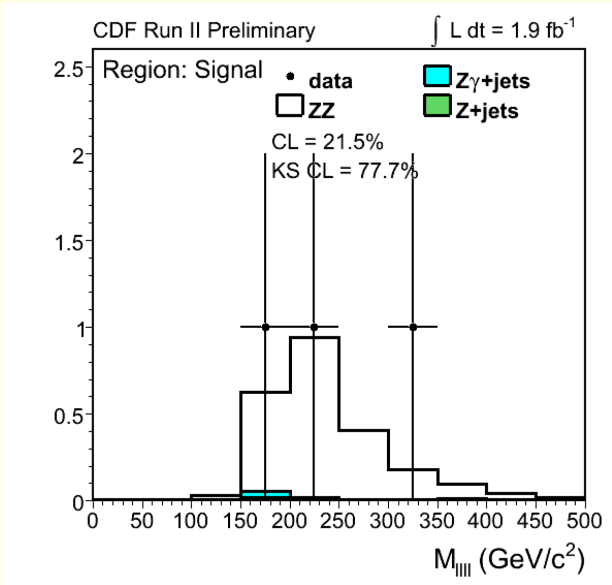
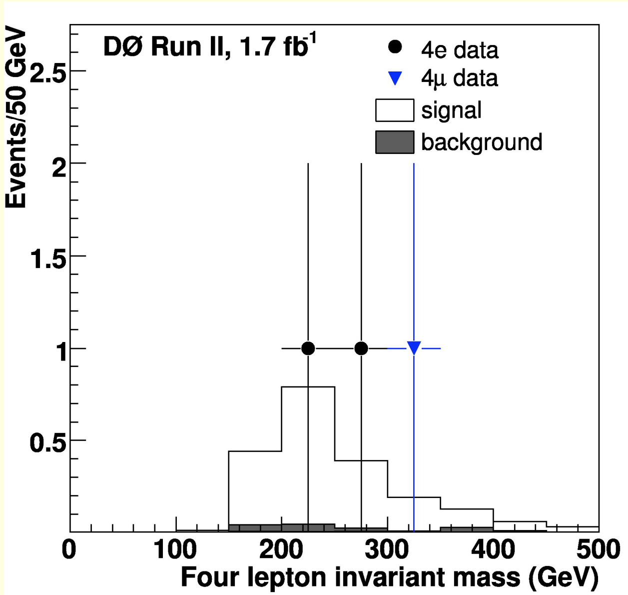
    - $Z\gamma \to ll\gamma$
    - $Z\gamma \to \nu\nu\gamma$
    - $WW \to ll\nu\nu$
    - $WW \to l\nu qq$
    - $WZ \to l\nu qq$
    - $WZ \to lll\nu$
    - $WZ \to qq\nu\nu$
    - $ZZ \to qq\nu\nu$
    - $\boldsymbol{ZZ \to llll}$
    - $\boldsymbol{ZZ \to ll\nu\nu}$
    - $ZZ \to llqq$





CDF Collaboration,
PRL 100, 201801 (2008)

4.4σ evidence

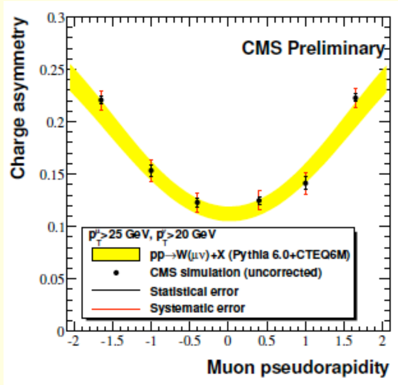


DØ Collaboration,
PRL 101, 171803 (2008)

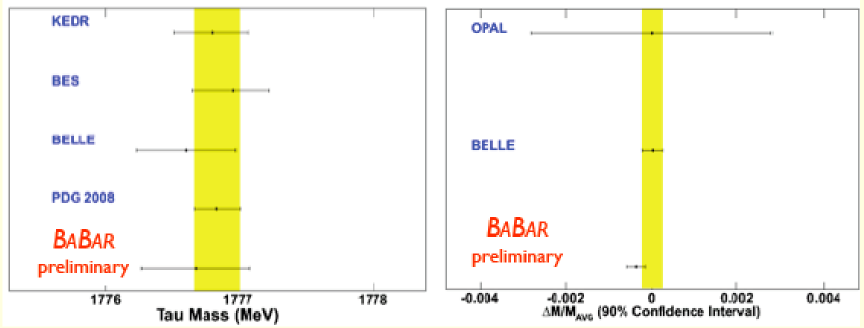
5.7σ observation

More Results

- PDFs and m_W at LHC
  - *Lepton charge asymmetry can constrain PDFs*
  - *W^+/W^- production asymmetry complicates m_W measurement*



- Tau measurements at BaBar
  - *Lepton universality $Z/\gamma^* \to \tau\tau / Z/\gamma^* \to \mu\mu = 1$ (ignoring masses)*
    - $R_{\tau\mu}(\Upsilon(1s)) = 1.009 \pm 0.010_{stat} \pm 0.024_{sys}$
  - *Tau mass*
    - $m_\tau = 1776.68 \pm 0.12_{stat} \pm 0.41_{sys}$ MeV
    - $(m_{\tau+} - m_{\tau-})/ m_\tau = (-3.5 \pm 1.3) \times 10^{-4}$

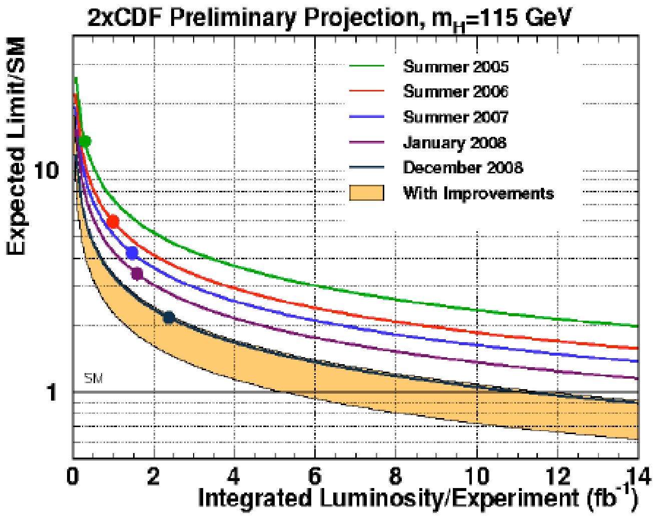


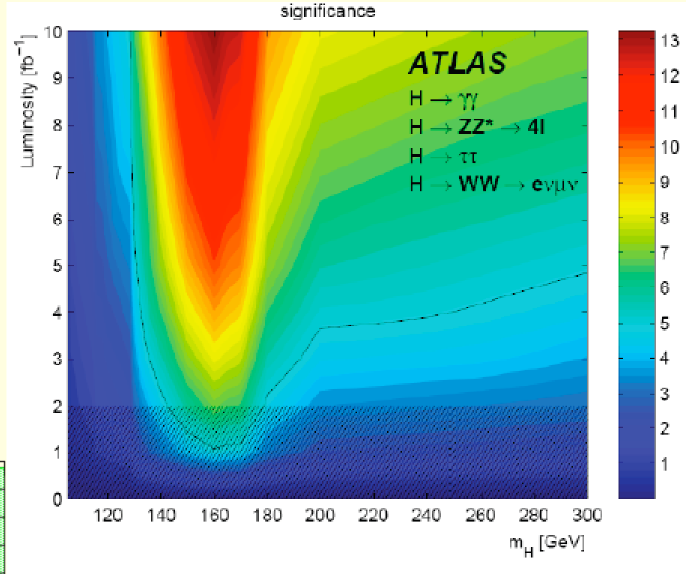
- $(g - 2)_\mu$
  - *New tau-based a_μ^{had} more consistent with electron-based a_μ^{had} ($<3\sigma$)*
  - *g-2 data - theory discrepancy 1.9σ (τ) 3.5σ (e)*

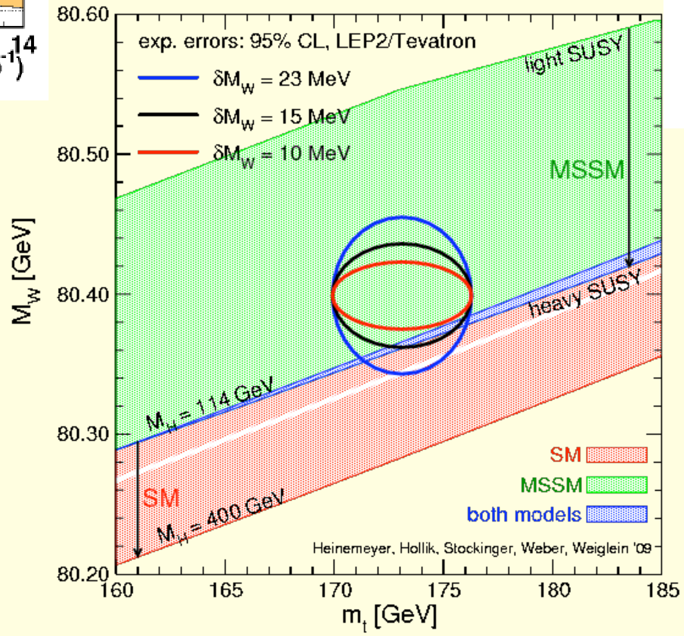
Summary

- Steadily improving precision on m_W
  - *CDF and DØ have the two best measurements in the world*
  - *Pieces coming together to allow single measurements with $\delta m_W < 25$ MeV*
  - *Expect ultimate hadron-collider precision of $\delta m_W < 10$ MeV*
- Precision measurement of $\sin^2\theta_W$ possible with full Run 2 data set
  - *CDF and DØ have initial measurements using A_{FB} in electron data*
- HERA producing best measurements of NC quark couplings
  - *Now also able to observe triple-gauge couplings*
- Tevatron experiments probing TGC with unprecedented precision
  - *New hadronic channels an important step on the road to the Higgs*

If there is no SM Higgs...







...who will exclude it first?