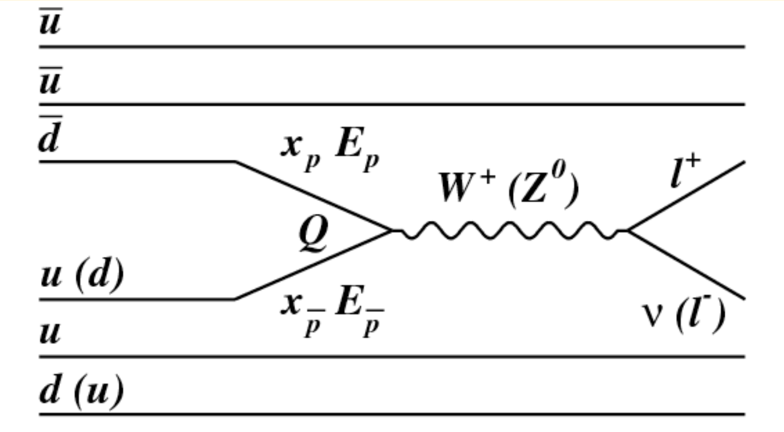
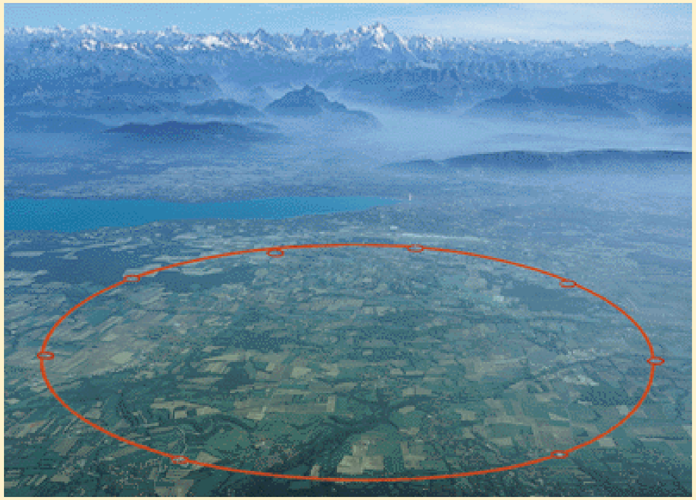
W and Z Production at Hadron Colliders





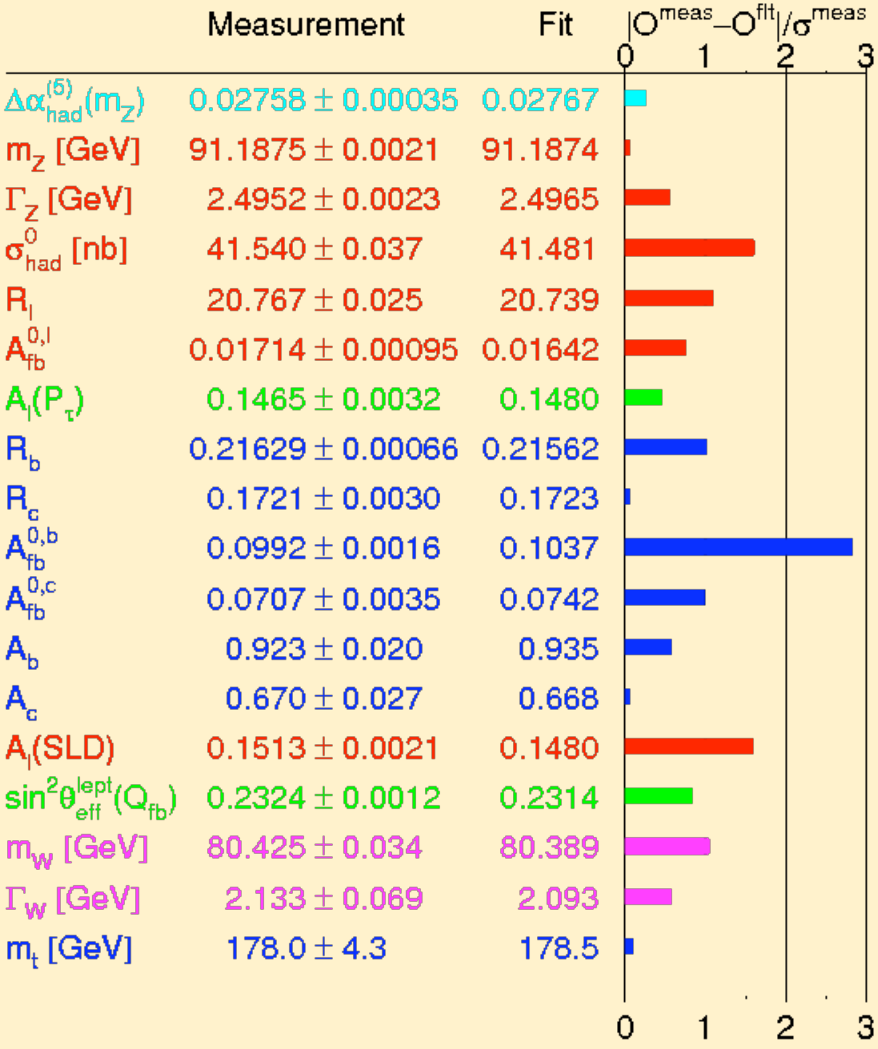
Chris Hays,

Oxford University

July 28, 2009

DPF, Wayne State University

Electroweak Parameters



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$\Delta\alpha_{had}^{(5)}(m_Z)$	0.02758 ± 0.00035	0.02767
m_Z [GeV]	91.1875 ± 0.0021	91.1874
Γ_Z [GeV]	2.4952 ± 0.0023	2.4965
σ_{had}^{0} [nb]	41.540 ± 0.037	41.481
R_l	20.767 ± 0.025	20.739
$A_{fb}^{0,l}$	0.01714 ± 0.00095	0.01642
$A_l(P_\tau)$	0.1465 ± 0.0032	0.1480
R_b	0.21629 ± 0.00066	0.21562
R_c	0.1721 ± 0.0030	0.1723
$A_{fb}^{0,b}$	0.0992 ± 0.0016	0.1037
$A_{fb}^{0,c}$	0.0707 ± 0.0035	0.0742
A_b	0.923 ± 0.020	0.935
A_c	0.670 ± 0.027	0.668
A_l(SLD)	0.1513 ± 0.0021	0.1480
$\sin^2\theta_{eff}^{lept}(Q_{fb})$	0.2324 ± 0.0012	0.2314
m_W [GeV]	80.425 ± 0.034	80.389
Γ_W [GeV]	2.133 ± 0.069	2.093
m_t [GeV]	178.0 ± 4.3	178.5

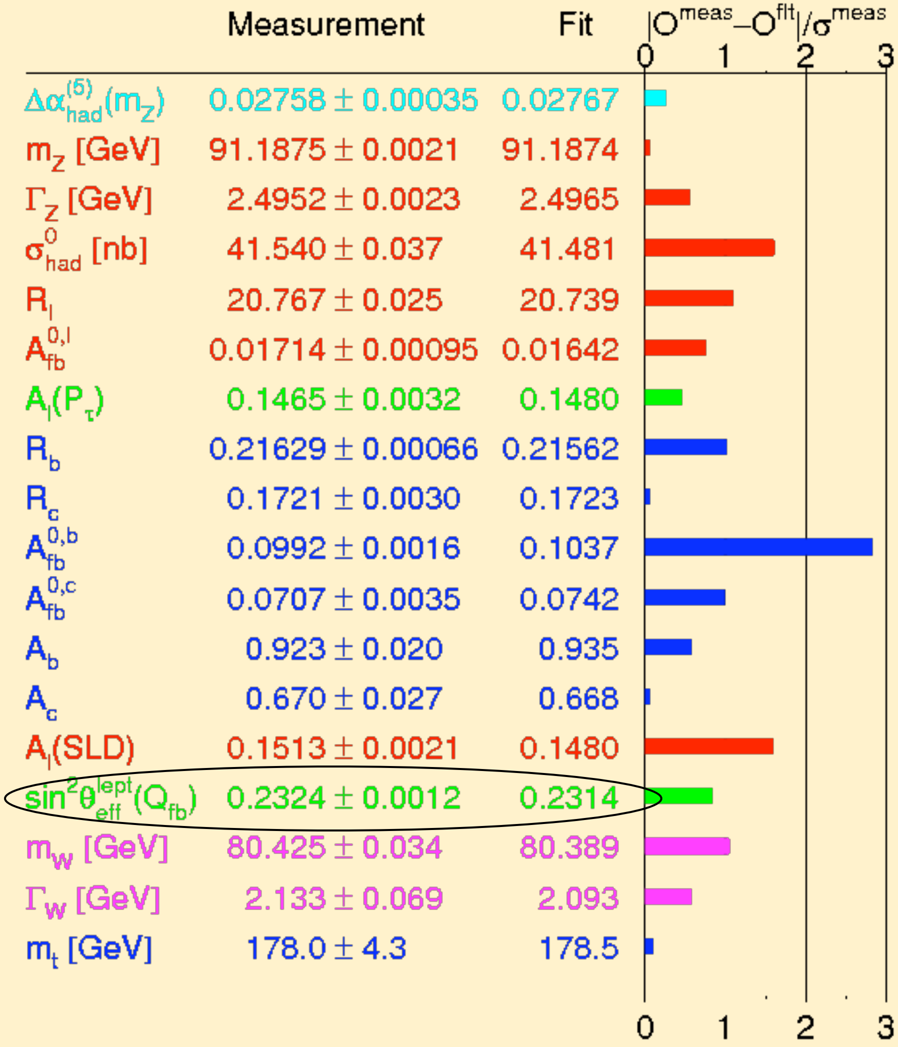
Overconstrained theory

3 parameters at tree level (couplings & vev)

Precise measurements probe loop couplings

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

Electroweak Parameters



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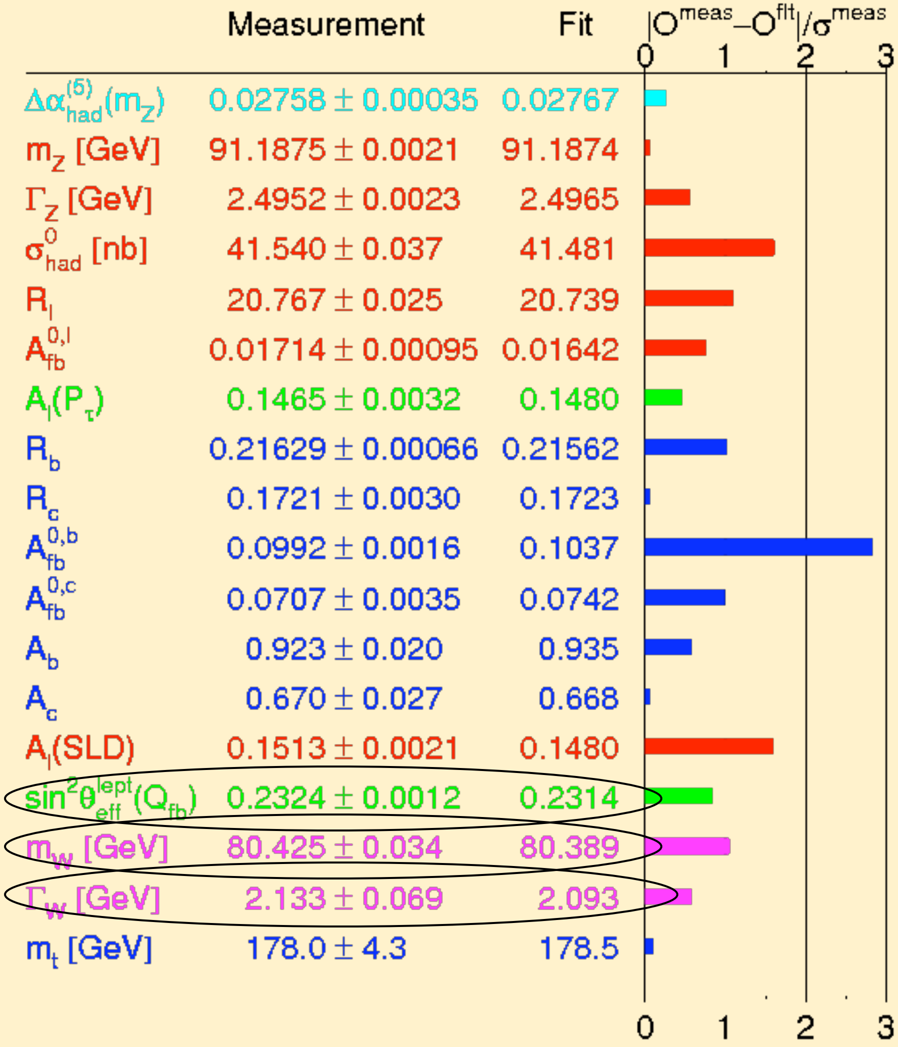

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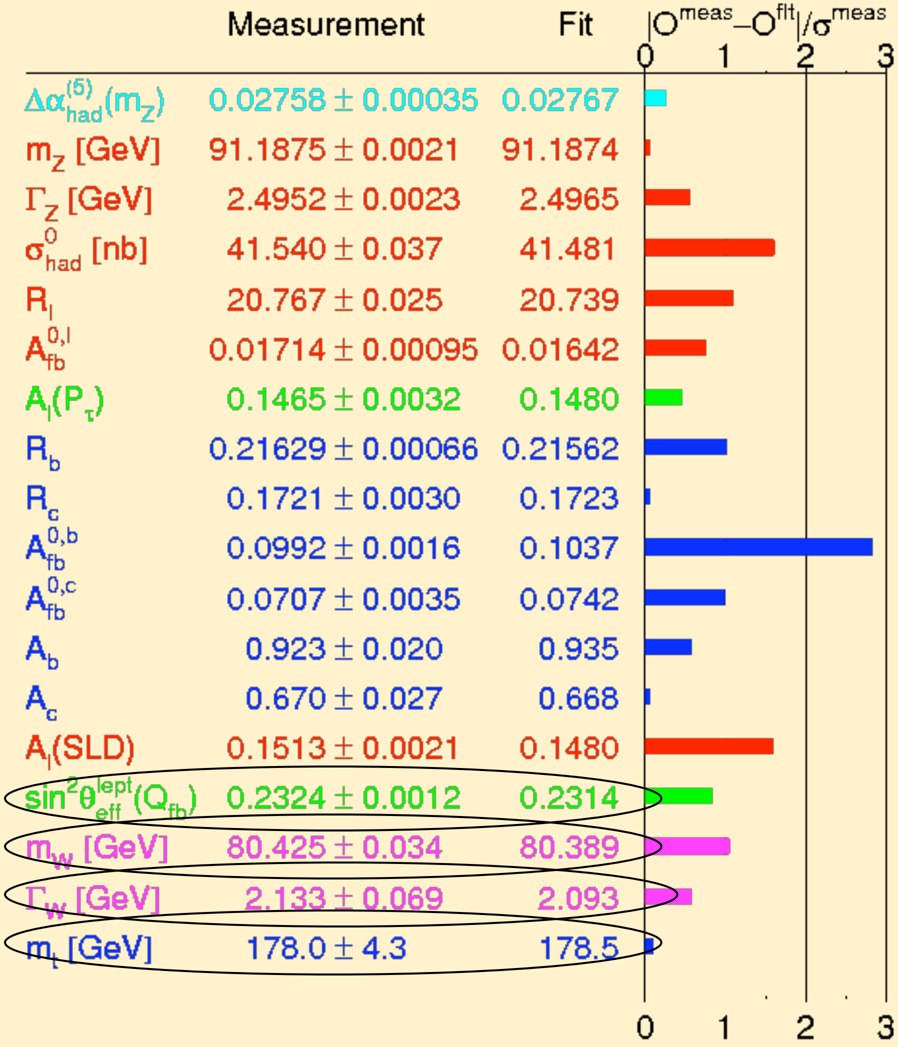

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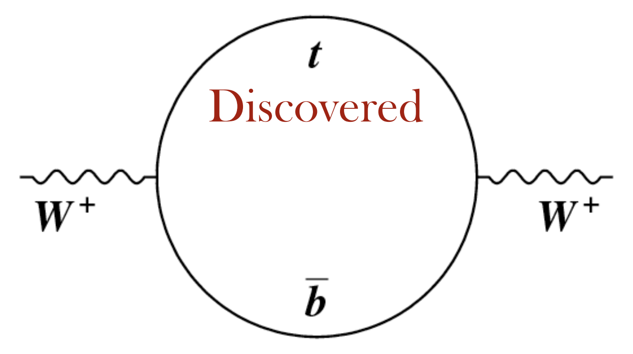
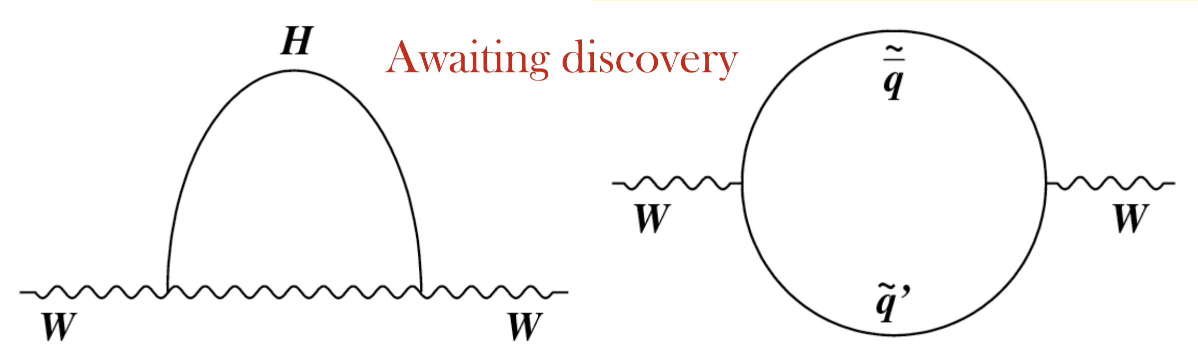
Most precise measurement from CDF
Measured at the Tevatron to 0.75% precision

W Mass as a Loop-Level Probe

- m_W receives contributions from top ($\propto m_t^2$) and Higgs ($\propto \ln m_H$)
  - And any new particle with weak charge
  - Sensitivity currently limited by experimental uncertainty on m_W

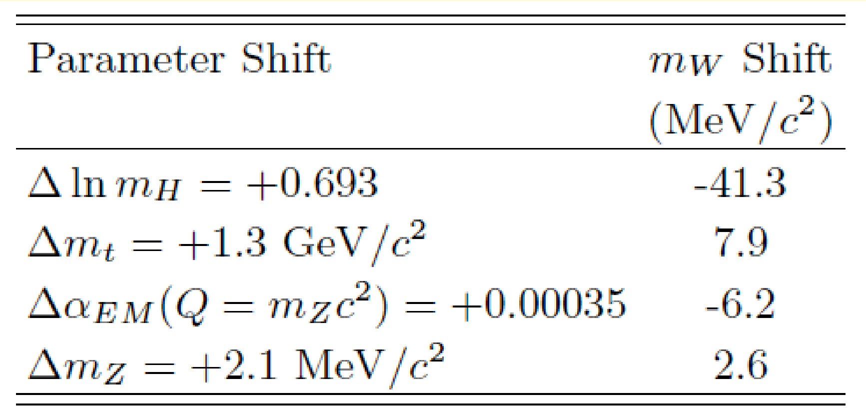

Discovered


Awaiting discovery

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

Tree level: m_W = 79.964 ± 0.005 GeV

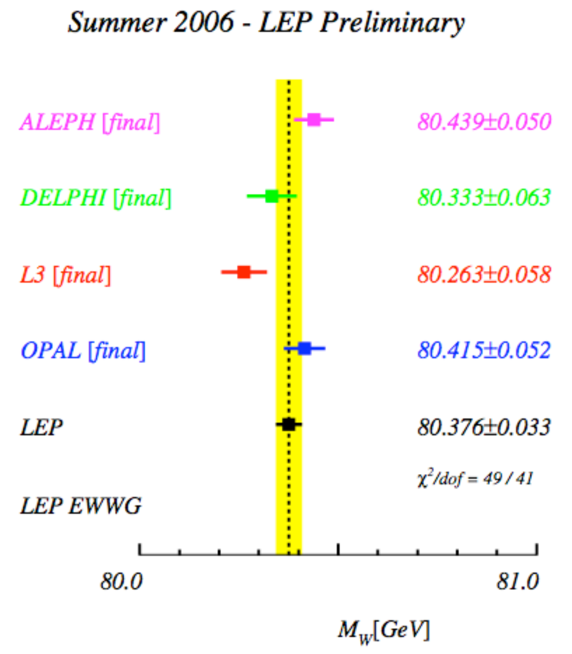
Measurement: m_W = 80.399 ± 0.023 GeV

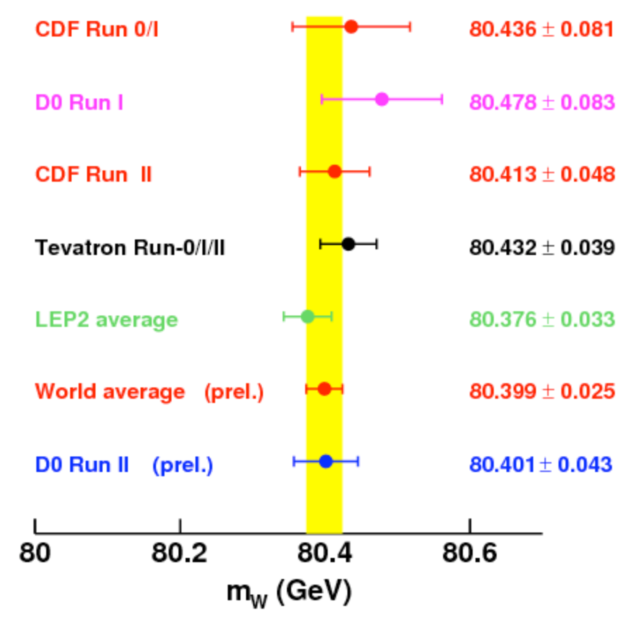


Parameter Shift	m_W Shift (MeV/c^2)
$\Delta \ln m_H = +0.693$	-41.3
$\Delta m_t = +1.3\ \mathrm{GeV}/c^2$	7.9
$\Delta\alpha_{EM}(Q = m_Z c^2) = +0.00035$	-6.2
$\Delta m_Z = +2.1\ \mathrm{MeV}/c^2$	2.6

W Boson Mass Measurements

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

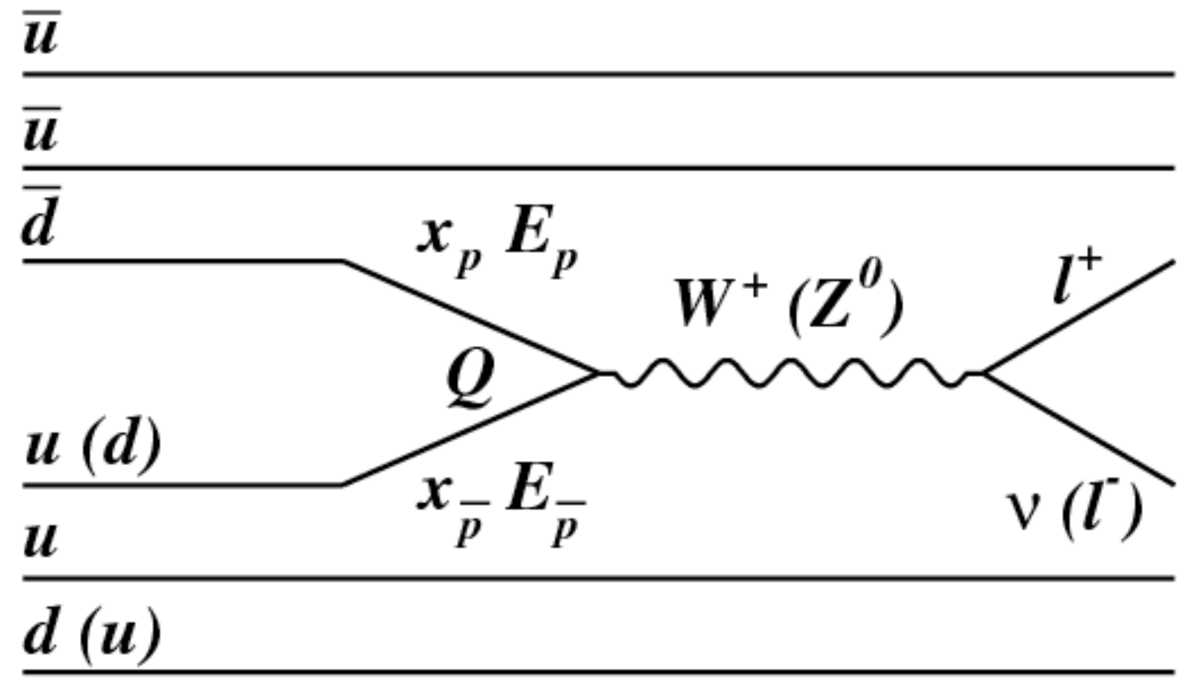




- Future hadron-collider measurements promise <10 MeV precision
  - Expect next measurements to be more precise than the world average
    - CDF: 2.3 fb^{-1}, DØ: 5 fb^{-1}
  - Requires exquisite understanding of W & Z production

W & Z Production at Hadron Colliders

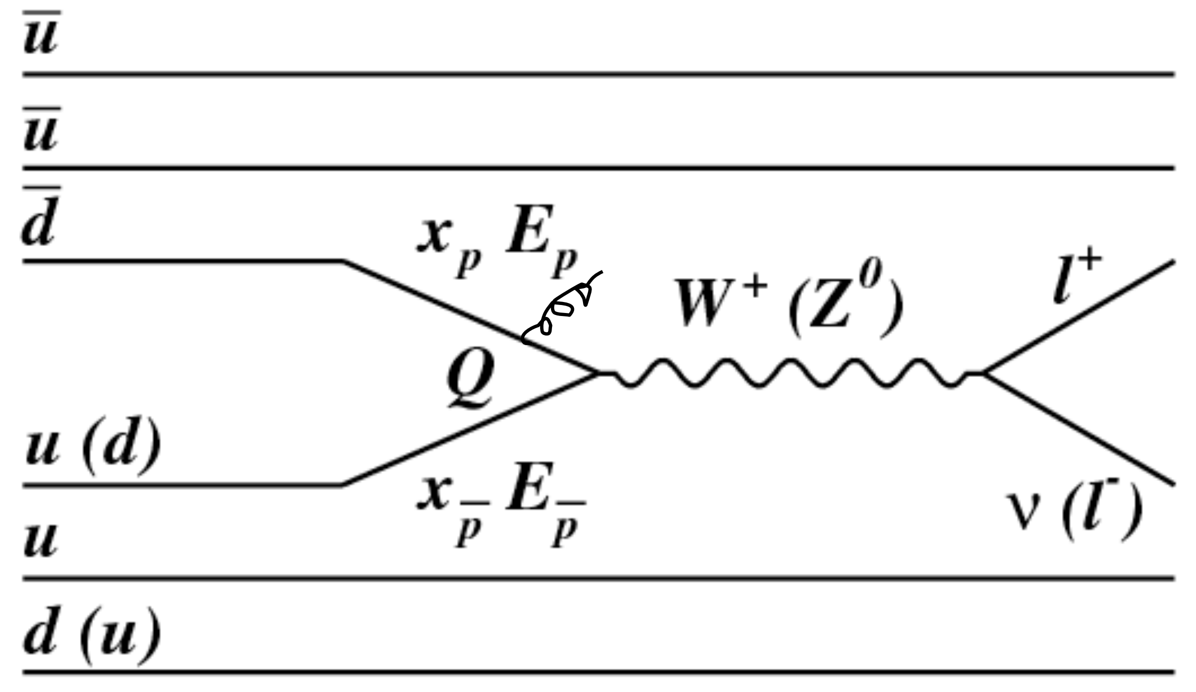
- Many components enter m_W measurement



W & Z Production at Hadron Colliders

- Many components enter m_W measurement

Initial state radiation gives boson a boost



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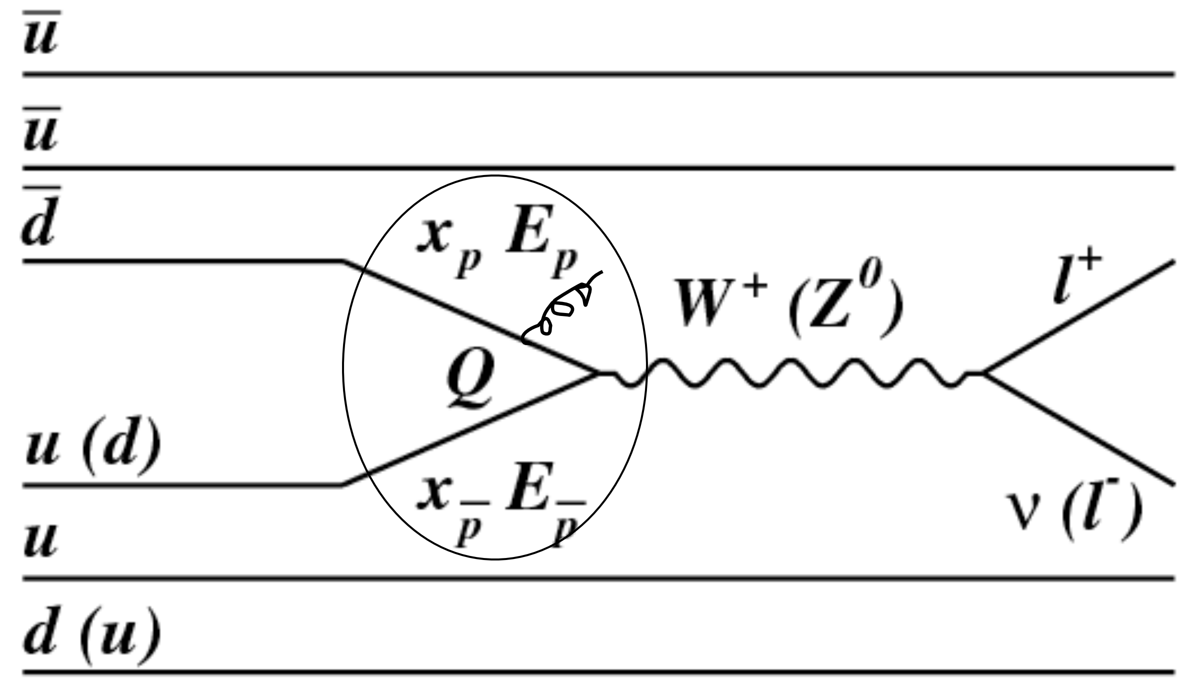

Parton momenta determine boson's longitudinal momentum

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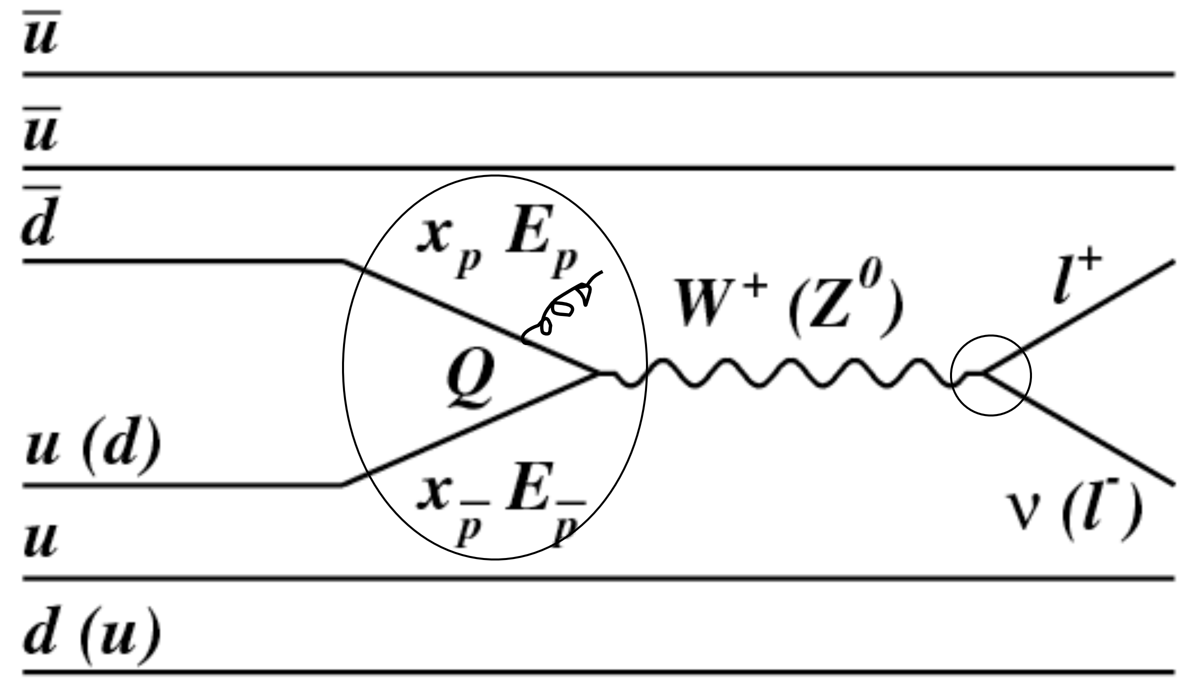


Parton momenta determine boson’s longitudinal momentum

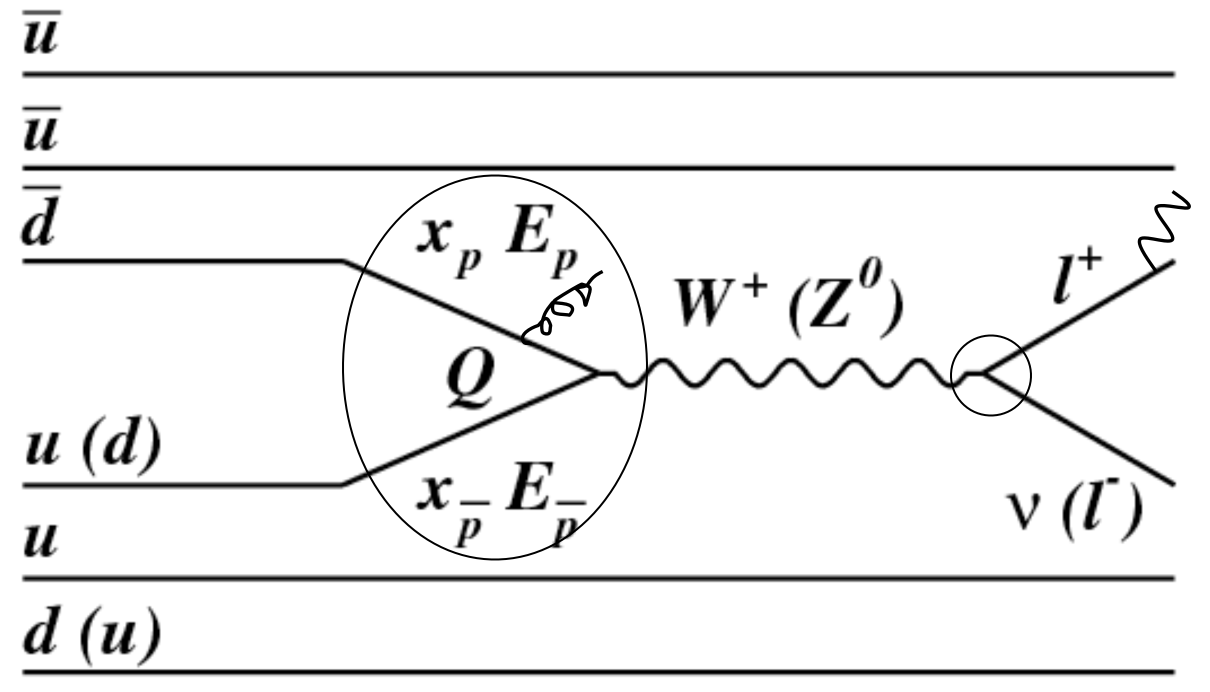
V-A coupling affects angular distributions

W & Z Production at Hadron Colliders

- Many components enter m_W measurement

Initial state radiation gives boson a boost

Final state radiation reduces lepton momentum



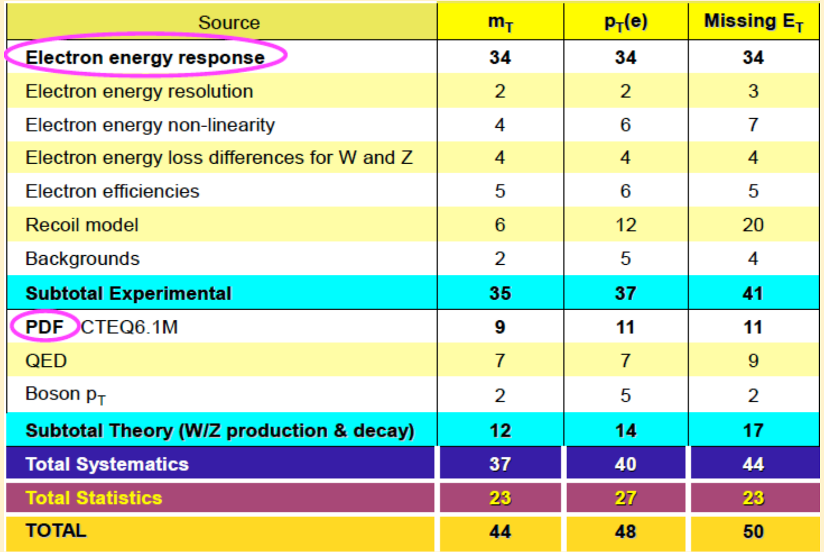
Parton momenta determine boson’s longitudinal momentum

V-A coupling affects angular distributions

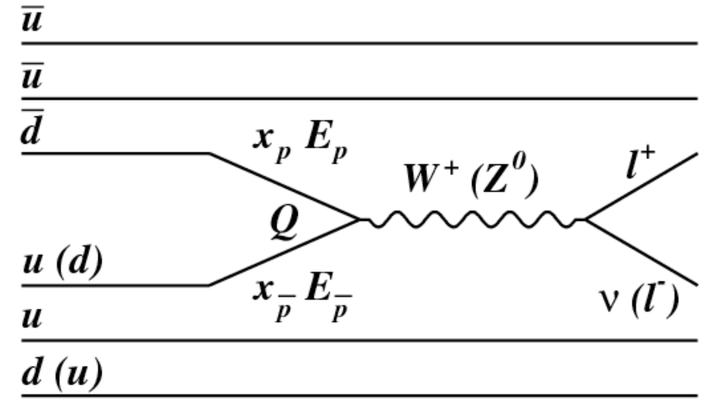
Measuring m_W at a Hadron Collider

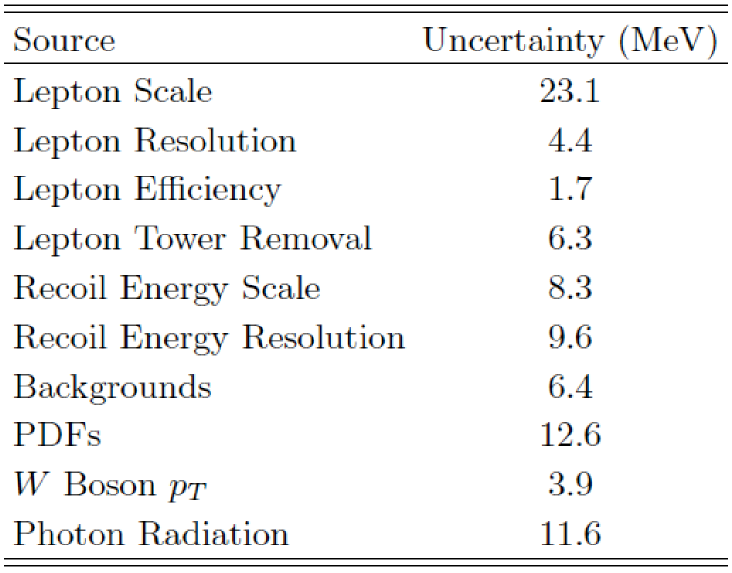
- Theoretical inputs:
  - Details of W production and decay
- Experimental inputs:
  - In situ calibration of response to $l^\pm$ and ν
    - Only transverse momenta used in mass fit

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



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**





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)

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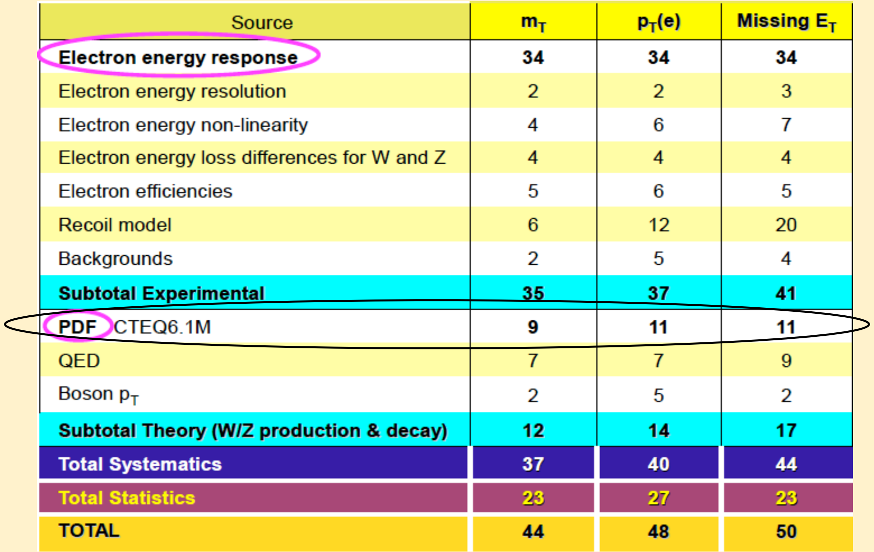

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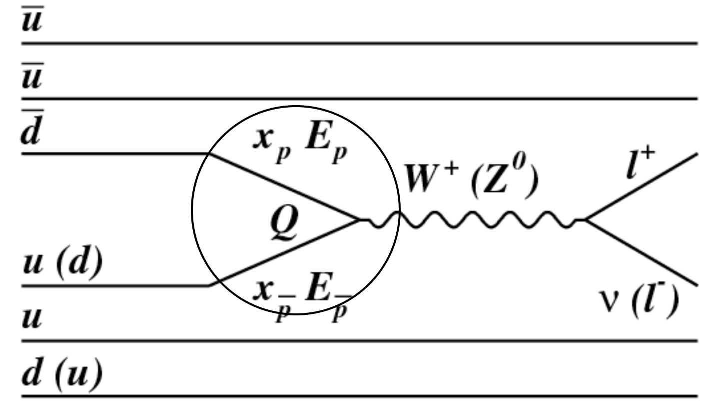

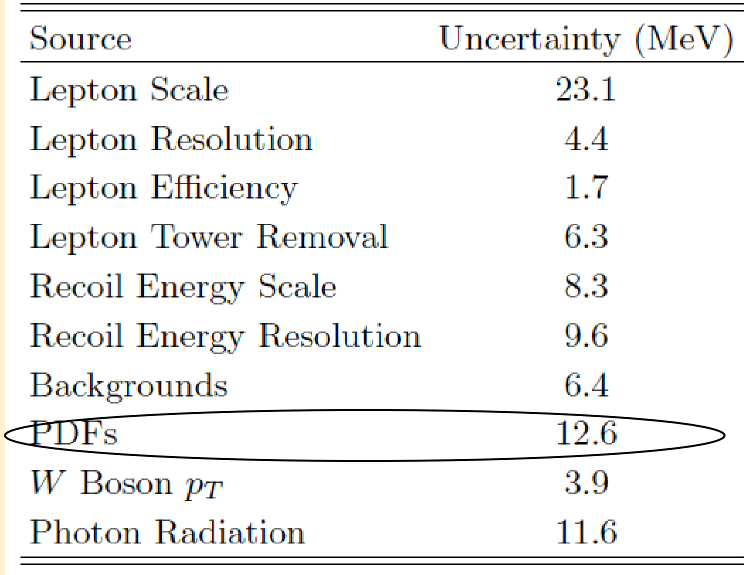

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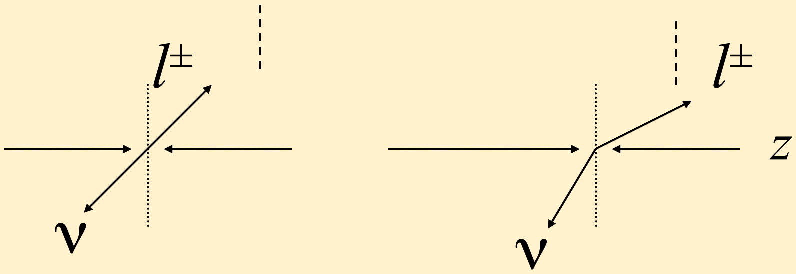
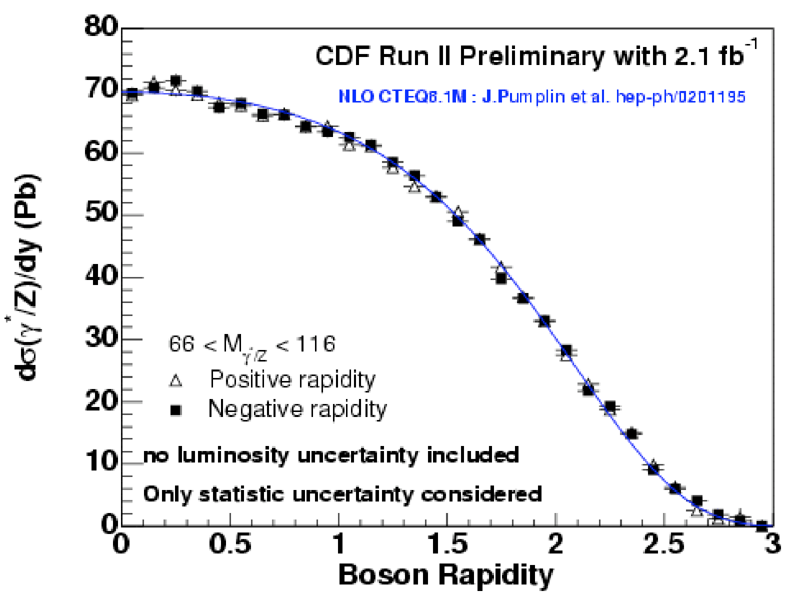
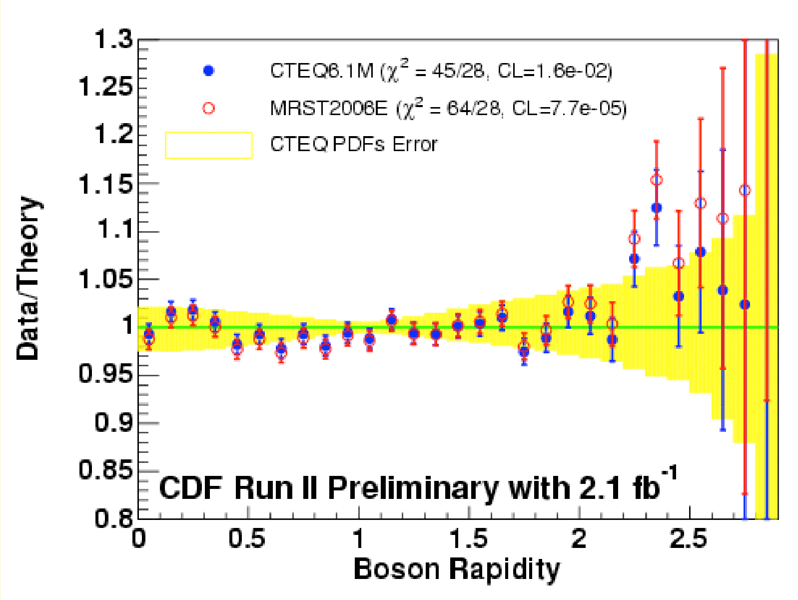
W Boson Production

- 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 results improving PDF accuracy



$$x\,f(x,Q_0) = A_0 x^{A1}(1-x)^{A2}\, e^{(A3)x} \times (1+A_4 x)^{A5}$$

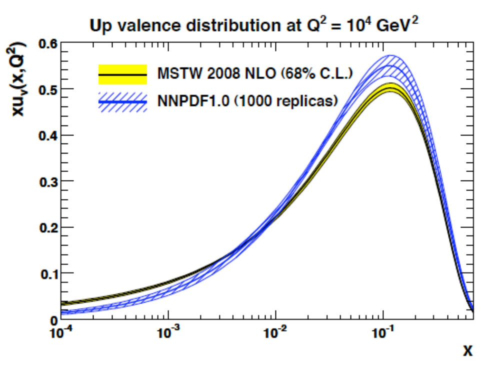


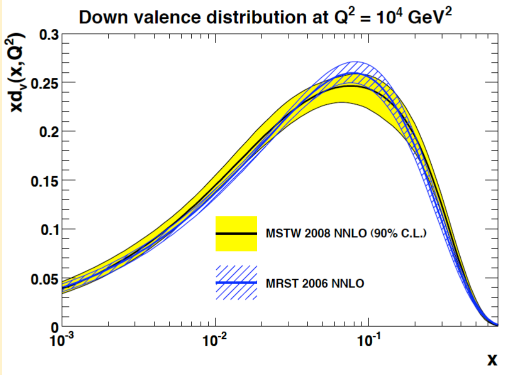


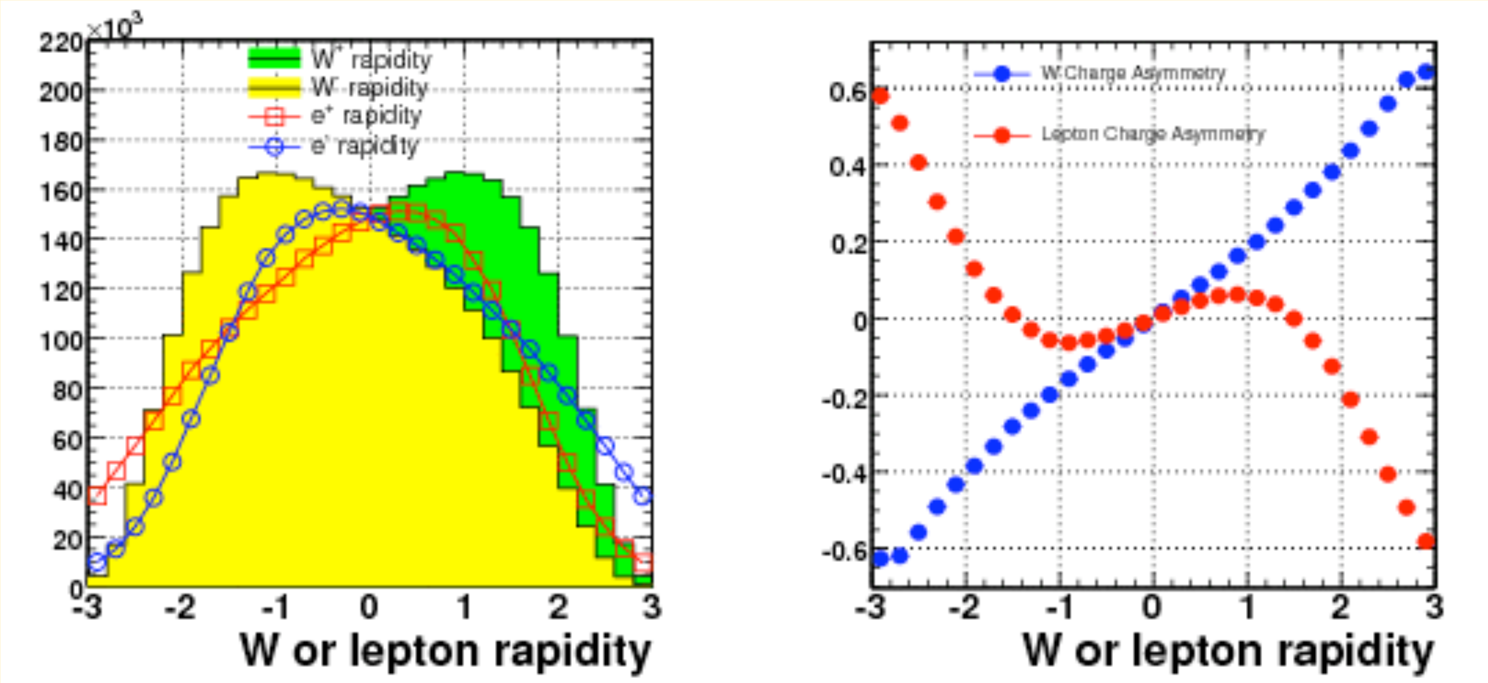
W Boson Production

- Parton distribution functions
  - W boson charge asymmetry

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

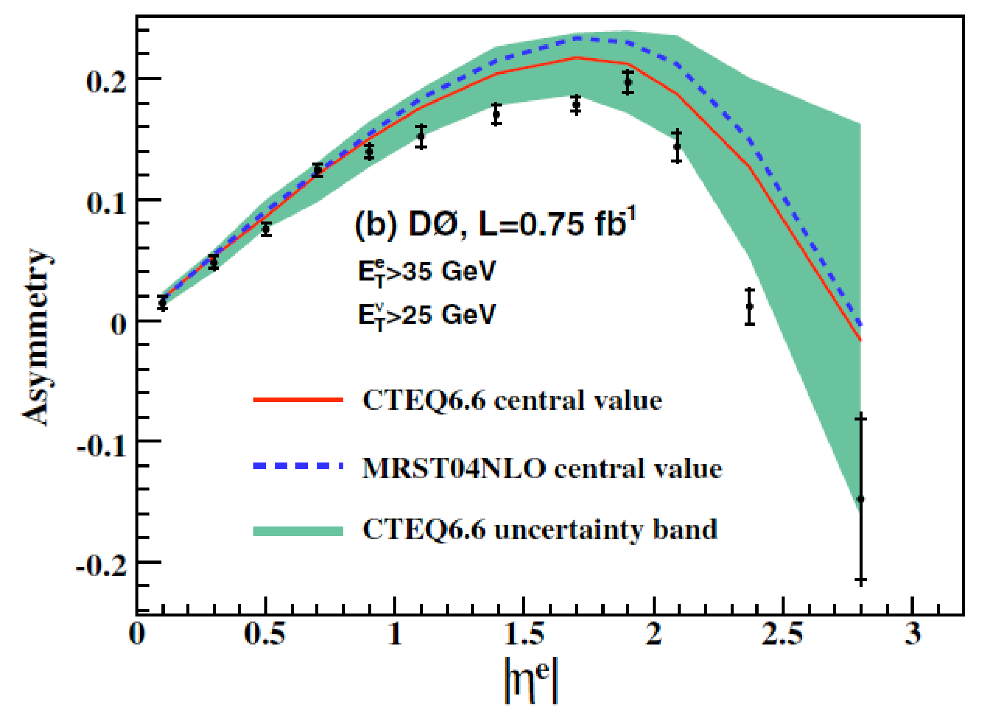

Up valence distribution at $Q^2 = 10^4$ GeV^2


Down valence distribution at $Q^2 = 10^4$ GeV^2

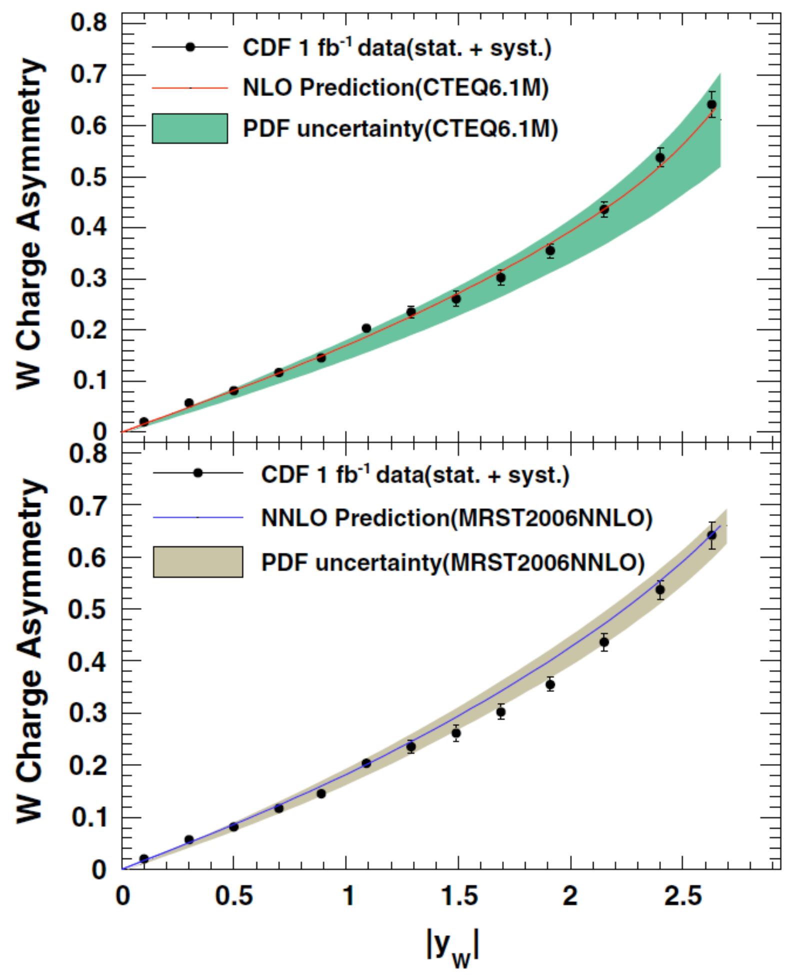


W Boson Production

- Parton distribution functions
  - W boson charge asymmetry
  - New results not yet incorporated



DØ Collaboration,
PRL 101, 211801 (2008)



CDF Collaboration,
PRL 102, 181801 (2009)

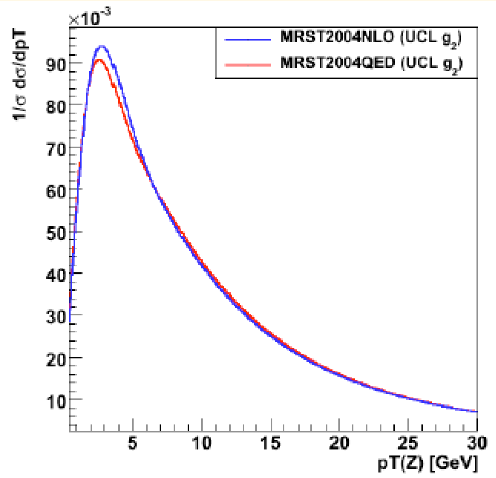
PDF Issues

- Input data sets generally not consistent within uncertainties
  - Overall uncertainty inflated to cover range of data
  - Should m_W measurements rescale 90% CL δm_W to 68% CL?
    - Spread of data on valence parton distributions mostly Gaussian

- Assumptions required in form of PDFs
  - Would reasonable alternative forms give significant uncertainty?
    - Usefulness of multiple PDF sets (CTEQ, MSTW, NNPDF)

- How can we make the uncertainty more robust?
  - m_W measurement using forward leptons
  - Fit mass in two lepton rapidity bins as a cross-check?
  - Uncertainty from (e.g.) Tevatron data alone?

- QED PDFs?



M. Lancaster and
D. Beecher,
Milan Workshop

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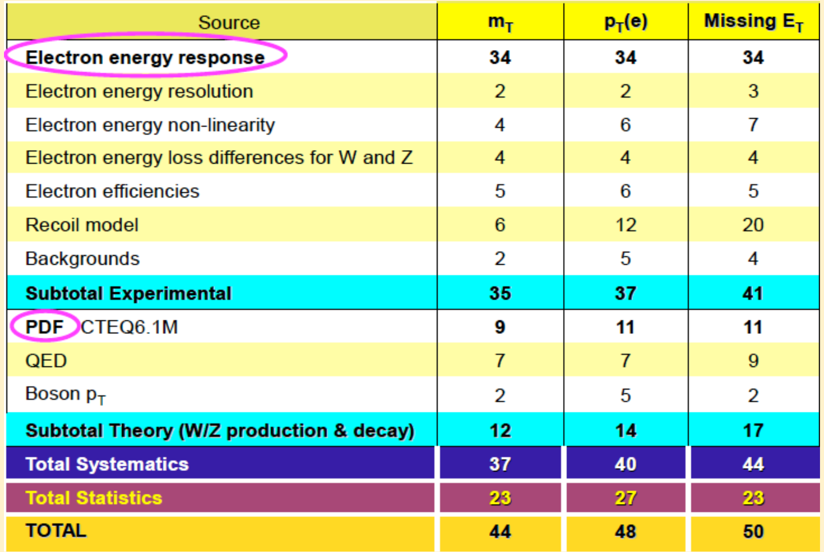

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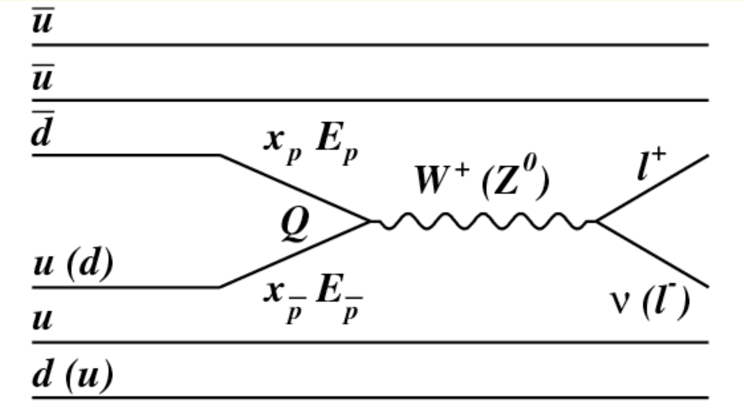

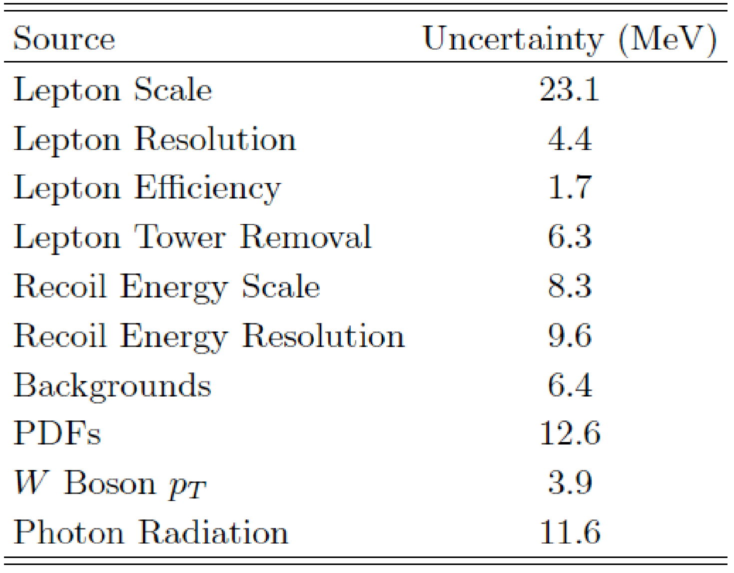

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CDF Collaboration,
PRL 99, 151801 (2007),
PRD 77, 112001 (2008)

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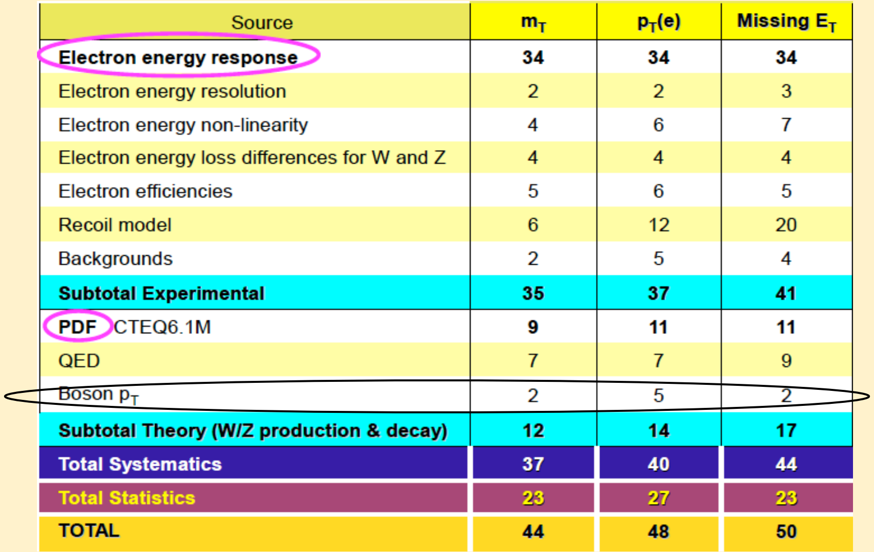

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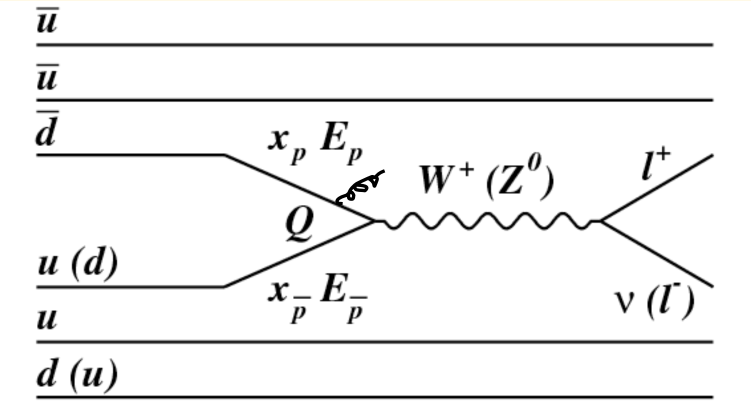

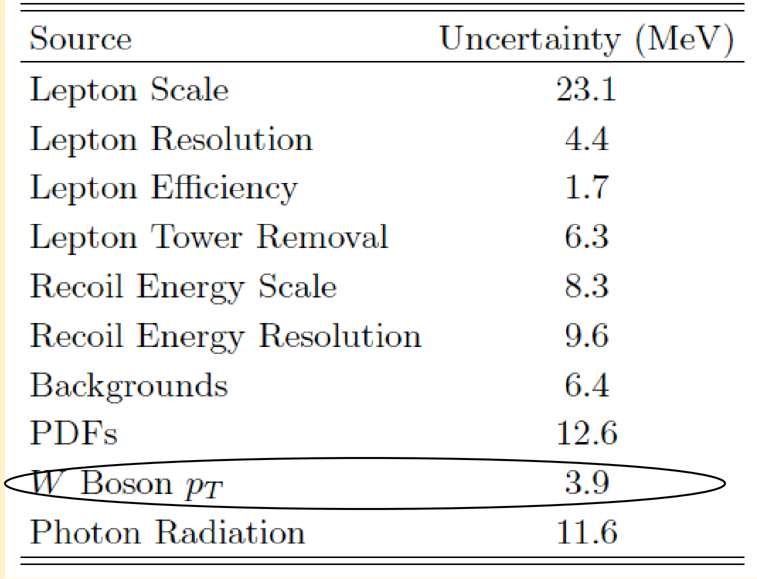

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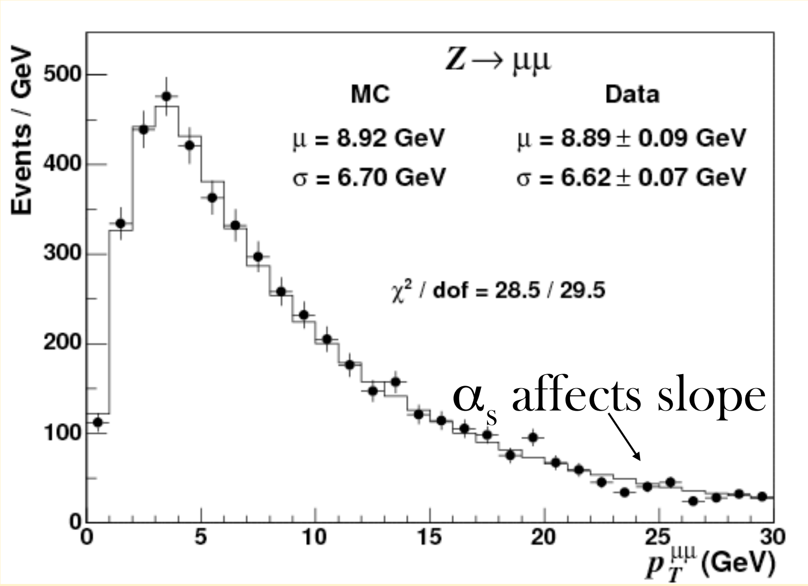
Modelling W Boson p_T

- Non-perturbative regime most relevant for m_W measurement



α_s affects slope

RESBOS prediction based on resummation

$$d\sigma/(ds\, dp_T\, dy) \propto \int d^2b\, e^{ip_T b}\, W(b, s, x) + Y(p_T, s, x)$$

Non-perturbative component W_{NP} uses BLNY form

Calculated at fixed order

$$W_{NP} = \exp[g_1 - g_2 \ln(Q/2Q_0) - g_1 g_3 \ln(x_1 x_2)]\, b^2$$

g_2 affects position of the peak

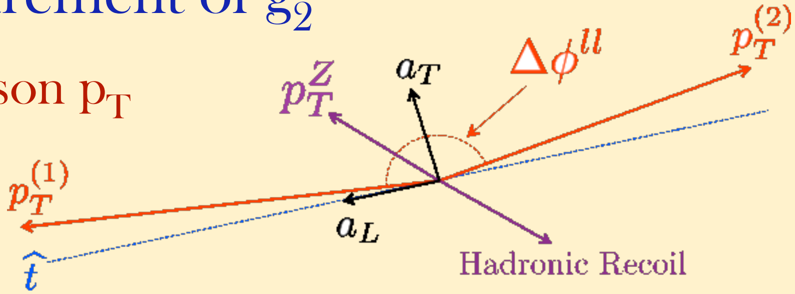
CDF Run II: in situ determination of g_2 = 0.685 ± 0.048 (CTEQ6M) using Z→ll data

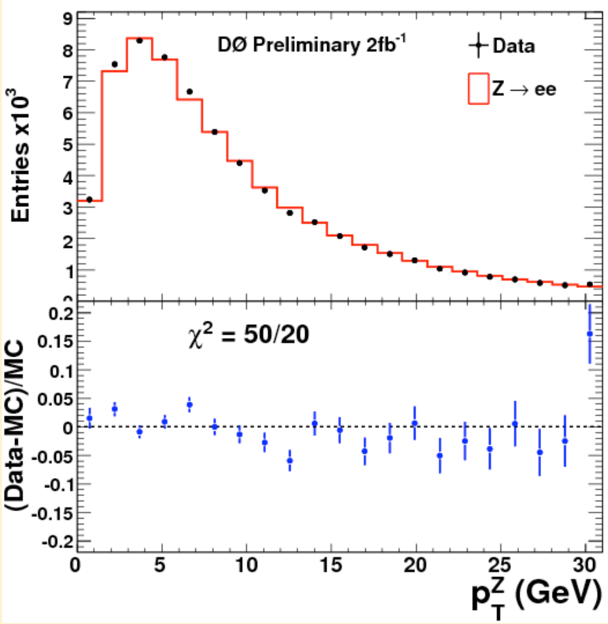
Consistent with prior Drell-Yan data (CTEQ3M)

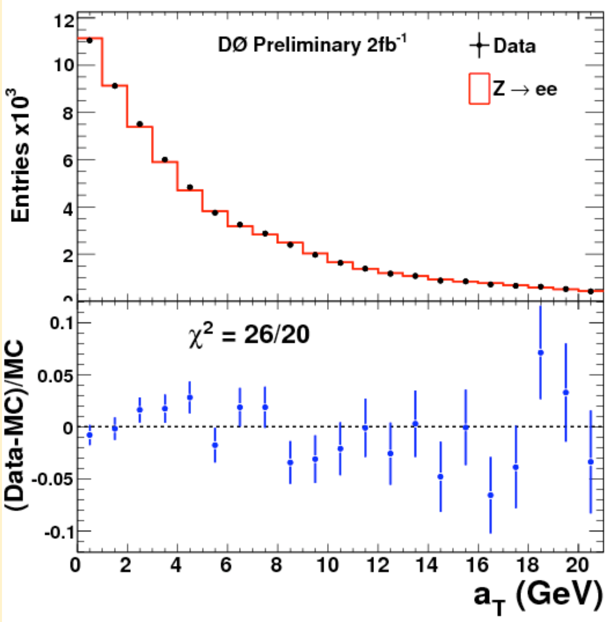
Other g_i parameters correlated: varying g_3 has negligible effect on m_W

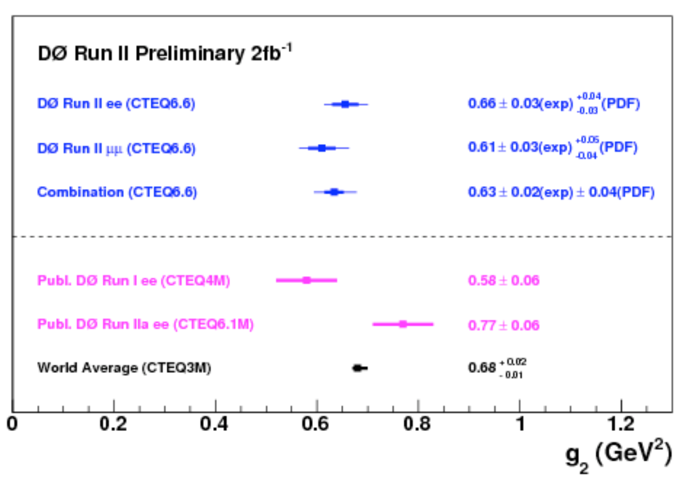
Z Boson p_T

- DØ has performed dedicated measurement of g_2
  - Optimizes sensitivity using projected boson p_T
  - Measure 0.63 ± 0.02 with CTEQ6.6
    - Quote PDF uncertainty of 0.04



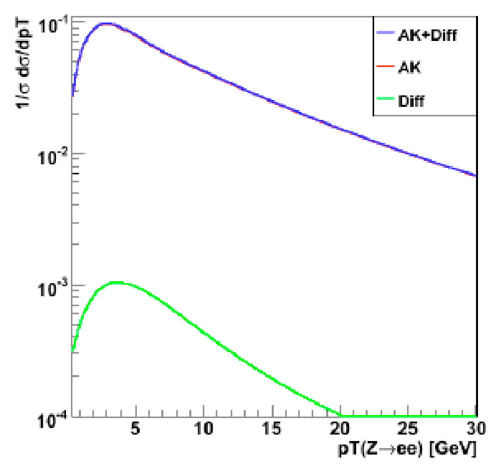






Boson p_T Issues

- Theory required to transfer measured p_T^Z to p_T^W
  - Is the RESBOS parametrization sufficient?
- Is uncertainty covered by RESBOS g_2 parameter?
  - α_s?
  - Perturbative components?
  - Correlation with PDFs?
  - QED ISR?
  - Diffractive boson production?



M. Lancaster and
D. Beecher,
Milan Workshop

- p_T^l and p_T^ν fits provide important cross-check
  - More sensitive to p_T^W

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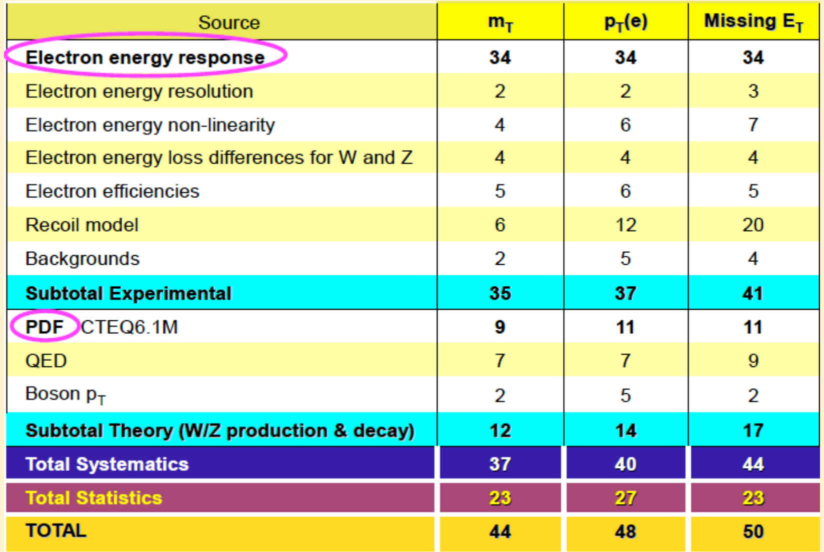

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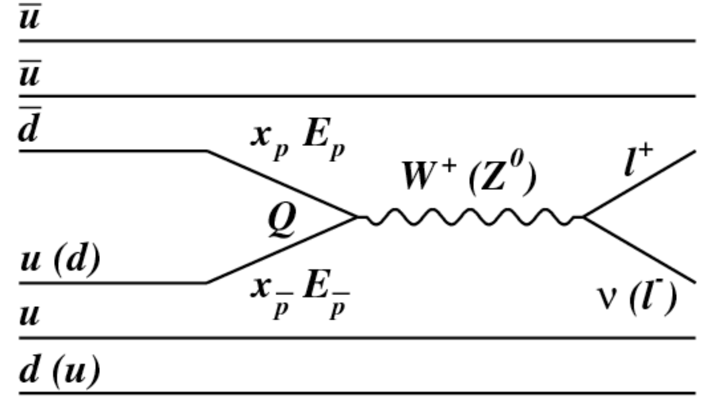

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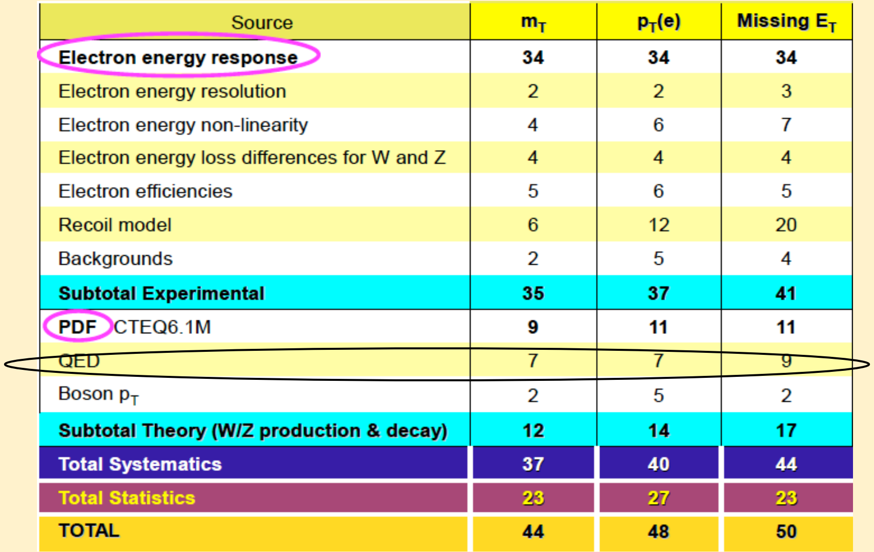

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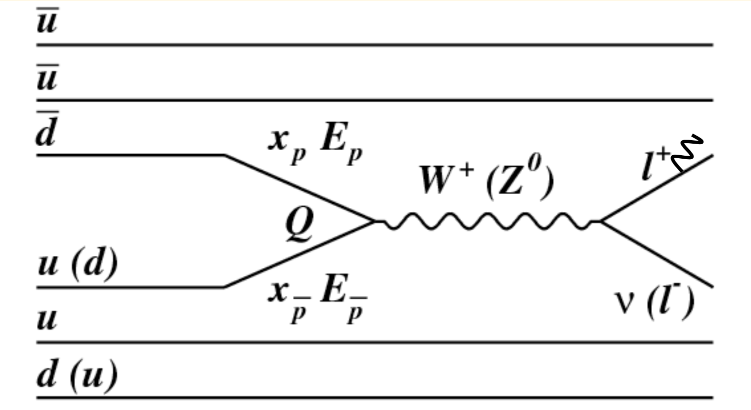

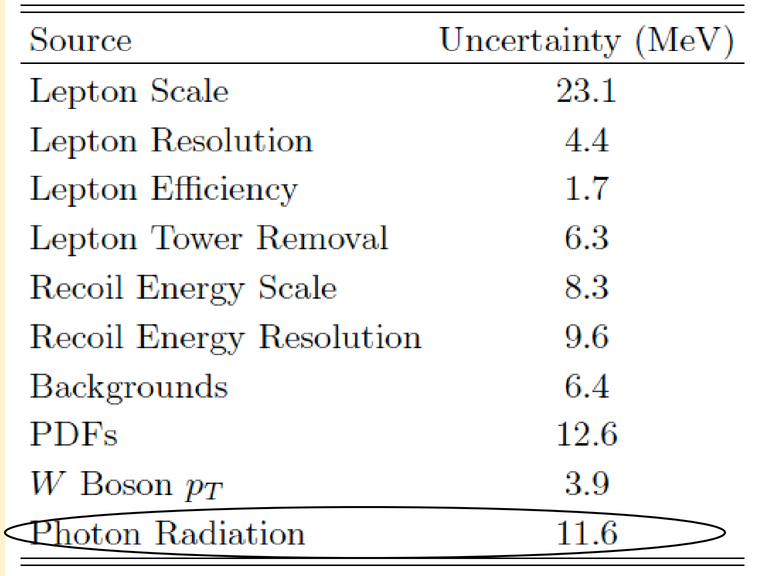

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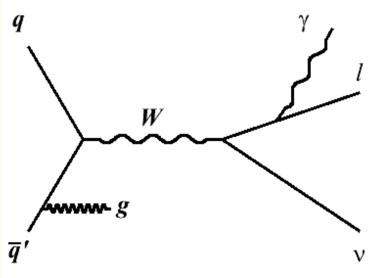
Modelling Photon Radiation

- Dominant effect on m_W due to FSR
  - O(150 MeV) effect



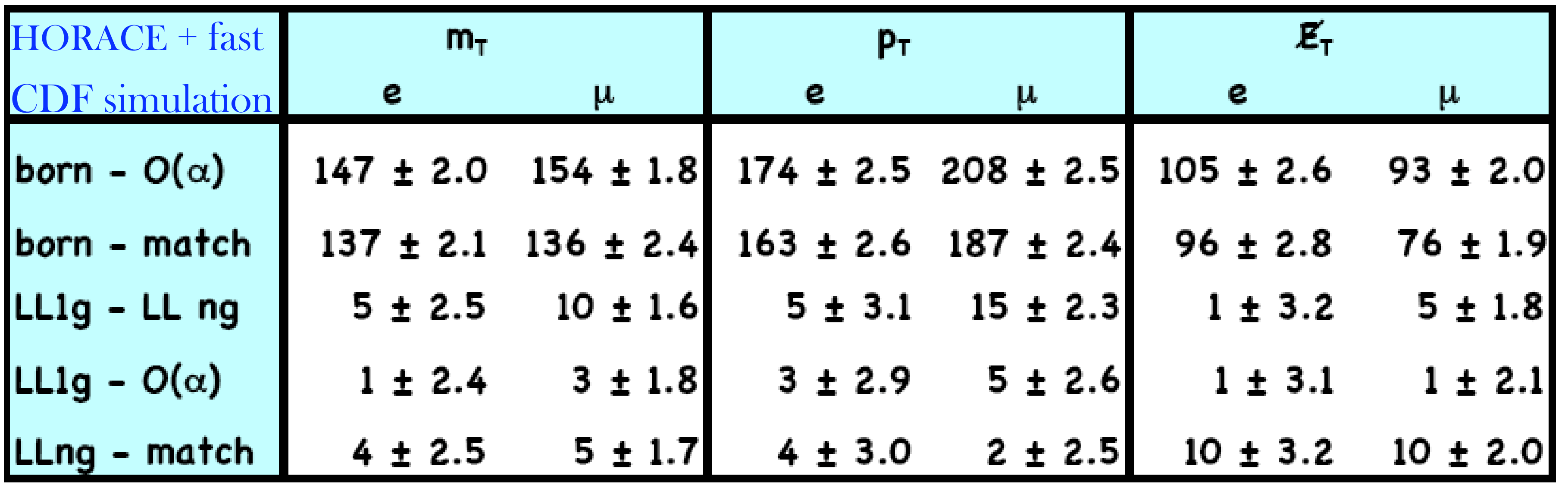
- Run II measurements add an FSR model to RESBOS
  - DØ: Use PHOTOS (resummed calculation), compare to WGRAD (O(α))
  - CDF: Add photons from a histogram (E_γ/E_l vs ΔR) extracted from WGRAD

- Sources of quoted uncertainties:
  - PHOTOS vs WGRAD differences (almost certainly an overestimate)
  - Full O(a) WGRAD vs FSR WGRAD (statistics-limited test at CDF)
  - Infrared cutoff (also statistics-limited)

- Thorough investigation with HORACE in progress at CDF

HORACE Model and Effect on m_W

- HORACE generator reweights leading logarithms to reproduce α^n
  - Hard radiation scale factor:
    - $F_H = 1 + (|\mathcal{M}_1|^2 - |\mathcal{M}_{1,LL}|^2) / |\mathcal{M}_{1,LL}|^2$
  - Soft and virtual scale factor:
    - $F_{SV} = 1 + (C_\alpha - C_{\alpha,LL})$
  - Factors derived from exact $O(\alpha)$ calculation:
    - $d\sigma_\alpha = F_{SV}\,(1 + C_{\alpha,LL})\,|\mathcal{M}_0|^2\,d\Phi_0 + F_H\,|\mathcal{M}_{1,LL}|^2\,d\Phi_1$

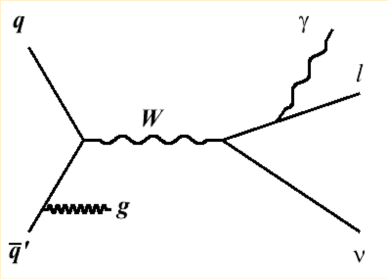


HORACE + fast CDF simulation	m_T		p_T		$\not{E}_T$	
	e	μ	e	μ	e	μ
born - O(α)	147 ± 2.0	154 ± 1.8	174 ± 2.5	208 ± 2.5	105 ± 2.6	93 ± 2.0
born - match	137 ± 2.1	136 ± 2.4	163 ± 2.6	187 ± 2.4	96 ± 2.8	76 ± 1.9
LL1g - LL ng	5 ± 2.5	10 ± 1.6	5 ± 3.1	15 ± 2.3	1 ± 3.2	5 ± 1.8
LL1g - O(α)	1 ± 2.4	3 ± 1.8	3 ± 2.9	5 ± 2.6	1 ± 3.1	1 ± 2.1
LLng - match	4 ± 2.5	5 ± 1.7	4 ± 3.0	2 ± 2.5	10 ± 3.2	10 ± 2.0

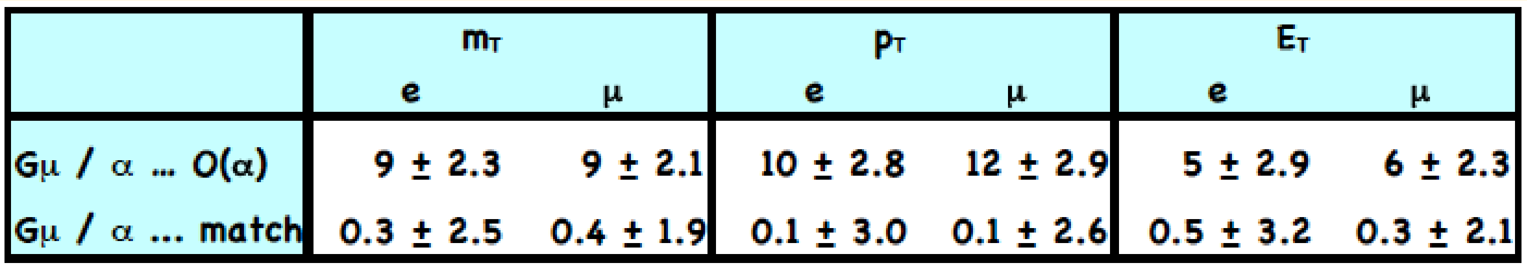
I. Bizjak, Milan Workshop

Higher Orders

- Inclusion of leading logarithms reduces m_W shift
  - Next order of corrections suppresses radiation



- Have investigated HORACE scheme dependence
  - Calculation implemented in G_μ and α schemes
    - Truncate perturbative series in different ways



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Gμ / α … match	0.3 ± 2.5	0.4 ± 1.9	0.1 ± 3.0	0.1 ± 2.6	0.5 ± 3.2	0.3 ± 2.1

<1 MeV effect for full (“matched”) HORACE

I. Bizjak,
Milan Workshop

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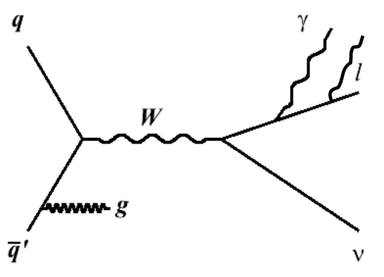

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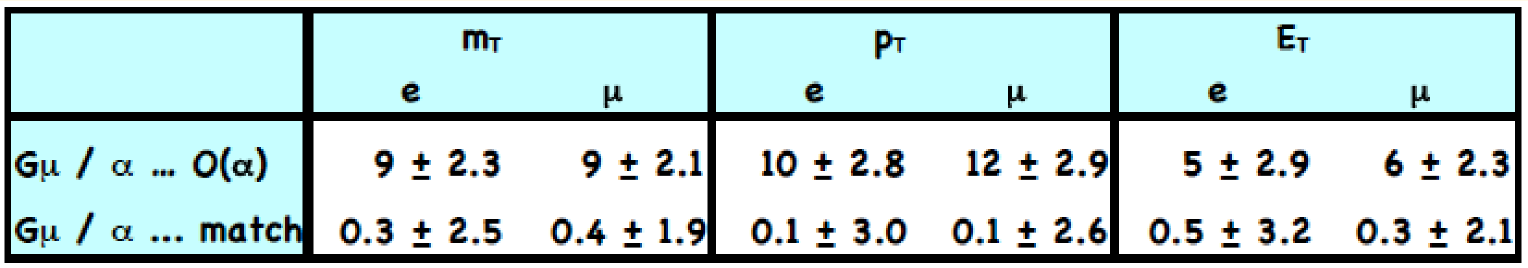

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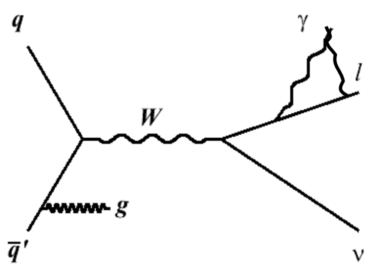

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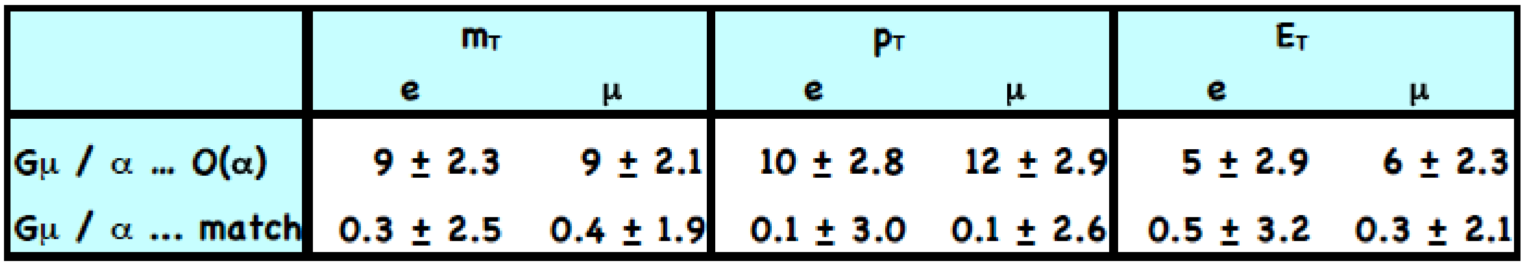

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Photon Radiation Issues

- Unclear how to obtain uncertainty on HORACE prediction
  - Full NNLO calculation would be a useful test
  - Should we compare with other generators (e.g., WINHAC)?
  - Are there uncertainties due to missing diagrams?

- Should determine relevance of higher multiplicity radiation
  - Radiation of two hard (>100 MeV) photons
  - Radiation of electron-positron pairs

- Not using generators with combined QED & QCD radiation
  - Currently custom-produce final-state QED on top of RESBOS or vice versa
  - Useful to have a single generator for both
    - HORACE authors have added MC@NLO
    - RESBOS authors have added WGRAD ("RESBOS-A")
  - Do mixed QED and QCD terms matter?

- Uncertainty mitigated by calibrating lepton momentum with $Z \rightarrow ll$

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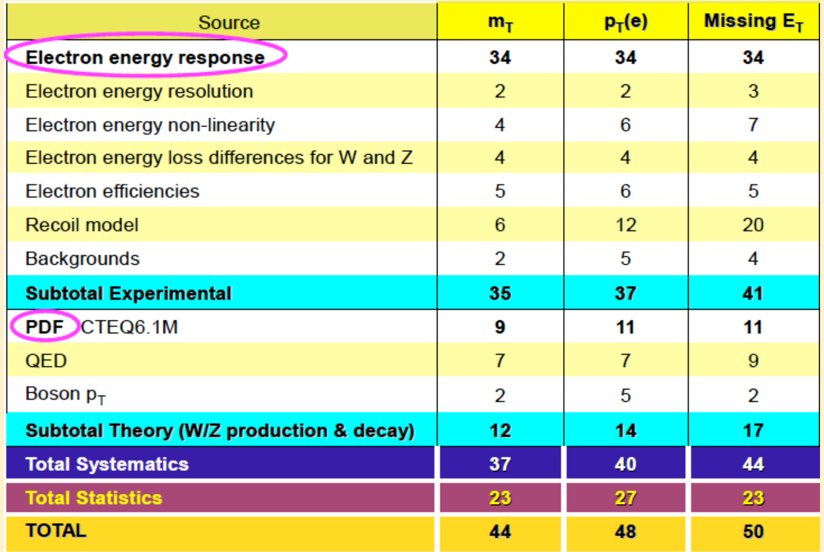

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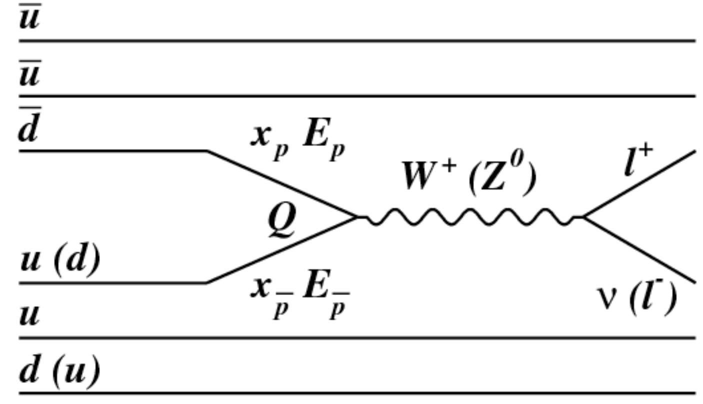

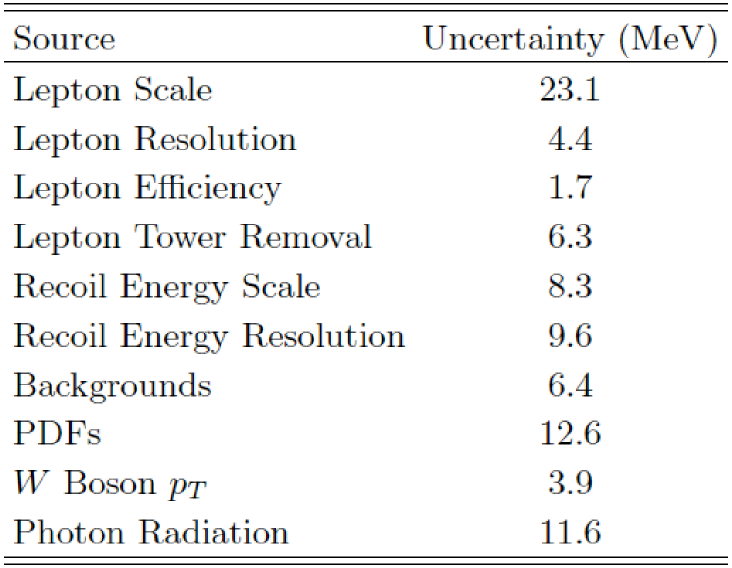

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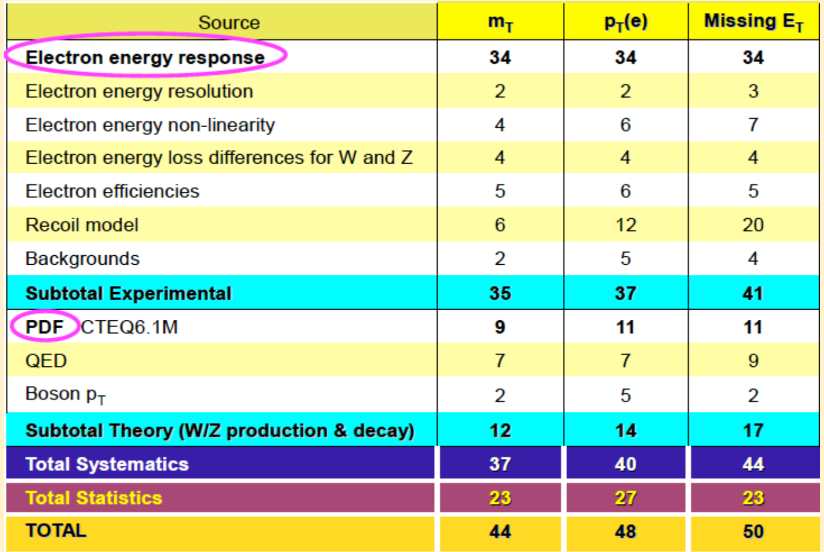

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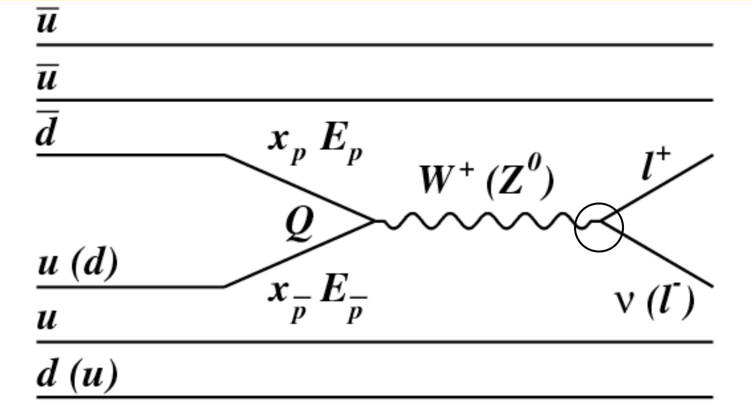

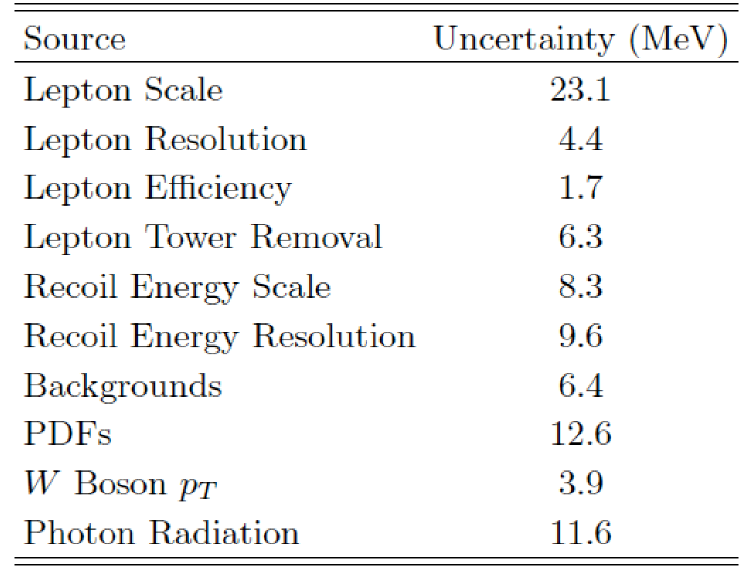

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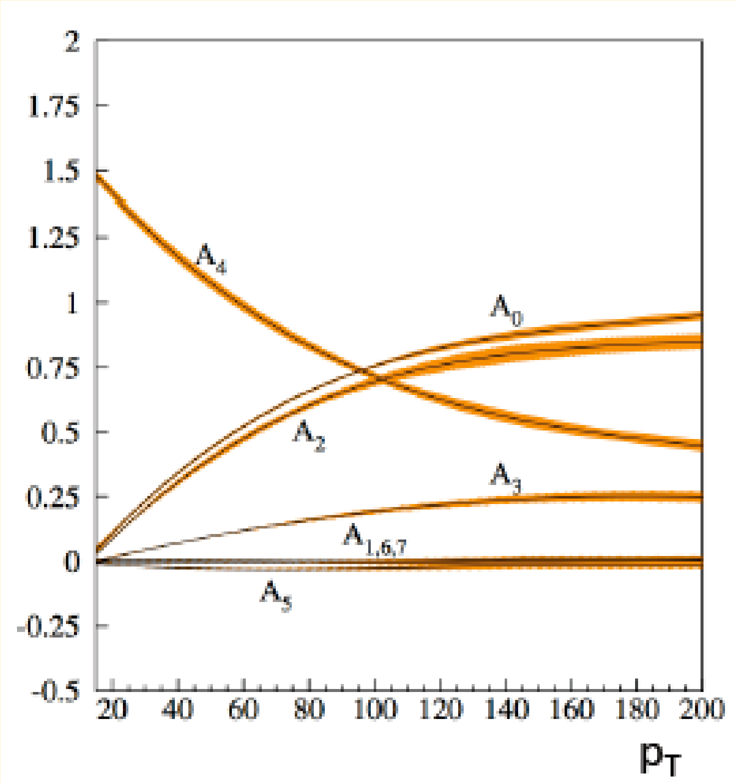
W Polarization and Decay

- Decay angle determines transverse fraction of momentum
  - Distribution different for valence and sea quarks
  - Parameters for differential cross section calculated to NLO in QCD



$$\frac{d^4\sigma}{dQ_T^2\,dy\,d\phi\,d(\cos\theta)} = \frac{3}{16\pi}\frac{d^2\sigma}{dQ_T^2\,dy} \times \Big[(1+\cos^2\theta) + \frac{A_0}{2}(1-3\cos^2\theta) + A_1\sin 2\theta\cos\phi + \frac{A_2}{2}\sin^2\theta\cos 2\phi + A_3\sin\theta\cos\phi + A_4\cos\theta + A_5\sin^2\theta\sin 2\phi + A_6\sin 2\theta\sin\phi + A_7\sin\theta\sin\phi\Big]$$

CDF moments analysis:

RESBOS agrees with DYRAD in high-p_T region

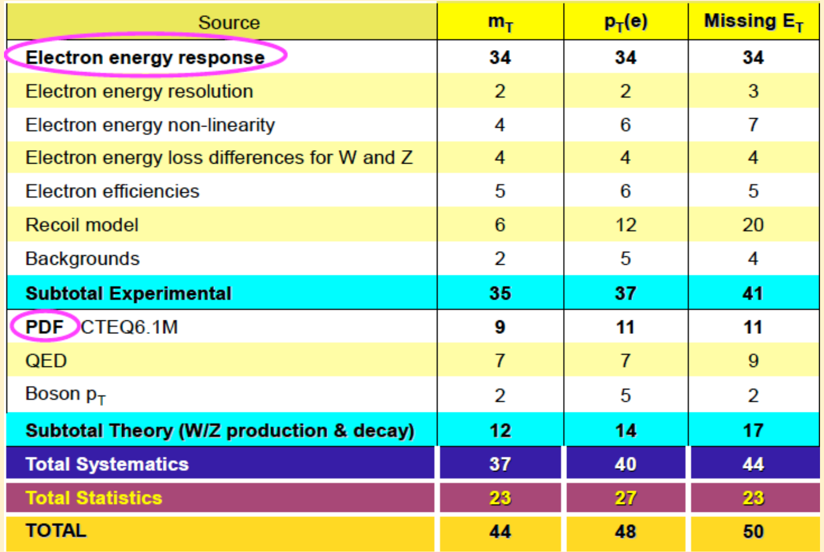
Issues:

- What is the polarization uncertainty at low p_T?
- Should resummations be separated by helicity?

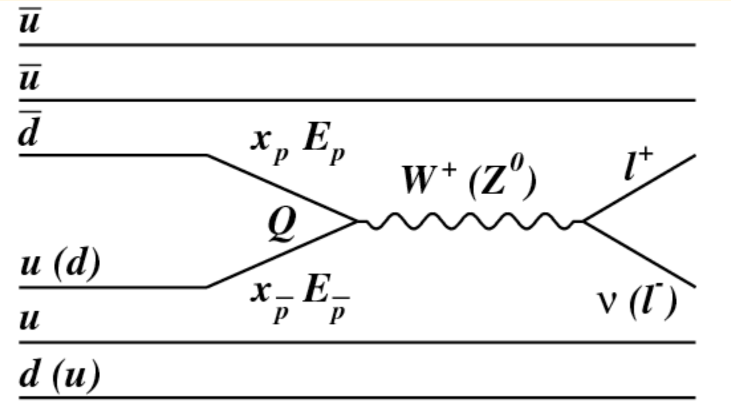
Measuring m_W at a Hadron Collider

- Theoretical inputs:
  - Details of W production and decay
- Experimental inputs:
  - In situ calibration of response to $l^\pm$ and ν
    - Only transverse momenta used in mass fit

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



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**



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)

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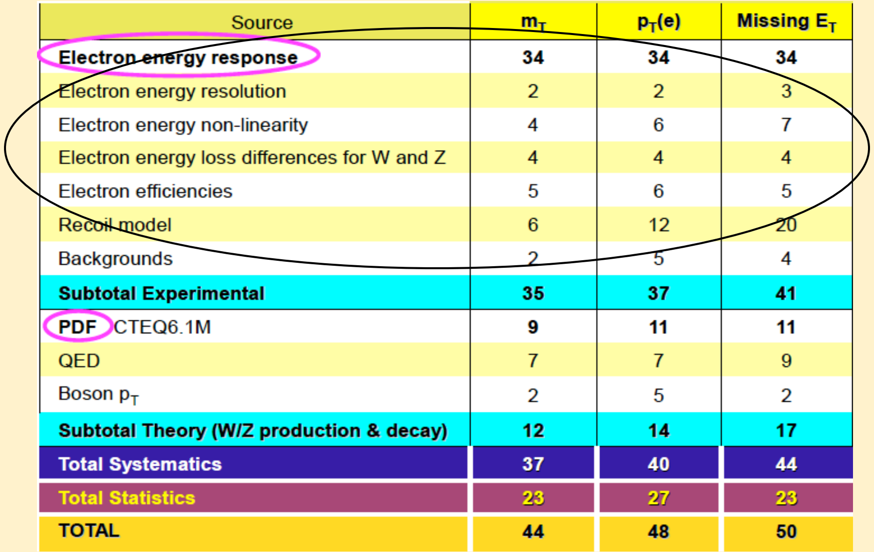

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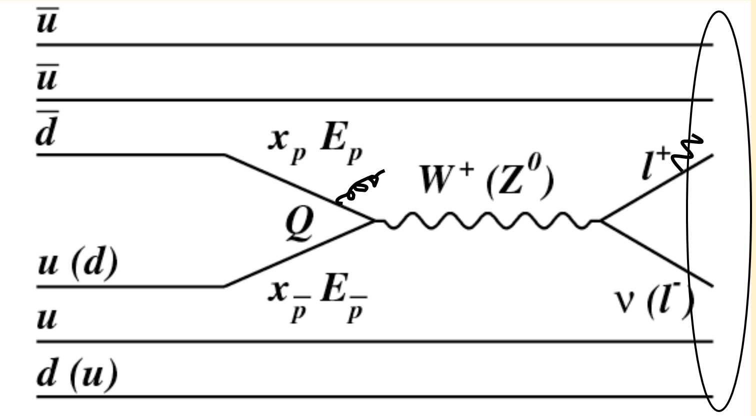

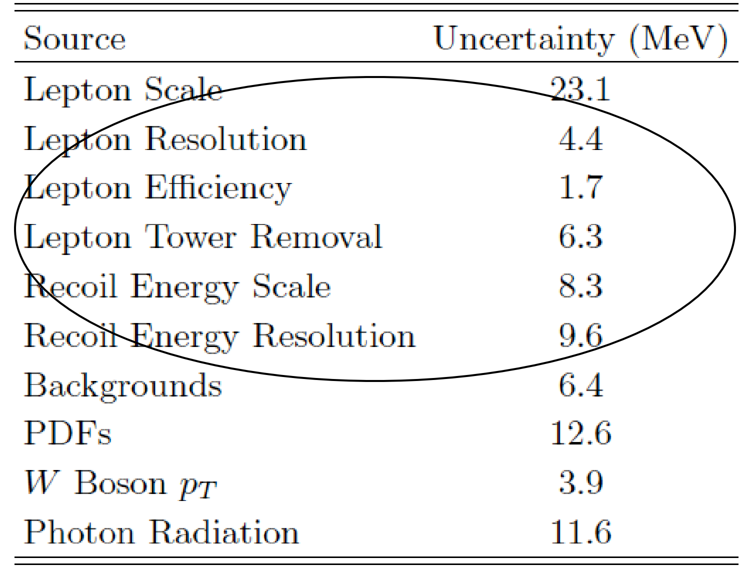

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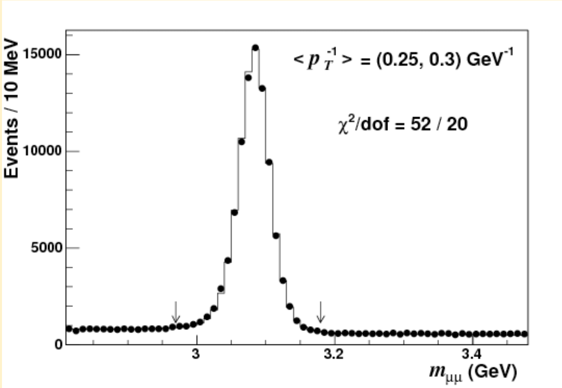
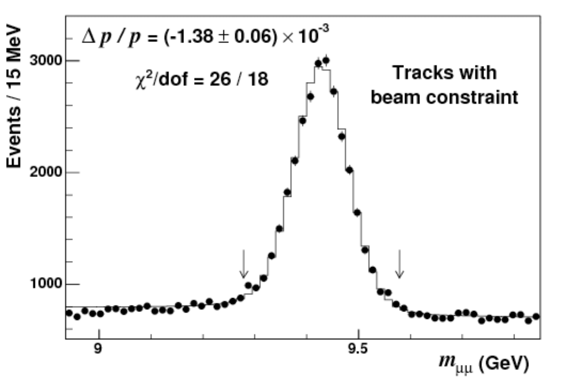
CDF Collaboration,
PRL 99, 151801 (2007),
PRD 77, 112001 (2008)

Charged Lepton Calibration

- CDF
  - Muon calibration includes J/ψ→μμ, Υ→μμ resonances
    - 600k J/ψ and 35k Υ candidates in 200 pb^{-1}
  - Mass fits sensitive to energy loss model
    - Bethe-Bloch mean
    - Landau distribution improves model of peak shape
      - Non-trivial to preserve the mean
  - In situ energy loss tune using scale vs <1/p>
    - Scale factor for Bethe-Bloch mean

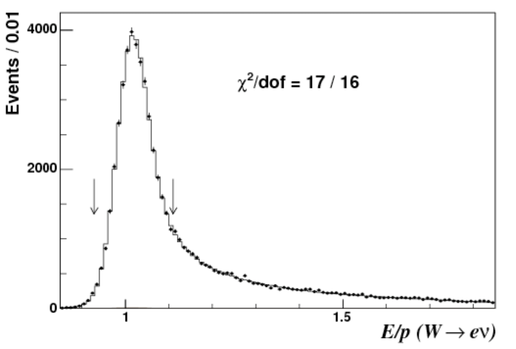




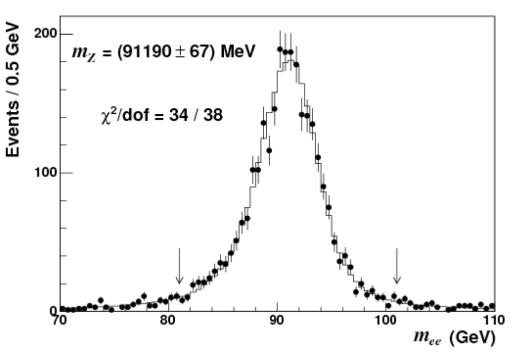
  - Shape of peaks sensitive to intrinsic resolution and multiple scattering
    - Add tails to multiple scattering based on low-energy muon data
  - Systematics-dominated despite careful modelling of J/ψ, Υ peaks

Charged Lepton Calibration

- CDF
  - Electron calibration transfers track calibration to calorimeter with W electrons



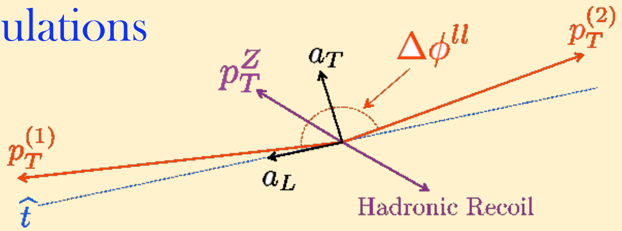
  - Peak position sensitive to soft radiation in tracker
    - Tune tracker material using tail of distribution
    - Rely on theoretical model for radiation spectrum
    - Model quantum effects for low-energy radiation: O(50 MeV)

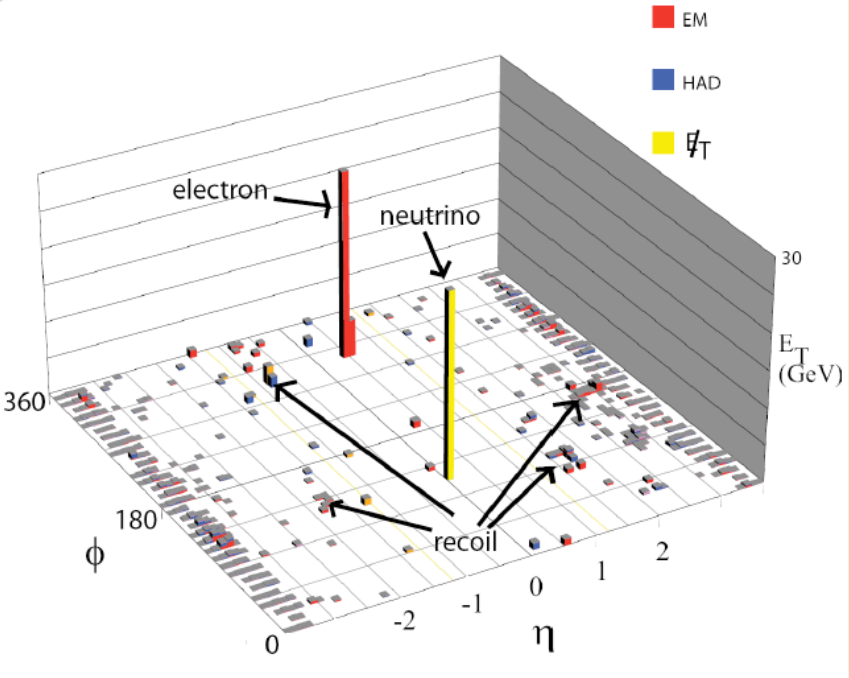


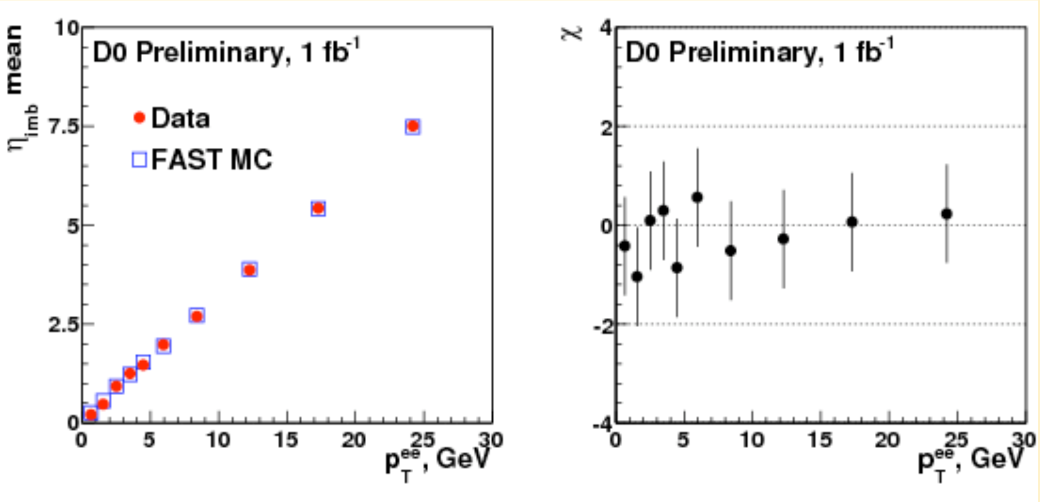
  - Combine with Z boson peak
    - Important cross-check
- DØ
  - Calibration relies on Z boson peak
    - What effects do not cancel when transferring scale from Z to W?

Recoil Calibration

- In situ calibration of detector response to ν
    - Develop model using GEANT and randomly collected events (zero bias)
    - Tune parameters with Z → ee events
    - Response to hadrons (< 1) results in measured momentum imbalance
        - Well modeled by CDF & DØ fast simulations

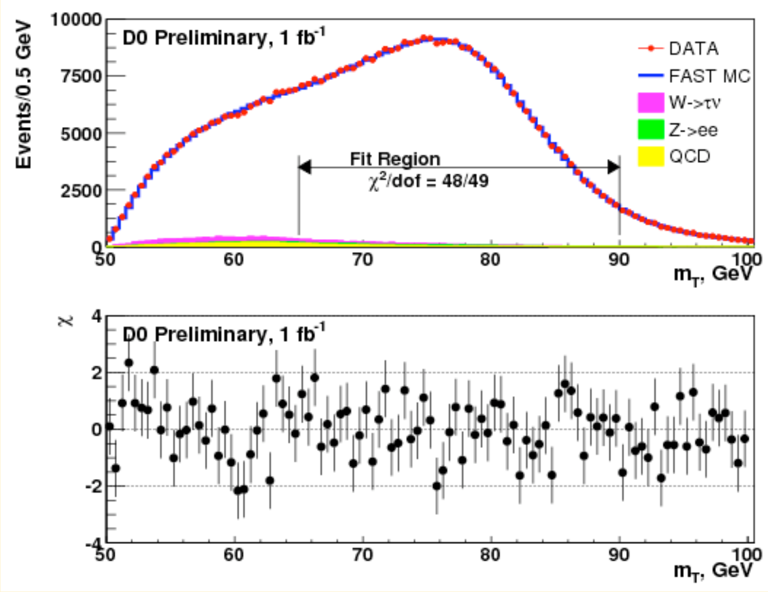




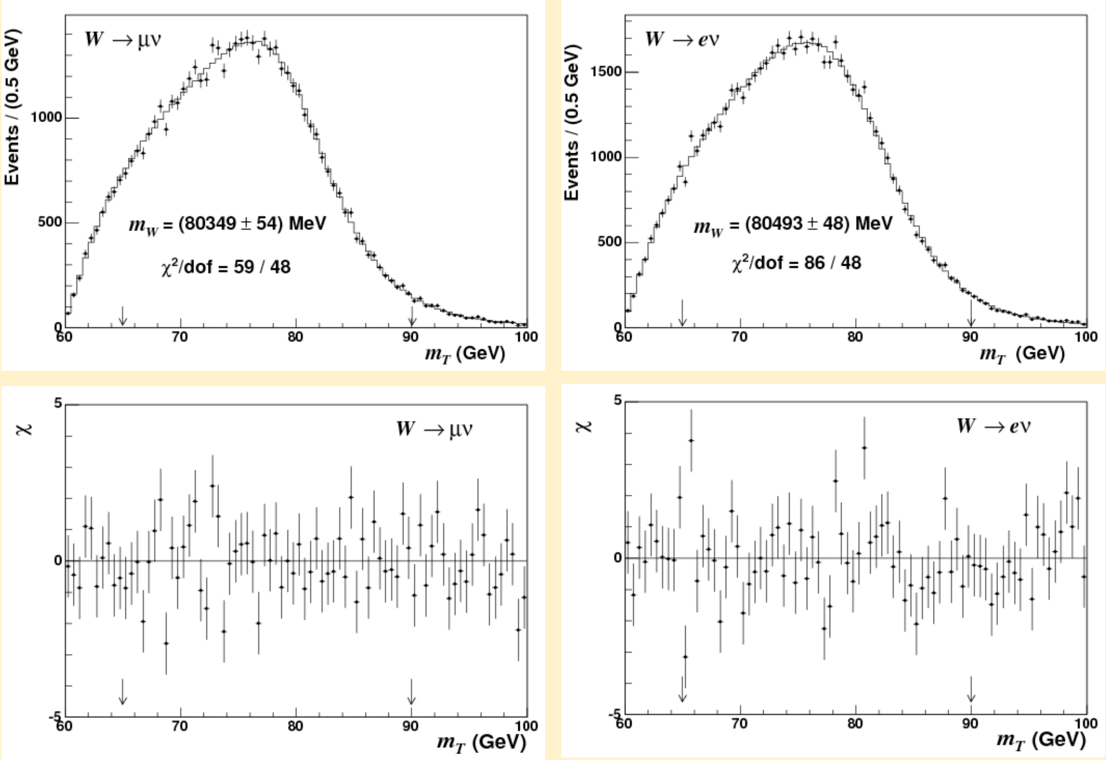


Mass Fits

- CDF and DØ measurements model fit distributions well



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

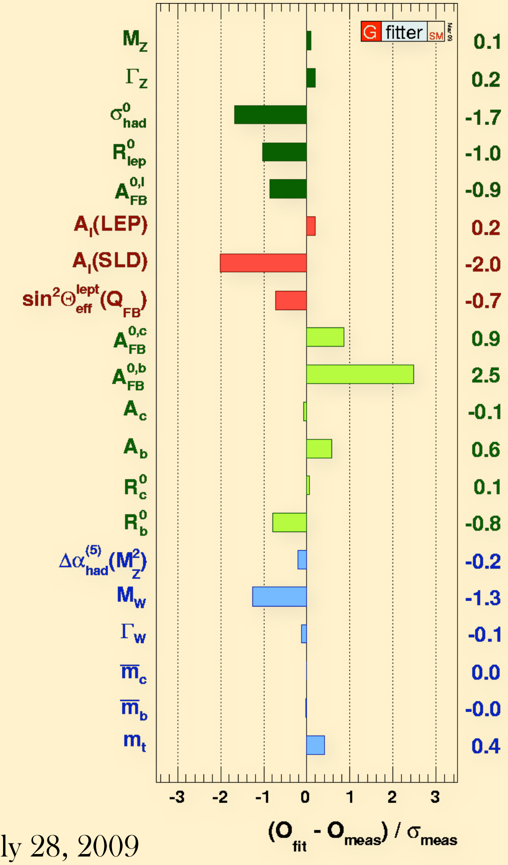


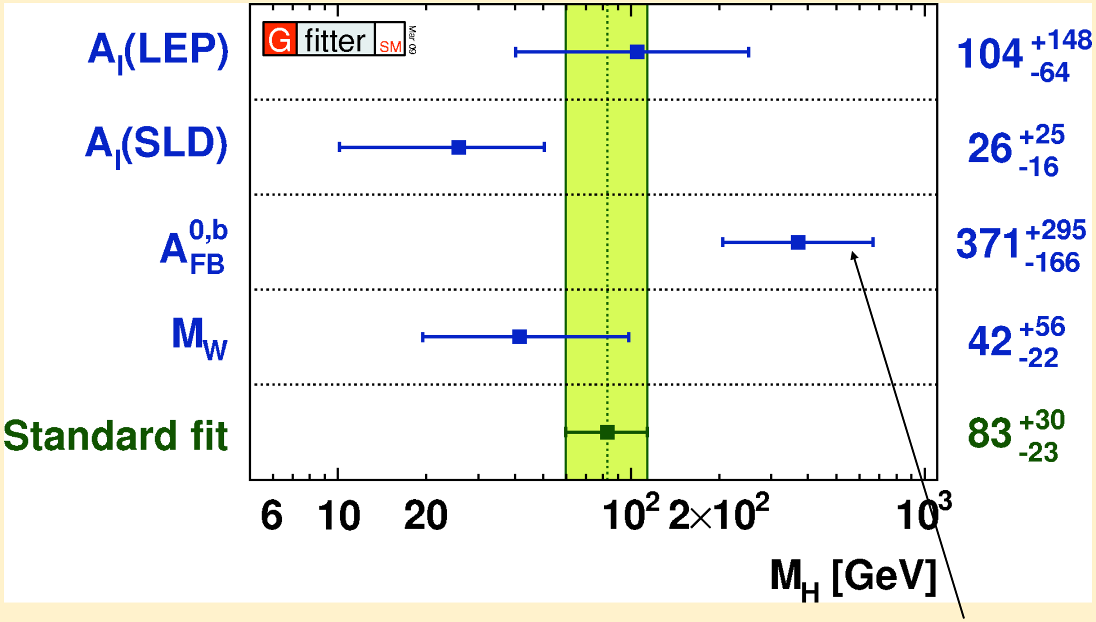
Combined Tevatron precision should be better than LEP

$$m_W = 80.413 \pm 0.034_{\text{stat}} \pm 0.034_{\text{sys}}\ \text{GeV}$$
$$= 80.413 \pm 0.048\ \text{GeV}$$

World-Average m_W

- Tevatron average not yet available
- Gfitter group has calculated its own world-average m_W
  - $m_W = 80.399 \pm 0.023$ GeV : O(10%) reduction in uncertainty



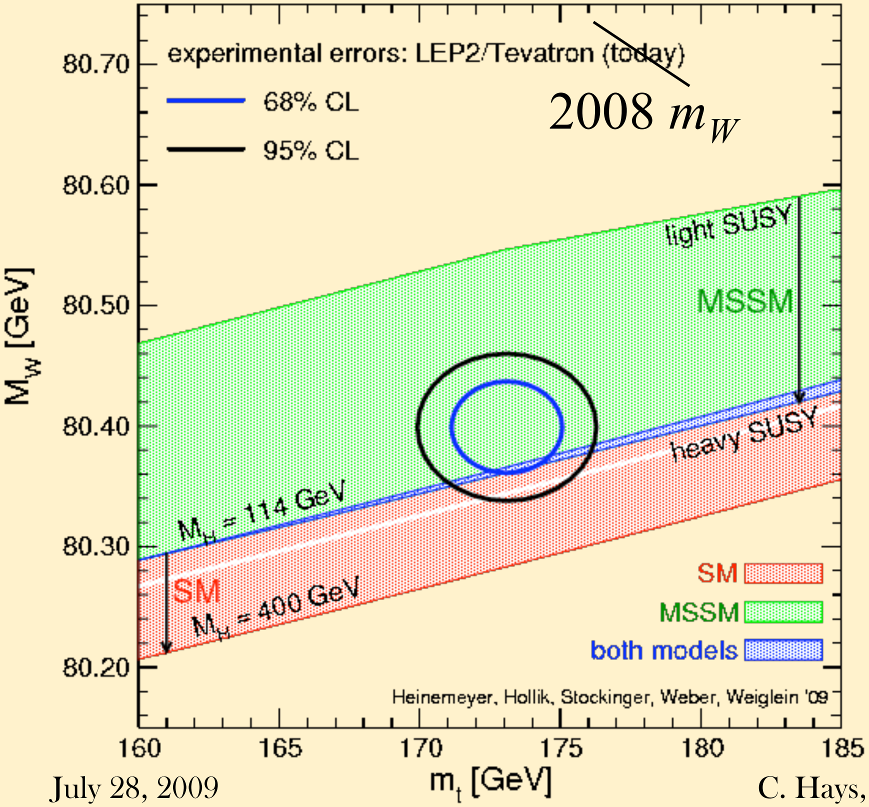


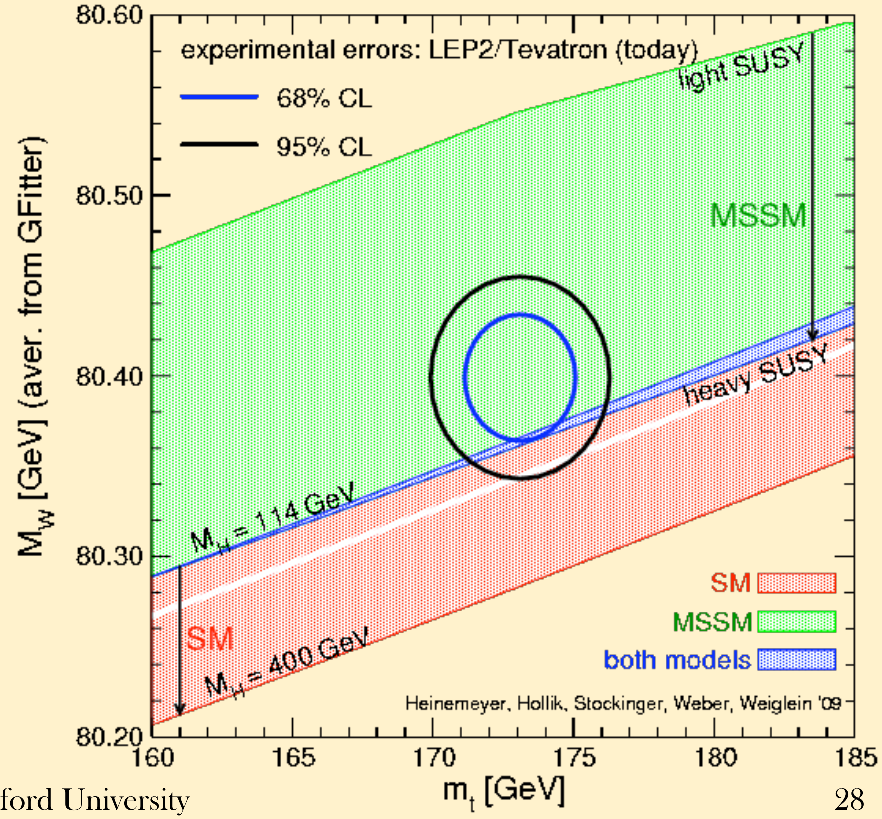
1.4% probability to find such a deviant outlier

Gfitter Group,
EPJC 60, 543 (2009)

Constraints from m_W

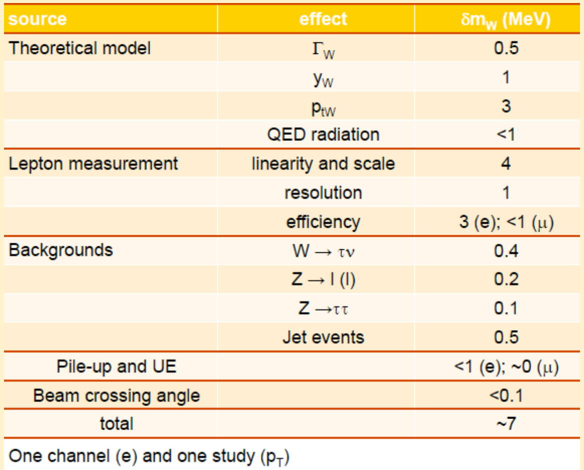
- Electroweak measurements prefer light Higgs, heavy **SUSY**
  - Some tension in both cases
    - Something else?
    - Need increased precision





m_W at the LHC

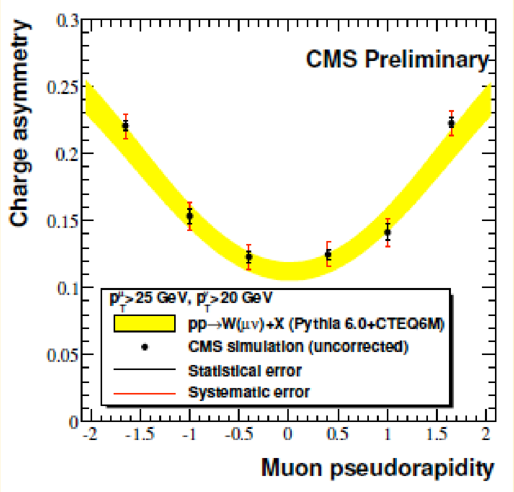
- ATLAS predicts a 7 MeV measurement with 10 fb^{-1} of data
  - No recoil uncertainty included
    - Assumed negligible for p_T fit
  - CDF uncertainty: 17 MeV (p_T fit), 11 MeV (m_T fit)
    - Due to cut on recoil & uncertainty on recoil scale
  - Expect 45 million W events, 4.5 million Z events
    - Have statistics to parametrize recoil
    - Hard to predict precision without data



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	$W \rightarrow \tau\nu$	0.4
	$Z \rightarrow l\ (l)$	0.2
	$Z \rightarrow \tau\tau$	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)

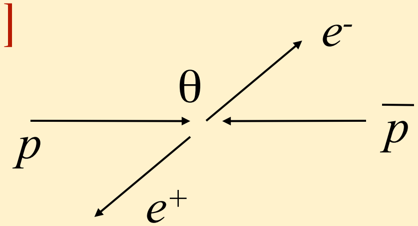
- Expect PDF uncertainties to be important
  - Will have more statistics to measure Z rapidity and W charge asymmetry

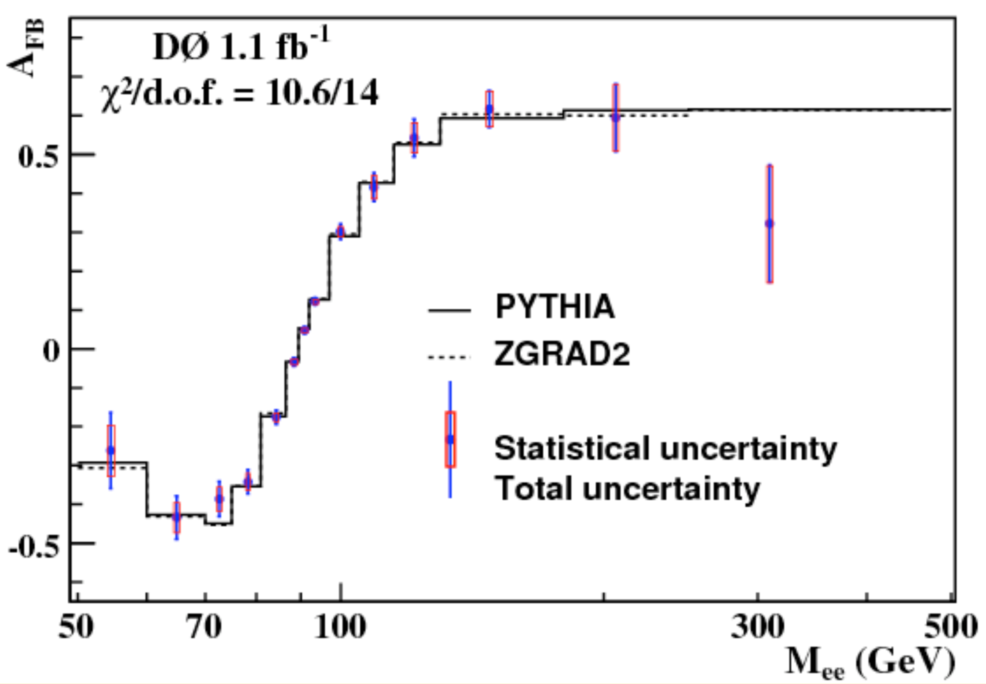


- Will have statistics for <10 MeV measurement

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:
    - $v_f = I^3_L - 2e \sin^2\theta_W$; $a_f = I^3_L$
  - 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)

Summary

- m_W measurement most important for constraining new physics

- Measurements driving improvements in W & Z modelling
  - CDF & DØ have the two most precise measurements
  - Next measurement will have similar theory and experimental uncertainties
    - New Tevatron results and theoretical progress will reduce input uncertainties
    - Expect measurement to be more precise than the world average
  - Should achieve <10 MeV precision from hadron colliders

- Potential for $\sin^2\theta_W$ precision measurement at the Tevatron
  - Much work to be done to demonstrate scaling of uncertainties and sensitivity of muon channel

- Exciting time to work on Electroweak physics at hadron colliders

If there is no SM Higgs...

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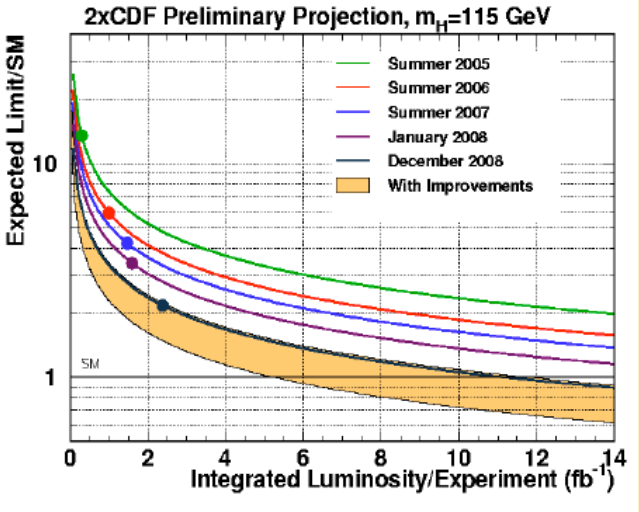

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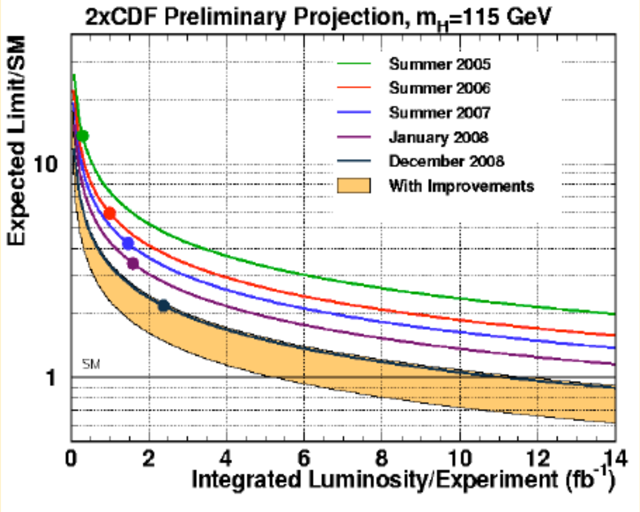

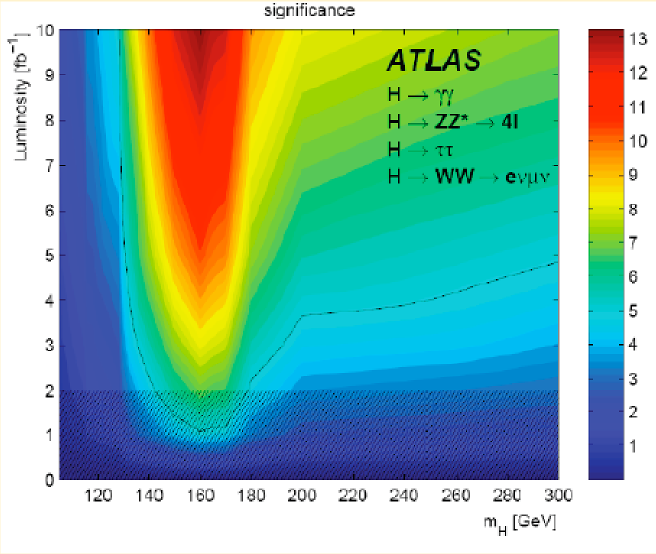

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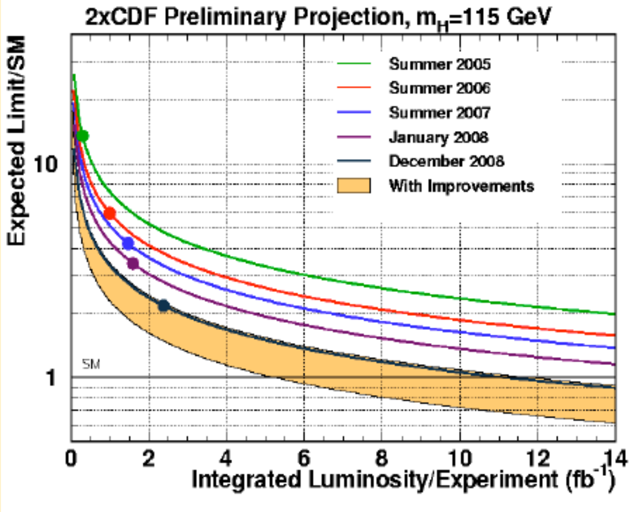

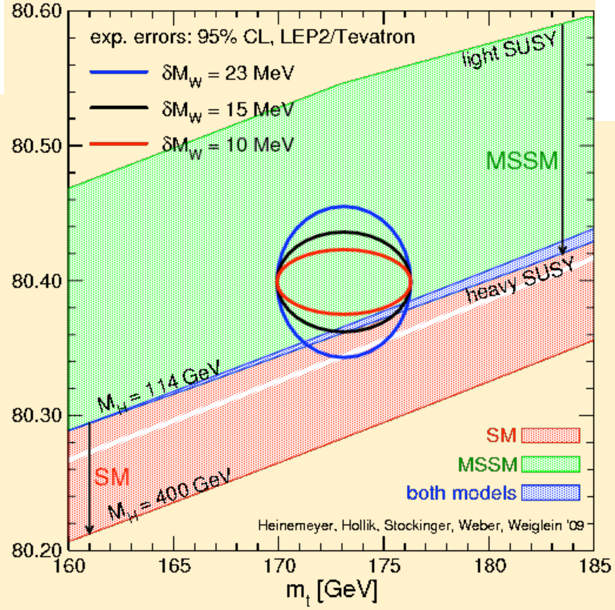

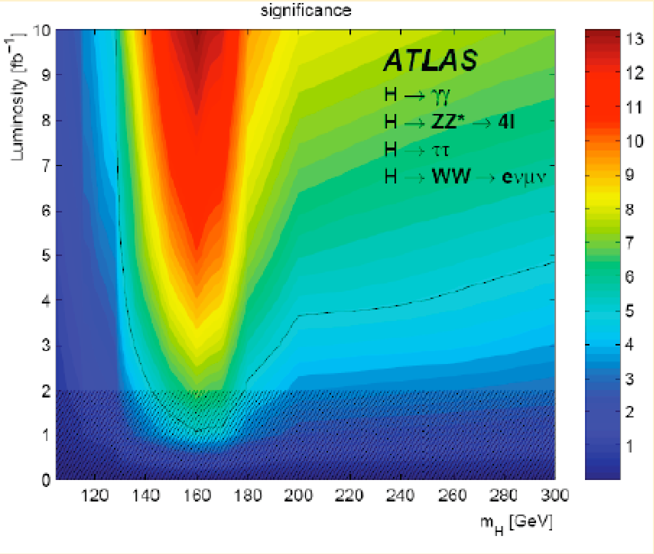

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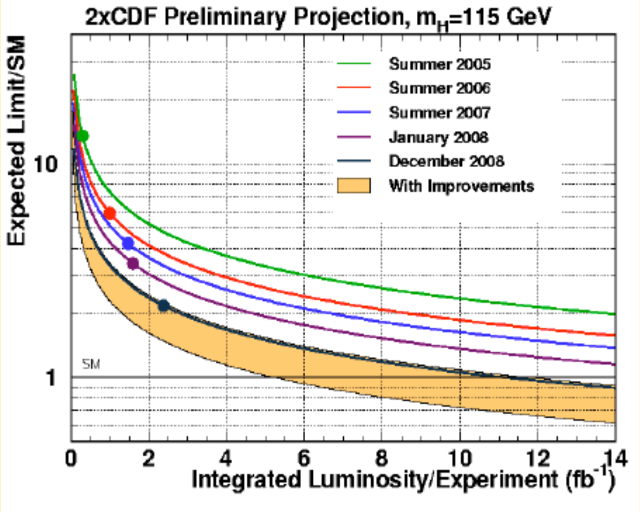

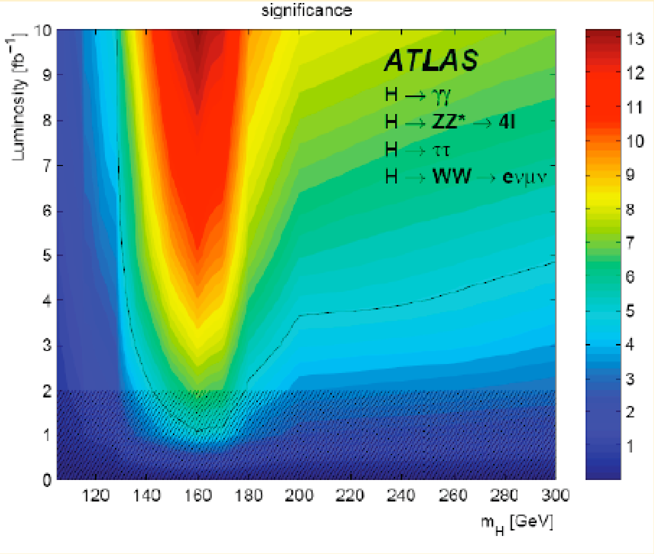

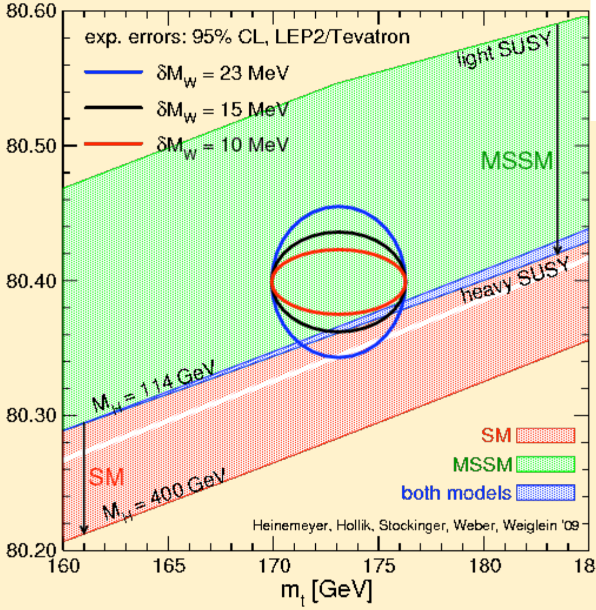

...who will exclude it first?