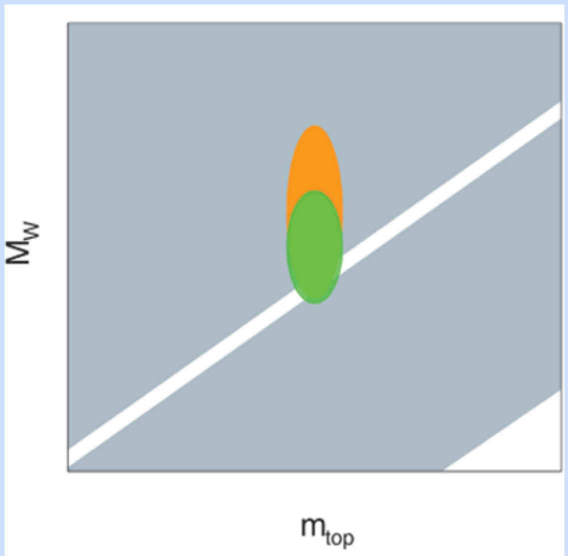
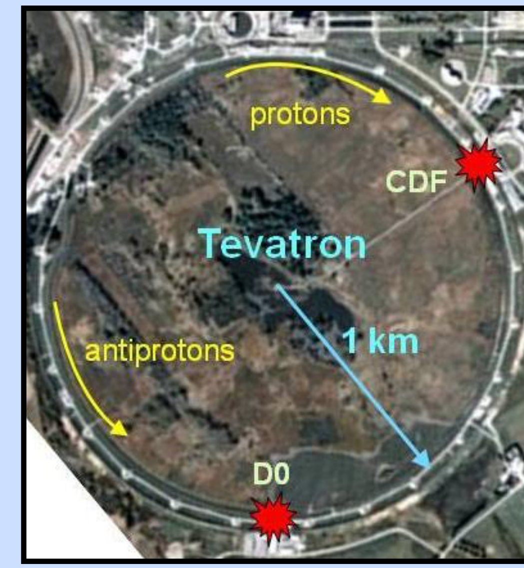
Electroweak measurements at the Fermilab Tevatron



Chris Hays,
Oxford University



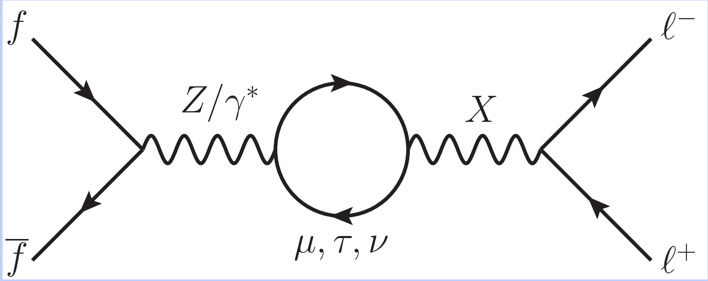
on behalf of the CDF and D0 Collaborations

Rencontres de Moriond Electroweak
12 March 2018

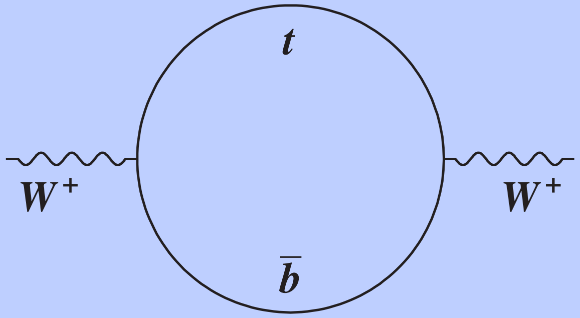
Overview

Tevatron collider

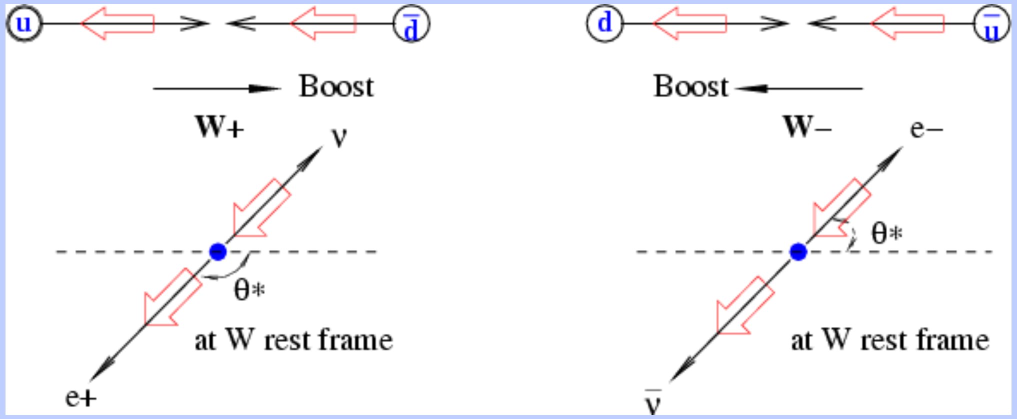
Z boson couplings



W boson mass



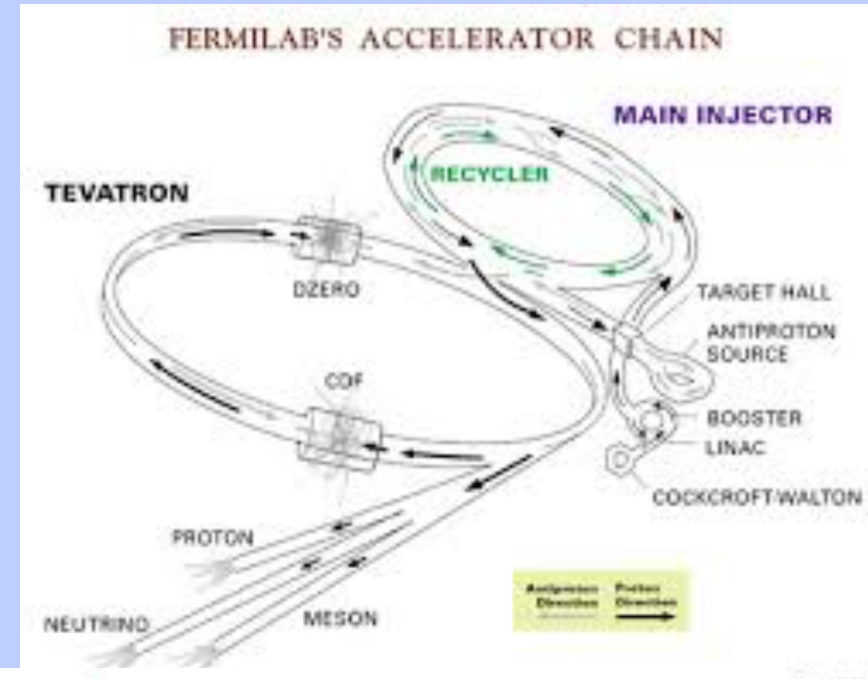
W charge asymmetry

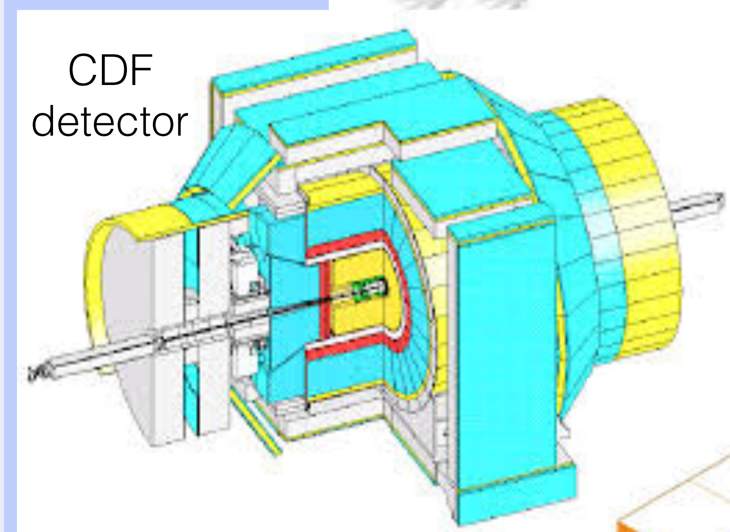


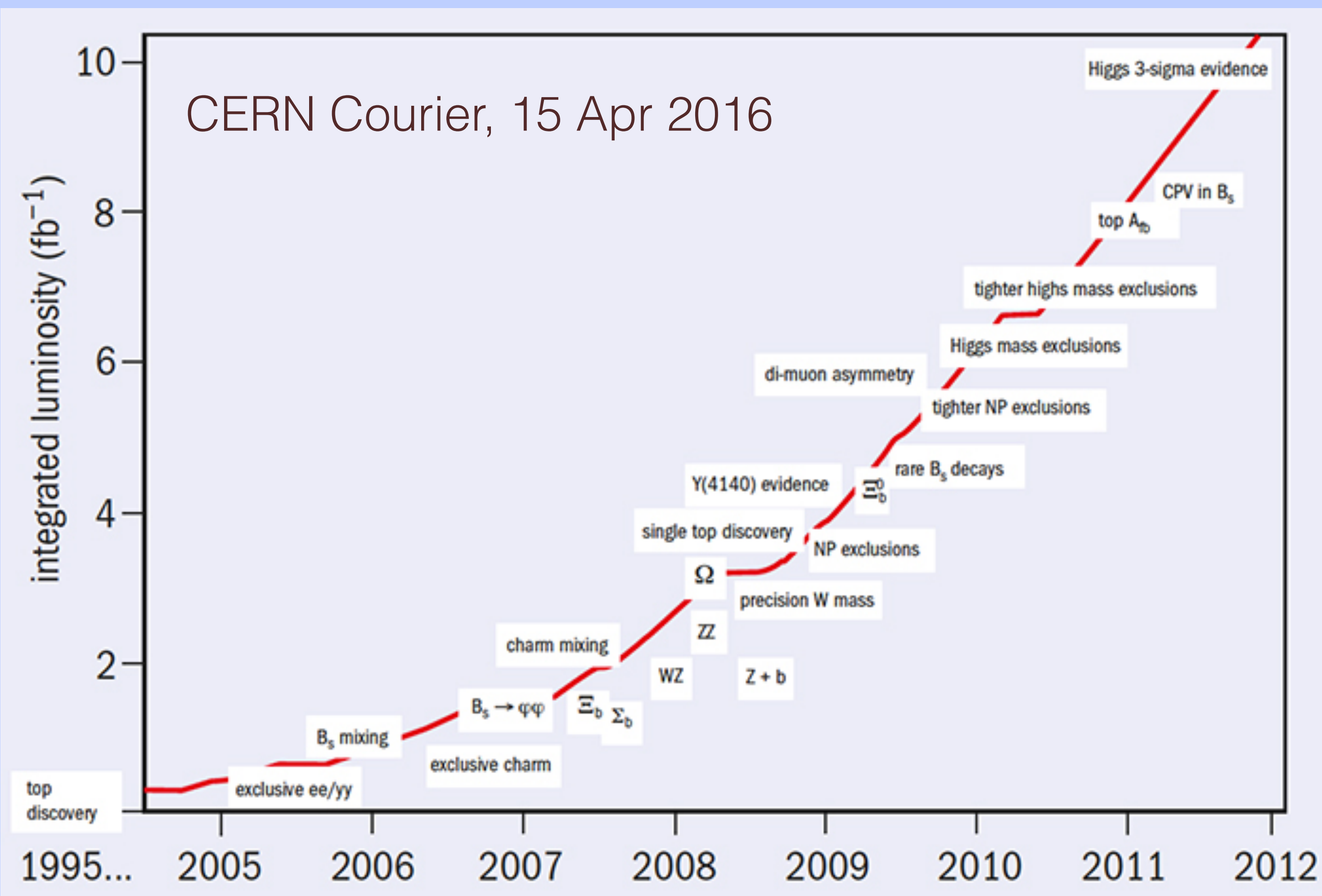
Fermilab Tevatron

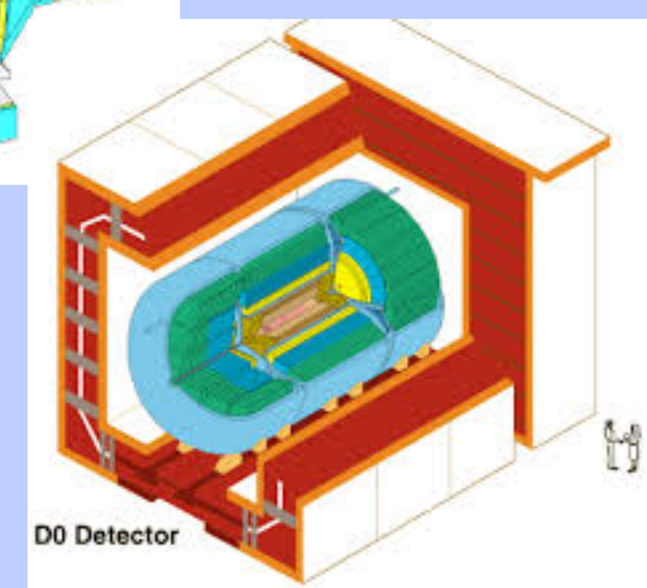
The Fermilab Tevatron delivered >10 fb^{-1} of proton-antiproton collisions at $\sqrt{s}$=1.96 TeV from 2001-2011

Many discoveries and measurements made by the CDF and D0 experiments







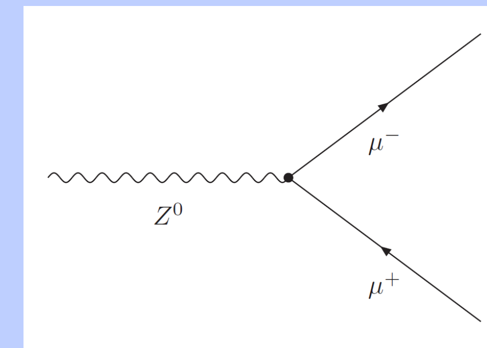


Z boson couplings

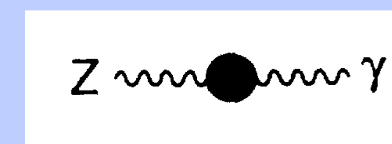
Vector coupling of the Z boson to fermions has contributions from weak and hypercharge couplings (electroweak mixing)

$$-\,i\frac{g}{2\cos\theta_W}\bar{f}\gamma^{\mu}(g_V^f - g_A^f\gamma_5)fZ_{\mu}$$

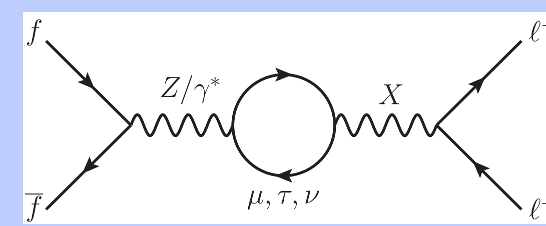
$$g_V^f = T_3^f - 2Q_f\sin^2\theta_W \quad \text{and} \quad g_A^f = T_3^f$$



Loop corrections modify the vector coupling relative to axial



Couplings can be affected by e.g. dark matter interacting with leptons



PLB 744, 330 (2015)

Forward-backward asymmetry of Z-pole leptons probes relative vector and axial couplings

$$\frac{\int_0^1 d\cos\theta\,\frac{d\sigma}{d\cos\theta} - \int_{-1}^0 d\cos\theta\,\frac{d\sigma}{d\cos\theta}}{\int_0^1 d\cos\theta\,\frac{d\sigma}{d\cos\theta} + \int_{-1}^0 d\cos\theta\,\frac{d\sigma}{d\cos\theta}} = \frac{3g_A^{\ell}g_V^{\ell}g_V^{q}g_A^{q}}{[(g_V^{\ell})^2 + (g_A^{\ell})^2][(g_V^{q})^2 + (g_A^{q})^2]}$$

Capture leading loop effects with the replacements $g_V^f \to \sqrt{\rho_{eq}}(T_3^f - 2Q_f\kappa_f\sin^2\theta_W)$ and $g_A^f \to \sqrt{\rho_{eq}}T_3^f$

Define $\sin^2\theta_{\rm eff}^f = \kappa_f \sin^2\theta_W$

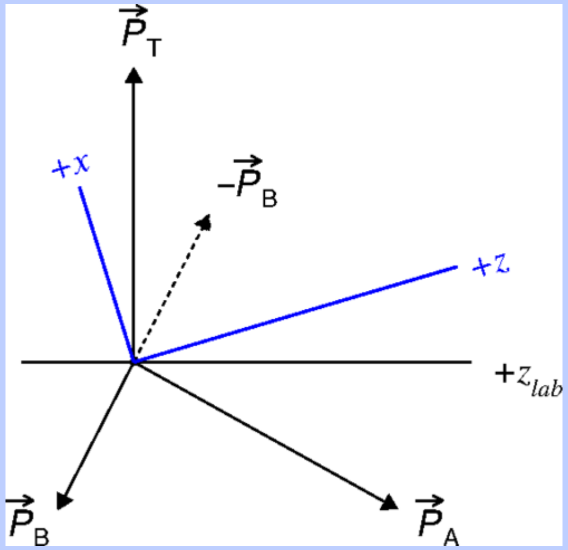
"Enhanced Born Approximation"

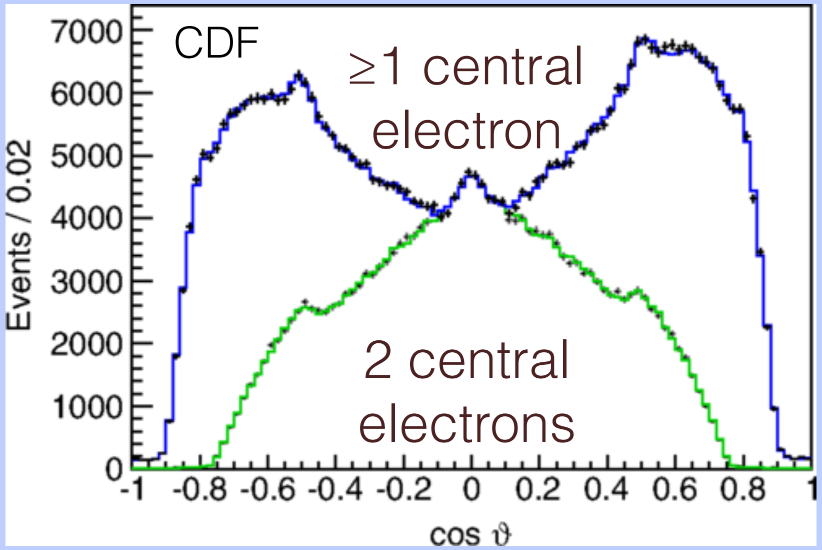
Forward-backward asymmetry @ the Tevatron

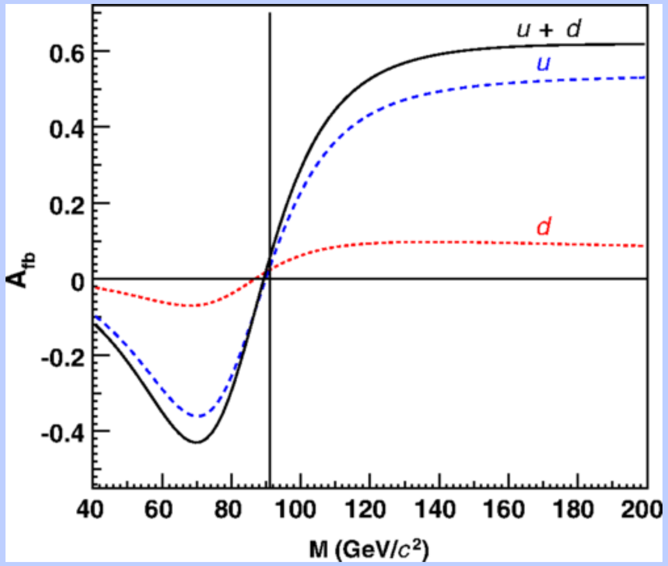
Leptons have more sensitivity to κ variations: fix κ_q to the SM value and measure $\sin^2\theta_{eff}^{lept}$

Measurement strategy:

Measure number of selected negative leptons in the forward and backward regions as a function of mass
Correct for detector acceptances and resolutions







Experimental and theoretical requirements:

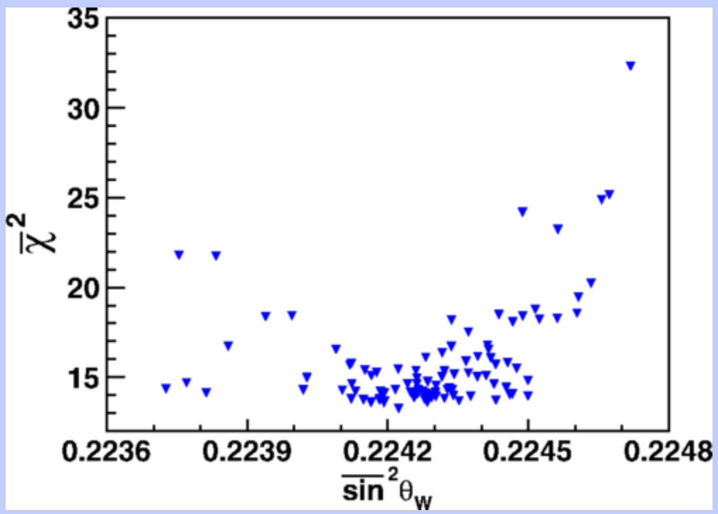
Accurate simulation of detector response and acceptance
Accurate model of the parton distribution functions (affect detector acceptance & quark couplings)

D0 & CDF have performed measurements in e and μ channels with complete data sets
Final combination submitted for publication

Forward-backward asymmetry @ the Tevatron

CDF use an event weighting to effectively measure asymmetry as a function of cosθ
Reduces reliance on simulated acceptance

PRD 93, 112016 (2016)



Also constrain NNPDF sets in situ

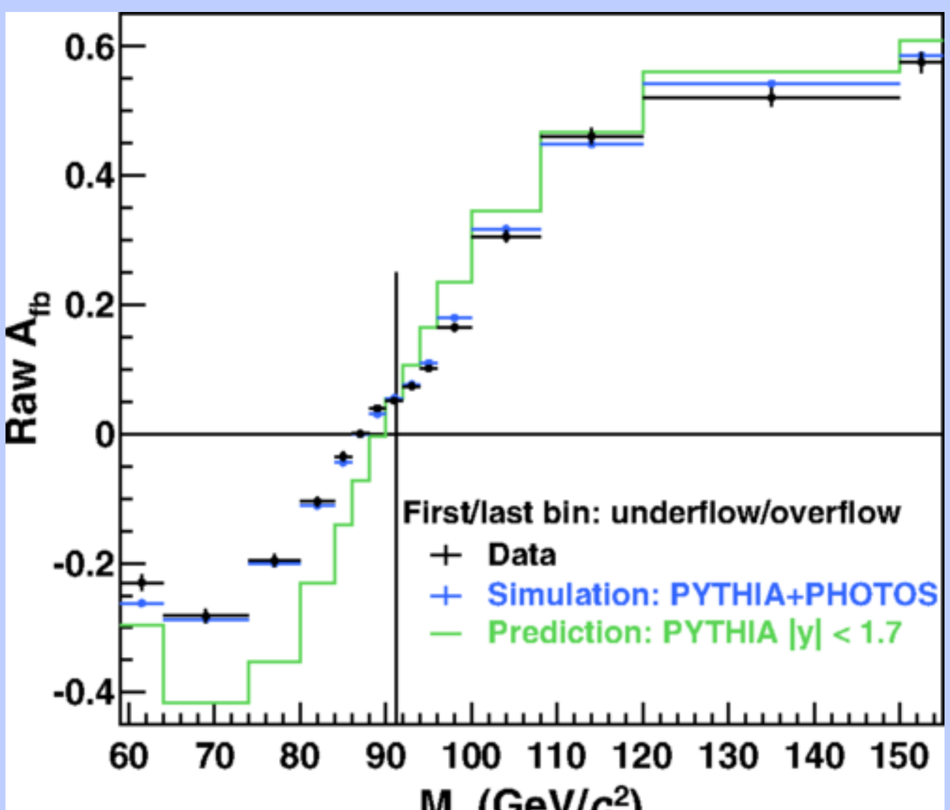
Source	$\sin^2\theta_{\text{eff}}^{\text{lept}}$
Energy scale	± 0.00003
Backgrounds	± 0.00002
NNPDF-3.0 PDF	± 0.00019
QCD scale	± 0.00002
Form factor	–

$$A'_{\text{fb}} = \frac{N^+ - N^-}{N^+ + N^-} = \frac{8}{3} A_{\text{fb}} \left(\frac{|\cos\vartheta|}{1 + \cos^2\vartheta + \cdots} \right)$$

Weighting factor for $A_{\text{fb}}(\cos\theta)$

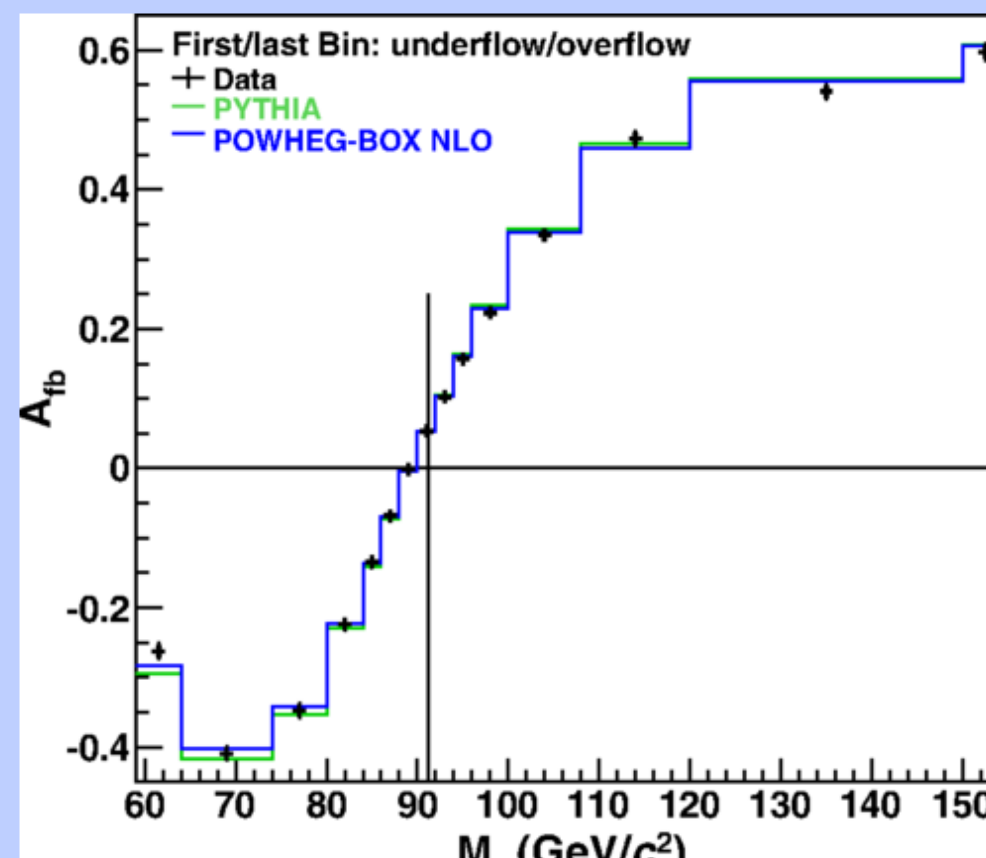
e: $\sin^2\theta_{\text{eff}}^{\text{lept}} = 0.23248 \pm 0.00049 \pm 0.00019$

e + μ: $\sin^2\theta_{\text{eff}}^{\text{lept}} = 0.23221 \pm 0.00043 \pm 0.00018$



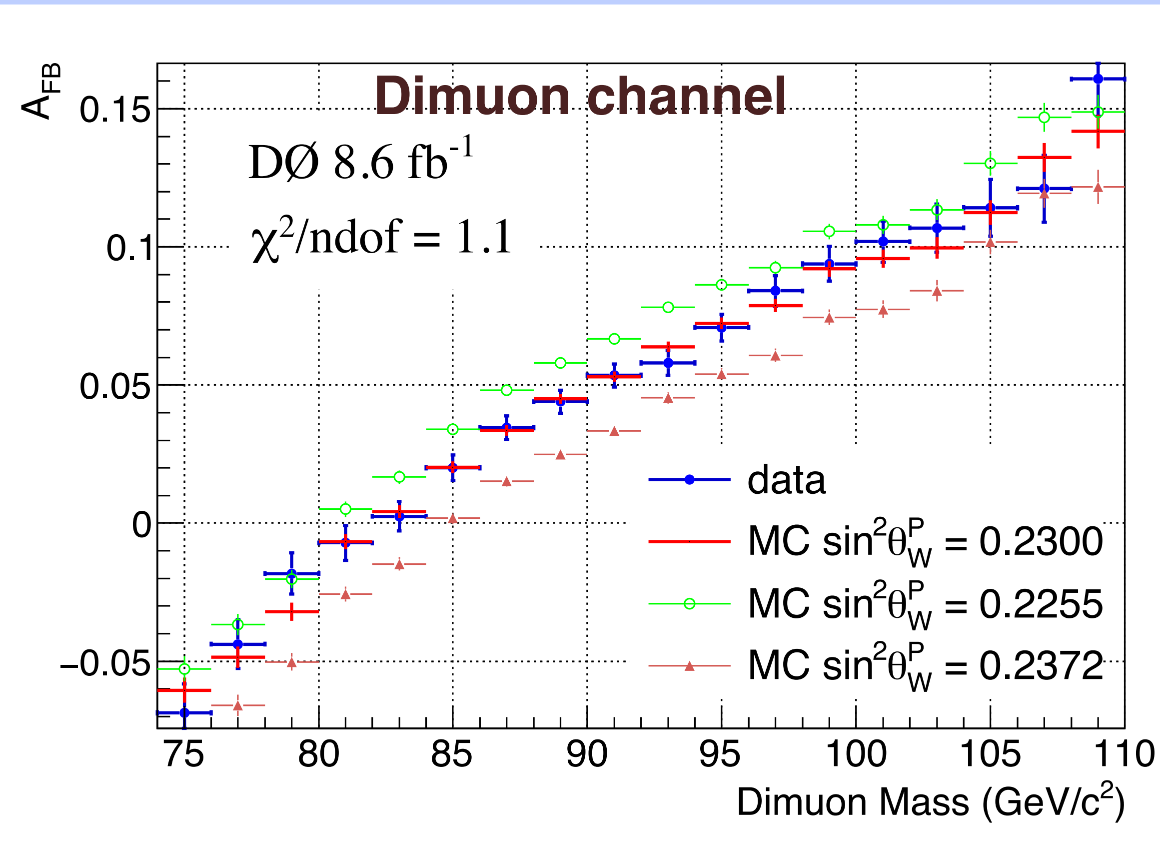
Fully unfold asymmetry

Allows for reinterpretation in any context



Forward-backward asymmetry @ the Tevatron

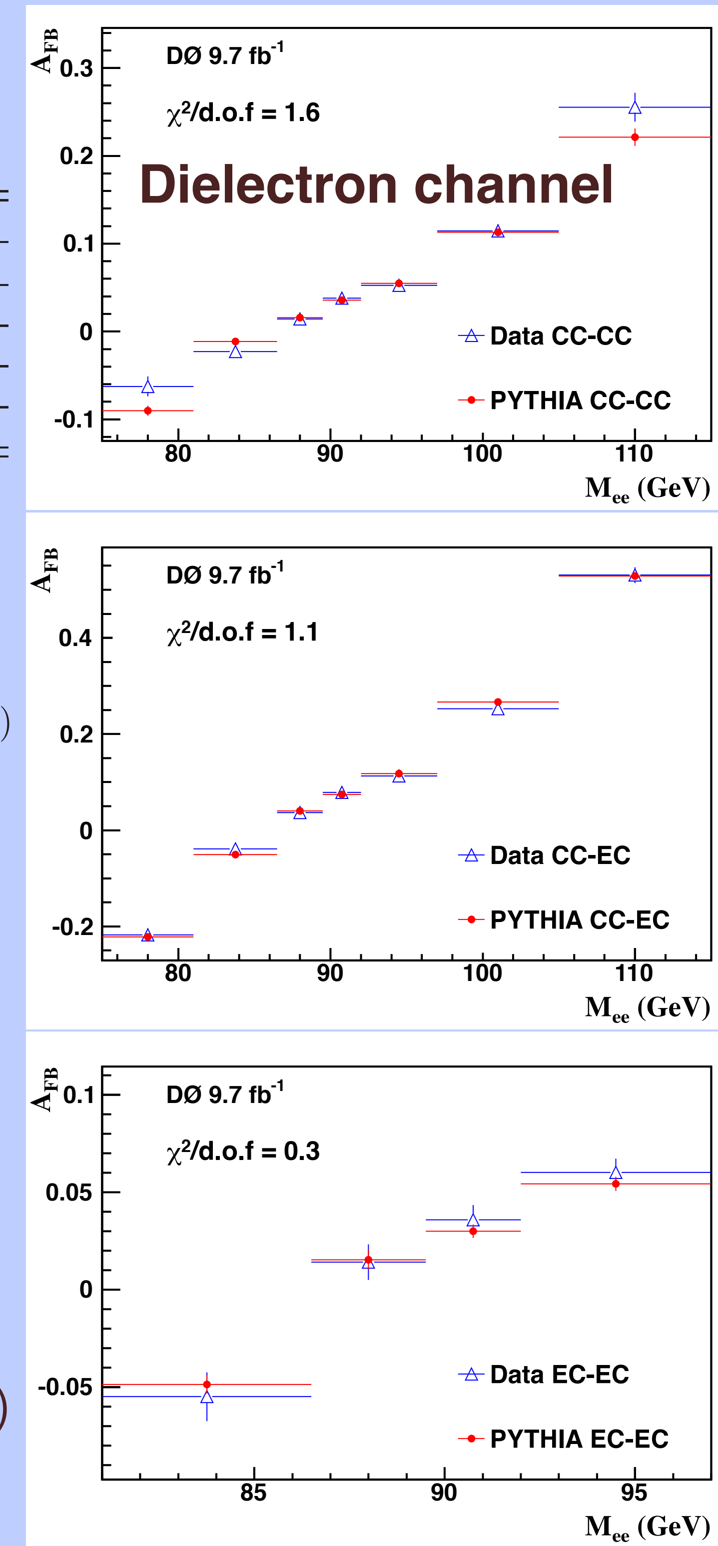
D0 have recently completed a measurement in the muon channel using the full data set



arXiv:1710.03951

	e^+e^- channel	$\mu^+\mu^-$ channel	Combined
$\sin^2\theta^{\ell}_{\text{eff}}$	0.23137	0.23016	0.23095
Statistical	0.00043	0.00059	0.00035
Systematic	0.00009	0.00006	0.00007
PDF	0.00017	0.00024	0.00019
Total	0.00047	0.00064	0.00040

$$\sin^2\theta^{\ell}_{\text{eff}}[\text{comb.}] = 0.23095 \pm 0.00035\,(\text{stat.}) \pm 0.00007\,(\text{syst.}) \pm 0.00019\,(\text{PDF})$$



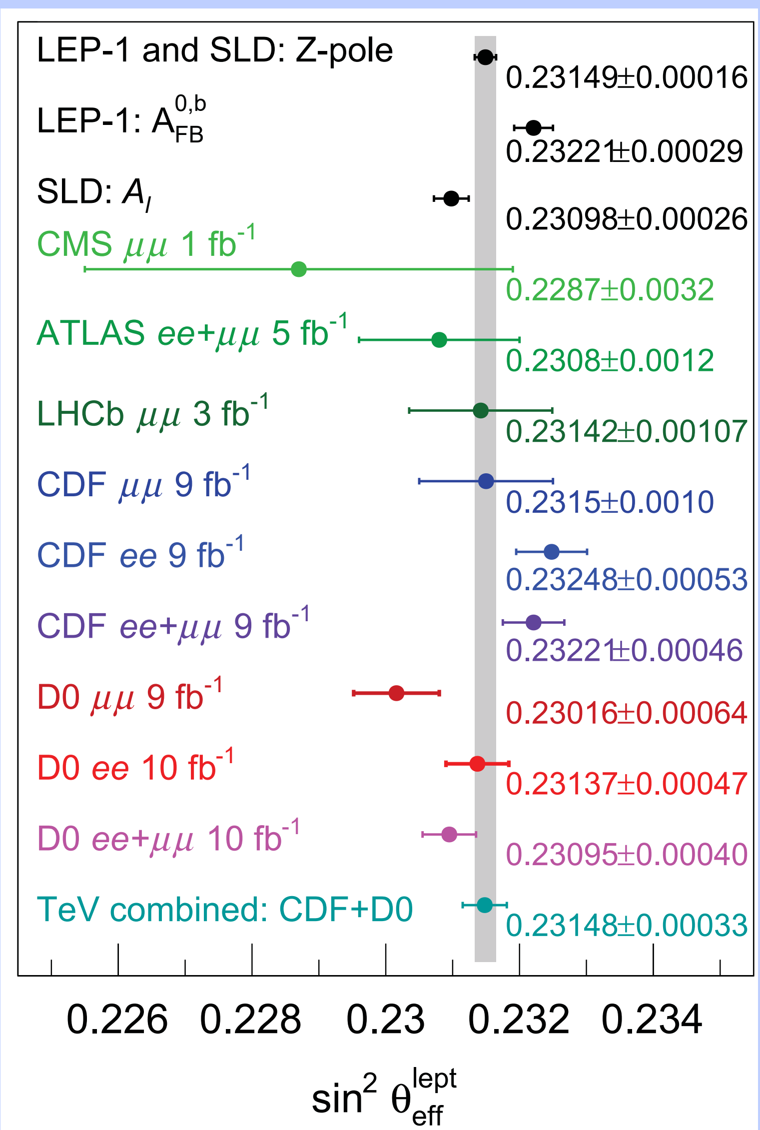
Combine with previous measurement in electron channel to give a precision of two parts per thousand

PRL 115, 041801 (2015)

Forward-backward asymmetry @ the Tevatron

Combined results use common PDFs (NNPDF 3.0) and EW corrections (from ZFITTER)

Source	CDF inputs	D0 inputs	Tevatron combination
		Uncertainties on $\sin^2\theta^{\rm lept}_{\rm eff}$	
Statistics	$\pm\,0.00043$	$\pm\,0.00035$	$\pm\,0.00027$
Uncorrelated syst.	$\pm\,0.00007$	$\pm\,0.00007$	$\pm\,0.00005$
PDF	$\pm\,0.00016$	$\pm\,0.00019$	$\pm\,0.00018$

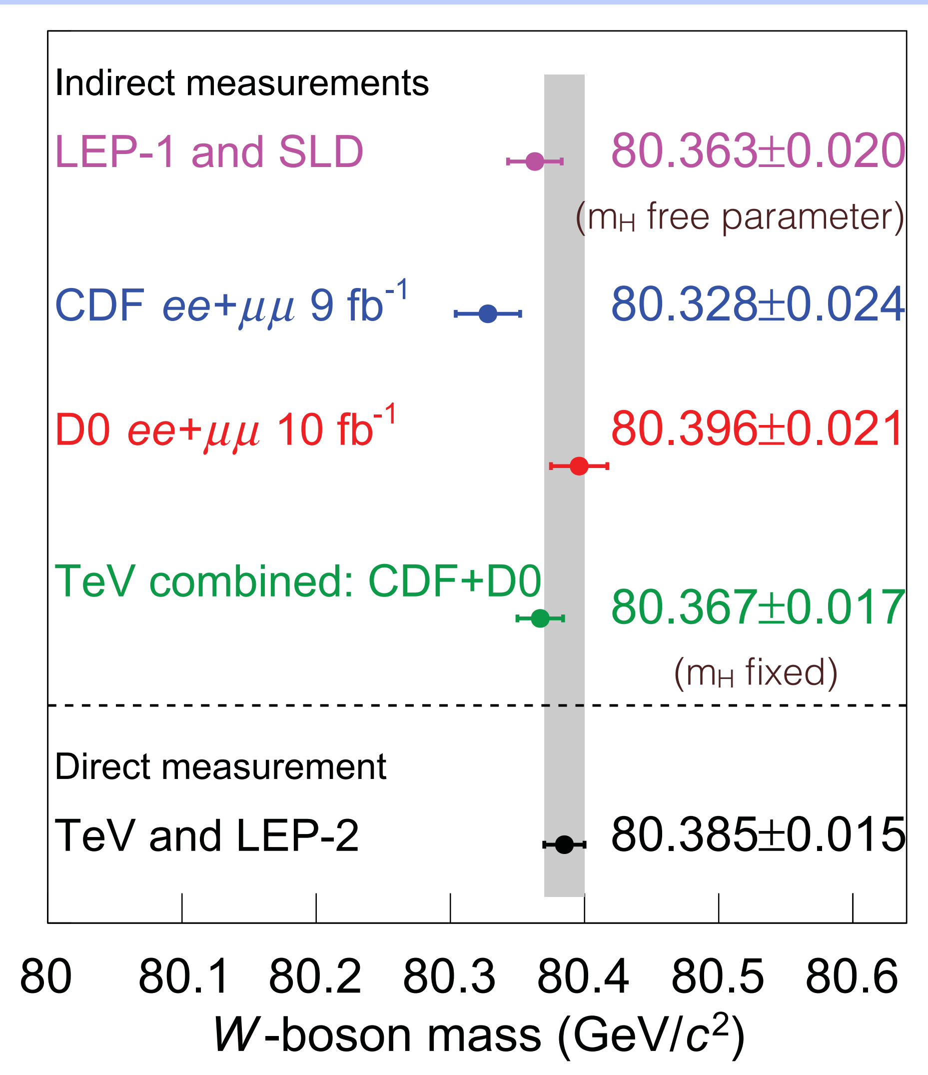


Tevatron uncertainty a factor of ~2 higher than all e+e- measurements combined

Combined measurements consistent

Applying SM higher-order corrections indirectly determines W boson mass

Comparison with the direct measurement provides a test of the SM prediction

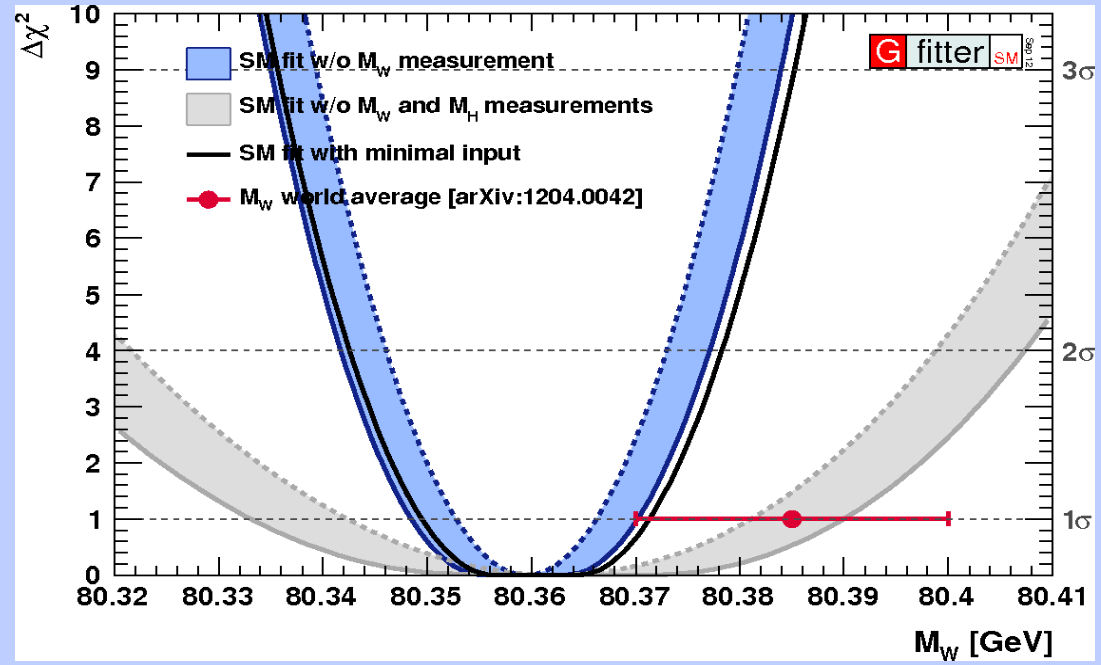


$\sin^2\theta_W = 1 - M_W^2/M_Z^2$

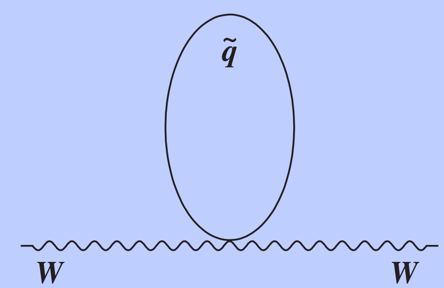
W boson mass

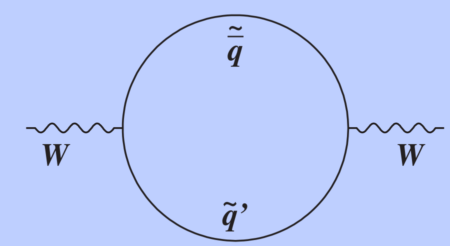
W boson mass predicted at tree level using Fermi & EM couplings, and Z boson mass

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



Loop corrections constrained the Higgs boson mass prior to its discovery

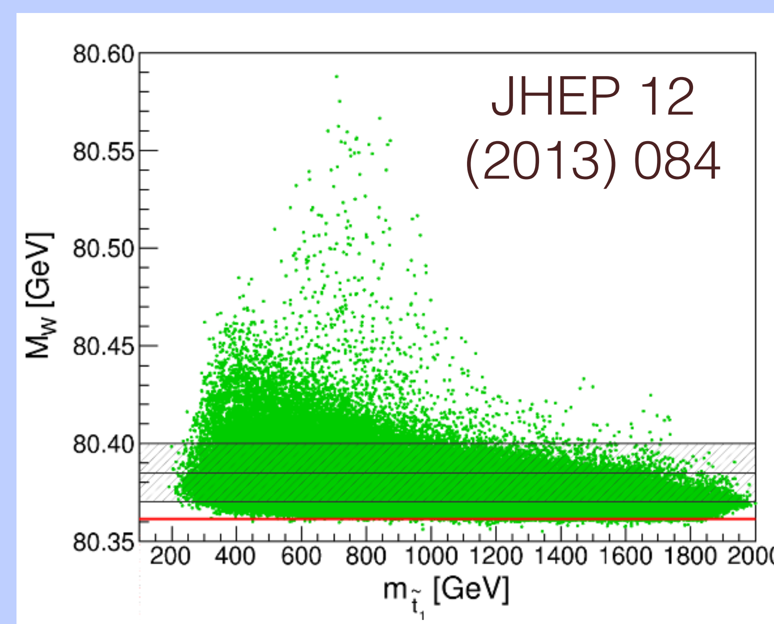




Given the measured m_H, constrain loop corrections from Supersymmetry or other new physics

$$\begin{aligned}\Delta\rho_0^{\rm SUSY}=\frac{3G_\mu}{8\sqrt{2}\pi^2}\Big[&-\sin^2\theta_{\tilde t}\cos^2\theta_{\tilde t}{\rm F}_0\left(m^2_{\tilde t_1},m^2_{\tilde t_2}\right)-\sin^2\theta_{\tilde b}\cos^2\theta_{\tilde b}{\rm F}_0\left(m^2_{\tilde b_1},m^2_{\tilde b_2}\right)\\&+\cos^2\theta_{\tilde t}\cos^2\theta_{\tilde b}{\rm F}_0\left(m^2_{\tilde t_1},m^2_{\tilde b_1}\right)+\cos^2\theta_{\tilde t}\sin^2\theta_{\tilde b}{\rm F}_0\left(m^2_{\tilde t_1},m^2_{\tilde b_2}\right)\\&+\sin^2\theta_{\tilde t}\cos^2\theta_{\tilde b}{\rm F}_0\left(m^2_{\tilde t_2},m^2_{\tilde b_1}\right)+\sin^2\theta_{\tilde t}\sin^2\theta_{\tilde b}{\rm F}_0\left(m^2_{\tilde t_2},m^2_{\tilde b_2}\right)\Big]\end{aligned}$$

$$\rho\;=\;\frac{M_W^2}{M_Z^2\cos^2\theta_W}=\frac{1}{1-\Delta\rho}\qquad {\rm F}_0\left(x,y\right)=x+y-\frac{2xy}{x-y}\ln\left(\frac{x}{y}\right).$$



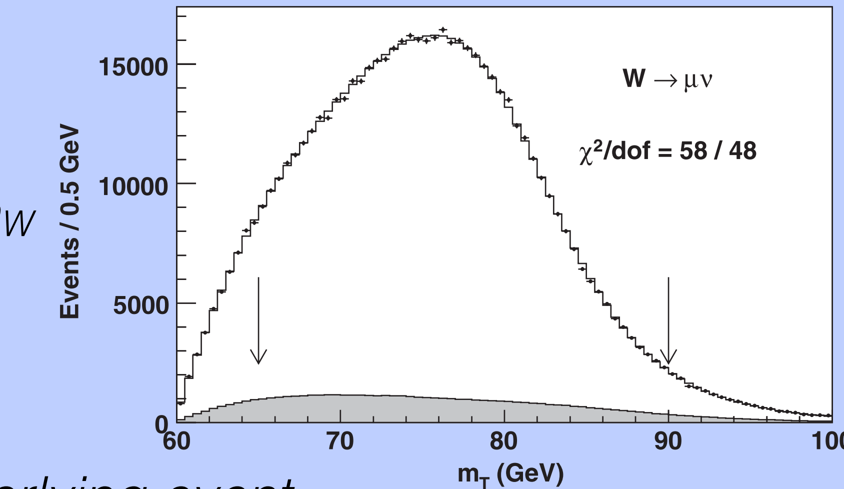
arXiv:hep-ph/0412214

W boson mass @ the Tevatron

Measurement strategy:

Measure momenta of charged lepton and neutrino in transverse plane

Construct the transverse mass in this plane and fit three distributions for m_W



PRD 89, 072003 (2014)

Experimental and theoretical requirements:

Precise calibration of lepton momentum

Accurate calibration of detector response to initial-state radiation and underlying event

Accurate model of longitudinal and transverse momentum of the W boson

Tevatron instantaneous luminosities produce <10 overlapping collisions on average

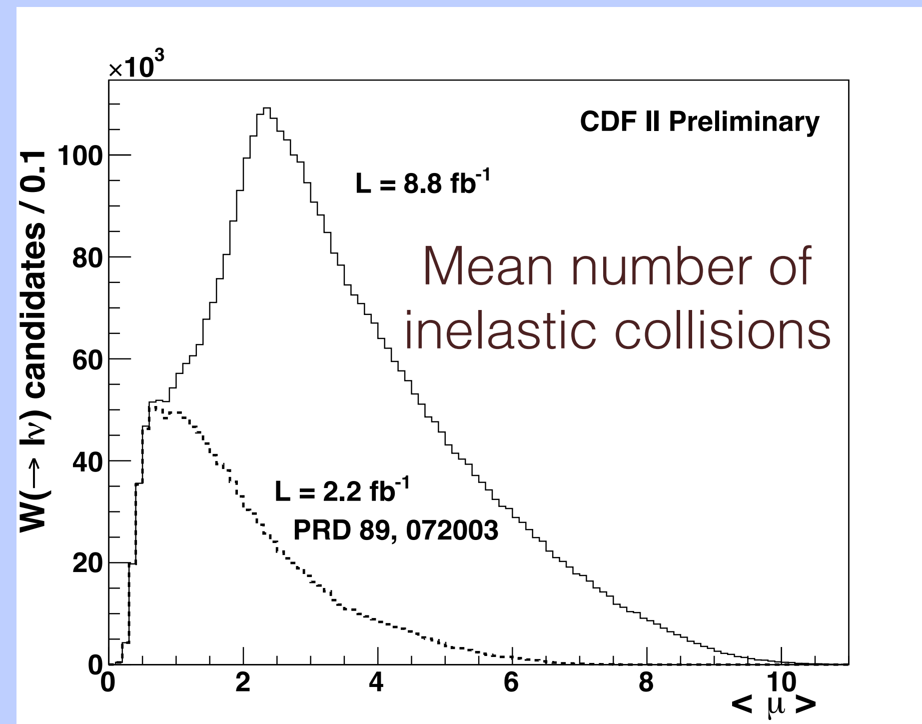
A large majority of W bosons are produced by valence quarks

CDF, 2.2 fb^{-1}

Source	Uncertainty (MeV)
Lepton energy scale and resolution	7
Recoil energy scale and resolution	6
Lepton removal from recoil	2
Backgrounds	3
Experimental subtotal	10
Parton distribution functions	10
QED radiation	4
$p_T(W)$ model	5
Production subtotal	12
Total systematic uncertainty	15
W-boson event yield	12
Total uncertainty	19

D0, 4.3 fb^{-1}

Source	Uncertainty (MeV)
Electron energy calibration	16
Electron resolution model	2
Electron shower modeling	4
Electron energy loss model	4
Recoil energy scale and resolution	5
Electron efficiencies	2
Backgrounds	2
Experimental subtotal	18
Parton distribution functions	11
QED radiation	7
$p_T(W)$ model	2
Production subtotal	13
Total systematic uncertainty	22
W-boson event yield	13
Total uncertainty	26



PRD 88, 052018 (2013)

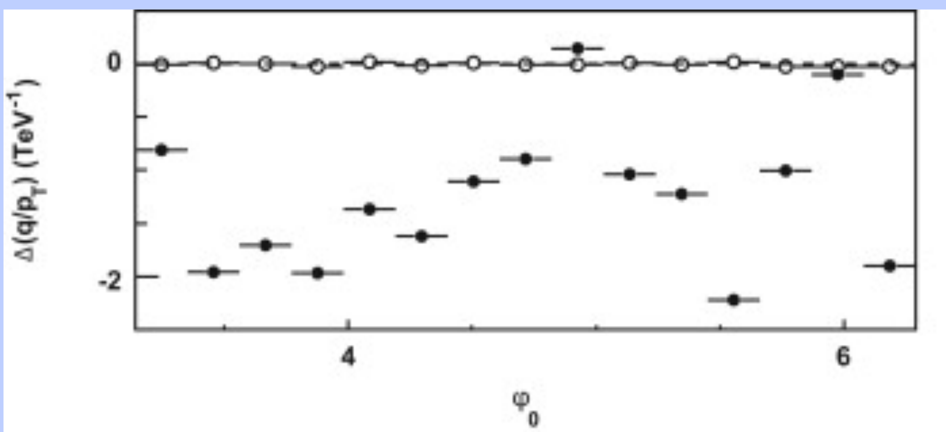
W boson mass @ the Tevatron

CDF & D0 analysing complete data sets

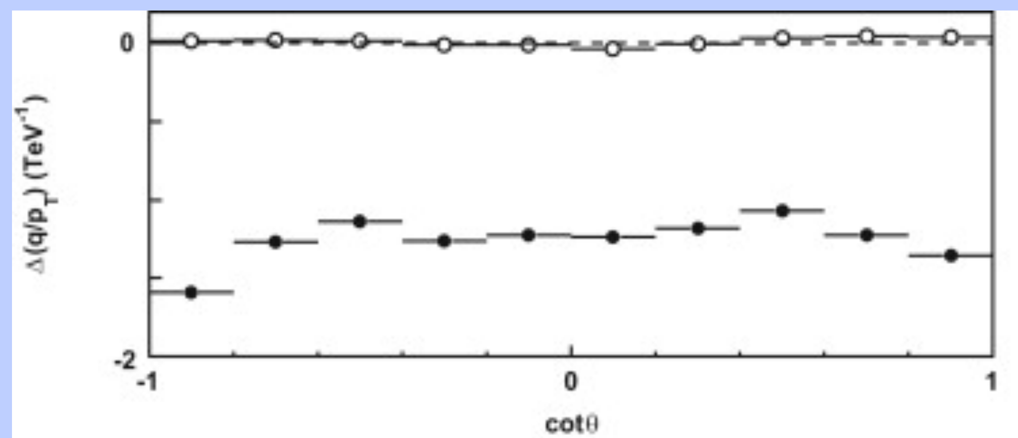
CDF tracker alignment for m_W updated

NIM A 762, 85 (2014)

Azimuthal dependencies removed



Polar dependencies removed



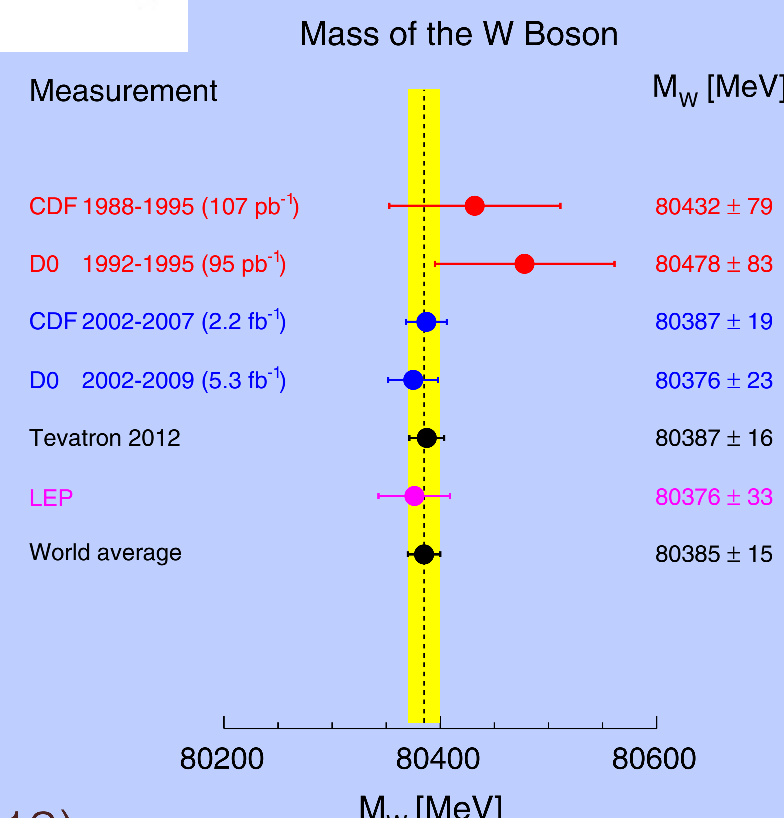
Locations of wires at ends of drift chamber relatively aligned with cosmic tracks to a statistical precision of ~1 micron

4.2 million $W \to l\nu$ candidates in complete CDF data set

Potential to reduce Tevatron uncertainty to ~10 MeV (~0.01%)

Will require reduction of PDF uncertainty to ~5 MeV

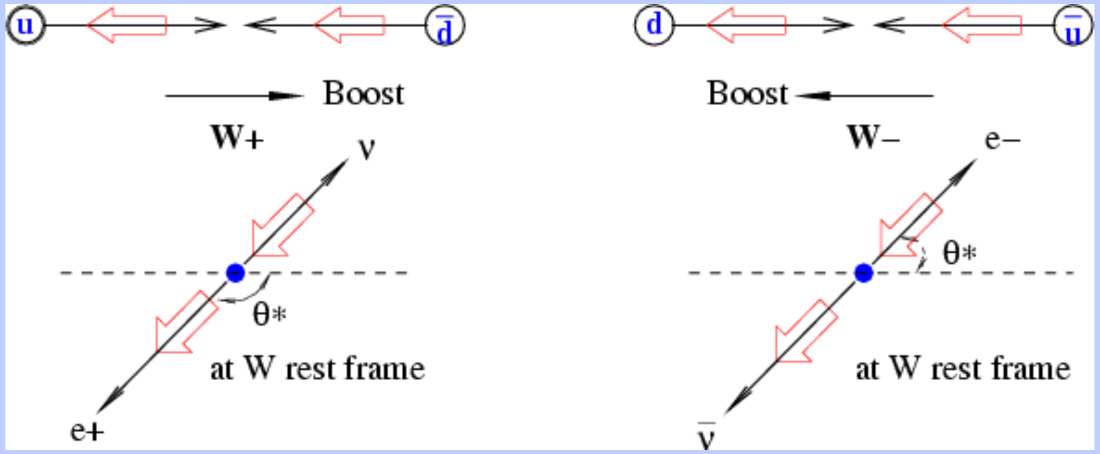
Important to include Tevatron charge asymmetry measurements in PDFs

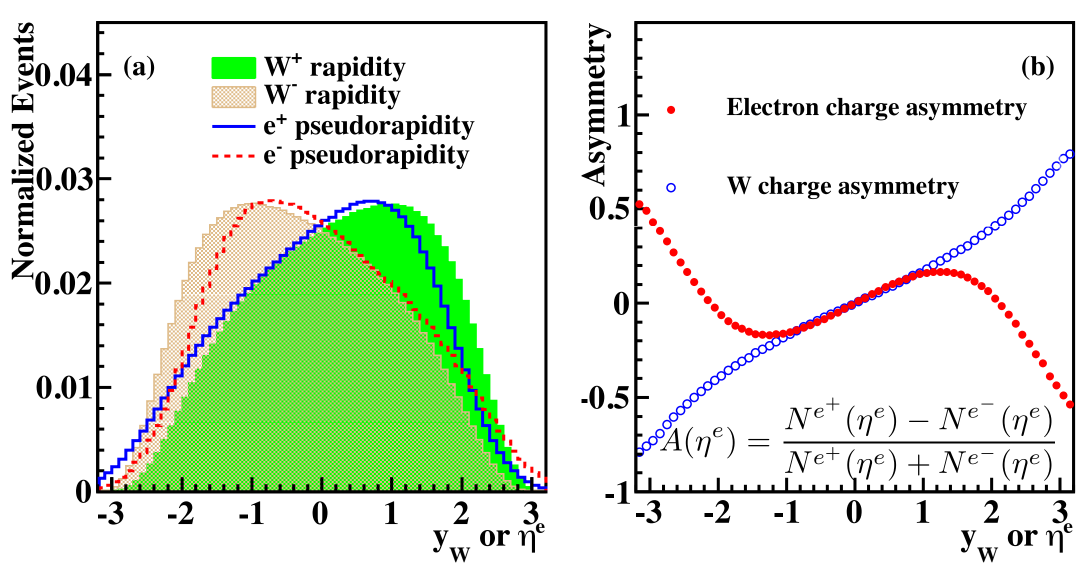


PRD 88, 052018 (2013)

W boson charge asymmetry @ the Tevatron

PRL 102, 181801 (2009)



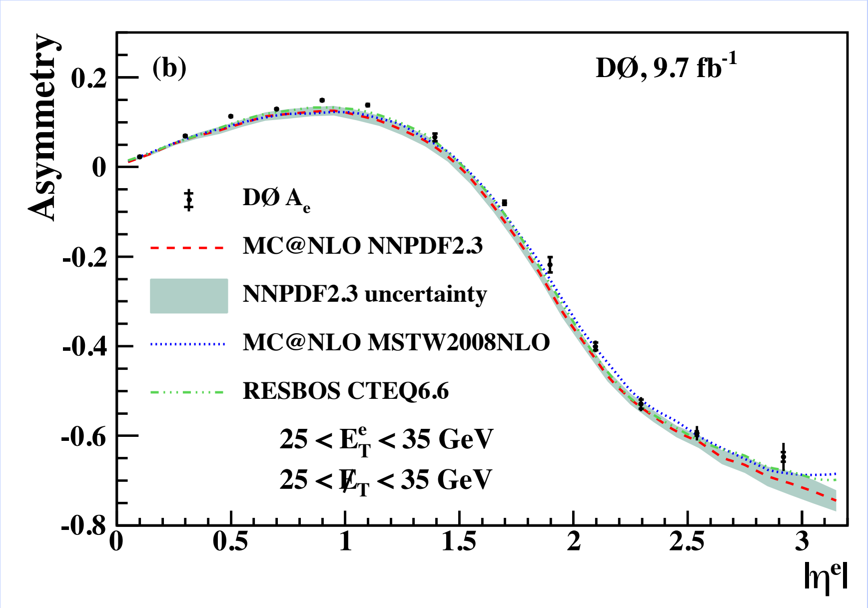


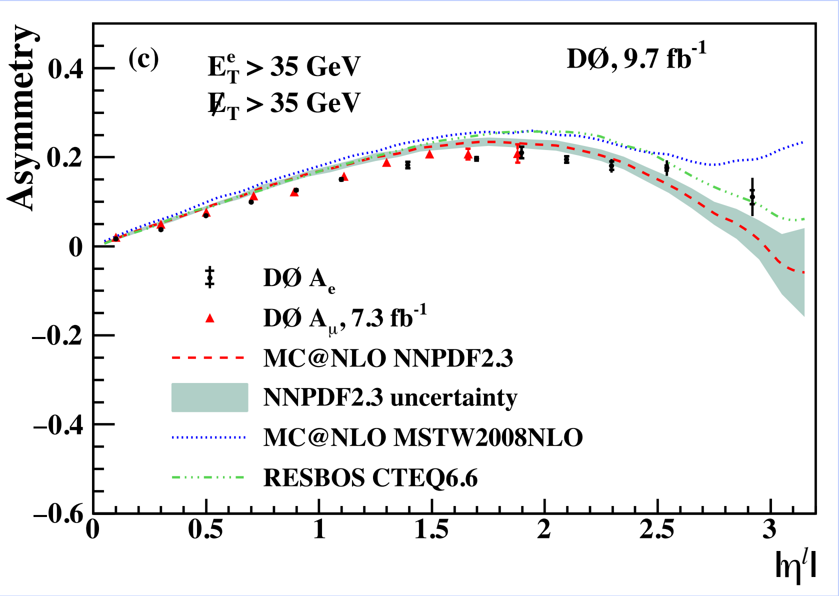
Asymmetry in valence u and d quark momentum distributions leads to W^+/W^- asymmetry as a function of boson rapidity

Left-handed decay counteracts asymmetry for charged leptons

Comparisons of measurements in ranges of lepton p_T to predictions constrains PDFs

D0 asymmetries with complete data set included in NNPDF 3.1





PRD 91, 032007 (2015)

CDF electron asymmetry with complete data set ongoing

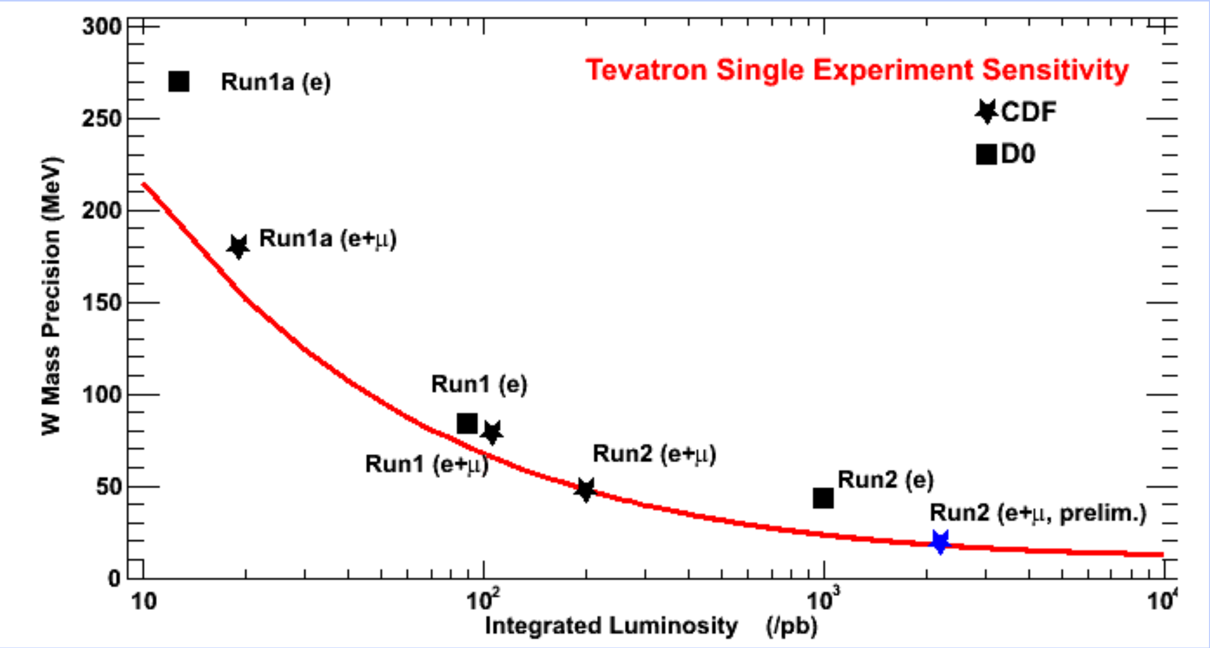
C. Hays, Oxford University

Summary

Tevatron completing legacy electroweak measurements

Z boson coupling final measurements combined

W boson mass final measurements ongoing



Summary

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