The Tevatron's Legacy: Some Selected Measurements

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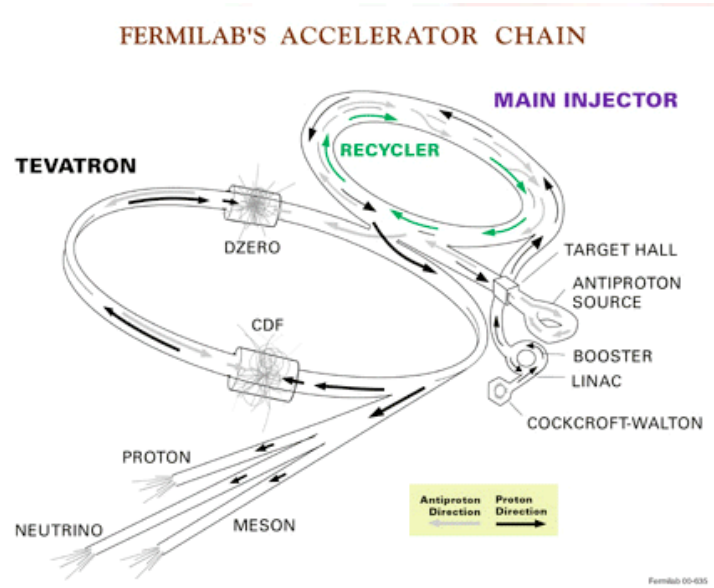
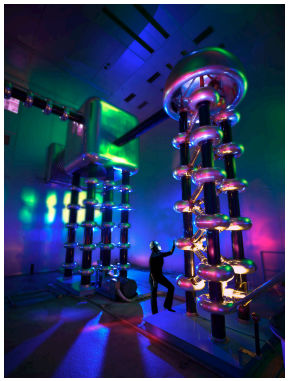
Fermilab

- The Tevatron and its Experiments
- Weak Vector Bosons W and Z
  - Cross Sections
  - Asymmetries
  - W mass
- Top Quark Mass
- B_s Mixing

The Tevatron and Associated Accelerators





Cockroft-Walton

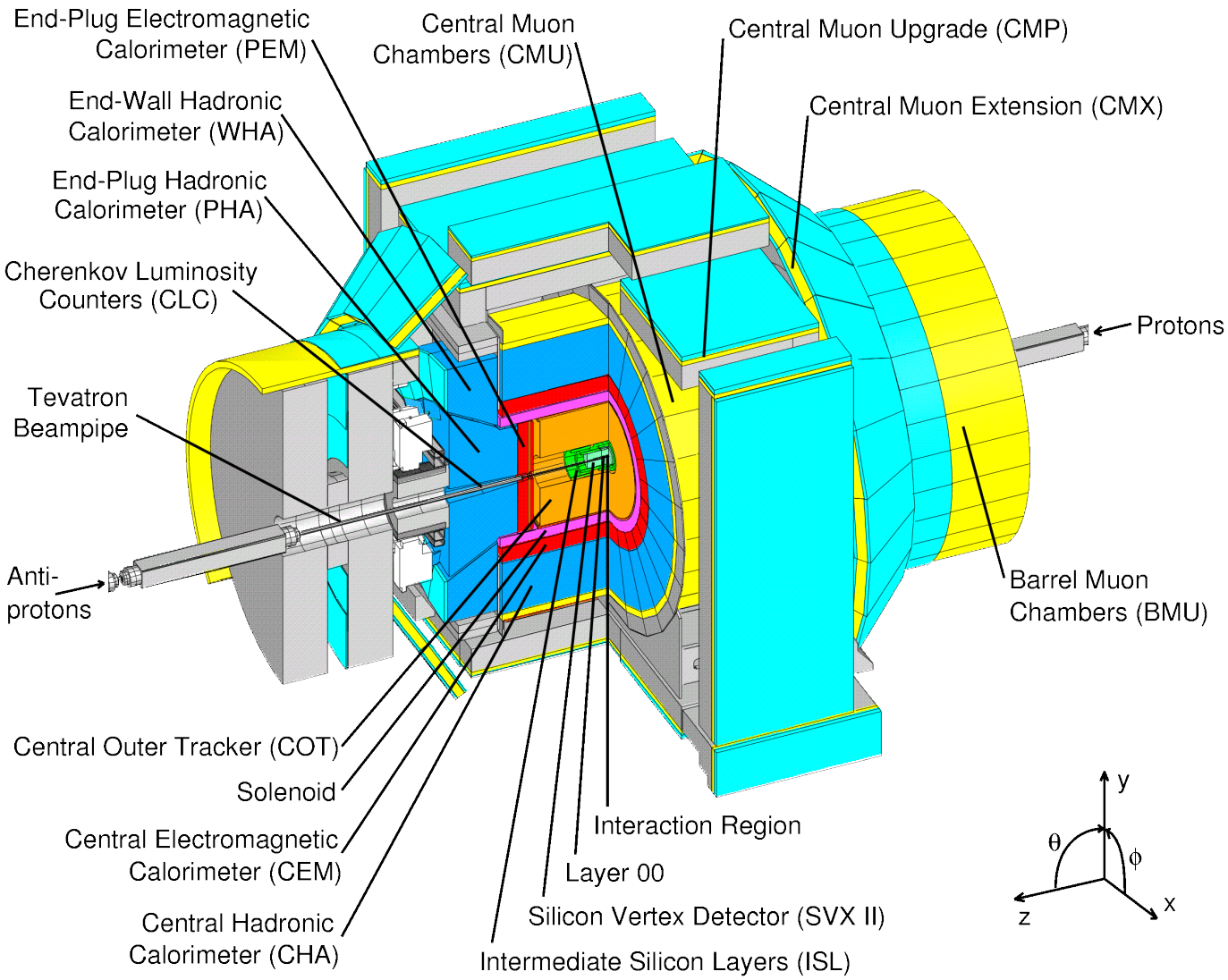
Linac

Booster

pbar debuncher and accumulator

ppbar collisions at 1.96 TeV
Luminosity up to 400E30 $cm^{-2}s^{-1}$
A very good week: ~80 pb^{-1}

First CDF $p\bar{p}$ event: 1985
End of operations: 2011



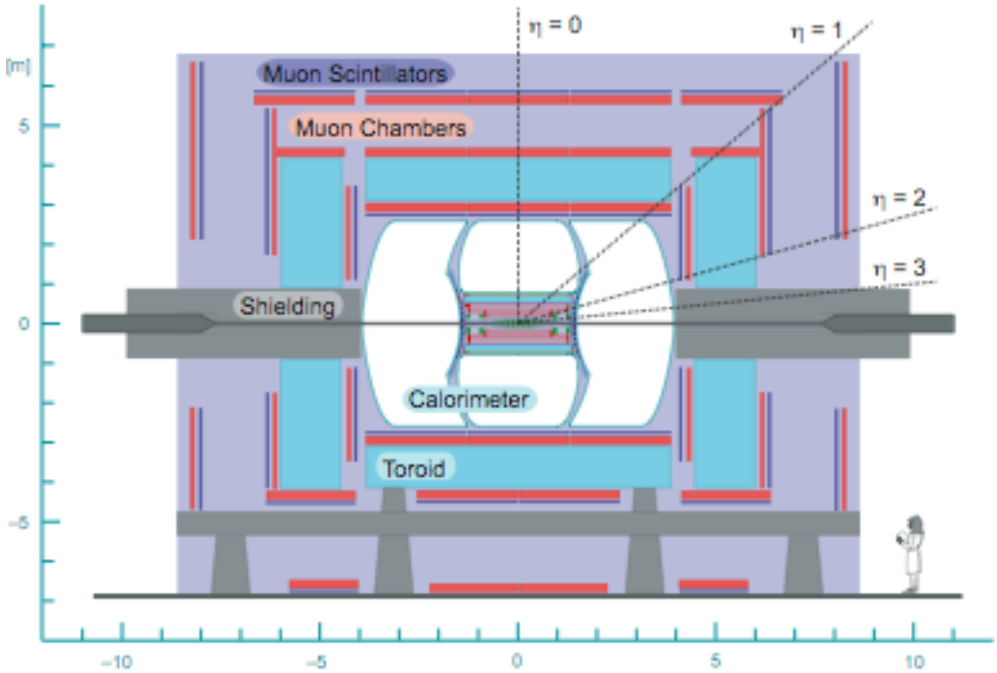
Lepton coverage:
$|\eta| < 1.5$ (muons)
$|\eta| < 2.0$ (electrons)

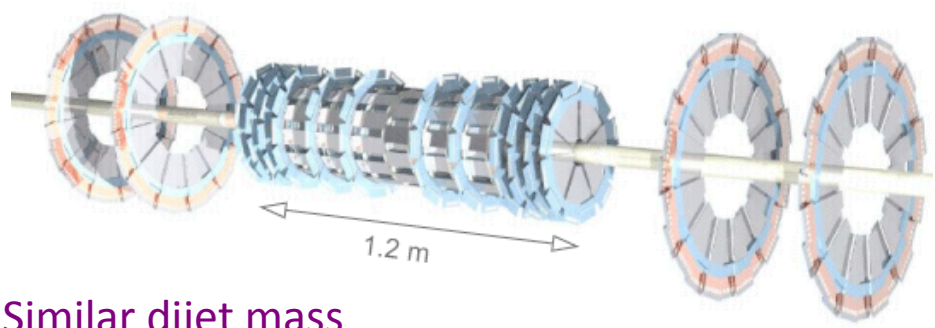
b-tagging with
$|\eta| < \sim 1.4$

Jets to
$|\eta| < 2.8$
Higgs analyses restrict to
$|\eta| < 2.0$

Dijet mass resolution: ~16%

The DØ Detector





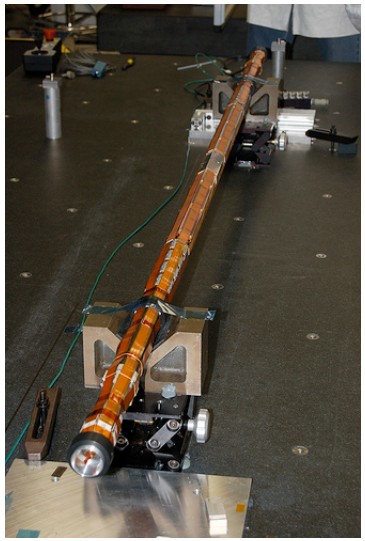
Lepton coverage:
|η| < 2 (muons)
|η| < 2.6 (electrons)

b-tagging with
|η| < ~2

Jets to
|η| < 3

Scintillating fiber tracker

Trigger similar to CDF's



Similar dijet mass resolution to CDF

Good Feature: Regular Switching of Solenoid Field – Cancels Some Systematic Uncertainties

New Innermost Silicon Layer added between Run IIa and Run IIb

CDF Run II Trigger System

Bunch Crossing Rate: ~1.7 MHz

Level 1 trigger ~15 KHz

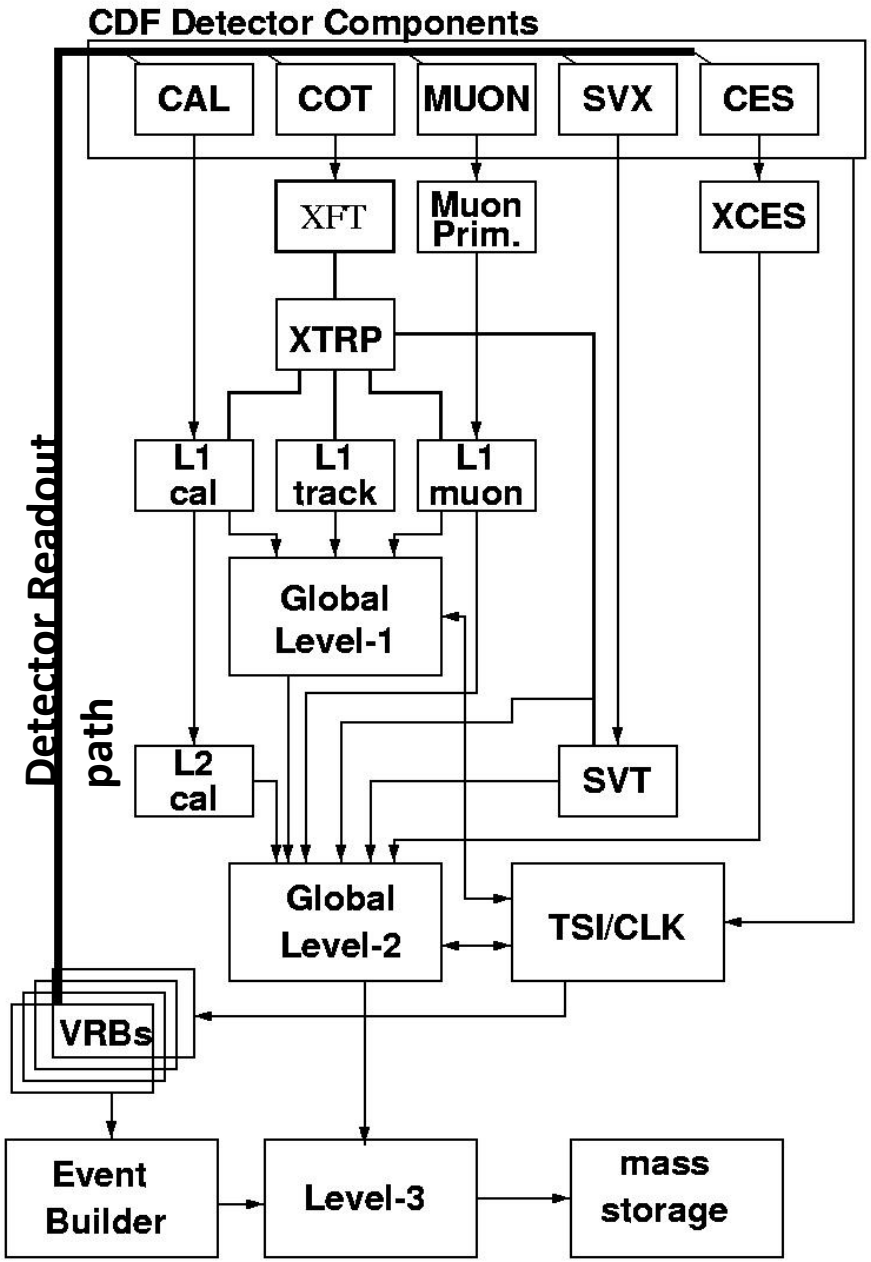
- tracking
- calorimeter: jets & electrons
- muons

Level 2 trigger ~800 Hz

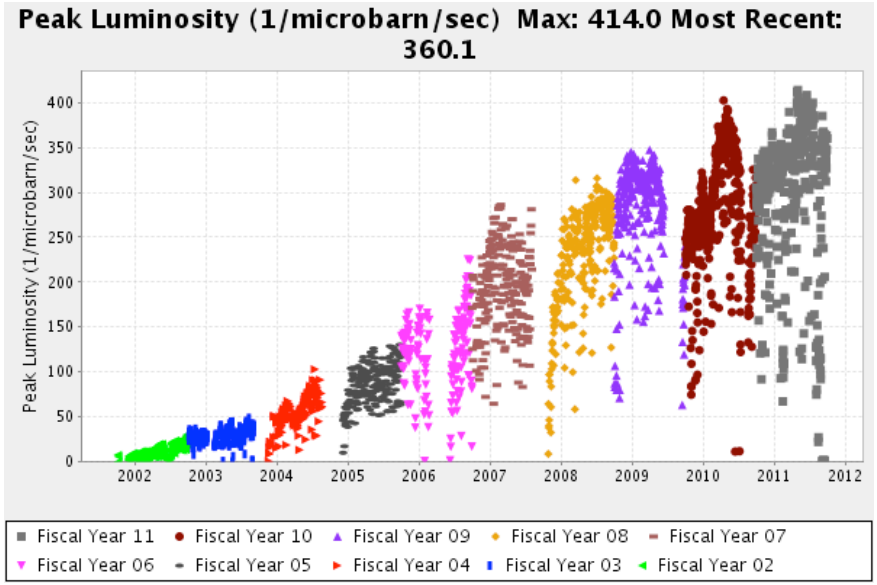
- L1 information (tracks, e, μ)
- calorimeter shower max
- silicon information
- algorithms run in L2 processor

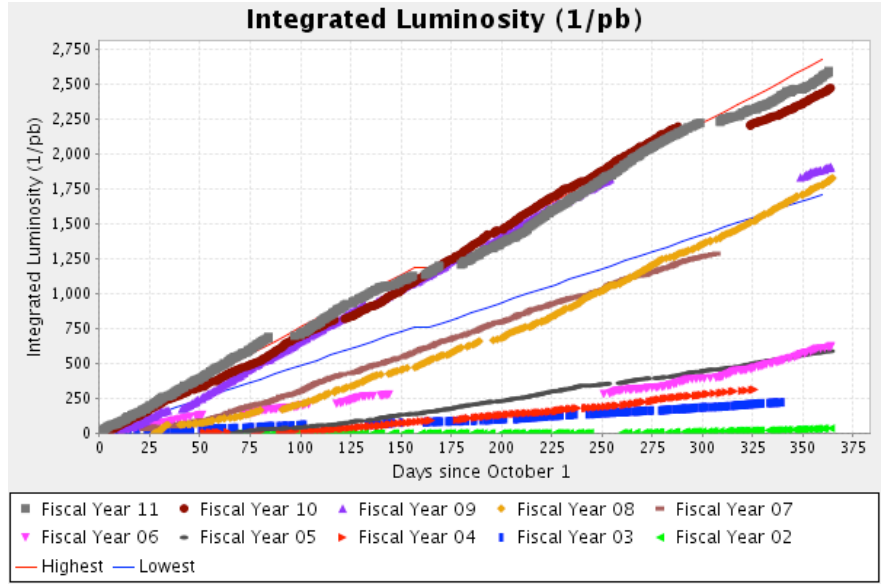
Level 3 trigger ~200 Hz to tape

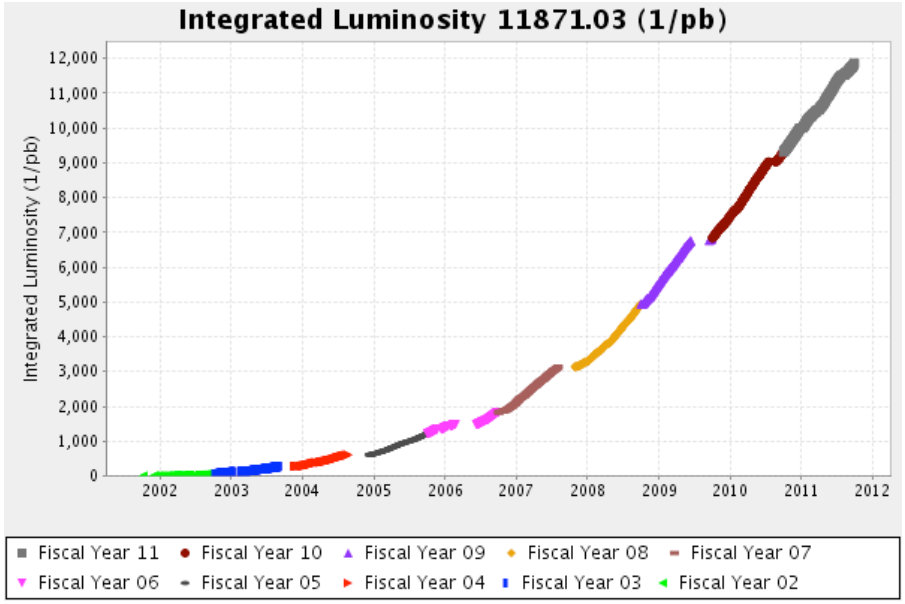
- full detector readout
- event building
- "offline" processing



The Tevatron, Like All Accelerators, Improved in Performance Over Time



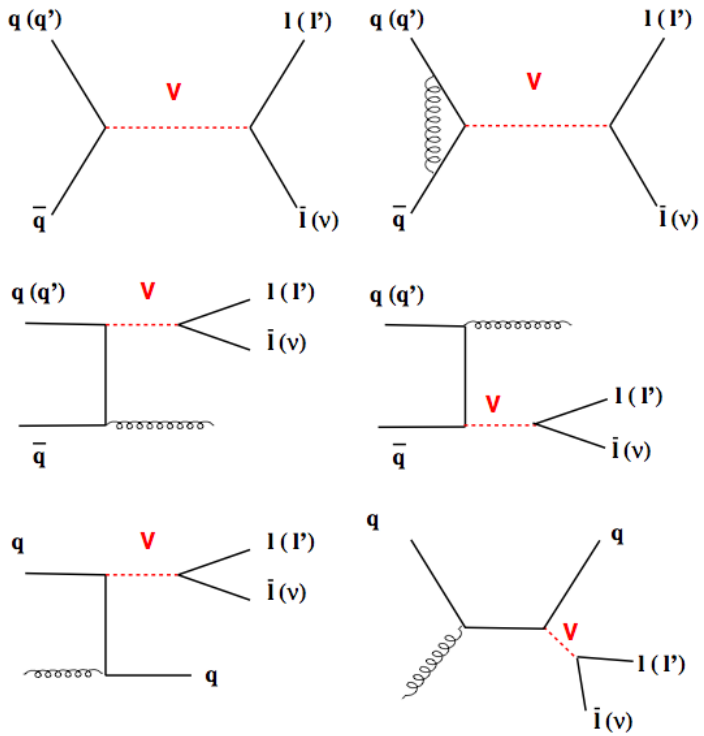


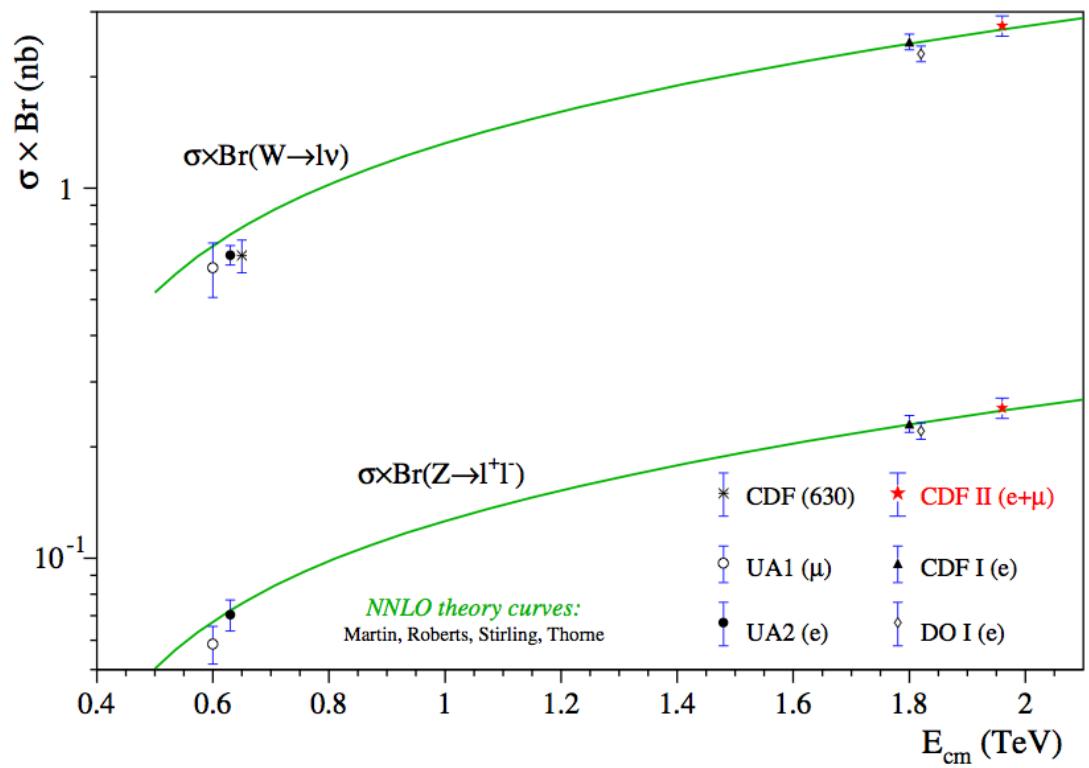


Total delivered luminosity:
~12 fb^{-1} each to CDF and D0.

Acquired and analyzed:
~10 fb^{-1} each.

CDF's W and Z Production Cross Section Measurements

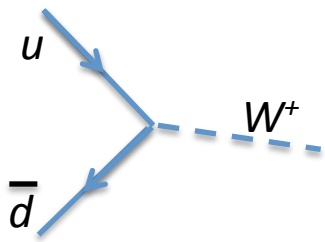




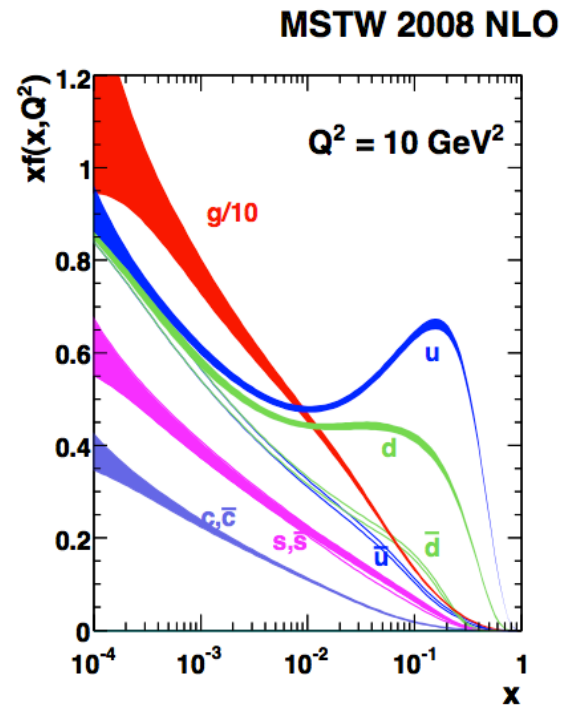
Many additional processes (these are only at NLO)

J. Phys. G Nucl. Part. Phys. **34**, 2457 (2007)

Measurement of the Forward-Backward Asymmetry of W Bosons with D0



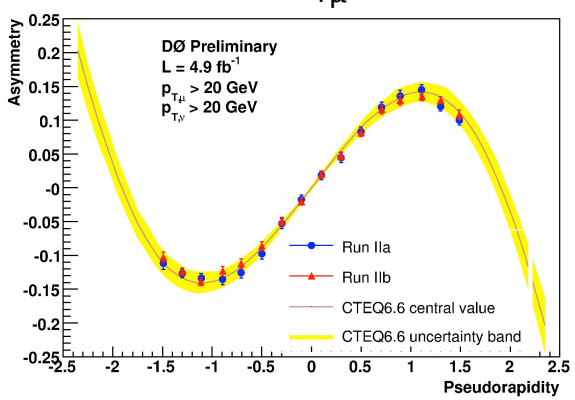
Forward-Backward Asymmetry comes largely from the difference between u and d PDF's.
The compton diagram gq→Wq also participates.



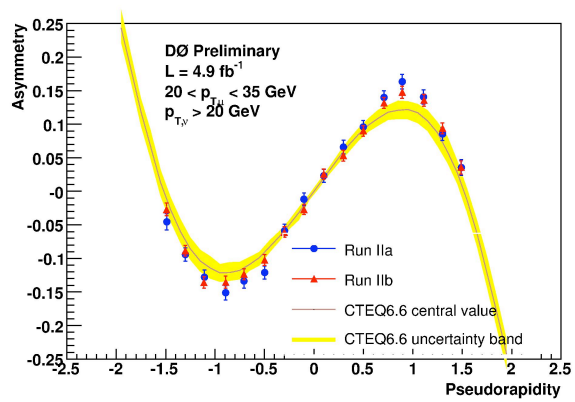
$$A(\eta) = \frac{1}{(1-2g)}\left[\frac{N^+(\eta) - N^-(\eta)}{N^+(\eta) + N^-(\eta)}\right]$$

Is the LEPTON asymmetry (directly observable. $p_{z,W}$ ambiguous due to neutrino solution.

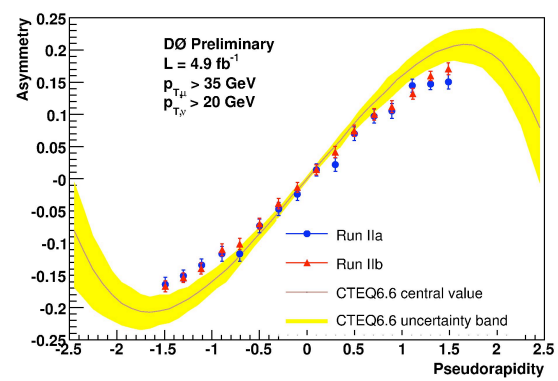
Inclusive $p_{T\mu}$>20 GeV



20 < $p_{T\mu}$ < 35 GeV



$p_{T\mu}$ > 35 GeV



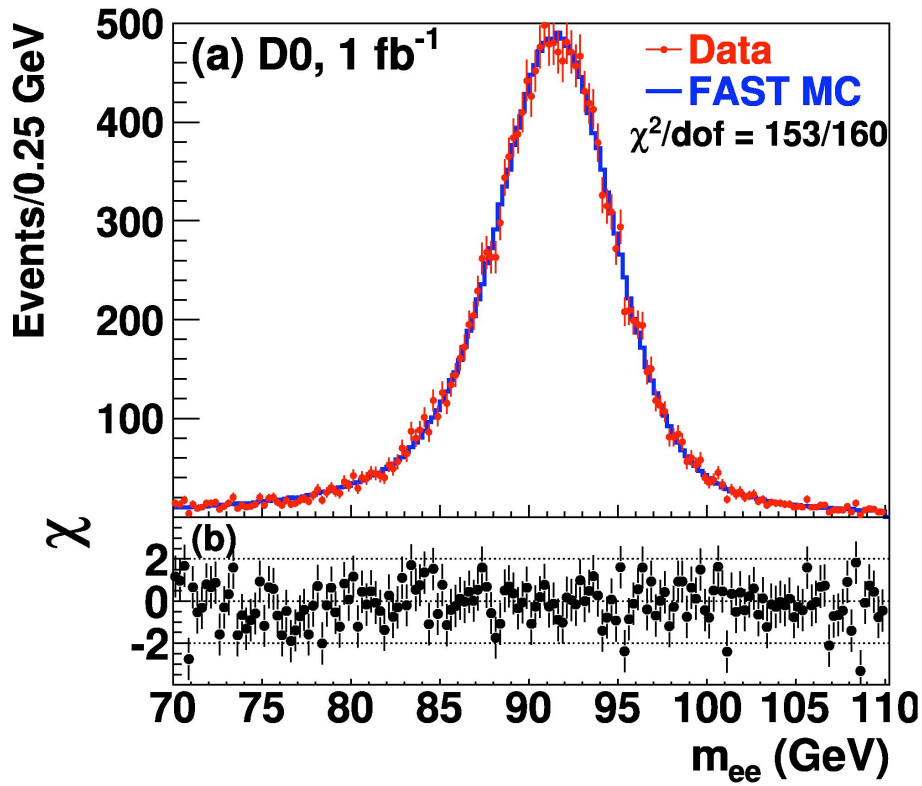
g accounts for the charge misidentification rate, determined with like-sign Z→μμ candidate events. Solenoid reversal results are consistent.

Towards a Measurement of the W boson mass: Calibration of Detector Response

- m_Z known very precisely from LEP
- Z→ee lepton rapidity and momentum spectrum similar to W→ev

- Z+hadronic recoil events used to calibrate hadronic response, and electron ID efficiency vs. P_T and proximity to the hadronic recoil

Material tuned in a fast simulation to make electron energies match in Z→ee in each calorimeter layer.

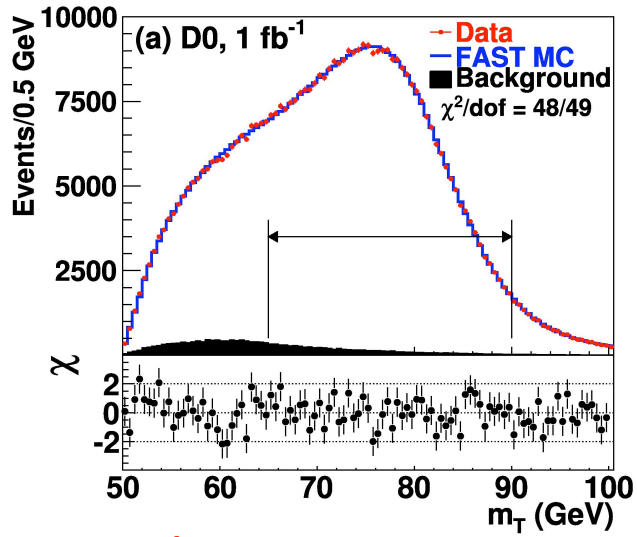


18,725 Z→ee candidates selected – negligible backgrounds

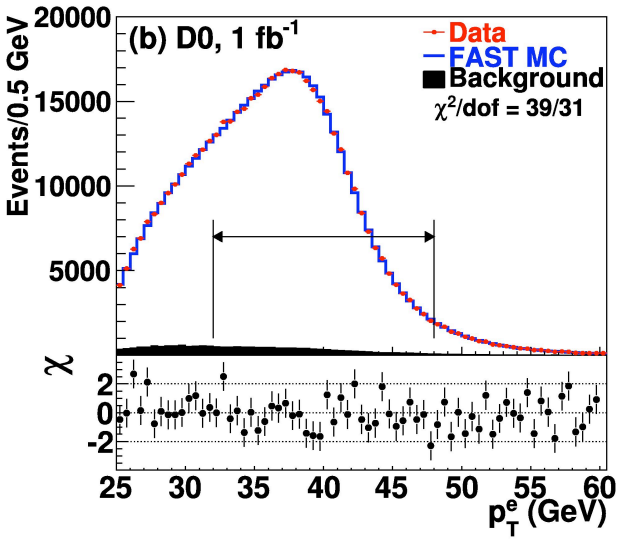
D0's Measurement of the W mass in W→eν Events

499830 candidate events

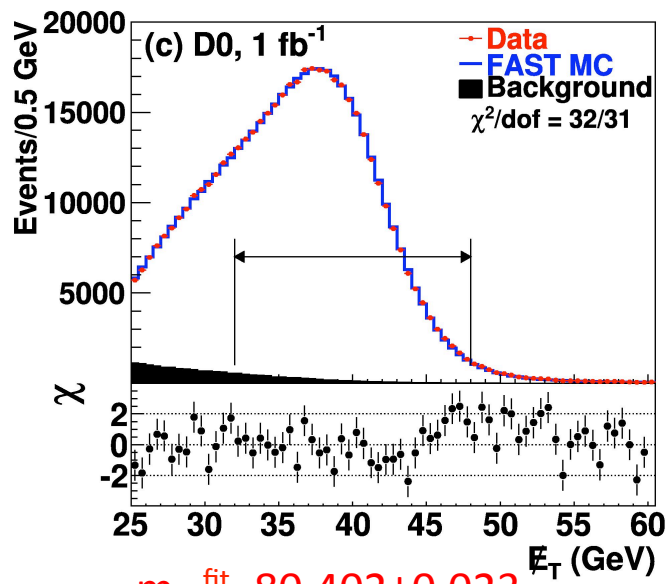
Background consists of
- Z→ee with a missing electron (inter-cryostat crack for example)
- Multijets
- W→τν→eνν



m_W^{fit}=80.401±0.023



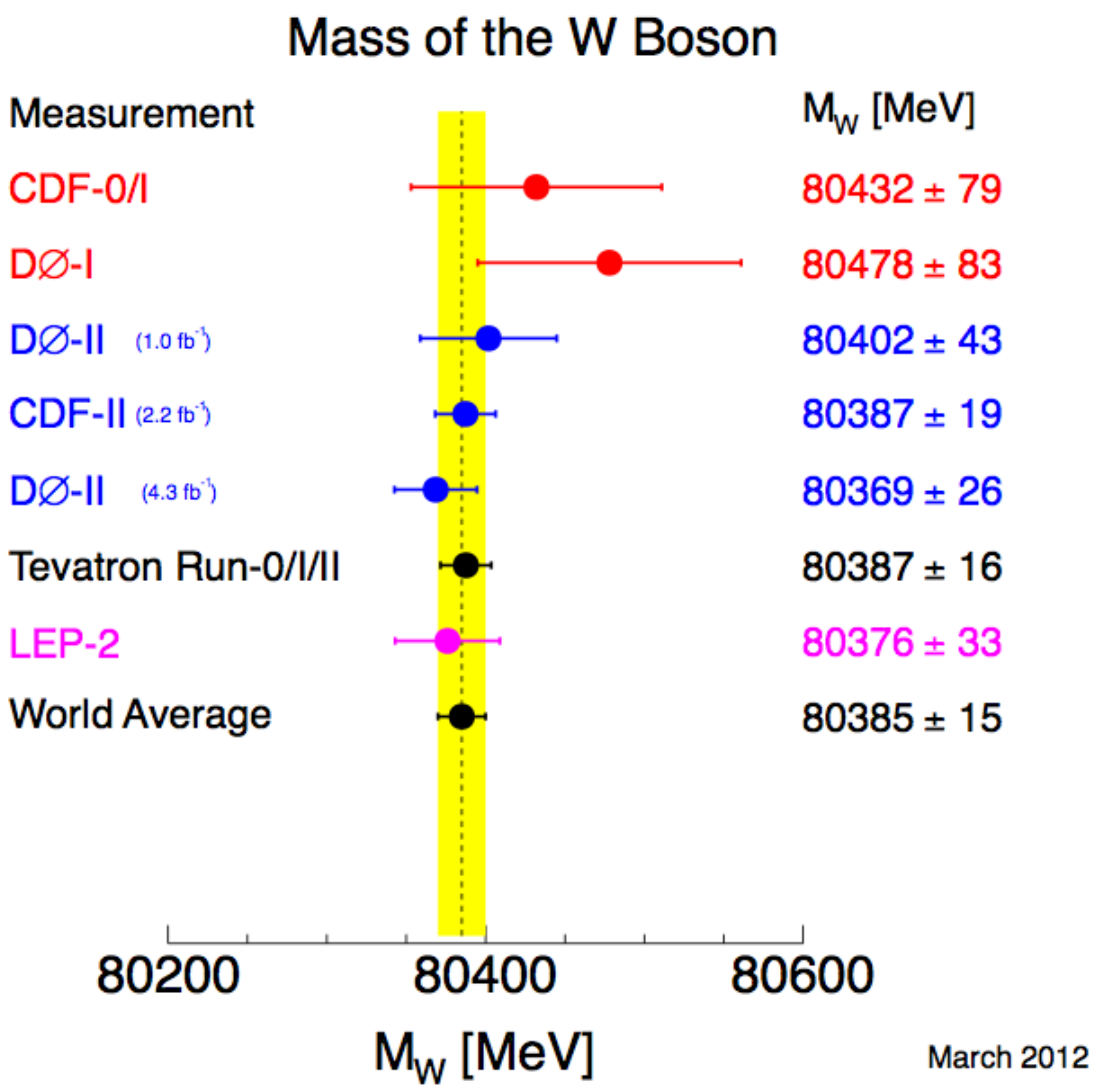
m_W^{fit}=80.400±0.027



m_W^{fit}=80.402±0.023

D0 Collaboration, Phys. Rev. Lett **103**, 141801 (2009)

Tevatron W Mass Combinations

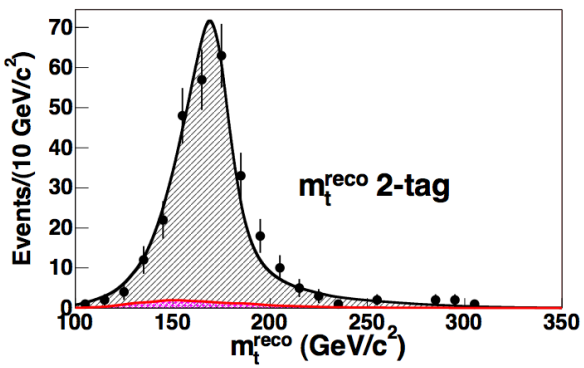


Very Precise!

Onward to the top quark mass!

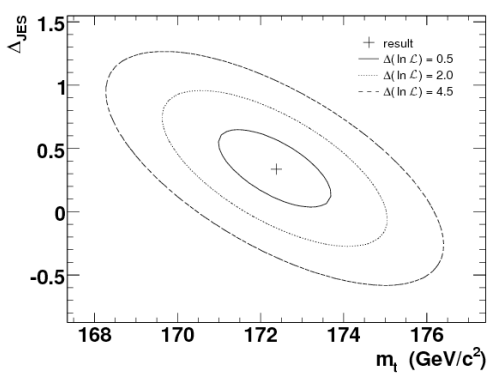
Measuring the Top Quark Mass

CDF Collab, PRD **83**, 11101 (2011)

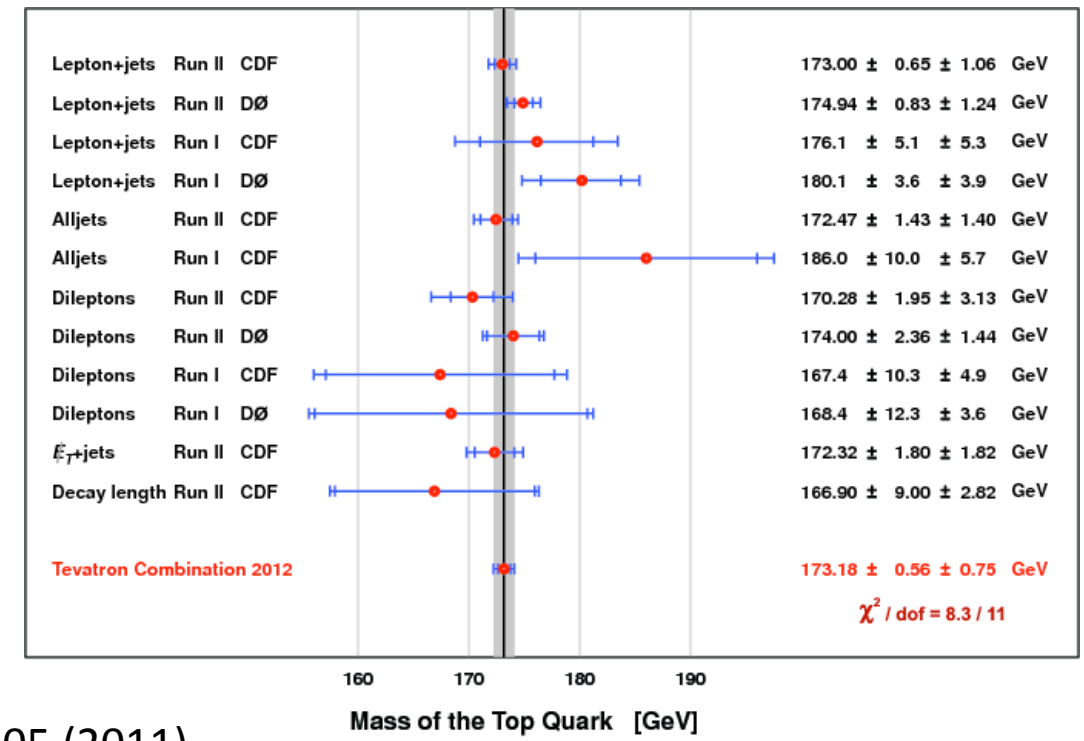


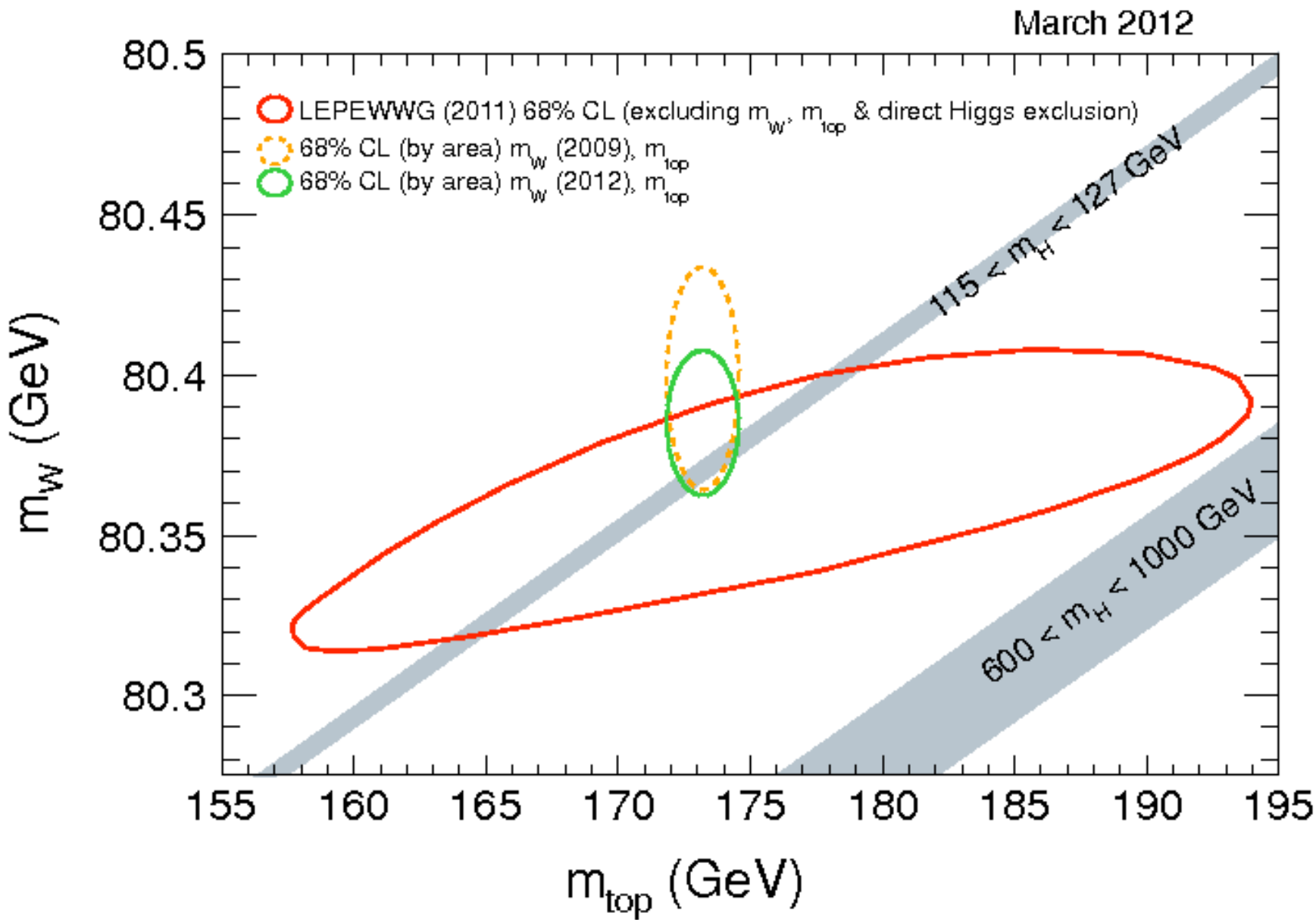
Ingredients: Select events, estimate backgrounds. Reconstruct invariant masses: Select assignment of jets to top quarks – or consider all such pairings, weighted with matrix-element probabilities.

Largest source of systematic uncertainty that can be calibrated in the same sample is the jet energy scale. Use m_{jj}(W-candidate jets) to constrain jet energy scale.



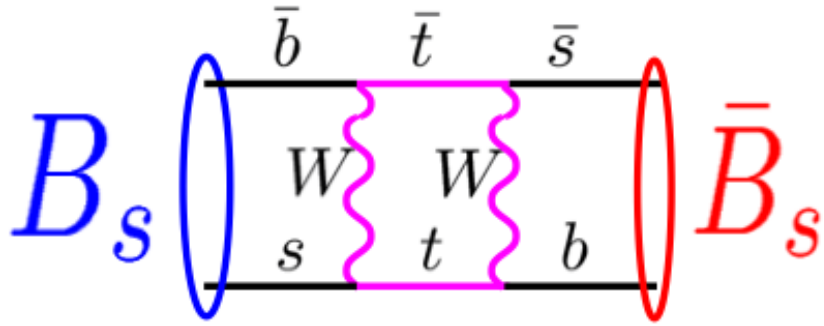
CDF Collab., PRD **84**, 071105 (2011)




March 2012
LEPEWWG (2011) 68% CL (excluding m_W, m_top & direct Higgs exclusion)
68% CL (by area) m_W (2009), m_top
68% CL (by area) m_W (2012), m_top
115 < m_H < 127 GeV
600 < m_H < 1000 GeV
80.5
80.45
80.4
80.35
80.3
m_W (GeV)
155
160
165
170
175
180
185
190
195
m_top (GeV)

B_s Oscillations

There are diagrams which allow a B_s meson to transform into its own anti-particle

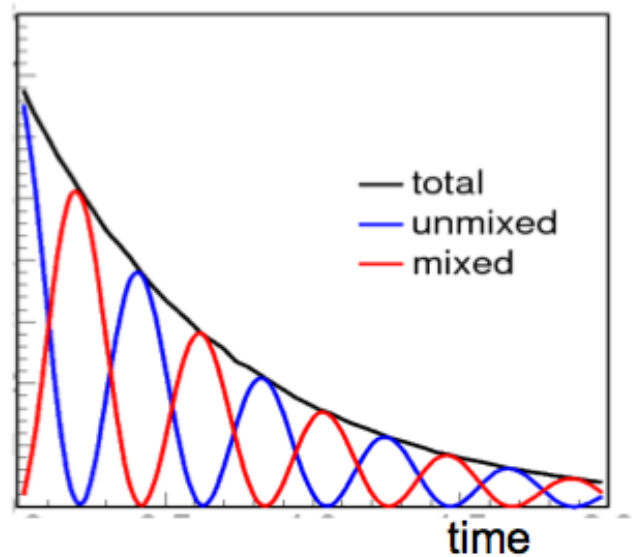


$$|\psi\rangle = e^{-iMt}\left(\cos\frac{\Delta m}{2}t|B_s\rangle + \sin\frac{\Delta m}{2}t|\bar{B}_s\rangle\right)$$

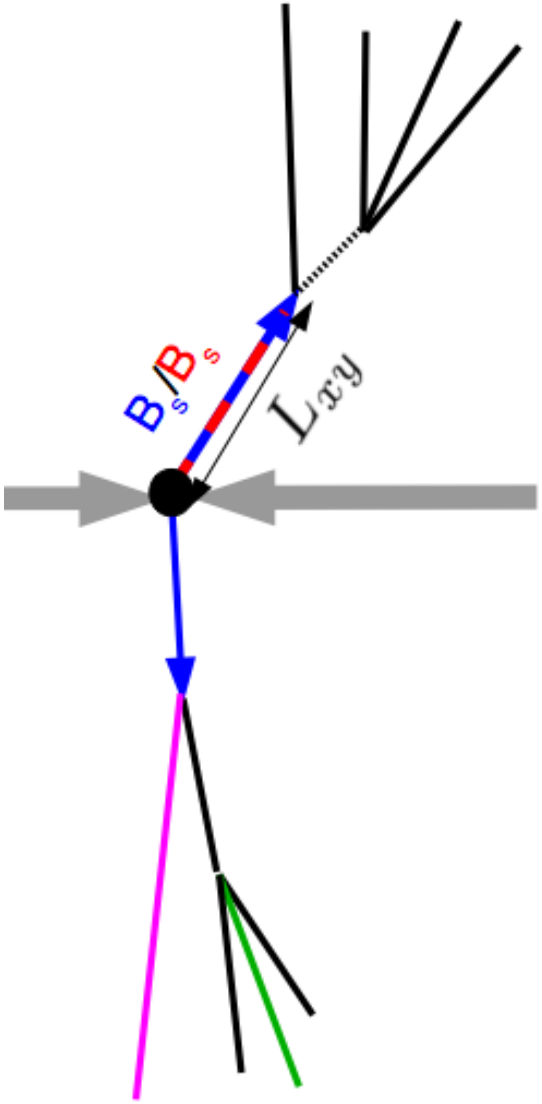
$$|\psi\rangle = e^{-iM_H t}|B_H> + e^{-iM_L t}|B_L>$$

$$|B_H\rangle = \frac{1}{\sqrt{2}}(|B\rangle - |\bar{B}\rangle), \quad M_H = M + \Delta m/2$$

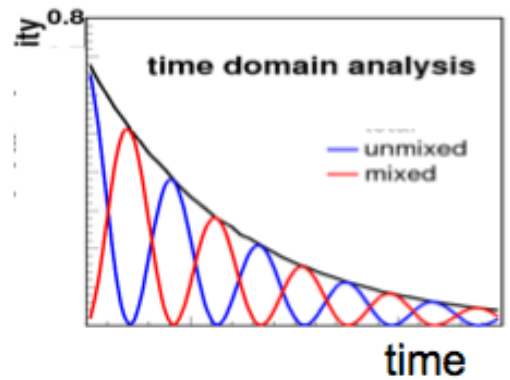
$$|B_L\rangle = \frac{1}{\sqrt{2}}(|B\rangle + |\bar{B}\rangle), \quad M_L = M - \Delta m/2$$

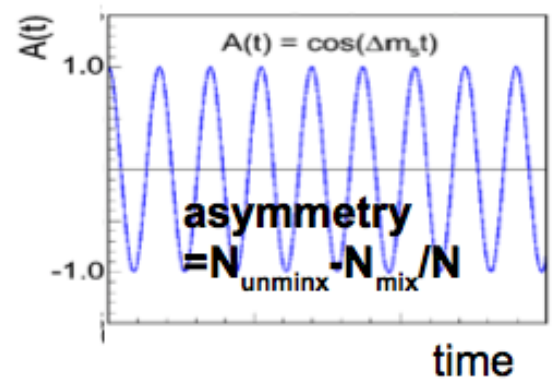


Measuring the B_s Oscillation Rate

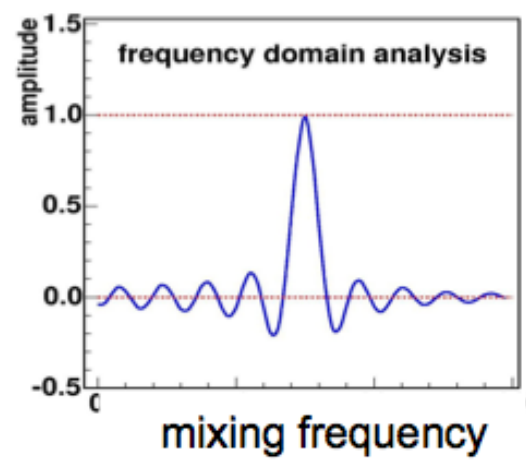


- Make a B_s meson and measure its flavour when it decays
- Identify the flavour at production (tagging)
- Look at oscillation probability vs proper decay time.

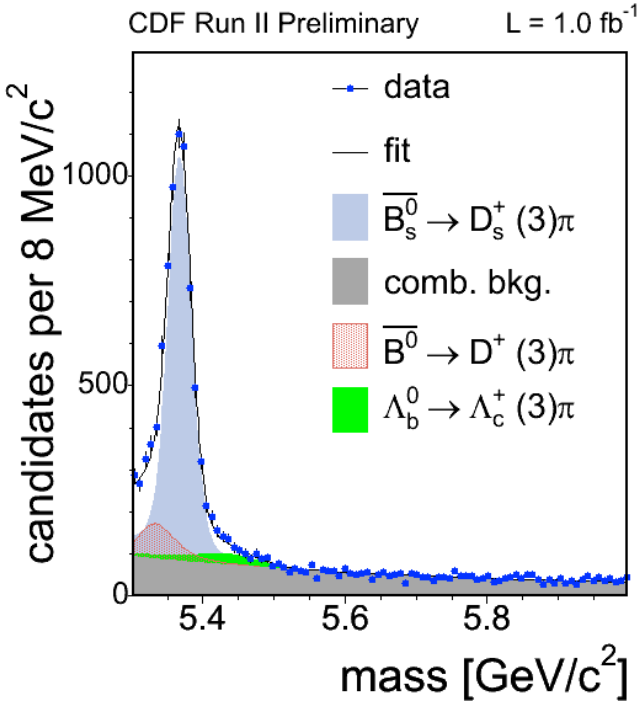


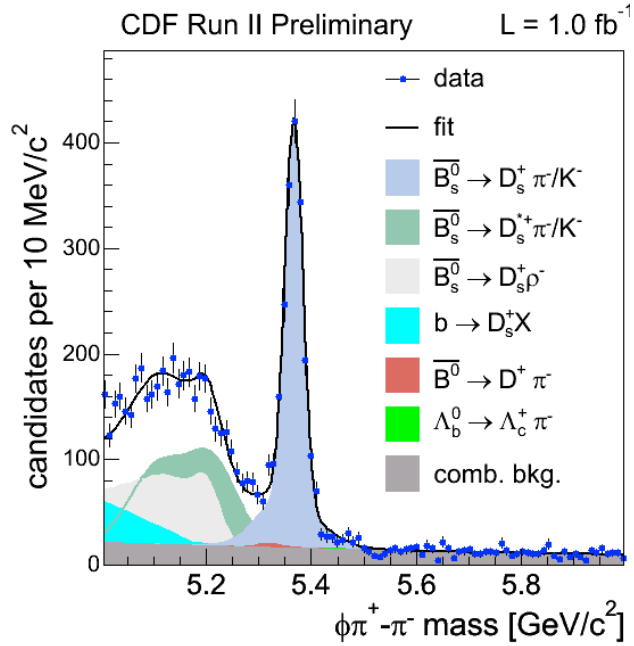


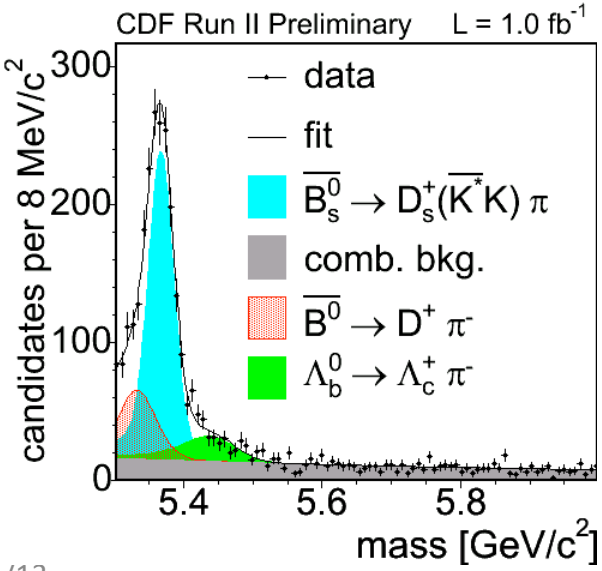
Fourier component of asymmetry: Mixing *amplitude*

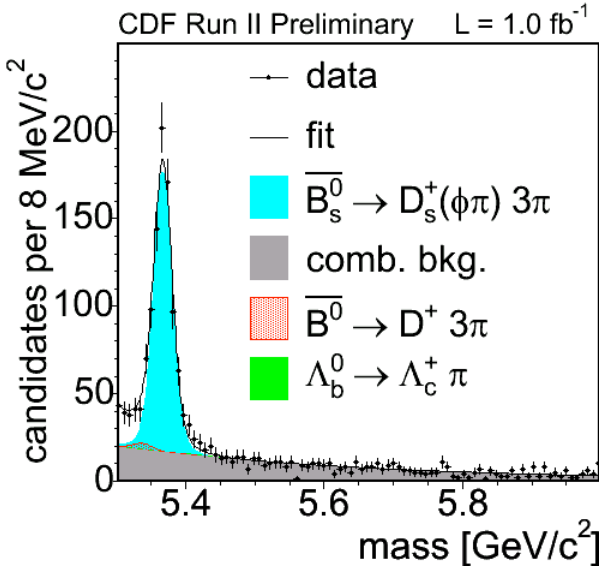


The Signals

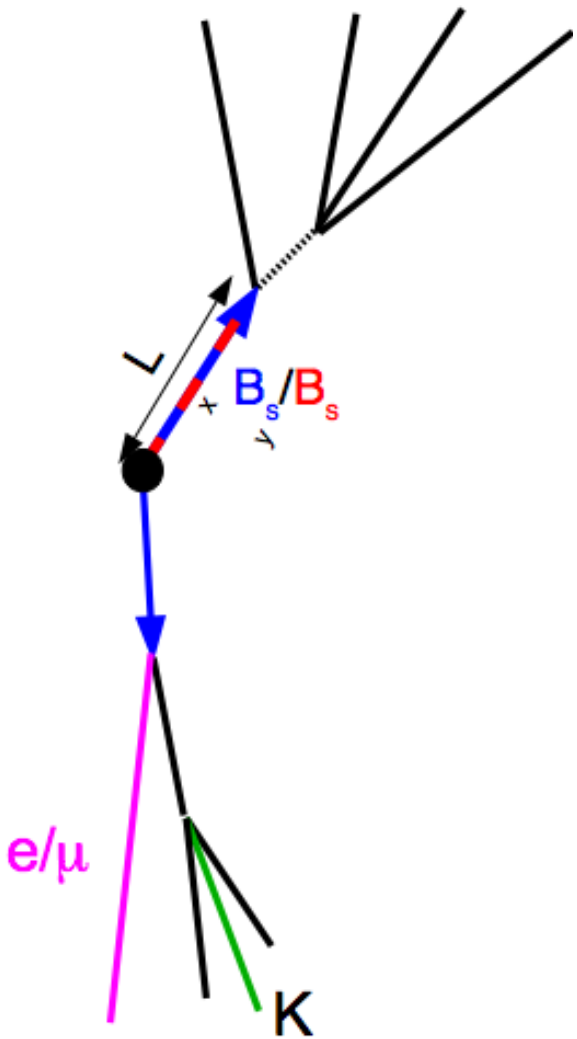

CDF Run II Preliminary
L = 1.0 fb^{-1}
data
fit
$\overline{B}_s^0 \to D_s^+ (3)\pi$
comb. bkg.
$\overline{B}^0 \to D^+ (3)\pi$
$\Lambda_b^0 \to \Lambda_c^+ (3)\pi$
candidates per 8 MeV/c^2
mass [GeV/c^2]


CDF Run II Preliminary
L = 1.0 fb^{-1}
data
fit
$\overline{B}_s^0 \to D_s^+ \pi^-/K^-$
$\overline{B}_s^0 \to D_s^{*+} \pi^-/K^-$
$\overline{B}_s^0 \to D_s^+ \rho^-$
$b \to D_s^+ X$
$\overline{B}^0 \to D^+ \pi^-$
$\Lambda_b^0 \to \Lambda_c^+ \pi^-$
comb. bkg.
candidates per 10 MeV/c^2
$\phi\pi^+$-π^- mass [GeV/c^2]


CDF Run II Preliminary
L = 1.0 fb^{-1}
data
fit
$\overline{B}_s^0 \to D_s^+(\overline{K}^*K)\,\pi$
comb. bkg.
$\overline{B}^0 \to D^+ \pi^-$
$\Lambda_b^0 \to \Lambda_c^+ \pi^-$
candidates per 8 MeV/c^2
mass [GeV/c^2]

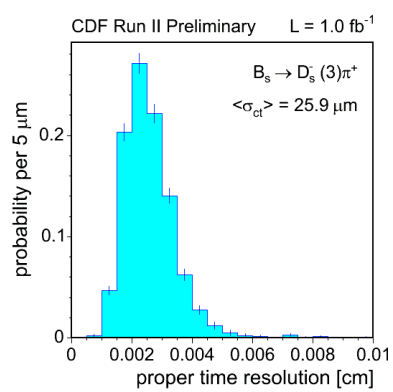

CDF Run II Preliminary
L = 1.0 fb^{-1}
data
fit
$\overline{B}_s^0 \to D_s^+(\phi\pi)\,3\pi$
comb. bkg.
$\overline{B}^0 \to D^+ 3\pi$
$\Lambda_b^0 \to \Lambda_c^+ \pi$
candidates per 8 MeV/c^2
mass [GeV/c^2]

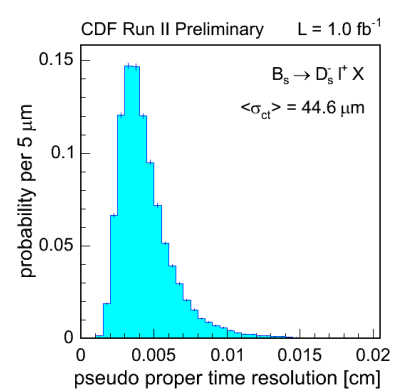
Charge Sign Assignment and Decay Time Resolution



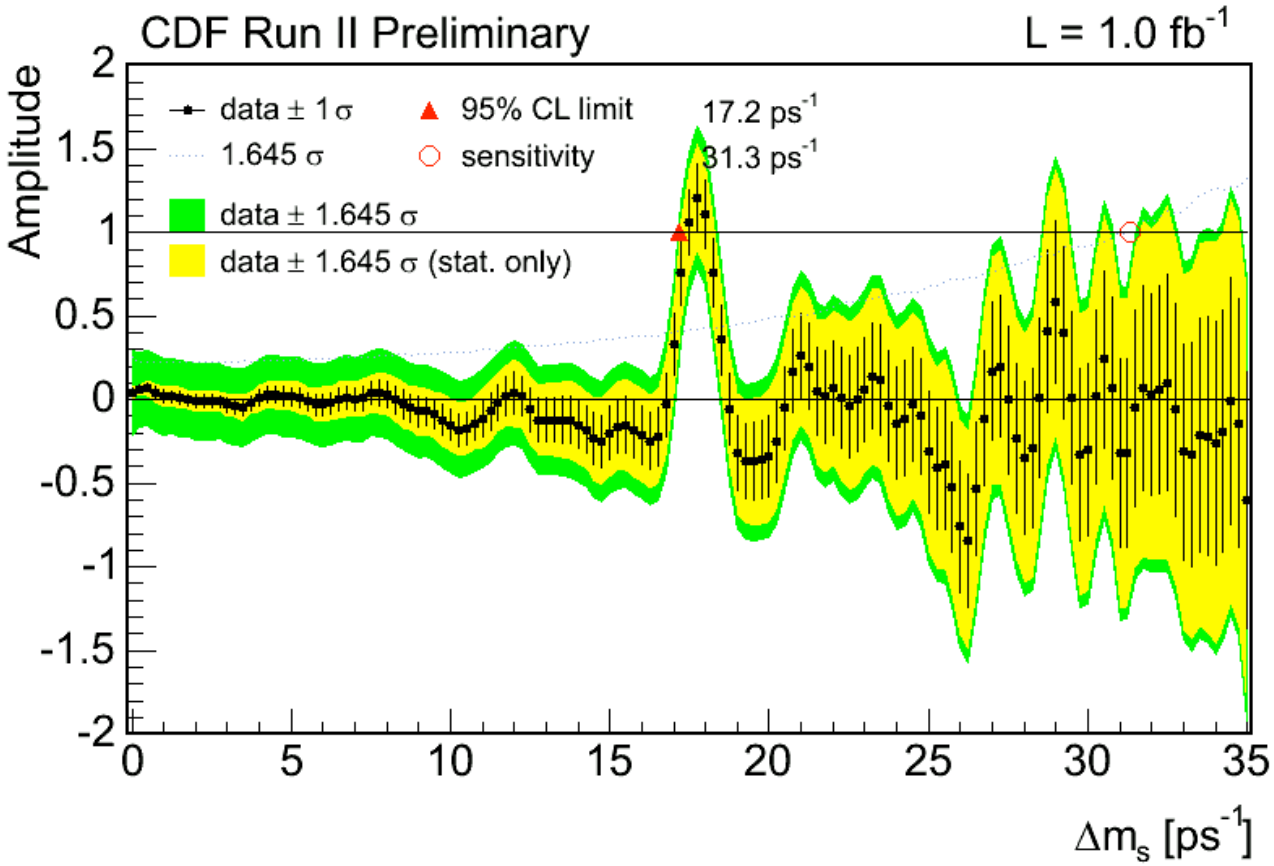
- Opposite side lepton charge
- Opposite side kaon charge
- Opposite side vertex charge
- Same-side kaon charge – fragmentation kaons are correlated in sign with the B_s at production

Decay Time Resolution
$\sigma(c\tau)$ = 25.9 μm for fully hadronic decay modes, and 44.6 μm for semileptonic decay modes





The Amplitude Scan for B_s Mixing



Δm_s=17.77±0.10(stat)±0.07(syst) ps^{-1}

$|V_{td}/V_{ts}|=0.2060\pm0.0007(\Delta m_s)_{-0.0060}^{+0.0081}(\Delta m_d+\text{theor})$

Summary

The Tevatron has been a very successful accelerator, with two very productive collaborations, CDF and D0.

More than 500 papers in refereed journals per collaboration!

Many joint papers documenting combined results – inter-collaboration cooperation has been very good.

Highlights:

- Discovery of the top quark
- Precise measurement of the masses of the top quark and the W boson
- Observation of B_s mixing and precise measurement of its rate
- Observation of single top quark production and measurement of its rate
- Evidence for the SM Higgs boson and measurement of production rates time decay branching fractions
- And many more: observation of many new hadrons, charm mixing, characterization of top quarks, CP violation in inclusive muon production