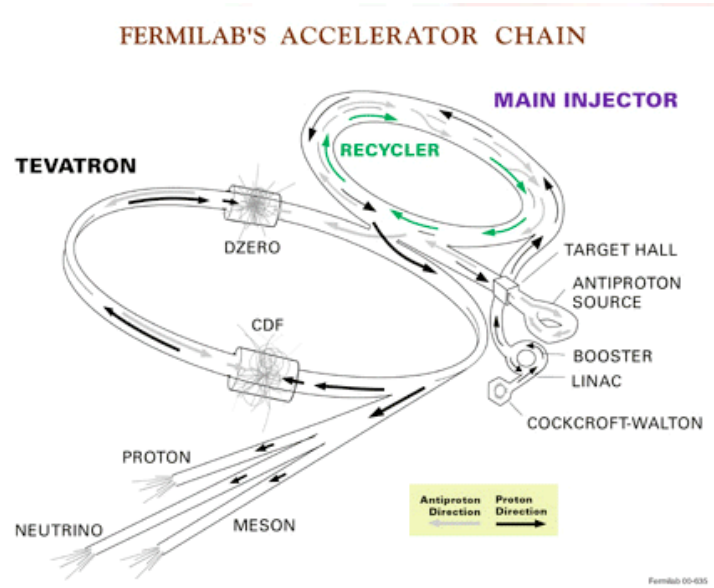
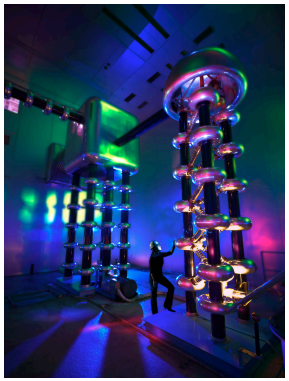
Measurement and Discovery at the Tevatron

Thomas R. Junk
Fermilab

- The Tevatron and its Experiments
- The Basics: Jets and the Weak Vector Bosons W and Z
- The Top Quark
  - Discovery
  - Cross Section
  - Mass
  - Single Top
- B_s Mixing – a Technical Challenge
- Higgs Boson Searches and Measurements

The Tevatron and Associated Accelerators





Cockroft-Walton

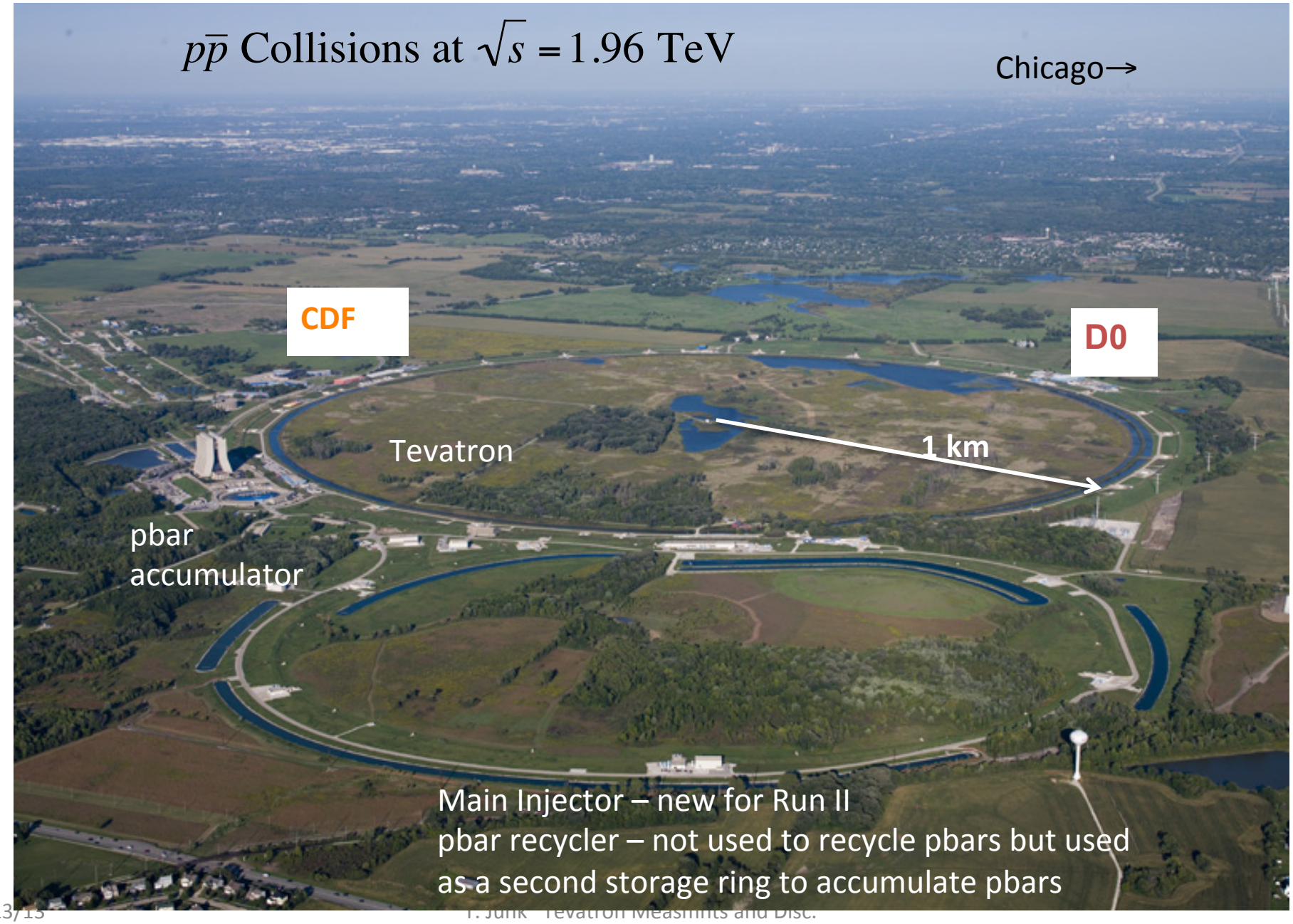
Linac

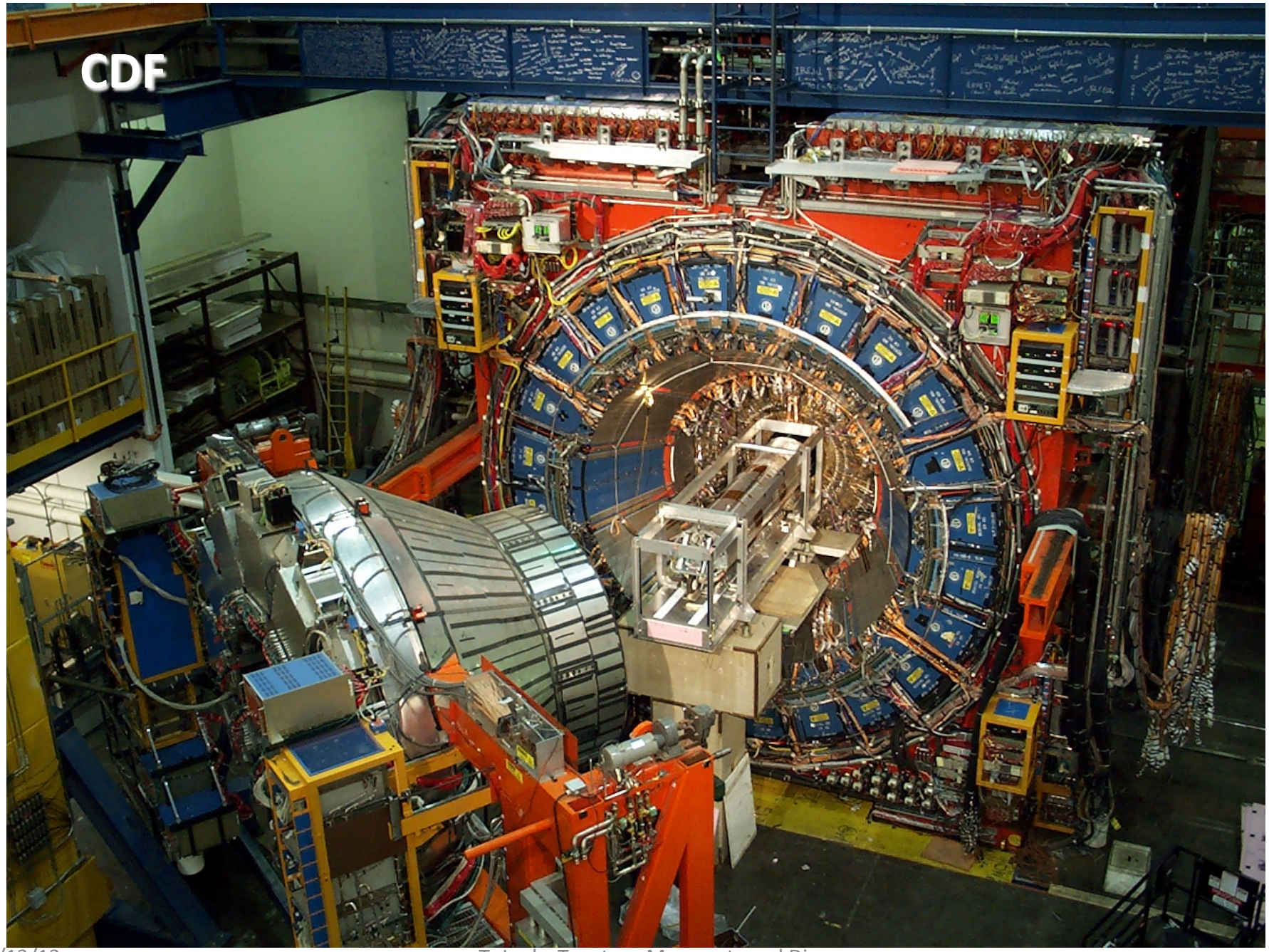
Booster

pbar debuncher and accumulator

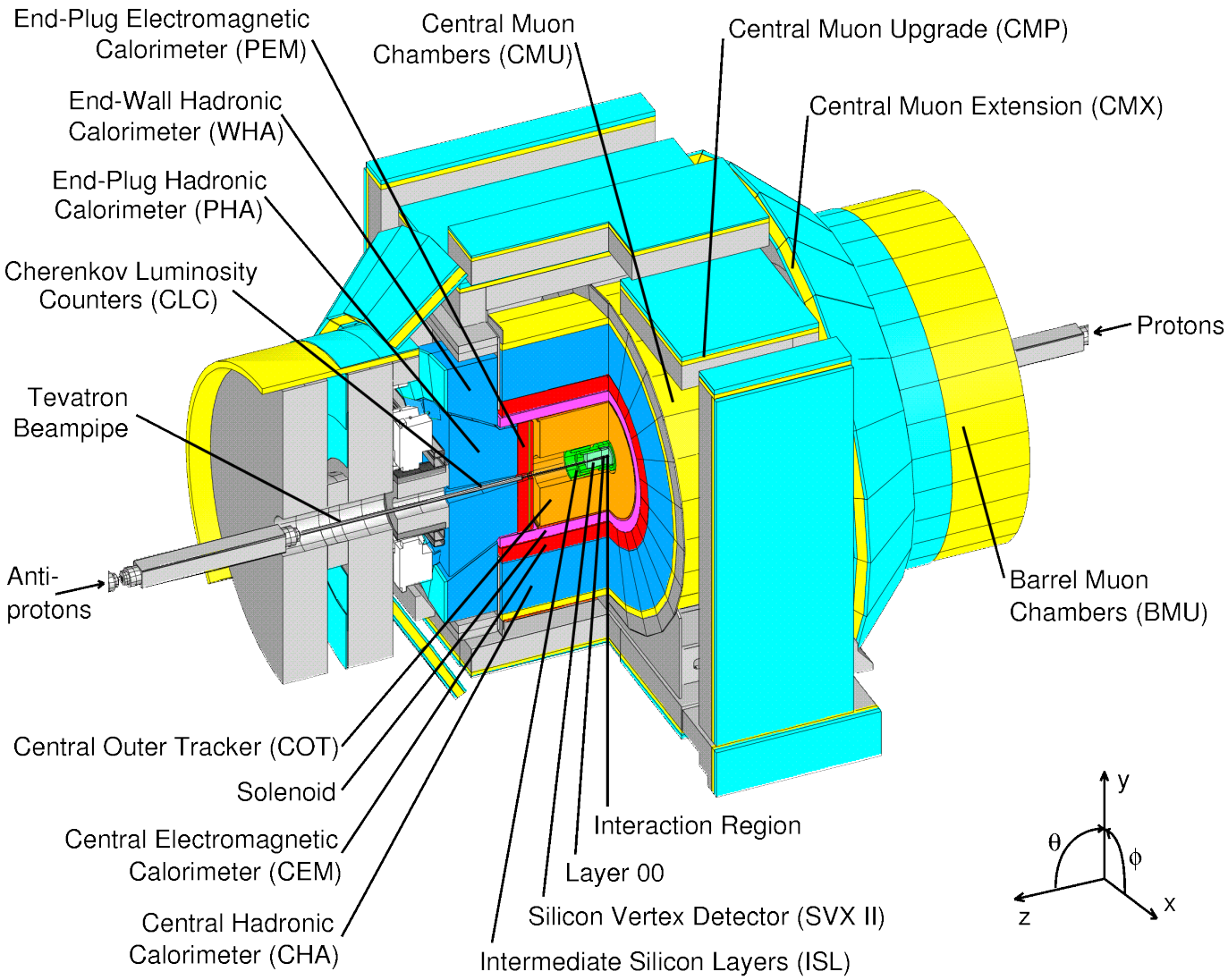
ppbar collisions at 1.96 TeV
Luminosity up to 400E30 $cm^{-2}s^{-1}$
A very good week: ~80 pb^{-1}

Fermilab from the Air




CDF

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%

CDF Run II Trigger System

Bunch Crossing Rate: ~1.7 MHz

Level 1 trigger ~15 KHz

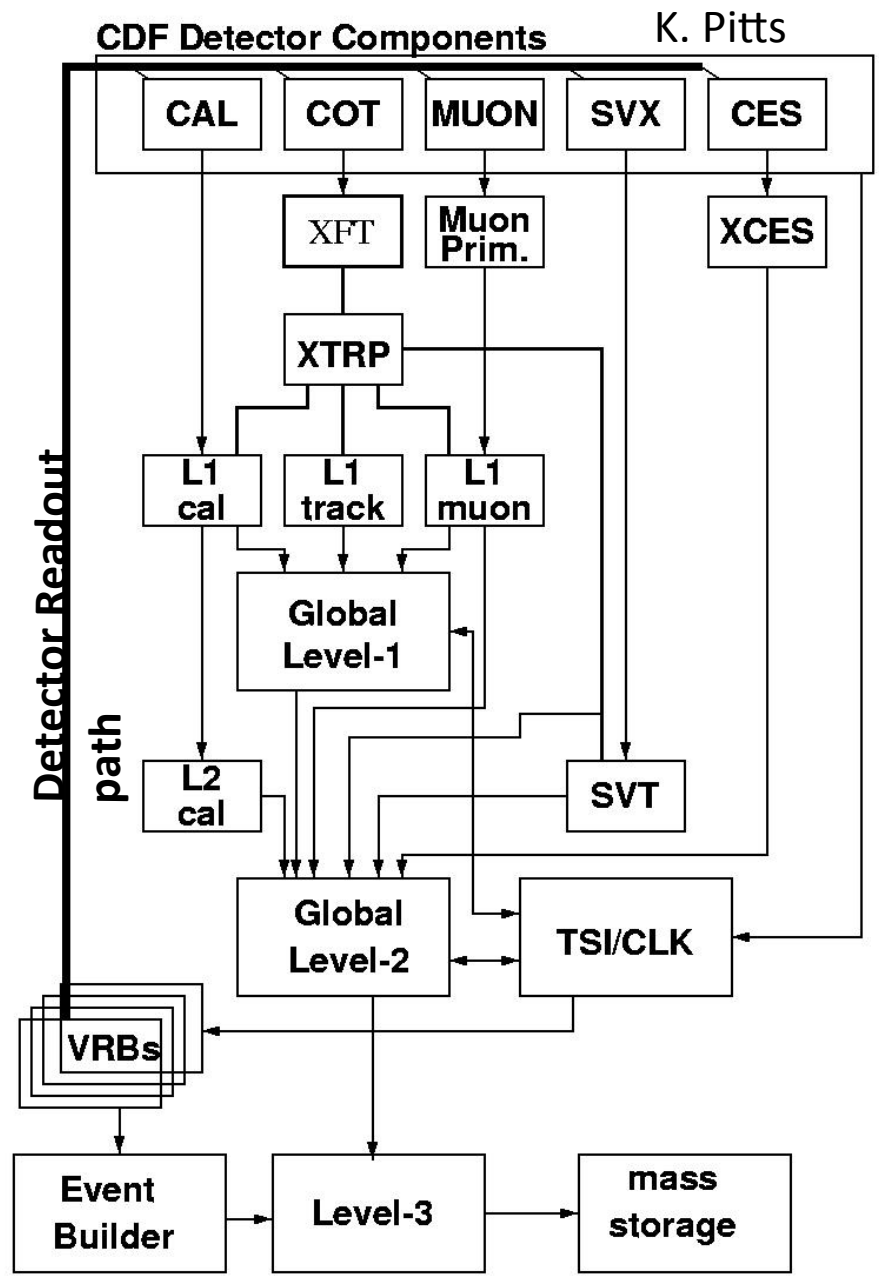
- tracking
- calorimeter: jets & electrons
- muons

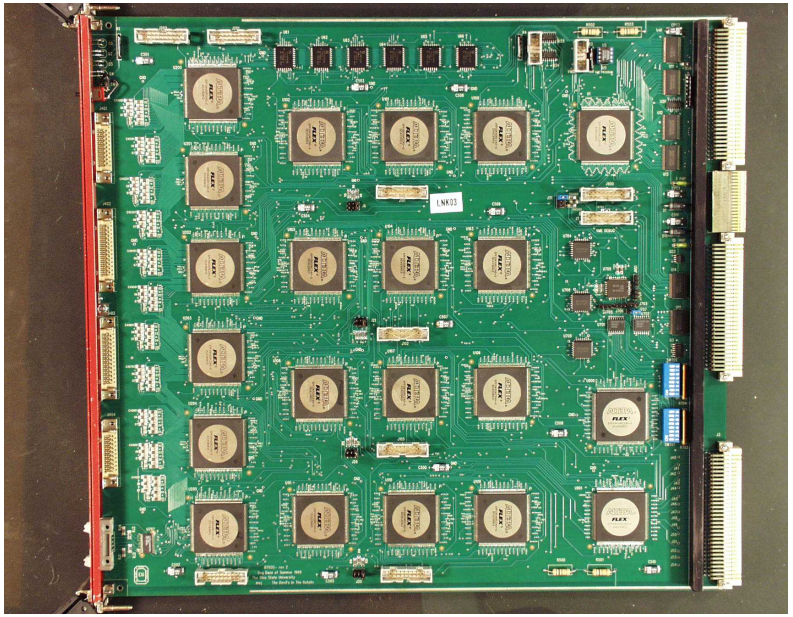
Level 2 trigger ~800 Hz

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

Level 3 trigger ~200 Hz to tape

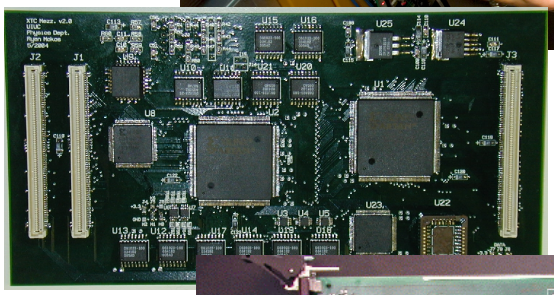
- full detector readout
- event building
- "offline" processing



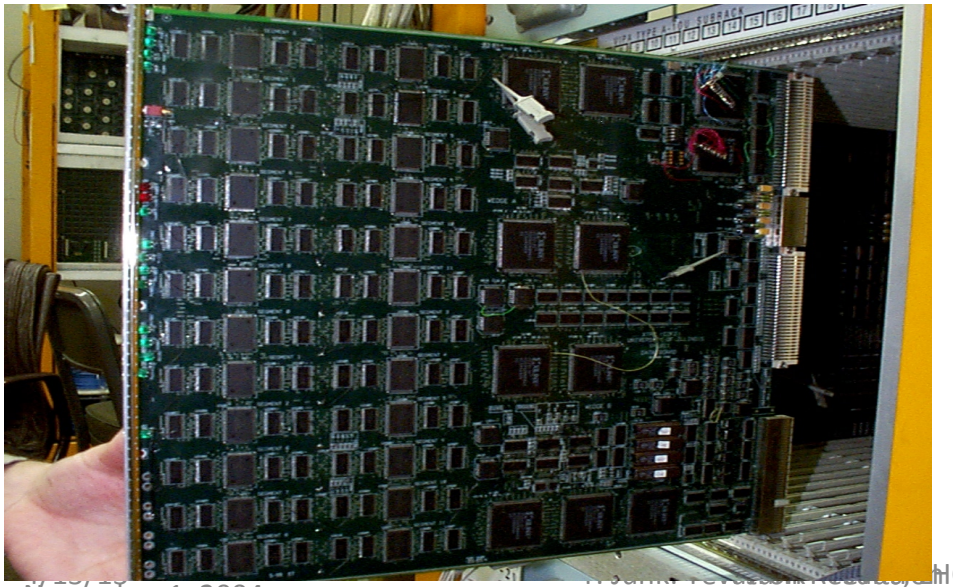


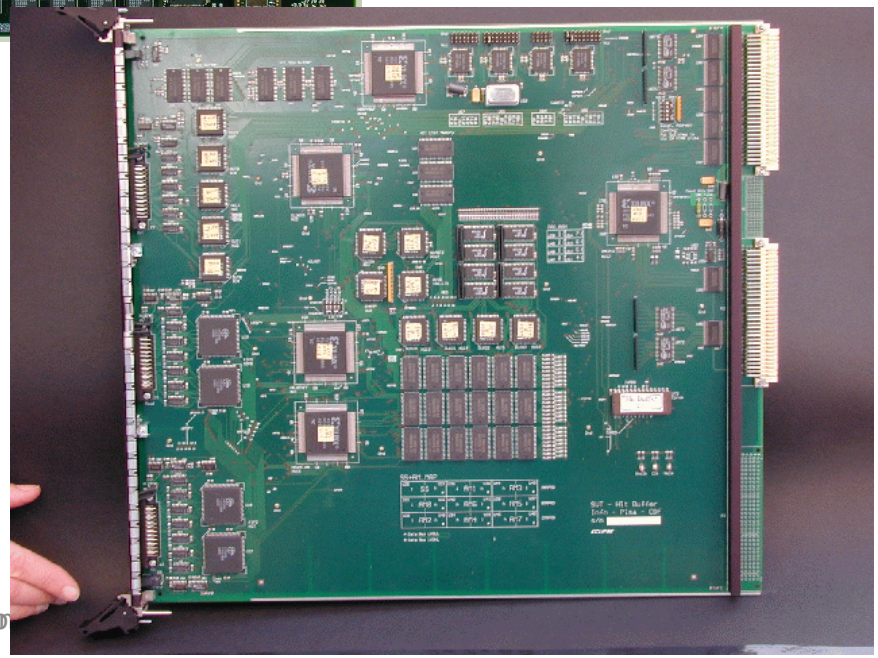
K.Pitts

Hundreds of application- specific boards working together, passing and processing data on the nanosecond timescale…

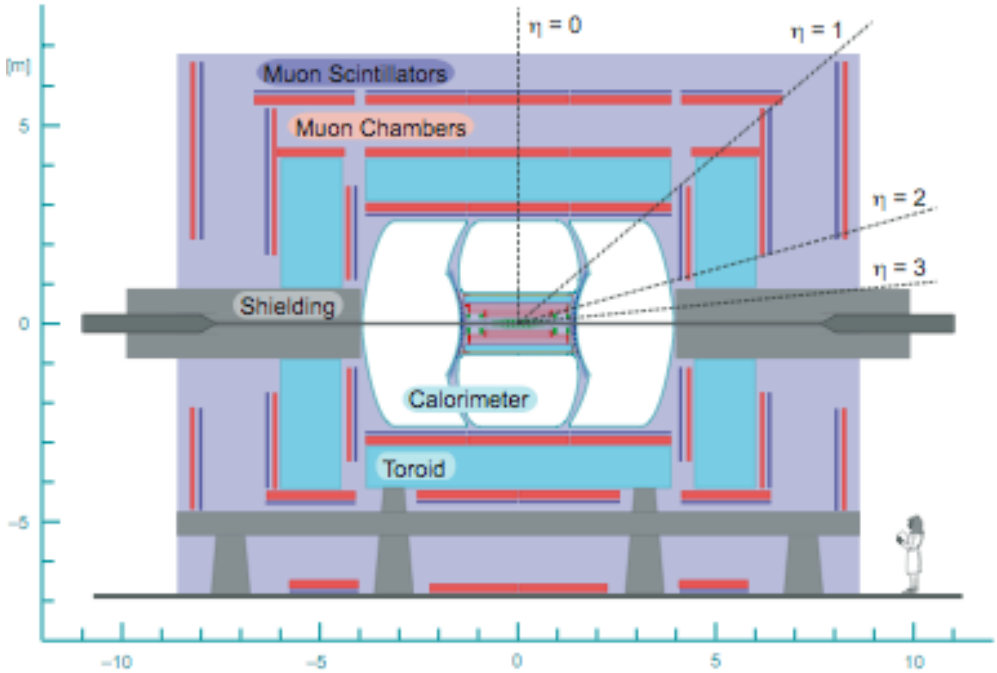


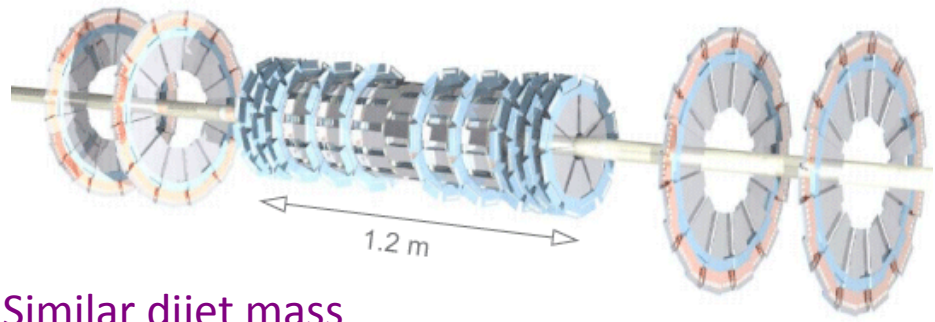
System continually upgraded to deal with increasing luminoity/ pileup





The DØ Detector





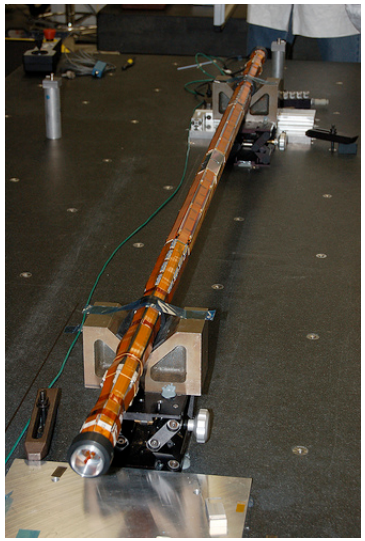
Lepton coverage:
|η| < 2 (muons)
|η| < 2.6 (electrons)

b-tagging with
|η| < ~2

Jets to
|η| < 3

Scintillating fiber tracker

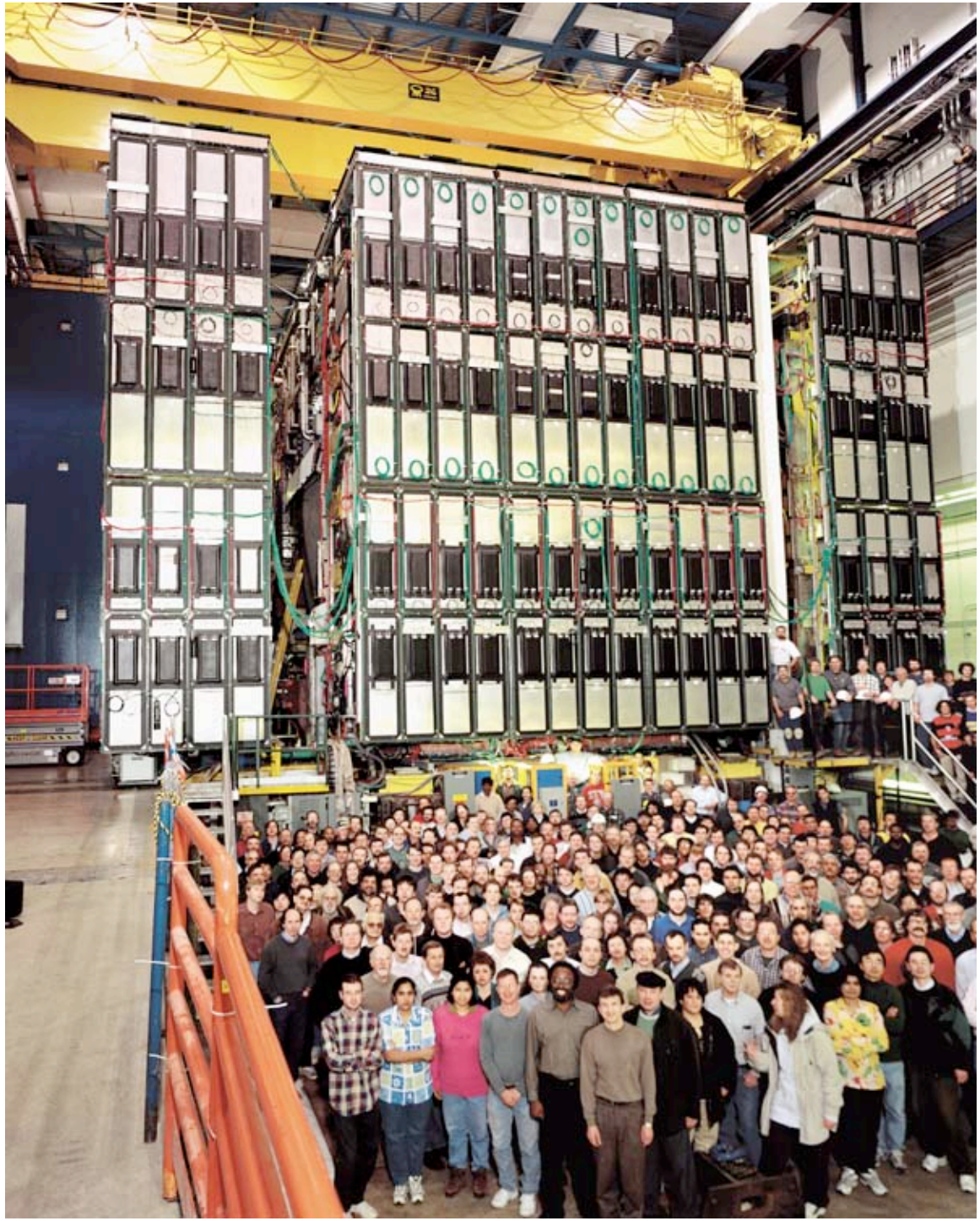
Trigger similar to CDF's



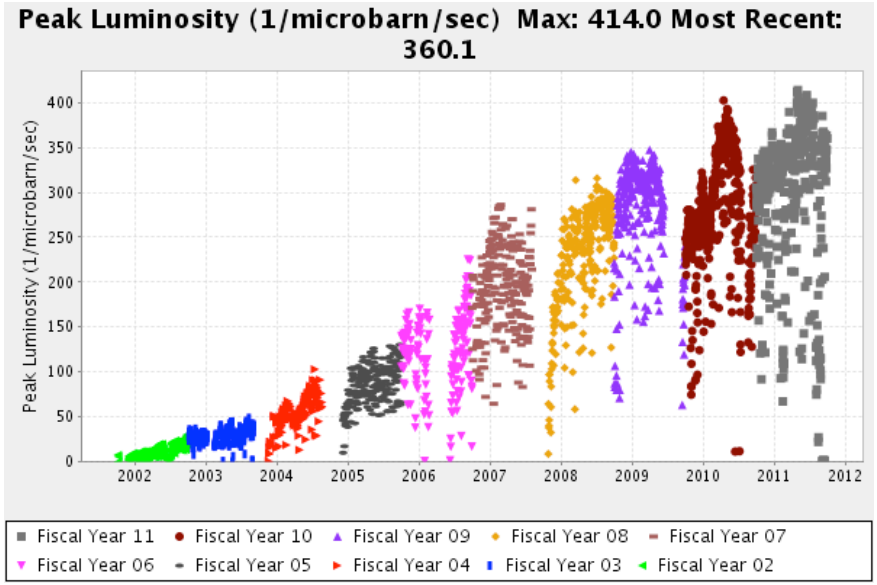
Similar dijet mass resolution to CDF

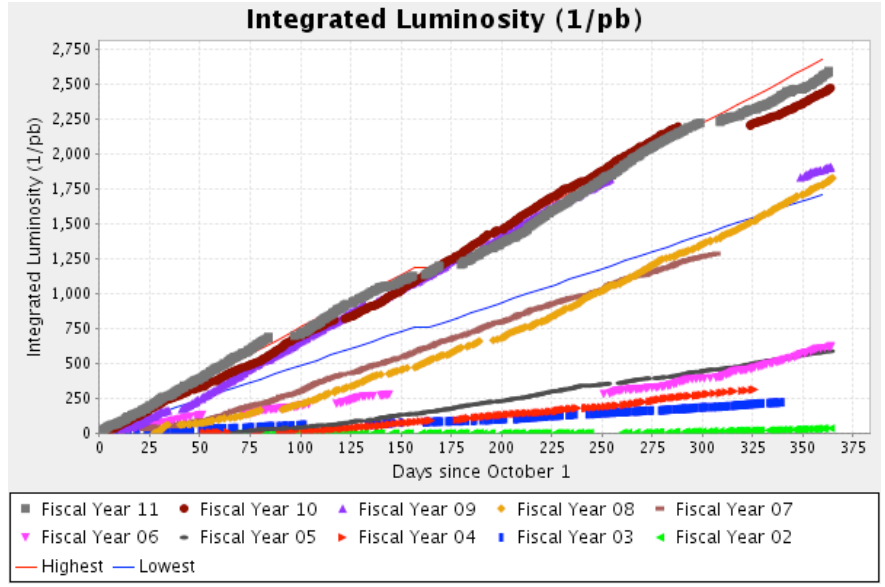
Good Feature: Regular Switching of Solenoid Field – Cancels Some Systematic Uncertainties

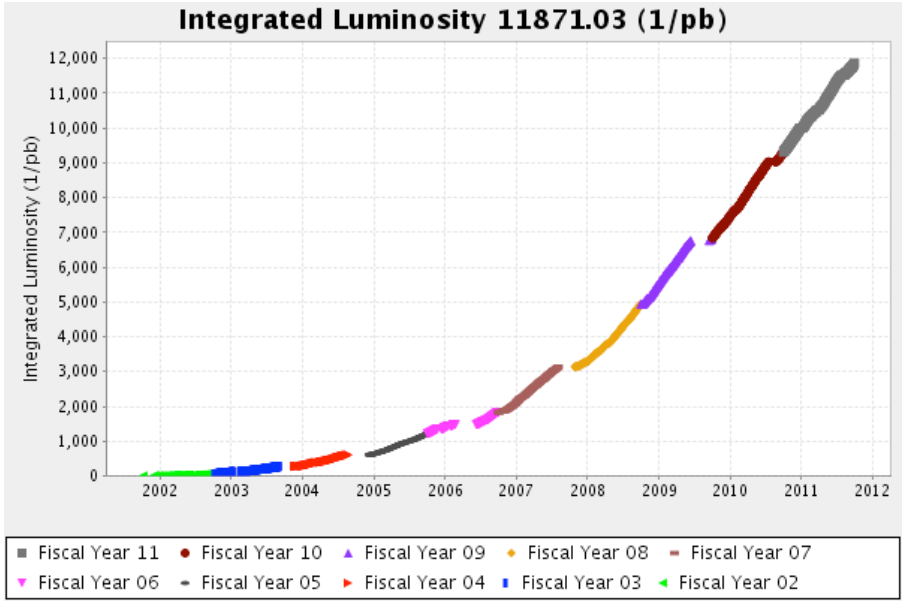
New Innermost Silicon Layer added between Run IIa and Run IIb



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





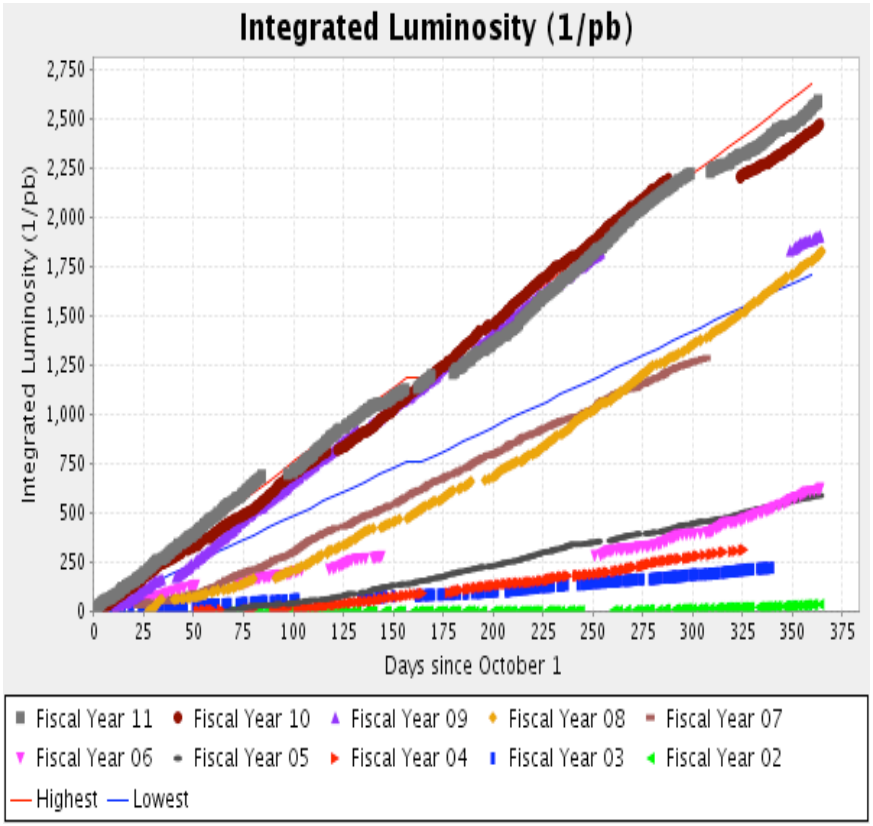


Total delivered luminosity:
~12 fb^{-1} each to CDF and D0.

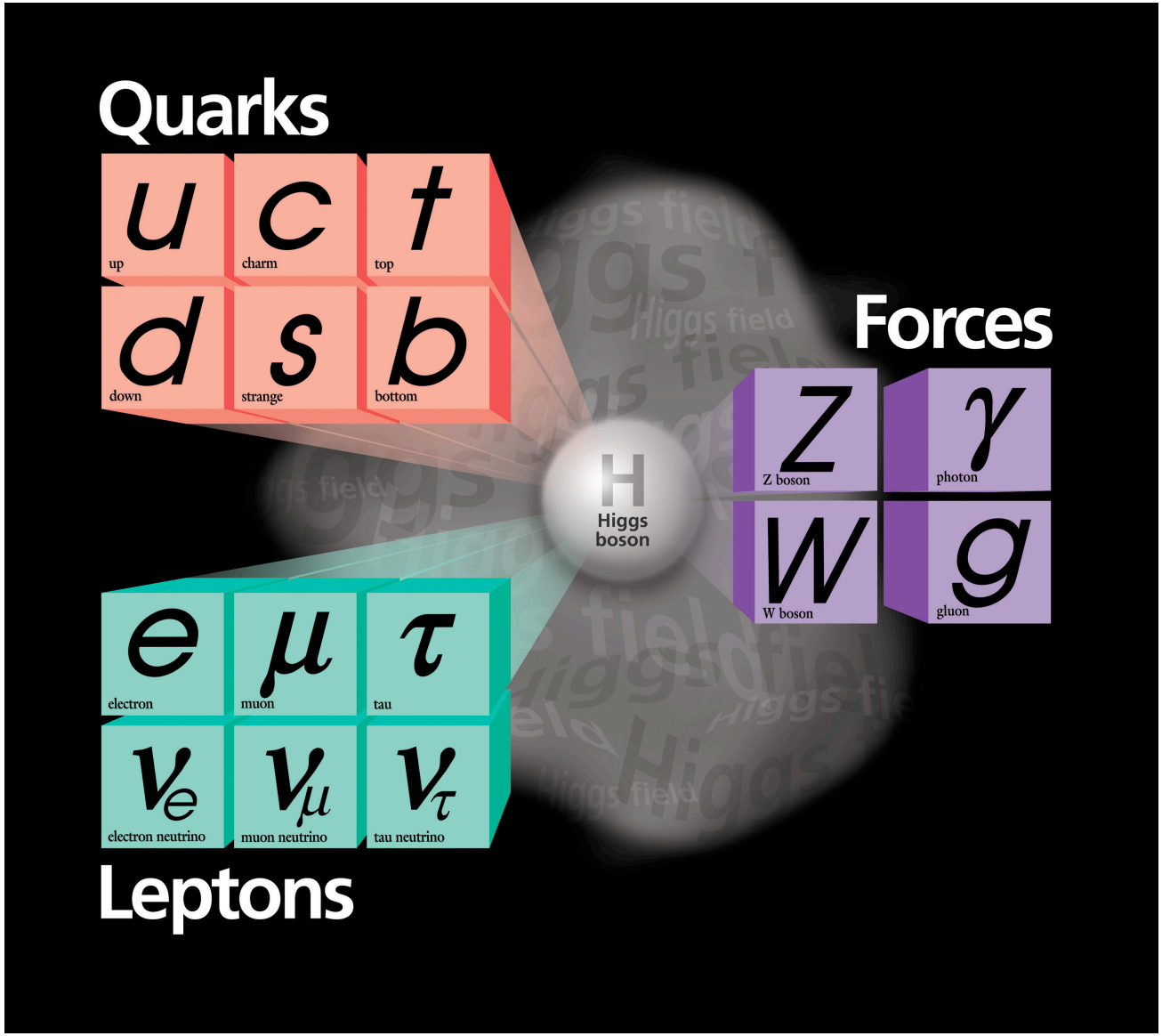
Acquired and analyzed:
~10 fb^{-1} each.

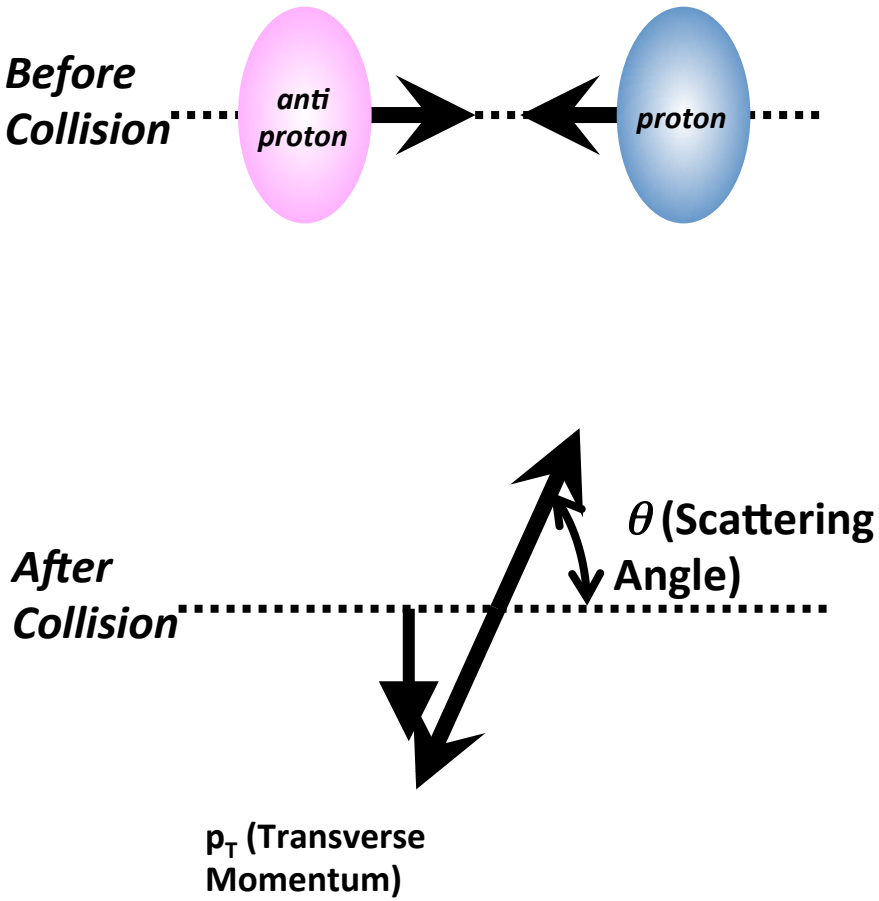
Tevatron Performance Improvements

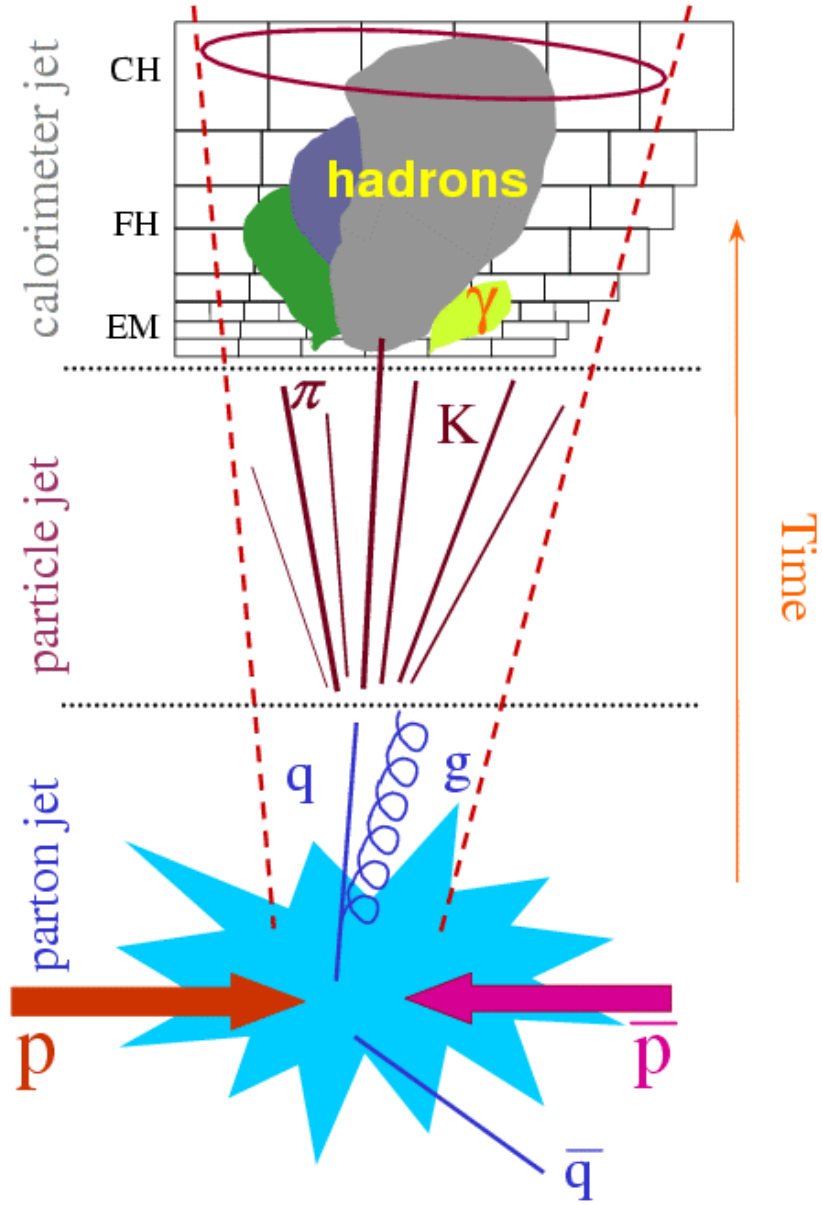
A partial list of improvements:



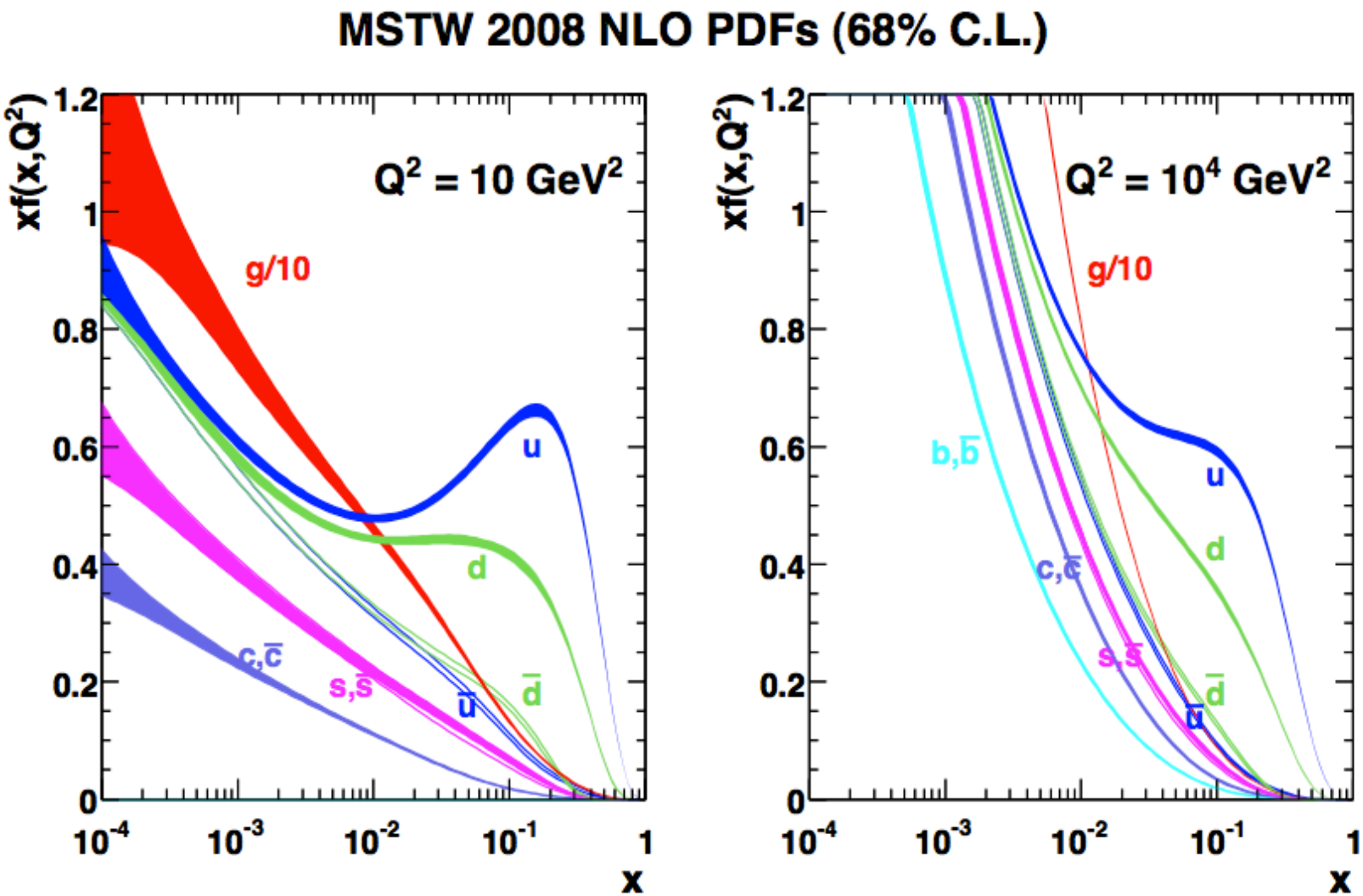
- Store antiprotons in recycler
- Faster transfers from pbar accumulator to recycler
- Electron cooling of pbars in recycler
- Efficiency and reliability of injection
- Faster shot setup
- Separation of orbits at parasitic crossings
- Replacement of 1200 He relief valves
- Faster beam aborts during quenches
- "cogging" pbars to prevent quenches during acceleration


Quarks
u
up
c
charm
t
top
d
down
s
strange
b
bottom
Forces
Z
Z boson
γ
photon
W
W boson
g
gluon
H
Higgs boson
e
electron
μ
muon
τ
tau
νe
electron neutrino
νμ
muon neutrino
ντ
tau neutrino
Leptons

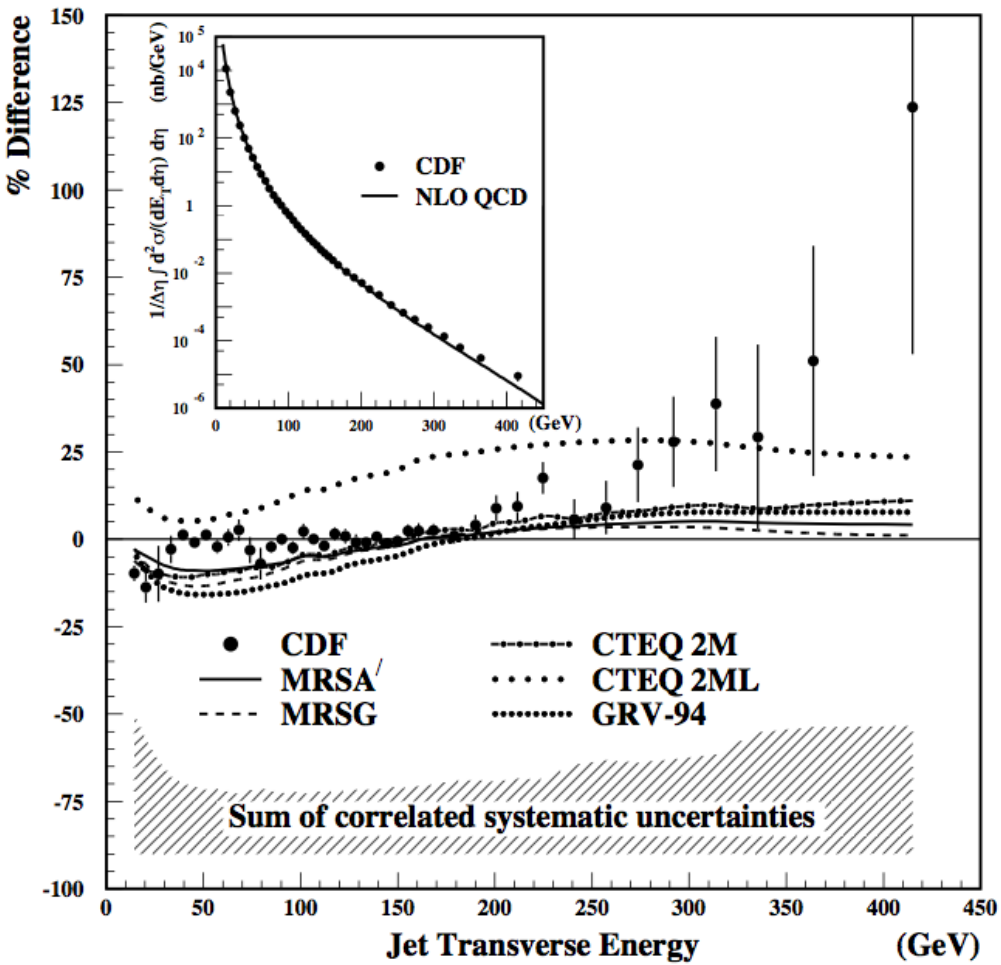

Before Collision
anti proton
proton
After Collision
θ (Scattering Angle)
p_T (Transverse Momentum)


calorimeter jet
CH
FH
EM
hadrons
γ
particle jet
π
K
parton jet
q
g
p
p̄
q̄
Time

Parton Distribution Functions



Jet Transverse Energy Distribution in Tevatron Run I – 1.8 GeV



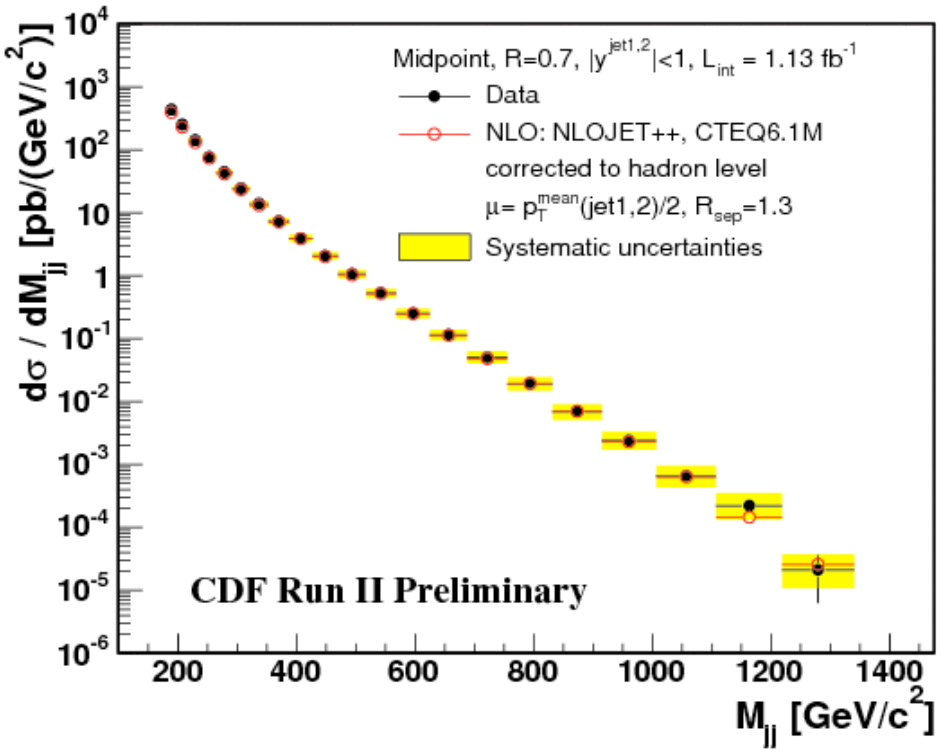
Phys.Rev.Lett. 77 (1996) 438-443

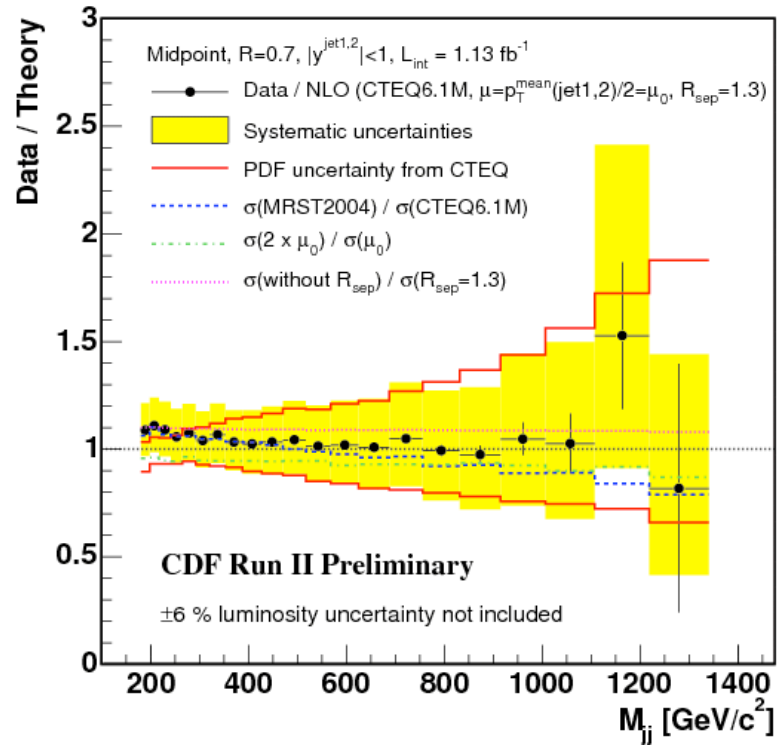
More very hard scatters than expected from prediction.

Analysis was motivated by a desire to test for quark substructure: uncertainties were large, but it looked like quarks may have had hard scattering centers in them.

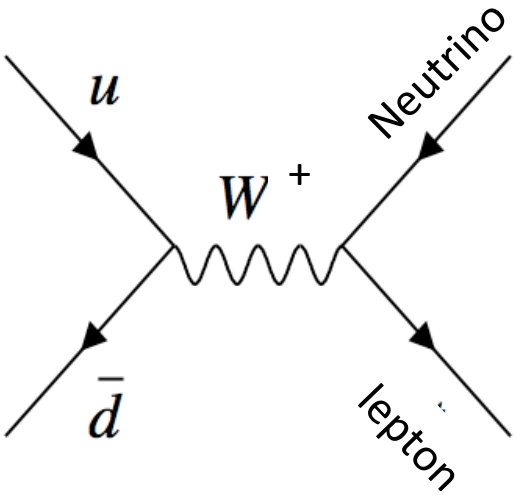
Parton distribution functions had more freedom than expected. High-x gluons were not otherwise well constrained. Further data did not come in quite so high and eventually were dropped in favor or Run II jet data (of which there was much more)

Dijet Mass Distribution in Run II



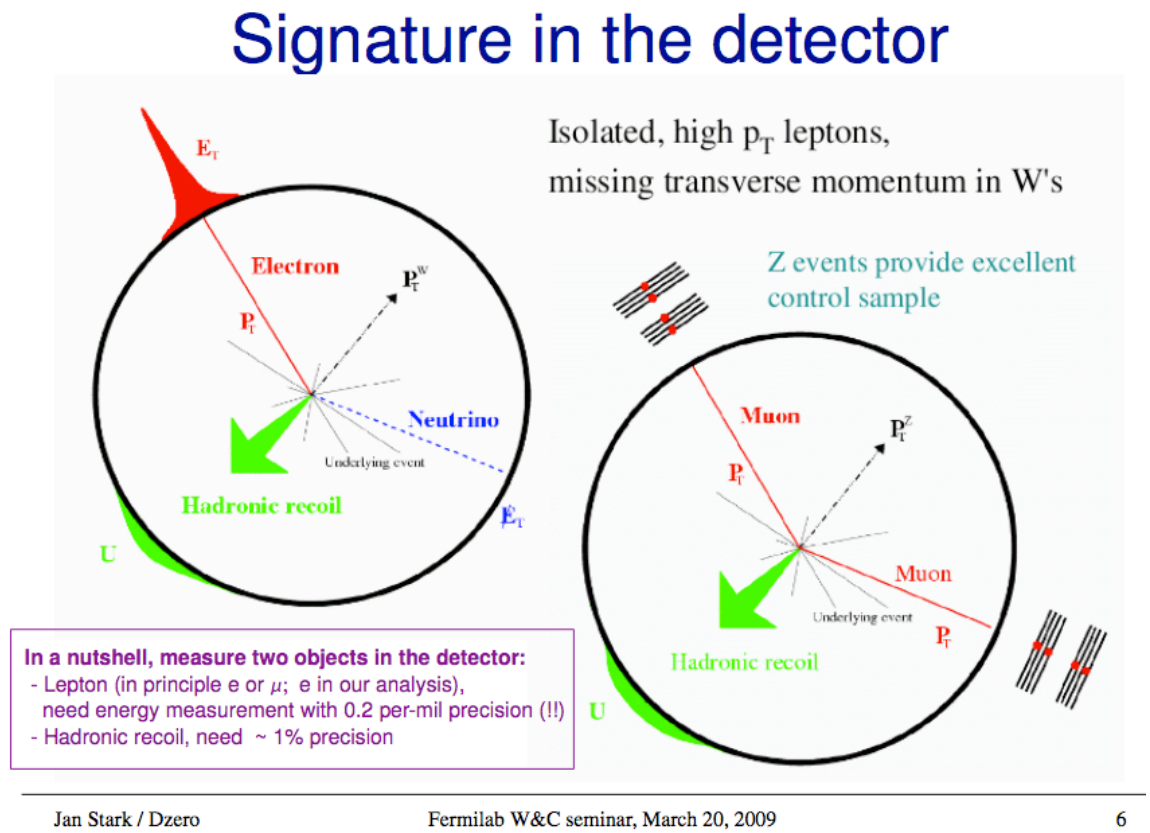


Production of the Weak Gauge Bosons W and Z



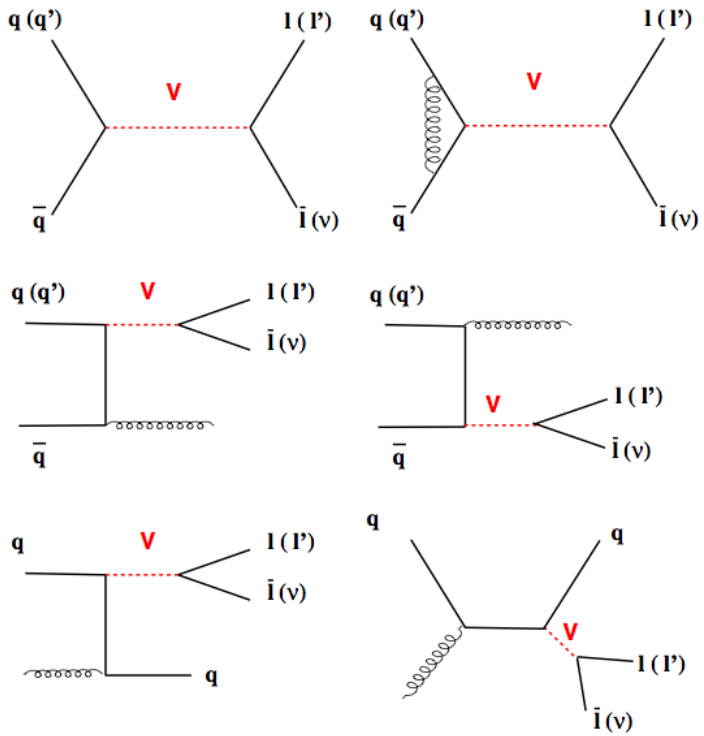
"Drell-Yan Production"

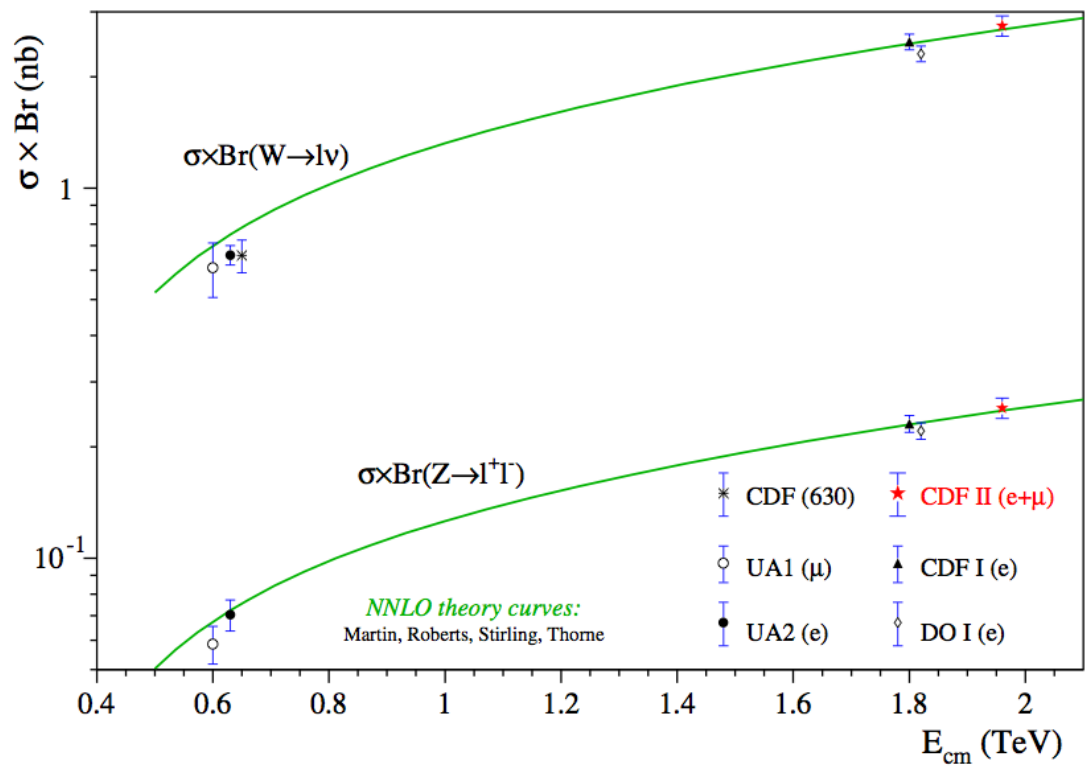
Similar diagram for u-ubar →Z→l^+l^-



CDF's W and Z Production Cross Section Measurements

A long story! Mostly concerned about acceptance and backgrounds.

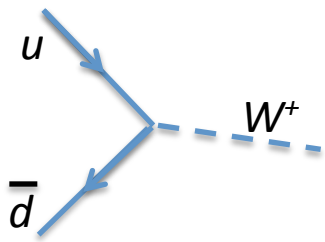




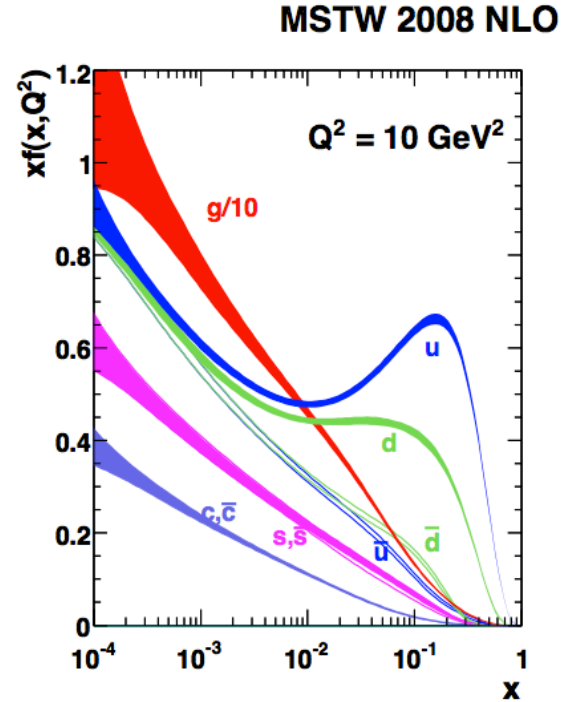
Many additional processes (these are only at NLO)

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

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



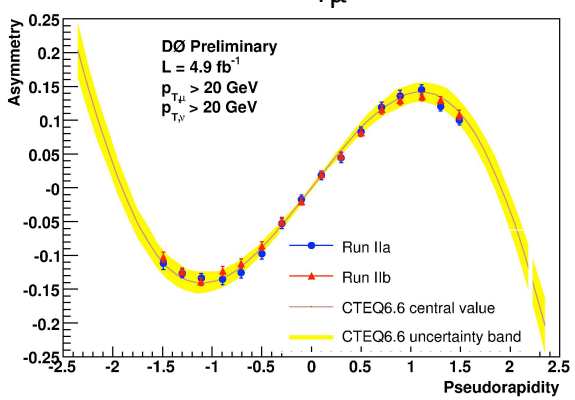
Forward-Backward Asymmetry comes largely from the difference between u and d PDF's.
The compton diagram gq→Wq also participates.



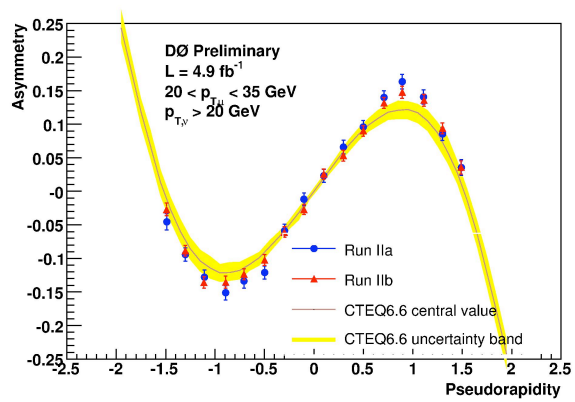
$$A(\eta) = \frac{1}{(1-2g)}\left[\frac{N^+(\eta) - N^-(\eta)}{N^+(\eta) + N^-(\eta)}\right]$$

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

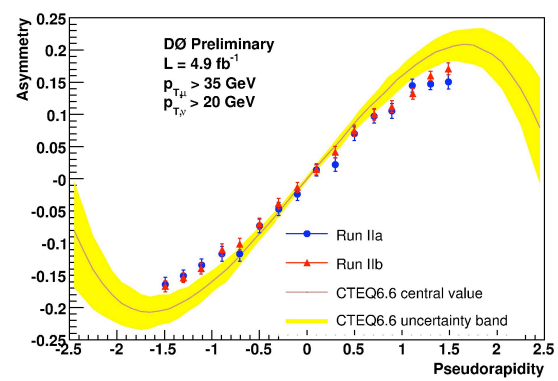
Inclusive $p_{T\mu}$>20 GeV



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.

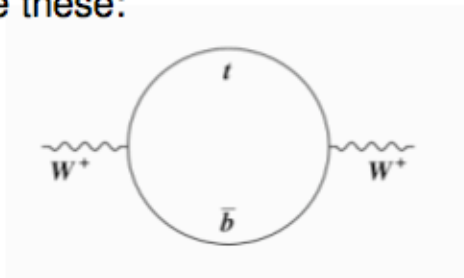
Motivation for Measuring the mass of the W Boson

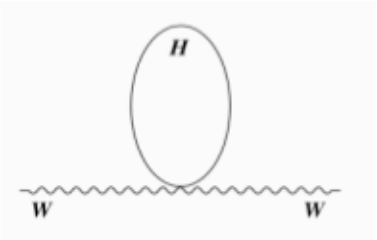
The Z Boson's mass is very well measured at LEP ~ 2 MeV unc. out of 91.6 GeV

W mass is a key parameter in the Standard Model. This model does not predict the value of th W mass, but it predicts this relation between the W mass and other experimental observables:

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

Radiative corrections (Δ r) depend on M_t as ~M_t^2 and on M_H as ~log M_H. They include diagram like these:



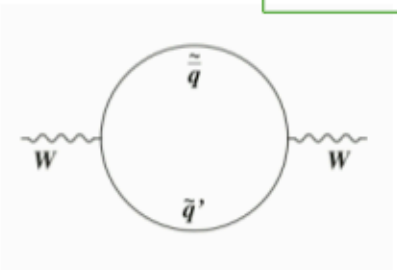


Precise measurements of M_W and M_t constrain SM Higgs mass.

For equal contribution to the Higgs mass uncertainty need:
$\Delta M_W \approx 0.006\ \Delta M_t$.

The limiting factor here will be ΔM_W, not ΔM_t !

Additional contributions to Δr arise in various extensions to the Standard Model, *e.g.* in SUSY:



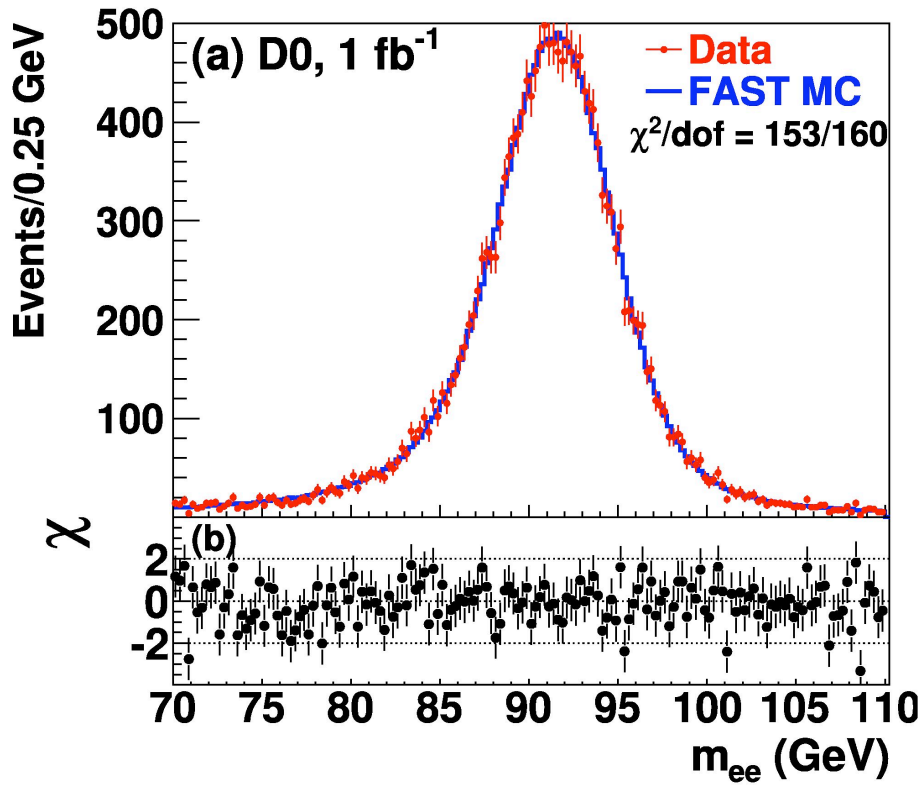
Jan Stark / Dzero Fermilab W&C seminar, March 20, 2009 2

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.

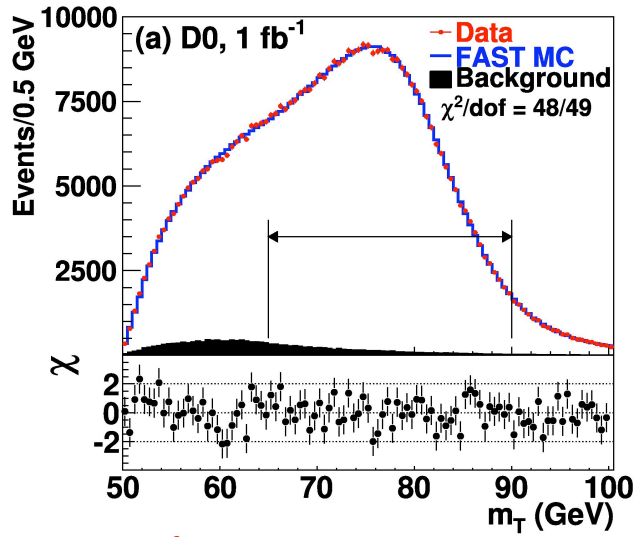


18,725 Z→ee candidates selected – negligible backgrounds

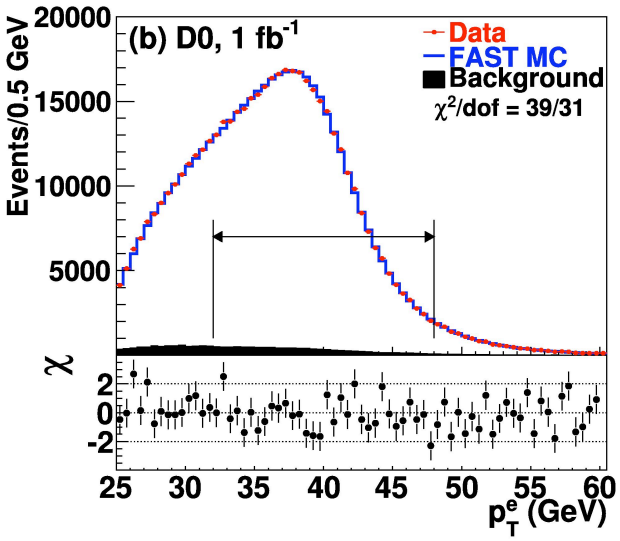
D0's Measurement of the W mass in W→eν Events

499830 candidate events

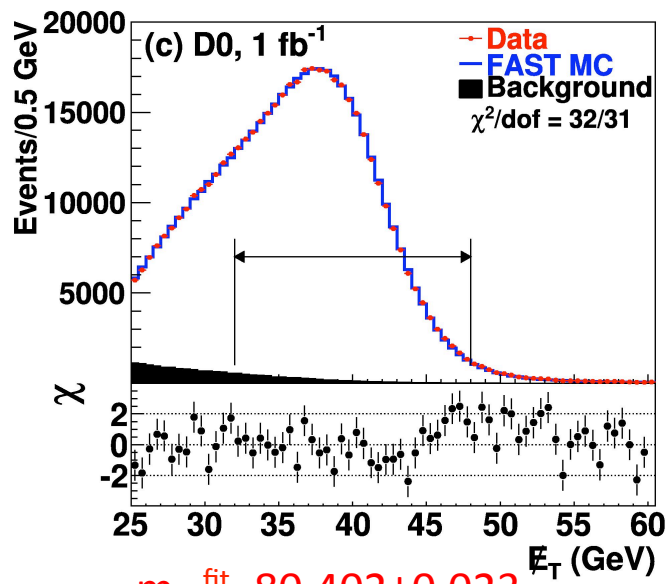
Background consists of
- Z→ee with a missing electron (inter-cryostat crack for example)
- Multijets
- W→τν→eνν



m_W^{fit}=80.401±0.023



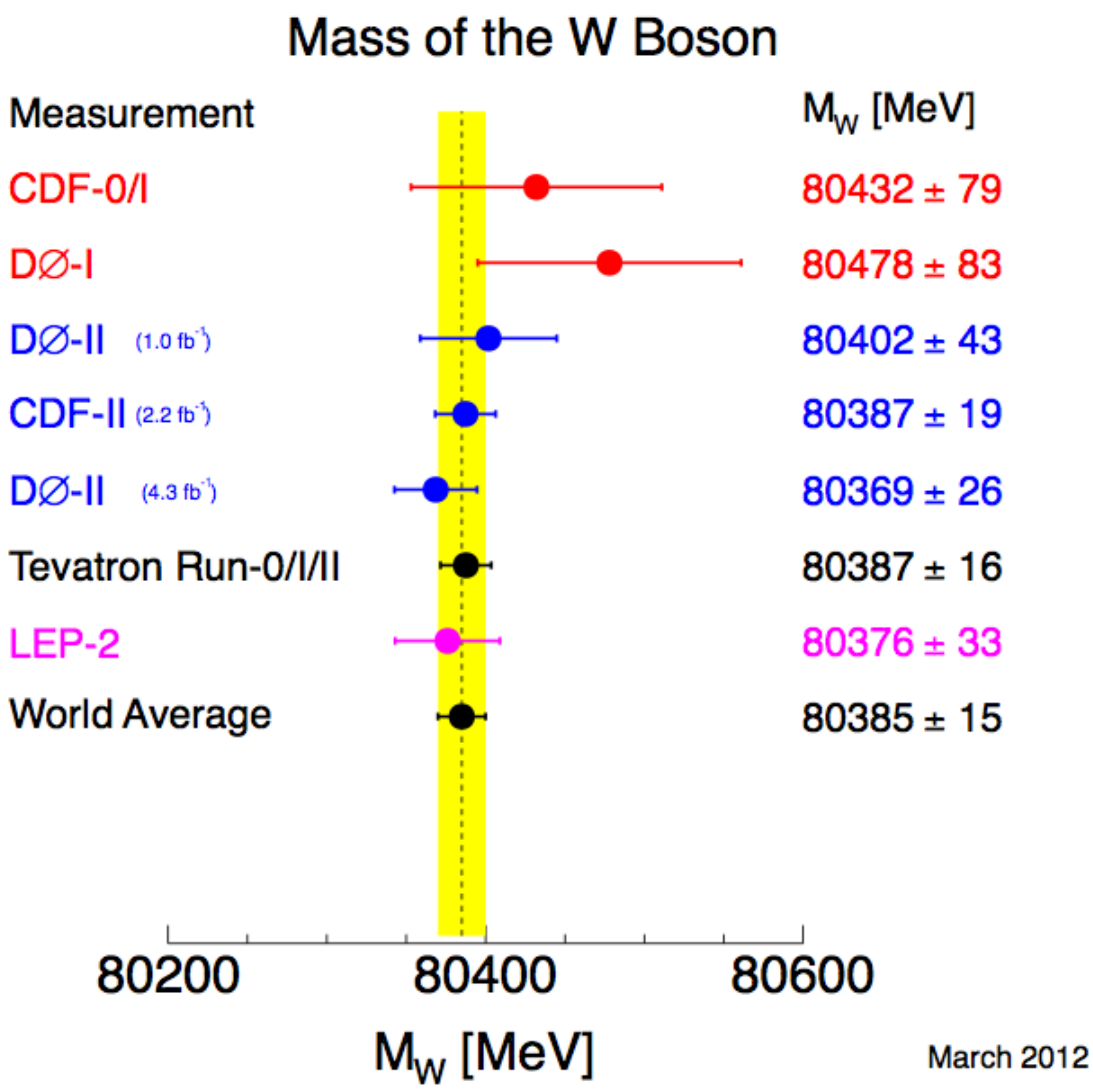
m_W^{fit}=80.400±0.027



m_W^{fit}=80.402±0.023

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

Tevatron W Mass Combinations

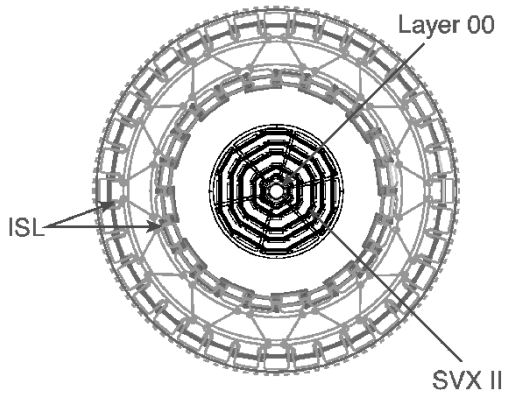


Very Precise!

Onward to the top quark mass!

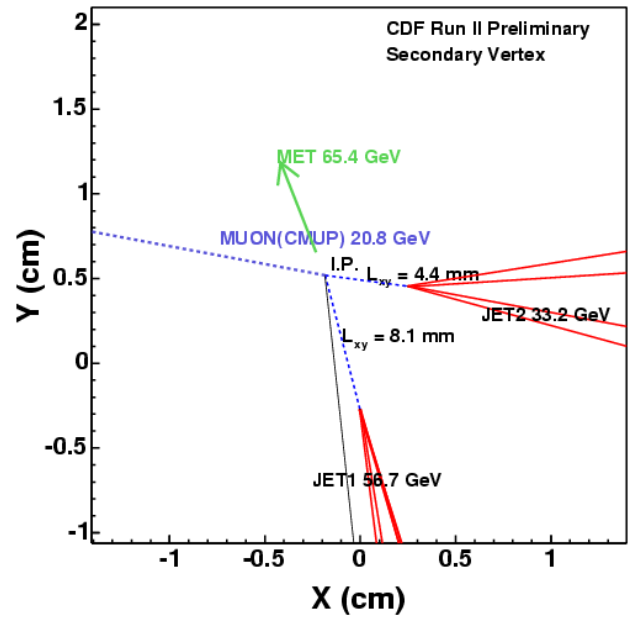
B-Tagging at CDF

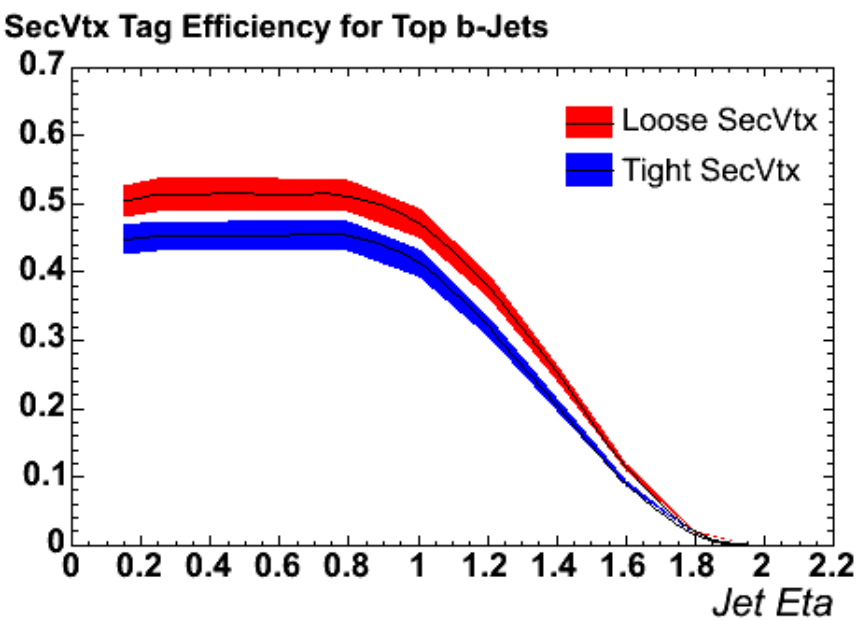
L00 single-sided silicon +
5-layer double-sided silicon+
2-layer ISL



Impact parameter resolution for high-p_T tracks ~18μm

B-tagging relies on displaced vertex reconstruction





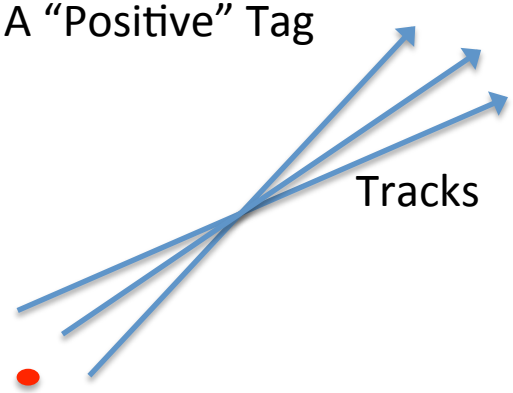
Mistag rates typically ~1% for light-flavor jets

Example candidate event

D0 B-tagging per-jet efficiency = 50-70% (of taggable jets) for 1-5% Mistag rate

B-Tagging Calibration

A "Positive" Tag

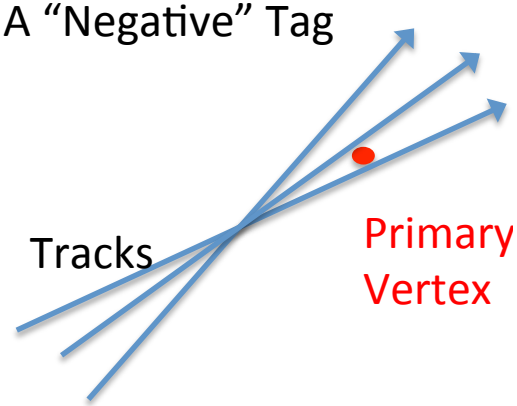


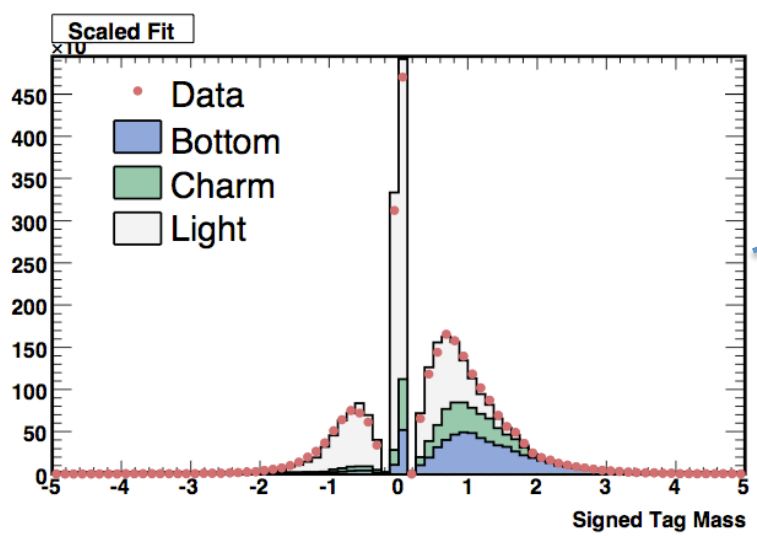
Fake tags calibrated with data – resolution dominated negative tags.

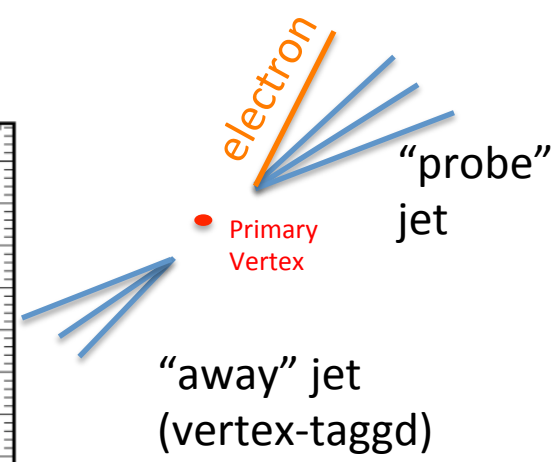
Watch out for asymmetry: scatters in detector material and long-lived strange particles cause more positive mistags than negative ones

Positive b-tags Calibrated in data with a sample of dijets – "away" jet is b-tagged, "probe" jet has a high-$P_{T,rel}$ electron. Tag rates compared in data and MC

A "Negative" Tag

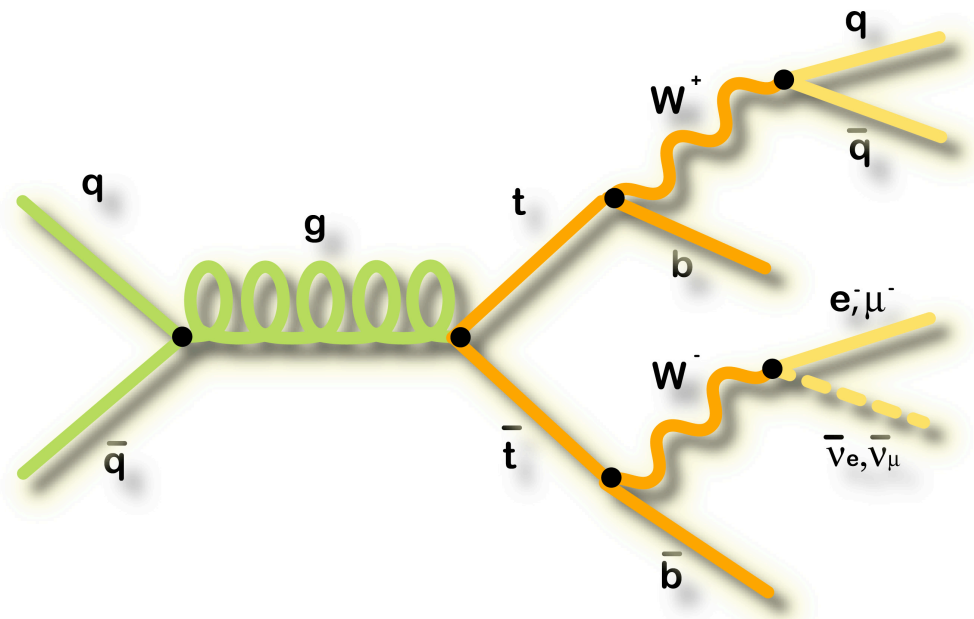




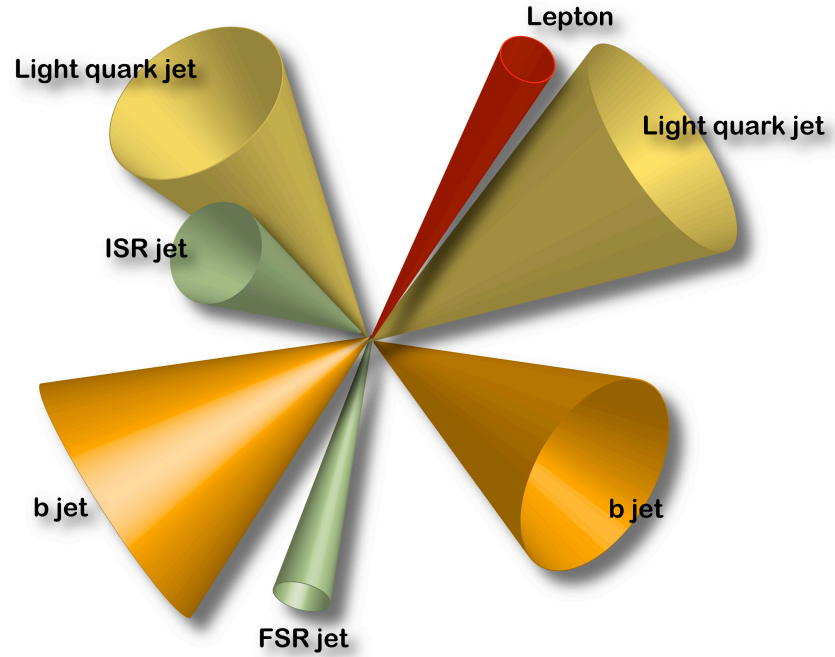


Top Quark Pair Production with Lepton+Jets Decay

Feynman Diagram



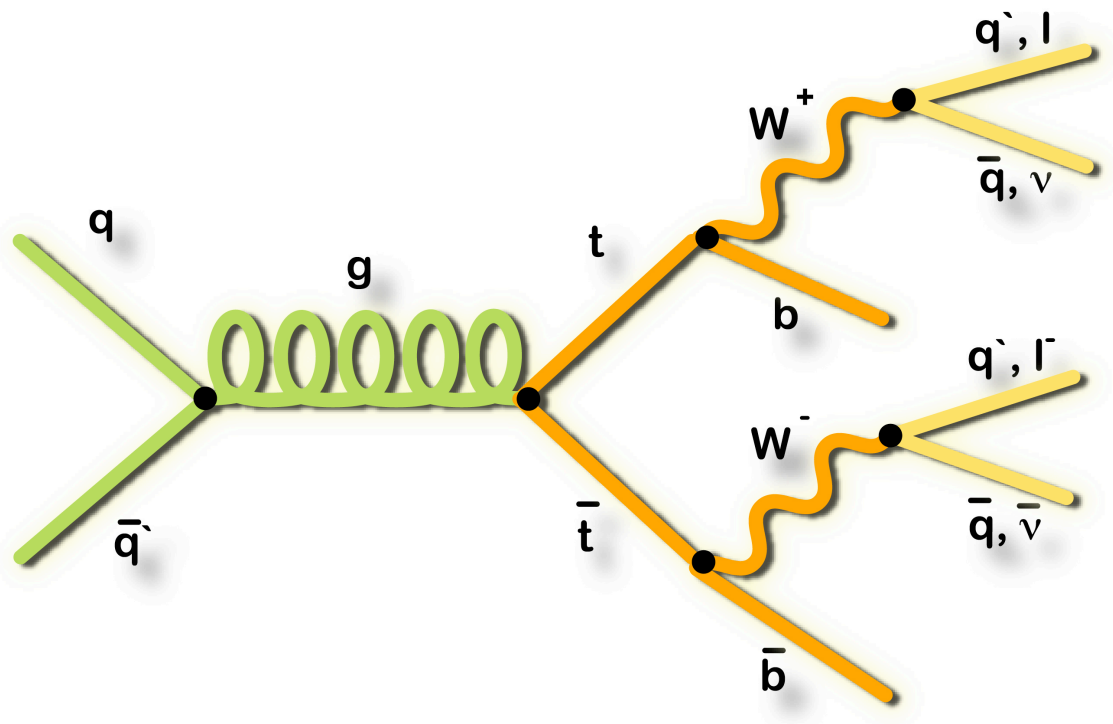
How it Looks in the Detector



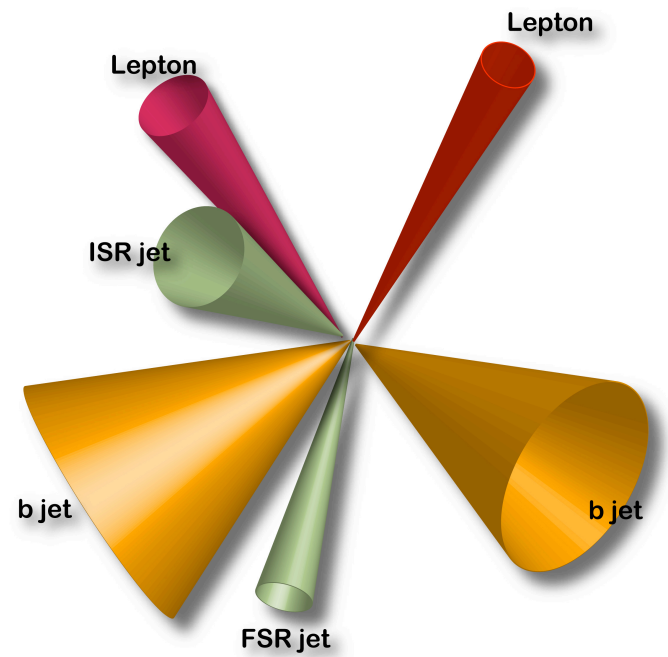
Also missing transverse energy due to the neutrino!

Top Quark Pair Production with Dilepton Decay

Feynman Diagram



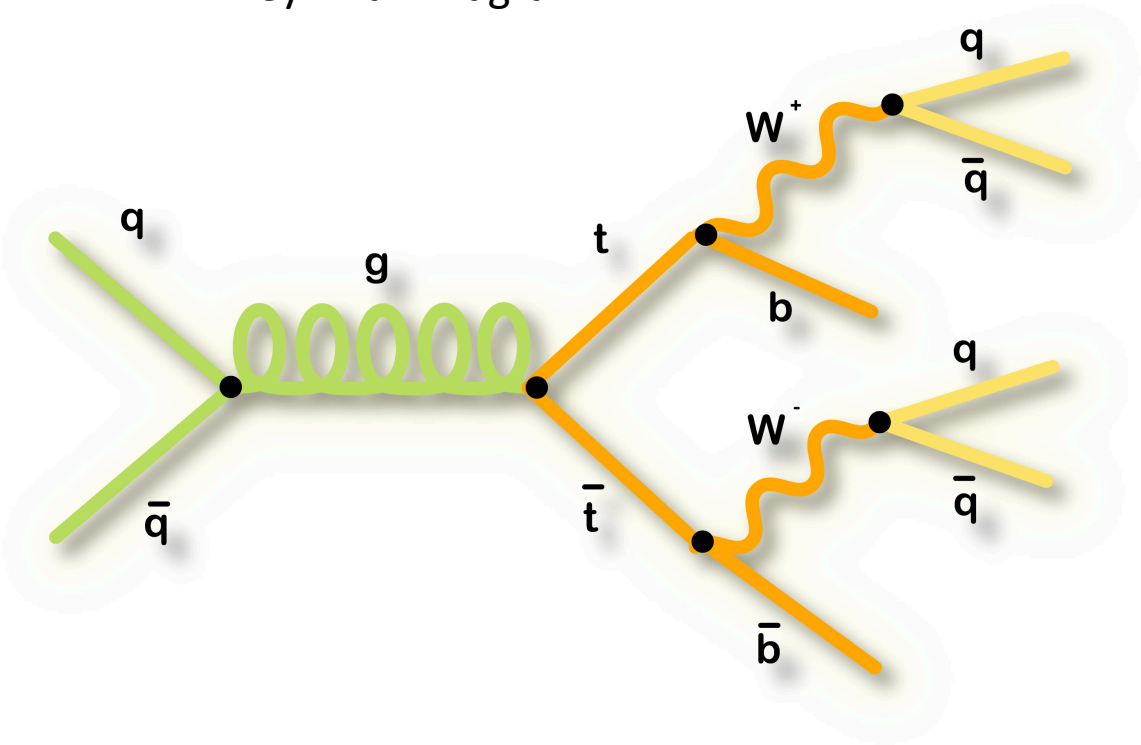
How it Looks in the Detector



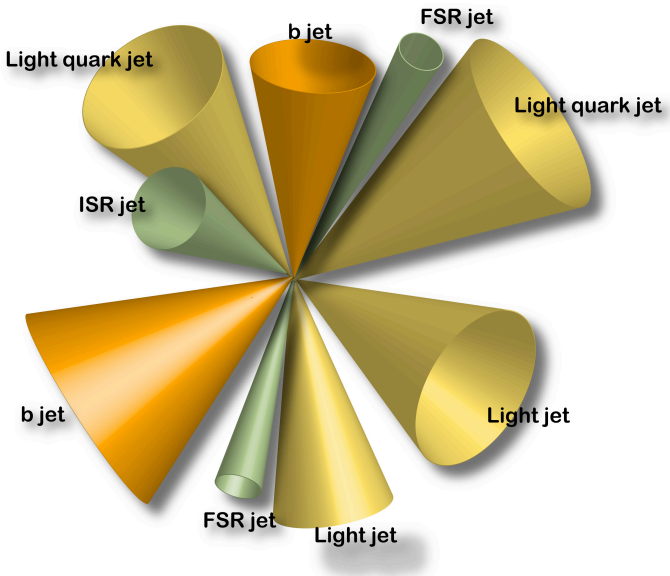
Also missing transverse energy due to the two neutrinos!

Top Quark Pair Production with All-Hadronic Decay

Feynman Diagram



How it Looks in the Detector



No real missing transverse energy (but plenty of opportunity to mismeasure jets!)

Top Quark Pair Production Cross Section Measurements

Ingredients: Select events with the right ingredients:

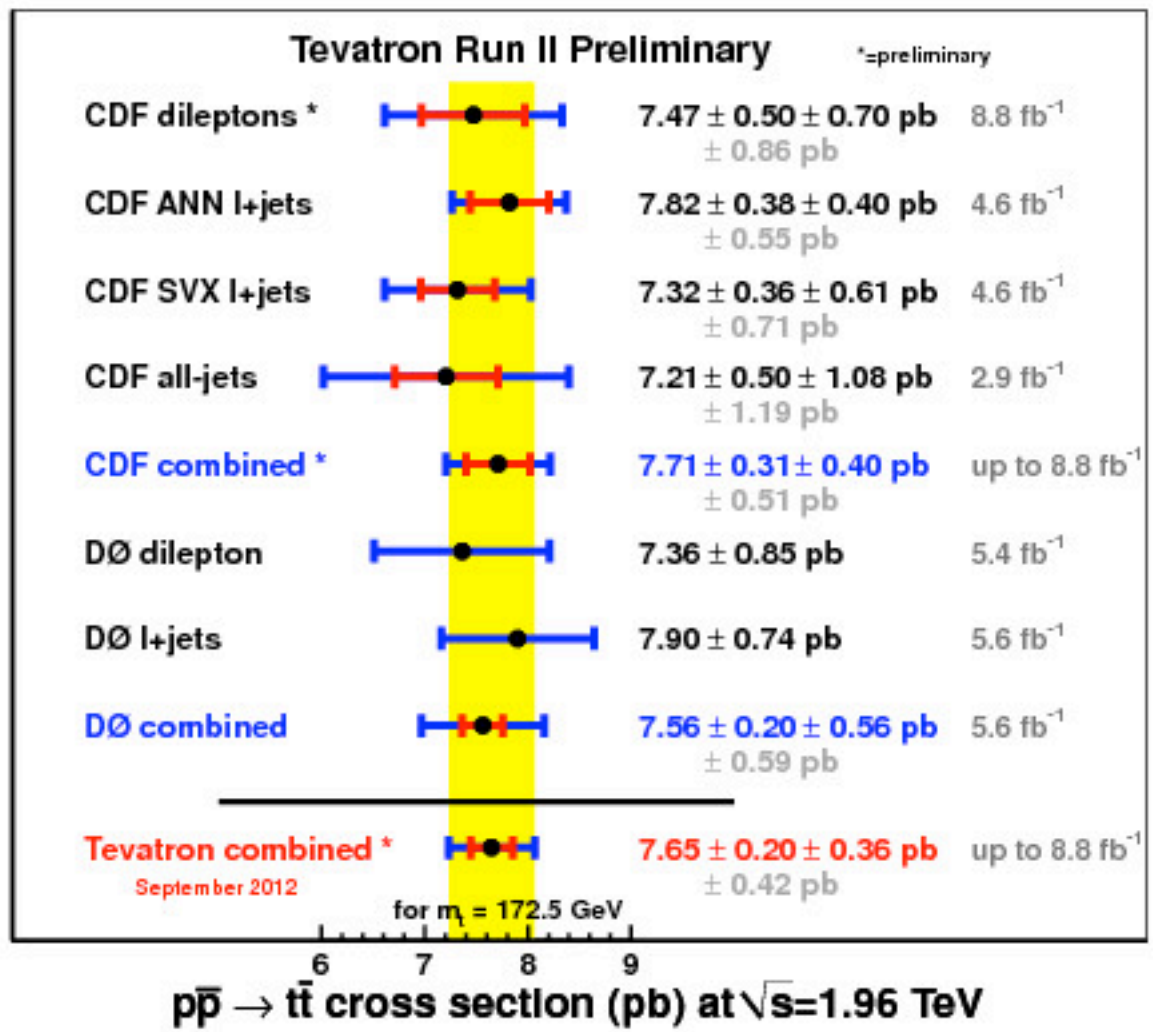
Leptons+jets(b)+Missing E_T

Dileptons + jets(b) + Missing E_T

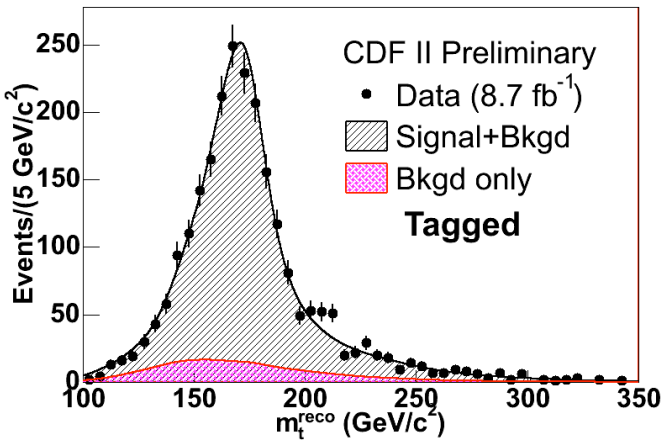
All-hadronic

Calibrate efficiencies and backgrounds – data and simulation techniques.

Measure total integrated luminosity. Or normalize to another production mode like Z production.

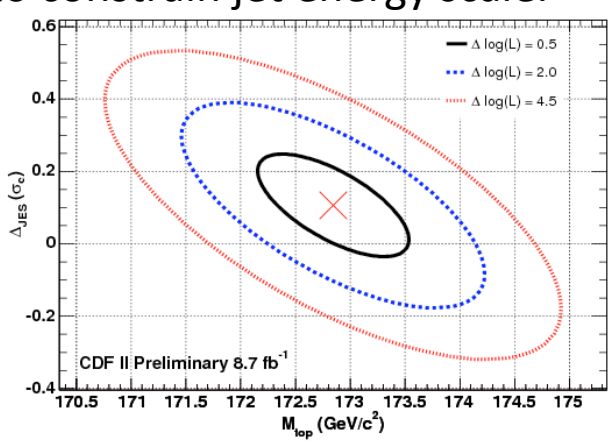


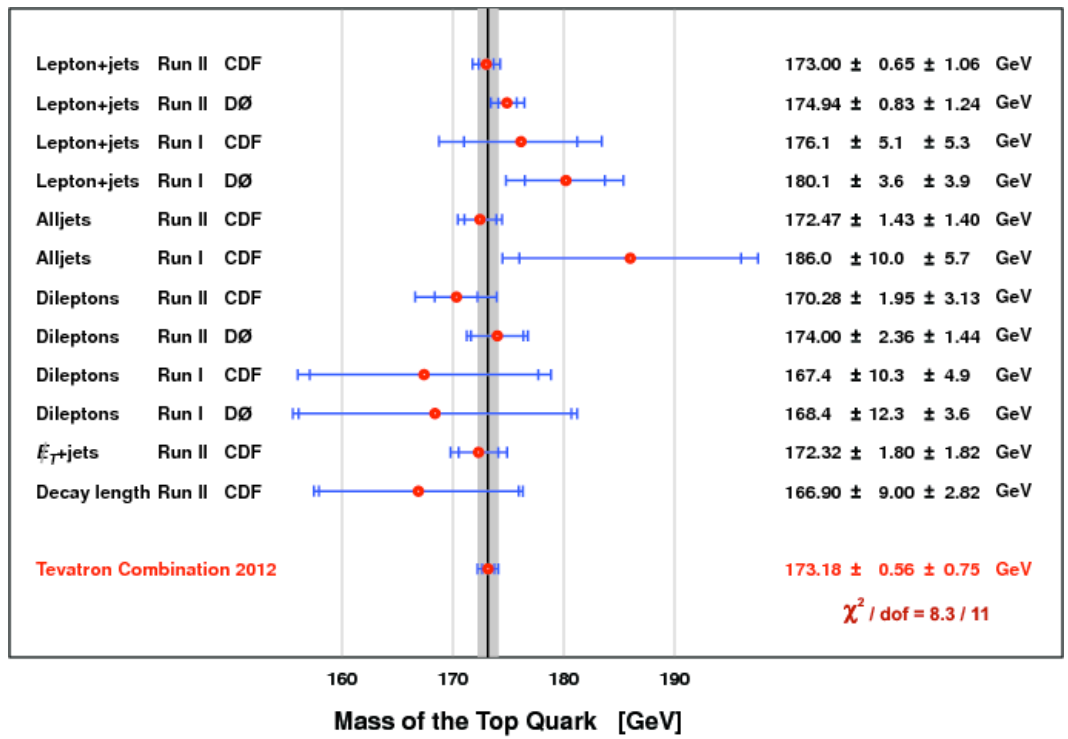
Measuring the Top Quark Mass

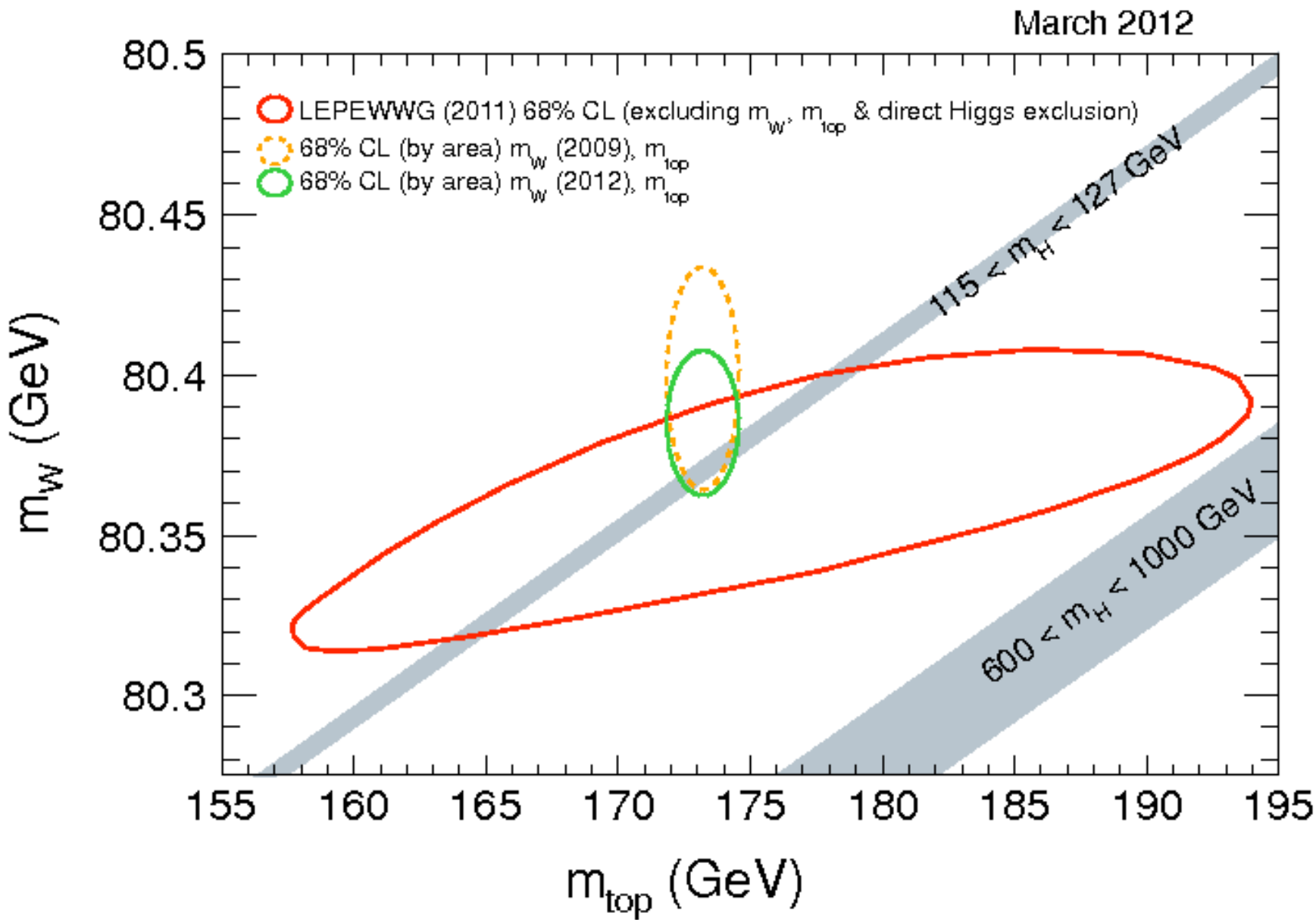


Ingredients: Select events, estimate backgrounds. Reconstruct invariant masses: Select assignment of jets to top quarks – or consider all such pairings, weighted with matrix-element probabilities.

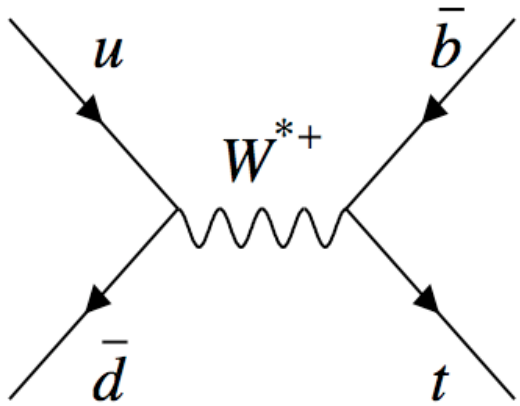
Largest source of systematic uncertainty that can be calibrated in the same sample is the jet energy scale. Use m_{jj}(W-candidate jets) to constrain jet energy scale.



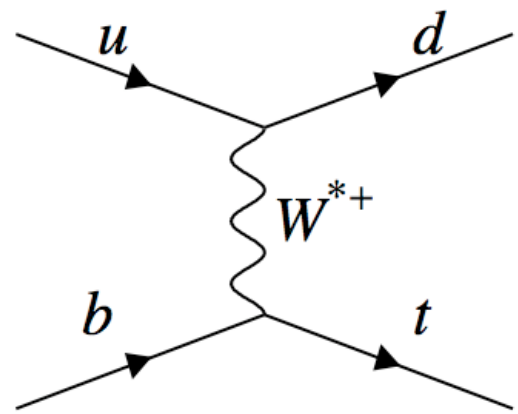



March 2012
LEPEWWG (2011) 68% CL (excluding m_W, m_top & direct Higgs exclusion)
68% CL (by area) m_W (2009), m_top
68% CL (by area) m_W (2012), m_top
115 < m_H < 127 GeV
600 < m_H < 1000 GeV
80.5
80.45
80.4
80.35
80.3
m_W (GeV)
155
160
165
170
175
180
185
190
195
m_top (GeV)

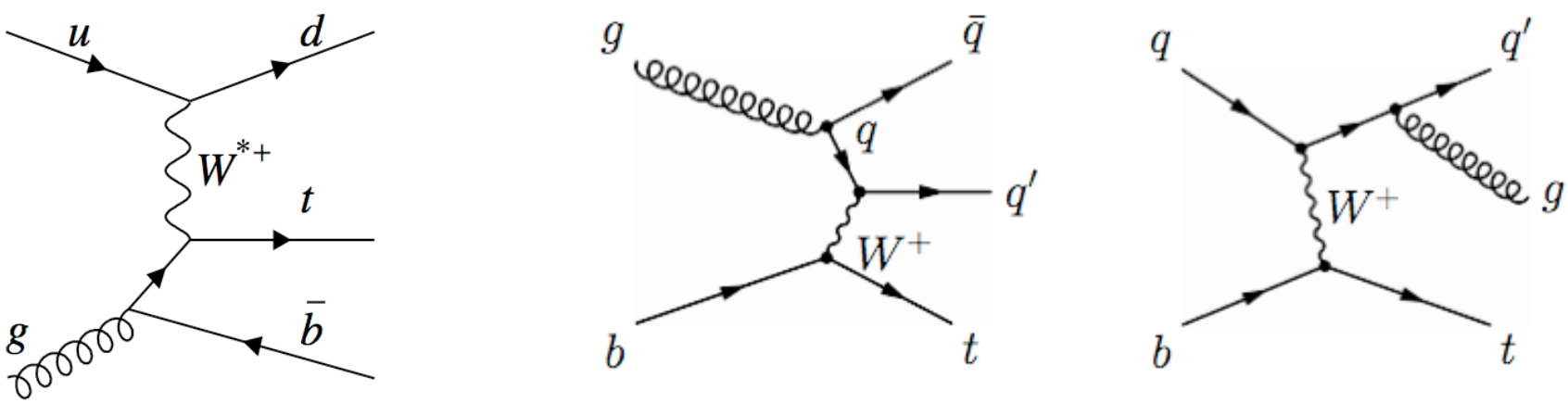
Single Top Production Mechanisms



"*s*-Channel"

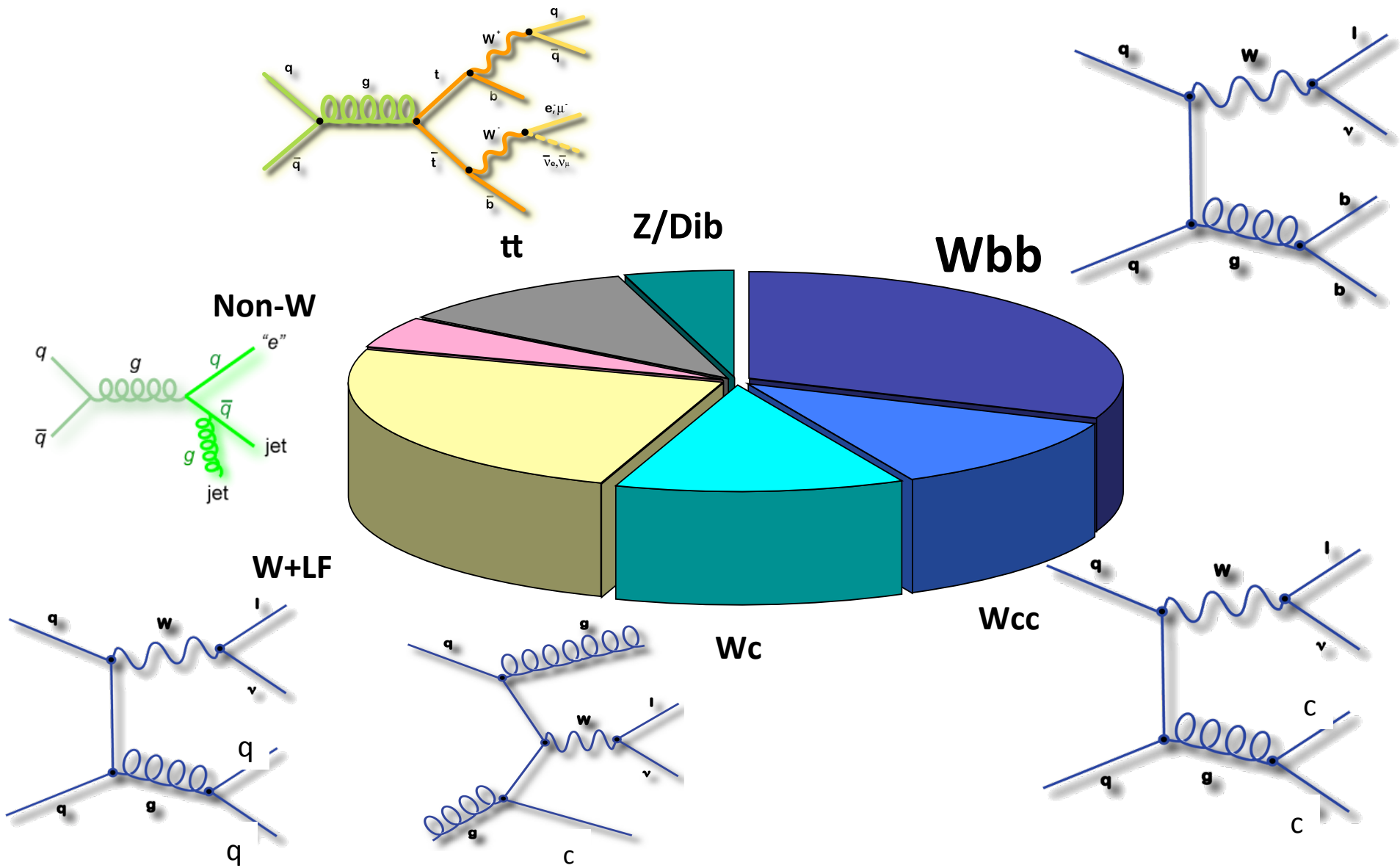


"*t*-Channel"

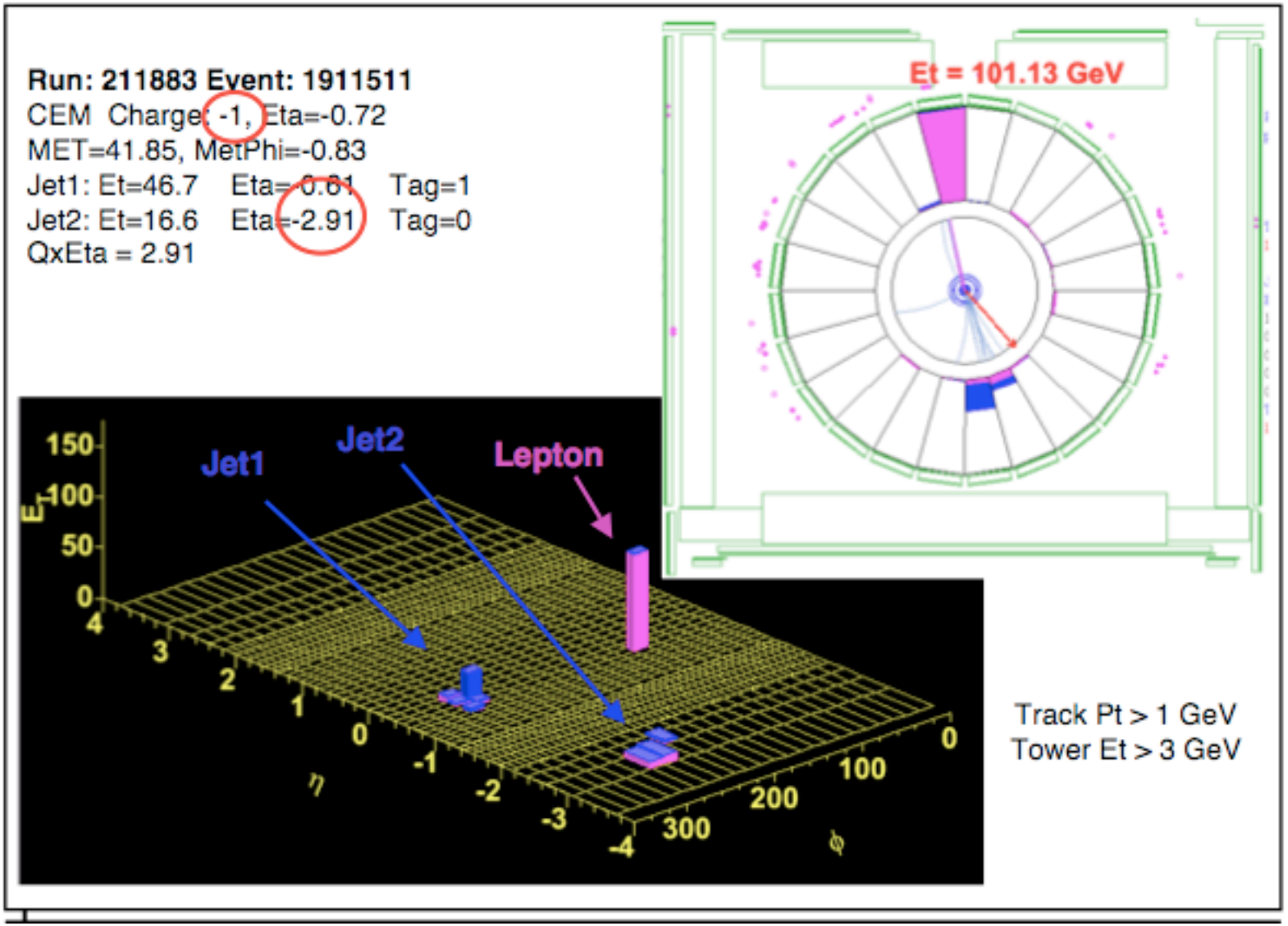


"NLO Contributions to *t*-Channel Production"

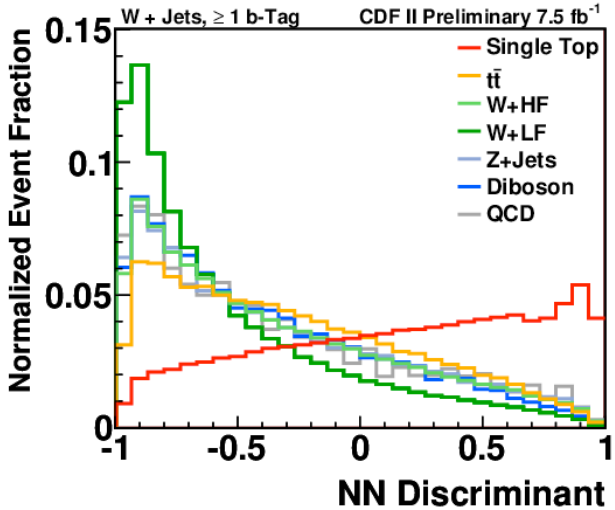
Backgrounds for Single Top and Higgs

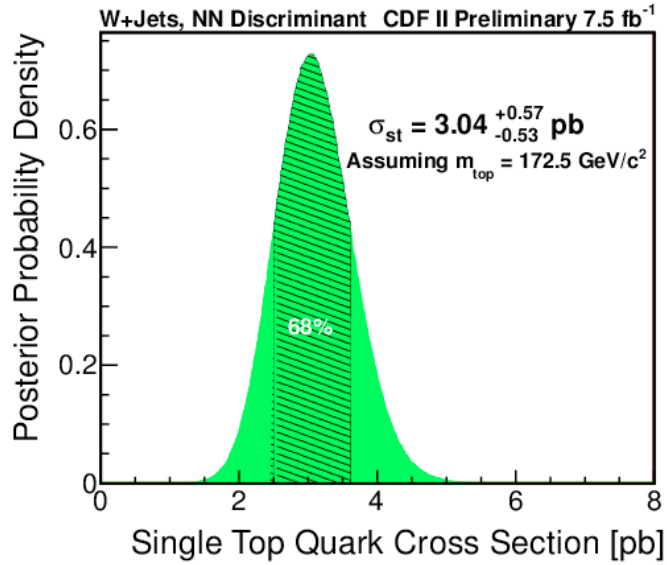


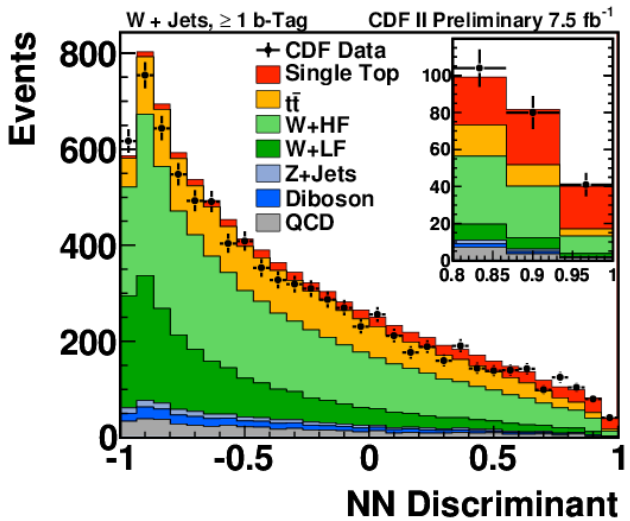
A High-Score Single Top Candidate Event

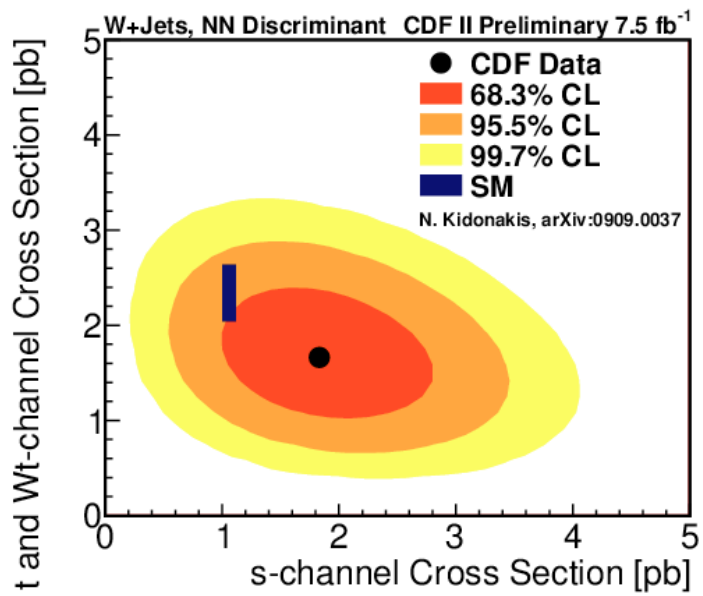


CDF's Single Top Production Measurements



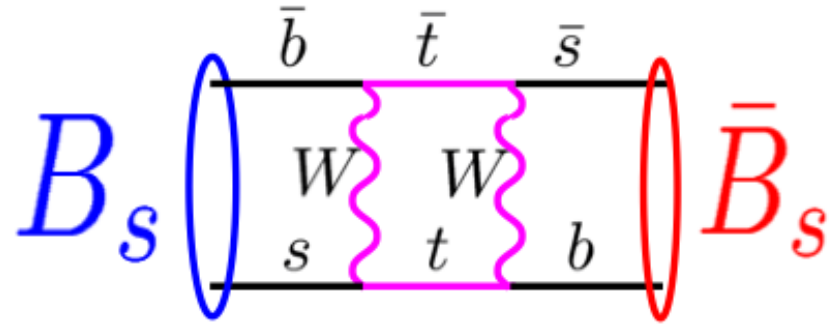






B_s oscillations

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

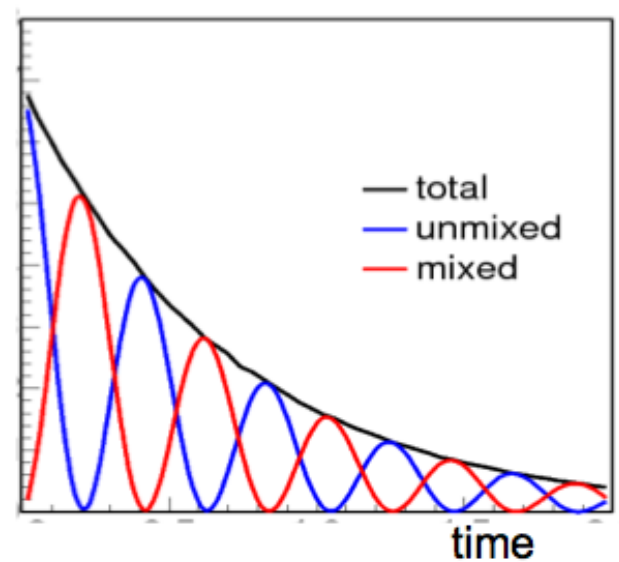


$$|\psi\rangle = e^{-iMt}\left(\cos\frac{\Delta m}{2}t|B_s\rangle + \sin\frac{\Delta m}{2}t|\bar{B}_s\rangle\right)$$

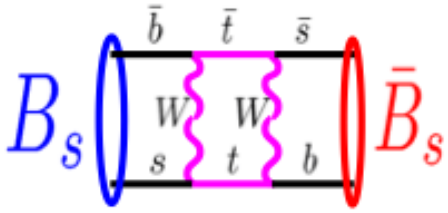
$$|\psi\rangle = e^{-iM_H t}|B_H> + e^{-iM_L t}|B_L>$$

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

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



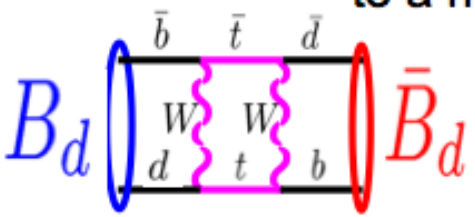
Δm_s and the CKM matrix



uncertainty ~10%

$$\Delta m_s \propto m_{B_s} f_{B_s}^2 B_{B_s} |V_{tb}V_{ts}^*|^2$$

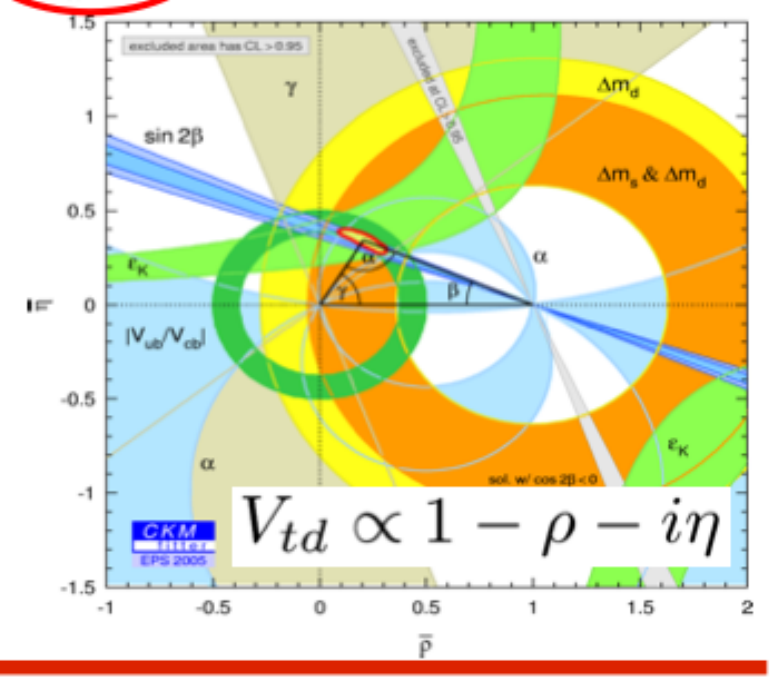
Can extract $|V_{ts}|$ with ~10% accuracy, or... translate to a measurement of $|V_{td}|$, combining with:



$$\Delta m_d \propto m_{B_d} f_{B_d}^2 B_{B_d} |V_{tb}V_{td}^*|^2$$

Hadronic uncertainty much reduced in the ratio:

$$\frac{\Delta m_s}{\Delta m_d} = \frac{m_{B_s} f_{B_s}^2 B_{B_s}}{m_{B_d} f_{B_d}^2 B_{B_d}} \left|\frac{V_{ts}}{V_{td}}\right|^2 = 1.21 \pm 0.05 \left|\frac{V_{ts}}{V_{td}}\right|^2$$

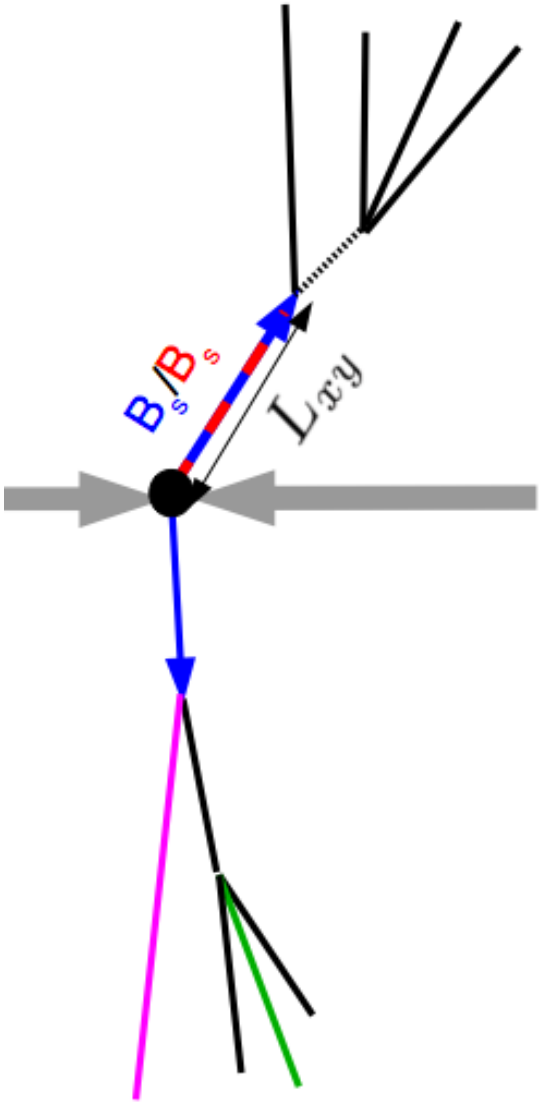


Turn the argument around: prediction for Δm_s:

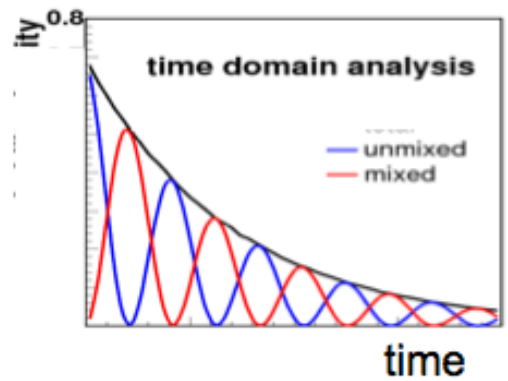
Δm_s: $18.3^{+6.5}_{-1.5}$ (1σ) : $^{+11.4}_{-2.7}$ (2σ) ps^{-1}

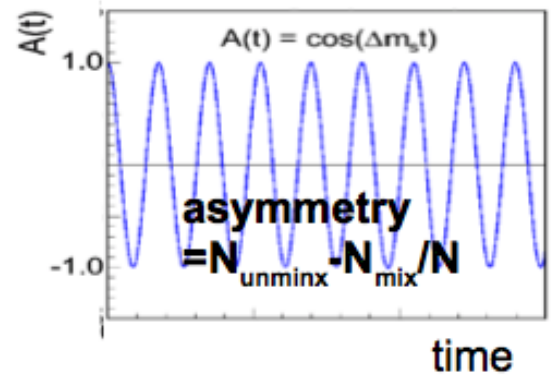
Go and measure if SM is right..

How do we look for mixing?

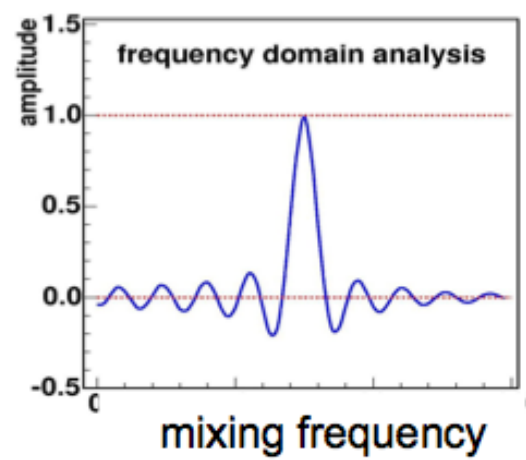


- Make a B_s meson and measure its flavour when it decays
- Identify the flavour at production (tagging)
- Look at oscillation probability vs proper decay time.



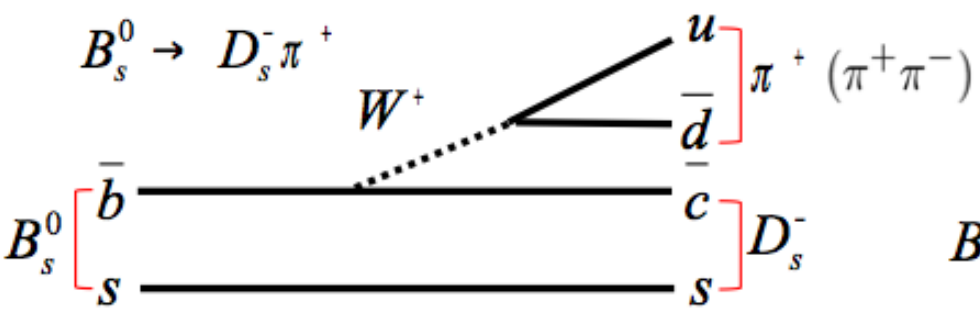


Fourier component of asymmetry: Mixing *amplitude*



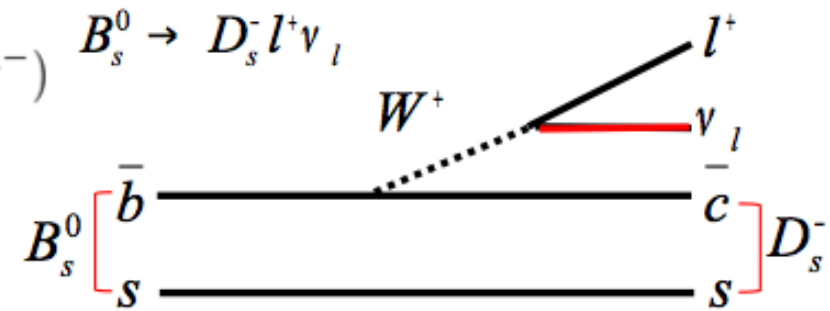
The signals

Hadronic



- B_s Momentum is measured
- B_s mass used for good S/N
- Small branching ratio: low yield

Semileptonic

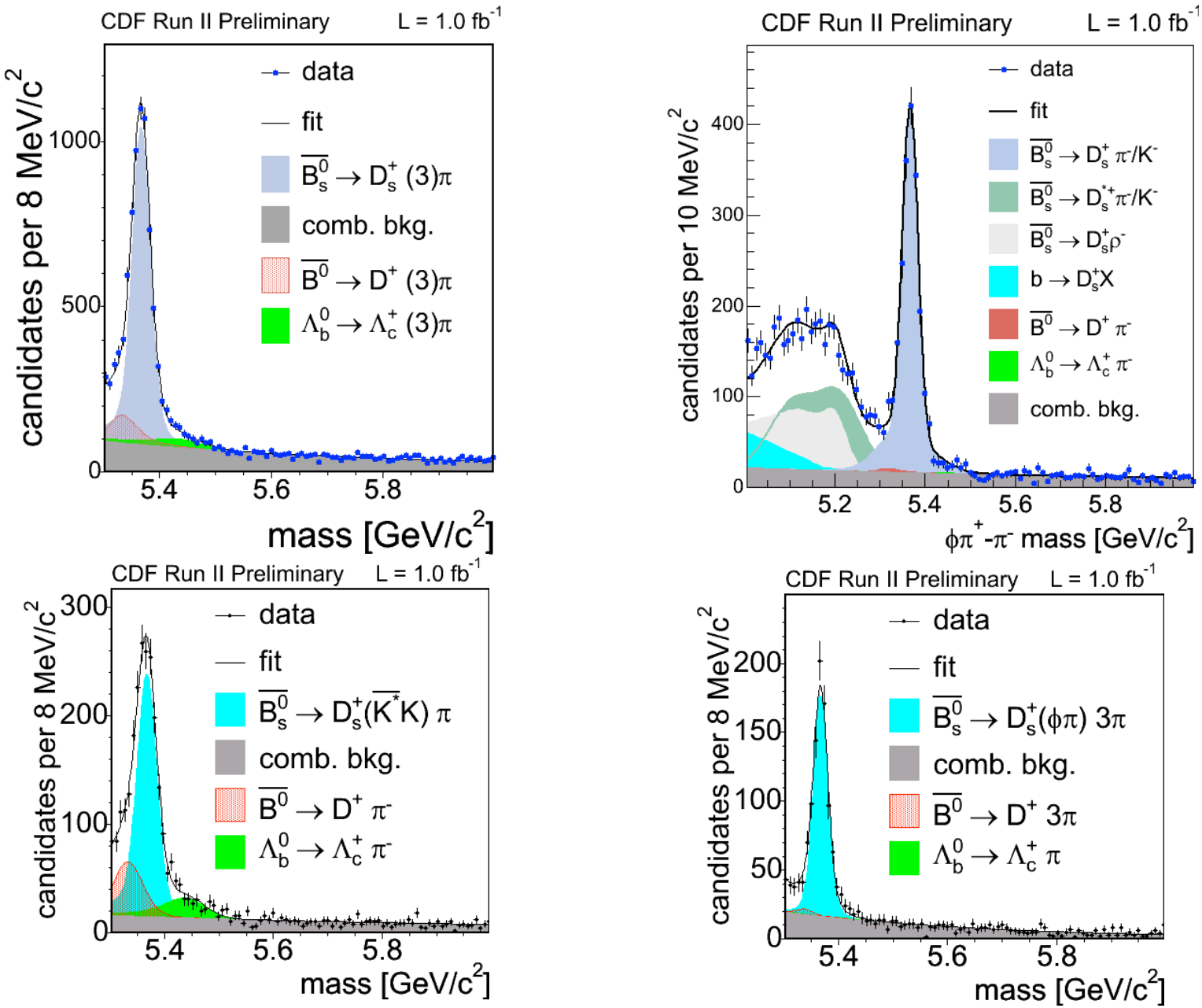


- Missing momentum (ν)
- Need to rely on lD_s and D_s mass
- Large branching ratio: high yield

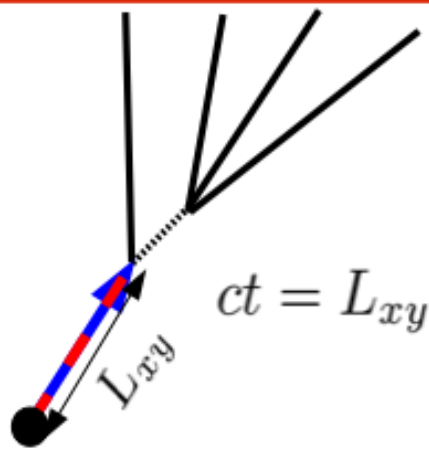
$$D_s^- \to \phi\pi^-, \quad \phi \to K^+K^-;$$
$$D_s^- \to K^{*0}K^-, \quad K^{*0} \to K^+\pi^-;$$
$$D_s^- \to \pi^+\pi^-\pi^-.$$

data collected using:
- Hadronic: Two Track Trigger
- semileptonic: TTT & lepton+SVT

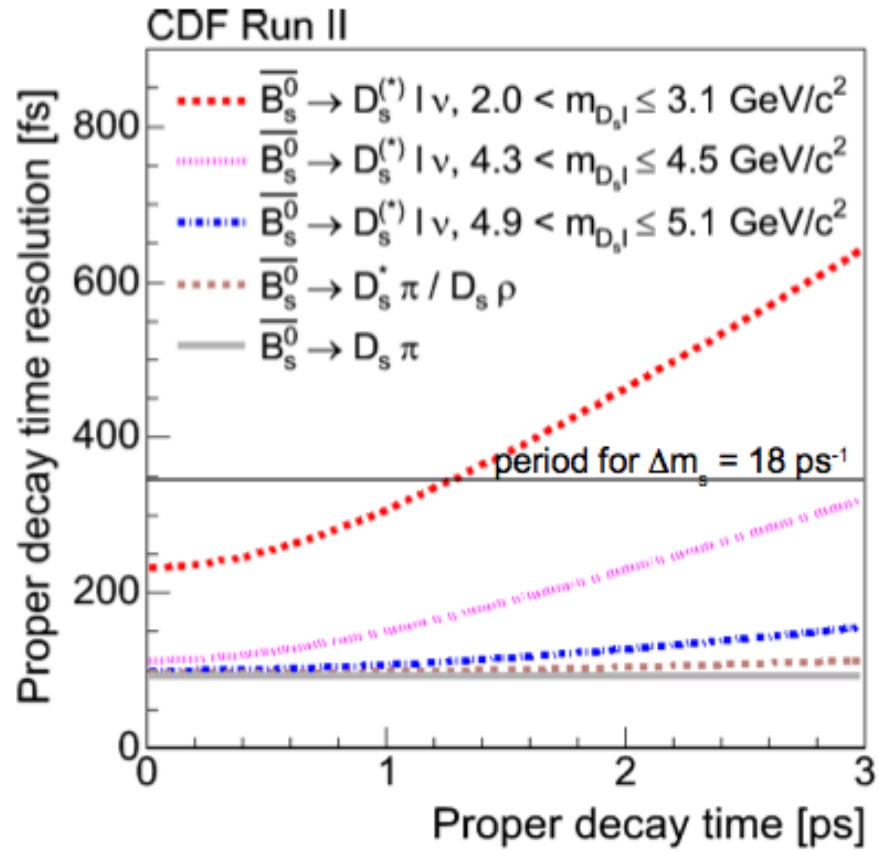
SVT rules!


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]

Proper time resolution



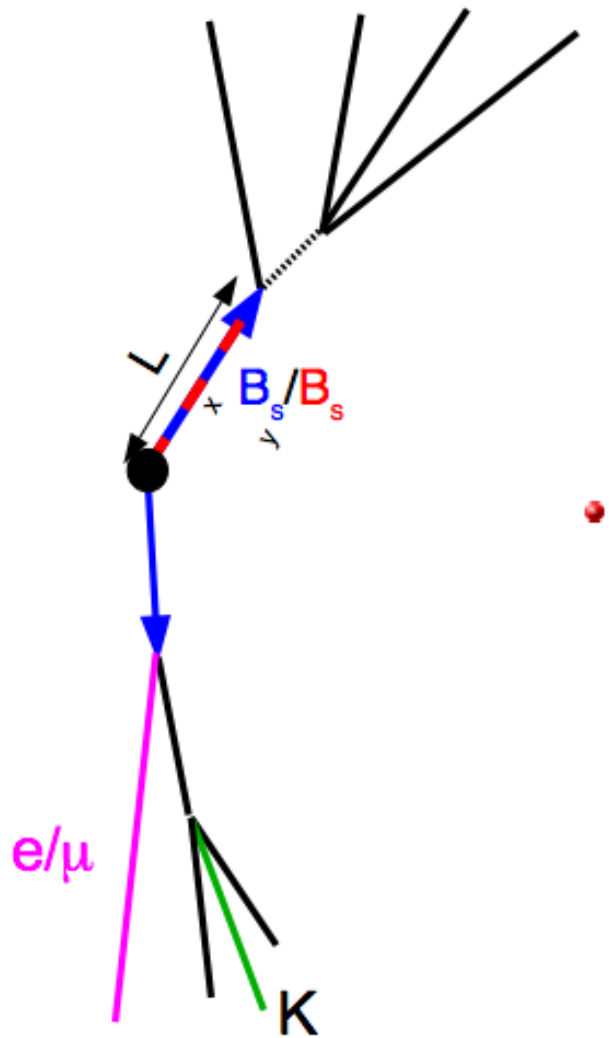
$$ct = L_{xy}\frac{m_{B_s}}{p_T}$$



- Fully rec. hadronic:
  P_T measured perfectly, only contribution from $\sigma(L_{xy})$. Excellent ct resolution
- Semileptonic:
  Uncertainty due to missing momentum
  - more important at large L_{xy} (i.e. large ct)
  - PDF of missing momentum fraction from MC
  - Dependence on Mass of Ds l-system used in the fit
- Partially reconstructed hadronic:
  almost as good as fully rec. (small missing p_T)

decay time resolution
=
¼ oscillation period

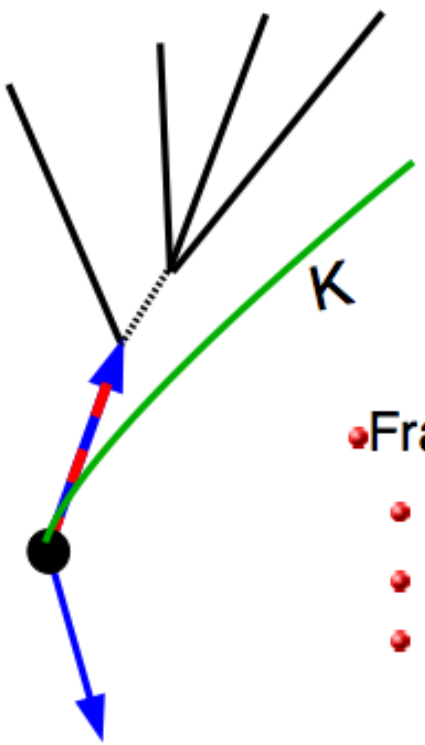
Opposite side flavor tagging (OST)

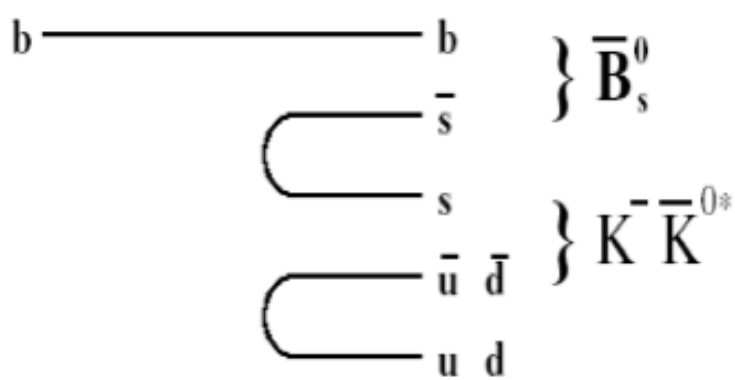


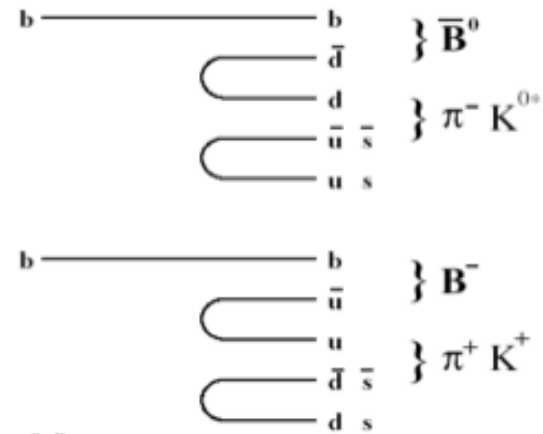
- Look at the decay products of the other b quark in the event to determine B_s production flavor
  - Lepton
  - Kaon
  - Charge of the b-jet
- The two b quarks fragment *independently*: can calibrate opposite side taggers with B_d & B_u
- Opposite side often outside acceptance

- Improvements:
  - Added the Kaon tagger
  - In stead of exclusively applying taggers, combine all three OST using NN
    - uses the 3 tagger decisions, predicted dilutions, kinematics, Kaon- and lepton PID likelihoods
  - **tagging quality (εD^2) from 1.5% to 1.8% improvement of 20%!**

Same side kaon tagging

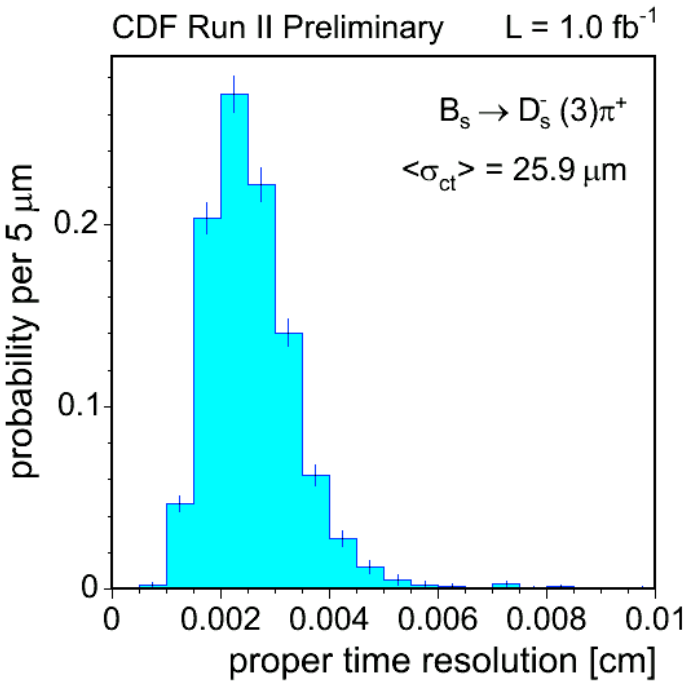


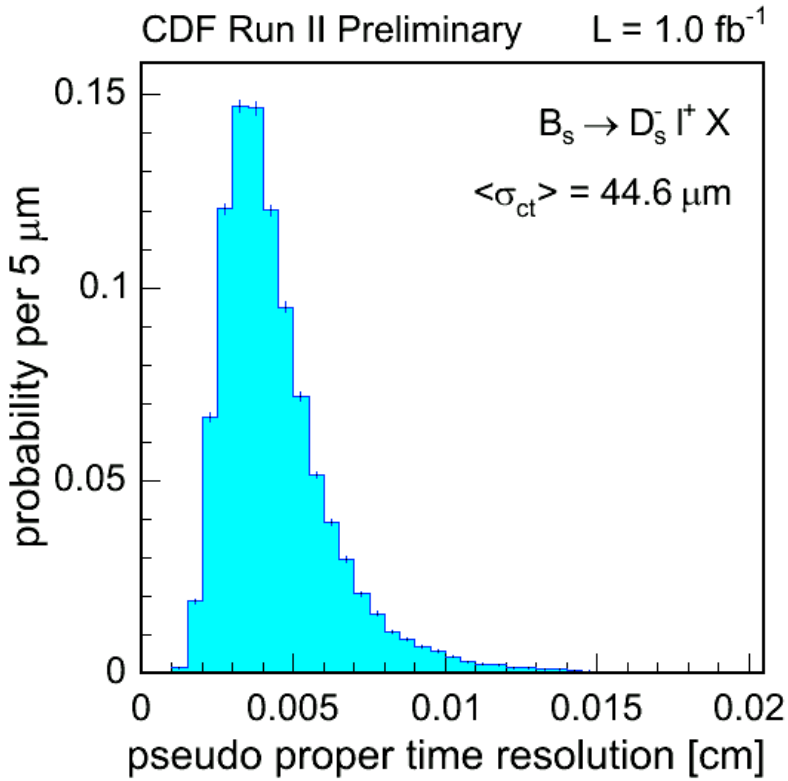




- Fragmentation into B_s tends to produce Kaon
  - Charge of K identifies B_s flavor at production
  - B^0 and B^+ mostly accompanied by pions
  - High efficiency, since K is close to the Bs
    - >2 times as powerful as OST: εD^2=3.5% (had) / 4.8% (SL)
- previously:
  - Used PID to select kaon tracks and predict the Dilution
- now:
  - Combine PID with kinematic info of the tracks using neural network.
  - 6% relative improvement in εD^2 (seen in MC)

Decay Time Resolutions

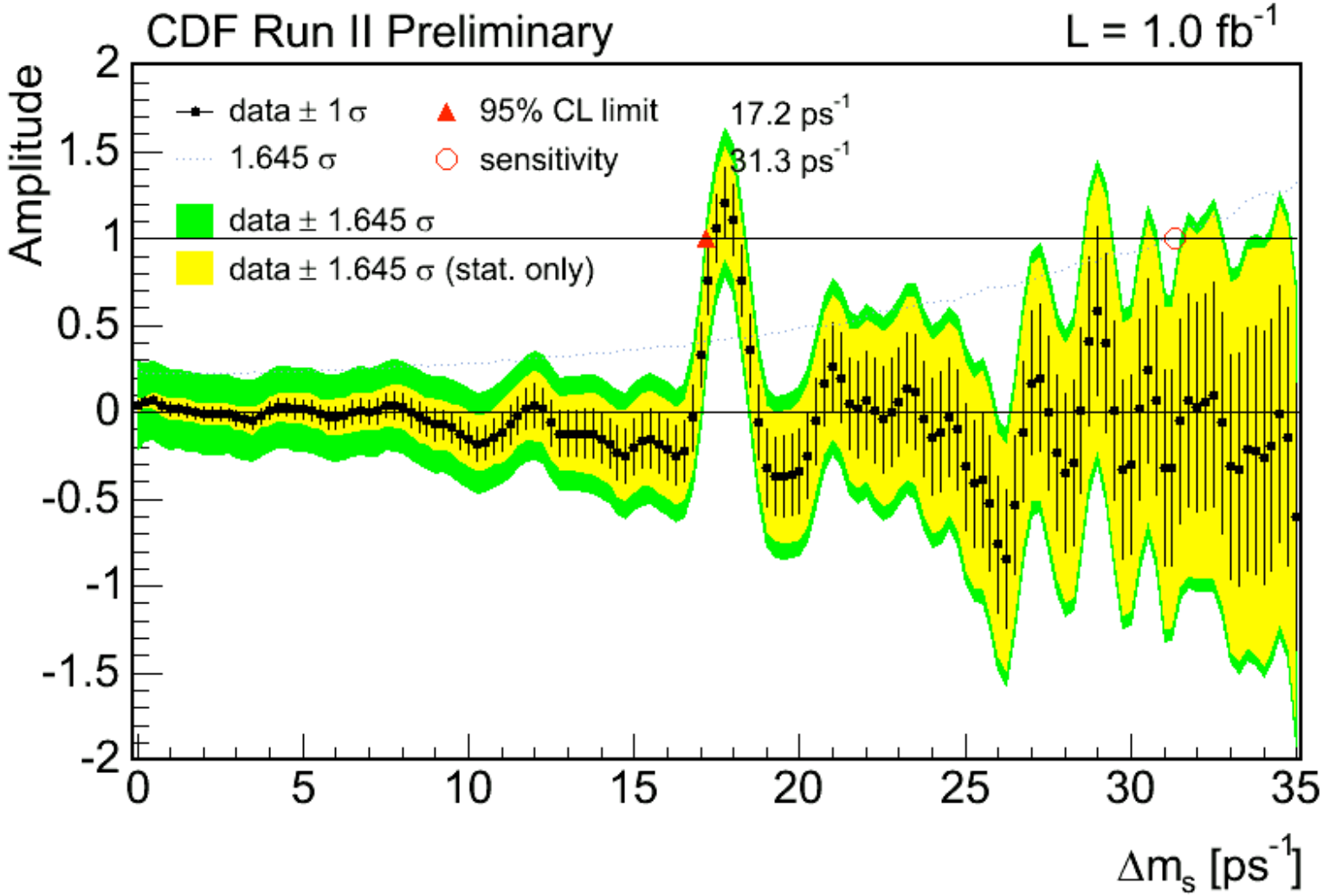




Hadronic modes – fully reconstructed

Semileptonic modes – missing a neutrino

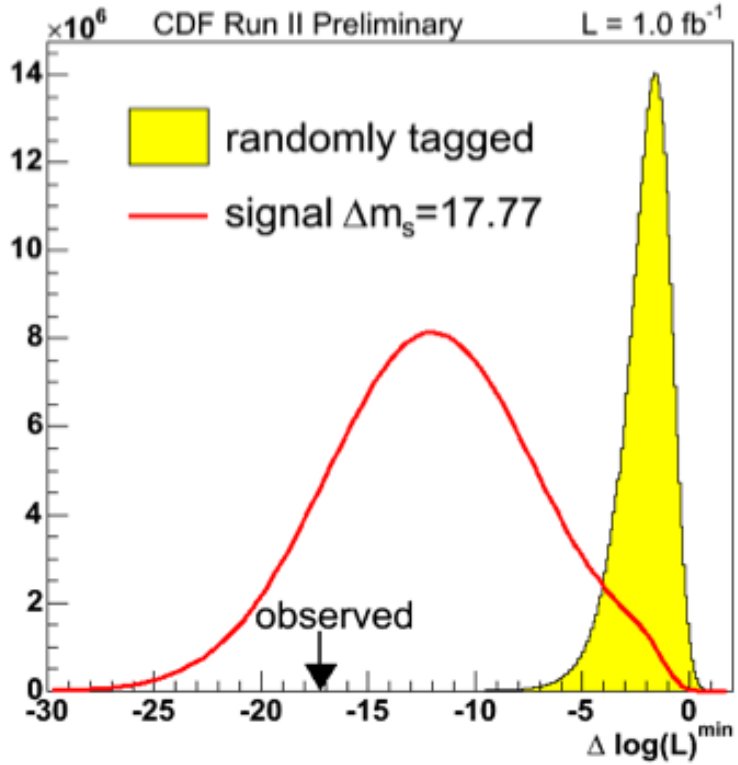
The Amplitude Scan for B_s Mixing

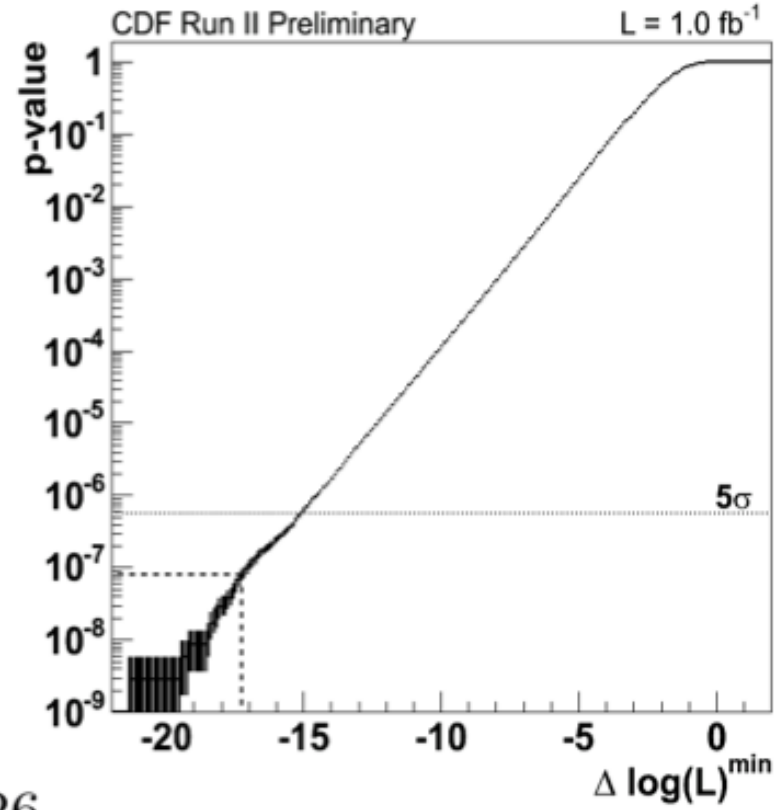


Significance

Randomize the tagger decisions of the data events and repeat the likelihood scan

many many, many, many, many, **many**, many, many, many, many, **many**, many, many, many, many, **many**, many, many, many, *many*, many, **many**, many times



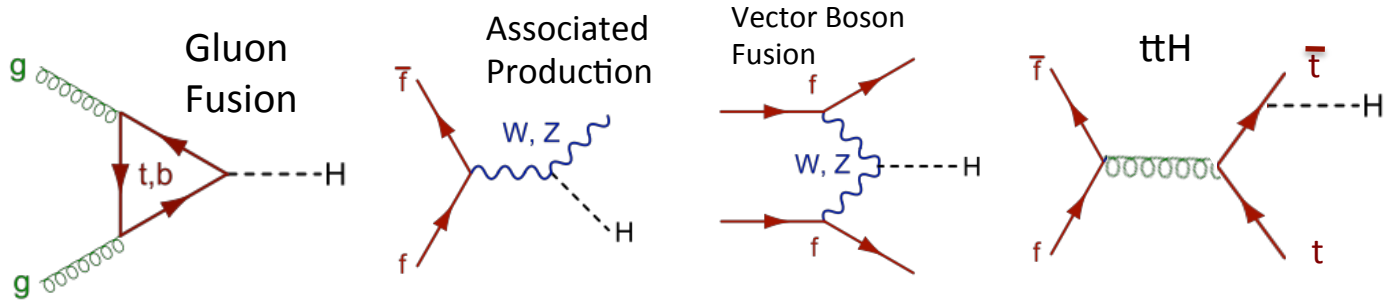


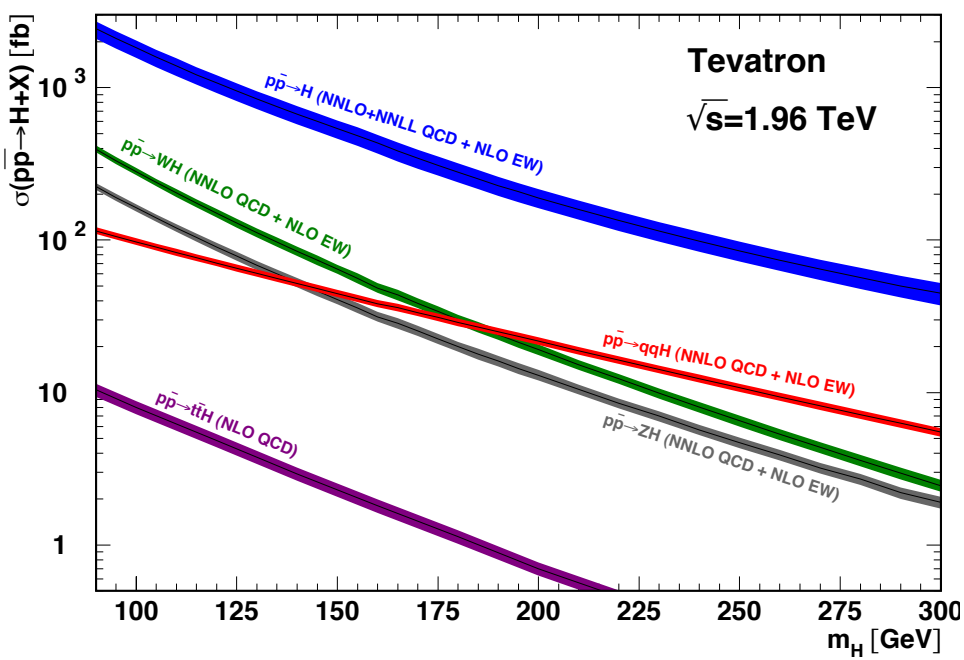
$$p = \frac{28 \text{ scans with } \Delta\log(\mathrm{L}) < -17.26}{3.5 \times 10^8 \text{trials}} = 8 \times 10^{-8}$$

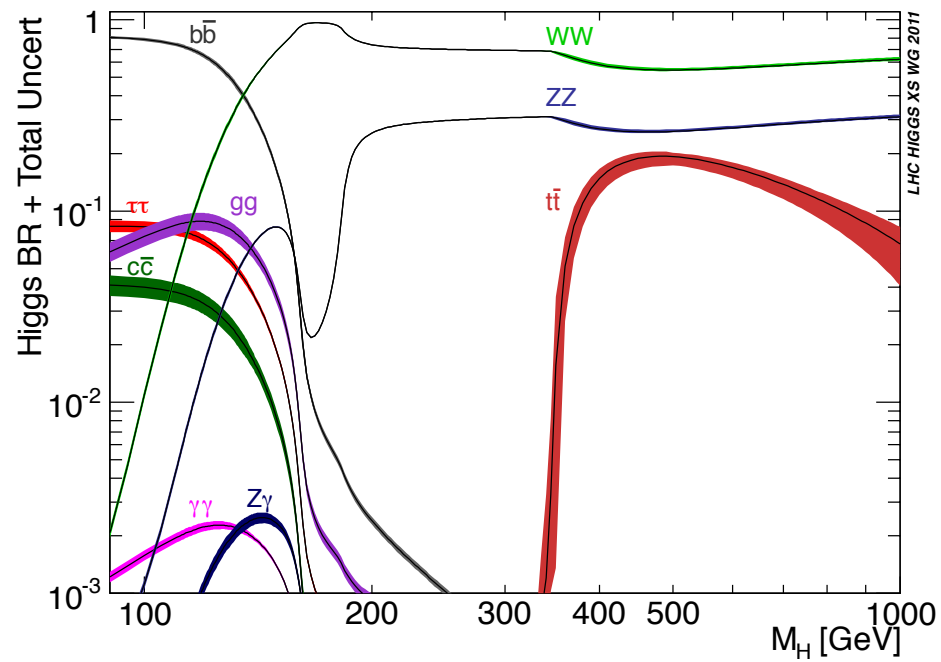
$$\text{significance} = 5.4\sigma$$

"Observation"

SM Higgs Boson Production and Decay Rates







Primary analysis modes:

m_H<130 GeV: VH→Vbb
m_H>130 GeV: gg→H→WW

Additional modes:

H→ττ, H→γγ, H→ZZ→4l
ttH→ttbb

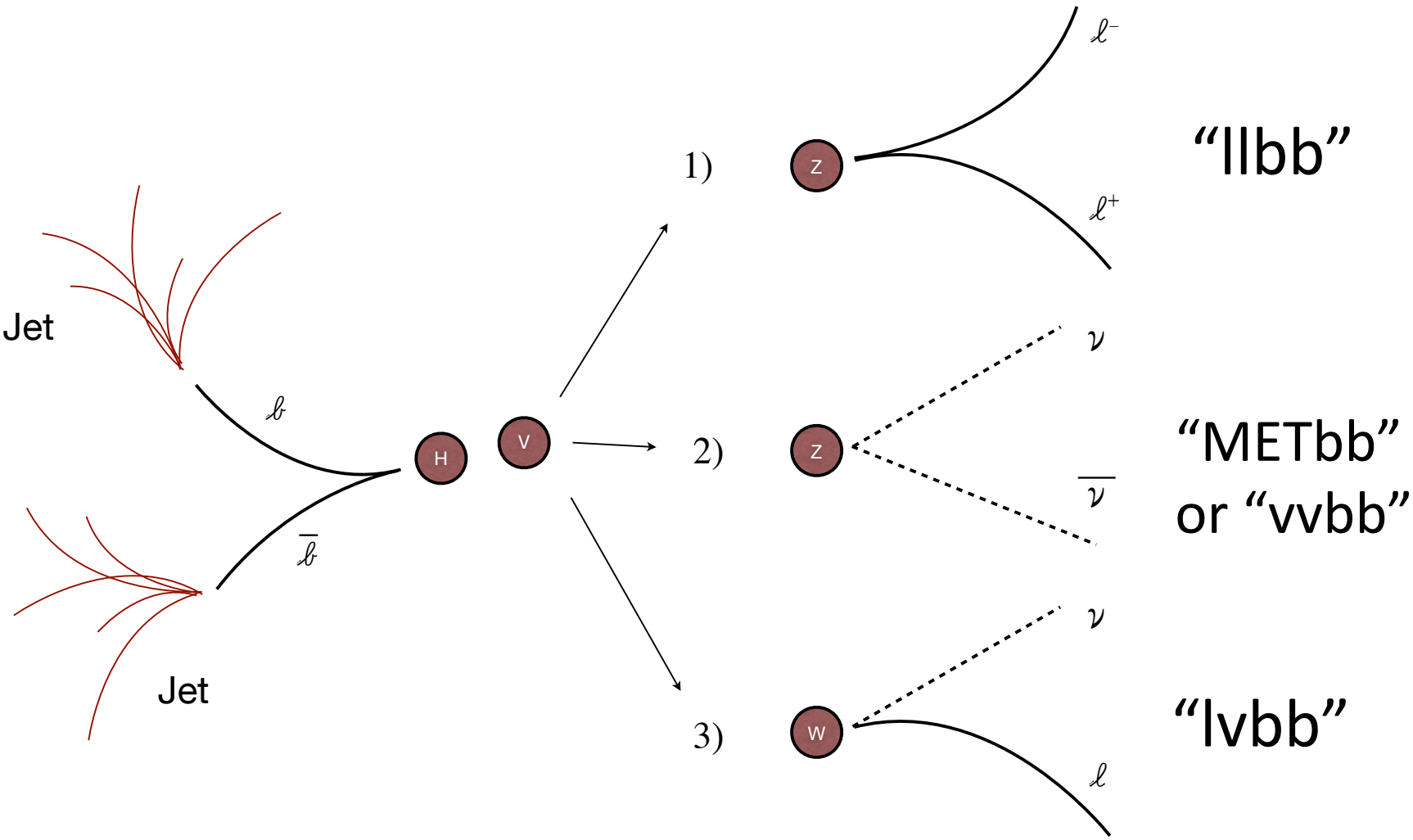
All CDF SM Search Channels

Channel		Luminosity (fb^{-1})	m_H range (GeV/c^2)
$WH \to \ell\nu b\bar{b}$ 2-jet channels 4×(5 b-tag categories)		9.45	90–150
$WH \to \ell\nu b\bar{b}$ 3-jet channels 3×(2 b-tag categories)		9.45	90–150
$ZH \to \nu\bar{\nu}b\bar{b}$ (3 b-tag categories)		9.45	90–150
$ZH \to \ell^+\ell^-b\bar{b}$ 2-jet channels 2×(4 b-tag categories)	$H \to b\bar{b}$	9.45	90–150
$ZH \to \ell^+\ell^-b\bar{b}$ 3-jet channels 2×(4 b-tag categories)		9.45	90–150
$WH + ZH \to jjb\bar{b}$ (2 b-tag categories)		9.45	100–150
$t\bar{t}H \to W^+bW^-\bar{b}b\bar{b}$ (4 jets,5 jets,≥6 jets)×(5 b-tag categories)		9.45	100-150
$H \to W^+W^-$ 2×(0 jets)+2×(1 jet)+1×(≥2 jets)+1×(low-$m_{\ell\ell}$)		9.7	110–200
$H \to W^+W^-$ (e-$\tau_{\rm had}$)+(μ-$\tau_{\rm had}$)		9.7	130–200
$WH \to WW^+W^-$ (same-sign leptons)+(tri-leptons)	$H \to W^+W^-$	9.7	110–200
$WH \to WW^+W^-$ (tri-leptons with 1 $\tau_{\rm had}$)		9.7	130–200
$ZH \to ZW^+W^-$ (tri-leptons with 1 jet,≥2 jets)		9.7	110–200
$H \to \tau^+\tau^-$ (1 jet)+(≥2 jets)	$H \to \tau^+\tau^-$	6.0	100–150
$H \to \gamma\gamma$ 1×(0 jet)+1×(≥1 jet)+3×(all jets)	$H \to \gamma\gamma$	10.0	100–150
$H \to ZZ$ (four leptons)	$H \to ZZ$	9.7	120–200

All D0 SM Search Channels

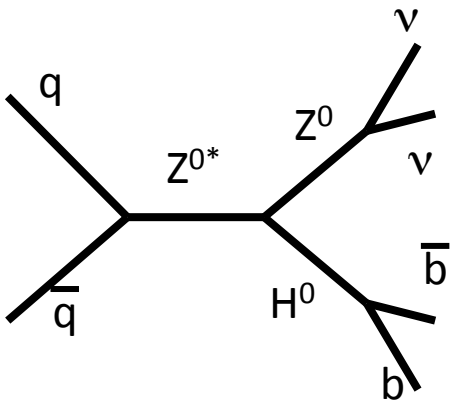
Channel		Luminosity (fb^{-1})	m_H range (GeV/c^2)
$WH \to \ell\nu b\bar{b}$ (4 b-tag categories)×(2 jets, 3 jets)	$H \to b\bar{b}$	9.7	90–150
$ZH \to \nu\bar{\nu}b\bar{b}$ (2 b-tag categories)		9.5	100–150
$ZH \to \ell^+\ell^-b\bar{b}$ (2 b-tag categories)×(4 lepton categories)		9.7	90–150
$H \to W^+W^- \to \ell^\pm\nu\ell^\mp\nu$ (0 jets,1 jet,≥2 jets)	$H \to W^+W^-$	9.7	115–200
$H + X \to W^+W^- \to \mu^\mp\nu\tau^\pm_{\rm had}\nu$		7.3	115–200
$H \to W^+W^- \to \ell\bar{\nu}jj$ (2 b-tag categories)×(2 jets, 3 jets)		9.7	100–200
$VH \to e^\pm\mu^\pm + X$		9.7	100–200
$VH \to \ell\ell\ell + X$		9.7	100–200
$VH \to \ell\bar{\nu}jjjj$ (≥4 jets)		9.7	100-200
$VH \to \tau_{\rm had}\tau_{\rm had}\mu + X$	$H \to \tau^+\tau^-$	8.6	100-150
$H+X \to \ell^\pm\tau^\mp_{\rm had}jj$		9.7	105–150
$H \to \gamma\gamma$		9.6	100-150

The Main Associated Production Search Channels



Drawing Credit: CMS Higgs TWiki.
CDF also seeks qqH→qqbb and ttH→ttbb

ZH→llbb: A Fully Reconstructed Channel

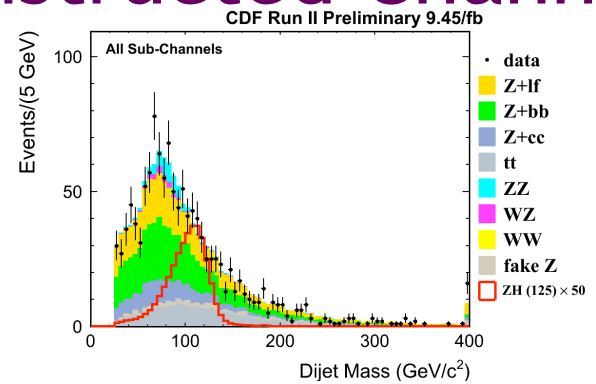


Excellent reconstruction countered by low Z→ll branching ratio

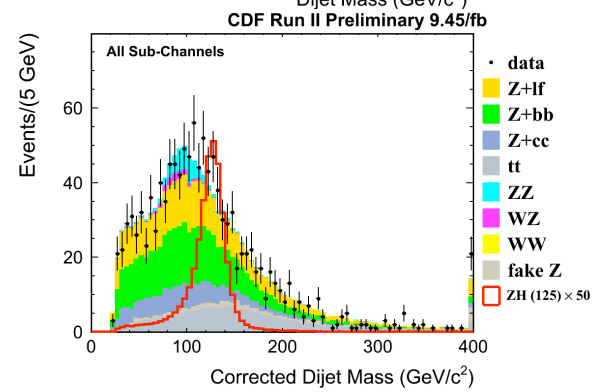
Double Tight Tag yields (CDF)
Signal (ZH) 1.9±0.3 events (m_H=125 GeV)
Background: 131±26 events
Data: 117 Events
Expected limit @125: 3.9*SM CDF, (5.1*SM for D0)

Very innovative channel!

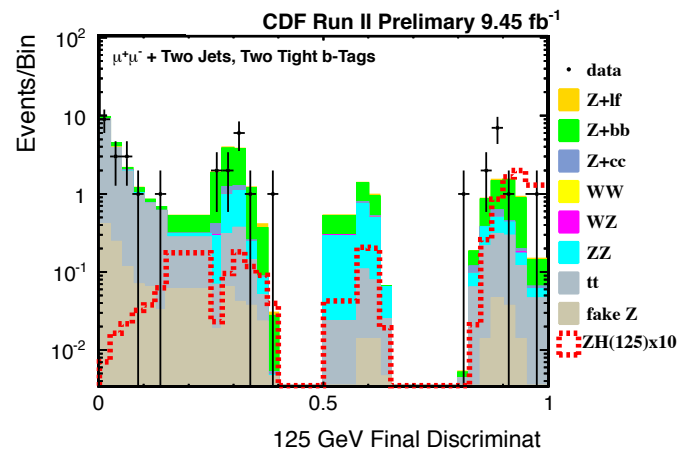
- Loose lepton ID. Tag and probe lepton ID efficiency calibration in data
- Split into 2 jet, 3 jet, single, double, tight, and loose b-tags
- NN dijet mass using MET projections
- Cascade of neural networks: Train networks to separate ttbar, Diboson, Wbb backgrounds from signal.



"Raw" dijet mass

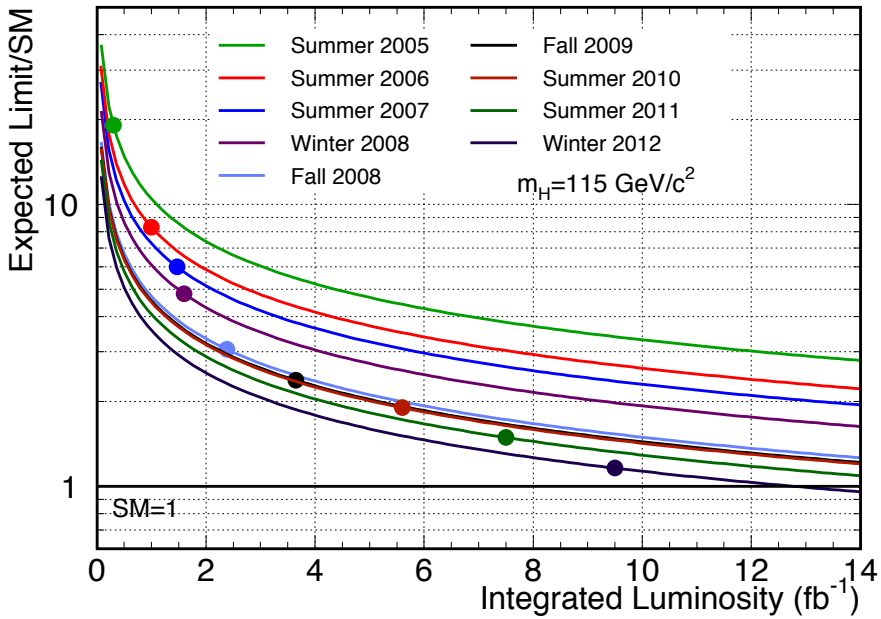


Dijet mass after NN Correction 12% resol. in some channels

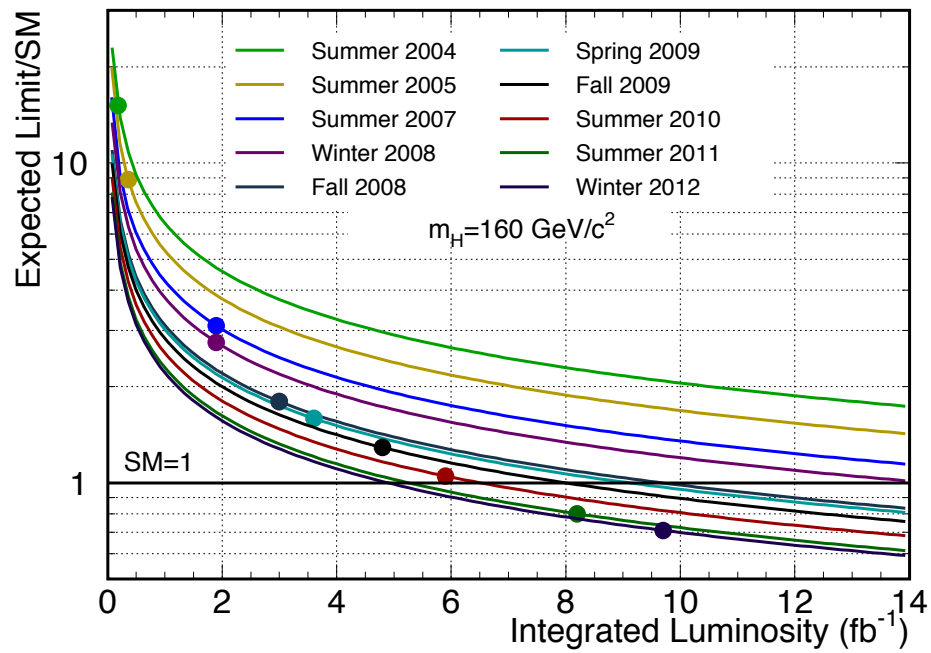


CDF Collab., PRL **109**, 11803 (2012)
D0 Collab., PRL **109**, 121803 (2012)

Sensitivity Evolution over Time



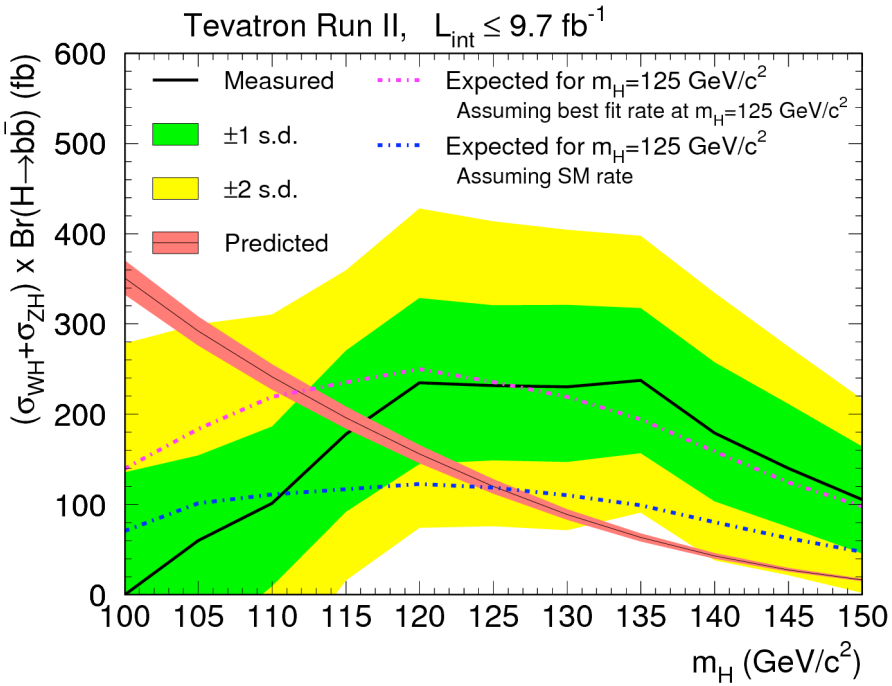
CDF sensitivities shown. D0's sensitivities are similar



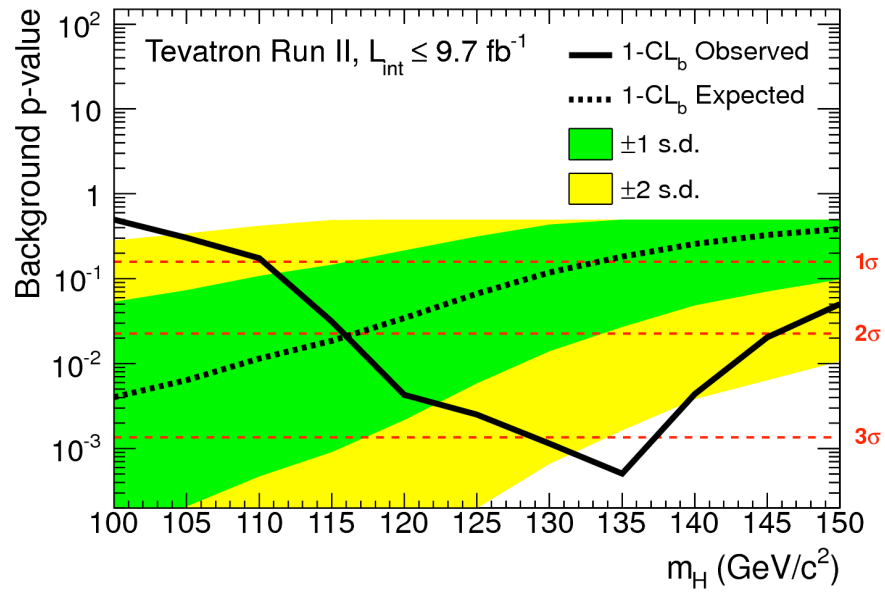
We collected data, and we also learned how to get more out of the data.

- Better MVA's
- Better Event Selection
- Better lepton ID
- Better jet energy resolution
- More triggers
- More analysis categories
- Sharing improvements between analyses

Tevatron H→bb Results, Summer 2012



Phys. Rev. Lett. **109**, 071804 (2012)



Cross section fit at m_H=125 GeV/c^2

$$(\sigma_{WH}+\sigma_{ZH}) \times B(H \rightarrow b\bar{b}) = 0.23^{+0.090}_{-0.080} \text{ (stat+syst) pb}$$

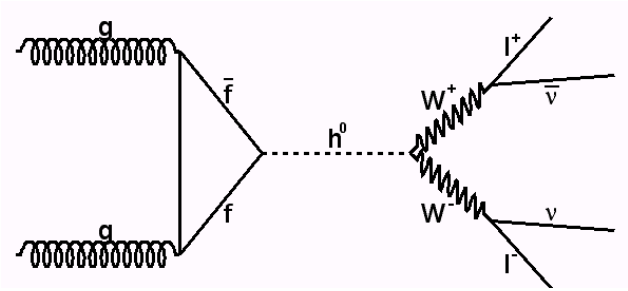
SM Prediction: 0.12 ± 0.01 pb

Maximum local significance: 3.3σ at m_H=135 GeV/c^2

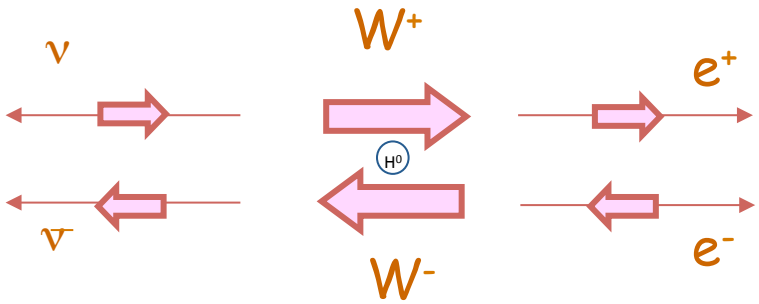
Global significance: 3.1σ – Evidence for VH→Vbb.

Local significance at m_H=125 GeV/c^2 is 2.8σ

H→WW Searches

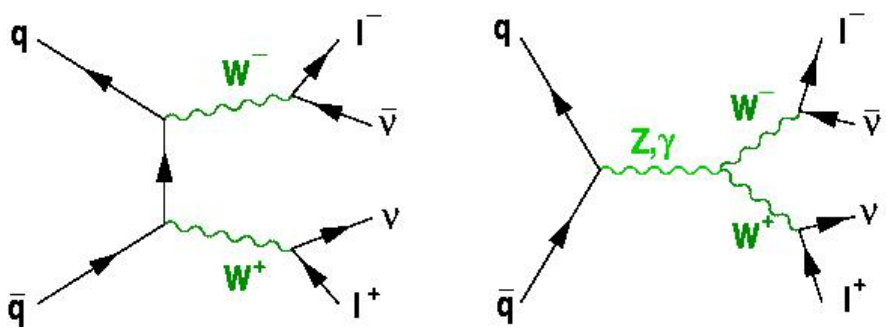


Largest signal is from gluon fusion, but WH, ZH, and VBF contribute as well.



ΔR_{ll} tends to be smaller in signal events than for background events

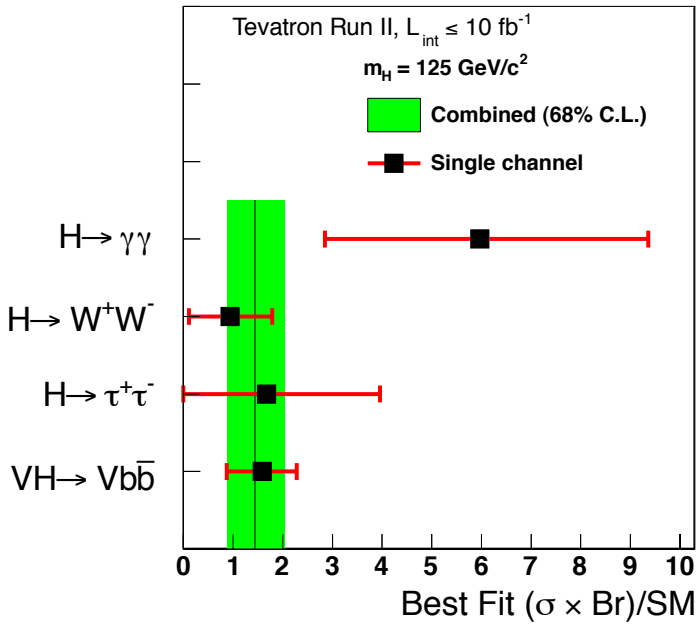
Dominant background at the Tevatron is nonresonant WW production

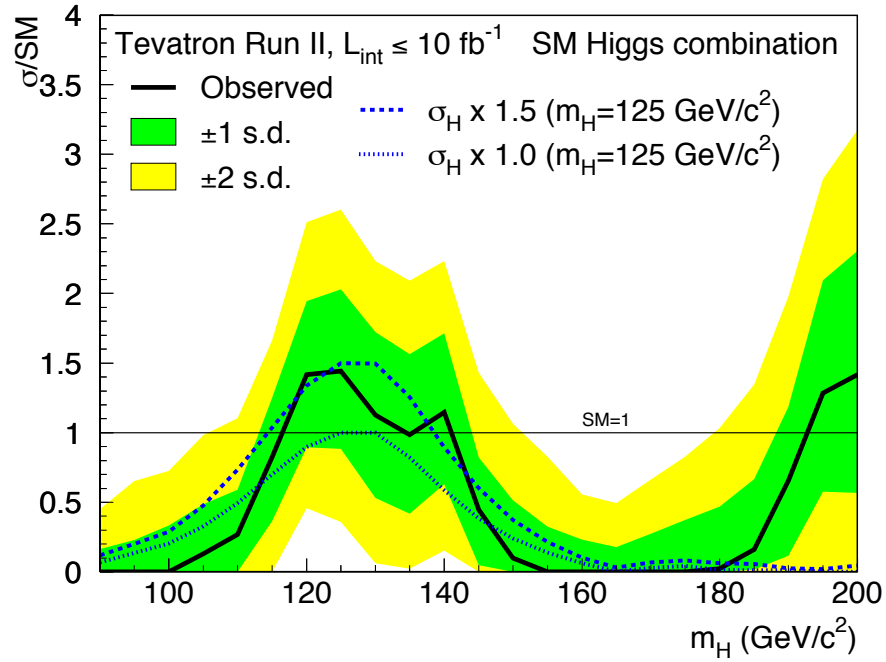


But we split the samples into
lvlv + 0j
lvlv + 1j
lvlv + 2 or more jets
and the backgrounds vary by subsample.

D0 Collab., PRD **86**, 032010 (2012)
CDF Collab., FERMILAB-PUB-13-029-E (in preparation)

Best-Fit Tevatron Combined Cross Sections at m_H=125 GeV/c^2





$$H \to \gamma\gamma: \quad 5.97^{+3.39}_{-3.12} \times \mathrm{SM}$$

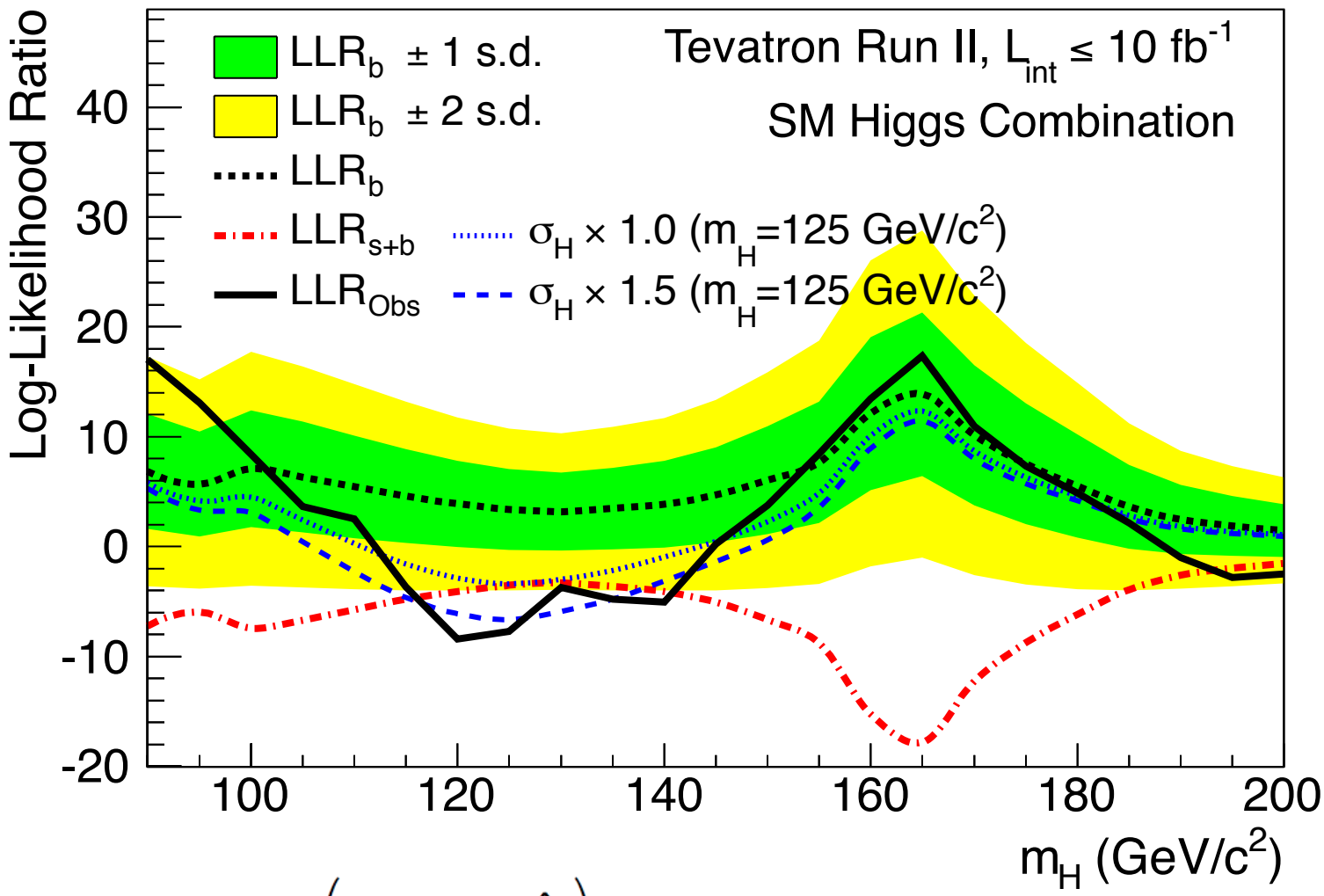
$$H \to \tau^+\tau^-: \quad 1.68^{+2.28}_{-1.68} \times \mathrm{SM}$$

$$VH \to Vb\bar{b}: \quad 1.59^{+0.69}_{-0.72} \times \mathrm{SM}$$

$$H \to W^+W^-: \quad 0.94^{+0.85}_{-0.83} \times \mathrm{SM}$$

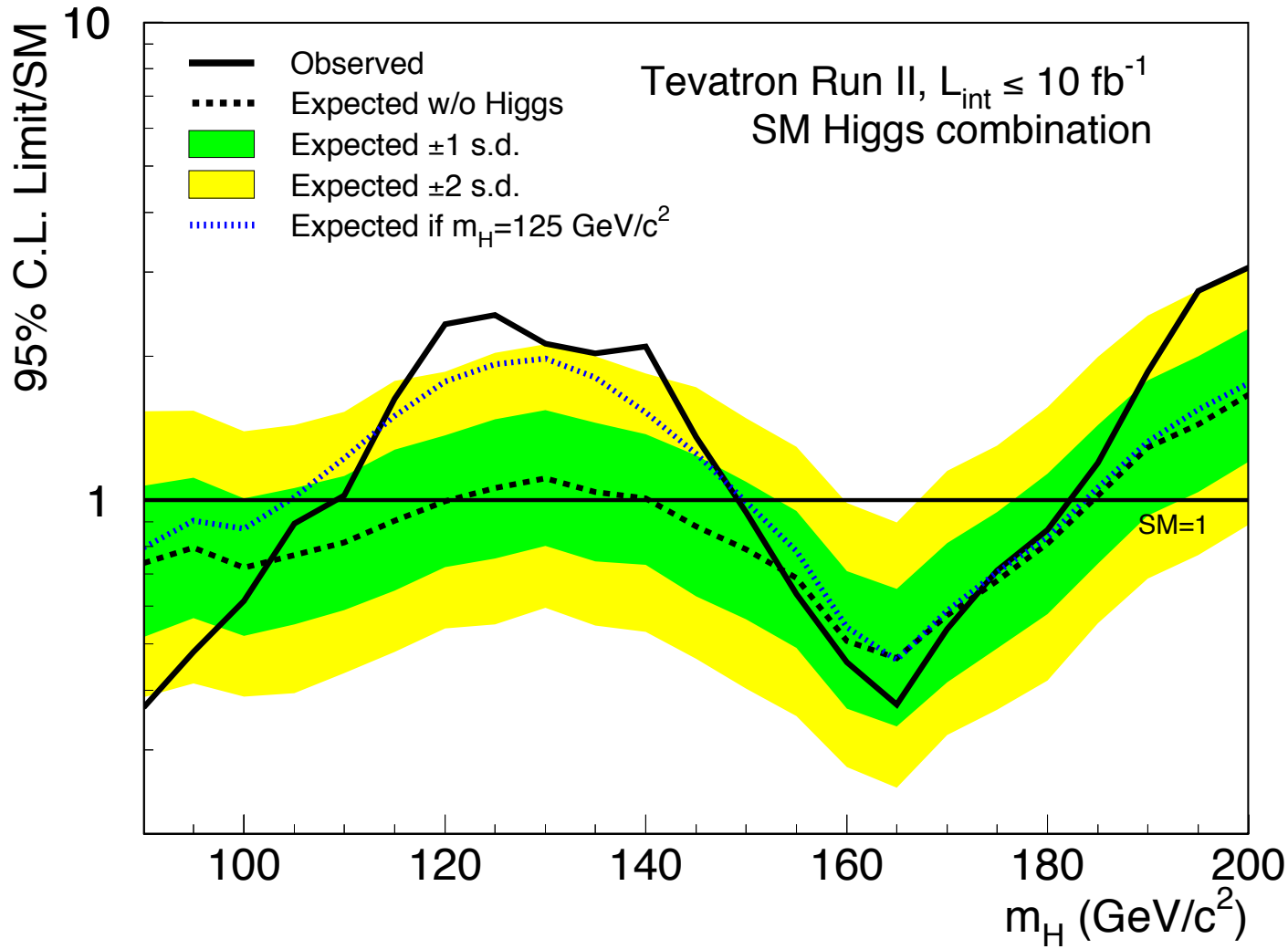
$$\mathrm{Combined}: \quad 1.44^{+0.59}_{-0.56} \times \mathrm{SM}$$

Tevatron Combined SM LLR Distributions



$$-2\ln Q \equiv LLR \equiv -2\ln\left(\frac{L(\text{data}\,|\,H_1,\hat{\theta})}{L(\text{data}\,|\,H_0,\hat{\hat{\theta}})}\right)$$

Tevatron Final SM Higgs Rate and Mass Limits

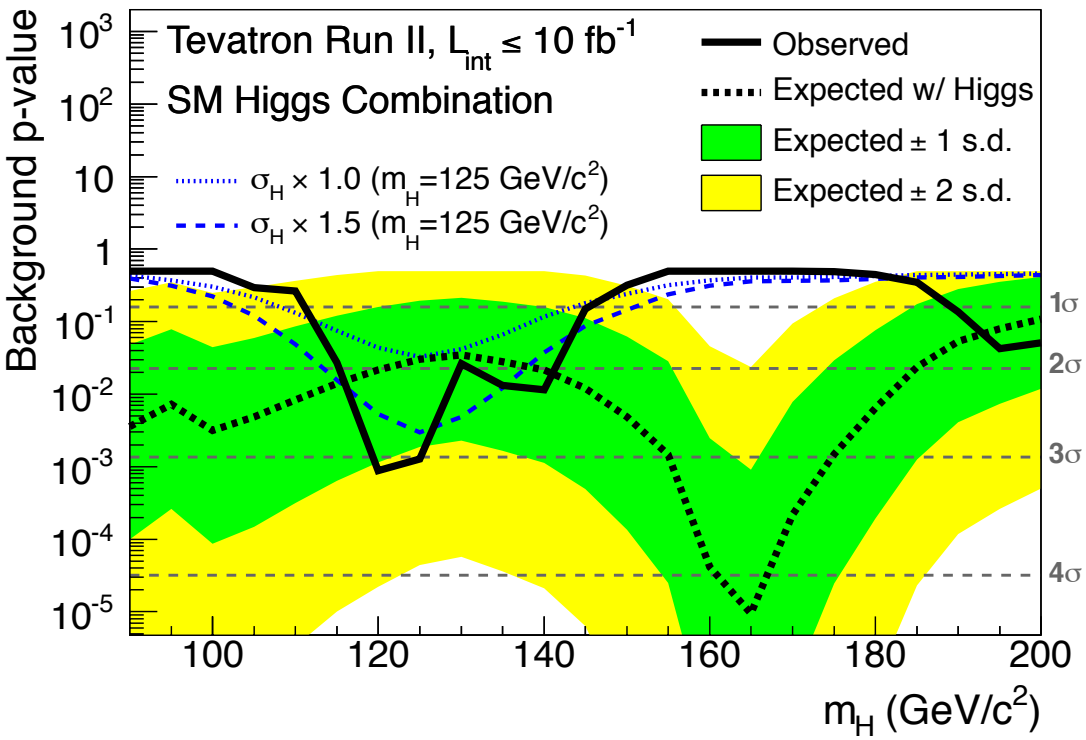


Excluded regions: $90 < m_H < 109$ GeV/c^2 and $149 < m_H < 182$ GeV/c^2

Expect to exclude if no Higgs: $90 < m_H < 120$ GeV/c^2 and

$140 < m_H < 184$ GeV/c^2

Tevatron Combined SM Higgs Boson Search p-value



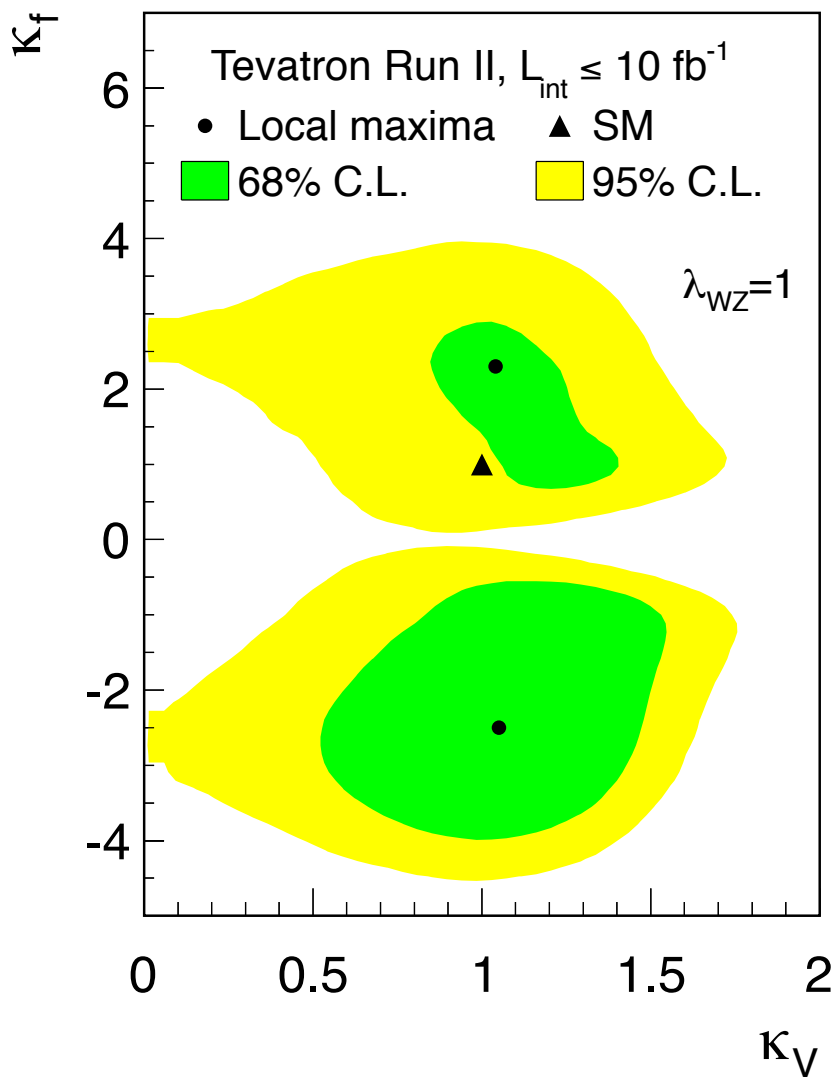
Observed local significance at m_H=125 GeV/c^2 is 3.1σ

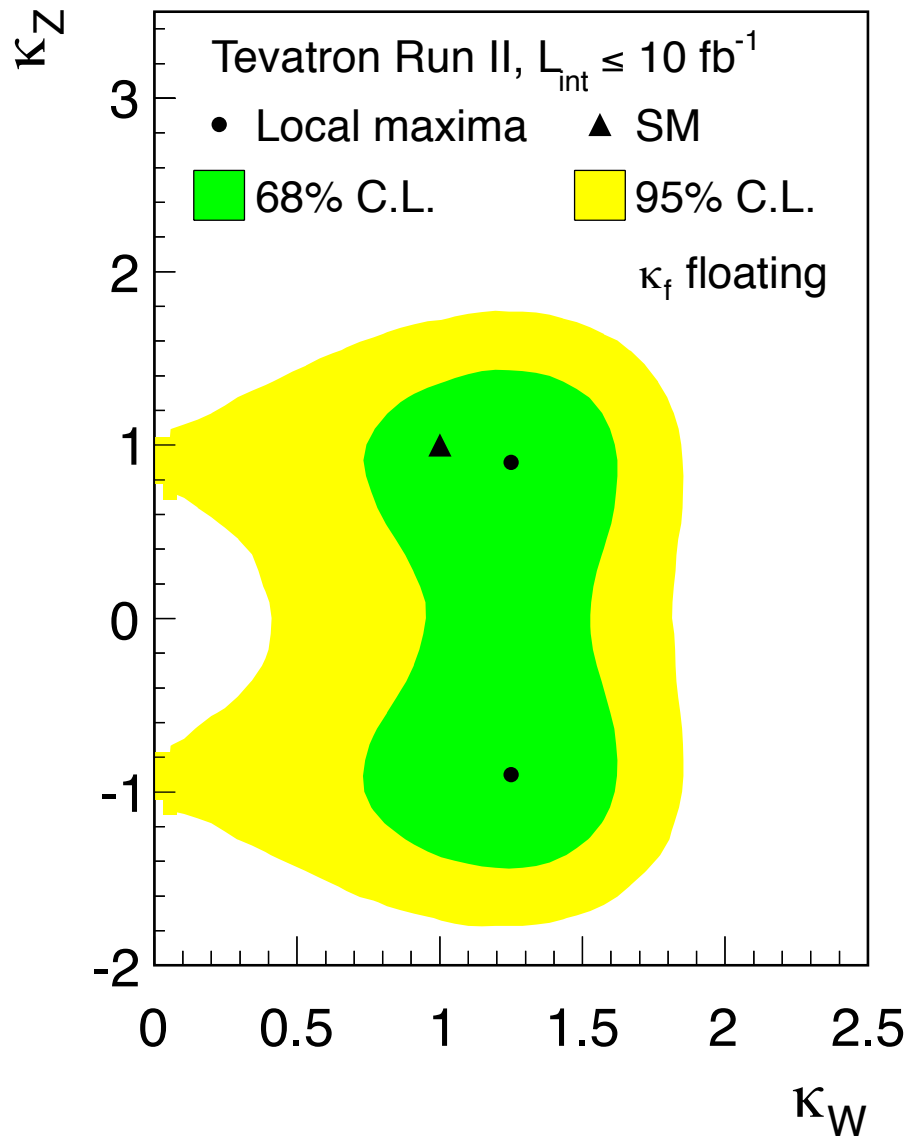
Expected significance assuming m_H=125 GeV/c^2 is shown with a dotted line (not quite 2σ)

Look-Elsewhere Effect:

- m_H~125 GeV has been firmly established by the LHC
- CDF+D0's mass resolution is not very sharp -- ~2 independent search results in H→bb, ~2 in H→WW
- Technical challenge – MVA's trained at each m_H separately. Histograms of predictions exchanged. Would need to exchange correlated pseudoexperiments to compute LEE exactly.

Two-Dimensional Coupling Parameter Constraints





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!

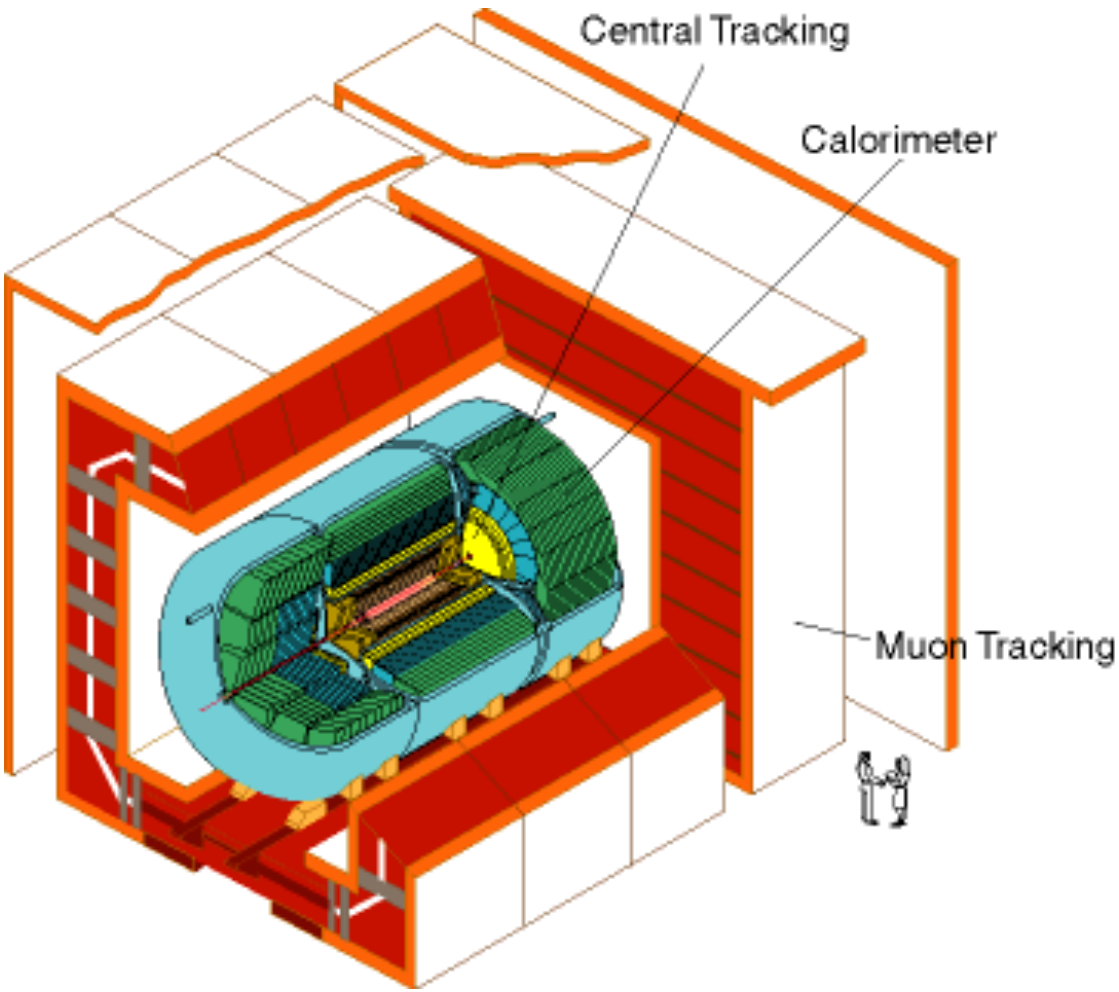
Many joint papers documenting combined results – inter-collaboration cooperation has been very good.

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 I didn't cover: observation of many new hadrons, charm mixing, characterization of top quarks, CP violation in inclusive muon production

Extras

The D0 Detector



Technical Highlights

Inner silicon detector, 700,000 channels
Scintillating fiber tracker & preshower 100,000 channels
Uranium/liquid argon calorimeter, 50,000 channels
Muon system (wire chambers and scintillator), 70,000 channels

D0's dimensions are 30 x 30 x 50' and it weighs about 5,000 tons.