Tevatron:
New Results and Prospects

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on behalf of the CDF and DØ collaborations

Overview

- Recent highlights:
  - M_W
  - Observation of single (electroweak) top production
  - Higgs searches
- A very broad programme ……….
  - B, QCD, EW (incl. top), Searches (incl. Higgs)
  - (50 journal publications, 30 PhDs, per annum, per experiment)

………. that is now at its peak of productivity

➢ Prospects

The Fermilab Tevatron Collider

1992-95 Run I:

$\int Ldt \sim 0.1\ fb^{-1}$, 1.8 TeV

Discovered the t quark

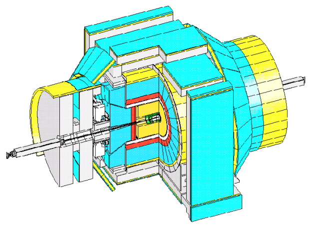
Major accelerator/detector upgrades
(UK groups joined CDF/DØ in 1998/1999)

2002-05 Run IIa:

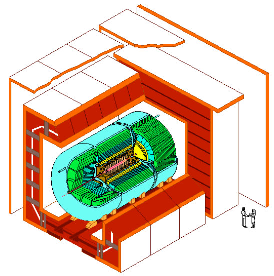
$\int Ldt \sim 1.6\ fb^{-1}$, 1.96 TeV

Further upgrades
2006-10 Run IIb: (2011 run likely)

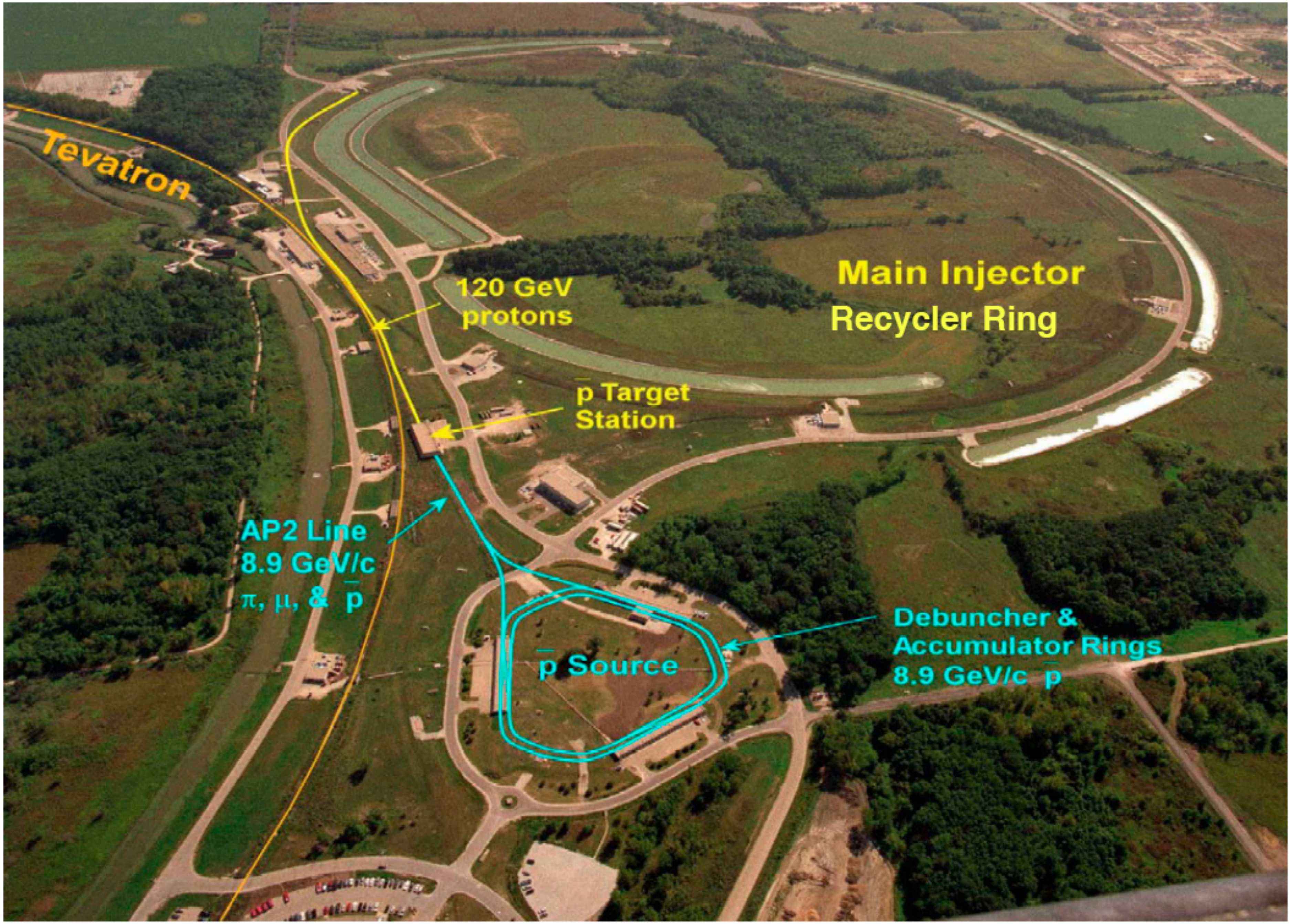
$\int Ldt \sim 9\ fb^{-1}$ ($\int Ldt \sim 12\ fb^{-1}$)



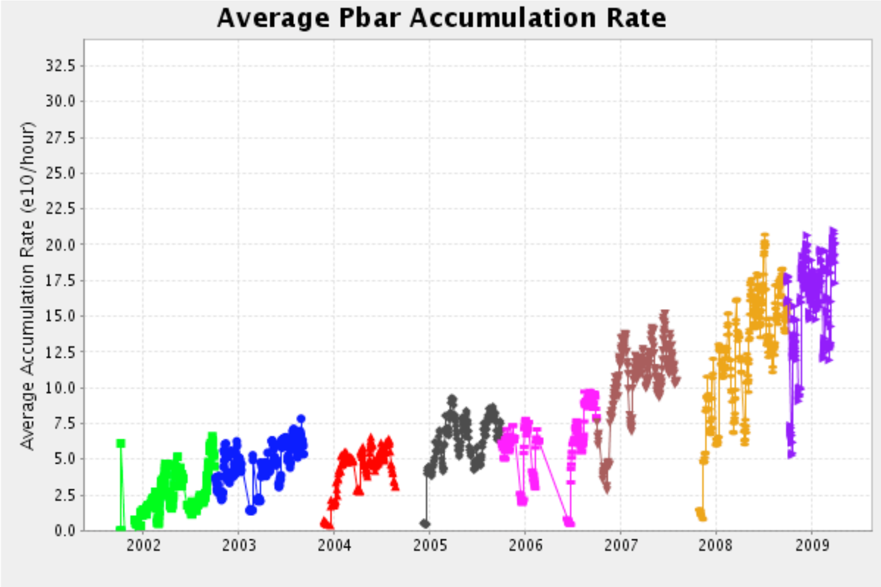
CDF

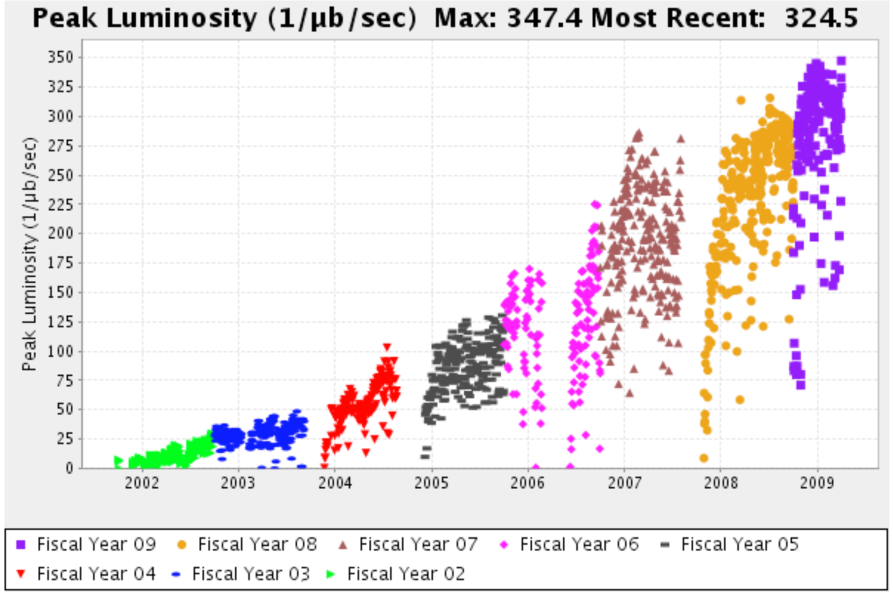


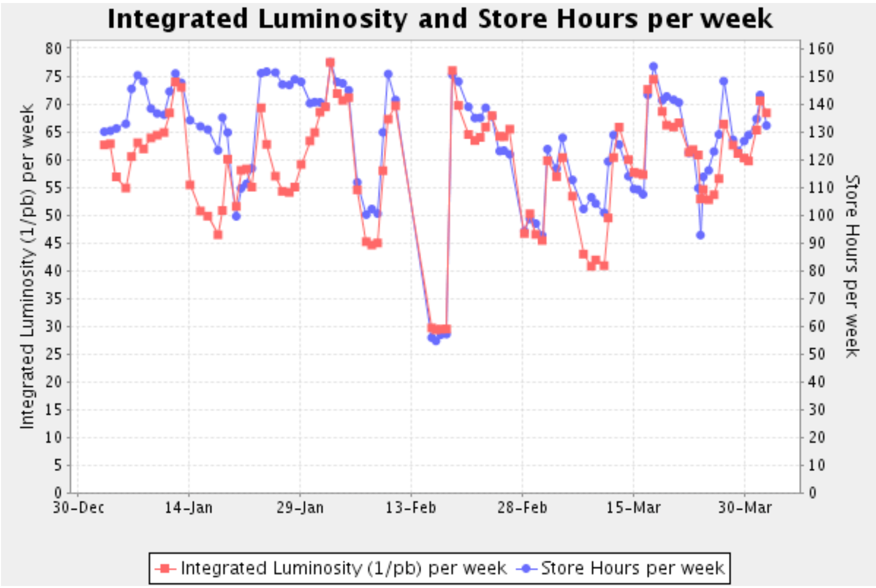
DØ

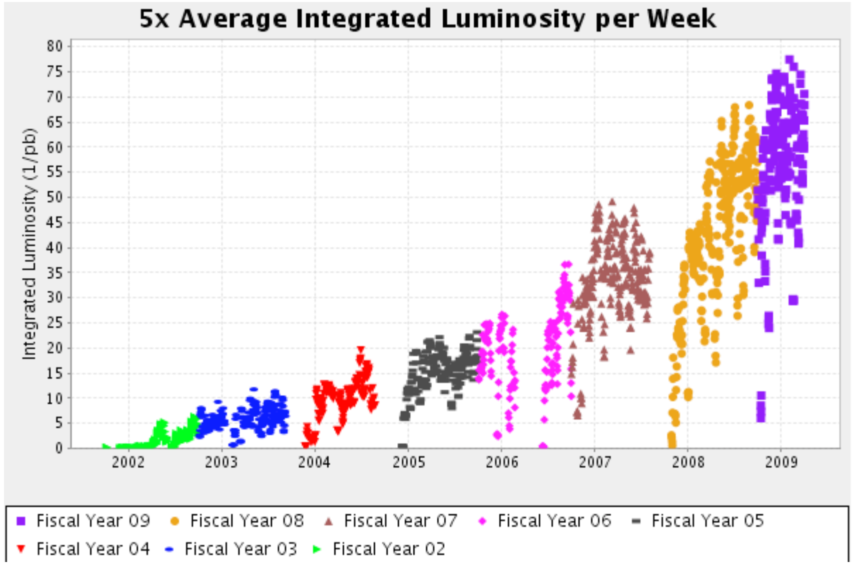

Tevatron
120 GeV
protons
Main Injector
Recycler Ring
$\bar{p}$ Target
Station
AP2 Line
8.9 GeV/c
π, μ, & $\bar{p}$
$\bar{p}$ Source
Debuncher &
Accumulator Rings
8.9 GeV/c $\bar{p}$

Tevatron History Plots

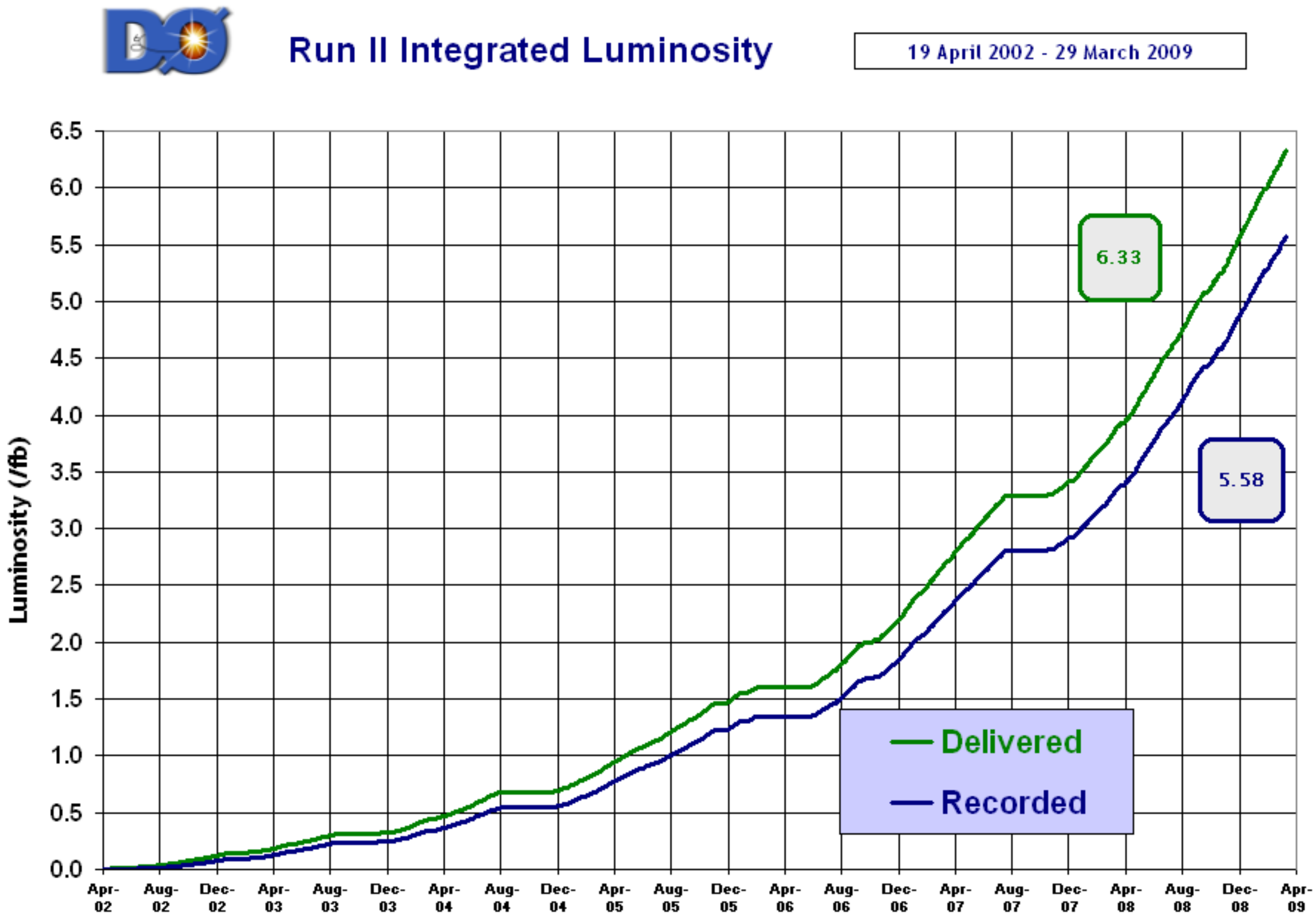








Integrated Luminosity History

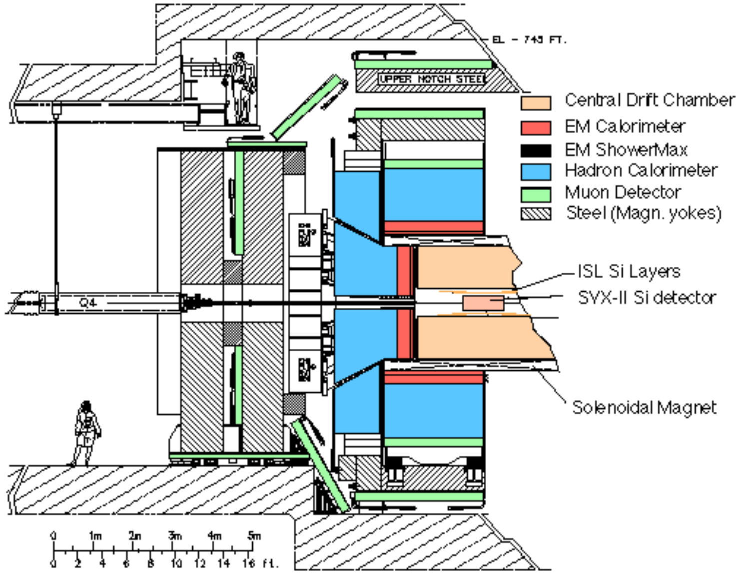


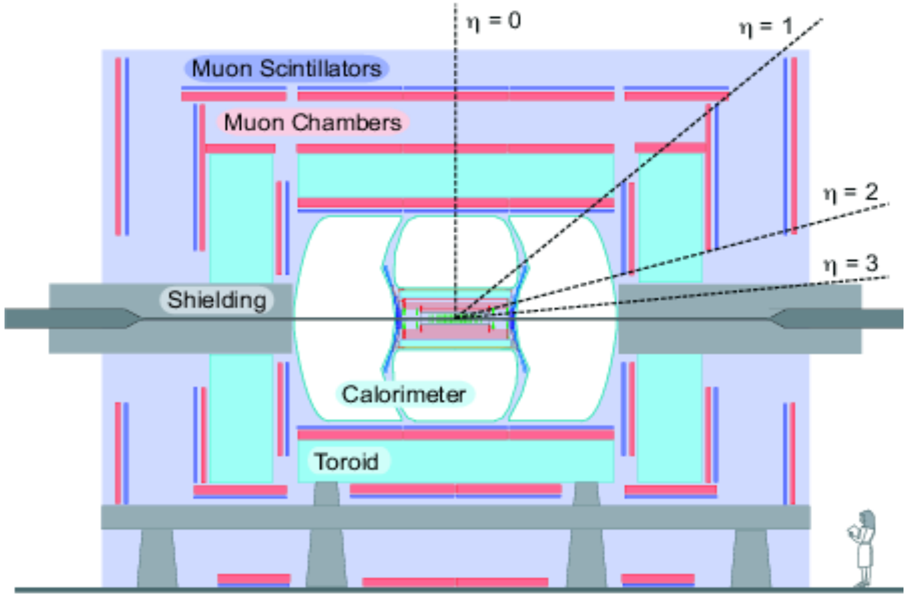
Average data taking efficiency since December 2006 over 90%!

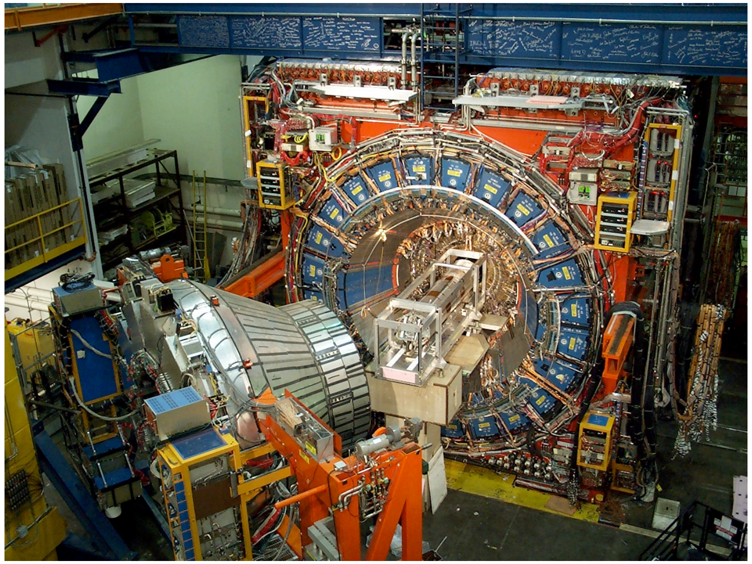
CDF

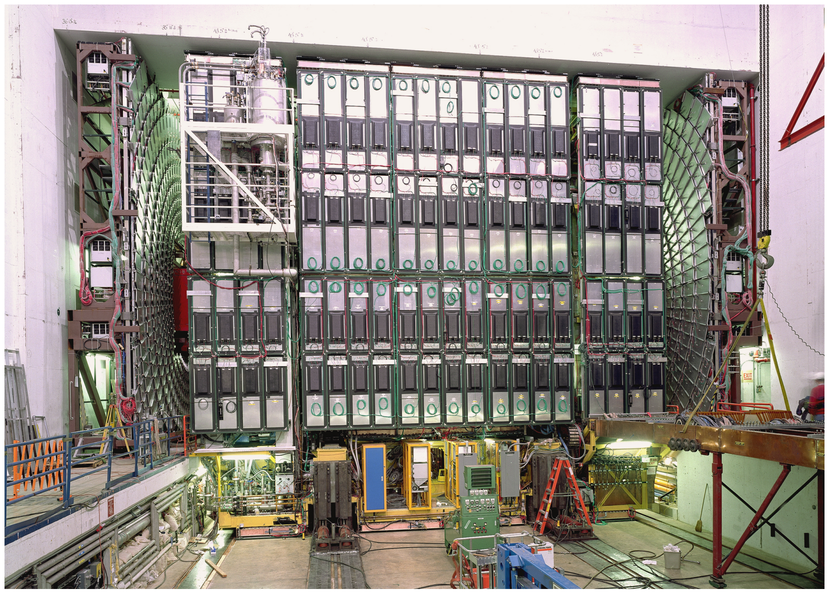
DØ

$\eta = -\ln(\tan\theta/2)$

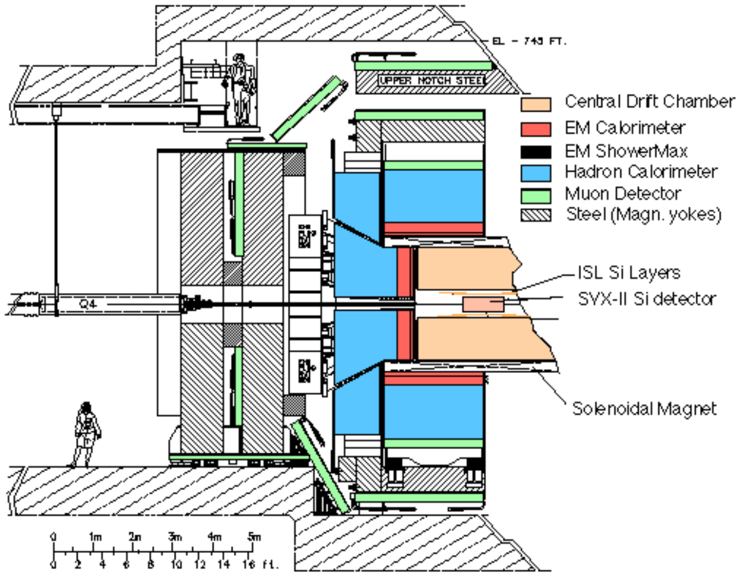




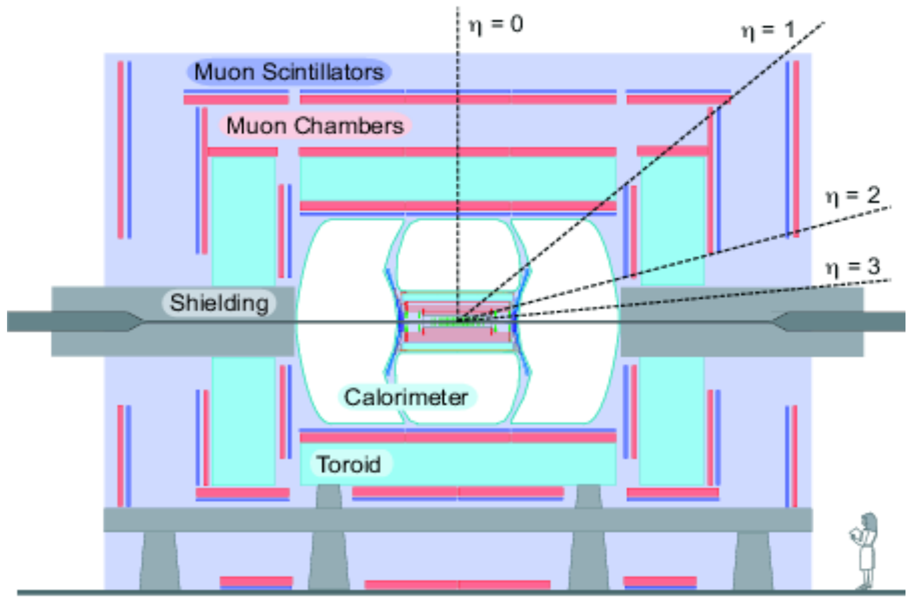




CDF



DØ



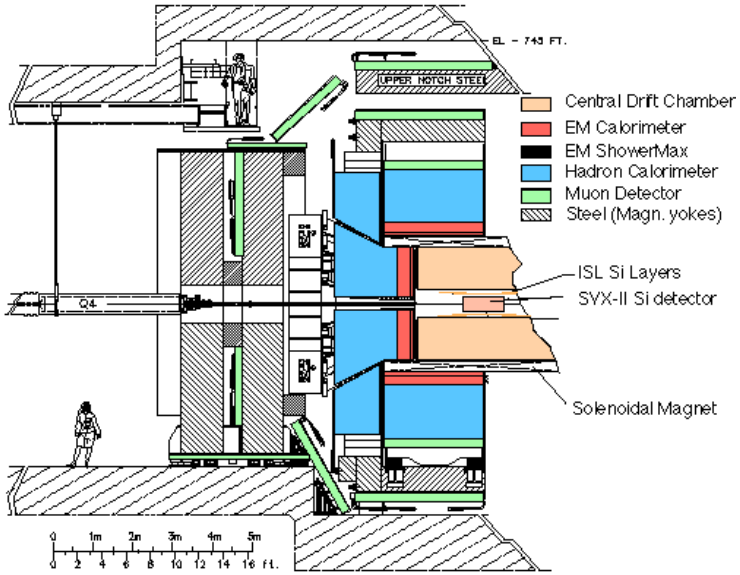
CDF detector highlight

- large volume, high precision, charged particle tracker
  - 9-layer silicon tracker
  - 96-layer drift chamber
  - 1.4 m outer radius

DØ detector highlight

- high acceptance, low background, muon system
  - trigger and ID acceptance $|\eta|<2$
  - ~14 interaction length absorber
  - 0.5 m outer radius for DØ central tracker
  - 1.8 T muon toroid

CDF



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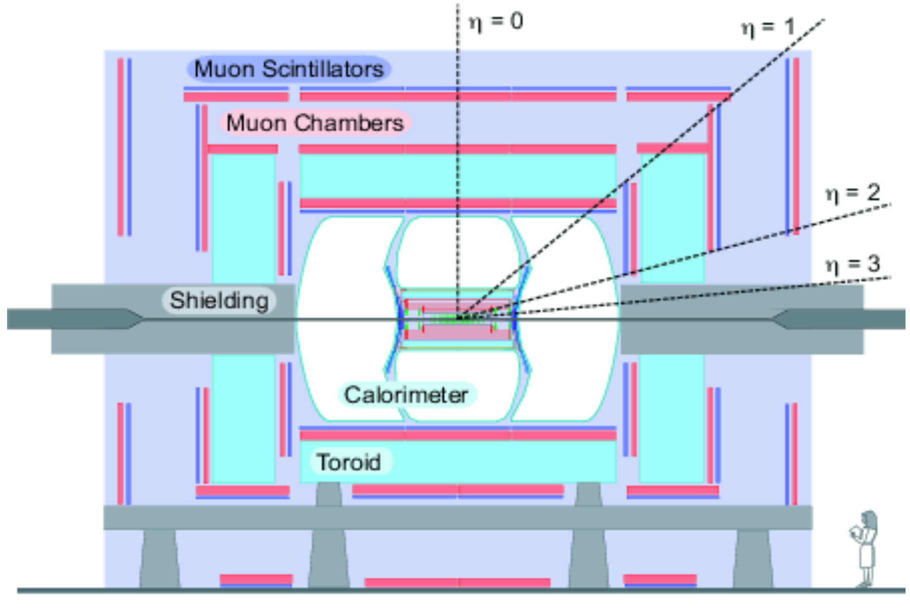

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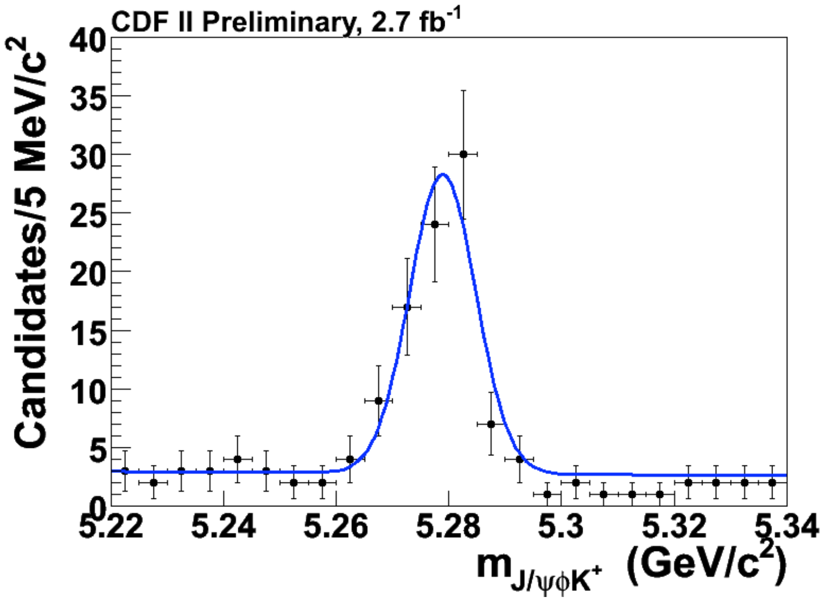
Look at a couple of examples from B physics to illustrate these relative strengths

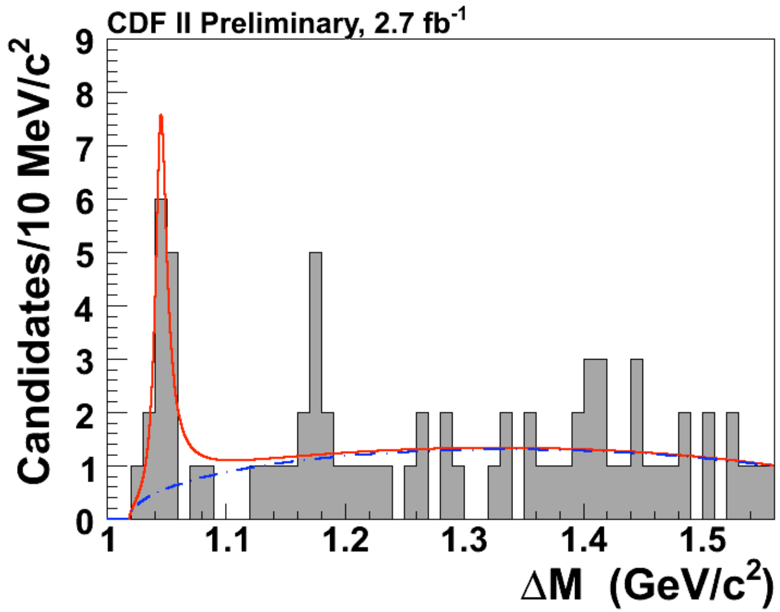
Structure in the $J/\psi\phi$ Mass Spectrum in $B^+ \to J/\psi\phi K^+$ (CDF)

- $J/\psi \to \mu^+\mu^-$, $\phi \to K^+K^-$
- All three $K^\pm$ positively identified
  - by means of dE/dx, TOF
- B^+ decay length cut
- World's largest sample of $B^+ \to J/\psi\phi K^+$! (75 events)

Mass for $B^+ \to J/\psi\phi K^+$



$\Delta M = M(\mu^+\mu^-K^+K^-) - M(\mu^+\mu^-)$



- Evidence for a structure near threshold
  - 3.8 σ significance

  $m = 4143.0 \pm 2.9$ (stat.) $\pm$ 1.2(syst.) MeV

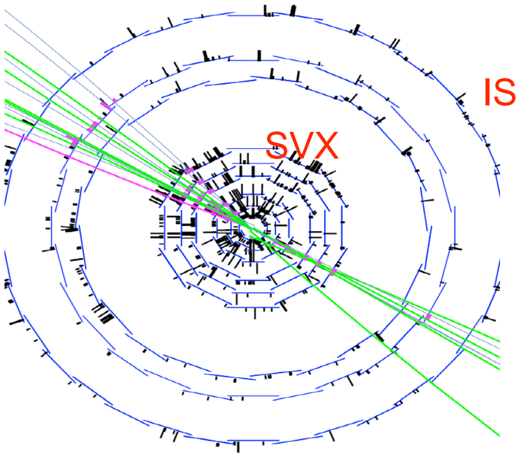
  $\Gamma = 11.7\ ^{+8.3}_{-5.0}$ (stat.) $\pm$ 3.7(syst.) MeV
- Analogous to Y(3930)?

  which decays to $J/\psi\omega$ just above threshold

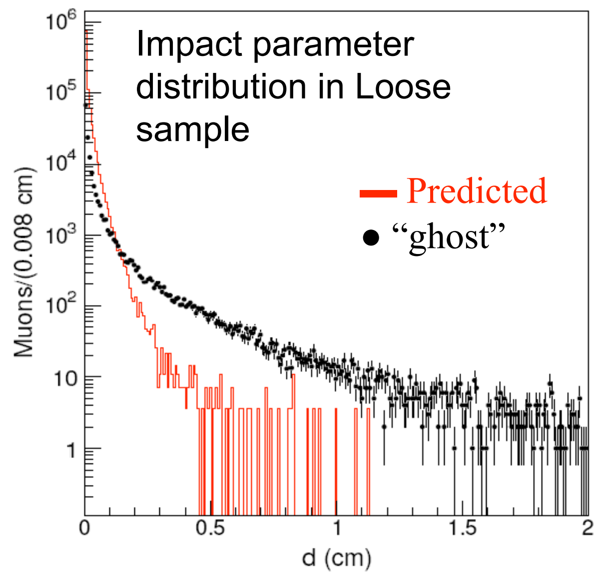
Anomalous Dimuon Events? (CDF)

(2.1 pb^{-1}, arXiv:0810.5357)

- Muons:
  - $p_T > 3$ GeV
  - $|\eta| < 0.7$
- Dimuon events:
  - $5 < M_{\mu\mu}$ (GeV) < 80
- Silicon hit requirements:
  - "Loose" (590970 events)
    - ≥3 hits in L0-L4 plus ISL
  - "Tight" (143743 events)
    - hits in L00, L0 plus ≥2 of L1-L4



- Number and properties of "Tight" events consistent with bb, cc, plus Drell-Yan
- Predict number of "Loose" events:
  - $N_{Loose} = N_{Tight} / \varepsilon_{\text{Tight wrt. Loose}}$
- See an excess of 72553 ± 7264 "Loose" events ("ghosts") with very broad impact parameter distribution



- CDF unable to explain "ghost" events in terms of punch-through/decay in flight
- Other features of "ghost" events
  - Equal numbers of same-sign and opposite-sign
  - Contain anomalous number of additional muons

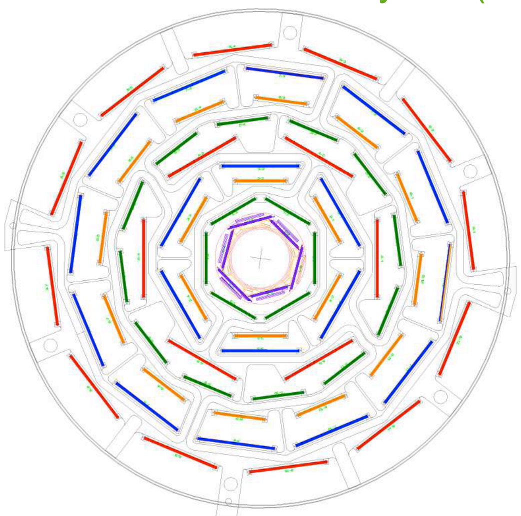
Anomalous Dimuon Events? (DØ)

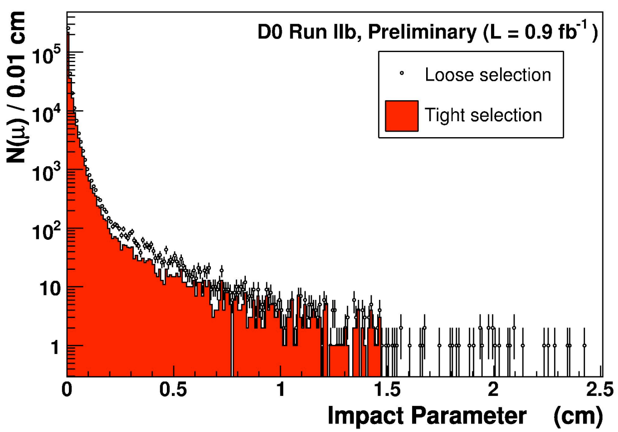
0.9 fb^{-1}

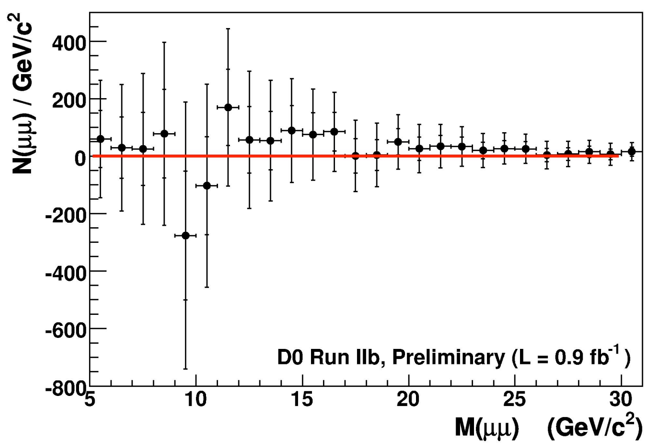
http://www-d0.fnal.gov/Run2Physics/WWW/results/prelim/B/B57/B57.pdf

- Mimic CDF geometrical and kinematic acceptance cuts
- Silicon hit requirements:
  - "Loose"
    - ≥3 silicon hits
  - "Tight"
    - "Loose" plus both tracks have hit in Layer-0 (radius 1.6 cm)

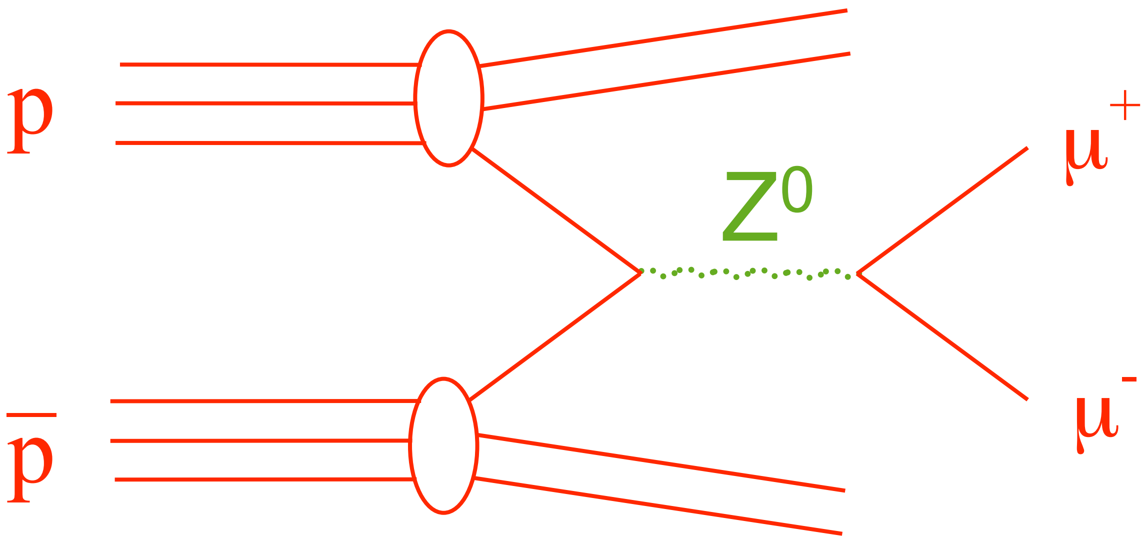
- Evaluate $\varepsilon_{\text{Tight wrt. Loose}}$ using $J/\psi \to \mu^+\mu^-$ events
  - as function of relevant kinematic variables
- N_{Loose} = 177 535
- N_{Tight} = 149 161
- N_{Excess} = 712 ± 462 (stat) ± 942 (syst)
- or [0.40 ± 0.26 ± 0.53]% of N_{Loose}
- N.B. No correction for any decay in flight or punch through contribution!
- DØ does not confirm CDF observation of anomalous dimuon events with large impact parameters







Producing W and Z in $p\bar{p}$

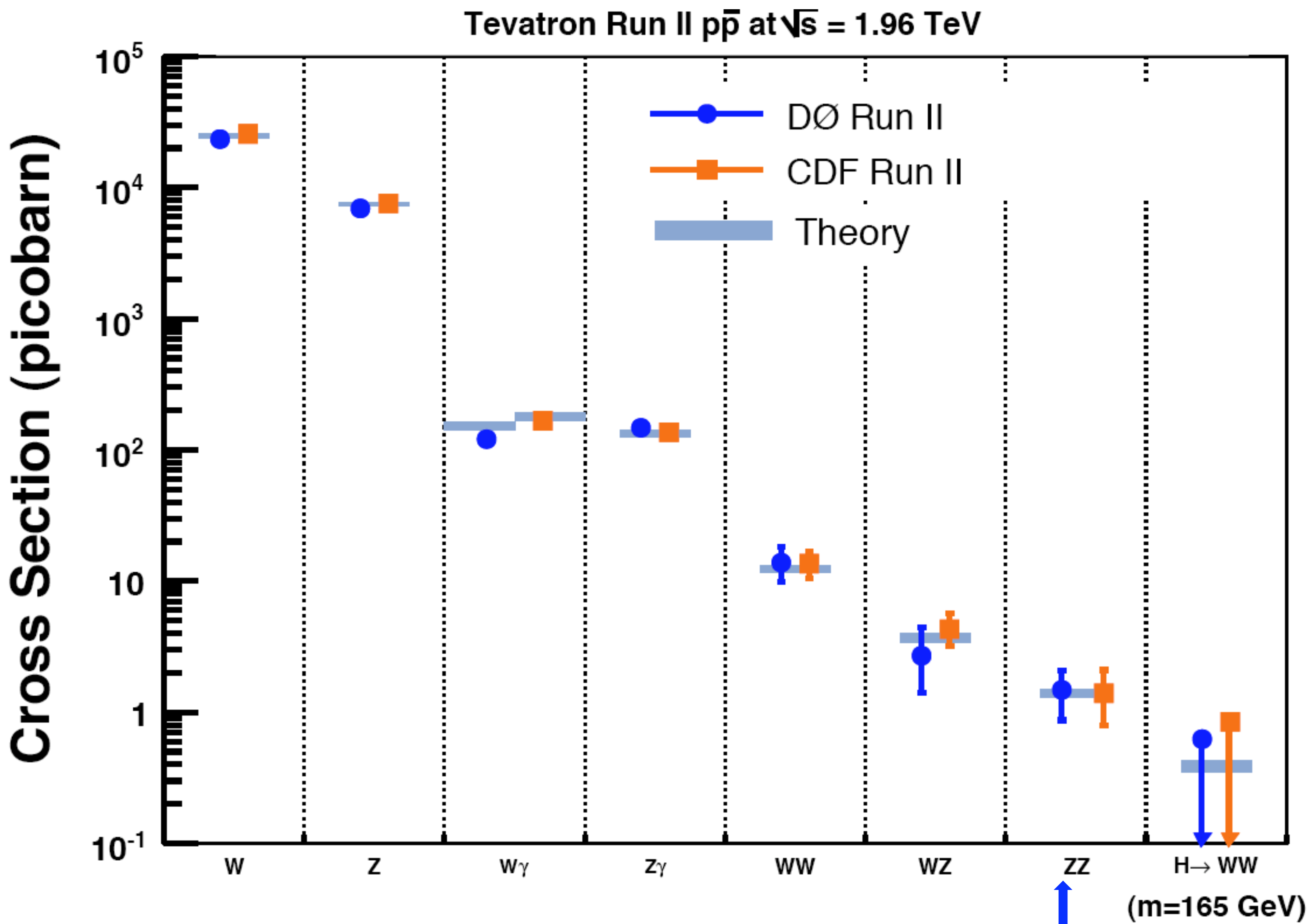


Hadron collider is a difficult environment!

- proton is a composite object
  - PDFs (Parton Distribution Functions)
  - proton remnants, gluon bremsstrahlung
- huge total cross section
  - ~12 collisions per bunch crossing at design luminosity! (every 396 ns)
  - backgrounds
  - need to trigger

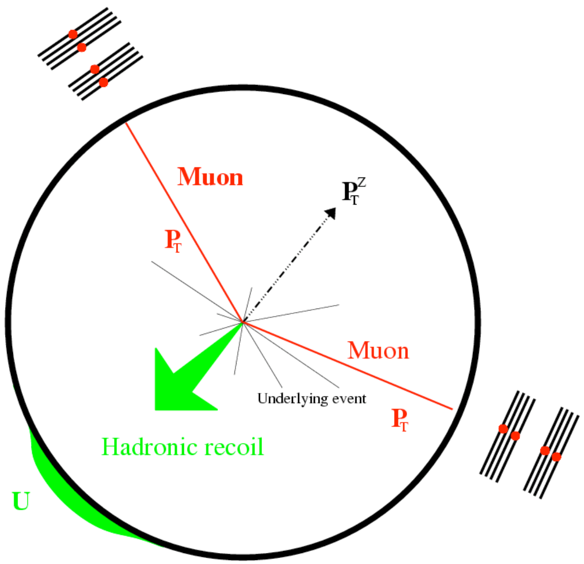
Select ~ 10^6 tagged $W \rightarrow \ell\nu$ and ~ 10^5 $Z^0 \rightarrow \ell^+\ell^-$ events per fb^{-1}

EW Cross Sections at the Tevatron

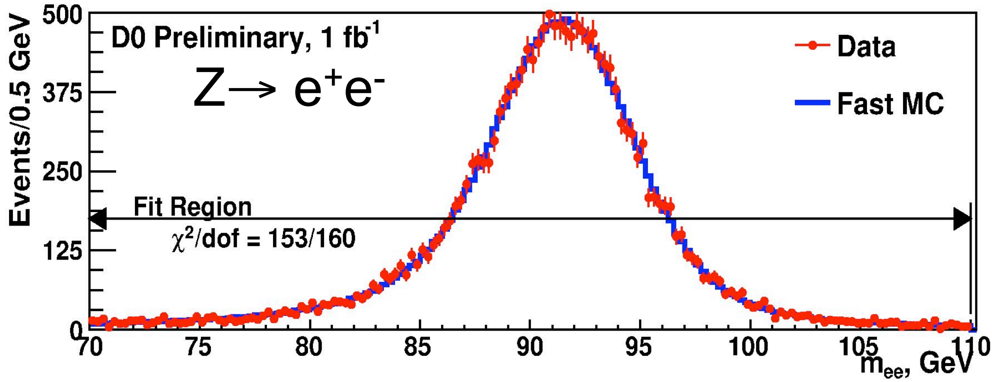


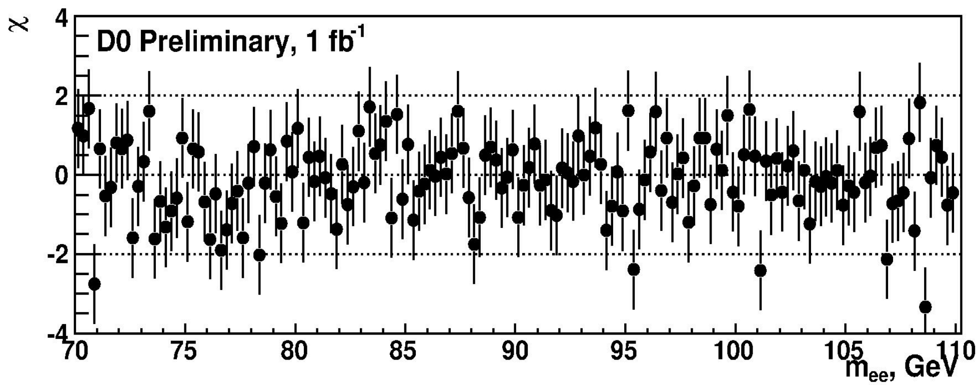
First Observed by DØ: summer 2008

Signatures of W and Z Production at the Tevatron



- $Z \to \ell^+\ell^-$: pair of charged leptons:
  - high p_T
  - isolated
  - opposite-charge
- peak in $\ell^+\ell^-$ invariant mass





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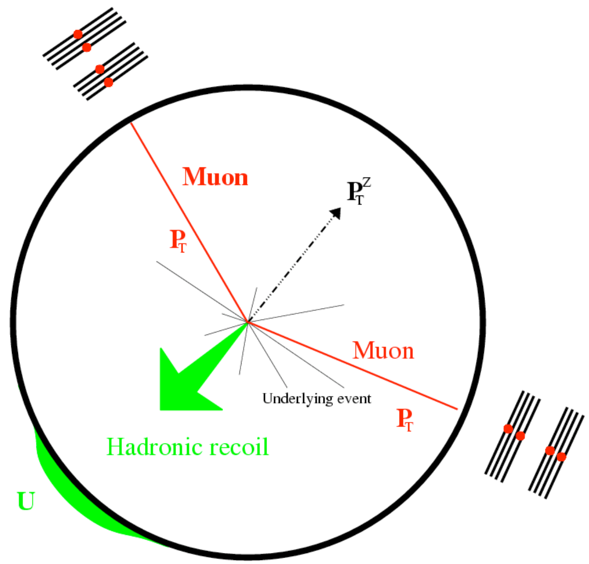

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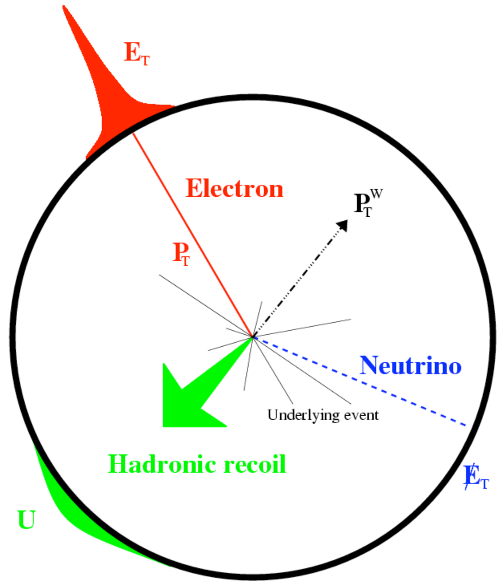

- $W \rightarrow \ell\,\upsilon$: single charged lepton:
  - high p_T
  - isolated
- E_T^{miss} (from υ)
  - cannot measure longitudinal υ
- peak in "transverse mass"

transverse mass: $m_T = \sqrt{2 p_T^{\,l} p_T^{\,\nu} (1 - \cos\phi_{l\nu})}$

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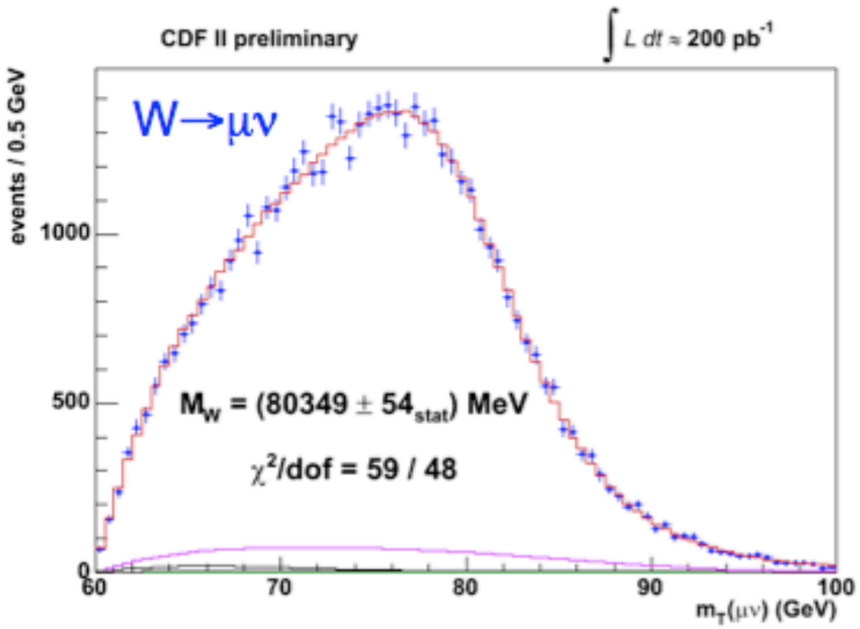

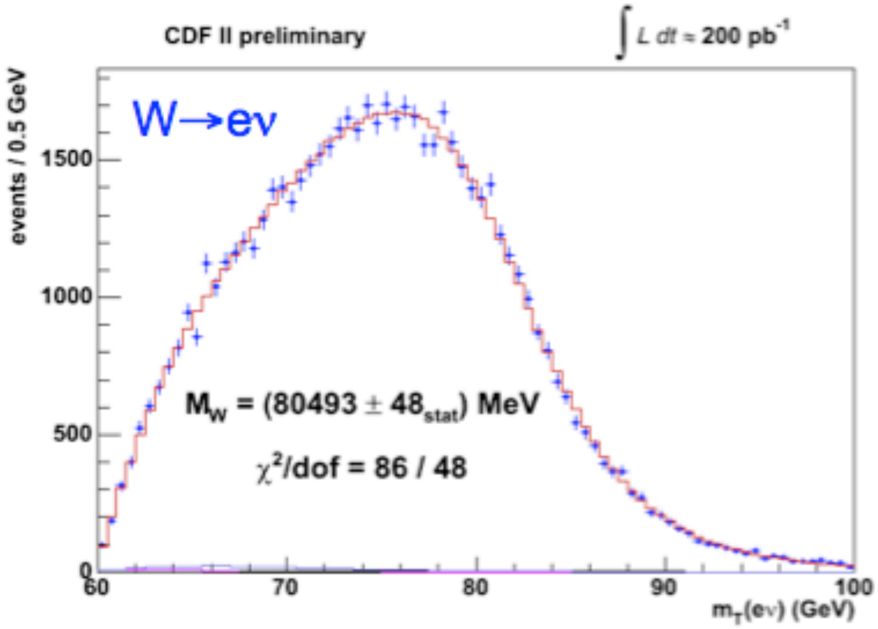

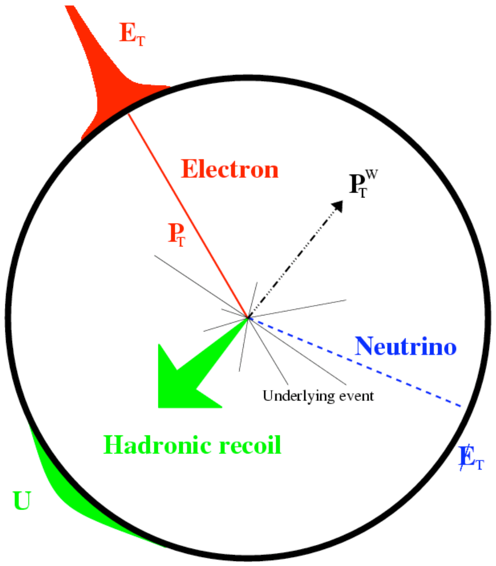

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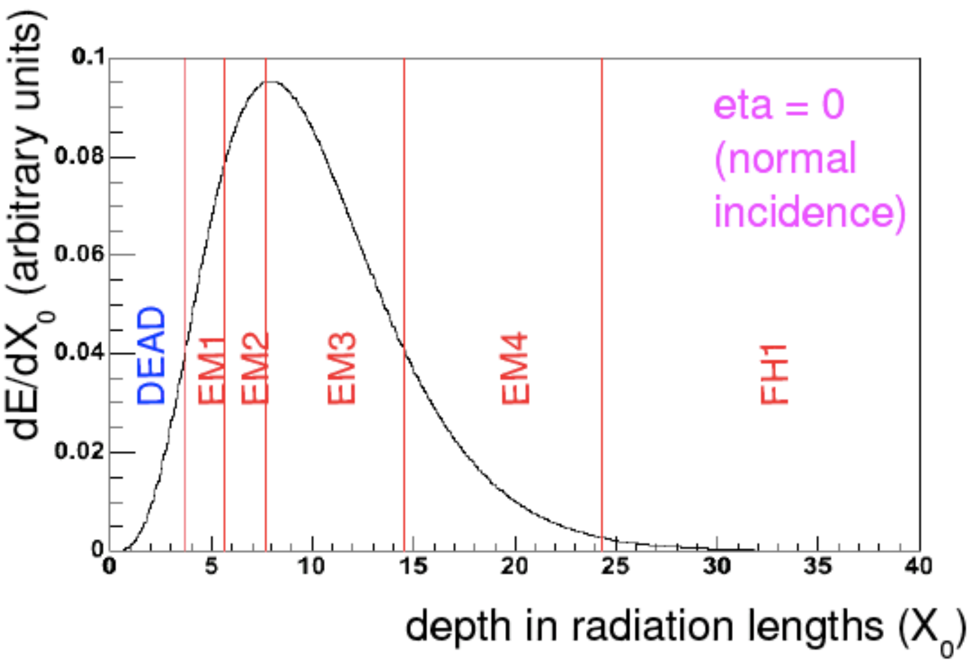
W Mass in W→eυ (DØ)

- 1 fb^{-1}: ~500k W→eυ events, ~19k $Z \to e^+e^-$ events
- The main challenge:
  - Measure electron energy response at the level of few per mille
    - Including dependence on energy, |η|, etc.
    - Including effect of nearly 4 X_o dead material in front of calorimeter

- Increased "weights" for energy deposited in EM1,2 layers helps compensate partially for energy lost in dead material



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  - Calibrate using $Z \rightarrow e^+e^-$ events making use of information from:
    - Four samplings in depth in EM calorimeter, |η| dependence
    - Divide $Z \rightarrow e^+e^-$ data set into 15 sub-samples in η_1 vs. η_2

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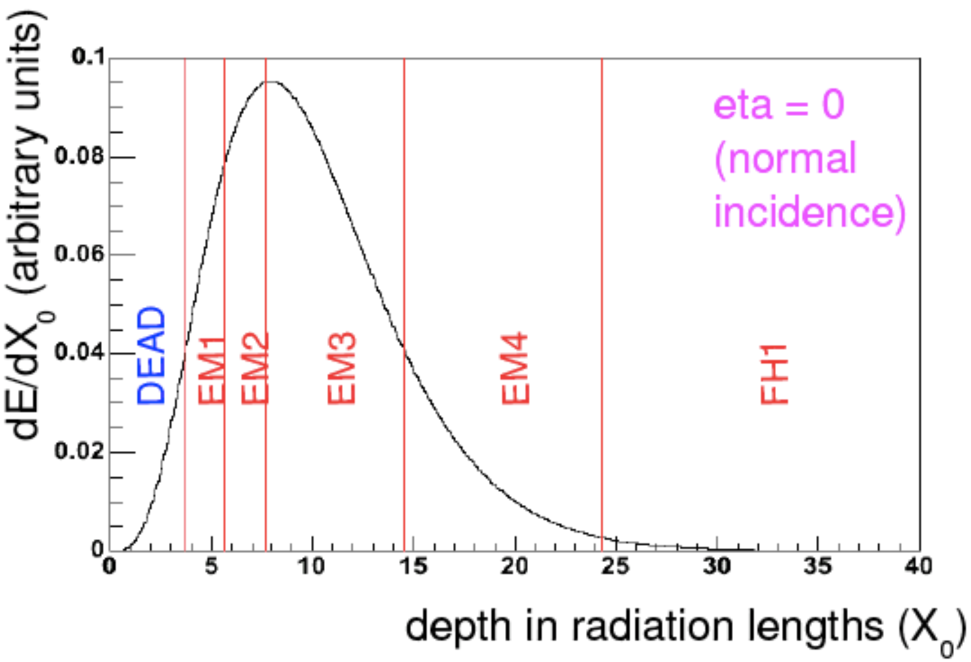

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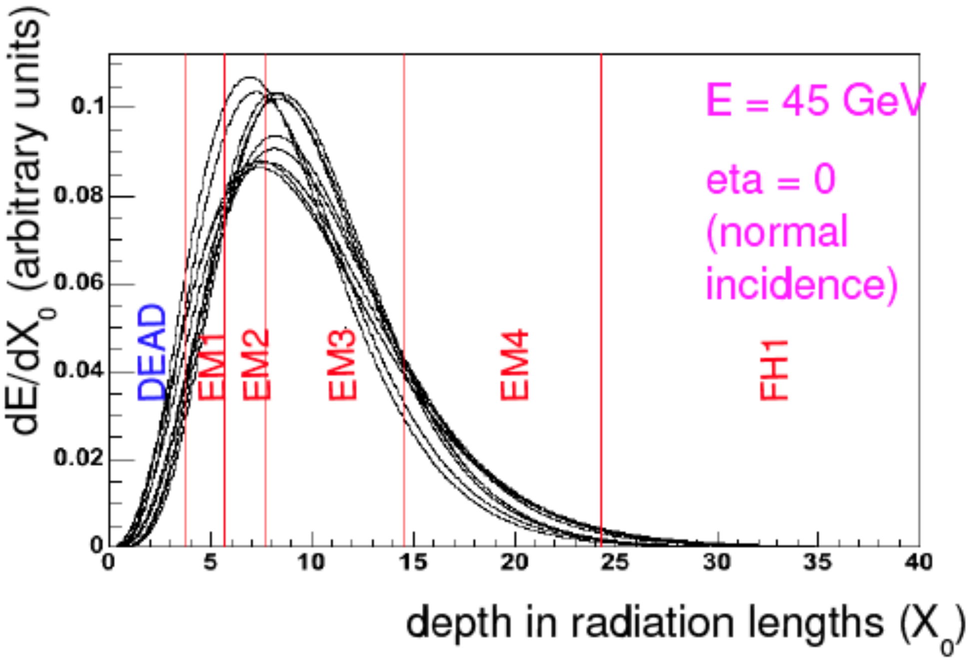
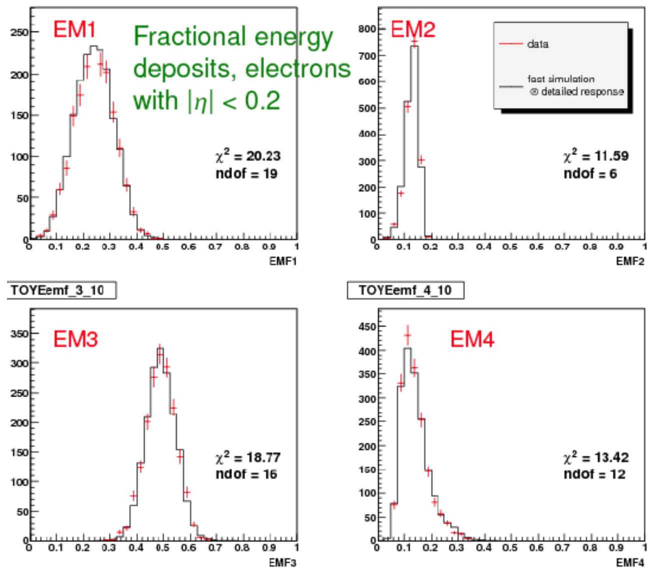
- Shower to shower fluctuations are significant

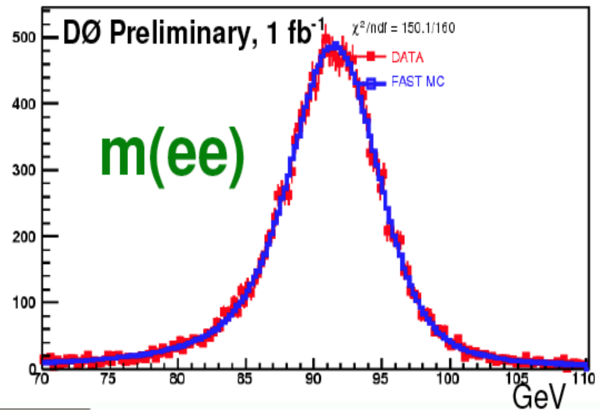


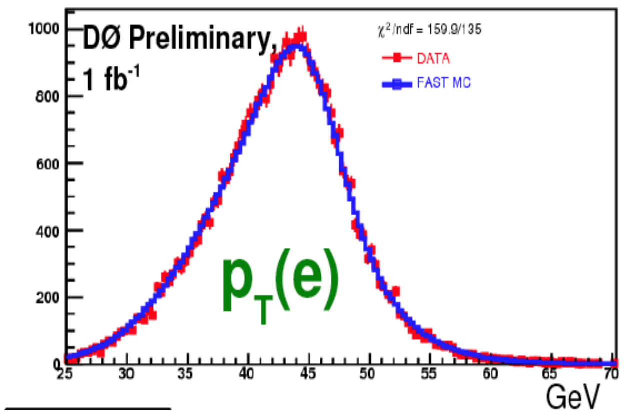
Electron Energy Response Calibration with $Z \rightarrow e^+e^-$

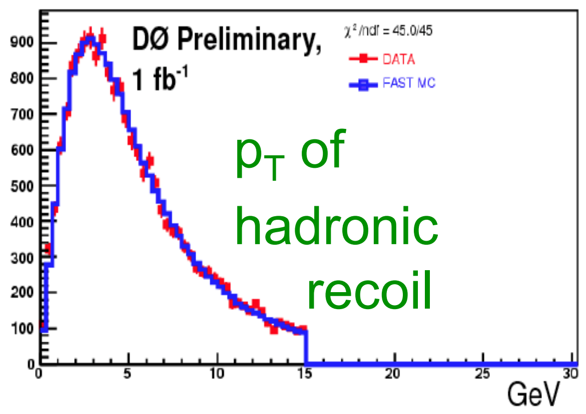


- Dead material known to $\pm 0.01X_0$!

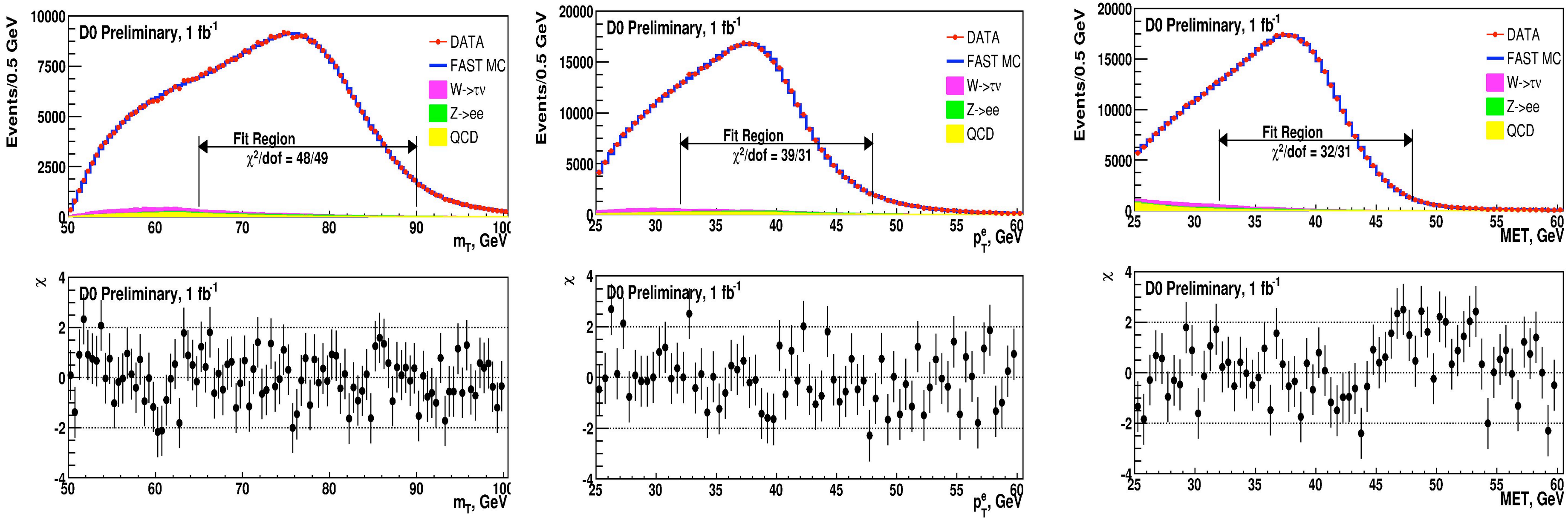
- $E_{measured} = \alpha \times E_{true} + \beta$
- Use energy spread of electrons in Z decay to constrain α and β
- Uncertainties on α and β translate to Δm_W = 34 MeV
  - By far the largest single uncertainty
  - Dominated by $Z \rightarrow e^+e^-$ statistics
    - so will improve with more data



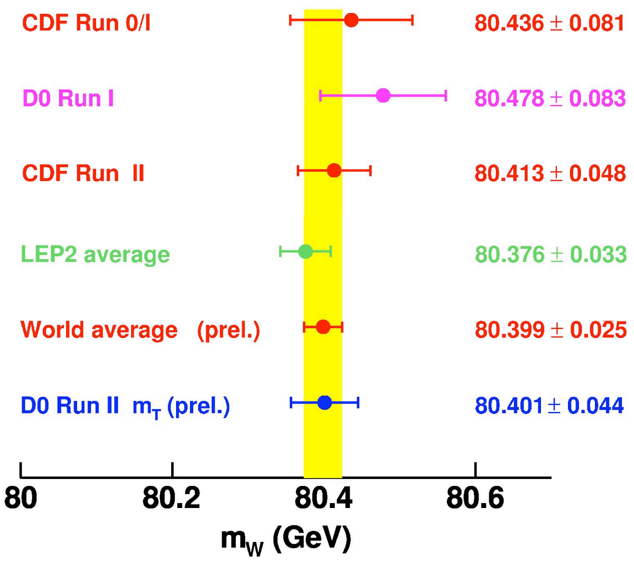




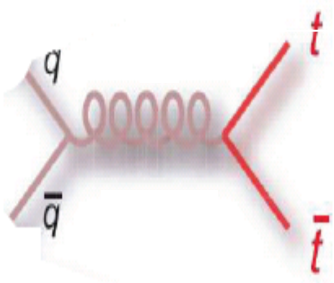
W Mass Fits

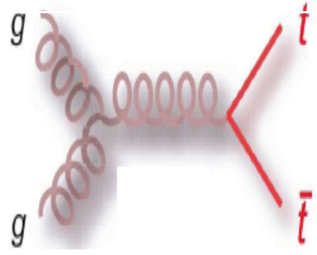


- Currently quote result from m_T fit:
  - m_W = 80.401 ± 0.023 (stat) ± 0.037 (syst) GeV
- World's most precise single-experiment m_W measurement
- Combination with p^e_T and MET fit will reduce uncertainty slightly
- Energy scale uncertainties fairly uncorrelated between CDF and DØ

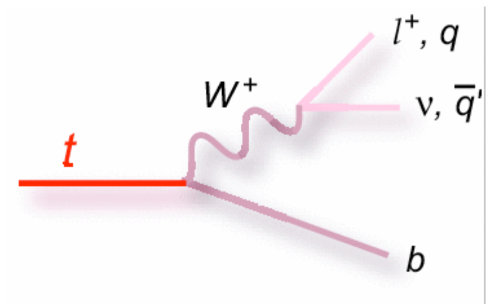


Top Quark Production and Decay at Tevatron

- Pair production: 85% 

15% 

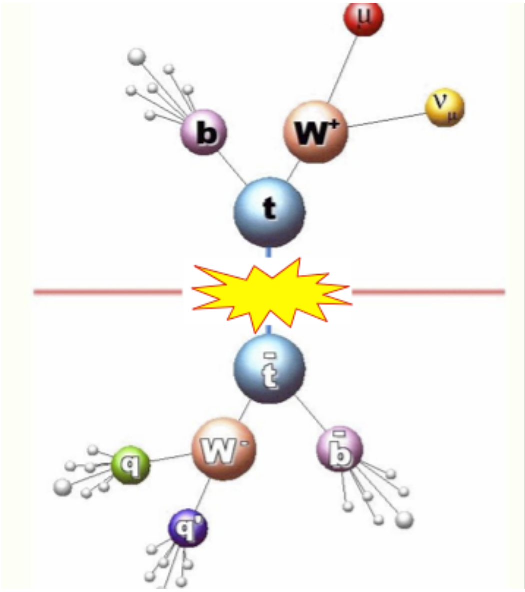
- Decay

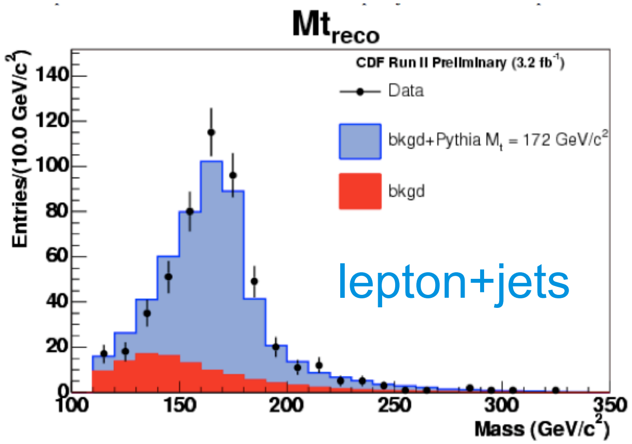


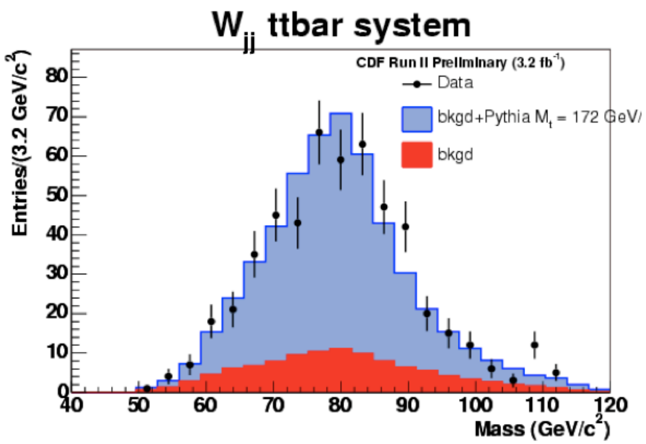
  - Final state determined by decay of the two Ws
  - Discovered by CDF and DØ in 1995
  - Lifetime ~5 x 10^{-25} s
    - Decays before "hadronization" takes place (timescale ~10^{-25} s)
    - Our only opportunity to study a "bare" quark
  - Is the object we see the SM top quark?

Top Mass Measurement

- Reconstruct t quark mass and W→qq mass
  - constrain Jet Energy Scale(JES) at ~1% level!





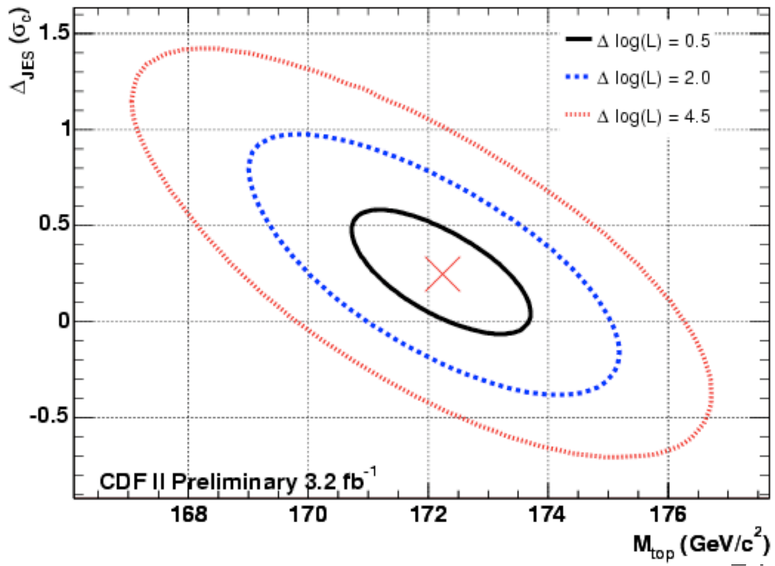


m_{top} =173.1 ± 1.3 GeV

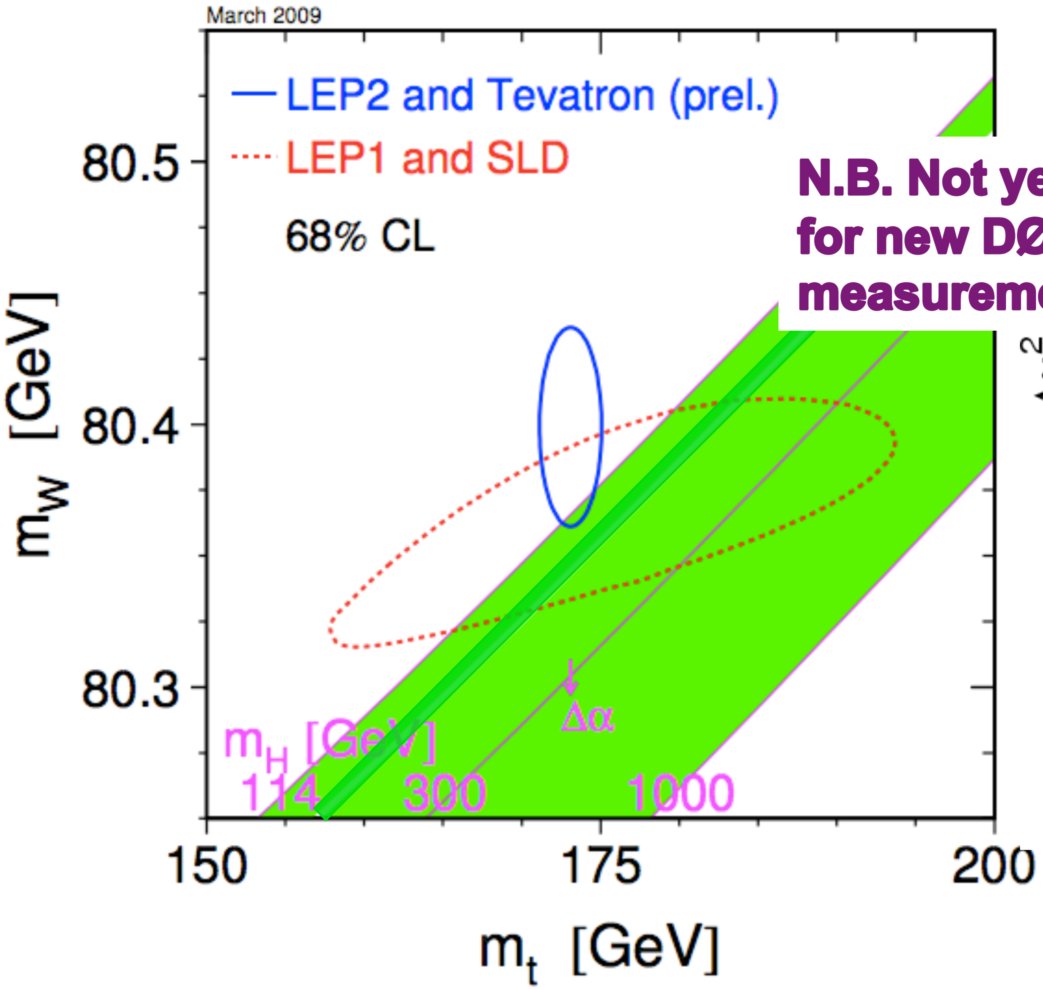
(Including *± 0.7 GeV* from JES, which will improve with more data)

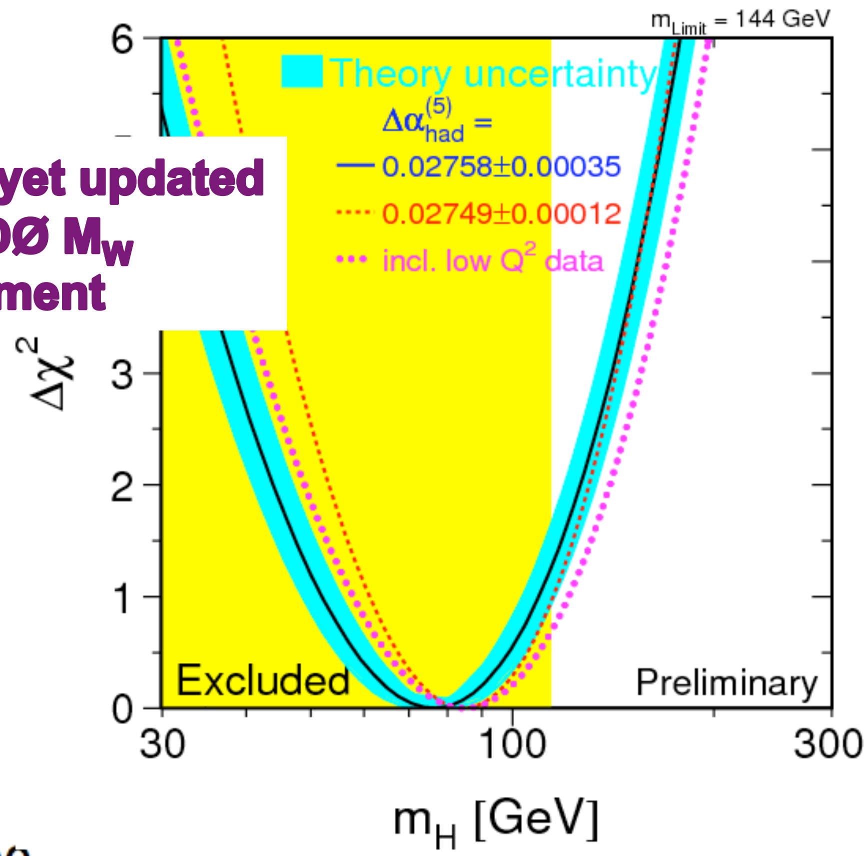
$\Delta m_{top} / m_{top}$~0.7%

(by far the most precisely known quark mass!)



m_W and m_t (compared to m_H)

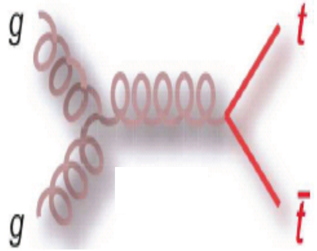




- Data prefer a light Higgs!
- $m_H = 90^{+36}_{-27}$ GeV $m_H < 163$ GeV (@95%CL)

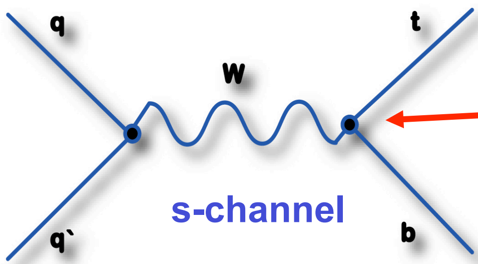
Observation of Single Top Production

- Top pairs:



σ_{tt} **= 6.7 ± 0.8 pb**

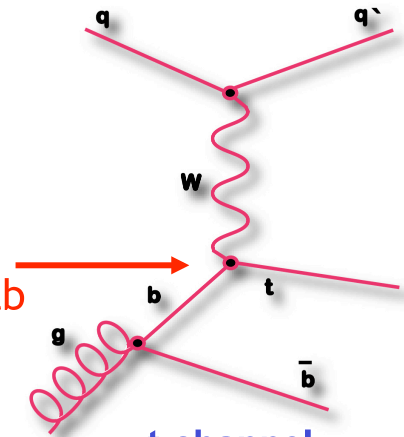
- Single top:



s-channel

σ_s **= 0.88±0.07 pb**

V_{tb}

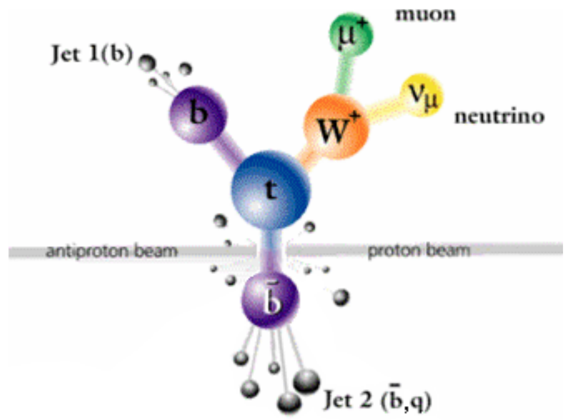


t-channel

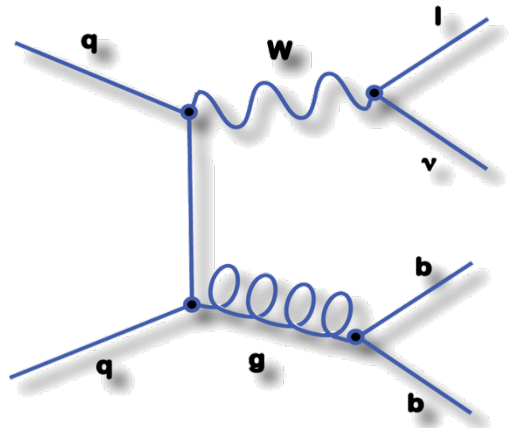
σ_t **= 1.98±0.21 pb**

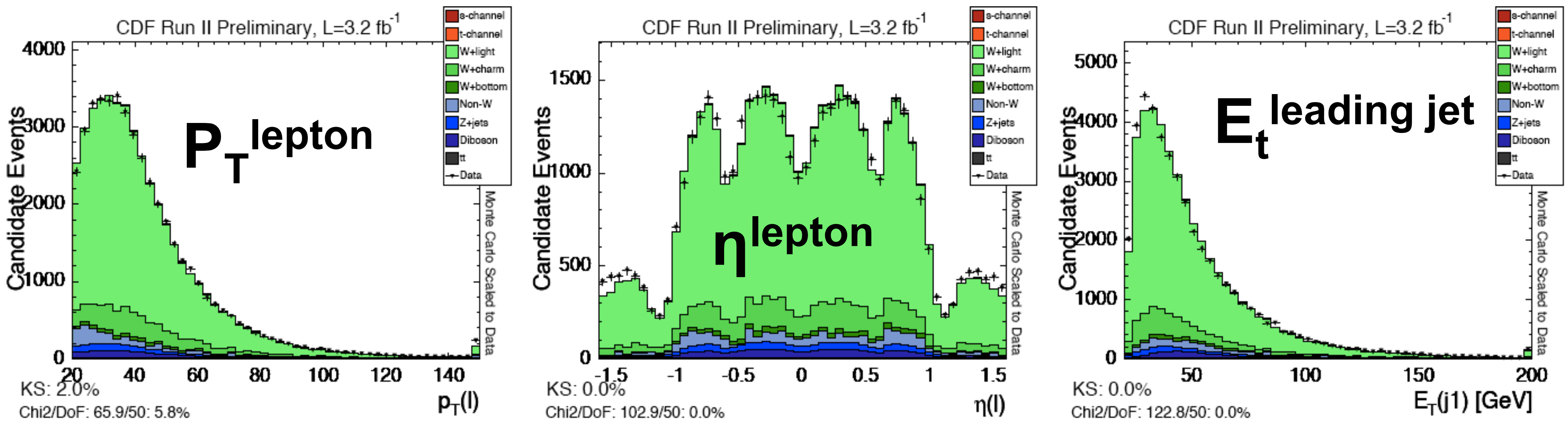
- The most direct way to study the W→tb vertex!

Backgrounds to Single Top



- σ_{s+t} only a factor of ~two lower than σ_{tt}
  - but event signature much less pronounced
    - fewer high p_T objects
- Backgrounds much more of a challenge!
- W+jets poorly understood
  - especially W+heavy flavour
  - considerable tuning of MC to data required

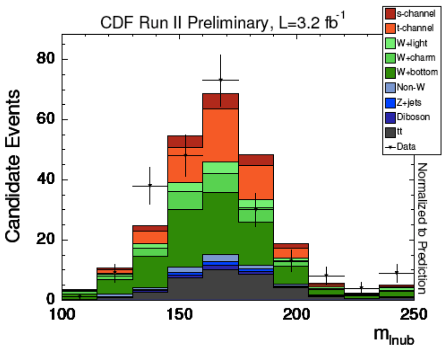


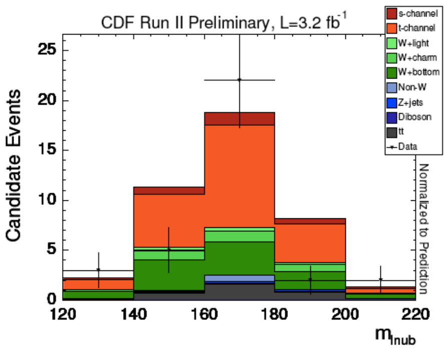


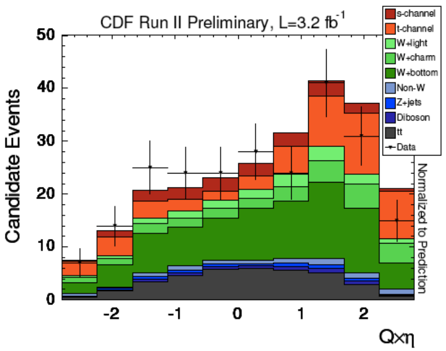
CDF Observation of Single Top Production

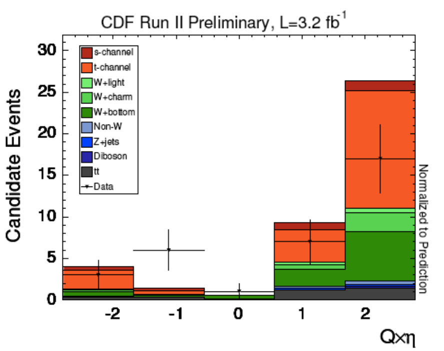
- Cut on discriminant selects single top-like background
  - a general feature of such analyses!

BDT>0.25 | BDT>0.6





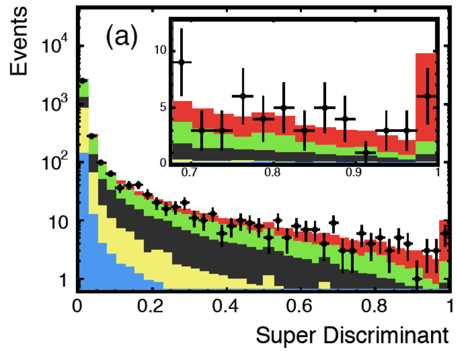


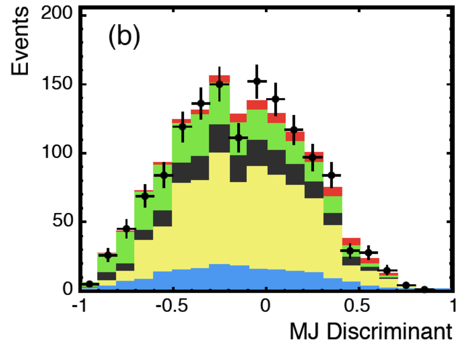


Discriminant output distributions

Combination of five lepton+jets+MET analyses

Jets+MET analysis





3.2 fb^{-1}

4.8σ (5.9σ expected)

2.1 fb^{-1}

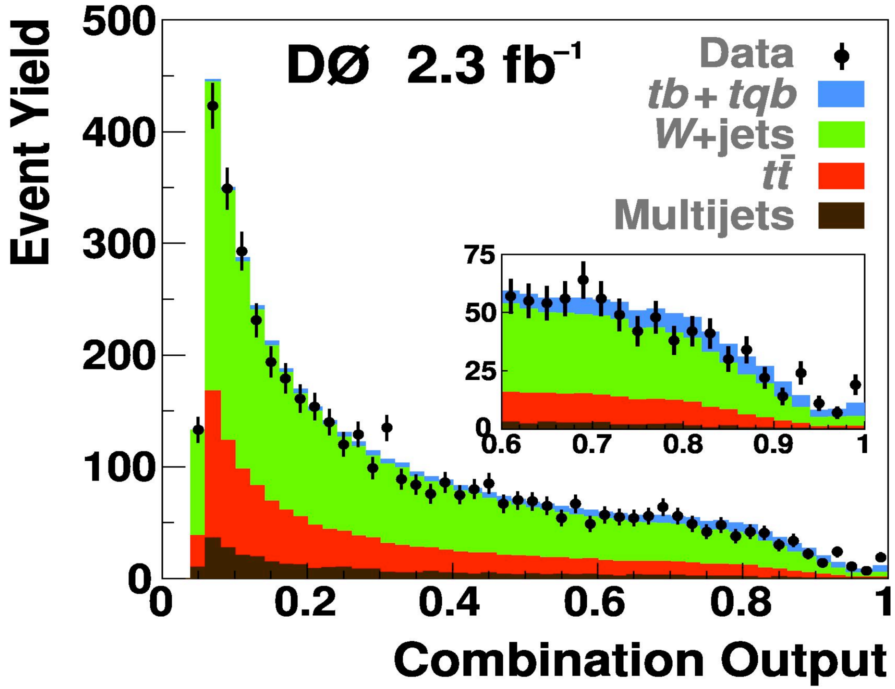
2.1σ (1.4σ expected)

- Combined significance 5.0σ

$$\sigma_{s+t} = 2.3^{+0.6}_{-0.5}(\text{stat} + \text{syst})\ \text{pb}$$

DØ Observation of Single Top Production

- $2.3\ fb^{-1}$
- Combination of three lepton+jets +MET analyses
- Significance 5.0σ (4.5σ expected)
- σ_{s+t} = 3:94±0:88 (stat + syst) pb



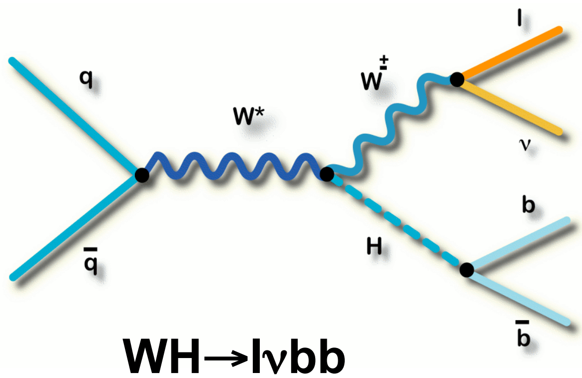
The only direct determination of $|V_{tb}|$

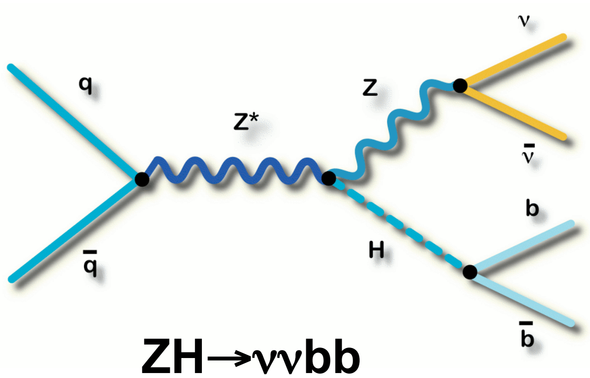
	CDF	DØ
$\lvert V_{tb}\rvert$	0:91±0:11	1:07 ± 0:12
$\lvert V_{tb}\rvert$ @ 95% CL	> 0.71	> 0.78

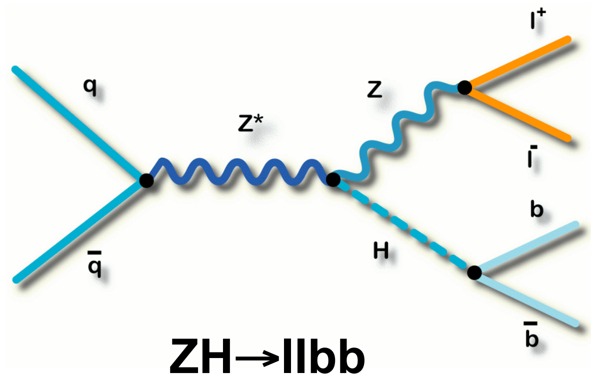
- Plus, a really important calibration analysis for **WH→lνbb**, etc.
  - and will get increasingly precise with more data!

Searches for the SM Higgs Boson at the Tevatron

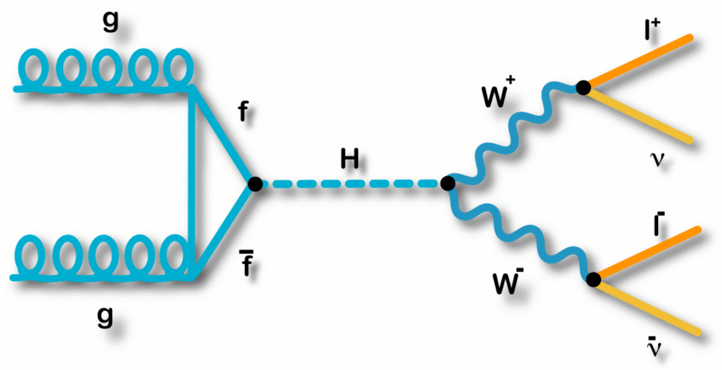
"Associated Production": Low mass only, three final states







"Gluon Fusion": Most interesting at intermediate to high masses



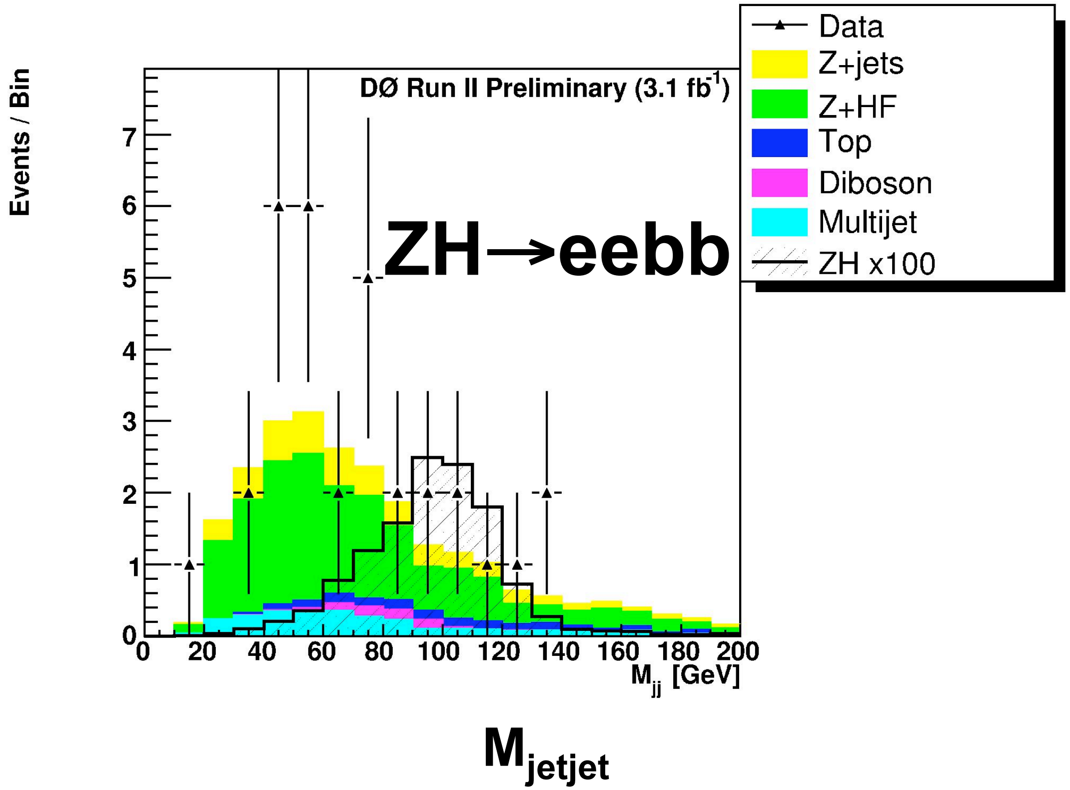
Higher cross section
- but can only distinguish from backgrounds with H→WW decay

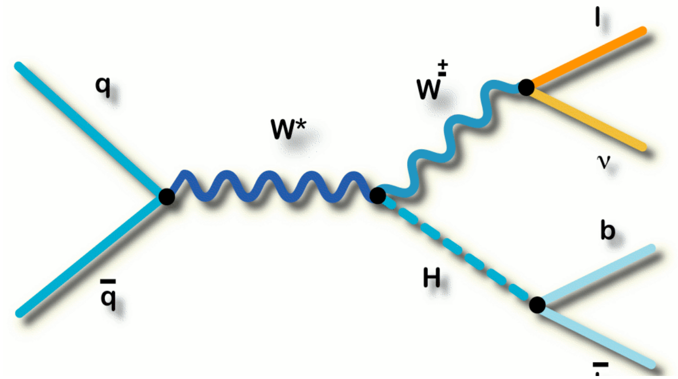
Also **WH→WWW** interesting at intermediate masses

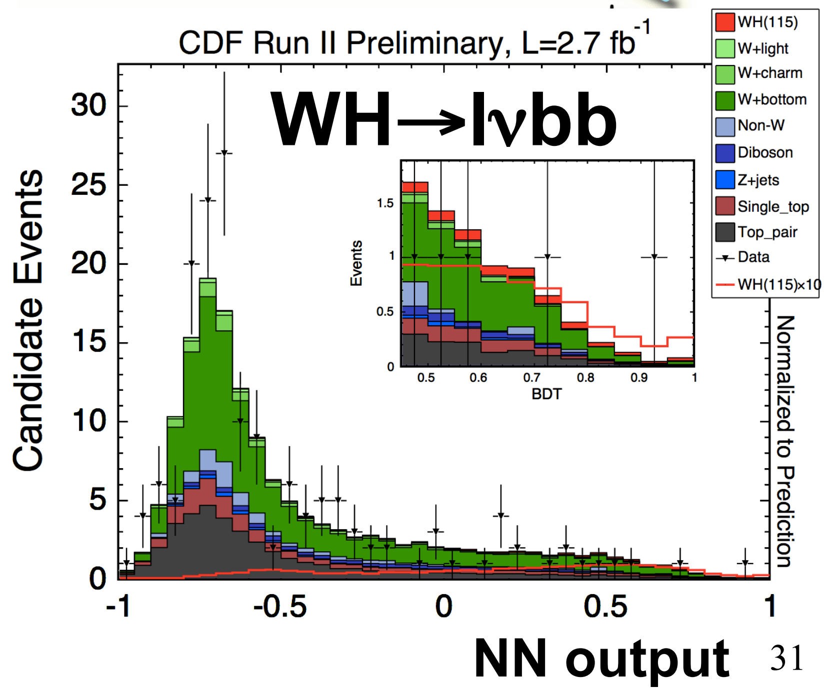
About 1 in 10^{12} proton-antiproton interactions will contain a Higgs
"The Higgs is underneath the needle in the haystack!"

Higgs Searches at Low Mass

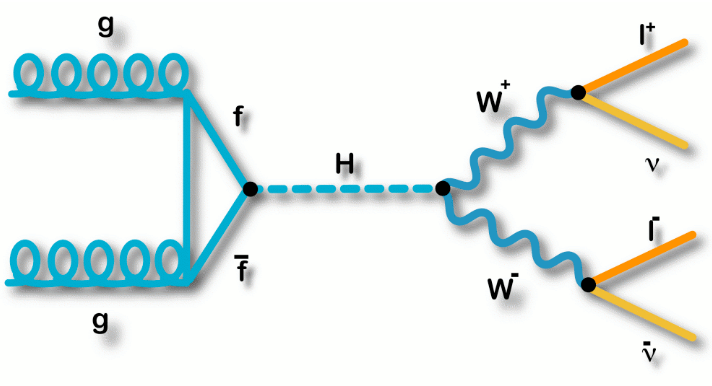
- Backgrounds very similar to single top!!!
  - top pair and single top production, W or Z + jets, “Di-boson” (WW, WZ, ZZ)



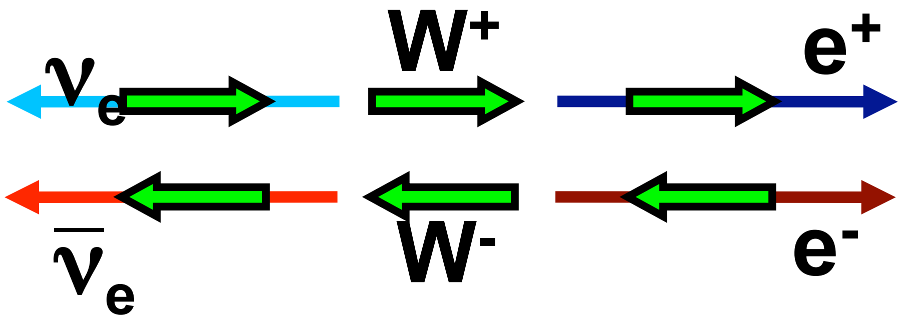




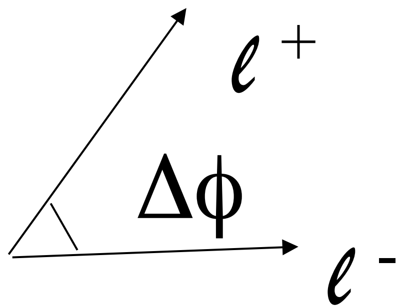
Higgs Searches at High Mass

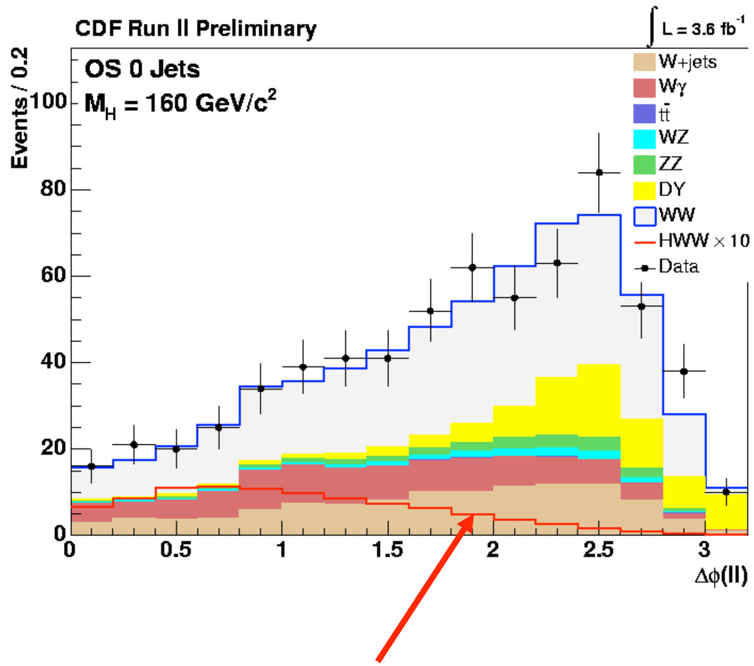


•Higgs is a spin zero particle



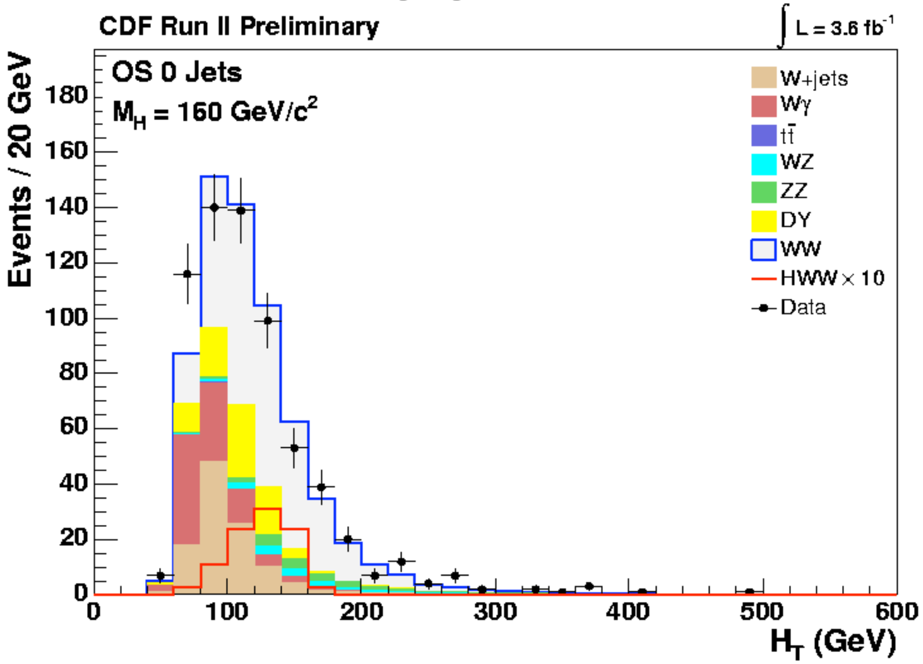
- Look for leptonic decays of WW
- Look at azimuthal angle between the two charged leptons
  - Higgs: small $\Delta\phi$
  - Standard WW events: large $\Delta\phi$

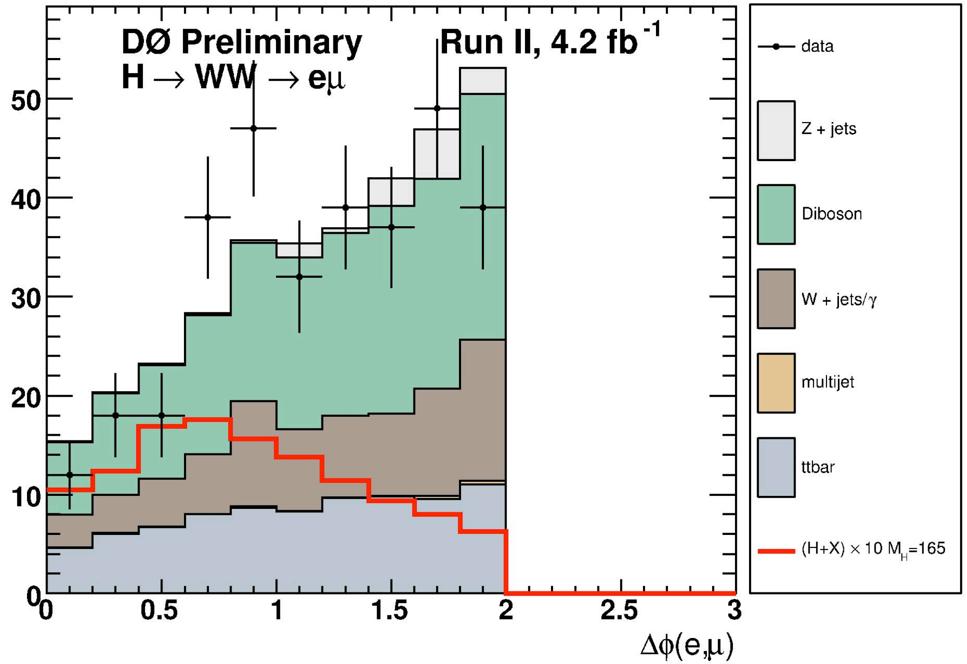


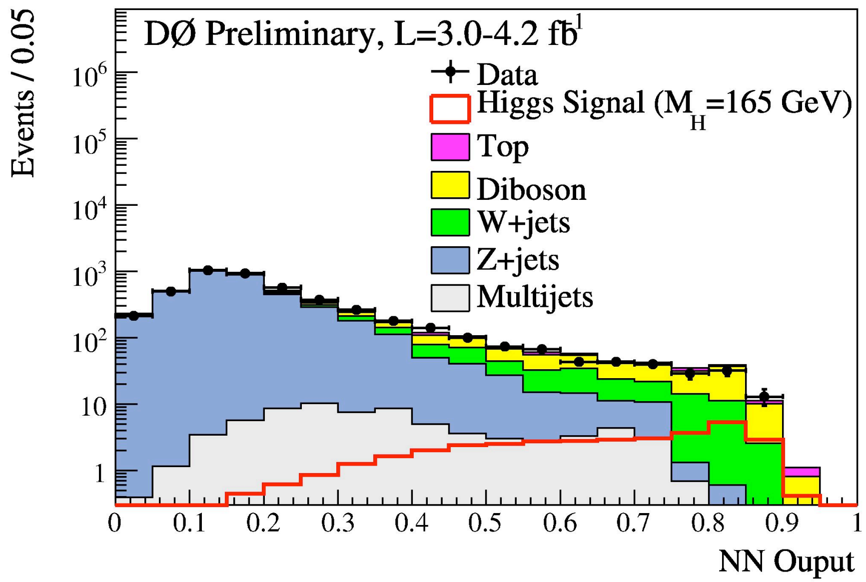


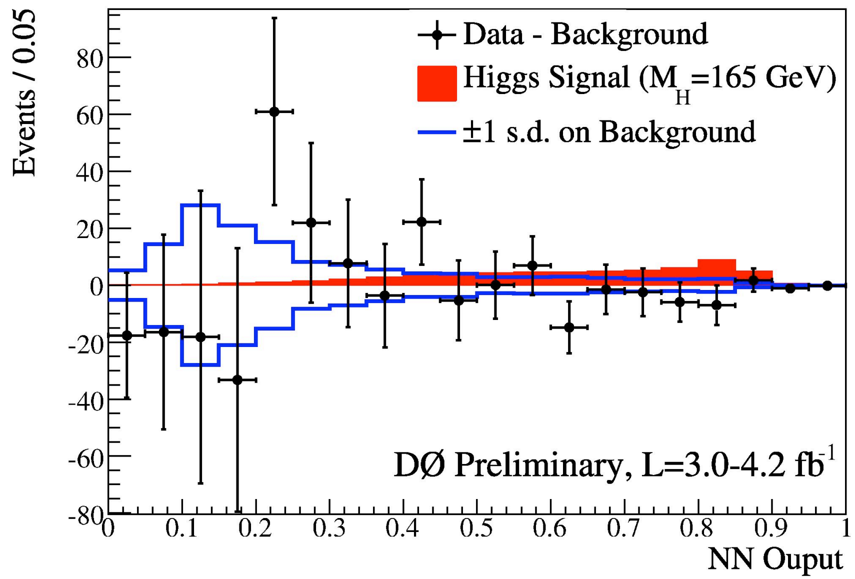
Higgs

Higgs Searches at High Mass





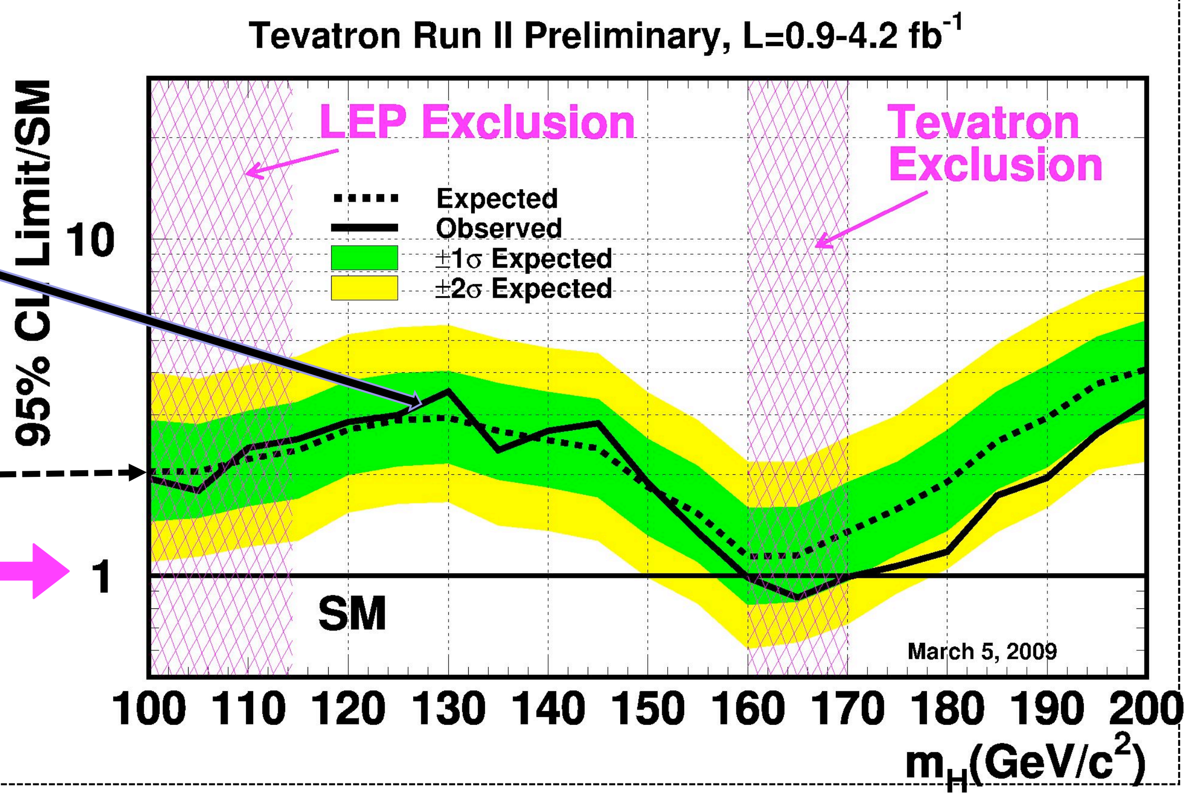




Current CDF+DØ Combined Limits

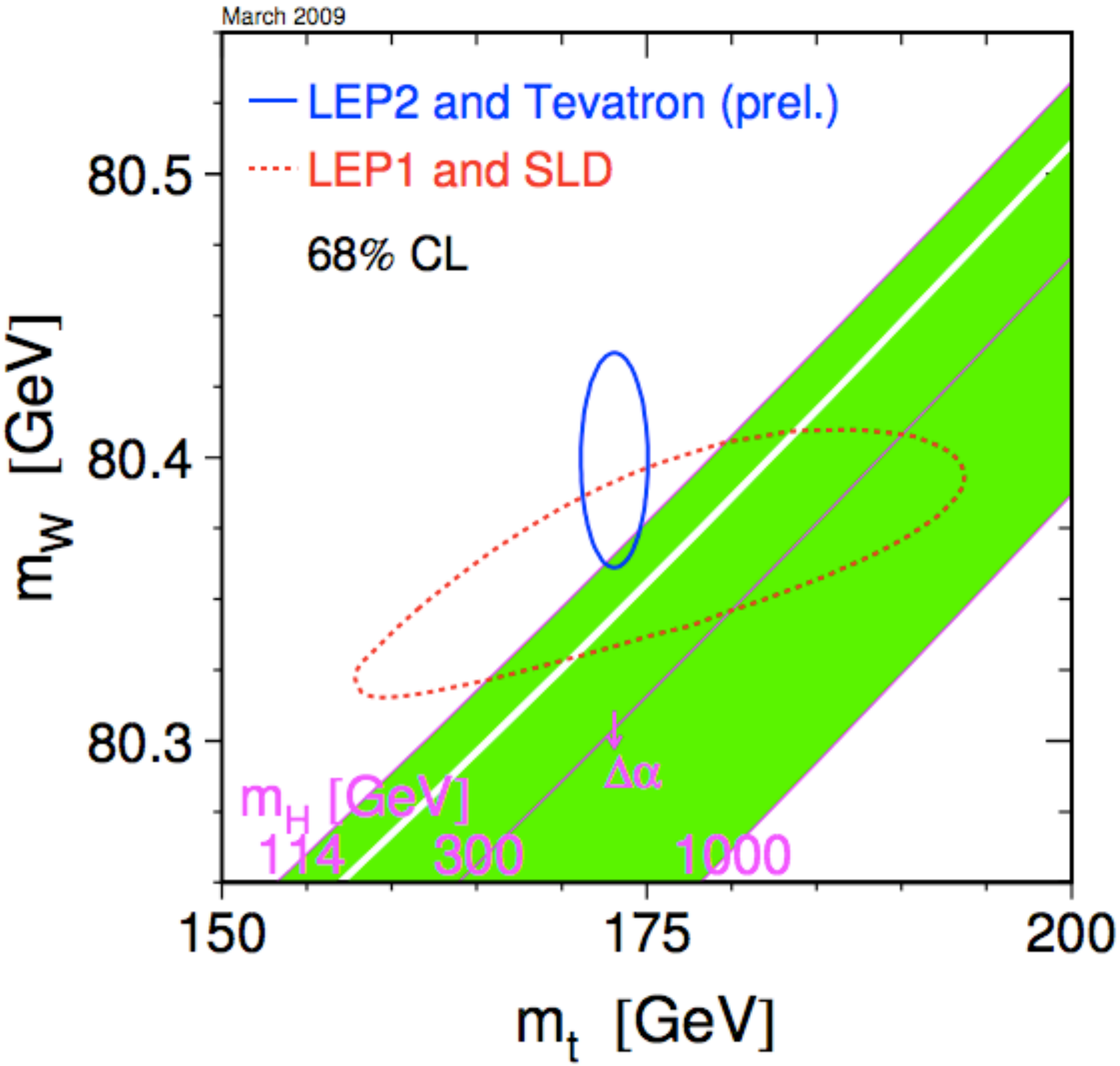
- In the absence of a signal
  - Set a limit on the allowed cross section times branching ratio for Higgs production
    - that is, how large could cross section times branching ratio for Higgs production be before it would have been visible?
  - Express limit as a ratio to the cross section expected in the Standard Model

- "Observed limit" obtained from DØ data
-
- "Expected limit" obtained by repeating the analysis on "background-only" Monte Carlo "experiments"

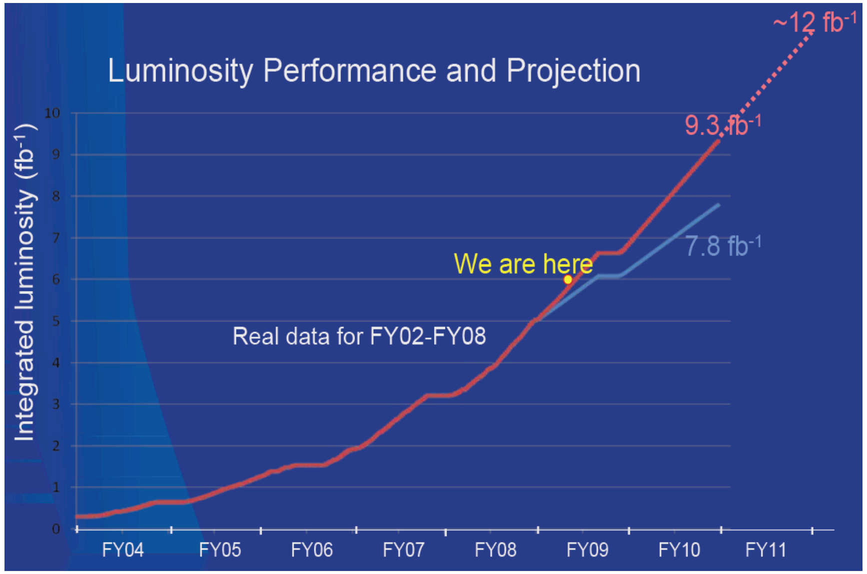


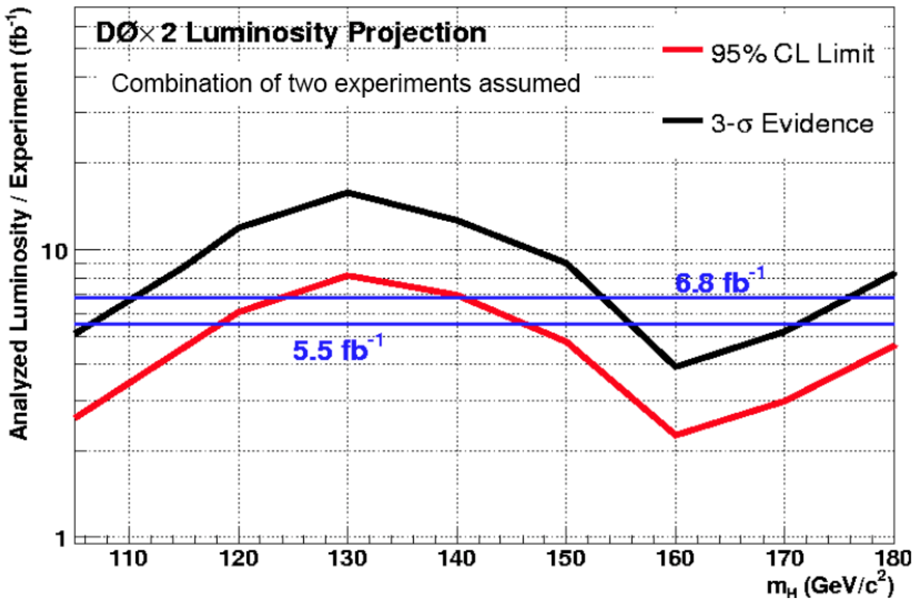
Standard Model Higgs ruled out @ 95% CL if the limit reaches this level!

Updated m_W, m_t, m_H) Plot



Prospects





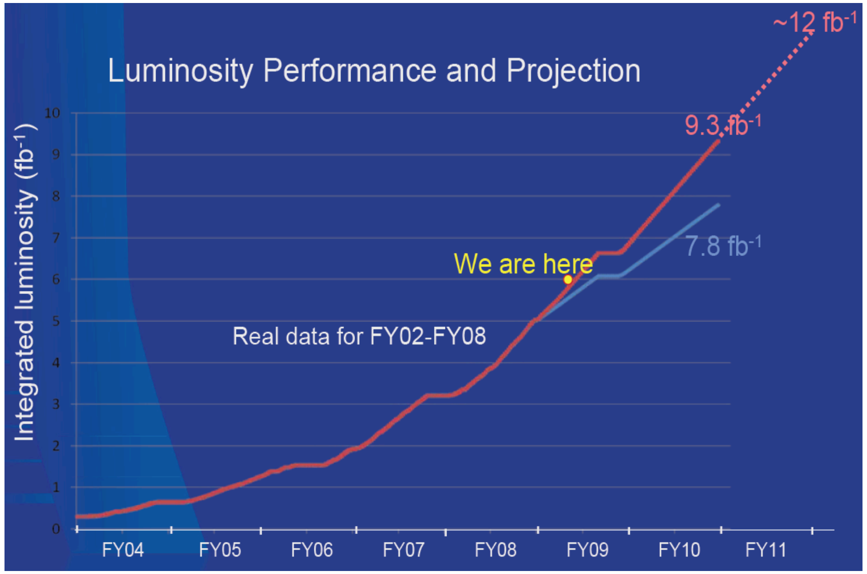
2010

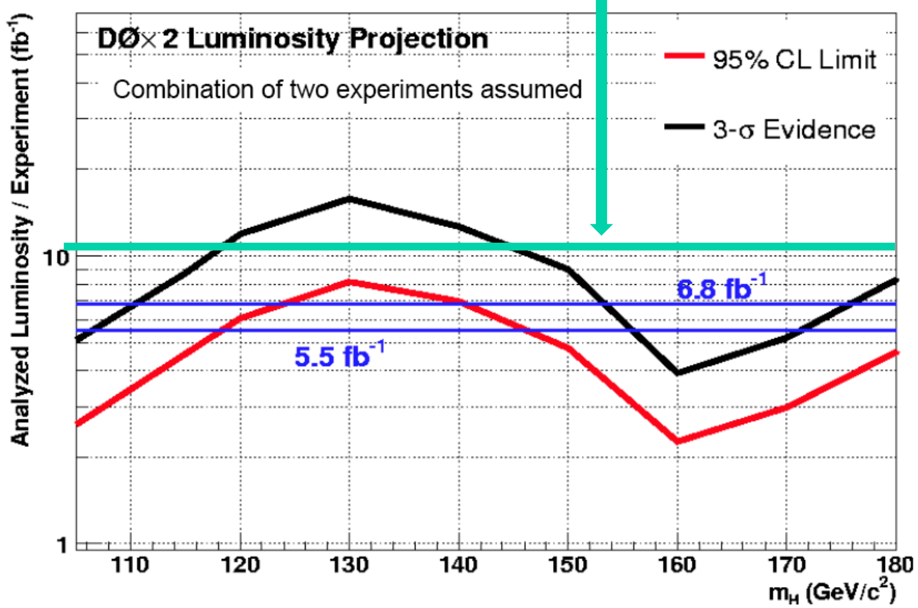
2009

Analyzed by
summer of ?

Prospects

Ultimate sensitivity?





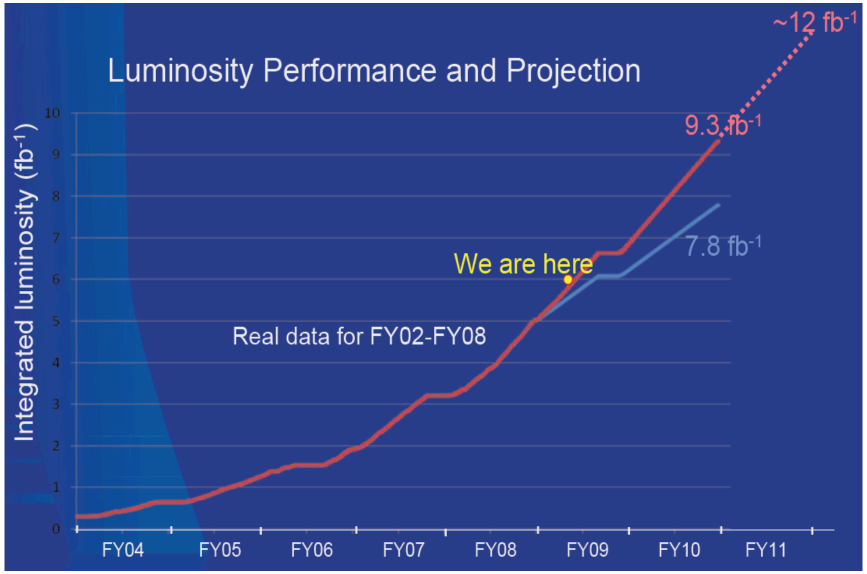
2010
2009

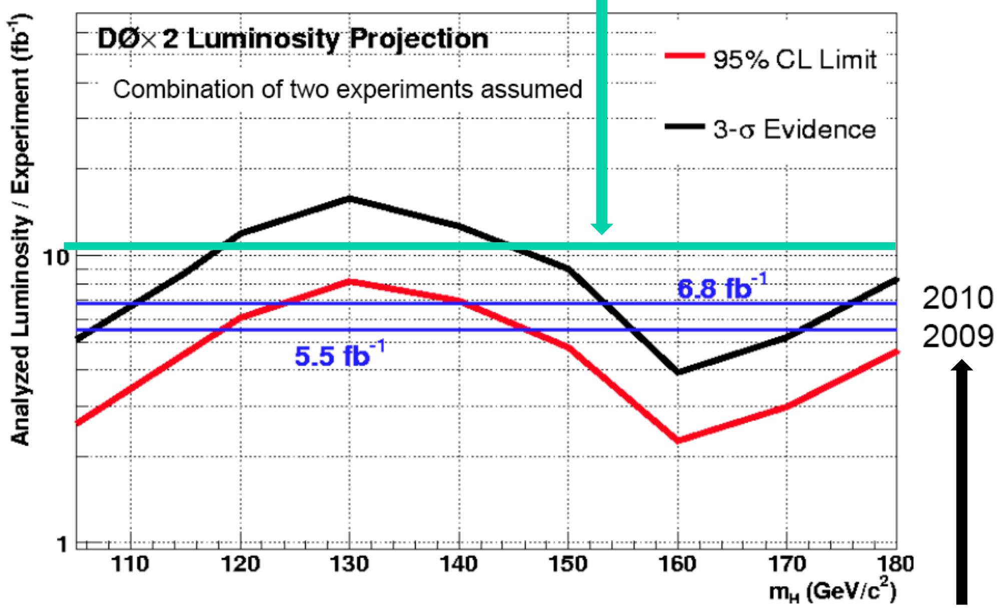
Analyzed by summer of ?

- Lots of creative work to improve Higgs sensitivity still going on!
  - plus several important SM “calibration analyses”
    - single top, Di-bosons in semileptonic modes

Prospects

Ultimate sensitivity?





Analyzed by summer of ?

- Lots of creative work to improve Higgs sensitivity still going on!
- Most non-Higgs analyses also still stats limited, e.g.,
  - $B_s \to \mu\mu$, CP violation search Φ_s
  - top properties
  - M_W and other measurements with W & Z
    - QCD phenomenology of high energy hadron-hadron collisions

(to do in the next 2-3 years while the LHC experiments are calibrating ;-)

Backup Slides

M_W Summary of uncertainties

systematic uncertainties

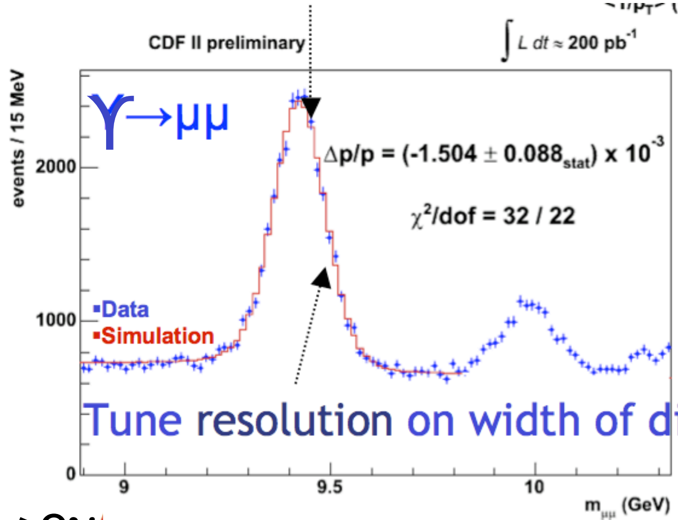
Source	$\sigma(m_W)$ MeV m_T	$\sigma(m_W)$ MeV p_T^e	$\sigma(m_W)$ MeV $\not{E}_T$
Experimental			
Electron Energy Scale	34	34	34
Electron Energy Resolution Model	2	2	3
Electron Energy Nonlinearity	4	6	7
W and Z Electron energy loss differences (material)	4	4	4
Recoil Model	6	12	20
Electron Efficiencies	5	6	5
Backgrounds	2	5	4
Experimental Total	35	37	41
W production and decay model			
PDF	9	11	14
QED	7	7	9
Boson p_T	2	5	2
W model Total	12	14	17
Total	37	40	44
statistical	23	27	23
total	44	48	50

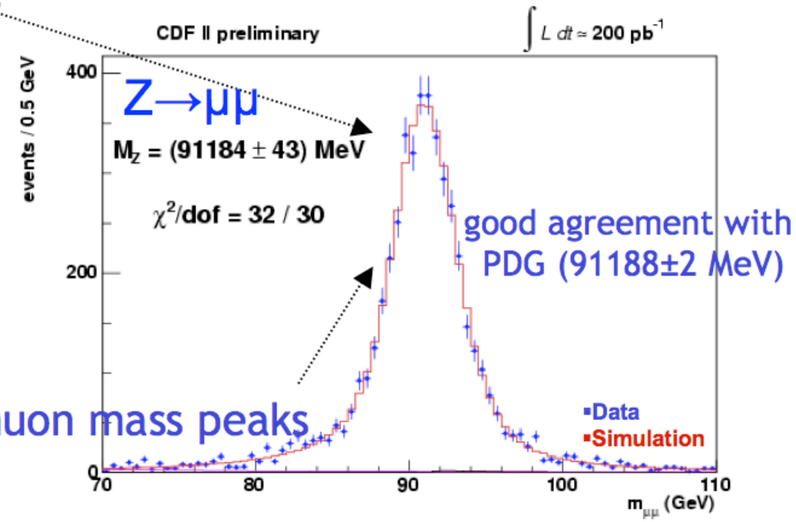
W Mass: Calibration

200 pb^{-1} data set (CDF)

51,128 $W \to \mu\nu$ candidates	4,960 $Z \to \mu\mu$ candidates
63,964 $W \to e\nu$ candidates	2,919 $Z \to ee$ candidates

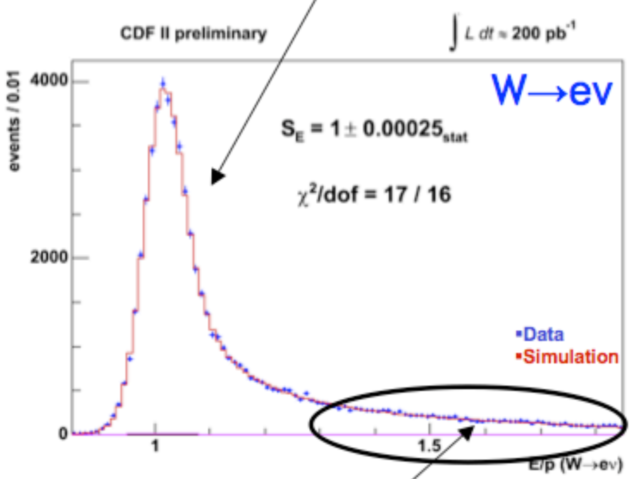
- Many handles to calibrate tracker and calorimeter p_T scale and resolution



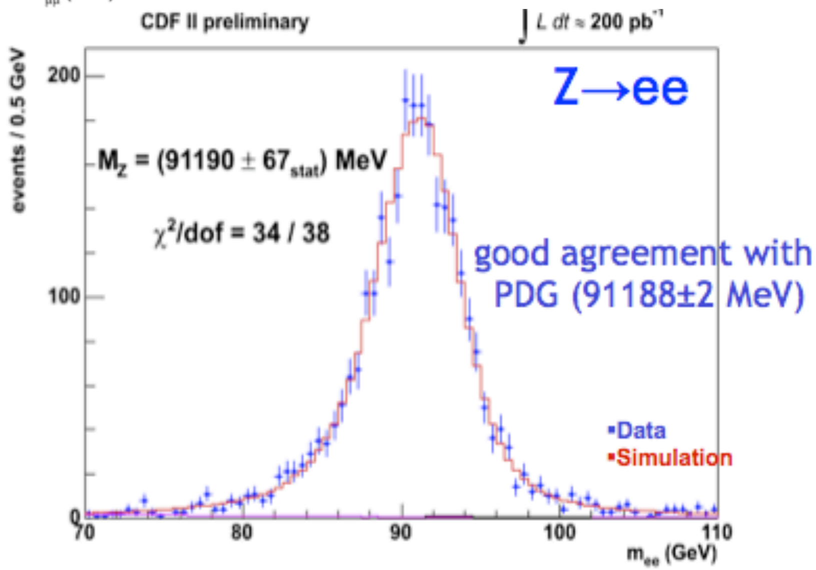


Tune resolution on width of di-muon mass peaks

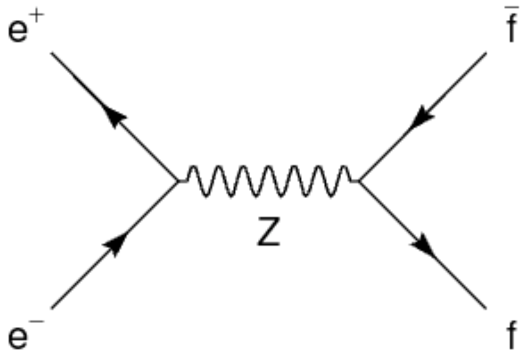
- E/p in $W \to e\nu$



dead material



Parameters of The Standard Model

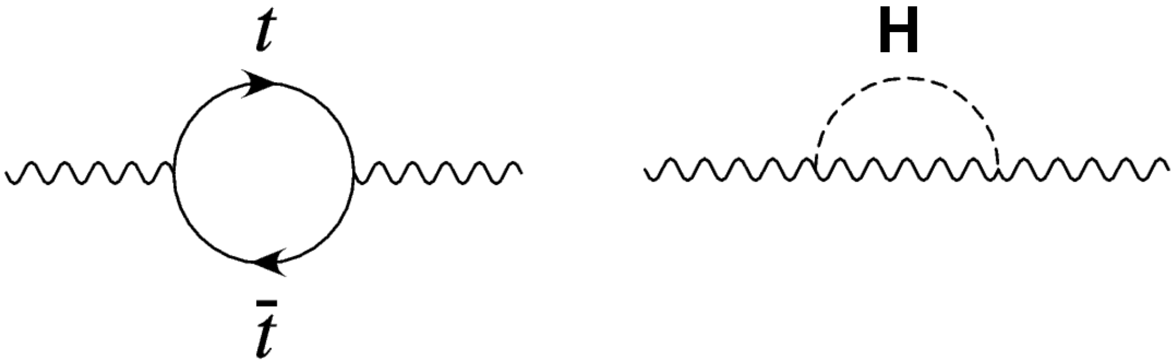


- At the level of simple "tree level" diagrams the EW interactions are determined by three "input" parameters
- Masses of W and Z also given in terms of coupling constants

$$m_W{}^2 = m_Z{}^2 \cos^2\theta_W = \frac{\pi\alpha}{\sqrt{2}G_F \sin^2\theta_W}$$

- For practical purposes we use as inputs the three most precisely known EW experimental observables:
  - The fine structure constant: $\alpha = e^2/2\varepsilon hc$
  - Fermi constant (measured in muon decay $\mu^- \rightarrow e^- \bar{\nu}_e \nu_\mu$): G_F
  - Z mass: m_Z
- Adding QCD requires an additional constant:
  - The strong coupling constant: α_s

Loops



- Loops cause running of coupling constants
  - $\alpha \rightarrow \alpha(Q^2)$
  - $\sin^2\theta_W \rightarrow \sin^2\theta_W^{eff}$
- EW observables then depend on:
  - α, G_F, m_Z, m_t, m_H
- Basic programme:
  - Measure precisely L and R couplings of each fermion to γ, Z, W
  - Measure precisely boson self-interactions
  - Measure precisely α_s, α, G_F, m_Z, m_t
  - Test consistency of measurements with Standard Model predictions
  - Find the Higgs!
    - (or other new particles beyond the Standard Model)

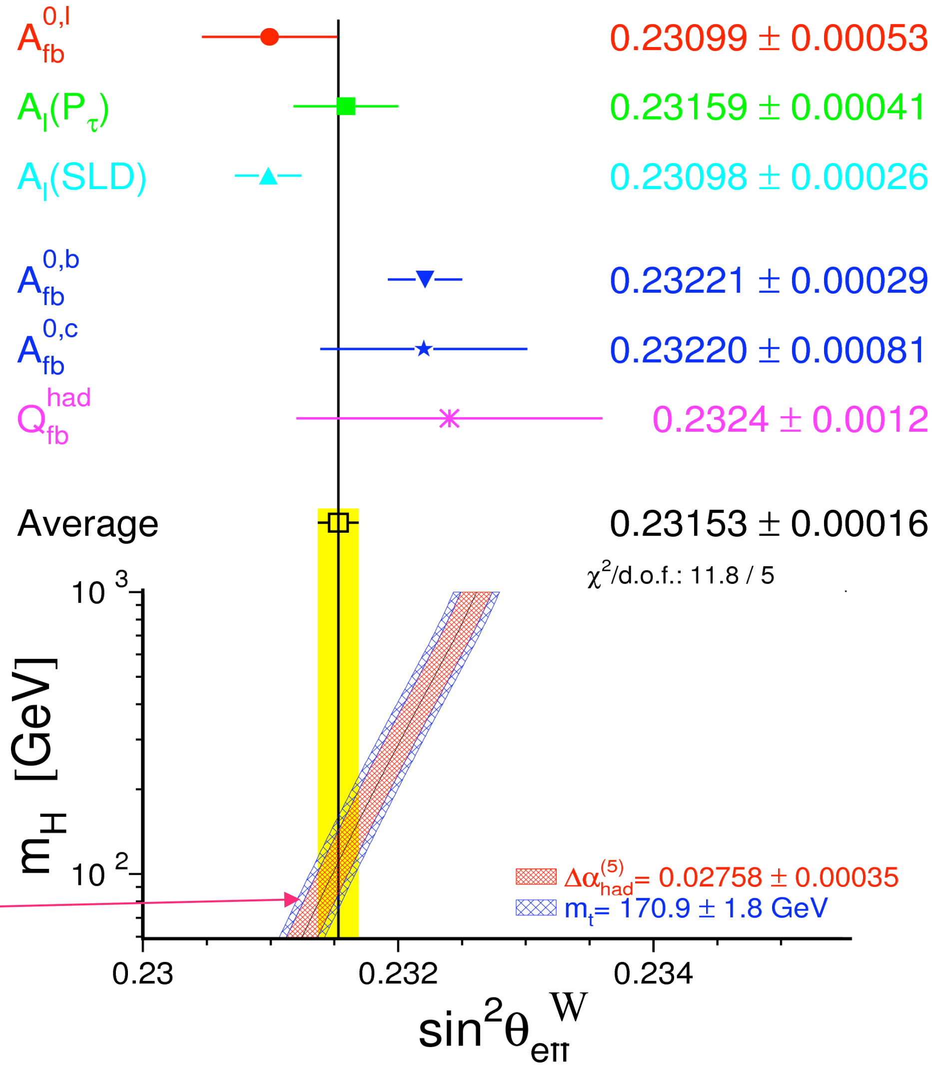
Summary of EW Data from LEP/SLC

- Asymmetries measure:

$$\frac{(g_L^f)^2 - (g_R^f)^2}{(g_L^f)^2 + (g_R^f)^2}$$

- Combine all measurements

- Prediction of Standard Model
  - width of band depends on uncertainty in m_t running of α
  - value depends on m_H



- a