Tevatron:
Recent 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), BSM Searches
  - (50 journal publications, 30 PhDs, per annum, per experiment)

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

………. and over the next couple of years faces rather little competition from the LHC experiments

➢ Prospects

PLEASE ASK QUESTIONS AS WE GO ALONG!!!

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)

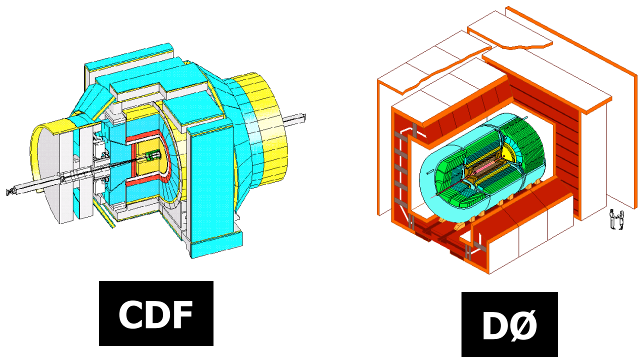
2002-05 Run IIa:

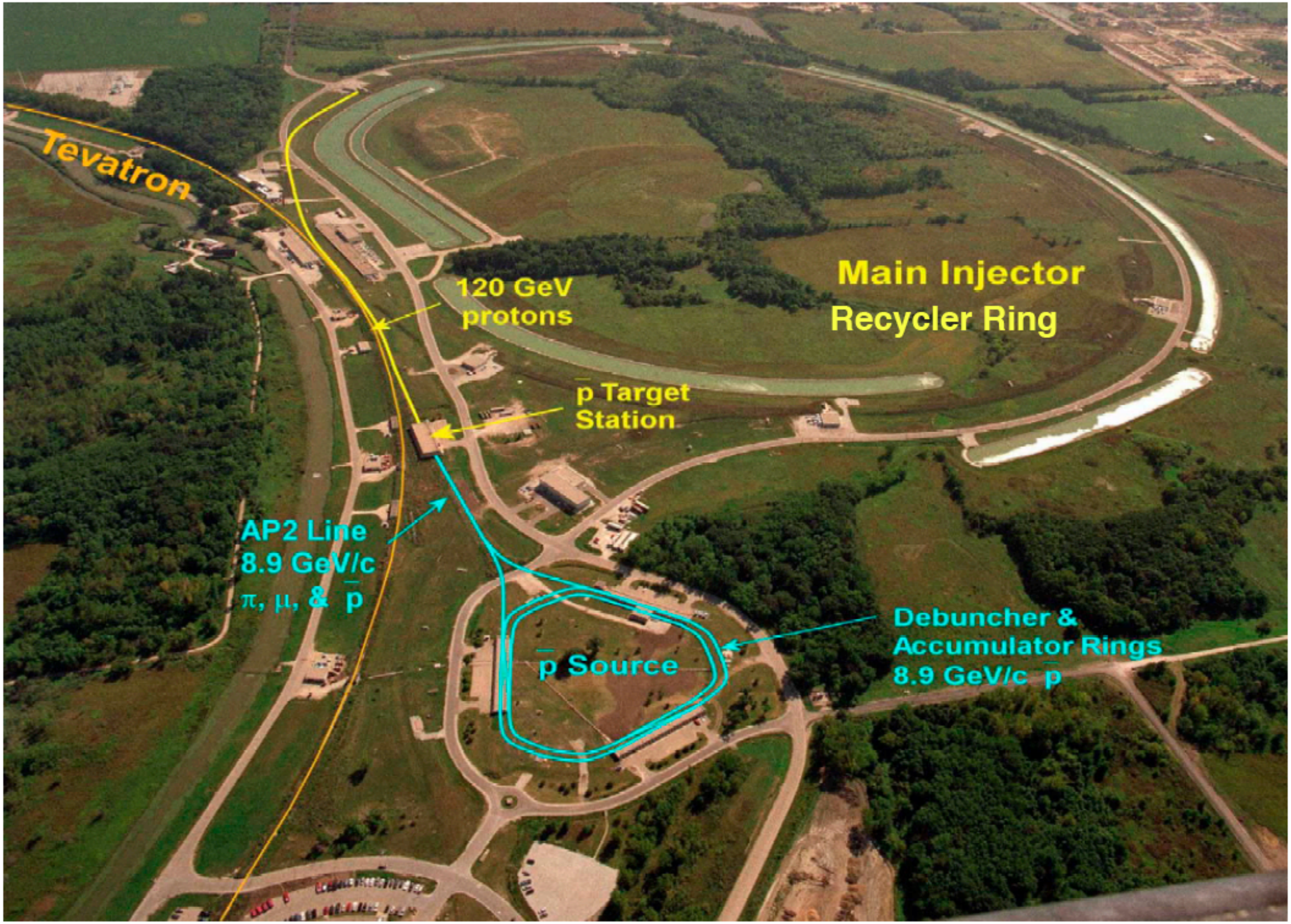
$\int Ldt \sim 1.6\ fb^{-1}$, 1.96 TeV

Further upgrades

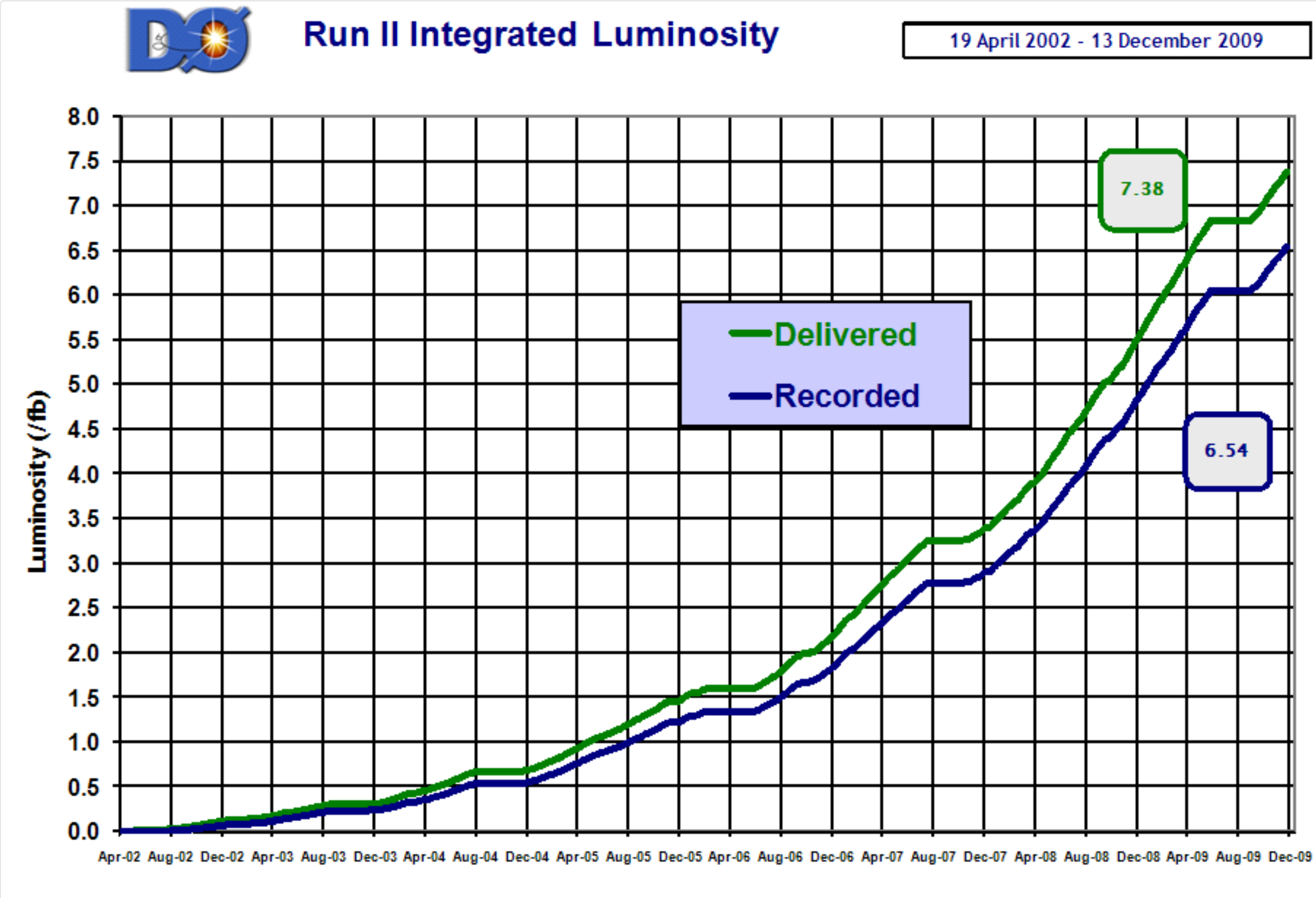
2006-10 Run IIb: (2011 run very likely)

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



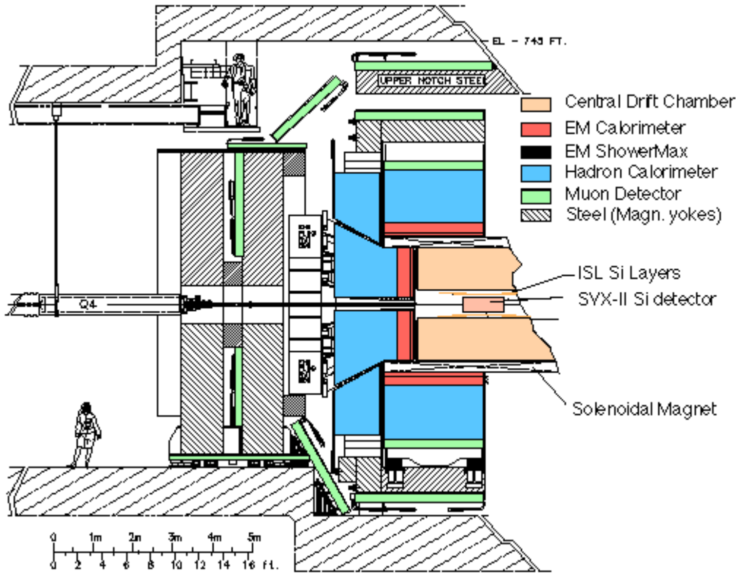

Tevatron
120 GeV
protons
Main Injector
Recycler Ring
$\bar{p}$ Target
Station
AP2 Line
8.9 GeV/c
π, μ, & $\bar{p}$
$\bar{p}$ Source
Debuncher &
Accumulator Rings
8.9 GeV/c $\bar{p}$

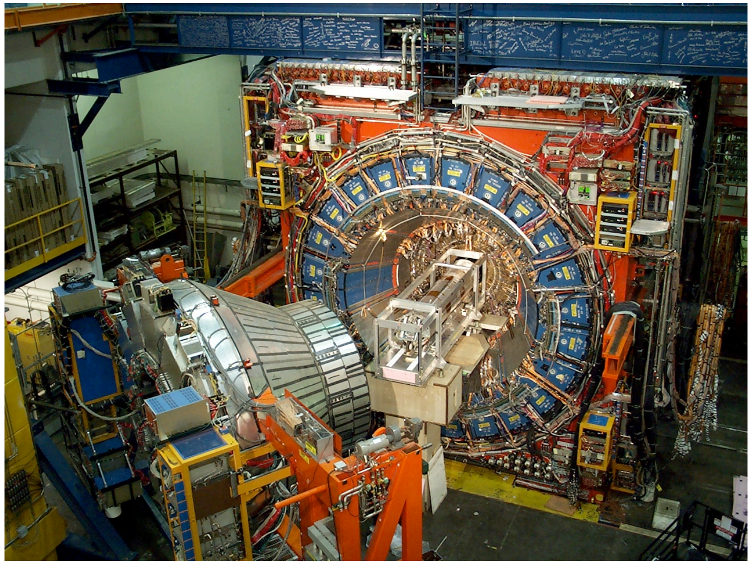
Integrated Luminosity History



Average DØ data taking efficiency since April 2002 is 89%!

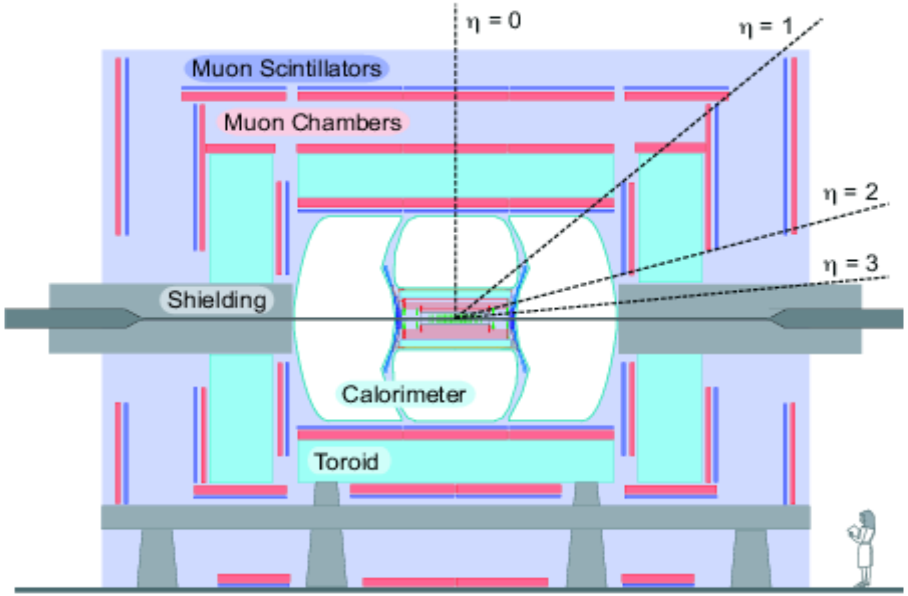
CDF

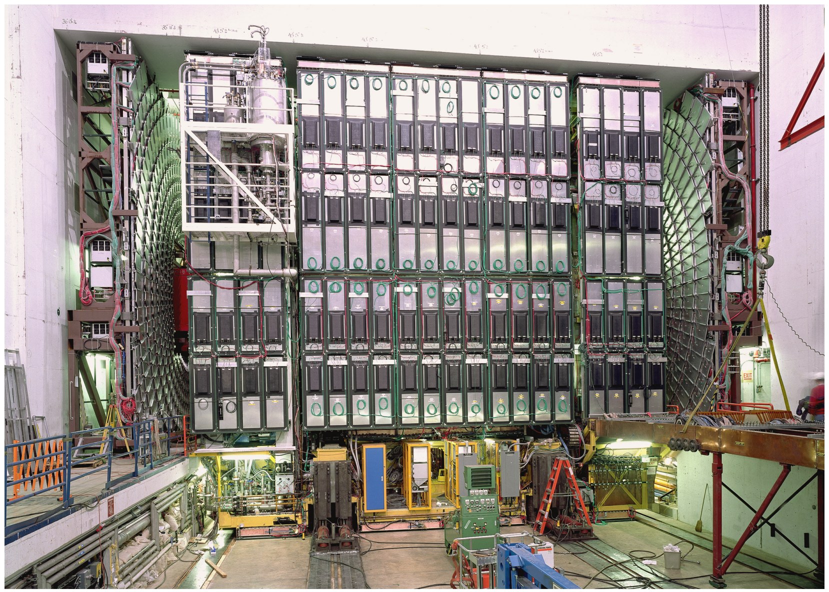




DØ

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





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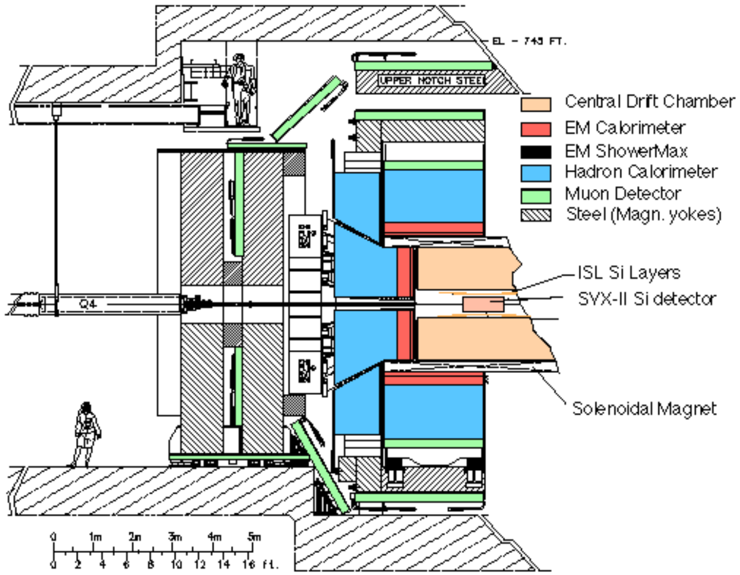

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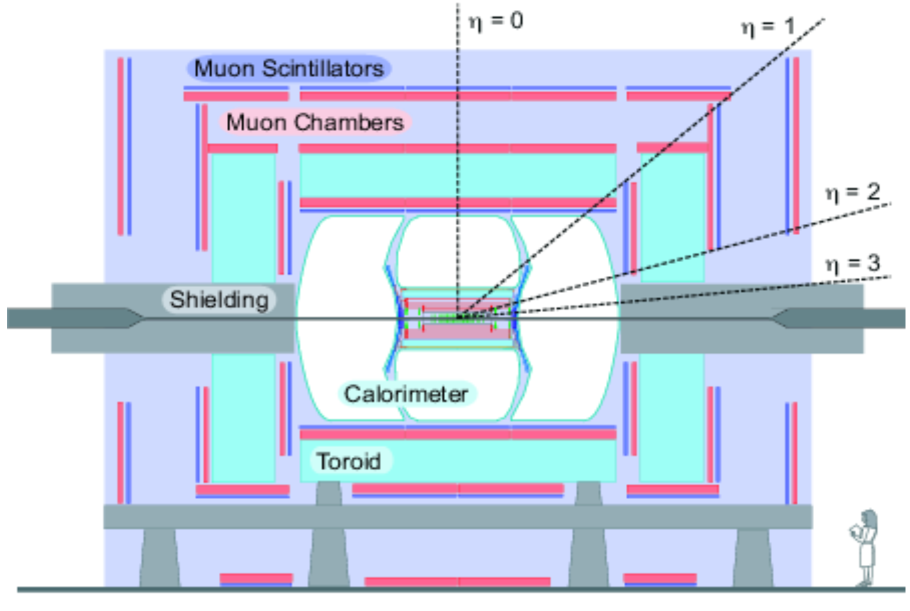


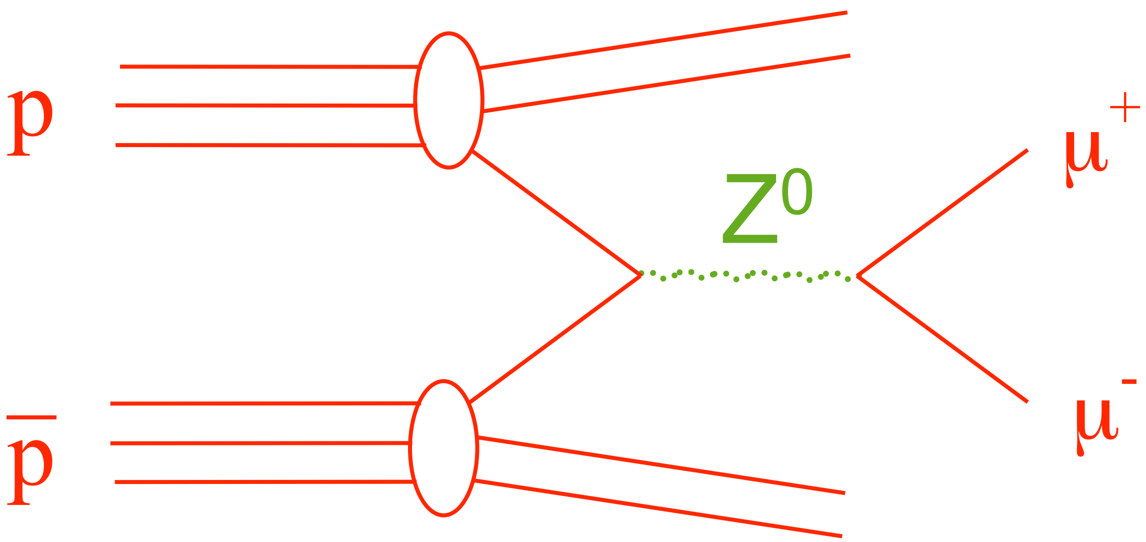
CDF detector highlight

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

DØ detector highlight

- Liquid Argon/Uranium calorimeter
  - longitudinal shower sampling
- High acceptance, low background, muon system
  - 0.5 m outer radius for DØ central tracker!

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

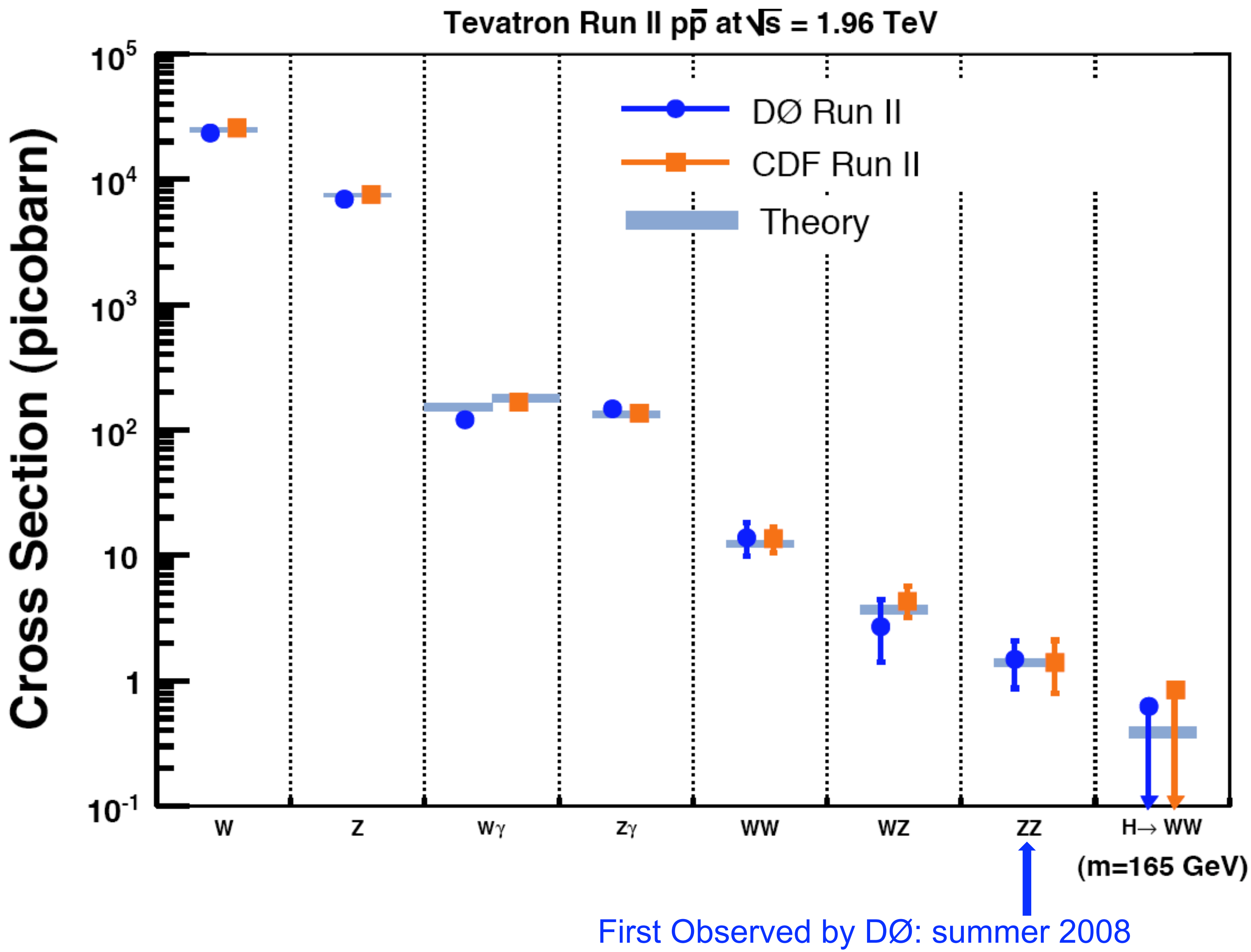


Hadron collider is a difficult environment!

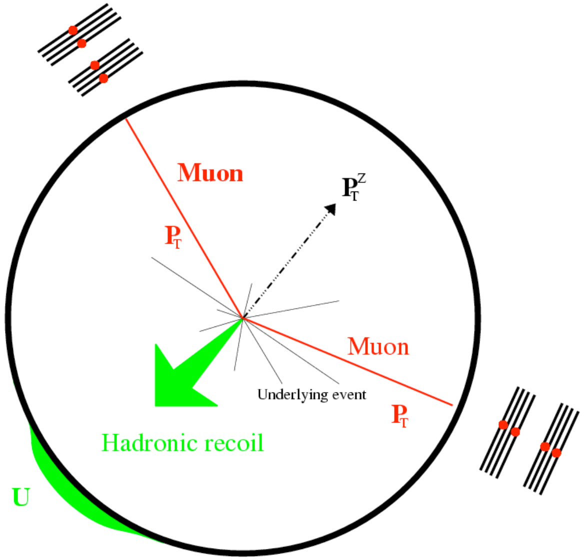
- proton is a composite object
  - PDFs (Parton Distribution Functions)
  - proton remnants, gluon bremsstrahlung
- huge total cross section
  - ~12 collisions per bunch crossing at design luminosity! (every 396 ns)
  - backgrounds
  - trigger

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

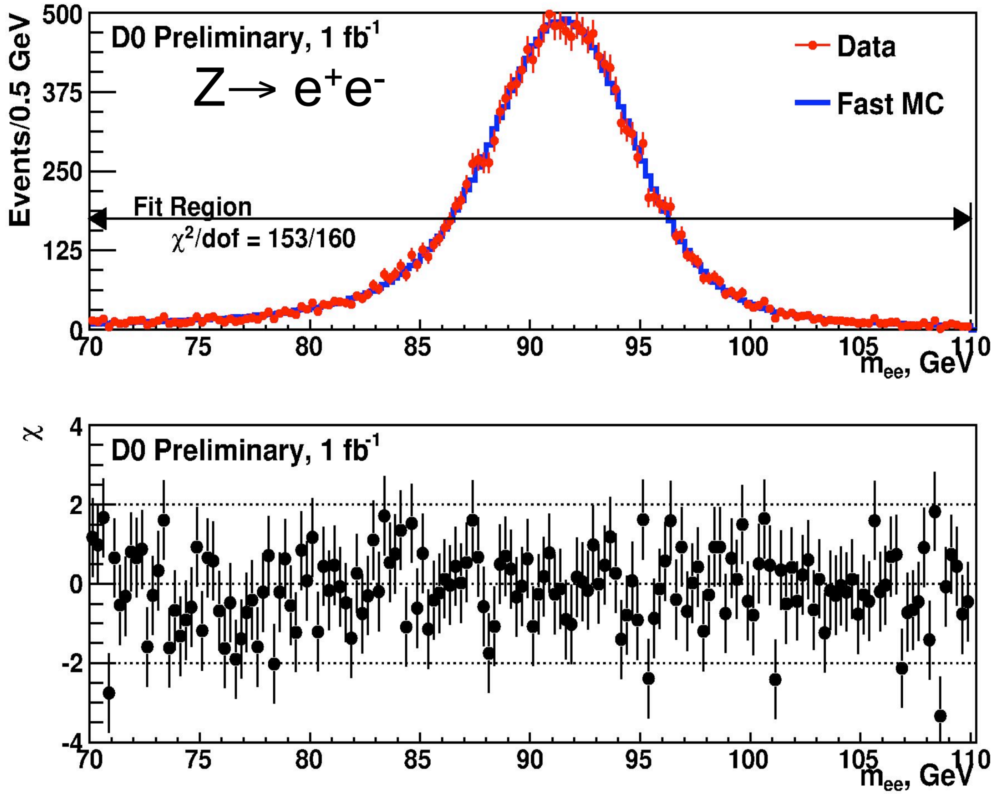
EW Cross Sections at the Tevatron



Signatures of W and Z Production at the Tevatron



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



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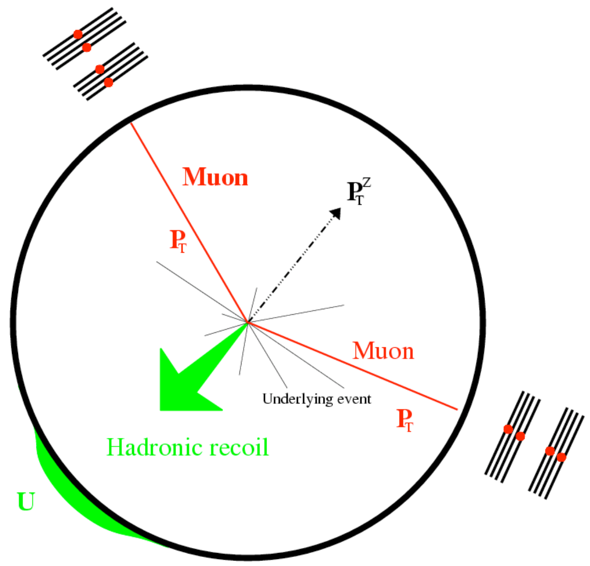

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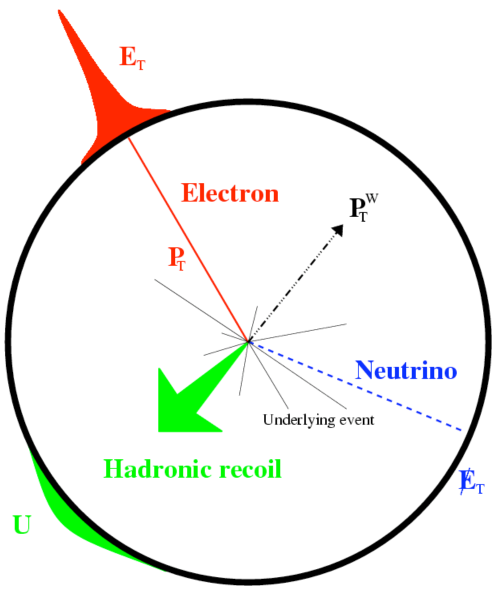

- $W \rightarrow \ell\upsilon$: single charged lepton:
  - high p_T
  - isolated
- E_T^{miss} (from υ)
  - cannot measure longitudinal υ
- peak in "transverse mass"

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

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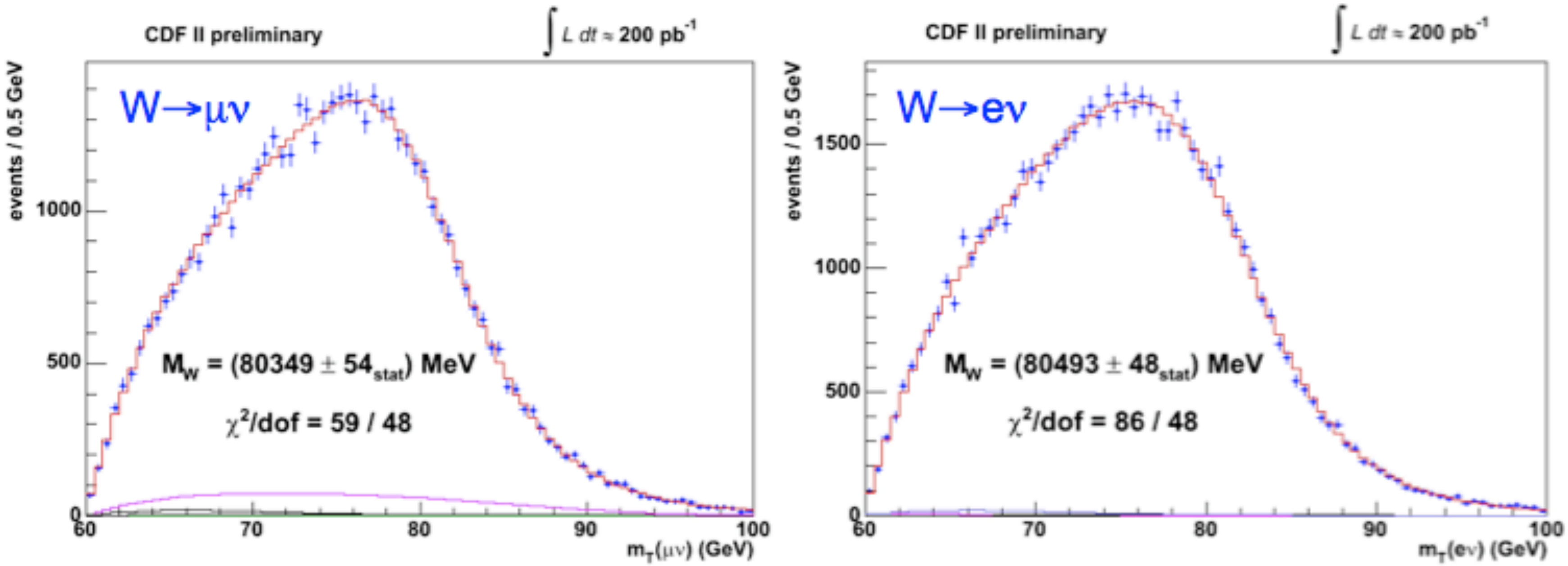

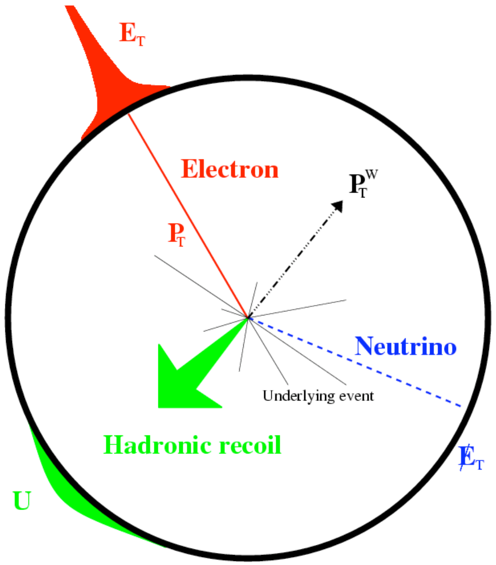

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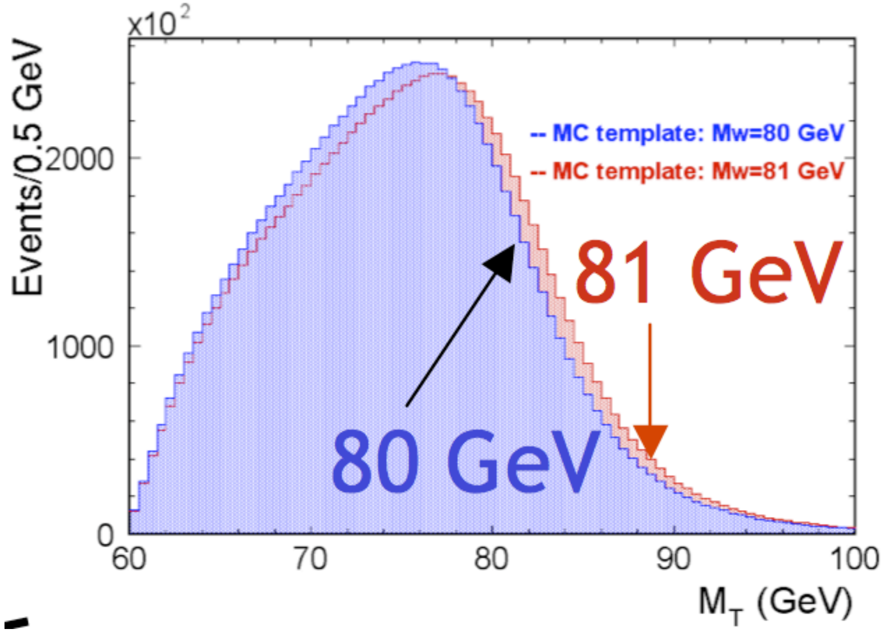
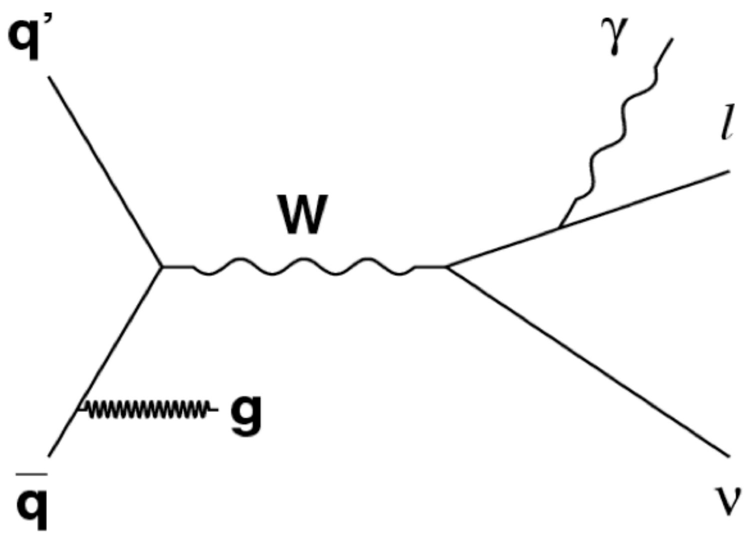
Measuring the W Mass

- Use Monte Carlo samples to generate m_T distribution expected for different values of m_W
  - "templates"
- Need to simulate accurately:
  - production and decay of W
  - passage of produced particles through the detector
  - signals produced in the detector
- Need to understand precisely:
  - lepton p_T scale and resolution
  - initial and final state bremsstrahlung
  - longitudinal motion of W along beam direction

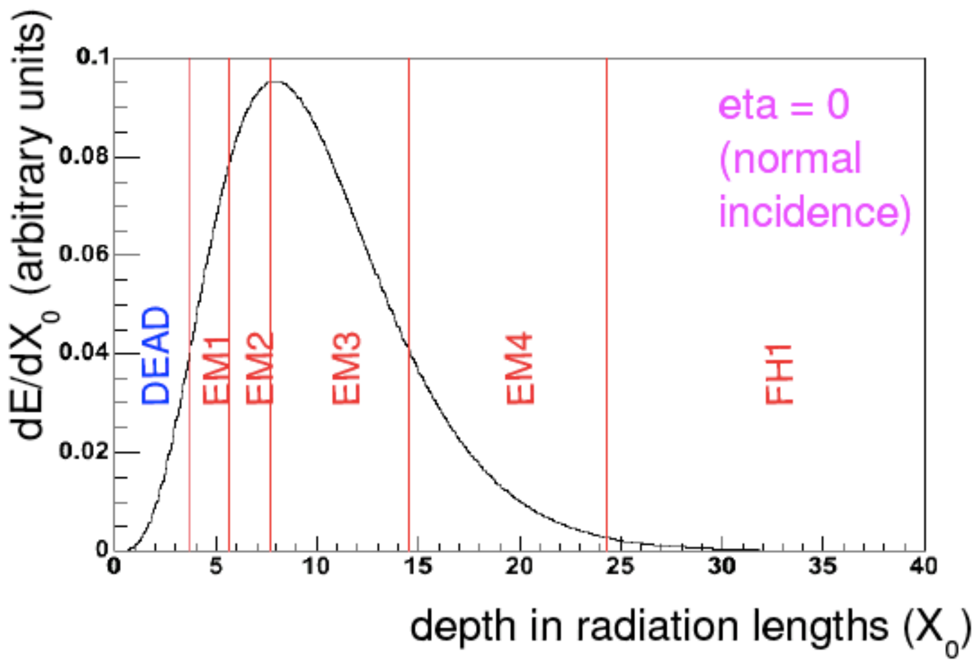




W Mass in W→eυ (DØ)

- 1 fb^{-1}: ~500k W→eυ events, ~19k Z→e^+e^- events
- The main challenge:
  - Measure electron energy response at better than per mille level
    - Including dependence on energy, |η|, etc.
    - Including effect of nearly 4 X_o dead material in front of calorimeter
  - Calibrate using Z→e^+e^- events making use of information from:
    - Four samplings in depth in EM calorimeter, |η| dependence
    - Divide Z→e^+e^- into 15 sub-samples in η_1 vs. η_2

Blind Analysis!



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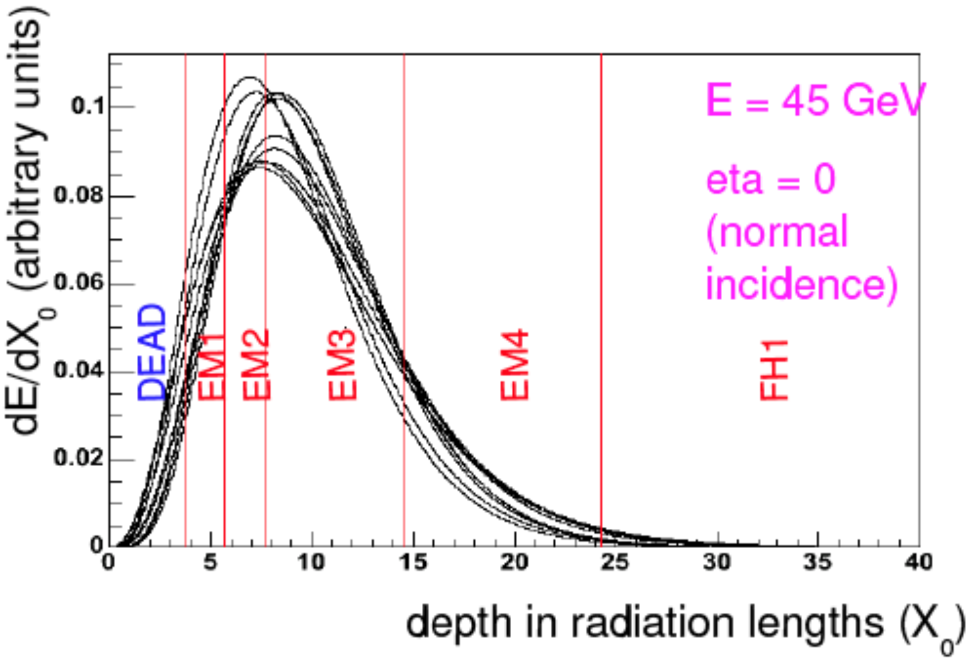
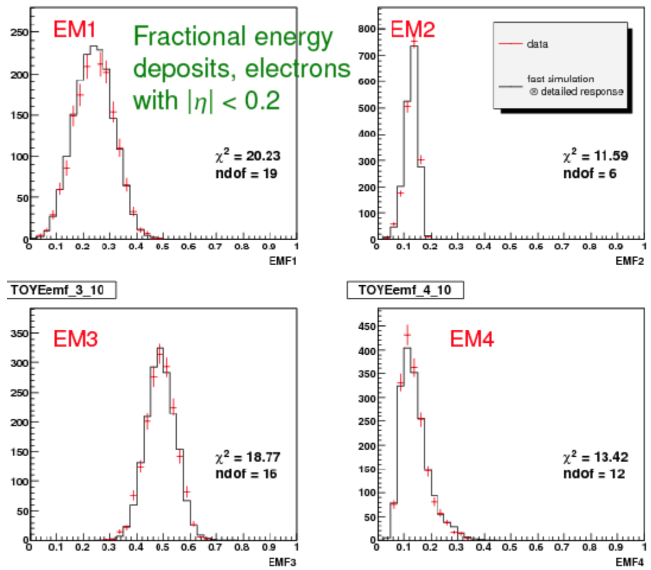
- Shower to shower fluctuations are significant
- Fraction of shower energy deposited in EM1,2 layers helps compensate partially for energy lost in dead material

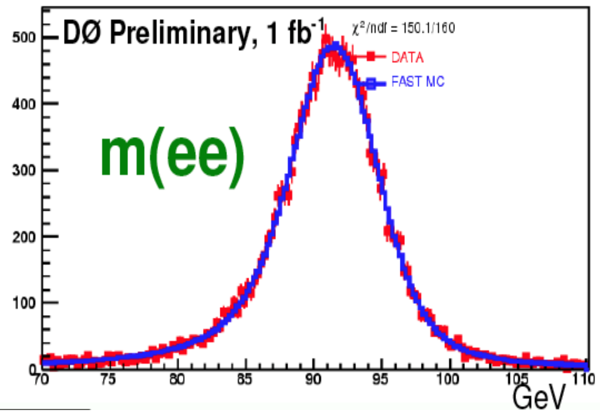


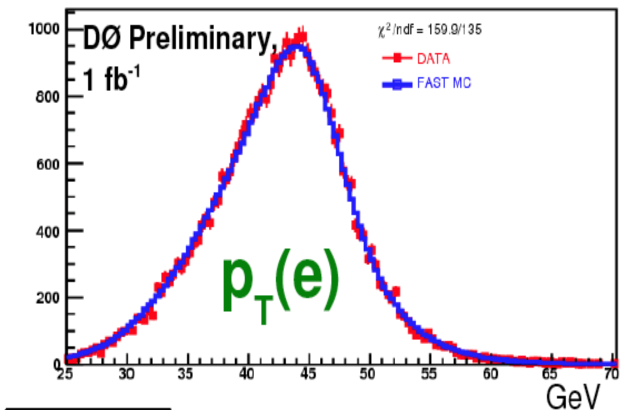
Electron Energy Response Calibration with $Z \rightarrow e^+e^-$

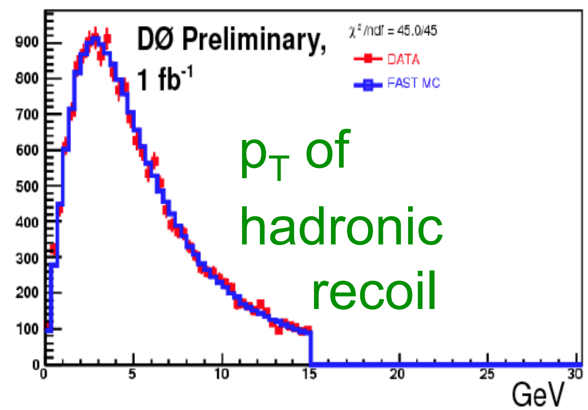


- $E_{measured} = \alpha \times E_{true} + \beta$
- Use energy spread of electrons in Z decay to constrain α and β
- Uncertainties on α and β translate to Δm_W = 34 MeV
  - By far the largest single uncertainty
  - Dominated by $Z \rightarrow e^+e^-$ statistics
    - so will improve with more data

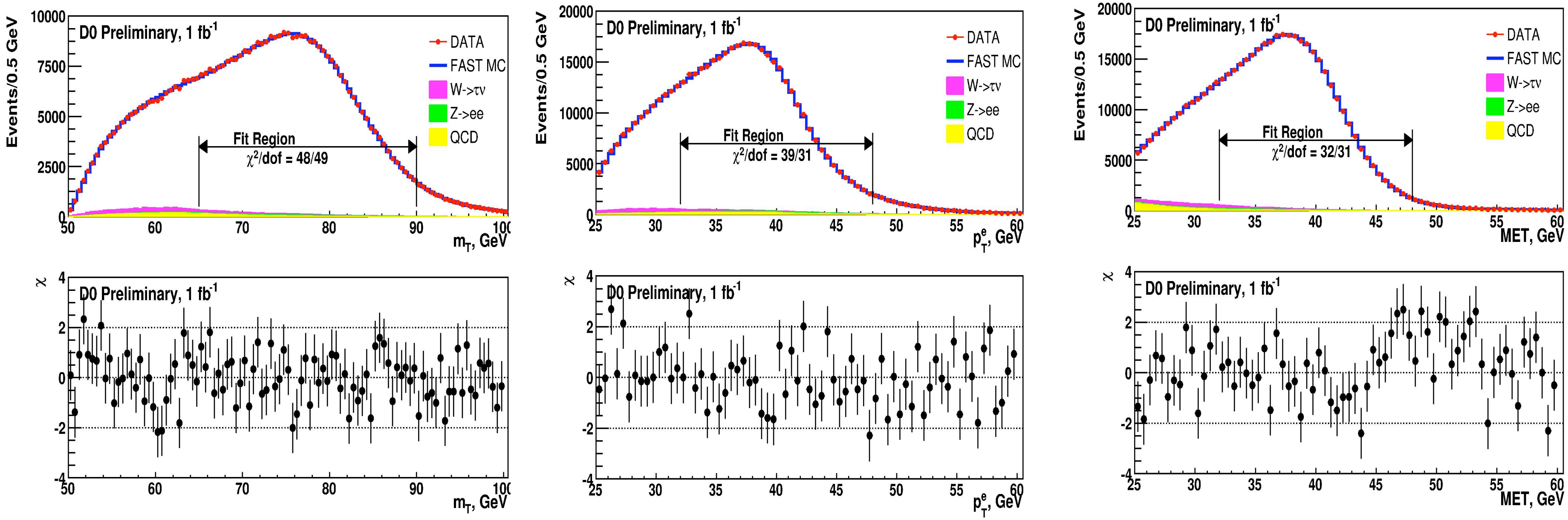
- Dead material known to $\pm 0.01 X_0$!



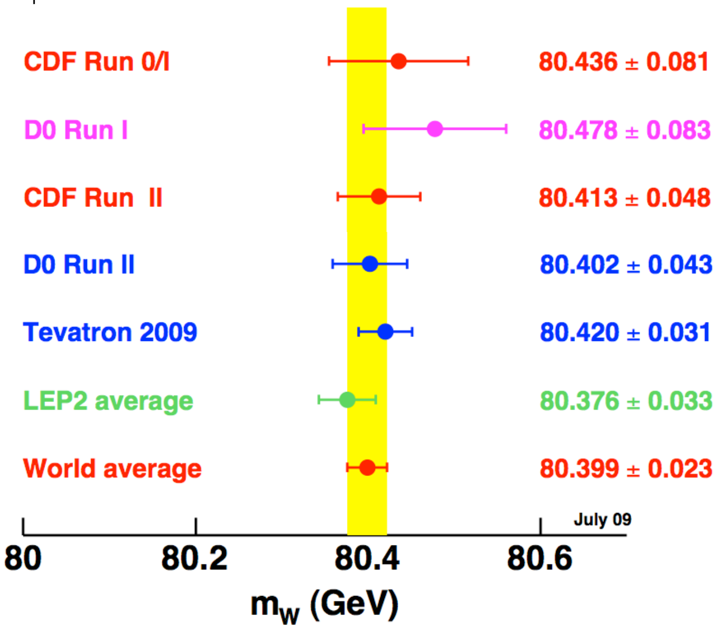




W Mass Fits



- Combination of fits to m_T, p^e_T and MET:
  - m_W = 80.401 ± 0.021 (stat) ± 0.038 (syst) GeV
- World's most precise single-experiment m_W measurement
- Tevatron average M_W now slightly more precis than LEP average
- Energy scale uncertainties
  - fairly uncorrelated between CDF and DØ
  - dominated by available number of Z candidates!

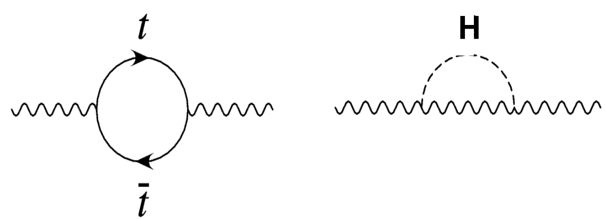


Summary of EW Data from LEP/SLC

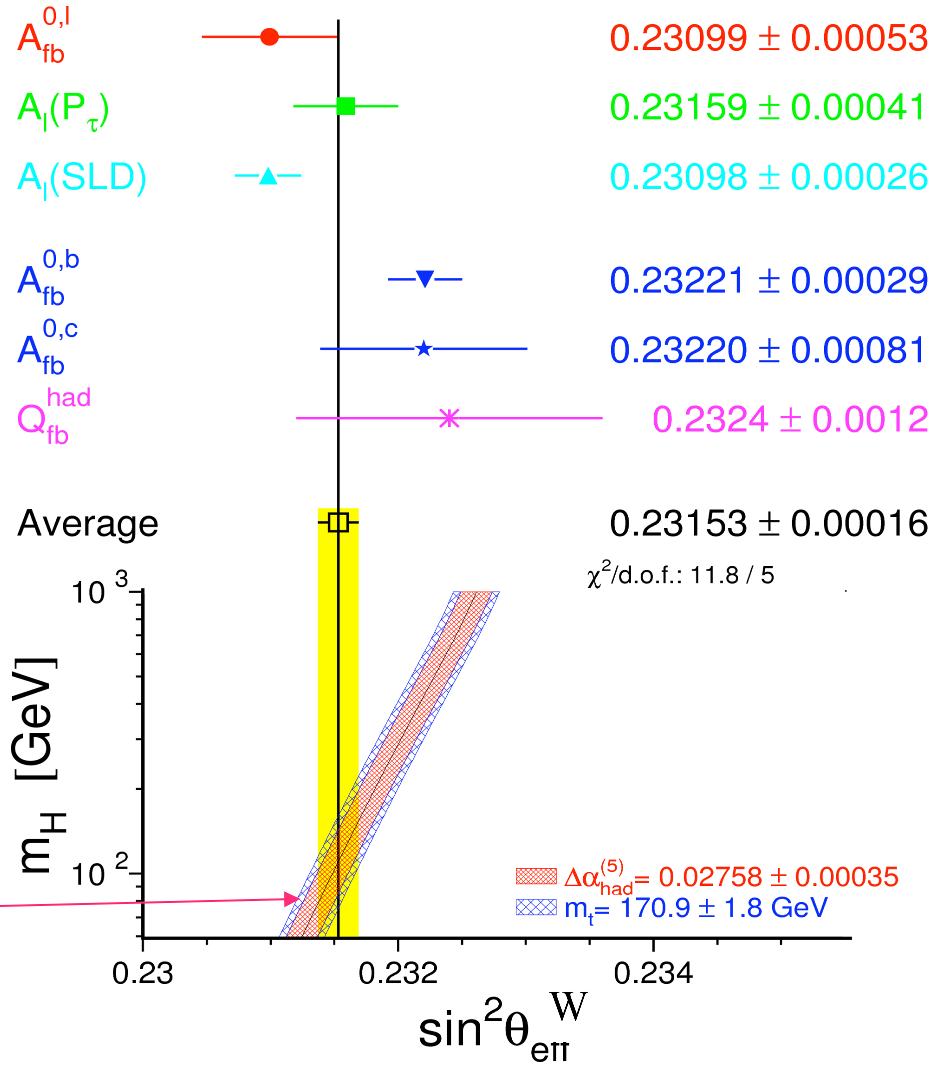
- Asymmetries measure:

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

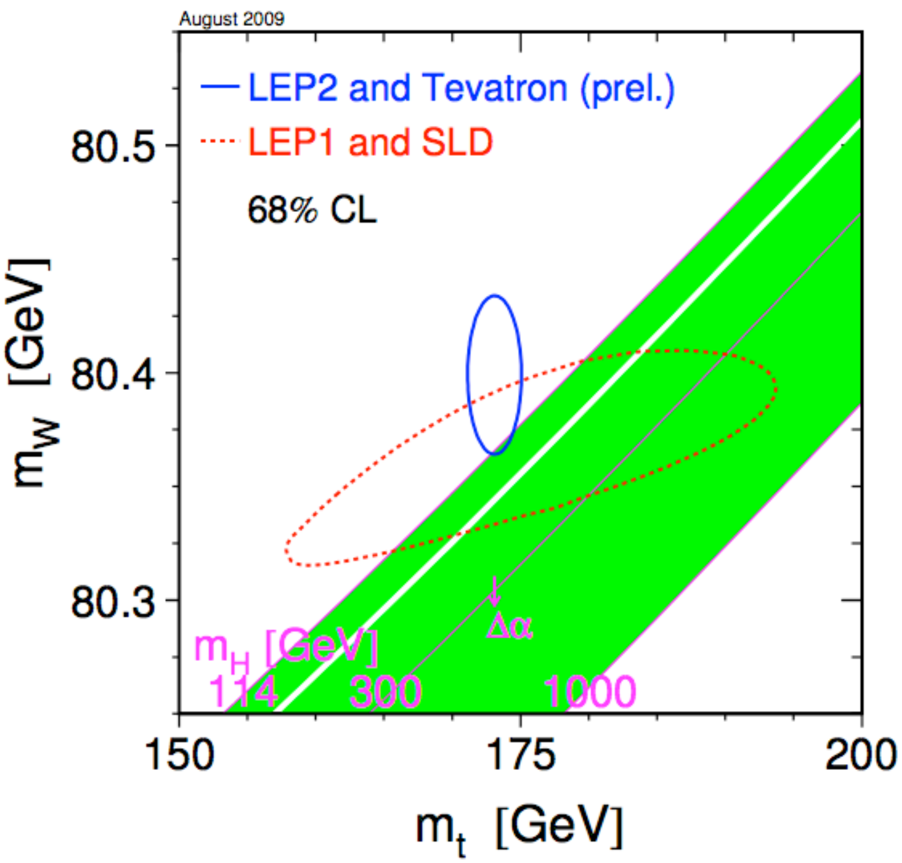
- Combine all measurements

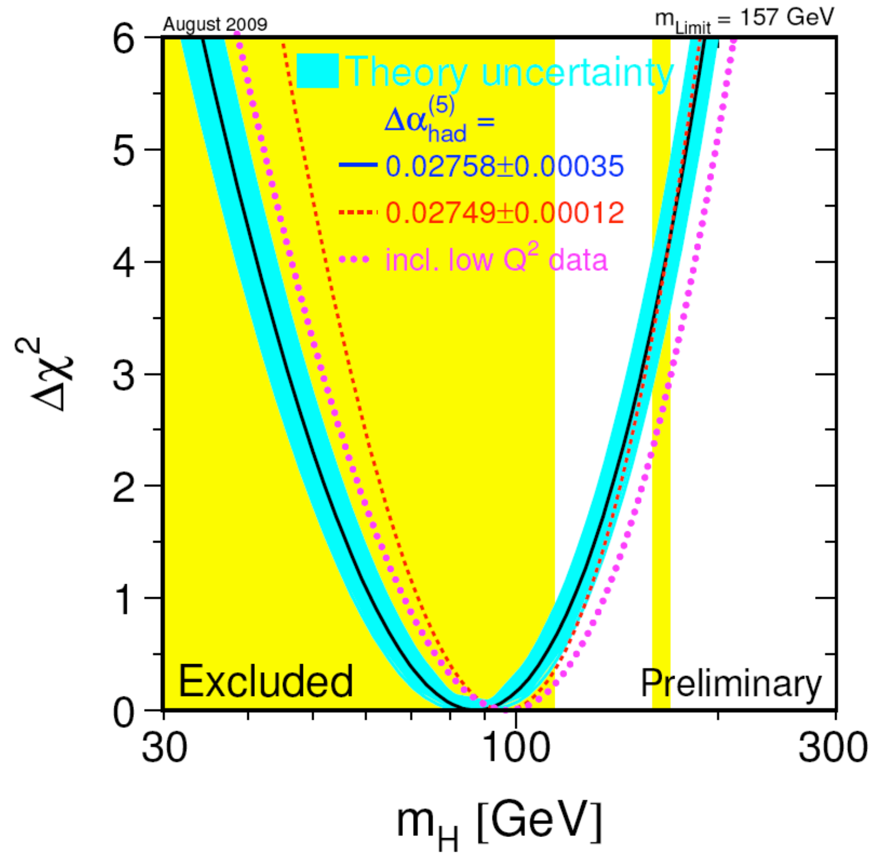


- Prediction of Standard Model
  - width of band depends on uncertainty in m_t running of α
  - value depends on m_H



m_W and m_t (compared to m_H)



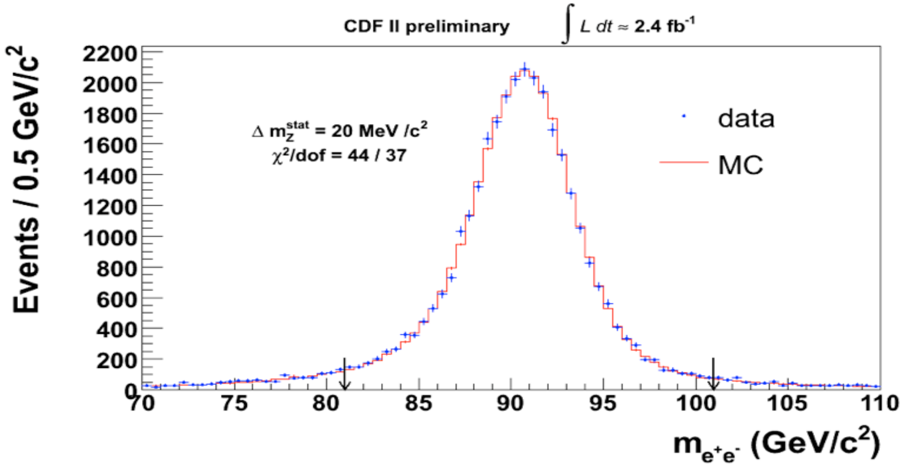


- Data prefer a light Higgs!
- $m_H = 87^{+35}_{-26}$ GeV $m_H < 157$ GeV (@95%CL)

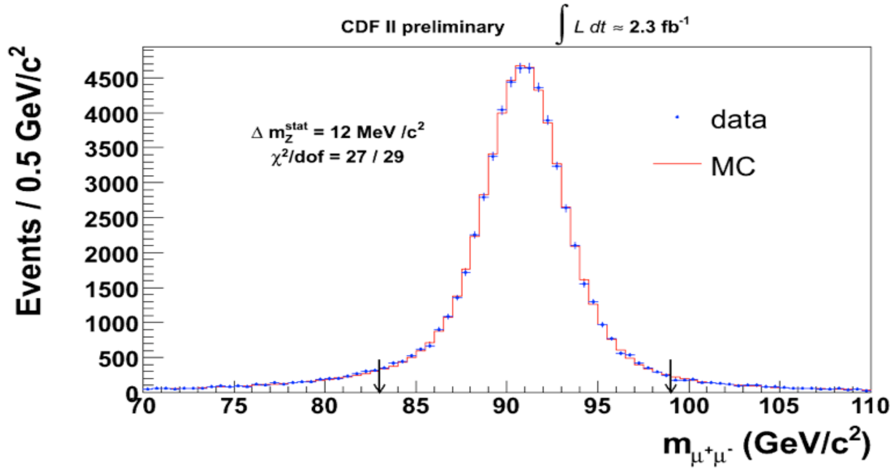
Prospects for M_W

- CDF analysis of 2.3 fb^{-1} data set already well advanced

$Z \to e^+e^-$ invariant mass distribution

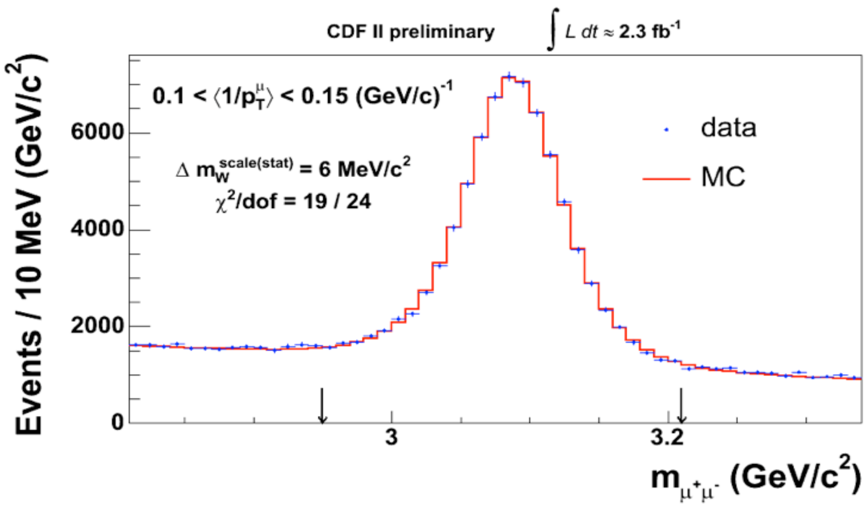


$Z \to \mu^+\mu^-$ invariant mass distribution

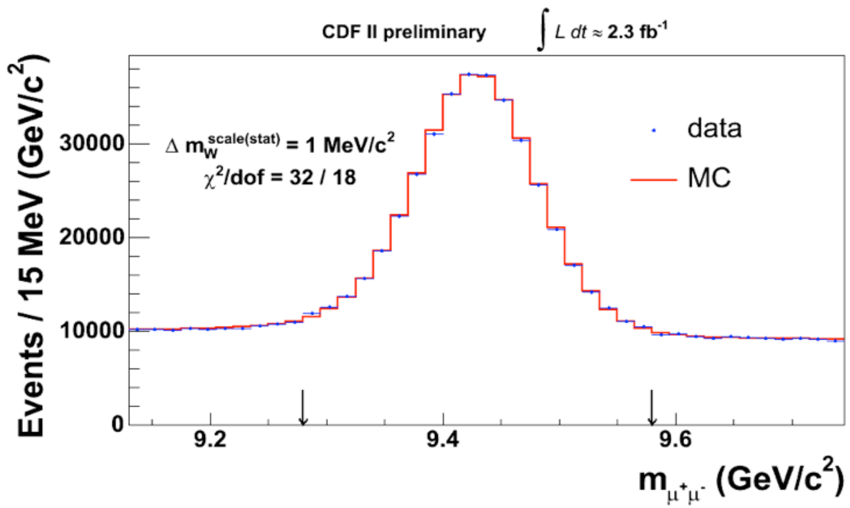


- Calibrate tracker and p_T scale and resolution

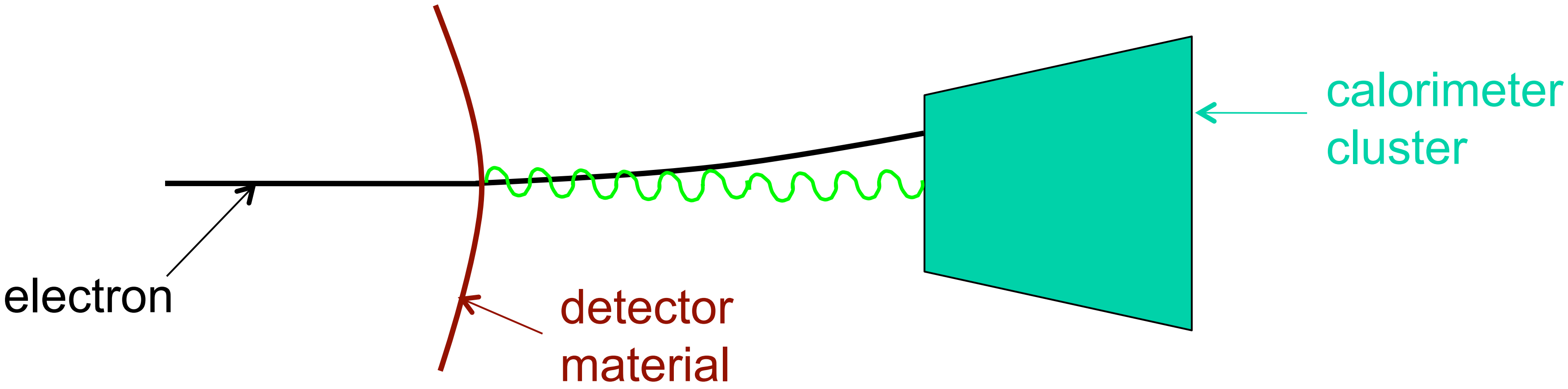
$J/\psi \to \mu^+\mu^-$ invariant mass distribution



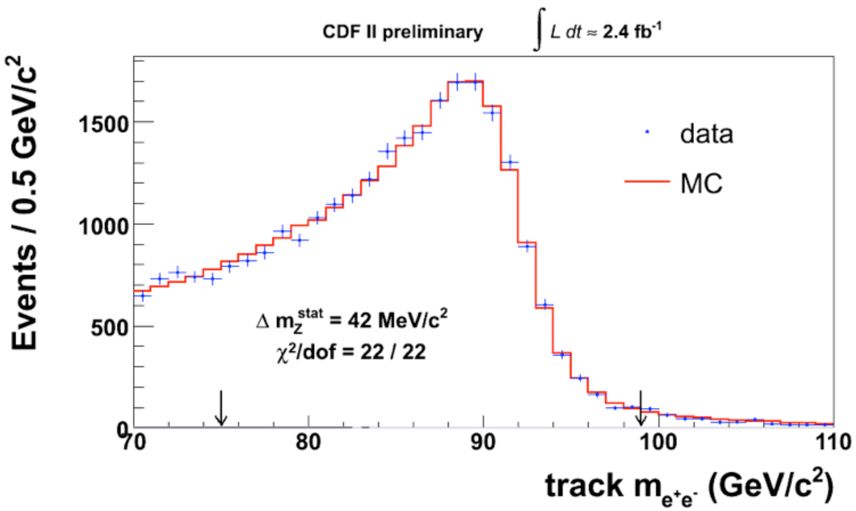
$Y(1S) \to \mu^+\mu^-$ invariant mass distribution



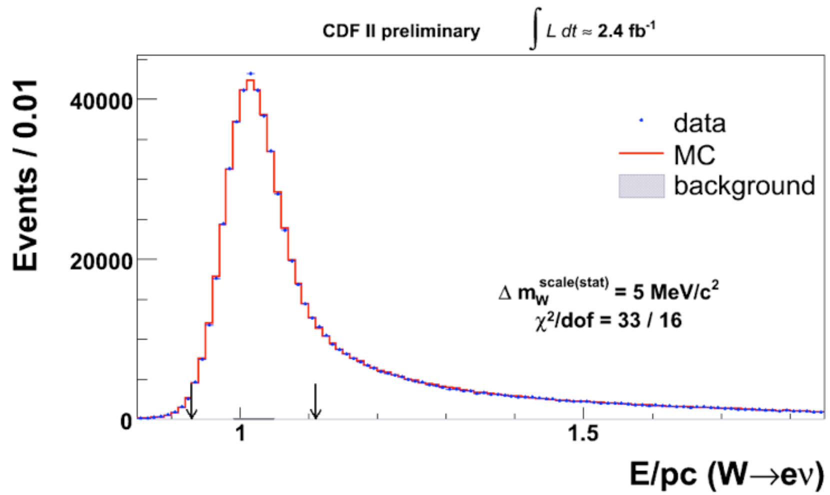
- Calibrate MC description of material in tracker
  - Because of bremsstrahlung in detector material p (track) tends to be smaller than E (calorimeter)



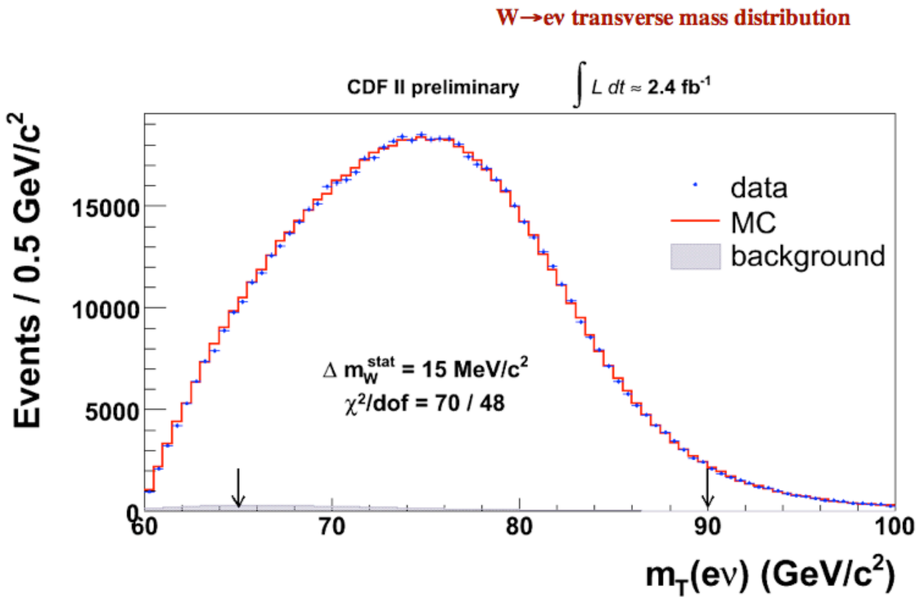
Z→e⁺e⁻ invariant mass plot using track information only

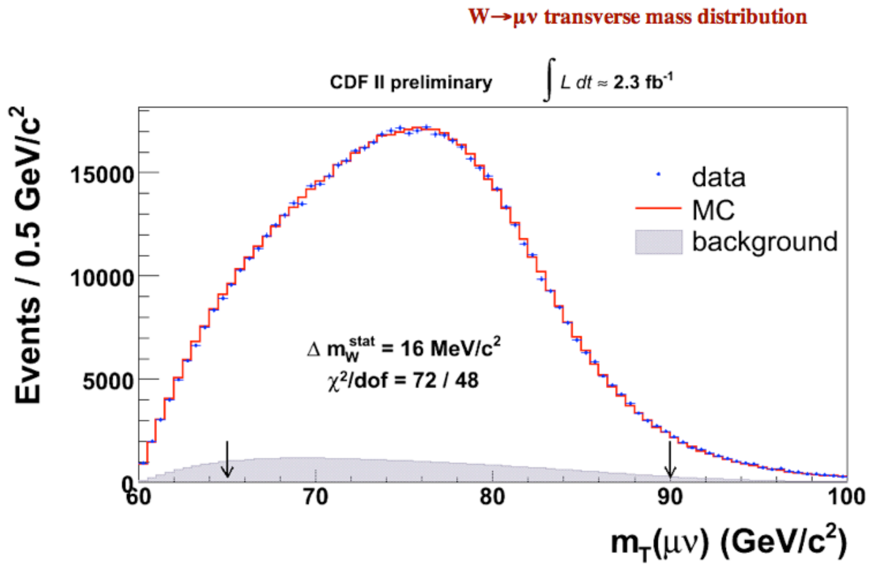


W→eν E/pc distribution



Prospects for M_W

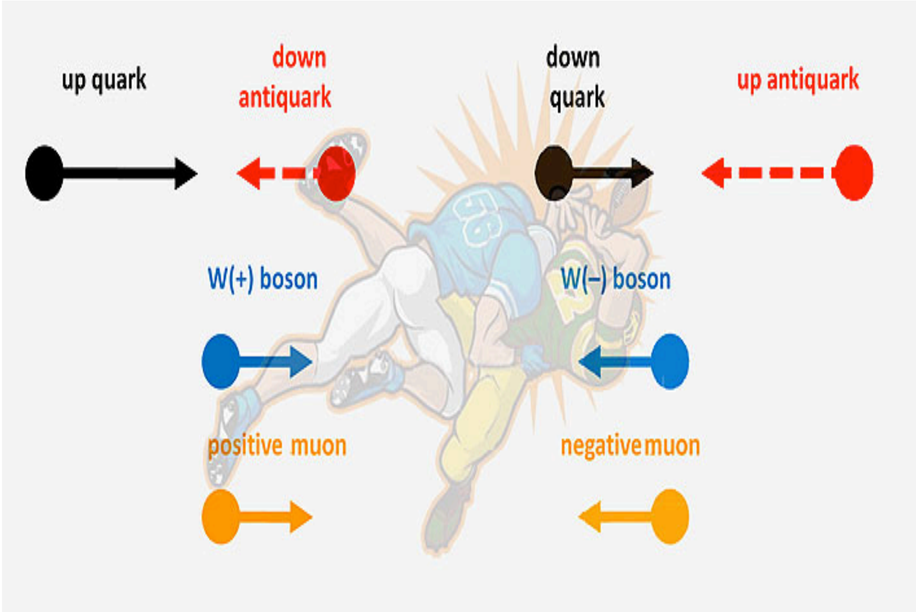


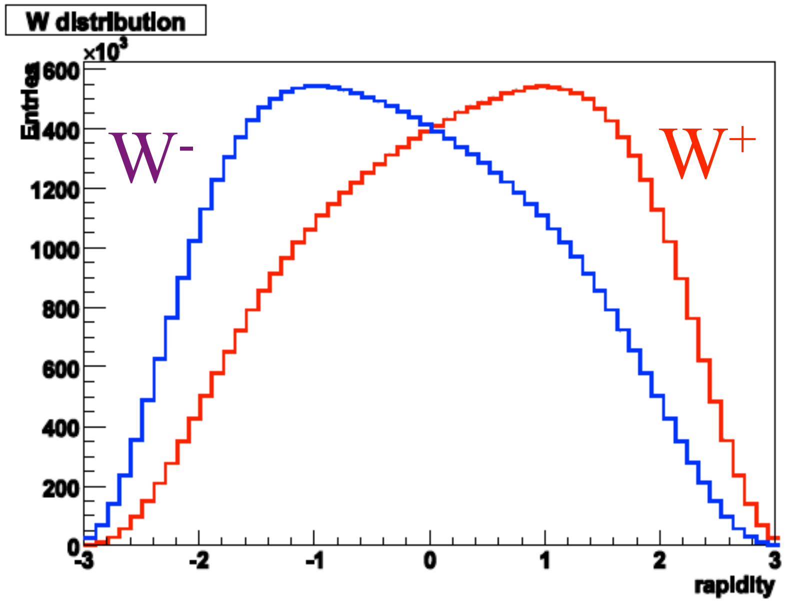


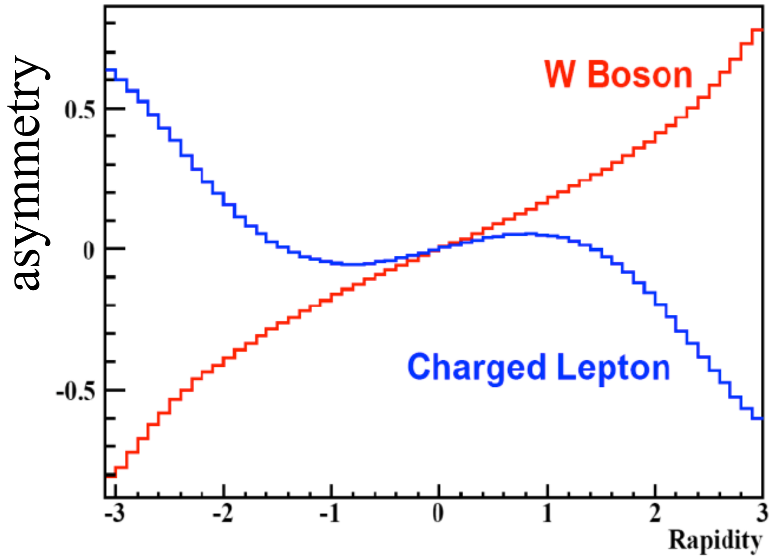
- Expected statistical uncertainty $\Delta M_W \approx 11$ MeV
  - (CDF e+μ 2.3 fb^{-1})
- N.B. Current theoretical uncertainties:
  - ΔM_W (PDF) ≈ 10 MeV
  - ΔM_W (QED radiative corrections) ≈ 10 MeV
- will become dominant unless improved in the long term

W Charge Asymmetry and PDFs

- u quark PDF is harder than d quark PDF
- W^+ (W^-) tends to be boosted along proton (antiproton) direction
- asymmetry = $(N^+ - N^-)/(N^+ + N^-)$
- We actually observe the charged lepton
- W decay partially washes out asymmetry

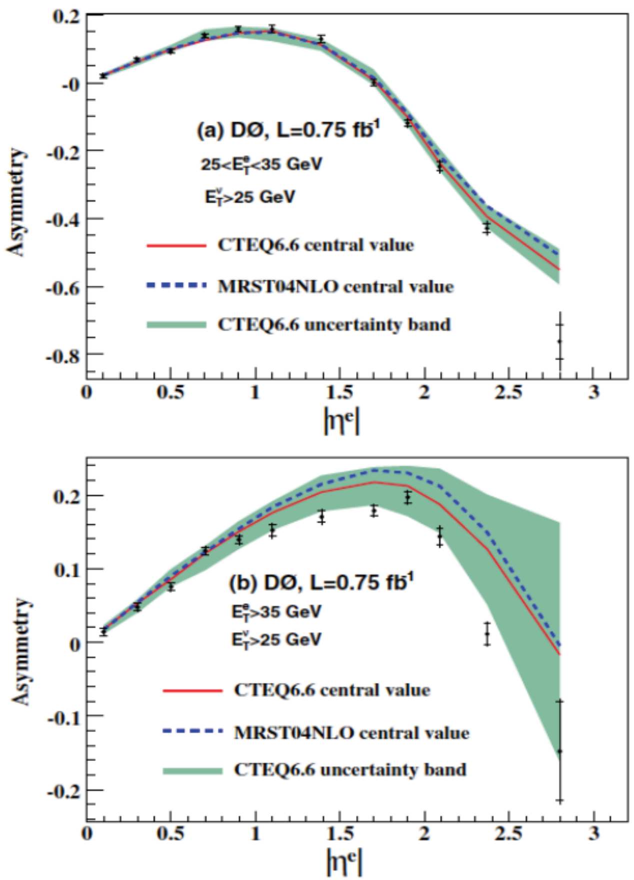


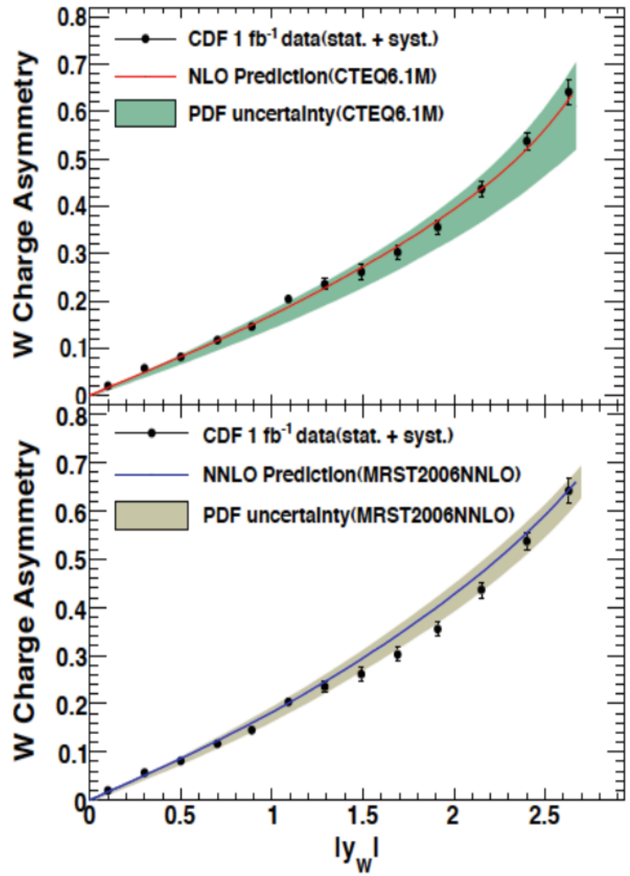




W Charge Asymmetry and PDFs

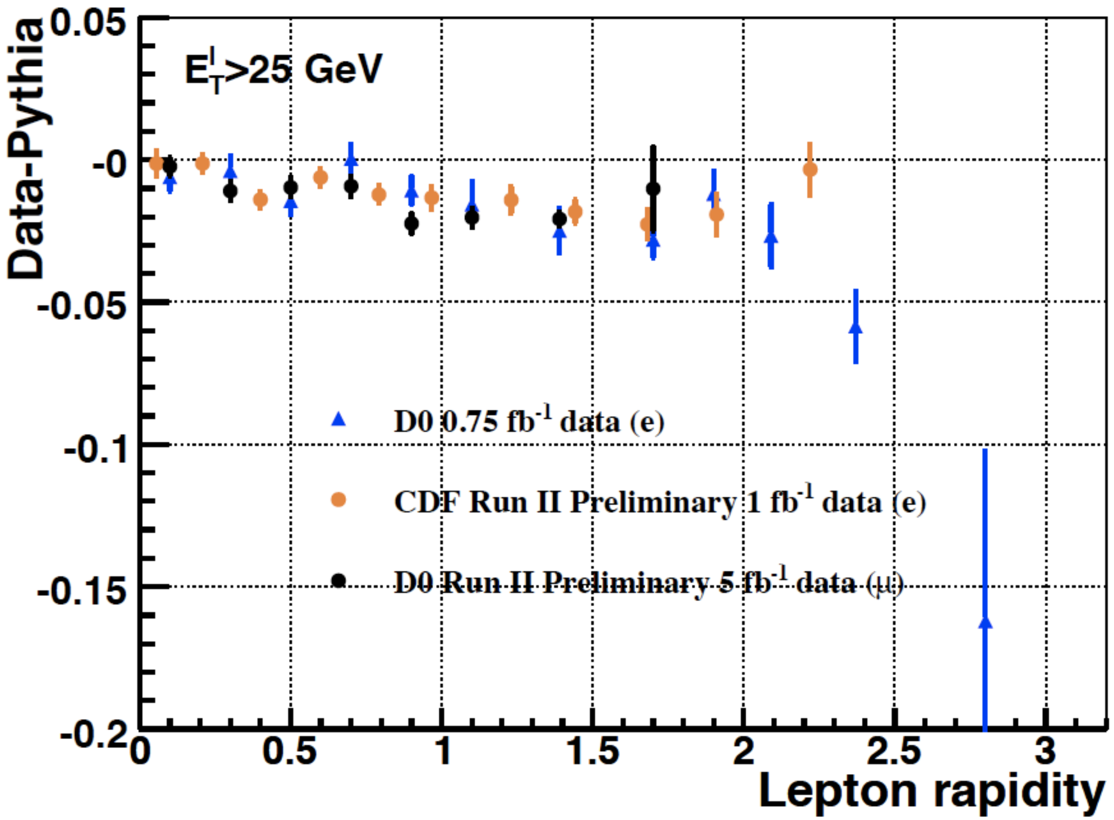
- Experiments publish measurement in different form
  - Charged lepton charge asymmetry in different electron p_T bins (DØ)
  - Inclusive W boson charge asymmetry (CDF)
- MSTW and CTEQ have problems to incorporate both CDF and DØ data into their global PDF fits





W Charge Asymmetry and PDFs

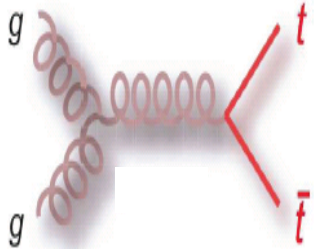
- CDF have re-analyzed their data (stat. uncertainties only) to allow a direct comparison with DØ



- The experiments agree!
- The problem looks to be in the theory!

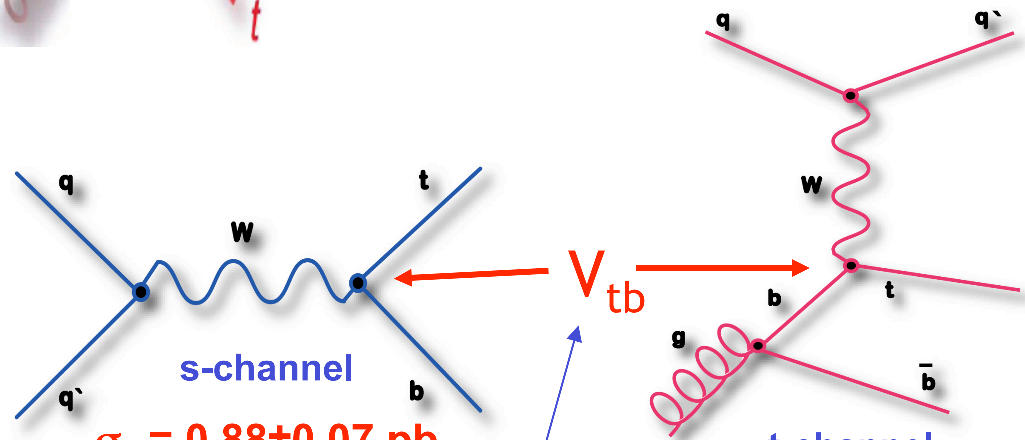
Observation of Electroweak Single Top Production

- Top pairs:



σ_{tt} = 6.7 ± 0.8 pb

- Single top:

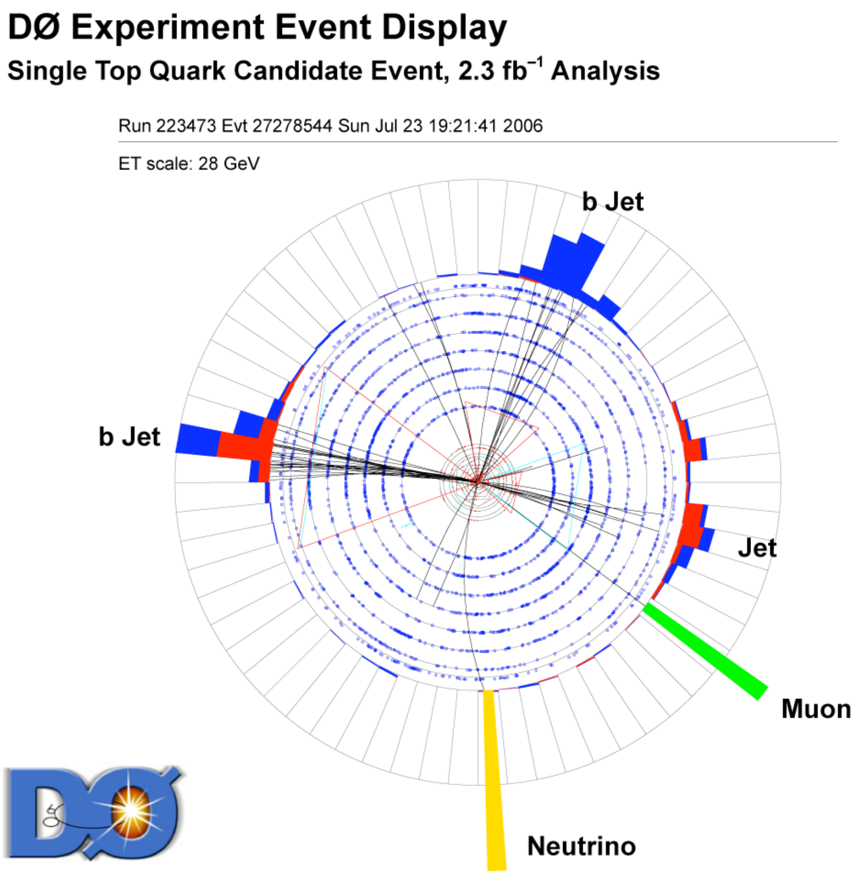


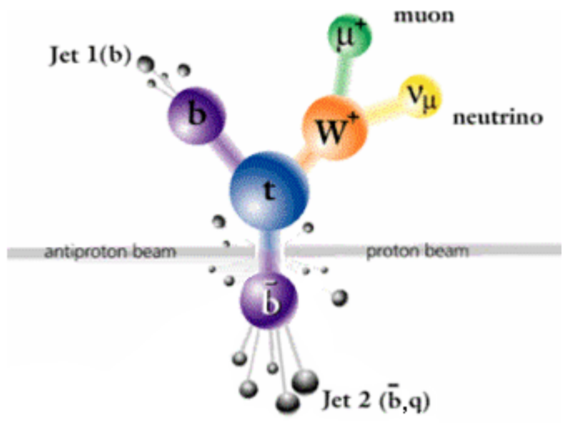
σ_s = 0.88±0.07 pb

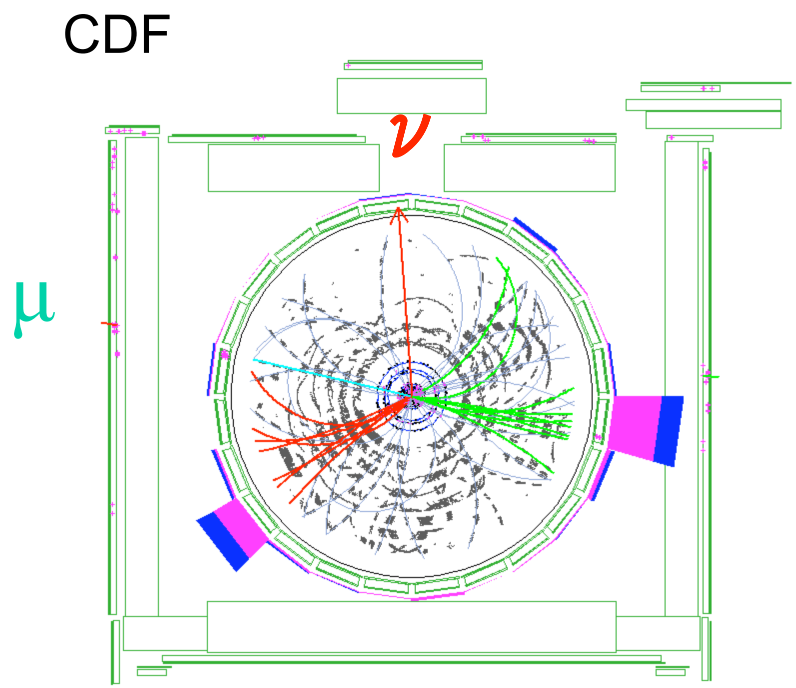
σ_t = 1.98±0.21 pb

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

Candidate Event Pictures



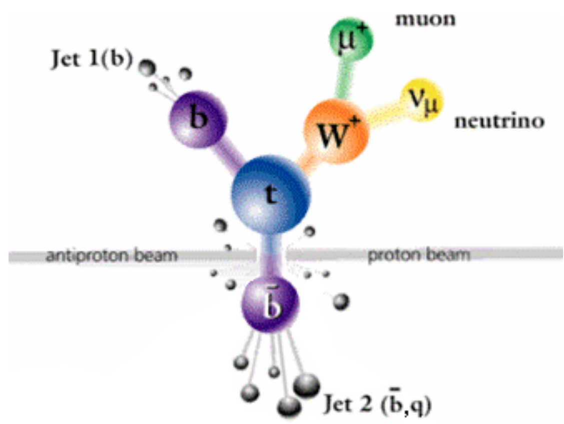


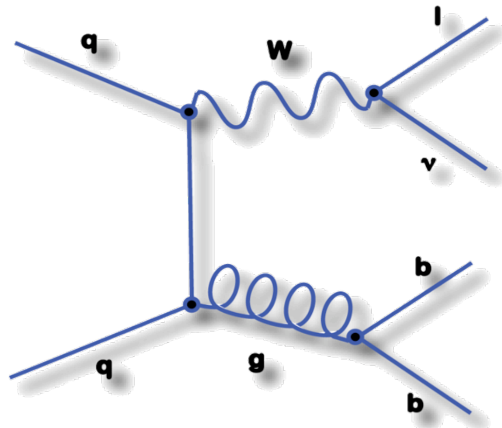


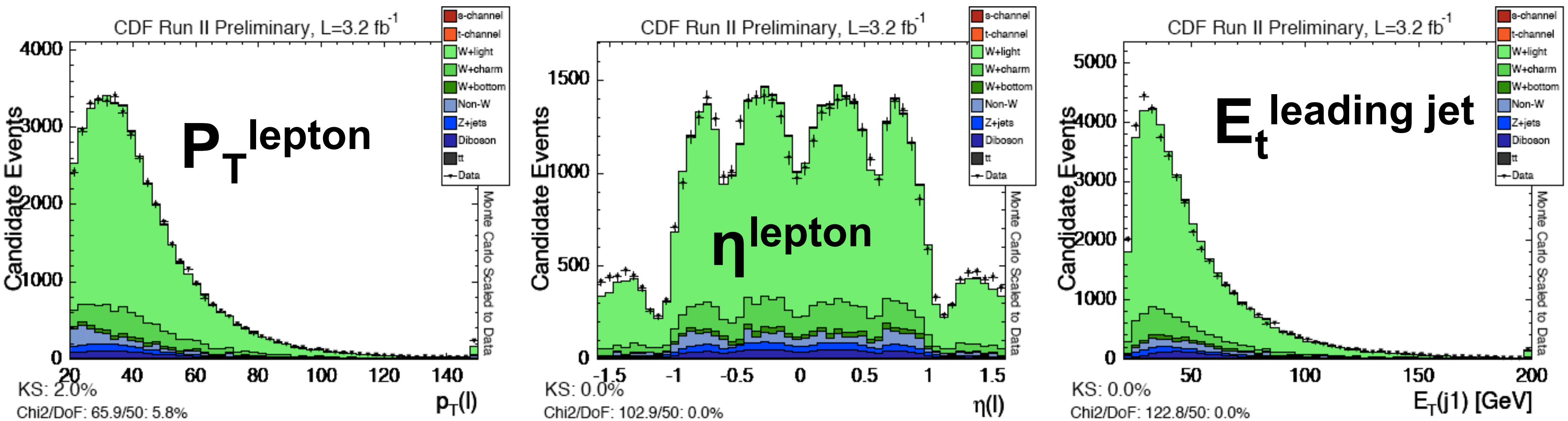
- But observing "candidate events" does not, in itself, constitute a "discovery"!

Backgrounds to Single Top

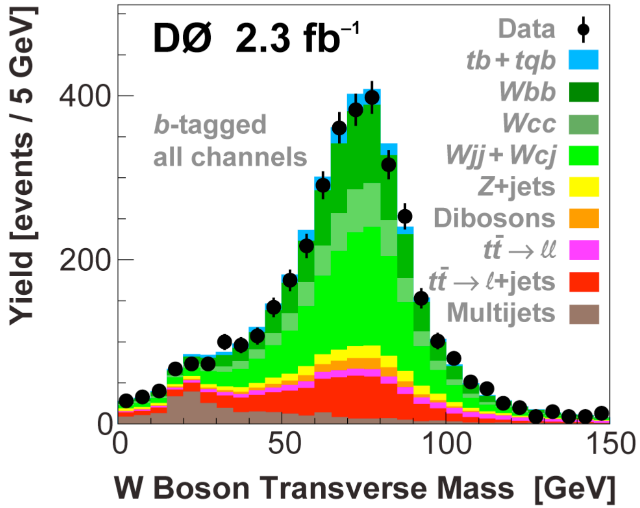
- σ_{s+t} only a factor of ~two lower than σ_{tt}
  - but event signature much less pronounced
    - fewer high p_T objects
- Backgrounds much more of a challenge!
- W+jets poorly understood
  - especially W+heavy flavour
  - considerable tuning of MC to data required

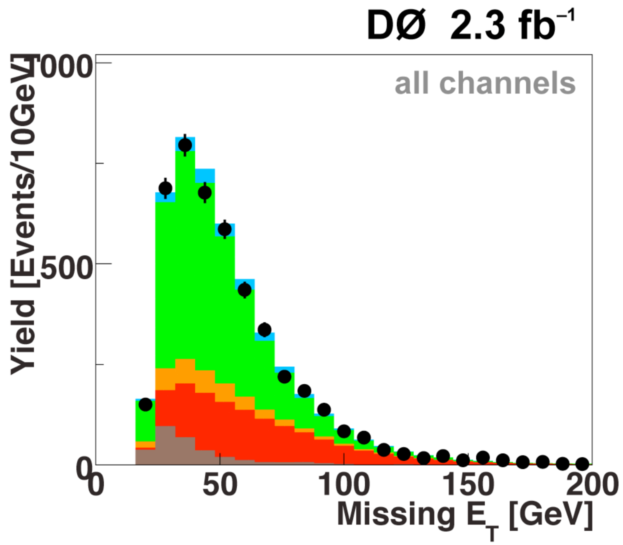


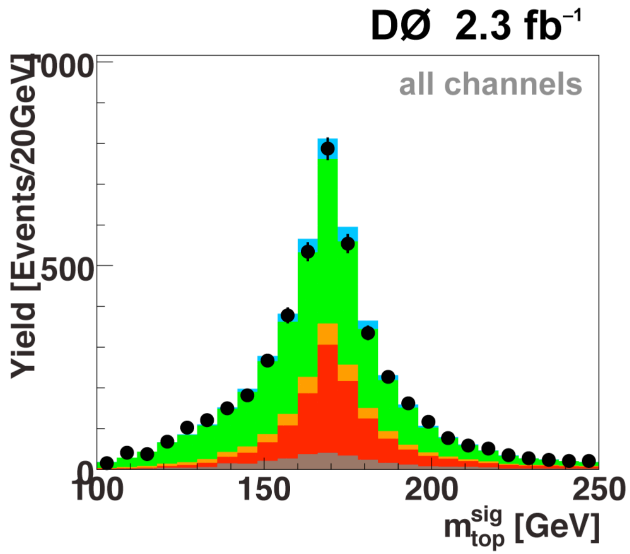


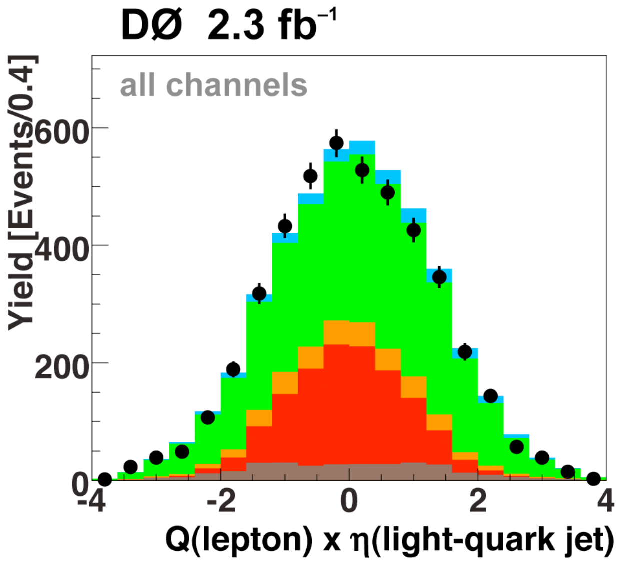


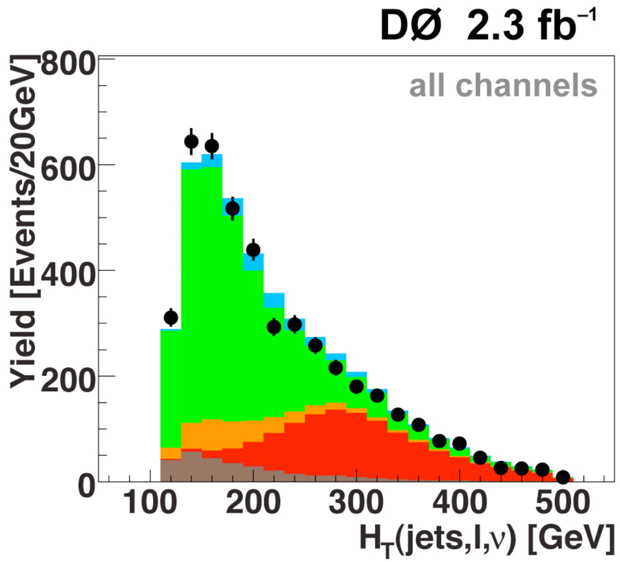
• Even after b-tagging, ……..











Event Yields in 2.3 fb^{-1} of DØ Data

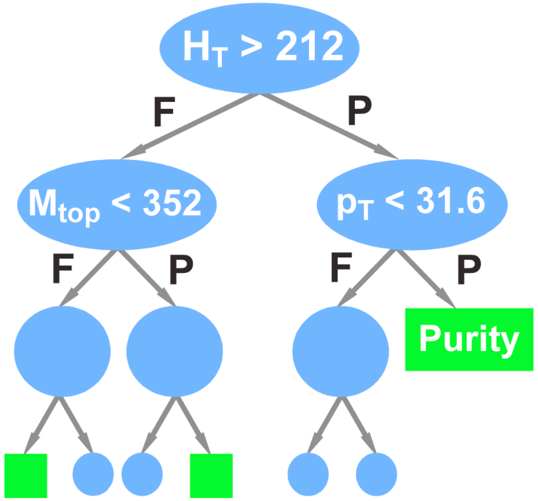
e,μ, 2,3,4-jets, 1,2-tags combined

tb + tqb	223 ± 30
W+jets	2,647 ± 241
Z+jets, dibosons	340 ± 61
$t\bar{t}$ pairs	1,142 ± 168
Multijets	300 ± 52
Total prediction	4,652 ± 352
Data	4,519

……… the signal is swamped by background!

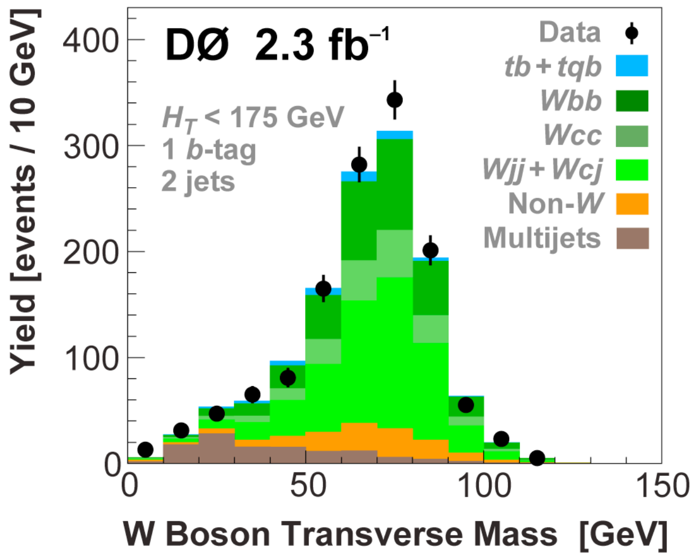
Kinematic Discriminants

- Use multivariate kinematic discriminants
  - e.g., "Neural Network", "Decision Tree"

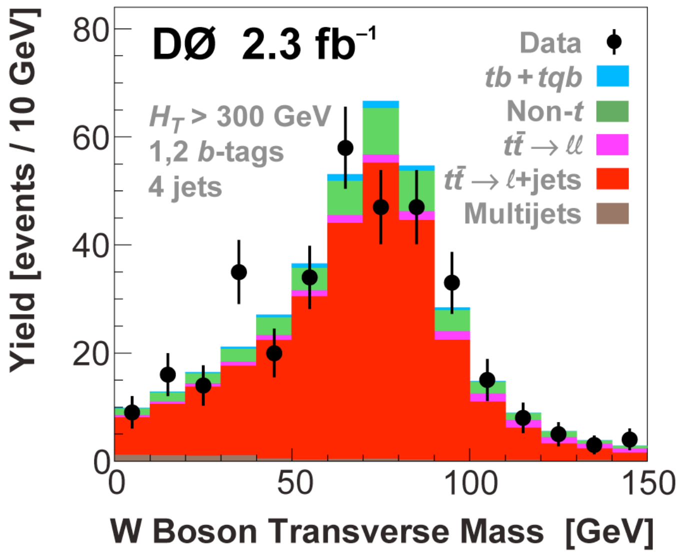


- Validate on "background-enriched" sub-samples

"W-like" (low total visible E_T)



"tt-like" (very high total visible E_T)

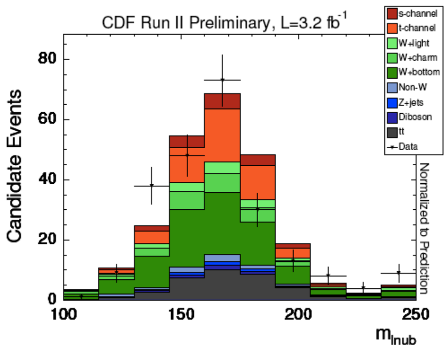


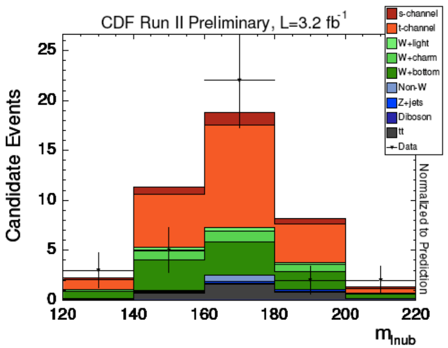
CDF Observation of Single Top Production

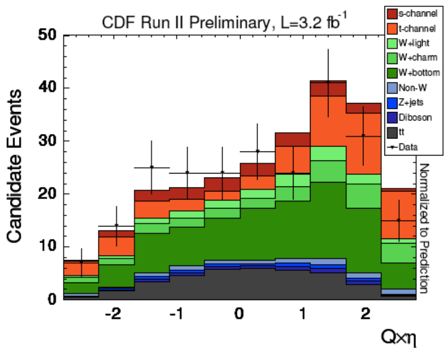
- Cut on discriminant selects single top-like background
  - a general feature of such analyses!

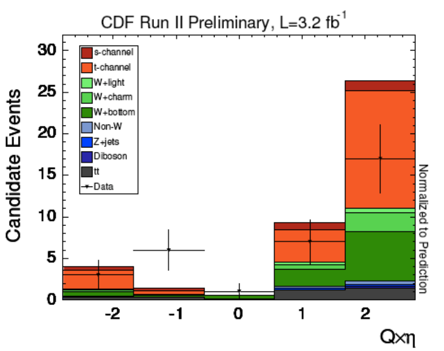
BDT>0.25

BDT>0.6





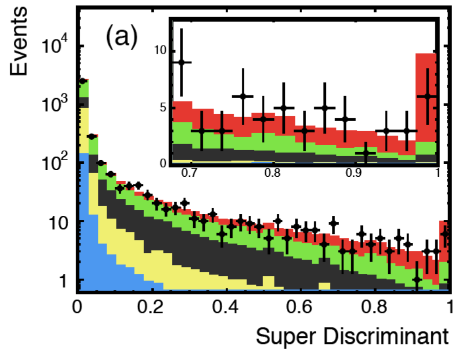


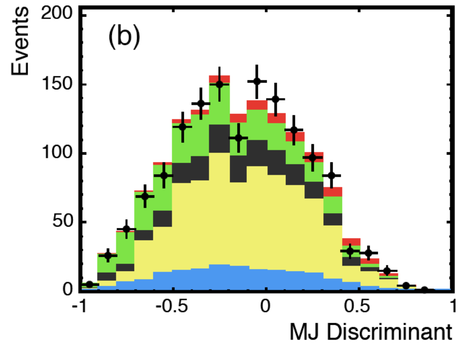


Discriminant output distributions

Combination of five lepton+jets+MET analyses

Jets+MET analysis



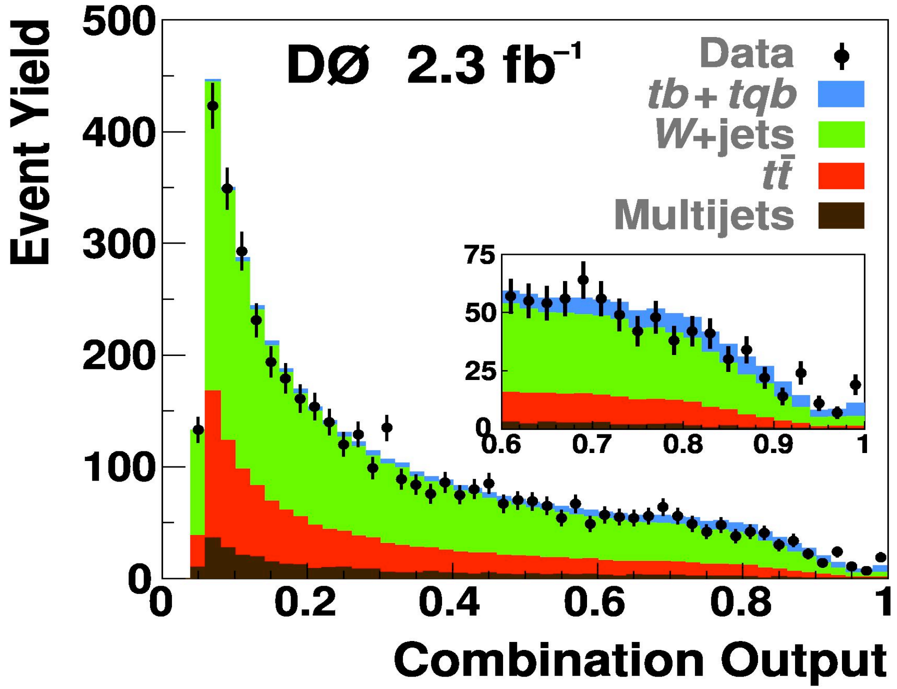


- Combined significance 5.0σ

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

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



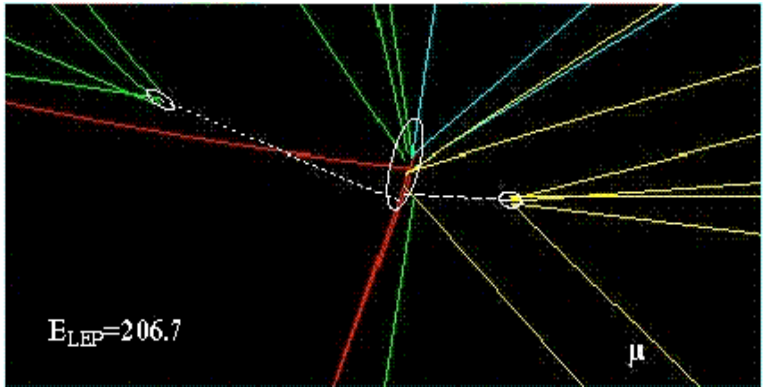
The only direct determination of $|V_{tb}|$

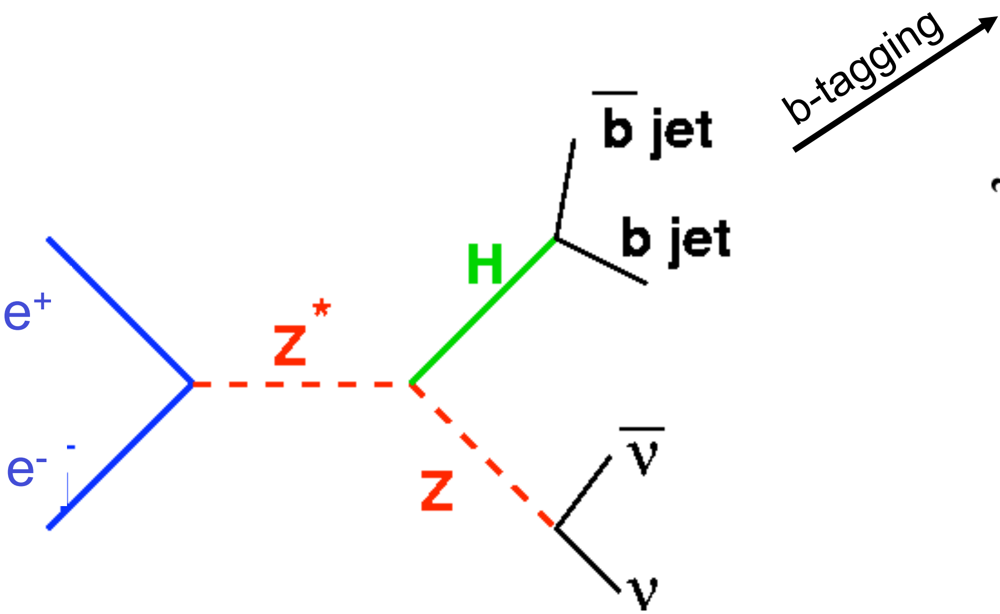
	CDF	DØ
$\lvert V_{tb}\rvert$	0:91±0:11	1:07 ± 0:12
$\lvert V_{tb}\rvert$ @ 95% CL	> 0.71	> 0.78

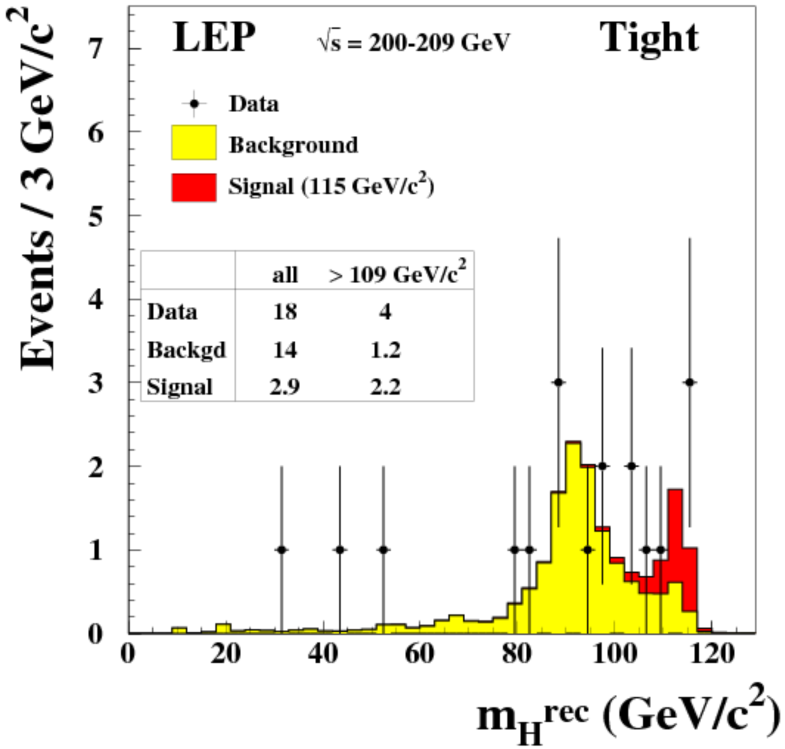
- Plus, a really important calibration analysis for **WH→lνbb**, etc.
  - and will get increasingly precise with more data!

Reminder: Direct Searches for Higgs at LEP2

- A particle's mass depends on how strongly it couples to the Higgs
  - Higgs produced by interactions containing heavy particles
  - Higgs decays predominantly to heaviest particle kinematically allowed





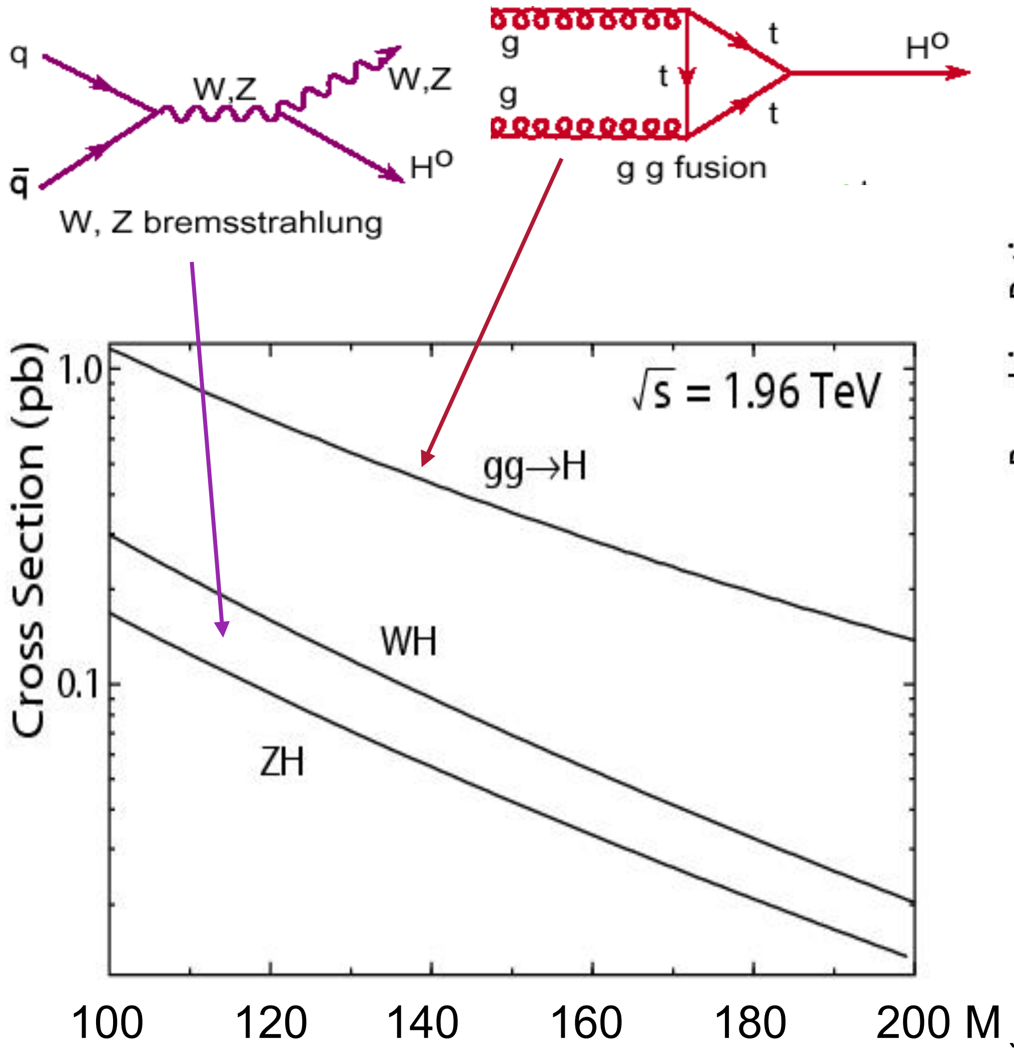


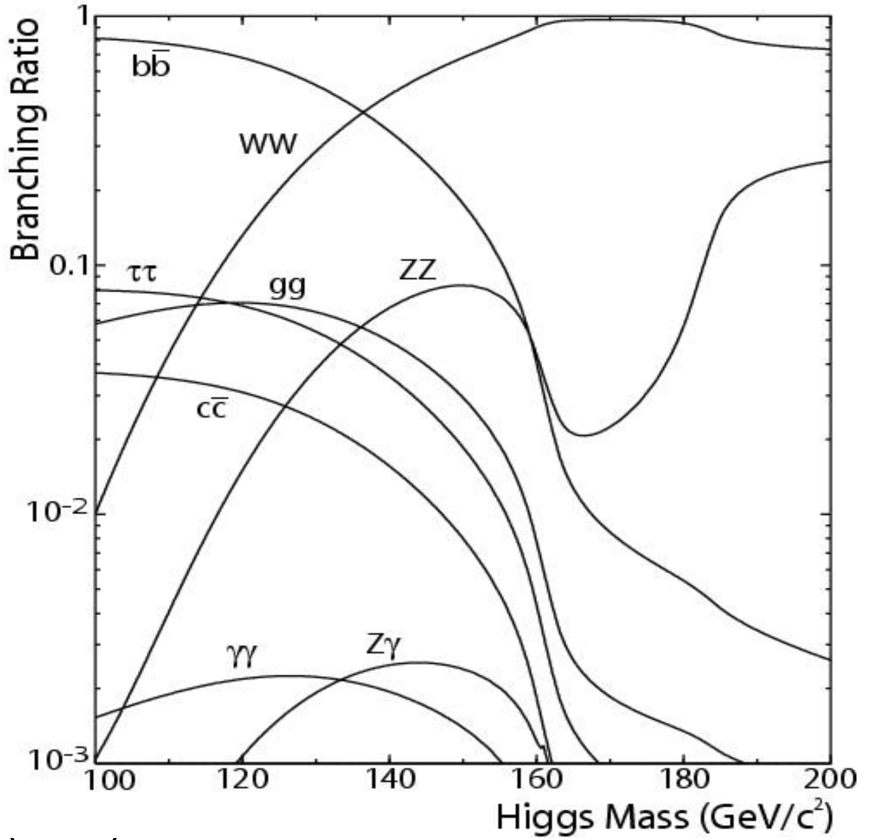
- Direct searches at LEP yielded limit:
  - $m_H > 114$ GeV

Higgs Production Cross Section at the Tevatron

Decay Branching Ratios

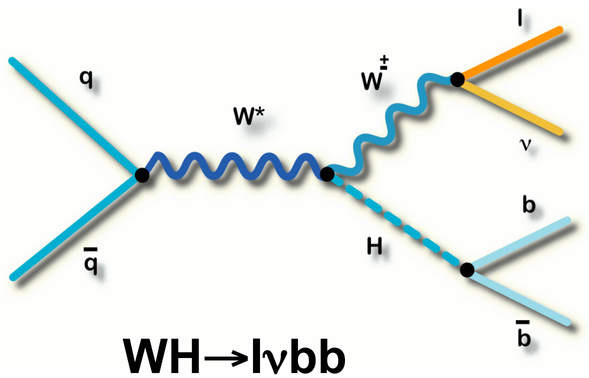
- bb dominates for $m_H < 130$ GeV
- WW dominates for $m_H > 130$ GeV

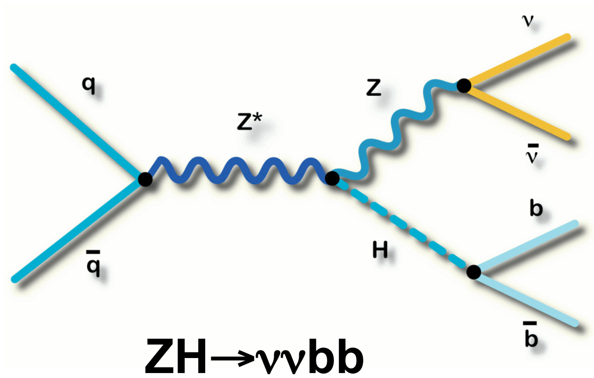


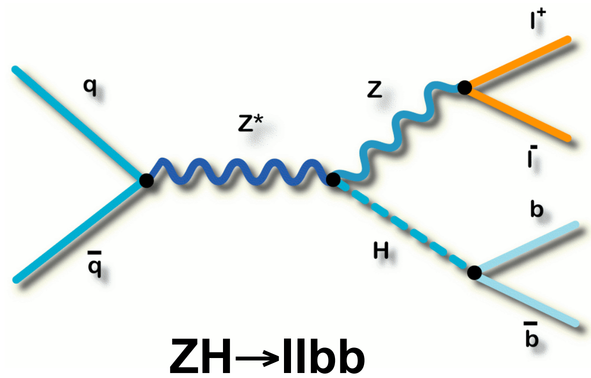


Searches for the SM Higgs Boson at the Tevatron

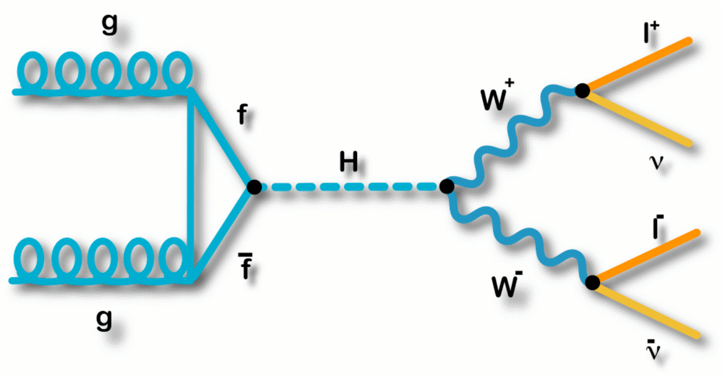
"Associated Production": Low mass only, three final states







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



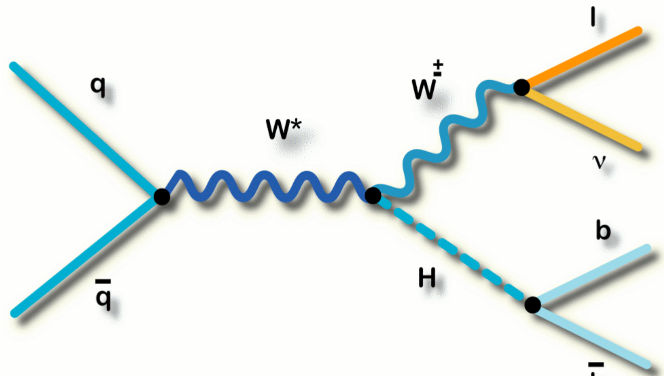
Higher cross section
- but can only distinguish from backgrounds with H→WW decay

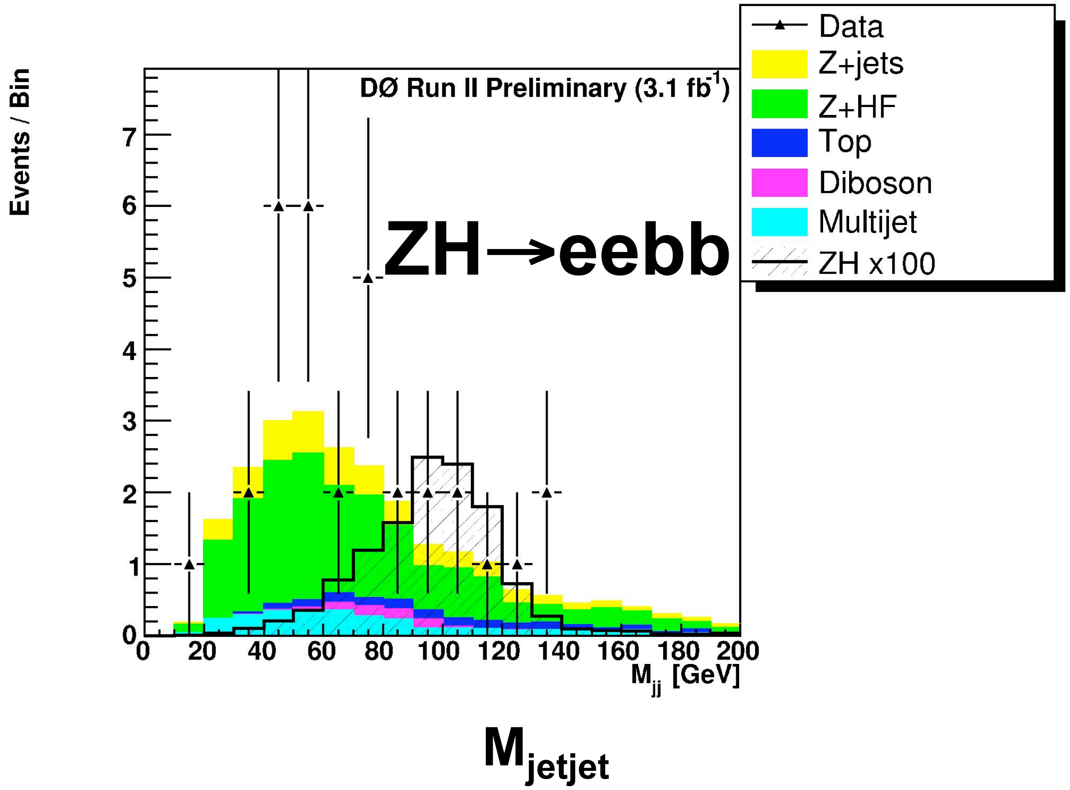
Also **WH→WWW** interesting at intermediate masses

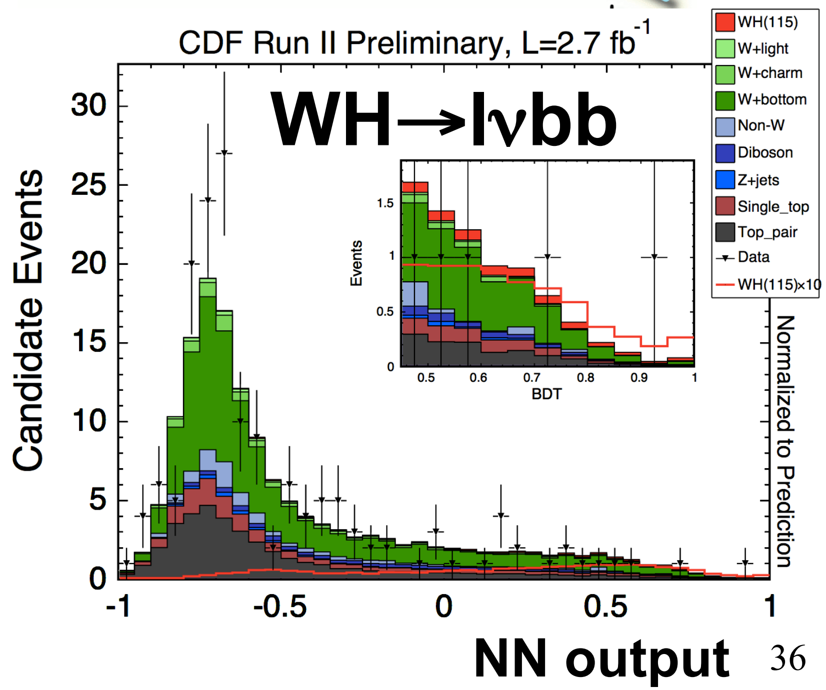
About 1 in 10^{12} proton-antiproton interactions will contain a Higgs
"The Higgs is underneath the needle in the haystack!"

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)





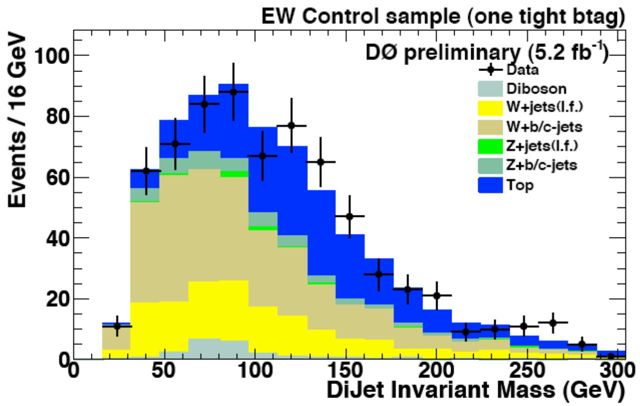


Cross Check Samples in **ZH→ννbb** Analysis

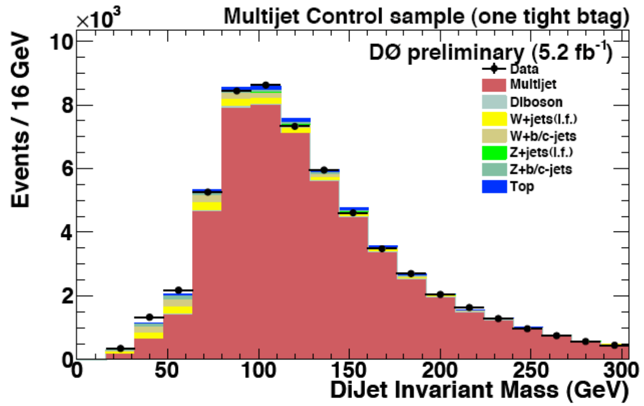
- W→μν+jets

“multi-jets”

- Events with one b-tagged jet

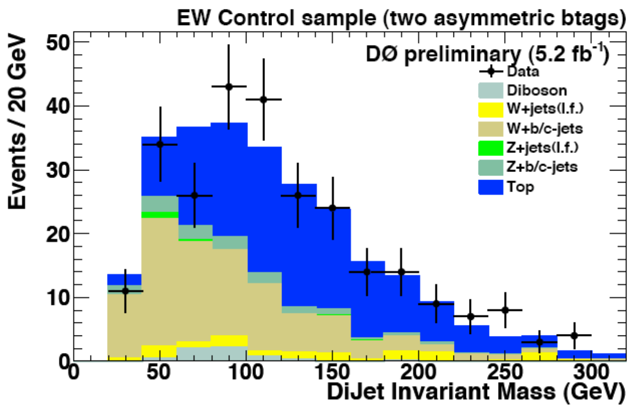


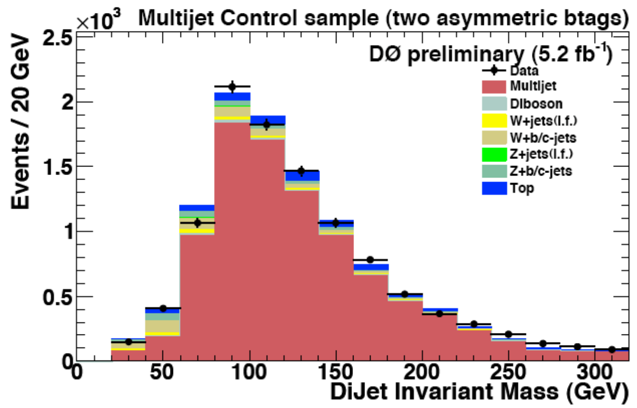
(a)



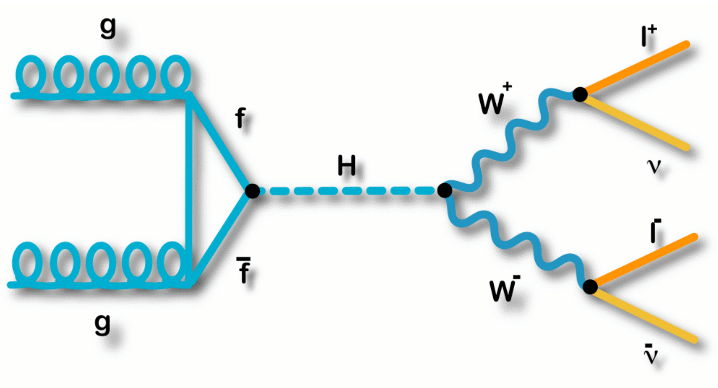
(b)

- Events with two b-tagged jets

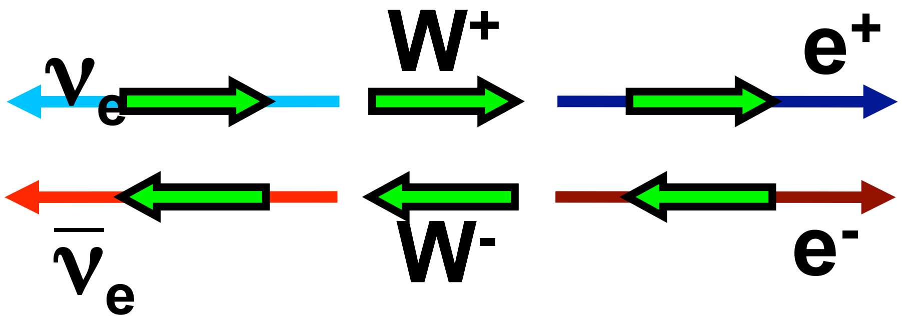




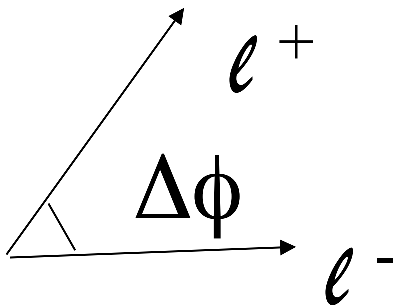
Higgs Searches at High Mass

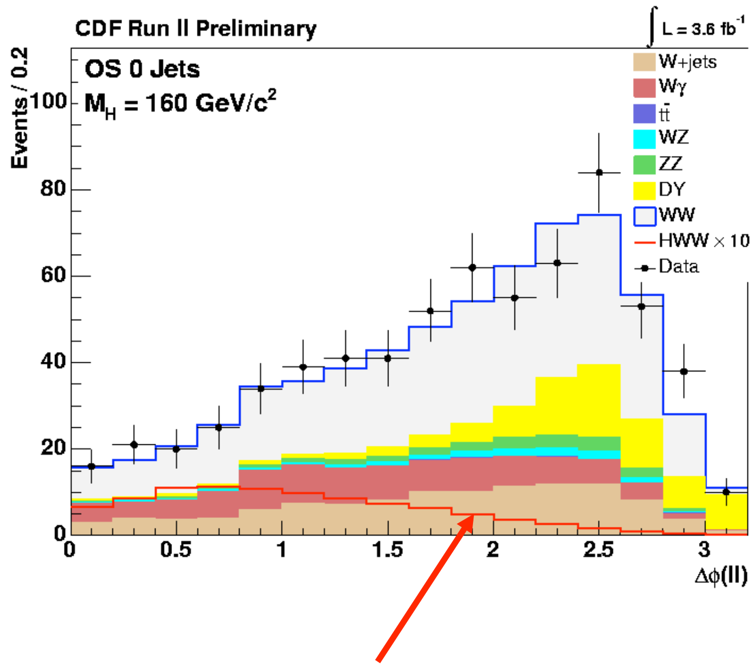


Higgs is a spin zero particle



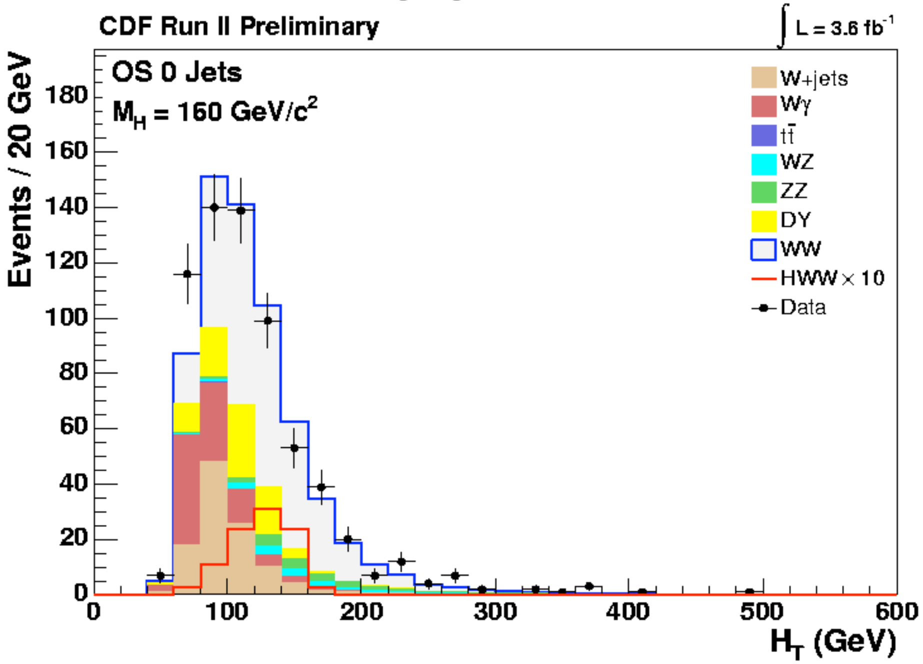
- Look for leptonic decays of WW
- Look at azimuthal angle between the two charged leptons
  - Higgs: small $\Delta\phi$
  - Standard WW events: large $\Delta\phi$

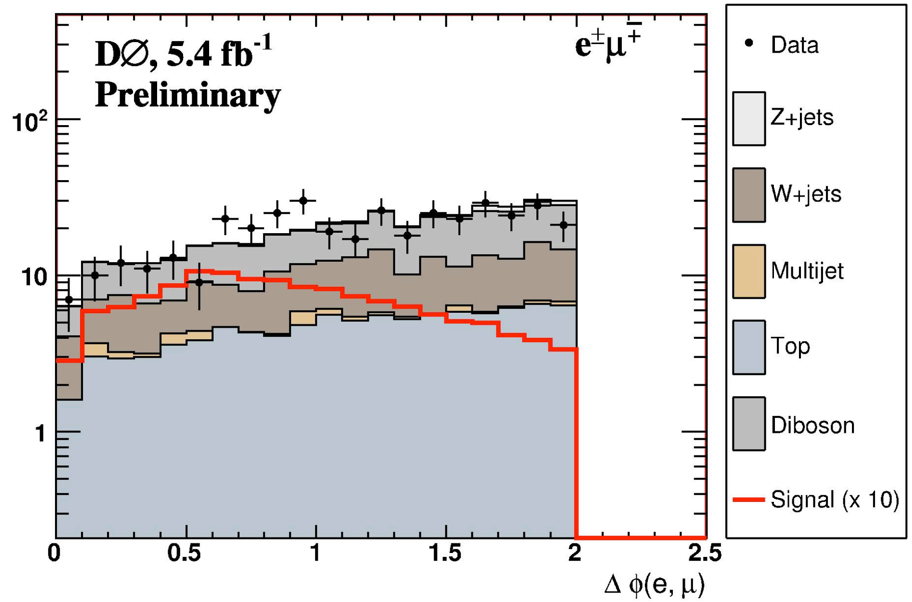


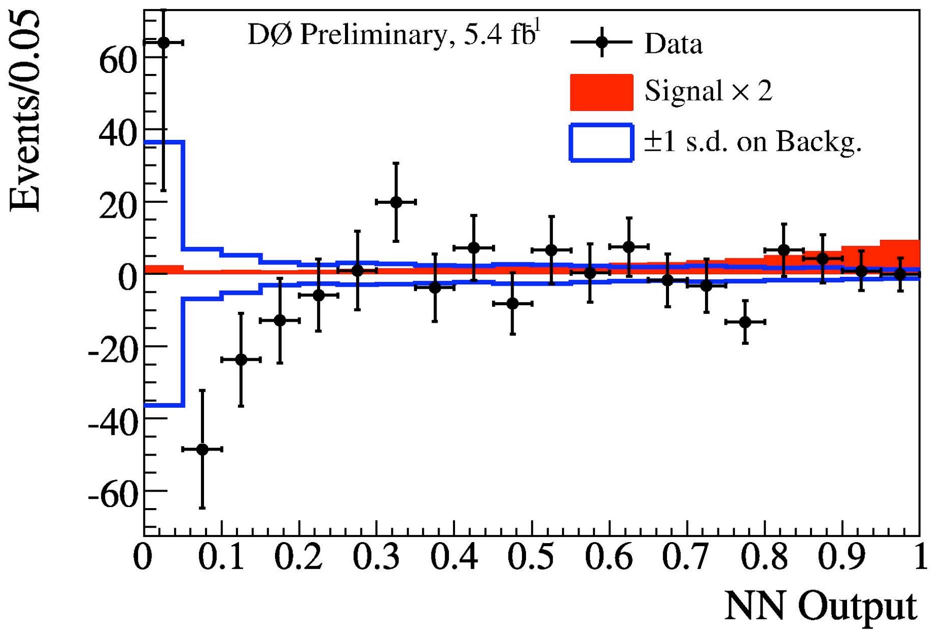


Higgs x 10

Higgs Searches at High Mass

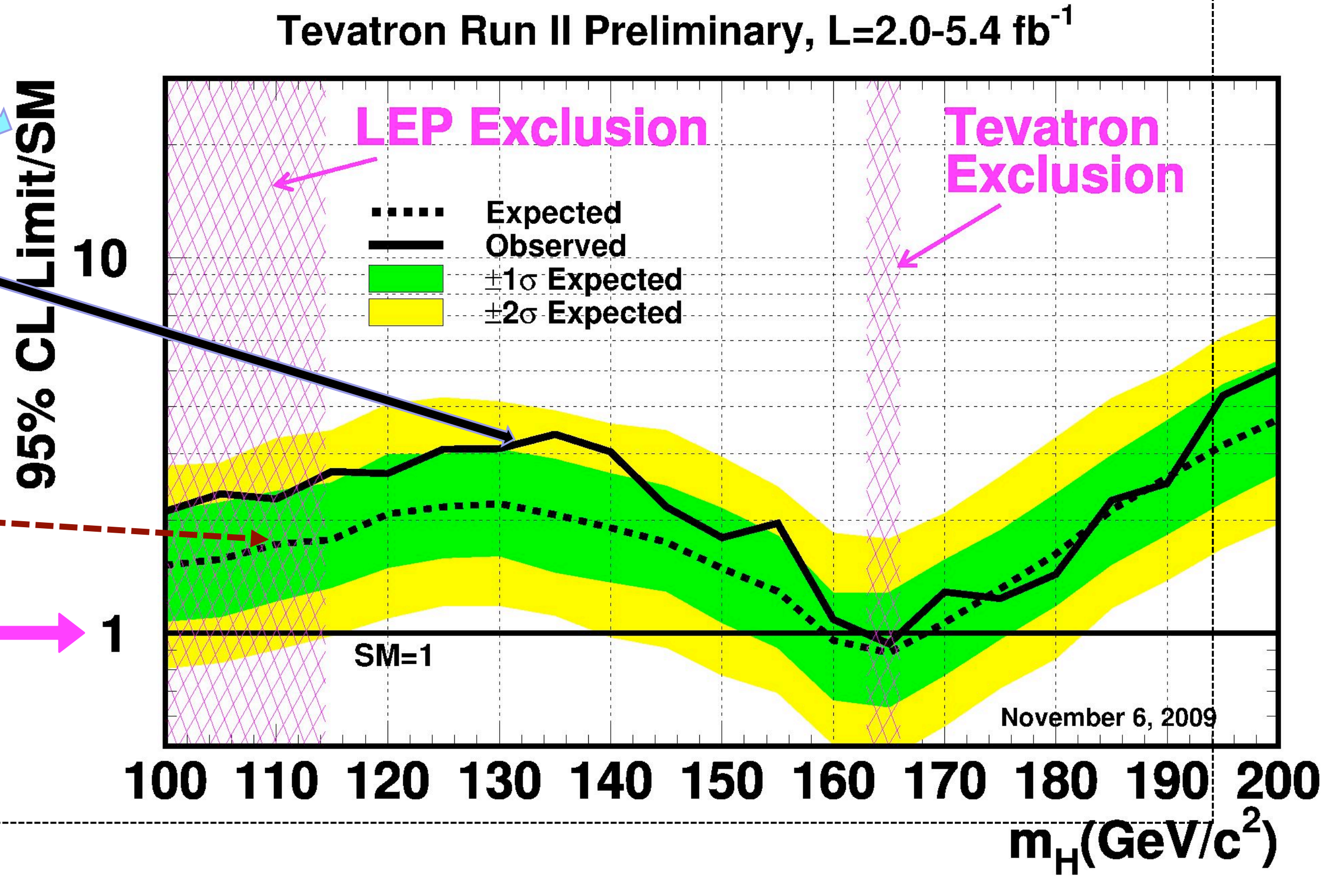






Current CDF+DØ Combined Limits

- 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

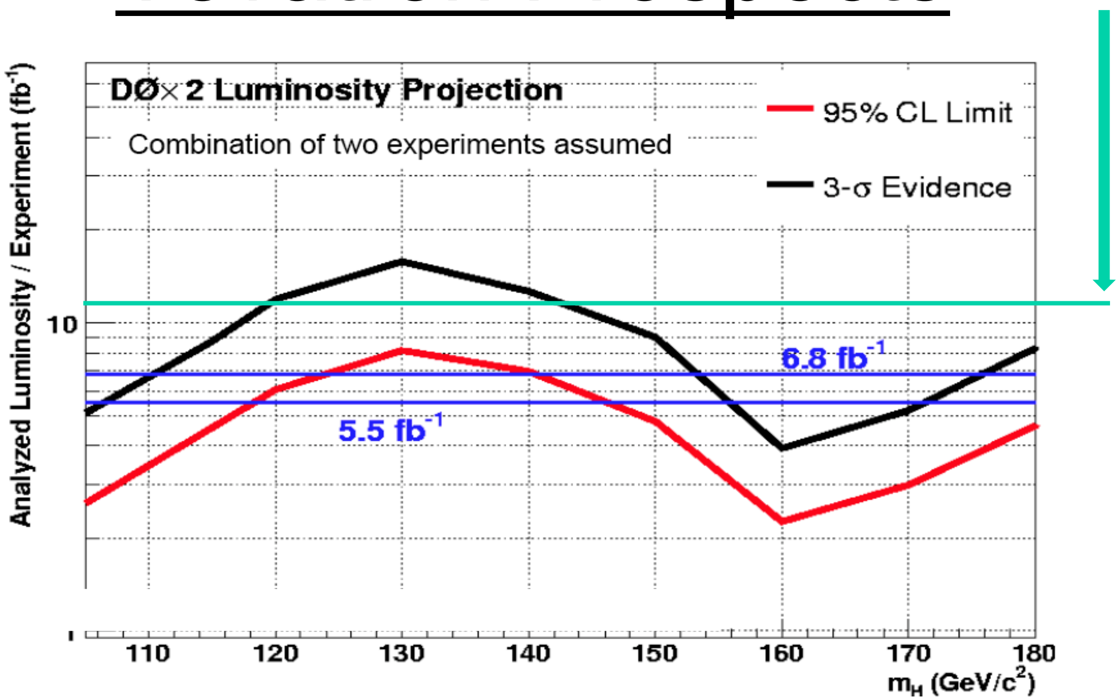


- "Observed limit" obtained from DØ+CDF data
- "Expected limit" obtained by repeating the analysis on a large number of "background-only" Monte Carlo "experiments"

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

Tevatron Prospects

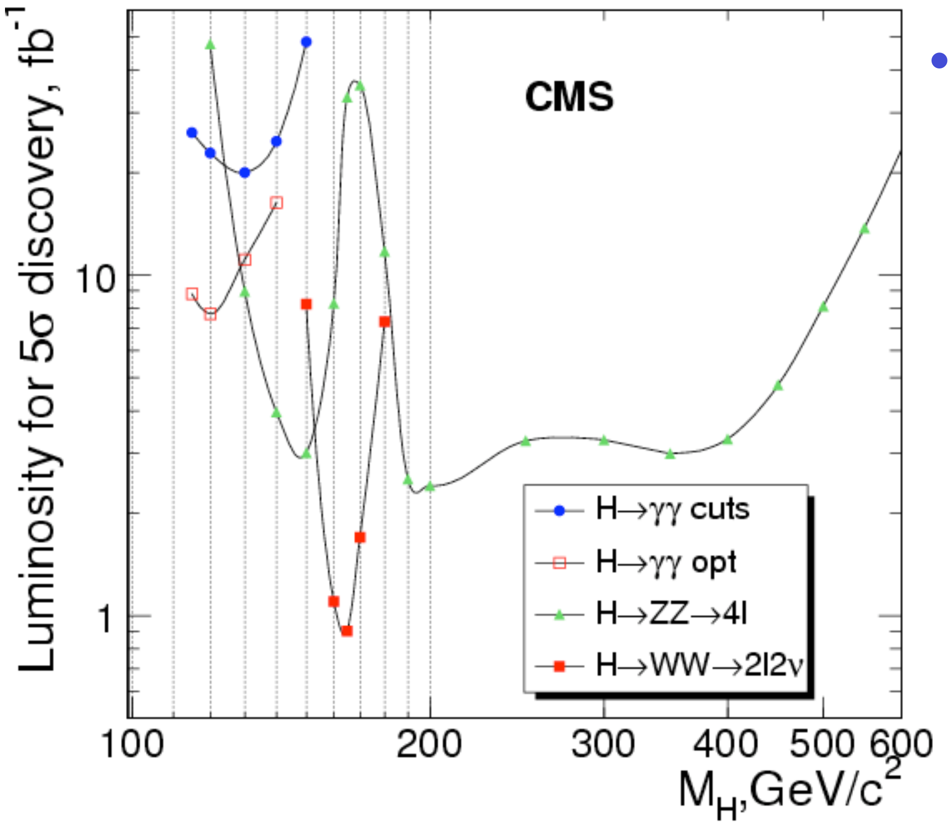
Ultimate sensitivity including 2011 data?



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

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

LHC Sensitivity



- Huge EW event samples crucial to commission detector, trigger and event reconstruction
  - in 1 fb^{-1}
    - 1M Z→ll events
    - 250k "lepton+jet" tt events

- But it will take a few years of commissioning and "low luminosity" running to achieve this sensitivity!

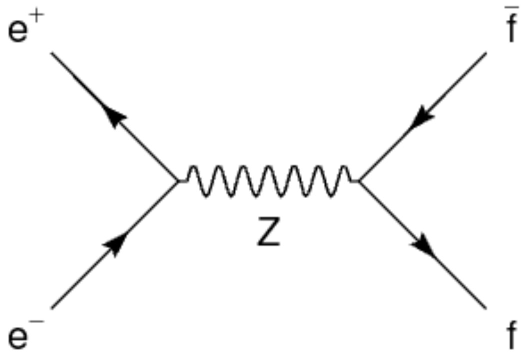
Backup Slides

M_W Summary of 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

systematic uncertainties (bracket spanning Experimental through Total)

Parameters of The Standard Model

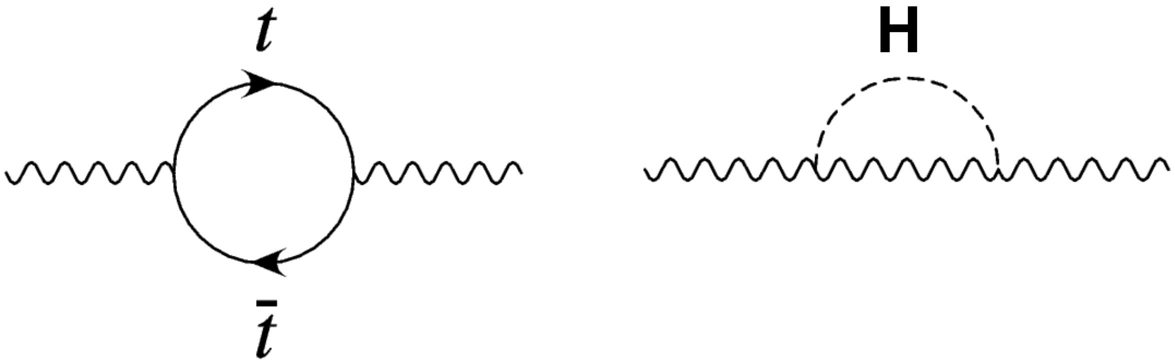


- At the level of simple "tree level" diagrams the EW interactions are determined by three "input" parameters
- Masses of W and Z also given in terms of coupling constants

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

- 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



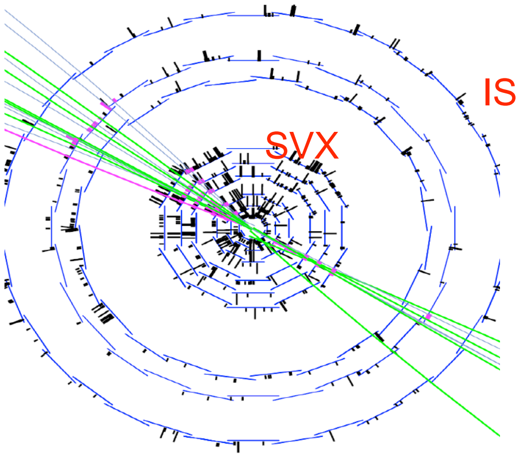
- Loops cause running of coupling constants
  - $\alpha \rightarrow \alpha(Q^2)$
  - $\sin^2\theta_W \rightarrow \sin^2\theta_W^{eff}$
- EW observables then depend on:
  - α, G_F, m_Z, m_t, m_H
- Basic programme:
  - Measure precisely L and R couplings of each fermion to γ, Z, W
  - Measure precisely 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)

- a

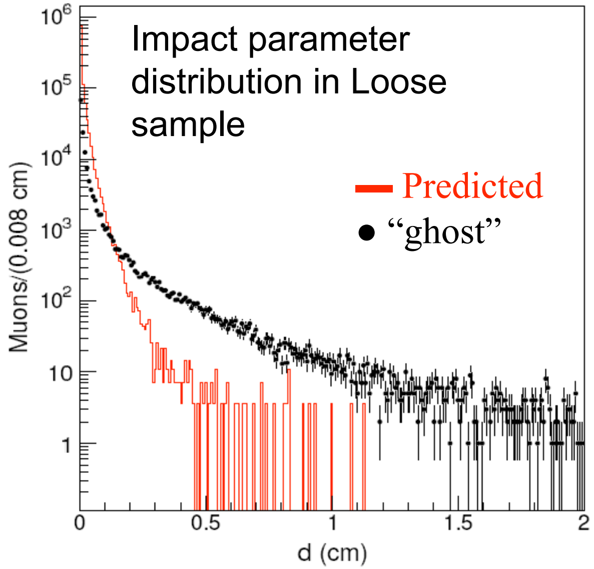
Anomalous Dimuon Events? (CDF)

(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

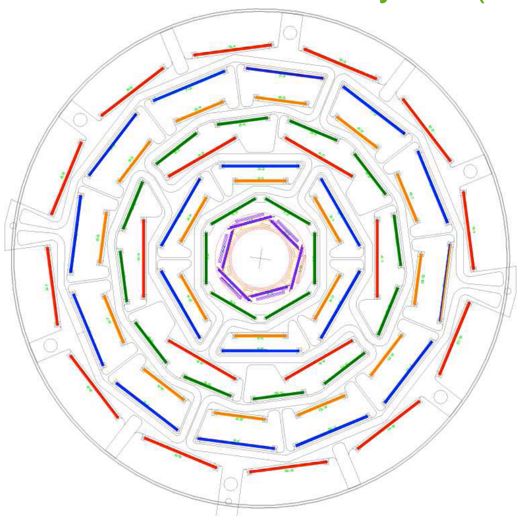
Anomalous Dimuon Events? (DØ)

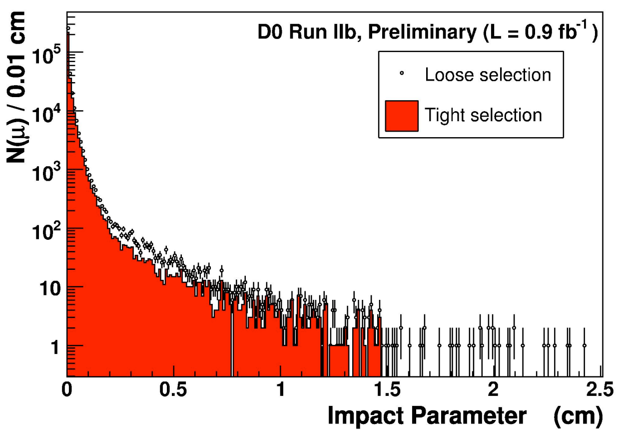
0.9 fb^{-1}

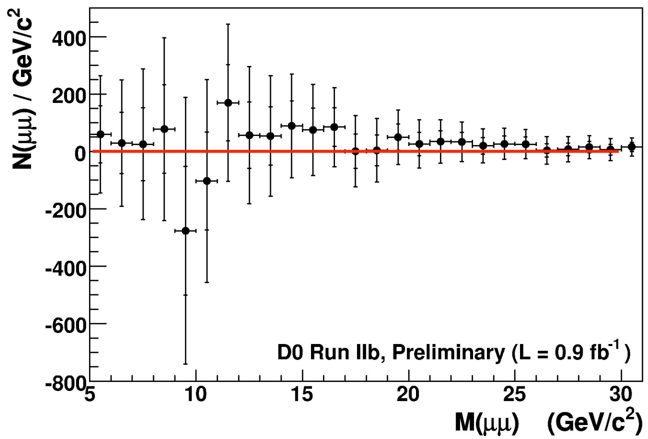
http://www-d0.fnal.gov/Run2Physics/WWW/results/prelim/B/B57/B57.pdf

- 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 $J/\psi \rightarrow \mu^+\mu^-$ 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

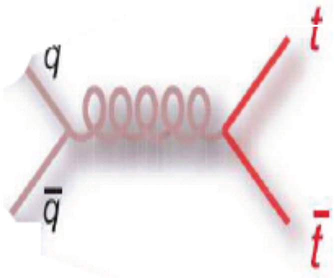




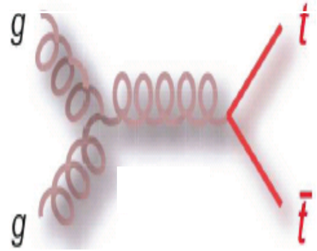


Top Quark Production and Decay at Tevatron

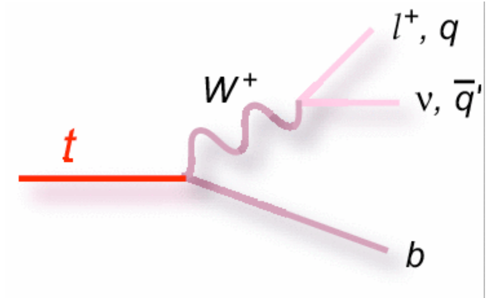
- Pair production: 85%



15%



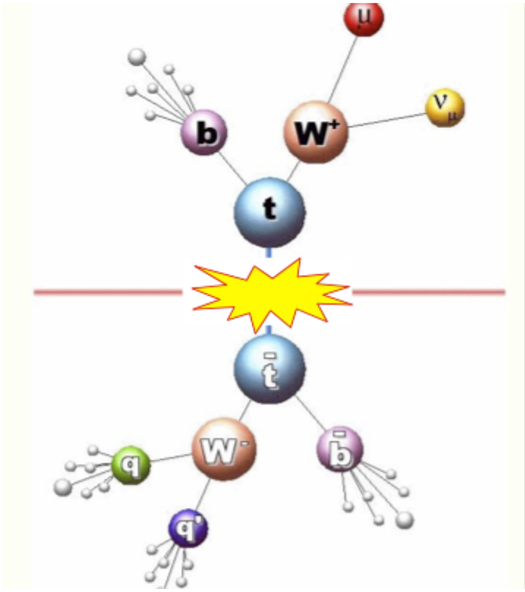
- Decay

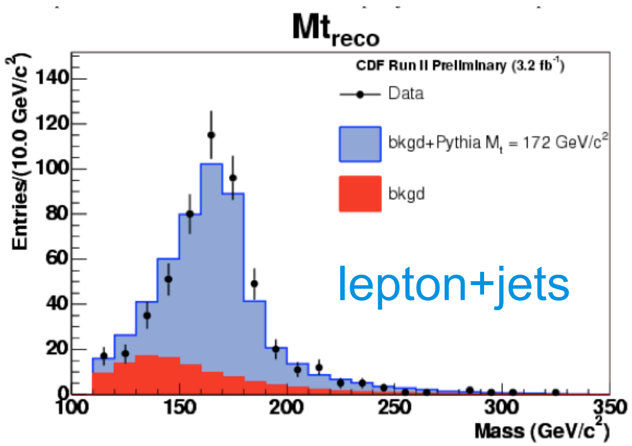


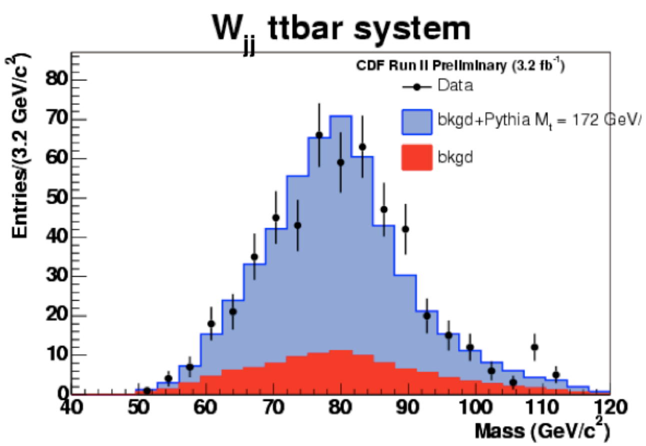
  - Final state determined by decay of the two Ws
  - Discovered by CDF and DØ in 1995
  - Lifetime ~5 x 10^{-25} s
    - Decays before "hadronization" takes place (timescale ~10^{-22} s)
    - Our only opportunity to study a "bare" quark
  - Is the object we see the SM top quark?

Top Mass Measurement

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





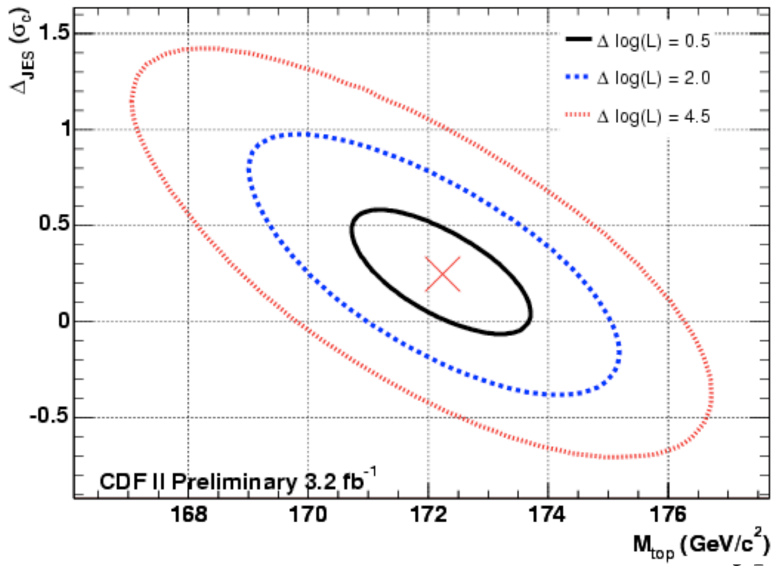


m_{top} =173.1 ± 1.3 GeV

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

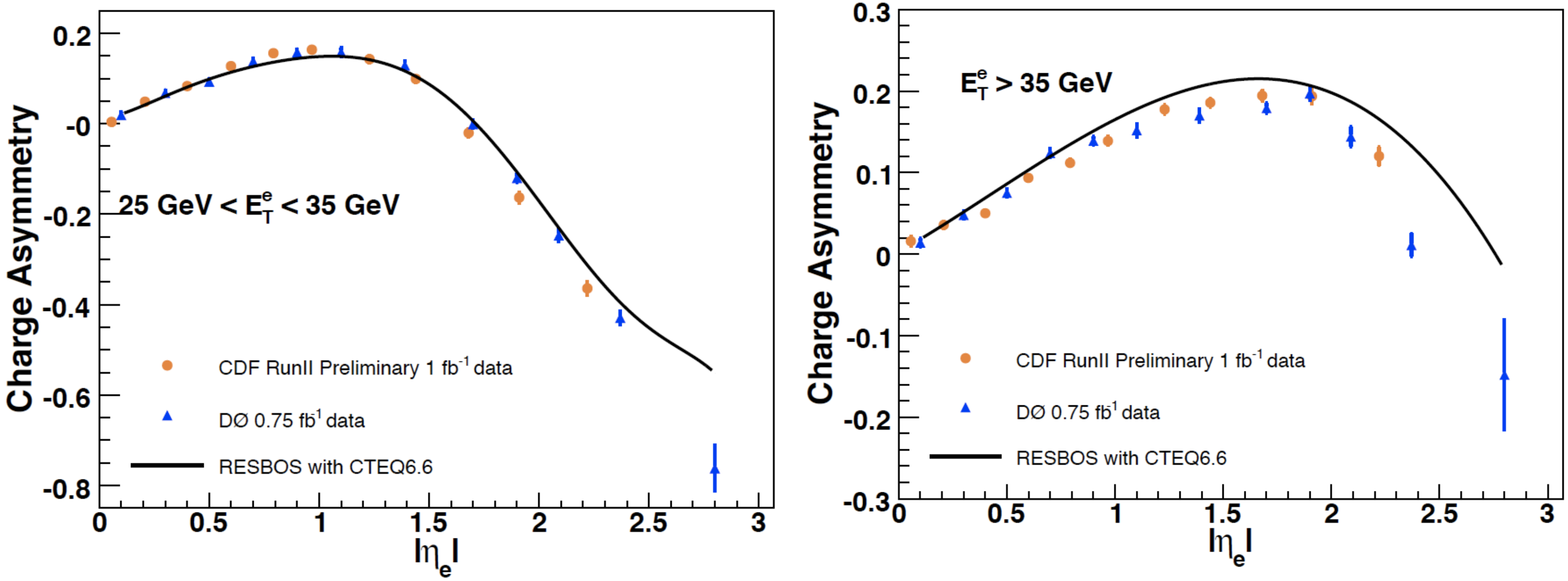
$\Delta m_{top}/m_{top}$~0.7%

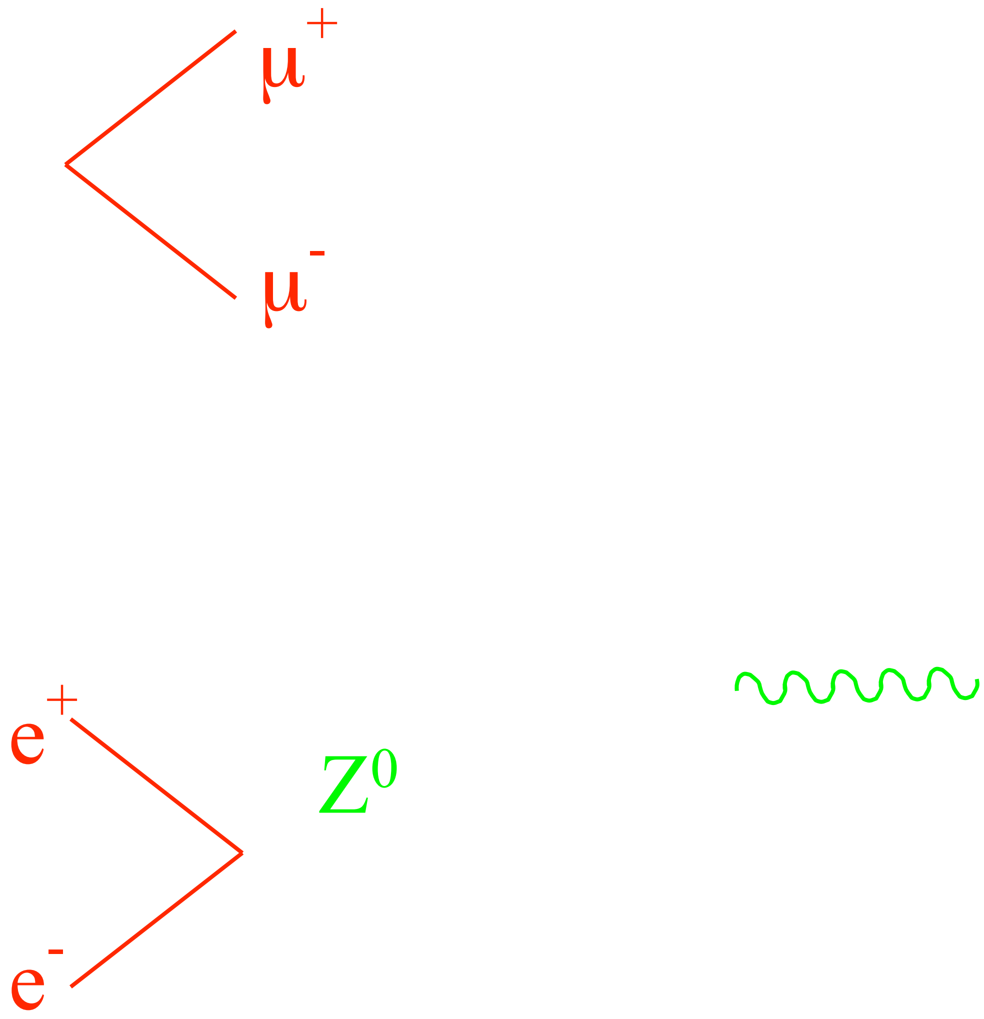
(by far the most precisely known quark mass!)



W Charge Asymmetry and PDFs

- CDF have re-analyzed their data (stat. uncertainties only) to allow a direct comparison with DØ





μ^+
μ^-
e^+
Z^0
e^-