Top Physics

ElectroWeak

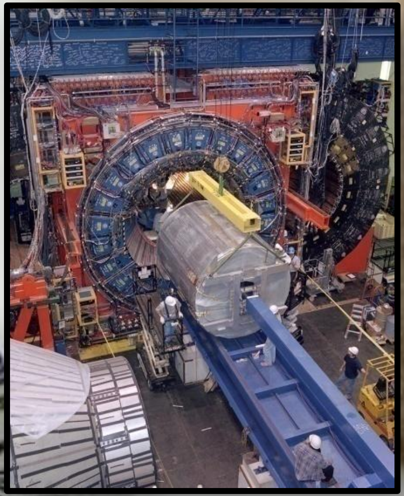
QCD

B Physics

TEVATRON STANDARD MODEL PHYSICS

G. Watts

University of Washington (Seattle)



History…

Apr 27, 2001 (6 Years Ago): The lab had a party to celebrate the beginning of Run II

- Same day: first 36x36 store in the Tevatron (#449)
- Luminosity of ~1×10^{30}
- From a stack in the Accumulator of 74×10^{10} antiprotons.

May 2005 (1 Years Ago): The lab had a party to celebrate 1 fb^{-1} delivered to each experiment.

- Store #4666
- Luminosity of ~1.6×10^{32}
- From a stash in the Recycler of 243×10^{10} antiprotons.

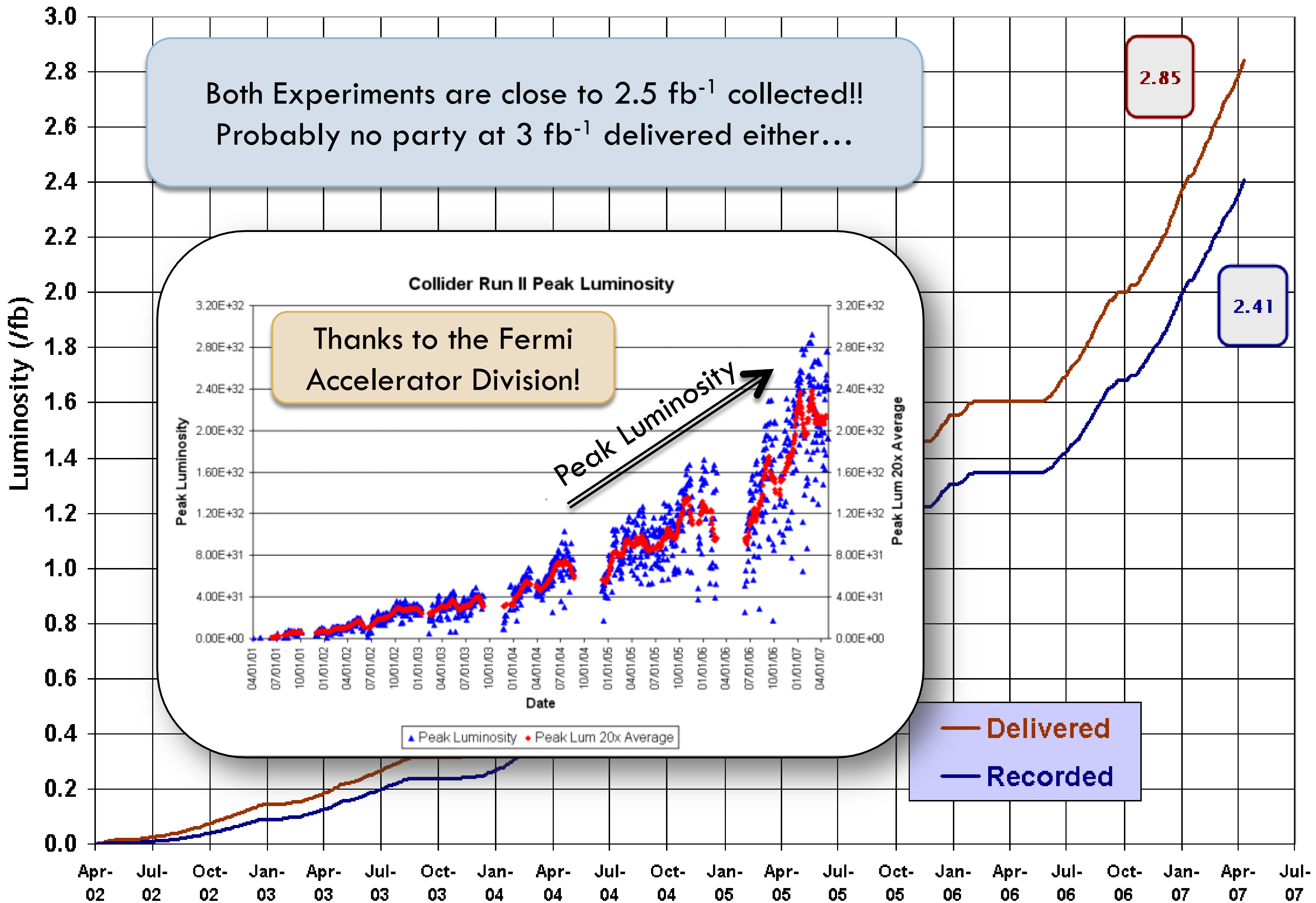
Oct 2006 (6 Months Ago): 2 fb^{-1} delivered. No party??

Now : 2.85 fb^{-1} delivered. Next party at 10 fb^{-1}?

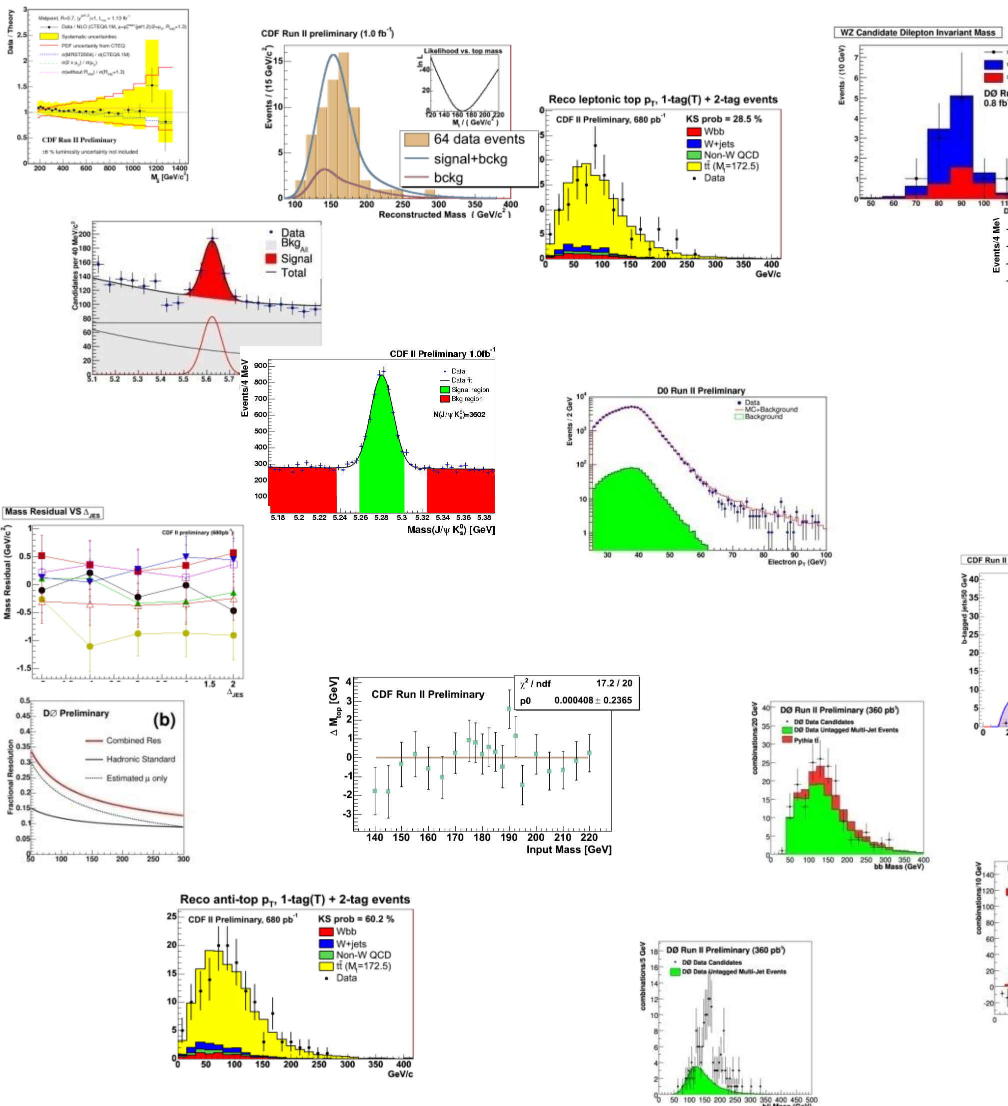
- Store #5376
- Luminosity of ~2.7×10^{32}

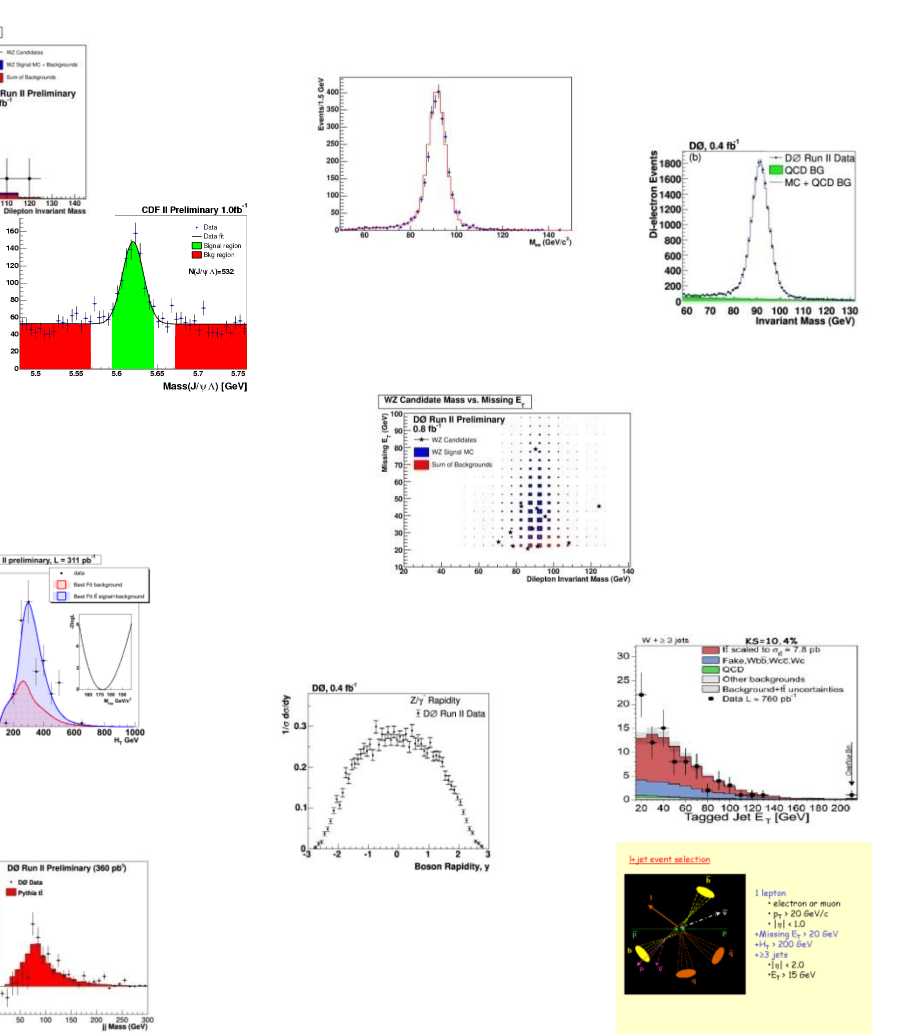
Run II Integrated Luminosity

19 April 2002 - 29 April 2007



What Can You Do With That Data?

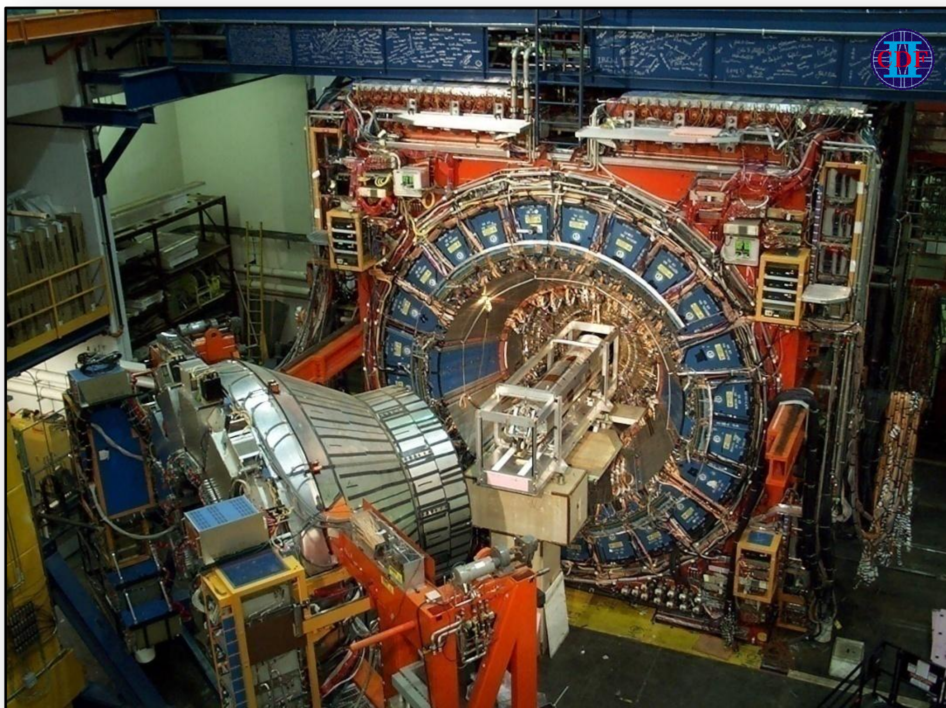




G. Watts (UW)

But Only If You Have CDF & DØ…

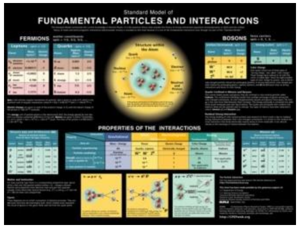
Silicon detectors for precision tracking
Solenoid for p_T measurement
High bandwidth multi-level trigger systems.
Calorimitry
Muon System



Excellent Muon ID Capability
Large Tracking Acceptance ($|\eta|<$2-3)

Excellent Tracking Resolution
High Rate L1 Accept Rate (B Physics)

Tevatron Collider Physics



- Gauge Sector
- Flavor Sector
- Electro-weak Symmetry Breaking

The Standard Program

✓ Complete the Standard Model
✓ Precision Measurements (BSM hunt)
✓ The Hunt for New Phenomena

Recent Developments

✓ Dark Matter
? Dark Energy
? Neutrino Mass/Oscillation

Standard Model Precision Measurements

M_W, M_{top}, …
Cross Sections σ_W, σ_Z, σ_{tt}, σ_t, …
Heavy Flavor Production & Decays

Standard Model & Beyond Searches

Higgs
Supersymmetry, Large Extra Dimensions
New Guage Bosons
New Fermions
…

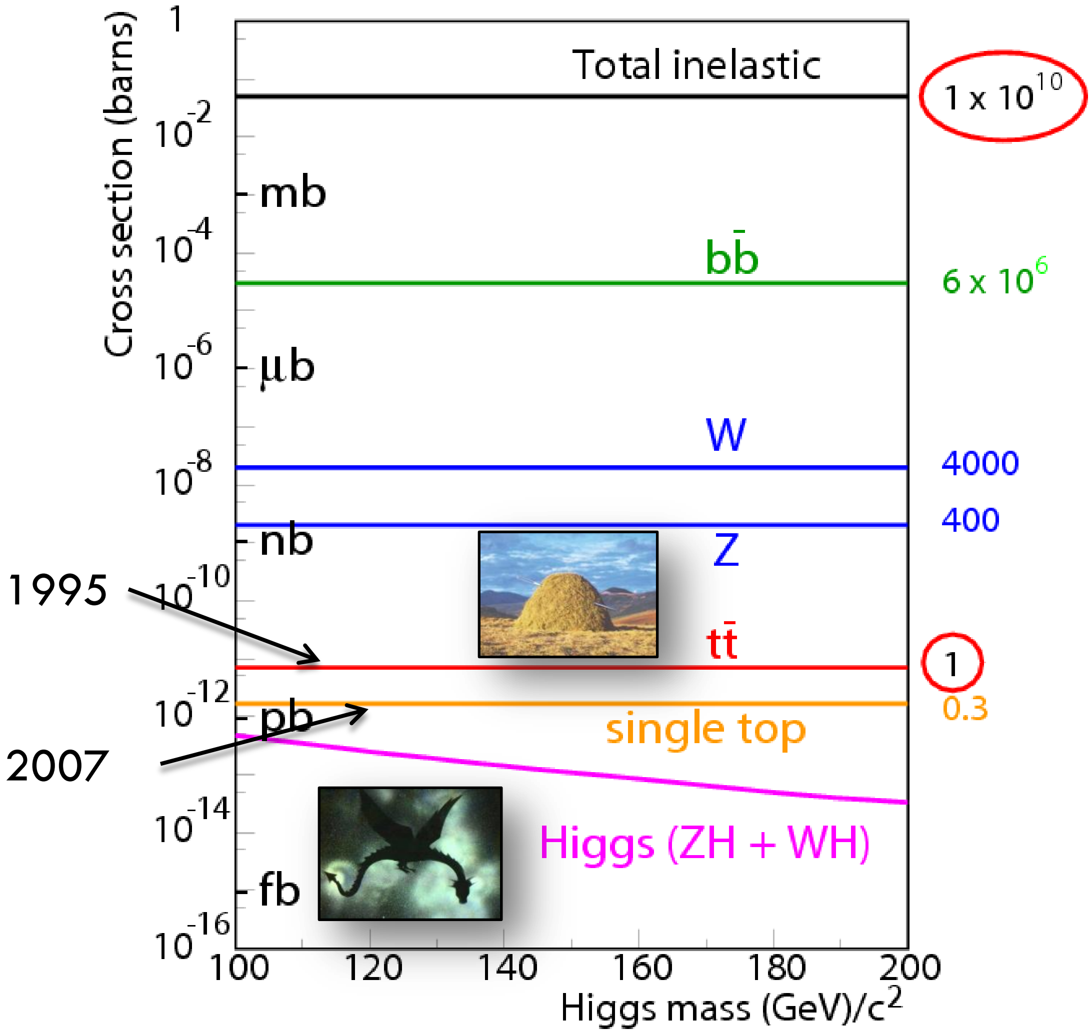
Down The Ladder…

It is getting harder!

- Top quark observation in 1995
- Single Top Quark Evidence 2007

WW, WZ, ZZ…

Higgs…



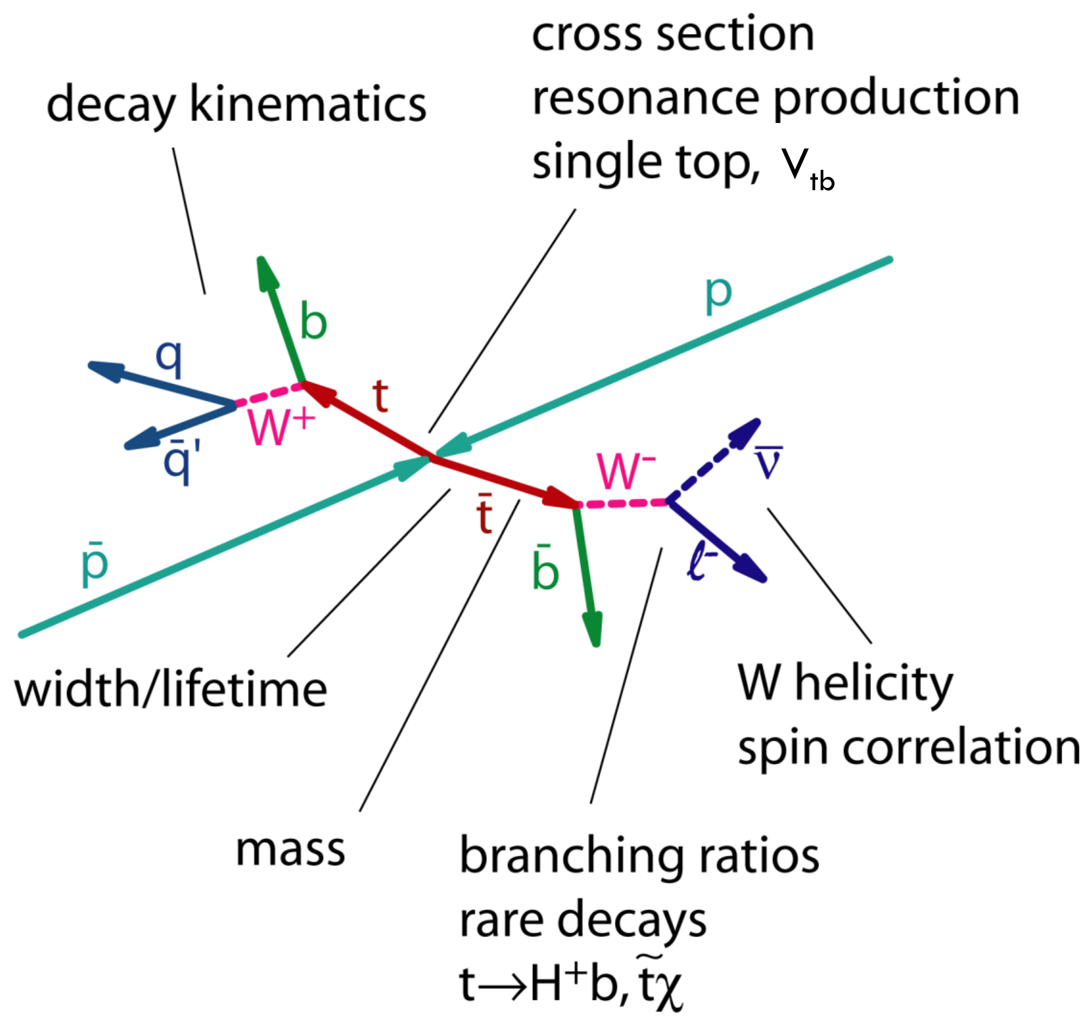
The Top Quark

The Tevatron Lab: Top Quark

Wealth of information to be extracted from the top quark system!

- Discovered in 1995
- Only place for direct measurement is the Tevatron
- Much heavier than expected
    - Implications?

Single Top Production
Top Cross Section
Top Mass Measurement



Top Cross Section

Classify our channels by the W decay mode

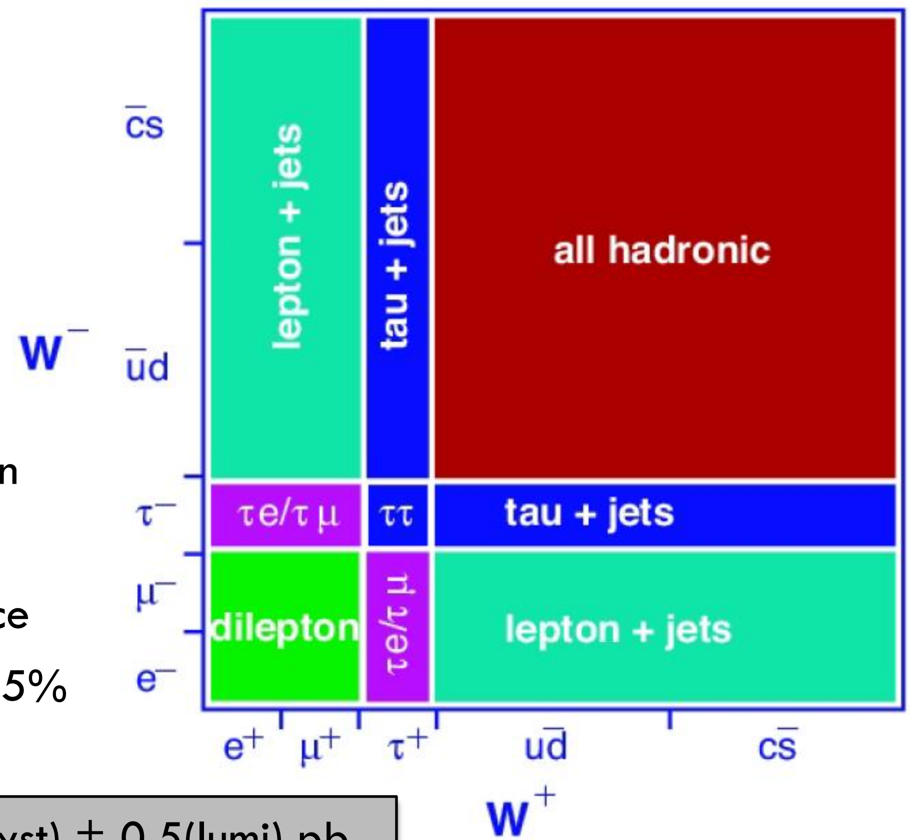
- $WW \rightarrow ll\nu_l\nu_l$ - dilepton
- $WW \rightarrow l\nu_l qq$ – letpon + jets
- $WW \rightarrow qqqq$ – all hadronic

CDF dilepton

Increase acceptance: allow second lepton to be just a track

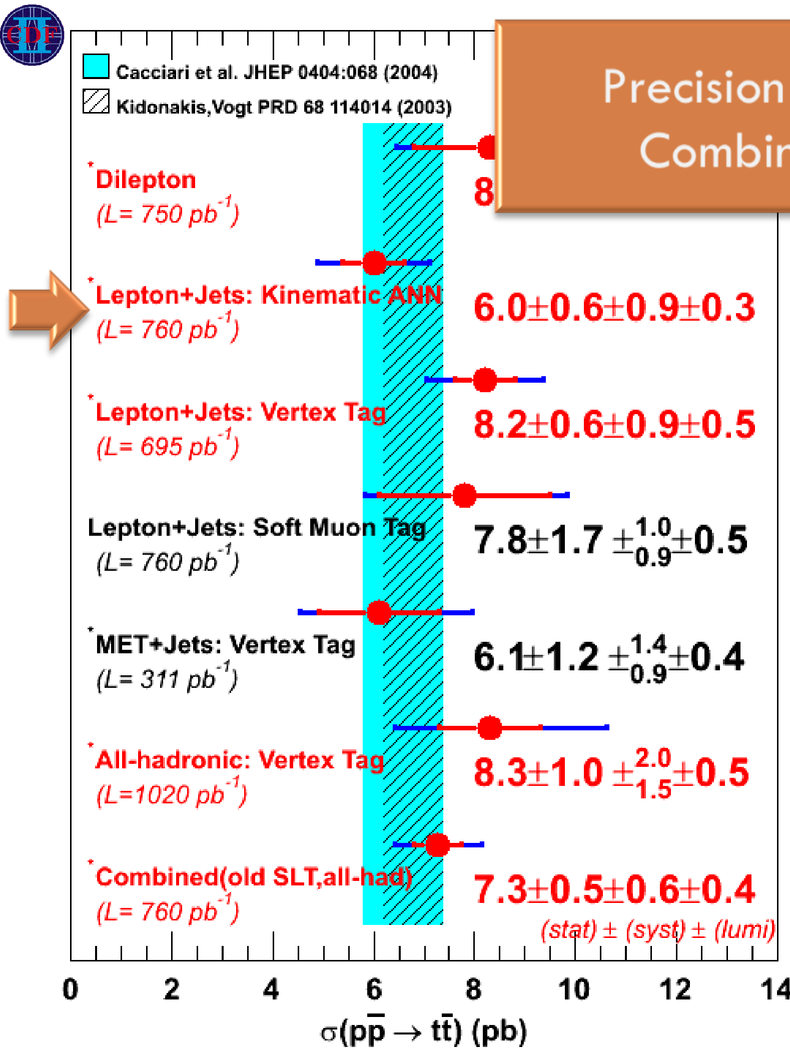
Close to a x2 increase in acceptance

For a counting experiment the S/B is 5% better.

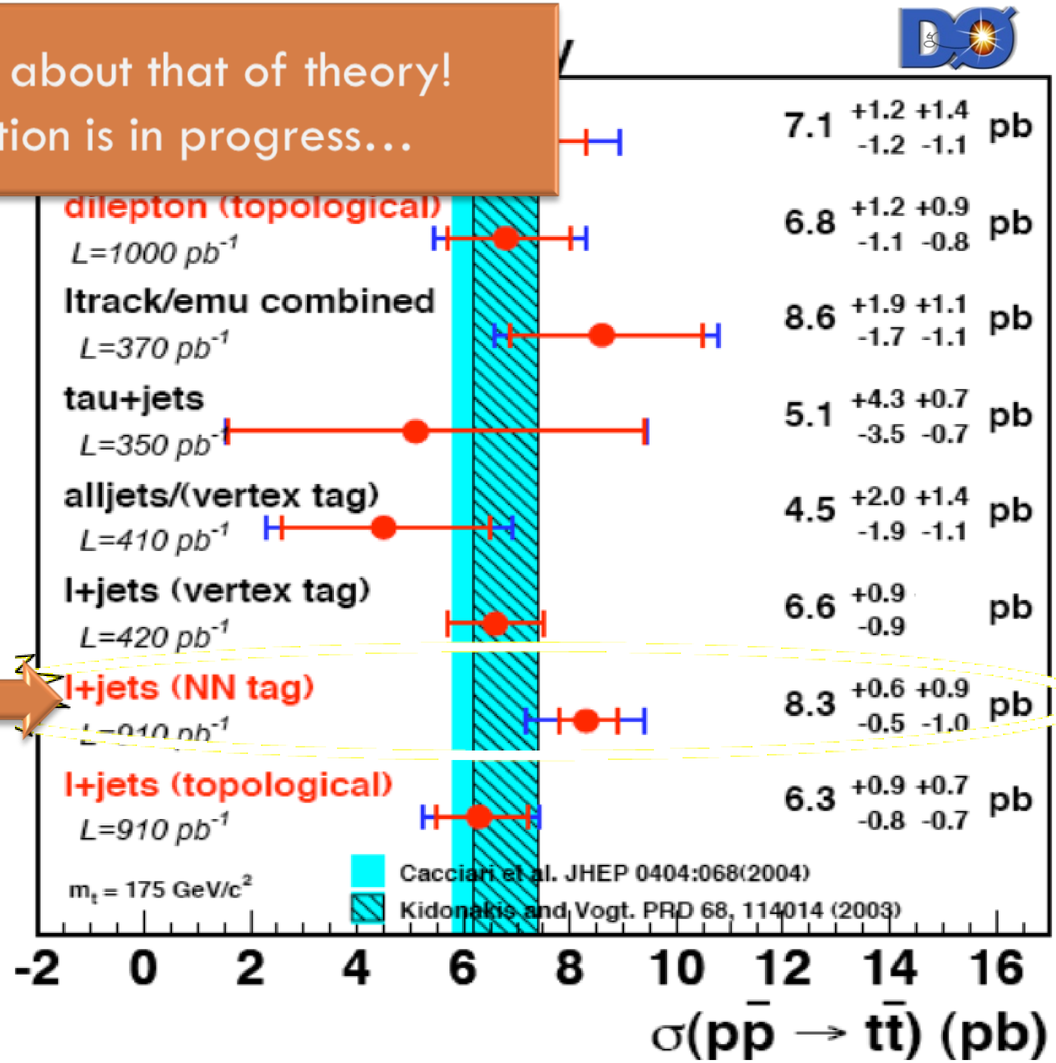


$\sigma(tt\rightarrow \text{dilepton}+X) = 8.3 \pm 1.5(\text{stat}) \pm 1.0(\text{syst}) \pm 0.5(\text{lumi})$ pb

Top Cross Section Summary



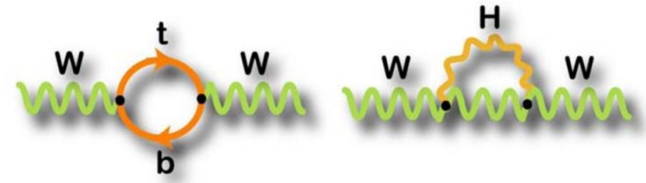
Precision is about that of theory!
Combination is in progress…



The Top Mass

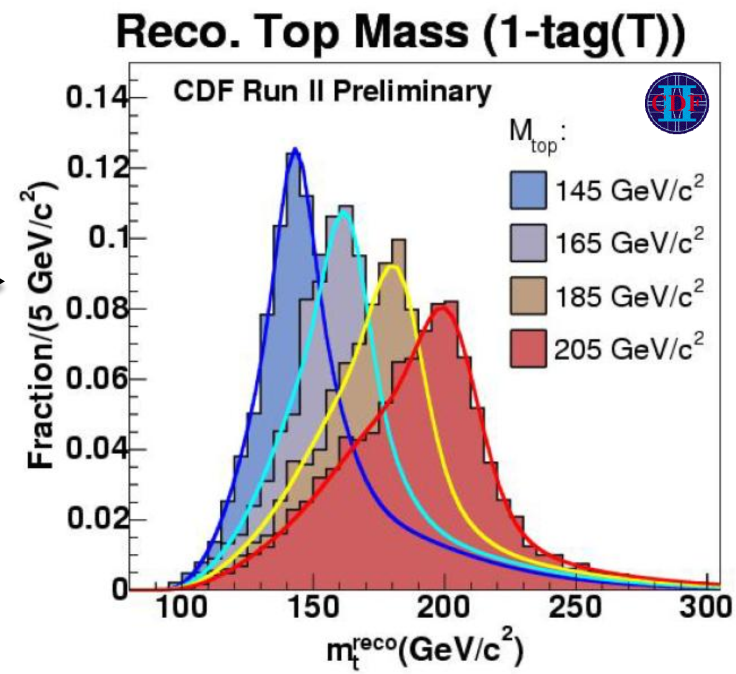
M_t is a fundamental parameter of the SM

Correlated with M_H via loop corrections



Measurement Techniques

- Template Methods compare data M_t *distributions* to similar ones generated with a variety of MC at different M_ts.



- Event-by-Event. Weight events in final M_t distribution according to their similarity to signal or background.

Currently Giving Smallest Errors

The Top Mass

The Matrix Element Method

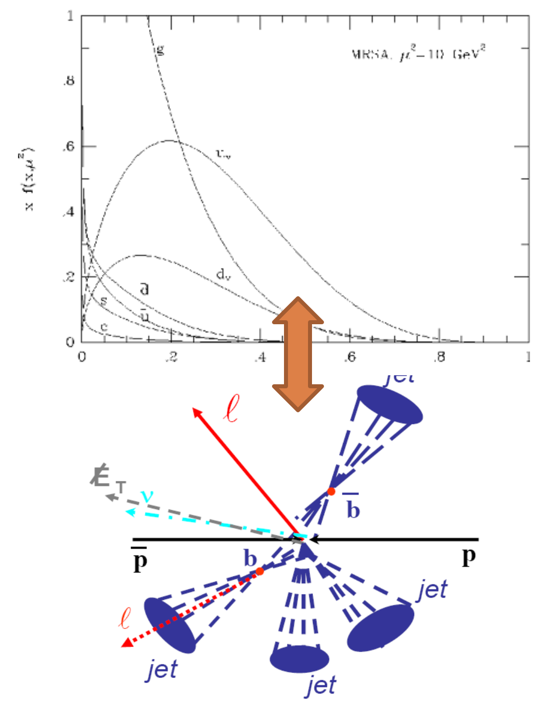
Inverted Monte Carlo: what is the differential cross section that a particular event final state could have come from a signal matrix element or a background matrix element.

$$P(x; m_{top}) = \frac{1}{\sigma}\int d^n\sigma(y; m_{top})\,dq_1\,dq_2\,f(q_1)\,f(q_2)\,W(x, y)$$

$f(q_1)\,f(q_2)$ Parton Distribution Functions

$d^n\sigma(y; m_{top})$ What is likelihood of a particular parton configuration?

$W(x, y)$ What is the chance that the final state partons (y) could produce the measured objects (x).



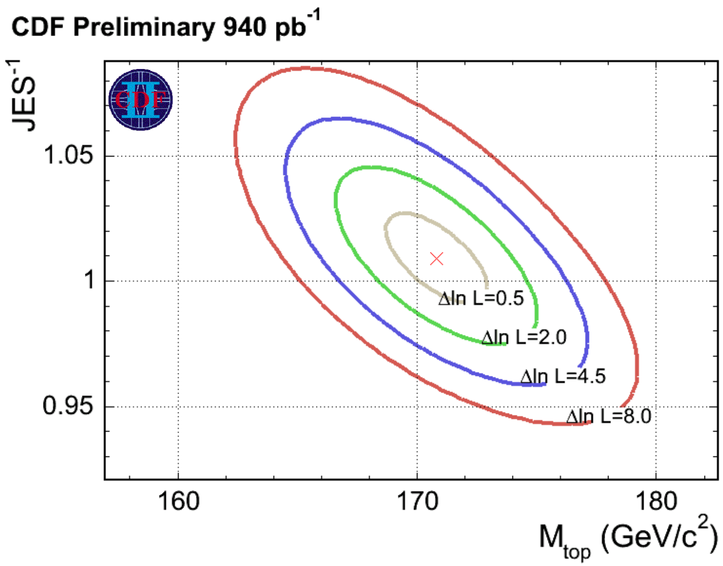
Top Mass

Lepton + Jets

New trick in tool box: In-stiu Jet Energy Scale (JES) calibration

- JES is normally determined on photon+jet events.
- Let JES float: another parameter similar to M_t.
- Constrain JES to best of knowledge, if possible (D0).

This works because we know the W mass better than we know the JES at these jet energies!



CDF (fit of M_{top}, f_{top}, and JES):

M_{top} = 170.9 ± 2.2 (stat+JES) ± 1.4 (syst) GeV/c^2

DØ (fit of M_{top} and JES): (0+1+2 tags)

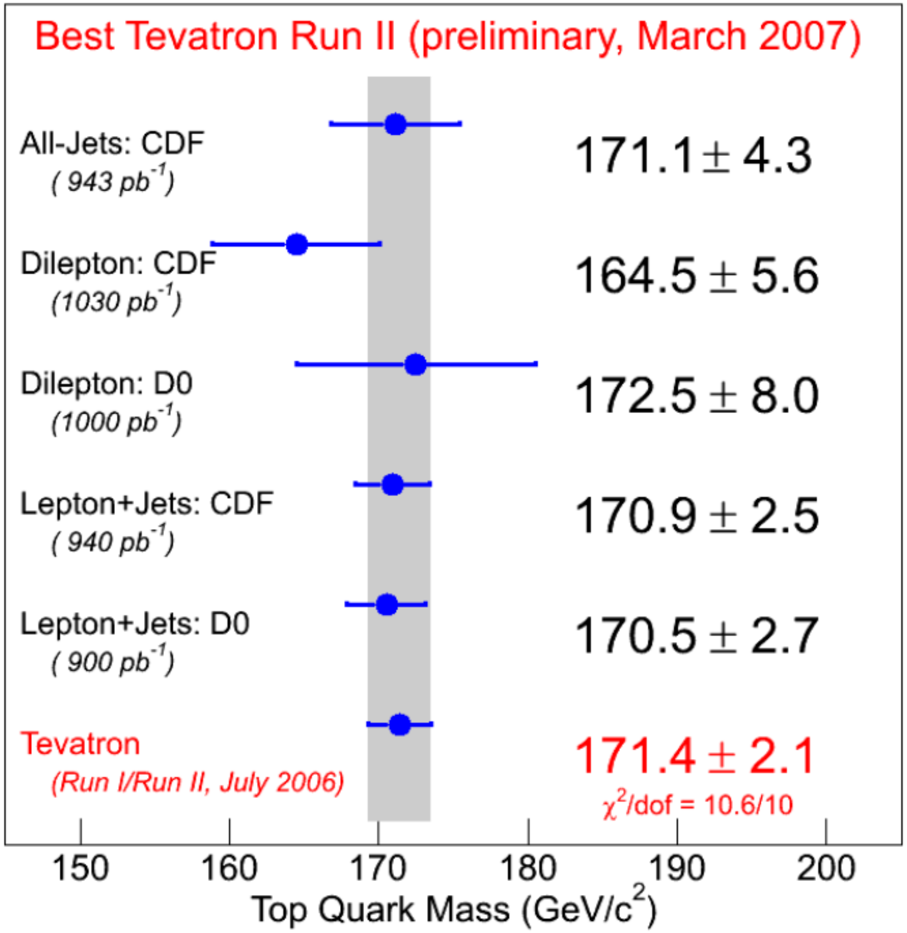
M_{top} = 170.5 ± 2.5 (stat+JES) ± 1.4 (syst) GeV/c^2

(1+2 tags)

M_{top} = 170.5 ± 2.4 (stat+JES) ± 1.2 (syst) GeV/c^2

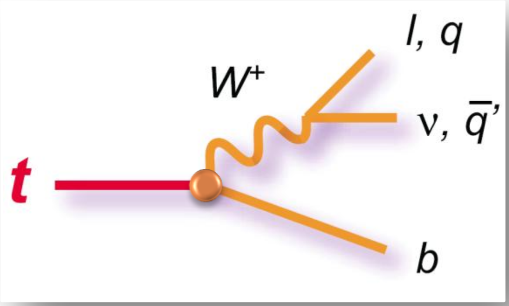
Top Mass Combination

dilepton	Very few backgrounds in SM, but relatively small statistics and two neutrinos add ambiguity.
All hadronic	Largest fraction of production, but multijet backgrounds are very large
lepton + jets	A perhaps happy compromise. Currently yields *best measurements* (but all are competitive).



Run 2 expectation: ±1 GeV

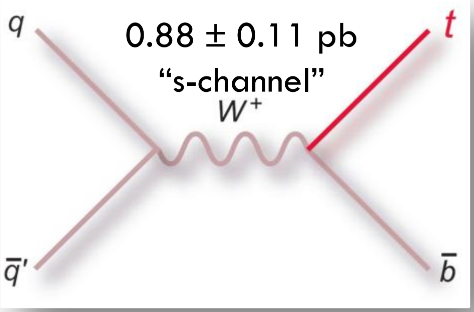
Single Top Production

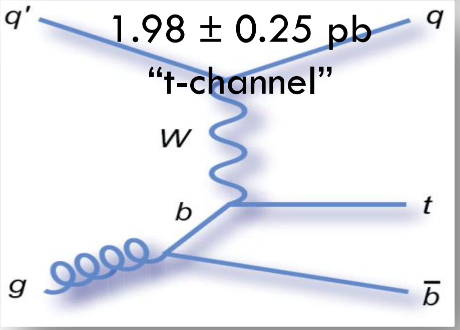


Direct Access to the W-t-b coupling (σ_{st})
- Measure V_{tb} of the CKM directly
- CKM Unitarity

Sensitive to new resonances: W', top pions, SUSY, FCNC, anomalous couplings...

Backgrounds to Higgs!





Single Top Final State

Typical for Top: Lepton, missing E_T, and jets

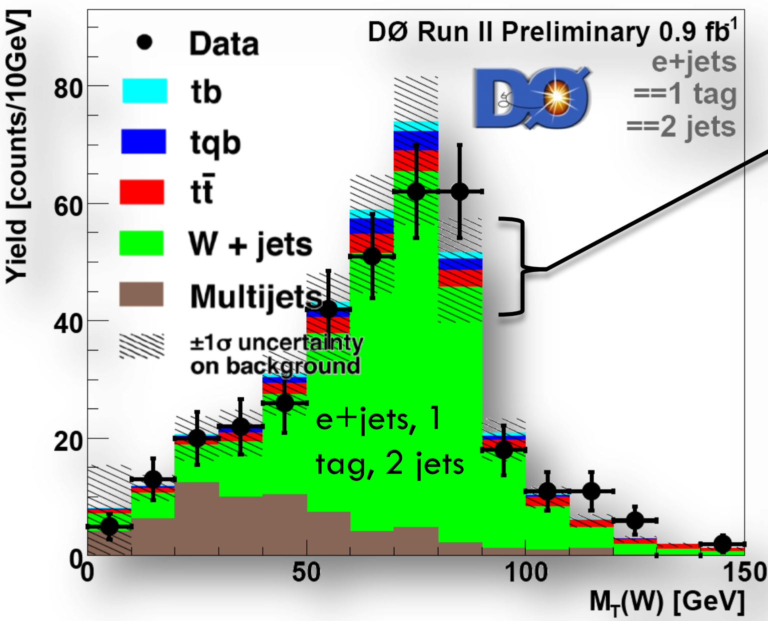
Backgrounds

W+Jets – σ = 1000 pb

tt – σ = 7 pb

QCD multi-jet background/jet mistaken ID

Sophisticated Separation Techniques



The estimated systematic error is larger than the expected signal!

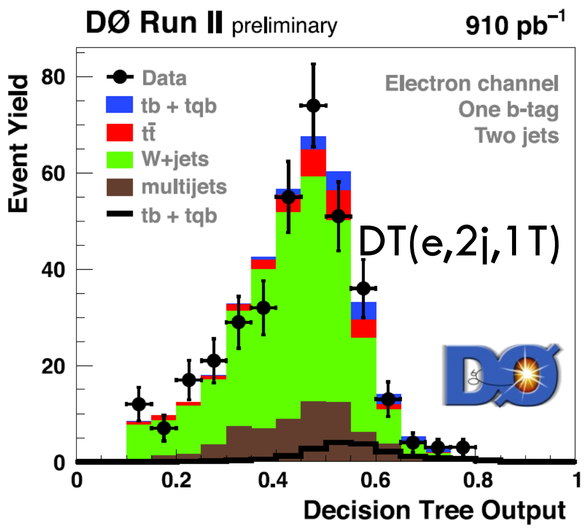
A simple counting experiment isn't going to work!

Neural Network
Likelihood
Matrix Element

Decision Tree
Matrix Element
Bayesian Neural Network

Monte Carlo Trained Techniques

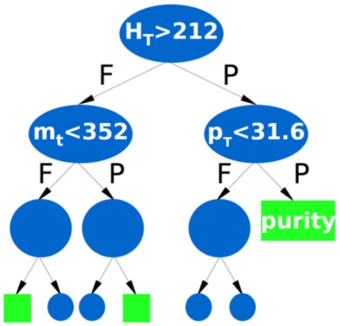
Train on MC signal and background to separate signal and background



Decision Tree(DT): Branch at each node depending on a selection cut. Each leaf contains a purity determined on MC: the result of the DT discriminate. Boosting re-trains to improve incorrect assignments.

Neural Network (NN): functional combination with weights determined by training.

Likelihood: Combined likelihood of multiple variables, all with some minimal separation.



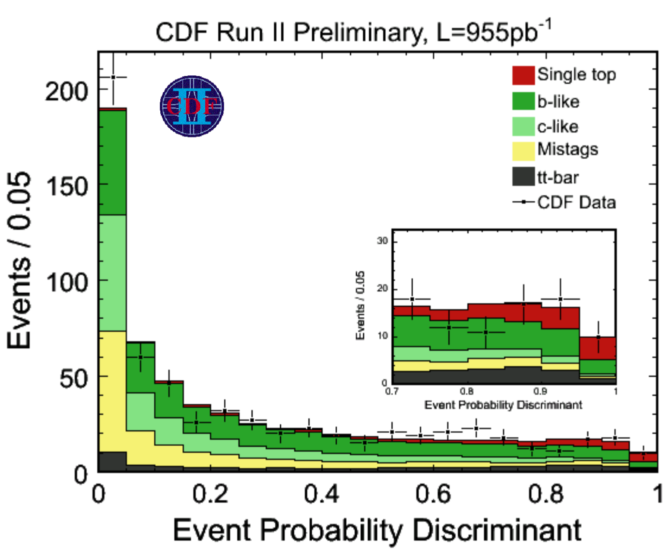
- Analyzer must carefully pick variables to increase separation.
- Training and over training
- Very Fast to redo the analysis.

Matrix Element Technique

Use MC LO Matrix Element to predict probability an event is signal or background.

The probability a measured detector topology (x) is a particular process (M):

$$P(\vec{x}) = \frac{1}{\sigma}\int \underbrace{f(q_1;Q)dq_1\, f(q_2;Q)dq_2}_{\text{CTEQ6 Parton Distribution Functions}} \times \underbrace{|M(\vec{y})|^2 \phi(\vec{y})dy}_{\text{Leading Order ME from MadGraph and phase space \& parton level cuts}} \times \underbrace{W(\vec{x},\vec{y})}_{\text{Transfer Function: Map Detector to Partons}}$$



- Matrix Element should extract maximal separation information from event. But is only LO.
- Very slow: must integrate over all unknowns (minutes/event)

Results

	DØ		CDF	
Technique	Expected Sensitivity	Result & Sensitivity	Expected Sensitivity	Result & Sensitivity
Neural Network	1.3σ (Bayesian)	$\sigma_{s+t} = 5.0^{+1.9}_{-1.9}$ pb 2.2σ	$\sigma_{s+t} < 5.7$ pb	$\sigma_{s+t} < 2.6$ pb @ 95% CL
Likelihood			$\sigma_{s+t} < 2.9$ pb	$\sigma_{s+t} < 2.7$ pb @ 95% CL
Matrix Element	1.8σ	$\sigma_{s+t} = 4.6^{+1.8}_{-1.5}$ pb 2.9σ	2.5σ	$\sigma_{s+t} = 2.7^{+1.5}_{-1.3}$ pb 2.3σ
Decision Tree	2.1σ	$\sigma_{s+t} = 4.9^{+1.4}_{-1.4}$ pb 3.4σ		

CDF has determined their results are compatible at the 6.5% level.

DØ Single Top Result Combination

The analyses are not fully correlated

$$\delta = \begin{array}{c} \\ \\ \end{array}\begin{array}{cccc} DT & ME & BNN & \\ \end{array}$$
$$\delta = \left(\begin{array}{cccc} 1 & 0.57 & 0.51 & DT \\ 0.57 & 1 & 0.45 & ME \\ 0.51 & 0.45 & 1 & BNN \end{array} \right).$$

BLUE MetZhod

f = w_{DT}•DT+w_{ME}•ME+w_{BNN}•BNN

Use the SM Ensemble

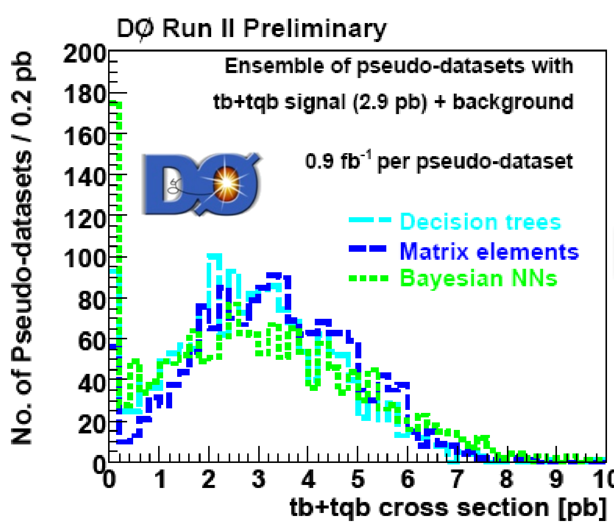
Determine the weights such that the mean square error on f is minimal.

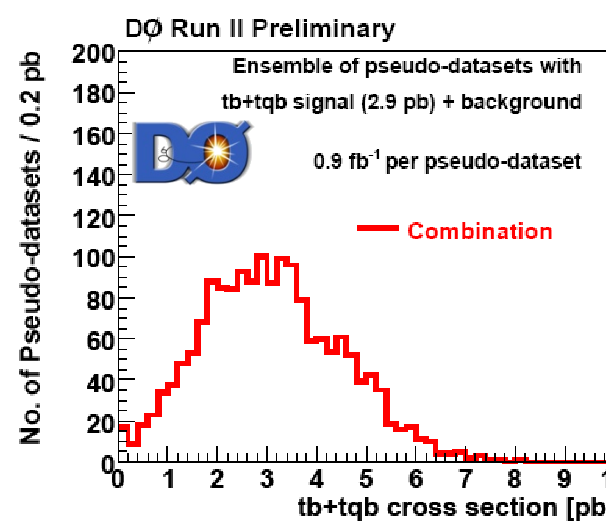
$$w_{\mathrm{DT}} = 0.401$$

$$w_{\mathrm{ME}} = 0.452$$

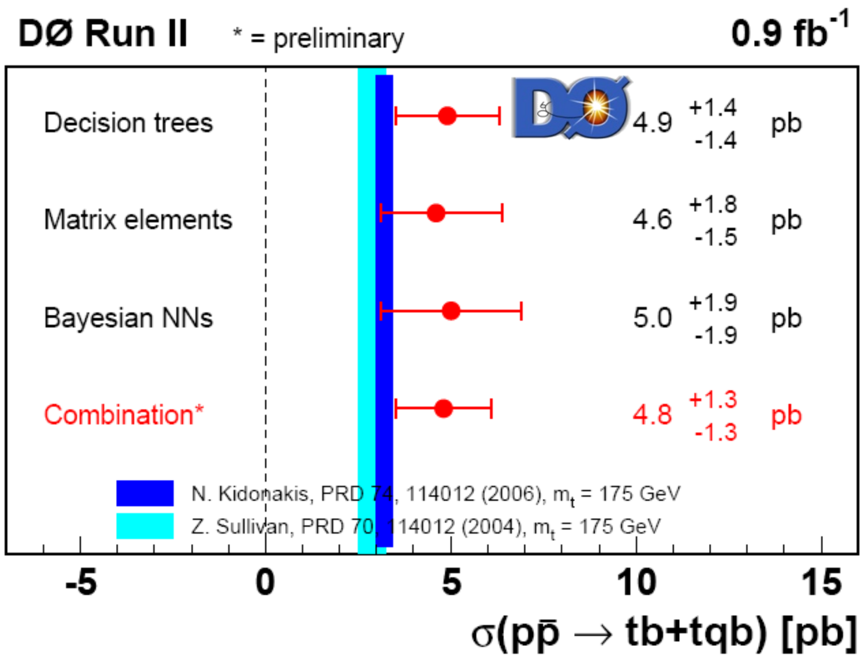
$$w_{\mathrm{BNN}} = 0.146$$

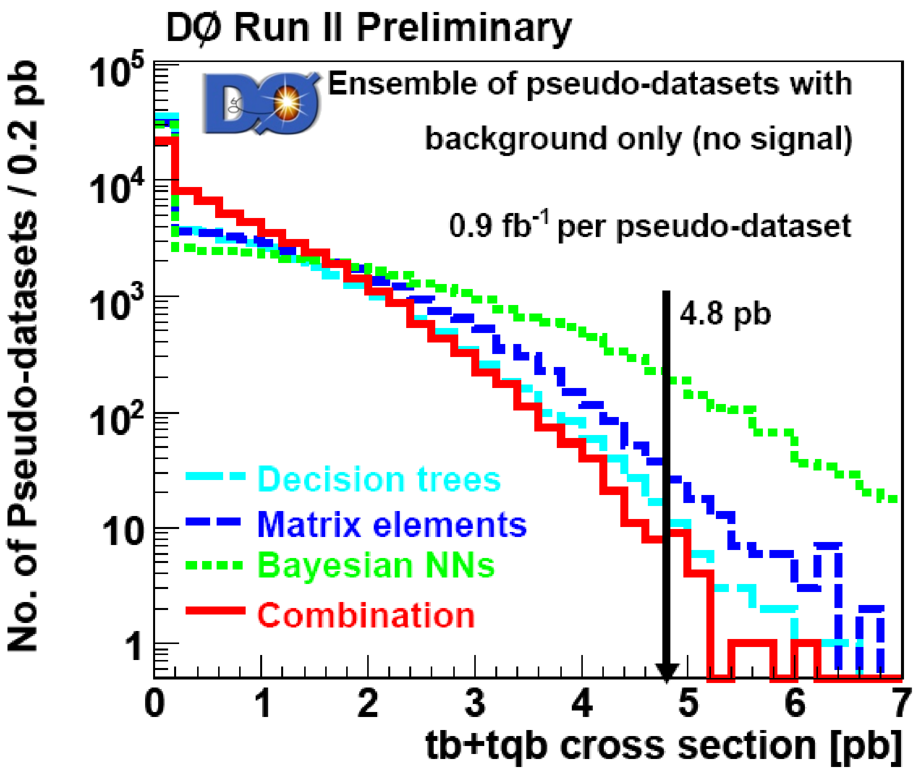
σ(s+t) = 4.8 ± 1.3 pb





Single Top Results



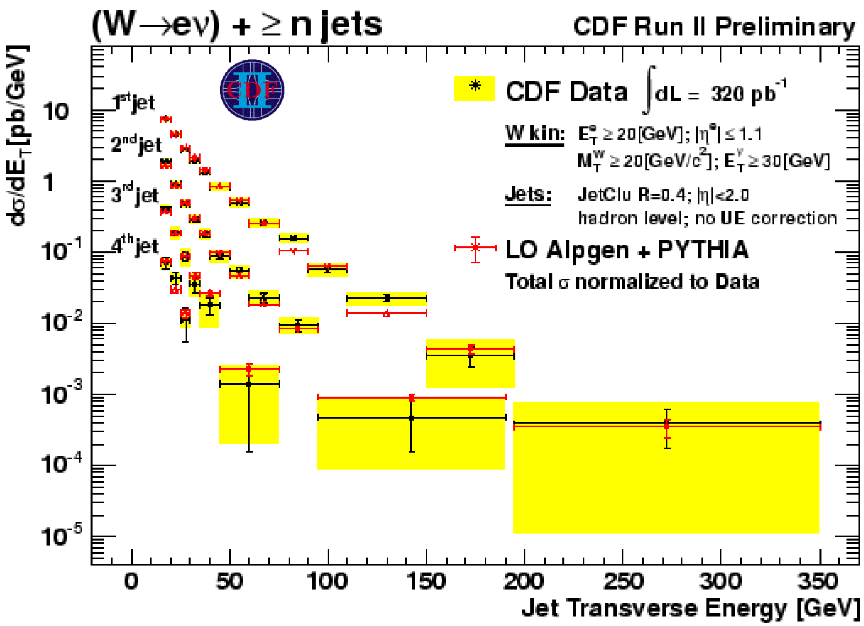


Expected Significance: 2.2σ

Observed Significance: 3.5σ

W+Jets

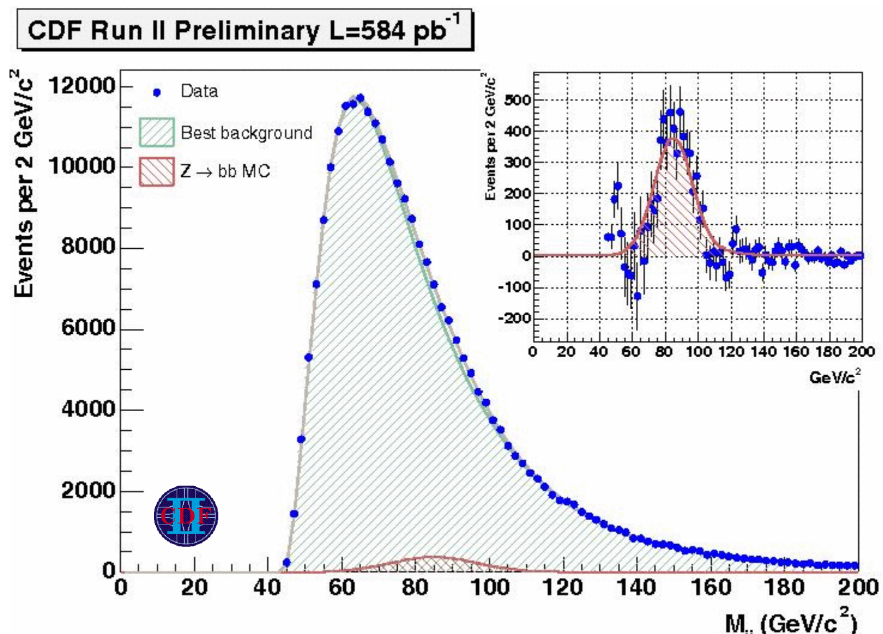
To better top and Higgs searches we have to understand W+Jets and b-quarks at a new level



W+Jets Data comparison ALPJEN

- Normalize each jet multiplicity cross section
- Inspect behavior vs E_T, jet-jet ΔR, jet-jet invariant mass.

Z+Jets Too



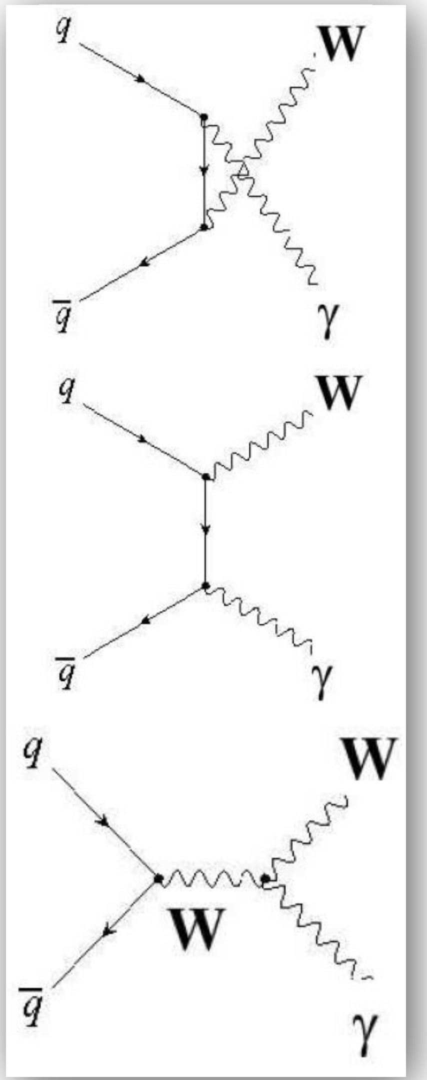
b-jet Energy Scale (in Z→bb events)

- 5674 ± 727 Z→bb events in fit.
- Determine response relative to light quark JES
- Will help with Higgs and with Top

Electro
Weak

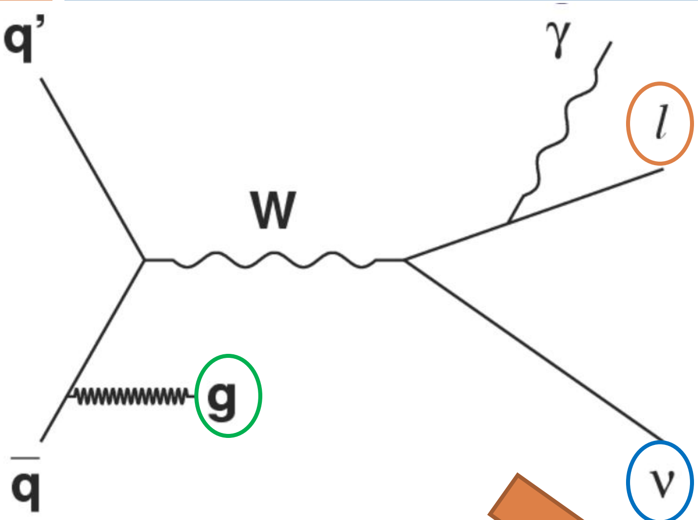
The W and Z Boson

- The W Mass And Width
  - First Run 2 Results!
- Di Boson Production
  - 1 fb^{-1} data sets have given the Tevatron to see WW, WZ, and evidence for ZZ.
  - SM Constraints to hunt for new physics
- $W\gamma$ Production
  - SM Constraints to hunt for new physics

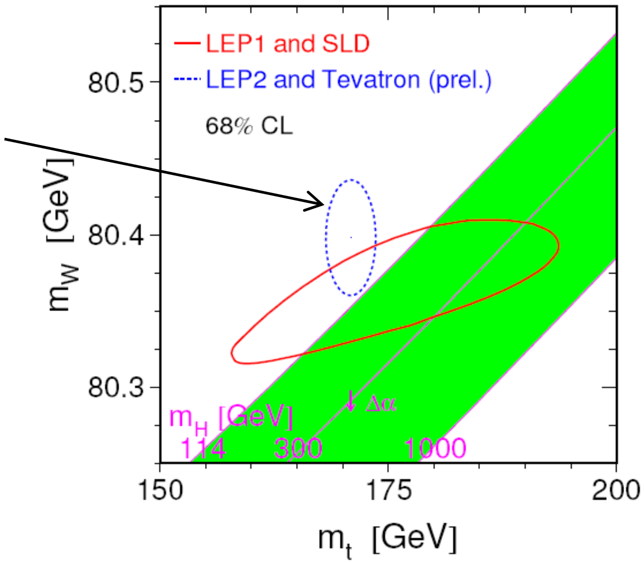


W Mass

Endurance sport!

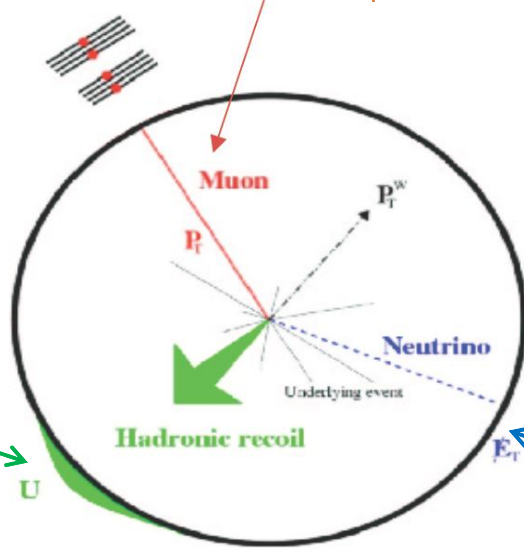


The best way to make progress on M_H constraints is better M_W!



Muon p_T

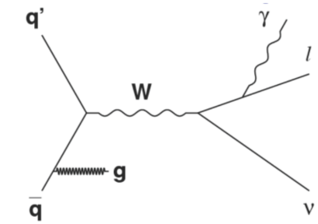
You really have to know everything about the event!



Recoil (< 15 GeV)

Missing E_T

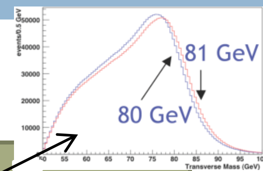
W Mass



RESBOS+WGRAF(NLO)
Fast Simulation
Backgrounds

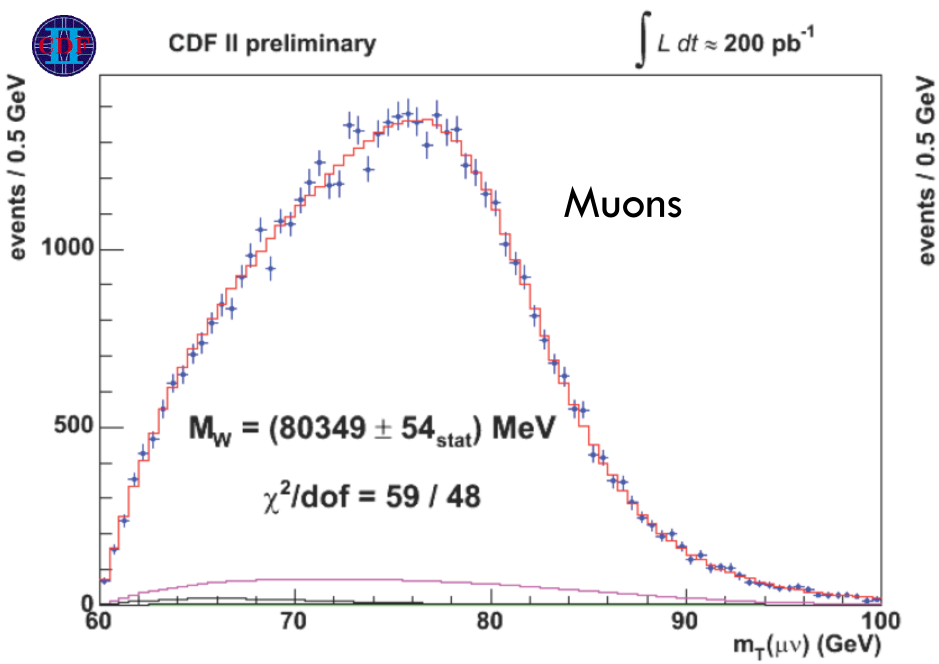
Data
Detector Calibration

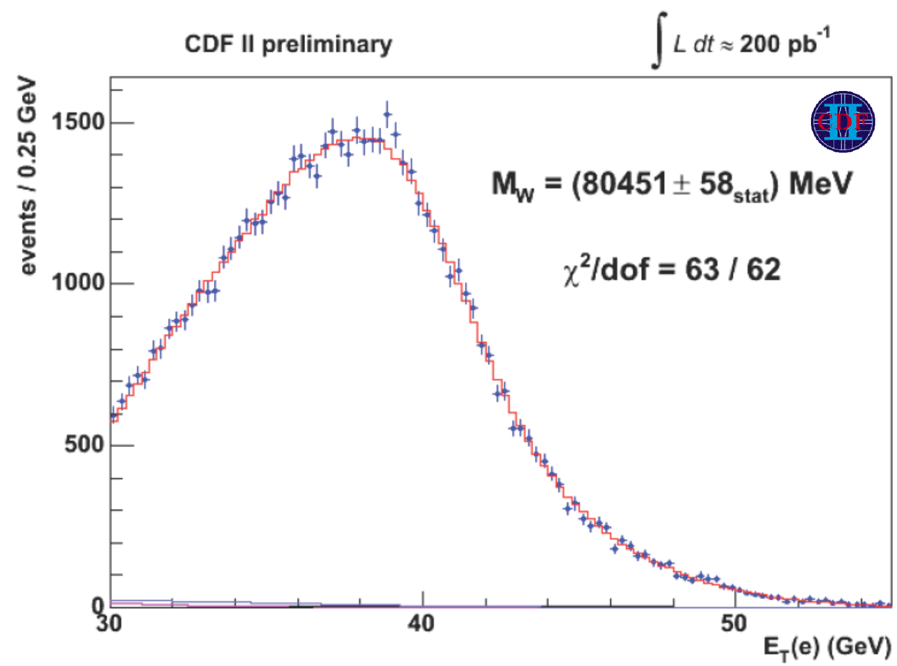
Templates
M_T, E_T, Missing E_T



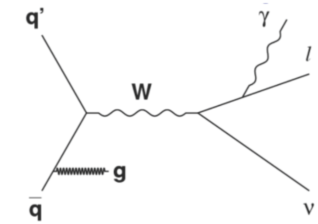
Binned likelihood fit

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





W Mass



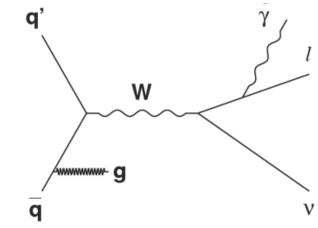
Combined Uncertainty:
± 48 MeV

CDF expects < 25 MeV with data already collected

CDF II preliminary $L = 200\ pb^{-1}$

m_T Uncertainty [MeV]	Electrons	Muons	Common
Lepton Scale	30	17	17
Lepton Resolution	9	3	0
Recoil Scale	9	9	9
Recoil Resolution	7	7	7
$u_{\parallel}$ Efficiency	3	1	0
Lepton Removal	8	5	5
Backgrounds	8	9	0
$p_T(W)$	3	3	3
PDF	11	11	11
QED	11	12	11
Total Systematic	39	27	26
Statistical	48	54	0
Total	62	60	26

W Mass



$M_W = 80.413 \pm 0.048\ \text{GeV}/c^2$

$P(\chi^2) = 44\%$

Effects:

World Average: 80.392 → 80398

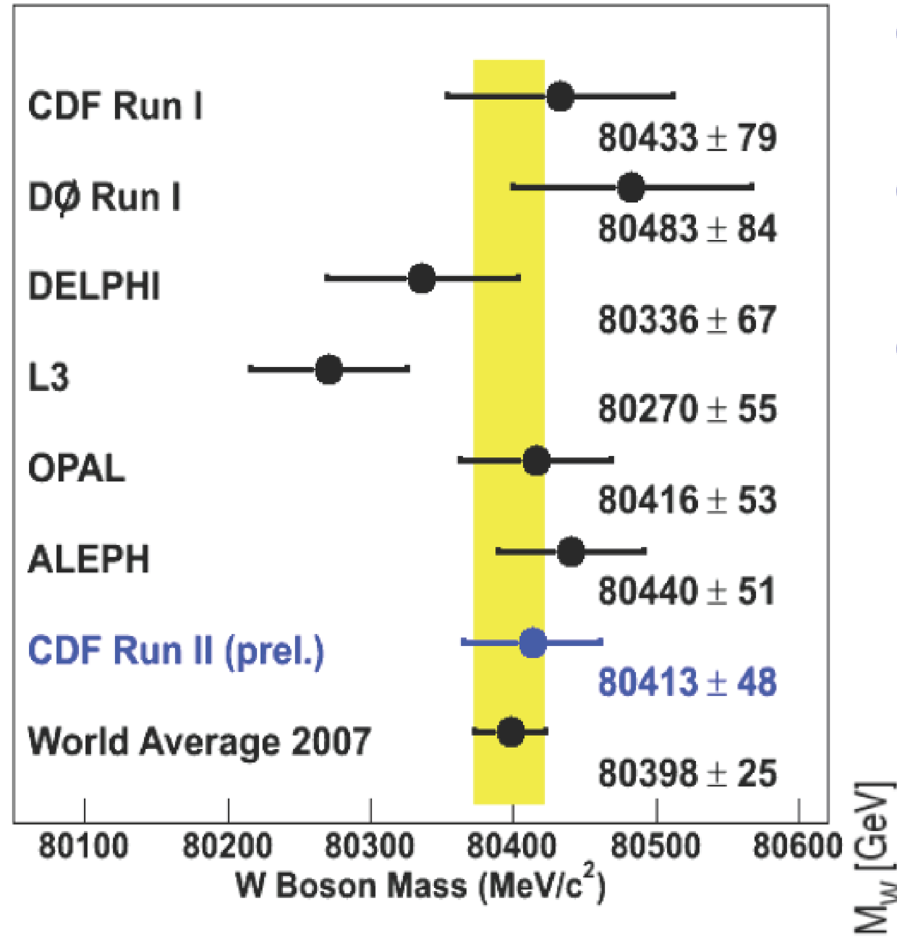
World Uncertainty: 0.029 → 0.025

Higgs: $85^{+39}_{-28} \rightarrow 80^{+36}_{-26}$

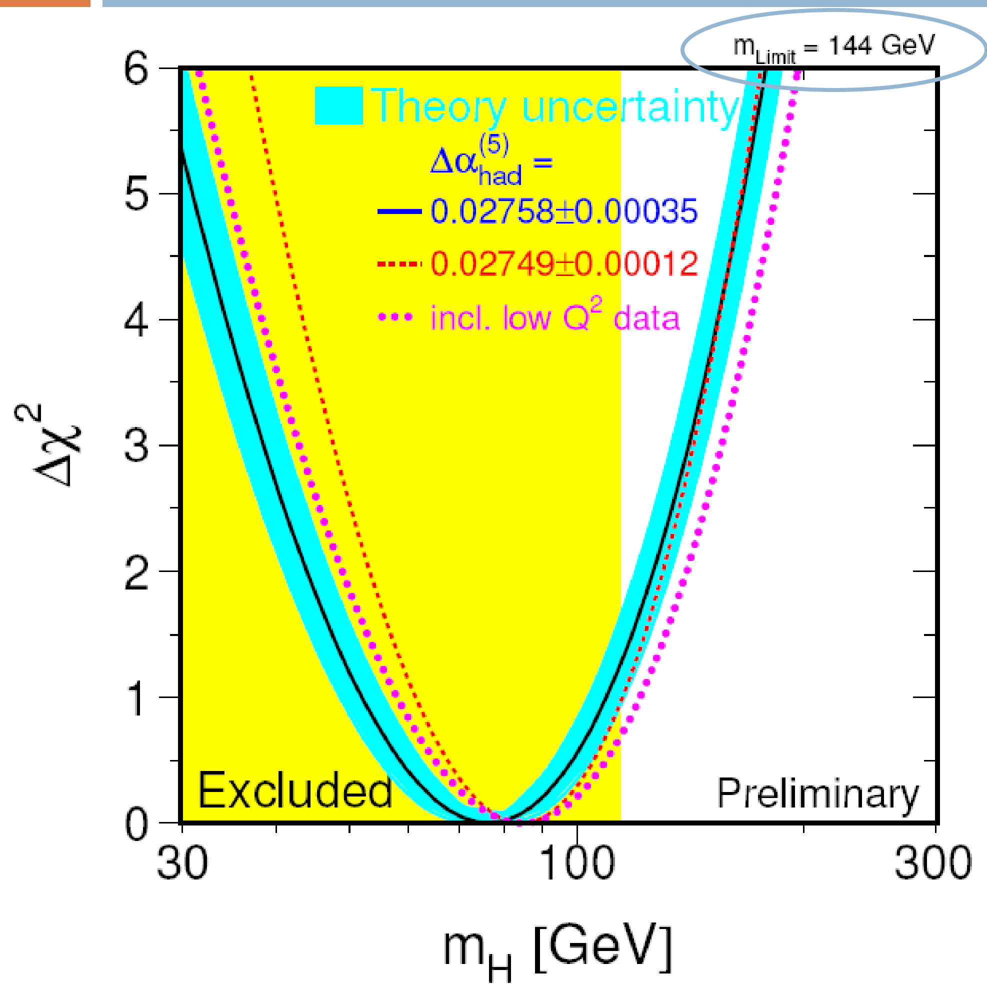
From 200 pb^{-1}!

Best Single Measurement in World!

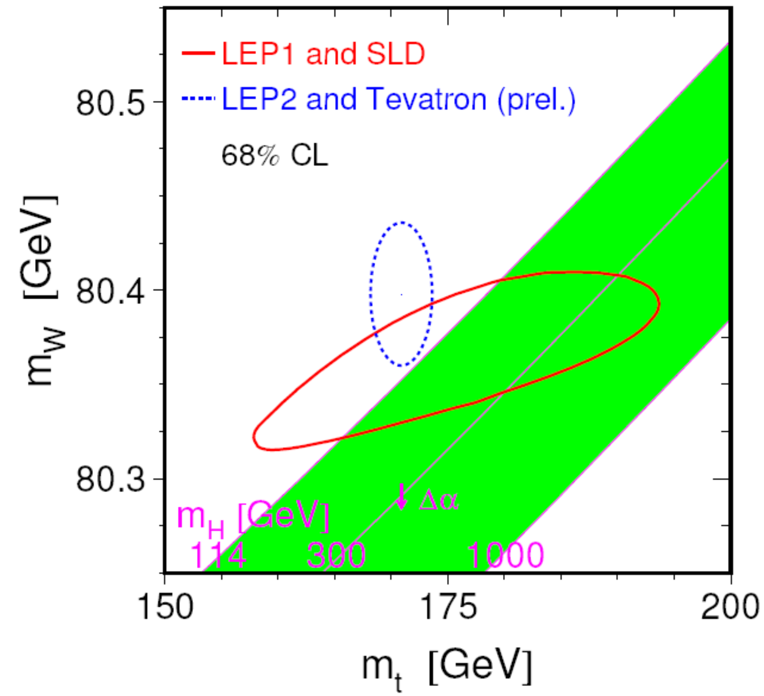
A lot of work ahead!



EWWG Standard Model Fit

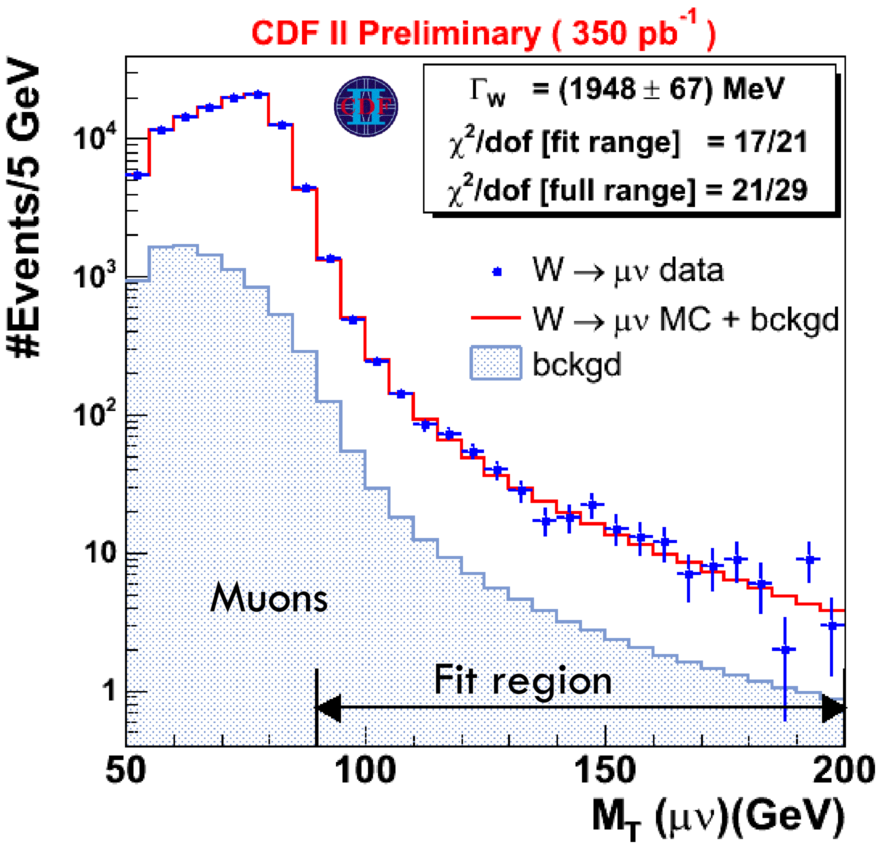


Was 154 last summer!



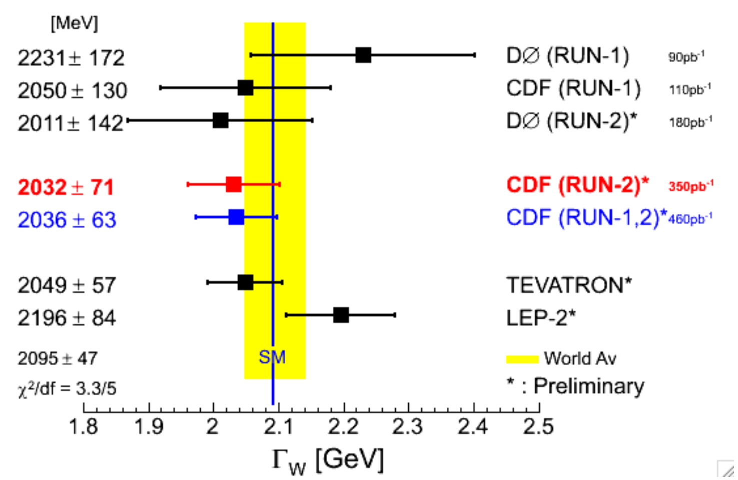
March 2007 Plots

W Width



$\Gamma_W = 2032 \pm 71$ MeV/c^2

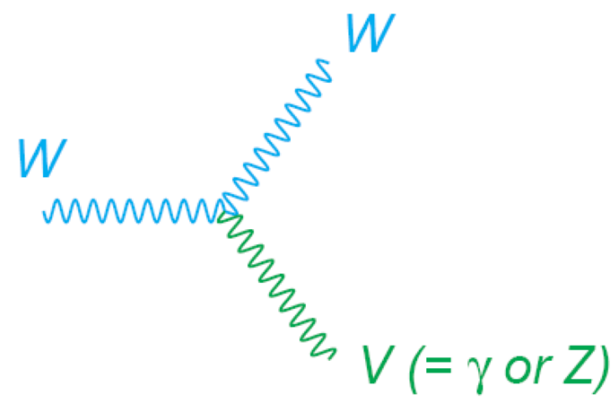
Use same infrastructure as for M_W.
Use fast simulation with different widths
Normalize below fit region

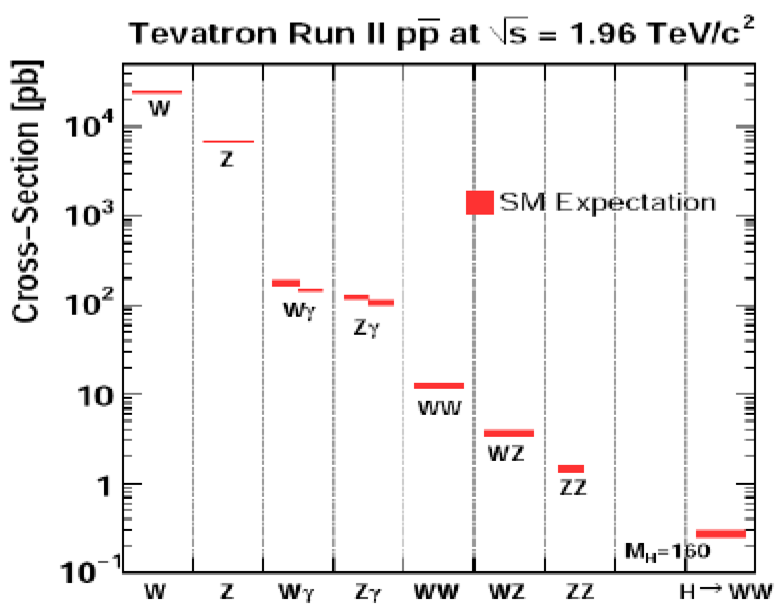


World Average Uncertainty: 60 → 47 MeV/c_2

Di Boson Production

- Triple Gauge Couplings: Non-Abelian structure of the SM
- Tight Limits from Tevatron
  - A few fb^{-1} before we are competitive
  - Complimentary: Higher center of mass, some non LEP couplings available.
- Anomalous Couplings – New Physics
- Backgrounds to SUSY, $H \to WW$, etc..



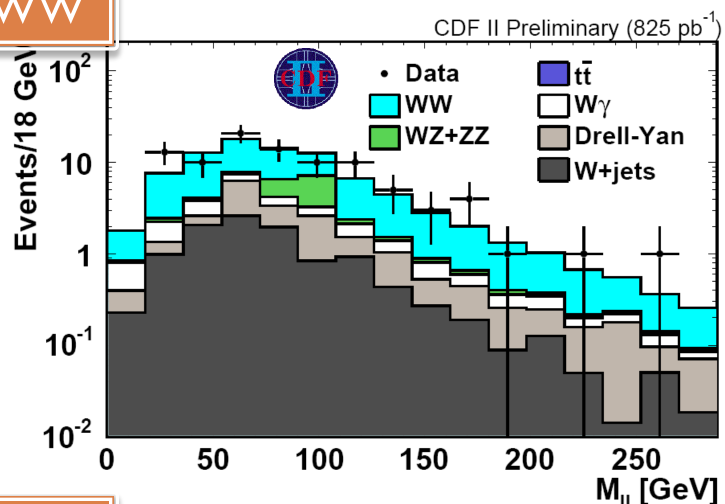


note: this is σ, not $\sigma \times BR$

WW	Observed
WZ	Observed
ZZ	Evidence…

Di Boson Production

WW



CDF: Observe 95 events

expected background of 37 ± 2

825 pb^{-1}

σ(WW)=13.6 ± 2.3(stat) ± 1.6 (sys) ± 1.2 (lumi)

DØ: Observe 25 events

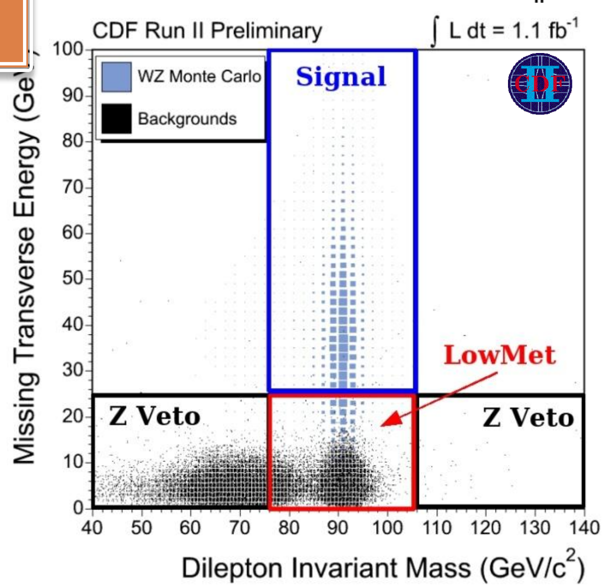
on expected background of 8 ± 0.5

224-252 pb^{-1}

σ(WW)=14.6$^{+5.8}_{-5.1}$(stat)$^{+1.8}_{-3.0}$ (sys) ± 0.9 (lumi)

Good Agreement with NLO: 12.4 ± 0.8 pb

WZ



CDF: Observe 95 events

expected background of 2.7 ± 0.44

1.1 fb^{-1}

6 σ

σ(WZ)=5.0$^{+1.8}_{-1.6}$ pb

DØ: Observe 12 events

on expected background of 3.6 ± 0.20

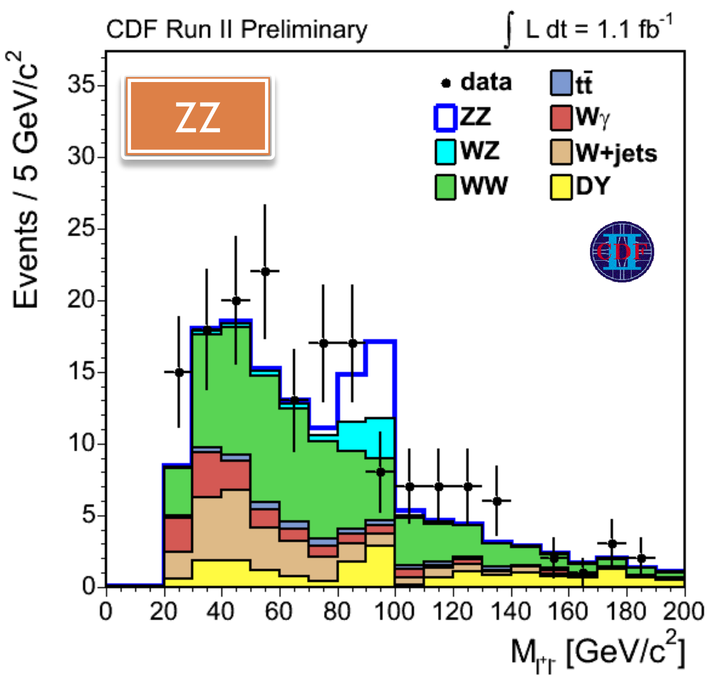
760-860 pb^{-1}

3.3 σ

σ(WZ)=3.9$^{+1.9}_{-1.5}$ pb

Good Agreement with MCFM: 3.68 ± 0.25 pb

Di Boson Production



CDF: Search in both 4 lepton and 2 lepton+2 jet

$\sigma(ZZ) < 2.1$ pb @ 95% CL

$\sigma(ZZ) = 0.8^{+0.7}_{-0.5}$ pb ← **3.0 σ**

DØ: Observe 1 events (4-lepton only)

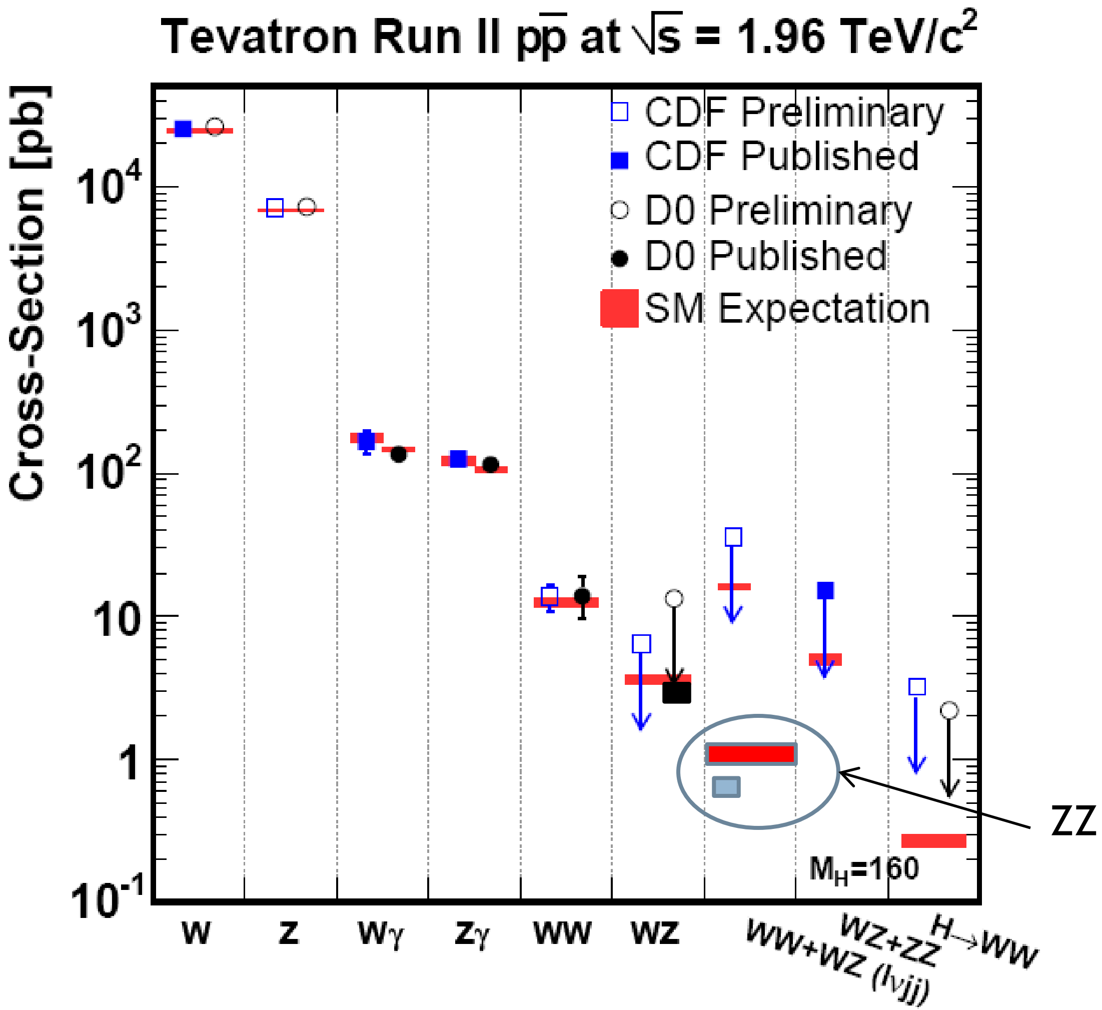
on expected background of 0.17 ± 0.04

224-252 pb^{-1}

$\sigma(ZZ) < 4.3$ pb @ 95% CL

Good Agreement with SM: 1.4 ± 0.1 pb

Di Boson Summary



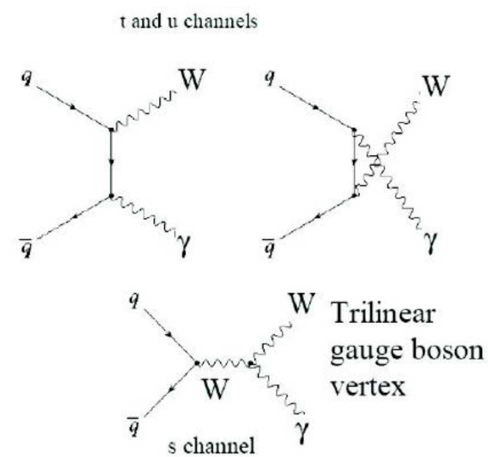
G. Watts (UW)

Wγ Production

Photon acceptance

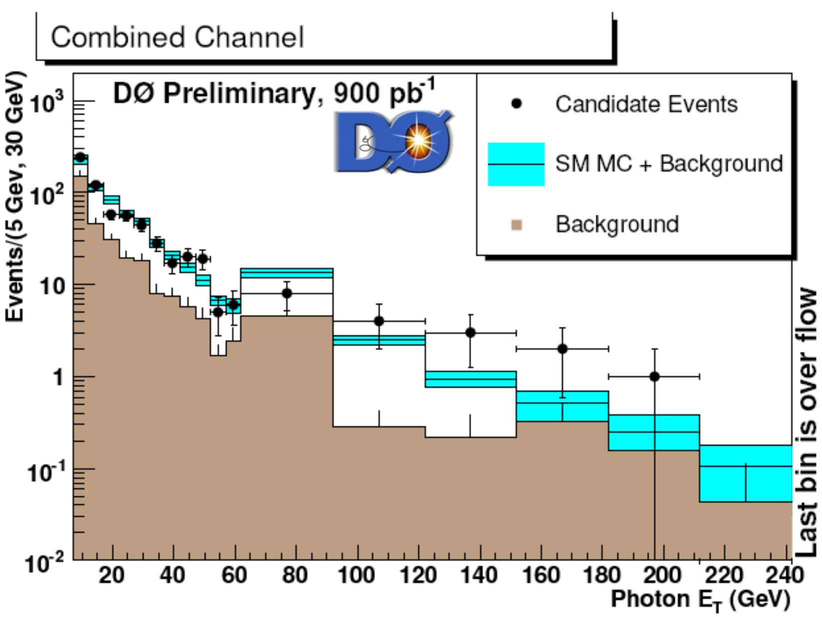
CDF: E_T > 7 GeV, $|\eta|$< 1.1

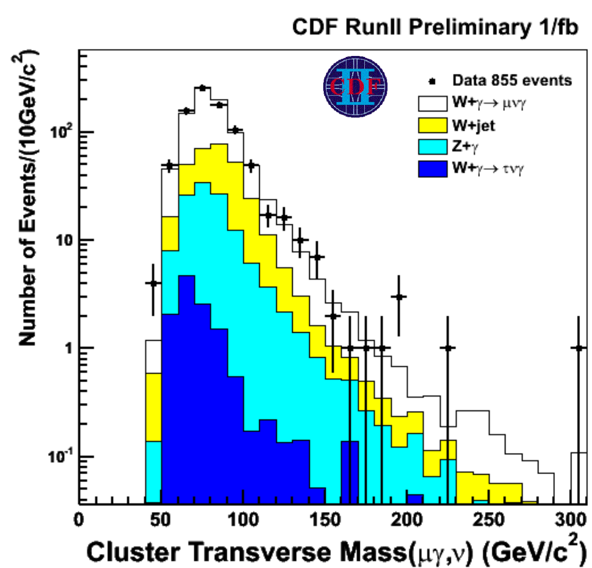
DØ: E_T > 7 GeV, $|\eta|$<1.1 or 1.5<$|\eta|$<2.5



Photon E_T and $M_{W\gamma}$ shapes are in good agreement with predictions!

Sensitive to the WWγ coupling





$W\gamma$ Production

DØ preliminary (0.9 fb^{-1}): $E_T(\gamma) > 7$ GeV , deltaR(l,γ) > 0.7 , $M_T(l\gamma\nu) > 90$ GeV:

muon channel:	$\sigma(p\ pbar \to l\ \nu\ \gamma\ X) = 3.21 \pm 0.49$ (stat+sys) ± 0.19 (lum) pb
electron channel:	$\sigma(p\ pbar \to l\ \nu\ \gamma\ X) = 3.12 \pm 0.49$ (stat+sys) ± 0.20 (lum) pb
theory:	$\sigma(p\ pbar \to l\ \nu\ \gamma\ X) = 3.21 \pm 0.08$ (PDF) pb

CDF preliminary (1.1 fb^{-1}): $E_T(\gamma) > 7$ GeV , deltaR(e,γ) > 0.7 , $30 < M_T(\mu\nu) < 120$ GeV:

muon channel:	$\sigma(p\ pbar \to \mu\ \nu\ \gamma\ X) = 19.11 \pm 1.04$ (stat) ± 2.40 (sys) ± 1.11 (lum) pb
theory:	$\sigma(p\ pbar \to \mu\ \nu\ \gamma\ X) = 19.3 \pm 1.4$ (sys) pb

The Cross Sections are also in good agreement

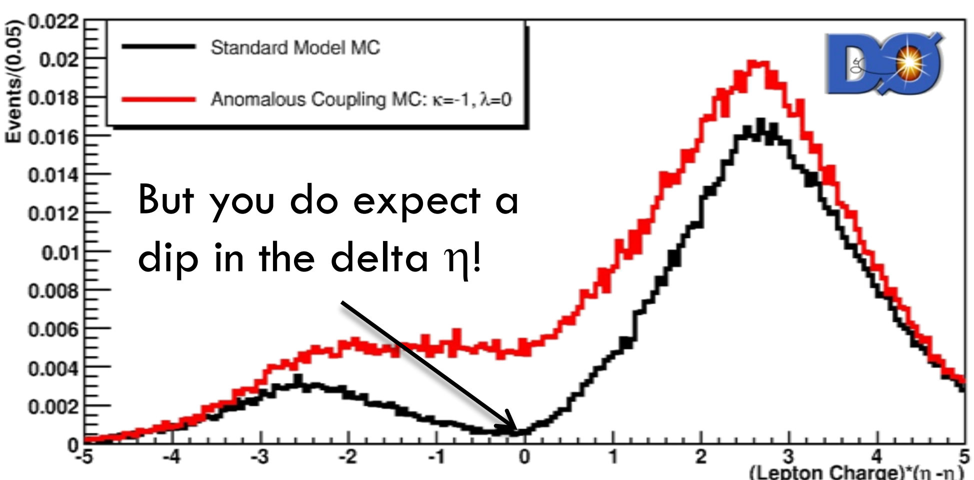
Radiation Amplitude Zero

Three SM Tree Level Wγ diagrams interfere

- Zero production when center of mass angle (θ*) satisfies: $$\cos(\theta^*) = \pm\frac{1}{3}$$

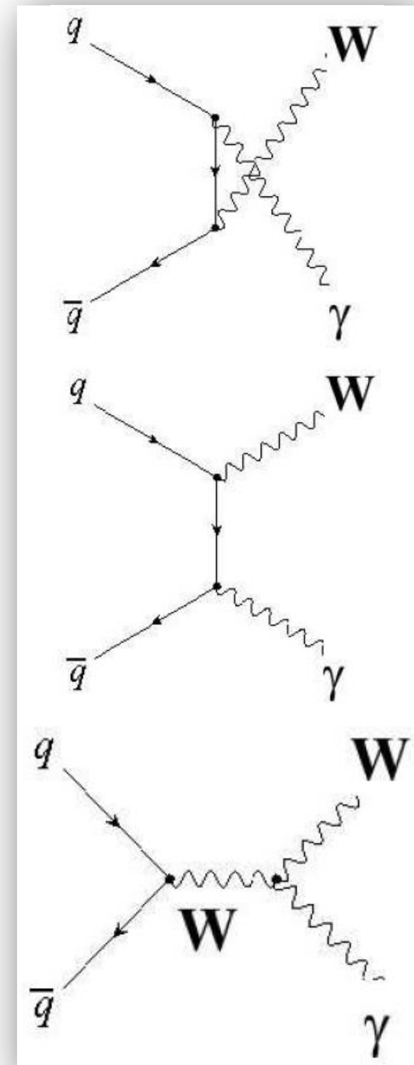
Final state is electron or muon, missing E_T, and a photon

- Don't reconstruct the neutrino 4-vector
  - Usually get two solutions for W's rapidity: can't calculate θ*!

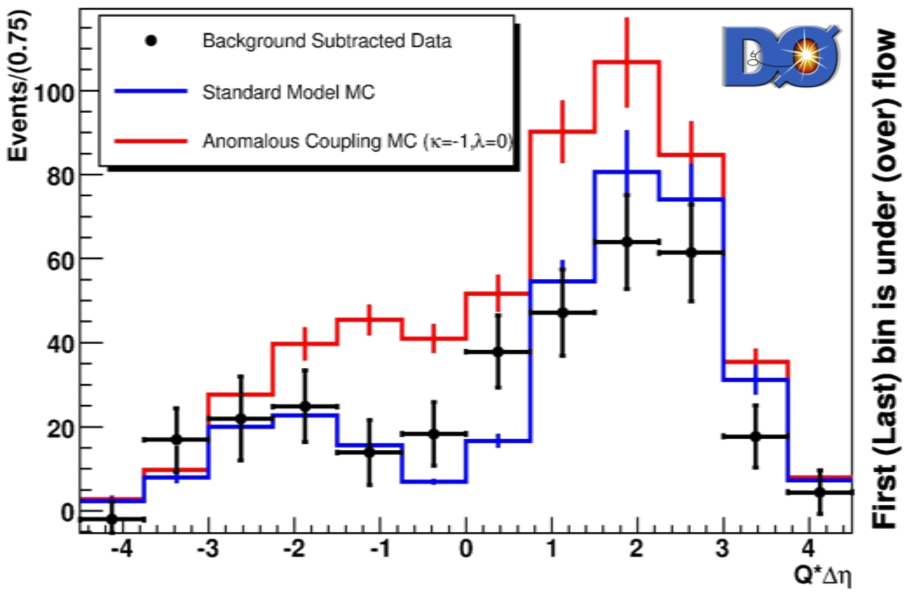


But you do expect a dip in the delta η!

G. Watts (UW)



Radiation Amplitude Zero



$\chi^2 = 16$ (12 dof)

Data is consistent with SM

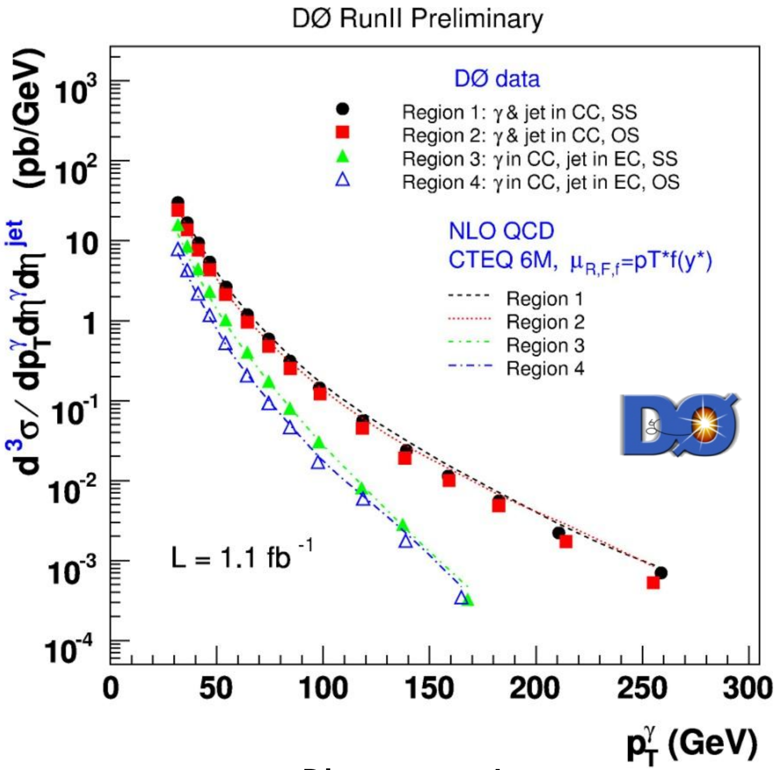
Is the dip real?

- Split distribution into 3 bins
- Calculate probability that unimodal distribution could fluctuate to actual data.
- Dip exists at 90% CL.

QCD

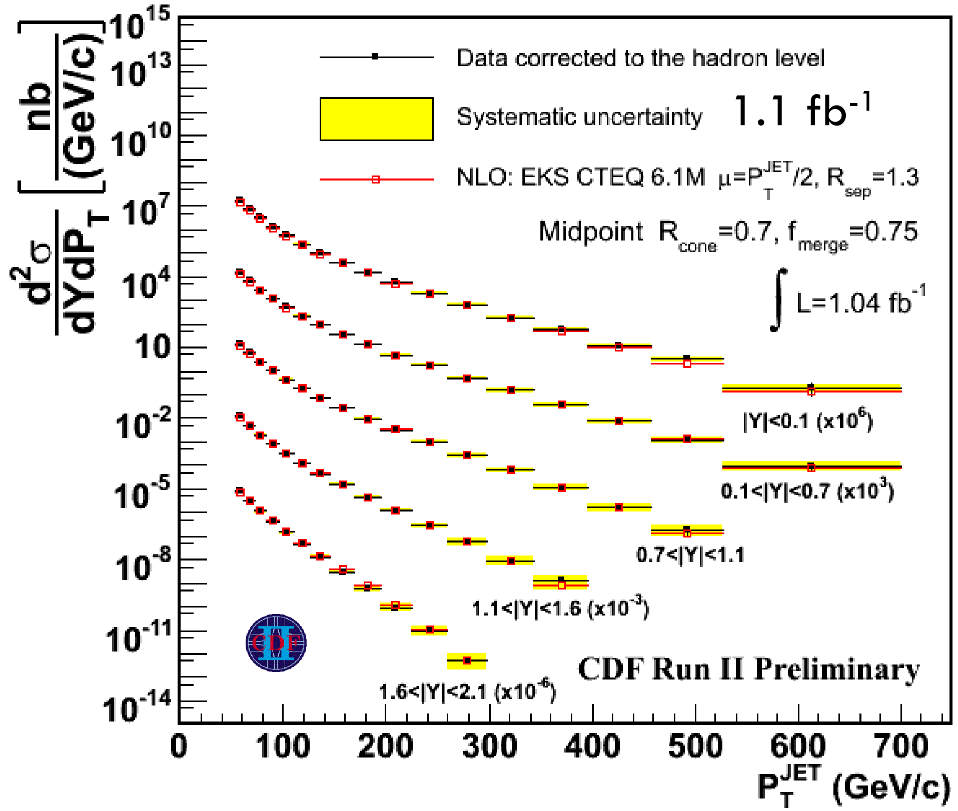
Inclusive Photon and Jet Production

Triple Differential Cross Section



Photon + Jet

Inclusive Jet Production Cross Section



Note Shown: Dijet Cross section from CDF

b-Jet Properties

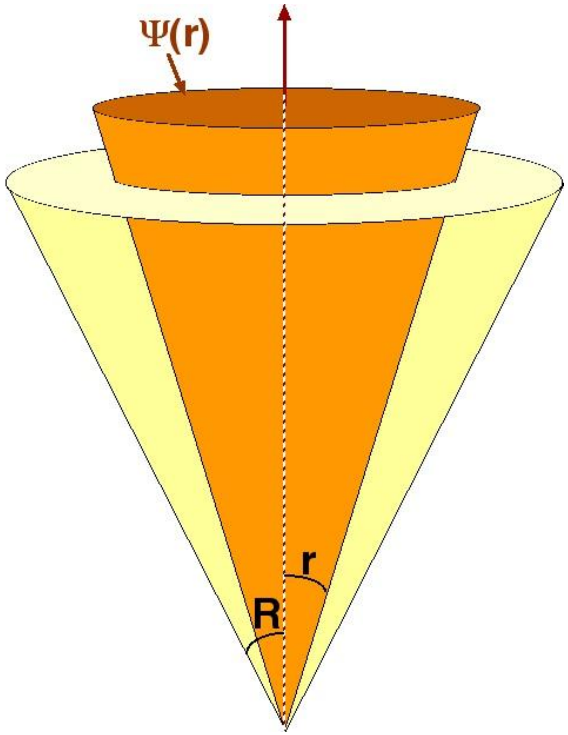
b-jets are backgrounds in top, Higgs, etc.

We tend to study exclusive B decays, not QCD production, however!

- What fraction of jets have 2 b's vs 1 b
- Is the distribution of energy and calorimeter response the same?

$\Psi(r) = p_T^R / p_T$

Profile of energy in the cone



b-Jet Properties

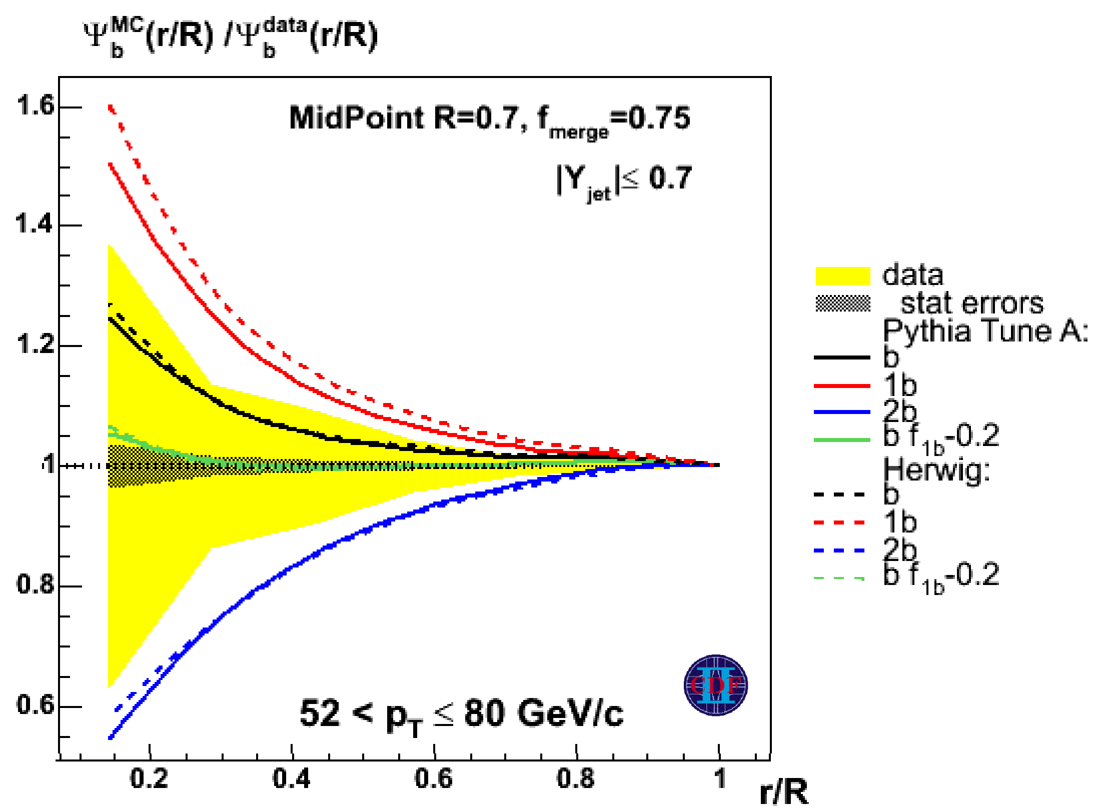
Data/MC Comparison

Correction account for contamination from non-b-jet jets

The fraction of 1-b quark jets vs. 2-b quark jets is different in LO and NLO generation

By adjusting the 1-b jet fraction by 0.2 (vs. what Pythia gave)

Best Fit



CDF has also measured a photon+b-jet production cross section

B Physics

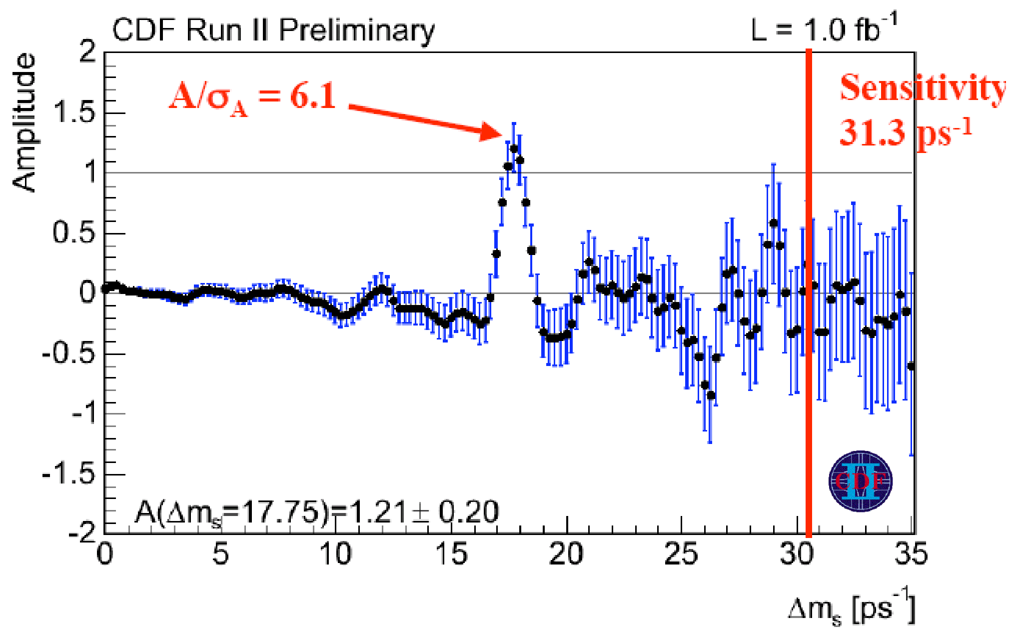
Bottom Introduction

- The Tevatron is a b-factory
  - Both Experiments have an overwhelming number of results!
    - Lifetimes as well as mass measurements!

B_s Mixing

We have measured all the B_s mixing parameters at the Tevatron now!

- Δm_s is consistent with the SM
    - Precision measurement of V_{td}/V_{ts}
- $\Delta\Gamma s$ also consistent with the SM
- Charge Parity Violating phase ϕ_S



$\Delta m_s = 17.77 \pm 0.10$ (stat) ± 0.07 (sys) ps^{-1}

$|V_{td}|/|V_{ts}| = 0.208^{+0.008}_{-0.007}$ (sys + stat)

Good agreement with SM

$\phi_s = -0.70^{+0.47}_{-0.39}$ Still Some Room for New Physics

Σ_b Search

b-Baryons

Λ_b seen

LEP evidence for Ξ_b^0 and $\Xi_b^\pm$

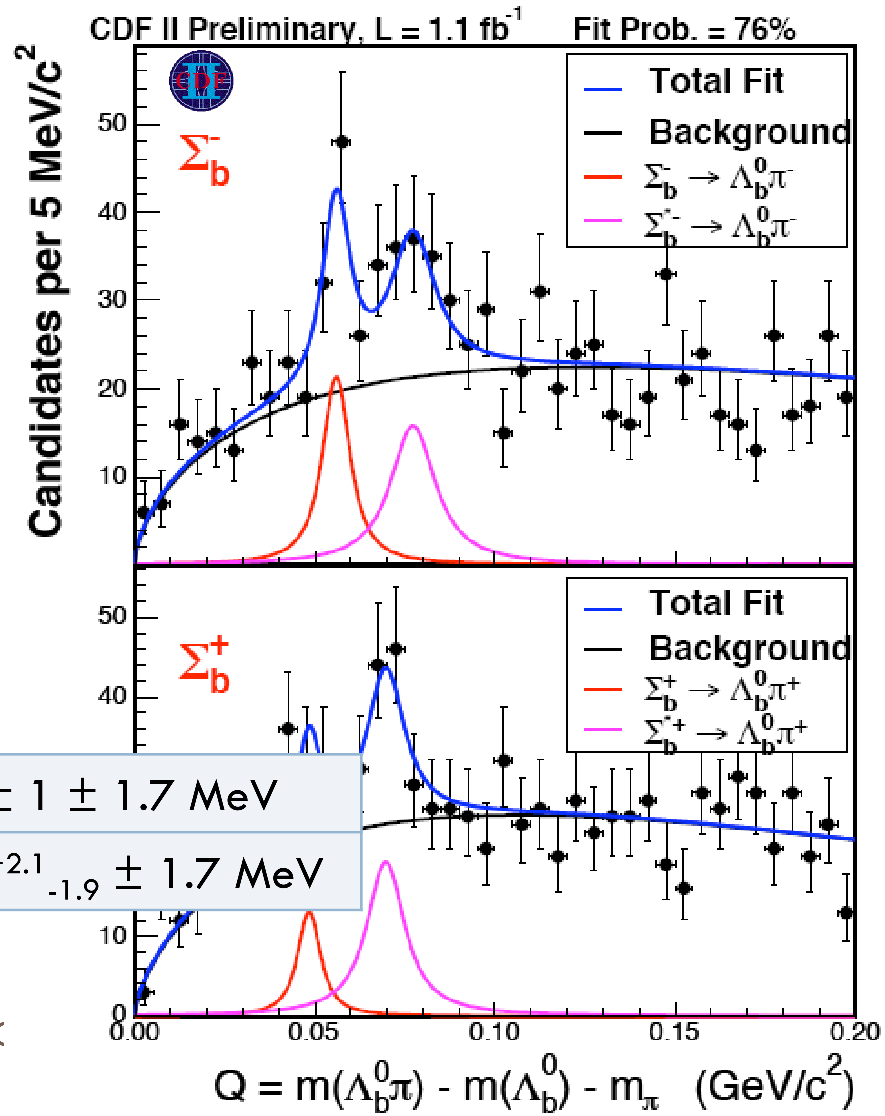
$\Sigma_b^{(*)\pm} \rightarrow \Lambda_b\pi^\pm$

$\Lambda_b \rightarrow \Lambda_c^+\pi^-$

$\Lambda_c^+ \rightarrow pK^-\pi^+$

Fully Hadronic Decay chain!

⇨ Displaced Track Trigger



$m(\Sigma_b^+)=5808^{+2.0}_{-2.3} \pm 1.7$ MeV	$m(\Sigma_b^-)=5816 \pm 1 \pm 1.7$ MeV
$m(\Sigma_b^{*+})=5829^{+1.6}_{-1.8} \pm 1.7$ MeV	$m(\Sigma_b^{*-})=5827^{+2.1}_{-1.9} \pm 1.7$ MeV

Good Agreement with Theory

The B System

Look for Excited B decays:

$$B_1 \rightarrow B^{*+}\pi^-$$
$$B_2^* \rightarrow B^{*+}\pi^-$$
$$B_2^* \rightarrow B^{+}\pi^-$$

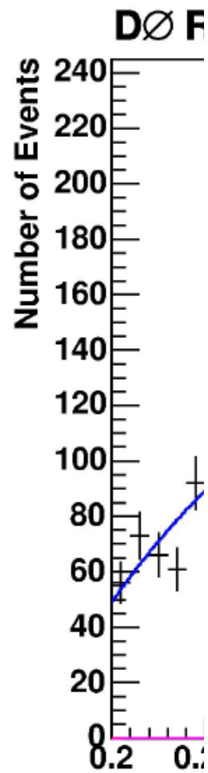
DØ & CDF: $J/\psi K^+$

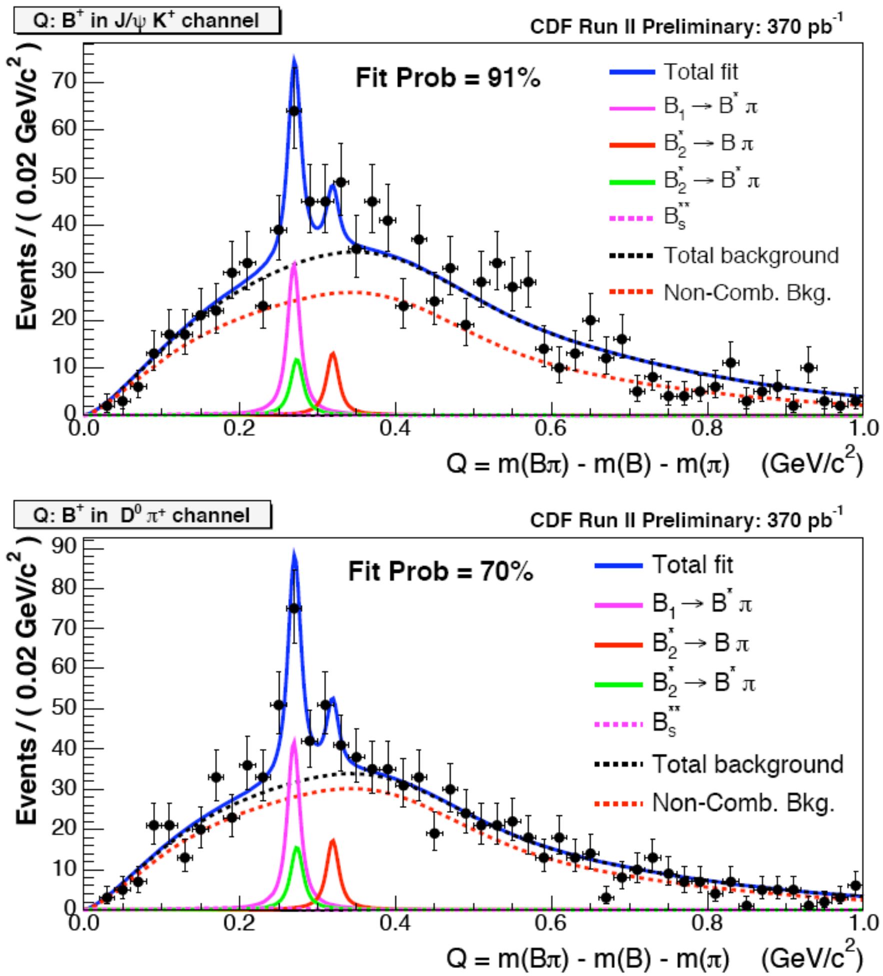
CDF: $D_0\pi^+$

DØ: $\Delta m(B_1 - B_2^*) = 25$ MeV

CDF: $\Delta m(B_1 - B_2^*) = 4$ MeV

Theory: $\Delta m(B_1 - B_2^*) = 14$ MeV





Conclusion

- B_S, M_W, and Single Top were big results this year!
- Experiments almost done updating 1 fb^{-1} results
  - Internally concentrating on 2 fb^{-1} results.
  - Both experiments have new hardware (triggers, Layer 0, etc.) that will increase sensitivity.
  - Increased Luminosity is causing difficulty and making analyses more complex
- Please watch talks in parallel sessions!
- I apologize for all the results I didn't cover