Top Quark Physics

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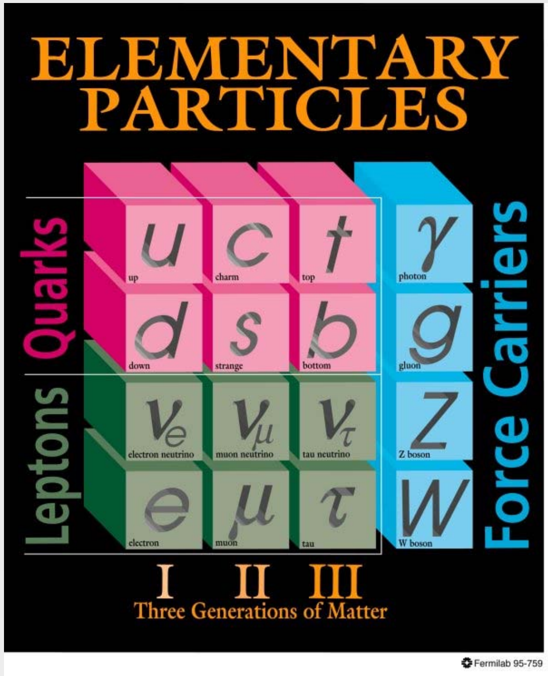
Outline

- Introduction
- Exploring top properties
  - Top quark production
  - Top quark mass
  - Other top properties
    - Forward backward asymmetry, tWb coupling, spin correlation
  - Search for beyond the Standard Model (SM) physics
- Summary and prospects

Top Quark Physics

- Existence required by the SM
  - Spin 1/2 fermion, charge +2/3, weak-isospin partner of the bottom quark
- Discovered in 1995 at Tevatron
- Mass surprisingly large ⇒ ~40x heavier than the bottom quark
  - Only SM fermion with mass at the EW scale
- Top decays before hadronization: Γ~1.4 GeV >>ΛQCD
  - Provide an unique opportunity to study a "bare" quark
- Currently only produced at Tevatron



Why Study Top Properties?

Try to address some of the questions:

- Why is top so heavy ?
- Is top related to the EWSB mechanism?
  - Seesaw theory of EWSB ((PRD 59, 075003 (1999); PRD 65, 055006 (2002)))
- Is it the SM top?
- Search for beyond SM physics: Does top decay into new particles? Couple via new interactions?

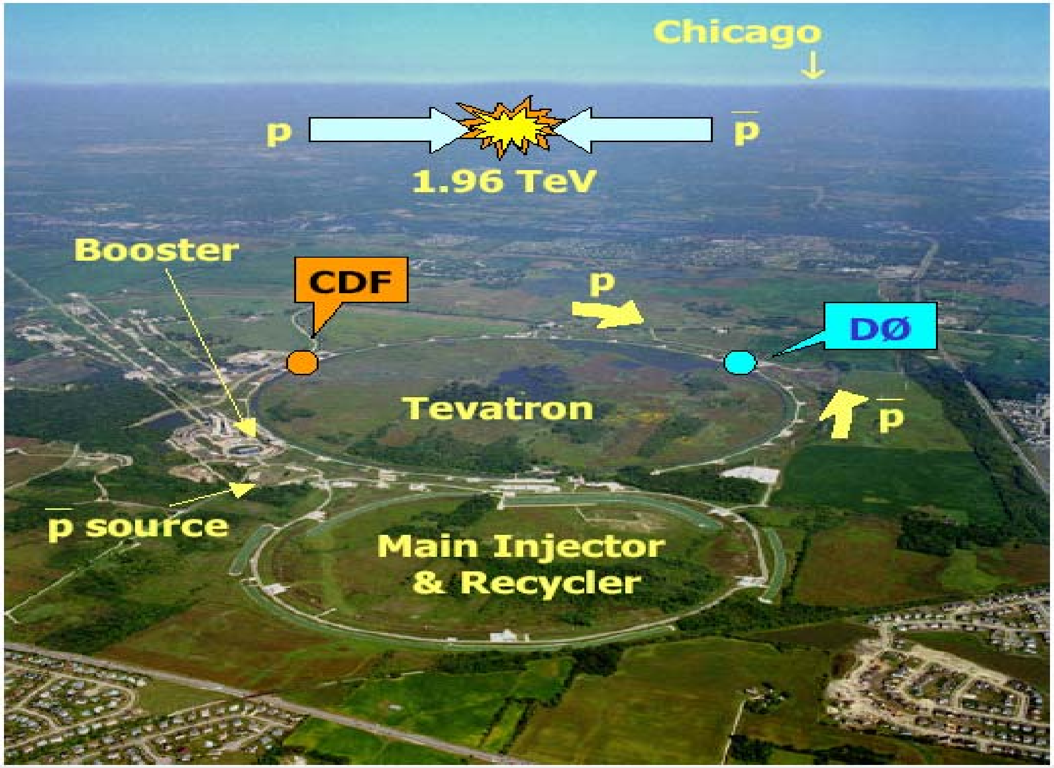
Pair production
- **Cross section**
- **tt resonance search**
- **Forward-backward asymmetry**
- *Production mechanism*
- *Spin-correlations, FCNC,*

EW-single top
- **Cross section**
- **Anomalous coupling**
- *W' search, …*

Decay
- **W helicity**
- **Anomalous couplings**
- *Charged Higgs*

Characteristics
- **Mass**
- *Life-time, Charge, Spin....*

Accelerators



Tevatron Run II

Proton-antiproton collider (2001-2011)

$\sqrt{s}$ = 1.96 TeV

σ_{tt} = ~6.7 pb at m_{top} = 175 GeV/c^2

$\sigma_{single\ top}$ = ~2.9 pb at m_{top} = 175 GeV/c^2

Experiments: CDF, DØ

Large Hadron Collider (LHC)

Proton-proton collider (2009-)

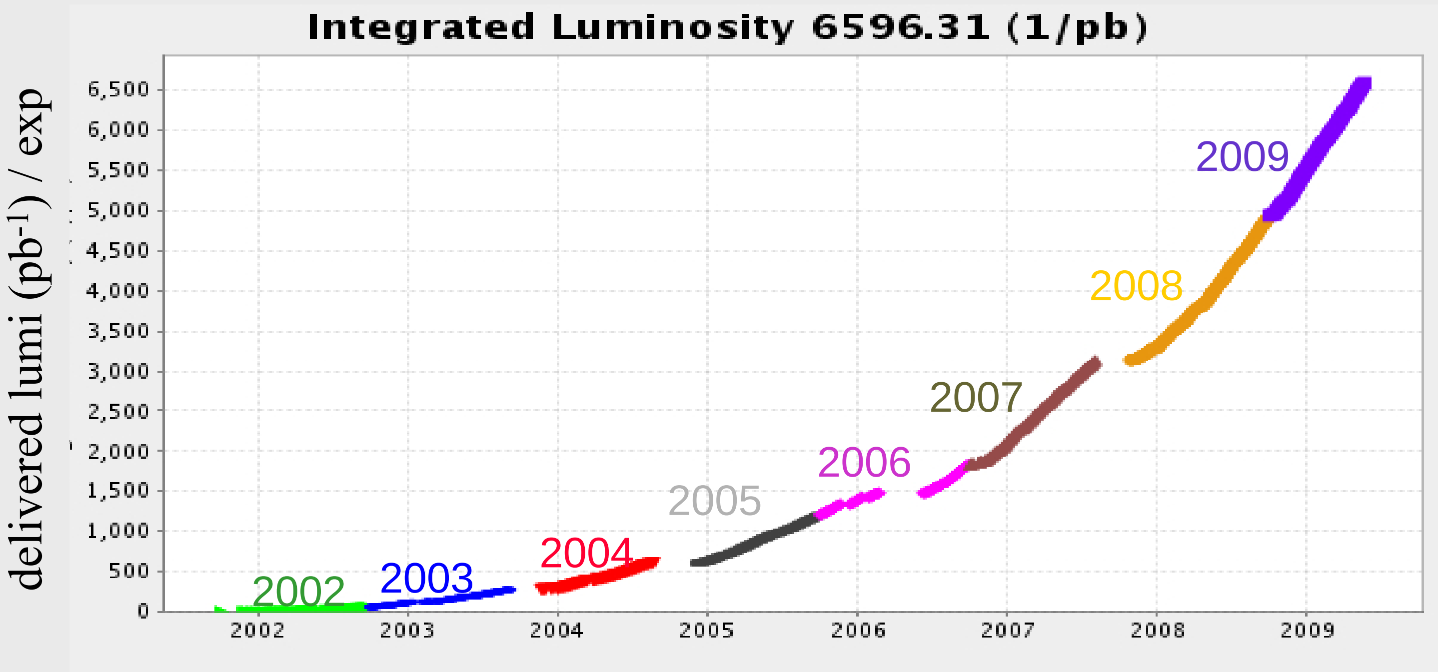
$\sqrt{s}$ = 10-14 TeV

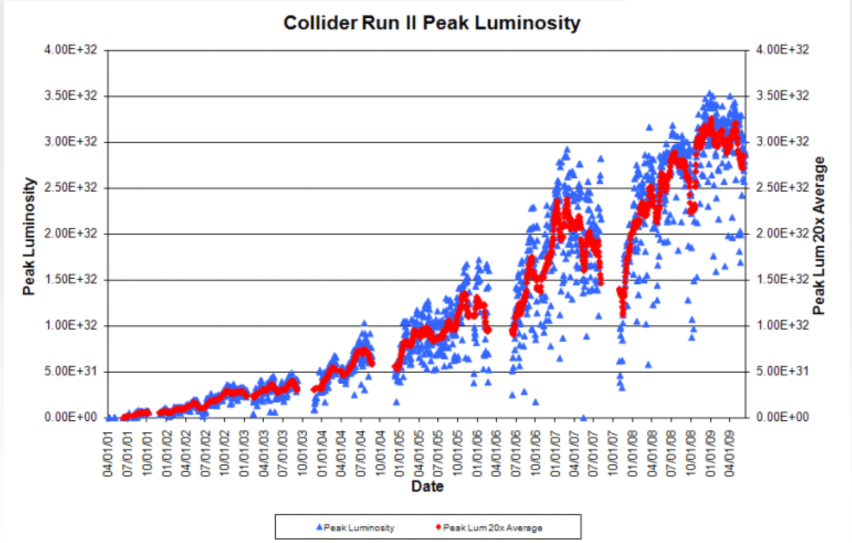
σ_{tt} = ~833 pb at m_{top} = 175 GeV/c^2

$\sigma_{single\ top}$=~315 pb at m_{top} = 175 GeV/c^2

Experiments: ATLAS, CMS

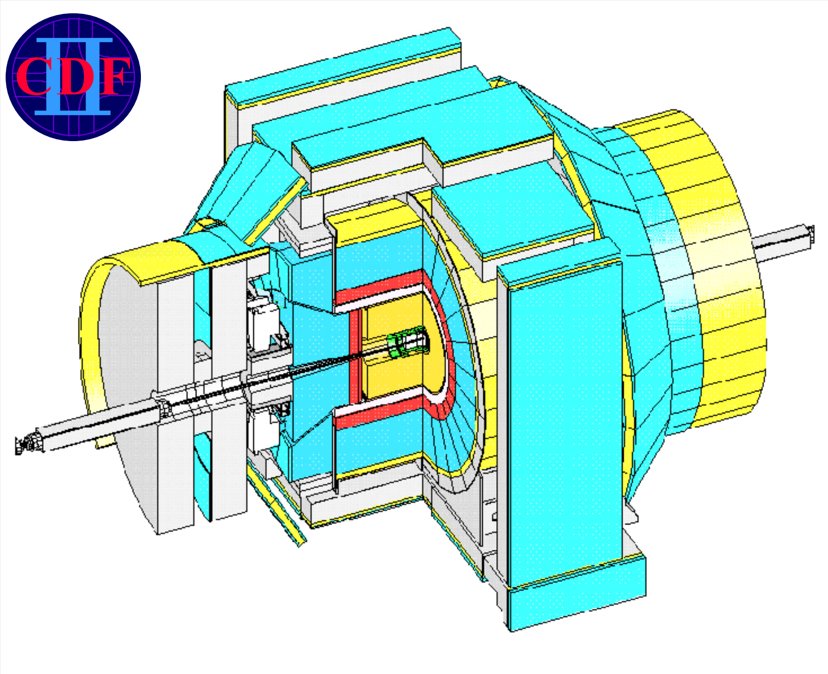
Tevatron Run II Performance

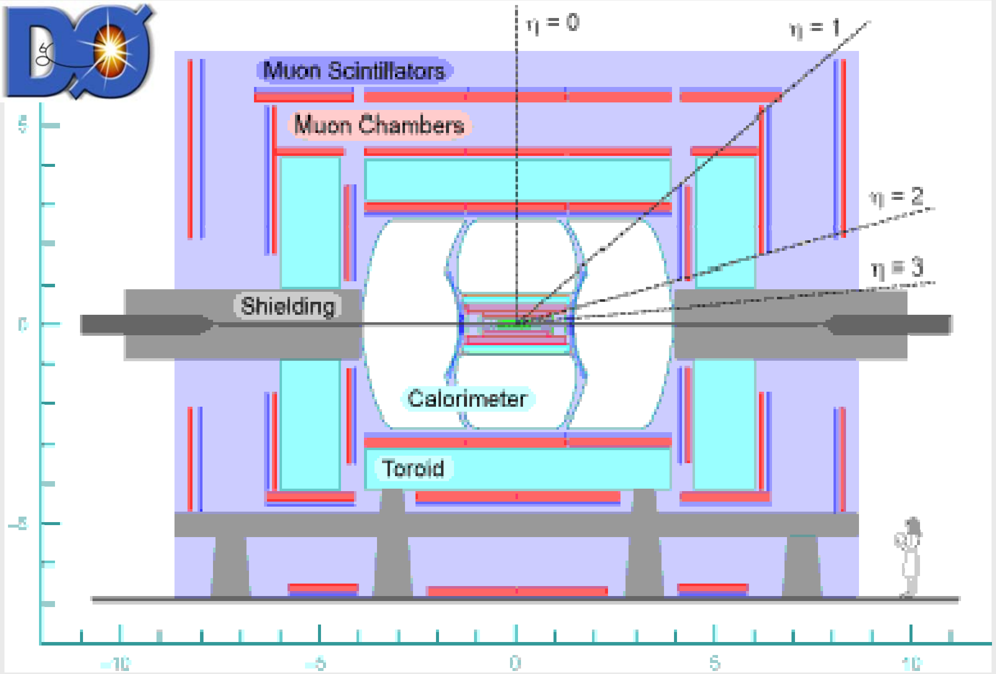




- Doubled data set each year for four years
- Peak Luminosity record $3.18 \cdot 10^{32}$ $cm^{-2}sec$
- Total integrated luminosity delivered ~6.7 fb^{-1}
- ~6 fb^{-1} recorded per experiment

The CDF and DØ Detectors





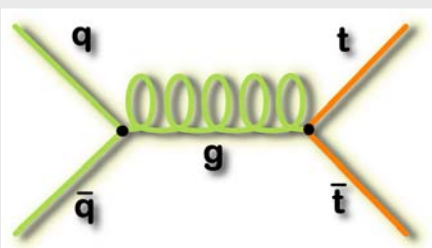
- Silicon tracking
- Large radius drift chamber (r=1.4m)
- 1.4 T solenoid
- Projective calorimetry (|η| < 3.5)
- Muon chambers (|η| < 1.0)
- Particle identification
- Silicon Vertex Trigger

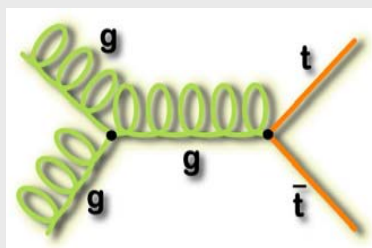
- Silicon tracking
- Outer fiber tracker (r=0.5m)
- 2.0 T solenoid
- Hermetic calorimetry (|η| < 4)
- Muon chambers (|η| < 2.0)
- New trigger and more silicon in Summer 2006 (Run2b)

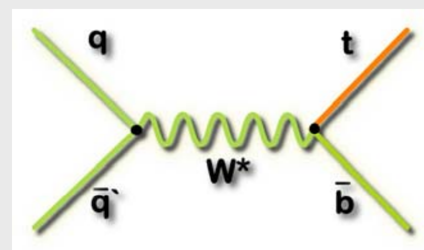
All crucial for top physics!

Top Quark Production

- **At hadron colliders**
  - **Predominantly pair produced via strong interaction**
  - **Electro-weak single top production**

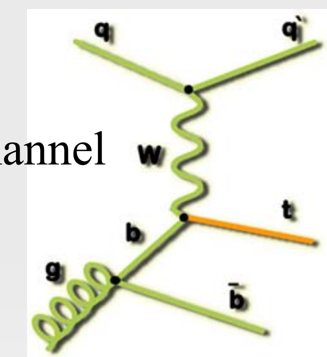






s channel

t channel

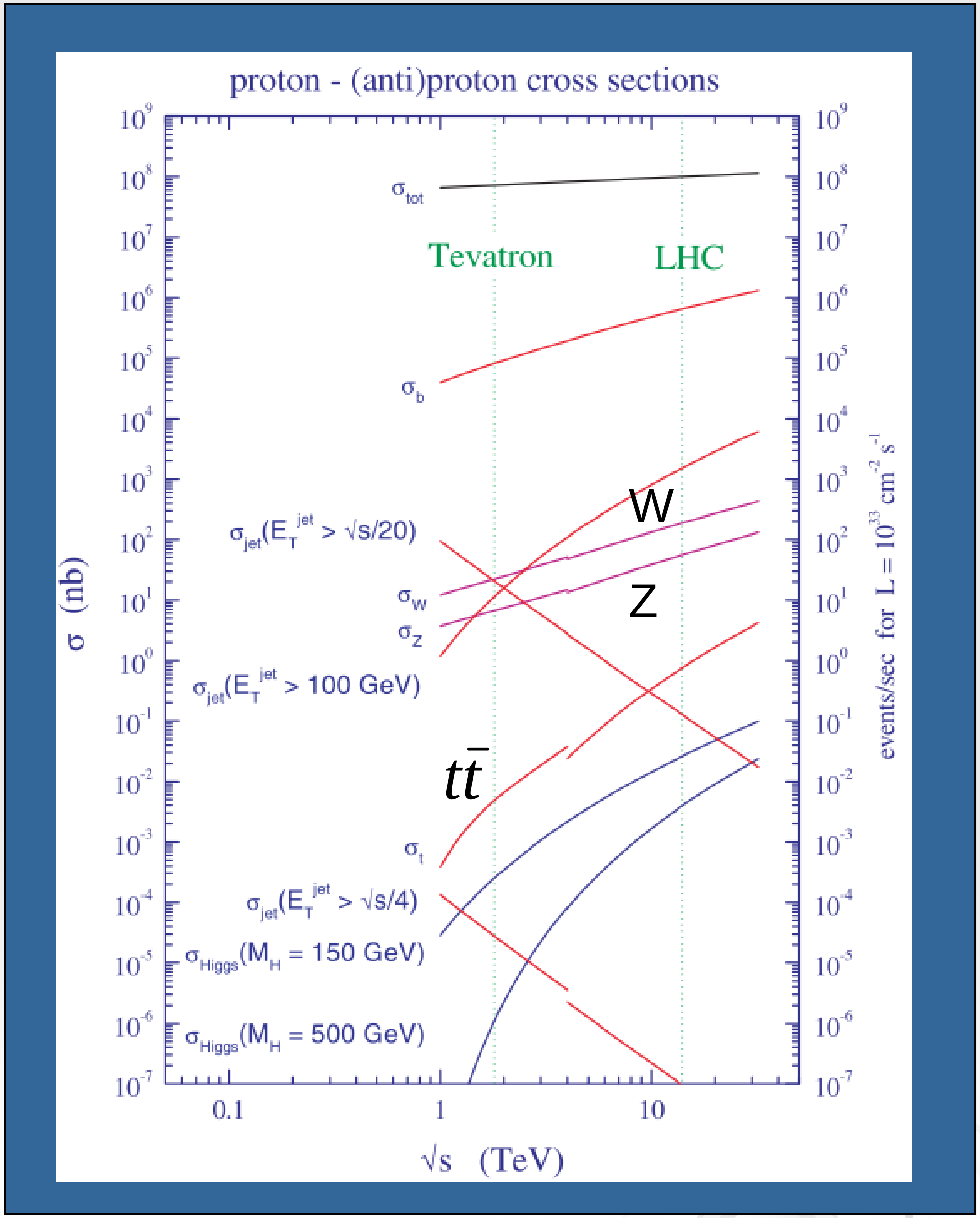


Tevatron ~85% ~15%

Tevatron: $\sigma_{s\text{-}channel}$=0.9 pb, $\sigma_{t\text{-}channel}$=2.0 pb

(for m_{top}=175 GeV/c^2)

Top Quark Production (Cont')

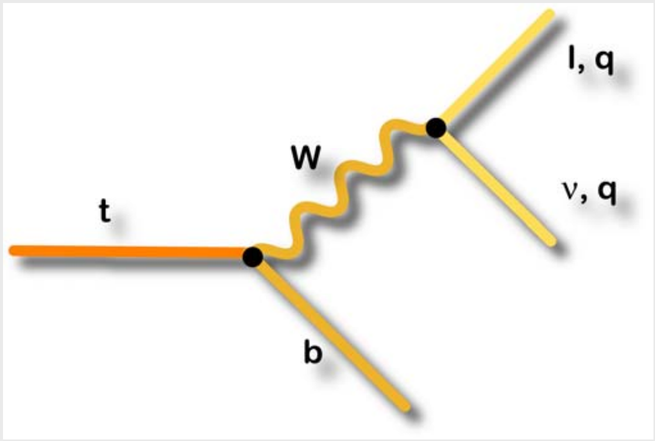


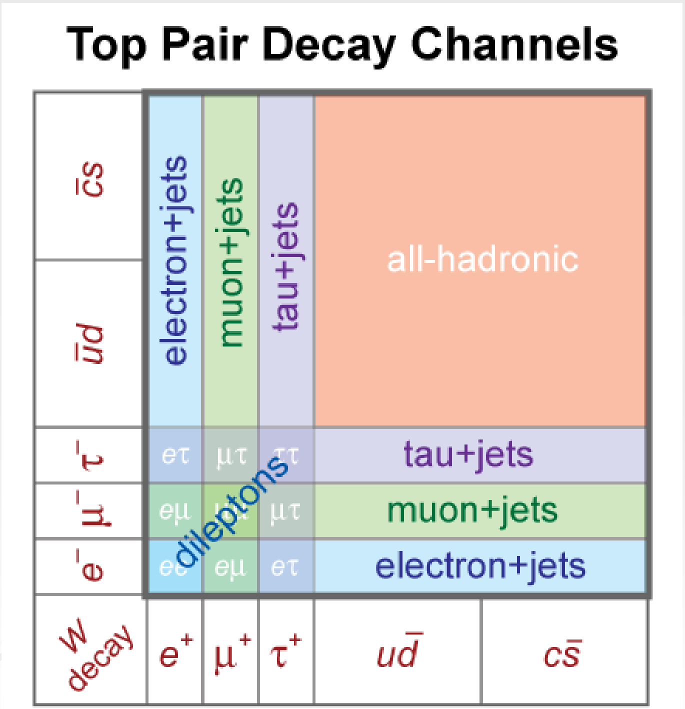
- One top pair per 10 billion inelastic collisions at Tevatron

Top Quark Decay

- In the SM: Br(t →Wb) ~ 100%
- Decay channels classified by W decays
- Top pair decay channels ($l=e,\mu$)
  - Dilepton: $l\nu l\nu bb$
  - Lepton+jets: $l\nu qqbb$
  - All-hadronic: $qqqqbb$
- Single top decay channels
  - s-channel: $tb \to Wbb \to l\nu bb$
  - t-channel: $tq(b) \to Wbq(b) \to l\nu bq(b)$

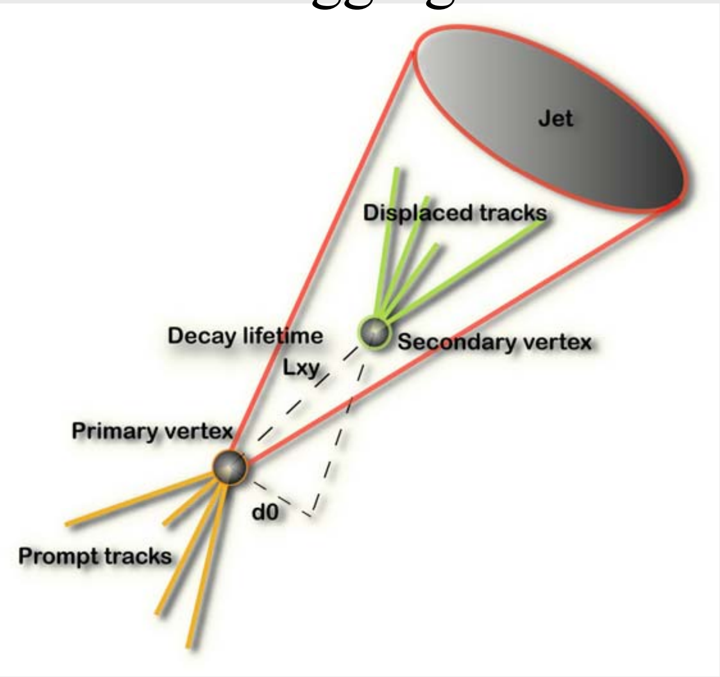
(overwhelming background prevents using hadronic W decays for single top)



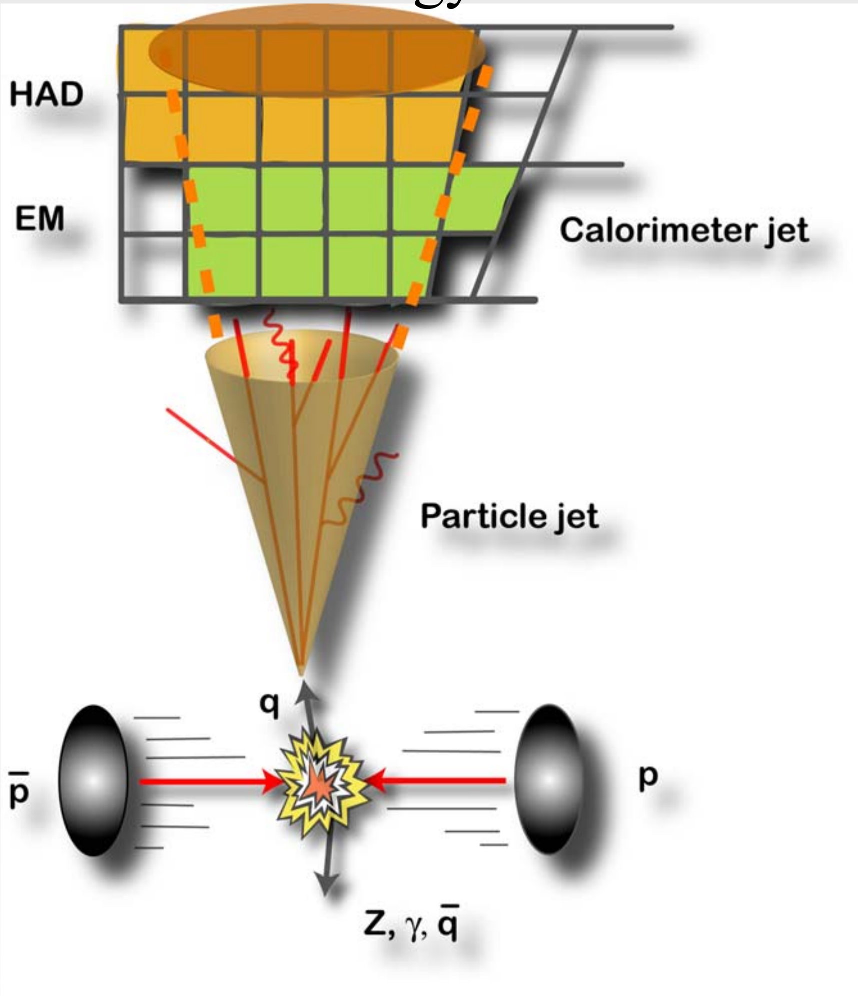


Experimental Challenges

b-tagging



Jet Energy Scale



- And more: background and signal modeling, background estimation, etc.

Signal-to-Background Ratio (S/B)

- b-tagging provides significant background suppression
- Dilepton: Manageable S/B even without b-tagging
- Lepton+Jets: Good S/B after b-tagging
  - Remaining dominant background from W+jets
- All-hadronic: Huge QCD background
  - S/B ~1/1000 at trigger level
  - Needs additional effort for background suppression
    - Neural network (NN) based event selection has been used

<table>
<tr><th>S/B at Tevatron</th><th>Dilepton</th><th>Lepton+Jets (≥4 jets)</th><th>All-hadronic (After NN Selection)</th></tr>
<tr><td>0 b-tag</td><td>1:1</td><td>~1:4</td><td>~1:20</td></tr>
<tr><td>1 b-tag</td><td rowspan="2">20:1</td><td>4:1</td><td>1:5</td></tr>
<tr><td>2 b-tags</td><td>20:1</td><td>1:2</td></tr>
</table>

Most top properties analyses use relatively clean event sample

Top Physics at Tevatron

Robust program of top quark measurements

- Many measurements in all the different channels → consistency
- Different methods of extraction with different sensitivity → confidence
- Combine all channels and all methods → precision

Top Quark Production

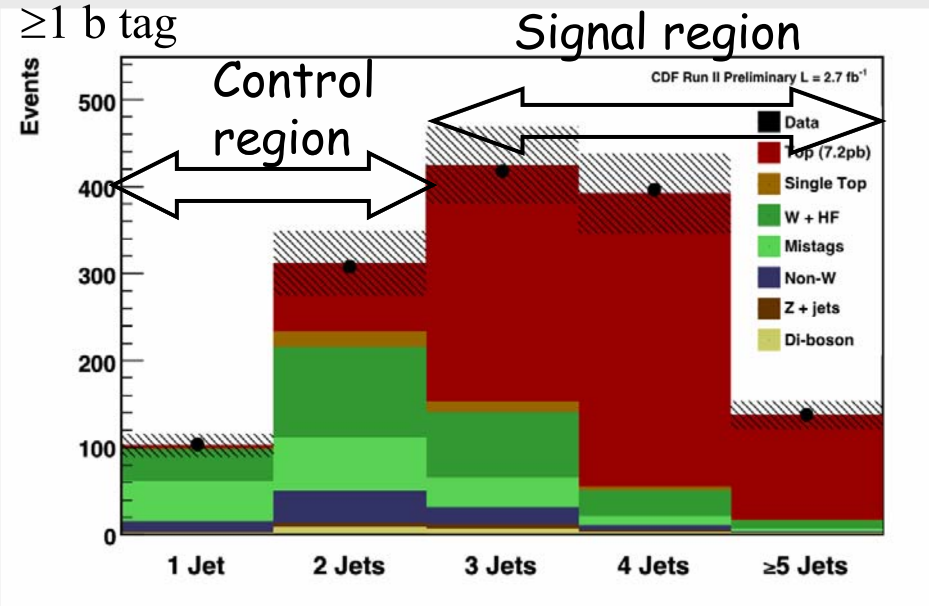
Top pair production cross section

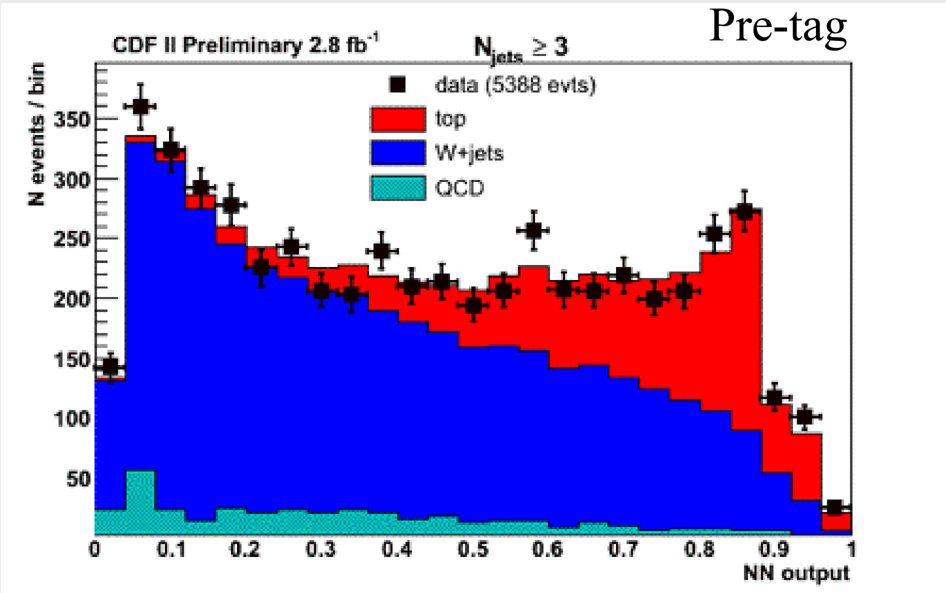
Single top production cross section

Top Pair Production Cross-Section

- Tests QCD in very high Q^2 regime.
- Compare measured cross sections among various ttbar final states
  - Anomalies in the tt rate would indicate the presence of non-QCD production channels: for example resonant state $X \rightarrow$ tt
- Provides important sample composition for all other top property measurements.

ttbar Cross Section : Lepton+Jets





Measure using b-tagged (≥1 b-tags) and pre-tag (≥0 b-tags) events

σ_{tt}(b-tagged)=7.2±0.4(stat)±0.5(syst)±0.4(lumi) pb

σ_{tt} (pre-tag) = 7.1±0.4(stat)±0.4(syst)±0.4(lumi) pb

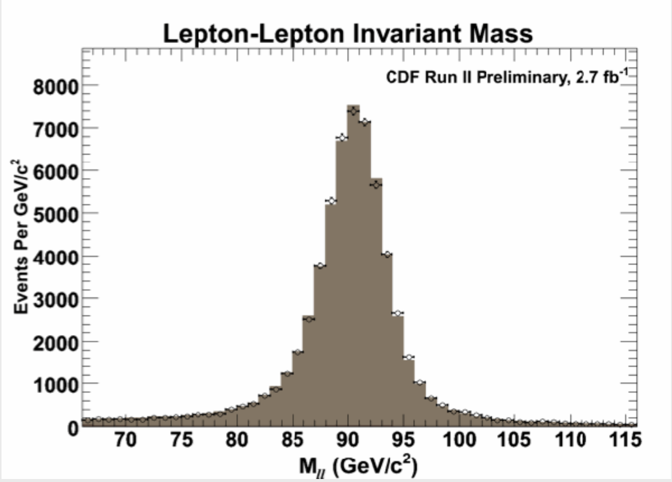
$\Delta\sigma/\sigma$ = ~10 %. Dominated by uncertainty on luminosity

$\sigma_{t\bar{t}} / \sigma_Z$

- Reduce luminosity systematic by normalizing with respect to Z cross section

$$\sigma_{t\bar{t}} = R\sigma^{theory}_{Z\to\ell\ell}, \quad R = \frac{\sigma_{t\bar{t}}}{\sigma_Z}$$

$$\sigma^{theory}_{Z\to\ell\ell} = 251.3 \pm 5.0 \quad pb$$



$$\sigma_{t\bar{t}}\,(\text{pre-tag}) = 7.0\ ^{+0.4}_{-0.4}\,(\text{stat})^{+0.4}_{-0.4}(\text{syst}) \pm 0.4\,(\text{lumi})\,\text{pb}$$

$$\sigma_Z = 253.3 \pm 1.0(\text{stat})\ ^{+4.4}_{-4.6}\ (\text{syst})^{+16.6}_{-13.7}\ (\text{lumi})\ \text{pb}$$

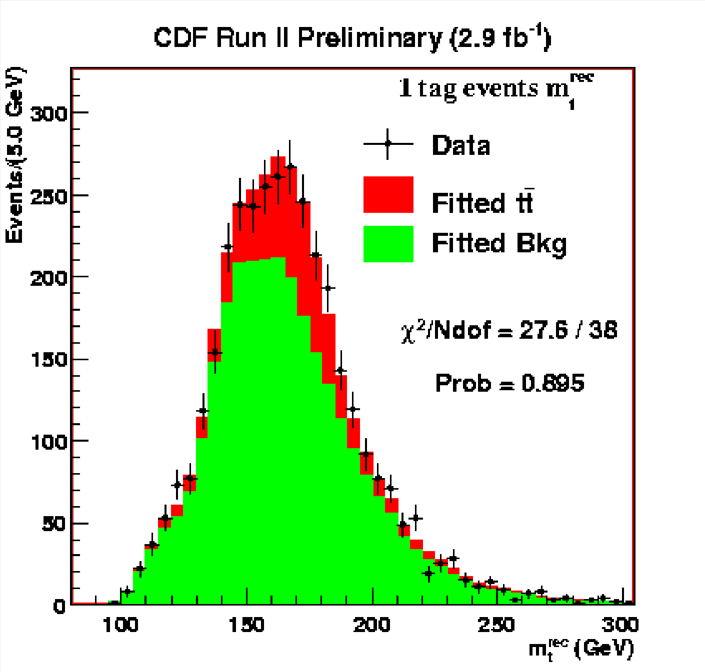
$$\frac{1}{R} = 36.5\ ^{+2.1}_{-2.3}\ (\text{stat})^{+1.9}_{-2.0}(\text{syst})$$

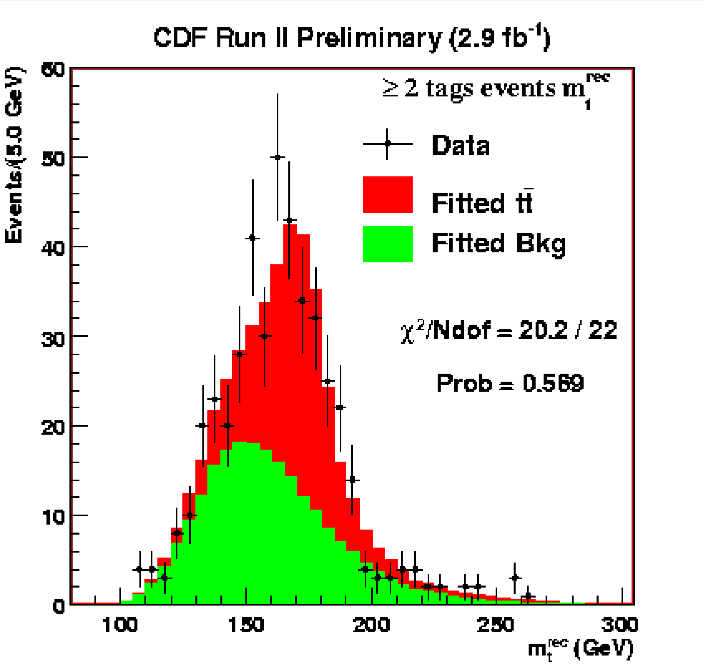
$$\sigma_{t\bar{t}}\,(\text{pre-tag}) = 6.9 \pm 0.4\,(\text{stat}) \pm 0.4(\text{syst}) \pm 0.1\,(\text{theory})\,\text{pb}, \quad \Delta\sigma_{t\bar{t}} / \sigma_{t\bar{t}} =\sim 8\%$$

$$\sigma_{t\bar{t}}(b-tagged) = 7.0 \pm 0.4(\text{stat}) \pm 0.6(\text{syst}) \pm 0.1(\text{theory})$$

All-Hadronic Channels

Measurement performed using the signal yields derived from a previous top quark mass measurement

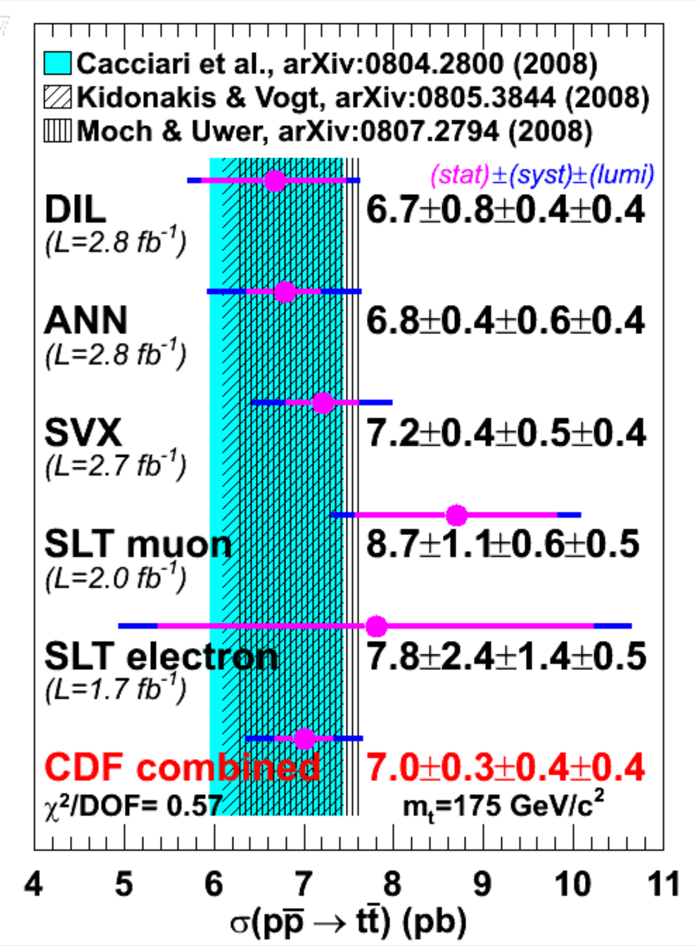


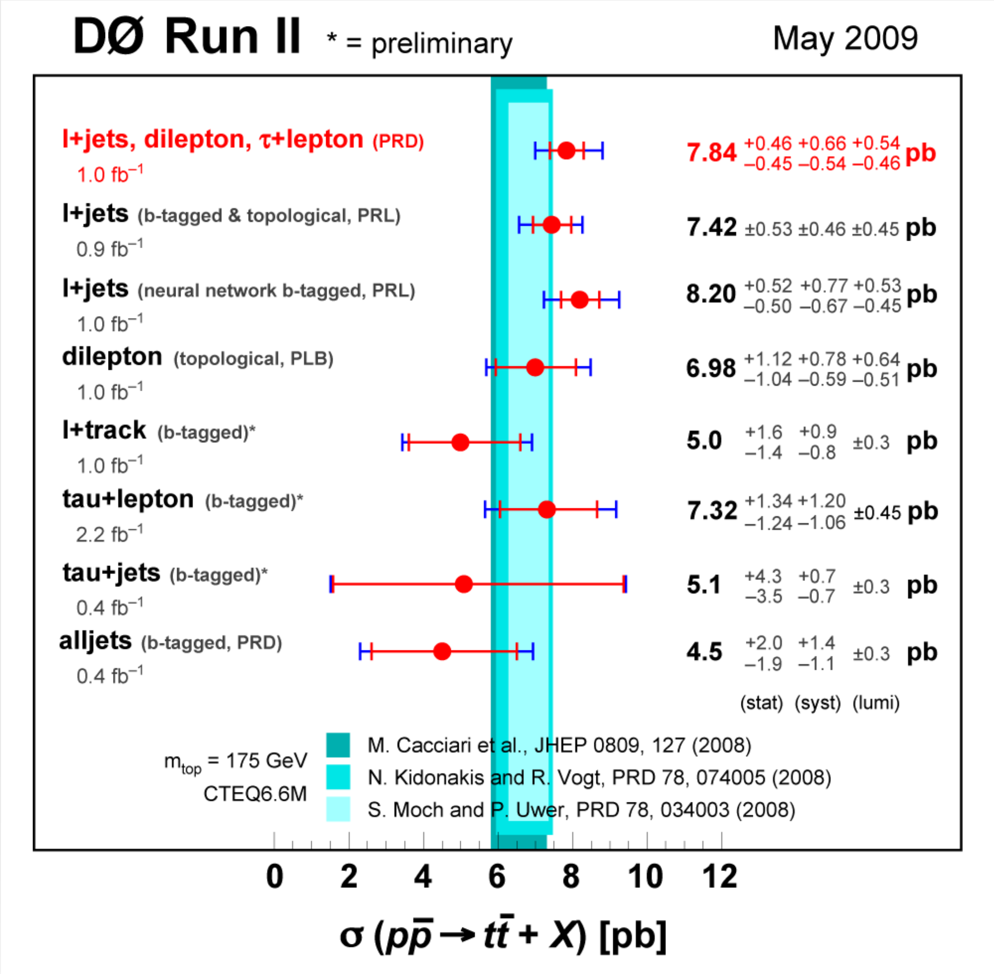


σ_{tt} = 7.2 ± 0.5(stat) ± 1.4(syst) ± 0.4 (lumi) pb

for M_{top}=172.5 GeV/c^2

ttbar Cross Section Results





- Consistent among channels, methods and experiments
- Limited by systematic uncertainties
- Uncertainties comparable to the theoretical uncertainty

ttbar + jet Cross Section

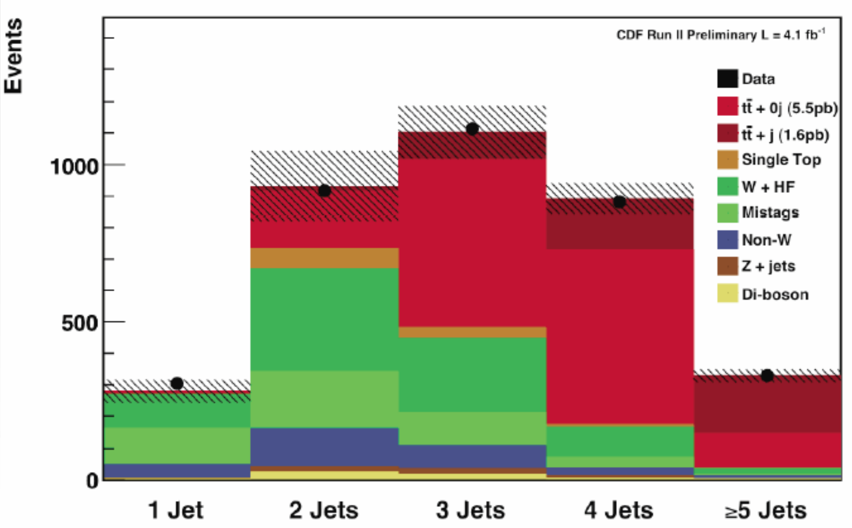
- Test of pQCD
- Use events in lepton+jets channel with ≥1 b tag and ≥3 jets
- Break up ttbar sample into 2 samples 0j and +j
- Simultaneously measure cross sections for both samples

$$\sigma_{t\bar{t}+j} = 1.6 \pm 0.2_{stat} \pm 0.5_{syst} \ \ \text{pb}$$

$$\sigma^{theory}_{t\bar{t}+j} = 1.79^{+0.16}_{-0.31}$$

Dittmaier, Uwer, and Weinzierl hep-ph/0810.0452v2

$$\sigma_{t\bar{t}+0j} = 5.5 \pm 0.4_{stat} \pm 0.7_{syst} \ \ \text{pb}$$

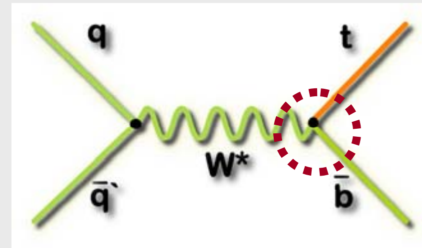


Physics of EW Single Top Production

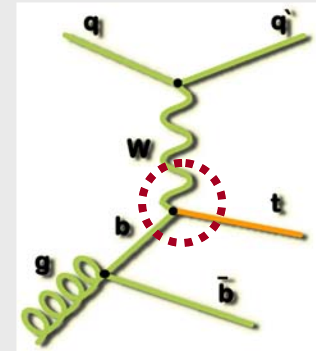
- The SM predictions (PRD70, 114012 (2004))
  - $\sigma_{\text{s-channel}} = 0.88 \pm 0.11$ pb
  - $\sigma_{\text{t-channel}} = 1.98 \pm 0.25$ pb

  (for $m_{top} = 175$ GeV/c^2)
- Direct measurement of V_{tb}: *(S. Willenbrock,* Rev. Mod. Phys. 72, 1141-1148*)*

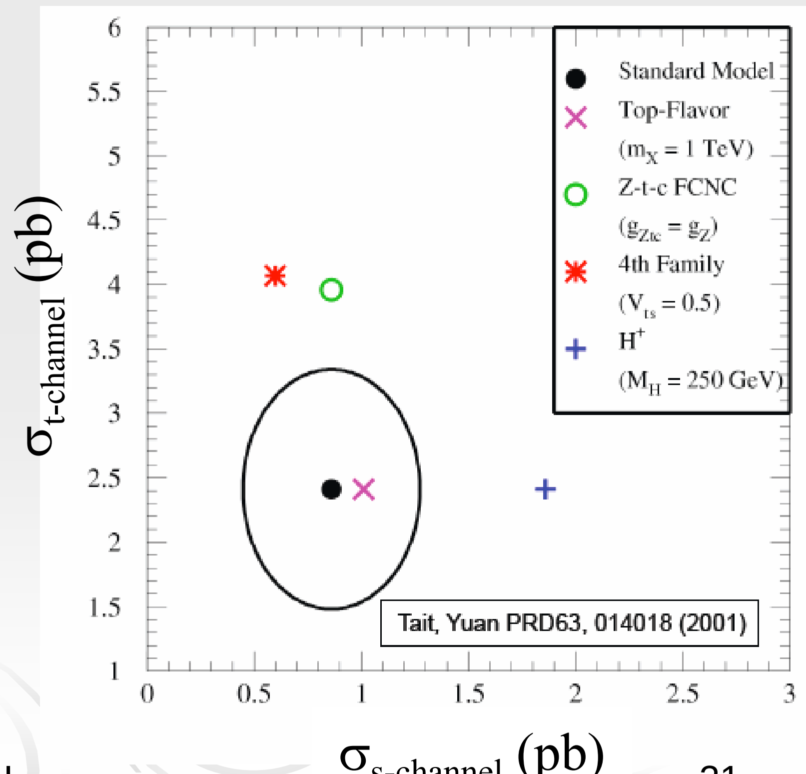
  $\sigma_{\text{single top}} \propto |V_{tb}|^2$
- Produced ~100% polarized top, can be used to test the V-A structure of the top EW interaction. *(G. Mahlon, hep-ph/9811219)*
- Sensitive to beyond SM physics
  - t-channel: 4^{th} family, FCNC
  - s-channel: W', H^+



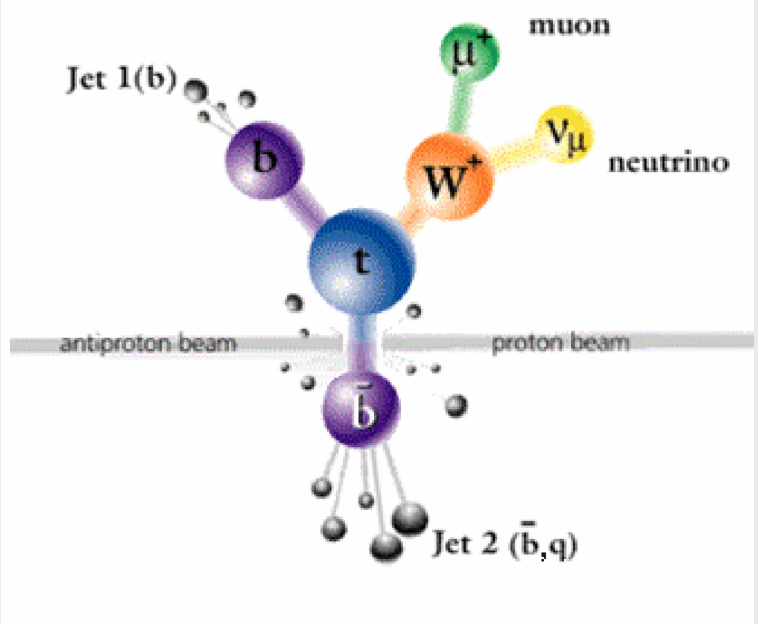
s-channel

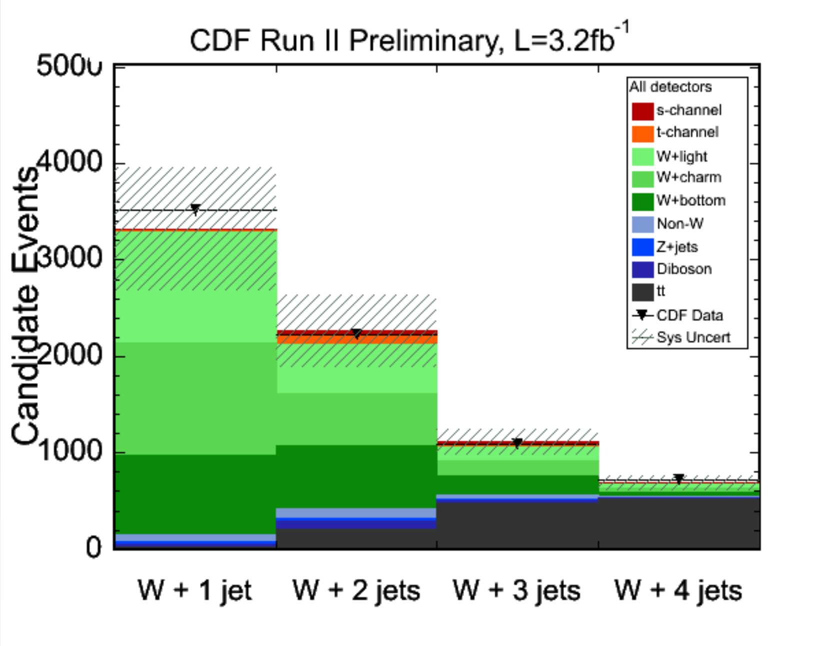


t-channel



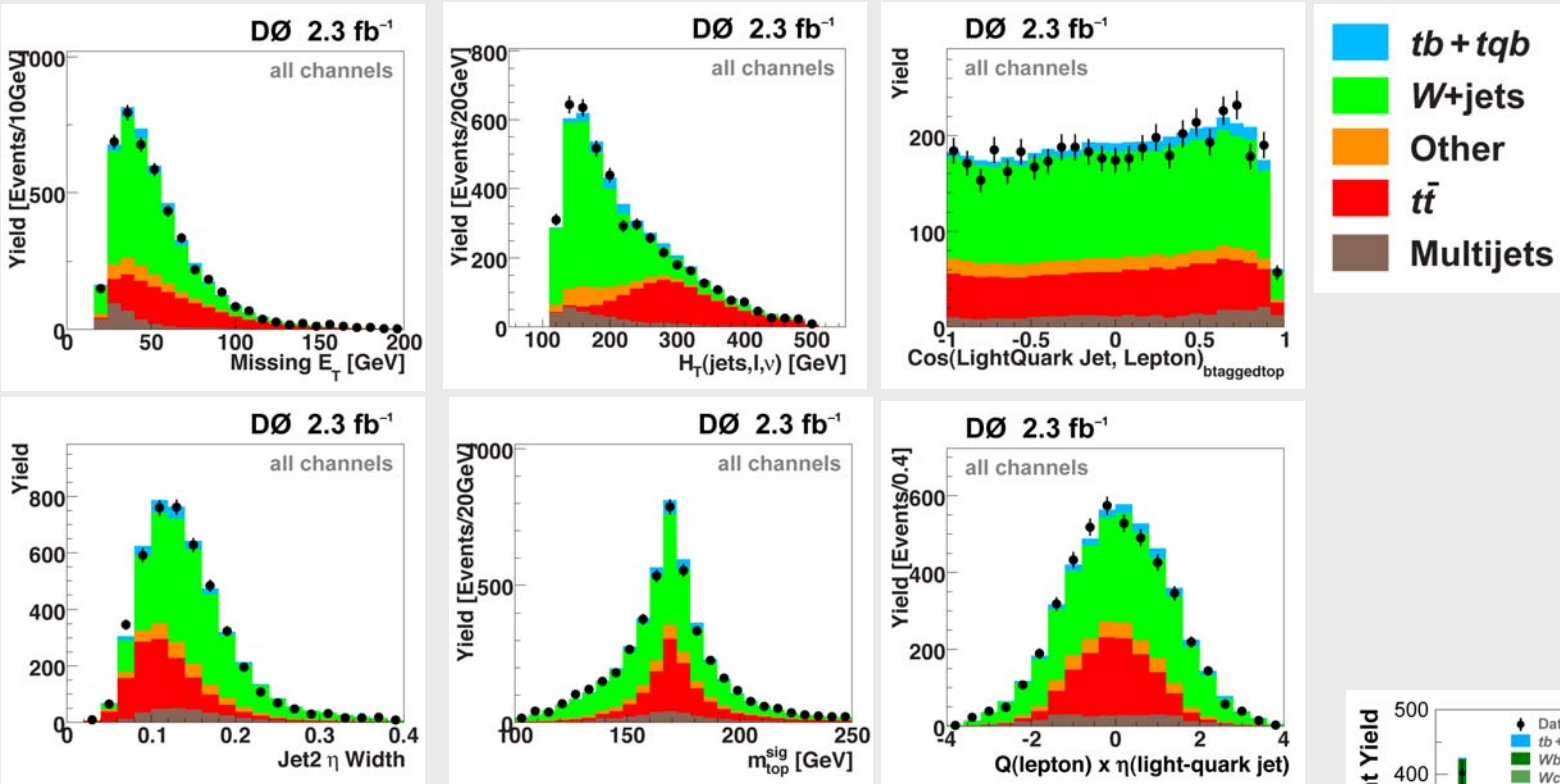
Experimental Challenge

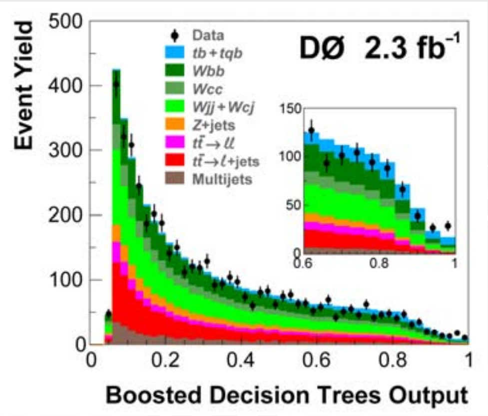




- Experimental signatures:
  - One high P_T isolated e or μ
  - Large missing transverse energy
  - ≥ 2 jets (≥ 1 b-tag)
- Suffers from large amount of W+jets backgrounds

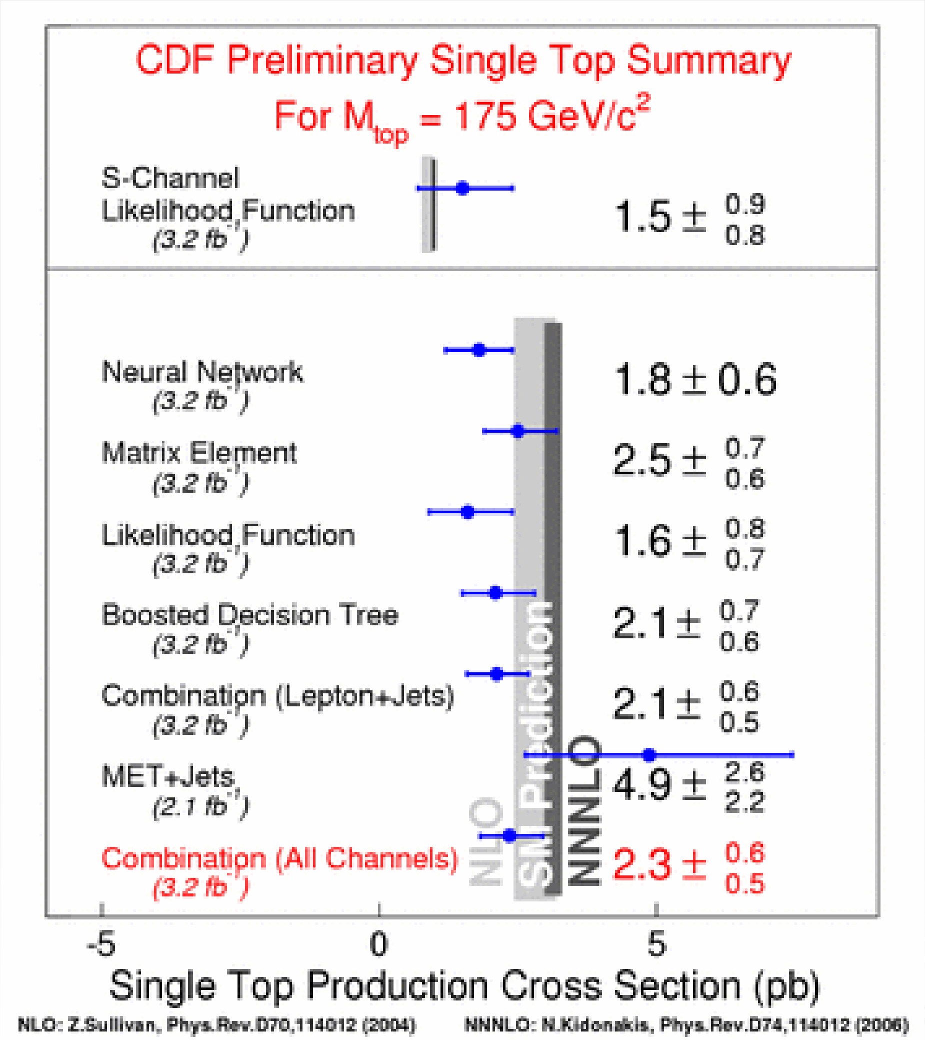
Extracting Single Top Signal

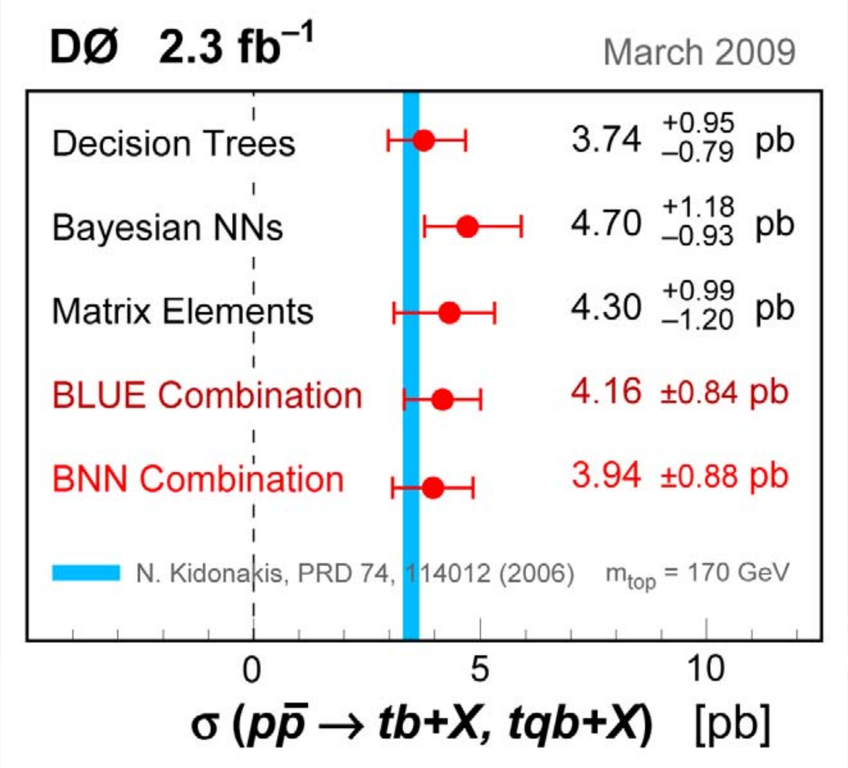




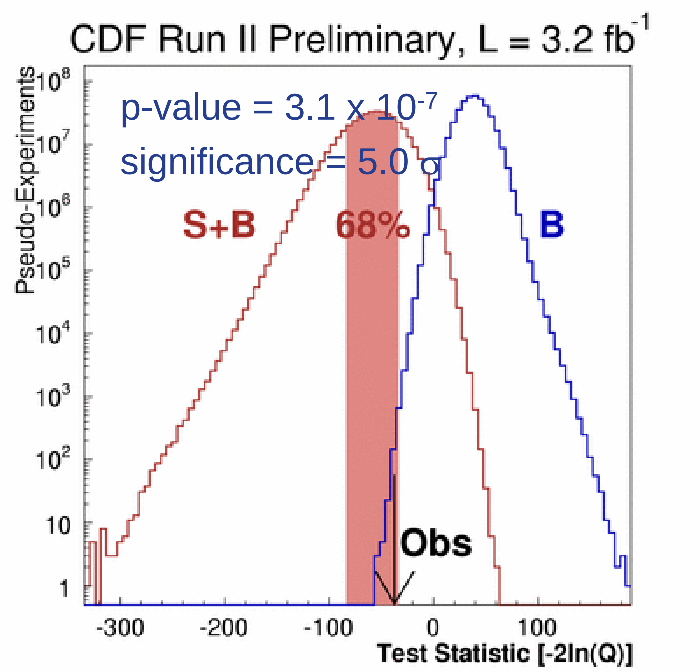
- No single variable provide significant signal-background separation
- Perform multivariate analysis ⇒ take advantage of small signal background separation in many variables

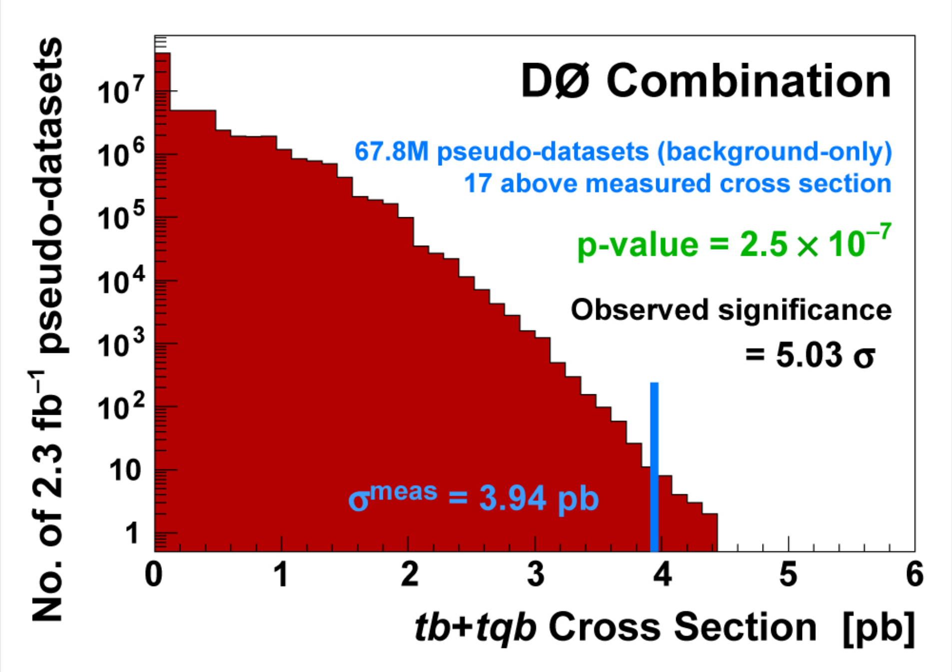
Single Top Measuremets





Observation of Single Top Production



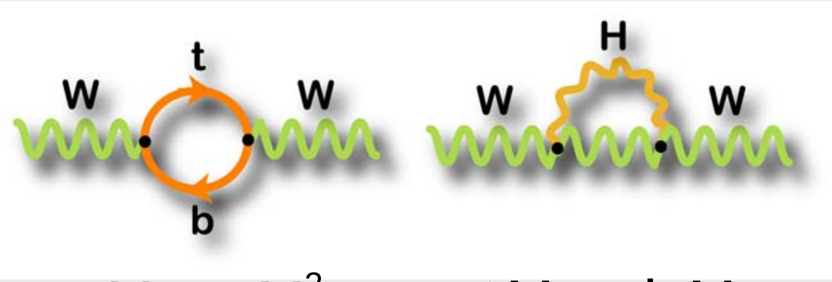


- CDF and D0 both report >5σ observation Mar-2009
- V_{tb} measurement
  - CDF: $|V_{tb}| = 0.91 \pm 0.11$ (exp.) ± 0.07 (theory), $|V_{tb}| > 0.71$ at 95% CL
  - D0 : $|V_{tb}\, f^L_1| = 1.07 \pm 0.12$, $|V_{tb}| > 0.78$ at 95% CL

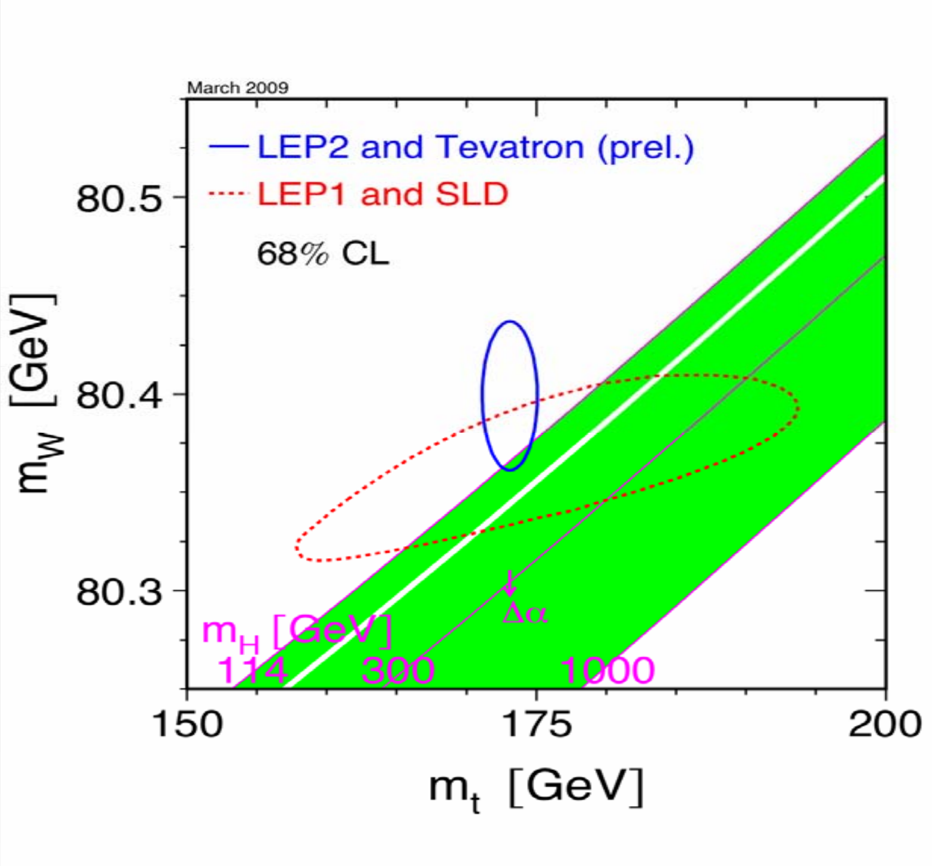
Top Mass

Why measure the Top Quark Mass?

- Related to standard model observables and parameters through **loop diagrams**
- Consistency checks of SM parameters

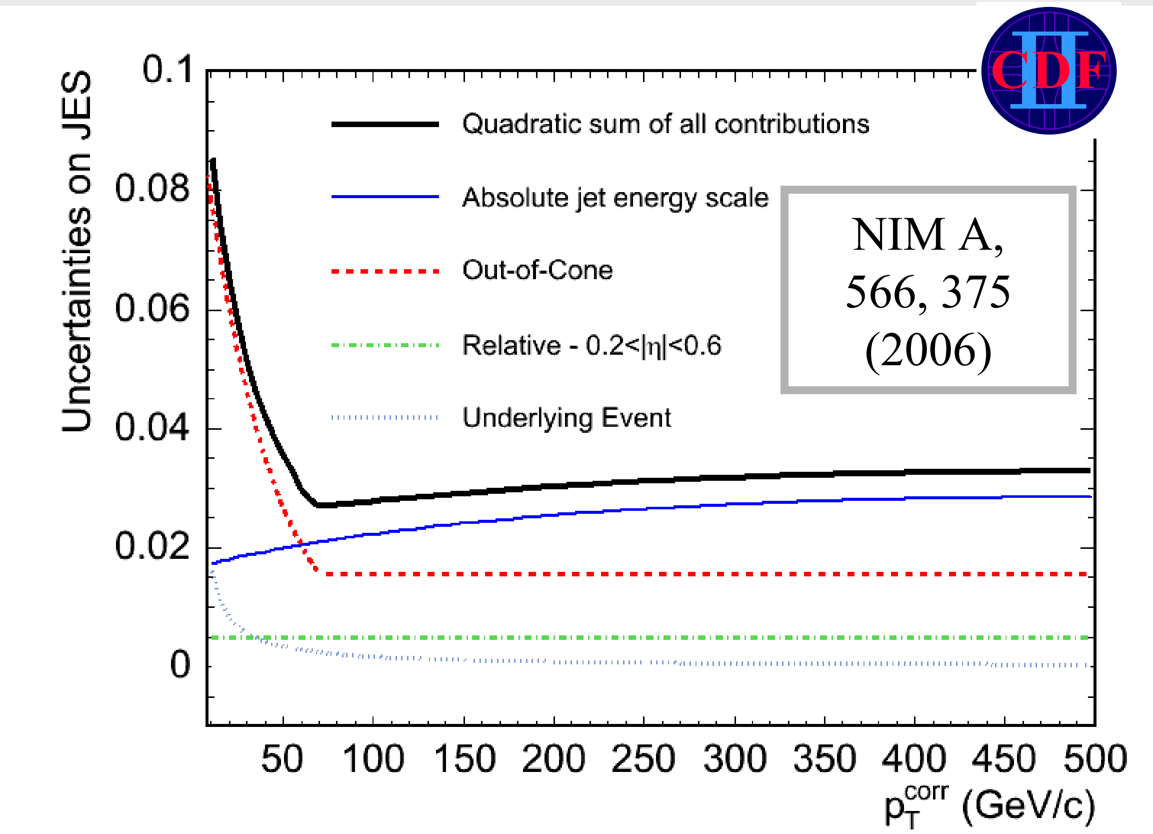


$\Delta M_W \propto M_{top}^2$ $\Delta M_W \propto \ln M_H$



- Precision measurements of the M_{top} (and M_W) allow prediction of the M_{Higgs}
- Constraint on Higgs mass can point to physics beyond the standard model

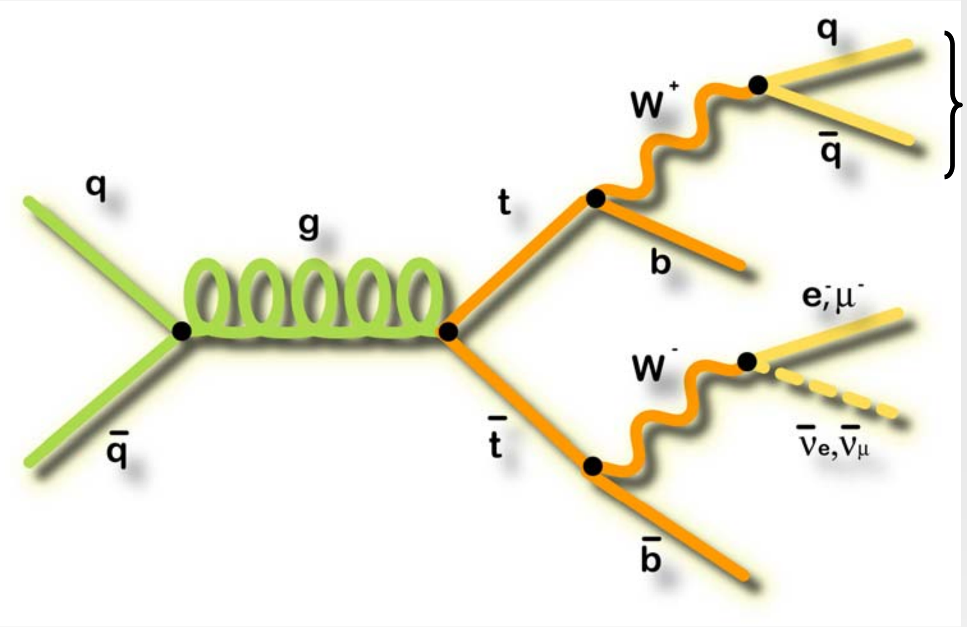
Jet Energy Scale Uncertainty



- Uncertainty on JES ⇒ About 3% systematic uncertainty on Top mass measurement when convoluted with ttbar p_T spectrum

In-situ Measurement of JES

- Additionally, we use $W \rightarrow jj$ mass resonance (M_{jj}) to measure the jet energy scale (JES) uncertainty



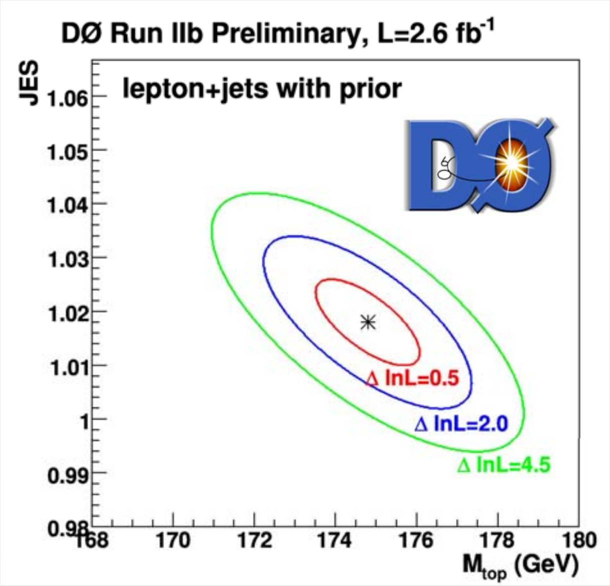
M_{jj}

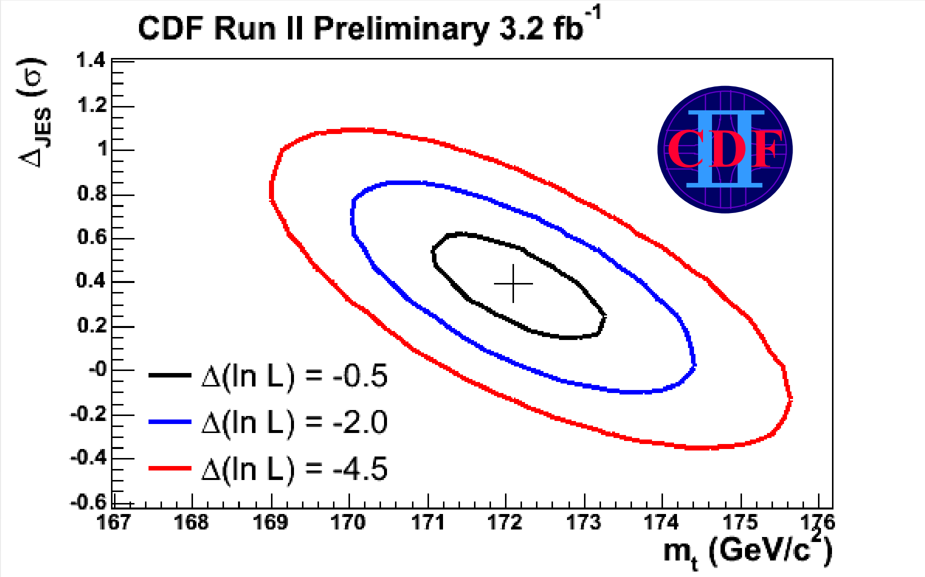
Constrain the invariant mass of the non-b-tagged jets to be 80.4 GeV/c^2

Measurement of JES scales directly with statistics!

Top Mass : Lepton+Jets Channel

- Use event-by-event likelihood based on leading order ttbar differential cross section.
  - *Most precise top mass measurements from single channels*

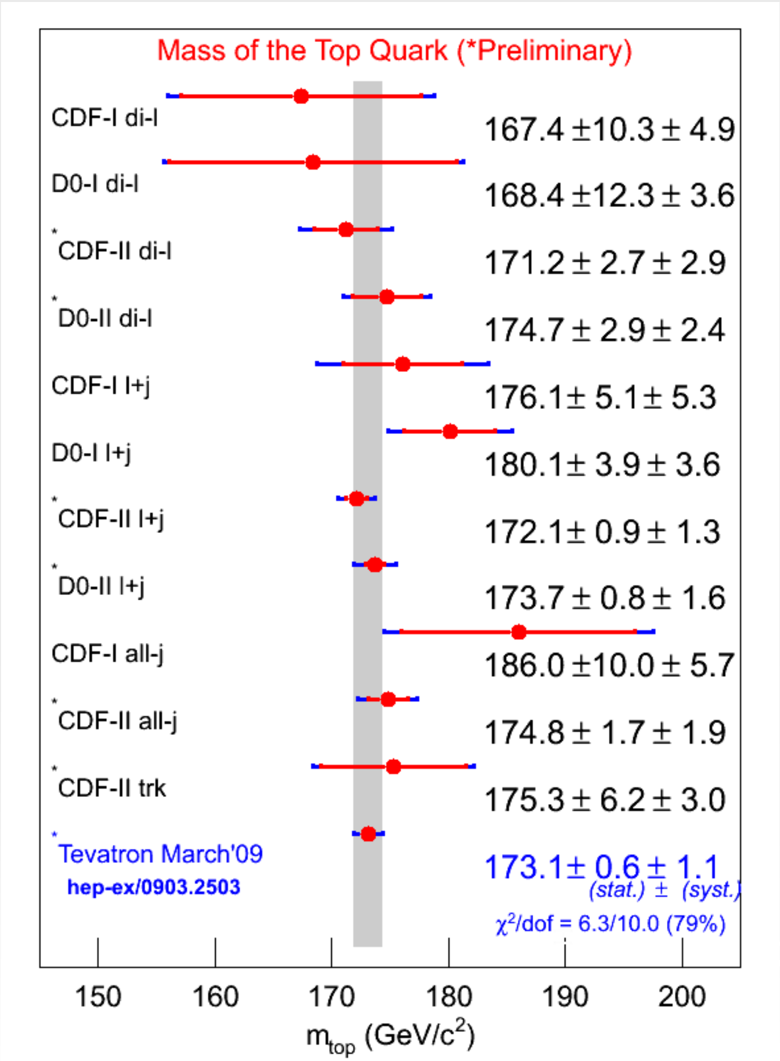




m_{top} with 3.6 fb^{-1} D0 data:
173.7 ± 1.3 (stat+JES) ± 1.4 (syst) GeV/c^2

m_{top} with 3.2 fb^{-1} CDF data:
172.1 ± 1.2 (stat+JES) ± 1.1 (syst) GeV/c^2

Top Mass : Combination



- Combine Run I measurements with most recent Run II measurements
- Take into account the statistical and systematic uncertainties and their correlations (NIM A270 (1988) 110, NIM A500 (2003) 391)
- Combined top mass

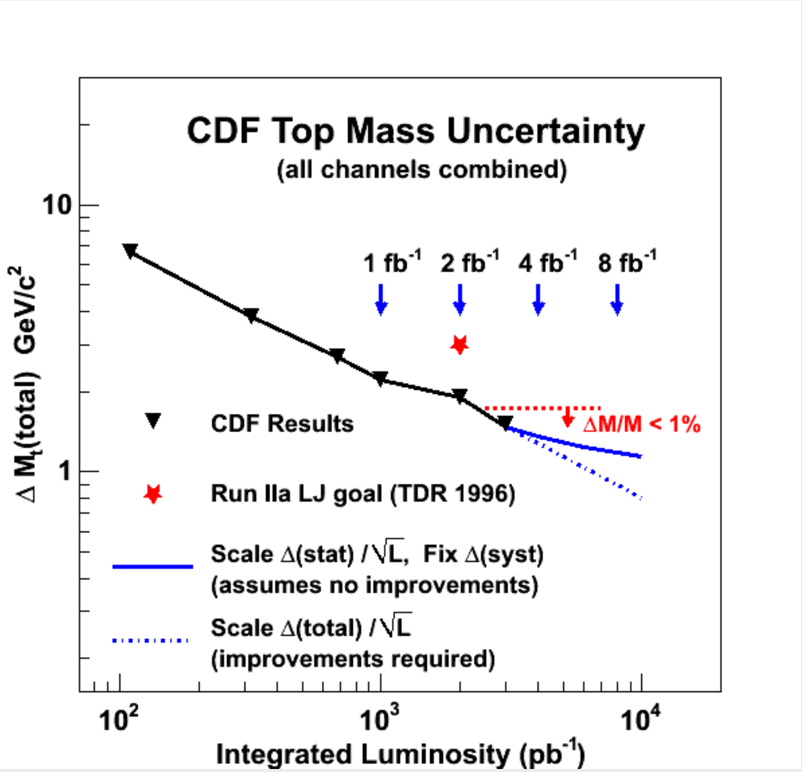
  173.1 ± 1.3 GeV/c^2

  $\chi 2$/ndof 6.3/10 ⇒ 79% prob

  - Good agreement among all input measurements
- Top mass known with relative precision of 0.75%

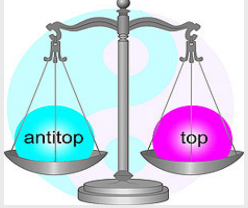
Uncertainties on Measured Top Mass

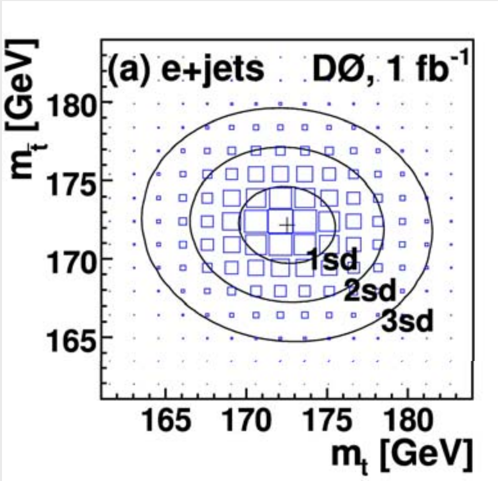
Source	ΔM_t (GeV/c^2)
jet energy scale:	0.73
* t-tbar modeling:	0.71
background:	0.26
lepton energy scale:	0.11
miscellaneous:	0.18
Systematic:	1.07
Statistical:	0.65

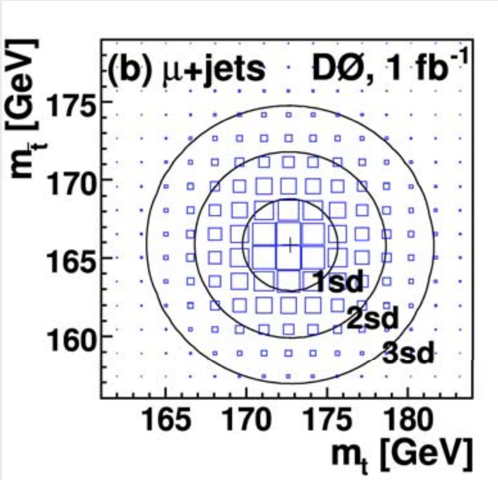


- Uncertainty dominated by sources which should continue scale with the statistics of the sample
- With full Run II data set could reach a total uncertainty of $\Delta M_t \sim 1$ GeV/c^2

Direct Measurement of the Mass Difference Between Top and Anti-top



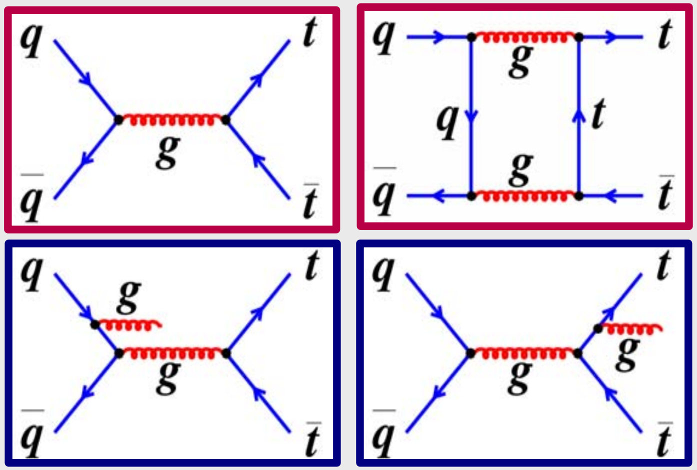




- Test of CPT invariance
- Use lepton+Jets events and matrix element method
- $M_{top} - M_{anti\text{-}top} = 3.8 \pm 3.7$ GeV/c^2
- Relative mass difference (2.2±2.2)%
- The first measurement of a mass difference of bare quarks.

Other Top Properties

Forward Backward Asymmetry (A_{fb}) in Top Pair Production



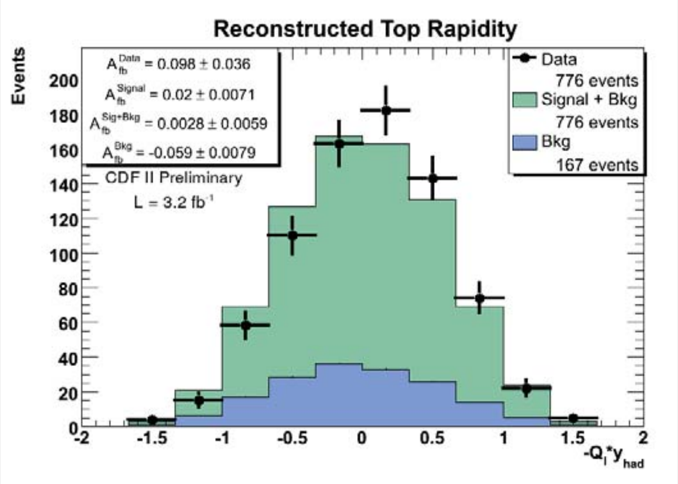
- Asymmetry caused by interference of ME amplitudes for same final state
- The SM prediction:
  - In ttbar frame: $A_{fb}^{ttbar} = 0.05 \pm 0.015$ (QCD at NLO)
- Can be significantly enhanced in different BSM models:
  - Z'-like states with parity violating coupling (PLB 387, 113 (1996)), theories with chiral color (PLB 190, 157 (1987), PLB 200, 211(1988))

Forward Backward Asymmetry (A_{fb}) in Top Pair Production

- A_{fb} measured in the ttbar rest frame

$$A_{fb}^{t\bar{t}} = \frac{N(\Delta Y > 0) - N(\Delta Y < 0)}{N(\Delta Y > 0) + N(\Delta Y < 0)}$$

$$\Delta Y = -Q_{\ell}.(Y_{t,leptonic} - Y_{t,hadronic})$$

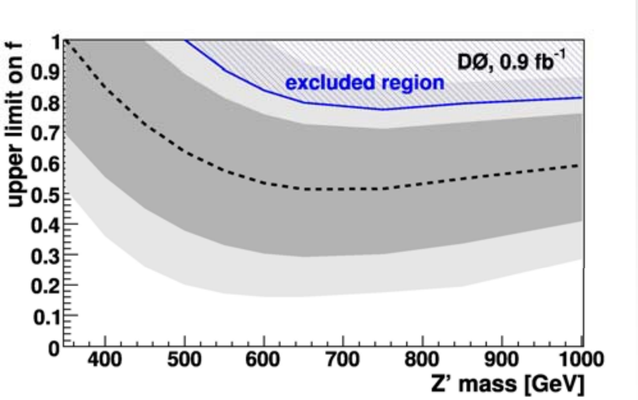


- CDF apply unfolding to go from reconstructed to parton level

$A_{fb} = 0.193 \pm 0.065$ (stat) ± 0.024 (syst)

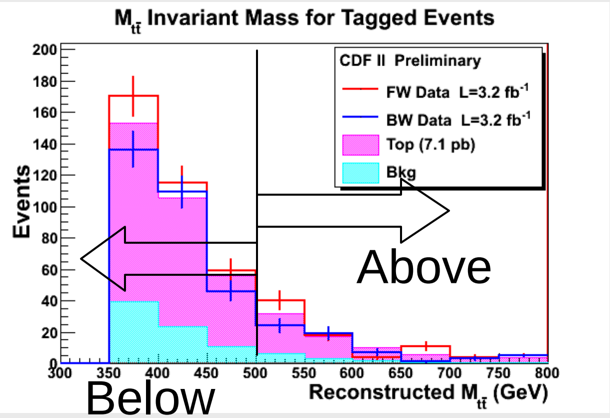
SM Prediction: $A_{fb} = 0.05 \pm 0.015$

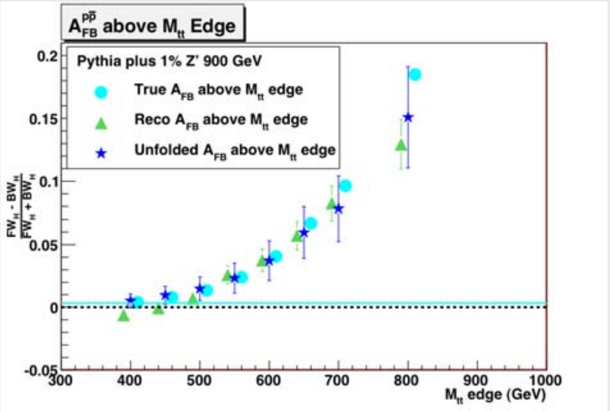
- DØ: no unfolding and acceptance correction: $A_{fb} = (12 \pm 8 \pm 1)$ % (PRL 100, 142002 (2008))
  - Set limits on Z' production

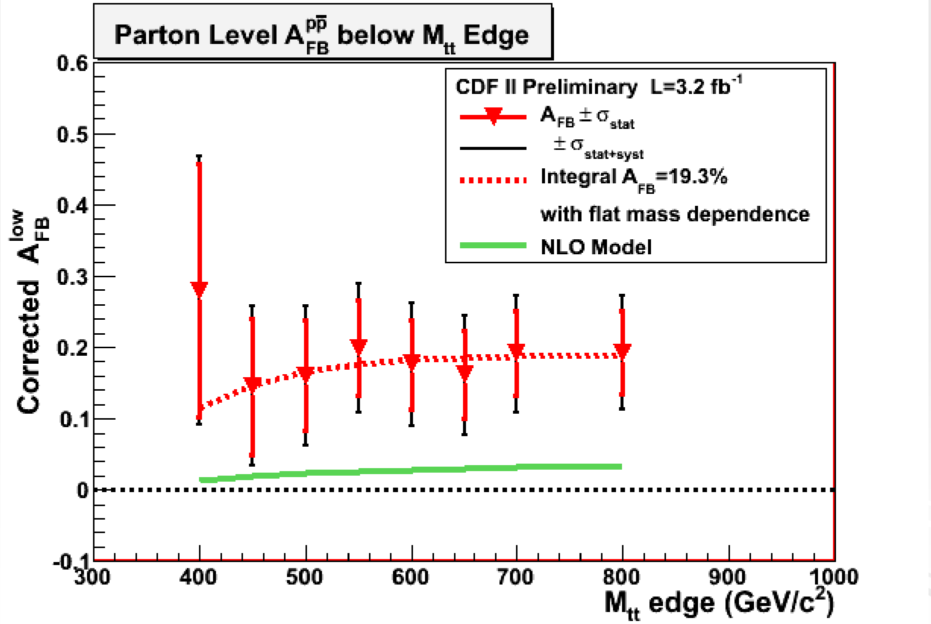


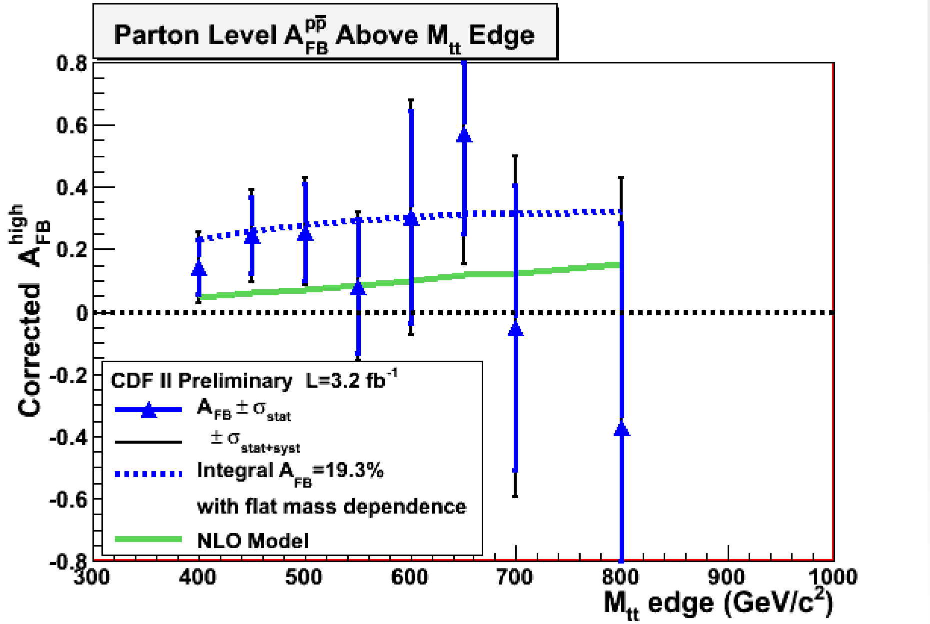
A_{fb} Dependence on the Invariant Mass of ttbar

- Scan for A_{fb} above and below 8 different M_{tt} thresholds
- Sensitive to new physics effect

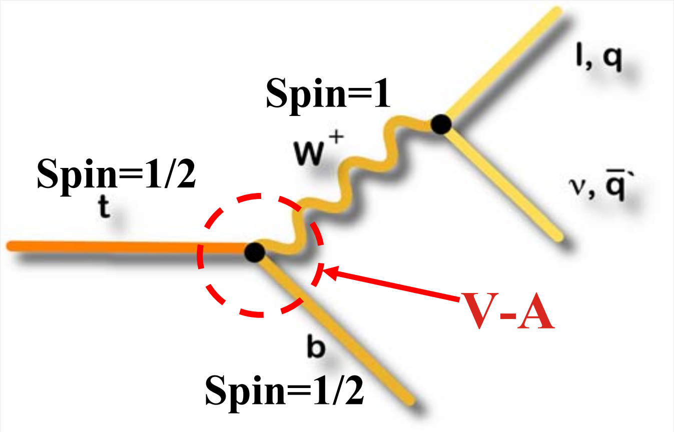


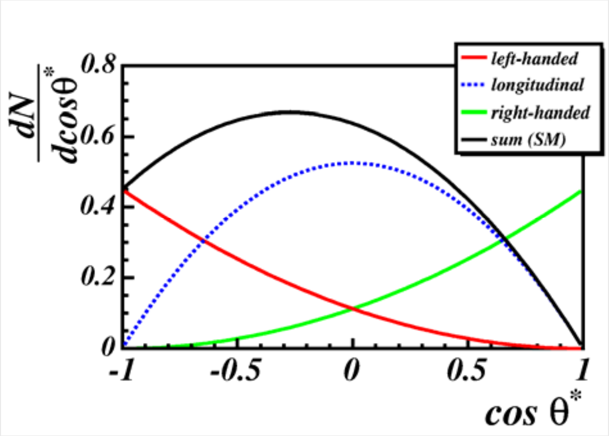






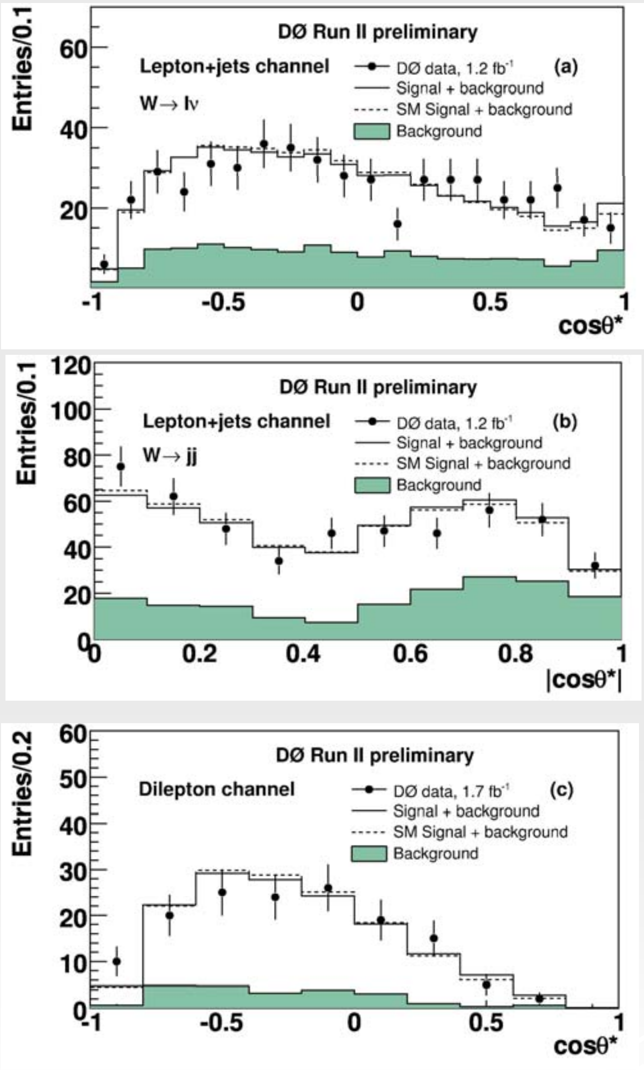
tbW coupling





- The SM top decays via EW interaction: Br($t \rightarrow bW$)~100%
  - Top decays as a bare quark ⇒ spin info transferred to final states
- V-A coupling in the SM ⇒
  - longitudinal fraction f_0 ~70%
  - left-handed fraction f_- ~30%
  - right-handed fraction f_+ ~0%
- The SM prediction modified in various new physics models
- Can use cosθ* to measure f_0, f_+, f_-.
  - cosθ* : Angle between lepton and b in W rest frame.

W-boson Helicity Fractions



- Measure f_0 and f_+ simultaneously $\Rightarrow$ model independent
- D0 Lepon+jet and Dilepton 2.7 fb^{-1}

$$f_0 = 0.49 \pm 0.11\,(\text{stat}) \pm 0.09\,(\text{syst})$$

$$f_+ = 0.11 \pm 0.06\,(\text{stat}) \pm 0.05\,(\text{syst})$$

- CDF Lepton+Jets 2 fb^{-1}

$$f_0 = 0.62 \pm 0.10\,(\text{stat}) \pm 0.05\,(\text{syst})$$

$$f_+ = -0.04 \pm 0.04\,(\text{stat}) \pm 0.03\,(\text{syst})$$

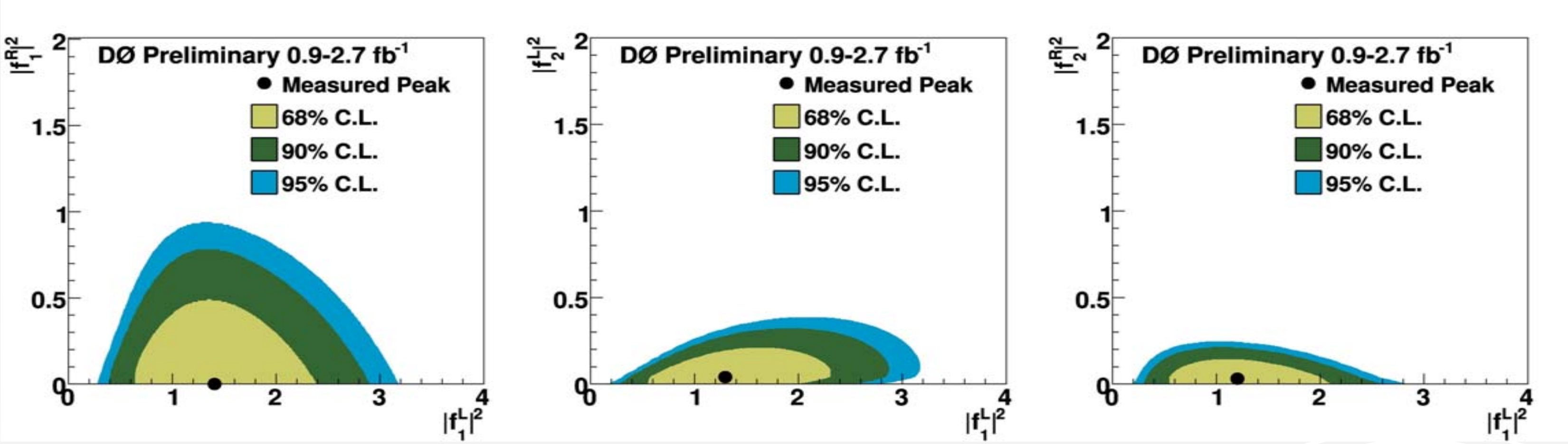
Consistent with the Standard Model

Generic Wtb Coupling

- Constrain form factors for anomalous tWb coupling
  - Combine information from single top production and W helicity measurement from ttbar decay

$$L_{tWb} = \frac{g}{\sqrt{2}} W_\mu^- \bar{b} \gamma^\mu \left(f_1^L P_L + f_1^R P_R \right) t - \frac{g}{\sqrt{2} M_W} \partial_\nu W_\mu^- \bar{b} \sigma^{\mu\nu} \left(f_2^L P_L + f_2^R P_R \right) t$$

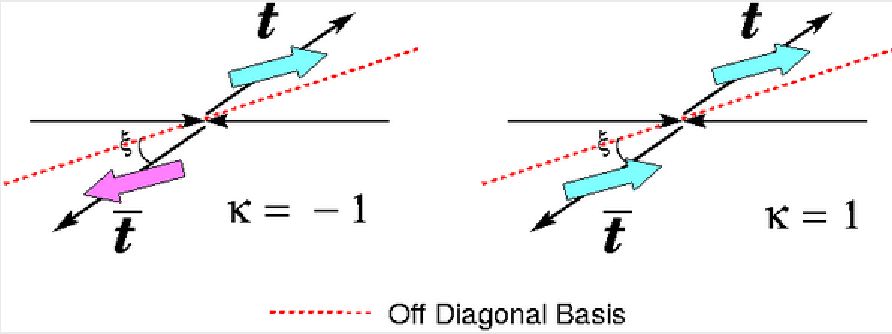
Standard Model $f_1^L = 1, \quad f_2^L = f_1^R = f_2^R = 0$

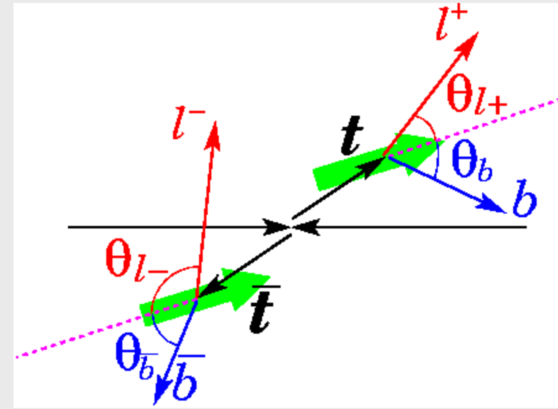


$$\text{for } \left|f_1^L\right|^2 = 1 \quad \begin{array}{l} \left|f_1^R\right|^2 < 0.72 \\ \left|f_2^L\right|^2 < 0.19 \text{ @ 95\% CL} \\ \left|f_2^R\right|^2 < 0.20 \end{array}$$

Consistent with Standard Model

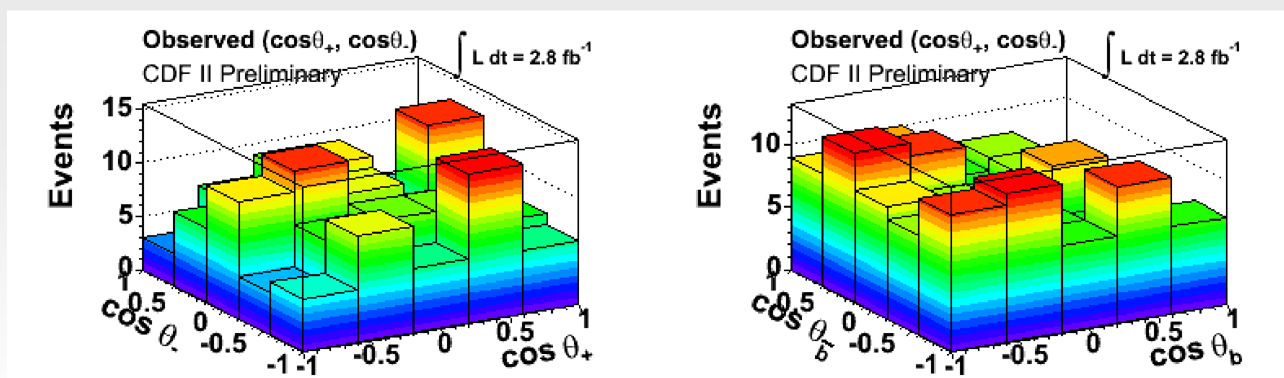
ttbar Spin Correlations





$$\frac{1}{\sigma}\frac{d^2\sigma}{d\cos\theta_+ d\cos\theta_-} = \frac{1+\kappa\cos\theta_+\cos\theta_-}{4}$$

- Use off-diagonal basis : tan $\xi \equiv$sqrt$(1-\beta^2)$ tan θ^*. In ttbar frame: $\beta \equiv$ top velocity and $\theta^* \equiv$ top flight direction w.r.t. proton direction.
- Templates: angular distribution of (cos θ_{l+}, cos θ_{l-}) and (cosθ_b, cos θ_{bbar})
- CDF Results
  $-0.455<\kappa<0.865$ (68% C.L.) or
  $\kappa = 0.320^{+0.545}_{-0.775}$
  for $M_t = 175$ GeV/c^2



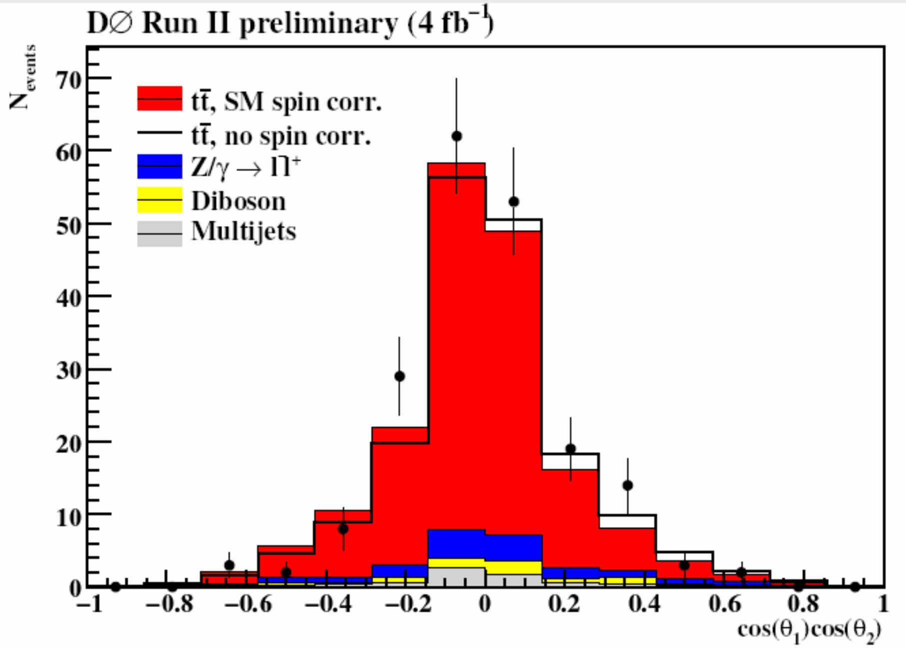
- The SM predicts $\kappa \sim 0.8$.

ttbar Spin Correlations (Cont')

- D0 measures decay products (l^+,l^-) angular correlation coefficient C

$$\frac{1}{\sigma}\frac{d\sigma}{d\cos\theta_1 d\cos\theta_2} = \frac{1}{4}(1 - C\cos\theta_1\cos\theta_2)$$

- θ_1 (θ_2): angle between the flight direction of l^+ (l^-) and direction of flight of one of the colliding hadrons in the ttbar rest frame



- D0 result:

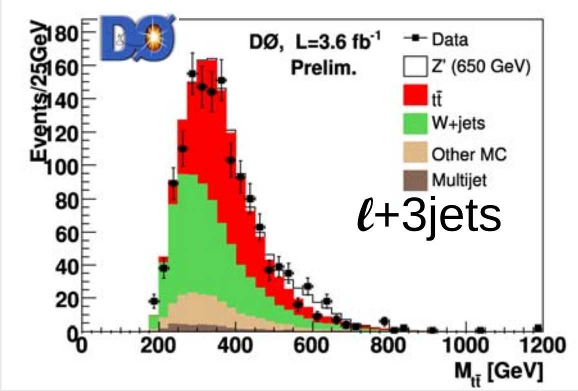
$$C = -0.17^{+0.64}_{-0.53}\,(\text{stat} + \text{syst})$$

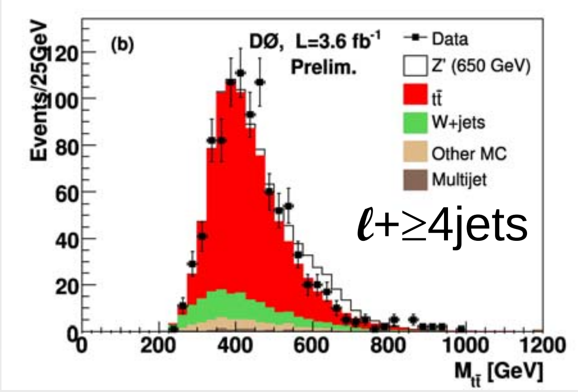
coefficient	LO	NLO
C	0.928	0.777

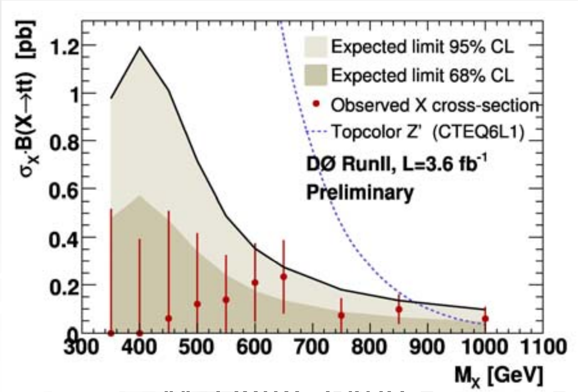
Search for Beyond the Standard Model Physics

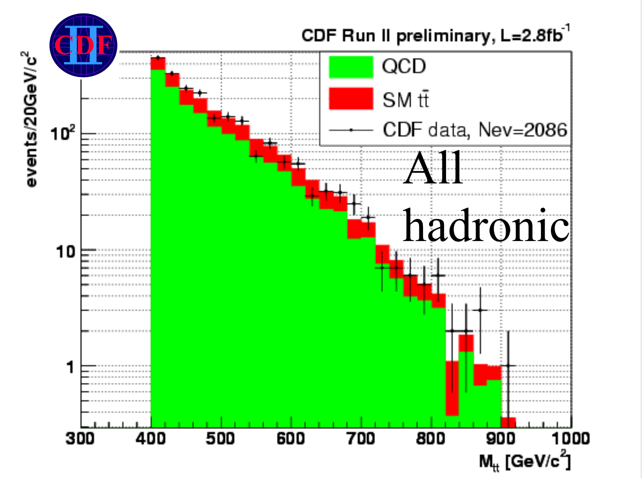
Resonant ttbar Production

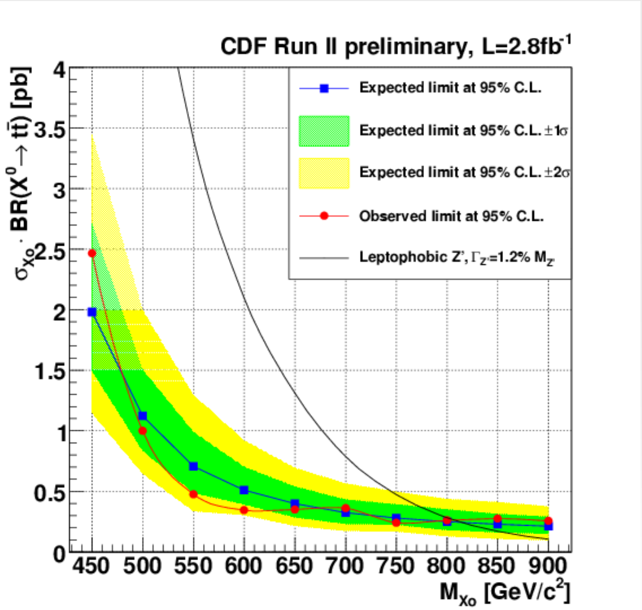
- Search for resonant ttbar production from the decays of massive Z-like bosons
  - Topcolor (PRD49, 4454, 1994) , KK gluon excitation in RS model (hep-ph/0701166))
- Set upper limits on Leptophobic Z' boson with mass $M_{Z'}$
- Lepton+Jets channel: $M_{Z'} > 820$ GeV/c^2 at 95% CL
- All-hadronic channel: $M_{Z'} > 805$ GeV/c^2 at 95% CL











More Top Physics Results From Tevatron

Apologies for my many omissions.

For a full listing of results go to:

http://www-cdf.fnal.gov/physics/new/top/top.html

http://www-d0.fnal.gov/Run2Physics/WWW/results/top.htm

Summary and Outlook

- Top quark properties are currently being studied at Tevatron
  - ttbar cross-section and top mass measurements
    - Most measurements are systematically limited
    - Mass measured to 0.8% precision
  - First observation of single top
  - Study other properties of top quark, search for new physics
    - Almost all the measurements are limited by statistics at present
    - Increasing data from Tevatron will further help reveal the true nature of top quark ⇒ **Expect ~10 fb^{-1} by 2011**
- LHC will open up a new era of Top physics ⇒**Top factory**
    - Understanding of systematic uncertainties would become crucial
    - Top is a standard candle, tool for calibrating JES, b-tagging
- Tevatron's top physics program and understanding of systematic effects will continue to play a significant role for years to come