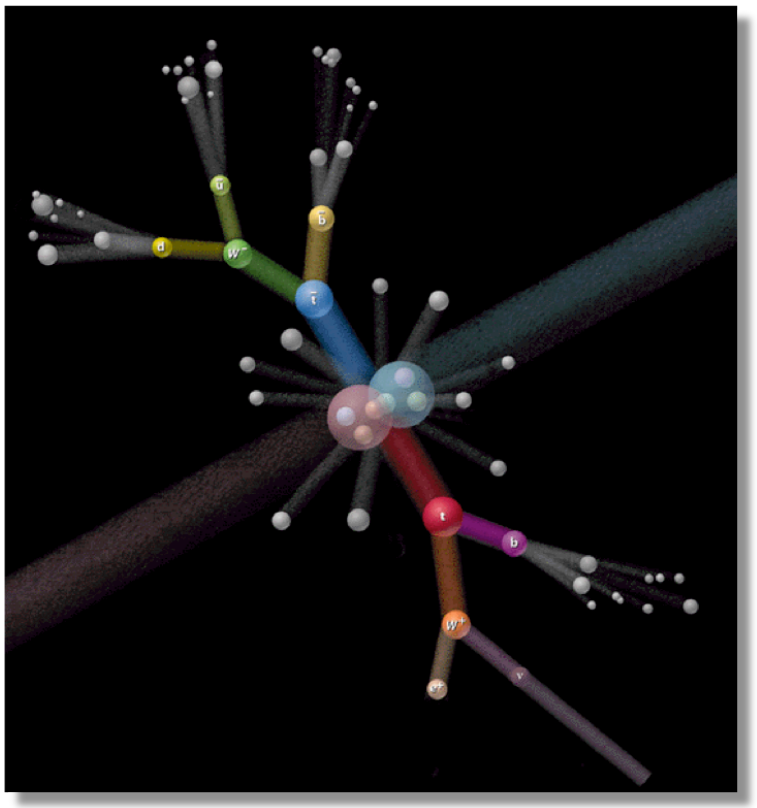
Top Quark Physics at CDF



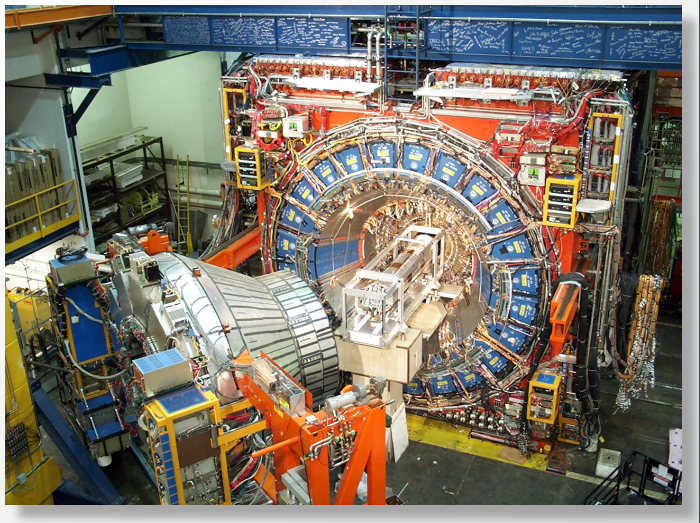
Bernd Stelzer

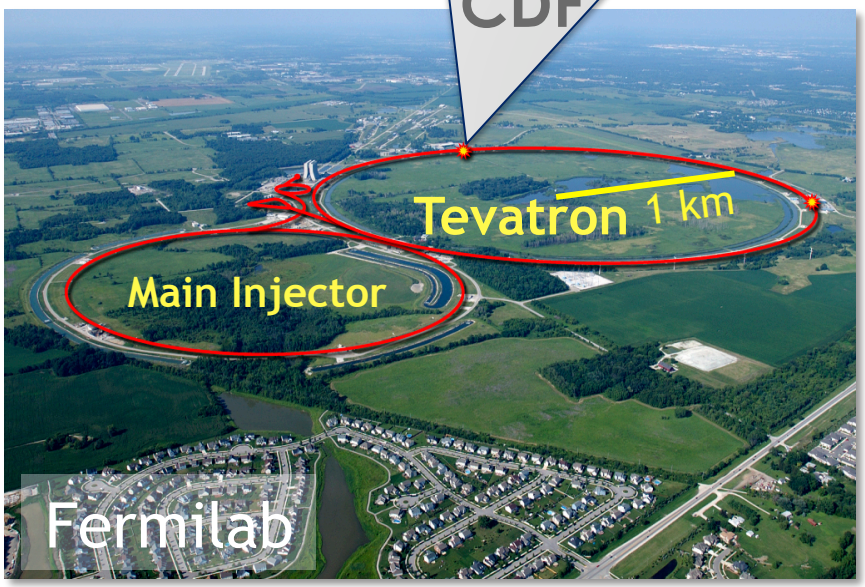
Simon Fraser University

On behalf of the CDF Collaboration

Lake Louise Winter Institute Feb 23rd 2011

Collider Detector at Fermilab (CDF)

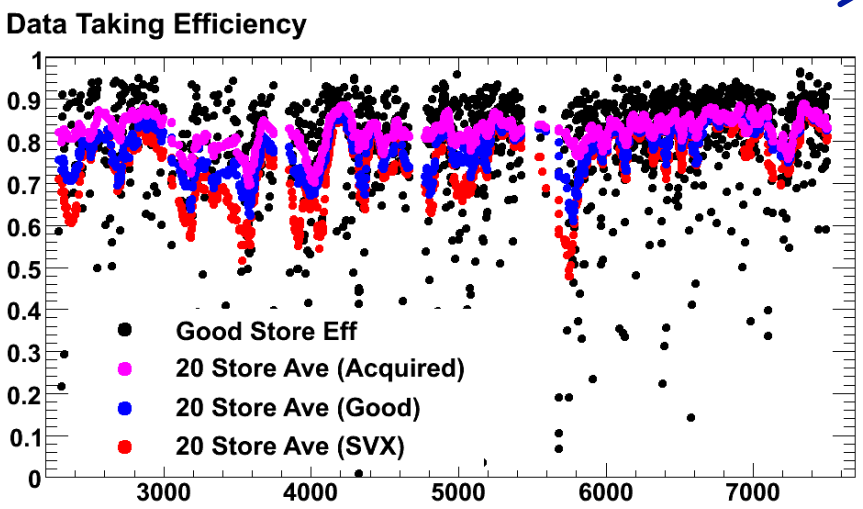




- *Tevatron $p\bar{p}$ collider operates at 1.96 TeV*
- *Surpassed design luminosity*
  (Record Inst. Lum. $4 \cdot 10^{32}$ [$cm^{-2}sec^{-1}$])
- *Efficient data taking since 2002*

- Status: ~ 8.5 fb^{-1} of good data!
- Results using up to 6 fb^{-1} in this talk

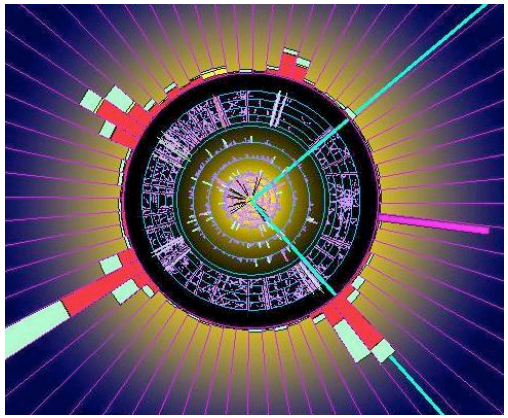
~ 8 years of stable data taking



record: 85-90 % of delivered luminosity

Top Quark Physics

- Exciting physics!
  - *The Tevatron discovery in 1995 ended a 20 year quest for the top*
  - *Single top observation in 2009 added a new source of top quarks*



- Open question persists…

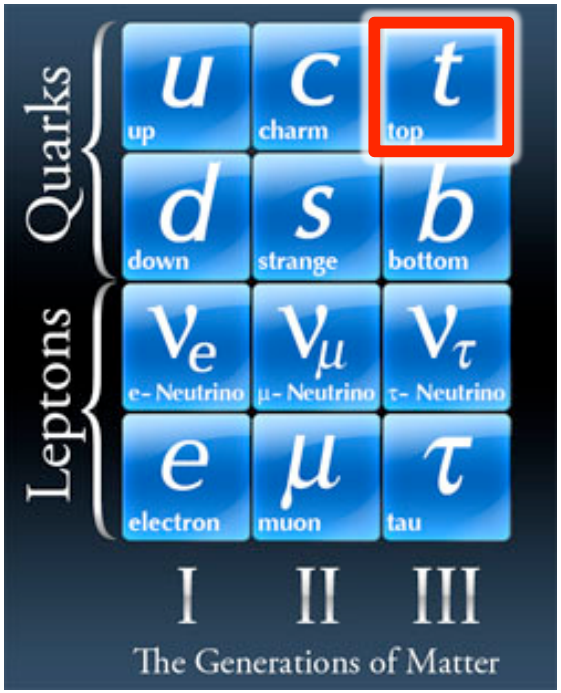
  Why is the top so massive?

  m_{top} ~ 175 GeV/c^2 ! Is the top quark special?

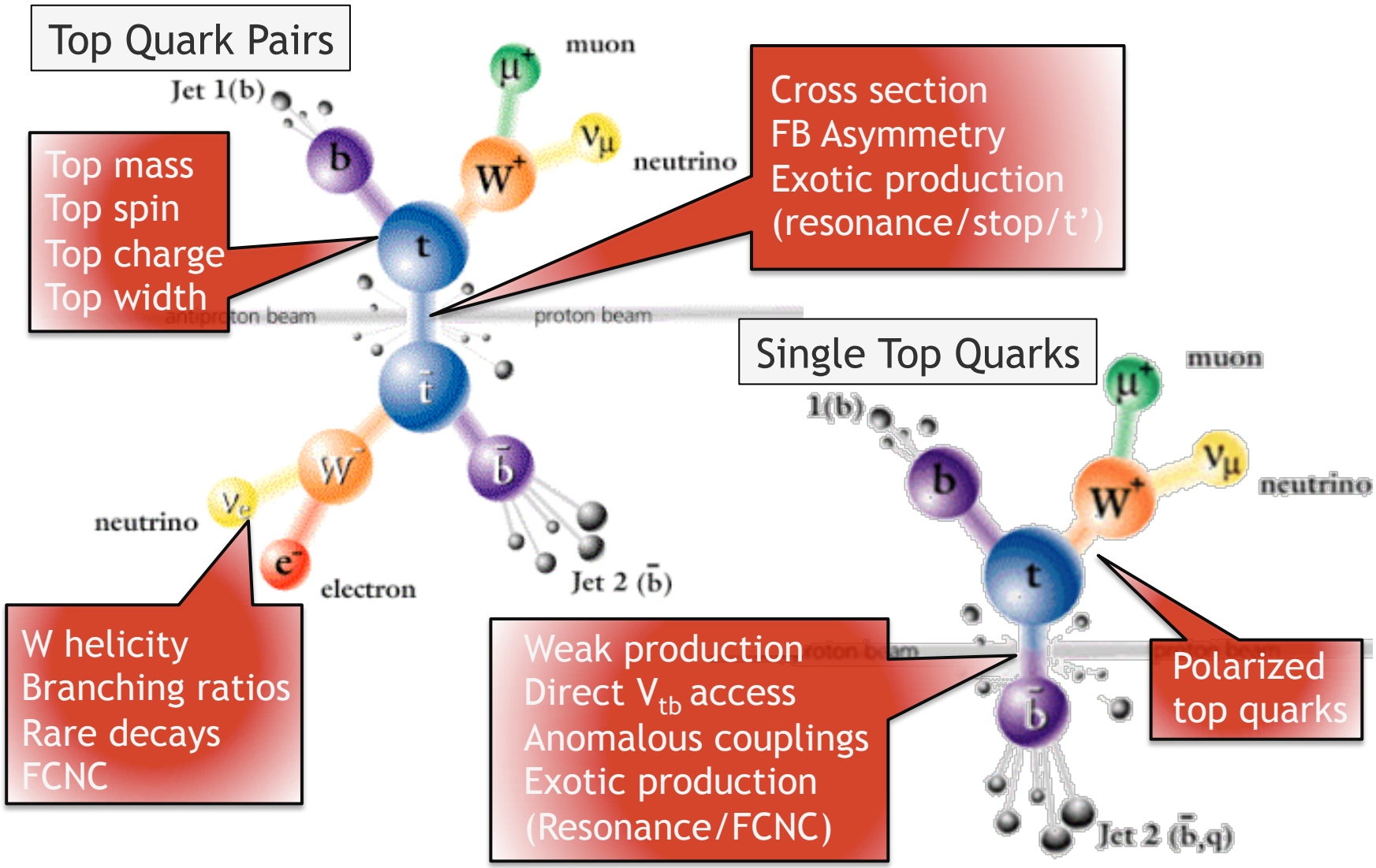
- Top Quark in the Standard Model
  - *SU(2) partner of the bottom quark*
  - *Spin-1/2, Charge +2/3e, Width ~ 1.5 GeV*

- Determine nature of top quark experimentally

- Large mass comes with interesting features
  - *Decay through t→Wb kinematically allowed*
  - *Top decays before hadronization, study "bare quark"*



CDF Top Quark Physics Program

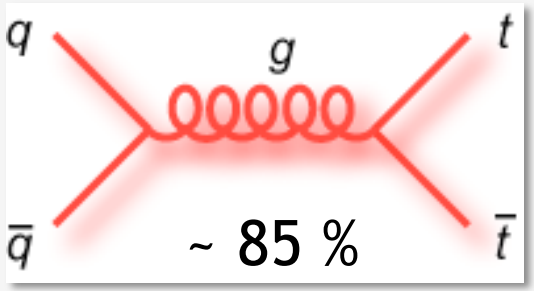


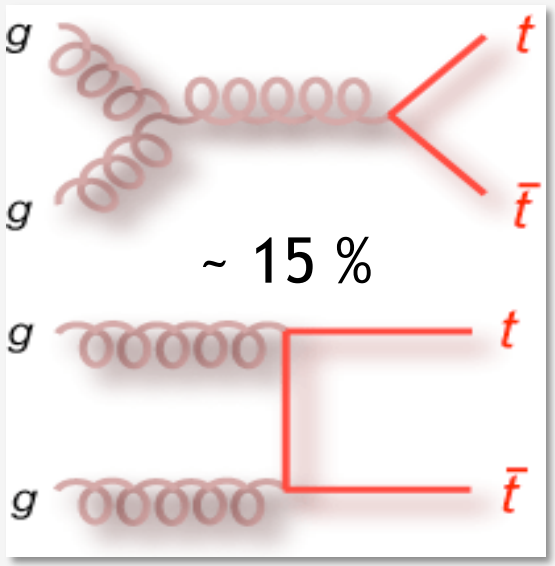
CDF program is systematically studying the physics of top quarks…

Top Quark Production at the Tevatron

Production

In Pairs

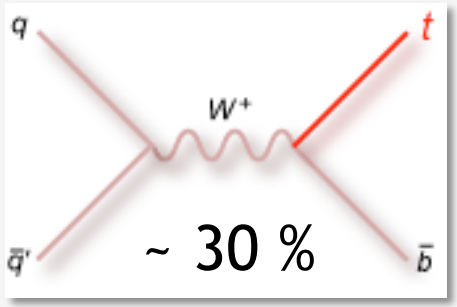


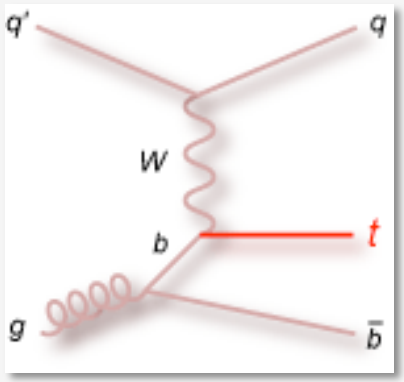


$\sigma_{NLO} = 7.4^{+0.5}_{-0.7}$ pb

JHEP 0809, 127 (2008)

Single



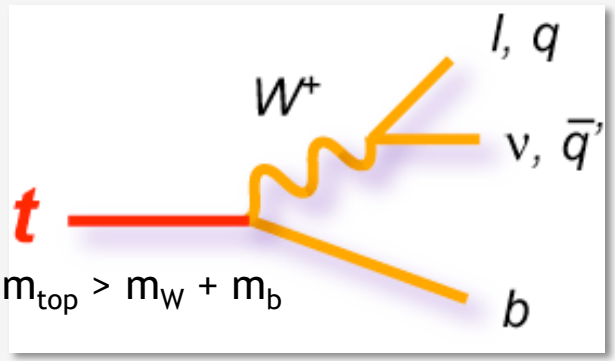


$\sigma_{NLO} = 3.0 \pm 0.4$ pb

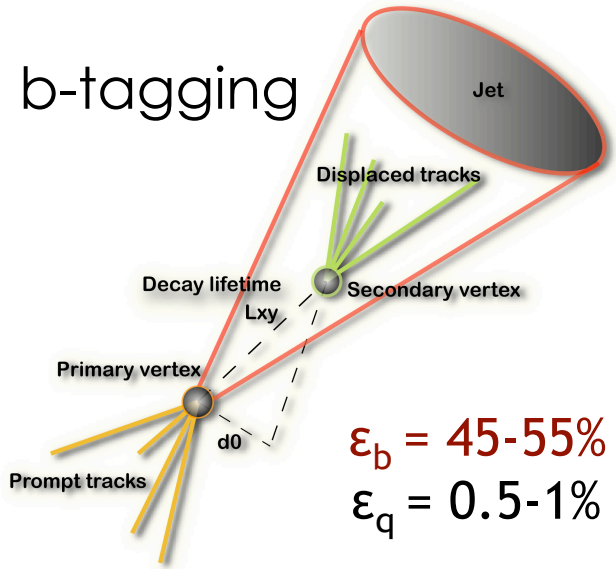
PRD 66, 054024 (2002)

Decay

BR(t→Wb) ~100 %



b-tagging

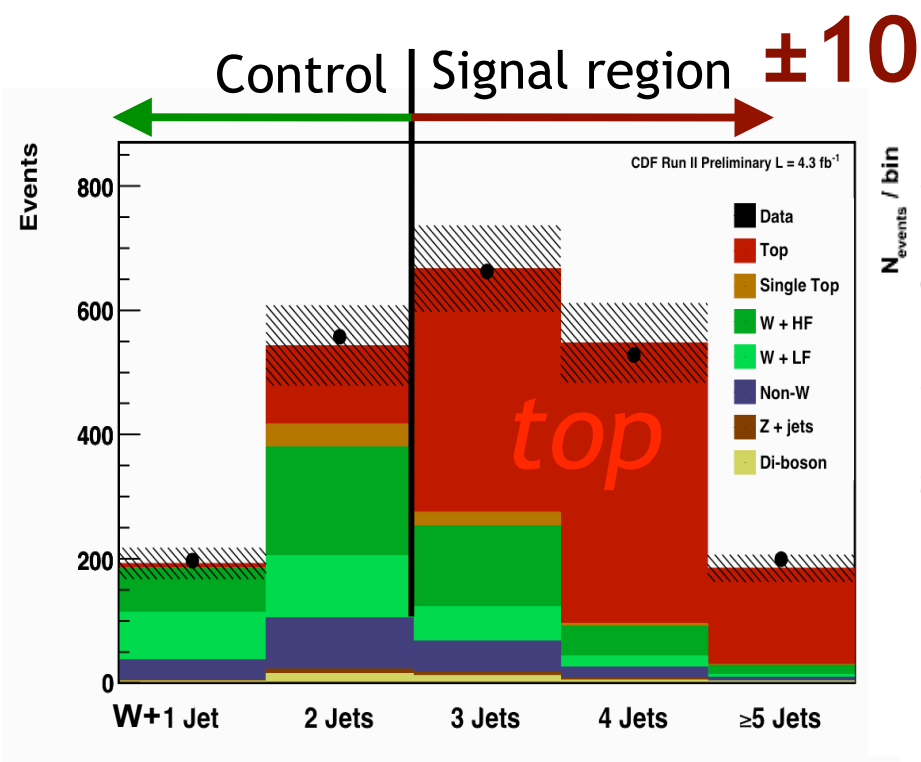


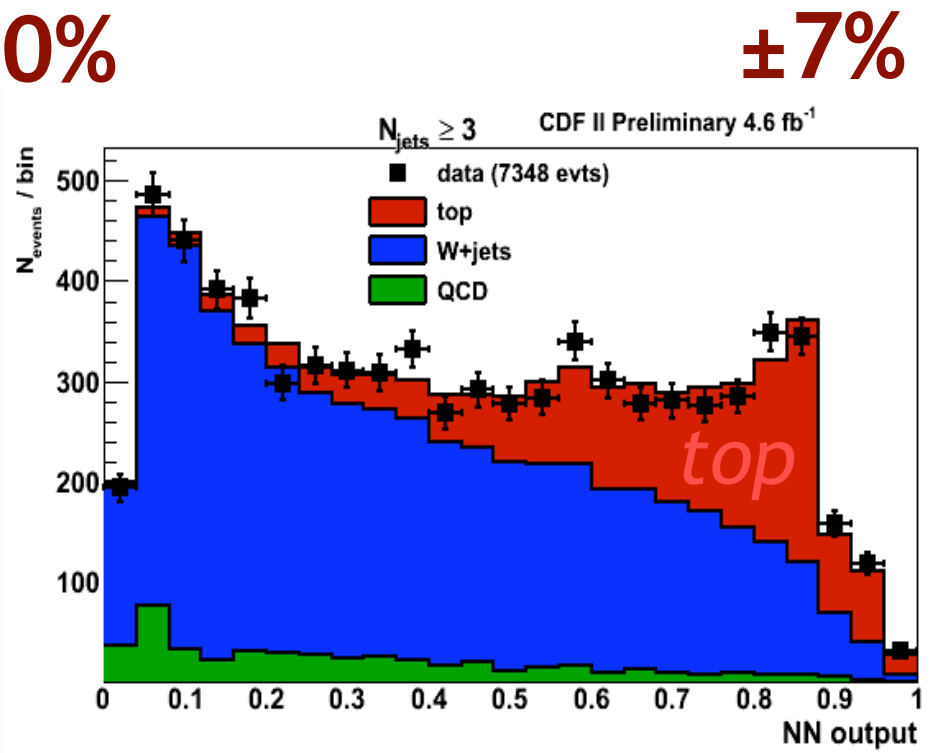
ε_b = 45-55%

ε_q = 0.5-1%

m_t=172.5 GeV

(Golden) Lepton + Jets Channel





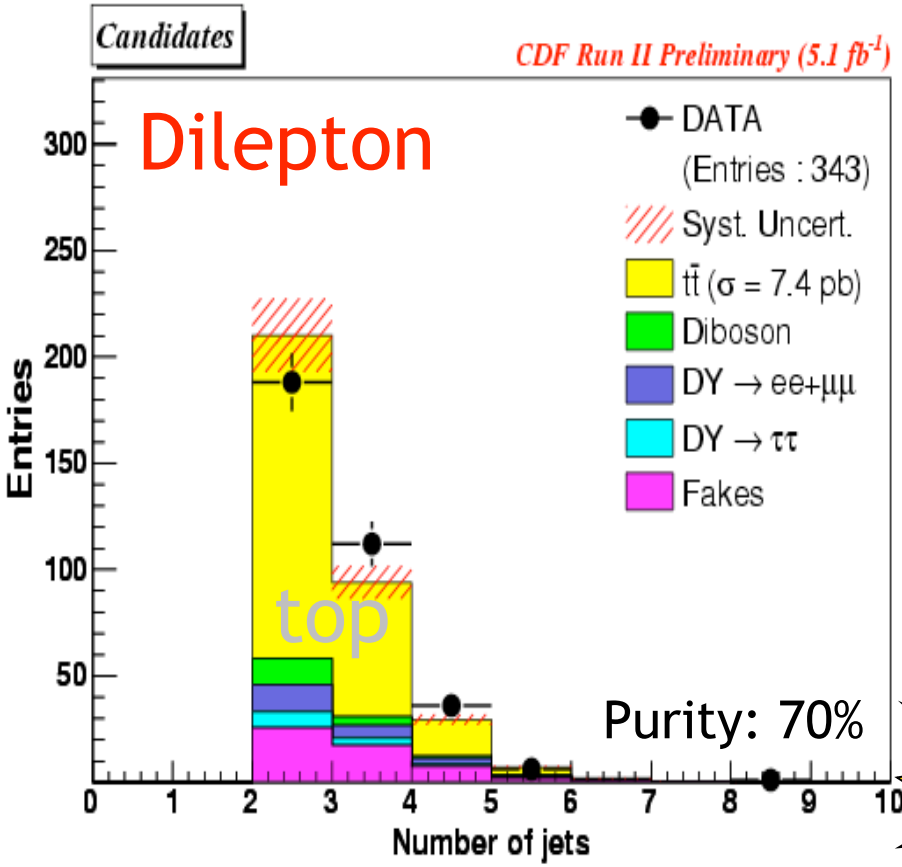
- Measure top using b-tagging *or* using topological Neural Network
- Luminosity is the largest uncertainty in both measurements
  - Reduced by normalizing to *Z cross section* $\sigma_{t\bar{t}} = R \bullet \sigma_Z^{theory}$

CDF (4.3 fb^{-1}, m_t= 172.5 GeV), b-tagged:
$\sigma_{t\bar{t}}$=7.32±0.35(stat)±0.59(syst)±0.14(Z_{theo}) pb

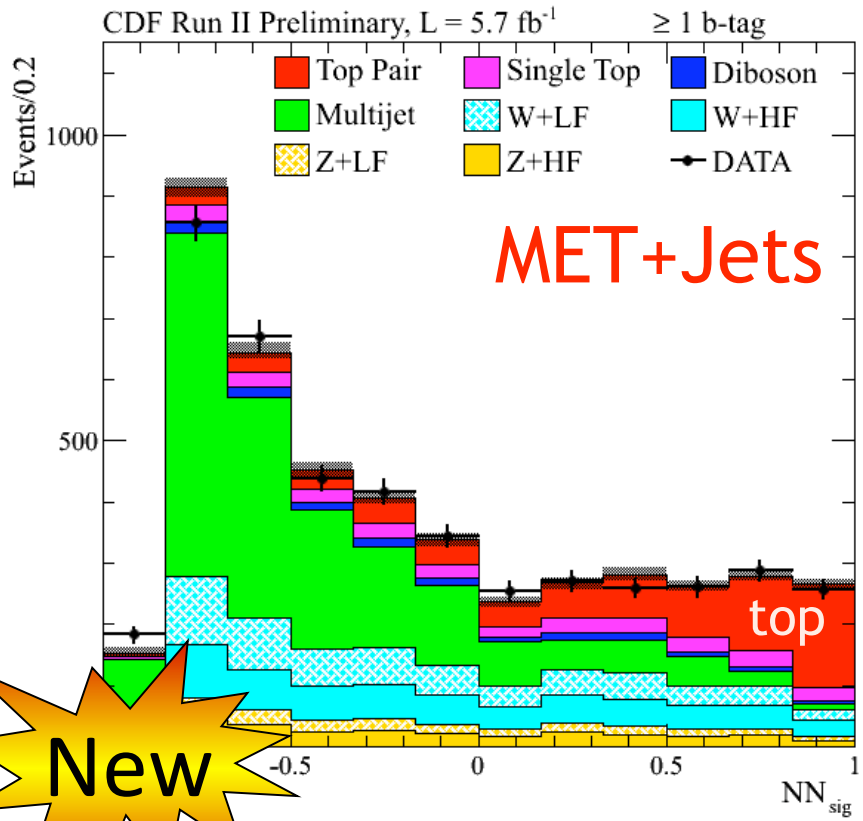
CDF (4.6 fb^{-1}, m_t= 172.5 GeV), topo NN:
$\sigma_{t\bar{t}}$=7.8±0.4(stat)±0.4(syst)±0.15(Z_{theo}) pb

Dilepton Channel and MET+Jet Channel

±13%



±17%



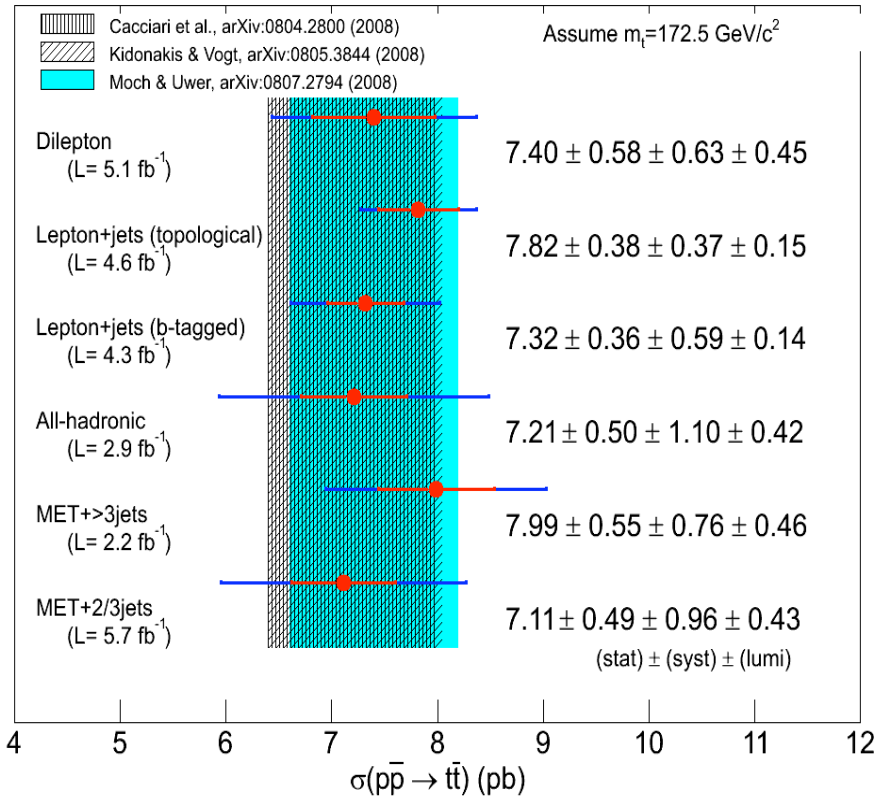
New

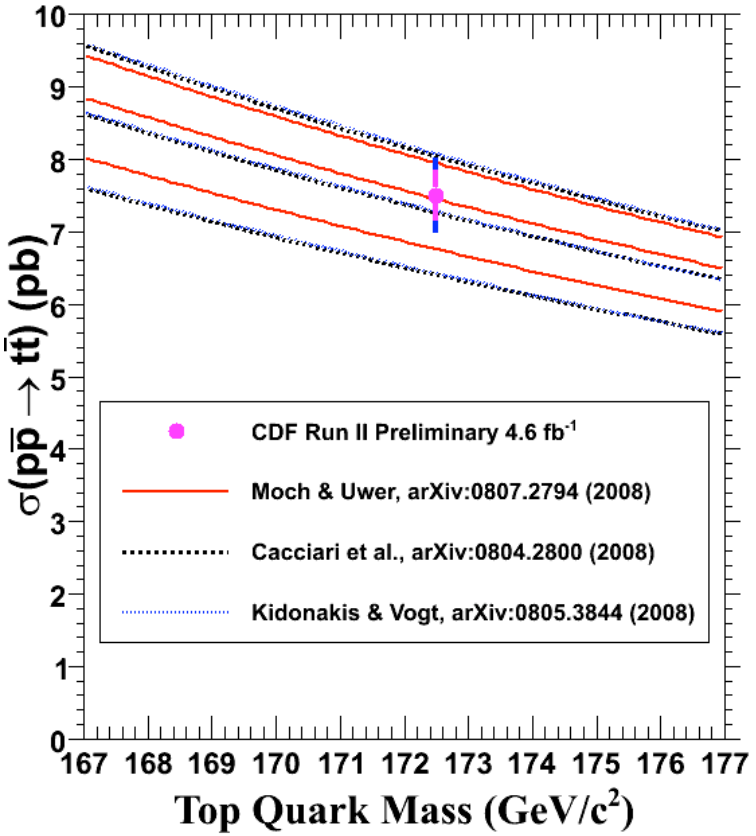
CDF (4.5 fb^{-1}, m_t= 172.5 GeV)
σ_{tt} = 7.4±0.6(stat)±0.6(syst)±0.5(lumi) pb

CDF (5.7 fb^{-1}, m_t= 172.5 GeV)
$\sigma_{tt} = 7.12^{+1.20}_{-1.12}$(stat+syst) pb

CDF Combination

±6%

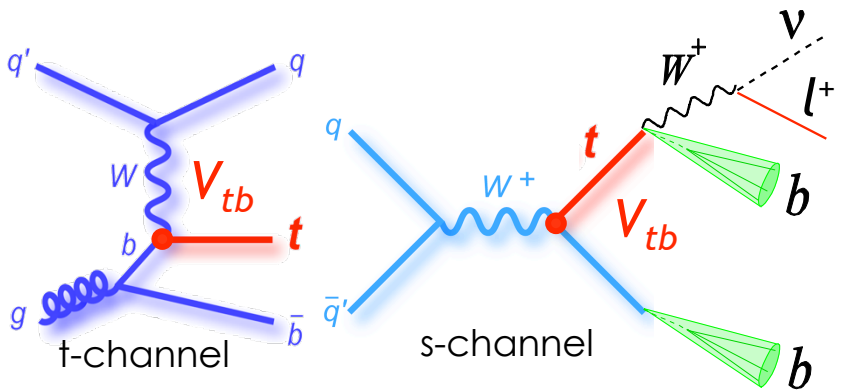




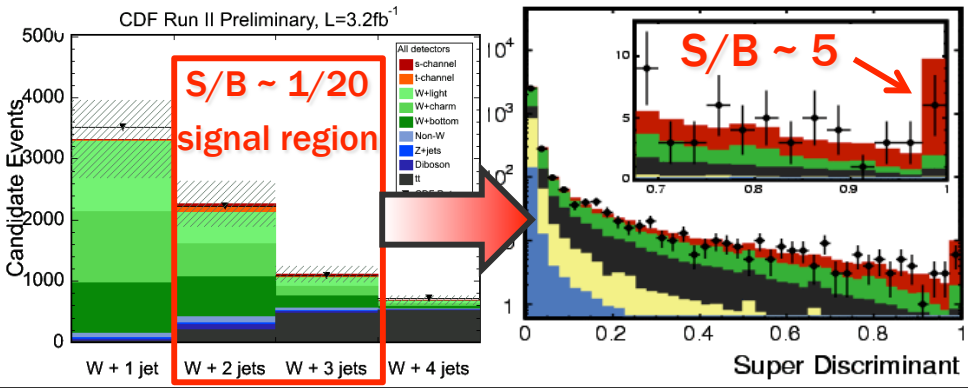
CDF Combined (4.6 fb^{-1}, m_t= 172.5 GeV)
σ_{tt} = 7.5±0.3(stat)±0.3(syst)±0.15(Z_{theo}) pb

Good agreement with Standard Model in all channels

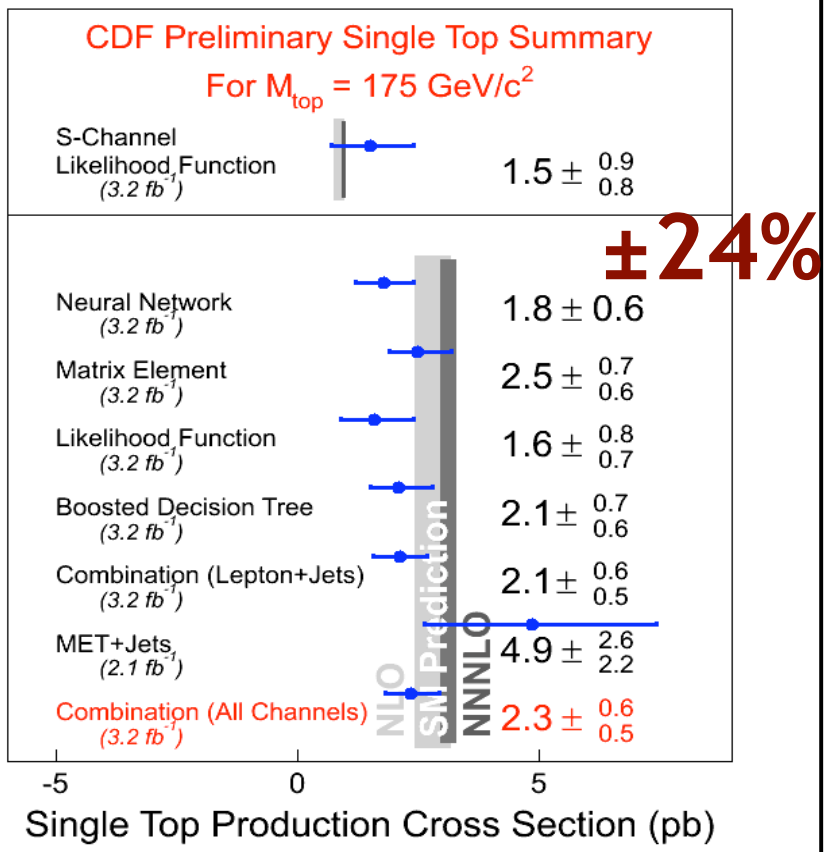
Electroeak Single Top Quark Production



- Difficult measurement
  - Small cross section / less distinct final state
  - Large backgrounds with large uncertainties
- Need advanced techniques + *b* tagging
  - *Matrix Elements, Neural Networks, BDTs,…*
  - *Added additional channel (MET+jets)*

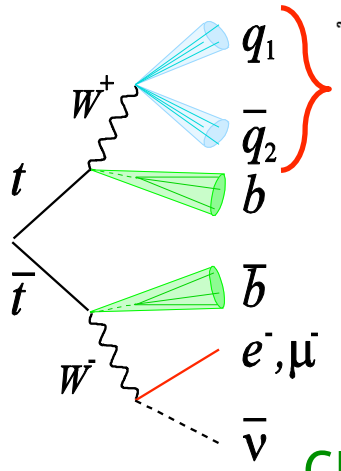


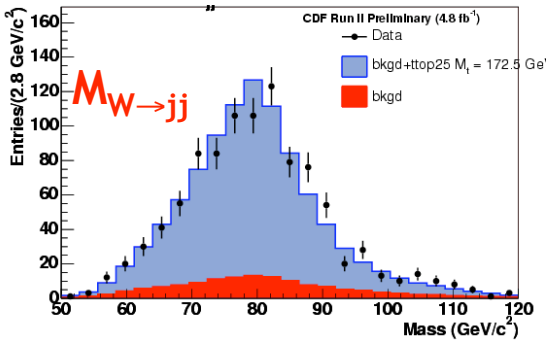
- Cross section results using different MV techniques are *consistent*
- Determine V_{tb} using combination



CDF (3.2 fb^{-1}) Combination
V_{tb}=0.91±0.11(exp)±0.07(theory)

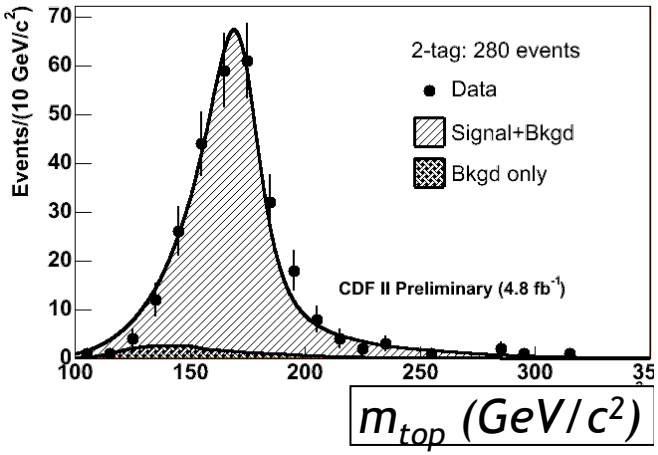
Top Quark Mass Measurement

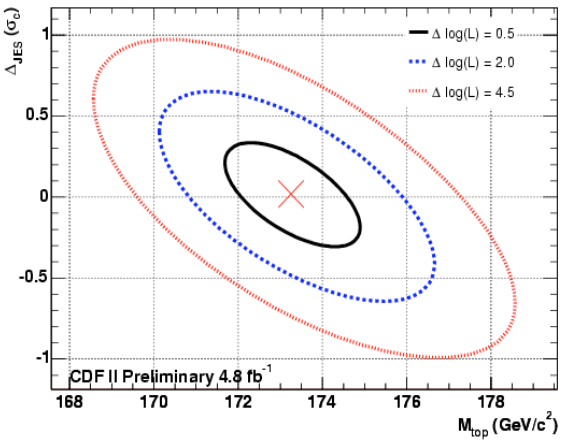


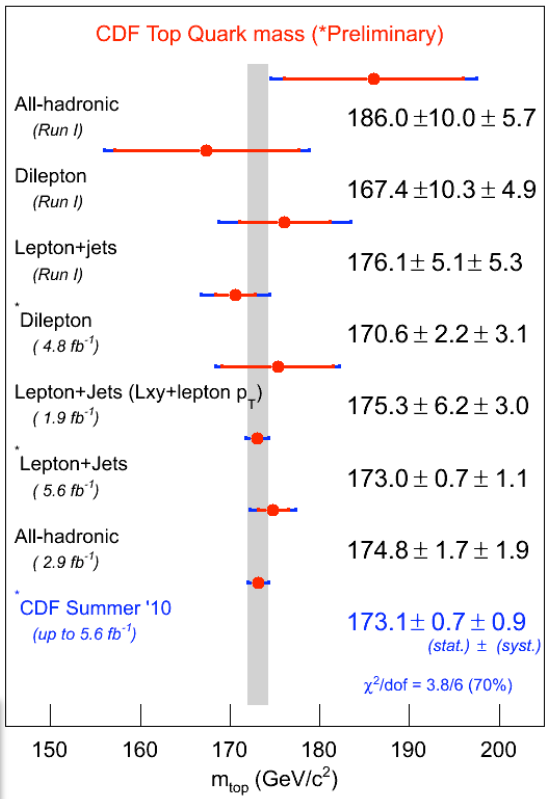


- In-situ JES calibration (*W* constraint)
- Careful evaluation of systematic effects
  → *In collaboration with theory community*
- Extract top quark mass:
  → *Templates, Matrix Element Method*

CDF Dilepton+LeptonJets combination







Main uncertainties:

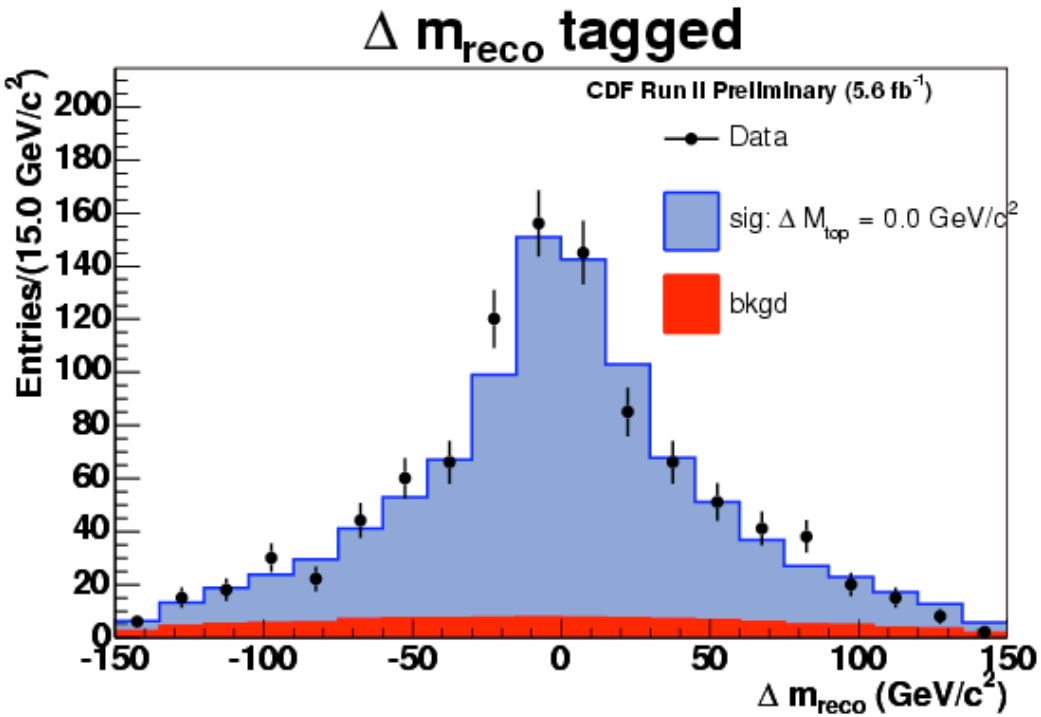
- Jet-energy-scale
- MC modeling

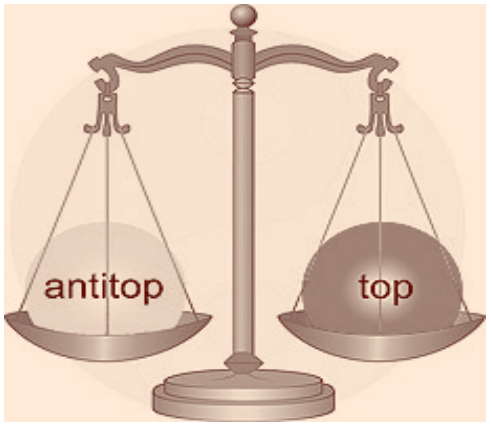
CDF (5.6 fb^{-1}) Combination

M_{top}=173.1±0.7(stat)±0.9(syst) GeV/c^2

Top Anti-top Mass Difference

- If *CPT is a good symmetry of nature:* $\Delta M_t = M_{top} - M_{anti\text{-}top} = 0$





Only measurement for a "bare quark"

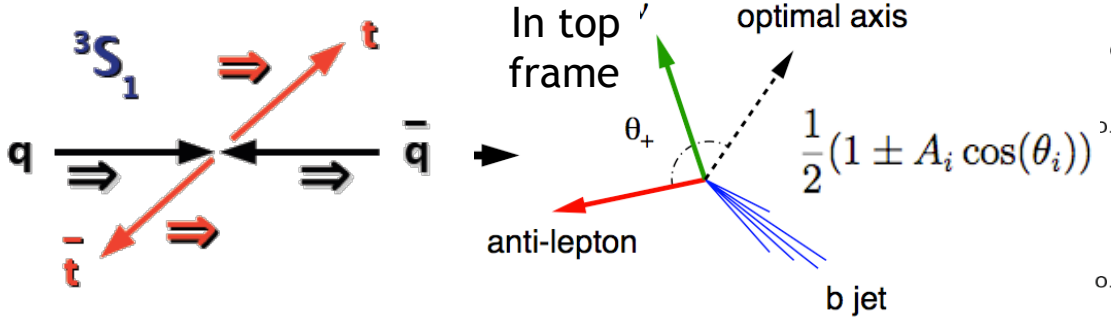
Consistent with SM expectations

CDF (5.6 fb^{-1}):
ΔM_t=-3.3 ±1.4(stat)±1.0(sys)GeV

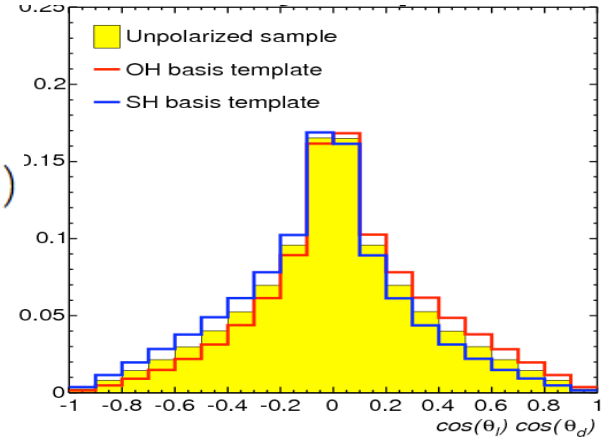
statistics limited

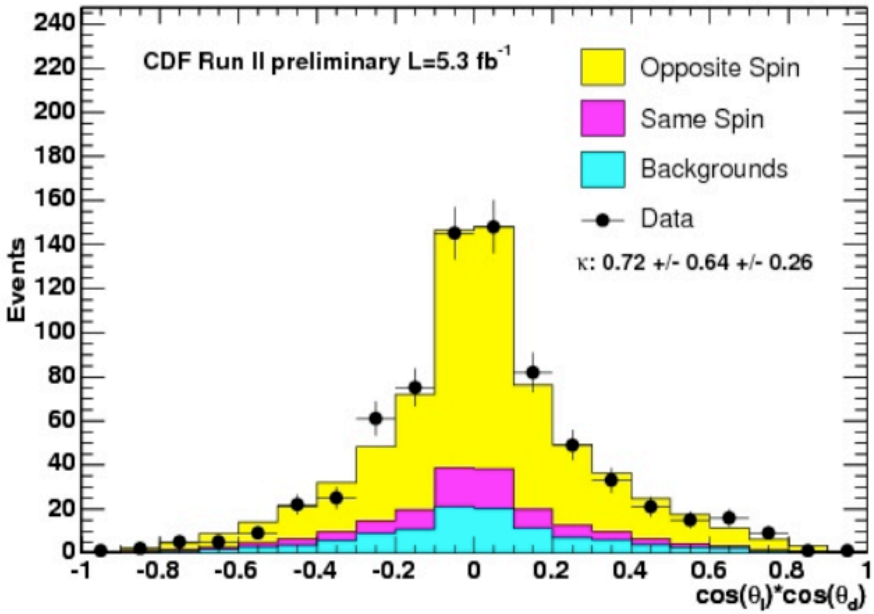
Top Quark Spin-Spin Correlations

- Top spins are correlated since *top lifetime is short (no spin decoherence)*
  - Spin-spin correlation is observable in the top quark decay products (V-A)



$$\frac{1}{2}(1 \pm A_i \cos(\theta_i))$$





$$\kappa = \frac{N(\uparrow\uparrow) + N(\downarrow\downarrow) - N(\uparrow\downarrow) - N(\uparrow\downarrow)}{N(\uparrow\uparrow) + N(\downarrow\downarrow) + N(\uparrow\downarrow) + N(\uparrow\downarrow)}$$

CDF (5.3 fb^{-1}) Lepton+Jets

κ =0.7 ±0.6(stat)±0.3(sys)

CDF (2.8 fb^{-1}) Dilepton Channel

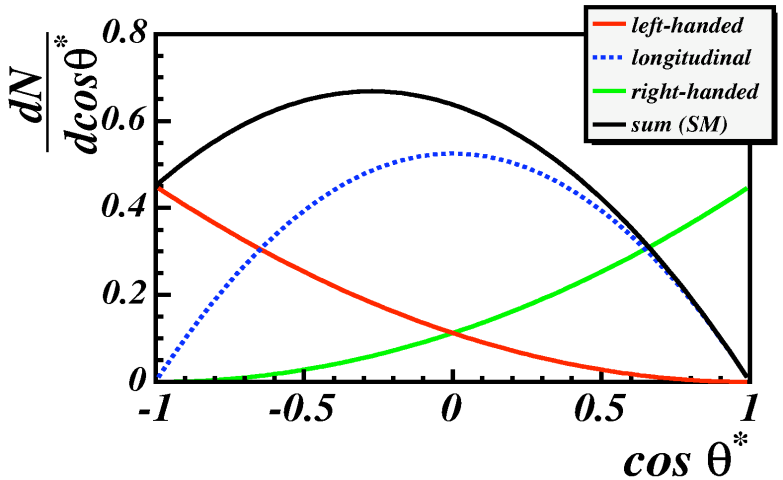
$\kappa = 0.3^{+0.6}_{-0.8}$

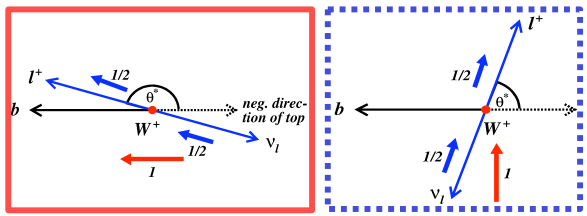
Statistically limited!

SM κ =0.77 (0.78) for beam (off-diagonal) basis

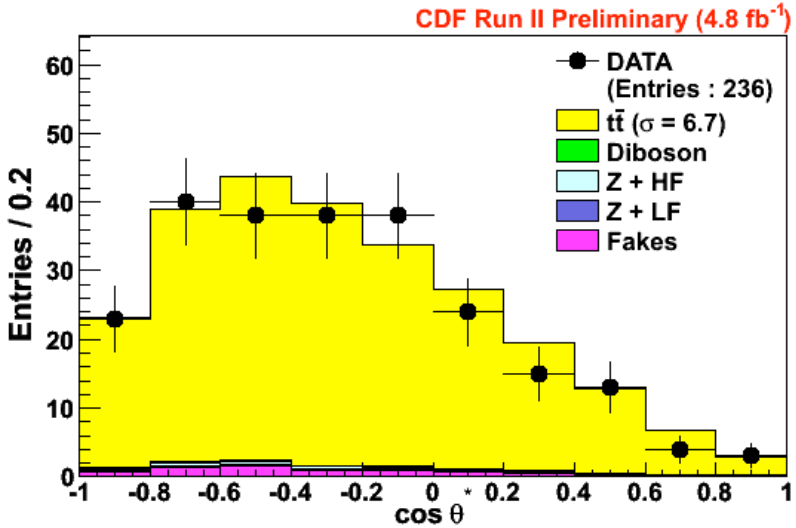
W-boson Helicity Fraction in Top Quark Decays

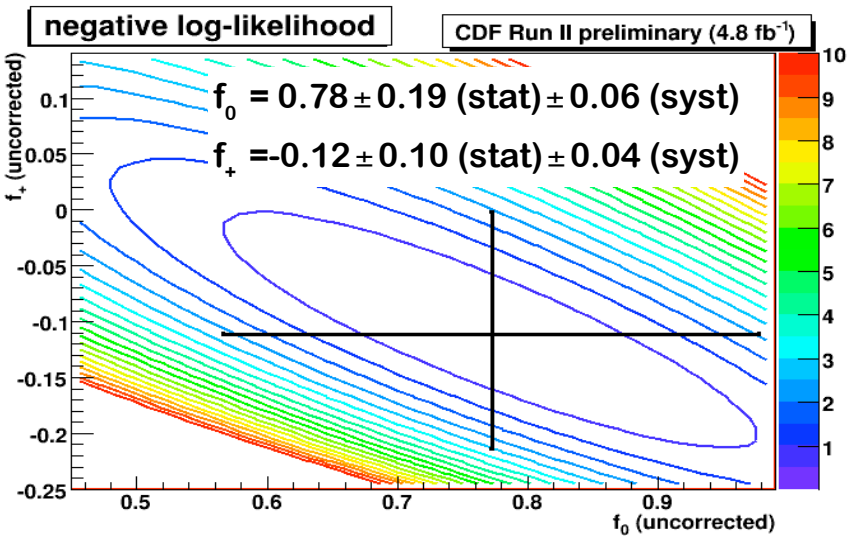
- SM top decays with (V-A) *t*-*W*-*b* coupling
- The helicity of *W* boson is predicted as:
  - Longitudinal fraction f_0 ~70%
  - Left-handed fraction f_- ~30%
  - Right-handed fraction f_+ ~0%
- Can use cosθ* to measure f_0, f_+, f_-





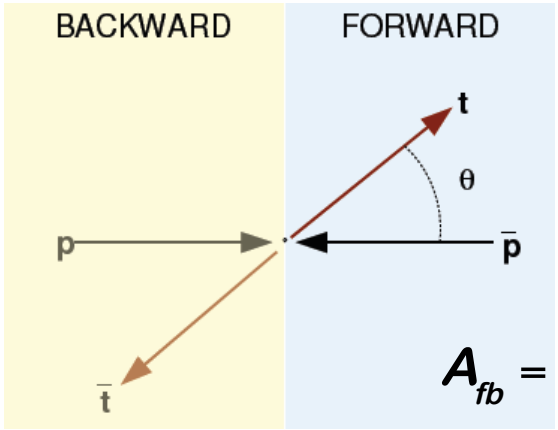
$$\frac{1}{\Gamma}\frac{d\Gamma}{d\cos\theta^*} = f_- \cdot \frac{3}{8}(1-\cos\theta^*)^2 + f_0 \cdot \frac{3}{4}(1-\cos^2\theta^*) + f_+ \cdot \frac{3}{8}(1+\cos\theta^*)^2$$



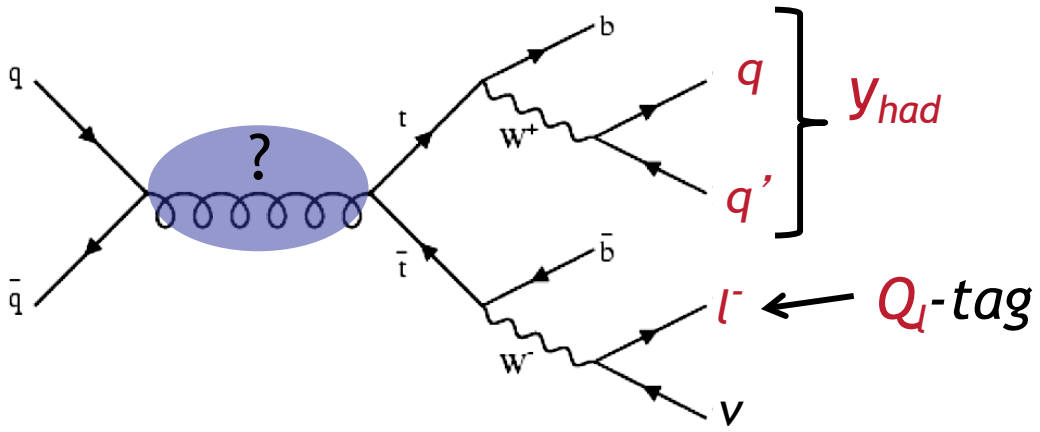


First model independent result in dilepton channel!

Forward Backward Asymmetry

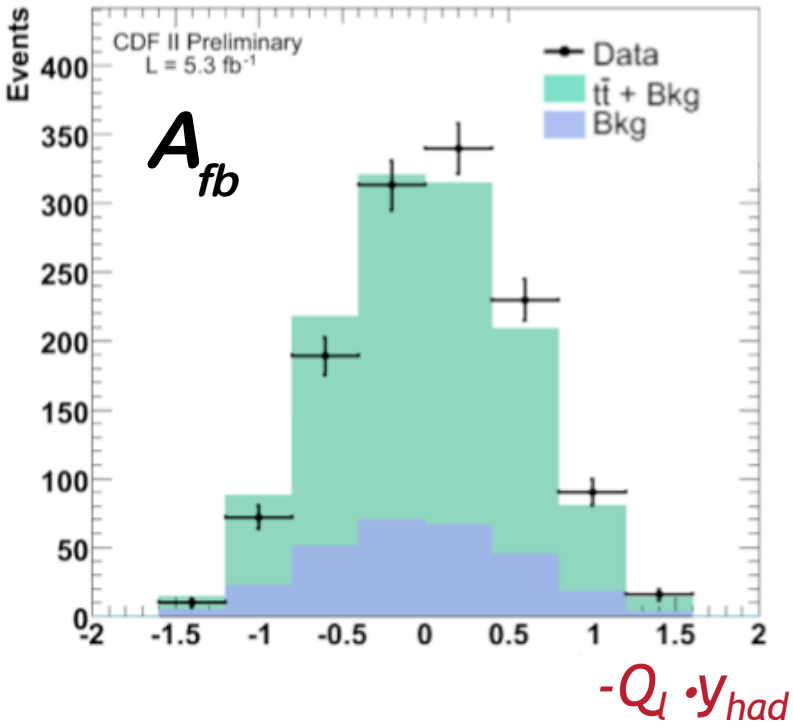


$$A_{fb} = \frac{F - B}{F + B}$$



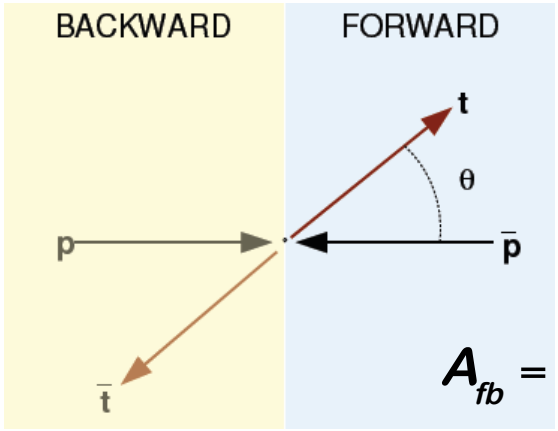
- New physics could give rise to a *asymmetry* (Z´,axigluons,..)
- Standard Model predicts at NLO: A_{fb}= ~ 5 ± 1.5 %

CDF (5.3 fb^{-1}):
A_{fb}= 15 ± 5 (stat+sys)



arXiv:1101.0034v1

Forward Backward Asymmetry



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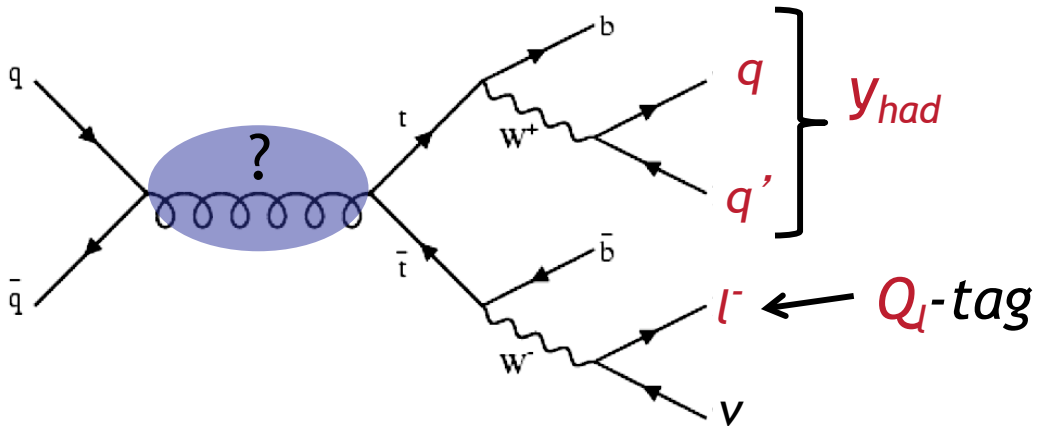

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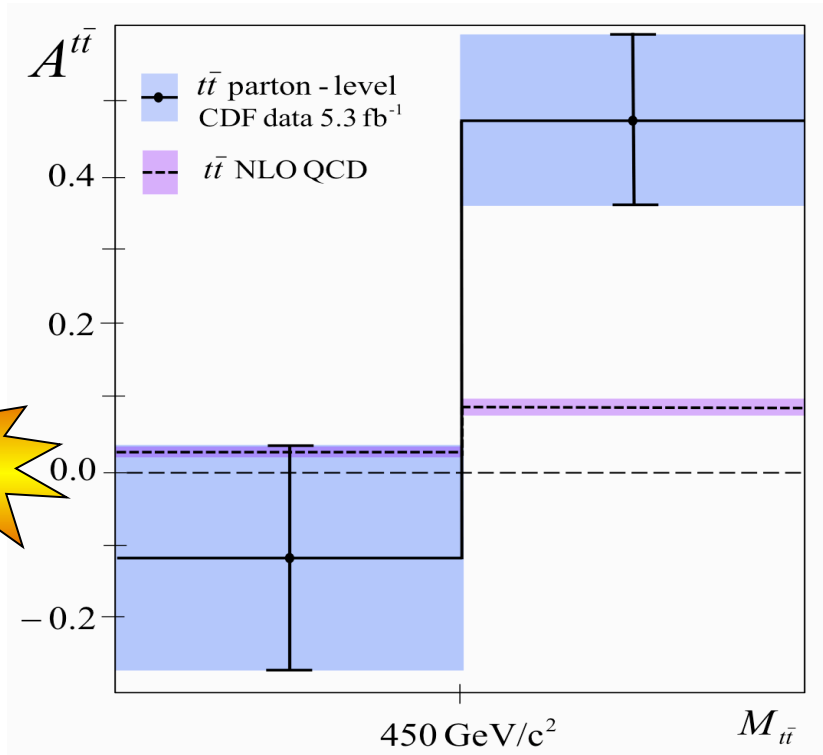
3σ

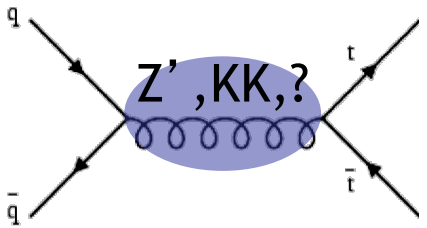


CDF (5.3 fb^{-1}):
A_{fb}= 15 ± 5 (stat+sys)

arXiv:1101.0034v1

Search for Narrow Resonance in M_{tt}

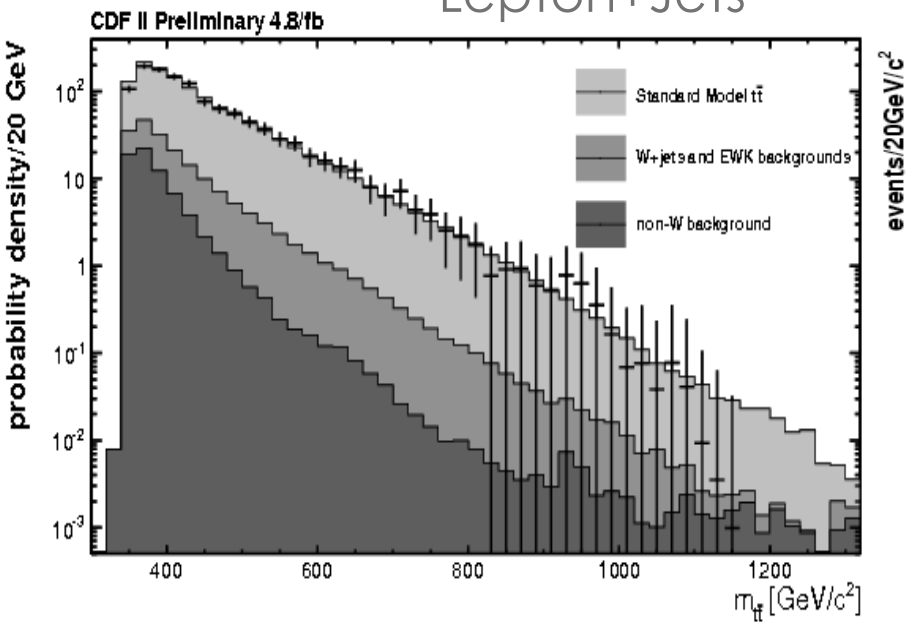
- Resonant *top pair production* is predicted by several models *beyond* the SM
  - Top color assisted technicolor with leptophobic Z´
  - Randall Sundrum KK-gluons, colorons, etc..



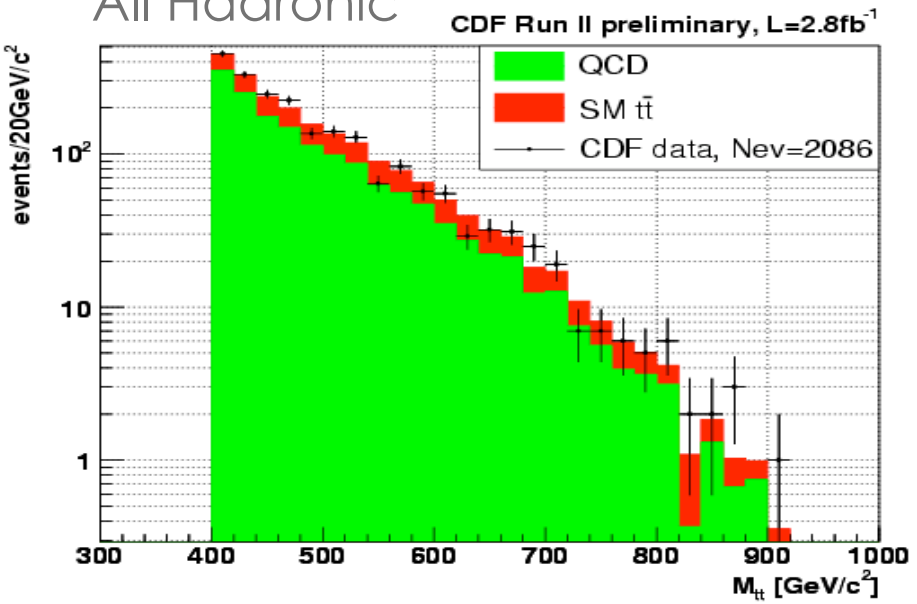
- Search for bumps in M_{tt}
  - Assume narrow width (1.2%), dominated by resolution

CDF Lepton+Jets (4.8 fb^{-1}):
M_{tt} > 900 GeV/c^2 at 95% CL
No evidence yet beyond SM prediction

Lepton+Jets

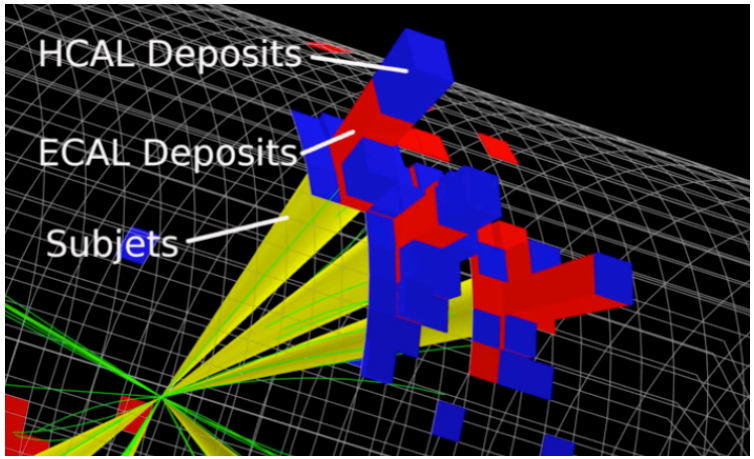


All Hadronic

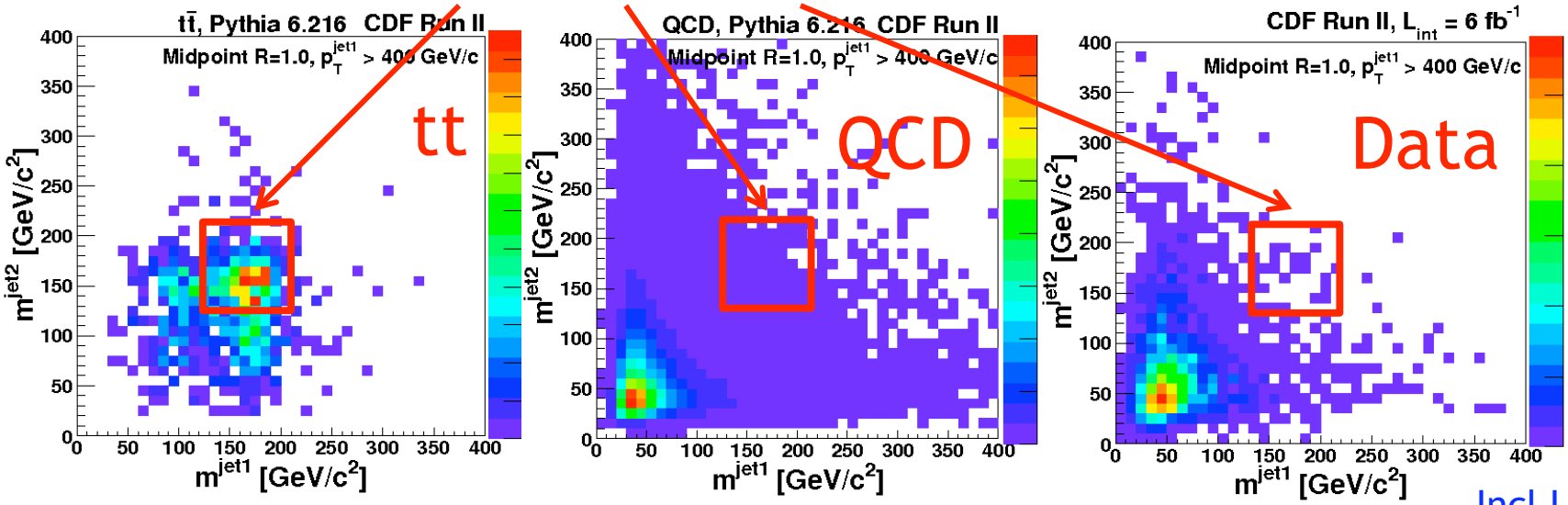


Boosted Top Quarks

- Resonant top pair production at very high mass will suffer from "***jet merging***" due to highly boosted tops
- Search for massive top-jets in high p_T inclusive jet sample (p_T>400 GeV)



Search Window



Expect: N_{ttbar} ~ 5 events N_{QCD} = 44±8(stat)±13(syst) N_{obs}=58 events

Incl L+Jets (not shown)

For at least one (two) boosted top jets we limit: σ < 40 (20) fb at 95% C.L.

Conclusions

- The discovery of the top quark opened up a rich field in HEP
- Precision top quark physics is a reality at CDF
  - *Several thousand top events are currently selected and analyzed*
  - *Precision on top quark mass < 0.7 %*
  - *Production cross section measurements are theory limited*
- Searches are now a very active part of the program
  - Constitute ~30% of all new results
  - Tension with Standard Model (A_{FB}) is intriguing
- Several measurements/searches will greatly benefit from full Tevatron Run-II dataset (~9-10 fb^{-1} for top analyses)

Continue to explore the truth about the top...

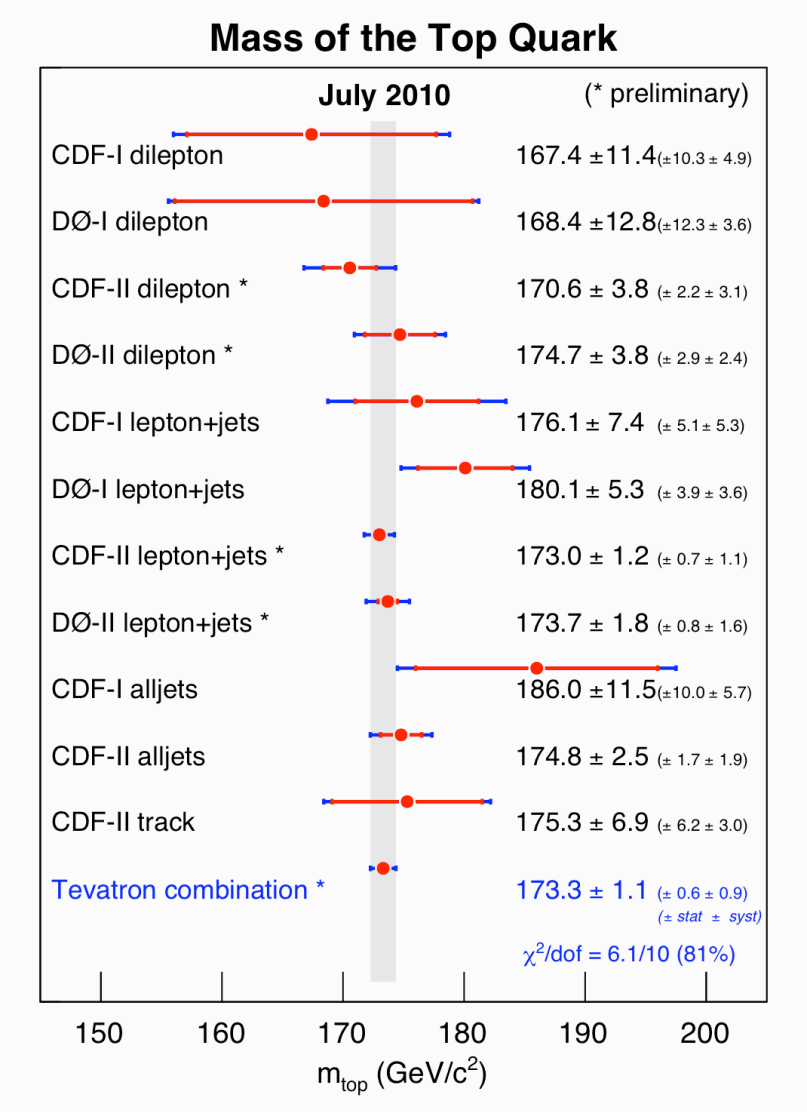
http://www-cdf.fnal.gov/physics/new/top/top.html

Backup

Summary

How is Top Produced	How Does Top Decay	What are Top's Intrinsic Properties
$\sigma_{tt} = 7.50$ $\delta \sim 6\ \%$	$F_0 = 0.88$ $\delta \sim 10\ \%$	$M_t = 173.3$ $\delta \sim 0.6\ \%$
$\sigma_{s+t} = 2.8$ $\delta \sim 19\ \%$	$F_+ = -0.15$ $\delta \sim 10\ \%$	$\Gamma_t = 2.1$ $\delta \sim 25\ \%$
$\sigma_t = 3.1$ $\delta \sim 30\ \%$	$V_{tb} = 0.88$ $\delta \sim 9\ \%$	$\kappa = 0.7$ sig ~ 1 σ
		$q \neq -4/3$ @ 95%CL
• Strong Force $\sigma_{tt} \sim 7.5$ pb • Electroweak $\sigma_{s+t} \sim 3$ pb	• V-A $F_0 \sim 0.7$, $F_+ \sim 0$ • $V_{TB} \sim 1$	• Mass • Width $\Gamma_t \sim 1.3$ GeV • Spin 1/2 • Charge +2/3

Tevatron Results



Tevatron (July 2010):
m_t=173.3 ± 0.6(stat) ± 0.9(syst) GeV

Results from different channels are *consistent*

Different techniques to measure m_{top} produce *consistent* results

Ongoing work on improving systematic uncertainties (CDF+D0+theory community)

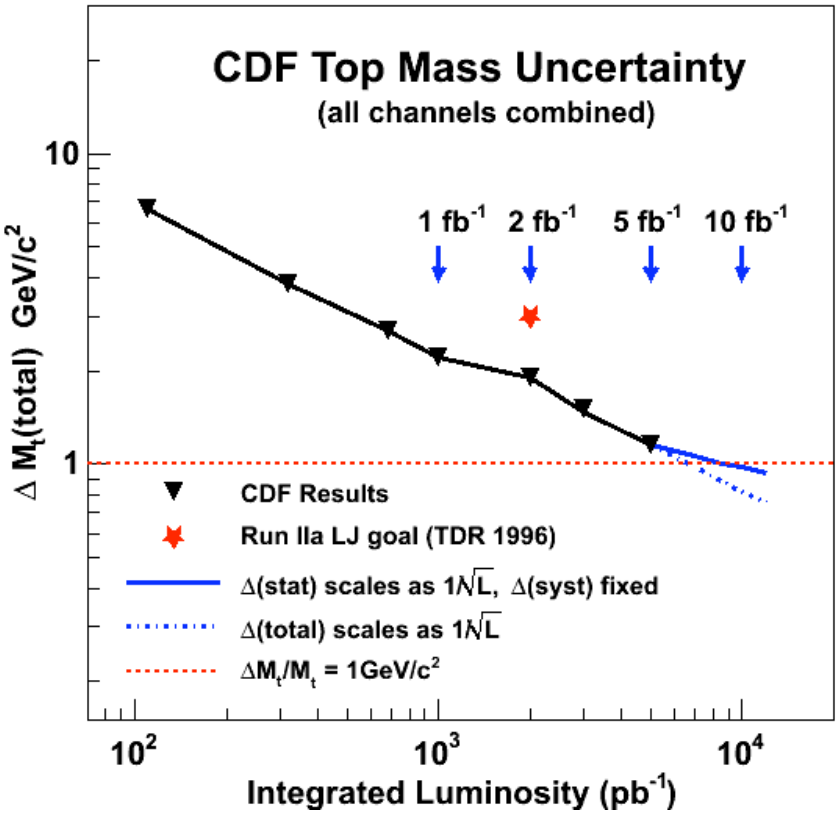
- *Are all sources of uncertainty covered?*
- *Is there overlap?*

χ^2/ndof 6.1/10 ⇒ 81 % probable

arXiv:1007.3178

Top Quark Mass - Projecting the Future

CDF projections:

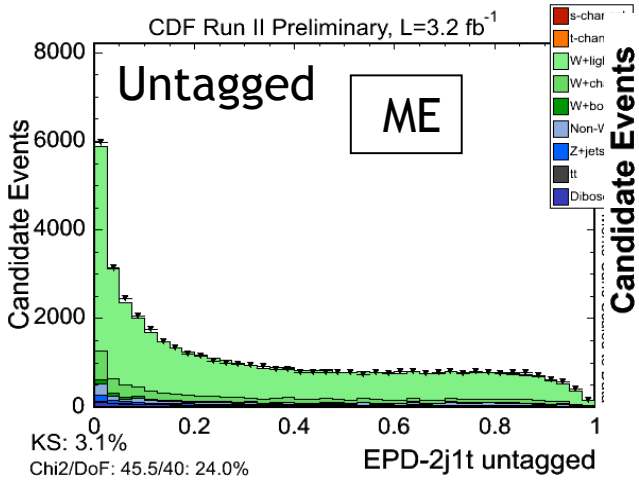


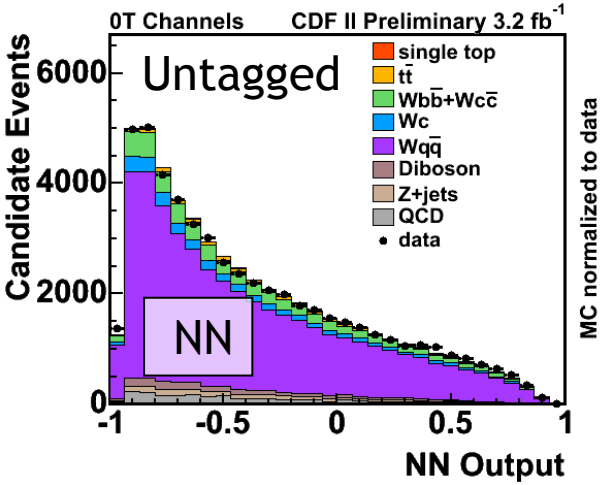
Lepton + Jets 4.3 fb^{-1}

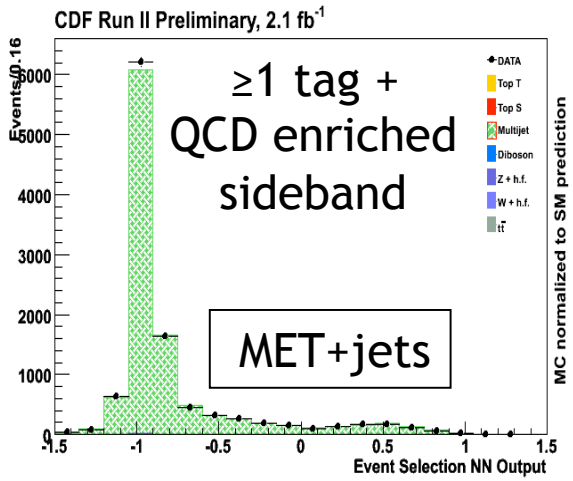
Systematic Source	Δm_{top} [GeV]
Calibration	0.1
MC generator	0.5
QCD Radiation	0.4
Residual jet energy scale	0.5
b-jet energy scale	0.4
Lepton p_T	0.2
Multiple hadron interactions	0.1
PDFs	0.2
Background	0.5
Color reconnection	0.3
Total	**1.1**

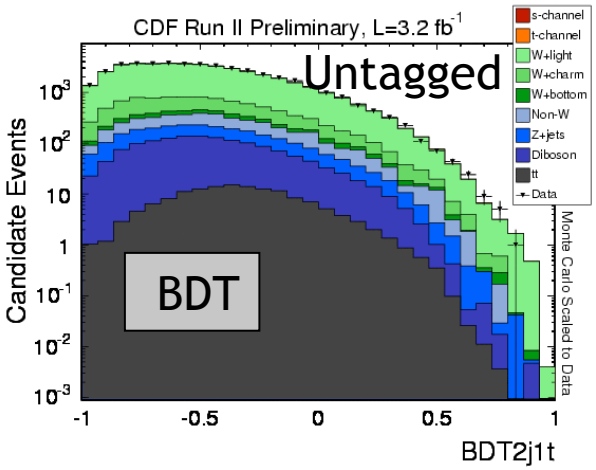
Magnitude of systematic uncertainties are comparable.
Top quark mass precision for single measurement approaches 1 GeV

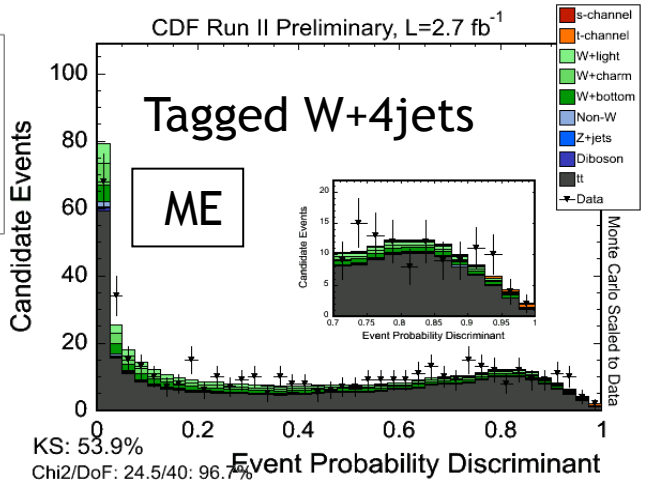
Single Top MVA Validation in Data Control Samples

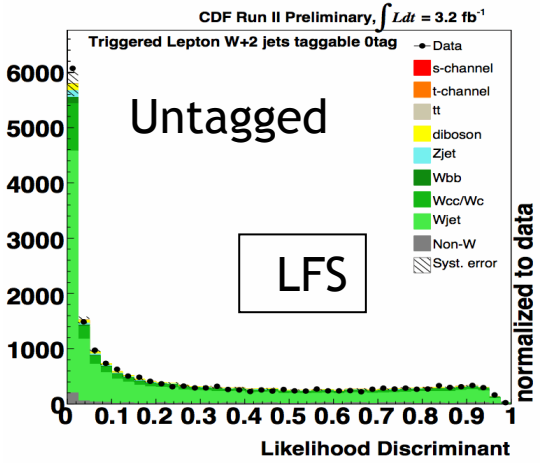












Extensive cross checks to validate MC modeling before unblinding the signal region.