Top quark physics at CDF: status and prospects

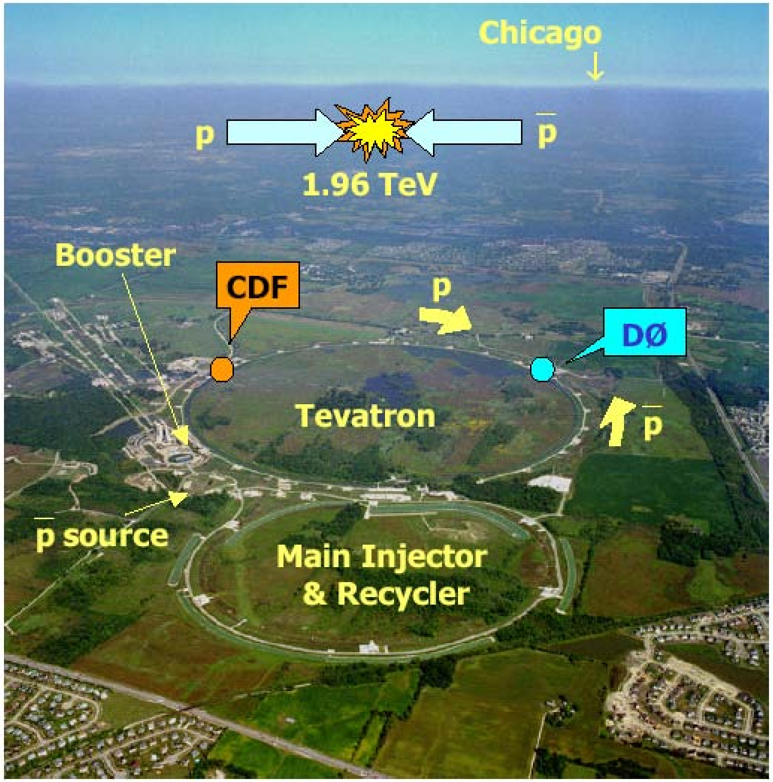
Sandra Leone
(INFN Pisa)
for the CDF Collaboration

HQL10 Frascati, October 14th, 2010

Outline

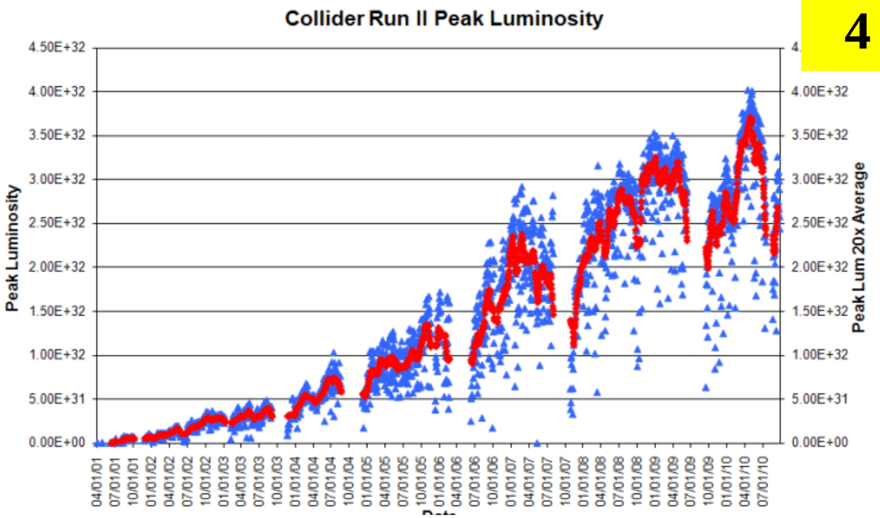
- The Tevatron & CDF
- Exploring top quark physics at the Tevatron:
  - ✓Pair production cross section
  - ✓Single top production
  - ✓Top mass and other properties
  - ✓Search for new physics in top sample
- Prospects & Conclusion

Tevatron Performances



Run II: $\sqrt{s}$ = 1.96 TeV

Performances have kept improving since the start of Run II.



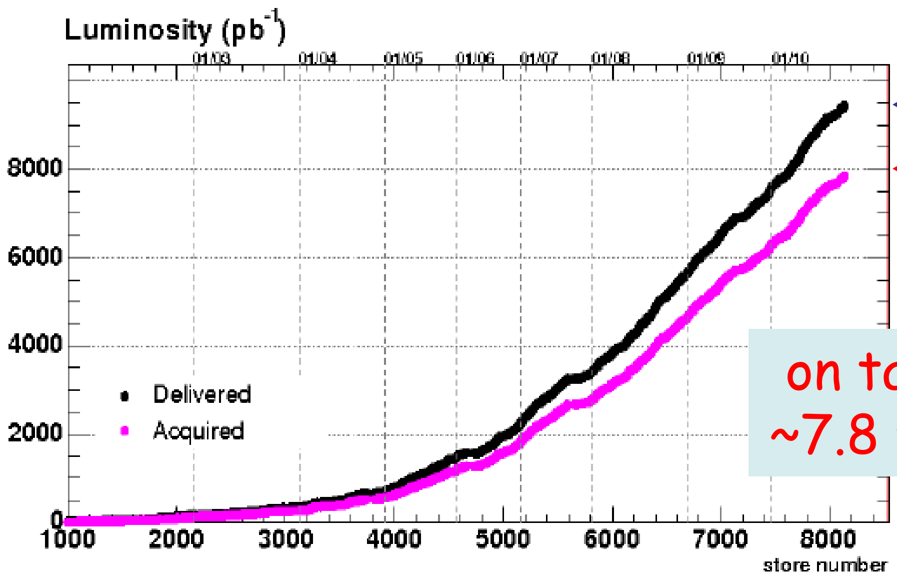
Peak luminosity

Accelerator complex breaking records all the time:

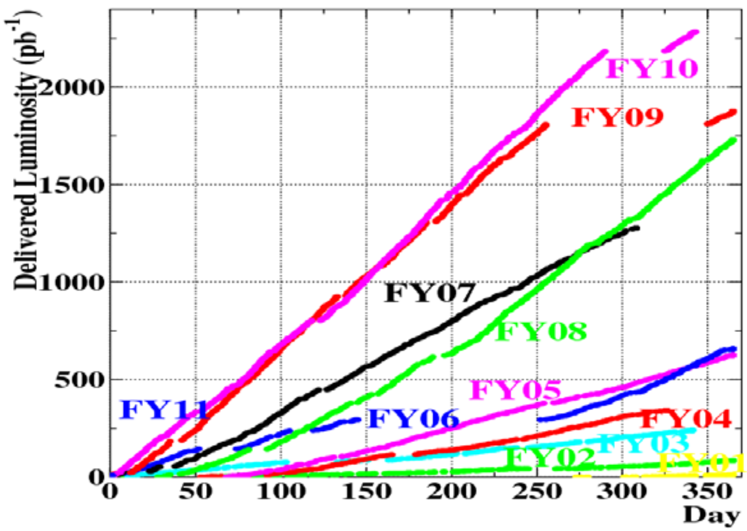
Peak Luminosity record ~ $4 \cdot 10^{32}$ cm^{-2} s^{-1}

Weekly integrated luminosity record 73 pb^{-1}

Integrated Luminosity



on tape
~7.8 fb^{-1}



We have collected > 100 times more data than what was used to discover the top quark.

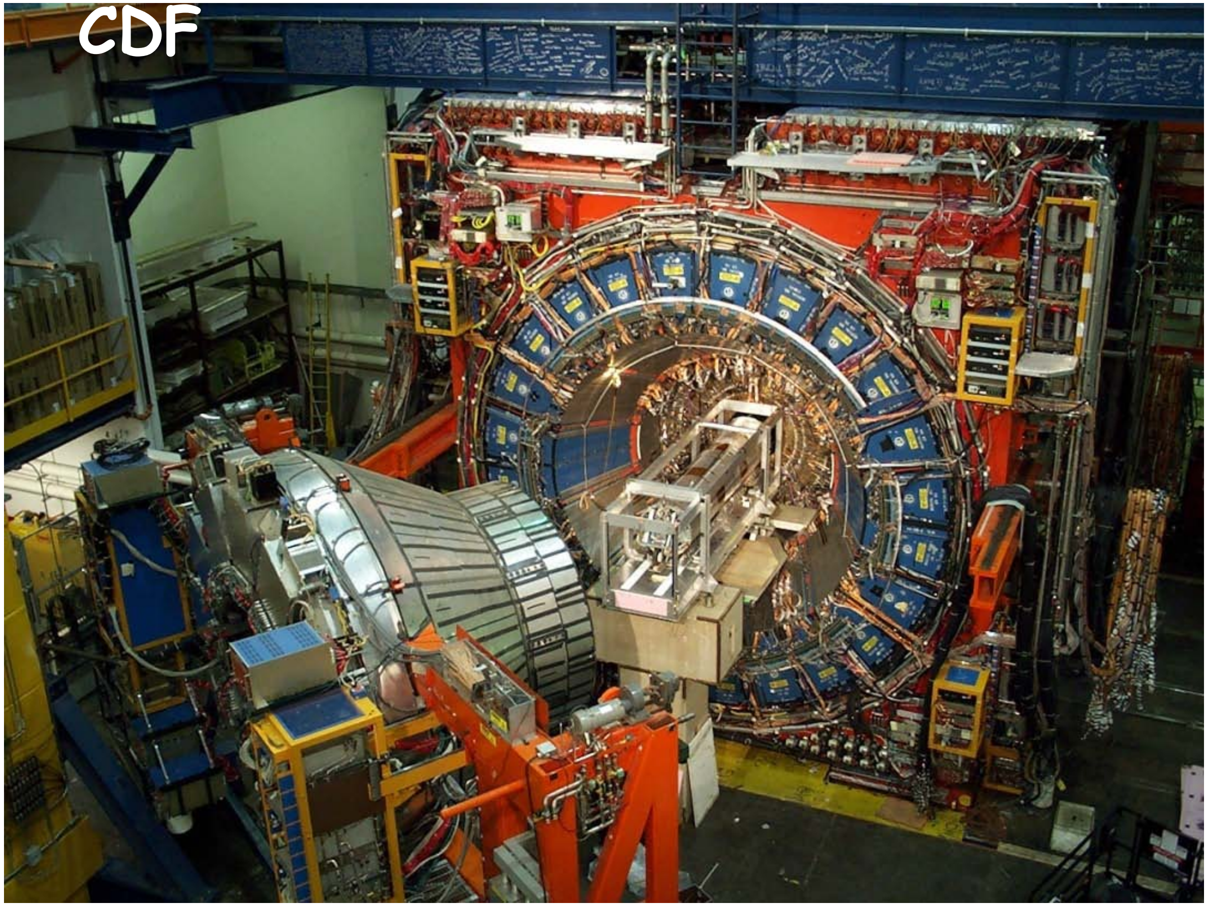
delivered: ~ 9.4 fb^{-1}

Detector running stably since Feb. '02

Data taking efficiency L(recorded)/L(delivered) commonly > 85%

All results shown in the following based on datasets up to 5.7 fb^{-1}

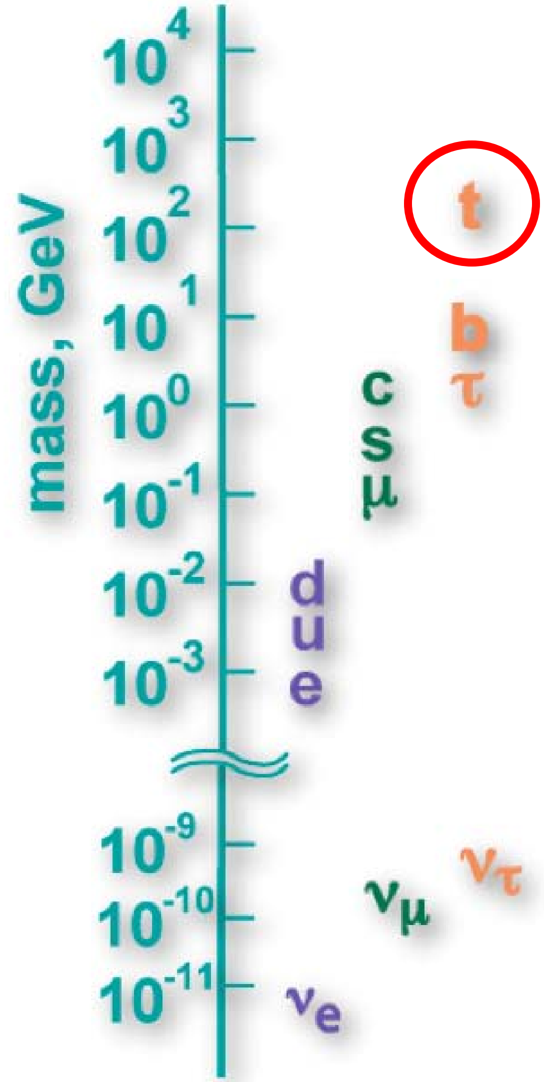
The CDF Experiment



- CDF is a general purpose detector, capable of many different physics measurements
- Large international collaboration, 500+ members

Why study the Top Quark?

- Top quark discovered in 1995 at the Tevatron
- It is a very special particle:
  - ⇒ Heavier than all known particles
  - ⇒ Decays before hadronizing: Γ_{top}=1.5 GeV > Λ_{QCD}



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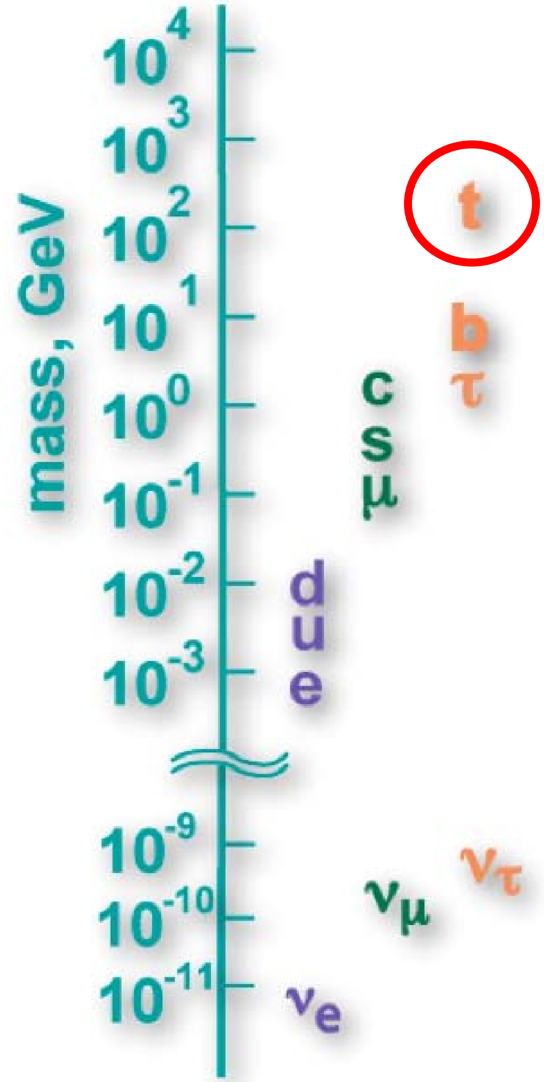

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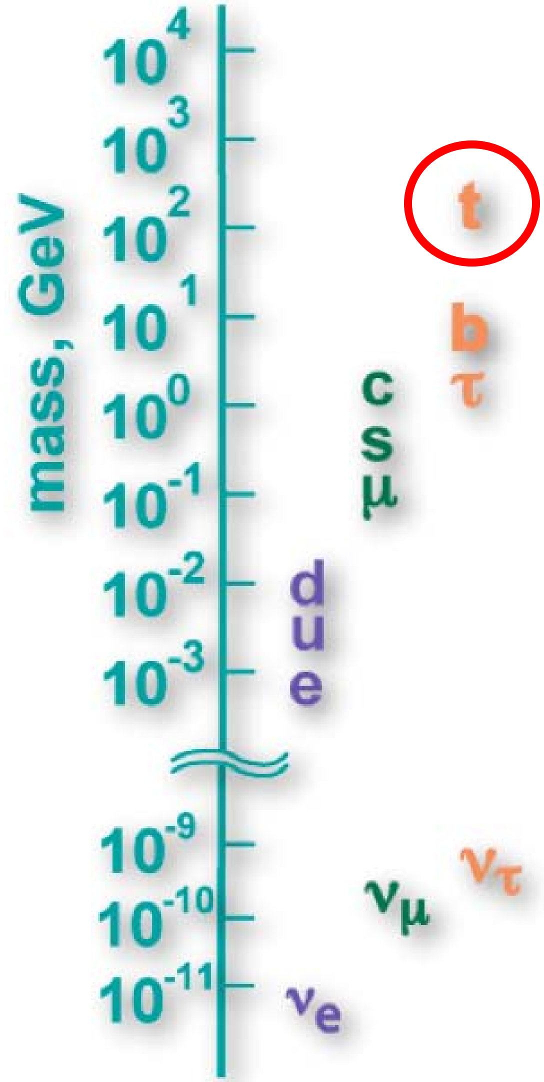

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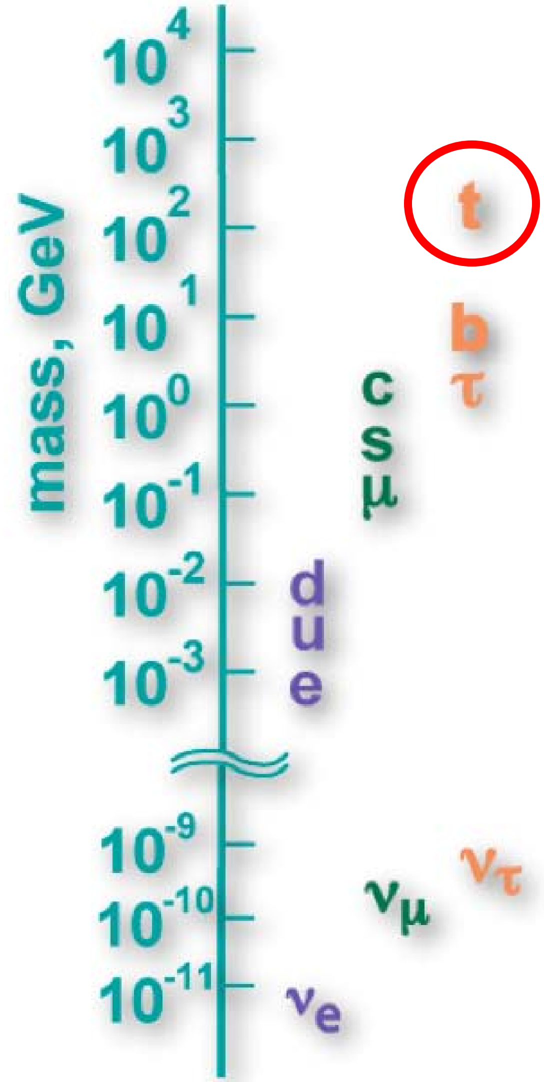
- Tevatron program explores all these possibilities



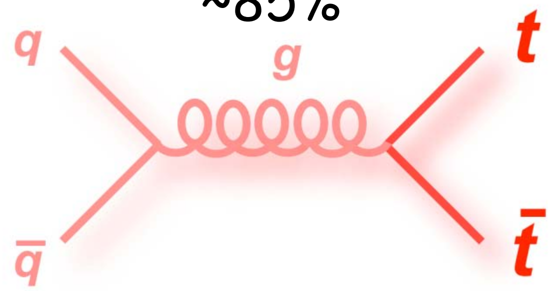
Top Quark Production at Tevatron

- QCD pair production

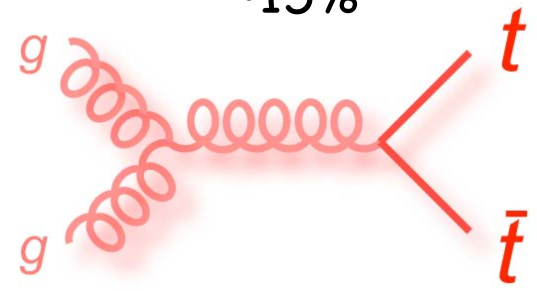
$\sigma_{NNLO} = 7.4\ ^{+0.5}_{-0.7}$ pb
(for m_{Top}= 172.5 GeV)

JHEP 0809, 127 (2008)

~85%



~15%



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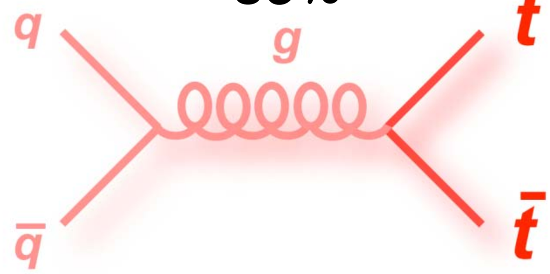
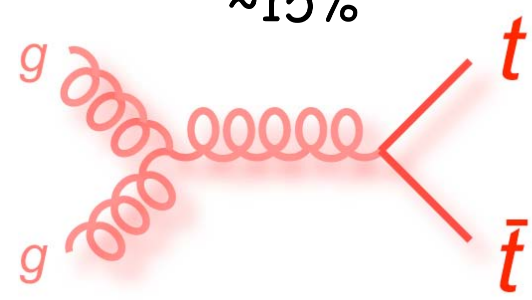


~15%

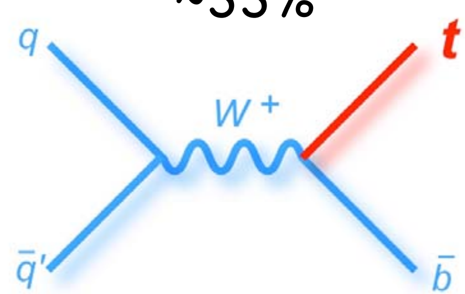


- EWK single-top production
  - s-channel: σ_{NLO} = 0.9 pb
  - t-channel: σ_{NLO} = 2.0 pb

(Both for m_{Top}= 175 GeV)
PRD 66, 054024 (2002)

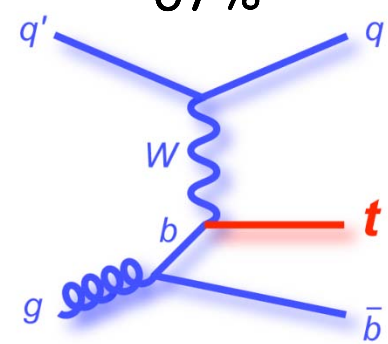
s-channel

~33%



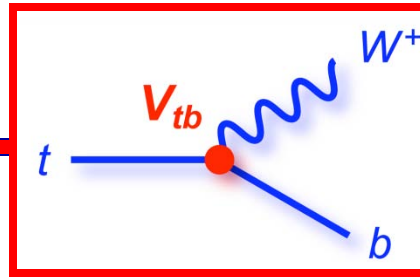
t-channel

~67%

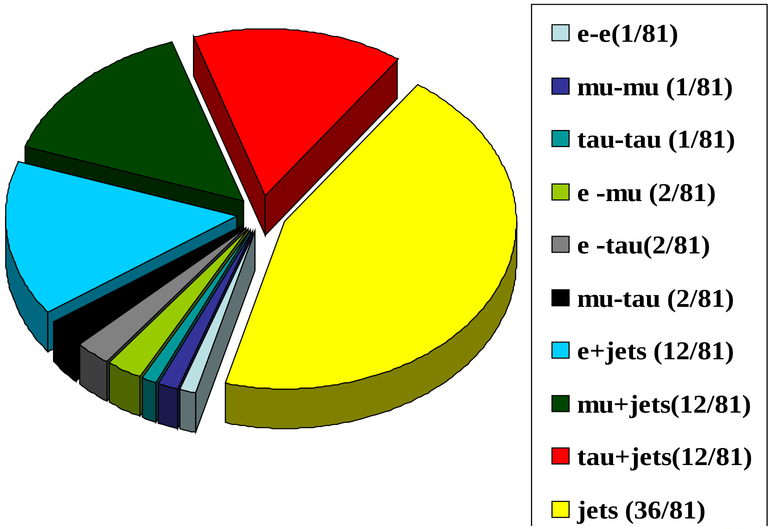


- σ smaller than top pair production, but ➡ allows direct access to V_{tb} CKM matrix element: cross section $\propto |V_{tb}|^2$

Top Quark Decay



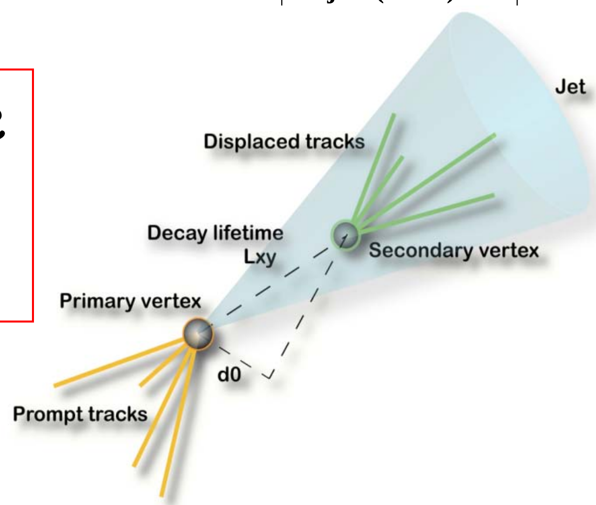
SM predicts BR($t \to Wb$) ≈ 100%



For ttbar pairs:
Event topology determined by the decay modes of the 2 W's in final state. Always b jets are present

- Dilepton (ee, μμ, eμ)
  - ⇒BR = 5%, 2 high-P_T leptons + 2 b-jets + large missing-E_T
- Lepton (e or μ) + jets
  - ⇒BR = 30%, single lepton + 4 jets (2 from b's) + missing-E_T
- All Hadronic:
  - ⇒BR = 44%, six jets, no missing-ET
- τ_{had} +X
  - ⇒BR = 21%

b jets are always present



Top pair production: Dilepton Channel

High purity sample, good test of signal model

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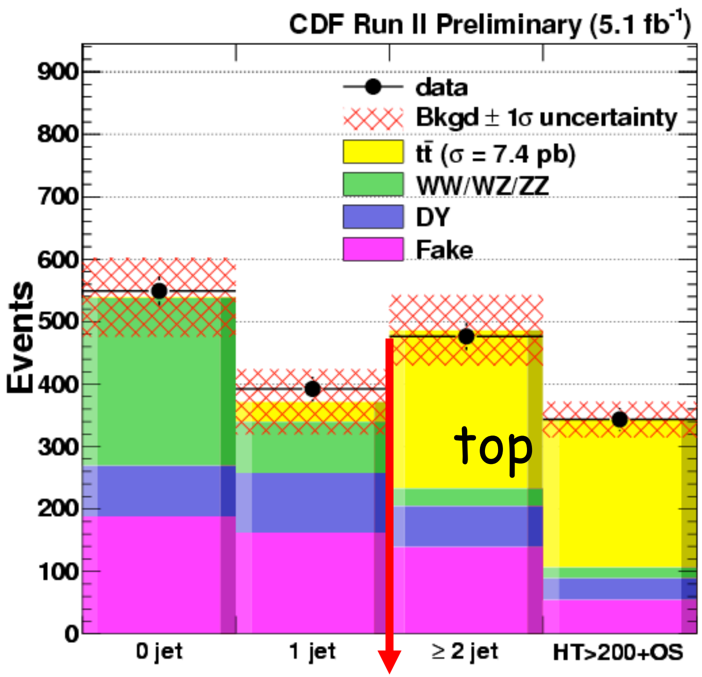
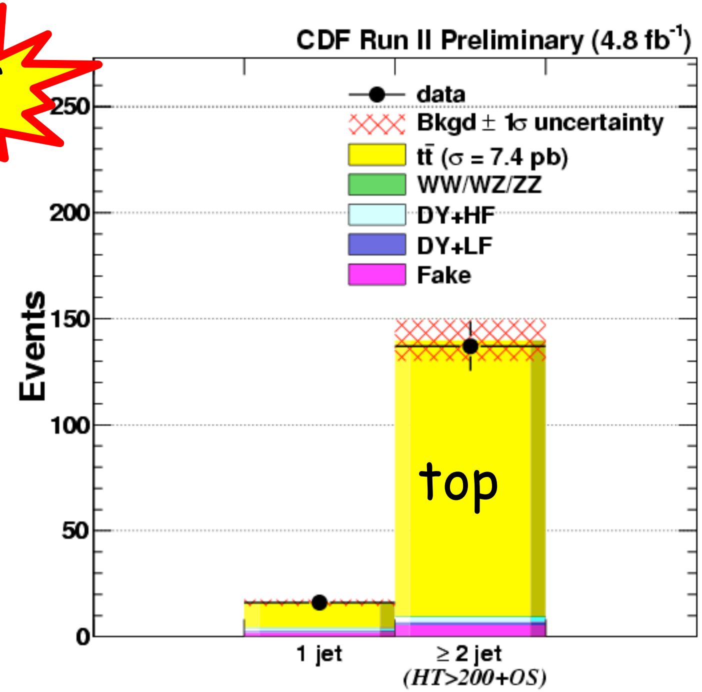


Control Signal region

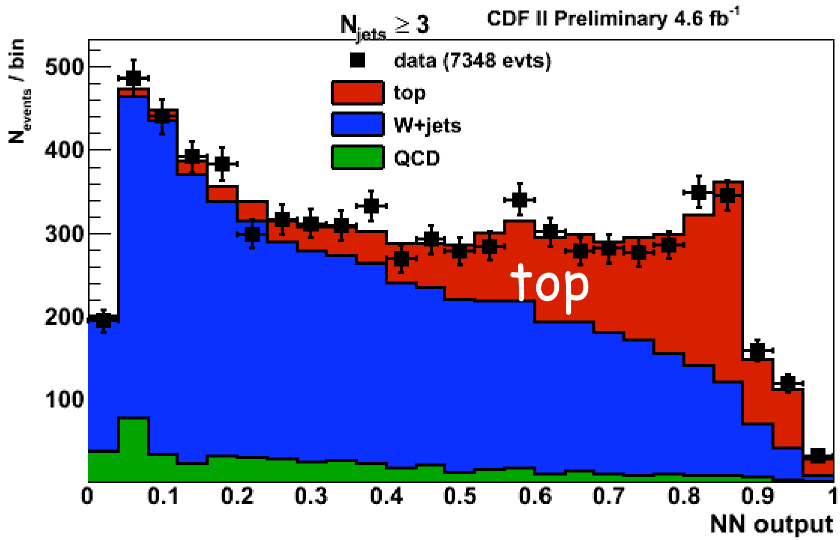


CDF (4.8 fb^{-1}, m_t= 172.5 GeV), b-tagged,
σ_{tt}(dil)=7.25±0.7(stat)±0.5(syst)±0.4(lum)pb

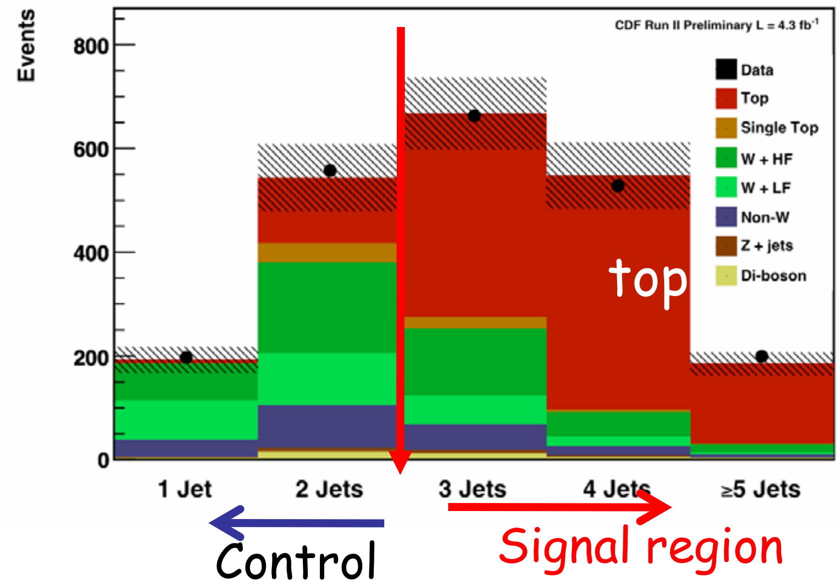
CDF (5.1 fb^{-1}, m_t= 172.5 GeV), pre-tagged,
σ_{tt} (dil)=7.4±0.6(stat)±0.6(syst)±0.5(lum) pb

Top pair production: Lepton +Jets

Pre-tagged sample, NN discriminant



B-tagged sample, counting events



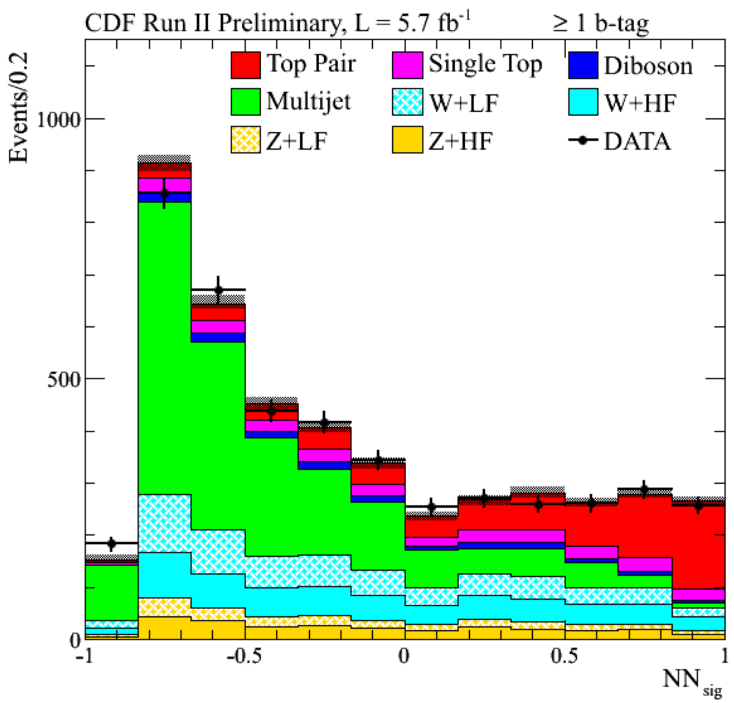
- Luminosity is the largest uncertainty in both measurements (6%)
  - Reduce by normalizing to the measured *Z cross section*
  - Measure R and multiply by Z cross section from theory: $\sigma_{tt} = R \bullet \sigma_Z^{theory}$

CDF (4.6 fb^{-1}, m_t= 172.5 GeV), pre-tagged	CDF (4.3 fb^{-1}, m_t= 172.5 GeV), b-tagged:
σ_{tt} =7.82±0.38(stat)±0.37(syst)±0.15(theo) pb	σ_{tt}=7.32±0.36(stat)±0.59(syst)±0.14(theo)pb

Combined: σ_{tt} = 7.70 ± 0.52 pb   PRL 105 012001 (2010)

Missing energy plus b jets

- MET + jets:
  - ⇒ Independent from "lepton+jets" channel
  - ⇒ Interesting channel to searches for new physics (i.e. low mass Higgs)
- 2 or 3 identified jets, at least one b-tagged jet
- NN trained against QCD background
- Another NN to isolate top pair from remaining background



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CDF (5.7 fb^{-1}, m_t= 172.5 GeV):

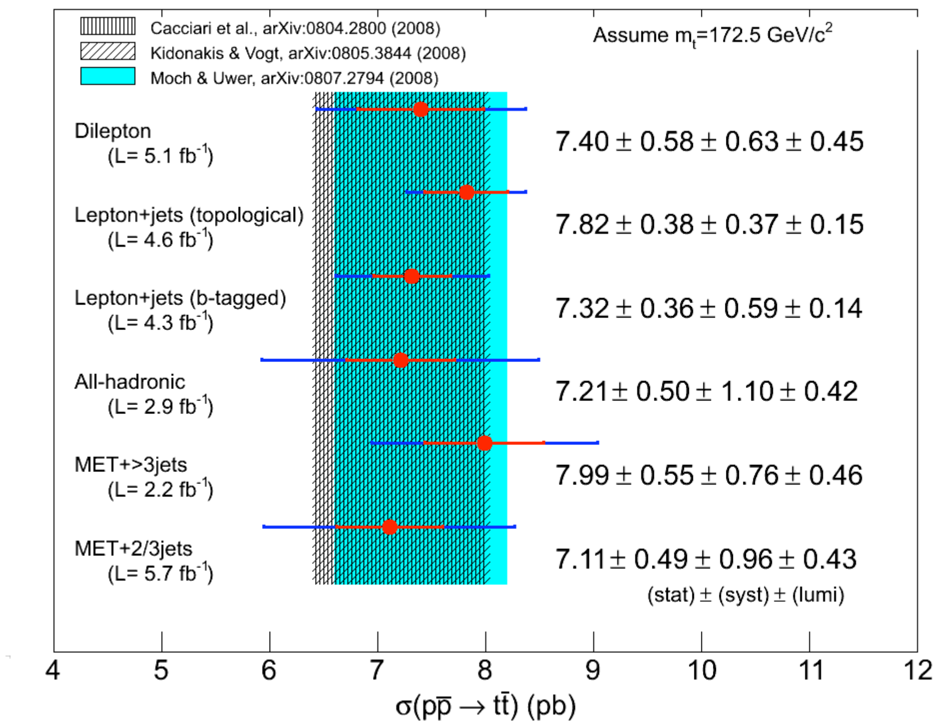
$\sigma_{tt} = 7.12\ ^{+1.20}_{-1.12}$ (stat+syst+lumi) pb

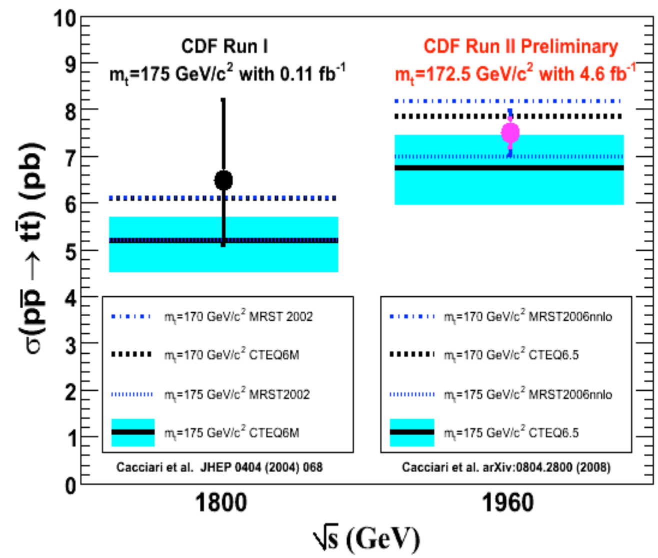
Measurements of σ_{tt}

- <u>Experimental uncertainty: Δσ/σ ~ 6.5%</u>
- Dominant exp. uncertainties: JES, b-tag accept., W+bjet background
- σ is measured in all final states: first step of any analysis studying the top quark properties.
- Tevatron combination underway

$$\sigma_{tt} = \frac{N_{Data} - N_{Background}}{Acc\int Ldt}$$

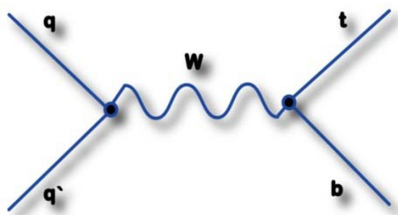
Consistent across channels, methods



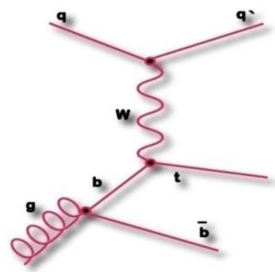


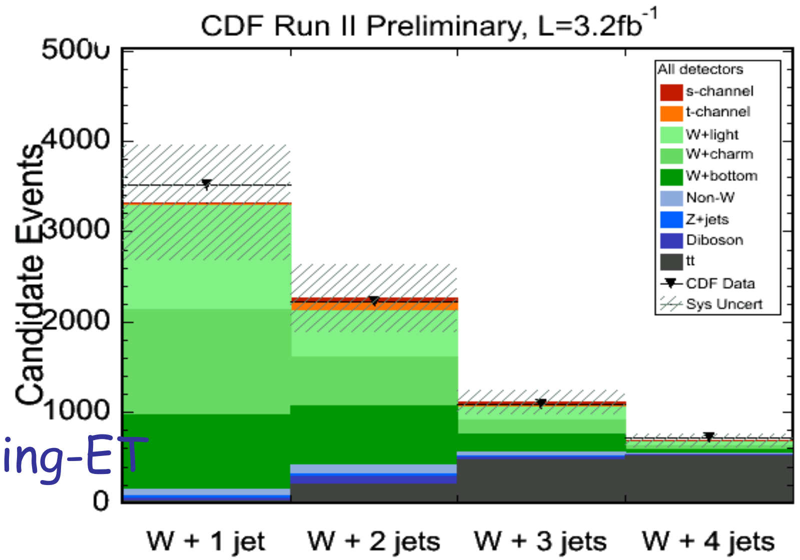
Single Top Production

s-channel



t-channel



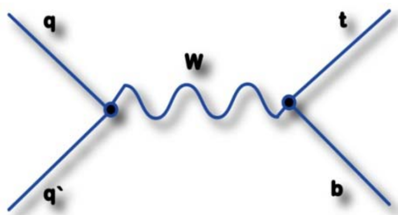


s: 1 high-P_T lepton + 2 b-jets + missing-ET

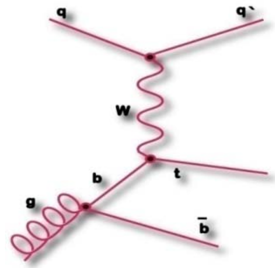
t: 1 high-P_T lepton + 1 b-jet + 1 other jet + missing-ET

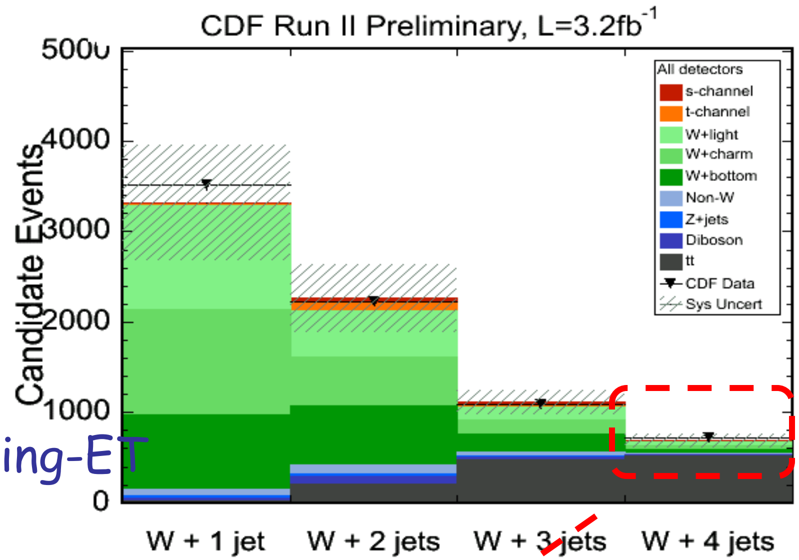
Single Top Production

s-channel



t-channel





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Top-pair has better s/b and very distinct final state:
→ Counting experiment after b-quark tagging 'fairly easy'

Single Top Production

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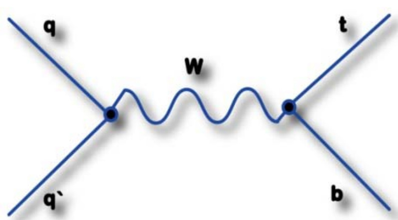

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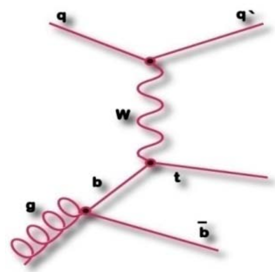

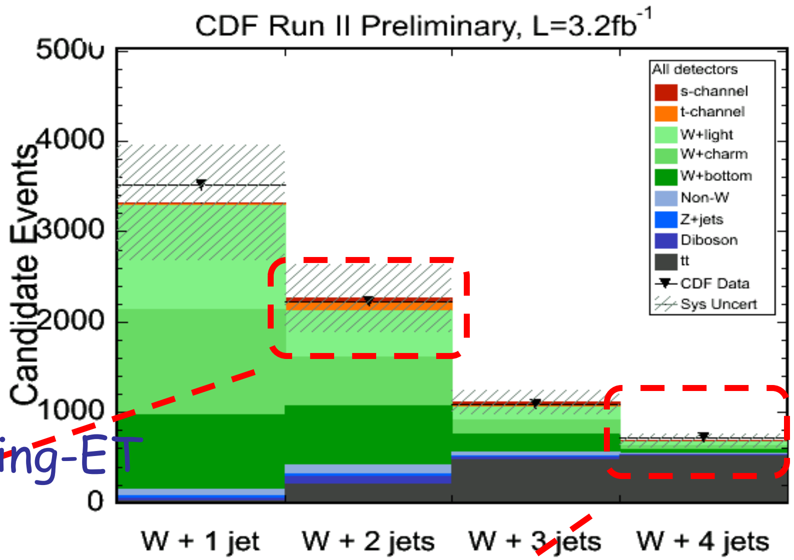

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Single top hidden behind large backgrounds with large uncertainties
→Makes counting experiment impossible!
→s-channel single top has the same final state as WH→lνbb
→benchmark for WH Higgs search!

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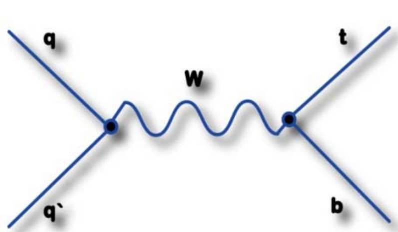
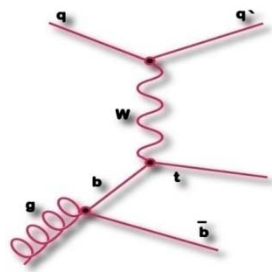
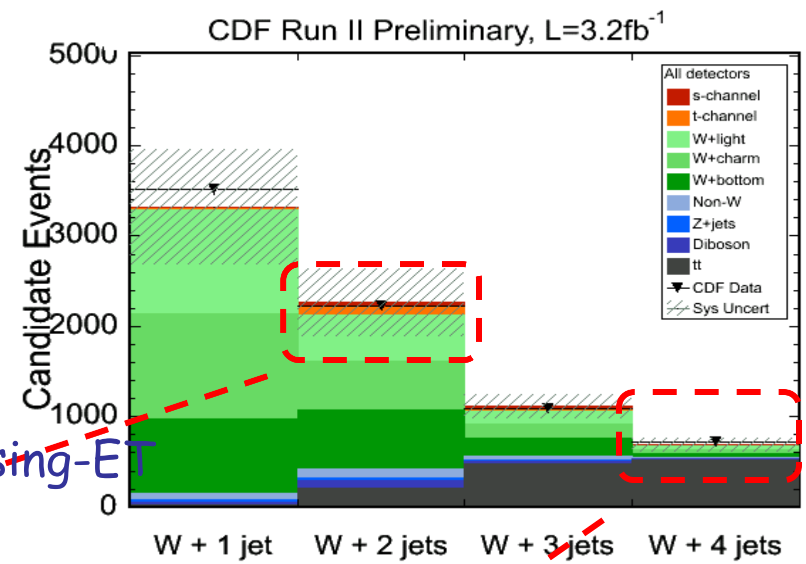


t-channel





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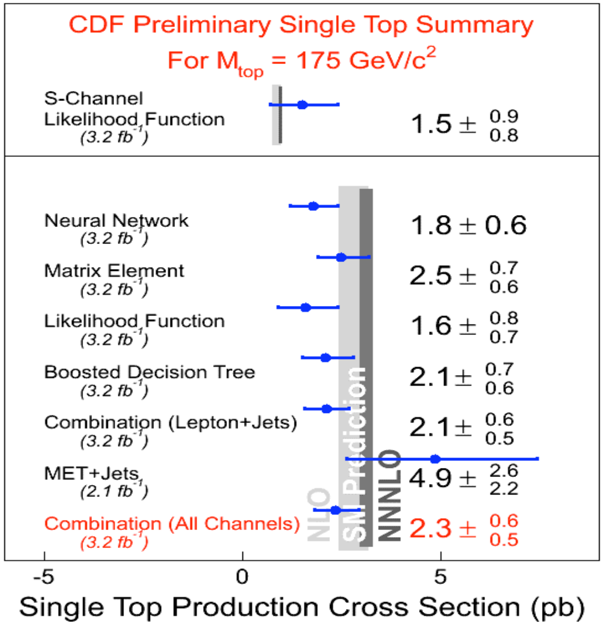
- Single top requires more sophisticated techniques: no single variable provides significant signal-background separation

⇒ Perform multivariate analysis (MV)

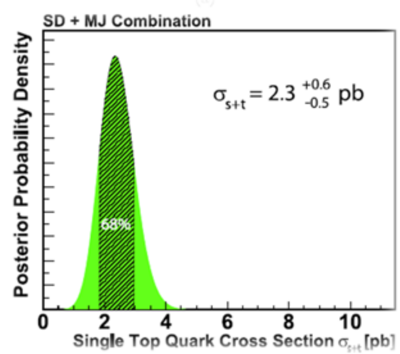
⇒ take advantage of small signal-background separation in many variables

Single Top Observation

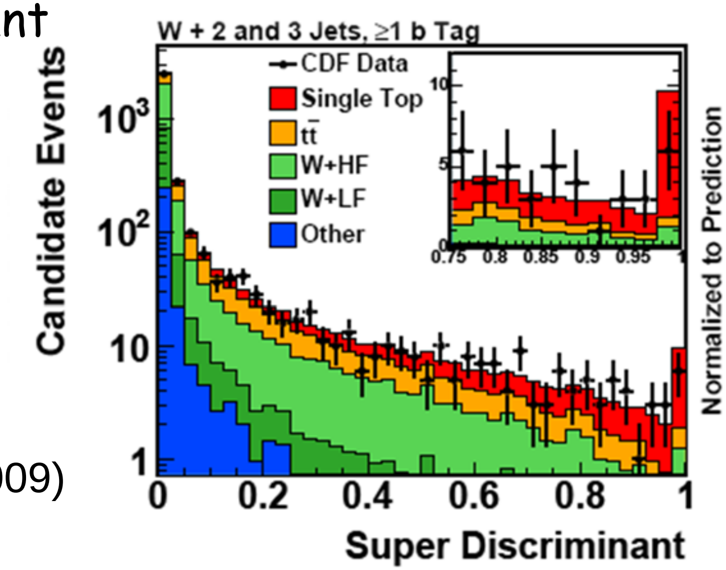
CDF and D0 both report >5σ observation March 2009



The various MV methods give consistent results
Combine the separate MVAs into one, more powerful discriminant



PRL 103, 092002 (2009)



	Lumi (fb^{-1})	Cross Section(pb)	Exp Signif	Obs Signif
CDF	3.2	$2.3^{+0.6}_{-0.5}$	5.9σ	5.0σ

Tevatron (3.2 fb^{-1}), fb^{-1}, m_t = 175 GeV :
$\sigma_t = 2.76^{+0.58}_{-0.47}$ (stat+syst) pb

Direct $|V_{tb}|$ measurement

- Using cross section result to measure $|V_{tb}|$: $\sigma_{\text{single top}} \propto |V_{tb}|^2$
- Assume Standard Model (V-A) coupling and

$|V_{tb}| \gg |V_{ts}|, |V_{td}|$ (from BR($t \to Wb$) meas.)

- Measurement assumes SM production mechanisms, does not assume 3 generations or unitarity

$$|V_{tb,meas}|^2 = \frac{\sigma_{meas}}{\sigma_{SM}} \cdot |V_{tb,SM}|^2$$

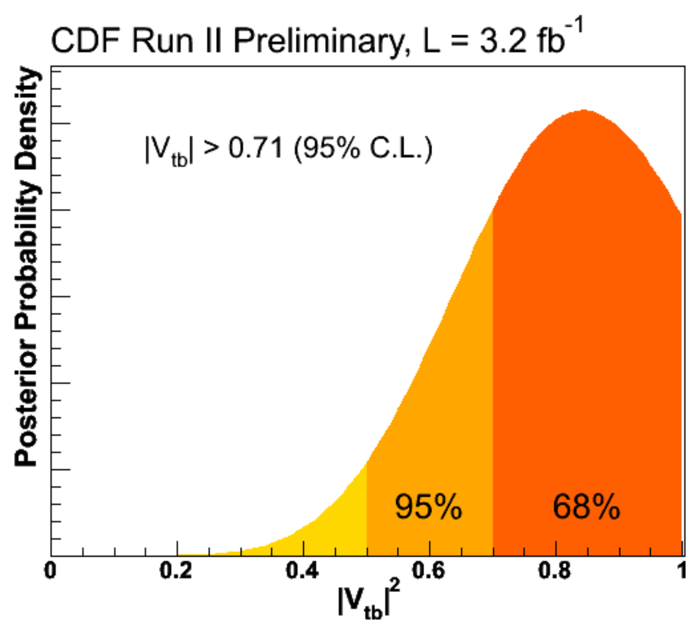
$|V_{tb}|$= 0.91 ± 0.11 (stat+syst) ± 0.07 (theory)

$|V_{tb}|$>0.71 at 95% C.L.

Best direct measurement of V_{tb}:

Tevatron (3.2 fb^{-1}):

$|V_{tb}|$=0.91 ± 0.08 (stat+syst)

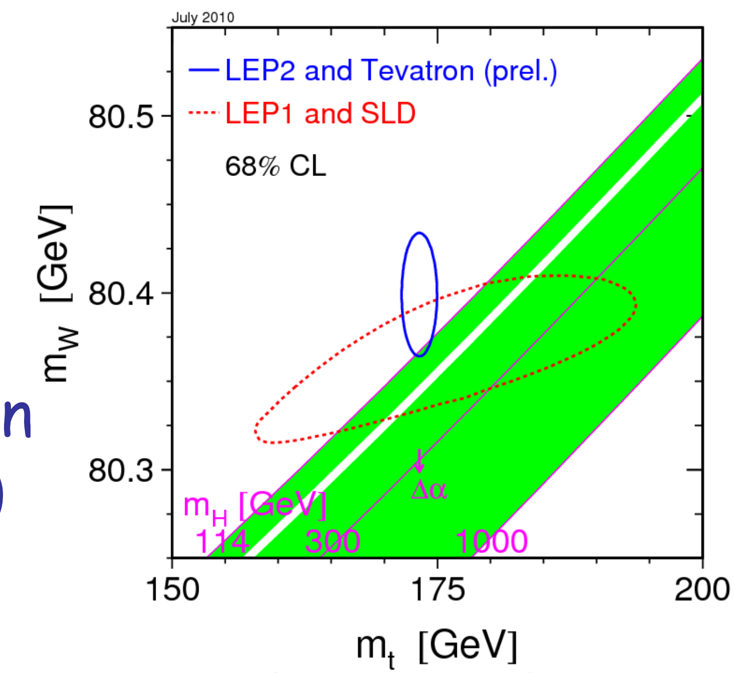


Top quark mass

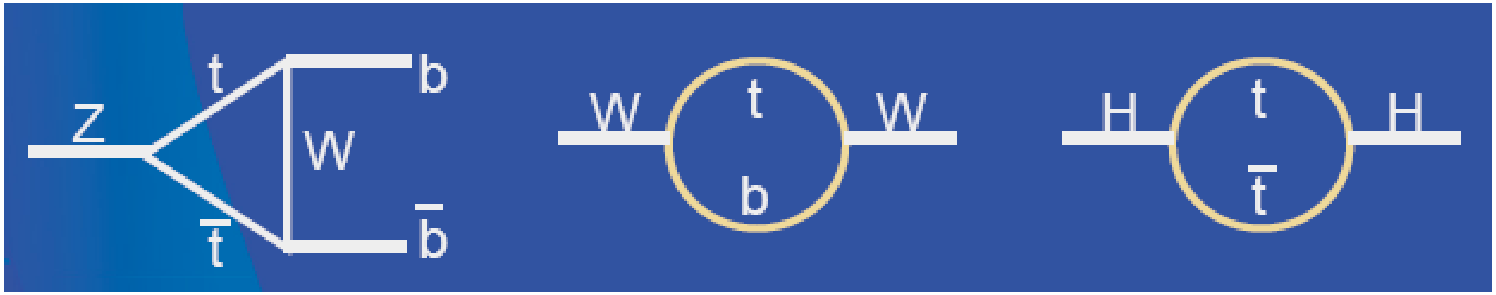
- M_{top} is a free parameter of the Standard Model

- Since M_{top} is large, quantum loops involving top quarks are important to include when calculating precision observables (e.g. $\sin\theta_W^2$, R_b, M_W, …)

LEPEWWG



- Within SM, with the measured W mass constrains the mass of the Higg through radiative corrections



Top mass: most precise single result

- Matrix Element Technique in Lepton+Jets channel:

- The probability of being signal or background is calculated per event as a function of M_{top}

- Jet Energy Scale is reduced by measuring simultaneously with M_{top}

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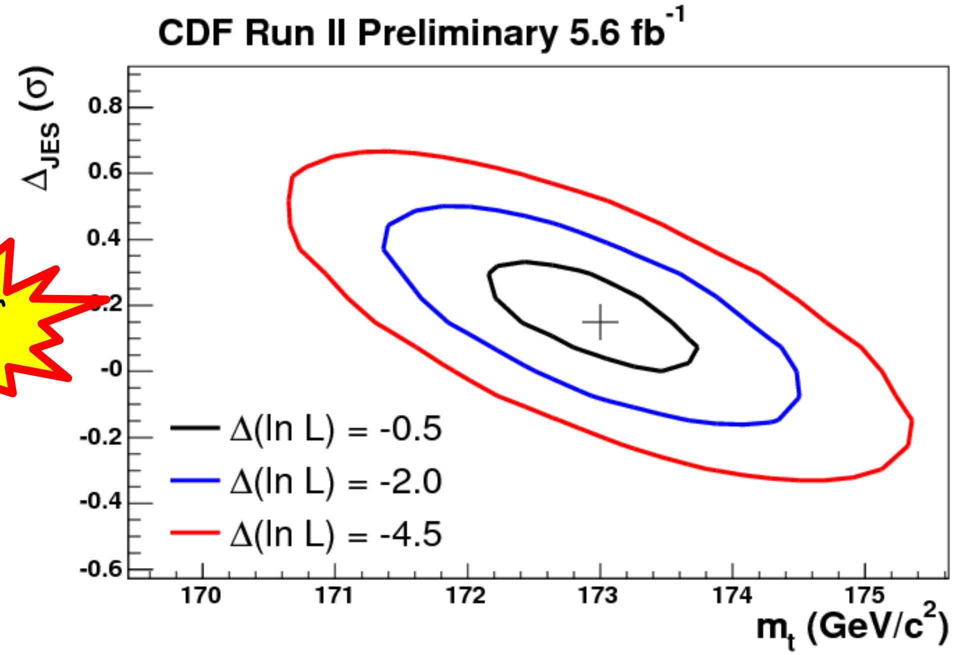
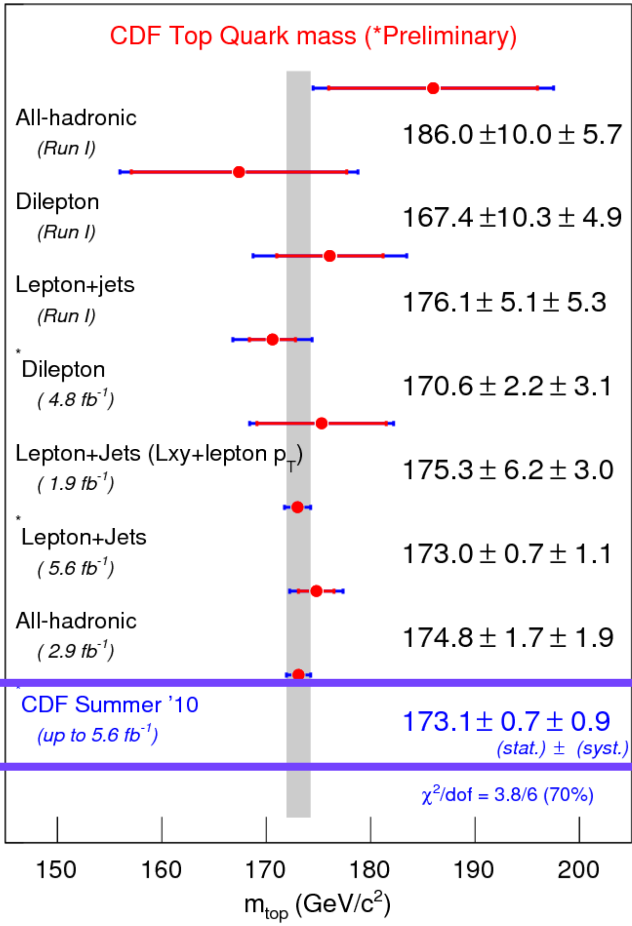
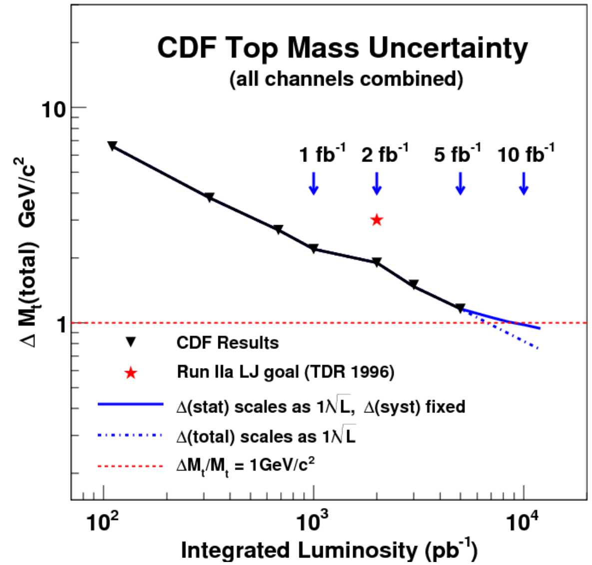


This is the best individual top mass measurement in the world to date

CDF (5.6 fb^{-1}):
m_t=173.0±0.7(stat)±0.6(JES) ±0.9 (syst) GeV

CDF top mass summary





- Current CDF precision = 1.2 GeV/c^2 $\Delta M/M \sim 0.67$ %
- Have surpassed Run II goal by a factor of > 2
- 1 GeV/c^2 precision might be possible without any improvement at 10 fb^{-1}

Consistent across channels and methods

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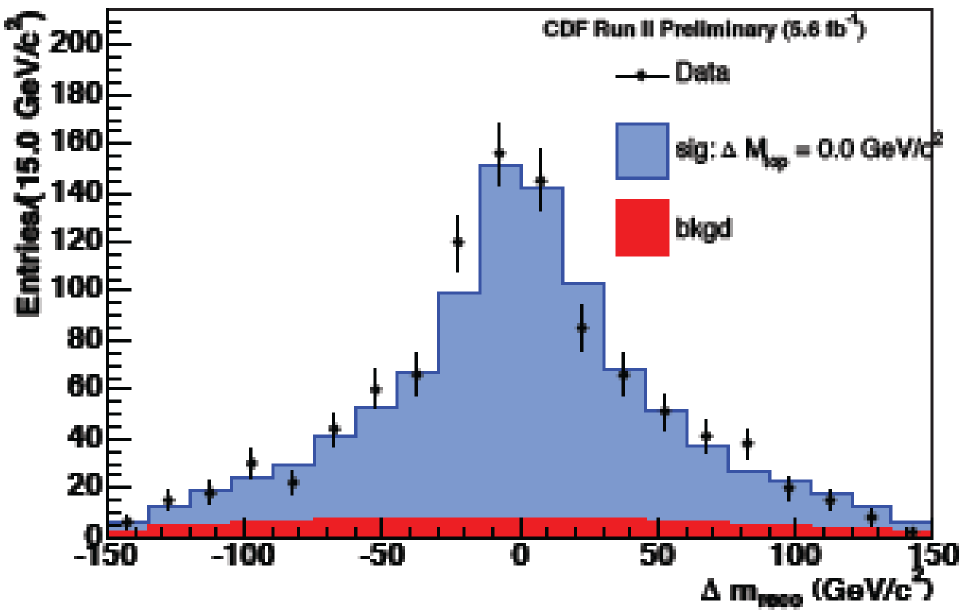
Tevatron July 2010 combination:

M_{top} = 173.3 ± 1.1 (total) GeV/c^2

$\Delta M/M$ ~ 0.61 %

Top Anti-Top Mass Difference

- If CPT is conserved, Mt = Mtbar
- Mass measurements until now have held this assumption
- Similar techniques to mass measurements: template technique in the lepton+jets channel



L = 5.6 fb^{-1}

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~ 2σ deviation from Standard Model

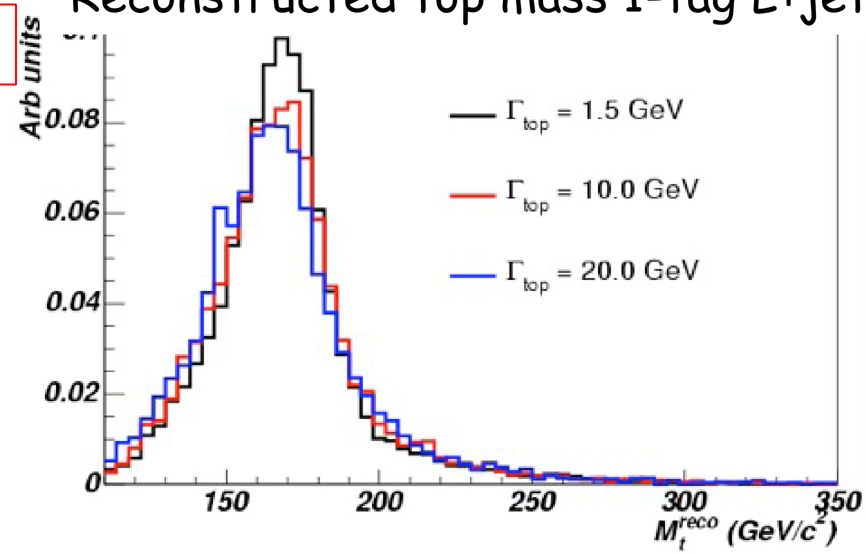
$\Delta M = -3.3 \pm 1.4(\text{stat}) + 1.0(\text{syst})$ GeV/c^2

Top Width

- Top decays very quickly:
  - ⇒ No direct detection -> its properties from decay products
  - ⇒ SM predicts Γ_{top} = 1.3 GeV
- Direct measurement:
  - ⇒ Reconstruct top mass event-by-event in lepton + jets
  - ⇒ Extract width from fitting data to templates

L = 4.3 fb^{-1}

Reconstructed top mass 1-tag L+jets



First direct bound of
top quark width:

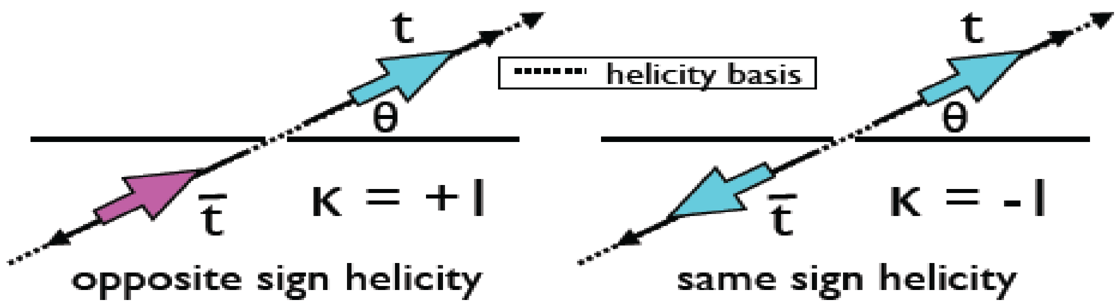
Γ_{top} < 7.5 GeV @ 95% C.L.

τ_{top} > 8.7 x 10^{-26} s @ 95% C.L.

0.3 < Γ_{top} < 4.4 GeV @ 68% C.L.

Top anti-Top Spin Correlations

- Top spins are correlated only if top lifetime is short enough
- Information on of the spin carried by the decay products



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

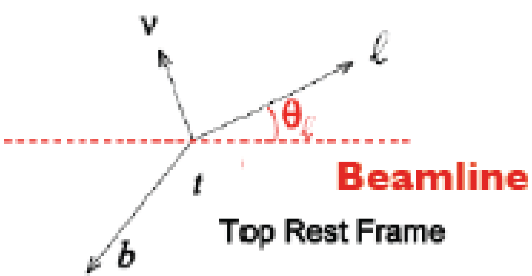
- **SM predicts κ=0.78** NPB690, 81 (2004)

- New physics could change the spin-correlation parameter
  PRD 45 124(1992), PRD75 095008 (2007)

κ related to decay products angle through:

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

where:



Top anti-Top Spin Correlations

Lepton+Jets Channel

L = 5.3 fb^{-1}

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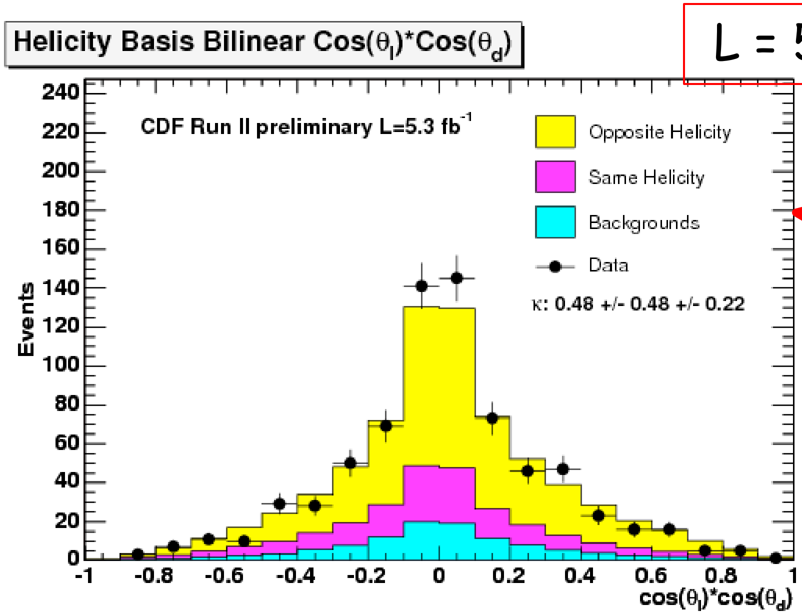
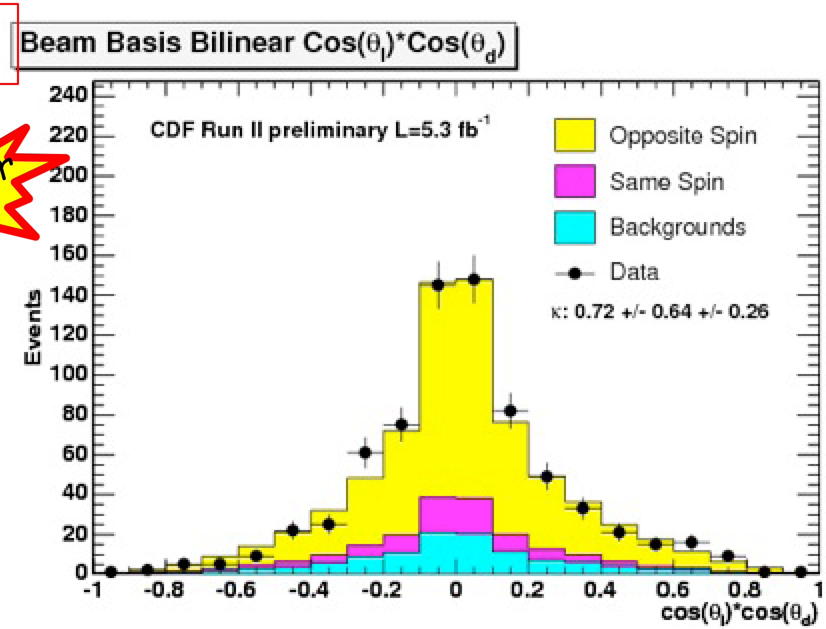


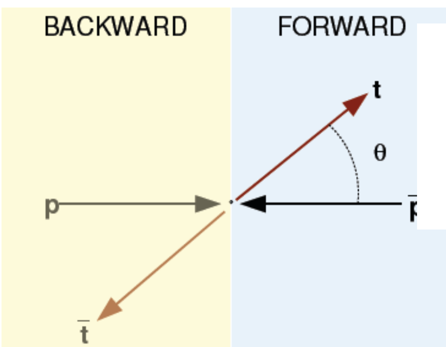


Basis	NLO Expectation	Measured
Helicity	κ = 0.35	κ = 0.48 ± 0.48stat ± 0.22syst
Beam	κ = 0.77	κ = 0.72 ± 0.64stat ± 0.26syst

NPB690, 81 (2004)

Forward-Backward Asymmetry

- In leading order QCD, top production is symmetric.
- NLO QCD predicts small asymmetry:
  - ⇒ A_{fb}= 3.8 ± 0.6 % in lab frame
  - ⇒ A_{fb}= 5.8 ± 0.9 % in ttbar rest frame
- New physics could give rise to a bigger asymmetry (Z′ ,axigluons,...)

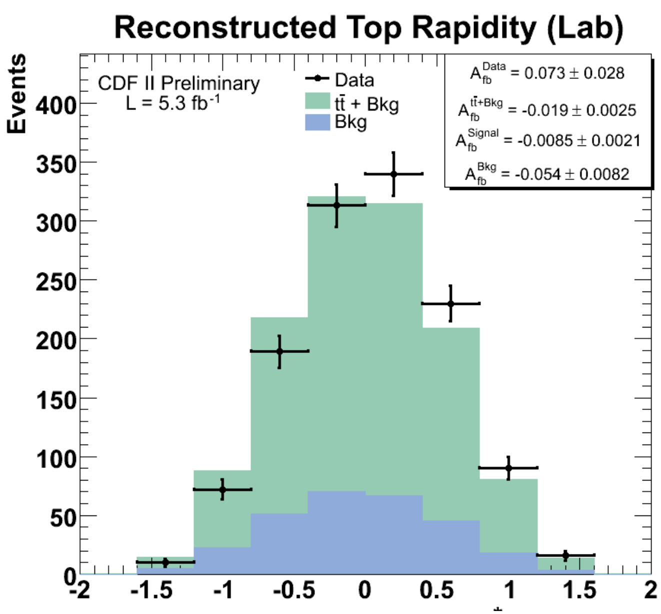


$$A_{FB} = \frac{N_{\cos\Theta>0} - N_{\cos\Theta<0}}{N_{\cos\Theta>0} + N_{\cos\Theta<0}} = \frac{N_{\Delta Y>0} - N_{\Delta Y<0}}{N_{\Delta Y>0} + N_{\Delta Y<0}}$$

- Reconstruct the rapidity of top and anti-top quarks
- $\cos \Theta_{ttbar}$ □ $Y_t - Y_{tbar} = \Delta Y$

Forward-Backward Asymmetry

L = 5.3 fb^{-1}



$-Q_{lep} \times y_{had}$

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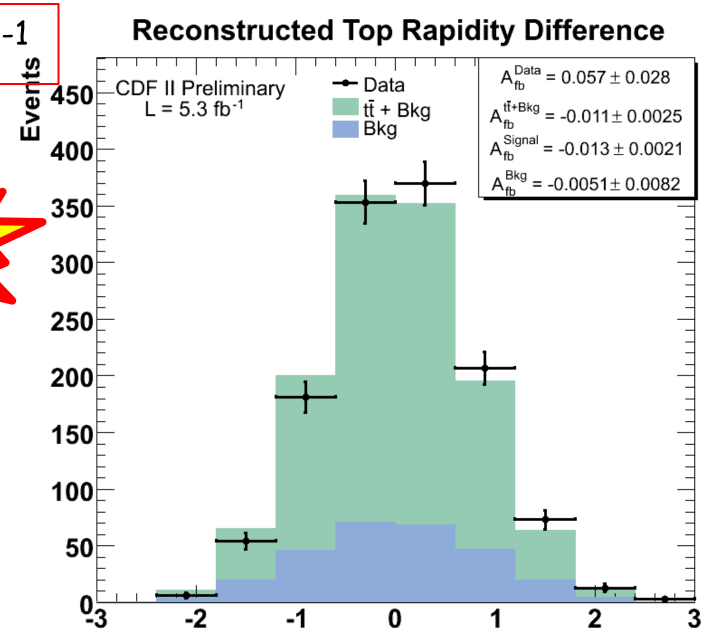


$Q_{lep} \times \Delta y$

After unfolding to parton level:

Afb	Measured	MCFM Predicted	Signif. from 0
Lab frame	15.0 ± 5.0stat ± 2.4sys%	3.8 ± 0.6%	2.7
t-tbar frame	15.8 ± 7.2stat ± 1.7sys%	5.8 ± 0.9%	2.1

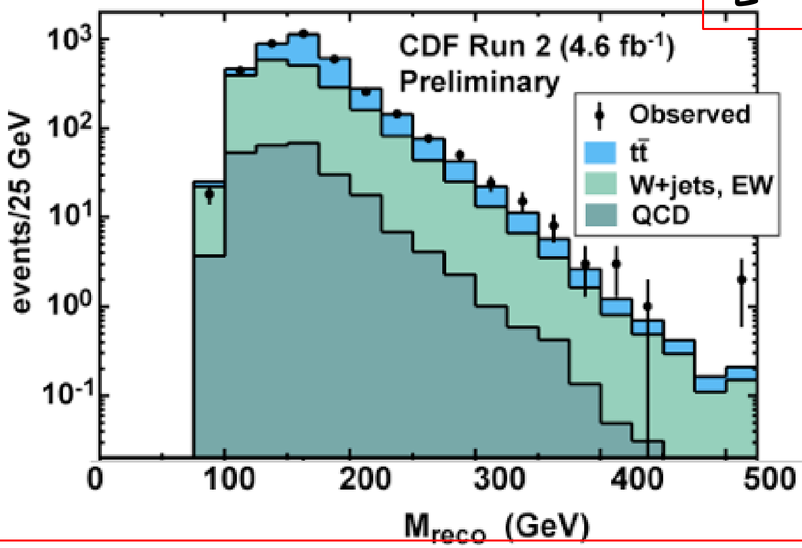
Search for Heavy t′

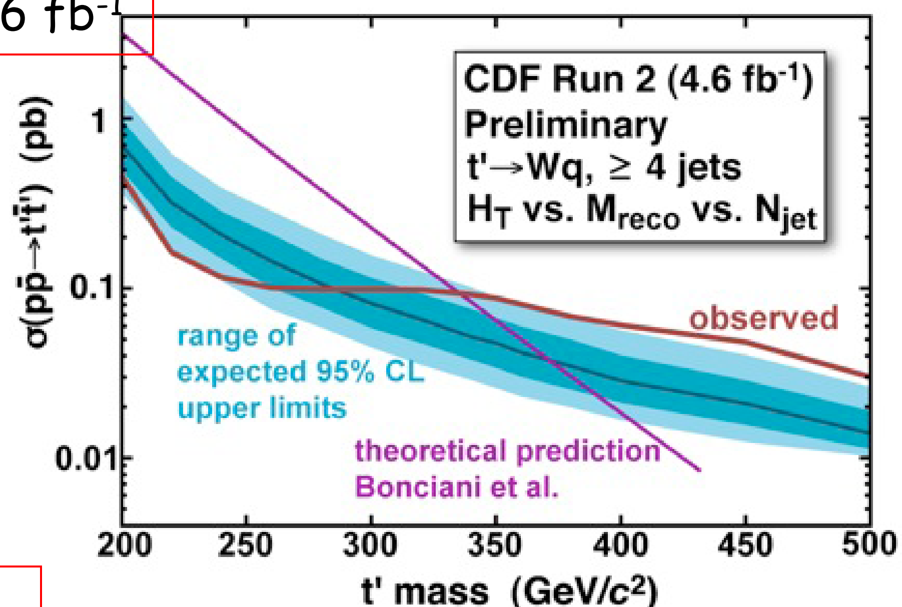
- Why are there only 3 generations? No theoretical reason
- Heavy t´ production

  ⇒ *suggested in 4th generation models, little Higgs, etc.*

- Search for t´t´ in Lepton + Jets, treat t´ as just a more massive top quark (t´ ➜ Wq , where q is a down-type quark q = d,s,b)

L = 4.6 fb^{-1}





CDF (4.6 fb-1):

M(t´) > 335 GeV/c² at 95% C.L.

Search for b´ -> t W -> WWb

- Signature is very energetic events, with many jets
- search in lepton +jets, high H_T, high jet multiplicity
- Largest background is tt+jets

L = 4.8 fb^{-1}

≥ 2 b-Tags

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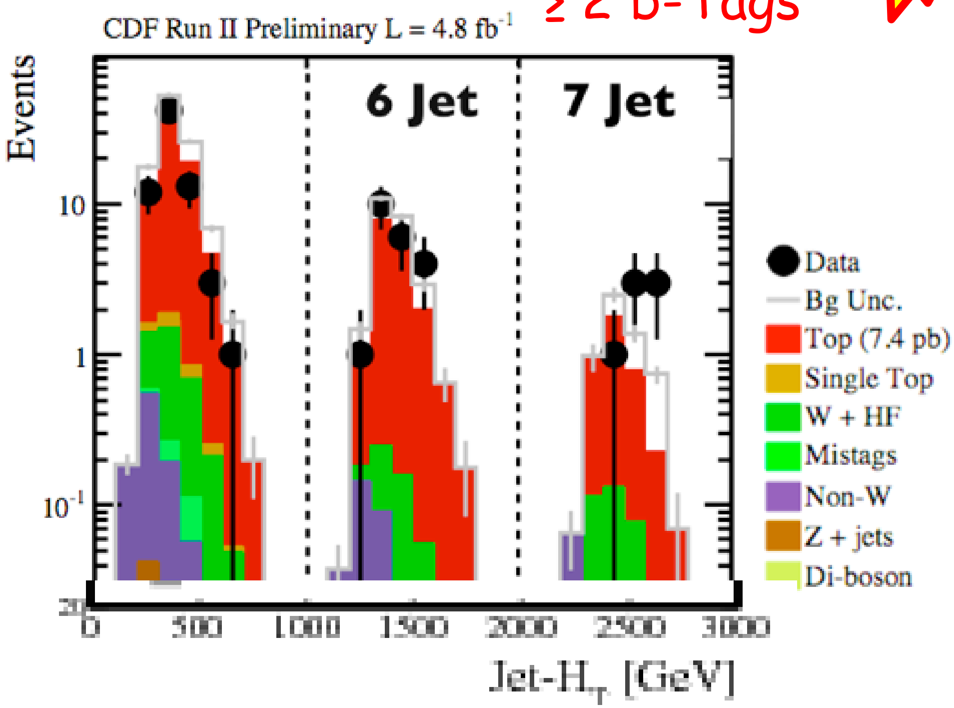

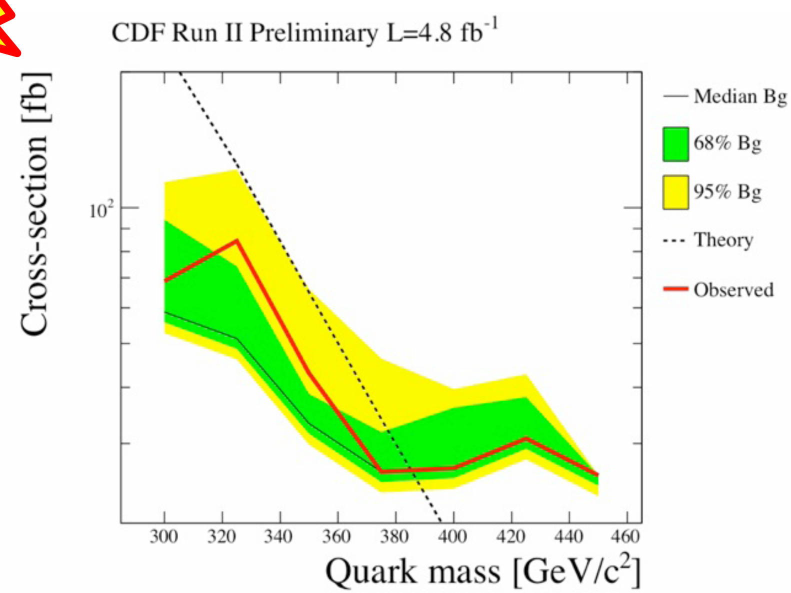

CDF (4.8 fb-1):

M(b´) > 385 GeV/c² at 95% C.L.

Summary and Outlook

- Top quark production and decay are currently being studied at Tevatron
  - ⇒ So far top quark seems to be Standard Model top quark
    - ✓ ttbar cross section known to 6.5% (better than theory!)
    - ✓ Mass measured to 0.6% precision
  - ⇒ Single top quarks have been observed, V_{tb} directly measured
  - ⇒ Many top measurements are statistically limited

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Thank you!

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

For more information:

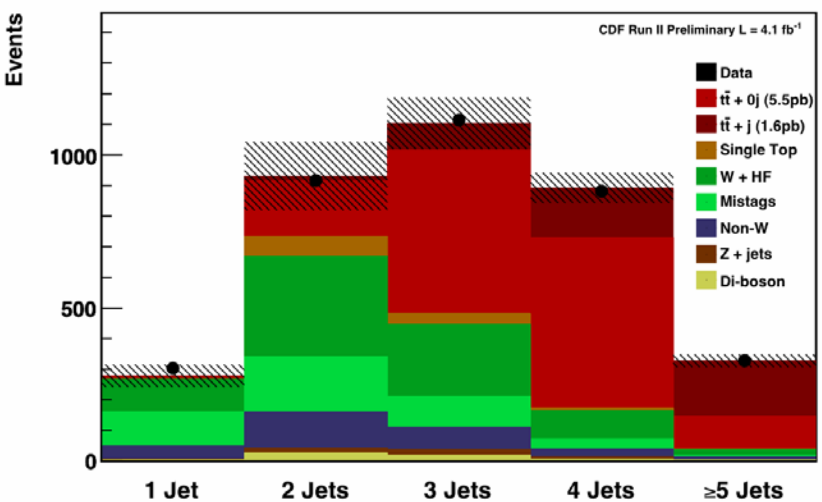
- Top Physics Results at CDF

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

BACKUP

t-tbar + jet Cross Section

- First σ measurement of t-tbar associated with an additional hard jet
- Important test of perturbative QCD
- Use b-tagged events in lepton + jets channel.
- Data-driven approach is used to predict the background content
- Standard model prediction $\sigma_{tt+j} = 1.79\ ^{+0.16}_{-0.31}$ pb (EPJ C59 625 (2009))



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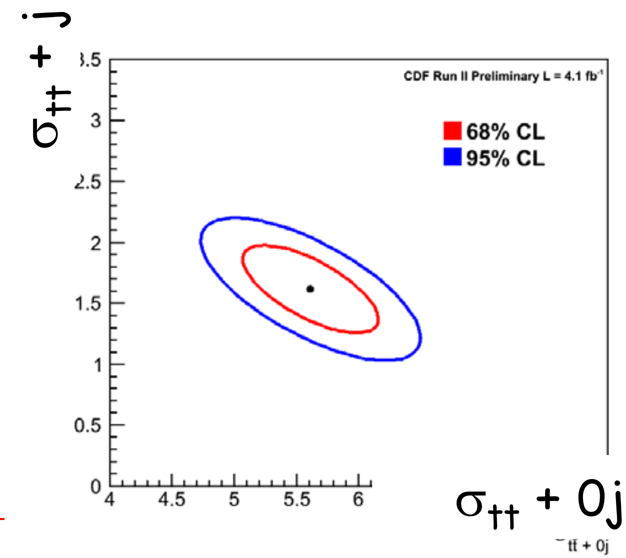


CDF (4.1 fb^{-1}, m_t= 172.5 GeV):
σ_{tt} (tt+j)=1.6±0.2(stat)± 0.5(syst) pb

Top mass: most precise single result

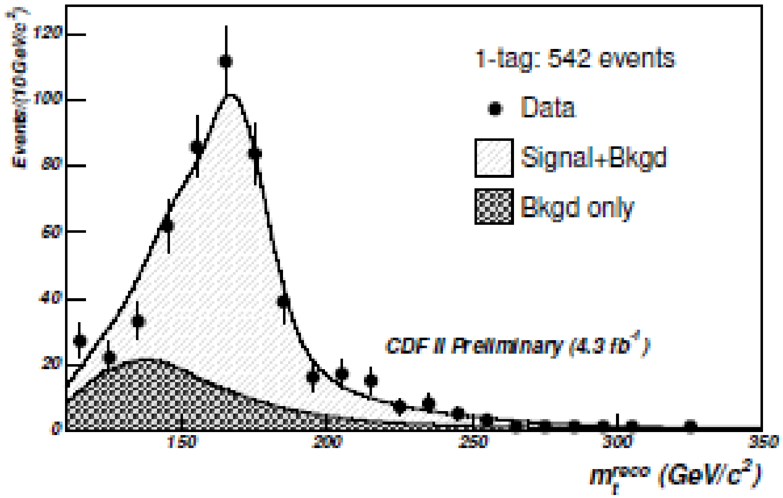
CDF Run II Preliminary, 5.6 fb^{-1}

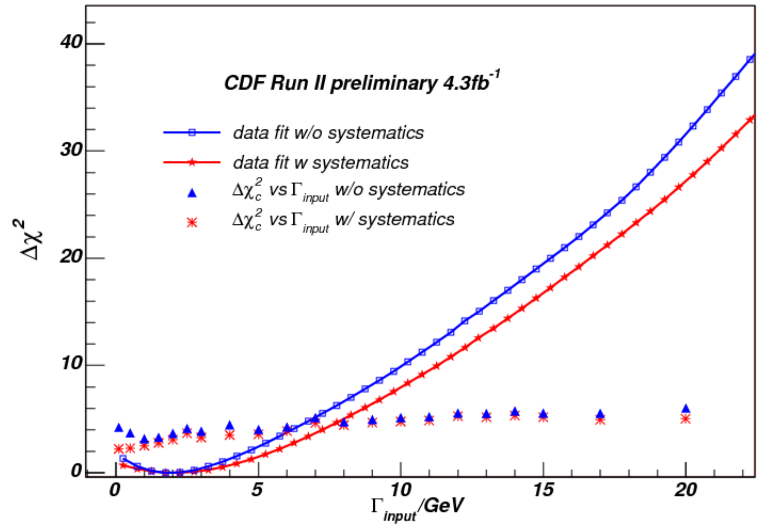
Background	1 tag	$\geq$ 2 tags
non-W QCD	50.1 ± 25.5	5.5 ± 3.8
W+light mistag	48.5 ± 17.1	1.0 ± 0.4
diboson (WW, WZ, ZZ)	10.5 ± 1.1	1.0 ± 0.1
$Z \rightarrow \ell\ell$ + jets	9.9 ± 1.3	0.8 ± 0.1
$W + b\bar{b}$	67.5 ± 23.9	12.9 ± 4.7
$W + c\bar{c}$	41.3 ± 14.8	1.9 ± 0.7
$W + c$	20.7 ± 7.4	0.9 ± 0.4
Single top	13.3 ± 0.9	4.0 ± 0.4
Total background	261.8 ± 60.6	28.0 ± 9.6
Predicted top signal ($\sigma = 7.4$ pb)	767.3 ± 97.2	276.5 ± 43.0
Events observed	1016	247

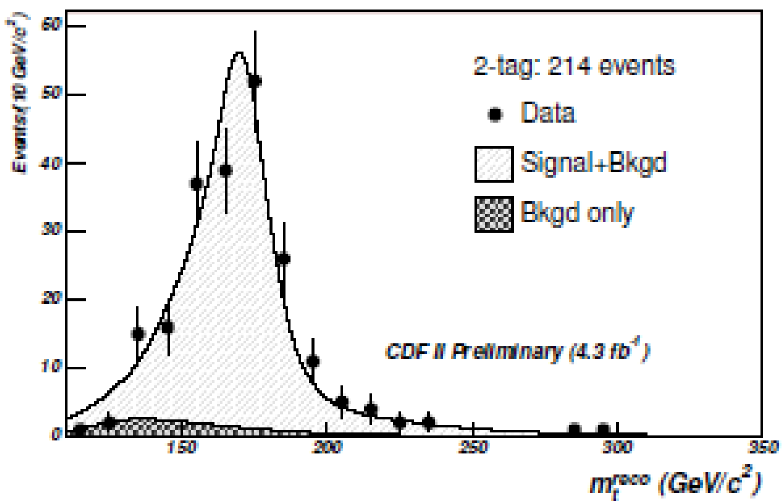
CDF Run II Preliminary, 5.6 fb^{-1}

Systematic source	Systematic uncertainty (GeV/c^2)
Calibration	0.10
MC generator	0.37
ISR and FSR	0.15
Residual JES	0.49
b-JES	0.26
Lepton P_T	0.14
Multiple hadron interactions	0.10
PDFs	0.14
Background modeling	0.34
Gluon fraction	0.03
Color reconnection	0.37
Total	0.88

Top quark width





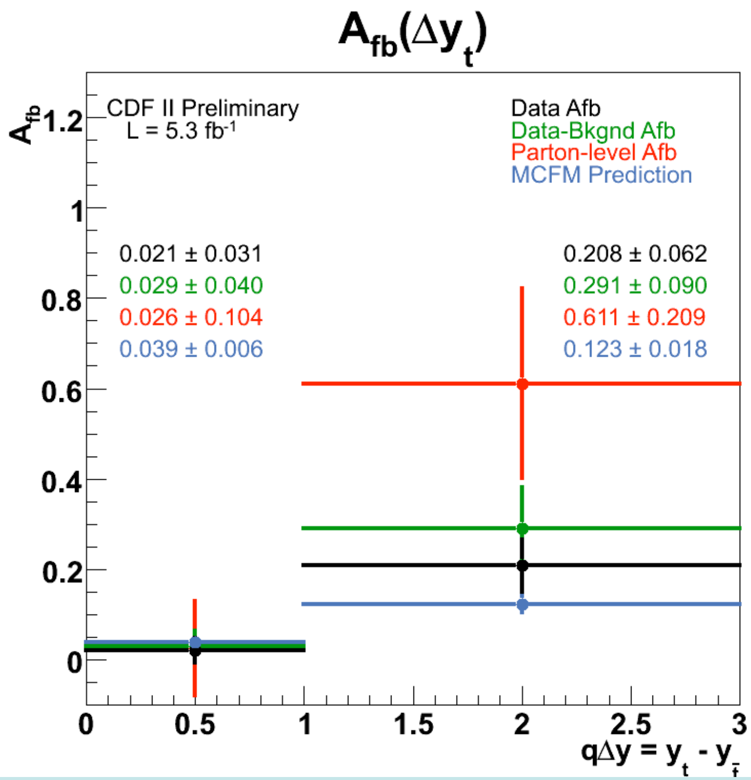


Summary of shift top width due to systematic effects. All numbers have units of GeV.

CDF Run II Preliminary, 4.3 fb^{-1}

Systematic (GeV)	$\Delta\Gamma_{top}$
Residual JES	0.3
Jet Resolution	1.1
Generator:	0.4
PDFs	0.3
b jet energy	0.2
Background shape	0.1
gg fraction	0.3
Radiation	0.2
Lepton energy	0.2
Multiple Hadron Interaction	0.3
Color Reconnection	0.9
Total Effect	1.6

Forward-Backward Asymmetry



Study rapidity dependence using A_{ttbar}

$\Delta y < 1.0$: $A_{FB} = 0.026 \pm 0.104_{stat} \pm 0.055_{syst}$

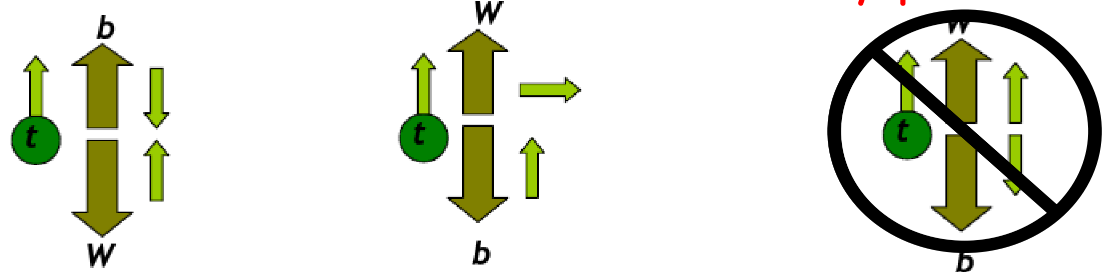
$\Delta y > 1.0$: $A_{FB} = 0.611 \pm 0.210_{stat} \pm 0.141_{syst}$

MCFM : 0.039 ± 0.006 (<1), 0.123 ± 0.018 (>1)

W Helicity in top decay

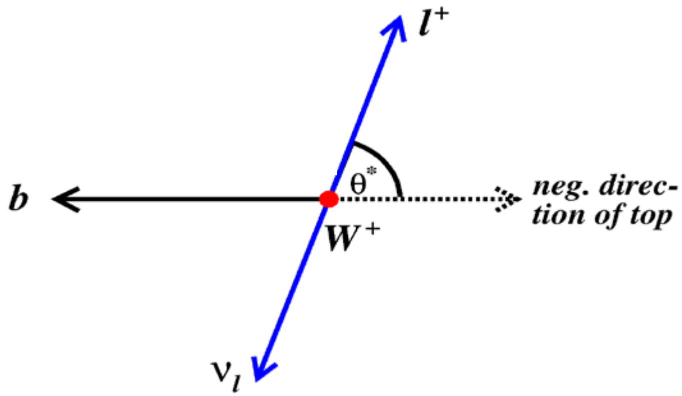
W helicity in top decays is fixed by M_{top}, M_W, and V-A structure of the tWb vertex. It is reflected in kinematics of W decay products.

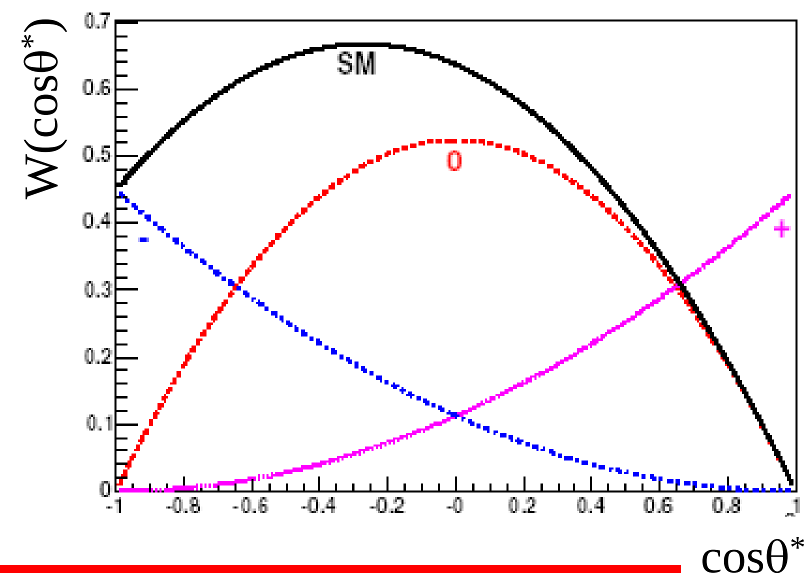
W helicity states:



	left-handed fraction: f_-	longitudinal fraction: f_0	right-handed fraction: f_+
In Standard Model:	**~30%**	**~70%**	**suppressed: ~0.036%**

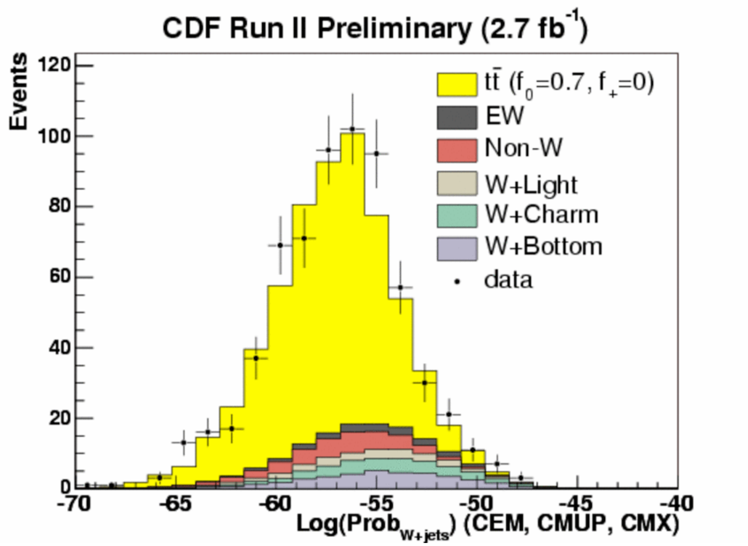
⇒ Measure angular distribution of charged lepton wrt. top in W rest frame: $\cos\theta^*$





W Helicity in Top Decay

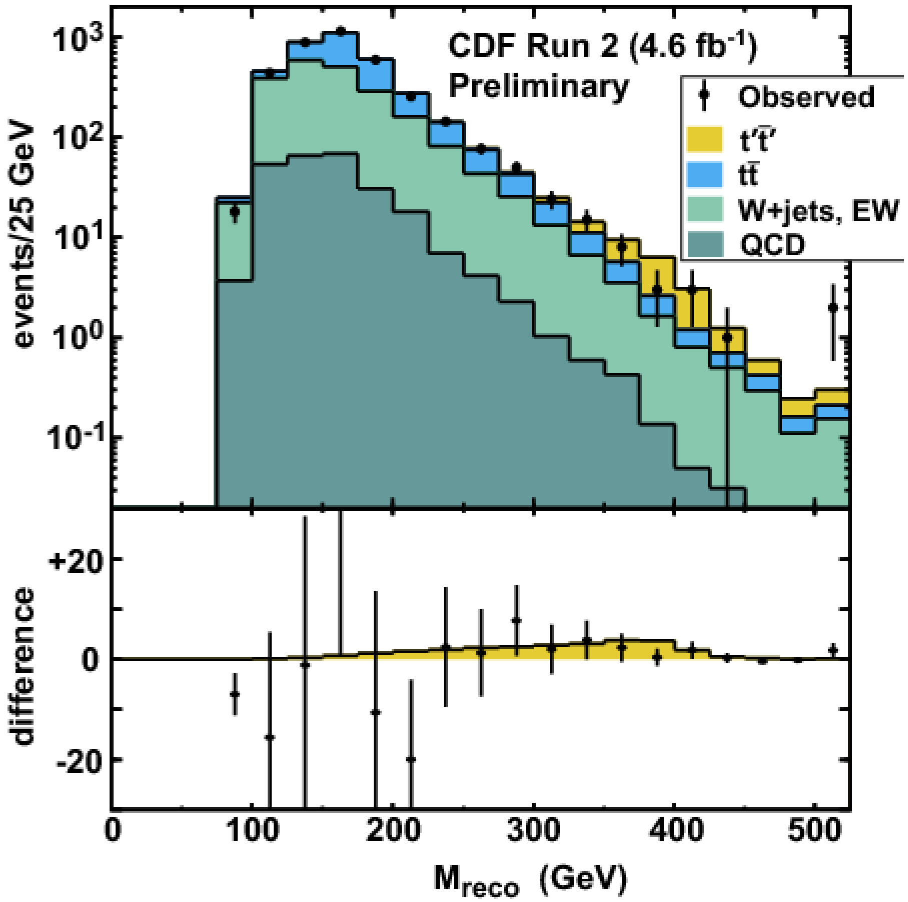
- Using Matrix Element Method, express probability of each event in terms of ttbar and background (W+jets) production
- Use the probabilities to compute a log-likelihood function in terms of the helicity fractions and the signal purity coefficient



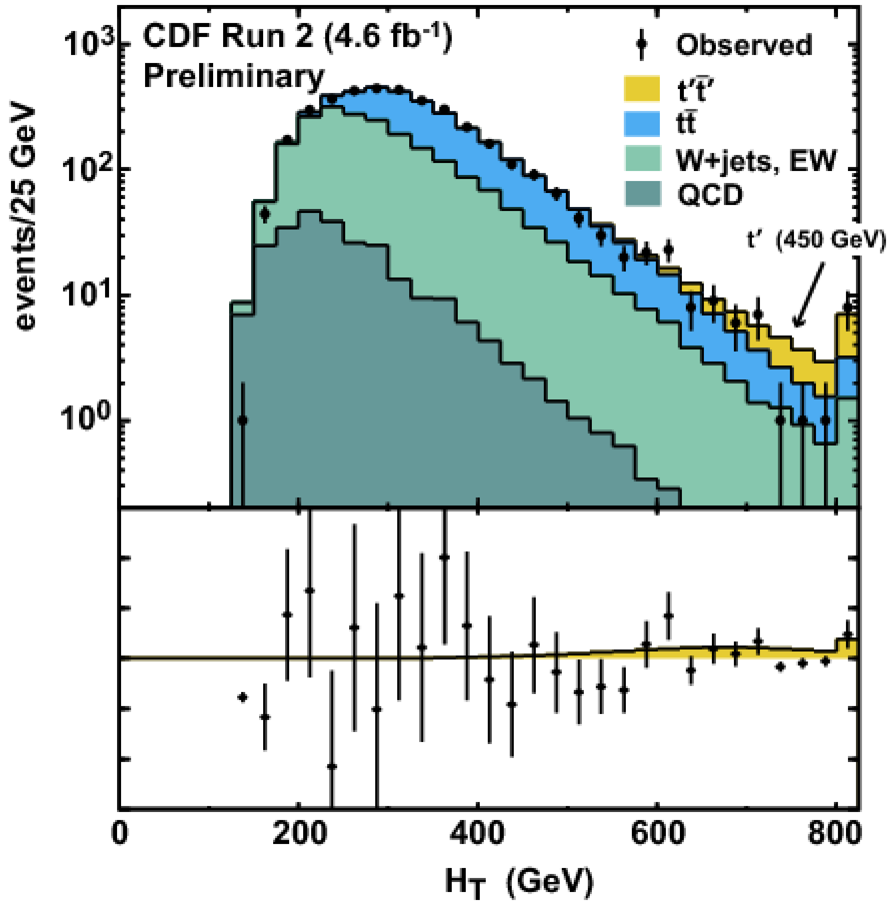
Results consistent with the Standard Model

Method	f+	f0
Simultaneous	-0.15 ± 0.07stat ± 0.06sys	0.88 ± 0.11stat ± 0.06sys
Fixed f+	0.00	0.70 ± 0.07stat ± 0.04sys
Fixed F0	-0.01 ± 0.02stat ± 0.05sys	0.70

Search for t'



CDF Run 2 (4.6 fb-1)
Preliminary
Observed
t't'
tt
W+jets, EW
QCD
events/25 GeV
difference
Mreco (GeV)



CDF Run 2 (4.6 fb-1)
Preliminary
Observed
t't'
tt
W+jets, EW
QCD
t' (450 GeV)
events/25 GeV
HT (GeV)