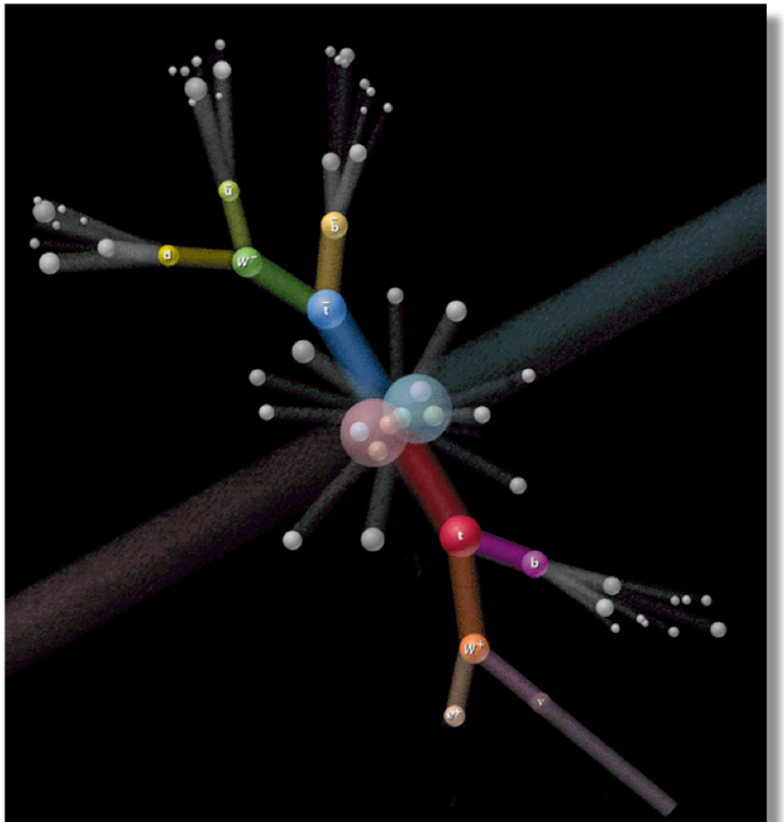
Top Physics at the Tevatron



Bernd Stelzer

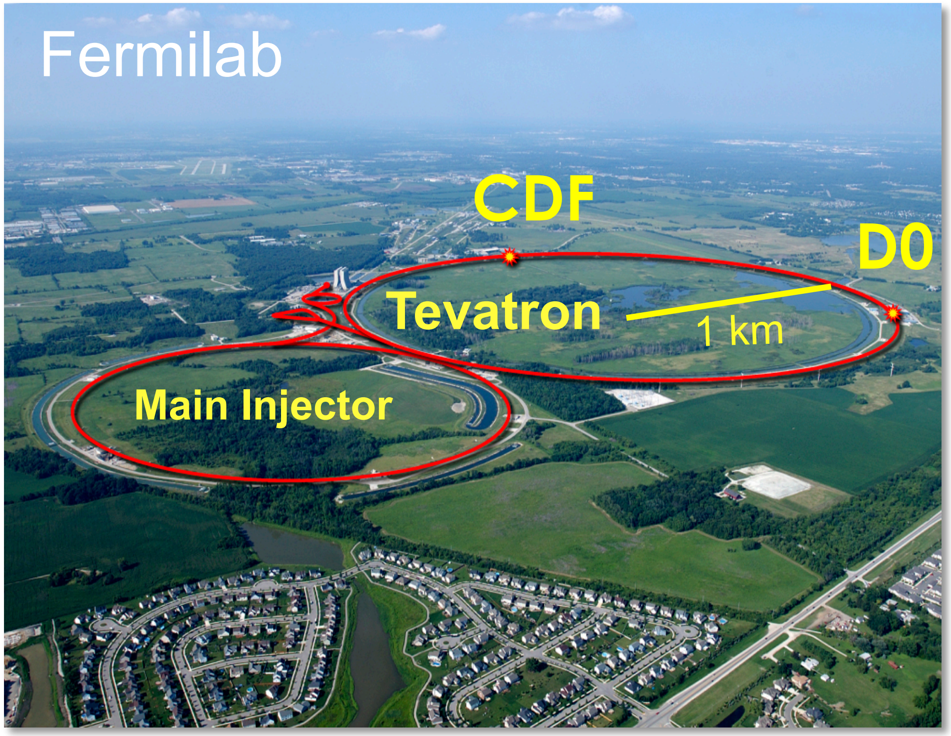
Simon Fraser University

Dept. of Physics, Burnaby • Vancouver • Surrey, Canada

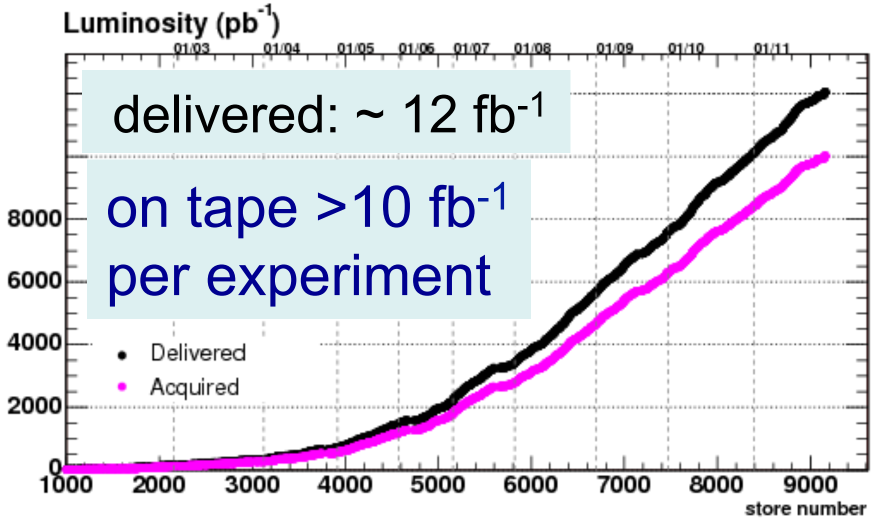
7th Physics at the LHC
Vancouver, June 4-9, 2012

Results from the Tevatron, on behalf of the CDF and D0 Collaborations

Tevatron



Tevatron had its last collisions on Sep 30, 2011



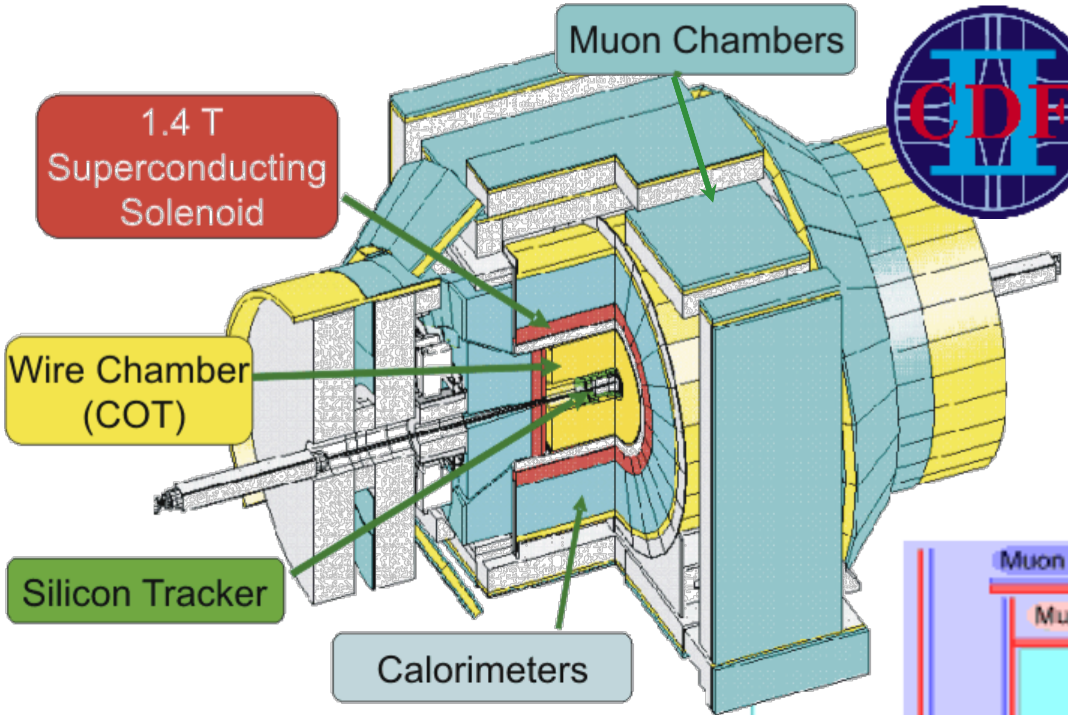
delivered: ~ 12 fb^{-1}

on tape >10 fb^{-1} per experiment

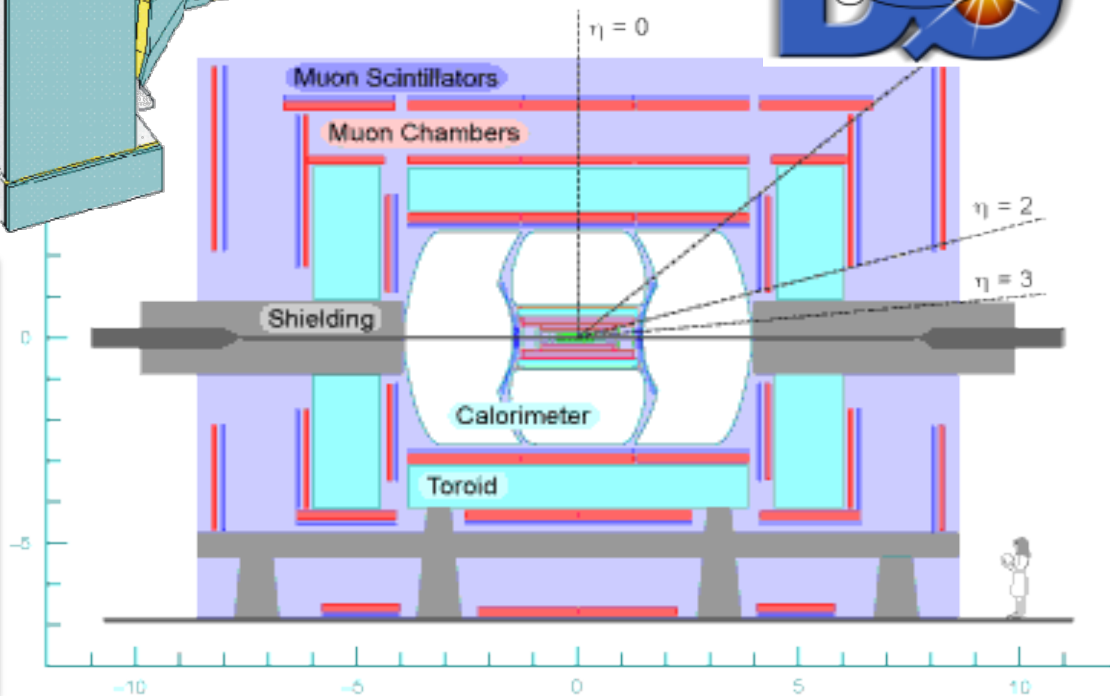
- 1.96 TeV proton anti-proton collider
- Record Inst. Lum. $4.3 \cdot 10^{32}$ [cm^{-2}sec^{-1}]
- Run II from 2001 - 2011
- *Birth place of top quarks*

Results shown in the following based on datasets up to 8.7 fb^{-1}

Tevatron Run II Experiments



D0 and CDF in very efficient data taking mode 2002 - 2011

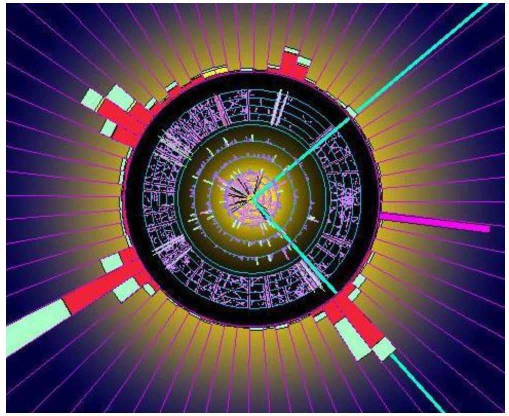


- Silicon strip detector for precision vertexing
- Precision tracking
- Calorimetry *(hermetic → missing E_T)*
- Muon systems

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*

top quark discovery

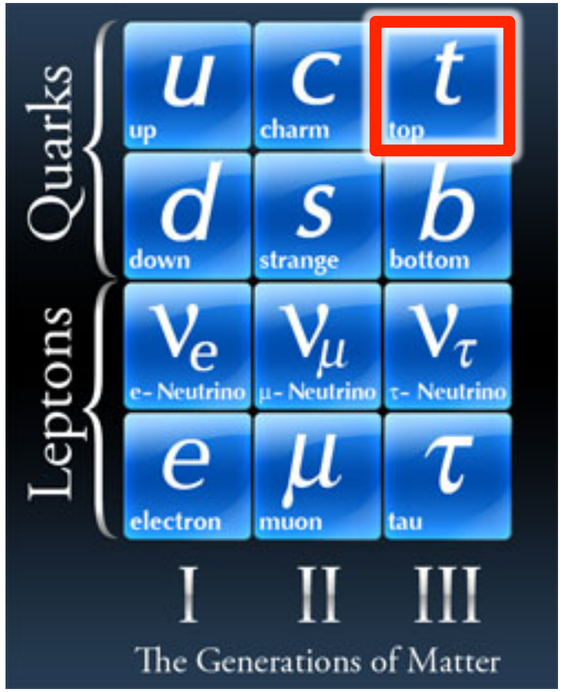


- Open question persists…
  Why is the top so massive?
  m_{top} ~ 175 GeV/c^2 ! Is the top quark special?

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

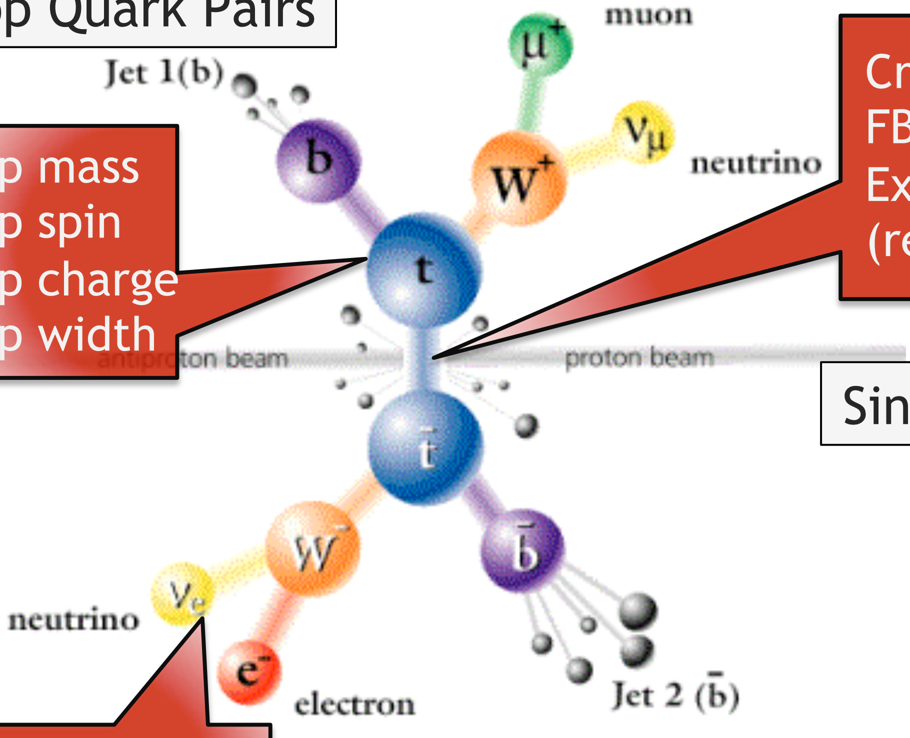
- Determine nature of top quark experimentally

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



Tevatron Top Quark Physics Program

Top Quark Pairs

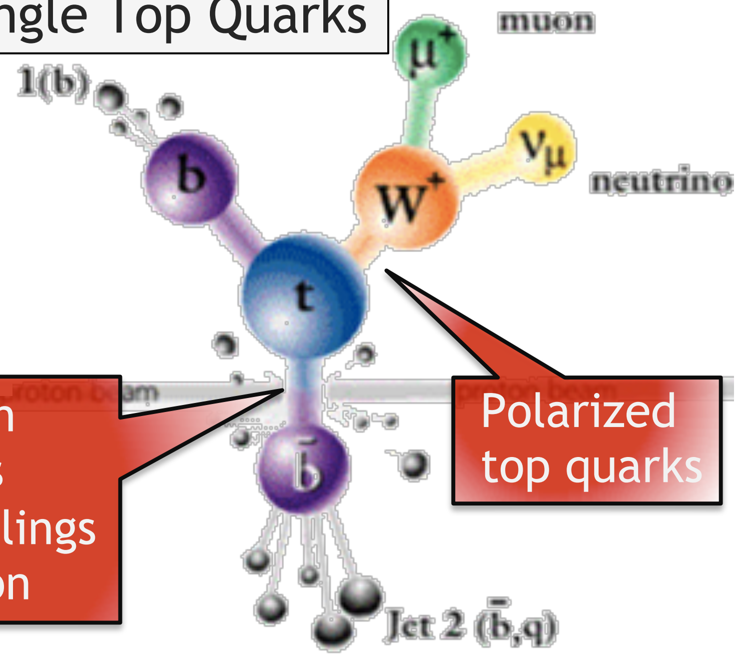


- Top mass
- Top spin
- Top charge
- Top width

- Cross section
- FB Asymmetry
- Exotic production
- (resonance/stop/t')

- W helicity
- Branching ratios
- Rare decays
- FCNC

Single Top Quarks



- Weak production
- Direct V_{tb} access
- Anomalous couplings
- Exotic production

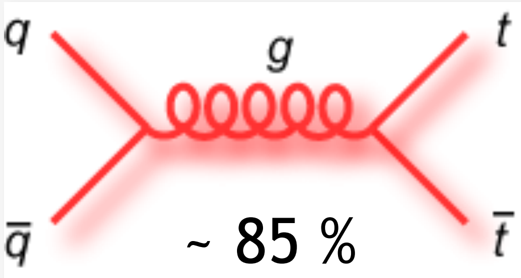
- Polarized top quarks

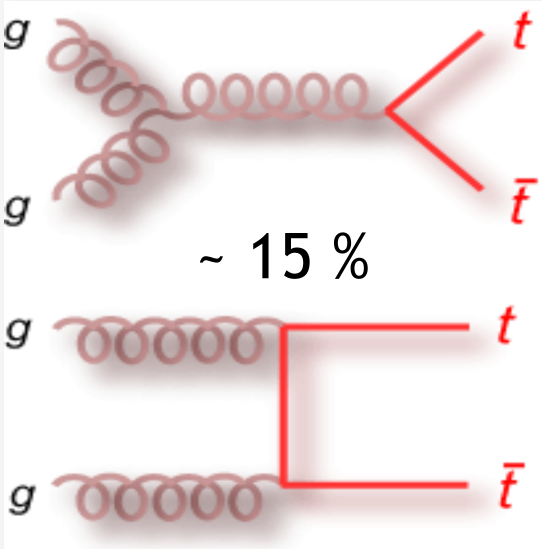
Tevatron program is systematically studying the physics of top quarks…

Top Quark Production at the Tevatron

Production

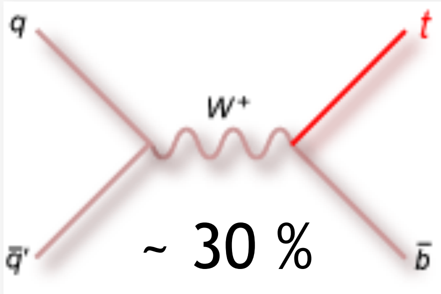
In Pairs

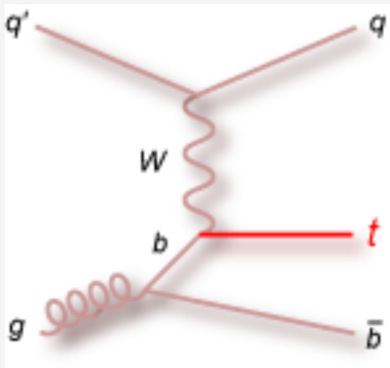




$\sigma_{NLO} = 7.3^{+0.5}_{-0.7}$ pb

Single





~ 70 %

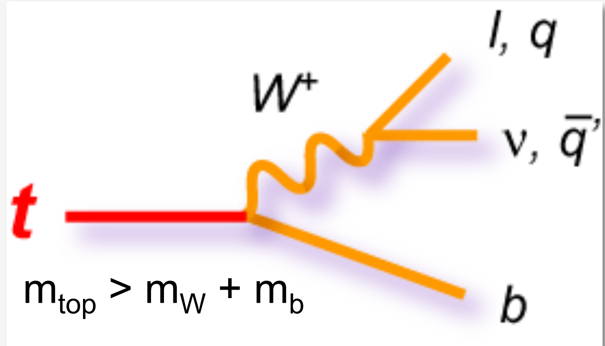
Wt: σ ~ 0.2pb (small)

$\sigma_{theory} = 3.3 \pm 0.3$ pb

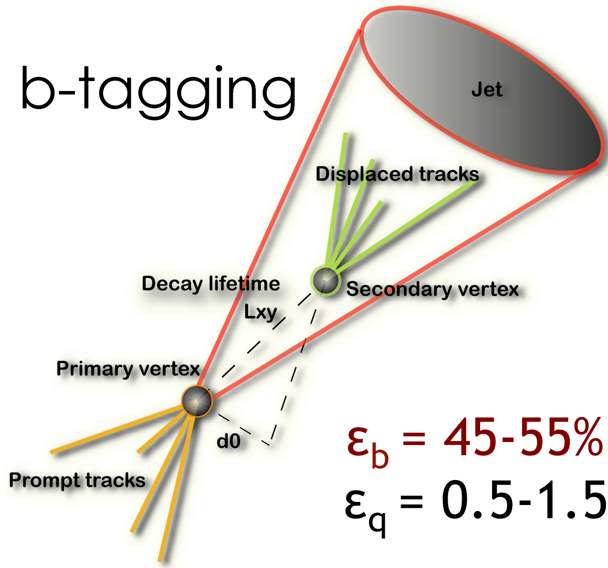
JHEP 0809, 127 (2008) m_t=172.5 GeV PRD 83, 091503 (2011)

Decay

BR(t→Wb) ~100 %



$m_{top} > m_W + m_b$



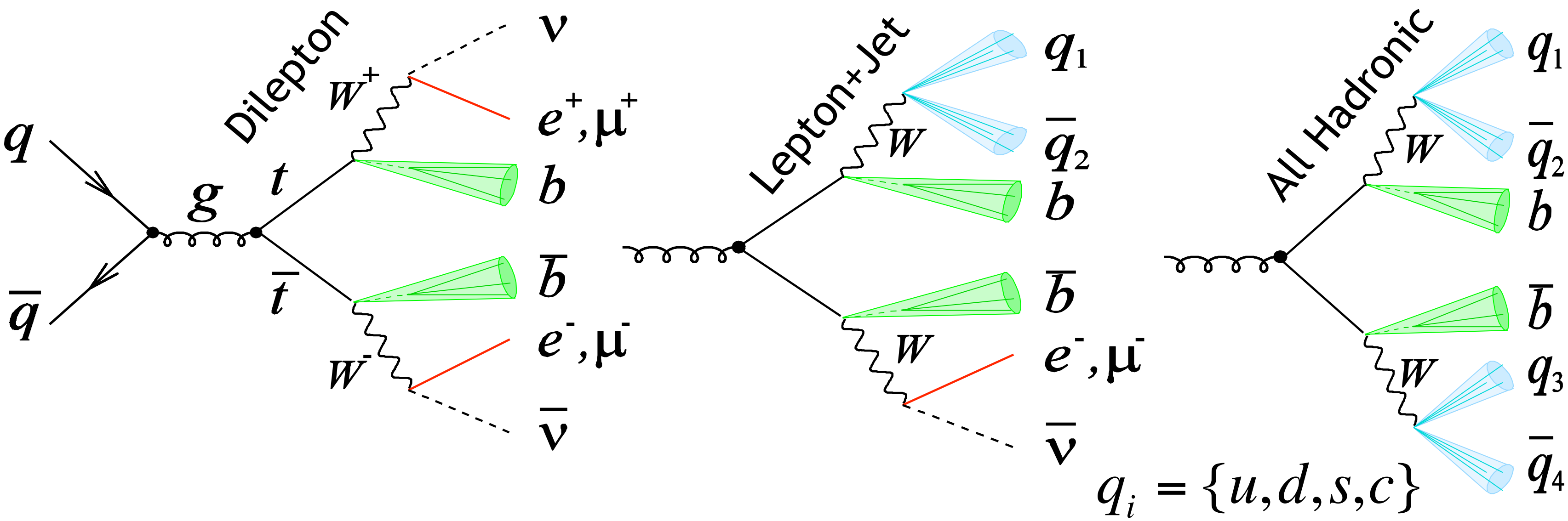
ε_b = 45-55%

ε_q = 0.5-1.5%

Top Quark Property Measurements

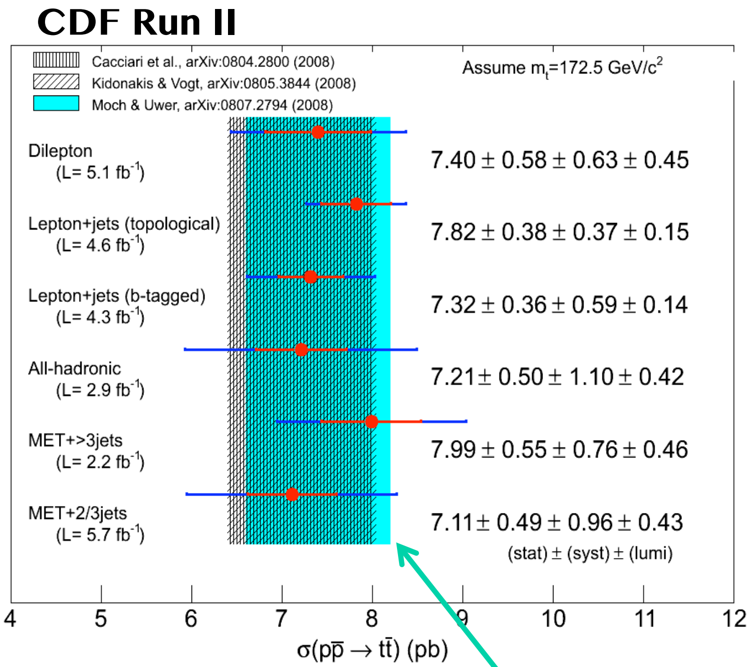
Property	Run II Measurement	SM prediction	Lumi (fb^{-1})
m_t	CDF: 172.8 ± 0.5(stat) ± 0.9(syst) GeV D0: 174.2 ± 0.9(stat) ± 1.5(syst) GeV		8.7 3.6
σ_{ttbar} (m_t=172.5 GeV) σ_{ttbar} (m_t=170 GeV)	CDF: 7.50 ± 0.31 (stat) ± 0.34 (syst) ± 0.15 (lumi) pb D0: 7.84 $^{+0.46}_{-0.45}$ (stat) $^{+0.66}_{-0.54}$ (syst) $^{+0.54}_{-0.46}$ (lumi) pb	7.5 ± 0.5 pb 7.4 ± 0.6 pb	4.5 5.3
$\sigma_{singletop}$ (@m_t=172.5 GeV)	CDF: 3.04 $^{+0.57}_{-0.53}$ (stat+syst) D0: 3.43 $^{+0.73}_{-0.74}$ (stat+syst)	3.1±0.8 pb	7.5 / 5.4
$\|V_{tb}\|$	CDF: 0.96 ± 0.09 (exp) ± 0.05 (theo) / D0: 1.02$^{+0.10}_{-0.10}$	1	7.5 / 5.4
σ(gg->ttbar)/σ(qq->ttbar)	D0: 0.07+0.15-0.07(stat+sys)	0.18	1
m_t - m_{tbar}	CDF: -2.0 ± 1.1 (stat) ± 0.6 (sys) GeV D0: 0.8 ± 1.8 (stat) ± 0.5 (sys) GeV	0 0	7.5 3.6
σ(tt→ll)/σ(tt→l+jets)	D0: 0.86 $^{+0.19}_{-0.17}$ (stat+syst)	1	1
σ(tt→τl)/σ(tt→ll + l+jets)	D0: 0.97 $^{+0.32}_{-0.29}$ (stat+syst)	1	1
$\sigma_{ttbar+jets}$ (@m_t=172.5 GeV)	CDF: 1.6 ± 0.2 (stat) ± 0.5 (syst)	1.79+0.16 -0.31 pb	4.1
$c\tau_{top}$	CDF: 52.5μm @ 95%C.L.	10^{-10} μm	0.3
Top width	CDF: <7.6 GeV @ 95% C.L. / D0: 2.0 ± 0.5 GeV	1.5 GeV	4.3 / 5.4
BR(t->Wb)/BR(t->Wq)	CDF: 0.91 ± 0.9 (stat+syst) D0: 0.90 ± 0.4 (stat+syst)	1 1	7.5 5.3
W-boson Helicity	Tevatron: f_0=0.72 ± 0.08 f_+=-0.03 ± 0.05	f_0 = 0.7, f_+ = 0	5
Charge	CDF: 4e/3 excluded with 99% C.L. D0: 4e/3 excluded at 92% C.L.	2/3	5.8 0.37
Spin correlations	CDF: κ^{LJ} = 0.72 ± 0.69, κ^{Dil}= 0.04 ± 0.56 (stat + syst) D0: κ = 0.66 ± 0.23 (stat + syst)	0.78 $^{+0.027}_{-0.022}$	5.1 5.3
Charge asymmetry	CDF: 16.2 ± 4.7 % (stat + syst) D0: 19.6 ± 6 % (stat + syst)	6.6 %	8.7 5.4

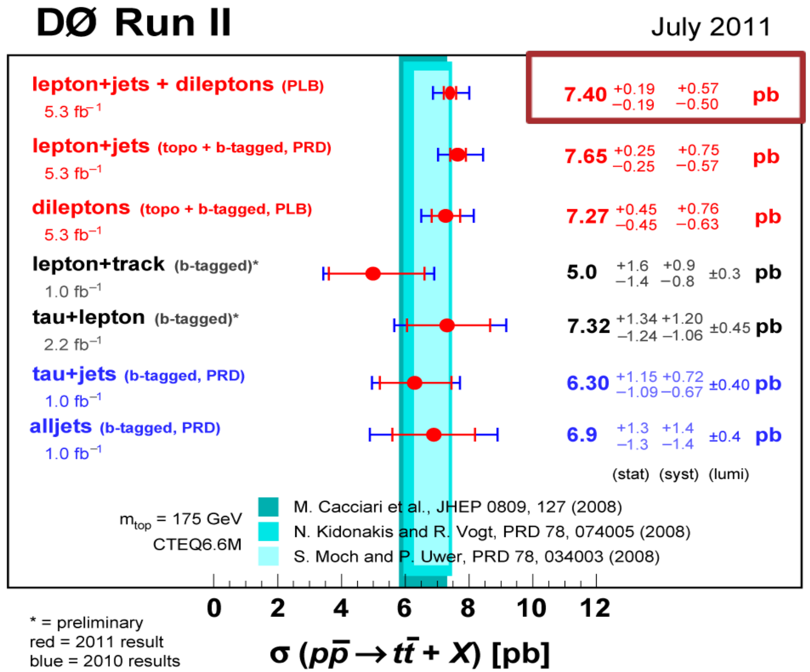
Top Quark Pair Production and Decay



- **Dilepton** (lepton = e or μ) (6%)
  - Small rate, small backgrounds
  - Main background: Drell-Yan
  - *Highest purity*
- **Lepton+Jets** (lepton = e or μ) (34%)
  - Good rate and manageable backgrounds
  - Main background: W+jets,
  - *Good purity "Golden Channel"*
- **All-hadronic (46%)**
  - Large rate, large background
  - Main background: QCD multijet
  - *Least purity*
- **Hadronic Taus** (tau+jets/lep, "MET+jets") (14%)
  - Small rate and large backgrounds
  - Main background: Multijets, W+jets
  - *Challenging purity*

Top Pair Production Cross Section

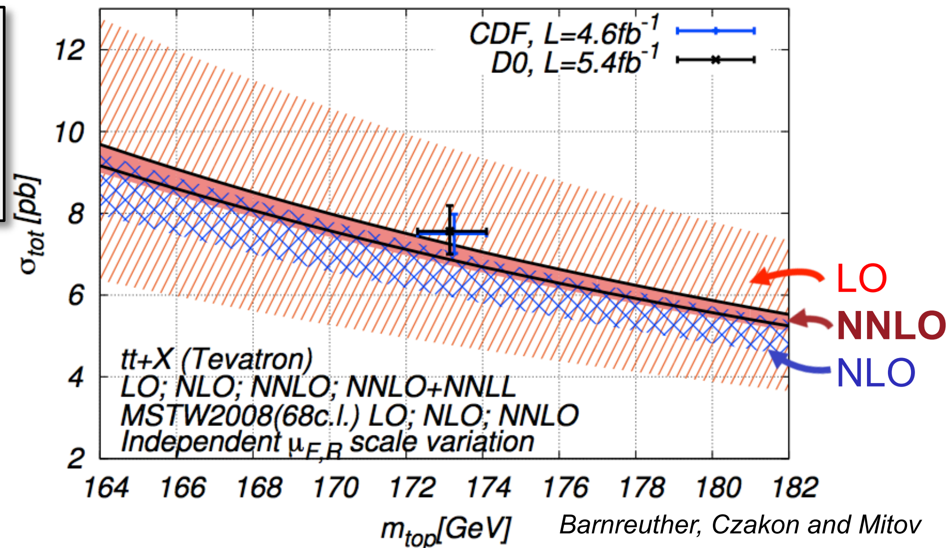




CDF:
σ_{tt} = 7.50 ± 0.48 pb

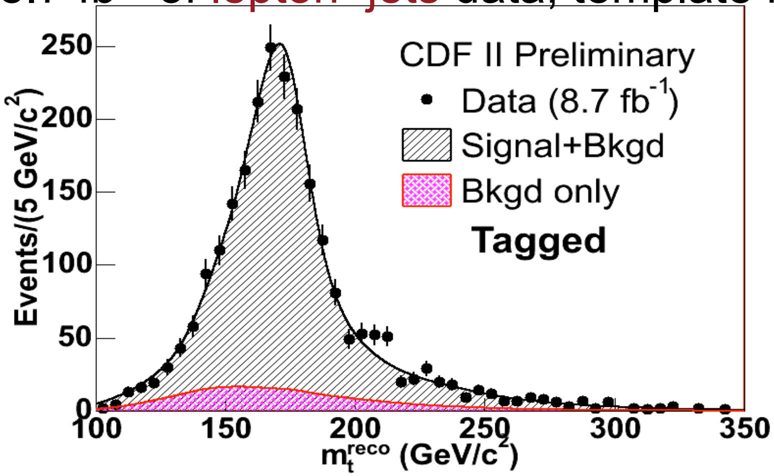
6.4 % exp. precision challenges theory
***But see* (NNLO): arXiv:1204.5201**

- Consistency among channels, methods and experiments
- All channels limited by systematic uncertainties (JES, *b*-tag, *W*+jets)
- Tevatron combination in progress

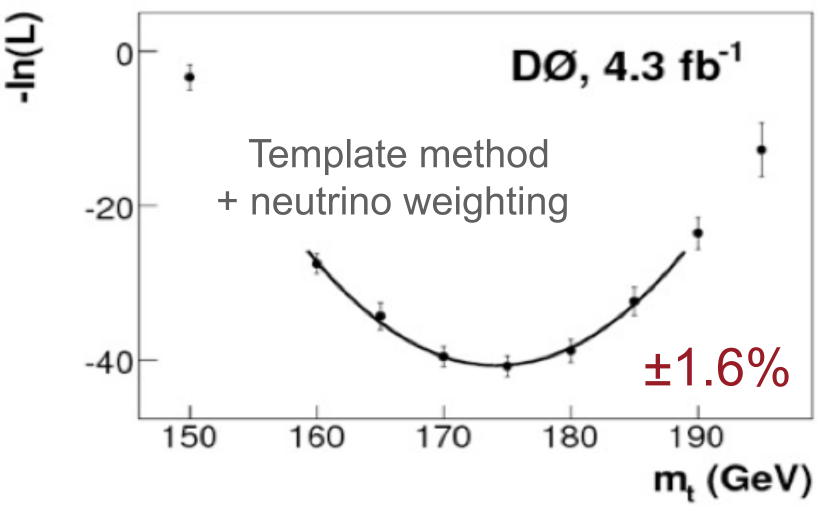


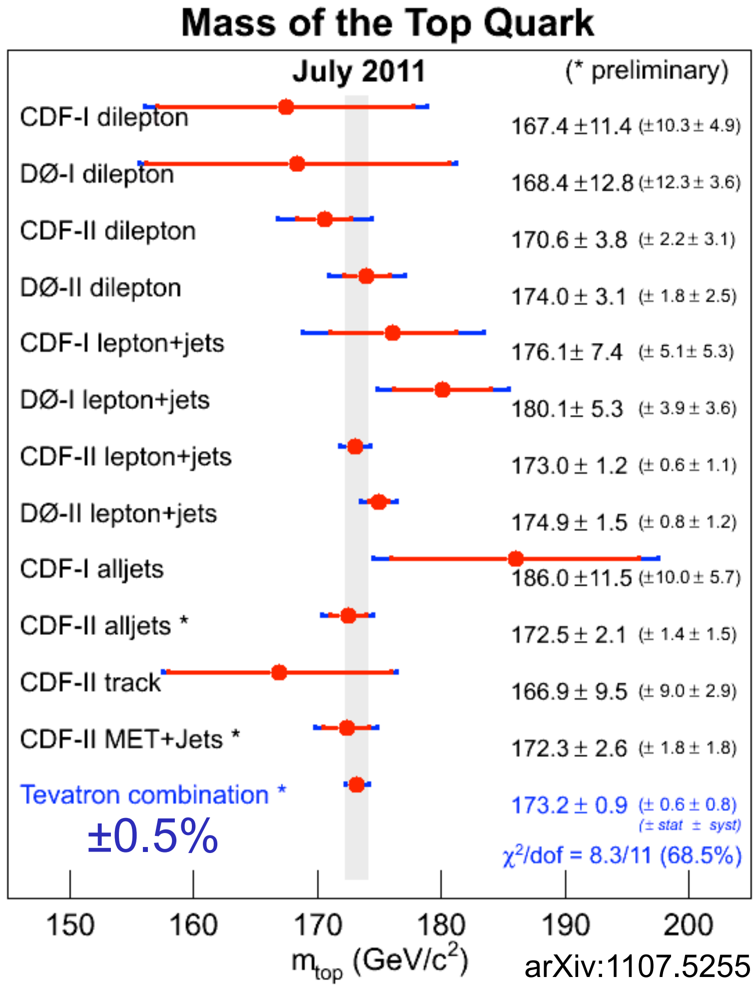
Top Quark Mass

- New CDF top mass. Simultaneous fit with JES in 8.7 fb^{-1} of lepton+jets data, template method



m_t=172.9 ± 0.7 (JES+stat) ± 0.8(syst) GeV ±0.6%





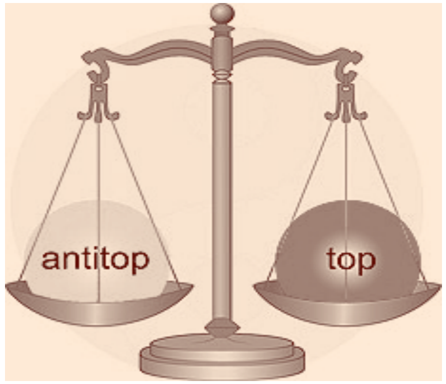
- New D0 top mass in dilepton channel. Transfer JES from L+J channel

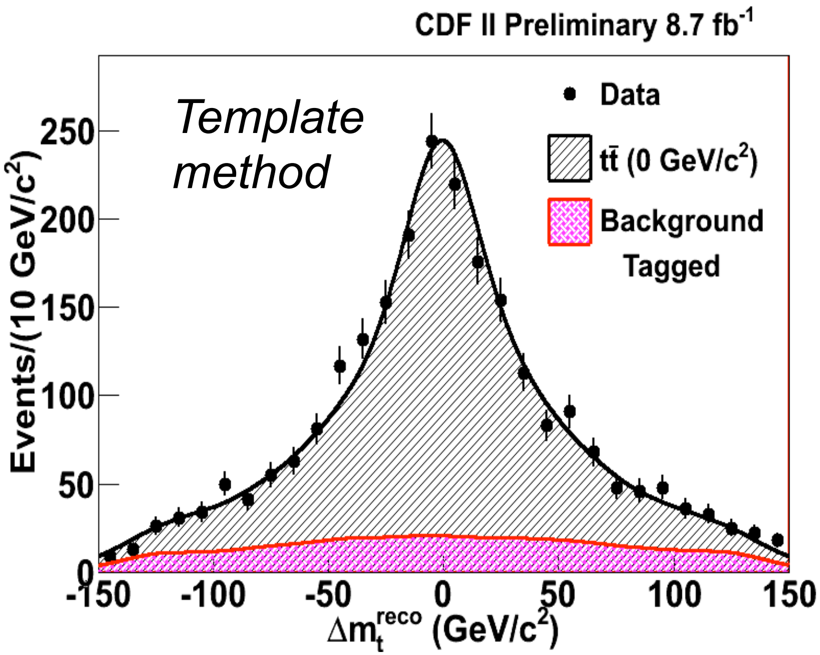
m_t=174.0 ± 2.4 (stat) ± 1.4 (syst) GeV

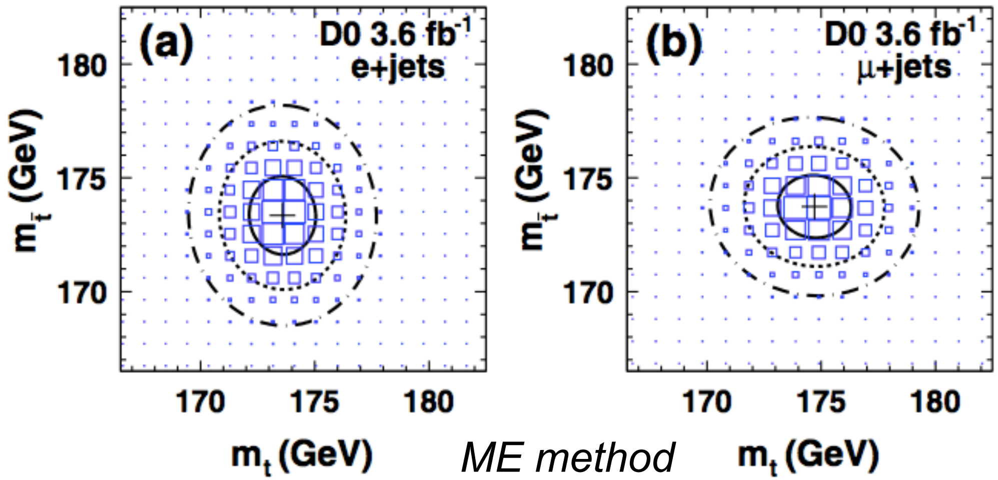
Top Anti-top Mass Difference

- If *CPT is a good symmetry of nature:*

$$\Delta M_t = M_{top} - M_{anti\text{-}top} = 0$$







CDF (8.7 fb^{-1}):
ΔM_t=-2.0 ± 1.1(stat) ± 0.6(sys)GeV

CDF Conf note: 10777

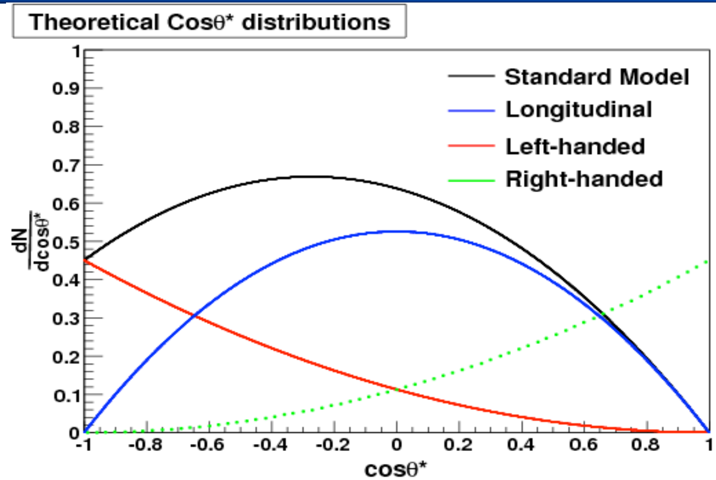
D0 (3.6 fb^{-1}):
ΔM_t=0.8 ± 1.8(stat) ± 0.5(sys) GeV

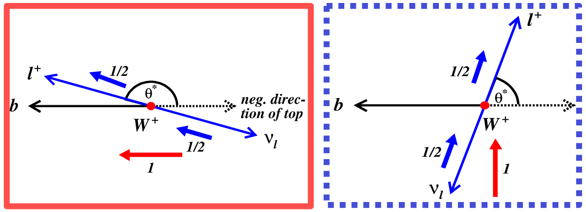
PRD 84, 052005 (2011)

Only measurement for a "bare quark" - consistent with SM expectations

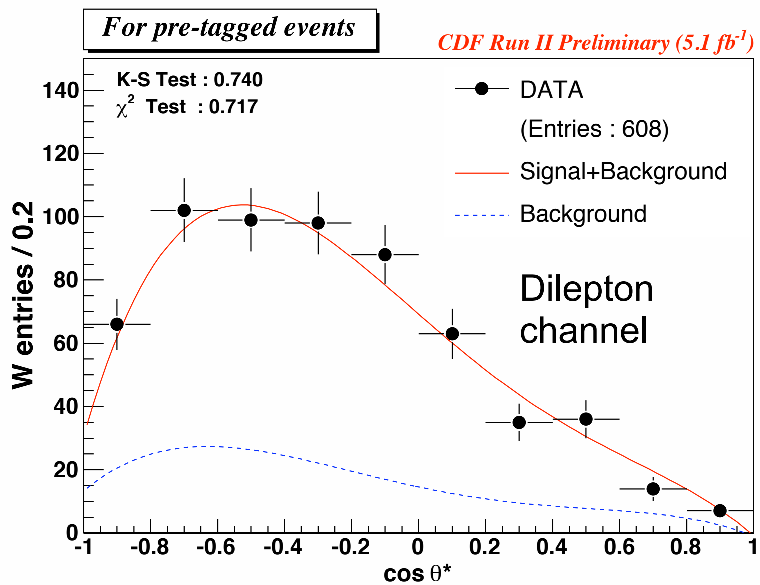
W-boson Helicity Fraction in Top Decays

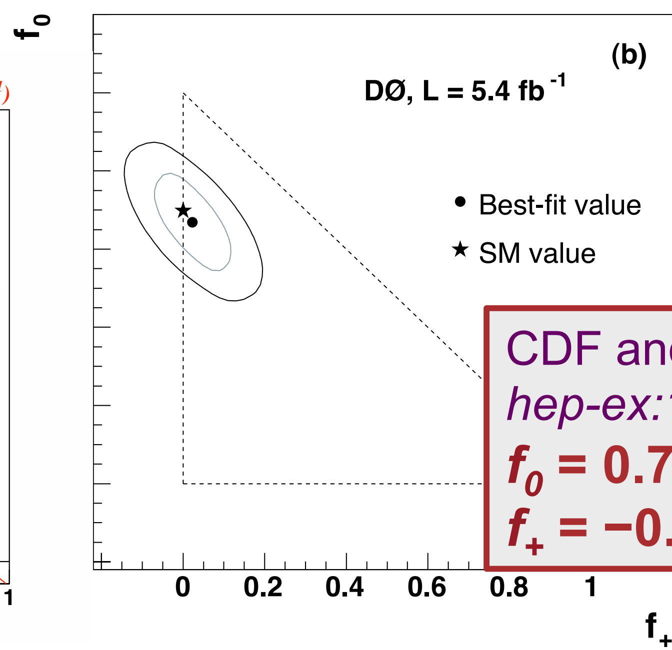
- SM top decays with (V-A) *t-W-b* coupling
- The helicity of *W* boson is predicted as:
  - Longitudinal fraction f_0 ~70%
  - Left-handed fraction f_- ~30%
  - Right-handed fraction f_+ ~ 0%
- Use cosθ* to measure fractions: f_0, f_+, f_-





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





D0:

f_0 = 0.669 ± 0.102

f_+ = 0.023 ± 0.053

PRD **83**, 032009 (2011)

CDF:

f_0 = 0.71 ± 0.19

f_+ = −0.07 ± 0.10

CDF Conf. Note 10543

CDF and D0 Combination

hep-ex:1202.5272 (BLUE)

f_0 = 0.722 ± 0.081

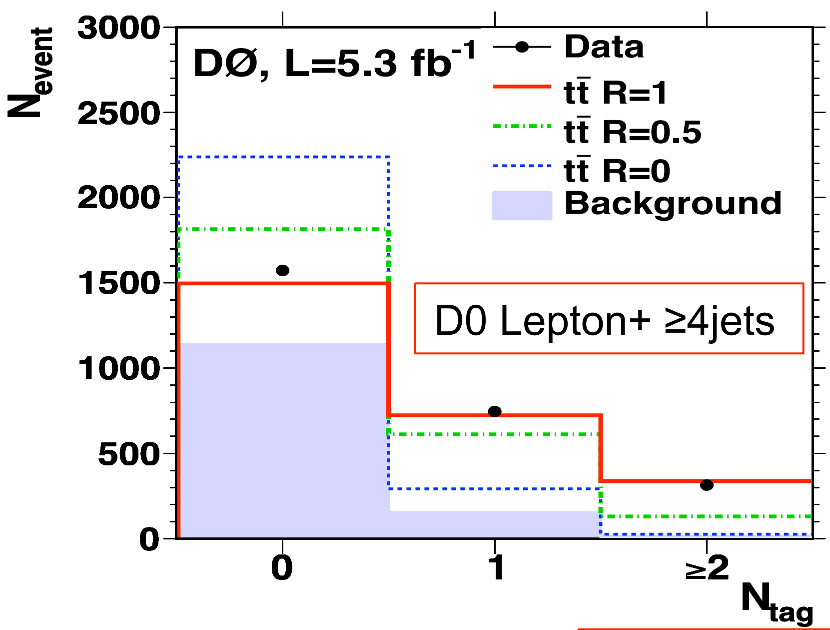
f_+ = −0.033 ± 0.046

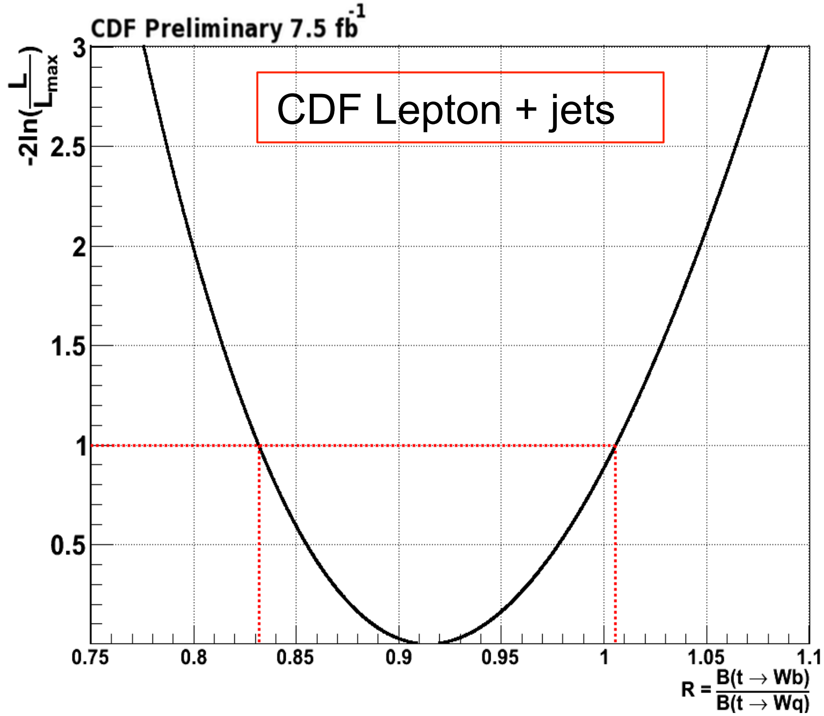
Top Branching Fraction Ratio

- Expect 2 *b*'s for each top anti-top event
  - b-tagging efficiency determines expected yield with 0, 1, or 2 tagged jets
  - Determine *R* from N_{tag} distribution
  - Derive $|V_{tb}|$ from R (*assumes* CKM unitary)

Standard Model predicts R~1

$$R = \frac{BR(t \to Wb)}{BR(t \to Wq)} = \frac{|V_{tb}|^2}{|V_{td}|^2 + |V_{ts}|^2 + |V_{tb}|^2}$$





D0: $R = 0.90 \pm 0.04$

$|V_{tb}| = 0.95 \pm 0.02$

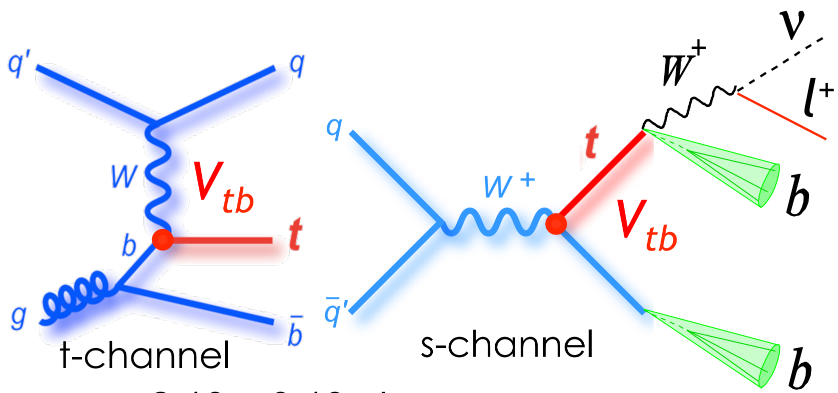
combined with D0 Dilepton

PRL **107**, 121802 (2011)

CDF: $R = 0.91 \pm 0.09$

$|V_{tb}| = 0.95 \pm 0.05$

Single Top Quark Production



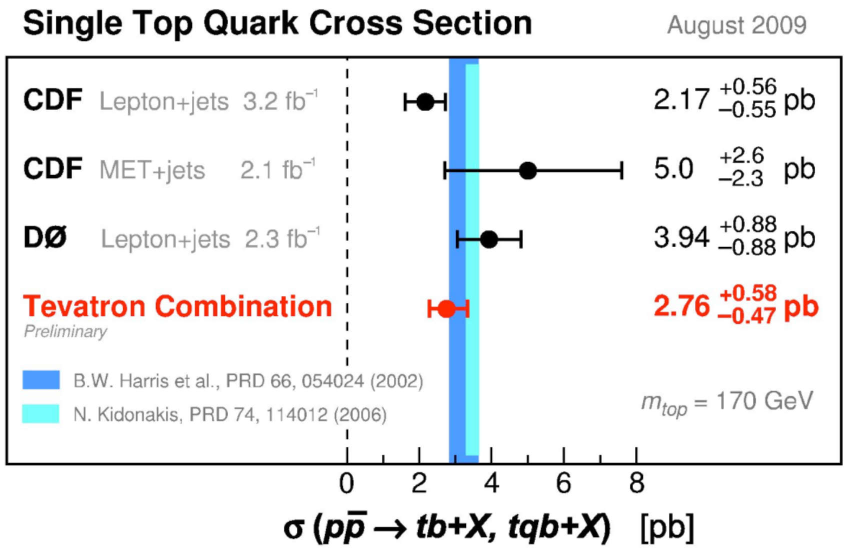
σ_{NLO} = 2.10 ± 0.19 pb σ_{NLO} = 1.05 ± 0.07 pb

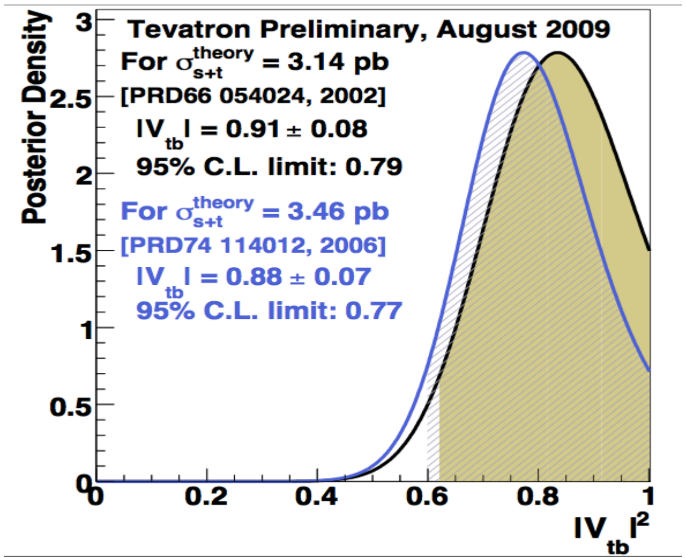
B.W. Harris, Phys. Rev. D66, 054024 (2002), Sullivan, Phys. Rev. D70, 114012 (2004).
Campbell/Ellis/Tramontano, Phys. Rev. D70, 094012 (2004).
N. Kidonakis, Phys. Rev. D83 091503 (2011).

- Joint CDF/D0 Observation, March 2009
  PRL 103, 092002 (2009), PRL 103, 092001 (2009)
- Direct access to CKM element $|V_{tb}|$
- Difficult measurement
  - Small cross section / less distinct final state
  - Large backgrounds with large uncertainties
  - Need advanced techniques + *b* tagging
  - *Matrix Elements, Neural Networks, BDTs,…*

Tevatron (3.2 fb^{-1}) Combination
$|V_{tb}|$= 0.91 ± 0.08 ; $|V_{tb}|$>0.79 at 95% C.L.

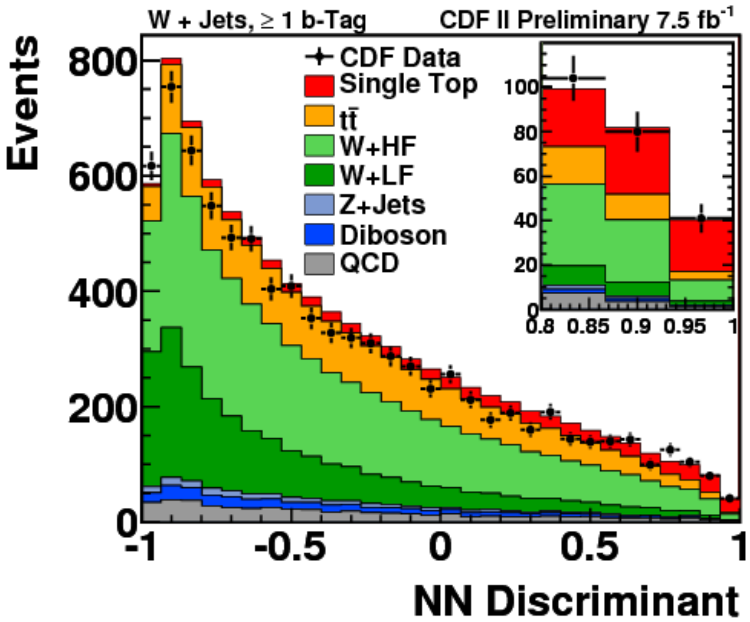
- Measure V_{tb} from Tevatron combination



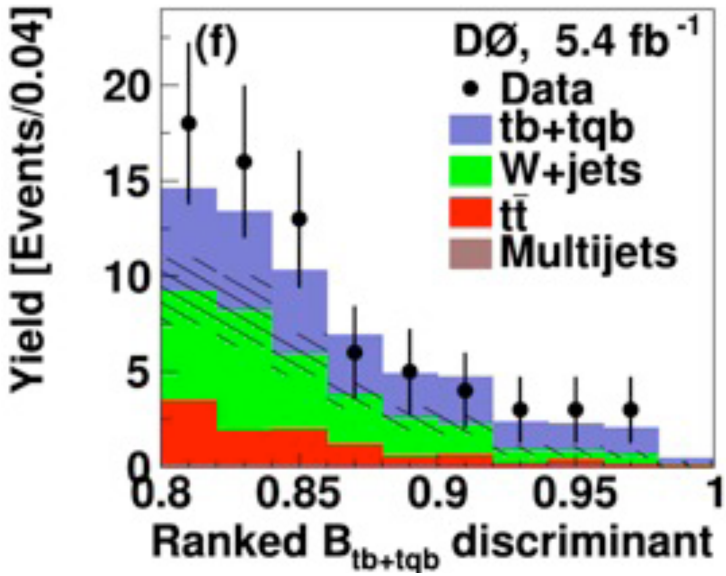


Updated Single Top Measurements

CDF Neural Network analysis



D0 Superdiscriminant (NN, BDT, Neat)



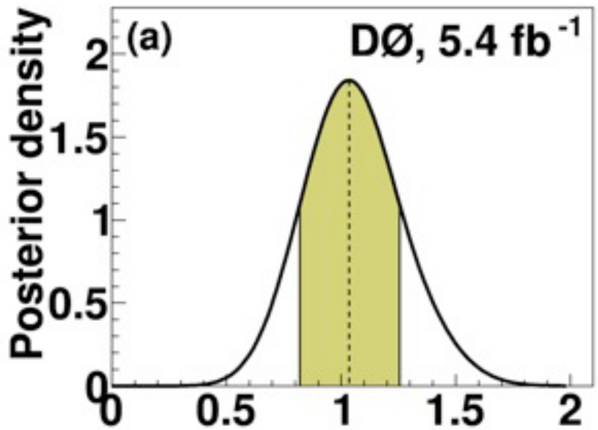
Sizable single top *signal* from CDF and D0:

CDF (7.5 fb^{-1}): $\sigma_{s+t}=3.04\ ^{+0.57}_{-0.53}$ **pb**	**D0 (5.4 fb^{-1}):** $\sigma_{s+t}=3.43\ ^{+0.73}_{-0.74}$ **pb**

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

$|V_{tb}| = 0.96\ ^{+0.10}_{-0.08}$ (stat+syst) ± 0.05 (theory)

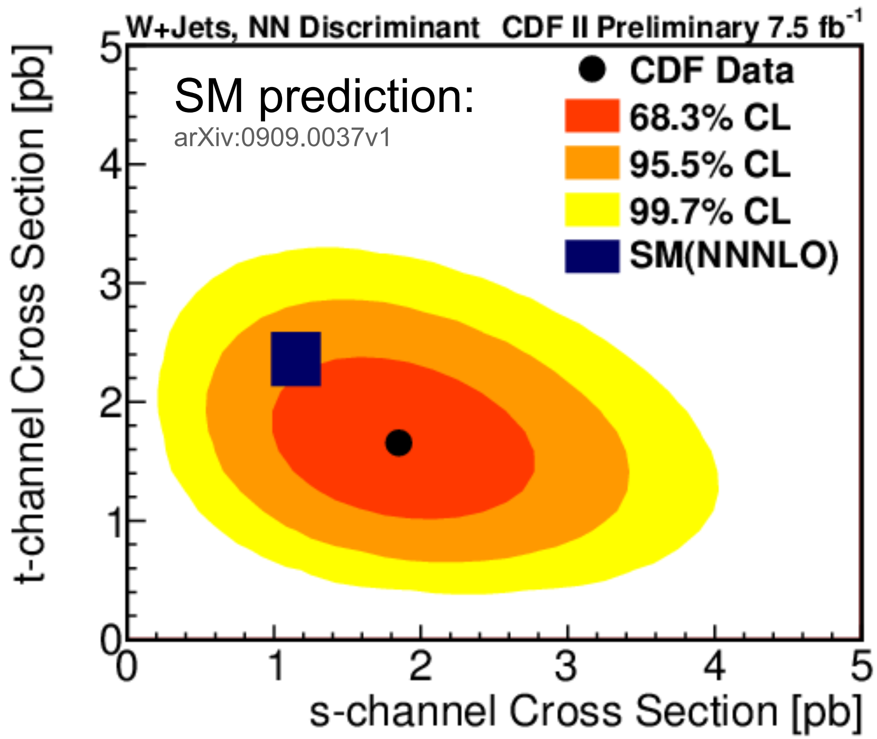
CDF Conf note: 10793

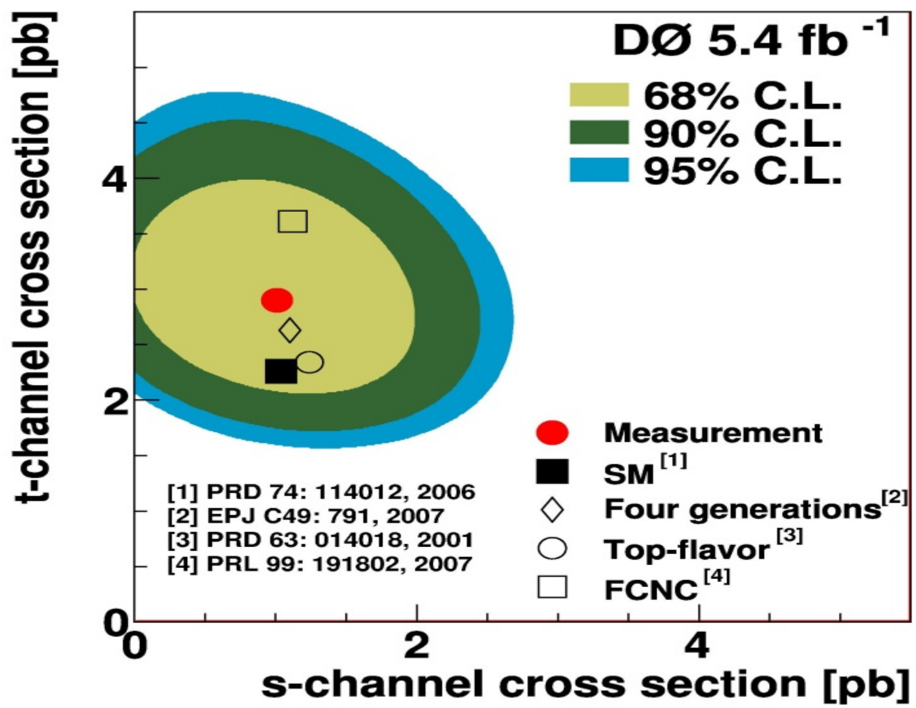


$|V_{tb}f_1^L| = 1.02^{+0.10}_{-0.11}$

PRD84, 112001 (2011)

Single Top Separate Channels (2D)





PLB 705, 313 (2011)

- Measured cross section:
  - $\sigma_s = 1.81^{+0.63}_{-0.58}$ pb (± ~33%)
  - $\sigma_t = 1.49^{+0.47}_{-0.42}$ pb

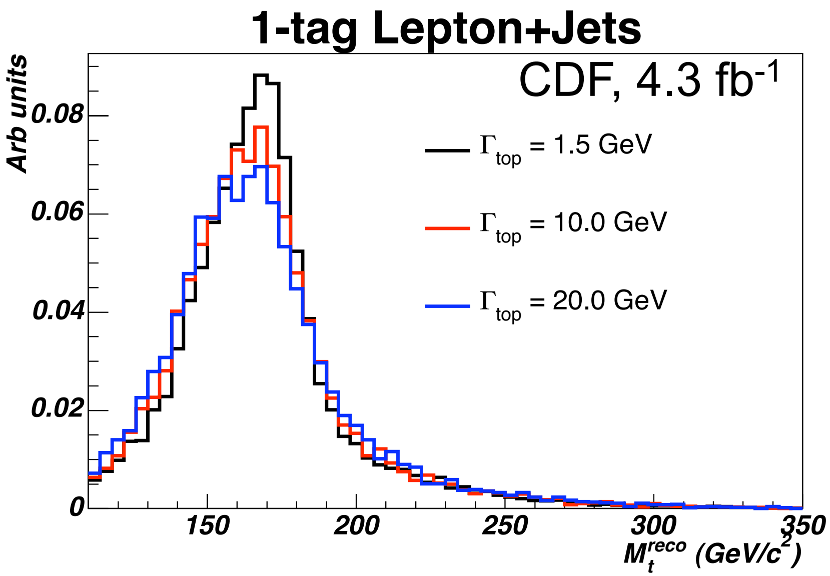
- Measured cross section:
  - $\sigma_s = 0.98 \pm 0.63$ pb
  - $\sigma_t = 2.90 \pm 0.59$ pb (± 20%) >5 SD!

Both channels are sensitive to different BSM scenarios

"Single top as window to new Physics"

Top Quark Width

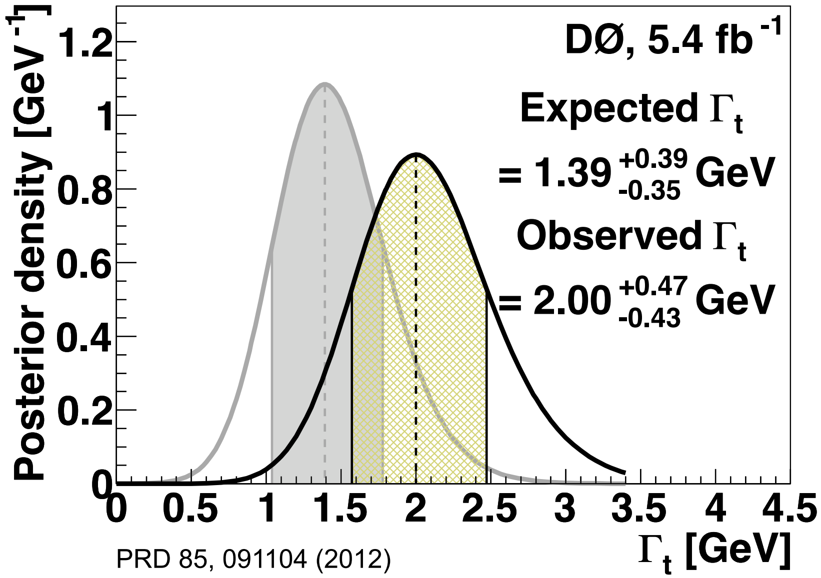
- SM Prediction: **Γ_t ~1.5 GeV**
  - Direct measurement of top decay width
  - Based on template top mass measurement extended to floating top quark width



0.3 GeV < Γ_t < 4.4 GeV at 68% C.L.

Γ_t < 7.6 GeV at 95% C.L.

- Derive width from other properties
  - Complementary to direct measure



PRD 85, 091104 (2012)

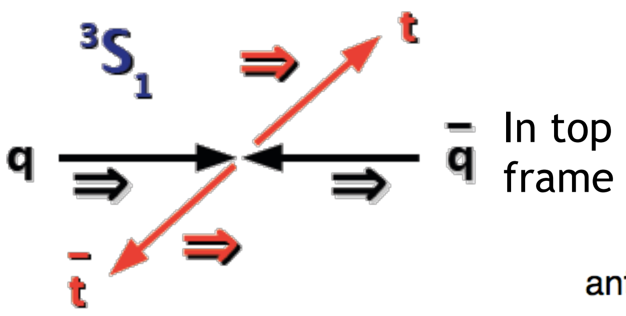
$$\Gamma_t = \frac{\Gamma(t \to Wb)}{B(t \to Wb)} = 2.00^{+0.47}_{-0.43} GeV$$

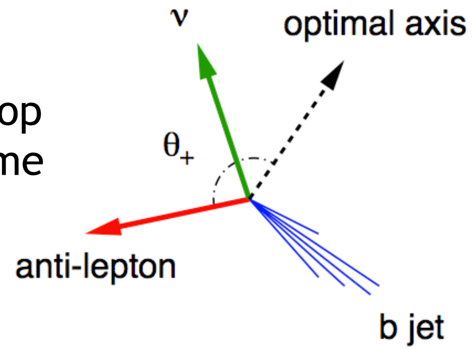
From top pair production — t-channel single top

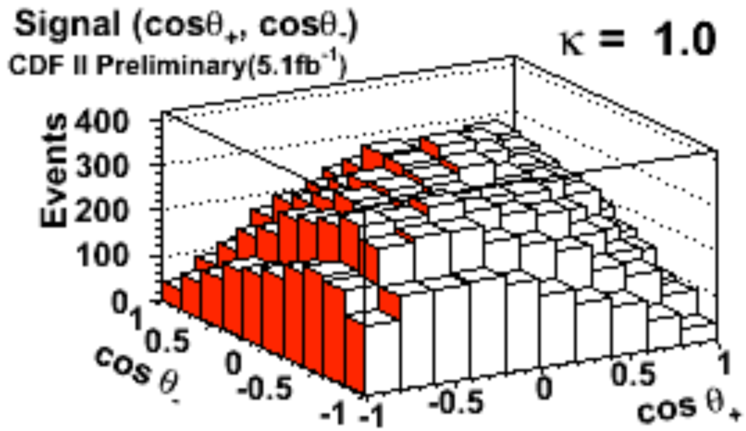
$$\Gamma(t \to Wb) = \sigma(t - channel)\frac{\Gamma_{SM}(t \to Wb)}{\sigma_{SM}(t - channel)}$$

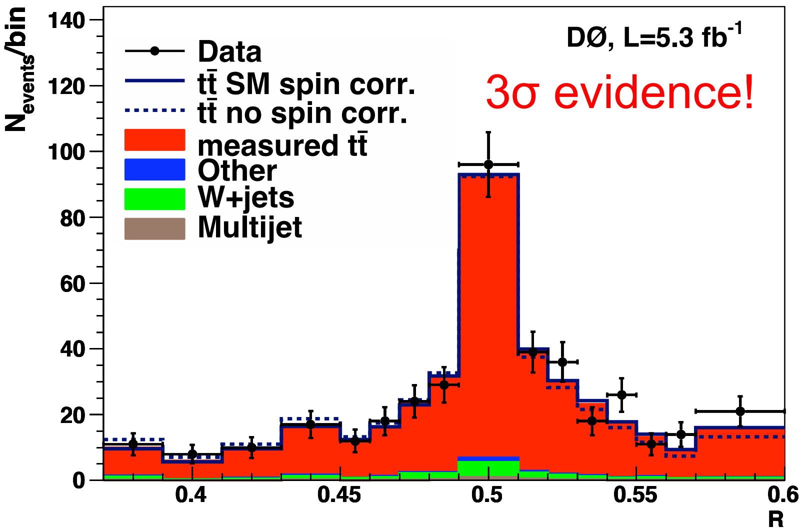
Top Anti-Top Quark Spin Correlations

- Top spins are correlated only if *top lifetime is short enough*
  - Spin-spin correlation is observable in the top quark decay products









PRL **108**, 032004 (2012)

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

SM predicts κ = 0.78 Nucl.Phys.B690, 81 (2004)

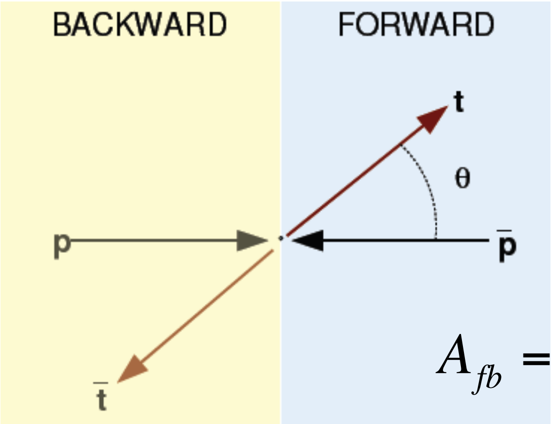
D0 (5.3 fb^{-1}):
κ_{Dil+LJ} = 0.66 ± 0.23

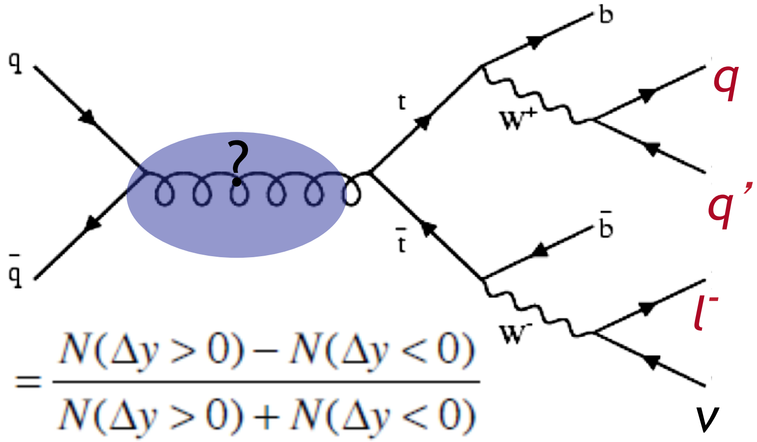
ME analysis

CDF (5.1 fb^{-1}):
κ_{LJ} = 0.72 ± 0.69
κ_{Dil} = 0.04 ± 0.56

Template analysis

Forward Backward Asymmetry





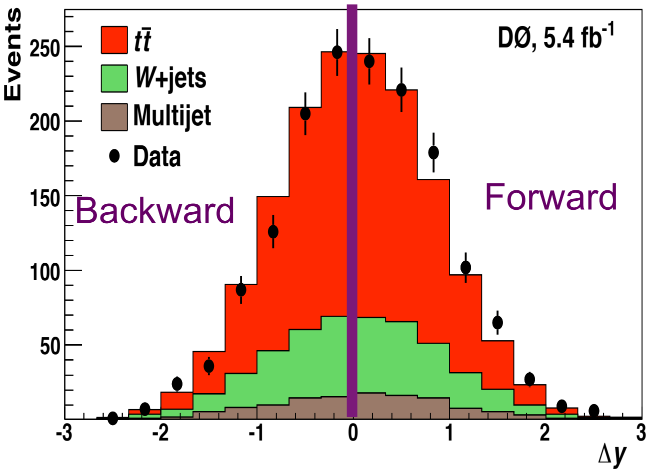
$$\Delta y = y_t - y_{\bar{t}}$$

$$A_{fb} = \frac{F - B}{F + B} = \frac{N(\Delta y > 0) - N(\Delta y < 0)}{N(\Delta y > 0) + N(\Delta y < 0)}$$

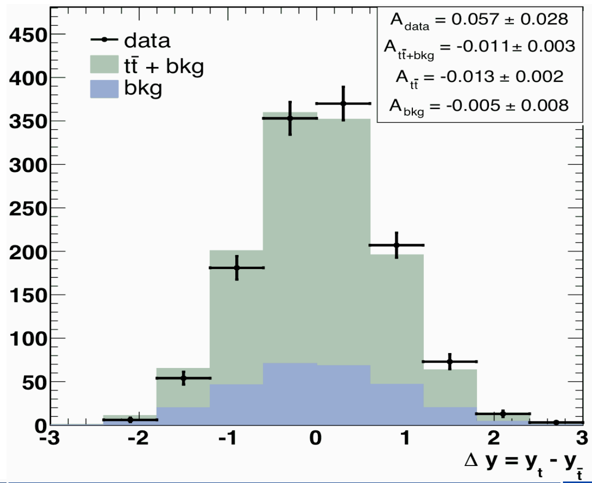
- SM predicts small asymmetry at NLO QCD: A_{fb}=0.066
- New physics could enhance observed A_{fb}

Powheg + EW Corrections:
JHEP **0709**, 126 (2007),
Phys. Rev. D **84**, 093003 (2011);
JHEP **1201**, 063 (2012)

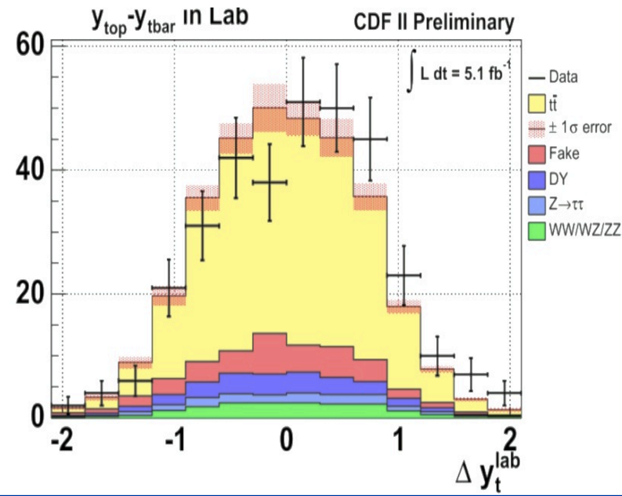
D0 Lepton + jets



CDF Lepton + jets

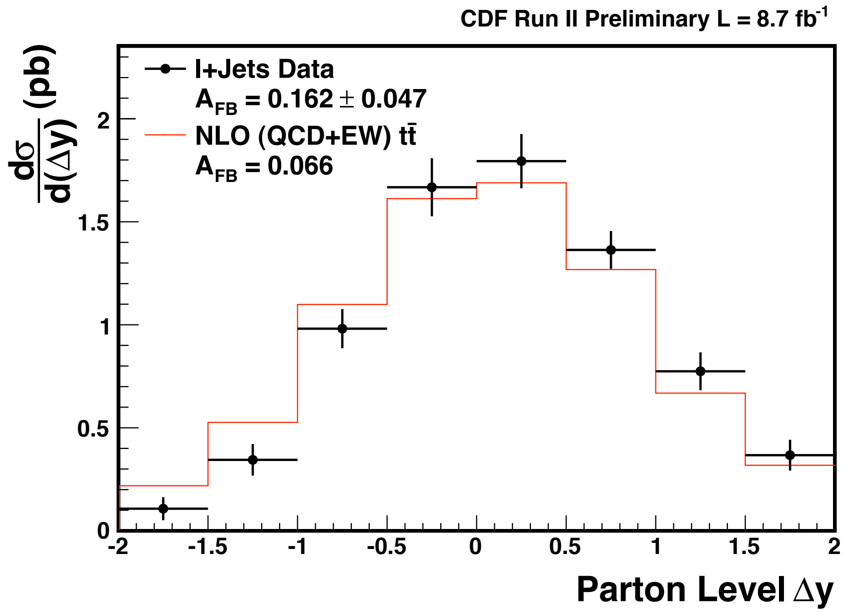


CDF Dilepton



Forward Backward Asymmetry

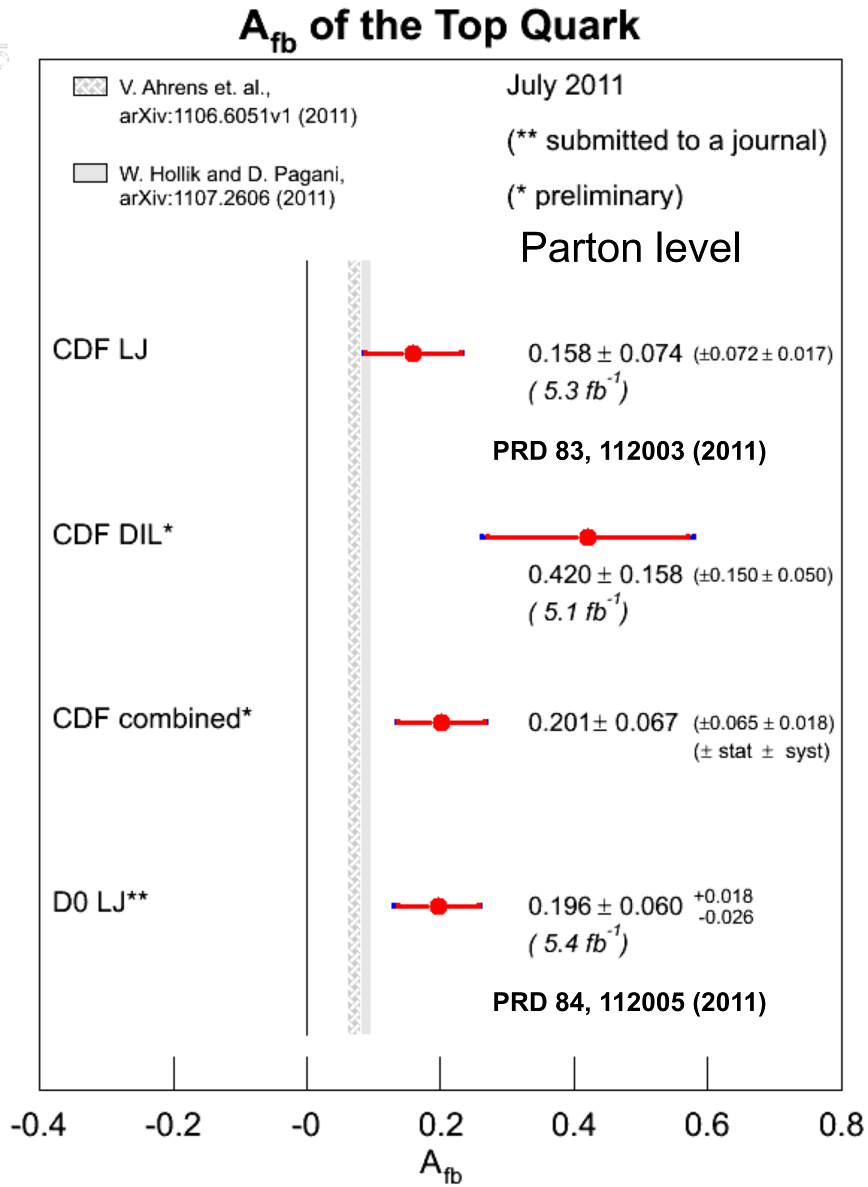
- To compare to theory, *data is corrected for background, acceptance and resolution effects* (back to *parton level*)



- Updates from CDF using 8.7 fb^{-1} Inclusive parton level asymmetry:

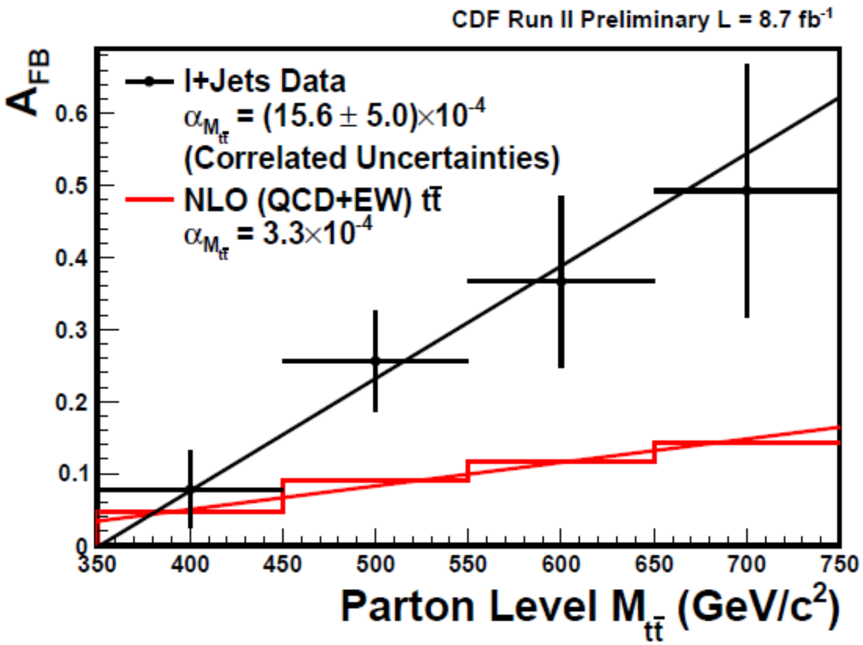
$$A^{\Delta y}_{FB} = 0.162\% \pm 0.047\%$$

- Comparable to previous CDF and D0 results



Forward Backward Asymmetry

- A_{FB} vs mass of the ttbar system
- NLO A_{FB} dependence on $\mathbf{M_{ttbar}}$ is more shallow than observed data
- Corrected for acceptance and detector resolution

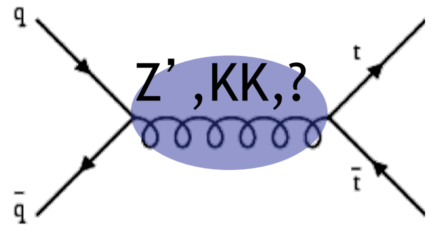


Slope	A_{FB} vs. M_{tt}
Data	$(15.6 \pm 5.0)\times10^{-4}$
SM	3.3×10^{-4}

M_{tt} (GeV)	NLO (QCD+EW)	CDF 5.3 fb^{-1}	CDF 8.7 fb^{-1}	D0 5.4 fb^{-1}
Inclusive	0.066	0.158 ± 0.074	0.162 ± 0.047	0.196 ± 0.065
< 450	0.047	−0.116 ± 0.153	0.078 ± 0.054	
> 450	0.100	0.475 ± 0.112	0.296 ± 0.067	

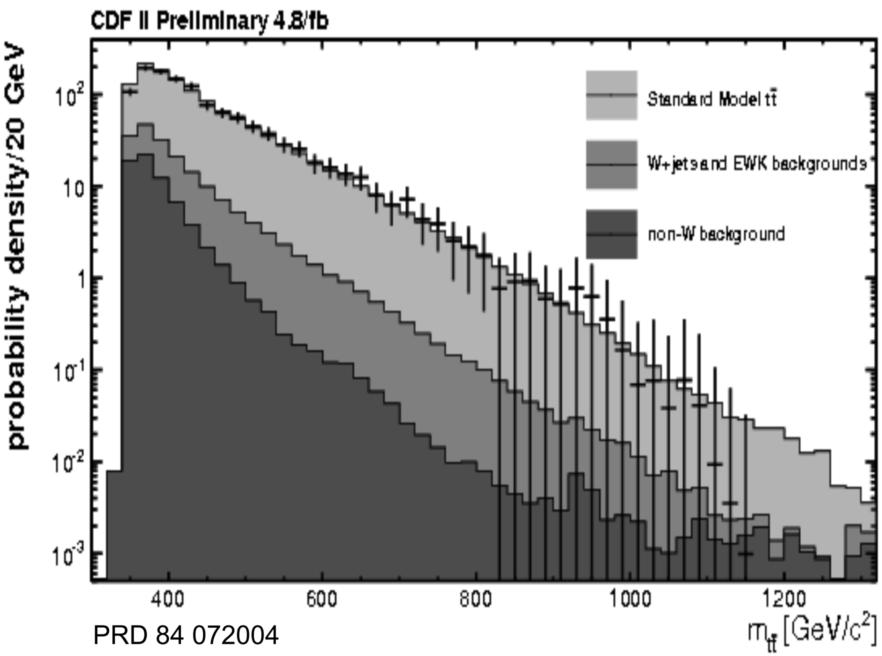
Search for ttbar Resonances

- Resonance production of *tt* is predicted by several new physics models
  - 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
  - Lepton plus Jets channel

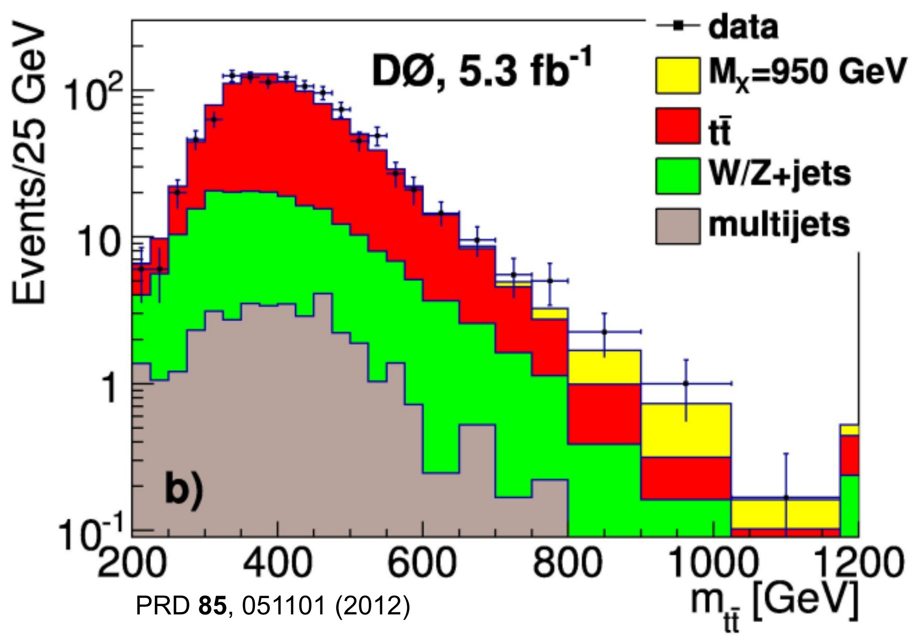


D0 (5.3 fb^{-1}):
>835 GeV/c^2 at 95% CL

CDF (4.8 fb^{-1}):
>900 GeV/c^2 at 95% CL



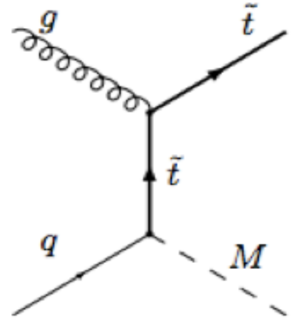
PRD 84 072004

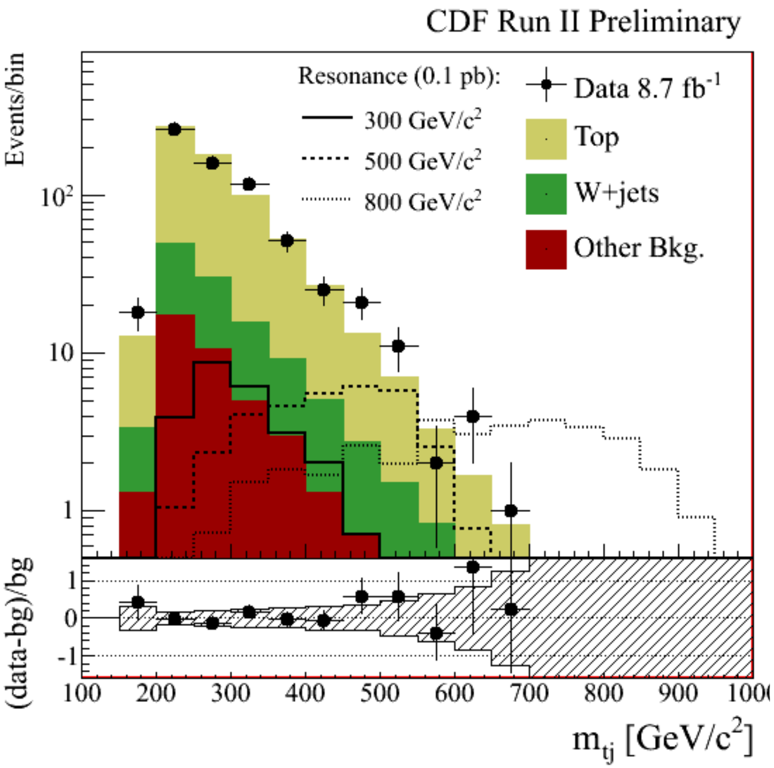


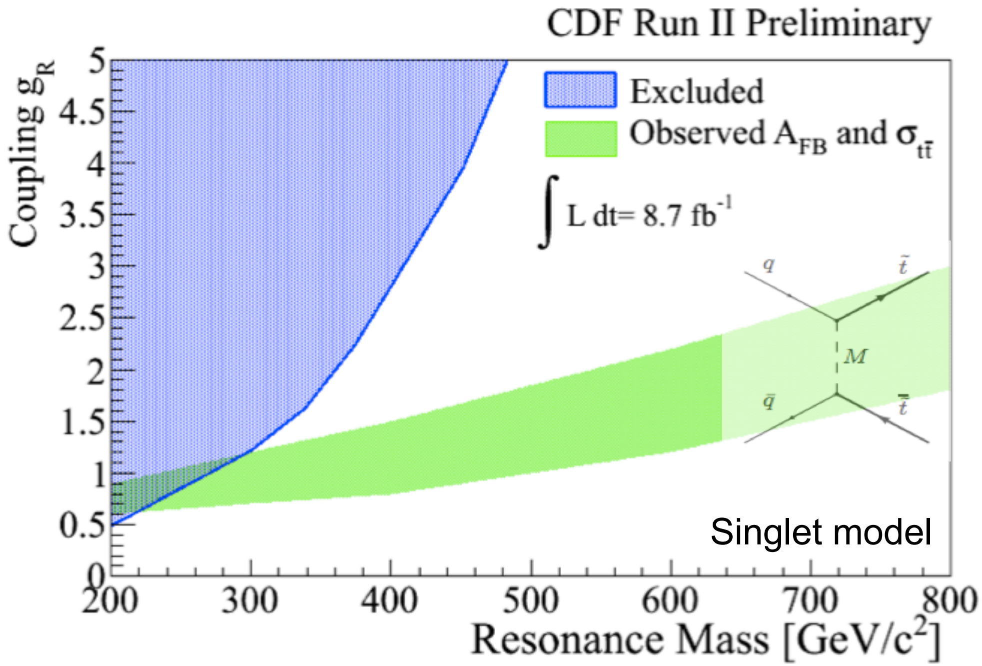
PRD **85**, 051101 (2012)

Search for Top-Jet Resonances

- Search for a heavy new particle *M* produced in association with a top quark $p\bar{p} \rightarrow Mt \rightarrow \bar{t}qt$
- Search for a resonance in the t+q system
- Lot's of activity in BSM phenomenology BSM attempting to explain large top anti-top A_{FB}







Summary

- The discovery of the top quark opened up a rich field in HEP
- Precision top quark physics at the Tevatron
  - → *Precision on top quark mass ~0.6 % (single measurement) ~0.5% Tevatron*
  - → *Production cross section (~6%) measurements are theory limited*
  - → *Single top measured to <20%, $|V_{tb}|$~10%, observation of t-channel*
  - → Several measurements competitive and *complementary* to LHC program
  - → Tension with Standard Model (A_{FB}) remains intriguing (NNLO computation anticipated)
- Stay tuned for legacy measurements from the Tevatron

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

  http://www-d0.fnal.gov/Run2Physics/top/top_public_web_pages/

Top results from D0 - Oleg Brandt (this afternoon)

Accelerator Innovations

- First major SC synchrotron
- Industrial production of SC cable (MRI)
- Electron cooling
- New RF manipulation techniques

Detector innovations

- Silicon vertex detectors in hadron environment
- LAr-U238 hadron calorimetry
- Advanced triggering

Analysis Innovations

- Data mining from Petabytes of data
- Use of neural networks, boosted decision trees
- Major impact on LHC planning and developing
- GRID pioneers

Major discoveries

- Top quark
- B_s mixing
- Precision W and Top mass → Higgs mass prediction
- Direct Higgs searches
- Ruled out many exotica

The next generation

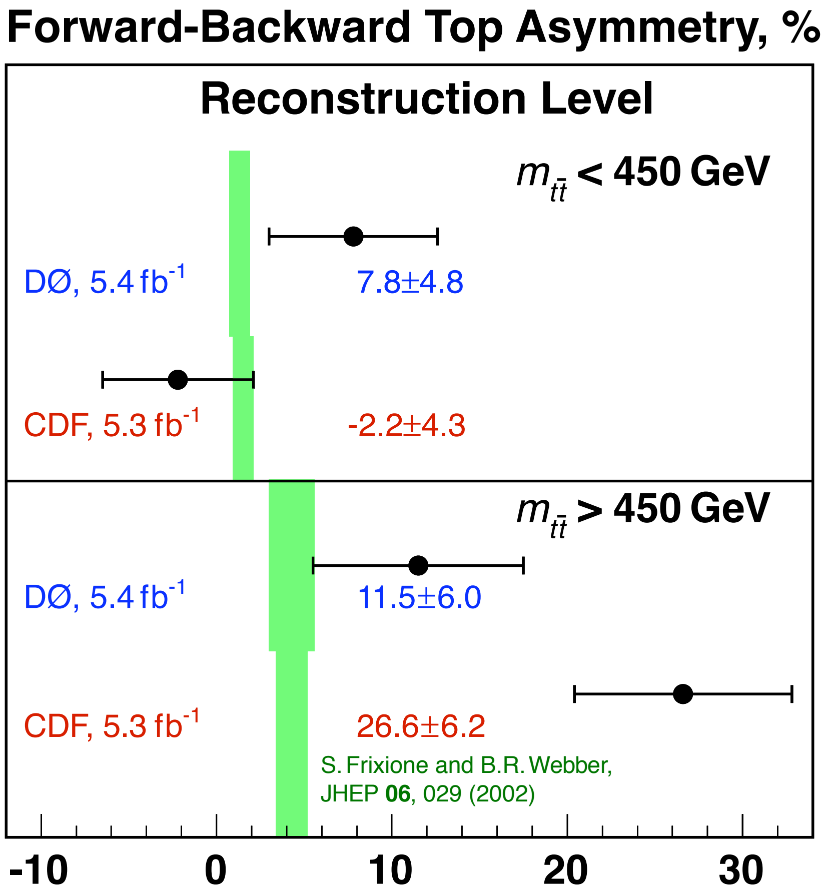
- Fantastic training ground for next generation
- More than 500 Ph.D.s
- Produced critical personnel for the next steps, especially LHC

Backup

A_{FB} Details

Somewhat ambiguous mass and rapidity dependence (two bins in $M_{tt}/\Delta y$)

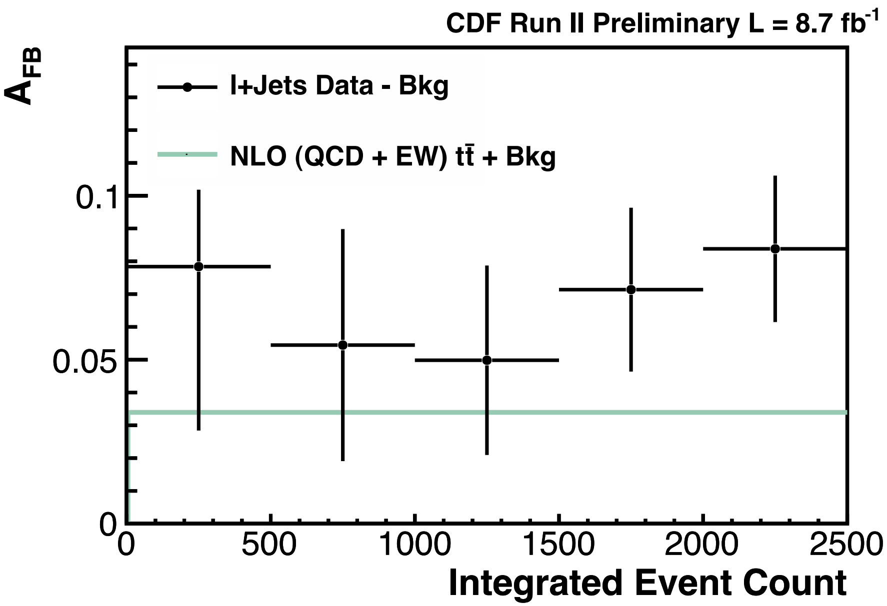
Background Subtracted A_{FB} (%)	$\vert\Delta y\vert < 1.0$	$\vert\Delta y\vert \geq 1.0$
D0 Lep+Jet	6.1 ± 4.1	21.3 ± 9.7
CDF Lep+Jet	2.9 ± 4.0	29.1 ± 9.6

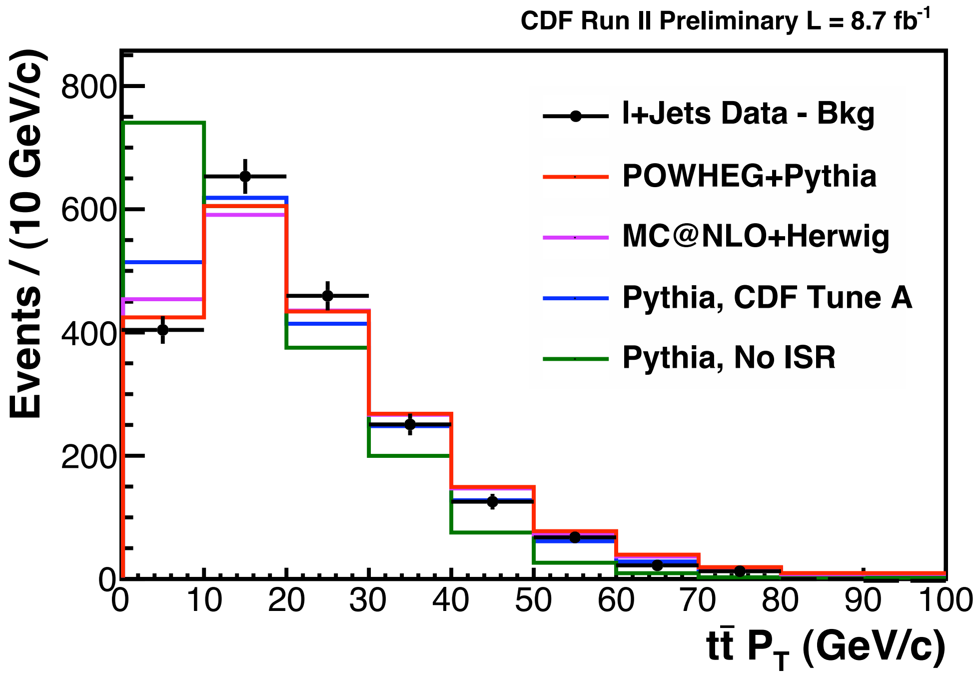


A_{FB} over Time

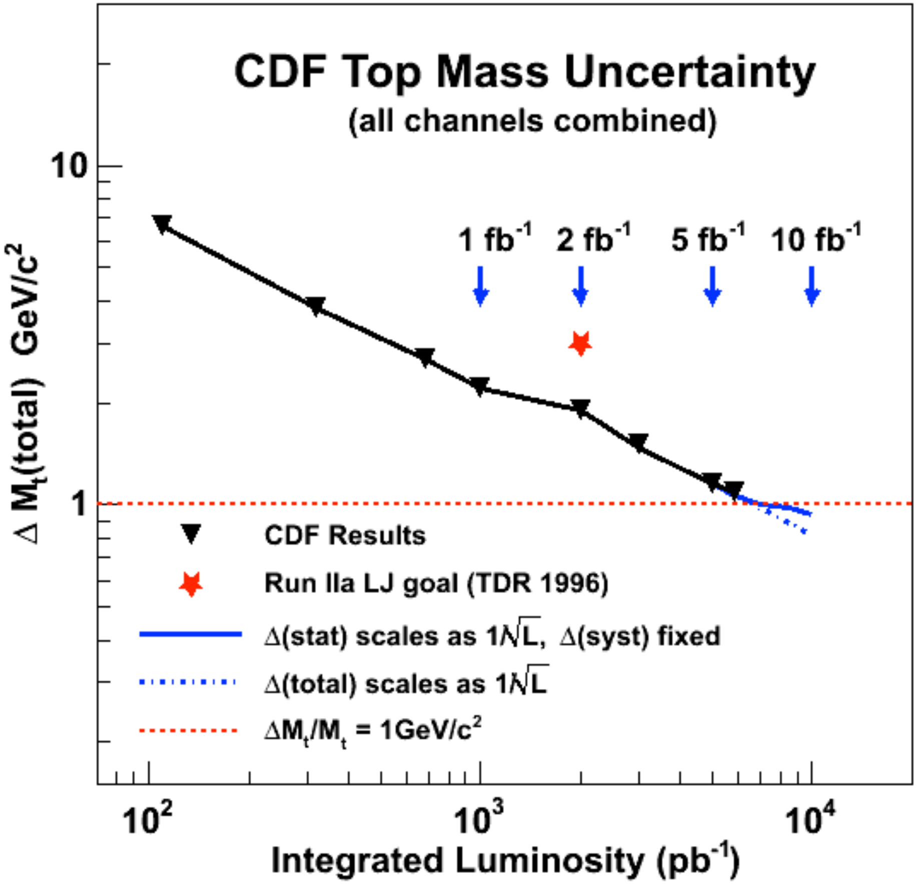
- Look at the background-subtracted asymmetry as a function of the number of events
  - Verify robustness over time
  - "0 events" = start of Run II

- Modeling of pT(tt)
  - Unfolded spectrum in good agreement with NLO prediction





Top Quark Mass



	Tevatron combined values (GeV/c^2)
M_t	173.18
iJES	0.39
aJES	0.09
bJES	0.15
cJES	0.05
dJES	0.20
rJES	0.12
Lepton p_T	0.10
Signal	0.51
Detector Modeling	0.10
UN/MI	0.00
Background from MC	0.14
Background from Data	0.11
Method	0.09
MHI	0.08
Systematics	0.75
Statistics	0.56
Total	0.94

arXiv:1107.5255