

# A (Hi)Story Of The D0 Top Quark



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Special Session of the D0 Collaboration Week  
30-September-2011

# The Beginning of the Story

- 1984-1985
  - commissioning of the Tevatron
  - first collisions at CDF in 1985
  - D0 was just a hole in the ground



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- towards Run I

- 1987: Run 0 of CDF ( $0.4 \text{ pb}^{-1}$ )
- 1992-1996: Run I for CDF and D0 ( $1.8 \text{ TeV}$ ,  $120 \text{ pb}^{-1}$ )

- the top quark before 1995

- existence needed after the discovery of the b-quark in 1976 at Fermilab
- direct searches:

1984: Petra ( $e^+e^-$ ):  $M_t > 23.3 \text{ GeV}$

80s: Tristan ( $e^+e^-$ ):  $M_t > 30.3 \text{ GeV}$

1988: UA1 ( $p\bar{p}$ ):  $M_t > 44 \text{ GeV}$

~ 1990: LEP ( $e^+e^-$ ):  $M_t > 45.8 \text{ GeV}$

1990: UA2 ( $p\bar{p}$ ):  $M_t > 69 \text{ GeV}$

1992: CDF ( $p\bar{p}$ ):  $M_t > 91 \text{ GeV}$

1994: D0 ( $p\bar{p}$ ):  $M_t > 131 \text{ GeV}$

+ indirect constraints  
from the electroweak fit



1985

# The Discovery

## Observation of the Top Quark

S. Abachi,<sup>12</sup> B. Abbott,<sup>33</sup> M. Abolins,<sup>23</sup> B. S. Acharya,<sup>40</sup> I. Adam,<sup>10</sup> D. L. Adams,<sup>34</sup> M. Adams,<sup>15</sup> S. Ahn,<sup>12</sup> H. Aihara,<sup>20</sup>

The D0 Collaboration reports on a search for the standard model top quark in  $p\bar{p}$  collisions at  $\sqrt{s} = 1.8$  TeV at the Fermilab Tevatron with an integrated luminosity of approximately  $50 \text{ pb}^{-1}$ . We have searched for  $t\bar{t}$  production in the dilepton and single-lepton decay channels with and without tagging of  $b$ -quark jets. We observed 17 events with an expected background of  $3.8 \pm 0.6$  events. The probability for an upward fluctuation of the background to produce the observed signal is  $2 \times 10^{-6}$  (equivalent to 4.6 standard deviations). The kinematic properties of the excess events are consistent with top quark decay. We conclude that we have observed the top quark and measured its mass to be  $199^{+19}_{-21}$  (stat)  $\pm 22$  (syst)  $\text{GeV}/c^2$  and its production cross section to be  $6.4 \pm 2.2 \text{ pb}$ .

## Observation of Top Quark Production in $\bar{p}p$ Collisions with the Collider Detector at Fermilab

F. Abe,<sup>14</sup> H. Akimoto,<sup>32</sup> A. Akopian,<sup>27</sup> M. G. Albrow,<sup>7</sup> S. R. Amendolia,<sup>24</sup> D. Amidei,<sup>17</sup> J. Antos,<sup>29</sup> C. Anway-Wiese,<sup>4</sup>

We establish the existence of the top quark using a  $67 \text{ pb}^{-1}$  data sample of  $\bar{p}p$  collisions at  $\sqrt{s} = 1.8$  TeV collected with the Collider Detector at Fermilab (CDF). Employing techniques similar to those we previously published, we observe a signal consistent with  $t\bar{t}$  decay to  $Wb\bar{b}$ , but inconsistent with the background prediction by  $4.8\sigma$ . Additional evidence for the top quark is provided by a peak in the reconstructed mass distribution. We measure the top quark mass to be  $176 \pm 8$  (stat)  $\pm 10$  (syst)  $\text{GeV}/c^2$ , and the  $t\bar{t}$  production cross section to be  $6.8^{+3.6}_{-2.4} \text{ pb}$ .

submitted to PRL on Feb 24<sup>th</sup>, 1995

- D0:  $50 \text{ pb}^{-1}$ ,  $4.6 \sigma$

$$M_t = 199 \pm 30 \text{ GeV}$$

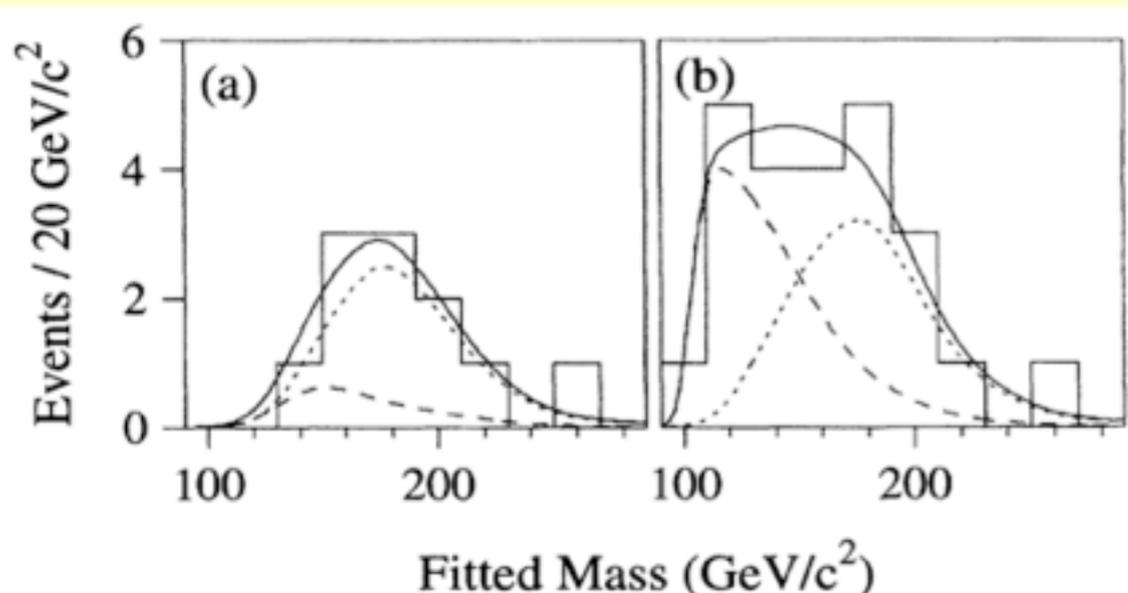
$$\sigma_{t\bar{t}} = 6.4 \pm 2.2 \text{ pb}$$

- CDF:  $67 \text{ pb}^{-1}$ ,  $4.8 \sigma$

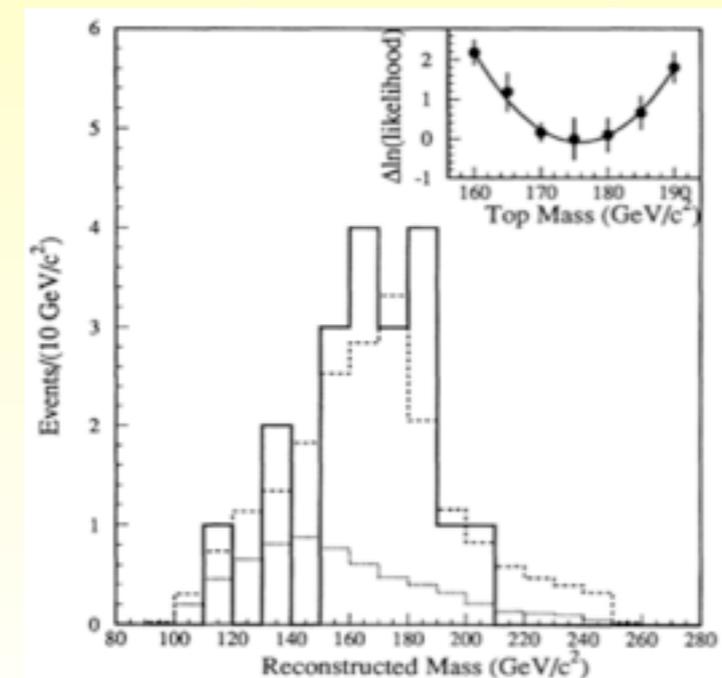
$$M_t = 176 \pm 13 \text{ GeV}$$

$$\sigma_{t\bar{t}} = 6.8^{+3.6}_{-2.4} \text{ pb}$$

standard and loose selections



W +  $\geq 4$  jets events with b-tag



# Top Discovery Seminar at Fermilab

- March 2<sup>nd</sup>, 1995



some of the D0 PhD students in 1995



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1995

# PDG on the Top Quark After the Discovery

## t-Quark Mass in $p\bar{p}$ Collisions

PRD 54, 1 (1996)

The  $t$  quark has now been observed. Its mass is sufficiently high that decay is expected to occur before hadronization.

Preliminary results for the top mass based on the full (Run Ia+Ib) data set have been presented by CDF and DØ at conferences in early 1996:

$m_t = 175.6 \pm 5.7 \pm 7.1$ GeV	CDF	lepton + jets
$m_t = 159^{+24}_{-22} \pm 17$ GeV	CDF	dilepton
$m_t = 187 \pm 8 \pm 12$ GeV	CDF	hadronic
$m_t = 170 \pm 15 \pm 10$ GeV	DØ	lepton + jets
$m_t = 158 \pm 24 \pm 10$ GeV	DØ	$e\mu$

Because of the high current interest, we mention these preliminary results here but do not average them or include them in the Listings or Tables. See the note on the top quark for references.

Search limits, which are now primarily of historical interest, are based on the assumption that no nonstandard decay modes such as  $t \rightarrow bH^+$  are available, except as noted in the comments.

VALUE (GeV)	CL%	DOCUMENT ID	TECN	COMMENT
<b>180 ± 12 OUR AVERAGE</b>				
$199^{+19}_{-21} \pm 22$		1 ABACHI	95 D0	$\ell + \text{jet}$
$176 \pm 8 \pm 10$		2 ABE	95F CDF	$\ell + b\text{-jet}$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
>128	95	3 ABACHI	95B D0	$\ell\ell + \text{jets}, \ell + \text{jets}$
		4 ABACHI	95F D0	$\ell\ell + \text{jets}, \ell + \text{jets}$
		5 ABE	95O CDF	
		6 ABE	95V CDF	
		7 ABE,F	95 CDF	$W + \geq 4 \text{ jets}$
>131	95	8 ABACHI	94 D0	$\ell\ell + \text{jets}, \ell + \text{jets}$
$174 \pm 10^{+13}_{-12}$		9 ABE	94E CDF	$\ell + b\text{-jet}$
>118	95	9 ABE	94E CDF	$\ell\ell$
		10 ABE	94H CDF	$t \rightarrow bH^+, H^+ \rightarrow \tau^+ \nu_\tau$
		11 ABE	94I CDF	$t \rightarrow bH^+, H^+ \rightarrow \tau^+ \nu_\tau$
> 91	95	12 ABE	92 CDF	$\ell\ell, \ell + b\text{-jet}$
		13 ALITTI	92F UA2	$t \rightarrow bH^+, H^+ \rightarrow \tau^+ \nu_\tau$
> 60	95	14 ALBAJAR	91B UA1	$t \rightarrow bH^+, H^+ \rightarrow \tau^+ \nu_\tau$
		15 BAER	91B RVUE	$t \rightarrow \bar{t}_1 \bar{\chi}_1^0$
> 72	95	16 ABE	90B CDF	$e + \mu$
> 77	95	17 ABE	90C CDF	$e + \text{jets} + \text{missing } E_T$
> 69	95	18 AKESSON	90 UA2	$e + \text{jets} + \text{missing } E_T$
> 60	95	ALBAJAR	90B UA1	$e \text{ or } \mu + \text{jets}, \mu\mu + \text{jet}$
		19 BARGER	90E RVUE	$t \rightarrow bH^+$
> 41	95	20 ALBAJAR	88 UA1	$e \text{ or } \mu + \text{jets}$

# And the Story Continues

- Run II begins in 2001

- 1.96 TeV

- 2005: 230 pb<sup>-1</sup>

t $\bar{t}$  cross section measurements in the ljets channel (M<sub>t</sub> = 175 GeV):

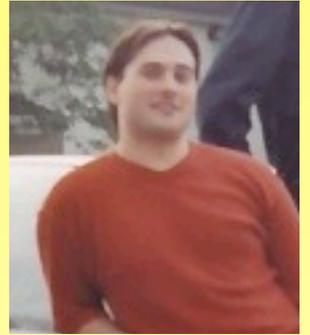
without b-tagging:

$$\sigma_{t\bar{t}} = 6.7_{-1.3}^{+1.4} (\text{stat})_{-1.1}^{+1.6} (\text{syst}) \pm 0.4 (\text{lumi}) \text{ pb.}$$

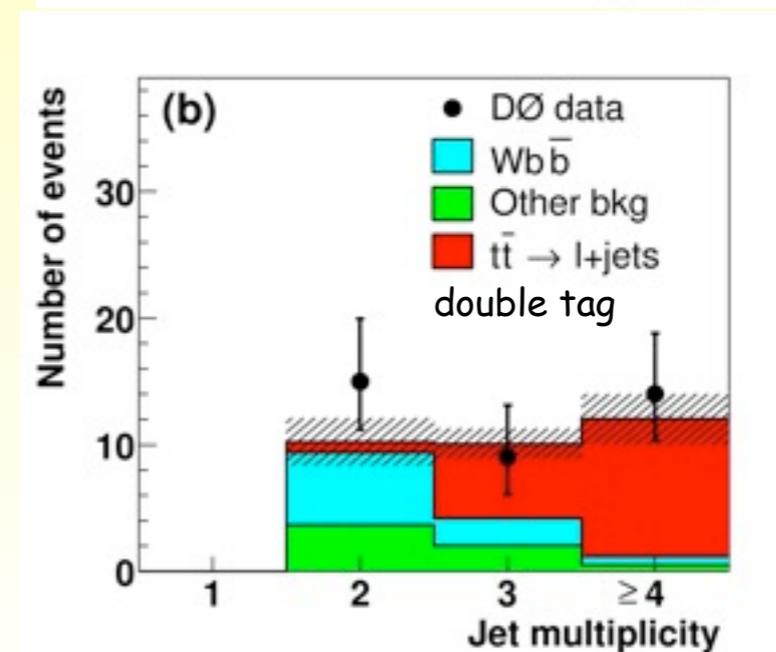
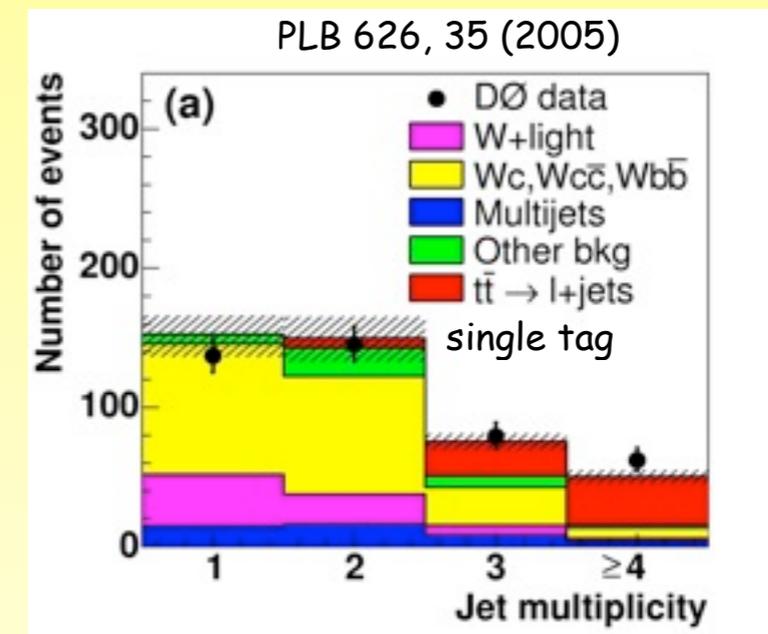
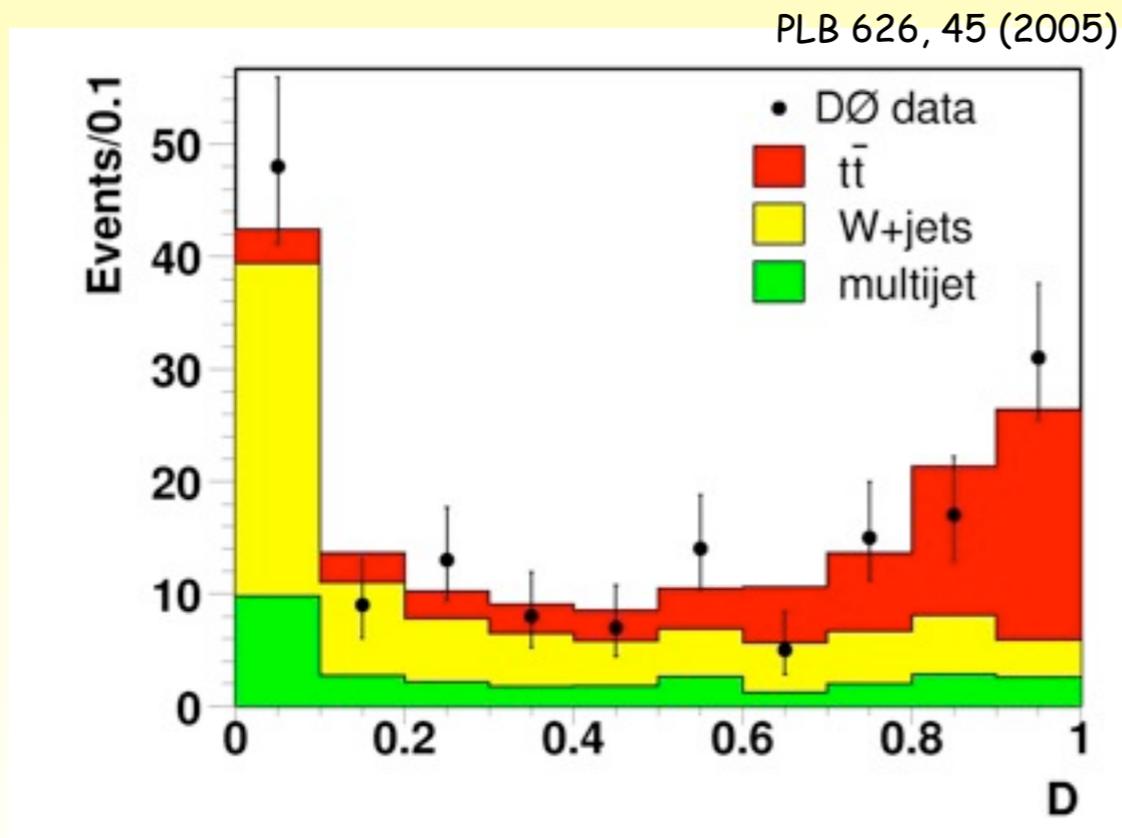
with b-tagging:

$$\sigma_{t\bar{t}} = 8.6_{-1.5}^{+1.6} (\text{stat.} + \text{syst.}) \pm 0.6 (\text{lumi.}) \text{ pb}$$

~ 20 %



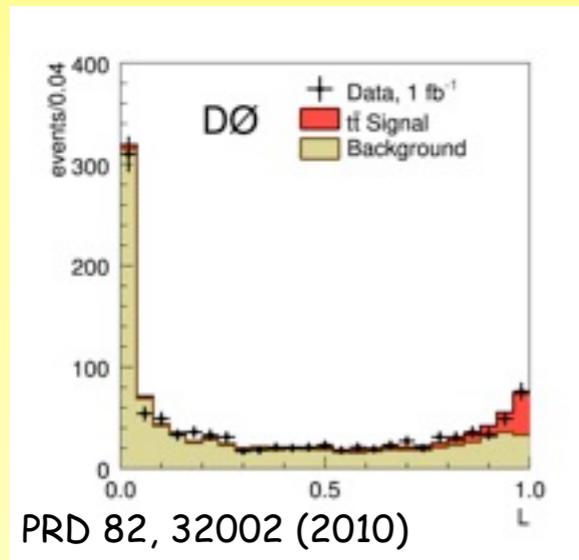
2001



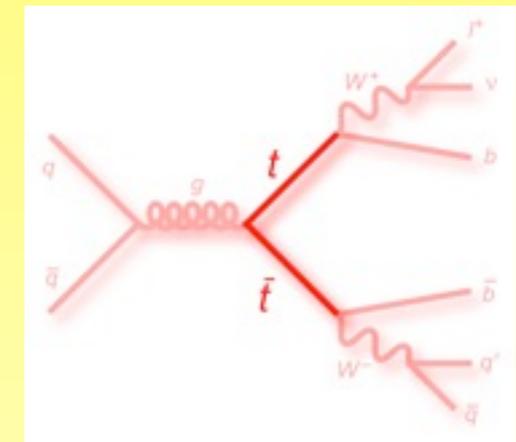
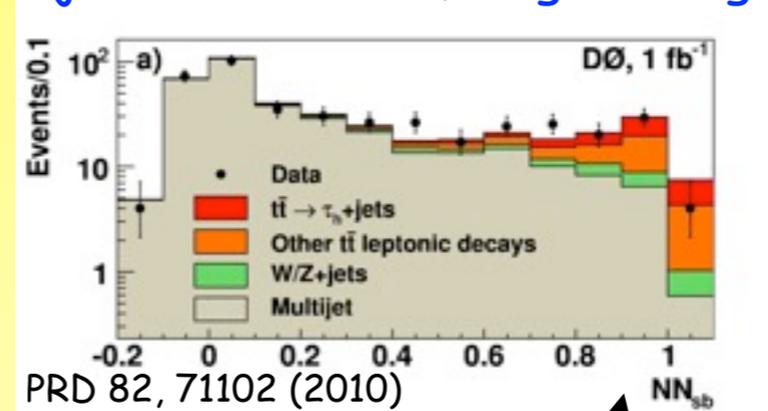
# Measurements in All Possible Channels

alljets:

large rate, large background

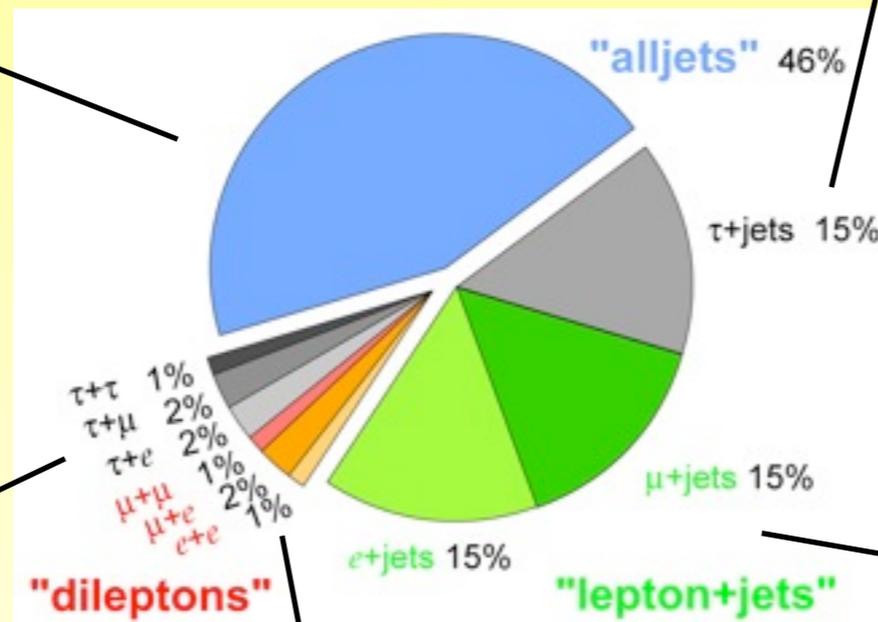
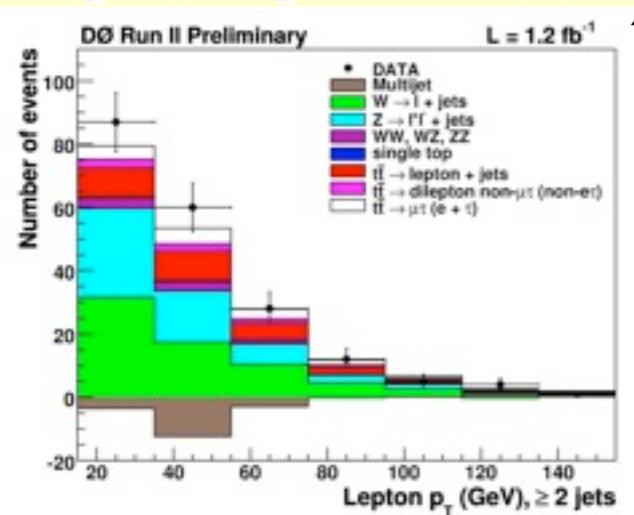


$\tau$ +jets: small rate, large background

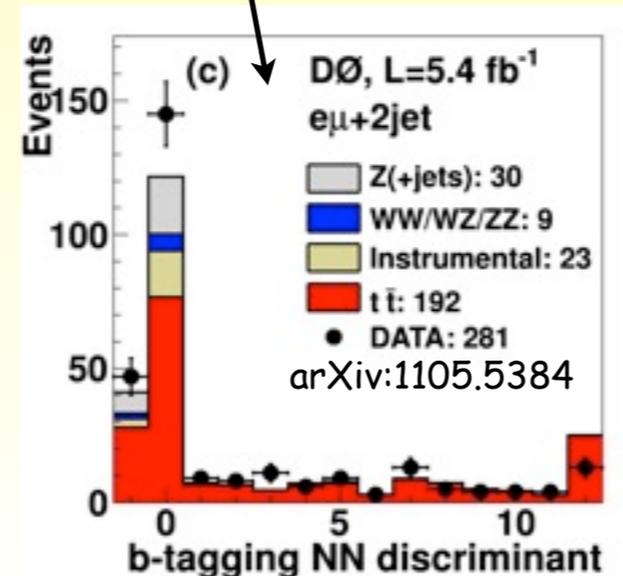
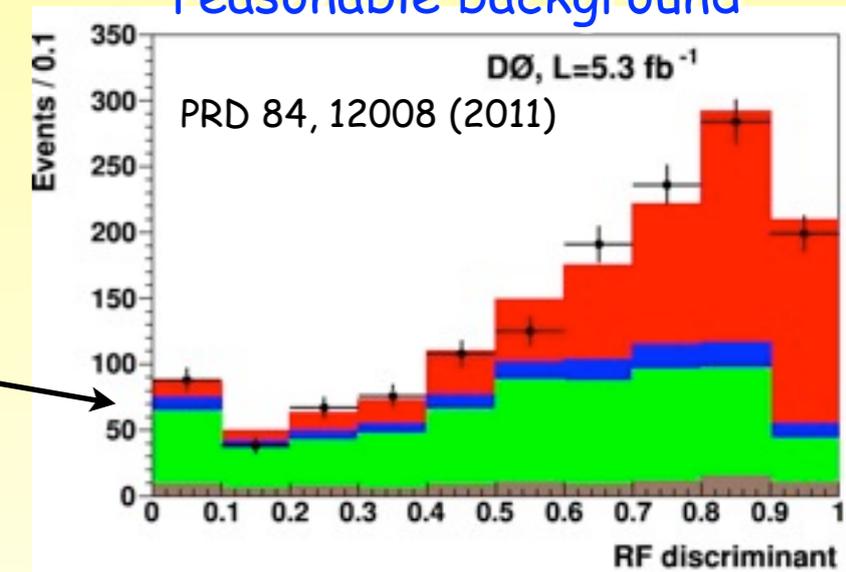


lepton+ $\tau$ +jets: small rate,

large background



$\mu$ +jets: good rate,  
reasonable background

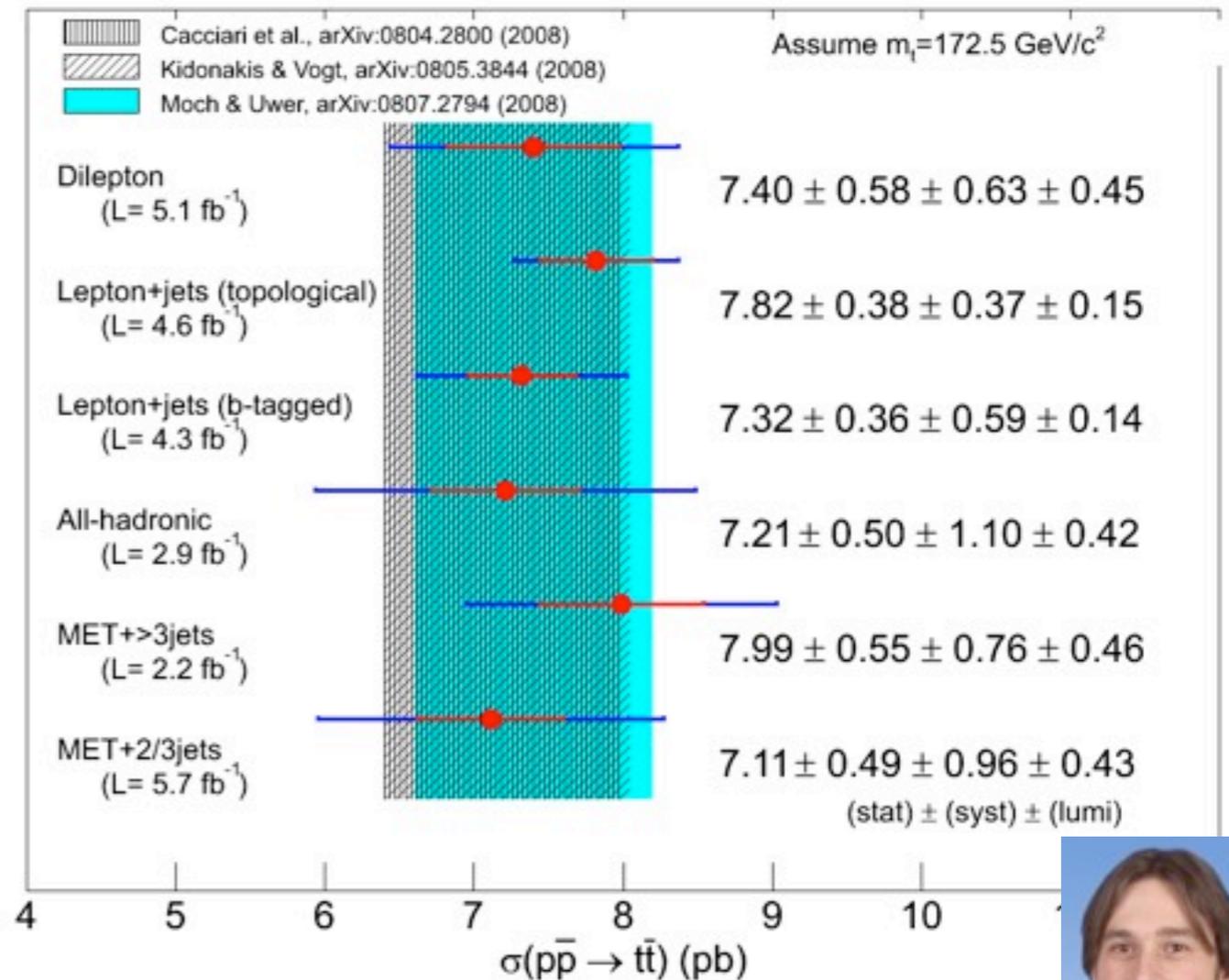
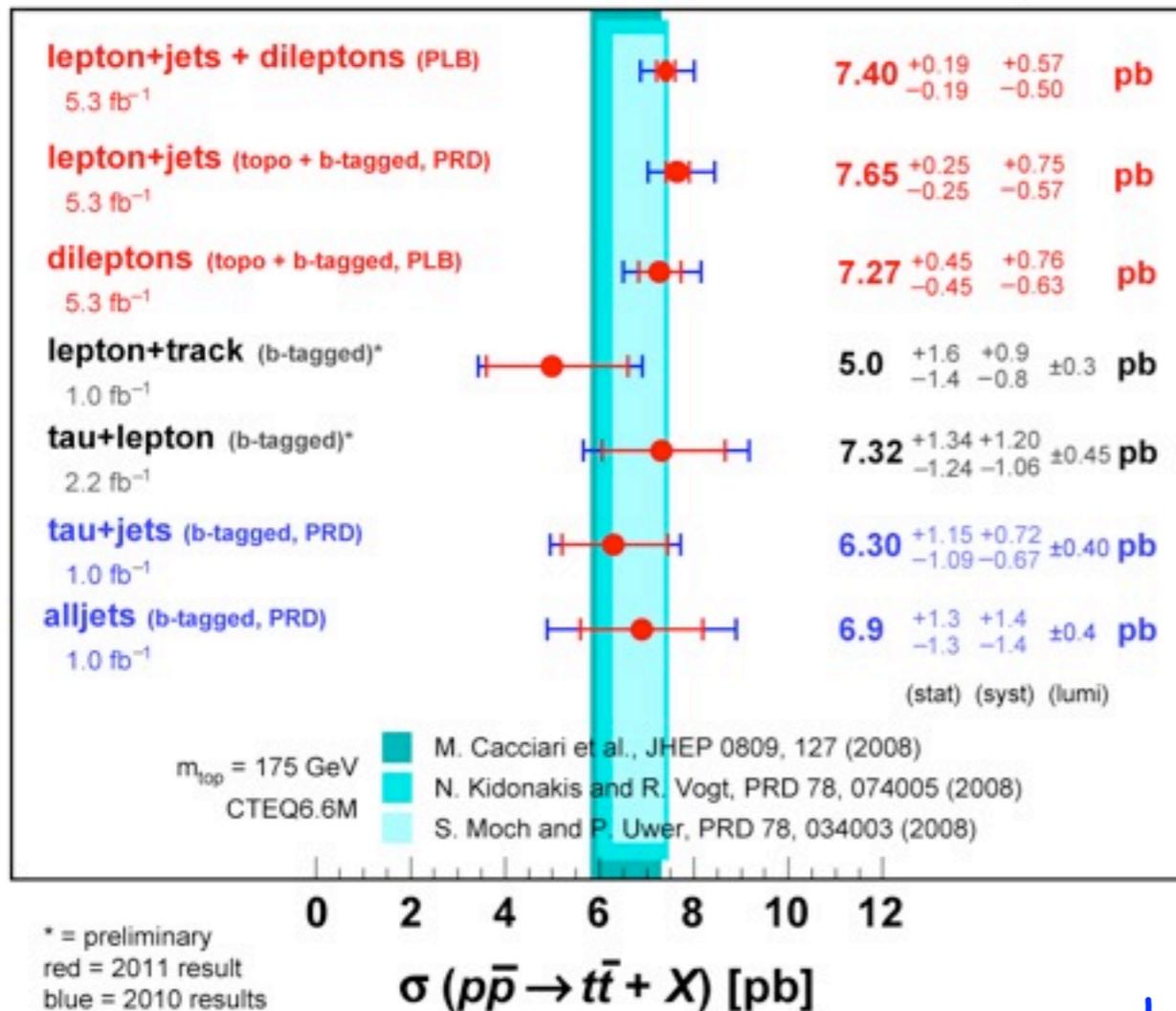


dilepton: small rate,  
small background

# Top Pair Cross Sections at 1.96 TeV

DØ Run II

July 2011



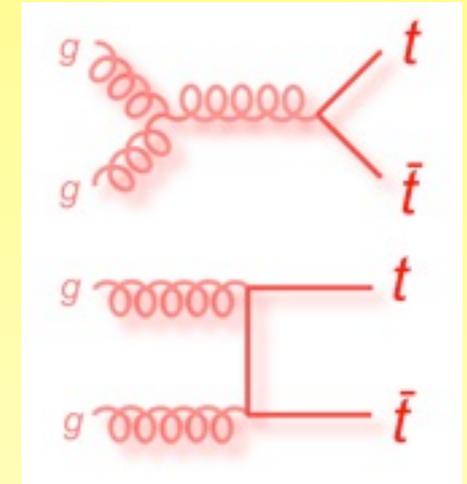
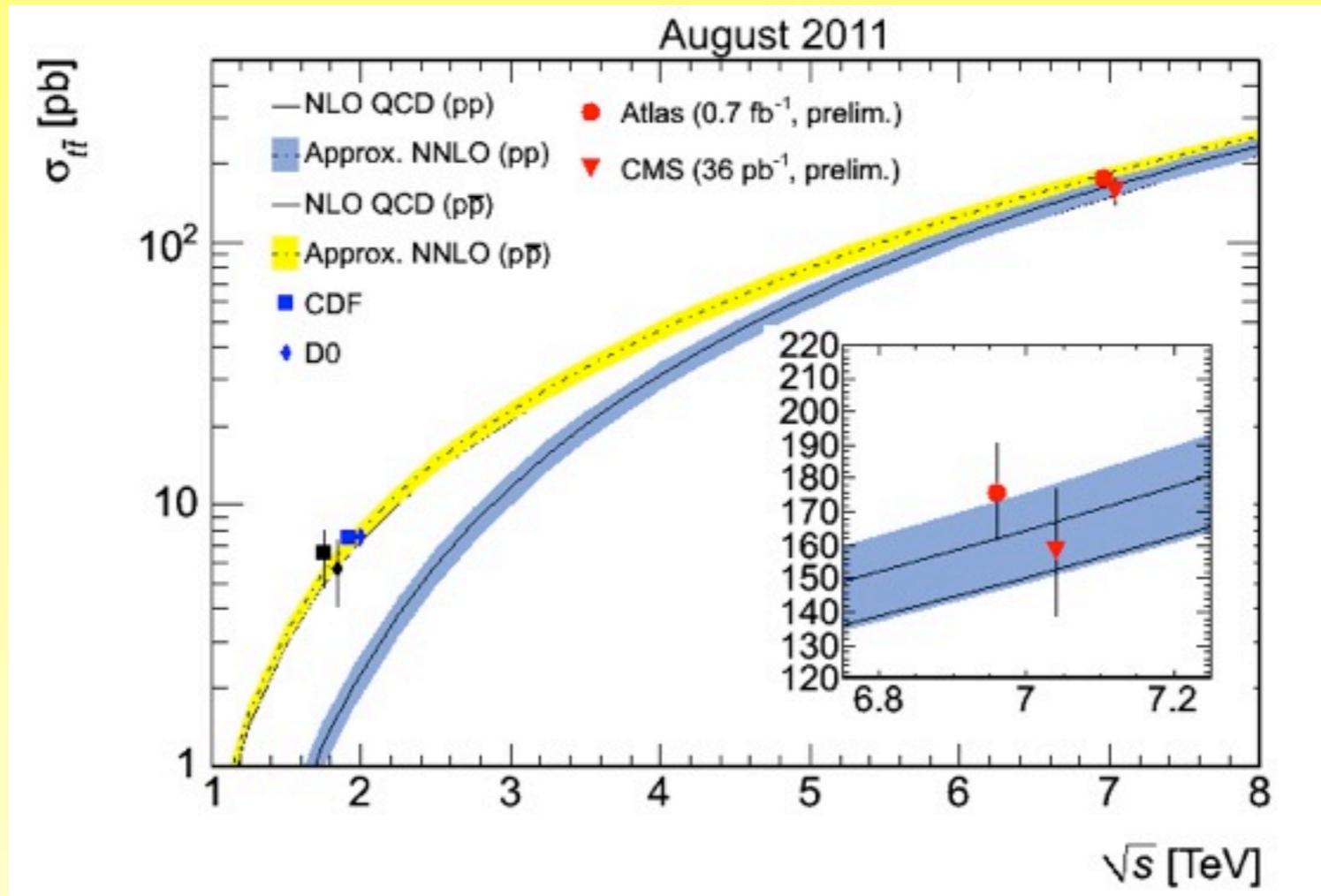
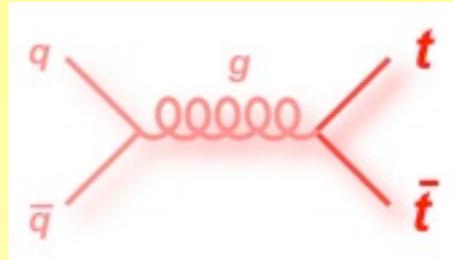
working on the CDF-DØ combination

- in addition to the cross section
  - cross section ratios (limit on  $t \rightarrow H^+ b$ )
  - fit the cross section together with R to extract  $V_{tb}$ :

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

$$|V_{tb}| = 0.95 \pm 0.02 \quad \text{assuming CKM unitarity} \\ \text{arXiv:1106.5436}$$

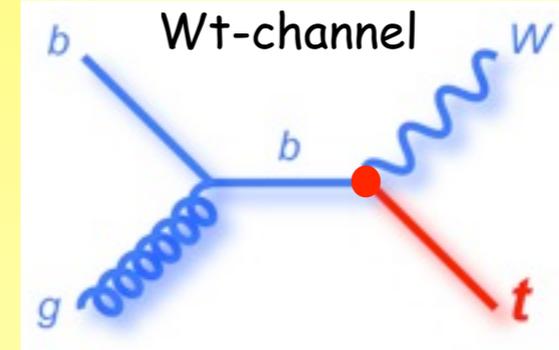
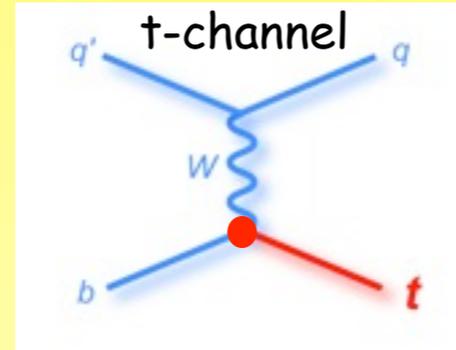
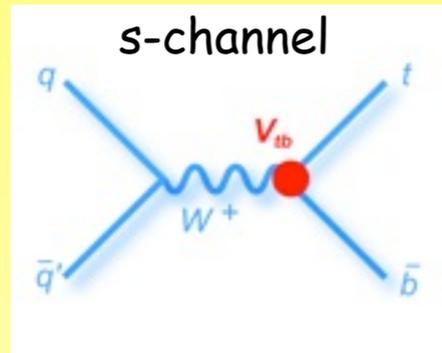
# $t\bar{t}$ Cross Section Summary



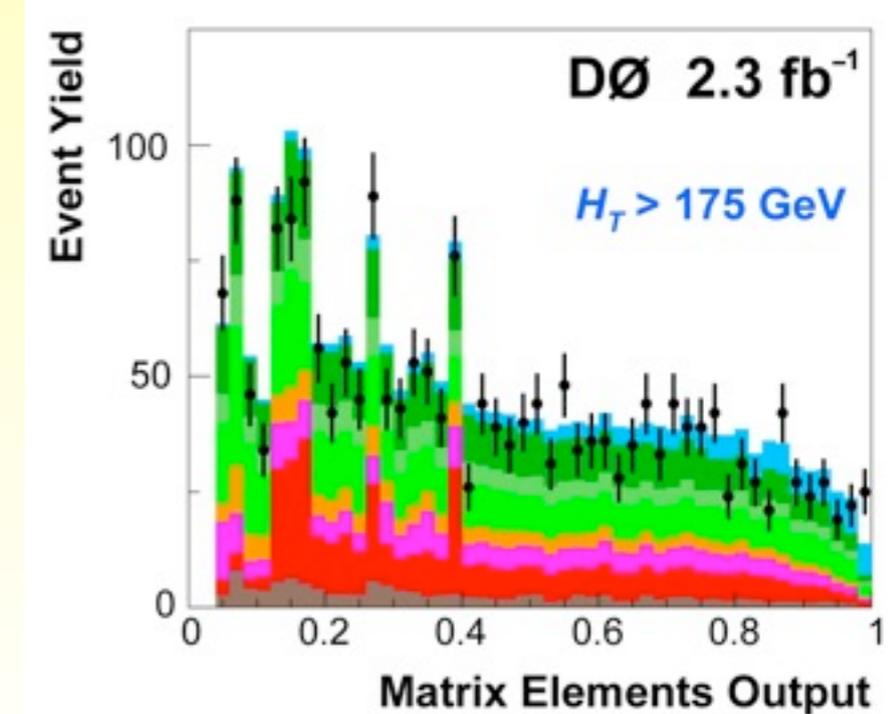
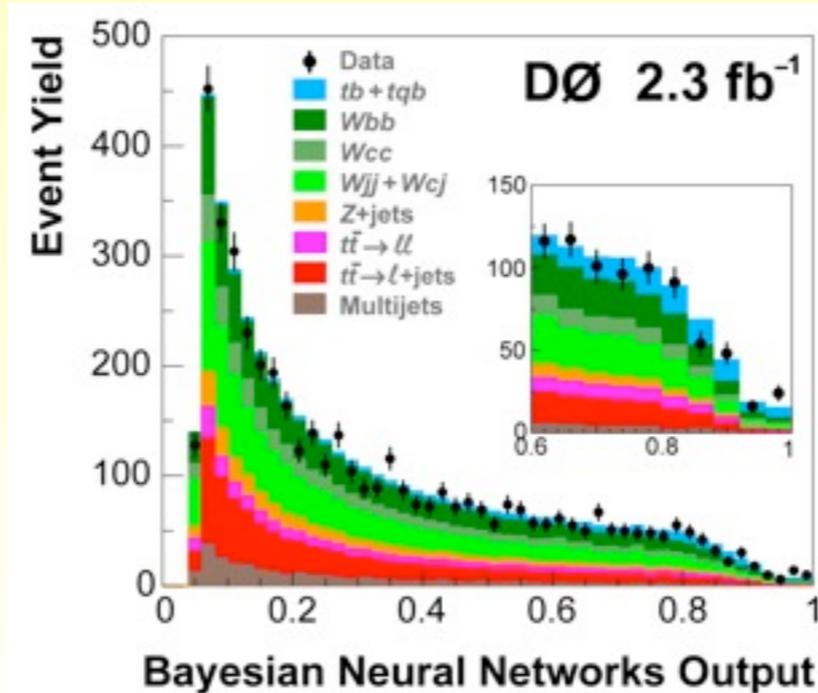
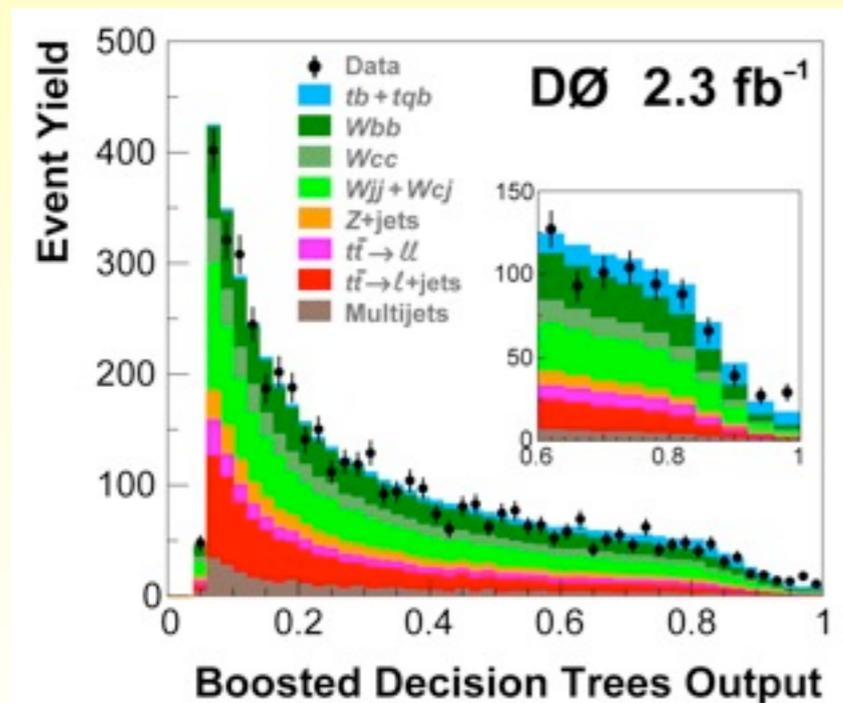
decay channel combined for $m_t = 172.5$ GeV:		systematically limited
CDF (up to $4.6 \text{ fb}^{-1}$ )	$\sigma(p\bar{p} \rightarrow t\bar{t}) = 7.5 \pm 0.31(\text{stat}) \pm 0.34(\text{syst}) \pm 0.15(\text{theory}) \text{ pb}$	$\sim 6.5 \%$
D0 ( $5.6 \text{ fb}^{-1}$ , arXiv:1105.5384)	$\sigma(p\bar{p} \rightarrow t\bar{t}) = 7.56^{+0.63}_{-0.56} (\text{stat} + \text{syst} + \text{lumi}) \text{ pb}$	
Atlas ( $0.7 \text{ fb}^{-1}$ )	$\sigma(pp \rightarrow t\bar{t}) = 179.0 \pm 9.8(\text{stat} + \text{syst}) \pm 6.6(\text{lumi}) \text{ pb}$	$\sim 6.6 \%$
CMS ( $36 \text{ pb}^{-1}$ )	$\sigma(pp \rightarrow t\bar{t}) = 158 \pm 10(\text{uncor.}) \pm 15(\text{cor.}) \pm 6(\text{lumi}) \text{ pb}$	

Measurements agree with the QCD predictions  
 Future measurements will focus on differential cross sections  
 Only Tevatron can measure them at 1.96 TeV

# Electroweak Top Production at Hadron Colliders



- predicted since the 80s
- allows to directly measure  $V_{tb}$
- challenging to measure
  - small cross section and background similar signature than signal
  - not possible with counting only (uncertainty on the bkg larger than the signal):  
multivariate techniques



# Another Top Discovery

- March 10<sup>th</sup>, 2009: Fermilab seminar announcing the single top discovery

## Observation of Single Top-Quark Production

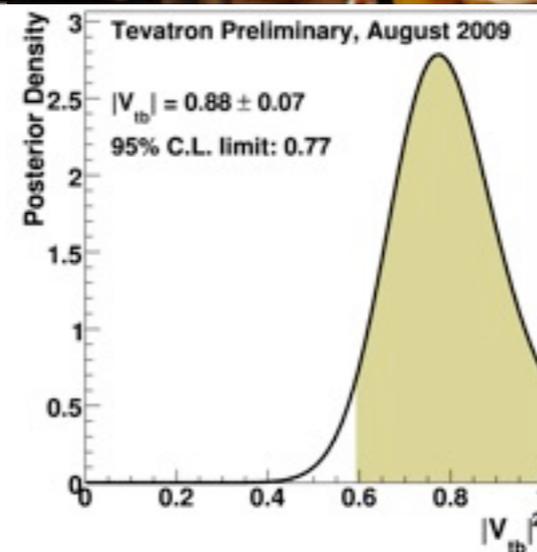
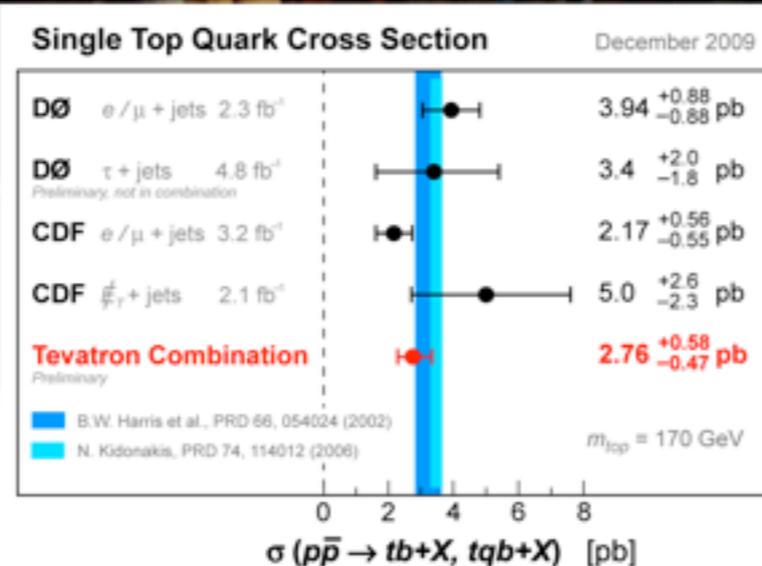
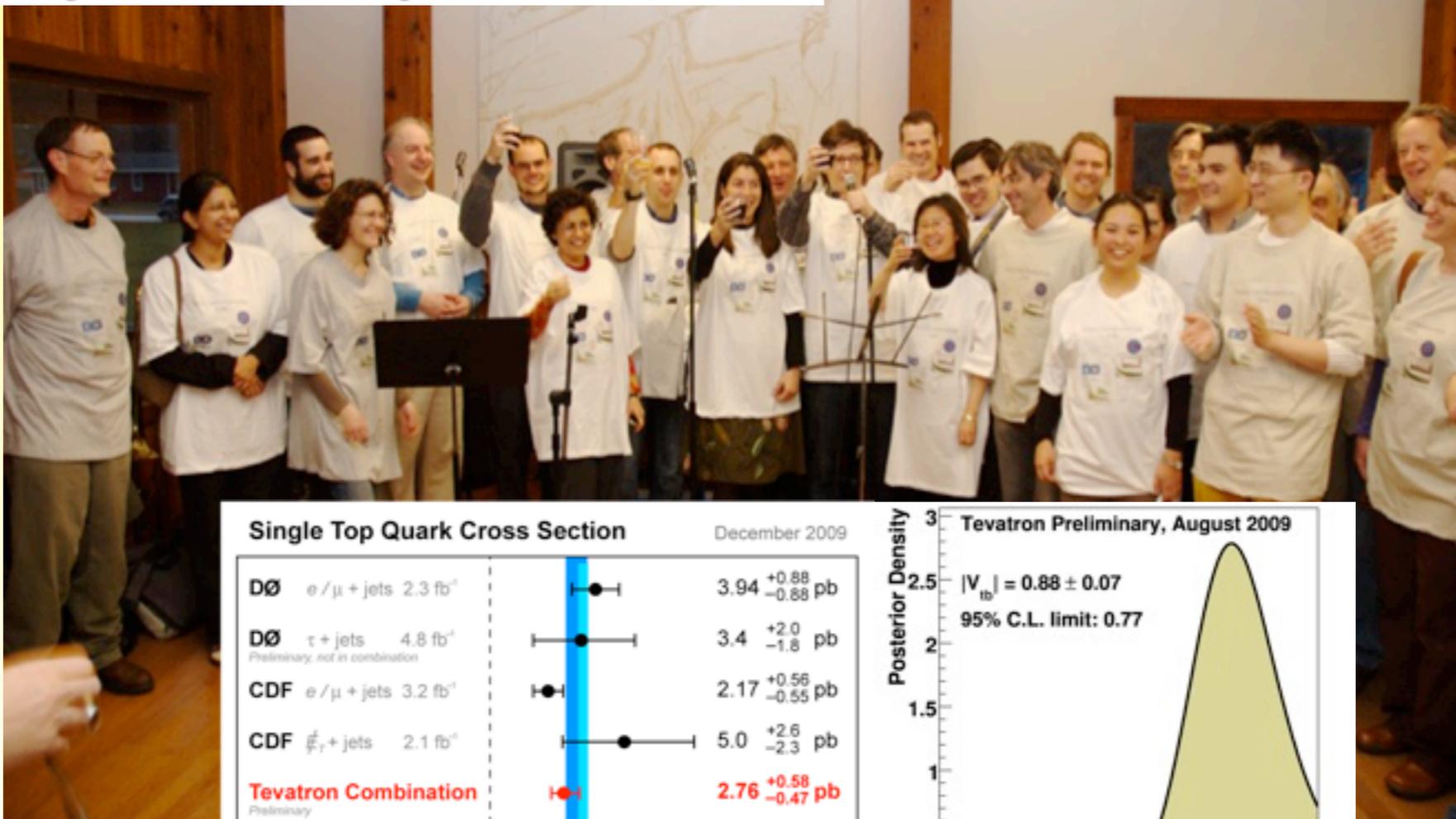
V. M. Abazov,<sup>36</sup> B. Abbott,<sup>74</sup> M. Abolins,<sup>64</sup> B. S. Acharya,<sup>29</sup> M. Adams,<sup>50</sup> T. Adams,<sup>48</sup> E. Aguilo,<sup>6</sup> M. Ahsan,<sup>58</sup>

We report observation of the electroweak production of single top quarks in  $p\bar{p}$  collisions at  $\sqrt{s} = 1.96$  TeV based on  $2.3 \text{ fb}^{-1}$  of data collected by the D0 detector at the Fermilab Tevatron Collider. Using events containing an isolated electron or muon and missing transverse energy, together with jets originating from the fragmentation of  $b$  quarks, we measure a cross section of  $\sigma(p\bar{p} \rightarrow tb + X, tqb + X) = 3.94 \pm 0.88 \text{ pb}$ . The probability to measure a cross section at this value or higher in the absence of signal is  $2.5 \times 10^{-7}$ , corresponding to a 5.0 standard deviation significance for the observation.

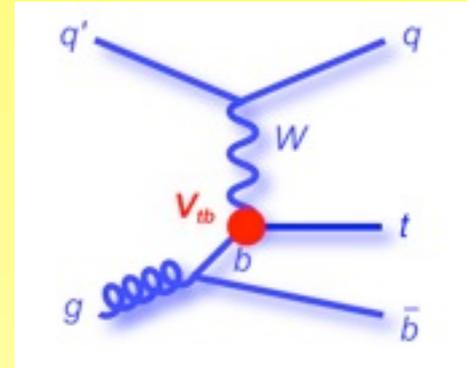
## Observation of Electroweak Single Top-Quark Production

T. Aaltonen,<sup>24</sup> J. Adelman,<sup>14</sup> T. Akimoto,<sup>56</sup> B. Álvarez González,<sup>12,1</sup> S. Amerio,<sup>44b,44a</sup> D. Amidei,<sup>35</sup> A. Anastasov,<sup>39</sup>

We report the observation of single top-quark production using  $3.2 \text{ fb}^{-1}$  of  $p\bar{p}$  collision data with  $\sqrt{s} = 1.96$  TeV collected by the Collider Detector at Fermilab. The significance of the observed data is 5.0 standard deviations, and the expected sensitivity for standard model production and decay is in excess of 5.9 standard deviations. Assuming  $m_t = 175 \text{ GeV}/c^2$ , we measure a cross section of  $2.3_{-0.5}^{+0.6}(\text{stat} + \text{syst}) \text{ pb}$ , extract the CKM matrix-element value  $|V_{tb}| = 0.91 \pm 0.11(\text{stat} + \text{syst}) \pm 0.07(\text{theory})$ , and set the limit  $|V_{tb}| > 0.71$  at the 95% C.L.

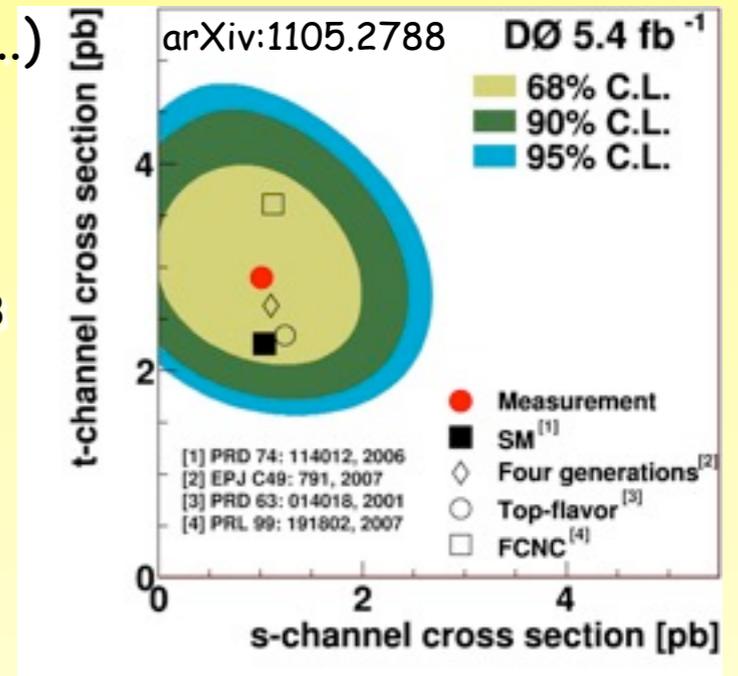


# t-Channel Single Top Cross Section



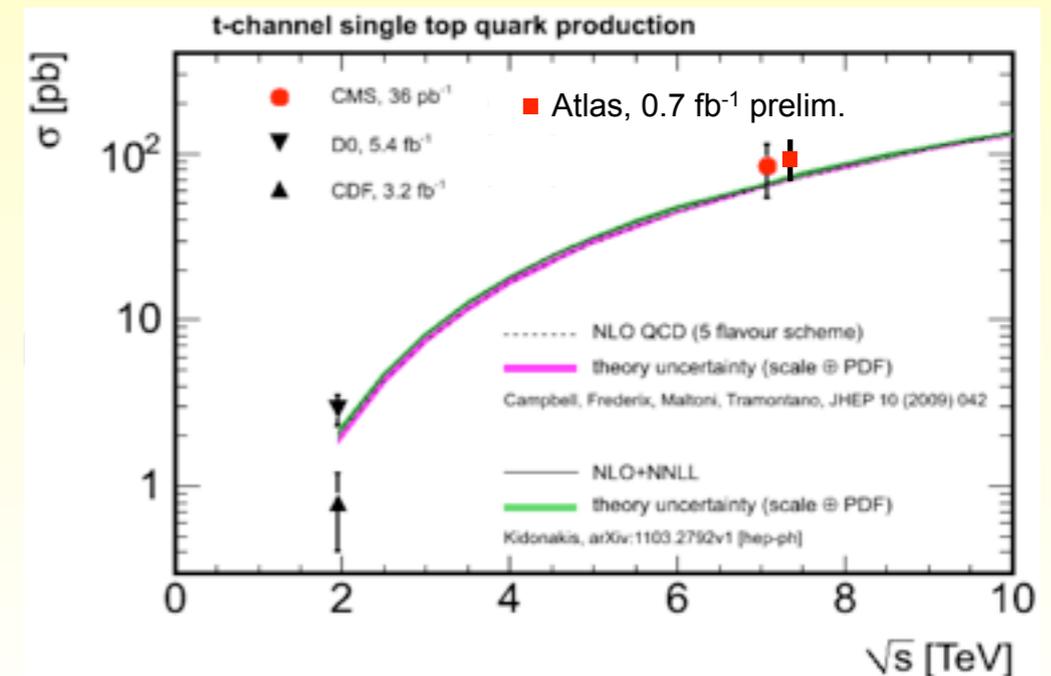
- a step further: discriminate between the single top channels:
  - new physics can affect the single top channels differently
  - signal: t-channel, background (other single top, W+jets,  $t\bar{t}$ ):
    - \* Tevatron: multivariate (Neural Networks, Boosted Decision Trees, ...)
    - \* LHC: cut-based or multivariate

\*combination of 3 multivariate discriminants



$\sigma_{tqb}$ (pb) for $m_t = 172.5$ GeV:		
CDF ( $3.2 \text{ fb}^{-1}$ )	$0.8 \pm 0.4$	
DØ ( $5.4 \text{ fb}^{-1}$ , arXiv:1105.2788)	$2.90 \pm 0.59$	$5.5\sigma$
CMS ( $36 \text{ pb}^{-1}$ , arXiv:1106.3052)	$83.6 \pm 29.8(\text{stat} + \text{syst}) \pm 3.3(\text{lumi})$	$3.7\sigma$
Atlas ( $0.7 \text{ fb}^{-1}$ )	$90^{+32}_{-22}$	$7.6\sigma$

Observation of the t-channel single top in 2011



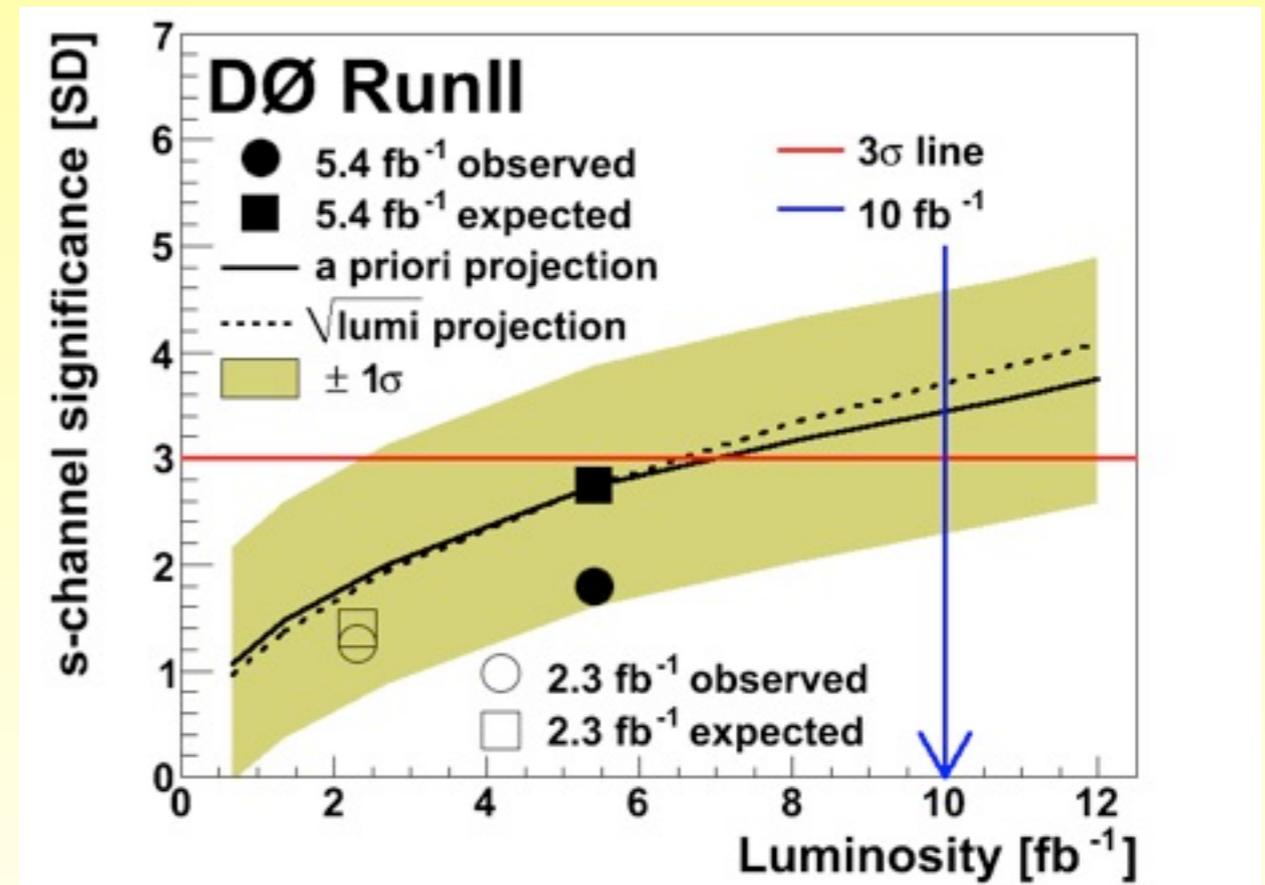
# Single Top Perspectives at the Tevatron

for $m_t = 172.5$ GeV: (in pb)	$\sigma_{tb}$	$\sigma_{tqb}$	$\sigma_{tW}$
$p\bar{p}$ @ 1.96 TeV	$1.04 \pm 0.04$	$2.26 \pm 0.12$	$0.28 \pm 0.06$
	PRD 74, 114012 (2006)		
pp @ 7 TeV	$4.6 \pm 0.3$	$64.6^{+3.3}_{-2.6}$	$15.7 \pm 1.4$
	PRD81, 054028 (2010)	PRD83, 091503 (2011)	PRD82, 054018 (2010)

- s-channel**

- challenging at LHC
- legacy measurement of the Tevatron

latest D0 measurement  
(5.4 fb<sup>-1</sup>, arXiv:1105.2788):  
expected sensitivity close to 3  $\sigma$



with 10 fb<sup>-1</sup>, should get evidence  
maybe observation when combination with CDF ?

# Top Quark Mass

- the top quark is the only natural quark:

- coupling to the Higgs boson close to 1:  
special role in the electroweak symmetry breaking ?

$$\mathcal{L}_{\text{Yukawa}} = -\lambda_t \overline{\psi_{Lt}} \Phi \psi_{Rt}$$

$\lambda_t \approx 1 !!$   
 $m_t \gg m_b$

- together with  $M_W$ , predict the Higgs boson mass

- how to measure the top mass ?

- template method:

- \* compare an observable in data with MC generated with different masses

- ideogram method:

- \* event likelihood computed as a convolution of a Gaussian resolution function with a Breit-Wigner (signal)

- matrix element method:

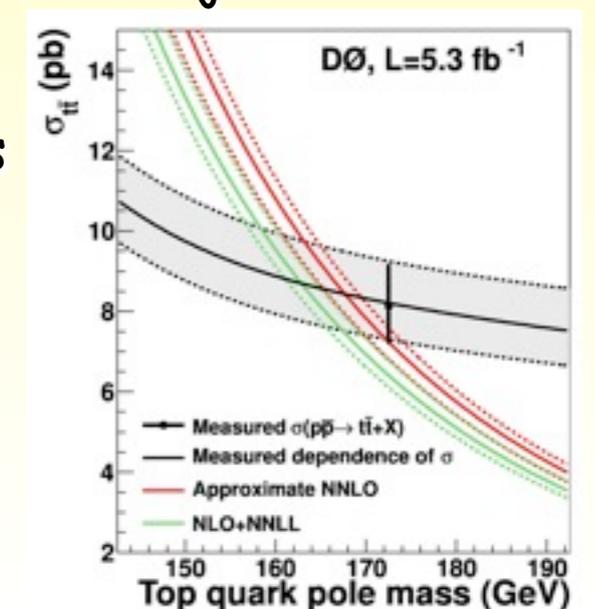
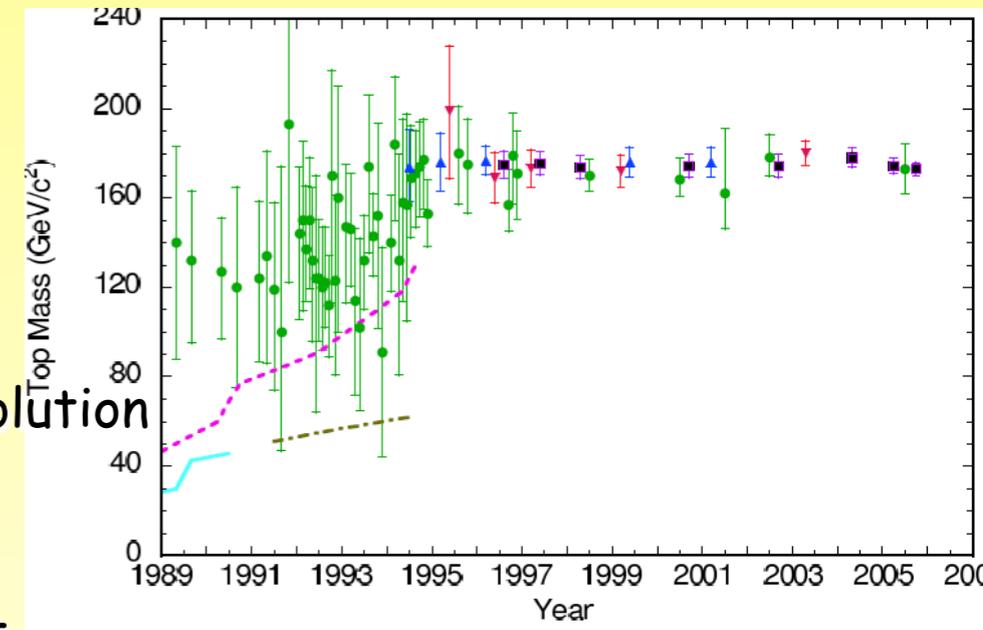
- \* build an event probability based on the LO  $t\bar{t}$  matrix element using the full kinematics of the event

- for channel with at least one  $W$  decaying hadronically, can calibrate the jet energy scale (JES) constraining  $M_{jj}$  to  $M_W$

- need to calibrate the method to correct for any potential biases

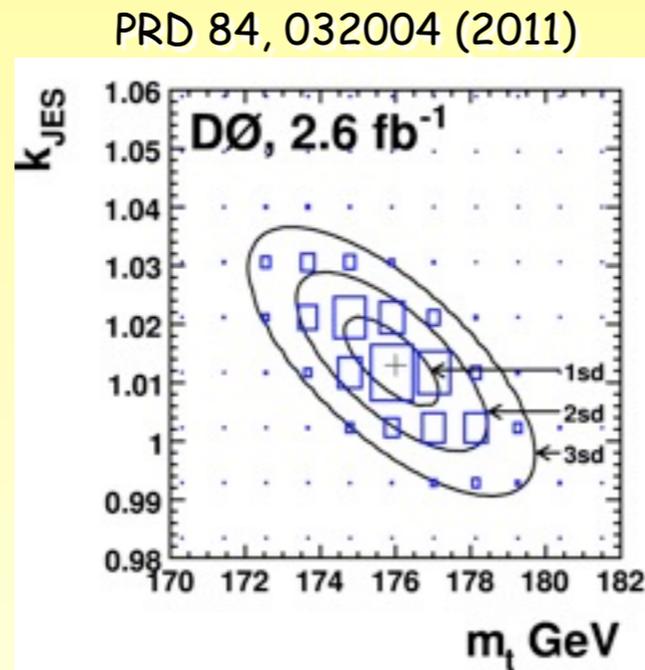
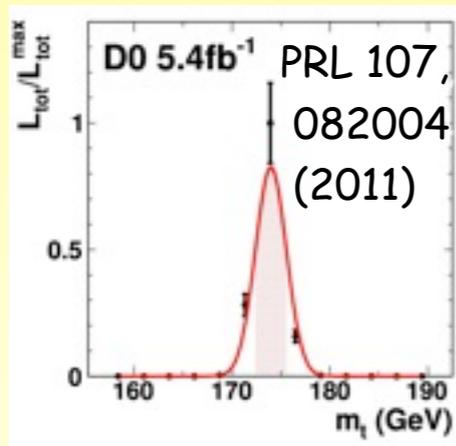
- mass extraction from the  $t\bar{t}$  cross section

- using the experimental and theoretical cross sections vs mass (well defined renormalization scheme): method first used at D0 to extract both the pole mass and the  $\overline{MS}$  mass (PLB 703, 422 (2011))



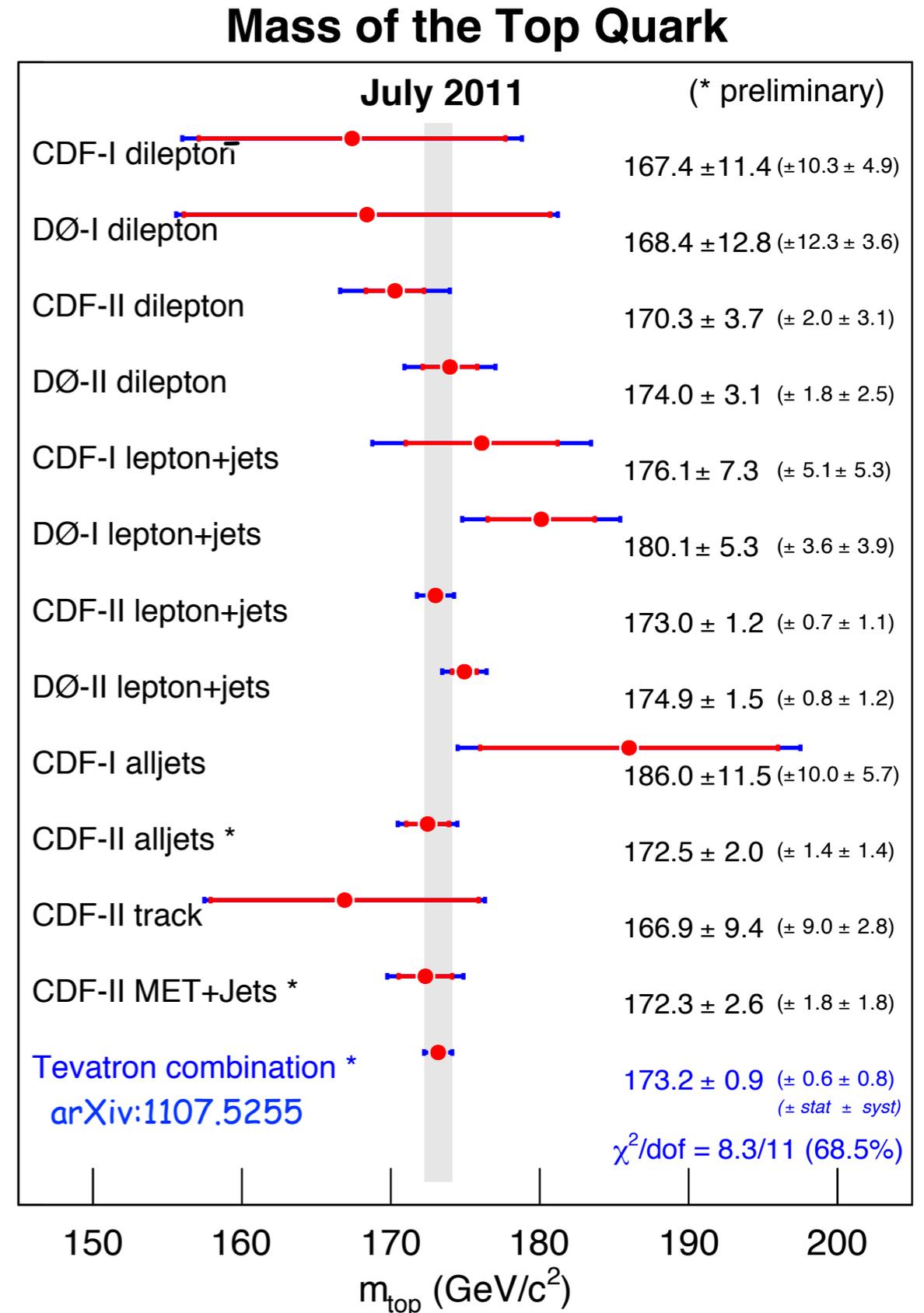
# Top Quark Mass Measurements

- **discovery:**
  - lepton+jets:  $\pm 30 \text{ GeV}$  ( $50 \text{ pb}^{-1}$ )
- **first D0 Run II measurement:**
  - lepton+jets:  $\pm 4.5 \text{ GeV}$  ( $0.37 \text{ fb}^{-1}$ )
- **latest D0 measurements:**
  - lepton+jets ( $3.6 \text{ fb}^{-1}$ ):  
 $m_t = 174.94 \pm 1.49 \text{ GeV}$
  - dilepton ( $5.4 \text{ fb}^{-1}$ ):  
 $m_t = 174.0 \pm 3.1 \text{ GeV}$



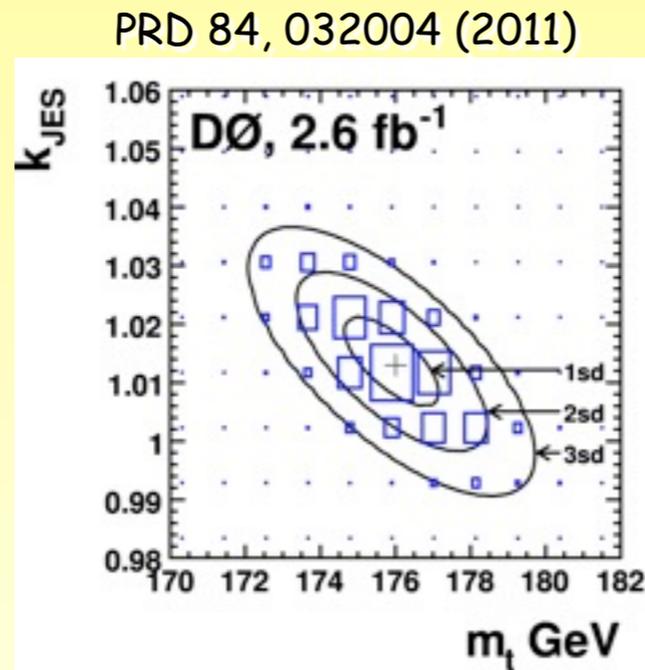
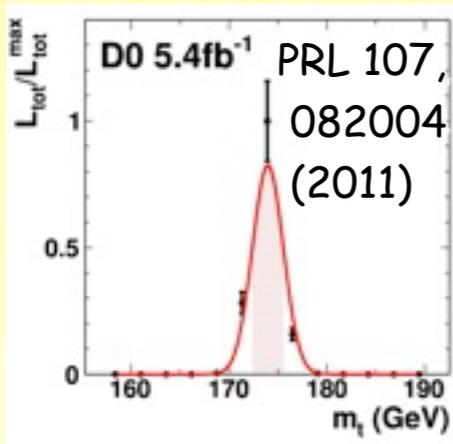
see Zhenyu's W&C seminar yesterday for all the details

- **new Tevatron combination (arXiv:1107.5255):**
  - **uncertainty below 1 GeV for the first time**
  - all channels give consistent results
  - still working on decreasing the systematic uncertainties



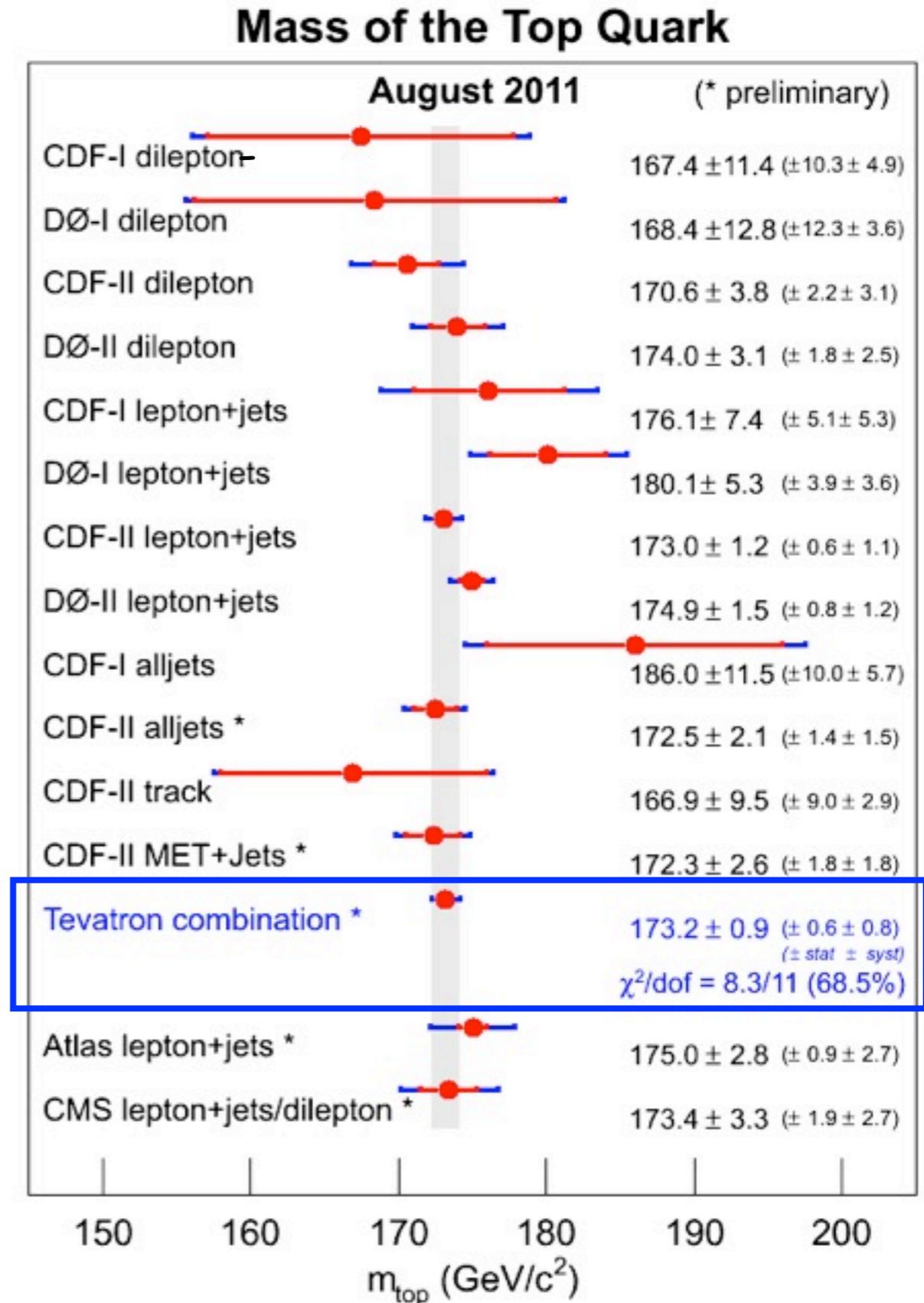
# Top Quark Mass Measurements

- **discovery:**
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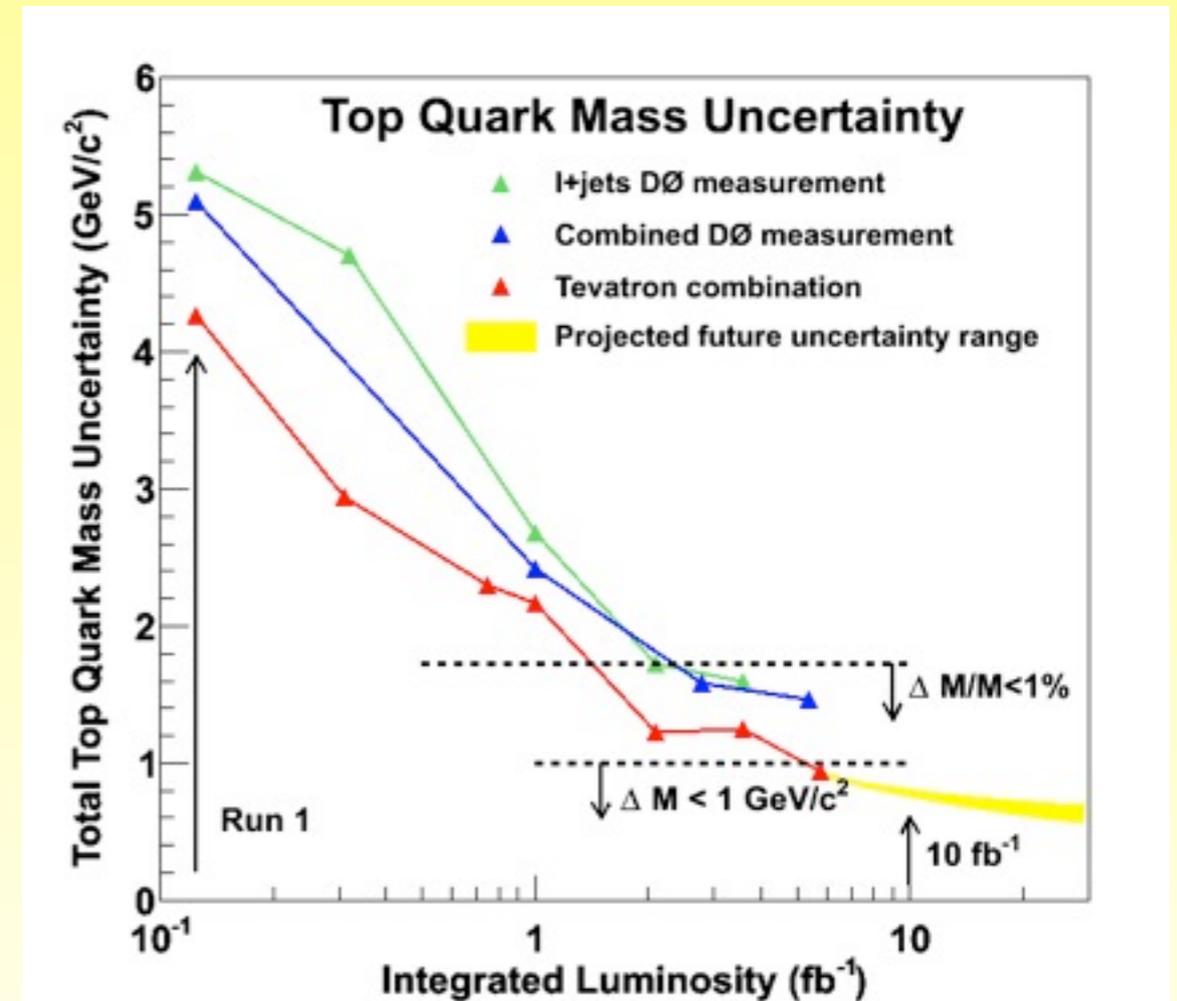


# Perspectives for Tevatron Top Mass Measurements

- this is all about systematics

- iJES scales with luminosity
- largest one: Signal modeling (ISR/FSR, color reconnection, hadronization, higher order effects)
  - \* remove double counting as much as possible
  - \* constraints from data

arXiv:1107.5255	Tevatron combined values ( $\text{GeV}/c^2$ )	
$M_t$		173.18
iJES		0.39
aJES		0.09
bJES		0.15
cJES		0.05
dJES		0.21
rJES		0.12
Lepton $p_T$		0.10
Signal		0.51
Detector Modeling		0.10
UN/MI		0.00
Background from MC		0.23
Background from Data		0.12
Method		0.09
MHI		0.08
Systematics		0.76
Statistics		0.56
Total		0.94



- Tevatron final results

- single experiment: 0.9 - 1.0  $\text{GeV}$
- D0-CDF combination: 0.7-0.8  $\text{GeV}$

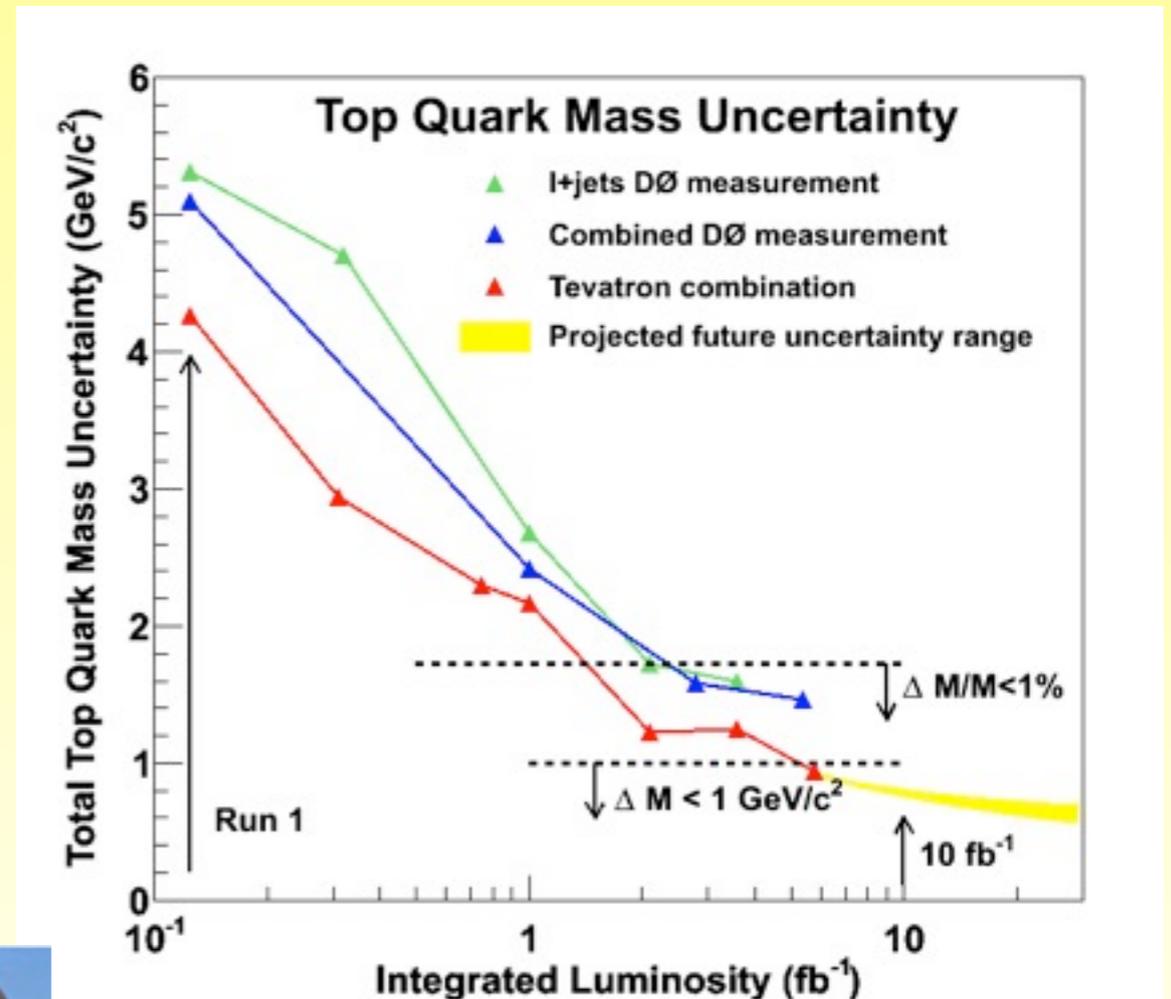
challenging precision for LHC

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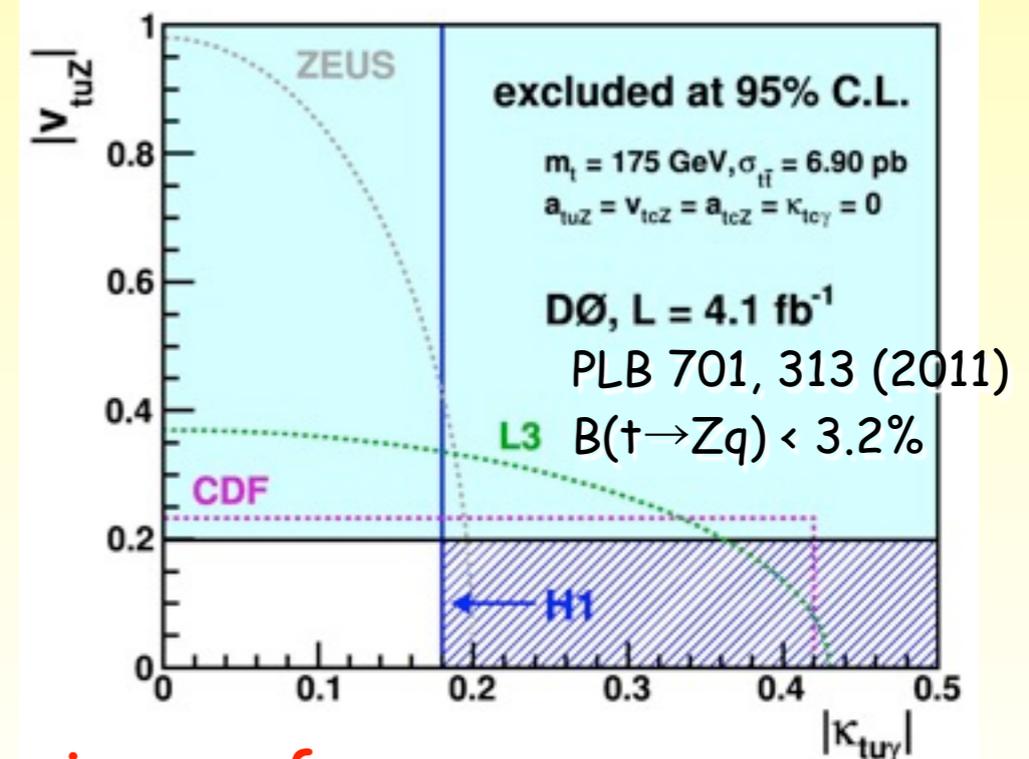
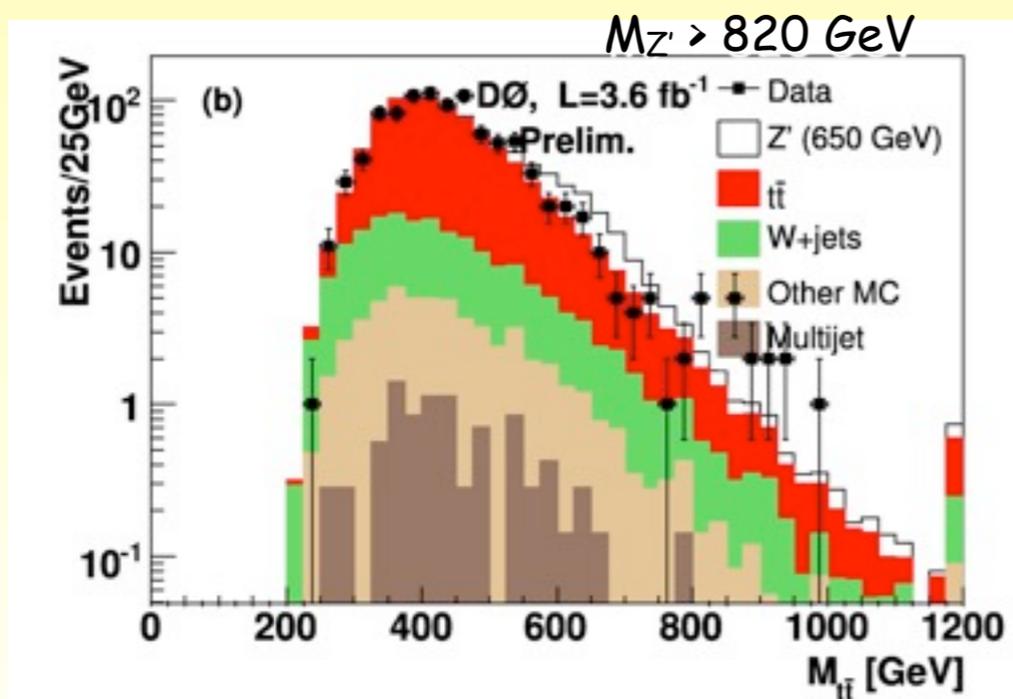
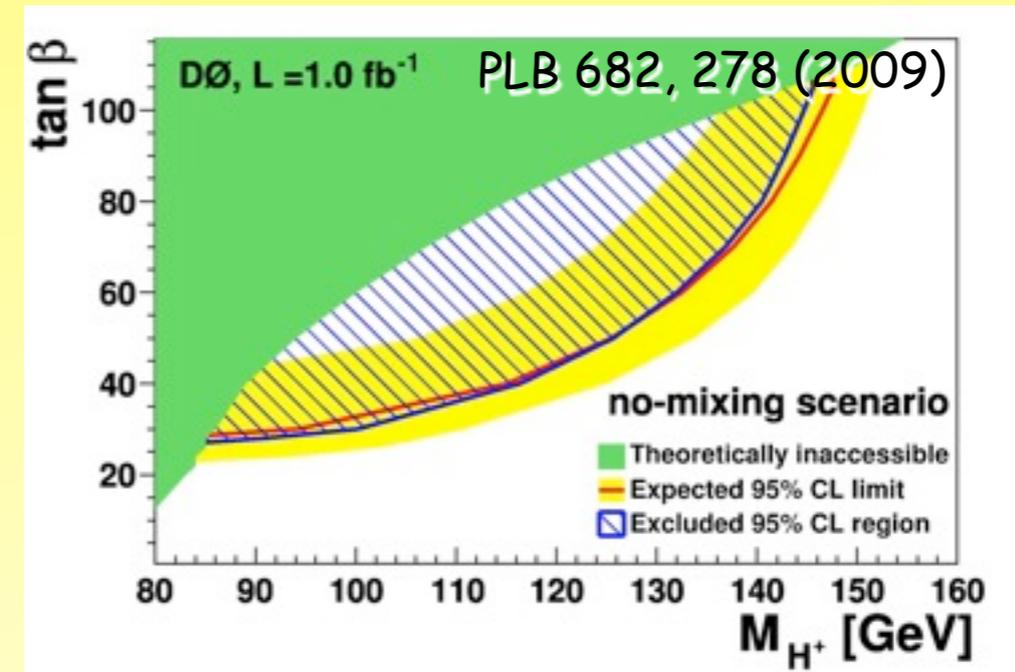
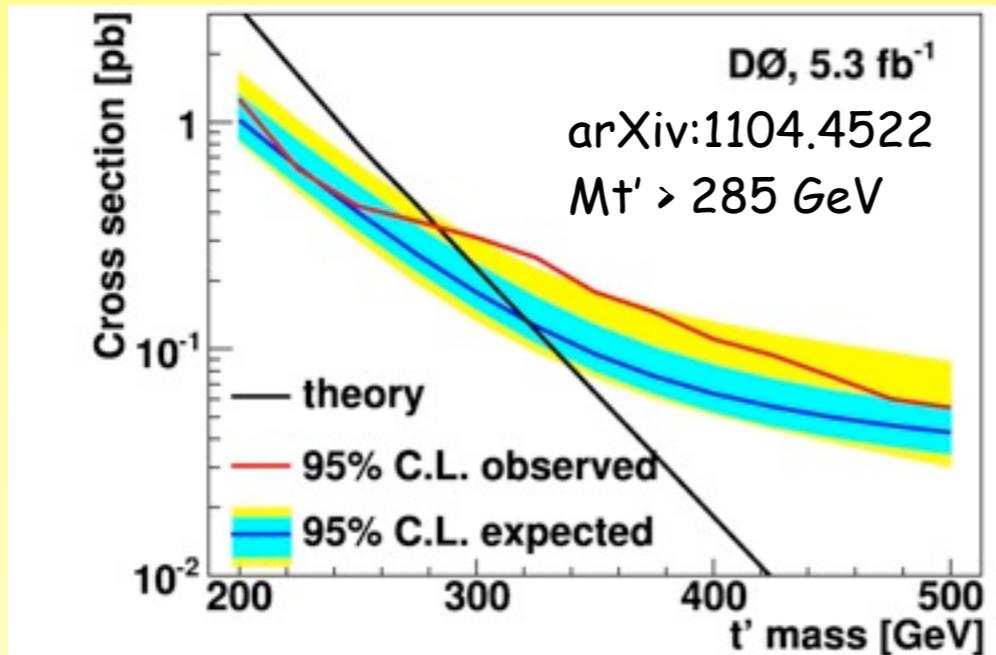
challenging precision for LHC



20??

# Searches in the Top Sector

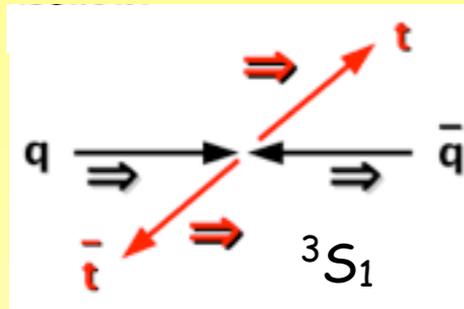
- only a few examples



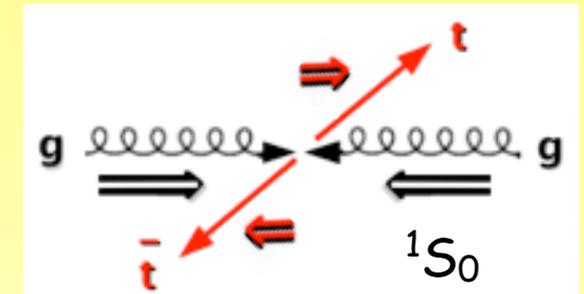
No sign of new physics so far

# Top Pair Spin Correlations

- in the SM, the spin of the top and of the antitop are produced correlated
  - correlation preserved in the decay products
  - very sensitive observable to search for new physics



	$q\bar{q}$	$gg$
$p\bar{p}$ @ 1.96 TeV	85 %	15 %
$pp$ @ 7 TeV	15 %	85 %



## measurement method:

- latest measurements use a new method based on matrix element: measure  $f$ , fraction of events with spin correlation using a template fit of  $R$

$$R = \frac{P_{\text{sgn}}(H = c)}{P_{\text{sgn}}(H = u) + P_{\text{sgn}}(H = c)}$$

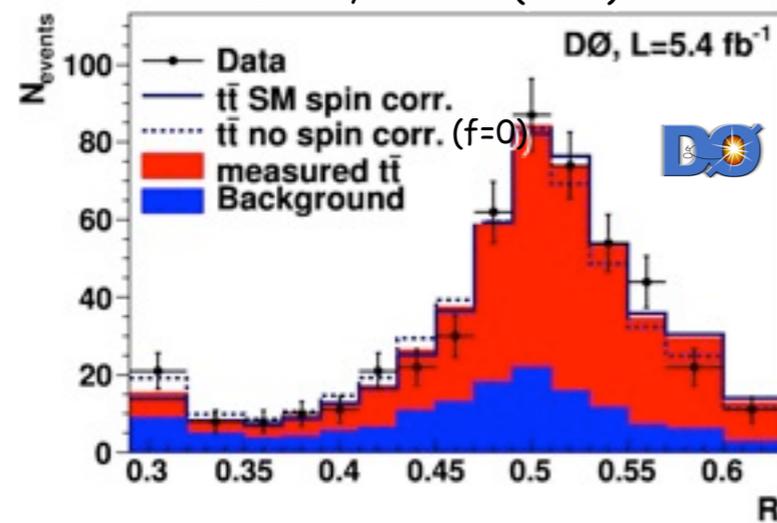
using ME without spin corr.

using ME with spin corr.

dilepton channel

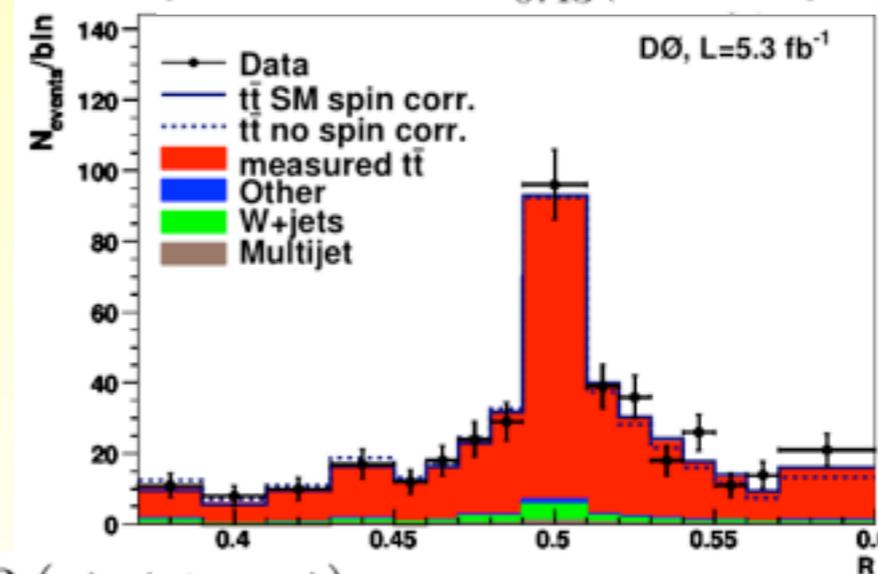
$$f_{\text{meas}} = 0.74_{-0.41}^{+0.40} \text{ (stat+syst)}$$

PRL 107, 032001 (2011)



ljets channel:

$$f_{\text{meas}} = 1.15_{-0.43}^{+0.42} \text{ (stat + syst)}$$



$$C_{\text{meas}} = 0.66 \pm 0.23 \text{ (stat+syst)}$$

first evidence for  $t\bar{t}$  spin correlation ( $3.1 \sigma$ )

# Perspectives for Spin Correlation Measurements

- complementary measurement at the LHC

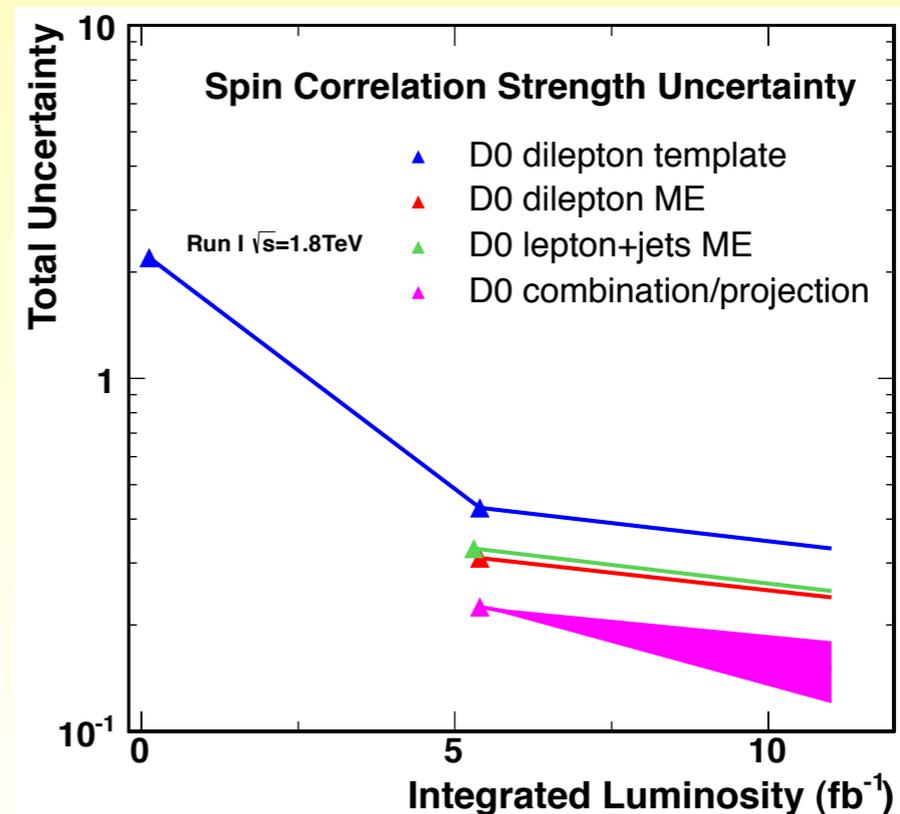
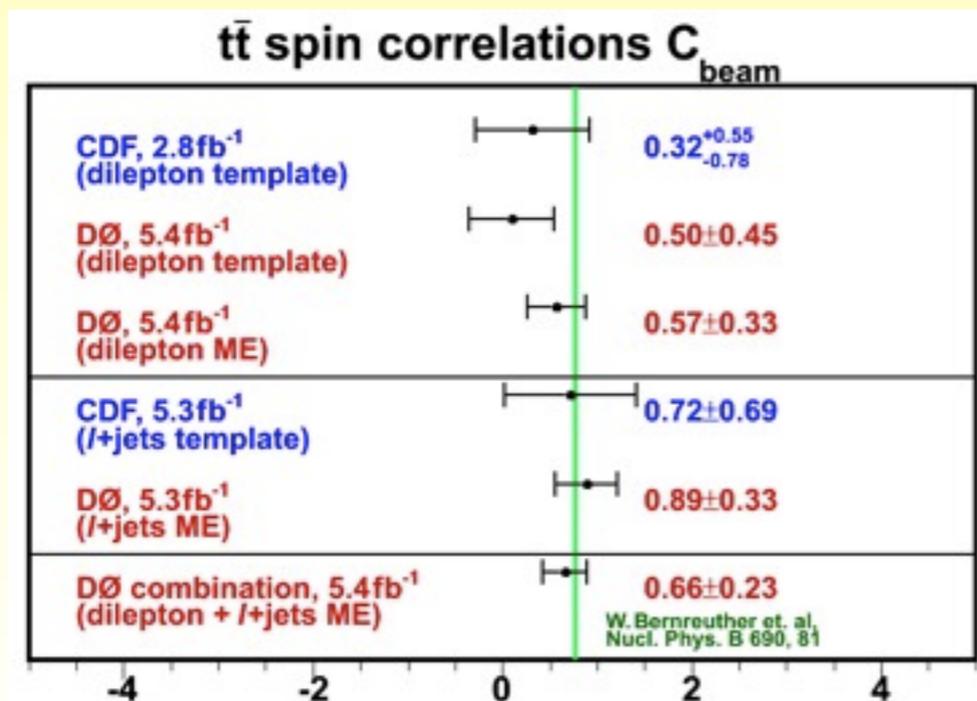
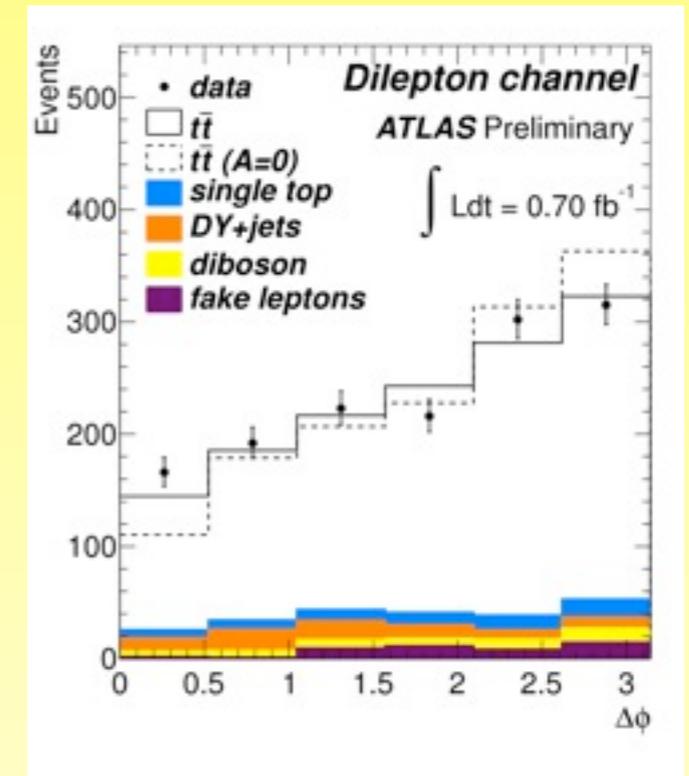
- mainly  $gg \rightarrow t\bar{t}$
- ATLAS dilepton:  $A=0.34^{+0.15}_{-0.11}$  (helicity basis,  $A_{SM}=0.32$ )
- also  $\sim 3\sigma$  sensitivity

$$\Delta\Phi = |\Phi_{l+} - \Phi_{l-}|$$

(in the lab frame)

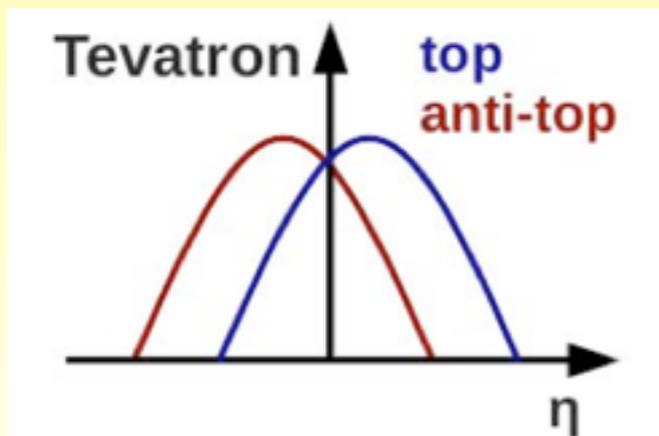
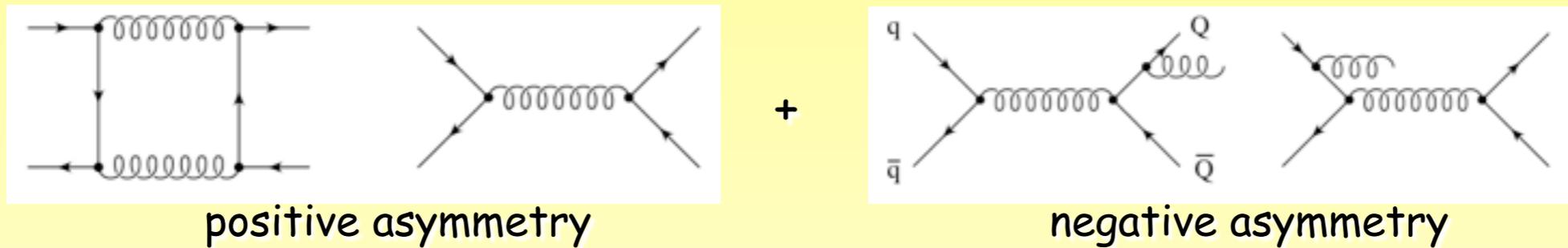
- at the Tevatron, still statistically limited

- using the full dataset should at least improve the error by  $\sqrt{2}$
- possible analysis improvement (c-tagging in the lepton+jets channel)
- combination with CDF



# Top-Antitop Charge Asymmetry

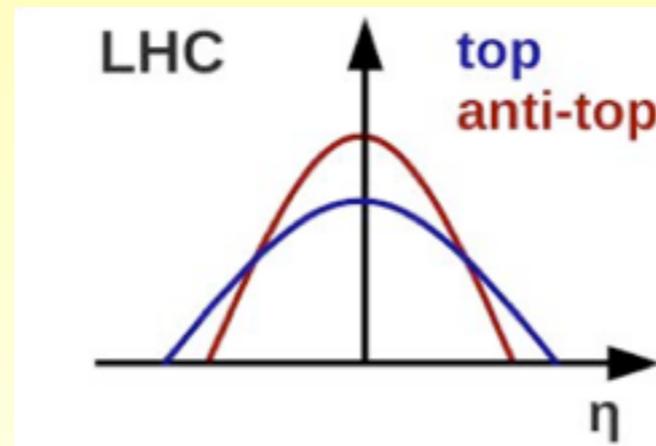
- At NLO, QCD predicts an asymmetry for  $t\bar{t}$  produced via  $q\bar{q}$  initial state
  - the top quark is predicted to be emitted preferably in the direction of the incoming quark
  - the exchange of new particles like  $Z'$  or axigluon could modify it



forward-backward asymmetry

$$A^{t\bar{t}} = \frac{N(\Delta y > 0) - N(\Delta y < 0)}{N(\Delta y > 0) + N(\Delta y < 0)}$$

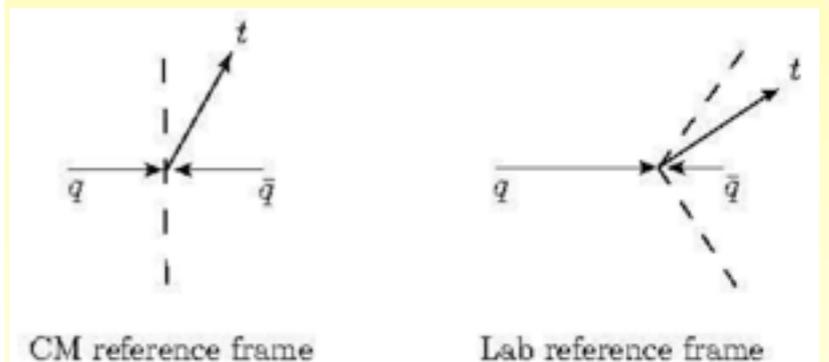
$$\Delta y = y_t - y_{\bar{t}}$$



central-forward asymmetry

$$A_C = \frac{N(\Delta|Y| > 0) - N(\Delta|Y| < 0)}{N(\Delta|Y| > 0) + N(\Delta|Y| < 0)}$$

$$\Delta|Y| = |Y_t| - |Y_{\bar{t}}|$$



smaller at LHC since low  $q\bar{q}$  fraction

# Tevatron Top Charge Asymmetry Results

- CDF measurements

ljets, PRD83, 112003 (2011)

$A_{t\bar{t}}$	ljets	ljets ( $M_{t\bar{t}} \geq 450$ GeV)	dilepton
unfolded data	$0.158 \pm 0.074$	$0.475 \pm 0.114$	$0.42 \pm 0.16$
SM prediction (MCFM)	$0.058 \pm 0.009$	$0.088 \pm 0.013$	$0.06 \pm 0.01$

3.4  $\sigma$  difference

- D0 ljets measurement

- unfold the reconstructed distribution to correct for acceptance and detector effects

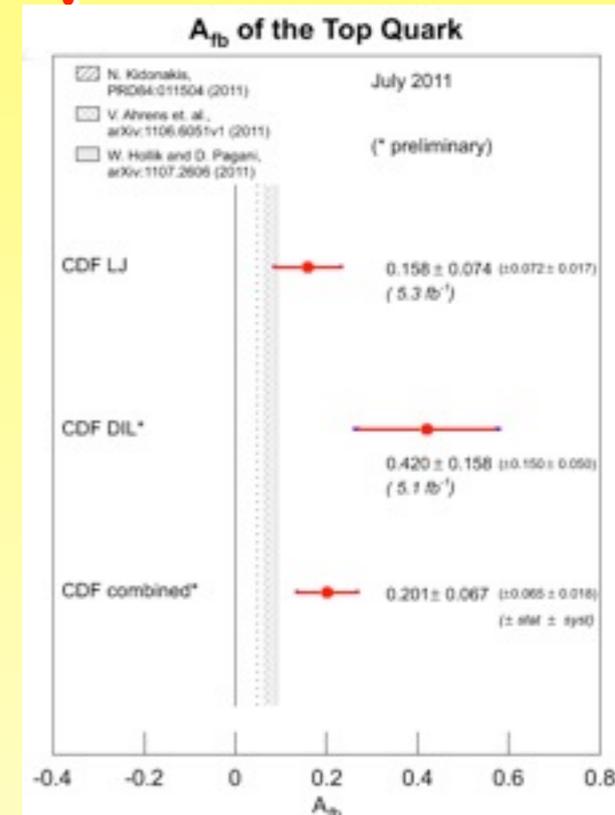
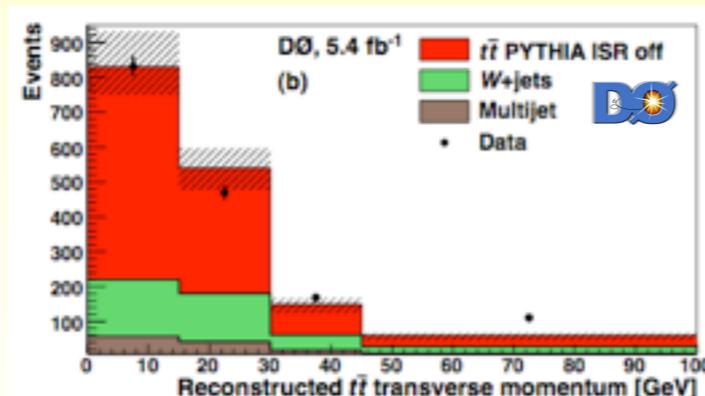
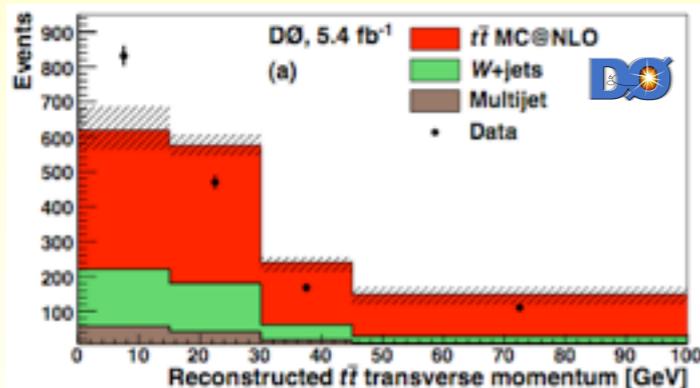
	$A_{FB}$ (%)	
	Reconstruction level	Production level
Data	$9.2 \pm 3.7$	$19.6 \pm 6.5$
MC@NLO	$2.4 \pm 0.7$	$5.0 \pm 0.1$

$\sim 2.4 \sigma$

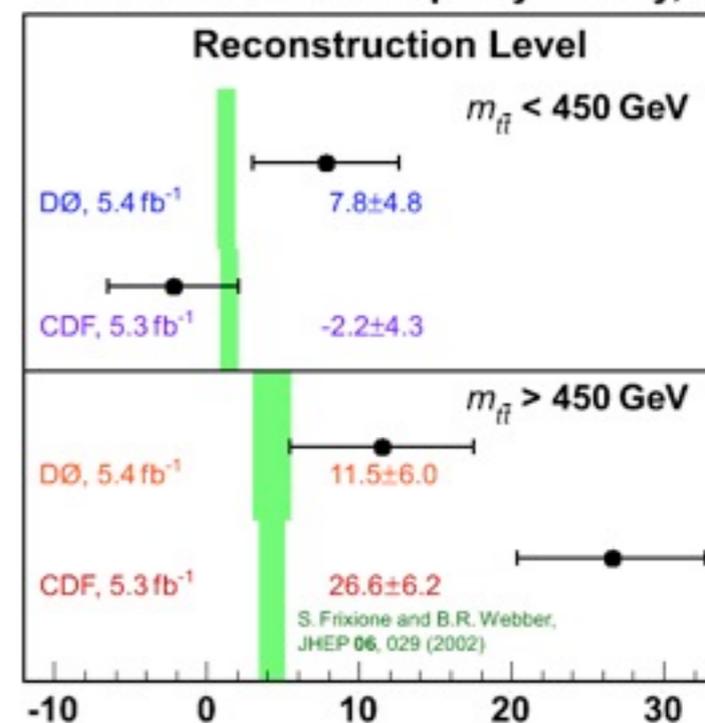
$$A_{FB}^l = \frac{N(qly > 0) - N(qly < 0)}{N(qly > 0) + N(qly < 0)}$$

	$A_{FB}^l$ (%)	
	Reconstruction level	Production level
Data	$14.2 \pm 3.8$	$15.2 \pm 4.0$
MC@NLO	$0.8 \pm 0.6$	$2.1 \pm 0.1$

$> 3 \sigma$



## Forward-Backward Top Asymmetry, %



Statistically limited measurements, need better understanding of the predictions

# Top Charge Asymmetry Perspectives

- LHC results

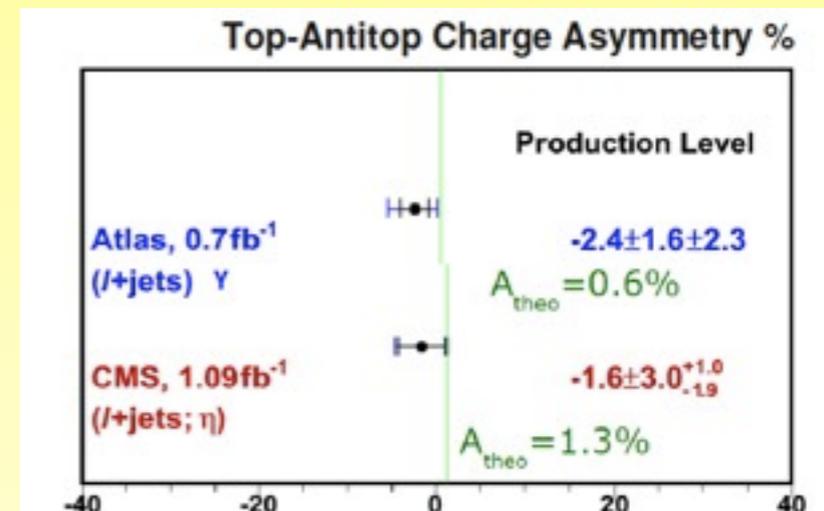
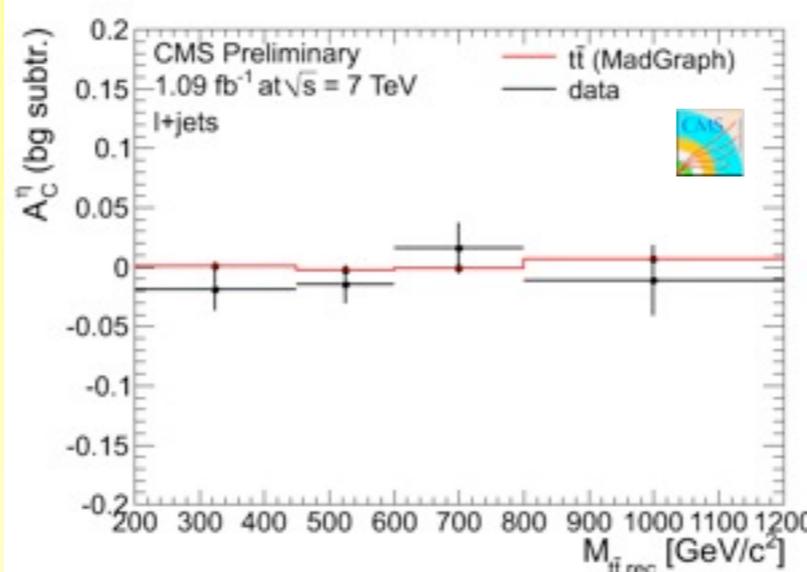
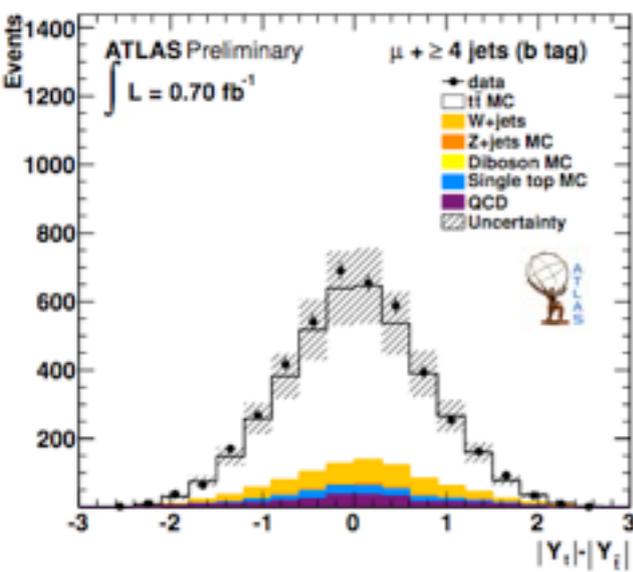
- different observables
- not yet sensitive to a potential Tevatron excess

$$A_C = \frac{N(\Delta > 0) - N(\Delta < 0)}{N(\Delta > 0) + N(\Delta < 0)}$$

- Atlas:  $\Delta^y = |y_t| - |y_{\bar{t}}|$

- CMS:  $\Delta^\eta = |\eta_t| - |\eta_{\bar{t}}|$

$$\Delta^{y^2} = (y_t - y_{\bar{t}})(y_t + y_{\bar{t}})$$

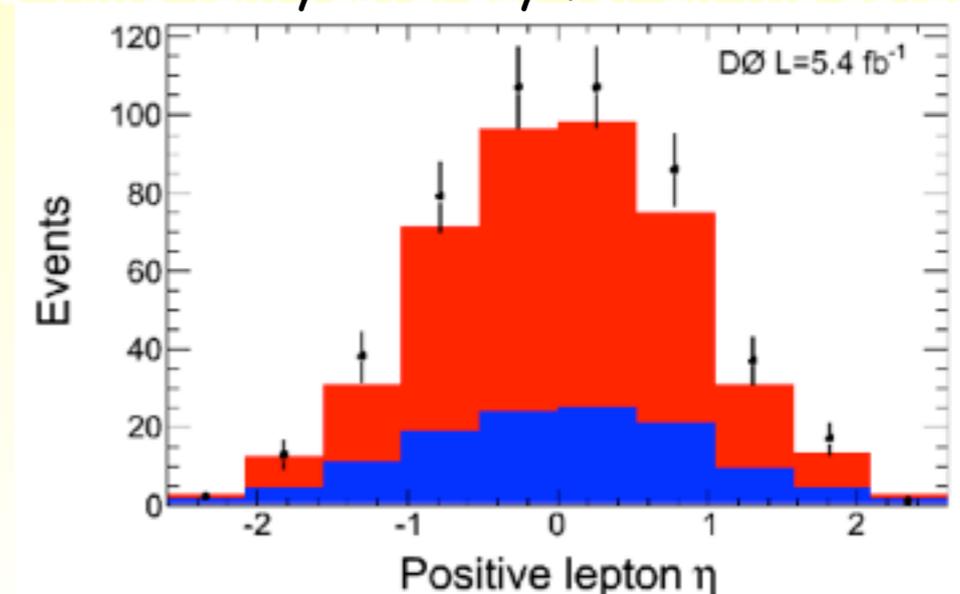


Currently no deviation from the predictions

- Tevatron perspectives

- D0 dilepton result with 5.4 fb<sup>-1</sup> soon in review :  $\sqrt{2}$  improvement
- combination with CDF: another  $\sqrt{2}$
- we have to conclude on the effect with the full dataset:  
is it really new physics ?

see Tim's talk yesterday for all the details



# PDG'10 on the Top Quark

J.Phys. G37, 075021 (2010)

## t-Quark Mass in $p\bar{p}$ Collisions

OUR EVALUATION of  $172.0 \pm 0.9 \pm 1.3$  GeV (TEVEWWG 10) is an average of top mass measurements from Tevatron Run-I (1992–1996) and Run-II (2001–present) that were published at the time of preparing this Review. This average was provided by the Tevatron Electroweak Working Group (TEVEWWG). It takes correlated uncertainties properly into account and has a  $\chi^2$  of 5.8 for 10 degrees of freedom.

For earlier search limits see PDG 96, Physical Review **D54** 1 (1996). We no longer include a compilation of indirect top mass determinations from Standard Model Electroweak fits in the Listings (our last compilation can be found in the Listings of the 2007 partial update). For a discussion of current results see the reviews "The Top Quark" and "Electroweak Model and Constraints on New Physics."

VALUE (GeV)	DOCUMENT ID	TECN	COMMENT
<b><math>172.0 \pm 0.9 \pm 1.3</math></b>	<b>OUR EVALUATION</b>		See comments in the header above.
$172.7 \pm 1.8 \pm 1.2$	<sup>1</sup> AALTONEN 09J	CDF	$\ell + \mathcal{E}_T + 4$ jets ( $b$ -tag)
$171.1 \pm 3.7 \pm 2.1$	<sup>2</sup> AALTONEN 09K	CDF	6 jets, vtx $b$ -tag
$171.2 \pm 2.7 \pm 2.9$	<sup>3</sup> AALTONEN 09O	CDF	dilepton
$174.7 \pm 4.4 \pm 2.0$	<sup>4</sup> ABAZOV 09AH	D0	dilepton + $b$ -tag ( $\mu$ -W+MWT)
$171.5 \pm 1.8 \pm 1.1$	<sup>5</sup> ABAZOV 08AH	D0	$\ell + \mathcal{E}_T + 4$ jets
$180.7^{+15.5}_{-13.4} \pm 8.6$	<sup>6</sup> ABULENCIA 07J	CDF	lepton + jets
$180.1 \pm 3.6 \pm 3.9$	<sup>7,8</sup> ABAZOV 04G	D0	lepton + jets
$176.1 \pm 5.1 \pm 5.3$	<sup>9</sup> AFFOLDER 01	CDF	lepton + jets
$167.4 \pm 10.3 \pm 4.8$	<sup>10,11</sup> ABE 99B	CDF	dilepton
$168.4 \pm 12.3 \pm 3.6$	<sup>8</sup> ABBOTT 98D	D0	dilepton
$186 \pm 10 \pm 5.7$	<sup>10,12</sup> ABE 97R	CDF	6 or more jets

• • • We do not use the following data for averages, fits, limits, etc. • • •

$180.5 \pm 12.0 \pm 3.6$	<sup>13</sup> AALTONEN 09AK	CDF	$\ell + \mathcal{E}_T +$ jets (soft $\mu$ $b$ -tag)
$171.9 \pm 1.7 \pm 1.1$	<sup>14</sup> AALTONEN 09L	CDF	$\ell +$ jets, $\ell\ell +$ jets
$165.5^{+3.4}_{-3.3} \pm 3.1$	<sup>15</sup> AALTONEN 09X	CDF	$\ell\ell + \mathcal{E}_T$ ( $\nu\phi$ weighting)
$169.1^{+5.9}_{-5.2}$	<sup>16</sup> ABAZOV 09AG	D0	cross sects, theory + exp
$171.5^{+9.9}_{-9.8}$	<sup>17</sup> ABAZOV 09R	D0	cross sects, theory + exp
$170.7^{+4.2}_{-3.9} \pm 3.5$	<sup>18,19</sup> AALTONEN 08C	CDF	dilepton, $\sigma_{\ell\ell}$ constrained
$177.1 \pm 4.9 \pm 4.7$	<sup>20,21</sup> AALTONEN 07	CDF	6 jets with $\geq 1$ $b$ vtx
$172.3^{+10.8}_{-9.6} \pm 10.8$	<sup>22</sup> AALTONEN 07B	CDF	$\geq 4$ jets ( $b$ tag)
$174.0 \pm 2.2 \pm 4.8$	<sup>23</sup> AALTONEN 07D	CDF	$\geq 6$ jets, vtx $b$ -tag
$170.8 \pm 2.2 \pm 1.4$	<sup>24,25</sup> AALTONEN 07I	CDF	lepton + jets ( $b$ -tag)
$173.7 \pm 4.4^{+2.1}_{-2.0}$	<sup>21,26</sup> ABAZOV 07F	D0	lepton + jets
$176.2 \pm 9.2 \pm 3.9$	<sup>27</sup> ABAZOV 07W	D0	dilepton (MWT)
$179.5 \pm 7.4 \pm 5.6$	<sup>27</sup> ABAZOV 07V	D0	dilepton ( $\nu$ -W+)
$164.5 \pm 3.9 \pm 3.9$	<sup>25,28</sup> ABULENCIA 07D	CDF	dilepton
$170.3^{+4.1+1.2}_{-4.5-1.8}$	<sup>25,29</sup> ABAZOV 06U	D0	lepton + jets ( $b$ -tag)
$173.2^{+2.6}_{-2.4} \pm 3.2$	<sup>30,31</sup> ABULENCIA 06D	CDF	lepton + jets
$173.5^{+3.7}_{-3.6} \pm 1.3$	<sup>19,30</sup> ABULENCIA 06D	CDF	lepton + jets
$165.2 \pm 6.1 \pm 3.4$	<sup>29,32</sup> ABULENCIA 06G	CDF	dilepton
$170.1 \pm 6.0 \pm 4.1$	<sup>19,33</sup> ABULENCIA 06V	CDF	dilepton
$178.5 \pm 13.7 \pm 7.7$	<sup>34,35</sup> ABAZOV 05	D0	6 or more jets
$176.1 \pm 6.6$	<sup>36</sup> AFFOLDER 01	CDF	dilepton, lepton+jets, all-jets
$172.1 \pm 5.2 \pm 4.9$	<sup>37</sup> ABBOTT 99C	D0	di-lepton, lepton+jets
$176.0 \pm 6.5$	<sup>11,38</sup> ABE 99B	CDF	dilepton, lepton+jets, all-jets
$173.3 \pm 5.6 \pm 5.5$	<sup>8,39</sup> ABBOTT 98R	D0	lepton + jets
$175.9 \pm 4.8 \pm 5.3$	<sup>10,40</sup> ABE 98E	CDF	lepton + jets
$161 \pm 17 \pm 10$	<sup>10</sup> ABE 96F	CDF	dilepton
$172.1 \pm 5.2 \pm 4.9$	<sup>41</sup> BHAT 98E	RVUE	dilepton and lepton+jets
$173.8 \pm 5.0$	<sup>42</sup> BHAT 98R	RVUE	dilepton, lepton+jets, all-jets
$173.3 \pm 5.6 \pm 6.2$	<sup>8</sup> ABACHI 97E	D0	lepton + jets
$199^{+19}_{-21} \pm 22$	ABACHI 95	D0	lepton + jets
$176 \pm 8 \pm 10$	ABE 95F	CDF	lepton + $b$ -jet
$174 \pm 10^{+13}_{-12}$	ABE 94E	CDF	lepton + $b$ -jet

## $t$ BRANCHING RATIOS

$\Gamma(Wb)/\Gamma(Wq(q=b,s,d))$	DOCUMENT ID	TECN	COMMENT	$\Gamma_2/\Gamma_1$
<b><math>0.99^{+0.09}_{-0.08}</math></b>	<b>OUR AVERAGE</b>			
$0.97^{+0.09}_{-0.08}$	<sup>1</sup> ABAZOV 98H	D0	$\ell + n$ jets with 0,1,2 $b$ -tag	
$1.12^{+0.25+0.17}_{-0.19-0.13}$	<sup>2</sup> ACOSTA 95A	CDF		
$1.03^{+0.19}_{-0.17}$	<sup>3</sup> ABAZOV 95K	D0		
$0.94^{+0.20+0.17}_{-0.25-0.12}$	<sup>4</sup> AFFOLDER 91C	CDF		

• • • We do not use the following data for averages, fits, limits, etc. • • •

<sup>1</sup>Result is based on 0.9 fb<sup>-1</sup> of data. The 95% CL lower bound  $R > 0.79$  gives  $|V_{tb}| > 0.89$  (95% CL).

<sup>2</sup>ACOSTA 95A result is from the analysis of lepton + jets and di-lepton + jets final states of  $t\bar{t}$  candidate events with  $\sim 162$  pb<sup>-1</sup> of data at  $\sqrt{s} = 1.96$  TeV. The first error is statistical and the second systematic. It gives  $R > 0.61$ , or  $|V_{tb}| > 0.78$  at 95% CL.

<sup>3</sup>ABAZOV 95K result is from the analysis of  $t\bar{t} \rightarrow \ell\nu + \geq 3$  jets with 230 pb<sup>-1</sup> of data at  $\sqrt{s} = 1.96$  TeV. It gives  $R > 0.61$  and  $|V_{tb}| > 0.78$  at 95% CL. Supported by ABAZOV 98H.

<sup>4</sup>AFFOLDER 91C measures the top-quark decay width ratio  $R = \Gamma(Wb)/\Gamma(Wq)$ , where  $q$  is a  $d$ ,  $s$ , or  $b$  quark, by using the number of events with multiple  $b$ -tags. The first error is statistical and the second systematic. A numerical integration of the likelihood fraction gives  $R > 0.61$  (0.56) at 90% (95%) CL. By assuming three generation unitarity,  $|V_{tb}| = 0.97^{+0.16}_{-0.12}$  or  $|V_{tb}| > 0.78$  (0.75) at 90% (95%) CL is obtained. The result is based on 109 pb<sup>-1</sup> of data at  $\sqrt{s} = 1.8$  TeV.

$\Gamma(\ell\nu_{\text{anything}})/\Gamma_{\text{total}}$	DOCUMENT ID	TECN	COMMENT	$\Gamma_3/\Gamma$
<b><math>0.094 \pm 0.024</math></b>	<sup>1</sup> ABE 96X	CDF		

<sup>1</sup> $\ell$  means  $e$  or  $\mu$  decay mode, not the sum. Assumes lepton universality and  $W$ -decay acceptance.

$\Gamma(\tau\nu_{\tau}b)/\Gamma_{\text{total}}$	DOCUMENT ID	TECN	COMMENT	$\Gamma_4/\Gamma$
<b><math>0.094 \pm 0.024</math></b>	<sup>1</sup> ABE 96X	CDF		

• • • We do not use the following data for averages, fits, limits, etc. • • •

<sup>1</sup>ABULENCIA 06R looked for  $t\bar{t} \rightarrow (\ell\nu_{\tau})(\tau\nu_{\tau})b\bar{b}$  events in 194 pb<sup>-1</sup> of  $p\bar{p}$  collisions at  $\sqrt{s} = 1.96$  TeV. 2 events are found where 1.00  $\pm 0.17$  signal and 1.29  $\pm 0.25$  background events are expected, giving a 95% CL upper bound for the partial width ratio  $\Gamma(t \rightarrow \tau\nu)/\Gamma_{\text{total}}(t \rightarrow \tau\nu q) < 5.2$ .

<sup>2</sup>ABE 97V searched for  $t\bar{t} \rightarrow (\ell\nu_{\tau})(\tau\nu_{\tau})b\bar{b}$  events in 109 pb<sup>-1</sup> of  $p\bar{p}$  collisions at  $\sqrt{s} = 1.8$  TeV. They observed 4 candidate events where one expects  $\sim 1$  signal and  $\sim 2$  background events. Three of the four observed events have jets identified as  $b$  candidates.

$\Gamma(\gamma q(q=u,c))/\Gamma_{\text{total}}$	DOCUMENT ID	TECN	COMMENT	$\Gamma_5/\Gamma$
$<0.8054$	<sup>1</sup> AARON 09A	HL	$t \rightarrow \gamma u$	
<b><math>&lt;0.0089</math></b>	<sup>2</sup> CHEKANOV 03	ZEUS	$B(t \rightarrow \gamma q)$	
$<0.8465$	<sup>3</sup> ABDALLAH 04C	DLPH	$B(\gamma c \text{ or } \gamma q)$	
$<0.8132$	<sup>4</sup> AKTAS 04	HL	$B(t \rightarrow \gamma q)$	
$<0.841$	<sup>5</sup> ACHARD 02J	L3	$B(t \rightarrow \gamma c \text{ or } \gamma q)$	
$<0.832$	<sup>6</sup> ABE 98C	CDF	$t\bar{t} \rightarrow (Wb)(\gamma c \text{ or } \gamma q)$	

• • • We do not use the following data for averages, fits, limits, etc. • • •

<sup>1</sup>AARON 09A looked for single top production via FCNC in  $e^+p$  collisions at HERA with 474 pb<sup>-1</sup>. The upper bound of the cross section gives the bound on the FCNC coupling  $|k_{t\gamma q}|/\Lambda < 1.03$  TeV<sup>-1</sup>, which corresponds to the result for  $m_t = 175$  GeV.

<sup>2</sup>CHEKANOV 03 looked for single top production via FCNC in the reaction  $e^+p \rightarrow e^+(t \text{ or } \bar{t})X$  in 136.1 pb<sup>-1</sup> of data at  $\sqrt{s} = 300$ –310 GeV. No evidence for top production and its decay into  $bW$  was found. The result is obtained for  $m_t = 175$  GeV when  $B(\gamma c) = B(Zq) = 0$ , where  $q$  is a  $u$  or  $c$  quark. Bounds on the effective  $t \rightarrow \gamma$  and  $t \rightarrow Z$  couplings are found in their Fig. 4. The conversion to the constraint listed is from private communication, E. Gallo, January 2004.

<sup>3</sup>ABDALLAH 04C looked for single top production via FCNC in the reaction  $e^+e^- \rightarrow \bar{t}c$  or  $t\bar{u}$  in 541 pb<sup>-1</sup> of data at  $\sqrt{s} = 189$ –208 GeV. No deviation from the SM is found, which leads to the bound on  $B(t \rightarrow \gamma q)$ , where  $q$  is a  $u$  or  $c$  quark, for  $m_t = 175$  GeV when  $B(\gamma c) = B(Zq) = 0$  is assumed. The conversion to the listed bound is from private communication, O. Yushchenko, April 2005. The bounds on the effective  $t \rightarrow \gamma$  and  $t \rightarrow Z$  couplings are given in their Fig. 7 and Table 4, for  $m_t = 170$ –180 GeV, where most conservative bounds are found by choosing the chiral couplings to maximize the negative interference between the virtual  $\gamma$  and  $Z$  exchange amplitudes.

<sup>4</sup>AKTAS 04 looked for single top production via FCNC in  $e^+p$  collisions at HERA with 110.3 pb<sup>-1</sup>, and found 5 events in the  $e$  or  $\mu$  channels. By assuming that they are due to statistical fluctuation, the upper bound on the  $t \rightarrow \gamma$  coupling  $|k_{t\gamma q}| < 0.27$  (95% CL) is obtained. The conversion to the partial width limit, when  $B(\gamma c) = B(Zq) = 0$ , is from private communication, E. Perez, May 2005.

<sup>5</sup>ACHARD 02J looked for single top production via FCNC in the reaction  $e^+e^- \rightarrow \bar{t}c$  or  $t\bar{u}$  in 634 pb<sup>-1</sup> of data at  $\sqrt{s} = 189$ –209 GeV. No deviation from the SM is found, which leads to a bound on the top quark decay branching fraction  $B(\gamma q)$ , where  $q$  is a  $u$  or  $c$  quark. The bound assumes  $B(\gamma q) = 0$  and is for  $m_t = 175$  GeV; bounds for  $m_t = 170$  GeV and 180 GeV and  $B(Zq) \neq 0$  are given in Fig. 5 and Table 7.

<sup>6</sup>ABE 98C looked for  $t\bar{t}$  events where one  $t$  decays into  $q\gamma$  while the other decays into  $bW$ . The quoted bound is for  $\Gamma(\gamma q)/\Gamma(Wb)$ .

## $\Gamma(Zq(q=u,c))/\Gamma_{\text{total}}$

VALUE	CLS	DOCUMENT ID	TECN	COMMENT	$\Gamma_6/\Gamma$
<b><math>&lt;0.037</math></b>	95	<sup>1</sup> AALTONEN 08AD	CDF	$t \rightarrow Zq(q=u,c)$	
$<0.159$	95	<sup>2</sup> ABDALLAH 04C	DLPH	$e^+e^- \rightarrow t\bar{c}$ or $t\bar{u}$	
$<0.137$	95	<sup>3</sup> ACHARD 02J	L3	$e^+e^- \rightarrow t\bar{c}$ or $t\bar{u}$	
$<0.14$	95	<sup>4</sup> HEISTER 02Q	ALEP	$e^+e^- \rightarrow t\bar{c}$ or $t\bar{u}$	
$<0.137$	95	<sup>5</sup> ABBIENDI 01Y	OPAL	$e^+e^- \rightarrow t\bar{c}$ or $t\bar{u}$	
$<0.093$	95	<sup>6</sup> AALTONEN 09AL	CDF	$t \rightarrow Zq(q=c)$	
$<0.17$	95	<sup>7</sup> BARATE 00S	ALEP	$e^+e^- \rightarrow t\bar{c}$ or $t\bar{u}$	
$<0.33$	95	<sup>8</sup> ABE 98C	CDF	$t\bar{t} \rightarrow (Wb)(Zc \text{ or } Zq)$	

Test for  $\Delta F = 1$  weak neutral current. Allowed by higher-order electroweak interaction.

<sup>1</sup>Result is based on 1.9 fb<sup>-1</sup> of data at 1.96 TeV.  $t\bar{t} \rightarrow WbZq$  or  $ZqZq$  processes have been looked for in  $Z \rightarrow 4$  jet events with and without  $b$ -tag. No signal leads to the bound  $B(t \rightarrow Zq) < 0.037$  (0.041) for  $m_t = 175$  (170) GeV.

<sup>2</sup>ABDALLAH 04C looked for single top production via FCNC in the reaction  $e^+e^- \rightarrow t\bar{c}$  or  $t\bar{u}$  in 541 pb<sup>-1</sup> of data at  $\sqrt{s} = 189$ –208 GeV. No deviation from the SM is found, which leads to the bound on  $B(t \rightarrow Zq)$ , where  $q$  is a  $u$  or  $c$  quark, for  $m_t = 175$  GeV when  $B(\gamma q) = 0$  is assumed. The conversion to the listed bound is from private communication, O. Yushchenko, April 2005. The bounds on the effective  $t \rightarrow \gamma$  and  $t \rightarrow Z$  couplings are given in their Fig. 7 and Table 4, for  $m_t = 170$ –180 GeV, where most conservative bounds are found by choosing the chiral couplings to maximize the negative interference between the virtual  $\gamma$  and  $Z$  exchange amplitudes.

<sup>3</sup>ACHARD 02J looked for single top production via FCNC in the reaction  $e^+e^- \rightarrow t\bar{c}$  or  $t\bar{u}$  in 634 pb<sup>-1</sup> of data at  $\sqrt{s} = 189$ –209 GeV. No deviation from the SM is found, which leads to a bound on the top quark decay branching fraction  $B(Zq)$ , where  $q$  is a  $u$  or  $c$  quark. The bound assumes  $B(\gamma q) = 0$  and is for  $m_t = 175$  GeV; bounds for  $m_t = 170$  GeV and 180 GeV and  $B(\gamma q) \neq 0$  are given in Fig. 5 and Table 7. Table 6 gives constraints on  $t \rightarrow c$  or  $u$  four fermi contact interactions.

<sup>4</sup>HEISTER 02Q looked for single top production via FCNC in the reaction  $e^+e^- \rightarrow \bar{t}c$  or  $t\bar{u}$  in 214 pb<sup>-1</sup> of data at  $\sqrt{s} = 204$ –209 GeV. No deviation from the SM is found, which leads to a bound on the branching fraction  $B(Zq)$ , where  $q$  is a  $u$  or  $c$  quark. The bound assumes  $B(\gamma q) = 0$  and is for  $m_t = 174$  GeV. Bounds on the effective  $t \rightarrow (c \text{ or } u)\gamma$  and  $t \rightarrow (c \text{ or } u)Z$  couplings are given in their Fig. 2.

<sup>5</sup>ABBIENDI 01Y looked for single top production via FCNC in the reaction  $e^+e^- \rightarrow t\bar{c}$  or  $t\bar{u}$  in 609 pb<sup>-1</sup> of data at  $\sqrt{s} = 189$ –209 GeV. No deviation from the SM is found, which leads to bounds on the branching fractions  $B(Zq)$  and  $B(\gamma q)$ , where  $q$  is a  $u$  or  $c$  quark. The result is obtained for  $m_t = 174$  GeV. Bounds on the effective  $t \rightarrow (c \text{ or } u)\gamma$  and  $t \rightarrow (c \text{ or } u)Z$  couplings are given in their Fig. 4.

<sup>6</sup>Based on  $p\bar{p}$  data of 1.52 fb<sup>-1</sup>, AALTONEN 09AL compared  $t\bar{t} \rightarrow WbWb \rightarrow \ell\nu b\bar{b}$  and  $t\bar{t} \rightarrow ZcWb \rightarrow \ell c\bar{c}j\bar{b}$  decay chains, and absence of the latter signal gives the bound. The result is for 100% longitudinally polarized  $Z$  boson and the theoretical  $t\bar{t}$  production cross section. The results for different  $Z$  polarizations and those without the cross section assumption are given in their Table XI.

<sup>7</sup>BARATE 00S looked for single top production via FCNC in the reaction  $e^+e^- \rightarrow \bar{t}c$  or  $t\bar{u}$  in 411 pb<sup>-1</sup> of data at c.m. energies between 100 and 202 GeV. No deviation from the SM is found, which leads to a bound on the branching fraction. The bound assumes  $B(\gamma q) = 0$ . Bounds on the effective  $t \rightarrow (c \text{ or } u)\gamma$  and  $t \rightarrow (c \text{ or } u)Z$  couplings are given in their Fig. 4.

<sup>8</sup>ABE 98C looked for  $t\bar{t}$  events where one  $t$  decays into three jets and the other decays into  $qZ$  with  $Z \rightarrow \ell\ell$ . The quoted bound is for  $\Gamma(Zq)/\Gamma(Wb)$ .

## t-quark EW Couplings

$F_0$  is the fraction of longitudinal and  $F_{\pm}$  the fraction of right-handed  $W$  bosons.  $F_{V\pm A}$  is the fraction of  $V \pm A$  current in top decays. The effective Lagrangian (cited by ABAZOV 08A) has terms  $\tilde{t}_L^c$  and  $\tilde{t}_R^c$  for  $V-A$  and  $V+A$  couplings,  $\tilde{t}_2^c$  and  $\tilde{t}_3^c$  for tensor couplings with  $b_R$  and  $b_L$  respectively.

VALUE	CLS	DOCUMENT ID	TECN	COMMENT
$0.62 \pm 0.18 \pm 0.05$		<sup>1</sup> AALTONEN 09Q	CDF	$F_0 = B(t \rightarrow W_0 b)$
$-0.04 \pm 0.04 \pm 0.05$		<sup>1</sup> AALTONEN 09Q	CDF	$F_{\pm} = B(t \rightarrow W_{\pm} b)$
$ \tilde{t}_L^c ^2 < 1.01$	95	<sup>2</sup> ABAZOV 09J	DO	$ \tilde{t}_L^c  = 1,  \tilde{t}_R^c  =  \tilde{t}_2^c  = 0$
$ \tilde{t}_L^c ^2 < 0.28$	95	<sup>2</sup> ABAZOV 09J	DO	$ \tilde{t}_L^c  = 1,  \tilde{t}_R^c  =  \tilde{t}_2^c  = 0$
$ \tilde{t}_L^c ^2 < 0.23$	95	<sup>2</sup> ABAZOV 09J	DO	$ \tilde{t}_L^c  = 1,  \tilde{t}_R^c  =  \tilde{t}_2^c  = 0$
$ \tilde{t}_L^c ^2 < 2.5$	95	<sup>3</sup> ABAZOV 08A	DO	$ \tilde{t}_L^c  = 1,  \tilde{t}_R^c  =  \tilde{t}_2^c  = 0$
$ \tilde{t}_L^c ^2 < 0.5$	95	<sup>3</sup> ABAZOV 08A	DO	$ \tilde{t}_L^c  = 1,  \tilde{t}_R^c  =  \tilde{t}_2^c  = 0$
$ \tilde{t}_L^c ^2 < 0.3$	95	<sup>3</sup> ABAZOV 08A	DO	$ \tilde{t}_L^c  = 1,  \tilde{t}_R^c  =  \tilde{t}_2^c  = 0$
$0.425 \pm 0.166 \pm 0.102$		<sup>4</sup> ABAZOV 08B	DO	$F_0 = B(t \rightarrow W_0 b)$
$0.119 \pm 0.098 \pm 0.053$		<sup>4</sup> ABAZOV 08B	DO	$F_{\pm} = B(t \rightarrow W_{\pm} b)$
$0.096 \pm 0.088 \pm 0.057$		<sup>5</sup> ABAZOV 07D	DO	$F_{\pm} = B(t \rightarrow W_{\pm} b)$
$-0.66 \pm 0.22 \pm 0.12$		<sup>6</sup> ABULENCIA 07C	CDF	$F_{V+A} = B(t \rightarrow W_0 b)$
$< 0.29$	95	<sup>6</sup> ABULENCIA 07C	CDF	$F_{V+A} = B(t \rightarrow W_0 b)$
$0.85^{+0.15}_{-0.22} \pm 0.06$		<sup>7</sup> ABULENCIA 07I	CDF	$F_0 = B(t \rightarrow W_0 b)$
$0.85^{+0.11}_{-0.05} \pm 0.03$		<sup>7</sup> ABULENC		

# PDG'10 on the Top Quark

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<sup>1</sup> Results are based on 1.9 fb<sup>-1</sup> of data in pp collisions at 1.96 TeV. F<sub>0</sub> result is obtained assuming F<sub>+</sub> = 0, while F<sub>-</sub> result is obtained for F<sub>0</sub> = 0.70, the SM value. Model independent fits for the two fractions give F<sub>0</sub> = 0.66 ± 0.36 ± 0.05 and F<sub>+</sub> = -8.03 ± 0.06 ± 0.05.

<sup>2</sup> Based on 1 fb<sup>-1</sup> of data at pp collisions √s = 1.96 TeV. Combined result of the W helicity measurement in tt events (ABAZOV 08a) and the search for anomalous t-b-W couplings in the single top production (ABAZOV 08b). Constraints when F<sub>+</sub> and one of the anomalous couplings are simultaneously allowed to vary are given in their Fig. 1 and Table 1.

<sup>3</sup> Result is based on 0.9 fb<sup>-1</sup> of data at 1.96 TeV. Single top quark production events are used to measure the Lorentz structure of the tbW coupling. The upper bounds on the non-standard couplings are obtained when only one non-standard coupling is allowed to be present together with the SM one, i.e. F<sub>+</sub> = V<sub>tb</sub><sup>+</sup>.

<sup>4</sup> Based on 1 fb<sup>-1</sup> at √s = 1.96 TeV.

<sup>5</sup> Based on 329 pb<sup>-1</sup> of data at √s = 1.96 TeV, using the t + jets and dilepton decay channels. The result assumes F<sub>0</sub> = 0.70, and it gives F<sub>+</sub> < 0.23 at 95% CL.

<sup>6</sup> Based on 700 pb<sup>-1</sup> of data at √s = 1.96 TeV.

<sup>7</sup> Based on 310 pb<sup>-1</sup> of data at √s = 1.96 TeV.

<sup>8</sup> Based on 200 pb<sup>-1</sup> of data at √s = 1.96 TeV. t → Wb → ℓνb (ℓ = e or μ). The errors are stat + syst.

<sup>9</sup> ABAZOV 05c studied the angular distribution of leptonic decays of W bosons in tt candidate events with lepton + jets final states, and obtained the fraction of longitudinally polarized W under the constraint of no right-handed current, F<sub>+</sub> = 0. Based on 125 pb<sup>-1</sup> of data at √s = 1.8 TeV.

<sup>10</sup> ABAZOV 05a studied the angular distribution of leptonic decays of W bosons in tt events, where one of the W's from t or t decays into e or μ and the other decays hadronically. The fraction of the "++" helicity W boson is obtained by assuming F<sub>0</sub> = 0.7, which is the generic prediction for any linear combination of V and A currents. Based on 230 ± 15 pb<sup>-1</sup> of data at √s = 1.96 TeV.

<sup>11</sup> ACOSTA 85b measures the m<sub>ℓℓ</sub><sup>2</sup> distribution in tt production events where one or both W's decay leptonically to ℓ = e or μ, and finds a bound on the V+A coupling of the tbW vertex. By assuming the SM value of the longitudinal W fraction F<sub>0</sub> = B(t → W<sub>0</sub>b) = 0.70, the bound on F<sub>+</sub> is obtained. If the results are combined with those of AFFOLDER 08a, the bounds become F<sub>+</sub> < 0.61 (95% CL) and F<sub>+</sub> < 0.18 (95% CL), respectively. Based on 109 ± 7 pb<sup>-1</sup> of data at √s = 1.8 TeV (run II).

<sup>12</sup> AFFOLDER 08a studied the angular distribution of leptonic decays of W bosons in t → Wb events. The ratio F<sub>0</sub> is the fraction of the helicity zero (longitudinal) W bosons in the decaying top quark rest frame. B(t → W<sub>0</sub>b) is the fraction of positive helicity (right handed) positive charge W bosons in the top quark decays. It is obtained by assuming the Standard Model value of F<sub>0</sub>.

• • • We do not use the following data for averages, fits, limits, etc. • • •

3.14 <sup>+0.94</sup> <sub>-0.80</sub>	<sup>3</sup> ABAZOV	18	DO	t channel	
1.95 ± 0.01	<sup>3</sup> ABAZOV	18	DO	s channel	
2.2 <sup>+0.7</sup> <sub>-0.6</sub>	<sup>4</sup> AALTONEN	88b	CDF	s + t channel	
4.7 ± 1.3	<sup>5</sup> ABAZOV	88b	DO	s + t channel	
4.9 ± 1.4	<sup>5</sup> ABAZOV	87a	DO	s + t channel	
< 6.4	95	<sup>7</sup> ABAZOV	85f	DO	pp → tb + X
< 5.0	95	<sup>7</sup> ABAZOV	85f	DO	pp → tqb + X
< 10.1	95	<sup>8</sup> ACOSTA	85a	CDF	pp → tqb + X
< 13.6	95	<sup>8</sup> ACOSTA	85a	CDF	pp → tqb + X
< 17.8	95	<sup>8</sup> ACOSTA	85a	CDF	pp → tqb + X, tqb + X

<sup>1</sup> Based on 3.2 fb<sup>-1</sup> of data. Events with isolated t + E<sub>T</sub> + jets with at least one b tag are analyzed and s- and t-channel single top events are selected by using the likelihood function, matrix element, neural network, boosted decision tree, likelihood function or limited for s channel process, and neural network based analysis of events with E<sub>T</sub> that has sensitivity for W → τν decays. The result is for m<sub>t</sub> = 175 GeV, and the mean value decreases by 8.03 pb/GeV for smaller m<sub>t</sub>. The signal has 5.0 sigma significance. The result gives |V<sub>tb</sub><sup>+</sup>| = 0.91 ± 0.11 (stat+syst) ± 0.07 (theory), or |V<sub>tb</sub><sup>+</sup>| > 0.71 at 95% CL.

<sup>2</sup> Based on 2.5 fb<sup>-1</sup> of data. Events with isolated t + E<sub>T</sub> + ≥ 2 jets with 1 or 2 b tag are analyzed and s- and t-channel single top events are selected by using boosted decision tree, Bayesian neural networks and neural network based analysis. The signal has 5.0 sigma significance. The result gives |V<sub>tb</sub><sup>+</sup>| = 1.07 ± 0.12, or |V<sub>tb</sub><sup>+</sup>| > 0.78 at 95% CL. The analysis assumes m<sub>t</sub> = 170 GeV.

<sup>3</sup> Result is based on 2.3 fb<sup>-1</sup> of data. Events with isolated t + E<sub>T</sub> + 2, 3, 4 jets with one or two b-tags are selected. The analysis assumes m<sub>t</sub> = 170 GeV.

<sup>4</sup> Result is based on 2.2 fb<sup>-1</sup> of data. Events with isolated t + E<sub>T</sub> + 2, 3 jets with at least one b-tag are selected, and s- and t-channel single top events are selected by using likelihood, matrix element, and neural network discriminants. The result can be interpreted as |V<sub>tb</sub><sup>+</sup>| = 0.88<sup>+0.12</sup><sub>-0.12</sub> (stat + syst) ± 0.07 (theory), and |V<sub>tb</sub><sup>+</sup>| > 0.66 (95% CL) under the |V<sub>tb</sub><sup>+</sup>| < 1 constraint.

<sup>5</sup> Result is based on 0.9 fb<sup>-1</sup> of data. Events with isolated t + E<sub>T</sub> + 2, 3, 4 jets with one or two b-vertex-tag are selected, and contributions from W + jets, tt, s- and t-channel single top events are identified by using boosted decision trees, Bayesian neural networks, and matrix element analysis. The result can be interpreted as the measurement of the CKM matrix element |V<sub>tb</sub><sup>+</sup>| = 1.31<sup>+0.29</sup><sub>-0.25</sub>, or |V<sub>tb</sub><sup>+</sup>| > 0.68 (95% CL) under the |V<sub>tb</sub><sup>+</sup>| < 1 constraint.

<sup>6</sup> Result is based on 0.9 fb<sup>-1</sup> of data. This result constrains V<sub>tb</sub><sup>+</sup> to 0.60 < |V<sub>tb</sub><sup>+</sup>| ≤ 1 at 95% CL.

<sup>7</sup> ABAZOV 05f bounds single top-quark production from either the s-channel W-exchange process, q'q' → tb, or the t-channel W-exchange process, q'q' → qtb, based on ~ 230 pb<sup>-1</sup> of data.

<sup>8</sup> ACOSTA 95a bounds single top quark production from the t channel W exchange process (q'q' → qtb), the s-channel W exchange process (q'q' → ttb), and from the combined cross section of t- and s-channel. Based on ~ 162 pb<sup>-1</sup> of data.

### Single t-Quark Production Cross Section in ep Collisions

• • • We do not use the following data for averages, fits, limits, etc. • • •

< 0.25	95	<sup>1</sup> AARON	05a	III	e <sup>+</sup> p → e <sup>+</sup> tX
< 0.55	95	<sup>2</sup> AKTAS	04	III	e <sup>+</sup> p → e <sup>+</sup> tX
< 0.225	95	<sup>3</sup> CHEKANOV	03	ZEUS	e <sup>+</sup> p → e <sup>+</sup> tX

<sup>1</sup> AARON 05a looked for single top production via FCNC in e<sup>+</sup>p collisions at HERA with 474 pb<sup>-1</sup> of data at √s = 301-319 GeV. The result supersedes that of AKTAS 04.

<sup>2</sup> AKTAS 04 looked for single top production via FCNC in e<sup>+</sup>p collisions at HERA with 118.3 pb<sup>-1</sup>, and found 5 events in the e or μ channels while 1.35 ± 0.22 events are expected from the Standard Model background. No excess was found for the hadronic channel. The observed cross section of σ(ep → e<sup>+</sup>tX) = 0.29<sup>+0.15</sup><sub>-0.14</sub> pb at √s = 319 GeV gives the quoted upper bound if the observed events are due to statistical fluctuation.

<sup>3</sup> CHEKANOV 03 looked in 130.1 pb<sup>-1</sup> of data at √s = 300 and 318 GeV. The limit for √s = 318 GeV and assumes m<sub>t</sub> = 175 GeV.

### tt production cross section in pp collisions at √s = 1.8 TeV

Only the final combined tt production cross sections obtained from Tevatron Run I by the CDF and DO experiments are quoted below.

• • • We do not use the following data for averages, fits, limits, etc. • • •

5.69 ± 1.21 ± 1.04	<sup>1</sup> ABAZOV	03a	DO	Combined Run I data
6.5 ± 1.7	<sup>2</sup> AFFOLDER	01a	CDF	Combined Run I data

<sup>1</sup> Combined result from 110 pb<sup>-1</sup> of Tevatron Run I data. Assume m<sub>t</sub> = 172.1 GeV.

<sup>2</sup> Combined result from 105 pb<sup>-1</sup> of Tevatron Run I data. Assume m<sub>t</sub> = 175 GeV.

### tt production cross section in pp collisions at √s = 1.96 TeV

• • • We do not use the following data for averages, fits, limits, etc. • • •

9.6 ± 1.2 <sup>+0.6</sup> <sub>-0.5</sub> ± 0.6	<sup>1</sup> AALTONEN	09a	CDF	tt + E <sub>T</sub> / vtx b-tag
9.1 ± 1.1 ± 1.0 ± 0.6	<sup>2</sup> AALTONEN	09a	CDF	t + ≥ 3 jets + E <sub>T</sub> / soft μ b-tag
8.18 ± 0.95	<sup>3</sup> ABAZOV	09a	DO	t + jets, tt and tτ + jets
7.5 ± 1.0 ± 0.7 ± 0.6	<sup>4</sup> ABAZOV	09a	DO	tt and tτ + jets
8.18 ± 0.90 ± 0.50	<sup>5</sup> ABAZOV	08a	DO	t + n jets with 0,1,2 b-tag

7.6 ± 0.1	<sup>6</sup> AALTONEN	08b	DO	tt + b-tag or kinematics
8.3 ± 1.0 ± 0.9	<sup>7</sup> AALTONEN	08b	DO	tt + b-tag
8.3 ± 1.0 ± 0.9	<sup>8</sup> AALTONEN	08b	DO	tt + b-tag
7.4 ± 1.4 ± 1.0	<sup>9</sup> ABAZOV	07b	DO	tt + jets, vtx b-tag
4.5 ± 2.0 ± 1.4 ± 1.9 ± 1.1 ± 0.3	<sup>10</sup> ABAZOV	07b	DO	≥ 6 jets, vtx b-tag
6.4 ± 1.3 ± 1.2 ± 0.7 ± 0.4	<sup>11</sup> ABAZOV	07b	DO	t + ≥ 4 jets
6.6 ± 0.9 ± 0.4	<sup>12</sup> ABAZOV	06c	DO	t + jets, vtx b-tag
8.7 ± 0.9 ± 1.1 ± 0.9	<sup>13</sup> ABULENCIA	06c	CDF	t + jets, vtx b-tag
5.8 ± 1.2 ± 0.9 ± 0.7	<sup>14</sup> ABULENCIA,A	06c	CDF	missing E <sub>T</sub> + jets, vtx b-tag
7.5 ± 2.1 ± 3.3 ± 0.5 ± 2.2 ± 0.4	<sup>15</sup> ABULENCIA,A	06c	CDF	6-8 jets, b-tag
8.9 ± 1.0 ± 1.1 ± 1.0	<sup>16</sup> ABULENCIA,A	06f	CDF	t + ≥ 3 jets, b-tag
8.6 ± 1.6 ± 1.5 ± 0.6	<sup>17</sup> ABAZOV	05d	DO	t + n jets
8.6 ± 3.2 ± 1.1 ± 0.6	<sup>18</sup> ABAZOV	05k	DO	di-lepton + n jets
6.7 ± 1.4 ± 1.6 ± 1.3 ± 1.1 ± 0.4	<sup>19</sup> ABAZOV	05k	DO	t + jets / kinematics
5.3 ± 3.3 ± 1.3 ± 1.0	<sup>20</sup> ACOSTA	05b	CDF	t + jets / soft μ b-tag
6.6 ± 1.1 ± 1.5 ± 1.5	<sup>21</sup> ACOSTA	05t	CDF	t + jets / kinematics
6.0 ± 1.5 ± 1.2 ± 1.6 ± 1.3	<sup>22</sup> ACOSTA	05u	CDF	t + jets/kinematics + vtx b-tag
5.6 ± 1.2 ± 0.9 ± 1.1 ± 0.6	<sup>23</sup> ACOSTA	05v	CDF	t + n jets
7.0 ± 2.4 ± 1.6 ± 2.1 ± 1.1 ± 0.4	<sup>24</sup> ACOSTA	04c	CDF	di-lepton + jets + missing ET

<sup>1</sup> Based on 1.1 fb<sup>-1</sup>. The last error is from luminosity. The result is for B(W → tℓ) = 10.0%, and m<sub>t</sub> = 175 GeV; the mean value is 9.6 for m<sub>t</sub> = 172.5 GeV and 10.1 for m<sub>t</sub> = 170 GeV. AALTONEN 08ad used high p<sub>T</sub> e or μ with an isolated track to select tt decays into dileptons including ℓ = τ. The result is based on the candidate event samples with and without vertex b-tag.

<sup>2</sup> Based on 2 fb<sup>-1</sup>. The last error is from luminosity. The result is for m<sub>t</sub> = 175 GeV; the mean value is 3% higher for m<sub>t</sub> = 170 GeV and 4% lower for m<sub>t</sub> = 180 GeV.

<sup>3</sup> Result is based on 1 fb<sup>-1</sup> of data. The result is for m<sub>t</sub> = 170 GeV, and the mean value decreases with increasing m<sub>t</sub>; see their Fig. 2. The result is obtained after combining t + jets, tt, and tτ final states, and the ratios of the extracted cross sections are R<sup>tt/tt</sup> = 0.86<sup>+0.14</sup><sub>-0.17</sub> and R<sup>tτ/tt</sup> = 0.97<sup>+0.32</sup><sub>-0.29</sub>, consistent with the SM expectation of R = 1. This leads to the upper bound of B(t → bH<sup>±</sup>) as a function of m<sub>H<sup>±</sup></sub>. Results are shown in their Fig. 1 for B(H<sup>±</sup> → τν) = 1 and B(H<sup>±</sup> → cν) = 1 cases. Comparison of the m<sub>t</sub> dependence of the extracted cross section and a partial NNLO prediction gives m<sub>t</sub> = 169.1<sup>+3.9</sup><sub>-3.2</sub> GeV.

<sup>4</sup> Result is based on 1 fb<sup>-1</sup> of data. The last error is from luminosity. The result is for m<sub>t</sub> = 170 GeV, and the mean value changes by -0.07 [m<sub>t</sub>(GeV) - 170] pb near the reference m<sub>t</sub> value. Comparison of the m<sub>t</sub> dependence of the extracted cross section and a partial NNLO QCD prediction gives m<sub>t</sub> = 171.5<sup>+0.9</sup><sub>-0.9</sub> GeV. The tτ channel alone gives 7.6<sup>+4.9+3.5+1.4</sup><sub>-4.3-3.4-0.4</sub> pb and the tt channel gives 7.5<sup>+1.2+0.7+0.7</sup><sub>-1.1-0.6-0.5</sub> pb.

<sup>5</sup> Result is based on 0.9 fb<sup>-1</sup> of data. The first error is from stat + syst, while the latter error is from luminosity. The result is for m<sub>t</sub> = 175 GeV, and the mean value changes by -0.09 pb [m<sub>t</sub>(GeV) - 175].

<sup>6</sup> Result is based on 0.9 fb<sup>-1</sup> of data. The cross section is obtained from the t + ≥ 3 jet event rates with 1 or 2 b-tag, and also from the kinematical likelihood analysis of the t + 3, 4 jet events. The result is for m<sub>t</sub> = 172.6 GeV, and its m<sub>t</sub> dependence shown in Fig. 3 leads to the constraint m<sub>t</sub> = 179 ± 7 GeV when compared to the SM prediction.

<sup>7</sup> Result is based on 360 pb<sup>-1</sup> of data. Events with high p<sub>T</sub> oppositely charged dileptons ℓ<sup>+</sup>ℓ<sup>-</sup> (ℓ = e, μ) are used to obtain cross sections for tt, W<sup>+</sup>W<sup>-</sup>, and Z<sup>0</sup> → τ<sup>+</sup>τ<sup>-</sup> production processes simultaneously. The other cross sections are given in Table IV.

<sup>8</sup> Based on 1.02 fb<sup>-1</sup> of data. Result is for m<sub>t</sub> = 175 GeV. The last error is from luminosity. Secondary vertex b tag and neural network selections are used to achieve a signal to background ratio of about 1/2.

<sup>9</sup> Based on 425 pb<sup>-1</sup> of data. Result is for m<sub>t</sub> = 175 GeV. For m<sub>t</sub> = 178.9 GeV, 7.8 ± 1.8 (stat + syst) pb is obtained.

<sup>10</sup> Based on 405 ± 25 pb<sup>-1</sup> of data. Result is for m<sub>t</sub> = 175 GeV. The last error is from luminosity. Secondary vertex b tag and neural network are used to separate the signal events from the background.

<sup>11</sup> Based on 425 pb<sup>-1</sup> of data. Assumes m<sub>t</sub> = 175 GeV. The last error is from luminosity.

<sup>12</sup> Based on ~ 425 pb<sup>-1</sup>. Assuming m<sub>t</sub> = 175 GeV. The first error is combined statistical and systematic, the second one is luminosity.

<sup>13</sup> Based on ~ 310 pb<sup>-1</sup>. Assuming m<sub>t</sub> = 178 GeV. The cross section changes by ± 0.08 pb for each ± 1 GeV change in the assumed m<sub>t</sub>. Result is for at least one b tag. For at least two b-tagged jets, tt signal of significance greater than 5σ is found, and the cross section is 30.1<sup>+1.6+2.0</sup><sub>-1.4-1.3</sub> pb for m<sub>t</sub> = 178 GeV.

<sup>14</sup> Based on ~ 311 pb<sup>-1</sup>. Assuming m<sub>t</sub> = 178 GeV. The first error is statistical and the second systematic. For m<sub>t</sub> = 175 GeV, the result is 6.0 ± 1.2<sup>+0.9</sup><sub>-0.7</sub>. This is the first CDF measurement without lepton identification, and hence it has sensitivity to the W → τν mode.

<sup>15</sup> ABULENCIA,A 06c measures the tt production cross section in the all hadronic decay mode by selecting events with 6 to 8 jets and at least one b-jet. S/B = 1/5 has been achieved. Based on 311 pb<sup>-1</sup>. Assuming m<sub>t</sub> = 178 GeV. The first error is statistical, the second is systematic, and the third one is luminosity.

<sup>16</sup> Based on ~ 318 pb<sup>-1</sup>. Assuming m<sub>t</sub> = 178 GeV. Result is for at least one b-tag. For at least two b tagged jets, the cross section is 11.1<sup>+2.3+2.5</sup><sub>-1.9-1.9</sub> pb.

<sup>17</sup> ABAZOV 85a measures the top-quark pair production cross section with ~ 250 pb<sup>-1</sup> of data, based on the analysis of W plus n-jet events where W decays into e or μ

plus neutrino, and at least one of the jets is b-jet like. The first error is statistical and systematic, and the second accounts for the luminosity uncertainty. The result assumes m<sub>t</sub> = 175 GeV; the mean value changes by [(175 - m<sub>t</sub>)(GeV)] × 0.06 pb in the mass range 160 to 190 GeV.

<sup>18</sup> ABAZOV 05a measures the top quark pair production cross section with 224-243 pb<sup>-1</sup> of data, based on the analysis of events with two charged leptons in the final state. The first error is statistical, the second one is systematic, and the last one gives the luminosity uncertainty. The result assumes m<sub>t</sub> = 175 GeV; the mean value changes by [(175 - m<sub>t</sub>)(GeV)] × 0.06 pb in the mass range 160 to 190 GeV.

<sup>19</sup> Based on 230 pb<sup>-1</sup>. Assuming m<sub>t</sub> = 175 GeV. The last error accounts for the luminosity uncertainty.

<sup>20</sup> Based on 104 pb<sup>-1</sup>. Assuming m<sub>t</sub> = 175 GeV.

<sup>21</sup> Based on 134 ± 11 pb<sup>-1</sup>. Assuming m<sub>t</sub> = 175 GeV.

<sup>22</sup> Based on 152 ± 10 pb<sup>-1</sup>. Assuming m<sub>t</sub> = 175 GeV.

<sup>23</sup> ACOSTA 05v measures the top-quark pair production cross section with ~ 162 pb<sup>-1</sup> of data, based on the analysis of W plus n-jet events where W decays into e or μ plus neutrino, and at least one of the jets is b-jet like. Assumes m<sub>t</sub> = 175 GeV. The first error is statistical and the latter is systematic, which include the luminosity uncertainty.

<sup>24</sup> ACOSTA 04c measures the top-quark pair production cross section with 197 ± 12 pb<sup>-1</sup> of data, based on the analysis of events with two charged leptons in the final state. Assumes m<sub>t</sub> = 175 GeV. The first error is statistical, the second one is systematic, and the last one gives the luminosity uncertainty.

### gg → tt fraction in pp collisions at √s = 1.96 TeV

VALUE (%)	CLS.	DOCUMENT ID	TECH.	COMMENT
0.07 ± 0.14 ± 0.07		<sup>1</sup> AALTONEN	08aa	CDF low p <sub>T</sub> number of tracks
< 0.33	60	<sup>2</sup> AALTONEN	09f	CDF tt correlations

<sup>1</sup> Result is based on 0.95 fb<sup>-1</sup> of data. The contribution of the subprocesses gg → tt and qq → tt is distinguished by using the difference between quark and gluon initiated jets in the number of small p<sub>T</sub> (0.3 GeV < p<sub>T</sub> < 3 GeV) charged particles in the central region (|η| < 1.1).

<sup>2</sup> Based on 955 pb<sup>-1</sup>. AALTONEN 09f used differences in the tt production angular distribution and polarization correlation to discriminate between gg → tt and qq → tt subprocesses. The combination with the result of AALTONEN 08aa gives 0.07<sup>+0.15</sup><sub>-0.07</sub>.

### A<sub>FB</sub> of tt in pp collisions at √s = 1.96 TeV

• • • We do not use the following data for averages, fits, limits, etc. • • •

17 ± 0	<sup>1</sup> AALTONEN	08aa	CDF	pp frame
24 ± 14	<sup>1</sup> AALTONEN	08aa	CDF	tt frame
12 ± 0 ± 1	<sup>2</sup> ABAZOV	08c	DO	t + E <sub>T</sub> + ≥ 4 jets

<sup>1</sup> Result is based on 1.9 fb<sup>-1</sup> of data. The FB asymmetry in the tt events has been measured in the t + jets mode, where the lepton charge is used as the flavor tag. The asymmetry in the pp frame is defined in terms of cos(θ) of hadronically decaying t-quark momentum, whereas that in the tt frame is defined in terms of the t and t rapidity difference. The results are consistent (≤ 2σ) with the SM predictions.

<sup>2</sup> Result is based on 0.9 fb<sup>-1</sup> of data. The asymmetry in the number of tt events with y<sub>2</sub> > y<sub>1</sub> and those with y<sub>2</sub> < y<sub>1</sub> has been measured in the lepton + jets final state. The observed value is consistent with the SM prediction of 0.8% by MC@NLO, and an upper bound on the Z' → tt contribution for the SM Z'-like couplings is given in Fig. 2 for 350 GeV < m<sub>Z'</sub> < 1 TeV.

### t-Quark Electric Charge

• • • We do not use the following data for averages, fits, limits, etc. • • •

17 ± 0	<sup>1</sup> ABAZOV	07c	DO	fraction of  q  = 4e/3 pair
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<sup>1</sup> ABAZOV 07c reports an upper limit q < 0.80 (90% CL) on the fraction μ of exotic quark pairs Q<sub>μ</sub>Q<sub>μ</sub> with electric charge |q<sub>μ</sub>| = 4e/3 in tt candidate events with high p<sub>T</sub> leptons, missing E<sub>T</sub> and ≥ 4 jets. The result is obtained by measuring the fraction of events in which the quark pair decays into W → b and W' → b, where b and b jets are discriminated by using the charge and momenta of tracks within the jet cones. The maximum CL at which the model of CHIANG 99 can be excluded is 92%. Based on 370 pb<sup>-1</sup> of data at √s = 1.96 TeV.

### t-Quark REFERENCES

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AALTONEN	09AD	PR 075 112807	T. Aaltonen et al.	(CDF Collab.)
AALTONEN	09AK	PR 080 051104R	T. Aaltonen et al.	(CDF Collab.)
AALTONEN	09AL	PR 080 053030	T. Aaltonen et al.	(CDF Collab.)
AALTONEN	09AT	PR 083 070303	T. Aaltonen et al.	(CDF Collab.)
AALTONEN	09B	PR 075 021105	T. Aaltonen et al.	(CDF Collab.)
AALTONEN	09C	PR 075 022007	T. Aaltonen et al.	(CDF Collab.)
AALTONEN	09J	PR 075 072301	T. Aaltonen et al.	(CDF Collab.)
AALTONEN	09K	PR 075 072310	T. Aaltonen et al.	(CDF Collab.)
AALTONEN	09L	PR 075 072305	T. Aaltonen et al.	(CDF Collab.)
AALTONEN	09M	PR 082 042301	T. Aaltonen et al.	(CDF Collab.)
AALTONEN	09N	PR 082 151801	T. Aaltonen et al.	(CDF Collab.)
AALTONEN	09O	PR 082 152001	T. Aaltonen et al.	(CDF Collab.)
AALTONEN	09Q	PL 0674 103	T. Aaltonen et al.	(CDF Collab.)
AALTONEN	09R	PR 075 072305	T. Aaltonen et al.	(CDF Collab.)
AARON	05a	PL 0670 403	F.E. Aarøe et al.	(H1 Collab.)
ABAZOV	08Aa	PR 083 122001	V.M. Abazov et al.	(DO Collab.)
ABAZOV	08Ab	PR 080 071328R	V.M. Abazov et al.	(DO Collab.)
ABAZOV	08Ac	PR 080 05230a	V.M. Abazov et al.	(DO Collab.)
ABAZOV	08Ad	PR 083 070303	V.M. Abazov et al.	(DO Collab.)

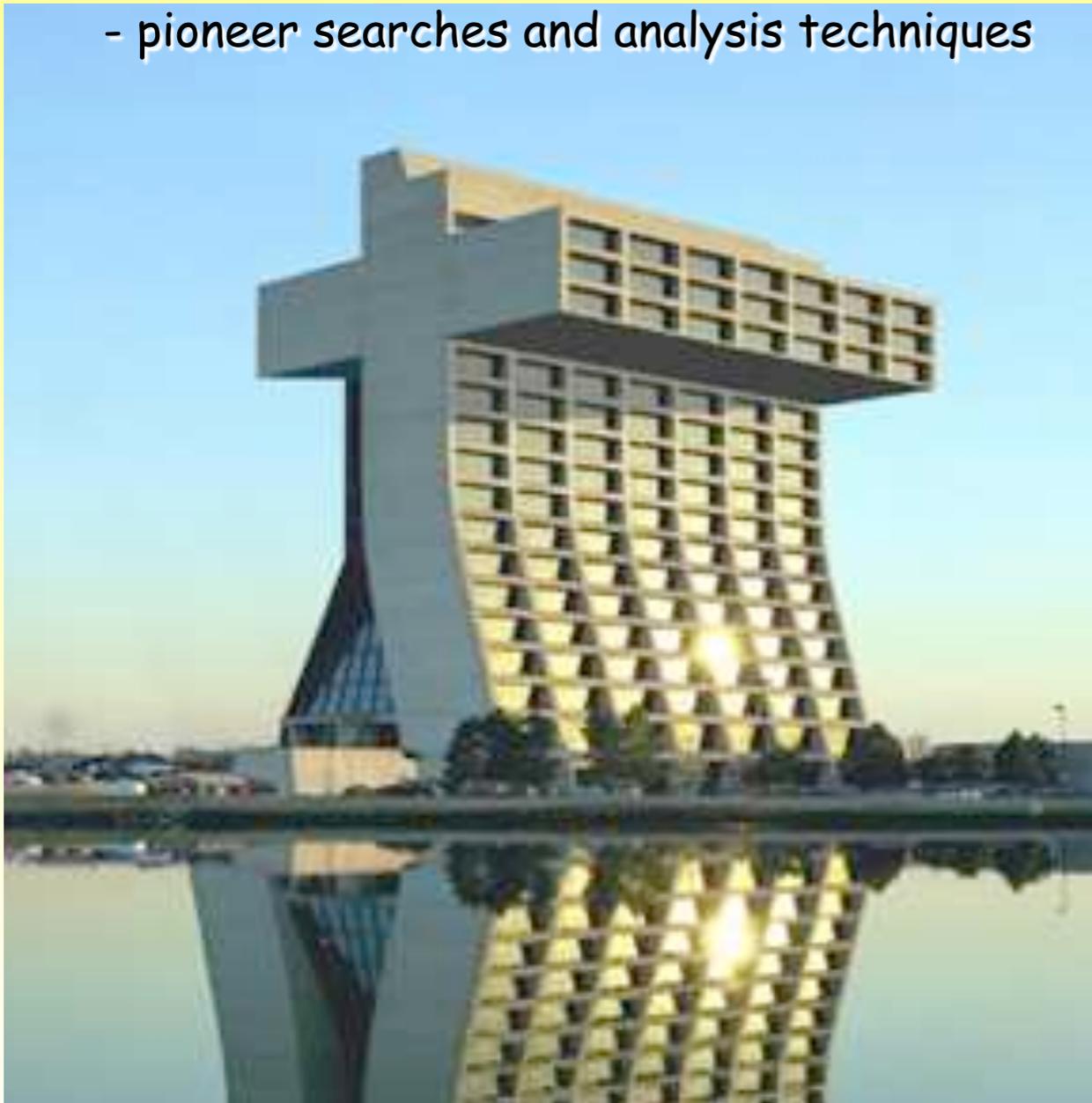
# Summary of the Tevatron Top Quark Measurements

Property	Measurement	SM Prediction	Luminosity (fb <sup>-1</sup> )
$\sigma_{t\bar{t}}$ (for $M_t = 172.5$ GeV)	CDF: $7.5 \pm 0.31(\text{stat}) \pm 0.34(\text{syst}) \pm 0.15(\text{theory})$ pb D0: $7.56^{+0.63}_{-0.56}$ (stat + syst + lumi) pb	$7.46^{+0.48}_{-0.67}$ pb	up to 4.6 5.6
$\sigma_{tbq}$ (for $M_t = 172.5$ GeV)	CDF: $0.8 \pm 0.4$ pb ( $M_t = 175$ GeV) D0: $2.90 \pm 0.59$ pb	$2.26 \pm 0.12$ pb	3.2 5.4
$\sigma_{tb}$ (for $M_t = 172.5$ GeV)	CDF: $1.8^{+0.7}_{-0.5}$ pb ( $M_t = 175$ GeV) D0: $0.68^{+0.38}_{-0.35}$ pb	$1.04 \pm 0.04$ pb	3.2 5.4
Charge asymmetry	CDF: $0.158 \pm 0.074$ D0: $0.196 \pm 0.065$	0.06	5.3 5.4
spin correlation	CDF: $0.72 \pm 0.64(\text{stat}) \pm 0.26(\text{syst})$ D0: $0.66 \pm 0.23(\text{stat} + \text{syst})$	$0.777^{+0.027}_{-0.042}$	5.3 5.4
$M_t$	Tev: $173.2 \pm 0.9$ GeV	-	up to 5.8
$\sigma_{t\bar{t}\gamma}$	CDF: $0.18 \pm 0.08$ pb	$0.17 \pm 0.03$ pb	6.0
$ V_{tb} $	CDF: $ V_{tb}  = 0.91 \pm 0.11(\text{stat} + \text{syst}) \pm 0.07(\text{theory})$ D0: $ V_{tb}  = 1.02^{+0.10}_{-0.11}$	1	3.2 5.4
$R = B(t \rightarrow Wb)/B(t \rightarrow Wq)$	CDF: $> 0.61$ @ 95% CL D0: $0.90 \pm 0.04$	1	0.2 5.4
$\sigma(gg \rightarrow t\bar{t})/\sigma(p\bar{p} \rightarrow t\bar{t})$	CDF: $0.07^{+0.15}_{-0.07}$	0.18	1
$M_t - M_{\bar{t}}$	CDF: $-3.3 \pm 1.4(\text{stat}) \pm 1.0(\text{syst})$ GeV D0: $0.8 \pm 1.8(\text{stat}) \pm 0.5(\text{syst})$ GeV	0	5.6 3.6
W helicity fraction	Tev: $f_0 = 0.732 \pm 0.063(\text{stat}) \pm 0.052(\text{syst})$	0.7	up to 5.4
Charge	CDF: -4/3 excluded @ 95% CL D0: 4/3 excluded @ 92% CL	2/3	5.6 0.37
$\Gamma_t$	CDF: $< 7.6$ GeV @ 95% CL D0: $1.99^{+0.69}_{-0.55}$ GeV	1.26 GeV	4.3 up to 2.3

Both the searches and the precise measurements of its properties tell us that currently the top quark is the Standard Model particle (asymmetry?)

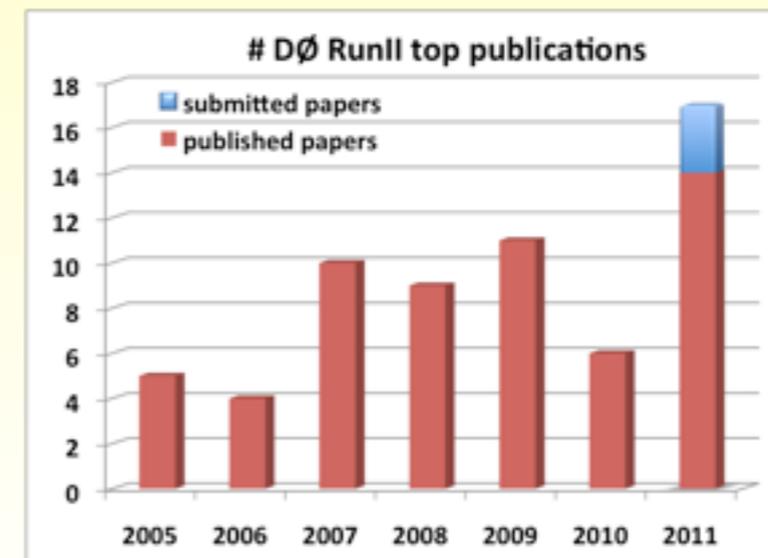
# Summary

- almost all what we know today about the top quark comes from the Tevatron
  - measurements in all possible final states
  - precise measurements of numerous top properties
  - pioneer searches and analysis techniques



thanks to P. Grannis, C. Schwanenberger, Y. Peters

- LHC is already producing very precise top measurements
  - much larger top cross sections
  - higher reach for searches
- $10 \text{ fb}^{-1}$  of  $p\bar{p}$  colliding data from Tevatron will remain unique
  - 1.96 TeV, mainly  $q\bar{q} \rightarrow t\bar{t}$
  - focus on complementary measurements to LHC



# Back-up

# Top Pair Cross Sections at 7 TeV

- LHC is also measuring the  $t\bar{t}$  cross section:
  - ljets: most precise channel, measurements with or without b-tagging
  - measurements several different channels

