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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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  - commissioning of the Tevatron
  - first collisions at CDF in 1985
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- **towards Run I**
  - 1987: Run 0 of CDF (0.4 pb^{-1})
  - 1992-1996: Run I for CDF and D0 (1.8 TeV, 120 pb^{-1})

1985

- **the top quark before 1995**
  - existence needed after the discovery of the b-quark in 1976 at Fermilab
  - direct searches:
    1984: Petra (e^+e^-): Mt > 23.3 GeV
    80s: Tristan (e^+e^-): Mt > 30.3 GeV
    1988: UA1 ($p\bar{p}$): Mt > 44 GeV
    ~ 1990: LEP (e^+e^-): Mt > 45.8 GeV
    1990: UA2 ($p\bar{p}$): Mt > 69 GeV
    1992: CDF ($p\bar{p}$): Mt > 91 GeV
    1994: D0 ($p\bar{p}$): Mt > 131 GeV

+ indirect constraints from the electroweak fit

The Discovery

VOLUME 74, NUMBER 14 PHYSICAL REVIEW LETTERS 3 APRIL 1995

Observation of the Top Quark

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

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 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 ± 0.6 events. The probability for an upward fluctuation of the background to produce the observed signal is 2×10^{-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) ±22 (syst) GeV/c^2 and its production cross section to be 6.4 ± 2.2 pb.

VOLUME 74, NUMBER 14 PHYSICAL REVIEW LETTERS 3 APRIL 1995

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

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

We establish the existence of the top quark using a 67 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 $WWb\bar{b}$, but inconsistent with the background prediction by 4.8σ. 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 ± 8(stat) ± 10(syst) GeV/c^2, and the $t\bar{t}$ production cross section to be $6.8^{+3.6}_{-2.4}$ pb.

submitted to PRL on Feb 24th, 1995

- D0: 50 pb^{-1}, 4.6 σ

  M_t = 199 ± 30 GeV

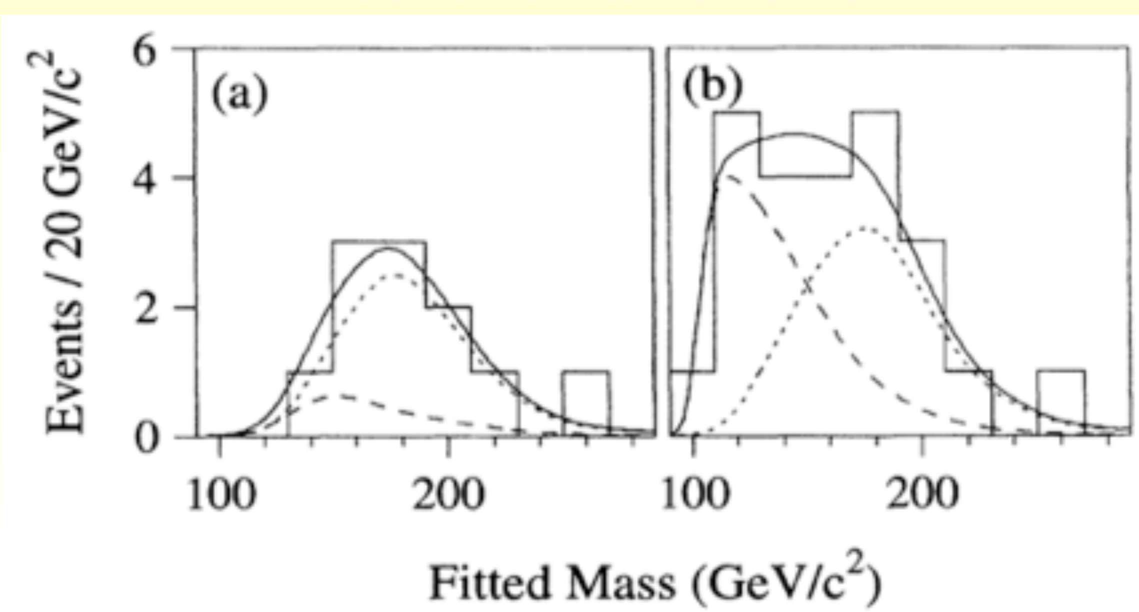
  σ_{ttbar} = 6.4 ± 2.2 pb

- CDF: 67 pb^{-1}, 4.8 σ

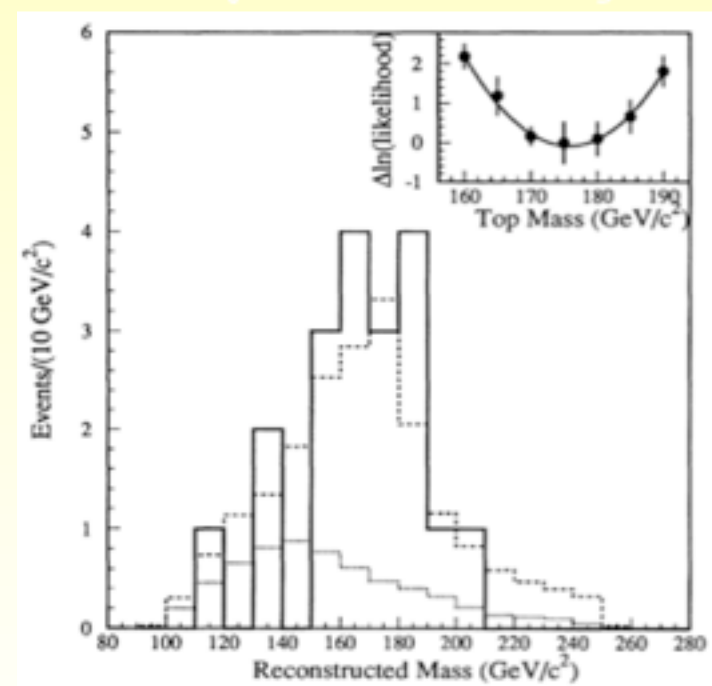
  M_t = 176 ± 13 GeV

  σ_{ttbar} = $6.8^{+3.6}_{-2.4}$ pb

standard and loose selections



W + ≥4 jets events with b-tag



Top Discovery Seminar at Fermilab

- March 2nd, 1995

some of the D0 phD students in 1995

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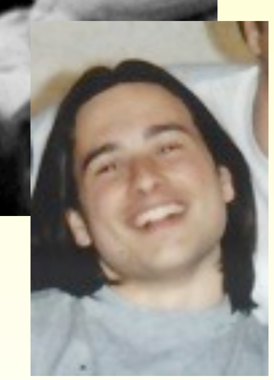


1995

PDG on the Top Quark After the Discovery

PRD 54, 1 (1996)

t-Quark Mass in $p\overline{p}$ Collisions

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 $t \to bH^+$ are available, except as noted in the comments.

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

And the Story Continues

2001

- Run II begins in 2001
  - 1.96 TeV
  - 2005: 230 pb^{-1}

  $t\bar{t}$ cross section measurements in the ljets channel (Mt = 175 GeV):

  without b-tagging:

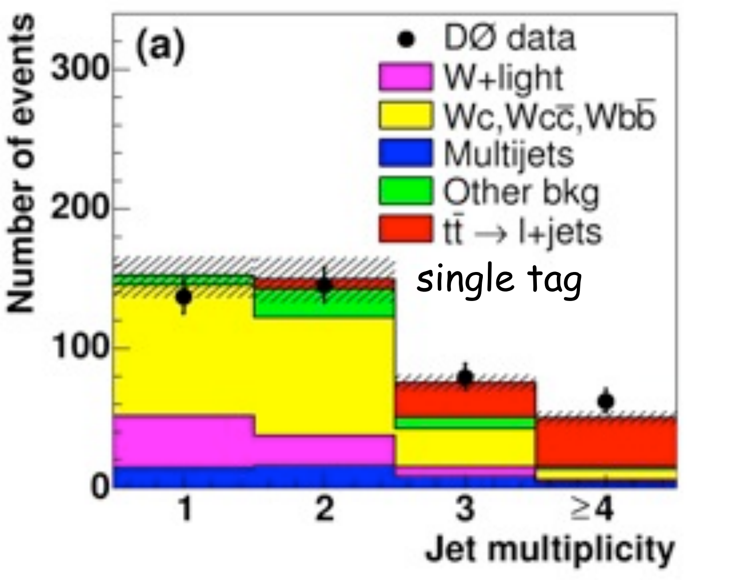
  $$\sigma_{t\bar{t}} = 6.7^{+1.4}_{-1.3}\,(\text{stat})\,^{+1.6}_{-1.1}\,(\text{syst}) \pm 0.4\,(\text{lumi})\,\text{pb}.$$

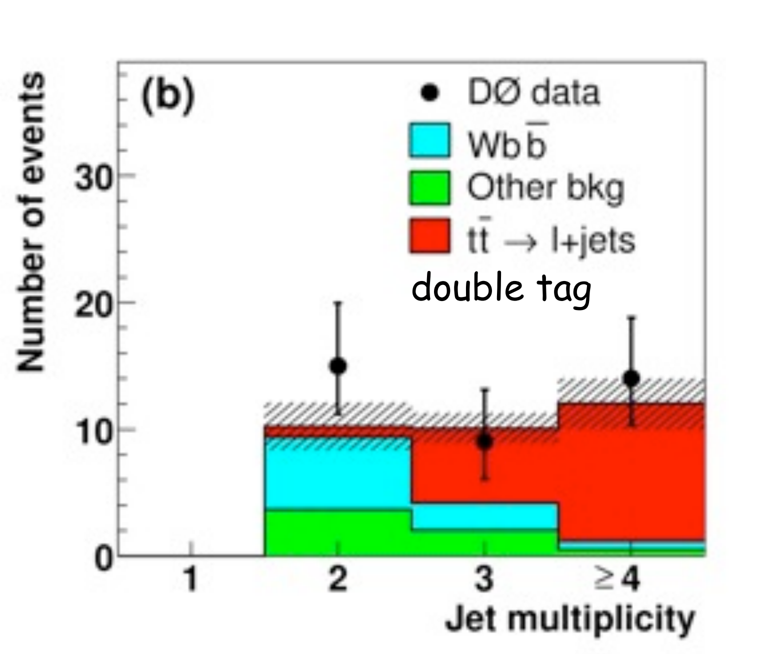
  with b-tagging:

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

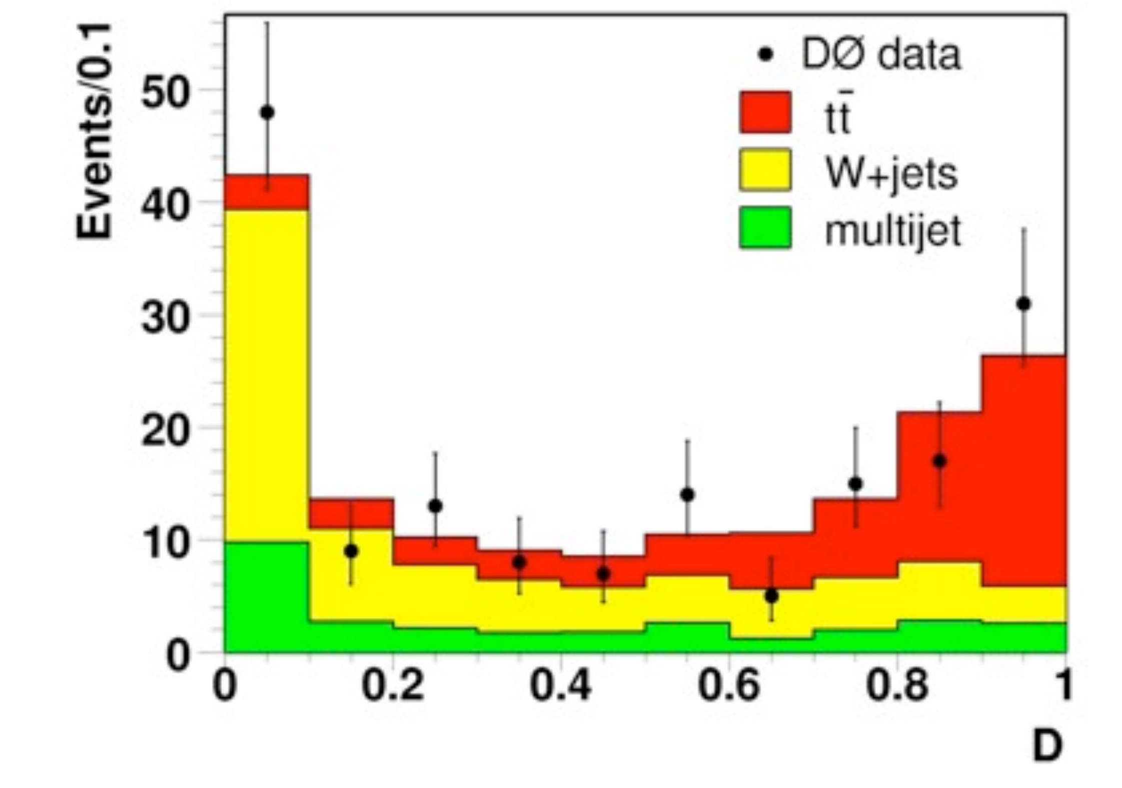
  ~ 20 %

PLB 626, 35 (2005)



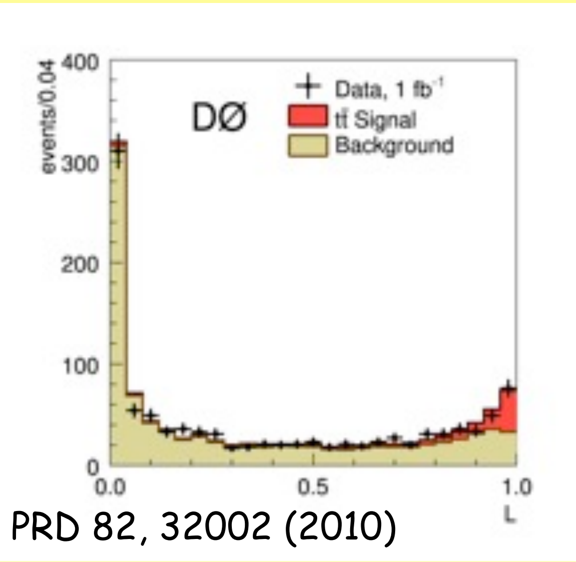


PLB 626, 45 (2005)

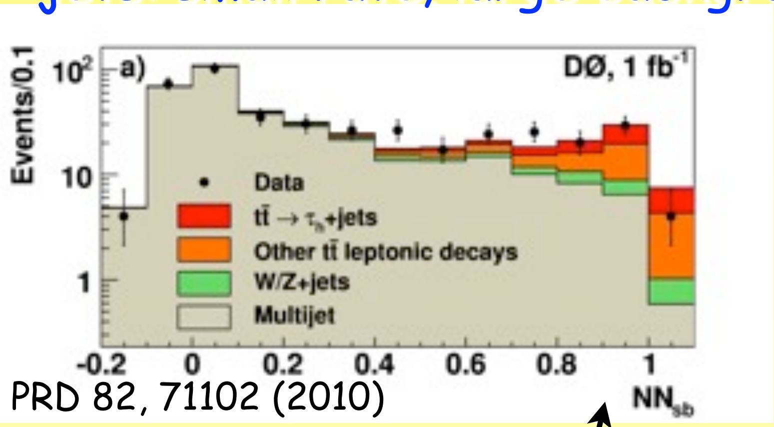


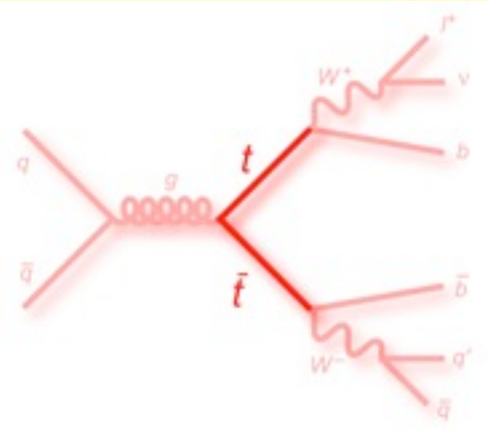
Measurements in All Possible Channels

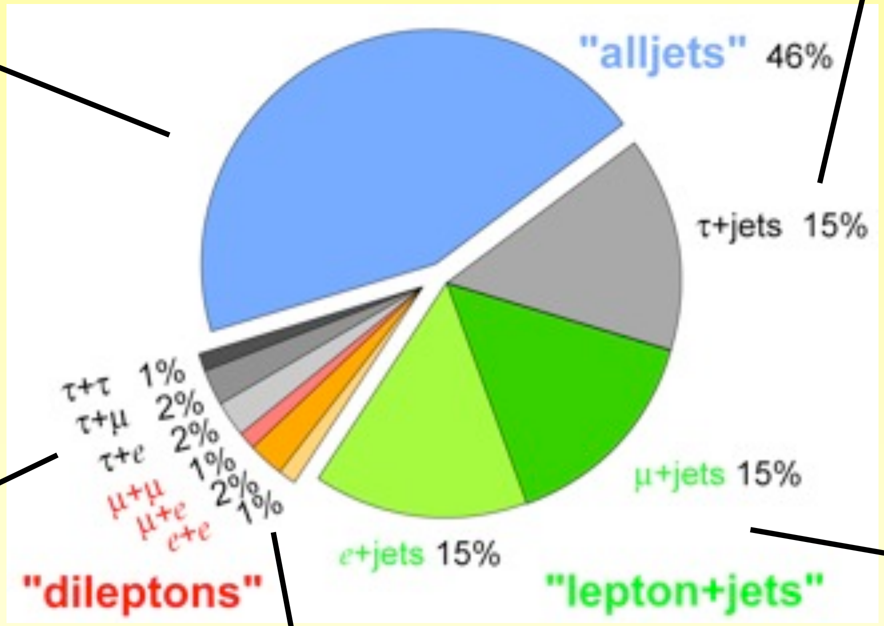
alljets:
large rate, large background



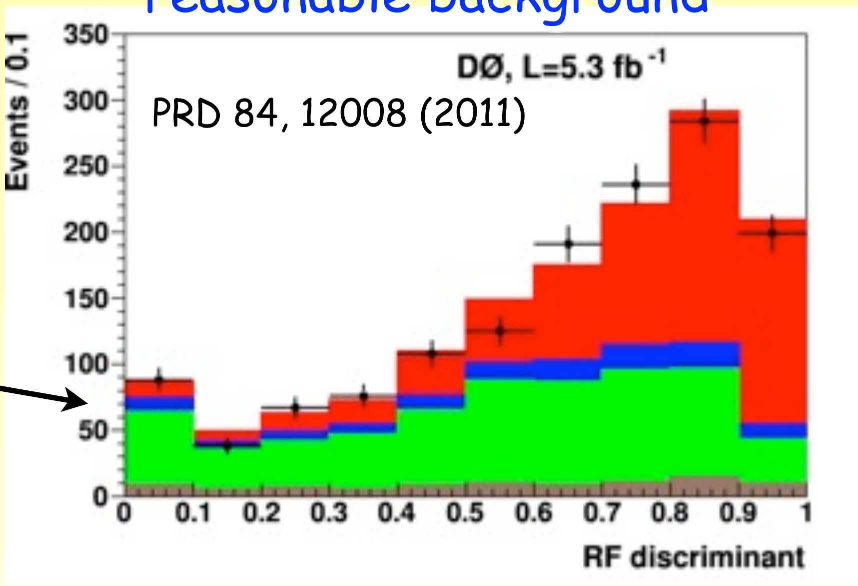
τ +jets: small rate, large background





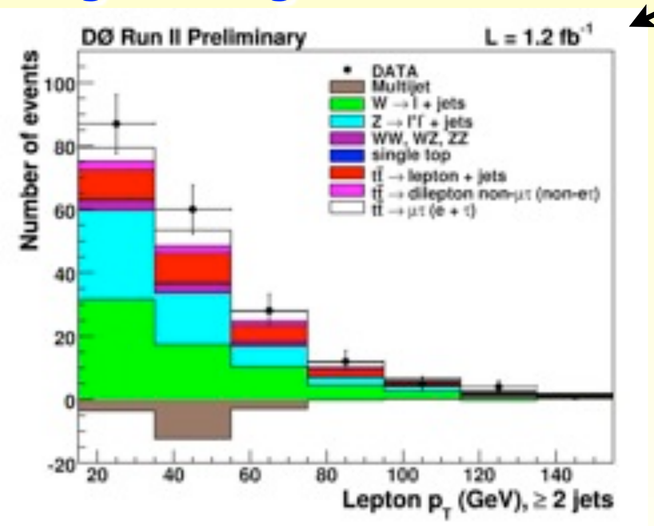


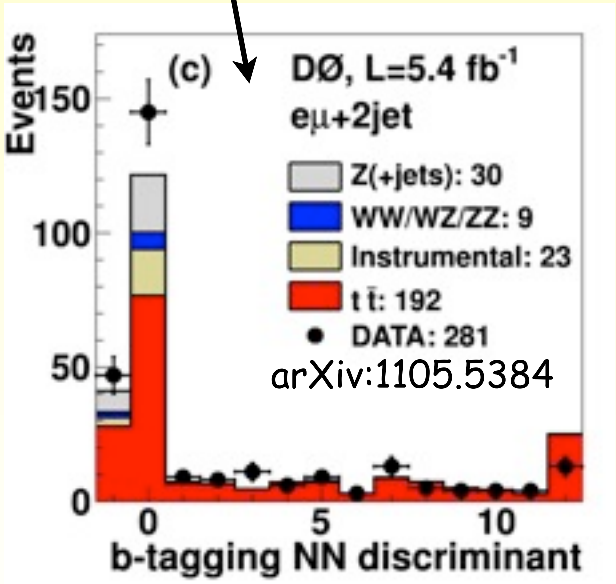
l+jets: good rate,
reasonable background



lepton+ τ +jets: small rate,

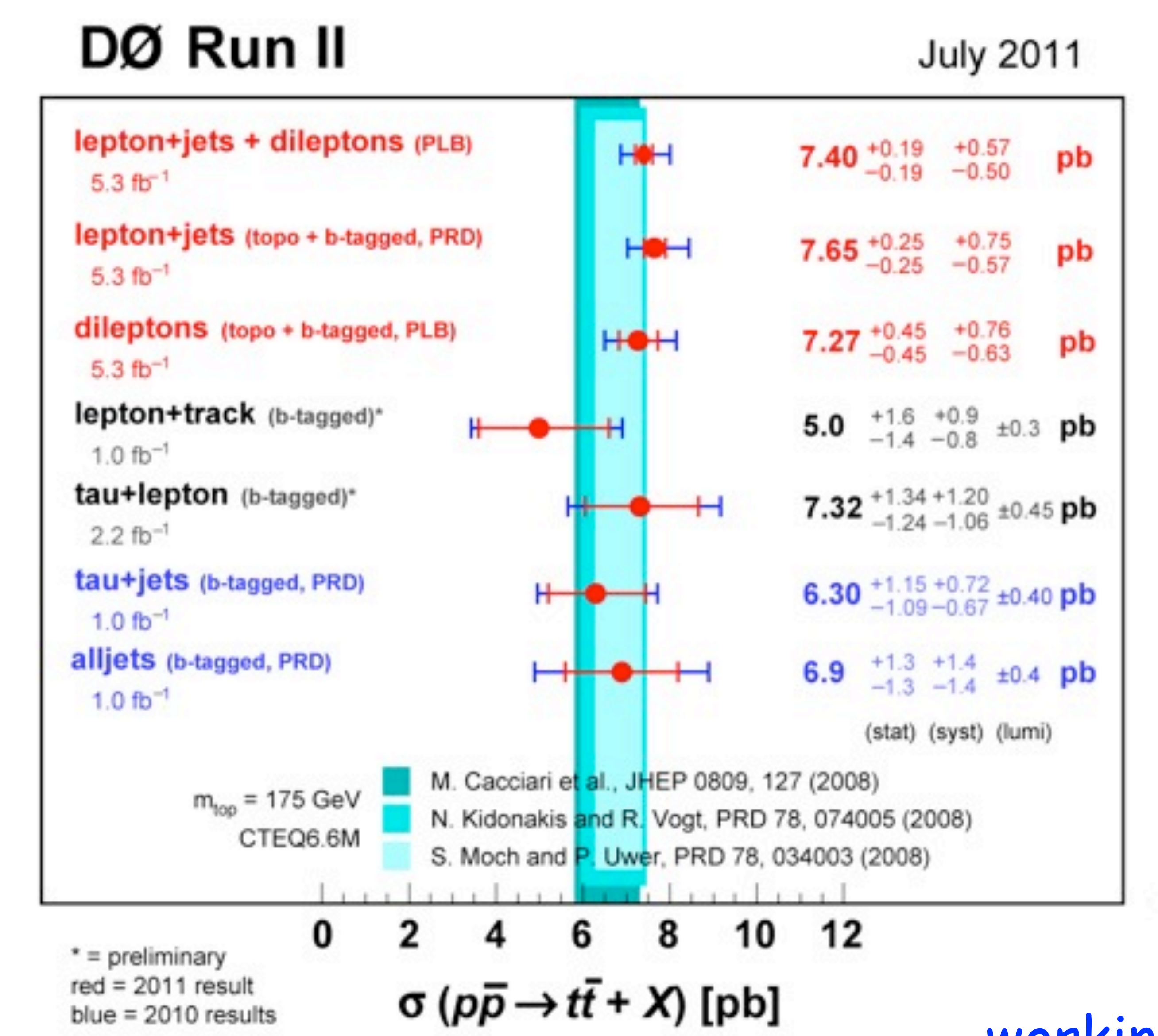
large background

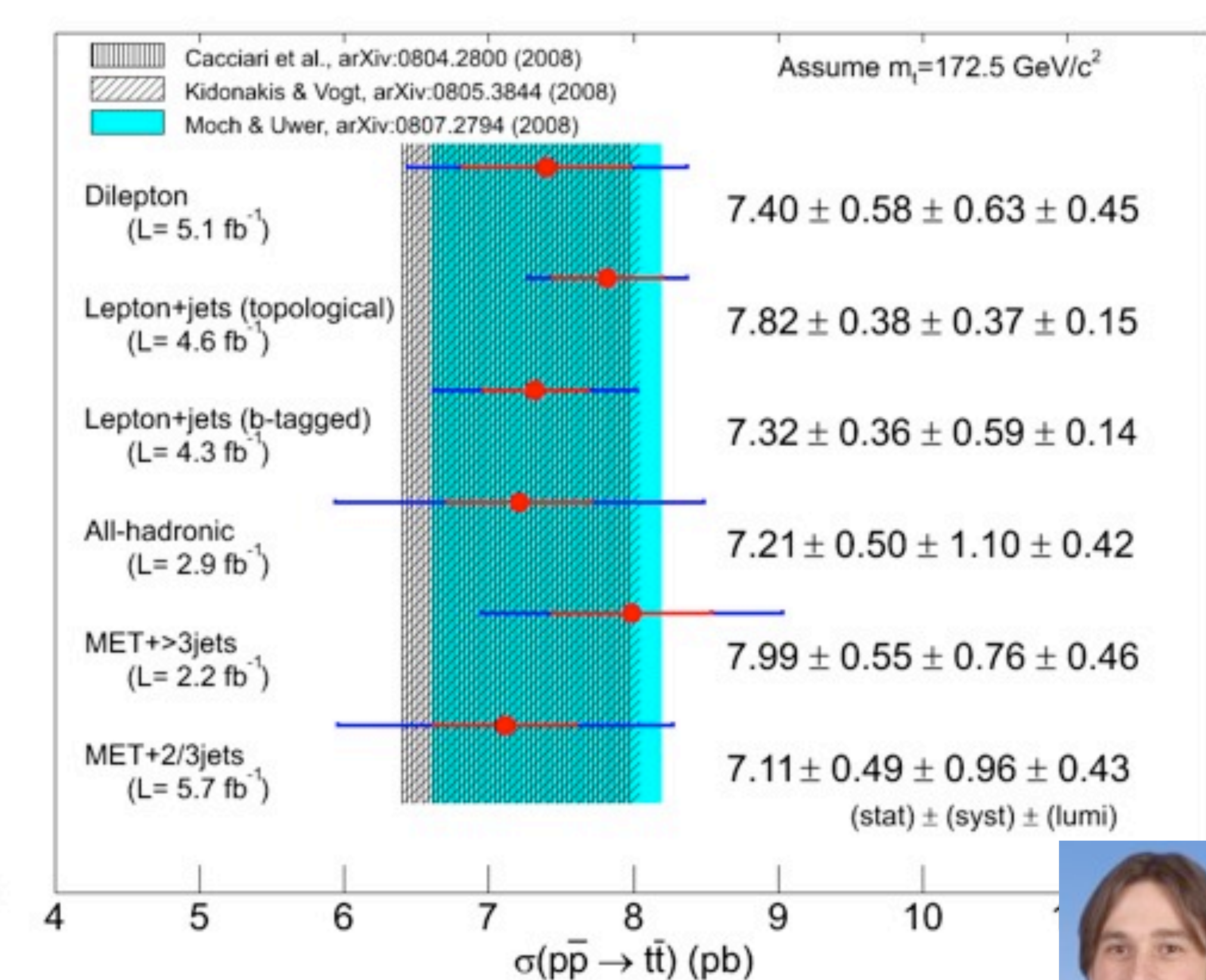




dilepton: small rate,
small background

Top Pair Cross Sections at 1.96 TeV





working on the CDF-D0 combination

2009

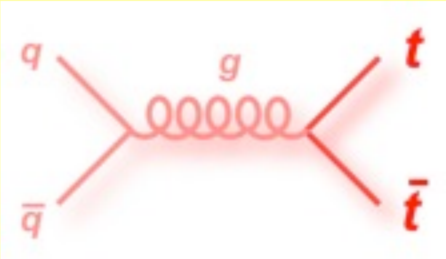
- in addition to the cross section
  - cross section ratios (limit on $t \to H^+ b$)
  - fit the cross section together with R to extract V_{tb}:

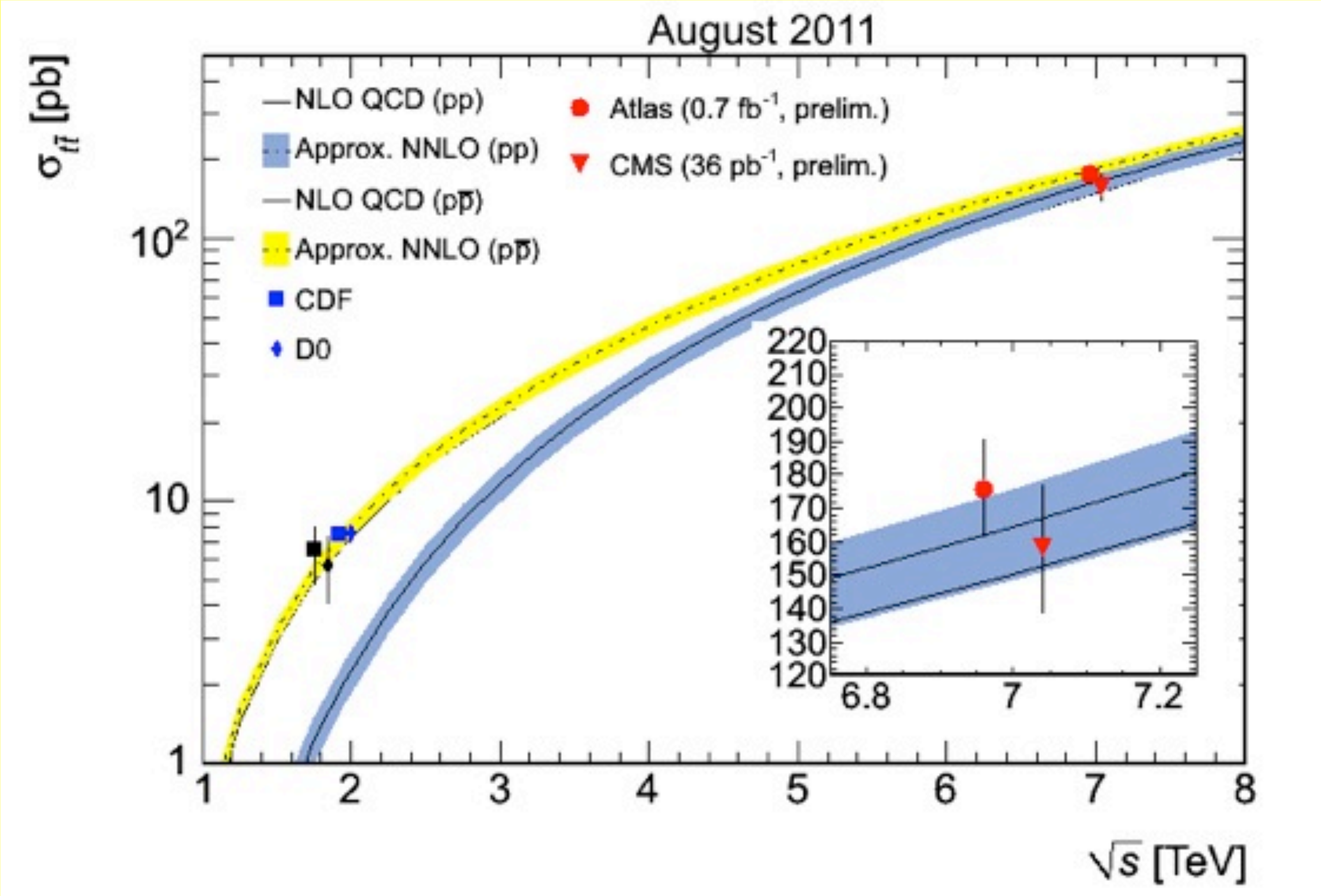
$$R = \frac{\mathcal{B}(t \to Wb)}{\mathcal{B}(t \to Wq)} = \frac{|V_{tb}|^2}{|V_{tb}|^2 + |V_{ts}|^2 + |V_{td}|^2}$$

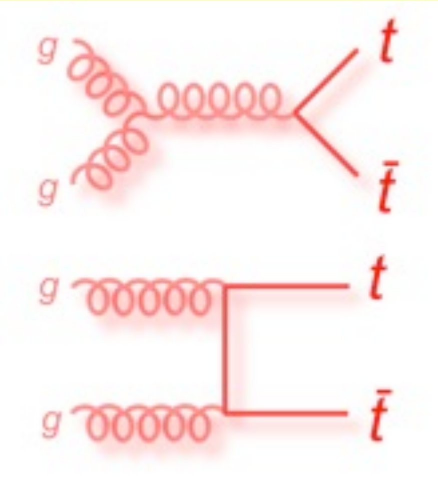
$|V_{tb}| = 0.95 \pm 0.02$ assuming CKM unitarity

arXiv:1106.5436

$t\bar{t}$ Cross Section Summary







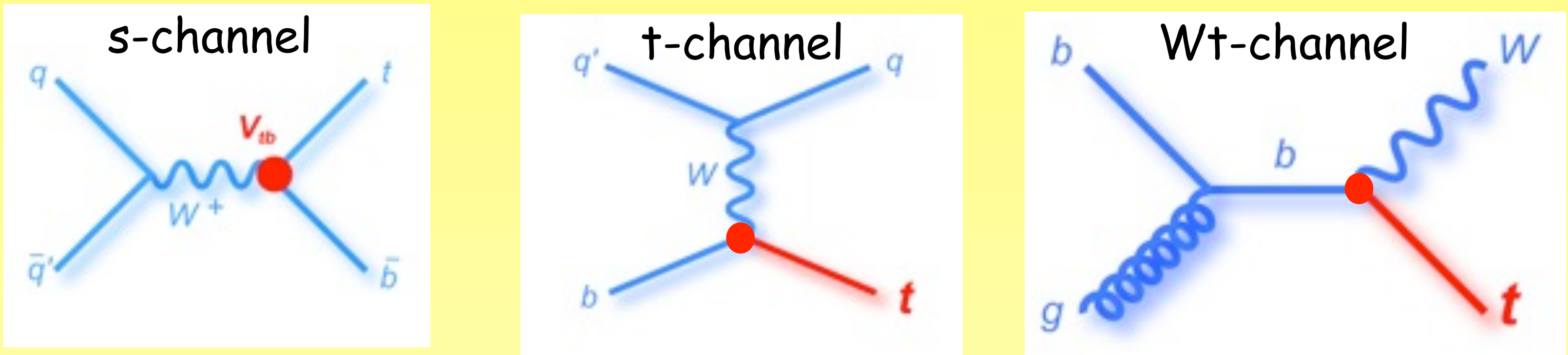
decay channel combined for $m_t = 172.5$ GeV:		systematically limited	
CDF (up to 4.6 fb^{-1})	$\sigma(p\bar{p} \to t\bar{t}) =$	$7.5 \pm 0.31(\text{stat}) \pm 0.34(\text{syst}) \pm 0.15(\text{theory})$ pb	~ 6.5 %
D0 (5.6 fb^{-1}, arXiv:1105.5384)	$\sigma(p\bar{p} \to t\bar{t}) =$	$7.56^{+0.63}_{-0.56}$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

Measurements agree with the QCD predictions

Future measurements will focus on differential cross sections

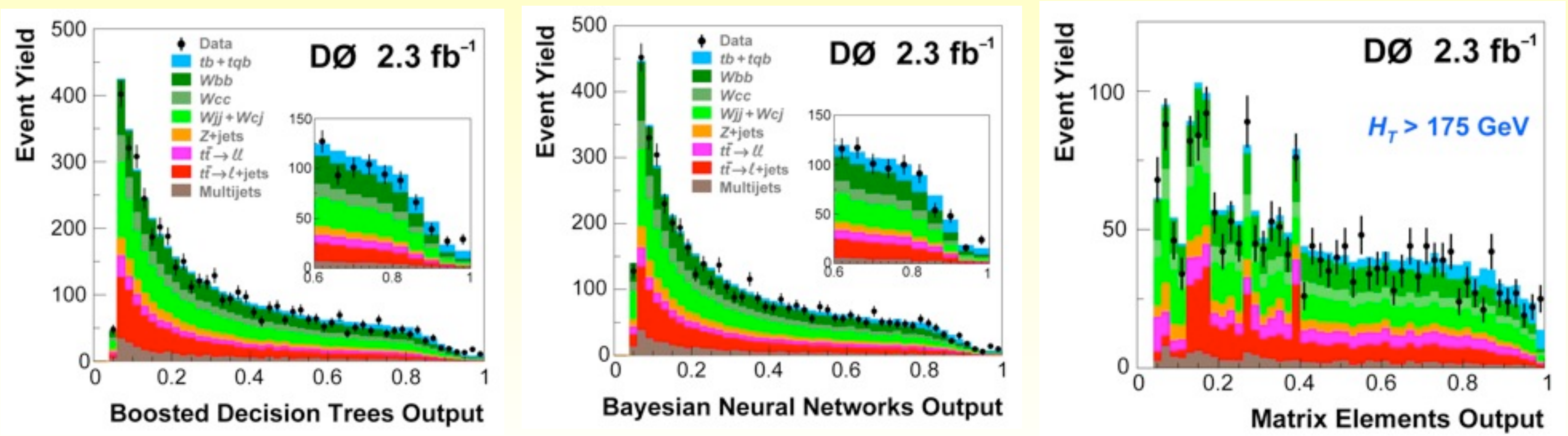
Only Tevatron can measure them at 1.96 TeV

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 10th, 2009: Fermilab seminar announcing the single top discovery

PRL **103**, 092001 (2009) PHYSICAL REVIEW LETTERS week ending 28 AUGUST 2009

Observation of Single Top-Quark Production

V. M. Abazov,[36] B. Abbott,[74] M. Abolins,[64] B. S. Acharya,[29] M. Adams,[50] T. Adams,[48] E. Aguilo,[6] M. Ahsan,[58]

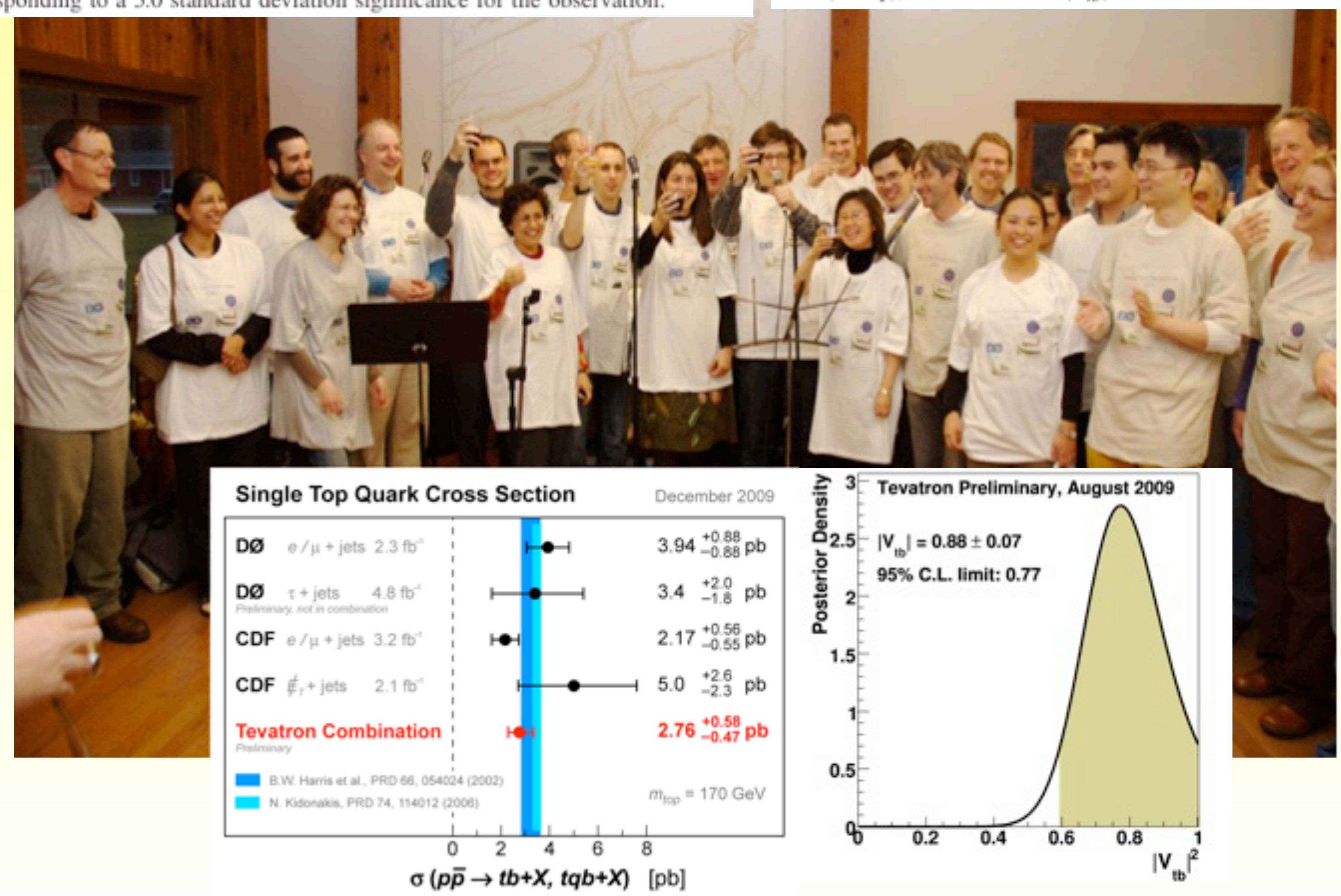
We report observation of the electroweak production of single top quarks in $p\bar{p}$ collisions at $\sqrt{s} = 1.96$ TeV based on 2.3 fb^{-1} of data collected by the D0 detector at the Fermilab Tevatron Collider. Using events containing an isolated electron or muon and missing transverse energy, together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

PRL **103**, 092002 (2009) PHYSICAL REVIEW LETTERS week ending 28 AUGUST 2009

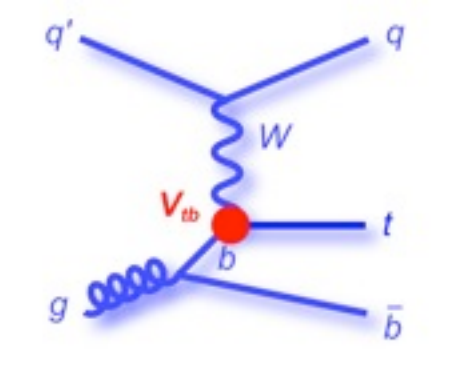
Observation of Electroweak Single Top-Quark Production

T. Aaltonen,[24] J. Adelman,[14] T. Akimoto,[56] B. Álvarez González,[12,t] S. Amerio,[44b,44a] D. Amidei,[35] A. Anastassov,[39]

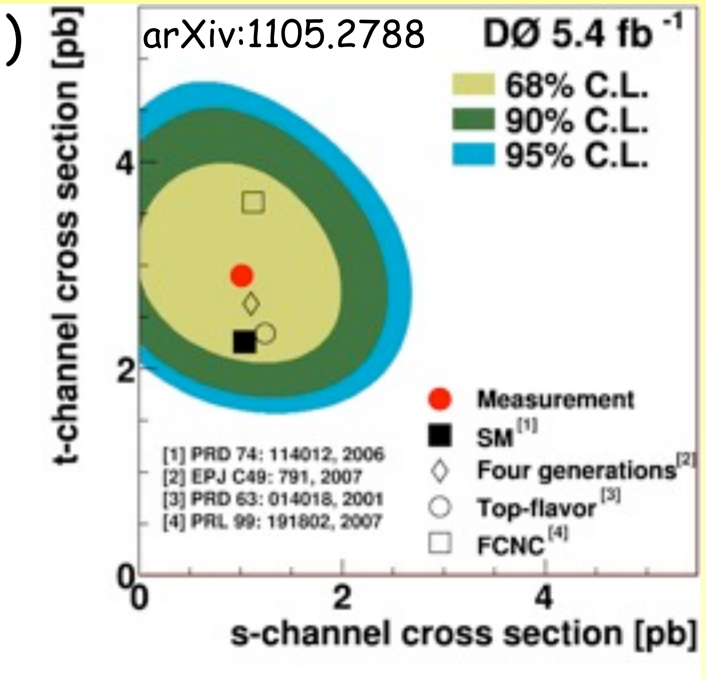
We report the observation of single top-quark production using 3.2 fb^{-1} of $p\bar{p}$ collision data with $\sqrt{s} = 1.96$ TeV collected by the Collider Detector at Fermilab. The significance of the observed data is 5.0 standard deviations, and the expected sensitivity for standard model production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



t-Channel Single Top Cross Section



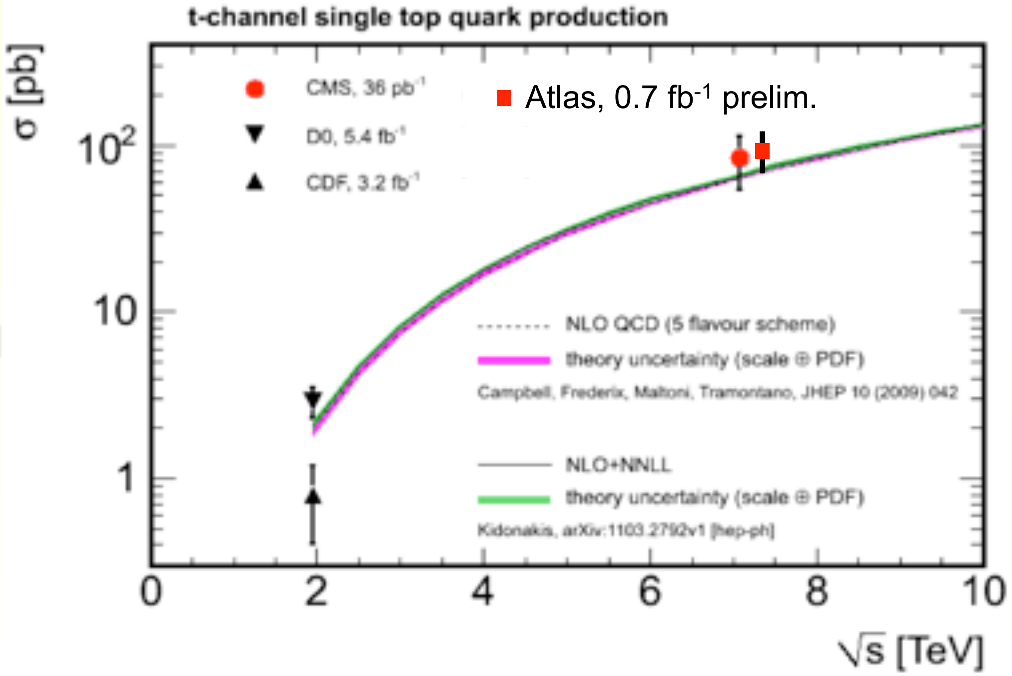
- a step further: discriminate between the single top channels:
  - new physics can affect the single top channels differently
  - signal: t-channel, background (other single top, W+jets, $t\bar{t}$):
    * Tevatron: multivariate (Neural Networks, Boosted Decision Trees, ...)
    * LHC: cut-based or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



*combination of 3 multivariate discriminants

σ_{tqb} (pb) for $m_t = 172.5$ GeV:		
CDF (3.2 fb^{-1})	0.8 ± 0.4	
D0 (5.4 fb^{-1}, arXiv:1105.2788)	2.90 ± 0.59	5.5σ
CMS (36 pb^{-1}, arXiv:1106.3052)	$83.6 \pm 29.8(stat + syst) \pm 3.3(lumi)$	3.7σ
Atlas (0.7 fb^{-1})	90^{+32}_{-22}	7.6σ

Observation of the t-channel single top in 2011

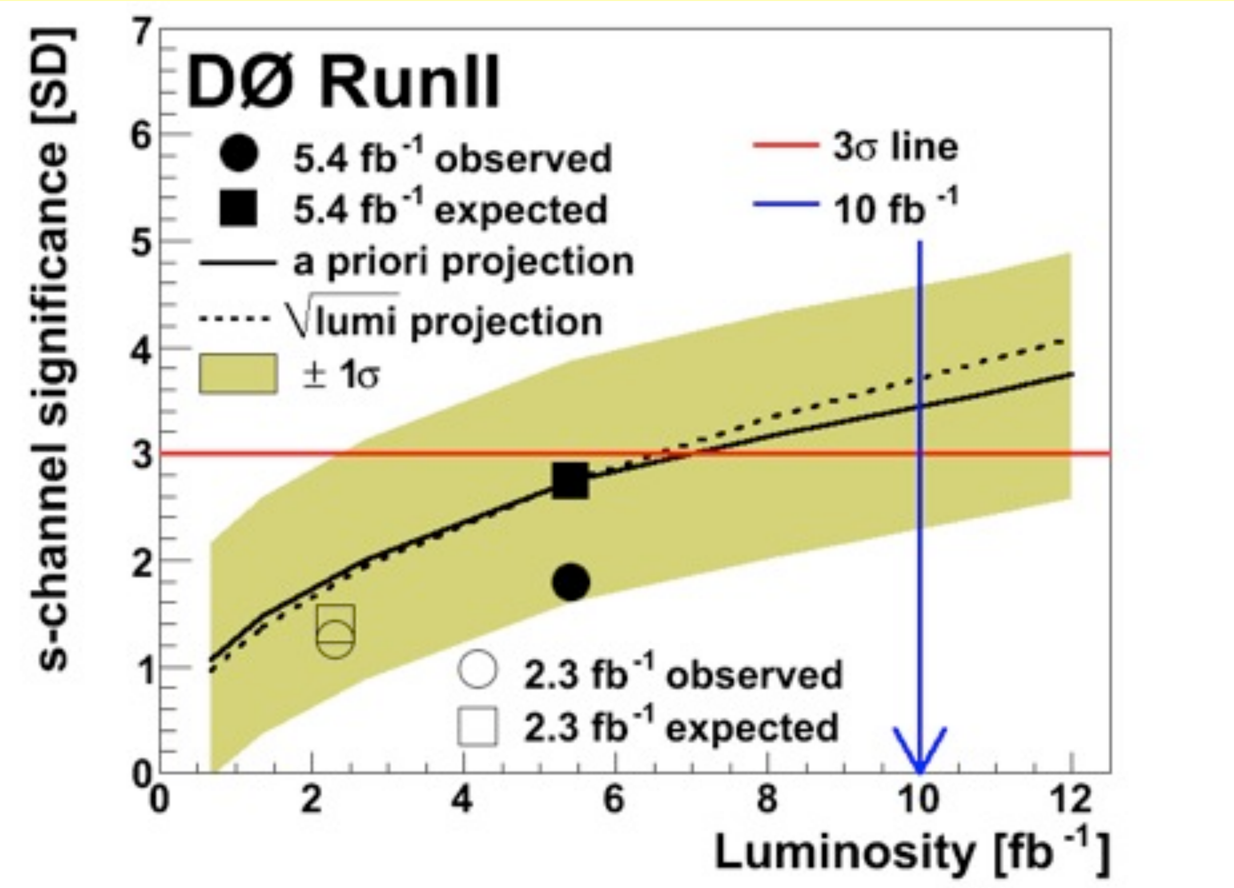


Single Top Perspectives at the Tevatron

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

- s-channel
  - challenging at LHC
  - legacy measurement of the Tevatron

  latest D0 measurement
  (5.4 fb-1, arXiv:1105.2788):
  expected sensitivity close to 3 σ



with 10 fb^{-1}, should get evidence
maybe observation when combination with CDF ?

Top Quark Mass

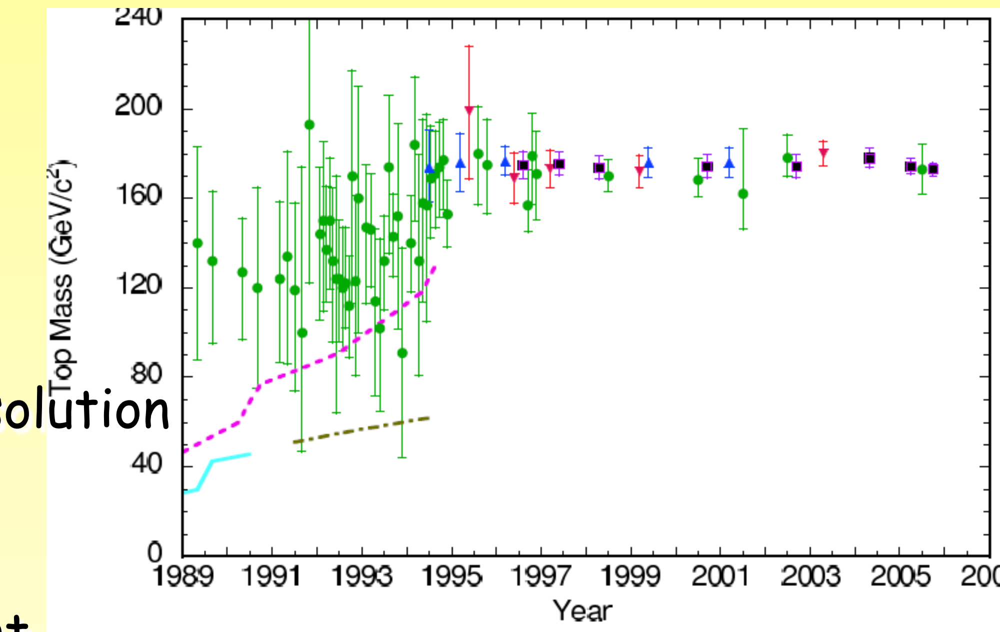
- the top quark is the only natural quark:
  - coupling to the Higgs boson close to 1:
    special role in the electroweak symmetry breaking ?

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

$$\lambda_t \approx 1 \;!!$$

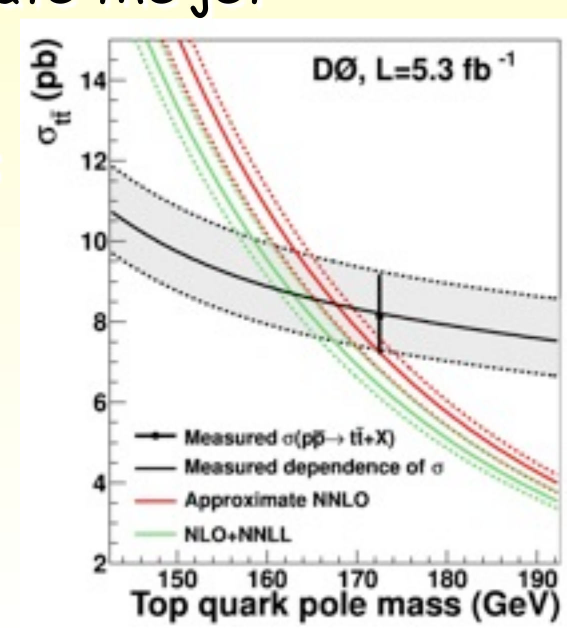
$$m_t >> m_b$$

- 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



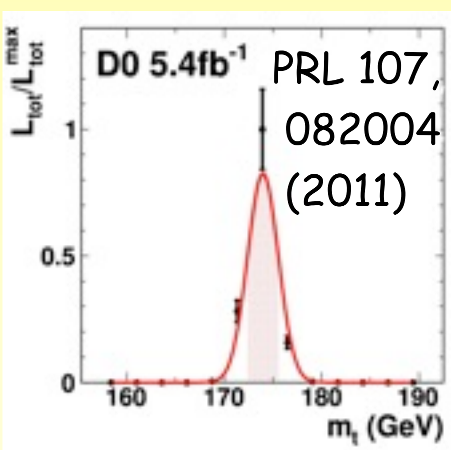
- for channel with at least one W decaying hadronically, can calibrate the jet energy scale (JES) constraining M_{jj} to M_W
- need to calibrate the method to correct for any potential biases

- 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))

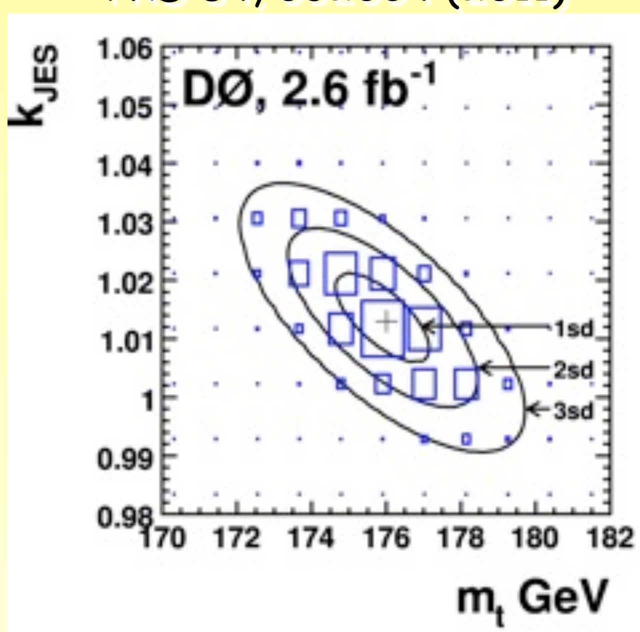


Top Quark Mass Measurements

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

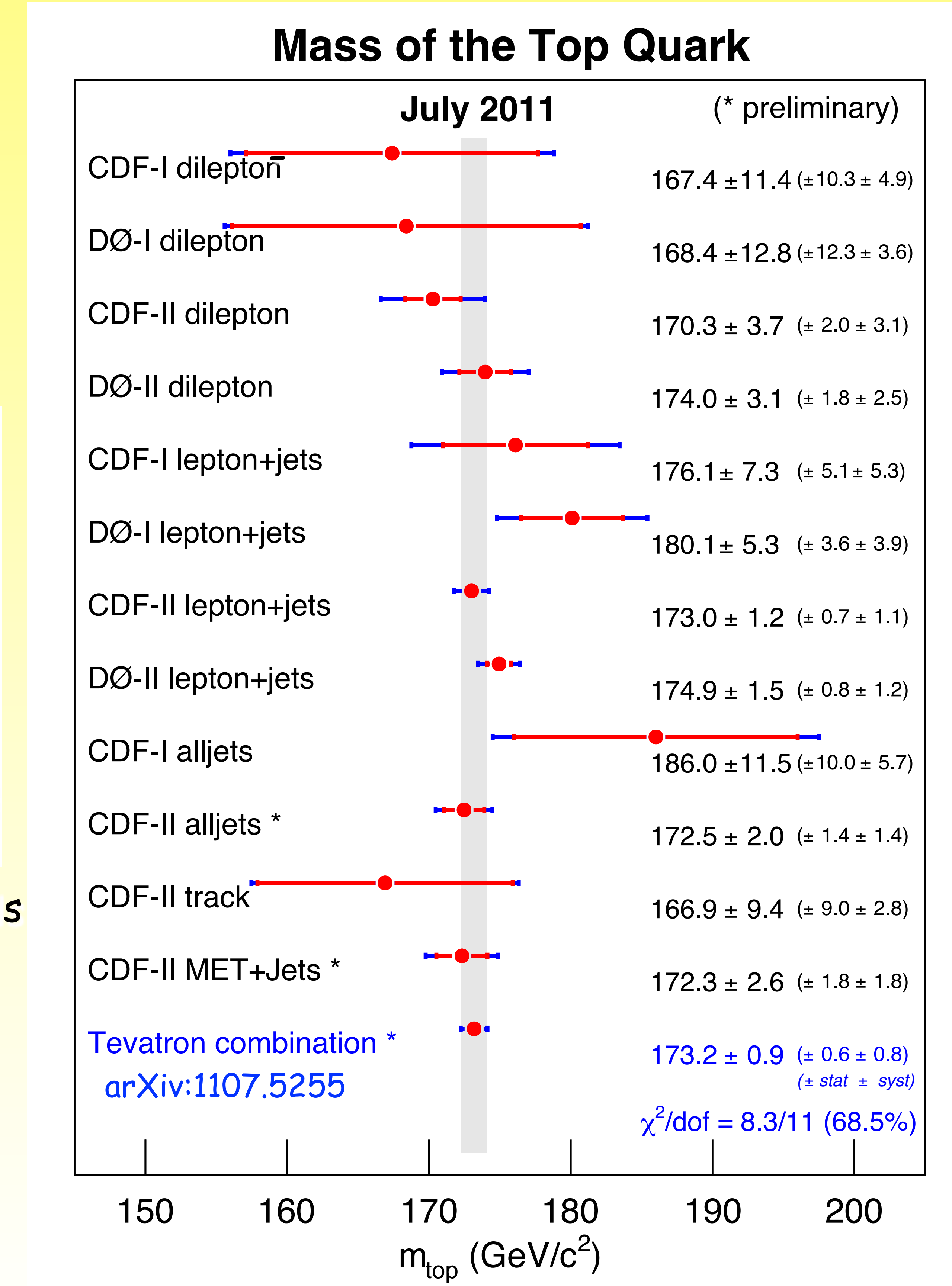


PRD 84, 032004 (2011)



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



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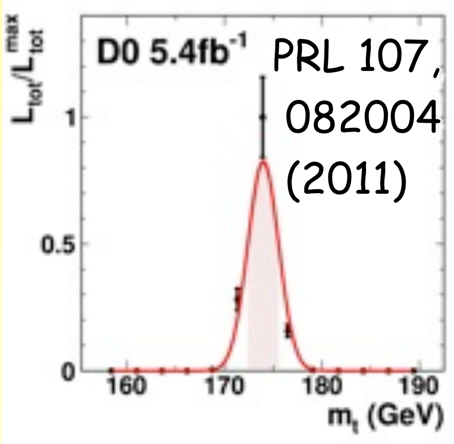
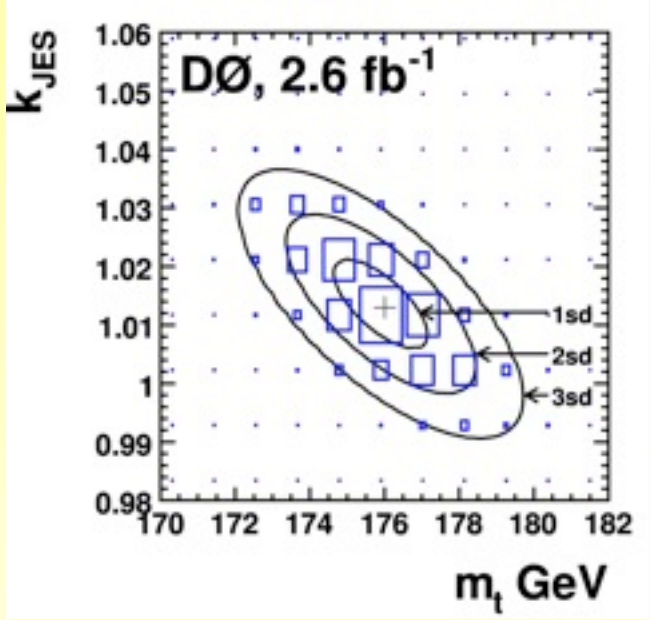
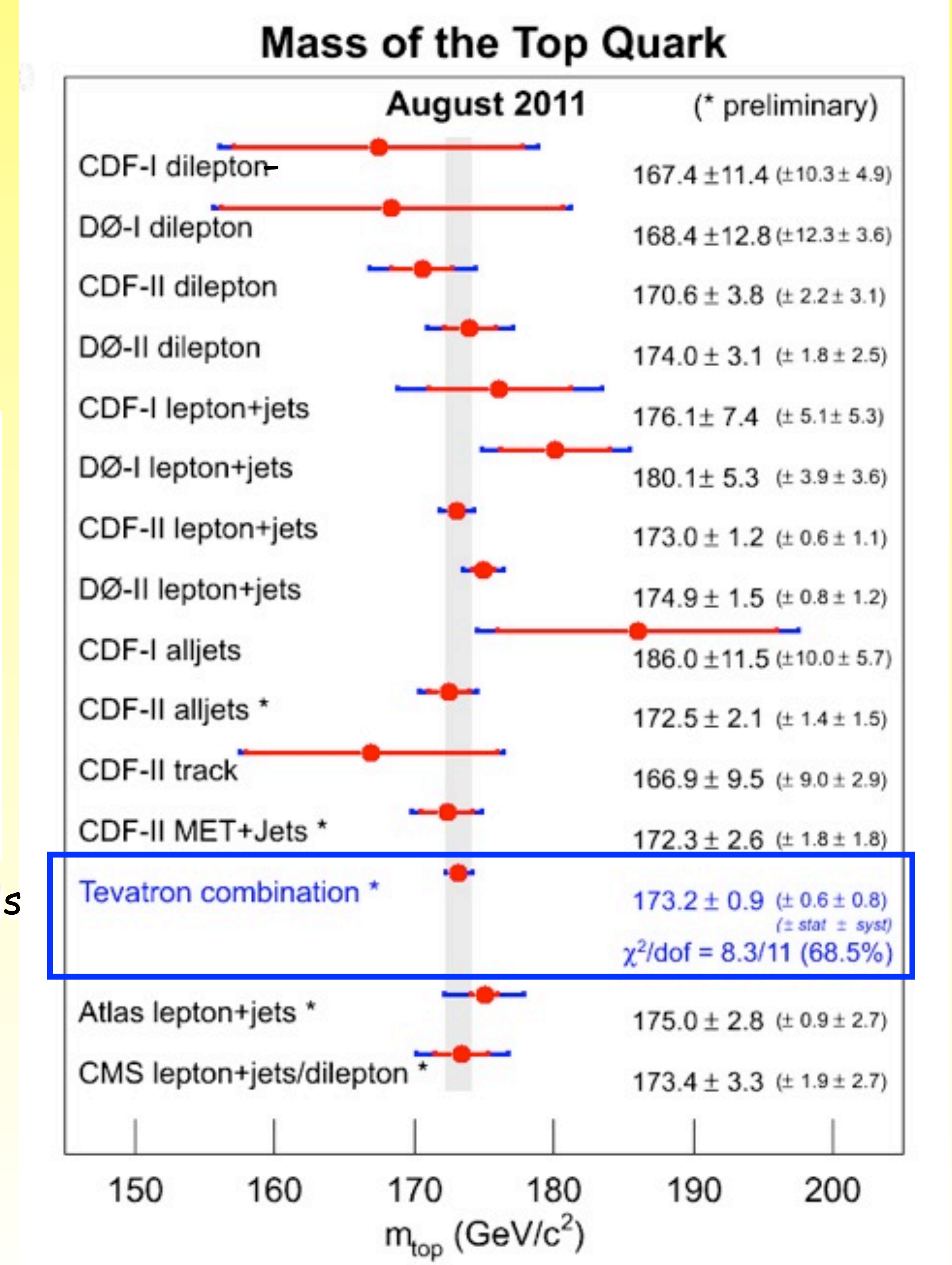
PRL 107, 082004 (2011)



PRD 84, 032004 (2011)



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



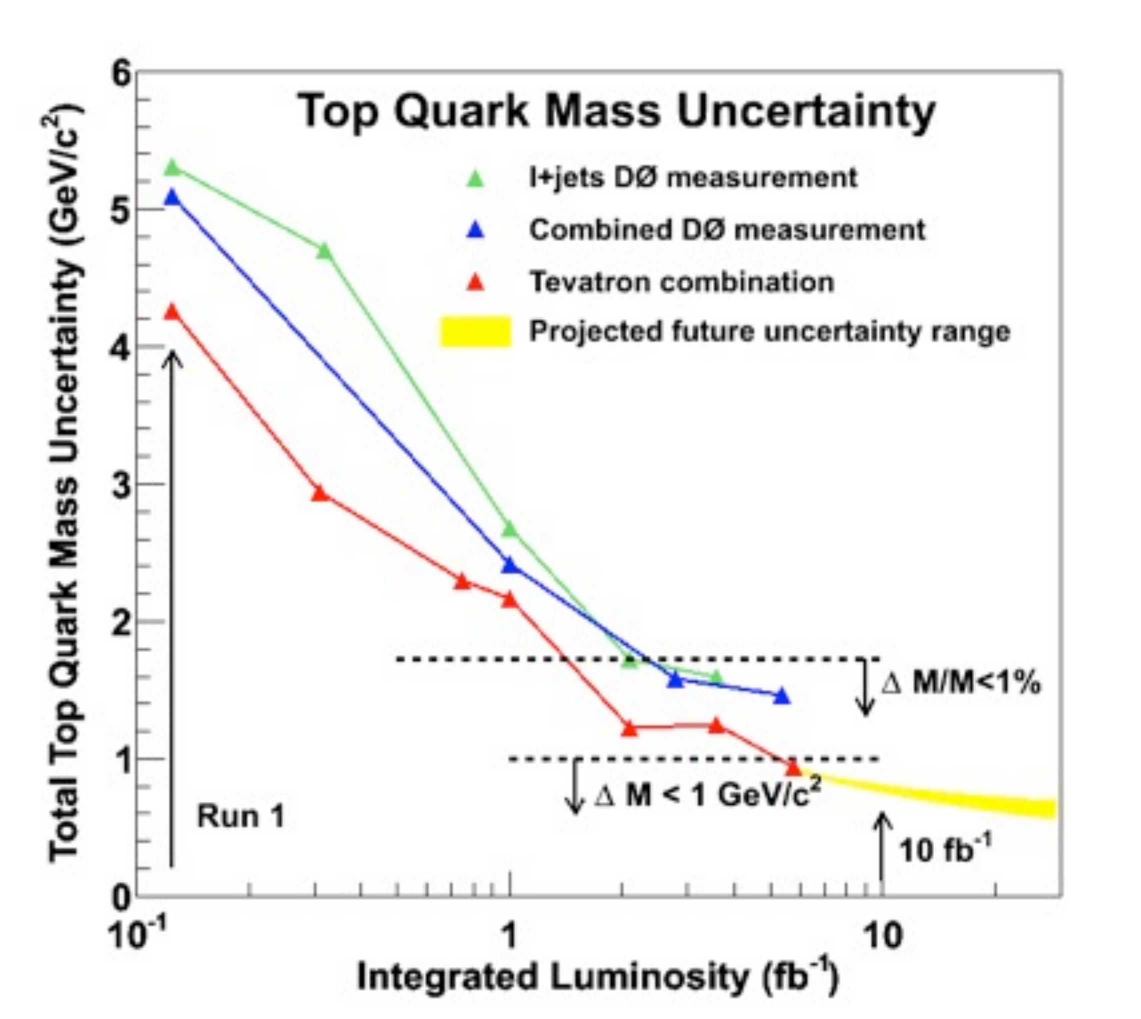
- new Tevatron combination (arXiv:1107.5255):
  - uncertainty below 1 GeV for the first time
  - all channels give consistent results
  - still working on decreasing the systematic uncertainties

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 (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 GeV
 - D0-CDF combination: 0.7-0.8 GeV

 challenging precision for LHC

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)
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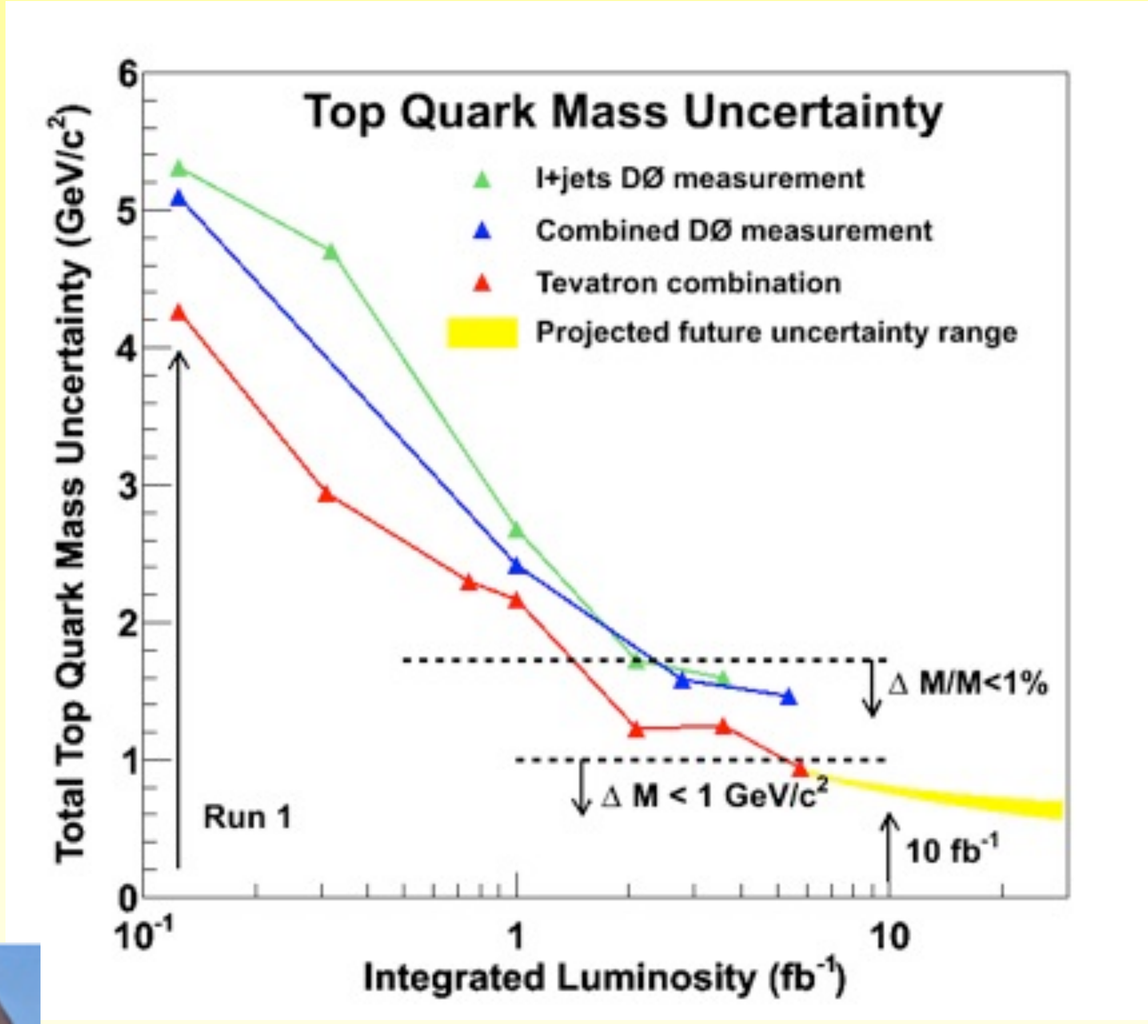


- Tevatron final results

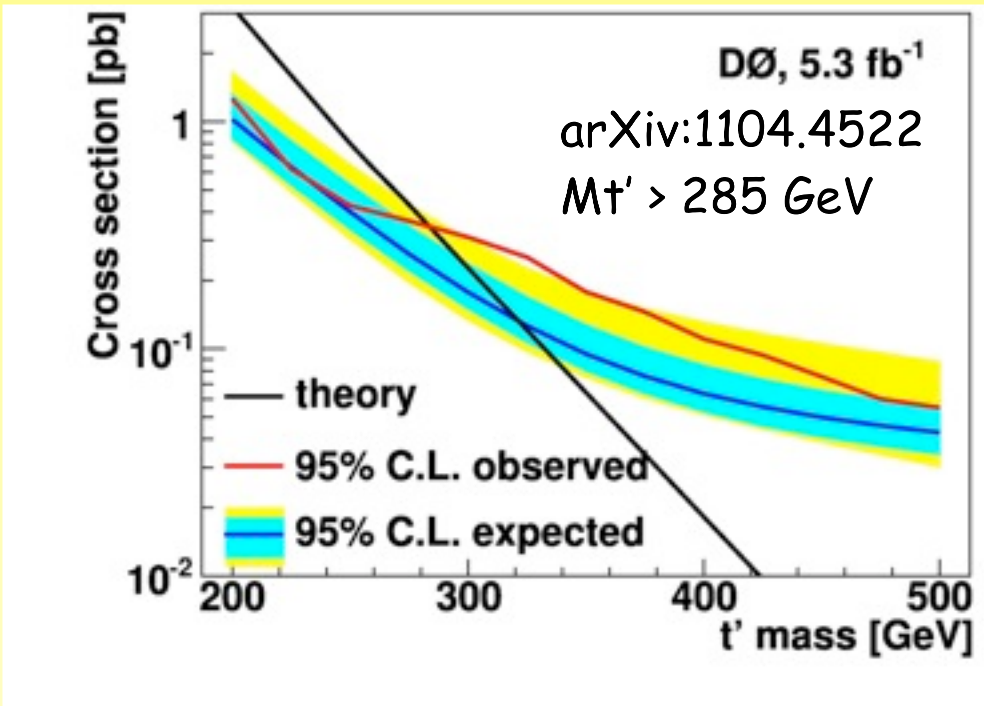
  - single experiment: 0.9 - 1.0 GeV
  - D0-CDF combination: 0.7-0.8 GeV

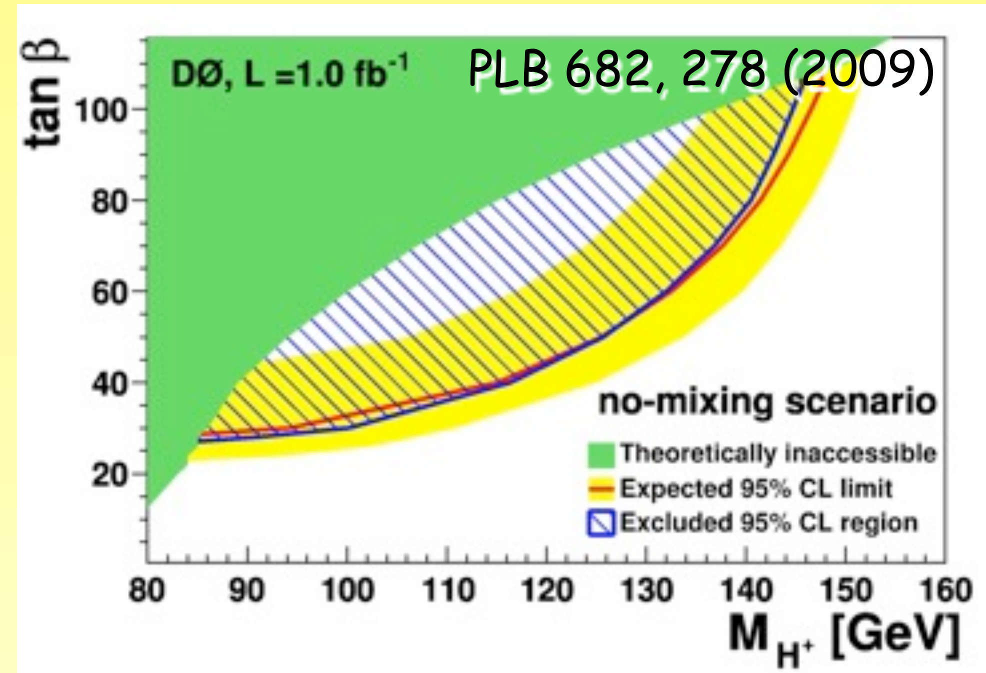
  challenging precision for LHC

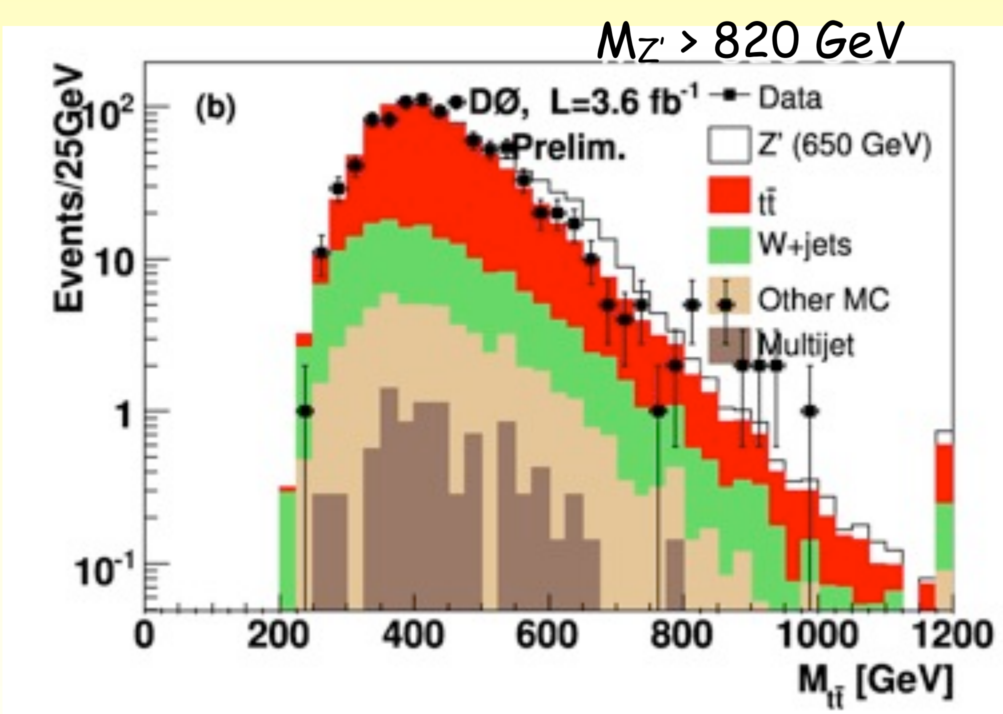
20??

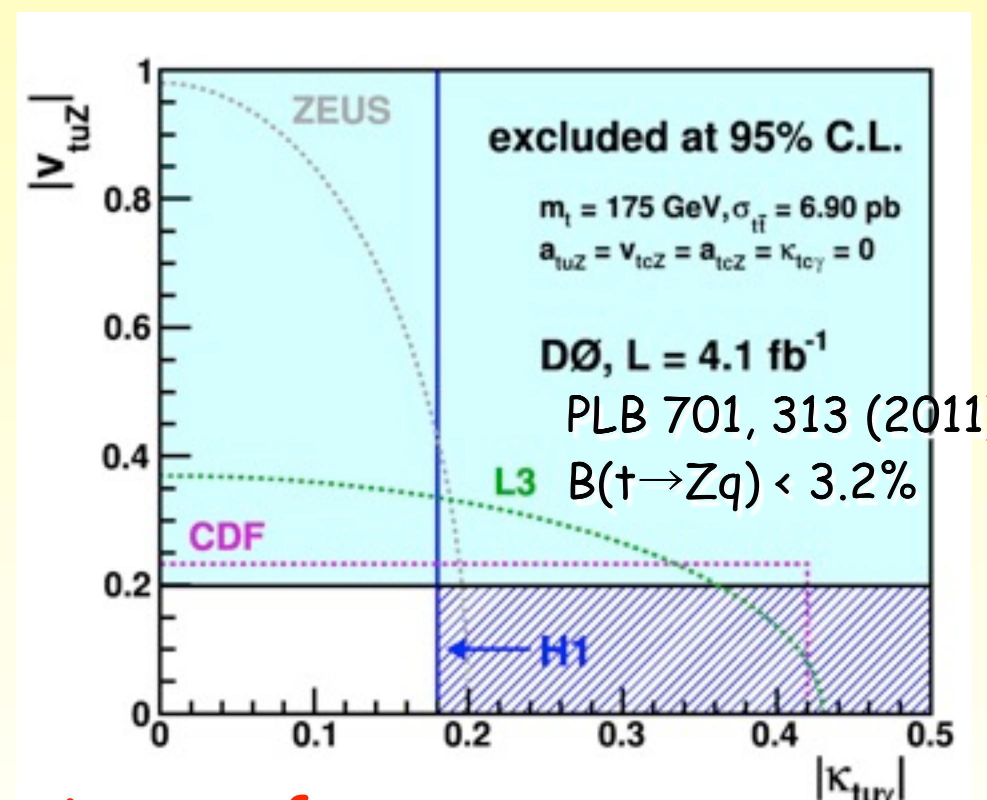
Searches in the Top Sector

- only a few examples





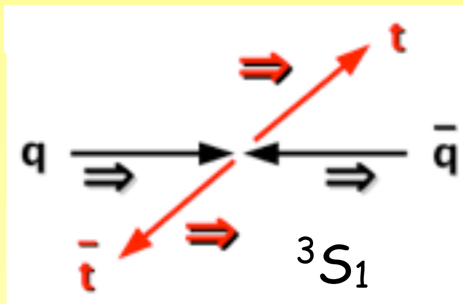




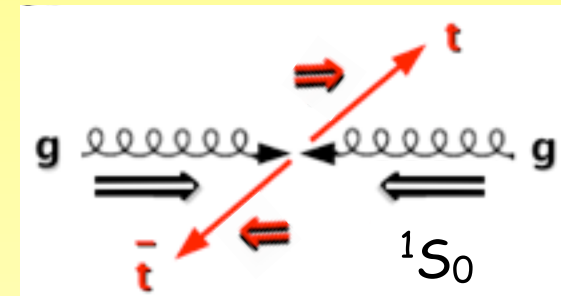
No sign of new physics so far

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

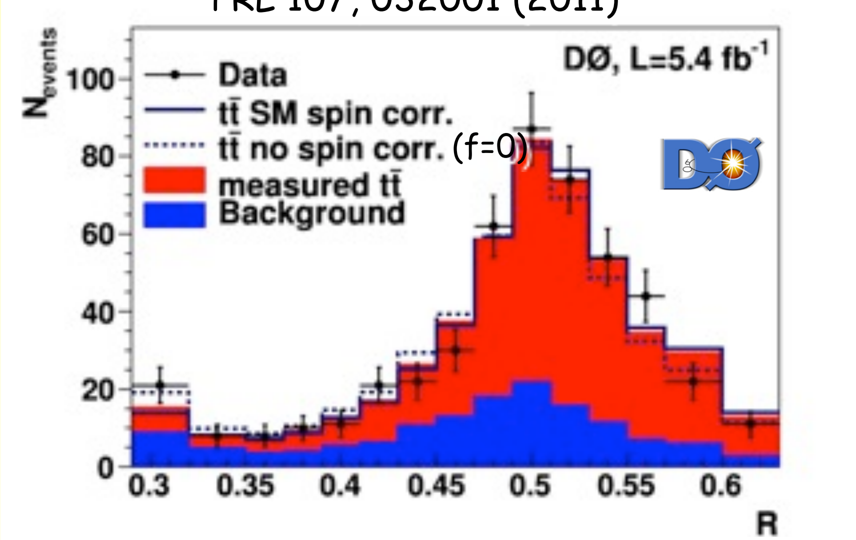
$$R = \frac{P_{\rm sgn}(H=c)}{P_{\rm sgn}(H=u) + P_{\rm sgn}(H=c)}$$

using ME without spin corr. (points to $P_{\rm sgn}(H=u)$); using ME with spin corr. (points to $P_{\rm sgn}(H=c)$)

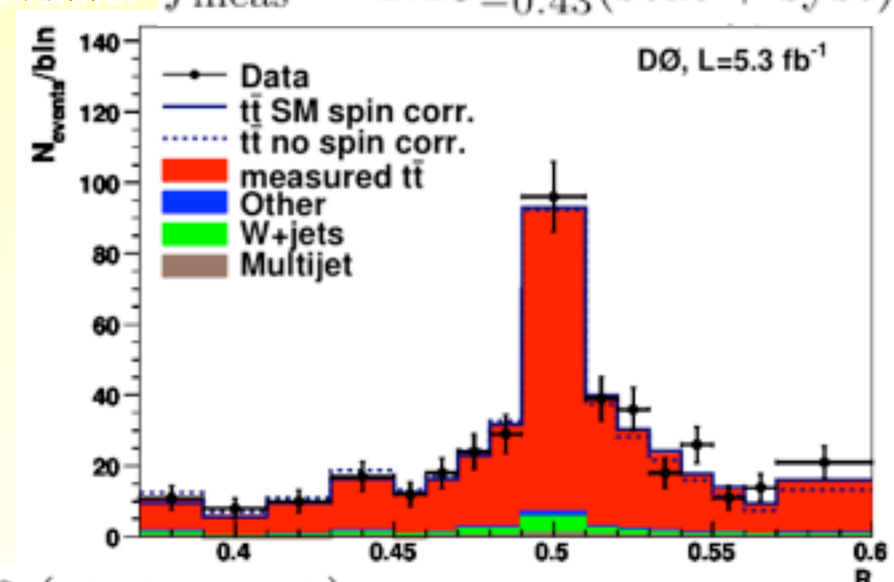
dilepton channel

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

PRL 107, 032001 (2011)



ljets channel: $f_{\rm meas} = 1.15^{+0.42}_{-0.43}({\rm stat} + {\rm syst})$



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

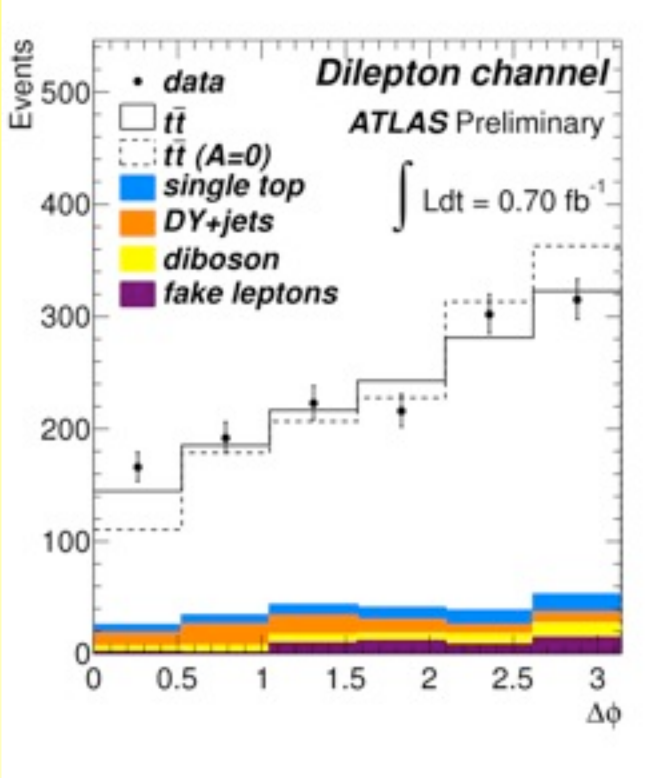
first evidence for $t\bar{t}$ spin correlation (3.1 σ)

Perspectives for Spin Correlation Measurements

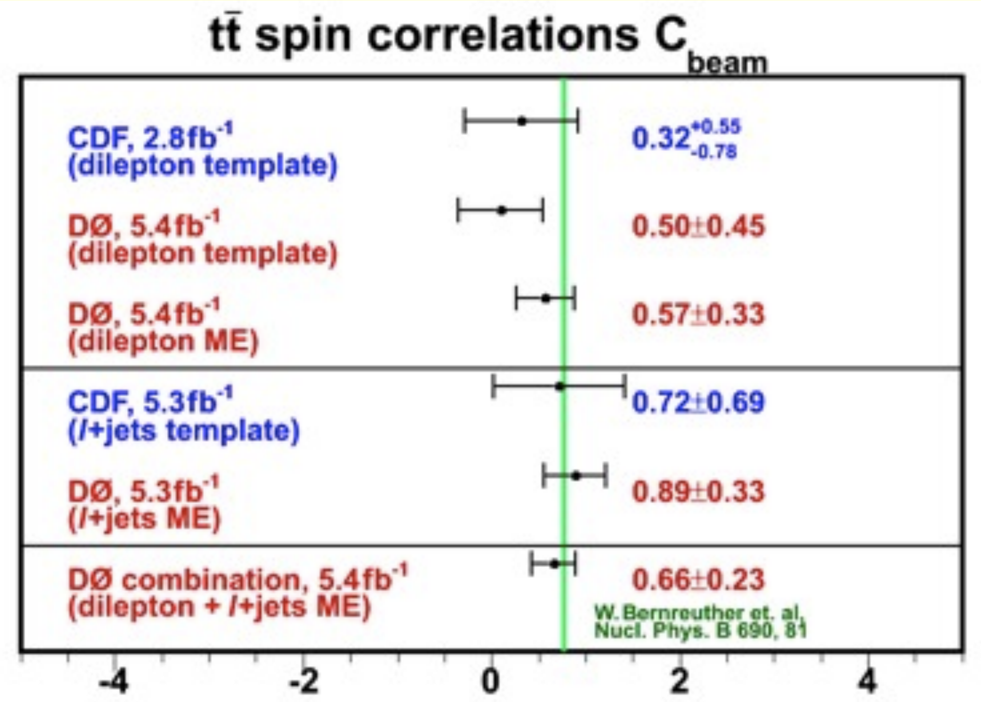
- complementary measurement at the LHC
  - mainly gg-> $t\bar{t}$
  - ATLAS dilepton: $A=0.34^{+0.15}_{-0.11}$ (helicity basis, $A_{SM}=0.32$)
  - also ~ 3 σ sensitivity

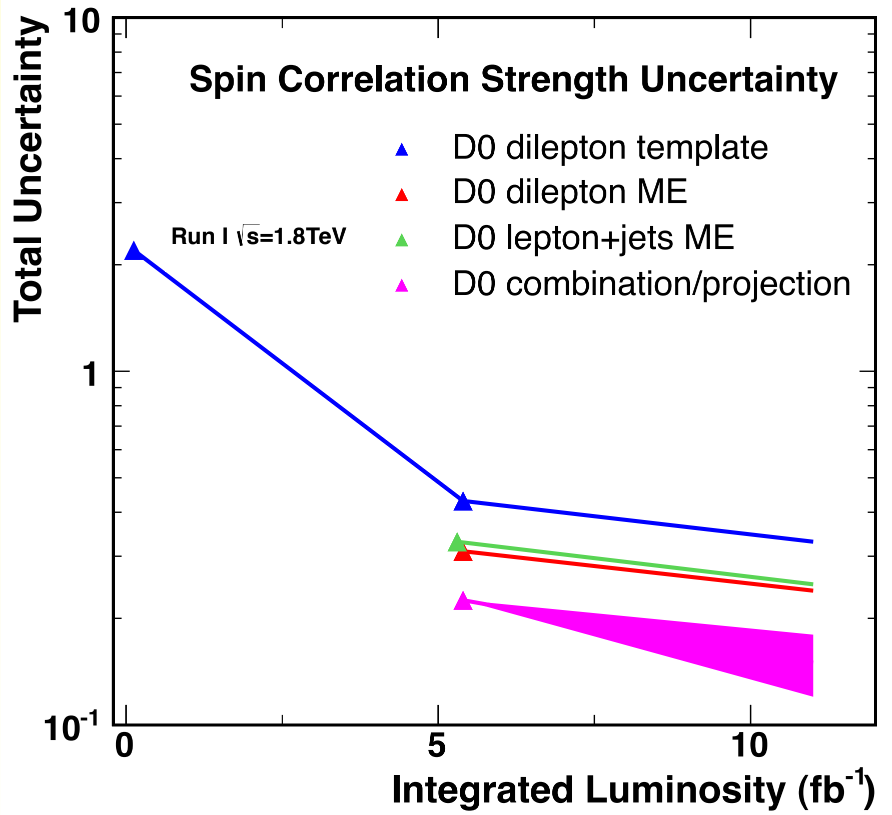
$\Delta\Phi = |\Phi_{l+} - \Phi_{l-}|$

(in the lab frame)



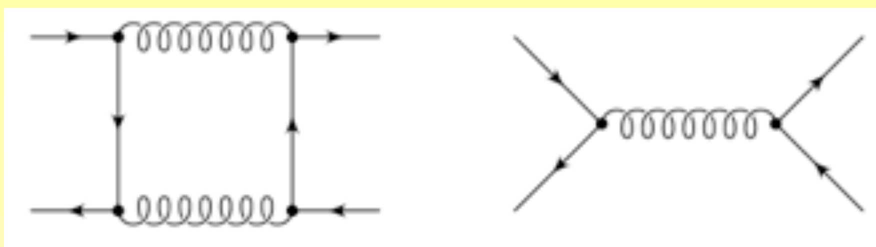
- at the Tevatron, still statistically limited
  - using the full dataset should at least improve the error by √2
  - possible analysis improvement
    (c-tagging in the lepton+jets channel)
  - combination with CDF





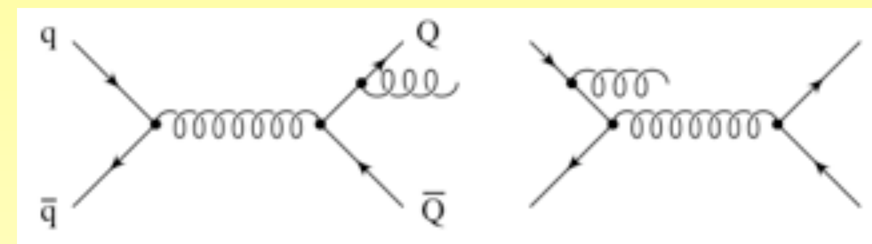
Top-Antitop Charge Asymmetry

- 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

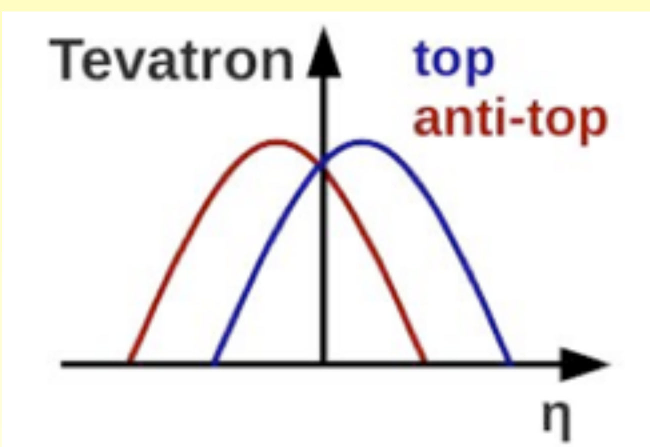


positive asymmetry

+



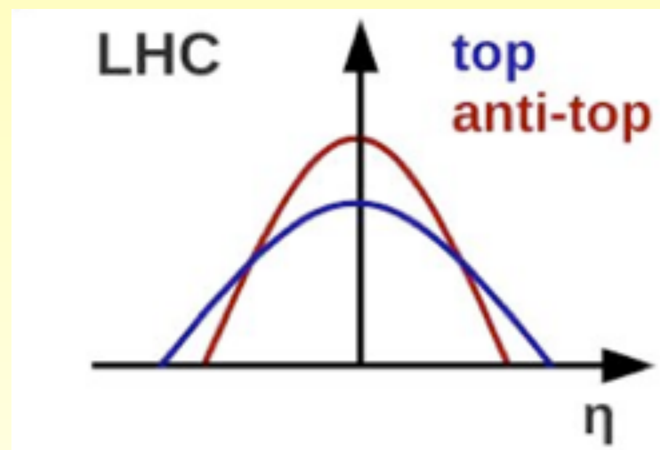
negative asymmetry

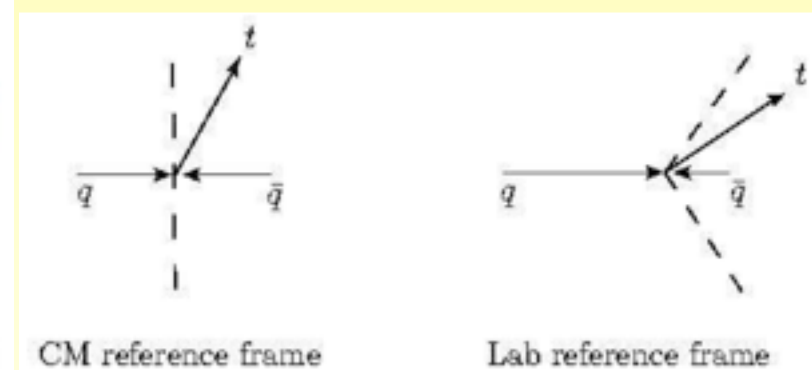


forward-backward asymmetry

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

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





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

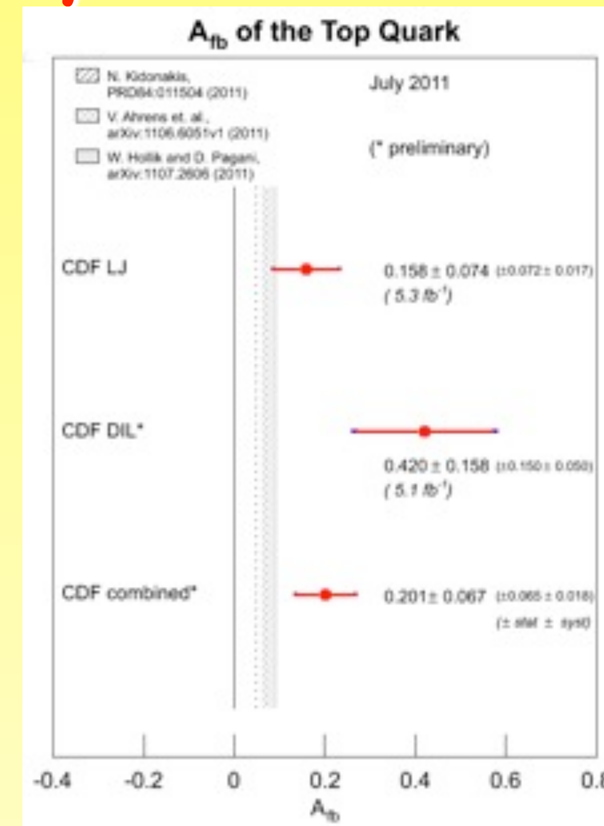
Tevatron Top Charge Asymmetry Results

- CDF measurements

ljets, PRD83, 112003 (2011)

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

3.4 σ difference



- D0 ljets measurement

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

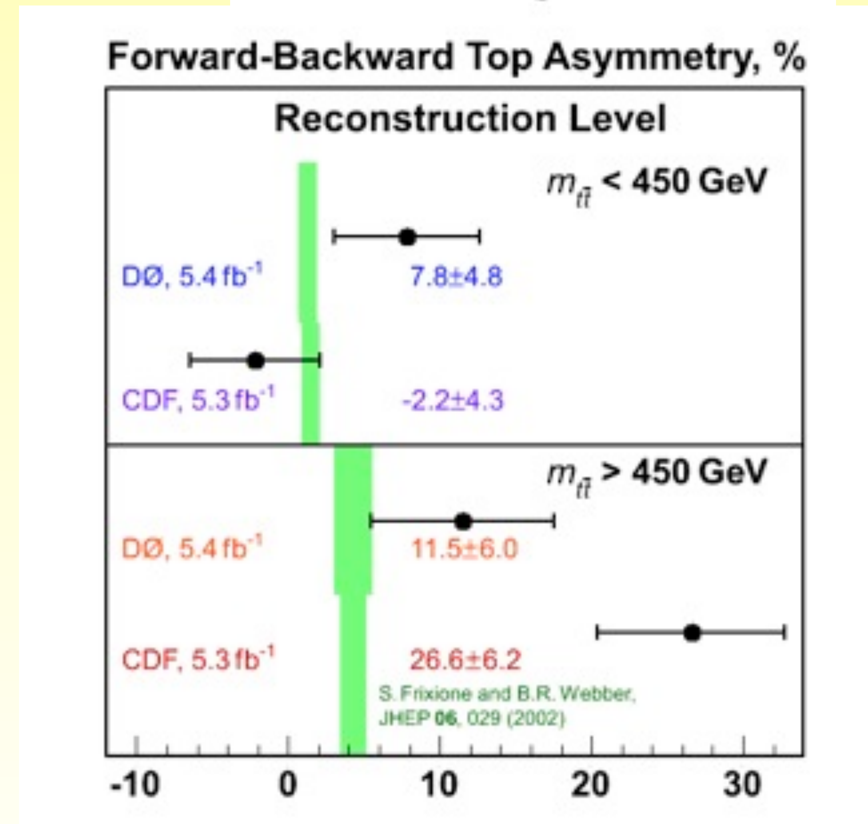
	A_{FB} (%)	
	Reconstruction level	Production level
Data	9.2 ± 3.7	19.6 ± 6.5
MC@NLO	2.4 ± 0.7	5.0 ± 0.1

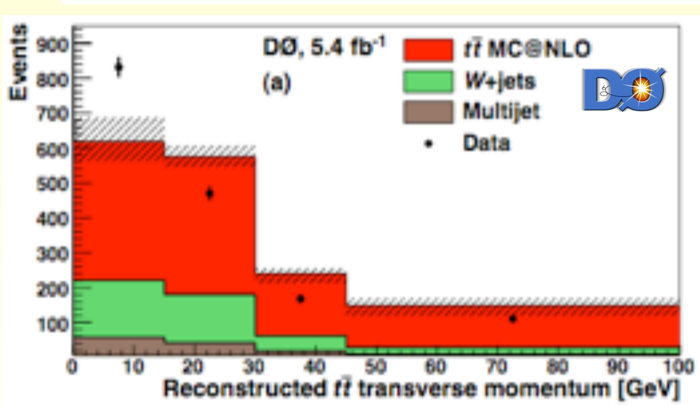
~ 2.4 σ

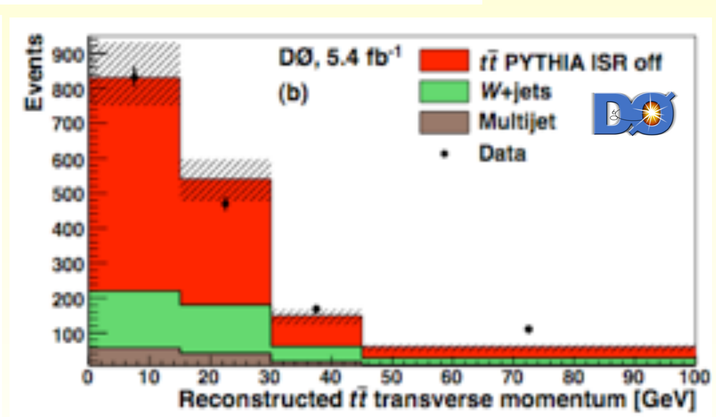
$$A^l_{FB} = \frac{N(q_l y_l > 0) - N(q_l y_l < 0)}{N(q_l y_l > 0) + N(q_l y_l < 0)}$$

	A^l_{FB} (%)	
	Reconstruction level	Production level
Data	14.2 ± 3.8	15.2 ± 4.0
MC@NLO	0.8 ± 0.6	2.1 ± 0.1

> 3 σ







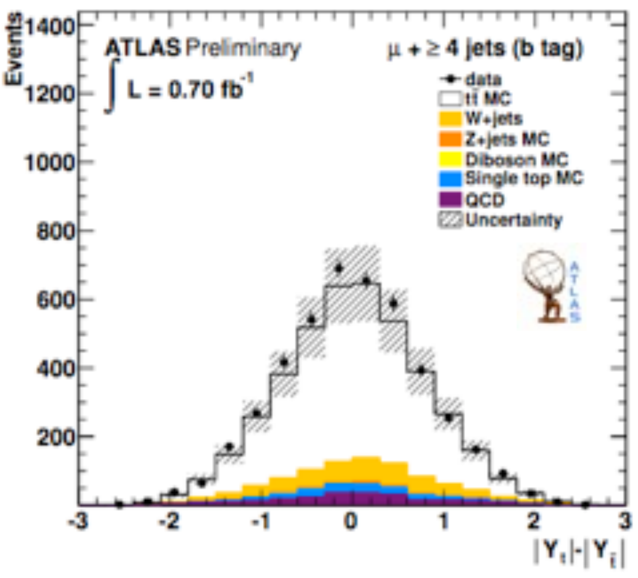
Statistically limited measurements, need better understanding of the predictions

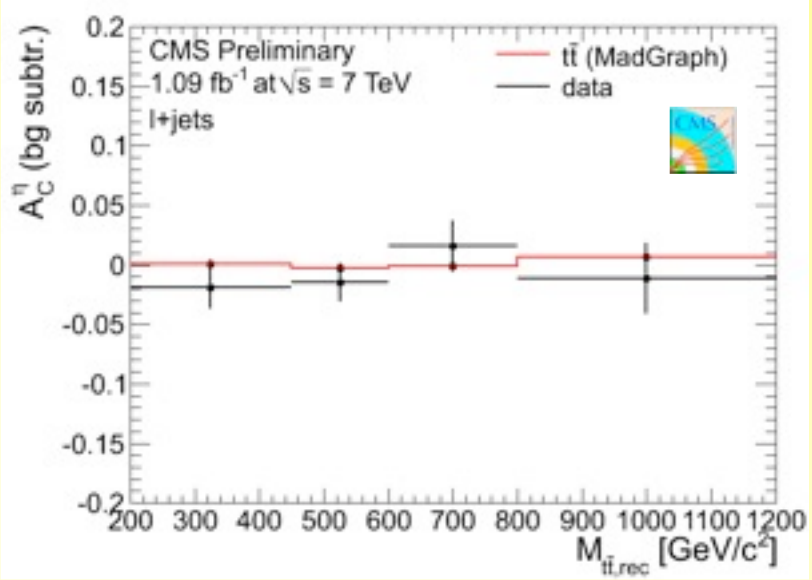
Top Charge Asymmetry Perspectives

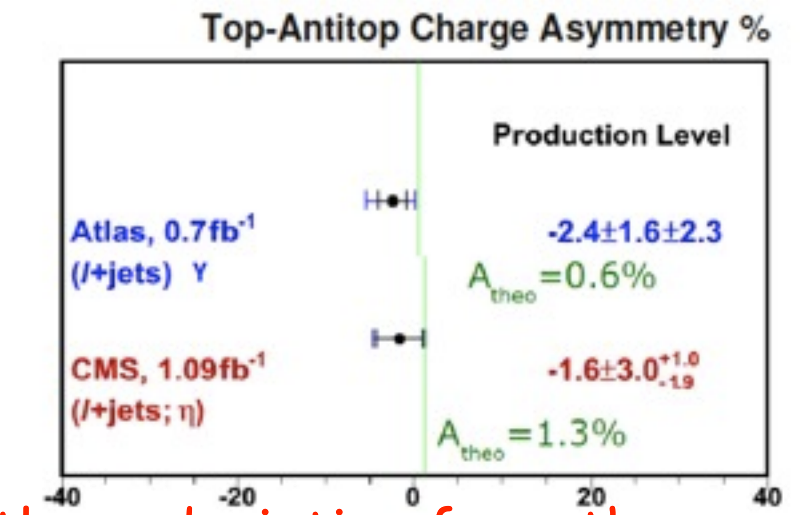
- LHC results
  - different observables
  - not yet sensitive to a potentiel Tevatron excess

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

- Atlas: $\Delta^y = |y_t| - |y_{\bar{t}}|$
- CMS: $\Delta^\eta = |\eta_t| - |\eta_{\bar{t}}|$, $\Delta^{y^2} = (y_t - y_{\bar{t}})(y_t + y_{\bar{t}})$



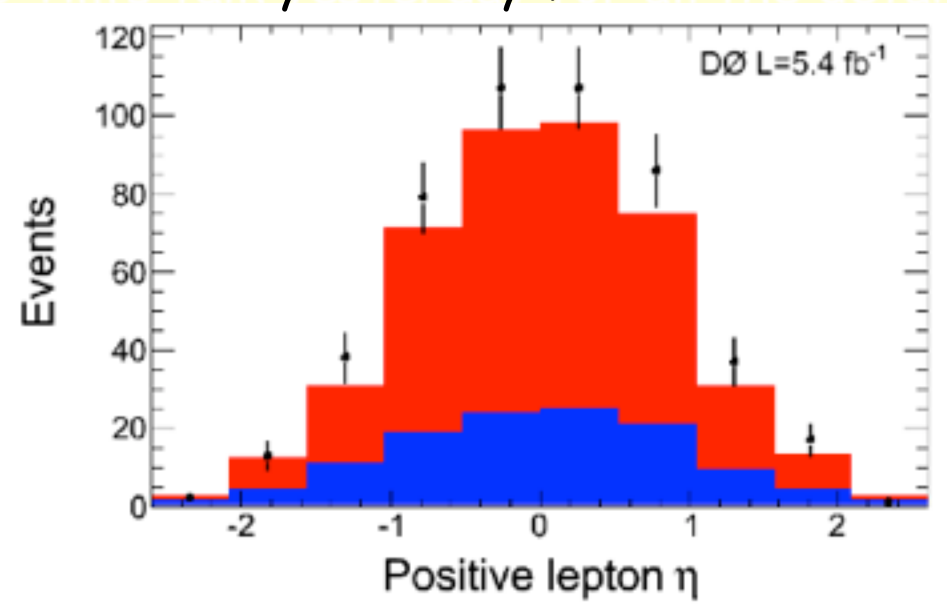




Currently no deviation from the predictions

- Tevatron perspectives
  - D0 dilepton result with 5.4 fb^{-1} 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 ± 0.9 ± 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 χ^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
172.0± 0.9± 1.3 OUR EVALUATION				See comments in the header above.
172.7± 1.8± 1.2	[1] AALTONEN	09J	CDF	$\ell + \not{E}_T$ + 4 jets(b-tag)
171.1± 3.7± 2.1	[2] AALTONEN	09K	CDF	6 jets, vtx b-tag
171.2± 2.7± 2.9	[3] AALTONEN	09O	CDF	dilepton
174.7± 4.4± 2.0	[4] ABAZOV	09AH	D0	dilepton + b-tag (νWT+MWT)
171.5± 1.8± 1.1	[5] ABAZOV	08AH	D0	$\ell + \not{E}_T$ + 4 jets
$180.7^{+15.5}_{-13.4}$± 8.6	[6] ABULENCIA	07J	CDF	lepton + jets
180.1± 3.6± 3.9	[7,8] ABAZOV	04G	D0	lepton + jets
176.1± 5.1± 5.3	[9] AFFOLDER	01	CDF	lepton + jets
167.4±10.3± 4.8	[10,11] ABE	99B	CDF	dilepton
168.4±12.3± 3.6	[8] ABBOTT	98D	D0	dilepton
186 ±10 ± 5.7	[10,12] ABE	97R	CDF	6 or more jets
• • • We do not use the following data for averages, fits, limits, etc. • • •				
180.5±12.0± 3.6	[13] AALTONEN	09AK	CDF	$\ell + \not{E}_T$ + jets (soft μ b-tag)
171.9± 1.7± 1.1	[14] AALTONEN	09L	CDF	ℓ + jets, $\ell\ell$ + jets
$165.5^{+3.4}_{-3.3}$± 3.1	[15] AALTONEN	09X	CDF	$\ell\ell + \not{E}_T$ ($\nu\phi$ weighting)
$169.1^{+5.9}_{-5.2}$	[16] ABAZOV	09AG	D0	cross sects, theory + exp
$171.5^{+9.9}_{-9.8}$	[17] ABAZOV	09R	D0	cross sects, theory + exp
$170.7^{+4.2}_{-3.9}$± 3.5	[18,19] AALTONEN	08C	CDF	dilepton, $\sigma_{t\bar{t}}$ constrained
177.1± 4.9± 4.7	[20,21] AALTONEN	07	CDF	6 jets with ≥ 1 b vtx
$172.3^{+10.8}_{-9.6}$±10.8	[22] AALTONEN	07B	CDF	≥ 4 jets (b tag)
174.0± 2.2± 4.8	[23] AALTONEN	07D	CDF	≥ 6 jets, vtx b-tag
170.8± 2.2± 1.4	[24,25] AALTONEN	07I	CDF	lepton + jets (b-tag)
173.7± 4.4$^{+2.1}_{-2.0}$	[21,26] ABAZOV	07F	D0	lepton + jets
176.2± 9.2± 3.9	[27] ABAZOV	07W	D0	dilepton (MWT)
179.5± 7.4± 5.6	[27] ABAZOV	07W	D0	dilepton (νWT)
164.5± 3.9± 3.9	[25,28] ABULENCIA	07D	CDF	dilepton
$170.3^{+4.1}_{-4.5}{}^{+1.2}_{-1.8}$	[25,29] ABAZOV	06U	D0	lepton + jets (b-tag)
$173.2^{+2.6}_{-2.4}$± 3.2	[30,31] ABULENCIA	06D	CDF	lepton + jets
$173.5^{+3.7}_{-3.6}$± 1.3	[19,30] ABULENCIA	06D	CDF	lepton + jets
165.2± 6.1± 3.4	[25,32] ABULENCIA	06G	CDF	dilepton
170.1± 6.0± 4.1	[19,33] ABULENCIA	06V	CDF	dilepton
178.5±13.7± 7.7	[34,35] ABAZOV	05	D0	6 or more jets
176.1± 6.6	[36] AFFOLDER	01	CDF	dilepton, lepton+jets, all-jets
172.1± 5.2± 4.9	[37] ABBOTT	99C	D0	di-lepton, lepton+jets
176.0± 6.5	[11,38] ABE	99B	CDF	dilepton, lepton+jets, all-jets
173.3± 5.6± 5.5	[8,39] ABBOTT	98F	D0	lepton + jets
175.9± 4.8± 5.3	[10,40] ABE	98E	CDF	lepton + jets
161 ±17 ±10	[10] ABE	98F	CDF	dilepton
172.1± 5.2± 4.9	[41] BHAT	98B	RVUE	dilepton and lepton+jets
173.8± 5.0	[42] BHAT	98B	RVUE	dilepton, lepton+jets, all-jets
173.3± 5.6± 6.2	[8] ABACHI	97E	D0	lepton + jets
199^{+19}_{-21} ±22	ABACHI	95	D0	lepton + jets
176 ± 8 ±10	ABE	95F	CDF	lepton + b-jet
174 ±10 $^{+13}_{-12}$	ABE	94E	CDF	lepton + b-jet

t BRANCHING RATIOS

$\Gamma(Wb)/\Gamma(Wq(q=b,s,d))$ — Γ_2/Γ_1

VALUE	DOCUMENT ID		TECN	COMMENT
$\mathbf{0.99^{+0.09}_{-0.08}}$ **OUR AVERAGE**				
$0.97^{+0.09}_{-0.08}$	[1] ABAZOV	08M	D0	ℓ + n jets with 0,1,2 b-tag
$1.12^{+0.21}_{-0.19}{}^{+0.17}_{-0.13}$	[2] ACOSTA	05A	CDF	
• • • We do not use the following data for averages, fits, limits, etc. • • •				
$1.03^{+0.19}_{-0.17}$	[3] ABAZOV	06K	D0	
$0.94^{+0.26}_{-0.21}{}^{+0.17}_{-0.12}$	[4] AFFOLDER	01C	CDF	

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

[2] ACOSTA 05A result is from the analysis of lepton + jets and di-lepton + jets final states of $t\bar{t}$ candidate events with ~ 162 pb^{-1} 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.

[3] ABAZOV 06K result is from the analysis of $t\bar{t}$ → $\ell\nu$ + ≥ 3 jets with 230 pb^{-1} of data at $\sqrt{s}$ = 1.96 TeV. It gives R > 0.61 and $|V_{tb}|$ > 0.78 at 95% CL. Superseded by ABAZOV 08M.

[4] AFFOLDER 01C measures the top-quark decay width ratio R= Γ(W b)/Γ(W q), 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 function 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^{-1} of data at $\sqrt{s}$ = 1.8 TeV.

$\Gamma(\ell\nu_\ell\,\text{anything})/\Gamma_{\text{total}}$ — Γ_3/Γ

VALUE	DOCUMENT ID		TECN
0.094±0.024	[1] ABE	98X	CDF

[1] ℓ means e or μ decay mode, not the sum. Assumes lepton universality and W-decay acceptance.

$\Gamma(\tau\nu_\tau b)/\Gamma_{\text{total}}$ — Γ_4/Γ

VALUE	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •				
	[1] ABULENCIA	06R	CDF	$\ell\tau$ + jets
	[2] ABE	97V	CDF	$\ell\tau$ + jets

[1] ABULENCIA 06R looked for $t\bar{t}$ → $(\ell\nu_\ell)(\tau\nu_\tau)b\bar{b}$ events in 194 pb^{-1} of $p\bar{p}$ collisions at $\sqrt{s}$ = 1.96 TeV. 2 events are found where 1.00 ± 0.17 signal and 1.29 ± 0.25 background events are expected, giving a 95% CL upper bound for the partial width ratio Γ(t → τνq) / Γ_{SM}(t → τνq) < 5.2.

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

$\Gamma(\gamma q(q=u,c))/\Gamma_{\text{total}}$ — Γ_5/Γ

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
<0.0064	95	[1] AARON	09A	H1	$t \to \gamma u$
<0.0059	95	[2] CHEKANOV	03	ZEUS	B($t \to \gamma u$)
• • • We do not use the following data for averages, fits, limits, etc. • • •					
<0.0465	95	[3] ABDALLAH	04C	DLPH	B(γc or γu)
<0.0132	95	[4] AKTAS	04	H1	B($t \to \gamma u$)
<0.041	95	[5] ACHARD	02J	L3	B($t \to \gamma c$ or γu)
<0.032	95	[6] ABE	98G	CDF	$t\bar{t} \to (Wb)(\gamma c$ or $\gamma u)$

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

[2] CHEKANOV 03 looked for single top production via FCNC in the reaction $e^\pm p \to e^\pm (t$ or $\bar{t})$ X in 130.1 pb^{-1} of data at $\sqrt{s}$=300–318 GeV. No evidence for top production and its decay into bW was found. The result is obtained for m_t=175 GeV when B(γc)=B($Z q$)=0, where q is a u or c quark. Bounds on the effective $t u \gamma$ and $t u Z$ couplings are found in their Fig. 4. The conversion to the constraint listed is from private communication, E. Gallo, January 2004.

[3] ABDALLAH 04C looked for single top production via FCNC in the reaction $e^+ e^- \to \bar{t} c$ or $\bar{t} u$ in 541 pb^{-1} of data at $\sqrt{s}$=189–208 GeV. No deviation from the SM is found, which leads to the bound on B($t \to \gamma q$), where q is a u or a c quark, for m_t = 175 GeV when B($t \to Z q$)=0 is assumed. The conversion to the listed bound is from private communication, O. Yushchenko, April 2005. The bounds on the effective t-q-γ and t-q-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 γ and Z exchange amplitudes.

[4] AKTAS 04 looked for single top production via FCNC in $e^\pm$ collisions at HERA with 118.3 pb^{-1}, and found 5 events in the e or μ channels. By assuming that they are due to statistical fluctuation, the upper bound on the $t u \gamma$ coupling $\kappa_{tu\gamma}$ < 0.27 (95% CL) is obtained. The conversion to the partial width limit, when B(γc) = B($Z u$) = B($Z c$) = 0, is from private communication, E. Perez, May 2005.

[5] ACHARD 02J looked for single top production via FCNC in the reaction $e^+ e^- \to t c$ or $t u$ in 634 pb^{-1} 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(γq), where q is a u or c quark. The bound assumes B($Z q$)=0 and is for m_t= 175 GeV; bounds for m_t=170 GeV and 180 GeV and B($Z q$) ≠ 0 are given in Fig. 5 and Table 7.

[6] ABE 98G looked for $t\bar{t}$ events where one t decays into qγ while the other decays into bW. The quoted bound is for Γ(γq)/Γ(W b).

$\Gamma(Zq(q=u,c))/\Gamma_{\text{total}}$ — Γ_6/Γ

Test for ΔT=1 weak neutral current. Allowed by higher-order electroweak interaction.

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
<0.037	95	[1] AALTONEN	08AD	CDF	$t \to Z q$ (q = u, c)
<0.159	95	[2] ABDALLAH	04C	DLPH	$e^+e^- \to \bar{t}c$ or $\bar{t}u$
<0.137	95	[3] ACHARD	02J	L3	$e^+e^- \to \bar{t}c$ or $\bar{t}u$
<0.14	95	[4] HEISTER	02Q	ALEP	$e^+e^- \to \bar{t}c$ or $\bar{t}u$
<0.137	95	[5] ABBIENDI	01T	OPAL	$e^+e^- \to \bar{t}c$ or $\bar{t}u$
• • • We do not use the following data for averages, fits, limits, etc. • • •					
<0.083	95	[6] AALTONEN	09AL	CDF	$t \to Z q$ (q=c)
<0.17	95	[7] BARATE	00S	ALEP	$e^+e^- \to \bar{t}c$ or $\bar{t}u$
<0.33	95	[8] ABE	98G	CDF	$t\bar{t} \to (W b)(Z c$ or $Z u)$

[1] Result is based on 1.9 fb^{-1} of data at 1.96 TeV. $t\bar{t}$ → $WbZq$ or $ZqZq$ processes have been looked for in Z + ≥ 4 jet events with and without b-tag. No signal leads to the bound B($t \to Zq$) < 0.037 (0.043) for m_t = 175 (170) GeV.

[2] ABDALLAH 04C looked for single top production via FCNC in the reaction $e^+e^- \to \bar{t}c$ or $\bar{t}u$ in 541 pb^{-1} of data at $\sqrt{s}$=189–208 GeV. No deviation from the SM is found, which leads to the bound on B($t \to Zq$), where q is a u or a c quark, for m_t = 175 GeV when B($t \to \gamma q$)=0 is assumed. The conversion to the listed bound is from private communication, O. Yushchenko, April 2005. The bounds on the effective t-q-γ and t-q-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 γ and Z exchange amplitudes.

[3] ACHARD 02J looked for single top production via FCNC in the reaction $e^+e^- \to t c$ or $t u$ in 634 pb^{-1} 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($Z q$), where q is a u or c quark. The bound assumes B(γq)=0 and is for m_t= 175 GeV; bounds for m_t=170 GeV and 180 GeV and B(γq) ≠0 are given in Fig. 5 and Table 7. Table 6 gives constraints on t c e e four fermi contact interactions.

[4] HEISTER 02Q looked for single top production via FCNC in the reaction $e^+e^- \to \bar{t}c$ or $\bar{t}u$ in 214 pb^{-1} 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($Z q$), where q is a u or c quark. The bound assumes B(γq)=0 and is for m_t= 174 GeV. Bounds on the effective t- (c or u)- γ and t- (c or u)- Z couplings are given in their Fig. 2.

[5] ABBIENDI 01T looked for single top production via FCNC in the reaction $e^+e^- \to t c$ or $t u$ in 600 pb^{-1} of data at $\sqrt{s}$= 189–209 GeV. No deviation from the SM is found, which leads to bounds on the branching fractions B($Z q$) and B(γq), where q is a u or c quark. The result is obtained for m_t= 174 GeV. The upper bound becomes 9.7% (20.6%) for m_t= 169 (179) GeV. Bounds on the effective t- (c or u)–γ and t- (c or u) Z couplings are given in their Fig. 4.

[6] Based on $p\bar{p}$ data of 1.52 fb^{-1}. AALTONEN 09AL compared $t\bar{t} \to WbWb \to \ell\nu b jjb$ and $t\bar{t} \to ZcWb \to \ell\ell c jjb$ 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 XII.

[7] BARATE 00S looked for single top production via FCNC in the reaction $e^+e^- \to \bar{t}c$ or $\bar{t}u$ in 411 pb^{-1} of data at c.m. energies between 189 and 202 GeV. No deviation from the SM is found, which leads to a bound on the branching fraction. The bound assumes B(γq)=0. Bounds on the effective t (c or u) γ and t (c or u) Z couplings are given in their Fig. 4.

[8] ABE 98G looked for $t\bar{t}$ events where one t decays into three jets and the other decays into qZ with Z → ℓℓ. The quoted bound is for Γ(Z q)/Γ(W b).

t-quark EW Couplings

W helicity fractions in top decays. F_0 is the fraction of longitudinal and F_+ the fraction of right-handed W bosons. F_{V+A} is the fraction of V+A current in top decays. The effective Lagrangian (cited by ABAZOV 08AI) has terms f_1^L and f_1^R for V−A and V+A couplings, f_2^L and f_2^R for tensor couplings with b_R and b_L respectively.

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •					
0.62 ±0.10 ±0.05		[1] AALTONEN	09Q	CDF	F_0 = B($t \to W_0 b$)
−0.04 ±0.04 ±0.03		[1] AALTONEN	09Q	CDF	F_+ = B($t \to W_+ b$)
$\lvert f_1^R\rvert^2$ < 1.01	95	[2] ABAZOV	09J	D0	$\lvert f_1^L\rvert$ = 1, $\lvert f_2^L\rvert$=$\lvert f_2^R\rvert$=0
$\lvert f_2^L\rvert^2$ < 0.28	95	[2] ABAZOV	09J	D0	$\lvert f_1^L\rvert$ = 1, $\lvert f_1^R\rvert$=$\lvert f_2^R\rvert$=0
$\lvert f_2^R\rvert^2$ < 0.23	95	[2] ABAZOV	09J	D0	$\lvert f_1^L\rvert$ = 1, $\lvert f_1^R\rvert$=$\lvert f_2^L\rvert$=0
$\lvert f_1^R\rvert^2$ < 2.5	95	[3] ABAZOV	08A	D0	$\lvert f_1^L\rvert^2$ = $1.8^{+1.0}_{-1.3}$
$\lvert f_2^L\rvert^2$ < 0.5	95	[3] ABAZOV	08A	D0	$\lvert f_1^L\rvert^2$ = $1.4^{+0.9}_{-0.8}$
$\lvert f_2^R\rvert^2$ < 0.3	95	[3] ABAZOV	08A	D0	$\lvert f_1^L\rvert^2$ = $1.4^{+0.6}_{-0.5}$
0.425±0.166±0.102		[4] ABAZOV	08B	D0	F_0 = B($t \to W_0 b$)
0.119±0.090±0.053		[4] ABAZOV	08B	D0	F_+ = B($t \to W_+ b$)
0.056±0.080±0.057		[5] ABAZOV	07D	D0	F_+ = B($t \to W_+ b$)
−0.06 ±0.22 ±0.12		[6] ABULENCIA	07G	CDF	F_{V+A} = B($t \to W b_R$)
< 0.29	95	[6] ABULENCIA	07G	CDF	F_{V+A} = B($t \to W b_R$)
$0.85^{+0.15}_{-0.22}$ ±0.06		[7] ABULENCIA	06I	CDF	F_0 = B($t \to W_0 b$)
$0.05^{+0.11}_{-0.05}$ ±0.03		[7] ABULENCIA	06I	CDF	F_+ = B($t \to W_+ b$)
< 0.26	95	[7] ABULENCIA	06I	CDF	F_+ = B($t \to W_+ b$)
0.74 $^{+0.22}_{-0.34}$		[8] ABULENCIA	06U	CDF	F_0 = B($t \to W_0 b$)
< 0.27	95	[8] ABULENCIA	06U	CDF	F_+ = B($t \to W_+ b$)
0.56 ±0.31		[9] ABAZOV	05G	D0	F_0 = B($t \to W_0 b$)
0.00 ±0.13 ±0.07		[10] ABAZOV	05L	D0	F_+ = B($t \to W_+ b$)
< 0.25	95	[10] ABAZOV	05L	D0	F_+ = B($t \to W_+ b$)
< 0.80	95	[11] ACOSTA	05D	CDF	F_{V+A} = B($t \to W b_R$)
< 0.24	95	[11] ACOSTA	05D	CDF	F_+ = B($t \to W_+ b$)
0.91 ±0.37 ±0.13		[12] AFFOLDER	00B	CDF	F_0 = B($t \to W_0 b$)
0.11 ±0.15		[12] AFFOLDER	00B	CDF	F_+ = B($t \to W_+ b$)

PDG'10 on the Top Quark

J.Phys. G37, 075021 (2010)

t-quark FCNC couplings κ^{utg}/Λ and κ^{ctg}/Λ

Single t-Quark Production Cross Section in $p\bar{p}$ Collisions at $\sqrt{s}$ = 1.8 TeV

Single t-Quark Production Cross Section in $p\bar{p}$ Collisions at $\sqrt{s}$ = 1.96 TeV

Single t-Quark Production Cross Section in ep Collisions

$t\bar{t}$ production cross section in $p\bar{p}$ collisions at $\sqrt{s}$ = 1.8 TeV

$t\bar{t}$ production cross section in $p\bar{p}$ collisions at $\sqrt{s}$ = 1.96 TeV

$gg \rightarrow t\bar{t}$ fraction in $p\bar{p}$ collisions at $\sqrt{s}$ = 1.96 TeV

A_{FB} of $t\bar{t}$ in $p\bar{p}$ collisions at $\sqrt{s}$ = 1.96 TeV

t-Quark Electric Charge

t-Quark REFERENCES

Summary of the Tevatron Top Quark Measurements

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

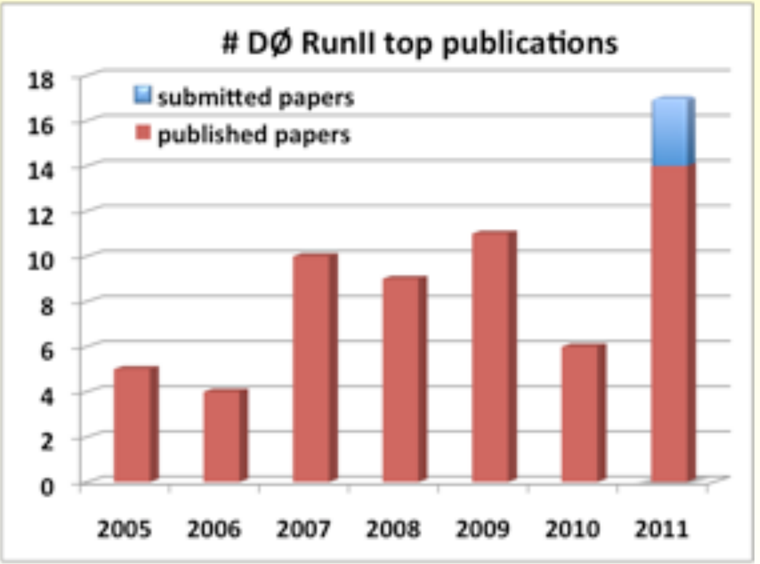
Summary

- 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 fb^{-1} of $p\bar{p}$ colliding data from Tevatron will remain unique
  - 1.96 TeV, mainly $q\bar{q} \to t\bar{t}$
  - focus on complementary measurements to LHC

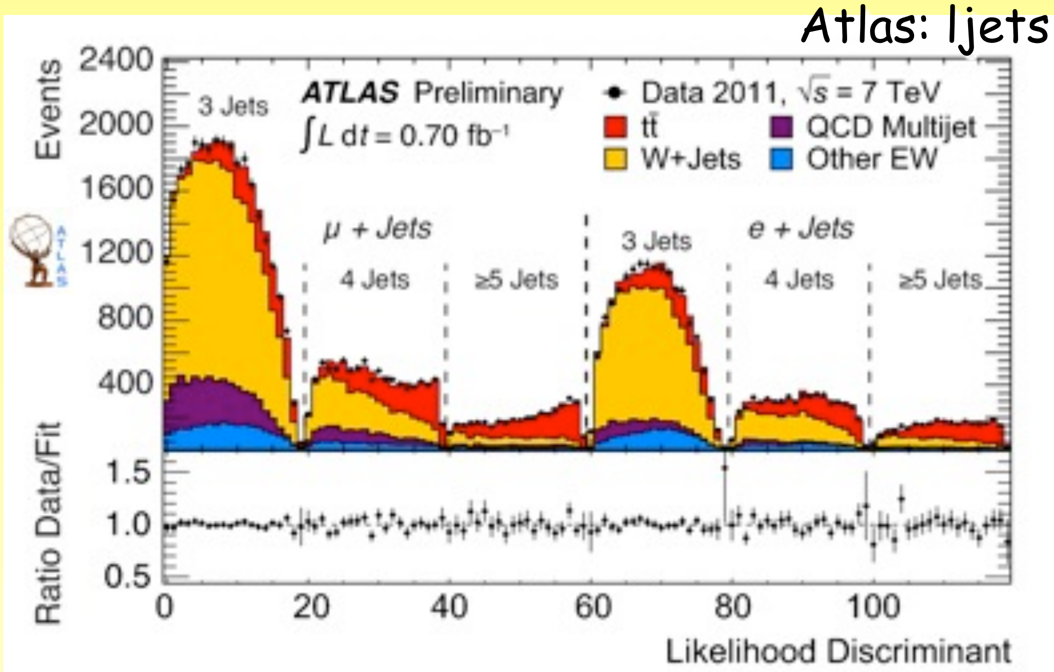


Back-up

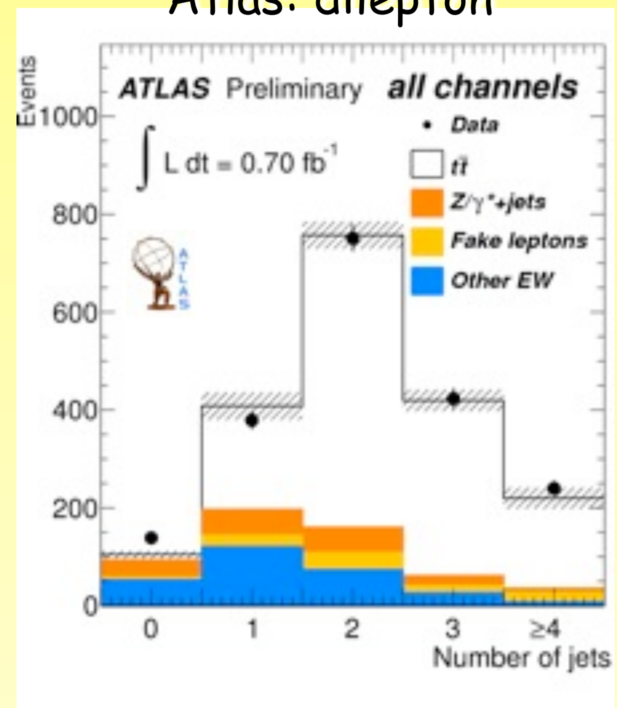
Top Pair Cross Sections at 7 TeV

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

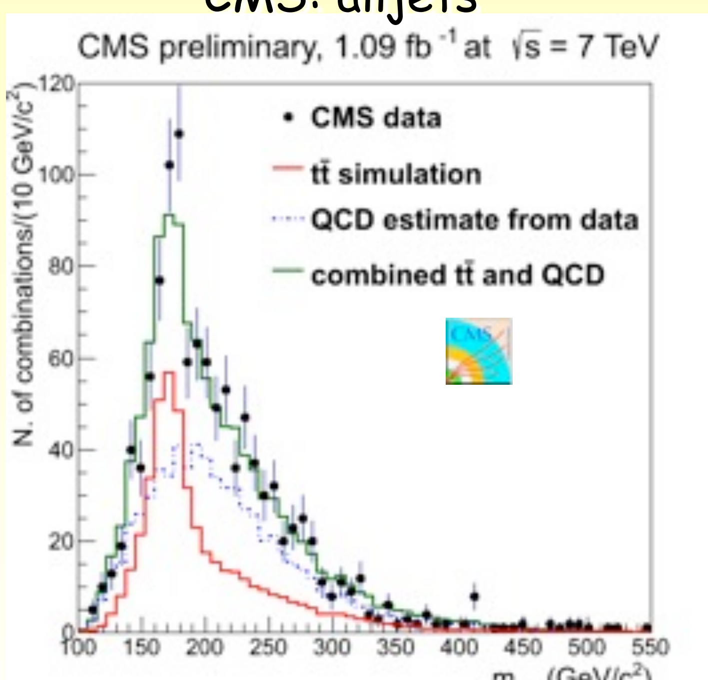
Atlas: ljets



Atlas: dilepton



CMS: alljets



CMS: μ τ