Measurements of Top Quark Properties at the Tevatron

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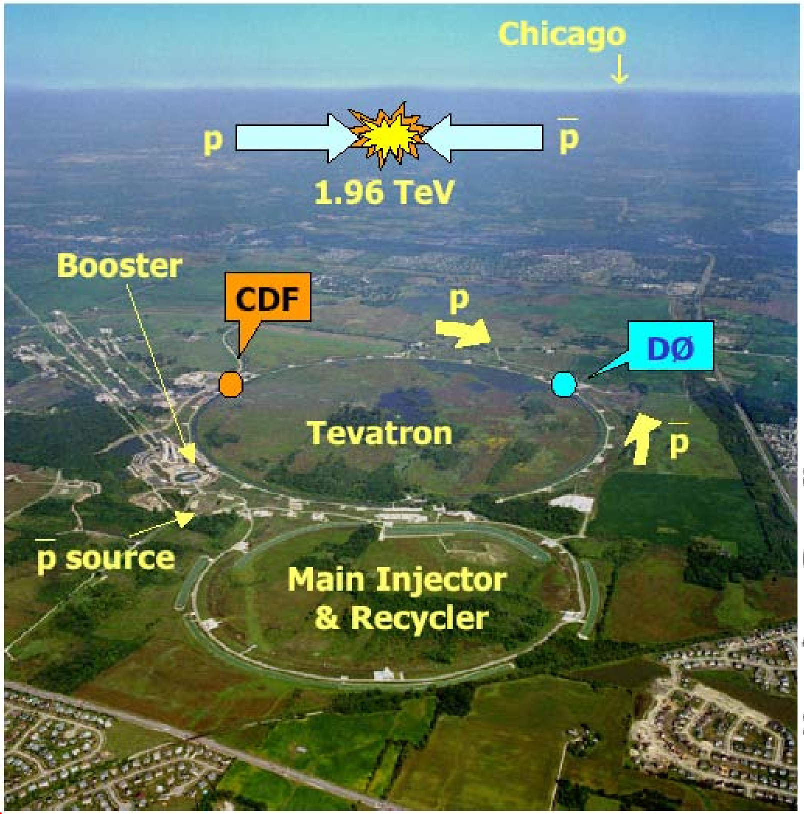
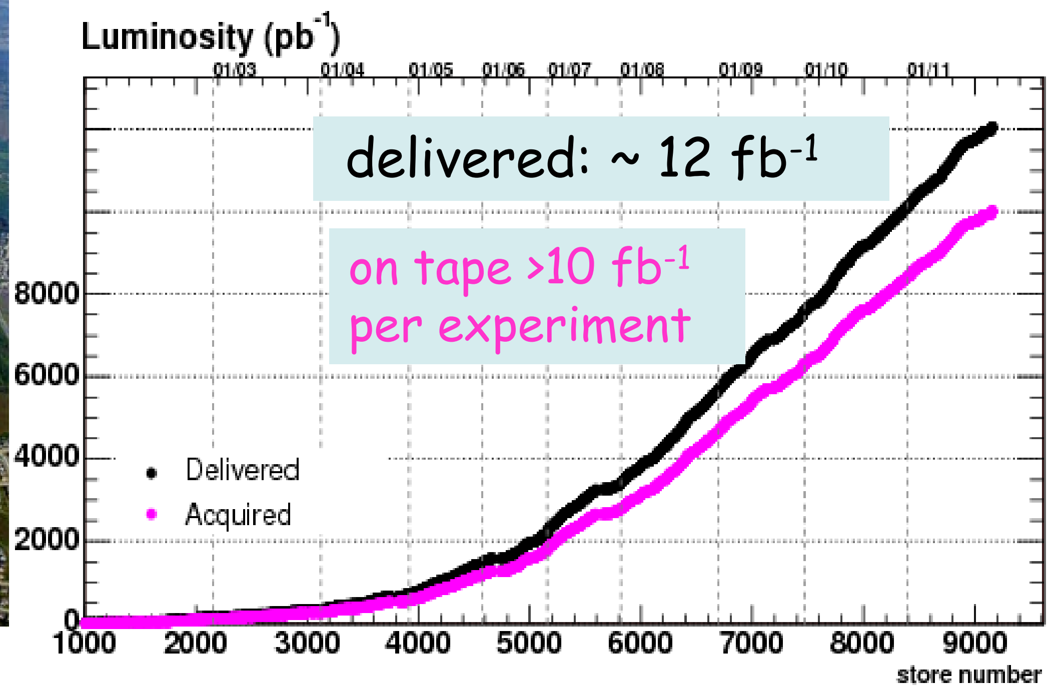
LC13 ECT* Trento, September 17, 2013

The Fermilab Tevatron

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

Tevatron stopped taking data on september 30, 2011





The birthplace of the top quark,
observed in 1995 by CDF and D0

Top Quark Production at Tevatron

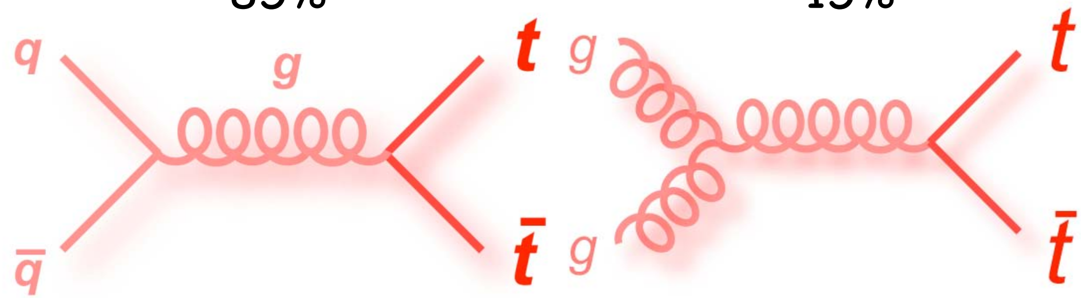
- QCD pair production

$\sigma_{SM} = 7.35^{+0.28}_{\ 0.33}$ pb

(for m_{Top}= 173 GeV)

(arXiv:1303.6254)

~85% ~15%



Dominant process at Tevatron

Dominant process at LHC

Tevatron is the right place to study the $q\bar{q}$ annihilation in $t\bar{t}$ production

Top Quark Production at Tevatron

- <u>QCD pair production</u>

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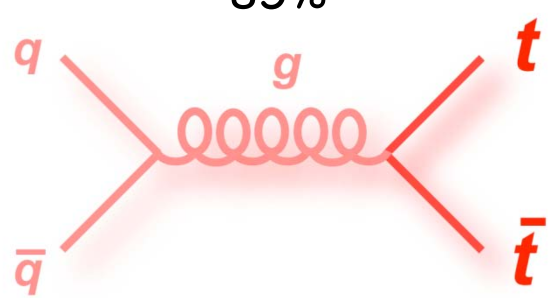
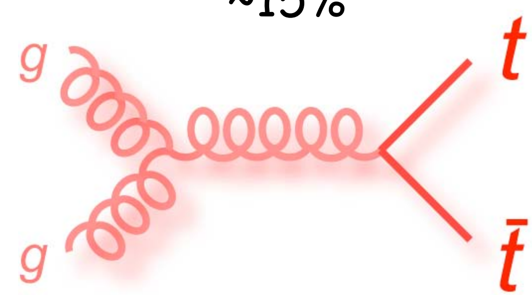


Dominant process at Tevatron

~15%



Dominant process at LHC

Tevatron is the right place to study the $q\bar{q}$ annihilation in $t\bar{t}$ production

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- <u>EWK single-top production</u>

> s-channel: σ_{SM} = 1.04 ± 0.06 pb

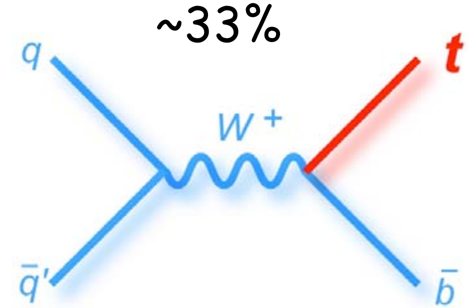
> t-channel: σ_{SM} = 2.1 ± 0.1 pb

(for m_{Top}= 173 GeV)

PRD 83, 091503 (2011)
PRD 81, 054028 (2010)
PRD 82, 054018 (2010)
arxiv:1210.7813.

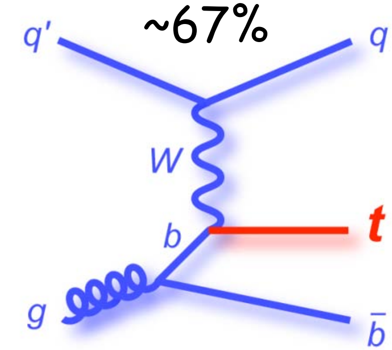
s-channel

~33%



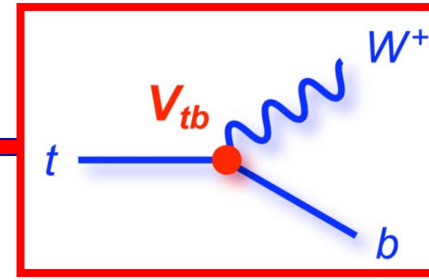
t-channel

~67%

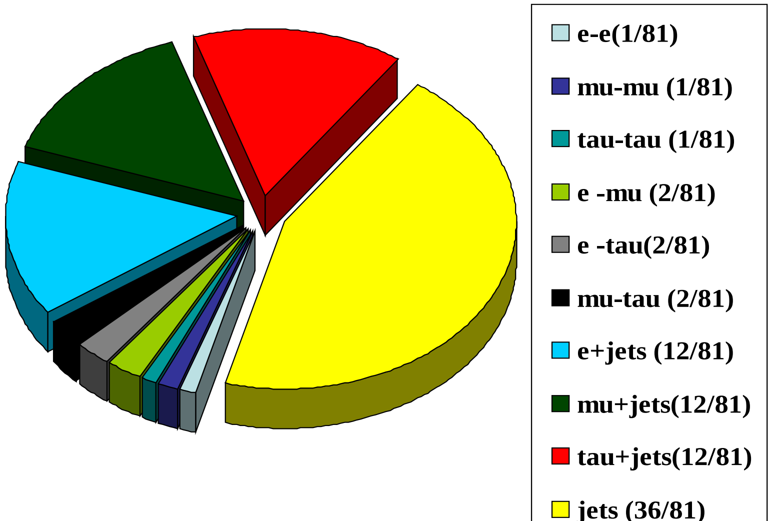


- Single top associated production Wt: σ ~ 0.2 pb, too small at the Tevatron

Top Quark Decay



SM predicts BR($t \rightarrow Wb$) ≈ 100%

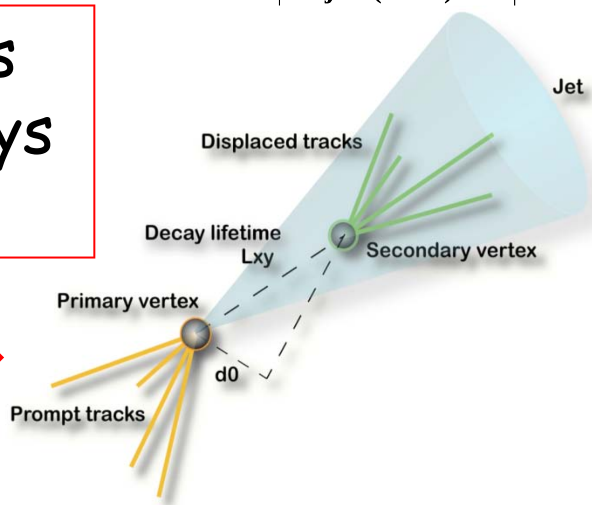


Event topology determined by the W decay modes

For ttbar pairs:

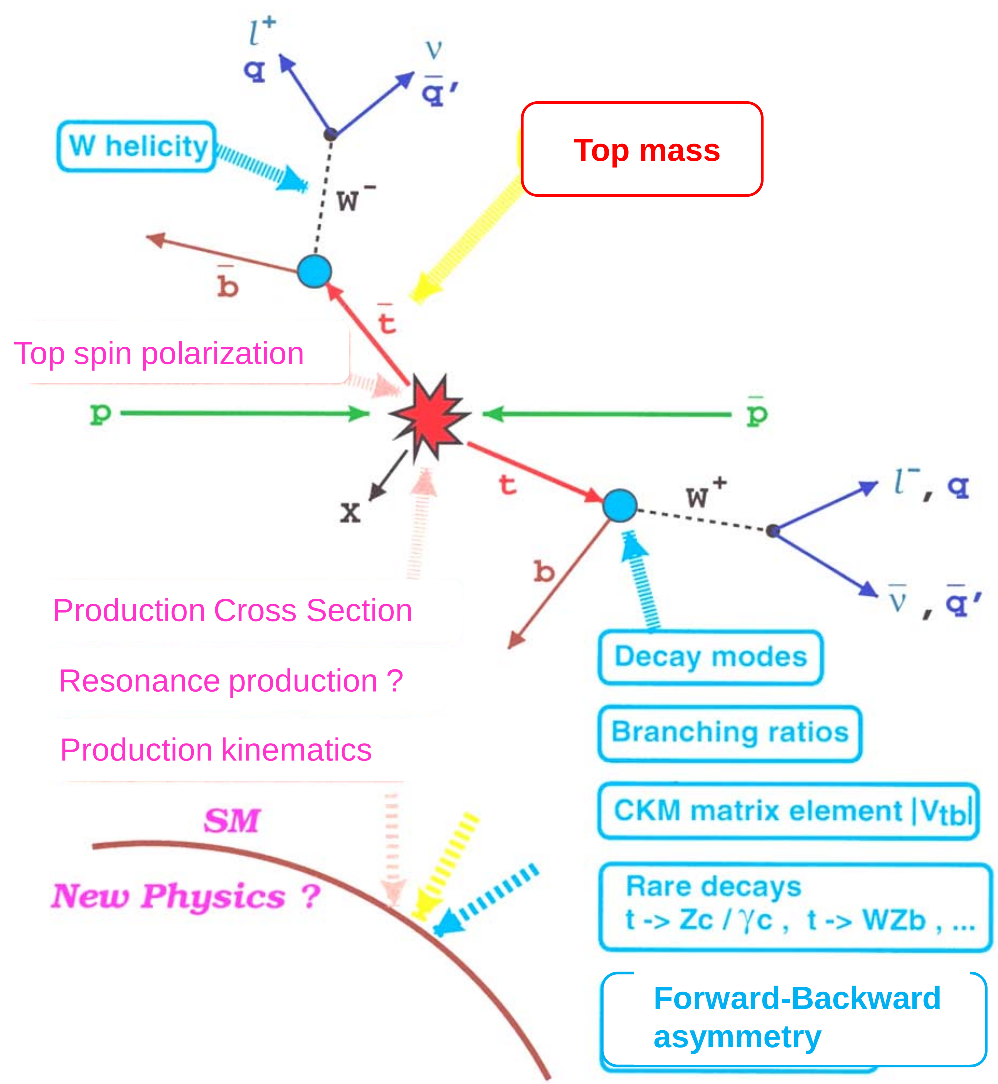
- Dilepton (ee, μμ, eμ)
  ⇒BR = 5%, 2 high-P_T leptons + 2 b-jets + 2 neutrinos
- Lepton (e or μ) + jets
  ⇒BR = 30%, single lepton + 4 jets (2 from b's) + 1 neutrino
- All Hadronic:
  ⇒BR = 45%, six jets, no neutrinos
- τ + X
  ⇒ BR = 20%

b quarks are always present



Study of top quark properties

- Since top discovery, ~ 20 years of top properties studies
- With full Tevatron dataset, era of precision measurements reached



- Is the observed top quark the Standard Model top quark?
- Any contribution from new physics?

Study of top quark properties

- Will present some of the properties measured in ttbar events in lepton+jets and dilepton channel, and the EWK single lepton channel, using up to the full RunII dataset (~9 fb^{-1}):

  ⇒ ttbar production cross section

  ⇒ single top production

  ⇒ evidence for s-channel production

  ⇒ top mass

  ⇒ A_{FB} asymmetry

  ⇒ Other top quark properties:

  ⇒ Branching ratios & V_{tb} measurement

  ⇒ Width of the top quark

  ⇒ Spin correlations

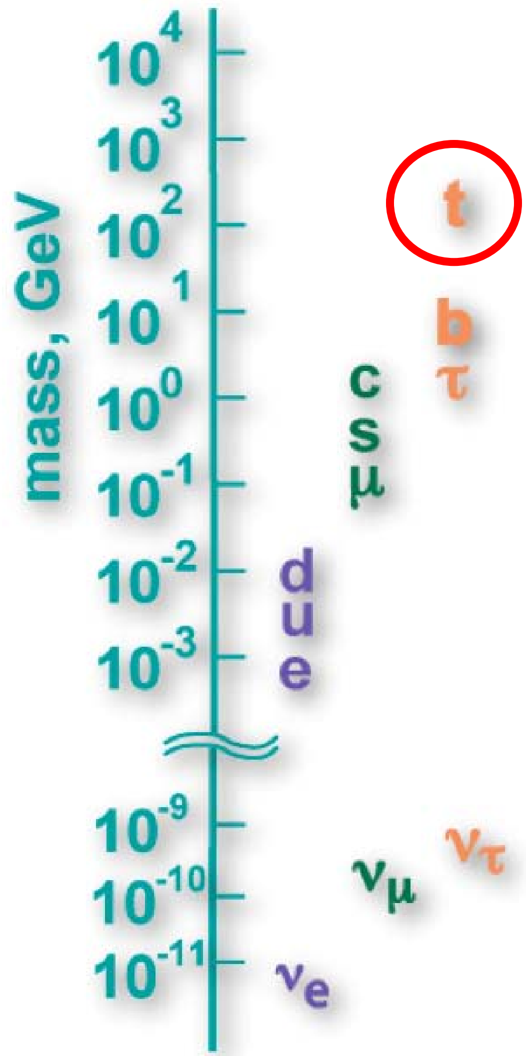
  ⇒ W helicity in top decays

  ⇒ Search for new physics in top production

Top pairs production

- Top quark is a very special particle:
  - ⇒ Heavier than all known particles
  - ⇒ decays before hadronizing →
    - ✓ Properties can be studied from distributions of decay products
- Measuring the production cross section is the first step in understanding any selected ttbar sample
- Test of theoretical QCD calculations

- New physics can cause:
  - ⇒ Change in overall production rate
  - ⇒ Change of rate in different channels



ttbar production cross section

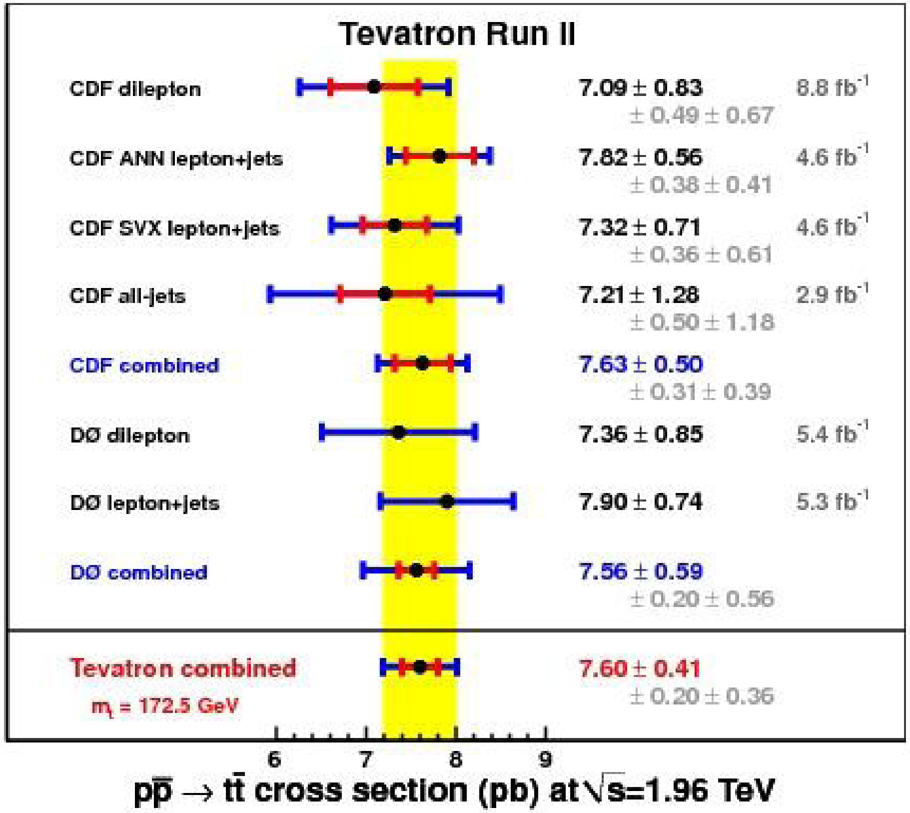
- Top pair XS measured in different decay channels
- Recent Tevatron combination:

⇒ Precise measurements from each experiment are combined for a detector and a Tevatron combination

⇒ Combination is performed taking into account statistical and systematic correlations

	CDF	D0		Tevatron
Central value of $\sigma_{t\bar{t}}$	7.71	7.56		7.65
Uncertainties			Corr.	
Statistical	0.31	0.20	no	0.20
Detector modeling	0.17	0.22	no	0.13
Signal modeling	0.22	0.13	yes	0.18
Jet modeling	0.21	0.11	no	0.13
Method	0.01	0.07	no	0.03
Background from theory	0.10	0.08	yes	0.10
Background based on data	0.07	0.06	no	0.05
Z boson theoretical normalization	0.13	0.00	yes	0.08
Inelastic $p\bar{p}$ cross section	0.05	0.32	yes	0.16
Luminosity detector	0.06	0.33	no	0.14
Total systematic	0.40	0.56		0.36

ttbar production cross section



Per experiment combination:

CDF

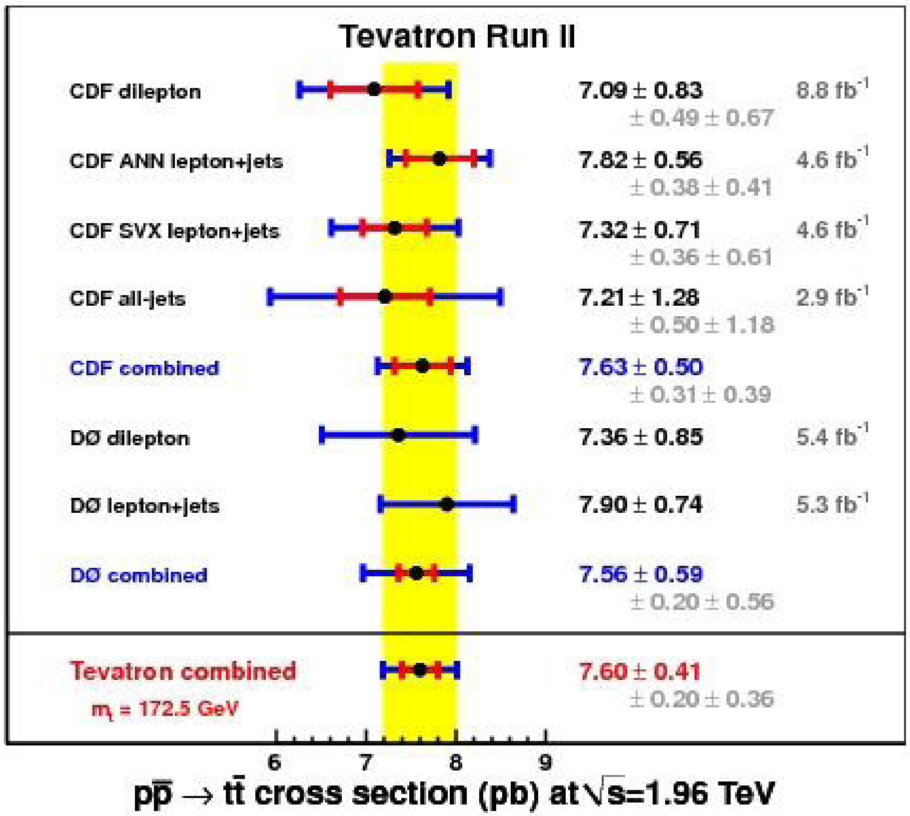
σ = 7.63 ± 0.50 (stat+syst) pb

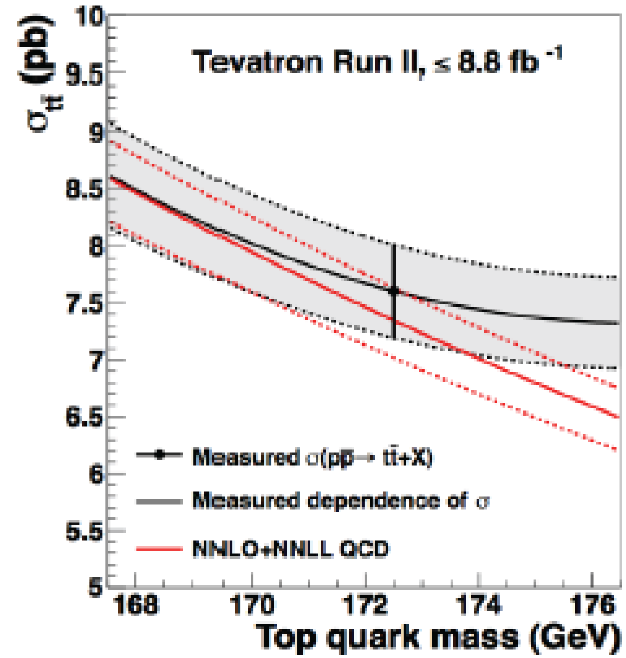
D0

σ = 7.56 ± 0.59 (stat+syst) pb

Consistent results from the different channels, methods, and detectors

ttbar production cross section





Experimental uncertainty 5.4%
Theory prediction: ≈4%

Tevatron combination:

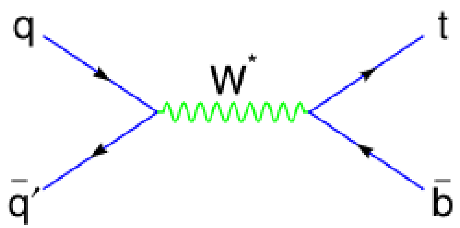
σ = 7.60 ± 0.41 (stat+syst) pb

NEW!

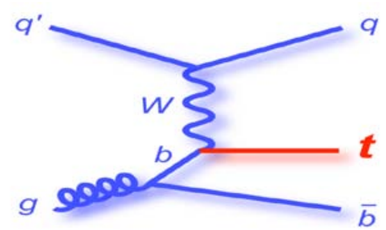
EWK Single top production

3 production processes:

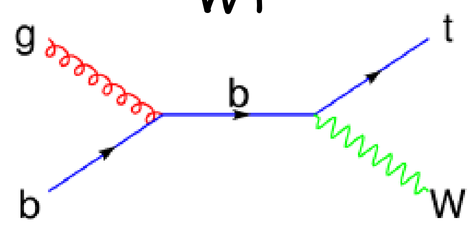
TeV: 1.04±0.06 pb
LHC8: 5.6±0.2pb
s-channel



2.1±0.1 pb
87±3 pb
t-channel

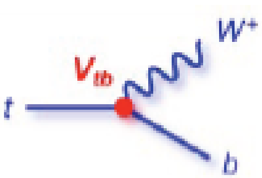


0.22±0.08 pb
22±2 pb
Wt



- Give access to the W-t-b vertex:
- Allows direct measurement of CKM matrix element $|V_{tb}|$
- Challenging measurement → extract small signal out of a large background with large uncertainties
- Use of multivariate techniques is mandatory
  → No single variable provides enough signal-background separation
- Cross section of s-channel at 8 TeV LHC only increased a little compared to Tevatron → s/b ratio lower for s-ch at LHC
  - **Single top quark observed by CDF & D0 in March 2009**

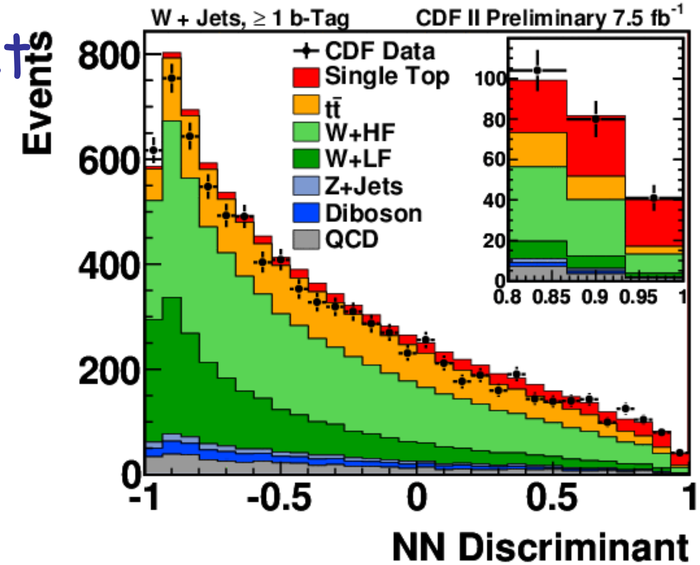
$\sigma \sim |V_{tb}|^2$



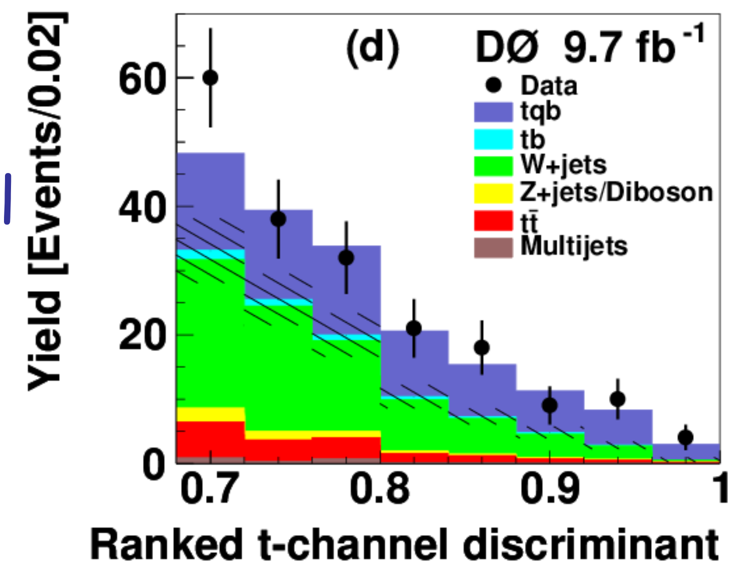
Single top: s+t channel cross section

- Starting from lepton+jets data-sets

- CDF NN analysis 7.5 fb^{-1}
- Added new lepton category to increase acceptance
- Train NN with 11-14 variables



- DO multivariate analysis 9.7 fb^{-1}
- Optimized selection for s-channel
- DO has used three different techniques: BDT, BNN, ME

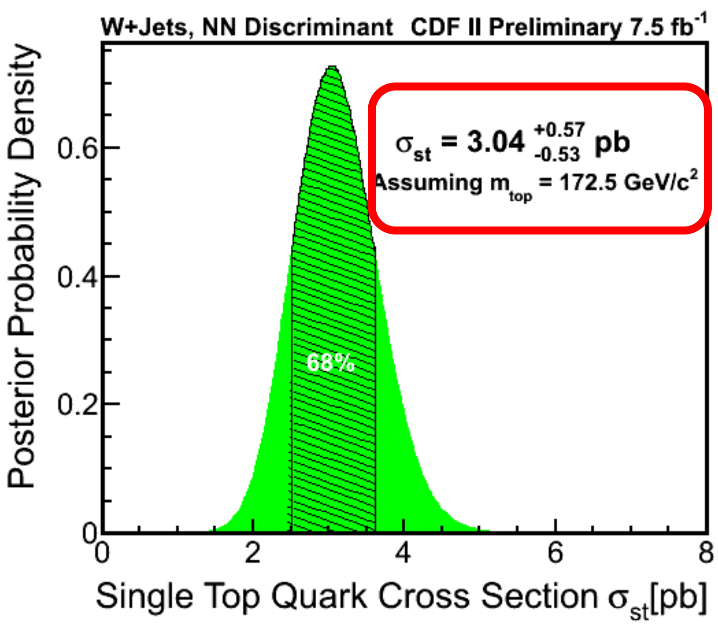


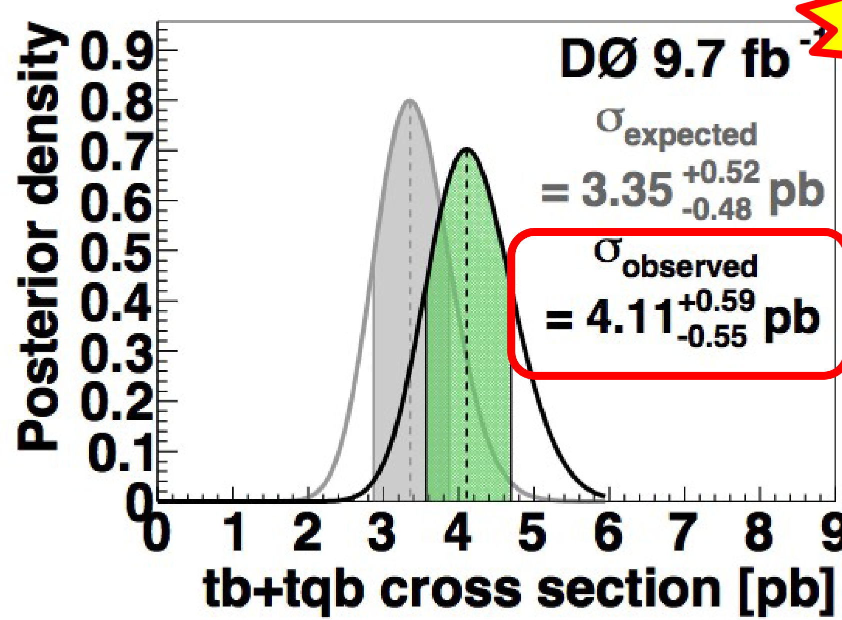
Single top: s+t channel cross section

- CDF 7.5 fb^{-1} (mt=172.5 GeV/c^2) Note 10793
  ⇒ $\sigma(s+t) = 3.0\ ^{+0.6}_{-0.5}$ pb (± 19%)
- DO 9.7 fb^{-1} (m_t=172.5 GeV/c^2) arXiv: 1307.0731
  ⇒ $\sigma(s+t) = 4.1 \pm 0.6$ pb (± 14%)
- Previous Tevatron combination (3.2-2.3 fb^{-1}):
  $\sigma(s+t) = 2.76\ ^{+0.58}_{-0.47}$ pb (±21%, m_t=170 GeV)

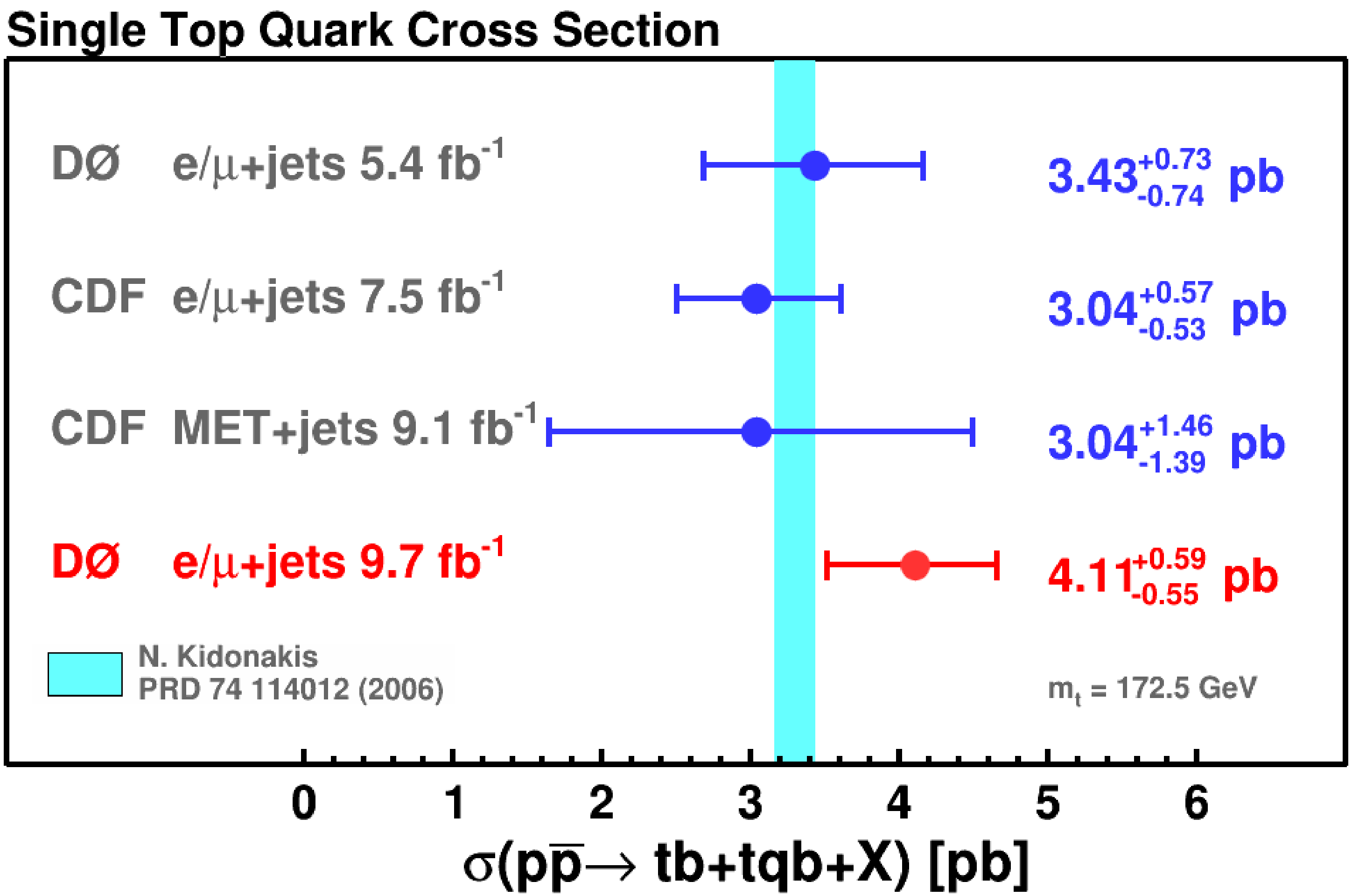
Main systematics:
- B-tagging
- W+jets normalization
- Jet energy scale /
- resolution

NEW!





Summary of s+t measurements



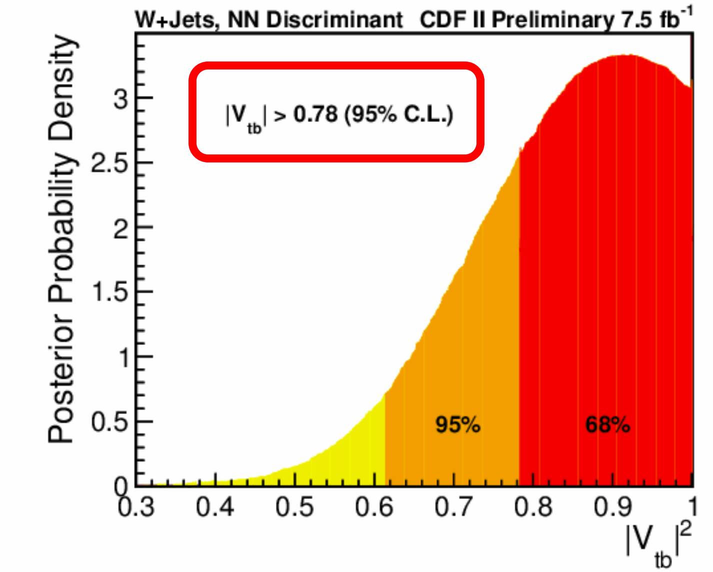
Direct $|V_{tb}|$ measurement from single top

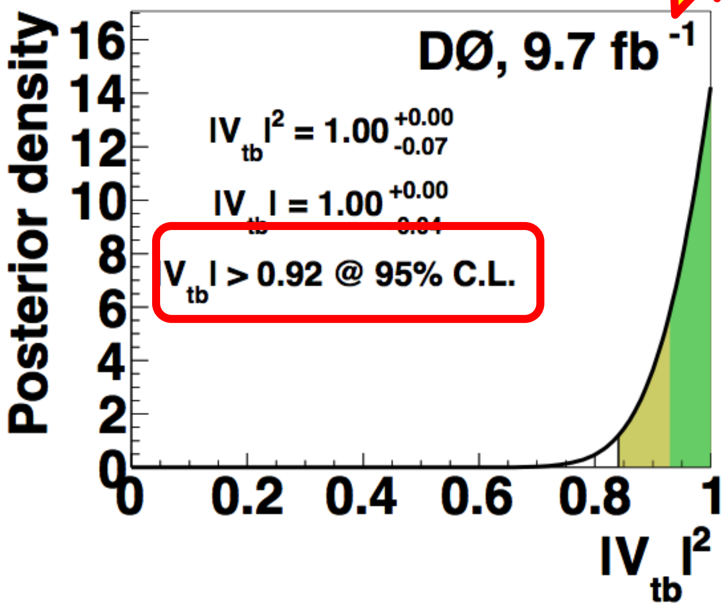
- Using cross section result to measure $|V_{tb}|$

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

- To transform $\sigma(s+t)$ measurement into V_{tb}, assume:
  - ⇒ SM top quark decay: $|V_{td}|^2+|V_{ts}|^2 \ll |V_{tb}|^2$
  - ⇒ V-A and CP conserving Wtb vertex
  - ⇒ No assumption on number of families or CKM unitarity

NEW!





$|V_{tb}| = 0.92\ ^{+0.10}_{-0.08}$ (stat+syst) ± 0.05 (theory)

Measure strength of V-A coupling:

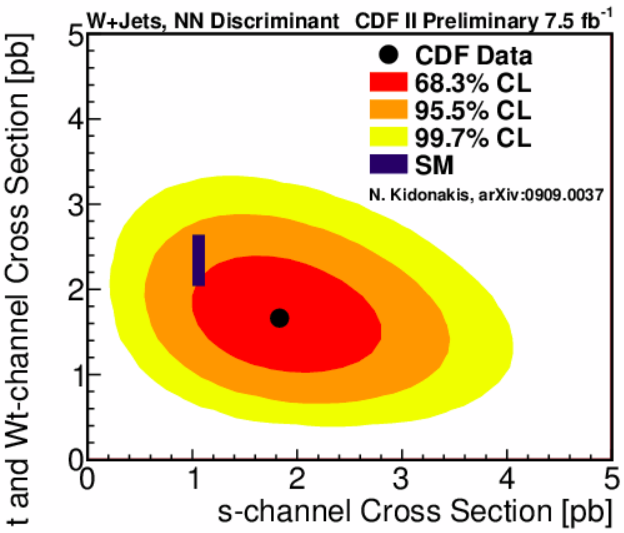
$|V_{tb} f^L_V| = 1.12\ ^{+0.09}_{-0.08}$

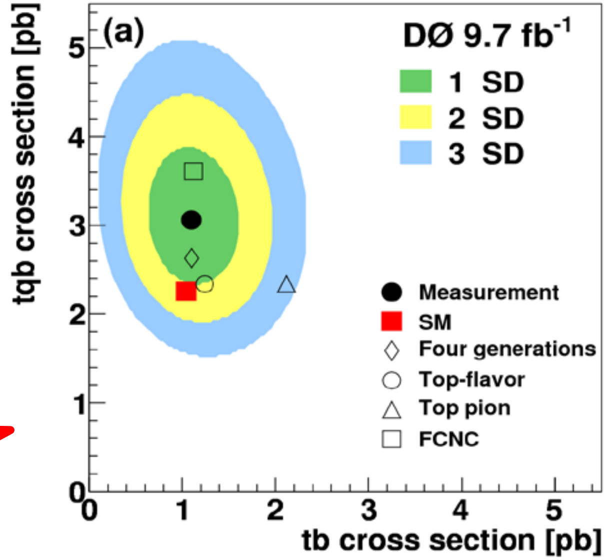
2D measurement of σ(s) and σ(t)

- s and t-channel sensitive to different BSM physics
- Relax t vs s SM ratio in posterior

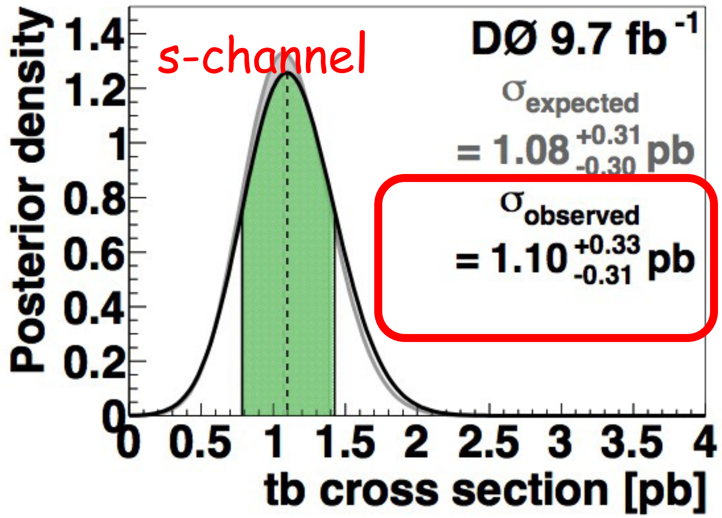
- CDF 7.5 fb^{-1}:
  - ⇒ σ (s) = 1.81 ± 0.63 pb (±33%)
  - ⇒ σ (t) = 1.49 ± 0.47 pb (±30%)

- DO 9.7 fb^{-1}:
  - ⇒ σ (s) = 1.10 ± 0.33 pb (±29%)
  - ⇒ σ (t) = 3.07 ± 0.53 pb (±17%)

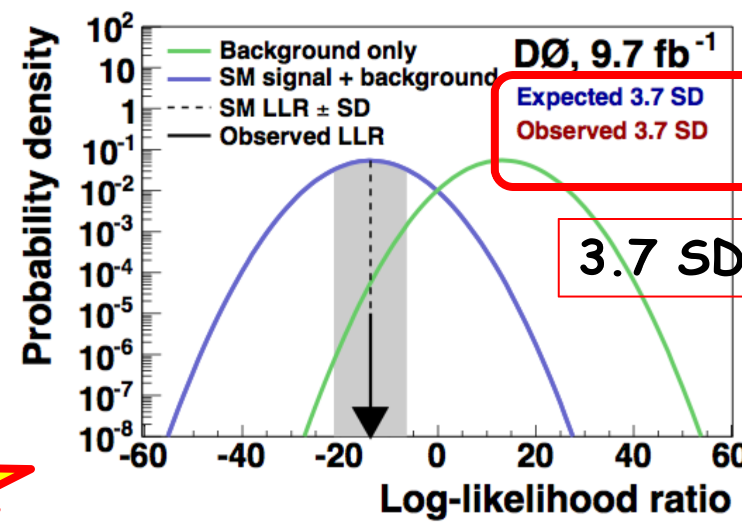




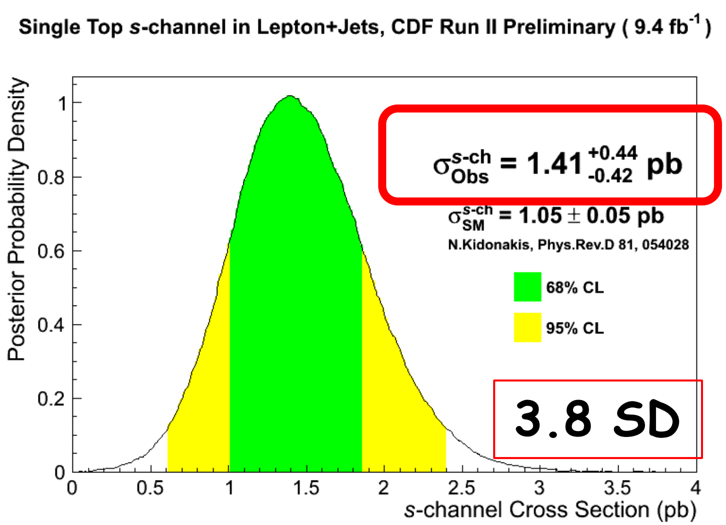
First evidence for s-channel



NEW!

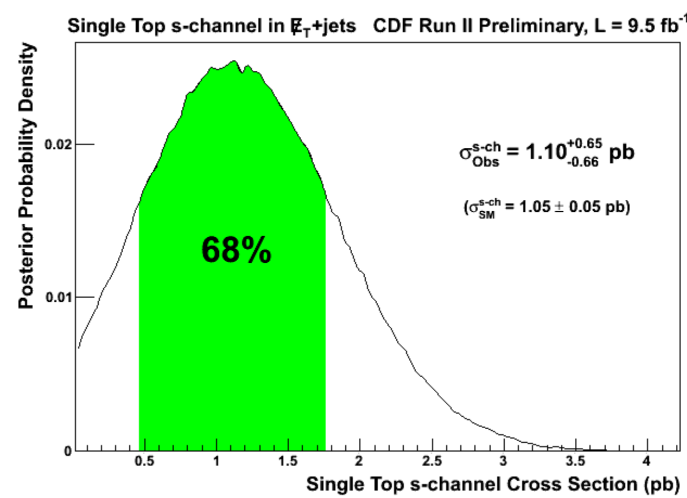


3.7 SD



3.8 SD

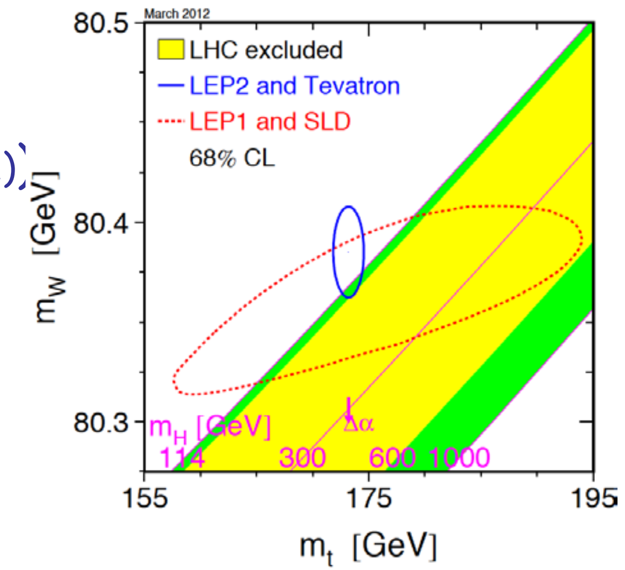
CDF Lepton +jets



CDF MET + jets

Measurement of top quark properties

- Top mass → free parameter of the SM
- Several methods explored for precision top mass measurement:
  - ⇒ Many clever tricks to improve sensitivity, such as in situ systematic uncertainty constraints
- Most sensitive analyses are lepton+jets from both CDF(PRL 109 152003 (2012)) and D0 (PRD 84 032004 (2011))

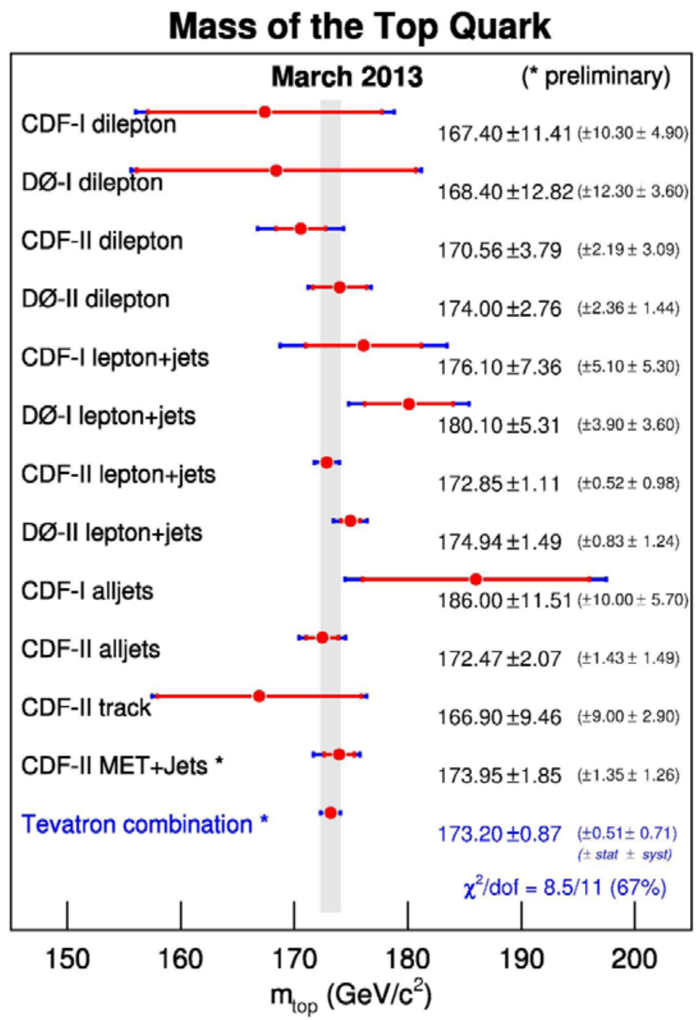


- Other properties → new physics can cause:
  - ⇒ Deviation of the measured top quark properties from the SM prediction

Tevatron top mass combination

- Results using up to 8.7fb^{-1}
- Run I and Run II results
- Combination performed using BLUE
- Limited by systematic uncertainties
  - ⇒ Dominant: signal modeling and jet energy scale uncertainties
- Good combination fit
  → probability of 67%

- **Total uncertainty of 0.5%**



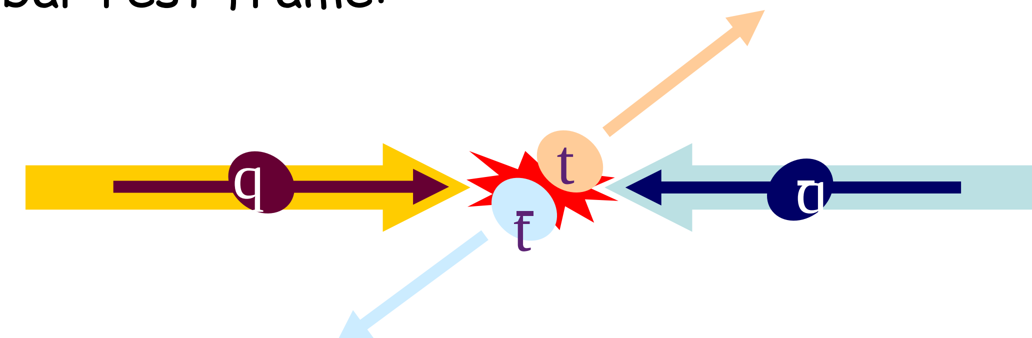
$$M_{top} = 173.20 \pm 0.51\ (stat) \pm 0.71\ (syst)\ GeV/c^2$$

arXiv:1305.3929

Forward backward asymmetry (A_{FB})

- NLO QCD predicts small (~7%) asymmetry from qqbar➔ttbar
- New physics could give rise to an asymmetry (Z´,axigluons,..)
- Reconstruct the top direction and the rapidity of top and anti-top quarks
- We use the rapidity difference (ΔY) of t➔lvb and antitop t➔jjb, which is proportional to Y_t in ttbar rest frame:

$$Y_t \propto q_{lepton} \cdot \Delta Y$$



- In terms of frame-independent rapidity difference:

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

- In terms of rapidity of lepton from top decay:

$$A_l = \frac{N(q_l y_l > 0) - N(q_l y_l < 0)}{N(q_l y_l > 0) + N(q_l y_l < 0)}$$

Forward backward asymmetry (A_{FB})

Lepton + jets system

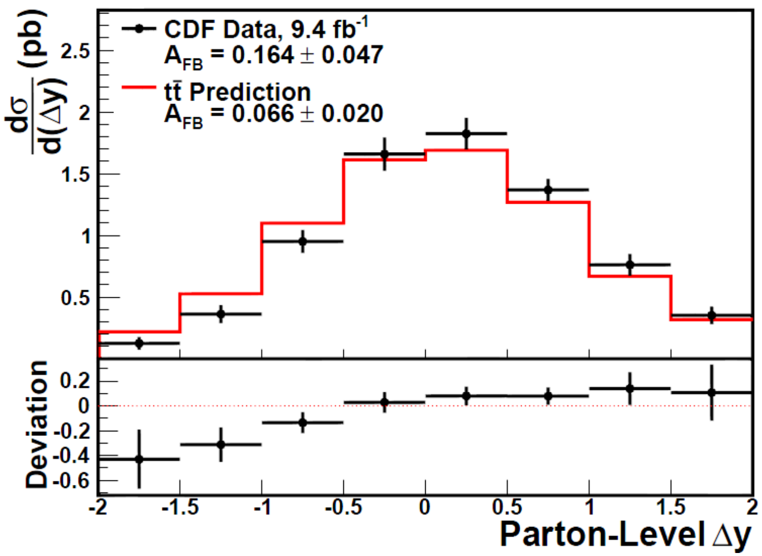
CDF 9.4 fb^{-1}

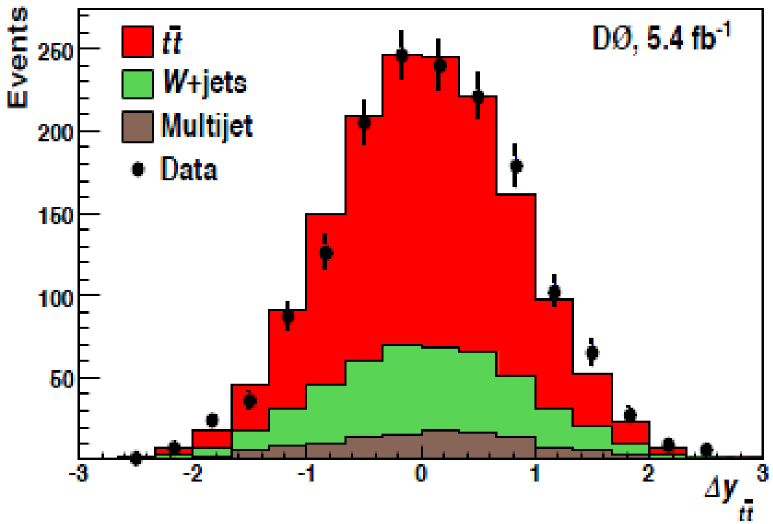
- Measure Δy spectrum in data
- Subtract background distributions
- Correct for acceptance and detector resolution effects
- Parton level result:

$\Rightarrow A = 0.164 \pm 0.047$ (stat+syst)

- D0 5.4 fb^{-1}, similar analysis:

$\Rightarrow A = (19.6 \pm 6.0(\text{stat})^{+1.8}_{-2.6}(\text{syst}))\%$

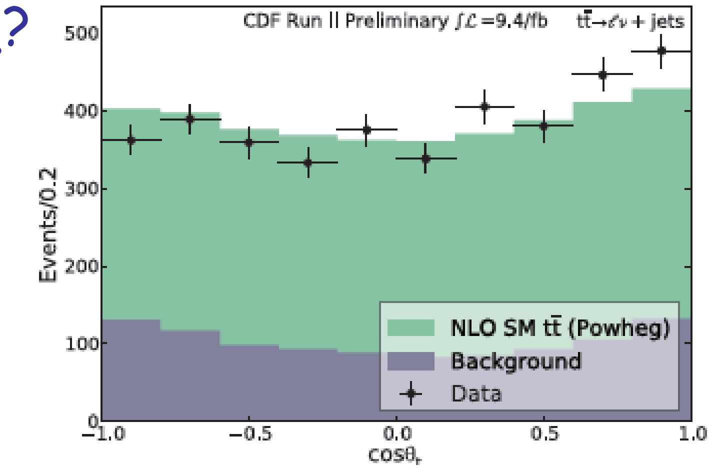




Angular differential cross section

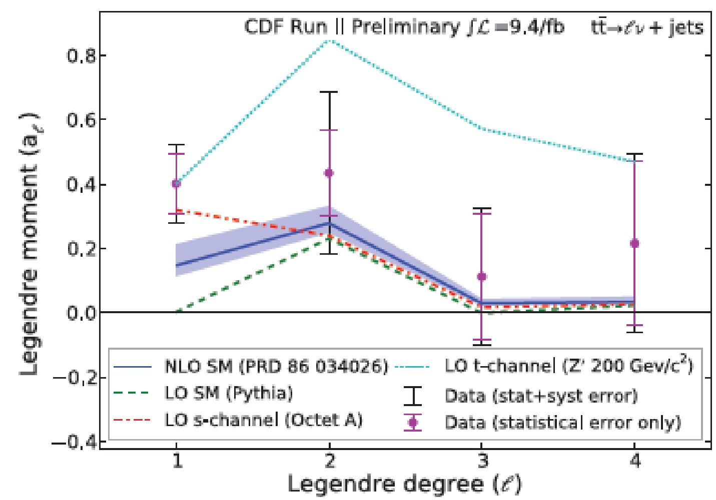
- cosθ of top quark wrt the beam axis in ttbar rest frame
- Asymmetry summarizes the angular distribution in one number: what component of angular shape explains A_{FB}?
- Use expansion in Legendre polynomials:

$$\frac{d\sigma(t\bar{t})}{d\cos\theta} = \sum a_l P_l(\cos\theta)$$



- Measure moments a_1 – a_8

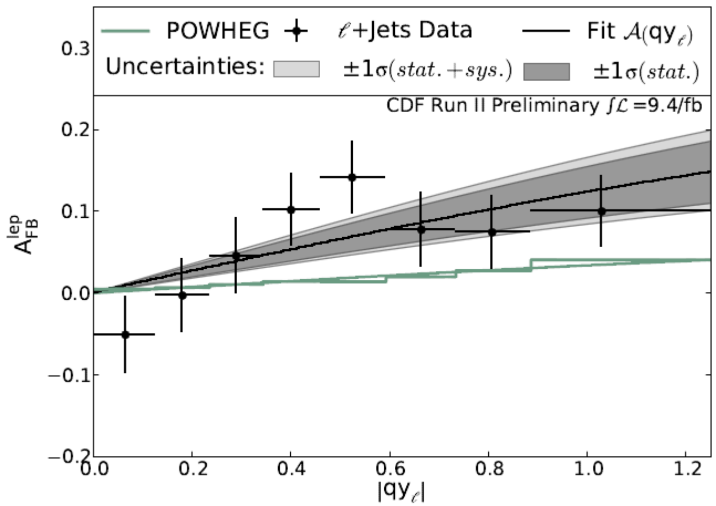
ℓ	$P_\ell(x)$
0	1
1	x
2	$\frac{1}{2}(3x^2-1)$
3	$\frac{1}{2}(5x^3-3x)$
4	$\frac{1}{8}(35x^4-30x^2+3)$
5	$\frac{1}{8}(63x^5-70x^3+15x)$

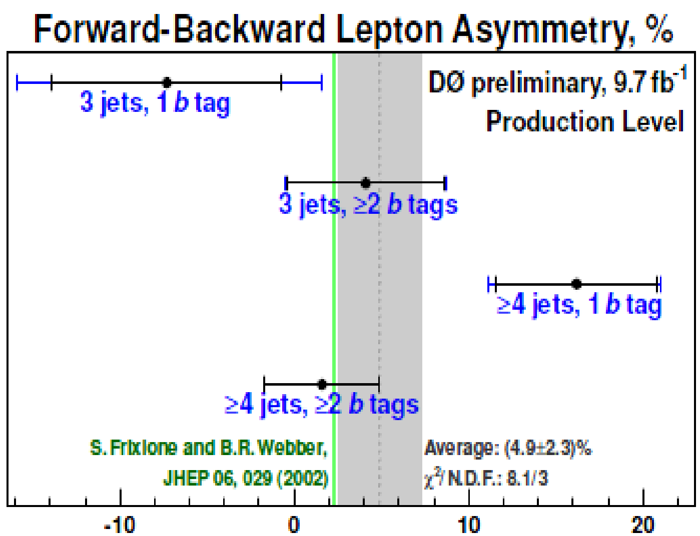


- Legendre moments consistent with SM except 1st (2.2σ): sufficient to explain excess in A_{FB}

Lepton Forward-Backward Asymmetry

- A^ℓ use lepton η from W decay
  - ⇒ Insensitive to biases from top reconstruction procedure
- A^ℓ kinematically correlated with $A_{FB} \rightarrow A^\ell \sim(0.5)A_{FB}$ (PRD 86 034026)





NEW!

1+3 jets - New channels

1 tag - Was high in 5.4fb^{-1}

2 tags - Now has higher weight because of higher purity

CDF: $A^\ell_{FB} = 0.094^{+0.032}_{-0.029}$ 2.3 SD from NLO SM

D0: $A^\ell_{FB} = 0.047 \pm 0.023(\text{stat})^{+0.011}_{-0.014}(\text{syst})$

Expect. from POWHEG ~ 0.03

Forward-Backward Asymmetry (A_{FB})

- Dilepton system
- CDF 5.1 fb^{-1}

  $\Rightarrow A_{FB\ (corrected)} = 0.42 \pm 0.15_{stat} \pm 0.05_{syst}$

- D0 9.7 fb^{-1}

  $\Rightarrow A^{\ell} = 4.4 \pm 3.7\ (stat) \pm 1.1\ (syst)\%$

  ✓ A^{ℓ} *(predicted)* $= 3.8 \pm 0.3\%$

  $\Rightarrow A^{\ell\ell} = 12.3 \pm 5.4\ (stat) \pm 1.5\ (syst)\%.$

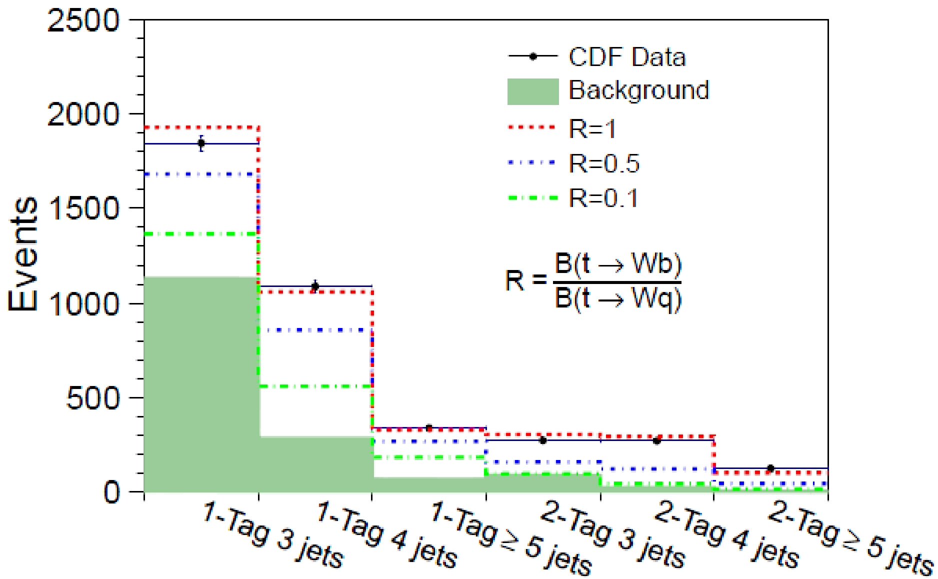
  ✓ $A^{\ell\ell}$ *(predicted)* $= 4.8 \pm 0.4\%$

Ratio of branching fractions R

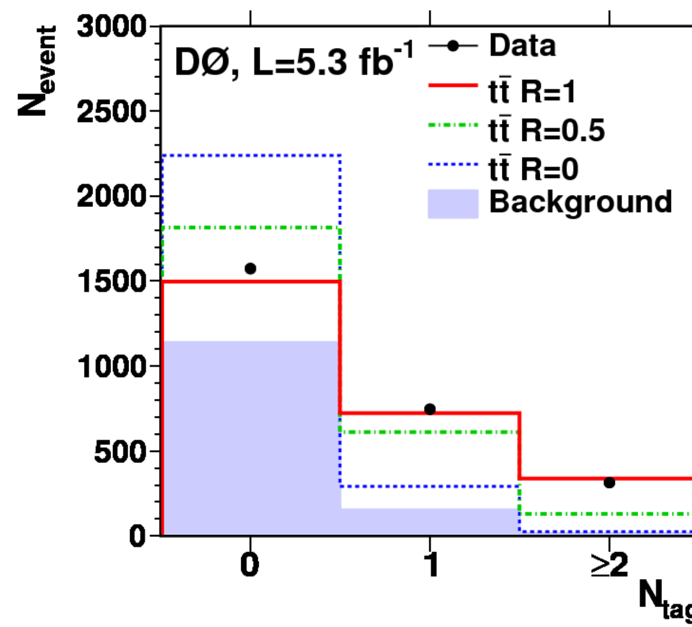
$$R = \frac{BR(t \to Wb)}{BR(t \to Wq)} = \frac{|V_{tb}|^2}{|V_{td}|^2 + |V_{ts}|^2 + |V_{tb}|^2}$$

- SM: R~1 constrained by CKM unitarity
- Expect 2 b's in each top-antitop event.
- Changes in R affect jet and b-tagged jet multiplicity.
- R<1 would indicate new physics

CDF L=8.7 fb^{-1} full RunII



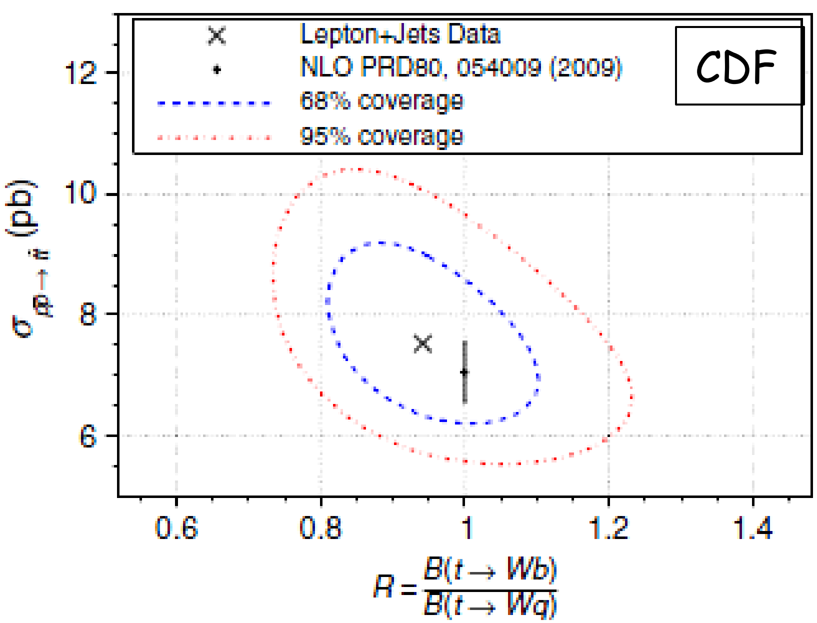
D0 L=5.4 fb^{-1} events >= 4 jets



Ratio of branching fractions R

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

- Likelihood fit to jet/b-tagged jet multiplicity
- Simultaneously minimize for both R and total cross section
- $|V_{tb}|$ derived assuming CKM unitarity



CDF L=8.7 fb^{-1}, Lepton+jets

σ = (7.5 ± 1.0) pb

R = 0.94 ± 0.09 (stat+syst)

$|V_{tb}|$ = 0.97 ± 0.05

PRD 87, 111101 (2013)

D0 L=5.4 fb^{-1} Lepton+jets and Dilepton

$\sigma = (7.74\ ^{+0.67}_{-0.57})$ pb

R = 0.90 ± 0.04 (stat+syst)

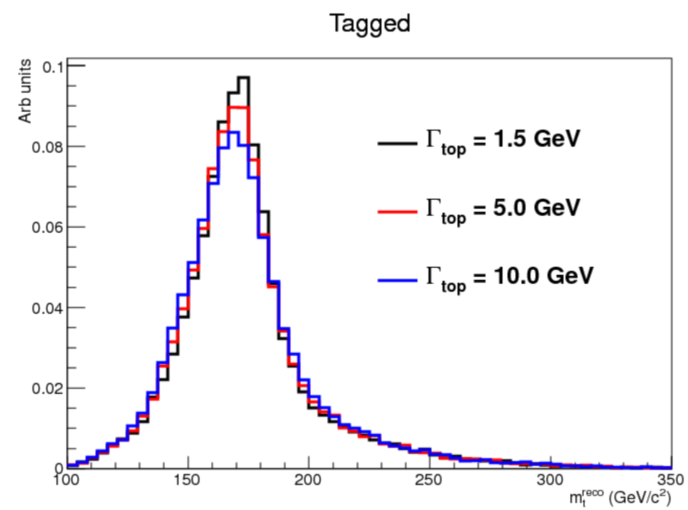
$|V_{tb}|$ = 0.95 ± 0.02

PRL 107, 121802 (2011)

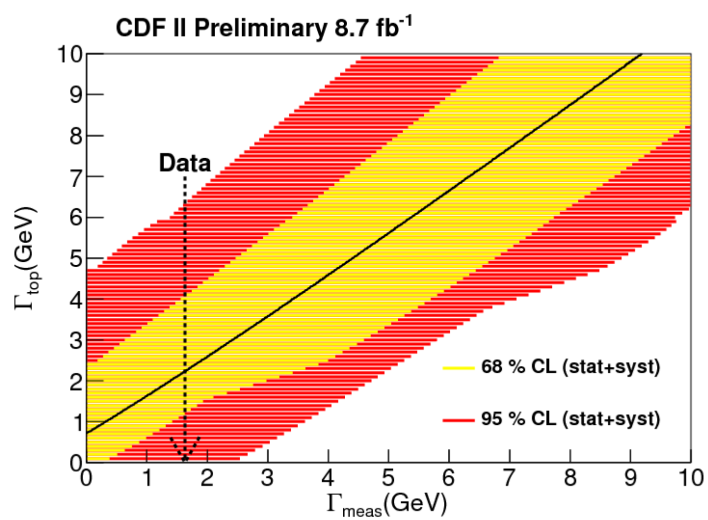
Top quark width

- SM predicts Γ_{top} ~ 1.3 GeV
- Test for invisible decays
- Reconstruct top mass in lepton+jets
- Derive confidence bands from simulated experiments
- Systematic effects folded in the likelihood function

CDF L=8.7 fb^{-1} full RunII



- Γ_{top} < 6.38 GeV @ 95% CL
- 1.10 GeV < Γ_{top} < 4.05 GeV @ 68% CL

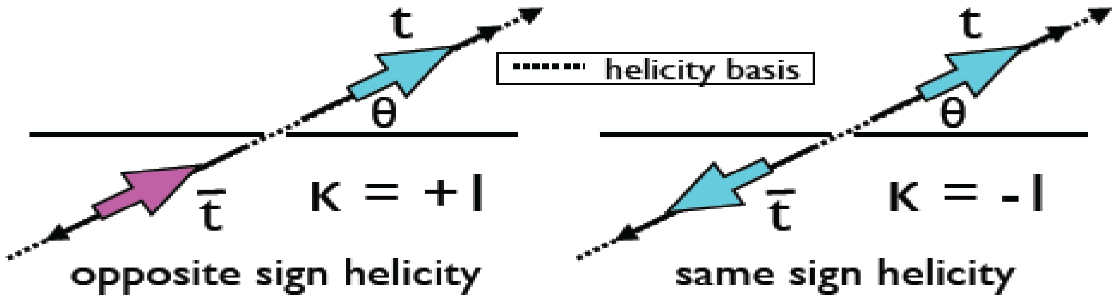


- Conf note 10936, PRL in preparation

Top-antitop spin correlation

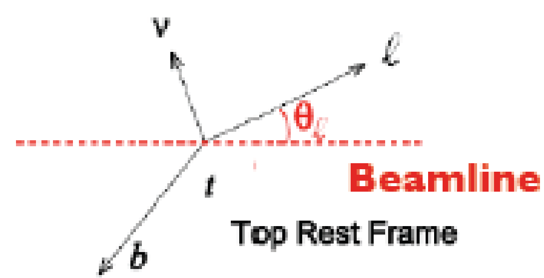
- Top pairs are produced with a definite spin state
- Information on the spin carried by the decay products

Depends on the production mechanism!



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

  - Quark-antiquark annihilation (~85%): spin 1
  - Gluon fusion (~15%): spin 0
- New physics could change the spin-correlation parameter
  PRD 45 124(1992), PRD75 095008 (2007)
- Correlation strength **κ** (frame dependent) related to decay products angle through:
- $$\frac{1}{\sigma}\frac{d^2\sigma}{d\cos\theta^+ d\cos\theta^-} = \frac{1+\kappa\cos\theta^+\cos\theta^-}{4}$$ where:

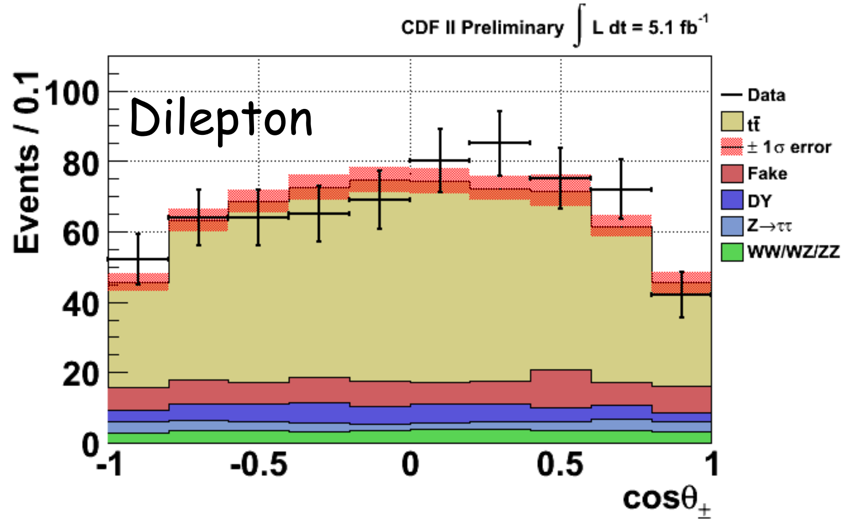


Top-antitop spin correlation

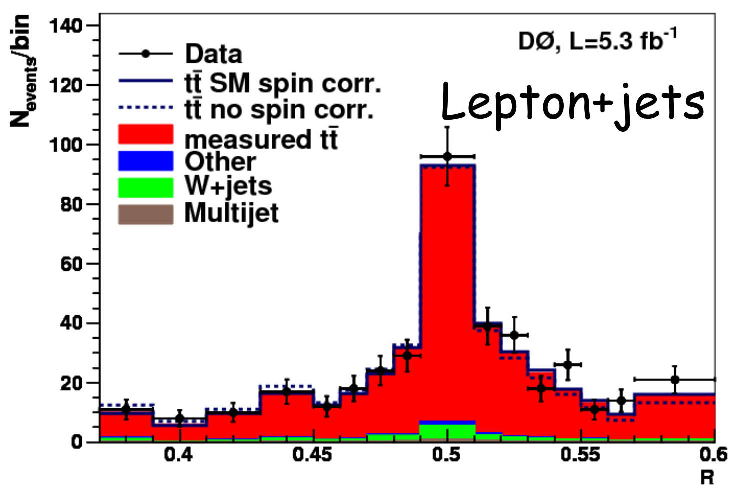
- CDF uses 5.1/5.3 fb^{-1}
- Results shown assume spin quantized along beam axis

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

- K $_{(lep+jets)}$ = 0.72 ± 0.69 conf note 10211
- K $_{(dilepton)}$ = 0.042 ± 0.563 conf note 10719



- D0 uses 5.4 fb^{-1}
- Matrix element method
- Evaluate event probability of SM-correl. ME and no-correl. ME
- Measured fraction of SM correlation 0.85 ± 0.29 (combining dilepton and lepton+jets)



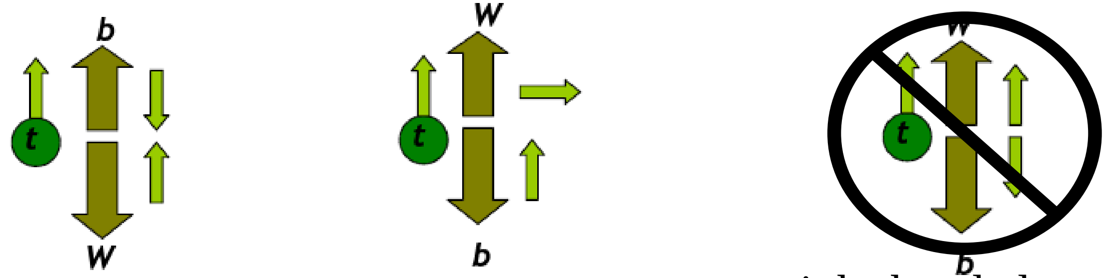
- Exclude no-correlation hyphotesis at 3.1σ

PRL108, 032004 (2012)

W Helicity in top decay

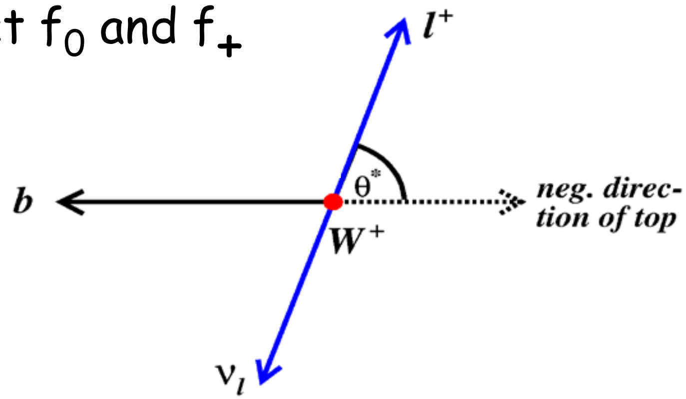
W helicity in top decays is fixed by M_{top}, M_W, and V-A structure of the tWb vertex. It is reflected in kinematics of W decay products.

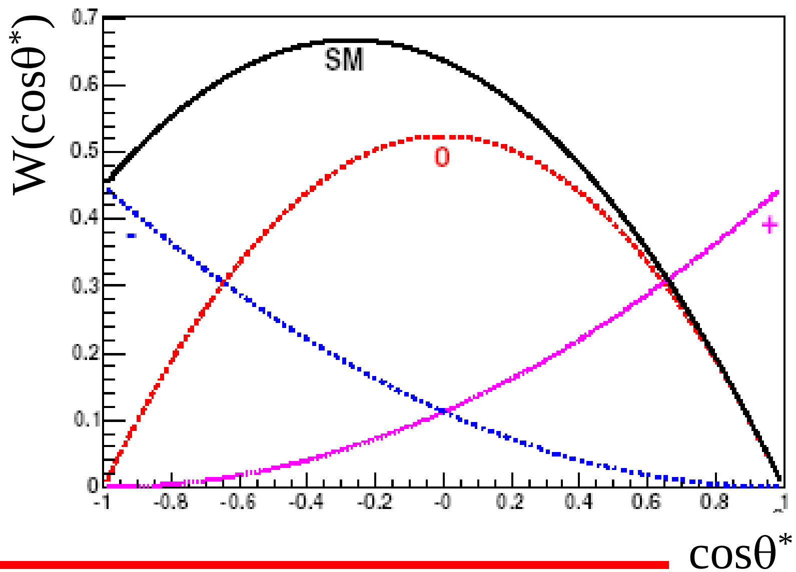
W helicity states:



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

⇒ Measure angular distribution of charged lepton wrt. top in W rest frame: cosθ* to extract f_0 and f_+

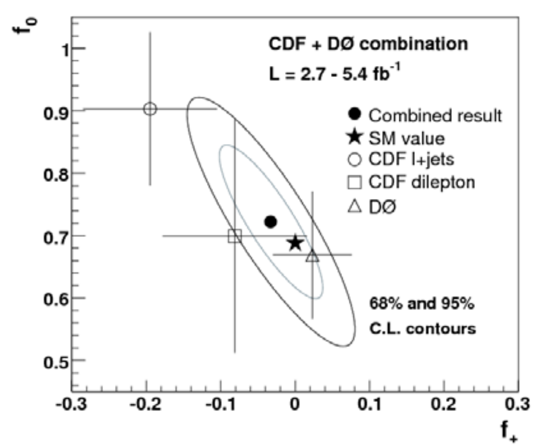




W Helicity in top decay

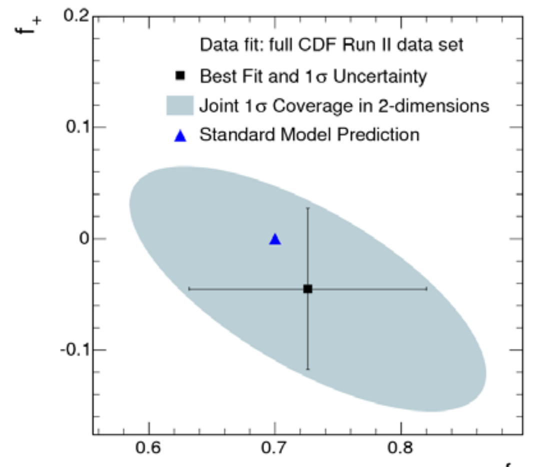
- CDF lepton+jets uses matrix element method
- CDF dilepton and D0 use fits to $\cos\theta^*$ distribution
- Fractions determined simultaneously (2D fit)
- Tevatron combination from 2.7-5.4 fb^{-1}:
  - $\Rightarrow f_+ = -0.033 \pm 0.046$
  - $\Rightarrow f_0 = 0.722 \pm 0.081$

  PRD 85, 071106 (2012)



- CDF lepton+jets updated to 8.7 fb^{-1}
- Result of 2D fit:
  - $\Rightarrow f_+ = -0.045 \pm 0.072$
  - $\Rightarrow f_0 = 0.726 \pm 0.094$
  - $\Rightarrow$ Measurement of f_0 almost as precise as combination

  PRD 87, 031104 (2013)



x and y-axis are flipped

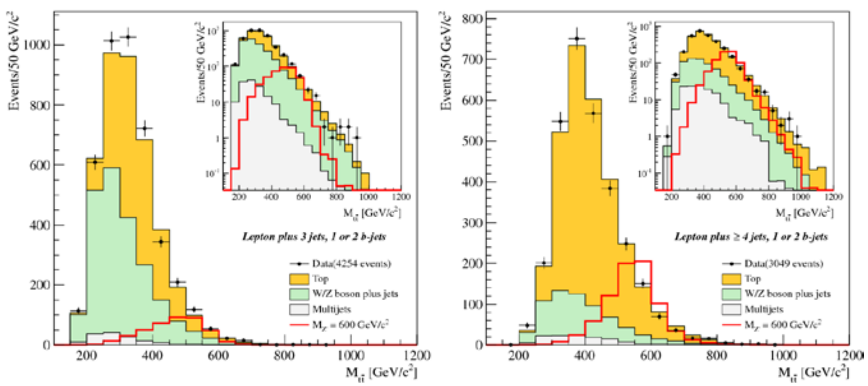
- **Results in good agreement with SM**

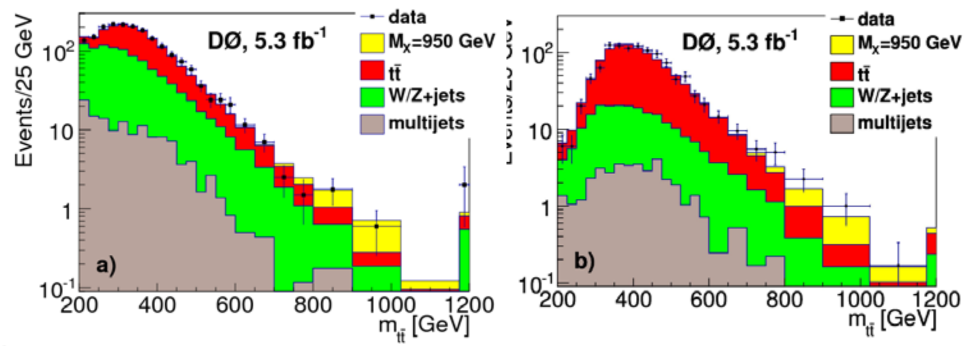
Search for resonant ttbar production

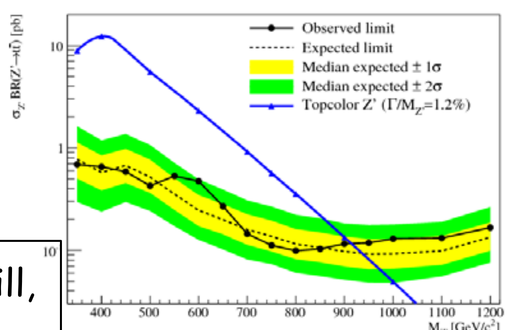
- Look at the M_{ttbar} spectrum in the lepton +jets final state, to see any deviation over the SM prediction

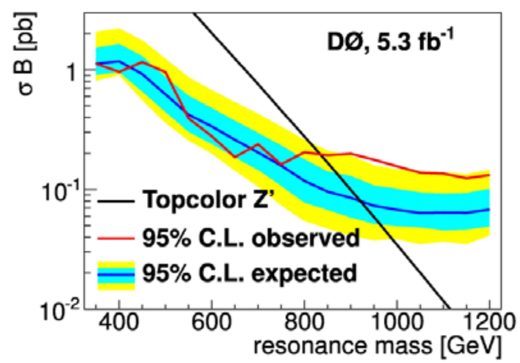
CDF L = 9.45 fb^{-1} full RunII dataset

D0 L = 5.3 fb^{-1}









* Harris, Hill, Parker '99

A topcolor leptophobic* Z' → ttbar is excluded at 95%CL with:

$M_{Z'} < 915\ GeV/c^2$

PRL 110, 121802 (2013)

$M_{Z'} < 835\ GeV/c^2$

PRD85, 051101 (2012)

Conclusion

- CDF & D0 are fully exploiting the Tevatron unique dataset and are in the process of making Tevatron legacy measurements
- Many top quark areas of study (i.e. cross sections, single top s-channel, spin correlations, A_{FB}) are complementary to LHC measurements
- All measurements shown here in agreement with SM prediction, except ~2.2σ effect deviation in A_{FB} from CDF data
- Data-taking is done, but there's still a lot to be learned from the Tevatron's top quark sample!
- See the websites of CDF's and D0's Top Groups and the Tevatron Electroweak Working Group for more information and results:
- http://www-cdf.fnal.gov/physics/new/top/top.html
- http://www-d0.fnal.gov/Run2Physics/top/top_public_web_pages/
- http://tevewwg.fnal.gov

Conclusion

- CDF & D0 are fully exploiting the Tevatron unique dataset and are in the process of making Tevatron legacy measurements
- Many top quark areas of study (i.e. cross sections, single top s-channel, spin correlations, A_{FB}) are complementary to LHC measurements
- All measurements shown … with SM prediction, except ~2.2σ ef… data

Thank you!

- Data-taking is … earned from the Tevatron's top quark sam…

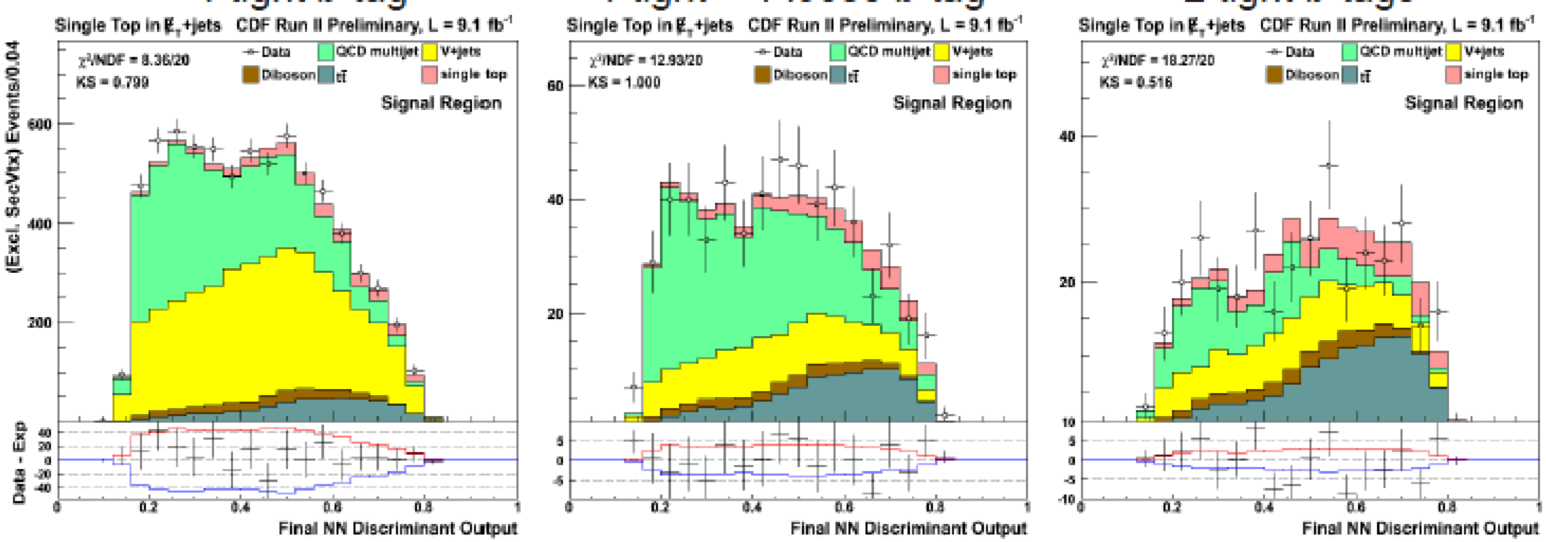
- See the websites of CDF's and D0's Top Groups and the Tevatron Electroweak Working Group for more information and results:
- http://www-cdf.fnal.gov/physics/new/top/top.html
- http://www-d0.fnal.gov/Run2Physics/top/top_public_web_pages/
- http://tevewwg.fnal.gov

Backup

MET+jets analysis

- MET+jets selection, 9.1fb^{-1}.
- Recover partially reconstructed electrons and muons
- Include $W \rightarrow \tau\nu$ (hadronically-decaying taus as jets)
- Completely orthogonal dataset to ℓ+jets selection
- Train several MVA against QCD and tt, then combine with NN

1 tight b-tag | 1 tight + 1 loose b-tag | 2 tight b-tags



$\Rightarrow$ $\sigma(s+t) = 3.0^{+1.5}_{-1.4}$ pb (±50%)

CDF Note 10979

D0 Single top analysis

Source of Uncertainty	Rate	Shape	Processes affected
Jet energy scale	0–8%	X	all
Initial and final state radiation	0–6%	X	single top, $t\bar{t}$
Parton distribution functions	0–1%	X	single top, $t\bar{t}$
Acceptance and efficiency scale	1–7%		single top, $t\bar{t}$, diboson, Z/γ^*+jets
Luminosity	6%		single top, $t\bar{t}$, diboson, Z/γ^*+jets
Jet flavor separator		X	all
Mistag model		X	W+light
Non-W model		X	Non-W
Factorization and renormalizatio		X	$Wb\bar{b}$
Jet η and ΔR distribution		X	W+light
Non-W normalization	40%		Non-W
$Wb\bar{b}$ and $Wc\bar{c}$ norm	30%		$Wb\bar{b}$, $Wc\bar{c}$
Wc normalization	30%		Wc
Mistag normalization	10–20%		W+light
$t\bar{t}$ normalization	8%		$t\bar{t}$
Monte Carlo generator	3–7%		single top, $t\bar{t}$
Single top normalization	7%		single top
Top mass	2-12%	X	single top, $t\bar{t}$

∗ X indicates the sources of uncertainty from shape variation

∗ Sources listed below double line are used only in $|V_{tb}|$ measurement

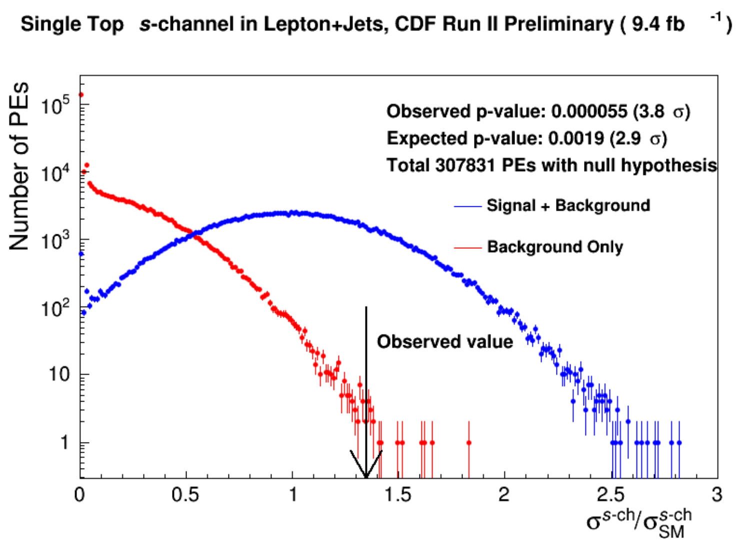
Top mass [GeV]	cross sections [pb]	
	t-channel	s-channel
170	$2.80^{+0.57}_{-0.61}$	$1.31^{+0.77}_{-0.74}$
172.5	**$2.90^{+0.59}_{-0.59}$**	**$0.98^{+0.62}_{-0.63}$**
175	$2.53^{+0.58}_{-0.57}$	$0.65^{+0.51}_{-0.50}$

CDF Single top analysis

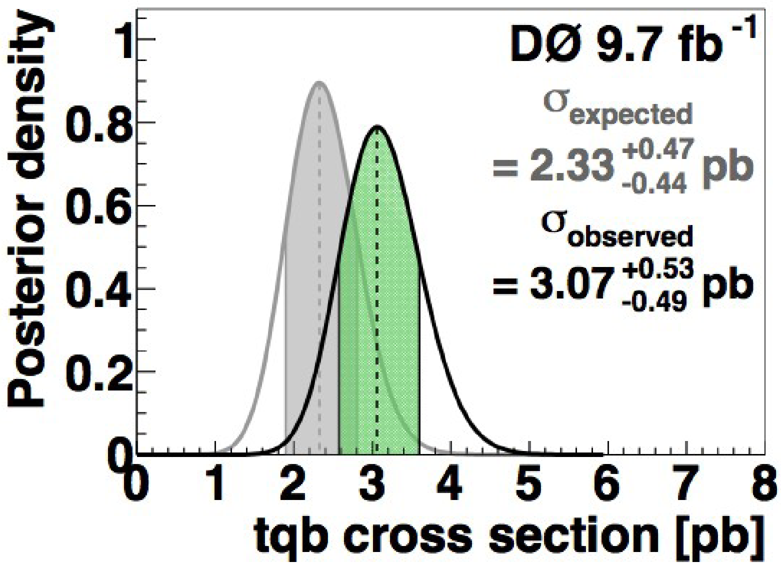
Source of uncertainty	Rate	Shape	Affected samples
b tagging scale factor uncertainty	4%-18%		$t\bar{t}$, single top, WZ, ZZ, Higgs
Charm mistag rate	7%-37%		WW
W+jets mistag rate	4%-37%		W + Mistag jets
Luminosity uncertainty	6%		$t\bar{t}$, single top, diboson, Higgs
Lepton acceptance uncertainty	2%-4%		$t\bar{t}$, single top, diboson, Higgs
Cross section uncertainty	6%-10%		$t\bar{t}$, single top, diboson, Higgs
Initial/Final state radiation	0%-10%	√	$t\bar{t}$, single top
Multijet normalization	40%		Multijet
Z+jets normalization	45%		Z+jets
Wbb and Wcc normalization	30%		Wbb, Wcc
Wc normalization	30%		Wc
Jet energy scale	0%-10%	√	All
Normalization and factorization scale		√	W+jets
Electron multijet background		√	Electron multijet

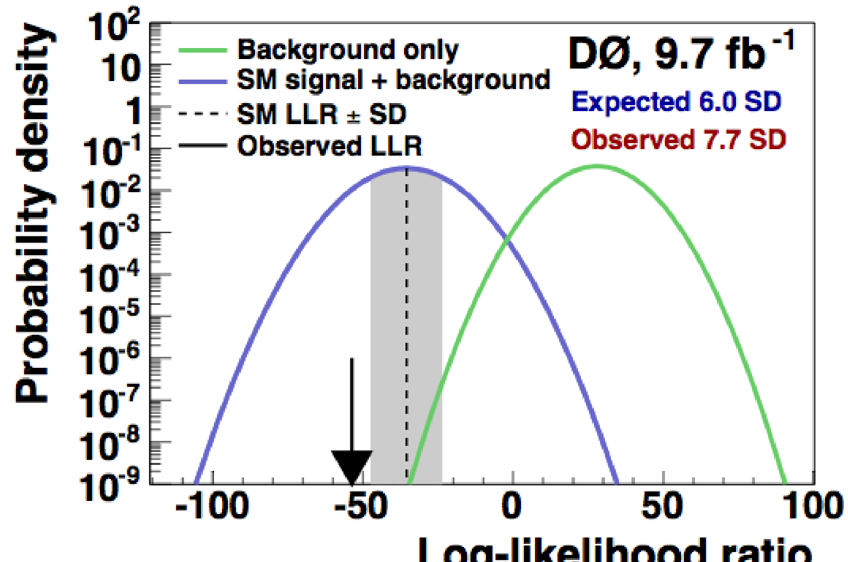
Table 1: Summary of all systematics considered in this analysis

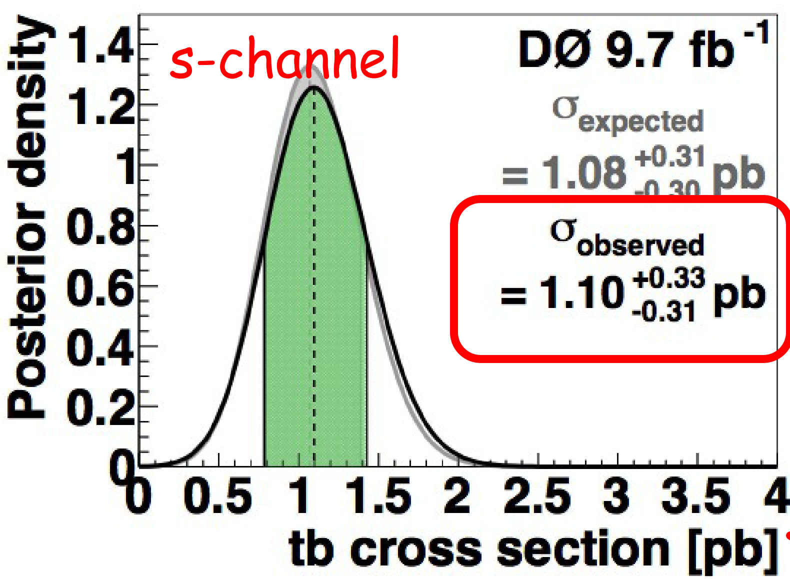
s-channel Lep+jets



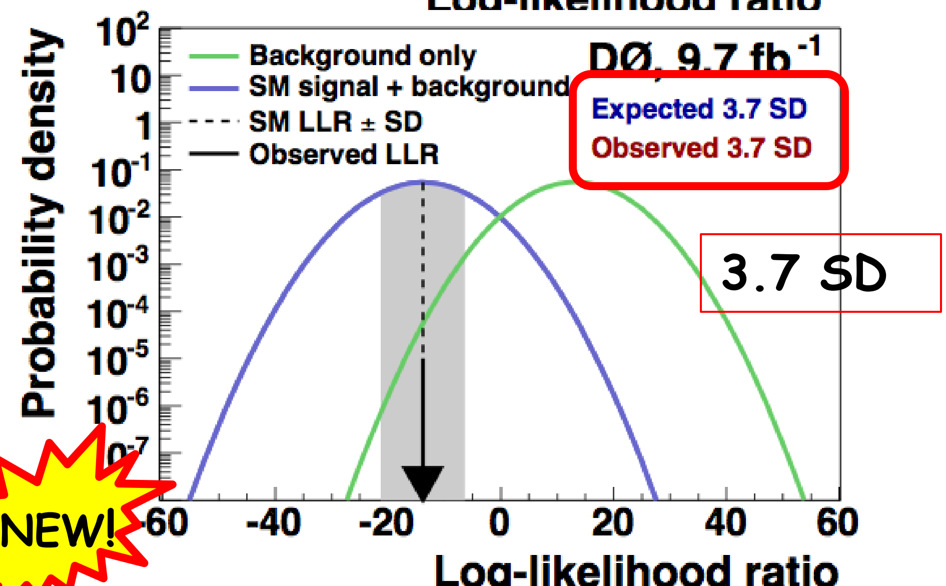
First evidence for s-channel







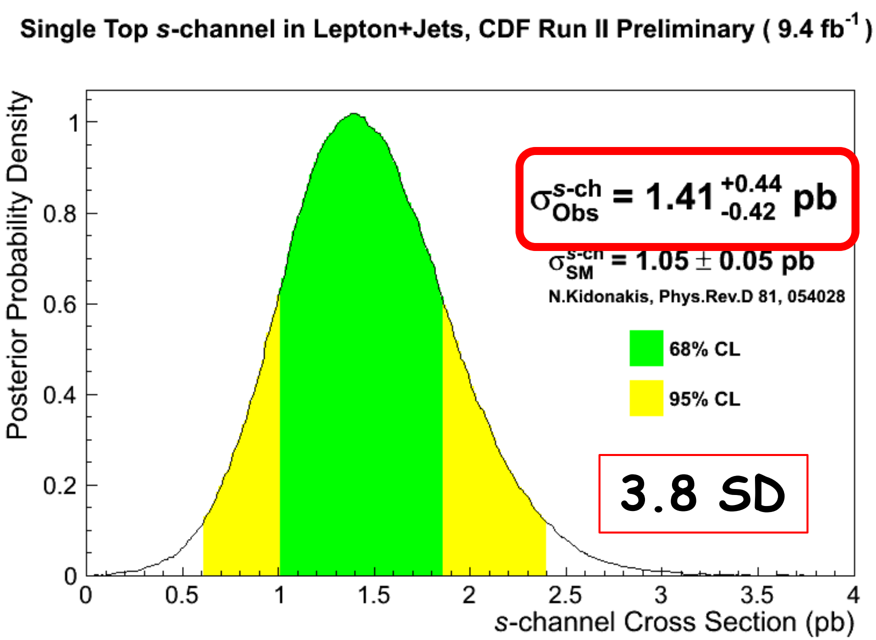
NEW!



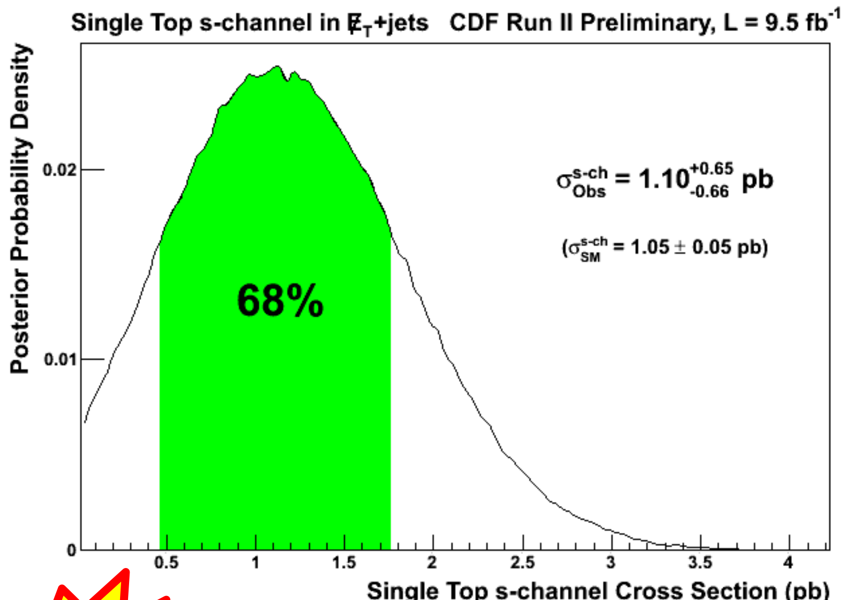
First evidence for s-channel

- Same strategy/tools developed for CDF WH analysis, 9.5 fb^{-1}
- Final cross section extracted from the posterior probability density distr.
- Cross section for t-channel is set to standard model prediction.

Lepton +jets



MET + jets

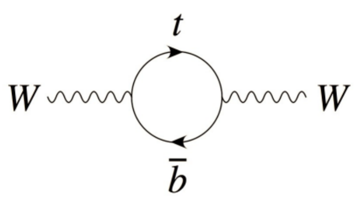


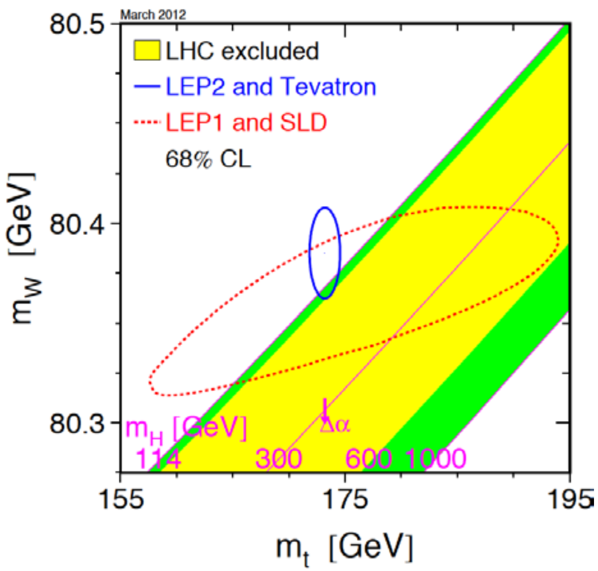
Expected signif: 2.9 sigma
Observed signif: 3.8 sigma

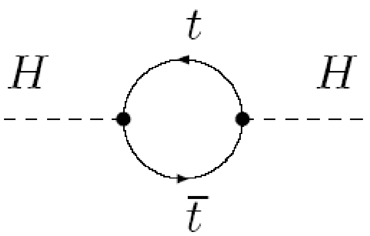
NEW!

Top quark mass measurement

- Free parameter of the SM
- Together with W mass: puts constraint on Higgs mass $\rightarrow$ self consistency check



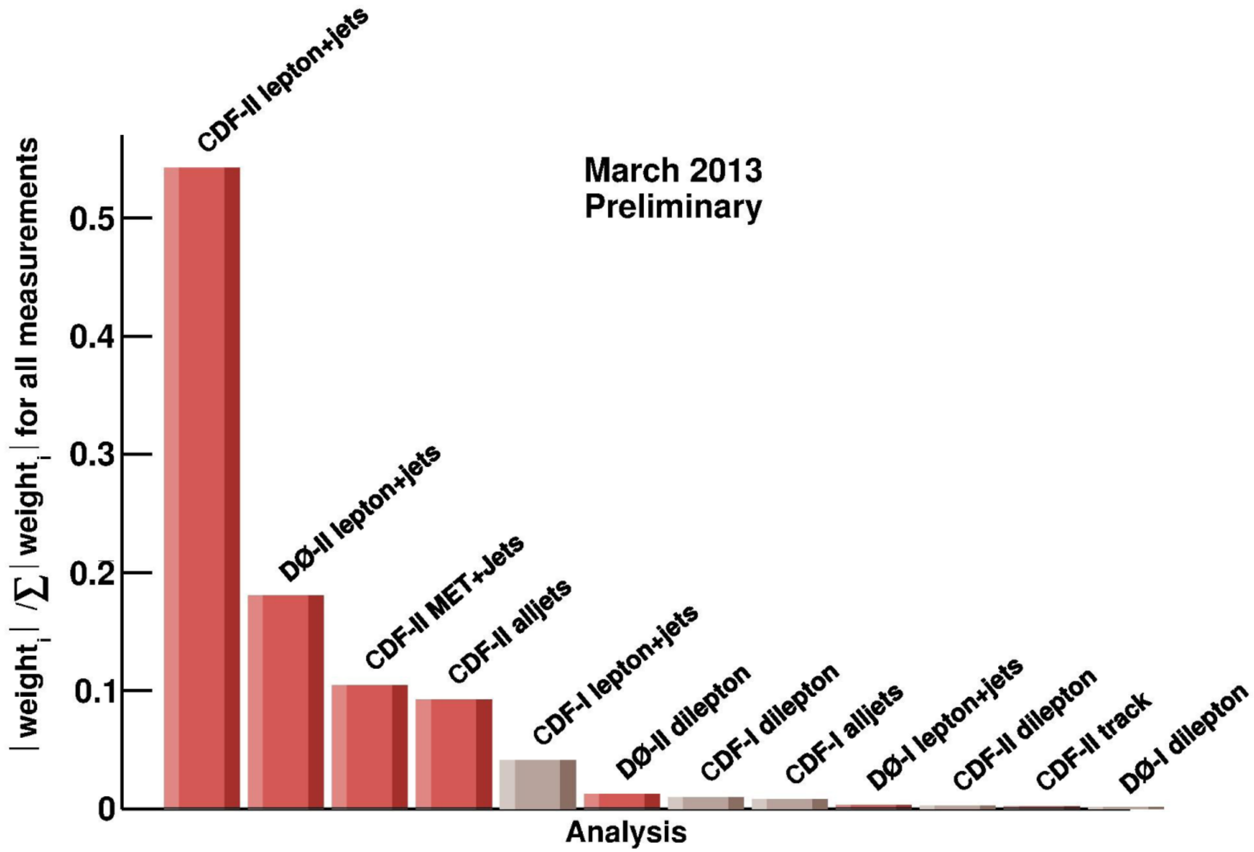




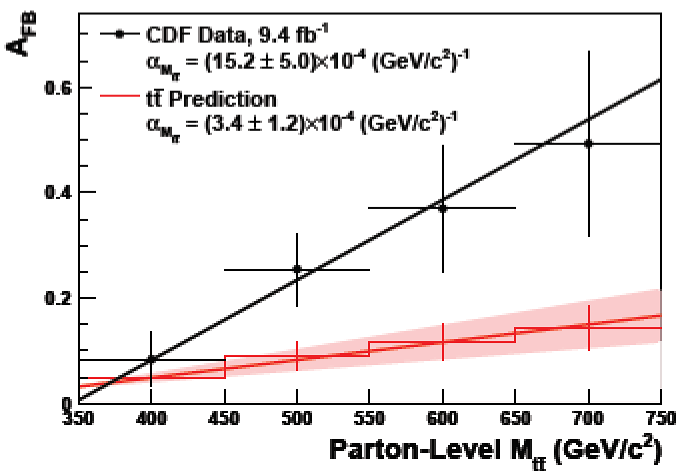
- Several methods explored for precision top mass measurement:
  - ⇒ Many clever tricks to improve sensitivity, such as in situ systematic uncertainty constraints
- Most sensitive analyses are lepton+jets from both CDF (PRL 109 152003 (2012) and D0 (PRD 84 032004 (2011))

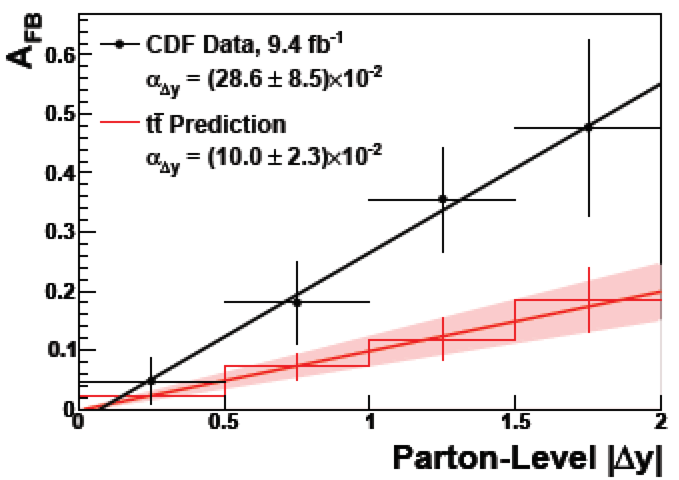
Tevatron top mass combination

- Weights per measurement:



Forward-Backward Asymmetry

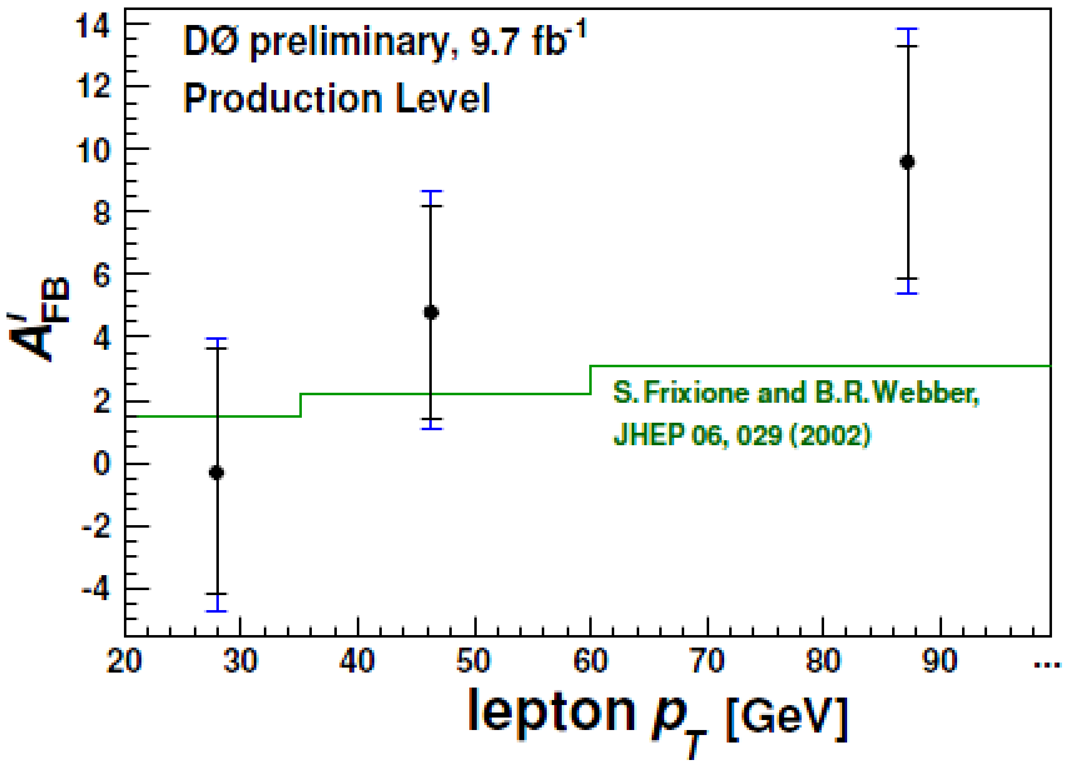




- Also important to investigate dependence of A_{FB} on top pair mass and on rapidity difference $|\Delta y|$
- Asymmetry rises steadily from near zero at threshold
- Fit a line to data and to prediction
- Slope in data exceeds prediction
- by ~2.3 sigma at the parton level
- The shape of A_{FB} as a function of Mtt and $|\Delta y|$ is a prediction of both the NLO SM and various new physics models
- This may help to discriminate different scenarios

D0: Asymmetry dependence on lepton pT

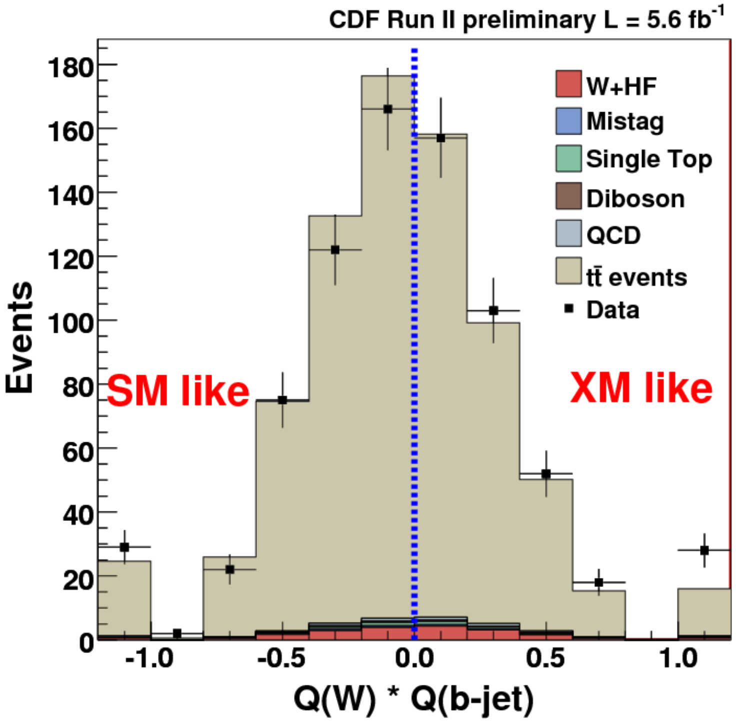
- Asymmetry in W+jets background was calibrated on data in 3 lepton pT bins



Top quark electric charge

- CDF 5.6 fb^{-1}, lepton+jets
- Top quark candidates could be interpreted as 2/3e ($t \rightarrow W^+b$) or -4/3e ("t" $\rightarrow W^-b$) (PRD 59, 091503 (1999))
- Use jet-charge algorithm
- Exclude -4/3e at 99% CL

arXiv:1304.4141



- In agreement with old D0 result, excluding -4/3e at 92% CL
  PRL98, 041801 (2007)

Top quark width

- Indirect measurement based on other top properties results, using 5.4 fb^{-1}
- Use t-channel single-top and measurement of R in ttbar

$$\Gamma_t = \frac{\Gamma(t \to Wb)}{\mathcal{B}(t \to Wb)}$$

$\Gamma(t \to Wb)$ → Use t-channel single top cross section measurement PLB 705, 313 (2011)

$\mathcal{B}(t \to Wb)$ → BR measured using $t\bar{t}$ decays PRL 107, 121802 (2011)

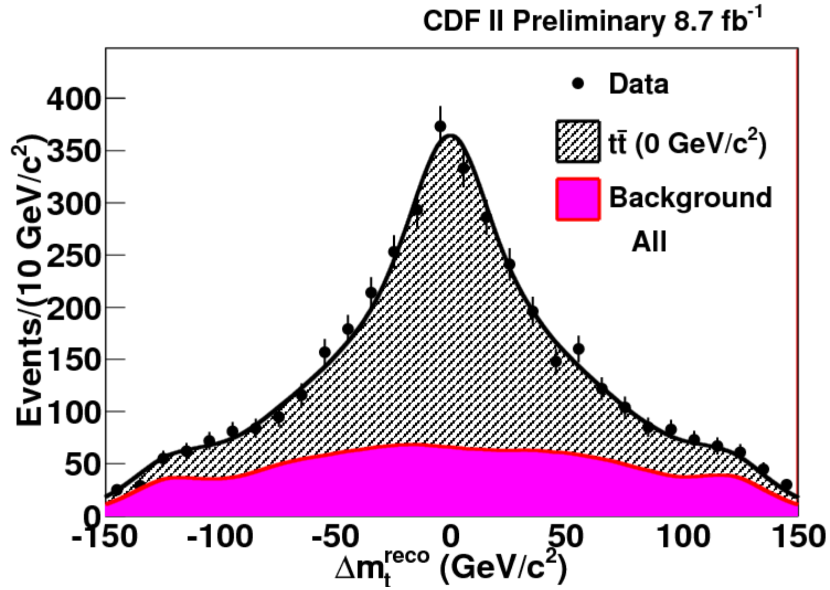
$$\Gamma_t = \frac{\sigma(t\text{–channel})\ \Gamma(t \to Wb)_{\mathrm{SM}}}{\mathcal{B}(t \to Wb)\ \sigma(t\text{–channel})_{\mathrm{SM}}}$$

- Assume the same proportionality as for the SM
- $\Gamma_{top} = 2.00\ ^{+0.47}_{-0.43}$ GeV
- $\tau_{top} = (3.29\ ^{+0.90}_{-0.63}) \times 10^{-25}$ s

PRD 85, 091104 (2012)

Top Anti-Top Mass Difference

- If CPT is conserved, $\Delta M_{top} = 0$
- We test this assumption by measuring ΔM_{top}
- Similar techniques to mass measurements



D0: Matrix element technique, allowing different mass of top and anti-top, 3.6 fb^{-1}

$\Delta M_{top} = +0.8 \pm 1.9$ GeV/c^2

PRD 84, 052005 (2011)

CDF: Kinematic reconstruction + template fit, 8.7 fb^{-1} full RunII dataset

$\Delta M_{top} = -1.95 \pm 1.26$ GeV/c^2

PRD 87, 052013 (2013)

Measurements in agreement with CPT invariance

Top quark charge

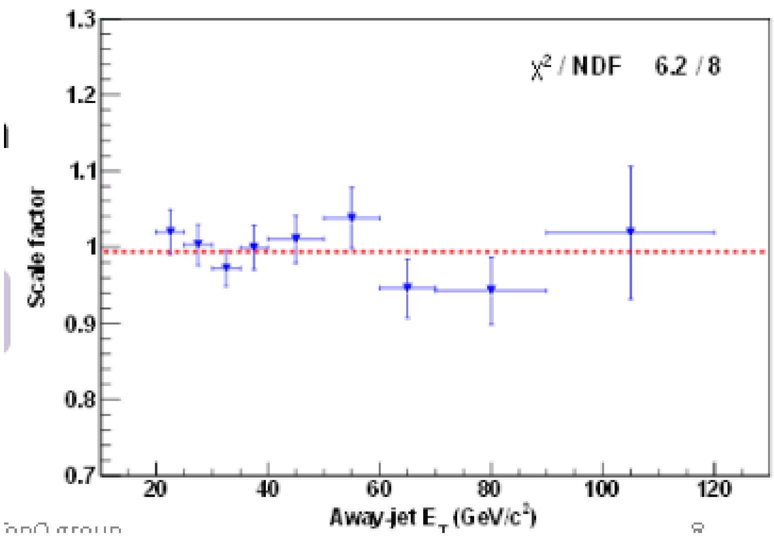
- Jet-charge algorithm:

$$JetQ = \frac{\sum_i q_i (\hat{n} \cdot \vec{p}_i)^{0.5}}{\sum_i (\hat{n} \cdot \vec{p}_i)^{0.5}}$$

$\hat{n}$ – jet axis
q_i – track's charge
$\vec{p}_i$ – track's p_T

- Calibration of algorithm, expressed as ScaleFactor:

$SF_{JQ} = 0.99 \pm 0.01$ (stat.) ± 0.03 (syst)



LHC results: no published yet

–> Public results:

ATLAS: XM excluded at ≥ 5σ

CMS: XM excluded with high significance: (A = 0.97±0.33; SM expectation: A=1)

W Helicity in top decay

- CDF lepton+jets updated to 8.7 fb^{-1}

Constrained measurement (1D):

$\Rightarrow f_0 = 0.686 \pm 0.042(stat) \pm 0.040(syst)$

$\Rightarrow f_+ = - 0.025 \pm 0.024(stat) \pm 0.040(syst)$

- Tevatron Combination 5.4 fb^{-1}

Constrained measurement: (1D)

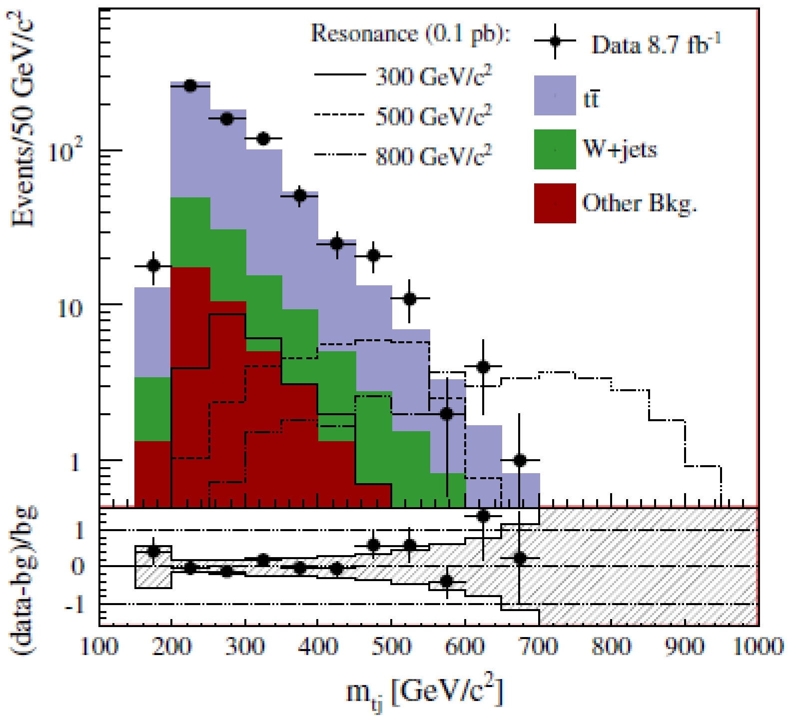
$\Rightarrow f_0 = 0.682 \pm 0.057$

$\Rightarrow f_+ = -0.015 \pm 0.035$

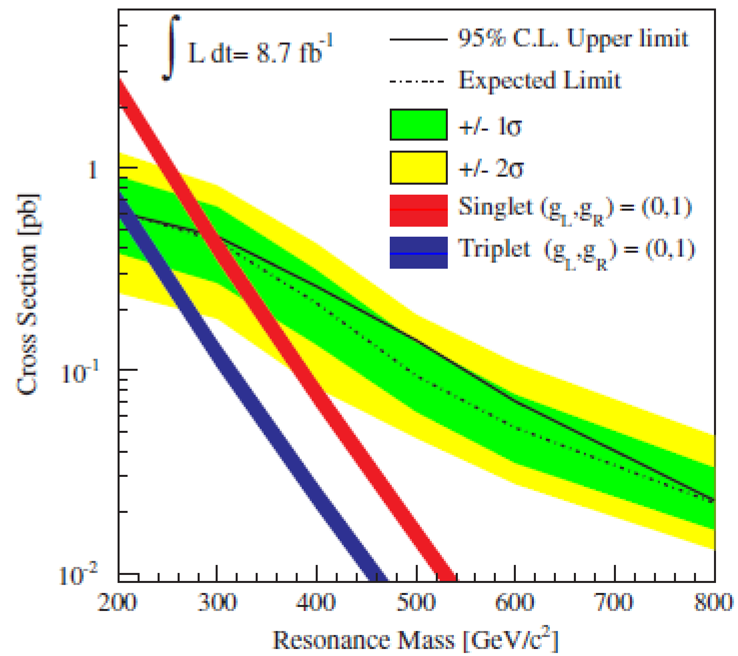
Search for top+jet resonances in ttbar +jet

- Search for a heavy new particle M produced in association with a top quark $p\bar{p} \rightarrow Mt \rightarrow \bar{t}qt$ leading to a resonance in the $\bar{t} + jet$ system of $t\bar{t} + jet$ events.*
- Select events in lepton +jets channel with at least 5 jets and 1 b-tag.

L = 8.7 fb^{-1} full RunII dataset



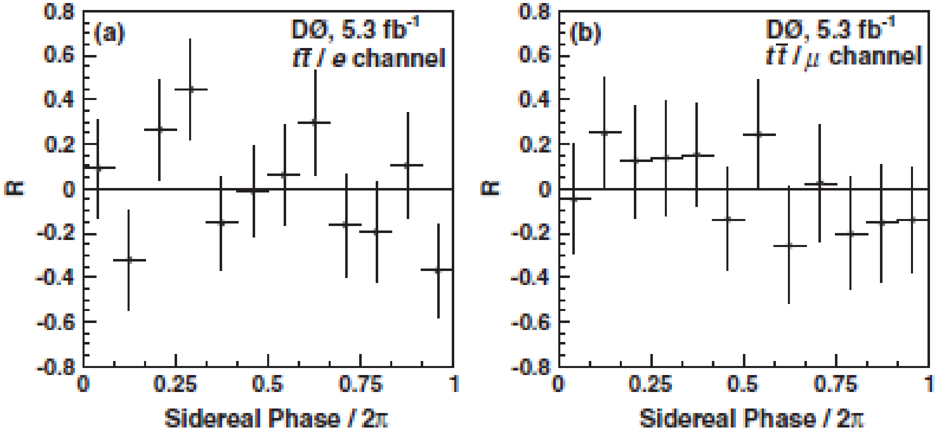
PRL 108, 211805 (2012)



* Zurek et al, 2011

Search for Lorentz Invariance Violation

- Standard Model extension adds Lorentz violating terms to SM lagrangian (PRD58, 116002 (1998), PRD69, 105009 (2004))
- Earth is a rotating reference frame with a repetition period of one sidereal day
- Lorentz violation predicts dependence of σ_{ttbar} on time of day



L = 5.3 fb^{-1}

PRL 108, 261603 (2012)

- R is the siderealy binned relative ttbar event rate
- Expect R = 0 for no Lorentz violation.
- No indication for time dependence of σ_{ttbar}. First constraints on LIV in top sector (and for a bare quark).

Search for Lorentz Invariance Violation

- c_U (right handed) and c_Q (left handed) are different component of SME matrices

TABLE III. Limits on SME coefficients at the 95% C.L., assuming $(c_U)_{\mu\nu} = 0$.

Coefficient	Value ± Stat ± Sys	95% C.L. Interval
$(c_Q)_{XX33}$	$-0.12 \pm 0.11 \pm 0.02$	$[-0.34, +0.11]$
$(c_Q)_{YY33}$	$0.12 \pm 0.11 \pm 0.02$	$[-0.11, +0.34]$
$(c_Q)_{XY33}$	$-0.04 \pm 0.11 \pm 0.01$	$[-0.26, +0.18]$
$(c_Q)_{XZ33}$	$0.15 \pm 0.08 \pm 0.02$	$[-0.01, +0.31]$
$(c_Q)_{YZ33}$	$-0.03 \pm 0.08 \pm 0.01$	$[-0.19, +0.12]$

TABLE IV. Limits on SME coefficients at the 95% C.L., assuming $(c_Q)_{\mu\nu} = 0$.

Coefficient	Value ± Stat ± Sys	95% C.L. Interval
$(c_U)_{XX33}$	$0.10 \pm 0.09 \pm 0.02$	$[-0.08, +0.27]$
$(c_U)_{YY33}$	$-0.10 \pm 0.09 \pm 0.02$	$[-0.27, +0.08]$
$(c_U)_{XY33}$	$0.04 \pm 0.09 \pm 0.01$	$[-0.14, +0.22]$
$(c_U)_{XZ33}$	$-0.14 \pm 0.07 \pm 0.02$	$[-0.28, +0.01]$
$(c_U)_{YZ33}$	$0.01 \pm 0.07 \pm <0.01$	$[-0.13, +0.14]$