Top Quark Properties at the Tevatron

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EPS HEP Stockolm, July 19, 2013

Top Quark Production at Tevatron

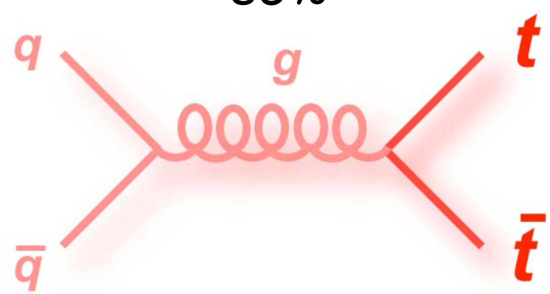
- QCD pair production

σ_{SM} = 7.35 pb

(for m_{Top}= 173.3 GeV)

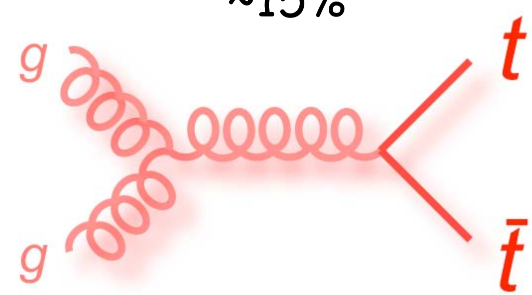
(arXiv:1303.6254)

~85%



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

- **EWK single-top production**
  - s-channel: σ_{SM} = 1.05 ± 0.07 pb
  - t-channel: σ_{SM} = 2.10 ± 0.19 pb

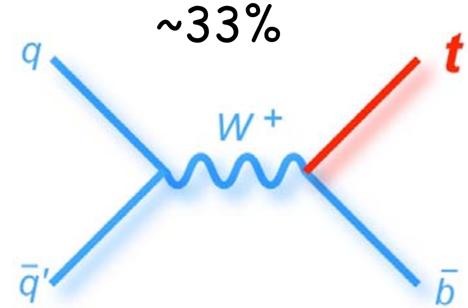
(Both for m_{Top}= 172.5 GeV)

PRD 83, 091503 (2011)

PRD 81, 054028 (2010)

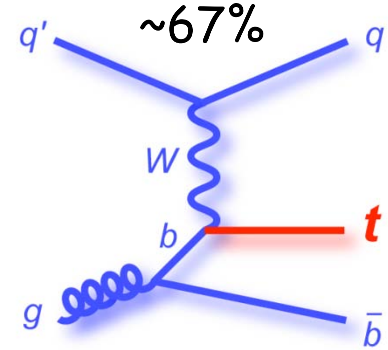
s-channel

~33%



t-channel

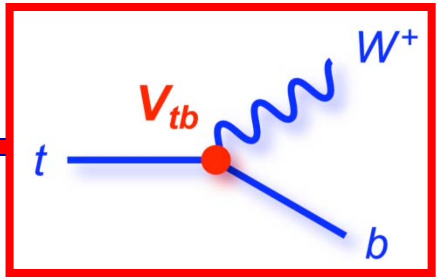
~67%



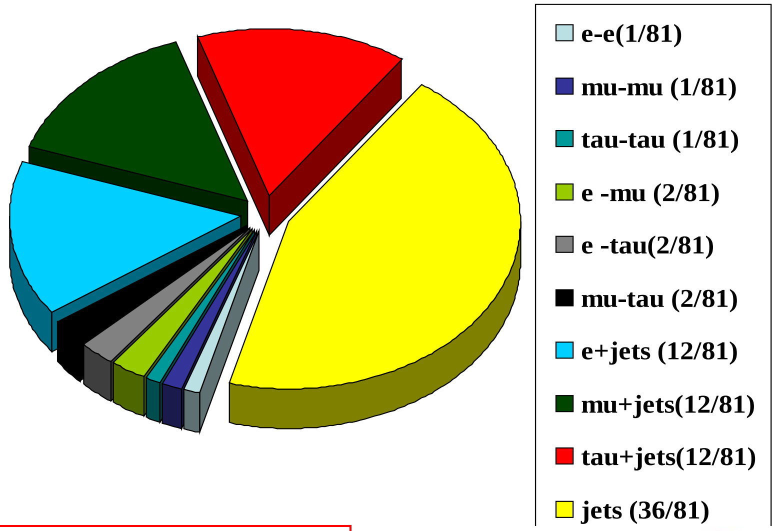
- Single top associated production Wt: σ ~ 0.2 pb, too small at the Tevatron

See A. Garcia-Bellido

Top Quark Decay



SM predicts BR($t \to Wb$) ≈ 100%

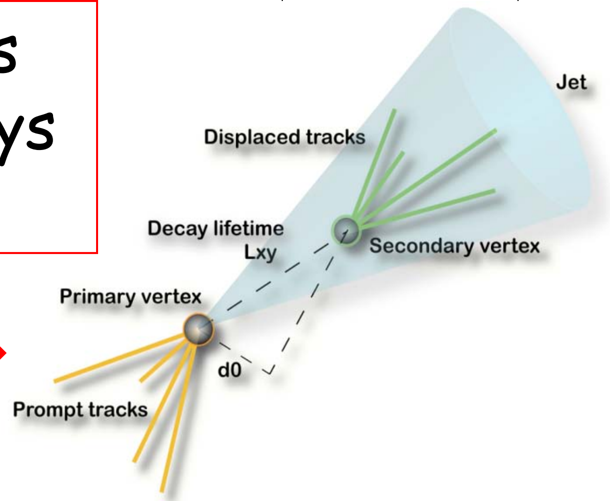


Event topology determined by the W decay modes

For ttbar pairs:

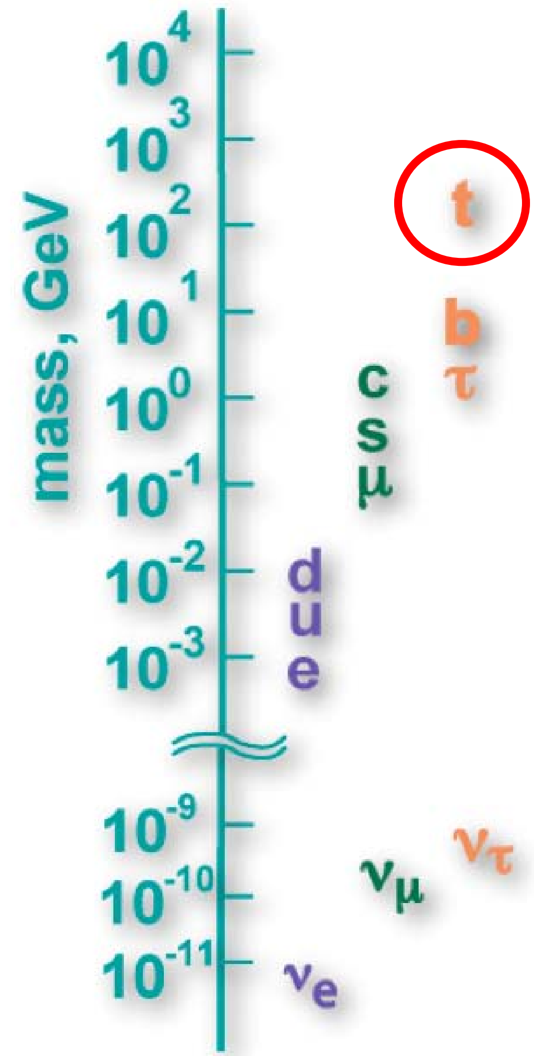
- Dilepton (ee, μμ, eμ)
  - ⇒BR = 5%, 2 high-P_T leptons + 2 b-jets + 2 neutrinos
- Lepton (e or μ) + jets
  - ⇒BR = 30%, single lepton + 4 jets (2 from b's) + 1 neutrino
- All Hadronic:
  - ⇒BR = 45%, six jets, no neutrinos
- τ + X
  - ⇒ BR = 20%

b quarks are always present



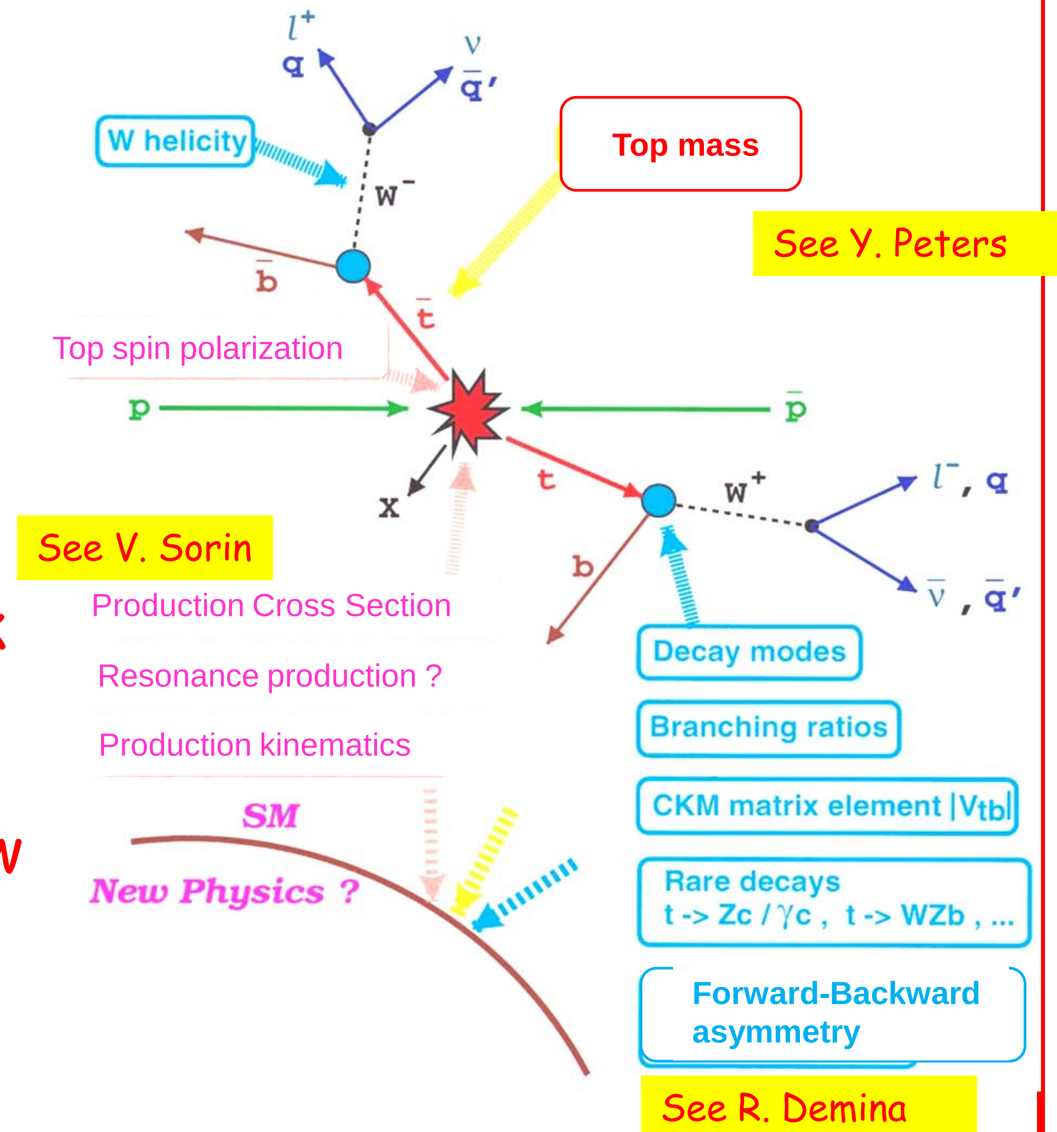
Top pairs production

- Top quark is a very special particle:
  - ⇒Heavier than all known particles
  - ⇒Short lifetime → decays before hadronizing →
    - ✓Properties can be studied from distributions of decay products
  - ⇒Provides a probe for electroweak symmetry breaking
- Deviation of the measured top quark properties from the SM prediction would be a signal of new physics



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

- Sir yea stu
- Wi dat me
- Is the qua
- Any phy

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

  ⇒Branching ratios & V_{tb} measurement

  ⇒Width of the top quark

  ⇒Charge of the top quark

  ⇒Spin correlations

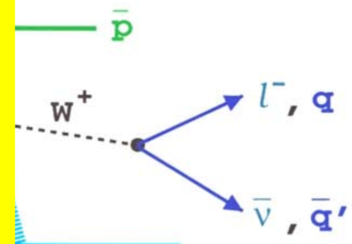
  ⇒W helicity in top decays

  ⇒Search for new physics in top production

  ⇒Tests for Lorentz invariance in top sector

mass

See Y. Peters



cay modes

anching ratios

KM matrix element |Vtb|

are decays
> Zc / γc , t -> WZb , ...

Forward-Backward asymmetry

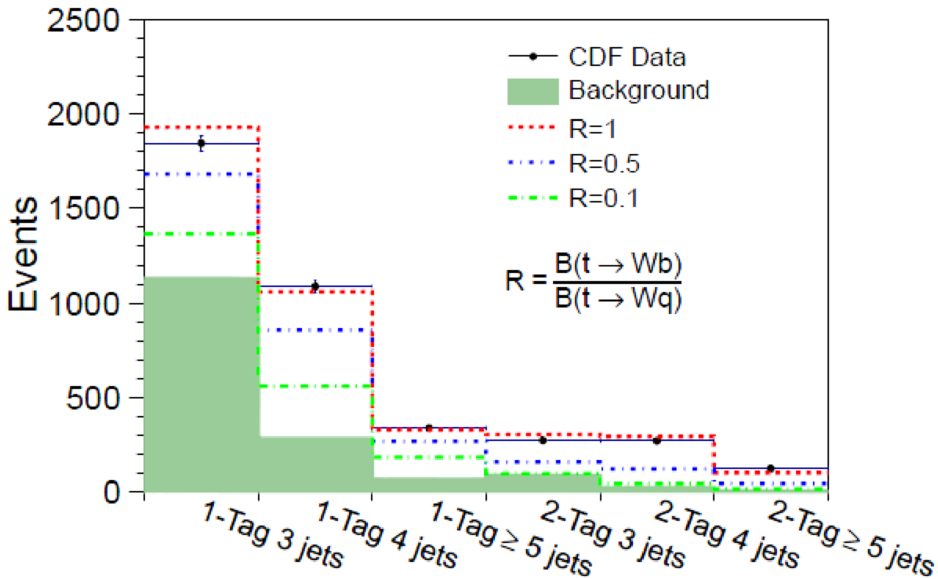
See R. Demina

Ratio of branching fractions R

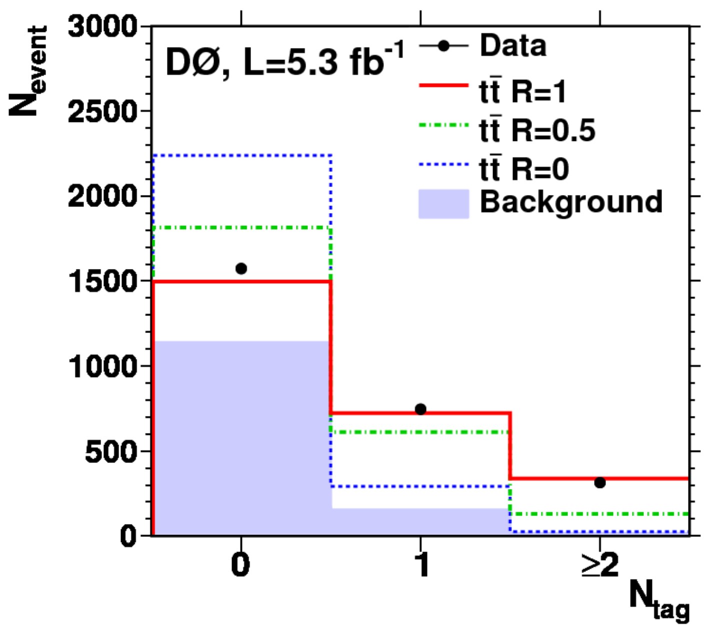
$$R = \frac{BR(t \to Wb)}{BR(t \to Wq)} = \frac{|V_{tb}|^2}{|V_{td}|^2 + |V_{ts}|^2 + |V_{tb}|^2}$$

- 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 could indicate new physics

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

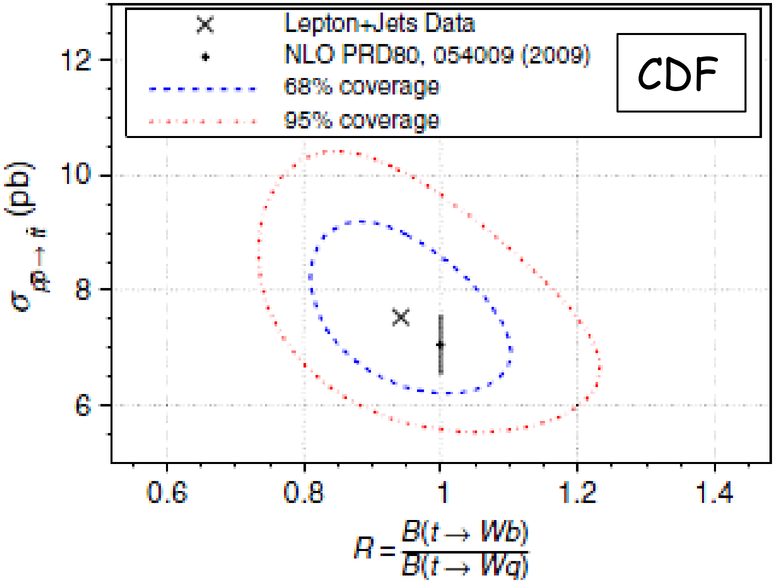


D0 L=5.4 fb^{-1} events >= 4 jets



Ratio of branching fractions R

- Drop assumption R=1 in dilepton (D0) and l+jets (D0 & CDF) cross section measurements
- Tagging efficiency determines number of events wth 0, 1, or 2 b-tagged jets
- Change the shape of the NN output distribution in dilepton channel (D0 only)
- 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} full RunII, Lepton+jets

$\sigma = (7.5 \pm 1.0)$ pb

$R = 0.94 \pm 0.09$ (stat+syst)

$|V_{tb}| = 0.97 \pm 0.05$

PRD 87, 111101 (2013)

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

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

$R = 0.90 \pm 0.04$ (stat+syst)

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

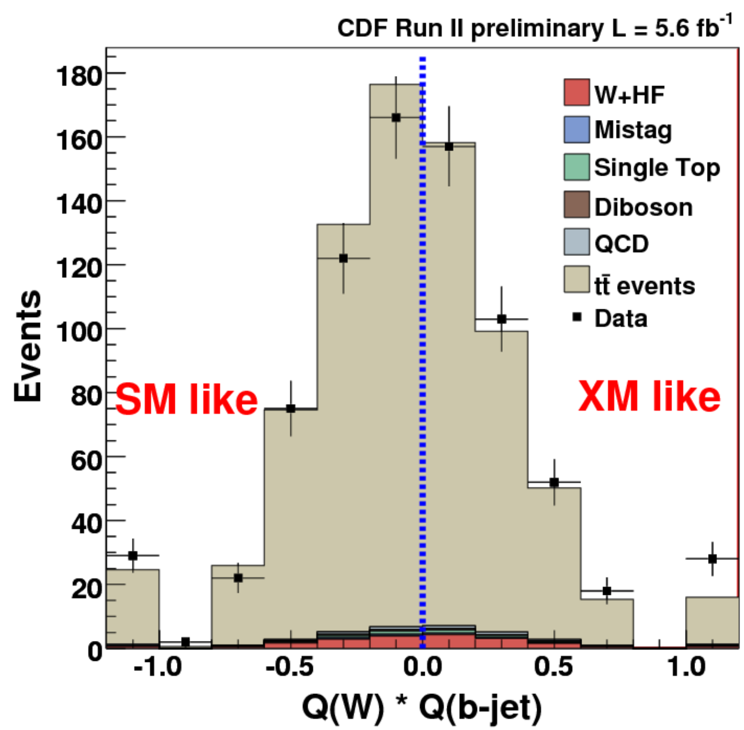
PRL 107, 121802 (2011)

Top quark electric charge

- CDF 5.6 fb^{-1}, lepton+jets
- Top quark candidates could be interpreted as 2/3e ($t \to W^{+}b$) or -4/3e ("t" $\to W^{-}b$) (PRD 59, 091503 (1999))

arXiv:1304.4141

- Use jet-charge algorithm
- Exclude -4/3e at 99% CL

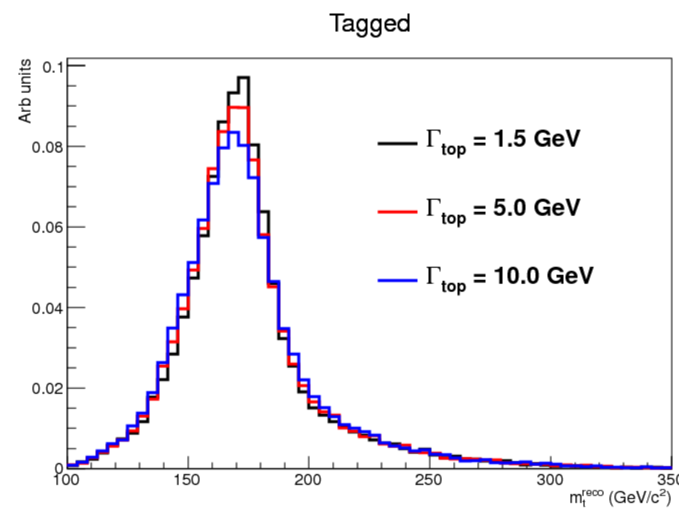


- In agreement with old D0 result, excluding -4/3e at 92% CL
  PRL98, 041801 (2007)

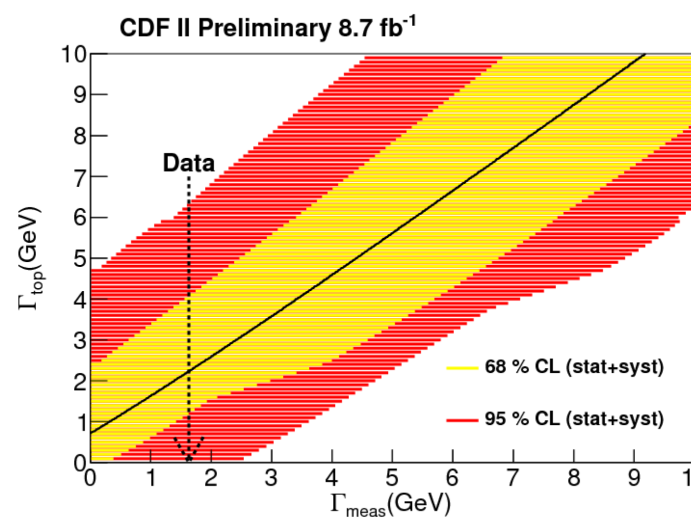
Top quark width

- 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 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

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

→ Use t-channel single top cross section measurement PLB 705, 313 (2011)

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

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

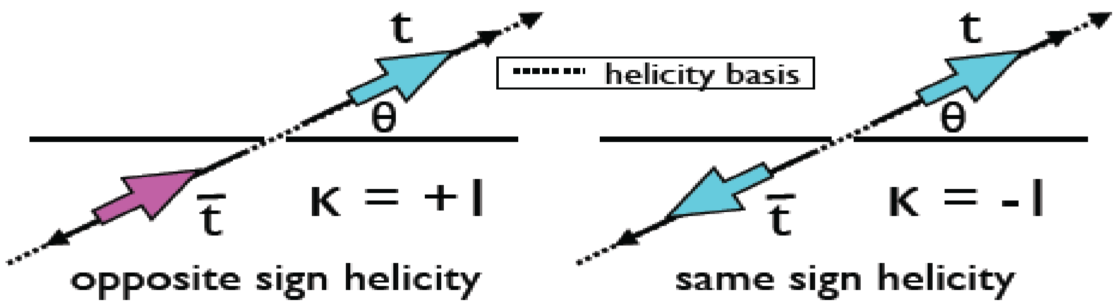
- Assume the same proportionality as for the SM
- $\Gamma_{top} = 2.00^{+0.47}_{-0.43}$ GeV
- $\tau_{top} = (3.29^{+0.90}_{-0.63}) \times 10^{-25}$ s

PRD 85, 091104 (2012)

Top-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!



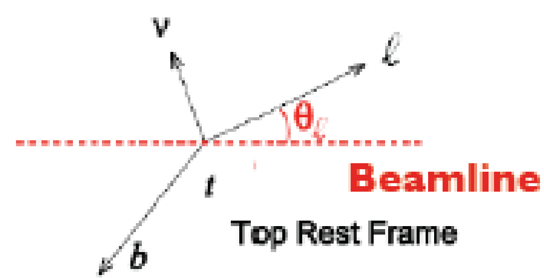
$$\kappa = \frac{N(\uparrow\uparrow)+N(\downarrow\downarrow)-N(\uparrow\downarrow)-N(\downarrow\uparrow)}{N(\uparrow\uparrow)+N(\downarrow\downarrow)+N(\uparrow\downarrow)+N(\downarrow\uparrow)} = \frac{N_o - N_s}{N_o + N_s}$$

- 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)

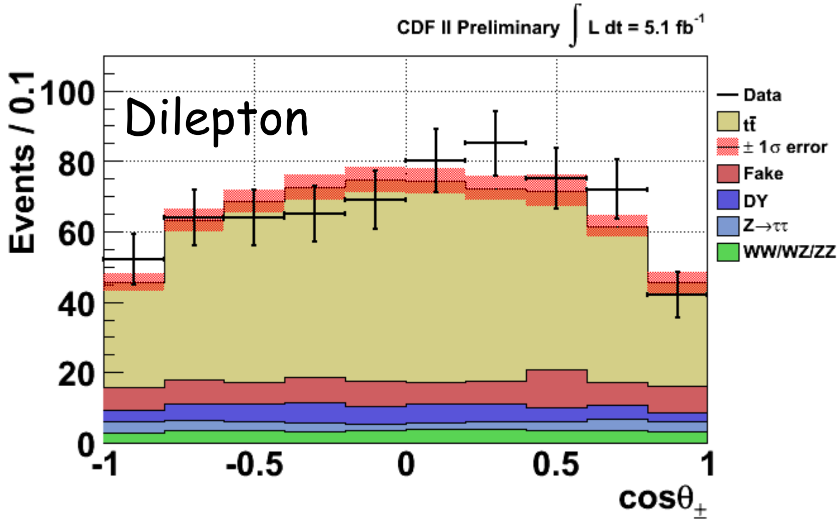
- Correlation strength **κ** (frame dependent) related to decay products angle through:

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

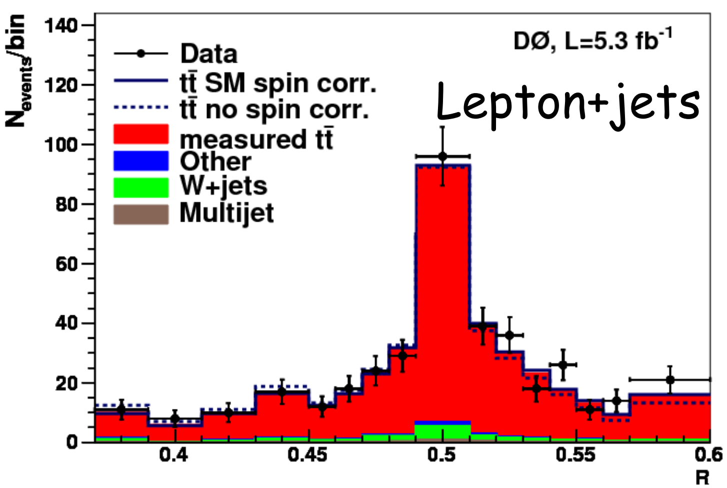


Top-antitop spin correlation

- CDF uses 5.1/5.3 fb^{-1}
- Results shown assume spin quantized along beam axis
  SM predicts **κ=0.78** NPB690, 81 (2004)
- $K_{(lep+jets)} = 0.72 \pm 0.69$ conf note 10211
- $K_{(dilepton)} = 0.042 \pm 0.563$ 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)



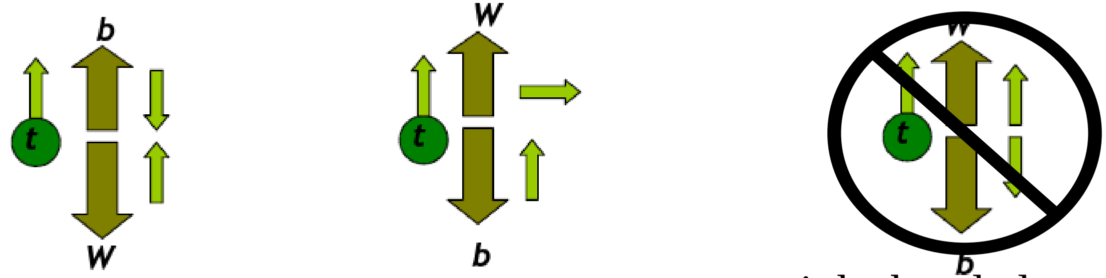
- Exclude no-correlation hyphotesis at 3.1σ

PRL108, 032004 (2012)

W Helicity in top decay

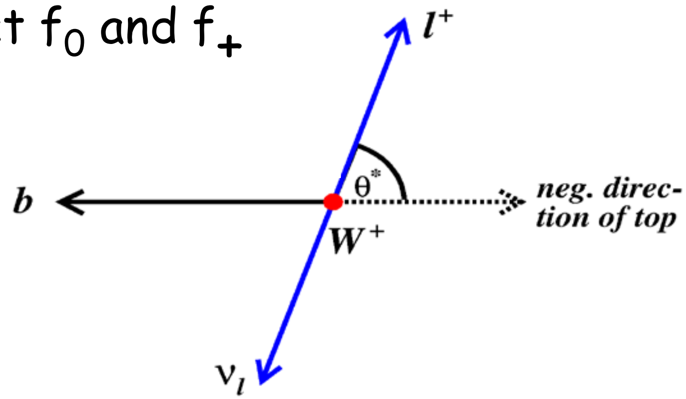
W helicity in top decays is fixed by M_{top}, M_W, and V-A structure of the tWb vertex. It is reflected in kinematics of W decay products.

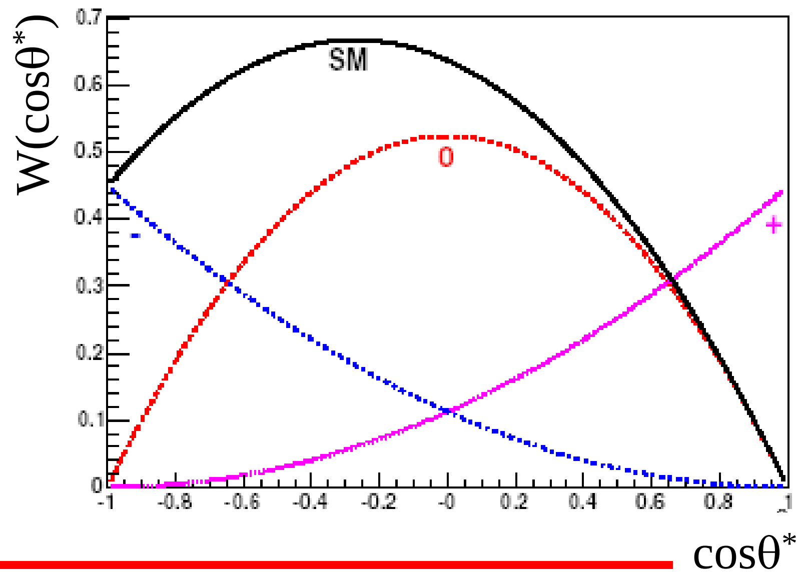
W helicity states:



	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: $\cos\theta^*$ to extract f_0 and f_+

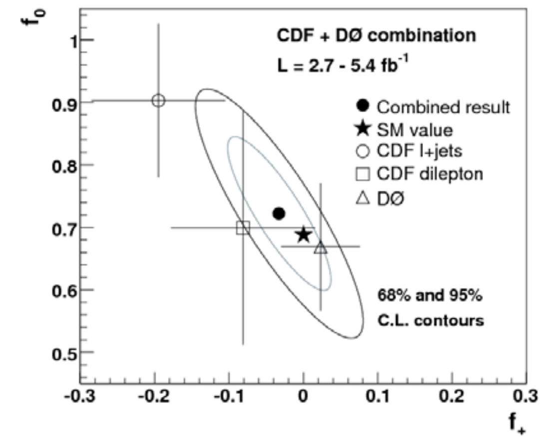




W Helicity in top decay

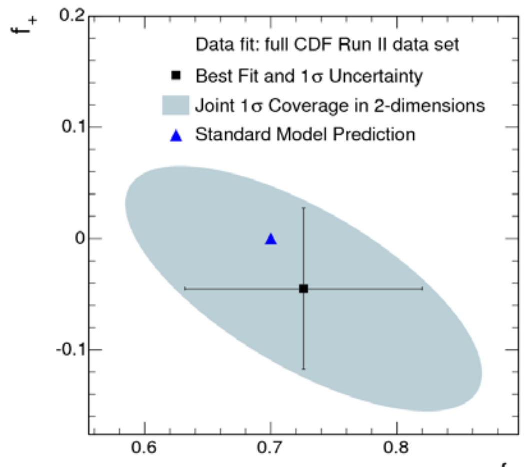
- CDF lepton+jets uses matrix element method
- CDF dilepton and D0 use fits to $\cos\theta^*$ distribution
- Fractions determined simultaneously (2D fit)
- Tevatron combination from 2.7-5.4 fb^{-1}:
  - ⇒ $f_+ = -0.033 \pm 0.046$
  - ⇒ $f_0 = 0.722 \pm 0.081$

  PRD 85, 071106 (2012)



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

  PRD 87, 031104 (2013)



x and y-axis are flipped

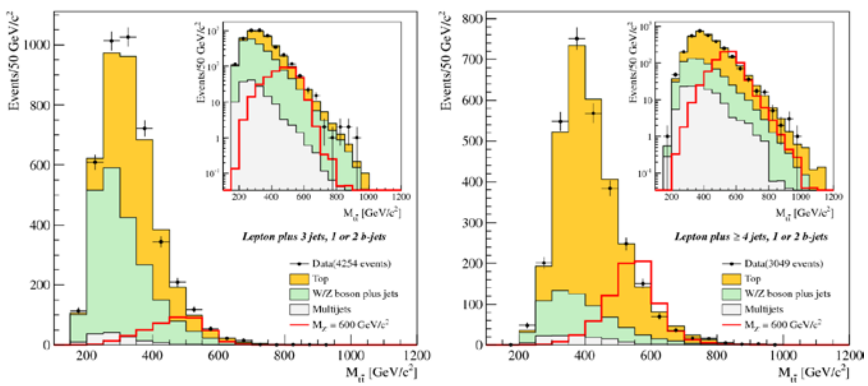
- Results in good agreement with SM

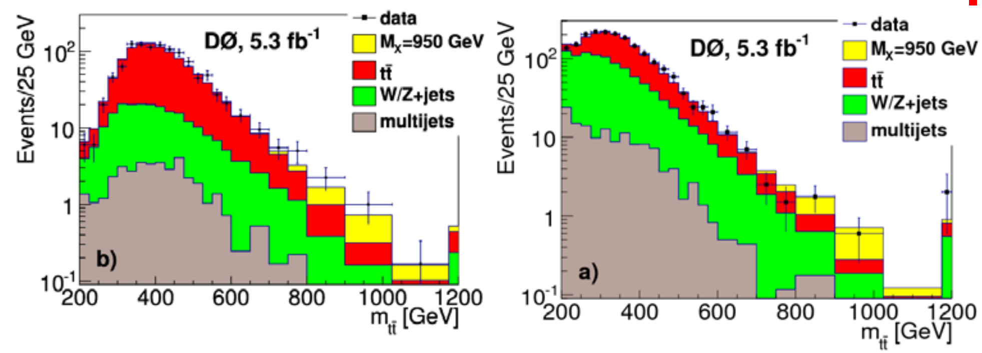
Search for resonant ttbar production

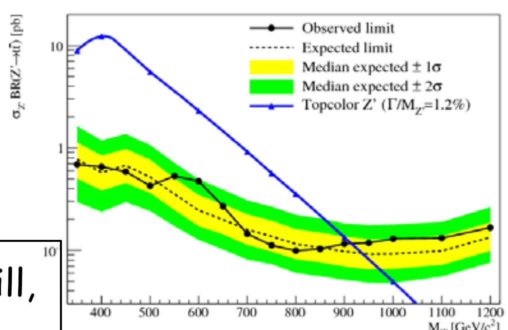
- Look at the M_{ttbar} spectrum in the lepton +jets final state, to see any deviation over the SM prediction

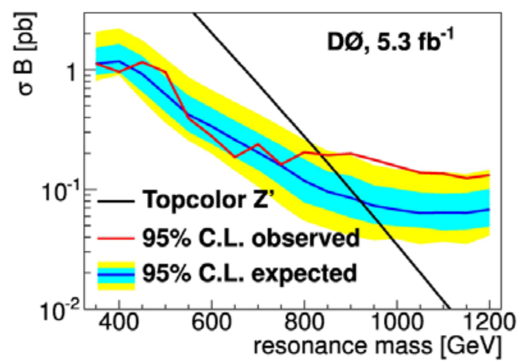
CDF L = 9.45 fb^{-1} full RunII dataset

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

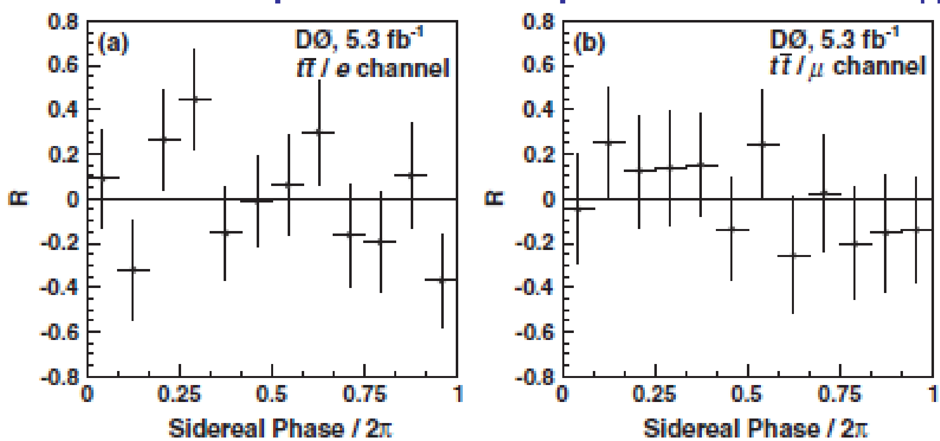
PRL 110, 121802 (2013)

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

PRD85, 051101 (2012)

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 sidereally 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).

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. spin correlations, A_{FB}) are complementary to LHC measurements
- All measurements shown here in agreement with the SM prediction

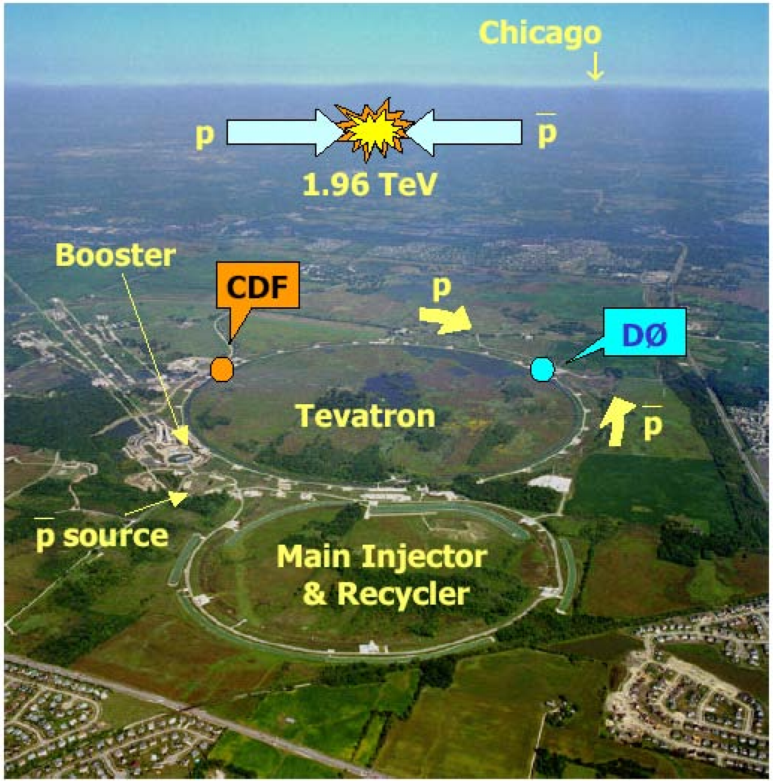
- Data-taking is done, but there's still a lot to be learned from the Tevatron's top quark sample!

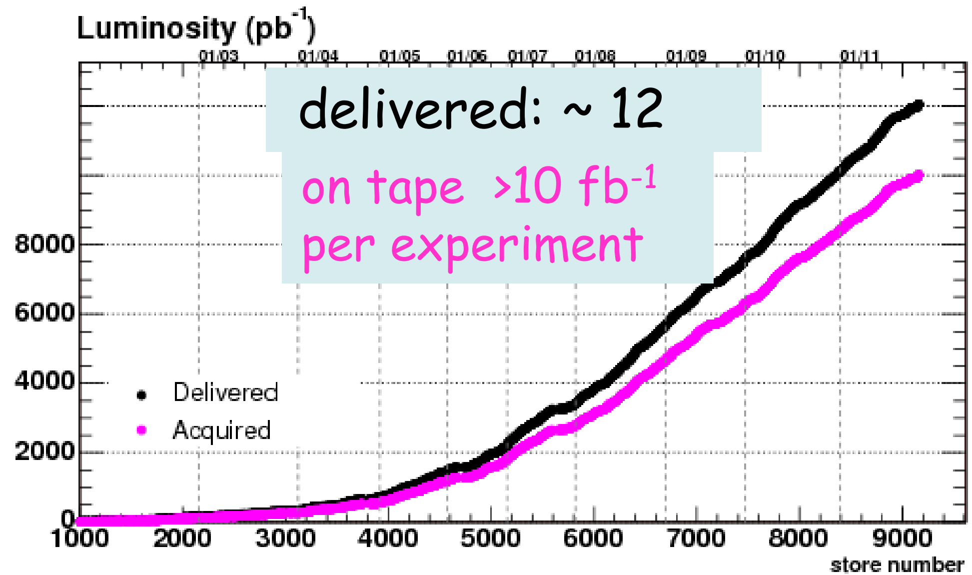
- See the websites of CDF's and D0's Top Groups and the Tevatron Electroweak Working Group for more information and results:
- http://www-cdf.fnal.gov/physics/new/top/top.html
- http://www-d0.fnal.gov/Run2Physics/top/top_public_web_pages/
- http://tevewwg.fnal.gov

Backup

The Fermilab Tevatron

Run II: $\sqrt{s}$ = 1.96 TeV
Tevatron stopped taking data on september 30, 2011



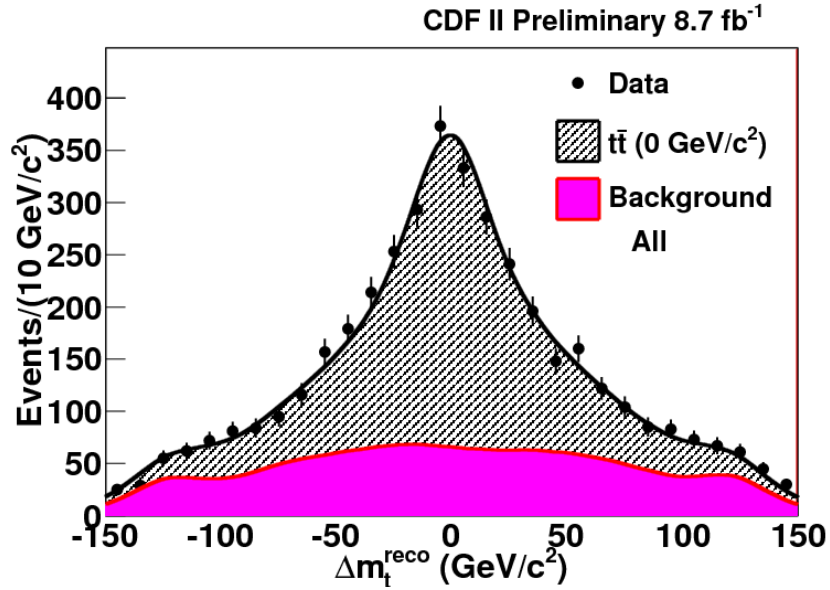


The birthplace of the top quark
The highest ppbar collider in the world ...... until December 2009

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

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

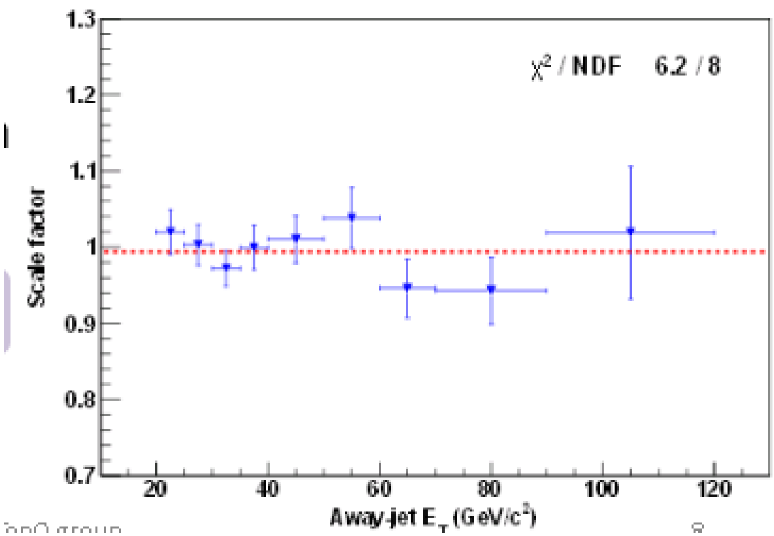
- Jet-charge algorithm:

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

$\hat{n}$ – 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±0.042(stat)±0.040(syst)

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

- Tevatron Combination 5.4 fb^{-1}

Constrained measurement: (1D)

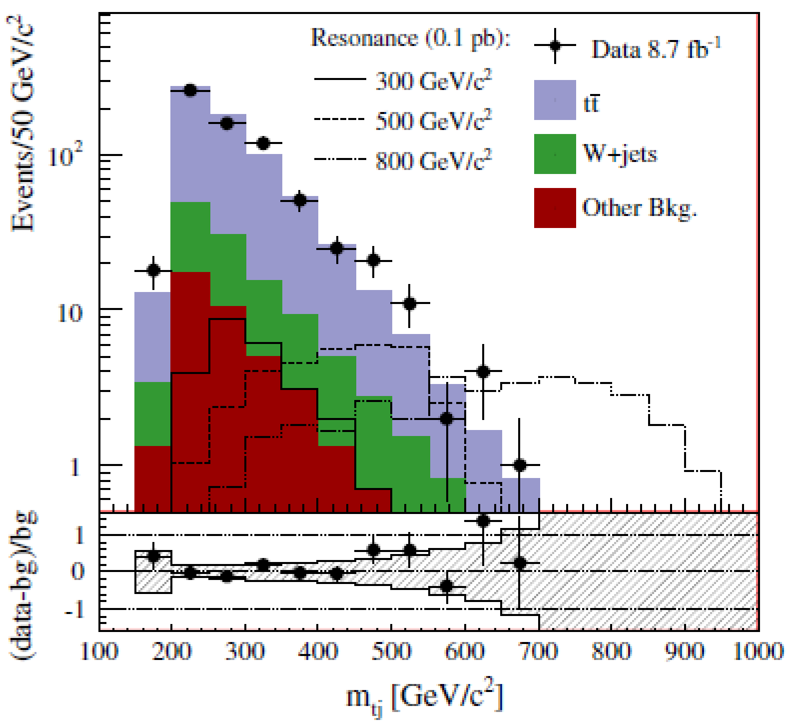
$\Rightarrow f_0 = 0.682 \pm 0.057$

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

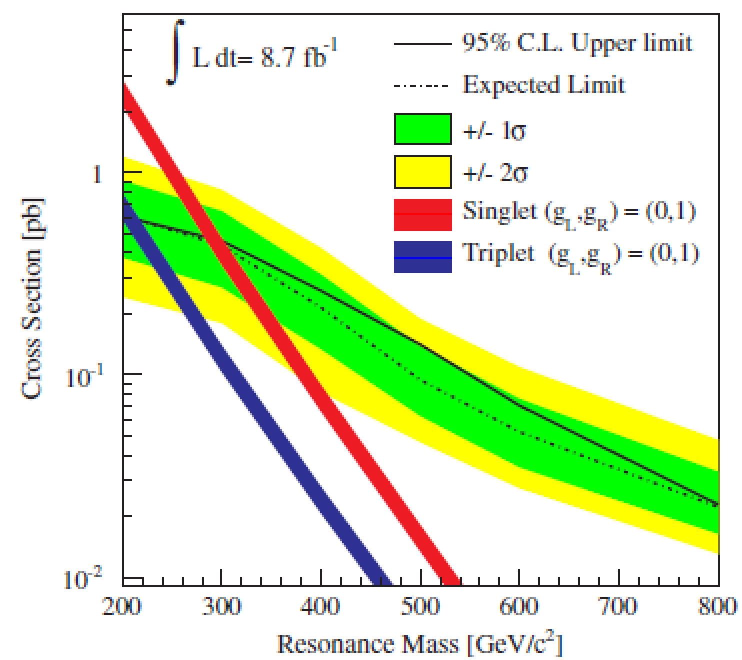
Search for top+jet resonances in ttbar +jet

- Search for a heavy new particle M produced in association with a top quark $p\bar{p} \to Mt \to \bar{t}qt$ 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

- 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
$(c_U)_{XX33}$	$0.10 \pm 0.09 \pm 0.02$	$[-0.08, +0.27]$
$(c_U)_{YY33}$	$-0.10 \pm 0.09 \pm 0.02$	$[-0.27, +0.08]$
$(c_U)_{XY33}$	$0.04 \pm 0.09 \pm 0.01$	$[-0.14, +0.22]$
$(c_U)_{XZ33}$	$-0.14 \pm 0.07 \pm 0.02$	$[-0.28, +0.01]$
$(c_U)_{YZ33}$	$0.01 \pm 0.07 \pm <0.01$	$[-0.13, +0.14]$