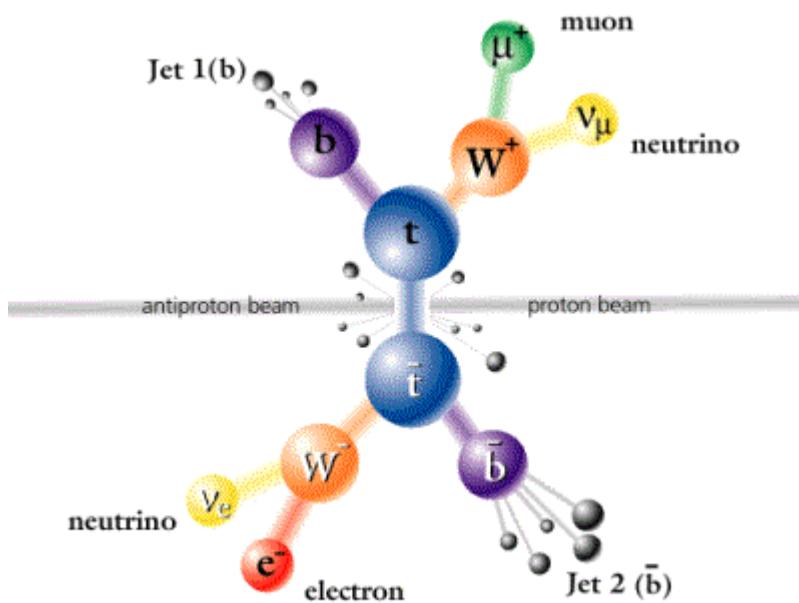


# *Studies of Top Quark Properties at the Tevatron*

*Viatcheslav Sharyy  
for the D0 and CDF collaborations*



**Rencontres de Moriond EW  
March 3 - 10, 2012**

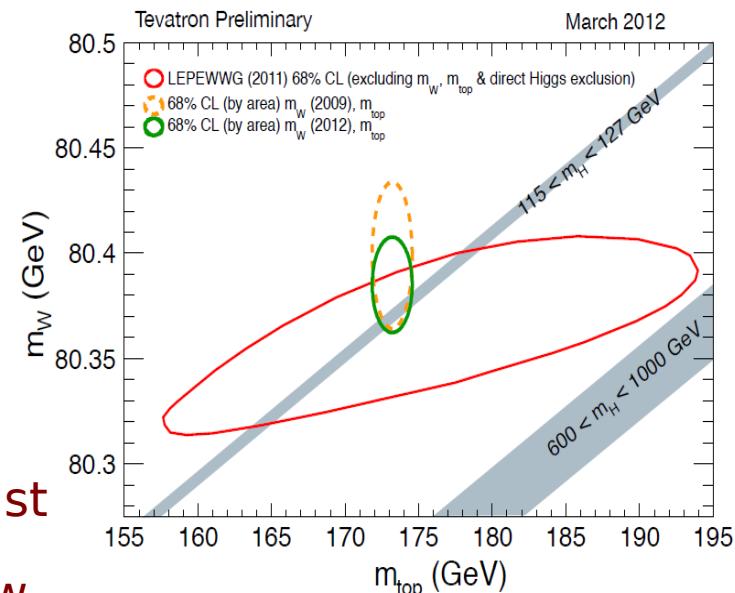
# *Introduction*

- Is the observed top quark is the Standard Model (SM) top quark?
  - Any contribution from the new physics?
- 
- Content
    - Top mass measurement
    - Top width determination
    - Spin correlation in top antitop events
    - W helicity and search for the anomalous top quark couplings
    - Searching for Lorentz Invariance Violation



# Top Quark Mass

- Why measure the top quark mass:
  - Free parameter in the SM
  - Constrain the scalar boson mass and check for SM consistency together with W boson mass.
- Two main method to measure top quark mass at Tevatron:
  - Template method → “Simple” and fast
  - Matrix element method → Precise, but slow

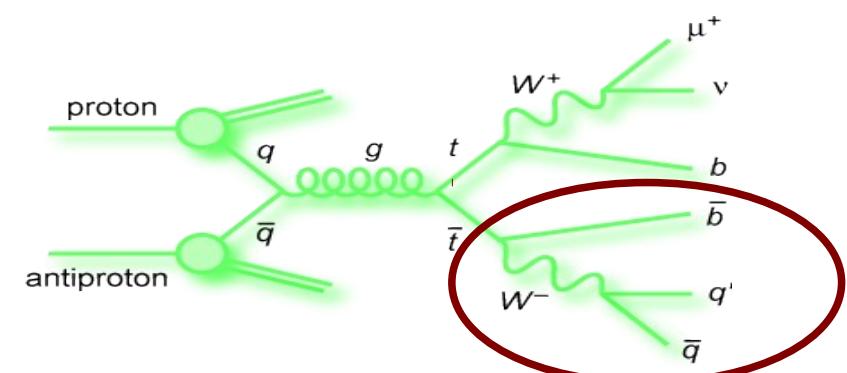


$$P(x, H) \sim \int d^6\sigma(y, H) W(x, y) f_{PDF}(q_1) f_{PDF}(q_2) dq_1 dq_2$$

Differential cross section

Detector response

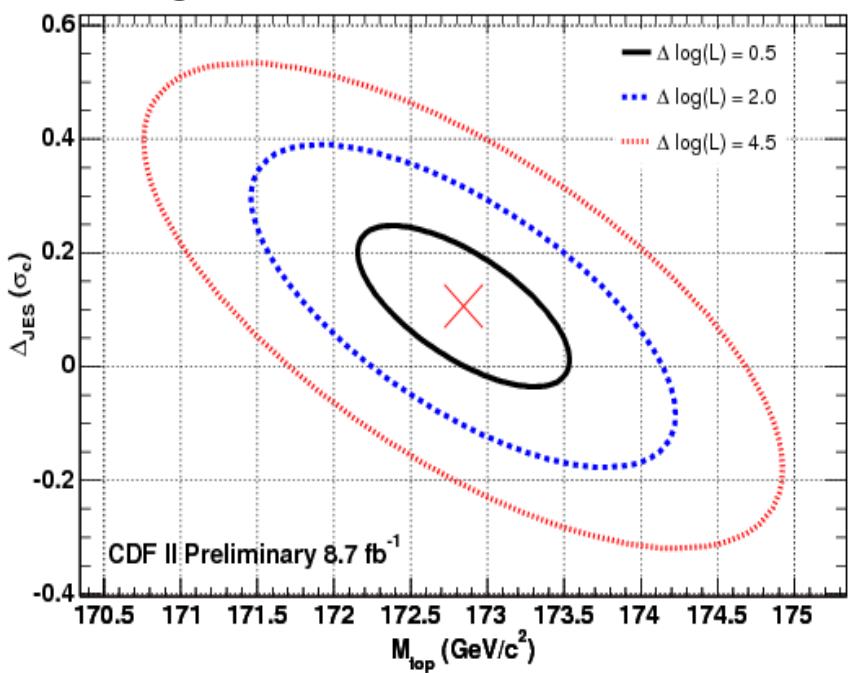
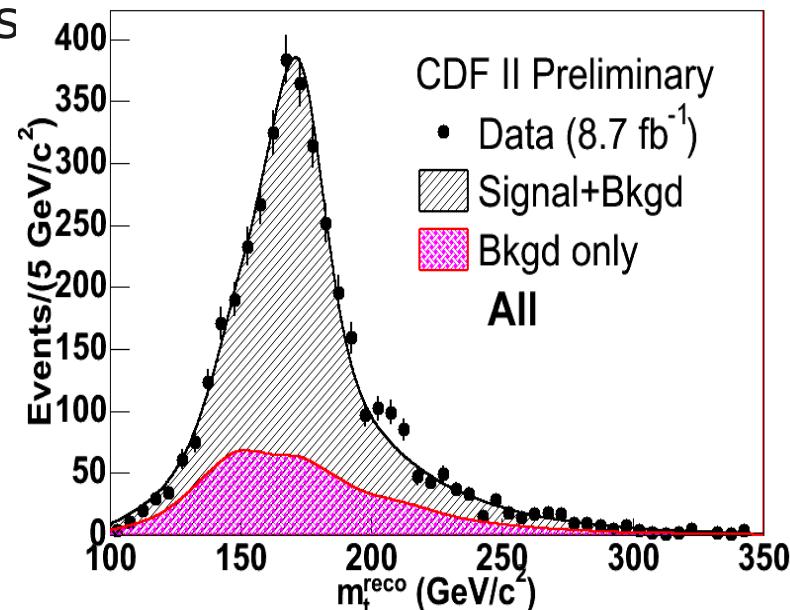
Parton density functions



FOR BOTH METHODS:  
Reduce jet energy scale (JES) uncertainty in the 1+jet channel by in-situ JES calibration using W boson mass constrain

# Measurement in $l+jet$ Channel With $8.7 \text{ fb}^{-1}$

- Separate final state in categories: 0/1/2 b-tags  
x loose/ tight jet requirements
- Use 3D kernel density estimator to build the probability for the reconstructed top mass ( $m_t^{\text{reco}}$ ), top mass for “wrong” combination ( $m_t^{\text{reco}(2)}$ ), reconstructed W mass ( $m_{jj}$ )
- Construct likelihood as a product of per event probabilities and a product over all different categories



**The most precise single channel measurement!**

$172.85 \pm 0.71 \text{ (stat)} \pm 0.84 \text{ (syst)} \text{ GeV}$   
 $172.85 \pm 1.10 \text{ GeV (precision: 0.6%)}$

CDF Conf Note 10761

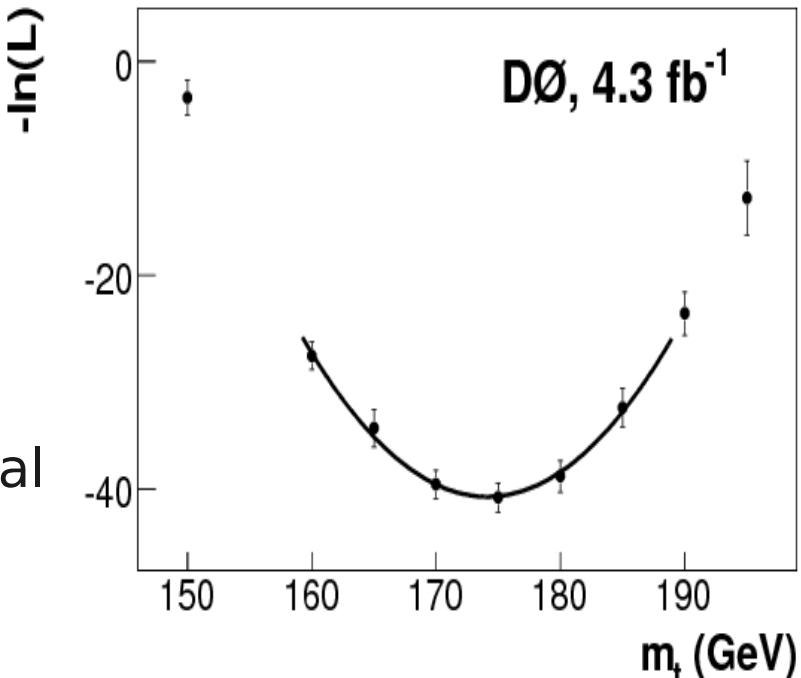
D0 I+jet Matrix Element measurement  $3.6 \text{ fb}^{-1}$ :  
 $174.94 \pm 0.83(\text{stat}) \pm 0.78(\text{JES}) \pm 1.02(\text{syst}) \text{ GeV}$   
(precision: 0.9%)  
PRD 84, 032004 (2011)

# Measurement in Dilepton Channel, $5.4 \text{ fb}^{-1}$



- Dilepton final state under-constrained  $\Rightarrow$  integrate over the neutrinos rapidity (“neutrino weighting”)
- Construct templates using per event weight
- Propagate l+jet JES correction factor to dilepton measurement
- Use JES corrections depending from the initial parton: light quark, gluon or b-quark

$174.0 \pm 2.4 \text{ (stat)} \pm 1.4 \text{ (syst) GeV}$   
(precision: 1.6%)

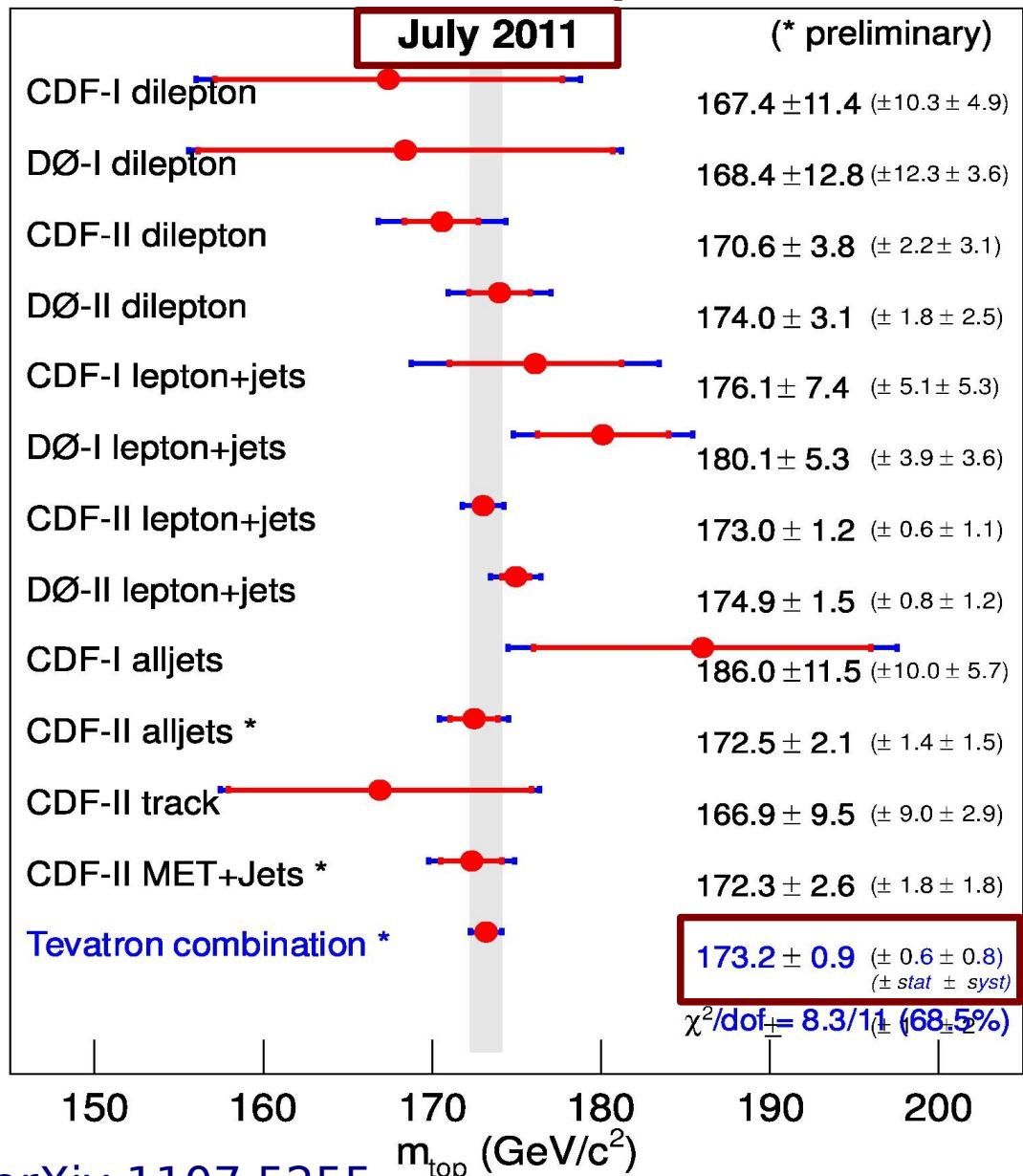


*Submitted to PRL, arXive 1201.5172*

D0 dilepton matrix element  $5.4 \text{ fb}^{-1}$ :  
 $174.0 \pm 1.8 \text{ (stat)} \pm 2.4 \text{ (syst) GeV}$  (precision 1.8%)  
*PRL 107, 082004 (2011)*

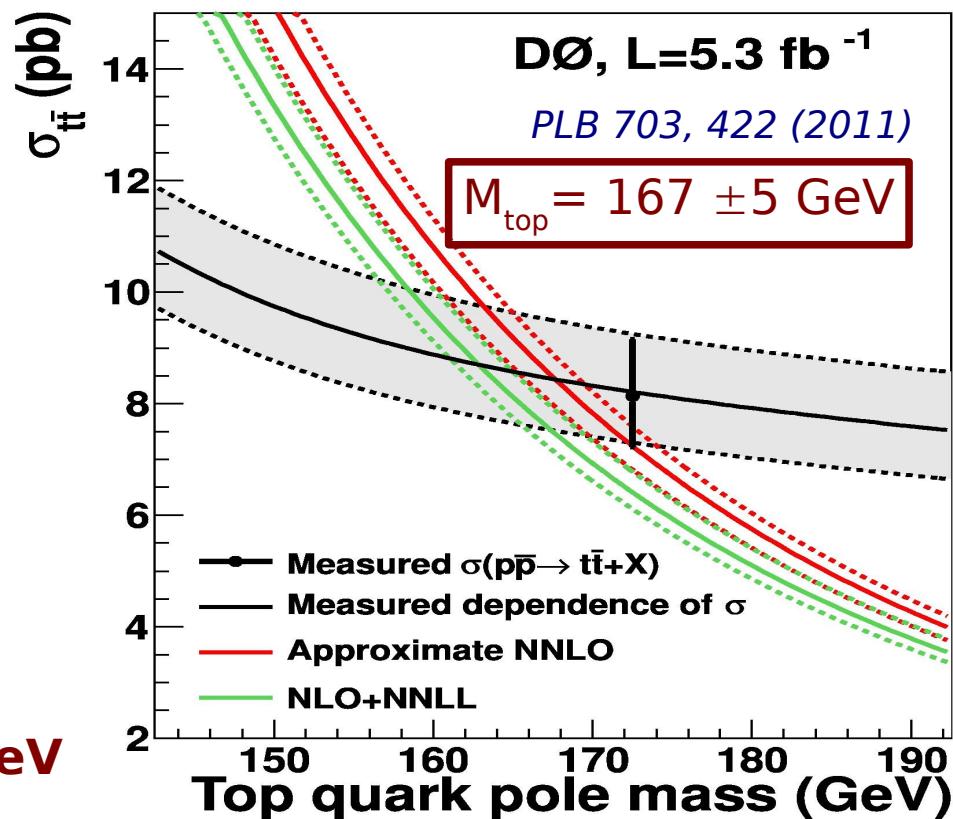
CDF dilepton Dalitz-Goldstein Method (analytical resolution of the kinematic)  $2.0 \text{ fb}^{-1}$   
without b-tagging:  $172.3 \pm 3.4 \text{ (stat)} \pm 2.1 \text{ (syst) GeV}$  (precision 2.3%)  
With b-tagging:  $170.5 \pm 3.7 \text{ (stat)} \pm 1.7 \text{ (syst) GeV}$  (precision 2.4%)  
*CDF Conf Note 10635*

# Mass Measurements Overview



**July 2011 combination:  $173.2 \pm 0.9 \text{ GeV}$   
precision 0.54%, better than 1 GeV!**

- Main uncertainties are from simulation/theory: simulation of the nonperturbative effects, ISR/FSR, color reconnection.
- Top mass definition in these measurements ?  $\Rightarrow$  measure the mass from cross section



# Top Width

- The top quark decay rate proportional to the t-channel single top cross-section
- Assume the same proportionality as for the SM

$$\Gamma(t \rightarrow Wb) = \sigma(t\text{-channel}) \frac{\Gamma(t \rightarrow Wb)_{\text{SM}}}{\sigma(t\text{-channel})_{\text{SM}}}$$

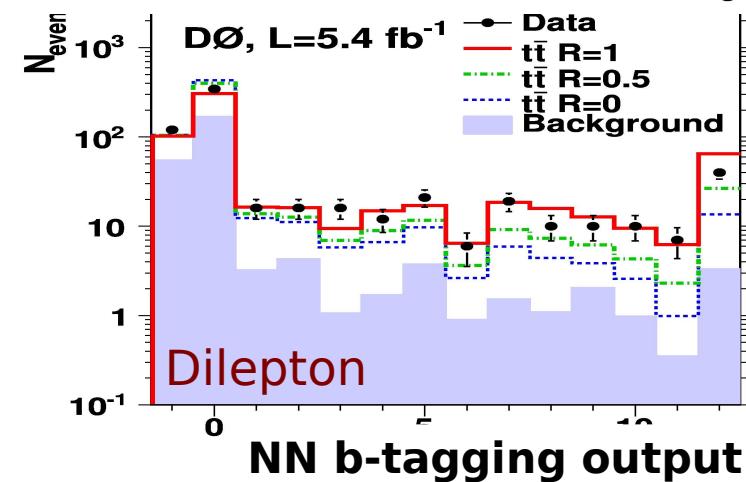
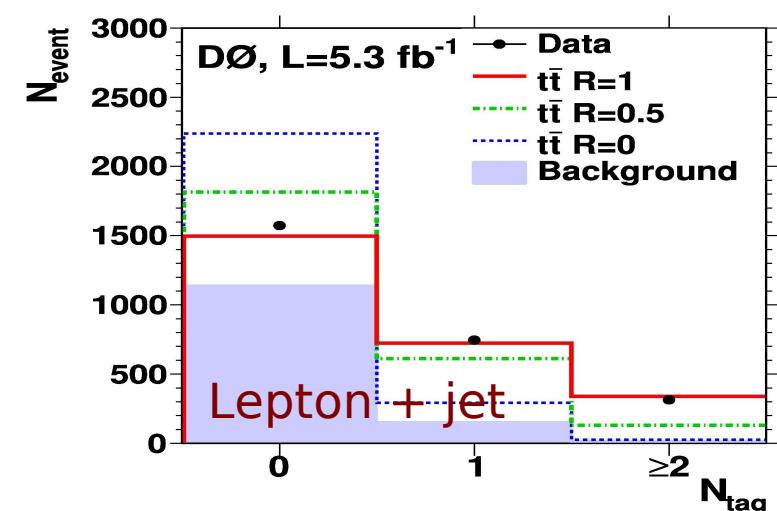
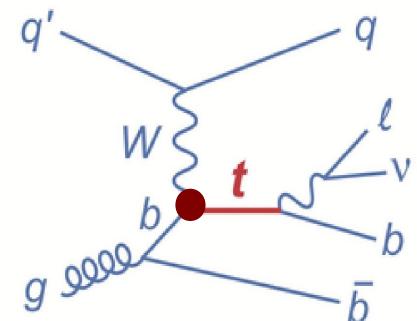
$$\Gamma_t = \frac{\sigma(t\text{-channel})}{\mathcal{B}(t \rightarrow Wb)} \frac{\Gamma(t \rightarrow Wb)_{\text{SM}}}{\sigma(t\text{-channel})_{\text{SM}}}$$

$$\tau_t = \hbar / \Gamma_t$$

- Combine with branching fraction measurement in ttbar production (lepton+jet and dilepton channels)

$$R = \frac{B(t \rightarrow Wb)}{B(t \rightarrow Wq)} = 0.90 \pm 0.04(\text{stat} + \text{syst})$$

PRL 107, 121802 (2011)



# Top Width

- Measured top width and lifetime

$$\Gamma_t = 2.00^{+0.47}_{-0.43} \text{ GeV}$$

$$\tau_t = (3.29^{+0.90}_{-0.63}) \times 10^{-25} \text{ s}$$

- $|V_{tb}| \sim \Gamma_t (t \rightarrow Wb)$ :

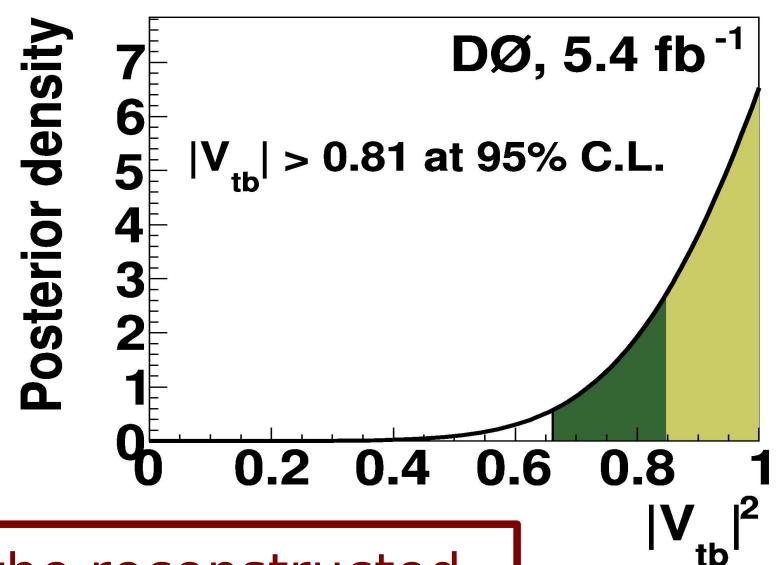
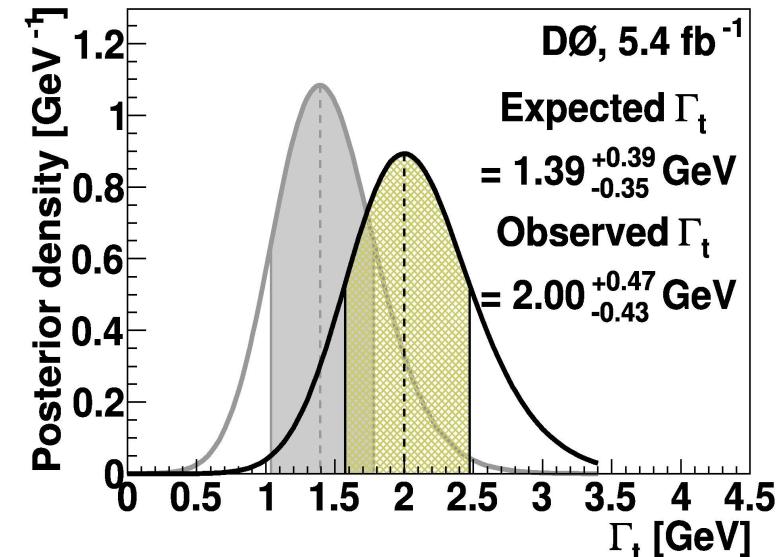
- Assumes SM production mechanisms.
- Pure V-A and CP-conserving interaction.
- Does not assume 3 generations or unitarity of the CKM matrix.
- Does not assume SM ration between s- and t-channel.
- Does not assume  $|V_{td}|^2 + |V_{ts}|^2 \ll |V_{tb}|^2$

$|V_{tb}| > 0.81$  at the 95% C.L.

Submitted to PRD (RC), arXive: 1201.4156

Direct measurement from the reconstructed mass distribution, CDF,  $4.3 \text{ fb}^{-1}$ :

$\Gamma_t < 7.6 \text{ GeV}$  at 95% CL



PRL 105, 232003 (2010)

# Spin Correlation

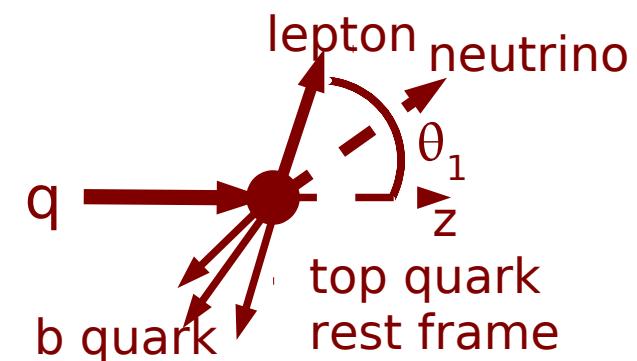
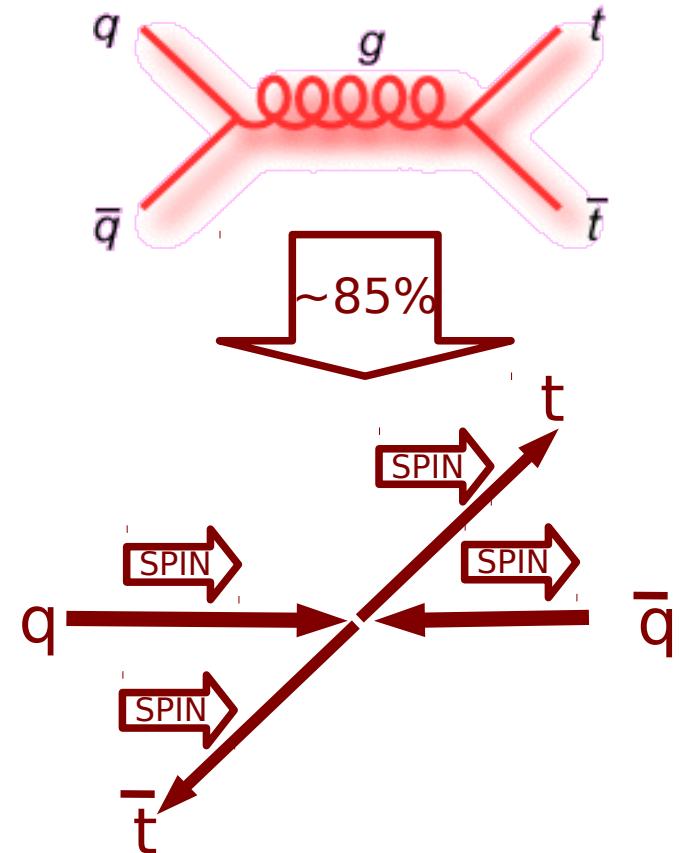
- Top produced unpolarized, but spins between quark and antiquark are correlated
- The spin correlation  $\frac{N_{||} - N_{\perp}}{N_{||} + N_{\perp}}$ 
  - depends on the production mode  $\Rightarrow$  **different at the LHC and the Tevatron**
  - depends on the basis choice
- Top quark decays before depolarization or hadronization ( $\tau \sim 10^{-25}$  sec)  $\Rightarrow$  spin information transmitted to the decay products (W boson, b quark).

coefficient	LO	NLO
$C$	0.928	0.777

beam basis

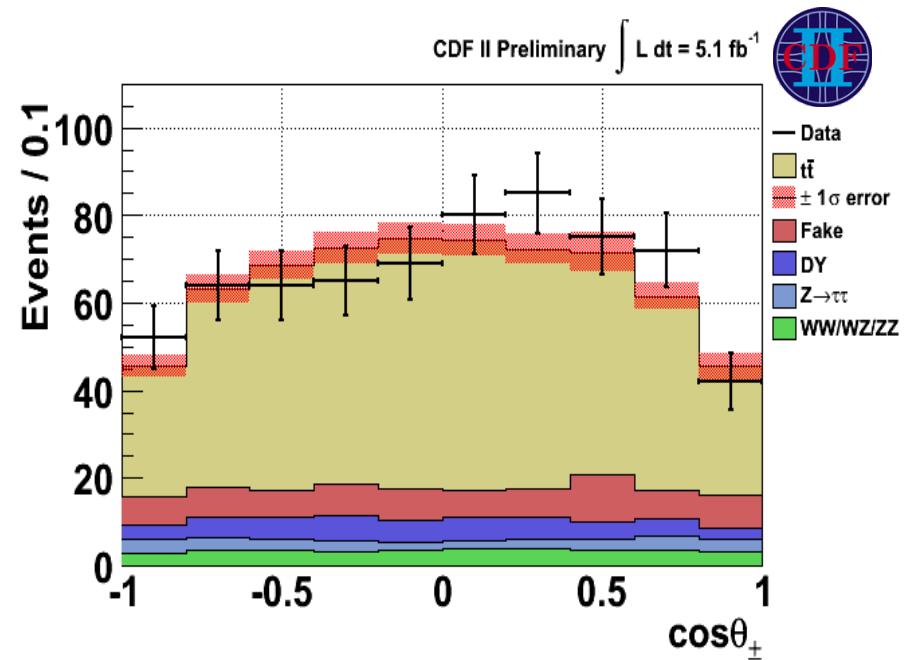
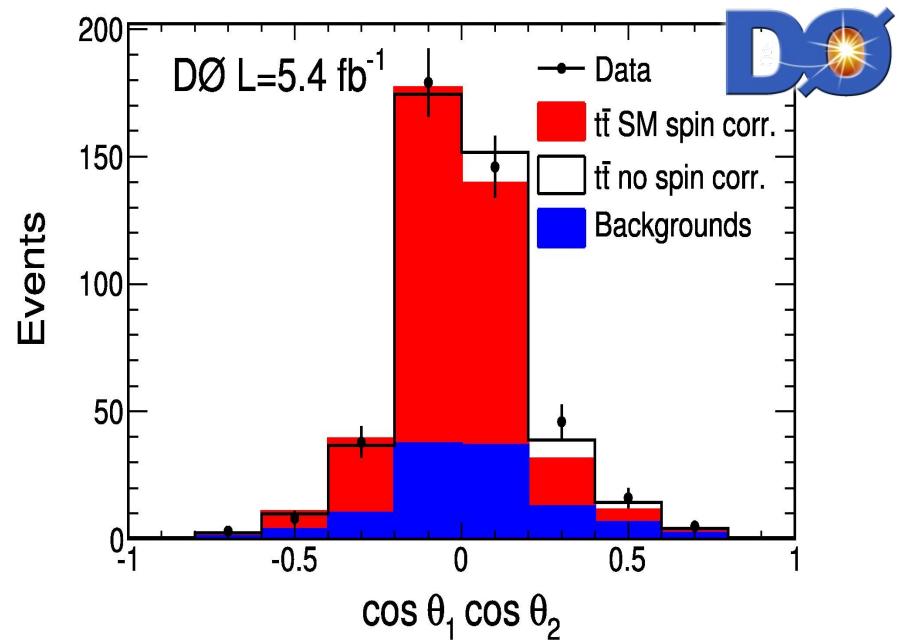
Bernreuther et al. Nucl. Phys. B 690, 81 (2004)

$$\frac{1}{\sigma} \frac{d\sigma}{d \cos \theta_1 d \cos \theta_2} = \frac{1}{4} (1 - C \cos \theta_1 \cos \theta_2)$$



# Template Based Measurements

- Make templates for different C values.  
Compare to data using Maximum Likelihood fit
- D0  $5.4 \text{ fb}^{-1}$  dilepton [PLB 702,16 \(2011\)](#):
  - $C_{\text{beam}} = 0.10 \pm 0.45 \text{ (stat+syst)}$
- CDF  $5.1 \text{ fb}^{-1}$  dilepton [CDF ConfNote 10719](#):
  - $C_{\text{beam}} = 0.04 \pm 0.56 \text{ (stat+syst)}$
- CDF  $5.3 \text{ fb}^{-1}$  lepton+jets [CDF ConfNote 102](#):
  - $C_{\text{beam}} = 0.72 \pm 0.69 \text{ (stat+syst)}$
- limited by statistical uncertainty
- consistent with SM expectation



# Matrix Element Approach

- Discriminate SM spin correlation ( $H=1$ ) and no correlation hypothesis ( $H=0$ )

- Use discrimination variable
- D0  $5.4 \text{ fb}^{-1}$  dilepton :

$$C_{\text{beam}} = 0.57 \pm 0.31 \text{ (stat+syst)}$$

- D0  $5.3 \text{ fb}^{-1}$  lepton+jets :
- $C_{\text{beam}} = 0.89 \pm 0.33 \text{ (stat+syst)}$

- 30% increased sensitivity
- agreement with SM
- Combination:

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

$C > 0.26$  @ 95% C.L.

$C=0$  excluded at 3.1 SD

**First evidence of the non-zero spin correlation!**

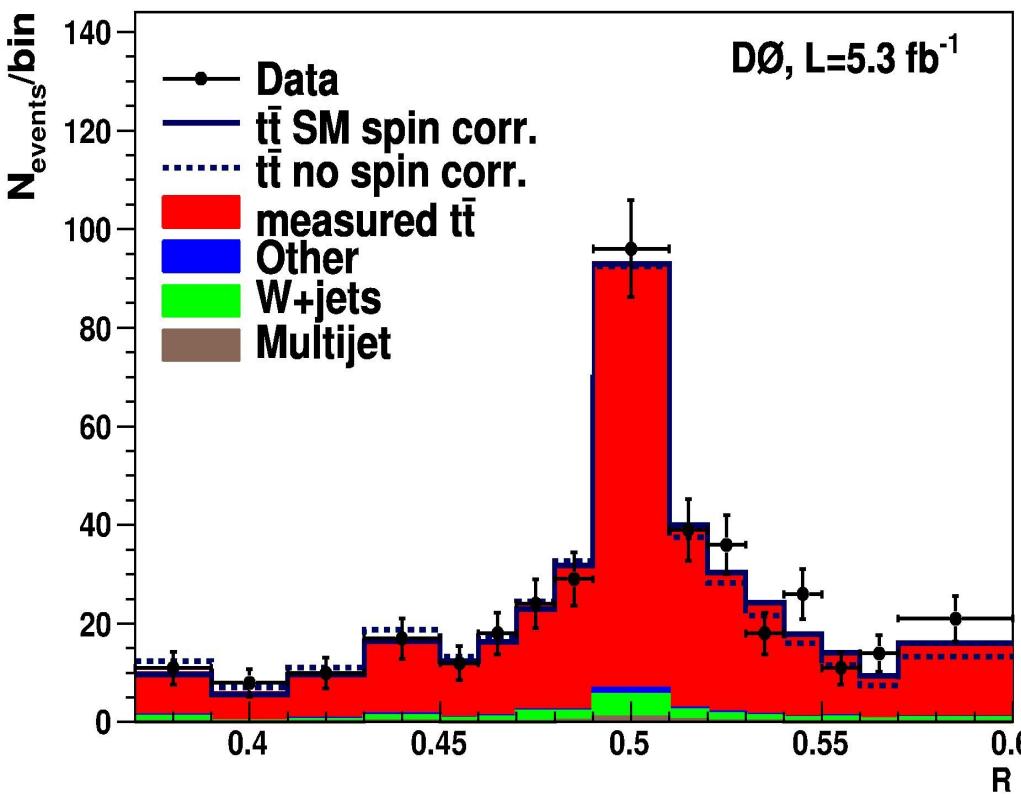
PRL 108, 032004 (2012)

Moriond EW 2012

$$P(x, H) \sim \int d^6\sigma(y, H) W(x, y) f_{PDF}(q_1) f_{PDF}(q_2) dq_1 dq_2$$

Differential Detector Parton density functions cross section response

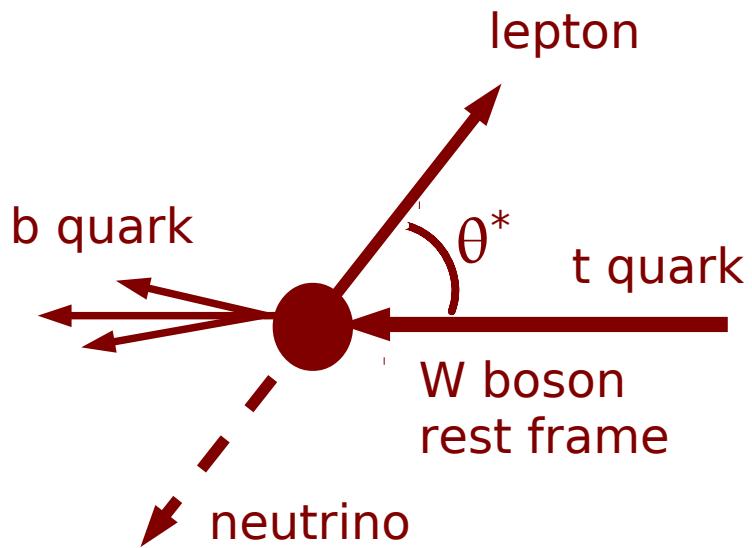
$$R = \frac{P(x, H = 1)}{P(x, H = 1) + P(x, H = 0)}$$



V. Shary: Top quark properties @ Tevatron

# *W* boson Helicity Studies

- V-A structure of  $t \rightarrow W b$  vertex in SM dictates small right handed polarization of  $W$  boson
  - non SM physics will enhance this contribution
- Distinguish between different  $W$  helicity state, by reconstructing angle of the  $W$  decay products



Longitudinal:

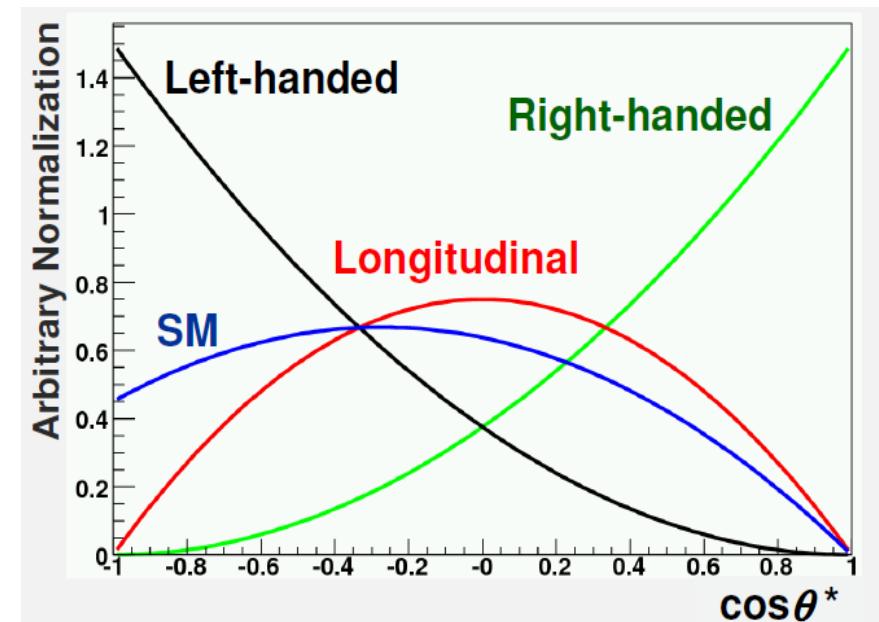
$$f_0 = \frac{\Gamma(t \rightarrow W_{\lambda=0} b)}{\Gamma(t \rightarrow W b)} \quad SM : 69.6\%$$

Left-handed:

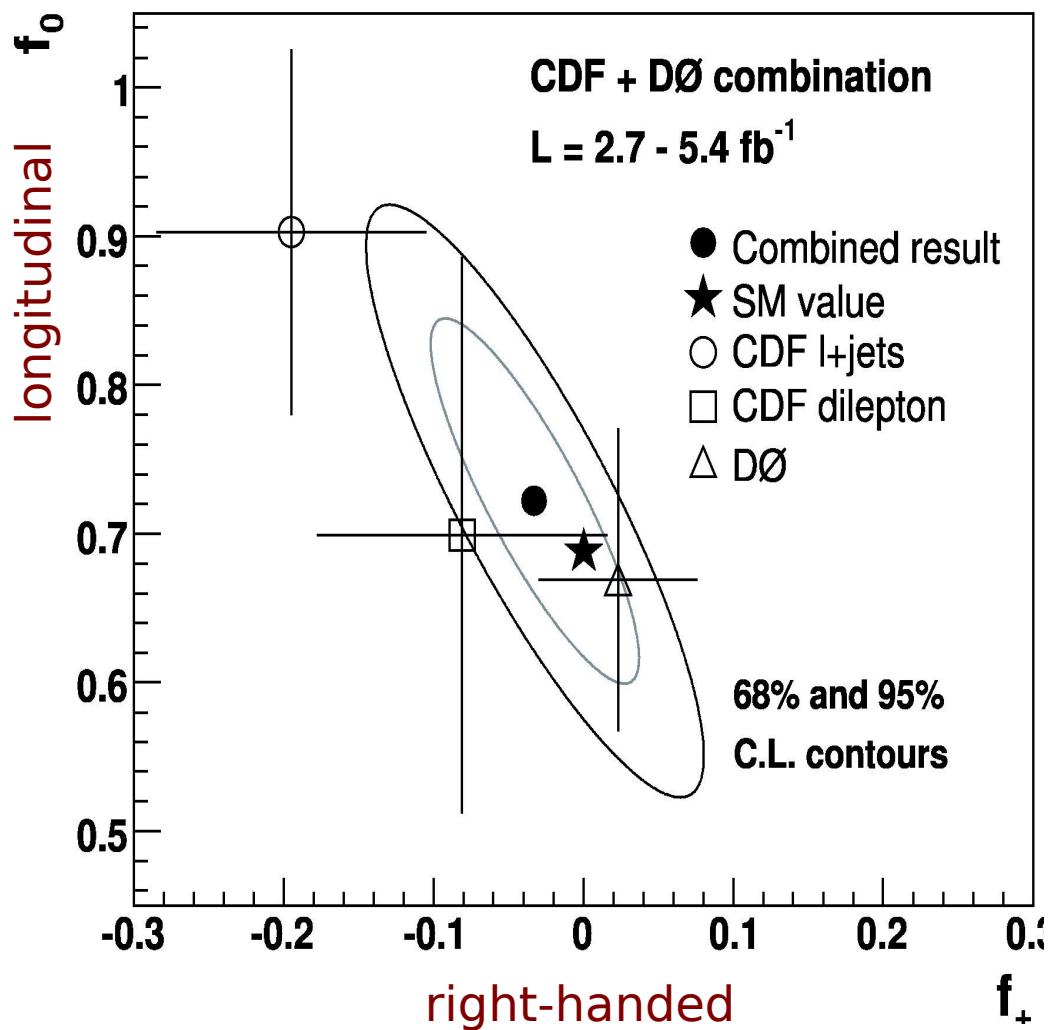
$$f_- = \frac{\Gamma(t \rightarrow W_{\lambda=-1} b)}{\Gamma(t \rightarrow W b)} \quad SM : 30.3\%$$

Right-handed:

$$f_+ = \frac{\Gamma(t \rightarrow W_{\lambda=+1} b)}{\Gamma(t \rightarrow W b)} \quad SM : 0.1\%$$



# $W$ Helicity: Results



- Binned Poisson likelihood is constructed  $L(f_0, f_+)$  for the data to be consistent with the sum of signal and background templates.
- Main systematics uncertainties are :
  - Signal modeling: underlying event, additional collisions, MC generator
  - Background modeling: shape and yield in low discriminant sample

*Submitted to PRD (arXiv:1202.5272)*

**First published Tevatron top quark combination!**

Longitudinal:  $f_0 = 0.722 \pm 0.062 \text{ (stat)} \pm 0.052 \text{ (syst)}$

Right-handed:  $f_+ = -0.033 \pm 0.034 \text{ (stat)} \pm 0.031 \text{ (syst)}$

# Search For Anomalous Top Quark Couplings

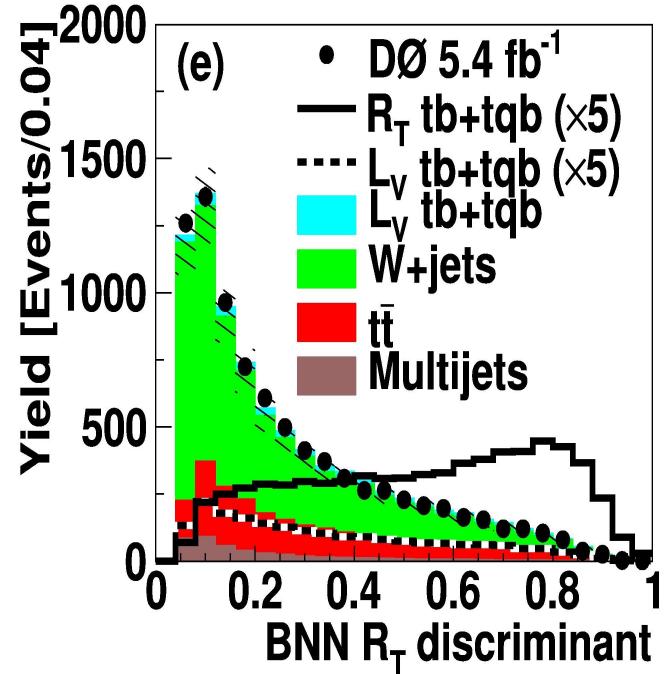
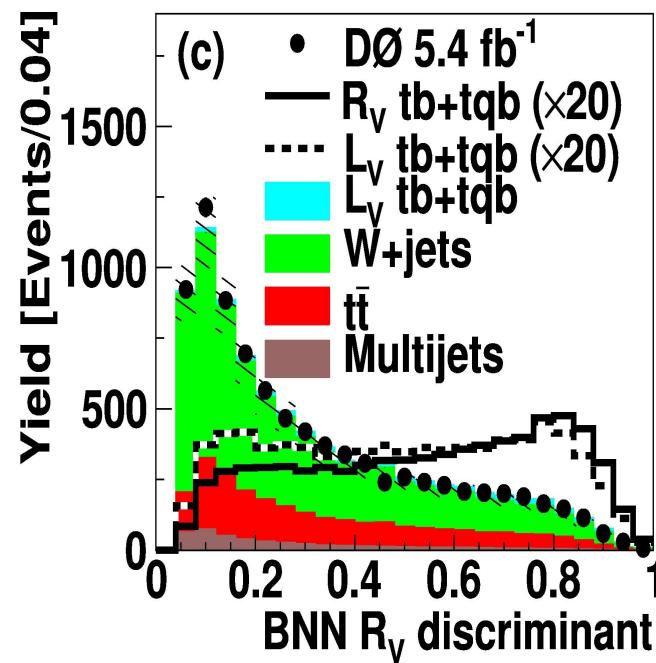
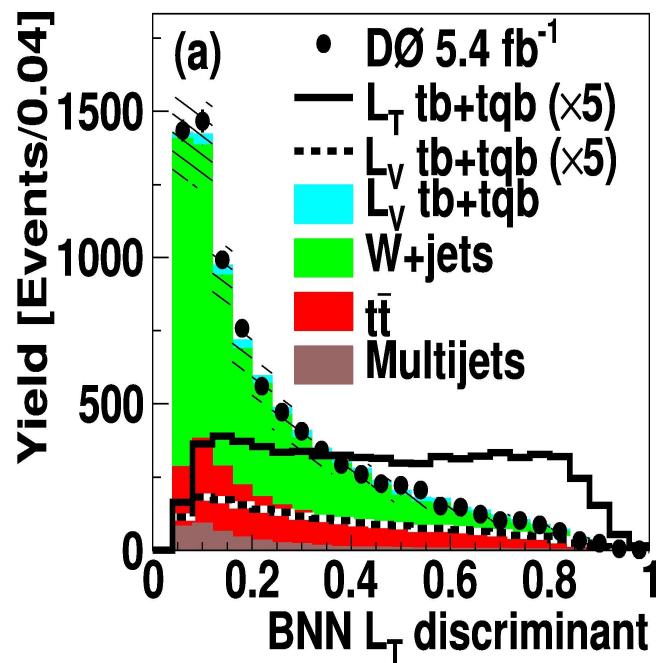


- Using CP-conserving effective Lagrangian for Wtb vertex as

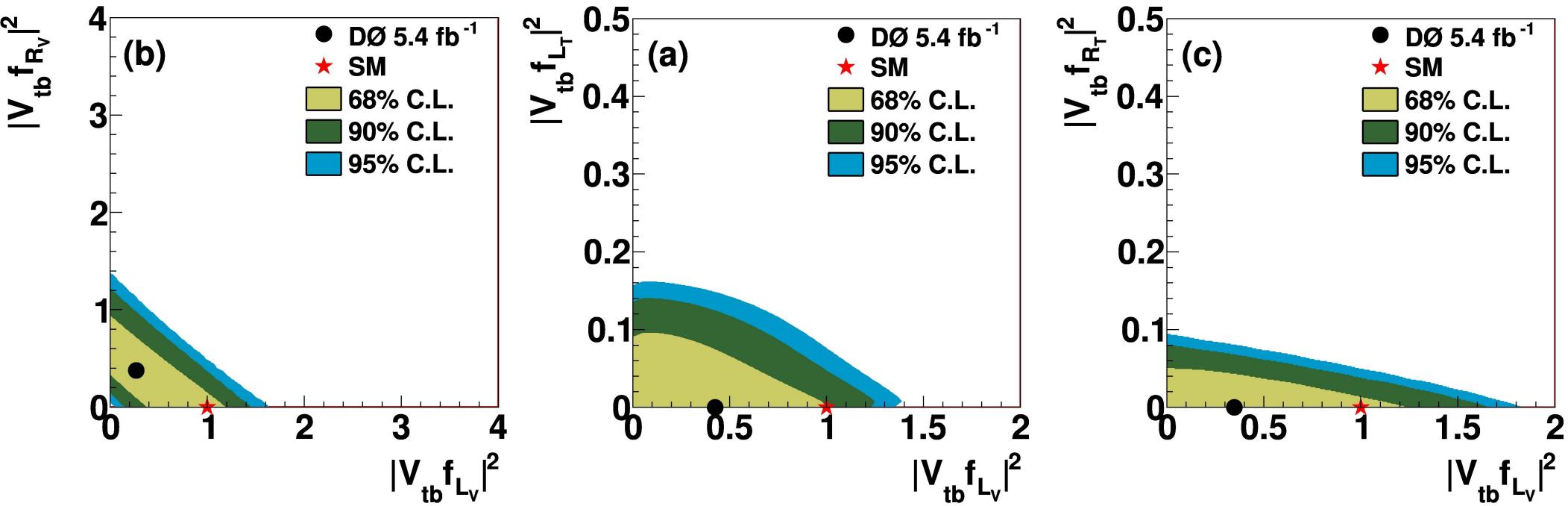
$$\mathcal{L} = -\frac{g}{\sqrt{2}} \bar{b} \gamma^\mu V_{tb} (f_1^L P_L + f_1^R P_R) t W_\mu^- - \frac{g}{\sqrt{2}} \bar{b} \frac{i \sigma^{\mu\nu} q_\nu V_{tb}}{M_W} (f_2^L P_L + f_2^R P_R) t W_\mu^- + \text{H.c.}$$

$P_L = \frac{1}{2}(1 - \gamma_5)$    **SM**   **Right-handed vector coupling**    $P_R = \frac{1}{2}(1 + \gamma_5)$   
}   }   }  
**tensor couplings**

- Train multivariate discriminant to separate between anomalous single top production from SM production and background



# Anomalous Couplings: Results



One-dimensional upper limits at 95% C.L. For anomalous Wtb couplings in the three scenarios.

Scenario	Cross section	Coupling
$(L_V, L_T)$	$< 1.21 \text{ pb}$	$ V_{tb} \cdot f_{L_T} ^2 < 0.13$
$(L_V, R_V)$	$< 2.81 \text{ pb}$	$ V_{tb} \cdot f_{R_V} ^2 < 0.93$
$(L_V, R_T)$	$< 0.60 \text{ pb}$	$ V_{tb} \cdot f_{R_T} ^2 < 0.06$

Submitted to PLB, arXive: 1110.4592

# Searching for Lorentz Invariance Violation



Standard Model Extension : adds terms for Lorentz Invariance violation to the matrix element

D. Colladay and V.A. Kostelecky, Phys. Rev. D 58, 116002 (1998);  
V.A. Kostelecky, Phys. Rev. D 69, 105009 (2004)

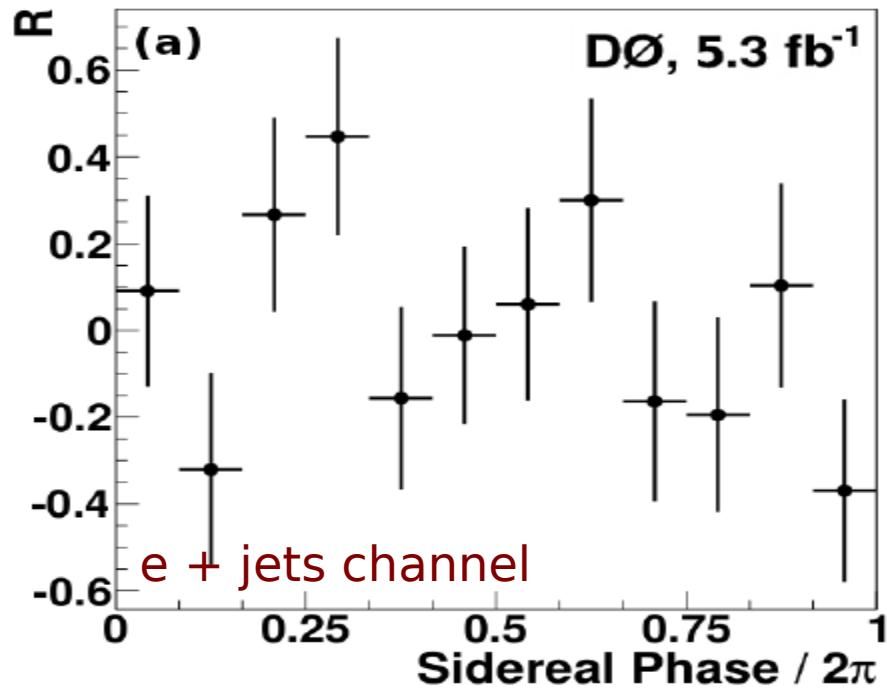
$$|\mathbf{M}|^2 = \underbrace{P F \bar{F}}_{\text{Standard Model}} + (c_R + c_L)_{\mu\nu} \underbrace{(\delta P_p + \delta P_v)^{\mu\nu} F \bar{F}}_{\text{Production Corrections}} + (c_L)_{\mu\nu} \underbrace{(P (\delta F)^{\mu\nu} \bar{F} + P F (\delta \bar{F})^{\mu\nu})}_{\text{Decay Corrections}}$$

$$c_{L(R)}^{\text{Apparatus}} = \hat{R}(\omega_{\text{side}} t)_{(\text{Sun} \rightarrow \text{Apparatus})} c_{L(R)}^{\text{Sun}}$$

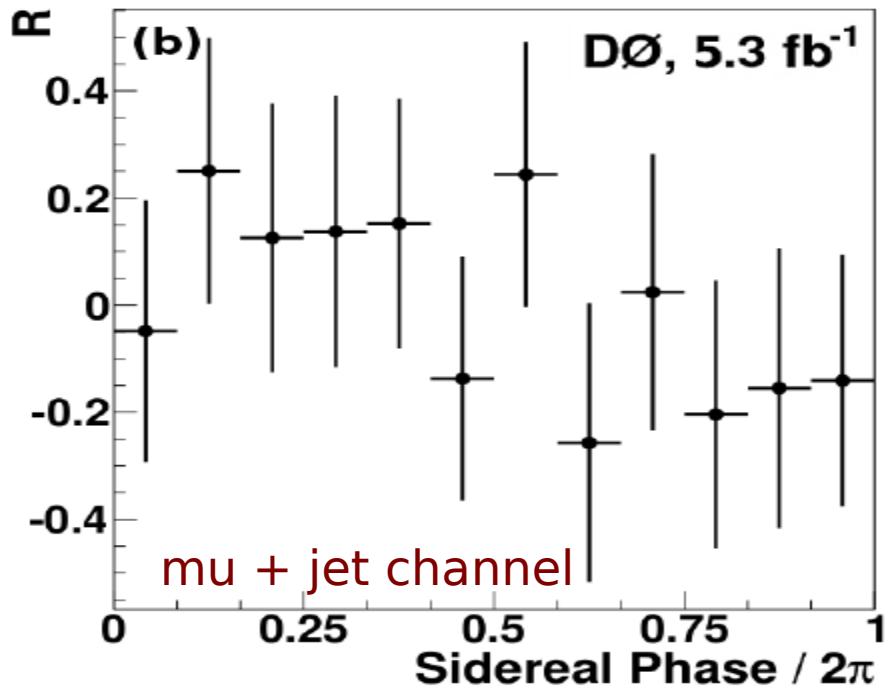
Measurement: estimate components of  $c_R$  and  $c_L$  matrices by searching the sidereal time-dependence ( $\sim 23h\ 56min$ ) in the cross section

$$\sigma(t) \approx \sigma_{\text{ave}} (1 + f_{\text{SME}}(t))$$

# Searching for Lorentz Invariance Violation



e + jets channel



assuming  $(c_U)_{\mu\nu} \equiv 0$       Limits on SME coefficients at the 95% C.L.      assuming  $(c_Q)_{\mu\nu} \equiv 0$

Coefficient	Fit Value	95% C.L. Interval
$(c_Q)_{XX33}$	$-0.11 \pm 0.11$	[ -0.33, +0.10 ]
$(c_Q)_{YY33}$	$0.11 \pm 0.11$	[ -0.10, +0.33 ]
$(c_Q)_{XY33}$	$-0.04 \pm 0.11$	[ -0.25, +0.17 ]
$(c_Q)_{XZ33}$	$0.15 \pm 0.08$	[ -0.01, +0.30 ]
$(c_Q)_{YZ33}$	$-0.03 \pm 0.08$	[ -0.19, +0.12 ]

Coefficient	Fit Value	95% C.L. Interval
$(c_U)_{XX33}$	$0.09 \pm 0.09$	[ -0.08, +0.26 ]
$(c_U)_{YY33}$	$-0.09 \pm 0.09$	[ -0.26, +0.08 ]
$(c_U)_{XY33}$	$0.04 \pm 0.09$	[ -0.13, +0.21 ]
$(c_U)_{XZ33}$	$-0.13 \pm 0.07$	[ -0.27, +0.01 ]
$(c_U)_{YZ33}$	$0.00 \pm 0.07$	[ -0.13, +0.14 ]

# Properties Summary

	SM	D0	CDF
t̄t cross section:	7.4 – 8.1 pb	7.6±0.6 pb	7.5±0.5 pb
Single top s+t cross section:	3.3 ± 0.13 pb	2.8 <sup>+0.6</sup> <sub>-0.5</sub> pb	
Cross section t-channel:	2.26 ± 0.12 pb	2.9 ± 0.6 pb	0.8 ± 0.4 pb
Cross section s-channel:	1.04 ± 0.04 pb	1.0 ± 0.6 pb	1.8 <sup>+0.7</sup> <sub>-0.5</sub> pb
$\sigma(gg \rightarrow t\bar{t})/\sigma(p\bar{p} \rightarrow t\bar{t})$	0.15 ± 0.05		0.07± 0.16
t̄tγ cross section ( $E_T^{\gamma} > 10$ GeV, $ \eta^{\gamma}  < 1$ )	0.17 ± 0.03 pb		0.18 ± 0.08 pb
Charge asymmetry	(2 ÷ 5)%	(19.6 ± 6.5 )%	(20.1 ± 6.7)%
Mass		173.2 ± 0.9 GeV	
M <sub>top</sub> - M <sub>antitop</sub>	0 GeV	0.8 ± 1.9 GeV	-3.3 ± 1.7 GeV
Width	1.33 GeV	2.0 <sup>+0.5</sup> <sub>-0.4</sub> GeV (via single top cross section)	< 7.6 GeV at 95% CL (direct measurement)
Lifetime		(3.3 +0.9 -0.6 ) × 10 <sup>-25</sup> s	(0.15 ÷ 2.2) × 10 <sup>-24</sup> s
V <sub>tb</sub>	1	> 0.81 at 95% CL	> 0.71 at the 95% CL
B(t → Wb)/B(t → Wq)	0.999	0.90 ± 0.04	1.12 <sup>+0.27</sup> <sub>-0.23</sub>
W boson helicity in top quark decays	f <sub>0</sub> ~ 0.696 f <sub>+</sub> ~ 0.001		f <sub>0</sub> = 0.72 ± 0.08 f <sub>+</sub> = -0.03 ± 0.05
Charge	+2/3	Q = -4/3 excluded at 92% CL	Q = -4/3 excluded at 99% CL
Spin correlation (beam frame)	0.78	0.66 ± 0.23 zero correlation excl. at 3.1σ	0.04 ± 0.56 (dilepton) 0.89 ± 0.33 (l+jet)
Color flow: W <sub>color-singlet</sub> / W <sub>all</sub>	1	0.56 ± 0.42	

# Conclusion

- Tevatron is in the process of making its legacy measurements
  - Cross sections, asymmetry, spin correlation measurements are complementary between Tevatron and LHC
  - Mass reach a precision of 0.6% and a further improvement requires a better understanding of the theory/simulation related uncertainties
- More details and updates:
  - D0 Top quark results:  
[www-d0.fnal.gov/Run2Physics/top/top\\_public\\_web\\_pages/top\\_public.html](http://www-d0.fnal.gov/Run2Physics/top/top_public_web_pages/top_public.html)
  - CDF Top quark results:  
[www-cdf.fnal.gov/physics/new/top/top.html](http://www-cdf.fnal.gov/physics/new/top/top.html)

# *Back-up*

# Mass Measurement in $l+jet$ Channel With $8.7 \text{ fb}^{-1}$



CDF II Preliminary  $8.7 \text{ fb}^{-1}$

Systematic	GeV/c <sup>2</sup>
Residual JES	0.52
Generator	0.56
Next Leading Order	0.09
PDFs	0.08
b jet energy	0.10
b tagging efficiency	0.03
Background shape	0.20
gg fraction	0.03
Radiation	0.06
MC statistics	0.05
Lepton energy	0.03
MHI	0.07
Color Reconnection	0.21
Total systematic	0.84

# $\mathcal{D}0$ ME $l+jet$ mass



Source	Uncertainty (GeV)
<i>Modeling of production:</i>	
<i>Modeling of signal:</i>	
Higher-order effects	$\pm 0.25$
ISR/FSR	$\pm 0.26$
Hadronization and UE	$\pm 0.58$
Color reconnection	$\pm 0.28$
Multiple $p\bar{p}$ interactions	$\pm 0.07$
Modeling of background	$\pm 0.16$
$W+jets$ heavy-flavor scale factor	$\pm 0.07$
Modeling of $b$ jets	$\pm 0.09$
Choice of PDF	$\pm 0.24$
<i>Modeling of detector:</i>	
Residual jet energy scale	$\pm 0.21$
Data-MC jet response difference	$\pm 0.28$
$b$ -tagging efficiency	$\pm 0.08$
Trigger efficiency	$\pm 0.01$
Lepton momentum scale	$\pm 0.17$
Jet energy resolution	$\pm 0.32$
Jet ID efficiency	$\pm 0.26$
<i>Method:</i>	
Multijet contamination	$\pm 0.14$
Signal fraction	$\pm 0.10$
MC calibration	$\pm 0.20$
Total	$\pm 1.02$

PRD 84, 032004 (2011)

$$174.94 \pm 0.83(\text{stat}) \pm 0.78(\text{JES}) \pm 1.02(\text{syst}) \text{ GeV}$$

$$174.9 \pm 1.5 \text{ GeV} \text{ (precision: 0.9%)}$$

# Mass Combination

Tevatron combined values ( $\text{GeV}/c^2$ )

$M_t$	173.18
iJES	0.39
aJES	0.09
bJES	0.15
cJES	0.05
dJES	0.21
rJES	0.12
Lepton $p_T$	0.10
Signal	0.51
Detector Modeling	0.10
UN/MI	0.00
Background from MC	0.23
Background from Data	0.12
Method	0.09
MHI	0.08
Systematics	0.76
Statistics	0.56
Total	0.94

