Recent Top quark Measurements at the Tevatron

Cecilia E. Gerber
University of Illinois-Chicago

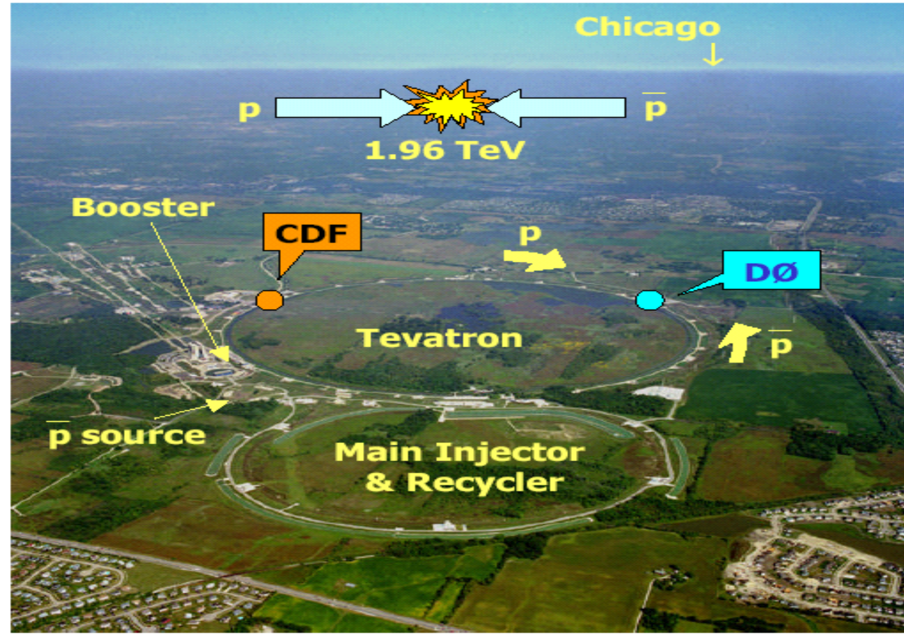
for the CDF & D0 Collaborations

24^{th} Recontres de Blois

Chateau Royal de Blois, May 27-June 1, 2012

Outline

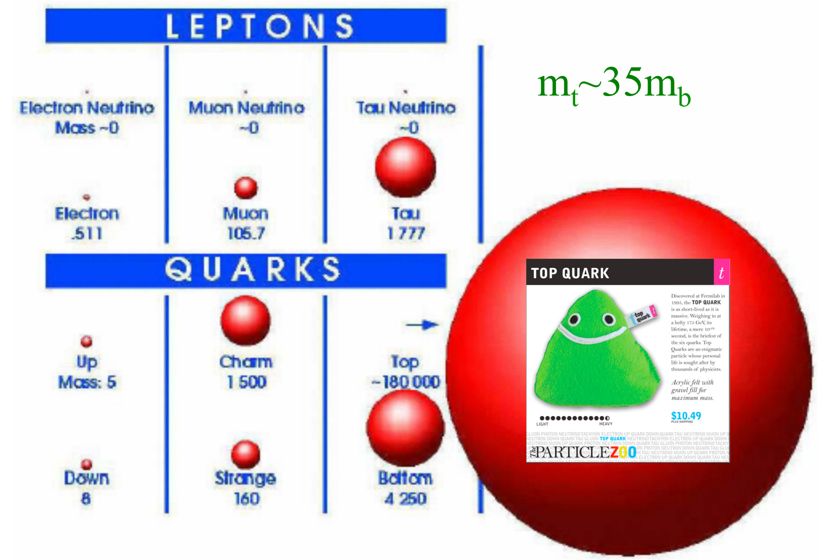
- Motivation
- Introduction to top quark production and decay
- Recent results
- Conclusions



Top Quark

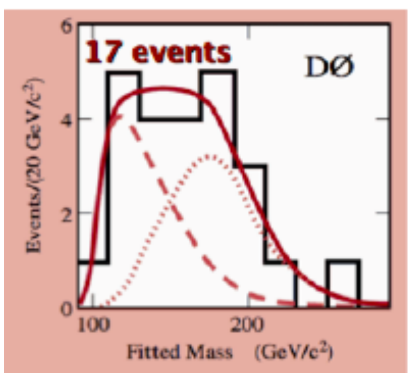
- Heaviest known elementary particle
  - Large Higgs Couplings
  - Special role in EWSB mechanisms
  - Many NP signatures decay to tops

$m_t \sim 35 m_b$

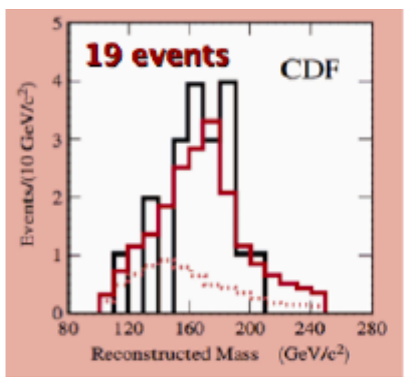


1995: Discovered @ the Tevatron

PRL 74, 2632 (1995)



PRL 74, 2626 (1995)



Today: thousands of events used for precision measurements & searches

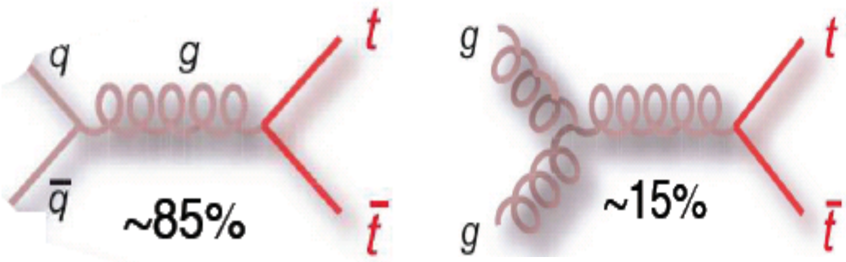
- Within the Standard Model
  - Single or Pair Production
  - Electric Charge +⅔ e
  - Short Lifetime $5\text{x}10^{-25}$s
    - Decays before hadronization
- Successful Tevatron program
- New results complement those from LHC

Top Quark Production at the Tevatron

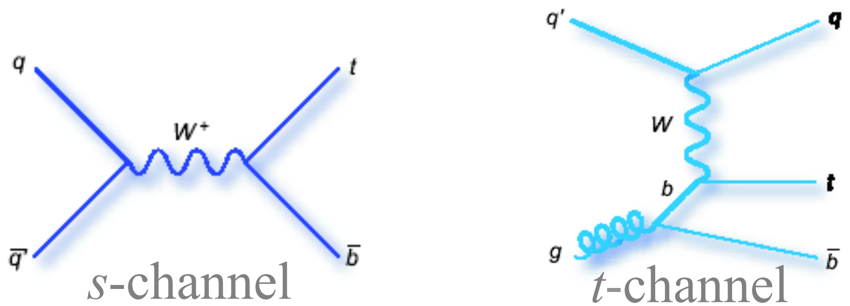
- Top quarks are mainly produced in pairs via the strong interaction

$\sigma_{tt} = 7.46 + 0.48 - 0.67$ pb
Moch & Uwer PRD 78, 034003 (2008)

(Calculated for top mass = 172.5 GeV)



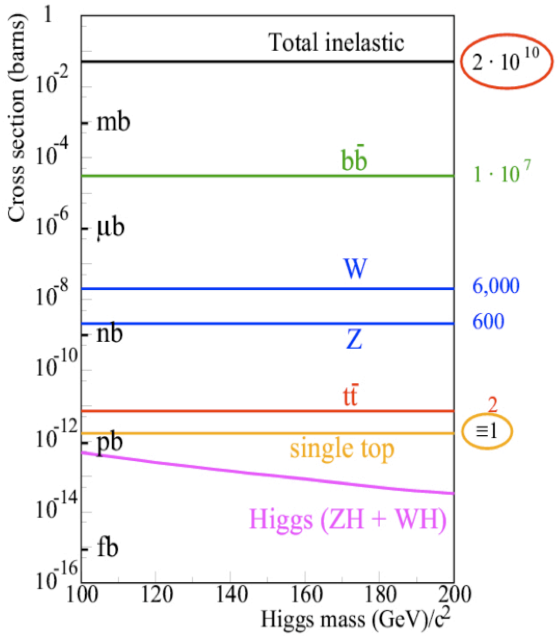
- EW Single Top production
  - Experimentally challenging due to large W+jets background in lower jet multiplicities than pair production



$\sigma_{tb} = 0.88 \pm 0.11$ pb

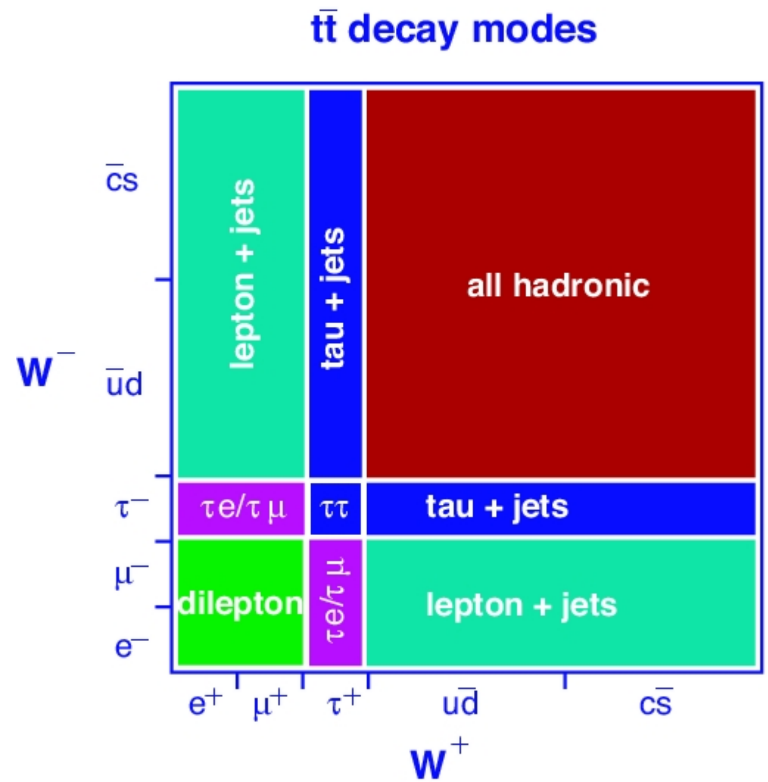
$\sigma_{tqb} = 1.98 \pm 0.25$ pb

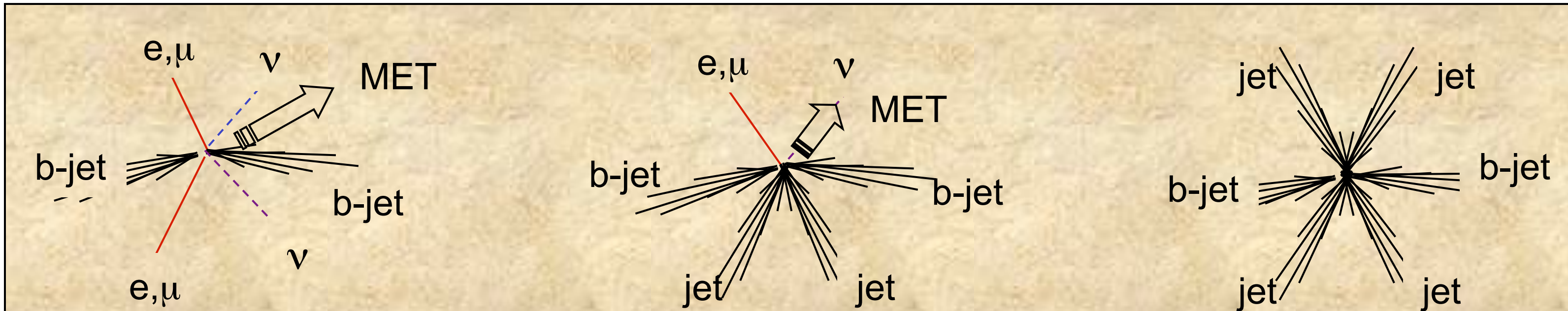
Kidonakis PRD 74 114012 (2006), m_t=172.5GeV
Associated production tW negligible



Top Quark Decay

- $m_t > m_W + m_b \Rightarrow$
  dominant 2-body decay $t \rightarrow Wb$
- Assuming unitarity of 3-generation CKM matrix $\Rightarrow B(t \rightarrow Wb) \sim 100\%$
- $\Gamma_t^{SM} \approx 1.4$ GeV at $m_t = 175$ GeV
  - Top decays before top-flavored hadrons or tt-quarkonium bound states can form
  - Top spin and kinematics is transferred to the final state



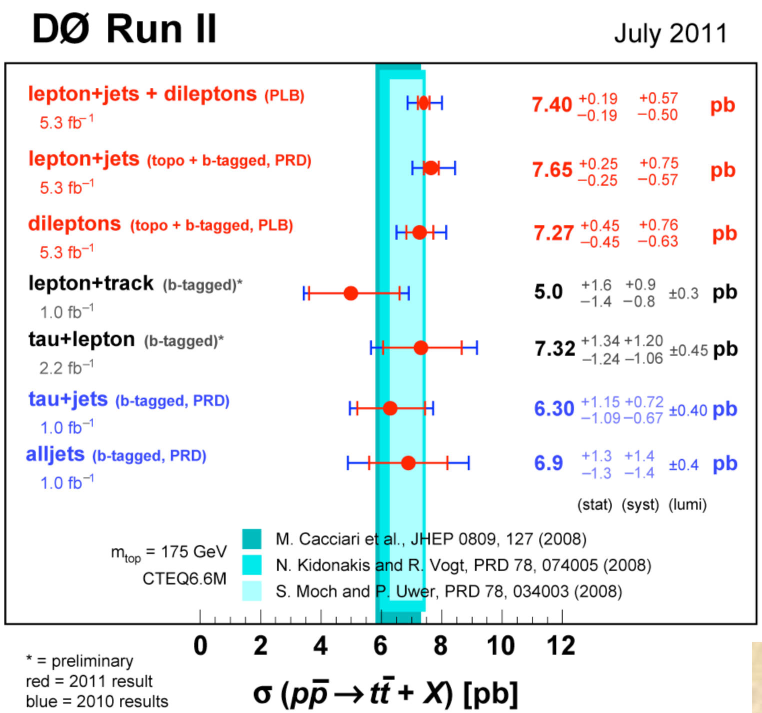


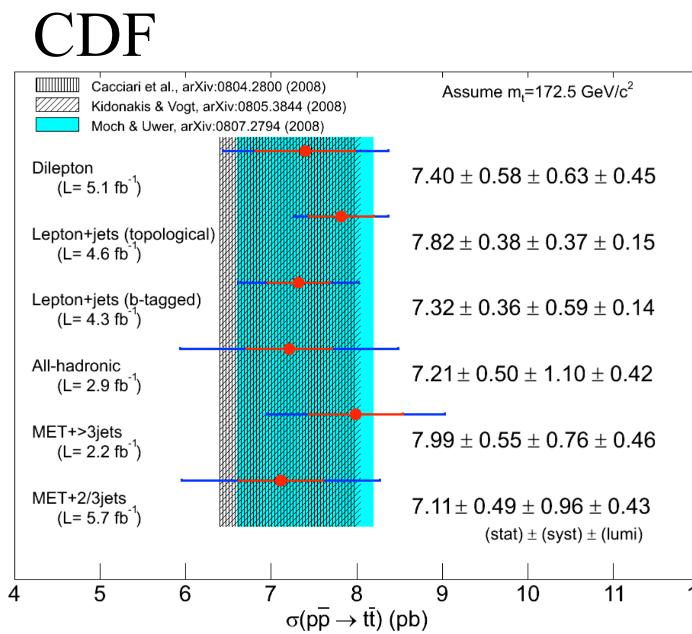
Dilepton
(BR~5%, low bckg)

Lepton+jets
(BR~30%, moderate bckg)

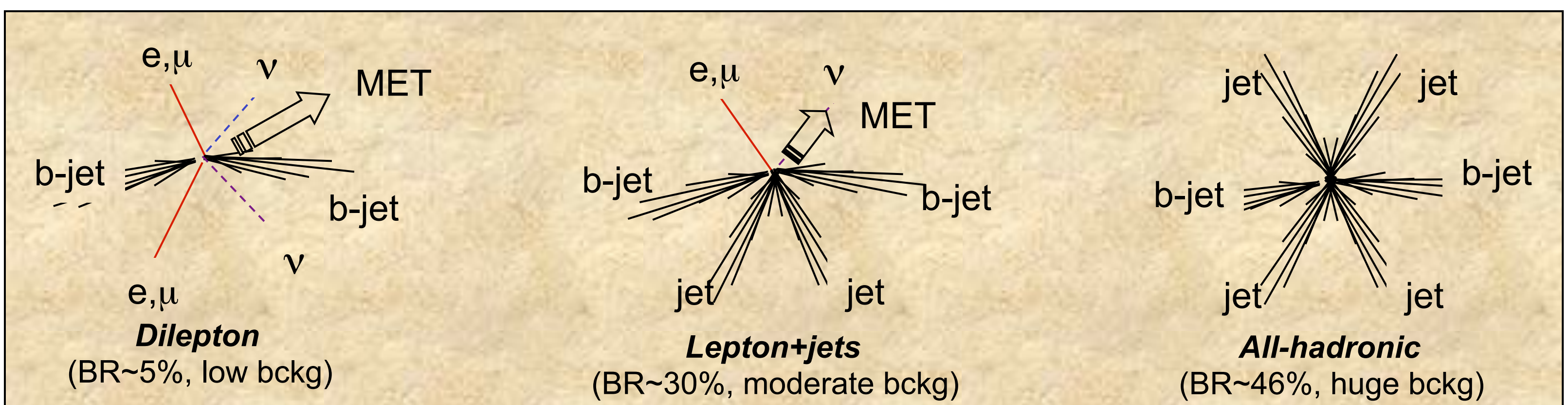
All-hadronic
(BR~46%, huge bckg)

Top Pair Production Cross Sections





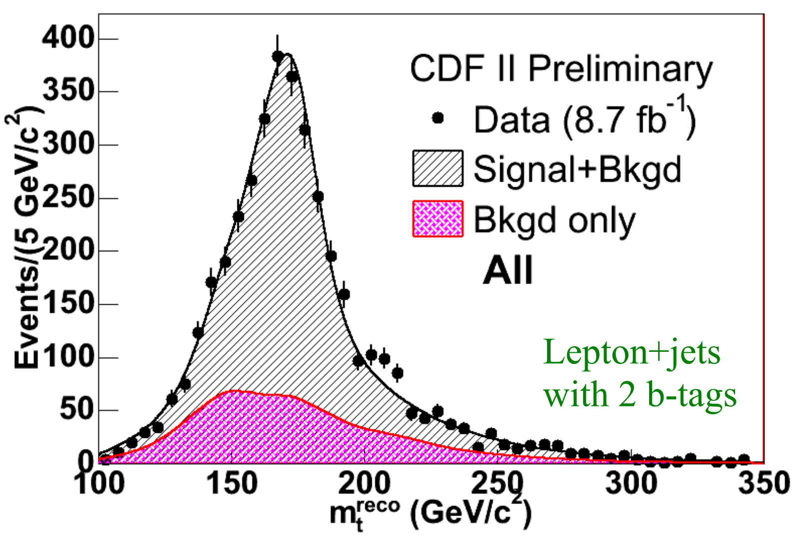
Measured in all channels except $\tau_{had}\,\tau_{had}$



Top Quark Mass

- Fundamental parameter of the SM
  - Affects predictions via radiative corrections
  - Together with the W mass, places constraints on the Higgs mass
- top anti-top mass difference
  - Test of CPT violation
  - Only possible to study with tops
  - Many systematics cancel in difference
    - Total systematics 0.59 GeV

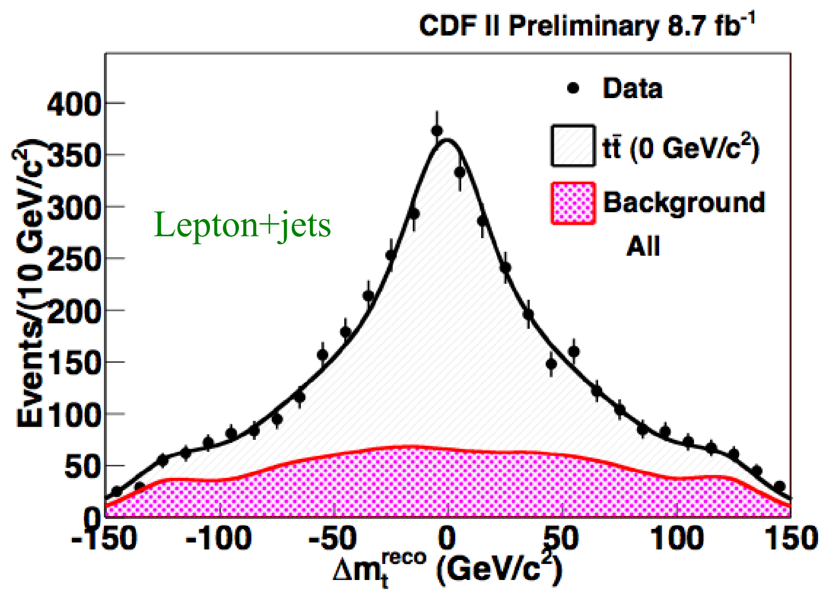
Single most precise measurement



$$M_{top} = 172.85 \pm 1.10 \text{GeV}$$

Total systematics 0.84 GeV

CDF/PUB/TOP/10761



$$\Delta M_{top} = -1.95 \pm 1.26 \text{GeV}$$

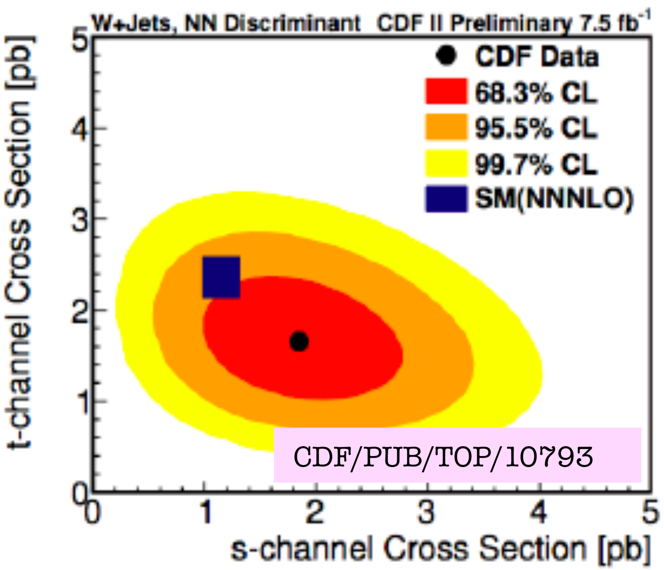
CDF/PUB/TOP/10777

Studies of Single Top Production

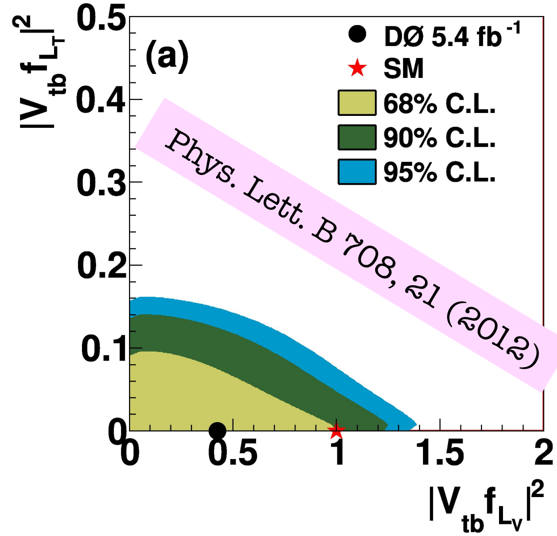
- First observed in 2009
  - 14y after pair production, 50x more data
- Probe of Wtb interaction
- Cross sections sensitive to BSM processes
- s-channel suppressed at the LHC

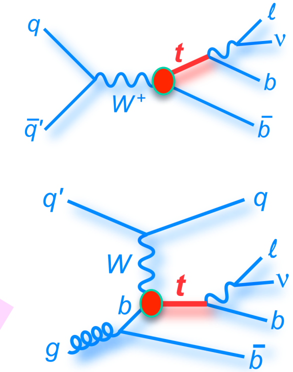
$$\sigma_{tb} = 1.81 \pm^{0.63}_{0.58}\ pb$$

World's best s-channel x-sec

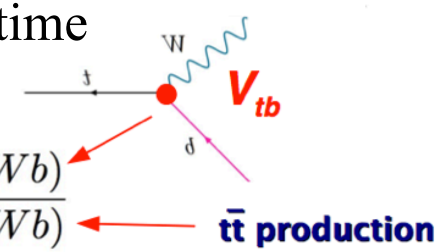


- Limits on anomalous Wtb couplings





- Top decay width and lifetime



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

Most precise

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

Phys. Rev. D 85 091104 (2012)

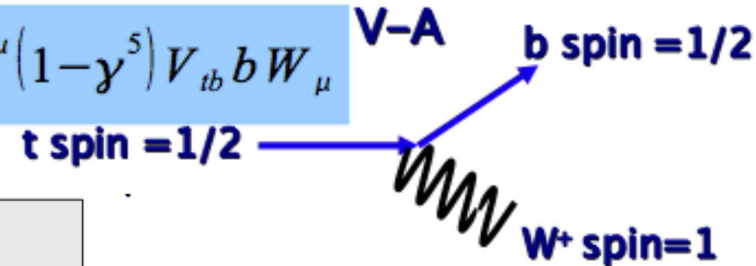
$$\tau_t = 3.29^{+0.90}_{-0.63} \times 10^{-25}\,\text{s}$$

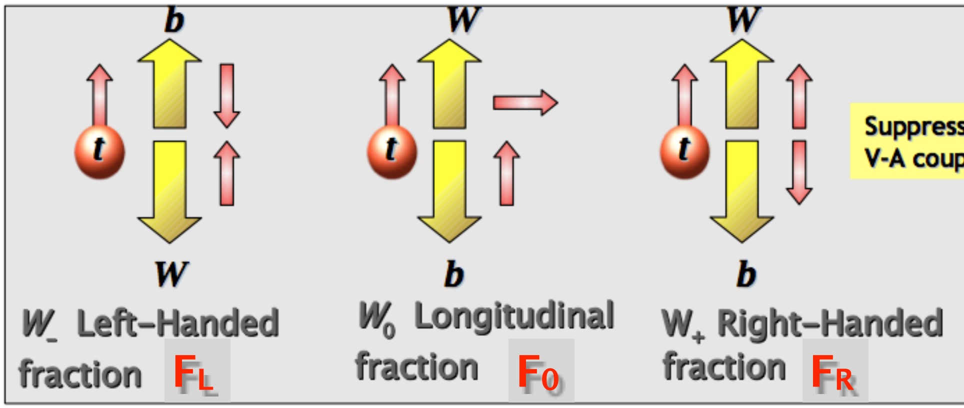
W Boson Helicity Fractions

Phys. Rev. D **85**, 071106 (2012)

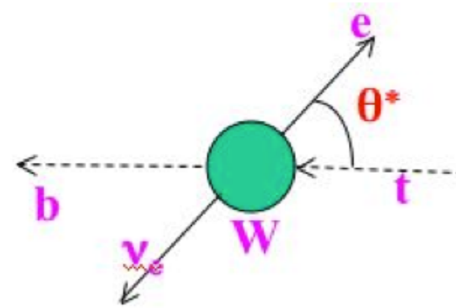
(2.7-5.4 fb^{-1}of data)

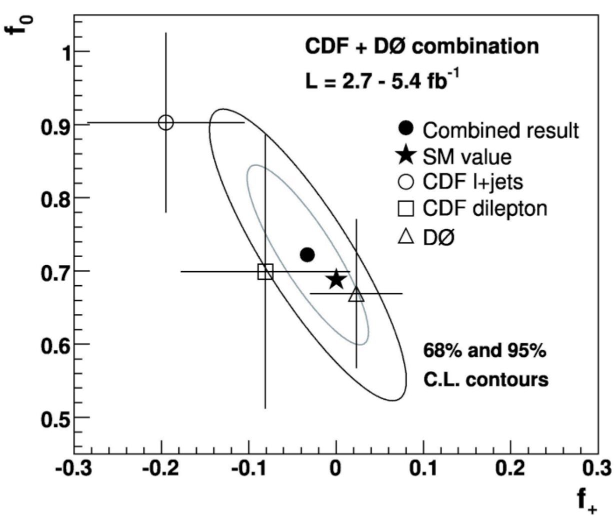
$$\frac{-ig}{2\sqrt{2}}\bar{t}\gamma^{\mu}(1-\gamma^{5})V_{tb}bW_{\mu}$$





Suppressed by the V-A coupling





Most precise

SM prediction: f_0=70%, f_+=0, f_-=30%

$$f_0 = 0.722 \pm 0.081$$
$$[\pm 0.062 \text{ (stat.)} \pm 0.052 \text{ (syst.)}],$$
$$f_+ = -0.033 \pm 0.046$$
$$[\pm 0.034 \text{ (stat.)} \pm 0.031 \text{ (syst.)}]$$

First Published Tevatron Combination in Top Physics

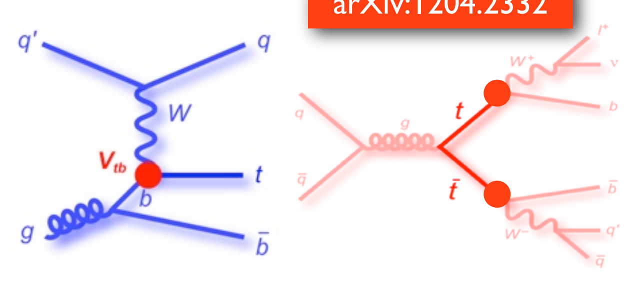
Anomalous Wtb Couplings

- Constrain Wtb vertex couplings by combining information from single top and W helicity analyses.

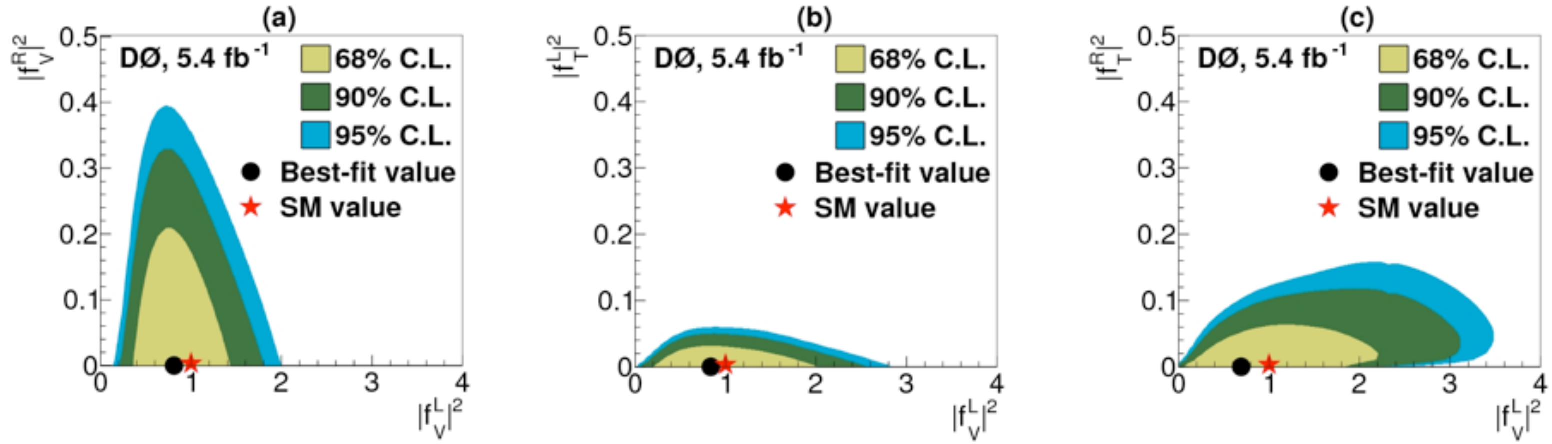
SM: $f_V^L = 1 \; f_V^R = f_T^L = f_T^R = 0$

$$\mathcal{L} = \frac{g}{\sqrt{2}}\bar{b}\gamma^{\mu}V_{tb}(f_V^L P_L + f_V^R P_R)tW_{\mu}^{-} - \frac{g}{\sqrt{2}}\bar{b}\frac{i\sigma^{\mu\nu}q_{\nu}V_{tb}}{M_W}(f_T^L P_L + f_T^R P_R)tW_{\mu}^{-} + h.c.$$

arXiv:1204.2332



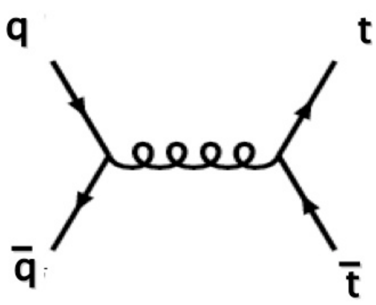
Scenario	only W helicity	only single top	combination
$\lvert f_V^R\rvert^2$	0.62	0.89	0.30
$\lvert f_T^L\rvert^2$	0.14	0.07	0.05
$\lvert f_T^R\rvert^2$	0.18	0.18	0.12

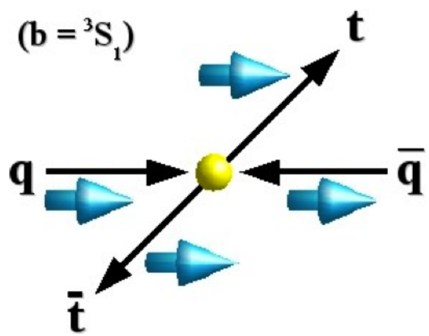


Spin Correlation Strength

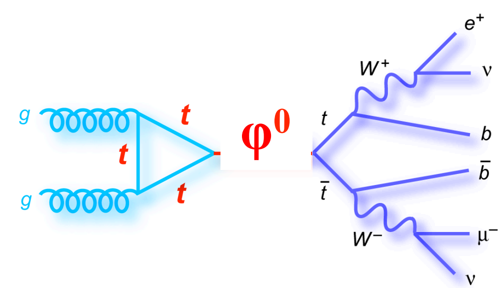
$$C = \frac{N_{\uparrow\uparrow} + N_{\downarrow\downarrow} - N_{\uparrow\downarrow} - N_{\downarrow\uparrow}}{N_{\uparrow\uparrow} + N_{\downarrow\downarrow} + N_{\uparrow\downarrow} + N_{\downarrow\uparrow}}$$

Tevatron: qq, tt at threshold



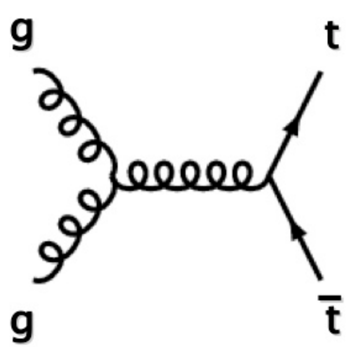


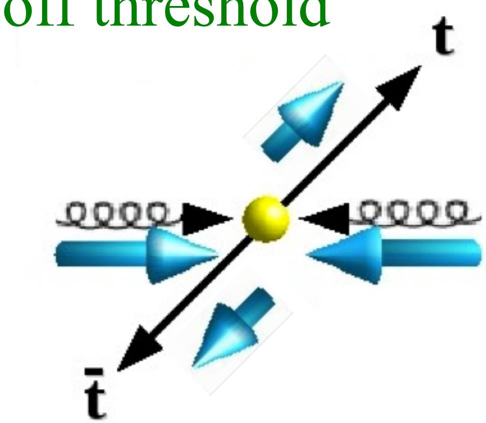
- Test of SM that analyzes the entire chain of production and decay
- Sensitive to BSM processes

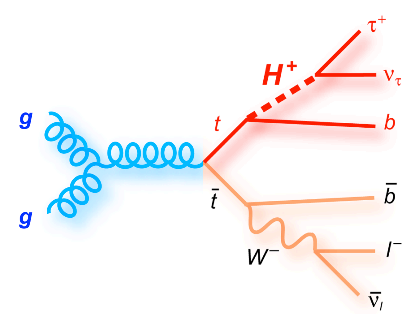


Higgs, KK gravitons, Z', stop pairs, …

LHC: qq, tt far off threshold







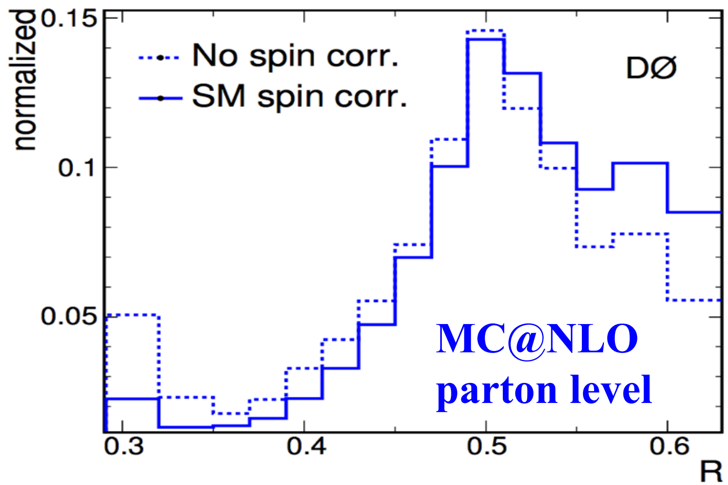
charged Higgs, b', …

$C_{tevatron} = 0.78$ $C_{LHC} = 0.32$

NLO QCD, Nucl. Phys. B 690, 81 (2004)

Spin Correlations

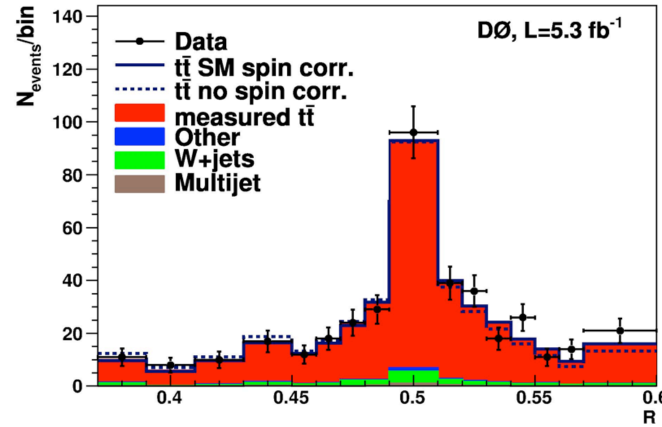
- Use ME method and build discriminant sensitive to the strength of the spin correlation

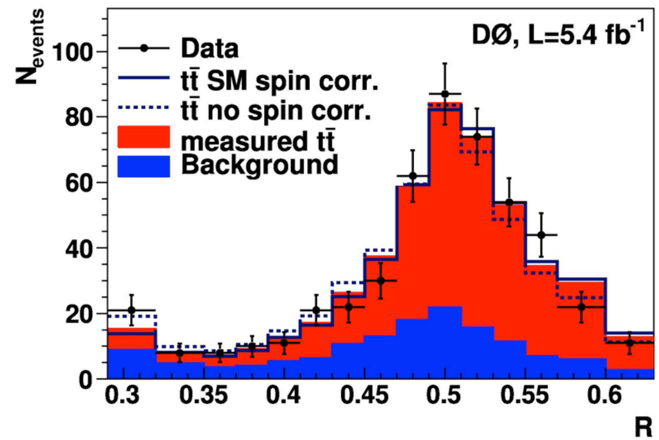


- Studied in dilepton and lepton+jet events & combined

Correlation Strength
$C = 0.66 \pm 0.23$ (stat+syst)

NLO QCD $C = 0.777^{+0.027}_{-0.042}$





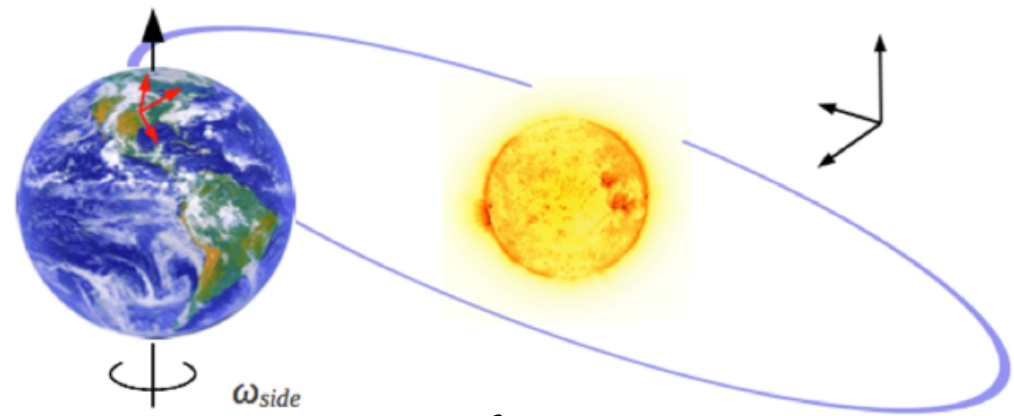
First Evidence for Spin Correlations with 3.1 σ

Phys. Rev. Lett. **108**, 032004 (2012)

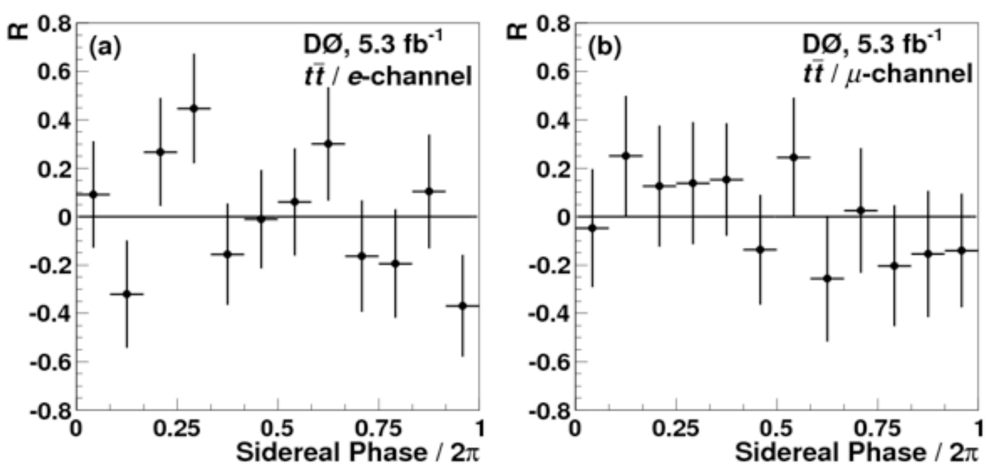
Search for Lorentz Invariance Violation

- Lorentz invariance violation (LIV) would affect both top pair production and decay
- Event rates would depend on sidereal time

arXiv:1203.6106, accepted by PRL



$$N_i \approx N_{\mathrm{tot}} \frac{\mathcal{L}_i}{\mathcal{L}_{\mathrm{int}}} \left[1 + f_{\mathrm{S}} f_{\mathrm{SME}}(\phi_i, \{c_{\mu\nu}\})\right]$$



$\mathcal{L}_i$: luminosity over sidereal phase ϕ_i

f_{S}: mean signal fraction

f_{SME}: signal fraction depend on ϕ_i

$$R_i = \frac{1}{f_{\mathrm{S}}} \left(\frac{N_i/N_{\mathrm{tot}}}{\mathcal{L}_i/\mathcal{L}_{\mathrm{int}}} - 1 \right)$$

$c_{\mu\nu} \approx 0$ (consistent SM)

20 years of Top Studies…

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

20 years of Top Studies…

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M_t	Tev: 173.2 ± 0.9 GeV	-	up to 5.8
$\sigma_{t\bar{t}\gamma}$	CDF: $0.18 \pm$ [illegible] pb	0.17 ± 0.03 pb	6.0
$\lvert V_{tb} \rvert$	CDF: $\lvert V_{tb} \rvert = 0.91 \pm 0.11$(stat + sys) ± 0.07(theory)	1	3.2
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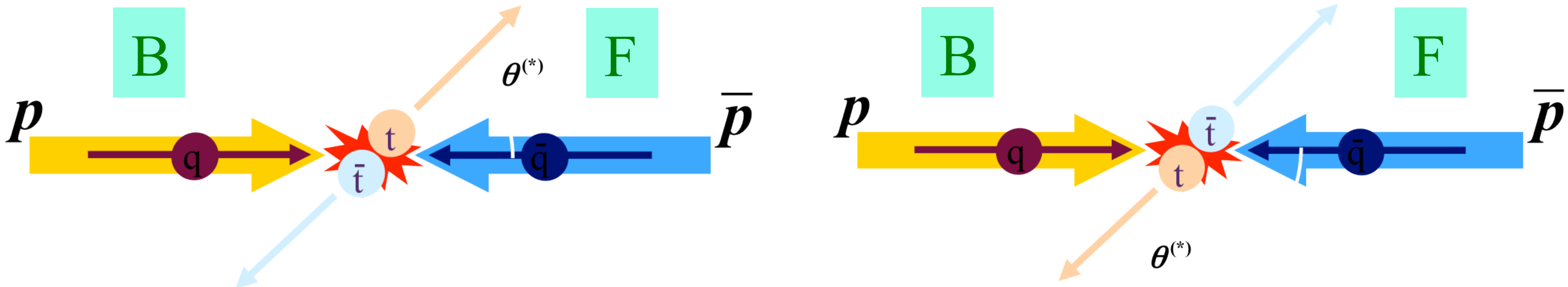
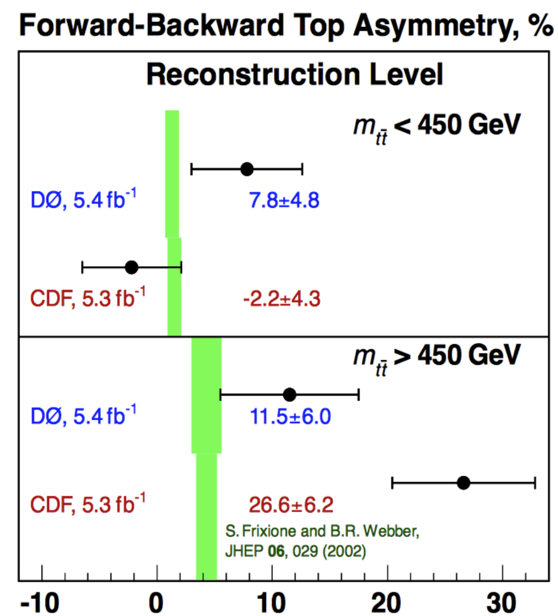
Standard Model Rules!!!!

One Surprise: Top FB Asymmetry



- Top quarks are preferentially emitted in the direction of the incoming quark, anti-top in the direction of the incoming anti-quark.
  - No asymmetry in gg production.
- SM predicts small (~6.6%) asymmetry from interference between ISR and FSR and between LO and box diagrams
- BSM production mechanisms that exchange new bosons could enhance the FB asymmetry
- Inclusive asymmetries measured using ~5fb^{-1} of Tevatron data exceed SM predictions by 1.5-2σ
  - Larger mass and rapidity dependence than predicted by the SM

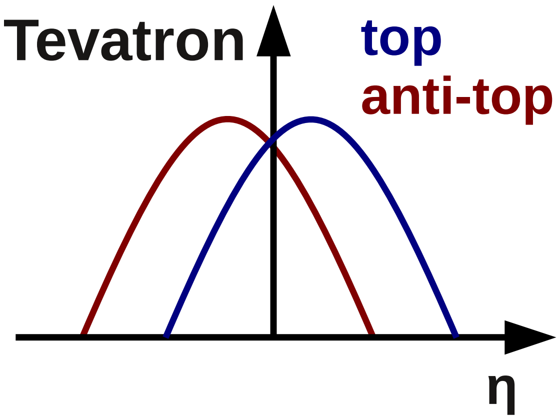


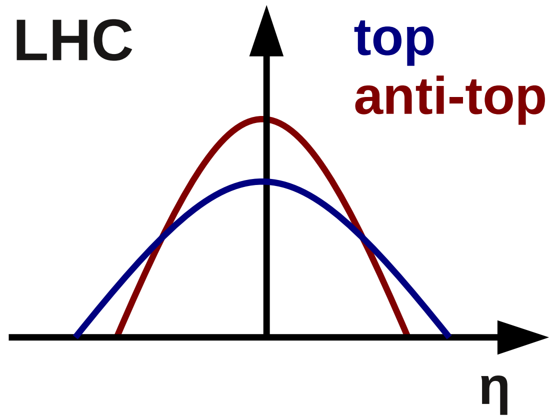
Definitions

Tevatron: p $\overline{p}$ is CP-eigenstate

LHC: $q\overline{q}$ fraction only 15%

Forward-Backward Asymmetry more significant at the Tevatron





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

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

$$A_{FB}^{t\bar{t}} \approx 6.6\%$$

NLO POWHEG with EW corrections

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

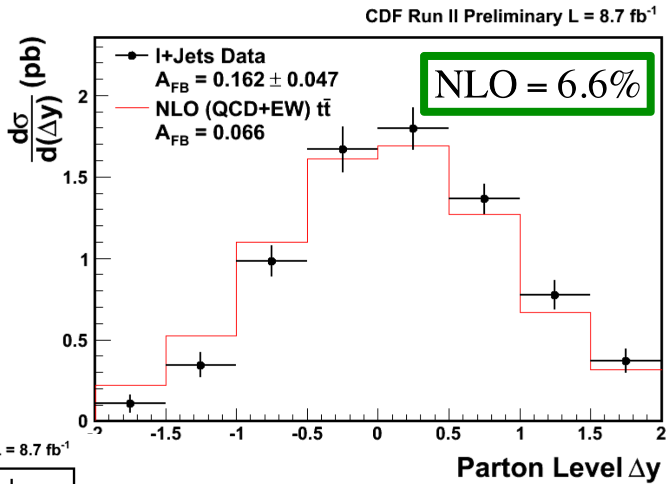
$$\Delta|y| = |y_t| - |y_{\bar{t}}|$$

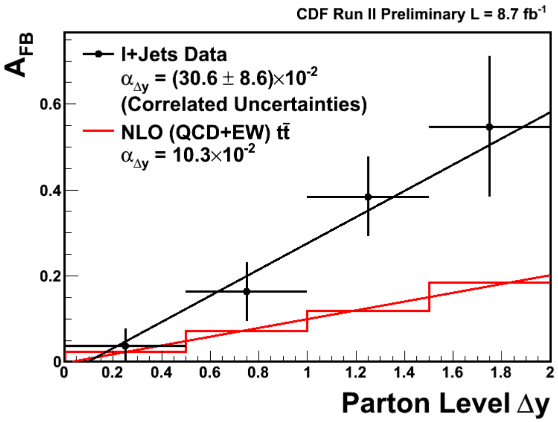
$$A_C \approx 1\%$$

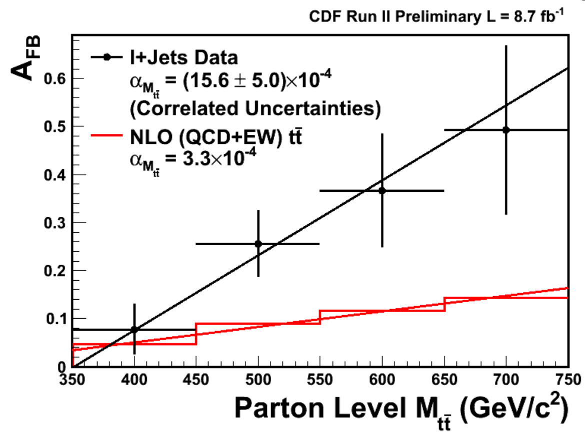
A_{FB}: Parton Level Results

- Analyze $8.7 fb^{-1}$
- NLO Powheg w/EW corrections for signal modeling
- Correct for acceptance and detector resolution – parton level results can be compared directly to theory

Inclusive result: $A_{FB}^{t\bar{t}} = 16.2 \pm 4.7\%$







	Data	NLO
A_{FB} vs M_{tt}	$(15.6 \pm 5.0) \times 10^{-4}$	$(3.3) \times 10^{-4}$
A_{FB} vs Δy	$(30.6 \pm 8.6) \times 10^{-2}$	$(10.3) \times 10^{-2}$

Best fit slope to data compared to NLO

p-value <1% (Probability of background to fluctuate to data)

CDF/PUB/TOP/10807

Conclusions

- Tevatron had a successful (Standard Model) top quark program
  - Observation
  - Precision Measurements
  - BSM Exclusions

- Legacy results on the full dataset are most precise or complement LHC

- LHC opens a new era of high statistics and BSM discoveries