Studies of Top Quark Properties at CDF

A. Eppig, University of Michigan, for the CDF Collaboration

23 July 2010

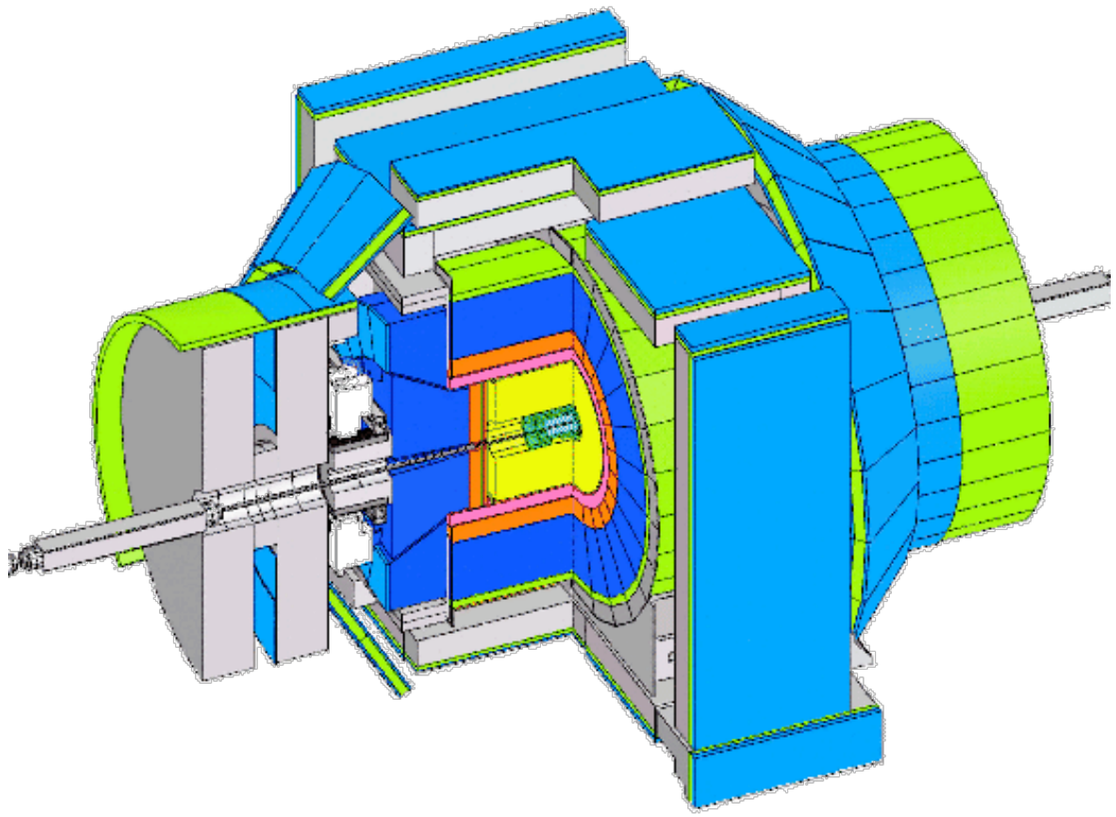
ICHEP, Paris

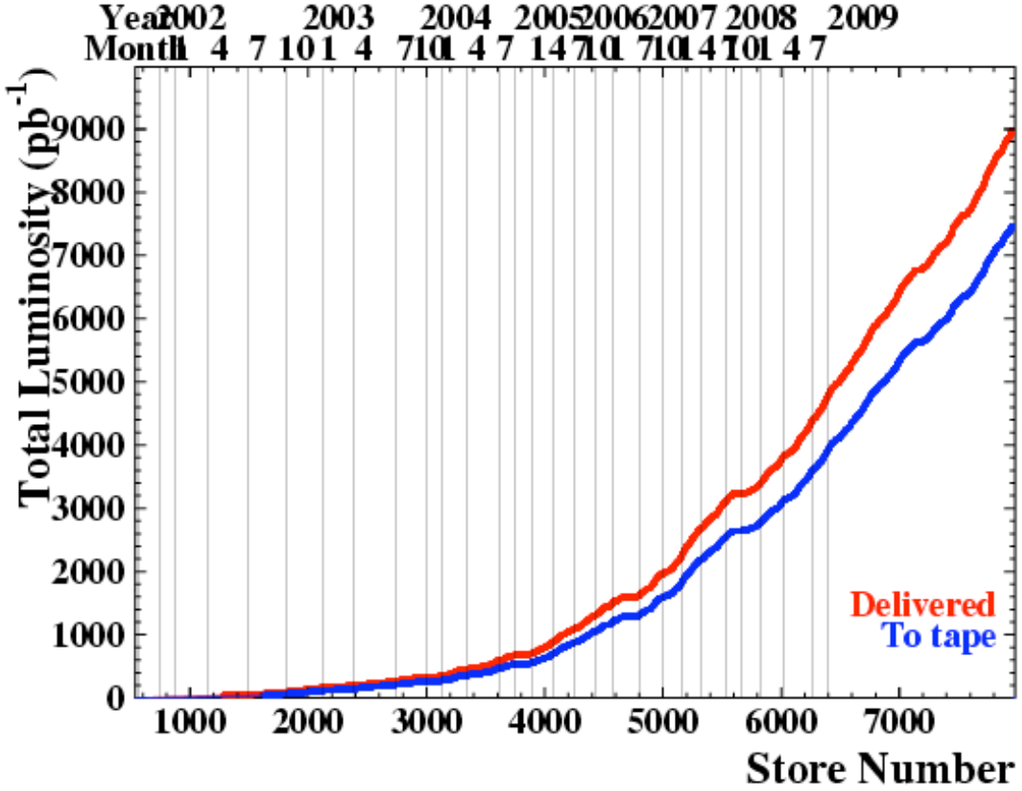
Overview

- Introduction
- Top Properties
  - Forward-Backward Asymmetry in T-Tbar Production
  - T-Tbar Spin Correlation
  - Measurement of W Polarization via Top Decay
  - Measurement of Top Charge
- Summary

Collider Detector at FermiLab

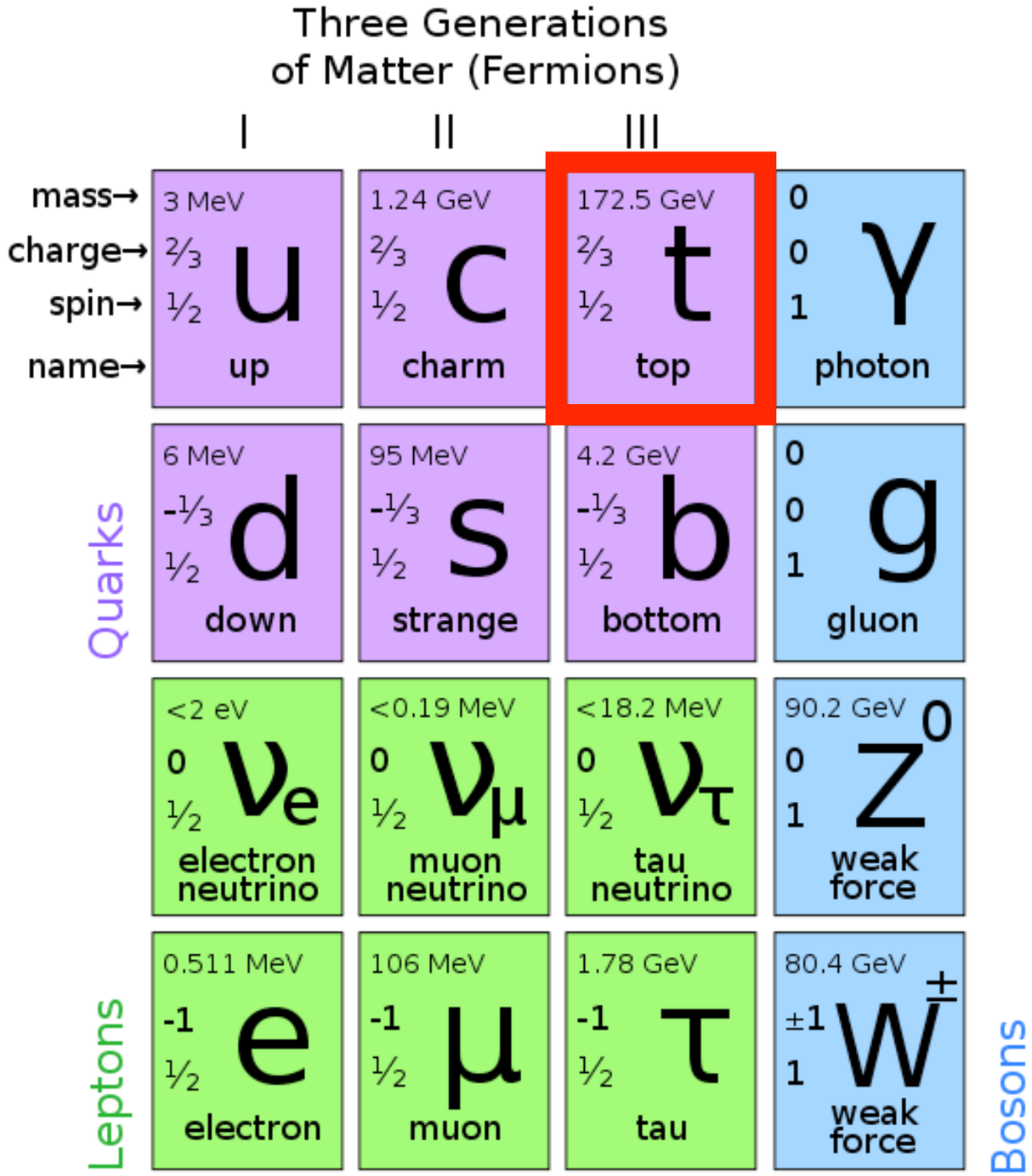
- Entering precision regime
  - L = 5.3 fb^{-1}
  - Well-understood detector and environment
- Large top quark sample
  - 1260 t-tbar events in lepton +jets channel
    - yields < 3% statistical error
  - Probe top quark properties with high precision





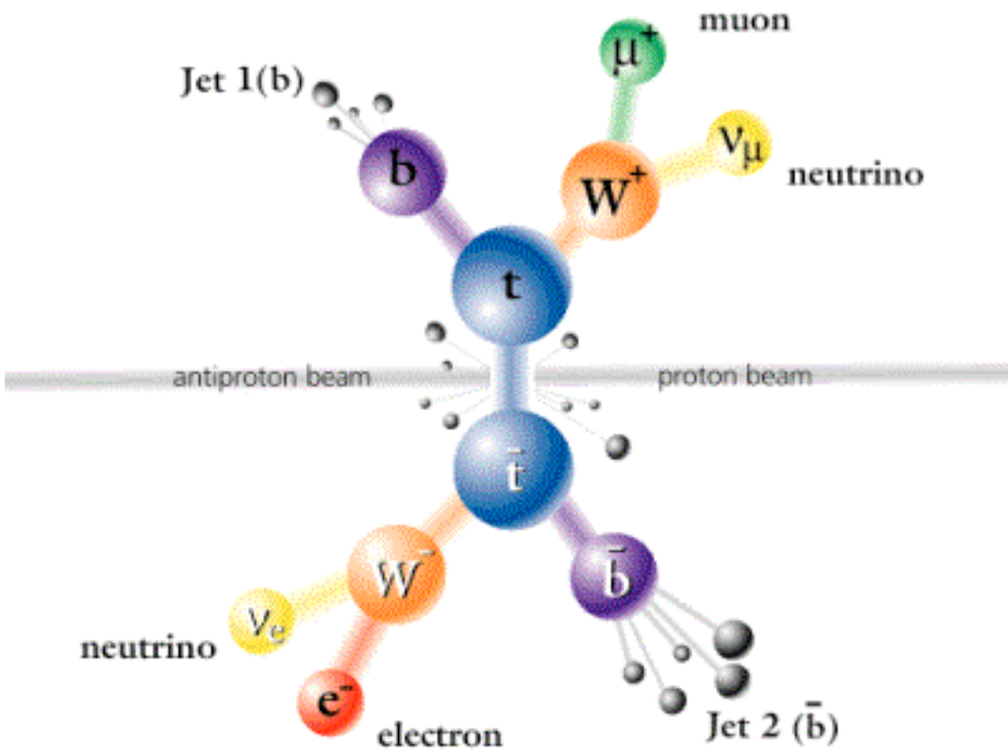
Top Quark

- Fermion with spin 1/2
- Fractional electric charge of +2/3
- Third generation quark with mass 172.5 GeV / c^2
  - Highest quark mass by orders of magnitude
  - Mass higher than $W^{\pm}$ and Z bosons



Other Top Quark Results at CDF

Property	CDF Measurement
Mass	M_{top} = 173.13 ± 1.16 GeV/c^2 [1]
Cross Section	σ_{top} = 7.5 ± 0.48 pb [2]
Lifetime	τ_{top} < 52.5 μm / c with 95% C.L.
Width	Γ_{top} < 7.5 GeV at 95% C.L. [1]

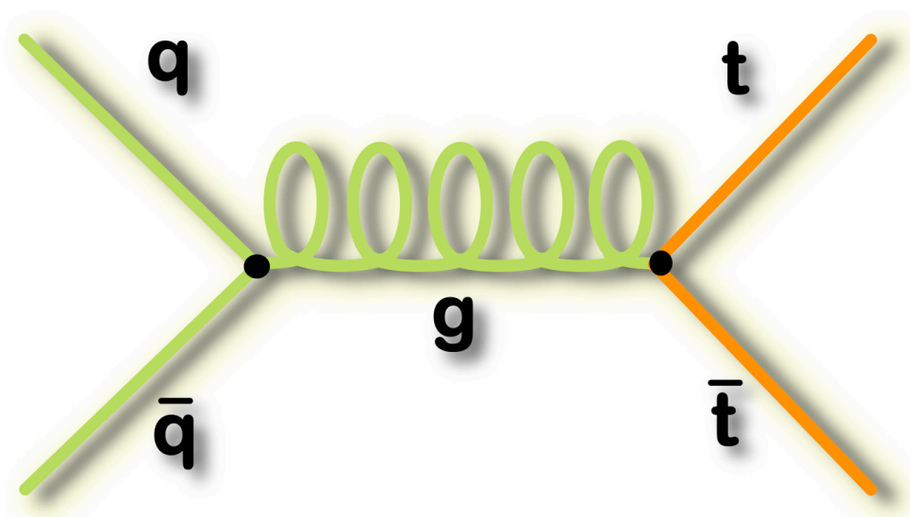


[1] "Measurement of the top quark mass and width with CDF detector" by Hyunsu Lee [Abs 1129, ICHEP 2010]

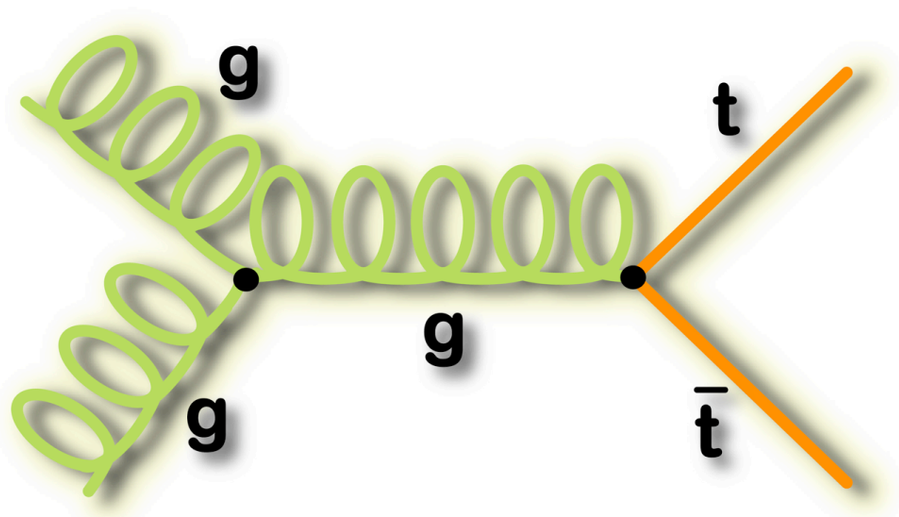
[2] "Measurement of the top quark pairs production cross sections and differential distributions of top quarks at the Tevatron" by Fabrizio Margaroli [Abs 1133, ICHEP 2010]

Top Quark Production and Decay

Top Production

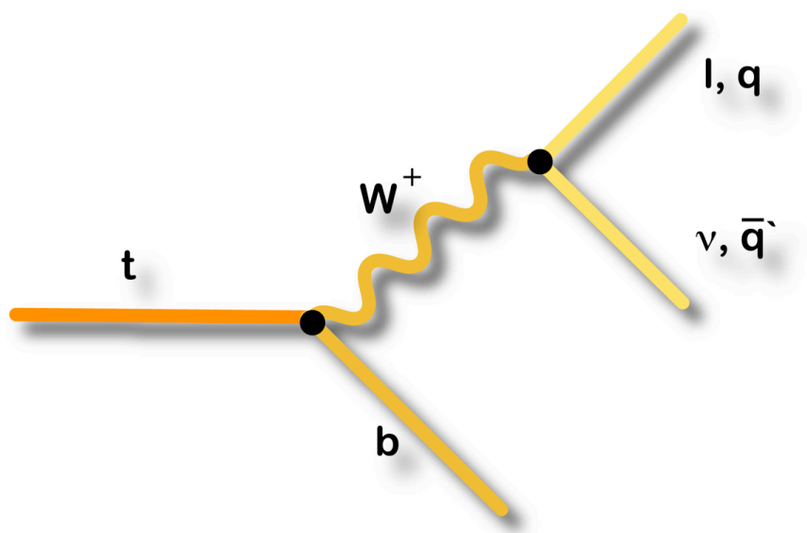


~85%



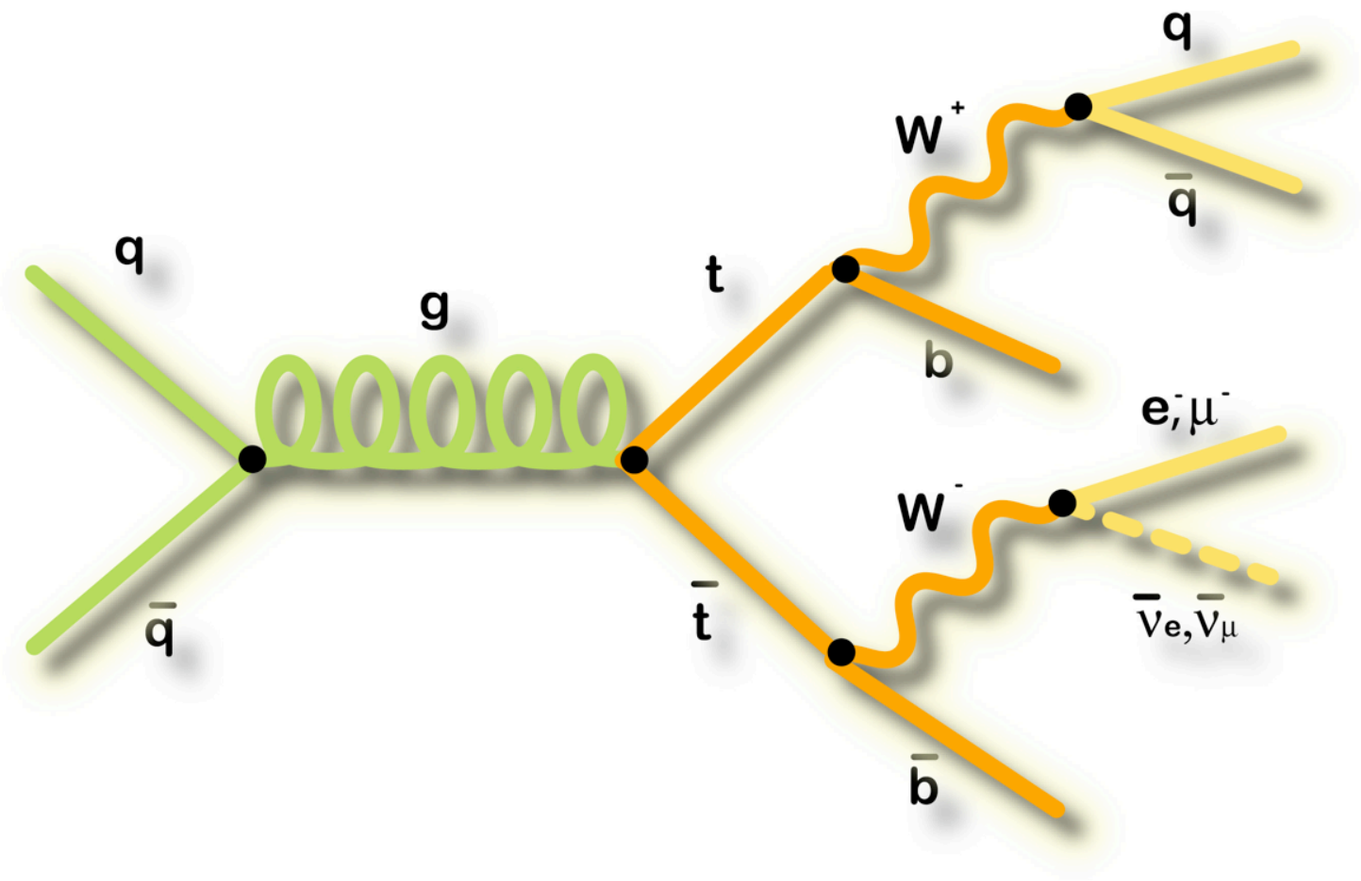
~15%

Top Decay



~100%

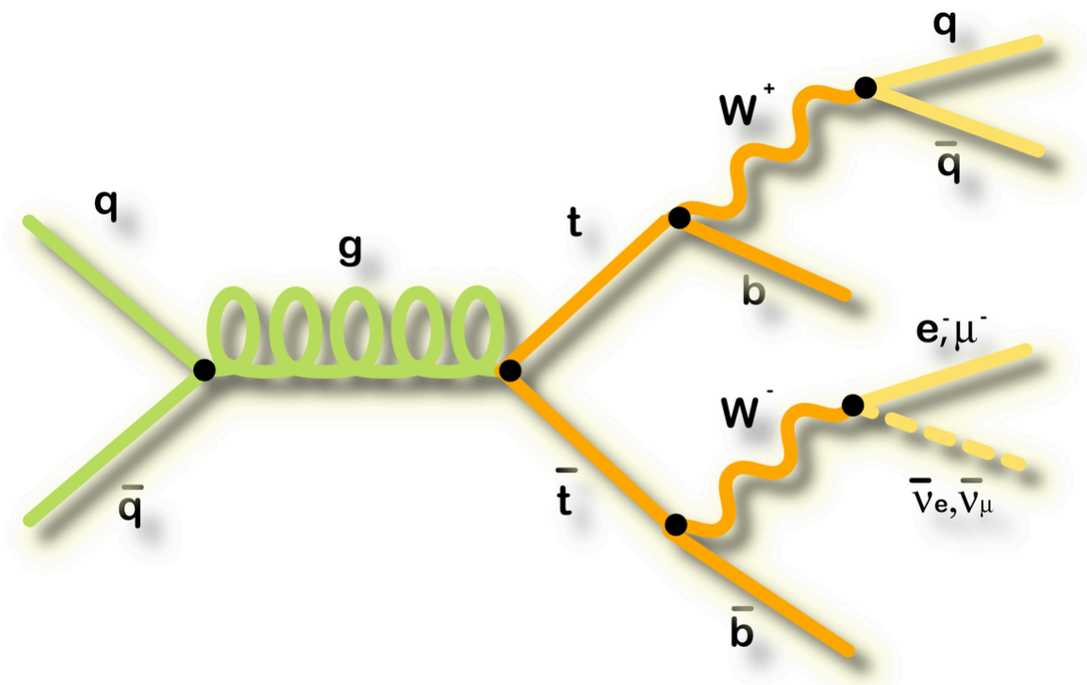
Top Quark Decay Channels

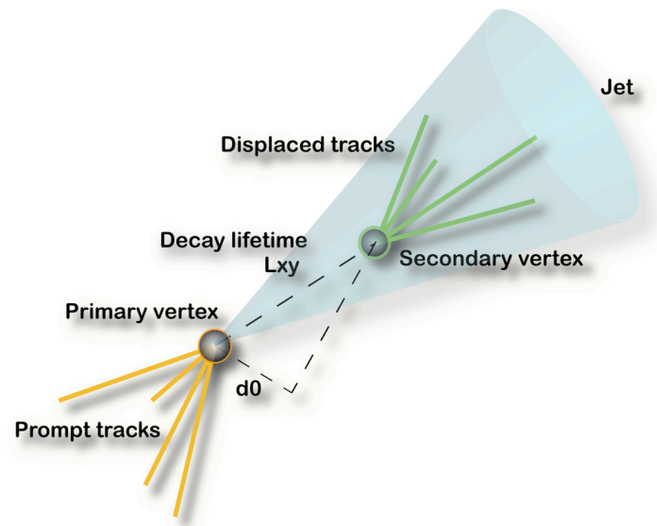


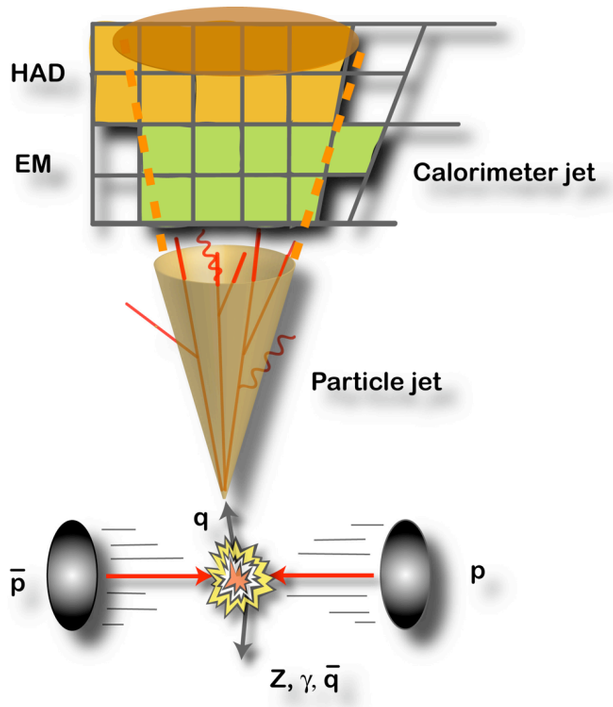
Channel	Percent
Di-lepton $W \rightarrow l\nu, W \rightarrow l\nu$	12%
Lepton+jets $W \rightarrow qq, W \rightarrow l\nu$	44%
All-hadronic $W \rightarrow qq, W \rightarrow qq$	44%

Lepton+Jets Event Selection

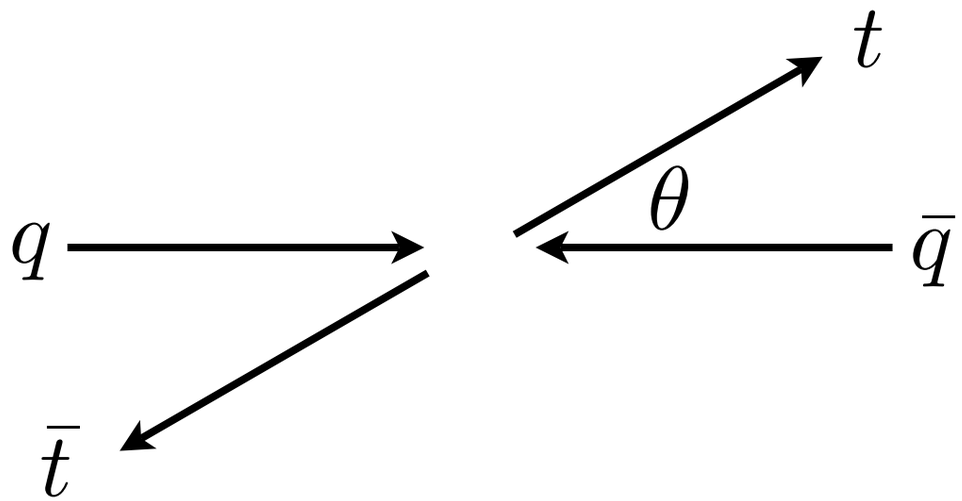
- Event selection requires
  - single lepton from electron or muon triggers
  - four or more jets
    - one or two b-tagged jets
    - jet E_T > 20 GeV
- MET > 20 GeV





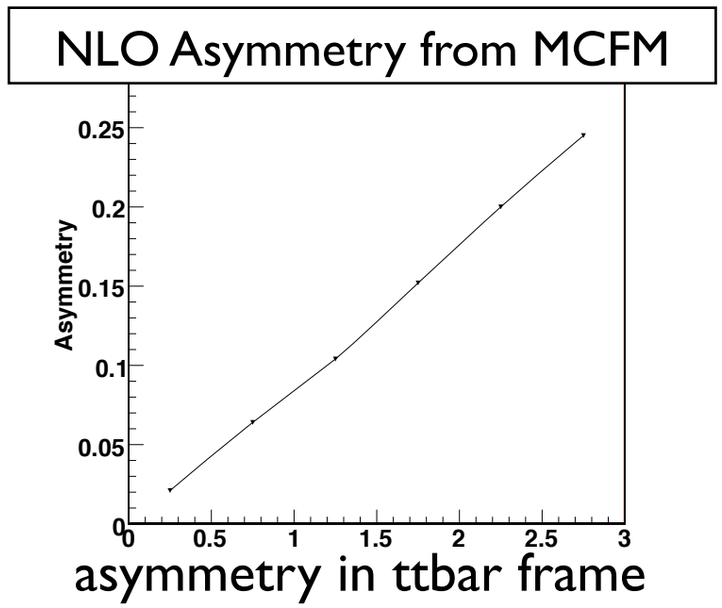


Forward-Backward Asymmetry in $t\bar{t}$



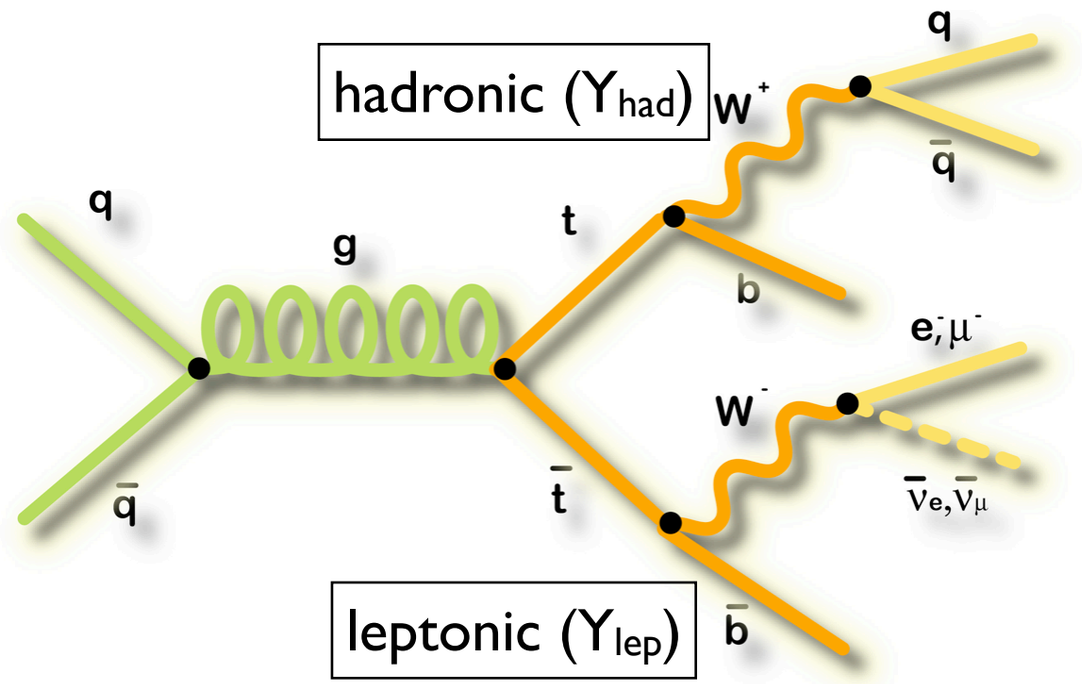
$$A_{FB} = \frac{N(Y > 0) - N(Y < 0)}{N(Y > 0) + N(Y < 0)}$$

- In leading order QCD, top production is symmetric; at NLO, top quark is repelled at high rapidities by soft Coulomb field of incoming light quark, anti-top is simultaneously attracted at low rapidity
- Predicted NLO asymmetries
  - A_{LAB} = 3.8 ± 0.6%
  - A_{ttbar} = 5.8 ± 0.9%



Asymmetry in $t\bar{t}$: Method

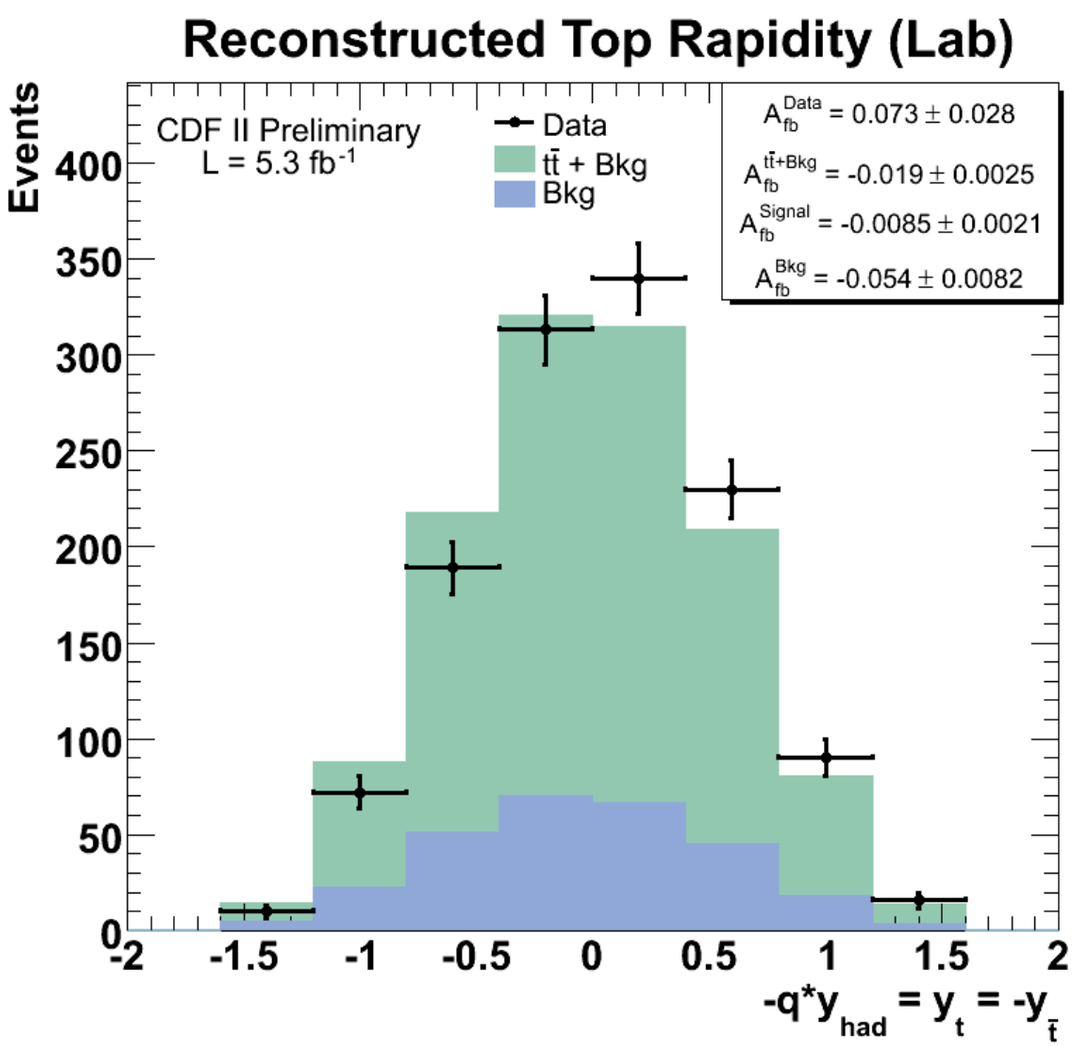
- Measure rapidity variables
- Subtract background events to extract signal
- Correct acceptance and detector effects to restore parton-level distribution
- Calculate forward-backward asymmetry
  - inclusive
  - rapidity-dependent

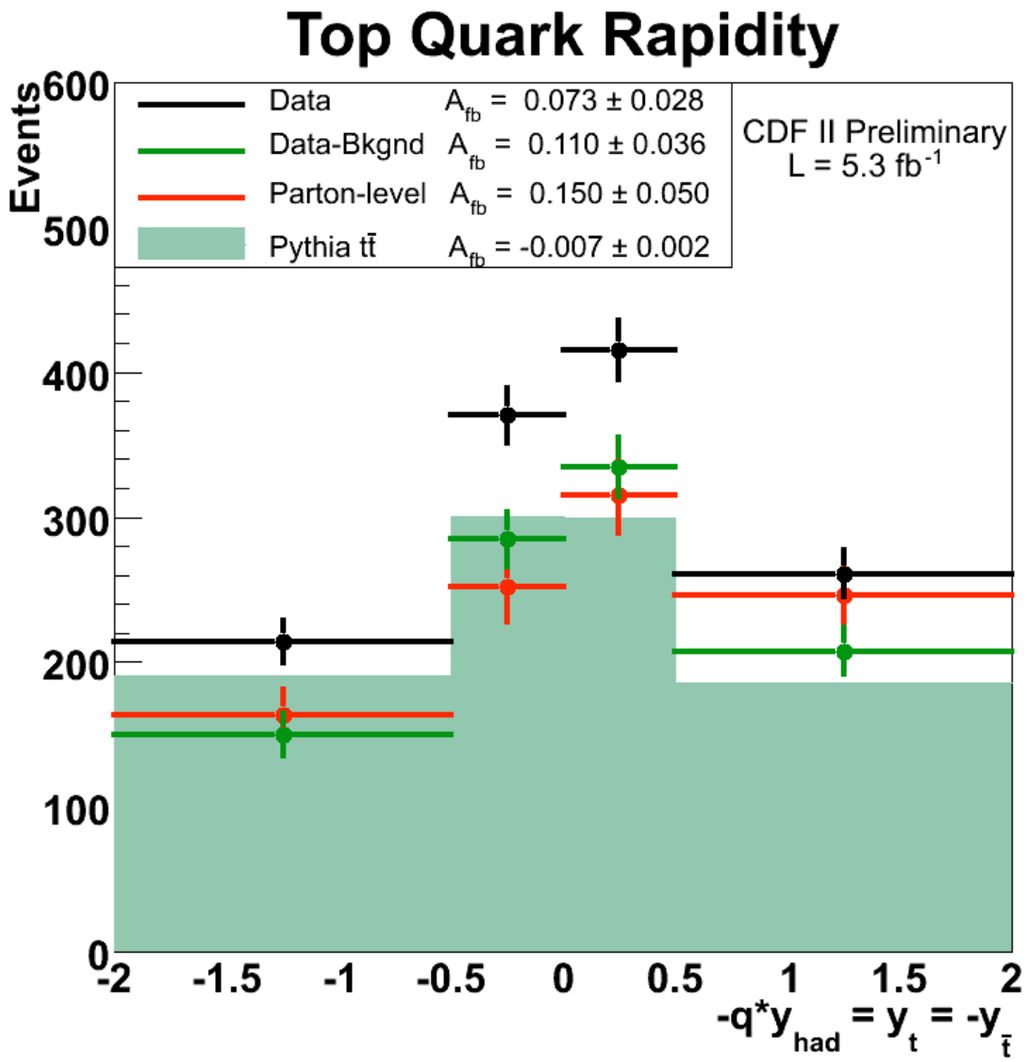


q	$t_{\rm lep}$	$t_{\rm had}$
+	t	$\bar{t}$
-	$\bar{t}$	t

$$-qY_{\rm had} = Y_t = -Y_{\bar{t}}$$
$$q(Y_{\rm lep} - Y_{\rm had}) = q\Delta Y = Y_t - Y_{\bar{t}}$$

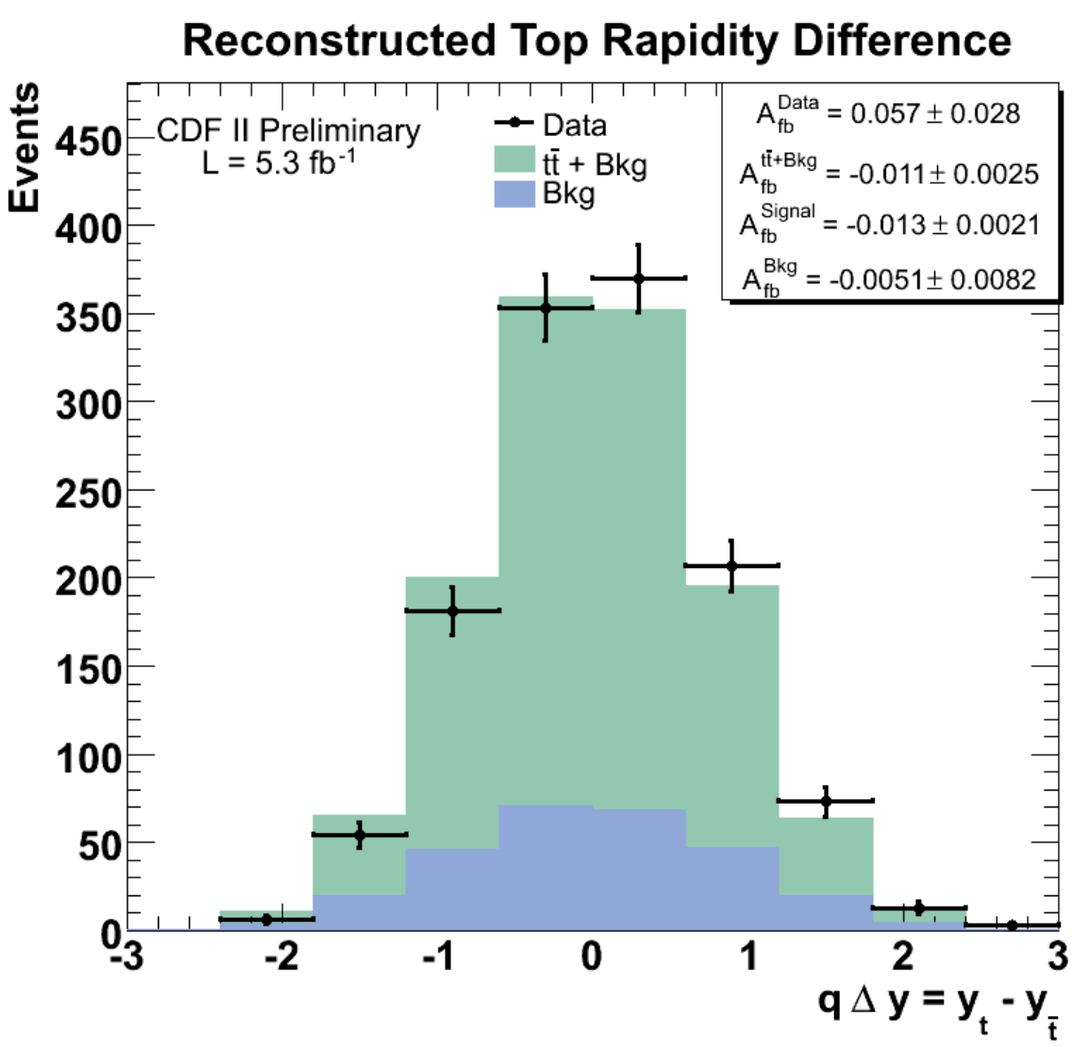
Asymmetry in $t\bar{t}$: LAB Frame

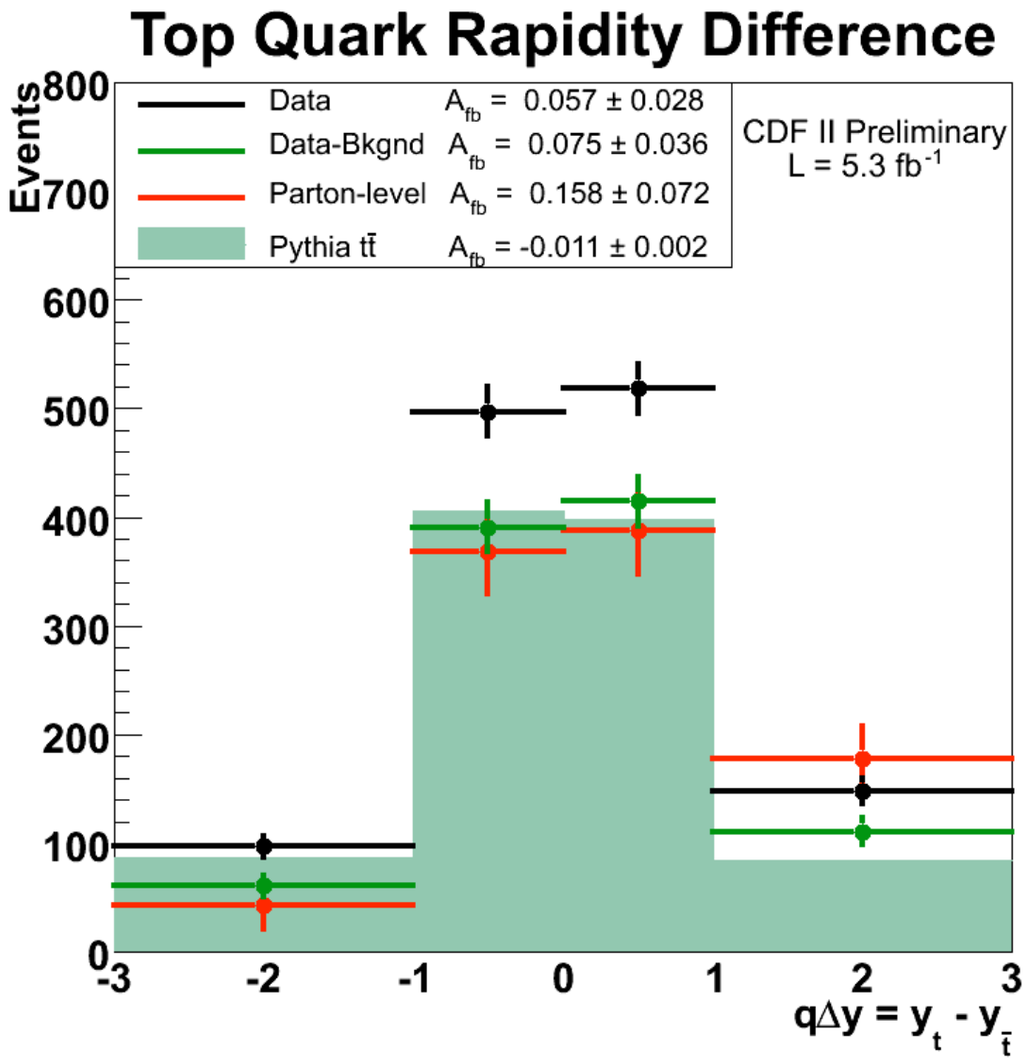




LAB Frame A_{FB}	Inclusive	Significance from 0
Measured	$15.0 \pm 5.0_{stat} \pm 2.4_{sys}\%$	2.7
MCFM Predicted	$3.8 \pm 0.6\%$	---

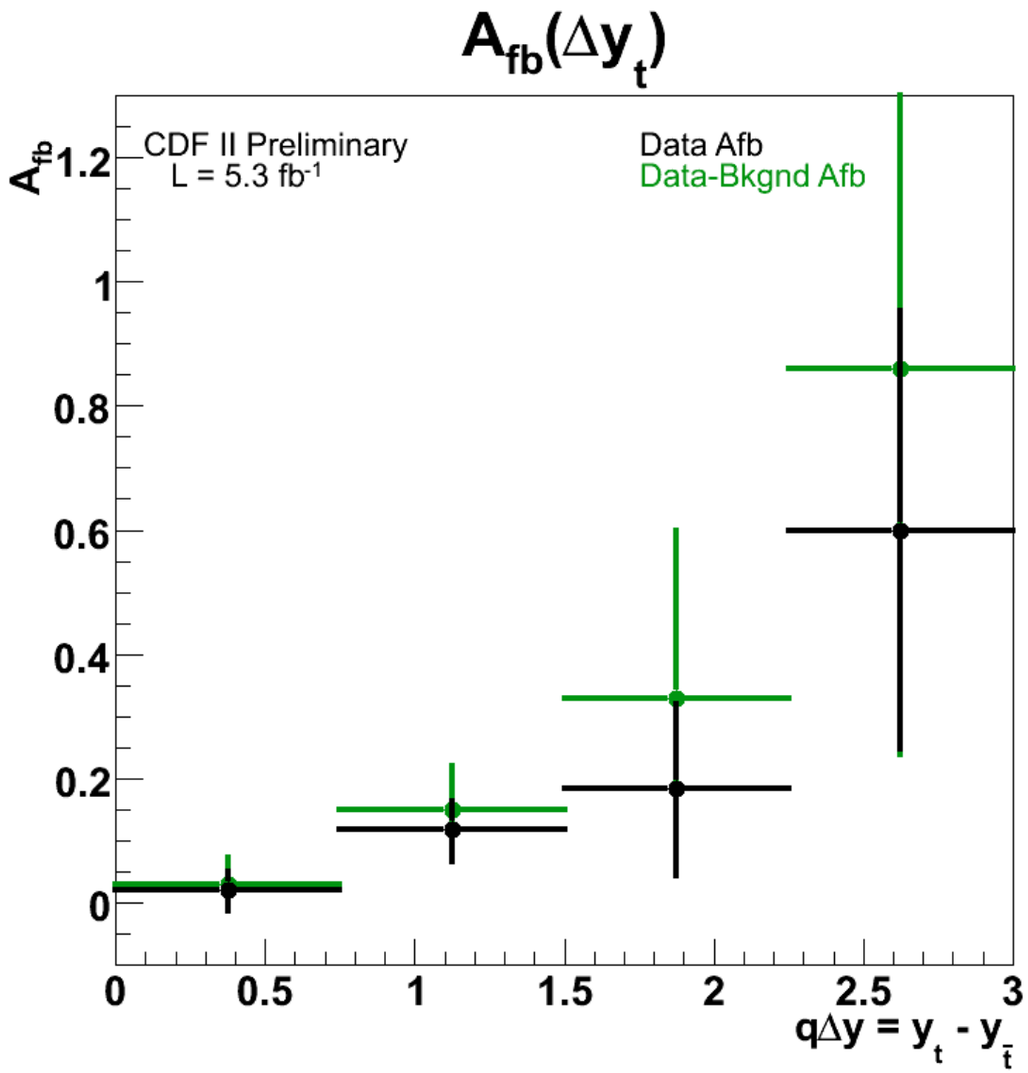
Asymmetry in $t\bar{t}$: $t\ \bar{t}$ Frame

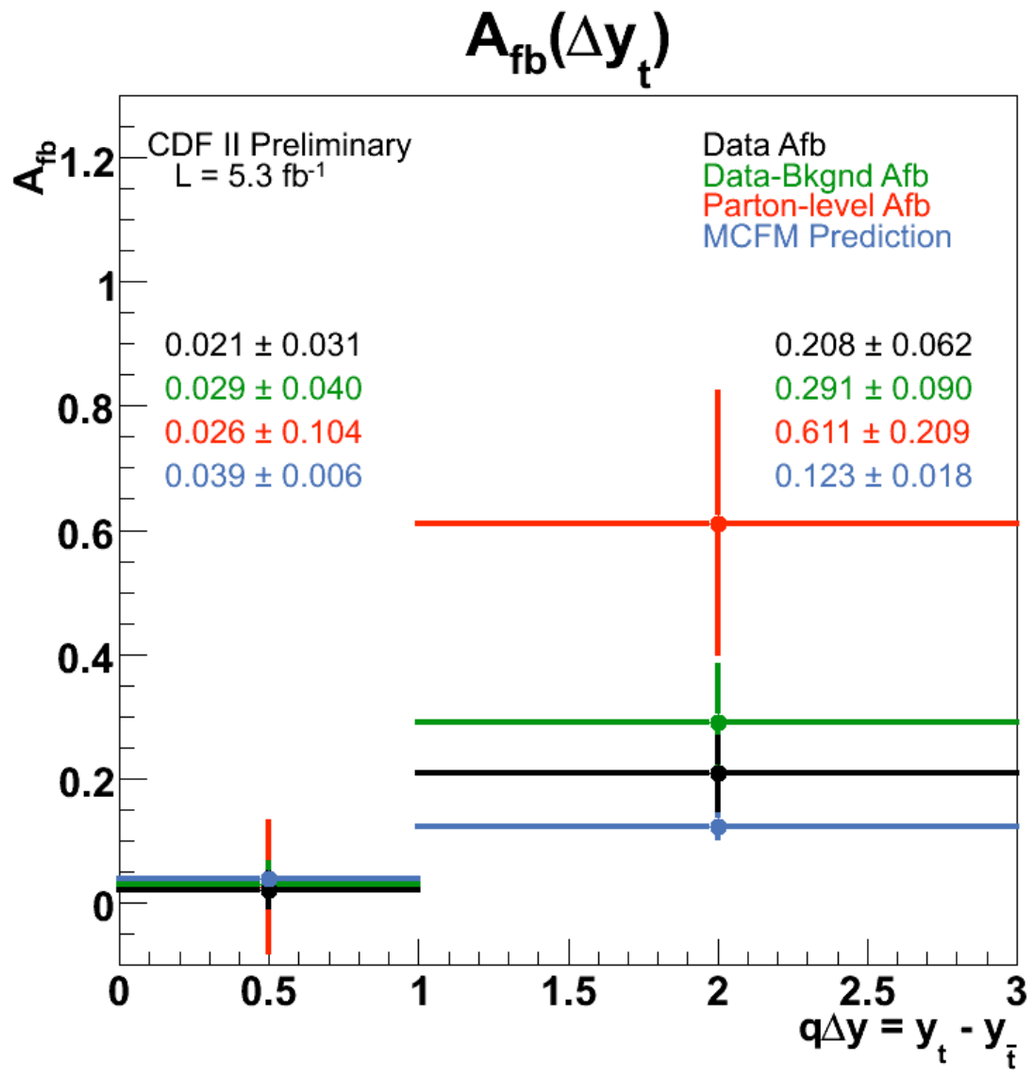




TTbar Frame A_{FB}	Inclusive	Significance from 0
Measured	$15.8 \pm 7.2_{stat} \pm 1.7_{sys}\%$	2.1
MCFM Predicted	$5.8 \pm 0.9\%$	---

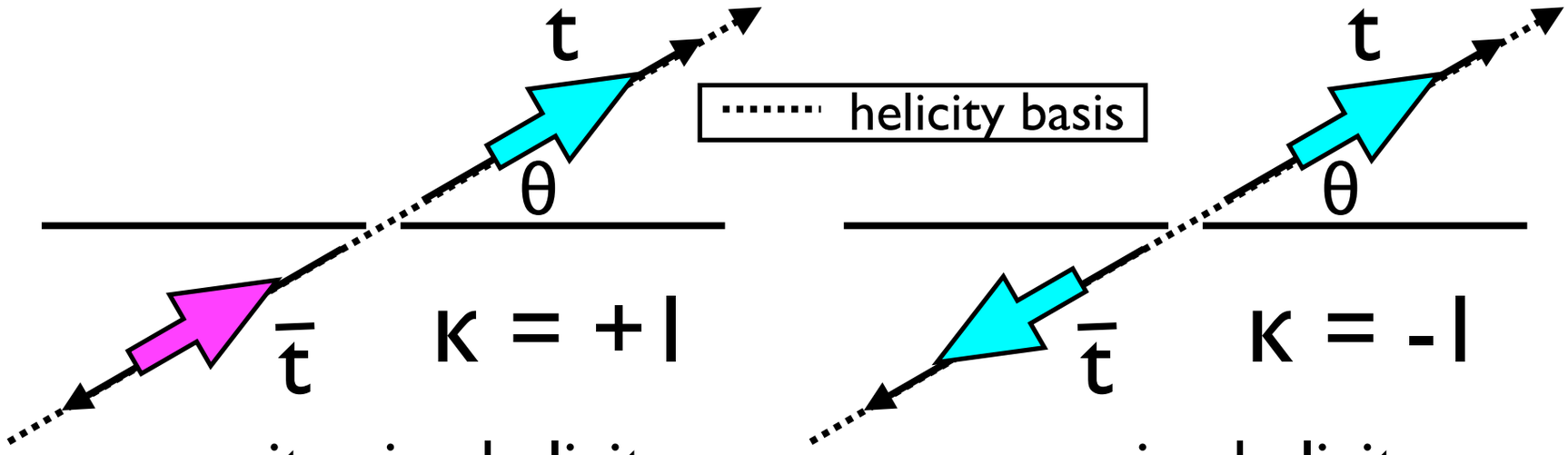
Asymmetry in $t\bar{t}$: Results





A_{FB}	Low Rapidity ($\|\Delta y\|<1$)	High Rapidity ($\|\Delta y\|>1$)
Measured	$2.6 \pm 10.4_{stat} \pm 5.5_{sys}\%$	$61.1 \pm 21.0_{stat} \pm 14.1_{sys}\%$
Significance from 0	0.2	2.4
MCFM Predicted	$3.9 \pm 0.6\%$	$12.3 \pm 1.8\%$

$t\bar{t}$ Spin Correlation

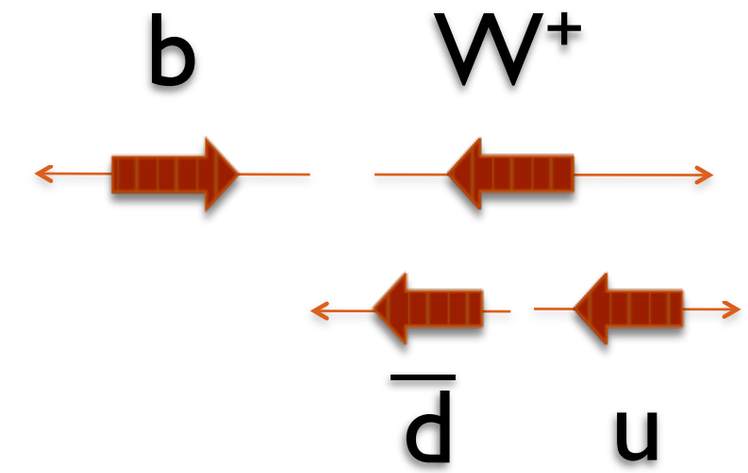


$$\kappa = \frac{N(\uparrow\uparrow) + N(\downarrow\downarrow) - N(\uparrow\downarrow) - N(\downarrow\uparrow)}{N(\uparrow\uparrow) + N(\downarrow\downarrow) + N(\uparrow\downarrow) + N(\downarrow\uparrow)} = \frac{N_o - N_s}{N_o + N_s}$$

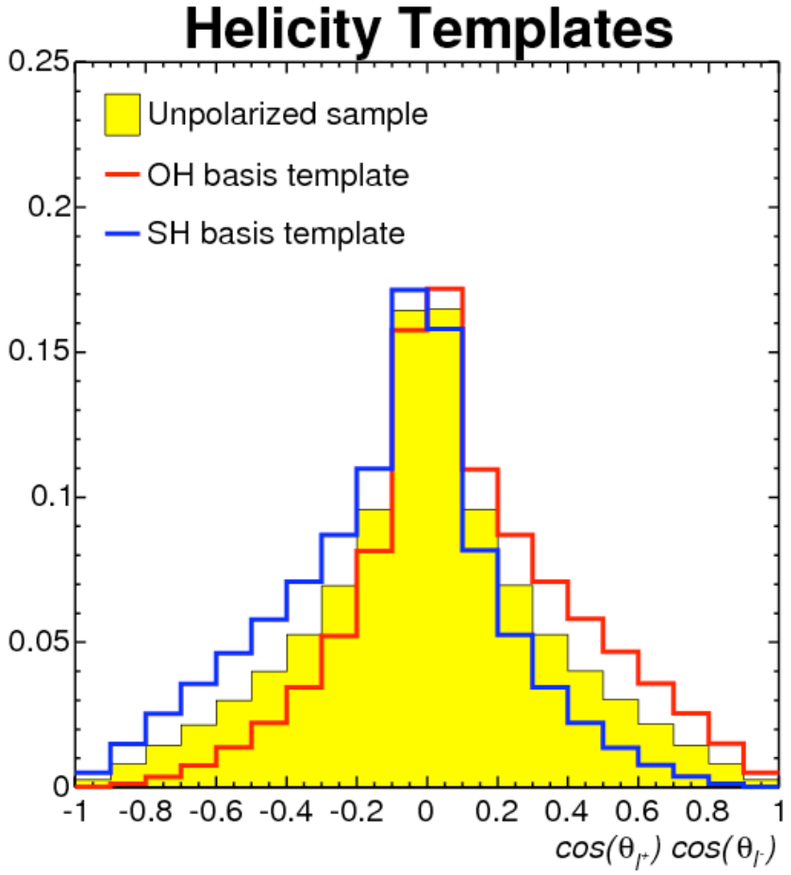
- High top mass leads to top decay before hadronization
- Spin information in V-A correlations in weak decay — leptons and d quarks are best way to measure
- Top pairs with the opposite spin are expected to dominate sample $\kappa \approx 0.40$ in the helicity basis
- Seek to evaluate expected spin correlation in QCD

$t\bar{t}$ Spin Correlation: Method

- In lepton+jets channel, identify down quark as jet closest to b jet in W rest frame
- Measure cosine of lepton and down quark helicity angle
  - $\cos\theta_{lep} \times \cos\theta_{d}$ gives a single variable to measure the helicity of the combined $t\bar{t}$ system
- Create custom, polarized HERWIG templates for same helicity, opposite helicity, and background
- Fit product of cosines to templates using binned likelihood fit to extract helicity fraction

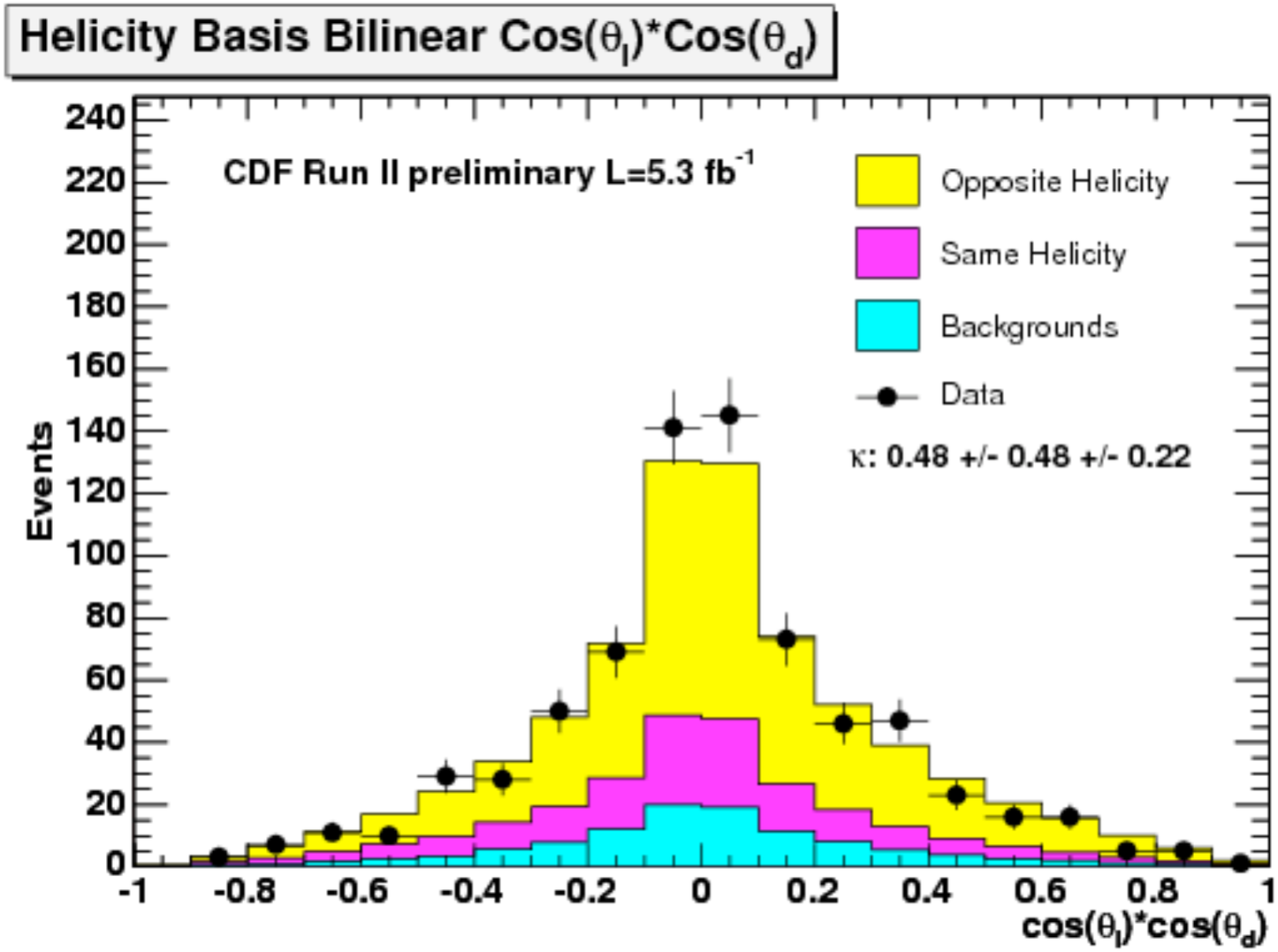


$$f(\cos\theta_i) = \frac{1}{2}(1 \pm A\cos\theta_i)$$



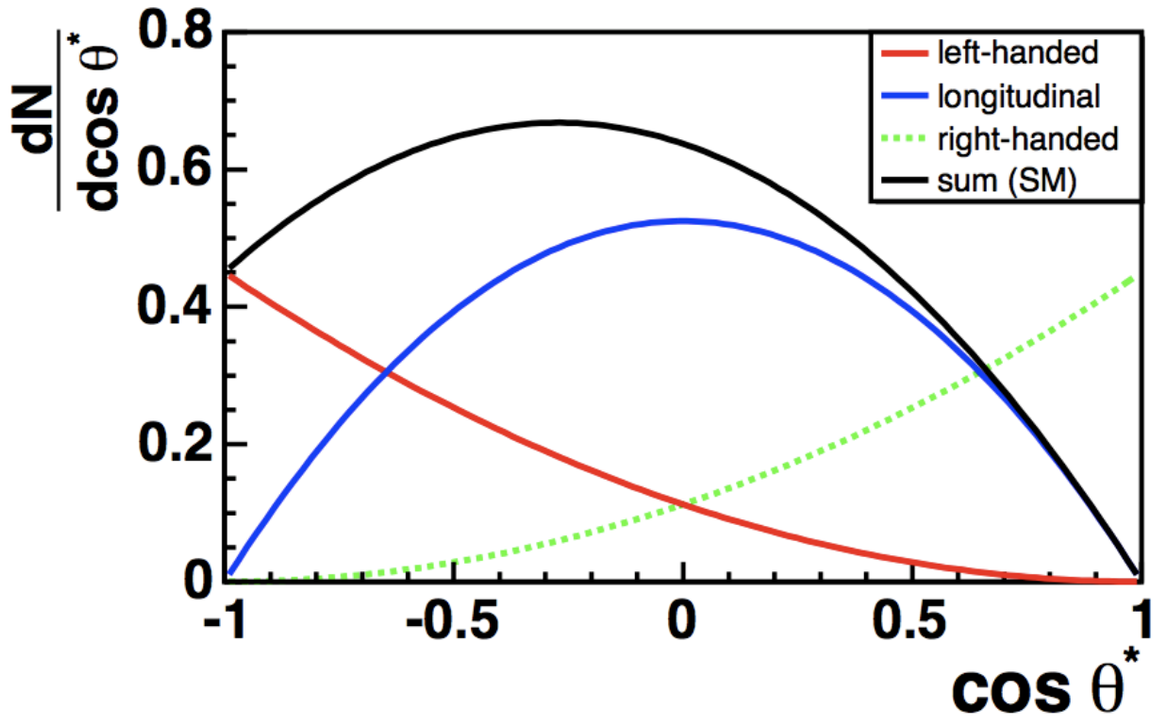
$$\kappa = f_o - f_s = 2f_o - 1$$

$t\bar{t}$ Spin Correlation: Results



Basis	NLO Expectation	Measured
Helicity	$\kappa = 0.35$	$\kappa = 0.48 \pm 0.48_{stat} \pm 0.22_{sys}$
Beam	$\kappa = 0.77$	$\kappa = 0.72 \pm 0.64_{stat} \pm 0.26_{sys}$

W Polarization in Top Decay



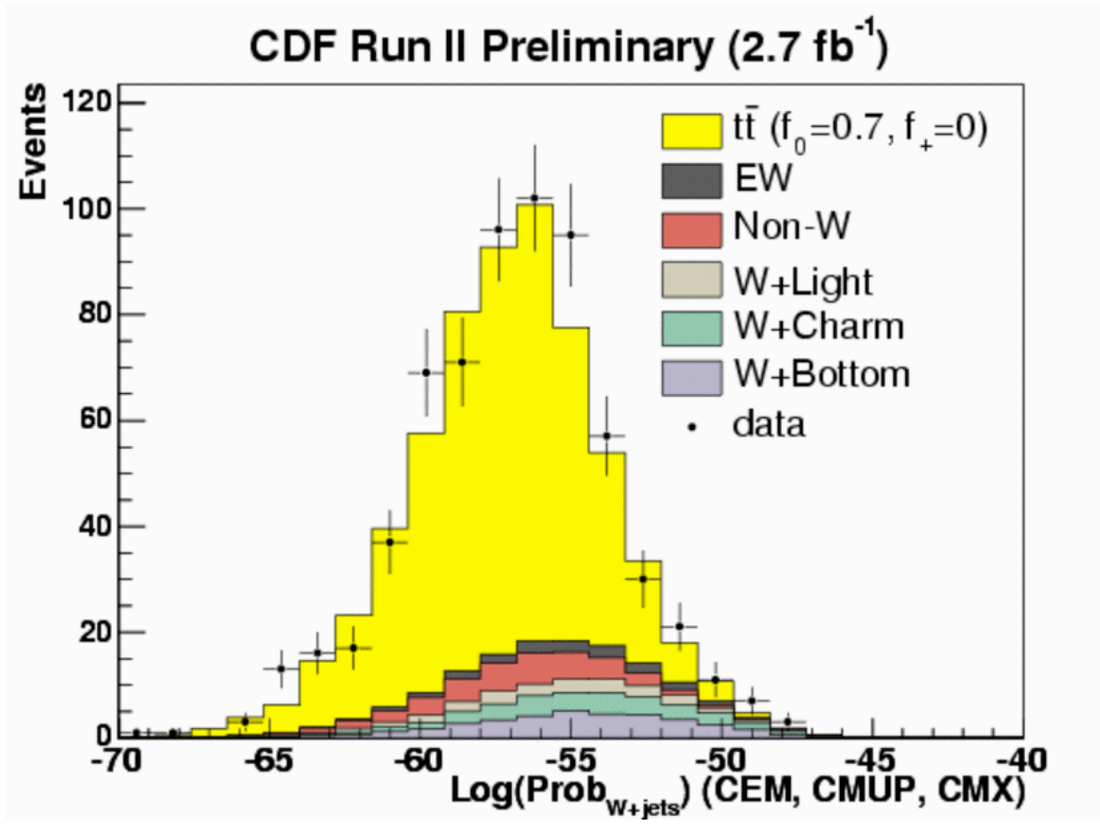
$$\frac{1}{\Gamma}\frac{d\Gamma}{d\cos\theta^*} = f_- \frac{3}{8}(1-\cos\theta^*)^2 + f_0 \frac{3}{4}(1-\cos^2\theta^*) + f_+ \frac{3}{8}(1+\cos\theta^*)^2$$

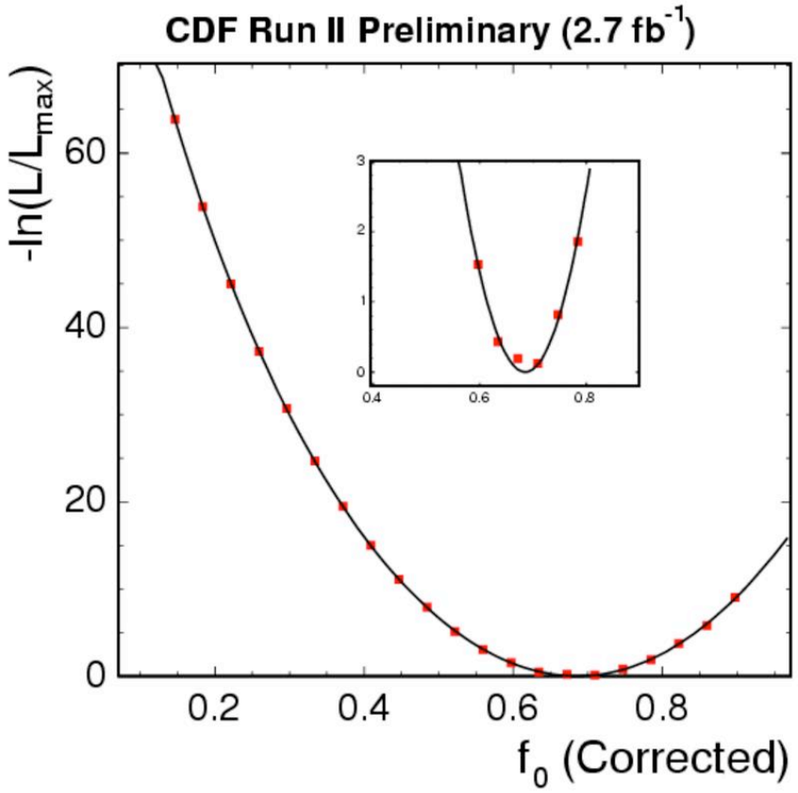
left-handed polarization	longitudinal polarization	right-handed polarization
$f_- \sim 0$	$f_0 = 0.703$	$f_+ = 0.297$

- Longitudinal W is "eaten" by Higgs
- Large top mass (Yukawa coupling) produces high fraction of longitudinally polarized W bosons

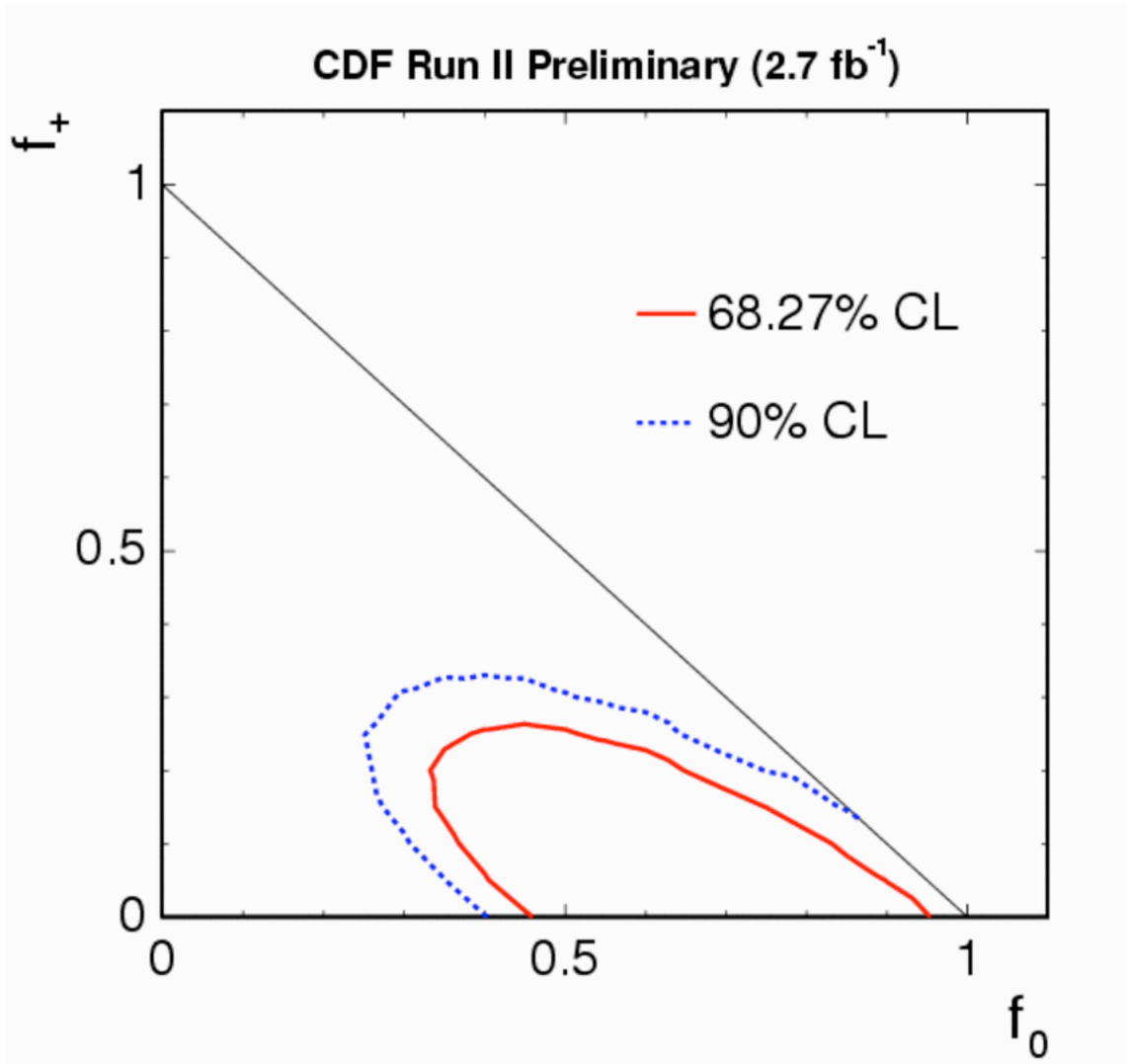
W Polarization in Top Decay: Method

- Using Matrix Element Method, express probability of each event in terms of ttbar and background (W+jets) production
- Use the probabilities to compute a log-likelihood function in terms of the helicity fractions and the signal purity coefficient, C_s
  - $-\ln L(f_0, f_+, C_s) = \prod_{i=1}^{N} C_s P_{t\bar{t}}(\vec{x}_i; f_0, f_+) + (1 - C_s) P_{W+\text{jets}}(\vec{x}_i)$
  - Minimize with respect to C_s
- Helicity fractions are determined by the minima of the log-likelihood curves



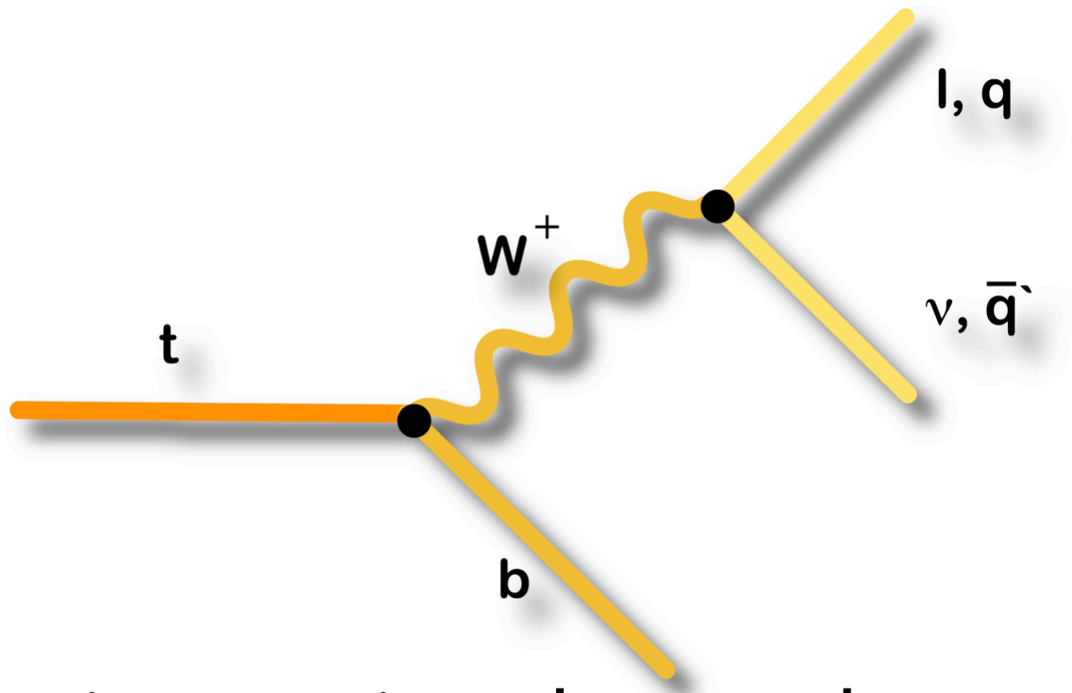


W Polarization in Top Decay: Results



Method	f_+	f_0
Simultaneous	$-0.15 \pm 0.07_{stat} \pm 0.06_{sys}$	$0.88 \pm 0.11_{stat} \pm 0.06_{sys}$
Fixed f+	0.00	$0.70 \pm 0.07_{stat} \pm 0.04_{sys}$
Fixed f0	$-0.01 \pm 0.02_{stat} \pm 0.05_{sys}$	0.70

Top Quark Charge



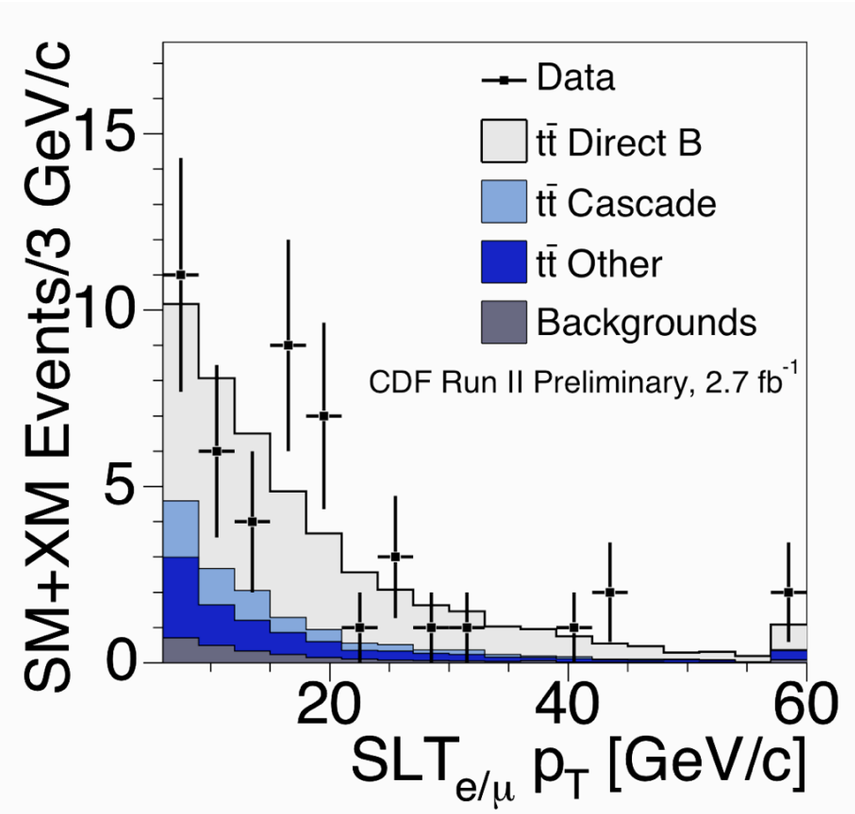
- Charge conservation requires the top charge to be the sum of the W and b charges

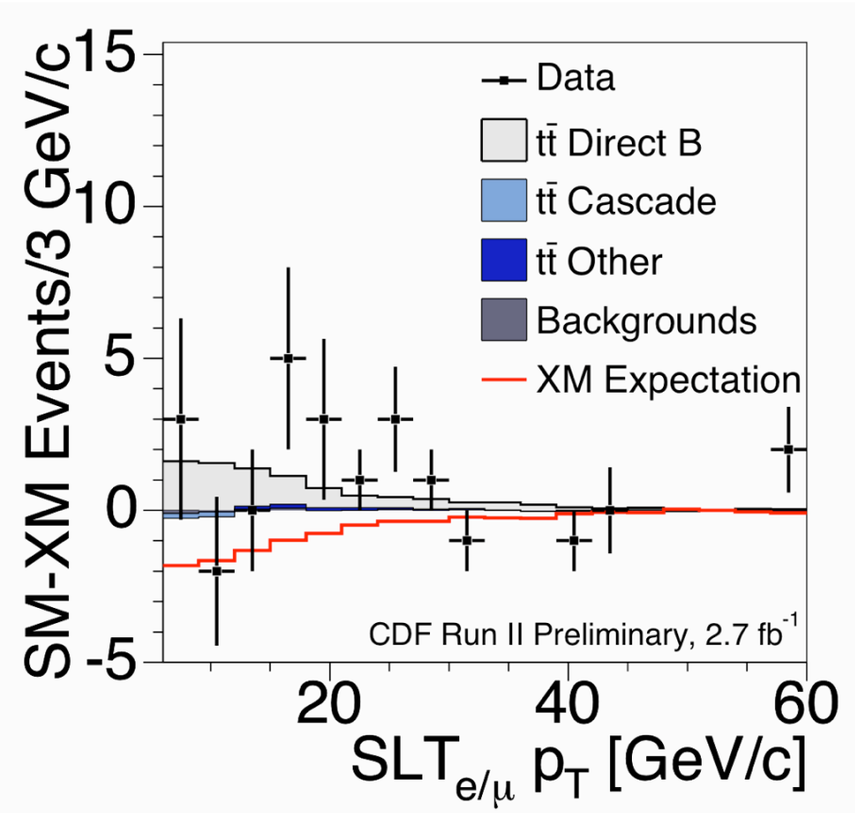
- Measurement of top charge probes exotic models where the top charge differs from the standard model charge

	Process	top charge	W charge	b charge	W-b parity
Standard Model	$t_{SM} \rightarrow W^{+}+b$	+2/3	+1	-1/3	opposite
Exotic Model	$t_{XM} \rightarrow W^{-}+b$	-4/3	-1	-1/3	same

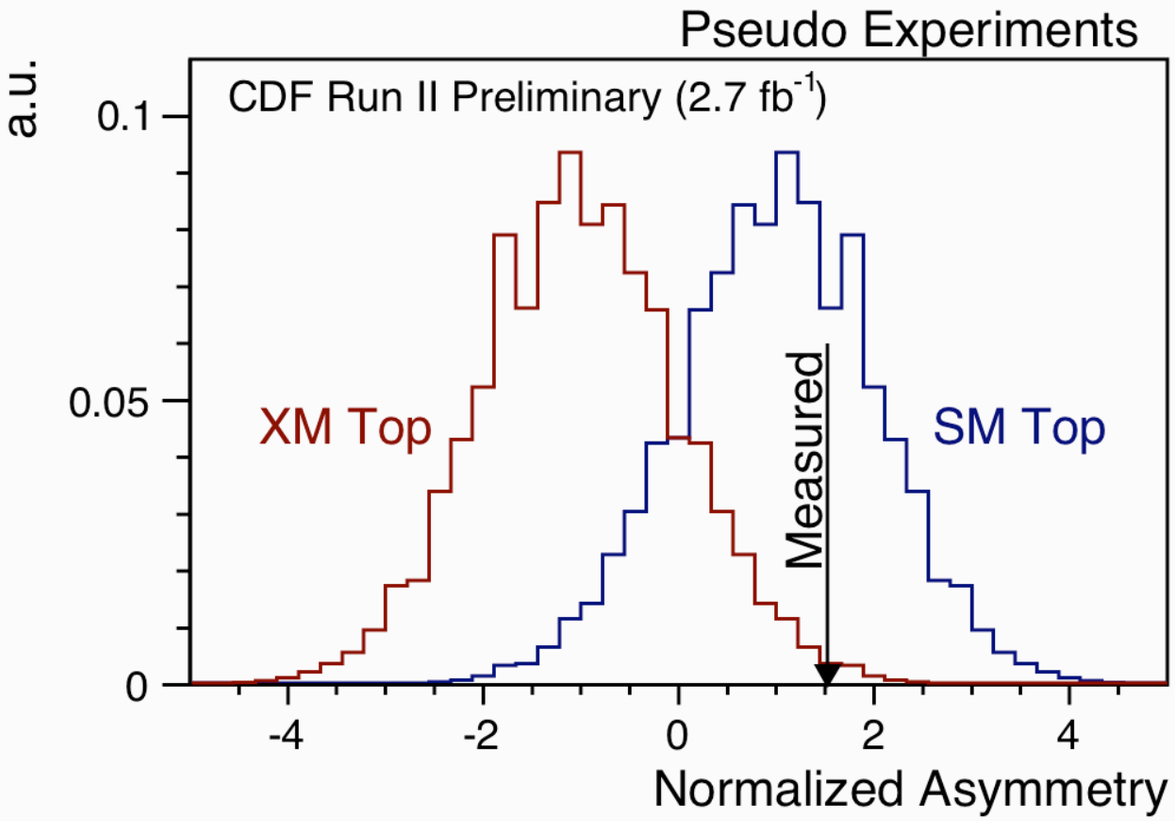
Top Quark Charge: Method

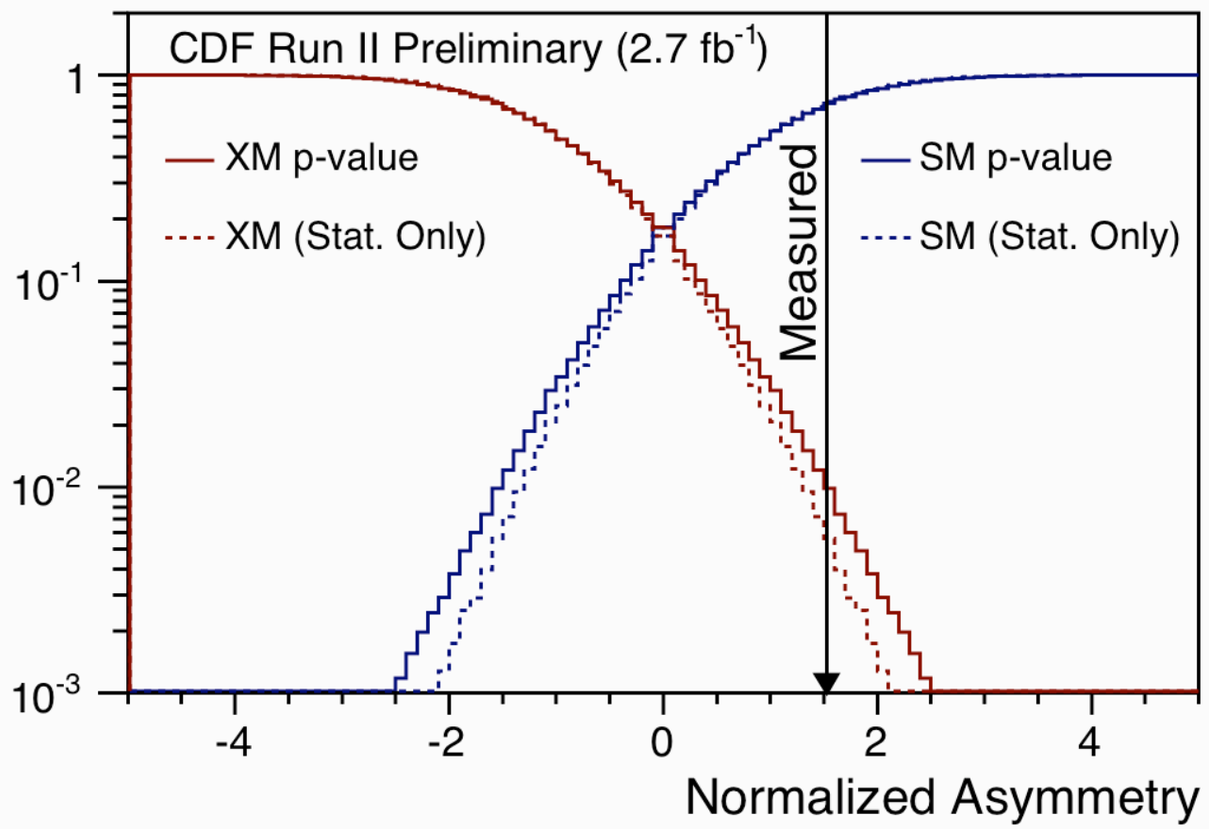
- Use lepton+jets events
- For each top or anti-top
  - Measure sign of charge of lepton using leptonic P_T
  - Measure sign of b using soft lepton tag (a muon in the b jet)
  - Classify top or anti-top as either SM or XM depending on parity of lepton and b charges
- Compute asymmetry
  - $A = \frac{1}{D}\frac{N_{SM} - N_{XM} - N_{\mathrm{Bkg}} D_{\mathrm{Bkg}}}{N_{SM} + N_{XM} - N_{\mathrm{Bkg}}}$
  - Dilution factor, D, determined from Monte Carlo





Top Quark Charge: Results





Exclude top charge of -4/3 with 95% C.L.

Summary: Top Quark Results at CDF

Charge Asymmetry A_{FB} (ppbar rest frame)	$A_{FB} = 15.8 \pm 7.2_{stat} \pm 1.7_{sys}\%$
Helicity Fraction and Spin Correlations	$\kappa = 0.48 \pm 0.48_{stat} \pm 0.22_{sys}$
W Helicity Matrix Element	$f_0 = 0.88 \pm 0.11_{stat} \pm 0.06_{sys}$ $f_+ = -0.15 \pm 0.07_{stat} \pm 0.06_{sys}$
Top Quark Charge	Exclude top charge of -4/3 with 95% C.L.