Measurements of Top Quark Properties at the Tevatron

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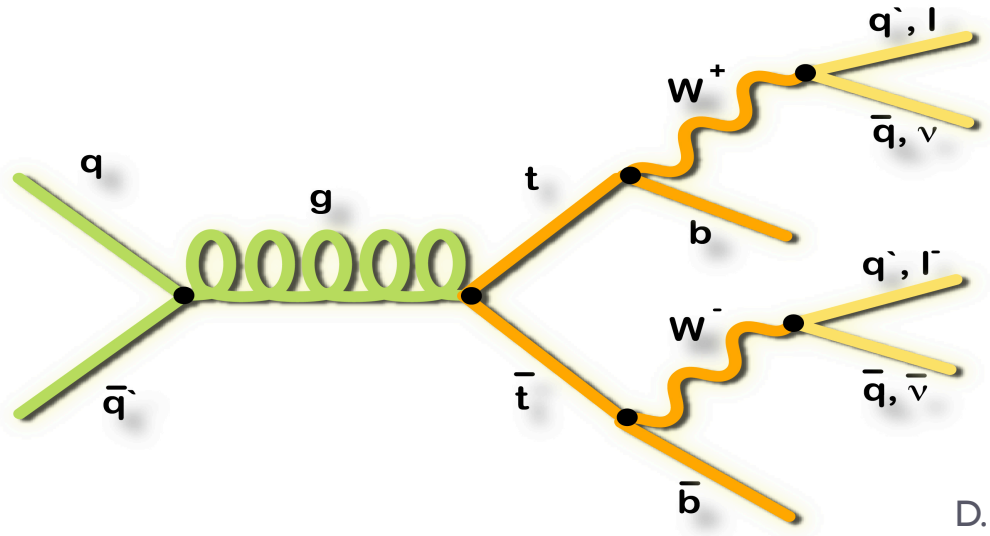
On behalf of the CDF and D0 Collaborations

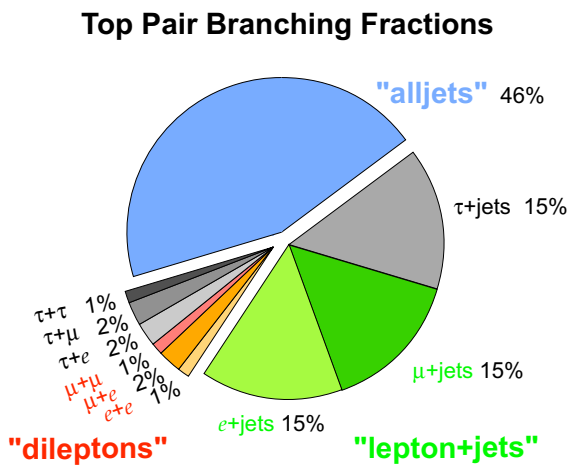
Why Study the Top Quark?

- Unique among quarks in many ways
  - Very heavy - special role in electroweak symmetry breaking or enhanced couplings to new physics?
  - Very short lifetime - spin information and other properties passed directly to decay products
- CDF and D0 have collected thousands of top events
  - Precision studies of top properties are possible
  - Many analyses are unique to the Tevatron and/or complementary to LHC measurements
- Covered today:
  - W helicity in top decay
  - Branching ratio
  - Top width
  - Spin correlations
  - Top forward-backward asymmetry

Measuring Top Properties

- Top almost always decays to *Wb*
  - Decay modes characterized by *W* decays
- Two main modes for top properties analyses:
  - Lepton+Jets: one *W* decays to quarks, one to e(μ) + ν
    - Moderate backgrounds, reasonable branching ratio; fully constrained kinematically
    - Usually require a *b*-tag to reduce backgrounds
  - Dilepton: both *W*'s decay to e(μ) + ν
    - Very low backgrounds, but small branching ratio; under-constrained kinematically

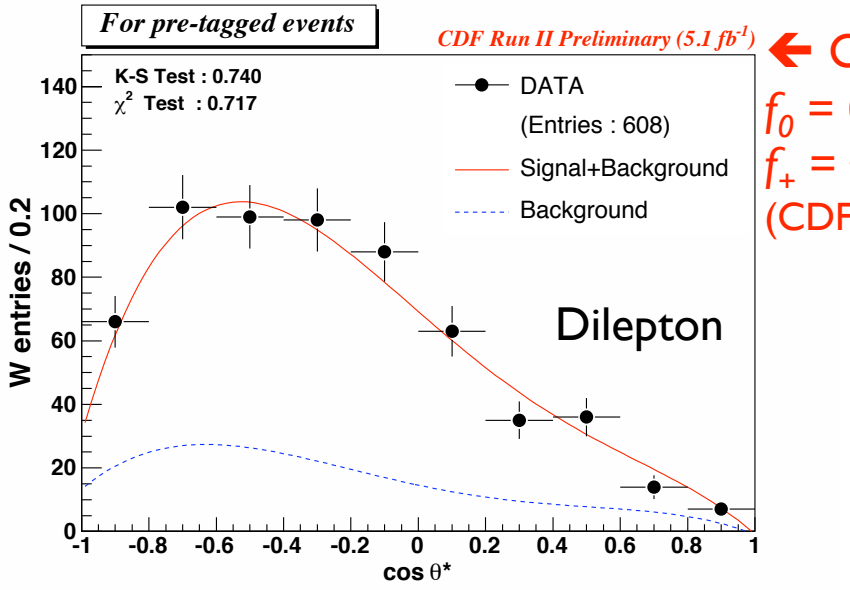




W Boson Helicity in Top Decays

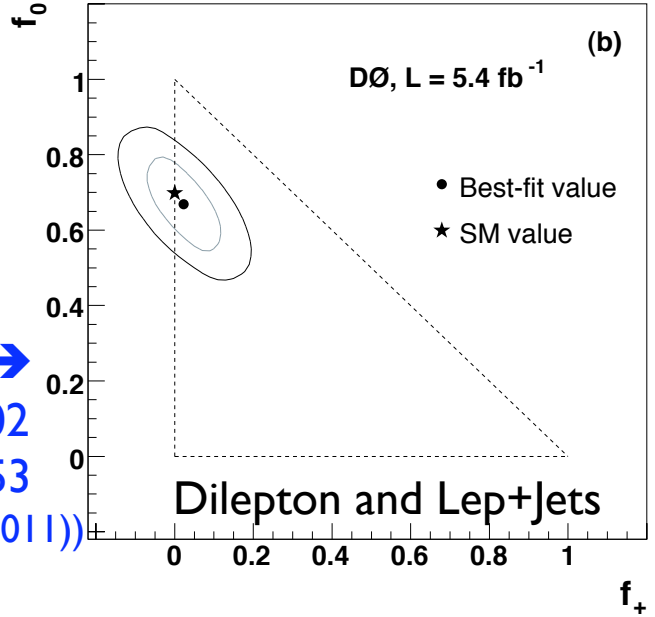
$$\omega(\cos\theta^*) \propto 2(1-\cos^2\theta^*) f_0 + (1-\cos\theta^*)^2 f_- + (1+\cos\theta^*)^2 f_+$$

- Study V-A nature of *Wtb* coupling
- Extract f_0, f_+ from distribution of θ^* (angle between lepton and top direction in W rest frame)



← CDF:
$f_0 = 0.71 \pm 0.19$
$f_+ = -0.07 \pm 0.10$
(CDF Conf. Note 10543)

D0: →
$f_0 = 0.669 \pm 0.102$
$f_+ = 0.023 \pm 0.053$
(PRD **83**, 032009 (2011))

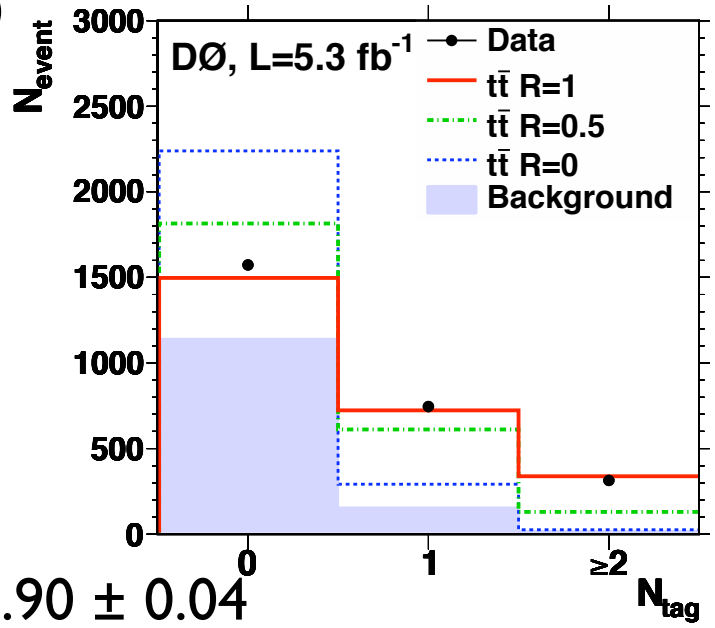


First Published CDF and D0 Combination (arXiv:1202.5272[hep-ex]):
$f_0 = 0.722 \pm 0.081$
$f_+ = -0.033 \pm 0.046$

Top ($t \rightarrow b$) Branching Ratio

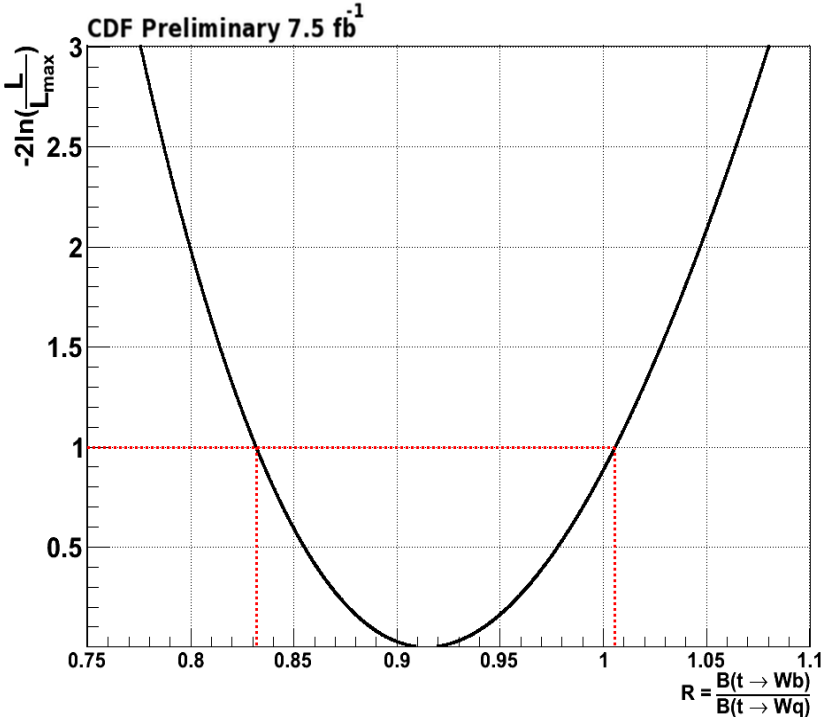
$$R = \frac{B(t \rightarrow Wb)}{B(t \rightarrow Wq)}$$

- SM: $t \rightarrow Wb$ in ~100% of decays
- Expect 2 b's in each top-antitop event
  - How often does this happen?
  - Tagging efficiency determines expected size of samples with 0, 1, or 2 tagged jets
  - Determine R from measured size of each subsample
- Derive $|V_{tb}|$ from result (assume CKM unitary)



D0: R = 0.90 ± 0.04

$|V_{tb}|$ = 0.95 ± 0.02 PRL **107**, 121802 (2011)



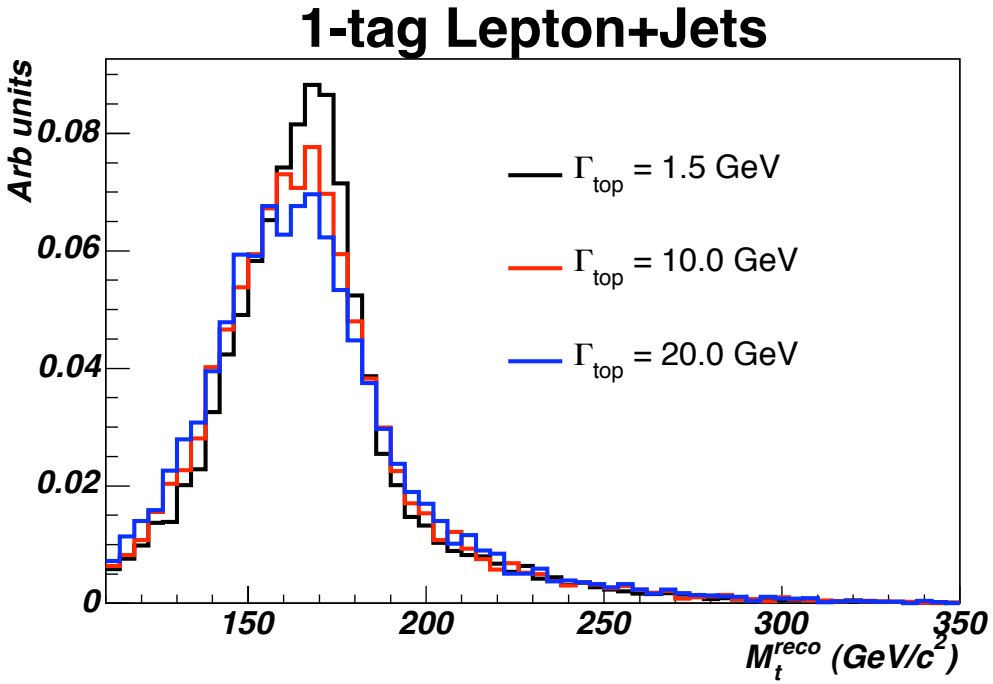
CDF: R = 0.91 ± 0.09

$|V_{tb}|$ = 0.95 ± 0.05

CDF Conf. Note In Preparation

Top Width at CDF

- SM Prediction: Γ_t ~1.5 GeV
- CDF: template method
  - 4.3 fb^{-1}
- Direct measurement of top decay width
  - Likelihood fit to the reconstructed top mass distribution based on templates with various input widths



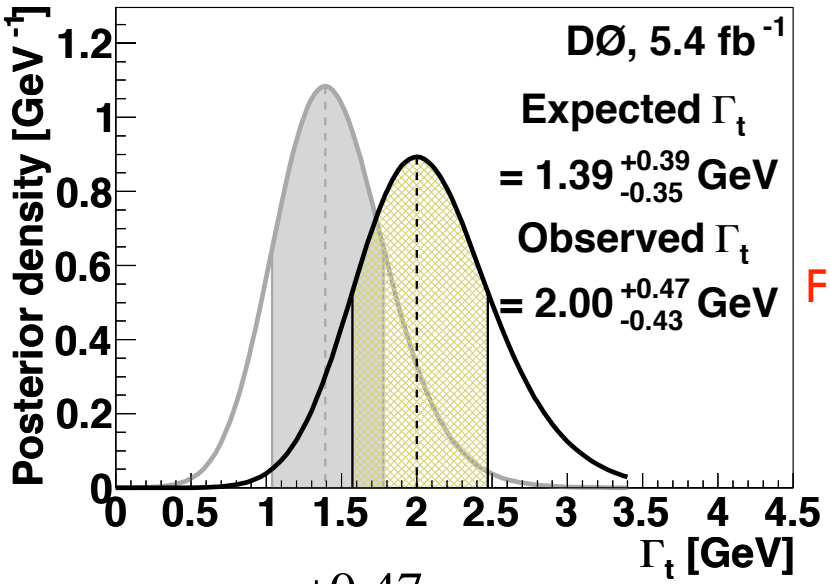
PRL **105**, 232003 (2010)

0.3 GeV < Γ_t < 4.4 GeV at 68% C.L.

Γ_t < 7.6 GeV at 95% C.L.

Top Width at D0

- D0: derived measurement based on other top properties results
  - Complementary to CDF measurement
- Requires theory input, but gains in sensitivity
- Also provides a limit on $|V_{tb}|$



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

From top pair production

From t-channel single top

$$\Gamma(t \to Wb) = \sigma(t-channel)\frac{\Gamma_{SM}(t \to Wb)}{\sigma_{SM}(t-channel)}$$

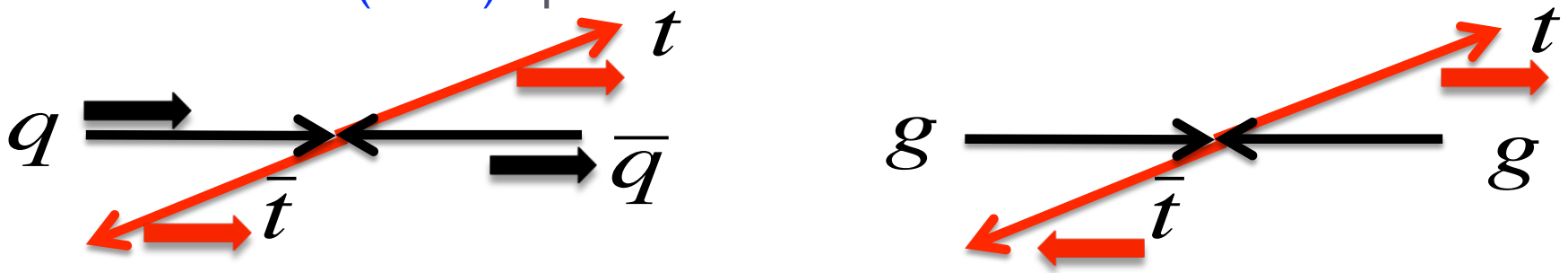
$$\Gamma_t = 2.00^{+0.47}_{-0.43} GeV$$

$0.81 < |V_{tb}| \leq 1$ at 95% C.L.

arXiv:1201.4156[hep-ex]

Top-Antitop Spin Correlations

- Top pairs are produced with a definite spin state depending on production mechanism
  - Quark-Antiquark Annihilation (~85%): Spin 1
  - Gluon Fusion (~15%): Spin 0



- Top decays before hadronization (only known quark to do so!)
  - Spin information passed to decay products – the correlated spins can be measured from decay product angular distributions
- Correlation strength (frame dependent!) is defined as:

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

$$\kappa_{beam}^{SM} = 0.78^{+0.03}_{-0.04}$$

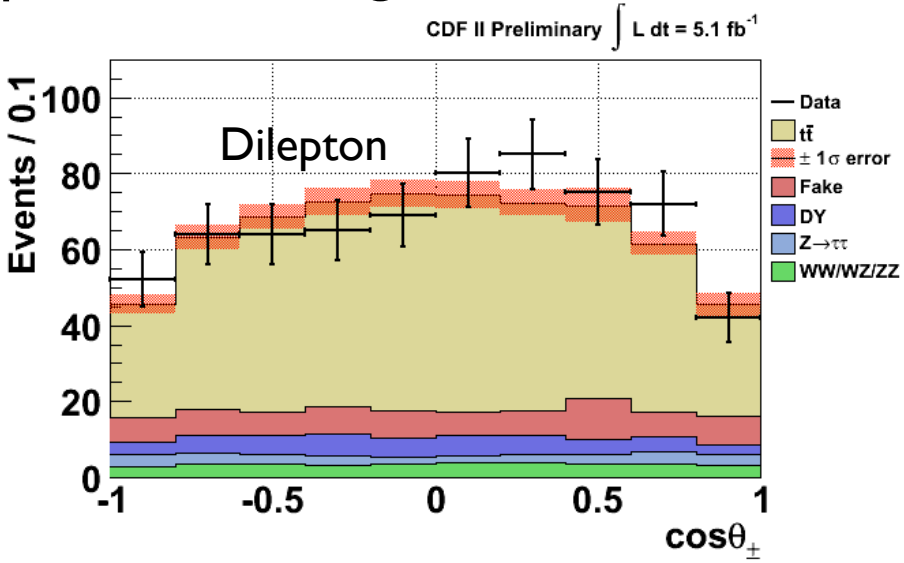
Nucl. Phys. **B 690**, 81 (2004)

Measuring the Spin Correlation

- Results shown here assume spin quantized along beam axis
  - CDF:
    - Template fits based on decay product angular distributions

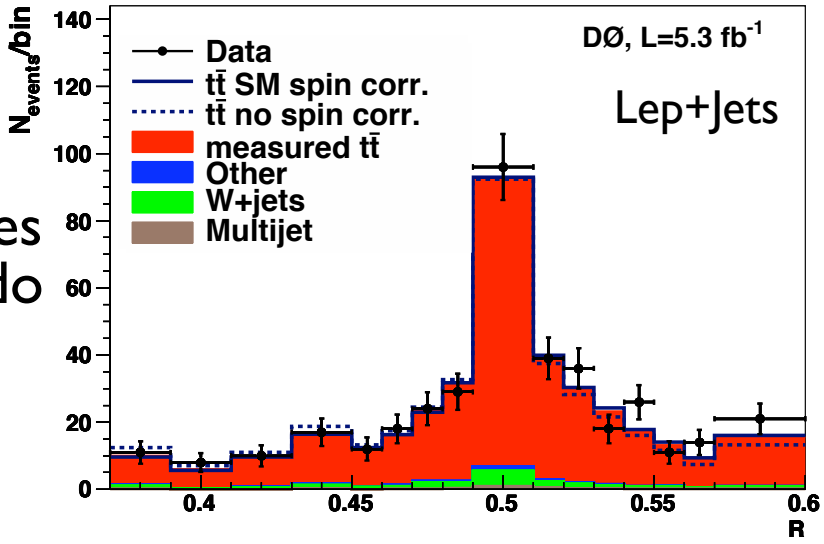
$$\kappa^{CDF}_{Lep+Jet} = 0.72 \pm 0.69$$ CDF Conf. Note 10211

$$\kappa^{CDF}_{Dilepton} = 0.042 \pm 0.563$$ CDF Conf. Note 10719



  - D0: 3 σ Evidence For Spin Correlations!
    - New matrix element approach
      - Significantly increased sensitivity
    - Likelihood fit based on probabilities that events are signal events and do (or do not) contain SM spin correlation

$$\kappa^{D0}_{Combo(Dil,Lep+Jet)} = 0.66 \pm 0.23$$

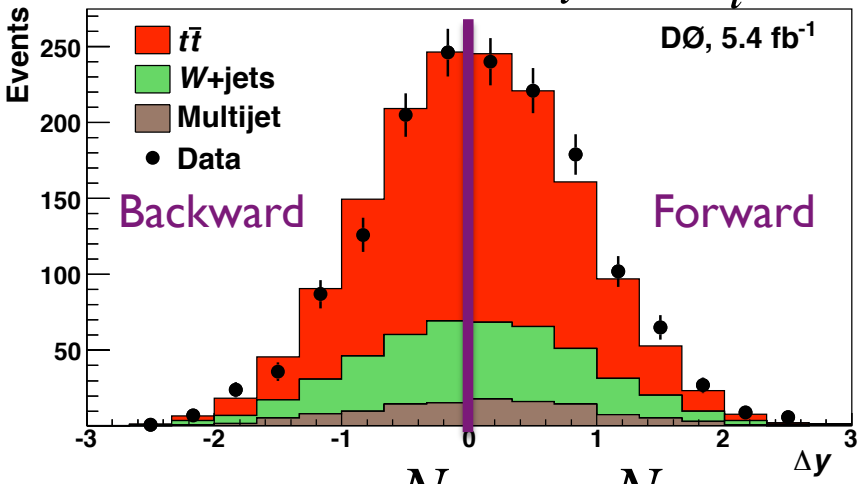


PRL **108**, 032004 (2012)

The Forward-Backward Asymmetry

- Do tops have a preference to travel along the proton or antiproton direction?
- Measure asymmetry in Δy
- Leading order: standard model predicts no asymmetry
- Next-to-leading order: small positive asymmetry
  - NLO predictions shown today based on MC generator Powheg with electroweak corrections added

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



$$A_{FB} = \frac{N_{\Delta y>0} - N_{\Delta y<0}}{N_{\Delta y>0} + N_{\Delta y<0}}$$

$$A_{FB}^{NLO} = 6.6\%$$

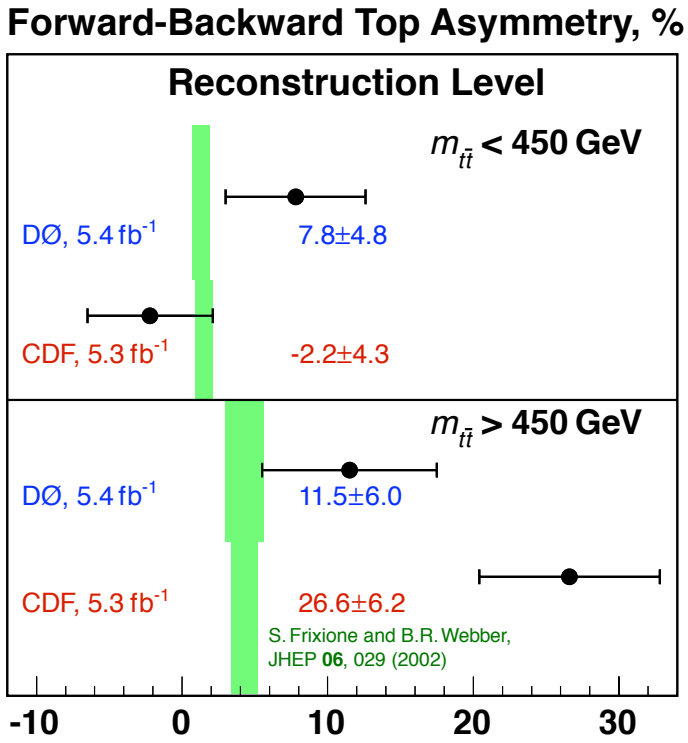
Powheg: JHEP **0709**, 126 (2007)

EW Corrections: Phys. Rev. D **84**, 093003 (2011); JHEP **1201**, 063 (2012); arXiv: 1201.3926[hep-ph]

The Asymmetry in ~5 fb^{-1}

- Inclusive asymmetries exceed standard model predictions by ~1.5-2 σ
- Somewhat ambiguous mass and rapidity dependence
  - Only two bins in $M_{tt}/\Delta y$

Background Subtracted A_{FB} (%)	$\lvert\Delta y\rvert < 1.0$	$\lvert\Delta y\rvert \geq 1.0$
D0 Lep+Jet	6.1 ± 4.1	21.3 ± 9.7
CDF Lep+Jet	2.9 ± 4.0	29.1 ± 9.6



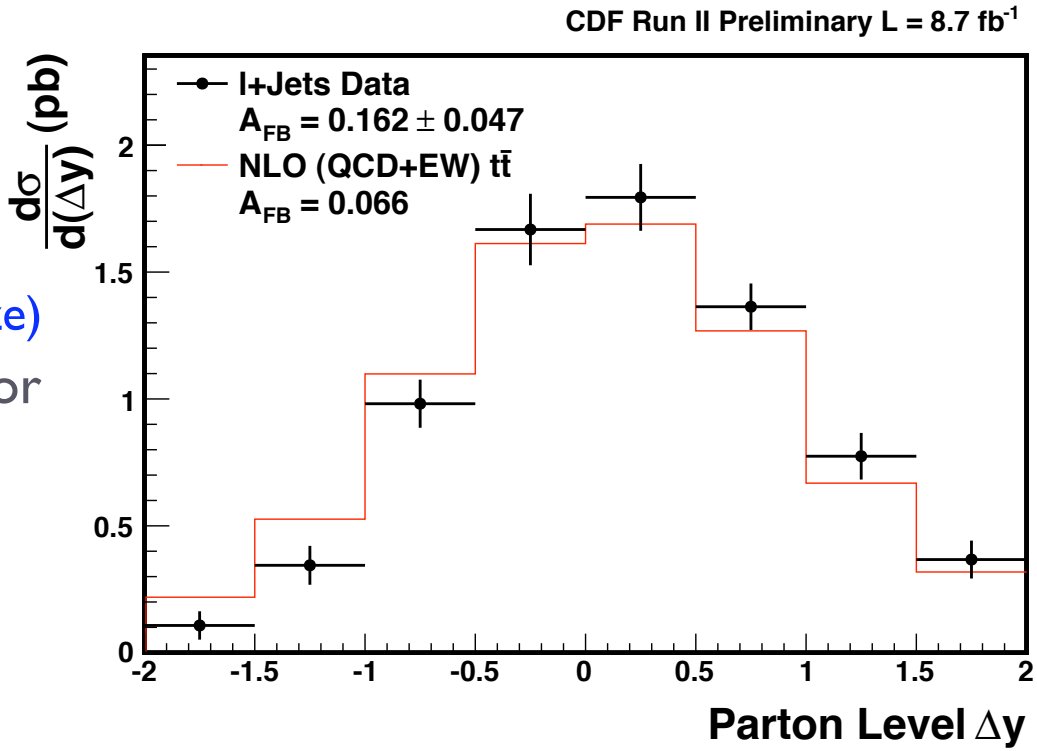
Measurement	Parton Level A_{FB} (%)
CDF Lep+Jets[1]	15.8 ± 7.4
CDF Dilepton[2]	42 ± 16
CDF Combined[3]	20.1 ± 6.7
D0 Lep+Jets[4]	19.6 ± 6.5

[1]CDF L+J: PRD **83**, 112003 (2011); [2]CDF Dil: CDF Conf. Note 10436;
[3]CDF Combo: CDF Conf. Note 10584; [4]D0 L+J: PRD **84**, 112055 (2011)

The Asymmetry at CDF in the Full Dataset

- Updates from CDF's 5.3 fb^{-1} lepton+jets analysis:
  - Add new data stream and increase luminosity to 8.7 fb^{-1}
    - 2498 events (double sample size)
  - Use NLO generator Powheg for signal modeling
  - Parton level shape corrections use regularized unfolding algorithm
    - Proper multi-binned measurement of rapidity and mass dependence
- Parton Level A_{FB}: 16.2 ± 4.7 %

  (NLO: 6.6%)

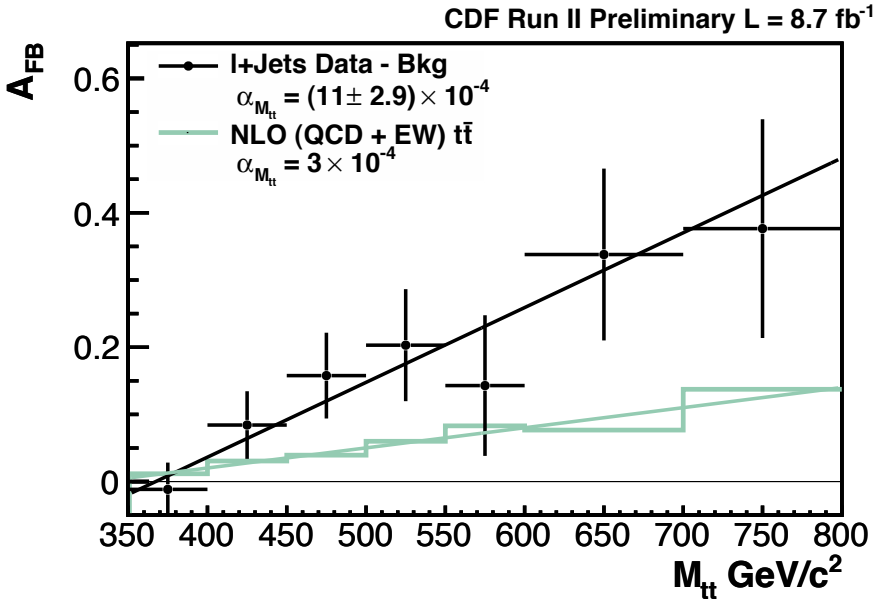


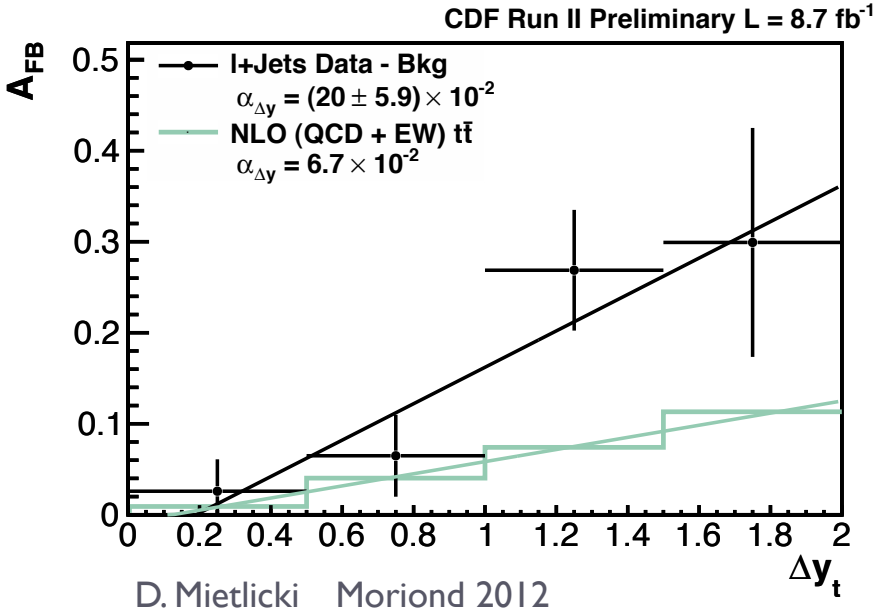
CDF Conf. Note 10807

Background-Subtracted M_{tt} and Δy Dependence

- Predicted background contribution has been removed
  - Measure asymmetry in only top events
- No correction to parton level yet
  - No assumptions about the underlying physics
- Data well-described by linear ansatz – determine best-fit slope
  - χ^2/d.o.f ≤ ~1 for both Δy and M_{tt} dependence
- Determine p-value by comparing observed slope to NLO prediction
  - How often will NLO slope fluctuate to be at least as large as in the data?

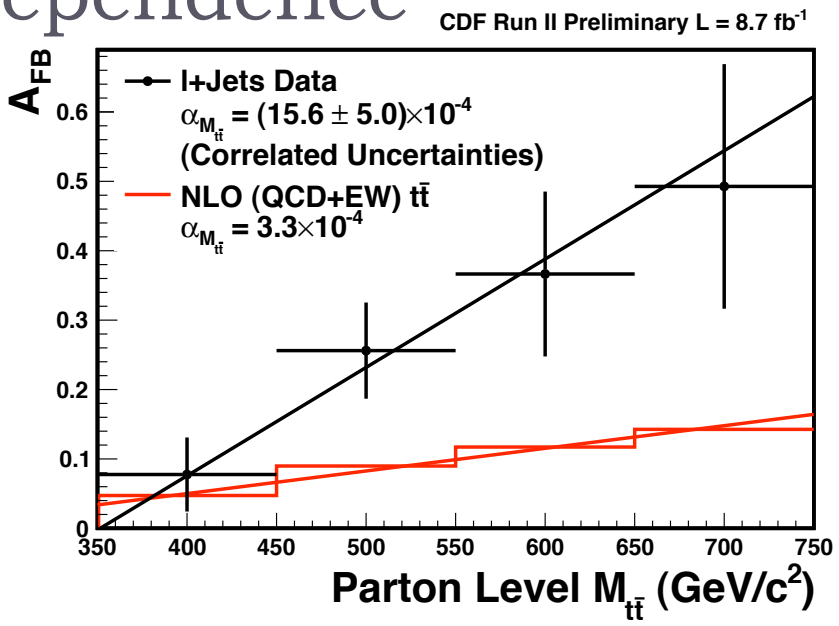
Slope Parameter α	A_{FB} vs. M_{tt}	A_{FB} vs. Δy
Data	$(11.1 \pm 2.9)\times10^{-4}$	$(20.0 \pm 5.9)\times10^{-2}$
SM	3.0×10^{-4}	6.7×10^{-2}
p-value	0.00646	0.00892

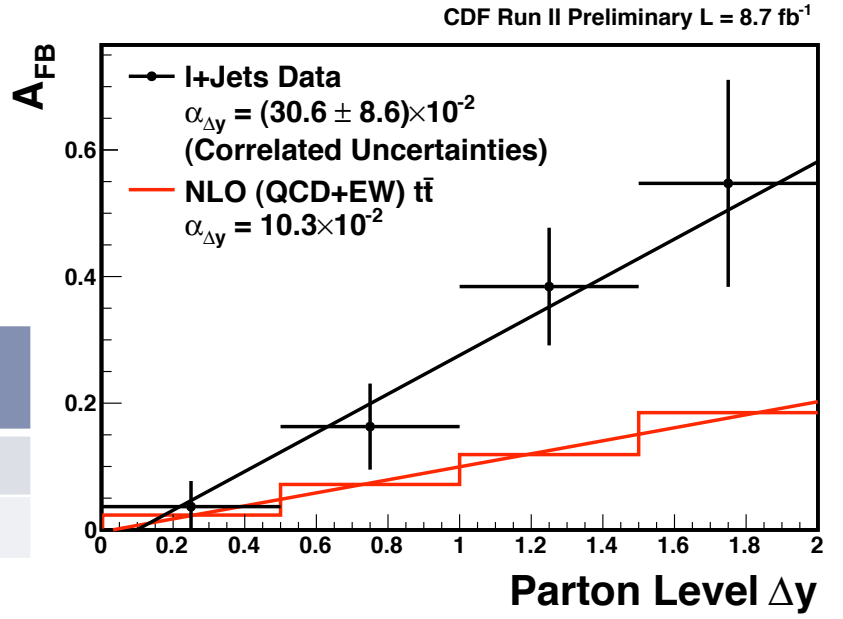




Parton Level M_{tt} and Δy Dependence

- Correct for acceptance and detector resolution
  - Regularized unfolding algorithm addresses resolution effects
  - Multiplicative acceptance correction factor applied to each bin
  - Both corrections use the NLO generator Powheg as the top model
- Parton level results can be compared directly to theory
- Determine best-fit slope for observed data and compare to NLO prediction





Slope Parameter α	A_{FB} vs. M_{tt}	A_{FB} vs. Δy
Data	$(15.6 \pm 5.0)\times10^{-4}$	$(30.6 \pm 8.6)\times10^{-2}$
SM	3.3×10^{-4}	10.3×10^{-2}

Conclusions

- The full Tevatron dataset is now being studied in top properties measurements
- Many areas of study (spin correlations, A_{FB}) are complementary to LHC measurements
- CDF and D0 combinations are available (W helicity) or in progress for many properties measurements
- Please see the websites of CDF's and D0's Top Groups and the Tevatron Electroweak Working Group for more information and results not presented today:

  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

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

Backup Slides

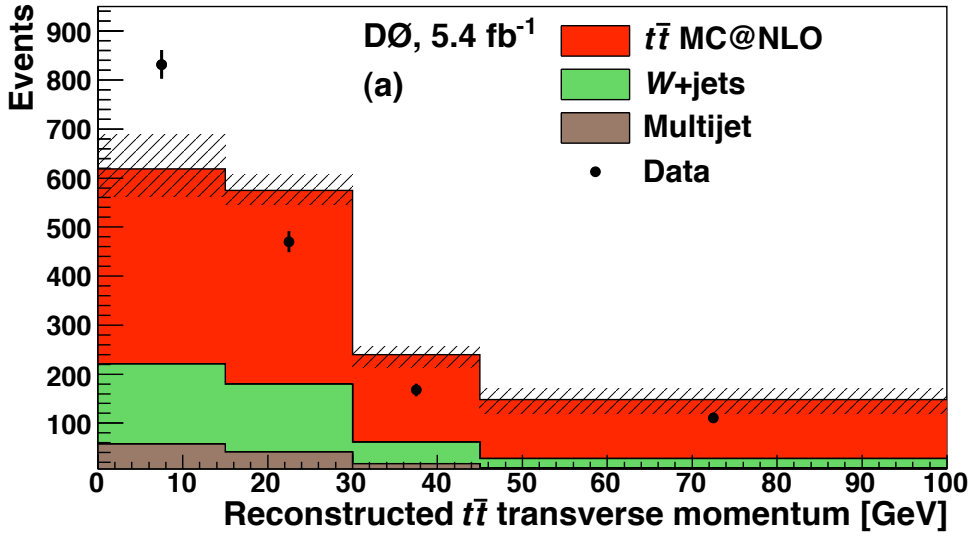
Comparison of Two-Bin Parton Level A_{FB} to Previous Results

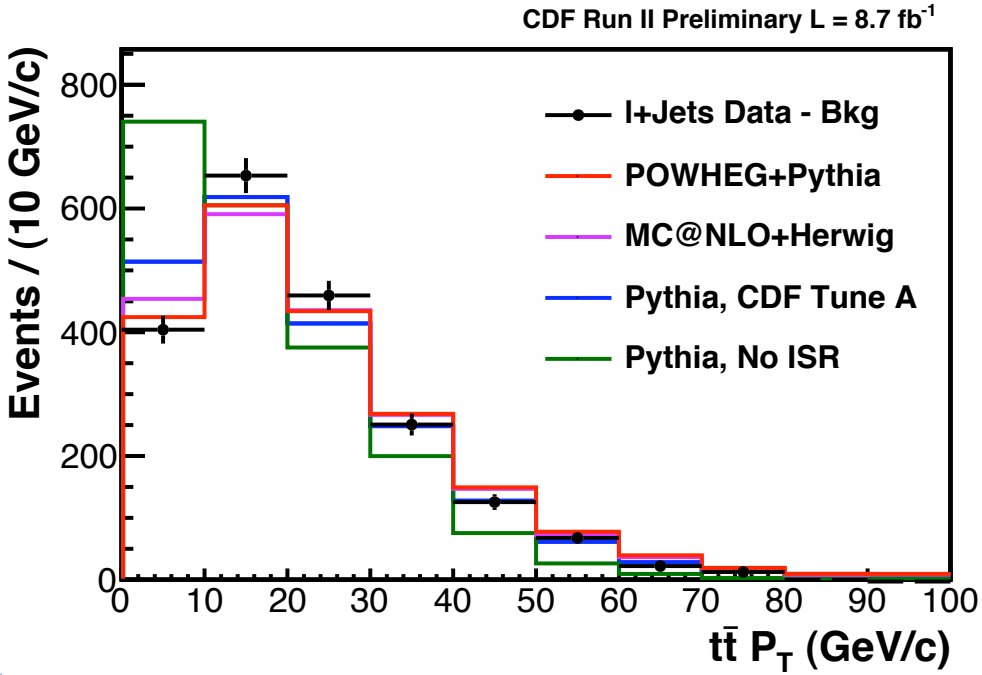
- Previous version of CDF analysis only provided parton-level results for two bins of M_{tt} and Δy
- Table compares the new result in the same two bins to the previous results (all numbers are percentages)

Selection	NLO (QCD+EW)	CDF, 5.3 fb^{-1}	D0, 5.4 fb^{-1}	CDF, 8.7 fb-1
Inclusive	6.6	15.8 ± 7.4	19.6 ± 6.5	16.2 ± 4.7
$M_{tt} < 450$ GeV/c^2	4.7	−11.6 ± 15.3	7.8 ± 4.8 (Bkg. Subtracted)	7.8 ± 5.4
$M_{tt} \geq 450$ GeV/c^2	10.0	47.5 ± 11.2	11.5 ± 6.0 (Bkg. Subtracted)	29.6 ± 6.7
$\lvert\Delta y\rvert < 1.0$	4.3	2.6 ± 11.8	6.1 ± 4.1 (Bkg. Subtracted)	8.8 ± 4.7
$\lvert\Delta y\rvert \geq 1.0$	13.9	61.1 ± 25.6	21.3 ± 9.7 (Bkg. Subtracted)	43.3 ± 10.9

Source of the Asymmetry?

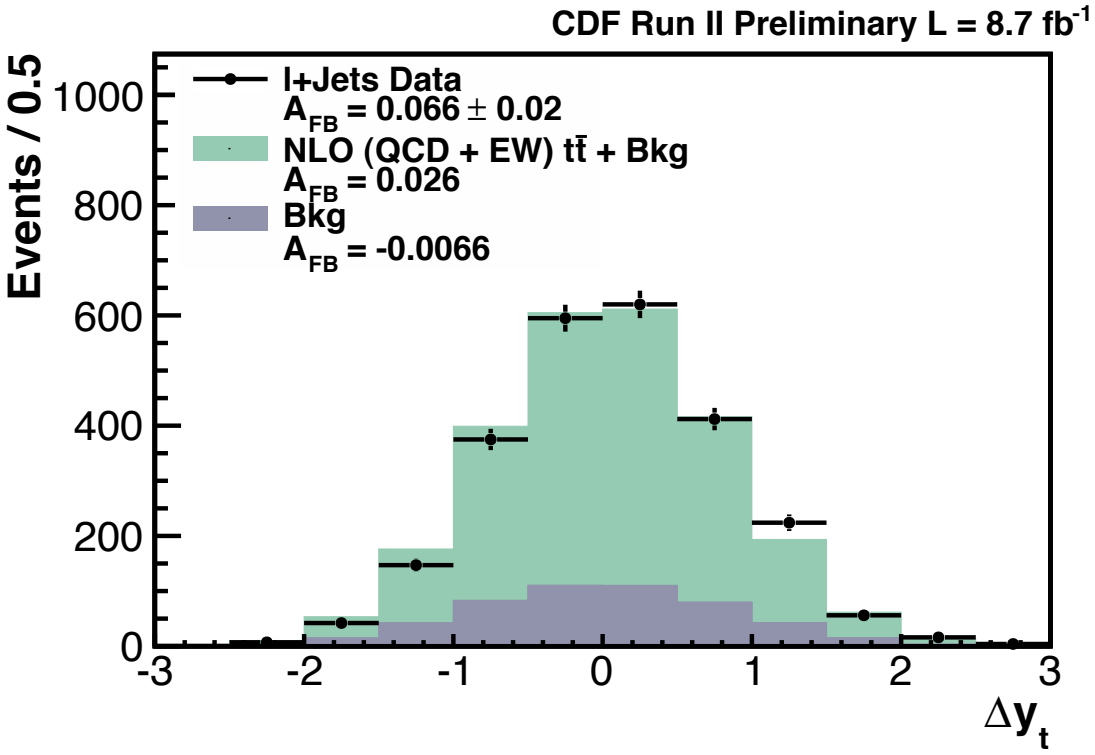
- Is it a problem with the current understanding of the SM?
  - Mis-modeled top pair P_T spectrum?
  - Higher order corrections?
- Is it new physics?
  - Many new models have been proposed
    - Axigluon, Z-prime, W-prime, …
  - Other top properties measurements can help differentiate between the possibilities
    - Differential cross-section in M_{tt}
    - Top spin or polarization





Reconstruction Level A_{FB}

- Event selection:
  - One high P_T central lepton
  - At least four jets
    - At least one *b*-tag
  - Large missing E_T
  - Total transverse energy H_T above 220 GeV
- Background model:
  - Diboson, single top, Z+jets from MC
  - W+jets shape from MC
  - QCD shape from data
  - W+jets and QCD normalization from fit to missing E_T spectrum
- Events reconstructed via χ^2-based kinematic fit to top-antitop hypothesis
- Event count:
  - 2498 total candidates
  - 505 predicted background

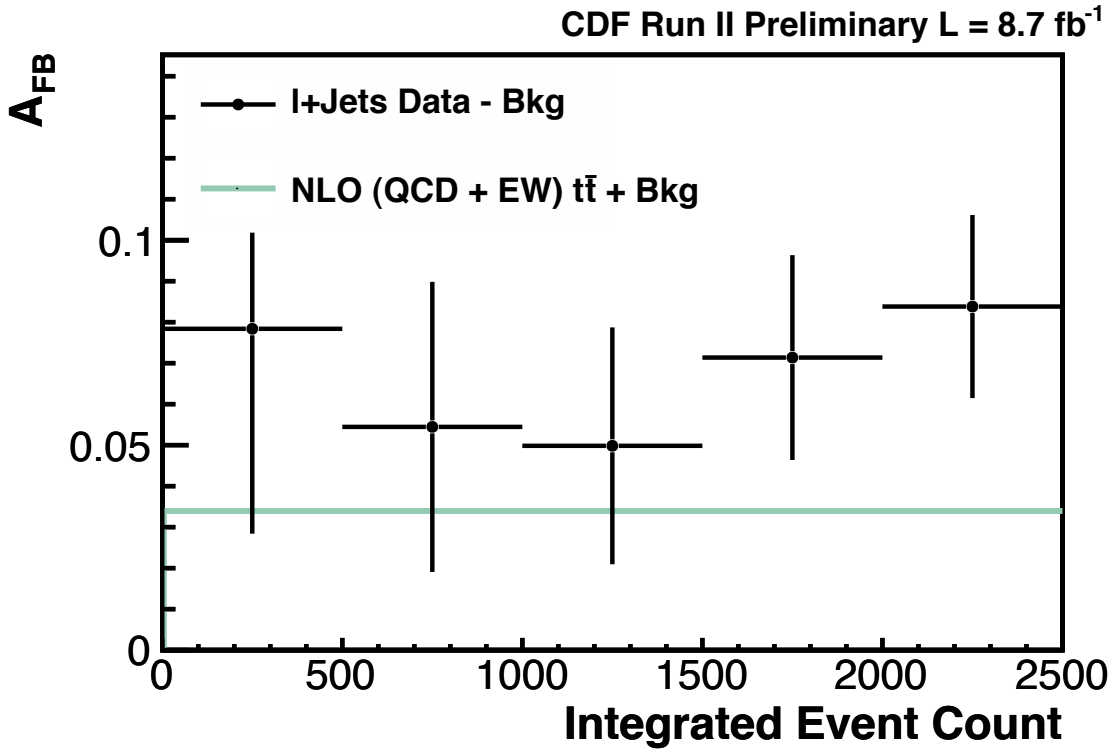


$$A_{FB}^{reco.} = 6.6 \pm 2.0\%$$

$$A_{FB}^{bkg.sub.} = 8.5 \pm 2.5\%$$

The Asymmetry Over the Data-Taking Period

- Look at the background-subtracted asymmetry as a function of the number of events in the sample
  - Verify it was not cause by some time-dependent detector effect
  - "0 events" = start of Run II
- A_{FB} remains constant (within uncertainties) over the entire sample



Leptonic Asymmetry

- Motion of lepton in semi-leptonic top decay correlated with parent top
  - A real top pair asymmetry will manifest itself here as well
- Measure asymmetry in $q^* \eta_{lep}$ [lepton +jets] or $(\eta^+_{lep} - \eta^-_{lep})$ [dilepton]
  - Smaller expected asymmetry than in Δy (~1–2% after event selection without backgrounds)

Analysis	Background Subtracted Leptonic A_{FB} (%)
D0 Lep+Jet	14.2 ± 3.8
CDF Lep+Jet	6.6 ± 2.5
CDF Dilepton	21 ± 7