The Top Pair Forward-Backward Asymmetry in the Full CDF Dataset

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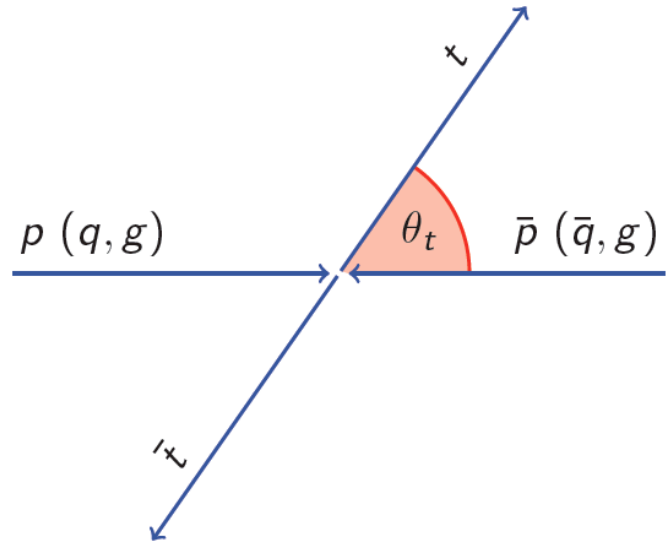
The Top Asymmetry

- Very large top mass ➔ intriguing possibilities for top quark interactions
  - Special role in EWSB? Enhanced couplings to new physics?
  - Precision top property measurements can provide the answers
- Previous measurements: large forward-backward asymmetry (A_{FB}) in the production angle
  - Equivalent to a charge asymmetry
- Use Δy as a proxy for production angle
  - Invariant to boosts along the beamline
    - A_{FB} measured in top pair rest frame
  - Inclusive A_{FB} is the same in Δy and $\cos\theta$
- A_{FB} measurement is unique to the Tevatron
  - LHC experiments can see a charge asymmetry
  - But it requires different techniques and the expected magnitude is much smaller



$$y = \frac{1}{2}\ln\left(\frac{E + p_z}{E - p_z}\right)$$

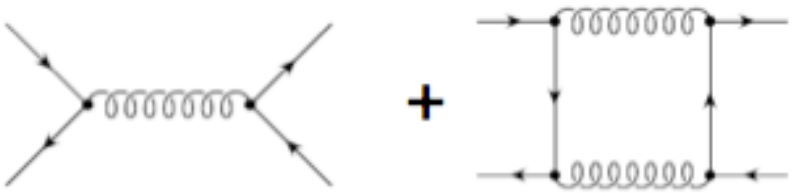
$$\Delta y = y_t - y_{\bar{t}}$$

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

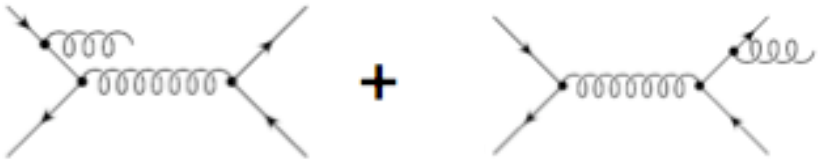
The Standard Model Prediction

- Leading order: no asymmetry
- Next-to-leading order: small positive asymmetry
- Some uncertainty regarding theory predictions
  - E.g., use LO or NLO cross-section for A_{FB} denominator?
- Predictions shown today are from NLO Monte Carlo generator POWHEG
  - Flat correction of 26% in Δy asymmetries for electroweak contributions

Born + Box Interference
Positive Contribution to A_{FB}



ISR/FSR Interference
Negative Contribution to A_{FB}



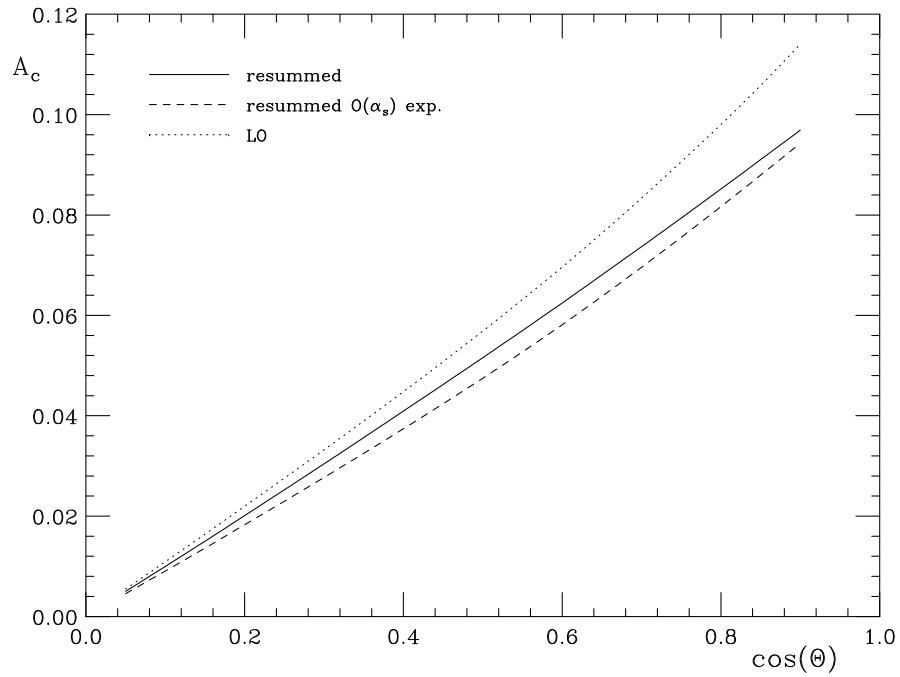
$$A_{FB}^{NLO} = 6.6\%$$

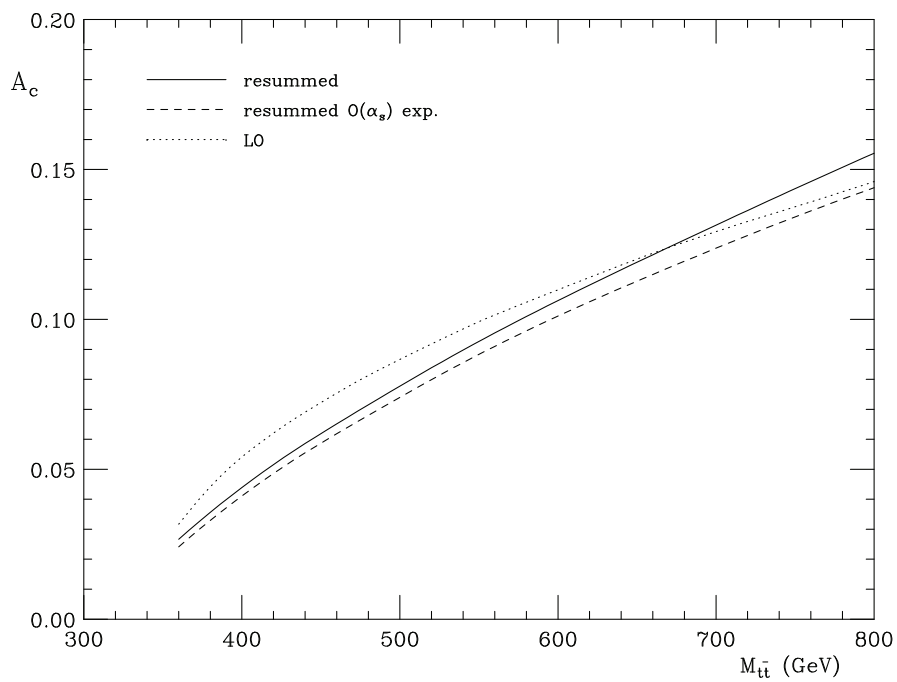
POWHEG:
Frixione, Nason, and Ridolphi, JHEP **0709**, 126 (2007)

EW Corrections:
Hollik and Pagani, Phys. Rev. D **84**, 093003 (2011)
Kuhn and Rodrigo, JHEP **1201**, 063 (2012)
Manohar and Trott, arXiv:1201.3926[hep-ph]

A_{FB} Functional Dependencies

- Expected standard model dependence of A_{FB} on $\cos\theta$ (top) and M_{tt} (bottom)
  - Plots from L. Almeida, G. Sterman, and W. Vogelsang, Phys. Rev. D **78**, 014008 (2008).





The Asymmetry in ~5 fb^{-1}

- Both CDF and D0 measure large inclusive A_{FB}
  - ~3 σ from no asymmetry
  - ~1.5-2 σ above SM prediction
  - Good consistency between measurements

Measurement	Parton Level A_{FB} (%)
[1]CDF Lep+Jets, 5.3 fb^{-1}	15.8 ± 7.4
[2]CDF Dilepton, 5.1 fb^{-1}	42 ± 16
[3]CDF Combined	20.1 ± 6.7
[4]D0 Lep+Jets, 5.4 fb^{-1}	19.6 ± 6.5
Informal Combination*	19.8 ± 4.7
NLO (QCD+EW)	6.6

*NOT an official result – just a simple weighted average of the D0 lepton+jets and the combined CDF results (correlations of systematics NOT included)

[1]Phys. Rev. D **83**, 112003 (2011). [2]CDF Conference Note 104367.
[3]CDF Conference Note 10584. [4]Phys. Rev. D **84**, 112005 (2011).

Mass and Rapidity Dependence

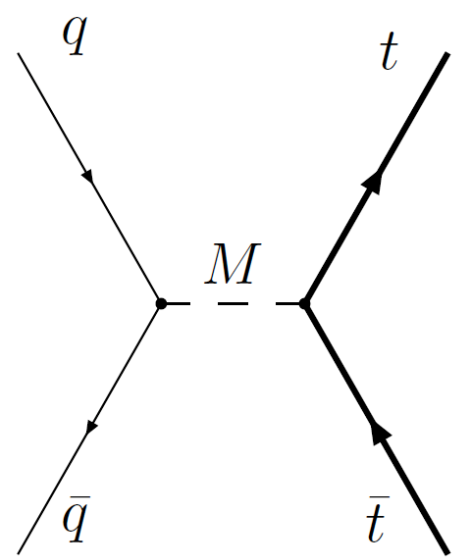
- Mass and rapidity dependence studied in only 2 bins of M_{tt} and Δy – results are somewhat ambiguous
  - Large mass dependence at CDF, no significant effect at D0
    - Consistent at ~1.7 σ level
  - CDF observes large rapidity dependence, smaller at D0
    - Consistent within 1 σ

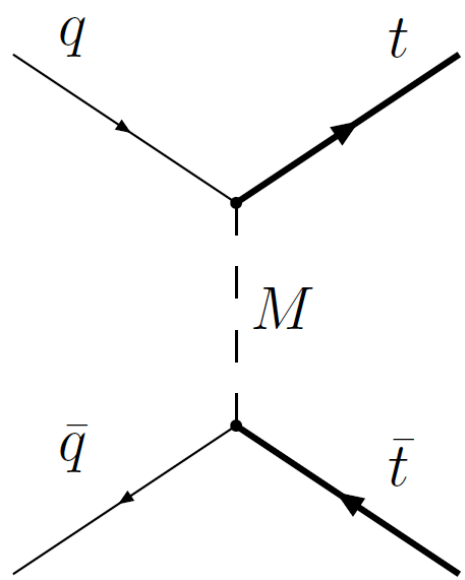
Background-Subtracted A_{FB} (%)	D0 Lep+Jet, 5.4 fb^{-1}	CDF Lep+Jet, 5.3 fb^{-1}	Informal Combination*
$M_{tt} < 450$ GeV/c^2	7.6 ± 4.8	−2.2 ± 4.3	2.1 ± 3.2*
$M_{tt} \geq 450$ GeV/c^2	11.5 ± 6.0	26.6 ± 6.2	18.6 ± 4.3*
$\lvert \Delta y \rvert < 1.0$	6.1 ± 4.1	2.9 ± 4.0	4.5 ± 2.9*
$\lvert \Delta y \rvert \geq 1.0$	21.3 ± 9.7	29.1 ± 9.6	25.2 ± 6.8*

*NOT an official result – just a simple weighted average of the D0 and CDF lepton+jets results

Theoretical Responses to a Large A_{FB}

- Some deviation from SM in 5 fb^{-1} results
  - Largest (CDF, high mass) > 3 σ
  - Much theoretical work followed
- Do we need better understanding of SM?
  - Refined calculations
    - EW corrections
    - NNLO calculations in progress
  - SM prediction increased, but not yet enough to match observed data
- Could it be new physics?
  - Two main classes of models:
    - s-channel mediator (e.g., axigluon)
    - t-channel flavor changing mediator (e.g., W', Z')
  - Mass/rapidity dependence can untangle new physics from QCD
  - For a review, see, e.g., M. Gresham, I.-W. Kim, and K. Zurek, Phys. Rev. D **83**, 114027 (2011).



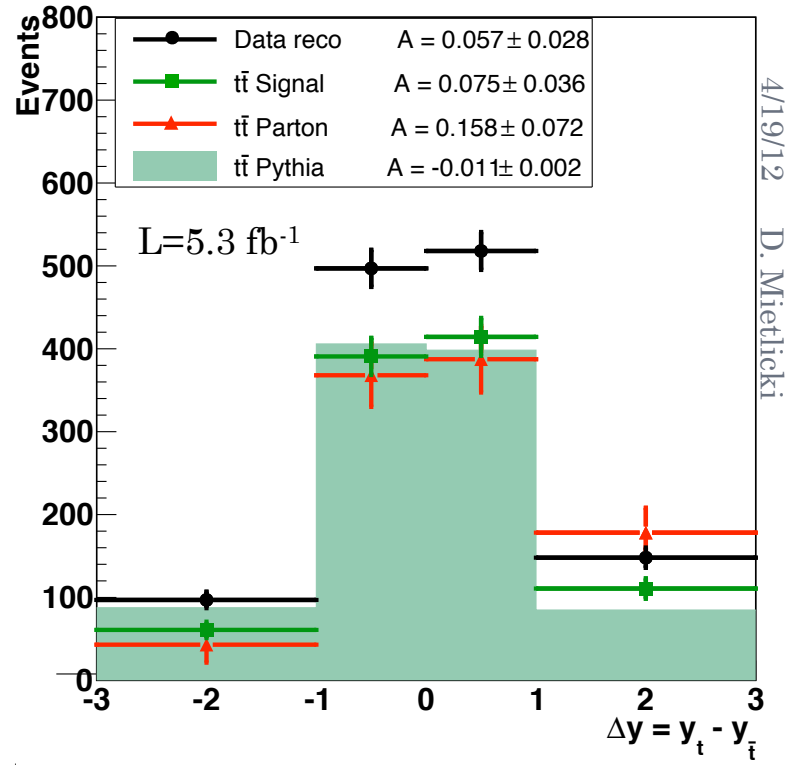


Overview of The CDF Analysis

- Full CDF dataset (8.7 fb^{-1} with full detector working)
  - New data stream also added
  - Lepton+jets selection: 1 lepton, ≥4 jets (≥1 *b*-tag), large missing E_T
  - 2498 candidate events – doubles the 5.3 fb^{-1} dataset (1260)
  - 505 predicted background events
- Events reconstructed with χ^2-based kinematic fit
  - Lepton charge fixes the charge of all final state objects
- NLO generator POWHEG for signal modeling
  - 5.3 fb^{-1} analysis used PYTHIA (LO)
- New regularized unfolding method for correction to parton level

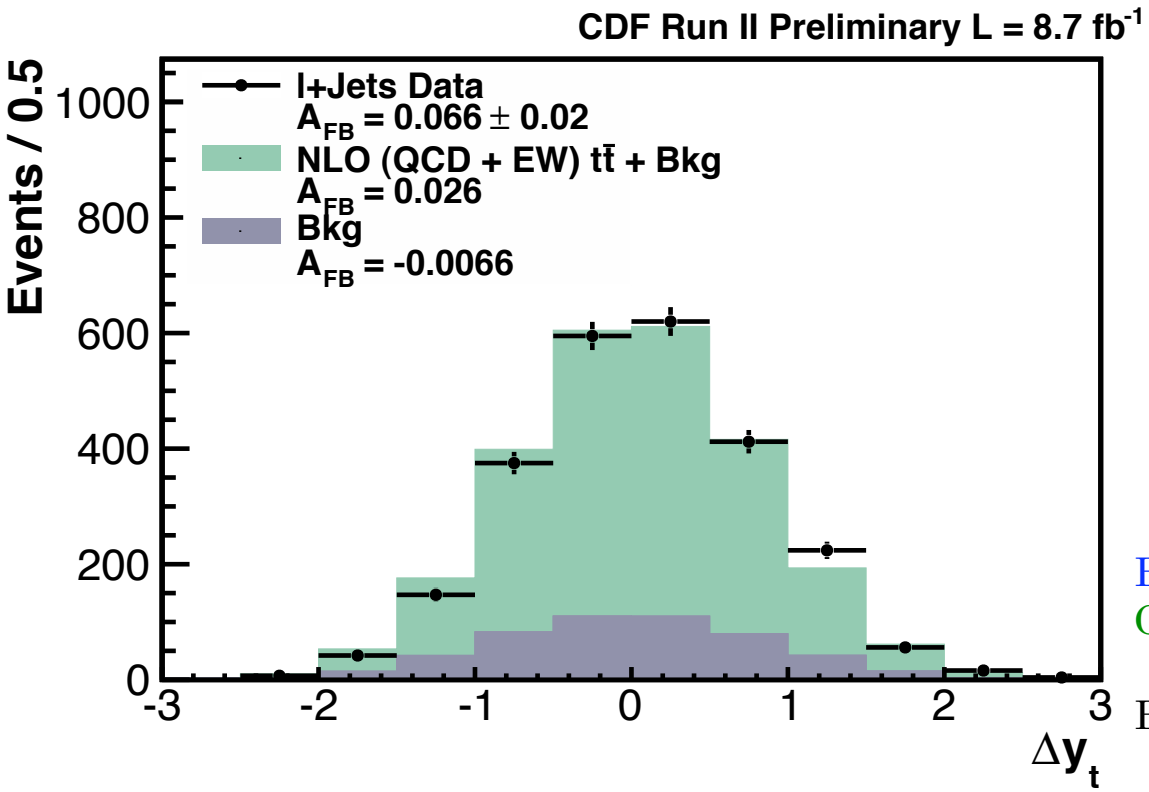
Three Measurement Levels

- A_{FB} at three levels of correction (focus on 2 and 3):
  - 1. Reconstruction (Raw Data) Level:
    - Observed data, no corrections
    - Includes background contributions
    - *NLO A_{FB} (with backgrounds): 2.6%
  - 2. Background Subtracted (Signal) Level:
    - Remove predicted backgrounds
    - Pure top sample, but includes selection and reconstruction effects
    - *NLO A_{FB}: 3.3%
  - 3. Parton Level:
    - Correct for acceptances and reconstruction
    - Direct comparison to theory models
    - *NLO A_{FB}: 6.6%



*NLO predictions in this talk always include flat 26% correction to POWHEG for electroweak contributions

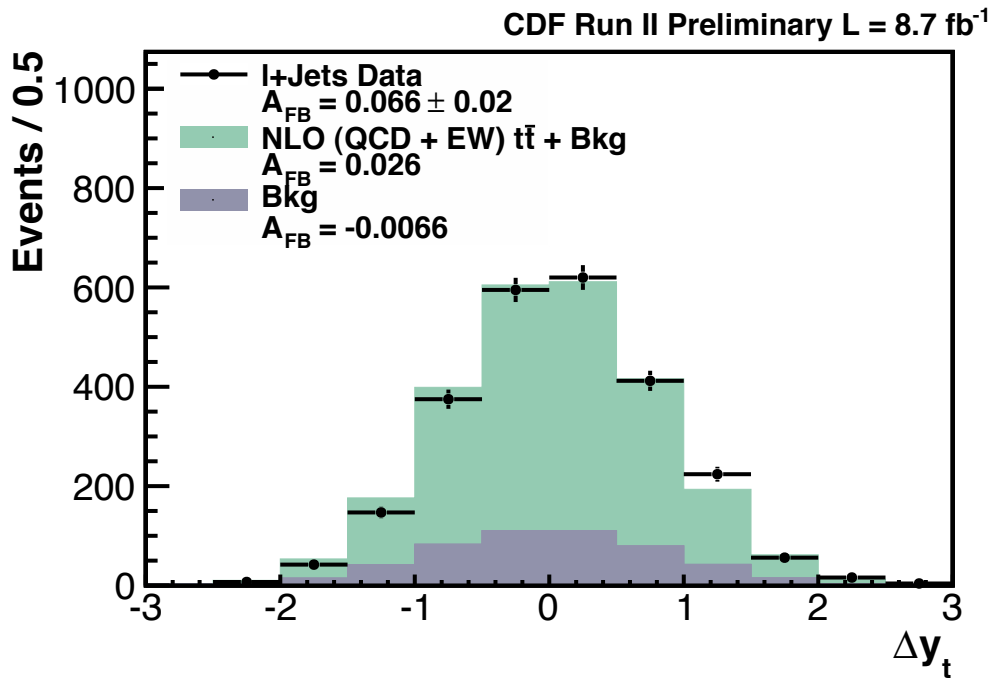
Reconstruction Level Δy in 8.7 fb^{-1}



Blue: background prediction
Green: NLO POWHEG signal
– Stacked with backgrounds
Black: observed data

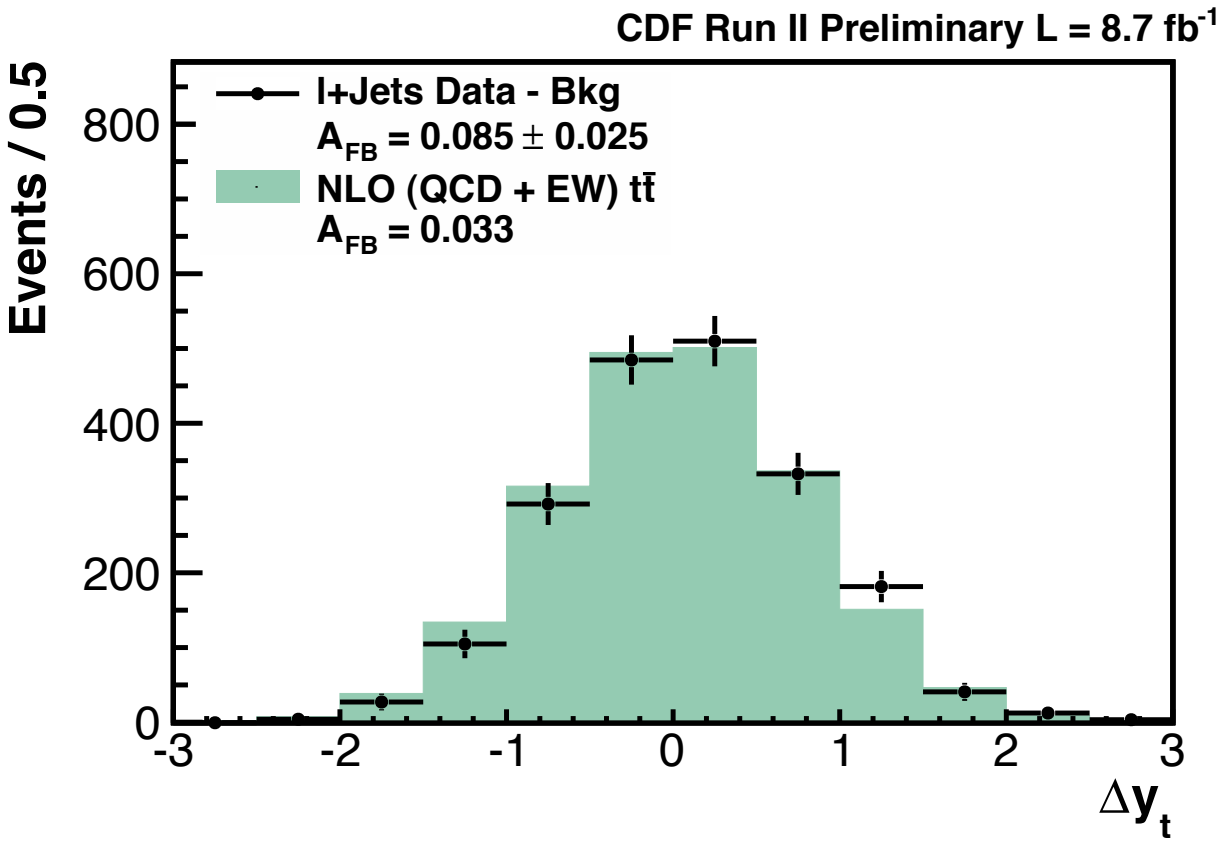
- NLO signal plus backgrounds predict $A_{FB} = 2.6\%$
  - Signal prediction includes reweighting for electroweak contributions
- Observed inclusive asymmetry is $(6.6 \pm 2.0)\%$
  - $> 3\sigma$ from no asymmetry

Removing the Backgrounds



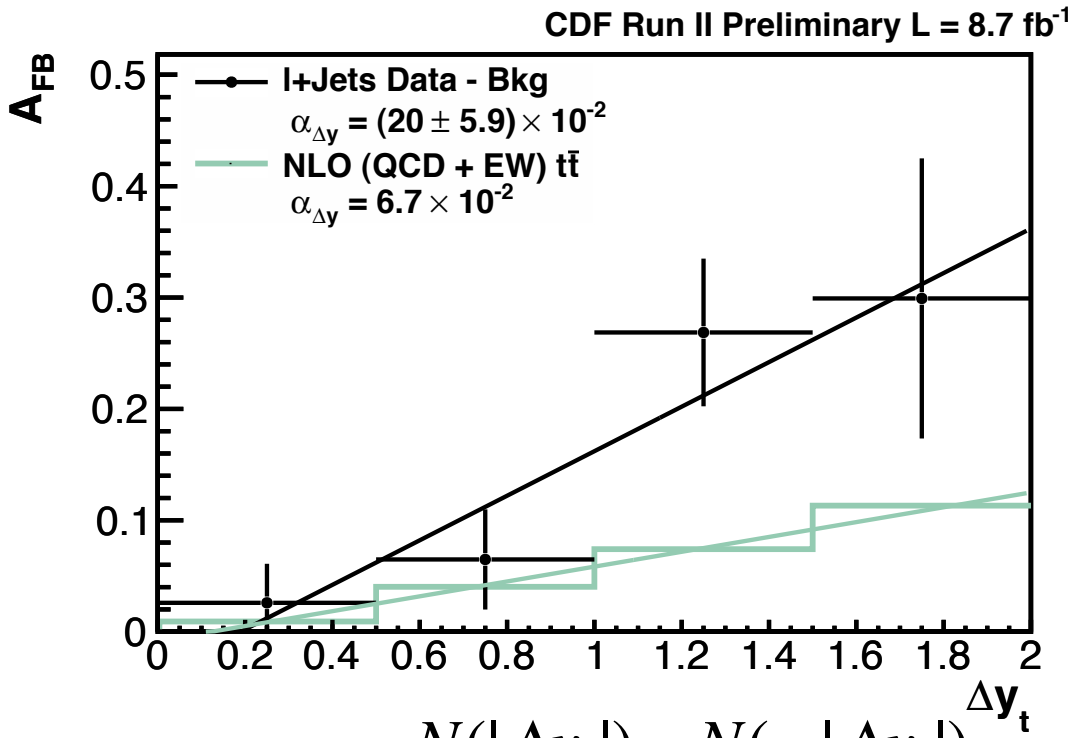
- ~20% of selected sample is composed of events from background sources
  - Dominant sources: W+jets, QCD multi-jet events
  - Backgrounds have small inherent asymmetry, but dilute any A_{FB} in top events
- Subtract predicted backgrounds from the observed data to yield the pure top signal

Δy After Background Subtraction



- Observed asymmetry after background subtraction is (8.5 ± 2.5)%
- NLO POWHEG predicts 3.3%
  - Observation is 3.4 σ from no A_{FB}, 2.1 σ from prediction

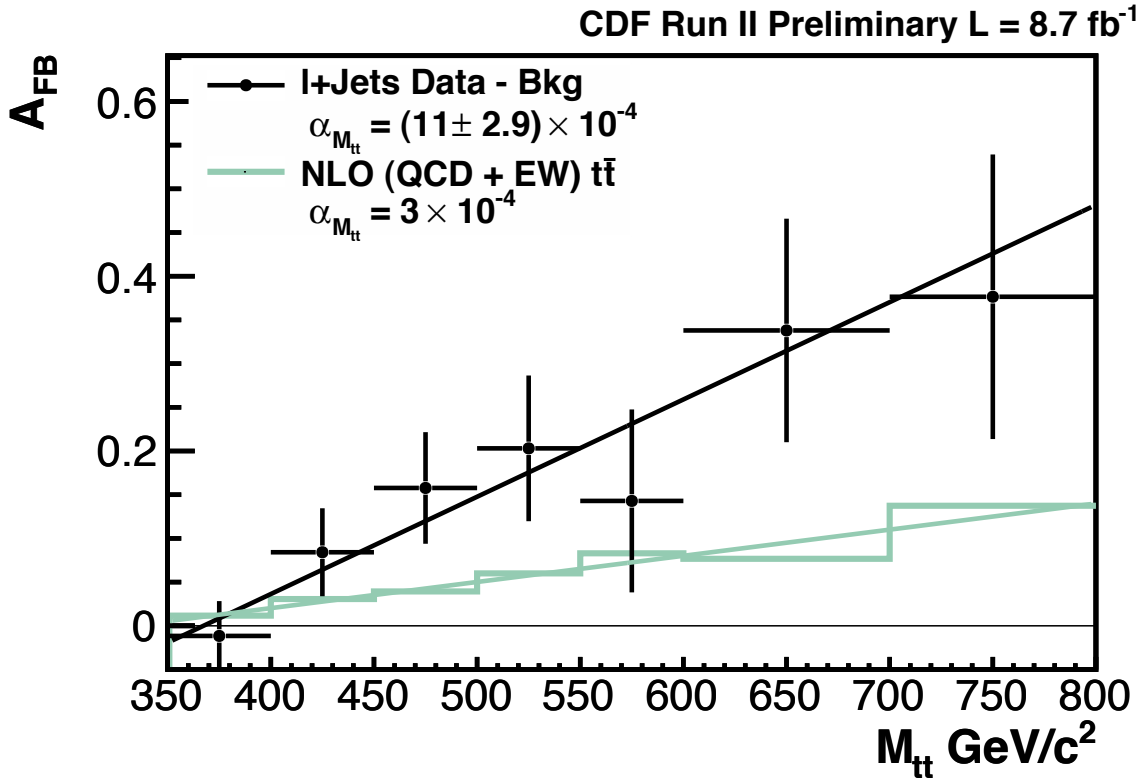
Rapidity-Dependent Differential A_{FB}



$$A_{FB}(|\Delta y|) = \frac{N(|\Delta y|) - N(-|\Delta y|)}{N(|\Delta y|) + N(-|\Delta y|)}$$

- Observed A_{FB} as a function of $|\Delta y|$ well-described by linear ansatz
  - Determine best-fit slope – easily compare data to prediction
  - χ^2/d.o.f. = 1.0, significant non-zero slope
  - Slope is not a specific theoretical parameter
    - Linear fit motivated by approximate linearity of SM prediction

Mass-Dependent Differential A_{FB}



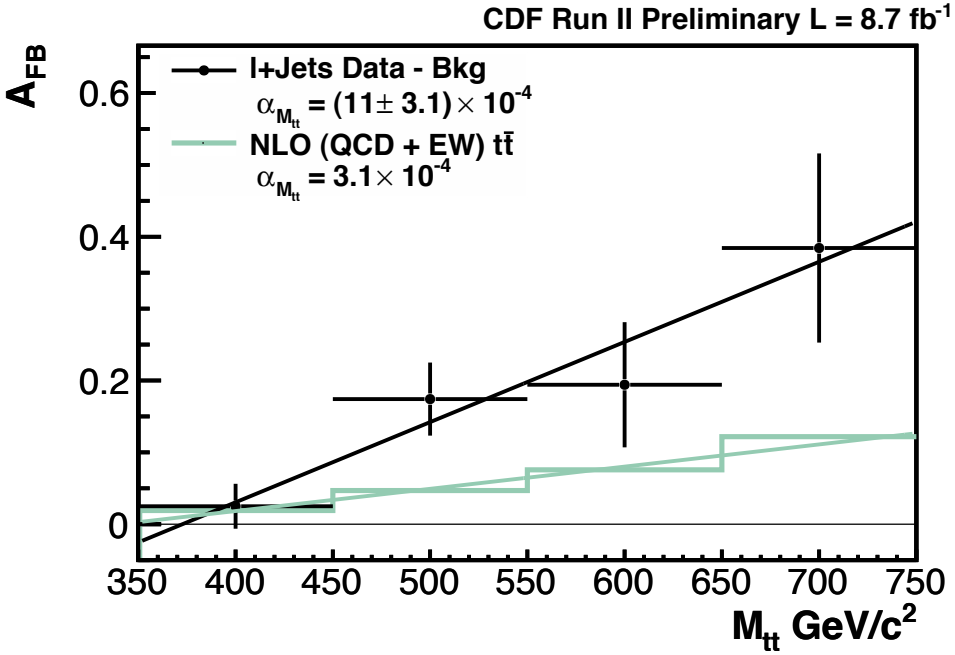
$$A_{FB}(M_{tt}) = \frac{N_F(M_{tt}) - N_B(M_{tt})}{N_F(M_{tt}) + N_B(M_{tt})}$$

- Determine A_{FB} as a function of M_{tt} with finer binning
- Again well-described by linear ansatz
  - Determine best-fit slope for data and prediction
  - χ^2/d.o.f. = 0.3

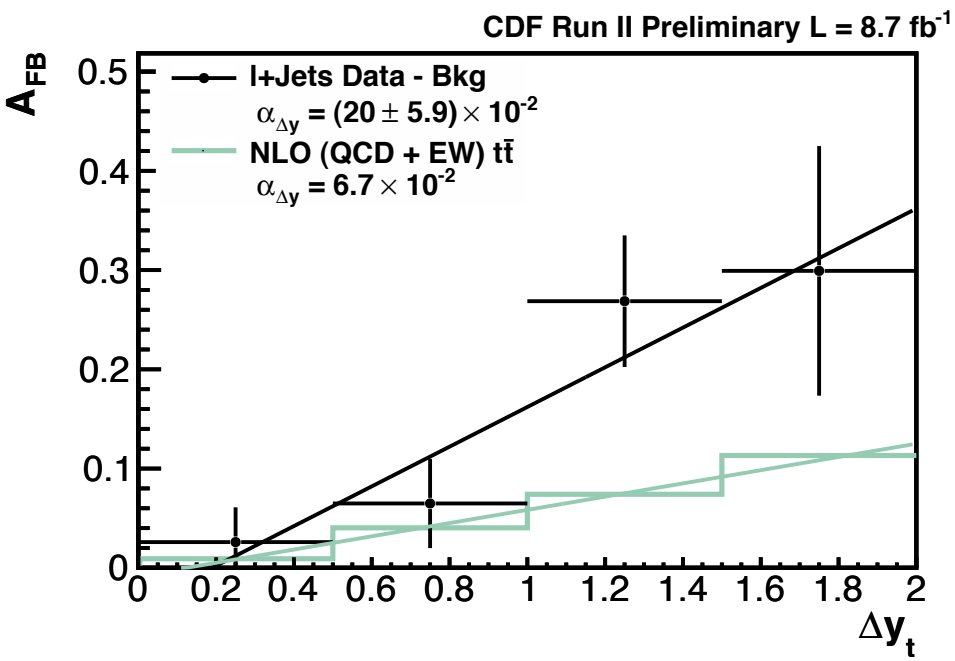
Determining the Significance

- How significant is the discrepancy between the POWHEG SM prediction and observed differential A_{FB}?
  - Evaluate at background-subtracted level – avoid complications from correction procedure
- Quantify by comparing best-fit slopes to find p-value
- Perform simulated experiments with Poisson fluctuations on nominal POWHEG prediction
  - No theory uncertainty included – compare specifically to the NLO POWHEG calculation (with EW corrections)
- p-value: fraction of experiments where $\alpha_{\mathrm{NLO}} \geq \alpha_{\mathrm{data}}$

P-VALUES FOR DATA SLOPES VS. PREDICTION



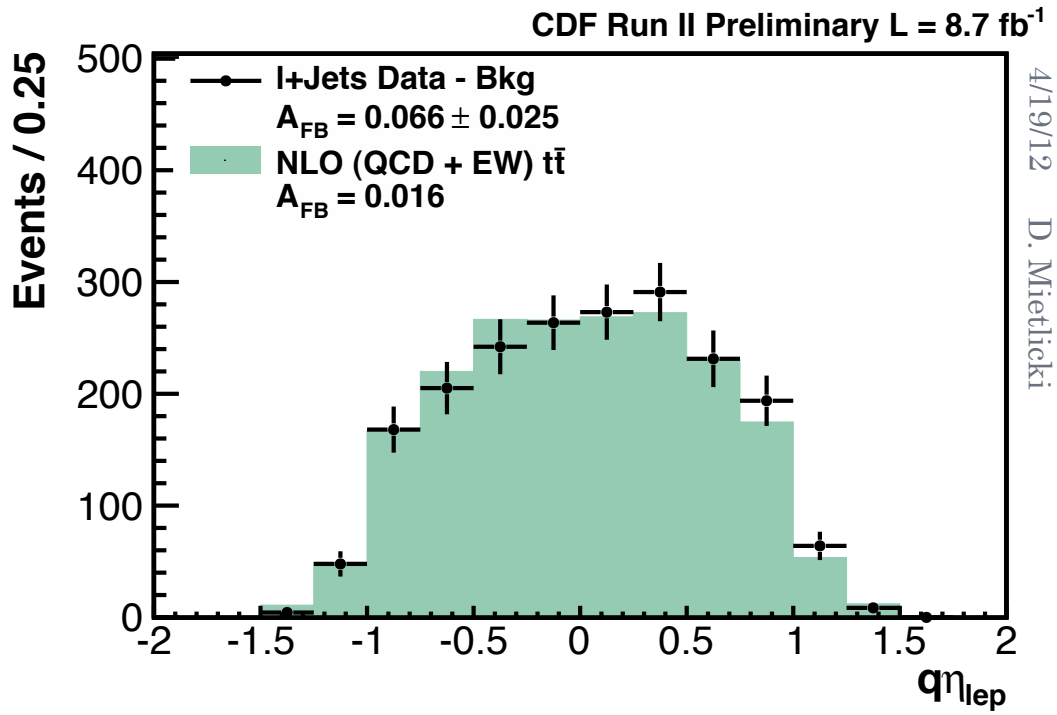
α (M_{tt}) p-value: 6.46×10^{-3}



α (Δ y) p-value: 8.92×10^{-3}

Background-Subtracted Leptonic A_{FB}

- Lepton allows independent measurement of the asymmetry
  - Direction of motion correlated with parent top quark
  - Measurement of lepton direction does not require event reconstruction
- Measure asymmetry in $q \times \eta_{lep}$

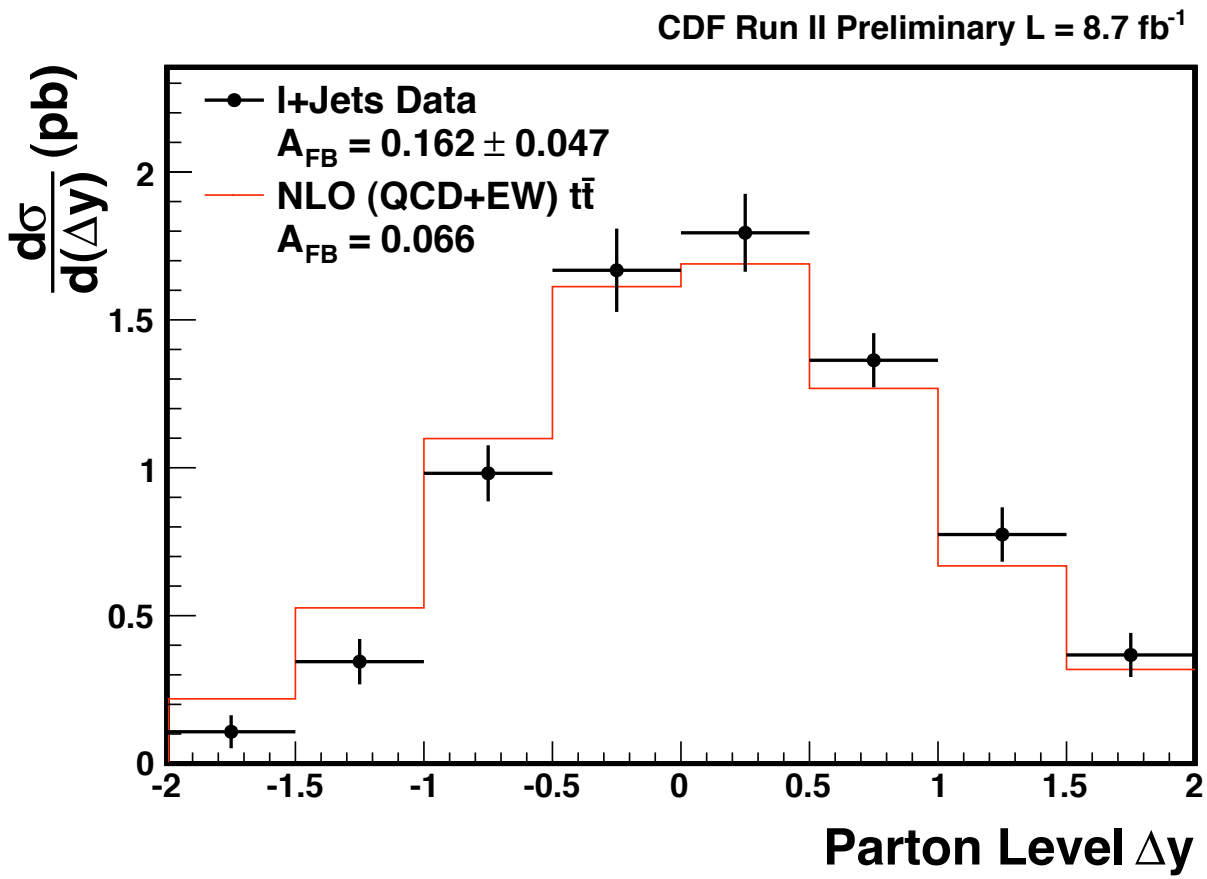


Sample	Predicted A_{FB} (%)	Observed A_{FB} (%)
Inclusive	1.6	6.6 ± 2.5
$M_{tt} < 450$ GeV/c^2	0.7	3.7 ± 3.1
$M_{tt} \geq 450$ GeV/c^2	3.2	11.6 ± 4.2

Correcting to the Parton Level

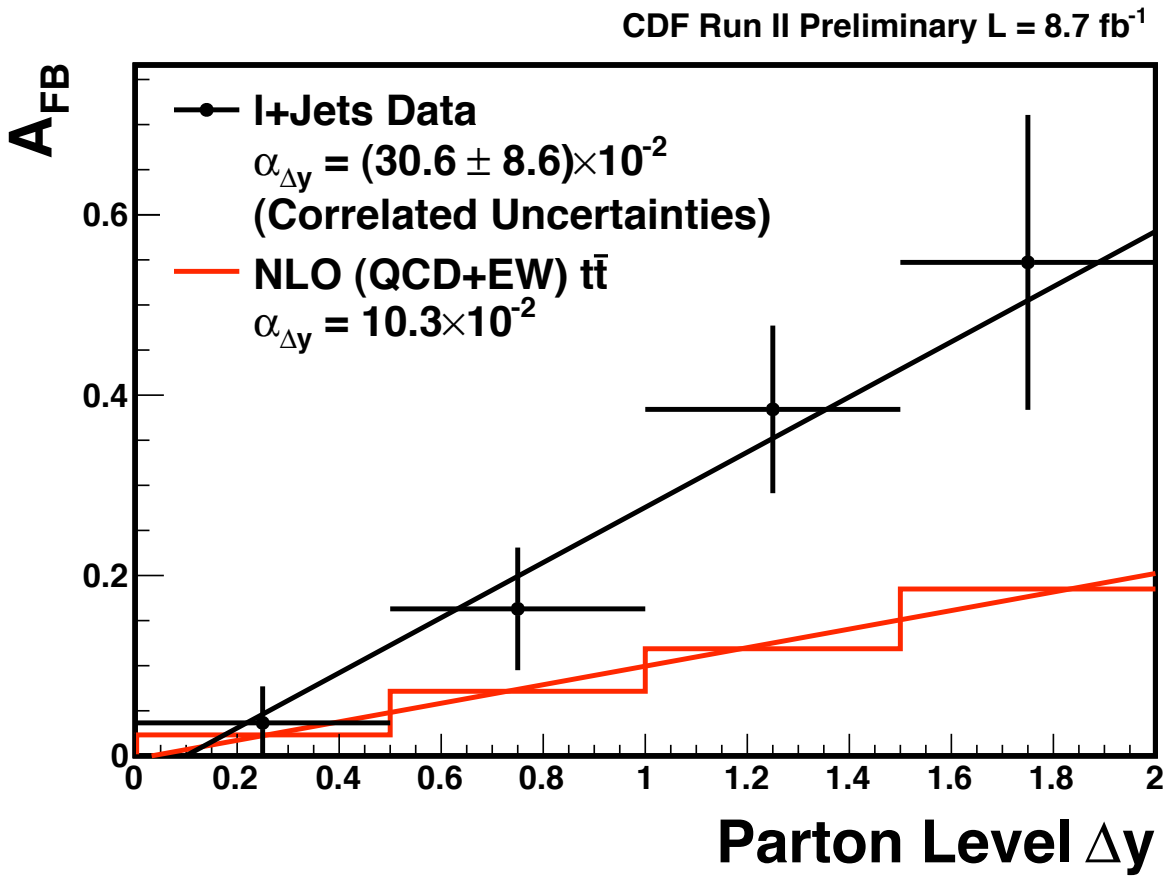
- Background-subtracted results use pure top sample
- Data cannot be directly compared to theoretical predictions
  - Limited acceptance
  - Finite detector resolution
  - Need full detector simulation to compare theory to background-subtracted data
- Correct to parton level in two steps:
  - 1. Unsmearing Correction (bin migration)
    - Regularized singular value decomposition unfolding algorithm
      - Höcker and Kartvelishvili, NIM A **372**, 496 (1996)
      - RooUnfold software package
  - 2. Acceptance Correction
    - Multiplicative correction to each bin based on POWHEG
- Test by correcting distributions created from SM and various BSM Monte Carlo samples
- Final results: differential cross-section and parton-level A_{FB} measurement

The Differential Cross-Section dσ/d(Δy)



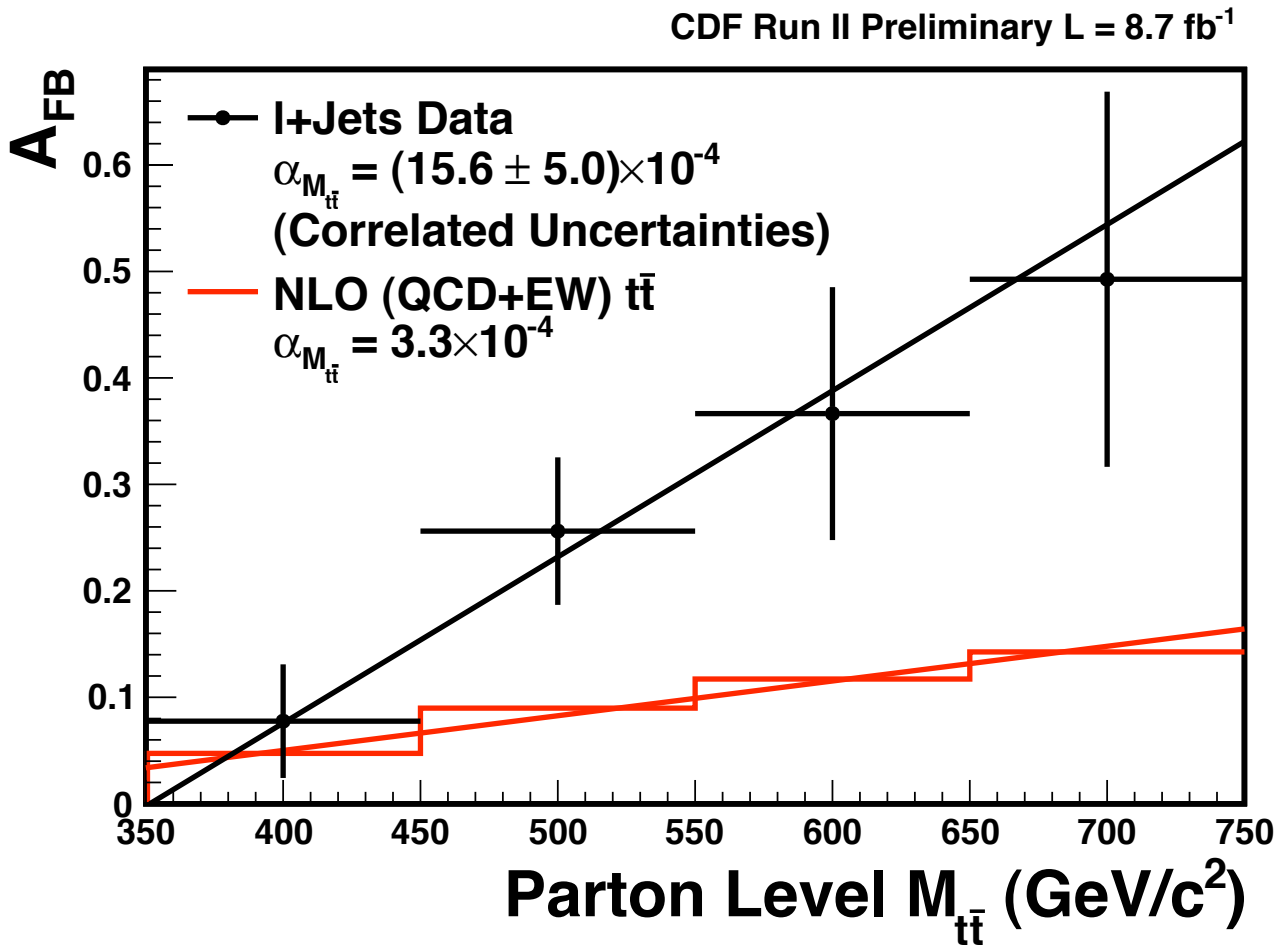
- Parton-level Δy distribution normalized to σ_{tot} = 7.4 pb
  - Result is dσ/d(Δy)
- Measured inclusive asymmetry is (16.2 ± 4.7)%
  - 3.4σ from null asymmetry
  - NLO prediction: 6.6%

Rapidity Dependence



- Linear ansatz applies also to parton level A_{FB} as a function of $|\Delta y|$
  - χ^2/d.o.f = 0.3
- After correction, bins are correlated – use full covariance matrix in performing the χ^2 fit

Mass-Dependent Differential A_{FB}



- Parton level A_{FB} vs. M_{tt} well-described by a line with slope larger than NLO prediction
  - χ^2/d.o.f = 0.1

CONCLUSIONS

- CDF has updated the top pair A_{FB} measurement using the full dataset
- Inclusive A_{FB} remains significant
  - Parton level $A_{FB} = (16.2 \pm 4.7)\%$
    - $3.4\,\sigma$ from no asymmetry, $2\,\sigma$ from NLO POWHEG prediction
- Mass and rapidity dependence from 5.3 fb^{-1} confirmed in full dataset at background-subtracted and parton levels
  - Behavior is well-described by a linear ansatz
    - Slopes are non-zero at $>3\,\sigma$ level
    - p-values (after background subtraction) relative to POWHEG of 6.46×10^{-3} for A_{FB} vs. M_{tt} and 8.92×10^{-3} for A_{FB} vs. $|\Delta y|$
- CDF has several additional A_{FB} analyses coming soon
  - Exploring new kinematic variables in the lepton+jets analysis
  - Analyzing the full CDF dataset in the dilepton channel
  - Measuring A_{FB} in bottom-antibottom pairs

Backup Slides

Sample Composition

- Top signal modeled with NLO POWHEG
- Electroweak backgrounds from Monte Carlo
- W+jets shape from Monte Carlo
- QCD shape from data
- W+jets and QCD normalizations determined from fit to the missing E_T spectrum
- 505 predicted background events
  - S:B ratio ~4:1

Source	Predicted Event Count, 8.7 fb^{-1}
W + Heavy Flavor	241 ± 78
Non-W (QCD)	98 ± 51
W + Light Flavor	96 ± 29
Single Top	33 ± 2
Diboson	19 ± 3
Z + Jets	18 ± 2
Total Background	505 ± 123
Top Pairs (7.4 pb)	2037 ± 277
Total Prediction	2542 ± 303
Data	2498

Reconstructing Top Pair Events

- Match observed jets to top decay products: χ^2-based kinematic fit to top-antitop hypothesis
  - $M_t = 172.5$ GeV/c^2
  - $M_W = 80.4$ GeV/c^2

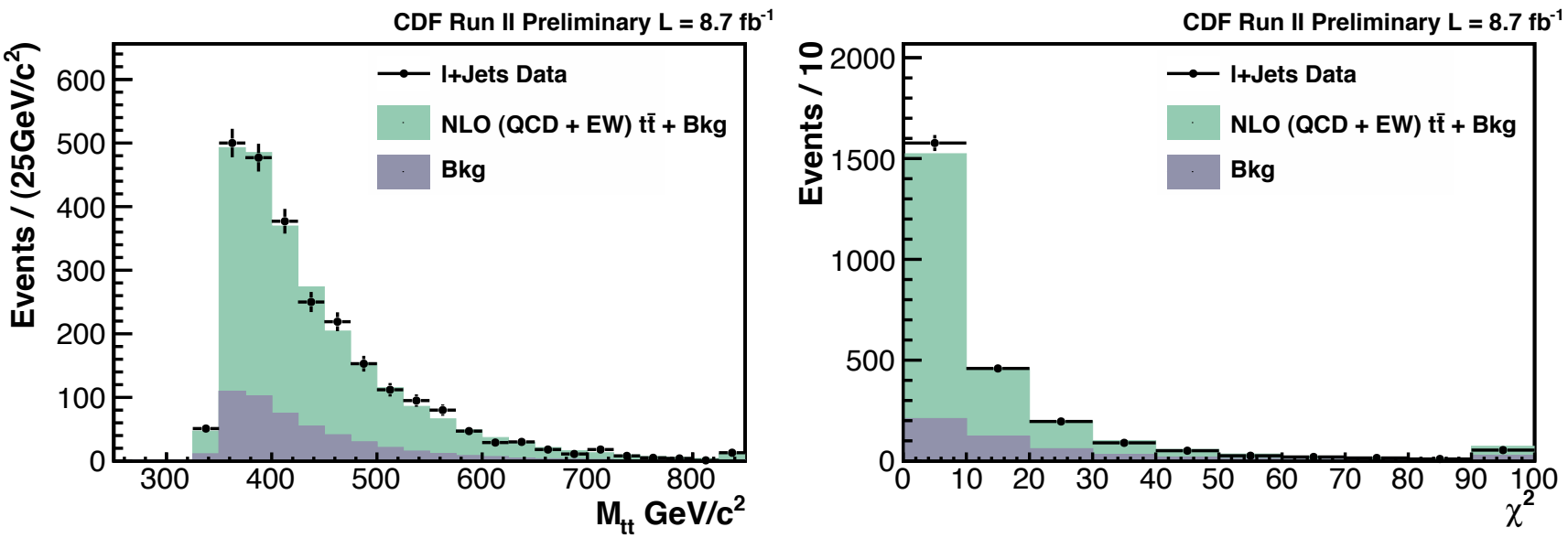
$$\chi^2 = \sum_{i=l,jets} \frac{(p_T^{i,fit} - p_T^{i,meas})^2}{\sigma_i} + \sum_{j=x,y} \frac{(p_j^{Unc.Energy,fit} - p_j^{Unc.Energy,meas})^2}{\sigma_j}$$

$$+ \frac{(M_{jj} - M_W)^2}{\Gamma_W^2} + \frac{(M_{l\nu} - M_W)^2}{\Gamma_W^2} + \frac{(M_{bjj} - M_t)^2}{\Gamma_t^2} + \frac{(M_{bl\nu} - M_t)^2}{\Gamma_t^2}$$

- Four leading jets enter the fit
- Measured energies float within uncertainties
- Choose solution with the smallest χ^2
- Determine top and antitop four-vectors from decay product momenta
- Lepton charge used to assign the charge of all final state objects

THE χ^2 AND M_{tt} DISTRIBUTIONS

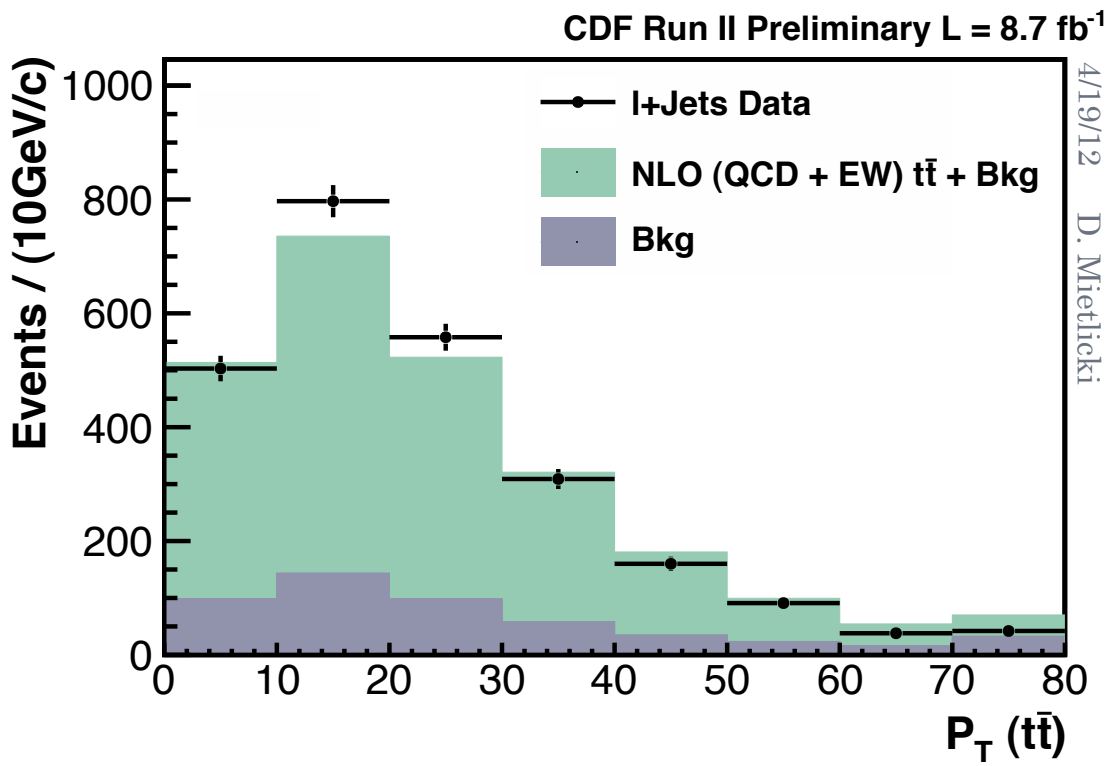
- M_{tt} and χ^2 of the kinematic reconstruction
  - Sensitive checks of reconstruction method
- Well-modeled by signal + background prediction
  - Even for events with large χ^2



Blue: background prediction
Green: NLO POWHEG signal
– Stacked with backgrounds
Black: observed data

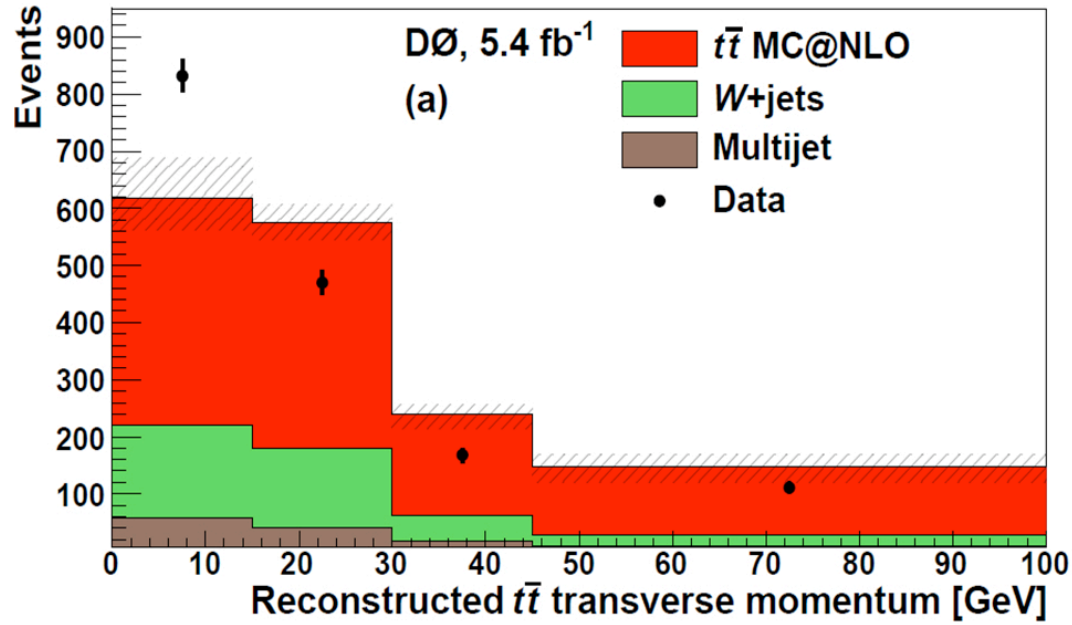
THE TOP PAIR P_T

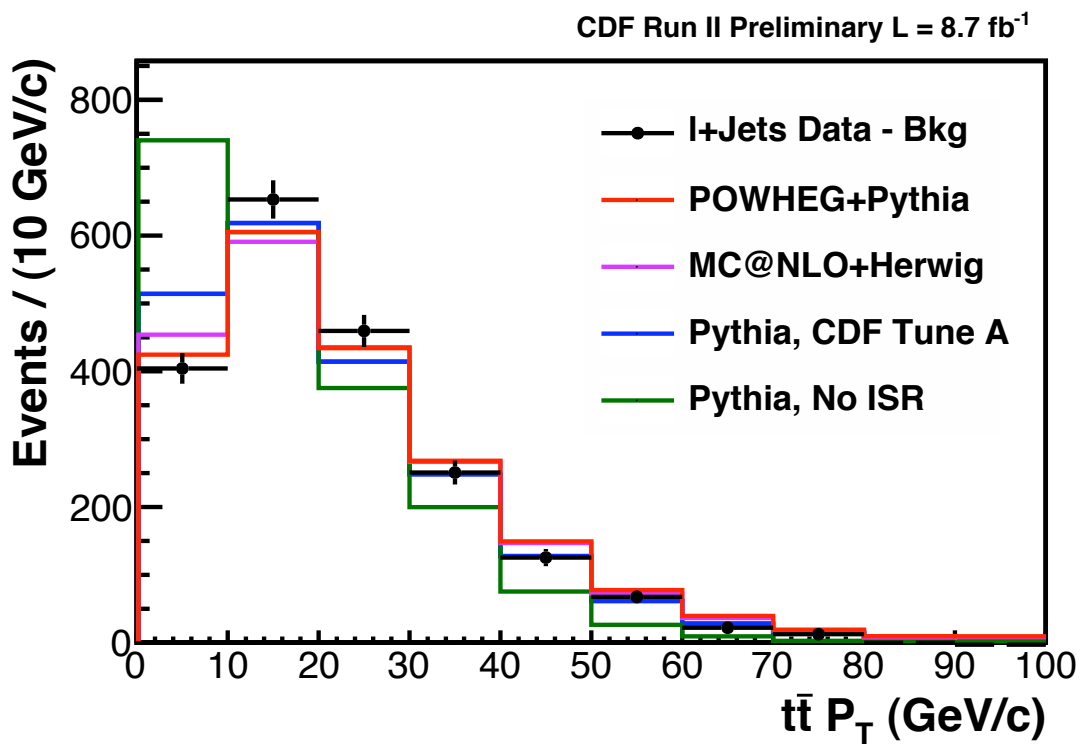
- Transverse momentum of top pair is a good check of background model, event reconstruction
  - Sensitive to soft jets
  - Correlated with A_{FB}
    - ISR/FSR give negative contribution to asymmetry
- Good agreement between data and NLO MC + background prediction



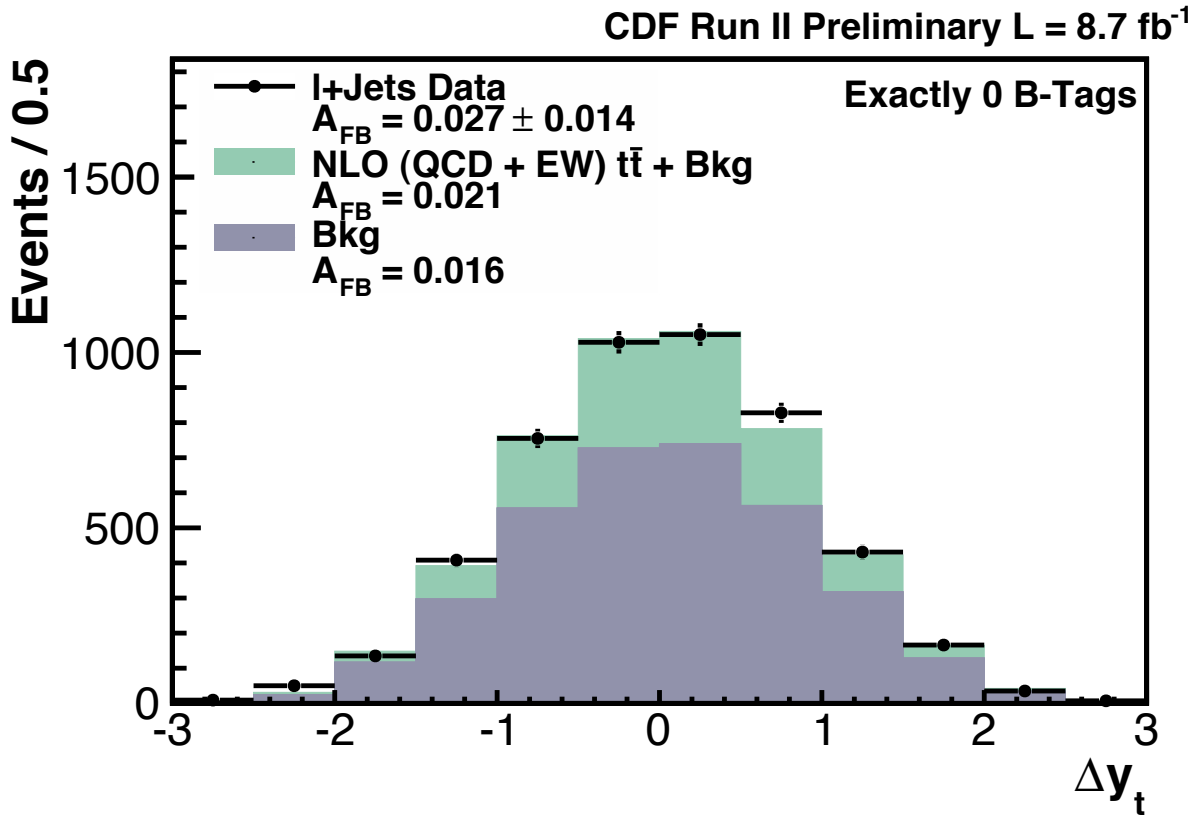
THE TOP PAIR P_T

- D0 5.4 fb-1 analysis observed mis-modeling at low P_T (top)
- CDF finds agreement with NLO predictions of POWHEG and MC@NLO (bottom)



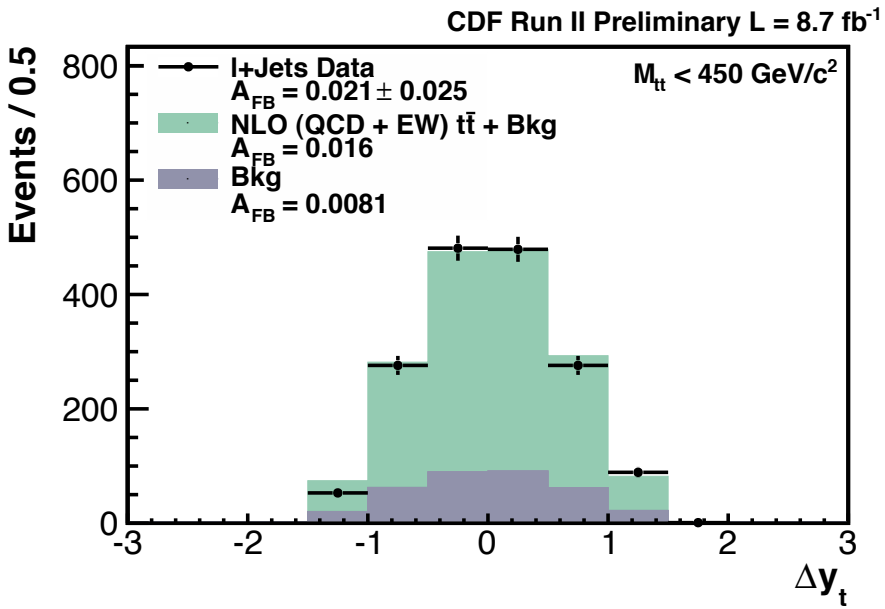


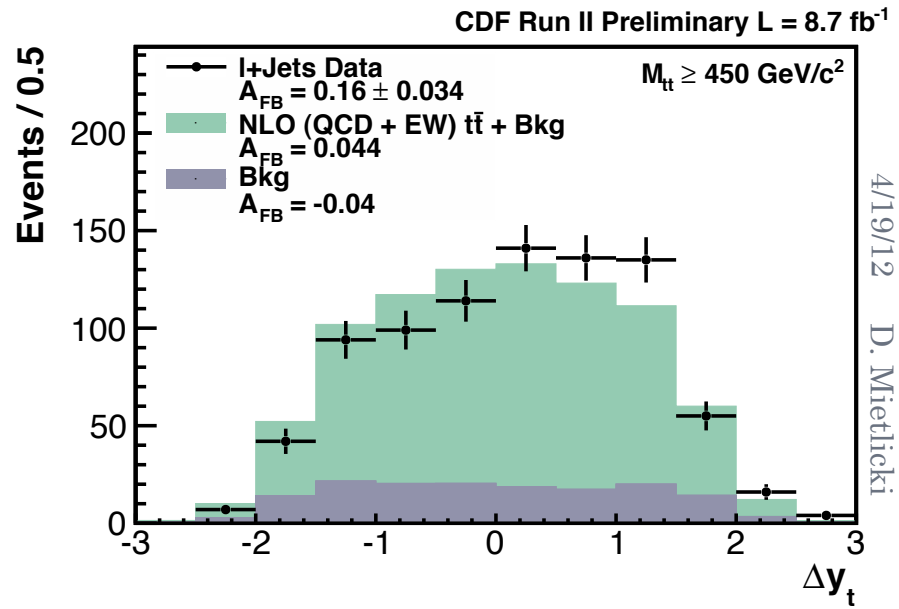
Δy in Events with No *b*-Tags



- Check background prediction in background-dominated region
- Events pass all selection requirements except they do not have any *b*-tagged jets
- Good agreement between data and expectation

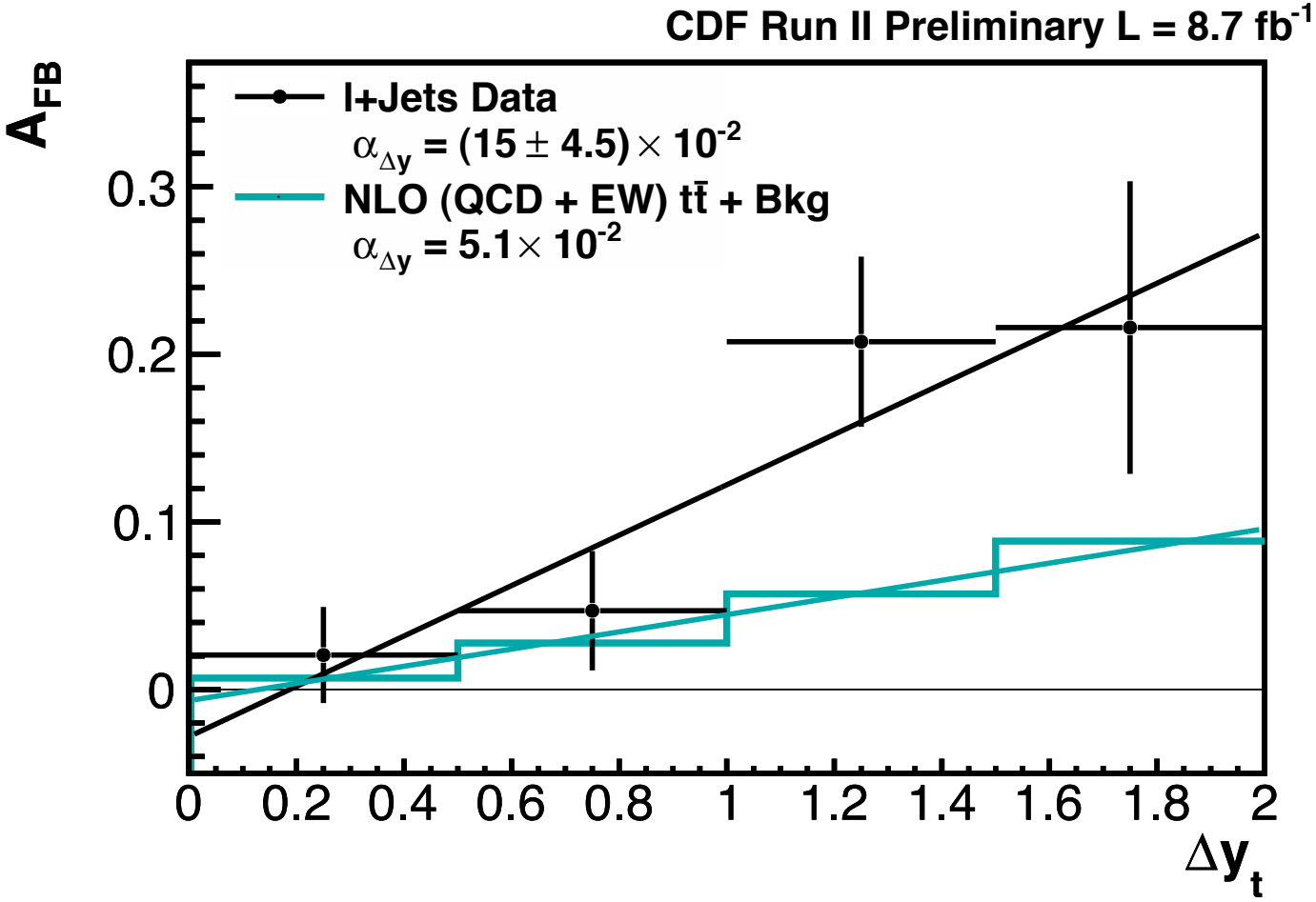
Reconstruction Level Δy at High and Low Mass





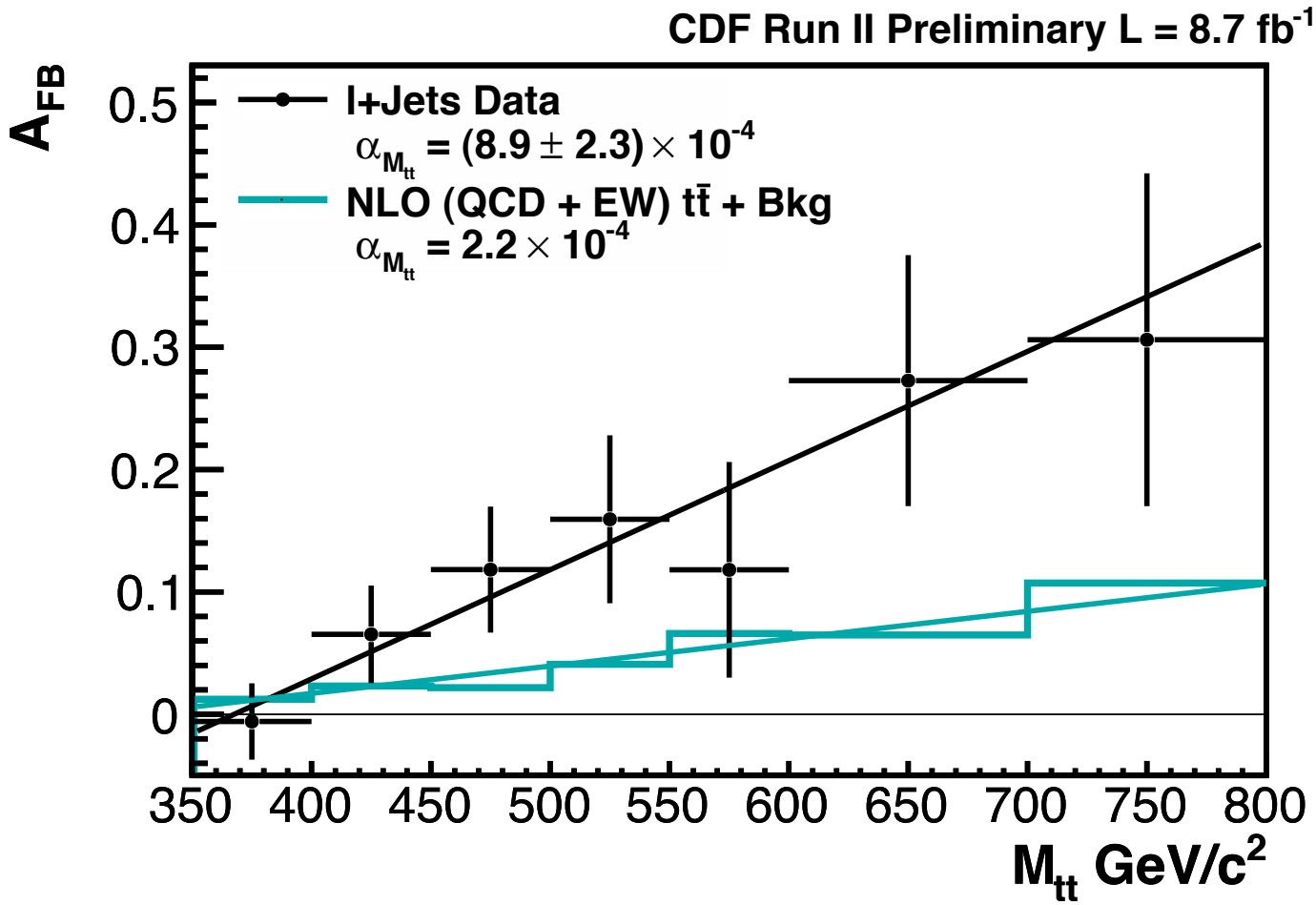
- Δy distribution for M_{tt} above and below 450 GeV/c^2
  - Cut-off defined in 5.3 fb^{-1} analysis
- Low mass consistent with expectation
- Large asymmetry at high mass: (15.5 ± 3.4)%
  - 4.5 σ from no asymmetry, 3.3 σ from prediction
  - Consistent in events with positive (15.5 ± 4.8)% and negative (15.6 ± 4.8)% leptons

Reconstruction Level Rapidity Dependence



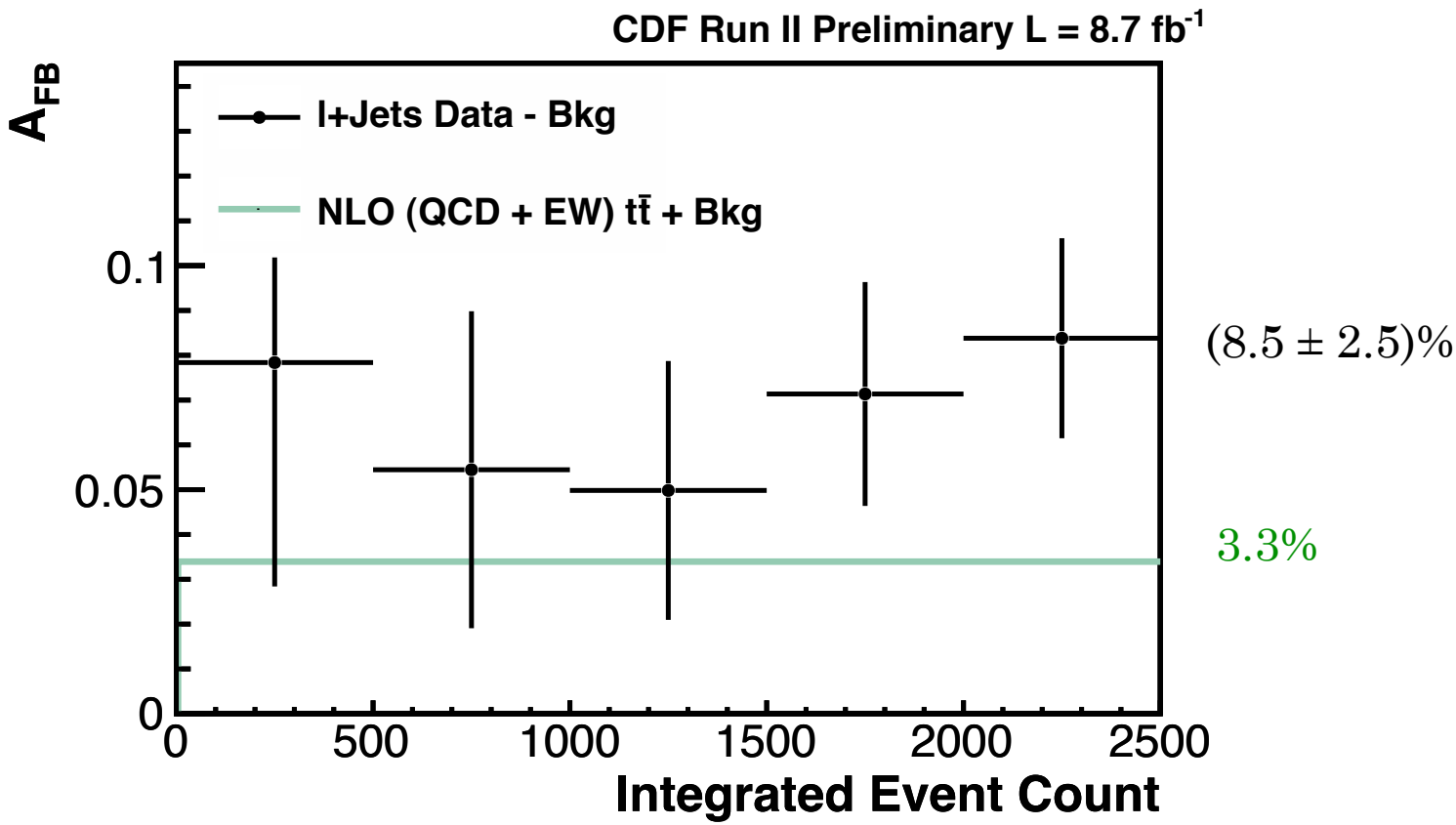
- Linear ansatz holds even at reconstruction level before any background subtraction
  - χ^2/d.o.f. = 1.1

Reconstruction Level Mass Dependence



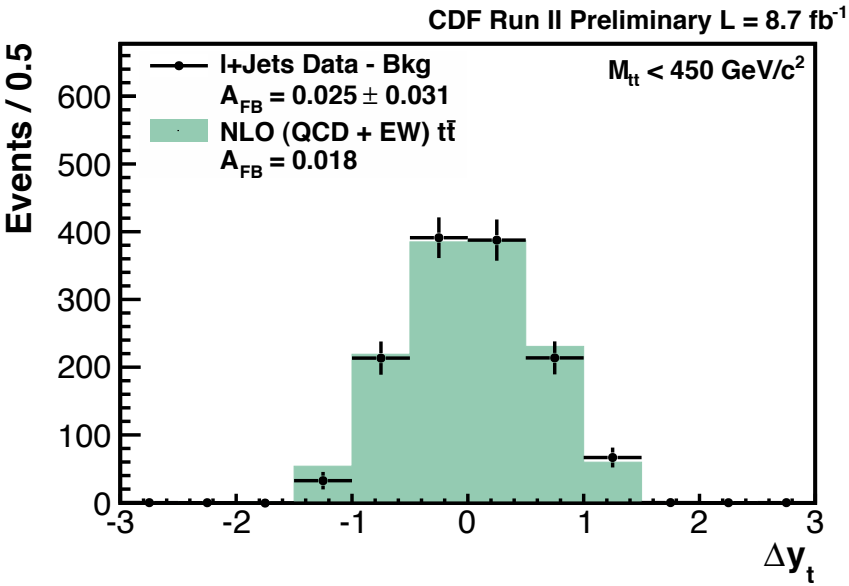
- A_{FB} as a function of M_{tt} at reconstruction level also well-described by linear ansatz
  - χ^2/d.o.f. = 0.2

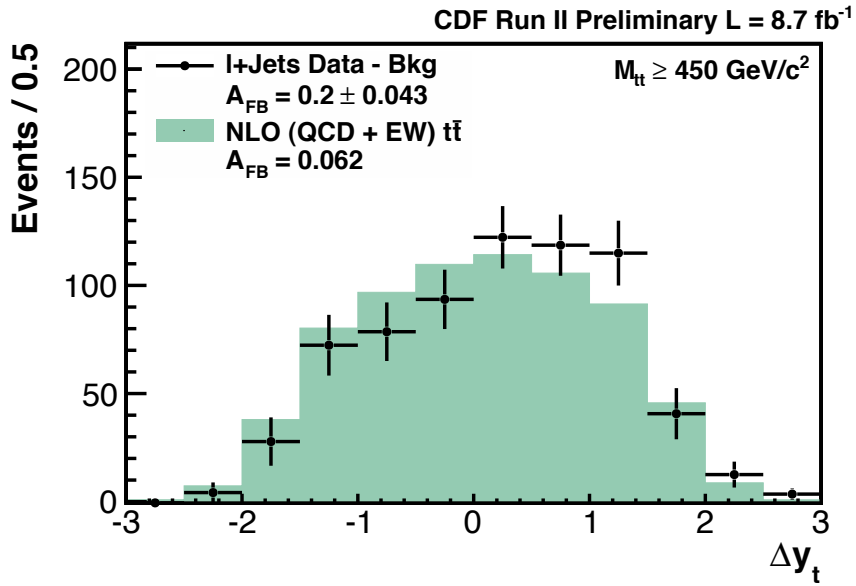
The Background-Subtracted A_{FB} Over Time



- Could the asymmetry result from a temporary detector effect, mis-calibration, etc.?
  - Measure A_{FB} as a function of the total number of observed events in the data sample
- A_{FB} constant within uncertainties through the entire course of Run II data taking

Background-Subtracted Δy at High and Low Mass





- Δy distribution for M_{tt} above and below 450 GeV/c^2
  - Cut-off defined in 5.3 fb^{-1} analysis
- Low mass distribution consistent with NLO prediction
- The large asymmetry predominantly arises at high mass – (19.8 ± 4.3)%
  - 4.6 σ from no asymmetry
  - NLO POWHEG predicts 6.2% at high mass

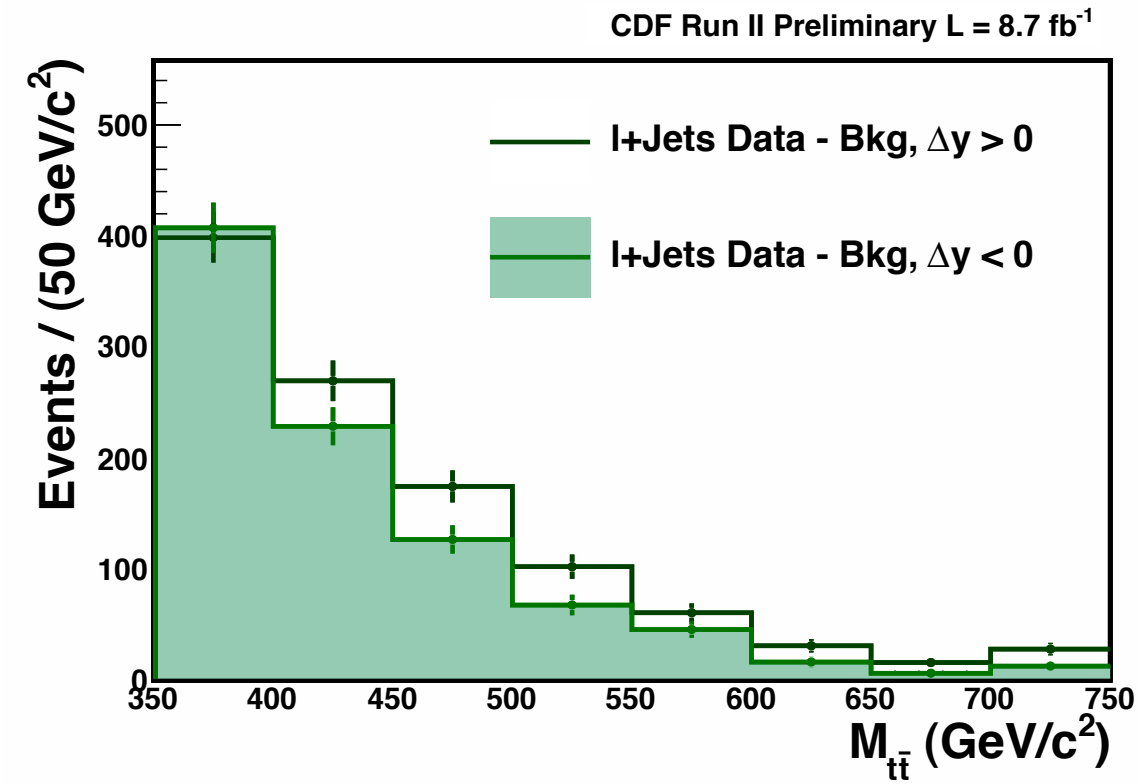
Comparison to Previous Background-Subtracted Mass-Dependent Results

Background -Subtracted A_{FB} (%)	D0 Lep+Jet, 5.4 fb^{-1}	CDF Lep +Jet, 5.3 fb^{-1}	Informal 5 fb^{-1} Combination*	CDF Lep +Jet, 8.7 fb^{-1}
$M_{tt} < 450$ GeV/c^2	7.6 ± 4.8	-2.2 ± 4.3	$2.1 \pm 3.2^*$	2.5 ± 3.1
$M_{tt} \geq 450$ GeV/c^2	11.5 ± 6.0	26.6 ± 6.2	$18.6 \pm 4.3^*$	19.8 ± 4.3

- Two-bin mass dependence statistically consistent among the D0 measurement and both CDF results
  - Very good agreement of new CDF data with simple weighted average of previous CDF and D0 results

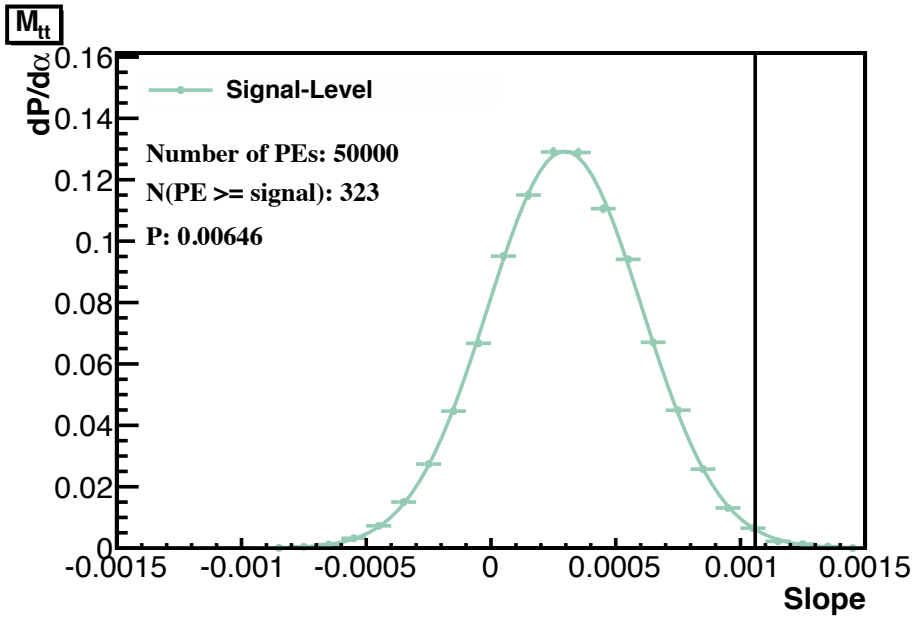
*NOT an official result – just a simple weighted average of the D0 and CDF lepton+jets results

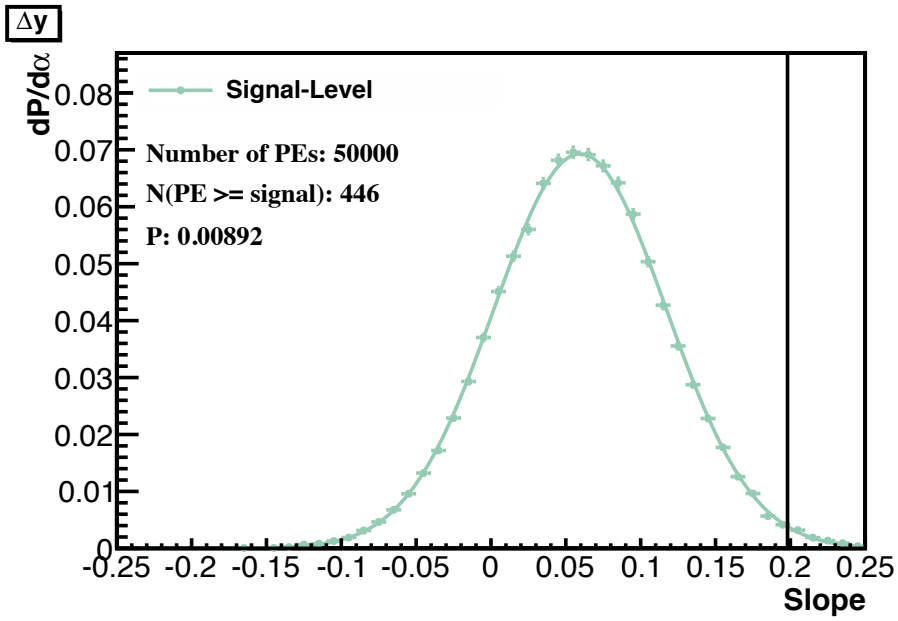
The Invariant Mass Distribution for Forward and Backward Events



- Compare the M_{tt} distributions for events with positive and negative Δy
  - Approximately equal at lowest masses, but excess of forward events at higher mass

P-VALUE DETERMINATION





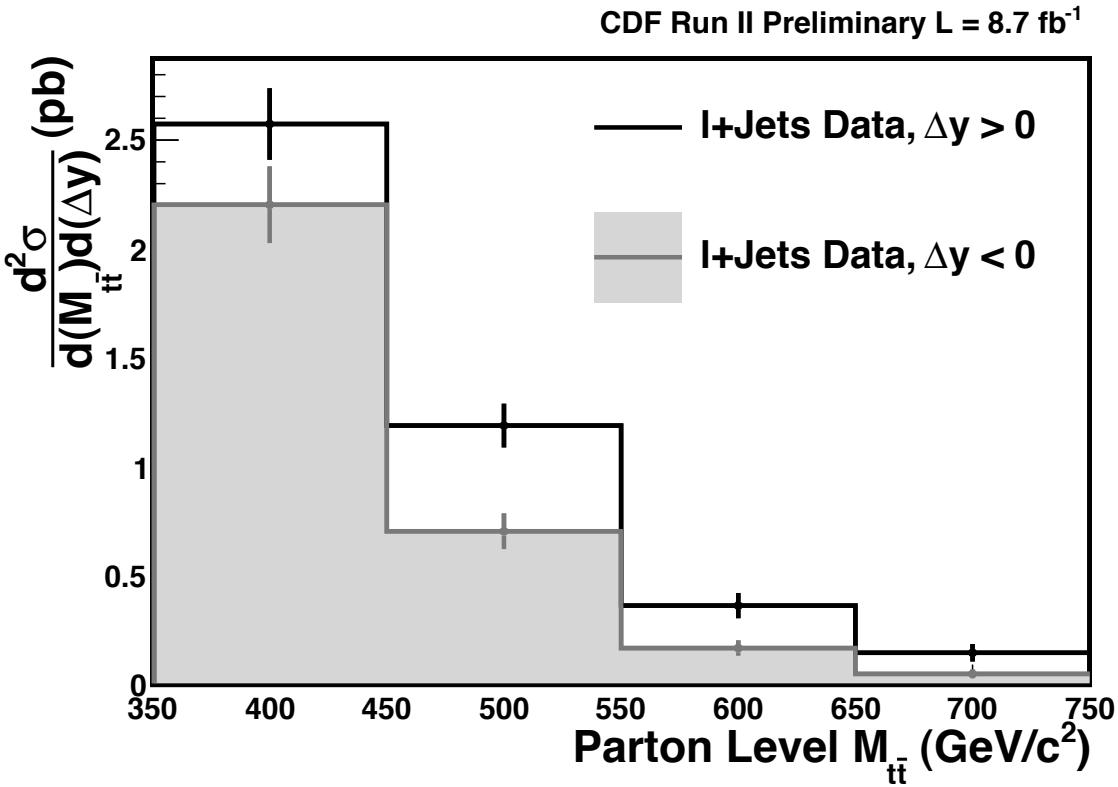
- Plots show slopes for A_{FB} vs. M_{tt} (top) and A_{FB} vs. Δy (bottom) measured from fluctuations on NLO prediction at the background-subtracted level
  - p-value: fraction of experiments in which $\alpha_{NLO} \geq \alpha_{Data}$

Systematic Uncertainties

- Correction procedure introduces systematic uncertainties related to the signal model, in addition to the background uncertainties discussed previously
  - Total is small compared to the statistical uncertainty

Source	Uncertainty (%)
Background Shape	1.4
Background Normalization	1.1
Parton Showering	1.0
Jet Energy Scale	0.5
Initial/Final State Radiation	0.5
Color Reconnection	0.1
Parton Distribution Functions	0.1
Correction Procedure	0.3
Total Systematic Uncertainty	2.2
Statistical Uncertainty	4.1
Total Uncertainty	4.7

Mass Distributions for Forward and Backward Events



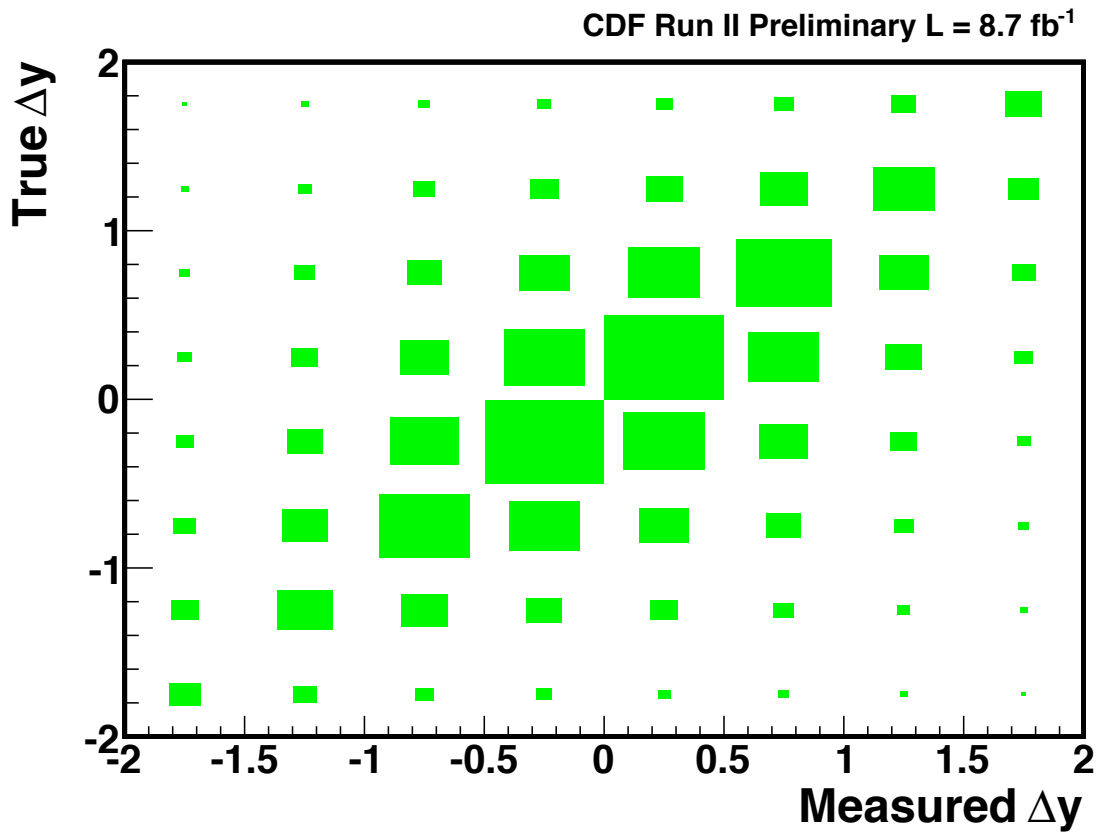
- Parton-level M_{tt} distributions for events with positive and negative Δy
- These distributions are then combined to find the differential asymmetry

Comparison to the 5 fb^{-1} Results

Selection	Prediction	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

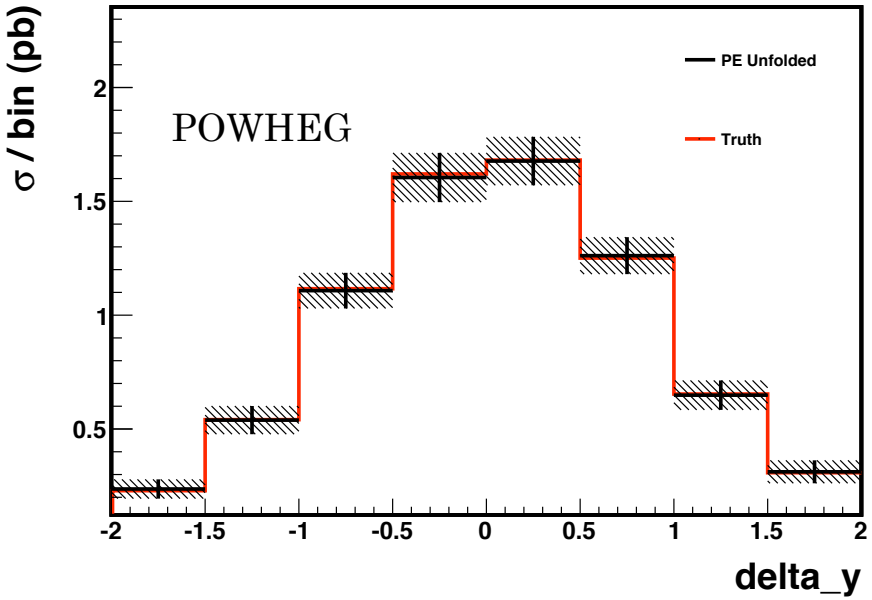
- Parton level asymmetries in two bins of M_{tt} and $\lvert \Delta y \rvert$ for direct comparison to previous results

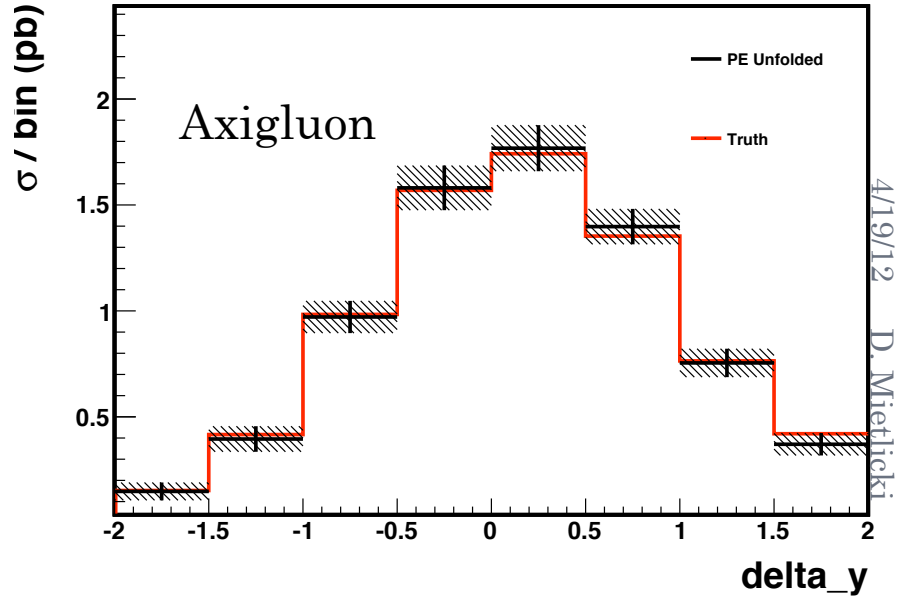
THE DETECTOR RESPONSE MATRIX



- Plot shows detector response matrix used for regularized unfold of Δy
  - Box sizes proportional to bin contents
  - Does not include acceptances (acceptance matrix is diagonal, simply a multiplicative correction to each bin)
- Predominantly diagonal (good resolution) and symmetric (no bias for forward or backward events)

Bias Tests





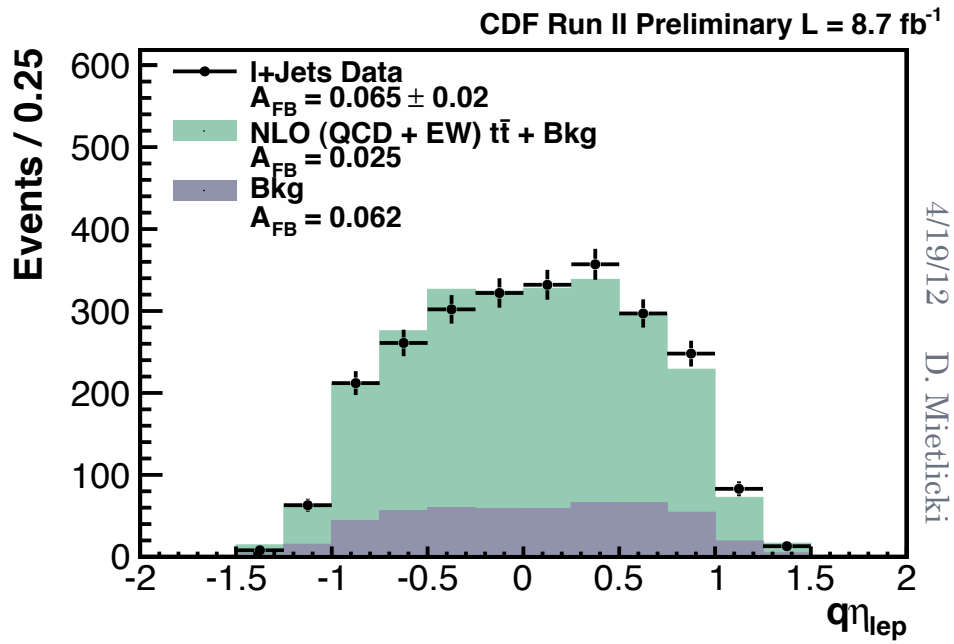
Inclusive A_{FB}	*Value*
True A_{FB}	5.2
Average Meas. A_{FB}	5.5
Average Uncertainty	4.0

Inclusive A_{FB}	*Value*
True A_{FB}	15.6
Average Meas. A_{FB}	16.2
Average Uncertainty	3.9

- Check the correction procedure in simulated experiments based on Monte Carlo samples
- Plots show average corrected results compared to true MC distributions in POWHEG (left) and an example new physics (axigluon) sample (right)

The Leptonic Asymmetry

- Could A_{FB} be an artifact of the reconstruction?
- Lepton allows independent measurement of the asymmetry
  - Direction of motion correlated with parent top quark
  - Measurement of lepton direction does not require event reconstruction
- Find asymmetry in $q \times \eta_{lep}$
- A_{FB} exceeds signal + background prediction
  - Significance similar to that of Δy A_{FB}



Sample	Predicted A_{FB} (%)	Observed A_{FB} (%)
Inclusive	2.5	6.5 ± 2.0
M_{tt} < 450 GeV/c^2	2.3	4.7 ± 2.5
M_{tt} ≥ 450 GeV/c^2	3.3	10.1 ± 3.4