Measurements of the Top Quark Charge Asymmetry at CDF

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Outline

- A little about the Top Quark at the Tevatron
  - *What is A_{FB}? How we measure it and why we care*
  - Standard Model Predictions
- Reconstructing tops/anti-tops and "Raw" Measurements of A_{FB} in both Lepton+Jets and Dilepton events
  - Raw Asymmetry results
- Checks: *"Is it real? Should I take this seriously?"*
- Going beyond the Raw measurement: *"What do inquiring Minds Want to Know?"*
  - Corrected A_{FB}
  - Differential Measurements of A_{FB}
- Summary and Conclusions

CDF Public Notes

- CDFNote 10436: Dileptons
- CDFNote 10774: Lepton+Jets
- CDFNote 10807: Differential Measurements

Top Quark and the Tevatron

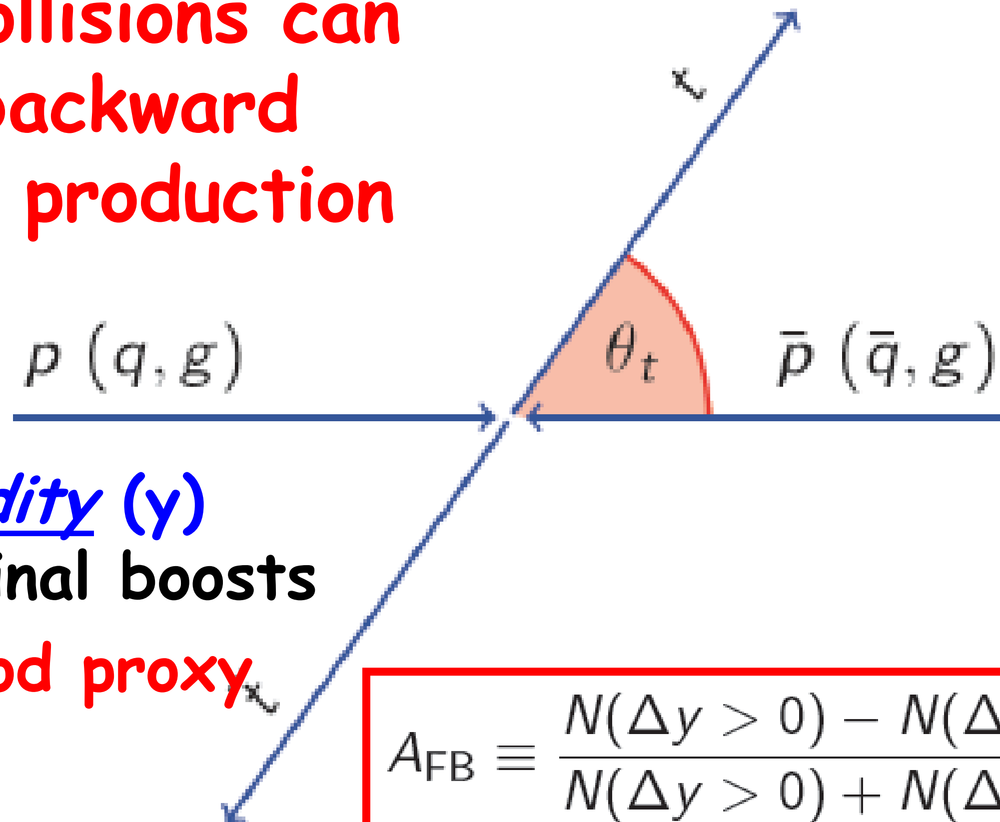
- "*Just the facts Ma'am*"
- Heaviest of the known particles
  - Mass ≈172.5 GeV/c^2
- Considering top quark pairs produced at the Fermilab Tevatron
  - Sqrt(s)=1.96 TeV
  - Just completed its data taking phase
  - Collected 8.7 fb^{-1} of data useful for these analyses
  - Cross section ≈7.5 pb
    - →Total of about 65k produced
    - →Identify and study about 3,000

First things first…

- *What is A_{FB}?*
- *How do we measure A_{FB}?*
- *Why do we care?*
  - Standard Model Predictions
  - Possible New Physics Models

What are A_{FB} and ΔY?

In proton-antiproton collisions can measure the forward-backward asymmetry (A_{FB}) in the production angle



Transform from Θ_t to *rapidity* (y)

Invariant under longitudinal boosts

Rapidity difference is a good proxy for production angle

$$A_{FB} \equiv \frac{N(\Delta y > 0) - N(\Delta y < 0)}{N(\Delta y > 0) + N(\Delta y < 0)}$$

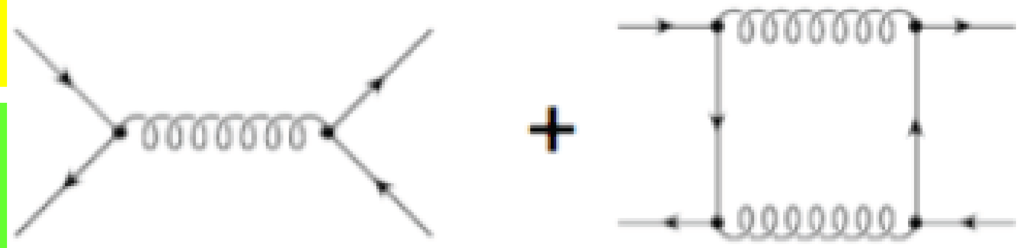
$$\text{Measure } \Delta y = y_t - y_{\bar{t}}, \text{ where } y = \frac{1}{2} ln\left(\frac{E+p_z}{E-p_z}\right)$$

Note: y doesn't have the usual geometric angle many of us are used to.
At hadron colliders we usually use pseudo-rapidity which assumes m=0
→ Here *E* and *p* not close to equal because of the top mass

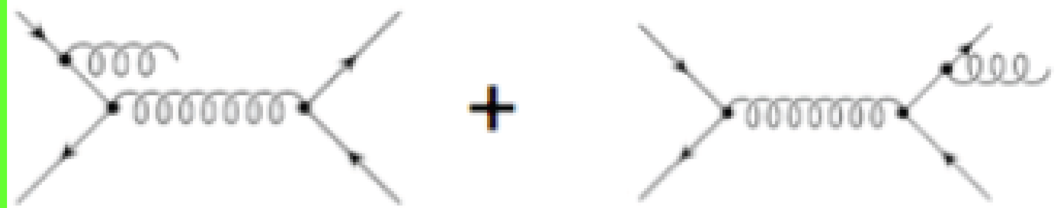
A_{FB} in the Standard Model

- Standard Model has no asymmetry at LO
- NLO has interference terms that give a small asymmetry
- Some uncertainty regarding theory predictions
  - Use POWHEG central value and a 26% correction for EWK contributions

Born + Box Interference
Positive Contribution to A_{FB}



ISR/FSR Interference
Negative Contribution to A_{FB}



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

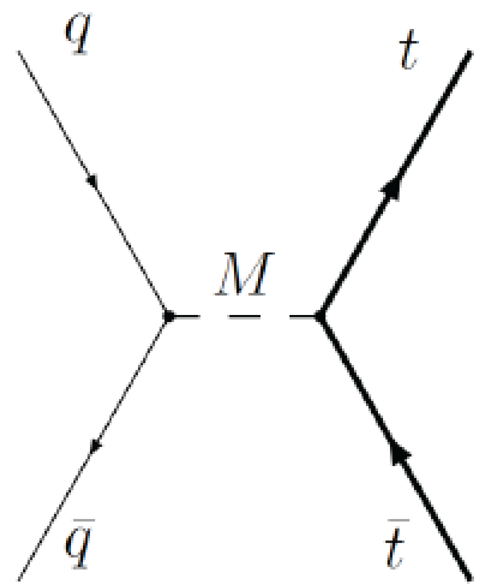
POWHEG: JHEP **0709**, 126 (2007)

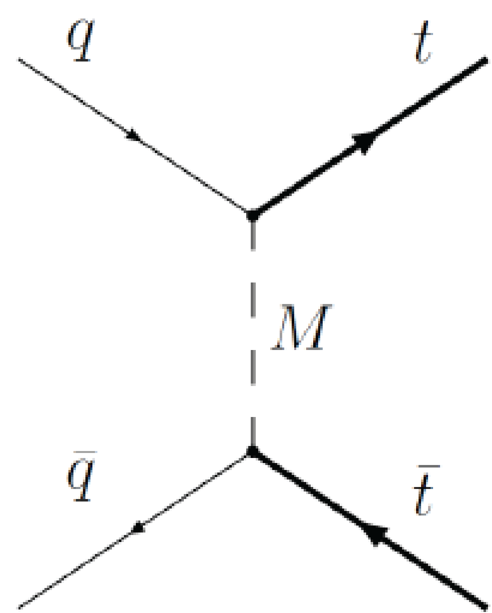
EW Corrections: Phys. Rev. D 84, 093003 (2011); JHEP **1201**, 063 (2012); arXiv:1201.3926[hep-ph]

Examples of New Physics That could give a Large A_{FB}

Two main classes of models

- S-channel mediator
  - e.g. axigluon
- T-channel flavor changing mediator
  - e.g. W' or Z'



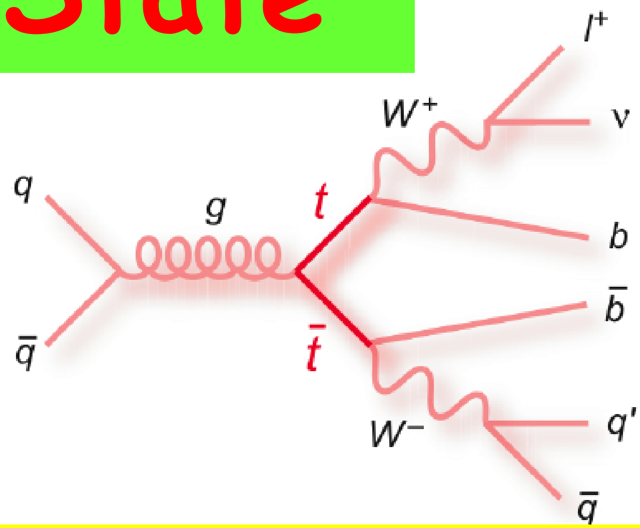


Although many of these have strong constraints, they provide a good model for searches

For a review see:
M. Gresham, I.-W. Kim and K. Zurek,
Phys. Rev. D83 114027 (2011)

Selecting Top Quark Events

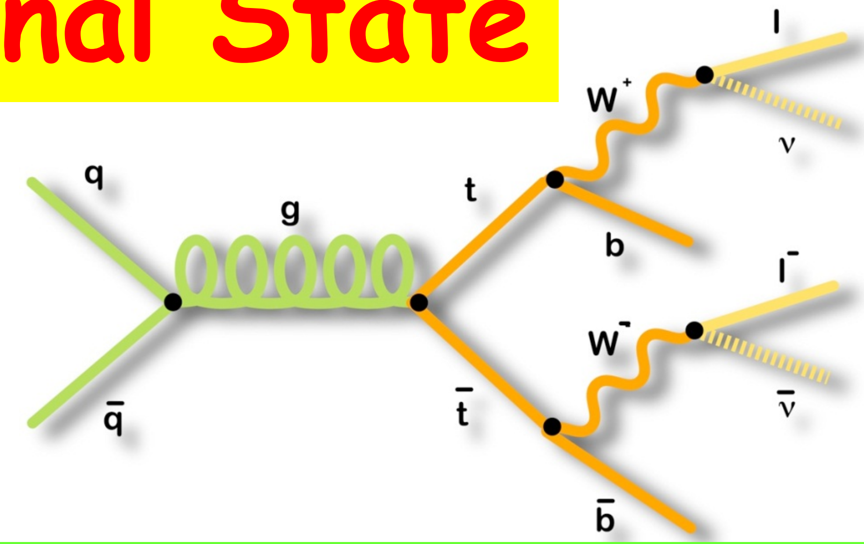
Lepton+Jets Final State



- 1 reconstructed lepton
- Missing transverse energy
- ≥4 jets (1 *b*-tag)
- ΣE_T > 220 GeV

Bigger branching fraction, more final state particles to measure, bigger backgrounds

Dilepton Final State



- 2 reconstructed leptons
- Missing transverse energy
- ≥2 jets
- ΣE_T > 200 GeV
- Higher purity sample, but smaller branching fraction, two leptons have better angles, but two neutrinos cause reconstruction ambiguities

Events Observed and Expected from Backgrounds

Lepton+Jets 8.7 fb^{-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

Dilepton 5.1 fb^{-1}

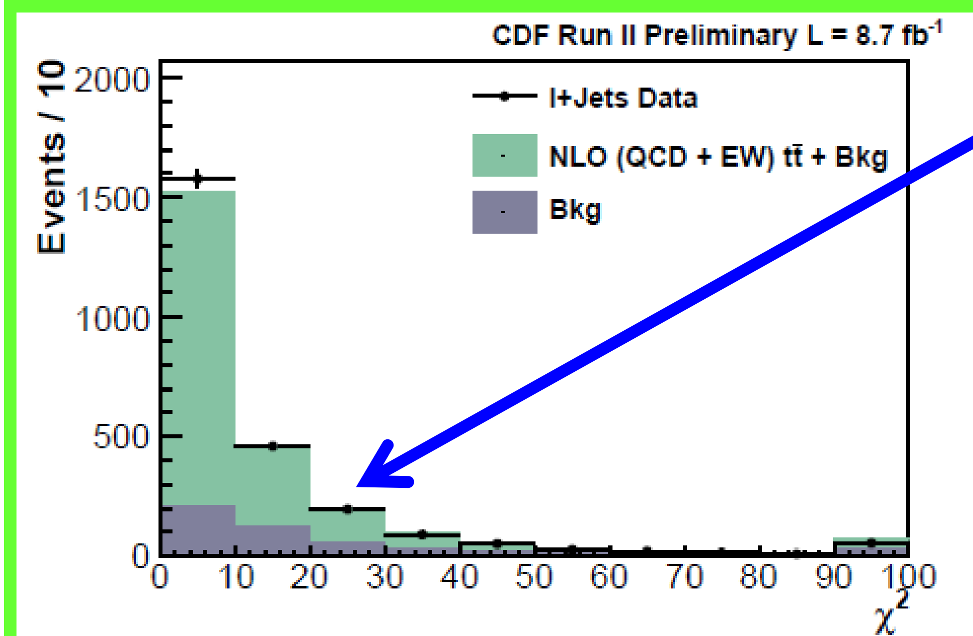
Process	Events
WW	11.7 ± 2.4
WZ	3.5 ± 0.6
ZZ	2.3 ± 1.8
$W\gamma$	0.4 ± 0.4
$DY \rightarrow \tau\tau$	12.3 ± 2.2
$DY \rightarrow ee + \mu\mu$	22.4 ± 3.2
Fakes	34.3 ± 14.7
$t\bar{t}$	237.1 ± 11.3
Total	324.0 ± 28.3
Data	334

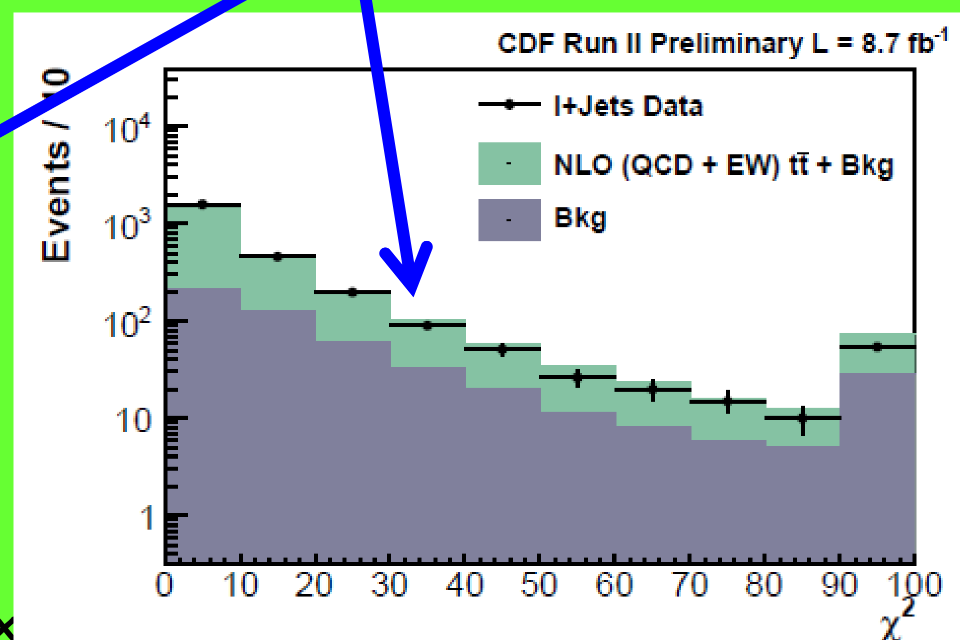
Excellent agreement Fairly pure samples

Reconstructing tops and anti-tops as well as their kinematics

- Reconstruct full $t\bar{t}$ system kinematics using a fitter
- Constrain to measured W mass and top masses
- Let reconstructed objects float in fitter within resolution
- Deal with ambiguities by taking best fit of matching to parton level
- Lots of things can go wrong, but this shows that things we can't fix are well understood

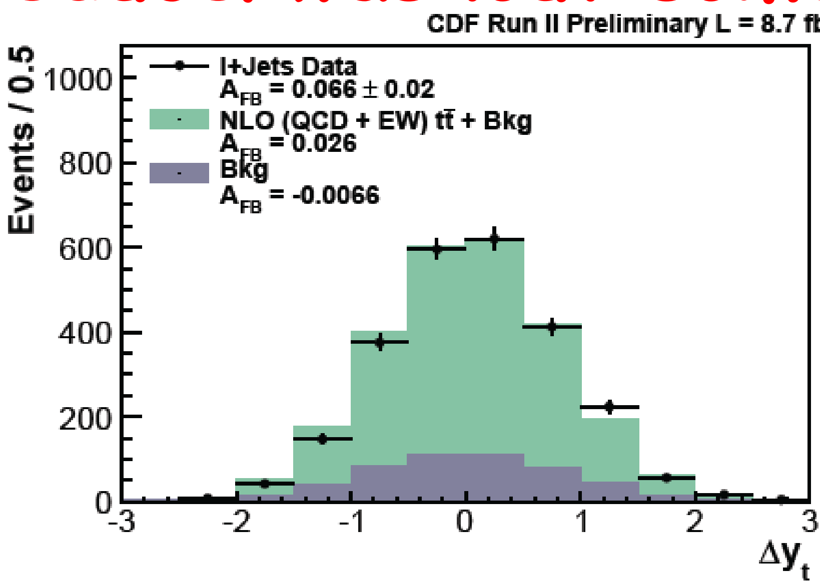
Results from Lepton+Jets

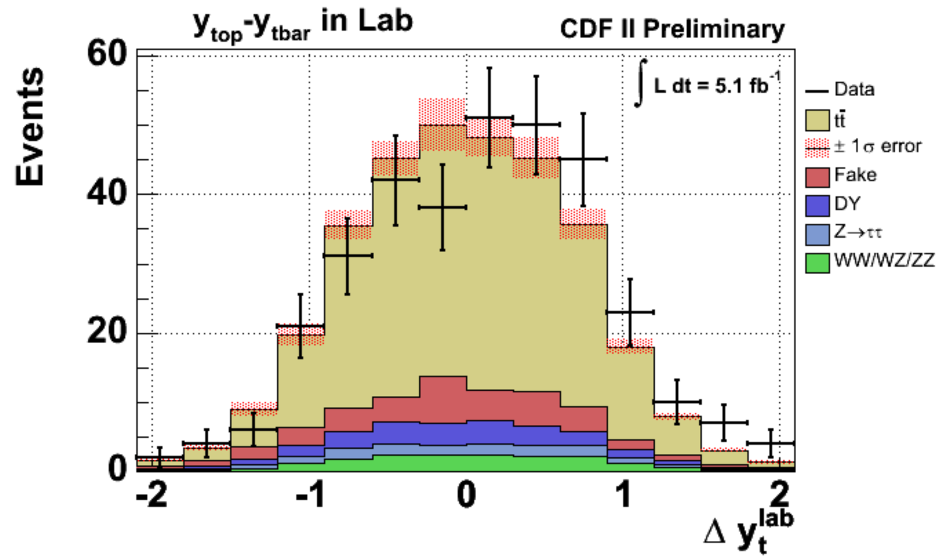




Raw Asymmetry

Detector and measurement effects reduce/washout some of the overall asymmetry





Lepton+Jets

A_{FB} pred = 2.6%

A_{FB} data = (6.6±2)%

Dileptons

N.B: MC for $t\bar{t}$ prediction uses LO only

A_{FB} pred = (-2±2)%

A_{FB} data = (14±5)%

Answers inconsistent with A_{FB}=0 at 3σ, also inconsistent with SM

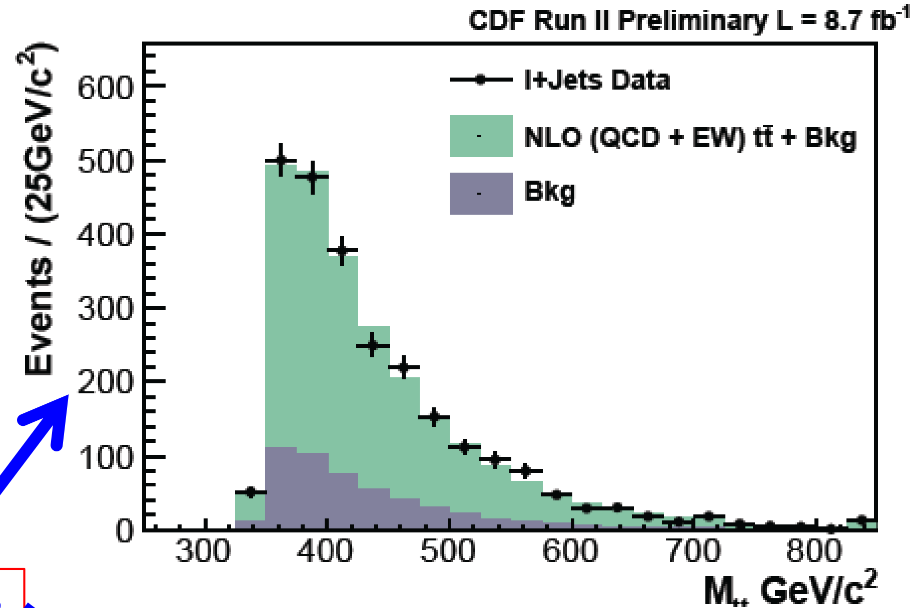
Problems with the modeling?

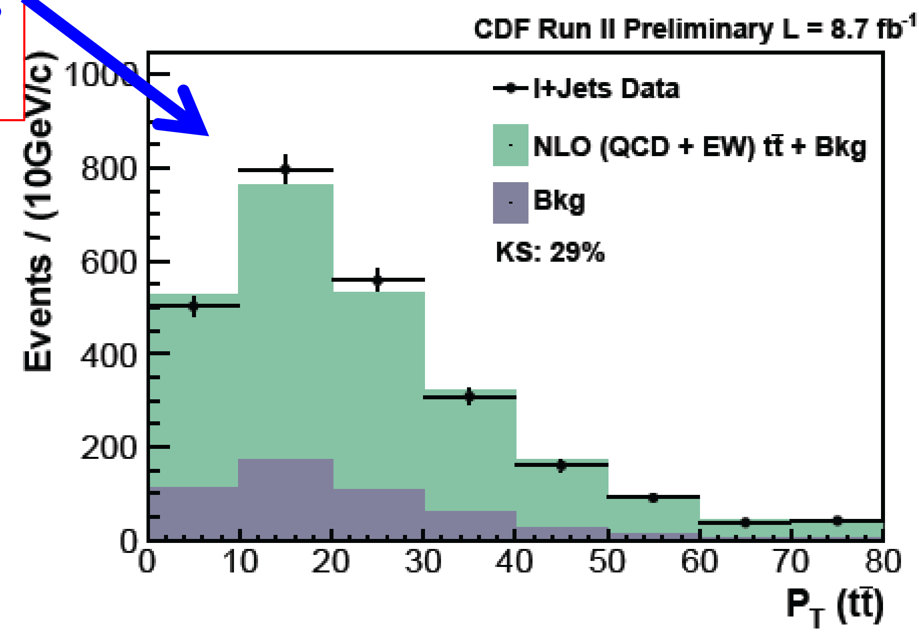
If we are going to take this seriously, we need to trust the kinematic modeling

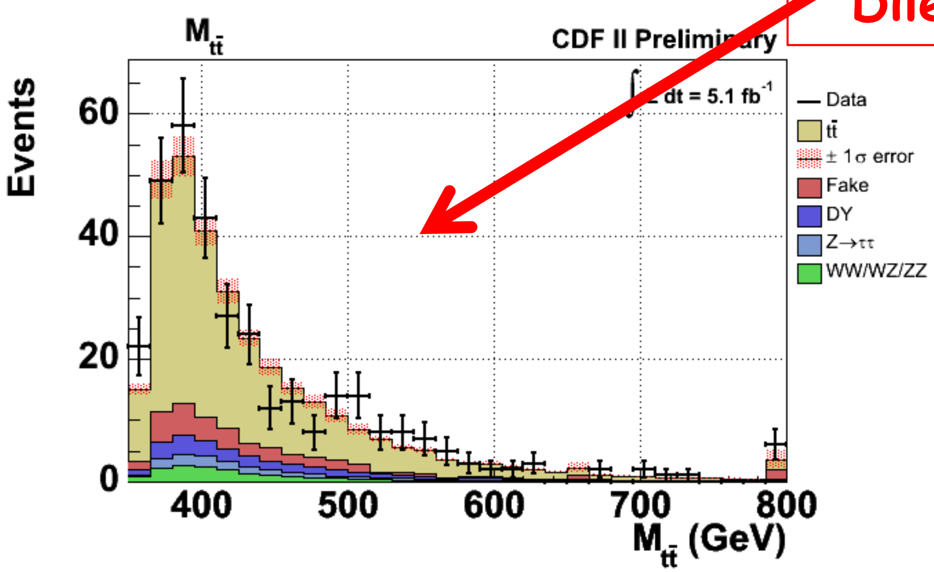
Both the Mass and P_T of the $t\bar{t}$ system look well modeled

Lepton+Jets

Dileptons



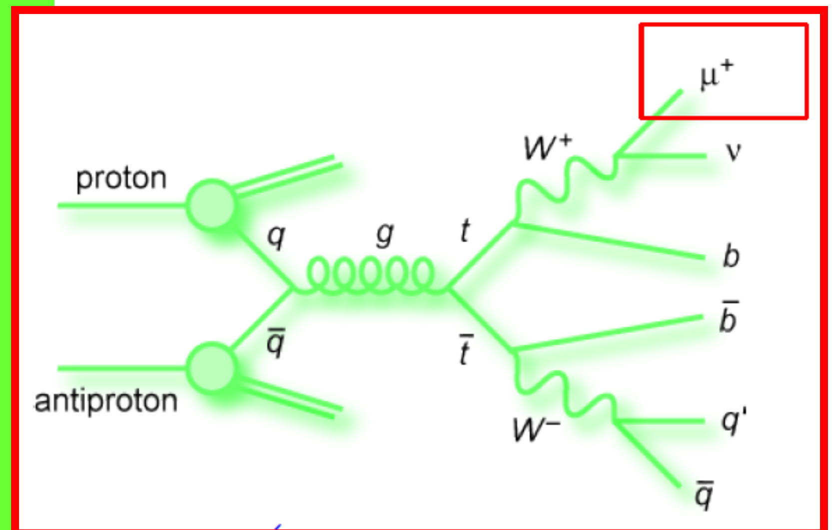




Independent check: remove the fitting

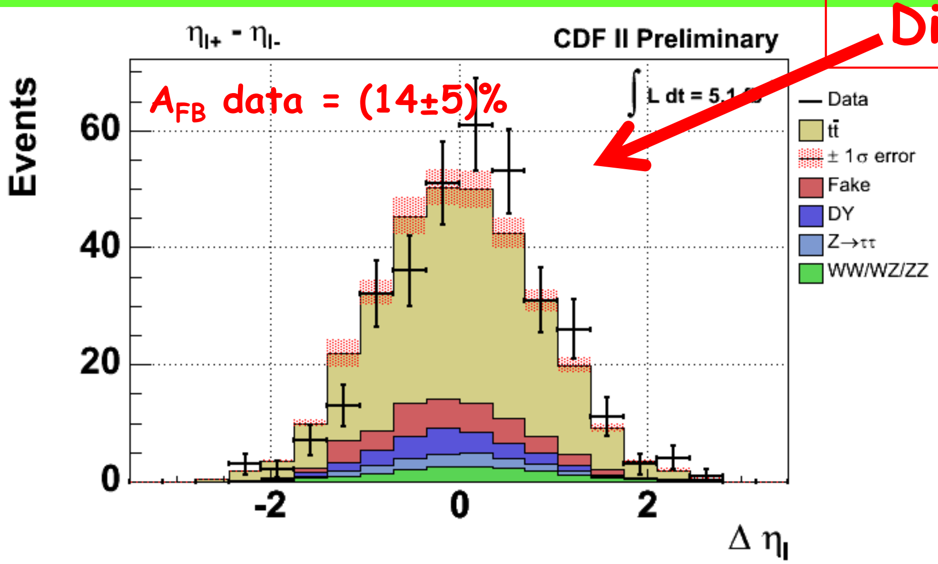
Effect still there using just the lepton η and charge?

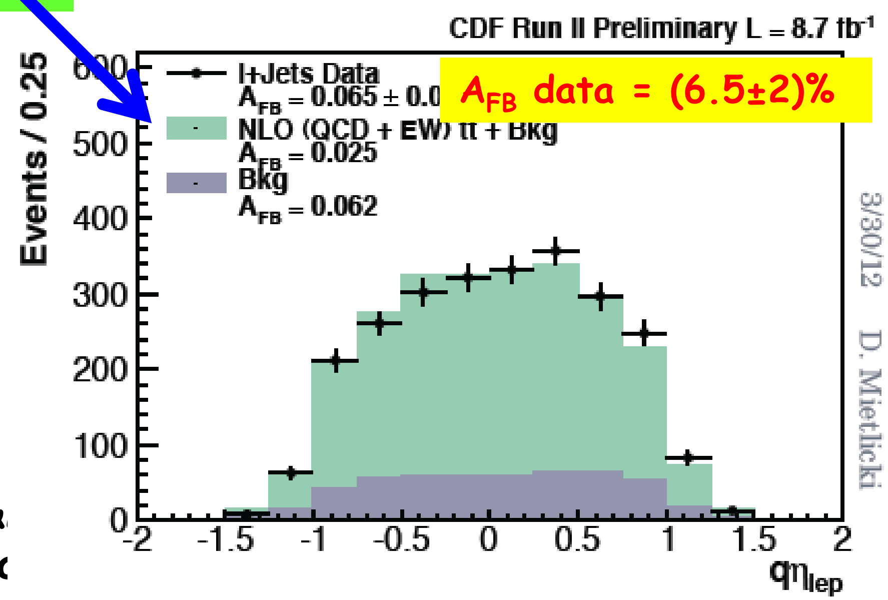
- Direction of motion of the lepton is correlated with the parent top quark → no reconstruction required
- Isn't really the same as A_{FB} since it includes spin correlations
- Asymmetry again significantly different from zero



Lepton+Jets

Dileptons





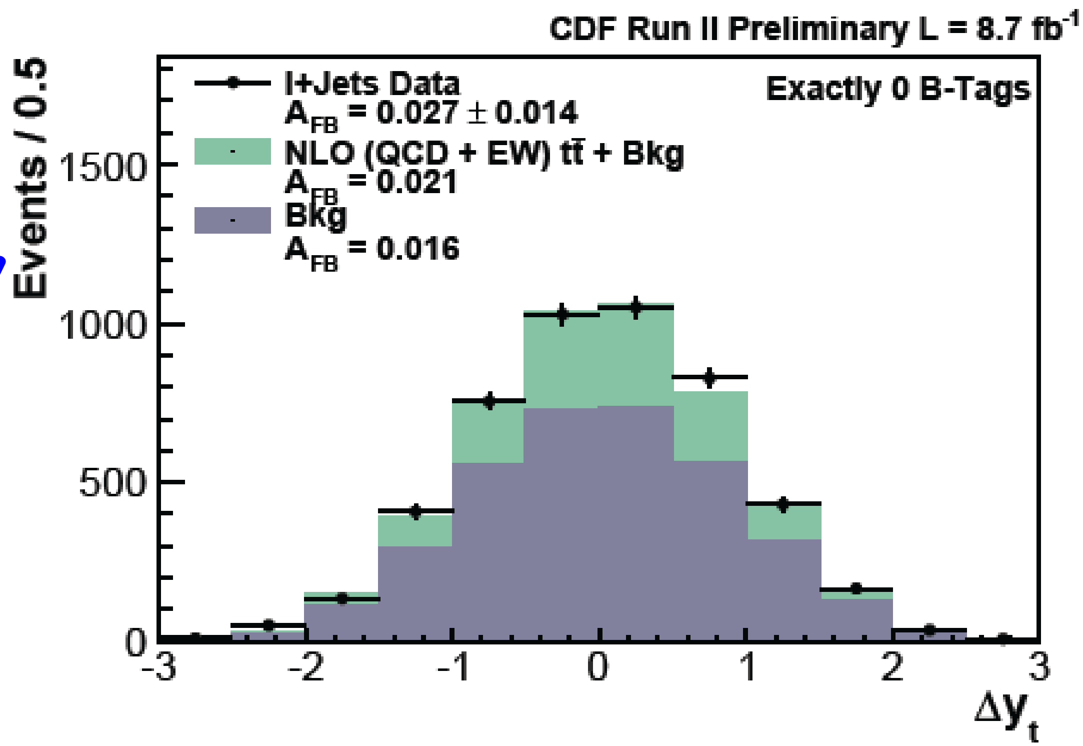
Texas A&

in Top Qu

Check: *Effect still exist in Background Dominated Region?*

Example in Lepton+Jets

- Same data, but require no *b*-tagged jets
- Lots of data, mostly background
- Expect a small asymmetry (2.1%)
- Observe a small asymmetry (2.7%)



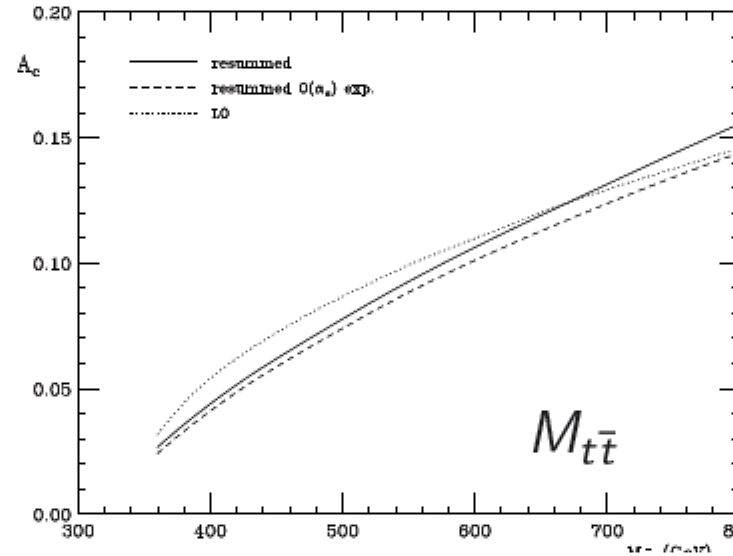
Beyond the Inclusive Raw Measurements: *Inquiring Minds Want to Know*

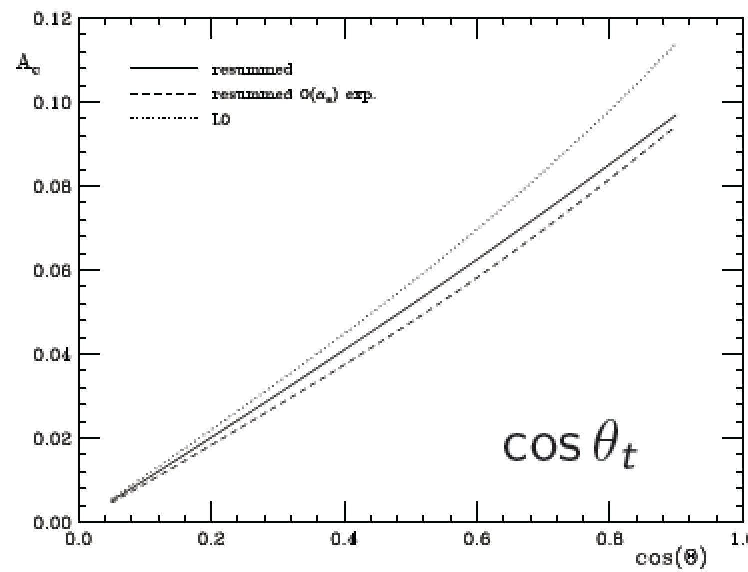
Goals:

- Calculate parton level quantities to compare to theory
- *Does the asymmetry depend on any observables? Should it?*
- *Can we look at these differential asymmetries at parton level?*

Standard Model Predictions

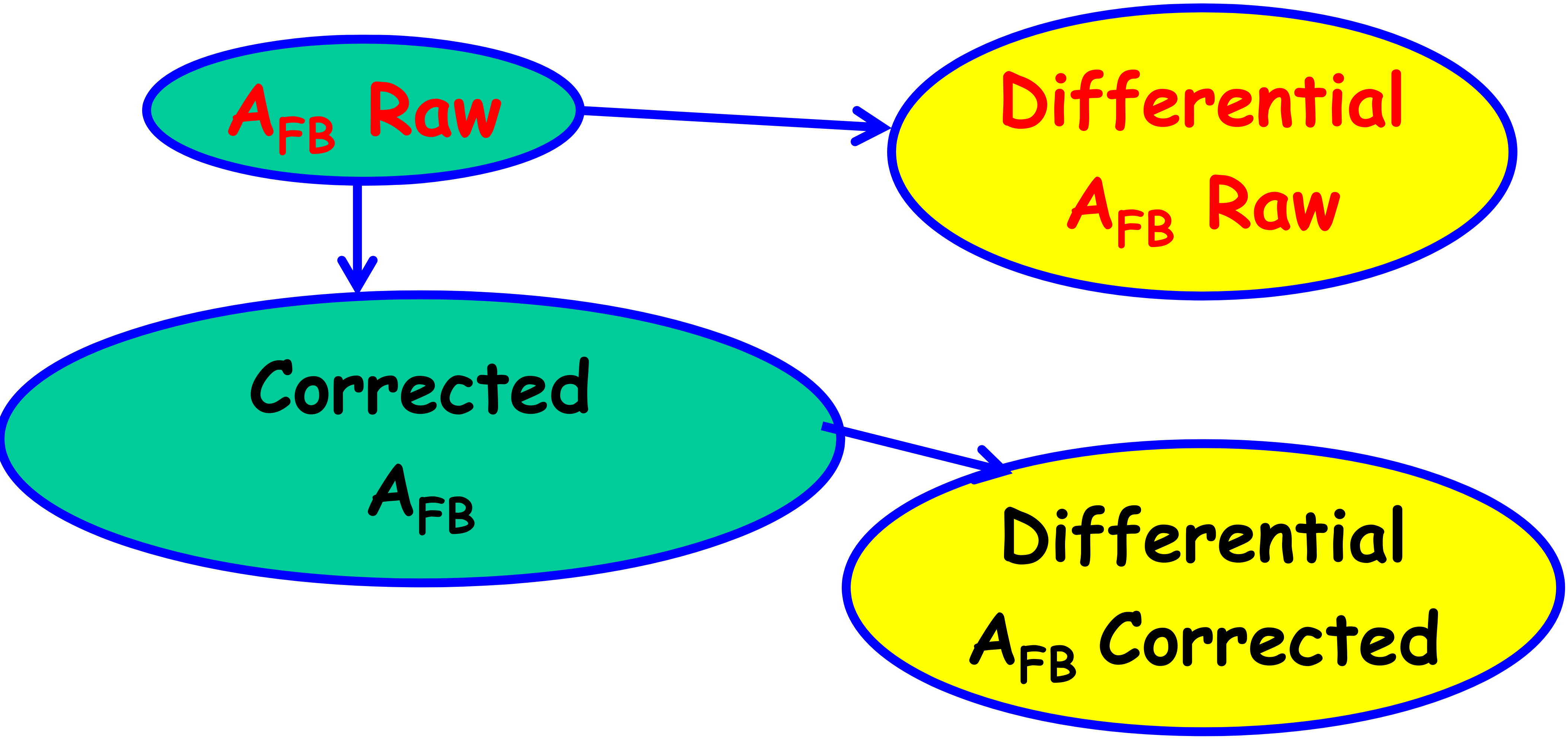
- Asymmetry expected to vary with the mass of the $t\bar{t}$ system as well as the $cos(\theta_t)$
  - Again use Δy as our best measure
- Expect an approximately linear dependence





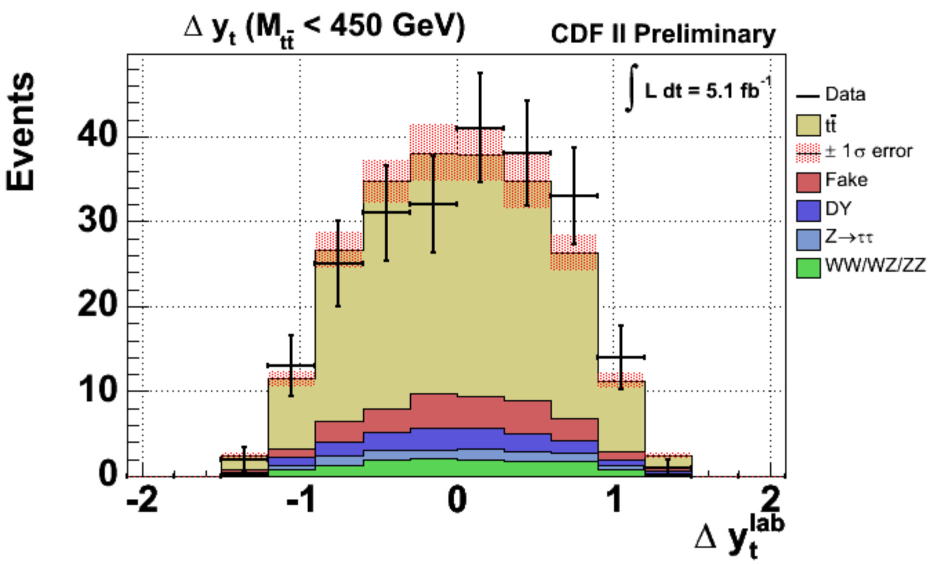
Plots from L. Almeida, G. Sterman and W. Vogelsang Phys. Rev. D78, 014008 (2008)

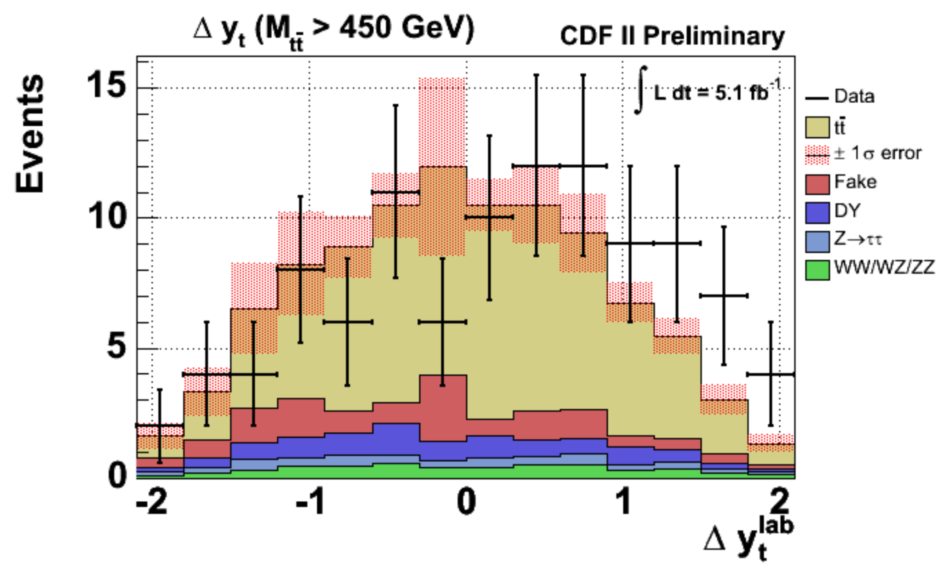
Let's do 4 separate types of things…



Dileptons: Asymmetry vs. Mass

- Measure the Asymmetry for low mass and high mass separately
- Small trend upward vs. $M_{t\bar{t}}$ in dileptons





M_{tt}<450 GeV/c²

A_{FB} pred = (0.3±3.1)%

A_{FB} data = (10.5±6.6)%

M_{tt}>450 GeV/c²

N.B: MC for $t\bar{t}$ prediction uses LO only

A_{FB} pred = (-4.0±5.5)%

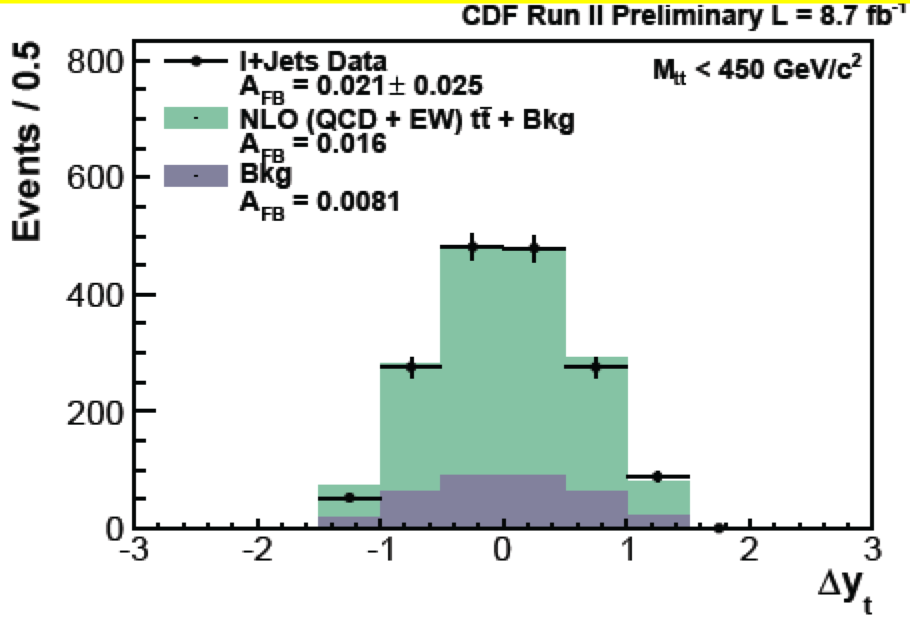
A_{FB} data = (12.2±9.6)%

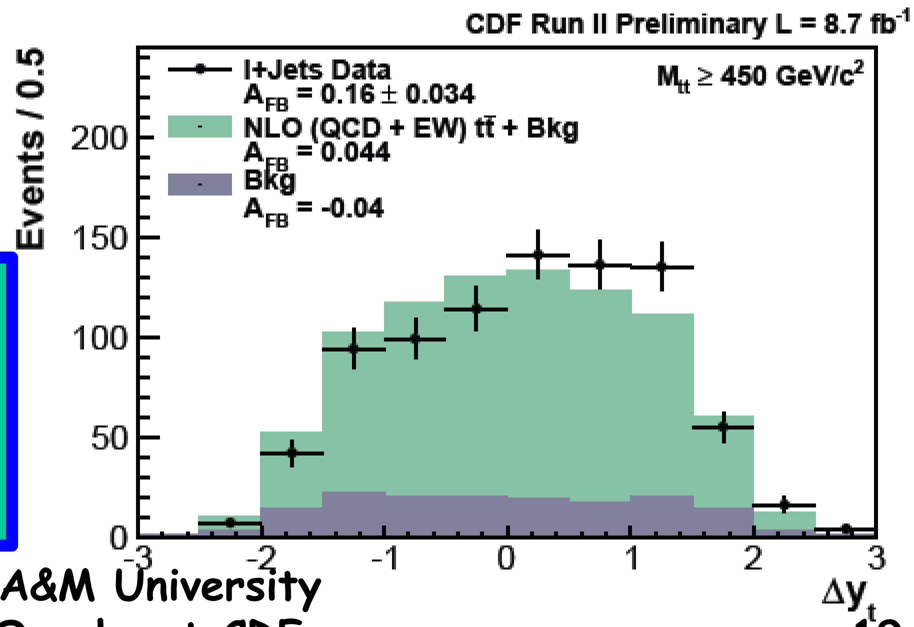
Lepton+Jets: Asymmetry vs. Mass

- Observe same trend with higher statistics
- For $M_{t\bar{t}}$ <450 GeV/c^2 asymmetry consistent with zero (2.1±2.5)%
- For $M_{t\bar{t}}$ >450 GeV/c^2 find

A_{FB} Pred = 4.4%

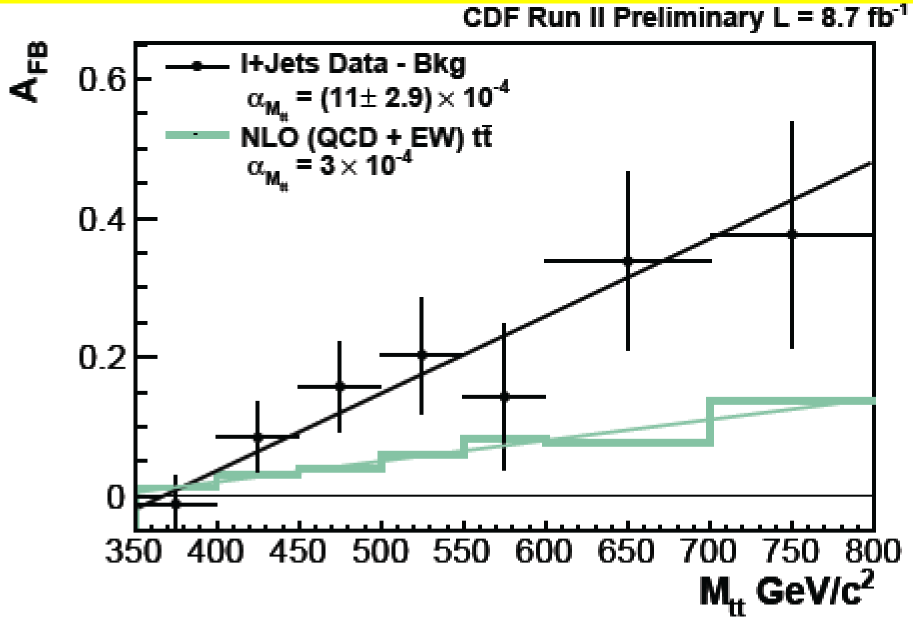
A_{FB} Data =(16.0±3.4)%

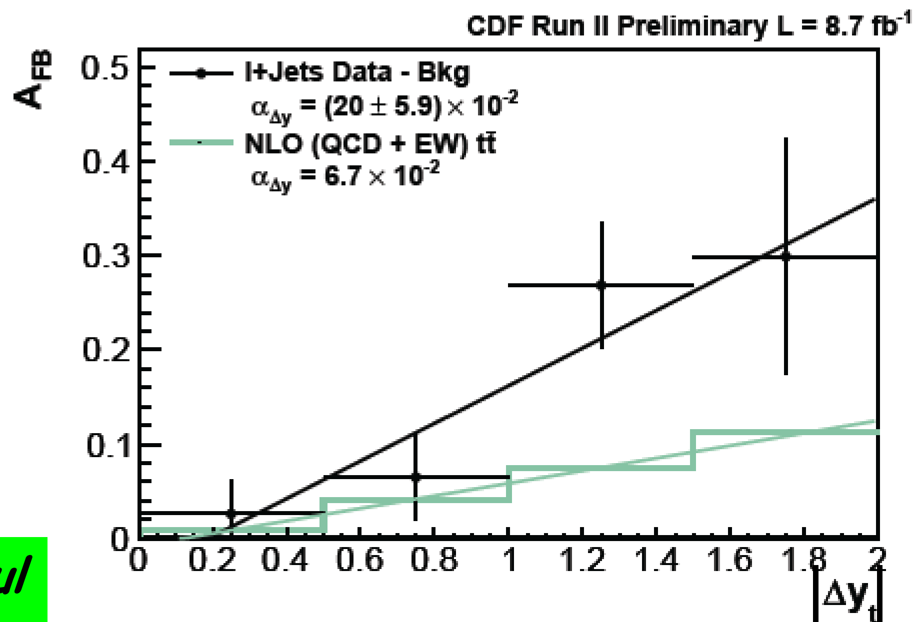




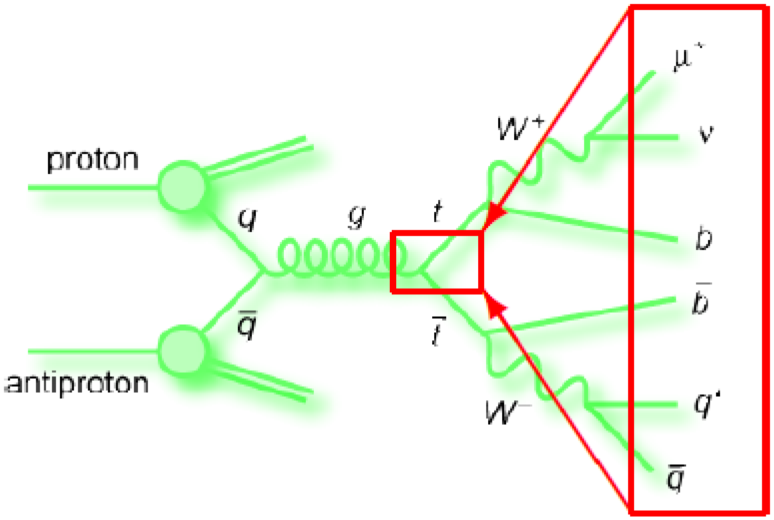
Lepton+Jets Asymmetry vs. $M_{t\bar{t}}$ and $|\Delta Y|$

- Can move beyond two bins with full dataset
- Look at the differential A_{FB} as a function of $M_{t\bar{t}}$ and $|\Delta Y|$ after background subtraction
- SM predicts both to be roughly linear
  - Observe a linear dependence in the data
  - Slopes are 3σ from zero and inconsistent with SM predicted slopes
  - *p*-values less than 1% from SM



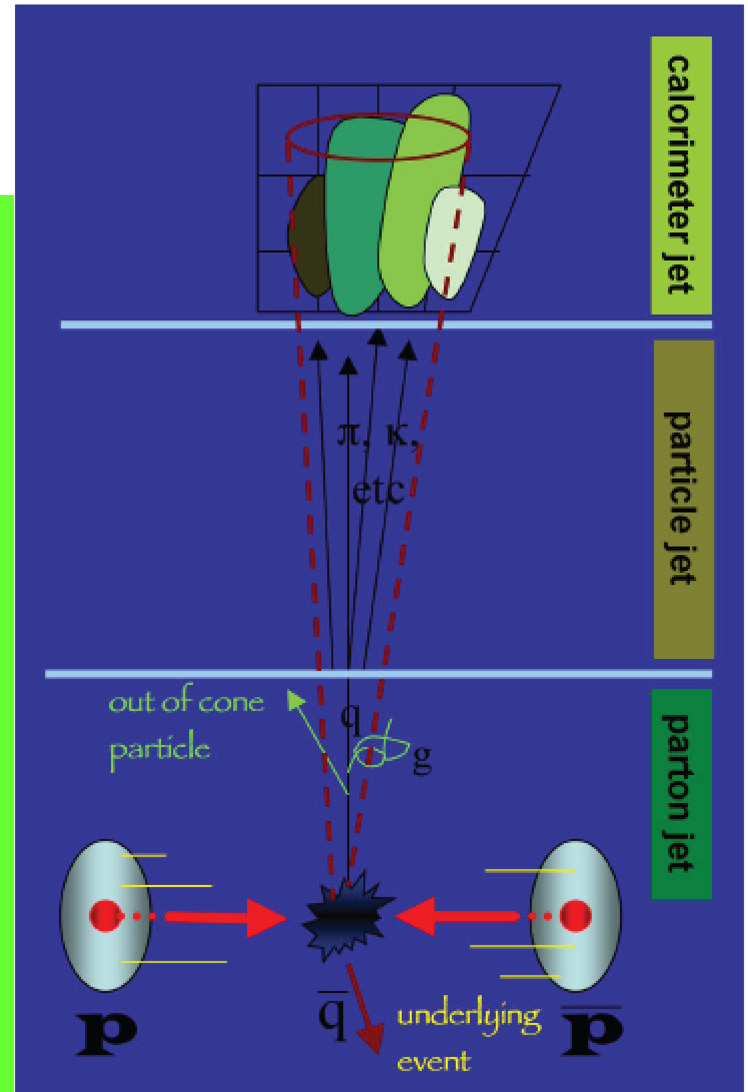


Can the numerical values of these slopes be useful to model builders?



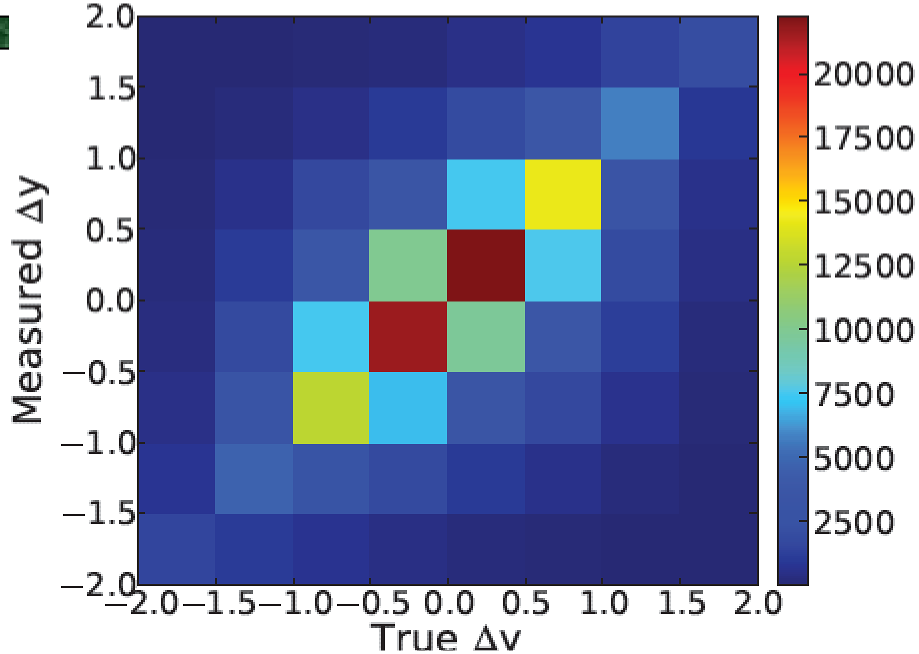
Working back to Parton Level A_{FB}

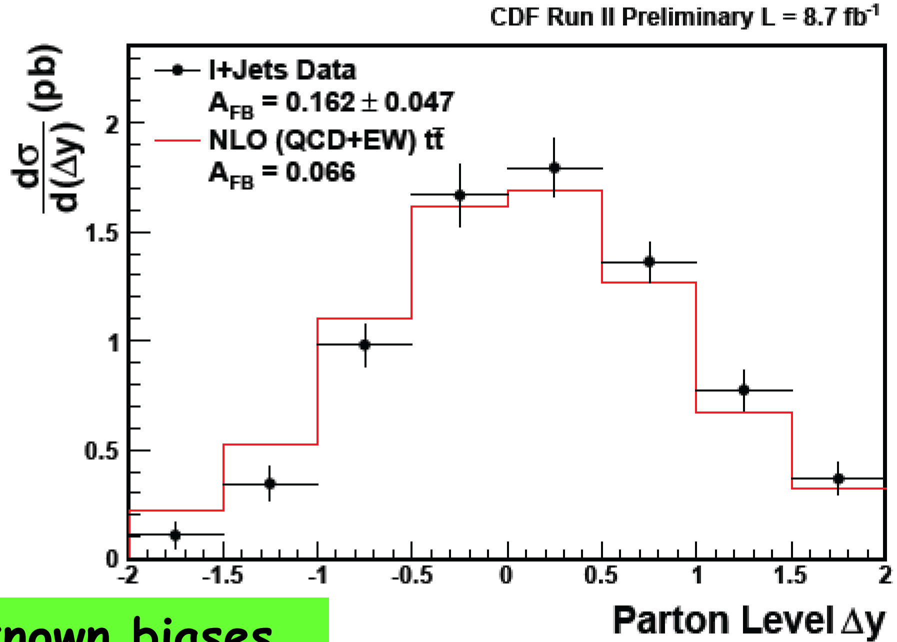
- Correct for
  - Finite detector resolution
  - Smearing from incorrect reconstruction
  - Selection Cuts
  - Geometry
  - Trigger
  - Statistics
- Acceptance correction bin-by-bin of Monte Carlo truth before and after selection



A Full Correction Matrix Method

- Use Monte Carlo to estimate detector response functions
- Matrix Methods
- Returns parton level distributions
- Can subtract off backgrounds





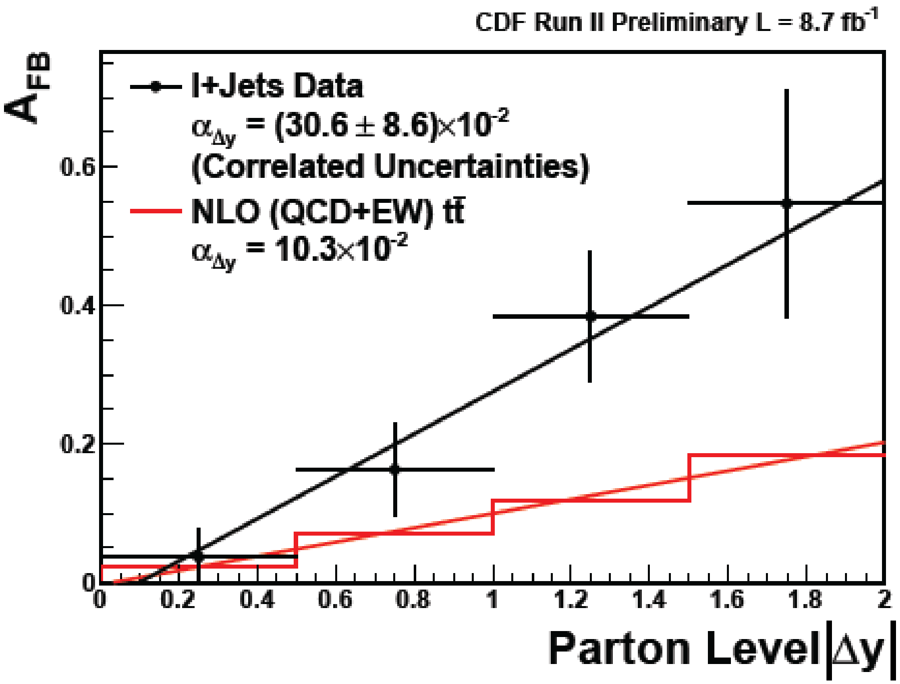
Many potential sources of uncertainty, but no known biases

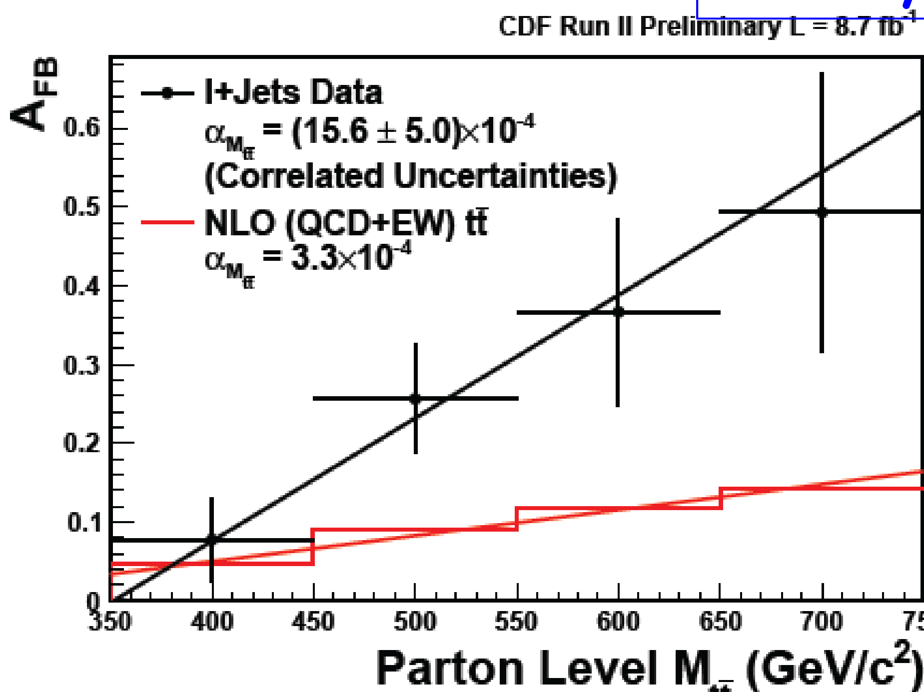
Measurement precision dominated by statistical uncertainties

Parton Level Asymmetries

Differential values of Asymmetry well described by a linear relationship

Lepton+Jets only





slope parameter α	A_{FB} vs $M_{t\bar{t}}$	A_{FB} vs Δy
DATA	$(15.6 \pm 5.0) \times 10^{-4}$	$(30.6 \pm 8.6) \times 10^{-2}$
SM	3.3×10^{-4}	10.3×10^{-2}

Slopes are 3σ from zero and inconsistent with SM predicted slopes

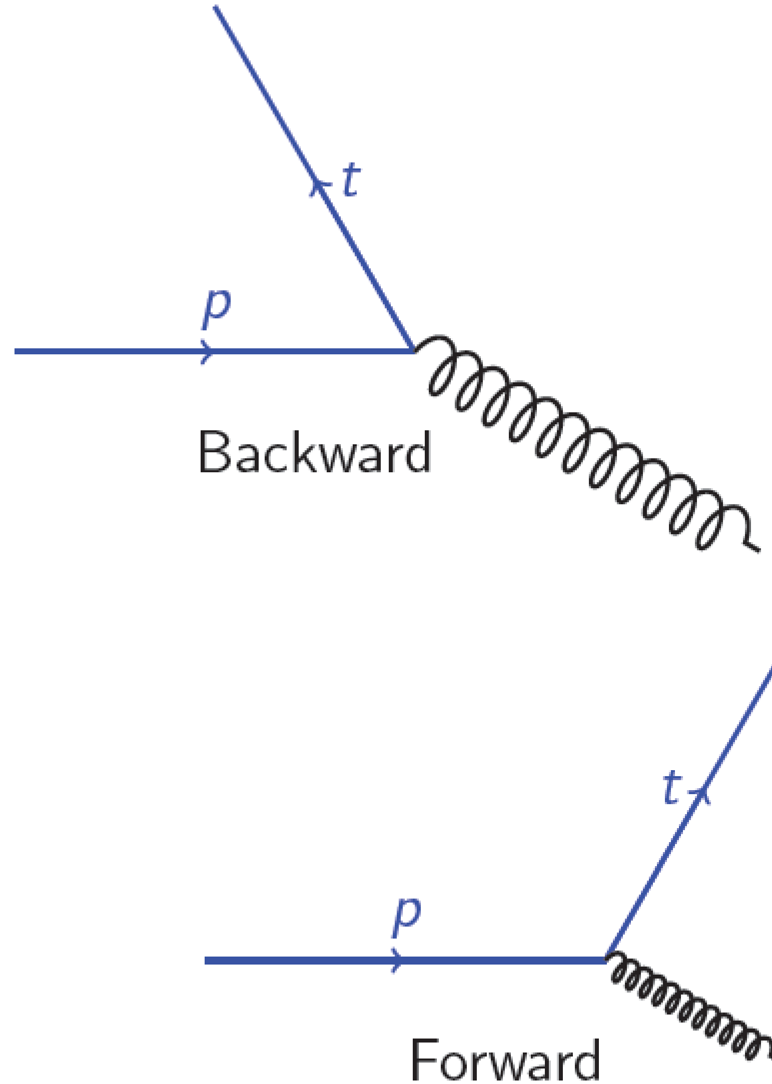
Summary and Conclusions

- Completed two independent studies of A_{FB} in top quark events using the Lepton+Jets and Dilepton Final states
- Asymmetries often 3σ away from zero, and consistently larger than NLO predictions
  - Observed in both datasets
  - Robust against multiple checks of backgrounds and reconstruction procedures
- Both raw and parton-level differential Asymmetries indicate a linear dependence on both $M_{t\bar{t}}$ and $|\Delta Y|$
- Have just begin an exciting program ahead of us
  - More studies of Lepton+Jets events
  - Full dataset in Dileptons (add *b*-tagging)
  - Collaborating with our friends across the ring, across the oceans and theorists around the world

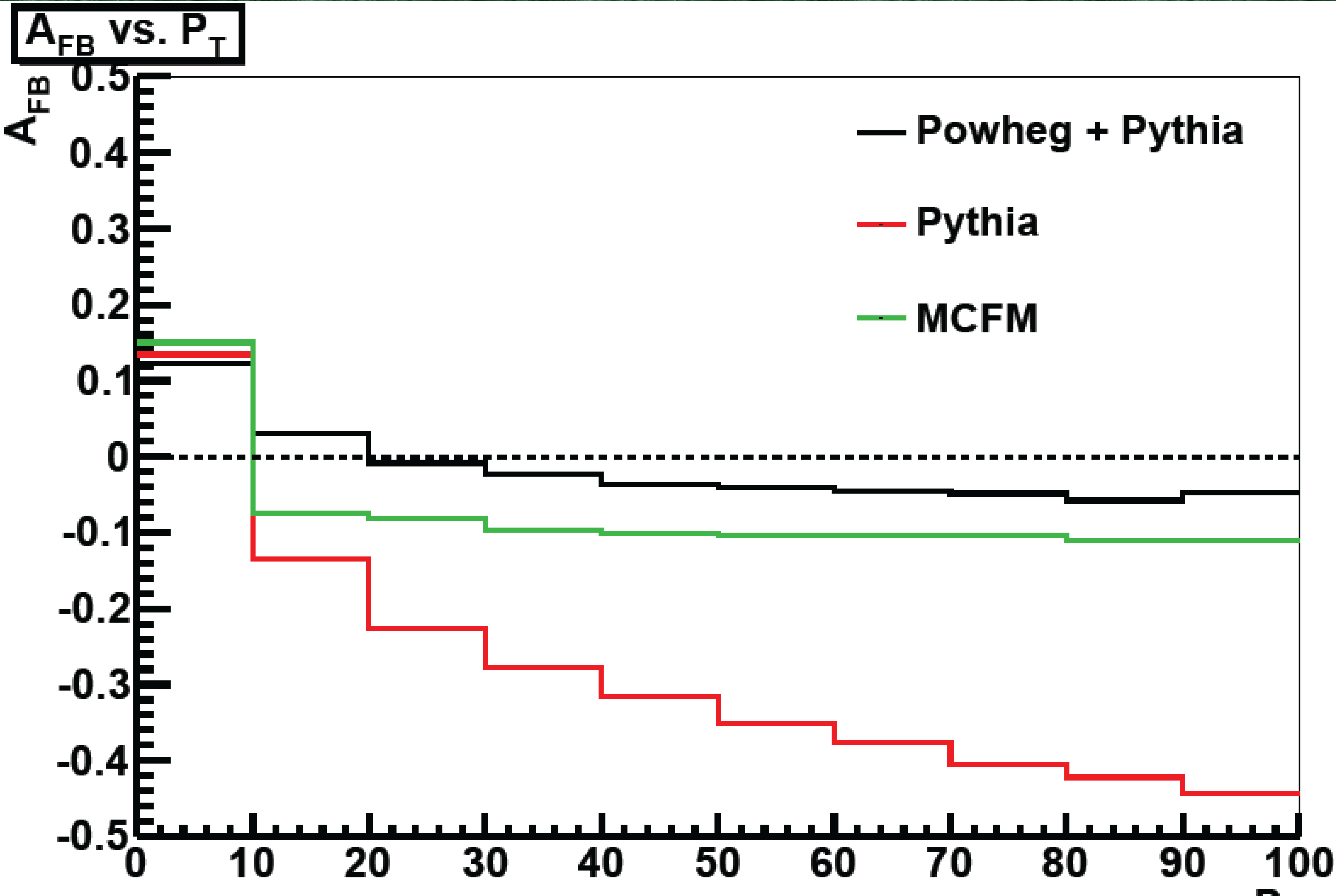
Backups

Backup Slides on P_T of the $t\bar{t}$ System

- Dependence of A_{FB} on transverse momentum of $t\bar{t}$ system is very important
- Sensitive to detailed QCD effects
- (Very) rough explanation: In events where top is backwards, color flow from proton to top bends sharply, leading to a "color bremsstrahlung"
- That is, backward events tend to have higher $t\bar{t}$ p_T
- Leads to positive A_{FB} at low p_T, negative at high p_T, even at LO
- Also NLO ISR/FSR interference contributes p_T dependent A_{FB}



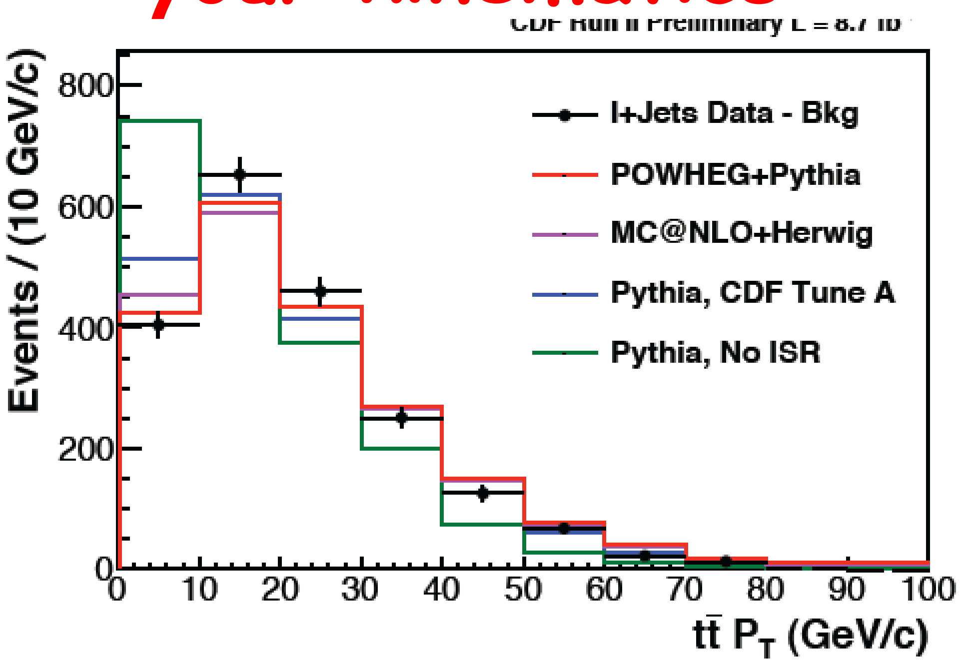
(NOT Feynman diagrams!)

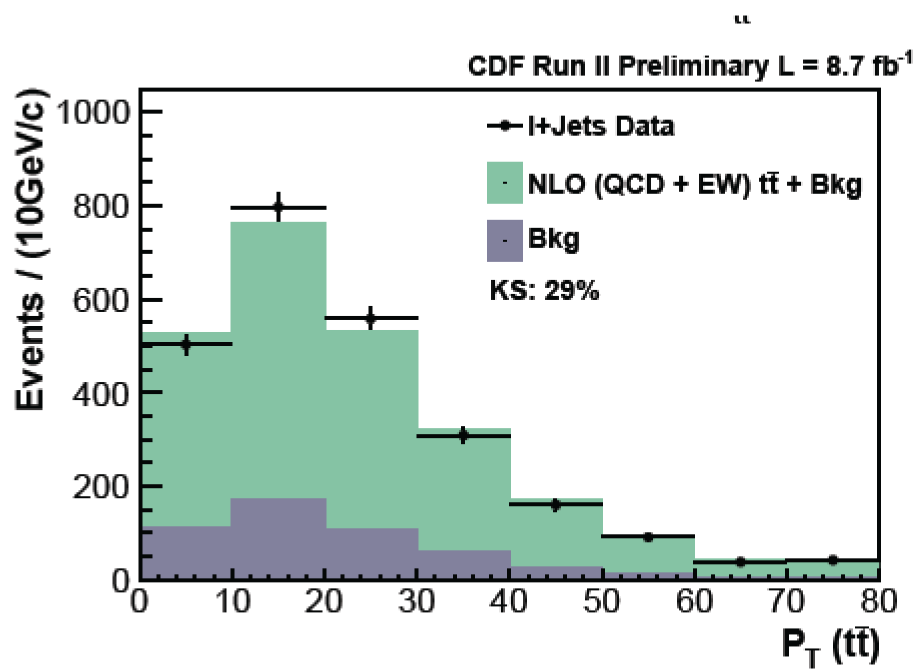


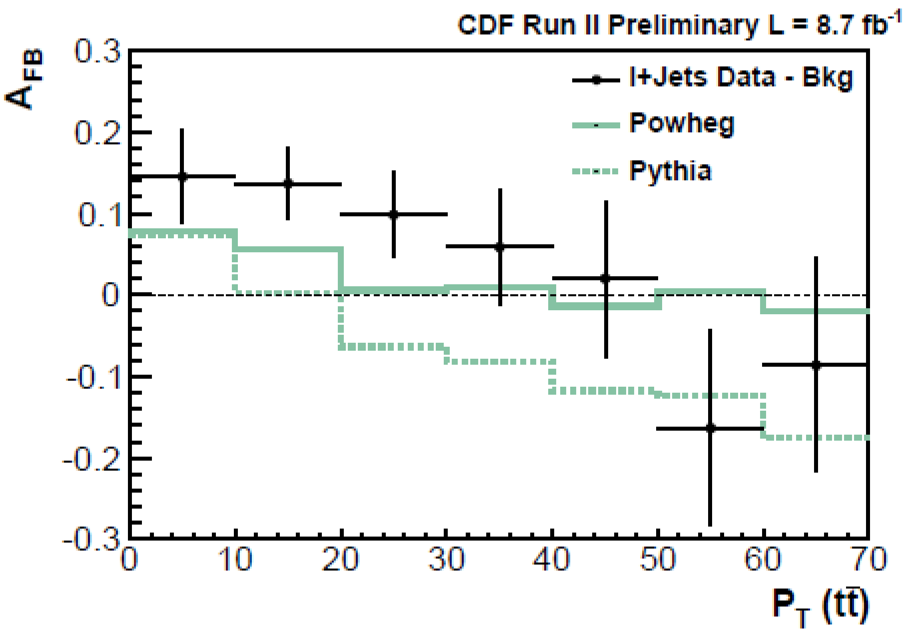
- POWHEG, MCFM, PYTHIA truth
- All same general shape: positive at low p_T, negative at high p_T

P_T is important

- Mostly because CDF and Dzero get different results.
- Results clearly depend on which MC you use
- Also must depend on the reconstruction of your kinematics







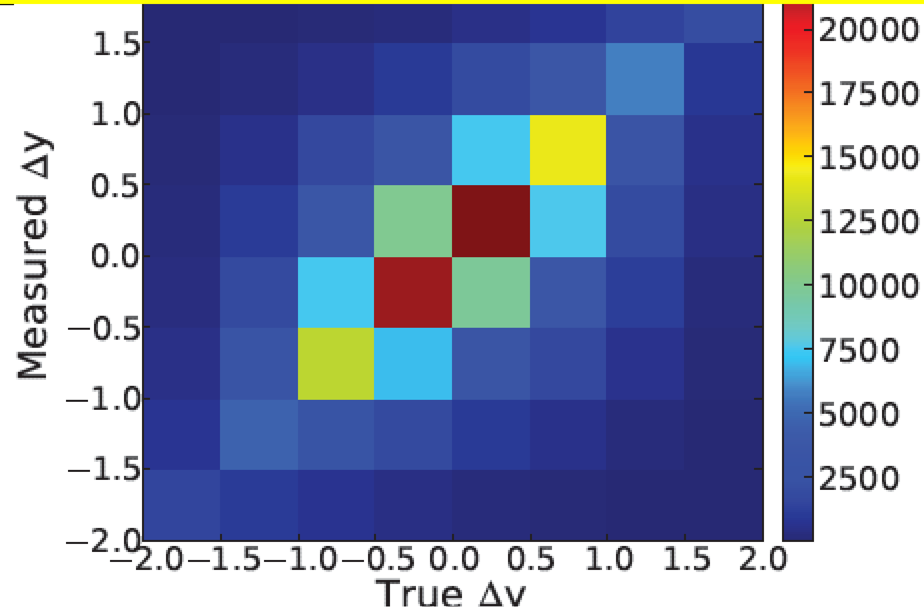
- Our data (background subtracted) shows a similar dependence on p_T
- Larger overall asymmetry
- Shape compatible with SM predictions from POWHEG and from PYTHIA, total asymmetry not compatible

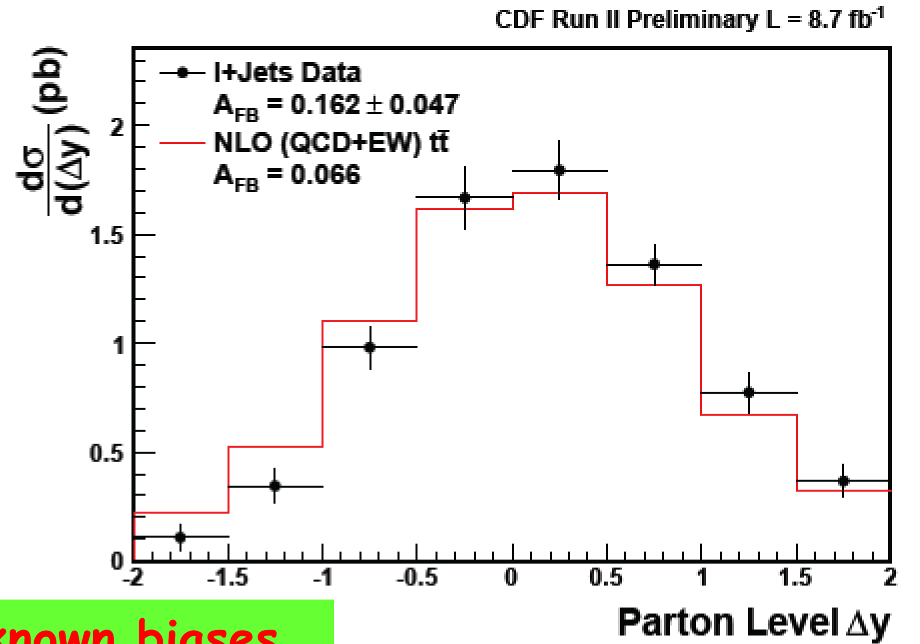
Backup Slides on the Systematic Uncertainties…

Small compared to the statistical

A Full Correction Matrix Method

- Estimate detector response matrix S from Monte Carlo
- Linear equation for corrected data $\vec{x}$ from data $\vec{b}$: $S\vec{x} = \vec{b}$
- Inverse problem is ill-conditioned
- Can only be solved in least squares sense ($\min \left| S\vec{x} - \vec{b} \right|^2$)
- Even then, solution grossly magnifies statistical imprecision
- Use technique from math. stats.: Tikhonov regularization (Höcker and Kartvelishvili 1995)
- Expect true parton level distribution to be smooth





Many potential sources of uncertainty, but no known biases
Measurement precision dominated by statistical uncertainties

Systematics for Lepton+Jets Unfolding

CDF Run II Preliminary L = 8.7 fb^{-1}

Source	Systematic Uncertainty
Background Shape	0.014
Background Normalization	0.011
Parton Showering	0.010
Jet Energy Scale	0.005
Initial and Final State Radiation	0.005
Color Reconnection	0.001
Parton Distribution Functions	0.001
Correction Procedure	0.003
Total Systematic Uncertainty	0.022
Statistical Uncertainty	0.041
Total Uncertainty	0.047

Dilepton Systematics for Corrections

CDF II Preliminary

Source	δA_{true}
Background shape	0.043
Detector effect	0.010
Signal MC stat.	0.010
Signal MC	0.018
ISR/FSR uncertainty	0.015
Jet energy scale	0.008
Color reconnection model	0.011
PDF	0.004
Systematics total	0.053
Statistical uncertainty	0.148
Total uncertainty	0.157

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

Random Slides I didn't use but could have

- After DIL event selection, likelihood fitting is applied to reconstruct the direction of t and tbar and Δy_t

$$\mathcal{L}\left(\vec{p}_{\nu},\vec{p}_{\bar{\nu}},E_b,E_{\bar{b}}\right)=P\left(p_z^{t\bar{t}}\right)P\left(p_T^{t\bar{t}}\right)$$
$$\frac{1}{\sigma_{\text{jet1}}}\exp\left[-\frac{1}{2}\left\{\frac{E_{\text{jet1}}^{\text{meas}}-E_{\text{jet1}}^{\text{guess}}}{\sigma_{\text{jet1}}}\right\}^2\right]\times\frac{1}{\sigma_{\text{jet2}}}\exp\left[-\frac{1}{2}\left\{\frac{E_{\text{jet2}}^{\text{meas}}-E_{\text{jet2}}^{\text{guess}}}{\sigma_{\text{jet2}}}\right\}^2\right]\times$$
$$\frac{1}{\sigma_x^{\text{MET}}}\exp\left[-\frac{1}{2}\left\{\frac{\not{E}_x^{\text{meas}}-\not{E}_x^{\text{guess}}}{\sigma_x^{\text{MET}}}\right\}^2\right]\times\frac{1}{\sigma_y^{\text{MET}}}\exp\left[-\frac{1}{2}\left\{\frac{\not{E}_y^{\text{meas}}-\not{E}_y^{\text{guess}}}{\sigma_y^{\text{MET}}}\right\}^2\right],$$

- Resolution functions of JES, MET and probability functions of P_T , P_z are estimated from MC samples

Checks with Leptons in L+J

- Probably for backups

CDF Run II Preliminary L = 8.7 fb^{-1}

Sample	A_{FB} (± [stat.+syst.]) Inclusive	A_{FB} (± [stat.+syst.]) $M_{t\bar{t}} < 450 GeV/c^2$	A_{FB} (± [stat.+syst.]) $M_{t\bar{t}} \geq 450 GeV/c^2$
All Data	0.085 ± 0.025	0.025 ± 0.031	0.198 ± 0.043
Positive Leptons	0.100 ± 0.037	0.044 ± 0.046	0.198 ± 0.060
Negative Leptons	0.071 ± 0.035	0.008 ± 0.043	0.198 ± 0.059
Exactly 0 b-tags	0.056 ± 0.052	0.079 ± 0.066	0.005 ± 0.085
Exactly 1 b-tags	0.103 ± 0.030	0.039 ± 0.037	0.226 ± 0.050
At least 2 b-tags	0.034 ± 0.046	-0.014 ± 0.057	0.122 ± 0.077
Electron Events	0.058 ± 0.038	-0.018 ± 0.048	0.199 ± 0.062
Muon Events	0.107 ± 0.034	0.060 ± 0.041	0.197 ± 0.057

Dileptons Summary

CDF II Preliminary

Δy_t:

$$A_{\text{obs}} = 0.14 \pm 0.05(\text{stat.})$$

$$A_{\text{sub}} = 0.21 \pm 0.07(\text{stat.}) \pm 0.02(\text{bkg. shape})$$

$$A_{\text{true}} = 0.42 \pm 0.15(\text{stat.}) \pm 0.05(\text{syst.})$$
$$= 0.42 \pm 0.16$$

$\Delta \eta_\ell$:

$$A_{\text{obs}}^{\Delta\eta_\ell} = 0.14 \pm 0.05(\text{stat.})$$

$$A_{\text{sub}}^{\Delta\eta_\ell} = 0.21 \pm 0.07(\text{stat.}) \pm 0.02(\text{bkg. shape})$$