Measurement of the Forward-Backward Asymmetry of $t\bar{t}$ at the Fermilab Tevatron

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CDF Collaboration

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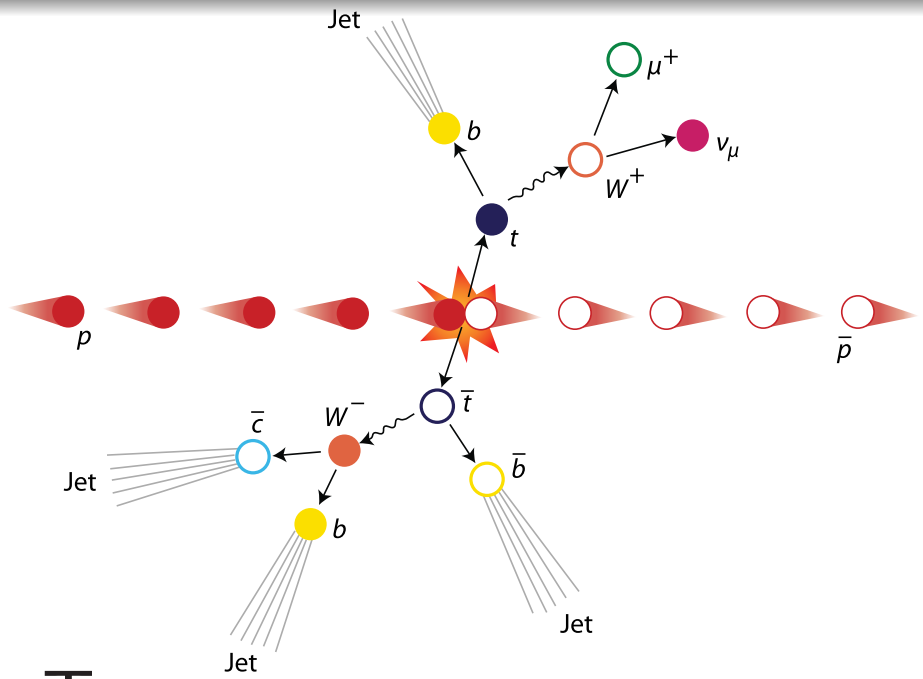
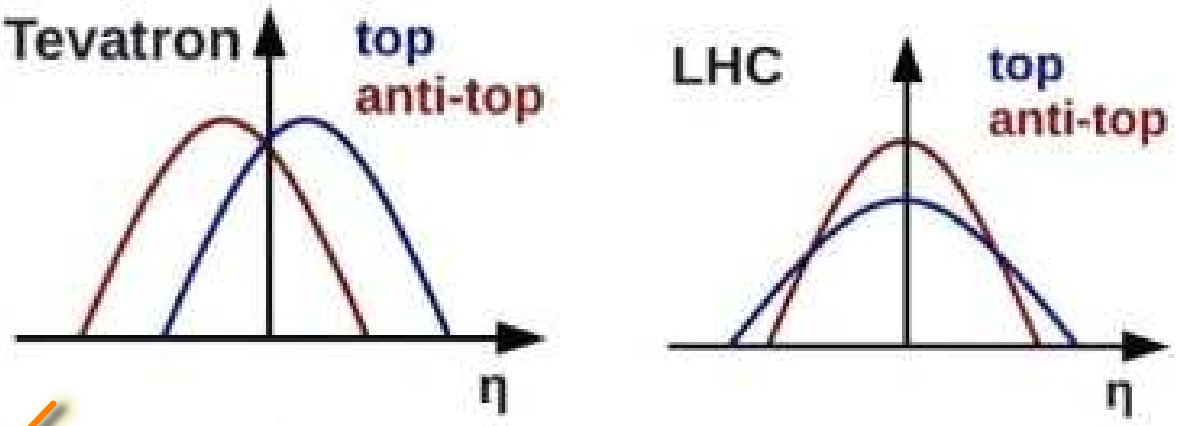
Forward–backward asymmetry

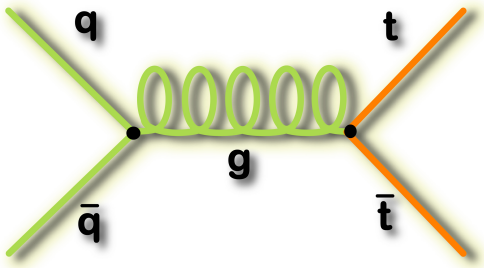


- $p\bar{p}$ collision at Tevatron
- Top quarks primarily pair produced ($p\bar{p} \to t\bar{t}$)
- Heavy and short-lived, **decay immediately**
- A_{FB} measurements are simply answering:

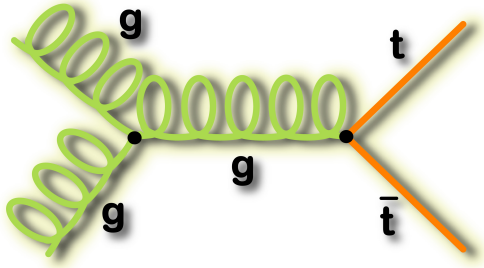
  Does the top quark prefer the proton direction or the opposite?

Complementarity between the Asymmetry at the Tevatron and the LHC





(a)



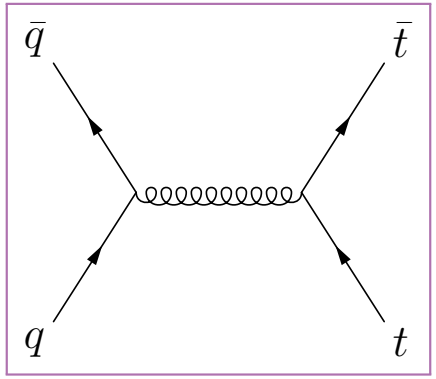
(b)

- $p\bar{p}$ collision at Tevatron instead of pp collision at LHC
- Asymmetry from $q\bar{q}$ annihilation (a)
  - Tevatron $t\bar{t}$ production dominated by $q\bar{q}$ annihilation (85%, a)
  - LHC dominated by gluon fusion (90%, b)
- Sizeable effect at Tevatron, very small asymmetry (central vs. outer) at LHC

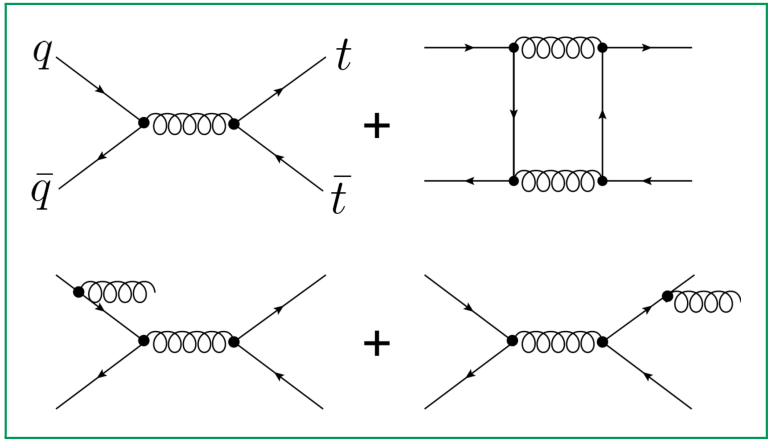
For details about asymmetry measurements at LHC, see next talk

Top A_{FB}: Why important?

- No net asymmetry in leading order diagram
  - Asymmetry only from higher order effects
- Slight asymmetry starting from next-to-leading order (NLO) effects
  - Interference among diagrams

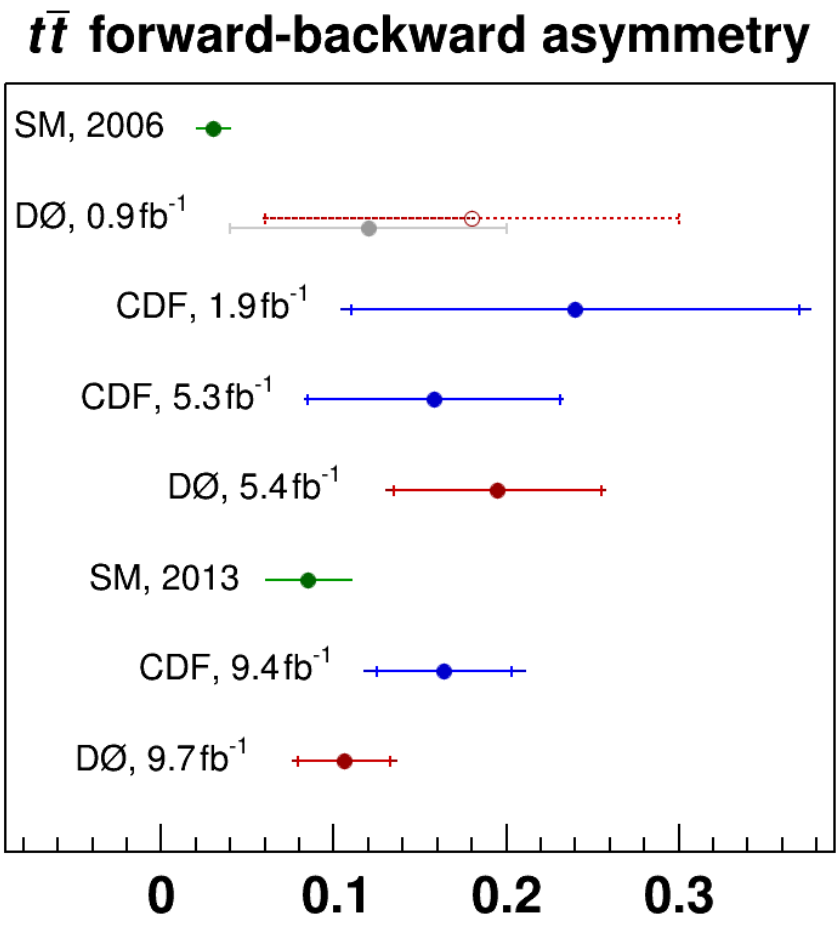


- Larger-than-expected EW correction and higher order QCD corrections complicate the calculation
- **Precision probe of SM predictions with large mass particles**



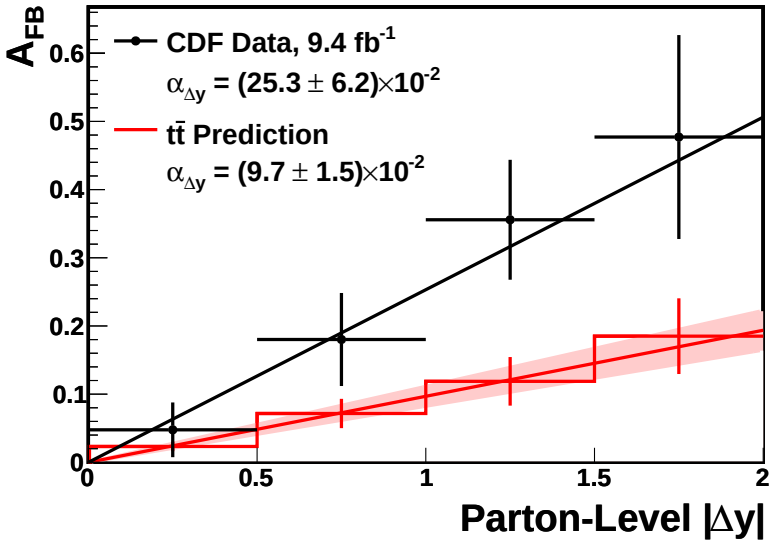
Top A_{FB}: Why interesting?

- First set of measurements showed larger-than-SM values
- Higher than SM asymmetry leaves room for various beyond-SM models
  - s-channel axigluon, t-channel W', Z', etc.



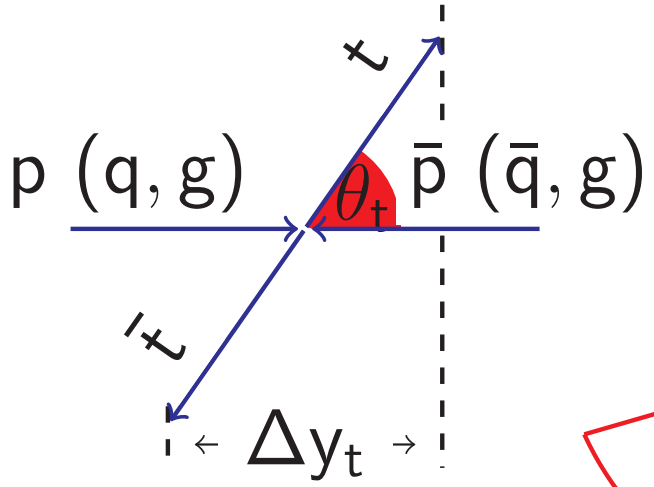
$A_{\mathrm{FB}}^{t\bar{t}}$ at Tevatron

- Perhaps more interesting: $A_{\mathrm{FB}}^{t\bar{t}}$ vs. Δy_t deviates from NLO (and NNLO) SM prediction
- Need to squeeze every drop from Tevatron data to understand this potential anomaly

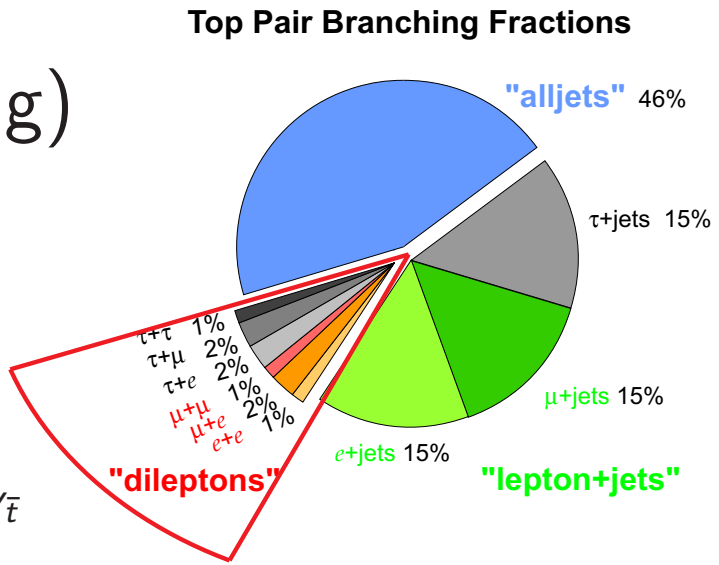


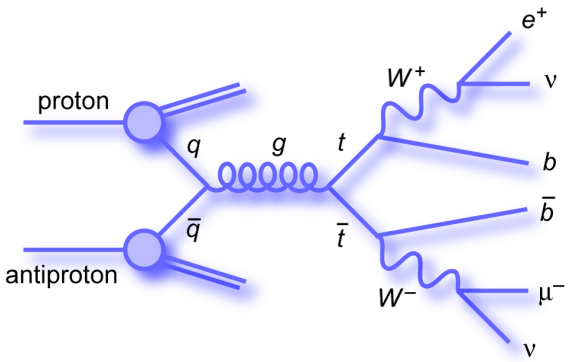
This talk

- Latest CDF top A_{FB} measurement
  - $A_{\mathrm{FB}}^{t\bar{t}}$ characterized with top rapidity (Δy_t)
  - In dilepton final state ($t\bar{t} \to \ell^+\nu\ell^-\bar{\nu}b\bar{b}$)
- Summary of the legacy results of top A_{FB} at CDF

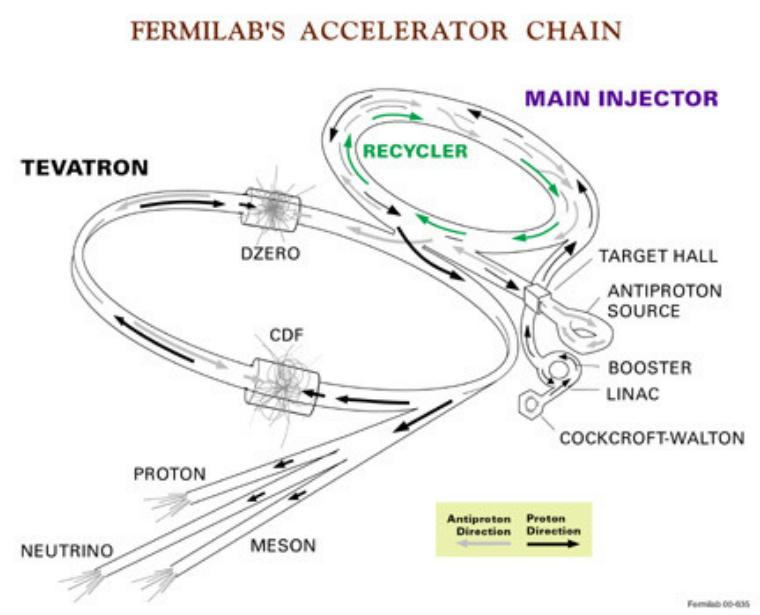


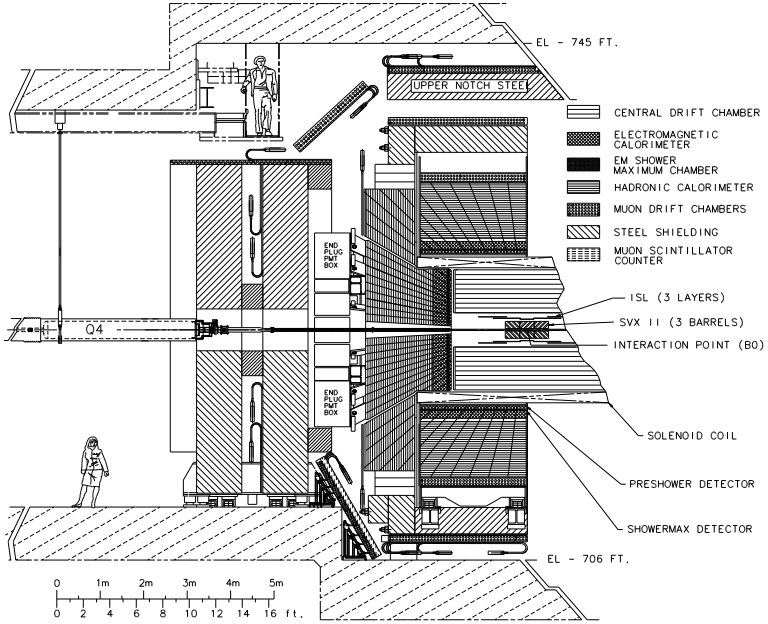
$$y = \frac{1}{2}\ln\frac{E+p_z}{E-p_z}, \Delta y_t = y_t - y_{\bar{t}}$$





Tevatron and CDF





Tevatron

- $p\bar{p}$ collider
- Center-of-mass energy 1.96 TeV
- Run II delivered $12\mathrm{fb}^{-1}$
- Acquired $\sim 10\mathrm{fb}^{-1}$ by CDF

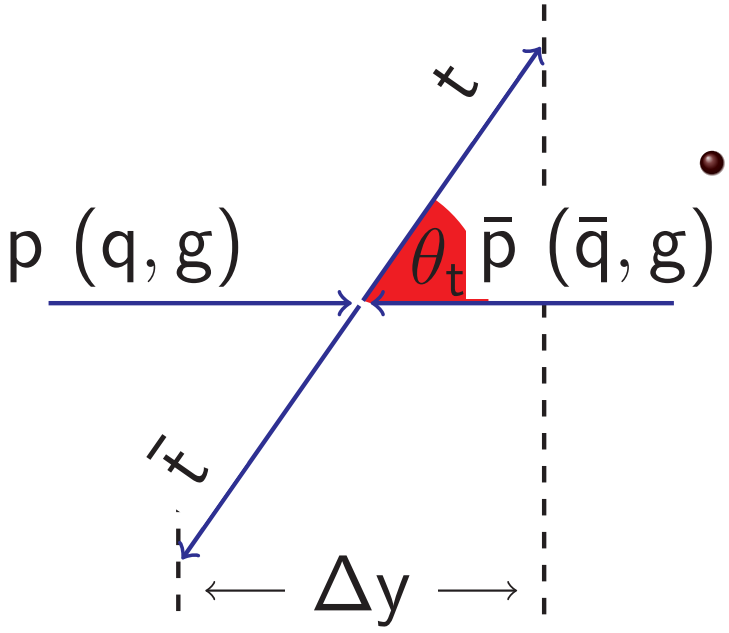
CDF

- General purpose detector
  - 1.4 T magnetic field
  - Tracking, Calorimeter and Muon systems
- Coverage in $t\bar{t}$ dilepton
  - Electron: $|\eta| < 2.0$
  - Muon : $|\eta| < 1.1$
  - Jets : $|\eta| < 2.5$

$A_{\mathrm{FB}}^{t\bar{t}}$ in dilepton

- $A_{\mathrm{FB}}^{t\bar{t}}$ measurement in dilepton

Definition of $A_{\mathrm{FB}}^{t\bar{t}}$



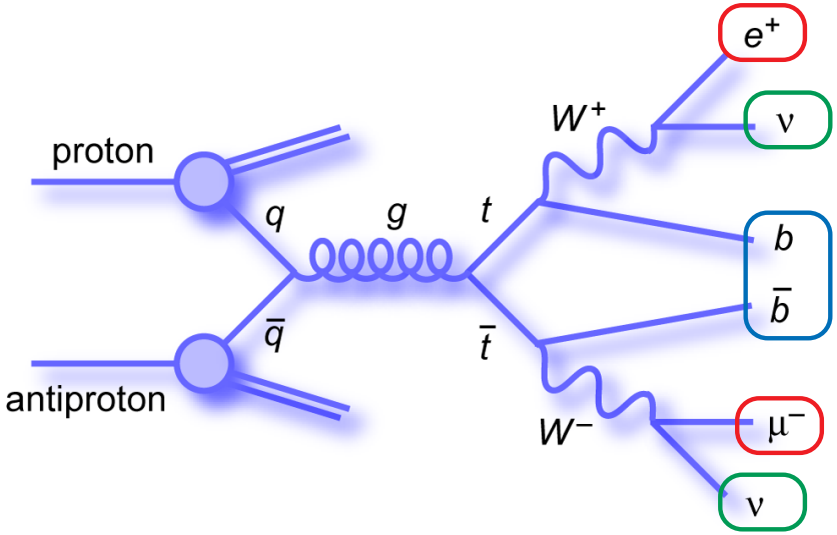
$$y = \frac{1}{2} \ln \frac{E + p_z}{E - p_z}$$

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

- $A_{\mathrm{FB}}^{t\bar{t}} = \dfrac{N(\Delta y > 0) - N(\Delta y < 0)}{N(\Delta y > 0) + N(\Delta y < 0)}$
  - NLO predictions from 0.05 to 0.125 (arxiv:1406.1798 and refs therein)
  - Recent NNLO prediction: $A_{\mathrm{FB}}^{t\bar{t}} = 0.095 \pm 0.007$ (PRL 115, 052001 (2015))
  - $\mathrm{aN^3LO}$ prediction: $A_{\mathrm{FB}}^{t\bar{t}} = 0.100 \pm 0.006$ (PRD 91, 071502 (2015)(R))
- Experimental results need to be unfolded to parton-level to be compared with these predictions

$t\bar{t} \rightarrow$ dilepton
Event selection

- Need a sample enriched by $t\bar{t}$ events with dilepton signature:
  - Two opposite charged leptons
  - At least two jets
  - Large $\not{E}_T$ (imbalanced p_T)
- Details of $t\bar{t} \rightarrow$dilepton data selection criteria in the backups



$t\bar{t} \to$ dilepton
Signal and background modeling

- Signal modeling:
  - Prediction with POWHEG MC (NLO SM w/ only QCD correction)
- Background modeling:
  - Diboson production (WW,WZ,ZZ,$W\gamma$)
    MC prediction
  - Z/γ^*+jets
    MC prediction with correction from data
  - W+jets
    Data-based
  - $t\bar{t}$ non-dilepton
    Prediction with POWHEG MC
- Agreement is excellent

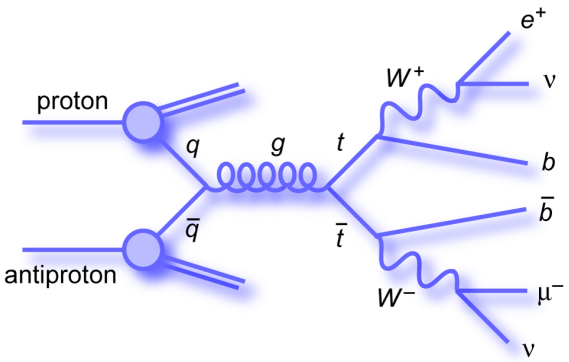
CDF Run II Preliminary (9.1 fb^{-1})

Expected and observed events ($t\bar{t} \to l^+l^- + 2\mathrm{jets} + \not{E}_T$)

Source	Events
Diboson	26±5
Z/γ^*+jets	37±4
W+jets	28±9
$t\bar{t}$ non-dilepton	5.3±0.3
Total background	96±18
Signal $t\bar{t}$ ($\sigma = 7.4$ pb)	386±18
Total SM expectation	482±36
Observed	495

$t\bar{t}$ Kinematic Reconstruction

- Need to reconstruct the $t\bar{t}$ 4-momenta
- Dilepton channel: **under-constrained system**
- Quadratic energy-momentum conservation equations
  - Two neutrino undetected, 6 unknown variables
  - 6 constraints (2 m_W, 2 m_t, $\vec{\not{E}}_T$)
  - **Multiple solutions exist**
- What makes it even more complicated
  - 2 lepton-jet pairings ($\mathrm{b} - \bar{\mathrm{b}}$ ambiguity) 2 sets of solutions
  - b-jet energy scaling, 2 more variables
  - $\vec{\not{E}}_T$ has large resolution, need to let them float, another 2 more variables



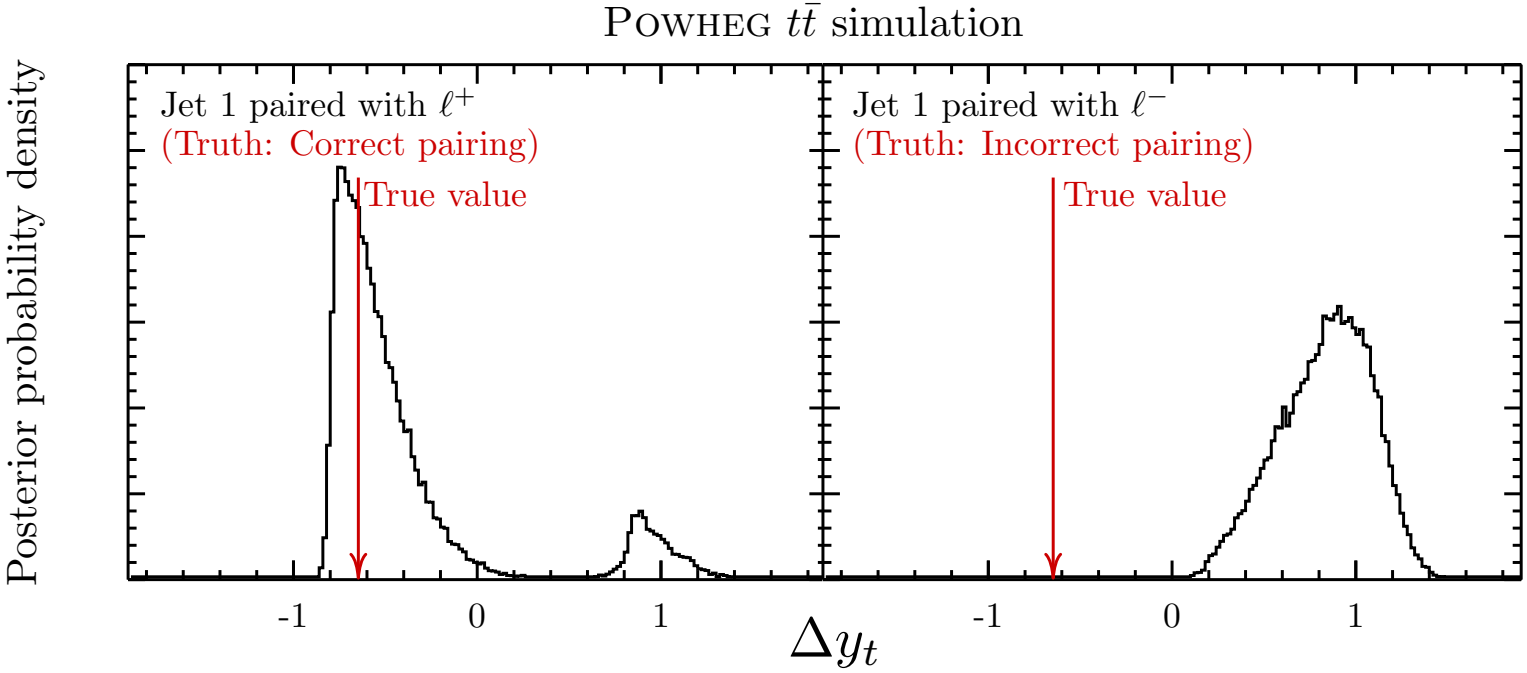
- 4-dimensional parameter space $\times$ 2 lepton-jet pairing choices

Full probability reconstruction

- 4-dimensional parameter space $\times$ 2 lepton-jet pairing choices
- A likelihood term quantifies the "goodness" of a solution
- Mapping out the full probability distribution of solutions using Markov-chain Monte Carlo
  - MCMC helps sample the parameter space efficiently
  - Used Bayesian Analysis Toolkit (BAT) for MCMC sampling (Comput. Phys. Commun. 180 (2009) 2197)

Reco. performance - Single event

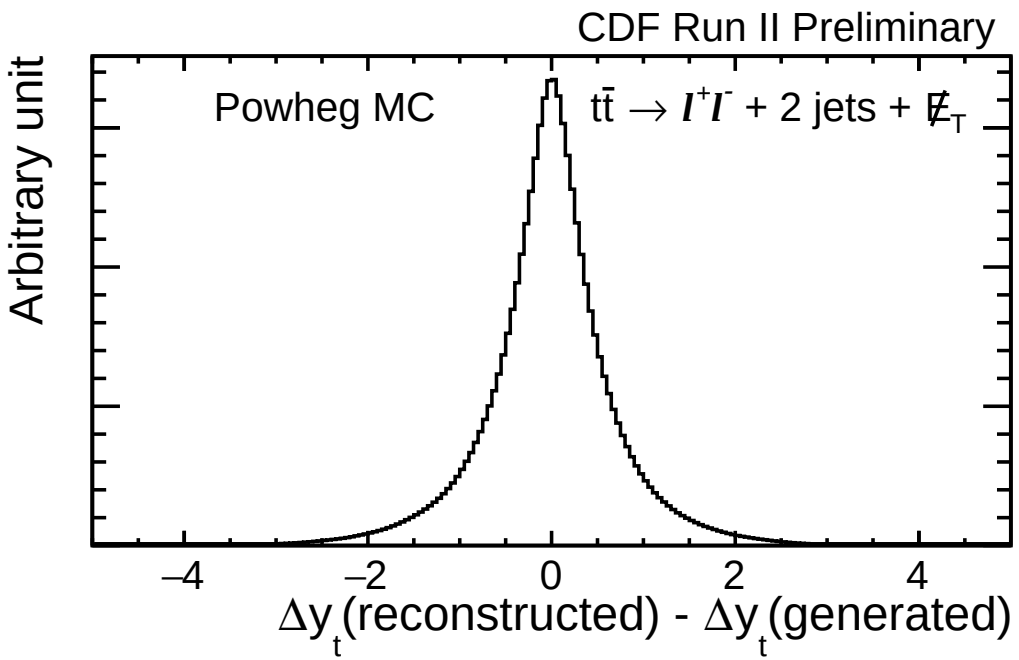
How well does the reconstruction do?



- Δy_t probability distribution from one (well-measured) event from simulation
- Two lep-jet pairings, multiple solution structure
- Use the full distribution in the measurement
  - It contains the maximum amount of information

Reco. performance - Δy resolution

How well does the reconstruction do?



POWHEG MC (NLO QCD)

- 61% having Δy_t reconstructed within 0.5 of truth value
- Unfold to extract parton-level $A_{\mathrm{FB}}^{t\bar{t}}$

Unfolding

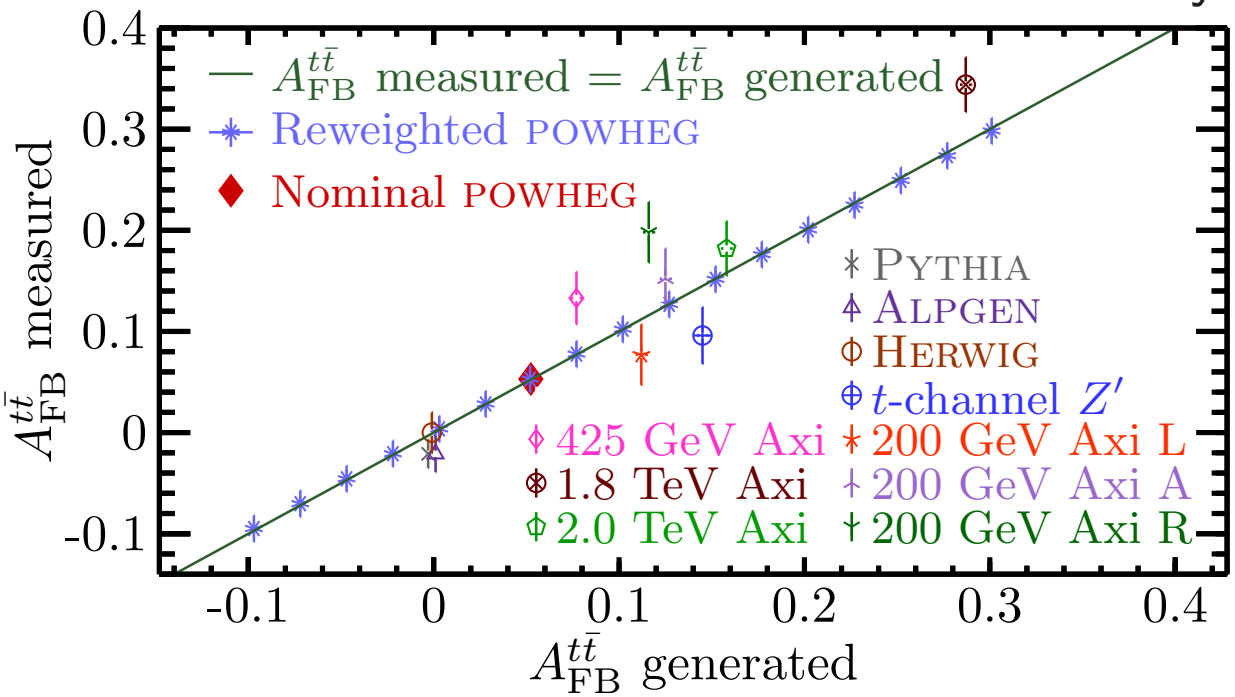
- Use these MC samples to create and vet an unfolding procedure to get truth-level $A_{\mathrm{FB}}^{t\bar{t}}$

$$\exp[r] = \sum_{t=1}^{4} \mathrm{truth}[t] * \mathrm{Eff}[t](A_{\mathrm{FB}}^{t\bar{t}}) * \mathrm{Det}[t][r] + \mathrm{bkg}[r]$$

- Compare observed events with the expectation $\exp[r]$ with compound Poisson distribution
- Include two effects in a Bayesian model
  - **Smearing** caused by detector response and $t\bar{t}$ reco
  - **Acceptance** imposed by detector coverage and **efficiency** caused by object ID and event selection
- Find truth-level $\mathrm{truth}[t]$ matches data best
- Truth-level $A_{\mathrm{FB}}^{t\bar{t}}$ obtained with $\mathrm{truth}[t]$

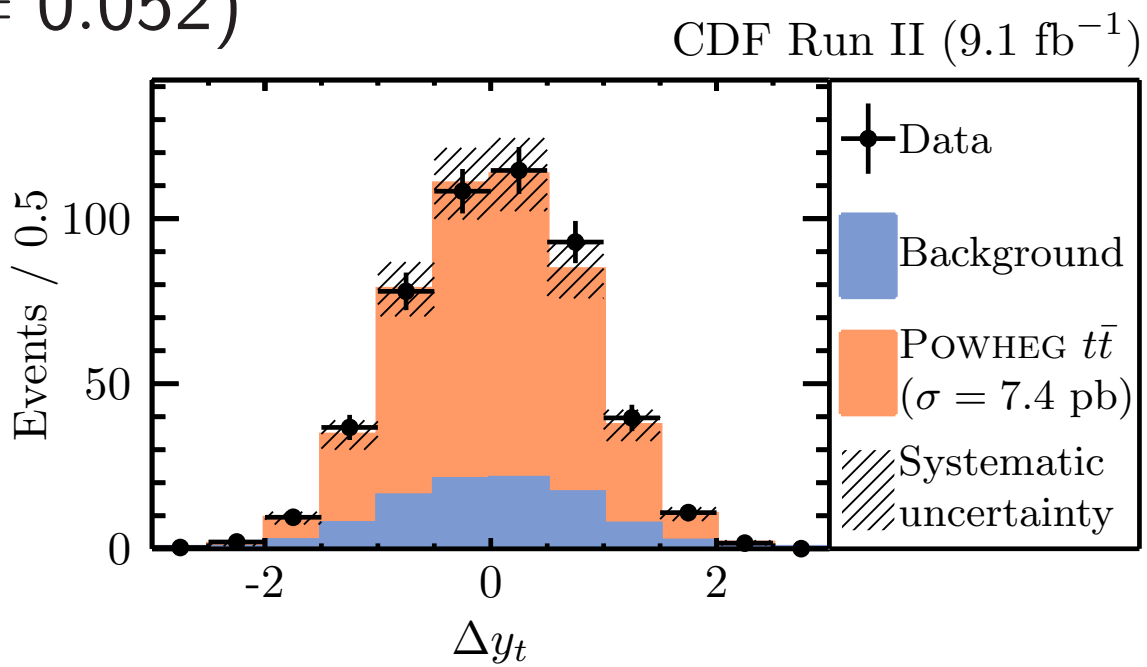
Unfolding: Extract $A_{\mathrm{FB}}^{t\bar{t}}$

- Use MCMC to find best parameters that match observation
- Extract $A_{\mathrm{FB}}^{t\bar{t}}$ from marginalized posterior distribution
- No bias with NLO based variations (reweighted POWHEG)
- BSM scenarios generated at LO, $p_T^{t\bar{t}}$ spectrum not realistic
  - Don't anticipate reco. & unfolding to work perfectly, though biggest deviation smaller than dominant uncertainty



Data

- Methodology fully vetted, now look at data
- Reconstructed Δy compared with POWHEG ($A_{\mathrm{FB}}^{t\bar{t}} = 0.052$)



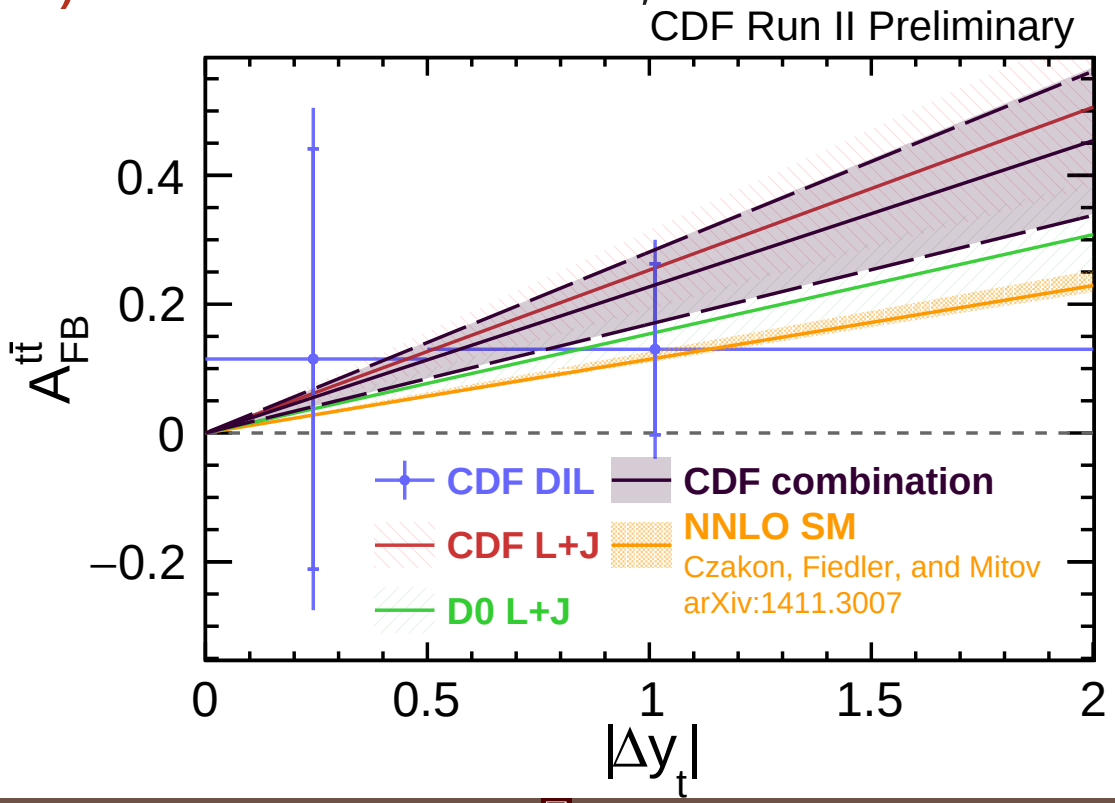
- $A_{\mathrm{FB}}^{t\bar{t}} = 0.12 \pm 0.11(\mathrm{stat}) \pm 0.07(\mathrm{syst})$
  $A_{\mathrm{FB}}^{t\bar{t}} = 0.12 \pm 0.13$
- Dominant uncertainty is statistical

$A_{\rm FB}^{t\bar{t}}$ from data

- Combined with CDF result in lepton+jets
- $\boxed{A_{\rm FB}^{t\bar{t}}(\text{CDF}) = 0.160 \pm 0.045}$
- Consistent with NNLO SM prediction
  $A_{\rm FB}^{t\bar{t}} = 0.095 \pm 0.007$ within 1.5σ

$A_{\mathrm{FB}}^{t\bar{t}}$ vs. Δy_t

- Also extracted $A_{\mathrm{FB}}^{t\bar{t}}$ vs. Δy_t from dilepton data
- Characterized by the slope α with zero intercept
- Combined all CDF measurements with a simultaneous fit for the slope α
- $\alpha(\mathrm{CDF}) = 0.277 \pm 0.057$, 2.0σ from NNLO SM



CDF top A_{FB} summary

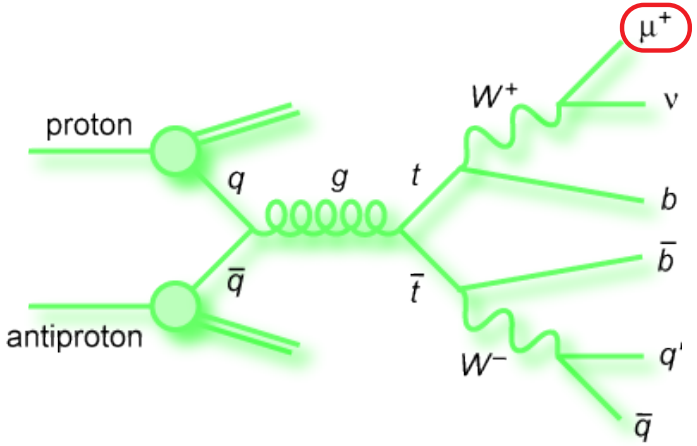
- Inclusive $A_{\mathrm{FB}}^{t\bar{t}}$ consistent with NNLO SM prediction within 1.5σ, differential result 2.0σ from NNLO SM
- Other top A_{FB} or related measurements at CDF?

- A_{FB}^{ℓ} and $A_{\mathrm{FB}}^{\ell\ell}$ based on leptons
- $b\bar{b}$ asymmetry measurements

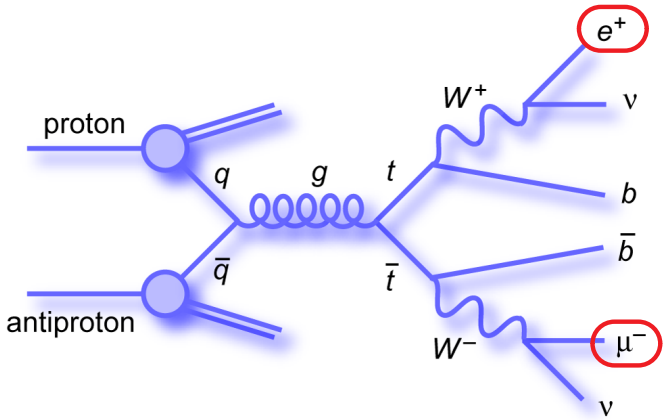
A^{ℓ}_{FB} and $A^{\ell\ell}_{FB}$

- Leptonic A_{FB}

$$A^{\ell}_{FB} = \frac{N(q_\ell \eta_\ell > 0) - N(q_\ell \eta_\ell < 0)}{N(q_\ell \eta_\ell > 0) + N(q_\ell \eta_\ell < 0)}$$



- Also lepton pair A_{FB} defined with lepton η difference, only in dilepton
  - Lepton angles precisely measured
  - Tend to follow direction of parent tops
  - Also carry information about top spin
- $A^{\ell}_{FB}(\mathrm{NLO, SM}) = 0.038 \pm 0.003$
  $A^{\ell\ell}_{FB}(\mathrm{NLO, SM}) = 0.048 \pm 0.004$
  PRD 86, 034026 (2012)

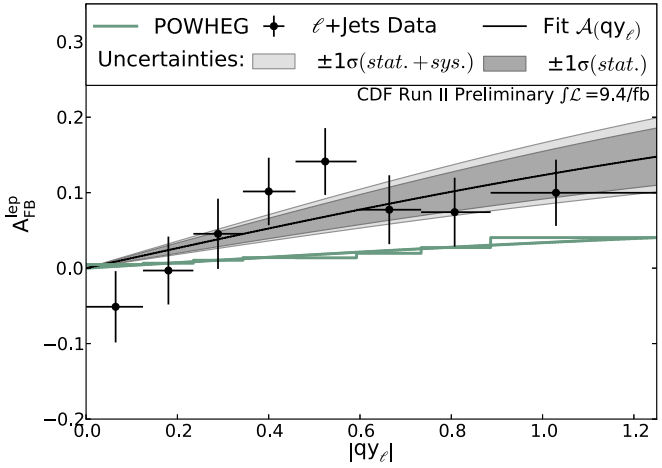


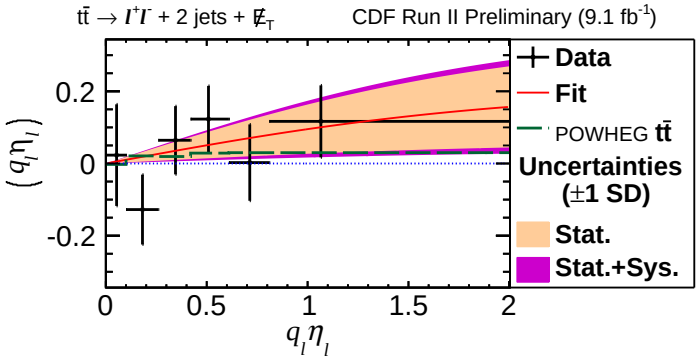
A^{ℓ}_{FB}: CDF lepton+jets & dilepton

$$A^{\ell}_{FB}(\mathrm{L+J}) = 0.094^{+0.032}_{-0.029} \;\&\; A^{\ell}_{FB}(\mathrm{DIL}) = 0.072 \pm 0.060$$

$$A^{\ell}_{FB}(\mathrm{CDF}) = 0.090^{+0.028}_{-0.026}$$

- Differential asymmetry ($A^{\ell}_{FB}(q_\ell \eta_\ell)$) is best sensitive observable
- Corrected for detector effects
- Parton-level measurement based on $a \cdot \tanh(\frac{1}{2} q_\ell \eta_\ell)$ modeling of $A^{\ell}_{FB}(q_\ell \eta_\ell)$
  - Methodology validated in PRD 90, 014040 (2014)
- CDF combination based on BLUE
- 2.0σ higher than NLO SM
- $A^{\ell\ell}_{FB}(\mathrm{CDF\ DIL}) = 0.076 \pm 0.082$, consistent with NLO SM





PRD 88, 072003 (2013)

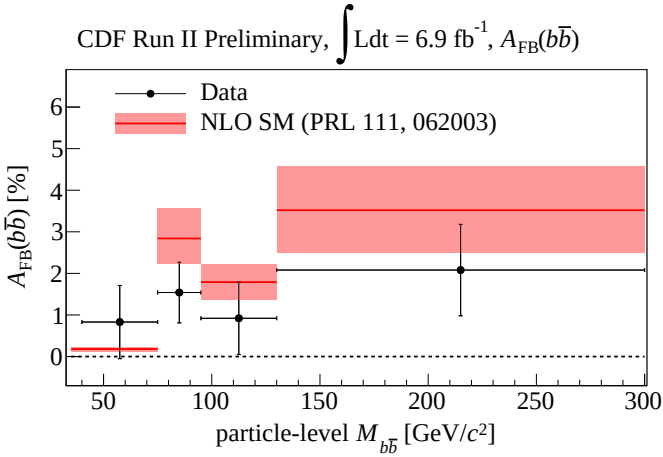
PRL 113, 042001 (2014)

$A_{FB}^{b\bar{b}}$

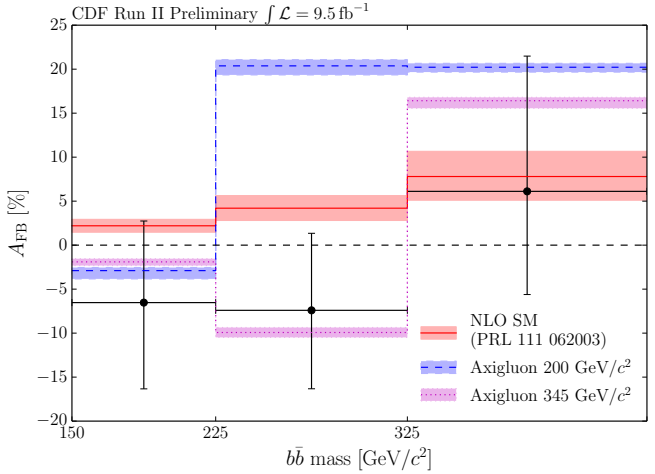
- If the $t\bar{t}$ production asymmetry is indeed non-SM, there is good reason to believe there should be observable effects in $b\bar{b}$ asymmetry
- Sensitive to axigluon hypothesis below $t\bar{t}$ threshold

$A_{FB}^{b\bar{b}}$ at CDF

- Low $b\bar{b}$ mass ($m_{b\bar{b}} > 40\mathrm{GeV/c^2}$)
  - Require a muon inside one b-jet and use it to identify quark charge
  - Result consistent with SM prediction, even some indication that we can see the electroweak A_{FB} at the Z pole
- High $b\bar{b}$ mass ($m_{b\bar{b}} > 150\mathrm{GeV/c^2}$)
  - Use momentum-weighted track charge sum to differentiate between b and $\bar{b}$
  - Result consistent with SM prediction
  - Exclude 200 $\mathrm{GeV/c^2}$ axigluon models



CDF Note 11156

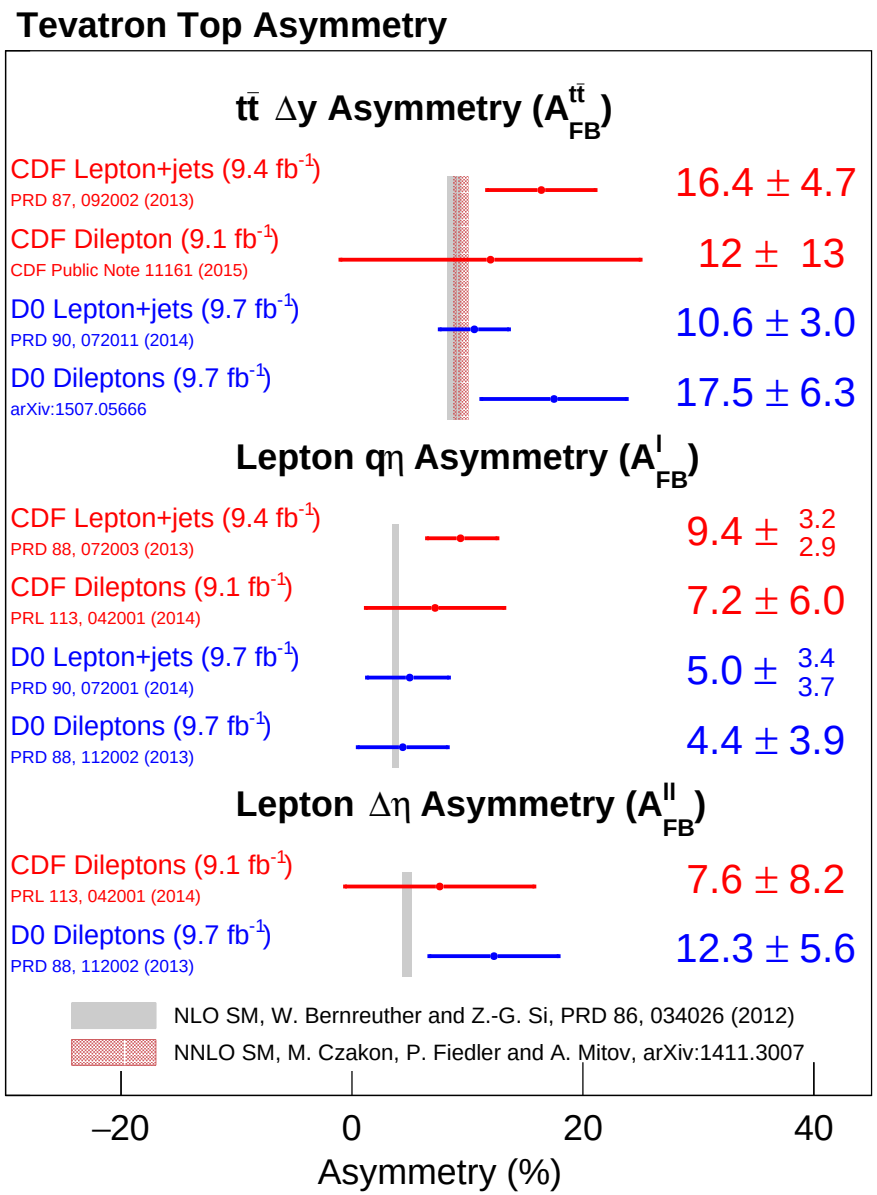


arXiv:1504.06888

Accepted by PRD

Top A_{FB} at CDF & Tevatron

- CDF inclusive A_{FB} consistent with predictions within 1.5σ
- Differential A_{FB} higher than predictions at 2σ level
- All results higher than quoted SM calculations
- Expect final Tevatron combination soon
- No anomaly shown in $b\bar{b}$ asymmetry



Conclusions: Top A_{FB}

- The A_{FB} of top-pairs at the CDF and Tevatron has been a hot topic for years
- Measurements of $A_{\mathrm{FB}}^{t\bar{t}}$, A_{FB}^{ℓ} and $A_{\mathrm{FB}}^{\ell\ell}$ provide complementary handles to probe the production and decay of $t\bar{t}$
- Last $A_{\mathrm{FB}}^{t\bar{t}}$ measurement in CDF dilepton done
- No clear sign of new physics
- Have been pushing top physics into a precision era
- NNLO calculation is really required!

Many thanks to the conference organizers!

Backup Slides

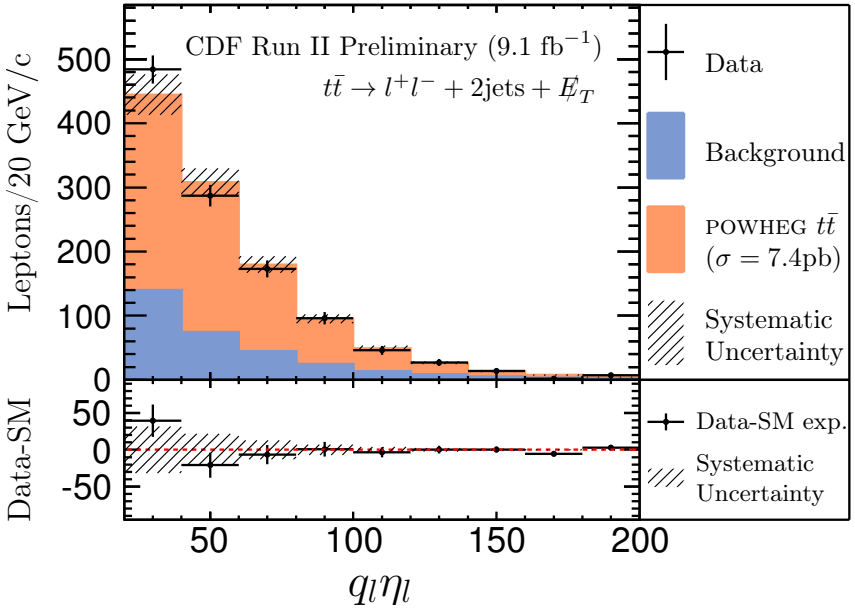
Backup slides

$t\bar{t} \rightarrow$ dilepton event selection criteria

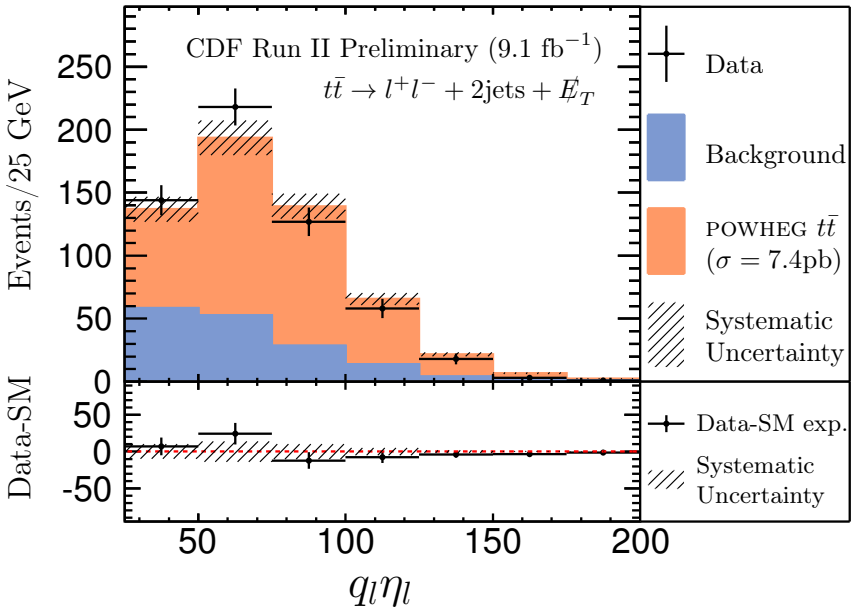
Baseline Cuts	Exactly two leptons with $E_T > 20$ GeV and passing standard identification requirements with following modifications -COT radius exit $>$ 140 cm for CMIO -$\chi^2/ndf < 2.3$ for muon tracks At least one trigger lepton At least one tight and isolated lepton At most one lepton can be loose and/or non-isolated
	$\not{E}_T > 25$ GeV, but $\not{E}_T > 50$ GeV when there is any lepton or jet within 20° of the direction of $\not{E}_T$
	MetSig $(= \frac{\not{E}_T}{\sqrt{E_T^{sum}}}) > 4\ \sqrt{\mathrm{GeV}}$ for ee and $\mu\mu$ events where 76 $\mathrm{GeV/c^2} < \mathrm{m_{ll}} < 106\ \mathrm{GeV/c^2}$
	$\mathrm{m_{ll}} > 10\ \mathrm{GeV/c^2}$
Signal Cuts	Two or more jets with $E_T > 15$ GeV within $\lvert\eta\rvert < 2.5$
	$\mathrm{H_T} > 200$ GeV
	Opposite sign of two leptons

$t\bar{t} \rightarrow$ dilepton
Signal and background modeling
Validation

Lepton p_T



$\not{E}_T$



Agreement is excellent

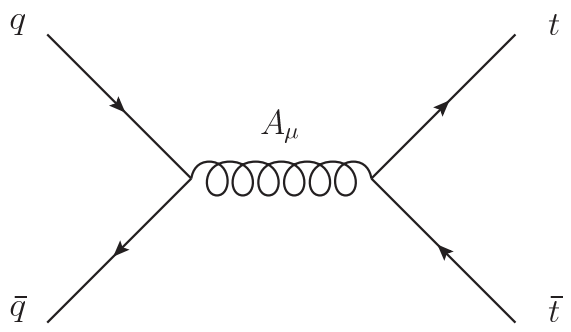
Alternative Signal Modeling

- What does the η_ℓ spectra look like in various scenarios?
  - Test the measurement with both SM and BSM models
- Simulate $t\bar{t}$ in various $t\bar{t}$ production mechanisms
  - SM sample: PYTHIA/ALPGEN (LO) and POWHEG (NLO)
  - Benchmark BSM model w/ axigluon
  - Many more simulated and studied
- Span large range of A_{FB}^{ℓ} and $A_{\mathrm{FB}}^{\ell\ell}$

Model	A_{FB}^{ℓ} (Parton Level)	$A_{\mathrm{FB}}^{\ell\ell}$ (Parton Level)	Description	
AxiL	-0.063(2)	-0.092(3)	Left-handed	Tree-level axigluon $m = 200\ \mathrm{GeV/c^2}$ $\Gamma = 50\ \mathrm{GeV}$
AxiR	0.151(2)	0.218(3)	Right-handed	
Axi0	0.050(2)	0.066(3)	Unpolarized	
ALPGEN	0.003(1)	0.003(2)	Tree-level Standard Model	
PYTHIA	0.000(1)	0.001(1)	LO Standard Model	
POWHEG	0.024(1)	0.030(1)	NLO Standard Model	
Calculation	0.038(3)	0.048(4)	NLO SM (PRD **86** 034026 (2012))	

$A_{\rm FB}^{\ell}$ at Tevatron

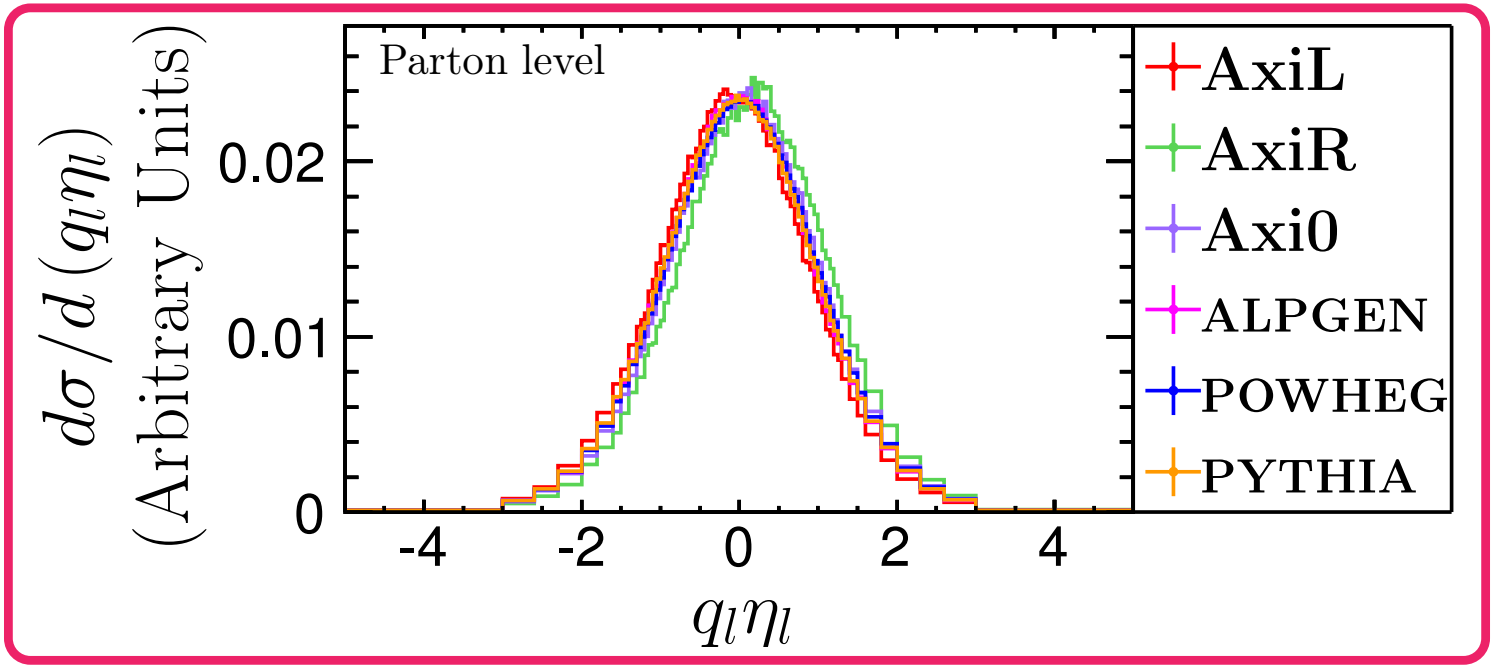
- NLO SM prediction: $A_{\rm FB}^{\ell} = 0.038 \pm 0.003$
  - Conventional renormalization scale ($\mu_R \sim m_t$) w/ EWK corrections.
  - No NNLO calculation yet
- Prediction with new physics?
- Based on CDF $A_{\rm FB}^{t\bar{t}}$ result (0.16 ± 0.05), assuming everything else SM-like: $0.070 < A_{\rm FB}^{\ell} < 0.076$
- In new physics models, correlations between $A_{\rm FB}^{t\bar{t}}$ and $A_{\rm FB}^{\ell}$ are model dependent
- **Independent measurements of $A_{\rm FB}^{t\bar{t}}$ and $A_{\rm FB}^{\ell}$ are crucial**



Example:
Axigluon model
(m = 200 $\mathrm{GeV/c^2}$,Γ = 50 GeV)
$\rightarrow A_{\rm FB}^{t\bar{t}} = 0.12$
$-0.06 < A_{\rm FB}^{\ell} < 0.15$
depending on handedness of couplings
(PRD **87**,034039 (2013))

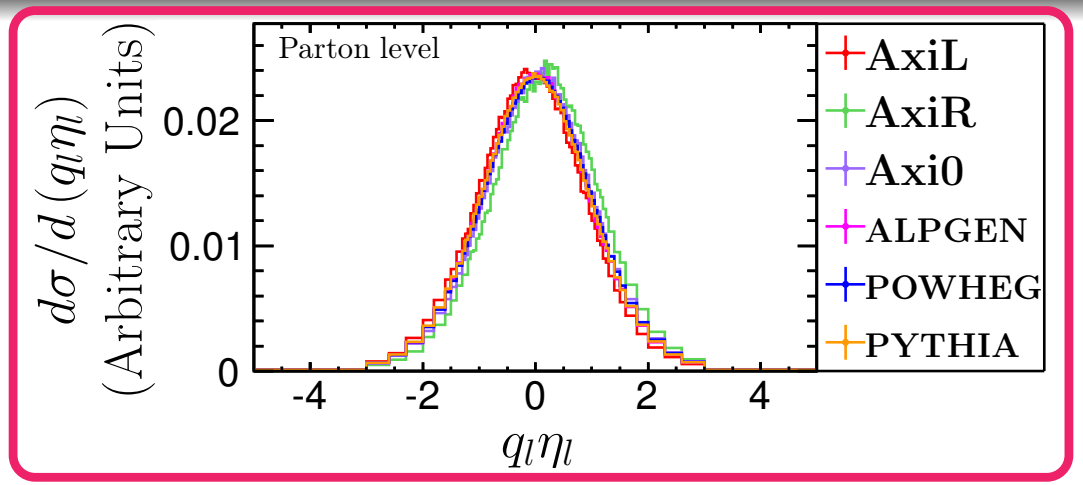
A_{FB}^{ℓ} Methodology - Introduction

$q_\ell \eta_\ell$ spectrum



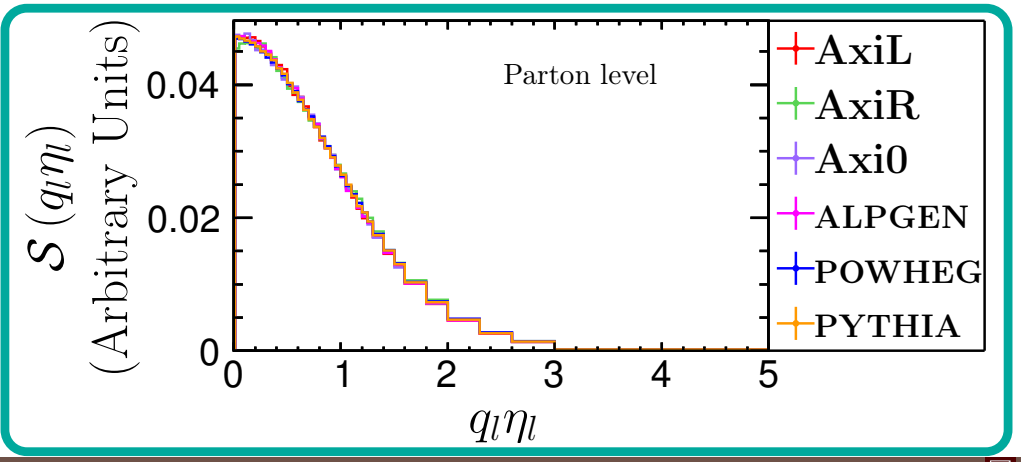
- Difference among models are small
  - Shapes almost identical, tiny shift in the mean
- Acceptance in detector limited
  - No acceptance beyond $|q_\ell \eta_\ell| = 2$
- Need a clever way to measure the subtle difference

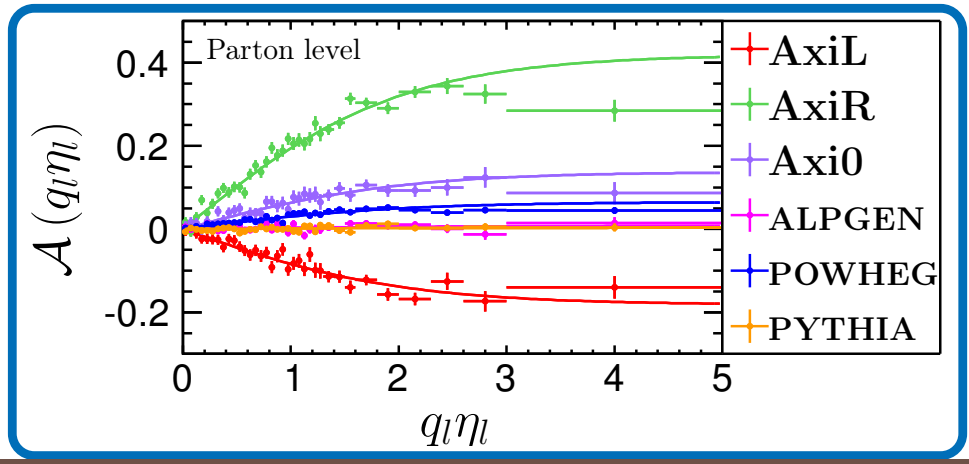
A_{FB}^{ℓ} Methodology - Introduction



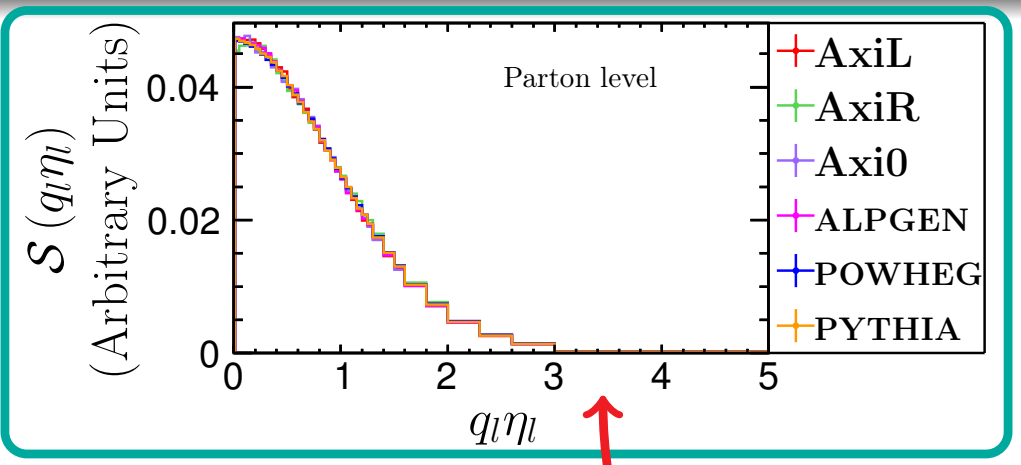
- Decomposition of $q_\ell\eta_\ell$ spectrum into symmetric and asymmetric components:

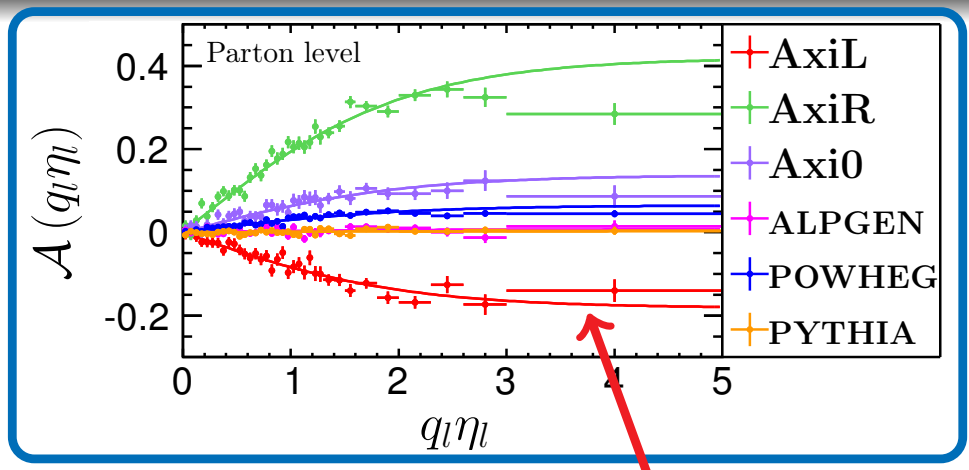
$$\mathcal{S}(q_\ell\eta_\ell) = \frac{\mathcal{N}(q_\ell\eta_\ell) + \mathcal{N}(-q_\ell\eta_\ell)}{2}; \mathcal{A}(q_\ell\eta_\ell) = \frac{\mathcal{N}(q_\ell\eta_\ell) - \mathcal{N}(-q_\ell\eta_\ell)}{\mathcal{N}(q_\ell\eta_\ell) + \mathcal{N}(-q_\ell\eta_\ell)}$$





A_{FB}^{ℓ} Methodology - Introduction





- $\mathcal{S}(q_\ell\eta_\ell)$ consistent among models
- $\mathcal{A}(q_\ell\eta_\ell)$ very different for different models
  - Sensitive to different values of A_{FB}^{ℓ}

Not well modelled for $q_\ell\eta_\ell > 2.5$

- $\mathcal{A}(q_\ell\eta_\ell)$ well modeled with $a \cdot \tanh(\frac{1}{2}q_\ell\eta_\ell)$

But contribution here is tiny

Detector only goes out to 2.0

  - Function empirically determined

A_{FB}^{ℓ} Measurement Methodology

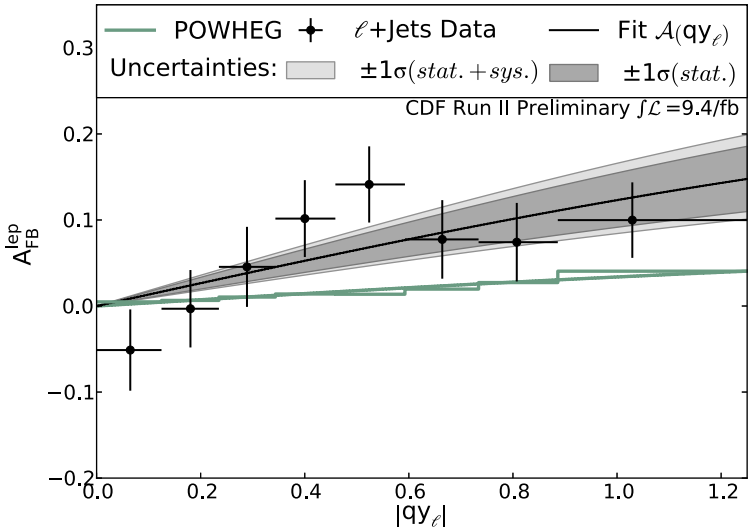
- A_{FB}^{ℓ} rewritten as

$$A_{\mathrm{FB}}^{\ell} = \frac{\int_0^\infty \mathrm{d}q_\ell\eta_\ell \mathcal{A}(q_\ell\eta_\ell)\mathcal{S}(q_\ell\eta_\ell)}{\int_0^\infty \mathrm{d}q'_\ell\eta'_\ell \mathcal{S}(q'_\ell\eta'_\ell)}$$

- A_{FB}^{ℓ} measurement in lepton+jets based on this decomposition and $a \cdot \tanh(\frac{1}{2}q_\ell\eta_\ell)$ modeling

$$A_{\mathrm{FB}}^{\ell} = 0.094^{+0.032}_{-0.029}$$

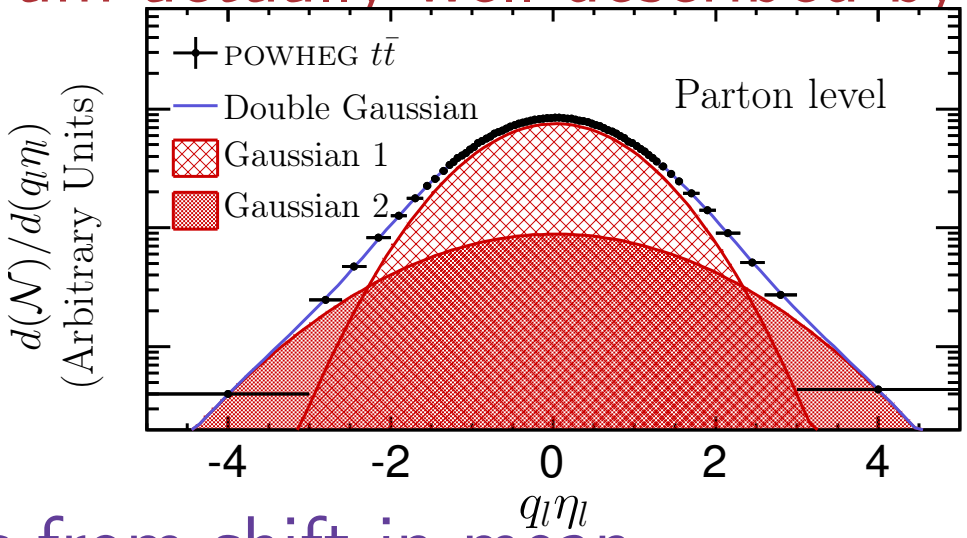
- 1.9σ larger than NLO SM



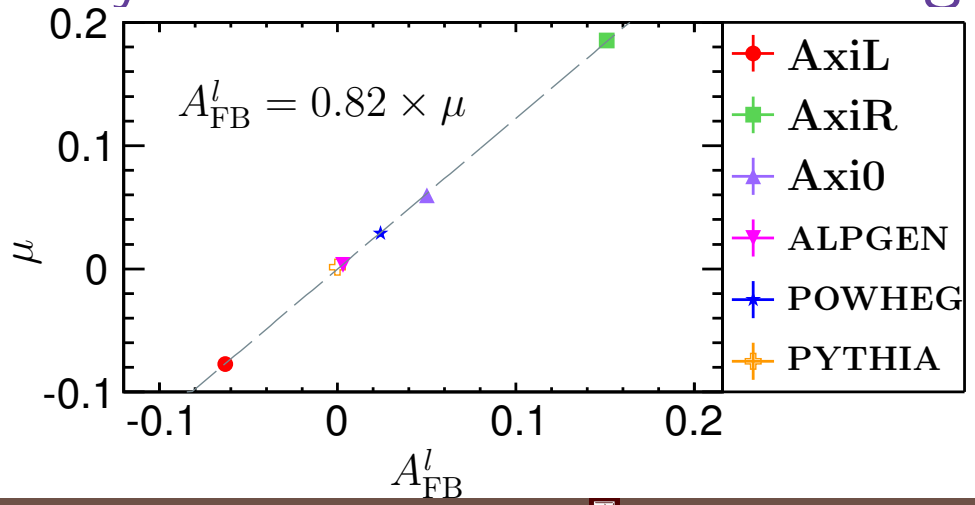
PRD **88** 072003 (2013), CDF

Why does the $a \cdot \tanh$ model work so well?

- $q_\ell \eta_\ell$ spectrum actually well described by a double-Gaussian



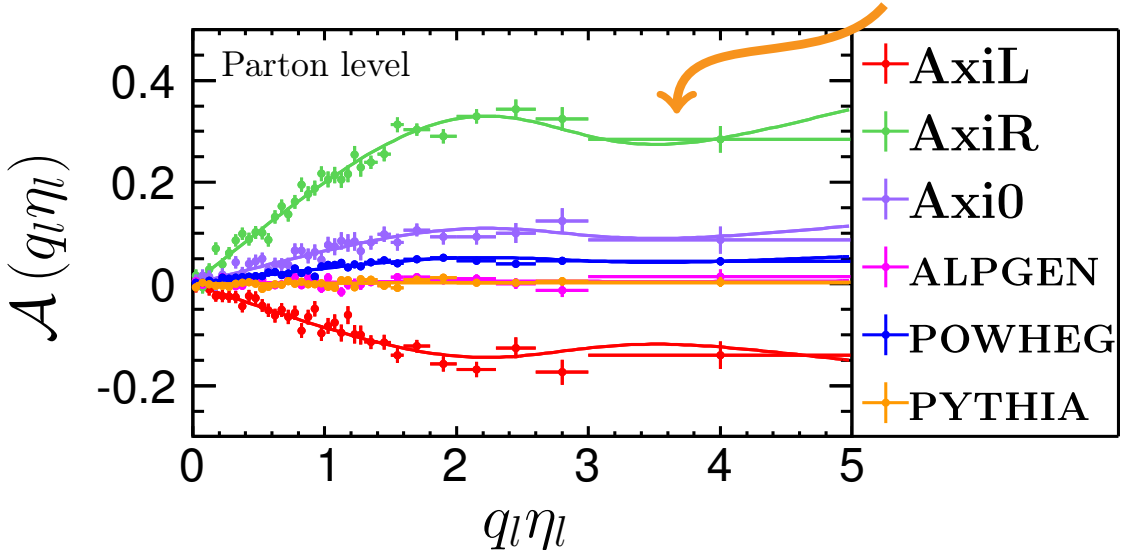
- $A_{\rm FB}^{\ell}$ comes from shift in mean
  $\rightarrow A_{\rm FB}^{\ell}$ linearly related with mean in regime of interest



Next few pages summarized in PRD **90**, 014040 (2014)
Z. Hong *et al.*

A_{FB}^{ℓ} Methodology Study

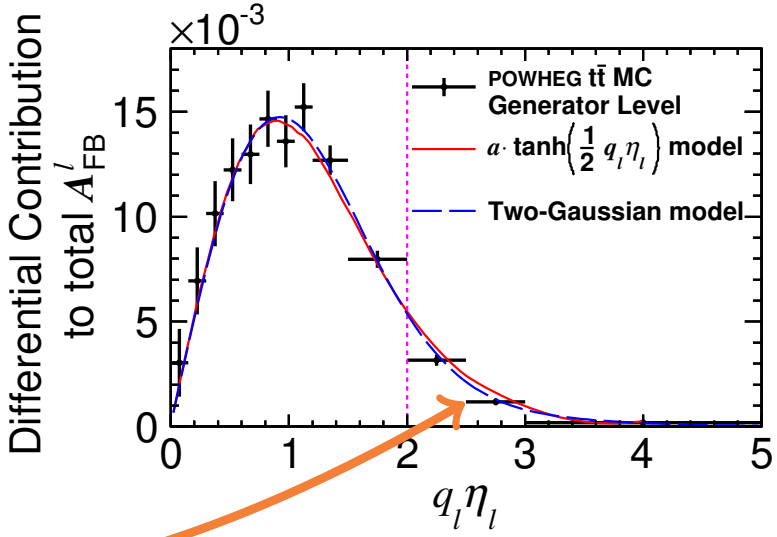
- Double-Gaussian does better job in modeling differential asymmetry in large $q_\ell \eta_\ell$ region



- $\mathcal{A}(q_\ell \eta_\ell)$ most sensitive way to measure A_{FB}^{ℓ}
  - Provides effective measure of mean
  - Acceptance of detector mostly cancels out

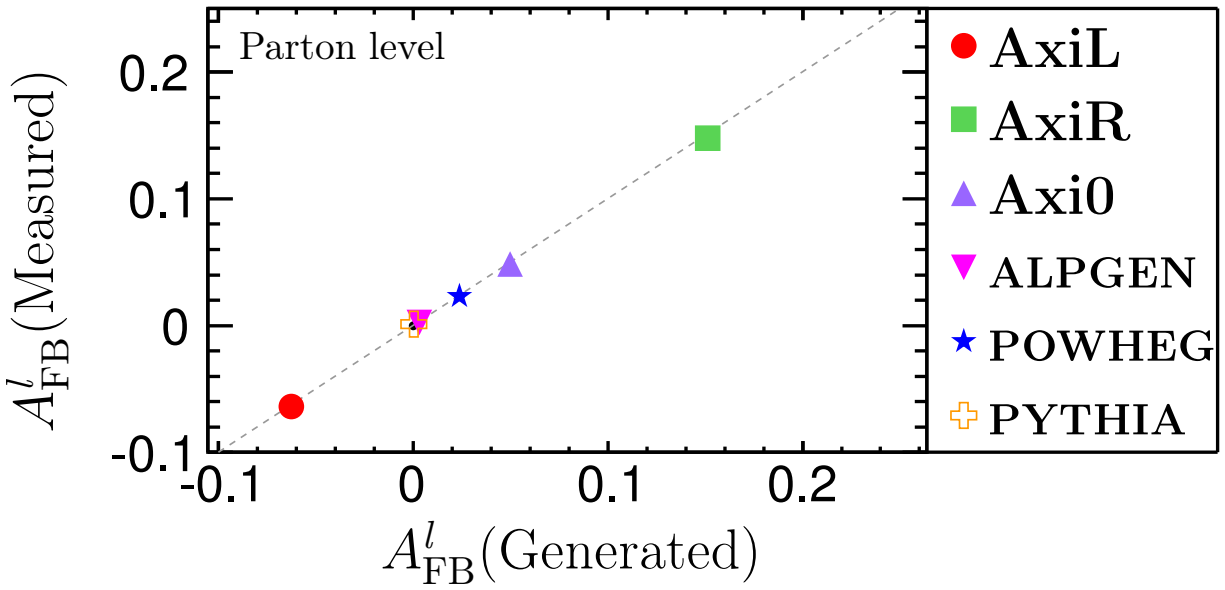
A_{FB}^{ℓ} Methodology Study

- Another way of looking at data: Differential contribution to A_{FB}^{ℓ}
- What do we learn?
  - Asymmetry mostly from $|\eta| < 2.0$
    - Best detector coverages here
  - $a \cdot \tanh\left(\frac{1}{2} q_\ell \eta_\ell\right)$ is excellent for $|q_\ell \eta_\ell| < 2.5$
  - Mismodeling in region with small contribution
  - More than good enough
- Moving forward with $a \cdot \tanh$ model with confidence



A_{FB}^{ℓ} Methodology - Introduction

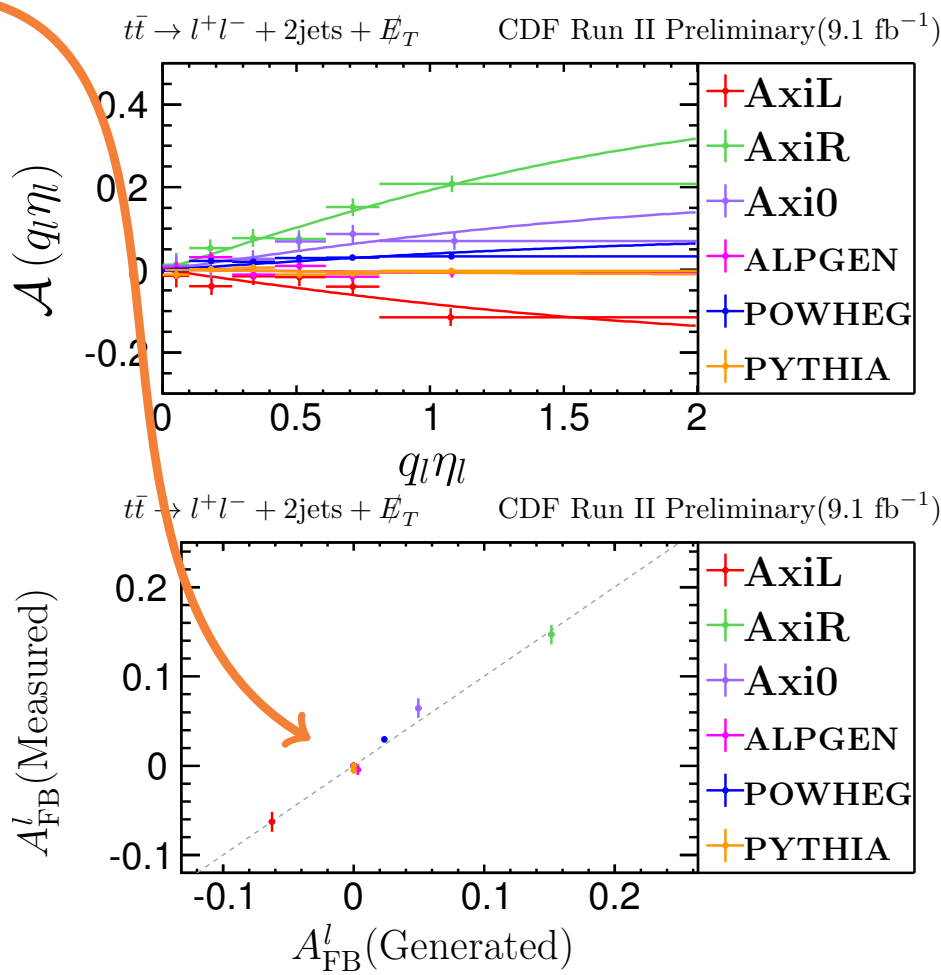
- $a \cdot \tanh$ model works well at parton level



- Does detector response affect the measurement?

A_{FB}^{ℓ} Methodology with Detector Response

- Detector response mostly cancels out in $\mathcal{A}(q_\ell \eta_\ell)$
- No noticeable bias observed
- Measurement strategy:
  - Subtract off backgrounds
  - Fit $\mathcal{A}(q_\ell \eta_\ell)$ with $a \cdot \tanh\left(\frac{1}{2} q_\ell \eta_\ell\right)$
  - Obtain $\mathcal{S}(q_\ell \eta_\ell)$ from POWHEG simulation at parton-level
  - Calculate A_{FB}^{ℓ} with $\mathcal{A}$ & $\mathcal{S}$
- Correct for detector response and extrapolate to inclusive A_{FB}^{ℓ} simultaneously



Systematic uncertainty of A_{FB}^{ℓ} measurement

CDF Run II Preliminary (9.1 fb^{-1})	
Source of Uncertainty (A_{FB}^{ℓ})	Value
Backgrounds	0.029
Asymmetric Modeling	0.006
Jet Energy Scale	0.004
Symmetric Modeling	0.001
Total Systematic	0.030
Statistical	0.052
Total Uncertainty	0.060

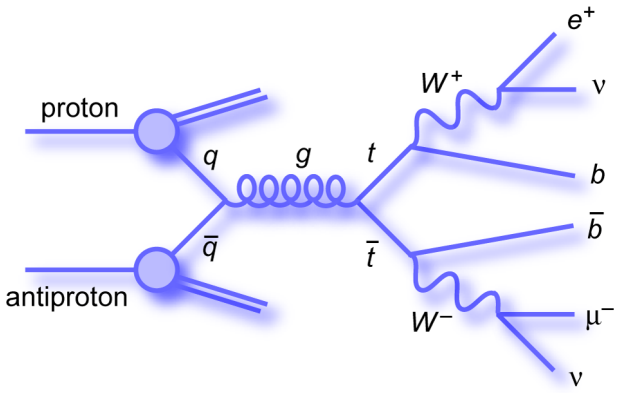
A_{FB}^{ℓ} CDF combination

CDF Run II Preliminary

Source of uncertainty	L+J (9.4fb^{-1})	DIL (9.1fb^{-1})	Correlation
Backgrounds	0.015	0.029	0
Recoil modeling (Asymmetric modeling)	$^{+0.013}_{-0.000}$	0.006	1
Symmetric modeling	-	0.001	
Color reconnection	0.0067	-	
Parton showering	0.0027	-	
PDF	0.0025	-	
JES	0.0022	0.004	1
IFSR	0.0018	-	
Total systematic	$^{+0.022}_{-0.017}$	0.030	
Statistics	0.024	0.052	0
Total uncertainty	$^{+0.032}_{-0.029}$	0.060	

$A_{\mathrm{FB}}^{\ell\ell}$

- Lepton pair A_{FB}
  - $$A_{\mathrm{FB}}^{\ell\ell} = \frac{N(\Delta\eta > 0) - N(\Delta\eta < 0)}{N(\Delta\eta > 0) + N(\Delta\eta < 0)}$$
- NLO SM prediction: $A_{\mathrm{FB}}^{\ell\ell} = 0.048 \pm 0.004$
- Larger expectations
- Only defined in dilepton, smaller statistics
- Provide extra information to help constraining new physics models



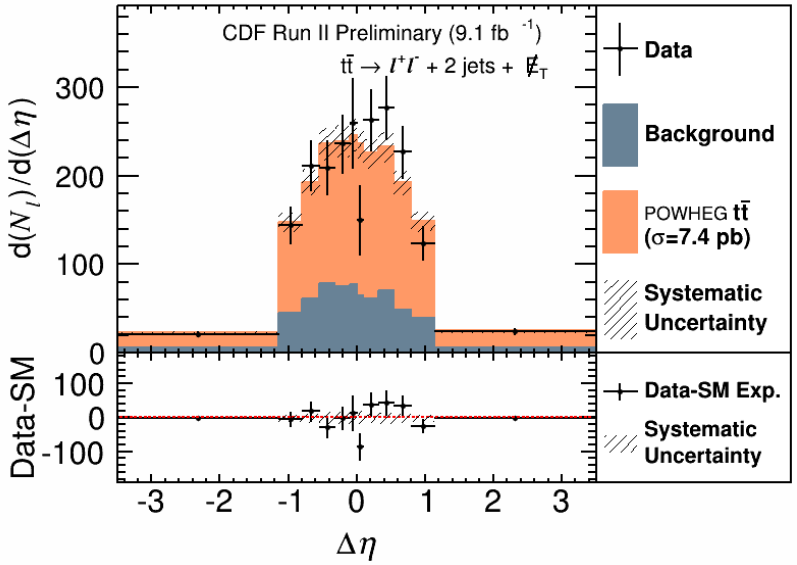
$A_{\mathrm{FB}}^{\ell\ell}$ in dilepton

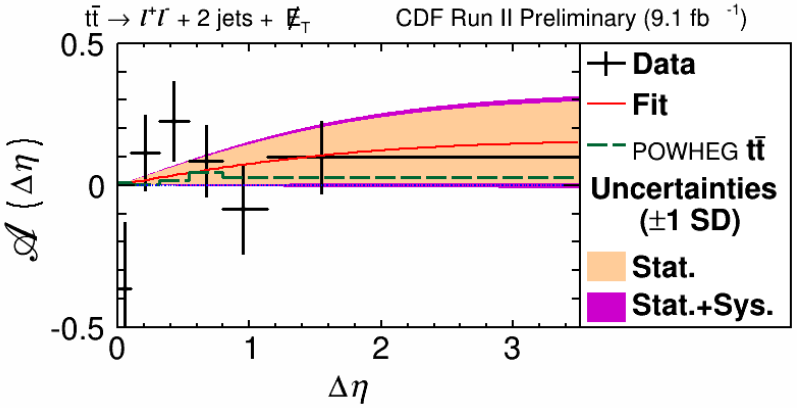
- Measurement techniques works equally well for $A_{\mathrm{FB}}^{\ell\ell}$
- Measure $A_{\mathrm{FB}}^{\ell\ell}$ with the same method

$$A_{\mathrm{FB}}^{\ell\ell} = 0.076 \pm 0.072(\mathrm{stat}) \pm 0.039(\mathrm{syst})$$
$$= 0.076 \pm 0.081$$

Cf. $A_{\mathrm{FB}}^{\ell}(\mathrm{SM,NLO}) = 0.048 \pm 0.004$

- Dominant uncertainty is statistical
- Result consistent with SM
- PRL **113**, 042001 (2014) (CDF)





Systematic uncertainty of $A_{\mathrm{FB}}^{\ell\ell}$ measurement

CDF Run II Preliminary (9.1 fb^{-1})	
Source of Uncertainty ($A_{\mathrm{FB}}^{\ell\ell}$)	Value
Backgrounds	0.037
Asymmetric Modeling	0.012
Jet Energy Scale	0.003
Symmetric Modeling	0.004
Total Systematic	0.039
Statistical	0.072
Total Uncertainty	0.082

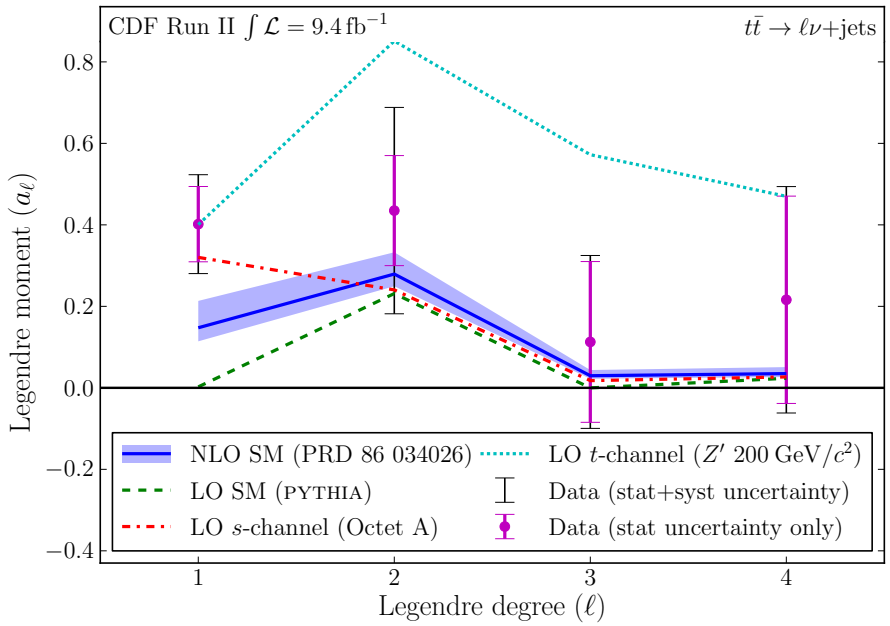
$t\bar{t}$ Reconstruction Equations

$$M^2_{l^+\nu} = (E_{l^+} + E_\nu)^2 - (\vec{p}_{l^+} + \vec{p}_\nu)^2 = M^2_W$$
$$M^2_{l^-\bar{\nu}} = (E_{l^-} + E_{\bar{\nu}})^2 - (\vec{p}_{l^-} + \vec{p}_{\bar{\nu}})^2 = M^2_W$$
$$M^2_{l^+\nu b} = (E_{l^+} + E_\nu + E_b)^2 - (\vec{p}_{l^+} + \vec{p}_\nu + \vec{p}_b)^2 = M^2_t$$
$$M^2_{l^-\bar{\nu}\bar{b}} = (E_{l^-} + E_{\bar{\nu}} + E_{\bar{b}})^2 - (\vec{p}_{l^-} + \vec{p}_{\bar{\nu}} + \vec{p}_{\bar{b}})^2 = M^2_t$$
$$(\vec{p}_\nu + \vec{p}_{\bar{\nu}})_x = (\not{E}_T)_x$$
$$(\vec{p}_\nu + \vec{p}_{\bar{\nu}})_y = (\not{E}_T)_y$$

$t\bar{t}$ Likelihood

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

Samples with varying $A_{\mathrm{FB}}^{t\bar{t}}$ for developing the unfolding model



PRL 111, 182002 (2013)
Parametrize $\cos\theta^*$ with Legendre Polynomials

- Motivated by CDF measurement of differential cross section in terms of Legendre polynomials
- The excess of $A_{\mathrm{FB}}^{t\bar{t}}$ comes in with an excess in the linear coefficient (a_1, 2.1σ)
- Reweight Powheg MC with various "excess" in a_1

Optimization

- Unfolding method validated, optimize before looking at data
  - Minimizing the expected uncertainty on $A_{\mathrm{FB}}^{t\bar{t}}$
- Big improvement by keeping more information
  - Keeping full probability distributions & weighting both lepton-jet pairings according to likelihoods
- Reject low-quality lepton-jet pairings, and the whole event if both pairings are rejected
  - Jet energy got dragged too far from measured values
  - m_{lb}^2 too high, not likely good top
  - Lepton lying on top of a jet
- Incorporate more information in weighting lepton-jet pairings
  - Track-momemtum-weighted jet charge

Table of uncertainties: Full set of results

CDF Run II Preliminary (9.1 fb^{-1})
$(t\bar{t} \to l^+l^- + 2\mathrm{jets} + \not{E}_T)$

Source of uncertainty $A_{\mathrm{FB}}^{t\bar{t}}$	Value
Statistical	0.11
Background	0.04
Parton Showering	0.03
Color reconnection	0.03
I/FSR	0.03
JES	0.02
Unfolding	0.02
PDF	0.01
Total systematic	0.07
Total uncertainty	0.13

- $A_{\mathrm{FB}}^{t\bar{t}} = 0.12 \pm 0.11(\mathrm{stat}) \pm 0.07(\mathrm{syst}) = 0.12 \pm 0.13$
- Result is dominated by statistical uncertainty
- Dominant systematic is Background

Optimization - performance

- Δy resolution and detector response matrix after optimization