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

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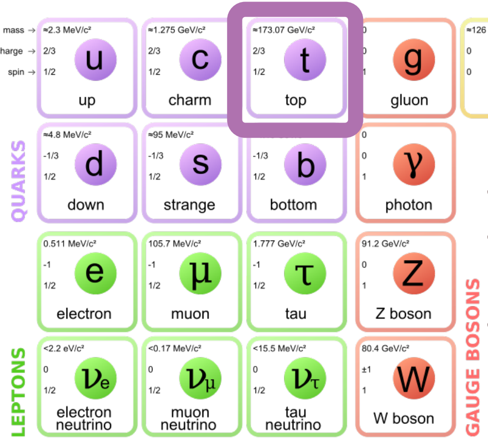
Dissertation Defense
Oct. 13, 2015

Top forward–backward asymmetry:
An exciting chase for new physics

- Hot topic at the Tevatron for years
- Will be glossing over the gory details and focusing on the measurement techniques, the data, and the interpretation of them

Table of contents for Top Asymmetry

The Standard Model - Top Quark



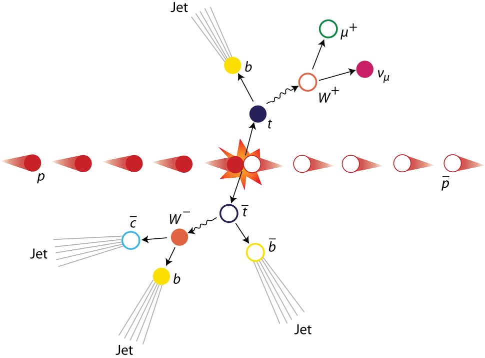
Top Quark

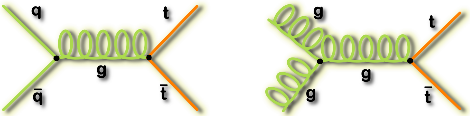
- Observed at Tevatron (1995)
- Very heavy
  - $m_t \simeq 173\ \mathrm{GeV/c^2}$
- Very short lived
  - No time to form hadrons
  - **Decay immediately after production**

Fascinating particle

Properties need to be further understood

Top-Quark Pair at the Fermilab **Tevatron**



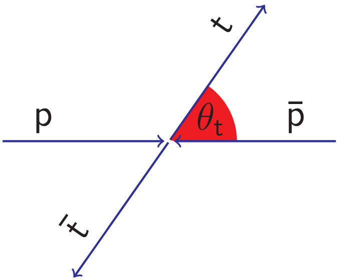


(a) (b)

- $p\bar{p}$ collision at Tevatron
  - Asymmetric initial state
  - ***pp* collision at LHC**
- Top quark (t) and top antiquark ($\bar{t}$) pair produced
  - 85% quark annihilation (a) 15% gluon fusion (b)
  - LHC is gluon fusion dominated
- $\sim$70,000 $t\bar{t}$ produced
- **Tevatron sensitive to certain top properties**

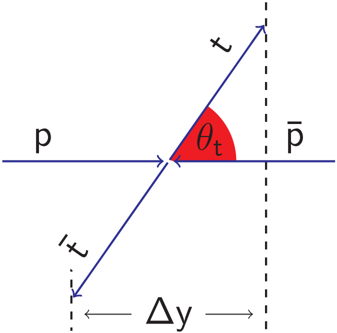
$t\bar{t}$ at Tevatron

- Cross-section, mass and width measured & agree with SM
- What else can we learn about $t\bar{t}$ produced at Tevatron?
- **Angular distribution**
- What direction do the top quarks go?



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

- **Angular distribution**



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

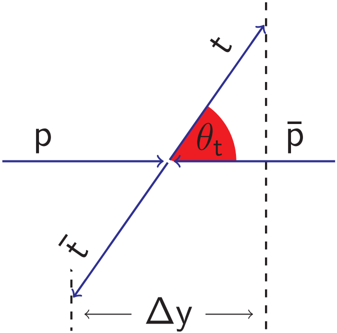
$$\Delta y = y_t - y_{\bar{t}}$$

- Simplest observable: forward–backward asymmetry (A_{FB})
- Does top quark prefer proton direction or the opposite?
- Quantified by rapidity difference between t and $\bar{t}$
    - Δy 1-1 mapped to θ_t
    - Invariant under longitudinal boost
- Define A_{FB} of $t\bar{t}$ production:

$$A_{\text{FB}}^{t\bar{t}} = \frac{N(\Delta y > 0) - N(\Delta y < 0)}{N(\Delta y > 0) + N(\Delta y < 0)}$$

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

- **Angular distribution**



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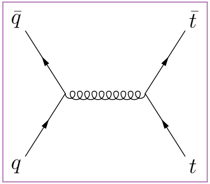
- Define A_{FB} of $t\bar{t}$ production:

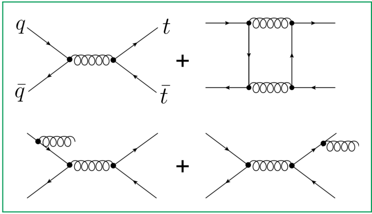
$$A_{FB}^{t\bar{t}} = \mathbf{P(top\rightarrow) - P(\leftarrow top)}$$

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**



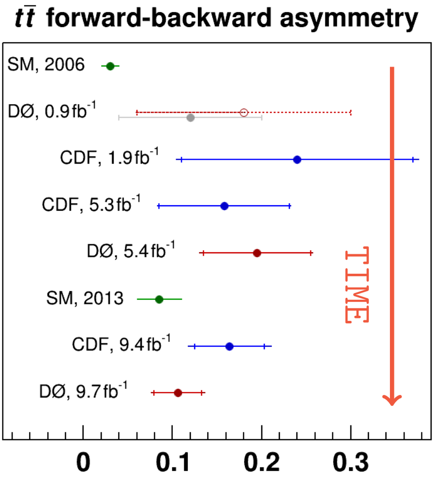
What does the SM predict?

- Original prediction suggests an asymmetry of 0.05
- Different SM calculation gives different answers (0.050-0.125)
- Benchmark NLO SM: $A_{FB}^{t\bar{t}} = 0.088 \pm 0.006$
  (PRD **86**,034026 (2012))
- Recent NNLO prediction: $A_{FB}^{t\bar{t}} = 0.095 \pm 0.007$
  (PRL **115**, 052001 (2015))
- aN^{3}LO: $A_{FB}^{t\bar{t}} = 0.100 \pm 0.006$
  (PRD **91**, 071502 (2015)(R))
- **SM calculation has been pushed forward by this measurement**

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

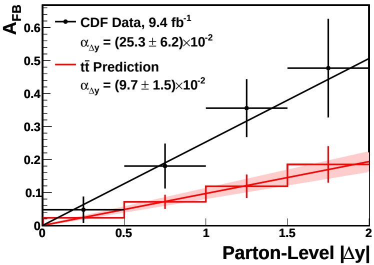
Previous experimental results?

- CDF: $A_{FB}^{t\bar{t}} = 0.164 \pm 0.047$
  (Lep+jets, PRD **87**, 092002 (2013))
- D0: $A_{FB}^{t\bar{t}} = 0.106 \pm 0.030$
  (Lep+jets, PRD **90**, 072011 (2014))
  $A_{FB}^{t\bar{t}} = 0.175 \pm 0.064$
  (Dilepton, PRD **92**, 052007 (2015))
- Final result from CDF in tension with aN^{3}LO SM calculation (0.100), with both results from D0 consistent with calculation



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

- Perhaps more important: $A_{FB}^{t\bar{t}}$ vs. Δy_t
  - Characterized by a linear function
  - Slope: 0.253 ± 0.062 (PRD **87**, 092002 (2012))
- 2.2σ higher than NNLO SM prediction
  - Slope: $0.114^{+0.005}_{-0.012}$ (PRL **115**, 052001 (2015))



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

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

- Calling for more accurate SM calculation?

Or

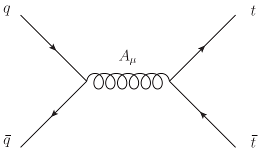
- Smoking gun for new physics?

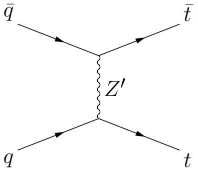
$A_{FB}^{t\bar{t}}$ at Tevatron

Possible alternative hypotheses?

Models beyond the SM can predict large $A_{FB}^{t\bar{t}}$

- Axigluons
- Flavor-changing Z' boson
- Beyond-SM W' boson
- Beyond-SM Higgs boson
- Extra dimensions
- ......





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

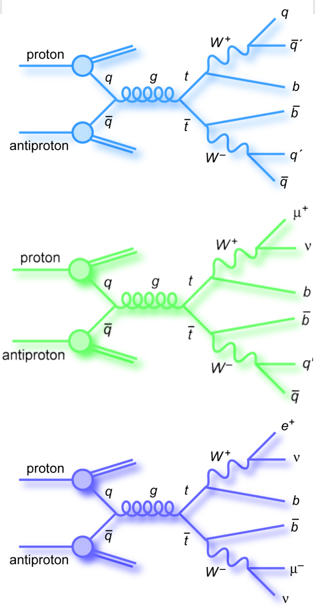
How to look for more evidence for/against new physics?

Pursue in two directions

- Measure $A_{\text{FB}}^{t\bar{t}}$ with more $t\bar{t}$ events in other final states
- Measure other related observables

Top-Quark Pair Decay Modes

- **How does the top quark decay?**
- $t \rightarrow Wb$ almost 100% of time
- Three types of final states based on W decay mode:



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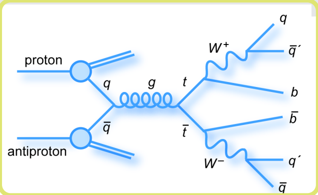
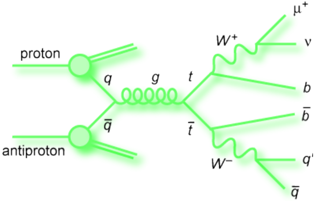
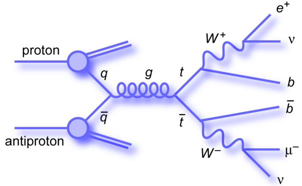
    - Large branching fraction
    - Hard to determine jet energy/charge
    - Hard to reconstruct $t\bar{t}$







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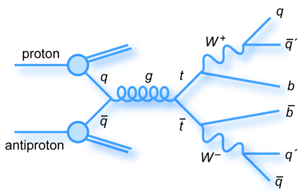
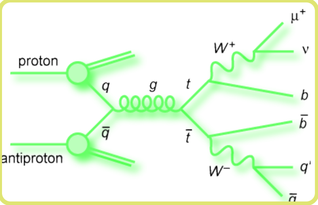
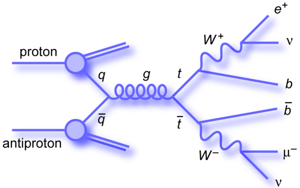
  - Lepton+jets←**Previous result**
    - Decent branching fraction
    - Lepton provides additional handle







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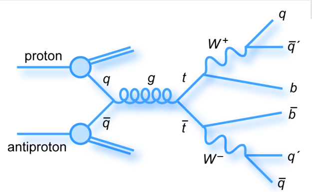
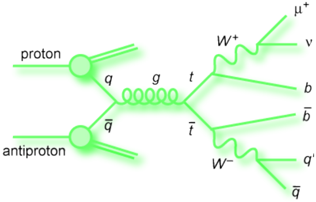
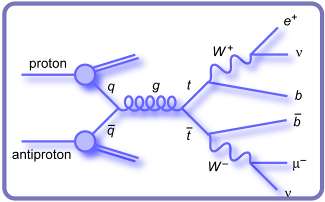
  - Lepton+jets$\leftarrow$**Previous result**
    - Decent branching fraction
    - Lepton provides additional handle
  - Dilepton $\leftarrow$**Focus of this talk**
    - Small branching fraction
    - Leptons precisely measured
    - Two ν's, hard to reconstruct $t\bar{t}$

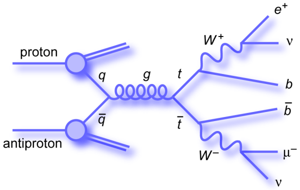






Additional $t\bar{t}$ events in dilepton

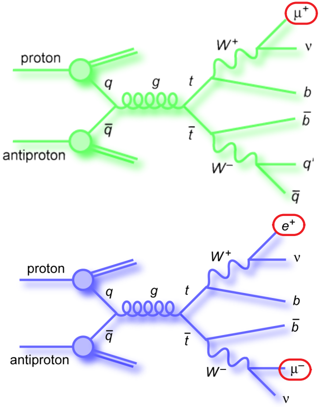
- Previous CDF measurement based on lepton+jets final state
- Can measure $A_{\mathrm{FB}}^{t\bar{t}}$ in dilepton



- Independent dataset with extended detector coverage, different background constitution and estimation methods
- Need to reconstruct 4-momenta of $t\bar{t}$
  $\rightarrow$Tough job in dilepton
- More on this later

Other observables?

- Besides $A_{FB}^{t\bar{t}}$, two equally important observables with leptons
- Leptonic A_{FB}
  - $$A_{FB}^{\ell} = \frac{N(q_\ell \eta_\ell > 0) - N(q_\ell \eta_\ell < 0)}{N(q_\ell \eta_\ell > 0) + N(q_\ell \eta_\ell < 0)}$$
- Also lepton pair A_{FB} defined with lepton η difference, only in dilepton
  - Details in backup.
- Why consider A_{FB}^{ℓ}?
  - Lepton angles precisely measured
  - Tend to follow direction of parent tops
  - Also carries top spin information



A^{ℓ}_{FB} at Tevatron

- Measurement of A^{ℓ}_{FB} in lepton+jets at CDF

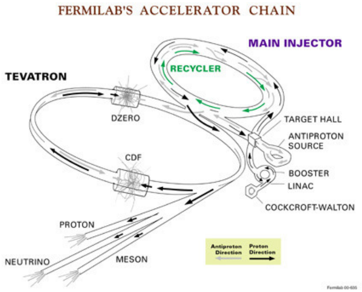
$$A^{\ell}_{\mathrm{FB}} = 0.094^{+0.032}_{-0.029}, \text{ PRD } \mathbf{88}, \text{ 072003 (2013)}$$

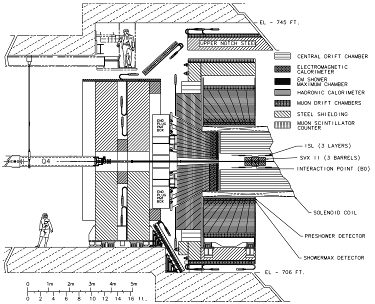
- 1.9σ larger than NLO SM calculation of 0.038 ± 0.003
- Large $A^{t\bar{t}}_{\mathrm{FB}}$ holds in A^{ℓ}_{FB} in the same dataset

Today

New results presented today:

1. **Confirm or deny this anomalous large asymmetry ($A_{\mathrm{FB}}^{t\bar{t}}$ and A_{FB}^{ℓ}) with the dilepton final state**
2. **What is the best-world-understanding of the A_{FB} results?**





Tevatron

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

CDF

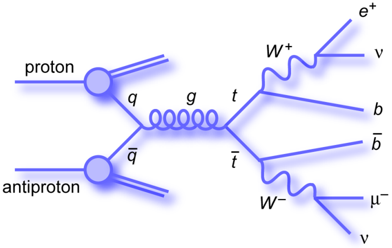
- General purpose detector
  - 1.4 T magnetic field
  - Tracking, Calorimeter and Muon systems
- Coverage in $t\bar{t}$ dilepton
  - Electron: $|\eta| < 2.0$
  - Muon : $|\eta| < 1.1$
  - Jets : $|\eta| < 2.5$

$t\bar{t} \rightarrow$ dilepton

- $A_{\mathrm{FB}}^{t\bar{t}}$ and A_{FB}^{ℓ} measurement in lepton+jets: *done*
- Go after the next important final state:
  $t\bar{t} \rightarrow$ dilepton

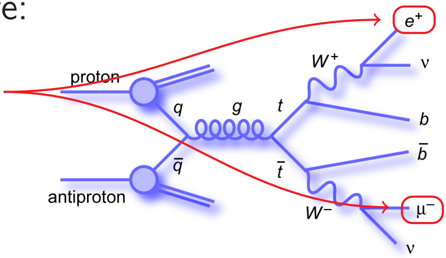
Event selection criteria

- Need a sample enriched by $t\bar{t}$ events with dilepton signature:



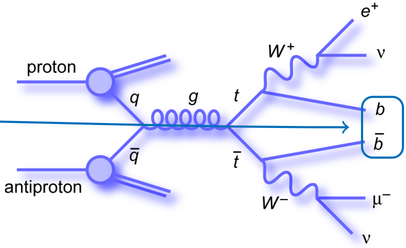
Event selection criteria

- Need a sample enriched by $t\bar{t}$ events with dilepton signature:
  - Two opposite charged leptons



Event selection criteria

- Need a sample enriched by $t\bar{t}$ events with dilepton signature:
  - Two opposite charged leptons
  - At least two jets



Event selection criteria

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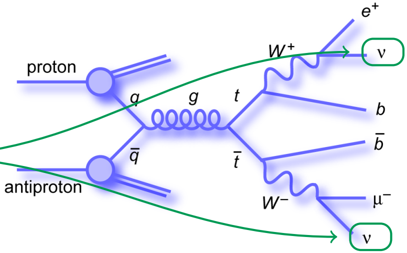
  - Large $\not\!\!E_T$ (imbalanced p_T)



Event selection criteria

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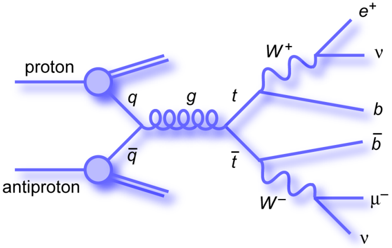
- Details of $t\bar{t}$ $\rightarrow$dilepton event selection criteria in the backups



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

Source	Events
Diboson	31.4±5.9
Z/γ^*+jets	50.5±6.2
W+jets fakes	64±17
$t\bar{t}$ non-dilepton	14.6±0.8
Total background	160±21
$t\bar{t}$ ($\sigma = 7.4$ pb)	408±19
Total SM expectation	568±40
Observed	569

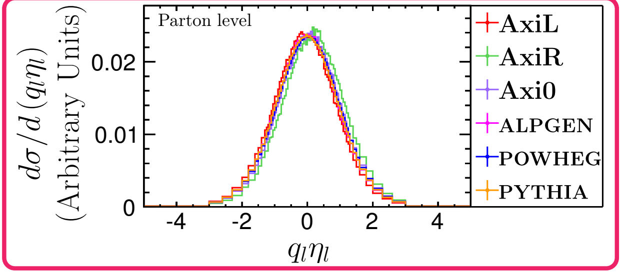
- Agreement is excellent (Maybe too good? Probably luck)

A_{FB}^{ℓ} Methodology

- **Start with $A_{\mathbf{FB}}^{\ell}$ measurement**

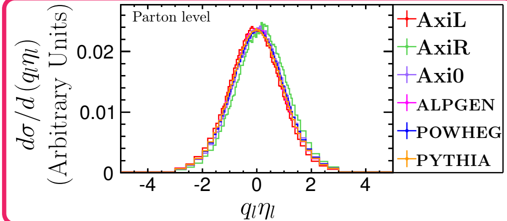
A_{FB}^{ℓ} Methodology

$q_\ell \eta_\ell$ spectrum



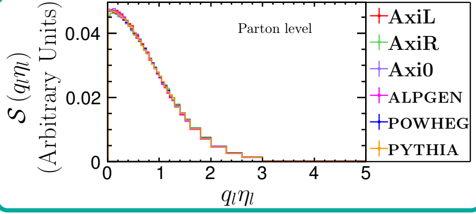
- Benchmark models with $-0.06 < A_{FB}^{\ell} < 0.15$
- Difference among models are small
  - Shapes almost identical, tiny shift in the mean
- Acceptance in detector limited
  - No acceptance beyond $|q_\ell \eta_\ell| = 2$
- Need a clever way to measure the subtle difference

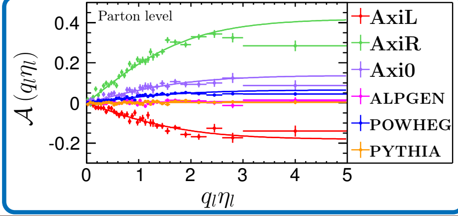
$A^{\ell}_{\rm FB}$ Methodology



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

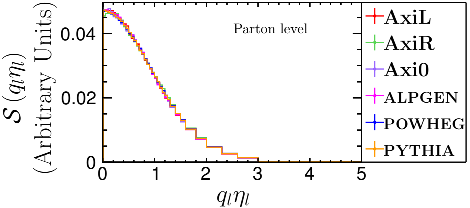
$$\mathcal{S}(q_\ell\eta_\ell) = \frac{\mathcal{N}(q_\ell\eta_\ell) + \mathcal{N}(-q_\ell\eta_\ell)}{2}; \mathcal{A}(q_\ell\eta_\ell) = \frac{\mathcal{N}(q_\ell\eta_\ell) - \mathcal{N}(-q_\ell\eta_\ell)}{\mathcal{N}(q_\ell\eta_\ell) + \mathcal{N}(-q_\ell\eta_\ell)}$$

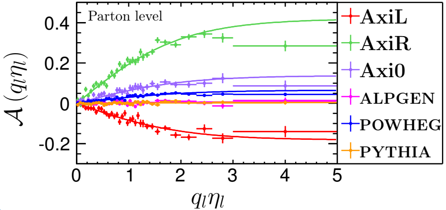




A_{FB}^{ℓ} Methodology

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





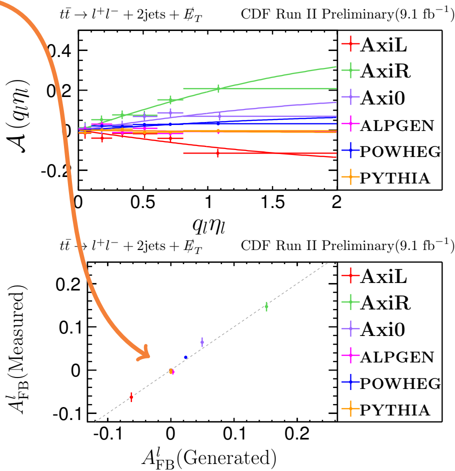
- $\mathcal{S}(q_\ell\eta_\ell)$ consistent among models
- $\mathcal{A}(q_\ell\eta_\ell)$ sensitive to different A_{FB}^{ℓ}
  - Well modeled with $a \cdot \tanh(\frac{1}{2}q_\ell\eta_\ell)$
- A_{FB}^{ℓ} rewritten as

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

Validation summarized as PRD **90**, 014040 (2014) Hong, Edgar, Henry, Toback, Wilson, Amidei

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



A_{FB}^{ℓ} in dilepton

- Measure A_{FB}^{ℓ} with CDF full dataset in dilepton ($9.1\ \mathrm{fb}^{-1}$)

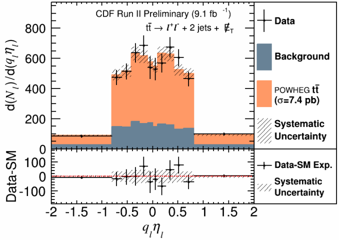
  $A_{FB}^{\ell} = 0.072 \pm 0.060$

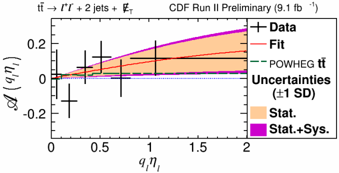
Cf. $A_{FB}^{\ell}(\mathrm{SM,NLO}) = 0.038 \pm 0.003$

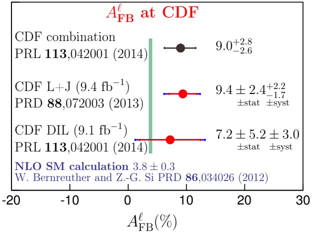
- Dominant uncertainty is statistical
- Table of systematics in backup
- Combined A_{FB}^{ℓ} measurements at CDF with BLUE
- Result is 2σ larger than NLO SM prediction:

$$A_{FB}^{\ell} = 0.090^{+0.028}_{-0.026}$$

- PRL **113**, 042001 (2014) (CDF)







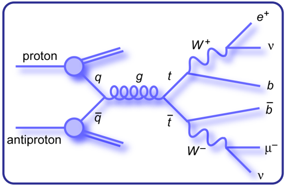
A_{FB}^{ℓ} in dilepton and CDF combination

- Conclusion: observed large A_{FB}^{ℓ} in dilepton as well, continue pursuing $A_{\mathrm{FB}}^{t\bar{t}}$ measurement in dilepton

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

$t\bar{t}$ Momenta Reconstruction

- Need to reconstruct the momenta of t and $\bar{t}$
- Quadratic energy-momentum conservation equations
  - Two neutrino undetected, 6 unknown variables
  - 6 constraints (2 m_W, 2 m_t, $\vec{\not{E}}_T$)
  - Up to **4** solutions
- What makes it even more complicated
  - 2 lepton-jet pairings ($b - \bar{b}$ ambiguity): 2 sets of solutions
  - Jet energy and $\vec{\not{E}}_T$ comes with large resolution Need to let them float within their uncertainties, 4 more variables



- Under-constrained system, 4-dimensional parameter space × 2 lepton-jet pairing choices

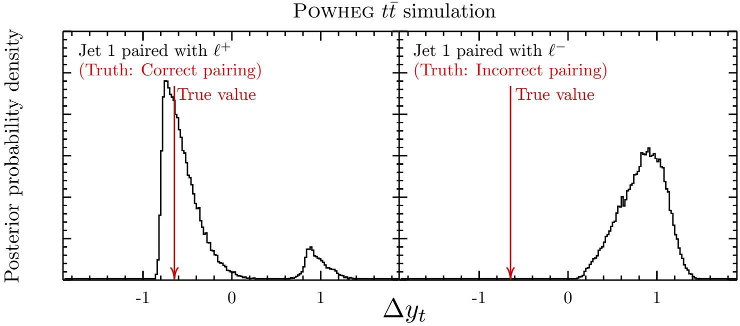
MCMC based full probability reconstruction

- 4-dimensional parameter space × 2 lepton-jet pairing choices
  - Each point in the space represents a valid $t\bar{t}$ pair
- A likelihood quantifies the "goodness" of a solution
  - How likely the measured leptons, jets, and $\vec{\not{E}}_T$ originates from this $t\bar{t}$ pair
- Mapping out the full probability distribution of solutions using Markov-chain Monte Carlo
  - Bayesian Analysis Toolkit (BAT)

    (Comput. Phys. Commun. 180 (2009) 2197)
- Computationally intensive algorithm (2 mins/event)
  - Fully utilized the Brazos Cluster for over a month (`brazos.tamu.edu`, 3000 cores)
  - Special thanks to the Brazos team!

Reco. performance - Single event

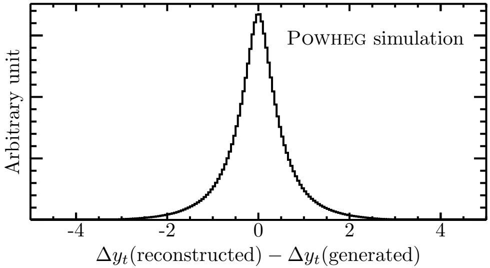
How well does the reconstruction do?



- 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 measured within 0.5 of truth value
- Need a sophisticated methodology to measure $A_{FB}^{t\bar{t}}$ at the **parton level**
  - As if it were measured with the the top quarks before they decay

$A_{FB}^{t\bar{t}}$ Measurement Methodology

- Need a measurement procedure for parton-level inclusive $A_{FB}^{t\bar{t}}$
    - So that results can be directly comparable to theoretical predictions
- Correct for two effects:
    - Not able to measure all events
        - Limited detector coverage
        - Imperfect event selection efficiency
    - Not able to measure Δy_t correctly for events we do have a measurement
        - Finite detector response resolution
        - Imperfect $t\bar{t}$ momenta reconstruction

$A_{\mathrm{FB}}^{t\bar{t}}$ Measurement Methodology

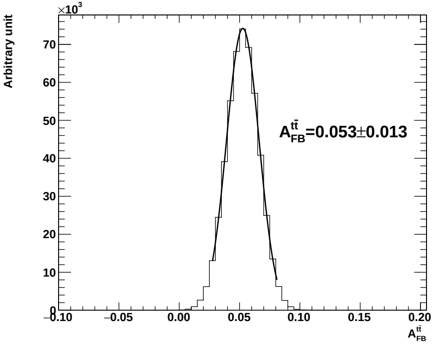
- Use a Bayesian inference model

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

- Compare observed events with the expectation $\exp[r]$ with compound Poisson distribution
- Include two effects in the 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 parton-level $\mathrm{parton}[p]$ matches data best
- Parton-level $A_{\mathrm{FB}}^{t\bar{t}}$ obtained with $\mathrm{parton}[p]$

Extract $A_{FB}^{t\bar{t}}$

- To extract parton-level $A_{FB}^{t\bar{t}}$, run MCMC to find most probable parameters that match observation
- Extract $A_{FB}^{t\bar{t}}$ from marginalized posterior distribution
- POWHEG sample with 10M events gives 0.053 ± 0.013 with 0.0524 generated



Methodology works!

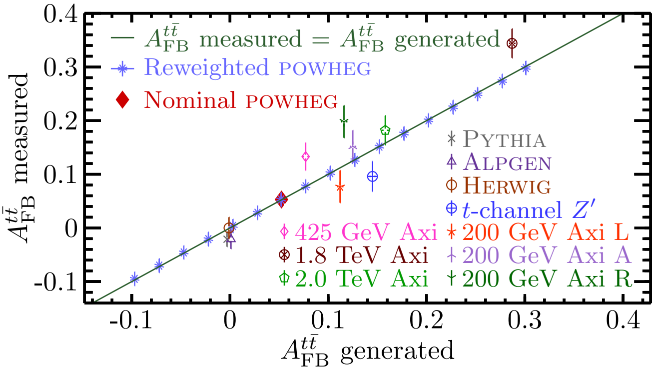
Optimization

- Optimize before looking at data
  - Minimize the expected uncertainty on $A_{FB}^{t\bar{t}}$
- Two categories of actions done:
  - Use more information in the measurement
    - Keep full probability distributions than pick the most probable solution
    - Weight both lep-jet pairings with likelihoods
    - Add information from jet charge
  - Reject $t\bar{t}$ with low reconstruction quality
    - Jet energy dragged too far from measured values
    - m_{lb}^2 too high, not likely good top
    - Lepton lying on top of a jet
    - Signal efficiency of 95% with background rejection of 40%

$\sigma(A_{FB}^{t\bar{t}}) =$ **0.144 before optimization and 0.114 after**

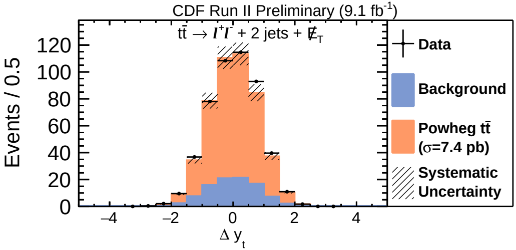
Bias test

- Compare $A_{FB}^{t\bar{t}}$ extracted with $A_{FB}^{t\bar{t}}$ generated
- No bias with SM or SM-like samples (reweighted POWHEG)
- Don't anticipate measurement to work perfectly in BSM scenarios
  - BSM scenarios calculated at LO, with known defects in $p_T^{t\bar{t}}$.



Data - Event yields

- Methodology vetted, now look at data
- Data event yield agrees with expected
- Reconstructed Δy compared with POWHEG ($A_{FB}^{t\bar{t}} = 0.052$) shown below



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

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

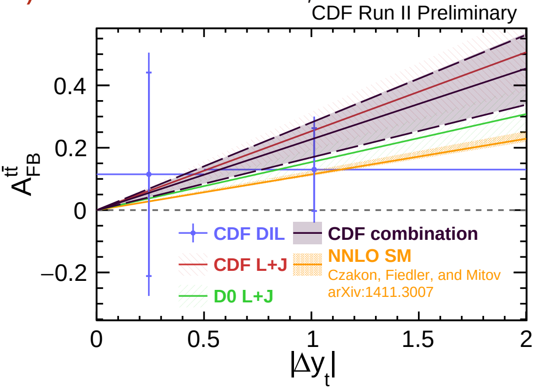
Source	Events
Diboson	26 ± 5
Z/γ^*+jets	37 ± 4
W+jets	28 ± 9
$t\bar{t}$ non-dilepton	5.3 ± 0.3
Total background	96 ± 18
Signal $t\bar{t}$ ($\sigma = 7.4$ pb)	386 ± 18
Total SM expectation	482 ± 36
Observed	495

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

- Applied the measurement to dilepton data
- $A_{\mathrm{FB}}^{t\bar{t}} = 0.12 \pm 0.11(\text{stat}) \pm 0.07(\text{syst})$
  $A_{\mathrm{FB}}^{t\bar{t}} = 0.12 \pm 0.13$
- Dominant uncertainty is statistical
- Table of systematics in backups
- Combined with CDF result in lepton+jets
- $A_{\mathrm{FB}}^{t\bar{t}}(\text{CDF}) = 0.160 \pm 0.045$
- Consistent with aN^{3}LO SM prediction
  $A_{\mathrm{FB}}^{t\bar{t}} = 0.100 \pm 0.006$ within 1.5σ
- Manuscript in preparation, to be submitted to PRD

$A_{FB}^{t\bar{t}}$ vs. Δy_t

- Also extracted $A_{FB}^{t\bar{t}}$ 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
- $\alpha(\text{CDF}) = 0.277 \pm 0.057$, 2.0σ from NNLO SM

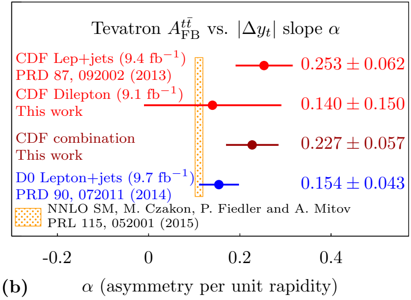


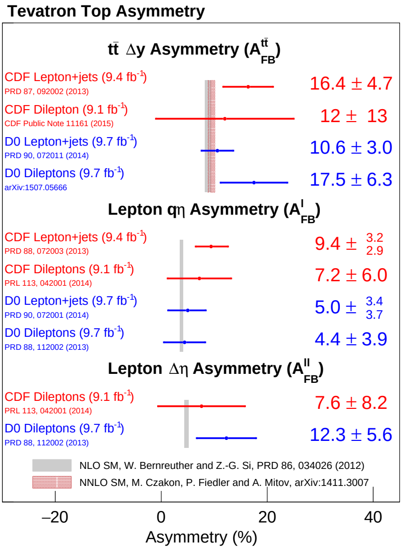
Best-world understanding of top A_{FB}

What is the best-world understanding of top A_{FB}?

Final word on A_{FB} from Tevatron

- All results consistent but higher than NLO (and NNLO) SM predictions





Conclusions: Top A_{FB}

- The A_{FB} of top-pairs at the 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 $t\bar{t}$
- All Tevatron legacy top A_{FB} measurement done
- No clear sign of new physics, which is kind of disappointing
- Have been pushing top physics calculation to higher precision
- **Either way it has been an exciting chase for new physics**

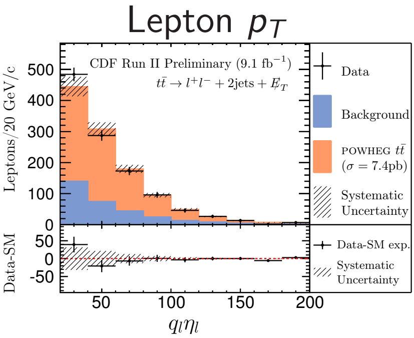
Backup Slides

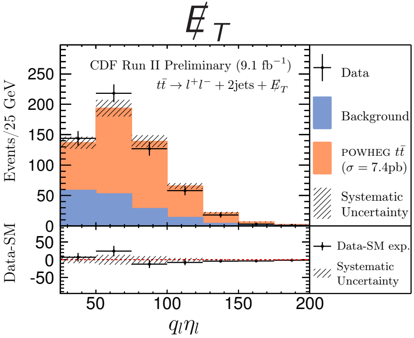
Backup slides

$t\bar{t} \to$ 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 $\|\eta\| < 2.5$
	$\mathrm{H_T} > 200$ GeV
	Opposite sign of two leptons

Validation





Agreement is excellent

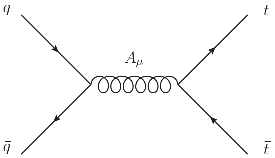
Alternative Signal Modeling

- 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^{ℓ}_{FB} and $A^{\ell\ell}_{\mathrm{FB}}$

Model	A^{ℓ}_{FB} (Parton Level)	$A^{\ell\ell}_{\mathrm{FB}}$ (Parton Level)	Description	
AxiL	-0.063(2)	-0.092(3)	Left-handed	Tree-level axigluon $m = 200$ GeV/c^2 $\Gamma = 50$ 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_{FB}^{ℓ} at Tevatron

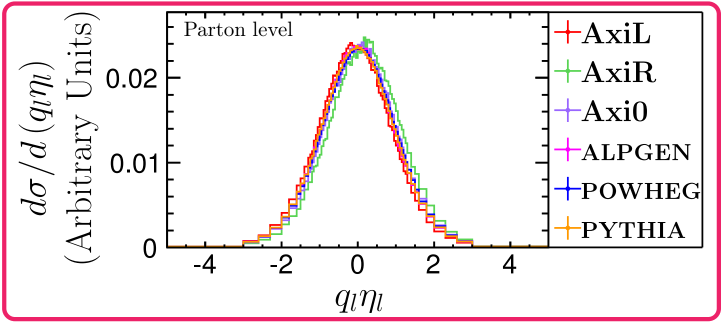
- NLO SM prediction: $A_{FB}^{\ell} = 0.038 \pm 0.003$
  - Conventional renormalization scale ($\mu_R \sim m_t$) w/ EWK corrections.
  - No NNLO calculation yet
- Prediction with new physics?
- Based on CDF $A_{FB}^{t\bar{t}}$ result (0.16 ± 0.05), assuming everything else SM-like: $0.070 < A_{FB}^{\ell}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



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

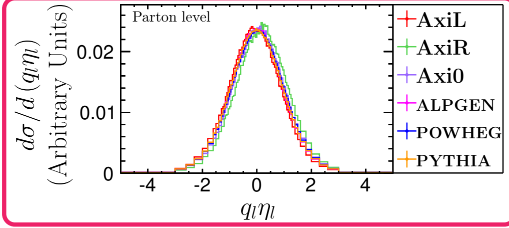
A^{ℓ}_{FB} Methodology - Introduction

$q_\ell \eta_\ell$ spectrum



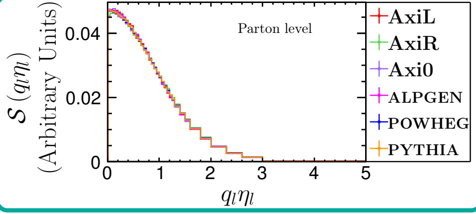
- Difference among models are small
  - Shapes almost identical, tiny shift in the mean
- Acceptance in detector limited
  - No acceptance beyond $|q_\ell \eta_\ell| = 2$
- Need a clever way to measure the subtle difference

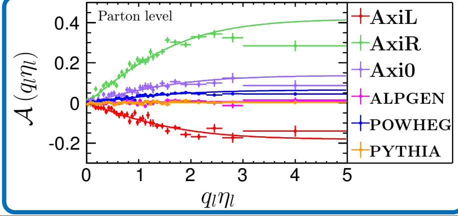
A_{FB}^{ℓ} Methodology - Introduction



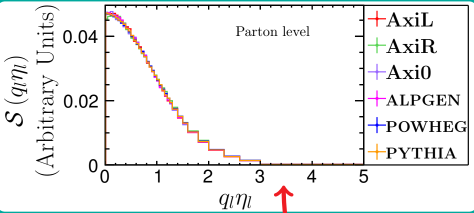
- Decomposition of $q_\ell\eta_\ell$ spectrum into symmetric and asymmetric components:

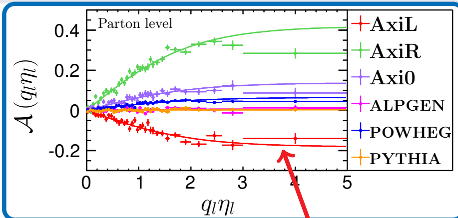
$$\mathcal{S}(q_\ell\eta_\ell) = \frac{\mathcal{N}(q_\ell\eta_\ell) + \mathcal{N}(-q_\ell\eta_\ell)}{2}; \mathcal{A}(q_\ell\eta_\ell) = \frac{\mathcal{N}(q_\ell\eta_\ell) - \mathcal{N}(-q_\ell\eta_\ell)}{\mathcal{N}(q_\ell\eta_\ell) + \mathcal{N}(-q_\ell\eta_\ell)}$$





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

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

But contribution here is tiny

Detector only goes out to 2.0

A_{FB}^{ℓ} Measurement Methodology

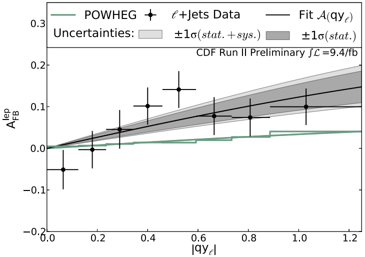
- A_{FB}^{ℓ} rewritten as

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

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

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

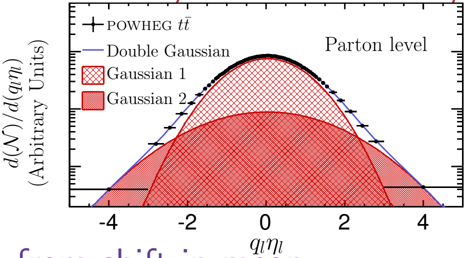
- 1.9σ larger than NLO SM



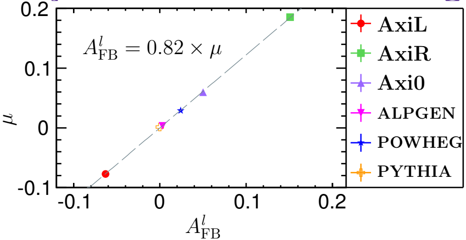
PRD **88** 072003 (2013), CDF

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

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



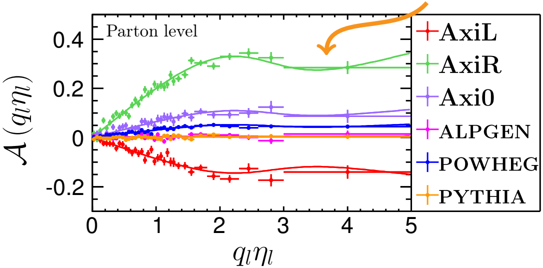
- A_{FB}^{ℓ} comes from shift in mean
  $\rightarrow A_{FB}^{\ell}$ linearly related with mean in regime of interest



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

A_{FB}^{ℓ} Methodology Study

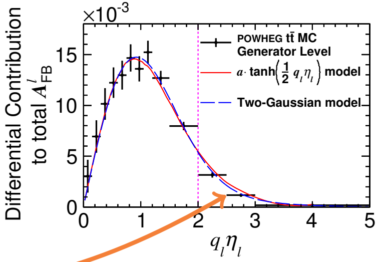
- Double-Gaussian does better job in modeling differential asymmetry in large $q_\ell \eta_\ell$ region



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

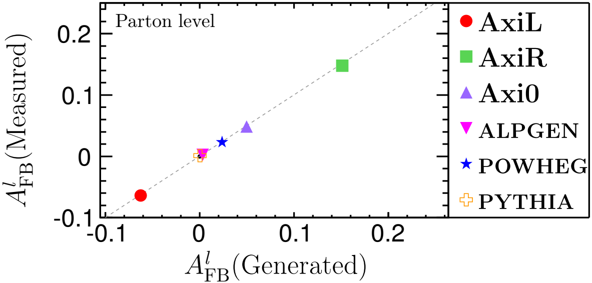
A_{FB}^{ℓ} Methodology Study

- 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

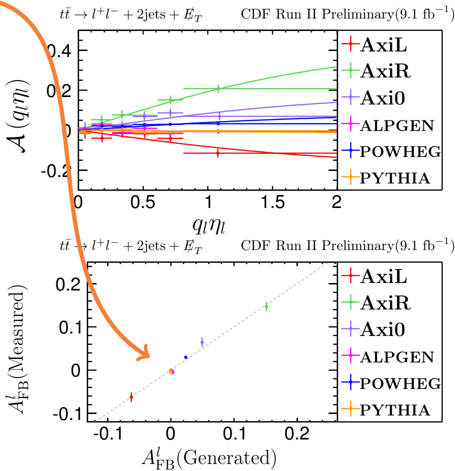
- $a \cdot \tanh$ model works well at parton level



- 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

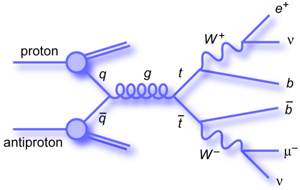
CDF Run II Preliminary

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	

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

- The ratio of $A_{\rm FB}^{t\bar{t}}/A_{\rm FB}^{\ell}$ observed to be consistent when $t\bar{t}$ produced unpolarized and decay like SM
- Based on CDF $A_{\rm FB}^{t\bar{t}}$ result (0.16 ± 0.05), this yields prediction of $0.070 < A_{\rm FB}^{\ell} < 0.076$

- Lepton pair A_{FB}
  - $$A_{\text{FB}}^{\ell\ell} = \frac{N(\Delta\eta > 0) - N(\Delta\eta < 0)}{N(\Delta\eta > 0) + N(\Delta\eta < 0)}$$
- NLO SM prediction: $A_{\text{FB}}^{\ell\ell} = 0.048 \pm 0.004$



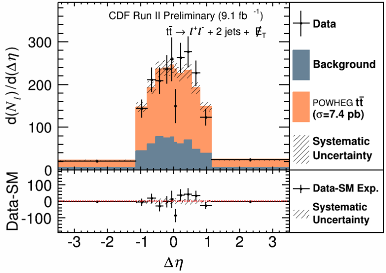
- Larger expectations
- Only defined in dilepton, smaller statistics
- Provide extra information to help constraining new physics models

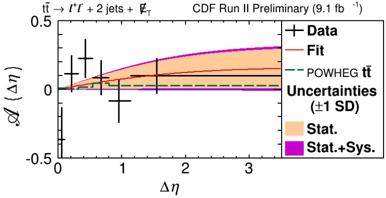
- Measurement techniques works equally well for $A_{FB}^{\ell\ell}$
- Measure $A_{FB}^{\ell\ell}$ with the same method

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

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

- 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

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

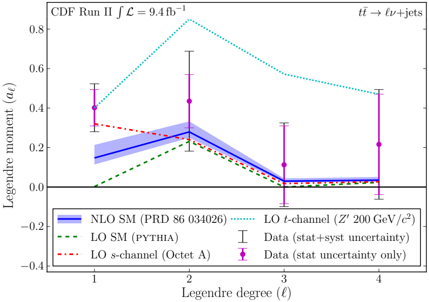
$t\bar{t}$ Likelihood

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

$t\bar{t}$ Kinematic Reconstruction - Strategy

- Parametrize the system (within each lepton-jet pairing) with **4** parameters
  - 2 ϕ of the two neutrinos (in the rest frame of the corresponding lepton+jet) ($\phi_{1,2}$)
  - 2 E_T deviations ($\frac{E_{\text{jet}}^{\text{measure}} - E_{\text{jet}}^{\text{fit}}}{\sigma_{\text{jet}}}$) for two b-jets ($\mathrm{jd}_{1,2}$)
- Determine the kinematics of the whole event with the 4 parameters
- Each set of (ϕ_1, ϕ_2, jd_1, jd_2) represents a possible solution to the event
- Assigning likelihood based on how reconstructed E_T^{jet} and $\not\!\!E_T$ matches measured ones
- Adding information from templates of $p_T^{t\bar{t}}$, $p_z^{t\bar{t}}$ and $M^{t\bar{t}}$

Samples with varying $A_{FB}^{t\bar{t}}$



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Parametrize $\cos\theta^*$ with Legendre Polynomials

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

Optimization - options

- Picking max-likelihood solution vs. using full probability
  - Full probability always provides better resolution
- Picking the more likely lepton-jet pairing according to likelihood or weight the two pairings
  - Two lepton-jet pairings (even, odd), max likelihood of each pairing $(L_{max,even}, L_{max,odd})$
  - Picking the larger L_{max} pairing, or weight both according to $\mathrm{w_{even}} = \dfrac{L_{max,even}}{L_{max,even} + L_{max,odd}}$, etc.
  - Weighting always gives better resolution
- More tunable parameters
  - Peak of $\mathrm{jd}_{1,2}$
  - Track-weighted jet charge
  - m_{lb}^2
  - $\Delta R_{\min}$(lepton, jet)

$\sigma(\mathrm{tot.})/\sigma(\mathrm{sig.only})$	Pick L-J pairing	Weight both
Max-likelihood	0.144/0.133	0.137/0.126
Full probability	0.131/0.114	0.122/0.106

Optimization - II

Extra optimizations

1. Reject low-quality lepton-jet pairings
   - Jet energy got dragged too far from measured values to make a $t\bar{t}$
   - m_{lb}^2 too high, not likely good top
   - Lepton lying on top of a jet, likely to be W+jets
2. Reject events with both lepton-jet pairings rejected
   - Rejected a good fraction of backgrounds while keeping signal almost not affected
3. Incorporate more information in weighting lepton-jet pairings
   - Track-momemtum-weighted jet charge

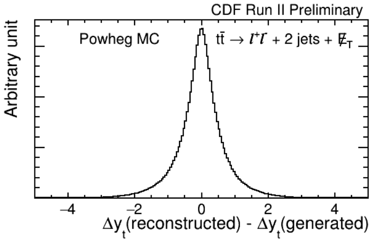
$\sigma(A_{\mathbf{FB}}^{t\bar{t}}) =$ **0.144 before optimization and 0.114 after**

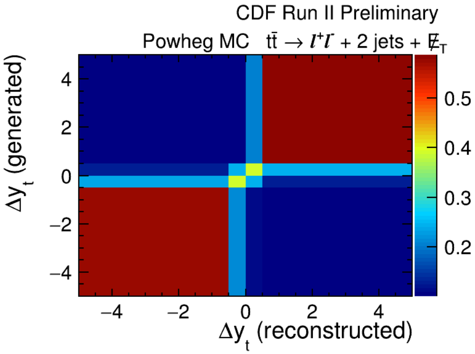
Table of uncertainties: Full set of results

CDF Run II Preliminary (9.1 fb^{-1}) ($t\bar{t} \to l^+l^- + 2\text{jets} + \not{E}_T$)	
Source of uncertainty $A_{\text{FB}}^{t\bar{t}}$	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

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

- Δy resolution and detector response matrix after optimization





Final word on A_{FB} from Tevatron

- Differential A_{FB} show mostly good agreement between CDF and D0
  - Some areas under study
- Both experiments working to understand the differences
  - Are the two experiments measuring the same observables?
  - Different techniques causing bias in either/both experiments?
  - Statistical fluctuation?