# Measurement of the Forward-Backward Asymmetry of $t\bar{t}$ in the Two-Lepton Final State at CDF

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Preliminary Examination
Texas A&M University
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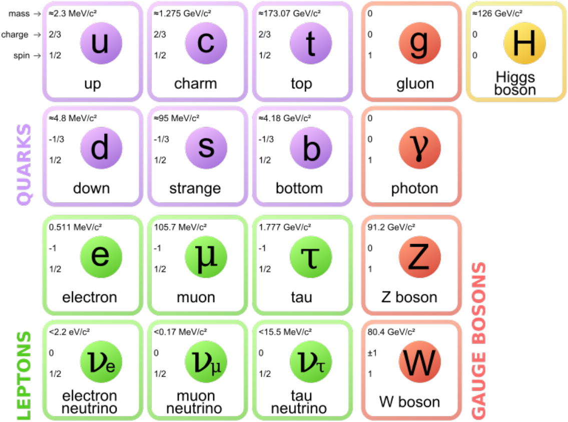
# The Standard Model



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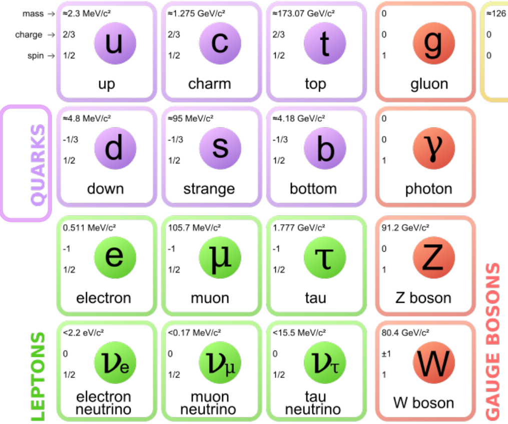

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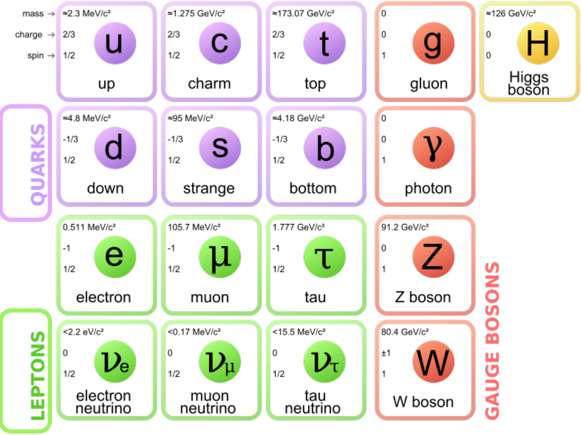

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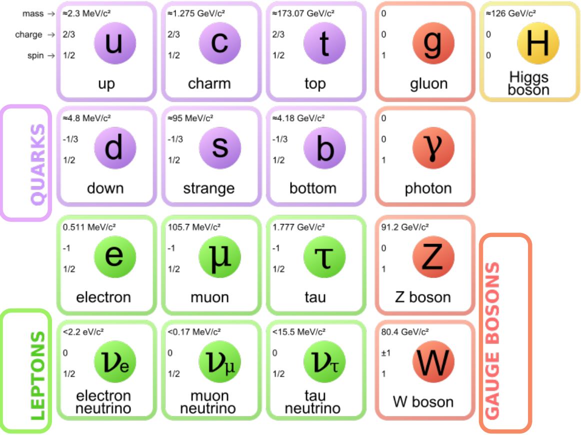

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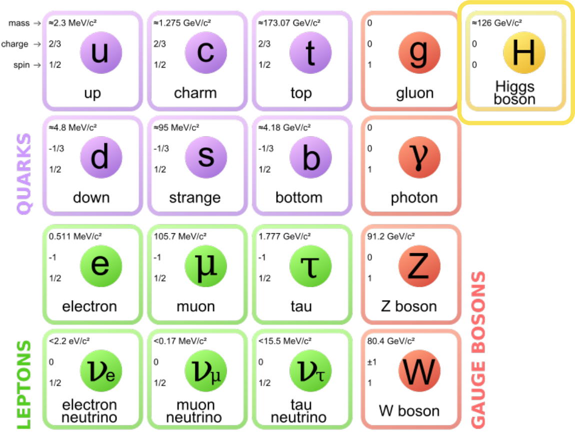
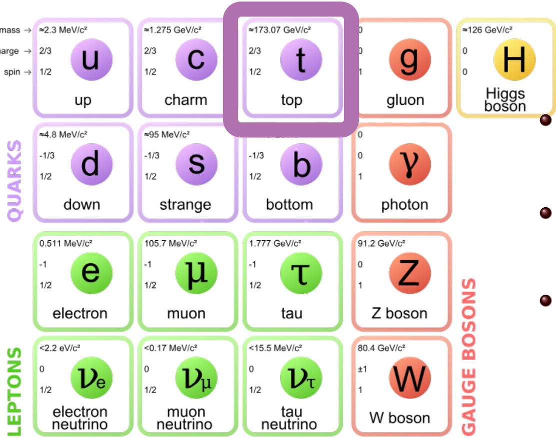



Observation of Higgs boson from CMS and ATLAS in 2012

$m_{\mathrm{H}} \simeq 125\ \mathrm{GeV/c^2}$

Very interesting topic, but **not** our focus today

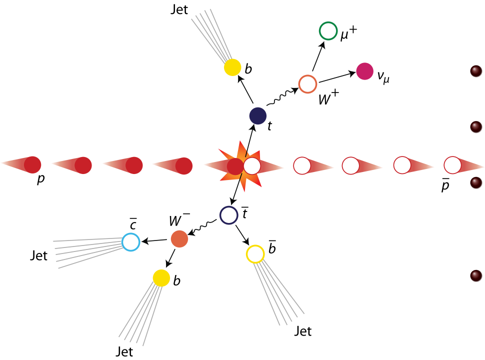
# The Standard Model - Top Quark




**Top Quark**

- Observed at Tevatron in 1995
- Very heavy
  - $m_t \simeq 173\ \mathrm{GeV/c^2}$
- Very short lived
  - No time to form hadrons
  - Decay almost immediately
  - Unique opportunity to study a "bare" quark

# Top-Quark Pair at Tevatron




## Top-quark pair at Tevatron

- $p\bar{p}$ collision at Tevatron
- CP even initial state
- 85% quark annihilation, 15% gluon fusion
- Decent amount of $t\bar{t}$ produced at Tevatron
  - Study events with certain properties to learn how particles interact

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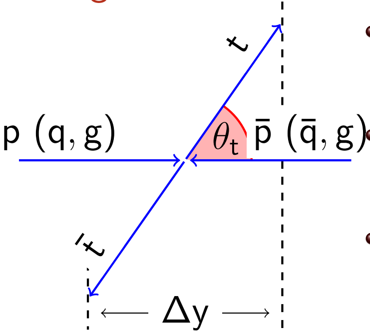
# $A_{FB}^{t\bar{t}}$ at Tevatron

- What else can we learn about $t\bar{t}$ produced at Tevatron?
- Angular distribution!



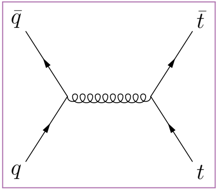

$$y = \frac{1}{2} \ln \frac{E + p_z}{E - p_z}$$

- Simplest observable: forward-backward asymmetry ($A_{FB}$)
- Does top quark prefer proton direction or the opposite?
- Measure rapidity difference between top and anti-top, $\Delta y$
- Define $A_{FB}$ of $t\bar{t}$ production:

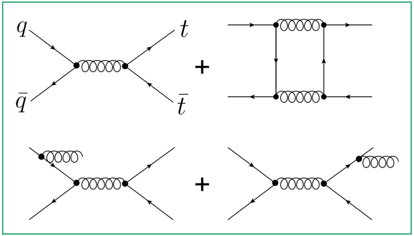
$$A_{FB}^{t\bar{t}} = \frac{N(\Delta y > 0) - N(\Delta y < 0)}{N(\Delta y > 0) + N(\Delta y < 0)}$$

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

- What does standard model (SM) predicts?
- No preference in leading order diagram




- At next-to-leading order (NLO): top quark slightly prefers proton direction (forward)
  $\rightarrow$Interference among diagrams
- $A_{FB}^{t\bar{t}}$(NLO SM) $= 0.088 \pm 0.006$ (PRD **86**,034026 (2012))



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

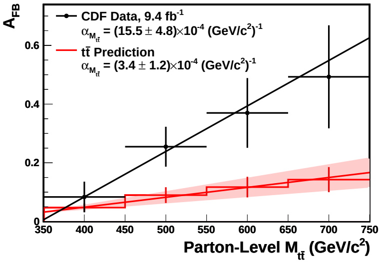
- Previous experimental result?

CDF: $A_{FB}^{t\bar{t}} = 0.164 \pm 0.047$ (PRD **87**, 092002 (2013))

D0: $A_{FB}^{t\bar{t}} = 0.196 \pm 0.065$ (PRD **84**, 112005 (2011))

- Measured results from CDF and D0 in tension with SM prediction

- $A_{FB}^{t\bar{t}}$ vs. $m_{t\bar{t}}$ deviates from SM prediction
- Anomalously large $A_{FB}^{t\bar{t}} \rightarrow$ Smoking gun for new physics?

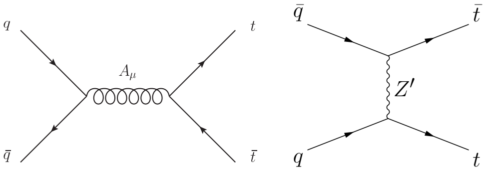


# $A_{FB}^{t\bar{t}}$ at Tevatron

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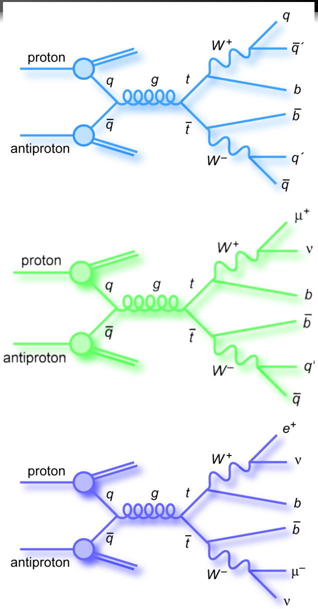
# $A_{\mathrm{FB}}^{t\bar{t}}$ at Tevatron

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

- Measure $A_{\mathrm{FB}}^{t\bar{t}}$ more precisely?
- Other related observables?

# Top-Quark Pair Decay Modes

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



# Top-Quark Pair Decay Modes

- **How does top quark decay?**
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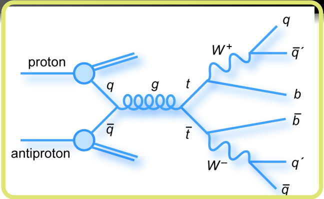
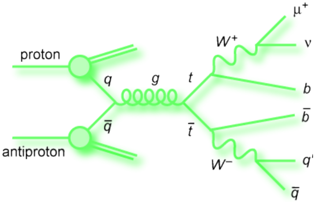
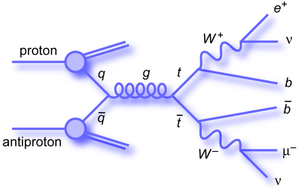
  - All hadronic←**Difficult channel**
    - Large branching fraction
    - Hard to determine jet energy/charge
    - Hard to reconstruct $t\bar{t}$



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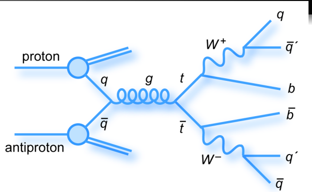
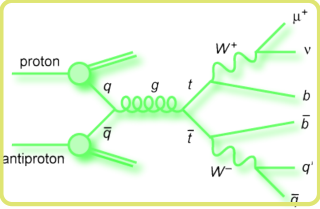
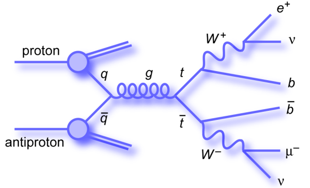
    - Hard to determine jet energy/charge
    - Hard to reconstruct $t\bar{t}$
  - Lepton+jets$\leftarrow$**Previous result**
    - Decent branching fraction
    - Lepton providing additional handle



# Top-Quark Pair Decay Modes

- **How does top quark decay?**
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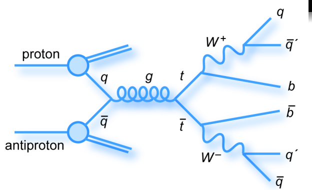
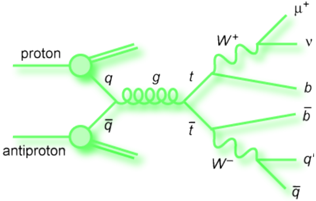
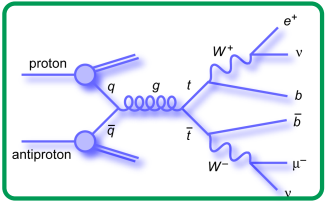
    - Hard to reconstruct $t\bar{t}$
  - Lepton+jets←**Previous result**
    - Decent branching fraction
    - Lepton providing additional handle
  - Dilepton ←**Focus of this talk**
    - Small branching fraction
    - Leptons precisely measured
    - Two $\nu$'s, hard to reconstruct $t\bar{t}$

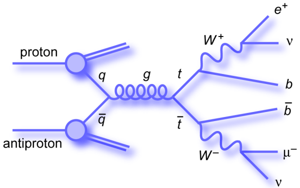


# Adding more data: $A_{\mathrm{FB}}^{t\bar{t}}$ in dilepton

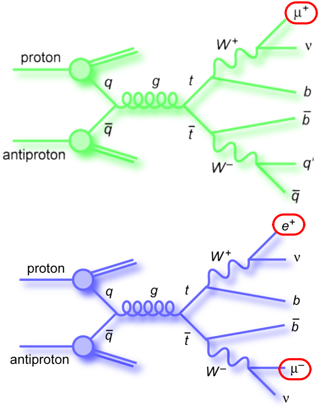
- More evidence for or against new physics?
- Previous measurement based on lepton+jets final state
- Can measure $A_{\mathrm{FB}}^{t\bar{t}}$ in dilepton




- Provide more data and additional sensitivity
- Need to reconstruct 4-momentums of $t\bar{t}$ $\rightarrow$Tough job in dilepton
- Details in later slides

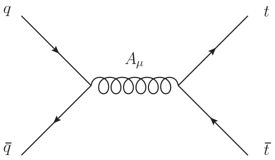
# Another observable to help answer the question

- Other possible hints?
- Two equally important observables with leptons
- Leptonic $A_{\text{FB}}$
  - $$A^{l}_{\text{FB}} = \frac{N(q_l\eta_l > 0) - N(q_l\eta_l < 0)}{N(q_l\eta_l > 0) + N(q_l\eta_l < 0)}$$
- Also lepton pair $A_{\text{FB}}$ defined with lepton $\eta$ difference, only in dilepton
- Why leptons?
  - Lepton angles precisely measured
  - Tend to follow direction of parent tops



# $A^{l}_{\mathrm{FB}}$ at Tevatron

- NLO SM prediction: $A^{l}_{\mathrm{FB}} = 0.038 \pm 0.003$
- Prediction with new physics?
- Based on CDF $A^{t\bar{t}}_{\mathrm{FB}}$ result $(0.16 \pm 0.05)$: $0.070 < A^{l}_{\mathrm{FB}} < 0.076$
- New physics models in certain parameter space allow for large $A^{t\bar{t}}_{\mathrm{FB}}$ (like observed value), but very large range (positive or negative) of $A^{l}_{\mathrm{FB}}$
- **Independent measurements of $A^{t\bar{t}}_{\mathrm{FB}}$ and $A^{l}_{\mathrm{FB}}$ are crucial**




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

# $A^{l}_{\text{FB}}$ at Tevatron

- Measurement of $A^{l}_{\text{FB}}$ in lepton+jets

$$A^{l}_{\text{FB}} = 0.094 \pm 0.024(\text{stat})^{+0.022}_{-0.017}(\text{syst})$$

- Large asymmetry holds in $A^{l}_{\text{FB}}$
- $A^{t\bar{t}}_{\text{FB}}$ and $A^{l}_{\text{FB}}$ measurement in lepton+jets published (by large group at Michigan)
- This thesis: confirm or deny this anomaly large asymmetry with dilepton

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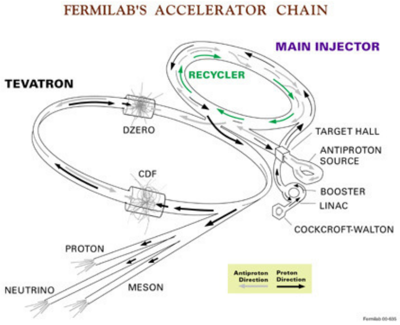
# Tevatron and CDF

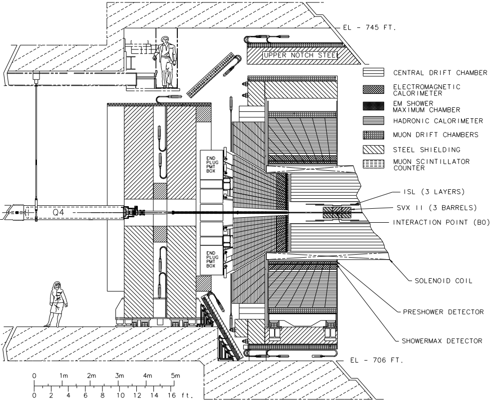
## Tevatron




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

# Tevatron and CDF

## CDF




- General purpose detector with
  - Solenoid (1.4 T magnetic field)
  - Tracking system
  - Calorimeter system
  - Muon detectors
- Coverage in $t\bar{t}$ dilepton
  - Electron: $|\eta| < 2.0$
  - Muon : $|\eta| < 1.1$
  - Jets : $|\eta| < 2.5$

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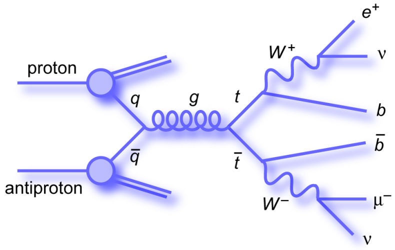
# $t\bar{t} \rightarrow$ dilepton

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

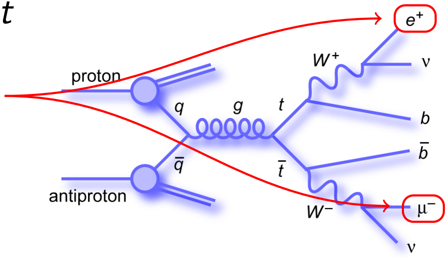
# $t\bar{t} \rightarrow$ dilepton
## Event selection

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



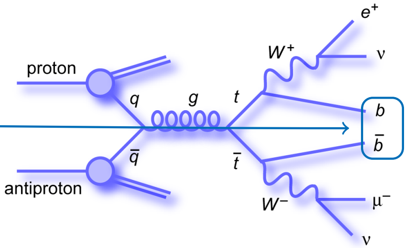
# $t\bar{t} \rightarrow$ dilepton
## Event selection

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



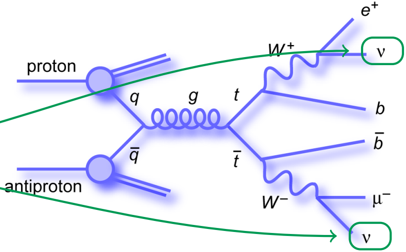
# $t\bar{t} \rightarrow$ dilepton
## Event selection

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



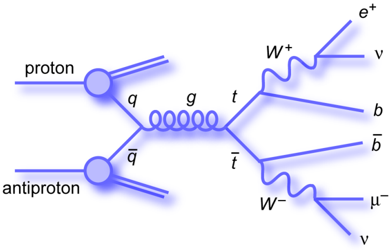
# $t\bar{t} \rightarrow$ dilepton
## Event selection

- Need a sample enriched by $t\bar{t}$ events:
  - Two opposite charged leptons
  - At least two jets
  - $\not{E}_T > 25$ GeV



# $t\bar{t} \to$ dilepton
## Event selection

- Need a sample enriched by $t\bar{t}$ events:
  - Two opposite charged leptons
  - At least two jets
  - $\not{E}_T > 25$ GeV
- Detailed event selection criteria in backup



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

- Signal modeling:
  - Prediction with POWHEG MC
    NLO SM with QCD correction
- Background modeling:
  - Diboson production ($WW$,$WZ$,$ZZ$,$W\gamma$)
    MC prediction
  - $Z/\gamma^*$
    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 |
| $Z/\gamma^*$ | 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

# Alternative Signal Modeling

- Simulate $t\bar{t}$ in various scenarios
  - Two LO SM sample (PYTHIA & PYTHIA)
  - NLO SM sample (POWHEG)
  - Benchmark beyond-SM model w/ axigluon
- Span large range of $A^{l}_{\text{FB}}$ and $A^{ll}_{\text{FB}}$

| Model | $A^{l}_{\text{FB}}$ (Parton Level) | $A^{ll}_{\text{FB}}$ (Parton Level) | Description |
|---|---|---|---|
| AxiL | -0.063(2) | -0.092(3) | Tree-level left-handed axigluon ($m = 200$ GeV/$c^2$, $\Gamma = 50$ GeV) |
| AxiR | 0.151(2) | 0.218(3) | Tree-level right-handed axigluon ($m = 200$ GeV/$c^2$, $\Gamma = 50$ GeV) |
| Axi0 | 0.050(2) | 0.066(3) | Tree-level unpolarized axigluon ($m = 200$ GeV/$c^2$, $\Gamma = 50$ GeV) |
| 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 |
| Theory | 0.038(3) | 0.048(4) | NLO SM calculation (PRD **86** 034026 (2012)) |

# $t\bar{t} \rightarrow$ dilepton

- Hard to reconstruct of 4-momentum of $t\bar{t}$ in dilepton
- Measure leptonic $A_{\text{FB}}$ first
- Continue with the full $A_{\text{FB}}^{t\bar{t}}$ if large asymmetry holds in leptonic $A_{\text{FB}}$

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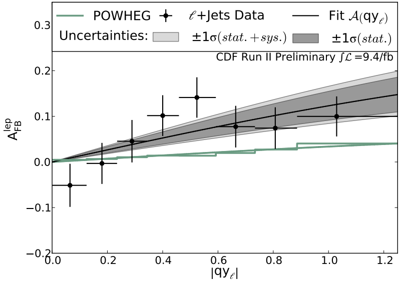
# $A_{FB}^{l}$ Measurement Methodology

- $A_{FB}^{l} = 0.094^{+0.032}_{-0.029}$ at CDF in lepton+jets
- $1.9\sigma$ larger than SM
- Measurement based on decomposition of $q_l\eta_l$ spectrum into symmetric and asymmetric components
- Empirical determined functional form for asymmetric component (differential asymmetry)

$$A_{FB}^{l}(q_l\eta_l) = a \cdot \tanh\left(\frac{1}{2}q_l\eta_l\right)$$

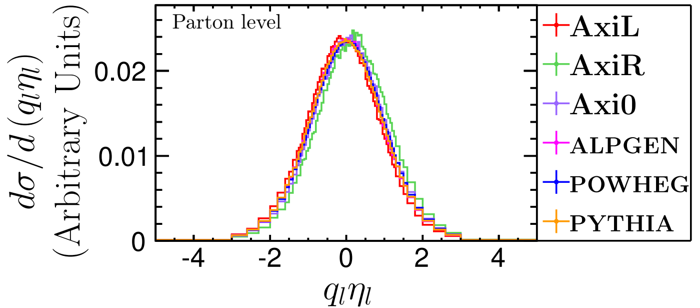



PRD **88** 072003 (2013)

- Details in following slides

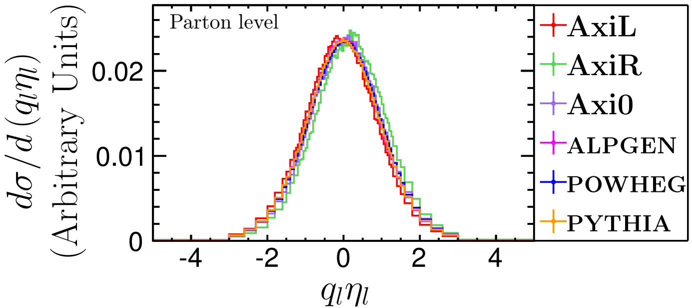
# $A_{FB}^{l}$ Methodology - Introduction

$q_l \eta_l$ spectrum




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

# $A_{FB}^{l}$ Methodology - Introduction




- Decomposition of $q_l\eta_l$ spectrum into symmetric and asymmetric components:

$$\mathcal{S}(q_l\eta_l) = \frac{\mathcal{N}(q_l\eta_l) + \mathcal{N}(-q_l\eta_l)}{2}; \mathcal{A}(q_l\eta_l) = \frac{\mathcal{N}(q_l\eta_l) - \mathcal{N}(-q_l\eta_l)}{\mathcal{N}(q_l\eta_l) + \mathcal{N}(-q_l\eta_l)}$$

# $A^l_{FB}$ Methodology - Introduction

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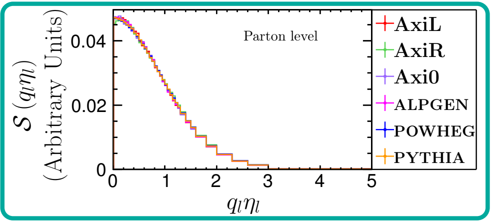


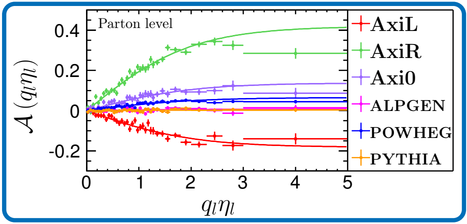


- $\mathcal{S}(q_l\eta_l)$ consistent among models

# $A_{FB}^{l}$ Methodology - Introduction

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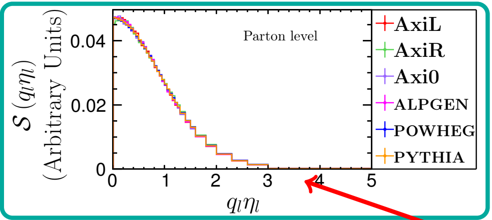
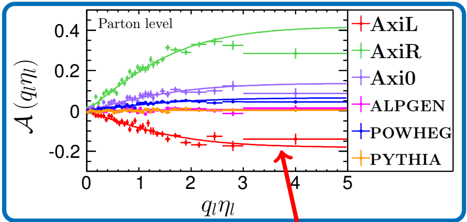
$$\mathcal{S}(q_l\eta_l) = \frac{\mathcal{N}(q_l\eta_l) + \mathcal{N}(-q_l\eta_l)}{2}; \mathcal{A}(q_l\eta_l) = \frac{\mathcal{N}(q_l\eta_l) - \mathcal{N}(-q_l\eta_l)}{\mathcal{N}(q_l\eta_l) + \mathcal{N}(-q_l\eta_l)}$$




- $\mathcal{S}(q_l\eta_l)$ consistent among models
- $\mathcal{A}(q_l\eta_l)$ well modeled with tanh function

Not $q_l\eta_l > 2.5$

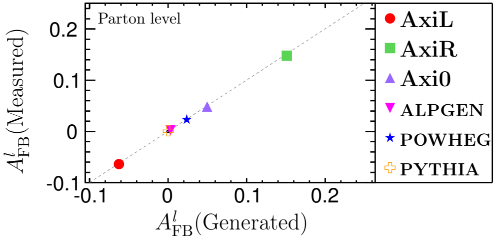
But contribution here is tiny

# $A_{FB}^{l}$ Methodology - Introduction

- $A_{FB}^{l}$ rewritten as

$$A_{FB}^{l} = \frac{\int_0^{\infty} \mathrm{d}q_l\eta_l \mathcal{A}(q_l\eta_l)\mathcal{S}(q_l\eta_l)}{\int_0^{\infty} \mathrm{d}q_l'\eta_l' \mathcal{S}(q_l'\eta_l')}$$

- Methodology works well




- Pheno paper on this topic about to be submitted to PRD

  On the Forward-Backward Asymmetry of Leptonic Decays of $t\bar{t}$ at the Fermilab Tevatron (Z. Hong *et. al.*)

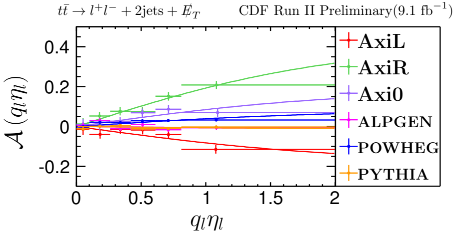
- Details in backup slides

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

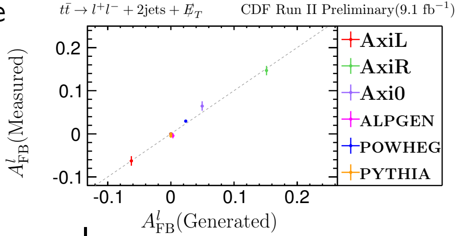
- Does detector response affect the measurement?

# $A^l_{FB}$ Methodology with Detector Response

- Detector response mostly cancels out in $\mathcal{A}(q_l\eta_l)$




- Measurement strategy:
  - Fit $\mathcal{A}(q_l\eta_l)$ with $a \cdot \tanh\left(\frac{1}{2}q_l\eta_l\right)$
  - Obtain $\mathcal{S}(q_l\eta_l)$ from POWHEG simulation at parton-level
  - Calculate $A^l_{FB}$ with $\mathcal{A}$ & $\mathcal{S}$ above
- Correct for detector response and extrapolate to inclusive $A^l_{FB}$ simultaneously




- Strategy validated with signal samples

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# $A_{FB}^{l}$ in dilepton

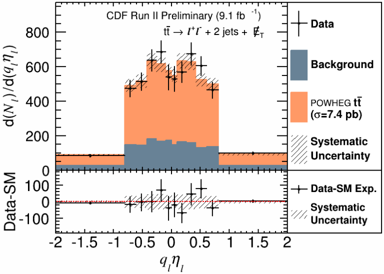
Part of thesis result

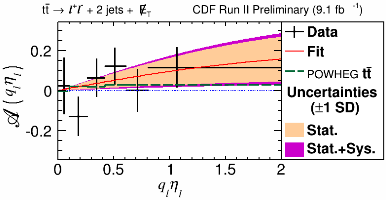
- Measure $A_{FB}^{l}$ with CDF full dataset in dilepton ($9.1\ \mathrm{fb}^{-1}$)

$$A_{FB}^{l} = 0.072 \pm 0.052(\text{stat}) \pm 0.030(\text{syst})$$
$$= 0.072 \pm 0.060$$

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

- Dominant uncertainty is statistical
- Table of systematic uncertainty in backup
- Result consistent with prediction of new physics from lepton+jets, but also consistent with SM



# $A^{ll}_{\text{FB}}$ in dilepton

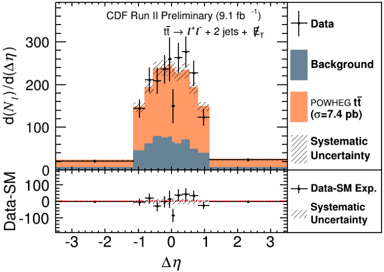
Part of thesis result

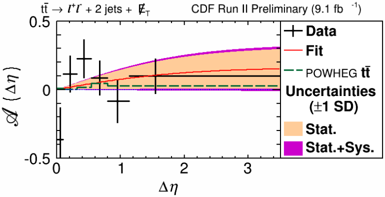
- Measure $A^{ll}_{\text{FB}}$ with the same method

$$A^{ll}_{\text{FB}} = 0.076 \pm 0.072(\text{stat}) \pm 0.039(\text{syst})$$
$$= 0.076 \pm 0.081$$

Cf. $A^{l}_{\text{FB}}(\text{SM,NLO}) = 0.048 \pm 0.004$

- Dominant uncertainty is statistical
- Result consistent with SM



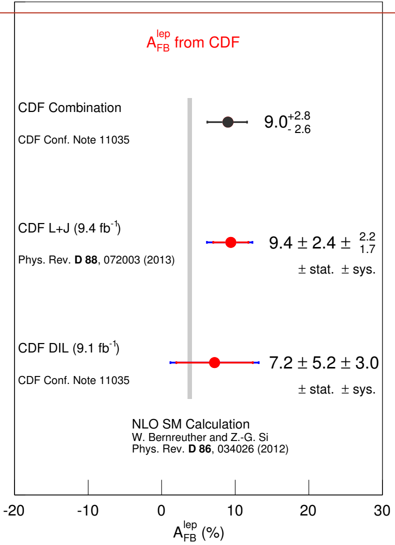
# $A_{FB}^{l}$ combination at CDF

Part of thesis result

- Combined $A_{FB}^{l}$ measurements at CDF
- Based on *best linear unbiased estimator* (BLUE)
- Result is $2\sigma$ larger than NLO SM prediction:

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

- Paper in 2nd collaboration review. To be submitted to PRL.



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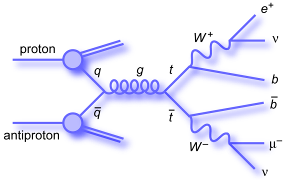
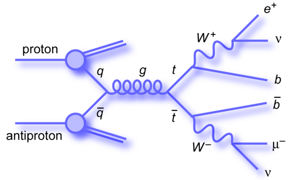
# $t\bar{t}$ Reconstruction in dilepton

- Need to reconstruct 4-momentum of top/anti-top quarks
- Known information:
  - 4-momentum of leptons→precisely
  - 4-momentum of jets→not so well
    Ambiguity between $b$ and $\bar{b}$
  - $\not{E}_T$ →Distributed between $\nu$'s
  - Constraints on $m_W$ & $m_t$
- 6 unknowns with 6 constraints
  Tough job!

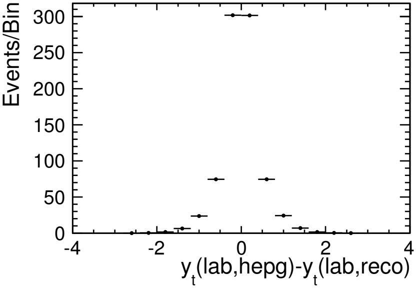


# $t\bar{t}$ Reconstruction in dilepton

- Basic idea straight forward: momentum-energy conservation
- Technically:
  - Assign scale factors for jets, $\not{E}_x$ & $\not{E}_y$
  - Fit for most likely solution

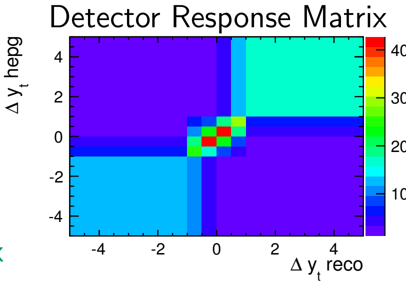



- Preliminary performance
- Reconstruct majority of top rapidities within 0.5
- Tails constituted of events with
  - Jet poorly measured
  - Wrong assignment of $b$-$\bar{b}$
  - Fitter picks a wrong solution



# $A_{\mathrm{FB}}^{t\bar{t}}$ Unfolding

- $A_{\mathrm{FB}}^{t\bar{t}}$ measured in detector biased
  - Limited detector coverage
  - Imperfect detector acceptance
  - Finite detector resolution
  - Biases caused by $t\bar{t}$ reconstruction
- Unfolding needed for inclusive parton-level $A_{\mathrm{FB}}^{t\bar{t}}$
- Two steps procedure
  - Inversion of detector response matrix based on *single value decomposition* and certain regularization condition
  - Bin-by-bin acceptance correction



# $A_{\text{FB}}^{t\bar{t}}$ CDF combination

- Once $A_{\text{FB}}^{t\bar{t}}$ in dilepton complete, want to combine this with previous measurement in lepton+jets
- $A_{\text{FB}}^{t\bar{t}}$ measurement at CDF

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# Prospect of Tevatron combination

- Measurement of $A^{l}_{\mathrm{FB}}$ and $A^{ll}_{\mathrm{FB}}$ done, $A^{t\bar{t}}_{\mathrm{FB}}$ in progress at CDF
- Corresponding measurements at D0 coming out
  - Results from D0 are smaller, consistent with both ours and SM
- Hoping to combine measurements at CDF and D0 for Tevatron legacy results

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# Conclusions

- The $A_{\mathrm{FB}}$ of top quarks at Tevatron continue to be an exciting measurement, and leptonic decays provide an important complementary handle
- Working on a full analysis of $A_{\mathrm{FB}}^{t\bar{t}}$, $A_{\mathrm{FB}}^{l}$ and $A_{\mathrm{FB}}^{ll}$
  Crucial to probe the production and decay of $t\bar{t}$
- Combined $A_{\mathrm{FB}}^{l}$ measurement at CDF shows $2\sigma$ deviation from NLO SM
  Paper in 2nd collaboration reading, for submission to PRL
- Pheno paper about methodology to be submitted to PRD
- Measurement of $A_{\mathrm{FB}}^{t\bar{t}}$ in progress, then CDF combination
- Looking to the future for Tevatron combination of $A_{\mathrm{FB}}^{l}$, $A_{\mathrm{FB}}^{ll}$ and $A_{\mathrm{FB}}^{t\bar{t}}$

# Backup Slides

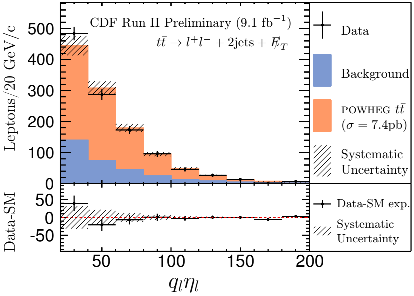
Backup slides

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

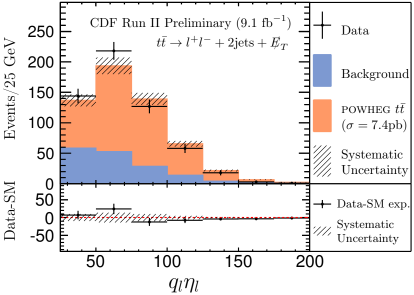
| | |
|---|---|
| Baseline Cuts | Exactly two leptons with $E_T > 20$ GeV and passing standard identification requirements with following modifications<br>-COT radius exit $> 140$ cm for CMIO<br>-$\chi^2/ndf < 2.3$ for muon tracks<br>At least one trigger lepton<br>At least one tight and isolated lepton<br>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 |

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

## Lepton $p_T$




## $\not\!\!E_T$




Agreement is excellent

# Systematic uncertainty of $A^{l}_{\mathrm{FB}}$ measurement

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

| Source of Uncertainty ($A^{l}_{\mathrm{FB}}$) | 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 |

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

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

| Source of Uncertainty ($A_{\mathrm{FB}}^{ll}$) | 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 |

Comparison of $A^l_{\text{FB}}$ among SM prediction and measurements at CDF and D0.

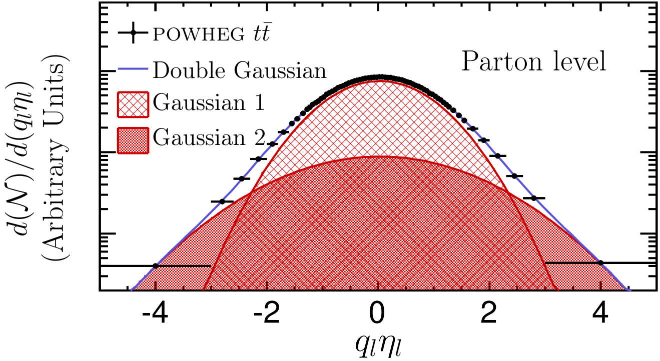
| Source | $A^l_{\text{FB}}$ | Description | Reference |
|---|---|---|---|
| Calculation | 0.038±0.003 | NLO SM | PRD **86**,034026 (2012) |
| CDF | $0.094^{+0.032}_{-0.029}$ | Lepton+jets | PRD **88** 072003 (2013) |
| | $0.072 \pm 0.060$ | Dilepton | To be submitted |
| | $0.090^{+0.028}_{-0.026}$ | Combination | to PRL soon |
| D0 | $0.047^{+0.025}_{-0.027}$ | Lepton+jets, $\lvert q_l \eta_l \rvert < 1.5$ | D0 Note 6394-CONF |
| | $0.044 \pm 0.039$ | Dilepton | PRD **88**, 112002 (2013) |

# $A^{l}_{\mathrm{FB}}$ Methodology Study

- Empirical determined methodology works well
- Need to know why it works
- Detailed study in following slides
- To be submitted to PRD, manuscript in preparation, Z. Hong *et al*

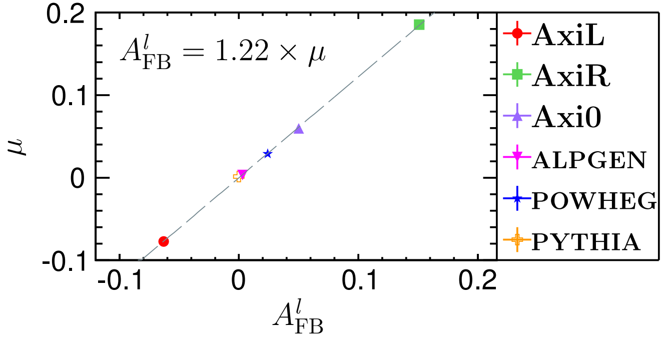
Results with MC study:

- $q_l\eta_l$ distribution well described by double-Gaussian



Results with MC study:

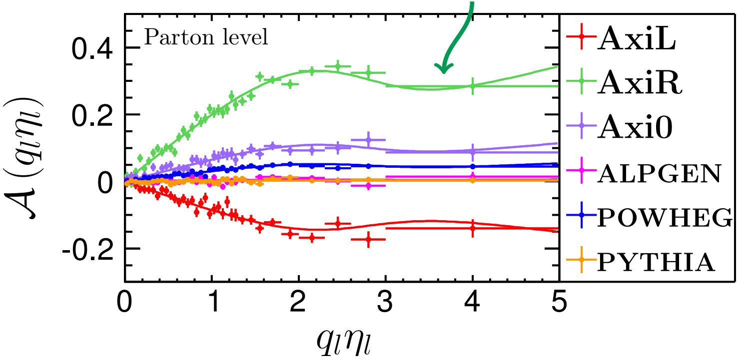
- $A_{\rm FB}^{l}$ comes from shift in mean
  $\rightarrow A_{\rm FB}^{l}$ linearly related with mean



# $A^l_{FB}$ Methodology Study

Results with MC study:

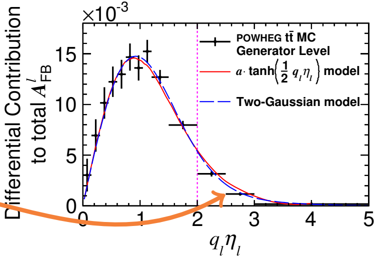
- Double-Gaussian does better job in modeling differential asymmetry in large $q_l\eta_l$ region




- $\mathcal{A}(q_l\eta_l)$ still most sensitive way to measure $A^l_{FB}$
  - Provides better effective measure of mean

# $A^l_{FB}$ Methodology Study

- New way of looking at the data: Differential contribution to $A^l_{FB}$
- What do we learn?
  - Asymmetry mostly from $|\eta| < 2.0$
    - Best detector coverages here
  - Mismodeling in region with small contribution
  - $a \cdot \tanh\left(\frac{1}{2} q_l \eta_l\right)$ is excellent for $|q_l \eta_l| < 2.5$
  - More than good enough
- Now we know why! Moving forward with confidence



# $A_{FB}^{l}$ CDF combination

CDF Run II Preliminary

| Source of uncertainty | L+J ($9.4 fb^{-1}$) | DIL ($9.1 fb^{-1}$) | 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 | |

# $t\bar{t}$ 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

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

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