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

Ziqing Hong

Preliminary Examination
Texas A&M University
March 26, 2014
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### The Standard Model

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<th>Mass (MeV/c^2)</th>
<th>Charge</th>
<th>Spin</th>
<th>Particle Type</th>
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</table>

**Observation of Higgs boson from CMS and ATLAS in 2012:**

\[ m_H \approx 125 \text{ GeV/c}^2 \]
The Standard Model

**Observation of Higgs boson from CMS and ATLAS in 2012**

\[ m_H \approx 125 \text{ GeV}/c^2 \]

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

---

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Introduction

The Standard Model

The Standard Model

Observation of Higgs boson from CMS and ATLAS in 2012

$m_H \approx 125 \text{ GeV}/c^2$

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The Standard Model

Observation of Higgs boson from CMS and ATLAS in 2012

\[ m_H \approx 125 \text{ GeV/c}^2 \]

Very interesting topic, but not our focus today

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The Standard Model

### Observation of Higgs boson from CMS and ATLAS in 2012

The Higgs boson mass, $m_H$, is approximately $125 \text{ GeV}/c^2$.

### Very interesting topic, but not our focus today
Introduction

The Standard Model and the Top Quark

The Standard Model - Top Quark

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

- $p\bar{p}$ 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
# Introduction

- The Standard Model and the Top Quark
- $A_{FB}^{t\bar{t}}$: Smoking gun for new physics?
- Searching for more evidence

## Tevatron and CDF

1. $t\bar{t} \rightarrow$ dilepton
2. $A_{FB}^{t\bar{t}}$ measurement methodology
3. $A_{FB}^{t\bar{t}}$ in dilepton and combination at CDF

## Remaining pieces of the puzzle

- $A_{FB}^{t\bar{t}}$ in dilepton and CDF combination
- Prospect of Tevatron combination

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

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

**Simplest observable:** forward-backward asymmetry ($A_{\text{FB}}$)

Does top quark prefer proton direction or the opposite?

Measure rapidity difference between top and anti-top, $\Delta y$

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

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

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

→ Interference among diagrams

$$A_{FB}^{t\bar{t}}(NLO \text{ SM}) = 0.088 \pm 0.006$$

(PRD 86, 034026 (2012))
At \( \bar{t}t \) FB: Smoking gun for new physics?

\( A_{\bar{t}t}^{FB} \) at Tevatron

- Previous experimental result?

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

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

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

- \( A_{\bar{t}t}^{FB} \) vs. \( m_{t\bar{t}} \) deviates from SM prediction

- Anomalously large \( A_{\bar{t}t}^{FB} \) → Smokes gun for new physics?
\( A_{\text{FB}}^{t\bar{t}} \) at Tevatron

Possible alternative hypotheses?
Models beyond the SM can predict large \( A_{\text{FB}}^{t\bar{t}} \)
- Axigluons
- Flavor-changing \( Z' \) boson
- Beyond-SM \( W' \) boson
- Beyond-SM Higgs boson
- Extra dimensions
- .......

\[ q \rightarrow A_{\mu} \rightarrow t \]
\[ \bar{q} \rightarrow Z' \rightarrow \bar{t} \]
\[ q \rightarrow \bar{q} \rightarrow \bar{t} \]
\[ t \rightarrow t \]

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## 7 Conclusions
How to look for more evidence for/against new physics?

- Measure $A_{FB}^{tt}$ 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?
  - $t \rightarrow Wb$ almost 100% of time

- Three types of final states based on $W$ decay mode:
  - All hadronic
    - Difficult channel
    - Large branching fraction
    - Hard to determine jet energy/charge
    - 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
Top-Quark Pair Decay Modes

How does top quark decay?

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Three types of final states based on $W$ decay mode:

- All hadronic $\rightarrow$ **Difficult channel**
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  - Hard to reconstruct $t\bar{t}$

- Lepton+jets $\rightarrow$ **Previous result**
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Top-Quark Pair Decay Modes

How does top quark decay?

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Three types of final states based on $W$ decay mode:

- All hadronic $\leftarrow$ Difficult channel
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  - Hard to reconstruct $t\bar{t}$

- Lepton+jets $\leftarrow$ Previous result
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  - Lepton providing additional handle

- Dilepton $\leftarrow$ Focus of this talk
  - Small branching fraction
  - Leptons precisely measured
  - Two $\nu$'s, hard to reconstruct $t\bar{t}$
Adding more data: $A^{t\bar{t}}_{FB}$ in dilepton

- More evidence for or against new physics?
- Previous measurement based on lepton+jets final state
- Can measure $A^{t\bar{t}}_{FB}$ in dilepton
- Provide more data and additional sensitivity
- Need to reconstruct 4-momentums of $t\bar{t}$
  → 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 $A_{FB}$
  
  \[ A'_{FB} = \frac{N(q_{\ell\eta} > 0) - N(q_{\ell\eta} < 0)}{N(q_{\ell\eta} > 0) + N(q_{\ell\eta} < 0)} \]

- Also lepton pair $A_{FB}$ defined with lepton $\eta$ difference, only in dilepton

- Why leptons?
  - Lepton angles precisely measured
  - Tend to follow direction of parent tops
$A_{FB}^l$ at Tevatron

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

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

Searching for more evidence

\( A^l_{FB} \) at Tevatron

- Measurement of \( A^l_{FB} \) in lepton+jets
  \[
  A^l_{FB} = 0.094 \pm 0.024 \text{(stat)} \pm ^{0.022}_{-0.017} \text{(syst)}
  \]

- Large asymmetry holds in \( A^l_{FB} \)
- \( A^{t\bar{t}}_{FB} \) and \( A^l_{FB} \) 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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7 Conclusions
Tevatron

- $p\bar{p}$ collider
- Center-of-mass energy 1.96 TeV
- Run II delivered $12\text{fb}^{-1}$
- Acquired $10\text{fb}^{-1}$ by 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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7 Conclusions
# $t\bar{t}$ → dilepton

- $A_{FB}$ measurement in lepton+jets done
- Go after the next important final state

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

- Two opposite charged leptons
Need a sample enriched by $t\bar{t}$ events:
- Two opposite charged leptons
- At least two jets
Need a sample enriched by $t\bar{t}$ events:
- Two opposite charged leptons
- At least two jets
- $E_T > 25$ GeV
Need a sample enriched by $t\bar{t}$ events:
- Two opposite charged leptons
- At least two jets
- $E_T > 25$ GeV

Detailed event selection criteria in backup
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**

<table>
<thead>
<tr>
<th>Source</th>
<th>Events</th>
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<tr>
<td>Diboson</td>
<td>31.4±5.9</td>
</tr>
<tr>
<td>$Z/\gamma^*$</td>
<td>50.5±6.2</td>
</tr>
<tr>
<td>$W+$jets fakes</td>
<td>64±17</td>
</tr>
<tr>
<td>$t\bar{t}$ non-dilepton</td>
<td>14.6±0.8</td>
</tr>
<tr>
<td>Total background</td>
<td>160±21</td>
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<tr>
<td>$t\bar{t}$ ($\sigma = 7.4$ pb)</td>
<td>408±19</td>
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<tr>
<td>Total SM expectation</td>
<td>568±40</td>
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<tr>
<td>Observed</td>
<td>569</td>
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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** $A_{FB}^l$ and $A_{FB}^\parallel$

<table>
<thead>
<tr>
<th>Model</th>
<th>$A_{FB}^l$ (Parton Level)</th>
<th>$A_{FB}^\parallel$ (Parton Level)</th>
<th>Description</th>
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<tbody>
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<td>AxiL</td>
<td>-0.063(2)</td>
<td>-0.092(3)</td>
<td>Tree-level left-handed axigluon (m = 200 GeV/c$^2$, $\Gamma = 50$ GeV)</td>
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<td>AxiR</td>
<td>0.151(2)</td>
<td>0.218(3)</td>
<td>Tree-level right-handed axigluon (m = 200 GeV/c$^2$, $\Gamma = 50$ GeV)</td>
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<td>Axi0</td>
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<td>PYTHIA</td>
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<td>LO Standard Model</td>
</tr>
<tr>
<td>POWHEG</td>
<td>0.024(1)</td>
<td>0.030(1)</td>
<td>NLO Standard Model</td>
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<td>Theory</td>
<td>0.038(3)</td>
<td>0.048(4)</td>
<td>NLO SM calculation (PRD 86 034026 (2012))</td>
</tr>
</tbody>
</table>
- Hard to reconstruct of 4-momentum of $t\bar{t}$ in dilepton
- Measure leptonic $A_{FB}$ first
- Continue with the full $A^{t\bar{t}}_{FB}$ if large asymmetry holds in leptonic $A_{FB}$
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4. **$A_{FB}^{l}$ measurement methodology**

5. **$A_{FB}^{l}$ in dilepton and combination at CDF**

6. **Remaining pieces of the puzzle**
   - $A_{FB}^{t\bar{t}}$ in dilepton and CDF combination
   - Prospect of Tevatron combination

7. Conclusions
\( A_{FB}^l = 0.094^{+0.032}_{-0.029} \) at CDF in lepton+jets

1.9\( \sigma \) larger than SM

Measurement based on decomposition of \( q/\eta_l \) spectrum into symmetric and asymmetric components

Empirical determined functional form for asymmetric component (differential asymmetry)

\[
A_{FB}^l(q/\eta_l) = a \cdot \tanh \left( \frac{1}{2} q/\eta_l \right)
\]

Details in following slides

PRD 88 072003 (2013)
- Difference among models are small
  - Shapes almost identical, tiny shift in the mean
- Acceptance in detector limited
- No acceptance beyond $|q_\parallel \eta_\parallel| = 2$
- Need a clever way to measure the subtle difference
Decomposition of $q_\parallel \eta_\parallel$ spectrum into symmetric and asymmetric components:

$$S(q_\parallel \eta_\parallel) = \frac{N(q_\parallel \eta_\parallel) + N(-q_\parallel \eta_\parallel)}{2} ; \quad A(q_\parallel \eta_\parallel) = \frac{N(q_\parallel \eta_\parallel) - N(-q_\parallel \eta_\parallel)}{N(q_\parallel \eta_\parallel) + N(-q_\parallel \eta_\parallel)}$$
\[ S(q_\parallel \eta_\parallel) = \frac{N(q_\parallel \eta_\parallel) + N(-q_\parallel \eta_\parallel)}{2}; \quad A(q_\parallel \eta_\parallel) = \frac{N(q_\parallel \eta_\parallel) - N(-q_\parallel \eta_\parallel)}{N(q_\parallel \eta_\parallel) + N(-q_\parallel \eta_\parallel)} \]

- \( S(q_\parallel \eta_\parallel) \) consistent among models
$A_{FB}^l$ Methodology - Introduction

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

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

- $S(q_\parallel \eta_\parallel)$ consistent among models
- $A(q_\parallel \eta_\parallel)$ well modeled with tanh function

$S(q_\parallel \eta_\parallel)$ consistent among models
$A(q_\parallel \eta_\parallel)$ well modeled with tanh function

Not $q_\parallel \eta_\parallel > 2.5$
But contribution here is tiny
$A_{FB}^l$ Methodology - Introduction

- $A_{FB}^l$ rewritten as

\[
A_{FB}^l = \frac{\int_{0}^{\infty} dq_{\eta l} A(q_\eta l) S(q_\eta l)}{\int_{0}^{\infty} dq_\eta l' S(q_\eta l')}
\]

- 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
Does detector response affect the measurement?
Detector response mostly cancels out in $A(q_l \eta_l)$

Measurement strategy:
- Fit $A(q_l \eta_l)$ with $a \cdot \tanh\left(\frac{1}{2} q_l \eta_l\right)$
- Obtain $S(q_l \eta_l)$ from POWHEG simulation at parton-level
- Calculate $A_{FB}^l$ with $A$ & $S$ above

Correct for detector response and extrapolate to inclusive $A_{FB}^l$ simultaneously

Strategy validated with signal samples
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$A_{FB}^l$ in dilepton

- Measure $A_{FB}^l$ with CDF full dataset in dilepton (9.1 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
Measure $A_{FB}^{ll}$ with the same method

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

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

Dominant uncertainty is statistical

Result consistent with SM
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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7 Conclusions
Need to reconstruct 4-momentum of top/anti-top quarks

Known information:

- 4-momentum of leptons \( \rightarrow \) precisely
- 4-momentum of jets \( \rightarrow \) not so well

Ambiguity between \( b \) and \( \bar{b} \)

\( E_T \rightarrow \) 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**: straightforward: momentum-energy conservation
- **Technically**:
  - Assign scale factors for jets, $E_x$ & $E_y$
  - 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
$A_{\bar{t}t}^{\bar{t}t}$ Unfolding

- $A_{\bar{t}t}^{\bar{t}t}$ 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 $A_{\bar{t}t}^{\bar{t}t}$

- Two steps procedure
  - Inversion of detector response matrix based on *single value decomposition* and certain regularization condition
  - Bin-by-bin acceptance correction
Once $A_{FB}^{t\bar{t}}$ in dilepton complete, want to combine this with previous measurement in lepton+jets

- $A_{FB}^{t\bar{t}}$ measurement at CDF
Table of contents

1 Introduction
   • The Standard Model and the Top Quark
   • $A_{FB}^{t\bar{t}}$: Smoking gun for new physics?
   • Searching for more evidence
2 Tevatron and CDF
3 $t\bar{t} \rightarrow$ dilepton
4 $A_{FB}^{l}$ measurement methodology
5 $A_{FB}^{l}$ in dilepton and combination at CDF
6 Remaining pieces of the puzzle
   • $A_{FB}^{t\bar{t}}$ in dilepton and CDF combination
   • Prospect of Tevatron combination
7 Conclusions
Prospect of Tevatron combination

- Measurement of $A_{FB}^{l}$ and $A_{FB}^{ll}$ done, $A_{FB}^{t\bar{t}}$ 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
Table of contents

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2 Tevatron and CDF

3 $t\bar{t} \rightarrow$ dilepton

4 $A_{FB}^l$ measurement methodology

5 $A_{FB}^l$ in dilepton and combination at CDF

6 Remaining pieces of the puzzle
   - $A_{FB}^{\bar{t}t}$ in dilepton and CDF combination
   - Prospect of Tevatron combination

7 Conclusions
Conclusions

- The $A_{ FB}$ 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 $A_{ FB}^{t\bar{t}}$, $A_{ FB}^{l}$ and $A_{ FB}^{ll}$.
  - Crucial to probe the production and decay of $t\bar{t}$.
- Combined $A_{ FB}^{l}$ 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 $A_{ FB}^{t\bar{t}}$ in progress, then CDF combination.
- Looking to the future for Tevatron combination of $A_{ FB}^{l}$, $A_{ FB}^{ll}$ and $A_{ FB}^{t\bar{t}}$. 

Backup slides
Backup Slides

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

<table>
<thead>
<tr>
<th>Baseline Cuts</th>
<th>Exactly two leptons with $E_T &gt; 20$ GeV and passing standard identification requirements with following modifications</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>- COT radius exit $&gt; 140$ cm for CMIO</td>
</tr>
<tr>
<td></td>
<td>- $\chi^2/ndf &lt; 2.3$ for muon tracks</td>
</tr>
<tr>
<td></td>
<td>At least one trigger lepton</td>
</tr>
<tr>
<td></td>
<td>At least one tight and isolated lepton</td>
</tr>
<tr>
<td></td>
<td>At most one lepton can be loose and/or non-isolated</td>
</tr>
<tr>
<td></td>
<td>$E_T &gt; 25$ GeV, but $E_T &gt; 50$ GeV when there is any lepton or jet within $20^\circ$ of the direction of $E_T$</td>
</tr>
<tr>
<td></td>
<td>MetSig ($= \frac{E_T}{\sqrt{E_{sum}}}$) $&gt; 4 \sqrt{\text{GeV}}$ for ee and $\mu\mu$ events where $76 \text{ GeV/c}^2 &lt; m_{ll} &lt; 106 \text{ GeV/c}^2$</td>
</tr>
<tr>
<td></td>
<td>$m_{ll} &gt; 10 \text{ GeV/c}^2$</td>
</tr>
</tbody>
</table>

| Signal Cuts | Two or more jets with $E_T > 15$ GeV within $|\eta| < 2.5$ |
|-------------|-------------------------------------------------------------|
|             | $H_T > 200$ GeV |
|             | Opposite sign of two leptons |
\( t\bar{t} \rightarrow \text{dilepton} \)

Signal and background modeling

Validation

Lepton \( p_T \)

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

\( t\bar{t} \rightarrow l^+l^- + 2\text{jets} + E_T \)

Data

Background

POWHEG \( t\bar{t} \)

\((\sigma = 7.4 \text{ pb})\)

Systematic Uncertainty

Data-SM exp.

Agreement is excellent
Systematic uncertainty of $A_{FB}^l$ measurement

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

<table>
<thead>
<tr>
<th>Source of Uncertainty</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Backgrounds</td>
<td>0.029</td>
</tr>
<tr>
<td>Asymmetric Modeling</td>
<td>0.006</td>
</tr>
<tr>
<td>Jet Energy Scale</td>
<td>0.004</td>
</tr>
<tr>
<td>Symmetric Modeling</td>
<td>0.001</td>
</tr>
<tr>
<td><strong>Total Systematic</strong></td>
<td>0.030</td>
</tr>
<tr>
<td>Statistical</td>
<td>0.052</td>
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<tr>
<td><strong>Total Uncertainty</strong></td>
<td>0.060</td>
</tr>
</tbody>
</table>
Systematic uncertainty of $A_{FB}^{II}$ measurement

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

<table>
<thead>
<tr>
<th>Source of Uncertainty</th>
<th>Value</th>
</tr>
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<tbody>
<tr>
<td>Backgrounds</td>
<td>0.037</td>
</tr>
<tr>
<td>Asymmetric Modeling</td>
<td>0.012</td>
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<tr>
<td>Jet Energy Scale</td>
<td>0.003</td>
</tr>
<tr>
<td>Symmetric Modeling</td>
<td>0.004</td>
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<tr>
<td>Total Systematic</td>
<td>0.039</td>
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<tr>
<td>Statistical</td>
<td>0.072</td>
</tr>
<tr>
<td>Total Uncertainty</td>
<td>0.082</td>
</tr>
</tbody>
</table>
Comparison of $A_{FB}^l$ among SM prediction and measurements at CDF and D0.

<table>
<thead>
<tr>
<th>Source</th>
<th>$A_{FB}^l$</th>
<th>Description</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Calculation</td>
<td>0.038±0.003</td>
<td>NLO SM</td>
<td>PRD 86,034026 (2012)</td>
</tr>
<tr>
<td>CDF</td>
<td>0.094$^{+0.032}_{-0.029}$</td>
<td>Lepton+jets</td>
<td>PRD 88 072003 (2013)</td>
</tr>
<tr>
<td></td>
<td>0.072 ± 0.060</td>
<td>Dilepton</td>
<td>To be submitted</td>
</tr>
<tr>
<td></td>
<td>0.090$^{+0.028}_{-0.026}$</td>
<td>Combination</td>
<td>to PRL soon</td>
</tr>
<tr>
<td>D0</td>
<td>0.047$^{+0.025}_{-0.027}$</td>
<td>Lepton+jets, $</td>
<td>q_\ell</td>
</tr>
<tr>
<td></td>
<td>0.044 ± 0.039</td>
<td>Dilepton</td>
<td>PRD 88, 112002 (2013)</td>
</tr>
</tbody>
</table>
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:

- $q/\eta$ distribution well described by double-Gaussian
Results with MC study:

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

\[ A_{FB}^l = 1.22 \times \mu \]
$A'_{FB}$ Methodology Study

Results with MC study:

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

\[ A(q_{l\eta_{l}}) \]

- $A(q_{l\eta_{l}})$ still most sensitive way to measure $A'_{FB}$
  - Provides better effective measure of mean
**$A_{FB}^l$ Methodology Study**

- **New way of looking at the data:**
  - Differential contribution to $A_{FB}^l$

- **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**

*Ziqing Hong (Texas A&M University)*

---

![Differential Contribution to total $A_{FB}^l$](chart.png)
<table>
<thead>
<tr>
<th>Source of uncertainty</th>
<th>L+J (9.4fb(^{-1}))</th>
<th>DIL (9.1fb(^{-1}))</th>
<th>Correlation</th>
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<tbody>
<tr>
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<td>0.015</td>
<td>0.029</td>
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</tr>
<tr>
<td>Recoil modeling (Asymmetric modeling)</td>
<td>+0.013</td>
<td>0.006</td>
<td>1</td>
</tr>
<tr>
<td>Symmetric modeling</td>
<td>-</td>
<td>0.001</td>
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<tr>
<td>Color reconnection</td>
<td>0.0067</td>
<td>-</td>
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<tr>
<td>Parton showering</td>
<td>0.0027</td>
<td>-</td>
<td></td>
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<tr>
<td>PDF</td>
<td>0.0025</td>
<td>-</td>
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<tr>
<td>JES</td>
<td>0.0022</td>
<td>0.004</td>
<td>1</td>
</tr>
<tr>
<td>IFSR</td>
<td>0.0018</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td>Total systematic</td>
<td>+0.022</td>
<td>0.030</td>
<td></td>
</tr>
<tr>
<td>Statistics</td>
<td>−0.017</td>
<td>0.052</td>
<td>0</td>
</tr>
<tr>
<td>Total uncertainty</td>
<td>+0.032</td>
<td>0.060</td>
<td></td>
</tr>
</tbody>
</table>
$t\bar{t}$ Reconstruction Equations

\[ M_{l+\nu}^2 = (E_{l+} + E_{\nu})^2 - (\vec{p}_{l+} + \vec{p}_\nu)^2 = M_{WW}^2 \]

\[ M_{l-\bar{\nu}}^2 = (E_{l-} + E_{\bar{\nu}})^2 - (\vec{p}_{l-} + \vec{p}_{\bar{\nu}})^2 = M_{WW}^2 \]

\[ M_{l+\nu b}^2 = (E_{l+} + E_{\nu} + E_{b})^2 - (\vec{p}_{l+} + \vec{p}_\nu + \vec{p}_b)^2 = M_t^2 \]

\[ M_{l-\bar{\nu}b}^2 = (E_{l-} + E_{\bar{\nu}} + E_{\bar{b}})^2 - (\vec{p}_{l-} + \vec{p}_{\bar{\nu}} + \vec{p}_{\bar{b}})^2 = M_t^2 \]

\[ (\vec{p}_\nu + \vec{p}_{\bar{\nu}})_x = (E_T)_x \]

\[ (\vec{p}_\nu + \vec{p}_{\bar{\nu}})_y = (E_T)_y \]
$t\bar{t}$ Likelihood

$$\mathcal{L}(\bar{p}_\nu, \bar{p}_{\bar{\nu}}, E_b, E_{\bar{b}}) = P(p_{z t\bar{t}}) P(p_{T t\bar{t}}) P(M_{t\bar{t}}) \times \frac{1}{\sigma_{\text{jet}1}} \exp \left( -\frac{1}{2} \left( \frac{E_{\text{jet}1}^{\text{measure}} - E_{\text{jet}1}^{\text{fit}}}{\sigma_{\text{jet}1}} \right) \right) \times \frac{1}{\sigma_{\text{jet}2}} \exp \left( -\frac{1}{2} \left( \frac{E_{\text{jet}2}^{\text{measure}} - E_{\text{jet}2}^{\text{fit}}}{\sigma_{\text{jet}2}} \right) \right) \times \frac{1}{\sigma_{T x}} \exp \left( -\frac{1}{2} \left( \frac{E_{x}^{\text{measure}} - E_{x}^{\text{fit}}}{\sigma_{x}^{T}} \right) \right) \times \frac{1}{\sigma_{T y}} \exp \left( -\frac{1}{2} \left( \frac{E_{y}^{\text{measure}} - E_{y}^{\text{fit}}}{\sigma_{y}^{T}} \right) \right) ,$$
The ratio of $A_{FB}^{t\bar{t}}/A_{FB}^{l}$ observed to be consistent when $t\bar{t}$ produced unpolarized and decay like SM

Based on CDF $A_{FB}^{t\bar{t}}$ result ($0.16 \pm 0.05$), this yields prediction of $0.070 < A_{FB}^{l} < 0.076$