The Top Forward-Backward Asymmetry at the Tevatron

J.S. Wilson
On Behalf of the CDF and DZero Collaborations

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The Seventh International Workshop on the CKM Unitarity Triangle
Part I

Introduction
The Top Quark

- Discovered in '95 by CDF, DØ
- 40× heavier than bottom
- \( \sim \) mass of caffeine molecule
- Special role in EWSB?
- Enhanced coupling to new physics?
- Characterize top pair production in \( p\bar{p} \) collisions via:
  - \( \alpha_s \): strong coupling
  - \( q^2 \): energy scale
  - \( s \): spin/polarization
  - \( \theta_t \): top production angle

**TOP QUARK**

Discovered at Fermilab in 1995, the Top Quark is as short-lived as it is massive. Weighing in at a hefty 175 GeV, its lifetime, a mere \( 10^{-24} \) second, is the briefest of the six quarks. Top Quarks are an enigmatic particle whose personal life is sought after by thousands of physicists.

*Acrylic felt with gravel fill for maximum mass.*

\$10.49**

PLUS SHIPPING

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J.S. Wilson (University of Michigan)
What is $A_{FB}$?

- At Tevatron, charge asymmetry appears as forward-backward asymmetry ($\theta_t$).
- Use top-antitop rapidity difference ($\Delta y = y_t - y_{\bar{t}}$) as proxy for production angle.
- Invariant under longitudinal boosts — good for hadron colliders.

$$A_{FB} \equiv \frac{N(\Delta y > 0) - N(\Delta y < 0)}{N(\Delta y > 0) + N(\Delta y < 0)}$$
At leading order, Standard Model predicts zero asymmetry.

Asymmetry at NLO due to:
- interference between Born and box diagrams (positive)
- interference between initial state and final state radiation (negative)

Some disagreement regarding SM predictions:
- LO/NLO for $A_{FB}$ denominator
- Size of electroweak corrections

Inclusive NLO prediction with 26% EWK correction:

$$A_{FB}^{NLO} = 6.6\%$$
Two broad classes of new physics add more asymmetry

- **s-channel models with heavy color octet:**
  - Asymmetry due to axial couplings
  - Expect to see $M_{t\bar{t}}$ resonance
  - Unless $G'$ width very large

- **t-channel models with flavor-changing $Z'$:**
  - Asymmetry due to flavor-changing into Rutherford peak
  - Expect less deviation from cross section and mass spectrum
Part II

Results
- Lepton+jets, 8.7 fb$^{-1}$, 2498 events, 505 ± 123 BG
- $\chi^2$ based $t\bar{t}$ reconstruction, constrain $M_t$, $M_W$
- SM estimation: Powheg with 26% EWK correction
- Modeling is good, $A_{FB}$ a little large
Unfold to parton level
SVD regularization
Predicted $A_{FB}$: (6.6 ± 2.0) %
Measured $A_{FB}$: (16.2 ± 4.7) %

Statistical uncertainties dominate systematic uncertainties

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CDF

Lepton+jets, 5.4 fb$^{-1}$, 1581 events, $455 \pm 39$ BG

Similar $\chi^2$ reconstruction

MC@NLO calculation for SM

Again, modeling is mostly good, $A_{FB}$ larger than SM

SVD regularized unfold

$A_{FB}^{\text{observed}} = (9.2 \pm 3.7)\%$

$A_{FB}^{\text{parton}} = (19.6 \pm 6.5)\%$

Two OS leptons, met, jets, 5.1 fb$^{-1}$, 337 events, 87 ± 17 BG

χ² reconstruction with $M_W$ constraint, $p_T(t\bar{t})$, $p_Z(t\bar{t})$ likelihoods

Parton level unfold via assumption $A_{FB}(\Delta y) = \alpha \Delta y$

$A_{FB}^{\text{observed}} = (13.8 \pm 5.4) \%$

$A_{FB}^{\text{parton}} = (41.7 \pm 15.7) \%$
N.B. NOT a formal combination — private calculation of weighted average only, and correlations are completely neglected.

Experimental results consistent with one another, inconsistent with predicted (6.6 ± 2.0) %

\[ A_{FB} = (18.7 ± 3.7)\% \]

Weighted Average (Wilson '12)
Part III

Kinematic dependences
Asymmetry expected to vary with $q^2$ ($M_{t\bar{t}}$) and with $|\cos \theta_t|$ ($|\Delta y|$).

Dependence approximately linear.

- Fit linear ansatz to measurement
- Fit is pretty good
- Asymmetry increases with $M_{t\bar{t}}$ and with $|\Delta y|$  
- Form of increase is as expected
- Magnitude of increase is not
- Run pseudoexperiments to evaluate significance
  - $M_{t\bar{t}}$: $p = 0.00646$
  - $|\Delta y|$: $p = 0.00892$
DZero also studies kinematic dependencies

- Two bins
- No evidence for mass dependence in this DZero data
- Some evidence for a rapidity dependent $A_{FB}$
- Perhaps a clearer picture with update to full DZero data set
Dependence of $A_{FB}$ on transverse momentum of $t\bar{t}$ system is very important

Sensitive to detailed QCD effects

(Very) rough explanation: In events where top is backwards, color flow from proton to top bends sharply, leading to a "color bremsstrahlung"

That is, backward events tend to have higher $t\bar{t} \ p_T$

Leads to positive $A_{FB}$ at low $p_T$, negative at high $p_T$, even at LO

Also NLO ISR/FSR interference contributes $p_T$ dependent $A_{FB}$

(NOT Feynman diagrams!)
POWHEG, MCFM, PYTHIA truth

All same general shape: positive at low $p_T$, negative at high $p_T$
First, is the $t\bar{t}$ $p_T$ spectrum well modeled?

Important point raised by DZero — if $p_T$ badly modeled, no reason to expect predicted $A_{FB}$ to match data

Not an easy quantity to do well with

Anything “left over” in event goes into $p_T$: underlying event, pileup, instrumental noise, etc.

Modeling looks fine in CDF data
Behavior of the models largely survives detector and reconstruction effects.

Our data (background subtracted) shows a similar dependence on \( p_T \)

Larger overall asymmetry

Shape compatible with SM predictions from POWHEG and from PYTHIA, total asymmetry not compatible
Part IV

Lepton asymmetries
- Lepton direction $\sim$ top direction
- Get lepton information without $t\bar{t}$ reconstruction
- Independent check of asymmetries
- If tops are produced polarized, can see this in lepton $A_{FB}$
- Falkowski ‘12
Charge-weighted lepton pseudorapidity ($Q \cdot \eta_\ell$)

- $A_{FB}^{\ell,obs} = (14.2 \pm 3.8)\%$
- $A_{FB}^{\ell,pred} = (0.8 \pm 0.6)\%$
- Also unfold to parton level
  - $A_{FB}^{\ell,parton} = (15.2 \pm 4.0)\%$
  - $A_{FB}^{\ell,pred} = (2.1 \pm 0.1)\%$

**Inclusive:**
- $A_{FB}^{\ell,obs} = (6.6 \pm 2.5)\%$
- $A_{FB}^{\ell,pred} = (1.6 \pm 0.5)\%$

**$M_{t\bar{t}} > 450 \text{ GeV} / c^2$:**
- $A_{FB}^{\ell,obs} = (11.6 \pm 4.2)\%$
- $A_{FB}^{\ell,pred} = (3.2 \pm 1.0)\%$
arXiv:1207.0364
5.4 fb\(^{-1}\), two OS leptons, Z veto, 2 jets, MET, \(H_T\)
649 events, 244 ± 18 BG
Only addresses the leptons — no \(t\bar{t}\) reconstruction
Many different measurements are possible in dileptons

All consistent with SM prediction, with large error bars

Combine single-lepton $A_{FB}$ ($5.8 \pm 5.3\%$) with same from lepton+jets

BLUE gives ($11.8 \pm 3.2\%$) — two measurements 68 % consistent with one another
• $A^{t\bar{t}}_{FB}$ remains an interesting and reproducible effect
• Not (yet?) well understood in the Standard Model
• At CDF and DZero, we have been and continue to be working hard to fully characterize the asymmetry
• Investigated dependence on mass, rapidity, and transverse momentum
• Lepton-only asymmetries give both a cross check and a polarization probe
Part V

Appendix
Look for lepton + jets:
\[ t\bar{t} \rightarrow WbWb \rightarrow ℓ\nu bqqb \]

Using the full Tevatron dataset of 8.7 fb\(^{-1}\), select a sample of events with

- Well-reconstructed lepton
- Missing transverse energy
- At least 4 jets with \( E_T > 20 \text{ GeV} \)
- At least one \( b \)-tagged jet
- Total energy \( (H_T) > 220 \text{ GeV} \)

2498 candidate \( t\bar{t} \) events

2037 expected \( t\bar{t} \) events, 505 expected background events

Quite pure sample of \( t\bar{t} \) (4:1)

<table>
<thead>
<tr>
<th>Source</th>
<th>Predicted Event Count, 8.7 fb(^{-1})</th>
</tr>
</thead>
<tbody>
<tr>
<td>W + Heavy Flavor</td>
<td>241 ± 78</td>
</tr>
<tr>
<td>Non-W (QCD)</td>
<td>98 ± 51</td>
</tr>
<tr>
<td>W + Light Flavor</td>
<td>96 ± 29</td>
</tr>
<tr>
<td>Single Top</td>
<td>33 ± 2</td>
</tr>
<tr>
<td>Diboson</td>
<td>19 ± 3</td>
</tr>
<tr>
<td>Z + Jets</td>
<td>18 ± 2</td>
</tr>
<tr>
<td>Total Background</td>
<td>505 ± 123</td>
</tr>
<tr>
<td>Top Pairs (7.4 pb)</td>
<td>2037 ± 277</td>
</tr>
<tr>
<td>Total Prediction</td>
<td>2542 ± 303</td>
</tr>
<tr>
<td>Data</td>
<td>2498</td>
</tr>
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</table>
- Reconstruct $t\bar{t}$ system using $\chi^2$ based fitter
- $W$ masses constrained to 80.4 GeV$/c^2 \pm \Gamma_W$ — get neutrino $p_Z$
- $t$ masses constrained to 172.5 GeV$/c^2 \pm \Gamma_t$
- Jet energies and unclustered energy float within uncertainties
- Try all permutations of leading 4 jets ($b$-tagged jets matched to $b$ quarks), use best fit
- Distribution of best $\chi^2$ well-modeled over 2 orders of magnitude, even for very large $\chi^2$
- $t\bar{t}$ mass spectrum (proxy variable for $q^2$) also well modeled
- Transverse momentum of $t\bar{t}$ system is a sensitive check of our reconstruction and modeling
- Anything left over in event goes into $p_T$ — modeling looks fine
Side-band: exactly ZERO $b$-tagged jets
Depleted in $t\bar{t}$
Plenty of data
Check variable of interest — $\Delta y$
Expected asymmetry small (2.1%)
Observed asymmetry small (2.7%)
Good modeling builds confidence for signal region
Back to signal region

Expected asymmetry due to NLO $t\bar{t}$ with EWK corrections plus backgrounds: 2.6 %

But we observe an asymmetry of $(6.6 \pm 2.0)$ %

This is enough to investigate further
Since SM asymmetry depends on $M_{t\bar{t}}$, split sample at 450 GeV/c$^2$

- $M_{t\bar{t}} < 450$ GeV/c$^2$ has asymmetry consistent with zero and with SM
- $M_{t\bar{t}} > 450$ GeV/c$^2$: $A_{FB} = (16.0 \pm 3.4)\%$ versus expected 4.4\%
To focus in on $t\bar{t}$, subtract the background model from data and compare to $t\bar{t}$ MC.

Still see similar effects in $\Delta y$, inclusively as well as above and below 450 GeV/$c^2$.
With the full Tevatron dataset, investigate mass dependence more thoroughly.

- Enough data for more than 2 bins.
- Mass spectrum for forward ($\Delta y > 0$) and backward ($\Delta y < 0$) events noticeably different in the data.
- $A_{FB}$ rises evenly with $M_{t\bar{t}}$.
- Magnitude of $A_{FB}$ increase not predicted by SM.
SM predicts $\sim$ linear dependence on $q^2$

Fit linear ansatz to data and to SM prediction

SM also predicts $\sim$ linear dependence on $\cos \theta_t$

Fit linear ansatz to $A_{\text{FB}}$ vs. $\Delta y$

Both SM prediction and data well described by linear dependence on $M_{t\bar{t}}$ and $\Delta y$

N.B. slope is not a theory parameter
Perform pseudoexperiments with POWHEG
Produce these distributions for each pseudoexperiment
Fit linear ansatz to each pseudoexperiment
Count number of pseudoexperiments with slope this large or larger

\[ p \text{-values:} \]
- \( M_{tt} \) dependence: 0.00646
- \( \Delta y \) dependence: 0.00892

To compare data directly to theory or other experiments, data must be corrected to parton level

CDF Run II Preliminary \( L = 8.7 \text{ fb}^{-1} \)

- \( \alpha_{M_{tt}} = (11 \pm 2.9) \times 10^{-4} \)
- \( \alpha_{M_{tt}} = 3 \times 10^{-4} \)
- \( \alpha_{\Delta y} = (20 \pm 5.9) \times 10^{-2} \)
- \( \alpha_{\Delta y} = 6.7 \times 10^{-2} \)
Part VI

Parton corrected
To estimate parton-level distributions from data, we must account for:

1. Finite detector resolution
2. Smearing due to incorrect reconstruction
3. Effect of selection cuts
4. Geometric acceptance
5. Trigger rate
6. Finite statistics

Two steps – first unsmear to correct for 1, 2, and 6, then correct acceptance for 3, 4 and 5

Acceptance correction is simple bin-by-bin ratio of MC truth before and after selection
Estimate detector response matrix $S$ from Monte Carlo.

Linear equation for corrected data $\vec{x}$ from data $\vec{b}$: $S\vec{x} = \vec{b}$.

Inverse problem is ill-conditioned.

Can only be solved in least squares sense ($\min |S\vec{x} - \vec{b}|^2$).

Even then, solution grossly magnifies statistical imprecision.

Use technique from math. stats.: Tikhonov regularization (Höcker and Kartvelishvili 1995).

Expect true parton level distribution to be smooth.

Minimize $|S\vec{x} - \vec{b}|^2 + \tau \cdot |C\vec{x}|^2$.

$C$ is matrix of second derivatives — encodes belief in smoothness.

Trade reduced statistical imprecision for small bias.
## Systematic uncertainties

### CDF Run II Preliminary $L = 8.7 \, \text{fb}^{-1}$

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- Many sources of systematic uncertainty
- Statistical uncertainty dominates systematic uncertainty
After correcting to parton level, get differential cross section $\frac{d\sigma}{d|\Delta y|}$.

From this, calculate $A_{FB}$ in each bin of $|\Delta y|$.

Fit linear ansatz again.

Similar behavior as observed before correction.

Linear ansatz describes both data and SM well.

Slope not well described by SM.
Also correct differential cross sections in mass, \( \frac{d\sigma}{dM_{t\bar{t}}} \), for forward and backward events

Use this to calculate \( A_{FB} \) as a function of \( M_{t\bar{t}} \)

Once again, linear ansatz describes data and SM, but slope not well described by SM.
Part VII

Additional Results
Lepton Asymmetry

- Lepton pseudorapidity is independent of $t\bar{t}$ reconstruction.
- Serves as a proxy for top quark rapidity.
- Observation of an asymmetry in this variable helps validate $t\bar{t}$ $A_{FB}$.
- $t\bar{t}$ $A_{FB}$ is not an artifact of $\chi^2$ fitter based $t\bar{t}$ reconstruction.

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

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<tr>
<th>$M_{t\bar{t}}$</th>
<th>$A_{FB}$ (± [stat.+syst.] )</th>
<th>$NLO (QCD+EW)$ $t\bar{t}$ $A_{FB}$</th>
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<tr>
<td>Inclusive</td>
<td>0.066 ± 0.025</td>
<td>0.016</td>
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<td>&lt; 450 GeV/$c^2$</td>
<td>0.037 ± 0.031</td>
<td>0.007</td>
</tr>
<tr>
<td>≥ 450 GeV/$c^2$</td>
<td>0.116 ± 0.042</td>
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