Measurements of forward-backward asymmetries in top-quark pair production at the D0 experiment

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on behalf of the
D0 Collaboration

36th International Conference on High Energy Physics 2012
July, 6th 2012
Melbourne, Australia
Overview

♦ Setting the stage
♦ $A_{FB}$ in 5.4 fb$^{-1}$ of l+jets events
♦ First D0 measurement of $A_{FB}^{l}$ in 5.4 fb$^{-1}$ of dilepton events
♦ $A_{FB}$ and top quark polarization
♦ Conclusion and outlook
Setting the Stage

♦ Does the top or anti-top quark more often follow the proton direction?

♦ different ways to answer this question and quantify asymmetry
  
  • rapidity difference of top and anti-top
    \[
    \Delta y = y_t - y_{\bar{t}} = q_l(\Delta y_{\text{lep}} - \Delta y_{\text{had}})
    \]
    
    \[
    y = \frac{1}{2} \ln\left(\frac{E + p_z}{E - p_z}\right)
    \]

  • rapidity gap used for a frame-independent definition
    \[
    A_{FB} = \frac{N(\Delta y > 0) - N(\Delta y < 0)}{N(\Delta y > 0) + N(\Delta y < 0)}
    \]
Asymmetry in the SM

- No asymmetry at LO QCD in SM
- At NLO asymmetries arise from interferences of process not symmetric under $t$ and $\bar{t}$ exchange

$A_{FB}$ at parton level including NNLL (arXiv:1106.6051) and QED corrections (arXiv:1107.2606):

<table>
<thead>
<tr>
<th></th>
<th>MC@NLO</th>
<th>NLO+NNLL</th>
<th>NLO+QED corr.</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$(5.0 \pm 0.1)%$</td>
<td>$(7.2 \pm 1.0)%$</td>
<td>$(8.9 \pm 0.8)%$</td>
</tr>
</tbody>
</table>
Data Sample and Event Challenge

- 5.4 fb⁻¹ of l+jets events: ~1600 t¯t candidates with 70% signal purity

- event selection:
  - isolated and high energetic jets and lepton (either electron or muon)
  - one identified b-quark jet

- t¯t modeled by MC@NLO+Herwig

- main background from W+jets (Alpgen+Pythia) and multijet events (estimated from data)
  - both nearly symmetric in Δy

- event reconstruction by kinematic fitter
  - using top and W mass constraints
  - including detector resolution
  → only most probable solution kept
Result on Detector Level

- measured $A_{FB}$ at detector level after background subtraction:

$$A_{FB}^{det} = (9.2 \pm 3.7 \text{ (stat+syst)})\%$$

- result agrees within 1.9 SD with the prediction from MC@NLO of $A_{FB}^{det} = (2.4 \pm 0.7)\%$

- result dominated by statistical uncertainty: 3.6%

- largest systematic uncertainty from jets: 0.5%
 Dependencies of $A_{fb}$

- asymmetry depends on several variables like $|\Delta y|$.
- new physics could e.g. cause different $m_{t\bar{t}}$ dependency
  - no significant dependency found at D0
  - largest deviation from SM prediction observed by CDF in high $m_{t\bar{t}}$ bin

Forward-Backward Top Asymmetry, %

![Graph showing Forward-Backward Top Asymmetry](image_url)

- S. Frixione and B.R. Webber, JHEP 06, 029 (2002)

- $|\Delta y| < 1$: 6.1±4.1
- $|\Delta y| > 1$: 21.3±9.7

- $m_{t\bar{t}} < 450$ GeV:
  - DØ, 5.4 fb$^{-1}$: 7.8±4.8
  - CDF, 5.3 fb$^{-1}$: -2.2±4.3
  - CDF, 8.7 fb$^{-1}$ (prelim): 2.5±3.1

- $m_{t\bar{t}} > 450$ GeV:
  - DØ, 5.4 fb$^{-1}$: 11.5±6.0
  - CDF, 5.3 fb$^{-1}$: 26.6±6.2
  - CDF, 8.7 fb$^{-1}$ (prelim): 20.0±4.3

~2.8 SD to NLO inc. QED corr.
Unfolding and Parton Level Result

- **regularized unfolding in $\Delta y$ to correct for acceptance and reconstruction**
  
  \[ A_{FB}^{\text{pat}} = (19.6 \pm 6.5 \,(\text{stat+syst}))\% \]

  - result agrees within 2.4 SD with the prediction from MC@NLO

- **performed cross check using maximum likelihood unfolding**

  - consistent results
  - better description of migrations across $\Delta y = 0$ using reg. unfolding
    \[ \rightarrow \text{better statistical strength} \]

unfolding illustration from “Statistical Data Analysis” by Glen Cowan
Lepton Based Asymmetry

- **lepton** based definition offers an alternative way to study $A_{fb}$

$$A_{FB,l}^{\text{det}} = \frac{N(q_{l}y_{l}>0) - N(q_{l}y_{l}<0)}{N(q_{l}y_{l}>0) + N(q_{l}y_{l}<0)}$$

- based on **well measured angles** → sufficient to correct for acceptance
- restrict to $|y_{l}|<1.5$ to avoid large acceptance corrections

- using ~1500 of tt candidate events:

$$A_{FB,l}^{\text{det}} = (14.2 \pm 3.8 \text{ (stat+syst)})\%$$

$$A_{FB,l}^{\text{pat}} = (15.2 \pm 4.0 \text{ (stat+syst)})\%$$

- result deviates by 3.4 SD from MC@NLO prediction of (2.1 ± 0.1)%
- dominated by statistical uncertainty
- largest systematic of 0.5% (1.6%) from $p_{T}^{t\bar{t}}$ modeling on detector (parton) level
Cross Checks

- extracted $A_{FB}$ and $A_{FB}^l$ for W+jets in background enriched sample
  - both agree well with Alpgen prediction of 2% and 14% resp.
- no dependencies observed on
  - solenoid/toroid polarities
  - lepton charge
  - lepton final state
A_{FB} in the Dilepton Channel

- **dilepton channel offers large variety of definitions** (arXiv:1003.3926)
  - the lepton based asymmetry:
    $$A_{FB}^{l} = \frac{N(q_l y_l > 0) - N(q_l y_l < 0)}{N(q_l y_l > 0) + N(q_l y_l < 0)}$$

- a definition based on the lepton difference in $\eta$:
  $$\Delta \eta = \eta_l - \eta_l$$
  $$A_{FB}^{ll} = \frac{N(\Delta \eta > 0) - N(\Delta \eta < 0)}{N(\Delta \eta > 0) + N(\Delta \eta < 0)}$$

- CP testing asymmetry:
  $$A_{FB}^{CP} = \frac{N_l(\eta > 0) - N_l(\eta < 0)}{N_l(\eta > 0) + N_l(\eta < 0)}$$

- **rewighted lepton $\eta$ distributions in MC@NLO considering QED corrections** (arXiv:1205.6580) to get parton level predictions:

<table>
<thead>
<tr>
<th>Prediction (%)</th>
<th>$A_{FB}^{l}$</th>
<th>$A_{FB}^{ll}$</th>
<th>$A_{FB}^{CP}$</th>
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<tr>
<td>4.7 ± 0.1</td>
<td>6.2 ± 0.2</td>
<td>-0.3 ± 0.1</td>
<td></td>
</tr>
</tbody>
</table>
- 5.4 fb\(^{-1}\) of dilepton events: \(~490 \, \bar{t}t\) candidates with 70% signal purity
- selection strategy follows event topology
- main background from Z+jets (Alpgen+Pythia)
  - background symmetric in \(\eta\), asymmetric in \(\Delta\eta\)
  - good agreement with prediction
- lepton angles well measured
  \(\rightarrow\) sufficient to correct for acceptance
  - checked correction from MC@NLO with acceptance from \(Z \rightarrow ll\) data
- fraction of events with mis-measured lepton charges only 0.2%
Asymmetry Results from Dilepton

- acceptance corrected asymmetries:

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<td>Unfolded (%)</td>
<td>$5.8 \pm 5.3$ (stat+syst)</td>
<td>$5.3 \pm 8.4$ (stat+syst)</td>
<td>$-1.8 \pm 5.3$ (stat+syst)</td>
</tr>
<tr>
<td>Prediction (%)</td>
<td>$4.7 \pm 0.1$</td>
<td>$6.2 \pm 0.2$</td>
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- good agreement with MC@NLO including QED corrections
- statistical uncertainty still large: 5-8%
- main systematic uncertainty from jet uncertainties

- l+jets and dilepton result for $A_{FB}^l$ consistent within 68%

- combined using the BLUE method (see talk by F. Déliot):
  \[ A_{FB}^l = (11.8 \pm 3.2) \% \]
  agreeing within 2.2 SD with MC@NLO prediction

- l+jets channel contributes ~2/3
First Study of Top Quark Polarization

- many BSM models trying to explain $A_{FB}$, couple to right-handed tops only → measurement of top polarization
- longitudinal polarization would show up in $B_1$ and $B_2 \neq 0$

\[
\frac{1}{\sigma} \frac{d\sigma}{d\cos\theta_1 d\cos\theta_2} = \frac{1}{4} \left( 1 + B_1 \cos\theta_1 + B_2 \cos\theta_2 + C \cos\theta_1 \cos\theta_2 \right)
\]

- leptophobic Z' with P-violating top couplings shows effect from polarized tops
  - good agreement between data and SM
Summary and Conclusion

- measured asymmetries in l+jets (arXiv:1107.4995) and dilepton (arXiv:1207.0364) channel
  - unfolded $A_{FB} = 19.6\%$ in l+jets agrees within 2.4 SD with MC@NLO prediction of 5.0%
  - combined lepton based asymmetry from l+jets and dilepton:
    \[ A_{FB}^l = (11.8 \pm 3.2) \% \]
    agrees within 2.2 SD with prediction of 4.7%
- however:
  - all results dominated by statistical uncertainty
  - ongoing work for improved predictions
- many models predict very different values for $A_{FB}$ and $A_{FB}^l$
  - new results with full data set (~9 fb$^{-1}$) in l+jets and dilepton in preparation