Charge asymmetry in top pair production at the LHC
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Fermilab, 09/29/2011
Large Hadron Collider (LHC)

- Delivered luminosity: $\sim 3.9 \text{ fb}^{-1}$
- Recorded luminosity: $\sim 3.5 \text{ fb}^{-1}$
- Max. instantaneous luminosity: $\sim 3.2 \cdot 10^{33} \text{ cm}^2 \text{s}^{-1}$
- Luminosity used in analyses: 0.7 fb$^{-1}$ (ATLAS), 1.1 fb$^{-1}$ (CMS)

$\sqrt{s} = 7 \text{ TeV}$
$L = 26.7 \text{ km}$

Started in March 2010
Top quark pair production

- Top quark pair production via strong interaction (dominant process)
- Electroweak production of single top quarks (factor 2-3 smaller than pair prod.)

<table>
<thead>
<tr>
<th></th>
<th>Tevatron</th>
<th>LHC</th>
<th>LHC / Tev</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cross section</td>
<td>7.5 pb</td>
<td>165 pb</td>
<td>~20</td>
</tr>
<tr>
<td>Gluon fusion</td>
<td>~15%</td>
<td>~80%</td>
<td>~5</td>
</tr>
</tbody>
</table>

Approximate NNLO:
1) arXiv:0807.2794
2) arXiv: 0909.0037
Top quark decay

SM:
\[ t \rightarrow b \ W \approx 100 \% \]

Decay of top quark pairs

<table>
<thead>
<tr>
<th>( \bar{c}s )</th>
<th>( u\bar{d} )</th>
<th>( \ell \ell' )</th>
<th>( \ell \ell )</th>
<th>all-hadronic</th>
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</thead>
<tbody>
<tr>
<td>electron+jets</td>
<td>muon+jets</td>
<td>tau+jets</td>
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<td>muon+jets</td>
<td></td>
<td></td>
<td></td>
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<td>tau+jets</td>
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<tr>
<td></td>
<td></td>
<td>electron+jets</td>
<td>muon+jets</td>
<td>tau+jets</td>
</tr>
</tbody>
</table>

LHC charge asymmetry analyses utilize "lepton+jets" channel (e+jets and \( \mu+jets \))
Survey of top quark

Production:
- Production rate of different processes (*strong and EW*)
- Differential distributions
- New production mechanisms

Intrinsic properties:
- Top quark mass → constraints on Higgs mass
- Charge
- Lifetime

Decay:
- Decay channels (SM and new)
- Couplings

Observed top quark is well consistent with the predictions of a SM top quark

But: Charge asymmetry in to pair production larger than expected

D0 papers: PRL 100, 142002 (2008), arXiv:1107.4995

+100 citations
Charge asymmetry in $pp$-collisions - $A_{FB}$

**SM:** Small asymmetry caused by higher order interference effect

**BSM:** - New particles with different vector and axial coupling
- New particles interfering with SM process

**Tevatron**

Sensitive variable: $y_t$

$\bar{t}t$-frame: $A_{FB}^{tt} \approx 0.06$

Lab-frame: $A_{FB}^{\text{Lab}} \approx A_{FB}^{tt} / 1.5$

Remark:
- MCFM calculation
- Full NLO $tt$ pred.: $\sim 1.5$ higher asym.

$pp$: $A_{FB}$ up to $\pm (0.2-0.3)$
**A_{FB} at the Tevatron**

### A_{fb} of the Top Quark

- **N. Kicionakis**, PRO084:011504 (2011)

**July 2011**

- (** submitted to a journal**)
- (*) preliminary

**top pair frame**

- **CDF LJ**
  - 0.158 ± 0.074 (±0.072 ± 0.017)
  - (5.3 fb⁻¹)

- **CDF DIL**
  - 0.420 ± 0.158 (±0.150 ± 0.050)
  - (5.1 fb⁻¹)

- **CDF combined**
  - 0.201 ± 0.067 (±0.065 ± 0.016)
  - (± stat ± syst)

- **D0 LJ**
  - 0.196 ± 0.060 ±0.015
  - (5.4 fb⁻¹)

- **New paper will come out soon**

- **CDF** measures large asymmetry for M_{tt} > 450 GeV, but D0 not

- **Tevatron** measures a larger inclusive A_{FB} than predicted by SM
Charge asymmetry at pp-colliders

Proton-antiproton (Tevatron):

\[ q \text{ (anti-}q\text{)} \text{ mostly from proton (antiproton)} \]
\[ \rightarrow \text{ forward-backward asymmetry } A_{FB} \]

Proton-proton (LHC):

average quark momentum fraction \( x_q > x_{\text{anti-}q} \)
\[ \rightarrow \text{ central-peripheral asymmetry } A_{C} \]

Asymmetry occurs for asymmetric initial states only \((q\bar{q},qg)\)

- Predicted SM \( A_{C} \) at LHC is tiny due to large gg-fraction: \( A_{C} \approx 0.01 \)
- Depending on underlying new physics scenario Tevatron result would lead in a substantially increased asymmetry \( A_{C} \) at LHC
Sensitive variables

Sensitive variables used at the LHC:

- $\Delta |\eta| = |\eta_t| - |\eta_\bar{t}|$

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

- $\Delta y^2 = y_t^2 - y_\bar{t}^2 = (y_t - y_\bar{t}) \times (y_t + y_\bar{t})$

Tevatron variable boosted into $t\bar{t}$ rest frame


The charge asymmetry can be defined as asymmetry in these variables:

$$A_C^\eta = \frac{N(\Delta |\eta| > 0) - N(\Delta |\eta| < 0)}{N(\Delta |\eta| > 0) + N(\Delta |\eta| < 0)}$$

$$A_C^y = \frac{N(\Delta |y| > 0) - N(\Delta |y| < 0)}{N(\Delta |y| > 0) + N(\Delta |y| < 0)} = \frac{N(\Delta y^2 > 0) - N(\Delta y^2 < 0)}{N(\Delta y^2 > 0) + N(\Delta y^2 < 0)}$$

SM prediction: $A_C \approx 0.01$ 

(G. Rodrigo)

Paper will come out soon
Charge asymmetry in new physics models

- Z': Flavor violating Z' exchanged in t-channel in $uu \rightarrow tt$ and with right-handed Z'tu couplings
- W': W' boson with right-handed couplings exchanged in t-channel in $dd \rightarrow tt$
- Ω⁴: Color-sextet scalar with right-handed flavor violating tu-couplings and exchanged in u-channel
- ω⁴: Color triplet with flavor violating tu-couplings, right-handed, exchanged in u-channel in $uu \rightarrow tt$
- $G_\mu$: Axigluon, color octet vector with axial couplings

CDF result

J. Aguilar-Saavedra, M. Perez-Victoria, arXiv:1105.4606

LHC charge asymmetry measurement provides complementary information
LHC measurements - overview

**ATLAS (ATLAS-CONF-2011-106):**
- used variable: $\Delta |y| = |y_t| - |y_i|

**CMS (CMS PAS TOP-11-014):**
- used variables: $\Delta |\eta| = |\eta_t| - |\eta_i|$ and $\Delta y^2 = y_t^2 - y_i^2$

**Common analysis strategy:**
- Selection of top quark pair events in e+jets/μ+jets channel
- Background estimation
- Reconstruction of top quark momenta
- Unfolding of the sensitive variable to correct for distortions due to selection efficiency and non-perfect reconstruction
- Measurement of the asymmetry in the corrected spectrum
Event selection

Event signature:
- One isolated e or μ with high $p_T$
- Missing transverse energy
- 4 jets, of which two are b-jets

Selection cuts:
- Trigger: – Atlas: single lepton trigger
  – CMS: lepton+3 jets trigger
- Exactly one isolated muon (electron):
  – Atlas: $p_T$ > 20 (25) GeV/c, $|\eta|$ < 2.5
  – CMS: $p_T$ > 20 GeV/c ($E_T$ > 30 GeV), $|\eta|$ < 2.1
- $\geq 4$ jets (anti-$k_T$ algorithm):
  – Atlas: $p_T$ > 25 GeV/c, $|\eta|$ < 2.5 ($\Delta R$=0.4)
  – CMS: $p_T$ > 30 GeV/c and $|\eta|$ < 2.4 ($\Delta R$=0.5)
- At least one jet tagged as b-jet:
  – Atlas: secondary vertex b-tag
  – CMS: IP significance of 2nd track
- Additional cuts against QCD (ATLAS only)
  – e: $E_T^{miss}$ > 35 GeV and $m_T(W)$ > 25 GeV
  – μ: $E_T^{miss}$ > 20 GeV and $E_T^{miss}+m_T(W)$ > 60 GeV
Background estimation

**ATLAS:**

- **QCD:** Matrix method using loose and tight lepton isolation selections → 2 equations with two unknowns
  \[ \varepsilon \text{ of add. lepton cut with respect to loose sel. obtained from Z and QCD sample, resp.} \]

- **W+jets:** Use W+/W− asymmetry to extract rate in pretag sample; use \( \varepsilon_b \) and W+HF corrections determined in data to get rate in tagged sample

- **Z+jets, diboson and single top**
  rates from MC prediction

**CMS:**

- Sample composition estimated from simultaneous likelihood fits to:
  - \( E_T^{\text{miss}} \) for \( E_T^{\text{miss}} < 40 \text{ GeV} \)
  - M3 for \( E_T^{\text{miss}} > 40 \text{ GeV} \)

- Fit the rates of tt, W+/jets, W−+jets, QCD e, QCD μ

- Z+jets and single top constrained to SM prediction in fit

- Use QCD template from data with less-well isolated leptons
### Event yields

<table>
<thead>
<tr>
<th>Channel</th>
<th>$\mu$ + jets pretag</th>
<th>$\mu$ + jets tagged</th>
<th>e + jets pretag</th>
<th>e + jets tagged</th>
</tr>
</thead>
<tbody>
<tr>
<td>$tt$</td>
<td>4784 ± 5</td>
<td>3247 ± 4</td>
<td>3293 ± 4</td>
<td>2218 ± 4</td>
</tr>
<tr>
<td>Single top</td>
<td>306 ± 2</td>
<td>171 ± 2</td>
<td>219 ± 2</td>
<td>124 ± 2</td>
</tr>
<tr>
<td>Z+Jets</td>
<td>632 ± 7</td>
<td>43 ± 2</td>
<td>535 ± 7</td>
<td>35 ± 1</td>
</tr>
<tr>
<td>Diboson</td>
<td>90 ± 2</td>
<td>8 ± 1</td>
<td>56 ± 1</td>
<td>5 ± 0</td>
</tr>
<tr>
<td>W+jets</td>
<td>5741 ± 915</td>
<td>494 ± 234</td>
<td>3436 ± 628</td>
<td>309 ± 144</td>
</tr>
<tr>
<td>QCD</td>
<td>1103 ± 552</td>
<td>227 ± 227</td>
<td>665 ± 332</td>
<td>84 ± 84</td>
</tr>
<tr>
<td>Total background</td>
<td>7871 ± 1068</td>
<td>943 ± 326</td>
<td>4910 ± 711</td>
<td>557 ± 167</td>
</tr>
<tr>
<td>Signal + background</td>
<td>12655 ± 1068</td>
<td>4189 ± 326</td>
<td>8203 ± 711</td>
<td>2775 ± 167</td>
</tr>
<tr>
<td>Observed</td>
<td>12705</td>
<td>4392</td>
<td>8193</td>
<td>2997</td>
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</table>

**$L = 0.7 \text{ fb}^{-1}$**

<table>
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<tr>
<th>process</th>
<th>electron+jets</th>
<th>muon+jets</th>
<th>total</th>
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<tbody>
<tr>
<td>$tt$</td>
<td>4401 ± 165</td>
<td>5835 ± 199</td>
<td>10236 ± 258</td>
</tr>
<tr>
<td>single top (t + tW)</td>
<td>213 ± 58</td>
<td>293 ± 81</td>
<td>507 ± 99</td>
</tr>
<tr>
<td>$W^+$+jets</td>
<td>313 ± 84</td>
<td>404 ± 106</td>
<td>718 ± 135</td>
</tr>
<tr>
<td>$W^-$+jets</td>
<td>299 ± 90</td>
<td>245 ± 109</td>
<td>544 ± 141</td>
</tr>
<tr>
<td>Z+jets</td>
<td>81 ± 24</td>
<td>85 ± 26</td>
<td>165 ± 35</td>
</tr>
<tr>
<td>QCD</td>
<td>355 ± 71</td>
<td>232 ± 79</td>
<td>587 ± 106</td>
</tr>
<tr>
<td>total fit result</td>
<td>5663 ± 226</td>
<td>7094 ± 276</td>
<td>12757 ± 357</td>
</tr>
<tr>
<td>observed data</td>
<td>5665</td>
<td>7092</td>
<td>12757</td>
</tr>
</tbody>
</table>

**$L = 1.1 \text{ fb}^{-1}$**

Several thousand top pair events selected with a purity of >75%
Reconstruction

Measurement of charge asymmetry requires full reconstruction of top quark 4-momenta

- Accessible objects: jets, charged lepton, $E_t^{\text{miss}}$
- Ambiguities in assignment of jets and leptons to top quark (24 hypotheses for 4 jet event)

- Select hypothesis which describes the top quark topology best by
  – using constraints on W and top masses
  – exploiting b-likeness of jets
- Charge of e or $\mu$ defines the charge of the leptonically decaying top; assume that hadronically decaying top quark has opposite charge
Sensitive variables – raw distributions

**ATLAS Preliminary**

**e+ jets (b tag)**

\[ L = 0.7 \text{ fb}^{-1} \]

**μ+ jets (b tag)**

\[ L = 0.7 \text{ fb}^{-1} \]

**CMS Preliminary**

1.09 fb\(^{-1}\) at \( \sqrt{s} = 7 \text{ TeV} \)

\[ A^\text{RAW}_{C} = -0.004 \pm 0.009 \]

**e+ jets & μ+ jets**

\[ L = 1.1 \text{ fb}^{-1} \]

**e+ jets & μ+ jets**

\[ L = 1.1 \text{ fb}^{-1} \]
Correction of sensitive variables

Observed asymmetry is affected by background and detector effects

Correction of sensitive variable:

Subtraction of background

Correction of smearing effects and detector acceptance
Unfolding

**ATLAS:**
- Iterative Bayesian unfolding
- Separate unfolding in e+jets and \( \mu+jets \)
- Response matrix from MC@NLO

**CMS:**
- Regularized unfolding based on generalized matrix inversion
- Combined unfolding of e+jets and \( \mu+jets \)
- Response matrix from MadGraph MC
Unfolded distributions

\[ A_C^y = -0.009 \pm 0.023 \, (\text{stat.}) \]

\[ A_C^y = -0.028 \pm 0.019 \, (\text{stat.}) \]

\[ L = 0.7 \, \text{fb}^{-1} \]

e+jets:

\[ A_C^y = -0.016 \pm 0.030 \, (\text{stat.}) \]

\[ A_C^y = -0.013 \pm 0.026 \, (\text{stat.}) \]

\[ L = 1.1 \, \text{fb}^{-1} \]
Systematics

ATLAS

<table>
<thead>
<tr>
<th>Source of systematic uncertainty</th>
<th>Electron channel</th>
<th>Muon channel</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>ΔA_C</strong></td>
<td></td>
<td></td>
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<tr>
<td><strong>Signal and background modelling</strong></td>
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<tr>
<td>$t\bar{t}$ generator</td>
<td>0.0243</td>
<td>0.0100</td>
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<tr>
<td>Parton shower/fragmentation</td>
<td>0.0108</td>
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<td>ISR/FSR</td>
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<td>PDF uncertainty</td>
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<td>0.0008</td>
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<td>QCD normalisation</td>
<td>0.0062</td>
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<td>W+jets normalisation</td>
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<td>0.0097</td>
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<td>W+jets shape</td>
<td>0.0043</td>
<td>0.0043</td>
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<td>Z+jets normalisation</td>
<td>0.0002</td>
<td>0.0002</td>
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<tr>
<td>Z+jets shape</td>
<td>0.0010</td>
<td>0.0010</td>
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<tr>
<td>Single Top normalisation</td>
<td>0.0002</td>
<td>0.0002</td>
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<td>Diboson normalisation</td>
<td>0.00001</td>
<td>0.00001</td>
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<tr>
<td>MC sample sizes</td>
<td>0.0043</td>
<td>0.0029</td>
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<tr>
<td><strong>Detector modelling</strong></td>
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<tr>
<td>Muon efficiencies</td>
<td>(n.a.)</td>
<td>0.0002</td>
</tr>
<tr>
<td>Muon momentum scale and resolution</td>
<td>0.0004</td>
<td>0.0004</td>
</tr>
<tr>
<td>Electron efficiencies</td>
<td>0.0004</td>
<td>(n.a.)</td>
</tr>
<tr>
<td>Electron energy scale and resolution</td>
<td>0.0004</td>
<td>0.0004</td>
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<tr>
<td>Lepton charge misidentification</td>
<td>0.0002</td>
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<tr>
<td>Jet energy scale</td>
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<td>0.0046</td>
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<td>Jet energy resolution</td>
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<td>0.0040</td>
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<td>Jet reconstruction efficiency</td>
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<td>0.0003</td>
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<tr>
<td>$b$-tagging scale factors</td>
<td>0.0038</td>
<td>0.0038</td>
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<tr>
<td>Charge asymmetry in $b$-tagging efficiency</td>
<td>0.0007</td>
<td>0.0007</td>
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<tr>
<td>Calorimeter readout</td>
<td>0.0015</td>
<td>0.0029</td>
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<tr>
<td>Combined uncertainty</td>
<td>0.032</td>
<td>0.022</td>
</tr>
</tbody>
</table>

CMS

<table>
<thead>
<tr>
<th>Source of Systematic</th>
<th>$A^+_C$</th>
<th>$A^-_C$</th>
<th>$A^+_C$</th>
<th>$A^-_C$</th>
</tr>
</thead>
<tbody>
<tr>
<td>JES</td>
<td>−0.003</td>
<td>0.000</td>
<td>−0.007</td>
<td>0.000</td>
</tr>
<tr>
<td>JER</td>
<td>−0.002</td>
<td>0.000</td>
<td>−0.001</td>
<td>0.001</td>
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<tr>
<td>Q^2 scale</td>
<td>−0.014</td>
<td>0.000</td>
<td>−0.013</td>
<td>+0.003</td>
</tr>
<tr>
<td>ISR/FSR</td>
<td>−0.006</td>
<td>+0.003</td>
<td>0.000</td>
<td>+0.024</td>
</tr>
<tr>
<td>Matching threshold</td>
<td>−0.006</td>
<td>0.000</td>
<td>−0.013</td>
<td>+0.006</td>
</tr>
<tr>
<td>PDF</td>
<td>−0.001</td>
<td>+0.001</td>
<td>−0.001</td>
<td>+0.001</td>
</tr>
<tr>
<td>b tagging</td>
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<td>+0.003</td>
<td>0.000</td>
<td>+0.001</td>
</tr>
<tr>
<td>Lepton ID/sel. efficiency</td>
<td>−0.002</td>
<td>+0.004</td>
<td>−0.002</td>
<td>+0.003</td>
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<tr>
<td>QCD model</td>
<td>−0.008</td>
<td>+0.008</td>
<td>−0.006</td>
<td>+0.006</td>
</tr>
<tr>
<td>Pileup</td>
<td>−0.002</td>
<td>+0.002</td>
<td>0.000</td>
<td>+0.000</td>
</tr>
<tr>
<td>Overall</td>
<td>−0.019</td>
<td>+0.010</td>
<td>−0.021</td>
<td>+0.026</td>
</tr>
</tbody>
</table>

- **ATLAS**: perform unfolding on data using alternative MC samples for smearing matrix/background subtraction
- **CMS**: draw pseudo experiments from systematically shifted samples and evaluate shifts of the asymmetry when doing the unfolding with the standard templates.
Final results

ATLAS:
- e+jets: \( A_C^γ = -0.009 \pm 0.023 \text{ (stat.)} \pm 0.032 \text{ (syst.)} \)
- μ+jets: \( A_C^γ = -0.028 \pm 0.019 \text{ (stat.)} \pm 0.022 \text{ (syst.)} \)
- Combined using BLUE method:
  \( A_C^γ = -0.024 \pm 0.016 \text{ (stat.)} \pm 0.023 \text{ (syst.)} \)

CMS:
- \( A_C^η = -0.016 \pm 0.030 \text{ (stat.)}^{+0.010}_{-0.019} \text{ (syst.)} \)
- \( A_C^γ = -0.013 \pm 0.026 \text{ (stat.)}^{+0.026}_{-0.021} \text{ (syst.)} \)

Inclusive charge asymmetry at the LHC is consistent with SM prediction of \( A_C^c \sim 0.01 \)
M_{tt} dependence of A_c

- CMS measures the charge asymmetry differentially in M_{tt}
- Results are corrected for background contributions, no full unfolding yet

No indication for a strong M_{tt} dependence of A_c
Conclusion

- Measurement of $A_c$ in top pair production at the LHC provides complementary information to the measurement of $A_{FB}$ at Tevatron.

- Measured $A_c$ at LHC have slight tendency to negative values but are consistent with SM prediction of $\sim 1\%$.

- More detailed studies of $A_c$ in differential distributions might show hints for new physics in top quark pair production.

- New results on $A_{FB}$ and $A_c$ will show whether new physics is responsible for the large $A_{FB}$ at Tevatron, and if yes both measurements can be used to constrain new physics models.