Top (and Bottom) asymmetries at the LHC

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on behalf of the ATLAS and CMS Collaborations
(including LHCb results)

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Introduction

**Charge asymmetry in $t\bar{t}$ events**

- At LO, $t\bar{t}$ production symmetric
- At NLO, QCD predicts an asymmetry for $q\bar{q} \rightarrow t\bar{t}$

$$q\bar{q} + q\bar{q}$$

positive asymmetry

$$q\bar{q} - q\bar{q}$$

negative asymmetry

(flavour excitation in $qg \rightarrow t\bar{t}$ much smaller)

- The top quark is predicted to be emitted preferably in the direction of the incoming quark
- The exchange of new particles like $Z'$ or axigluon could modify it

$$q\bar{q} + q\bar{q}$$

Top (and Bottom) asymmetries at the LHC
**Tevatron, \( p\bar{p} \):**
- \( q \) and \( \bar{q} \) carry equal \(< x >\)
- \( t \) preferential direction = \( p \) direction
- Forward/Backward asymmetry:
  \[
  A_{FB} = \frac{N(\Delta y > 0) - N(\Delta y < 0)}{N(\Delta y > 0) + N(\Delta y < 0)},
  \]
  \( \Delta y = y_t - y_{\bar{t}} \)

**LHC, \( pp \):**
- LAB frame: no \( t \) preferential direction, but system \( z \)-boost along \( q \) direction
- \( t \) at higher \(|y|\), \( \bar{t} \) more central
- Charge asymmetry defined as:
  \[
  A_c = \frac{N(\Delta |y| > 0) - N(\Delta |y| < 0)}{N(\Delta |y| > 0) + N(\Delta |y| < 0)},
  \]
  \( \Delta |y| = |y_t| - |y_{\bar{t}}| \)

Also: at the LHC \( q\bar{q} \) annihilation suppressed vs \( gg \) fusion ⇒ More diluted effect

<table>
<thead>
<tr>
<th></th>
<th>Tevatron</th>
<th>LHC</th>
</tr>
</thead>
<tbody>
<tr>
<td>Asymmetry at NLO</td>
<td>9%</td>
<td>1%</td>
</tr>
</tbody>
</table>
Introduction

Charge asymmetry measurements

<table>
<thead>
<tr>
<th></th>
<th>ATLAS</th>
<th>CMS</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>7 TeV [JHEP 1404 (2014) 191]</td>
<td>8 TeV [CMS PAS TOP-12-033]</td>
</tr>
<tr>
<td>dilepton</td>
<td>7 TeV [arXiv:1501.07383]</td>
<td>7 TeV</td>
</tr>
</tbody>
</table>

(new NNLO with Principle of Maximum Conformality: Brodsky, Si, Wang, Wu [PRD 90 (2014) 114034])

- $A_C$ measurement implies $t$ and $\bar{t}$ reconstruction: jet combinatorics, solve for $p_T$ ...
- Unfolding to correct for detector and acceptance effects
- Need for at least one lepton (e or µ) to define $\Delta|y|$  

Lower uncertainties in single lepton channel

- Statistics is one of the limiting factors in this measurement
- Only one neutrino $\Rightarrow$ full reconstruction of the system easier

In dilepton: Lepton Asymmetry also measured:

$$A_C^{lep} = \frac{N(\Delta|\eta\ell| > 0) - N(\Delta|\eta\ell| < 0)}{N(\Delta|\eta\ell| > 0) + N(\Delta|\eta\ell| < 0)}$$
**Single lepton channel**

**Selection and Backgrounds**

### $\ell^+ + \text{jets Event Selection}$
- Exactly one $e$ or $\mu$
- $\geq 4$ jets
- $\geq 1$ $b$-tag
- Requirements on $E_T^{\text{miss}}$ and/or $m^W_T$

### Backgrounds:

| Source     | Normalization | Shape            | Symmetric in $\Delta |y|$? |
|------------|---------------|-------------------|----------------------|
| $W + \text{jets}$ | data-driven   | from Simulation   | Asymmetric           |
| Multi-jet  | data-driven   | data-driven       | Symmetric            |
| Single top | NNLO          | from Simulation   | Asymmetric           |
| $Z + \text{jets, diboson}$ | (N)NLO        | from Simulation   | $\sim$Symmetric      |

**ATLAS:** $W + \text{jets}$ from $\ell^+ / \ell^-$ asymmetry, multi-jet from Matrix Method

**CMS:** fit $E_T^{\text{miss}}$ and $M_{jjj}$, multi-jet shape from inverted lepton ID & isolation

Top (and Bottom) asymmetries at the LHC
**System Reconstruction**

**CMS:**
- Neutrino $p_z$ found assuming $m_W$
- Decorrelation of reco masses $(m_{\text{had}}^t, m_{\text{lep}}^t, m_W) \rightarrow (m_1, m_2, m_3)$
- $b$-quark tag terms based on continuous $b$-tag values $P_b(x)$

$$\psi = L_1(m_1) L_2(m_2) L_3(m_3) P_b(x_{b1}) P_b(x_{b2})(1 - P_b(x_{q1}))(1 - P_b(x_{q2}))$$

**ATLAS:**
- Transfer functions for reco ($\hat{x}$) $\rightarrow$ partonic ($\tilde{x}$) quantities
- Breit-Wigner functions for mass terms
- Tagging term from single $b$-tag working point

$$L = B(\tilde{E}_p,1, \tilde{E}_p,2|m_W, \Gamma_W) \cdot B(\tilde{E}_{\text{lep}}, \tilde{E}_y|m_W, \Gamma_W) \cdot B(\tilde{E}_p,1, \tilde{E}_p,2, \tilde{E}_p,3|m_t, \Gamma_t) \cdot B(\tilde{E}_{\text{lep}}, \tilde{E}_y, \tilde{E}_p,4|m_t, \Gamma_t) \cdot W(\tilde{E}_x^{\text{miss}}|\tilde{p}_x,y) \cdot W(\tilde{E}_y^{\text{miss}}|\tilde{p}_y,v) \cdot W(\tilde{E}_{\text{lep}}|\tilde{E}_{\text{lep}}) \cdot \prod_{i=1}^{4} W(\tilde{E}_p,i|\tilde{E}_{\text{jet}},i) \cdot \prod_{i=1}^{4} W(\tilde{p}_p,i|\tilde{p}_{\text{jet}},i) \cdot \prod_{i=1}^{4} W(\tilde{\phi}_p,i|\tilde{\phi}_{\text{jet}},i) \cdot \prod_{i=1}^{4} P(\text{tagged} | \text{parton flavour})$$

**Both: correct sign for $\Delta|y|$ found $\sim75\%$ of the time**

Top (and Bottom) asymmetries at the LHC
Reconstructed $t\bar{t}$ system variables

- Reconstruction-level $\Delta |y| = |y_t| - |y_{\bar{t}}|$ distribution obtained and used as input for the measurement.
- Other distributions considered:
  - $A_C$ measurement vs $t\bar{t}$ system kinematics:
    - $y_t, y_{\bar{t}}$: sensitive to ratio of contributions $q\bar{q}/gg \to t\bar{t}$
    - $p_{T,t\bar{t}}$: sensitive to positive / negative asymmetry (large $p_T \Rightarrow$ large radiation $\Rightarrow$ more negative)
    - $m_{t\bar{t}}$: sensitive to ratio of contributions $q\bar{q}/gg \to t\bar{t}$ AND to BSM effects due to new heavy particles.
Single lepton channel

Unfolding

CMS: Regularized unfolding through generalized matrix inversion procedure

- Perturbing effects → Response / Smearing Matrix $S$: $\vec{w} = S\vec{x}$
  ($\vec{x}$ true spectrum, $\vec{w}$ reconstructed spectrum)

- Reconstruction and selection effects factorize $\Rightarrow S = M \times E$
  ($M$ migration matrix, $E$ efficiency (diagonal) matrix)

- Equations from matrix inversion solved with least squares (LS) technique $→ x_{LS}$

- To stabilize the result, two terms added: regularization and normalization terms

- Procedure generalized for 2-dimensional case
Single lepton channel

Unfolding - II

ATLAS: Fully Bayesian Unfolding (FBU)

- It applies the Bayes’ theorem to the solution of the unfolding problem

\[ p(T|D,M) \propto L(D|T,M) \cdot \pi(T) \]

- Spectra of $\Delta|y|$ distribution considered (or $(\Delta|y|,x)$ for $A_C$ vs $x$ measurement):
  - $A_C$ posterior from $\Delta|y|$ distributions (4 bins) $\forall$ point in integration space
  - mean and RMS of this posterior $\rightarrow A_C$ value and uncertainty

- No iterations needed for regularization: choice of the prior plays its role instead:
  - flat prior $\leftrightarrow$ numerical matrix inversion: used for $A_C$ vs $m_{t\bar{t}}$ and $|y_{t\bar{t}}|
  - curvature prior $\leftrightarrow$ regularization: used for inclusive and $A_C$ vs $p_{T,t\bar{t}}$
  - checked that the choice didn’t introduce significant biases

- Marginalization of systematics on the posterior probability performed
### Inclusive Asymmetry at 7 TeV

<table>
<thead>
<tr>
<th></th>
<th>$A_c$</th>
</tr>
</thead>
<tbody>
<tr>
<td>ATLAS</td>
<td>$0.006 \pm 0.010$(stat+syst*)</td>
</tr>
<tr>
<td>CMS</td>
<td>$0.004 \pm 0.010$(stat) $\pm 0.011$(syst)</td>
</tr>
<tr>
<td>Bernreuther &amp; Si</td>
<td>$0.0123 \pm 0.0005$</td>
</tr>
<tr>
<td>Kühn &amp; Rodrigo</td>
<td>$0.0115 \pm 0.0006$</td>
</tr>
</tbody>
</table>

- *: ATLAS result includes marginalization of systematics
- **Statistical uncertainty** still large
- Largest contribution to systematics from:
  - jet & lepton energy measurement, $E_T^{miss}$ and pile-up
  - $W$+jet background
  - model dependence of asymmetry (CMS)
- Different systematics related to model dependence assigned
- Result compatible with both zero and NLO+EW prediction
ATLAS and CMS $A_C$ 7 TeV measurements in $\ell + \text{jet}$ combined after unfolding (by TopLHC WG: [ATLAS-CONF-2014-012], [CMS PAS TOP-14-006])

**Combination:**
- For ATLAS, used separate statistical and systematic uncertainties before the FBU marginalization procedure
- Result improves on ATLAS by 18% and CMS by 40%
- Result compatible with both zero and NLO+EW prediction
## Single lepton channel

### Systematics

<table>
<thead>
<tr>
<th></th>
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<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>$A_C$</td>
<td>0.006</td>
<td>0.004</td>
<td>0.005</td>
<td>0.058</td>
</tr>
<tr>
<td>Statistical</td>
<td>0.010</td>
<td>0.010</td>
<td>0.007</td>
<td>0</td>
</tr>
<tr>
<td>Detector response model</td>
<td>0.004</td>
<td>0.007</td>
<td>0.004</td>
<td>0</td>
</tr>
<tr>
<td>Signal model</td>
<td>$&lt; 0.001$</td>
<td>0.002</td>
<td>0.001</td>
<td>1</td>
</tr>
<tr>
<td>W+jets model</td>
<td>0.002</td>
<td>0.004</td>
<td>0.003</td>
<td>0.5</td>
</tr>
<tr>
<td>QCD model</td>
<td>$&lt; 0.001$</td>
<td>0.001</td>
<td>0.000</td>
<td>0</td>
</tr>
<tr>
<td>Pileup+MET</td>
<td>0.002</td>
<td>$&lt; 0.001$</td>
<td>0.001</td>
<td>0</td>
</tr>
<tr>
<td>PDF</td>
<td>0.001</td>
<td>0.002</td>
<td>0.001</td>
<td>1</td>
</tr>
<tr>
<td>MC statistics</td>
<td>0.002</td>
<td>0.002</td>
<td>0.001</td>
<td>0</td>
</tr>
<tr>
<td>Model dependence</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Specific physics models</td>
<td>$&lt; 0.001$</td>
<td>*</td>
<td>0.000</td>
<td>0</td>
</tr>
<tr>
<td>General simplified models</td>
<td>*</td>
<td>0.007</td>
<td>0.002</td>
<td>0</td>
</tr>
<tr>
<td>Systematic uncertainty</td>
<td>0.005</td>
<td>0.011</td>
<td>0.006</td>
<td></td>
</tr>
<tr>
<td>Total uncertainty</td>
<td>0.011</td>
<td>0.015</td>
<td>0.009</td>
<td></td>
</tr>
</tbody>
</table>
Single lepton channel

Differential Asymmetries

(EAG: Effective AxiGluon, with 1 TeV scale)
Single lepton channel

**Asymmetry vs $t\bar{t}$ system velocity**

ATLAS measures $A_C$ for events with high $\beta_{z,t\bar{t}}$ ($t\bar{t}$ velocity/c along z axis):
- To enhance the contribution from $q\bar{q}$-initiated production
- To enhance potential effects of new physics

<table>
<thead>
<tr>
<th></th>
<th>$A_C(\beta_{z,t\bar{t}} &gt; 0.6)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>ATLAS</td>
<td>0.011 ±0.018 (stat+syst)</td>
</tr>
<tr>
<td>Bernreuther &amp; Si</td>
<td>0.020 $^{+0.006}_{-0.007}$</td>
</tr>
</tbody>
</table>
**Single lepton channel**

**Asymmetry at 8 TeV**

CMS measures $A_C$ in 8 TeV data, with the same procedure:
- Reduced stat uncertainty, smaller systematics
- Same precision as the 7 TeV CMS+ATLAS result

<table>
<thead>
<tr>
<th></th>
<th>$A_C$</th>
</tr>
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<tr>
<td>CMS</td>
<td>0.005 ± 0.007(stat) ± 0.006(syst)</td>
</tr>
<tr>
<td>Bernreuther &amp; Si</td>
<td>0.0102 ± 0.0005</td>
</tr>
<tr>
<td>Kühn &amp; Rodrigo</td>
<td>0.0111 ± 0.0004</td>
</tr>
</tbody>
</table>

![Graphs and plots showing top (and bottom) asymmetries at the LHC](image)

Top (and Bottom) asymmetries at the LHC
Comparison with BSM and Tevatron

- Comparison of $A_C (\ell+\text{jets}, 7 \text{ TeV})$ with various New Physics models ($W', \Omega^4, \phi, G_\mu, \omega^4$) generated with PROTOS to scan the mass-coupling parameter space
- Some models (e.g. $W'$) seem to be disfavoured

(Plots from [JHEP 1402 (2014) 107], Tevatron results from [PRD 87 (2013) 092002], [PRD 84 (2011) 112005])
Event Selection and Backgrounds

Dilepton Channel

Dilepton Event Selections:

- 2 OS leptons (ee, μμ, eμ)
- $m_{\ell\ell} > 15-20$ GeV
- $m_{\ell\ell}$ outside $Z$-mass window for $ee/\mu\mu$
- $E_T^{\text{miss}} > 60-40$ for $ee/\mu\mu$
- $H_T > 130$ GeV for $e\mu$ (ATLAS)
- $\geq 2$ jets
- $\geq 1$ b-tag (CMS)

Backgrounds from:

- $Wt$ single top, diboson: from simulation
- $Z$+jets: estimated from $m_{\ell\ell}$ sideband
- Fake & non-prompt leptons (from $W$+jets and QCD): from Data with Matrix Method
Event Reconstruction

For $A_C$, need to fully reconstruct $t\bar{t}$ kinematics:

- 2 neutrinos vs. 1 $E_T^{miss}$, lepton/$b$ pairing ambiguities

ATLAS & CMS: Neutrino Weighting techniques*

- Loop over the different possible solutions for $\eta_1^\nu, \eta_2^\nu$
- Assume $m_t$ and $m_W$ values
- Weight assigned to each solution based on the level of agreement with the measured $E_T^{miss}$, take solution with largest weight
- Jet energies floating within uncertainties: resolution functions and MC integration
- For CMS (ATLAS), $\sim 14\%$ ($20\%$) of events discarded due to no solution found
- $\sim 80\%$ of the time correct sign for $\Delta |y|$ in MC

(*: 'Analytical Matrix Weighting Technique (AMWT)' in CMS)

Lepton Asymmetry $A_C^{lep}$ needs just lepton $\eta$:

- Related to $A_C$, sensitive to anomalous top polarization
- No need to reconstruct $t\bar{t}$ system
- Less affected by unfolding complications
Dilepton Channel

CMS results

<table>
<thead>
<tr>
<th></th>
<th>$A_C$</th>
<th>$A_C^{lep}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>CMS</td>
<td>$-0.010 \pm 0.017$ (stat) $\pm 0.008$ (syst)</td>
<td>$0.009 \pm 0.010$ (stat) $\pm 0.006$ (syst)</td>
</tr>
<tr>
<td>Bernreuther &amp; Si</td>
<td>$0.0123 \pm 0.0005$</td>
<td>$0.0070 \pm 0.0003$</td>
</tr>
</tbody>
</table>

- Unfolding reco-level $\Delta |y|$ and $\Delta |\eta|$ distributions
- Systematics dominated by $t\bar{t}$ scale uncertainty (and unfolding for $A_C$)
- For $A_C^{lep}$ also shown results vs $|y_{t\bar{t}}|$, $p_T$, $t\bar{t}$ and $m_{t\bar{t}}$

Top (and Bottom) asymmetries at the LHC
### ATLAS results

<table>
<thead>
<tr>
<th></th>
<th>$A_C$</th>
<th>$A_{lep}^C$</th>
</tr>
</thead>
<tbody>
<tr>
<td>ATLAS</td>
<td>$0.021 \pm 0.025$ (stat) $\pm 0.017$ (syst)</td>
<td>$0.024 \pm 0.015$ (stat) $\pm 0.009$ (syst)</td>
</tr>
<tr>
<td>Bernreuther &amp; Si</td>
<td>$0.0123 \pm 0.0005$</td>
<td>$0.0070 \pm 0.0003$</td>
</tr>
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</table>

- Unfolding $\Delta |y|$ (FBU) and $\Delta |\eta|$ (bin-by-bin correction)
- Statistical uncertainty dominant
- Systematics: for $A_{lep}^C$ only lepton reconstruction relevant
- The two observables are **correlated** $\Rightarrow$ results shown in the plane $A_C$ and $A_{lep}^C$ and compared with BSM models:

![Graphs showing ATLAS results with correlations](attachment:image.png)
Summary

Top (and Bottom) asymmetries at the LHC
LHCb measured $b$-quark $A_C$ in $pp$ collisions [PRL 113 (2014) 082003]:

- Each $b$-quark from $b\bar{b}$ forms a single jet (anti-$k_T$ with $R = 0.7$)
- Two $b$-jets, each $2 < \eta < 4$, $E_T > 20$ GeV, $\Delta \phi > 2.6$ (restricted $\eta$ acceptance of forward geometry)
- Require at least one muon from semileptonic decay to tag charge of $b / \bar{b}$
- Purity of $70.3 \pm 0.3 \%$, measured with dimuon events
- Sample $\sim 400k$ events, $c\bar{c}$ contamination $\sim 4\%$

**Motivation:** some theories proposed to explain $A_{FB}^{t\bar{t}}$ predict large $A_{C}^{b\bar{b}}$

Measurement in 3 mass bins: $A_{C}^{bb}(x, y)$ GeV:

<table>
<thead>
<tr>
<th>$m_{b\bar{b}}$ [GeV]</th>
<th>$A_{C}^{bb}$ [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>40-75</td>
<td>$0.4 \pm 0.4$(stat) $\pm 0.3$(syst)</td>
</tr>
<tr>
<td>75-105</td>
<td>$2.0 \pm 0.9$(stat) $\pm 0.6$(syst)</td>
</tr>
<tr>
<td>$&gt;105$</td>
<td>$1.6 \pm 1.7$(stat) $\pm 0.6$(syst)</td>
</tr>
</tbody>
</table>

- Expected SM asymmetries up to $\sim 1\%$
- Additional $\sim 2\%$ contribution around $m_Z$ from $Z \rightarrow b\bar{b}$

Top (and Bottom) asymmetries at the LHC
### Summary & Outlook

**$t\bar{t}$ Charge Asymmetry Measurements**

<table>
<thead>
<tr>
<th></th>
<th>Asymmetry(%)</th>
<th>ATLAS</th>
<th>CMS</th>
<th>LHC comb</th>
<th>NLO+EW</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>7 TeV</strong></td>
<td>$\ell+\text{jets } A_C$</td>
<td>0.6±1.0±0.5</td>
<td>0.4±1.0±1.1</td>
<td>0.5±0.7±0.6</td>
<td>1.15±0.06</td>
</tr>
<tr>
<td></td>
<td>dilepton $A_C$</td>
<td>2.1±2.5±1.7</td>
<td>-1.0±1.7±0.8</td>
<td></td>
<td>1.15±0.06</td>
</tr>
<tr>
<td></td>
<td>dilepton $A_C^{\text{lep}}$</td>
<td>2.4±1.5±0.9</td>
<td>0.9±1.0±0.6</td>
<td></td>
<td>0.70±0.03</td>
</tr>
<tr>
<td><strong>8 TeV</strong></td>
<td>$\ell+\text{jets } A_C$</td>
<td>0.5±0.7±0.6</td>
<td></td>
<td></td>
<td>1.11±0.04</td>
</tr>
</tbody>
</table>

- Most precise $A_C$ measurements at level of $\sim$1%, dilepton $\sim$2%
- Both $A_C$ and $A_C^{\text{lep}}$ compatible with zero and with SM theory prediction

**Future prospects for 8 TeV and 13-14 TeV:**

- Not yet systematics limited for $A_C \Rightarrow$ exploit full statistics
- ATLAS+CMS (8 TeV): Potential to measure $A_C$ with $\sim$0.5% precision
- More statistics for high $m_{t\bar{t}}$ and high $\beta_{z,t\bar{t}}$:
  - enhanced sensitivity to $q\bar{q}$
  - but reduced $q\bar{q}$ fraction of 9% at 14 TeV ($gg$ dominates)
- Fiducial measurements (e.g. 4 vs 5 jet) to reduce unfolding corrections?