Charge Asymmetry in Top Pairs at ATLAS

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36th International Conference on High Energy Physics
July 6, 2012
Outline

1. Where does Charge Asymmetry originate from?
2. What do we want to measure?
3. How do we measure the Charge Asymmetry?
4. What do we observe?
Origin of Charge Asymmetry

LO pQCD predicts that heavy flavour pair production does not discriminate between quark and anti-quark

- $gg, q\bar{q} \rightarrow Q\bar{Q}$ yield identical differential distributions for $Q$ and $\bar{Q}$
Origin of Charge Asymmetry

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- \( gg, q\bar{q} \rightarrow Q\bar{Q} \) yield identical differential distributions for \( Q \) and \( \bar{Q} \)

NLO introduces charge-asymmetric corrections

- radiative corrections in \( q\bar{q} \) fusion (\( q\bar{q} \rightarrow Q\bar{Q}g \))
- interference terms in \( gq \) scattering (\( g\bar{q} \rightarrow Q\bar{Q}q \))
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Back-up material

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$Q$ ($\bar{Q}$) emitted preferably in the direction of the incoming $q$ ($\bar{q}$)

- effect diluted if production process is dominated by gluon-fusion
- kinematical selection targeting annihilation or flavour excitation
Charge Asymmetry in $t\bar{t}$: building suitable observables

Different possibilities, according to initial state
Charge Asymmetry in $t\bar{t}$: building suitable observables

Different possibilities, according to initial state

- **p\bar{p} collisions**: exploit forward-backward asymmetry in $t\bar{t}$ frame

\[
A_{fb} = \frac{N_t(p) - N_t(\bar{p})}{N_t(p) + N_t(\bar{p})}
\]

$N$ number of $t/\bar{t}$ emitted in $p/\bar{p}$ hemisphere
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$$A_{fb} = \frac{N_t(p) - N_t(\bar{p})}{N_t(p) + N_t(\bar{p})} \xrightarrow{CP} \frac{N_t(p) - N_\bar{t}(p)}{N_t(p) + N_\bar{t}(p)}$$

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Charge Asymmetry in t̅t: building suitable observables

Different possibilities, according to initial state

- **p¯p** collisions: exploit forward-backward asymmetry in t̅t frame
  \[
  A_{fb} = \frac{N_t(p) - N_t(\bar{p})}{N_t(p) + N_t(\bar{p})} \rightarrow \frac{N_t(p) - N_{\bar{t}}(p)}{N_t(p) + N_{\bar{t}}(p)}
  \]
  
  \(N\) number of t/\bar{t} emitted in p/\bar{p} hemisphere

- **pp** collisions: rely on charge asymmetry defined as
  \[
  A_C = \frac{N(\Delta|y| > 0) - N(\Delta|y| < 0)}{N(\Delta|y| > 0) + N(\Delta|y| < 0)}
  \]
  
  \(N\) number of events with \(\Delta|y| = |y_t| - |y_{\bar{t}}|\)
  - in q¯q → t̅t, valence quarks more energetic than sea antiquarks
  - t quarks expected more boosted than \(\bar{t}\) antiquarks
Charge Asymmetry in $t\bar{t}$: building suitable observables

Different possibilities, according to initial state

- $p\bar{p}$ collisions: exploit forward-backward asymmetry in $t\bar{t}$ frame

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- $pp$ collisions: rely on charge asymmetry defined as

$$A_C = \frac{N(\Delta|y| > 0) - N(\Delta|y| < 0)}{N(\Delta|y| > 0) + N(\Delta|y| < 0)} \rightarrow A_{C}^{\ell\ell}$$

$N$ number of events with $\Delta|y| = |y_t| - |y_{\bar{t}}| \rightarrow \Delta|\eta| = |\eta_\ell^+| - |\eta_\ell^-|$

- in $q\bar{q} \rightarrow t\bar{t}$, valence quarks more energetic than sea antiquarks
- $t$ quarks expected more boosted than $\bar{t}$ antiquarks

Charge Asymmetry in Top Pairs at ATLAS
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Analyses outline

Strategy
- select $t\bar{t}$-candidate events
- reconstruct the $t\bar{t}$ system
  - one or two-lepton decay channels

Common ingredients
- leptons: one or two opposite-sign electrons and/or muons
  - provide handle for triggering (inclusive-lepton paths)
  - $p_T > 25(20)$ GeV, $|\eta| < 2.47(2.5)$ e(µ), isolation
- jets: at least two (two-lepton) or four (one-lepton)
  - anti-$k_T$ with $R = 0.4$, $p_T > 25$ GeV and $|\eta| < 2.5$
  - corrected for detector effects and out-of-time deposits
- missing $E_T$: corrected for
  - energy scale of calorimeter clusters
  - muons
Some more details: one-lepton channel

**Additional requirements**

- missing $E_T$ cuts
  - e-channel: $E_T > 35$ GeV and $m_T(W) > 25$ GeV
  - $\mu$-channel: $E_T > 20$ GeV and $E_T + m_T(W) > 60$ GeV
- at least one b-tagged jet
  - topological tagger (explicit vertex reconstruction)
  - $r\phi$ and $z$ impact parameter significance (track-based)
- maximum likelihood combination of $\ell + 4jets$ identified as $t\bar{t}$
  - correct event topology identified in 74% of the cases

1.04 fb$^{-1}$ of $\sqrt{s} = 7$ TeV data
**Additional requirements**

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**Leading Backgrounds**

- $W(\rightarrow \ell\nu) + jets$
- QCD multijet with a *fake* lepton
- single top
- $Z + jets$
- di-boson (WW, WZ, ZZ)

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1.04 fb$^{-1}$ of $\sqrt{s} = 7$ TeV data
Some more details: $t\bar{t}$ reconstruction ($\ell + jets$)
Some more details: two-lepton channel

Additional requirements

- for same-flavour leptons
  - Z-veto: $|m_{\ell\ell} - m_Z| > 10$ GeV
  - $E_T > 60$ GeV

- for opposite-flavour leptons: $\Sigma(E_T^\ell + E_T^{jet}) > 130$ GeV

- kinematical fit to $t\bar{t}$: all solutions considered (and weighted)
  - correct $\ell\ell + 2jets$ combination identified in 47% of the cases

4.7 fb$^{-1}$ of $\sqrt{s} = 7$ TeV data
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Analyses outline
Some more details

Some more details: $E_T$ and $y_t$ distributions ($\ell\ell + jets$)
Results: $\Delta|y| = |y_t| - |y_{\bar{t}}|$
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Results: $\Delta |y| = |y_t| - |y_{\bar{t}}|$, $A_C$

- first: measure raw asymmetry
- second: subtract background
- third: apply unfolding
  correct distortions induced by detector
- parton level comparison with MC
Results: \[ \Delta|y| = |y_t| - |y_{\bar{t}}| \]
Results: $\Delta|y| = |y_t| - |y_{\bar{t}}|$, $\Delta|\eta| = |\eta_{e+}| - |\eta_{e-}|$
Comparison with theoretical predictions

Comparison with SM prediction (MC@NLO)

- measure raw differential asymmetry
- execute background subtraction
- correct for detector response & acceptance to parton level
  - one-lepton analysis applies unfolding procedure
  - two-lepton analysis follows calibration procedure
- all channels combined

<table>
<thead>
<tr>
<th>( A_C (\ell + \text{jets}) )</th>
<th>Data ( -0.018 \pm 0.028(\text{stat}) \pm 0.023(\text{syst}) )</th>
<th>MC@NLO ( 0.006 \pm 0.002 )</th>
<th>( p)-value</th>
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<th>Data ( 0.023 \pm 0.012(\text{stat}) \pm 0.008(\text{syst}) )</th>
<th>MC@NLO ( 0.004 \pm 0.001 )</th>
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| \( m_{t\bar{t}} < 450 \text{ GeV} \) | \( -0.053 \pm 0.070(\text{stat}) \pm 0.054(\text{syst}) \) | \( 0.005 \pm 0.002 \) | \( p\)-value | \( m_{t\bar{t}} > 450 \text{ GeV} \) | \( -0.008 \pm 0.035(\text{stat}) \pm 0.032(\text{syst}) \) | \( 0.007 \pm 0.002 \) | \( p\)-value | No deviation from the SM is observed (up to the level of \( 1 \div 2\sigma \))
Constraining BSM scenarios

- Several models BSM capable of inducing anomalous $A_C$
  - without violating other experimental constraints
    - $\sigma_{t\bar{t}}$ (from Tevatron), no bumps in $m_{t\bar{t}}$ spectrum (from LHC)
  - Their predictivity probed by LHC and Tevatron measurements
    - right-handed $V'tu$ FC $Z'$ and $W'$ $t$-channel exchange ($u\bar{u} \rightarrow t\bar{t}$, $d\bar{d} \rightarrow t\bar{t}$)
    - heavy axigluon $G_{\mu}$ $s$-channel exchange ($u\bar{u}$, $d\bar{d} \rightarrow t\bar{t}$)
    - colour-triplet $\omega^4$ and sextet $\Omega^4$ scalars $u$-channel exchanges ($u\bar{u} \rightarrow t\bar{t}$)
    - colour-singlet Higgs-like isodublet $\Phi$ $t$-channel exchange

![Graph showing $A_C$ versus $A_{FB}$}(inclusive) for various models and experiments.

Conclusions

1. Two ATLAS analyses focused on Charge Asymmetry in $t\bar{t}$ events collected at $\sqrt{s} = 7$ TeV
   - $A_C$ from inclusive $e$ and $\mu$ samples ($1.04 \text{ fb}^{-1}$)
     - two $m_{t\bar{t}}$ ranges considered
   - $A_C$ and $A_{\ell\ell}^C$ from $e^+e^-, e^\pm\mu^\mp$ and $\mu^+\mu^-$ samples ($4.7 \text{ fb}^{-1}$)

2. All measurements consistent with SM predictions
   - good agreement also in $A_C$ vs. $m_{t\bar{t}}$
     - no clear enhancement wrt $m_{t\bar{t}}$ observed

3. Results can be interpreted in terms of BSM scenarios
   - ATLAS results seem to disfavour minimal $Z'$ models
     - in particular in high-$m_{t\bar{t}}$ $\ell + jets$
     - coherent with search for same-sign top-quark production

4. Keep investigating: all this was just 2011 data...
   - reduced uncertainty will increase sensitivity to BSM physics
<table>
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<th>Back-up material</th>
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**Where does Charge Asymmetry originate from?**

**What do we want to measure?**

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**W+jets normalization**

**Fake-lepton backgrounds**

**Unfolding procedure**

**Calibration procedure**
**Detailed Results**

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<tr>
<th></th>
<th>Data</th>
<th>MC@NLO</th>
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<tbody>
<tr>
<td>$A_C (e^+e^- + \text{jets})$</td>
<td>$-0.047 \pm 0.045(\text{stat}) \pm 0.028(\text{syst})$</td>
<td>$0.006 \pm 0.002$</td>
<td>$-1$</td>
</tr>
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<td>$A_C (\mu^-\mu^- + \text{jets})$</td>
<td>$-0.002 \pm 0.036(\text{stat}) \pm 0.023(\text{syst})$</td>
<td>$0.006 \pm 0.002$</td>
<td>$-1$</td>
</tr>
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<td>$A_C (\ell^+\ell^- + \text{jets})$</td>
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<td>$-1$</td>
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</tr>
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<td>$A_C (e^+e^- + \text{jets})$</td>
<td>$0.079 \pm 0.087(\text{stat}) \pm 0.028(\text{syst})$</td>
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<td>$-1$</td>
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<td>$A_C (e^\pm\mu^\mp + \text{jets})$</td>
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<td>$A_C (\mu^+\mu^- + \text{jets})$</td>
<td>$0.000 \pm 0.046(\text{stat}) \pm 0.021(\text{syst})$</td>
<td>$0.006 \pm 0.002$</td>
<td>$41%$</td>
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<td>$9%$</td>
</tr>
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<td>$A_{ee}^C$</td>
<td>$0.091 \pm 0.041(\text{stat}) \pm 0.029(\text{syst})$</td>
<td>$-1$</td>
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</tr>
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<td>$A_{e\mu}^C$</td>
<td>$0.018 \pm 0.014(\text{stat}) \pm 0.009(\text{syst})$</td>
<td>$0.004 \pm 0.001$</td>
<td>$-1$</td>
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<td>$A_{\mu\mu}^C$</td>
<td>$0.026 \pm 0.023(\text{stat}) \pm 0.009(\text{syst})$</td>
<td>$-1$</td>
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<td>$A_{\ell\ell}^C$</td>
<td>$0.023 \pm 0.012(\text{stat}) \pm 0.008(\text{syst})$</td>
<td>$0.004 \pm 0.001$</td>
<td>$35%$</td>
</tr>
</tbody>
</table>
Data-driven $W + jets$ background normalization

1. **Exploit $W$ charge asymmetry**
   - more $u$ than $d$ valence quarks in proton beams
   - more $W^+$ than $W^-$ produced

2. **Compensate normalization uncertainty with**
   \[ r_{MC} = \frac{N(pp\rightarrow W^+)}{N(pp\rightarrow W^-)} \]
   - $r_{MC} = 1.56 \pm 0.06$ (electron), $1.65 \pm 0.08$ (muon)

3. **Determine $D^\pm$, number of data events with $\ell^\pm$ after all cuts**
   - $N_{jets} \geq 4$, no b-tag

4. **Expect**
   \[ N_{\geq 4, pretag} = N_{W^+} + N_{W^-} = \frac{r_{MC} + 1}{r_{MC} - 1} (D^+ - D^-) \]
   in data

5. **Estimate**
   \[ N_{\geq 4, tagged} = N_{\geq 4, pretag} \cdot f_{2, tagged} \cdot k_{2\rightarrow \geq 4} \]
   - $f_{2, tagged}$ fraction of $W + 2 jets$ with at least 1 b-tag
   - $k_{2\rightarrow \geq 4}$ transfer factor $W + 2 \rightarrow 4 jets$
   - reduce theoretical uncertainty on h.f. content in $W + jets$
Data-driven *fake*-lepton contamination

1. **By means of Matrix-Method**
   - relies on *loose* and *tight* lepton selections
   - for one-lepton sample, following equations hold

\[
\begin{pmatrix}
N_{\text{loose}} \\
N_{\text{tight}}
\end{pmatrix}
= \begin{pmatrix} 1 & 1 \\
\end{pmatrix}
\cdot
\begin{pmatrix}
N_{\text{loose}} \\
N_{\text{fake}}
\end{pmatrix}
\]

with \(r\) (\(f\)) probability of *real* (*fake*) *loose* to be *tight*

- invert matrix to determine *true* *loose* sample composition
- apply \(r\) or \(f\) factors for *true* *tight* sample composition
- same principle for two-lepton sample

2. **Determine \(r\) and \(f\) in suitable control samples**
   - \(Z \rightarrow \ell^+\ell^-\) for \(r\)
   - fake-dominated sample (reverse \(E_T\) and/or \(m_T(W)\) cuts) for \(f\)
Unfolding procedure (one-lepton channel)

1. Event selection and detector spoil $t\bar{t}$ native asymmetry
2. Unfolding relies on iterative Bayes-D’Agostini procedure
   - after background subtraction
   - detector response and acceptance folded in a response matrix

\[ O_i = \sum_j R_{ij} T_j \]

$R_{ij}$ probability of observe in bin $i$ what expected in bin $j$
- true $T_j$ value from observed $O_i$ value after matrix inversion

```
\begin{array}{c}
\text{Reconstructed } \Delta y \\
\text{Generated } \Delta y
\end{array}
```

Simulate

```
\begin{array}{c}
\text{ATLAS Simulation}
\end{array}
```

```
\begin{array}{c}
\text{ATLAS Simulation}
\end{array}
```

$e + \geq 4 \text{ jets (} \geq 1 \text{ b tag)}$
$\mu + \geq 4 \text{ jets (} \geq 1 \text{ b tag)}$

arXiv:1203.4211
Calibration procedure (two-lepton channel)

1. **Event selection and detector spoil $t\bar{t}$ native asymmetry**

2. **Calibration procedure on MC**
   - inject asymmetry ($-10\% \div +10\%$) by reweighting $t\bar{t}$ events
   - measure asymmetry from reweighted sample
   - build an reconstructed vs. true asymmetry (calibration) curve
   - calibration curve is straight line, insensitive to new physics

3. **calibrate asymmetry measured on reconstructed $t\bar{t}$ events**
   - after background subtraction