Measurement of the Charge Asymmetry in Top Quark Pair Production in $pp$ Collisions at 7 Tev using the CMS Detector

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Looking for new physics with ttbar

- Standard Model: Interference of leading order and box diagram (left) and initial and final state radiation diagrams (right) lead to small charge asymmetry in quark-antiquark annihilation mode

- Beyond standard model: axigluons, Z', W', Kaluza Klein
  - New resonances s-channel production in M(tt) not necessarily visible
  - Different couplings might lead to changes in their angular distributions
  - Charge asymmetry would be sensitive to t- and u-channel exchange
Charge asymmetry in ttbar events

\[ \Delta(y) = y_t - y_{\bar{t}} \]

\[ A_C = \frac{N^+ - N^-}{N^+ + N^-} \]

Asymmetric initial state
- **top** in direction of proton (quark)
- **anti-top** in direction of antiproton

- SM Theory: \( \sim 5\% \) [Kühn, Rodrigo]
- CDF measures \( A_C(y) \) 2\( \sigma \) larger than SM pred.
  - \( +3.4\sigma \) for \( M_{tt} > 450 \text{ GeV/c}^2 \)

Symmetric initial state
- **quark** is usually valence (higher \( p \))
- **anti-quark** is usually a sea quark

- SM Theory: 1.3\% (\( \eta \)) and 1.1\% (\( y \)) [Kühn, Rodrigo]
- **CMS 36 pb\(^{-1}\):** CMS-PAS-10-010
  - \( A_C(\eta) = 0.060 \pm 0.134 \) (stat) \( \pm 0.026 \) (syst)
- **Today:** Update to 1.09 fb\(^{-1}\)
Reconstructing ttbar decays

- Event signature: one leptonic decay, one hadronic decay
  - Require 1 high $p_T$ e or $\mu$, $\geq 4$ jets, and $\geq$ one b-tag
  - Additional loose lepton veto, conversion rejection
- Important to fully and correctly reconstruct the 4 momentum of the top quarks
- For the neutrino
  - $p_x(\nu)$ and $p_y(\nu)$ from missing $E_T$
  - constrain $W$ mass to 80.4 GeV
- Want to pick the best possible assignment of jets (with 4 jets, there are 12 combinations to consider)
  - Simulation: define “best possible” as best angular match for $W_{\text{had}}$, $W_{\text{lep}}$, $t_{\text{had}}$, and $t_{\text{lep}}$
  - Data: rank the hypotheses according to a likelihood (testing method on simulation)
Hypothesis Selection

Choose hypothesis with maximum

\[ \psi = L(m_1)L(m_2)L(m_3)P_b(x_{b,lep})P_b(x_{b,had})(1 - P_b(x_{q1}))(1 - P_b(x_{q2})) \]

- Consider the masses of the hadronic W and both tops
  - \( m_{W,\text{had}} \) and \( m_{t,\text{had}} \) are highly correlated
  - \( m_{t,\text{lep}}, m_{W,\text{had}}, \) and \( m_{t,\text{had}} \) ➞ \( m_1, m_2, \) and \( m_3 \)

- B tagging output is used to improve jet assignment

- Performance in MC
  - finds best possible hypothesis in 29% of all events
  - when all 4 final state jets are present, it’s 51%
Background Estimation (1)

- The main background in lepton+jets ttbar sample
  - $W$+jets, $Z$+Jets, Single Top, QCD
- Divide the data into 8 samples for simultaneous fit
  - leptons and charge: $\mu^+$, $\mu^-$, $e^+$, $e^-$
  - missing $E_T$: $MET<40$ GeV, $MET>40$ GeV
- For $MET<40$ GeV samples, fit $MET$
- For $MET>40$ GeV samples, fit invariant mass of three jets with largest vectoral $\Sigma p_T$ ($M_3$)
- MC templates for all channels except QCD
  - QCD: data with non-isolated lepton
Background Estimation (2)

- Excellent agreement between fit and data
- Largest background is W+jets
- Background estimation
  → background subtractions

### Event Yields

<table>
<thead>
<tr>
<th>process</th>
<th>electron+jets</th>
<th>muon+jets</th>
<th>total</th>
</tr>
</thead>
<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>
Raw Asymmetry

- Raw asymmetry for both variables <1%
- Effects between true asymmetry and raw asymmetry
  - selection efficiency (true $tt\bar{t} \rightarrow$ true selected $tt\bar{t}$)
  - imperfect reconstruction (true selected $\rightarrow$ reconstructed $tt\bar{t}$)
  - background contribution ($tt\bar{t} \rightarrow$ all data)
- Need to **unfold** the distributions to compare with theory
Unfolding the raw asymmetry

\[ \tilde{w} = A \tilde{x} \]

- Smearing matrix A translates true spectrum \( x \) into measured spectrum \( w \)
- A is factorizable:
  - Migration effects due to imperfect reconstruction
    - non perfect jet-parton assignment
    - detector resolution
  - Selection effects
    - selection efficiency not flat as a function of \( \eta \) and \( \gamma \)
    - Ex: our 4 jet selection enriches ISR/FSR \( \rightarrow \) changes asymmetry
- Solve the equation using regularized unfolding technique
Unfolding consistency check

- We use pseudo experiments (PEs) to test the performance of the unfolding algorithm.
  - The “data” for a single PE is drawn from the ttbar and background templates and then unfolded.
  - 50,000 PEs per study
- $A_C$ pull distribution are gaussian and centered: no bias in unfolding
- Linearity check: test if large values of $A_C$ would be unfolded correctly

\[
k \cdot (|\eta_t| - |\eta_{\bar{t}}|) + 1 \quad \quad \quad \quad \quad \quad k \cdot (y_t - y_{\bar{t}})(y_t + y_{\bar{t}}) + 1
\]

\[\Delta|\eta| \text{ agreement is very good.} \quad \Delta(y^2) \text{ will need a slight bias correction}\]
Systematic uncertainties

- $A_C$ is insensitive to absolute normalization effects such as luminosity and overall $ttbar$ efficiency and acceptance

- Pseudo data is also used to evaluate systematics uncertainties from source that could generate relative uncertainties
  - create pseudo data from systematically shifted distributions

<table>
<thead>
<tr>
<th>Source of Systematic</th>
<th>$A_C^\eta$ Variation</th>
<th>$A_C^\nu$ Variation</th>
<th>$A_C^\eta$ Variation</th>
<th>$A_C^\nu$ Variation</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>
</tr>
<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>
<td>-0.001</td>
<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>
</tr>
<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>
TTbar Charge Asymmetry Results

Both unfolded measurements are in agreement with theory predictions

\[ A^\eta_C(\text{theory}) = 0.013 \pm 0.001 \quad A^{y^2}_C(\text{theory}) = 0.011 \pm 0.001 \]  

[Rodrigo]
No hint yet of M(tt) dependence

• Background subtracted (but not unfolded) $A_C$ as a function of M(tt)
• Results so far are consistent with standard model expectations
• Next step: 2D unfolding in $\Delta|\eta|$ or $\Delta(y^2)$ and M(tt) to get unfolded $A_C$ as a function of M(tt)
Summary

• Charge asymmetry in ttbar production can provide a window into new physics at electroweak scale
• CMS has updated the $A_C$ measurement with 1.09 fb$^{-1}$ of data using two different variables
• Both (slightly) negative asymmetries are compatible with the standard model predictions of $\sim$1%
• Also compatible with Tevatron positive asymmetry measurements
  - Still room for new physics!
• Looking forward to future $A_C$ measurements
  - with smaller statistical uncertainties
  - and mapping $M(tt)$ dependence
Back-up slides
Analysis cuts

Muon Definition
- $p_T > 20$ GeV
- $|\eta| < 2.1$
- $\chi^2$ global fit < 10
- $N_{\text{trk-hits}} > 10$
- IP < 0.02 cm
- $|z(\mu) - z(PV)| < 1$ cm
- PF relIso < 0.125

Electron Definition
- ET > 30 GeV
- $|\eta| < 2.5$ - [1.442, 1.5660]
- electron ID
- IP < 0.02 cm
- $|z(\mu) - z(PV)| < 1$ cm
- PF relIso < 0.125

Jet Definition
- anti KT PF jets
- $p_T > 30$ GeV
- $|\eta| < 2.4$
- Particle Flow Jet ID

Loose Muon
- $p_T > 10$ GeV
- $|\eta| < 2.5$
- PF relIso <0.25

Loose Electron
- $p_T > 15$ GeV
- PF relIso <0.25
CMS: The Compact Muon Solenoid

- For reconstruction, we use particle flow
  - global perspective on reconstruction
  - sub-detector object $\rightarrow$ CMS wide object
  - effectively handles overlap (double counting) in muon/electron/jet collections
Statistical Uncertainty

\[ A_C = \frac{N^+ - N^-}{N^+ + N^-} \]

The statistical uncertainty can be calculated from the output of the unfolding procedure as follows:

\[ \sigma^2_{A_C/DC} = \left( \frac{\partial A_C/DC}{\partial N_1} \cdots \frac{\partial A_C/DC}{\partial N_6} \right) V_x \left( \begin{array}{c} \frac{\partial A_C/DC}{\partial N_1} \\ \vdots \\ \frac{\partial A_C/DC}{\partial N_6} \end{array} \right) \]

where the partial derivatives are given by

\[
\frac{\partial A_C/DC}{\partial N_i} = \begin{cases} 
-2N^+ & \text{for } i = 1 \ldots 3 \\
2N^- & \text{for } i = 4 \ldots 6 
\end{cases}
\]
Pull distributions for AC

\[ \Delta \eta \quad \text{true } A_C = -0.0016 \]

\[ \Delta (y^2) \quad \text{true } A_C = -0.0022 \]
Template Shapes
Extra information: hypothesis selection

\[
\begin{pmatrix}
  m_1 \\
  m_2 \\
  m_3
\end{pmatrix} = \begin{pmatrix}
  1.00 & -0.07 & -0.01 \\
  0.07 & 0.93 & 0.36 \\
 -0.02 & -0.36 & 0.93
\end{pmatrix}\begin{pmatrix}
  m_{t,\text{lep}} \\
  m_{t,\text{had}} \\
  m_{W,\text{had}}
\end{pmatrix}
\]