Charge Asymmetry in Top Pairs at ATLAS

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

Outline

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 $\bar{Q}$

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- radiative corrections in $q\bar{q}$ fusion ($q\bar{q} \rightarrow Q\bar{Q}g$)
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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

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

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N number of $t/\bar{t}$ emitted in $p/\bar{p}$ hemisphere

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- pp collisions: rely on charge asymmetry defined as

$$\mathcal{A}_C = \frac{N(\Delta|y| > 0) - N(\Delta|y| < 0)}{N(\Delta|y| > 0) + N(\Delta|y| < 0)}$$

N number of events with $\Delta|y| = |y_{\mathrm{t}}| - |y_{\mathrm{\bar{t}}}|$

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

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$$\mathcal{A}_C = \frac{N(\Delta|y| > 0) - N(\Delta|y| < 0)}{N(\Delta|y| > 0) + N(\Delta|y| < 0)} \xrightarrow[2\ell]{} \mathcal{A}_C^{\ell\ell}$$

N number of events with $\Delta|y| = |y_{\mathrm{t}}| - |y_{\mathrm{\bar{t}}}| \xrightarrow{2\ell} \Delta|\eta| = |\eta_{\ell^+}| - |\eta_{\ell^-}|$

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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

$1.04\,\mathrm{fb}^{-1}$ of $\sqrt{s} = 7\,\mathrm{TeV}$ data

- missing E_{T} cuts
  - e-channel: $\not{E}_{\mathrm{T}} > 35\,\mathrm{GeV}$ and $m_{\mathrm{T}}(\mathrm{W}) > 25\,\mathrm{GeV}$
  - μ-channel: $\not{E}_{\mathrm{T}} > 20\,\mathrm{GeV}$ and $\not{E}_{\mathrm{T}} + m_{\mathrm{T}}(\mathrm{W}) > 60\,\mathrm{GeV}$
- 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 $\mathrm{t\bar{t}}$
  - correct event topology identified in 74% of the cases

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Leading Backgrounds

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

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Leading Backgrounds

- $W(\rightarrow \ell\nu) + \textit{jets}$ data-driven
- QCD multijet with a *fake* lepton data-driven
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- $Z + \textit{jets}$
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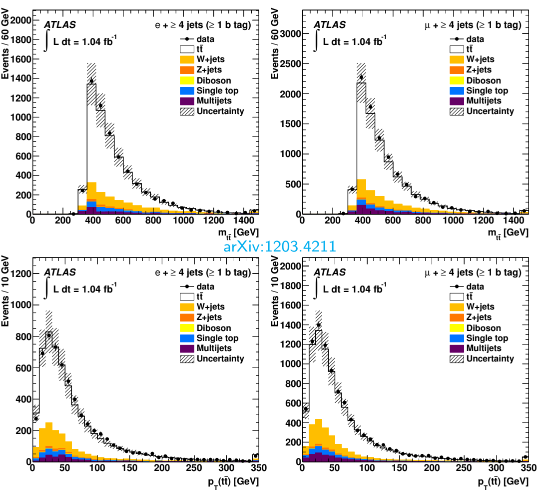
Some more details: $t\bar{t}$ reconstruction ($\ell + jets$)



arXiv:1203.4211

Some more details: two-lepton channel

Additional requirements

$4.7\,\mathrm{fb}^{-1}$ of $\sqrt{s} = 7$ TeV data

- for same-flavour leptons
  - Z-veto: $|m_{\ell\ell} - m_Z| > 10$ GeV
  - $\not{E}_T > 60$ 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)
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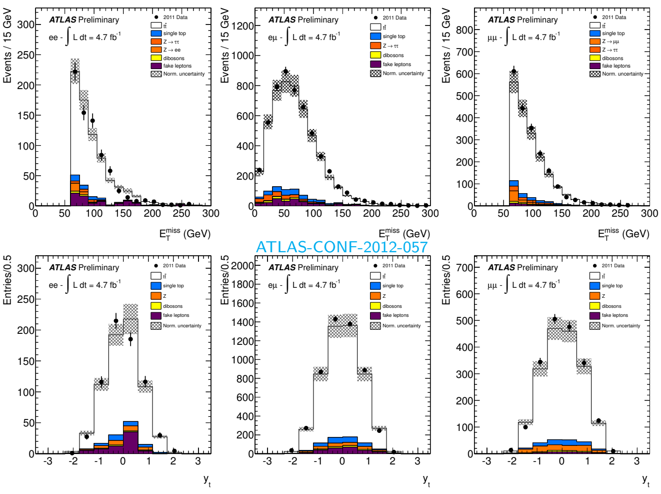
Leading Backgrounds

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

Some more details: $\not{E}_T$ and y_t distributions ($\ell\ell + jets$)



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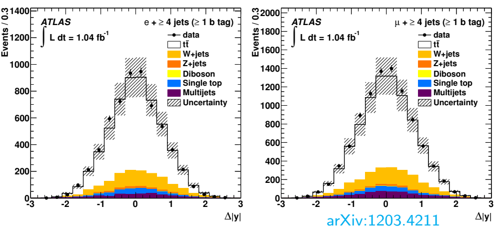
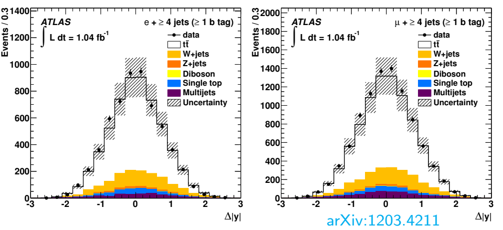
Results: $\Delta|y| = |y_t| - |y_{\bar{t}}|$



arXiv:1203.4211

- first: measure raw asymmetry

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



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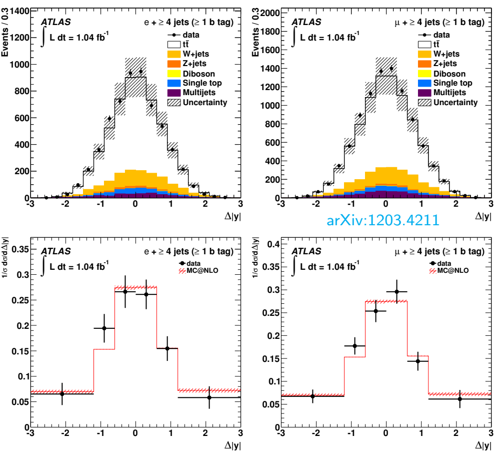
- first: measure raw asymmetry
- second: subtract background

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



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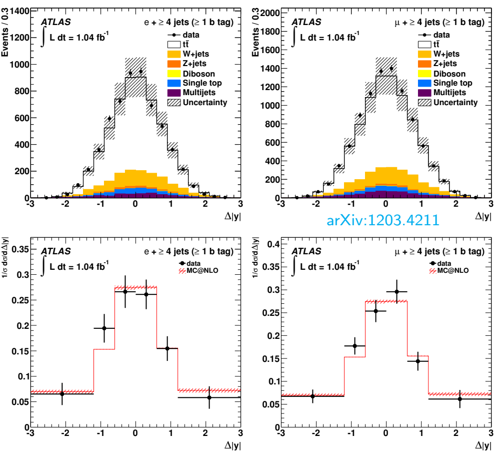
- first: measure raw asymmetry
- second: subtract background
- third: apply unfolding

  correct distortions induced by detector

Results: $\Delta|y| = |y_{t}| - |y_{\bar{t}}|$, $\mathcal{A}_C$



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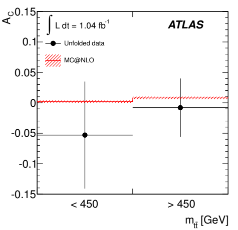

- first: measure raw asymmetry
- second: subtract background
- third: apply unfolding

  correct distortions induced by detector
- parton level comparison with MC

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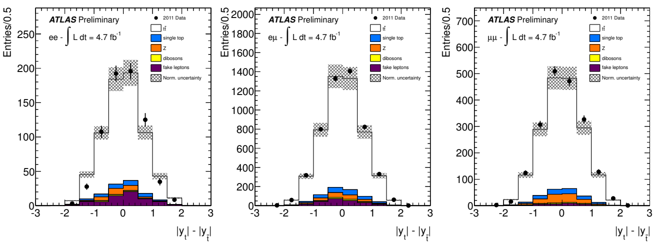
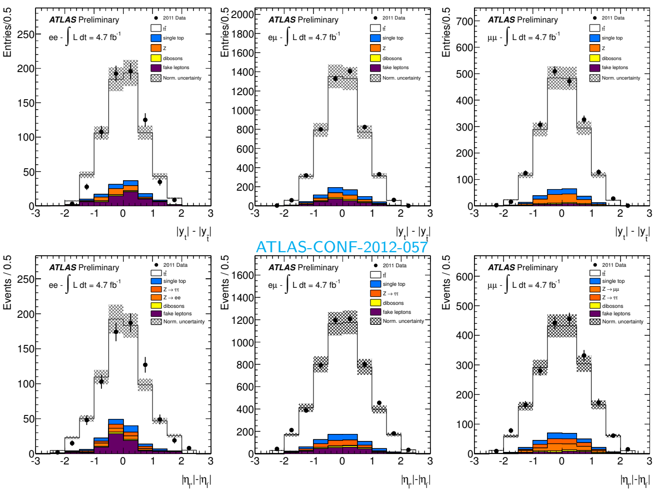


Results: $\Delta|y| = |y_{t}| - |y_{\bar{t}}|$, $\Delta|\eta| = |\eta_{\ell^+}| - |\eta_{\ell^-}|$



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Comparison with theoretical predictions

Comparison with SM prediction (MC@NLO)

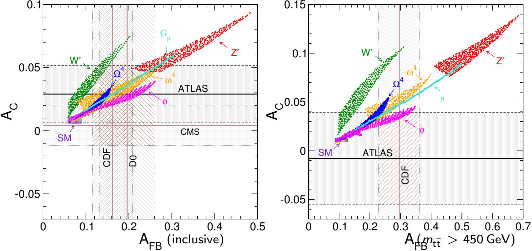
- measure raw differential asymmetry
- execute background subtraction
- correct for detector response & acceptance to parton level
  - one-lepton analysis applies unfolding procedure ▸
  - two-lepton analysis follows calibration procedure ▸
- all channels combined ▸

	Data	MC@NLO	p-value
$\mathcal{A}_C$ $(\ell + jets)$	$-0.018 \pm 0.028(stat) \pm 0.023(syst)$	0.006 ± 0.002	–
$m_{t\bar{t}} < 450$ GeV)	$-0.053 \pm 0.070(stat) \pm 0.054(syst)$	0.005 ± 0.002	–
$m_{t\bar{t}} > 450$ GeV)	$-0.008 \pm 0.035(stat) \pm 0.032(syst)$	0.007 ± 0.002	–
$\mathcal{A}_C$ $(\ell\ell + jets)$	$0.057 \pm 0.024(stat) \pm 0.015(syst)$	0.006 ± 0.002	41%
$\mathcal{A}_C$ (combined)	$0.029 \pm 0.018(stat) \pm 0.014(syst)$	0.006 ± 0.002	9%
$\mathcal{A}_C^{\ell\ell}$	$0.023 \pm 0.012(stat) \pm 0.008(syst)$	0.004 ± 0.001	35%

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 $\mathcal{A}_C$
  - 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 $\mathcal{G}_\mu$ s-channel exchange ($u\bar{u}$, $d\bar{d} \rightarrow t\bar{t}$)
  - colour-triplet ω^4 and sextet Ω^4 scalars u-channel exchanges ($u\bar{u} \rightarrow t\bar{t}$)
  - colour-singlet Higgs-like isodublet Φ t-channel exchange



ATLAS $\ell + jets$ and $\ell\ell + jets$ combined
ATLAS $\ell + jets$
CDF $\ell + jets$ (8.7 fb^{-1})

Conclusions

1. Two ATLAS analyses focused on Charge Asymmetry in $\mathrm{t\bar{t}}$ events collected at $\sqrt{s} = 7\,\mathrm{TeV}$
    - $\mathcal{A}_C$ from inclusive e and μ samples ($1.04\,\mathrm{fb}^{-1}$)
        - two $m_{\mathrm{t\bar{t}}}$ ranges considered
    - $\mathcal{A}_C$ and $\mathcal{A}_C^{\ell\ell}$ from $\mathrm{e^+e^-}$, $\mathrm{e}^{\pm}\mu^{\mp}$ and $\mu^+\mu^-$ samples ($4.7\,\mathrm{fb}^{-1}$)
2. All measurements consistent with SM predictions
    - good agreement also in $\mathcal{A}_C$ vs. $m_{\mathrm{t\bar{t}}}$
        - no clear enhancement wrt $m_{\mathrm{t\bar{t}}}$ observed
3. Results can be interpreted in terms of BSM scenarios
    - ATLAS results seem to disfavour minimal Z′ models
        - in particular in high-$m_{\mathrm{t\bar{t}}}$ $\ell + jets$
        - 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

Back-up material

Detailed Results

	Data	MC@NLO	p-value
$\mathcal{A}_C$ $(e + jets)$	$-0.047 \pm 0.045(stat) \pm 0.028(syst)$	0.006 ± 0.002	–
$\mathcal{A}_C$ $(\mu + jets)$	$-0.002 \pm 0.036(stat) \pm 0.023(syst)$		–
$\mathcal{A}_C$ $(\ell + jets)$	$-0.018 \pm 0.028(stat) \pm 0.023(syst)$	0.006 ± 0.002	–
$m_{t\bar{t}} < 450$ GeV	$-0.053 \pm 0.070(stat) \pm 0.054(syst)$	0.005 ± 0.002	–
$m_{t\bar{t}} > 450$ GeV	$-0.008 \pm 0.035(stat) \pm 0.032(syst)$	0.007 ± 0.002	–
$\mathcal{A}_C$ $(e^+e^- + jets)$	$0.079 \pm 0.087(stat) \pm 0.028(syst)$	0.006 ± 0.002	–
$\mathcal{A}_C$ $(e^\pm\mu^\mp + jets)$	$0.078 \pm 0.029(stat) \pm 0.017(syst)$		–
$\mathcal{A}_C$ $(\mu^+\mu^- + jets)$	$0.000 \pm 0.046(stat) \pm 0.021(syst)$		–
$\mathcal{A}_C$ $(\ell\ell + jets)$	$0.057 \pm 0.024(stat) \pm 0.015(syst)$	0.006 ± 0.002	41%
$\mathcal{A}_C$ (combined)	$0.029 \pm 0.018(stat) \pm 0.014(syst)$	0.006 ± 0.002	9%
$\mathcal{A}_C^{ee}$	$0.091 \pm 0.041(stat) \pm 0.029(syst)$	0.004 ± 0.001	–
$\mathcal{A}_C^{e\mu}$	$0.018 \pm 0.014(stat) \pm 0.009(syst)$		–
$\mathcal{A}_C^{\mu\mu}$	$0.026 \pm 0.023(stat) \pm 0.009(syst)$		–
$\mathcal{A}_C^{\ell\ell}$	$0.023 \pm 0.012(stat) \pm 0.008(syst)$	0.004 ± 0.001	35%

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 $r_{MC} = \frac{N(pp \to W^+)}{N_(pp \to W^-)}$
   - $r_{MC} = 1.56 \pm 0.06$ (electron), 1.65 ± 0.08 (muon)
3. Determine $D^\pm$, number of data events with $\ell^\pm$ after all cuts
   - $N_{jets} \geqslant 4$, no b-tag
4. Expect $N_{\geqslant 4,pretag} = N_{W^+} + N_{W^-} = \frac{r_{MC}+1}{r_{MC}-1}(D^+ - D^-)$ in data
5. Estimate $N_{\geqslant 4,tagged} = N_{\geqslant 4,pretag} \cdot f_{2,tagged} \cdot k_{2 \to \geqslant 4}$ in data
   - $f_{2,tagged}$ fraction of W + 2 *jets* with at least 1 b-tag
   - $k_{2 \to \geqslant 4}$ transfer factor $W + 2 \to 4$*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

$$\begin{pmatrix} N^{loose} \\ N^{tight} \end{pmatrix} = \begin{pmatrix} 1 & 1 \\ r & f \end{pmatrix} \cdot \begin{pmatrix} N^{loose}_{real} \\ N^{loose}_{fake} \end{pmatrix}$$

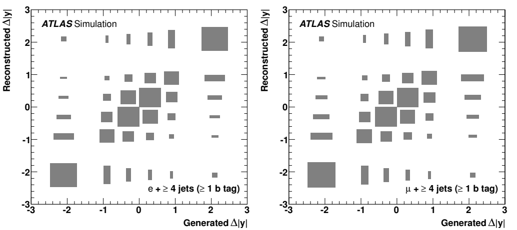
   with r (f) probability of *real* (*fake*) *loose* to be *tight*
   - invert matrix to determine *true loose* sample composition
   - apply r or f factors for *true tight* sample composition
   - same principle for two-lepton sample
2. Determine r and f in suitable control samples
   - $\mathrm{Z} \to \ell^+\ell^-$ for r
   - fake-dominated sample (reverse $\not{E}_\mathrm{T}$ and/or $m_\mathrm{T}(\mathrm{W})$ 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

     $$O_i = \Sigma_j R_{ij} T_j$$

     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



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