Measurement of the charge asymmetry in $t\bar{t}$ production with the ATLAS detector

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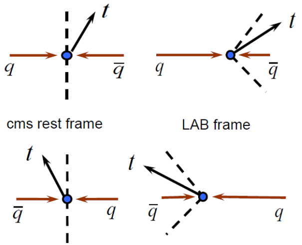
Introduction/Motivation

The top/antitop differential distributions in $t\bar{t}$ events are predicted to be different in perturbative QCD.

This is an NLO effect. Only $q\bar{q} \to t\bar{t}$ and $qg \to t\bar{t}q$ events exhibit an asymmetry. Due to interference of amplitudes with relative sign under the exchange of t and $\bar{t}$.

At the LHC, the asymmetry is diluted (mostly $gg \to t\bar{t}$), and $A_{FB} = 0$. Charge asymmetry $\leftrightarrow$ tops preferentially emitted in quark direction. Since quarks generally carry a larger momentum fraction of the proton than antiquarks, tops tend to be more forward than antitops in the lab frame.



Charge asymmetry at the LHC

The ATLAS measurement presented here (paper:arXiv:1203.4211) uses the observable:

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

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

The MC@NLO generator is used to model the $t\bar{t}$ process.

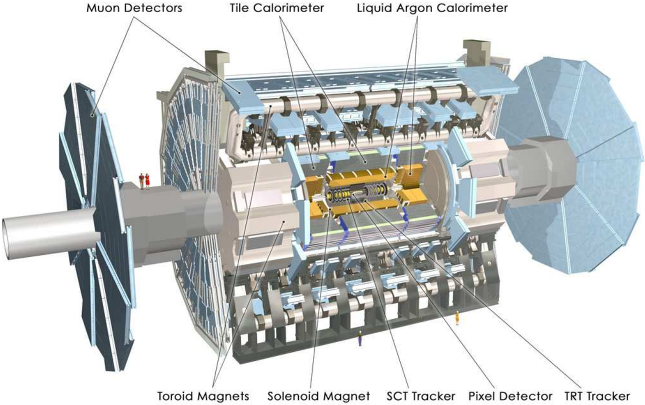
The MC@NLO prediction for A_C is 0.006 ± 0.002.

Inclusive measurement as well as measurement in two bins of $m_{t\bar{t}}$.

The integrated luminosity of the dataset used is 1.04fb^{-1}.

Overview of ATLAS

Calorimeters for energy measurements of e/γ and jets; tracking system immersed in magnetic field for precision measurement of momenta. Separate muon system in toroidal magnetic field.



Outline of the Analysis

The analysis is performed in the single lepton channel, where $t\bar{t} \to (bq\bar{q}')(\bar{b}\nu l), l = e, \mu$. The BR for this channel is 37.9%. Both tops can be reconstructed straightforwardly, so that the $t\bar{t}$ asymmetry is measured directly via reconstructing the $\Delta|y|$ distribution.

The reconstruction is not perfect and the distribution is distorted by detector effects, so unfolding to the 'true' distribution is necessary.

The backgrounds to $t\bar{t}$ signal in the single lepton channel are

- $W(\to l\nu)$+jets
- multijet QCD with fake leptons, arising from heavy flavour decays or jets faking lepton signatures
- single top
- Z+jets
- diboson $(WW/ZZ/WZ)$

Physics object definitions

1. electrons: $p_T > 25$ GeV, $|\eta| < 2.47$, exclude candidates in the calorimeter transition region $1.37 < |\eta| < 1.52$, isolation (to suppress fakes): energy in $\Delta R = 0.2$ cone < 3.5 GeV.
2. muons: $p_T > 20$ GeV, $|\eta| < 2.5$, isolation: energy and total track p_T in $\Delta R = 0.3$ cone < 4 GeV.
3. jets: anti-k_T algorithm with $d = 0.4$, $p_T > 25$ GeV and $|\eta| < 2.5$. Muons within $\Delta R = 0.4$ of jets removed - suppresses muons from heavy flavour decays.
4. b-tagging: 70% efficiency, light jets tagged with a rate of approximately $1/100$.

Event Selection

Selection cuts optimised to select $t\bar{t}$ events and reject background.

- single lepton triggers (e or μ)
- one good lepton required ($p_T > 25$ GeV for e, $p_T > 20$ GeV for μ)
- $\not{E}_T > 20$ GeV and $\not{E}_T + m_T(W) > 60$ GeV (μ channel)
- $\not{E}_T > 35$ GeV and $m_T(W) > 25$ GeV (e channel)
- ≥ 4 jets with $p_T > 25$ GeV
- at least one b-tagged jet

The harder $\not{E}_T$ cut in the e channel is necessary to reduce the QCD multijet background; event yields are correspondingly lower in e channel compared to μ channel.

Background estimation

QCD multijet background estimated using the “Matrix Method” technique, in both channels. Based on defining “loose” and “tight” samples, and equations

$$\begin{aligned} N^{\mathrm{loose}} &= N^{\mathrm{loose}}_{\mathrm{real}} + N^{\mathrm{loose}}_{\mathrm{fake}} \\ N^{\mathrm{tight}} &= r N^{\mathrm{loose}}_{\mathrm{real}} + f N^{\mathrm{loose}}_{\mathrm{fake}} \end{aligned}$$

Efficiencies r and f can be measured in control samples: $Z \to ll$ for r, and a fake-dominated sample obtained by reversing the $\not{E}_T$ and/or $m_T(W)$ cut, for measuring f.

The equations can then be solved for $N^{\mathrm{loose}}_{\mathrm{fake}}$, giving the fake contribution in the tight sample.

Normalisation uncertainty on QCD multijet background is 50% before the b-tagging requirement and 100% after.

W+jets background normalisation

Suffers from large theoretical uncertainty $\implies$ need to derive in a data-driven way.

W+jets normalisation determined using the W charge asymmetry technique. Done in two steps:

1. First the number W_{pretag} of W+jets events before tagging is determined using the equation

$$N_{W^+} + N_{W^-} = \left(\frac{r_{MC}+1}{r_{MC}-1}\right)(D^+ - D^-),$$

   $D^+, (D^-)$ are numbers of events in data with positively (negatively) charged leptons, and $r_{MC} \equiv \frac{\sigma(pp \to W^+)}{\sigma(pp \to W^-)}$. $r_{MC} = 1.56 \pm 0.06$ (e channel), 1.65 ± 0.08 (μ channel)

W+jets background estimation II

2. Now estimate the number of tagged W+jet events:

$$W_{\text{tagged}} = W_{\text{pretag}} \cdot f_{2,\text{tagged}} \cdot k_{2\to 4}$$

   Here $f_{2,\text{tagged}}$ is the 2-jet tag fraction from data, and $k_{2\to 4}$ is the ratio of 4- and 2-jet tag fractions from MC.

$k_{2\to 4}$ extrapolation factors are 2.52 ± 0.36 (2.35 ± 0.34) in the e (μ) channels.

Normalisation of heavy flavour component of W+jets has a large theory uncertainty $\Longrightarrow$ derive HF scale factors in $1-$ and $2-$jet bins, 1.63 ± 0.76 for $Wb\bar{b}$+jet and $Wc\bar{c}$+jet events and 1.11 ± 0.35 for Wc+jets.

Data/MC event yields

Other backgrounds (single top, Z+jets, $WW/WZ/ZZ$) taken from MC.

Channel	μ + jets pretag	μ + jets tagged	e + jets pretag	e + jets tagged
$t\bar{t}$	7200 ± 600	6300 ± 500	4800 ± 400	4260 ± 350
W+jets	8600 ± 1200	1390 ± 310	5400 ± 800	880 ± 200
Single top	460 ± 40	366 ± 32	320 ± 28	256 ± 22
Z+jets	940 ± 330	134 ± 47	760 ± 270	110 ± 40
Diboson	134 ± 7	22 ± 2	80 ± 5	13 ± 1
Multijets	1500 ± 800	500 ± 500	900 ± 500	250 ± 250
Total background	11700 ± 1400	2400 ± 600	7500 ± 900	1500 ± 320
Signal + background	18900 ± 1600	8800 ± 800	12000 ± 1000	5800 ± 500
Observed	19639	9124	12096	5829

Good agreement between data and MC is observed.

$t\bar{t}$ system reconstruction

Based on a likelihood fit:

$$\begin{aligned} L = \; & \mathcal{B}(\widetilde{E}_{\mathrm{p},1}, \widetilde{E}_{\mathrm{p},2} | m_W, \Gamma_W) \cdot \mathcal{B}(\widetilde{E}_{\mathrm{lep}}, \widetilde{E}_{\nu} | m_W, \Gamma_W) \cdot \\ & \mathcal{B}(\widetilde{E}_{\mathrm{p},1}, \widetilde{E}_{\mathrm{p},2}, \widetilde{E}_{\mathrm{p},3} | m_t, \Gamma_t) \cdot \mathcal{B}(\widetilde{E}_{\mathrm{lep}}, \widetilde{E}_{\nu}, \widetilde{E}_{\mathrm{p},4} | m_t, \Gamma_t) \cdot \\ & \mathcal{W}(\hat{E}_x^{\mathrm{miss}} | \widetilde{p}_{x,\nu}) \cdot \mathcal{W}(\hat{E}_y^{\mathrm{miss}} | \widetilde{p}_{y,\nu}) \cdot \mathcal{W}(\hat{E}_{\mathrm{lep}} | \widetilde{E}_{\mathrm{lep}}) \cdot \\ & \prod_{\mathrm{i}=1}^{4} \mathcal{W}(\hat{E}_{\mathrm{jet,i}} | \widetilde{E}_{\mathrm{p,i}}) \cdot \prod_{\mathrm{i}=1}^{4} P(\mathrm{tagged} \mid \mathrm{parton\ flavour}), \end{aligned}$$

$\tilde{X}$ are parton level quantities, $\hat{X}$ are reconstructed ones.

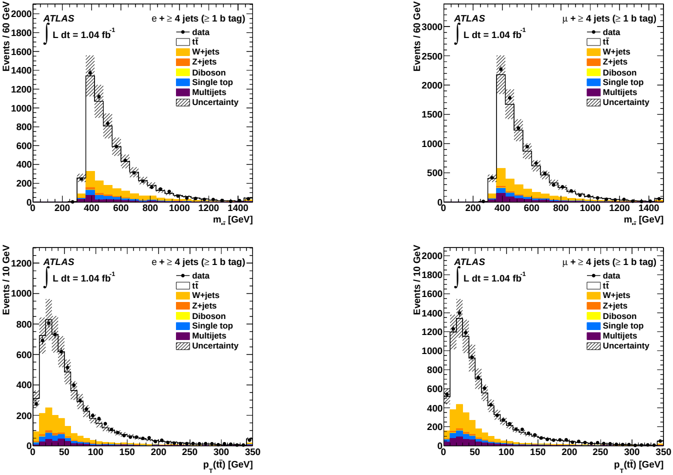
Using $m_W = 80.4$ GeV, $m_t = 172.5$ GeV, $\Gamma_W = 2.1$ GeV, $\Gamma_t = 1.5$ GeV.

Transfer functions $\mathcal{W}$ are derived from MC.

Using up to 5 leading jets in p_T in the fit; b-tagging information made use of via $P(\mathrm{tagged} \mid \mathrm{parton\ flavour})$ term.

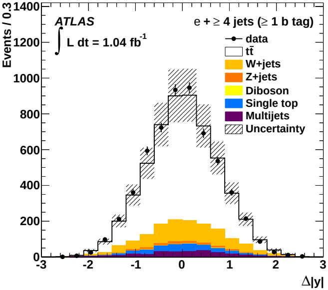
Maximise likelihood over all permutations of jets. Use assignment with highest value to reconstruct the $t\bar{t}$ system.

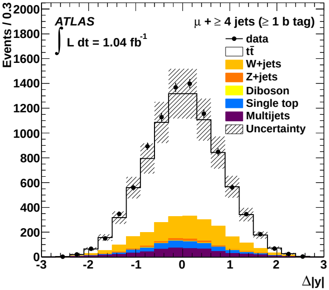
$m_{t\bar{t}}$ and $p_{t\bar{t}}$



Invariant mass and p_T of the reconstructed $t\bar{t}$ system.

Reconstructed A_C





Reconstructed $\Delta|y| \equiv |y_t| - |y_{\bar{t}}|$ distributions.

Reconstructed asymmetries, after background subtraction:

$$-0.034 \pm 0.019 \text{ (stat)} \pm 0.010 \text{ (syst)} \text{ } (e \text{ channel})$$
$$-0.010 \pm 0.015 \text{ (stat)} \pm 0.008 \text{ (syst)} \text{ } (\mu \text{ channel}).$$

Unfolding

Detector and acceptance effects distort the 'true' asymmetry distribution.

In order to compare the results with theoretical computations and other experiments, results need to be unfolded.

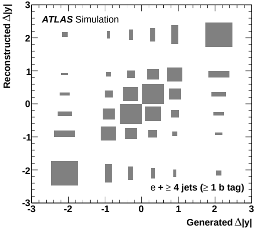
$$\mathbf{n} = R\mu + \beta \tag{1}$$

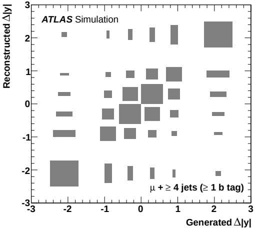
$\mathbf{n}$ is the data, μ the expectation values for the true histogram, and β the background. R is a response matrix, derived from MC simulation.

An iterative method based on Bayes' theorem is used to perform the unfolding.

Unfolding: procedure and uncertainties

Response matrices used in the unfolding:





When unfolding with respect to $m_{t\bar{t}}$, use two bins, separated at 450 GeV.

Use pseudoexperiments to check linearity and possible bias. Choose number of iterations such that convergence is achieved in data and pseudoexperiments.

Consider reweighted $t\bar{t}$ samples with different amounts of asymmetry in addition to default simulated sample.

Systematic uncertainties corresponding to choice of convergence criterion and bias of unfolded result with respect to true value. Small (0.001-0.004 on A_C).

Systematic uncertainties

Signal and background modelling:

- $t\bar{t}$ signal modelling (POWHEG vs MC@NLO)
- shower modelling in $t\bar{t}$ (POWHEG+Pythia vs POWHEG+Herwig)
- top mass dependence
- initial/final state radiation (ISR/FSR; AcerMC+Pythia)
- background normalisations
- PDF

Detector systematics:

- Jet energy scale (2.5-8% $\oplus$ 5-7% (pileup) $\oplus$ 0.8-2.5% (b-jets))
- Jet efficiency (1%) and resolution (10%)
- lepton efficiency and resolution (about 1%)
- lepton charge misidentification (0.2-3%)
- b-tagging uncertainties (data-MC scale factors known to 10-20%)
- luminosity (3.7%)

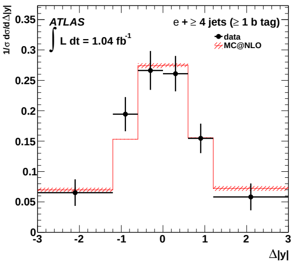
And systematics from unfolding.

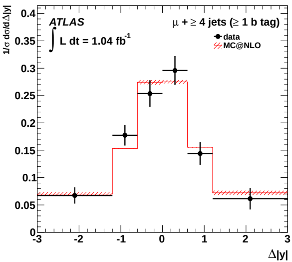
Systematics for inclusive A_C measurement

Source of systematic uncertainty on A_C	Electron channel	Muon channel
Detector modelling		
Jet energy scale	0.012	0.006
Jet efficiency and resolution	0.001	0.007
Muon efficiency and resolution	$<$0.001	0.001
Electron efficiency and resolution	0.003	0.001
b-tag scale factors	0.004	0.002
Calorimeter readout	0.001	0.004
Charge mis-ID	$<$0.001	$<$0.001
b-tag charge	0.001	0.001
Signal and background modelling		
Parton shower/fragmentation	0.010	0.010
Top mass	0.007	0.007
$\overline{t}t$ modelling	0.011	0.011
ISR and FSR	0.010	0.010
PDF	$<$0.001	$<$0.001
W+jets normalization and shape	0.008	0.005
Z+jets normalization and shape	0.005	0.001
Multijet background	0.011	0.001
Single top	$<$0.001	$<$0.001
Diboson	$<$0.001	$<$0.001
MC Statistics	0.006	0.005
Unfolding convergence	0.001	0.001
Unfolding bias	0.004	$<$0.001
Luminosity	0.001	0.001
Total systematic uncertainty	0.028	0.023

Unfolded results: inclusive asymmetry

A_C	reconstructed	detector and acceptance unfolded
e	-0.034 ± 0.019 (stat.) ± 0.010 (syst.)	-0.047 ± 0.045 (stat.) ± 0.028 (syst.)
μ	-0.010 ± 0.015 (stat.) ± 0.008 (syst.)	-0.002 ± 0.036 (stat.) ± 0.023 (syst.)





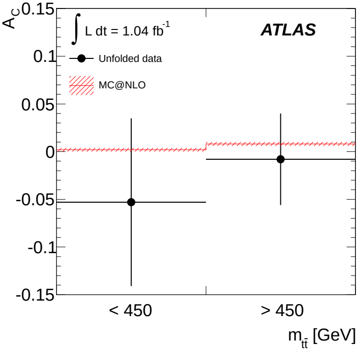
Unfolded $\Delta|Y|$ distributions; uncertainties shown are statistical and systematic.

Channel combination

Combine e and μ channels using the BLUE method.

$$A_C = -0.018 \pm 0.028\,(\text{stat.}) \pm 0.023\,(\text{syst.})$$

$$\begin{aligned} A_C &= -0.053 \pm 0.070\,(\text{stat.}) \pm 0.054\,(\text{syst.}) \\ &\quad \text{for } m_{t\bar{t}} < 450\text{GeV}, \\ A_C &= -0.008 \pm 0.035\,(\text{stat.}) \pm 0.032\,(\text{syst.}) \\ &\quad \text{for } m_{t\bar{t}} > 450\text{GeV}. \end{aligned}$$



Interpretation

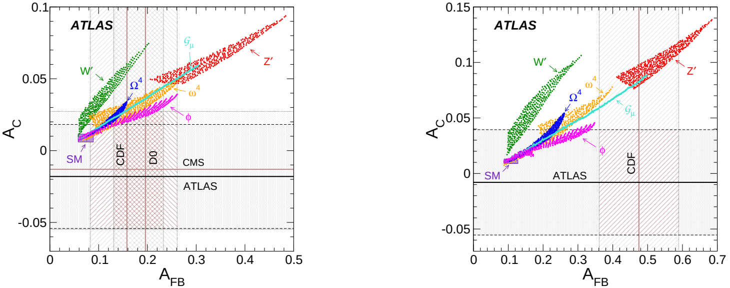
What do LHC measurements of A_C *together* with measurements of A_{FB} at Tevatron tell us about possible BSM explanations for A_{FB} excess?

Consider a few classes of BSM models that may explain the A_{FB} discrepancies observed at Tevatron:

- flavour-changing Z' boson exchanged in the t channel in $u\bar{u} \to t\bar{t}$ (Jung et al. '09)
- a W' boson contributing in $d\bar{d} \to t\bar{t}$ (Cheung et al. '09)
- a heavy axigluon $\mathcal{G}_\mu$ in the s channel (Ferrario '09; Frampton '09)
- a scalar doublet ϕ, with the same quantum numbers as the SM Higgs (Aguilar-Saavedra '11)
- a charge $4/3$ scalar, colour-sextet (Ω^4) or colour-triplet (ω^4) in the u channel, $u\bar{u} \to t\bar{t}$ (Shu '09; Dorsner '09)

A_C vs A_{FB} for BSM models

Scan over mass of new particle M and coupling g, taking into account contraints on new contributions to $\sigma_{t\bar{t}}$ (inclusive and in $m_{t\bar{t}}$ tail). Compute resulting A_C and A_{FB}.

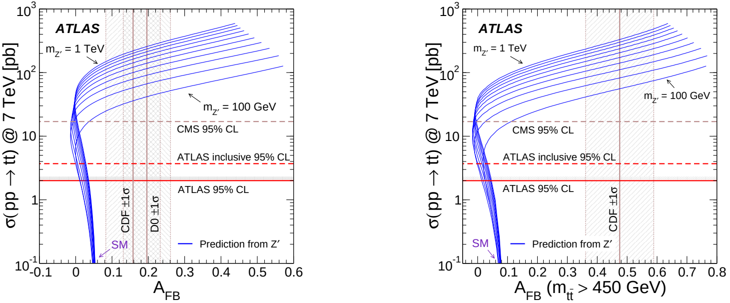


Left: inclusive A_C, A_{FB}. Right:A_C, A_{FB} for $m_{t\bar{t}} > 450$ GeV.

Considered together, CDF and ATLAS measurements at high $m_{t\bar{t}}$ in tension with BSM model predictions.

Same sign top searches at ATLAS

Minimal Z' models are excluded by ATLAS search for same sign top production (JHEP 1204 (2012) 069).



Non-minimal Z' models can survive the σ_{tt} constraint.

Conclusions

Presented a measurement of the $t\bar{t}$ charge asymmetry, A_C, at the ATLAS detector with $1.04\mathrm{fb}^{-1}$ of $\sqrt{s} = 7$ TeV pp collision data.

Systematics on the inclusive measurement are $2\% - 3\%$, somewhat larger for the measurement in bins of $m_{t\bar{t}}$.

The measured values are compatible with MC@NLO predictions.

Somewhat difficult to reconcile the high $m_{t\bar{t}}$ A_{FB} discrepancy observed at Tevatron with the ATLAS measurement of A_C.

Uncertainties will be further reduced with the expected integrated luminosity of the 2012 dataset, and more precise measurements of the behaviour of A_C vs $m_{t\bar{t}}$ are possible - an exciting year is ahead of us!