Top Production Properties in ATLAS & CMS

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Introduction

- The top quark is the heaviest known fundamental particle. Could it play a special role in electroweak symmetry breaking?
- The top quark has a very short lifetime and is the only quark that decays before forming hadronic bound states.
- This leads to a wealth of interesting, measurable properties that we can test.
- Precise studies of these properties could shed light on possible physics beyond the SM.

Analyses

Analysis		
Spin corr. & polarisation	JHEP 03 (2017) 113	PRD 93 (2016) 052007
CP asymmetries	JHEP 02 (2017) 071	JHEP 03 (2017) 101
Charge asymmetry	PRD 94 (2016) 032006	PLB 760 (2016) 365

Spin correlation and polarisation $(\ell^+\ell^-)$

$t\bar{t}$ spin correlations and polarisation

- At the LHC top quarks produced in $t\bar{t}$ pairs are (almost completely) unpolarised but with correlated spins.
- As the top quark decays before it hadronises, information about the top quark spin is transferred to the top decay products and can be measured using angular distributions.
- Charged leptons are the best spin analysers as they carry all the information about the top quark spin and are easily identified experimentally.
- Therefore precise measurements of spin correlations and polarisation can be performed *more easily* in the dilepton channel, although ATLAS and CMS have also performed measurements in the ℓ+jets channel.

Spin correlation

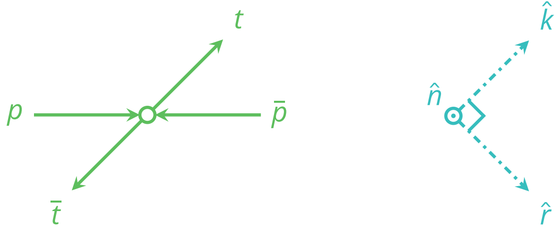
- The normalised double-differential cross-section for top pair production and decay is:

$$\frac{1}{\sigma}\frac{d^2\sigma}{d(\cos\theta_+^a)d(\cos\theta_-^b)} = \frac{1}{4}(1 + B_+^a\cos\theta_+ + B_-^b\cos\theta_- - C^{ab}\cos\theta_+^a\cos\theta_-^b)$$

- Where $B^{a,b}$ and C^{ab} are the polarisation and spin correlation along the spin quantisation axes a and b.
- θ is the angle between the spin quantisation axis and the direction of flight of the charged lepton in the top quark rest frame.

Spin quantisation axes

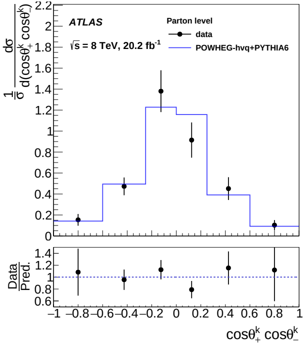
- The full top quark spin density matrix can be probed using three quantisation axes.

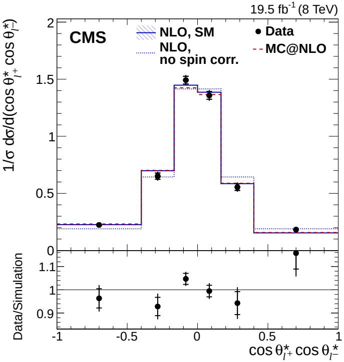


1. $\hat{k}$: Helicity axis (has traditionally been measured)
2. $\hat{n}$: Transverse axis
3. $\hat{r}$: Orthogonal to $\hat{k}$ and $\hat{n}$

Helicity basis spin correlation ($\cos\theta_+^{\hat{k}} \cos\theta_-^{\hat{k}}$)

- The $\cos\theta^{\hat{k}} \cos\theta^{\hat{k}}$ variable has a non-zero asymmetry in the standard model due to spin correlations.
- If there was no spin correlations then the distribution would be symmetric.





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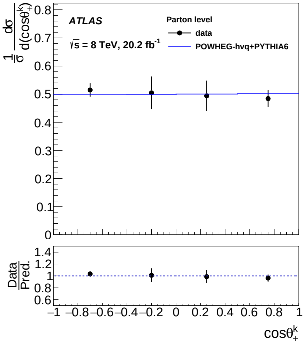
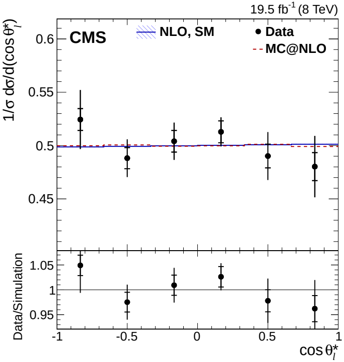
Helicity basis polarisation ($\cos \theta^{\hat{k}}_{\pm}$)

- Top quark polarisation is very small in SM (per mill level).
- We would expect a slope in this distribution if top quarks are produced with large polarisation.



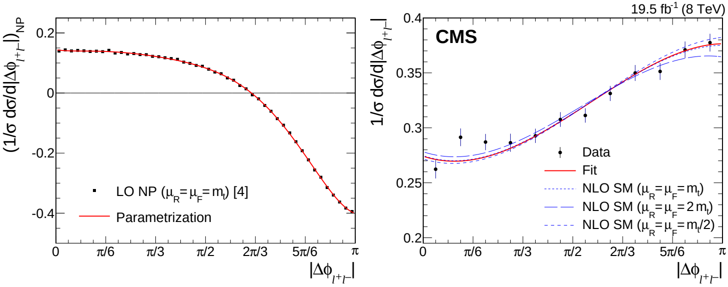


▸ JHEP 03 (2017) 113

▸ PRD 93 (2016) 052007

Limits on new physics

- We can use the measurements to set limits on new physics.
- CMS sets limits on chromo-magnetic and chromo-electric dipole moments (parameters in an effective Lagrangian).
- The measurements are dominated by systematic uncertainties ($t\bar{t}$ modelling).



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CP Asymmetries (ℓ+jets)

Searching for CP violation

- These analyses test for CP violation using $t\bar{t}$ events.
- The analyses have slightly different approaches but both use the ℓ+jets channel.
- CMS measures A_{CP} using four observables that are constructed using the kinematics of the leptons and jets.
- ATLAS use $t\bar{t}$ events to identify weakly decaying b-hadrons to probe CP violation.

CMS observables

- CMS measures the following observables.

$$O_2 \propto (\vec{p}_b + \vec{p}_{\bar{b}}) \cdot (\vec{p}_\ell \times \vec{p}_{j1}) \qquad \text{(lab)} \qquad (1)$$

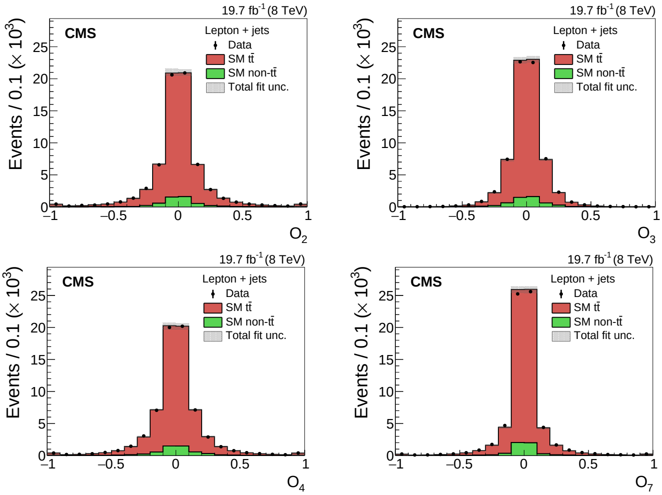
$$O_3 \propto Q_\ell \, \vec{p}_b \cdot (\vec{p}_\ell \times \vec{p}_{j1}) \qquad (b\bar{b}\ \text{CM}) \qquad (2)$$

$$O_4 \propto Q_\ell \, (\vec{p}_b - \vec{p}_{\bar{b}}) \cdot (\vec{p}_\ell \times \vec{p}_{j1}) \qquad \text{(lab)} \qquad (3)$$

$$O_7 \propto (\vec{p}_b - \vec{p}_{\bar{b}})_z (\vec{p}_b \times \vec{p}_{\bar{b}})_z \qquad \text{(lab)} \qquad (4)$$

- These observables are all symmetric around zero in the SM, but CPV effects can introduce asymmetries (up to 8% in $A_{\mathrm{CP}}(O_3)$ and $A_{\mathrm{CP}}(O_4)$).
- Results are presented as A'_{CP} (raw asymmetries) and A_{CP} (corrected using simulation).

CMS observables



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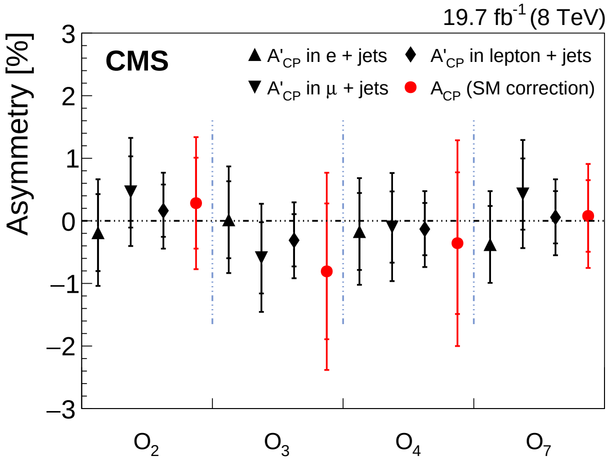
CMS results



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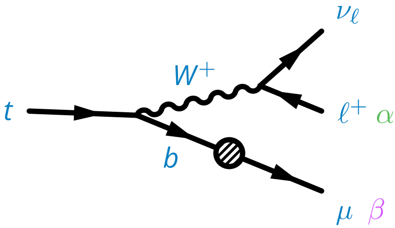
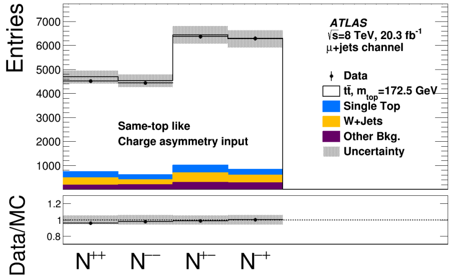
ATLAS analysis

- ATLAS uses weakly decaying *b*-hadrons from top decays to probe CP violation.
- Using the charge of the lepton from the leptonically decaying top quark and the charge of the lepton from a soft muon tag one can determine the charge of the *b*-quark at production and decay.



ATLAS analysis

- One can then determine the same-sign (SS) and opposite-sign (OS) charge asymmetries using the number of events with lepton charges α and β, $N^{\alpha\beta}$.



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$$A^{\mathrm{SS}} = \frac{(N^{++}/N^{+}) - (N^{--}/N^{-})}{(N^{++}/N^{+}) + (N^{--}/N^{-})}$$

$$A^{\mathrm{OS}} = \frac{(N^{+-}/N^{+}) - (N^{-+}/N^{-})}{(N^{+-}/N^{+}) + (N^{-+}/N^{-})}$$

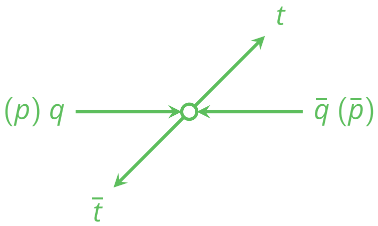
ATLAS results

- Results are in agreement with the SM prediction of ≈ 0 asymmetry.
- Statistical uncertainties dominate.
- One can convert the charge asymmetries into CP asymmetries using simulation (see backup).

Charge asymmetry $(\ell^+\ell^-)$

Forward-backward and charge asymmetry

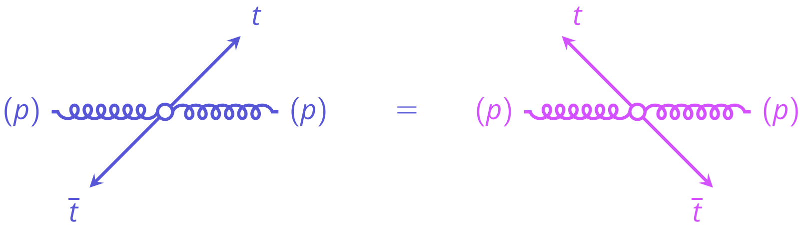
- Beyond LO there is a preference for the top quark travel in the same direction as the incoming quark.



- Measurements of the $t\bar{t}$ charge asymmetry became a hot topic due to tensions between measurements at the Tevatron and theoretical predictions.
- The asymmetry can be enhanced by new physics e.g. Z', KK gluon

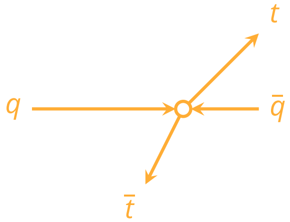
Forward-backward and charge asymmetry

- At the LHC we have a symmetric intial state (pp) and the dominant production mode of $t\bar{t}$ pairs is via two gluons, which is charge symmetric to all orders in QCD.



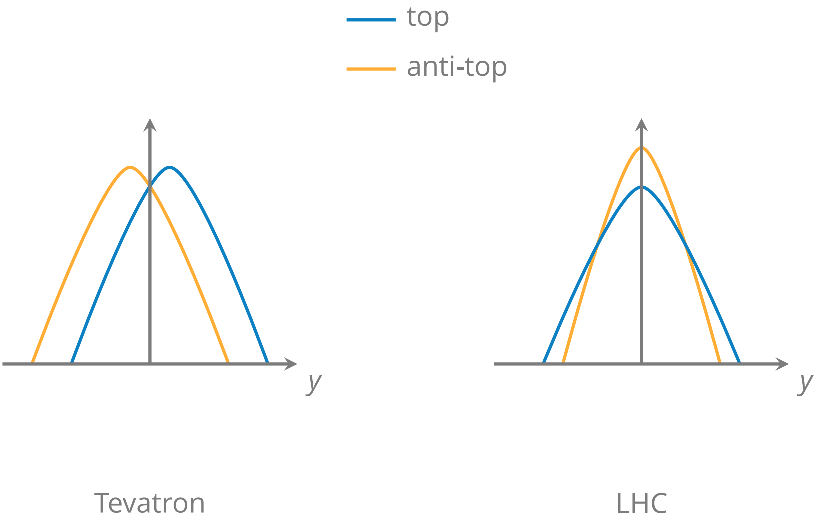
$t\bar{t}$ charge asymmetry

- However at the LHC in $q\bar{q} \rightarrow t\bar{t}$ the valence quark tends to have a higher momentum fraction leading to the t being produced in a more forward direction than the $\bar{t}$.

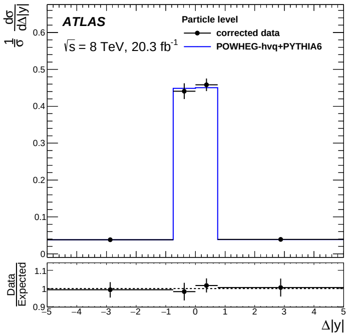


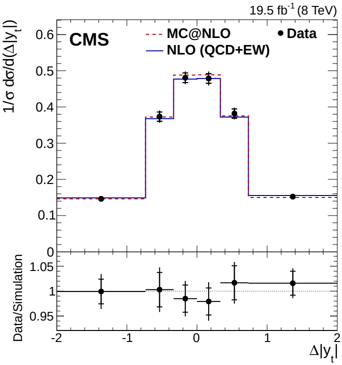
- Can measure $A = \frac{N(x>0)-N(x<0)}{N(x>0)+N(x<0)}$ where x is $\Delta|y| = |y_t| - |y_{\bar{t}}|$ or $\Delta|\eta| = |\eta_+| - |\eta_-|$ in the $\ell^+\ell^-$ channel.

A_{FB} vs A_{C}



- This variable requires us to reconstruct the $t\bar{t}$ system.





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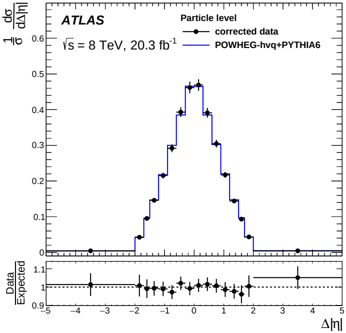
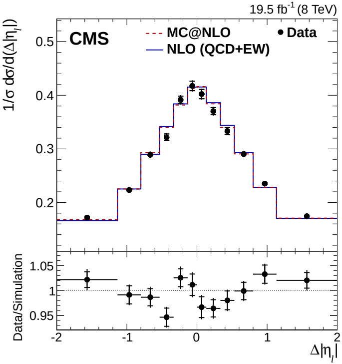
$A_c^{\ell^+\ell^-}$

- We can also look directly at the lepton directions.
- No $t\bar{t}$ reconstruction required- better resolution.





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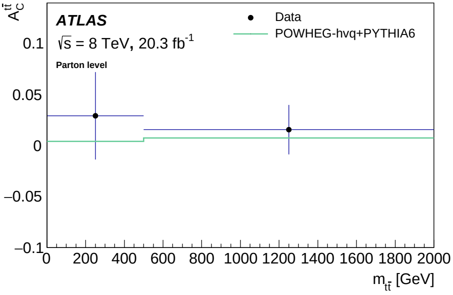
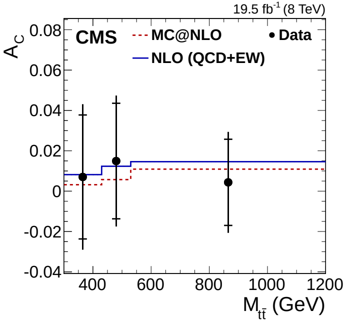
Differential $A_C^{t\bar{t}}$ distributions

- We can also look at the charge asymmetry versus properties of the $t\bar{t}$ system e.g. $m_{t\bar{t}}$.
- New physics might enhance asymmetry at high $m_{t\bar{t}}$ for example.





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Summary

- ATLAS & CMS are using the large number of top quarks pairs produced to make precise measurements of the properties of the top.
- The SM predictions are holding up very well to scrutiny!
- ATLAS & CMS are busy analysing the run-2 data!
- As statistical uncertainties become less relevant, understanding our $t\bar{t}$ modelling uncertainties will become more and more important.

Backup

Spin analysing power

- Leptons are the best analysers and thus the most precise spin correlation measurements are performed in the dilepton channel.
- Leptons have the highest spin analysing power and are easy to identify experimentally.

	$\bar{b}/W^+$	ℓ^+	$\bar{d}/\bar{s}$	$u/c/\nu$
α_i (LO)	0.41	1	1	-0.31
α_i (NLO)	0.39	0.998	0.93	-0.31

CP asymmetry from charge asymmetry

The decay chain fractions $r_x(\tilde{r}_x)$,

$$r_x = \frac{N_{r_x}}{N_{r_b} + N_{r_c} + N_{r_{c\bar{c}}}} \,, \tag{5}$$

where $x = b, c$ or $c\bar{c}$ relate the charge asymmetries A^{OS} and A^{SS} to the following CP asymmetries:

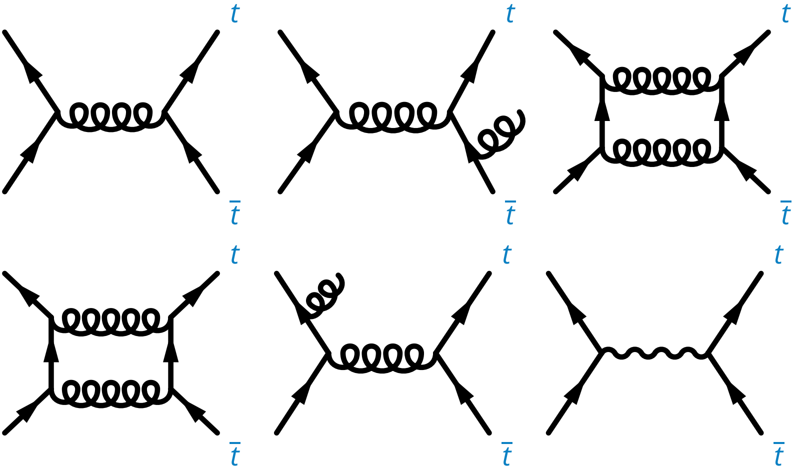
$$A^{b}_{\mathrm{mix}} = \frac{A^{\mathrm{SS}}}{r_b + r_{c\bar{c}}}$$

$$A^{b\ell}_{\mathrm{dir}} = \frac{A^{\mathrm{OS}}}{\tilde{r}_b}$$

$$A^{c\ell}_{\mathrm{dir}} = \frac{-A^{\mathrm{SS}}}{r_c + r_{c\bar{c}}}$$

$$A^{bc}_{\mathrm{dir}} = \frac{A^{\mathrm{SS}}}{r_c}$$

Origin of charge asymmetry



$t\bar{t}$ reconstruction

- $t\bar{t}$ reconstruction is easier in the $\ell +$ jets channel where the system is over-constrained.
- In the dilepton channel $t\bar{t}$ reconstruction is more challenging due to the presence of two neutrinos.
- Several different methods used:

	ATLAS	CMS
Spin corr./pol.	Neutrino weighting ▸ PRL 80 (1998) 2063 ▸ JHEP 05 (2015) 061	Analytic ▸ JHEP 07 (2011) 049 ▸ NIMA 736 (2014) 169 ▸ PLB 287 (1992) 225
Charge asymmetry	KIN ▸ PRD 73 (2006) 112006 ▸ PLB 722 (2013) 48	Analytic