Top (and Bottom) asymmetries at the LHC

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on behalf of the ATLAS and CMS Collaborations
(including LHCb results)

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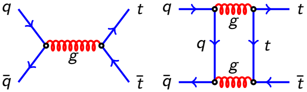
Top At Twenty Workshop - Fermilab, April 9^{th}-10^{th} 2015

Charge asymmetry in $t\bar{t}$ events

- At LO, $t\bar{t}$ production symmetric
- At NLO, QCD predicts an asymmetry for $q\bar{q} \to t\bar{t}$



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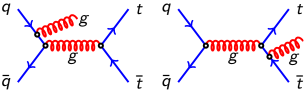
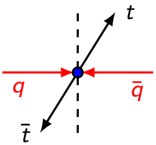


positive asymmetry

negative asymmetry

(flavour excitation in $qg \to t\bar{t}$ much smaller)

- The top quark is predicted to be emitted preferably in the direction of the incoming quark
- The exchange of new particles like Z' or axigluon could modify it



Charge asymmetry observables

Tevatron, $p\bar{p}$:

- q and $\bar{q}$ carry equal $< x >$
- t preferential direction $=$ p direction
- Forward/Backward asymmetry:

$$A_{FB} = \frac{N(\Delta y > 0) - N(\Delta y < 0)}{N(\Delta y > 0) + N(\Delta y < 0)},$$

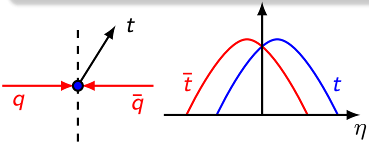
$$\Delta y = y_t - y_{\bar{t}}$$

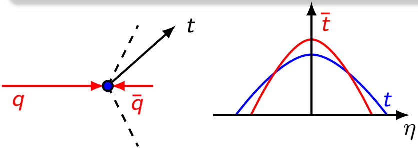
LHC, pp:

- LAB frame: no t preferential direction, but system z-boost along q direction
- t at higher $|y|$, $\bar{t}$ more central
- Charge asymmetry defined as:

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

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





Also: at the LHC $q\bar{q}$ annihilation suppressed vs gg fusion $\Rightarrow$ More diluted effect

	Tevatron	LHC
Asymmetry at NLO	9%	1%

Charge asymmetry measurements

	ATLAS	CMS
ℓ+jets	7 TeV [JHEP 1402 (2014) 107]	7 TeV [PLB 717 (2012) 129], 8 TeV [CMS PAS TOP-12-033]
dilepton	7 TeV [arXiv:1501.07383] NEW!	7 TeV [JHEP 1404 (2014) 191]

Theory NLO+EW: Bernreuther & Si [PRD 86 (2012) 034026], Kühn & Rodrigo [JHEP 1201 (2012) 063]
(new NNLO with Principle of Maximum Conformality: Brodsky, Si, Wang, Wu [PRD 90 (2014) 114034])

- A_C measurement implies t and $\bar{t}$ **reconstruction**: jet combinatorics, solve for p_z^ν...
- **Unfolding** to correct for detector and acceptance effects
- Need for at least one lepton (e or μ) to define $\Delta|y|$

Lower uncertainties in single lepton channel

- Statistics is one of the limiting factors in this measurement
- Only one neutrino $\Rightarrow$ full reconstruction of the system easier

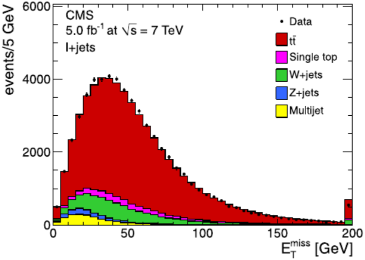
- In dilepton: Lepton Asymmetry also measured:

$$A_C^{lep} = \frac{N(\Delta|\eta_\ell| > 0) - N(\Delta|\eta_\ell| < 0)}{N(\Delta|\eta_\ell| > 0) + N(\Delta|\eta_\ell| < 0)}$$

Selection and Backgrounds

ℓ+jets Event Selection

- Exactly one e or μ
- ≥ 4 jets
- ≥ 1 b-tag
- Requirements on E_T^{miss} and/or m_T^W



Backgrounds:

	Normalization	Shape	Symmetric in $\Delta\|y\|$?
W+jets	data-driven	from Simulation	Asymmetric
Multi-jet	data-driven	data-driven	Symmetric
Single top	NNLO	from Simulation	Asymmetric
Z+jets, diboson	(N)NLO	from Simulation	~Symmetric

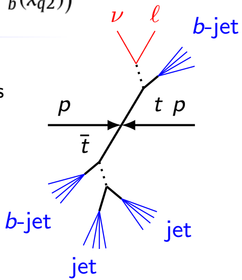
ATLAS: W+jets from ℓ^+/ℓ^- asymmetry, multi-jet from Matrix Method
CMS: fit E_T^{miss} and M_{jjj}, multi-jet shape from inverted lepton ID & isolation

System Reconstruction

CMS:

- Neutrino p_z found assuming m_W
- Decorrelation of reco masses $(m_t^{had}, m_t^{lep}, m_W^{had}) \rightarrow (m_1, m_2, m_3)$
- b-quark tag terms based on continuous b-tag values $P_b(x)$

$$\psi = L_1(m_1)L_2(m_2)L_3(m_3)\,P_b(x_{b1})P_b(x_{b2})\big(1 - P_b(x_{q1})\big)\big(1 - P_b(x_{q2})\big)$$



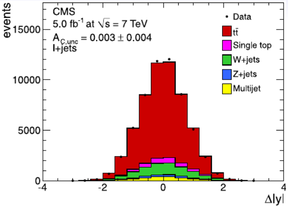
ATLAS:

- Transfer functions for reco $(\hat{x}) \rightarrow$ partonic $(\tilde{x})$ quantities
- Breit-Wigner functions for mass terms
- Tagging term from single b-tag working point

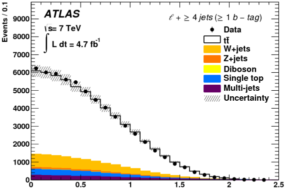
$$\begin{aligned} \mathrm{L} \;=\; & \mathcal{B}(\widetilde{E}_{\mathrm{p},1}, \widetilde{E}_{\mathrm{p},2}|m_W, \Gamma_W) \cdot \mathcal{B}(\widetilde{E}_{\mathrm{lep}}, \widetilde{E}_\nu|m_W, \Gamma_W) \cdot \\ & \mathcal{B}(\widetilde{E}_{\mathrm{p},1}, \widetilde{E}_{\mathrm{p},2}, \widetilde{E}_{\mathrm{p},3}|m_t,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

Both: correct sign for $\Delta|y|$ found $\sim$75% of the time

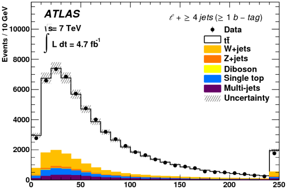
Reconstructed $t\bar{t}$ system variables



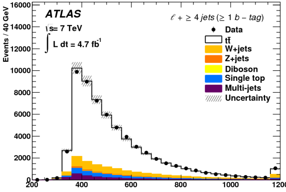
- Reconstruction-level $\Delta|y| = |y_t| - |y_{\bar{t}}|$ distribution obtained and used as input for the measurement
- Other distributions considered
  $\rightarrow A_C$ measurement vs $t\bar{t}$ system kinematics:



$y_{t\bar{t}}$: sensitive to ratio of contributions $q\bar{q}/gg \rightarrow t\bar{t}$



$p_{T,t\bar{t}}$: sensitive to positive / negative asymmetry (large $p_T \Rightarrow$ large radiation $\Rightarrow$ more negative)

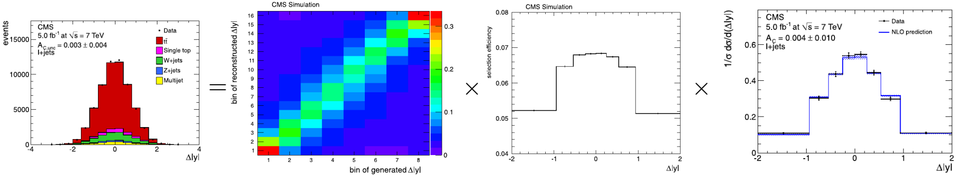


$m_{t\bar{t}}$: sensitive to ratio of contributions $q\bar{q}/gg \rightarrow t\bar{t}$ AND to BSM effects due to new heavy particles

Unfolding

CMS: Regularized unfolding through generalized matrix inversion procedure

- Perturbing effects → Response / Smearing Matrix S: $\vec{w} = S\vec{x}$ ($\vec{x}$ true spectrum, $\vec{w}$ reconstructed spectrum)
- Reconstruction and selection effects factorize ⇒ $S = M \times E$ (M **migration** matrix, E **efficiency** (diagonal) matrix)



- Equations from matrix inversion solved with least squares (LS) technique → x_{LS}
- To stabilize the result, two terms added: **regularization** and **normalization** terms
- Procedure generalized for 2-dimensional case

Unfolding - II

ATLAS: Fully Bayesian Unfolding (FBU)

- It applies the Bayes' theorem to the solution of the unfolding problem

$$\underbrace{p(\mathbf{T}\,|\,\mathbf{D},\, M)}_{\text{Posterior}} \propto \underbrace{L(\mathbf{D}\,|\,\mathbf{T},\, M)}_{\text{Likelihood}} \cdot \underbrace{\pi(\mathbf{T})}_{\text{Prior}}$$

Observed Spectrum (D) — Response Matrix (M) — Truth Spectrum (T)

- Spectra of $\Delta|y|$ distribution considered (or $(\Delta|y|,x)$ for A_C vs x measurement):
  - A_C posterior from $\Delta|y|$ distributions (4 bins) $\forall$ point in integration space
  - mean and RMS of this posterior $\rightarrow$ A_C value and uncertainty
- No iterations needed for **regularization**: choice of the **prior** plays its role instead:
  - flat prior $\leftrightarrow$ numerical matrix inversion: used for A_C vs $m_{t\bar{t}}$ and $|y_{t\bar{t}}|$
  - curvature prior $\leftrightarrow$ regularization: used for inclusive and A_C vs $p_{T,t\bar{t}}$
  - checked that the choice didn't introduce significant biases
- **Marginalization** of systematics on the posterior probability performed

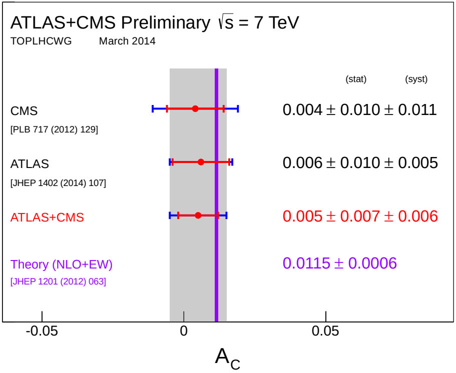
Inclusive Asymmetry at 7 TeV

	A_C
ATLAS	0.006 $\pm$0.010(stat+syst*)
CMS	0.004 $\pm$0.010(stat) $\pm$0.011(syst)
Bernreuther & Si	0.0123 $\pm$0.0005
Kühn & Rodrigo	0.0115 $\pm$0.0006

- *: ATLAS result includes marginalization of systematics
- **Statistical uncertainty** still large
- Largest contribution to systematics from:
  - jet & lepton energy measurement, E_T^{miss} and pile-up
  - W+jet background
  - model dependence of asymmetry (CMS)
- Different systematics related to model dependence assigned
- Result compatible with both zero and NLO+EW prediction

Combination at 7 TeV

ATLAS and CMS A_C 7 TeV measurements in ℓ+jet combined after unfolding (by TopLHC WG: [ATLAS-CONF-2014-012], [CMS PAS TOP-14-006])



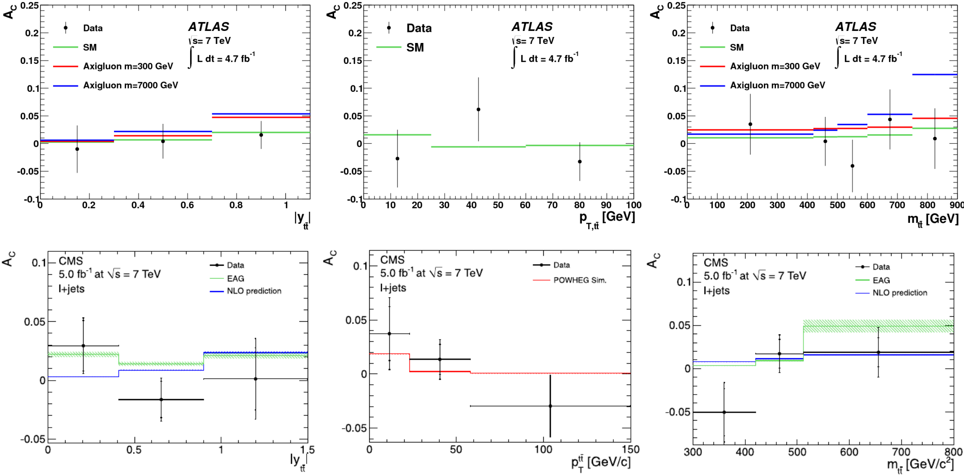
Combination:

- For ATLAS, used separate statistical and systematic uncertainties before the FBU marginalization procedure
- Result improves on ATLAS by 18% and CMS by 40%
- Result compatible with both zero and NLO+EW prediction

Systematics

		ATLAS	CMS	Comb.	Corr.
	A_C	0.006	0.004	0.005	0.058
Uncertainties	Statistical	0.010	0.010	0.007	0
	Detector response model	0.004	0.007	0.004	0
	Signal model	< 0.001	0.002	0.001	1
	W+jets model	0.002	0.004	0.003	0.5
	QCD model	< 0.001	0.001	0.000	0
	Pileup+MET	0.002	< 0.001	0.001	0
	PDF	0.001	0.002	0.001	1
	MC statistics	0.002	0.002	0.001	0
	Model dependence				
	Specific physics models	< 0.001	*	0.000	0
	General simplified models	*	0.007	0.002	0
	Systematic uncertainty	0.005	0.011	0.006	
	Total uncertainty	0.011	0.015	0.009	

Differential Asymmetries



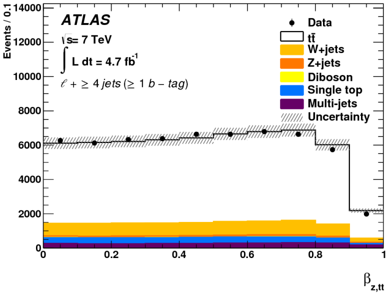
(EAG: Effective AxiGluon, with 1 TeV scale)

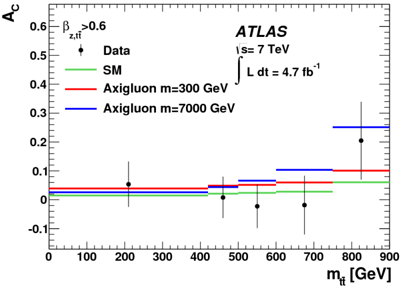
Asymmetry vs $t\bar{t}$ system velocity

ATLAS measures A_C for events with high $\beta_{z,t\bar{t}}$ ($t\bar{t}$ velocity/c along z axis):

- To enhance the contribution from $q\bar{q}$-initiated production
- To enhance potential effects of new physics

	$A_C(\beta_{z,t\bar{t}} > 0.6)$
ATLAS	0.011 ± 0.018(stat+syst)
Bernreuther & Si	$0.020\ ^{+0.006}_{-0.007}$



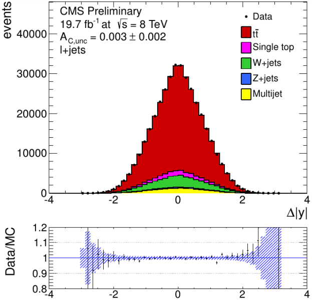


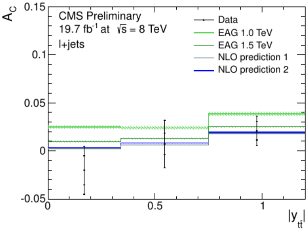
Asymmetry at 8 TeV

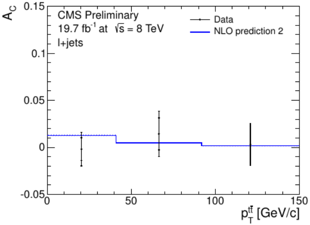
CMS measures A_C in 8 TeV data, with the same procedure:

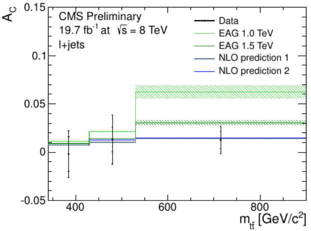
- Reduced stat uncertainty, smaller systematics
- Same precision as the 7 TeV CMS+ATLAS result

	A_C
CMS	0.005 $\pm$0.007(stat) $\pm$0.006(syst)
Bernreuther & Si	0.0102 $\pm$0.0005
Kühn & Rodrigo	0.0111 $\pm$0.0004



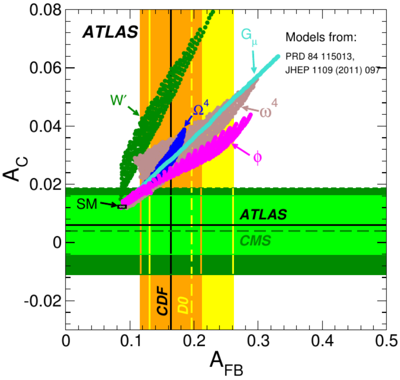


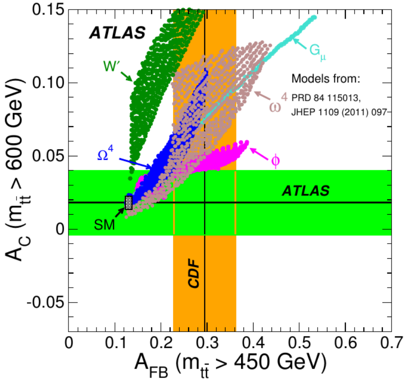




Comparison with BSM and Tevatron

- Comparison of A_C (ℓ+jets, 7 TeV) with various New Physics models (W', Ω^4, ϕ, G_μ, ω^4) generated with PROTOS to scan the mass-coupling parameter space
- Some models (e.g. W') seem to be disfavoured



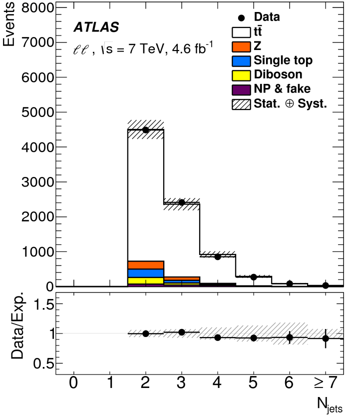


(Plots from [JHEP 1402 (2014) 107], Tevatron results from [PRD 87 (2013) 092002], [PRD 84 (2011) 112005])

Event Selection and Backgrounds

Dilepton Event Selections:

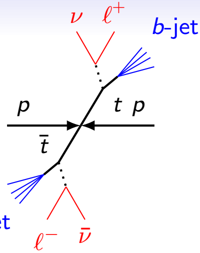
- 2 OS leptons (ee, $\mu\mu$, $e\mu$)
- $m_{\ell\ell}$ >15-20 GeV
- $m_{\ell\ell}$ outside Z-mass window for $ee/\mu\mu$
- E_T^{miss} >60-40 for $ee/\mu\mu$
- $H_T > 130$ GeV for $e\mu$ (ATLAS)
- ≥ 2 jets
- ≥ 1 b-tag (CMS)



Backgrounds from:

- Wt single top, diboson: from simulation
- Z+jets: estimated from $m_{\ell\ell}$ sideband
- Fake & non-prompt leptons (from W+jets and QCD): from Data with Matrix Method

Event Reconstruction



For A_C, need to fully reconstruct $t\bar{t}$ kinematics:

- 2 neutrinos vs. 1 E_T^{miss}, lepton/b pairing ambiguities

ATLAS & CMS: Neutrino Weighting techniques*

- Loop over the different possible solutions for η_1^ν, η_2^ν
- Assume m_t and m_W values
- Weight assigned to each solution based on the level of agreement with the measured E_T^{miss}, take solution with largest weight
- Jet energies floating withing uncertainties: resolution functions and MC integration
- For CMS (ATLAS), $\sim$14% (20%) of events discarded due to no solution found
- $\sim$80% of the time correct sign for $\Delta|y|$ in MC

(*: 'Analytical Matrix Weighting Technique (AMWT)' in CMS)

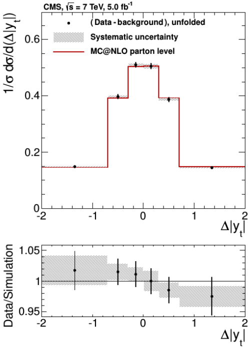
Lepton Asymmetry A_C^{lep} needs just lepton η:

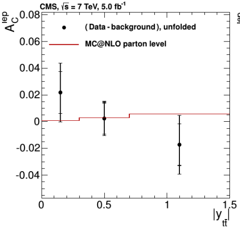
- Related to A_C, sensitive to anomalous top polarization
- No need to reconstruct $t\bar{t}$ system
- Less affected by unfolding complications

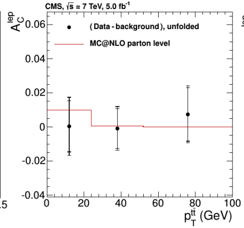
CMS results

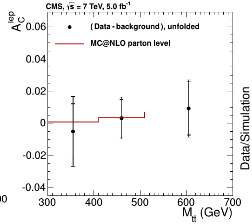
	A_C	A_C^{lep}
CMS	-0.010±0.017(stat)±0.008(syst)	0.009±0.010(stat)±0.006(syst)
Bernreuther & Si	0.0123 ±0.0005	0.0070 ±0.0003

- Unfolding reco-level $\Delta|y|$ and $\Delta|\eta|$ distributions
- Systematics dominated by $t\bar{t}$ scale uncertainty (and unfolding for A_C)
- For A_C^{lep} also shown results vs $|y_{t\bar{t}}|$, $p_{T,t\bar{t}}$ and $m_{t\bar{t}}$





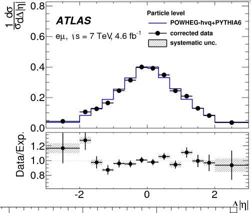


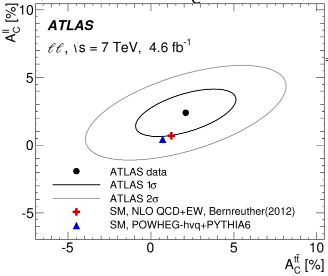


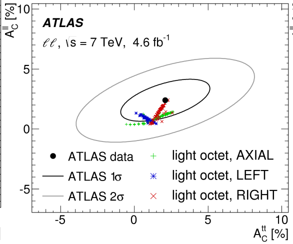
ATLAS results

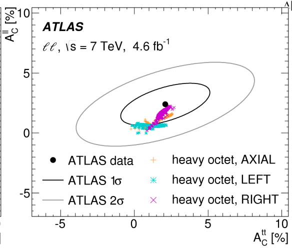
	A_C	A_C^{lep}
ATLAS	0.021 ±0.025(stat) ±0.017(syst)	0.024 ±0.015(stat) ±0.009(syst)
Bernreuther & Si	0.0123 ±0.0005	0.0070 ±0.0003

- Unfolding $\Delta|y|$ (FBU) and $\Delta|\eta|$ (bin-by-bin correction)
- Statistical uncertainty dominant
- Systematics: for A_C^{lep} only lepton reconstruction relevant
- The two observables are **correlated** ⇒ results shown in the plane A_C and A_C^{lep} and compared with BSM models:

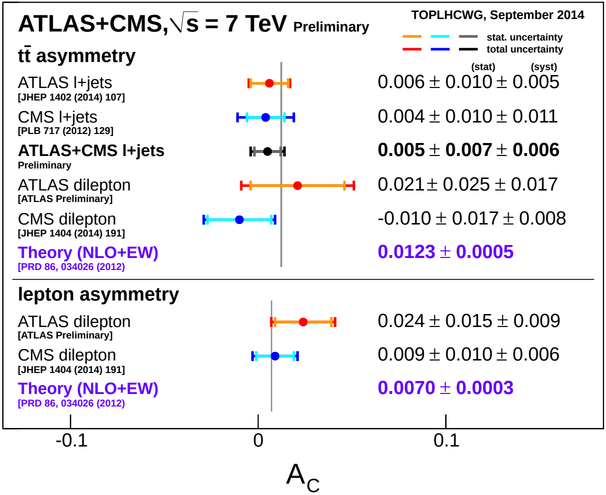








Summary


ATLAS+CMS, √s = 7 TeV Preliminary
TOPLHCWG, September 2014
stat. uncertainty
total uncertainty
tt̄ asymmetry
(stat) (syst)
ATLAS l+jets
[JHEP 1402 (2014) 107]
0.006 ± 0.010 ± 0.005
CMS l+jets
[PLB 717 (2012) 129]
0.004 ± 0.010 ± 0.011
ATLAS+CMS l+jets
Preliminary
0.005 ± 0.007 ± 0.006
ATLAS dilepton
[ATLAS Preliminary]
0.021± 0.025 ± 0.017
CMS dilepton
[JHEP 1404 (2014) 191]
-0.010 ± 0.017 ± 0.008
Theory (NLO+EW)
[PRD 86, 034026 (2012)]
0.0123 ± 0.0005
lepton asymmetry
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[ATLAS Preliminary]
0.024 ± 0.015 ± 0.009
CMS dilepton
[JHEP 1404 (2014) 191]
0.009 ± 0.010 ± 0.006
Theory (NLO+EW)
[PRD 86, 034026 (2012)]
0.0070 ± 0.0003
-0.1
0
0.1
A_C

Bottom-pair Production Charge Asymmetry

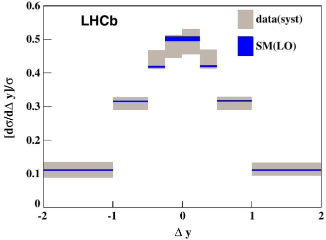
LHCb measured b-quark A_C in pp collisions [PRL 113 (2014) 082003]:

- Each b-quark from $b\bar{b}$ forms a single jet (anti-k_T with $R = 0.7$)
- Two b-jets, each $2 < \eta < 4$, $E_T > 20$ GeV, $\Delta\phi > 2.6$ (restricted η acceptance of forward geometry)
- Require at least one **muon** from semileptonic decay to **tag charge** of b / $\bar{b}$
- Purity of 70.3 $\pm$0.3 %, measured with dimuon events
- Sample ~400k events, $c\bar{c}$ contamination ~4%

Motivation: some theories proposed to explain $A_{FB}^{t\bar{t}}$ predict large $A_C^{b\bar{b}}$

Measurement in 3 mass bins: $A_C^{bb}(x, y)$ GeV:

$m_{b\bar{b}}$ [GeV]	$A_C^{b\bar{b}}$ [%]
40-75	0.4 $\pm$0.4(stat) $\pm$0.3(syst)
75-105	2.0 $\pm$0.9(stat) $\pm$0.6(syst)
>105	1.6 $\pm$1.7(stat) $\pm$0.6(syst)



- Expected SM asymmetries up to ~1%
- Additional ~2% contribution around m_Z from $Z \to b\bar{b}$

$t\bar{t}$ Charge Asymmetry Measurements

	Asymmetry(%)	ATLAS	CMS	LHC comb	NLO+EW
7 TeV	ℓ+jets A_C	0.6±1.0±0.5	0.4±1.0±1.1	0.5±0.7±0.6	1.15±0.06
	dilepton A_C	2.1±2.5±1.7	-1.0±1.7±0.8		1.15±0.06
	dilepton A_C^{lep}	2.4±1.5±0.9	0.9±1.0±0.6		0.70±0.03
8 TeV	ℓ+jets A_C		0.5±0.7±0.6		1.11±0.04

- Most precise A_C measurements at level of $\sim$1%, dilepton $\sim$2%
- Both A_C and A_C^{lep} compatible with zero and with SM theory prediction

Future prospects for 8 TeV and 13-14 TeV:

- Not yet systematics limited for A_C $\Rightarrow$ exploit full statistics
- ATLAS+CMS (8 TeV): Potential to measure A_C with $\sim$0.5% precision
- More statistics for high $m_{t\bar{t}}$ and high $\beta_{z,t\bar{t}}$:
  $\rightarrow$ enhanced sensitivity to $q\bar{q}$
  $\rightarrow$ but reduced $q\bar{q}$ fraction of 9% at 14 TeV (gg dominates)
- Fiducial measurements (e.g. 4 vs 5 jet) to reduce unfolding corrections?