CKM2016 - Asymmetries involved in the top quark sector (including A_c, A_{FB} and CP violation)

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$t\bar{t}$ asymmetries overview

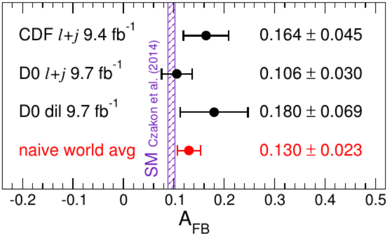
- Forward-backwards asymmetry measurements at the Tevatron
  - Latest results
- Charge asymmetry measurements at the LHC
  - ATLAS and CMS results
  - Measurements in multiple channels
  - Differential measurements
- CP violation asymmetries at the LHC
  - ATLAS and CMS are using $t\bar{t}$ events to measure CP violation
  - This has never been done before, 2016 sees the first 2 results

Forward-backward asymmetry - Rev.Mod.Phys. 87 (2015) 421-455

- The Tevatron is a $p - \bar{p}$ machine
- The forward-backward (FB) $t\bar{t}$ asymmetry is defined by the rapidity, y, of the top- and anti-top-quarks, where $\Delta y = y_t - y_{\bar{t}}$
- The FB asymmetry is expressed as:

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

- A Summary of the full Tevatron Run2 inclusive A_{FB} results



Charge asymmetry measurements at the LHC

- At LHC, there is no forward-backward asymmetry
- Not possible to define A_{FB}:
  - Due to symmetric initial state ($p - p$)
- Top-quark predicted to have larger $|y|$ than anti top-quark
  - Valance quarks typically have larger momentum than sea anti-quarks
  - This effect comes from the $q\bar{q} \rightarrow t\bar{t}$ process
  - The dominant $gg \rightarrow t\bar{t}$ process is symmetric and dilutes the effect
- With rapidity, y, we may define $\Delta|y| = |y_t| - |y_{\bar{t}}|$
- The charge asymmetry is expressed as:

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

- Any observed deviation from SM could indicate BSM physics

Multiple measurements of A_c

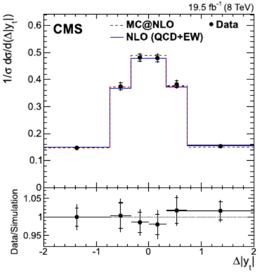
- Complementary ATLAS and CMS results
- A_c has been measured in multiple channels
  - Dilepton and ℓ+jets $t\bar{t}$ channels
- A_c has been measured differentially
  - As a function of $|y_{t\bar{t}}|$, $p_{\mathrm{T}}^{t\bar{t}}$, $m_{t\bar{t}}$ and $|\beta_{z,t\bar{t}}|$
- A_c has been measured in the boosted regime
  - Enriched with $q\bar{q} \to t\bar{t}$ process
  - Higher sensitivity to BSM physics

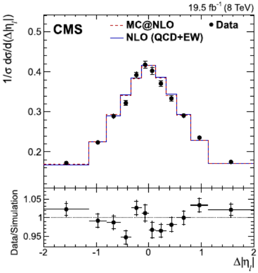
- Measurement of A_c requires the full reconstruction of the $t\bar{t}$ system
  - Need to reconstruct 2 top quarks from observed detector objects
  - Need to assign charge to each reconstructed top quark
  - Need to determine the rapidity of each top quark
  - Technically challenging with a probability of getting it wrong
- Dilepton measurements also measure A_c^{lep}
  - Analogous to A_c, but using the rapidity of the leptons
  - Does not require full $t\bar{t}$ reconstruction
  - Is not fully correlated to A_c, so provides extra information

CMS dilepton results - Phys. Lett. B 760 (2016) 365

- Event selection:
  - At least 2 jets:
    - $p_T > 30$ GeV, $|\eta| < 2.4$
    - One jet must be b-tagged
  - 2 isolated leptons (e or μ):
    - Opposite sign leptons
    - $p_T > 20$ GeV, $|\eta| < 2.4$
  - In the case of same-flavour leptons:
    - Veto $M_{\ell\ell}$ within 15 GeV of Z mass
    - $E_T^{miss} > 40$ GeV
- $t\bar{t}$ reconstruction:
  - Analytic solution for neutrinos
  - Matrix weighting technique
- Unfolding via TUnfold
- Inclusive results:

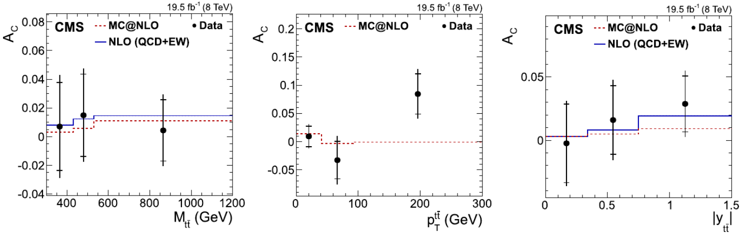
Variable	data
A_c	$0.011 \pm 0.011 \pm 0.007$
A_c^{lep}	$0.003 \pm 0.006 \pm 0.003$



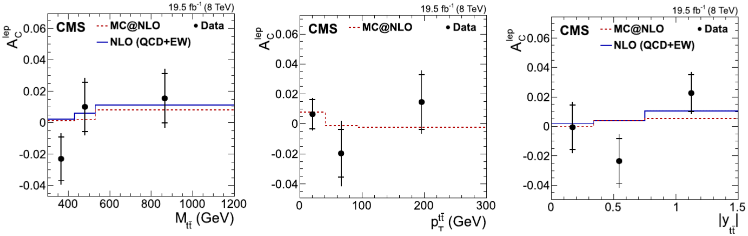


CMS dilepton results - Phys. Lett. B 760 (2016) 365

- A_c as a function of $m_{t\bar{t}}$, $p_T^{t\bar{t}}$ and $|y_{t\bar{t}}|$



- A_c^{lep} as a function of $m_{t\bar{t}}$, $p_T^{t\bar{t}}$ and $|y_{t\bar{t}}|$

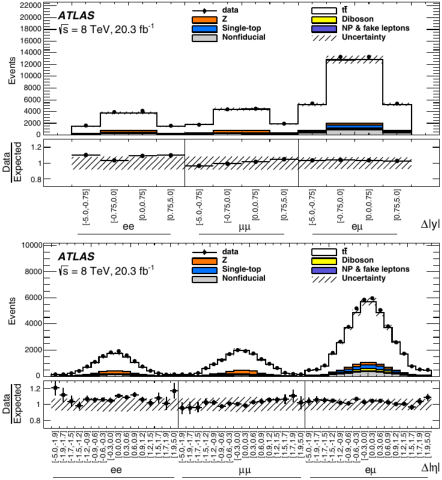


- Results are consistent with the Standard Model

ATLAS dilepton results - Phys. Rev. D 94, 032006 (2016)

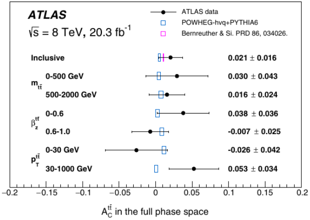
- Event selection:
  - At least 2 jets:
    - $p_T > 25$ GeV, $|\eta| < 2.5$
    - One jet must be b-tagged
  - 2 isolated leptons (e or μ):
    - Opposite sign leptons
    - $p_T > 25$ GeV, $|\eta| < 2.5$
  - $E_T^{miss} > 30$ GeV
  - $H_T > 130$ GeV
  - In the case of same-flavour leptons:
    - Veto $M_{\ell\ell}$ within 10 GeV of Z mass
- $t\bar{t}$ reconstruction:
  - KIN method solves for neutrinos and picks solution with lowest $t\bar{t}$ mass
- Fully Bayesian Unfolding (FBU)

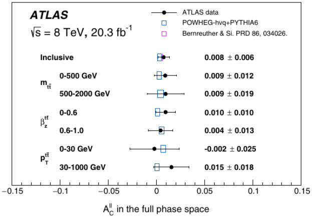
Variable	data
A_c	0.021 ± 0.016
A_c^{lep}	0.008 ± 0.006



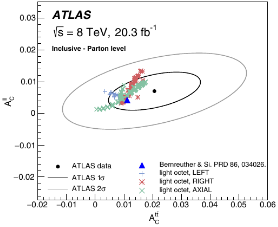
ATLAS dilepton results - Phys. Rev. D 94, 032006 (2016)

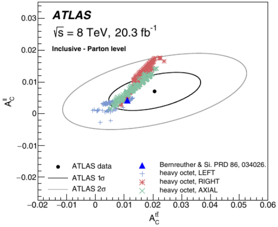
- A_c and A_c^{lep} for different bins of $m_{t\bar{t}}$, $|\beta_{z,t\bar{t}}|$ and $p_{\mathrm{T}}^{t\bar{t}}$





- A_c Vs A_c^{lep}, shown for a selection of BSM theories



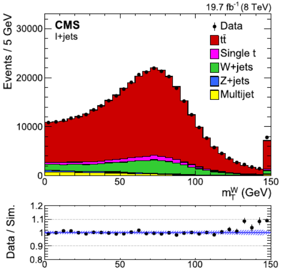


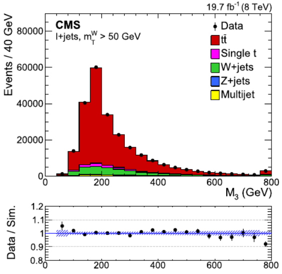
- Results are consistent with the Standard Model
- BSM models are not excluded

CMS ℓ+jets results - Phys. Lett. B 757 (2016) 154

- Event selection:
  - At least 4 jets:
    - $p_T > 25$ GeV, $|\eta| < 2.5$
    - One jet must be b-tagged
  - 1 isolated lepton (e or μ):
    - e : $p_T > 30$ GeV, $|\eta| < 2.5$
    - μ : $p_T > 26$ GeV, $|\eta| < 2.1$
- $t\bar{t}$ reconstruction:
  - Kinematic likelihood method
- Unfolding via generalized matrix inversion
- Inclusive results:

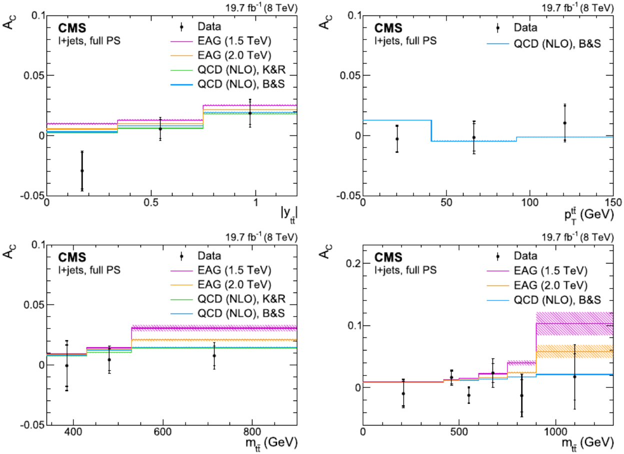
Variable	data
A_c	$0.0010 \pm 0.0068 \pm 0.0037$





CMS ℓ+jets results - Phys. Lett. B 757 (2016) 154

- A_c as a function of $|y_{t\bar{t}}|$, $p_{\mathrm{T}}^{t\bar{t}}$ and $m_{t\bar{t}}$

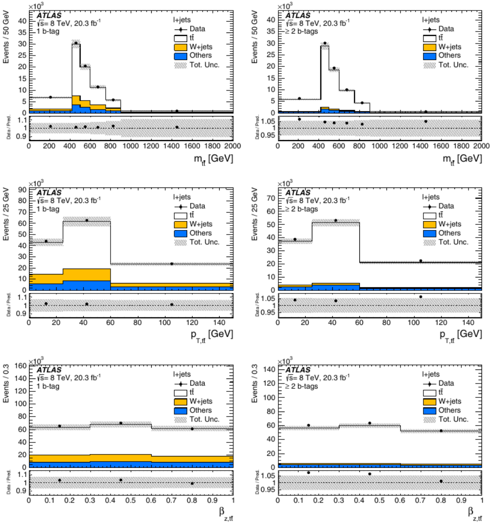


- Shown for 2 different binnings in $m_{t\bar{t}}$
- BSM Prediction not available for $p_{\mathrm{T}}^{t\bar{t}}$
- New physics excluded at scales below 1.5 TeV at 95% C.L.

ATLAS ℓ+jets results - Eur. Phys. J. C76 (2016) 87

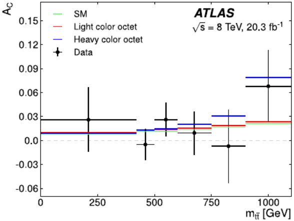
- Event selection:
  - At least 4 jets:
    - $p_{\mathrm{T}} > 25$ GeV, $|\eta| < 2.5$
  - 1 isolated lepton (e or μ):
    - e : $p_{\mathrm{T}} > 25$ GeV, $|\eta| < 2.47$
    - μ : $p_{\mathrm{T}} > 25$ GeV, $|\eta| < 2.5$
  - Events binned by 0,1,2 b-tags
- $t\bar{t}$ reconstruction:
  - Kinematic likelihood method
- Fully Bayesian Unfolding (FBU)
- Inclusive results:

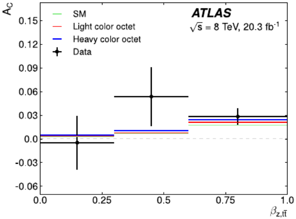
Variable	data
A_c	0.009 ± 0.005

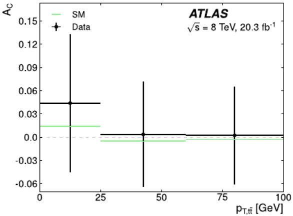


ATLAS ℓ+jets results - Eur. Phys. J. C76 (2016) 87

- A_c as a function of $m_{t\bar{t}}$, $|\beta_{z,t\bar{t}}|$ and $p_{\mathrm{T}}^{t\bar{t}}$



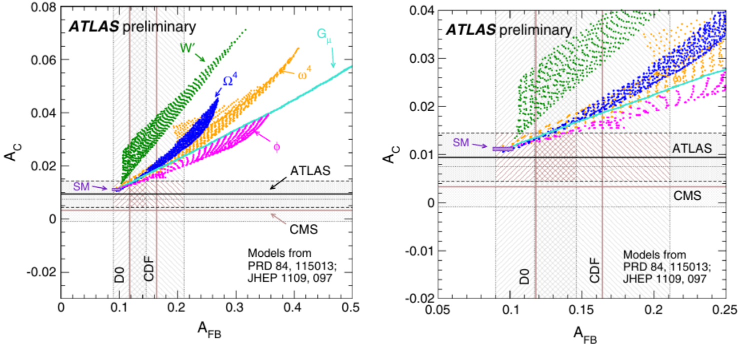




- BSM Prediction not available for $p_{\mathrm{T}}^{t\bar{t}}$
- Results compatible with SM and BSM models

LHC A_c Vs Tevatron A_{fb} - Eur. Phys. J. C76 (2016) 87

- Inclusive ATLAS and CMS A_c Vs CDF and D0 A_{fb}
- Various BSM models are shown:
  - W' boson, heavy axigluon (G_μ), scaler isodoublet (ϕ)
  - Colour-triplet scalar (ω^4), colour-sectec scalar (Ω^4)
- Right plot is zoomed-in version of left plot

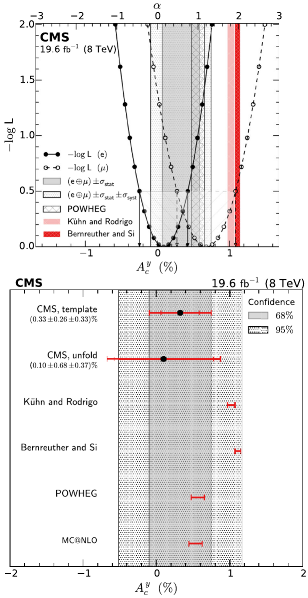


- Phase-space for parameters of BSM models shown is limited

CMS template method results - Phys. Rev. D 93, 034014 (2016)

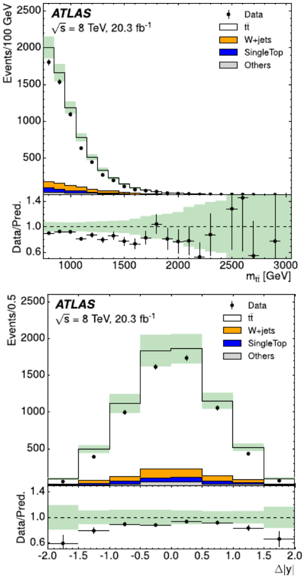
- Symmetric and asymmetric component of MC template is sensitive to:
  - $\Upsilon_{t\bar{t}} = \tanh \Delta|y_{t\bar{t}}|$
- Similar event selection to ℓ+jets
- More precise than ℓ+jets measurement with unfolding
- Larger modelling uncertainties

Variable	data
A_c	$0.0033 \pm 0.0026 \pm 0.0033$

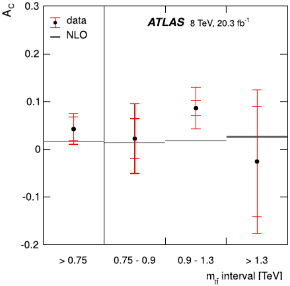


ATLAS boosted results - Phys. Lett. B 756 (2016) 756

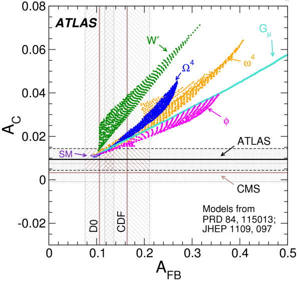
- Boosted ℓ+jets analysis
- Greater sensitivity to BSM
- Event selection - Leptonic t decay:
  - 1 isolated lepton $p_{\mathrm{T}} > 25$ GeV
  - $E_{\mathrm{T}}^{\mathrm{miss}} > 20$ GeV
  - $E_{\mathrm{T}}^{\mathrm{miss}} + m_{\mathrm{T}}^{w} > 60$ GeV
  - Highest p_{T} jet($R = 0.4$)
- Event selection - Hadronic t decay:
  - 1 large-R jet($R = 1.0$)
  - Trimmed : rsub=0.3
  - $p_{\mathrm{T}} > 300$ GeV
  - $m_{\mathrm{jet}}^{\mathrm{trim}} > 100$ GeV
- $m_{t\bar{t}} > 750$ GeV
- Fully Bayesian Unfolding (FBU)



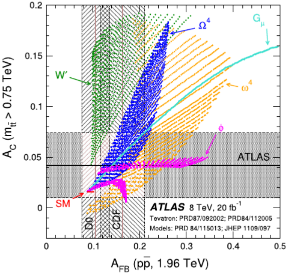
ATLAS boosted results - Phys. Lett. B 756 (2016) 756



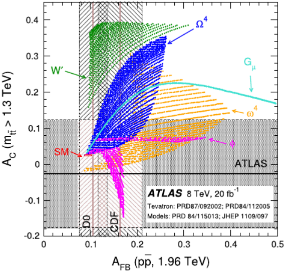
$m_{t\bar{t}}$	data	SM prediction
> 0.75 TeV	$(4.2 \pm 3.2)\%$	$(1.60 \pm 0.004)\%$
$0.75 - 0.9$ TeV	$(2.2 \pm 7.3)\%$	$(1.42 \pm 0.004)\%$
$0.9 - 1.3$ TeV	$(8.6 \pm 4.4)\%$	$(1.75 \pm 0.05)\%$
> 1.3 TeV	$(-2.9 \pm 15.0)\%$	$(2.55 \pm 0.18)\%$



- Resolved



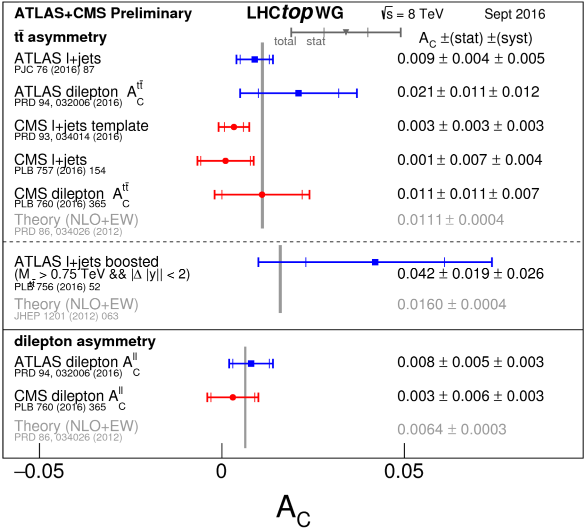
- $m_{t\bar{t}} > 0.75$ TeV



- $m_{t\bar{t}} > 1.3$ TeV

Summary of A_c

- A summary of all inclusive measurements of A_c



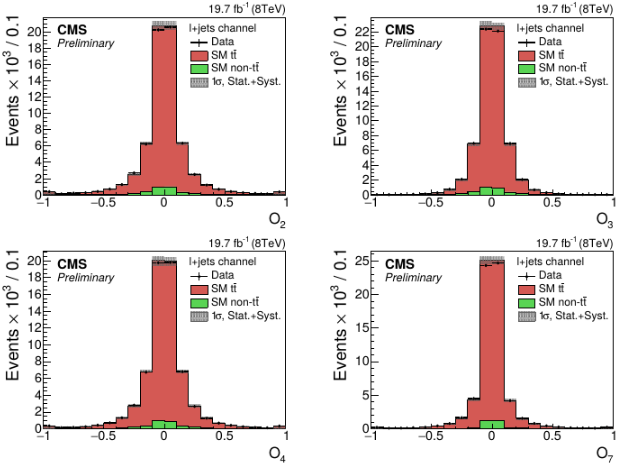
CP violation at CMS - CMS TOP-16-001

- First measurement of CP violation using $t\bar{t}$ events
- Based on the T-odd triple product correlations
- Semi-leptonic $t\bar{t}$ event selection
  - Similar event selection to CMS ℓ+jets A_c analysis
- 4 CP-sensitive observables, O_i.
- CP-asymmetry expressed as:

$$A_{CP}(O_i) = \frac{N(O_i > 0) - N(O_i < 0)}{N(O_i > 0) + N(O_i < 0)}$$

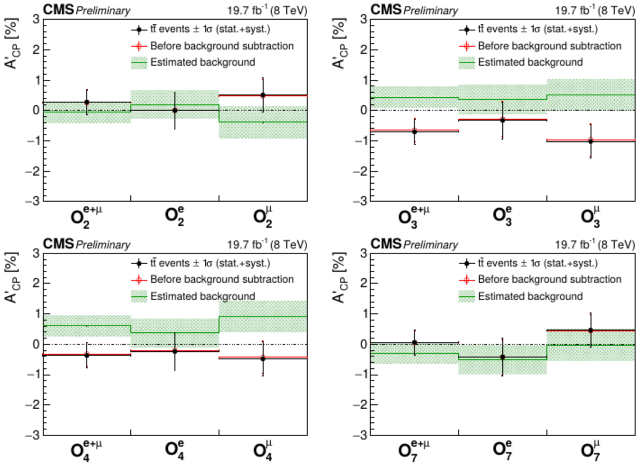
- Any non-zero $A_{CP}(O_i)$ would hint a BSM physics

CP violation at CMS - CMS TOP-16-001



$A'_{CP}(O_i)$	e+jets	μ+jets	ℓ+jets
O_2	$-0.01 \pm 0.61 \pm 0.01$	$+0.50 \pm 0.56 \pm 0.02$	$+0.27 \pm 0.41 \pm 0.01$
O_3	$-0.34 \pm 0.61 \pm 0.02$	$-1.03 \pm 0.56 \pm 0.04$	$-0.71 \pm 0.41 \pm 0.03$
O_4	$-0.24 \pm 0.61 \pm 0.02$	$-0.49 \pm 0.56 \pm 0.04$	$-0.38 \pm 0.41 \pm 0.03$
O_7	$-0.42 \pm 0.61 \pm 0.00$	$+0.46 \pm 0.56 \pm 0.01$	$-0.06 \pm 0.41 \pm 0.01$

CP violation at CMS - CMS TOP-16-001



- Measured asymmetries show no evidence for CP-violation
- In agreement with Standard Model prediction

CP violation at ATLAS - arXiv:1610.07869 (Submitted to JHEP)

- CP Violation occurs in neutral B-meson decays
- $t\bar{t}$ events offer an alternative b-quark production mechanism compared to b-factories such as BaBar and Belle
- Hard lepton from W-boson decay in semileptonic $t\bar{t}$ allows determination of b-quark charge ($t \to bW^+ \to b\ell^+\nu$)
- Charge of soft muon from ($b \to X\mu\nu$) probes decay chain
    - Tag jets containing a soft muon (SMT algorithm)
- Inclusive top decay chains which produce 2 leptons

- Same Sign
- $t \to \ell^+\nu\,(b \to \bar{b}) \to \ell^+\ell^+X$
- $t \to \ell^+\nu\,(b \to c) \to \ell^+\ell^+X$
- $t \to \ell^+\nu\,(b \to \bar{b} \to c\bar{c}) \to \ell^+\ell^+X$

- Opposite Sign
- $t \to \ell^+\nu b \to \ell^+\ell^-X$
- $t \to \ell^+\nu\,(b \to \bar{b} \to \bar{c}) \to \ell^+\ell^-X$
- $t \to \ell^+\nu\,(b \to c\bar{c}) \to \ell^+\ell^-X$

- These processes are sensitive to CPV in $B_q - \bar{B}_q$ $(q = d, s)$ mixing, semileptonic b and c decays and $b \to c$
- Theory paper: **PRL 110,232002 (2013)**

CP violation at ATLAS - arXiv:1610.07869 (Submitted to JHEP)

- Use semileptonic $t\bar{t}$ events in which B-hadron decays to a muon
- Consider number of SMT muons, N^{ab}, where:
  - a : Charge of W-lepton ⇒ identifies initial charge of b
  - b : Charge of SMT Muon ⇒ probes final state for CPV
- Consider probability of initial b decaying to a lepton ℓ

$$P\left(b \to \ell^+\right) = \frac{N\left(b \to \ell^+\right)}{N\left(b \to \ell^-\right) + N\left(b \to \ell^+\right)} = \frac{N^{++}}{N^{+-} + N^{++}} = \frac{N^{++}}{N^{+}}$$

$$P\left(\bar{b} \to \ell^-\right) = \frac{N\left(\bar{b} \to \ell^-\right)}{N\left(\bar{b} \to \ell^-\right) + N\left(\bar{b} \to \ell^+\right)} = \frac{N^{--}}{N^{--} + N^{-+}} = \frac{N^{--}}{N^{-}}$$

$$P\left(b \to \ell^-\right) = \frac{N\left(b \to \ell^-\right)}{N\left(b \to \ell^-\right) + N\left(b \to \ell+\right)} = \frac{N^{+-}}{N^{+-} + N^{++}} = \frac{N^{+-}}{N^{+}}$$

$$P\left(\bar{b} \to \ell^+\right) = \frac{N\left(\bar{b} \to \ell^+\right)}{N\left(\bar{b} \to \ell^-\right) + N\left(\bar{b} \to \ell^+\right)} = \frac{N^{-+}}{N^{--} + N^{-+}} = \frac{N^{-+}}{N^{-}}$$

- Measure same- and opposite-sign charge asymmetries:

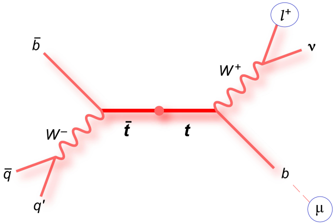
$$A^{ss} = \frac{P\left(b \to \ell^+\right) - P\left(\bar{b} \to \ell^-\right)}{P\left(b \to \ell^+\right) + P\left(\bar{b} \to \ell^-\right)} \qquad A^{os} = \frac{P\left(b \to \ell^-\right) - P\left(\bar{b} \to \ell^+\right)}{P\left(b \to \ell^-\right) + P\left(\bar{b} \to \ell^+\right)}$$

$$A^{ss} = \frac{\left(\frac{N^{++}}{N^{+}} - \frac{N^{--}}{N^{-}}\right)}{\left(\frac{N^{++}}{N^{+}} + \frac{N^{--}}{N^{-}}\right)} \qquad A^{os} = \frac{\left(\frac{N^{+-}}{N^{+}} - \frac{N^{-+}}{N^{-}}\right)}{\left(\frac{N^{+-}}{N^{+}} + \frac{N^{-+}}{N^{-}}\right)}$$

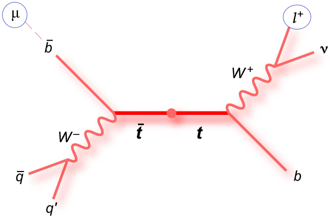
CP violation at ATLAS - arXiv:1610.07869 (Submitted to JHEP)

1. Perform a "standard" $t\bar{t}$ ℓ+jets event selection
2. Double tag jets with displaced-vertex and SMT algorithm
3. Fully reconstruct $t\bar{t}$ event with KLFitter
   - KLFitter tells us if an SMT muon is same- or different-top
   - Allows a determination of initial charge of the b
     - For same-top SMT muons : $W^{\pm} \Rightarrow b^{\mp}$
     - For different-top SMT muons : $W^{\pm} \Rightarrow b^{\pm}$
   - We get this correct with a purity of $\sim 80\%$
4. Unfold data to a fiducial volume and measure CP asymmetries
5. Fit results to obtain limits on direct and mixing CP parameters

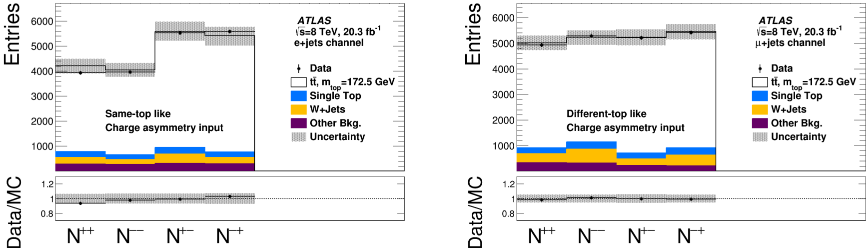
- Same Top SMT Muon



- Different Top SMT Muon



CP violation at ATLAS - arXiv:1610.07869 (Submitted to JHEP)



	Data (10^{-2})		MC (10^{-2})		Existing limits (2σ) (10^{-2})		SM prediction (10^{-2})	
A^{ss}	-0.7	$\pm\ 0.8$	0.05	$\pm\ 0.23$	-		$< 10^{-2}$	[19]
A^{os}	0.4	$\pm\ 0.5$	-0.03	$\pm\ 0.13$	-		$< 10^{-2}$	[19]
A^{b}_{mix}	-2.5	$\pm\ 2.8$	0.2	$\pm\ 0.7$	< 0.1	[95]	$< 10^{-3}$	[96] [95]
$A^{b\ell}_{\mathrm{dir}}$	0.5	$\pm\ 0.5$	-0.03	$\pm\ 0.14$	< 1.2	[94]	$< 10^{-5}$	[19] [94]
$A^{c\ell}_{\mathrm{dir}}$	1.0	$\pm\ 1.0$	-0.06	$\pm\ 0.25$	< 6.0	[94]	$< 10^{-9}$	[19] [94]
A^{bc}_{dir}	-1.0	$\pm\ 1.1$	0.07	$\pm\ 0.29$	-		$< 10^{-7}$	[97]

- All results are consistent with the Standard Model
- Largest uncertainty on all results is statistical
- First ever measurement of A^{bc}_{dir}
- Strengthens 2σ limit on $A^{c\ell}_{\mathrm{dir}}$, equivalent limit for $A^{b\ell}_{\mathrm{dir}}$

Summary

- Multiple measurements of A_c and A_c^{lep}
  - Dilepton and ℓ+jets
  - Resolved and boosted
  - Measured differential in many variables
- CP-violation using $t\bar{t}$ events is now producing results
  - Very exciting future
  - A new frontier for the CKM community?
- All ATLAS and CMS measurements are at 8 TeV
  - Statistical uncertainties are currently large
  - Anticipate future 13 TeV measurements