Top decays and CP violation at LHC

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On behalf of ATLAS and CMS collaborations at LHC

Outline

- Introduction
- Search for CP violation in top pair production and decay at 8 TeV with CMS
- Measurement of CP asymmetries in b-hadron decays using top quark events at 8 TeV with ATLAS
- Search for CP violation in the single top events in pp collision at 7 TeV with ATLAS
- Summary

Introduction: Top quark

- The heaviest fundamental particle, so far with m_{top} ~ 173 GeV
  → Yukawa coupling to the Higgs field is close to 1
  → Most interesting object to test the Standard Model (SM) and beyond
- Strongly interacting with the electroweak sector and the Higgs

  $$m_{top} = y_t\, v / \sqrt{2} \rightarrow y_t \sim 1$$

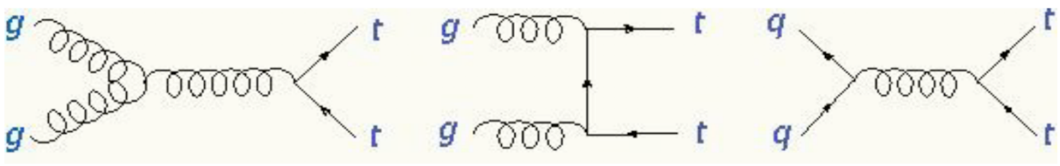
  - **Direct top-Higgs coupling in ttH observed by both CMS and ATLAS!**
- The only bare quark, decays weakly before hadronizing: $\tau \sim 5*10^{-25}$ s
  - **Allows to probe quark properties directly: mass, couplings, spin, charge**
- **CP violation (CPV) is commonly studied in strange and bottom quark sectors.**
- **CPV can also be studied in top sector:**
  - **Top pair production**
  - **Single top production**

Introduction: CP violation in top sector

- CPV in SM is not large enough to describe the matter-antimatter asymmetry of the universe
- LHC is a top factory that has high statistics to probe CPV in top events
- Top-quark pair production and decay provide a unique opportunity to study CPV
  - a large chain of linearly independent four momentum vectors that are correlated by spin
  - The new observables that can be studied are simple kinematic correlations of the form $\mathbf{v_1} \cdot (\mathbf{v_2} \times \mathbf{v_3})$ where $\mathbf{v_i}$ are spin/four momentum of top decay products
- **Sources of CP violation in top sector:**
  - **Anomalous top-quark couplings**
  - **Extended Scalar sectors**

Introduction: CP violation in top sector

- One of the hypothesis of new physics can enhance CPV in top sector: **Top quark anomalous coupling**
  - For CPV at production vertex (***ttg***) Include chromo-electric dipole moment (CEDM) of top quark in top pair production
  - At the decay vertex (***tbW***) several anomalous couplings are possible, only one coupling contributes



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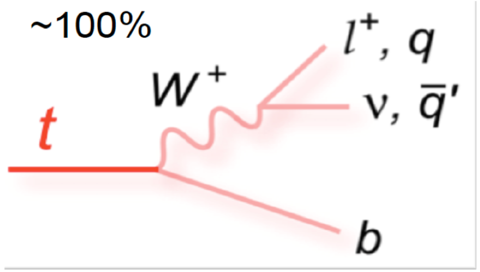
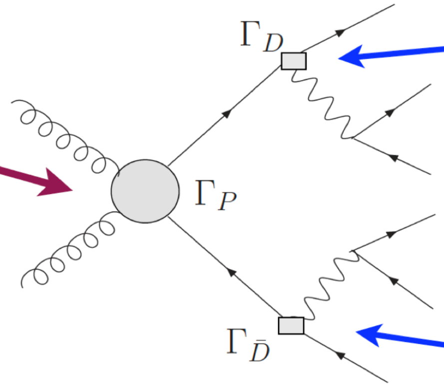


$\epsilon(p_t, p_{\bar{t}}, s_t, s_{\bar{t}})$

CP violation in the production vertex



$\epsilon(p_t, p_b, p_{\ell^+}, s_t)$

CP violation in the decay vertex

$\epsilon(p_{\bar{t}}, p_{\bar{b}}, p_{\ell^-}, s_{\bar{t}})$

Introduction: CP violation in top sector

- One of the hypothesis of new physics can enhance CPV in top sector: **Top quark anomalous coupling**
  - For **CPV at production vertex** (***ttg***) Include chromo-electric dipole moment (CEDM), d_t~, of top quark in top pair production
    - The coupling d_t~ is negligibly small in the SM
    - In models in which CPV is induced by exchange of neutral scalars have contribution to CEDM of top scales as $\boldsymbol{m_{top}^{3}}$ → a potentially large top-quark CEDM
    - Gauge invariance introduces ***a "sea-gull" ttgg*** term apart from ***ttg***

  - At **the decay vertex (*tbW*)** several anomalous couplings are possible, only one coupling contributes

$$\Gamma^{\mu}_{Wtb} = -\frac{g}{\sqrt{2}} V^{\star}_{tb}\, \bar{u}(p_b) \left[\gamma_\mu (f_1^L P_L + f_1^R P_R) - i\sigma^{\mu\nu}(p_t - p_b)_\nu (f_2^L P_L + f_2^R P_R)\right] u(p_t).$$

Introduction: CP violation in top sector

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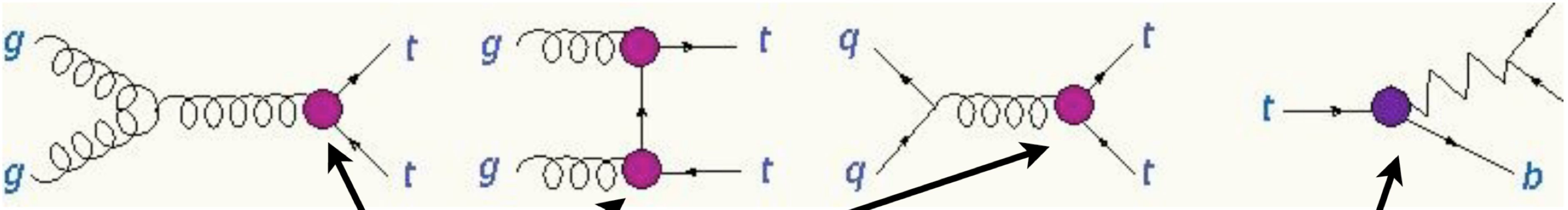
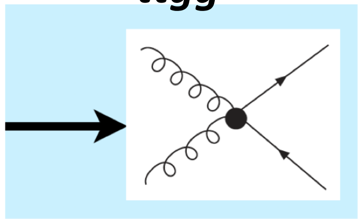


$f_2^R \; e^{i\phi} e^{i\delta}$

CP-odd or CP-even phase

ttgg



$$\mathcal{H} \sim \frac{1}{2} g_s \tilde{d}_t \, \bar{t} \sigma_{\mu\nu} \gamma_5 \lambda_a t \; G_a^{\mu\nu}$$

implies a ``sea-gull'' diagram also

$$\mathcal{H} \sim i \frac{g}{\sqrt{2}} V_{tb}^{\star} f_2^R \, \bar{b} \sigma^{\mu\nu} (p_t - p_b)_\nu (1 + \gamma_5) t \; W_\mu$$

Search for CP violation in top pair production and decay at 8 TeV with CMS

CP violation in top sector: CMS (1)

- The CP-violating asymmetries are measured using **four T-odd triple-product observables**, $\mathbf{v_1} \cdot (\mathbf{v_2} \times \mathbf{v_3})$, where T is the time-reversal operator.
  - Assume CPT conservation
  - These triple-product observables, O_i, are odd under the T transformation, and are thus also odd under CP, $\mathbf{CP}(O_i) = -O_i$ where O_i are proposed observables
- The presence of CPV would be manifested by a nonzero value of asymmetry defined by counting events in two bins of observable, O_i

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

- No NP model dependent dilution factor, ***D,*** for $A_{CP}(O_i)$ is considered
  - $A_{CP}'(O_i) = D\,A_{CP}(O_i)$
  - Corrections for SM case are considered.
- **First measurement of CPV in top pair events at CMS**

CP violation in top sector: CMS (2)

- Event topology: top pair in lepton + jets final state
  - 1 isolated muon or electron, at least 4 jets of which 2 b-jets
- Four triple-product observables:

$$O_2 = \epsilon(P, p_b + p_{\bar{b}}, p_\ell, p_{j_1}) \xrightarrow{\text{lab}} \propto (\vec{p}_b + \vec{p}_{\bar{b}}) \cdot (\vec{p}_\ell \times \vec{p}_{j_1}),$$

$$O_3 = Q_\ell\, \epsilon(p_b, p_{\bar{b}}, p_\ell, p_{j_1}) \xrightarrow{\text{b}\bar{\text{b}}\,\text{CM}} \propto Q_\ell\, \vec{p}_b \cdot (\vec{p}_\ell \times \vec{p}_{j_1}),$$

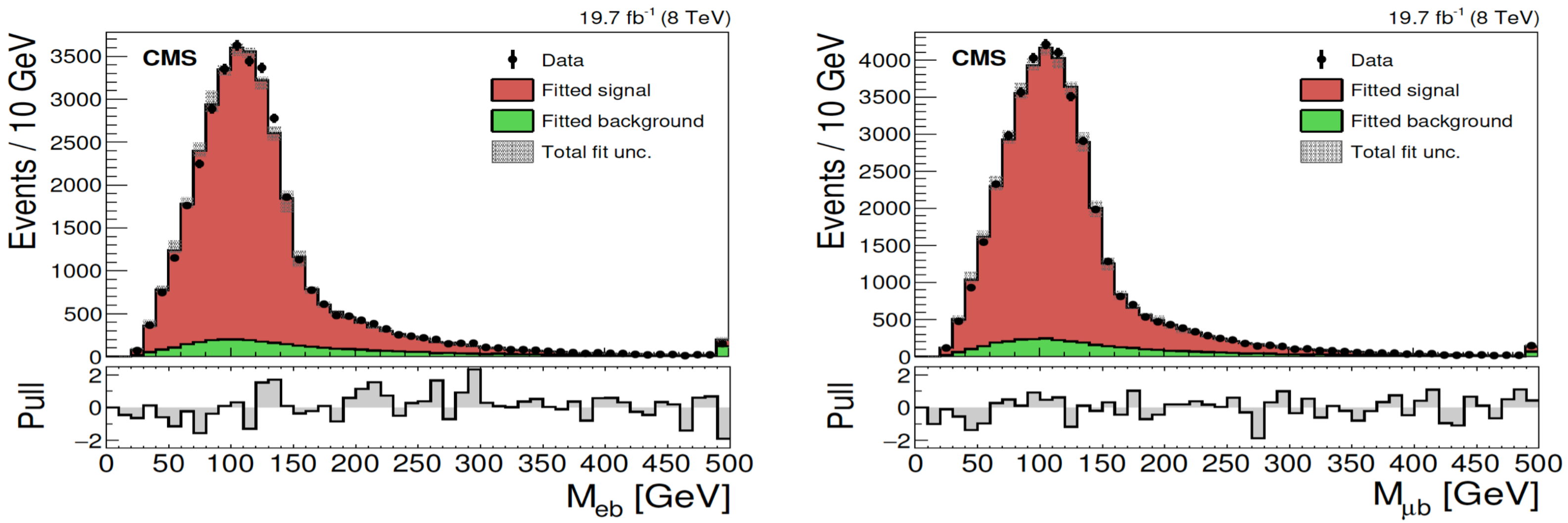
$$O_4 = Q_\ell\, \epsilon(P, p_b - p_{\bar{b}}, p_\ell, p_{j_1}) \xrightarrow{\text{lab}} \propto Q_\ell\, (\vec{p}_b - \vec{p}_{\bar{b}}) \cdot (\vec{p}_\ell \times \vec{p}_{j_1}),$$

$$O_7 = q \cdot (p_b - p_{\bar{b}})\, \epsilon(P, q, p_b, p_{\bar{b}}) \xrightarrow{\text{lab}} \propto (\vec{p}_b - \vec{p}_{\bar{b}})_z (\vec{p}_b \times \vec{p}_{\bar{b}})_z .$$

  - ϵ denotes Levi-Civita symbol, P is the sum and q is the difference between four momenta of the two initial state protons
- O_3 is measured in bb CM frame and O_2, O_4 & O_7 are in lab frame
- **O_2 & O_7 do not require distinguishing b and anti-b jets**
  - A_{CP} ~ 0.4% if anomalous couplings are involved
- **O_3 & O_4 need to know both b-tagged jets from b and anti-b quark**
  - A_{CP} ~ 8% if anomalous couplings are involved

CP violation in top sector: CMS (3)

- $M_{\ell b}$ fit → signal and background events yields
- Good agreement of $M_{\ell b}$ between data and estimated signal & background

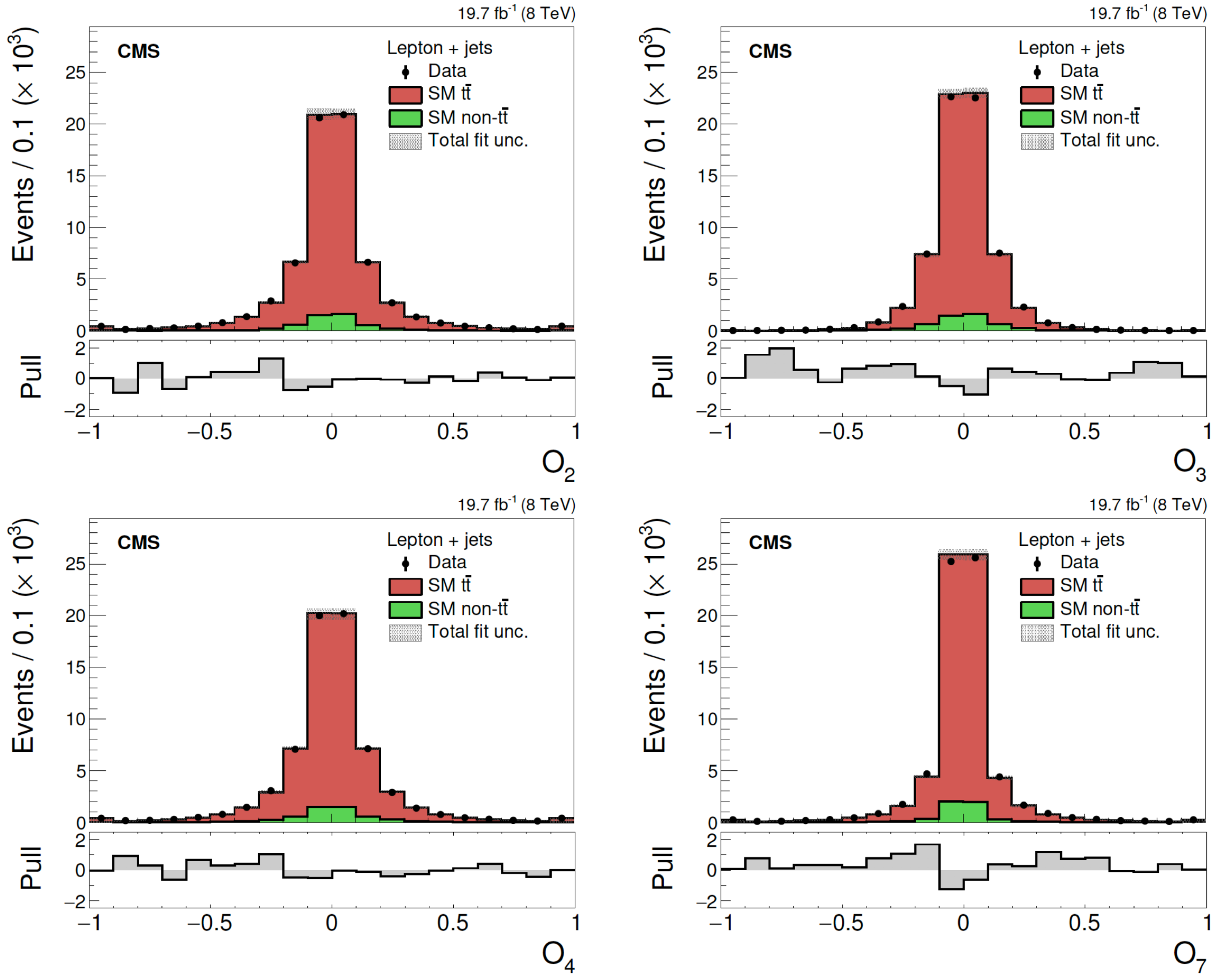


	e + jets	μ + jets
Data	31 129	36 467
Fitted events	31 280 ± 170 ± 40	36 510 ± 190 ± 50
Fitted $t\bar{t}$ fraction (%)	92.5 ± 0.5 ± 2.3	92.4 ± 0.6 ± 2.8

Table 2. The observed and fitted number of events in the electron and muon channels as well as the fitted $t\bar{t}$ fraction (purity) in percent. While the fit is performed over the full mass range, the fitted and observed results are for $M_{\ell b} < 200\,\text{GeV}$. The first uncertainty is statistical and the second systematic.

CP violation in top sector: CMS (4)

- Distributions of the four CPV observables are determined from the combined electron and muon channels from data (points) and simulated signal and background (filled histograms).
- Each observable is given in units of $\boldsymbol{m_{top}}^{3}$



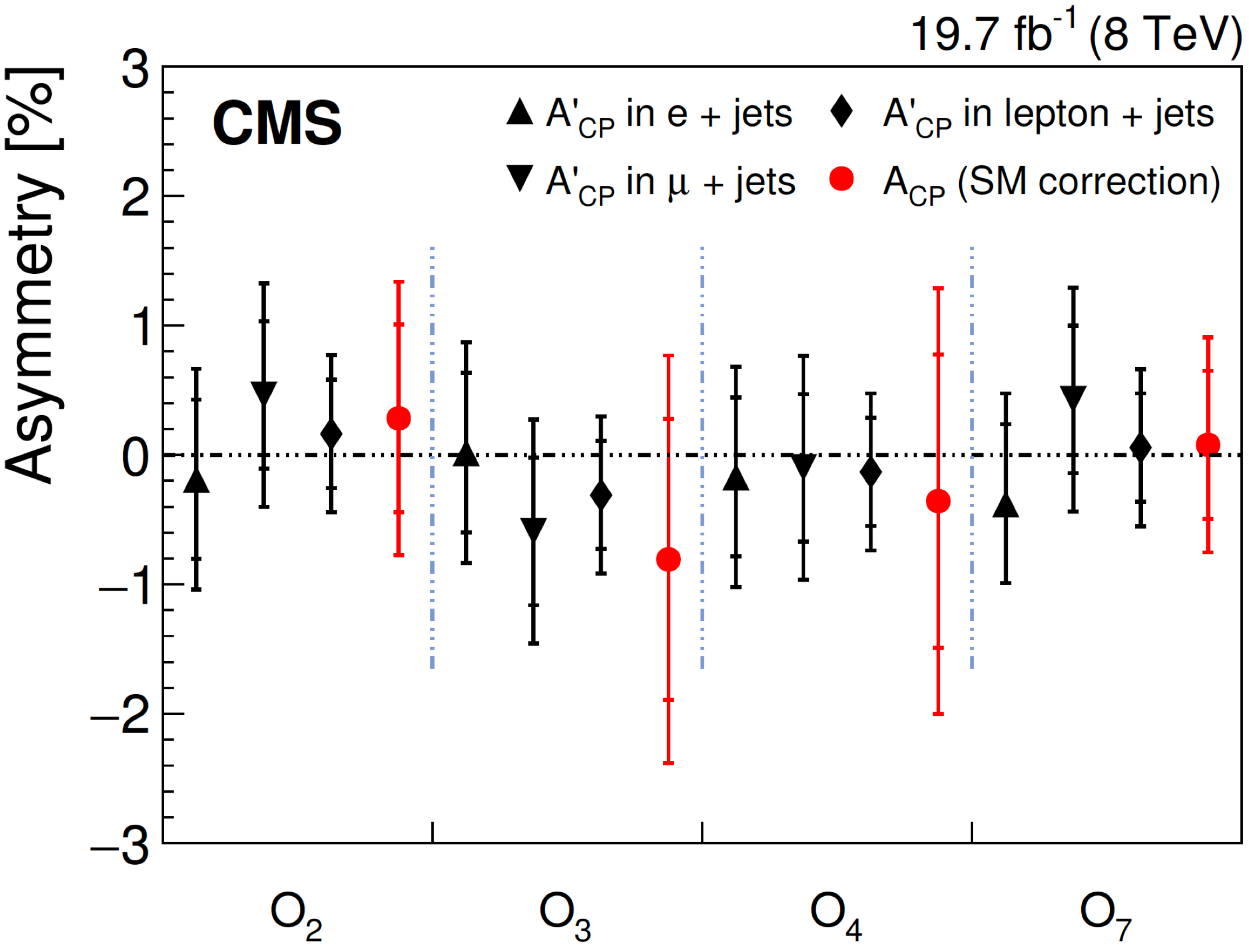
CP violation in top sector: CMS (5)

	A'_{CP} (%)			A_{CP} (%)
	e + jets	μ + jets	ℓ + jets	ℓ + jets
O_2	$-0.19 \pm 0.61 \pm 0.59$	$+0.46 \pm 0.57 \pm 0.65$	$+0.16 \pm 0.42 \pm 0.44$	$+0.3 \pm 1.1$
O_3	$+0.02 \pm 0.61 \pm 0.59$	$-0.59 \pm 0.57 \pm 0.65$	$-0.31 \pm 0.42 \pm 0.44$	-0.8 ± 1.6
O_4	$-0.17 \pm 0.61 \pm 0.59$	$-0.10 \pm 0.57 \pm 0.65$	$-0.13 \pm 0.42 \pm 0.44$	-0.4 ± 1.7
O_7	$-0.38 \pm 0.61 \pm 0.59$	$+0.43 \pm 0.57 \pm 0.65$	$+0.06 \pm 0.42 \pm 0.44$	$+0.1 \pm 0.8$

Table 4. The uncorrected (corrected) CP asymmetry A'_{CP} (A_{CP}), measured in percent, for each of the four CPV observables. Results for A'_{CP} are given for the electron and muon channels separately and for their combination. For the A'_{CP} results, the first uncertainty is statistical and the second systematic. The A_{CP} values assume the dilution factors found from the SM simulation. The uncertainties in the A_{CP} results are the combined statistical and systematic terms added in quadrature.

CP violation in top sector: CMS (6)

- Asymmetries calculated for T-odd observables
- A_{CP} (A'_{CP}) = (un)corrected for detector effects
- **No evidence of CPV effects in top pair events is observed**
- Measured A_{CP} values are consistent with SM
- Published in: [JHEP03(2017)101]



Measurement of CP asymmetries in b-hadron decays using top quark events at 8 TeV with ATLAS

CP violation in top sector: ATLAS (1)

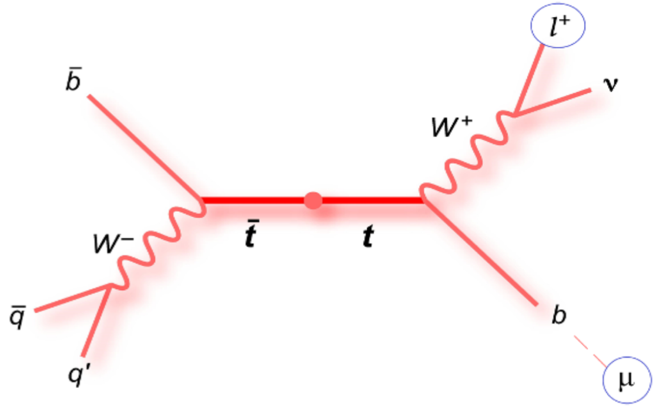
- The CPV is expected in b-quark decays
- Same and opposite sign charge asymmetries are measured in lepton+jet top pair events
- Using the above charge asymmetries, four CP asymmetries (one mixing and three direct) are deduced
- Measurement of CP asymmetries in heavy-flavour mixing and decay from top-quark decay products at LHC cane be done as LHC is a top factory
- The unique aspect presented in this analysis is the method by which the charge of the b-quark is determined, both at production and at decay.
  - If W-boson decays leptonically, **the charge of the lepton determines the charge of the produced b-quark**
  - The b-quark hadronises and when the resulting b-hadron decays semi-leptonically, **the charge of the soft lepton determines the b-quark charge at decay**

CP violation in top sector: ATLAS (2)

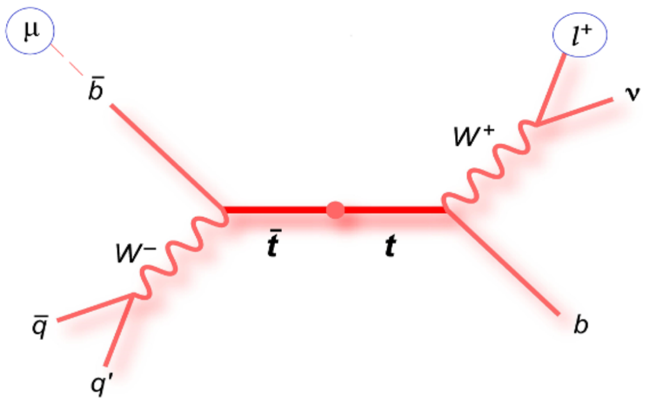
- Strategy:
  - select lepton+jets top pair events, at least 4 jets, at least 1 b-tag
    - one jet being b-tagged by standard algorithm and by presence of a soft muon
  - **use the lepton (from W)**
    - the charge of this lepton gives the b-quark charge at production
  - **use of soft muon b-tagging (SMT muon)**
    - the charge of the muon in the b-jet probes the decay chain
  - reconstruction of events using KLFitter, Kinematic Likelihood fitter
  - unfold data to a fiducial volume
  - measure charge asymmetries
  - Using measured charge asymmetries deduce CPV ones
- **First measurement of B properties in top quark decays**

CP violation in top sector: ATLAS (3)

- Same- or opposite-sign muons arise if SMT muon comes from same top or different top



(a) Same-top SMT muon



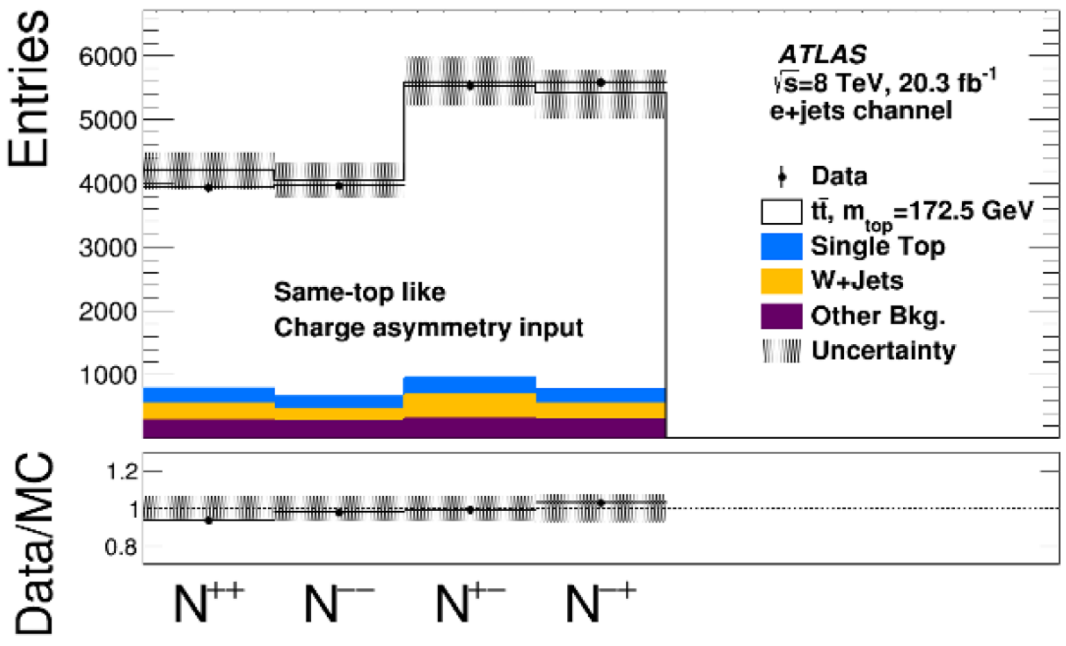
(b) Different-top SMT muon

- Observable same- and opposite-sign charge asymmetries are formed as probabilities of b/anti-b quark decay either to positively or negatively charged SMT muon

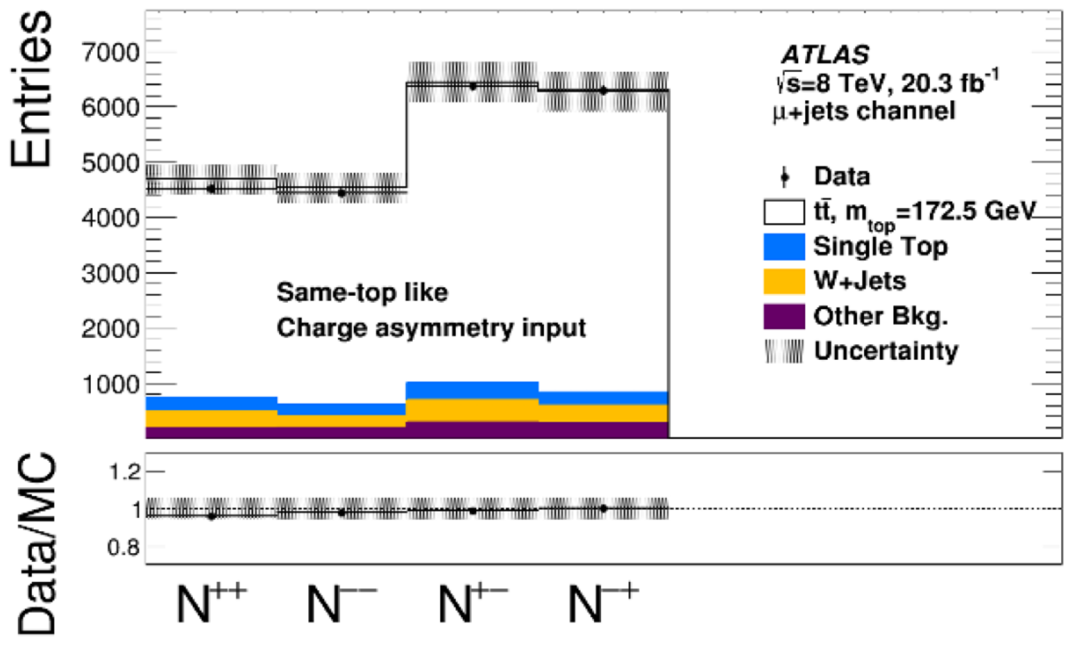
$$A^{\text{SS}} = \frac{P\left(b \to \ell^+\right) - P\left(\bar{b} \to \ell^-\right)}{P\left(b \to \ell^+\right) + P\left(\bar{b} \to \ell^-\right)}, \qquad A^{\text{OS}} = \frac{P\left(b \to \ell^-\right) - P\left(\bar{b} \to \ell^+\right)}{P\left(b \to \ell^-\right) + P\left(\bar{b} \to \ell^+\right)},$$

$$A^{\text{SS}} = \frac{\left(\frac{N^{++}}{N^+} - \frac{N^{--}}{N^-}\right)}{\left(\frac{N^{++}}{N^+} + \frac{N^{--}}{N^-}\right)}, \qquad A^{\text{OS}} = \frac{\left(\frac{N^{+-}}{N^+} - \frac{N^{-+}}{N^-}\right)}{\left(\frac{N^{+-}}{N^+} + \frac{N^{-+}}{N^-}\right)}.$$

CP violation in top sector: ATLAS (4)



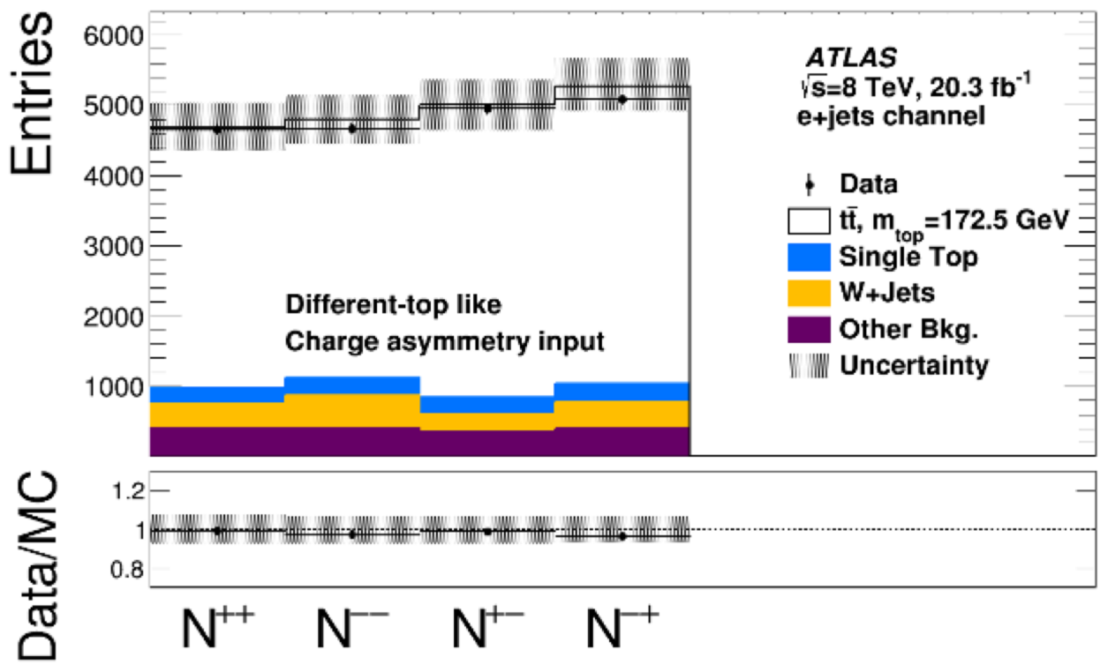
(a) e+jets channel.



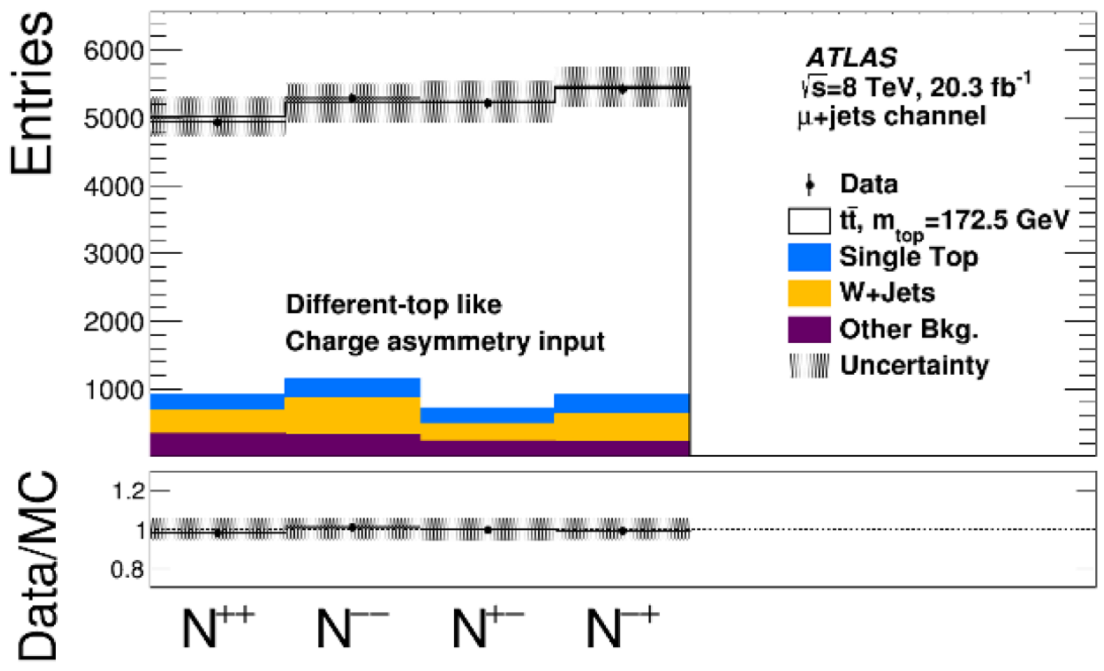
(b) μ+jets channel.

Figure 3. Same-top-like charge-pairings distributions. The hashed area represents all experimental systematic uncertainties as well as the b-hadron production and hadron-to-muon branching ratio uncertainties. The lower panel of the distributions show the ratio of the data divided by the simulation. (a) shows the e+jets channel while (b) shows the μ+jets channel.

CP violation in top sector: ATLAS (5)



(a) e+jets channel.



(b) μ+jets channel.

Figure 4. Different-top-like charge-pairings distributions. The hashed area represents all experimental systematic uncertainties as well as the b-hadron production and hadron-to-muon branching ratio uncertainties. The lower panel of the distributions show the ratio of the data divided by the simulation. (a) shows the e+jets channel while (b) shows the μ+jets channel.

CP violation in top sector: ATLAS (6)

- The charge asymmetries are related to CP asymmetries

$$A^{\mathrm{ss}} = r_b A^{b\ell}_{\mathrm{mix}} + r_c \left(A^{bc}_{\mathrm{dir}} - A^{c\ell}_{\mathrm{dir}} \right) + r_{c\bar{c}} \left(A^{bc}_{\mathrm{mix}} - A^{c\ell}_{\mathrm{dir}} \right)$$

$$A^{\mathrm{os}} = \tilde{r}_b A^{b\ell}_{\mathrm{dir}} + \tilde{r}_c \left(A^{bc}_{\mathrm{mix}} + A^{c\ell}_{\mathrm{dir}} \right) + \tilde{r}_{c\bar{c}} A^{c\ell}_{\mathrm{dir}}$$

- The CP asymmetries are related to heavy-flavour mixing and direct CPV b- and c-decays

$$A^{b\ell}_{\mathrm{mix}} = \frac{\Gamma\left(b \to \bar{b} \to \ell^+ X\right) - \Gamma\left(\bar{b} \to b \to \ell^- X\right)}{\Gamma\left(b \to \bar{b} \to \ell^+ X\right) + \Gamma\left(\bar{b} \to b \to \ell^- X\right)},$$

$$A^{bc}_{\mathrm{mix}} = \frac{\Gamma\left(b \to \bar{b} \to \bar{c} X\right) - \Gamma\left(\bar{b} \to b \to c X\right)}{\Gamma\left(b \to \bar{b} \to \bar{c} X\right) + \Gamma\left(\bar{b} \to b \to c X\right)},$$

$$A^{b\ell}_{\mathrm{dir}} = \frac{\Gamma\left(b \to \ell^- X\right) - \Gamma\left(\bar{b} \to \ell^+ X\right)}{\Gamma\left(b \to \ell^- X\right) + \Gamma\left(\bar{b} \to \ell^+ X\right)},$$

$$A^{c\ell}_{\mathrm{dir}} = \frac{\Gamma\left(\bar{c} \to \ell^- X_L\right) - \Gamma\left(c \to \ell^+ X_L\right)}{\Gamma\left(\bar{c} \to \ell^- X_L\right) + \Gamma\left(c \to \ell^+ X_L\right)},$$

$$A^{bc}_{\mathrm{dir}} = \frac{\Gamma\left(b \to c X_L\right) - \Gamma\left(\bar{b} \to \bar{c} X_L\right)}{\Gamma\left(b \to c X_L\right) + \Gamma\left(\bar{b} \to \bar{c} X_L\right)},$$

CP violation in top sector: ATLAS (7)

- The predictions of the MC simulation are found to be in good agreement with the data.

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

- **Both the data and the MC simulation are compatible with zero and with the SM prediction.**
- Published in JHEP02(2017)071

Search for CP violation in the single top events in pp collision at 7 TeV with ATLAS ($4.66\ fb^{-1}$)

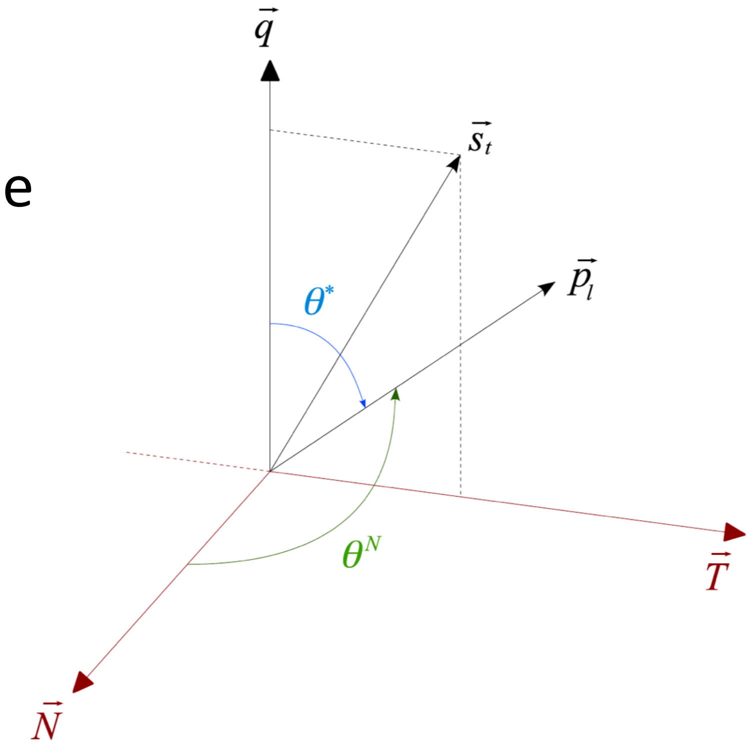
CP violation in single top sector: ATLAS (1)

$$\mathcal{L}_{Wtb} = -\frac{g}{\sqrt{2}}\bar{b}\gamma^{\mu}\left(V_L P_L + V_R P_R\right) t W_{\mu}^{-} - \frac{g}{\sqrt{2}}\bar{b}\frac{i\sigma^{\mu\nu}q_{\nu}}{m_W}\left(g_L P_L + g_R P_R\right) t W_{\mu}^{-} + \text{h.c.}$$

- We want to probe the coupling of the top quark in the Wtb vertex by measuring the **asymmetry in the angular distribution** of the charged lepton from the W decay in the single top quark t-channel.

$$A_z \equiv \frac{N_{\text{evt}}(\cos\theta > z) - N_{\text{evt}}(\cos\theta < z)}{N_{\text{evt}}(\cos\theta > z) + N_{\text{evt}}(\cos\theta < z)}$$

- For z=0 the asymmetry is called forward-backward (A_{FB}).



Top quark expected to be produced highly polarized along the direction of the spectator quark (s_t) → two new reference directions

$$\vec{N} = \vec{s}_t \times \vec{q},$$
$$\vec{T} = \vec{q} \times \vec{N}$$

Figure 2: Definition of the two directions $\vec{N}$ and $\vec{T}$ given the direction of polarisation of the top quark, $\vec{s}_t$, and the momentum of the W boson, $\vec{q}$ in the helicity basis. The angles which are shown are defined as the angles between their reference directions and the momentum direction of the charged lepton, $\vec{p}_l$.

CP violation in single top sector: ATLAS (2)

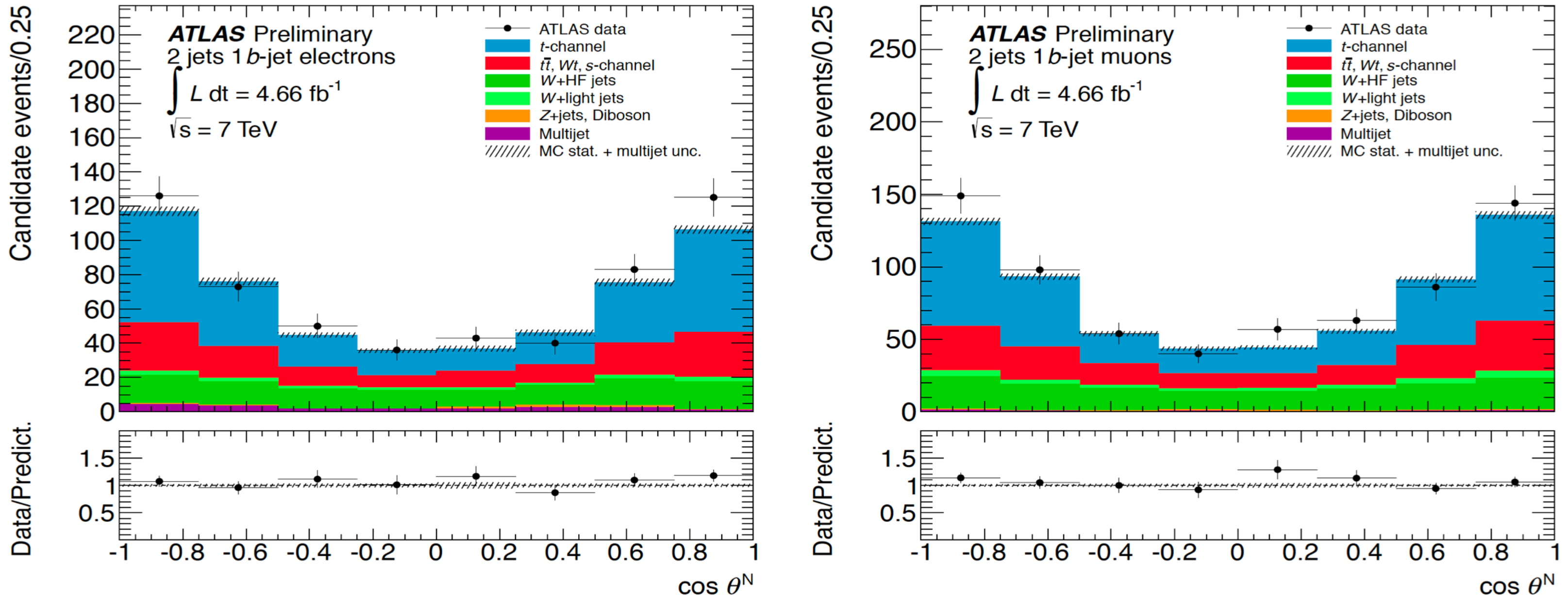
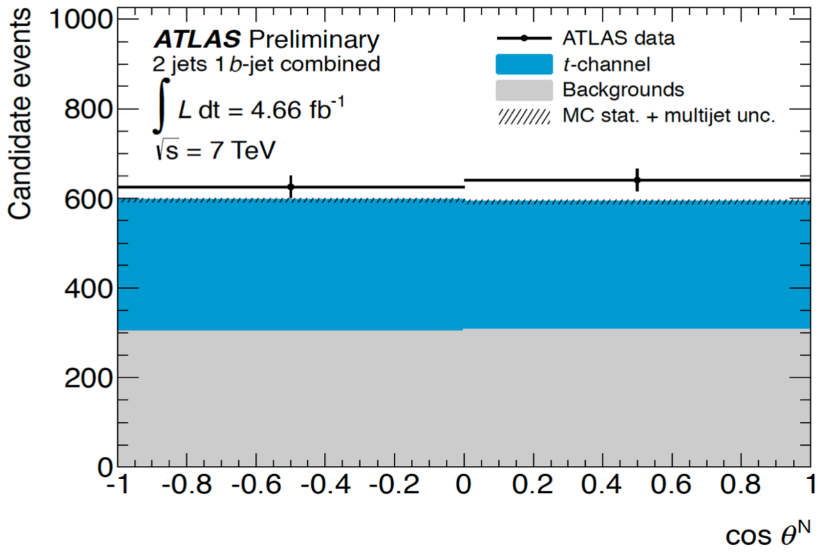


Figure 5: Reconstructed $\cos\theta^N$ angular distribution obtained at selection level for electron (left) and muon (right) channels. ATLAS data, simulated signal and different background contributions are shown. The uncertainties shown on the prediction take into account MC statistics and the 50% systematic uncertainty on the normalization of the multijet background.

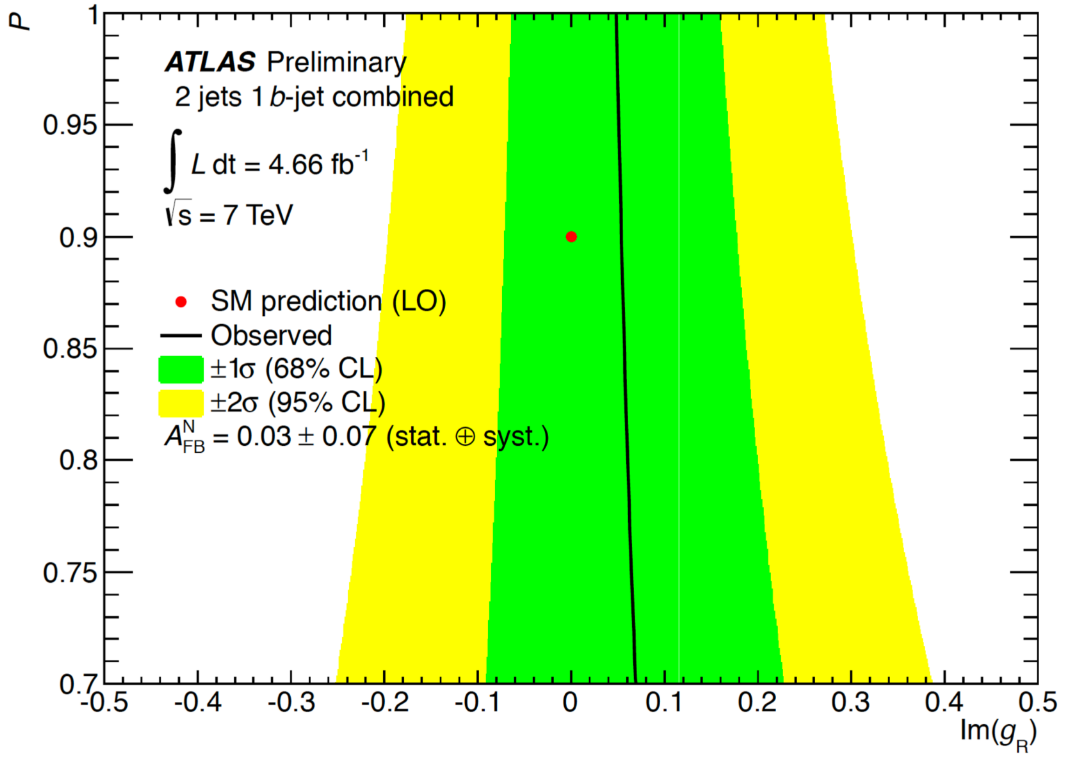


The combined results is shown on the right.

- The measured A_{FB}^{N} has to be unfolded for the comparison with the theoretical prediction. The efficiency of the signal selection is not flat in the bin of the angular distribution → this leads to migration of events between bins → migration matrix computed on MC to unfold the final distribution.

CP violation in single top sector: ATLAS (3)

	A_{FB}^{N}
Data, before background subtraction	0.012 ± 0.028 (stat.)
Data, after background subtraction	0.018 ± 0.055 (stat.)
Data unfolded	0.031 ± 0.065 (stat.) $^{+0.029}_{-0.031}$ (syst.)



- Using the unfolded value of the A_{FB}^{N} and the relation $A_{FB}^{N} \sim 0.64\, I(g_R)$ it is possible to constrain the imaginary part of the g_R coupling.
- The first experimental limits on I(gR):
  - with P*= 0.9, I(gR) is determined to be [−0.20, 0.30] at 95% confidence level.

(*) polarization of the top quark

ATLAS-CONF-2013-032

Summary

- First CPV measurements are done at CMS using top pair events in lepton+jets final state **at 8 TeV**
  - T-odd triple product correlation observables are measured
  - No evidence of CPV is observed and CP asymmetry parameter values are consistent with SM
- First measurement of B properties in top quark decays in muon+jet final state is done at ATLAS **at 8 TeV**
  - Same- and opposite sign charge asymmetries are used to deduce CP asymmetries
  - CP asymmetries in both the data and the MC simulation are compatible with zero and with the SM prediction.
- A measurement of a CP-violating forward-backward asymmetry A_{FB}^{N} in single-top quark decays has been presented.
  - The measurement is consistent with CP invariance in top quark decays, $A_{FB}^{N} = 0$
  - With P*= 0.9, first experimental limit on Im(gR) is determined to be [−0.20, 0.30] at 95% confidence level
- **Looking forward for updated results on CPV in top sector from LHC at 13 TeV and with more data!**

Thanks!

Backup

- **The way to distinguish b and anti-b quark in lepton+jets production.**

  Step 1

  — The objects after event selections

  * Isolated lepton == 1
  * N(selected jets) >= 4
  * b-tagged jets == 2

  Step 2.

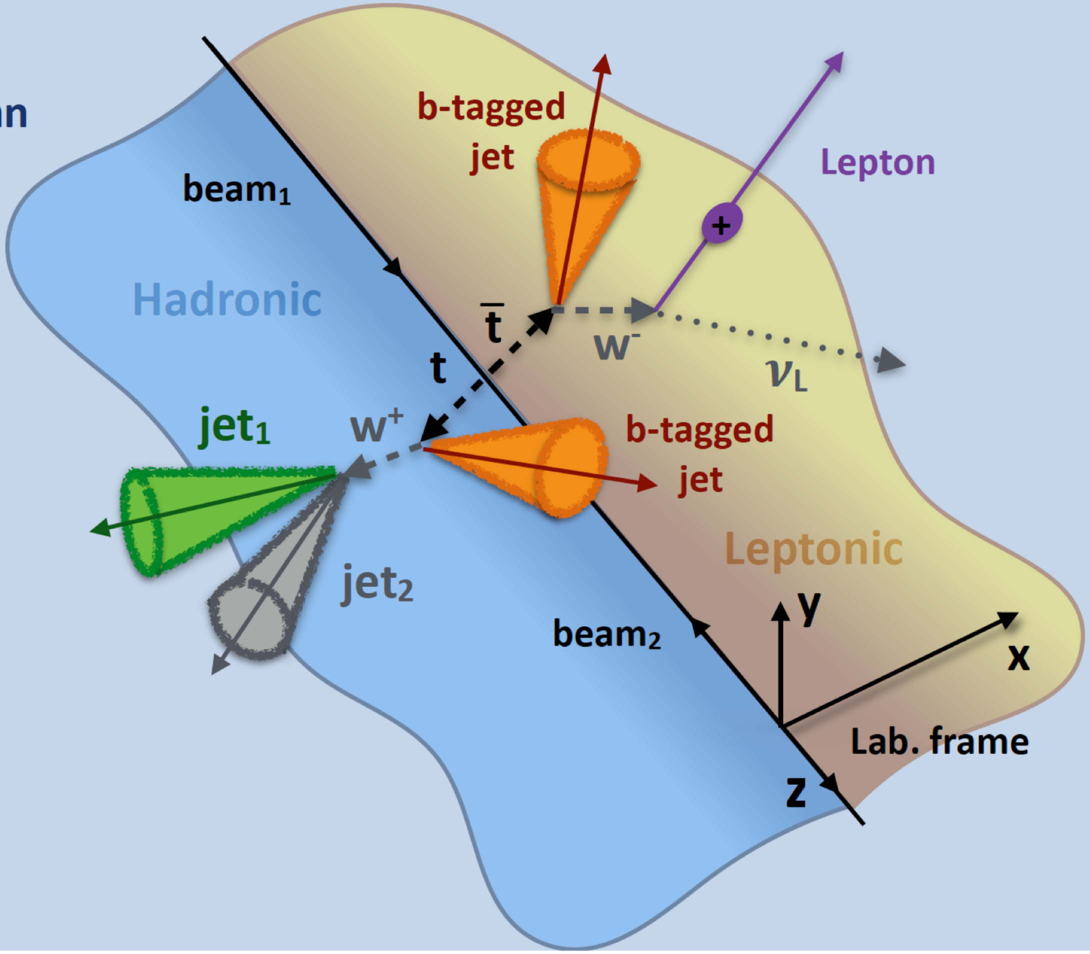
  — Look for b-jet and 2 non-b jets which can compose top and W in hadronic side.

  * X^2 sorting method

  Step 3.

  — Assign the flavor for 2 b-tagged jet

  * After step 2, the rest b-tagged jet will be considered from leptonic side.
  * The sign of b-tagged jet is assigned by isolated lepton's charge.



$$P\left(b \to \ell^+\right) = \frac{N\left(b \to \ell^+\right)}{N\left(b \to \ell^-\right) + N\left(b \to \ell^+\right)} = \frac{N^{++}}{N^{+-} + N^{++}} = \frac{N^{++}}{N^+}, \tag{1.7}$$

$$P\left(\bar{b} \to \ell^-\right) = \frac{N\left(\bar{b} \to \ell^-\right)}{N\left(\bar{b} \to \ell^-\right) + N\left(\bar{b} \to \ell^+\right)} = \frac{N^{--}}{N^{--} + N^{-+}} = \frac{N^{--}}{N^-}, \tag{1.8}$$

$$P\left(b \to \ell^-\right) = \frac{N\left(b \to \ell^-\right)}{N\left(b \to \ell^-\right) + N\left(b \to \ell^+\right)} = \frac{N^{+-}}{N^{+-} + N^{++}} = \frac{N^{+-}}{N^+}, \tag{1.9}$$

$$P\left(\bar{b} \to \ell^+\right) = \frac{N\left(\bar{b} \to \ell^+\right)}{N\left(\bar{b} \to \ell^-\right) + N\left(\bar{b} \to \ell^+\right)} = \frac{N^{-+}}{N^{--} + N^{-+}} = \frac{N^{-+}}{N^-}, \tag{1.10}$$

where $N^+ \equiv N^{++} + N^{+-}$ and $N^- \equiv N^{-+} + N^{--}$ represent the total number of positively and negatively charged W-boson leptons respectively. Observable same- and opposite-sign