

# Measurements of the top quark properties at production with CMS

**Mykola Savitskyi (DESY)**

*on behalf of CMS collaboration*

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# Introduction

- Some **top quark properties** are predicted by the SM, some are not (e.g. mass,  $V_{tq}$ )
  - precision measurements can reveal signs of new physics
  - unique opportunity to measure properties of "bare" quark
- **In this talk:**
  - latest measurements of top quark properties in  $t\bar{t}$  production with **CMS** detector
  - study of dilepton and lepton+jets final states

spin correlation &  
polarisation

charge  
asymmetry

CP violation

- Also see talks for other properties:
  - by J. E. Palencia Cortezon: [CMS Measurements of the top quark mass and width](#)
  - by J. Andrea: [Measurement of single top quark production with CMS](#)
  - by A. Castro: [Measurements of the top quark properties at decay with CMS](#)

# Spin correlations and polarization

- In SM, top quarks from pair production are almost unpolarized, but have correlated spins
- Top quark lifetime ( $\sim 10^{-25}$ s) is much shorter than the spin decorrelation time scale ( $\sim 10^{-21}$ s)
  - angular distributions of top quark decay products provide access to spin of top quark
- Study **spin correlation strength  $A$**  and **coefficient  $f_{SM}$**  shows its relation to SM correlation

$$A = \frac{(N_{\uparrow\uparrow} + N_{\downarrow\downarrow}) - (N_{\uparrow\downarrow} + N_{\downarrow\uparrow})}{(N_{\uparrow\uparrow} + N_{\downarrow\downarrow}) + (N_{\uparrow\downarrow} + N_{\downarrow\uparrow})}$$

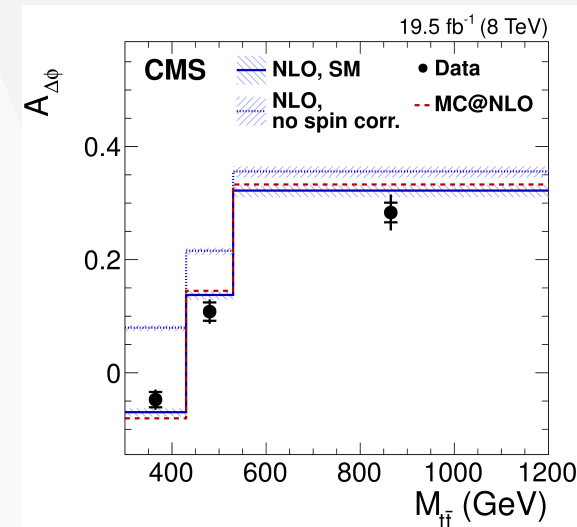
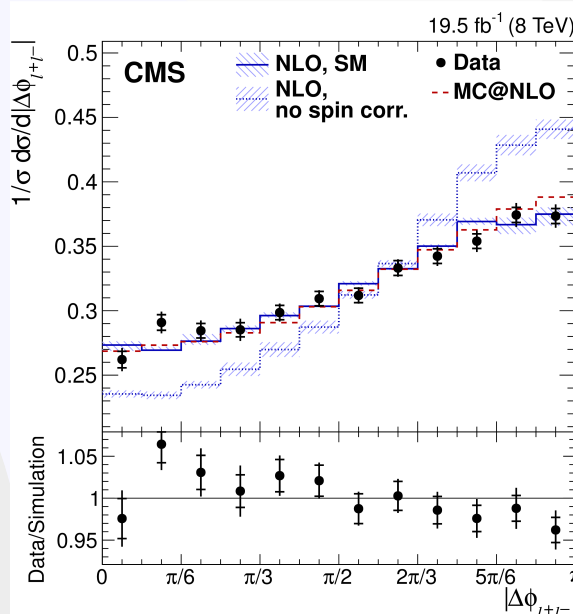
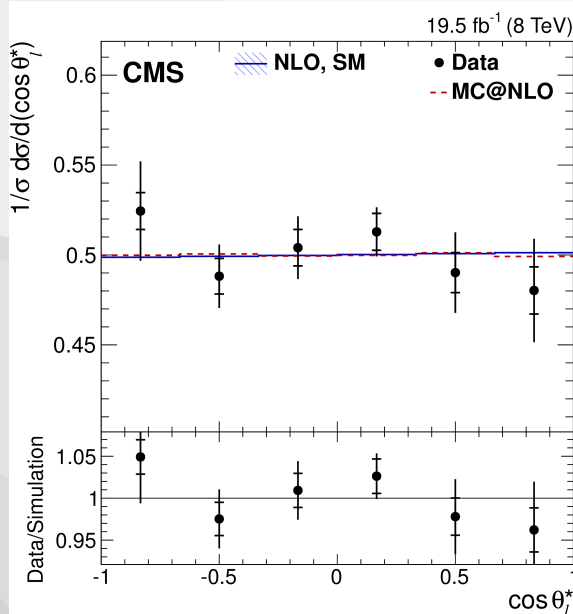
$$f_{SM} = \frac{N_{SM}^{t\bar{t}}}{N_{SM}^{t\bar{t}} + N_{uncorrelated}^{t\bar{t}}}$$

# Spin correlations & polarization in dileptons

- **Probing spin density matrix and extraction of  $f_{SM}$**
- Using asymmetries in angular observables of two leptons
  - $\Delta\varphi(\ell^+\ell^-)$ : difference in azimuthal angles in the laboratory frame
  - $\cos\theta^*(\ell^\pm)$  and  $\cos\theta^*(\ell^+)\cdot\cos\theta^*(\ell^-)$ : dependent from helicity angles  $\theta^*(\ell)$
  - $\cos\varphi$ : angle between leptons measured in rest frames of parental top quarks
- Inclusive and differential measurements of asymmetries
  - in bins of  $m_{\ell\ell}$ ,  $|y_{\ell\ell}|$ ,  $p_T^{\ell\ell}$
- Setting limits on **chromo-magnetic** and **chromo-electric** dipole moments

PRD 93, 052007 (2016)

available as RIVET routine in CMS\_2016\_I1413748

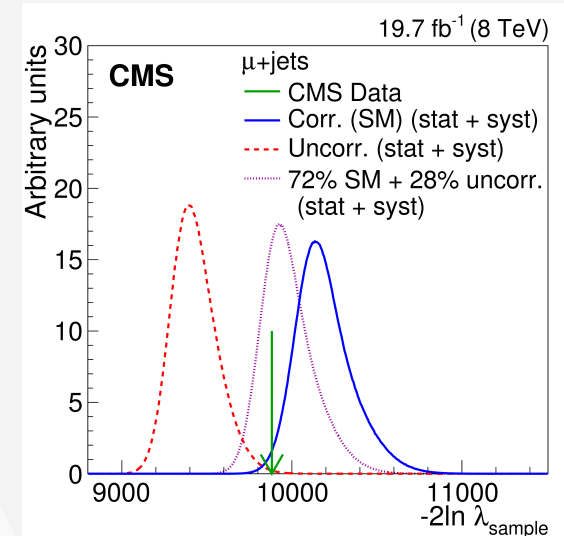


# Spin correlations in muon+jets

- Consistency check of spin correlation strength in  $t\bar{t}$  with the SM

PLB 758 (2016) 321

- Test of two hypothesis behind  $t\bar{t}$  production in data
  - spin correlation predicted by SM
  - no spin correlation
  - event probabilities  $P$  estimated via matrix element method
  - separation power given by sample likelihood ratio  $\lambda$

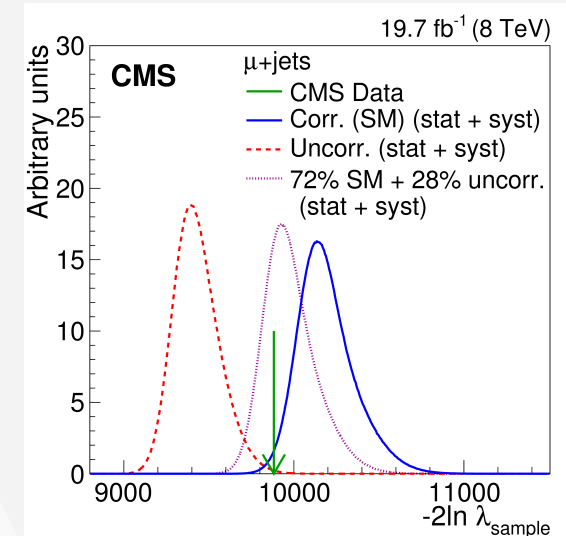


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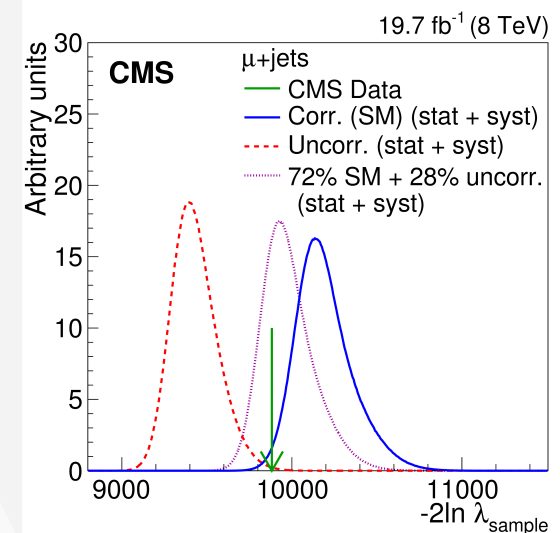


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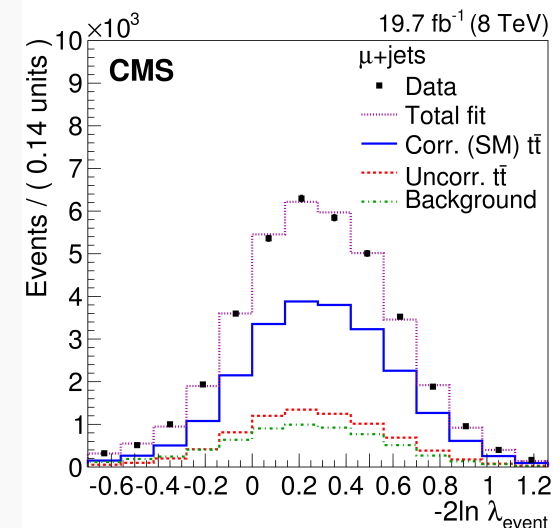
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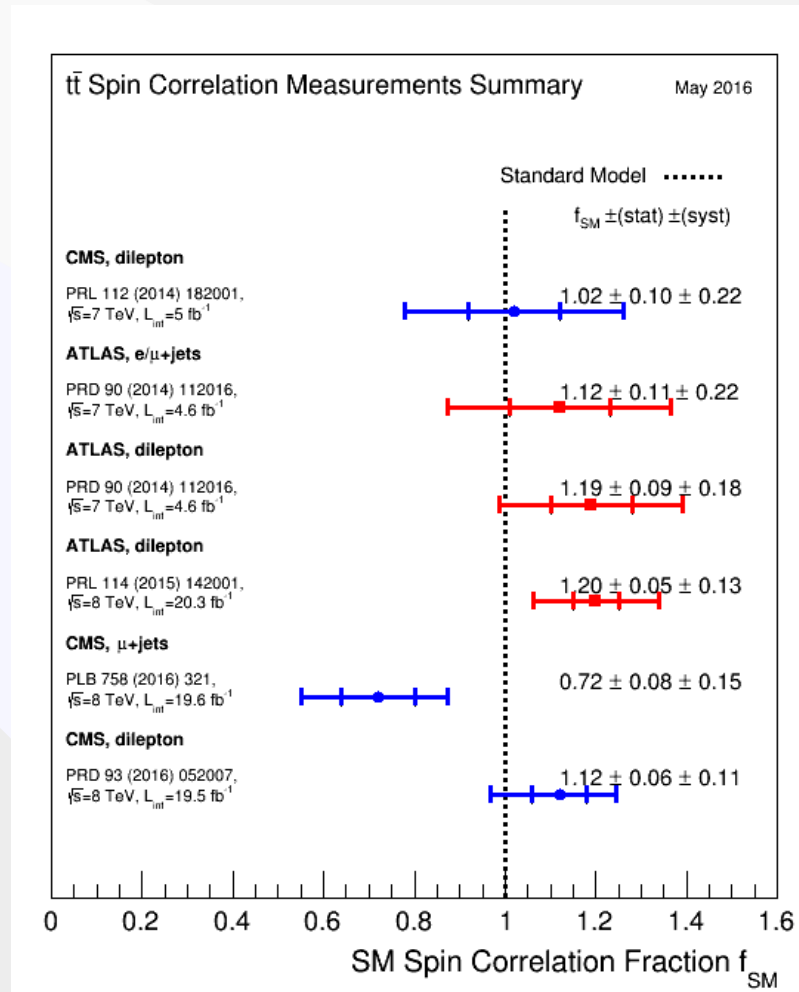
- Template fit for **extraction of  $f_{SM}$**  and background fraction

- using distribution of event likelihood ratio  $\lambda$
- SM contribution:  $f_{SM} = 0.72 \pm 0.08 (stat.)_{-0.13}^{+0.15} (syst.)$
- spin correlation strength:

$$A_{hel}^{measured} = f_{SM} \cdot A_{hel}^{SM, MC} = 0.23 \pm 0.03 (stat.)_{-0.04}^{+0.05} (syst.)$$



# Spin correlations

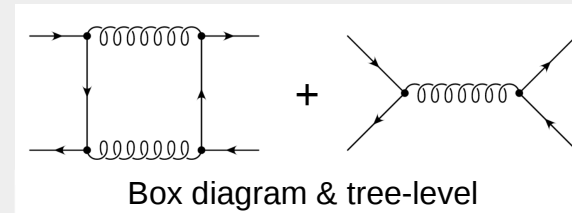
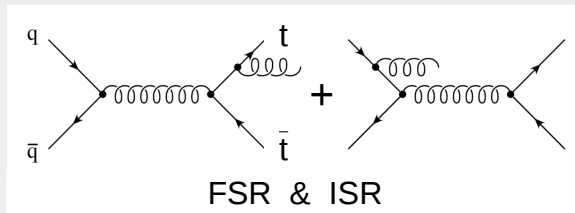


Good agreement between SM predictions and both experiments



# Charge asymmetry

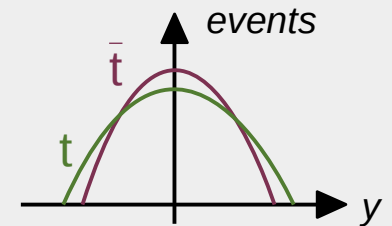
- Non-zero charge asymmetry in  $t\bar{t}$  production through  $q\bar{q}$  interaction beyond LO



Modified pictures from:  
PRL 81:49-52,1998

- At LHC, different centrality in rapidity for top quarks and anti-quarks
- Measure **charge asymmetry**  $A_C$  using observable  $\Delta|y_t| = |y_t| - |y_{\bar{t}}|$

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



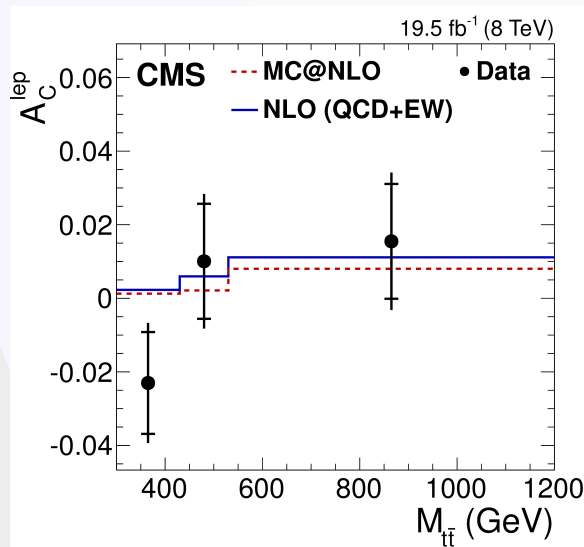
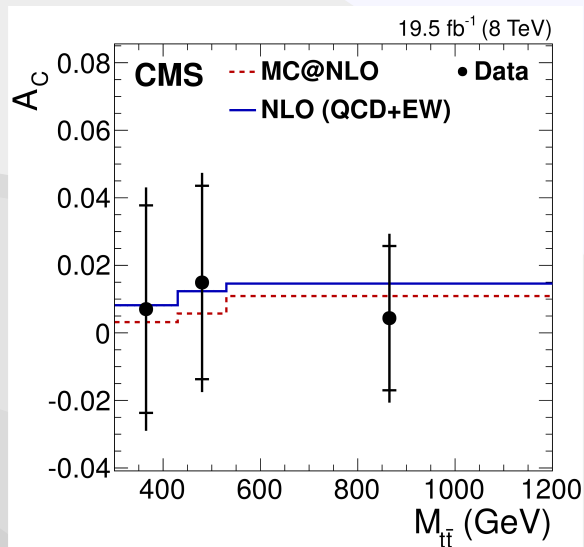
- Enhanced by BSM scenarios, e.g. axigluons,  $Z'$

# Charge asymmetry in dileptons

- **Inclusive and differential measurements of  $A_C$**
- Also measure observable  $A_C^{\text{lep}}$  using  $\Delta|\eta_\ell| = |\eta_{\ell+}| - |\eta_{\ell-}|$ 
  - better resolution and independent from top reconstruction
  - carries info about top quark polarization

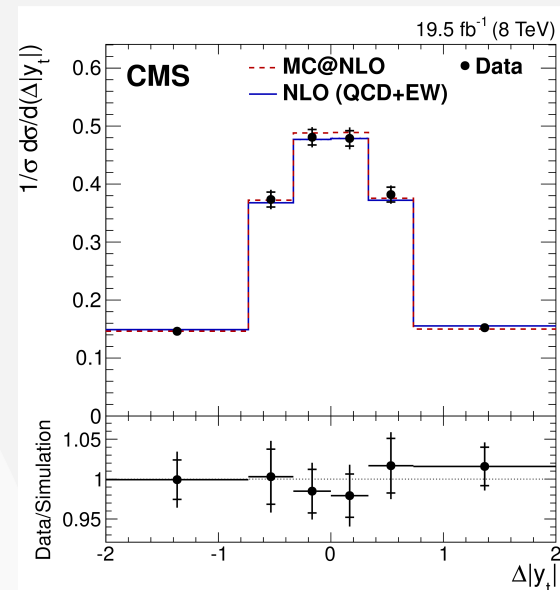
Variable	Data	MC@NLO	NLO (QCD+EW)
$A_C$	$0.011 \pm 0.011 \pm 0.007$	$0.006 \pm 0.001$	$0.0111 \pm 0.0004$
$A_C^{\text{lep}}$	$0.003 \pm 0.006 \pm 0.003$	$0.004 \pm 0.001$	$0.0064 \pm 0.0003$

- Extraction from unfolded spectrum in bins of  $m_{t\bar{t}}$ ,  $|y_{t\bar{t}}|$ ,  $p_T^{t\bar{t}}$



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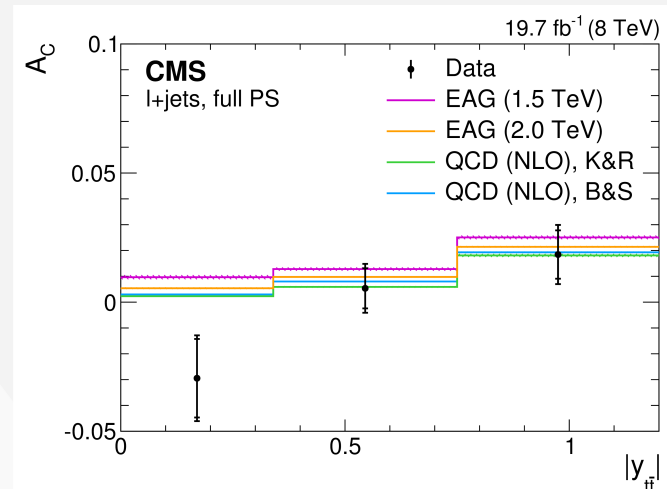
available as RIVET routine in CMS\_2016\_11430892



**All results in agreement with SM**

# Charge asymmetry in lepton+jets

- **Unfolding method** PLB 758 (2016) 321
- Inclusive and differential measurement of  $A_C$ 
  - unfolding of  $\Delta|y_t|$  back to parton level after background subtraction
  - presented in full and fiducial phase space
  - also as a function of  $m_{t\bar{t}}$ ,  $|y_{t\bar{t}}|$ ,  $p_T^{t\bar{t}}$

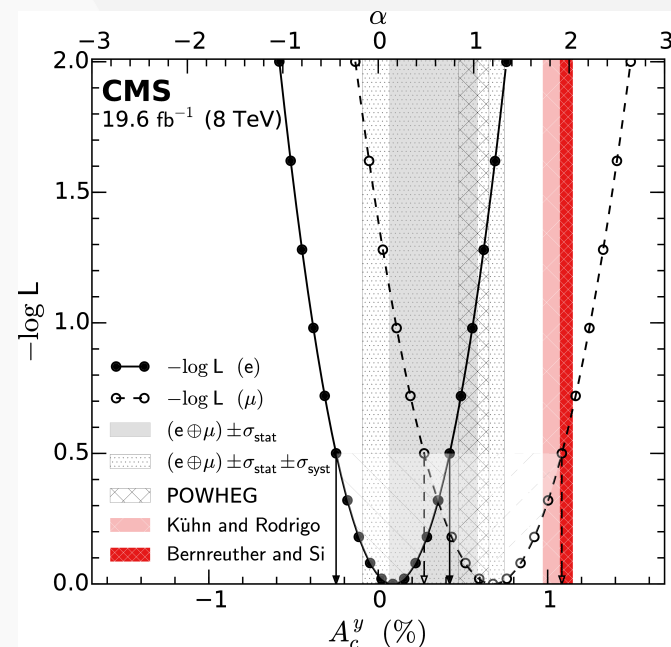
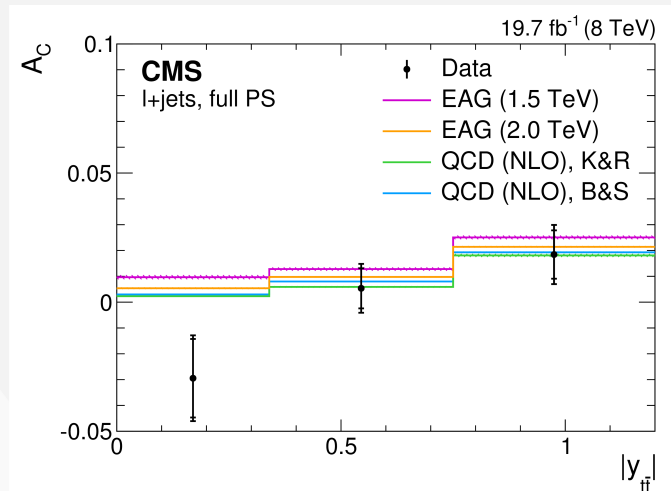


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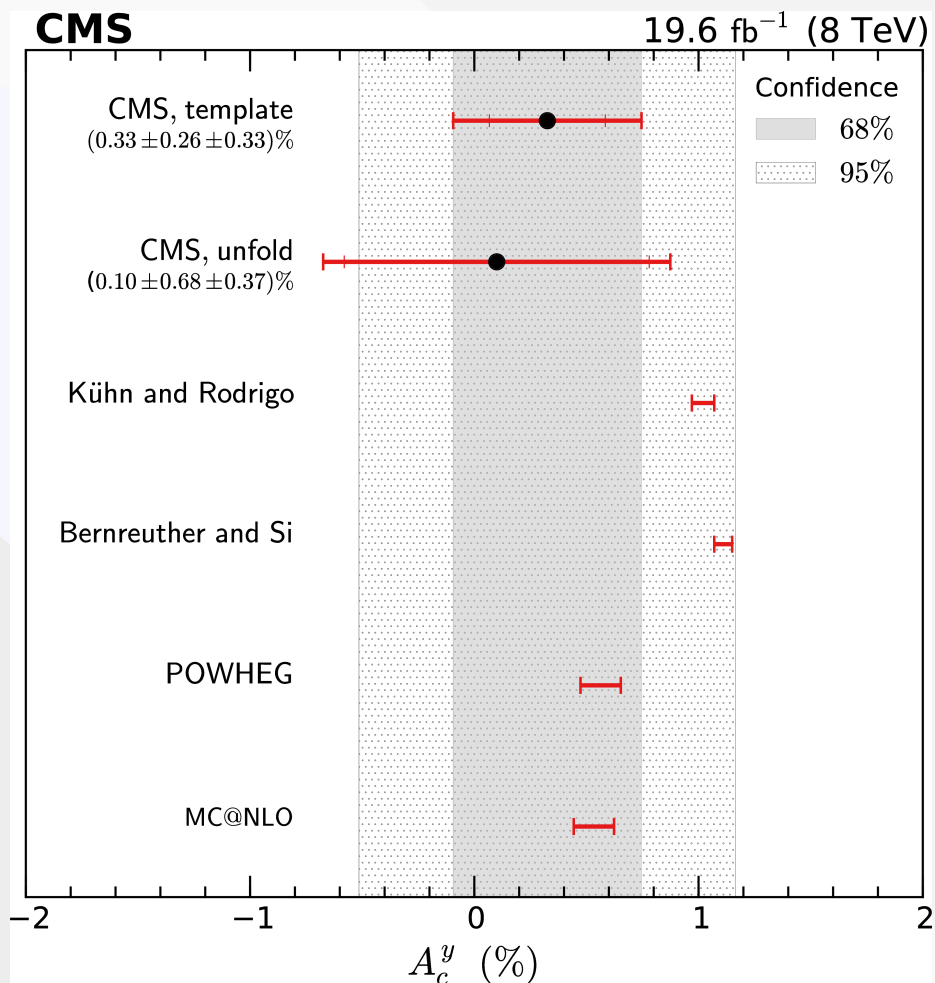
- **Template method** PRD 93, 034014 (2016)
  - Transformed rapidity observable:  $Y_{t\bar{t}} = \tanh \Delta|y_t|$
  - Extract  $A_C$  via template fit of reconstructed  $Y_{t\bar{t}}$ 
    - using (anti)symmetric  $x^{(-)+}$  components of probability density for  $Y_{t\bar{t}}$  from base model (SM)

$$X_\alpha^{data} = X^{+,rec} + \alpha \cdot X^{-,rec}$$



# Charge asymmetry in lepton+jets

Results in agreement with SM predictions



# CP violation in $t\bar{t}$ production and decay

- Very small in SM, but may be enhanced by potential new physics
- Search for effects induced by CP-violating anomalous top quark couplings
- Sizable deviations from the SM may shed light on the matter-antimatter asymmetry of the universe

# Search for CP violation in $t\bar{t}$ production and decay

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- **First measurement of CP-violating asymmetries in  $t\bar{t}$**

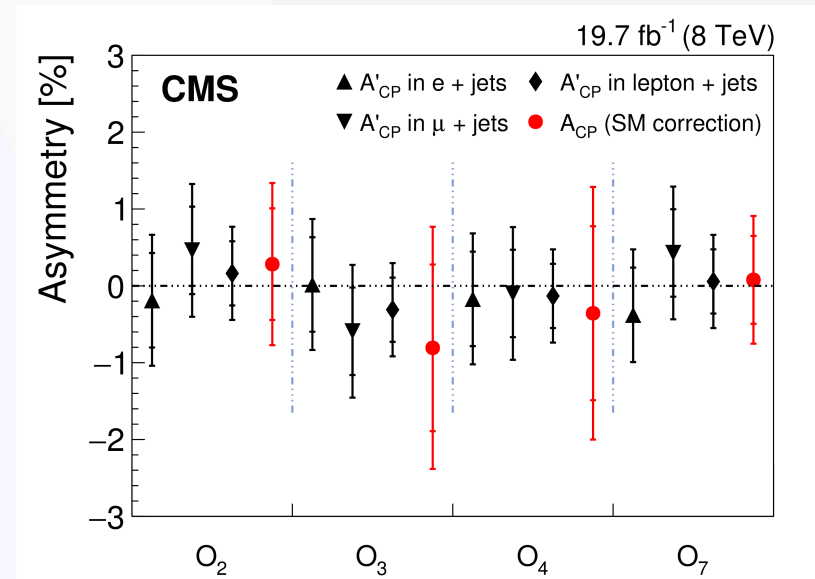
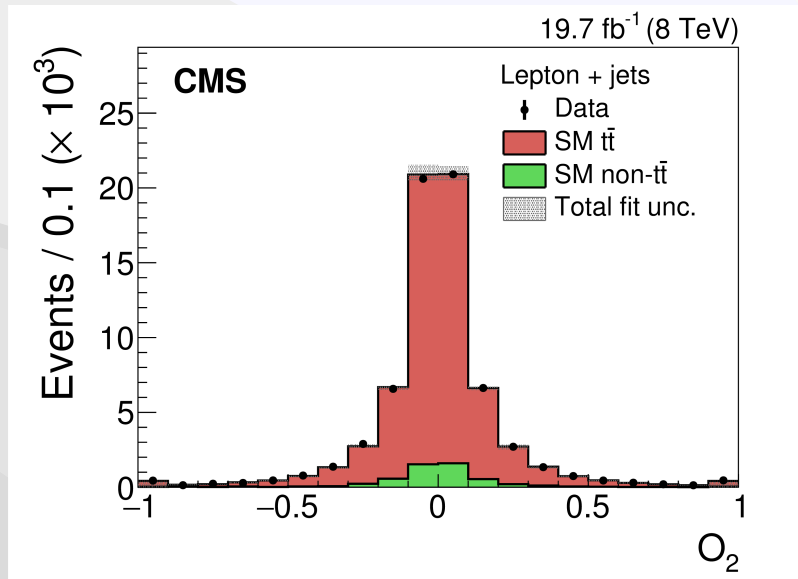
- Construct four T-odd observables  $O_i$

- use spin or momentum vectors of decay products in  $t\bar{t} \rightarrow \ell + \text{jets}$  final state

- Non-zero asymmetry as an evidence of CP violation :  $A_{CP}(O_i) = \frac{N_{events}(O_i > 0) - N_{events}(O_i < 0)}{N_{events}(O_i > 0) + N_{events}(O_i < 0)}$

- Up-to 8% CPV effects are expected in  $A_{CP}(O_i)$  depending on theory model

- **Consistent with SM, thus no observation of CP violating effects**



# Summary

- Probing nature with several measurements of top quark properties at production with CMS
  - spin correlation and polarization: unfolding and MEM methods
  - charge asymmetry: unfolding and template methods
  - CP violation
- All results are in agreement with SM and no evidence of new physics
- Next generation of new exciting results to come with study of latest 13 TeV data from LHC



# Summary

- Probing nature with several measurements of top quark properties at production with CMS
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**THANK YOU FOR YOUR ATTENTION**

See more:

<http://cms-results.web.cern.ch/cms-results/public-results/publications/TOP/>

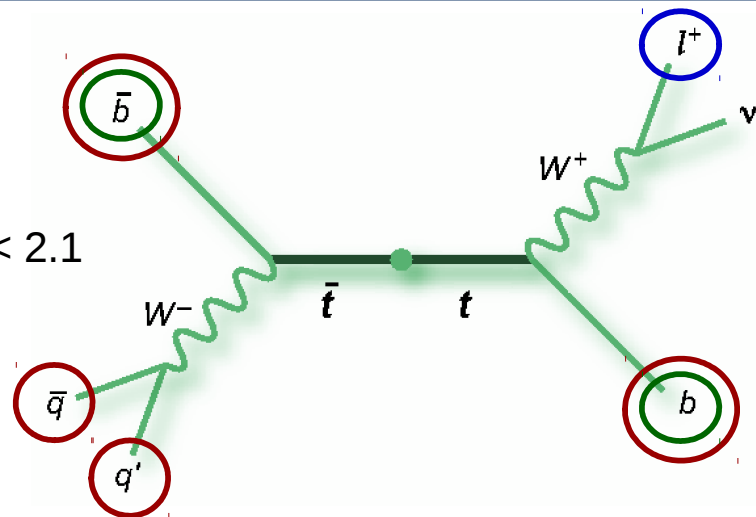


**BACKUP**

# Event selection

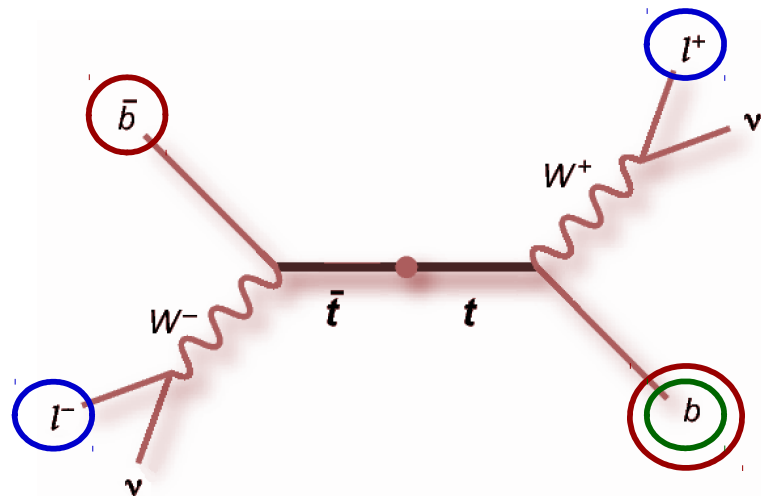
## Lepton+jets:

- Exactly 1 high- $p_T$  **isolated lepton** (e or  $\mu$ )
  - $p_T >$  around 30 GeV (analysis dependent),  $|\eta| < 2.1$
- $\geq 4$  **jets**:  $p_T > 30$  GeV,  $|\eta| < 2.4$
- $\geq 2$  **b-tagged jets**



## Dileptons:

- $\geq 2$  OS, high- $p_T$  **isolated leptons** (ee,  $\mu\mu$ ,  $\mu e$ )
  - $p_T > 20$  GeV,  $|\eta| < 2.4$
- QCD veto:  $m_{ll} > 20$  GeV
- $\geq 2$  **jets**:  $p_T > 30$  GeV,  $|\eta| < 2.4$
- $\geq 1$  **b-tagged jets**
- ee,  $\mu\mu$  channels:  $E_T^{\text{miss}} > 40$  GeV  
Z veto:  $|m_Z - m_{ll}| > 15$  GeV



In addition: kinematic reconstruction of  $t\bar{t}$  system

# Spin correlations in muon+jets

- Consistency check of spin correlation strength in  $t\bar{t}$  with the SM

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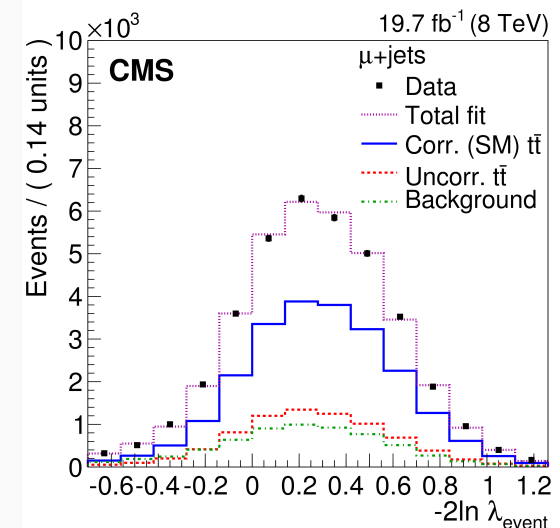
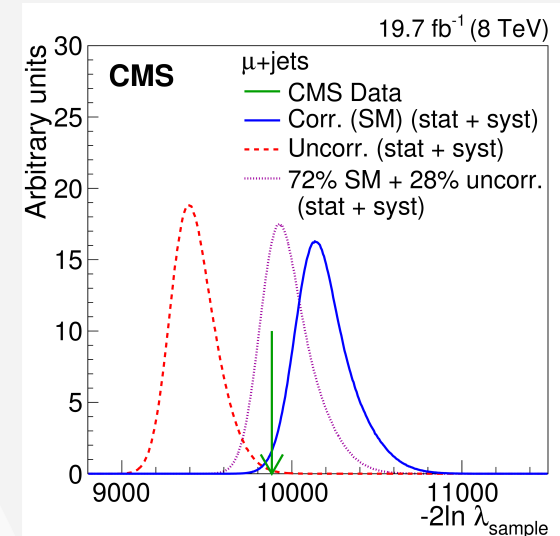
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  - spin correlation predicted by SM:** agrees within  $2.2\sigma$
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  - event probabilities  $P$  estimated via matrix element method
  - separation power given by sample likelihood ratio

$$-2 \ln \lambda_{\text{sample}} = - \sum 2 \ln \lambda_{\text{event}} \propto \frac{P_{\text{uncorrelated}}}{P_{\text{correlated}}}$$

- Template fit for **extraction of  $f_{SM}$**  and background fraction

- using distribution of event likelihood ratio
- SM contribution:  $f_{SM} = 0.72 \pm 0.08 (stat.)_{-0.13}^{+0.15} (syst.)$
- spin correlation strength:

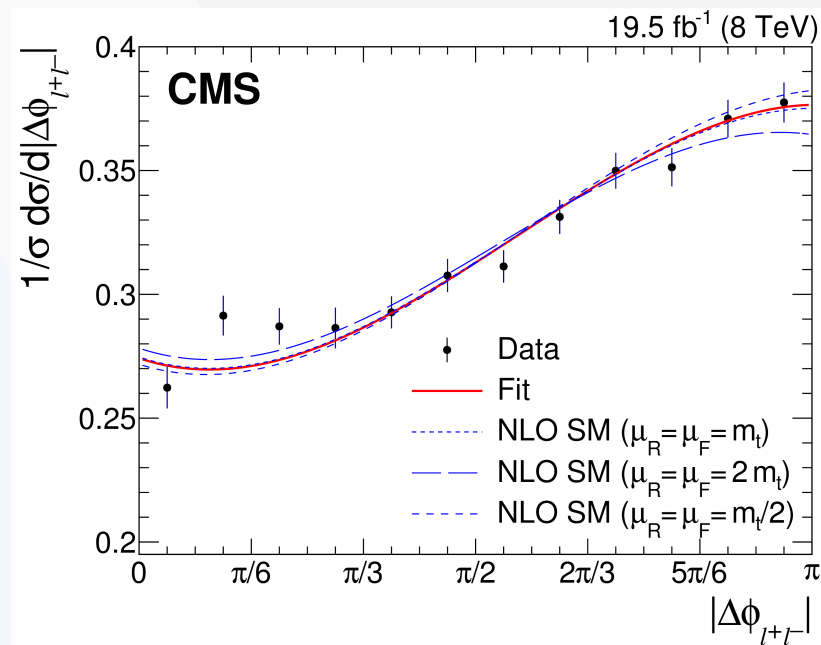
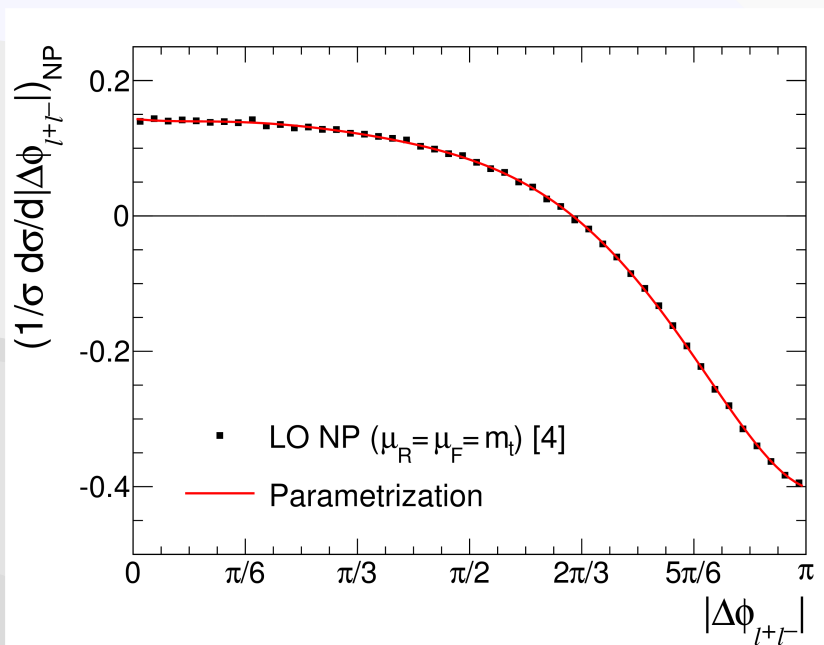
$$A_{hel}^{\text{measured}} = f_{SM} \cdot A_{hel}^{SM, MC} = 0.23 \pm 0.03 (stat.)_{-0.04}^{+0.05} (syst.)$$



# Spin correlations & polarization in dileptons

PRD 93, 052007 (2016)

- **Search for hypothetical top quark anomalous couplings**
  - setting limits on **chromo-magnetic** and **chromo-electric** dipole moments
  - parameters interfere with SM  $t\bar{t}$  production
  - fit of new physics contributions or extraction from spin coefficients
- No evidence of new physics



# Charge asymmetry in lepton+jets

## Unfolding method

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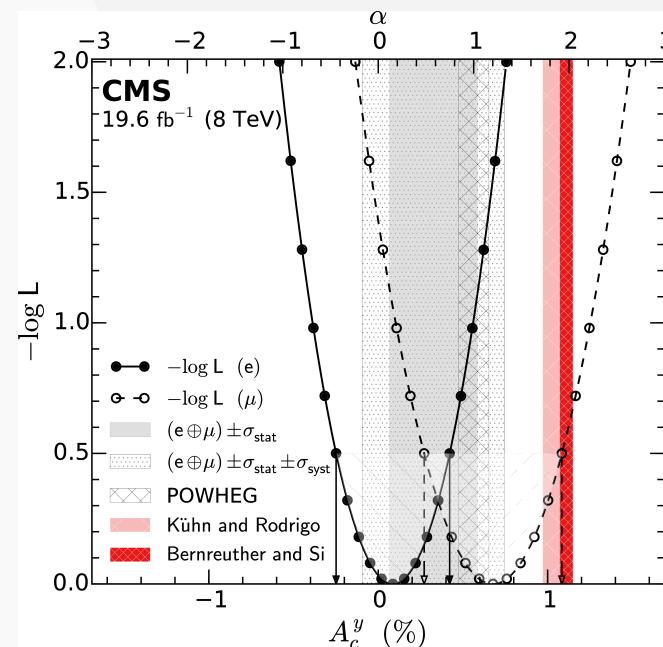
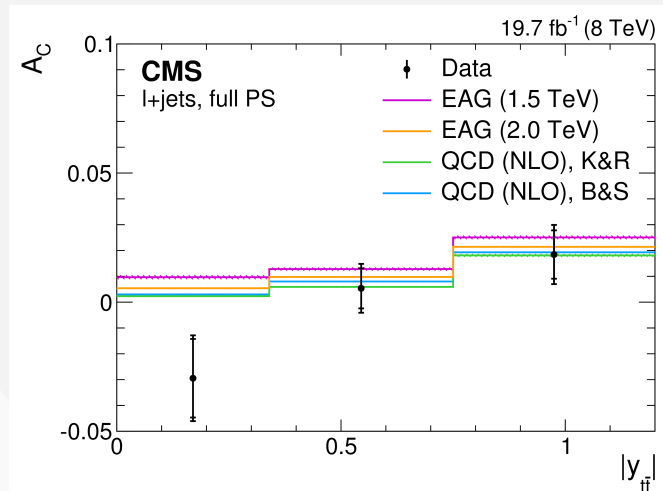
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## Template method

PRD 93, 034014 (2016)

- Transformed rapidity observable:  $Y_{t\bar{t}} = \tanh \Delta|y_t|$
- Extract  $A_C$  via template fit of reconstructed  $Y_{t\bar{t}}$ 
  - using (anti)symmetric ( $x^+$  and  $x^-$ ) components of probability density for  $Y_{t\bar{t}}$  from base model (SM)
  - connected with fit parameter  $\alpha$

$$A_C^{data} = \alpha \cdot A_C^{model} \iff X_\alpha^{data} = X^{+,rec} + \alpha \cdot X^{-,rec}$$



# Search for CP violation in $t\bar{t}$ production and decay

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- **First measurement of CP-violating asymmetries in  $t\bar{t}$**

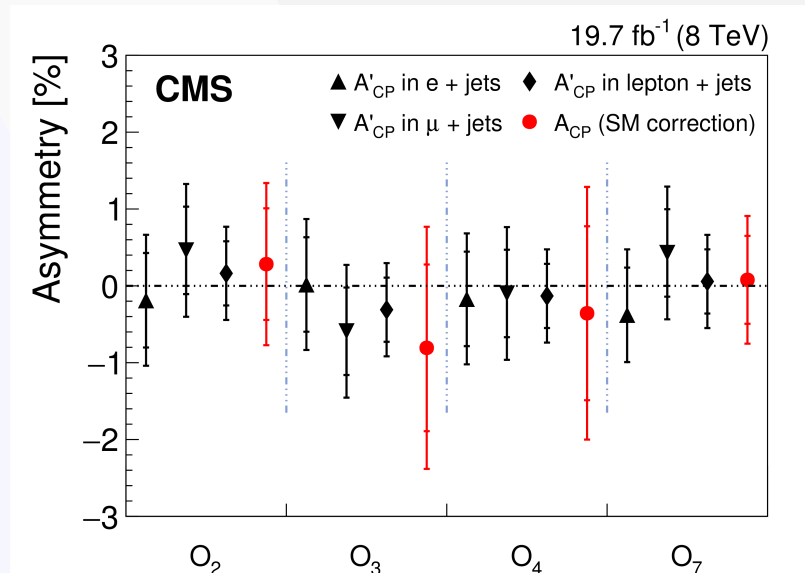
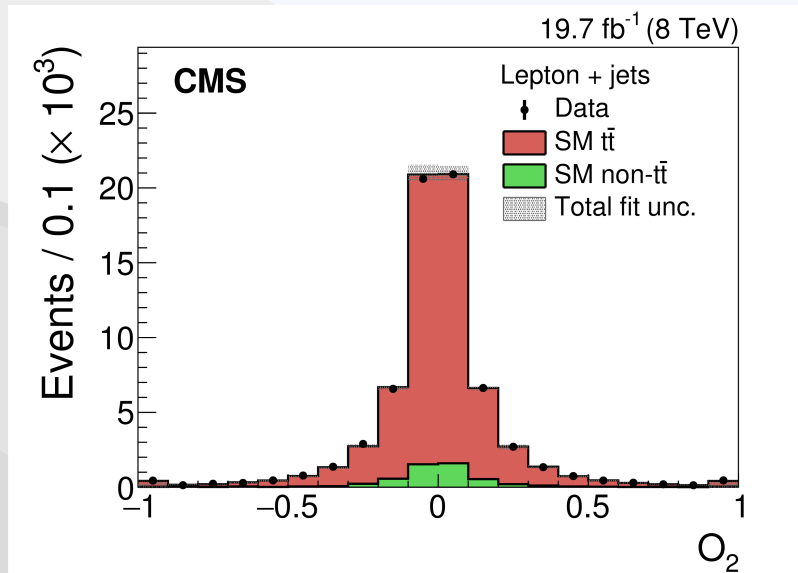
- Construct four T-odd observables  $O_i$  of the form  $\vec{v}_1 \cdot (\vec{v}_2 \times \vec{v}_3)$

- use spin or momentum vectors of decay products in  $t\bar{t} \rightarrow \ell + \text{jets}$  final state
- also CP-odd, if CPT conservation is valid
- e.g.,  $O_2 \propto (\vec{p}_b + \vec{p}_{\bar{b}}) \cdot (\vec{p}_\ell \times \vec{p}_{j_1})$

- Non-zero asymmetry as an evidence of CP violation :  $A_{CP}(O_i) = \frac{N_{events}(O_i > 0) - N_{events}(O_i < 0)}{N_{events}(O_i > 0) + N_{events}(O_i < 0)}$

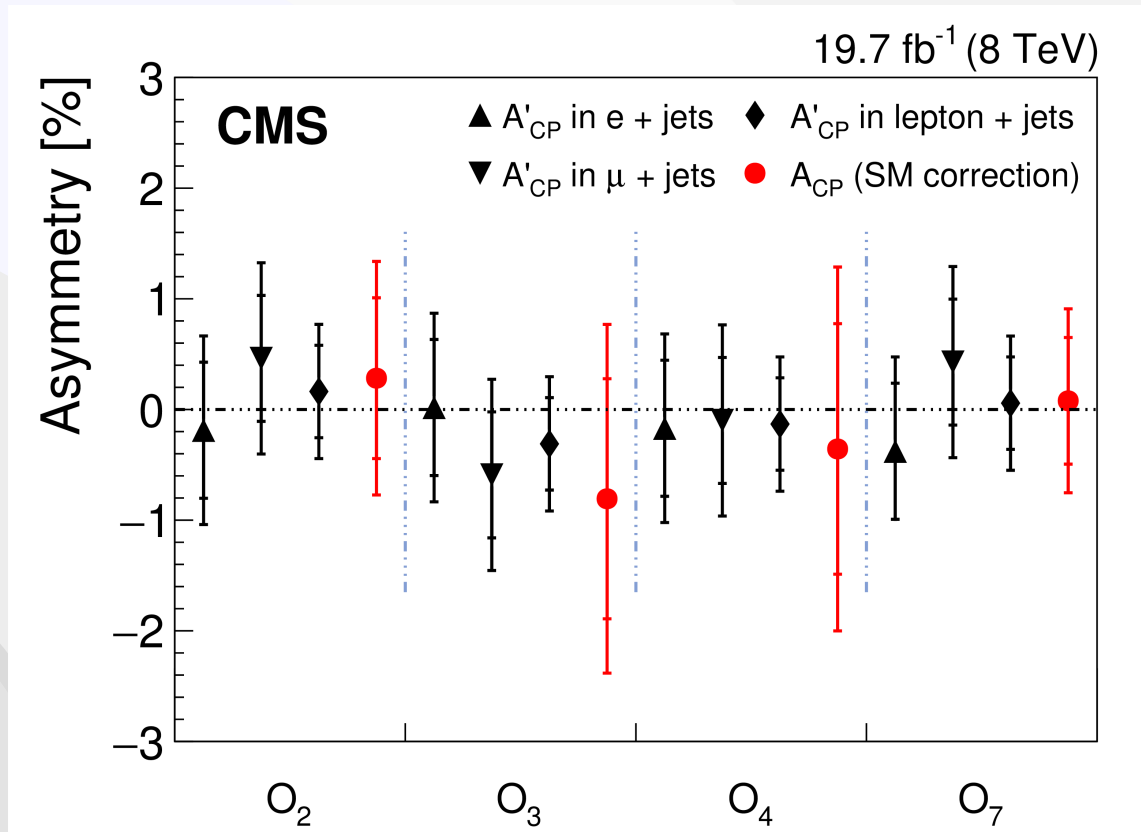
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# Search for CP violation in $t\bar{t}$ production and decay

- Results are presented as  $A'_{CP}$  (raw) and  $A_{CP}$  (corrected for detector effects) asymmetries
  - after background subtraction (determined from fit)
  - systematic uncertainty mostly arises from estimation of possible detector bias
- **Consistent with SM, thus no observation of CP violating effects**



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