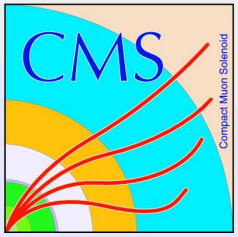


Measurements of the top quark properties at production with CMS

Mykola Savitskyi (DESY)

on behalf of CMS collaboration

European Physical Society Conference on High Energy Physics 2017, 07/07/2017

HELMHOLTZ GEMEINSCHAFT

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 (~10^{-25}s) is much shorter than the spin decorrelation time scale (~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

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

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

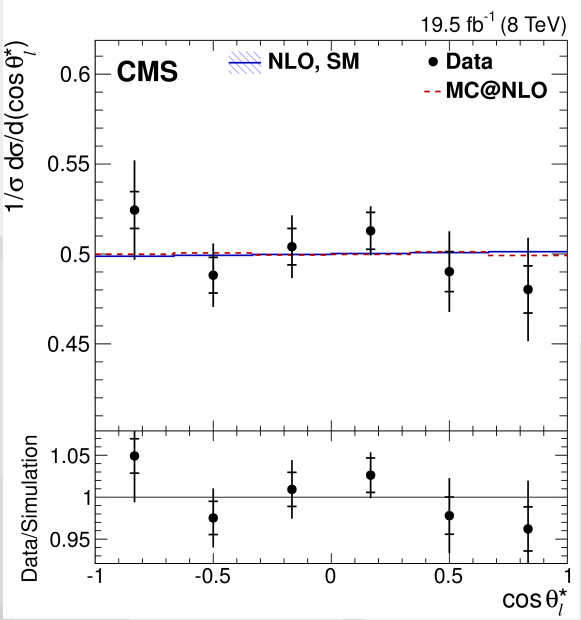
Spin correlations & polarization in dileptons

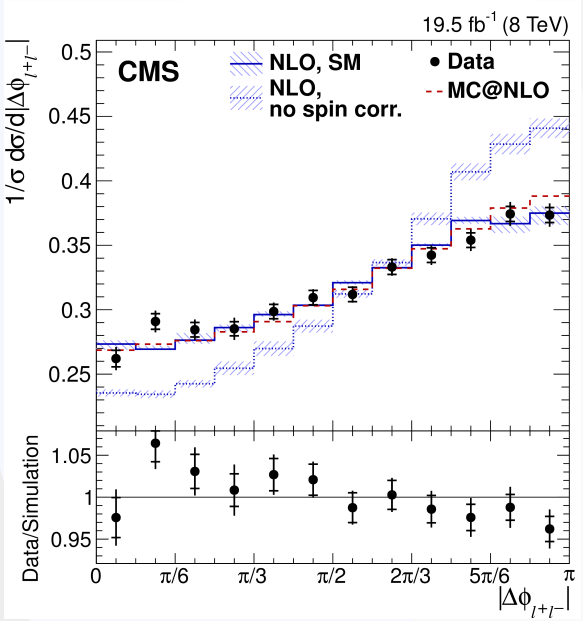
- **Probing spin density matrix and extraction of f_{SM}**

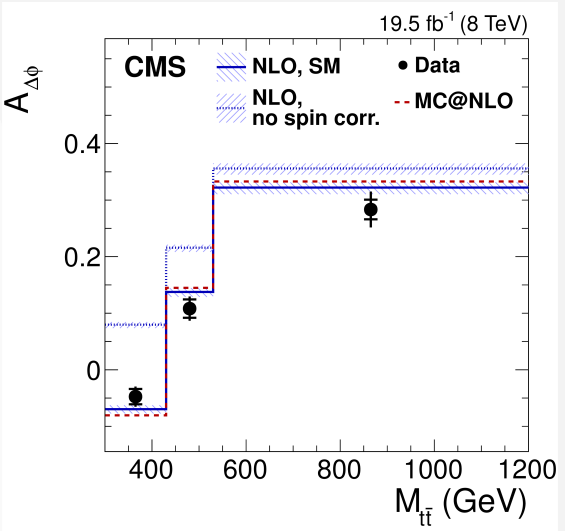
PRD 93, 052007 (2016)

available as RIVET routine in CMS_2016_I1413748

- 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 $m_{t\bar{t}}$, $|y_{t\bar{t}}|$, $p_T^{t\bar{t}}$
- Setting limits on **chromo-magnetic** and **chromo-electric** dipole moments



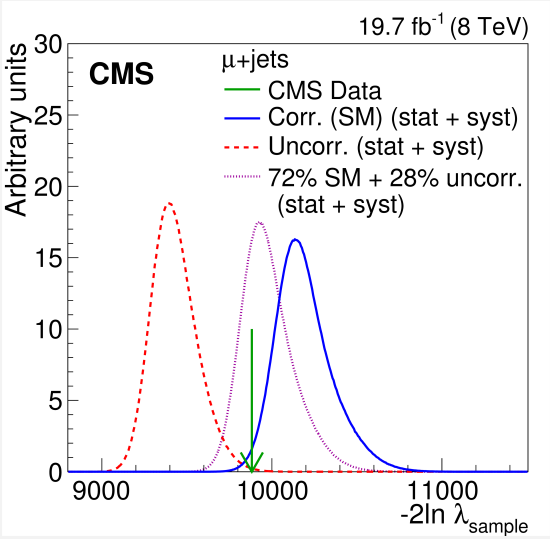




Spin correlations in muon+jets

- **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 λ



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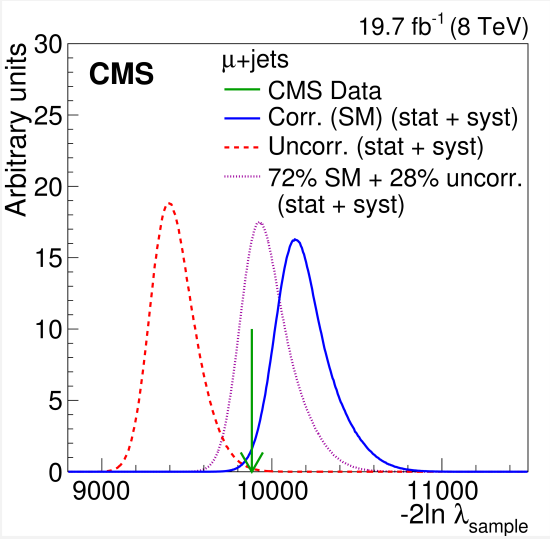

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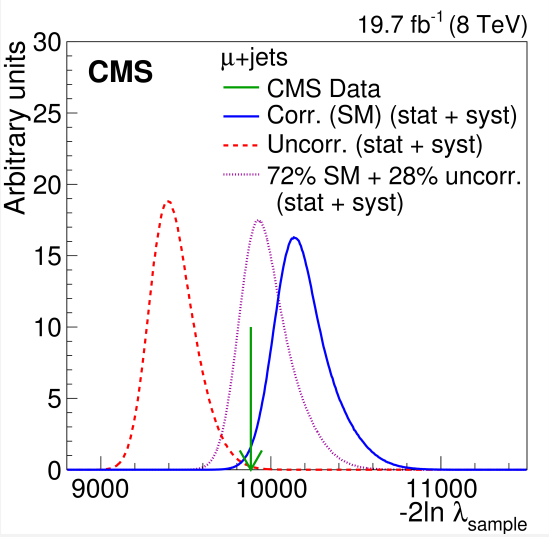
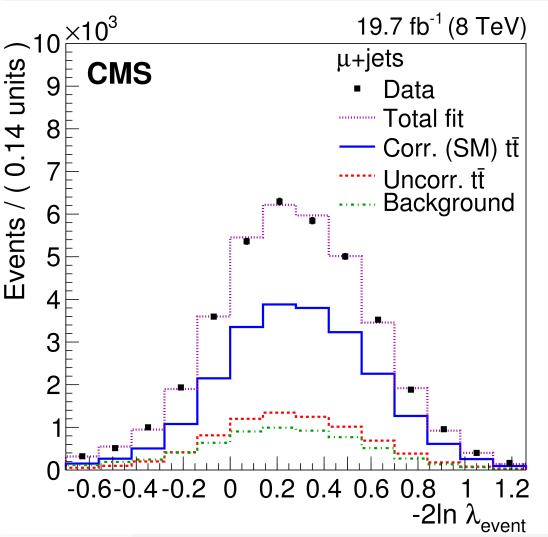
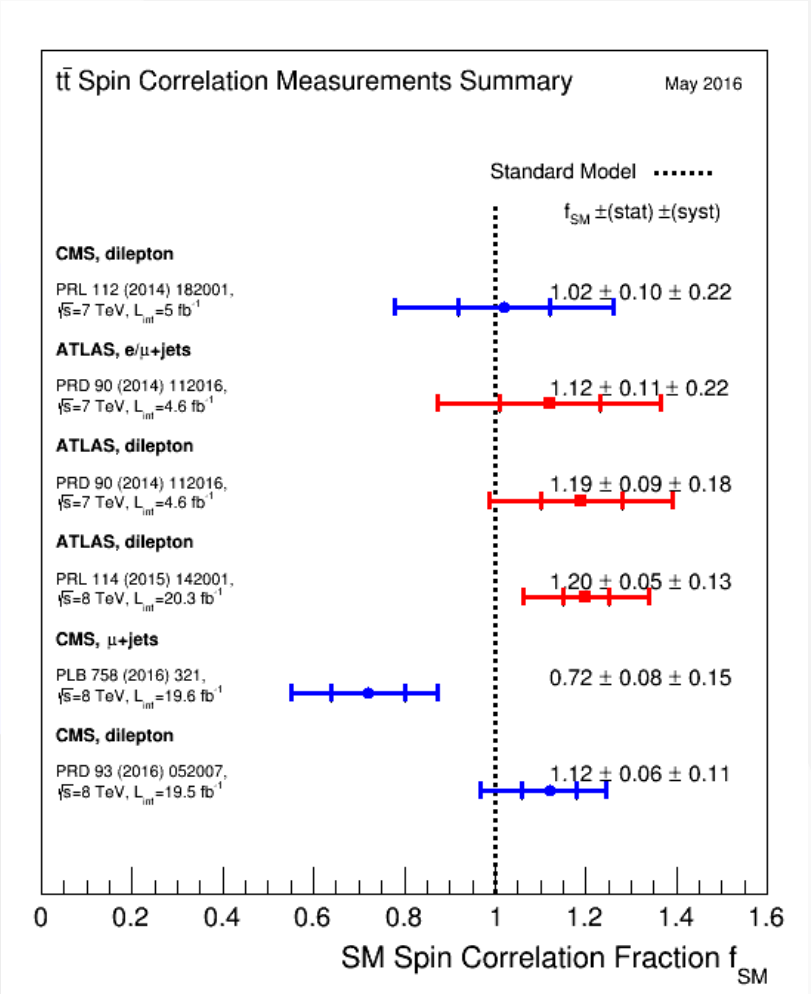


- Template fit for **extraction of f_{SM}** and background fraction
  - using distribution of event likelihood ratio λ
  - SM contribution: $f_{SM} = 0.72 \pm 0.08\,(stat.)^{+0.15}_{-0.13}\,(syst.)$
  - spin correlation strength:

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



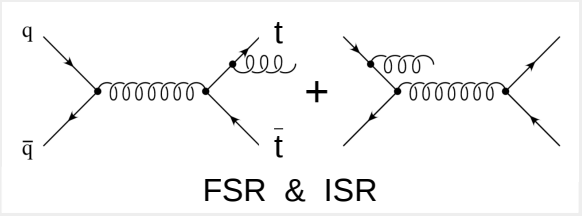
Spin correlations



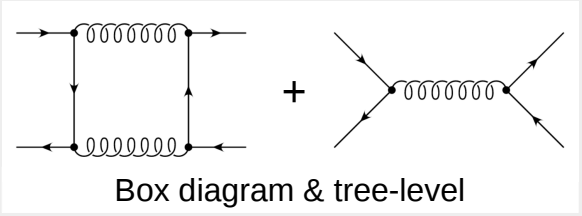
Good agreement between SM predictions and both experiments

Charge asymmetry

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



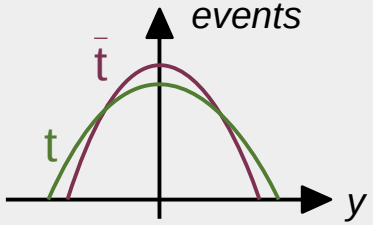
FSR & ISR



Box diagram & tree-level

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

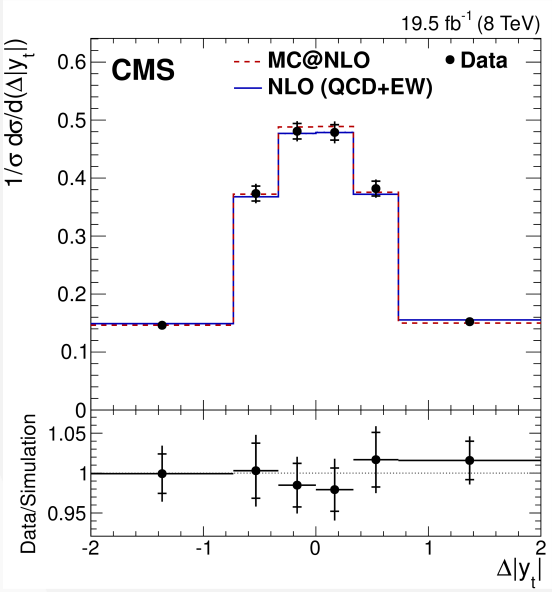
- **Inclusive and differential measurements of A_C**

PLB 760 (2016) 365

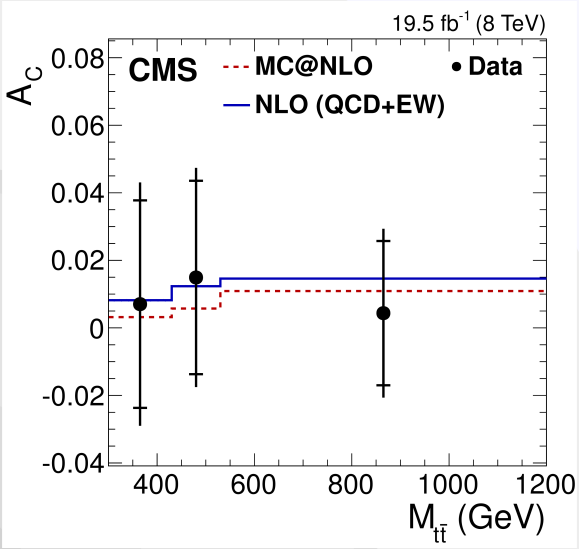
available as RIVET routine in CMS_2016_I1430892

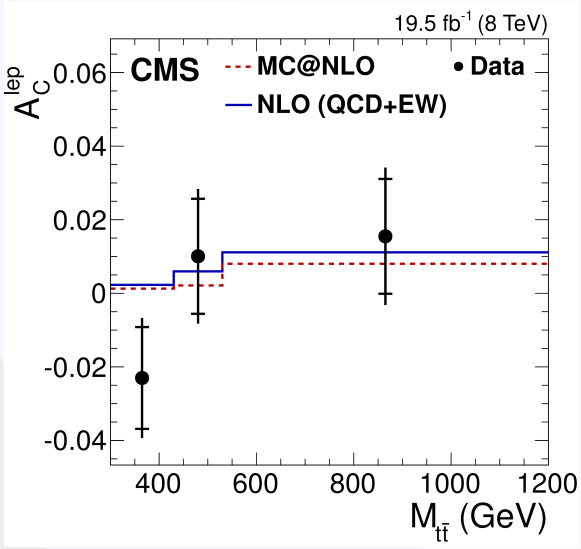
- Also measure observable A_C^{lep} using $\Delta|\eta_\ell| = |\eta_{\ell^+}| - |\eta_{\ell^-}|$
  - better resolution and independent from top reconstruction
  - carries info about top quark polarization

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



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

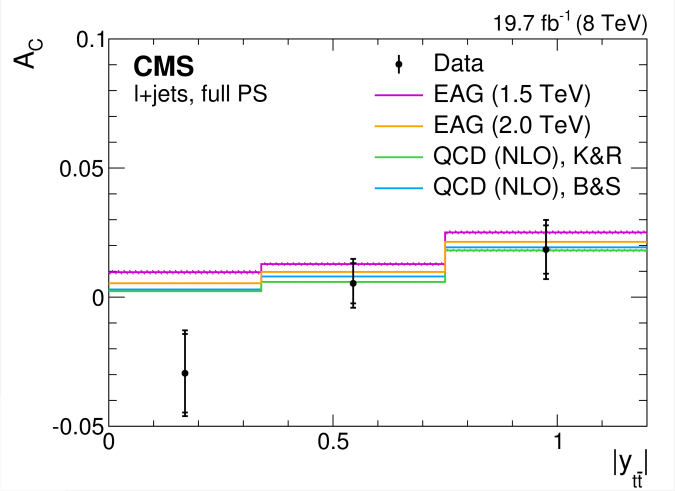




All results in agreement with SM

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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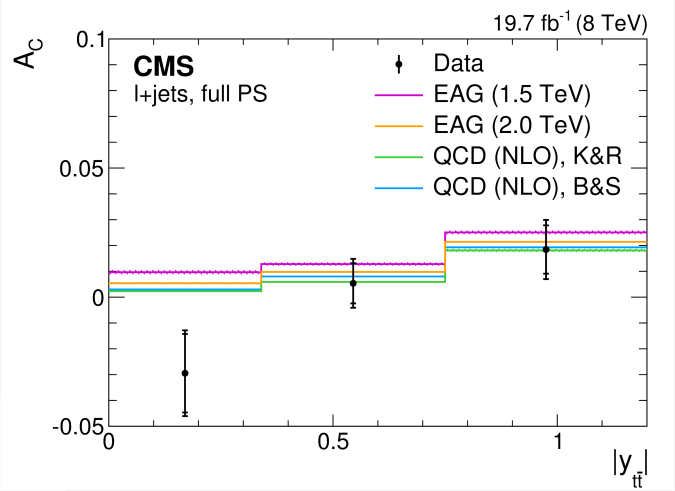
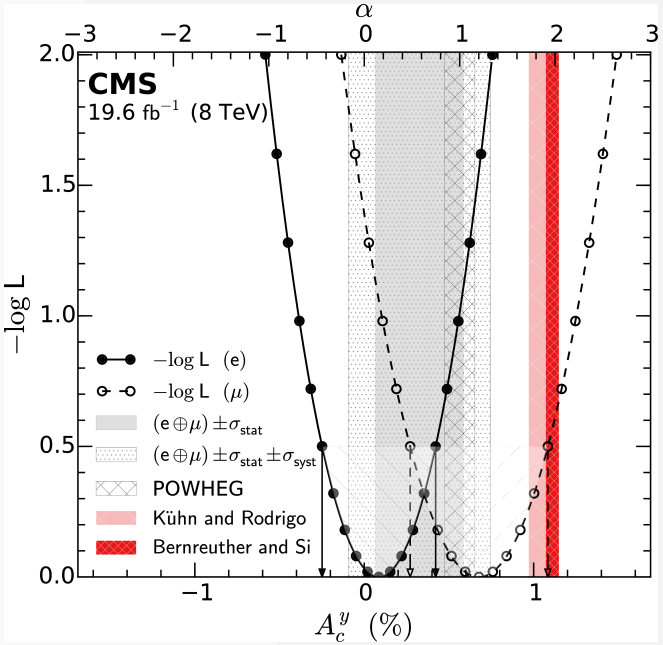


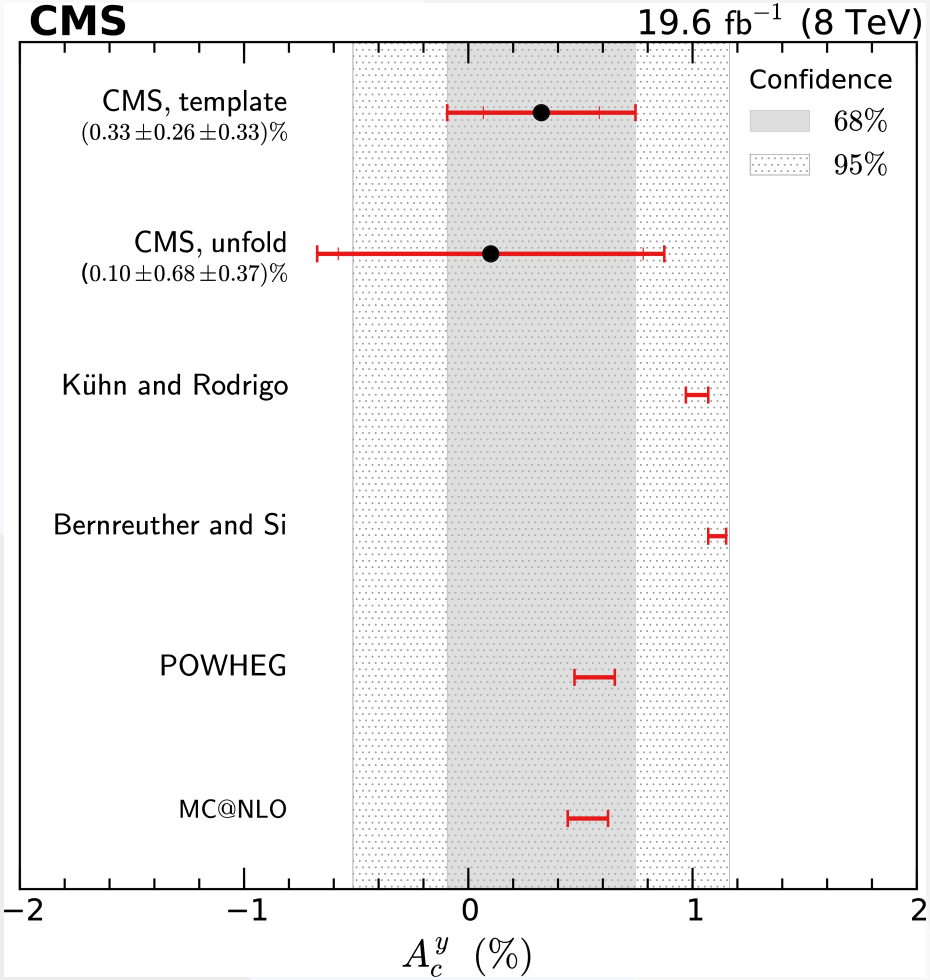
- **Template method** PRD 93, 034014 (2016)
- Transformed rapidity observable: $Y_{t\bar{t}} = tanh\ \Delta|y_t|$
- Extract A_C via template fit of reconstructed $Y_{t\bar{t}}$
  - using (anti)symmetric $x^{(-)+}$ components of probability density for $Y_{t\bar{t}}$ from base model (SM)

$$x_\alpha^{data} = x^{+,rec} + \alpha \cdot x^{-,rec}$$



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

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

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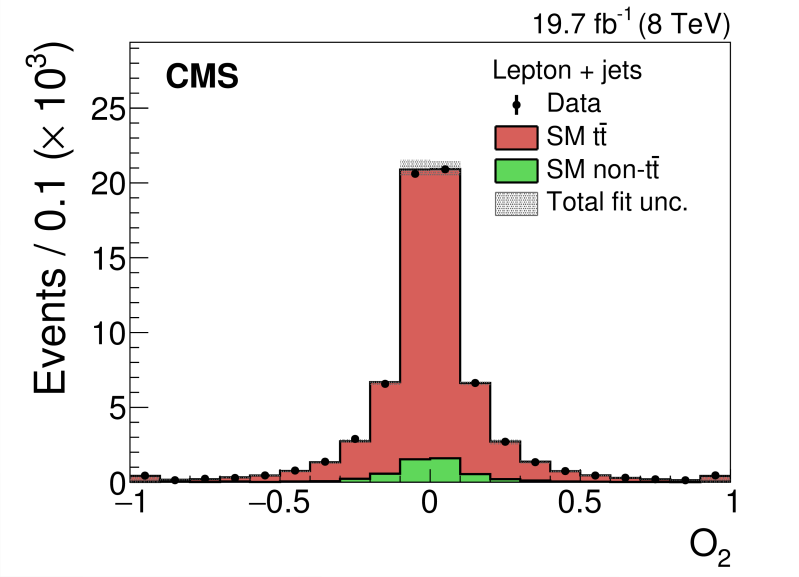
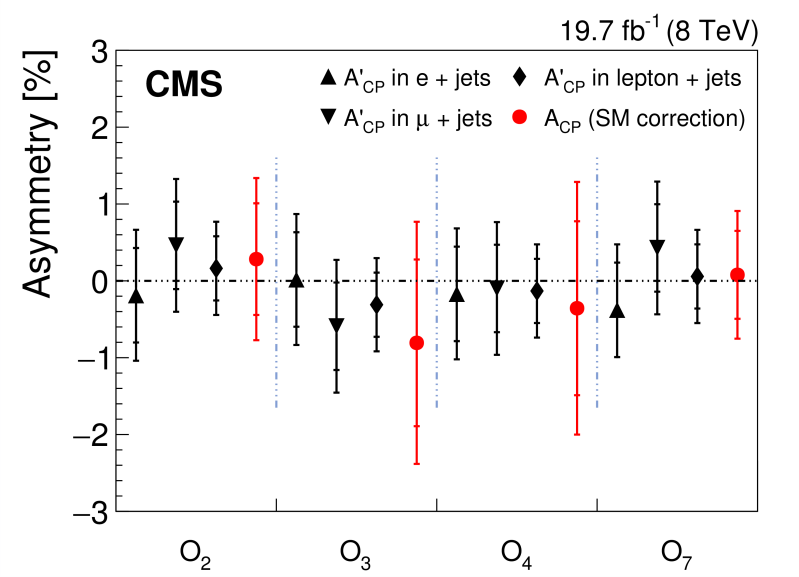
- Construct four T-odd observables O_i
  - use spin or momentum vectors of decay products in $t\bar{t} \to \ell$+jets final state
- Non-zero asymmetry as an evidence of CP violation : $A_{CP}(O_i) = \frac{N_{events}(O_i>0) - N_{events}(O_i<0)}{N_{events}(O_i>0) + N_{events}(O_i<0)}$
- Up-to 8% CPV effects 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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  - CP violation
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THANK YOU FOR YOUR ATTENTION

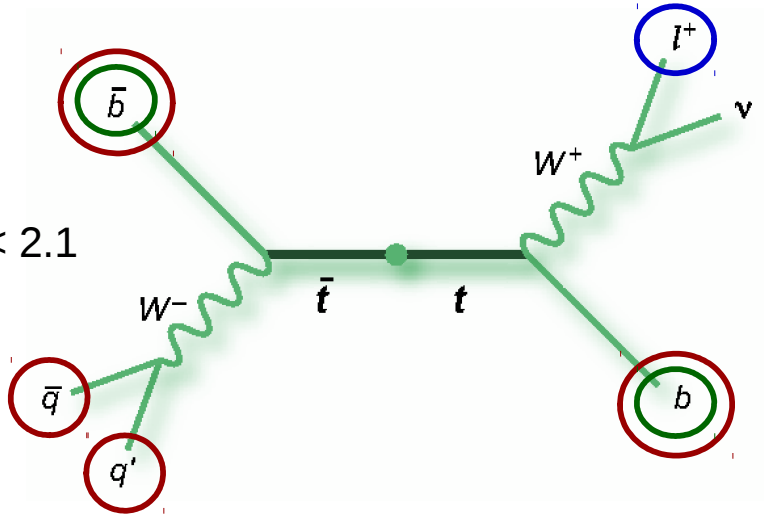
See more:
http://cms-results.web.cern.ch/cms-results/public-results/publications/TOP/

BACKUP

Event selection

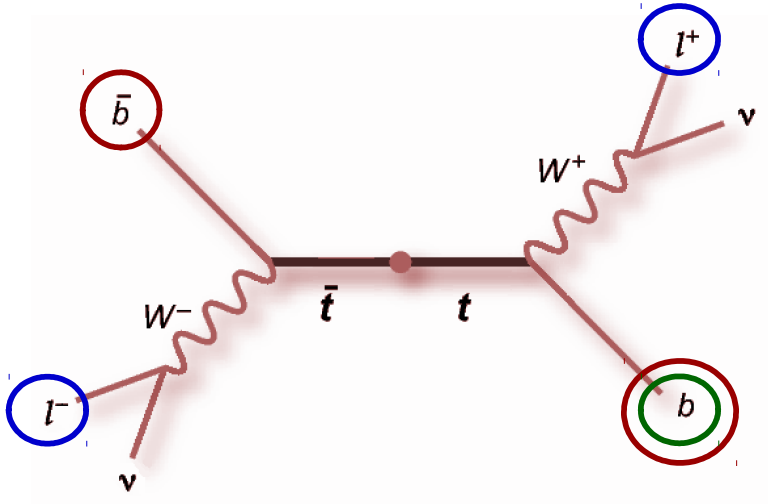
Lepton+jets:

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



Dileptons:

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



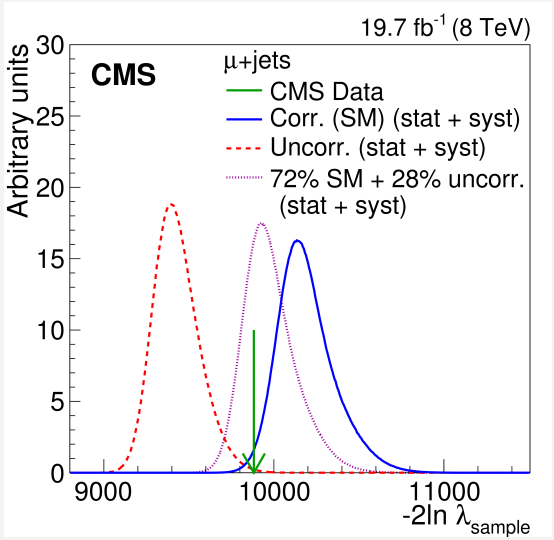
In addition: kinematic reconstruction of $t\bar{t}$ system

Spin correlations in muon+jets

- **Consistency check of spin correlation strength in $t\bar{t}$ with the SM** PLB 758 (2016) 321

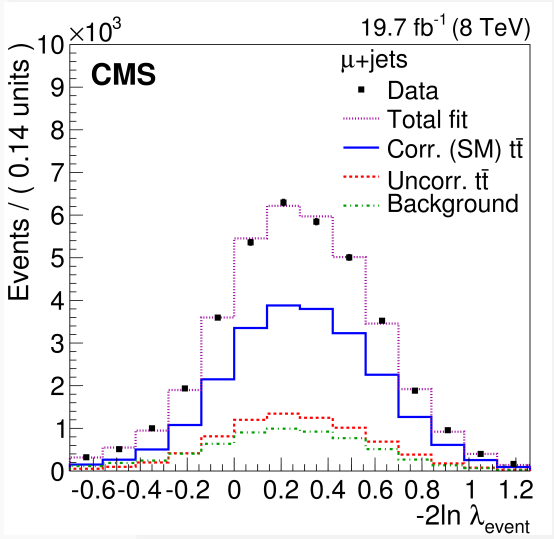
- Test of two hypothesis behind $t\bar{t}$ production in data
  - **spin correlation predicted by SM:** agrees within 2.2σ
  - **no spin correlation:** within 2.9σ
  - event probabilities *P* estimated via matrix element method
  - separation power given by sample likelihood ratio

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



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

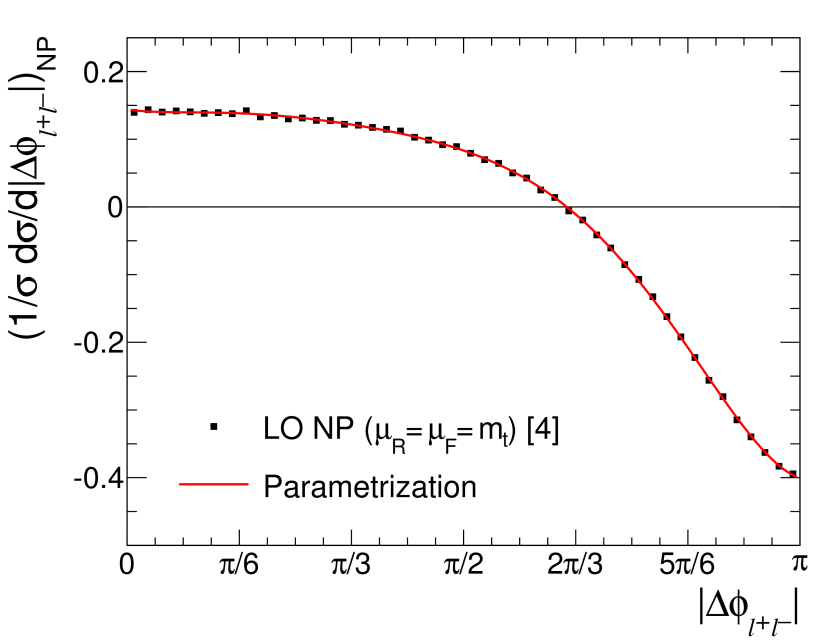
$$A_{hel}^{measured} = f_{SM} \cdot A_{hel}^{SM,MC} = 0.23 \pm 0.03(stat.)^{+0.05}_{-0.04}(syst.)$$

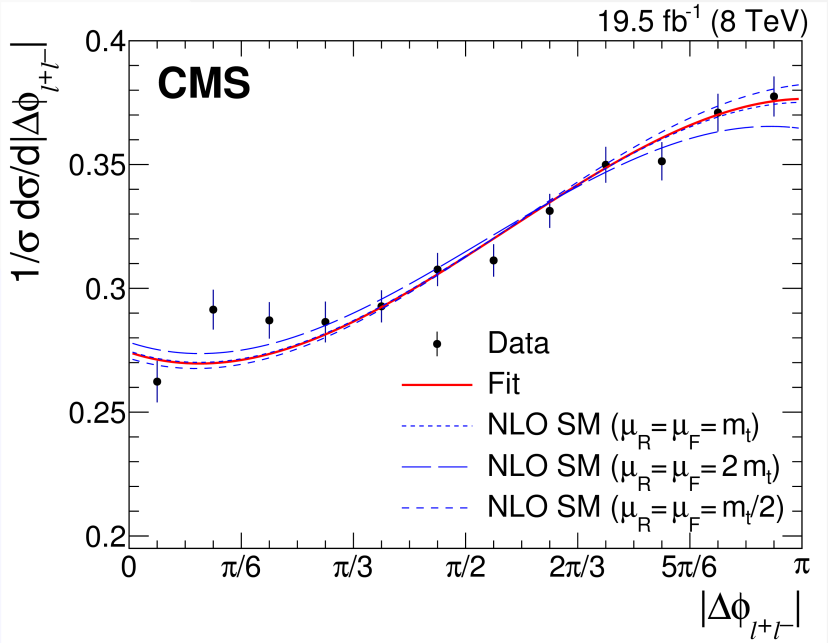


Spin correlations & polarization in dileptons

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** PLB 758 (2016) 321
- Inclusive and differential measurement of A_C
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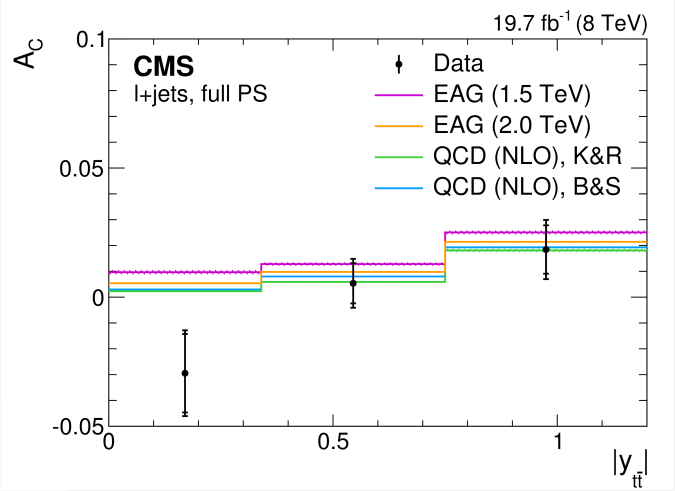

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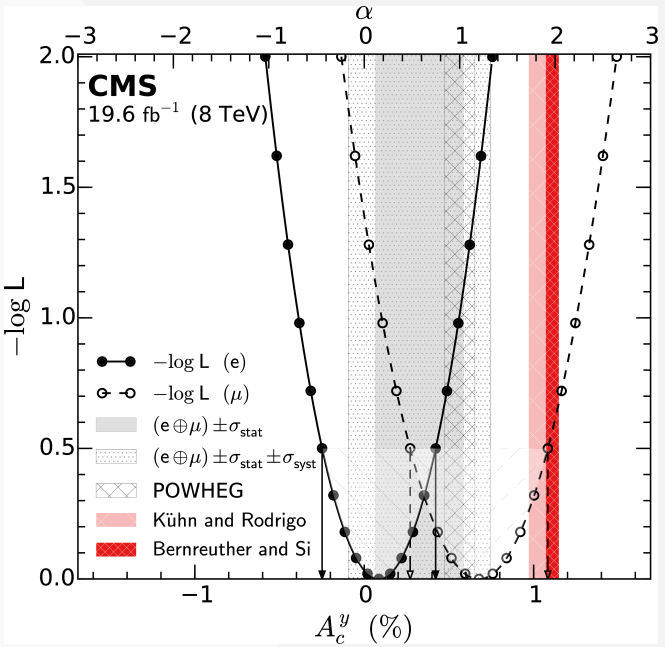
- Transformed rapidity observable: $Y_{t\bar{t}} = tanh\ \Delta|y_t|$
- Extract A_C via template fit of reconstructed $Y_{t\bar{t}}$
  - using (anti)symmetric (x^+ and x^-) components of probability density for $Y_{t\bar{t}}$ from base model (SM)
  - connected with fit parameter α

$$A_C^{data} = \alpha \cdot A_C^{model} \quad \Leftrightarrow \quad x_\alpha^{data} = x^{+,rec} + \alpha \cdot x^{-,rec}$$



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

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

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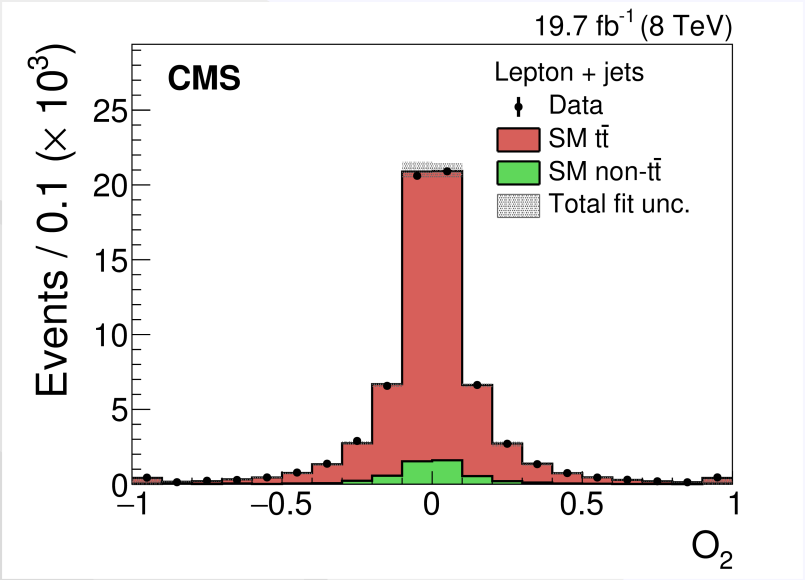
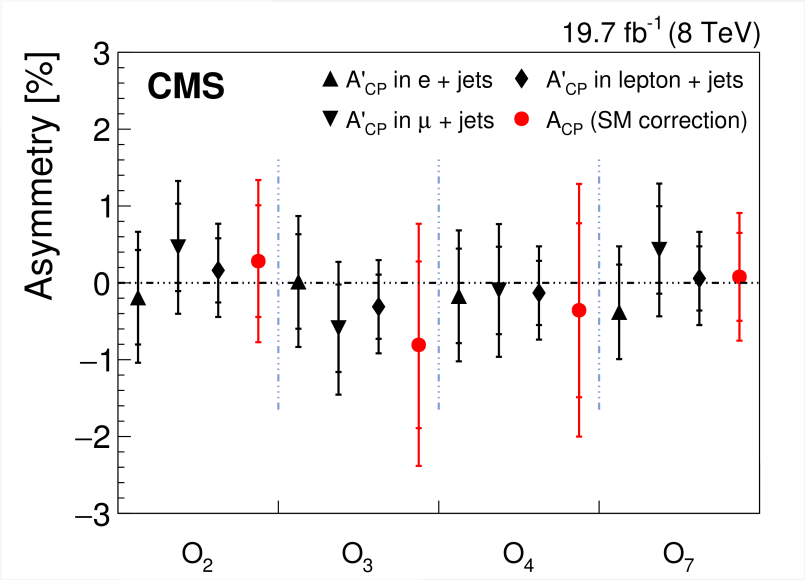
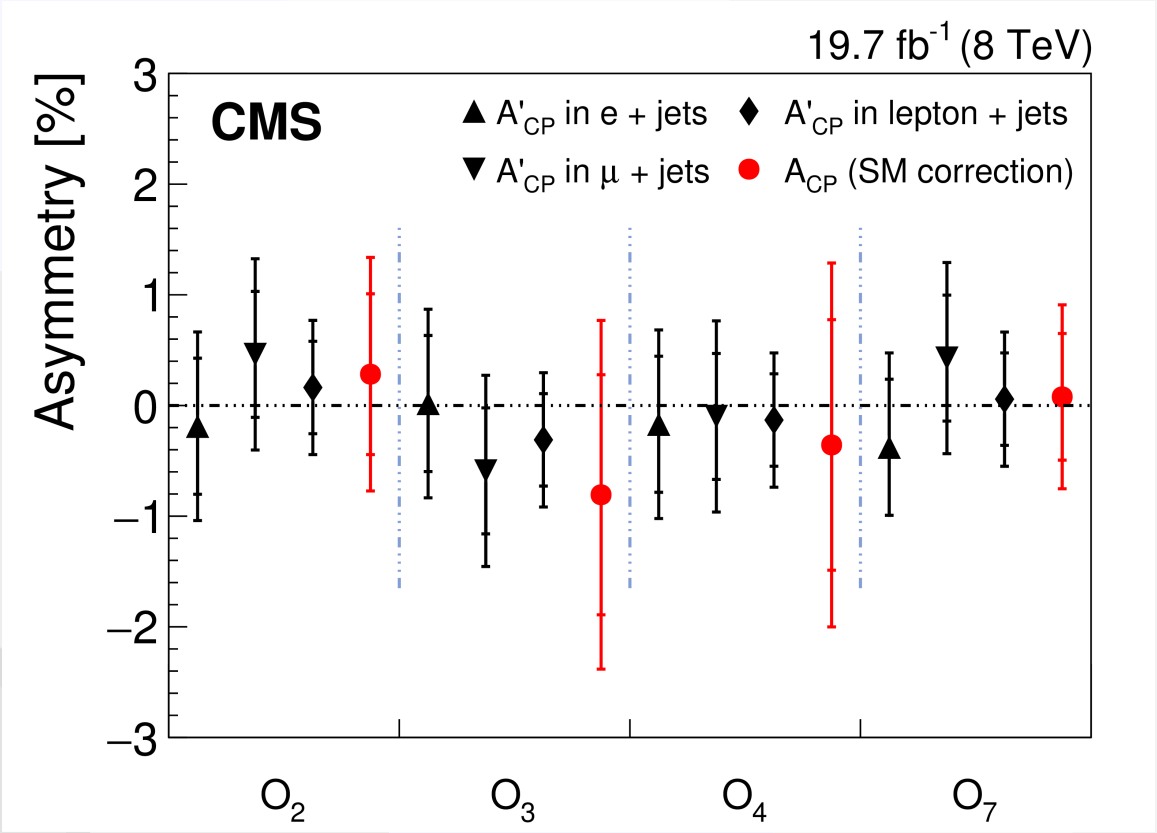
- Construct four T-odd observables O_i of the form $\vec{v}_1 \cdot (\vec{v}_2 \times \vec{v}_3)$
  - use spin or momentum vectors of decay products in $t\bar{t} \to \ell$+jets final state
  - also CP-odd, if CPT conservation is valid
  - e.g., $O_2 \propto (\vec{p}_b + \vec{p}_{\bar{b}}) \cdot (\vec{p}_\ell \times \vec{p}_{j_1})$
- Non-zero asymmetry as an evidence of CP violation : $A_{CP}(O_i) = \frac{N_{events}(O_i>0) - N_{events}(O_i<0)}{N_{events}(O_i>0) + N_{events}(O_i<0)}$
- 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**





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**



JHEP 03 (2017) 101