

# Top quark Spin Correlations and Polarizations at LHC

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## Outline

- Motivation
- Polarized Top Quark Decay
- Top Quark Spin Correlations and Polarization  
in  $t\bar{t}$  production and decay @NLO
  - Double Angular Distribution
  - Openning Angle Distribution
  - New Physics
- Summary

- Lifetime of Top Quark is extremely short
  - ⇒ Decay before hadronization
  - ⇒ Properties including spin information are not polluted
- Theoretical predictions for top quark production cross section and spin effects ... are reliable
- Large Cross Section for  $t\bar{t}$  production @ LHC
- Good opportunity to study top quark spin correlations and polarizations in  $t\bar{t}$  production and decay @LHC

# Polarized Top Quark Decay

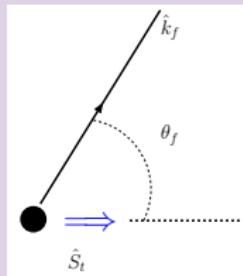
## Top Quark Spin Analyzer

Ensemble of Top Quarks **Self-Analyses** its Spin Polarization via its Parity-Violating Weak Decays

$$t \rightarrow W^+ + b \rightarrow \begin{bmatrix} l + v_l + b \\ q_1 + \bar{q}_2 + b \end{bmatrix}$$

Standard V-A Charged Current Interaction  $\rightarrow$  Charged Lepton

$l = e, \mu, \tau$  or d-type quark: the Best Analyzer of Top Spin



Decay Distribution of (100%) Polarized  $t \rightarrow f + \cdots$

$$\frac{1}{\Gamma} \frac{d\Gamma}{d \cos \vartheta_f} = \frac{1}{2} (1 + \kappa_f \cos \vartheta_f)$$

$\kappa_f$ : the top quark spin analyzing power of  $f$

$$\kappa_l = 1 \text{ (Maximal)}$$

$$\kappa_b = -\kappa_W = -0.41$$

# Polarized Top Quark Decay

## NLO QCD Corrections to Top Quark Spin Analyzing Power

Semi-leptonic Decays:  $t \rightarrow b l^+ \nu_l, b l^+ \nu_l + g$

Non-leptonic Decays:  $t \rightarrow b q_1 \bar{q}_2, b q_1 \bar{q}_2 + g \implies t \rightarrow j_b j_1 j_2, j_b j_1 j_2 j_3$

## Spin Analyzer Quality Factor $\kappa_f$ :

	$l^+$	$\bar{d}$	$u$	$b$	$j_{<}$	$j_{>}$
LO:	1	1	-0.32	-0.41	0.51	0.2
NLO:	0.999	0.966	-0.31	-0.39	0.47	

Czarnecki, Jezabek, Kühn '91 (semileptonic)

Brandenburg, Si, Uwer '02 (non-leptonic)

⇒ The charged lepton is the best analyzer of top quark spin

## For the $t\bar{t}$ production process at LHC

### 1 $t\bar{t}$ Spin Correlations:

- Large Effect in SM, mainly due to QCD
- Strength Depends on the Choice of  
Reference Axes  $\longrightarrow t, \bar{t}$  Spin Quantization Axes  
in On-shell Approximation

### 2 Polarization of $t, \bar{t}$ : (very) Small

- Normal to Production Plane(P-even, T-odd) due to QCD Absorptive Parts
- Polarization in Production Plane(Parity-violation) due to Weak Interactions

# Spin Correlations in Hadronic $t\bar{t}$ Production

$$A(\hat{\mathbf{a}}, \hat{\mathbf{b}}) = < 4(\hat{\mathbf{a}} \cdot \hat{\mathbf{s}}_t)(\hat{\mathbf{b}} \cdot \hat{\mathbf{s}}_{\bar{t}}) > = \frac{N(\uparrow\uparrow) + N(\downarrow\downarrow) - N(\uparrow\downarrow) - N(\downarrow\uparrow)}{N(\uparrow\uparrow) + N(\downarrow\downarrow) + N(\uparrow\downarrow) + N(\downarrow\uparrow)}$$

For on-shell  $t, \bar{t}$ :  $\hat{\mathbf{a}}, \hat{\mathbf{b}} \leftrightarrow$  Spin Axes, eg.,

$$\hat{\mathbf{a}} = \hat{\mathbf{k}}_t, \quad \hat{\mathbf{b}} = \hat{\mathbf{k}}_{\bar{t}} \quad (\textit{helicity basis})$$

$$\tilde{D} = < 4(\hat{\mathbf{s}}_t \cdot \hat{\mathbf{s}}_{\bar{t}}) > = \frac{\tilde{N}(\uparrow\uparrow) - \tilde{N}(\uparrow\downarrow)}{\tilde{N}(\uparrow\uparrow) + \tilde{N}(\uparrow\downarrow)}$$

$$\tilde{B} = < 4(\hat{\mathbf{s}}_t \cdot \hat{\mathbf{a}}) > = \frac{\tilde{N}(\uparrow) - \tilde{N}(\downarrow)}{\tilde{N}(\uparrow) + \tilde{N}(\downarrow)}$$

⇒ can be measured via angular distributions

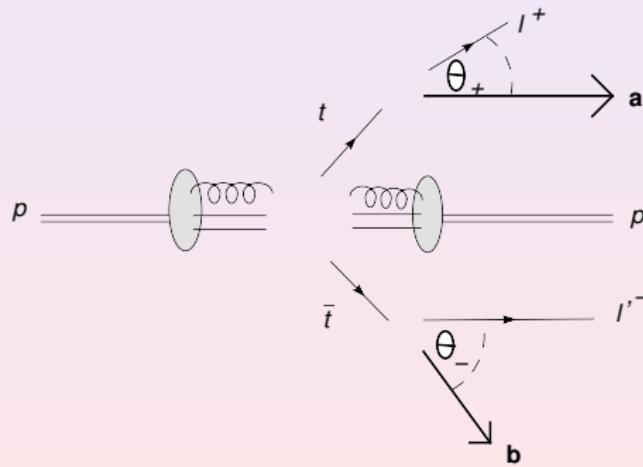


# Dilepton channel

Best process to study top quark spin effects

$$pp \rightarrow t\bar{t} + X \rightarrow l^+l'^- + X'$$

- $\theta_+ = \theta_1 = \angle(\hat{l}^+, \hat{\mathbf{a}})$ ,  $\theta_- = \theta_2 = \angle(\hat{l}'^-, \hat{\mathbf{b}})$
- $\phi = \angle(l^+, l'^-)$  in resp.  $t, \bar{t}$  rest frames



# Spin Effects in Hadronic $t\bar{t}$ Production and Decay

- Double Angular Distribution

$$\frac{1}{\sigma} \frac{d^2\sigma}{d\cos\theta_+ d\cos\theta_-} = \frac{1}{4} [1 + B_1 \cos\theta_+ + B_2 \cos\theta_- - C \cos\theta_+ \cos\theta_-]$$

- Opening Angle Distribution

$$\frac{1}{\sigma} \frac{d\sigma}{d\cos\phi} = \frac{1}{2} [1 - D \cos\phi]$$

- $C$  &  $D$  reflects spin-spin correlations between  $t$  and  $\bar{t}$

$$D = \kappa_+ \kappa_- \tilde{D} = -3 <\cos\phi>, \quad -1 \leq D \leq 1$$

$$C = \kappa_+ \kappa_- A = -9 <\cos\theta_+ \cos\theta_->, \quad -1 \leq C \leq 1$$

- $B_1$  and  $B_2$  reflects top quark spin polarization

$$B_1 = 3 <\cos\theta_+>, \quad B_2 = 3 <\cos\theta_->$$

$$\frac{1}{\sigma} \frac{d^2\sigma}{d\cos\theta_+ d\cos\theta_-} = \frac{1}{4} [1 + B_+^{\hat{\mathbf{a}}} \cos\theta_+ + B_-^{\hat{\mathbf{b}}} \cos\theta_- - C(\hat{\mathbf{a}}, \hat{\mathbf{b}}) \cos\theta_+ \cos\theta_-]$$

All observables based on  $\cos\theta_+$  &  $\cos\theta_-$  can be defined using three orthogonal spin quantisation axes:

- The helicity axis is defined as the top quark direction in the  $t\bar{t}$  rest frame:  $\hat{\mathbf{k}}$
- The transverse axis defined to be transverse to the production plane created by the top quark direction and the beam axis:  $\hat{\mathbf{n}}$
- The axis orthogonal to the other two axes  $\hat{\mathbf{k}}$  &  $\hat{\mathbf{n}}$ :  $\hat{\mathbf{r}}$

$$\Rightarrow \hat{\mathbf{r}} \cdot \hat{\mathbf{k}} = \hat{\mathbf{r}} \cdot \hat{\mathbf{n}} = \hat{\mathbf{n}} \cdot \hat{\mathbf{k}} = 0$$

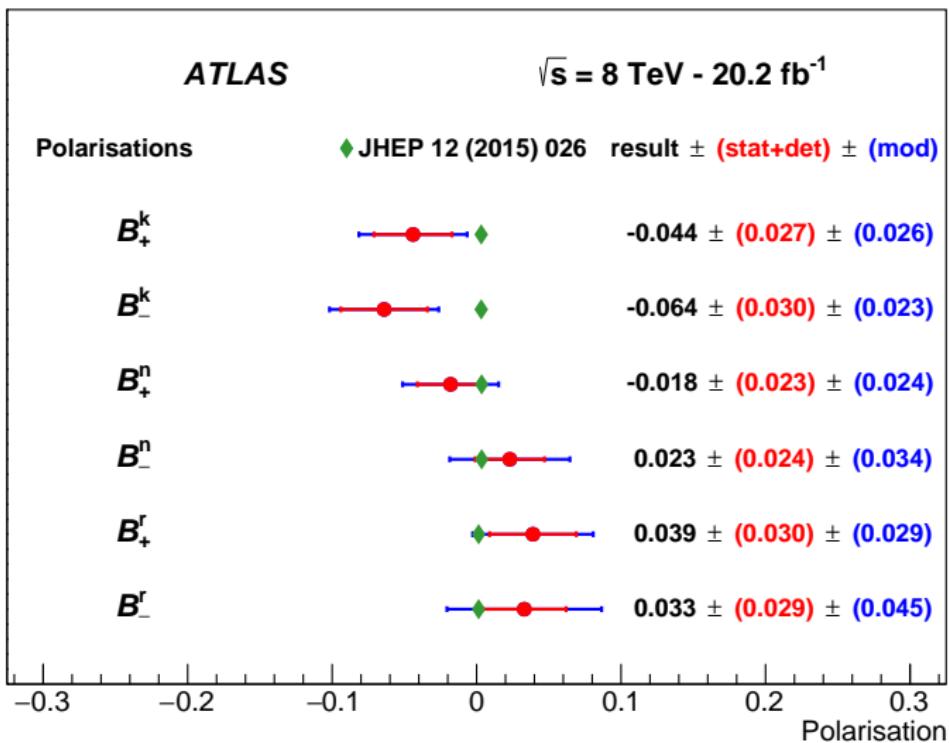
# Top Quark Polarizations

Expectation values	NLO predictions @LHC 8 TeV	Observables
$B_+^k$	$0.0030 \pm 0.0010$	$\cos \theta_+^k$
$B_-^k$	$0.0034 \pm 0.0010$	$\cos \theta_-^k$
$B_+^n$	$0.0035 \pm 0.0004$	$\cos \theta_+^n$
$B_-^n$	$0.0035 \pm 0.0004$	$\cos \theta_-^n$
$B_+^r$	$0.0013 \pm 0.0010$	$\cos \theta_+^r$
$B_-^r$	$0.0015 \pm 0.0010$	$\cos \theta_-^r$

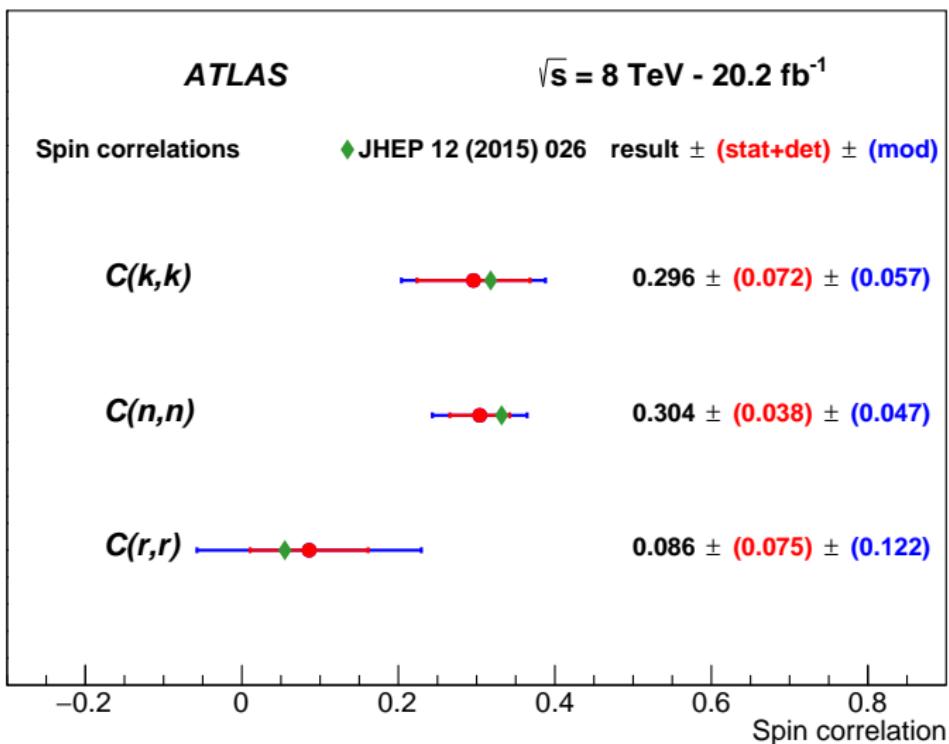
# Top Quark Spin Correlations

Expectation values	NLO predictions @LHC 8 TeV	Observables
$C(k, k)$	$0.318 \pm 0.003$	$\cos \theta_+^k \cos \theta_-^k$
$C(n, n)$	$0.332 \pm 0.002$	$\cos \theta_+^n \cos \theta_-^n$
$C(r, r)$	$0.055 \pm 0.009$	$\cos \theta_+^r \cos \theta_-^r$
$C(n, k) + C(k, n)$	0.0023	$\cos \theta_+^n \cos \theta_-^k + \cos \theta_-^n \cos \theta_+^k$
$C(n, k) - C(k, n)$	0	$\cos \theta_+^n \cos \theta_-^k - \cos \theta_-^n \cos \theta_+^k$
$C(n, r) + C(r, n)$	0.0010	$\cos \theta_+^n \cos \theta_-^r + \cos \theta_-^n \cos \theta_+^r$
$C(n, r) - C(r, n)$	0	$\cos \theta_+^n \cos \theta_-^r - \cos \theta_-^n \cos \theta_+^r$
$C(r, k) + C(k, r)$	$-0.226 \pm 0.004$	$\cos \theta_+^r \cos \theta_-^k + \cos \theta_-^r \cos \theta_+^k$
$C(r, k) - C(k, r)$	0	$\cos \theta_+^r \cos \theta_-^k - \cos \theta_-^r \cos \theta_+^k$

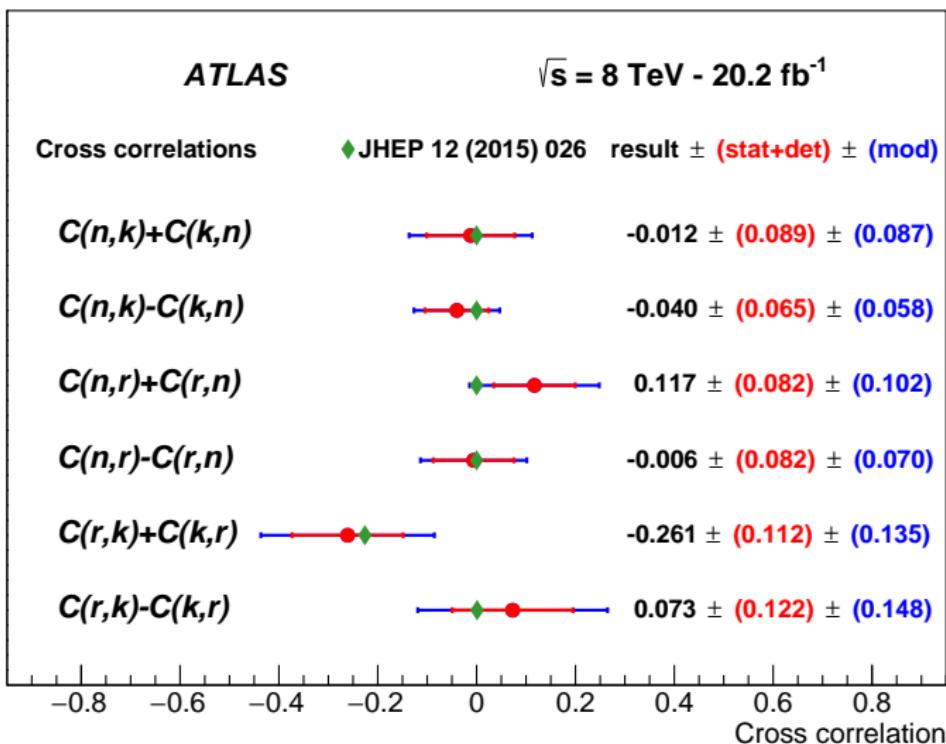
# Top Quark Polarizations @LHC 8 TeV



# Top Quark Spin Correlations @LHC 8 TeV



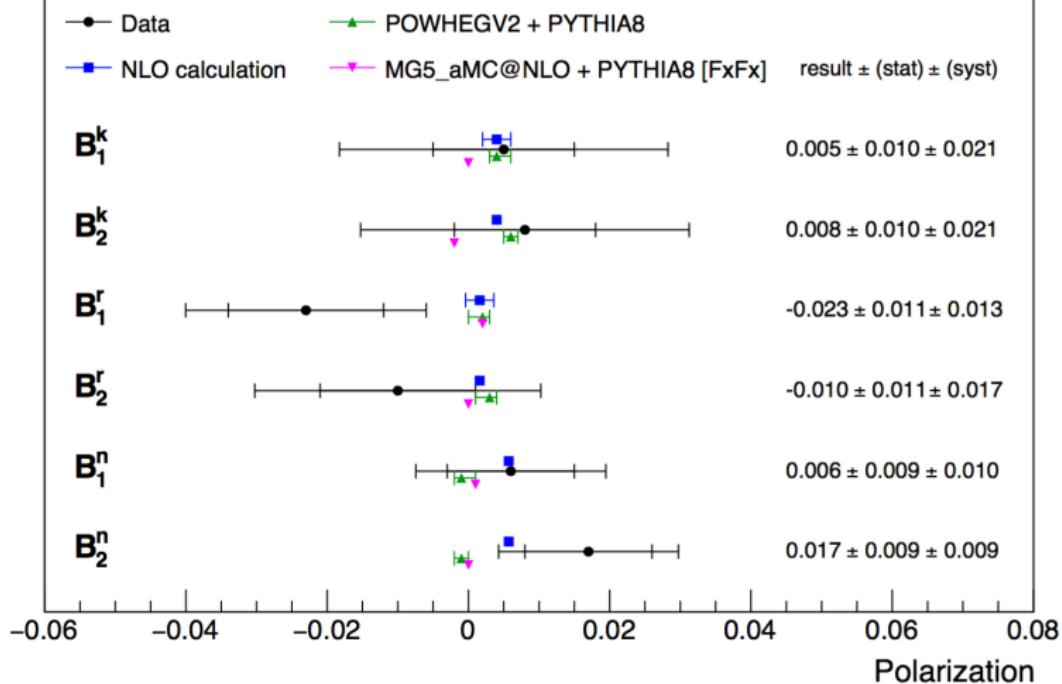
# Top Quark Spin Cross-Correlations @LHC 8 TeV



# Top Quark Polarizations @LHC 13 TeV

CMS Preliminary

35.9 fb<sup>-1</sup> (13 TeV)



**CMS Preliminary**35.9 fb<sup>-1</sup> (13 TeV)

- Data
  - POWHEGv2 + PYTHIA8
  - NLO calculation
  - ▼ MG5\_aMC@NLO + PYTHIA8 [FxFx]
- result ± (stat) ± (syst)

 $C_{kk}$  $0.299 \pm 0.022 \pm 0.031$  $C_{rr}$  $0.080 \pm 0.023 \pm 0.023$  $C_{nn}$  $0.329 \pm 0.012 \pm 0.017$  $-D$  $0.237 \pm 0.007 \pm 0.009$  $A_{\cos\varphi}^{\text{lab}}$  $0.167 \pm 0.003 \pm 0.011$  $A_{|\Delta\varphi|}$  $0.103 \pm 0.003 \pm 0.008$ 

Spin correlation

# Top Quark Spin Cross-Correlations @LHC 13 TeV

CMS Preliminary

35.9 fb<sup>-1</sup> (13 TeV)

● Data                   ▲ POWHEGv2 + PYTHIA8  
■ NLO calculation     ▼ MG5\_aMC@NLO + PYTHIA8 [FxFx]      result ± (stat) ± (syst)

$C_{rk} + C_{kr}$              $-0.193 \pm 0.035 \pm 0.053$

$C_{rk} - C_{kr}$              $0.057 \pm 0.035 \pm 0.029$

$C_{nr} + C_{rn}$              $-0.004 \pm 0.028 \pm 0.024$

$C_{nr} - C_{rn}$              $-0.001 \pm 0.028 \pm 0.025$

$C_{nk} + C_{kn}$              $-0.043 \pm 0.031 \pm 0.026$

$C_{nk} - C_{kn}$              $0.040 \pm 0.025 \pm 0.016$



- Top Quark Spin Correlations measured at LHC 8 & 13 TeV agree with SM predictions
- No Large Deviations observed

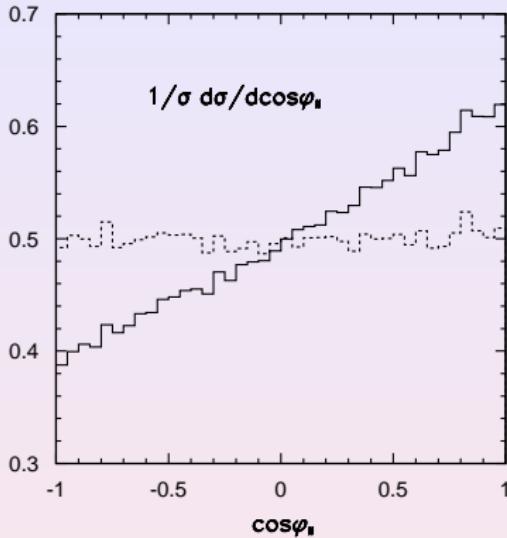
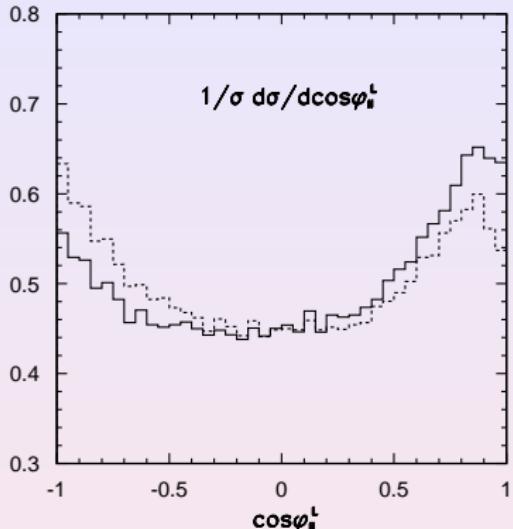
# Openning Angle Distribution

$$\frac{1}{\sigma} \frac{d\sigma}{d\cos\phi} = \frac{1}{2} [1 - D \cos\phi]$$

- **D defined w.r.t  $\phi = \triangle(I^+, I'^-)$  in resp.  $t, \bar{t}$  rest frames:**

<b>SM prediction:</b>	$-0.228 \pm 0.005$	@ NLO
<b>CMS '17:</b>	$-0.205 \pm 0.031$	@ 8TeV
<b>SM prediction:</b>	$-0.243^{+0.004}_{-0.003}$	@ NLO
<b>CMS '18:</b>	$-0.237 \pm 0.011$	@ 13TeV

# Opening Angle Distributions



- Opening angle distributions depend on the reference frame

## Transverse momentum between two charged leptons

- $\mathbf{p}_T^{I^+*}(\text{in top rest frame}) = \mathbf{p}_T^{I^+}(\text{in Lab. frame})$
- $\mathbf{p}_T^{I^-*}(\text{in anti-top rest frame}) = \mathbf{p}_T^{I^-}(\text{in Lab. frame})$

⇒ The azimuthal angle:

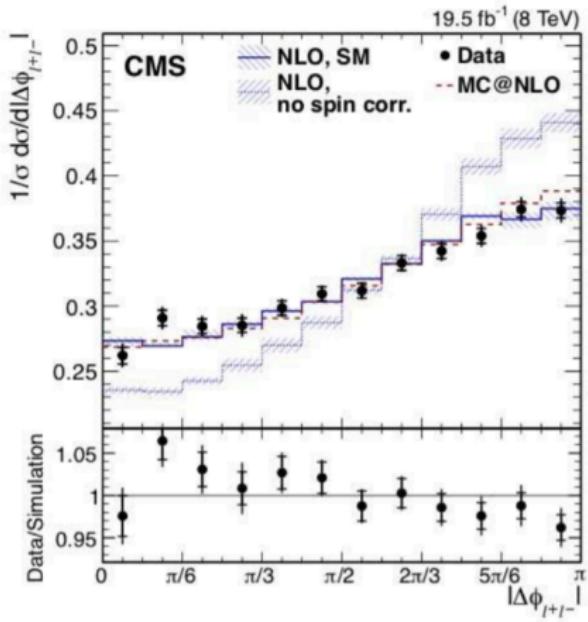
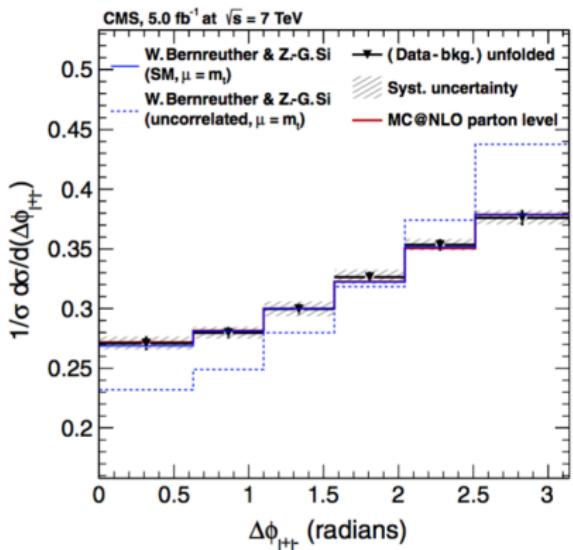
$$\Delta\phi_{||} = \cos^{-1} \left[ \hat{\mathbf{p}}_T^{I^+} \cdot \hat{\mathbf{p}}_T^{I^-} \right]$$

does not depend on reference fame

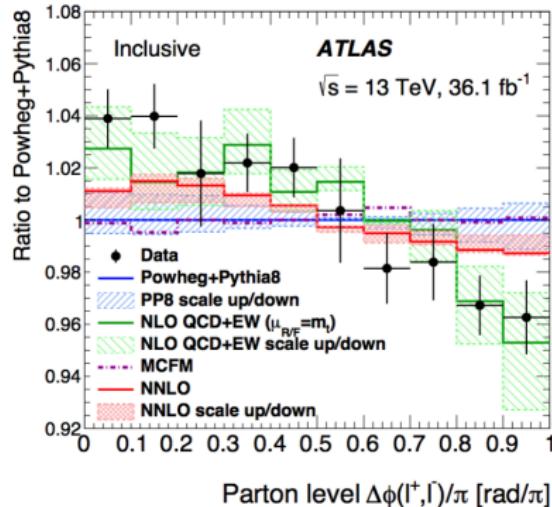
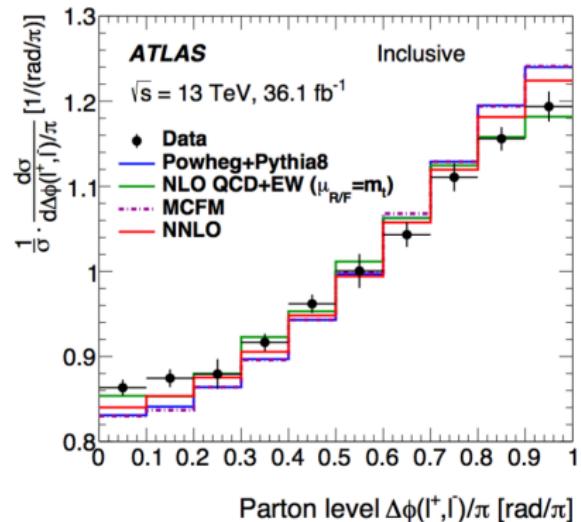
⇒ The distribution  $\frac{1}{\sigma} \frac{d\sigma}{d\Delta\phi_{||}}$  can be measured @LHC

without exact top quark momentum reconstruction!

# Azimuthal Angle $\Delta\phi_{\parallel}$ Distribution @7 & 8 TeV



# Azimuthal Angle $\Delta\phi_{\parallel}$ Distribution @13 TeV



## The measured azimuthal angle distribution

- agree with NLO QCD + mixed QCD-EW @ 7, 8 & 13 TeV
- higher than NLO MC generators & NNLO prediction @13TeV

## Effective NP Lagrangian for $t\bar{t}$ production

$$\mathcal{L}_{NP} = -\frac{g_s}{2m_t} \left[ \hat{\mu}_t \bar{t} \sigma^{\mu\nu} T^a t G_{\mu\nu}^a + \hat{d}_t \bar{t} i \sigma^{\mu\nu} \gamma_5 T^a t G_{\mu\nu}^a \right] + \dots$$

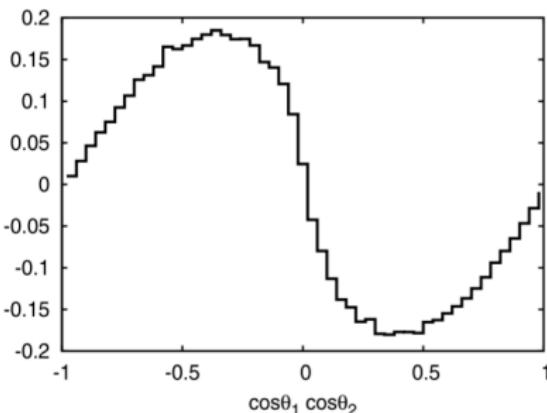
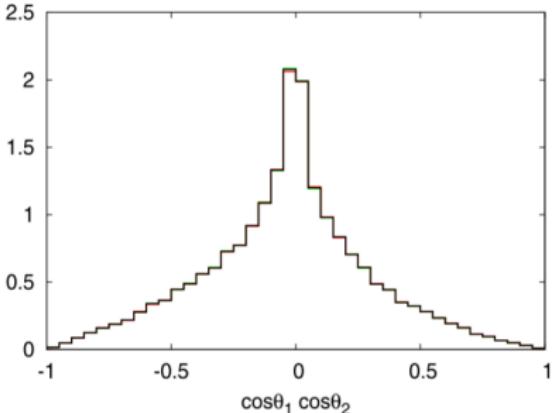
- $\hat{\mu}_t$ : chromo-magnetic (CMDM) dipole moments of the top quark
- $\hat{d}_t$ : chromo-electric (CEDM) dipole moments of the top quark

Top Quark Spin may be related to  $\hat{\mu}_t$  or  $\hat{d}_t$ , eg.,

$$C_{hel} = -9 < \cos \theta_1 \cos \theta_2 > = C_{hel}^{SM} + C_{hel}^{NP} \text{Re}[\hat{\mu}_t]$$

⇒ Precise measurement of  $C_{hel}$  can restrict  $\hat{\mu}_t$ , ...

## New Physics w.r.t top quark spin



Normalized distribution of SM and New Physics

Precise measurement can give constraint on  $\hat{\mu}_t, \dots$

CMS '14 @LHC 7 TeV :  $-0.043 \leq \hat{\mu}_t \leq 0.117$  @ 95% CL

- The measured top quark spin correlations and polarization w.r.t double angular agree with SM predictions @NLO
  - The measured azimuthal angle  $\Delta\phi_{\parallel}$  distributions
    - agree with SM predictions @NLO @LHC 7, 8 & 13 TeV
    - deviation from NLO MC generators & NNLO @13TeV
- ⇒ Top quark spin are correlated in  $t\bar{t}$  production and decay @LHC
- No obvious evidence for new physics w.r.t top quark spin
  - LHC is a top quark factory
    - ⇒ a precision era of top quark physics
    - ⇒ more studies on top quark physics are still necessary

Thanks a lot for your attention