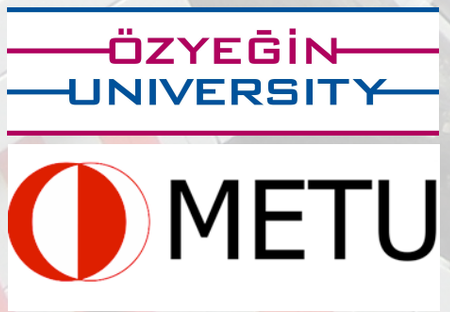
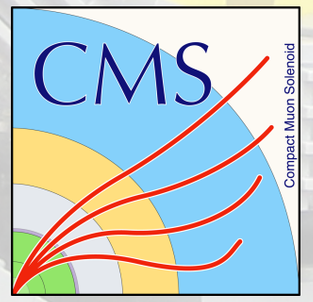
Spin correlations: Status of spin correlations in $pp \to t\bar{t}$

Bora Isildak
on behalf of the CMS Collaboration





ALPS2019: Fourth Alpine LHC Physics Summit
22-27 Apr 2019, Obergurgl (Austria)

Introduction and Motivation

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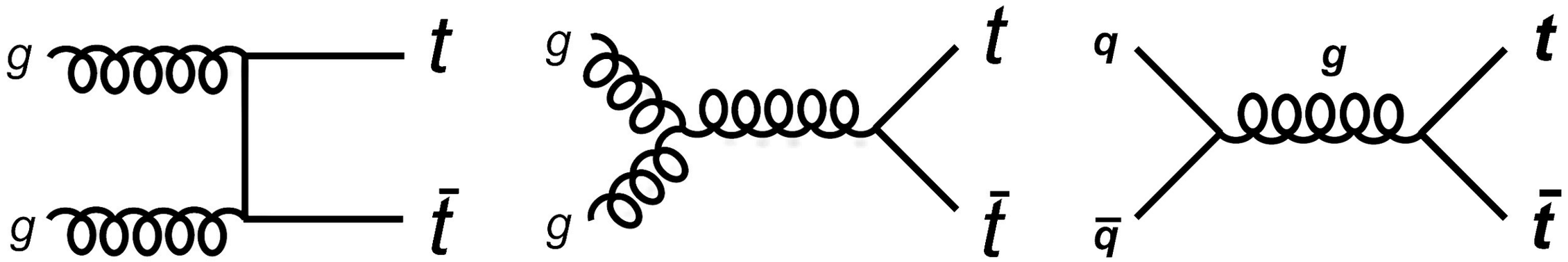
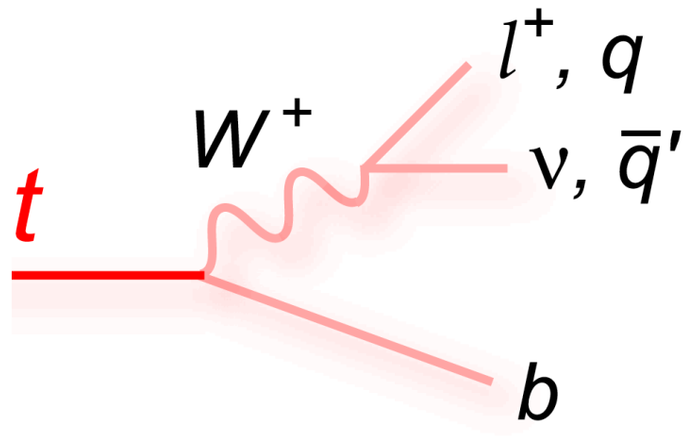


lifetime	$<$	QCD timescale	$\ll$	spin-flip timescale
10^{-25} s	$<$	10^{-24} s	$\ll$	10^{-21} s

- Top quark decays before hadronization.
- Spins does not decorrelate in this short time
- and the decay particles carry the spin information



Introduction and Motivation

- Top quarks produced by strong interaction are unpolarized but QCD causes top-quark spins to be correlated at production.

- For low $t\bar{t}$ invariant masses, the production is dominated by the fusion of pairs of gluons with the same helicities

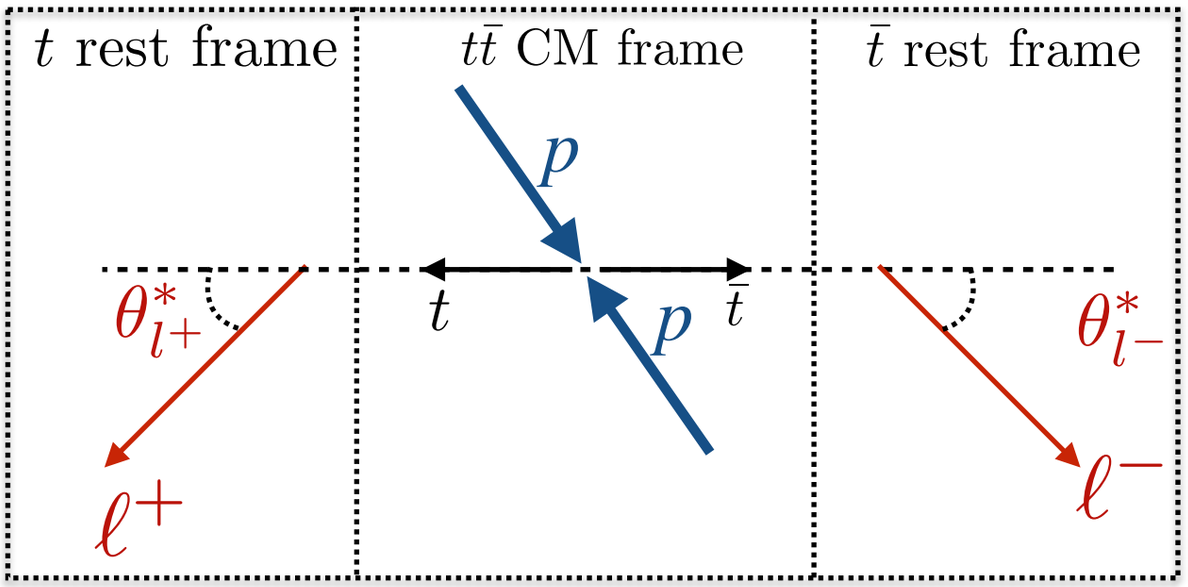
- There are BSM scenarios predicting polarized top quarks, hence affecting the spin correlation.

- Therefore, it is highly important to measure the spin correlations of top quark pairs

- Two methods to measure top spin correlations
  - Direct Measurement: Requires the reconstruction of the $t\bar{t}$ system
  - Indirect Measurement: Angle between two lepton $\Delta\phi(l^-l^+)$

experimentally preferred because lepton angles have excellent resolution

Observables



θ measured in helicity basis (lepton angle in parent top's rest frame, relative to parent top's direction in $t\bar{t}$ CM frame).

the variable $A_P^{\mathrm{CPV}} = (A_{P+} - A_{P-})/2$ measures possible polarization introduced by a maximally CP-violating process.

Polarization

$$P^{\pm} = 2A_{P\pm} \qquad A_{P\pm} = \frac{N\left(\cos\theta^{\star}_{\ell\pm} > 0\right) - N\left(\cos\theta^{\star}_{\ell\pm} < 0\right)}{N\left(\cos\theta^{\star}_{\ell\pm} > 0\right) + N\left(\cos\theta^{\star}_{\ell\pm} < 0\right)}$$

Correlation

$$A_{\Delta\phi} = \frac{N\left(|\Delta\phi_{\ell+\ell-}| > \pi/2\right) - N\left(|\Delta\phi_{\ell+\ell-}| < \pi/2\right)}{N\left(|\Delta\phi_{\ell+\ell-}| > \pi/2\right) + N\left(|\Delta\phi_{\ell+\ell-}| < \pi/2\right)}$$

indirect measurement of top spin correlation

Spin Correlation Coefficient

$$C_{\mathrm{hel}} = -4A_{c_1c_2} \qquad A_{c_1c_2} = \frac{N\left(c_1c_2 > 0\right) - N\left(c_1c_2 < 0\right)}{N\left(c_1c_2 > 0\right) + N\left(c_1c_2 < 0\right)}$$

$$c_1 = \cos\theta^{\star}_{\ell+} \text{ and } c_2 = \cos\theta^{\star}_{\ell-}$$

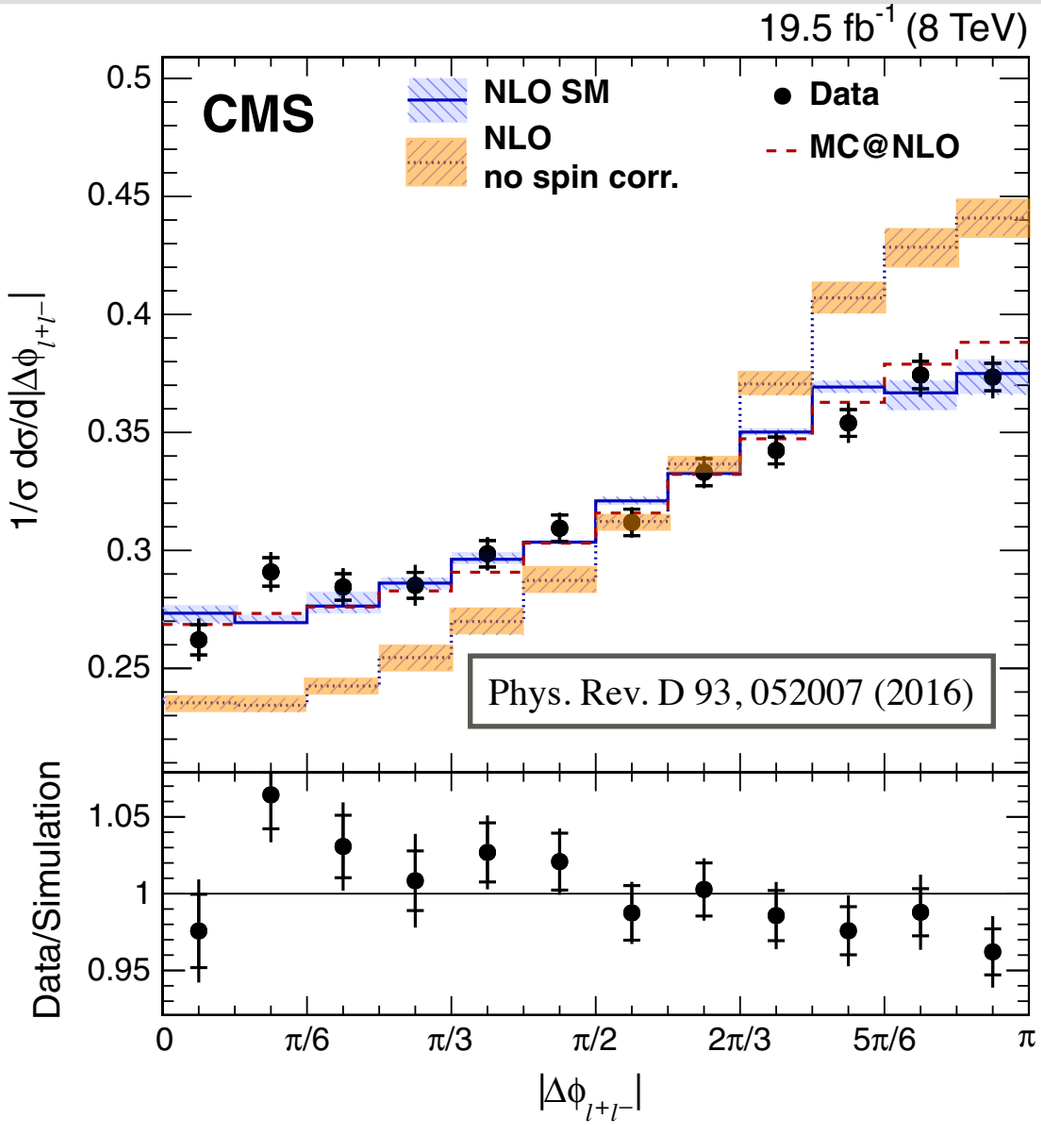
Spin Correlation Coefficient

$$D = -2A_{\cos\varphi} \qquad A_{\cos\varphi} = \frac{N(\cos\varphi > 0) - N(\cos\varphi < 0)}{N(\cos\varphi > 0) + N(\cos\varphi < 0)}$$

$$\varphi = \angle\left(\hat{\ell}_+, \hat{\ell}_-\right)$$

θ^*_{l+} and θ^*_{l-} are the helicity angles

CMS 8 TeV Results (unfolded to the parton level)



Asymmetry variable	Data (unfolded)	MC@NLO simulation	NLO, SM	NLO, no spin corr.
$A_{\Delta\phi}$	$0.094 \pm 0.005 \pm 0.012$	0.113 ± 0.001	$0.110^{+0.006}_{-0.009}$	$0.202^{+0.006}_{-0.009}$
$A_{\cos\varphi}$	$0.102 \pm 0.010 \pm 0.012$	0.114 ± 0.001	0.114 ± 0.006	0
$A_{c_1c_2}$	$-0.069 \pm 0.013 \pm 0.016$	-0.081 ± 0.001	-0.080 ± 0.004	0
A_P	$-0.011 \pm 0.007 \pm 0.028$	0	0.002 ± 0.001	...
A_P^{CPV}	$0.000 \pm 0.006 \pm 0.005$	0	0	...

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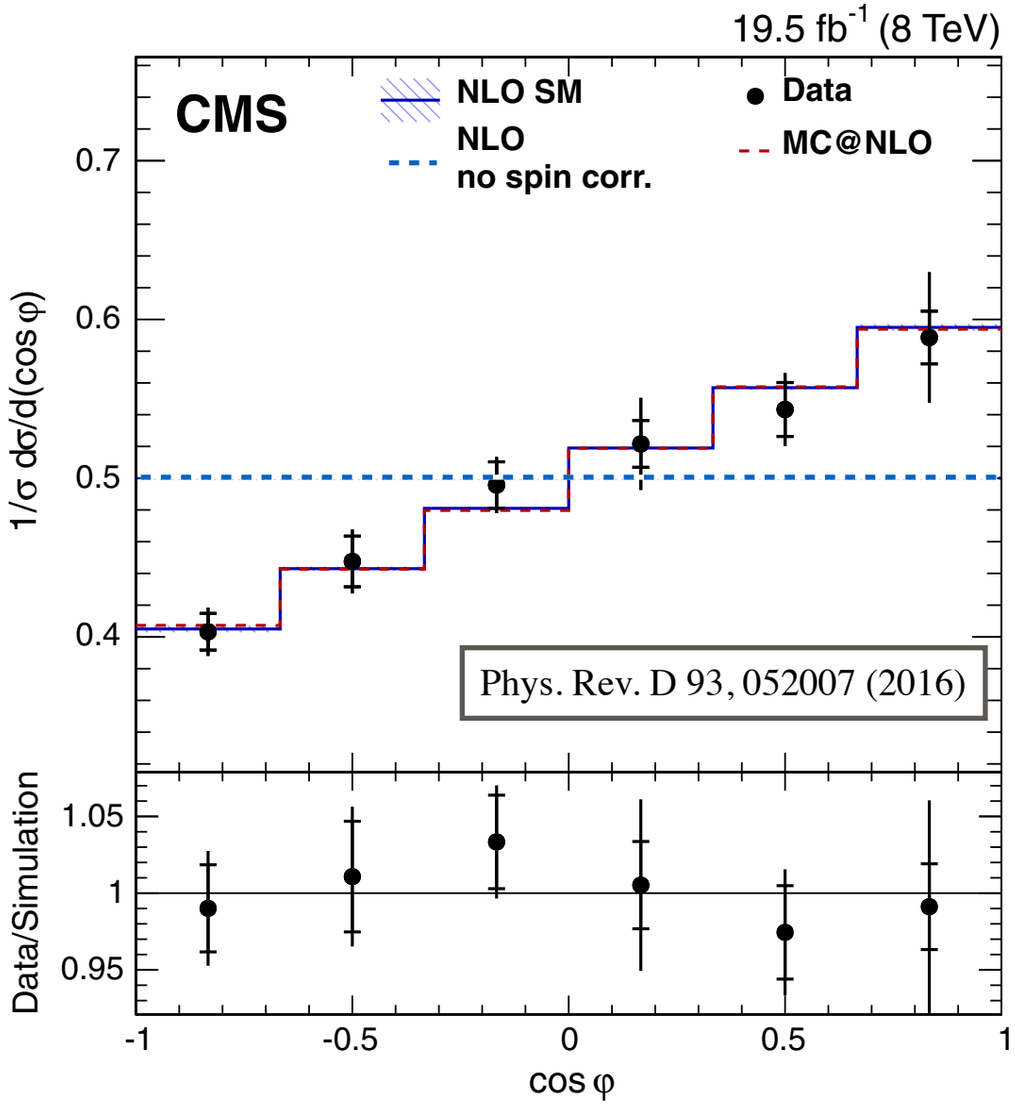

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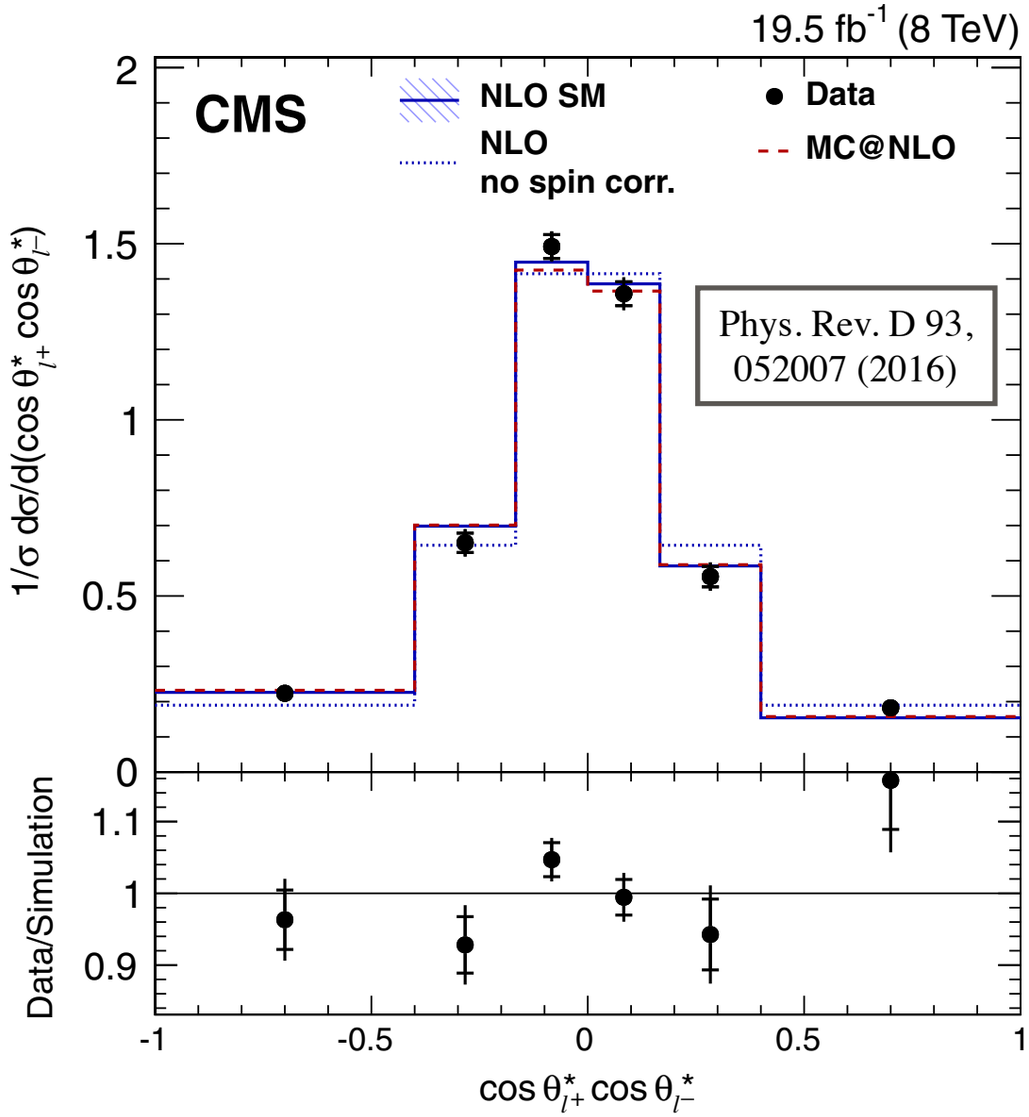

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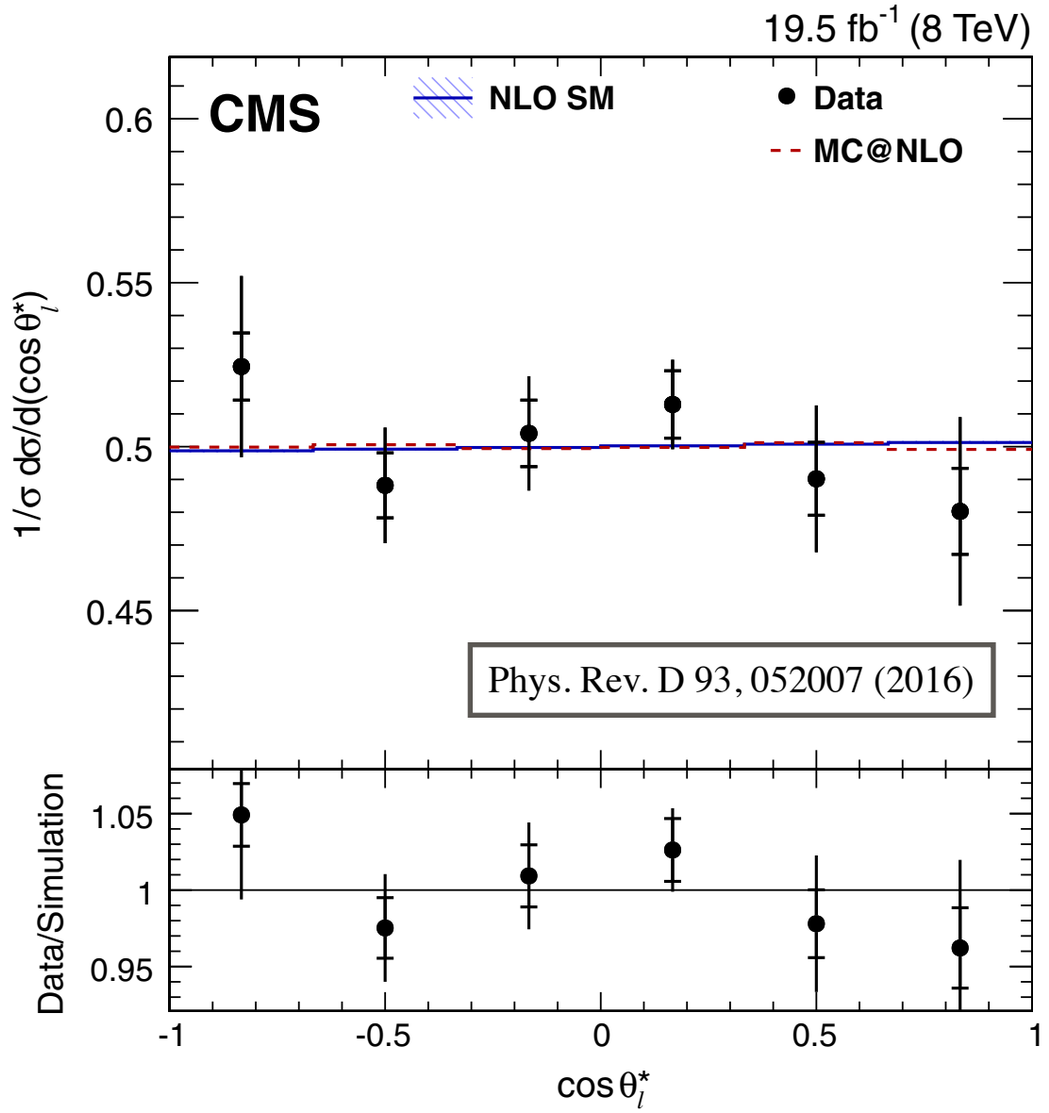

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CMS 8 TeV Results (unfolded to the parton level)

Fit spin correlation strength as **fraction f_{SM} of the SM prediction**

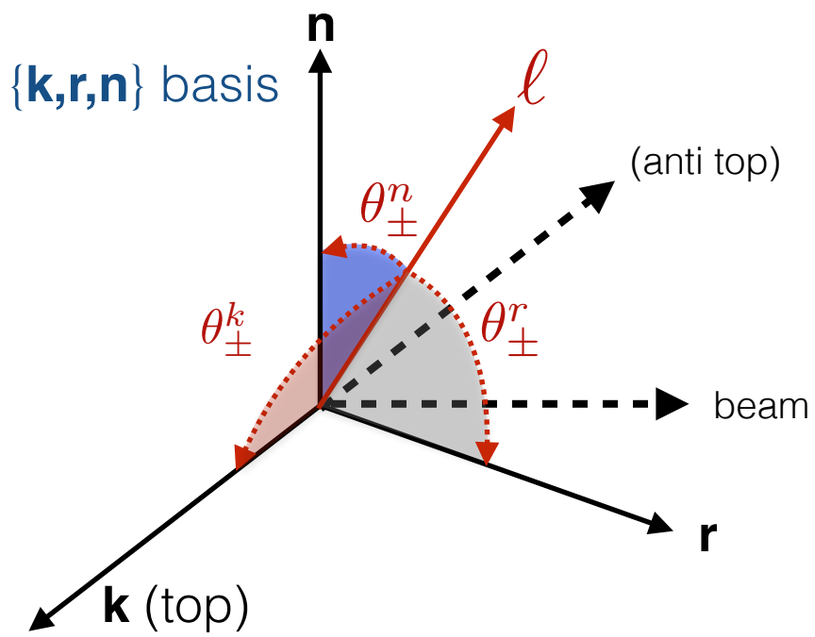
$$f = \frac{N^{\mathrm{t}}_{\mathrm{SM}}}{N^{\mathrm{t\bar{t}}}_{\mathrm{SM}} + N^{\mathrm{t\bar{t}}}_{\mathrm{uncor}}} \qquad f \in [0,1]$$

$$A^{\mathrm{meas}} = f A^{SM} + (1-f) A^{uncor}$$

Variable	$f_{\mathrm{SM}} \pm (\mathrm{stat}) \pm (\mathrm{syst}) \pm (\mathrm{theor})$	Total uncertainty
$A_{\Delta\phi}$	$1.14 \pm 0.06 \pm 0.13^{+0.08}_{-0.11}$	$^{+0.16}_{-0.18}$
$A_{\cos\varphi}$	$0.90 \pm 0.09 \pm 0.10 \pm 0.05$	± 0.15
$A_{c_1 c_2}$	$0.87 \pm 0.17 \pm 0.21 \pm 0.04$	± 0.27
$A_{\Delta\phi}$ (vs $M_{t\bar{t}}$)	$1.12 \pm 0.06 \pm 0.08^{+0.08}_{-0.11}$	$^{+0.12}_{-0.15}$

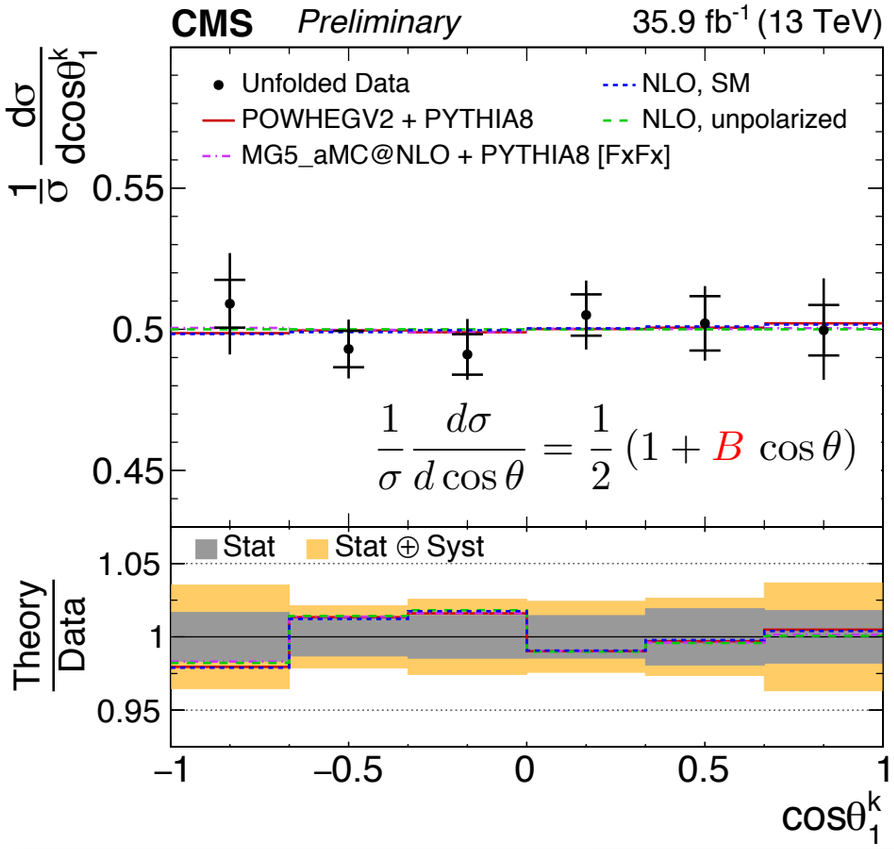
CMS 13 TeV Results (unfolded to the parton level)

See Afiq's Talk at YSF!

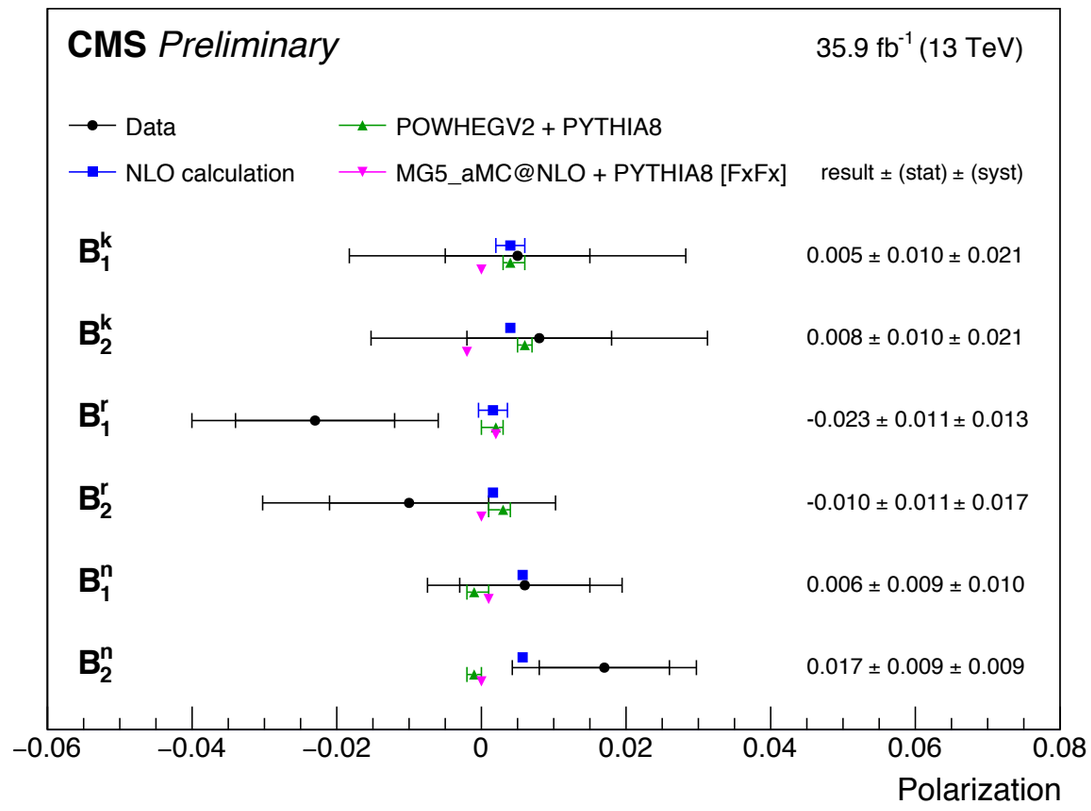


- Dilepton distribution **probes top spin in 3 dimensions**
- Leptons follow parent top spin (average polarization given by 3-vectors $\mathbf{B}^{+/-}$)
- Relative lepton directions follow 3x3 matrix **C** of spin correlation coefficients

$$\frac{1}{\sigma}\frac{d\sigma}{dx} = \frac{1}{2}(1 + [\mathrm{Coef.}]x)f(x)$$



CMS-PAS-TOP-18-006



CMS 13 TeV Results (unfolded to the parton level)

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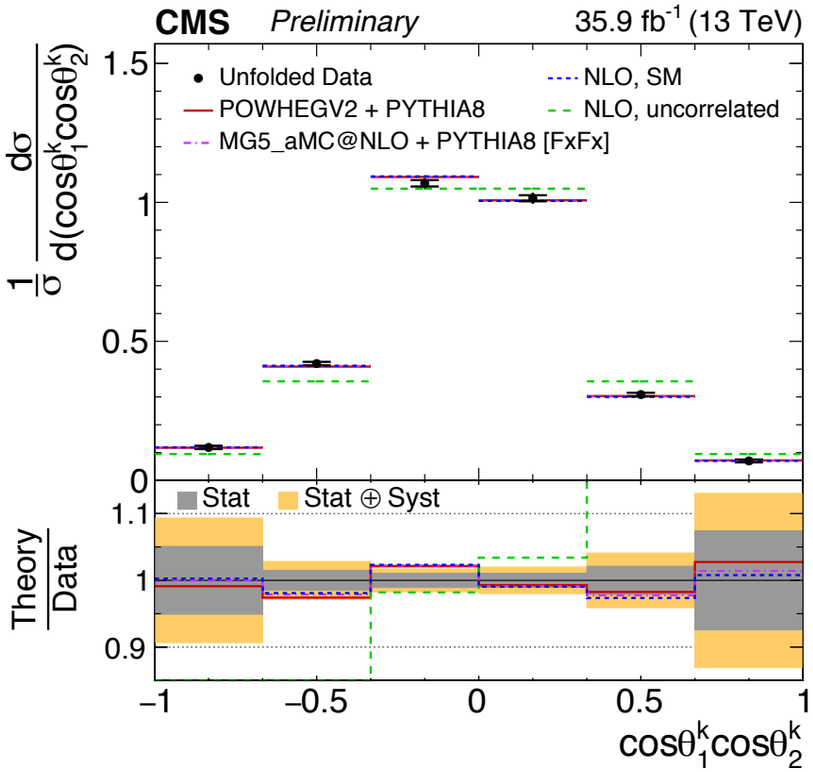
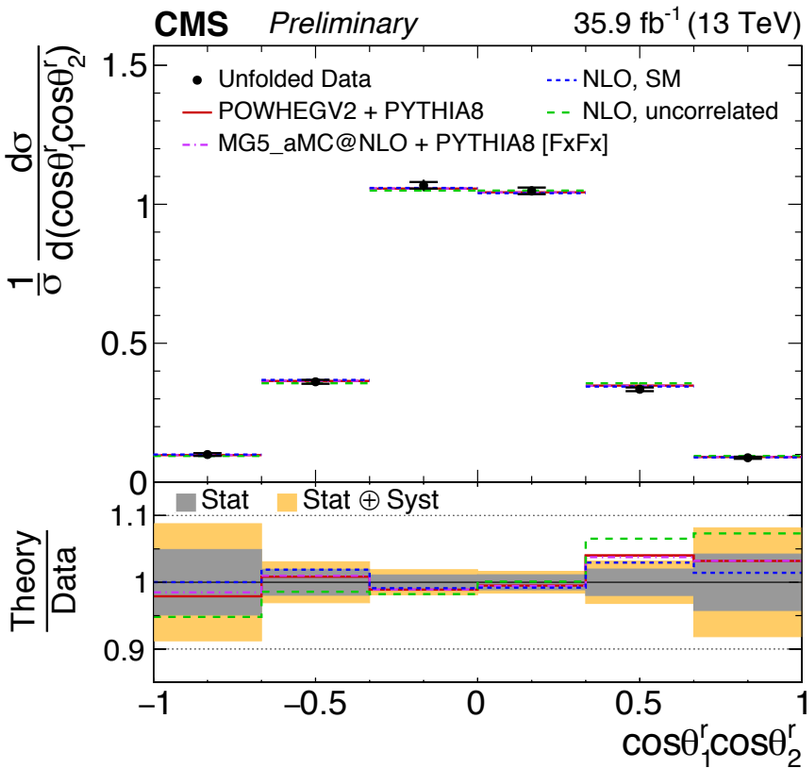
$$\frac{1}{\sigma}\frac{d\sigma}{d\cos\theta_1\cos\theta_2} = \frac{1}{2}\left(1 - C\cos\theta_1\cos\theta_2\right)\log\left(\frac{1}{|\cos\theta_1\cos\theta_2|}\right)$$



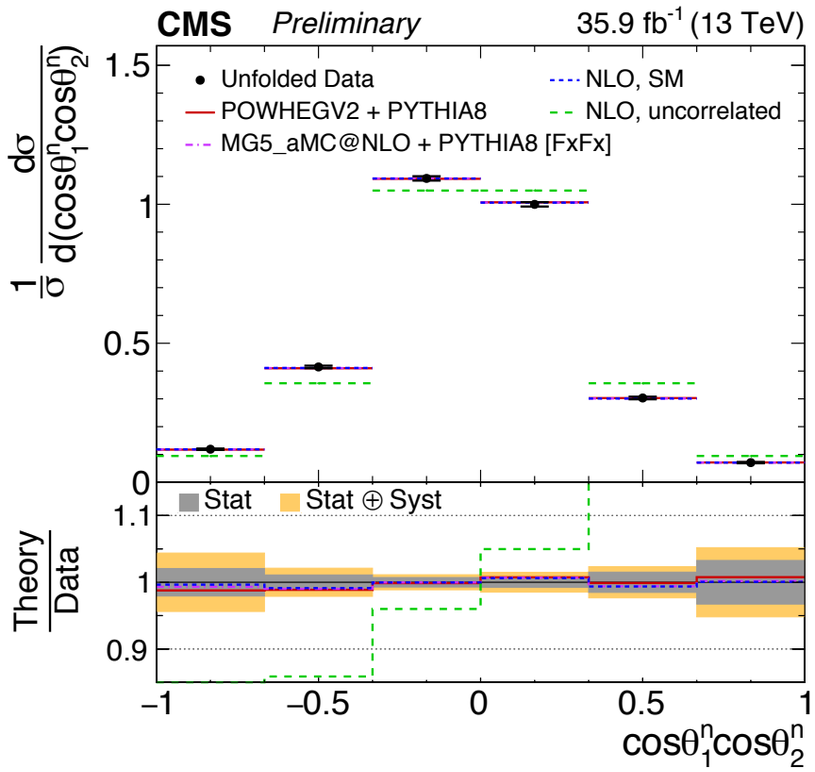
$C_{kk} = 0.30 \pm 0.02 \pm 0.03$

SM: 0.33



$C_{rr} = 0.08 \pm 0.02 \pm 0.02$

SM: 0.07



$C_{nn} = 0.33 \pm 0.01 \pm 0.02$

SM: 0.33

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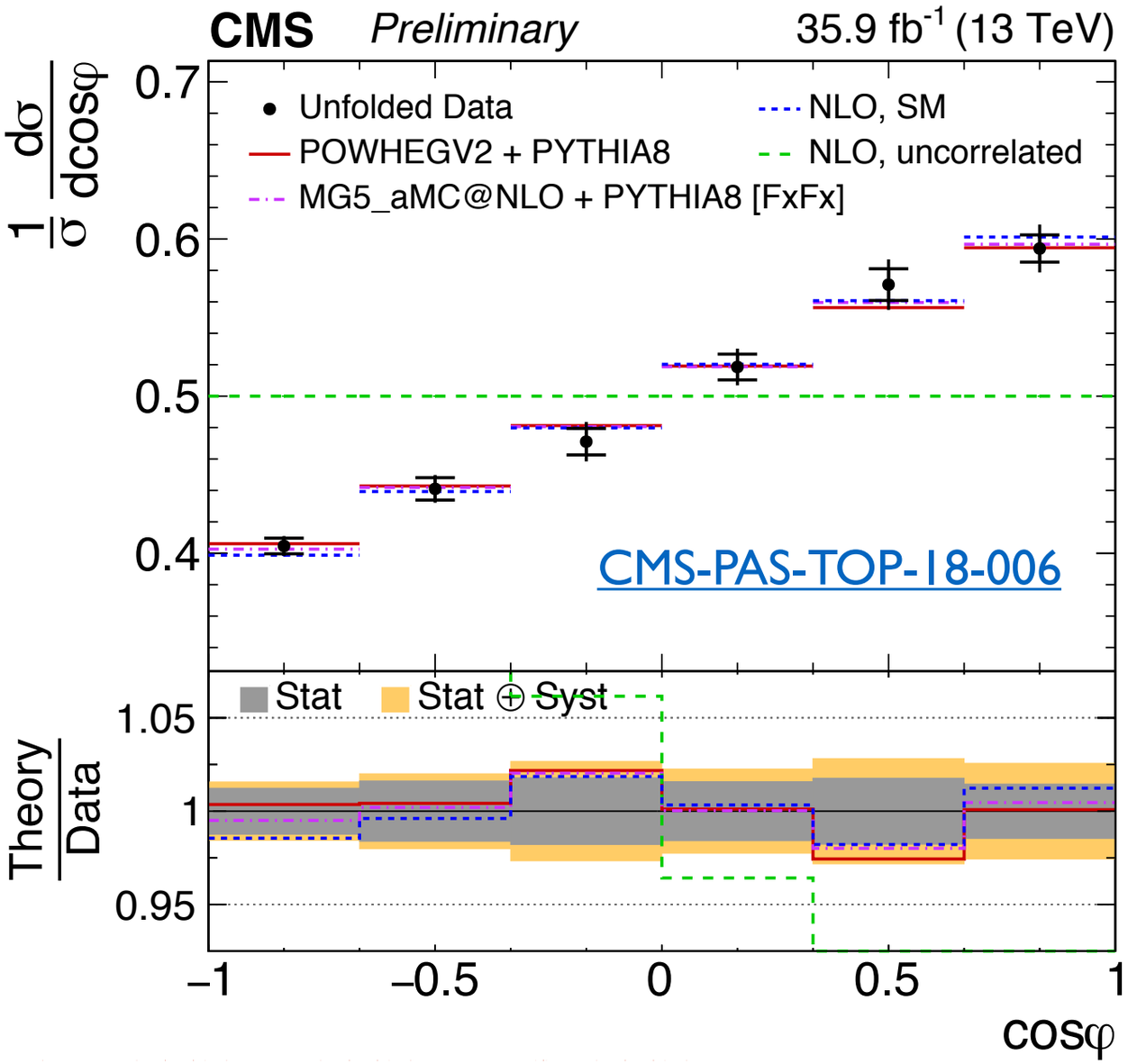


$$\frac{1}{\sigma}\frac{d\sigma}{d\cos\varphi} = \frac{1}{2}(1 - D\cos\varphi)$$

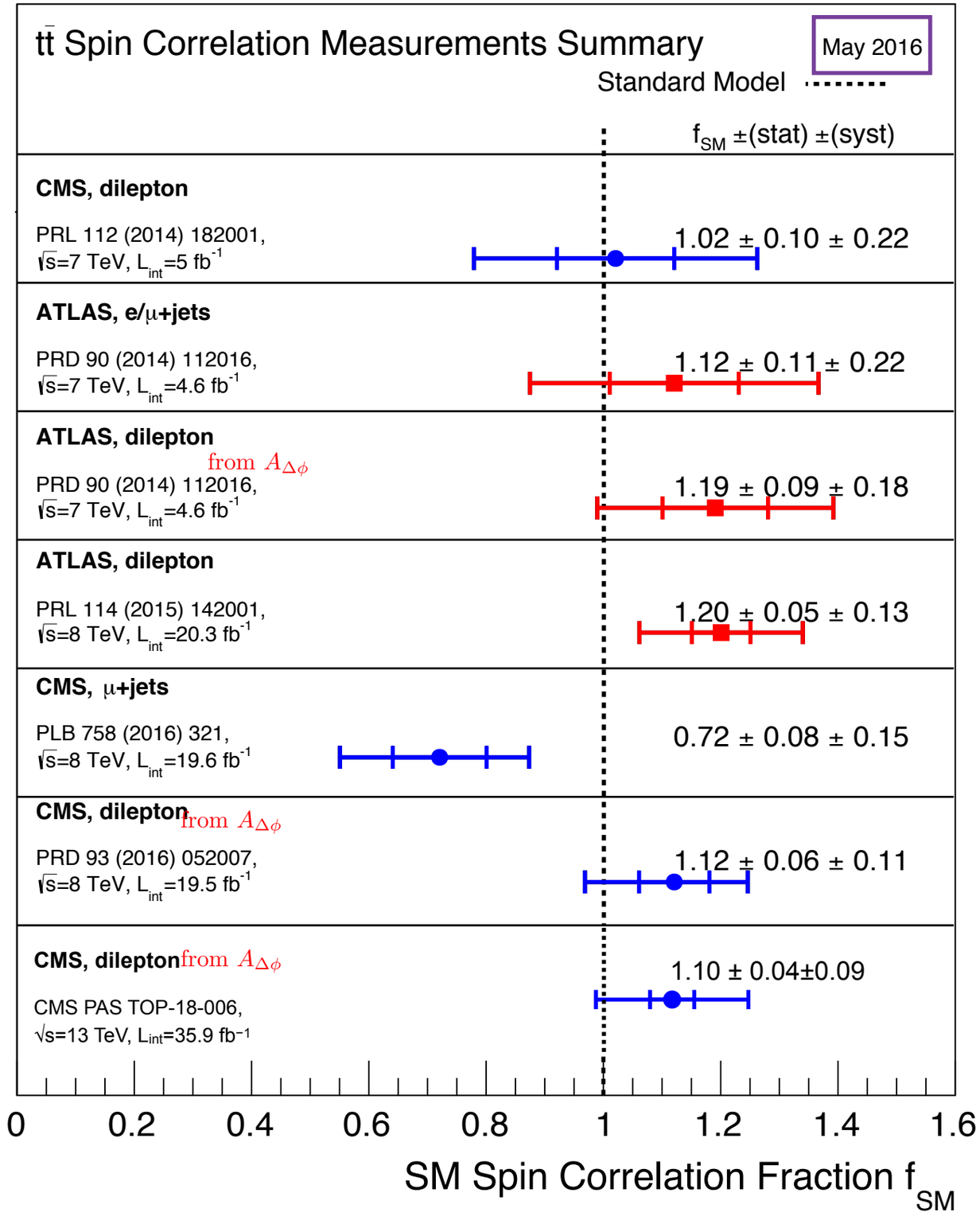
$$\mathrm{D} = -\left(\mathrm{C_{kk}} + \mathrm{C_{rr}} + \mathrm{C_{nn}}\right)/3$$

$$\mathrm{D} = -0.237 \pm 0.007 \pm 0.009$$

$$\mathrm{SM} : -0.243$$

$$f_{SM} = 0.97 \pm 0.05$$

Summary of Spin Correlation Fractions



New Physics?

L_{eff} is given in terms of chromo dipole couplings of the top quark to the gluon(s):

$$\mathcal{L}_{eff} = \mathcal{L}_{SM} - \frac{\tilde{\mu}_t}{2}\bar{t}\sigma^{\mu\nu}T^a t G^a_{\mu\nu} - \frac{\tilde{d}_t}{2}\bar{t}i\sigma^{\mu\nu}\gamma_5 T^a t G^a_{\mu\nu}$$

dimensionless chromo-moments:

$$\hat{\mu}_t \equiv \frac{m_t}{g_s}\tilde{\mu}_t, \quad \hat{d}_t \equiv \frac{m_t}{g_s}\tilde{d}_t$$

In the presence of a small new physics (NP) contribution such that $\mathrm{Re}\,(\hat{\mu}_t) \ll 1$, can be linearly expanded

$$\frac{1}{\sigma}\frac{d\sigma}{d\,|\Delta\phi_{\ell^+\ell^+}|} = \left(\frac{1}{\sigma}\frac{d\sigma}{d\,|\Delta\phi_{\ell^+\ell^-}|}\right)_{\mathrm{SM}} + \mathrm{Re}\,(\hat{\mu}_t)\left(\frac{1}{\sigma}\frac{d\sigma}{d\,|\Delta\phi_{\ell^+\ell^-}|}\right)_{\mathrm{NP}}$$

New Physics?

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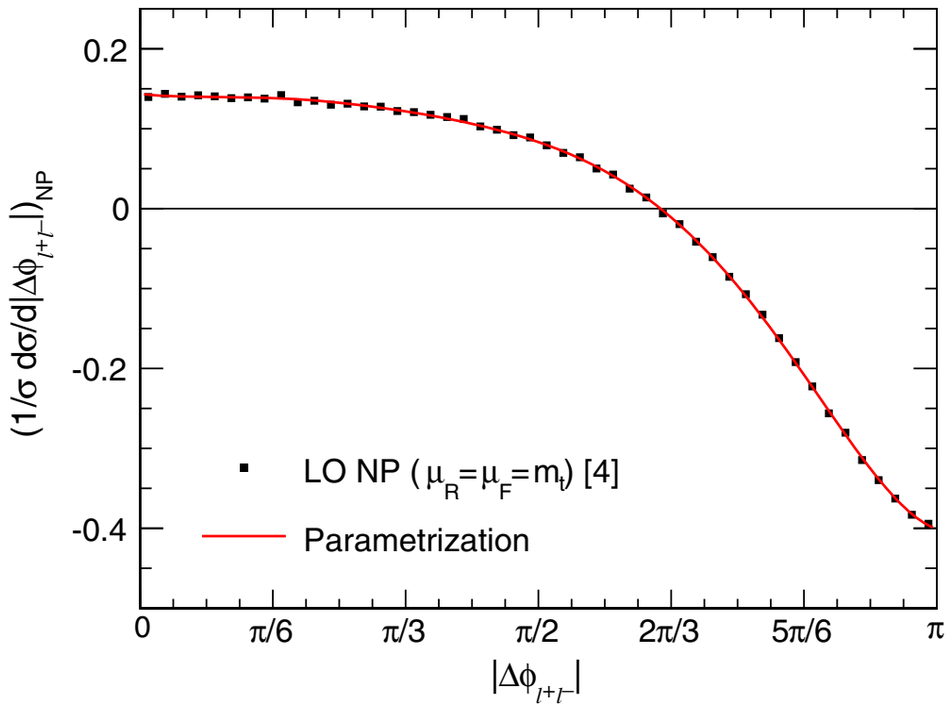

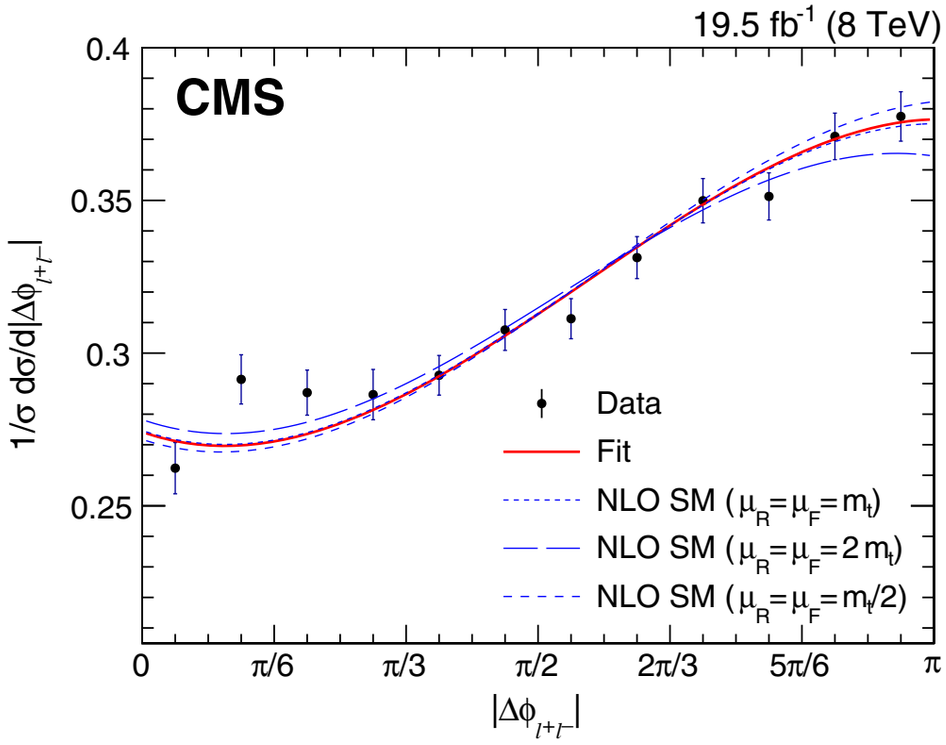

$$\mathrm{Re}\,(\hat{\mu}_t) = -0.006 \pm 0.024$$

corresponding 95% confidence level (C.L.) interval is $-0.053 < \mathrm{Re}\,(\hat{\mu}_t) < 0.042$

Also, $D = D_{\mathrm{SM}} + \mathrm{Re}\,(\hat{\mu}_t)\, D_{\mathrm{NP}}$

8 TeV	$M_{t\bar{t}} \geqslant 2m_t$	$M_{t\bar{t}} \leqslant 450$ GeV	$M_{t\bar{t}} > 450$ GeV
D_{SM} (NLOW) expanded	−0.228(5)	−0.336(2)	−0.130(5)
D_{SM} (NLOW) unexpanded	−0.217(11)	−0.330(6)	−0.120(14)
D_{NP}	−1.712(19)	−1.696(14)	−1.653(20)

W. Bernreuther, Z.G. Si / Physics Letters B 725 (2013) 115–122

$$\mathrm{Re}\,(\hat{\mu}_t) = -0.014 \pm 0.020$$

corresponding 95% confidence level (C.L.) interval is $-0.053 < \mathrm{Re}\,(\hat{\mu}_t) < 0.027$

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$$\text{Re}\,(\hat{\mu}_t) = -0.014 \pm 0.020$$

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Similarly P^{CPV} is related to $P^{\text{CPV}} = \text{Im}(\hat{d}_t) P^{\text{CPV}}_{\text{NP}}$

from W. Bernreuther, Z.G. Si / Physics Letters B 725 (2013) 115-122
$P^{\text{CPV}}_{\text{NP}} = 0.482 \pm 0.003$

$$\text{Im}(\hat{d}_t) = -0.001 \pm 0.034$$

with the corresponding 95% C.L. interval $-0.068 < \text{Im}(\hat{d}_t) < 0.067$

for 13 TeV constraints, again see Afiq's Talk at YSF!

Last

- Top quarks produced by strong interaction are unpolarized but QCD causes top-quark spins to be correlated at production.

- There are BSM scenarios predicting polarized top quarks, hence affecting the spin correlation.

- All measurements are in agreement with the SM expectations, and help constrain theories of physics beyond the SM.


Thanks !