# Measurements of Top Quark Polarizations and $t\bar{t}$ Spin Correlations in Dilepton Final States

Top Quark Physics at APS Division of Particles and Fields

Northeastern University

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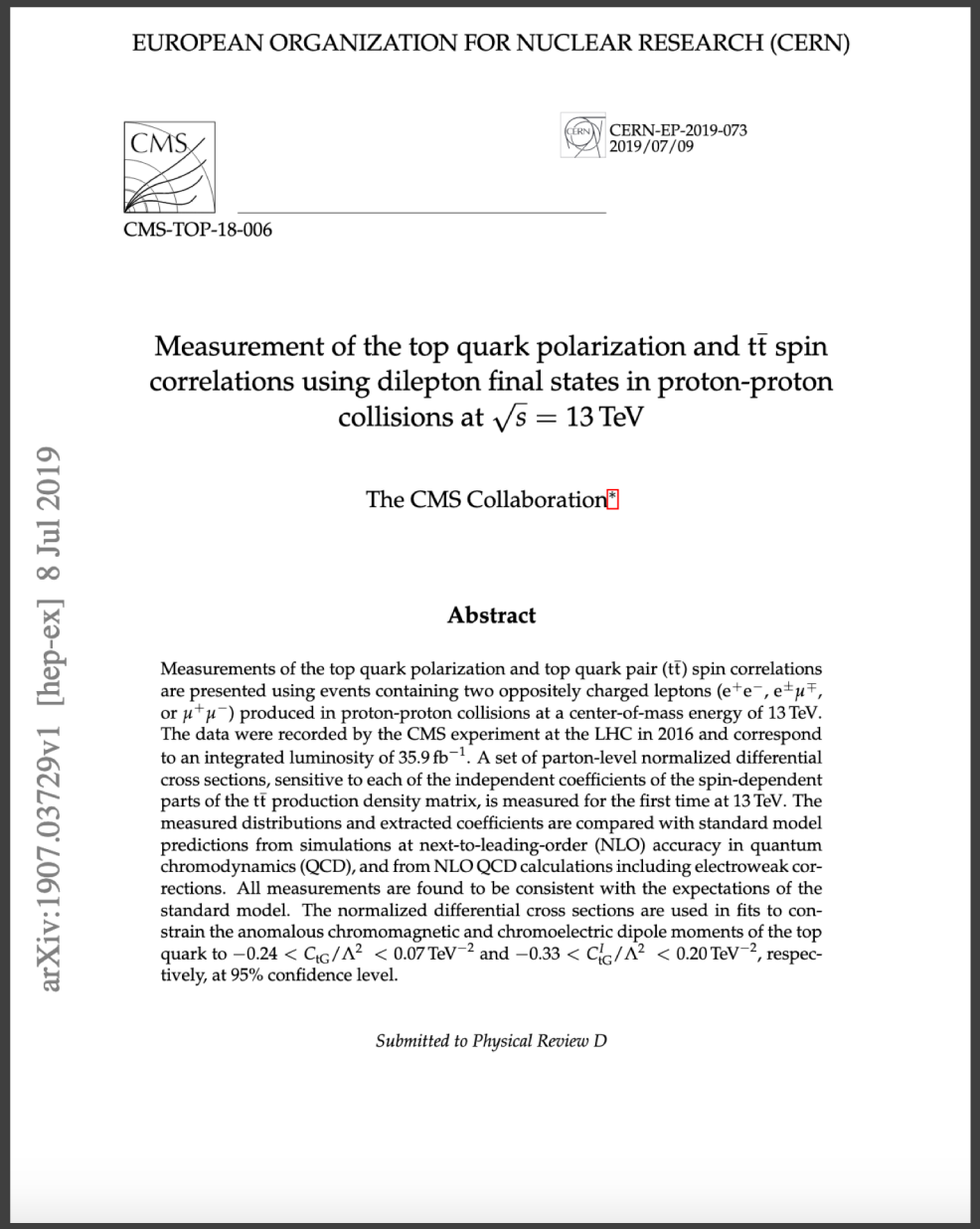

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Measurement of the top quark polarization and $t\bar{t}$ spin correlations using dilepton final states in proton-proton collisions at $\sqrt{s} = 13$ TeV

The CMS Collaboration*

**Abstract**

Measurements of the top quark polarization and top quark pair ($t\bar{t}$) spin correlations are presented using events containing two oppositely charged leptons ($e^+e^-$, $e^\pm\mu^\mp$, or $\mu^+\mu^-$) produced in proton-proton collisions at a center-of-mass energy of 13 TeV. The data were recorded by the CMS experiment at the LHC in 2016 and correspond to an integrated luminosity of 35.9 $fb^{-1}$. A set of parton-level normalized differential cross sections, sensitive to each of the independent coefficients of the spin-dependent parts of the $t\bar{t}$ production density matrix, is measured for the first time at 13 TeV. The measured distributions and extracted coefficients are compared with standard model predictions from simulations at next-to-leading-order (NLO) accuracy in quantum chromodynamics (QCD), and from NLO QCD calculations including electroweak corrections. All measurements are found to be consistent with the expectations of the standard model. The normalized differential cross sections are used in fits to constrain the anomalous chromomagnetic and chromoelectric dipole moments of the top quark to $-0.24 < C_{tG}/\Lambda^2 < 0.07\,\text{TeV}^{-2}$ and $-0.33 < C^I_{tG}/\Lambda^2 < 0.20\,\text{TeV}^{-2}$, respectively, at 95% confidence level.

*Submitted to Physical Review D*

# The Top Quark

- Heaviest known fundamental particle: $m_t = 172.44 \pm 0.13 \pm 0.47$ GeV  $m_{Au} = 187.9$ GeV $\sim$ 197 nucleons
  CMS Legacy PRD 93 (2016) 072004

- Extremely short lifetime: $\frac{1}{m_t} \sim \mathcal{O}(10^{-27}\text{s}) \ll \frac{1}{\Gamma(t\to Wb)} \sim \mathcal{O}(10^{-25}\text{s}) \ll \frac{1}{\Lambda_{QCD}} \sim \mathcal{O}(10^{-24}\text{s}) \ll \frac{m_t}{\Lambda^2} \sim \mathcal{O}(10^{-21}\text{s})$

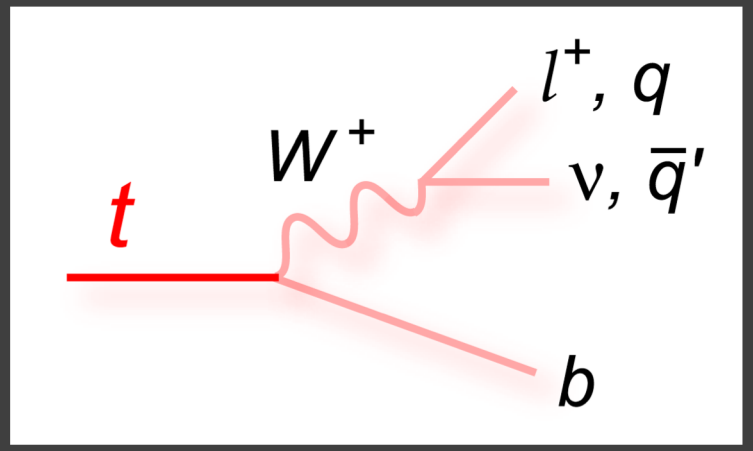
  **Production** **Decay** **Hadronization** **Spin Decorrelation**

- Spin information of the top quark is preserved in the angular distribution of its decay products

- Produced dominantly in pairs via gluon fusion ($gg \to t\bar{t}$) at 13 TeV LHC

- This analysis targets the dilepton final states ($\sim$9% BF) of $t\bar{t}$ decay:

$$t\bar{t} \to (b\, W^+)(\bar{b}\, W^-) \to (b\, \ell^+\, \upsilon_\ell)(\bar{b}\, \ell^-\, \bar{\upsilon}_\ell)$$



# $t\bar{t}$ Spin Density Matrix ($\boldsymbol{R}$) at Parton Level

- Squared matrix element for the $t\bar{t}$ production and decay:

**spin density matrix $\boldsymbol{R}$** related to on-shell $t\bar{t}$ production

$$\left|\mathcal{M}(gg/q\bar{q}) \to t\bar{t} \to (l^+\upsilon b)(l^-\bar{\upsilon}\bar{b})\right|^2 \sim Tr[\rho \boldsymbol{R} \bar{\rho}]$$

**decay density matrix** $\rho/\bar{\rho}$

- $\boldsymbol{R}$ can be decomposed into the spin space of $t$ and $\bar{t}$ using a basis of Pauli matrices:

$$\boldsymbol{R} \propto \widetilde{\boldsymbol{A}}\, \mathbb{I} \otimes \mathbb{I} + \widetilde{\boldsymbol{B}}_i^+\, \sigma^i \otimes \mathbb{I} + \widetilde{\boldsymbol{B}}_i^-\, \mathbb{I} \otimes \sigma^i + \widetilde{\boldsymbol{C}}_{ij}\, \sigma^i \otimes \sigma^j$$

Constant that characterizes spin-averaged production cross-section at parton level

3-vectors that characterize the net degree of **top quark/antiquark polarization** along each of the axes

3 x 3 matrix elements that characterizes the **correlation between the top/anti-top spins** along each pair of axes

Aim: Measurement of all the independent coefficients of the spin-dependent parts of the $t\bar{t}$ production density matrix in the dileptonic channel

# Helicity Basis: Spin Quantization Axes $\{\hat{k}, \hat{r}, \hat{n}\}$

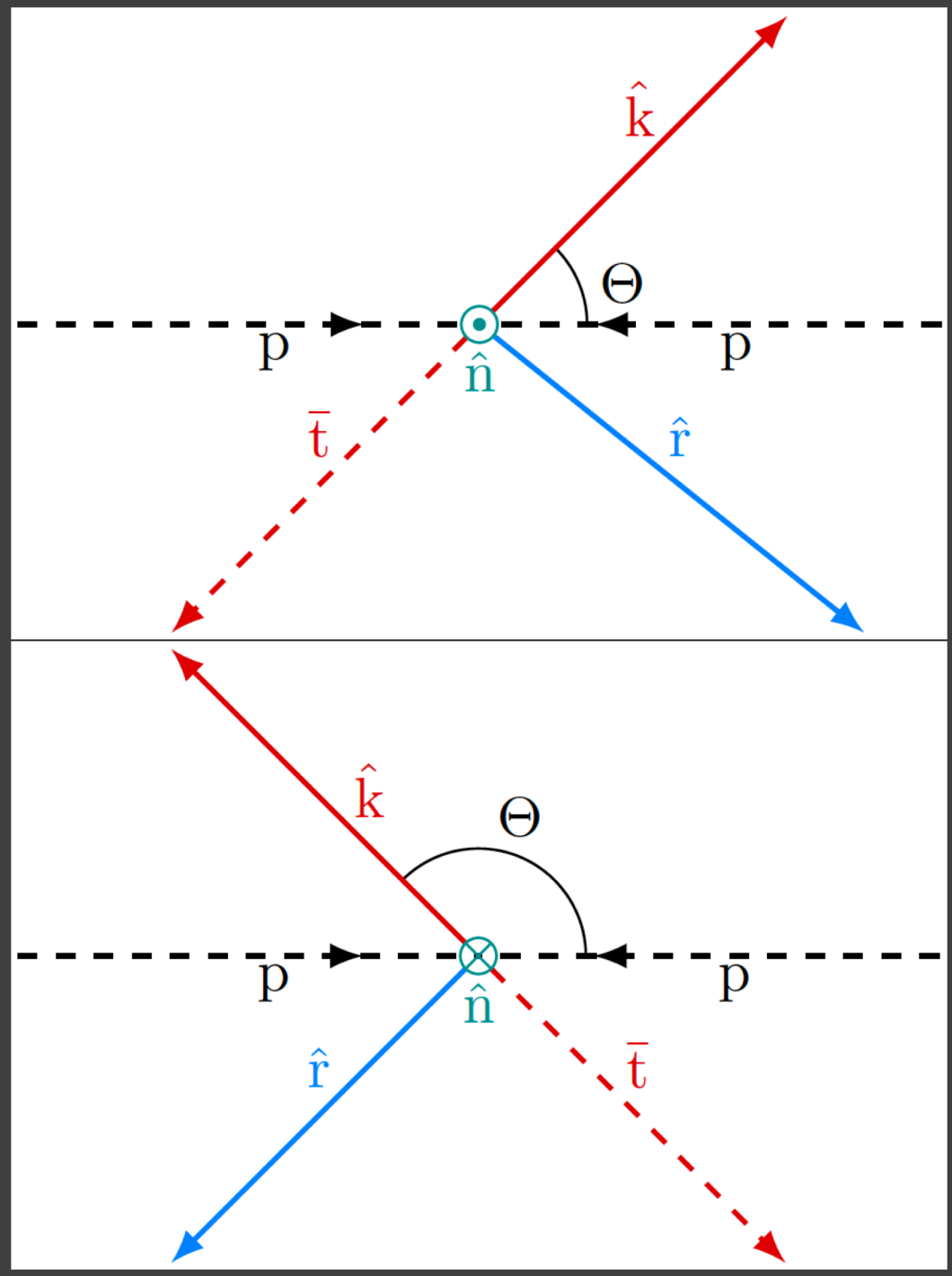
- Helicity $\hat{k}$-axis: top quark direction in $t\bar{t}$ rest frame
- Transverse $\hat{n}$-axis: transverse to production plane

$$\hat{n} = \frac{sign(\cos\Theta)}{\sin\Theta}(\hat{p}\times\hat{k})$$

- $\hat{r}$-axis: orthogonal to the other two axes

$$\hat{r} = \frac{sign(\cos\Theta)}{\sin\Theta}(\hat{p} - \hat{k}\cos\Theta)$$

- $\hat{p}$: direction of the incoming parton, i.e. the direction of the proton beam (z-direction in the laboratory frame)
- $\Theta$: top quark scattering angle in $t\bar{t}$ rest frame



# Differential Cross Sections

- The polar angle double-differential distributions:

$$\frac{1}{\sigma}\frac{d\sigma}{d\cos\theta_1^i\, d\cos\theta_2^j} = \frac{1}{4}(1 + \boldsymbol{B_1^i}\cos\theta_1^i + \boldsymbol{B_2^j}\cos\theta_2^j - \boldsymbol{C_{ij}}\cos\theta_1^i\cos\theta_2^j)$$

- A change of variable, if necessary, and integrating out one of the angles yield single-differential cross sections:

$$\frac{1}{\sigma}\frac{d\sigma}{d\cos\theta_1^i} = \frac{1}{2}(1 + \boldsymbol{B_1^i}\cos\theta_1^i)$$

Measure polarizations

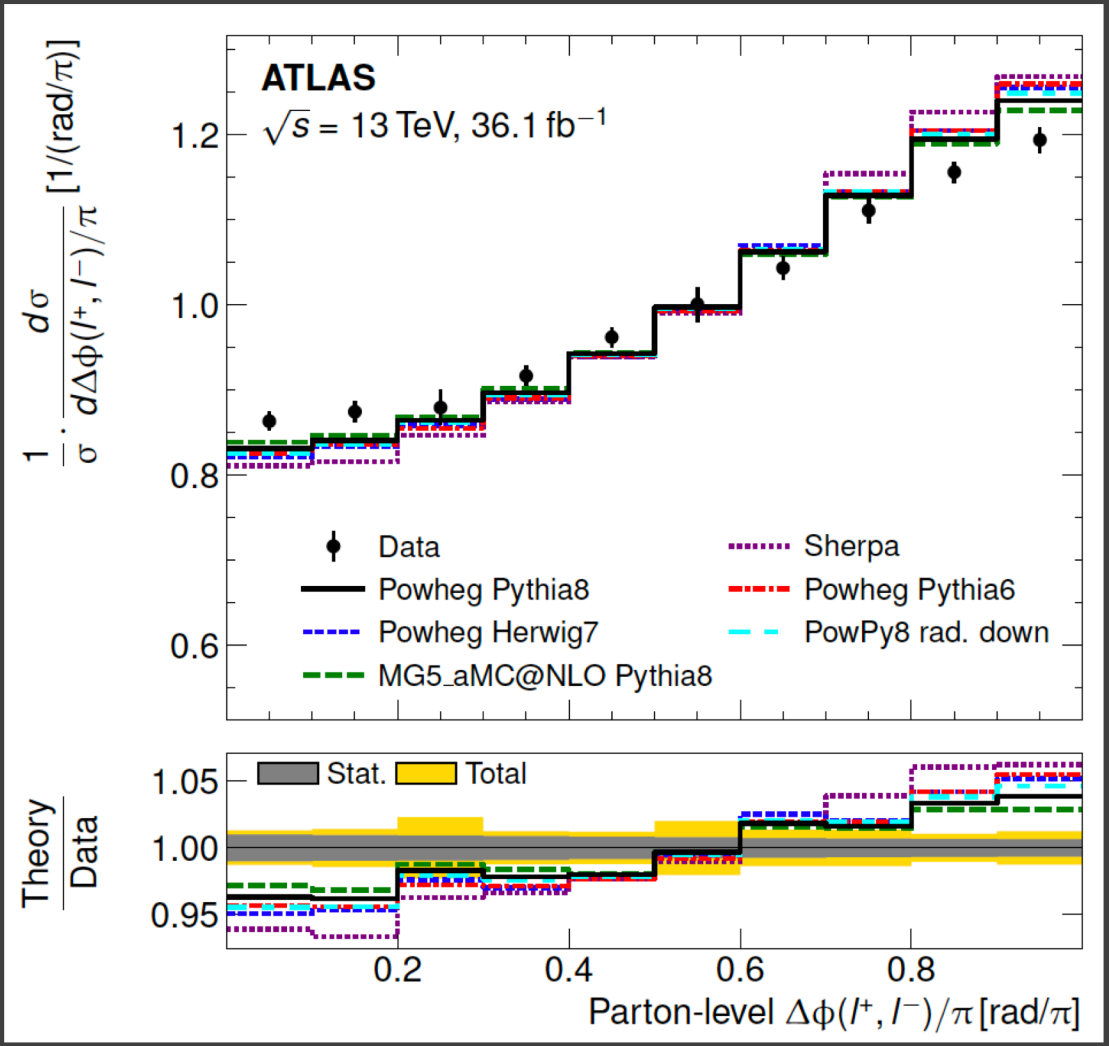
$$\frac{1}{\sigma}\frac{d\sigma}{d(\cos\theta_1^i\cos\theta_2^i)} = \frac{1}{2}[1 - \boldsymbol{C_{ii}}(\cos\theta_1^i\cos\theta_2^i)]\ln\frac{1}{|\cos\theta_1^i\cos\theta_2^i|}$$

Measure diagonal spin correlations

$$\frac{1}{\sigma}\frac{d\sigma}{d\cos\varphi} = \frac{1}{2}(1 + \boldsymbol{D}\cos\varphi) \quad \text{where} \quad \cos\varphi = \hat{l}_1\cdot\hat{l}_2 \quad \text{and} \quad \boldsymbol{D} = \frac{-Tr(\overleftrightarrow{C})}{3} = \frac{-1}{3}[C_{kk} + C_{rr} + C_{nn}]$$

- For today's talk, we will focus only on the measurements of $\boldsymbol{B_1^k}$, $\boldsymbol{C_{kk}}$, $\boldsymbol{D}$, and $A_{\Delta\phi_{ll}}$ from $|\boldsymbol{\Delta\phi_{ll}}| = \left|\left|\left|\phi_{l_1} - \phi_{l_2}\right| - \pi\right| - \pi\right|$

# Recent & Exciting Results from ATLAS

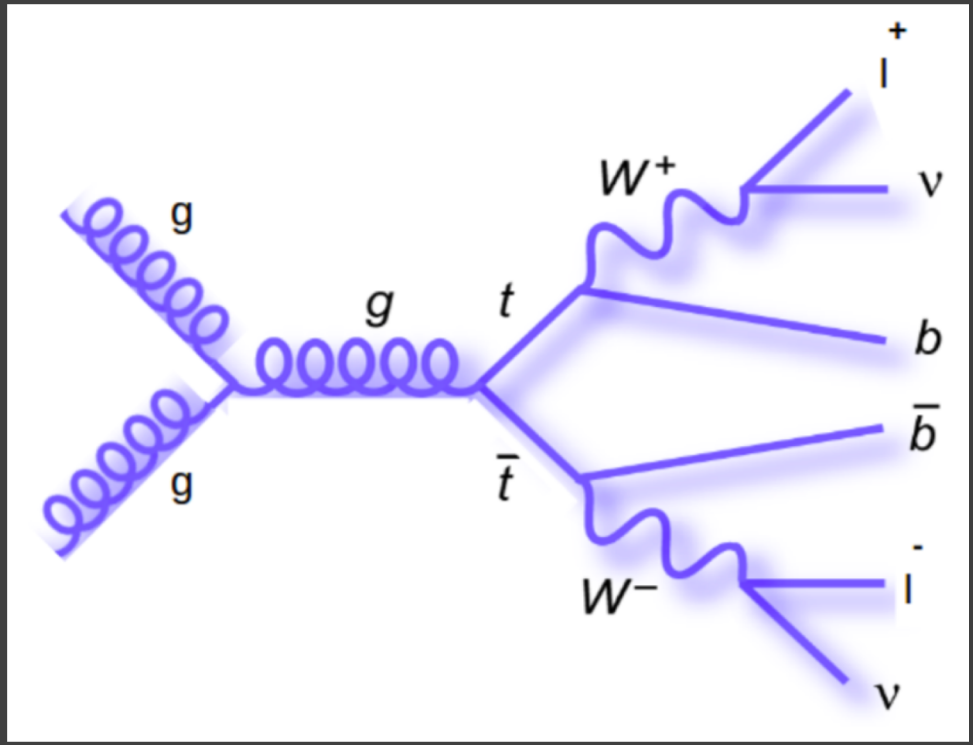



$|\Delta\phi_{ll}|$ distribution in data (parton level, full phase space)

$$|\Delta\phi_{ll}| = \left|\left||\phi_{l_1} - \phi_{l_2}| - \pi\right| - \pi\right|$$

- Provides an indirect measurement of spin correlations; does not require a full reconstruction of t and $\bar{t}$
- Shape comes from top kinematics and depends partly on the spin correlation coefficients
- Asymmetry: $A_{\Delta\phi_{ll}} = \frac{N(|\Delta\phi_{ll}| > 1/2) - N(|\Delta\phi_{ll}| < 1/2)}{N(|\Delta\phi_{ll}| > 1/2) + (|\Delta\phi_{ll}| < 1/2)}$
- Discrepancy between data and NLO simulations (~3 σ)

# Measurement Strategy




- Object and Event Selection
- Kinematic Reconstruction of $t\bar{t}$ system
- Binned Measurements of Single Differential Cross-Sections
- Background Subtraction and Normalization
- Simultaneous Unfolding of the Distributions using TUnfold to Correct for Migration and Acceptance
  - Obtain Parton-level, Normalized Differential Cross-Sections Extrapolated to the Full Phase Space
- Extraction of the $A_{\Delta\phi_{ll}}$, B, C, and D Coefficients
- Interpretation: Comparison to to SM Simulation, EFT, SUSY

# Signal, Backgrounds, and Event Yields

CMS 2016 Data at $\sqrt{s} = 13\ TeV$
$\mathcal{L} = 35.9\ fb^{-1}$

Signal: $\mathbf{t\bar{t}} \rightarrow (\mathbf{b}\ \boldsymbol{\ell}^{+}\ \boldsymbol{\upsilon}_{\ell})(\bar{\mathbf{b}}\ \boldsymbol{\ell}^{-}\ \bar{\boldsymbol{\upsilon}}_{\ell})$

- Two charged leptons ($e^{+}e^{-}$ or $e^{\pm}\mu^{\mp}$ or $\mu^{+}\mu^{-}$) originating from W boson decays, but not from $\tau$ decays
- Two jets originating from the hadronization of b-quarks (b-jets)
- Large $E_{T}^{miss}$

Main Backgrounds:

- $t\bar{t}$ events with leptonically decaying $\tau$ leptons ($t\bar{t}$ other)
- Single top quarks produced in association with a W boson ($tW$)
- $Z/\gamma^{*}$bosons produced with additional jets ($Z$+jets)

Other Backgrounds:

- W boson production with additional jets ($W$+jets)
- Diboson events ($WW, ZZ, WZ$)
- production of $t\bar{t}$ in association with $W$ or $Z$ boson ($t\bar{t}$+$W/Z$)

| | Fraction | Events |
|---|---|---|
| $t\bar{t}$ Signal | 0.788 | 206,177 |
| $t\bar{t}$ Other | 0.129 | 33,641 |
| $tW$ | 0.034 | 8,890 |
| $Z$+jets | 0.043 | 11,312 |
| Other | 0.006 | 1,564 |
| Total MC | 1 | 261,585 |
| Data | 0.977 | 255,646 |

# Unfolding with TUnfold

- Need to correct measured distributions for **Migration** and **Acceptance** before comparing to theoretical calculations

$\vec{x} = \boldsymbol{M} \cdot \boldsymbol{A} \cdot \vec{y}$ to be inverted with regularization $\vec{x}$ : Measured Bins $\vec{y}$ : True Bins

- Statistical extrapolation from fiducial phase space to full phase space
- Suppress statistical fluctuations by regularizing the difference between the unfolded distribution and the gen-level MC distribution of measured bins with respect to the SM expectation
- The distributions we measure are of particularly simple form at parton-level, depending on only one spin coefficient:

i.e. $$\frac{1}{\sigma}\frac{d\sigma}{d(\cos\theta_1^i \cos\theta_2^i)} = \frac{1}{2}[1 - \boldsymbol{C_{ii}}(\cos\theta_1^i \cos\theta_2^i)] \ln\frac{1}{|\cos\theta_1^i \cos\theta_2^i|}$$

- By multiplying the density by an appropriate factor before regularizing, i.e. $\left(\ln\frac{1}{|\cos\theta_1^i \cos\theta_2^i|}\right)^{-1}$, we can make the variation with respect to the coefficient exactly linear and therefore the regularization cannot bias the measured coefficient
- Use 6 uniform bins for each distribution, roughly matching the reconstruction resolution

# Systematic Uncertainties

Systematic Uncertainties for Measurement of $C_{kk}$

## Experimental

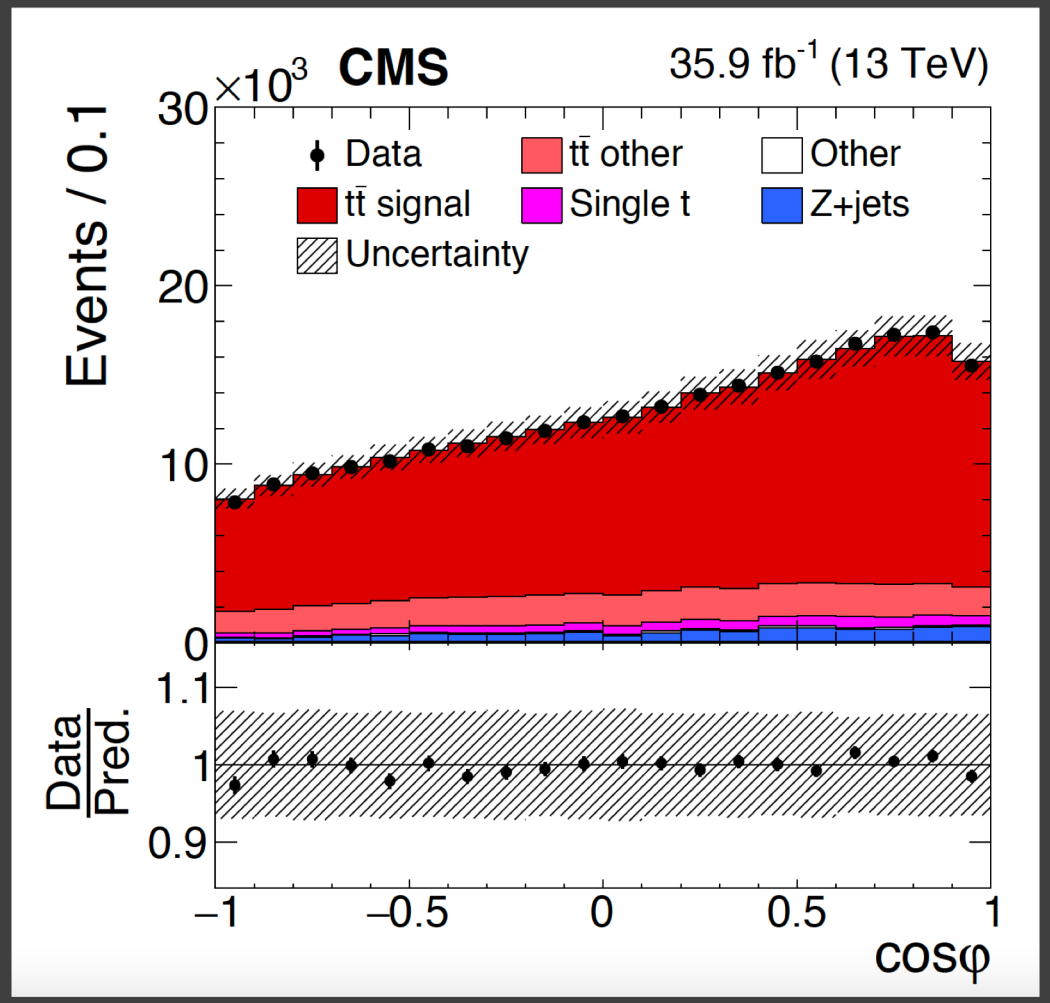
- Background Cross Section ~ 6 %
- Jet Energy Scale ~ 4 %
- B-Tagging ~ 1 %
- Kinematic Reconstruction Efficiency ~ 1 %
- Lepton ID and Selection ~ 1 %
- Unclustered Energy ~ 1 %
- Pile-up Reweighting ~ 0.5 %
- Jet Energy Resolution ~ 0.5 %
- Trigger Efficiency ~ 0 %
- (Luminosity and Branching Fraction)

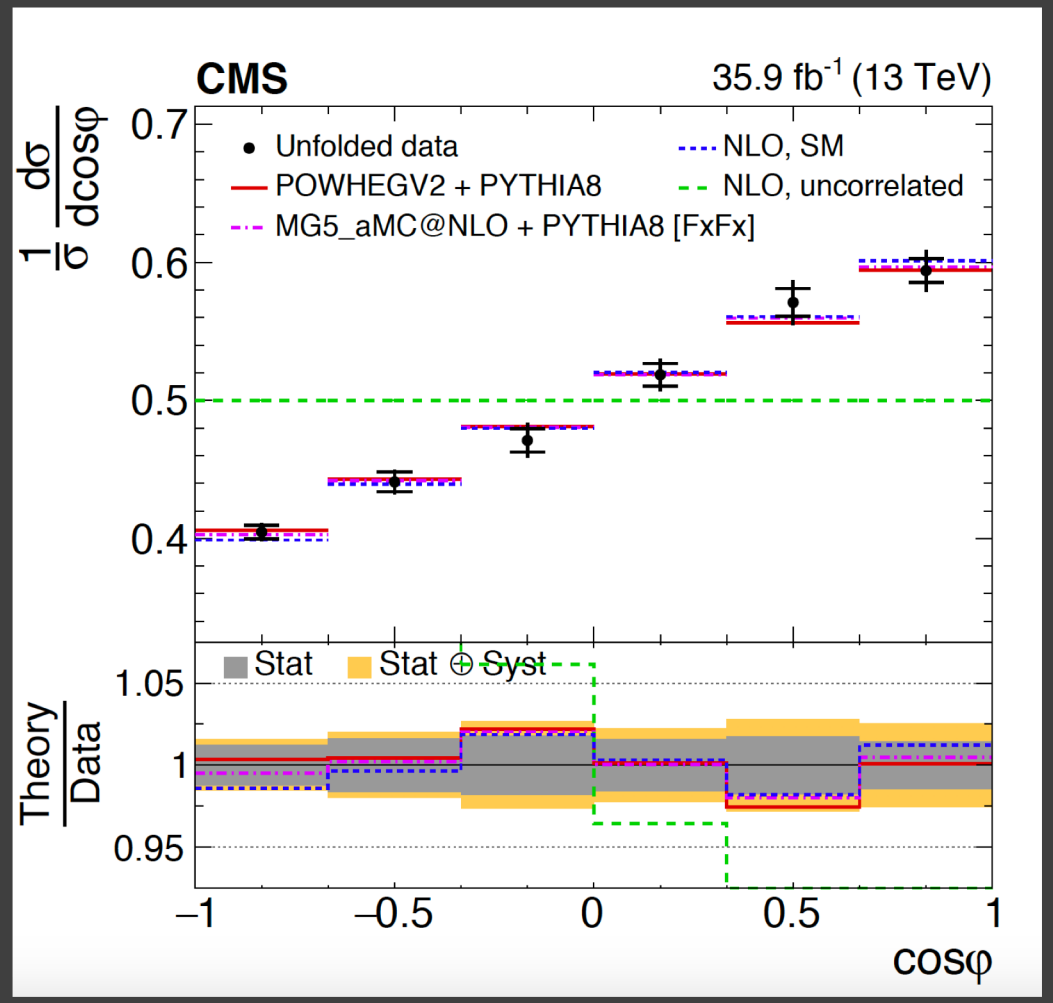
## Theoretical

- b-fragmentation ~ 5 %
- Scales ($\mu_R$ and $\mu_F$) ~ 4 %
- Top $p_T$ ~ 3 %
- UE-tune ~ 3 %
- PDF (replicas and $\alpha_s$) ~ 2 %
- Color reconnection ~ 2 %
- ME-PS matching ~ 1%
- Semi-leptonic BRs of b hadrons ~ 0 %
- Top Mass ~ 0 %
- $\alpha_s$ for ISR and FSR ~ 0 %

# Results:

$$\frac{1}{\sigma}\frac{d\sigma}{d\cos\varphi} = \frac{1}{2}(1 + D\cos\varphi) \qquad \cos\varphi = \hat{l}_1 \cdot \hat{l}_2 \qquad D = \frac{-Tr(\overleftrightarrow{C})}{3} = \frac{-1}{3}[C_{kk} + C_{rr} + C_{nn}]$$



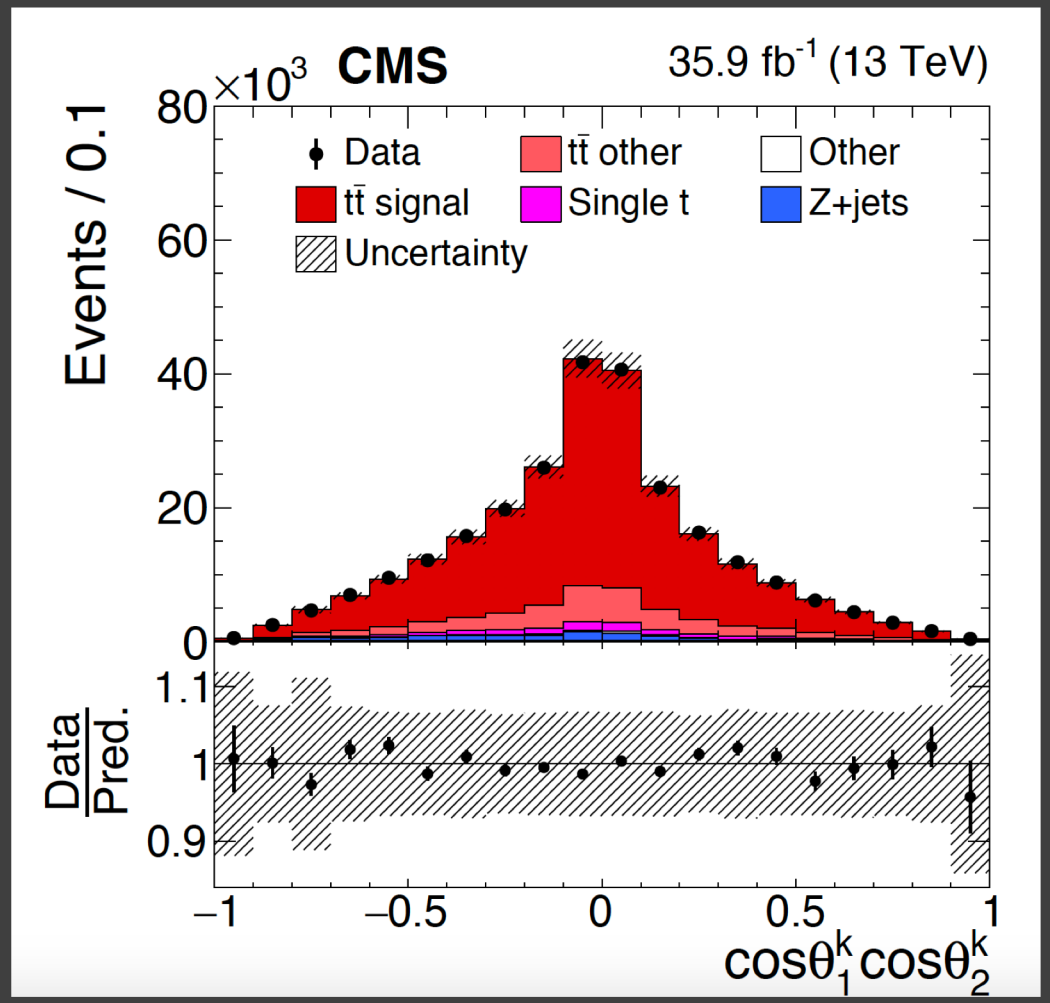



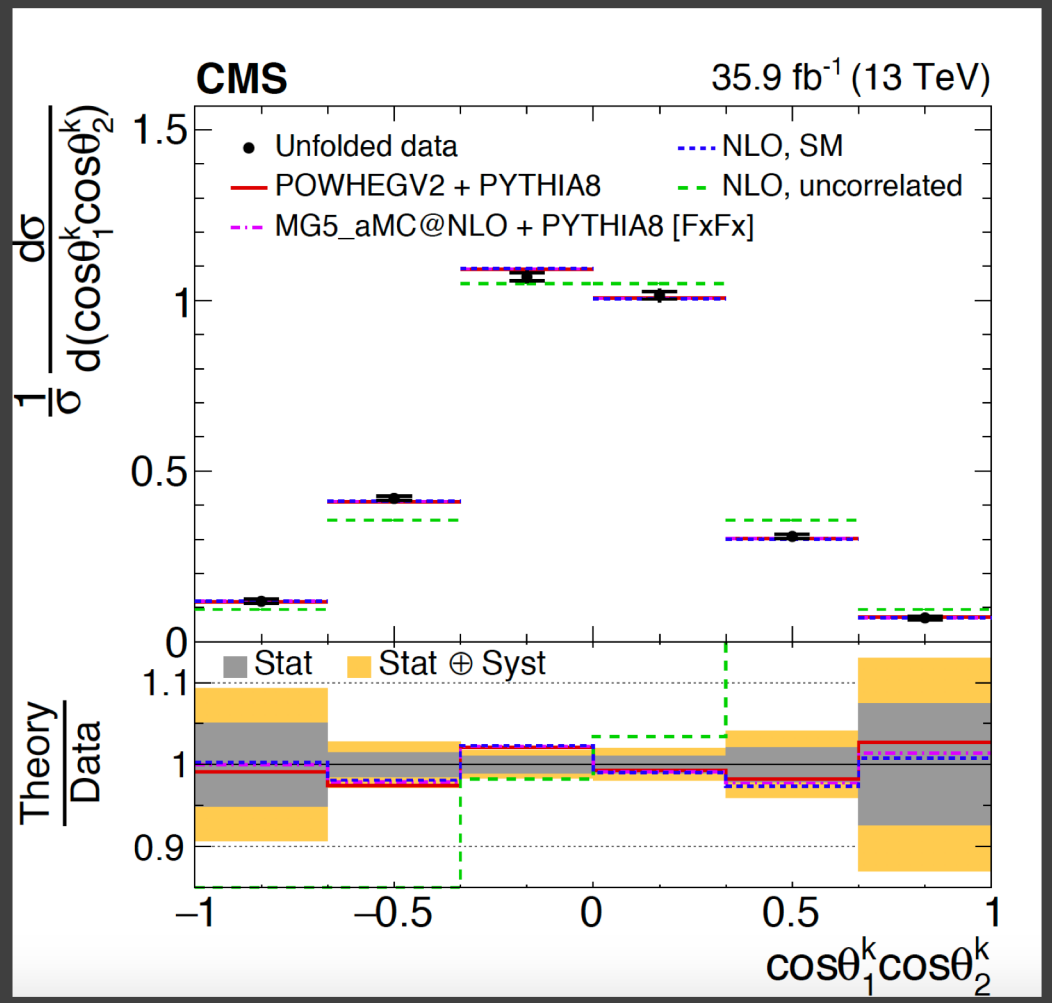

Most precise single variable!
Dominant systematics: Background and Top $p_T$ modelling

$D = -0.237 \pm 0.007 \pm 0.009$
SM NLO: - 0.243

# Results:

$$\frac{1}{\sigma}\frac{d\sigma}{d(\cos\theta_1^k\cos\theta_2^k)} = \frac{1}{2}[1 - C_{kk}(\cos\theta_1^k\cos\theta_2^k)]\ln\frac{1}{|\cos\theta_1^k\cos\theta_2^k|}$$



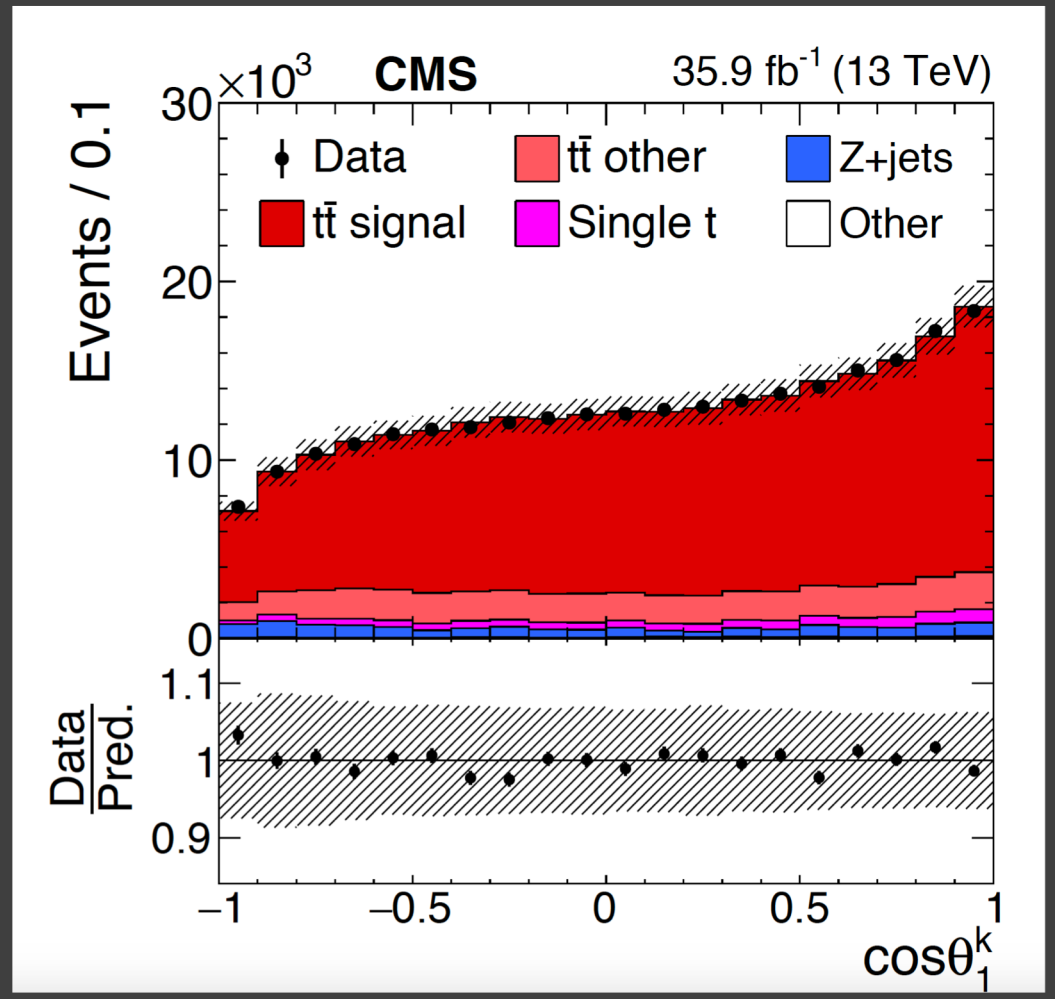



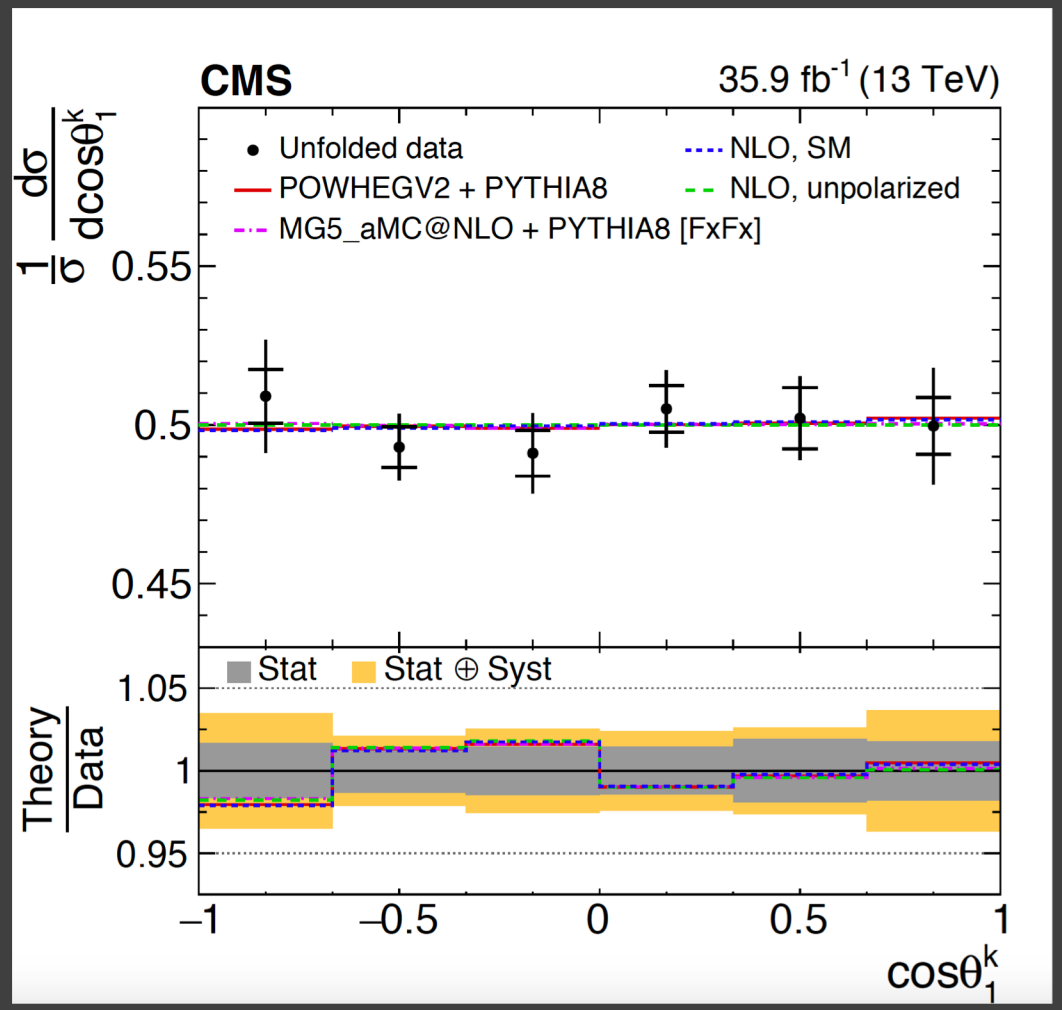

Spin correlations measurements are consistent with SM expectations
Dominant systematics: Background & JES

$C_{kk} = 0.30 \pm 0.02 \pm 0.03$
SM NLO: 0.33

# Results:

$$\frac{1}{\sigma}\frac{d\sigma}{d\cos\theta_1^k} = \frac{1}{2}(1 + B_1^k \cos\theta_1^k)$$



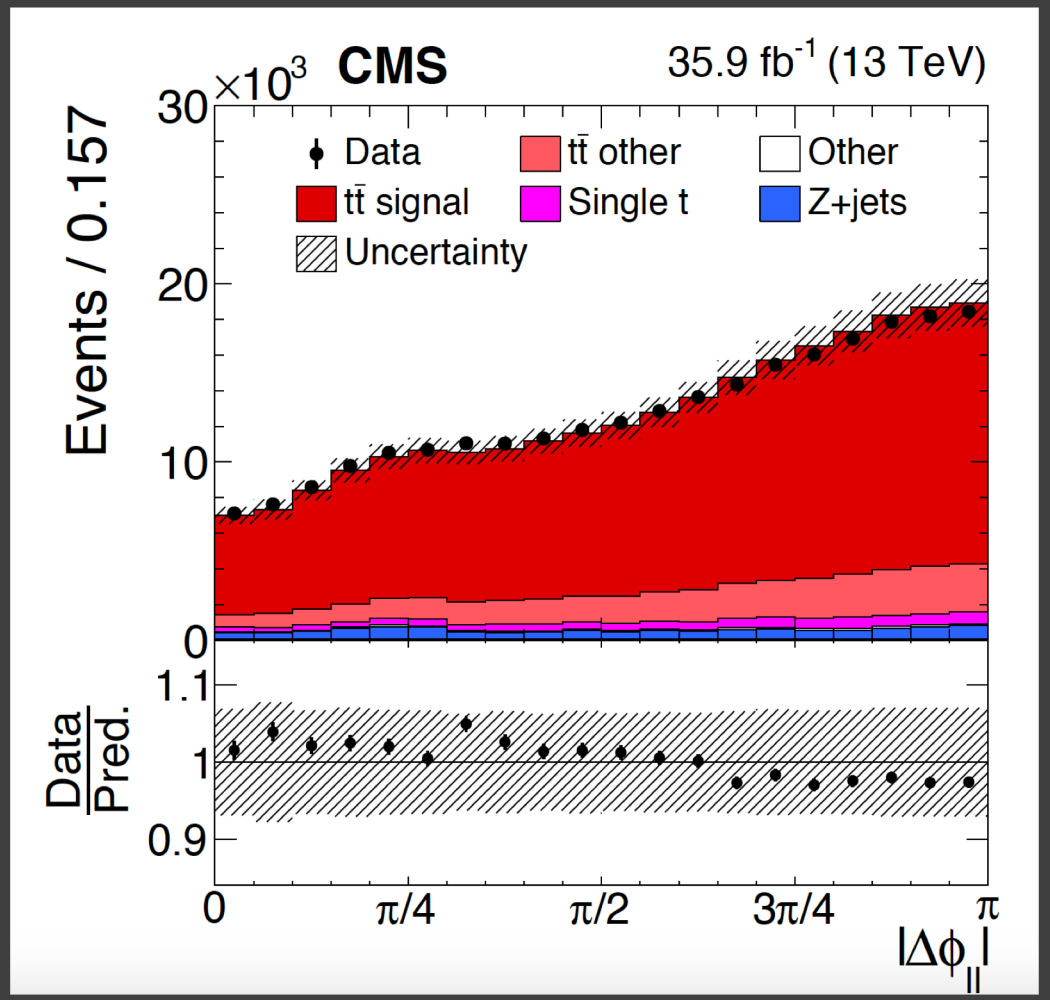



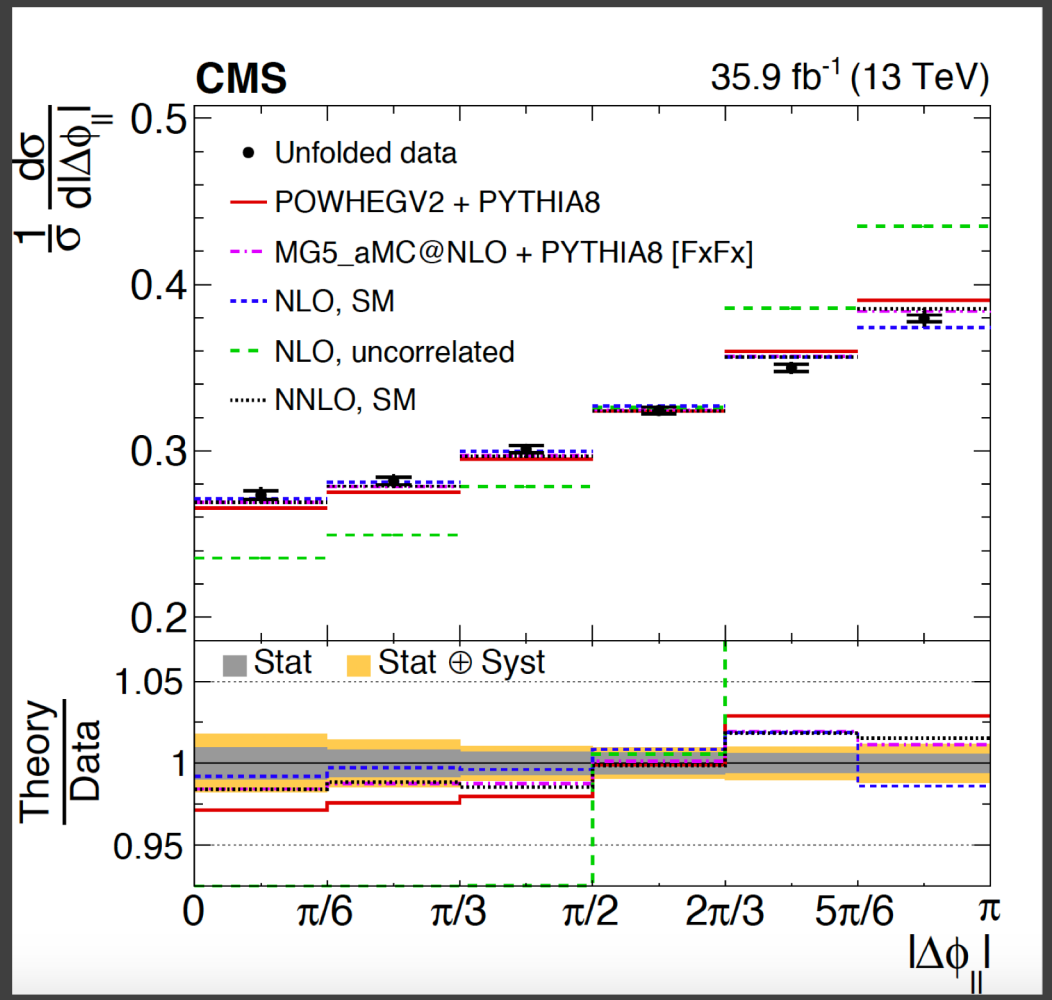

Not yet sensitive to the small level of polarization in the SM
Dominant systematics: JES, b-quark fragmentation, and Background

$B_1^k = 0.005 \pm 0.010 \pm 0.021$

SM NLO: $0.004\,^{+0.0017}_{-0.0012}$

# Results: $|\Delta\phi_{ll}| = \left|\left||\phi_{l_1} - \phi_{l_2}| - \pi\right| - \pi\right|$ to measure $A_{\Delta\phi_{ll}} = \frac{N(|\Delta\phi_{ll}| > \pi/2) - N(|\Delta\phi_{ll}| < \pi/2)}{N(|\Delta\phi_{ll}| > \pi/2) + (|\Delta\phi_{ll}| < \pi/2)}$



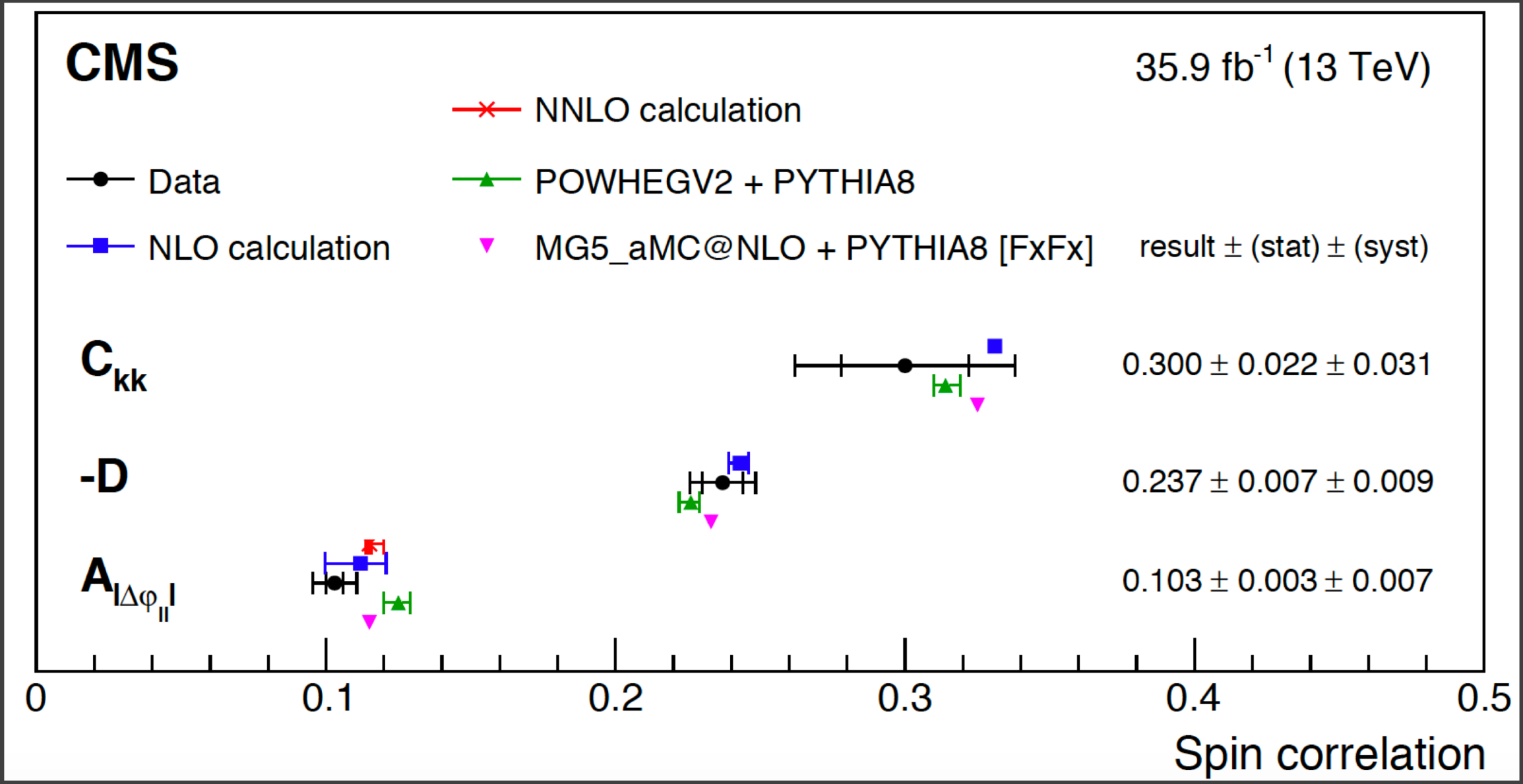

CMS observes a similar, but reduced, discrepancy in $|\Delta\phi_{ll}|$ as ATLAS

Dominant systematics: ME-PS Matching and Top $p_T$ modelling

$A_{\Delta\phi_{ll}} = 0.103 \pm 0.003 \pm 0.007$

SM NNLO: $0.115\,^{+0.005}_{-0.001}$

# Results Summary: Measured Observables and Coefficients



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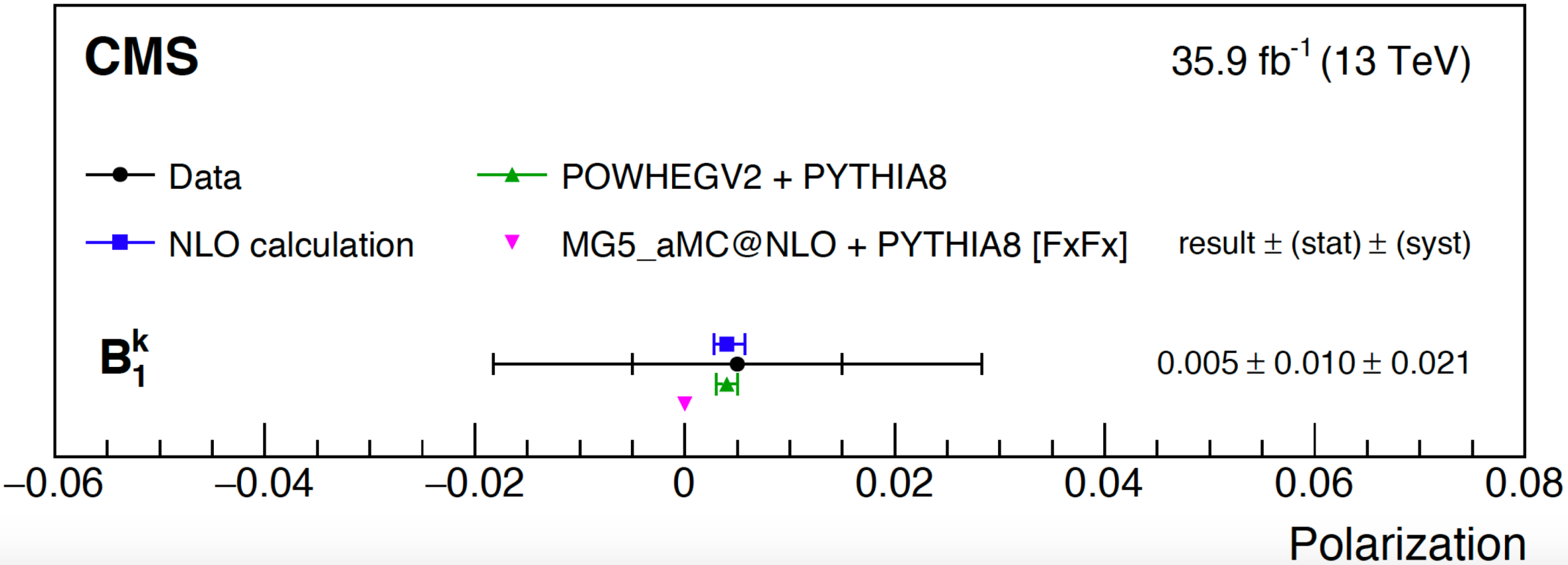


# Constraining the Top Quark Anomalous CMDM Operator Coefficient

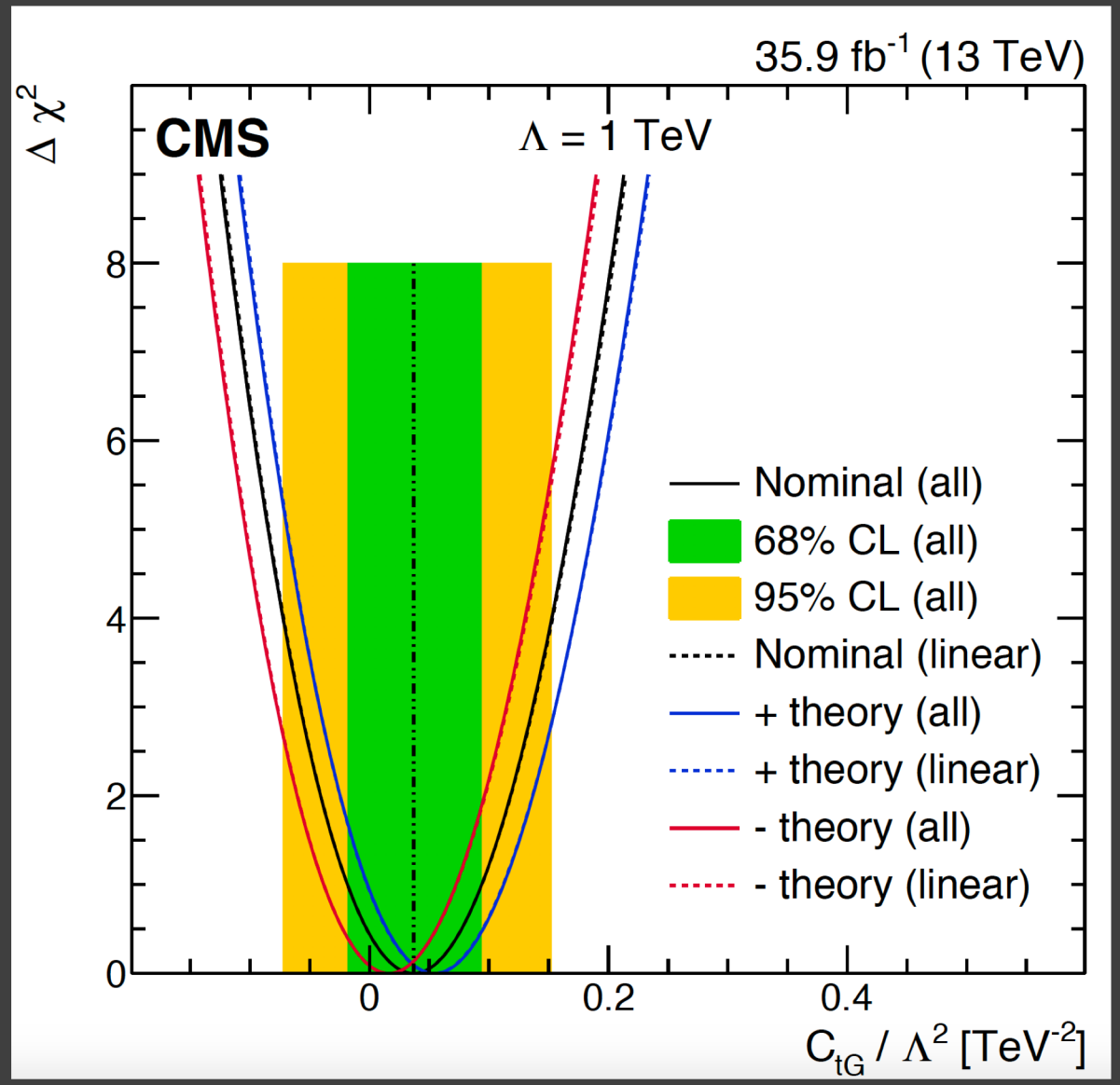
- Several models of physics Beyond SM (BSM) predict an anomalous top quark Chromo-Magnetic Dipole Moment (CMDM) that would induce top chirality flips affecting spin structure and kinematic properties of $t\bar{t}$ events

- $\chi^2$ minimization technique to constrain ${}^{C_{tG}}/_{\Lambda^2}$ Wilson coefficient of CMDM operator:

$$\chi^2\left({}^{C_{tG}}/_{\Lambda^2}\right) = \sum_{i=1}^{N}\sum_{j=1}^{N}(\mathrm{data}_i - \mathrm{pred}_i)\cdot(\mathrm{data}_j - \mathrm{pred}_j)\cdot \mathrm{Cov}_{i,j}^{-1}$$

Best fit value: ${}^{C_{tG}}/_{\Lambda^2} = 0.04\ \mathrm{TeV}^{-2}$

- 95% confidence level limits on ${}^{C_{tG}}/_{\Lambda^2}$ from simultaneous fit to measured differential cross sections:
  - $-0.07 < {}^{C_{tG}}/_{\Lambda^2} < 0.16\ \mathrm{TeV}^{-2}$
  - Strongest direct constraint to date!



# Summary

- First direct measurements at 13 TeV of all spin-dependent coefficients of the $t\bar{t}$ production density matrix are in close agreement with SM predictions
- Tensions between measured $|\Delta\phi_{ll}|$ distribution and NLO MC predictions reduced, but still substantial, with NNLO corrections
- Precision $t\bar{t}$ spin density matrix measurements are a powerful probe of BSM physics in $t\bar{t}$ production:
  - Simultaneous fit for constraint on top quark anomalous CMDM operator coefficient $C_{tG}/\Lambda^2$
  - EFT Interpretation: Sensitive to 10 out of the 11 independent dimension-6 operators relevant for hadronic $t\bar{t}$ production
  - SUSY Interpretation: Limits on light stop squark production

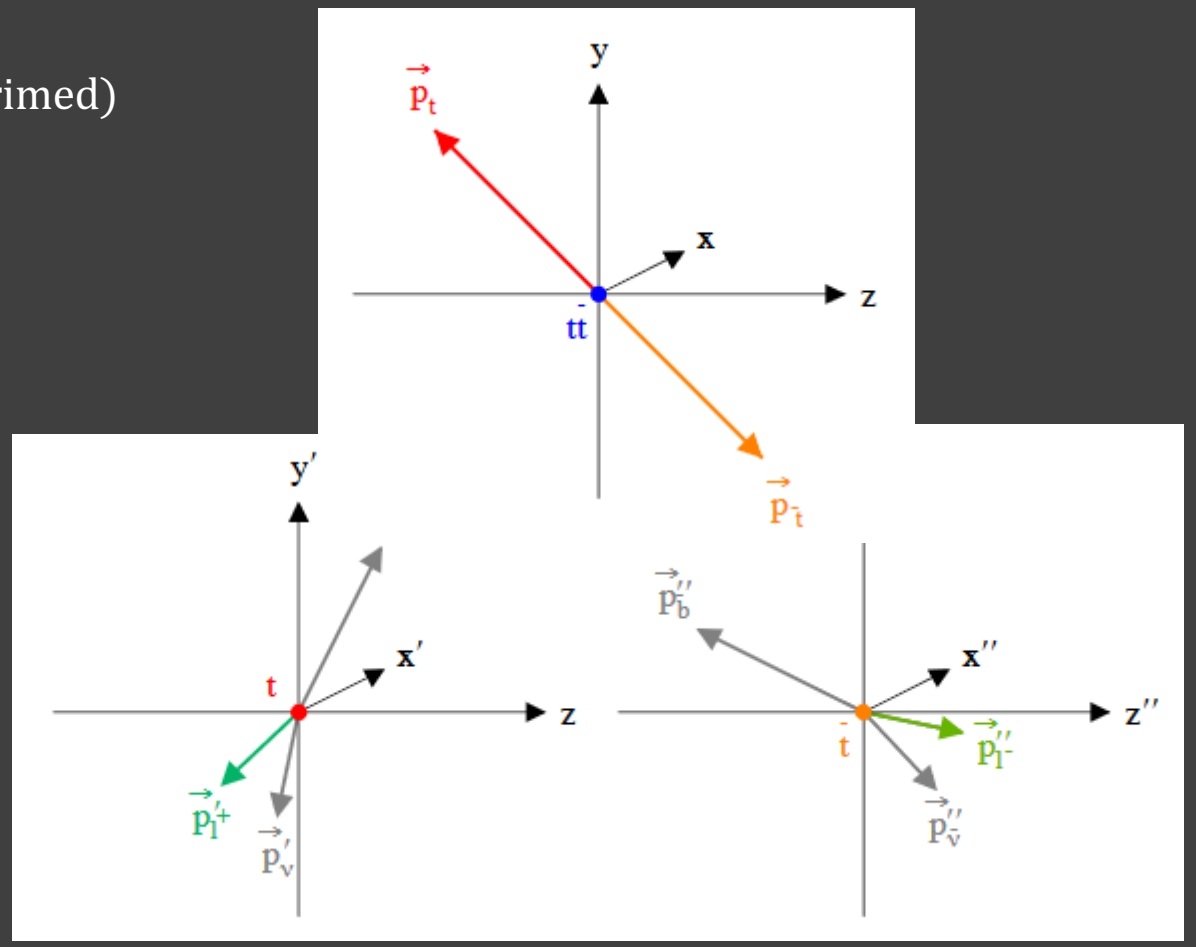
# Helicity Angle

- Helicity angle of a lepton is calculated from the angle between:
  - the lepton momentum in the rest frame of its parent top (primed)
  - the top momentum in the $t\bar{t}$ rest frame (not primed)

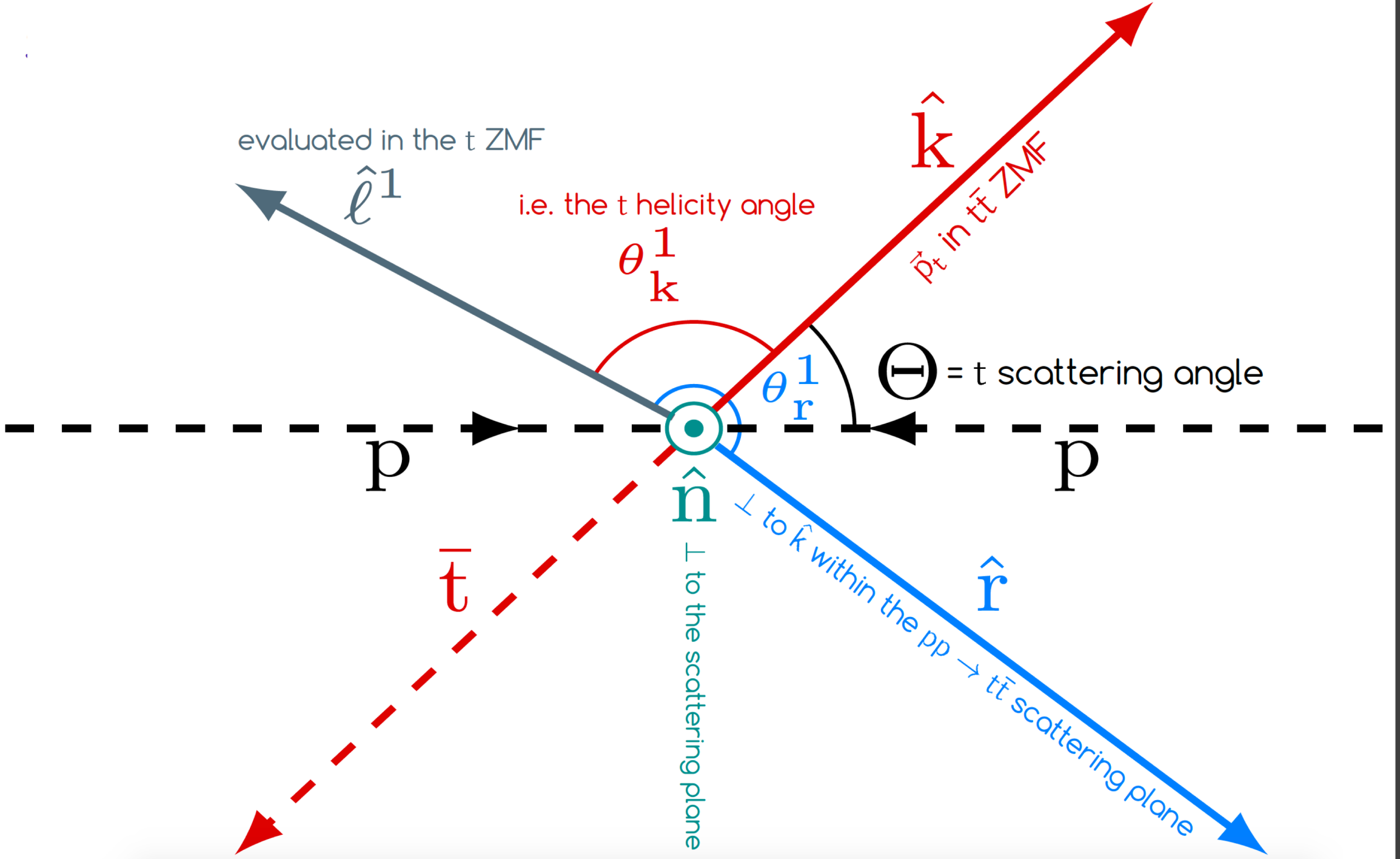
$$\cos\theta_{l^+} = \frac{\vec{p}'_{l^+}\cdot\vec{p}_t}{|\vec{p}'_{l^+}||\vec{p}_t|} \qquad \cos\theta_{l^-} = \frac{\vec{p}''_{l^-}\cdot\vec{p}_{\bar{t}}}{|\vec{p}''_{l^-}||\vec{p}_{\bar{t}}|}$$

- Helicity basis is stable with regard to reconstruction errors
- Helicity angle of a lepton can be expressed in terms of Lorentz- invariant quantities :

$$\cos\theta = \frac{2[m_t^2(p_l p_{t\bar{t}}) - (p_t p_{t\bar{t}})(p_t p_l)]}{\hat{s}\sqrt{1 - {4m_t^2}/{\hat{s}}}\sqrt{(p_t p_l)^2 - m_t^2 m_l^2}}$$




The scalar product of the three vectors $\vec{p}'_{l^+}$ & $\frac{\vec{p}_t}{|\vec{p}_t|}$ and the product of the four vectors $(0, \frac{\vec{p}_t}{|\vec{p}_t|})$ & $(E'_{l^+}, \vec{p}'_{l^+})$ are identical


evaluated in the t ZMF
$\hat{\ell}^1$
i.e. the t helicity angle
$\theta_k^1$
$\hat{k}$
$\vec{p}_t$ in $t\bar{t}$ ZMF
$\theta_r^1$
$\Theta$ = t scattering angle
p
p
$\hat{n}$
$\perp$ to $\hat{k}$ within the pp $\to$ $t\bar{t}$ scattering plane
$\bar{t}$
$\perp$ to the scattering plane
$\hat{r}$

# Expanding $\tilde{B}_i^{\pm}$ and $\tilde{C}_{ij}$ in terms of the orthonormal basis $\{\hat{k}, \hat{r}, \hat{n}\}$

- $\tilde{B}_i^{\pm} = b_k^{\pm}\hat{k}_i + b_r^{\pm}\hat{r}_i + b_n^{\pm}\hat{n}_i$
- $\tilde{C}_{ij} = c_{kk}\hat{k}_i\hat{k}_j + c_{nn}\hat{n}_i\hat{n}_j + c_{rr}\hat{r}_i\hat{r}_j$

$$+ c_{rk}(\hat{r}_i\hat{k}_j + \hat{k}_i\hat{r}_j) + c_{nr}(\hat{n}_i\hat{r}_j + \hat{r}_i\hat{n}_j) + c_{kn}(\hat{k}_i\hat{n}_j + \hat{n}_i\hat{k}_j)$$

$$+ c_n(\hat{r}_i\hat{k}_j - \hat{k}_i\hat{r}_j) + c_k(\hat{n}_i\hat{r}_j - \hat{r}_i\hat{n}_j) + c_r(\hat{k}_i\hat{n}_j - \hat{n}_i\hat{k}_j)$$

Small (QCD T Invariance)

Small (QCD P Invariance)

Small (QCD CP Invariance)

- Coefficients are functions of the partonic CM energy and cos Θ
- Large values are only allowed for the P and CP even spin correlations: $c_{kk}$, $c_{rr}$, $c_{nn}$, $c_{rk}$
- Any deviation from these expectations would be a sign of BSM production phenomena

# $t\bar{t} \to bW^+\bar{b}W^- \to b\ell^+\upsilon_\ell\bar{b}\ell^-\bar{\upsilon}_\ell$: Double Differential Distributions

- Normalized fourfold angular distributions for the two leptons (each measured in its parent top quark rest frame):

$$\frac{1}{\sigma}\frac{d\sigma}{d\Omega_1 d\Omega_2} = \frac{1}{(4\pi)^2}(1 + \vec{B}_1 \cdot \hat{l}_1 + \vec{B}_2 \cdot \hat{l}_2 - \hat{l}_1 \cdot \overleftrightarrow{C} \cdot \hat{l}_2)$$

Charged lepton directions of flight in the $t$ and $\bar{t}$ rest frames respectively

- $B_1^i$ and $B_2^i$, the top quark and antiquark polarization coefficients with respect to each reference axis $i$

  (sensitive to $\widetilde{B}_i^+$ and $\widetilde{B}_i^-$)

- $C_{ii}$, the "diagonal" spin correlation coefficient for each reference axis $i$

  (sensitive to $\widetilde{C}_{ij}$ )

- $C_{ij}$, the "cross" spin correlation coefficient for each pair of axes $i \neq j$

  (the sums and differences $C_{ij} \pm C_{ji}$ are sensitive to $\widetilde{C}_{ij}$ )

# Event and Object Selection Details

Triggers: Single-lepton and dilepton paths – maximize trigger efficiency

Leptons: Exactly two isolated electrons or muons of opposite electric charge

$p_T > 25(20)\ GeV$ for leading (trailing) candidate, $|\eta| < 2.4$ , Relative isolation criteria ($I_{rel}$),

$1.44 < |\eta_{cluster}| < 1.57$ excluded in ECAL, Identification requirements,

$m_{l^+l^-} < 20$ GeV and $76 < m_{l\bar{l}} < 106$ GeV excluded

Jets: At least two jets, with at least one b-tagged

$p_T > 30\ GeV$, $|\eta| < 2.4$, anti-$k_t$ jets ($R = 0.4$), Jet Cleaning: $\Delta R(l, jet) > 0.4$

$E_T^{miss}$: $p_T^{miss} > 40\ GeV$

# $t\bar{t}$ Kinematic Reconstruction

- The four momenta of the two neutrinos in the decay are needed to full reconstruct top quark four momenta
- Analytical solutions are obtained by applying six kinematic constraints:

$$E_x^{miss} = p_{x,\nu} + p_{x,\bar{\nu}}$$
$$E_y^{miss} = p_{y,\nu} + p_{y,\bar{\nu}}$$

$$m_{W^+}^2 = (E_{l^+} + E_\nu)^2 - \left(p_{x,l^+} + p_{x,\nu}\right)^2 - (p_{y,l^+} + p_{y,\nu})^2 - (p_{z,l^+} + p_{z,\nu})^2$$

$$m_{W^-}^2 = (E_{l^-} + E_{\bar{\upsilon}})^2 - \left(p_{x,l^-} + p_{x,\bar{\upsilon}}\right)^2 - (p_{y,l^-} + p_{y,\bar{\upsilon}})^2 - (p_{z,l^-} + p_{z,\bar{\upsilon}})^2$$

$$m_t^2 = (E_{l^+} + E_\nu + E_b)^2 - \left(p_{x,l^+} + p_{x,\nu} + p_{x,b}\right)^2 - (p_{y,l^+} + p_{y,\nu} + p_{y,b})^2 - (p_{z,l^+} + p_{z,\nu} + p_{z,b})^2$$

$$m_{\bar{t}}^2 = (E_{l^-} + E_{\bar{\upsilon}} + E_{\bar{b}})^2 - \left(p_{x,l^-} + p_{x,\bar{\upsilon}} + p_{x,\bar{b}}\right)^2 - (p_{y,l^-} + p_{y,\bar{\upsilon}} + p_{y,\bar{b}})^2 - (p_{z,l^-} + p_{z,\bar{\upsilon}} + p_{z,\bar{b}})^2$$

- Reconstruct each event 100 times smearing W mass, jet and lepton directions and energies by their resolutions.
- Take the top 4-momenta solution as a weighted average of all the solutions for all smearing
- All lepton-jet combinations are tried, and the one with highest sum of weights is chosen (preferring the one with most b-tags); this selects the one most likely based on kinematics

# Event Yields after Selection and Kinematic Reconstruction

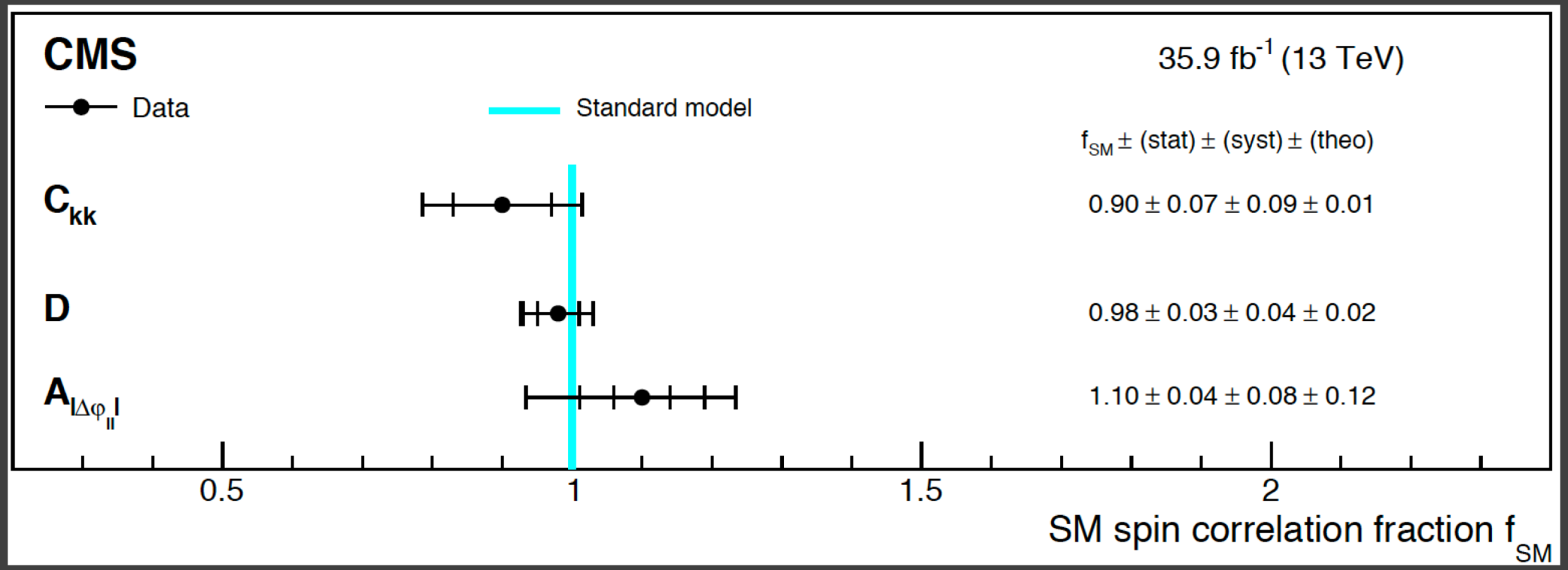
- Yields for the 3 dilepton channels and combined:

| | $e^+e^-$ | $e^\pm\mu^\mp$ | $\mu^+\mu^-$ | **Combined** |
|---|---|---|---|---|
| $t\bar{t}$ Signal | 26,764.7 | 124,539 | 54,873.5 | 206,177 |
| $t\bar{t}$ Other | 4,147.05 | 20,356.6 | 9,137.69 | 33,641.3 |
| Single $t$ | 1,142.39 | 5,490.33 | 2,257.13 | 8,889.86 |
| $Z$+jets | 3,135.8 | 1,305.76 | 6,881.75 | 11,311.8 |
| Other | 227.22 | 875.22 | 461.89 | 1,564.33 |
| Total MCs | 35,417.2 | 152,567 | 73,612 | 261,585 |
| Data | 34,890 | 150,410 | 70,346 | 255,646 |

- Data/MC agreement within uncertainties

- Fraction of Signal events in simulation: 79%

# $f_{SM}$ Results


CMS
35.9 fb-1 (13 TeV)
Data
Standard model
fSM ± (stat) ± (syst) ± (theo)
Ckk
0.90 ± 0.07 ± 0.09 ± 0.01
D
0.98 ± 0.03 ± 0.04 ± 0.02
A|Δφll|
1.10 ± 0.04 ± 0.08 ± 0.12
0.5
1
1.5
2
SM spin correlation fraction fSM