Measurement of the top quark polarization and ttbar spin correlations in dilepton final states

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LPC Physics Forum
5 September 2019

Analysis team & documentation

- Paper:
  - CMS-TOP-18-006
  - [arXiv:1907.03729]
  - submitted to Phys. Rev. D

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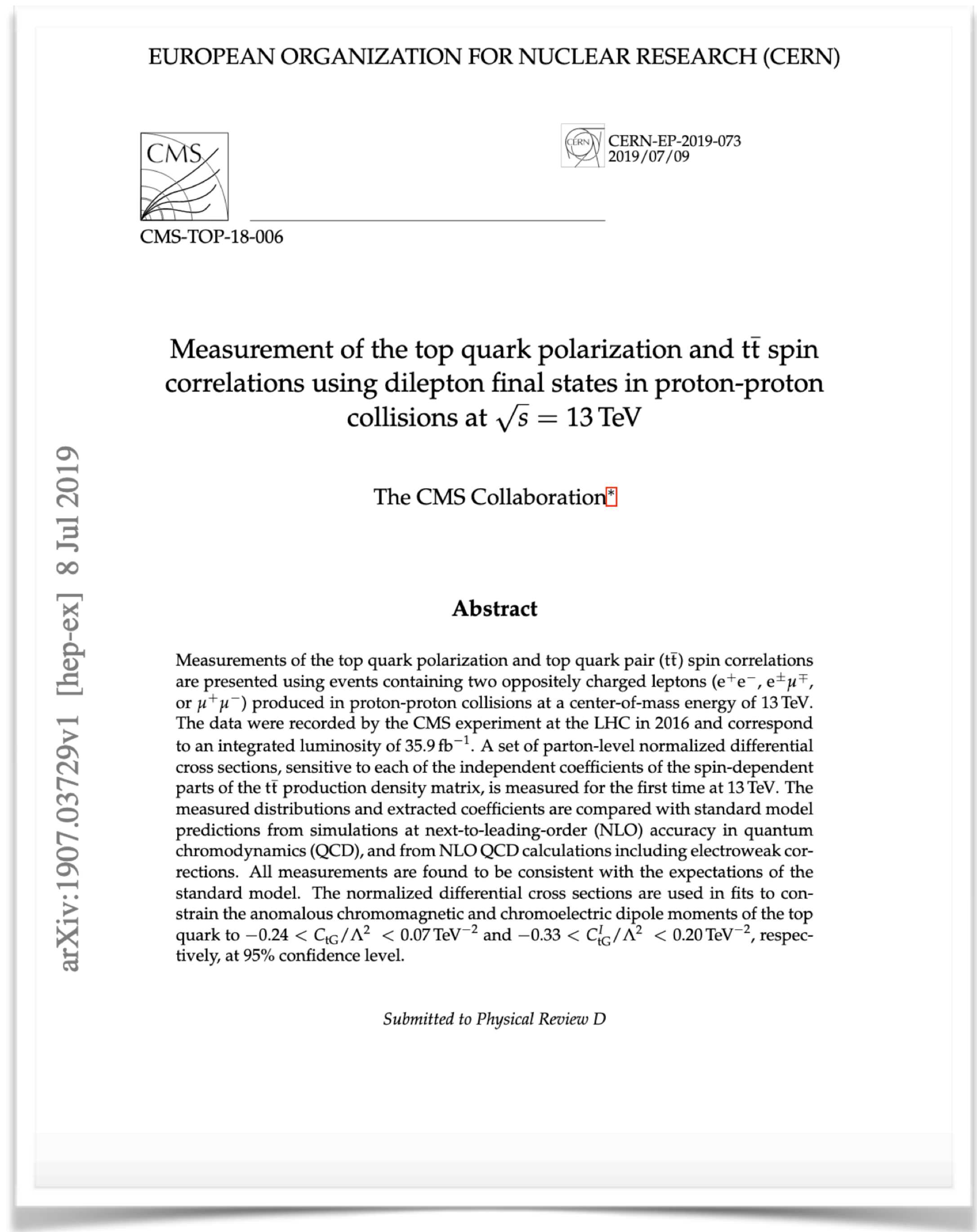

EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH (CERN)

CERN-EP-2019-073
2019/07/09

CMS-TOP-18-006

arXiv:1907.03729v1 [hep-ex] 8 Jul 2019

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 $-0.24 < C_{tG}/\Lambda^2 < 0.07\,TeV^{-2}$ and $-0.33 < C^I_{tG}/\Lambda^2 < 0.20\,TeV^{-2}$, respectively, at 95% confidence level.

Submitted to Physical Review D

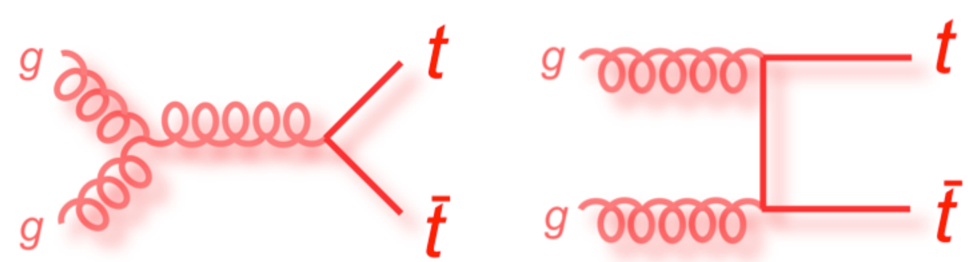
Outline

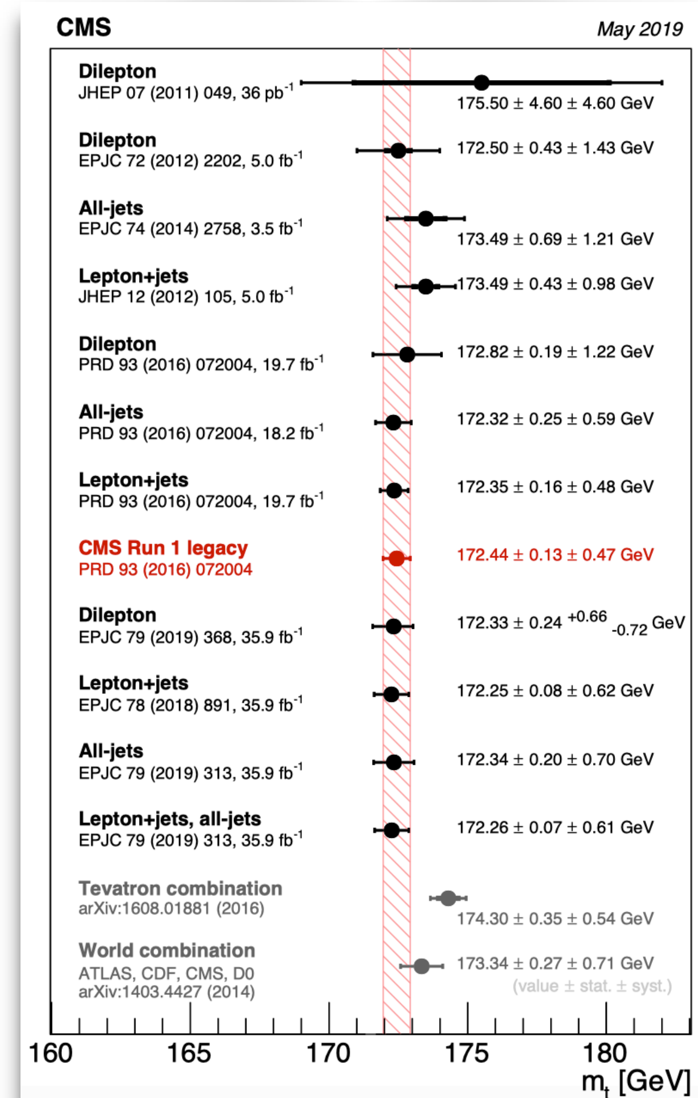
- Introduction
- Analysis:
  - direct measurements
  - indirect measurements
- Results
- Interpretations
- Summary

Introduction

- Top quark :
  - heaviest elementary particle discovered so far
  - large Yukawa coupling to Higgs boson

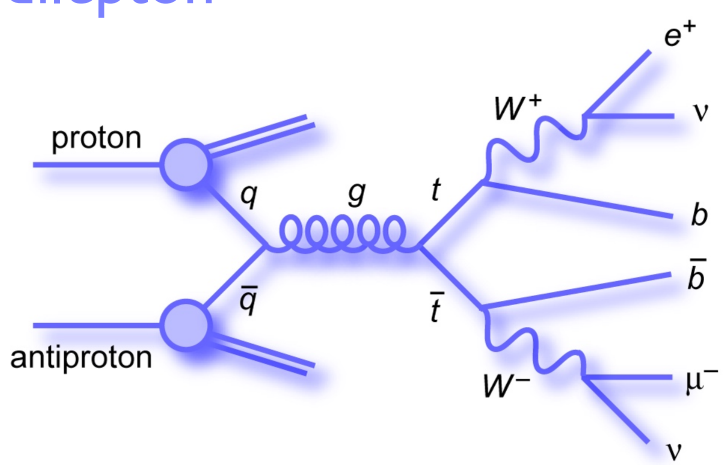
- Top quarks pairs production @ the LHC dominated by gluon fusion (~90%) → allows to:
  - constrain gluon PDF
  - extract α_S, m_t



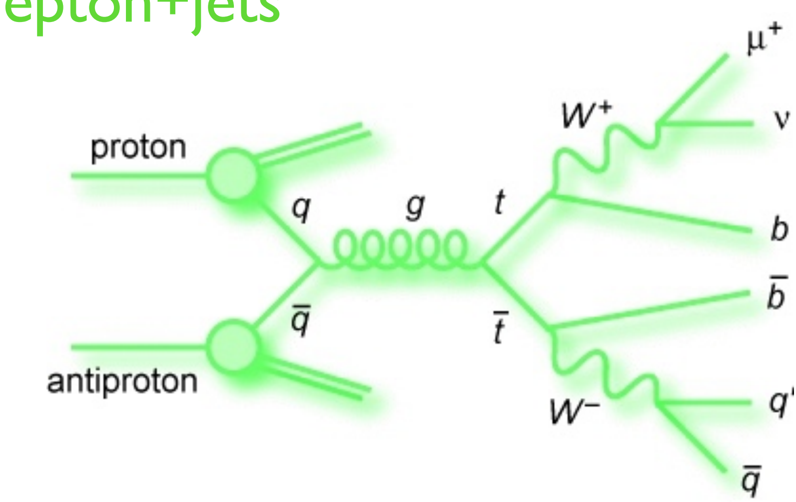


- Decay channels:

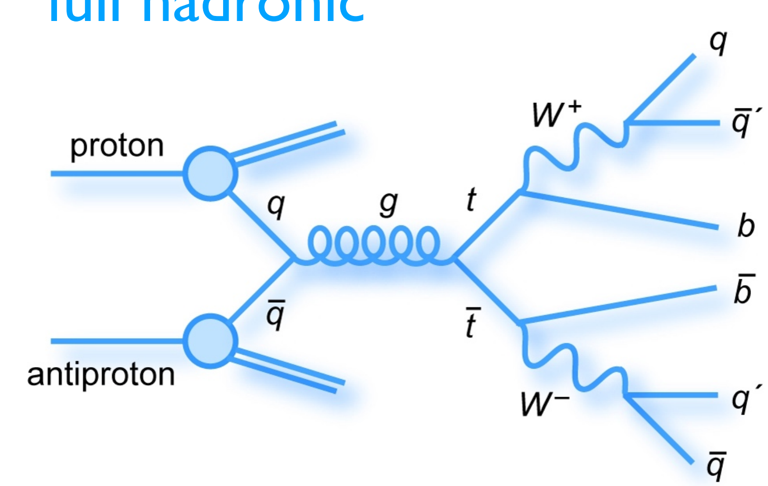
dilepton



lepton+jets



full hadronic

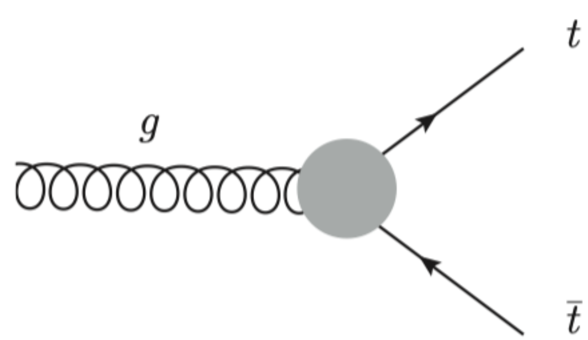


BR increases.. but background too!

Why top quark is so special?

- **Ideal candidate for spin measurements**:
  - extremely short lifetime → decays before forming bound states
  - spin information preserved in the angular distribution of its decay products
  - top spin observables (expected to be) well predicted by perturbative QCD

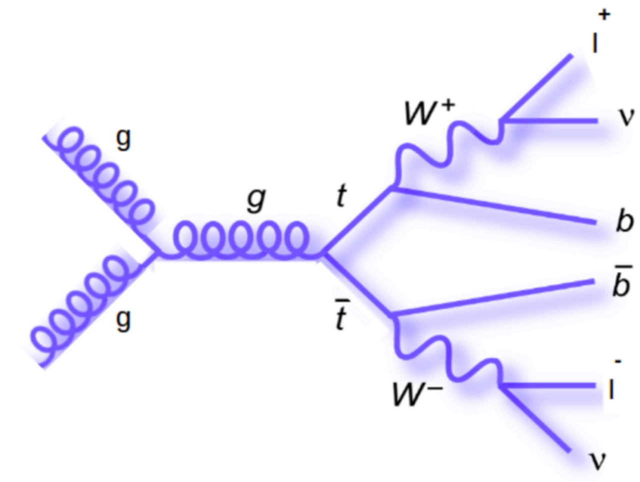
$$\underbrace{\frac{1}{m_t}}_{\substack{\text{production} \\ 10^{-27}\ \text{s}}} < \underbrace{\frac{1}{\Gamma_t}}_{\substack{\text{lifetime} \\ 10^{-25}\ \text{s}}} < \underbrace{\frac{1}{\Lambda_{QCD}}}_{\substack{\text{hadronization} \\ 10^{-24}\ \text{s}}} < \underbrace{\frac{m_t}{\Lambda^2}}_{\substack{\text{spin-flip} \\ 10^{-21}\ \text{s}}}$$



- Top spin measurements = **powerful probe of new physics** in ttbar production:
  - new mediator would change spin structure
  - sensitive to most dim-6 EFT operators

- In SM, ttbar production ~ unpolarized but top spins strongly correlated → **rich structure of spin correlations**

Goal of analysis



- Measurement of **all the independent coefficients of the spin-dependent parts of the ttbar production density matrix** in dilepton channel
- Squared matrix element for ttbar production and decay:

$$|\mathscr{M}(gg/q\bar{q} \to t\bar{t} \to (b\ell^+\nu_\ell)(\bar{b}\ell^-\bar{\nu}_\ell))|^2 \sim Tr[\rho R \bar{\rho}]$$

as described in Bernreuther et. al. [JHEP12(2015)026]

- $\rho/\bar{\rho}$ = decay density matrices for top and anti-top
- R = spin density matrix related to on-shell ttbar production
  - can be decomposed into t and tbar spin dependent parts using a basis of Pauli matrices:

$$R \propto \tilde{A}1 \otimes 1 + \tilde{B}_i^+ \sigma^i \otimes 1 + \tilde{B}_i^- 1 \otimes \sigma^i + \tilde{C}_{ij} \sigma^i \otimes \sigma^j$$

  - $\tilde{A}$ = constant characterizing spin-averaged production cross-section at parton level
  - $\tilde{B}^{\pm}$ = 3-vectors characterizing the degree of top quark/antiquark polarization along each axis
  - $\tilde{C}$ = 3x3 matrix characterizing the spin correlation between the top quarks and antiquarks for each pair of axes

Basis of spin quantization axes

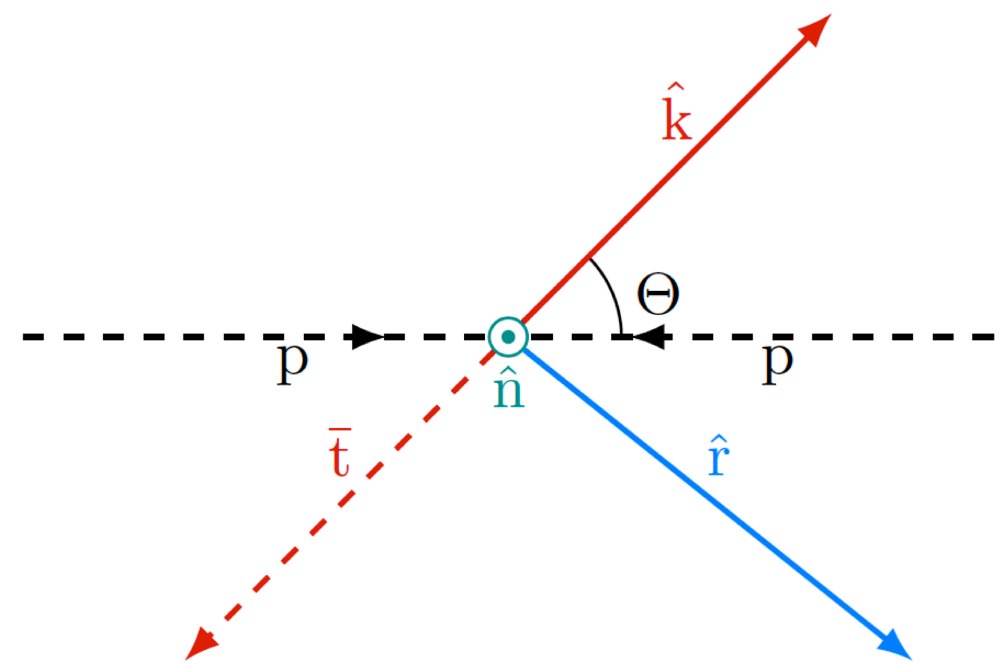
- B and C coefficients:
  - functions of $\sqrt{s}$ and of the top quark scattering angle
  - written in terms of **orthonormal basis** $\{\hat{k}, \hat{r}, \hat{n}\}$:
    - helicity $\hat{k}$-axis: top quark direction in ttbar rest frame
    - transverse $\hat{n}$-axis: transverse to production (ttbar scattering) plane

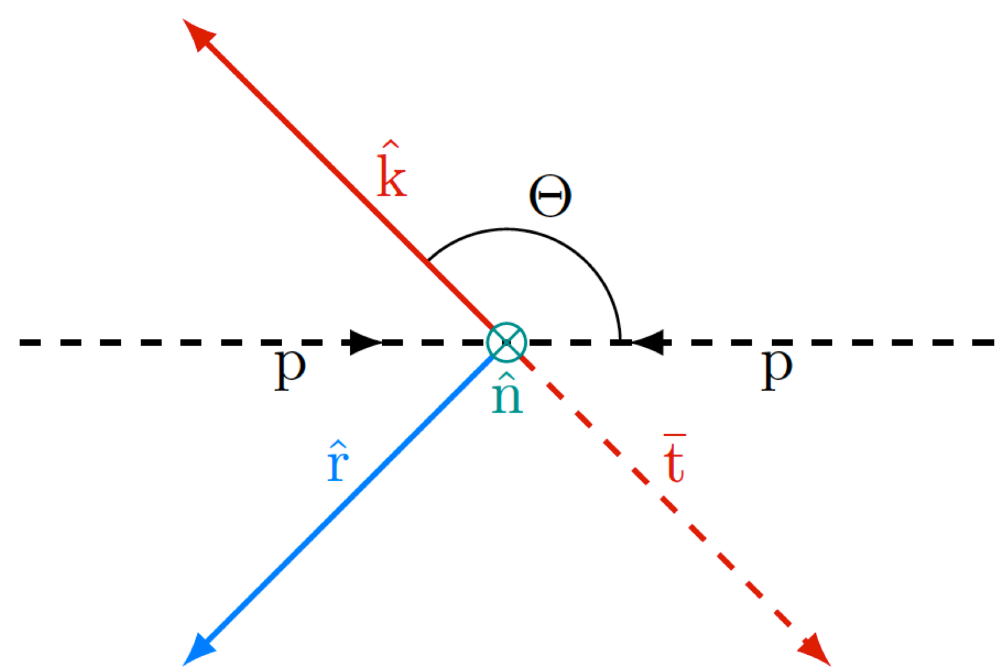
$$\hat{n} = \frac{sign(cos\Theta)}{sin\Theta}(\hat{p} \times \hat{k})$$

    - $\hat{r}$-axis: orthogonal to the other 2 axes (normal to k in ttbar scattering plane)

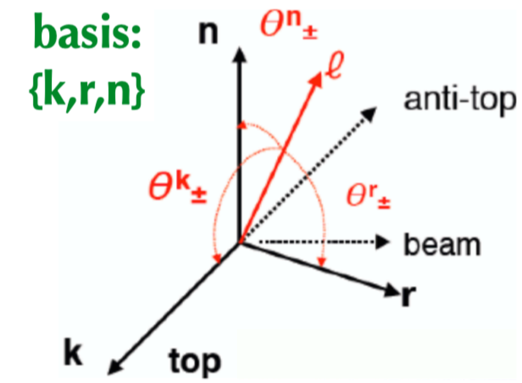
$$\hat{r} = \frac{sign(cos\Theta)}{sin\Theta}(\hat{p} - \hat{k}cos\Theta)$$

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



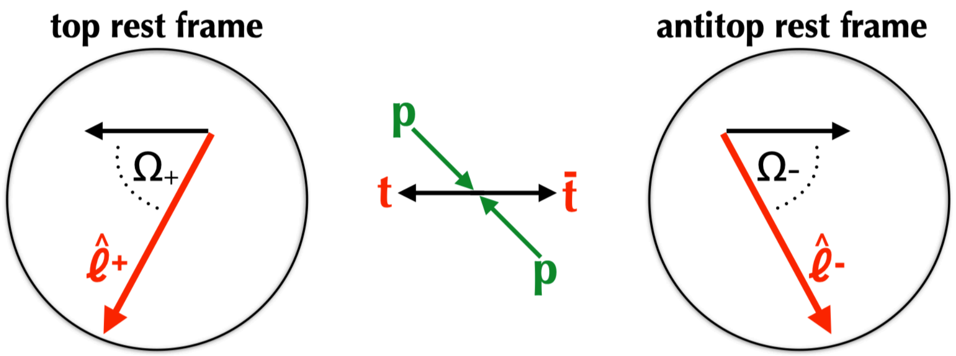


Dilepton angular distribution



- Dilepton angular distribution probes top spin in 3 directions:

$$\frac{1}{\sigma}\frac{d\sigma}{d\Omega_+ d\Omega_-} = \frac{1}{(4\pi)^2}\left(1 + \mathbf{B}^+ \cdot \hat{\ell}^+ + \mathbf{B}^- \cdot \hat{\ell}^- - \hat{\ell}^+ \cdot \mathbb{C} \cdot \hat{\ell}^-\right)$$



- For many variables, simplified form:

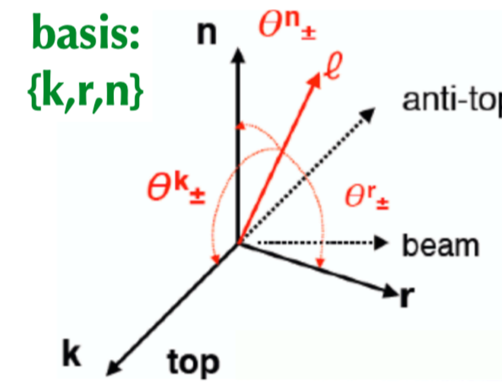
$$\frac{1}{\sigma}\frac{d\sigma}{dcos\theta_1^i dcos\theta_2^i} = \frac{1}{4}(1 + B_1^i cos\theta_1^i + B_2^i cos\theta_2^i - C_{ii} cos\theta_1^i cos\theta_2^i)$$

  - 3-vectors B_1^i and B_2^i= top and anti-top polarization coefficients w.r.t reference axis i, where i = $\hat{k}$, $\hat{r}$, $\hat{n}$ [plus modified axes $\hat{r}*$ and $\hat{k}*$ depending on $sign(|y_t| - |y_{\bar{t}}|)$]
  - 3x3 matrix C_{ii} = diagonal spin correlation coefficients for axis i

- Spin dependence of ttbar production **completely characterized by 15 coefficients**, individually probed by measuring 1D angular distribution at parton level:

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

Observables



- Single-differential cross sections yielded by a change of variable, necessary, and by integrating out one of the angles:
  - $\frac{1}{\sigma}\frac{d\sigma}{dcos\theta^i_{1/2}} = \frac{1}{2}(1 + B^i_{1/2} cos\theta^i_{1/2}) \rightarrow$ for polarization
  - $\frac{1}{\sigma}\frac{d\sigma}{d(cos\theta^i_1 cos\theta^i_2)} = \frac{1}{2}[1 - C_{ii}(cos\theta^i_1 cos\theta^i_2)]\ln\frac{1}{|cos\theta^i_1 cos\theta^i_2|} \rightarrow$ for diagonal spin correlations

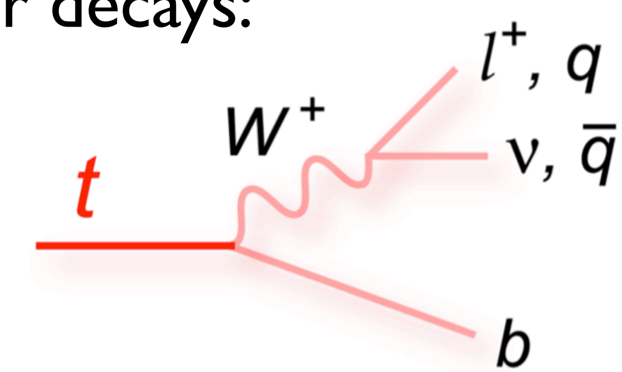
- Also measurements of:
  - sums and differences $C_{ij} \pm C_{ji}$ for axes i, j
  - $D = \frac{-Tr[C]}{3} = \frac{-[C_{kk} + C_{rr} + C_{nn}]}{3}$ from $cos\varphi = \hat{\ell}_1 \cdot \hat{\ell}_2$distribution (opening angle between the leptons in parent top rest frame)
    - $\frac{1}{\sigma}\frac{d\sigma}{dcos\varphi} = \frac{1}{2}(1 + Dcos\varphi)$
  - lab-frame distributions $\hat{\ell}^{lab}_1 \cdot \hat{\ell}^{lab}_2$ and $|\Delta\phi_{\ell\ell}| \rightarrow$ for asymmetry $A_{\Delta\phi_{\ell\ell}}$

→ **22 distribution in total**…
today focusing only on B^k_1, C_{kk}, C_{rr}, C_{nn}, D and $A_{\Delta\phi_{\ell\ell}}$

Strategy

- Analysis targets **dilepton final states** (~9% BR) of ttbar decays:

$$t\bar{t} \to (bW^+)(\bar{b}W^-) \to (b\ell^+\nu_\ell)(\bar{b}\ell^-\bar{\nu}_\ell)$$

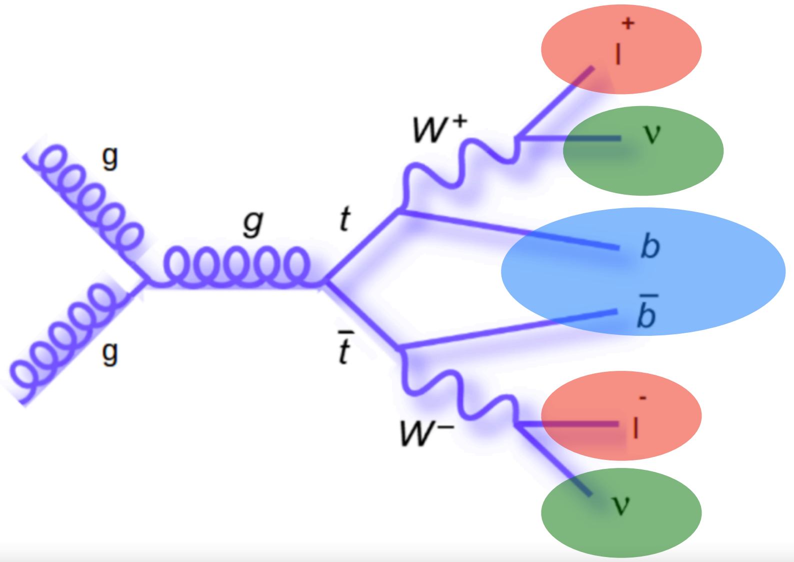


- Dilepton event selection
- Kinematic reconstruction of ttbar system
  - 6 unknowns (neutrino momenta) constrained measuring E_T^{miss} and assuming m_t and m_W
- Binned measurements of single differential cross-sections distributions
- Background subtraction and normalization
- Optimised unfolding technique for dileptonic angular distributions (simultaneous unfolding of the distributions) based on TUnfold to correct for detector effects and acceptance
  - obtain parton-level, normalized differential cross-sections extrapolated to the full phase space
- Extraction of the $A_{\Delta\phi_{\ell\ell}}$, B, C, and D coefficients
- Interpretations: comparison to SM simulation, EFT, SUSY
  - compare data to BSM predictions and set limits

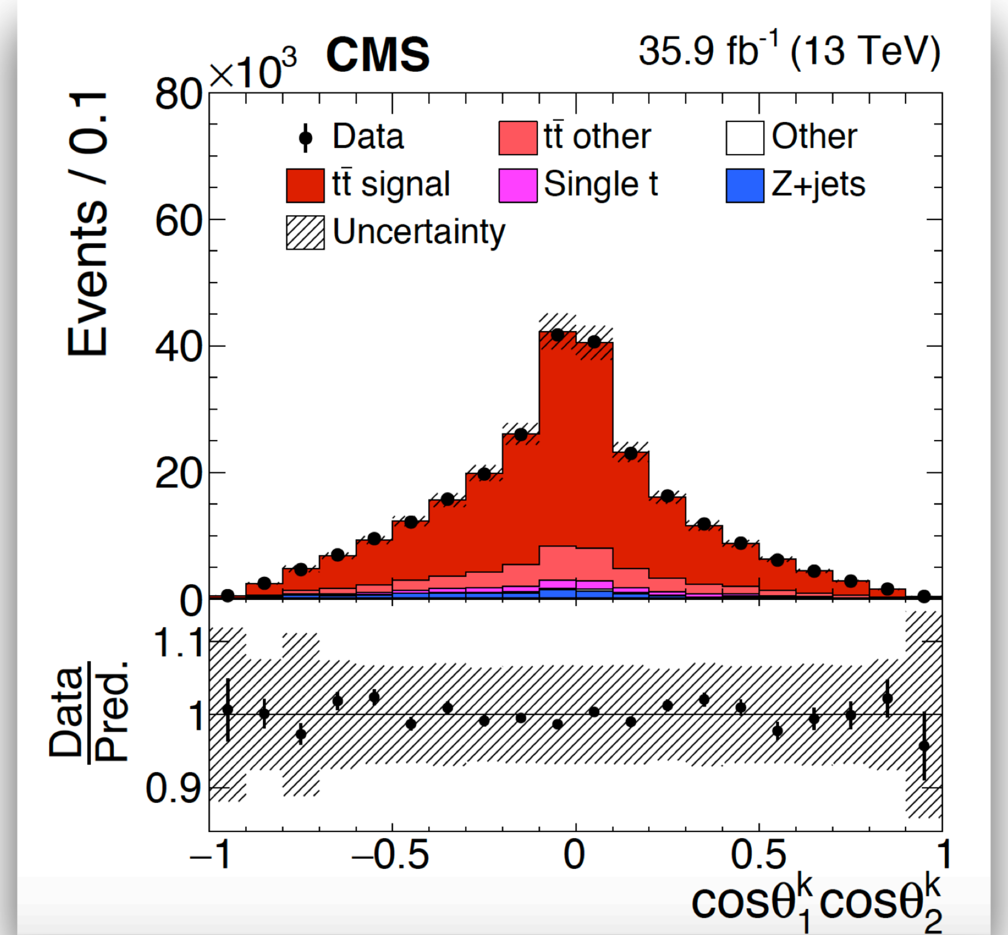
Signal and backgrounds

CMS 2016 data
@ $\sqrt{s} = 13$ TeV :
$\mathscr{L} = 35.9$ fb^{-1}

- **Signal**: $t\bar{t} \rightarrow (bW^+)(\bar{b}W^-) \rightarrow (b\ell^+\nu_\ell)(\bar{b}\ell^-\bar{\nu}_\ell)$
  - 2 charged leptons (e^+e^- or $e^\pm\mu^\mp$ or $\mu^+\mu^-$) originating from W boson decays, but not from tau decays
  - 2 jets originating from the hadronization of b-quarks (b-jets)
  - large E_T^{miss} from undetected neutrinos



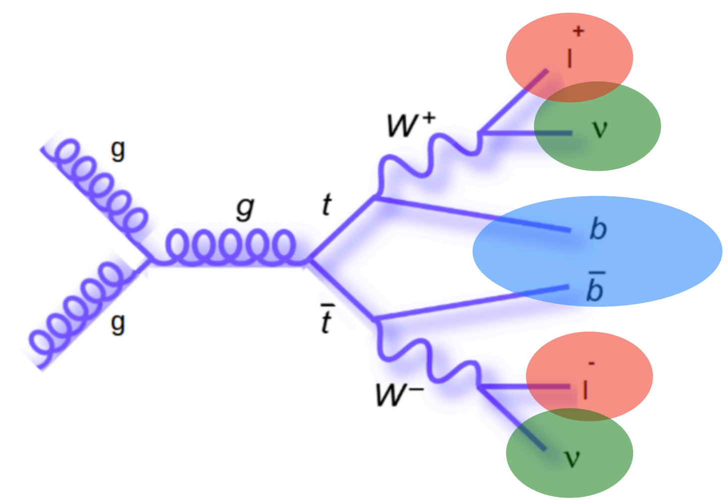
- **Main backgrounds**:
  - ttbar events with leptonically decaying tau leptons (ttbar other) ~13%
  - single top quarks produced in association with a W boson (tW) ~3%
  - Z/gamma* bosons produced with additional jets (Z+jets) ~4%
    - estimated using data driven method (everything else using simulation)
- **Other backgrounds** (< 1%):
  - W boson production with additional jets (W+jets)
  - diboson events (WW, ZZ, WZ)
  - production of ttbar in association with W or Z boson (ttbar+W/Z)
- Reasonable data-MC agreement in general



Event selection & kinematic reco

- Selections of events based on :
  - p_T, η of electrons and jets
  - m_{ll}
  - E_T^{miss}
- Direct spin measurement requires **reconstruction of ttbar system**
- Neutrino momenta solved analytically using a geometric method using constraints from E_T^{miss}, m_t and m_W:
  - input: 2 highest-pt reconstructed jets, 2 oppositely charged isolated leptons and missing transverse energy
  - fix top quark mass at 172.5 GeV and W mass at 80.4 GeV
  - up to 8 solutions per event:
    - choose most likely based on kinematics
    - choose closest approach between E_T^{miss} and sum of neutrino p_T

>90% pure sample of dileptonic ttbar events after selection

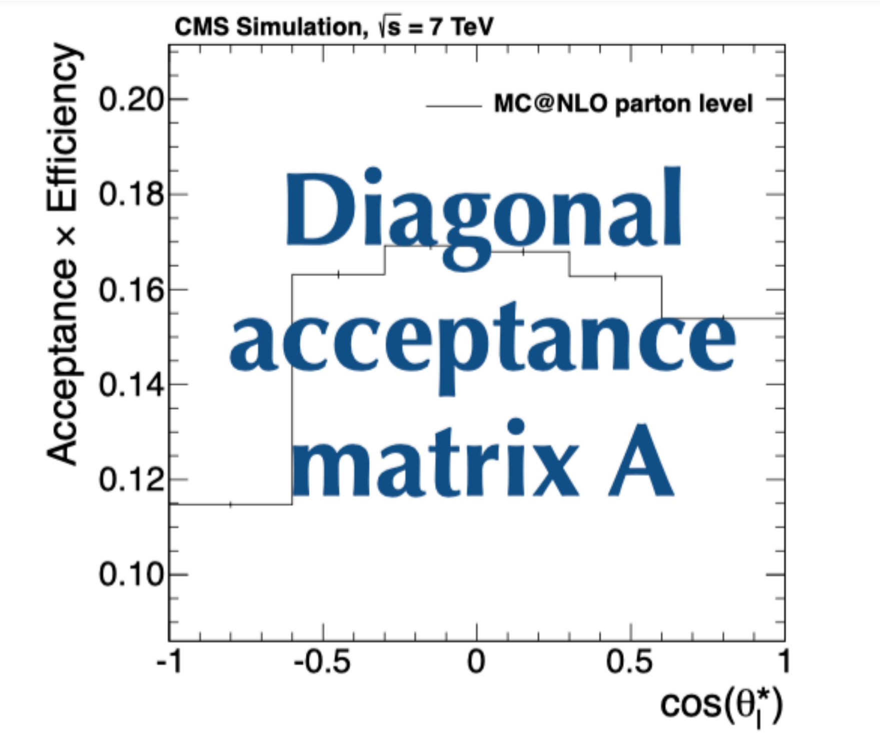


Unfolding

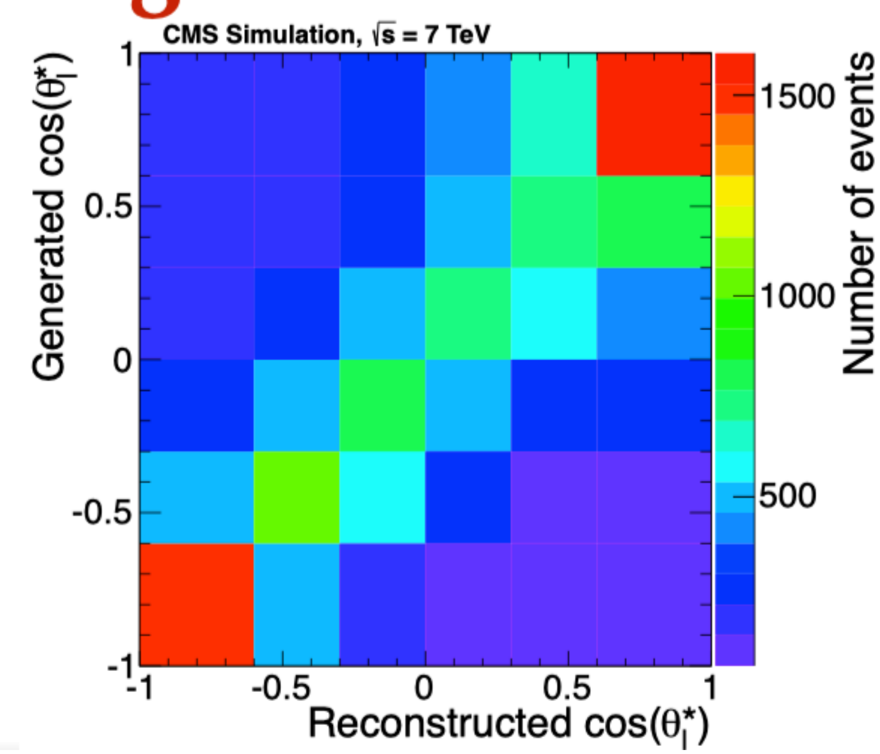
- Two corrections needed to compare measured distribution to theoretical calculations:
  - "**acceptance**" (from fiducial region of detector with selection cuts to full phase space with no cuts)
  - "**migration**" (to account for differences between true and reconstructed quantities)
- Acceptance and migration corrections parametrized by matrices that act on measured bins:
  - measured bins x related to true bins y by:

    $$\mathbf{x} = \mathbf{M}\ \mathbf{A}\ \mathbf{y}$$

  - equation to be inverted with "regularisation" to suppress statistical fluctuations:
    - statistical extrapolation from fiducial phase space to full phase space
    - statistical fluctuations suppressed by regularizing the difference between the unfolded distribution and the gen-level MC distribution of measured bins with respect to the SM expectation



Migration matrix M



Unfolding with TUnfold

- Measured distributions are of particularly simple form at parton-level, dependent on only the spin coefficient:
  - $x = cos\theta^i_{1/2}, \frac{1}{\sigma}\frac{d\sigma}{dx} = \frac{1}{2}(1 + B_{1/2}(i)x)$
  - $x = cos\theta^i_1 cos\theta^j_2, \frac{1}{\sigma}\frac{d\sigma}{dx} = \frac{1}{2}(1 - C_{ij}x) ln\frac{1}{|x|}$
  - $x = cos\theta^i_1 cos\theta^j_2 \pm cos\theta^j_1 cos\theta^i_2, \frac{1}{\sigma}\frac{d\sigma}{dx} = \frac{1}{2}\left(1 - \frac{C_{ij} \pm C_{ji}}{2}x\right) cos^{-1}|x|$
- The curvature of the vector of measured bins with respect to the SM expectation is regularized in TUnfold
- By multiplying the density by an appropriate factor before regularising (e.g. $1/cos^{-1}|x|$), the variation wrt the coefficient can be made exactly linear → the regularization cannot bias the measured coefficient
  - it's called "BinFactorFunction" in TUnfoldBinning
- 6 uniform bins used for each distribution, roughly matching the reconstruction resolution
  - narrower bins in the TUnfold χ^2 minimization sufficient to reduce the bin width bias to a negligible level

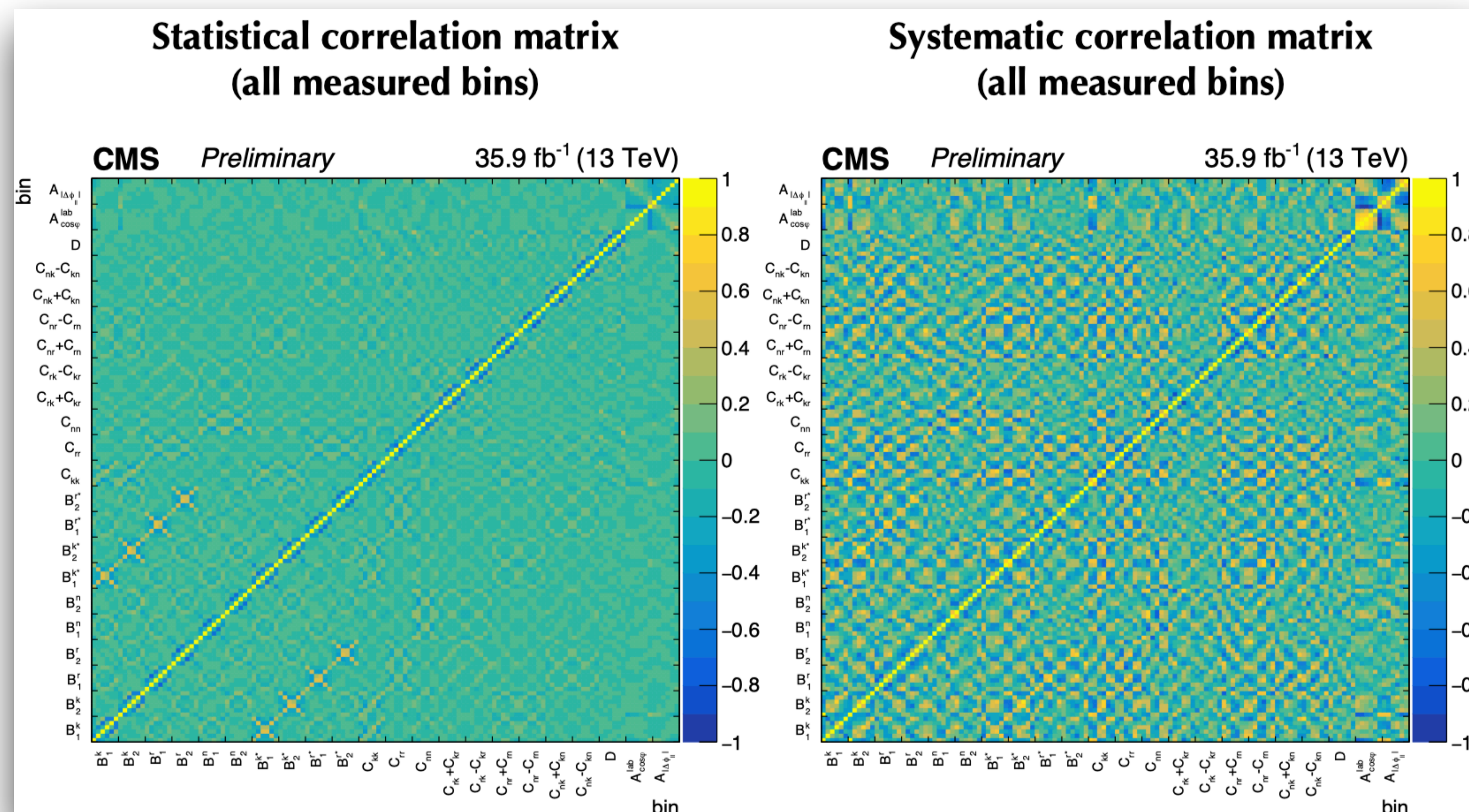
Systematics

- Each source of systematic uncertainty represented by a covariance matrix for the bins of the measured differential cross sections
- Total systematic uncertainty derived from the sum of these covariance matrices

Experimental	Theoretical
Trigger Efficiency	PDF (replicas and α_s)
Kinematic Reco Eff.	Scales (μ_R and μ_F)
Lepton ID and selection	α_s for ISR or FSR
JES (19 subcomponents)	ME-PS matching (PS)
Unclustered energy	b-fragmentation (PS)
Jet Energy Resolution	semileptonic BRs of b hadrons (PS)
b-tagging	Color reconnection (PS)
Pile-up reweighting	Top Mass
Background xsec (30%)	UE-tune
(Luminosity and BF)	Top p_T

Covariance matrices

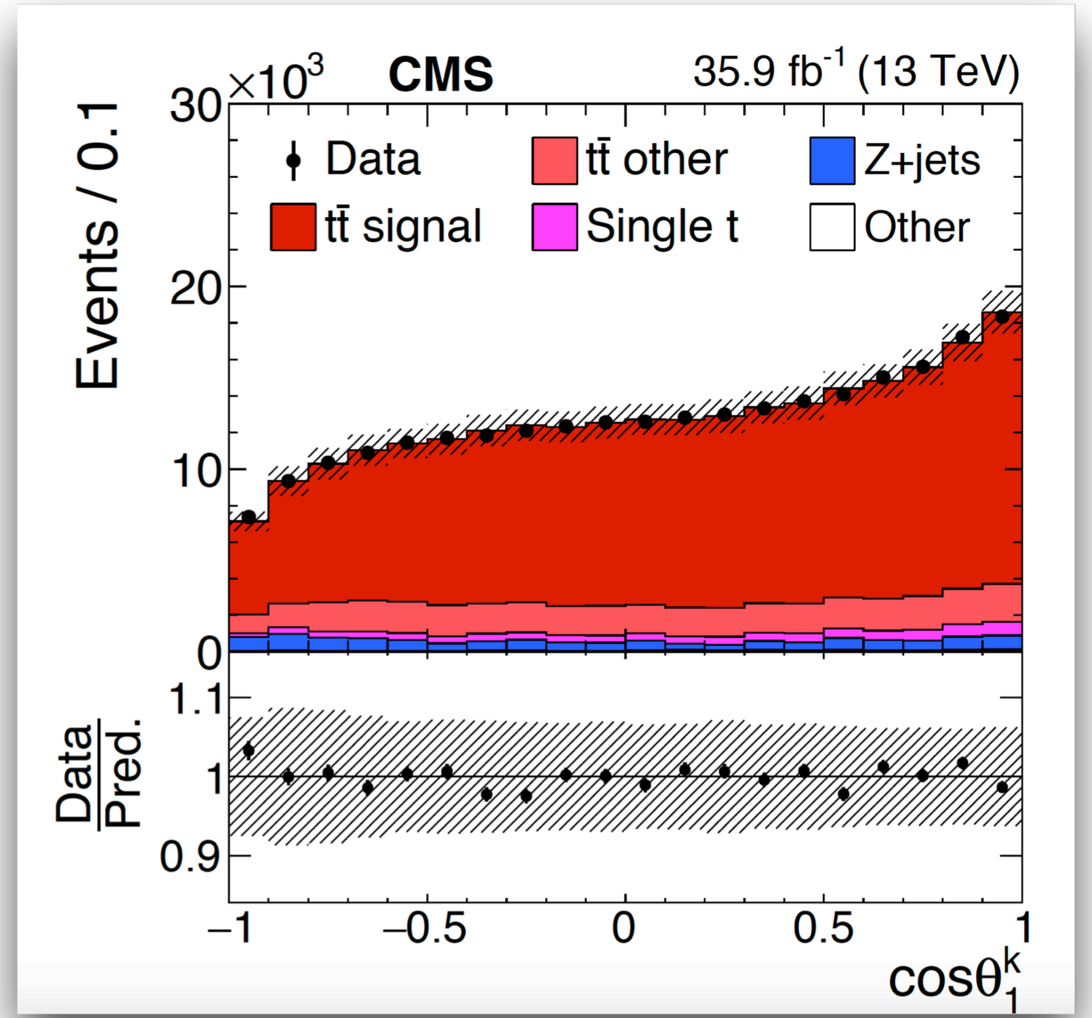
- Covariance (or correlation) matrices derived for all 132 measured bins (6 bins for each of the 22 observables) at once
  - allowing constraints/fits to be made using simultaneously several measured differential cross sections
- Largely statistically independent observables:
  - pattern of statistical correlation and anti-correlation among bins from same distribution arising from unfolding
- Much stronger systematics correlations:
  - pattern of positive and negative correlations reflects relative changes in shape of different distributions in response to systematic variations

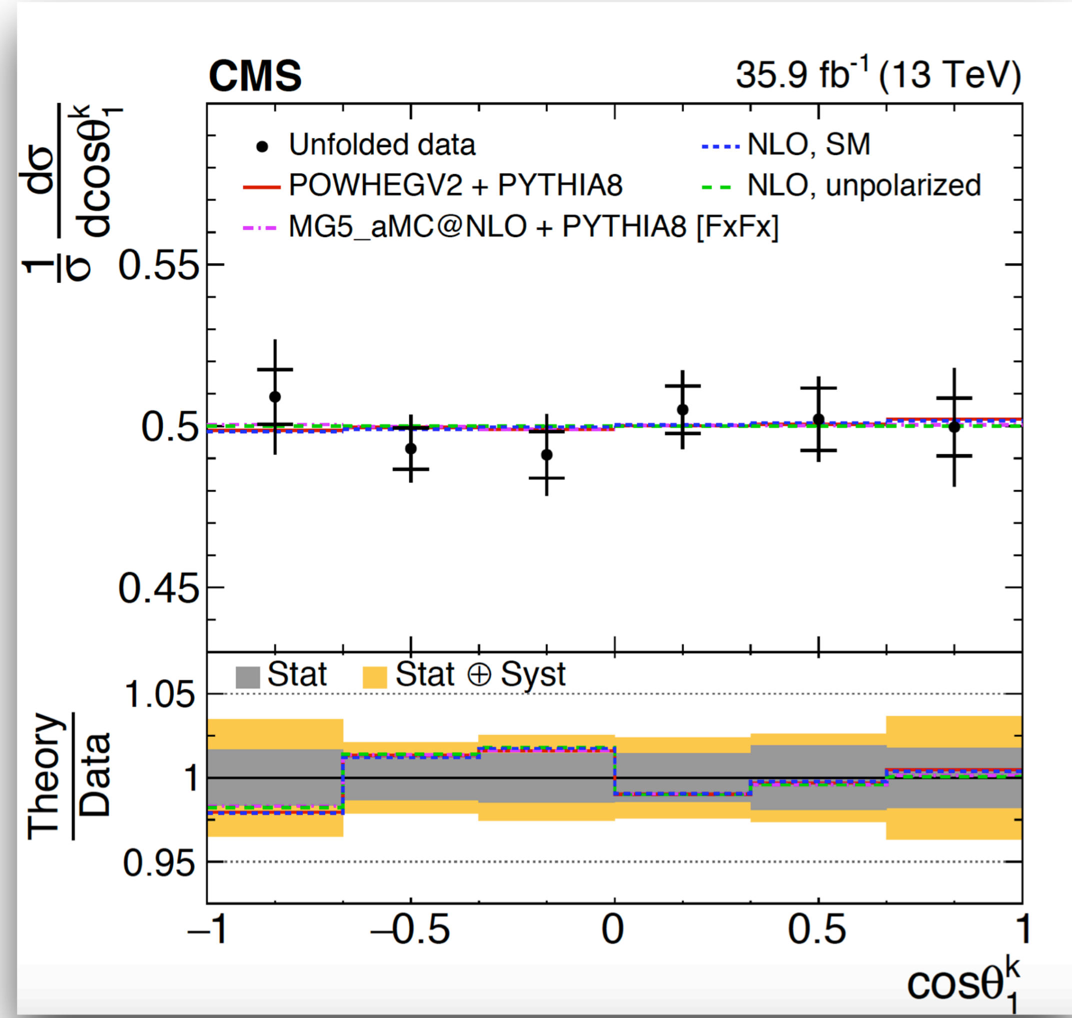


Results: polarizations

- Measured top quark polarization (6 B coefficients) consistent with zero for each axis:
  - measurements not yet sensitive to small level of polarization in the SM

$$\frac{1}{\sigma}\frac{d\sigma}{d\cos\theta} = \frac{1}{2}(1 + B\ \cos\theta)$$





Dominant systematics: JES, b-quark fragmentation, and background

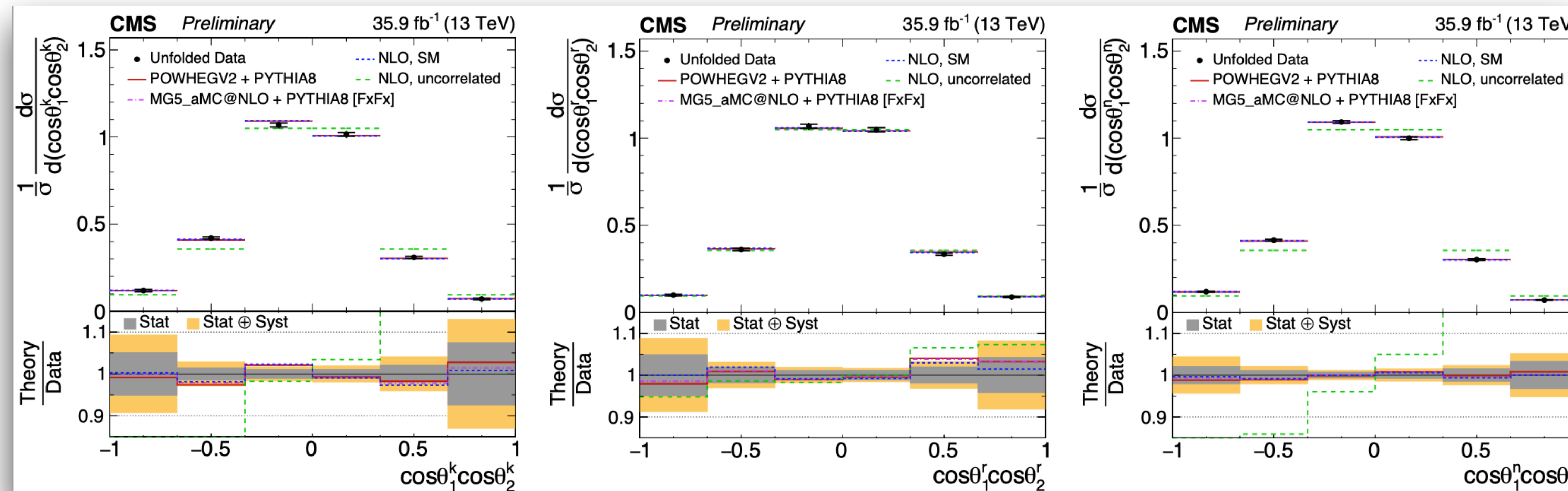
$B_1^k = 0.005 \pm 0.010 \pm 0.021$

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

Results: spin correlations

- Distributions for the correlation of top spins along each axis (probing diagonal of C matrix)
  - spin correlations consistent with SM expectations

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



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

$C_{rr} = 0.08 \pm 0.02 \pm 0.02$
SM NLO: 0.07

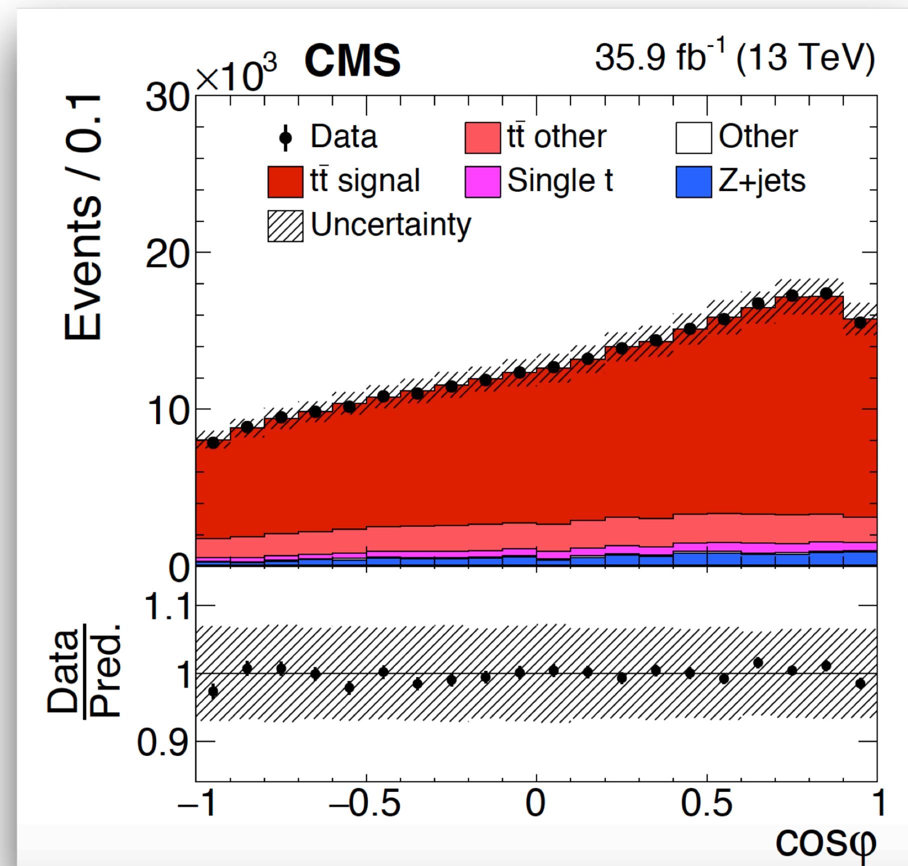
$C_{nn} = 0.33 \pm 0.01 \pm 0.02$
SM NLO: 0.33

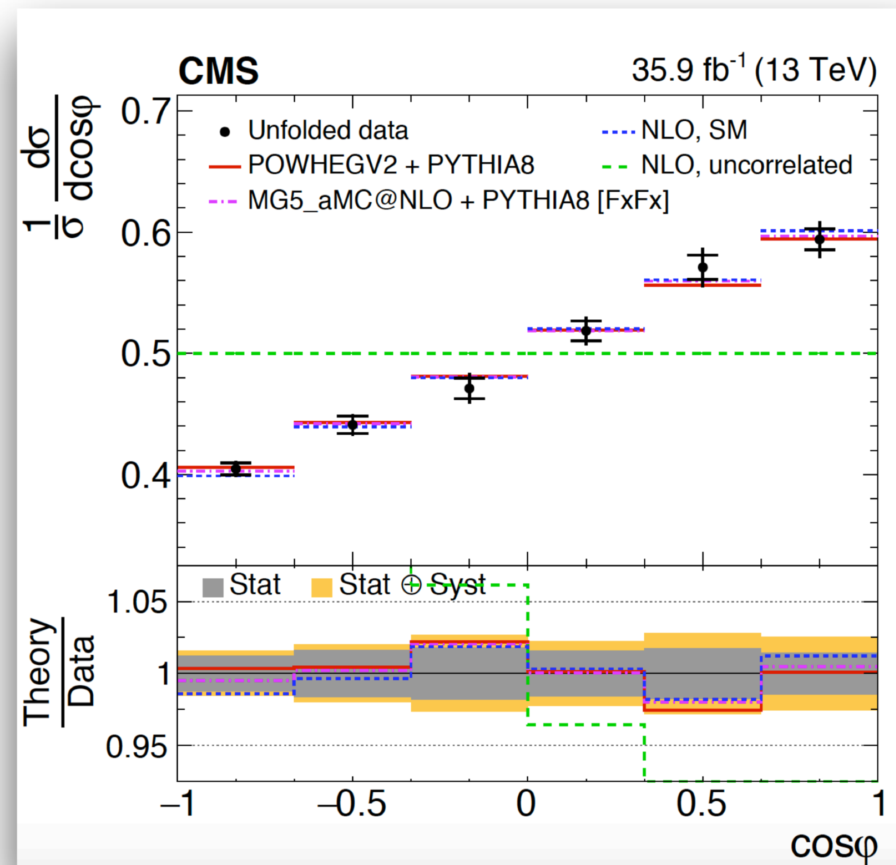
Dominant systematics: background and JES

Results: spin correlations

- Opening angle between leptons $cos\varphi = \hat{\ell}_1 \cdot \hat{\ell}_2$ has maximal sensitivity to the degree of alignment of the top quark spins
  - most precise single variable!

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



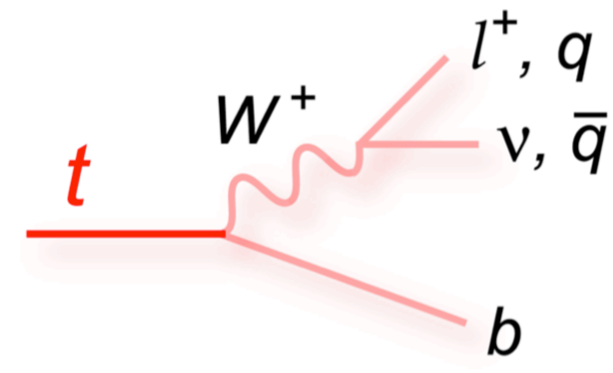


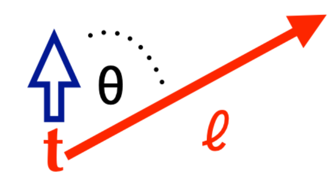
Dominant systematics: background and top pT modeling

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

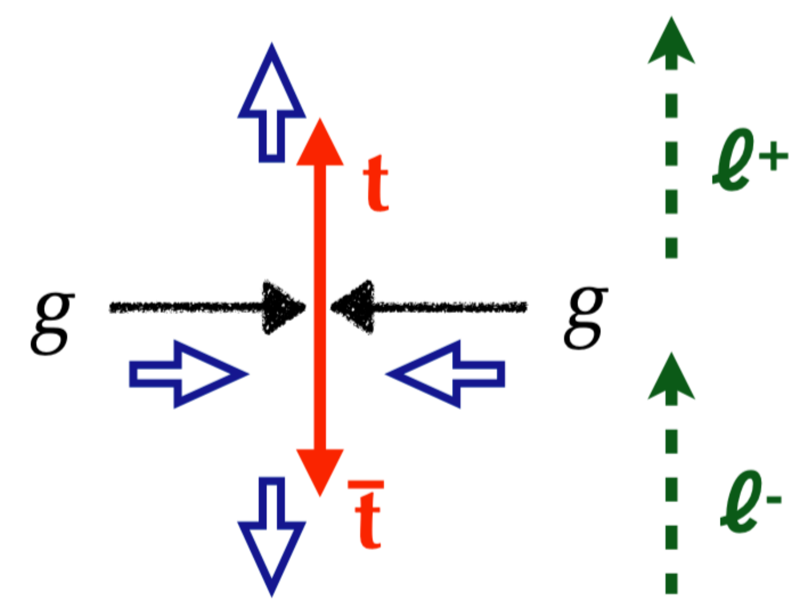
Indirect measurements

- **Direct measurement** of spin correlations requires full reconstruction of t and tbar
- Is it possible to also **probe them indirectly** with simple lab-frame variables?
  - $\ell^{\pm}$ angular distributions = $(1 \pm \cos\theta)/2$
    - preferred lepton directions in the top rest frames determined by top spins → lepton 3-momentum = good proxy for the top spin
    - but leptons preferentially aligned





→ angular correlation retained in lab frame Δφ

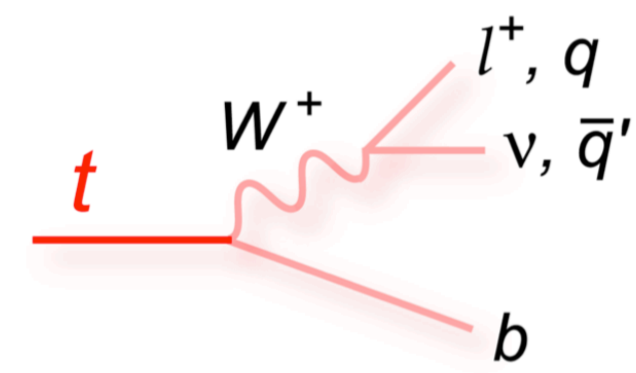


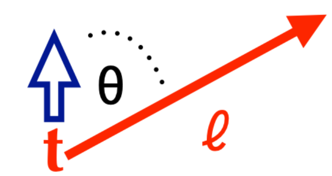
Indirect measurements

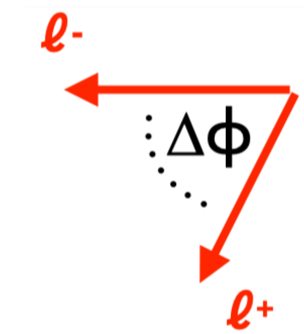
- **Direct measurement** of spin correlations requires full reconstruction of t and tbar
- Is it possible to also **probe them indirectly** with simple lab-frame variables?
  - $\ell^\pm$ angular distributions = $(1 \pm \cos\theta)/2$
  - angle between leptons in transverse plane (lab.):

$$|\Delta\phi_{\ell\ell}| = \left| \left| |\phi_{l1} - \phi_{l2}| - \pi \right| - \pi \right|$$

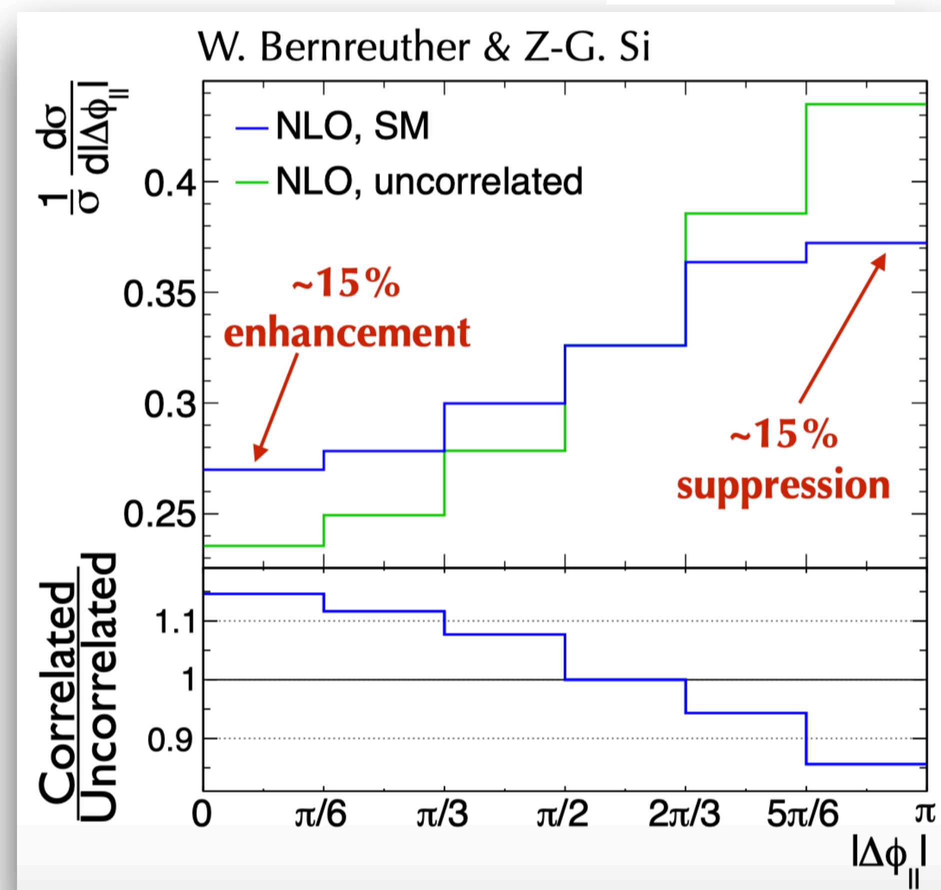
    - experimentally very precise for excellent resolution of lepton angles
    - shape comes from top kinematics
      - large Δφ preferred because tops are produced back to back
      - relative enhancement at low Δφ due to spin correlations





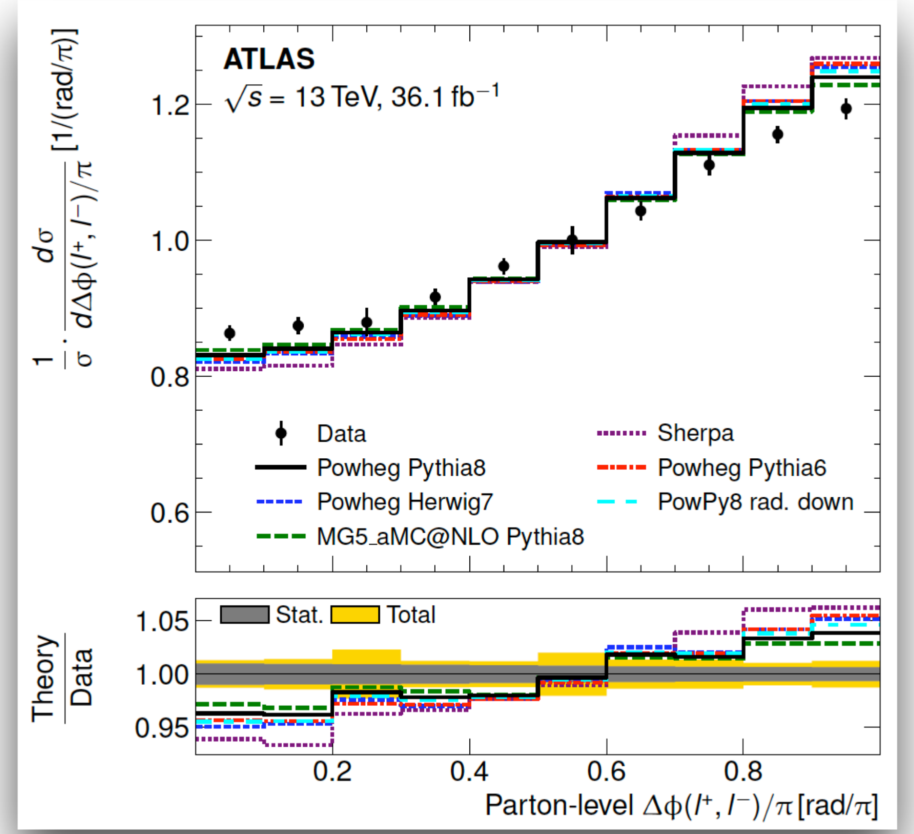


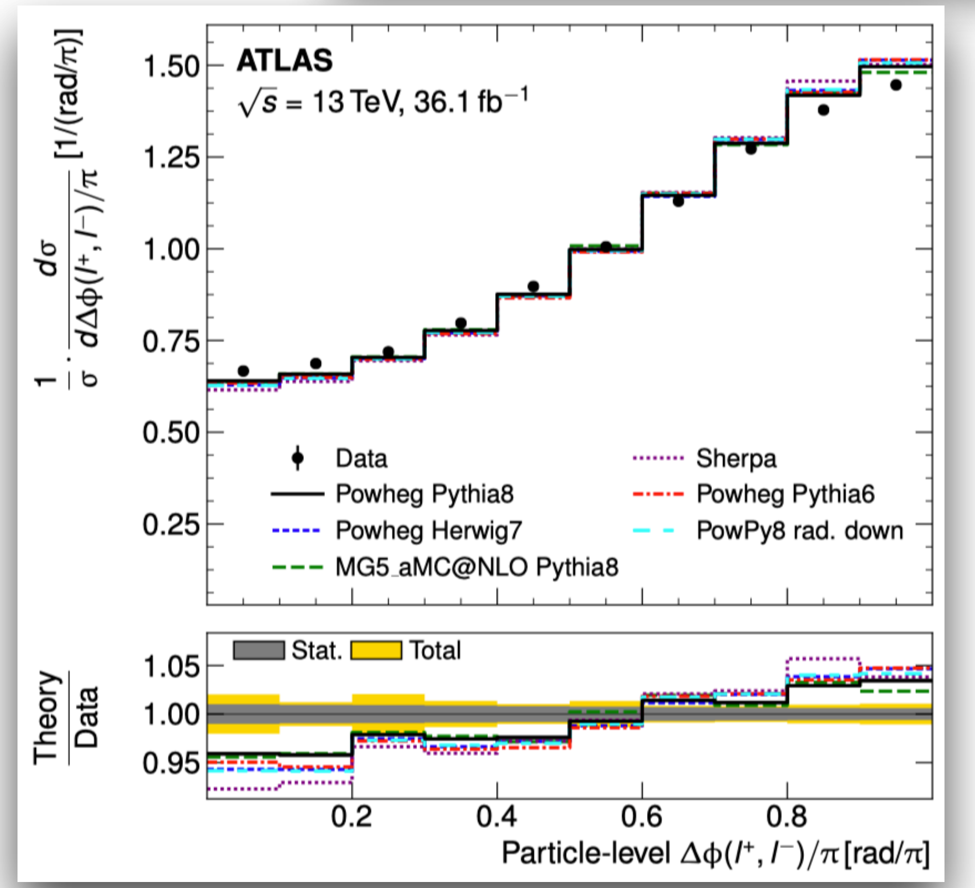
Predicted Δφ distribution in presence and absence of spin correlations



Δϕ distribution

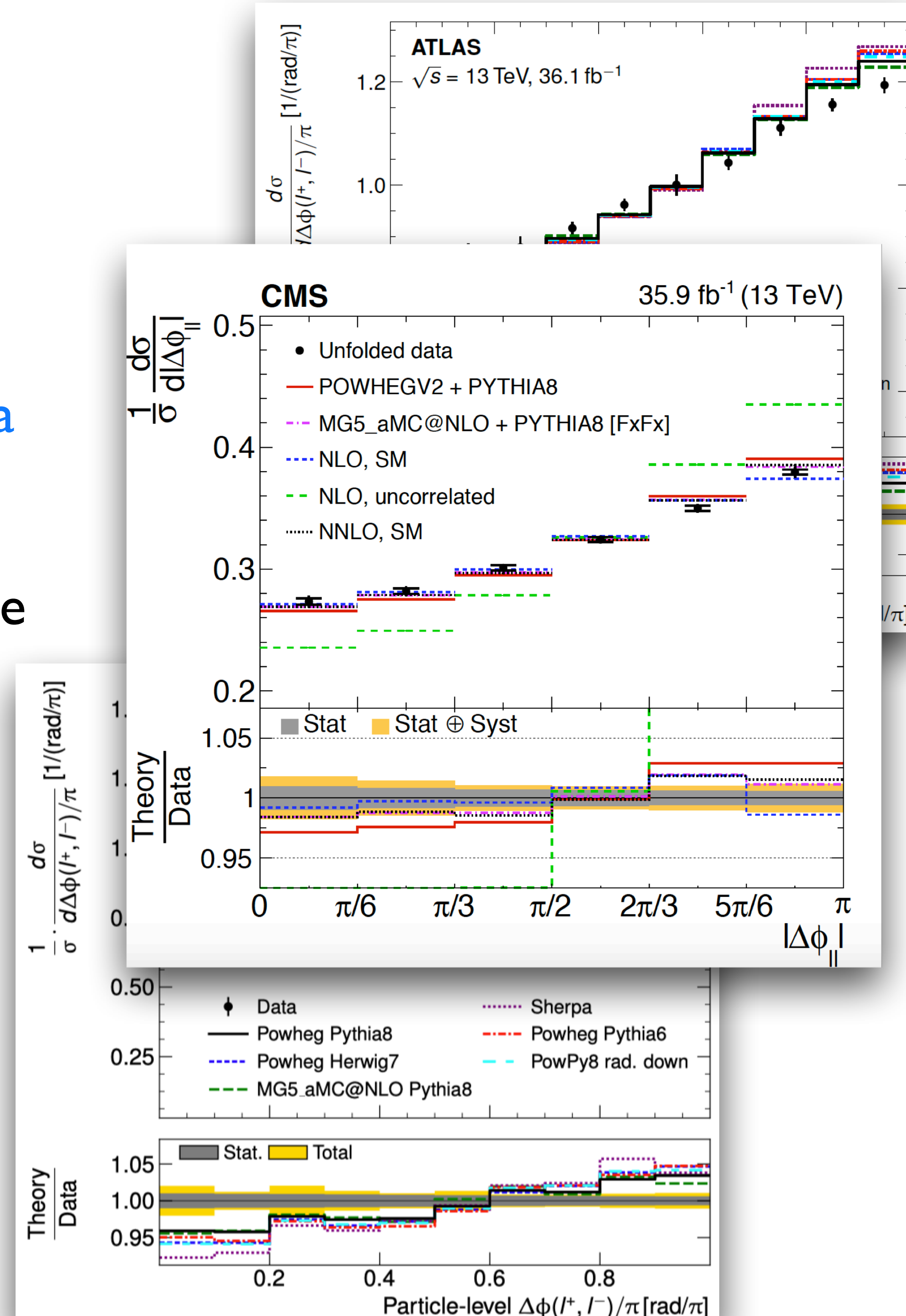
- "**Unfolding**": distribution in data corrected for acceptance and migration between bins
- In ATLAS:
  - parton level, full phase space:
    - clear discrepancy between data and NLO simulations (~3σ)
  - particle level, fiducial phase space
    - discrepancy remains even in the fiducial phase space of the detector (reduced extrapolation)





Δϕ distribution

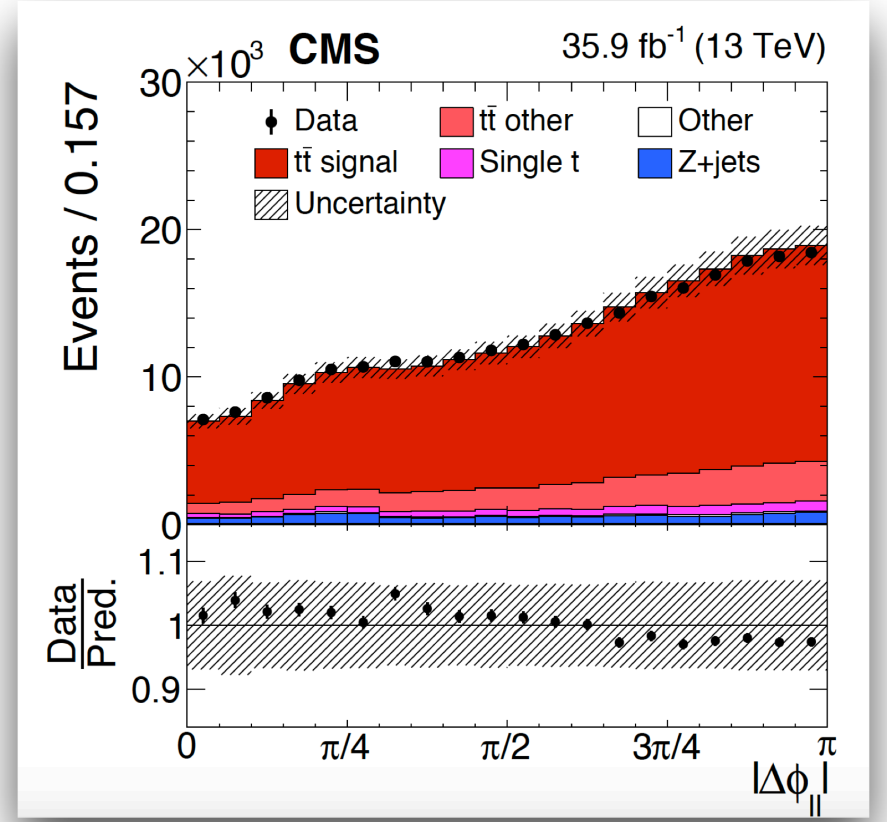
- "**Unfolding**": distribution in data corrected for acceptance and migration between bins
- In ATLAS:
  - parton level, full phase space:
    - clear discrepancy between data and NLO simulations (~3σ)
  - parton level, full phase space
    - discrepancy remains even in the fiducial phase space of the detector (reduced extrapolation)
- In CMS (parton level):
  - smaller discrepancy is observed
  - tensions between data and NLO simulation reduced when comparing to NNLO predictions

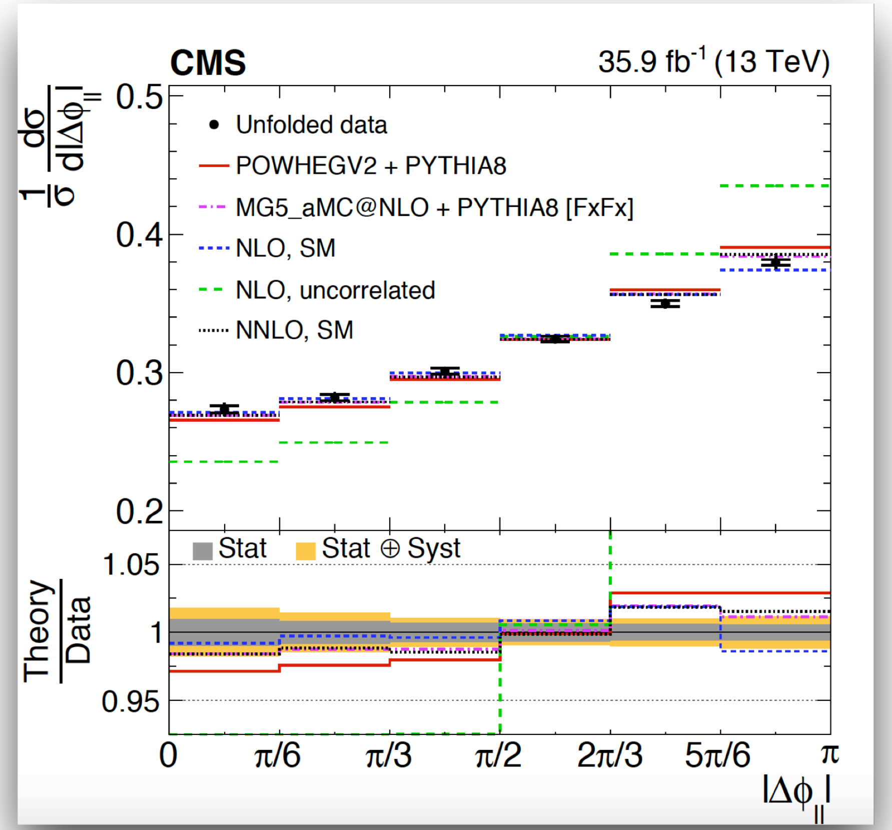


Results: spin correlations

$$|\Delta\phi_{\ell\ell}| = \Big| \big| |\phi_{l1} - \phi_{l2}| - \pi \big| - \pi \Big|$$

to measure $A_{\Delta\phi_{\ell\ell}} = \dfrac{N(|\Delta\phi_{\ell\ell}| > \pi/2) - N(|\Delta\phi_{\ell\ell}| < \pi/2)}{N(|\Delta\phi_{\ell\ell}| > \pi/2) + N(|\Delta\phi_{\ell\ell}| < \pi/2)}$





Dominant systematics: ME-PS Matching and top pT modelling

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

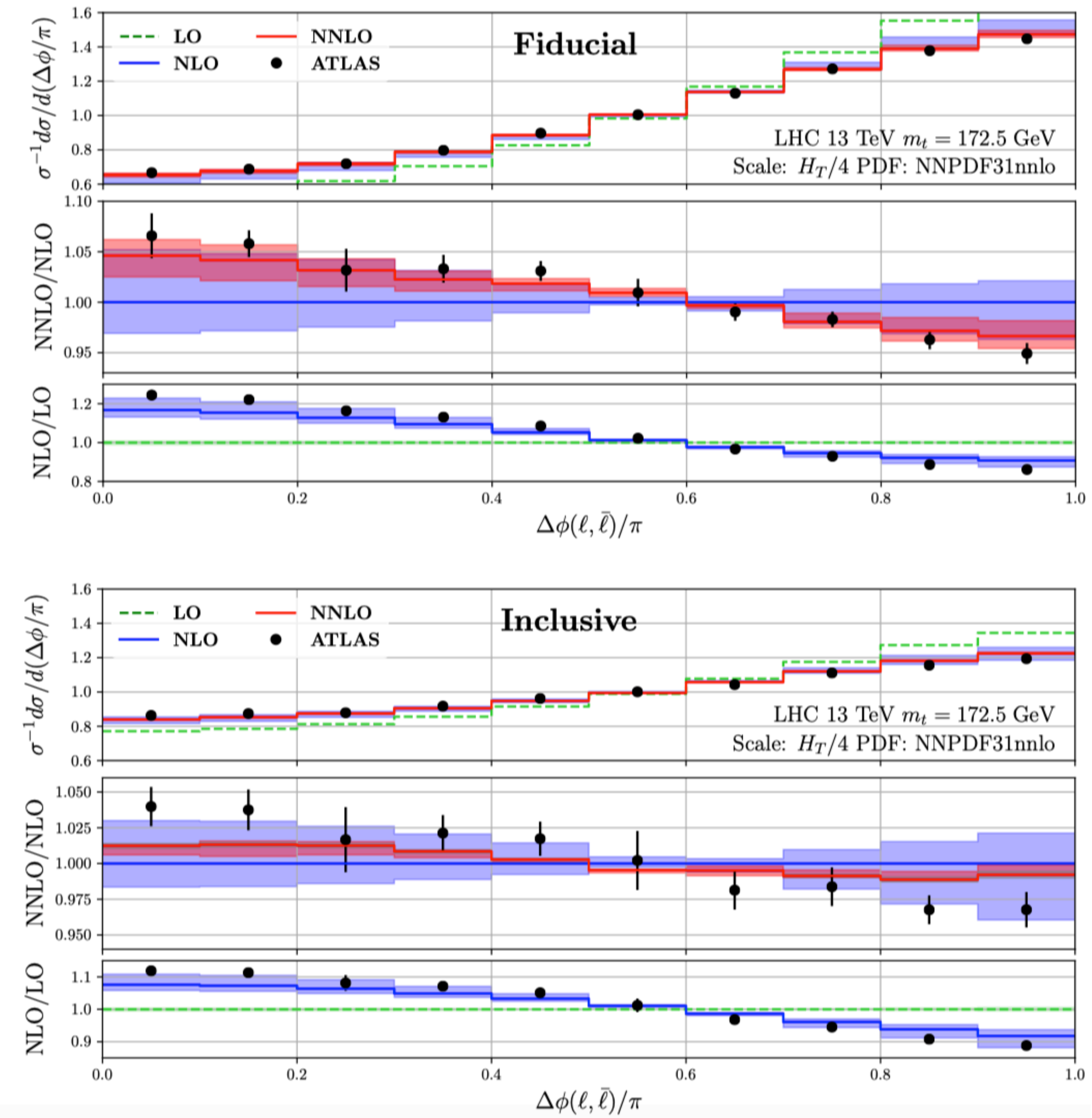
SM NNLO: $0.115^{+0.005}_{-0.001}$

NNLO corrections to Δϕ

- NNLO calculations have been made both inclusively and in a fiducial region similar to that used by the experiments

- NNLO corrections are significantly larger in the fiducial phase space than in the full phase space → use NNLO corrections (instead of the NLO MC currently used) in the extrapolation to the full phase space

- Calculated fiducial region not identical to those used in the analyses, but a correction of this size would account for the residual discrepancy



arxiv:1901.05407

Extraction of coefficients

- Coefficient extracted from corresponding normalized differential cross section combining the information from the measured bins to minimize its uncertainty

Coefficient	Measured	POWHEGV2	MG5_aMC@NLO	NLO calculation
B_1^k	0.005 ± 0.023	$0.004^{+0.002}_{-0.001}$	0.000 ± 0.001	$4.0^{+1.7}_{-1.2} \times 10^{-3}$
B_2^k	0.008 ± 0.024	$0.006^{+0.001}_{-0.001}$	-0.002 ± 0.001	$4.0^{+1.7}_{-1.2} \times 10^{-3}$
B_1^r	-0.023 ± 0.017	$0.002^{+0.001}_{-0.002}$	0.002 ± 0.001	$1.6^{+1.2}_{-0.9} \times 10^{-3}$
B_2^r	-0.010 ± 0.020	$0.003^{+0.001}_{-0.002}$	0.000 ± 0.001	$1.6^{+1.2}_{-0.9} \times 10^{-3}$
B_1^n	0.006 ± 0.013	$-0.001^{+0.002}_{-0.001}$	0.001 ± 0.001	$5.7^{+0.5}_{-0.4} \times 10^{-3}$
B_2^n	0.017 ± 0.013	$-0.001^{+0.001}_{-0.001}$	0.000 ± 0.001	$5.7^{+0.5}_{-0.4} \times 10^{-3}$
B_1^{k*}	-0.016 ± 0.018	$-0.001^{+0.001}_{-0.001}$	0.000 ± 0.001	$< 10^{-3}$
B_2^{k*}	0.007 ± 0.019	$0.001^{+0.002}_{-0.003}$	0.003 ± 0.001	$< 10^{-3}$
B_1^{r*}	0.001 ± 0.018	$0.000^{+0.001}_{-0.002}$	0.000 ± 0.001	$< 10^{-3}$
B_2^{r*}	0.010 ± 0.017	$0.001^{+0.001}_{-0.002}$	0.001 ± 0.001	$< 10^{-3}$
C_{kk}	0.299 ± 0.038	$0.314^{+0.005}_{-0.004}$	0.325 ± 0.002	$0.331^{+0.002}_{-0.002}$
C_{rr}	0.080 ± 0.033	$0.048^{+0.007}_{-0.006}$	0.052 ± 0.002	$0.071^{+0.008}_{-0.006}$
C_{nn}	0.329 ± 0.020	$0.317^{+0.001}_{-0.003}$	0.324 ± 0.002	$0.326^{+0.002}_{-0.002}$
$C_{rk} + C_{kr}$	-0.193 ± 0.064	$-0.201^{+0.004}_{-0.003}$	-0.198 ± 0.002	$-0.206^{+0.002}_{-0.002}$
$C_{rk} - C_{kr}$	0.057 ± 0.046	$-0.001^{+0.005}_{-0.002}$	0.004 ± 0.002	0
$C_{nr} + C_{rn}$	-0.004 ± 0.037	$-0.003^{+0.008}_{-0.002}$	0.001 ± 0.002	$1.06^{+0.01}_{-0.01} \times 10^{-3}$
$C_{nr} - C_{rn}$	-0.001 ± 0.038	$0.002^{+0.005}_{-0.002}$	0.001 ± 0.002	0
$C_{nk} + C_{kn}$	-0.043 ± 0.041	$-0.002^{+0.005}_{-0.002}$	0.003 ± 0.002	$2.15^{+0.04}_{-0.07} \times 10^{-3}$
$C_{nk} - C_{kn}$	0.040 ± 0.029	$-0.001^{+0.003}_{-0.002}$	-0.001 ± 0.002	0
D	-0.237 ± 0.011	$-0.226^{+0.003}_{-0.004}$	-0.233 ± 0.001	$-0.243^{+0.004}_{-0.003}$
$A_{\cos\varphi}^{\text{lab}}$	0.167 ± 0.012	$0.161^{+0.002}_{-0.002}$	0.174 ± 0.001	$0.181^{+0.004}_{-0.003}$
$A_{\|\Delta\phi_{\ell\ell}\|}$	0.103 ± 0.008	$0.125^{+0.004}_{-0.005}$	0.115 ± 0.001	$0.112^{+0.009}_{-0.012}$

Top polarisation coefficients uncertainties

Table 3: Summary of the systematic uncertainties in the extracted top quark polarization coefficients.

Source	**Uncertainty**									
	B_1^k	B_2^k	B_1^r	B_2^r	B_1^n	B_2^n	B_1^{k*}	B_2^{k*}	B_1^{r*}	B_2^{r*}
JER	0.001	0.002	0.001	0.001	0.001	0.001	0.000	0.001	0.001	0.001
JES	0.011	0.012	0.007	0.009	0.003	0.003	0.009	0.008	0.007	0.007
Unclustered energy	0.001	0.002	0.001	0.001	0.000	0.001	0.001	0.000	0.001	0.002
Pileup	0.000	0.000	0.002	0.002	0.000	0.001	0.001	0.001	0.000	0.000
Trigger	0.001	0.001	0.001	0.001	0.000	0.000	0.001	0.001	0.002	0.002
Lepton ID/isolation	0.001	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Kinematic reconstruction	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
b tagging	0.003	0.004	0.003	0.003	0.000	0.000	0.002	0.002	0.001	0.001
Background	0.008	0.008	0.005	0.008	0.001	0.001	0.004	0.005	0.002	0.002
Scale	0.005	0.004	0.004	0.009	0.003	0.004	0.003	0.004	0.006	0.005
B-fragmentation	0.009	0.009	0.004	0.005	0.000	0.001	0.001	0.001	0.001	0.001
B-hadron semi-lep. BF	0.001	0.001	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Color reconnection	0.005	0.003	0.003	0.004	0.008	0.005	0.006	0.008	0.006	0.008
Underlying event	0.001	0.003	0.001	0.003	0.002	0.003	0.003	0.002	0.004	0.004
ME/PS matching	0.006	0.006	0.004	0.001	0.003	0.004	0.003	0.003	0.004	0.004
Top quark mass	0.006	0.007	0.000	0.001	0.001	0.002	0.002	0.001	0.002	0.002
PDF	0.002	0.002	0.000	0.000	0.000	0.000	0.004	0.004	0.002	0.002
Top quark p_T	0.003	0.003	0.001	0.001	0.000	0.000	0.001	0.001	0.000	0.000
Total systematic	0.021	0.021	0.013	0.017	0.010	0.009	0.014	0.014	0.013	0.014
Data statistics	0.009	0.008	0.009	0.009	0.007	0.008	0.010	0.010	0.010	0.009
MC statistics	0.003	0.003	0.003	0.003	0.003	0.003	0.004	0.004	0.004	0.003
Background MC statistics	0.005	0.005	0.005	0.005	0.004	0.004	0.006	0.006	0.005	0.005
Total statistical	0.010	0.010	0.011	0.011	0.009	0.009	0.012	0.012	0.012	0.011
Total	0.023	0.024	0.017	0.020	0.013	0.013	0.018	0.019	0.018	0.017

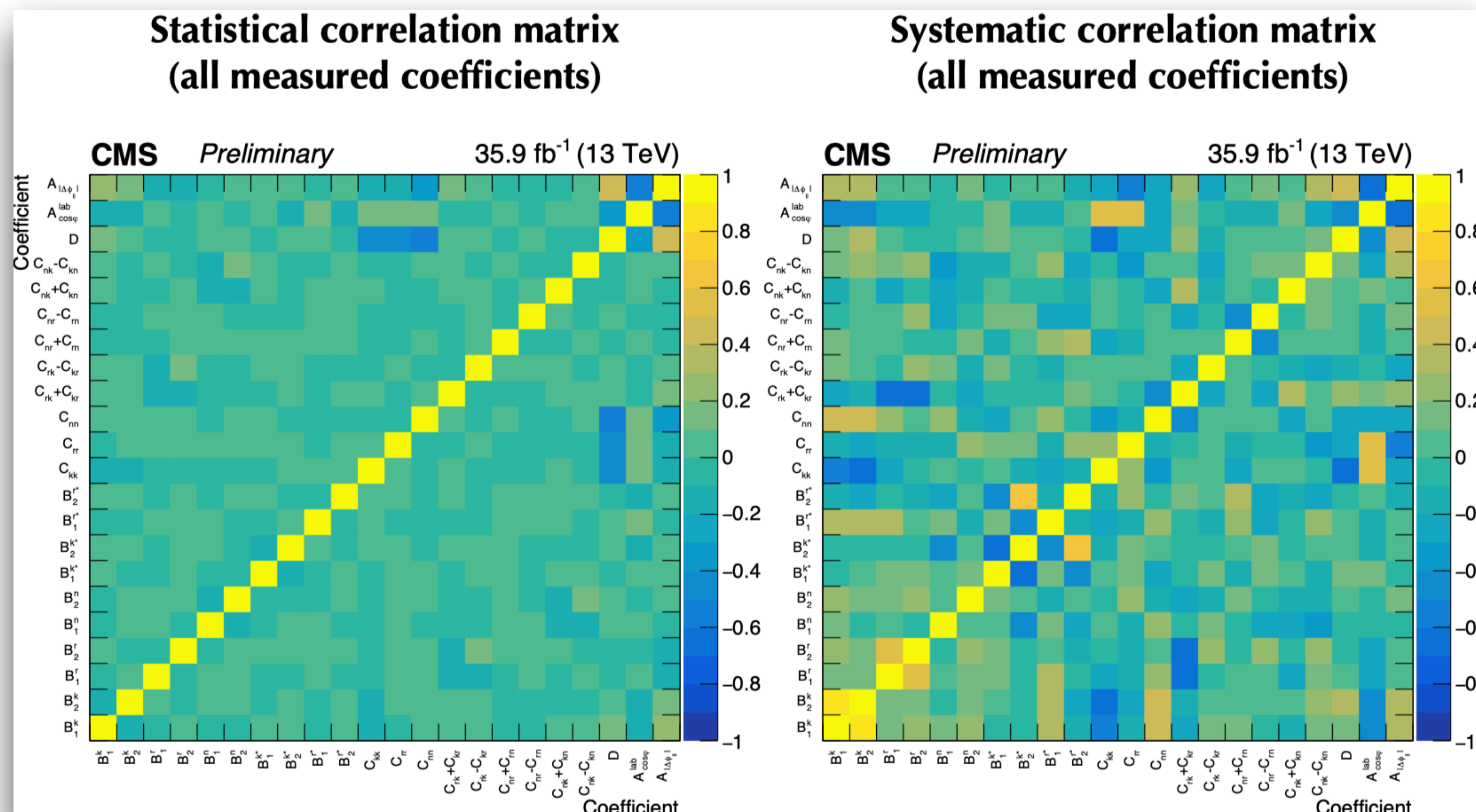
Ttbar spin correlation coefficients uncertainties

Table 4: Summary of the systematic uncertainties in the extracted $t\bar{t}$ spin correlation coefficients.

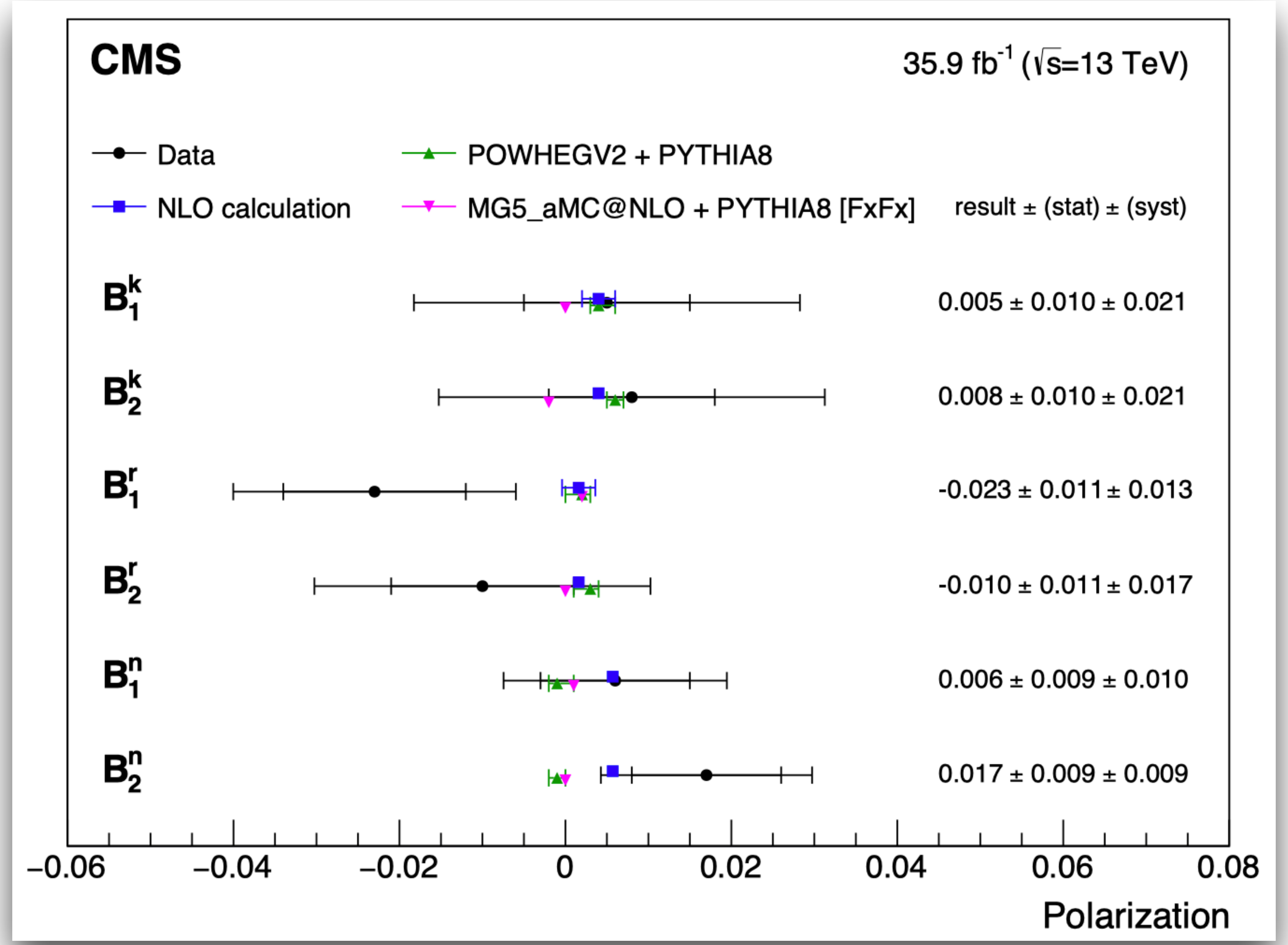
Source	**Uncertainty**											
	C_{kk}	C_{rr}	C_{nn}	$C_{rk}+C_{kr}$	$C_{rk}-C_{kr}$	$C_{nr}+C_{rn}$	$C_{nr}-C_{rn}$	$C_{nk}+C_{kn}$	$C_{nk}-C_{kn}$	D	$A^{\mathrm{lab}}_{\cos\varphi}$	$A_{\lvert\Delta\phi_{\ell\ell}\rvert}$
JER	0.001	0.001	0.001	0.004	0.002	0.001	0.001	0.003	0.001	0.000	0.000	0.000
JES	0.012	0.009	0.005	0.022	0.011	0.011	0.009	0.012	0.007	0.002	0.000	0.001
Unclustered energy	0.001	0.001	0.001	0.004	0.001	0.001	0.002	0.001	0.001	0.000	0.000	0.001
Pileup	0.002	0.000	0.001	0.004	0.001	0.001	0.002	0.001	0.001	0.001	0.000	0.001
Trigger	0.001	0.001	0.000	0.002	0.000	0.000	0.000	0.000	0.000	0.000	0.001	0.000
Lepton ID/isolation	0.001	0.001	0.000	0.001	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Kinematic reconstruction	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
b tagging	0.004	0.001	0.002	0.005	0.001	0.001	0.001	0.001	0.001	0.001	0.000	0.000
Background	0.017	0.009	0.008	0.025	0.006	0.004	0.004	0.007	0.003	0.004	0.008	0.002
Scale	0.012	0.006	0.007	0.026	0.011	0.007	0.014	0.011	0.007	0.003	0.002	0.003
B-fragmentation	0.014	0.002	0.005	0.017	0.001	0.001	0.001	0.002	0.001	0.003	0.000	0.001
B-hadron semi-lep. BF	0.000	0.001	0.001	0.002	0.000	0.001	0.000	0.000	0.000	0.001	0.000	0.000
Color reconnection	0.005	0.013	0.006	0.013	0.011	0.014	0.017	0.009	0.008	0.002	0.001	0.001
Underlying event	0.008	0.002	0.002	0.004	0.010	0.007	0.005	0.007	0.002	0.003	0.001	0.001
ME/PS matching	0.004	0.003	0.001	0.009	0.016	0.011	0.001	0.012	0.009	0.002	0.002	0.004
Top quark mass	0.001	0.002	0.006	0.006	0.009	0.002	0.002	0.009	0.001	0.002	0.001	0.000
PDF	0.005	0.005	0.001	0.004	0.001	0.001	0.001	0.001	0.001	0.002	0.007	0.002
Top quark p_{T}	0.008	0.010	0.005	0.019	0.000	0.001	0.000	0.001	0.000	0.004	0.003	0.005
Total systematic	0.031	0.023	0.017	0.053	0.029	0.024	0.025	0.026	0.016	0.009	0.011	0.008
Data statistics	0.018	0.019	0.010	0.029	0.029	0.024	0.025	0.025	0.020	0.006	0.003	0.003
MC statistics	0.007	0.007	0.004	0.011	0.011	0.009	0.009	0.010	0.008	0.002	0.001	0.001
Background MC statistics	0.011	0.010	0.005	0.018	0.017	0.012	0.010	0.015	0.012	0.003	0.002	0.002
Total statistical	0.022	0.023	0.012	0.035	0.035	0.028	0.028	0.031	0.025	0.007	0.003	0.003
Total	0.038	0.033	0.020	0.064	0.046	0.037	0.038	0.041	0.029	0.011	0.012	0.008

Correlation matrices for coefficients

- Coefficient largely statistically uncorrelated:
  - statistical correlations between D and the diagonal C coefficients, and the 2 lab-frame observables
- Much stronger systematics correlations:
  - evident for polarization measurements and for coefficients with significant statistical correlations

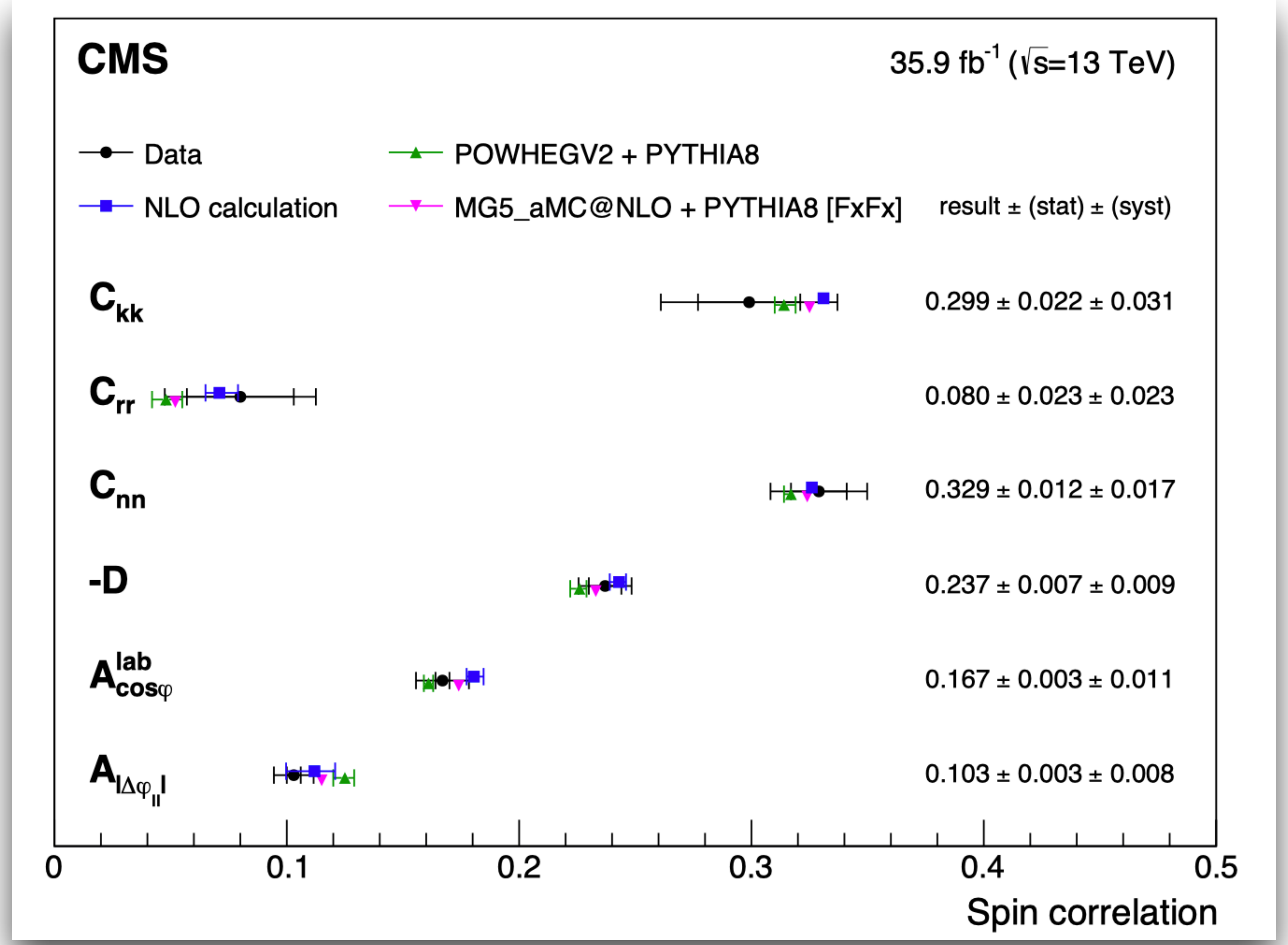


Polarisation coefficient summary plots



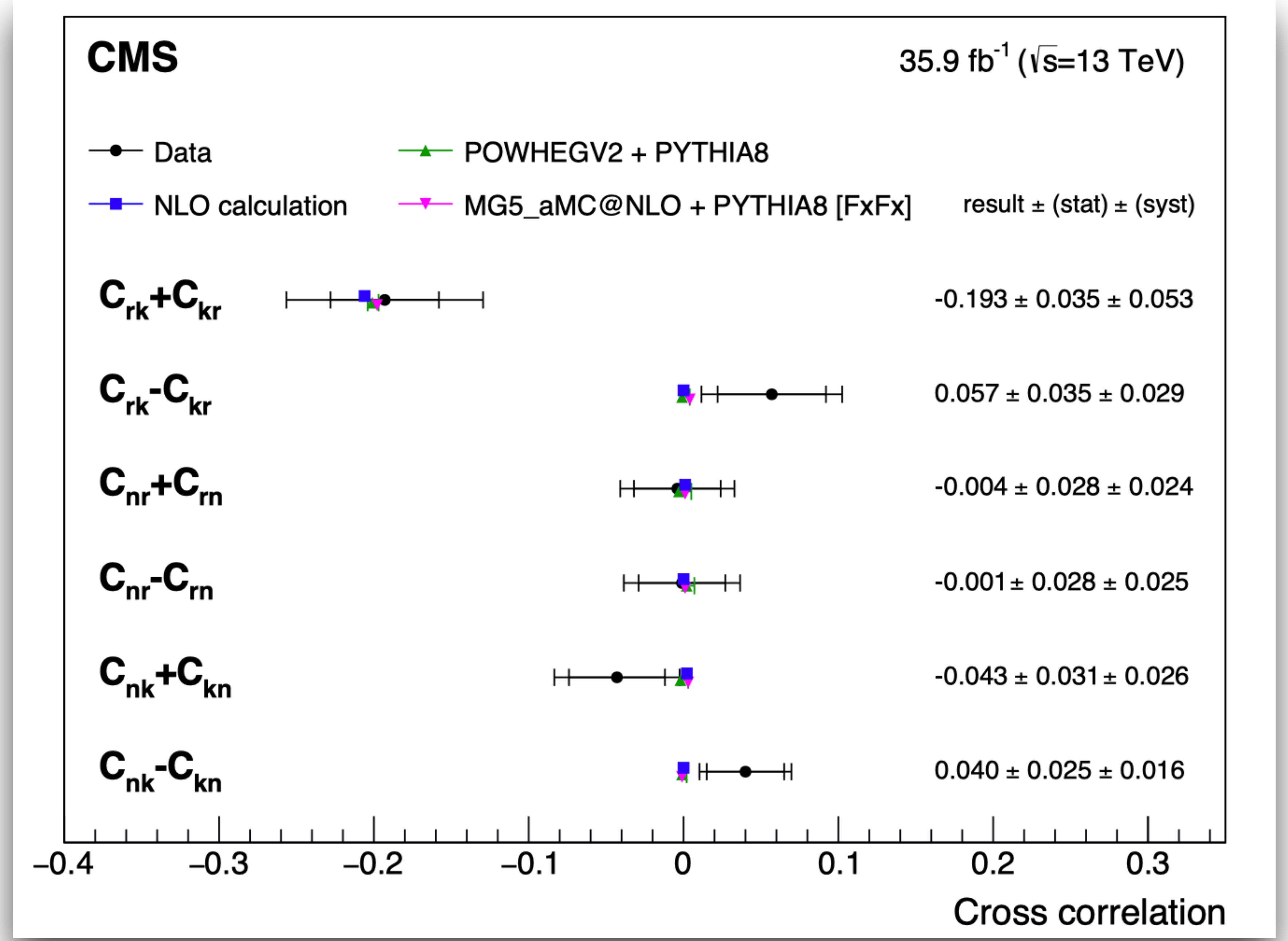
Spin correlation coefficient summary plots

- All direct spin correlation measurements in close agreement with SM predictions



Off-diagonal spin correlation coefficient summary plots

- Only 2 of the off-diagonal elements of the matrix C are not small in the SM
  - first 3σ evidence for spin correlation between r and k axes



Combination of B coefficients

- Sums and differences of B coefficients:
  - corresponding to the CP-even and CP-odd components of the polarization

Coefficient	Measured	NLO calculation
$B_1^k + B_2^k$	$0.013 \pm 0.014 \pm 0.041$	$8.0^{+3.4}_{-2.4} \times 10^{-3}$
$B_1^k - B_2^k$	$-0.003 \pm 0.015 \pm 0.011$	0
$B_1^r + B_2^r$	$-0.033 \pm 0.015 \pm 0.026$	$3.2^{+2.3}_{-1.7} \times 10^{-3}$
$B_1^r - B_2^r$	$-0.012 \pm 0.016 \pm 0.014$	0
$B_1^n + B_2^n$	$0.024 \pm 0.012 \pm 0.013$	$11.3^{+0.9}_{-0.7} \times 10^{-3}$
$B_1^n - B_2^n$	$-0.011 \pm 0.014 \pm 0.013$	0
$B_1^{k*} + B_2^{k*}$	$-0.010 \pm 0.016 \pm 0.012$	$< 10^{-3}$
$B_1^{k*} - B_2^{k*}$	$-0.023 \pm 0.018 \pm 0.025$	0
$B_1^{r*} + B_2^{r*}$	$0.011 \pm 0.016 \pm 0.018$	$< 10^{-3}$
$B_1^{r*} - B_2^{r*}$	$-0.008 \pm 0.016 \pm 0.020$	0

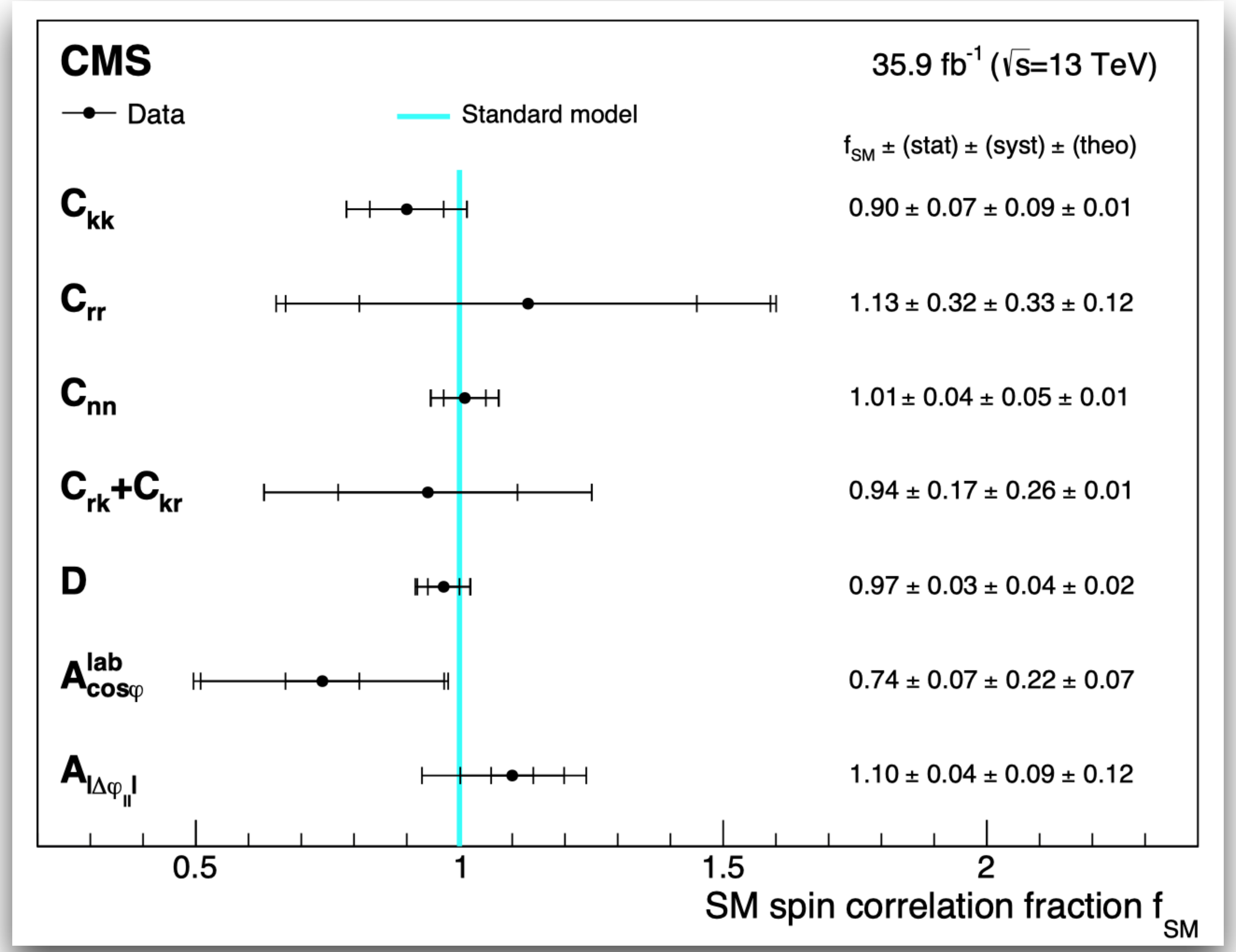
Extraction of f_{SM}

- f_{SM} = strength of the measured spin correlation relative to the SM prediction
  - f_{SM} = 1 for SM, f_{SM} = 0 for uncorrelated events
  - values derived using the measured coefficients and NLO calculations
  - allows easy comparison of results between different variables (and between different experiments)

Coefficient	$f_{SM} \pm$ (stat) $\pm$ (syst) $\pm$ (theor)	Total uncertainty
C_{kk}	$0.90 \pm 0.07 \pm 0.09 \pm 0.01$	± 0.12
C_{rr}	$1.13 \pm 0.32 \pm 0.33\,^{+0.10}_{-0.13}$	$^{+0.47}_{-0.48}$
C_{nn}	$1.01 \pm 0.04 \pm 0.05 \pm 0.01$	± 0.06
$C_{rk} + C_{kr}$	$0.94 \pm 0.17 \pm 0.26 \pm 0.01$	± 0.31
D	$0.97 \pm 0.03 \pm 0.04\,^{+0.01}_{-0.02}$	± 0.05
$A^{\text{lab}}_{\cos\varphi}$	$0.74 \pm 0.07 \pm 0.22\,^{+0.06}_{-0.08}$	$^{+0.24}_{-0.25}$
$A_{\lvert\Delta\phi_{\ell\ell}\rvert}$	$1.10 \pm 0.04 \pm 0.09\,^{+0.10}_{-0.14}$	$^{+0.14}_{-0.17}$

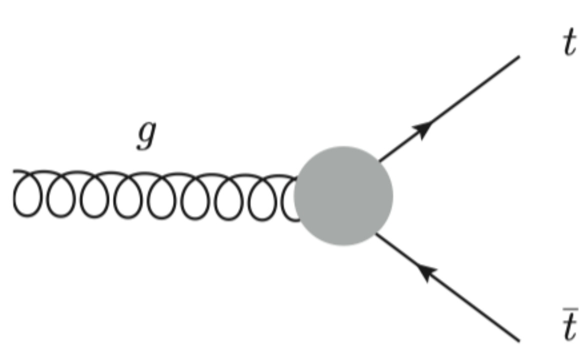
D coefficient: most precise measurement to date (5% uncertainty)

f_{SM} summary plot



EFT interpretation

- The measured coefficients probe most of the lowest-order EFT operators relevant to the LHC ttbar production
- Several models of BSM physics predict an **anomalous top quark Chromo-Magnetic Dipole Moment (CMDM)**
    - induces top chirality flips affecting spin structure and kinematic properties of ttbar events
- Initial focus on the top quark anomalous CMDM:
    - set 95% CL limits on EFT operator $\mathcal{O}_{tG}$
        - from simultaneous fit to measured differential cross sections
        - through its Wilson coefficient C_{tG}/Λ^2_{EFT}
            - with $\Lambda_{EFT} = 1$ TeV
    - [will be referred to as just C_{tG}]

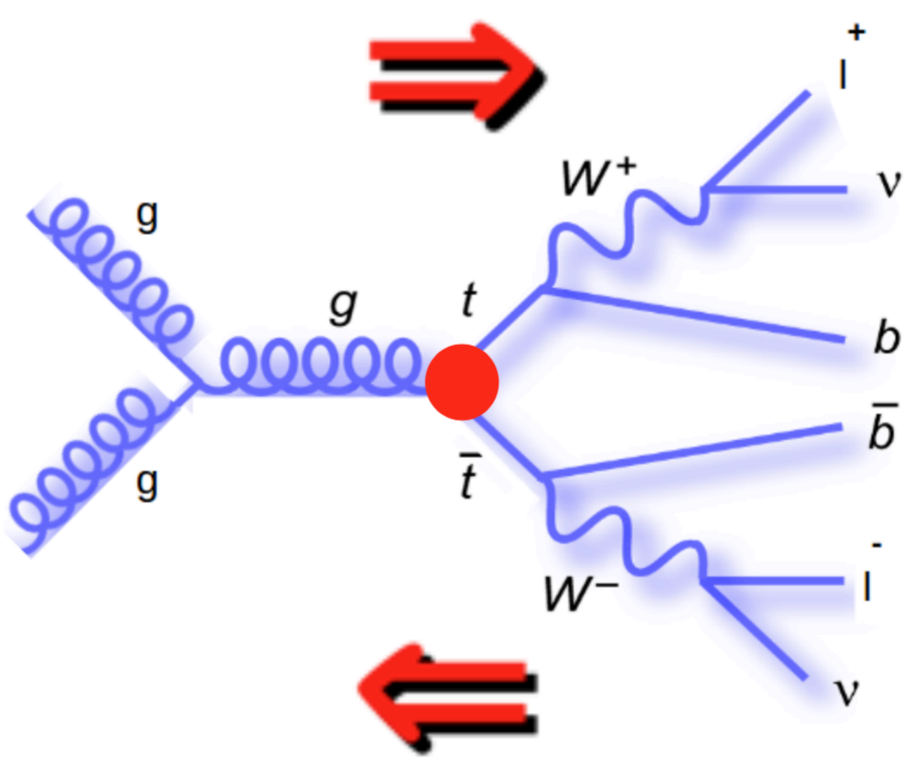


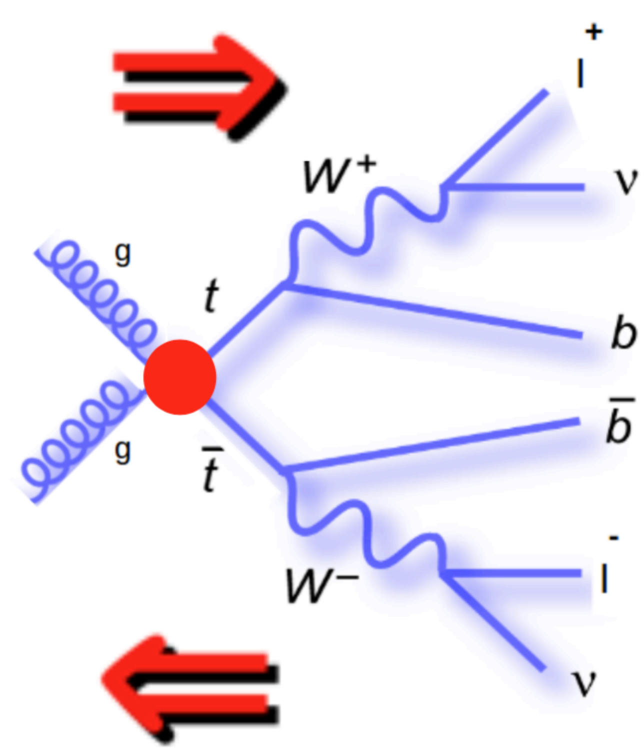
The $\mathcal{O}_{tG}$ operator

- Models top chromomagnetic dipole moment:

$$\mathcal{O}_{tG} = y_t g_s (\bar{Q}\sigma^{\mu\nu}T^A t)\tilde{\phi}G^A_{\mu\nu}$$

- Modifies the gttbar vertex
- Adds the ggttbar vertex
- Induces top chirality flip and altered kinematic properties in ttbar production → ttbar spin density matrix = powerful probe of top quark CMDM to be used to test BSM physics





Procedure

- Templates for predictions made with RIVET framework:
  - theoretical uncertainties estimated through scale variations
- χ^2 minimization technique to constrain C_{tG}/Λ^2 Wilson coefficient of CMDM operator:

$$\chi^2(C_{tG}/\Lambda^2) = \Sigma_{i=1}^{N}\Sigma_{j=1}^{N}\Delta_i \times \Delta_j \times M_{ij}$$

  - $\Delta =$ measured - predicted normalized differential cross section in bin i/j
  - $M_{ij} = Cov_{i,j}^{-1}$ = (i,j) element of the inverted covariance matrix of data
- $1\sigma(2\sigma)$ confidence intervals determined by $\Delta\chi^2 < 1(4)$ wrt best fit value
- Used 20 measured normalized differential distributions and covariance matrices:
  - lab frame variables excluded due to large theoretical uncertainties

Results - shape fit

- Best fit value:

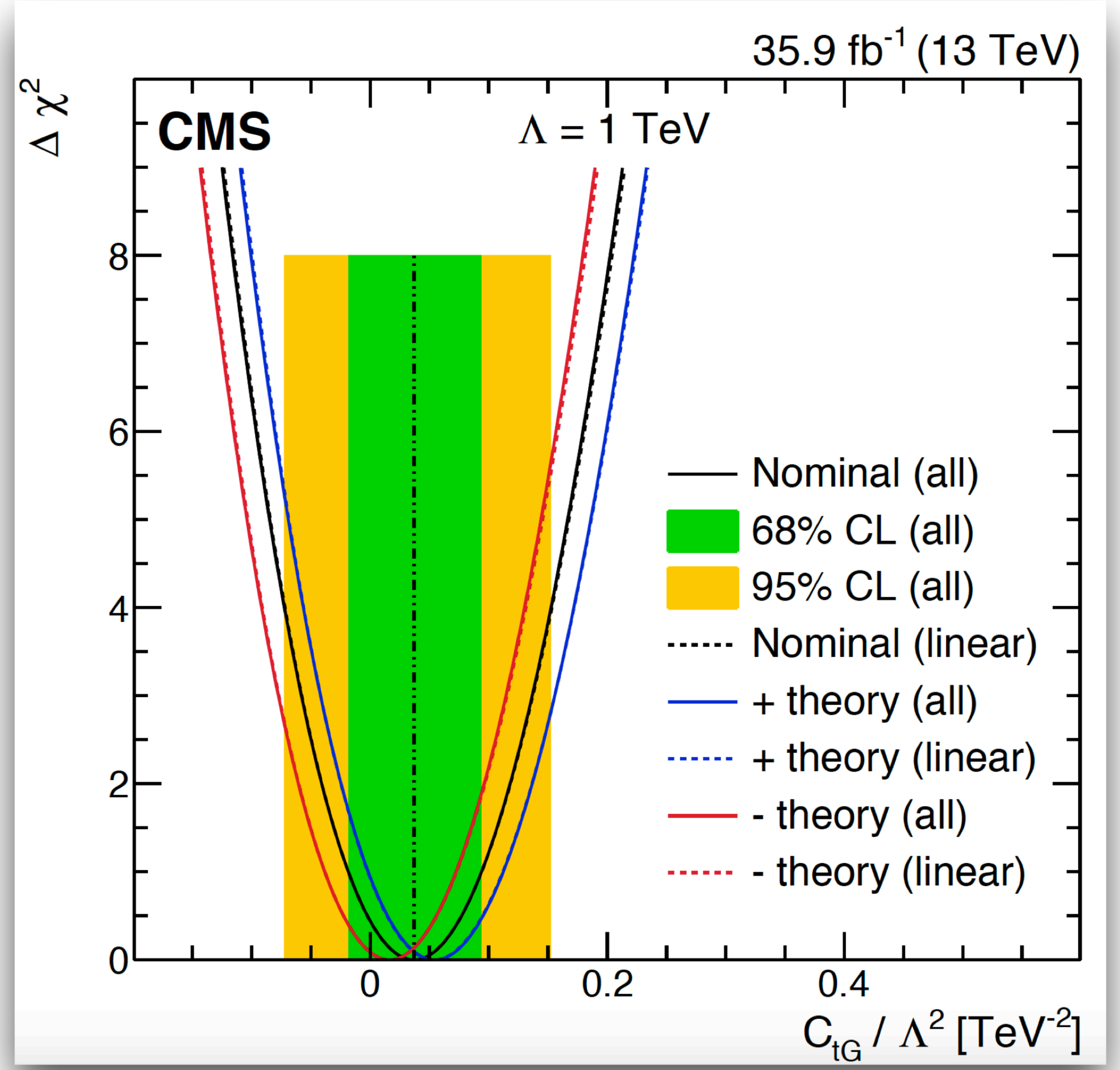
$$C_{tG}/\Lambda^2 = 0.04^{+0.12}_{-0.11}\ \text{TeV}^{-2}$$

- Shape fit results in 55% tighter constraint wrt best result so far (from CMS-TOP-17-014)

$$C_{tG}/\Lambda^2 = 0.18^{+0.23}_{-0.24}\ \text{TeV}^{-2}$$

- Impact of theoretical uncertainties is small
- 95% confidence level limits on C_{tG}/Λ^2 from simultaneous fit to measured differential cross sections:

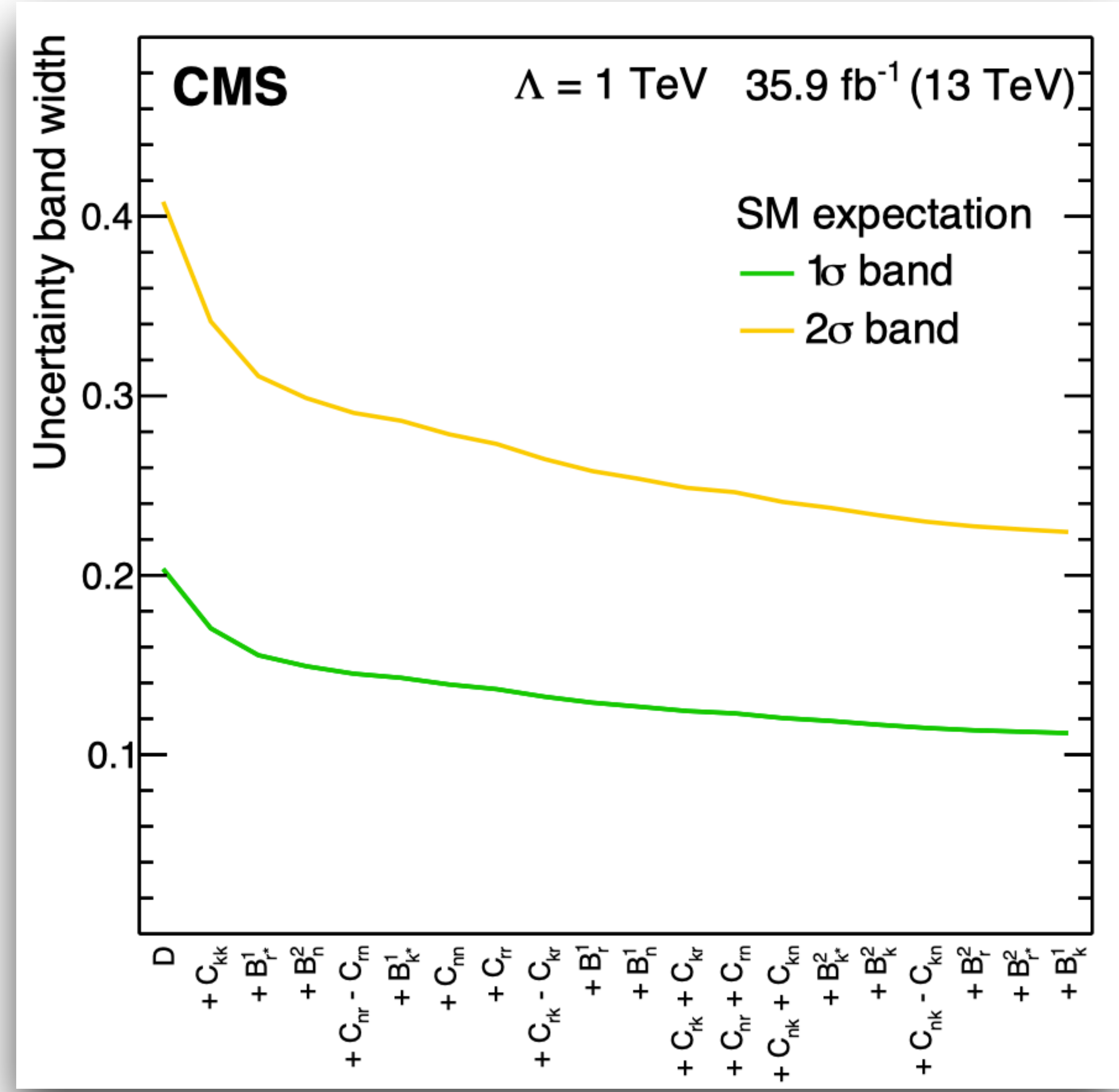
$$-0.07 < C_{tG}/\Lambda^2 < 0.16\ \text{TeV}^{-2}$$



Strongest direct constraint to date!

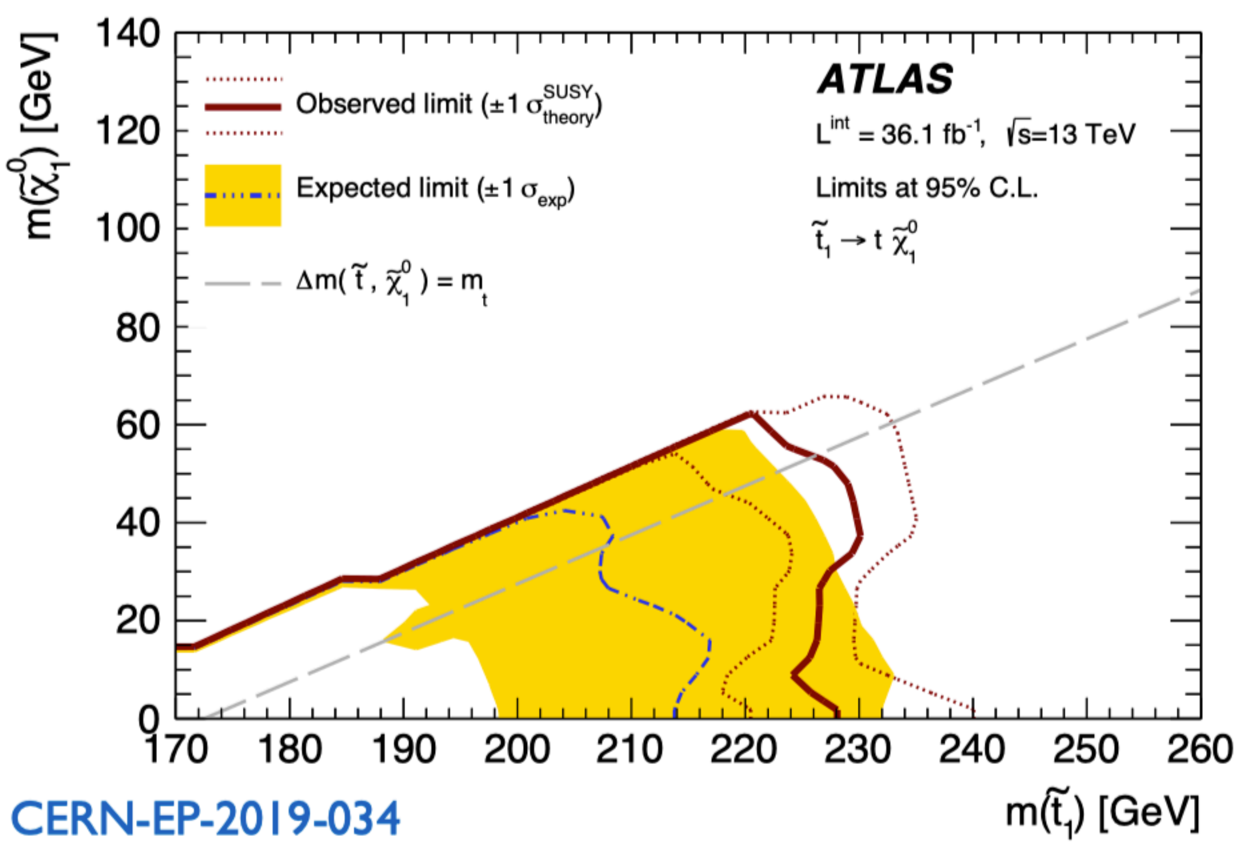
Results - sensitivity evolution

- Sensitivity evolution as variables are added
- From the left, iteratively fit a fixed number of variables
  - choose the combination with tightest constraint
- Most information in D, with others helping through correlations



SUSY interpretation

- In SUSY light stops quarks likely to decay as $\tilde{t} \rightarrow t\tilde{\chi}_1^0$:
  - $\tilde{t}\tilde{t}^*$ rate $< 1/6\, t\bar{t}$ rate for $m_{\tilde{t}} > m_t$
- When daughter top produced at rest ($\Delta m \sim m_t$):
  - $\tilde{t}\tilde{t}^*$ events look similar to uncorrelated $t\bar{t}$ events, visible in lepton Δϕ
- Scalar production typically more central, translates to lepton Δη
- Use double-differential distribution in Δϕ and Δη and total rate to set limits



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- In ATLAS, excluded regions near and below $\Delta m = m_t$ line:
  - $m_t < m_{\tilde{t}} < 230$ GeV
  - $m_{\tilde{\chi}_1^0} < 60$ GeV

New results from CMS coming soon!

Summary

- **First direct measurements at 13 TeV** of all spin-dependent coefficients of the ttbar production density matrix:
    - in close agreement with SM predictions

- Tension between measured Δϕ distributions and the NLO MC predictions:
    - likely explained by missing higher order corrections to top kinematics, which become more important in the fiducial phase space accessible to the experiments

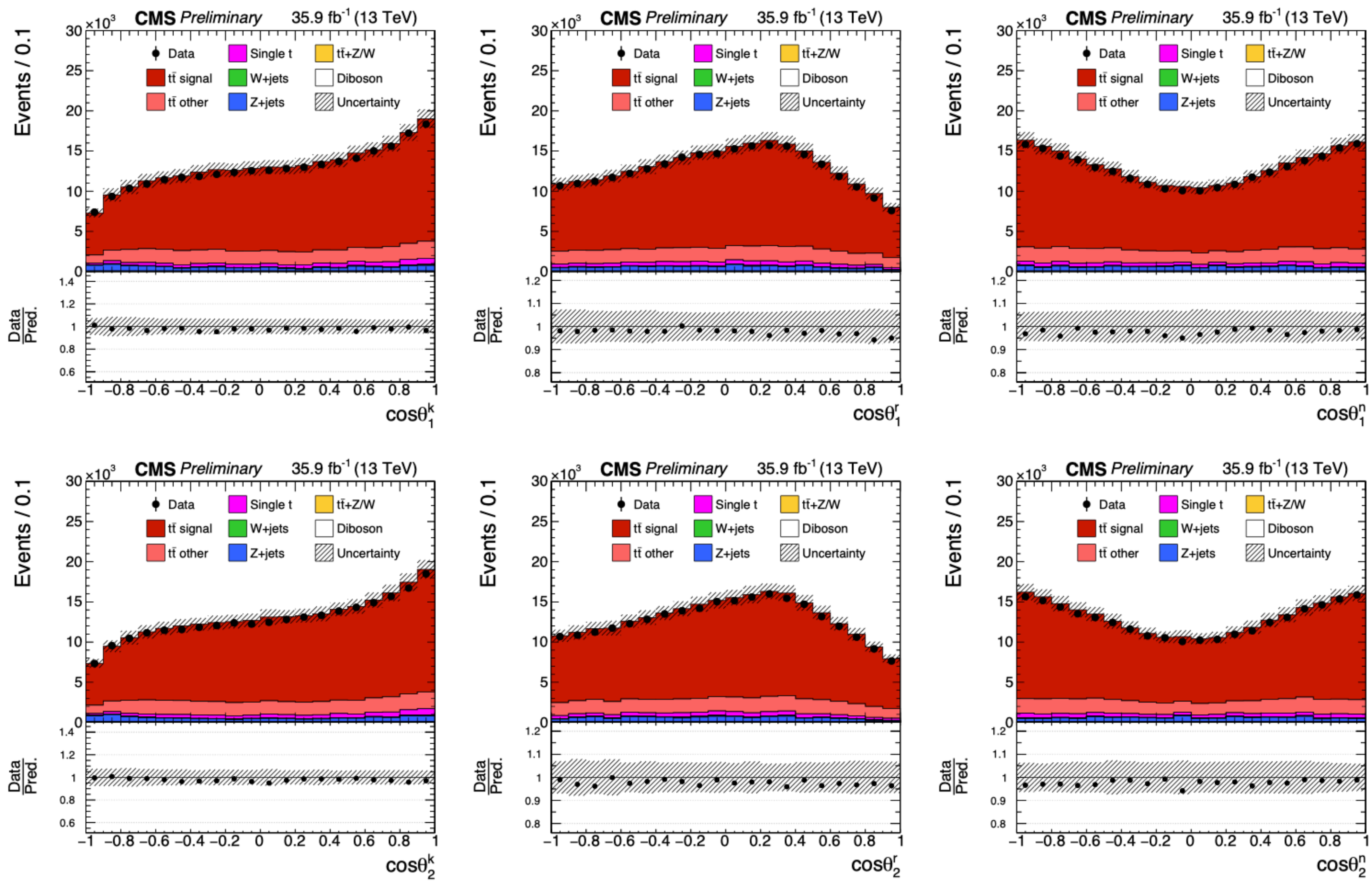
- Precision top quark spin measurements are a **powerful probe of new physics** in ttbar production:
    - EFT Interpretation: sensitive to 10 out of the 11 independent dimension-6 operators relevant for hadronic ttbar production
        - simultaneous fit to set stringent constraints (55% tighter wrt previous results) on top quark anomalous CMDM operator coefficient C_{tG}
    - SUSY Interpretation: limits on light stop squark production
        - work ongoing.. stay tuned!

Backup

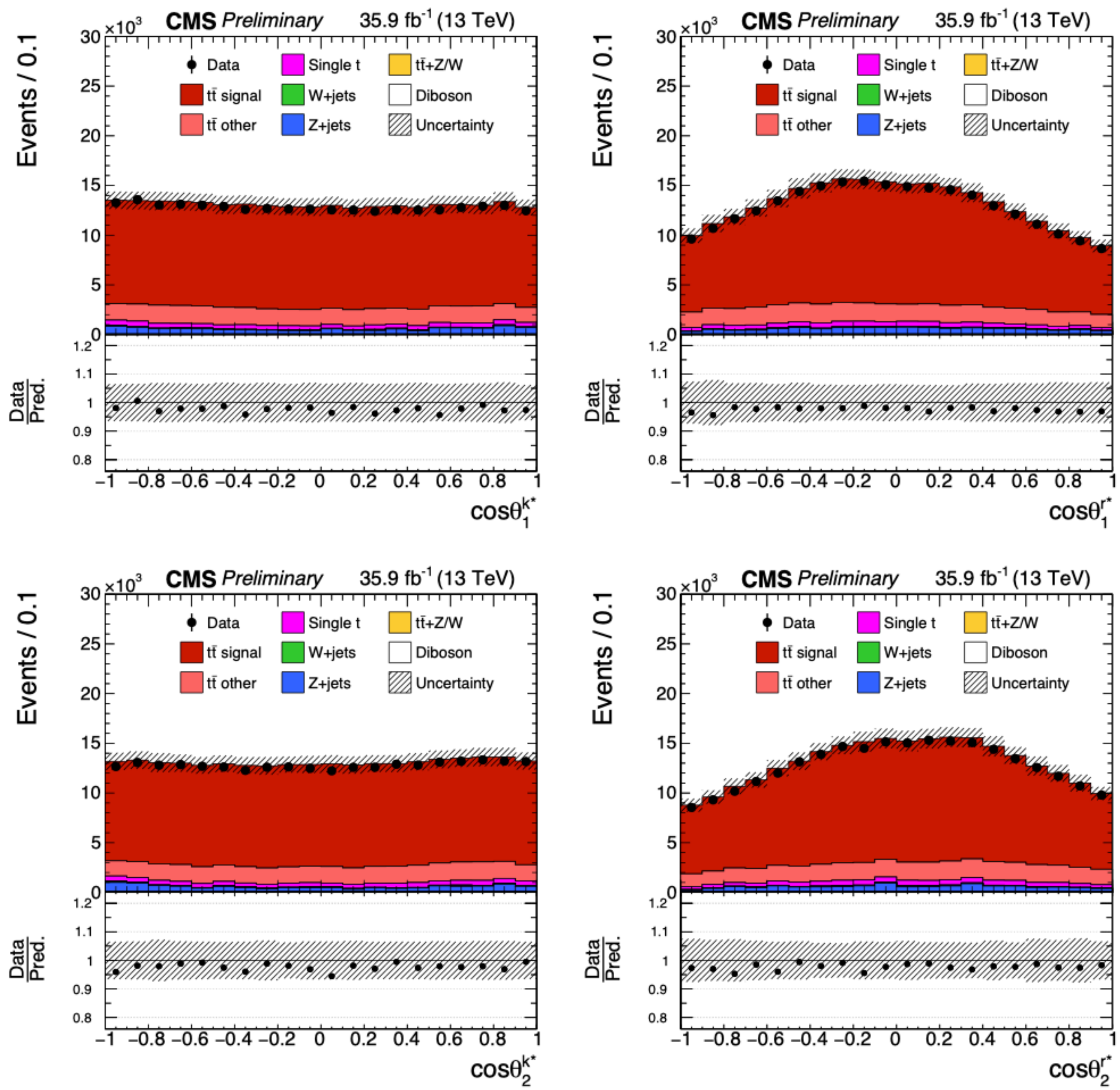
Detector-level distributions

- Set of 22 reco-level distributions are shown on the following slides.
  - Systematics are shown by hatched band.
  - Reasonable data-MC agreement in general.

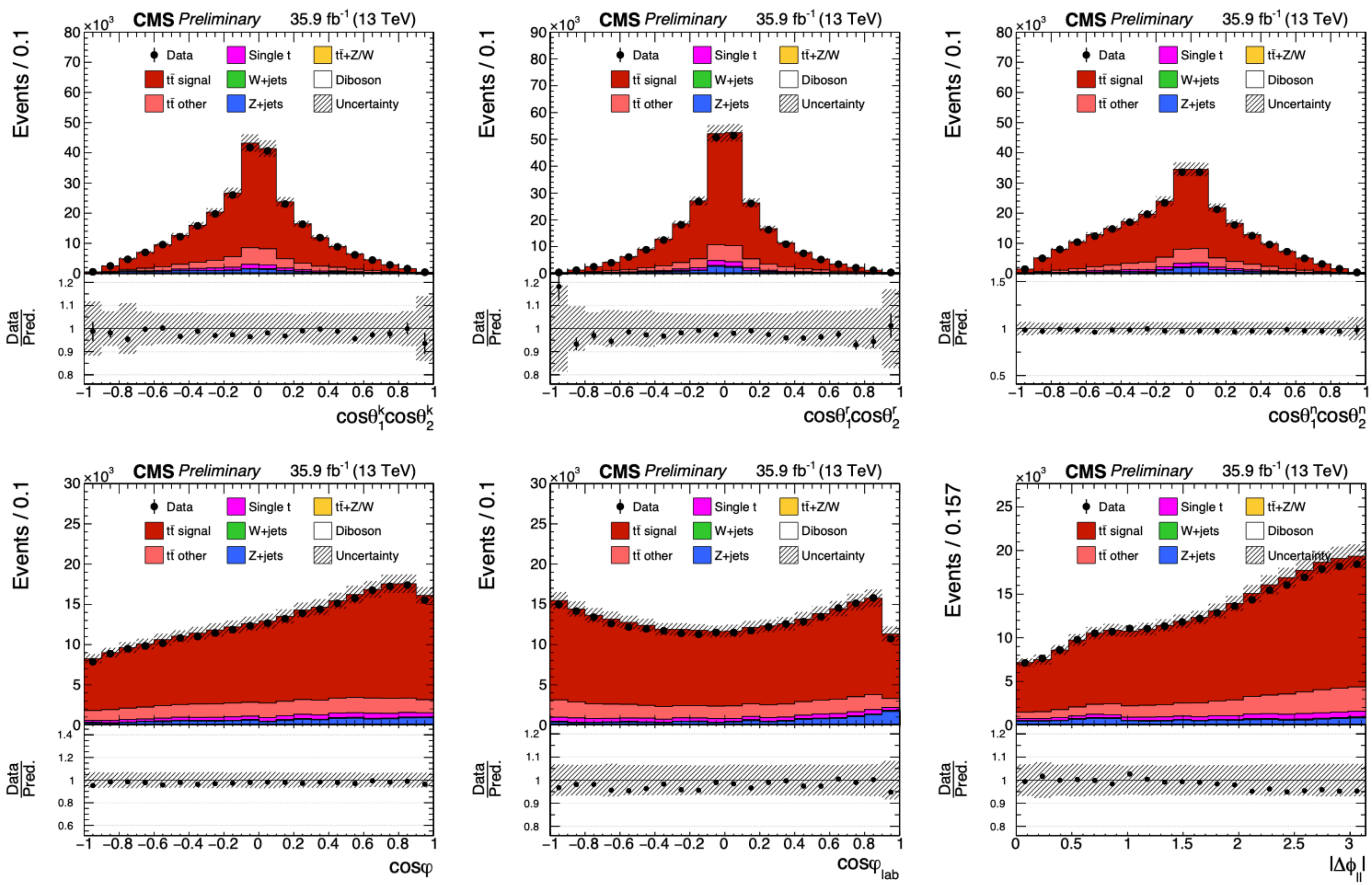
Top polarization observables (combined channel)



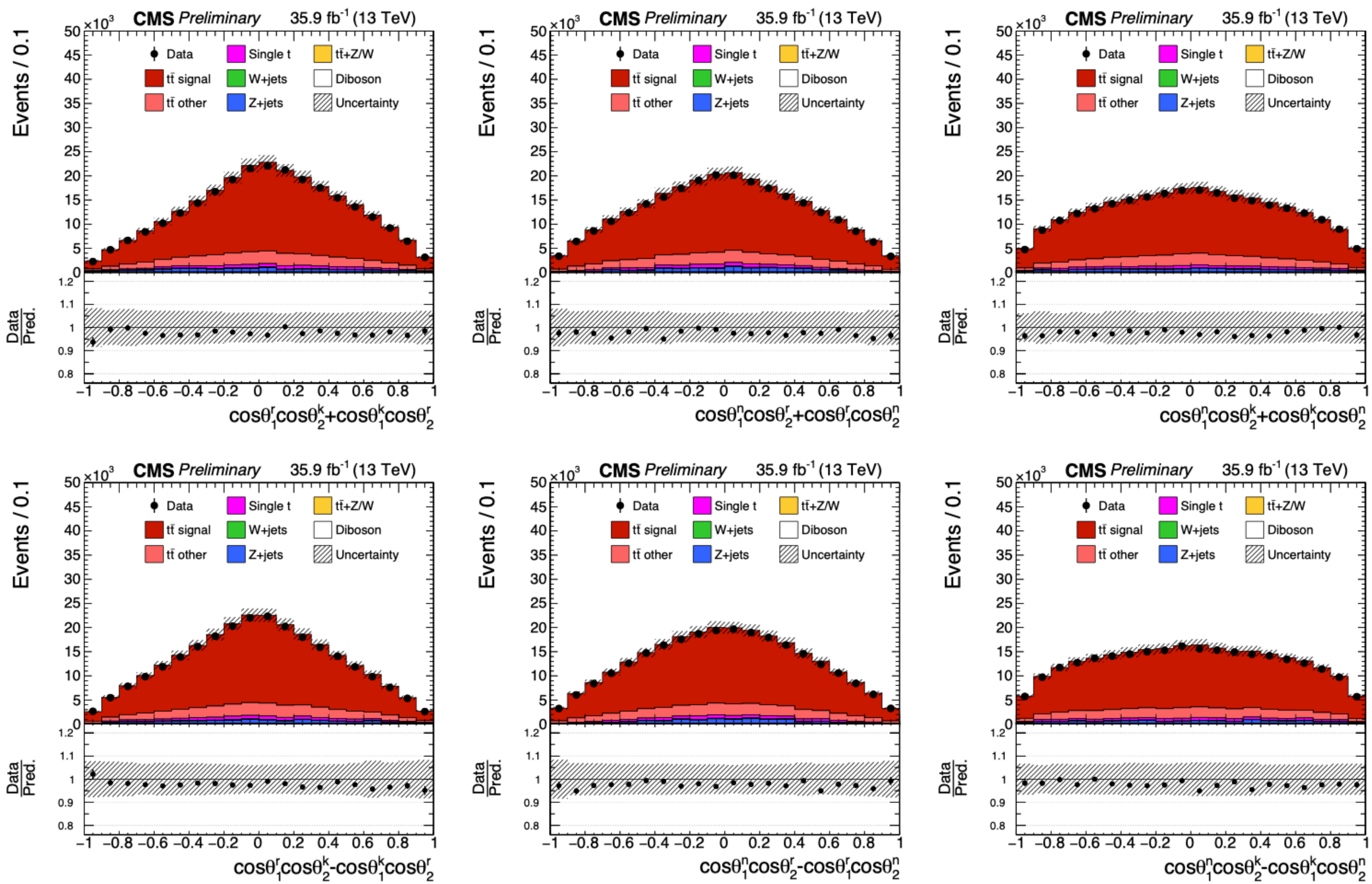
Top polarization observables (combined channel)



Ttbar spin correlation observables (combined channel)

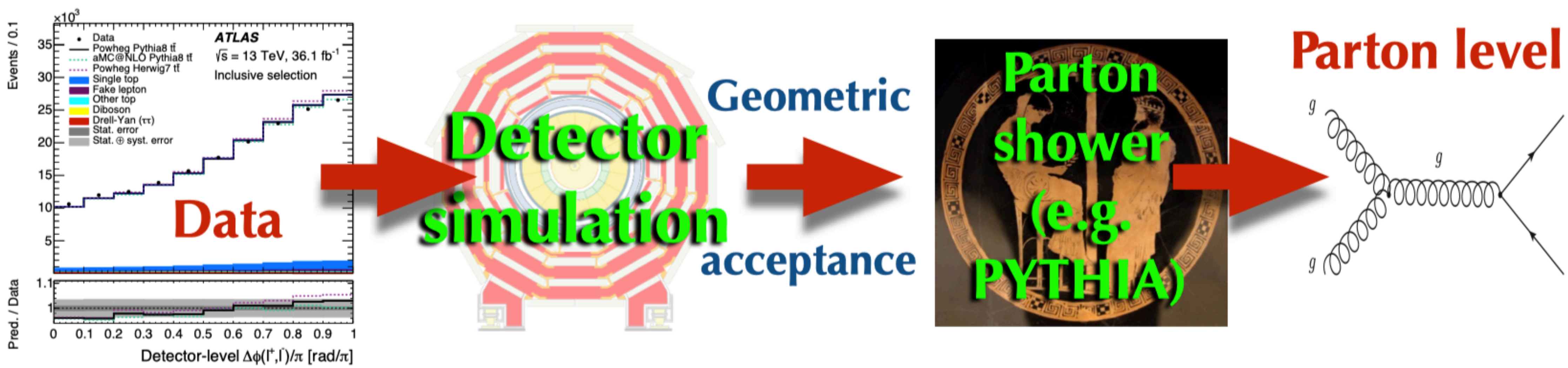


Ttbar spin correlation observables (combined channel)



Unfolding to parton level

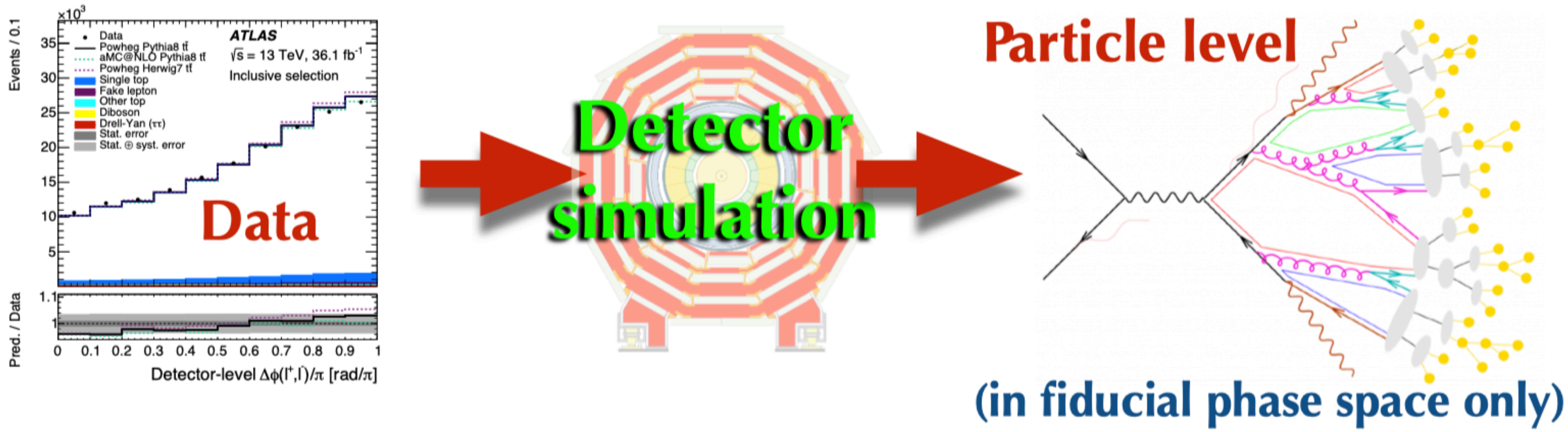
- To compare with fixed-order theoretical calculations, must correct to parton-level



ADVANTAGES	DISADVANTAGES
Compare with fixed-order calculations	Model-dependence of parton shower
Combine with other experiments	Model-dependence of extrapolation
Can be used as part of global fit	Difficult to accurately estimate systematics

Unfolding to particle level

- To reduce the model-dependence, we can unfold to particle-level and minimize the acceptance extrapolation



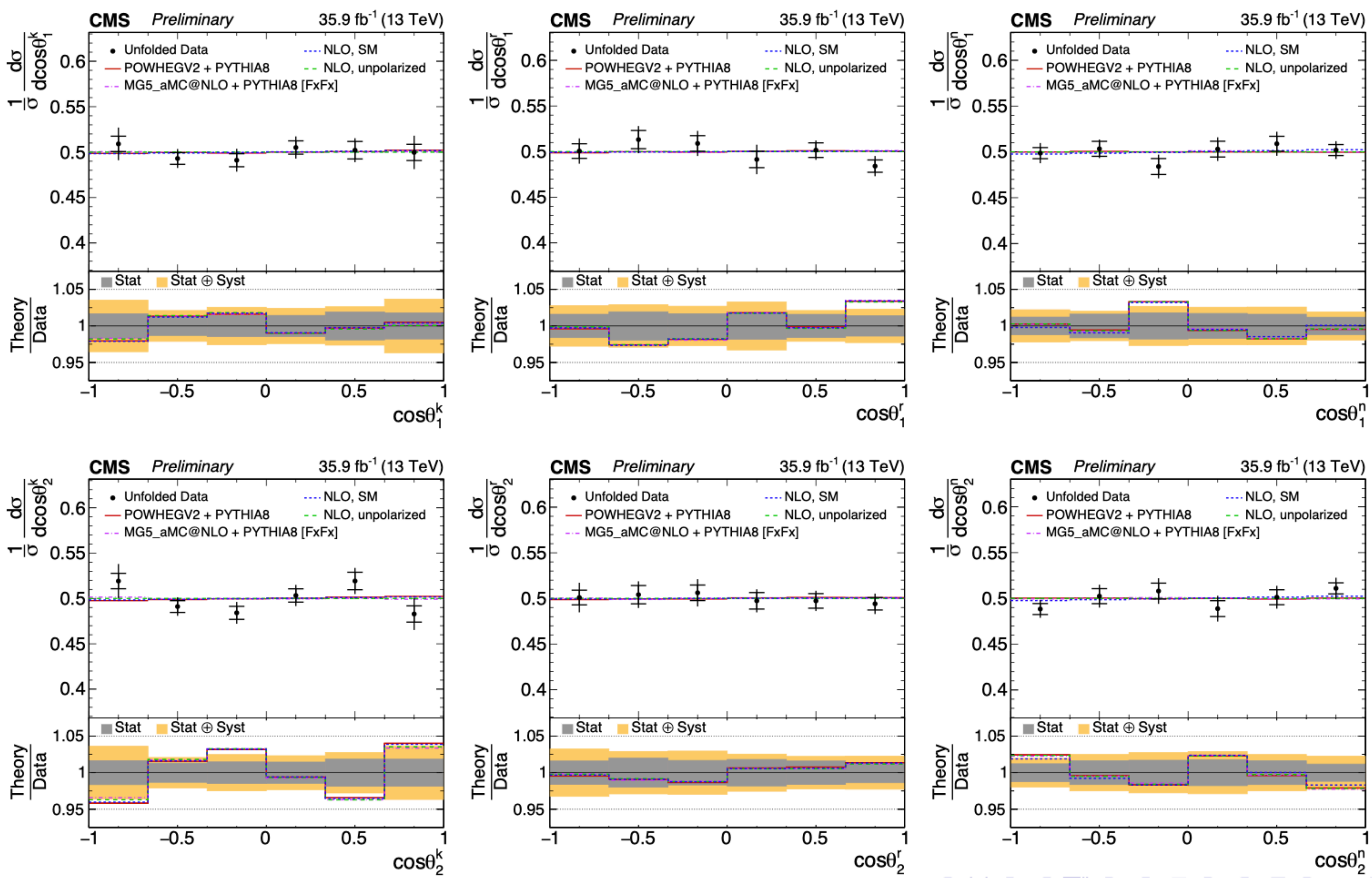
ADVANTAGES	DISADVANTAGES
Detector simulation (slow) not needed for BSM samples	Still have to produce particle-level MC
Results less dependent on model used for unfolding	No fixed-order calculations
Combinations, global fit	

Results

- We measure 22 normalised differential cross sections:
- 10 cos θ distributions for the B i
- 3 cos θ cos θ distributions for the Cii
- 6 cos θ cos θ ± cos θ cos θ distributions for the C ij ± Cji
- 2 laboratory frame dilepton angular distributions

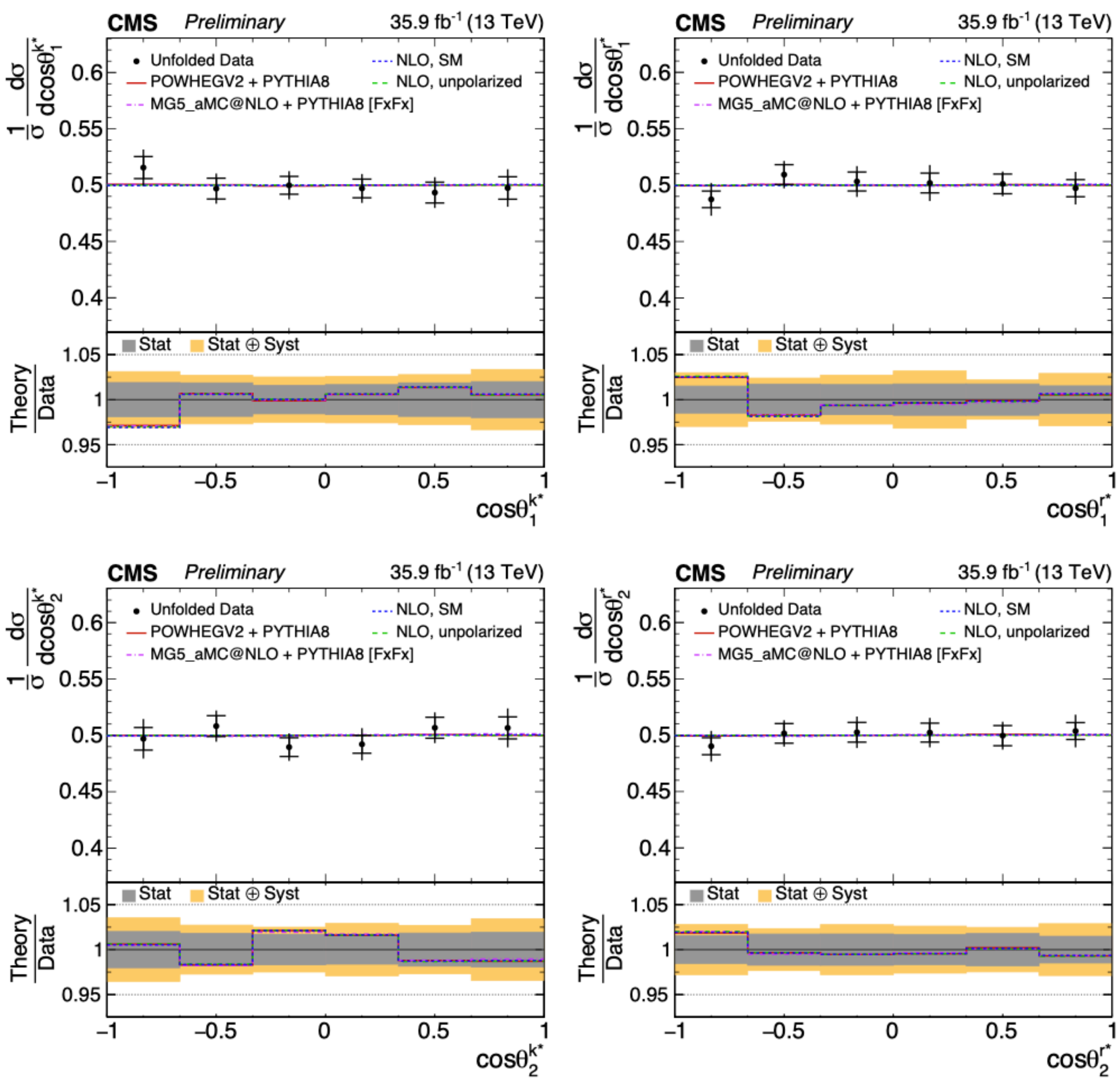
Unfolded top polarization distributions

- Distributions in data consistent with flatness (non significant non-zero B)



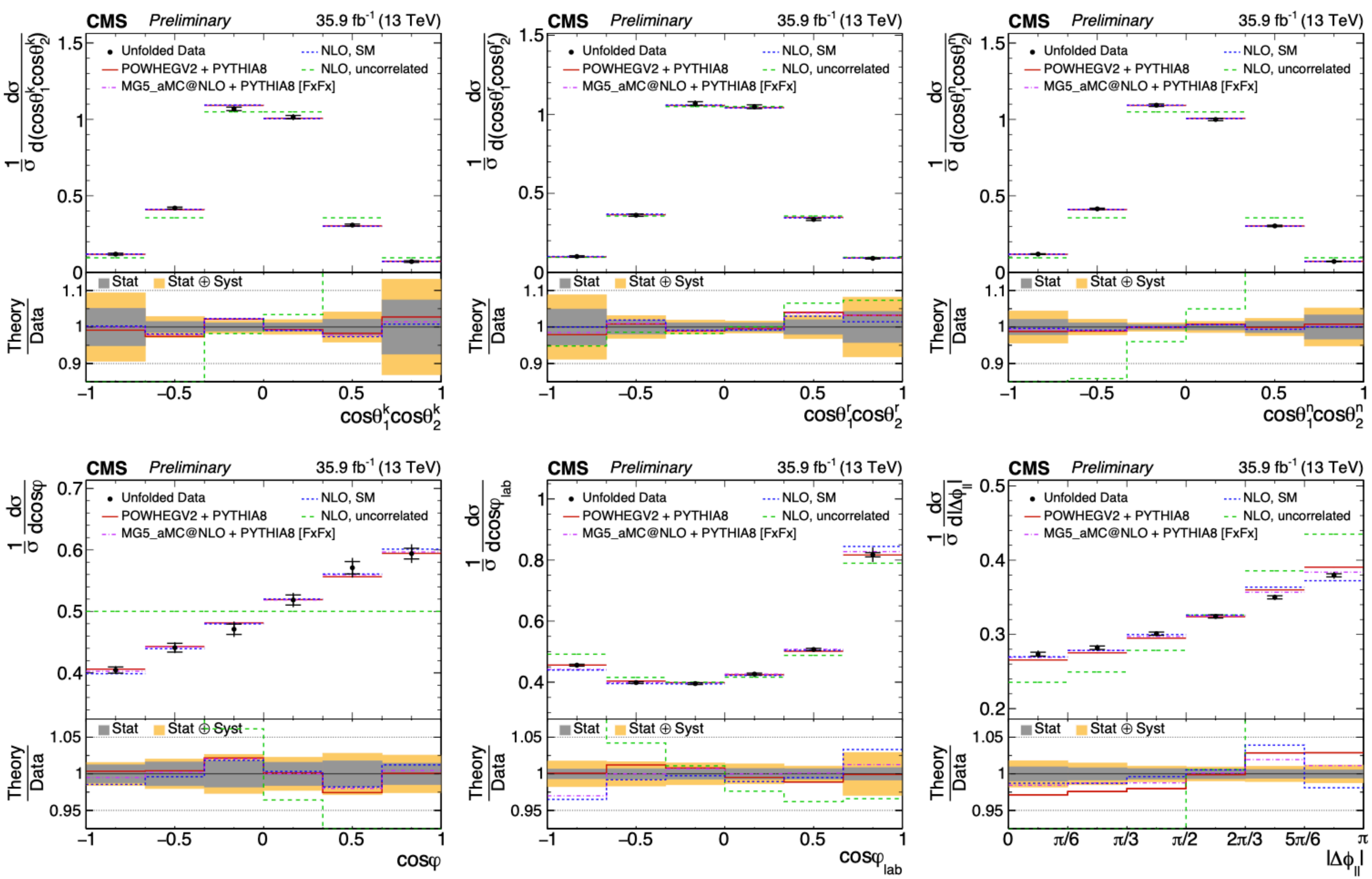
Unfolded top polarization distributions

- Data are compared with simulation and NLO calculation.



Unfolded ttbar spin correlation distributions

- SM prediction with spin correlations describes data for top rest-frame observables
- L
  la



Unfolded ttbar spin correlation distributions

- We can see the off-diagonal spin correlations between the r and k axes!