Studies of top quark spin and polarization in CMS

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15th International workshop on top quark physics
Durham (UK), September 6th, 2022

Institute of High Energy Physics
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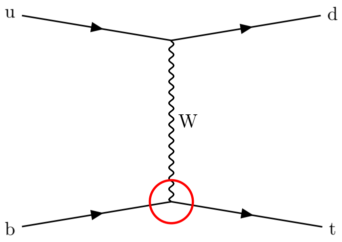
Introduction

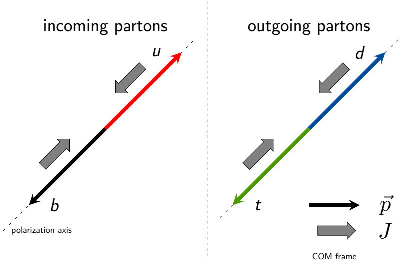
- Top quark is the heaviest fermion in the SM
  - Mean lifetime ($\approx 10^{-25}$ s) much shorter than typical QCD timescales
- **Top quark decays before QCD can randomize its spin**
- **Pure EW decay** (plus **V–A** kind of interaction) preserves strong **angular correlations among decay products**
- $t\bar{t}$: largest cross section but no single spin configuration in any basis
  - Process initiated by QCD ($gg \rightarrow t\bar{t}$)



- ***t*-channel single-top**: production through Wtb vertex (V–A interaction)
  - **Strongly polarized top quarks**

Introduction

- Incoming partons (ub) back-to-back in center-of-momentum (COM) frame
- **V–A interaction** at Wub vertex $\implies$ u,b have **LH chirality**
- **Ultra-relativistic regime** at LHC $\implies$ helicity == chirality $\implies$ u,b have **LH helicity**
  - Spin projection is 0
- d is ultra-relativistic $\implies$ d is LH
- **Conservation of angular momentum** $\implies$ **t is LH in this frame**
  - Polarization is frame-dependent



- Experimental and theoretical arguments[1] $\implies$ use **top quark rest frame; project along spectator quark direction**

[1] See e.g., Phys. Lett. B 476 (2000) 323

Introduction

- Study **top quark** polarization via its **decay products**
- **Powerful observable**: top quark polarization angle $\cos\theta^*_{\text{pol}}$:

$$\cos\theta^*_{\text{pol}} = \frac{\vec{p}^{\,*}_{q'} \cdot \vec{p}^{\,*}_{\ell}}{|\vec{p}^{\,*}_{q'}||\vec{p}^{\,*}_{\ell}|}$$

  where $\ell \equiv$ lepton from t decay; $q' \equiv$ spectator quark; $* \equiv$ t quark rest frame
- It also holds that:

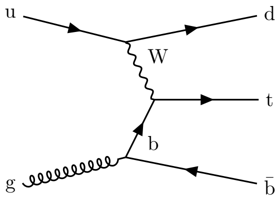
$$\frac{1}{\sigma}\frac{\mathrm{d}\sigma}{\mathrm{d}\cos\theta^*_{\text{pol}}} = \frac{1}{2}\left(1 + 2A_\ell \cos\theta^*_{\text{pol}}\right)$$

  where the top quark spin asymmetry is connected to the polarization P via

$$A_\ell = \frac{1}{2}P\alpha_\ell, \qquad \alpha_\ell \approx 1, \text{ lepton spin analyzing power}$$

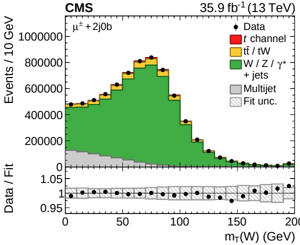
Spin asymmetry from t-channel single top, Eur. Phys. J. C 80 (2020) 370

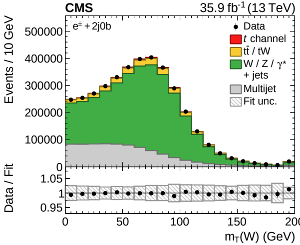
- **t-channel single top quark**
  - $L \simeq 36\ \text{fb}^{-1}$
- Target: **leptonic** (μ,e) **top quark decay**
  - Select events with exactly one isolated lepton
- **Main background**: **t$\bar{\text{t}}$** ; other backgrounds: tW, V+jets, QCD
- Events split into **NjMb categories**
  - 2j1b, signal enriched
  - 3j2b, to constrain t$\bar{\text{t}}$ background
  - 2j0b, for validation purposes (not used in final fit)
- **Top quark candidate** is reconstructed in 2j1b:
  - Get p_{z,ν_ℓ} by constraining $\vec{p}_{\mathrm{T}}^{\mathrm{miss}}$ and ℓ to m_W
  - Build candidate from 4 momenta of ℓ, ν_ℓ and b jet



Multijet background estimation

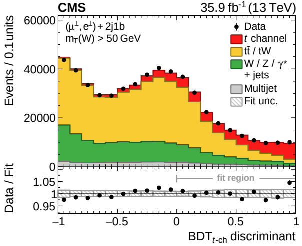
- Multijet background estimated with **two-step procedure**:
  1. Distributions from multijet events estimated from **sideband region in data**
  2. Normalization estimated through a **maximum-likelihood (ML) fit** to the data
- Definition of **sideband region**:
  - Muon channel: invert relative isolation requirement
  - Electron channel: fail loose ID criteria
- **Validate** the background estimation **in 2j0b category**
  - Has similar background composition of signal enriched 2j1b category
  - Not used in the final fit

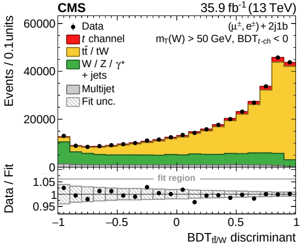




Signal extraction

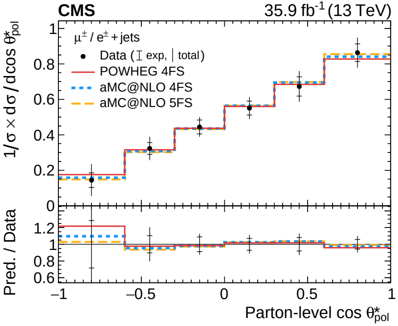
- **Train a BDT$_{t\text{-ch}}$** to separate signal from $t\bar{t}$, W+jets and QCD
  - Good separation power, but **similar shapes for $t\bar{t}$ and W+jets**
- **Train a BDT$_{t\bar{t}/W}$** to separate $t\bar{t}$ from W+jets
- **ML fit** performed using:
  - BDT$_{t\text{-ch}}$, BDT$_{t\bar{t}/W}$, $m_T(W)$ in 2j1b
  - $m_T(W)$ in 3j2b
- For each differential cross section measurement, observable is divided in intervals and independent **fit is performed in each interval**
- **Unfold** the resuting spectra **at parton level**





Results

- Spin asymmetry determined from parton-level $\frac{1}{\sigma}\frac{d\sigma}{d\cos\theta^{*}_{\mathrm{pol}}}$
- **Linear χ^2 fit** based on previously discussed functional dependence
- $$A_\ell = 0.440 \pm 0.031(\text{stat+exp}) \pm 0.062\,(\text{theo})$$
- **Good agreement with SM prediction** of 0.436 (POWHEG at NLO with negligible uncertainty)
- **Rules out a previous**[2] 2.0σ **tension** found by CMS at $\sqrt{s} = 8$ TeV

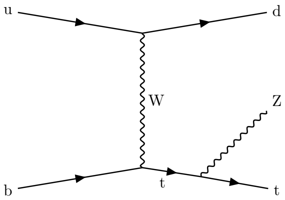


- Dominant uncertainties
  - Top quark mass
  - $t\bar{t}$ parton shower

[2] JHEP 04 (2016) 073

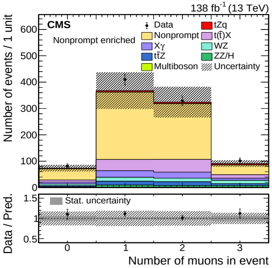
Spin asymmetry from tZq events, JHEP 02 (2022) 107

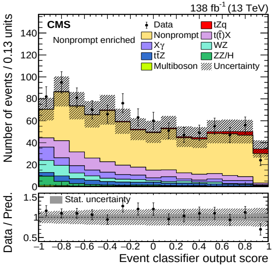
- **t-channel single top quark** plus a Z boson
  - $L \simeq 138\ \text{fb}^{-1}$
- Target: **leptonic** (μ, e) **top quark and Z decays**
  - Select events with exactly three isolated leptons (with an opposite-sign-same-flavor pair)
- **Main backgrounds**:
  - **Prompt leptons**: WZ+jets, $t\bar{t}$Z, ZZ
  - **Non-prompt leptons**: $t\bar{t}$ dileptonic, DY
- Events split into NjMb categories
  - $1 < j < 4$; $\geq 1b$
  - $\geq 4j$; $\geq 1b$ ($t\bar{t}$Z control region)
- Several validation regions defined to validate background modeling



Non-prompt background estimation

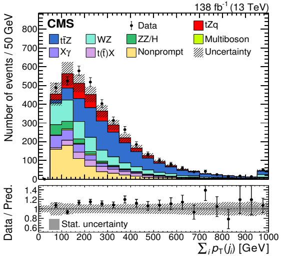
- Non-prompt background estimated with **fake rate method**
- Estimate **probability** (fake rate) **for a non-prompt lepton to pass analysis cuts**
  - Measured in a QCD enriched data sample
- Define two **lepton** selections: **loose and tight**
- Define a region identical to signal region but with at least one loose-non-tight lepton
- **Apply fake rate** there to get non-prompt yield in signal region
- **Validate method** in dedicated non-prompt lepton validation region

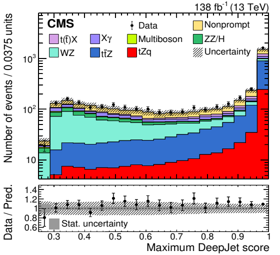




Signal extraction

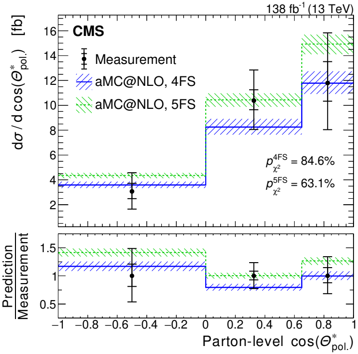
- **Train a multiclass neural network** (NN)
  - 22 input features
- 5 output nodes:
  1. tZq
  2. $t\bar{t}Z$
  3. WZ
  4. $t\bar{t}X$
  5. Others
- **ML fit** performed using:
  - tZq NN node in signal region
  - $t\bar{t}Z$ NN node in $t\bar{t}Z$ control region
  - m_T^W in WZ control region
  - n_e in $Z\gamma$ control region
  - Counting in ZZ and non-prompt control regions





Results

- Spin asymmetry determined from parton-level $\frac{1}{\sigma}\frac{d\sigma}{d\cos\theta^*_{pol}}$
- A_ℓ parametrized based on previously discussed functional dependence and fitted
- $A_\ell = 0.54 \pm 0.16(\text{stat}) \pm 0.06\,(\text{syst})$
- **Good agreement with SM prediction** of 0.44 (0.45) by MadGraph5_aMC@NLO in the 4FS (5FS)
- Measurement is **statistically dominated** in tZq channel

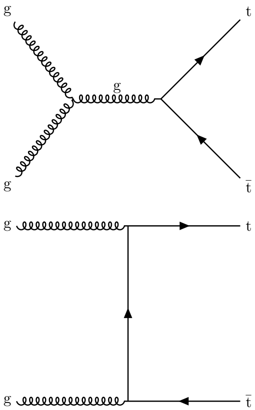


- Dominant uncertainties
  - Background modeling
  - b tagging efficiency
  - Jet energy scale

Polarization and spin coefficients in $t\bar{t}$, Phys. Rev. D 100, 072002 (2019)

- Top quarks mainly produced in pairs at the LHC
- **$t\bar{t}$** pairs are **unpolarized at tree level**
  - Parity conserving and time invariant QCD production
- Small **sources of polarization** come from
  - EW corrections
  - Absorbtive terms at one loop
- Measure all the independent coefficients of the spin-dependent part of the **$t\bar{t}$ production density matrix, R**
- Due to very narrow top quark width we can factorize production (R) and decay (ρ) processes

$$\mathcal{M}(gg/qq \to t\bar{t} \to \ell^+ \nu b \ell^- \bar{\nu} b) \propto \rho R \bar{\rho}$$



Introduction

- The production spin density matrix R can be decomposed like

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

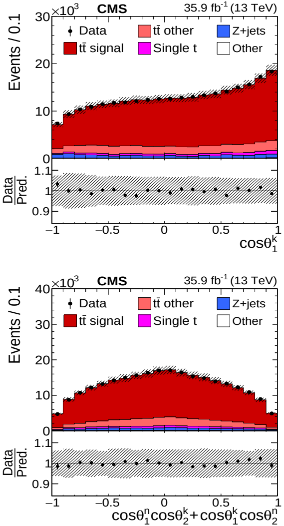
  with
  - $\tilde{\boldsymbol{B}}^{\pm} \equiv$ 3-D vector of t and $\bar{\mathrm{t}}$ polarization in each direction
  - $\tilde{C} \equiv$ 3x3 matrix of coefficients for spin correlations between t and $\bar{\mathrm{t}}$
- **Total: 15 coefficients**, measured wrt a convenient set of 3 orthonormal axes
- It also holds true that

$$\frac{1}{\sigma}\frac{\mathrm{d}^2\sigma}{\mathrm{d}\cos\theta_1^i \mathrm{d}\cos\theta_2^j} = \frac{1}{4}\left(1 + B_1^i \cos\theta_1^i + B_2^j \cos\theta_2^j - C_{ij}\cos\theta_1^i\cos\theta_2^j\right)$$

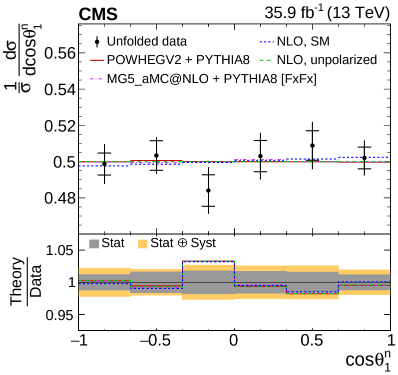
  with θ_1^i (θ_2^j) $\equiv$ angle of + (-) charged lepton wrt axis i (j) in rest frame of t ($\bar{\mathrm{t}}$)
- Integrating one angle out we get **15 single-differential distributions to measure**

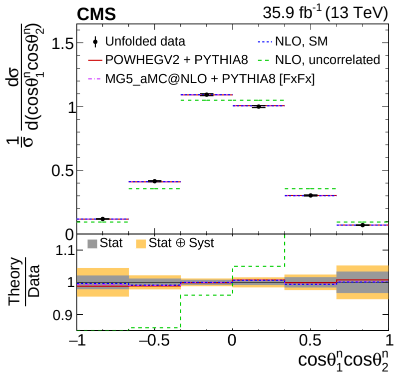
Signal selection

- **$t\bar{t}$ production**
  - $L \simeq 36\ \text{fb}^{-1}$
- Target: **dileptonic** $(\mu^+\mu^-,\ e^+e^-,\ e^\pm\mu^\mp)$ **decays**
- Ask for **exactly two leptons** with opposite charge, **at least two jets, at least one b jet**
- **Main backgrounds**: other $t\bar{t}$ decay channels, tW and Z+jets
- Reconstruct top quarks with **kinematic fit** constrained to W and t masses
- Build angular observable of interest
- Compute differential spectra and unfold and parton level



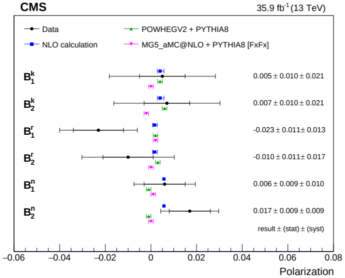
Results

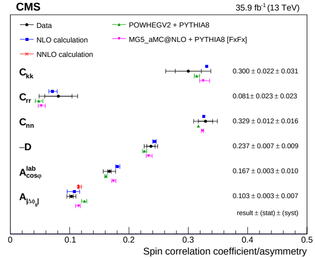


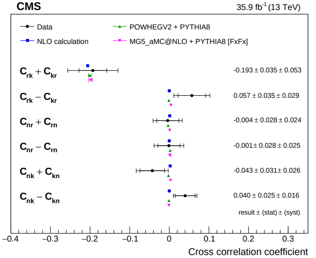


- Left: measurement is not sensitive to tiny polarization effects in the SM
- **Right**: measurement is **sensitive to spin correlation effects**

Results



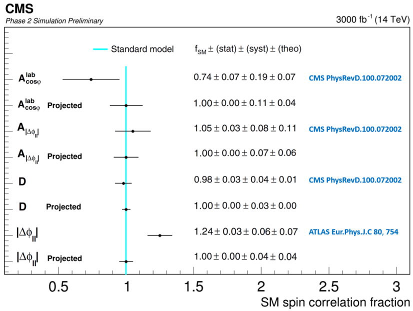




- **Good agreement** between measured and predicted values **for all the coefficients**
- **Statistical and systematic** uncertainties are in general **comparable**

Projection of spin correlation measurements at the HL-LHC
CMS-PAS-FTR-18-034

- **Same mathematical framework** of previous result
- **Similar selection** in terms of objects
  - Only use $e\mu$ channel
- Assume trigger and detector performance similar to Run2
- **Assume better control of** theory and experimental **uncertainties**
- **Unprecedented precision** in spin correlation observables **is expected**



- Can solve the $|\Delta\phi_{\ell\ell}|$ puzzle
- 2.2σ tension seen by ATLAS[3]...
  - ...but not by CMS

[3] Eur. Phys. J. C 80 754

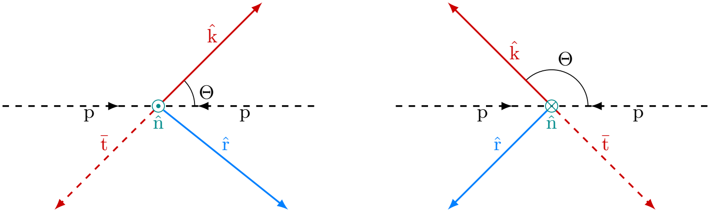
Summary

- CMS has measured top quark spin and polarization properties using different processes
- Measured the **spin asymmetry using t-channel** single top quark events
  - Measurement is systematics dominated
- Measured the **spin asymmetry in** rarer **tZq** events
  - Measurement is statistics dominated
- Measured the **polarization and spin coefficients of** the $\mathbf{t\bar{t}}$ production matrix
  - Also projected to HL-LHC scenario
- **All results are in agreement with the SM** predictions within uncertainties
  - Previous moderate tensions in spin asymmetry ruled out by these results
- Not the end of the story!
  - Extend results to full Run2
  - Profit from Run3 data

Stay tuned!

Backup slides

Orthonormal axes



- $\hat{\mathbf{k}} \equiv$ top quark direction
- $\hat{\mathbf{n}} = (\hat{\mathbf{p}} \times \hat{\mathbf{k}}) / \sin\Theta$ $\quad\hat{\mathbf{p}} \equiv$ incoming parton direction
- $\hat{\mathbf{r}} = (\hat{\mathbf{p}} - \hat{\mathbf{r}} \cos\Theta) / \sin\Theta$

Coefficients

Coefficient	Measured	Powhegv2	MG5	NLO
B_1^k	0.005 ± 0.023	$0.004^{+0.001}_{-0.001}$	$0.000^{+0.001}_{-0.001}$	$4.0^{+1.7}_{-1.2} \times 10^{-3}$
B_2^k	0.007 ± 0.023	$0.006^{+0.001}_{-0.001}$	$-0.002^{+0.001}_{-0.001}$	$4.0^{+1.7}_{-1.2} \times 10^{-3}$
B_1^r	-0.023 ± 0.017	$0.006^{+0.001}_{-0.001}$	$0.002^{+0.001}_{-0.001}$	$1.6^{+1.2}_{-0.9} \times 10^{-3}$
B_2^r	-0.010 ± 0.020	$0.003^{+0.001}_{-0.001}$	$0.000^{+0.001}_{-0.001}$	$1.6^{+1.2}_{-0.9} \times 10^{-3}$
B_1^n	-0.006 ± 0.013	$-0.001^{+0.001}_{-0.001}$	$0.001^{+0.001}_{-0.001}$	$5.7^{+0.5}_{-0.4} \times 10^{-3}$
B_2^n	0.017 ± 0.013	$-0.001^{+0.001}_{-0.001}$	$0.000^{+0.001}_{-0.001}$	$5.7^{+0.5}_{-0.4} \times 10^{-3}$
C_{kk}	0.300 ± 0.038	$0.314^{+0.005}_{-0.004}$	$0.325^{+0.011}_{-0.006}$	$0.331^{+0.002}_{-0.002}$
C_{rr}	0.081 ± 0.032	$0.048^{+0.007}_{-0.006}$	$0.052^{+0.007}_{-0.006}$	$0.071^{+0.008}_{-0.006}$
C_{nn}	0.329 ± 0.020	$0.317^{+0.001}_{-0.001}$	$0.324^{+0.002}_{-0.002}$	$0.326^{+0.002}_{-0.002}$
$C_{rk} + C_{kr}$	-0.193 ± 0.064	$-0.201^{+0.004}_{-0.003}$	$-0.198^{+0.004}_{-0.005}$	$-0.206^{+0.002}_{-0.002}$
$C_{rk} - C_{kr}$	0.057 ± 0.046	$-0.001^{+0.002}_{-0.002}$	$0.004^{+0.002}_{-0.002}$	0
$C_{nr} + C_{rn}$	-0.004 ± 0.037	$-0.003^{+0.002}_{-0.002}$	$0.001^{+0.002}_{-0.002}$	$1.6^{+0.01}_{-0.01} \times 10^{-3}$
$C_{nr} - C_{rn}$	-0.001 ± 0.038	$0.002^{+0.002}_{-0.002}$	$0.001^{+0.003}_{-0.002}$	0
$C_{nk} - C_{kn}$	-0.043 ± 0.041	$-0.002^{+0.002}_{-0.002}$	$0.003^{+0.002}_{-0.002}$	$2.15^{+0.04}_{-0.07} \times 10^{-3}$
$C_{nk} - C_{kn}$	0.040 ± 0.029	$-0.001^{+0.002}_{-0.002}$	$-0.001^{+0.002}_{-0.002}$	0