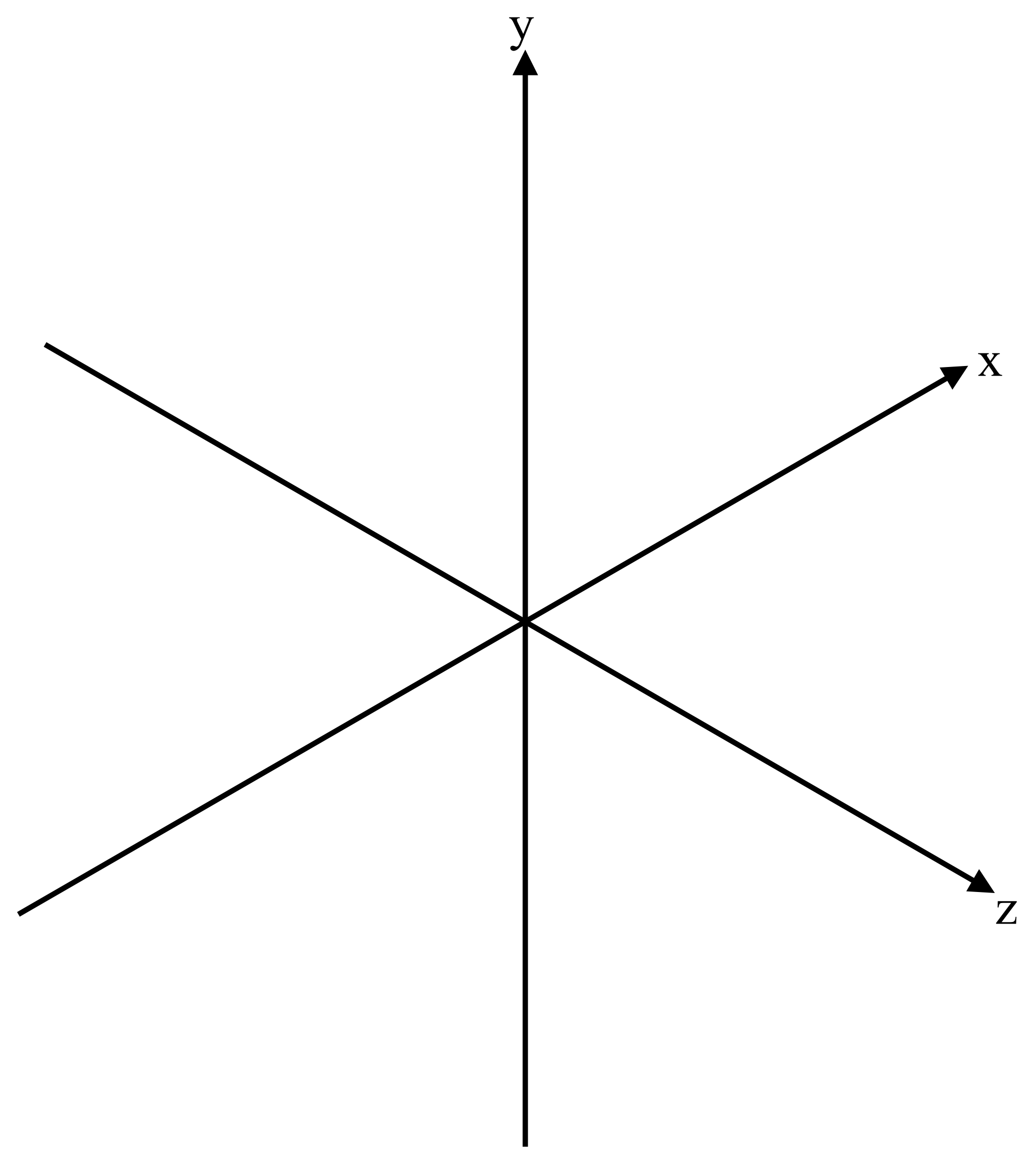
Top quark angular measurements with ATLAS and CMS

14th International Workshop on Top Quark Physics

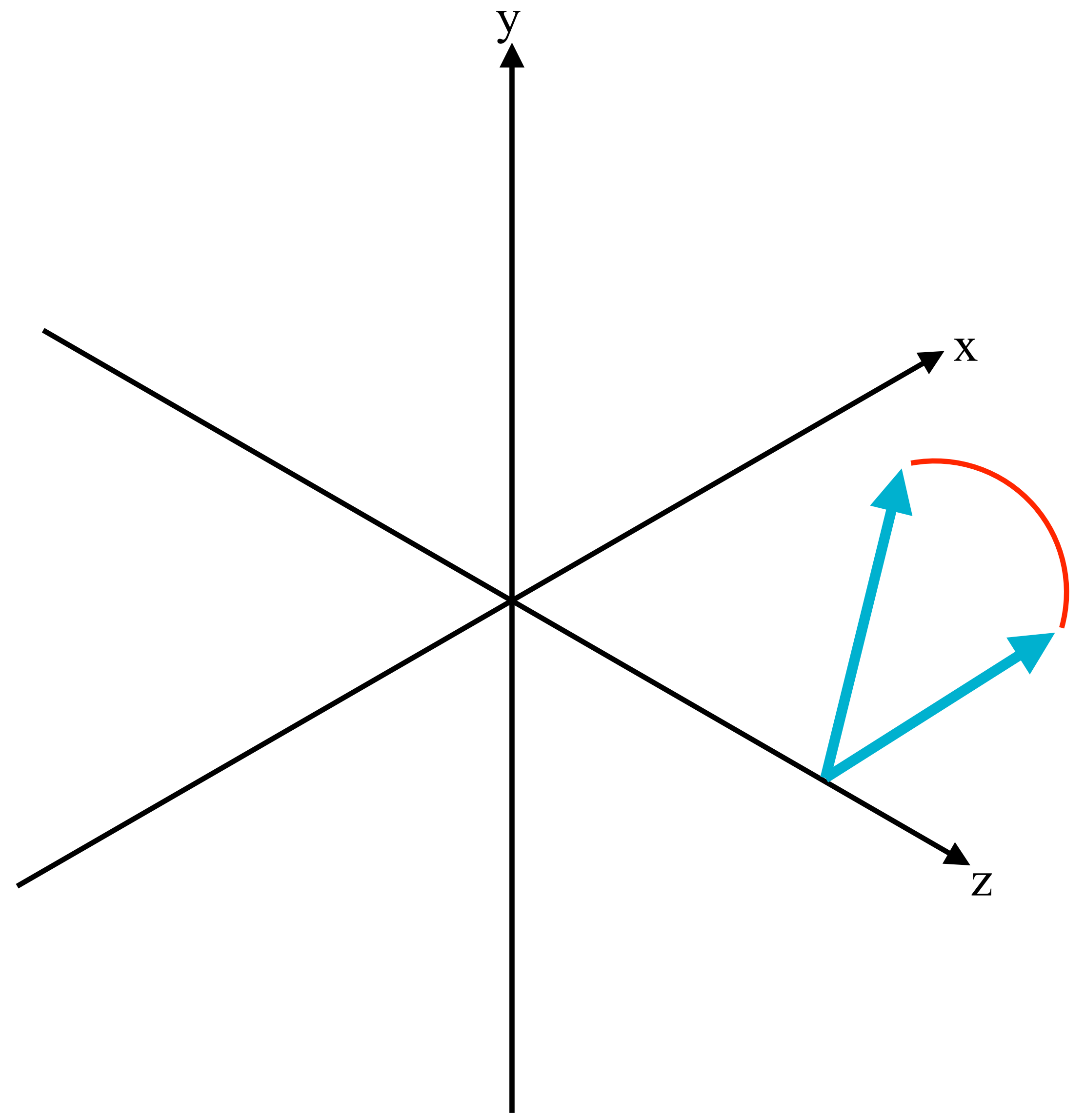
Angular Information



- **What types of physics can we access with angular information?**

Angular Information

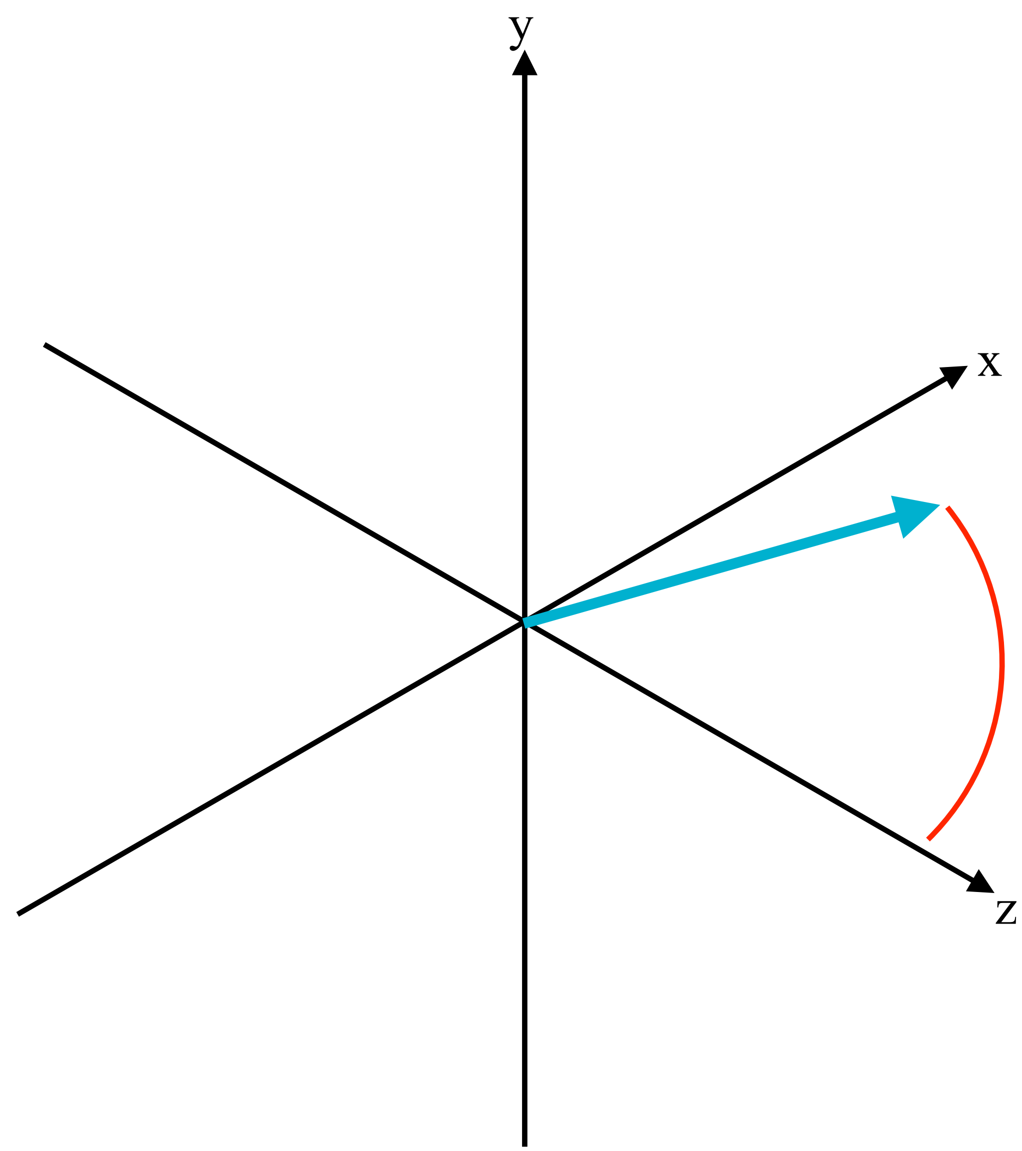
Azimuthal-type angles



- **Spin correlation** ($\Delta\varphi$)**, quantum entanglement** (D)**, Toponium** ($\Delta\varphi$ near threshold)**.**

Angular Information

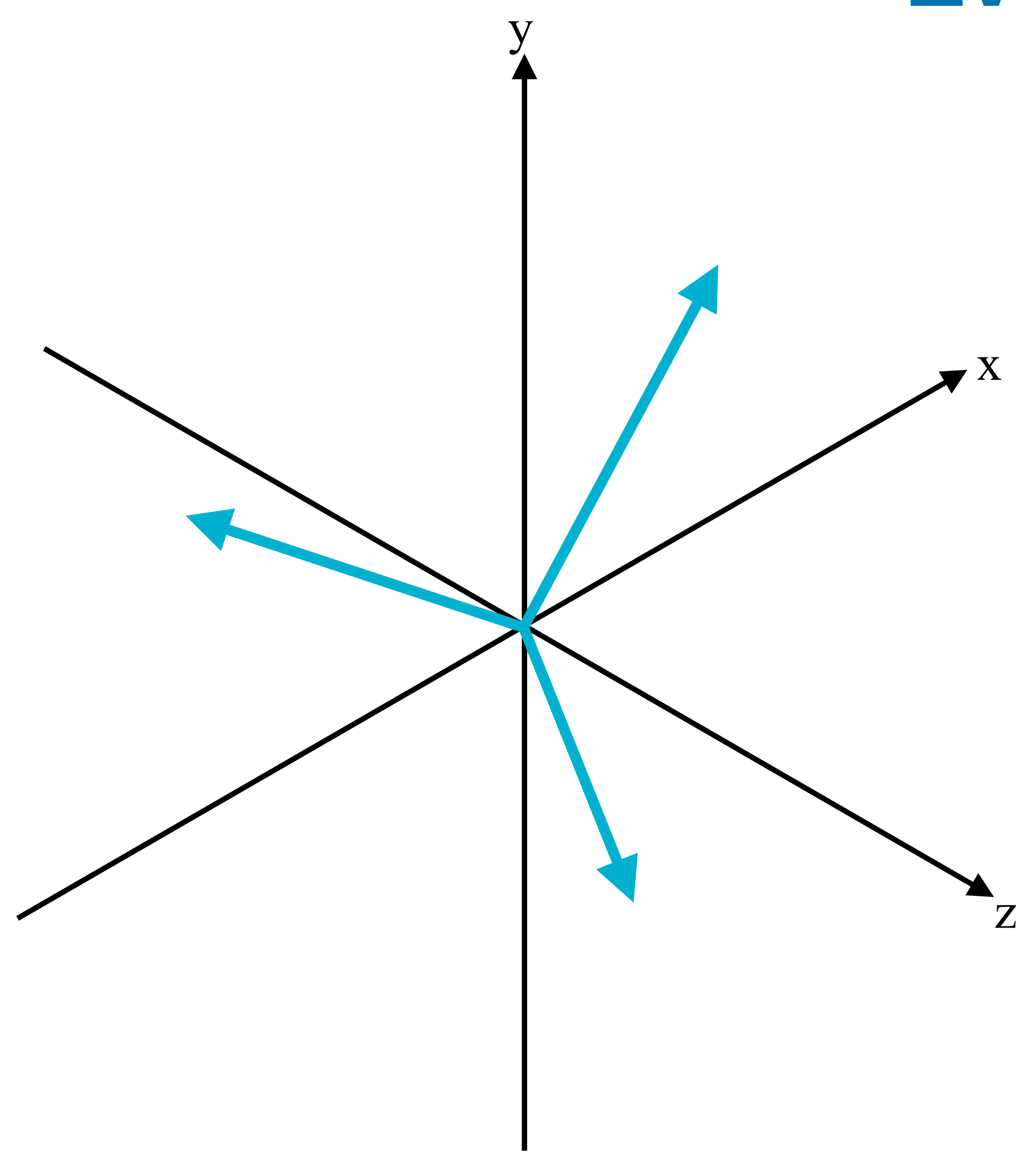
Polar-type angles



- **Forward-backward** (A_{FB})**, charge** $(\Delta|y|)$**, and energy asymmetries** $(A_E(\theta_j))$**.**

Angular Information

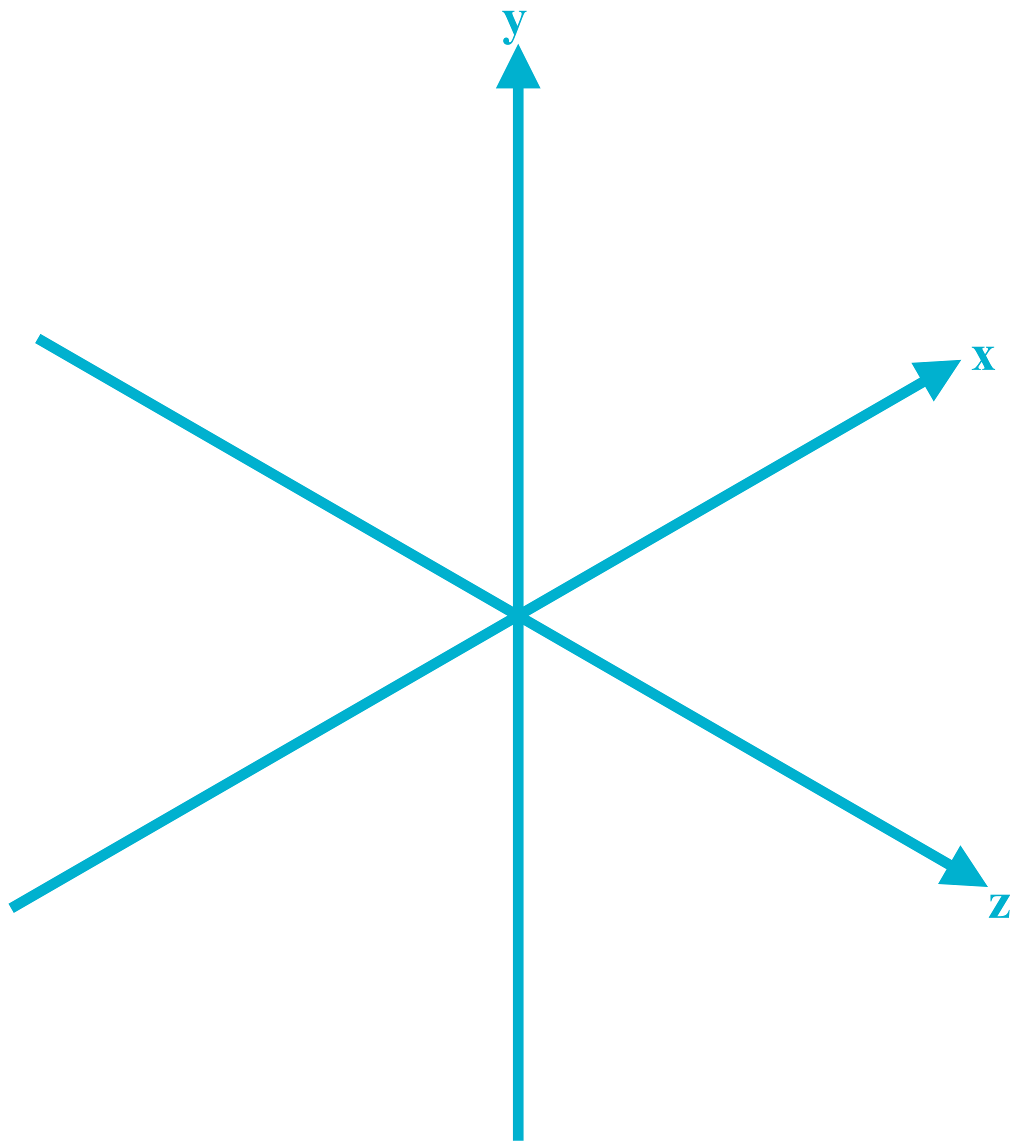
Event-specific basis



- **Spin density matrix $(\hat{k},\ \hat{n},\ \hat{r})$, t-channel polarisation $(\ell x,\ \ell y,\ \ell z)$.**

Angular Information

Cartesian basis



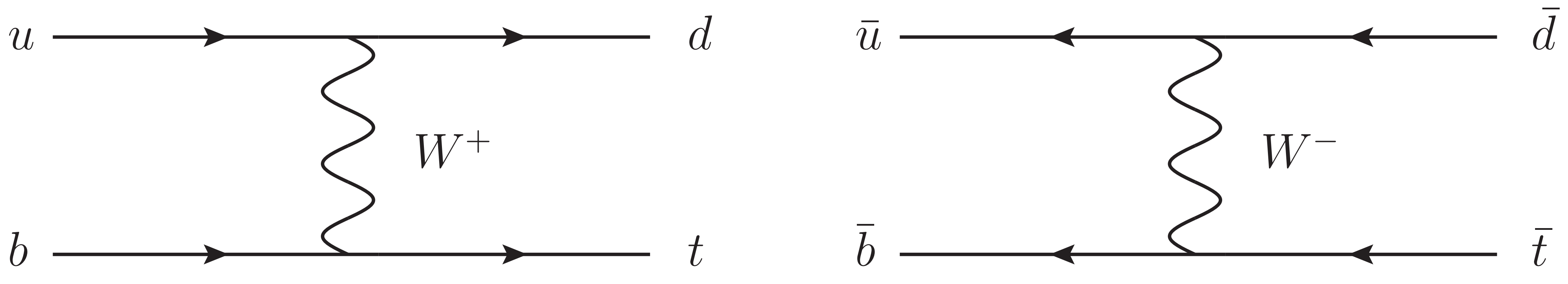
- **Quantum tomography.**

Spin Correlation and Polarisation

t-channel polarisation

NEW!

ATLAS-CONF-2021-027



- **Polarisation measured in t-channel production using full Run2 data.**
- **Events required to have exactly one lepton, two jets, and significant MET and exactly one b-tagged jet** (as well as some additional multi-jet suppression cuts)**.**
- **S/B after selection in signal region is 0.94.**

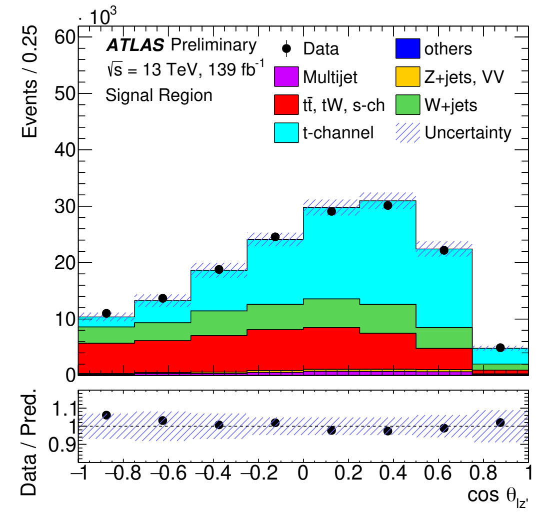
t-channel polarisation

NEW!

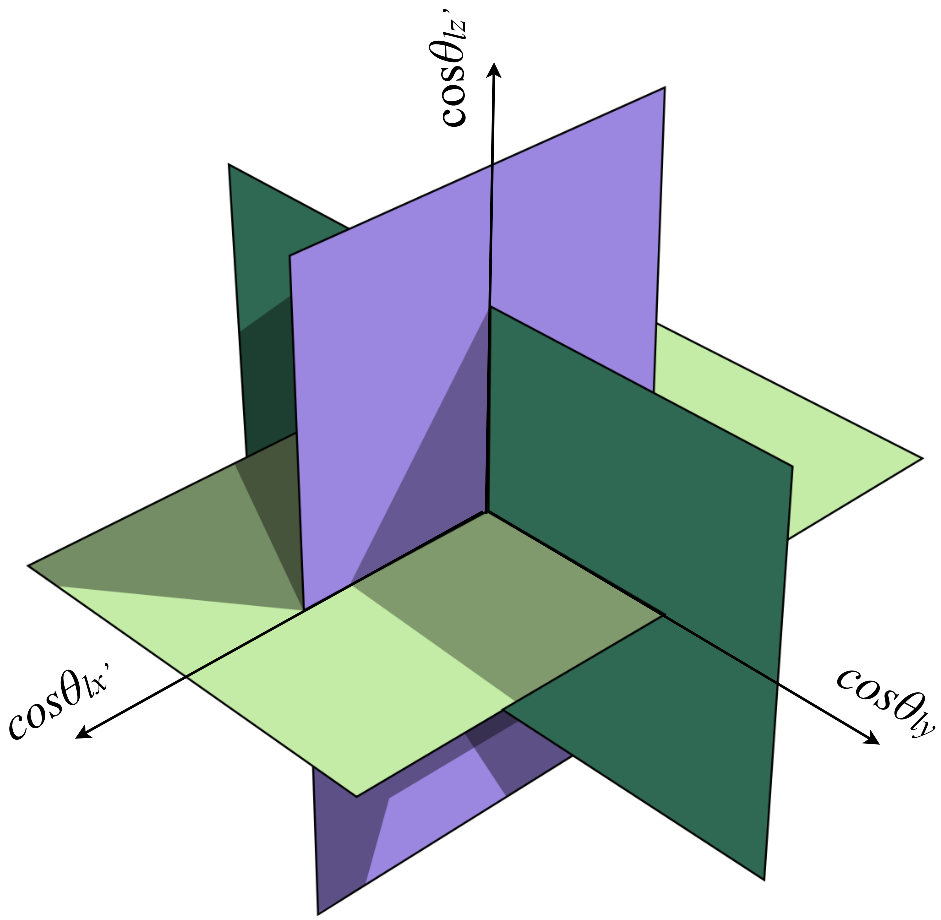
ATLAS EXPERIMENT

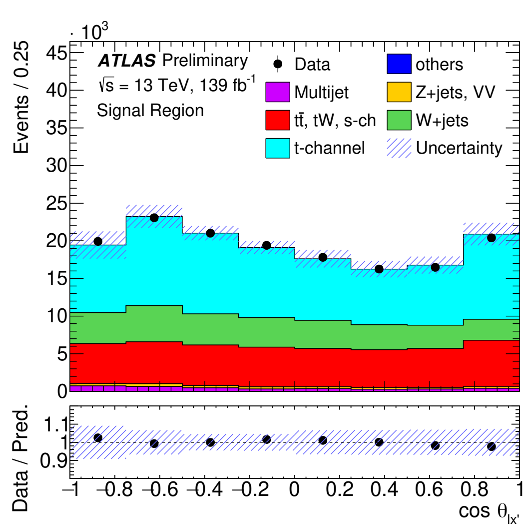
ATLAS-CONF-2021-027

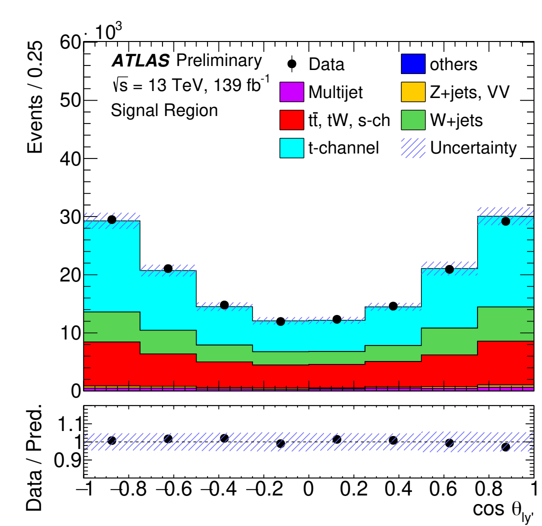
- Profile likelihood function used to extract polarisation vectors for top and anti-top.



- $\hat{x}', \hat{y}', \hat{z}$ angles constructed using spectator jet in top rest-frame.







t-channel polarisation

NEW!

ATLAS-CONF-2021-027

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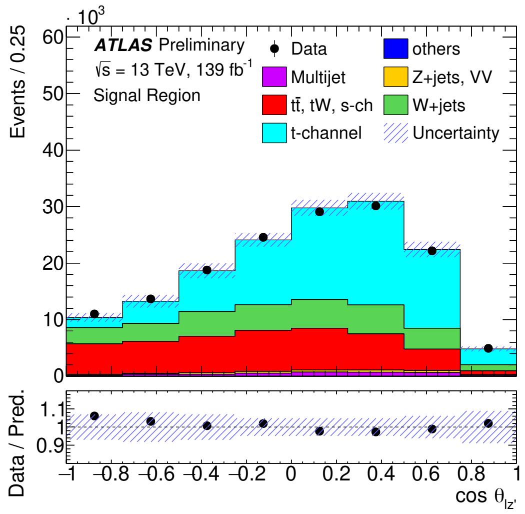

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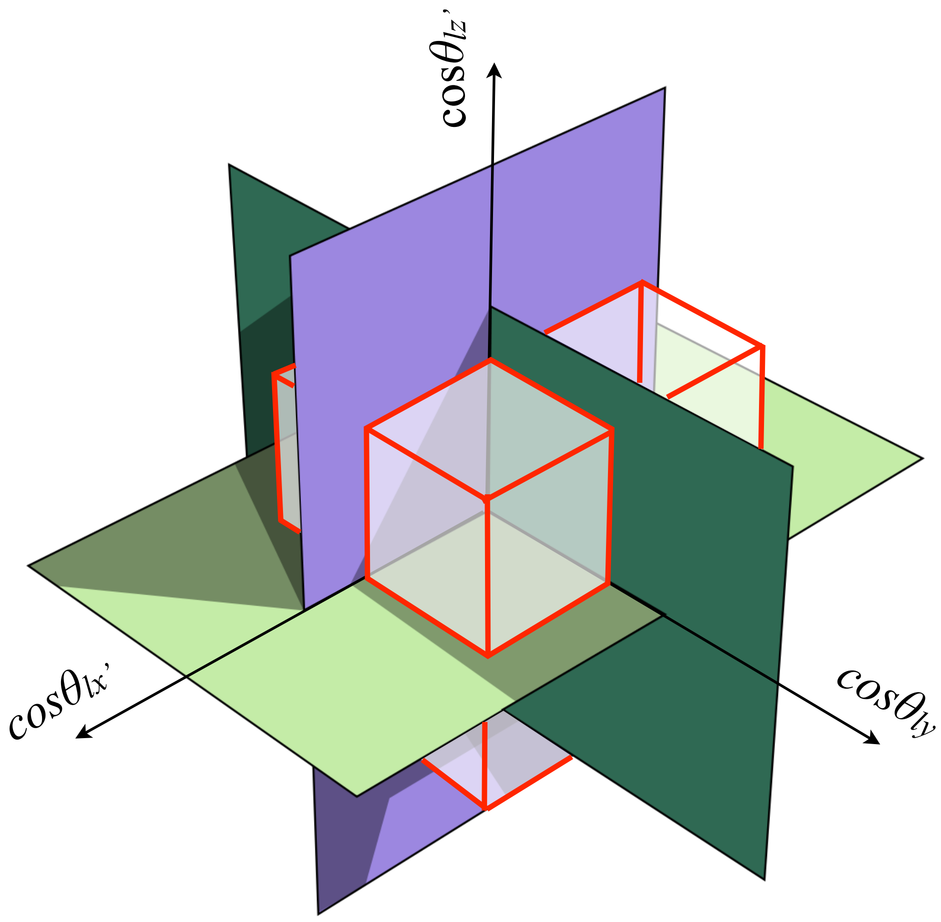
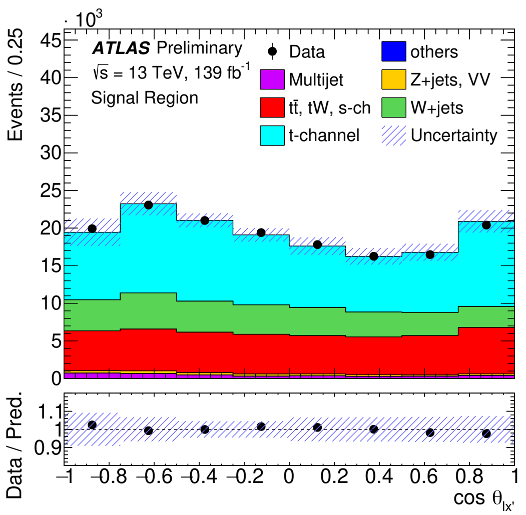
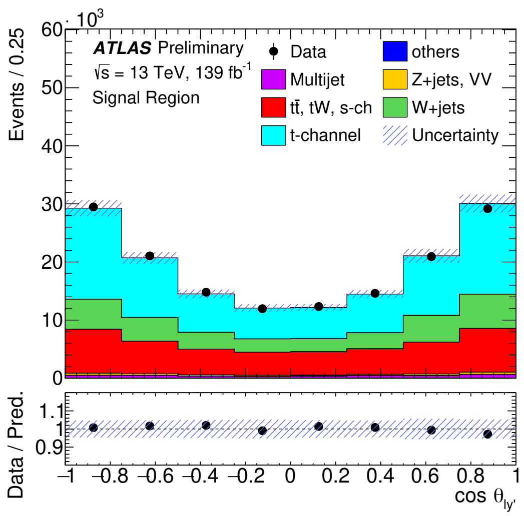






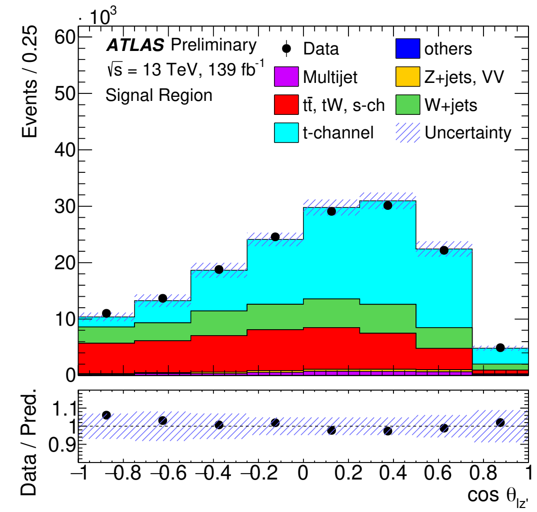
t-channel polarisation

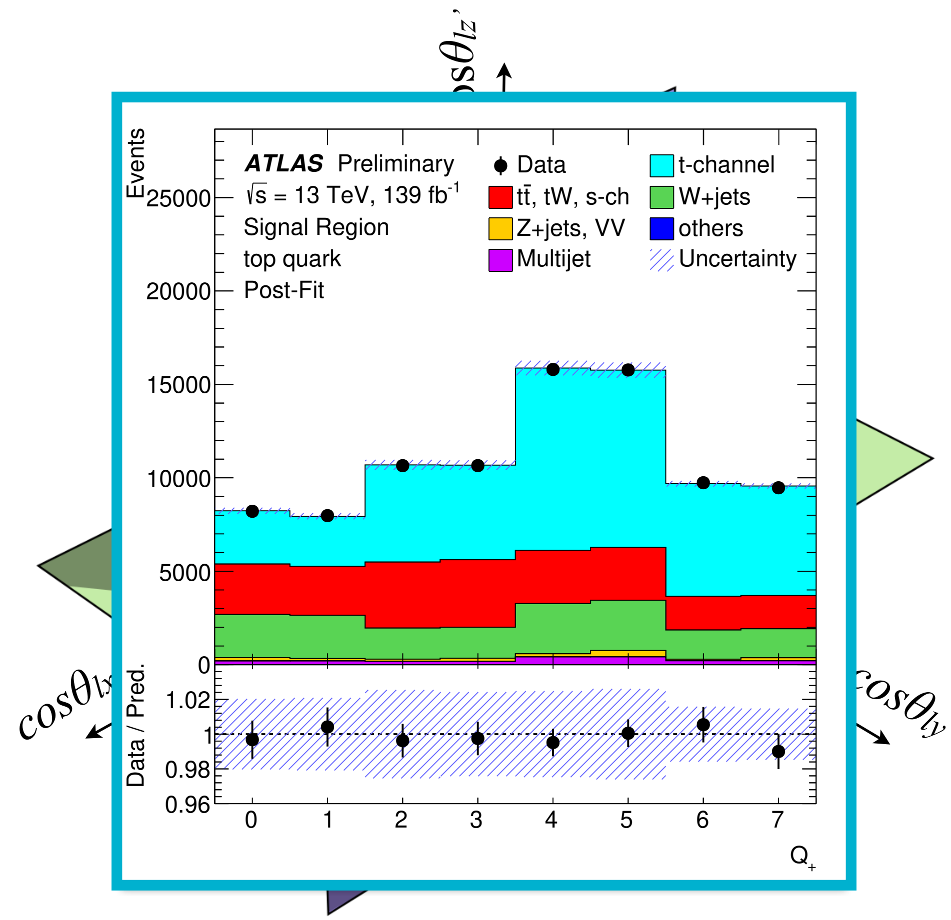
NEW!

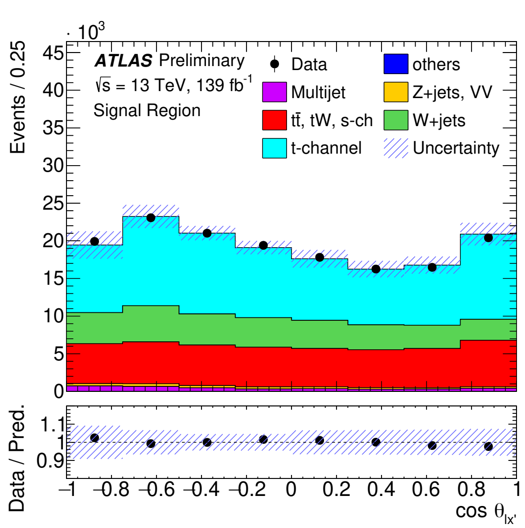
ATLAS EXPERIMENT

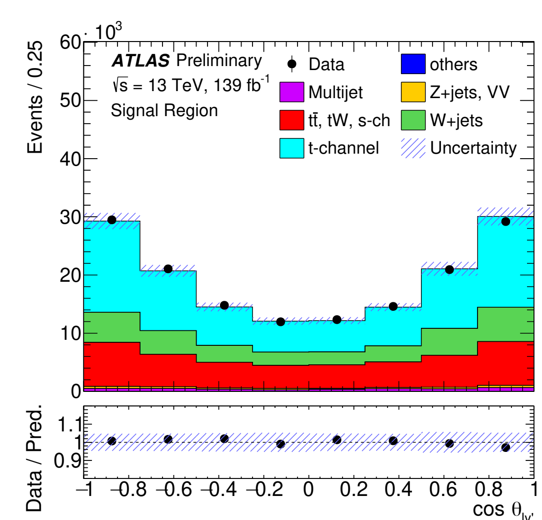
ATLAS-CONF-2021-027

- Octant variable constructed and used in fit by slicing phase-space.







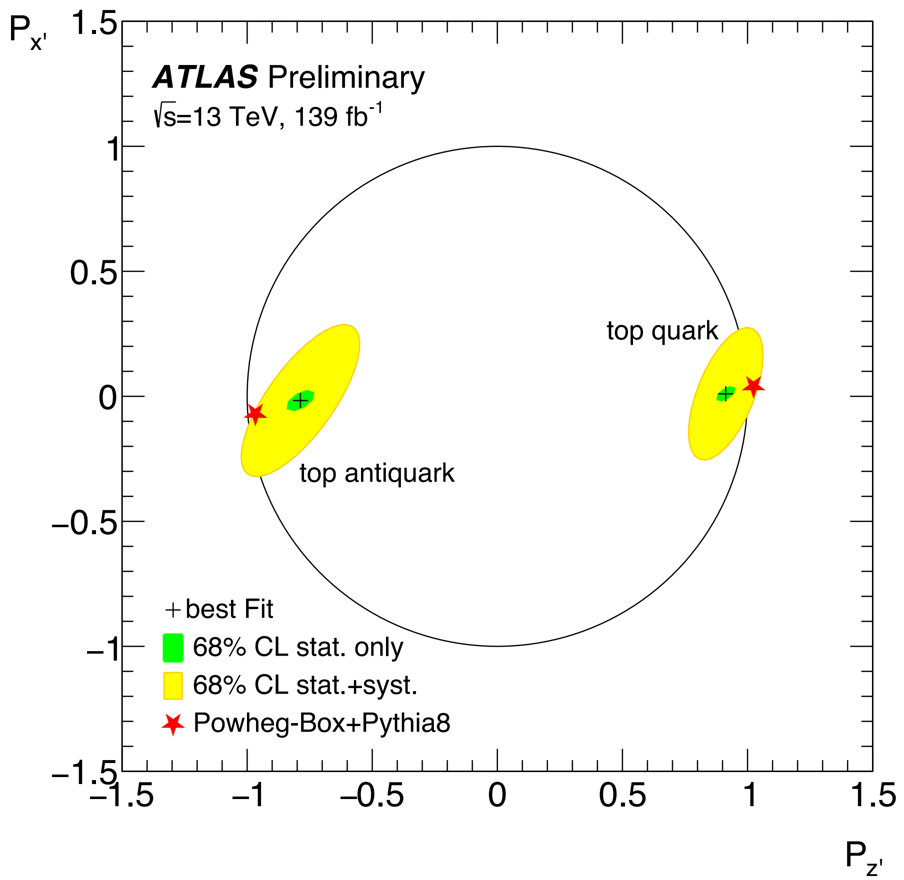


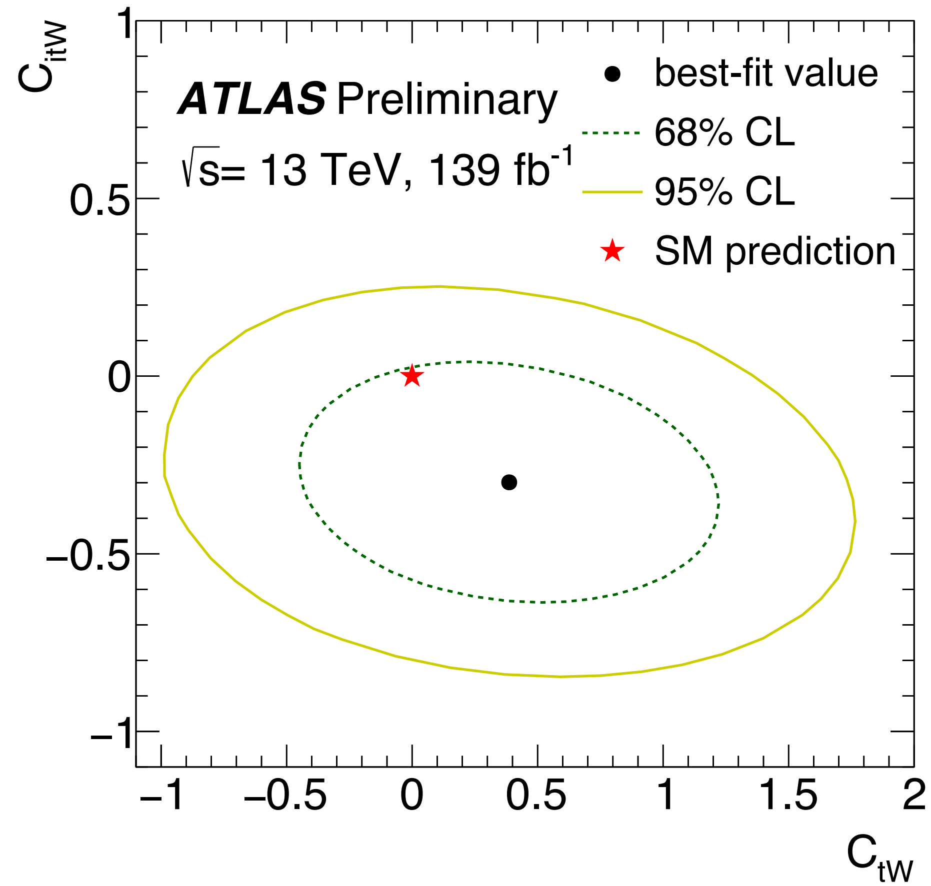
t-channel polarisation

NEW!

ATLAS EXPERIMENT

ATLAS-CONF-2021-027





- **Strong polarisation in z-direction** (as expected) **and little in other directions:**

$$P_x = -0.02 \pm 0.20 \qquad P_y = -0.007 \pm 0.051 \qquad P_z = 0.91 \pm 0.10$$

- **Limits set on CtW and CitW:**

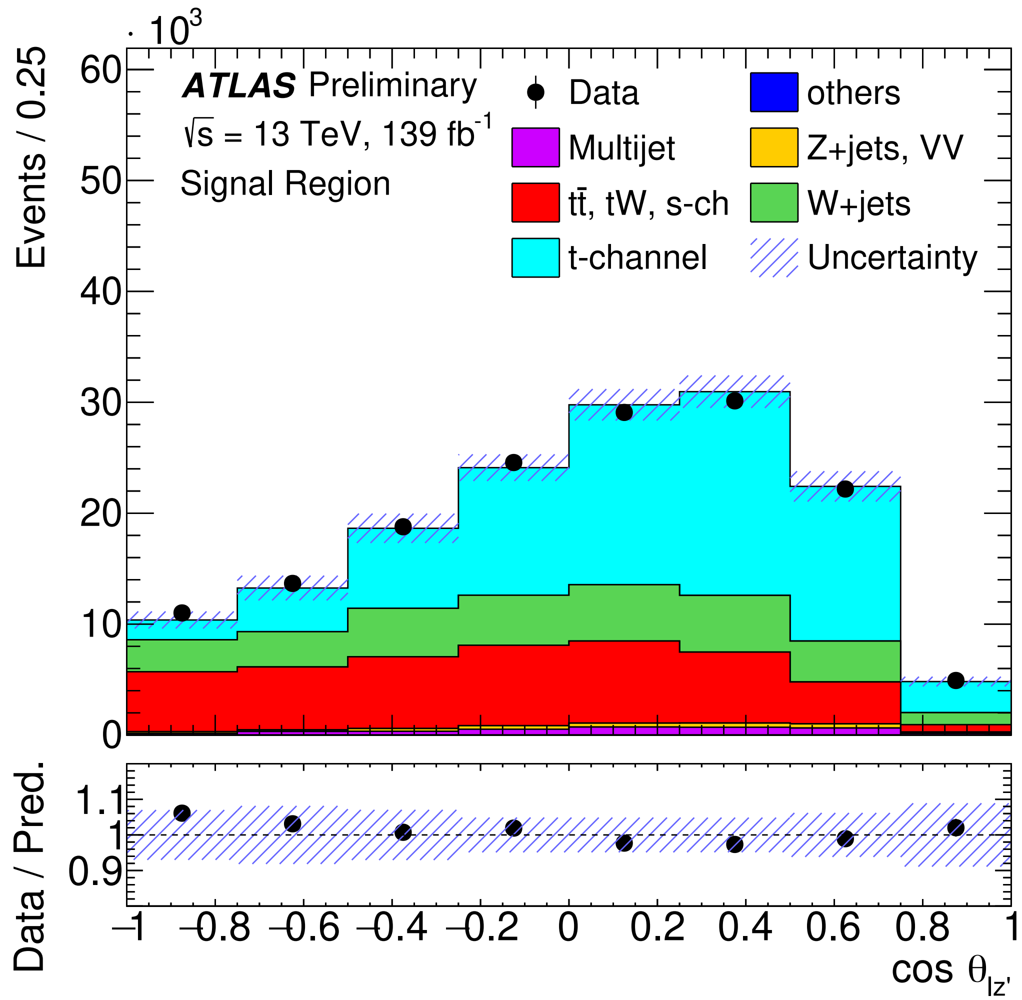
$$C_{tW} \in [-0.7, 1.5] \qquad C_{itW} \in [-0.7, 0.2]$$

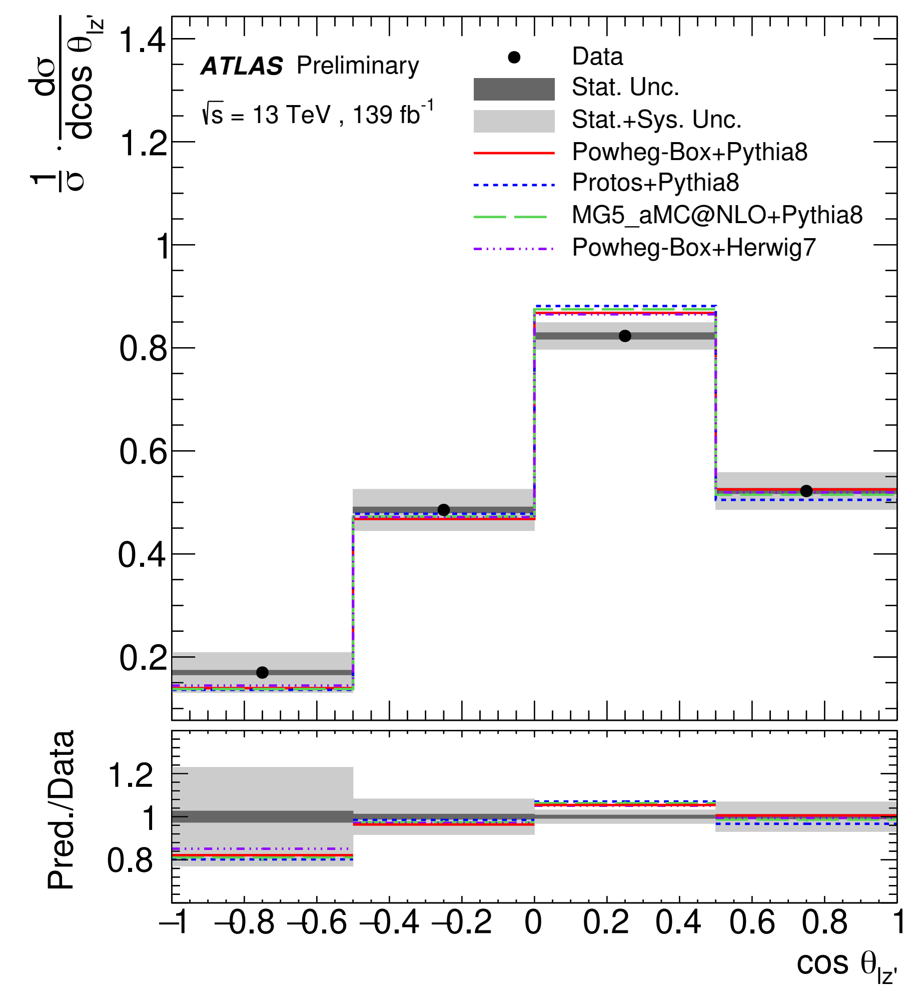
t-channel polarisation

NEW!

ATLAS EXPERIMENT

ATLAS-CONF-2021-027



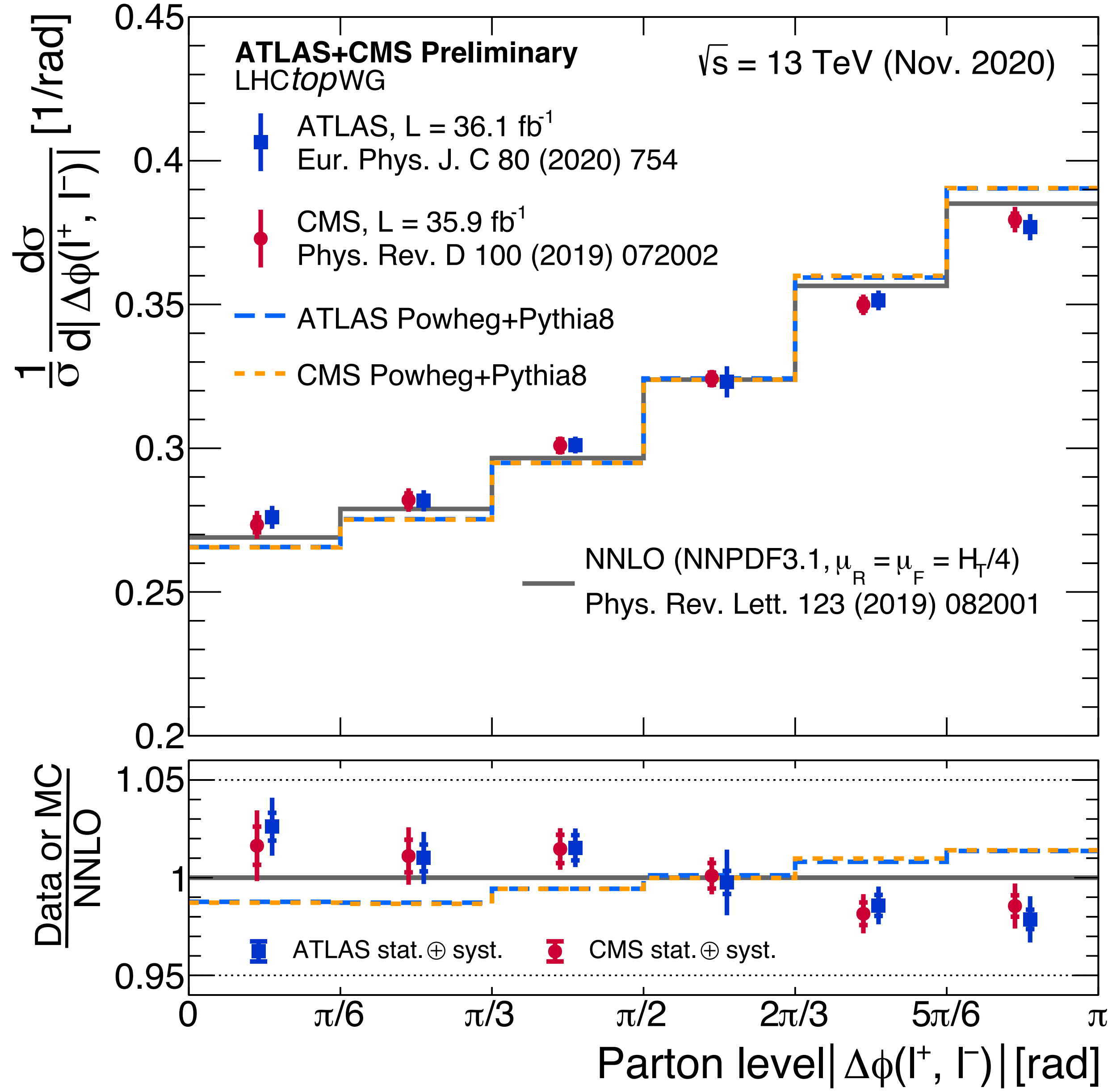


- Data also unfolded to particle level in fiducial phase space for EFT fit.
- Good agreement with SM predictions.

Spin Correlation ($\Delta\phi$)

NEW!

LHCTopWG



- **No new full Run2 $\Delta\phi$** (yet) **but ATLAS and CMS are progressing towards combining previous results.**

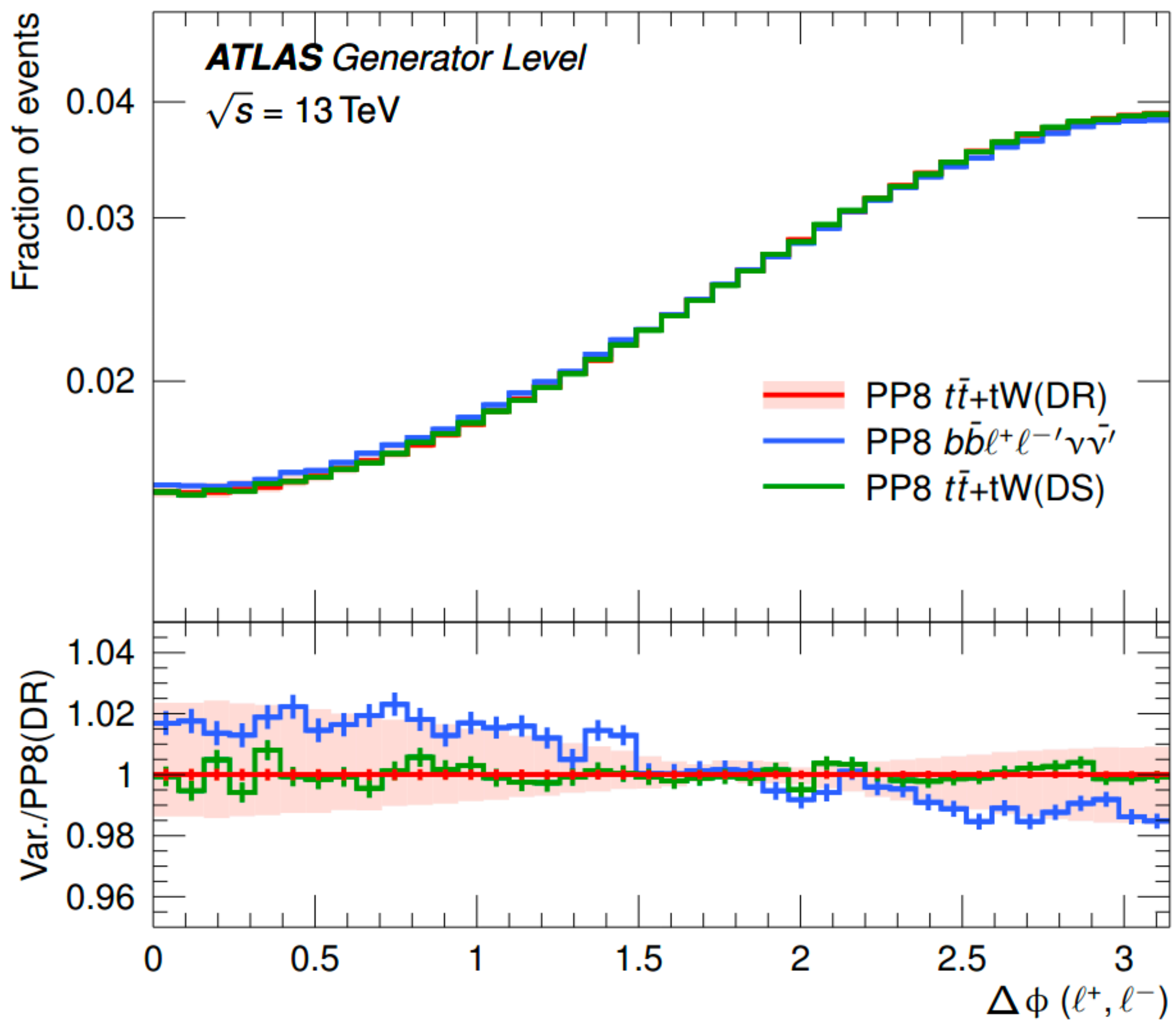
Spin Correlation (Δφ)

NEW!

Spin Correlation ($\Delta\varphi$)

NEW!

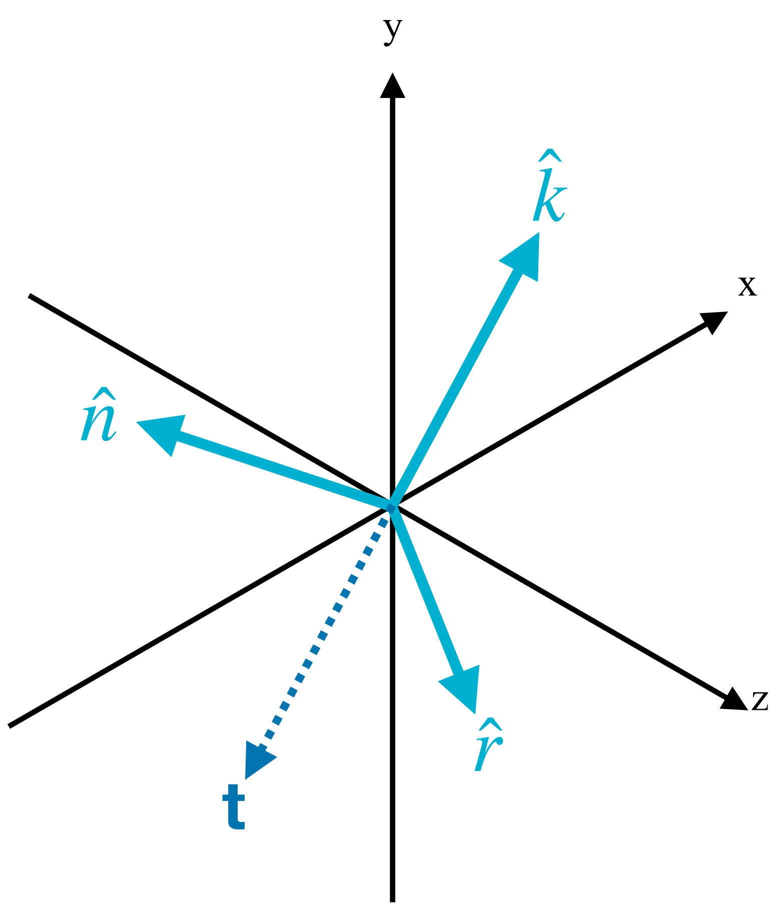
ATLAS webpage online shortly



- **"New" Monte Carlo predictions** (such as Powheg bb4l) **may also sculpt this observable.**

Spin Density Matrix

Phys. Rev. D 100 (2019) 072002



- **Gold standard measurement for spin structure of the top quark!**
- **Measure the single and double angles between leptons and a special *"spin analysing basis"* in dileptonic $t\bar{t}$ events .**
- **Angles correspond direction to elements of spin density matrix:**
  - ➡ C = 3x diagonal elements (spin corr.)
  - ➡ B = 6x polarisation
  - ➡ 6x Off diagonal "cross correlations"

Spin Density Matrix

$$\begin{bmatrix} C_{\hat{k}\hat{k}} & C_{\hat{n}\hat{k}} + C_{\hat{k}\hat{n}} & C_{\hat{r}\hat{k}} + C_{\hat{k}\hat{r}} \\ C_{\hat{n}\hat{k}} - C_{\hat{k}\hat{n}} & C_{\hat{n}\hat{n}} & C_{\hat{n}\hat{r}} + C_{\hat{r}\hat{n}} \\ C_{\hat{r}\hat{k}} - C_{\hat{k}\hat{r}} & C_{\hat{n}\hat{r}} - C_{\hat{r}\hat{n}} & C_{\hat{r}\hat{r}} \end{bmatrix}$$

Spin Density Matrix

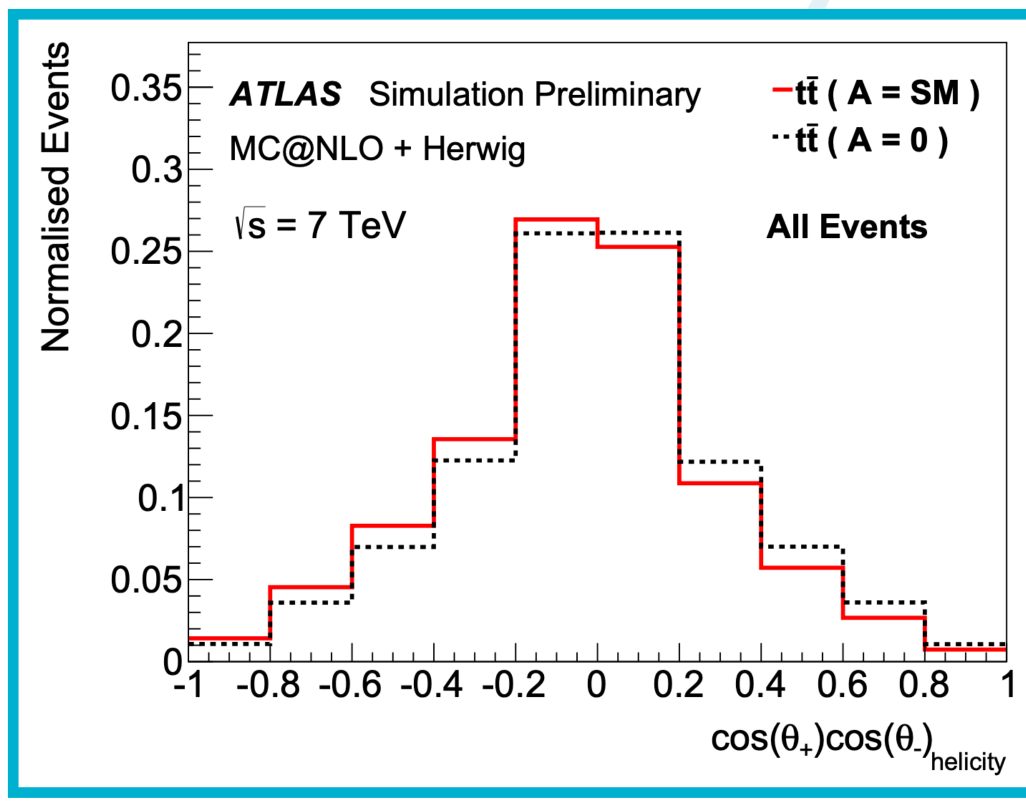
$$
\begin{bmatrix}
C_{\hat{k}\hat{k}} & C_{\hat{n}\hat{k}} + C_{\hat{k}\hat{n}} & C_{\hat{r}\hat{k}} + C_{\hat{k}\hat{r}} \\
C_{\hat{n}\hat{k}} - C_{\hat{k}\hat{n}} & C_{\hat{n}\hat{n}} & C_{\hat{n}\hat{r}} + C_{\hat{r}\hat{n}} \\
C_{\hat{r}\hat{k}} - C_{\hat{k}\hat{r}} & C_{\hat{n}\hat{r}} - C_{\hat{r}\hat{n}} & C_{\hat{r}\hat{r}}
\end{bmatrix}
$$

Spin Density Matrix

$-9 < \cos(\theta_+^k)cos(\theta_-^k) >$ $\quad C_{\hat{n}\hat{k}} + C_{\hat{k}\hat{n}} \quad C_{\hat{r}\hat{k}} + C_{\hat{k}\hat{r}}$

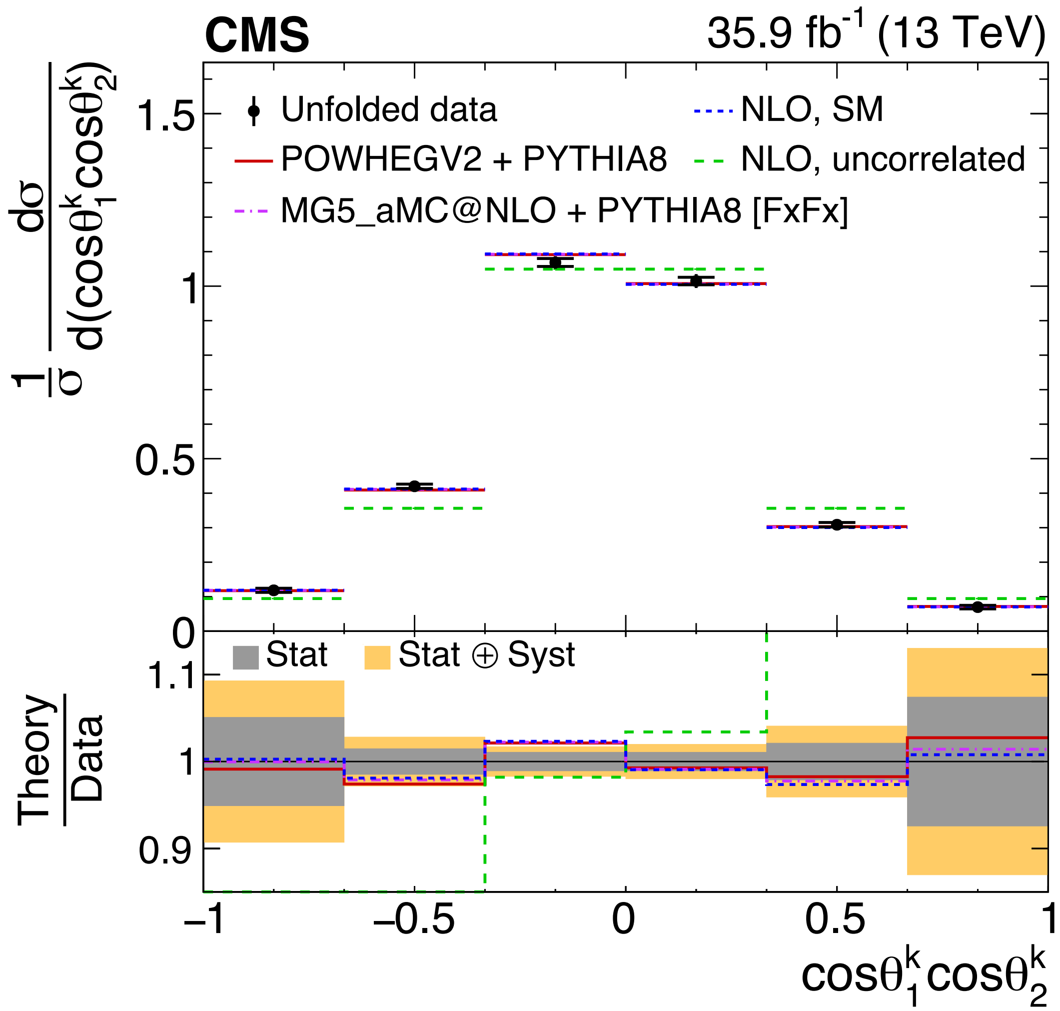
$C_{\hat{n}\hat{k}} - C_{\hat{k}\hat{n}} \quad \ldots \quad + C_{\hat{r}\hat{n}}$

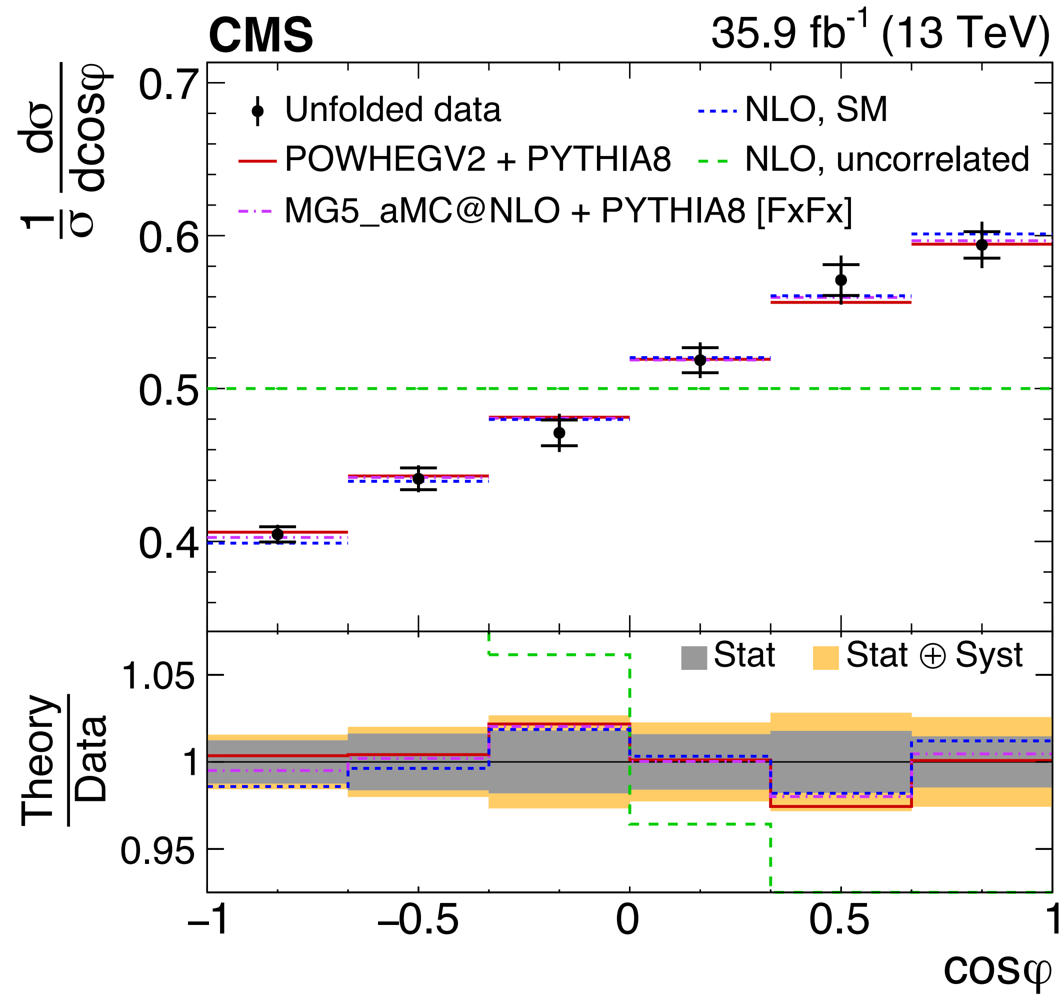
$C_{\hat{r}\hat{k}} - C_{\hat{k}\hat{r}} \quad \ldots \quad (\theta_+^r)cos(\theta_-^r) >$



Spin Density Matrix

[Phys. Rev. D 100 (2019) 072002](#)

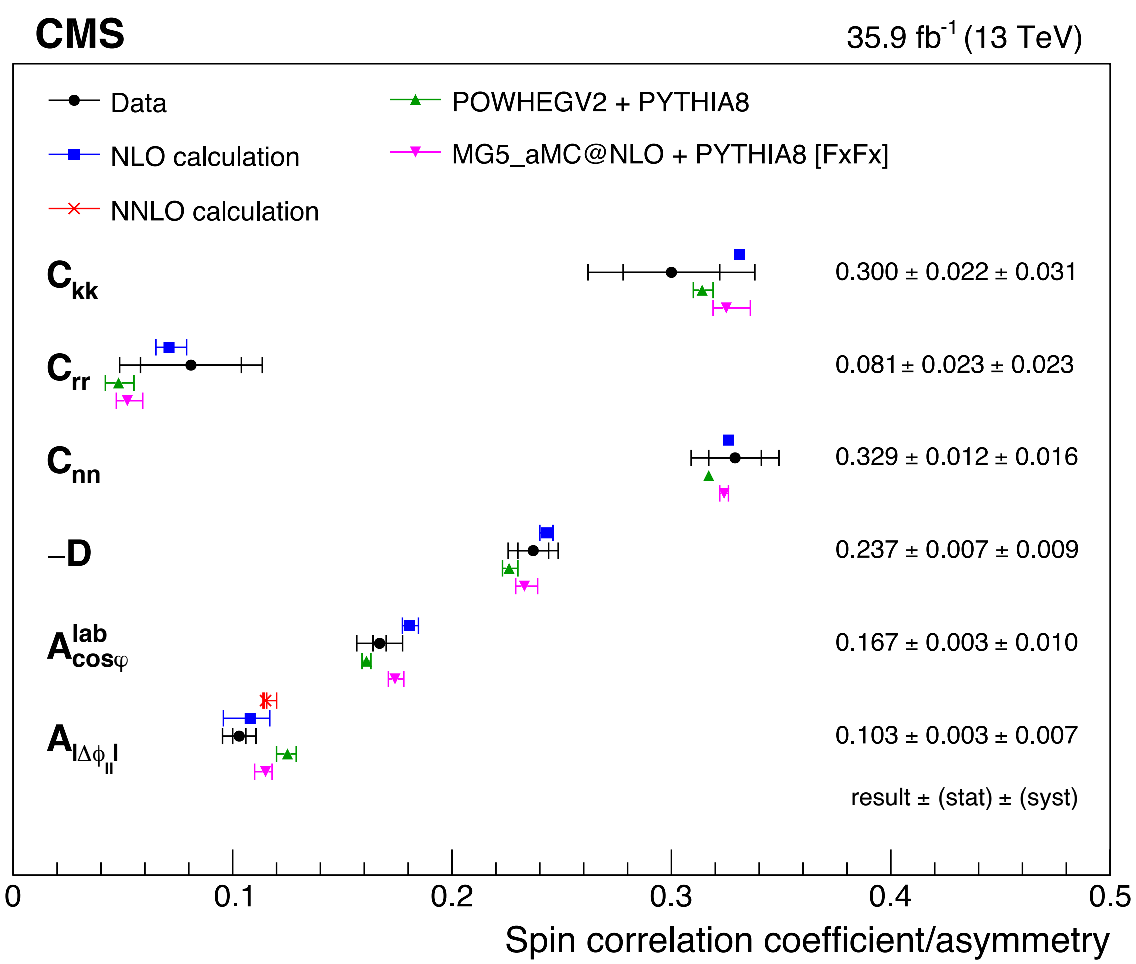


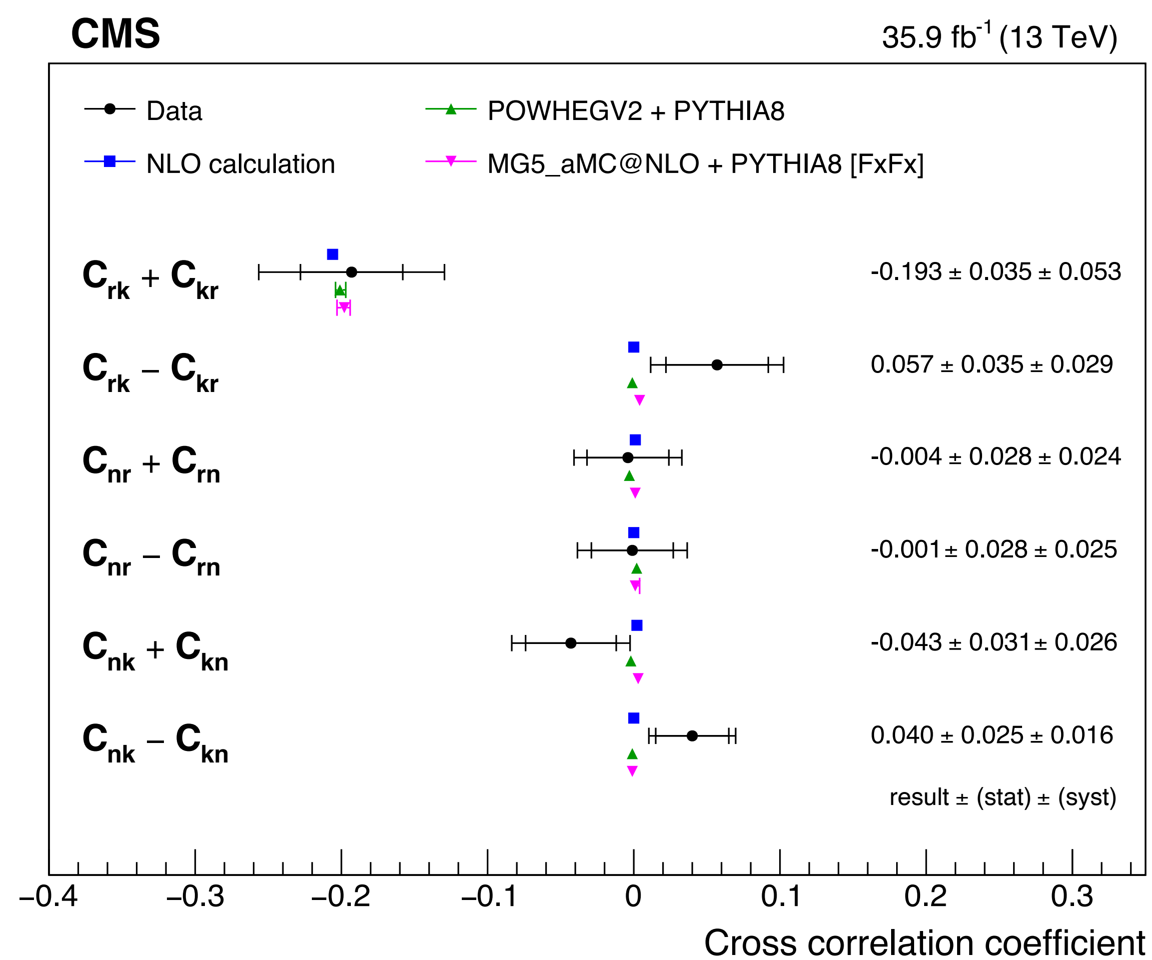


- **Observables are very sensitive to the presence of spin correlation, but tricky to reconstruct and unfold.**
- **From extracting all the information possible from these obs.**

Spin Density Matrix

Phys. Rev. D 100 (2019) 072002

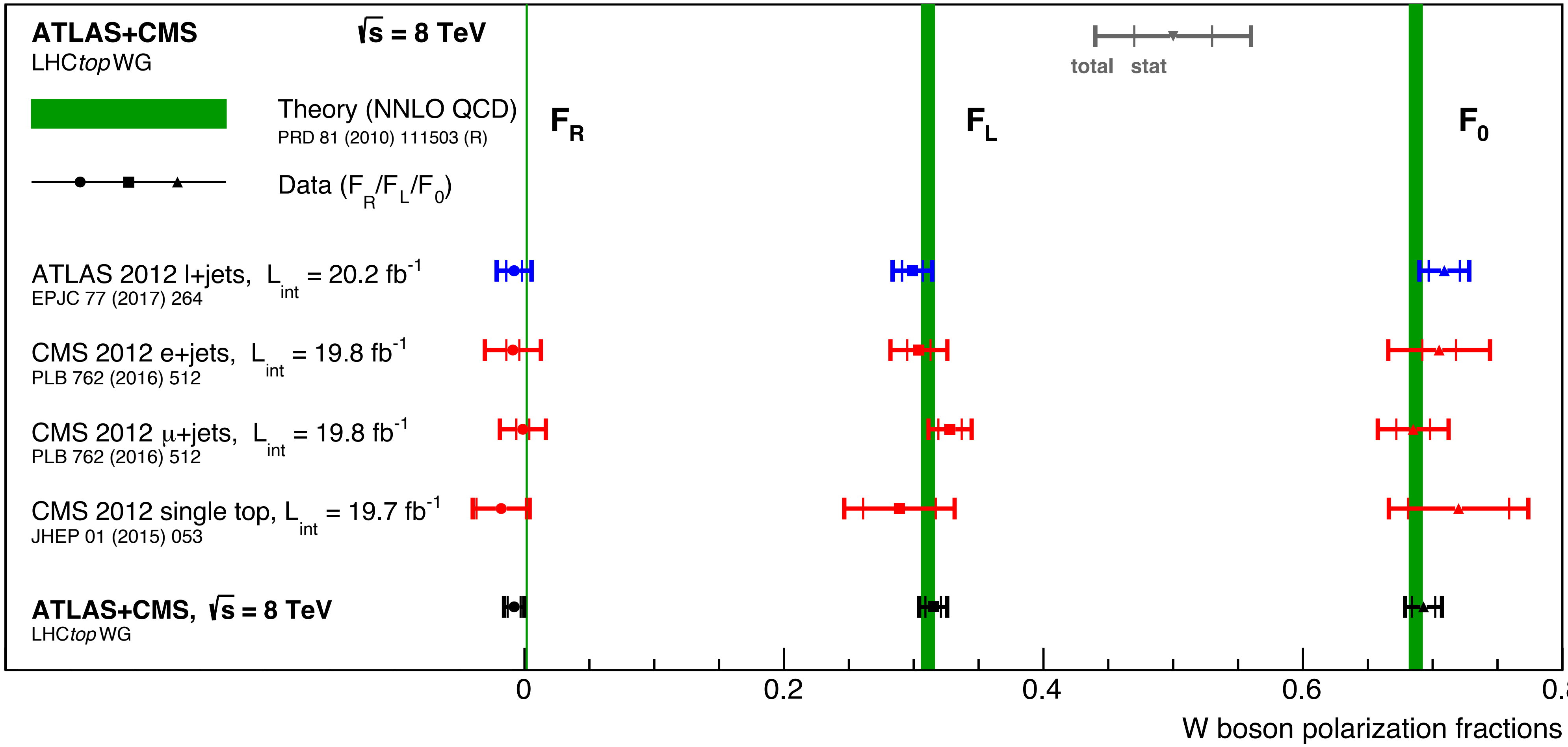




- **No new full Run2** (yet)**, previous results agree with SM predictions but are heavily affected by $t\bar{t}$ modelling uncertainties**
  - ➡ New techniques/better understanding of modelling needed as much as more data!

W boson helicity

JHEP 08 (2020) 051

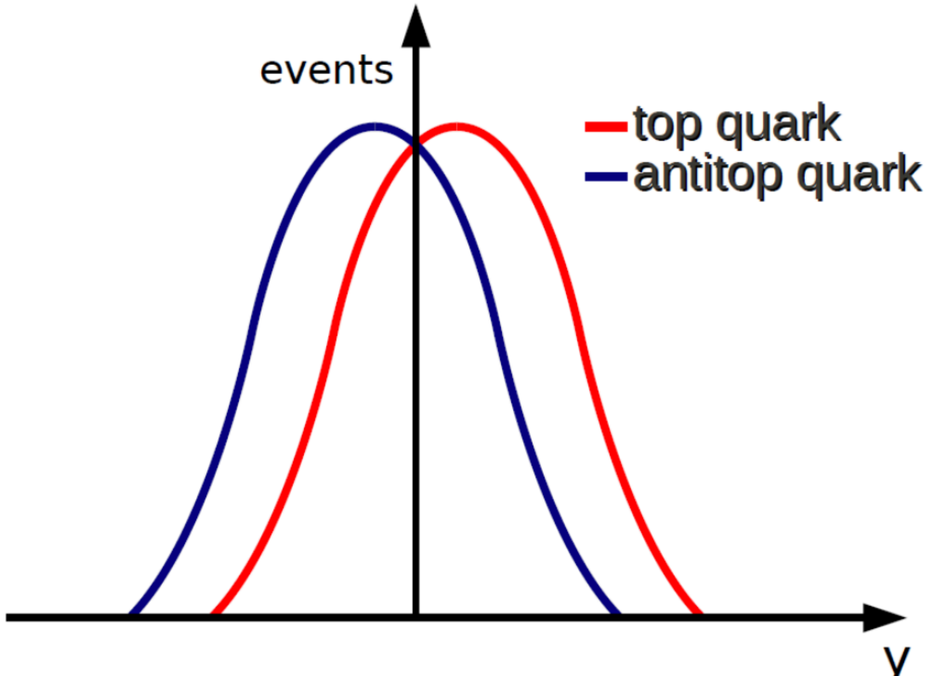


- **Can use similar observables** (with a slightly different definition) **to measure the helicity of the W boson.**
- **Recent ATLAS + CMS combination of Run1 results in excellent agreement with the SM.**

Production Asymmetries

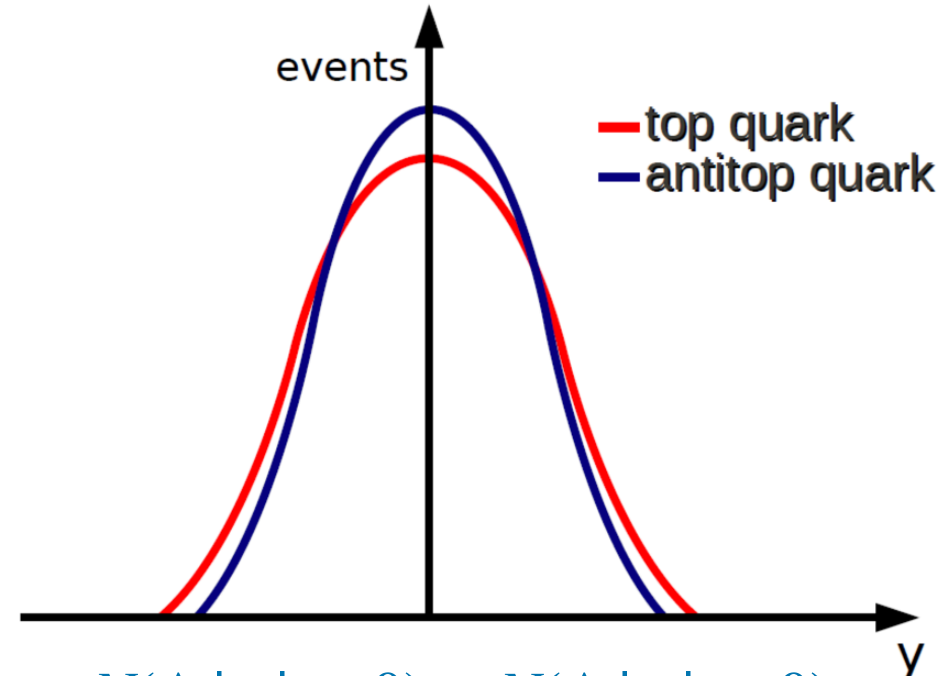
Asymmetries

qq anihilation



$$A_C = \frac{N_F - N_B}{N_F + N_B}$$

gg fusion

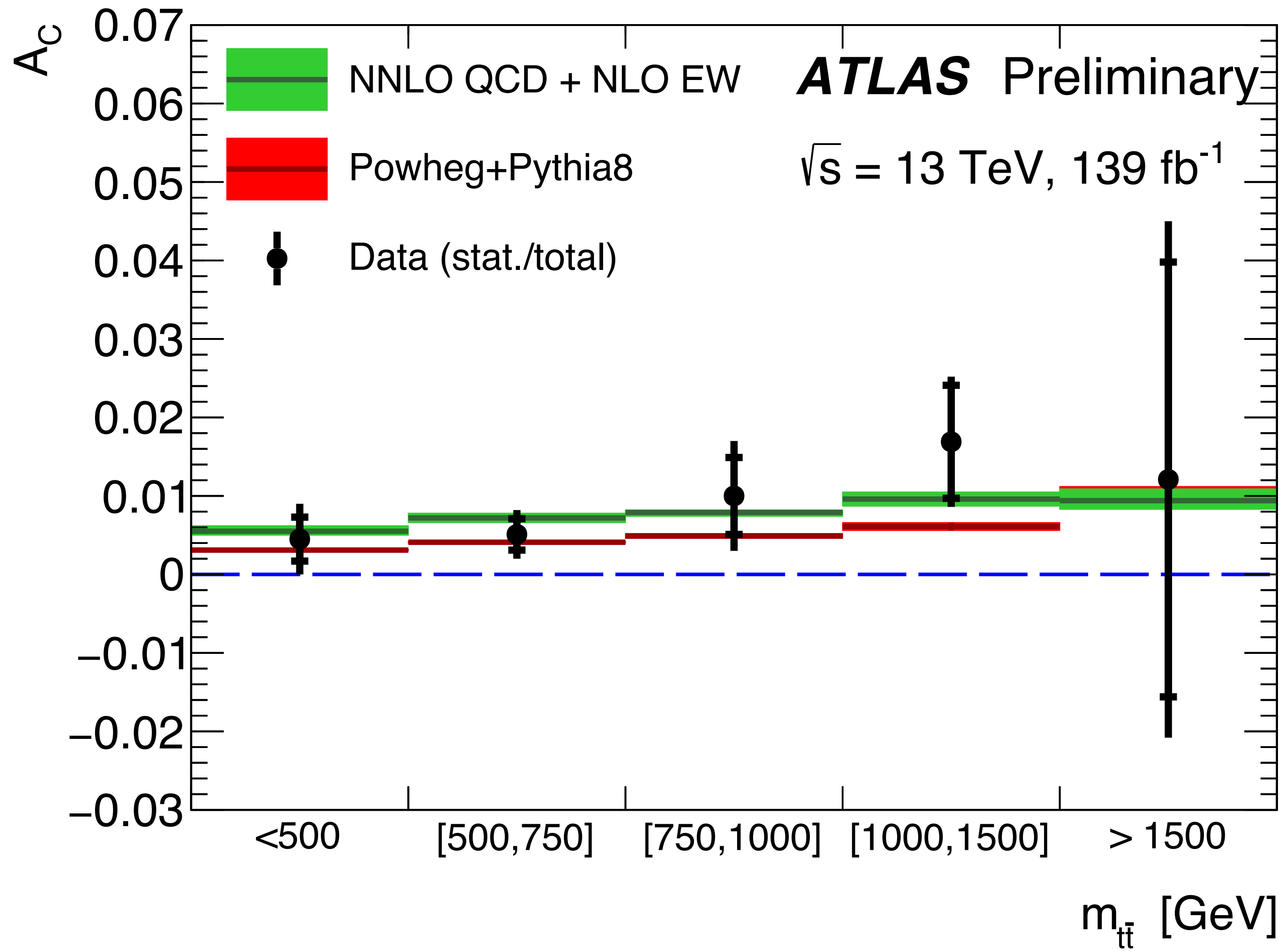


$$A_C = \frac{N(\Delta|y| > 0) - N(\Delta|y| < 0)}{N(\Delta|y| > 0) + N(\Delta|y| < 0)}$$

- **Preference in direction of top and anti-top in ppbar collisions.**
- **At the LHC, no directional preference, but tops are preferentially more forward than anti-tops.**
- **Effect arises due to higher order interference effects and are both sensitive to potential new physics.**

Charge Asymmetry

ATLAS-CONF-2019-026

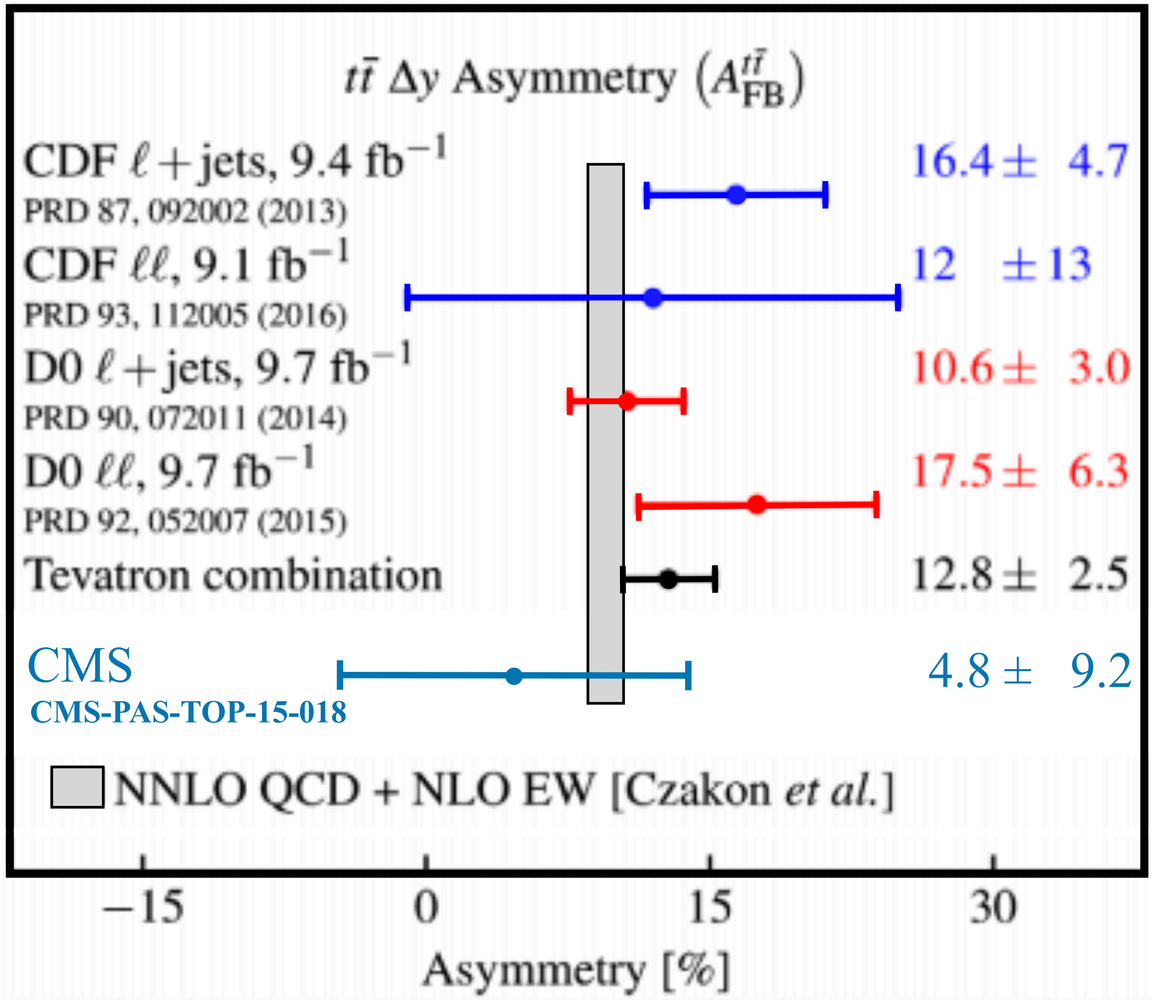


- **ATLAS found strong evidence** (4σ) **for charge asymmetry in the l+jets channel using full Run2 data.**

➡ Set limits on 4 linear combinations of 4-fermion EFT operators.

Forward/Backward Asymmetry

CMS PAS TOP-15-018



$$d = 0.002^{+0.017}_{-0.021} \qquad A_{FB} = 0.048^{+0.092}_{-0.089} \qquad \mu = -0.024^{+0.021}_{-0.009}$$

- **CMS use a template method to isolate the qqbar initial state and measure A_{FB} with 35.9 fb^{-1} in l+jets events.**
  - ➡ Also fit anomalous chromoelectric (d) & chromomagnetic (μ) moments.

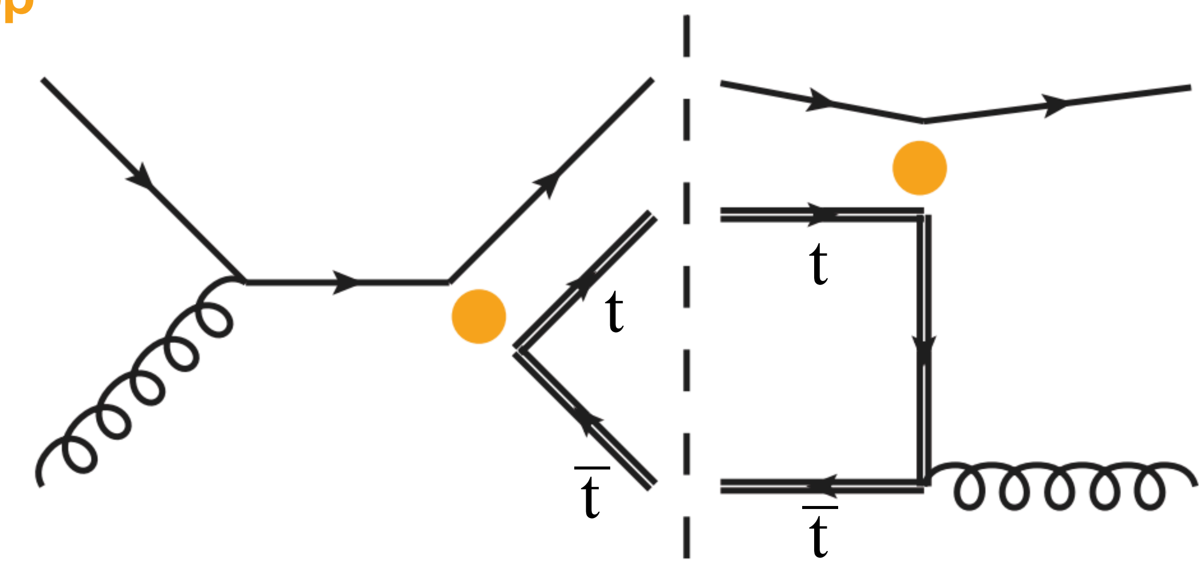
Energy Asymmetry

NEW!

ATLAS EXPERIMENT

TOPQ-2019-28-002

4-quark opp



$$A_E(\theta_j) = \frac{\sigma^{opt}(\Delta E > 0) - \sigma^{opt}(\Delta E < 0)}{\sigma^{opt}(\Delta E > 0) + \sigma^{opt}(\Delta E < 0)}$$

$$\Delta E = E_t - E_{\bar{t}}$$

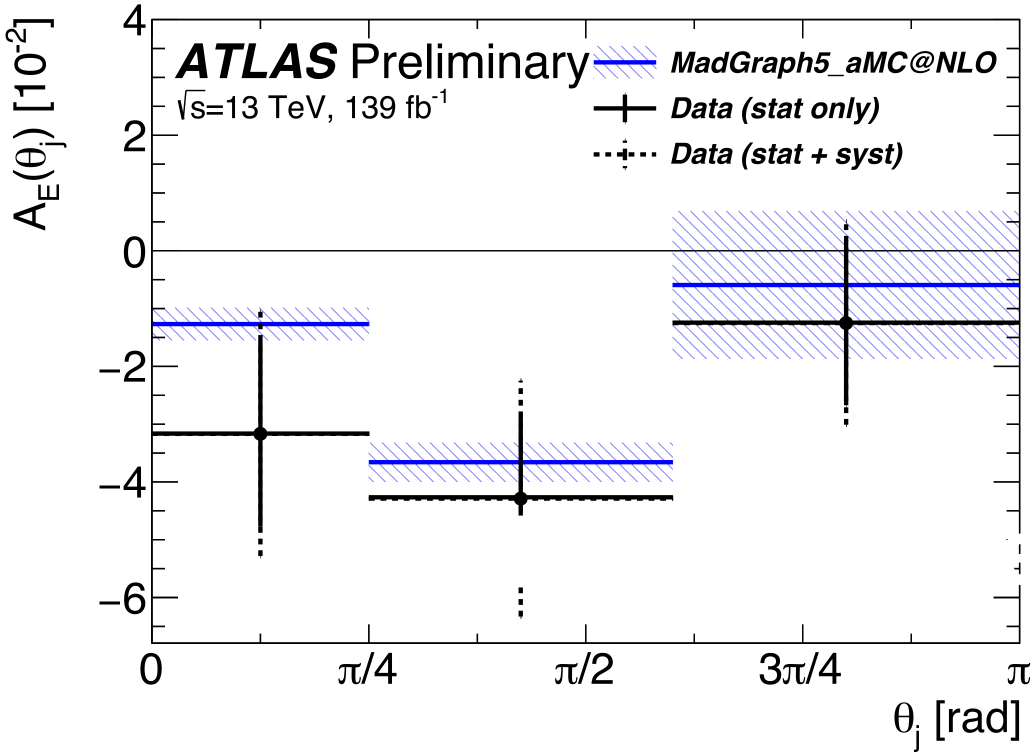
$$\sigma^{opt} = \sigma(\theta_j \,|\, y_{t\bar{t}j} > 0) + \sigma(\pi - \theta_j \,|\, y_{t\bar{t}j} < 0)$$

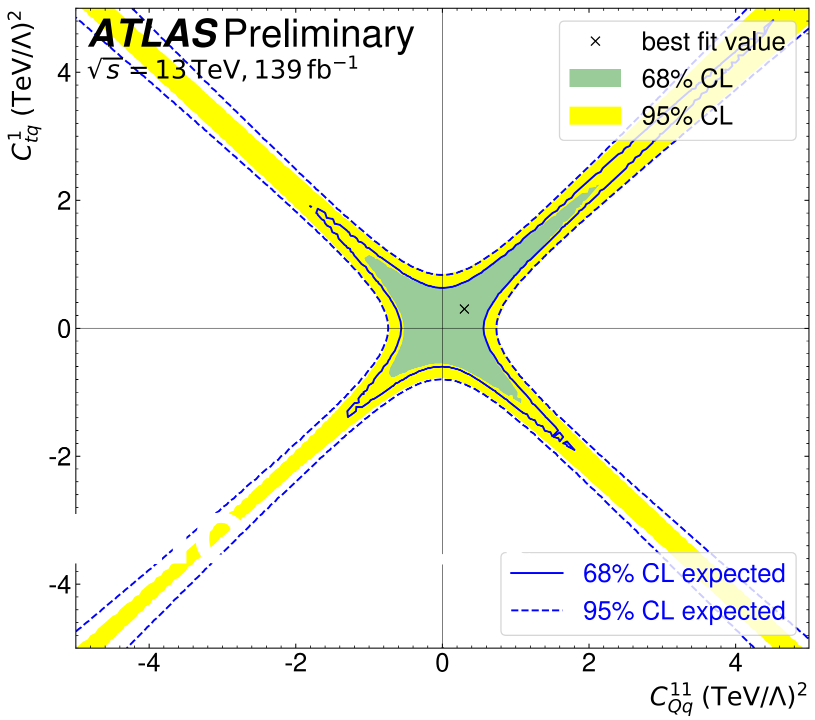
- **Asymmetry at tree-level in $t\bar{t}j$ events.**
- **Sensitive to four-quark operator insertions** (orange dots)**.**
- **Measured in boosted l+jets final state with hard additional jet** ($p_T > 100$ GeV) **using full Run2 data.**

Energy Asymmetry

NEW!

TOPQ-2019-28-002





- **Unfolded to particle level, no significant deviation from SM.**
- **Inclusive asymmetry $A_E^2 = -0.043 \pm 0.020$ in close agreement with SM expectation.**
- **Limits placed on 4-fermion operators.**

Spin in $t\bar{t}Z$ events

Spin in $t\bar{t}Z$ events

NEW!

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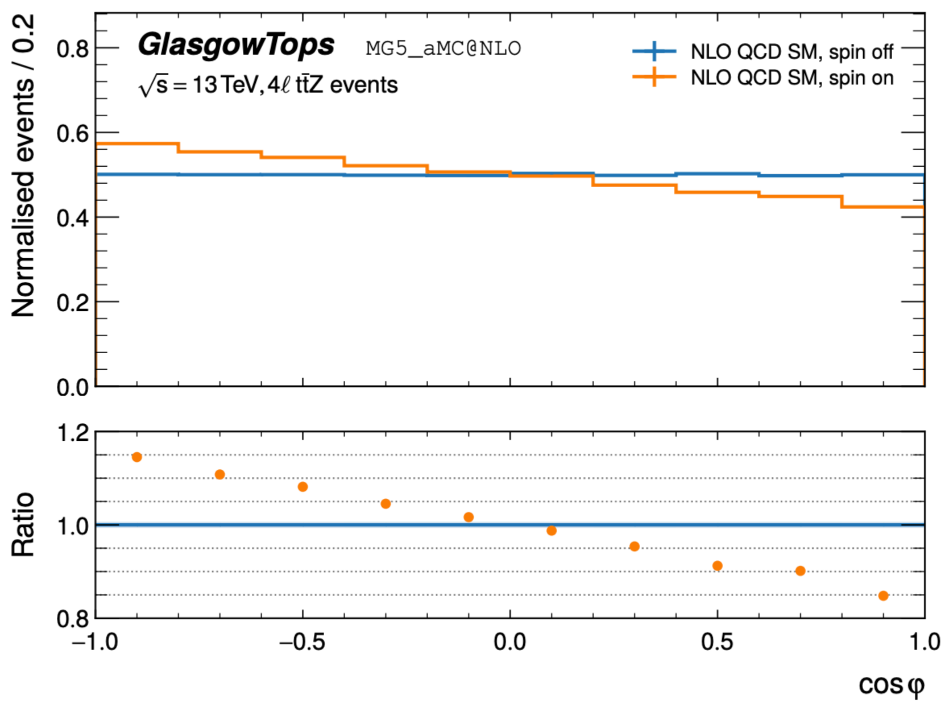
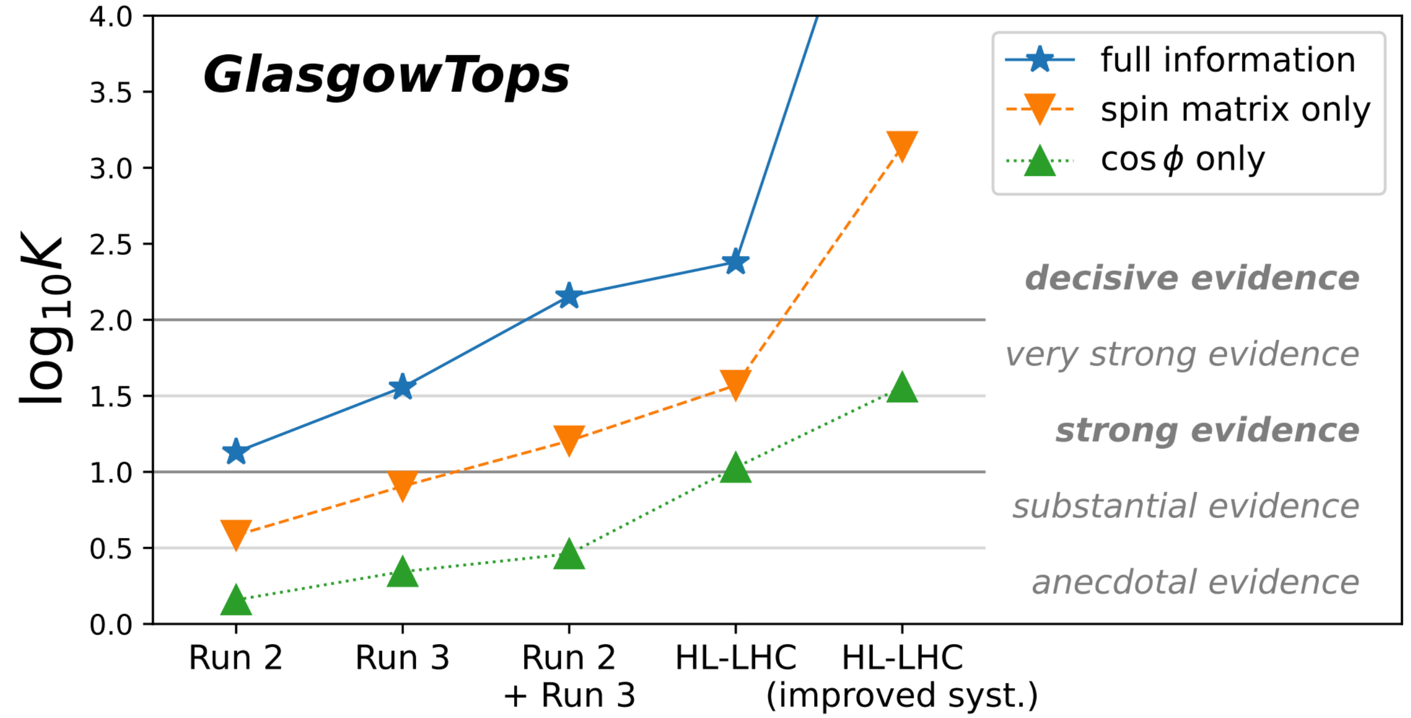
Accepted by EPJC





- **Spin correlation VERY different in $t\bar{t}X$ events than in $t\bar{t}$:**
  - ➡ Can't use lab-frame observables like Δφ.
  - ➡ Spin density matrix from **$t\bar{t}$** works well, along with cos(ϕ').

- **Could potentially find evidence with existing data and discover with full Run2+3 data.**

Spin in $t\bar{t}Z$ events

NEW!

Accepted by EPJC

Coefficient	$t\bar{t}Z$ NLO 13 TeV	$t\bar{t}$ NLOW 13 TeV	$t\bar{t}Z$ NLO 14 TeV	$t\bar{t}$ NLOW 14 TeV
c_{rr}	-0.198 ± 0.004	0.071 ± 0.008	-0.190 ± 0.004	0.072 ± 0.008
c_{kk}	-0.193 ± 0.004	0.331 ± 0.002	-0.182 ± 0.004	0.331 ± 0.002
c_{nn}	-0.117 ± 0.004	0.326 ± 0.002	-0.118 ± 0.004	0.325 ± 0.002
c_{rk}	-0.173 ± 0.006	-0.206 ± 0.002	-0.180 ± 0.006	-0.204 ± 0.004
c_{kn}	0.012 ± 0.006	$\lesssim 2 \cdot 10^{-3}$	-0.001 ± 0.006	$\lesssim 2 \cdot 10^{-3}$
c_{rn}	-0.004 ± 0.006	$\lesssim 1 \cdot 10^{-3}$	0.006 ± 0.006	$\lesssim 1 \cdot 10^{-3}$
c_r	0.007 ± 0.006	$\lesssim 1 \cdot 10^{-3}$	-0.004 ± 0.006	$\lesssim 1 \cdot 10^{-3}$
c_k	0.003 ± 0.006	$\lesssim 1 \cdot 10^{-3}$	0.001 ± 0.006	$\lesssim 1 \cdot 10^{-3}$
c_n	0.005 ± 0.006	$\lesssim 1 \cdot 10^{-3}$	-0.008 ± 0.006	$\lesssim 1 \cdot 10^{-3}$
b_r^+	0.055 ± 0.001	$\lesssim 2 \cdot 10^{-3}$	0.055 ± 0.001	$\lesssim 2 \cdot 10^{-3}$
b_r^-	0.055 ± 0.001	$\lesssim 2 \cdot 10^{-3}$	0.057 ± 0.001	$\lesssim 2 \cdot 10^{-3}$
b_k^+	-0.077 ± 0.001	$\lesssim 4 \cdot 10^{-3}$	-0.077 ± 0.001	$\lesssim 4 \cdot 10^{-3}$
b_k^-	-0.076 ± 0.001	$\lesssim 4 \cdot 10^{-3}$	-0.074 ± 0.001	$\lesssim 4 \cdot 10^{-3}$
b_n^+	0.001 ± 0.001	$\lesssim 3 \cdot 10^{-3}$	0.001 ± 0.001	$\lesssim 3 \cdot 10^{-3}$
b_n^-	0.001 ± 0.001	$\lesssim 3 \cdot 10^{-3}$	-0.001 ± 0.001	$\lesssim 3 \cdot 10^{-3}$

Spin in $t\bar{t}Z$ events

NEW!

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Coefficient	$t\bar{t}Z$ NLO 13 TeV	$t\bar{t}$ NLOW 13 TeV	$t\bar{t}Z$ NLO 14 TeV	$t\bar{t}$ NLOW 14 TeV
c_{rr}	-0.198 ± 0.004	0.071 ± 0.008	-0.190 ± 0.004	0.072 ± 0.008
c_{kk}	-0.193 ± 0.004	0.331 ± 0.002	-0.182 ± 0.004	0.331 ± 0.002
c_{nn}	-0.117 ± 0.004	0.326 ± 0.002	-0.118 ± 0.004	0.325 ± 0.002
c_{rk}	-0.173 ± 0.006	-0.206 ± 0.002	-0.180 ± 0.006	-0.204 ± 0.004
c_{kn}	0.012 ± 0.006	$\lesssim 2$ [illegible]	[illegible]	[illegible]
c_{rn}	-0.004 ± 0.006	$\lesssim 1$ [illegible]	[illegible]	[illegible]
c_r	0.007 ± 0.006	$\lesssim 1$ [illegible]	[illegible]	[illegible]
c_k	0.003 ± 0.006	$\lesssim 1$ [illegible]	[illegible]	[illegible]
c_n	0.005 ± 0.006	$\lesssim 1$ [illegible]	[illegible]	[illegible]
b_r^+	0.055 ± 0.001	$\lesssim 2$ [illegible]	[illegible]	[illegible]
b_r^-	0.055 ± 0.001	$\lesssim 2 \cdot 10^{-3}$	0.057 ± 0.001	$\lesssim 2 \cdot 10^{-3}$
b_k^+	-0.077 ± 0.001	$\lesssim 4 \cdot 10^{-3}$	-0.077 ± 0.001	$\lesssim 4 \cdot 10^{-3}$
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b_n^+	0.001 ± 0.001	$\lesssim 3 \cdot 10^{-3}$	0.001 ± 0.001	$\lesssim 3 \cdot 10^{-3}$
b_n^-	0.001 ± 0.001	$\lesssim 3 \cdot 10^{-3}$	-0.001 ± 0.001	$\lesssim 3 \cdot 10^{-3}$

- **Non-zero polarisations due to EW interaction when Z radiates from the top** (can be enhanced to above 15% with suitable kinematic cuts!)

Spin in $t\bar{t}Z$ events

NEW!

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University of Glasgow

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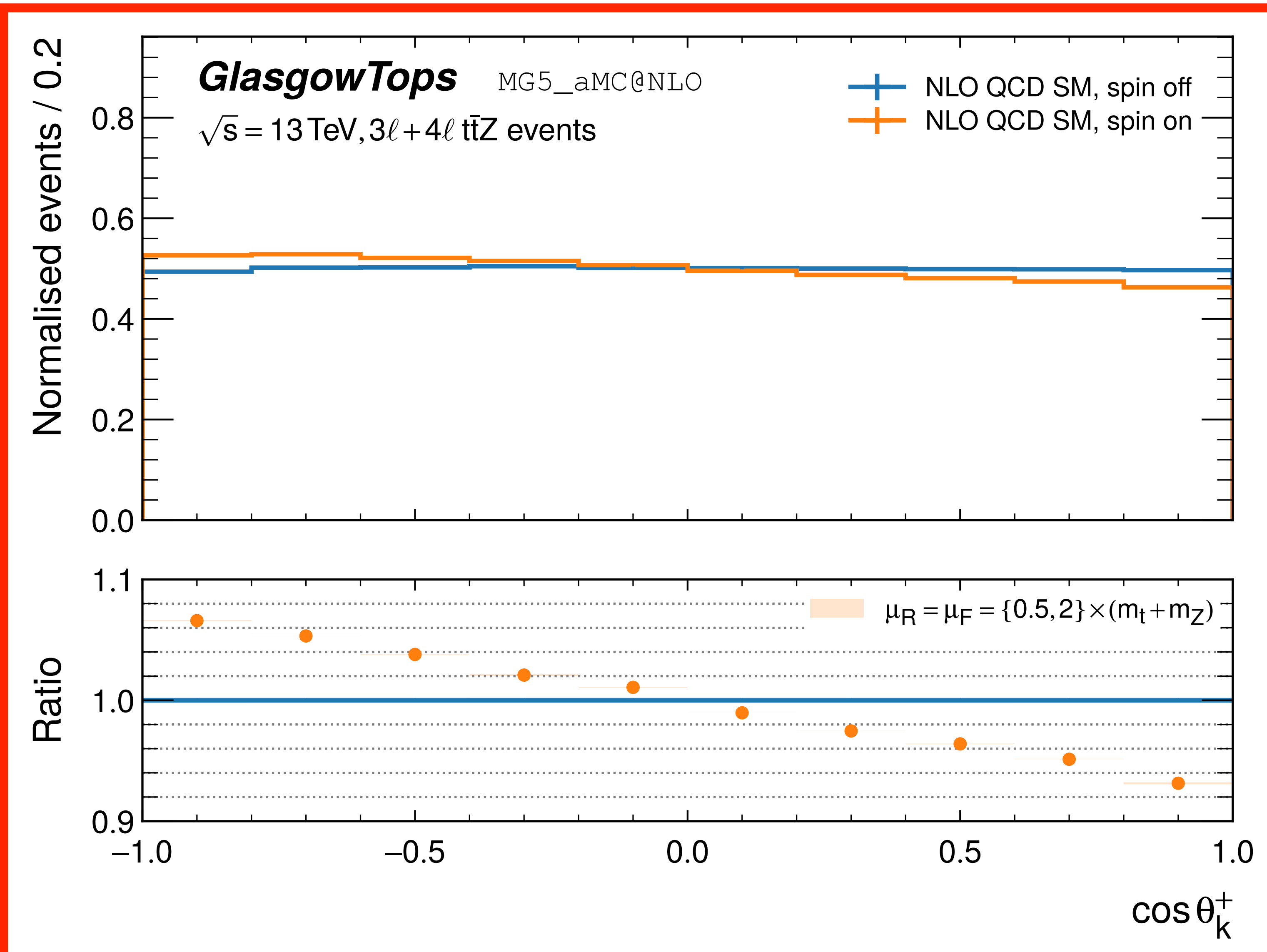

Coefficient				$t\bar{t}$ NLOW 14 TeV
c_{rr}				.072 ± 0.008
c_{kk}				.331 ± 0.002
c_{nn}				.325 ± 0.002
c_{rk}				
c_{kn}				
c_{rn}				
c_r				
c_k				
c_n				
b_r^+				
b_r^-				$\lesssim 2 \cdot 10^{-3}$
b_k^+	-0.077 ± 0.001	$\lesssim 4 \cdot 10^{-3}$	-0.077 ± 0.001	$\lesssim 4 \cdot 10^{-3}$
b_k^-	-0.076 ± 0.001	$\lesssim 4 \cdot 10^{-3}$	-0.074 ± 0.001	$\lesssim 4 \cdot 10^{-3}$
b_n^+	0.001 ± 0.001	$\lesssim 3 \cdot 10^{-3}$	0.001 ± 0.001	$\lesssim 3 \cdot 10^{-3}$
b_n^-	0.001 ± 0.001	$\lesssim 3 \cdot 10^{-3}$	-0.001 ± 0.001	$\lesssim 3 \cdot 10^{-3}$

tions due
when Z
top (can be
15% with
uts!)

Conclusions

Conclusions

- **Angular analyses are some of the most powerful tools we have in understanding the behaviour of the top quark.**

- **Full Run2 analyses are starting to mature** (song remains the same for many, modelling systematics are intolerably large)**.**

  "What's the point of having a 1% stat uncertainty if you're gonna stick a 20% Parton shower uncertainty on it…" ***Jay, ranting in a pub***

- **Some exciting never-before explored avenues to pursue:**
  - ➡ Interplay with Quantum information field (Entanglement).
  - ➡ Replacing *"the top decays before it can hadronise"* with *"the top almost always decays before it can hadronsie"* (i.e. discovering topponium)
  - ➡ Studying spin in ttZ events.

Backup

Energy Asymmetry

TOPQ-2019-28-002

C (TeV/Λ)^2	A_E (Λ^{-4})		A_E (Λ^{-2})	
	68% CL	95% CL	68% CL	95% CL
C^{11}_{Qq}	[−0.41, 0.47]	[−0.65, 0.67]	[−0.68, 4.06]	[−3.36, 6.16]
C^{18}_{Qq}	[−0.87, 1.24]	[−1.72, 2.10]	[−1.26, 4.76]	[−3.24, 9.64]
C^{1}_{tq}	[−0.43, 0.52]	[−0.69, 0.75]	[−0.60, 5.76]	[−3.42, 9.36]
C^{8}_{tq}	[−1.41, 0.84]	[−2.01, 1.43]	[−1.86, 1.70]	[−3.30, 3.98]
C^{1}_{tu}	[−0.50, 0.56]	[−0.78, 0.81]	[−0.96, 5.82]	[−4.72, 8.88]
C^{8}_{tu}	[−1.00, 1.01]	[−1.71, 1.56]	[−1.30, 2.52]	[−3.02, 4.66]

Spin Correlation and Polarisation

QCD Production

- Dominant production for $t\bar{t}$.
- Parity invariant $\Rightarrow$ no intrinsic polarisation.
- Some degree of spin correlation, depending on sensible choice of reference basis.

EW Production

- Dominant production for single top.
- Violates parity $\Rightarrow$ expect strong polarisation.

Energy Asymmetry

NEW!

TOPQ-2019-28-002