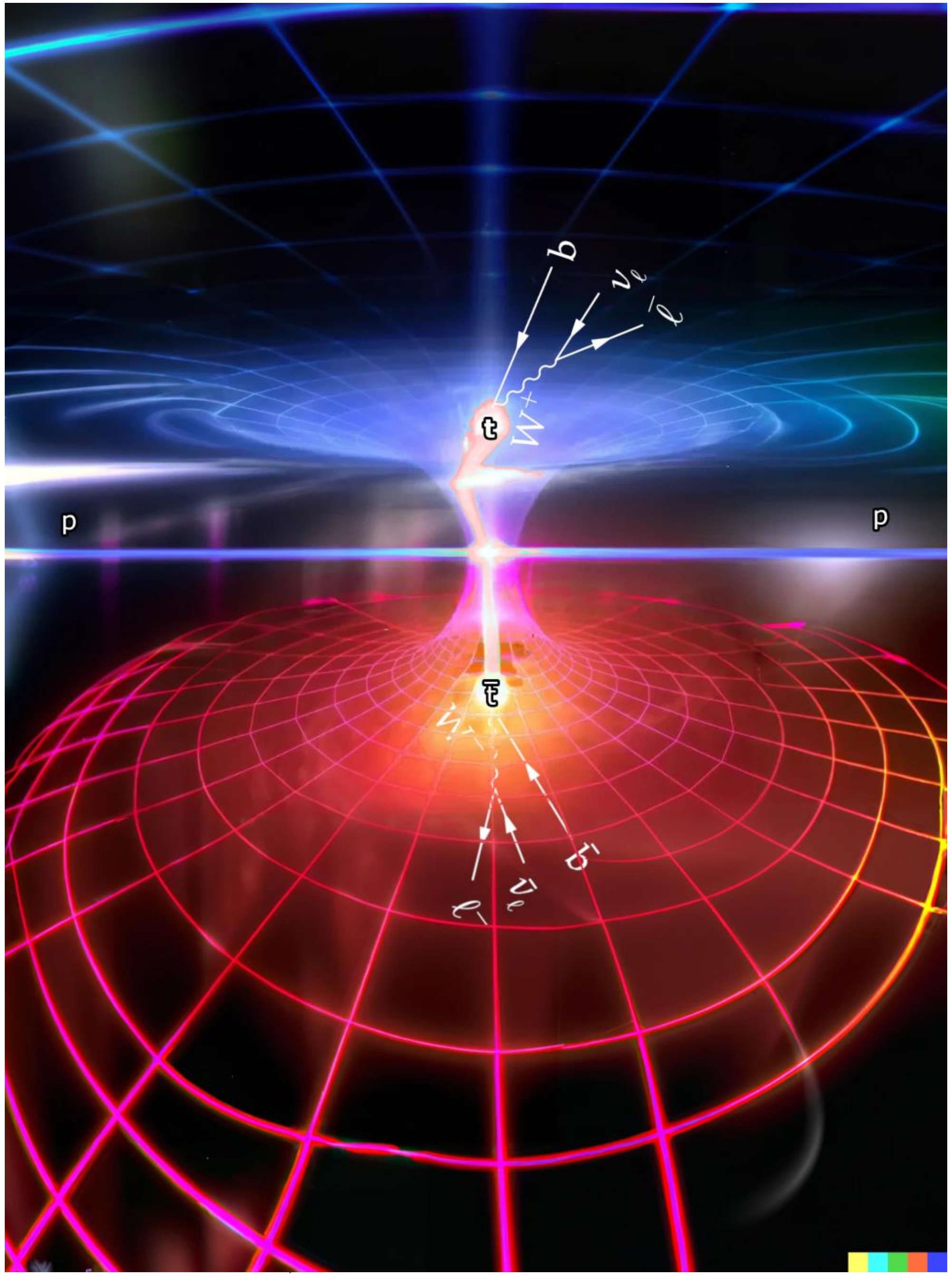


[2406.03976] (accepted to ROPP)

Entanglement of top quarks in the production threshold region at CMS

AJ Wildridge
on behalf of the CMS Collaboration

Quantum Tests in Collider Physics
Merton College, Oxford
October 1, 2024

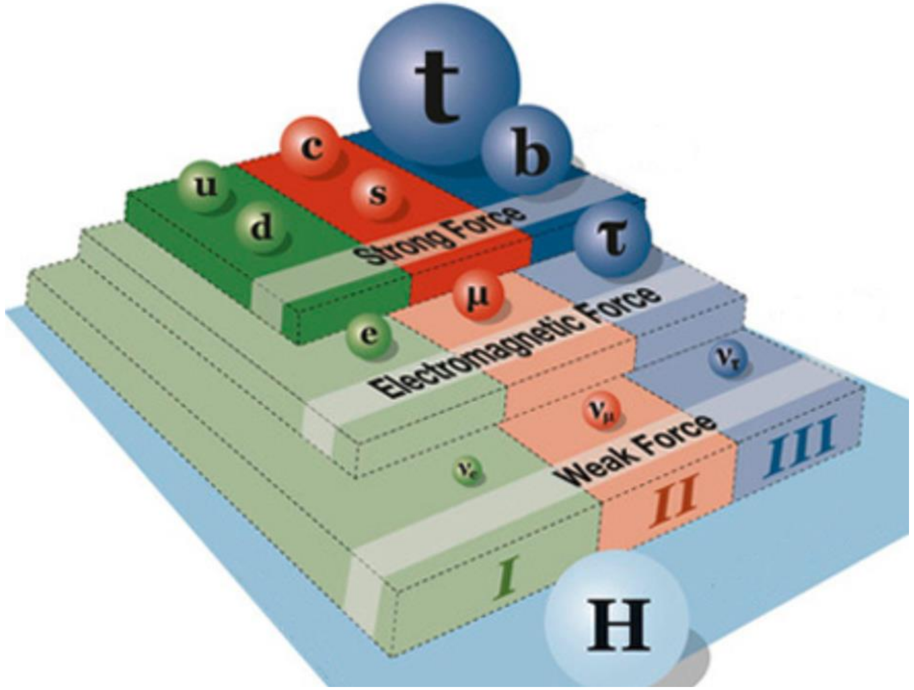

LHCb
ATLAS
CERN Meyrin
CERN Prévessin
SPS 7 km
SUISSE
FRANCE
CMS
ALICE
LHC 27 km

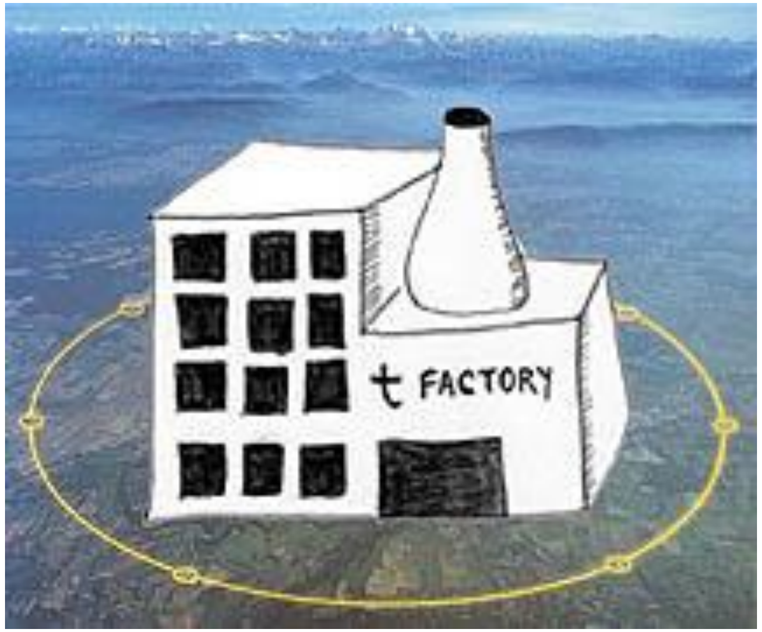
Top Quark Physics

- Top quark is the heaviest fundamental particle discovered thus far: m_t =172.52±0.33 GeV [arXiv:2402.08713]
- Unique:

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

- LHC is a top quark factory (**<u>100m+</u>** thus far)

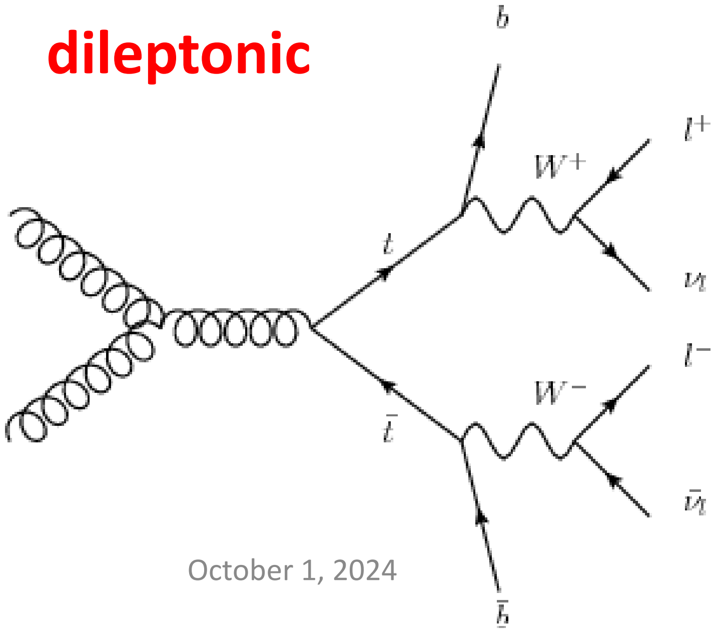




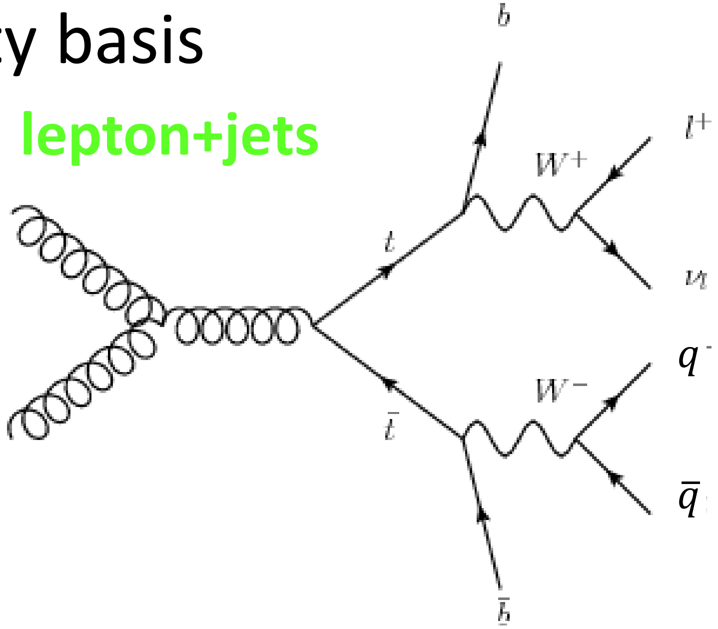
Top Quark Spin Correlations

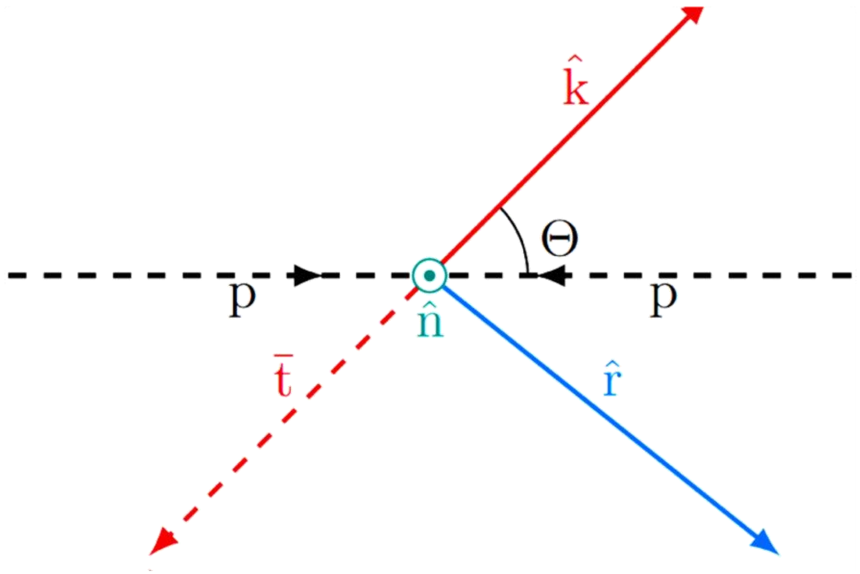
- Spin correlations are dependent on **production mode** ($gg\ vs.\ q\bar{q}$) and higher orbital momenta → function of e.g. $\boldsymbol{\Theta_t}, \boldsymbol{m(t\bar{t})}$
- Top quark spin cannot be measured directly
- Fully preserved in charged leptonic and down-type quark decays of W boson
- Measured in the helicity basis

dileptonic



lepton+jets





[PRD 100 (2019) 072002]

Measurement of Top Quark Spin Density Matrix in dilepton

- Spin density matrix fully captured by a four-fold angular distribution

$$\frac{1}{\sigma}\frac{d^4\sigma}{d\Omega d\bar{\Omega}} = \frac{1}{4\pi^2}\left(1 + \kappa\mathbf{P}\cdot\Omega + \bar{\kappa}\bar{\mathbf{P}}\cdot\bar{\Omega} - \kappa\bar{\kappa}\mathbf{\Omega}\cdot(\mathbb{C}\bar{\mathbf{\Omega}})\right)$$

- Spin Polarization $\mathbf{P}/\bar{\mathbf{P}} = \begin{pmatrix} P_k \\ P_r \\ P_n \end{pmatrix}$ Spin Correlation $\mathbb{C} = \begin{pmatrix} C_{kk} & C_{kr} & C_{kn} \\ C_{rk} & C_{rr} & C_{rn} \\ C_{nk} & C_{nr} & C_{nn} \end{pmatrix}$

- Can integrate above four-fold angular distribution to get 1D distributions for each spin coefficient

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

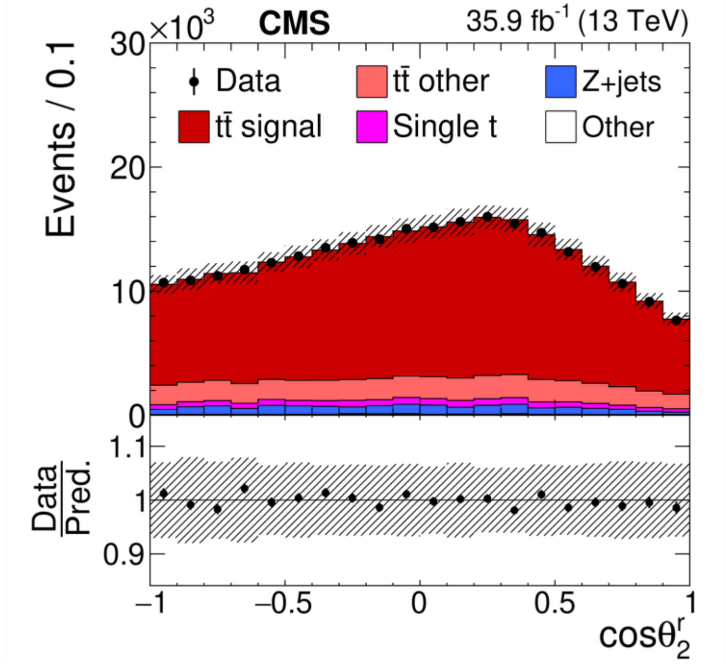
[PRD 100 (2019) 072002]

Measurement of Top Quark Spin Density Matrix in dilepton

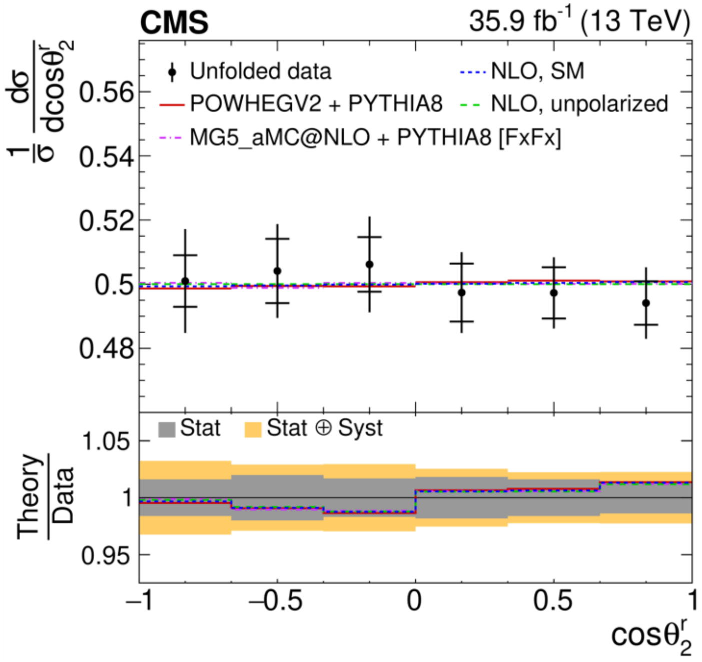
- SM predicts zero polarization for $t\bar{t}$ ($< 10^{-2}$) – QCD is CP even
  - Zero polarization → zero slope at parton level

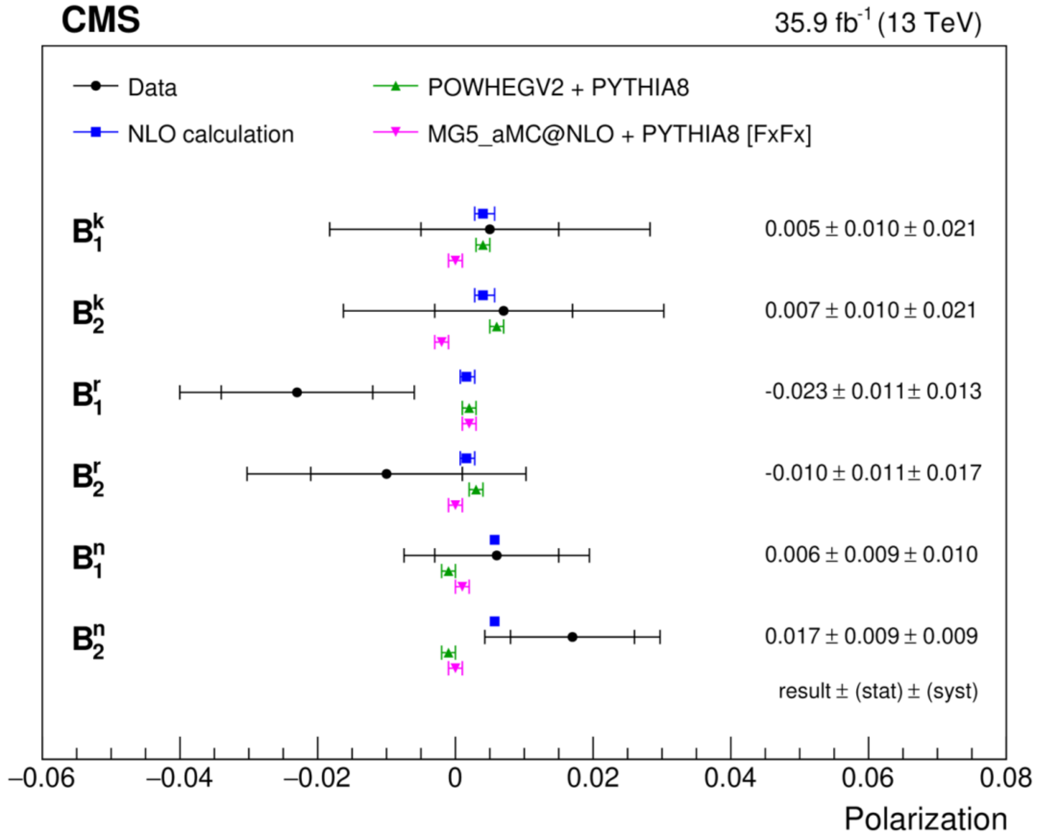
$$\frac{1}{\sigma}\frac{d\sigma}{dcos\theta^{i}_{1/2}} = \frac{1}{2}\left(1 + P_i cos\theta^{i}_{1/2}\right)$$

Reconstruction Level



Parton level





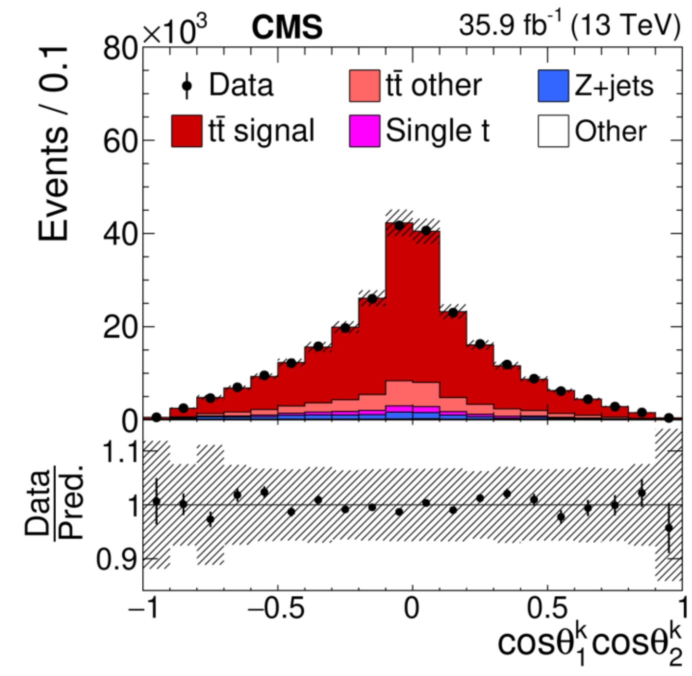
[PRD 100 (2019) 072002]

Measurement of Top Quark Spin Density Matrix in dilepton

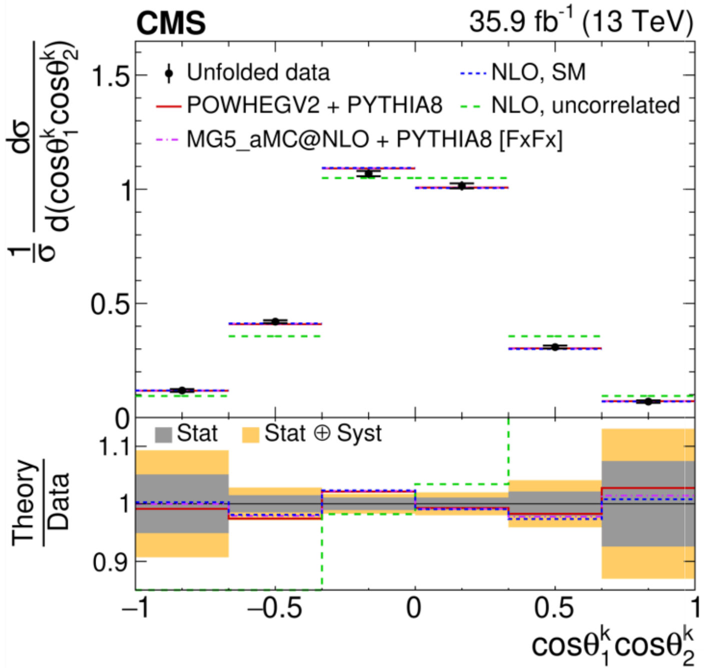
- SM predicts non-zero correlation for $t\bar{t}$
  - Non-zero correlation → asymmetry in $cos\theta_1^i cos\theta_2^j$ distribution at parton level

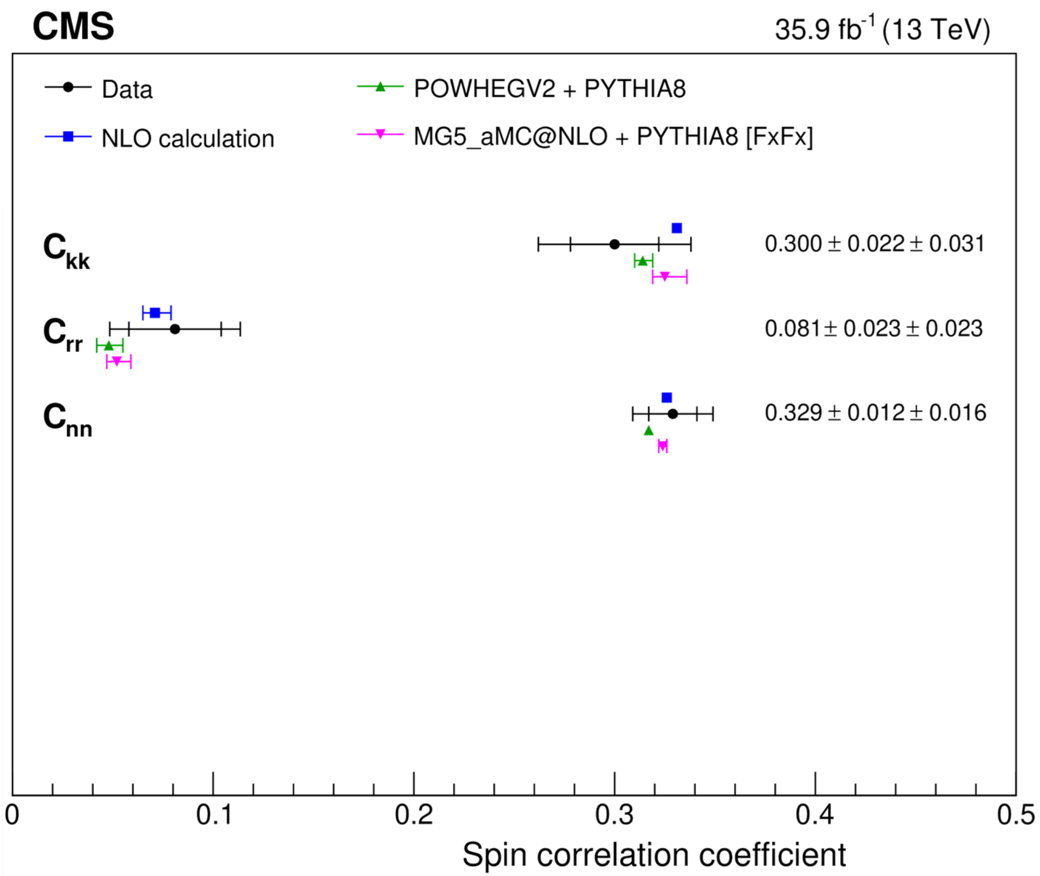
$$\frac{1}{\sigma}\frac{d\sigma}{d\cos\theta_1^i cos\theta_2^j} = \frac{1}{2}\left(1 + C_{ij}\cos\theta_1^i cos\theta_2^j\right)$$

Reconstruction Level



Parton level





How to probe entanglement

- What does it mean to be **<u>not</u>** entangled? **Separable**!

$$|\psi\rangle = |a\rangle_A \otimes |b\rangle_B$$

- For pure states this is easy → measure entanglement entropy

- At the LHC top quarks are produced in a mixed state and thus can be represented as a density operator

$$\rho = \frac{1}{4}\left[I_4 + \Sigma_i\left(B_i^+\sigma^i \otimes I_2 + B_i^- I_2 \otimes \sigma^i\right) + \Sigma_{i,j} C_{ij}\sigma^i \otimes \sigma^j\right]$$

- Need to determine an entanglement witness, Δ
- Hard to show density operator is separable but you can "easily" show it is non-separable → entangled!

Peres, Phys. Rev. Lett. **77**, 1413
Horodecki, Phys. Lett. A **232**, 5

How to probe entanglement: Peres-Horodecki Criterion

- If a state is separable → Unit trace, Hermitian, Eigenvalues ≥ 0
- Therefore, a state is **entangled** if the above conditions **don't** hold for the partial transpose of the spin density matrix, ρ
- A sufficient condition for **entanglement** using Peres-Horodecki Criterion:

$$\Delta = C_{nn} + |C_{kk} + C_{rr}| - 1 > 0$$ [*Eur. Phys. J. Plus* **136**, 907]

At **low** $m(t\bar{t})$

$$C_{kk} > 0 \,\&\, C_{rr} > 0 \rightarrow tr[C] > 1$$

$$D = -\frac{tr[C]}{3} \qquad \frac{1}{\sigma}\frac{d\sigma}{d\,cos\varphi} = \frac{1}{2}(1 - D\,cos\varphi)$$

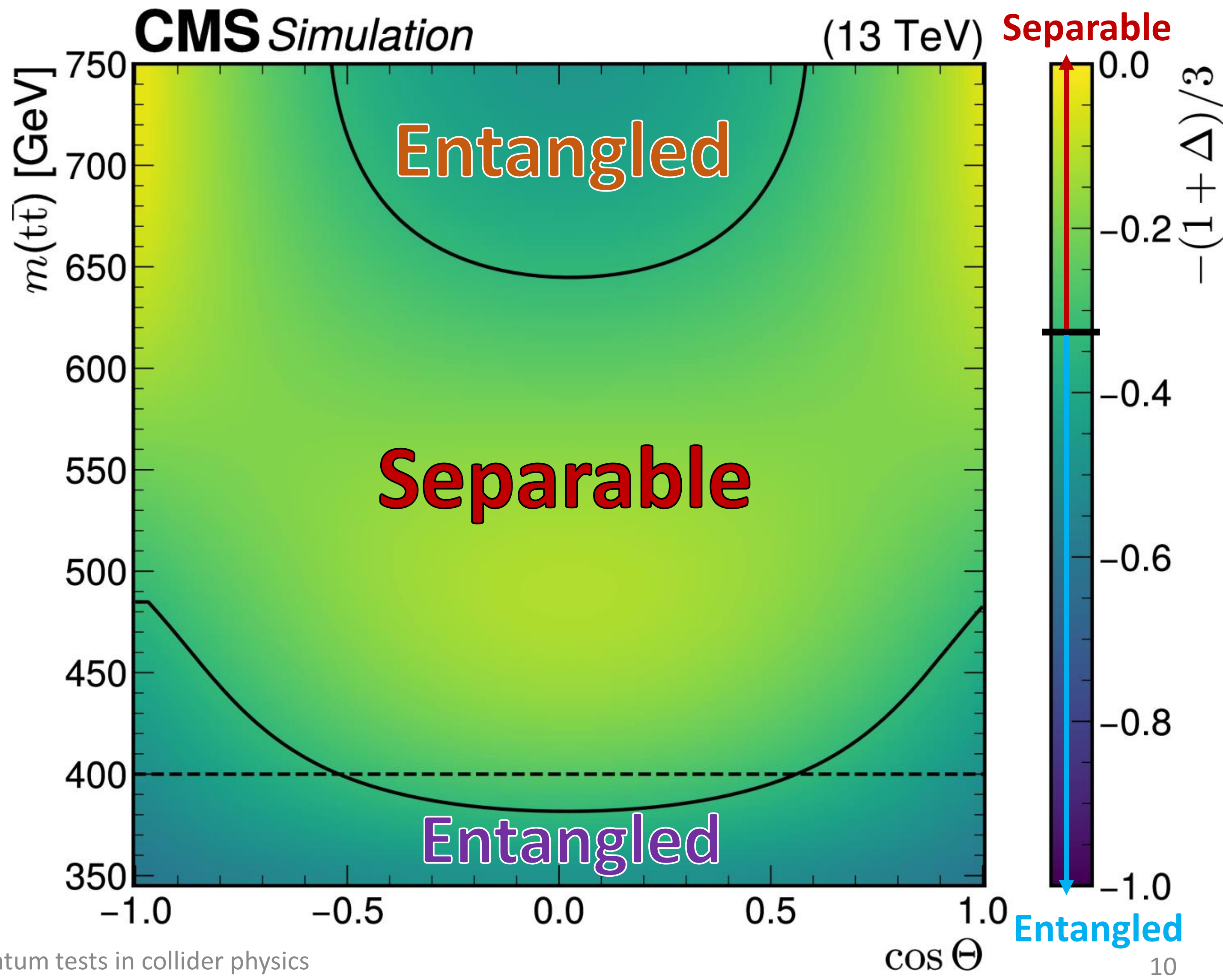
$$D < -\frac{1}{3}$$ →**entangled**!

Measure *D* to access entanglement information!

[2406.03976] (accepted to ROPP)

How to discover entangled top quarks

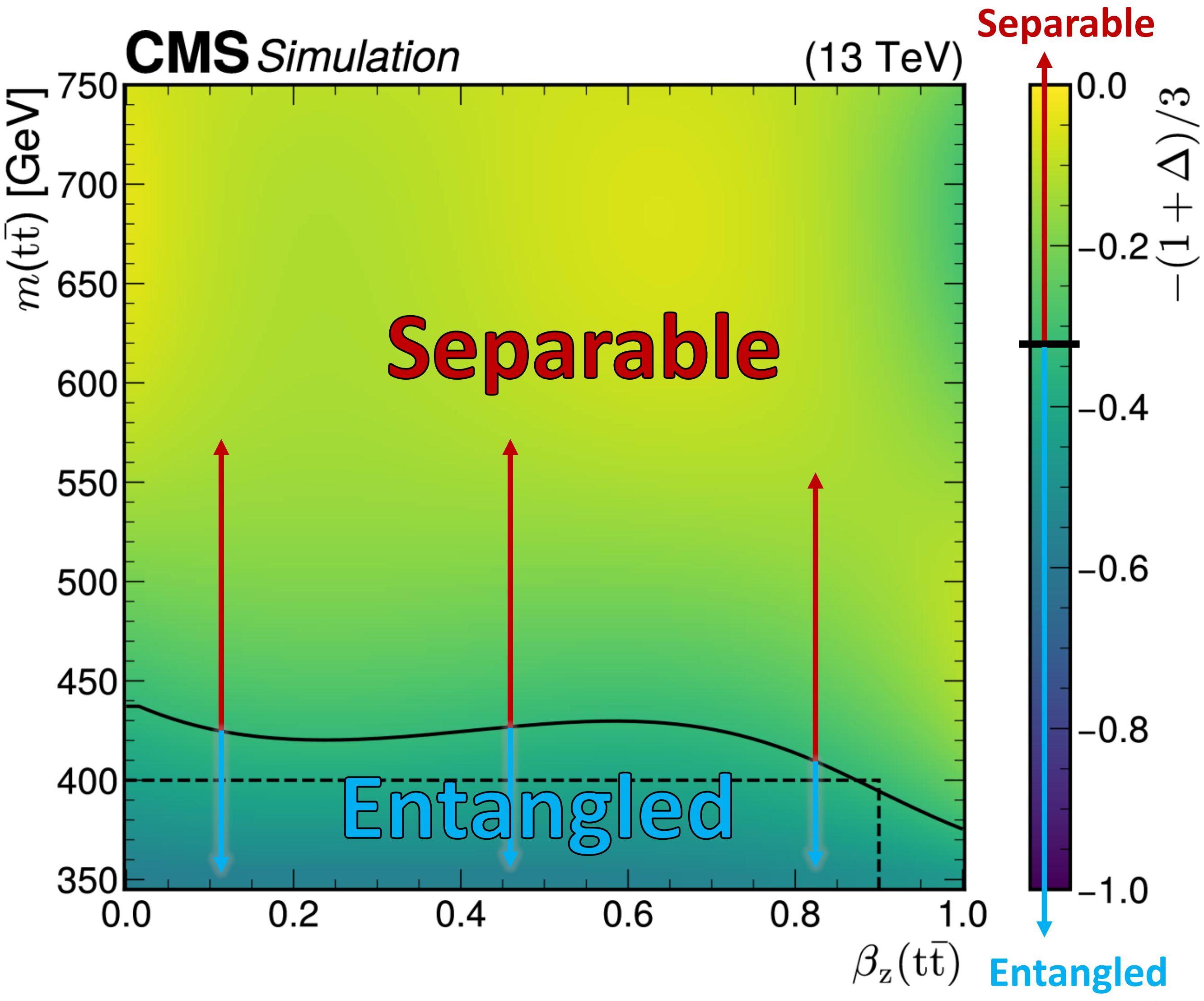
- CMS probed the **production threshold region** for entanglement
- Mostly **timelike** (**spacelike**) separated decays in **production threshold** (**boosted**) region



Measurement of Entanglement in Threshold Region - Method

- Dileptonic channel ($ee/\mu\mu/e\mu$) w/ 2016 data
- Used m_{lb} method for reconstructing both neutrinos
- Measured D using a binned profile likelihood fit of $\cos\varphi$
  - Performed fit in: 345 < $\mathrm{m}(\mathrm{t\bar{t}})$ < 400 GeV & $\beta_z(\mathrm{t\bar{t}}) < 0.9$
- Performed the fit both including & excluding the ground state of **toponium**, η_t

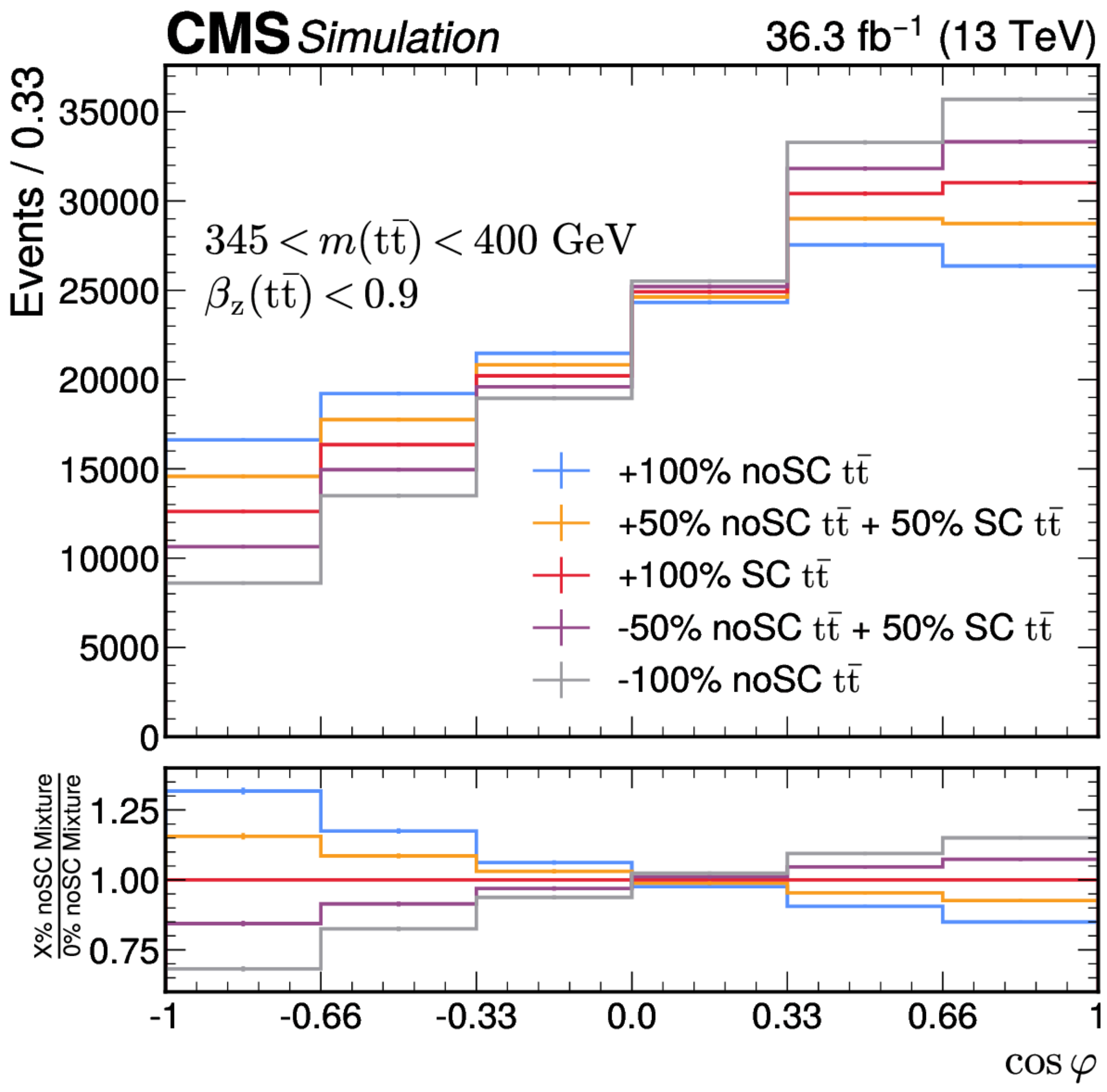
[2406.03976] (accepted to ROPP)



Measurement of Entanglement in Threshold Region - Method

- Need to fit POI D
  - Q: How to create variations of D?
  - A: Generate top quark pairs with zero spin correlation → $\mathrm{D} = 0$
- Can create new samples with mixtures of SM and no spin corr.
- These mixtures only probe $[\mathrm{D}_{\mathrm{SM}}, 0]$→ Mirror to probe $[-1, \mathrm{D}_{\mathrm{SM}}]$

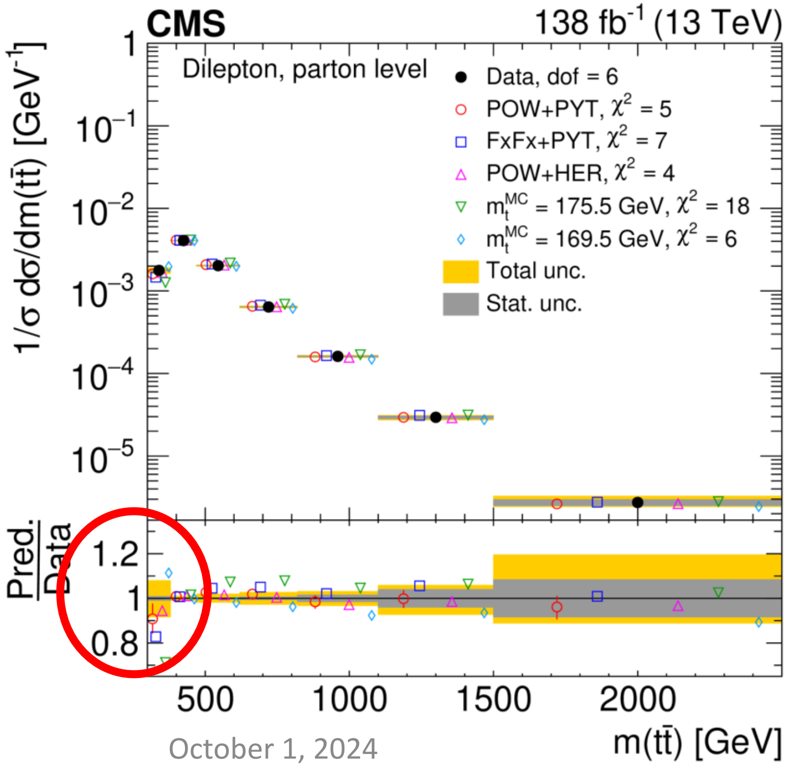
[2406.03976] (accepted to ROPP)



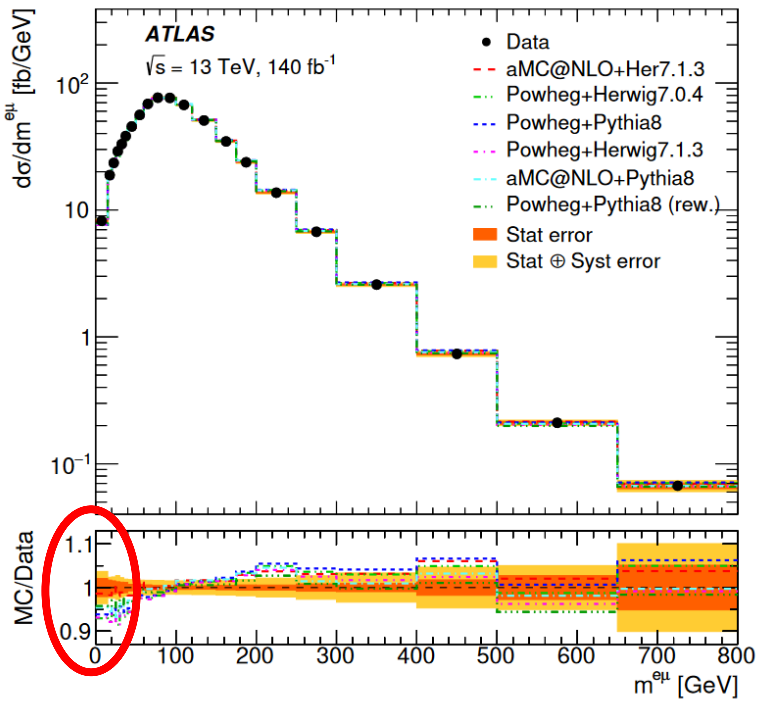
Measurement of Entanglement in Threshold Region

- Large mismodeling seen for $m(t\bar{t}) \approx 345$ GeV
- Consistent between dilepton & lepton+jets and CMS & ATLAS

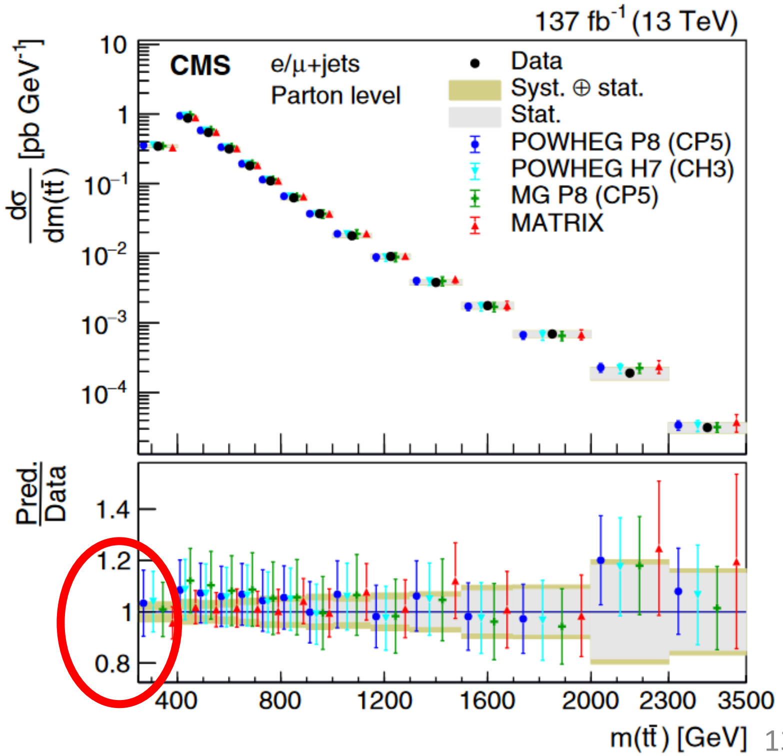
2402.08486 (submitted to JHEP)



JHEP 07 (2023) 141



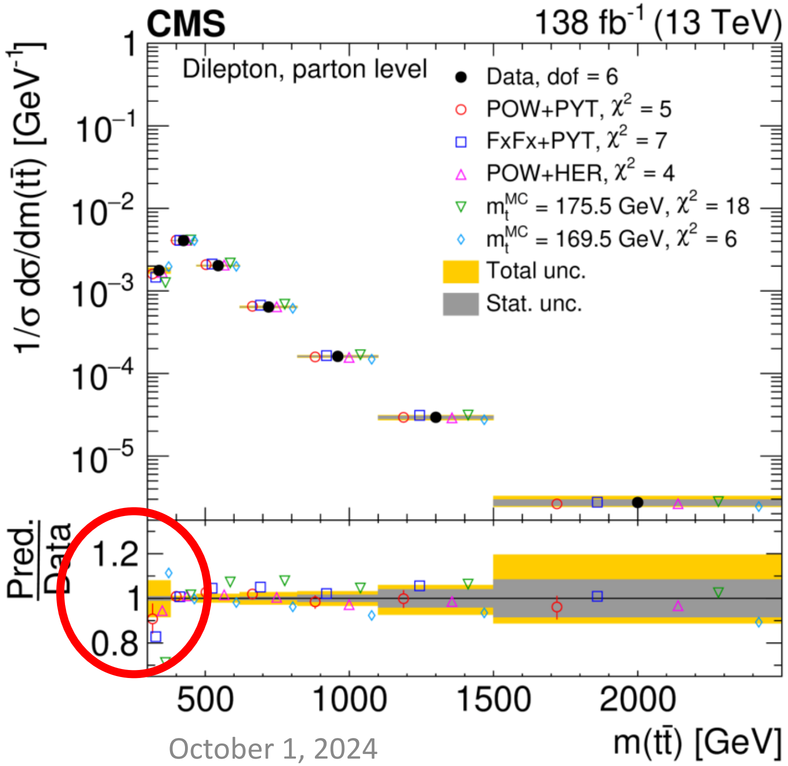
Phys. Rev. D 104, 092013

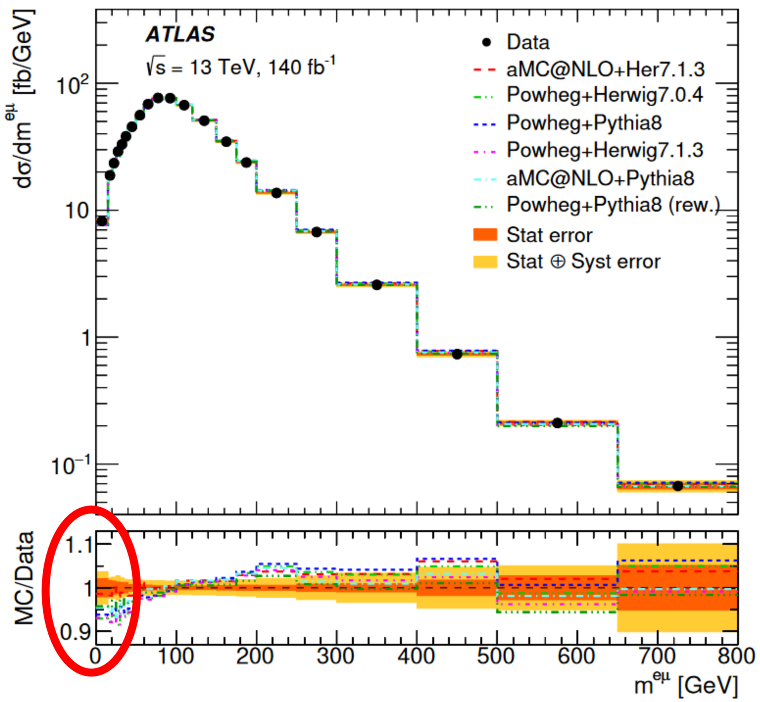


Measurement of Entanglement in Threshold Region

- Large mismodeling seen for $m_{t\bar{t}} \approx 345$ GeV
- Excesses seen could be from **toponium**
- New (hypothetical) exciting SM resonance
  - Spin singlet→ Maximally **entangled** $t\bar{t}$
  - Exciting implications for **entanglement** measurements!
- Signal model includes spin and color singlet $^1S_0^{[1]}$

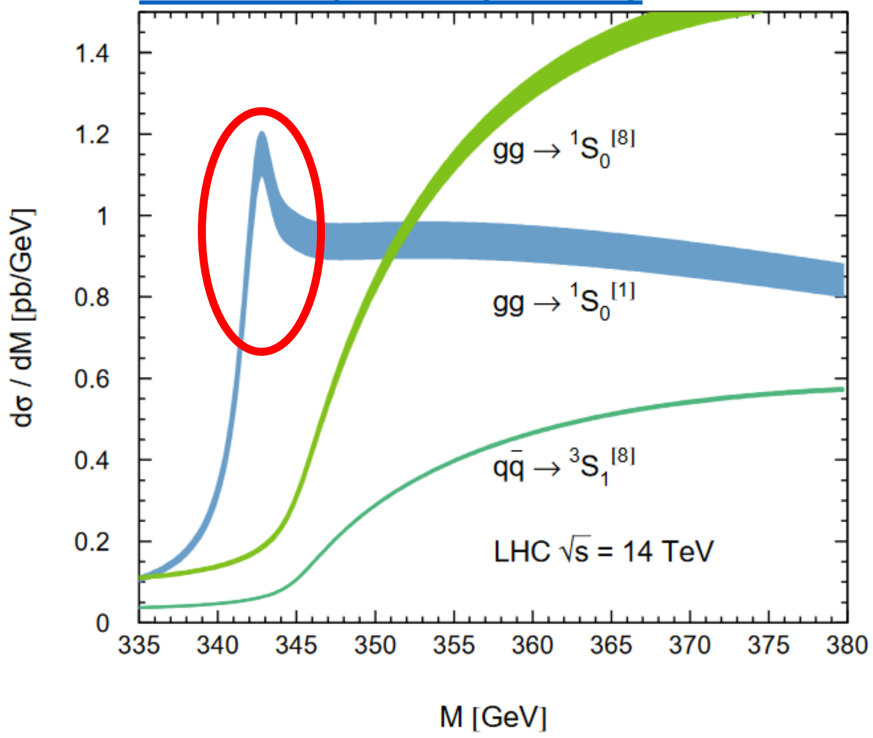
2402.08486 (submitted to JHEP) JHEP 07 (2023) 141





- Theory predictions with NRQCD
- Color **singlet** and **octet** contributions to spin singlet

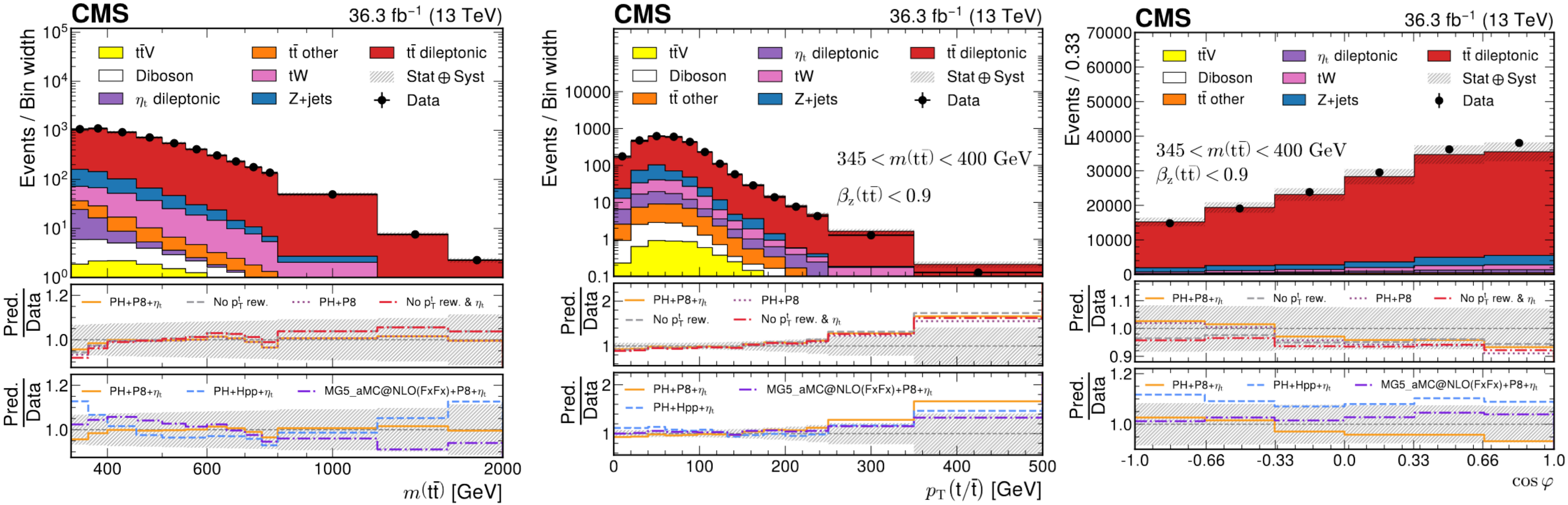
EPJC 60, 375 (2009)



Pre-fit Distributions

[2406.03976] (accepted to ROPP)

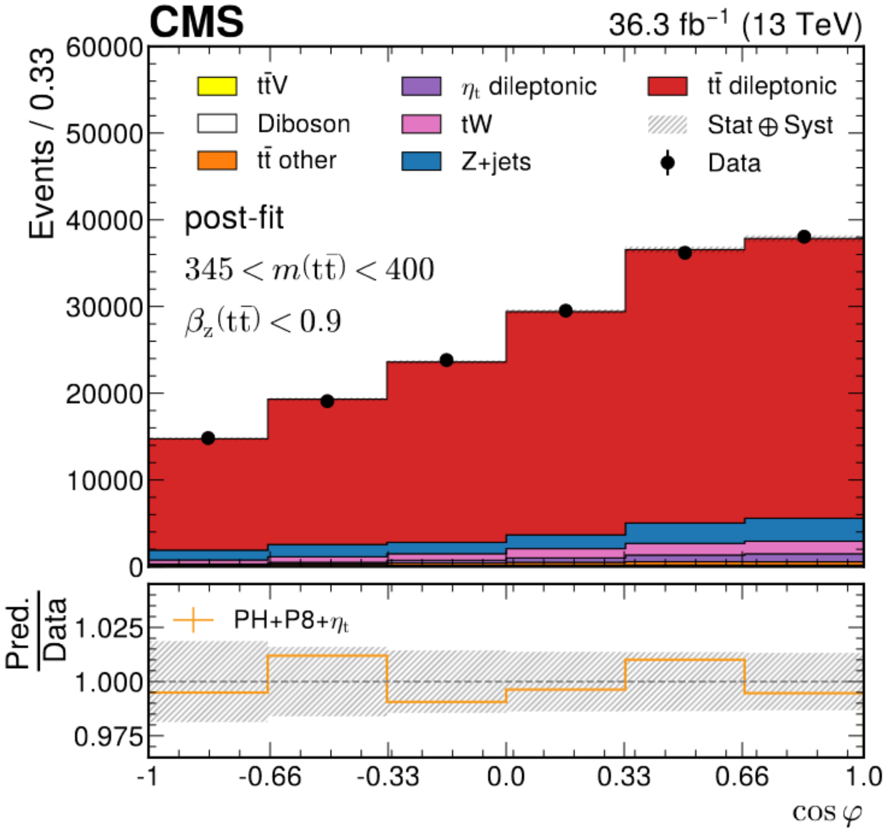
- Better agreement when including η_t
- MadGraph5 aMC@NLO+Pythia8 describes the $\cos\varphi$ distribution better near production threshold

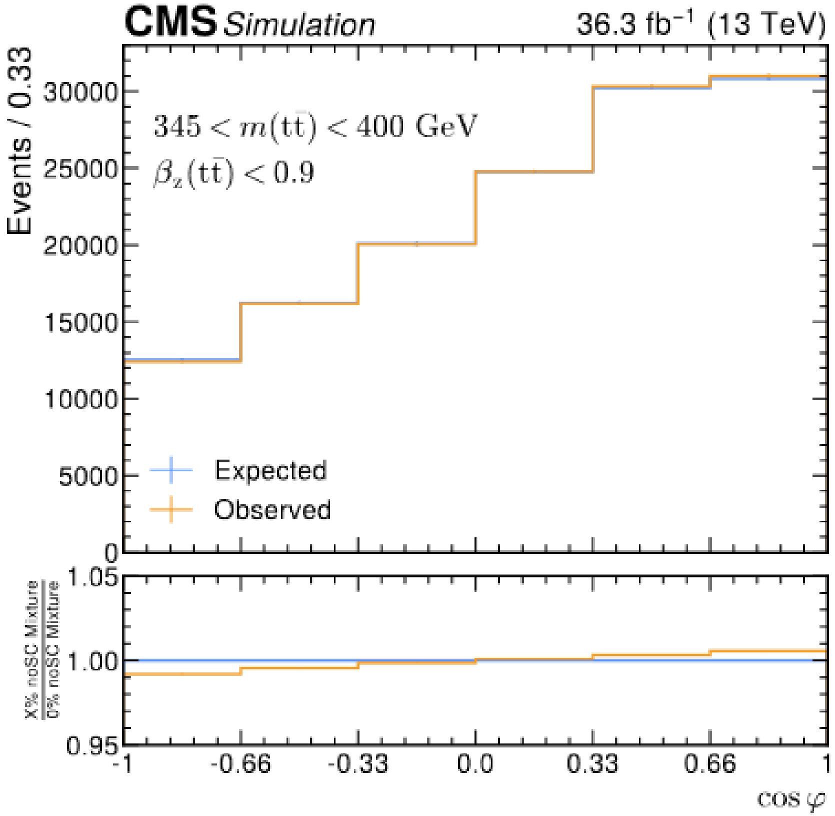


Post-fit Distribution

[2406.03976] (accepted to ROPP)

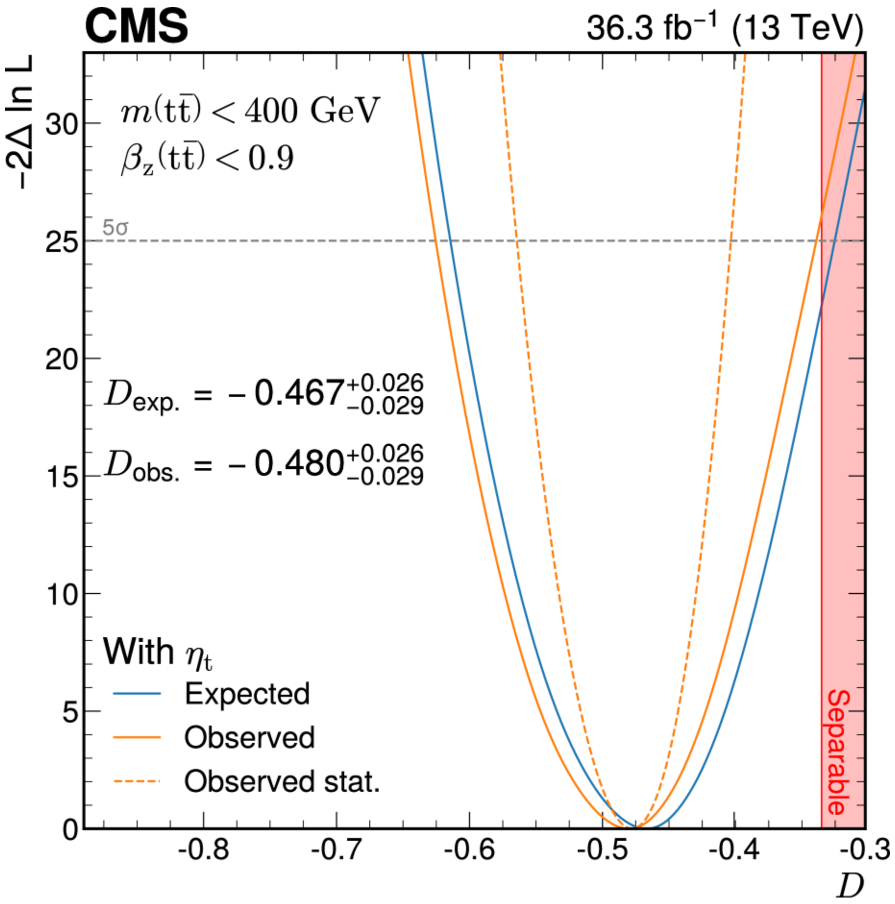
- Good agreement within uncertainties
- Post-fit value of 2.53% more spin correlated $t\bar{t}$ contribution

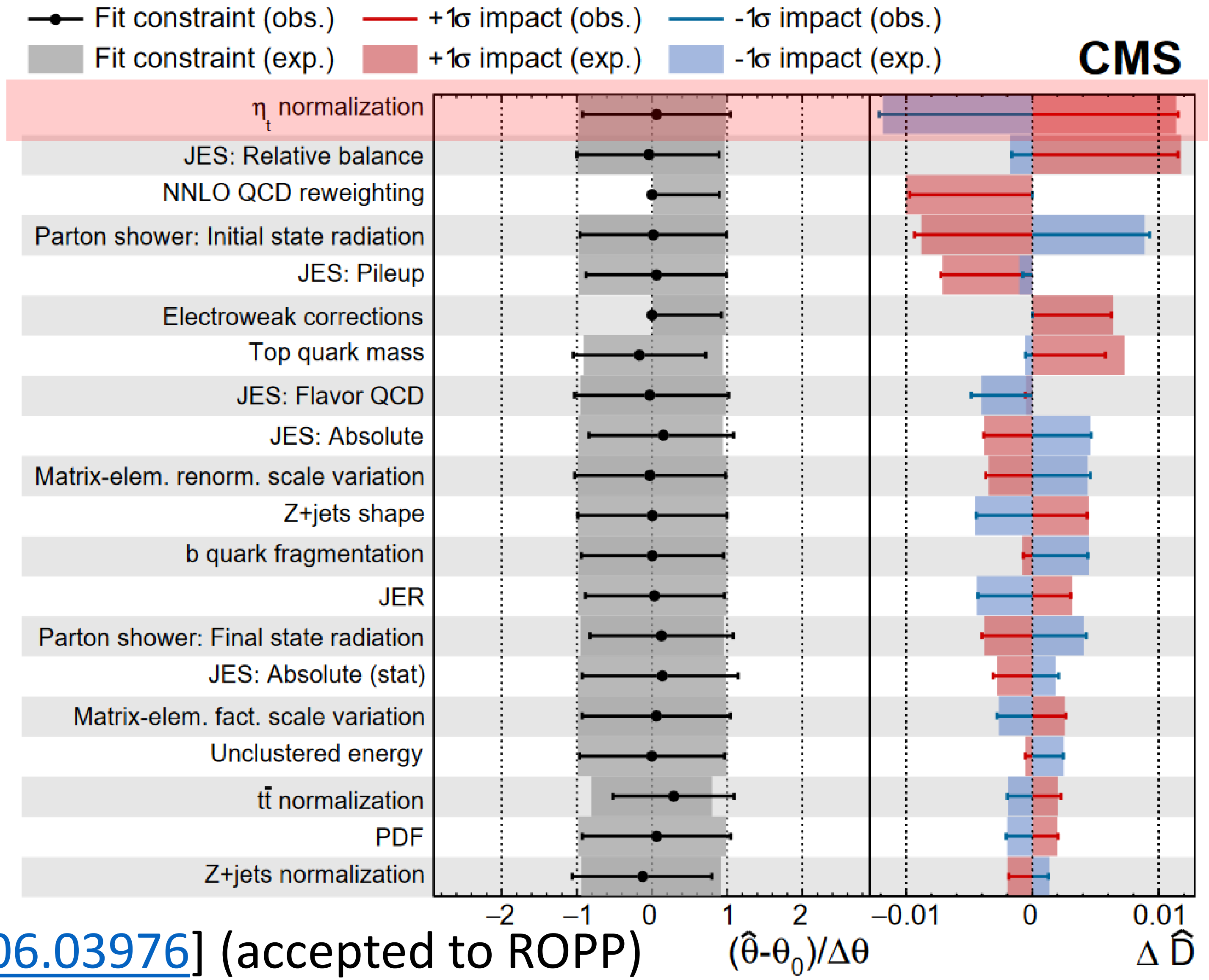




Measurement of Entanglement in Threshold Region - Results

- Significance $> 5\sigma$
- Observation of **entangled top quarks**!



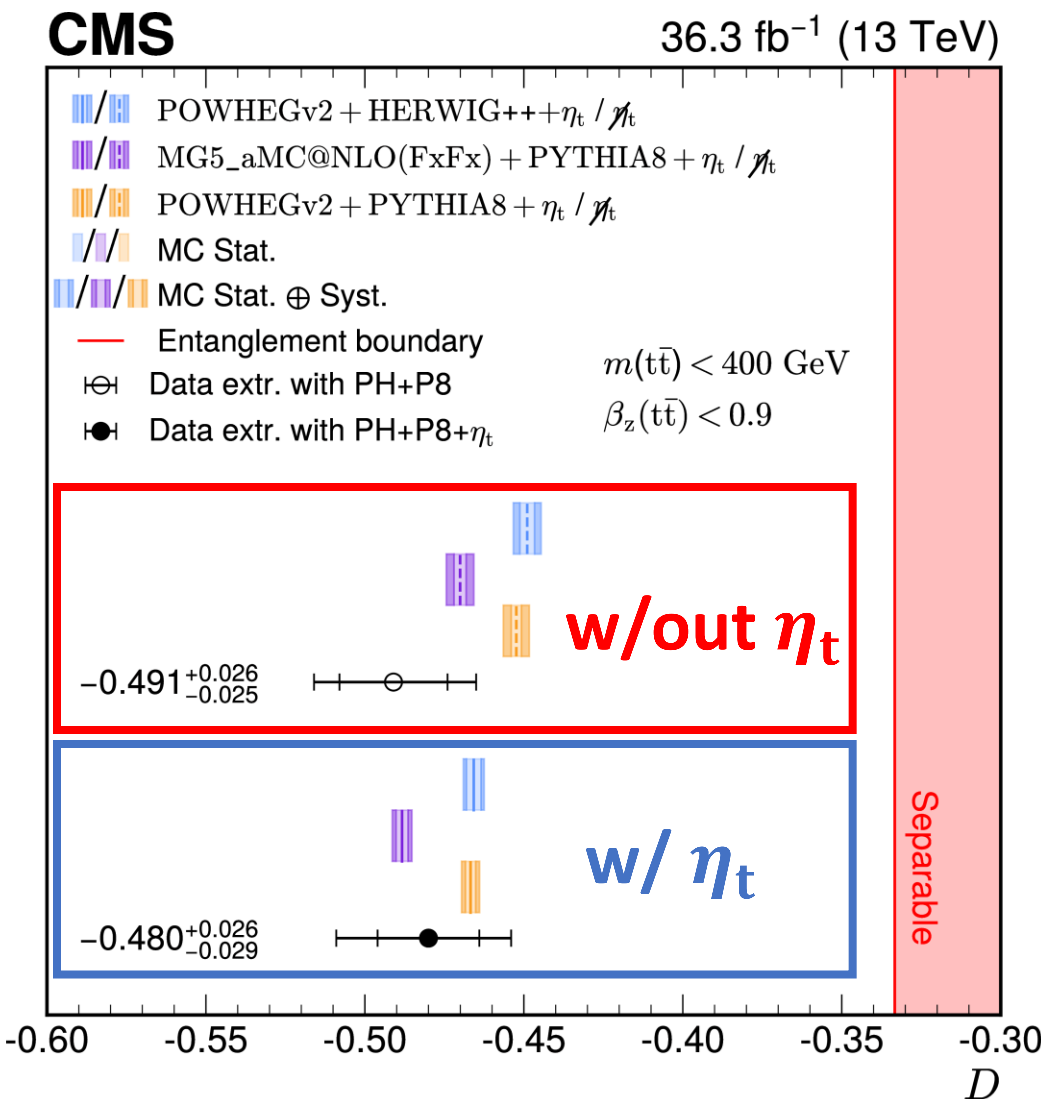


[2406.03976] (accepted to ROPP)

Conclusion

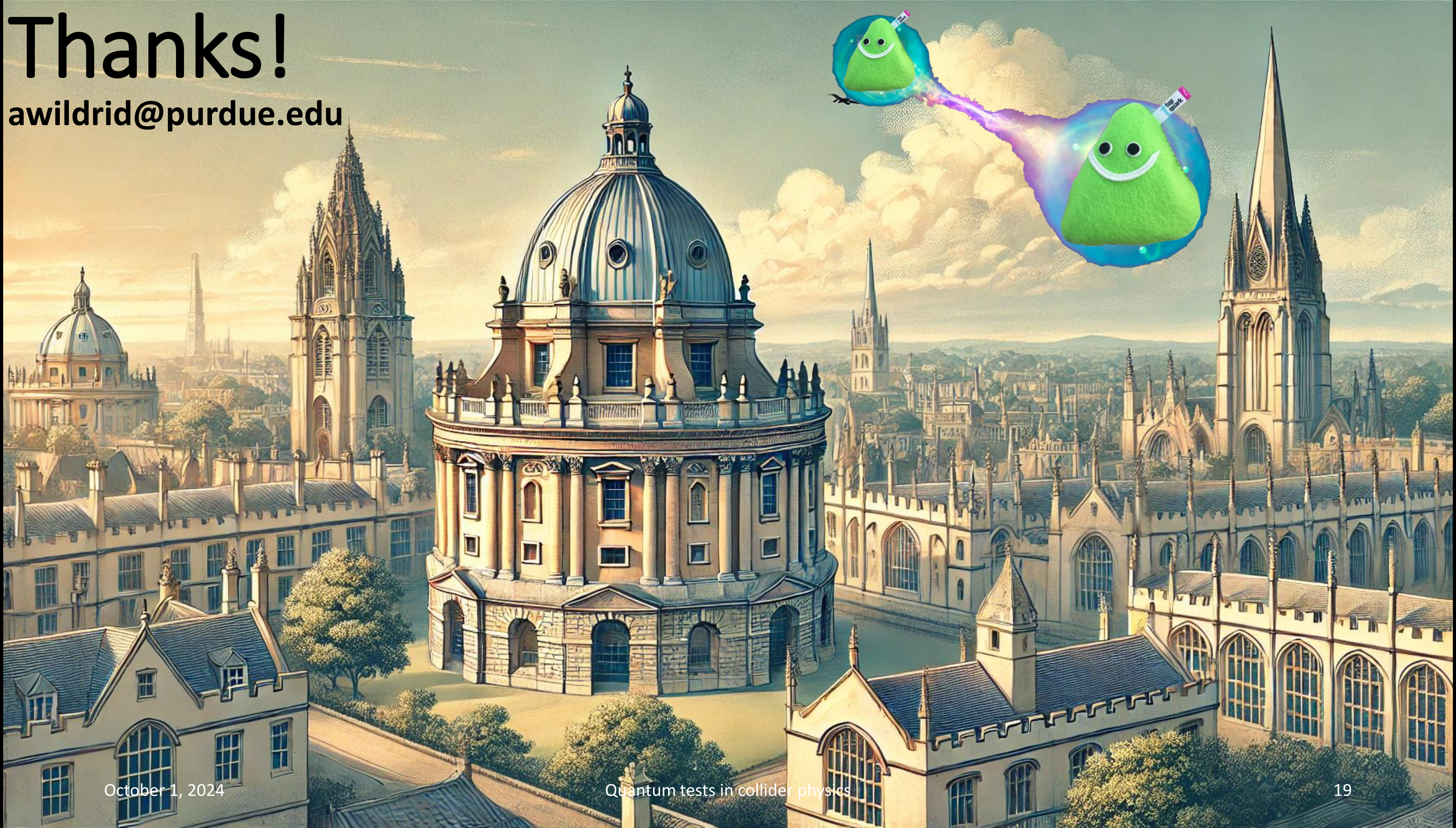
- Top quarks are **entangled**
- First inclusion of bound-state effects in the production threshold region via η_t
- Start of quantum information studies in high energy physics at the LHC
- New door into "old" physics

[2406.03976] (accepted to ROPP)



Thanks!

awildrid@purdue.edu



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

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

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

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

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

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