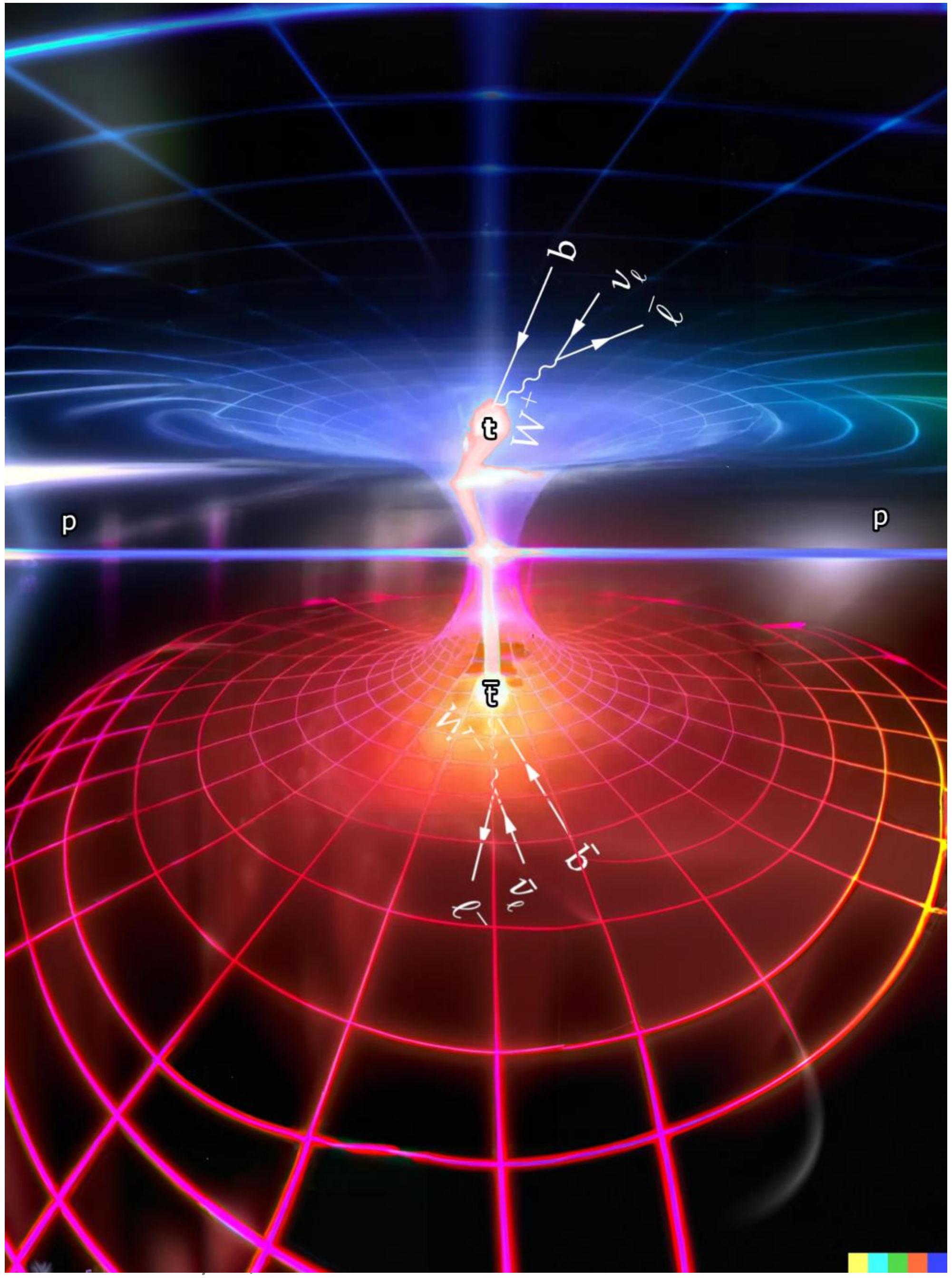


[2406.03976] (submitted to ROPP)
[CMS-PAS-TOP-23-007]

Measurement of the polarization, spin correlation, and entanglement between top quark pairs

AJ Wildridge
on behalf of the CMS Collaboration

ICHEP24

July 20, 2024

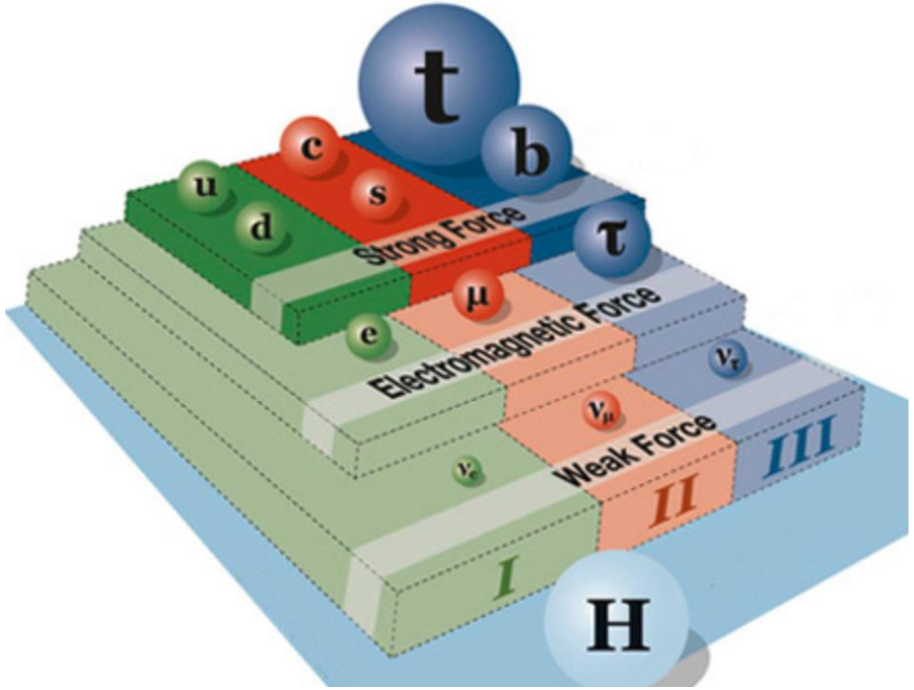
Top Quark Physics

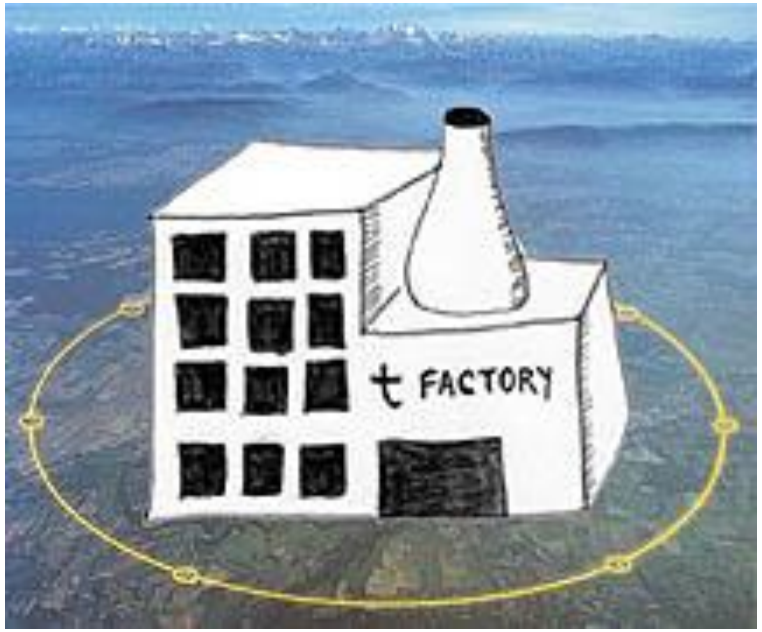
- Top quark is the heaviest fundamental particle discovered thus far: m_t =172.52±0.33 GeV
- Unique:

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

[arXiv:2402.08713]

- LHC is a top quark factory (**100m+** thus far)

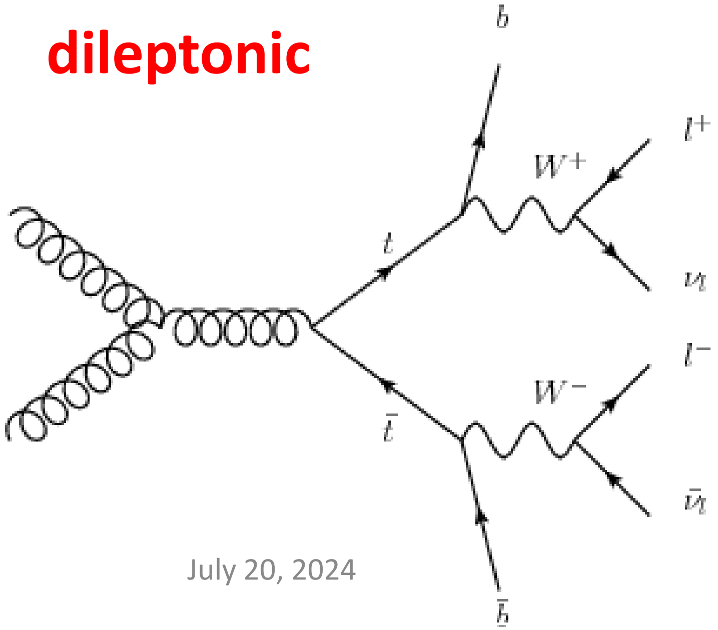




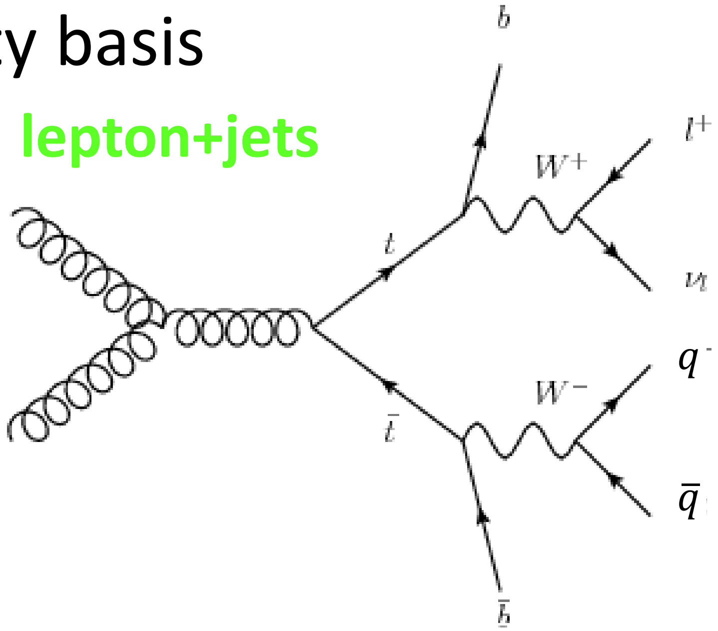
Top Quark Spin Correlations

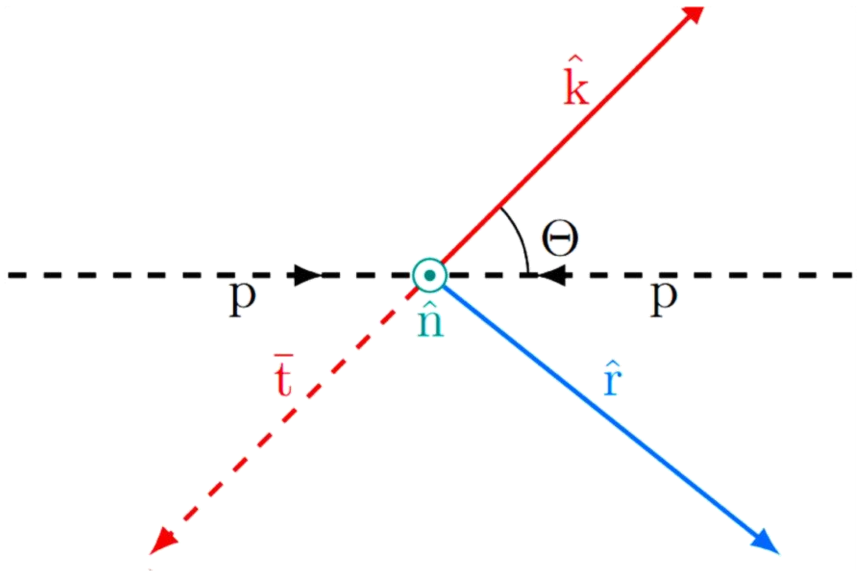
- Spin correlations are dependent on **production mode** ($gg\ vs.\ q\bar{q}$) and higher orbital momenta → function of e.g. $\boldsymbol{\Theta_t}, \boldsymbol{m(t\bar{t})}$
- Top quark spin cannot be measured directly
- Fully preserved in charged leptonic and down-type quark decays of W boson
- Measured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

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

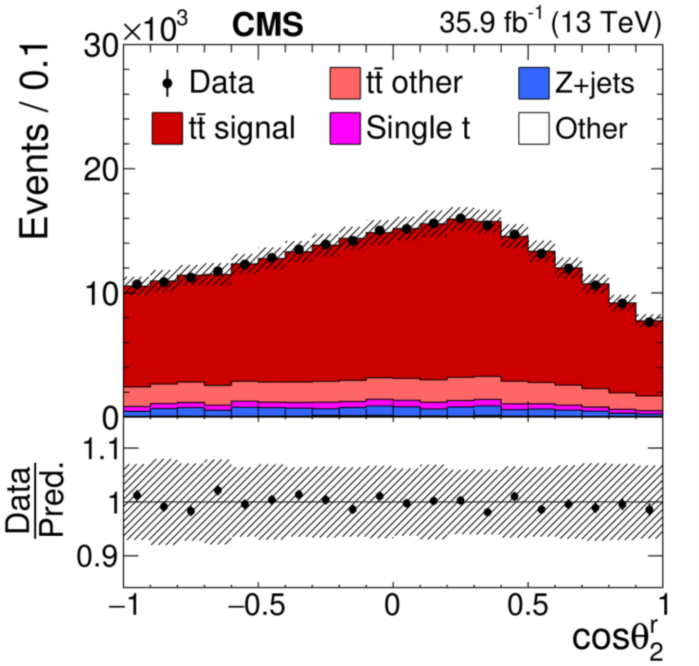
[PRD 100 (2019) 072002]

Measurement of Top Quark Spin Density Matrix in dilepton

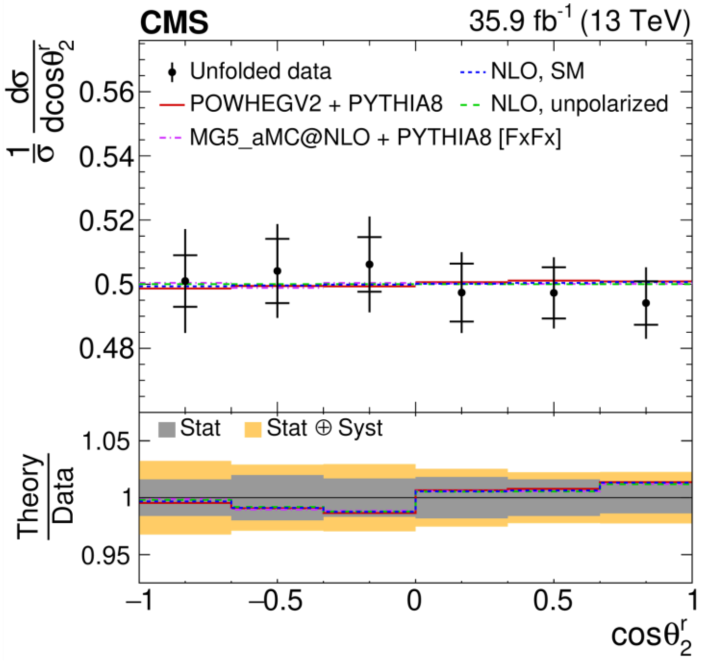
- SM predicts zero polarization for $t\bar{t}$ ($< 10^{-2}$) – QCD is CP even
  - Zero polarization → zero slope at parton level

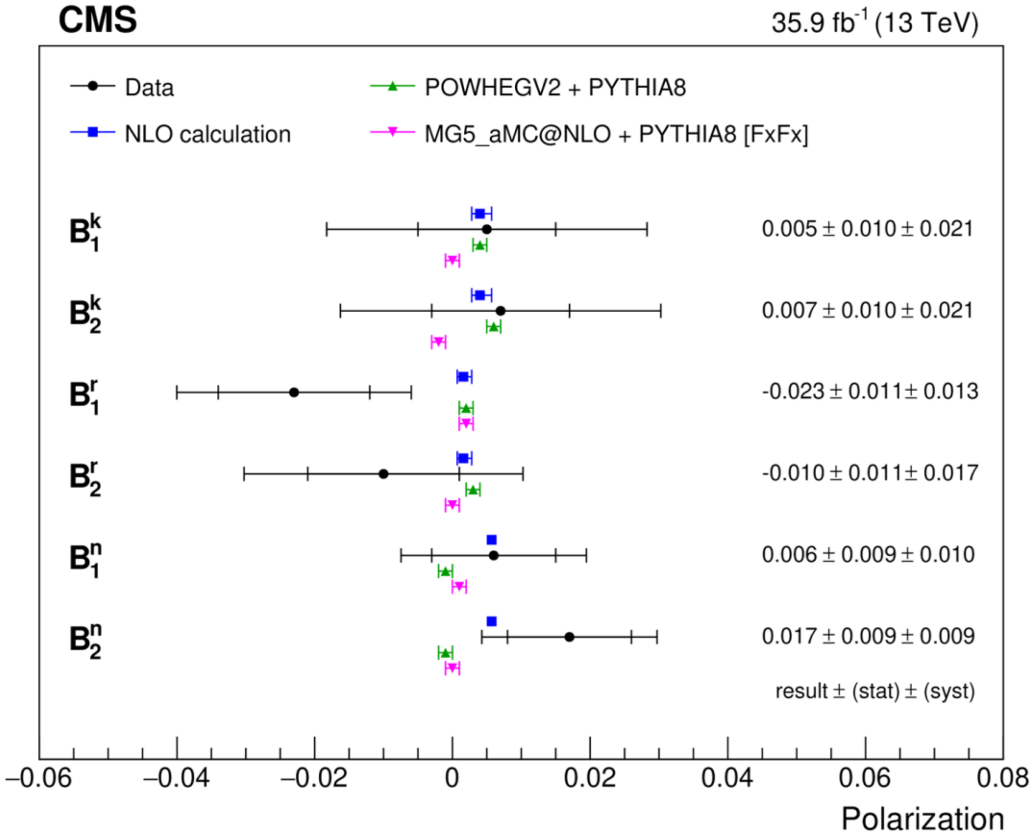
$$\frac{1}{\sigma}\frac{d\sigma}{d\cos\theta^{i}_{1/2}} = \frac{1}{2}\left(1 + P_i \cos\theta^{i}_{1/2}\right)$$

Reconstruction Level



Parton level





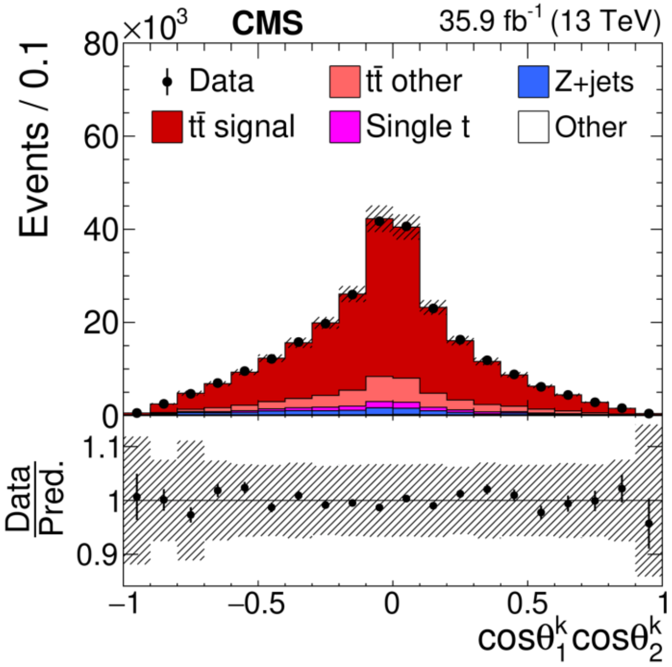
[PRD 100 (2019) 072002]

Measurement of Top Quark Spin Density Matrix in dilepton

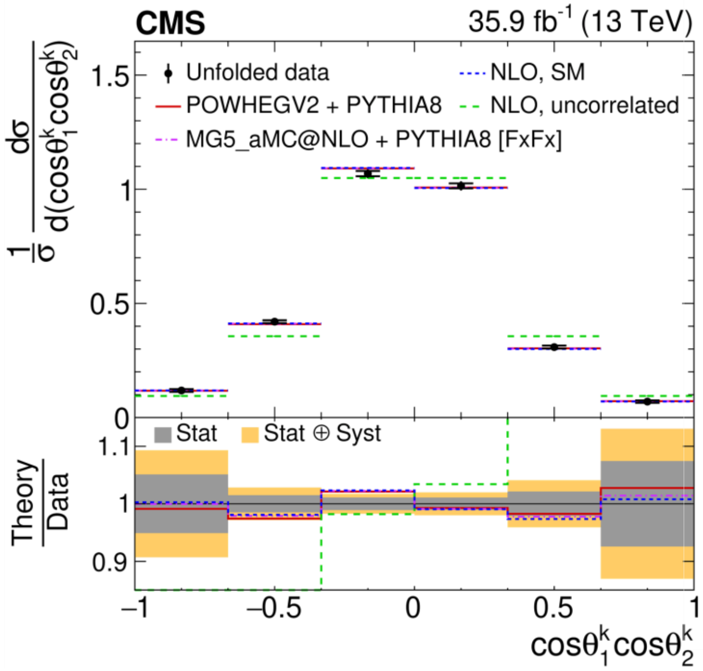
- SM predicts non-zero correlation for $t\bar{t}$
  - Non-zero correlation → asymmetry in $cos\theta_1^i cos\theta_2^j$ distribution at parton level

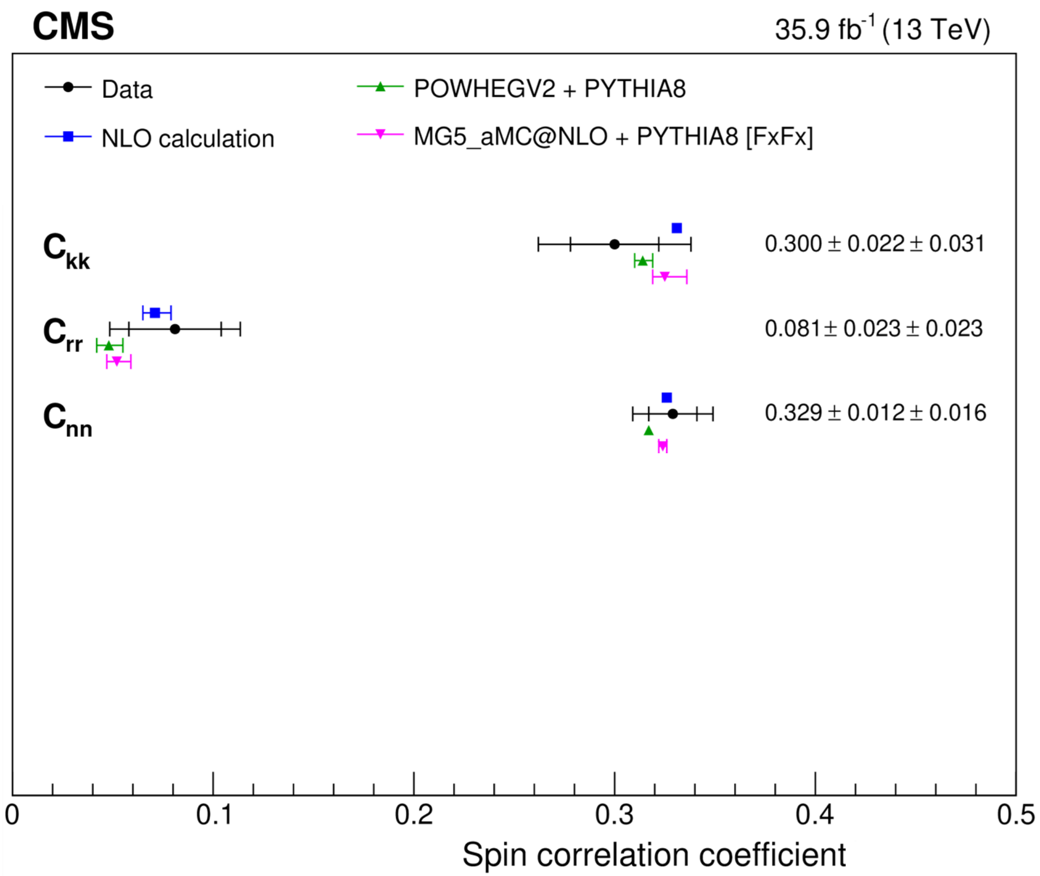
$$\frac{1}{\sigma}\frac{d\sigma}{d\cos\theta_1^i cos\theta_2^j} = \frac{1}{2}\left(1 + C_{ij}\cos\theta_1^i cos\theta_2^j\right)$$

Reconstruction Level



Parton level

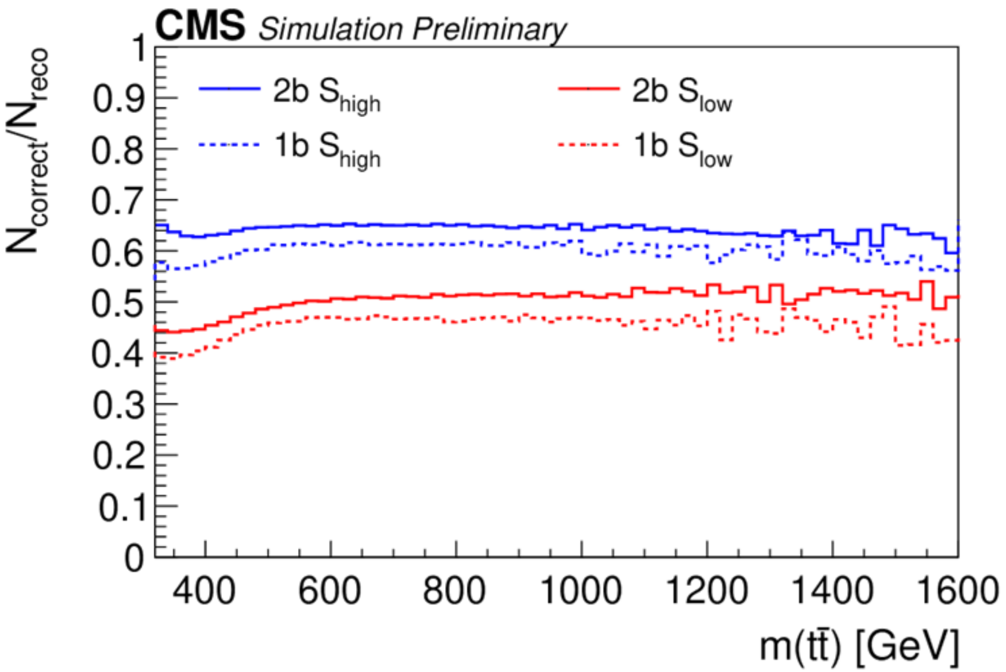


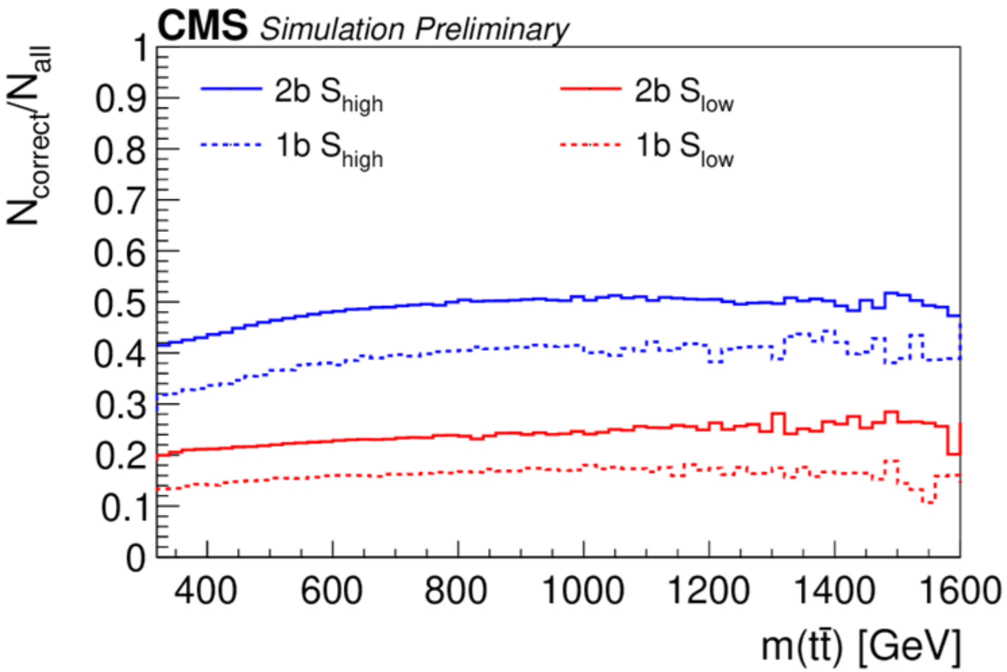


Measurement of Top Quark Spin Density Matrix in lepton+jets - Method

[CMS-PAS-TOP-23-007]

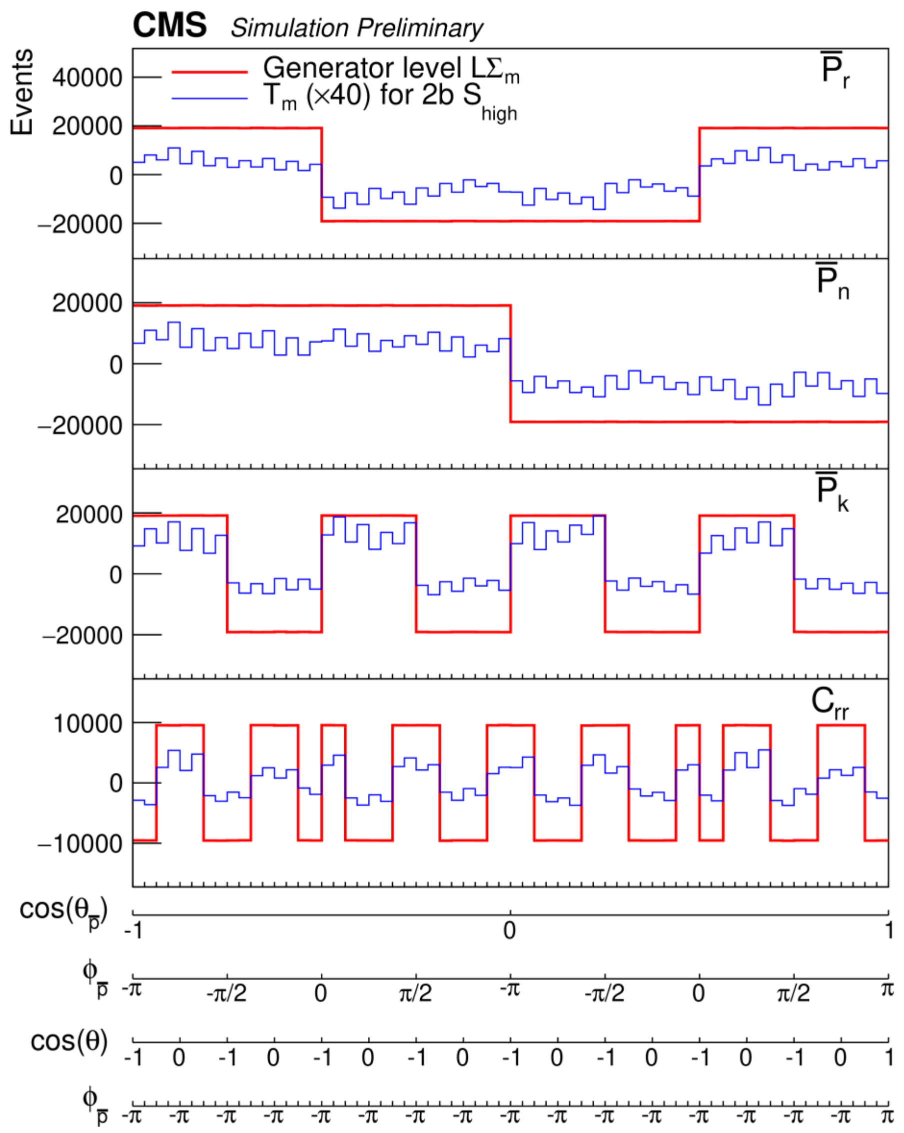
- Used e/μ+jets events with full Run II dataset
- Used DNN to perform jet-parton assignments
- W mass constraint to reconstruct neutrino
- Measured all 15 spin coefficients – **quantum state tomography**
    - Used four-fold angular distribution of decay products $\Sigma_{tot} = \frac{d^4\sigma}{d\Omega d\bar{\Omega}}$





Measurement of Top Quark Spin Density Matrix in lepton+jets - Method

- Binned profile likelihood fit of Σ_{tot}
  - Σ_{tot} = linearly dependent on 15 spin coefficients
  - Reweighting Σ_m gives templates T_m with varied coefficients Q_m



generator-level

$$\Sigma_{tot} = \Sigma_0 + \Sigma_{m=1}^{15} Q_m \Sigma_m$$

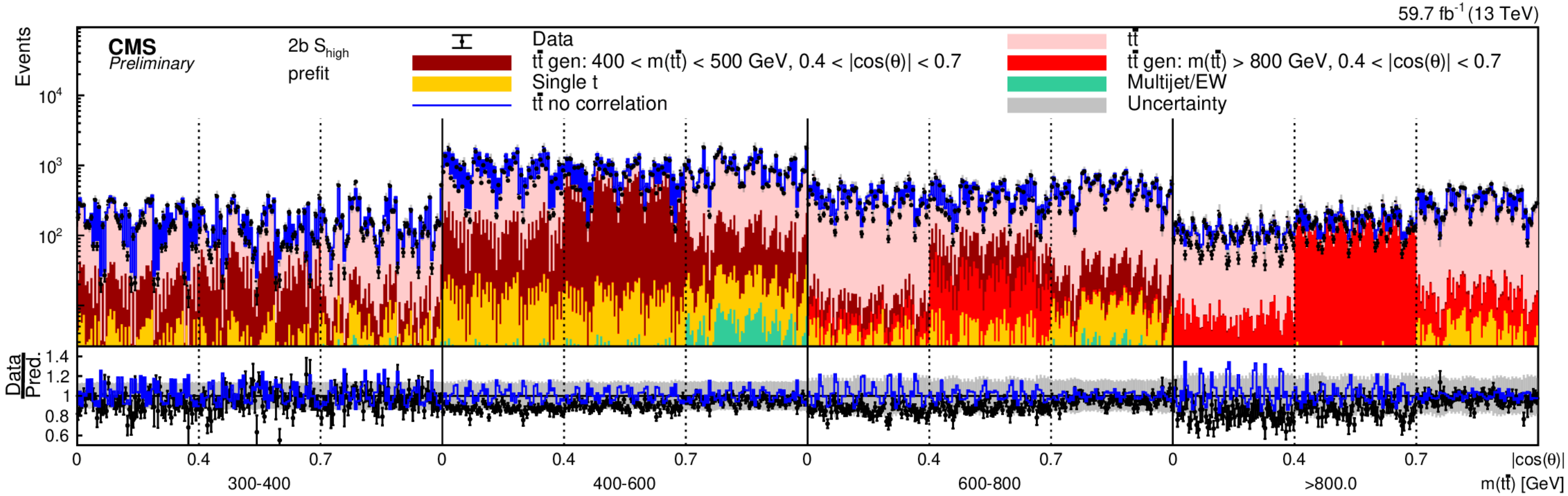
$$S_{ijn} = a_n(T_{ij0n}(\{v_k\}) + \Sigma_{m=1}^{15} Q_{mn} T_{ijmn}(\{v_k\}))$$

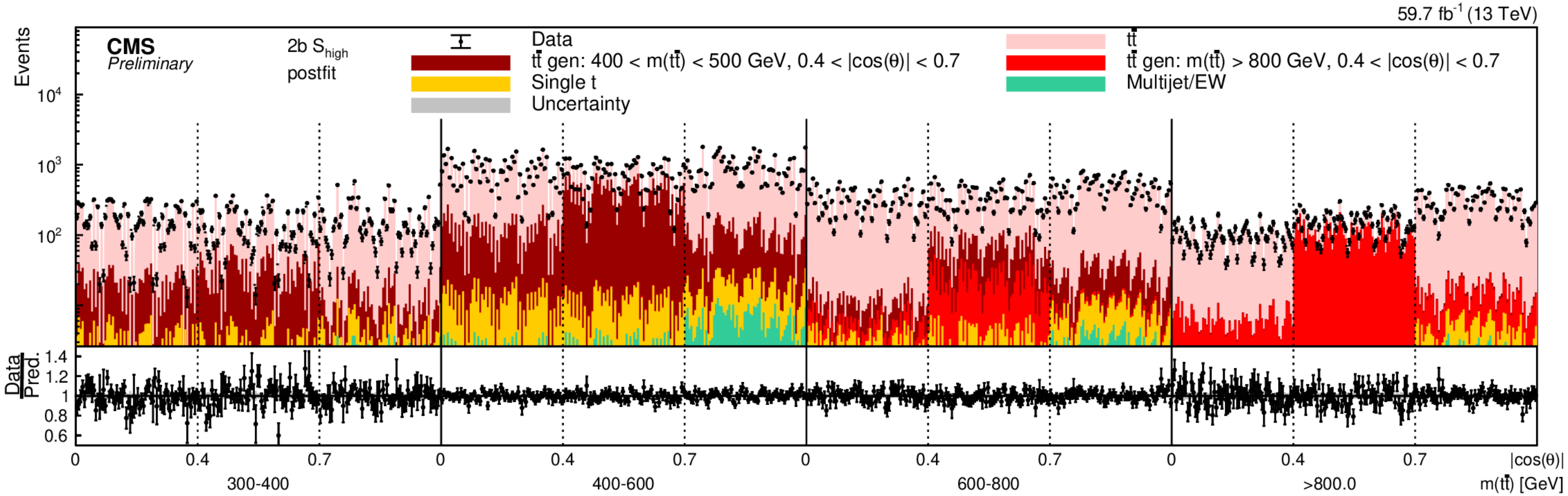
detector-level

[CMS-PAS-TOP-23-007]

Measurement of Top Quark Spin Density Matrix in lepton+jets - Method

[CMS-PAS-TOP-23-007]





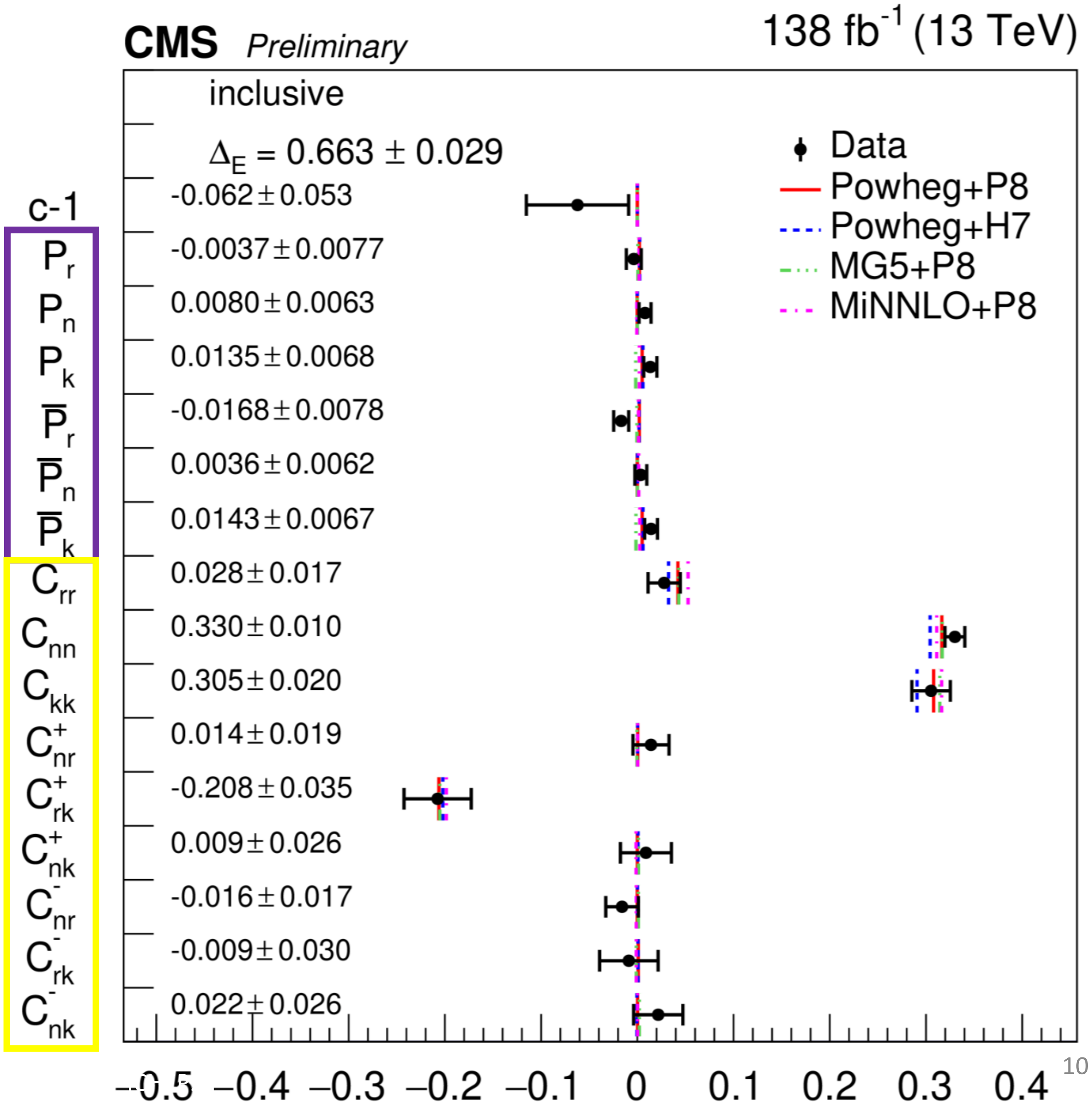
[CMS-PAS-TOP-23-007]

Measurement of Top Quark Spin Density Matrix in lepton+jets - Results

- 15 spin coefficients
  - 3 x 2 spin **polarizations** - P_i ($\bar{P}_i$)
  - 9 spin **correlations** - C_{ij}
- Constant normalization "c" also fit

spin **polarizations**

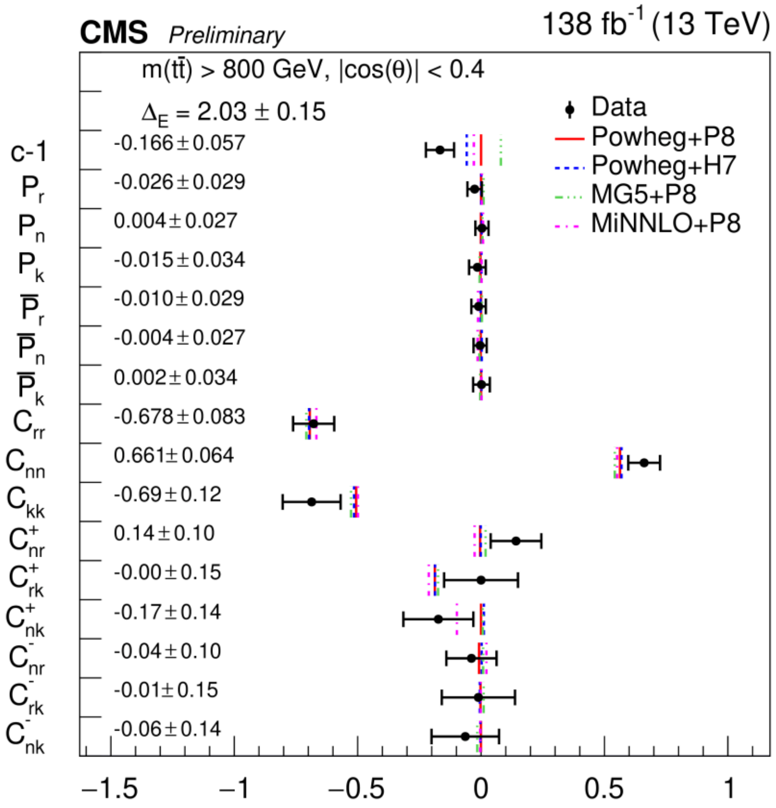
spin **correlations**

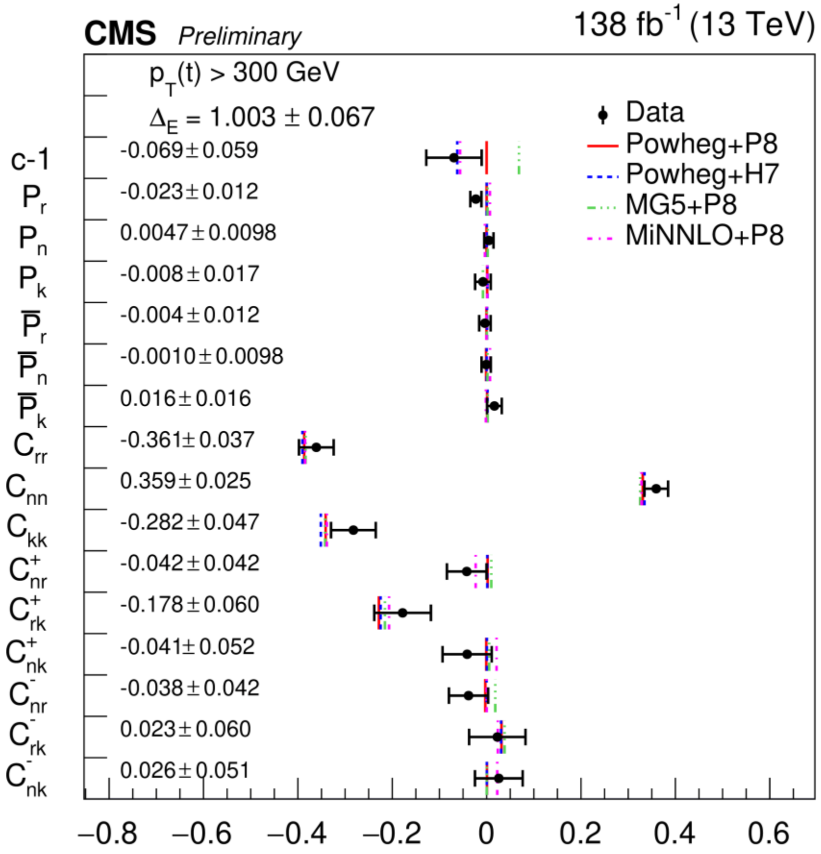


[CMS-PAS-TOP-23-007]

Measurement of Top Quark Spin Density Matrix in lepton+jets - Results

Measurement of full spin density matrix differentially in $m(\mathrm{t\bar{t}})$, $|\cos\theta_t|$ and $\mathrm{p_T(t)}$ agrees with the SM





How to probe entanglement

- What does it mean to be **not** 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** $m(t\bar{t})$

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

$$D = -\frac{tr[C]}{3}$$

$$D < -\frac{1}{3}$$ → **entangled**!

At **high** $m(t\bar{t})$ & **low** $|\cos\Theta_t|$

$$C_{kk} < 0 \ \& \ C_{rr} < 0 \rightarrow C_{nn} - C_{kk} - C_{rr} > 1$$

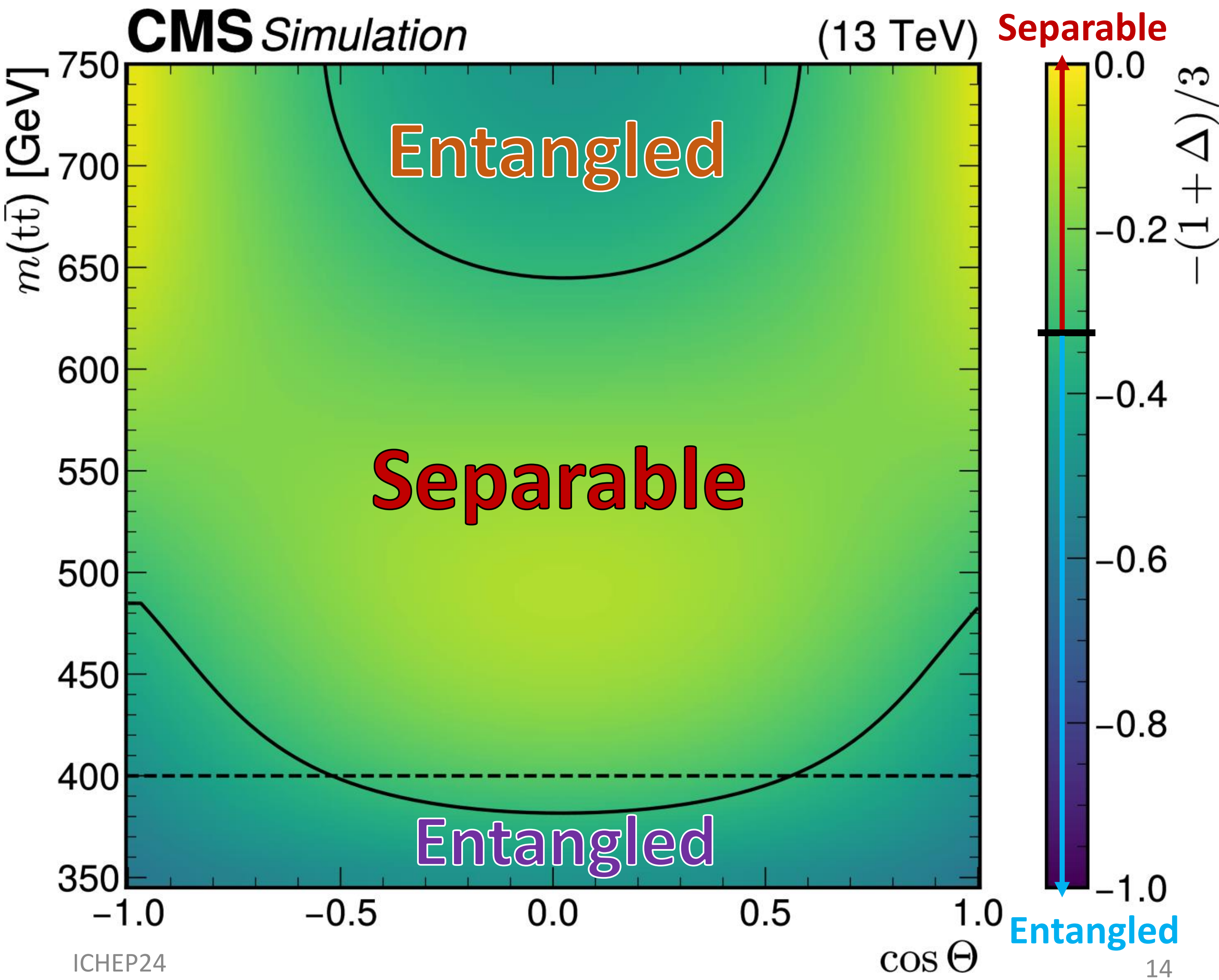
$$\widetilde{D} = \frac{C_{nn} - C_{kk} - C_{rr}}{3}$$

$$\widetilde{D} > \frac{1}{3}$$ → **entangled**!

Measure D or $\widetilde{D}$ to access entanglement information!

How to discover entangled top quarks

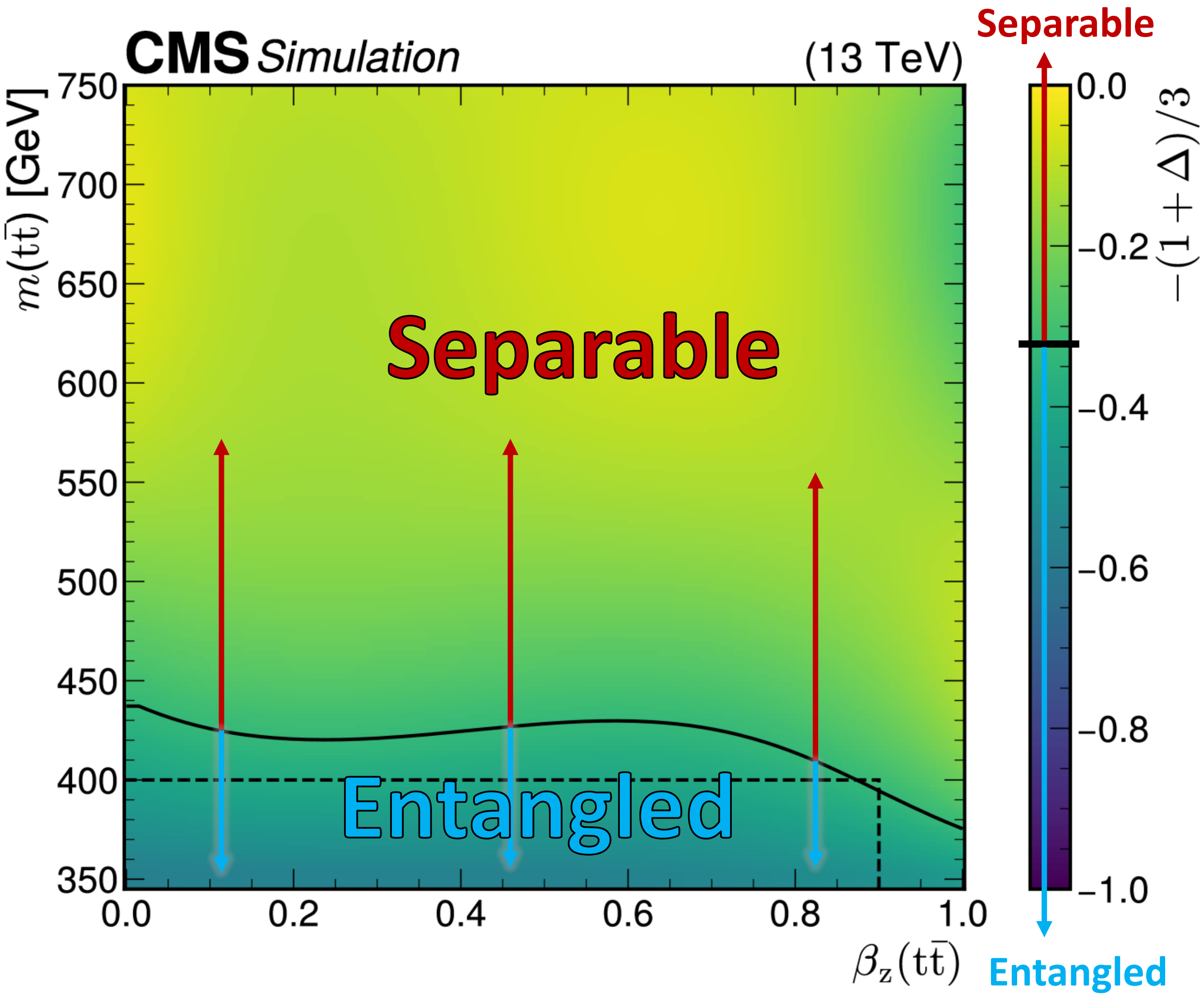
- CMS probed both the **boosted region** and the **production threshold region** for entanglement
- Mostly **timelike** (**spacelike**) separated decays in **production threshold** (**boosted**) region



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 < $\mathrm{m(t\bar{t})}$ < 400 GeV & $\beta_z(\mathrm{t\bar{t}}) < 0.9$
- Performed the fit both including & excluding the ground state of **toponium**, η_t

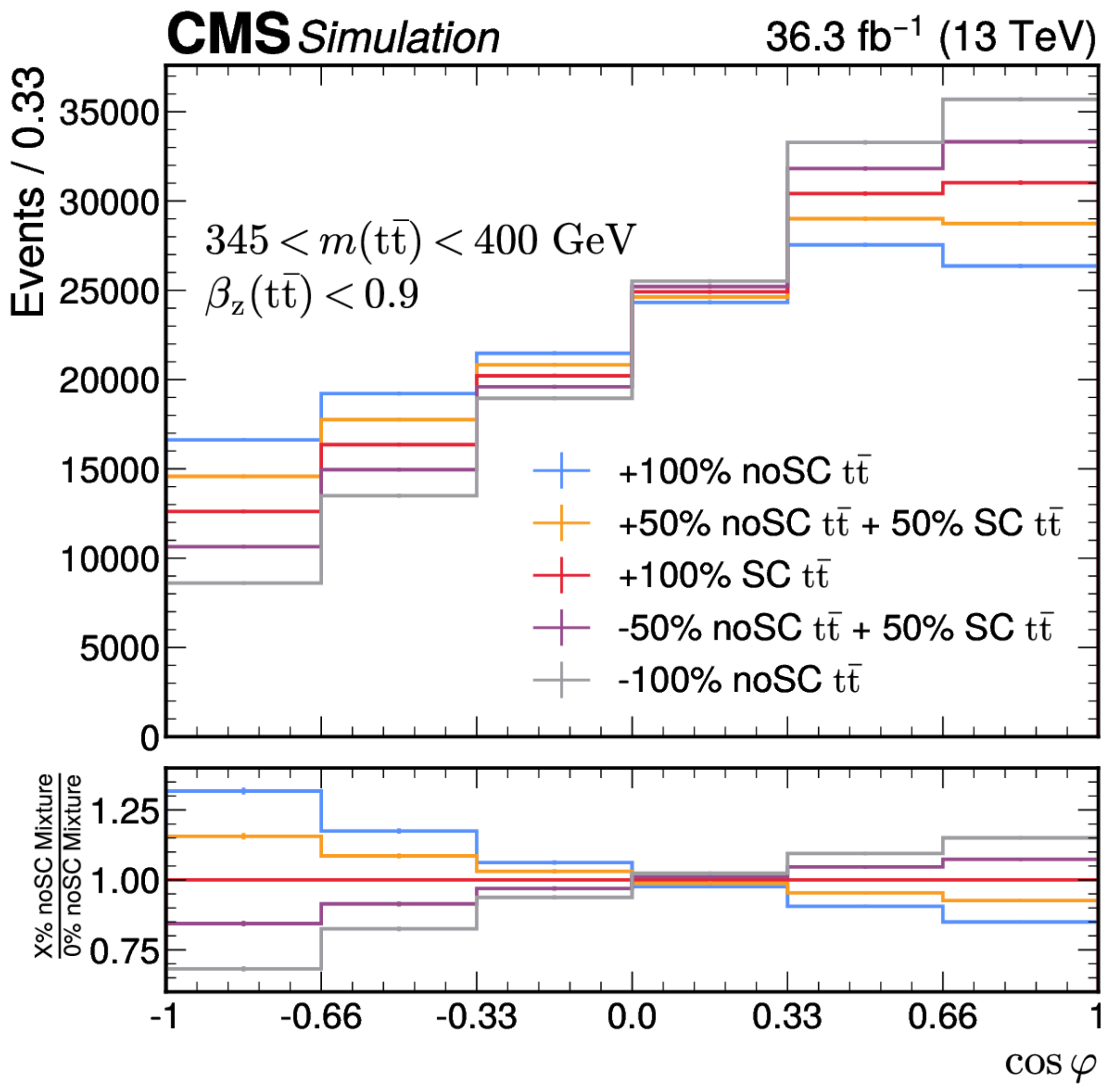
[2406.03976] (submitted to ROPP)



Measurement of Entanglement in Threshold Region - Method

[2406.03976] (submitted to ROPP)

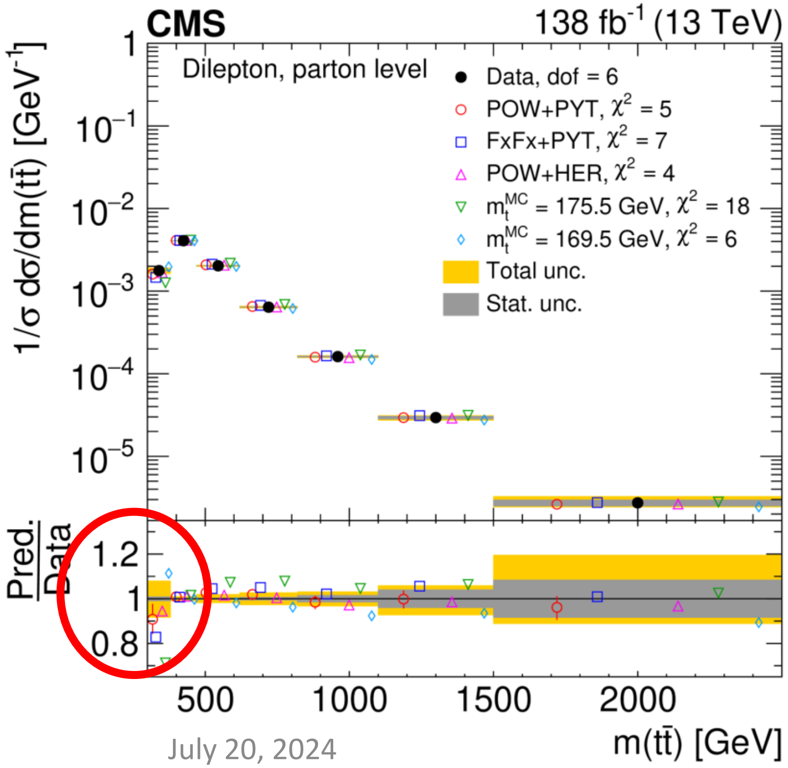
- Need to fit POI D
  - Q: How to create variations of D?
  - A: Generate top quark pairs with zero spin correlation → $\mathrm{D} = 0$
- Can create new samples with mixtures of SM and no spin corr.
- These mixtures only probe $[\mathrm{D_{SM}}, 0]$→ Mirror to probe $[-1, \mathrm{D_{SM}}]$



Measurement of Entanglement in Threshold Region

- Large mismodeling seen for $m(t\bar{t}) \approx 345$ GeV [2406.03976] (submitted to ROPP)
- Consistent between dilepton & lepton+jets and CMS & ATLAS

2402.08486 (submitted to JHEP)



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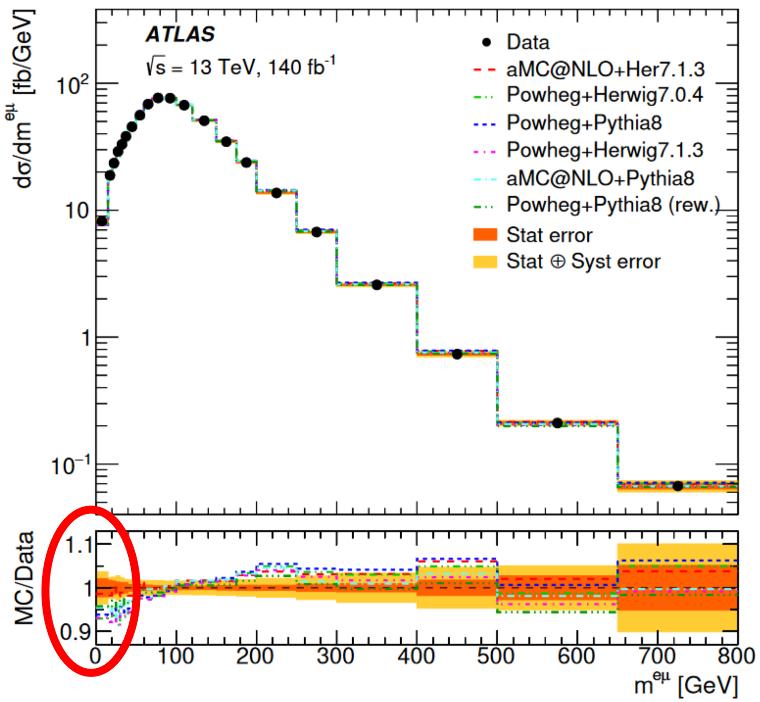
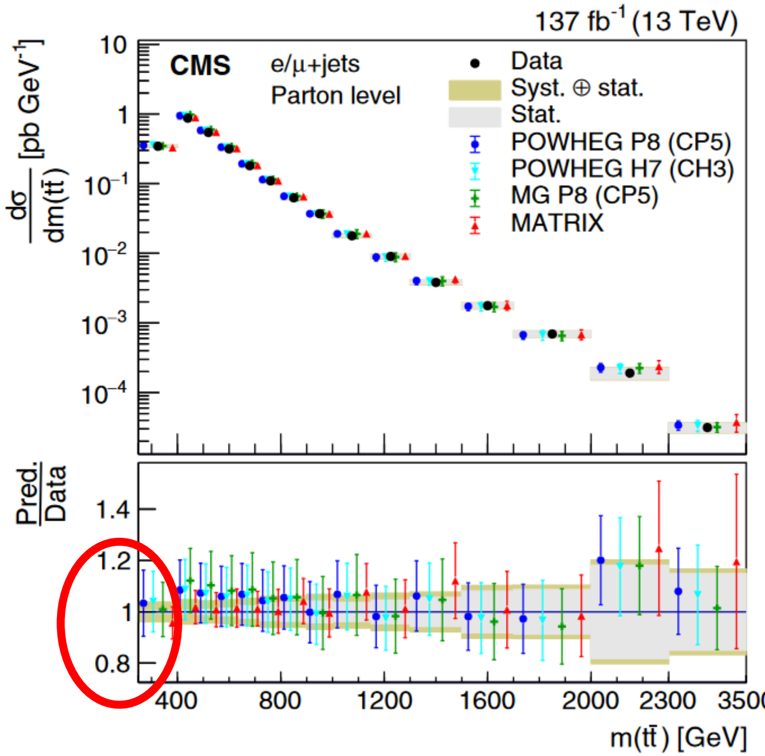


Phys. Rev. D 104, 092013

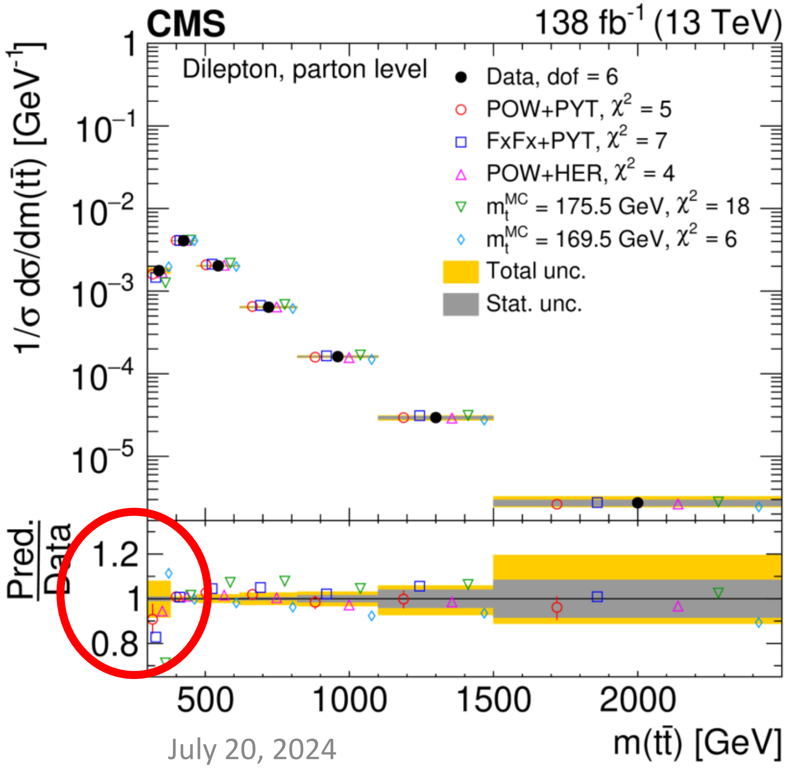


Measurement of Entanglement in Threshold Region

[2406.03976] (submitted to ROPP)

- 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)



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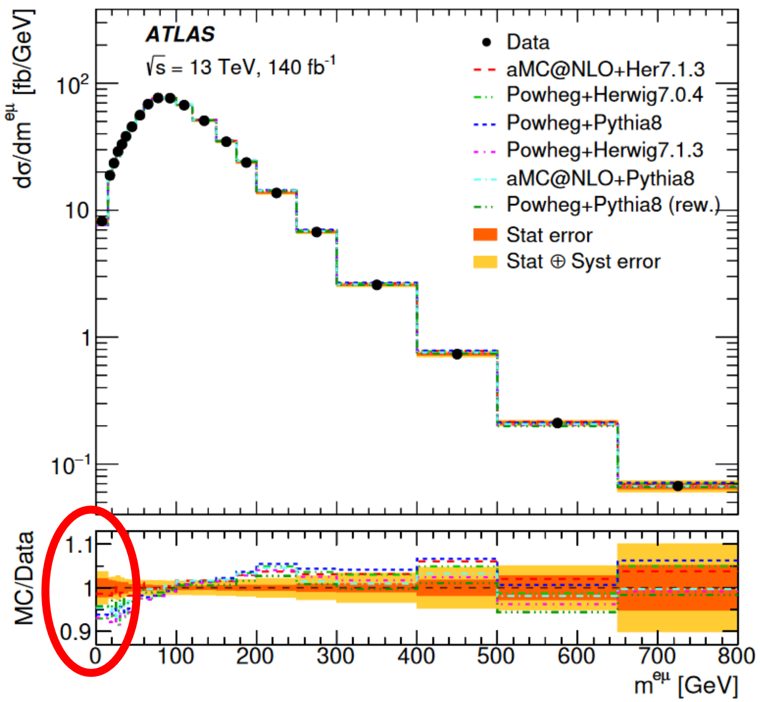
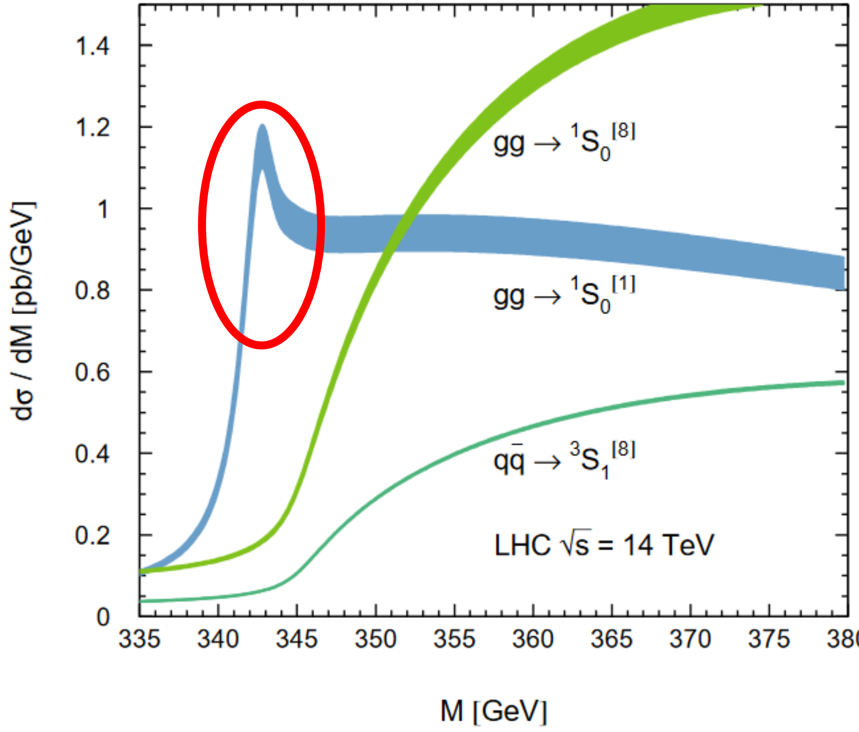


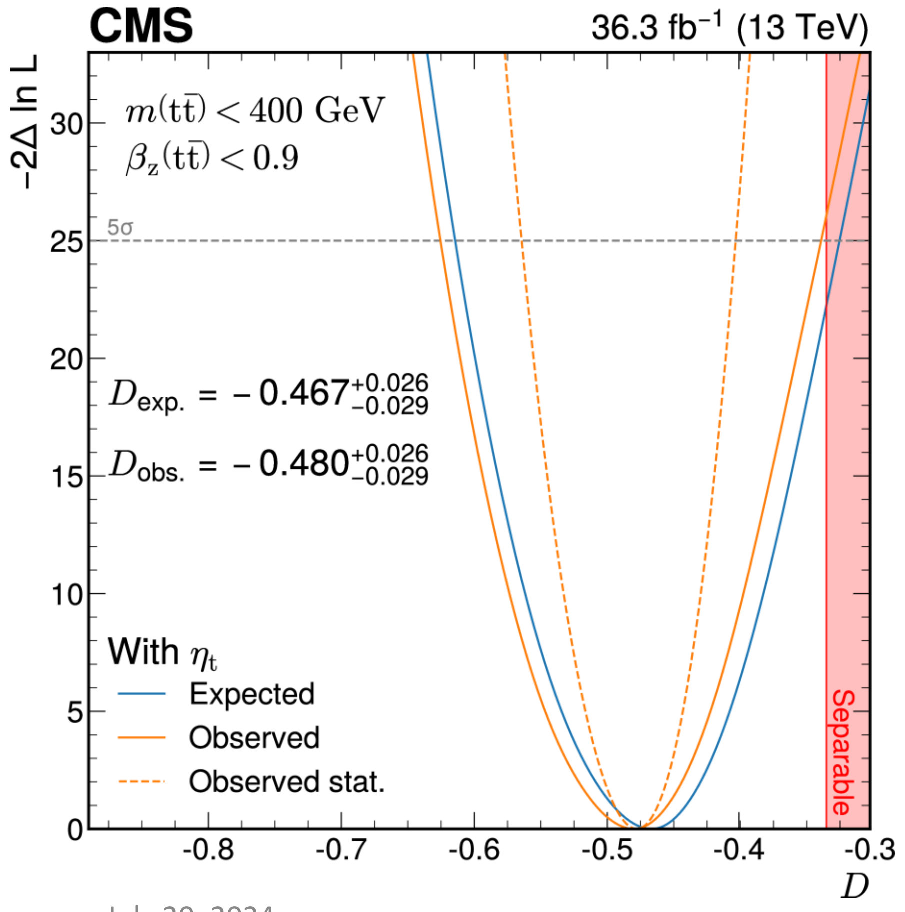
- Theory predictions with NRQCD
- Color **singlet** and **octet** contributions to spin singlet

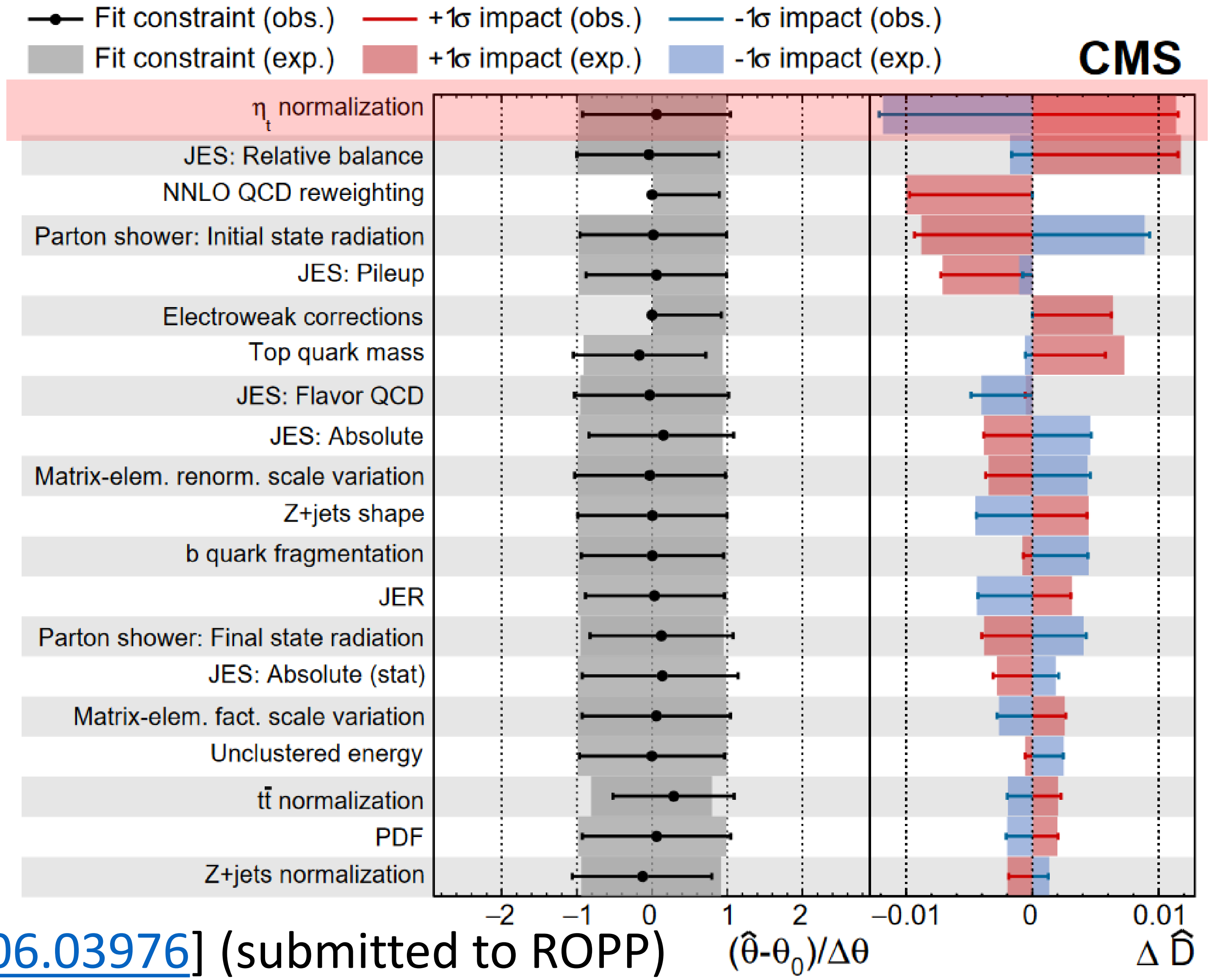
JHEP 06 (2020), 158



Measurement of Entanglement in Threshold Region - Results

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





[2406.03976] (submitted to ROPP)

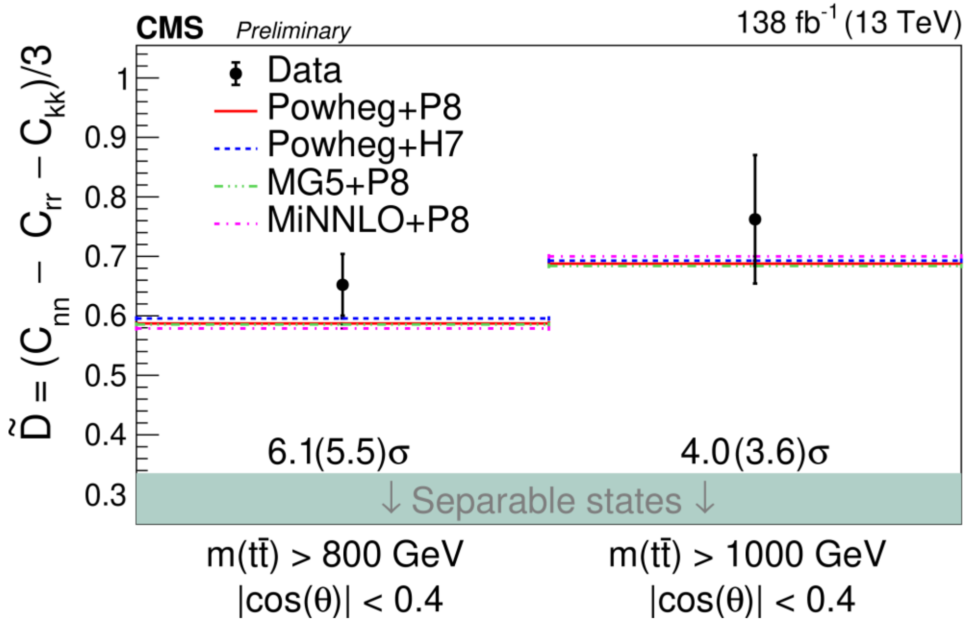
Measurement of Entanglement in Boosted Region - Results

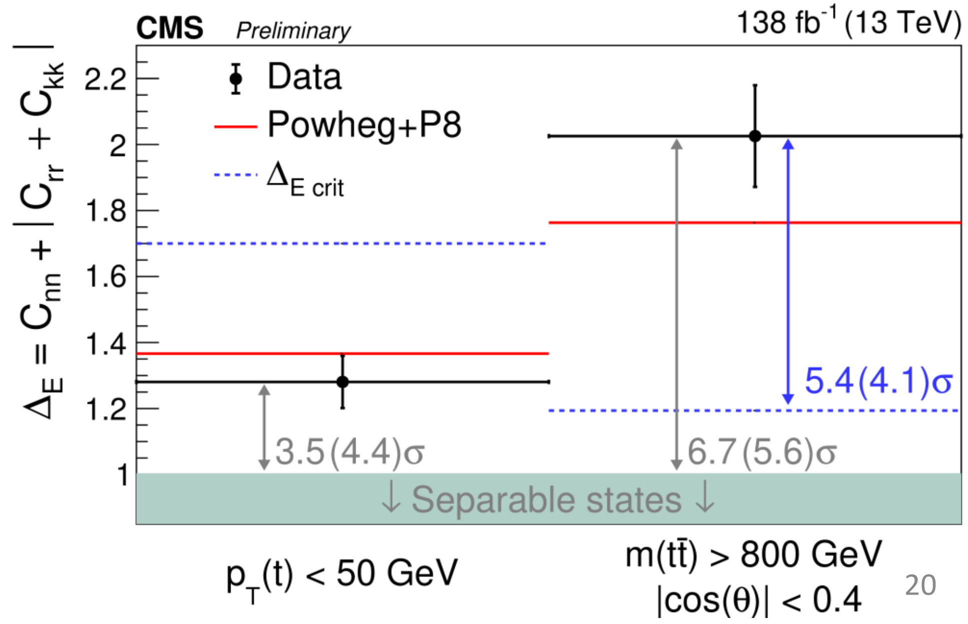
[CMS-PAS-TOP-23-007]

- Measured $\widetilde{\mathrm{D}}$ to be 0.652 ± 0.052
  - 6.1σ observation for **entanglement** in the **boosted region**!
- 90% of the top quark pairs are spacelike separated in the **boosted region** when they decay
- no interactions after decay for 90% of events
- Timelike separated events can interact resulting in entanglement
- If we say entanglement can only arise from timelike separated events:

$$\Delta_{E\ crit} = f\Delta_{E\ sep} + (1-f)\Delta_{\mathrm{E\ max}} = 0.9 * 1 + 0.1 * 3$$
$$\Delta_{E\ crit} = 1.2$$

5.4σ observed for $3\widetilde{\mathrm{D}} > 1.2$!

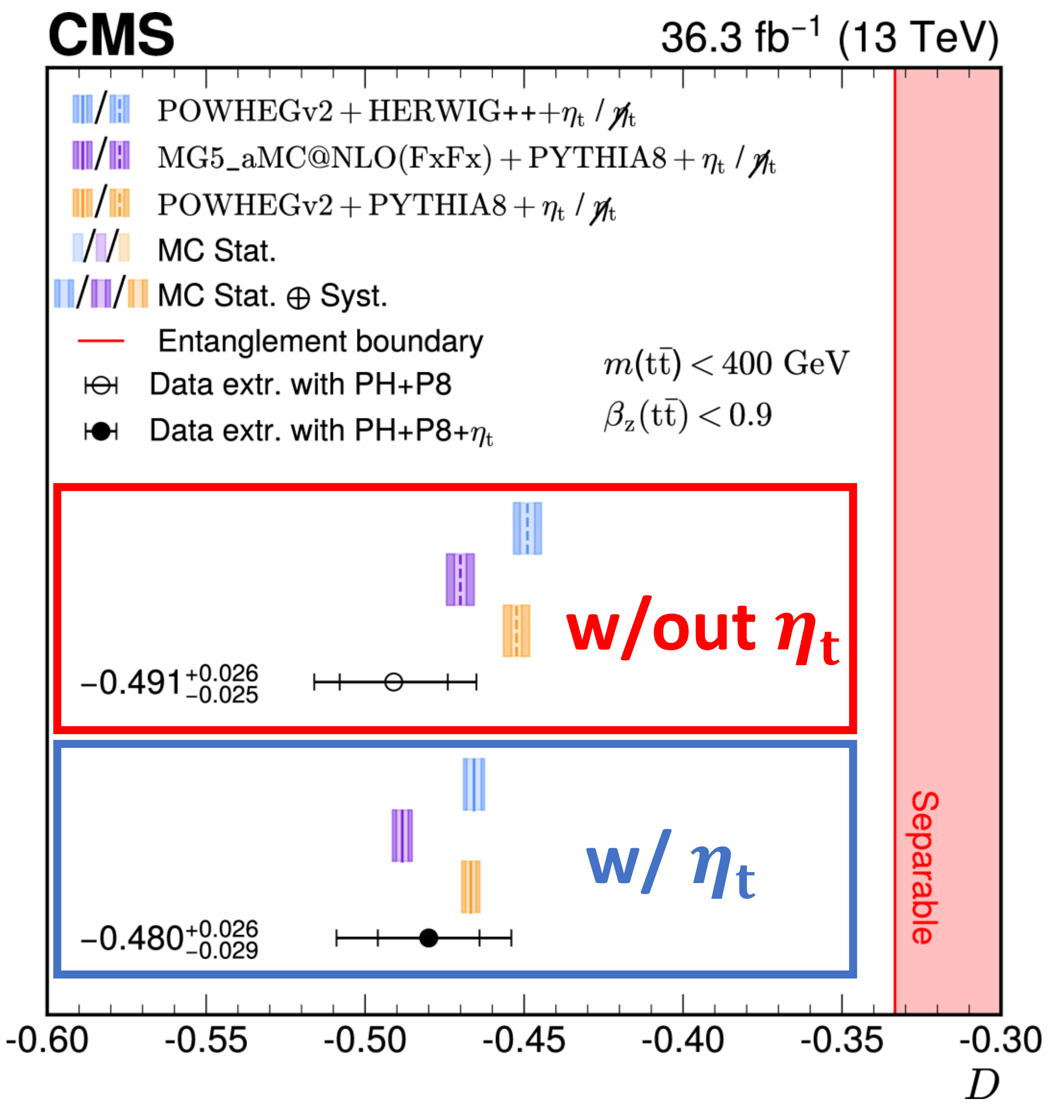




Conclusion

- Top quarks are **entangled** both when decaying spacelike and timelike separated
- First inclusion of bound-state effects in the production threshold region via η_t
- **Quantum tomography** of top quark-antiquark pair in lepton+jets final states
- Start of quantum information studies in high energy physics
- New door into "old" physics

[2406.03976] (submitted to ROPP)

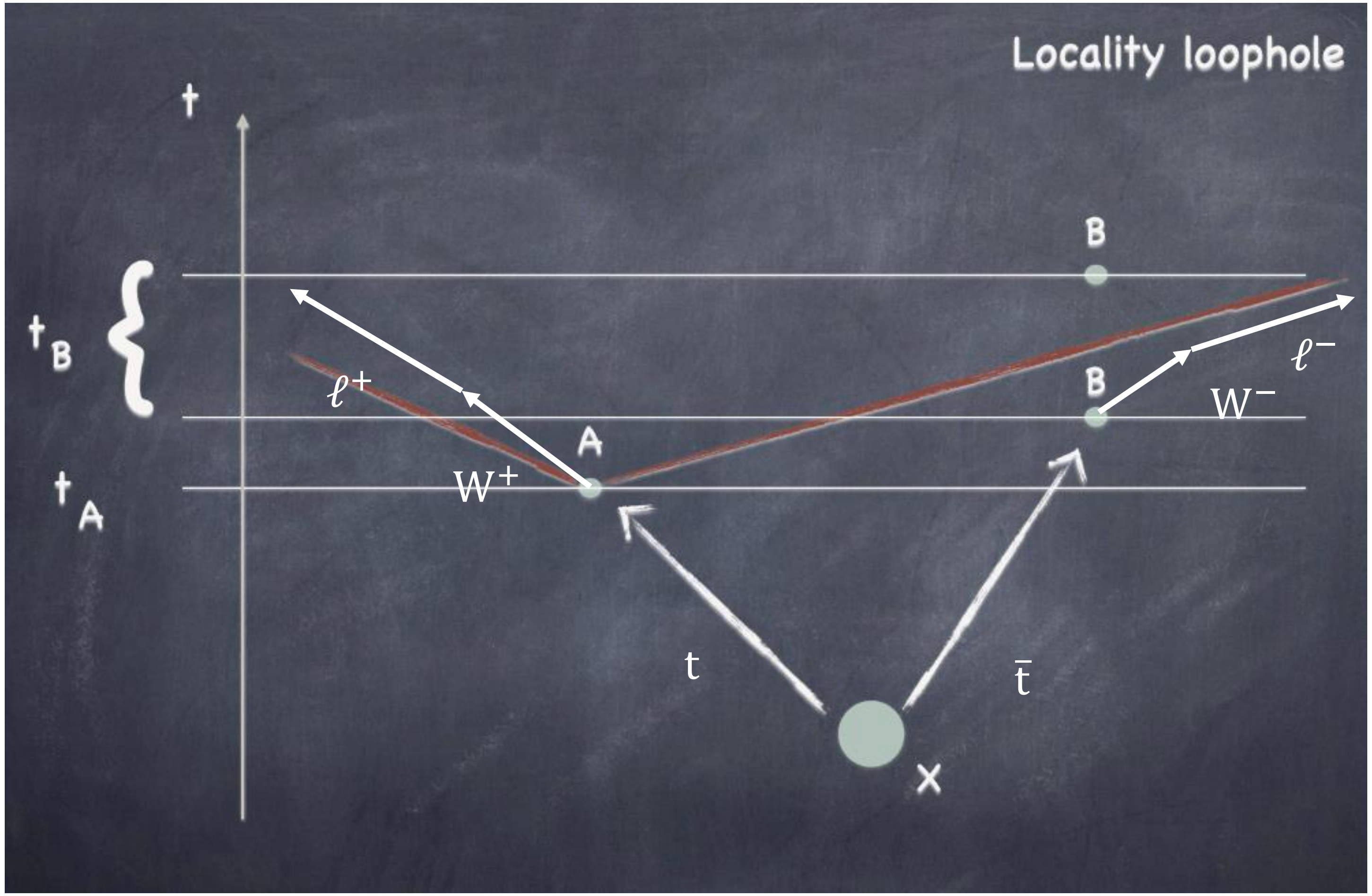


Thanks!

awildrid@purdue.edu

Spacelike separated entanglement

- First off, entanglement != violation of Bell inequality
- Because subsequent decays are **lighter**, spacelike separated events typically **stay spacelike separated**
- Closing locality loophole requirements:
    1. spacelike separated measurements
    2. Random measurement settings



Modified from [2402.07972]

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

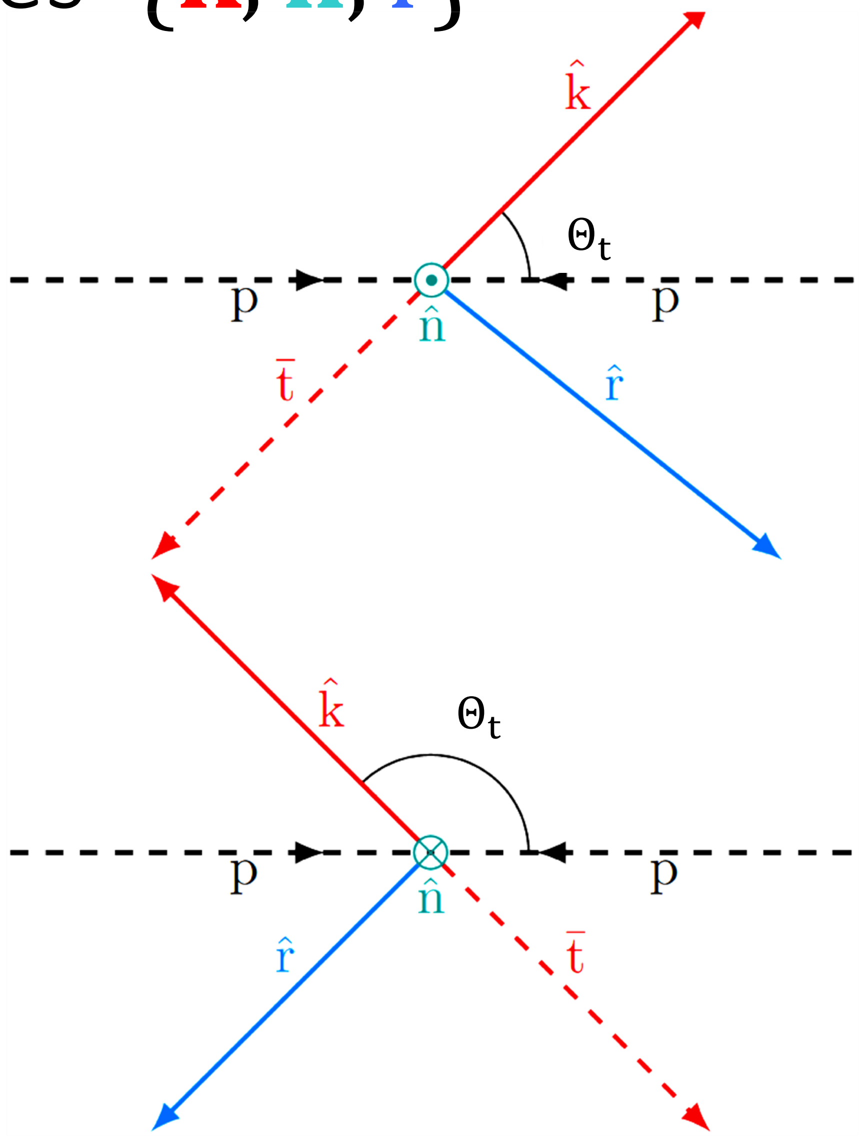
$$\hat{\mathbf{n}} = \frac{\mathrm{sign}(\cos\Theta_t)}{\sin\Theta_t}(\hat{\mathrm{p}} \times \hat{\mathbf{k}})$$

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

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

- $\hat{\mathrm{p}}$: 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



ATLAS top quark pair entanglement

- **ATLAS** observed entanglement last fall [arXiv:2311.07288]
- Significant differences to **CMS**
  - Calibrated results & entanglement boundary to particle-level
  - No toponium or electroweak corrections included in threshold treatment