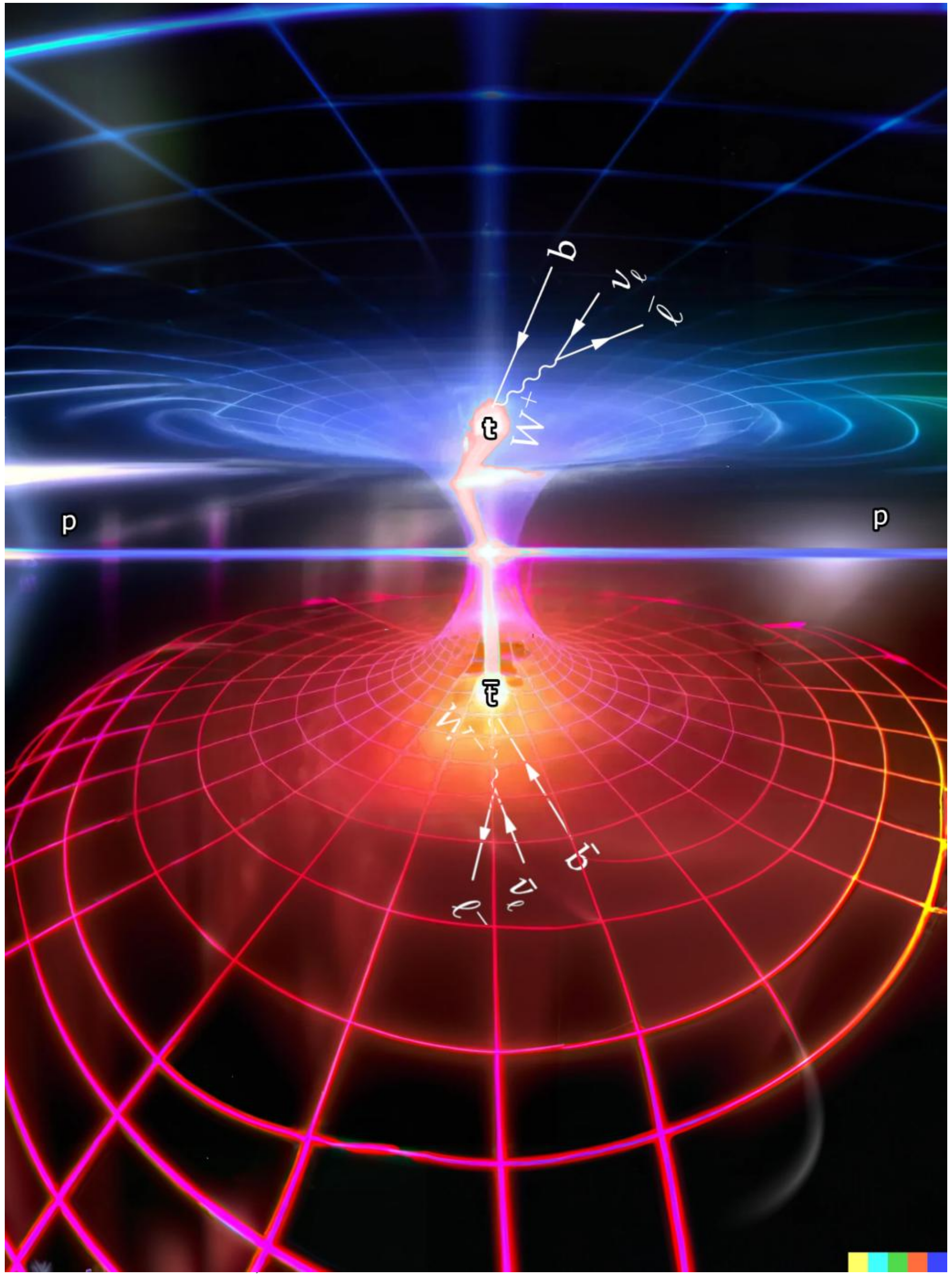


*Rep. Prog. Phys.* **87** 117801

# Observation of entangled top quarks with the CMS Detector

AJ Wildridge

**LPC Physics Forum**

Feb. 20, 2025

# Entanglement in QM

- Classical physics is void of phenomenon featuring entanglement

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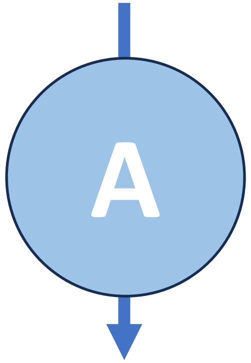



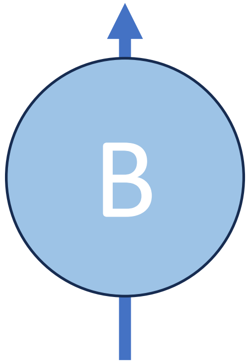

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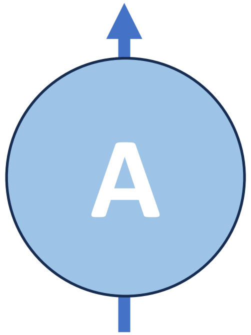


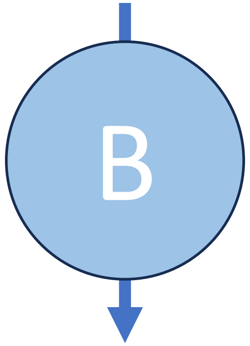

MAY 15, 1935 PHYSICAL REVIEW VOLUME 47

# Can Quantum-Mechanical Description of Physical Reality Be Considered Complete?

A. EINSTEIN, B. PODOLSKY AND N. ROSEN, *Institute for Advanced Study, Princeton, New Jersey*

(Received March 25, 1935)

"This makes the reality of P and Q depend upon the process of measurement carried out on the first system, which does not disturb the second system in any way. No reasonable definition of reality could be expected to permit this"

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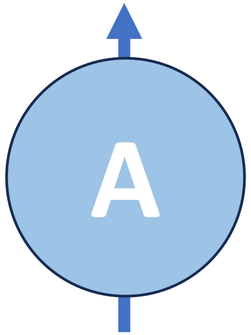


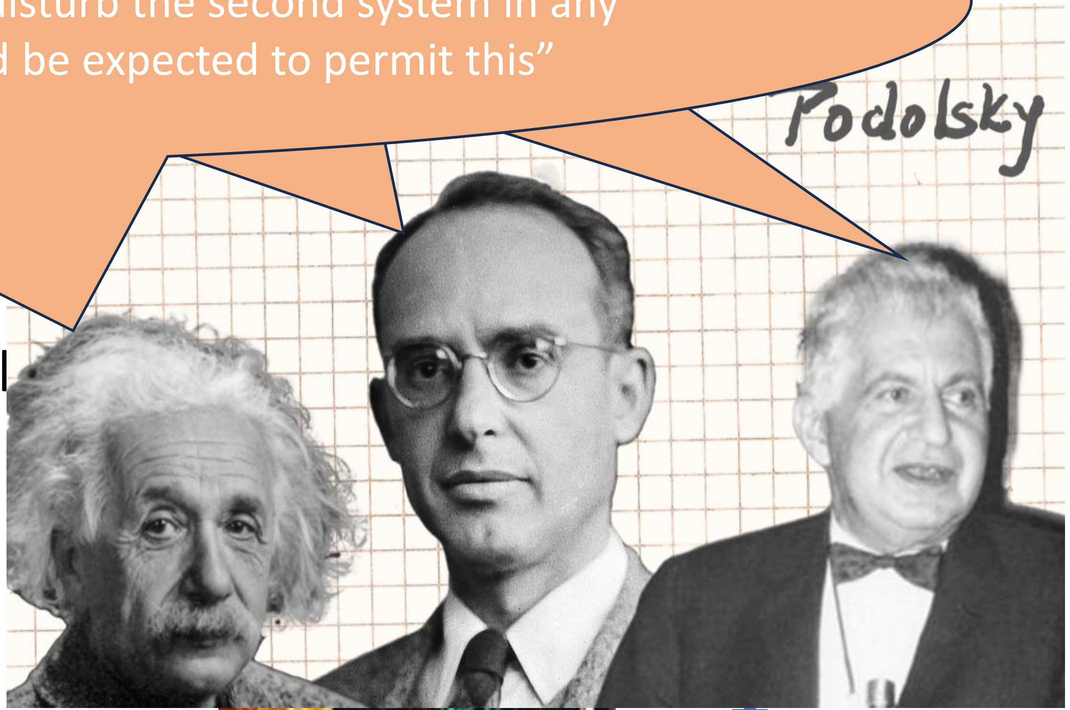


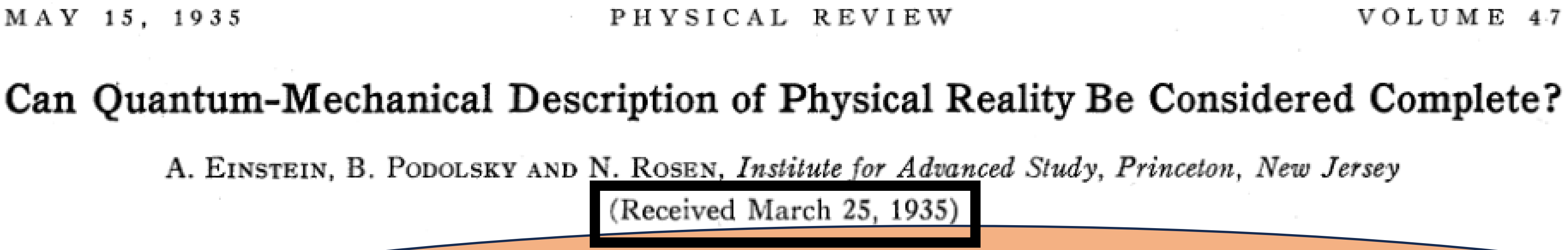
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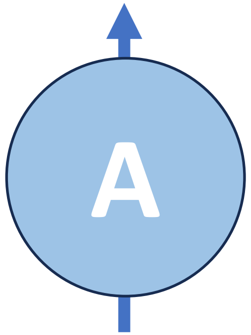


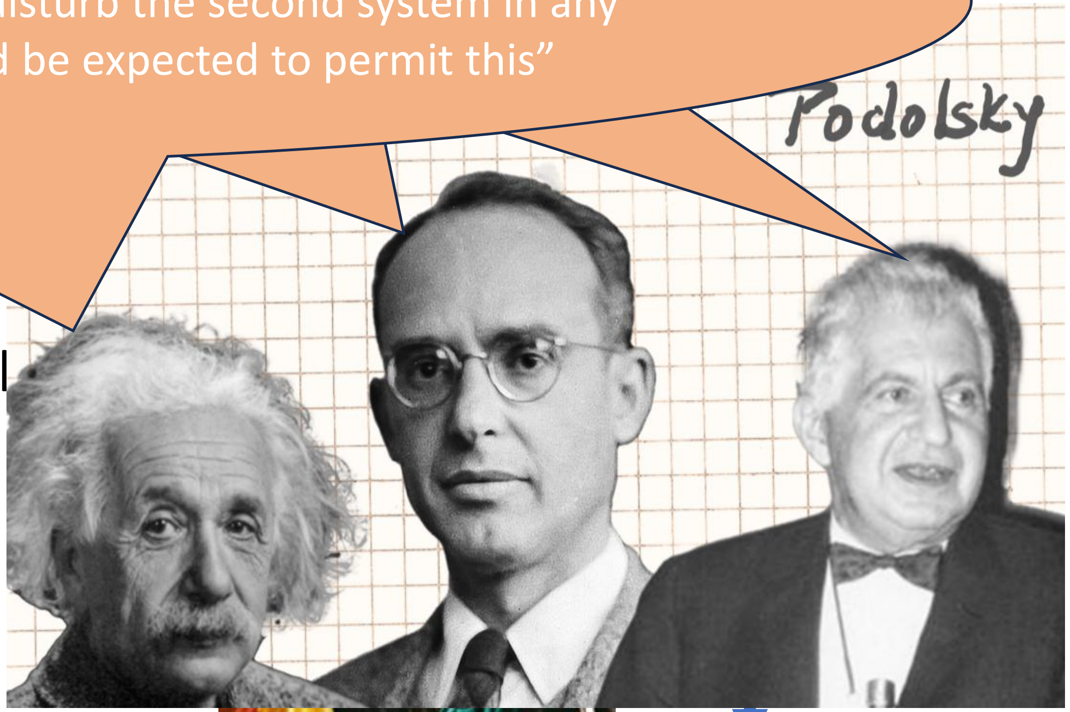


# John Stewart Bell

John Stewart Bell, CERN, 1973

VIEW VOLUME 47

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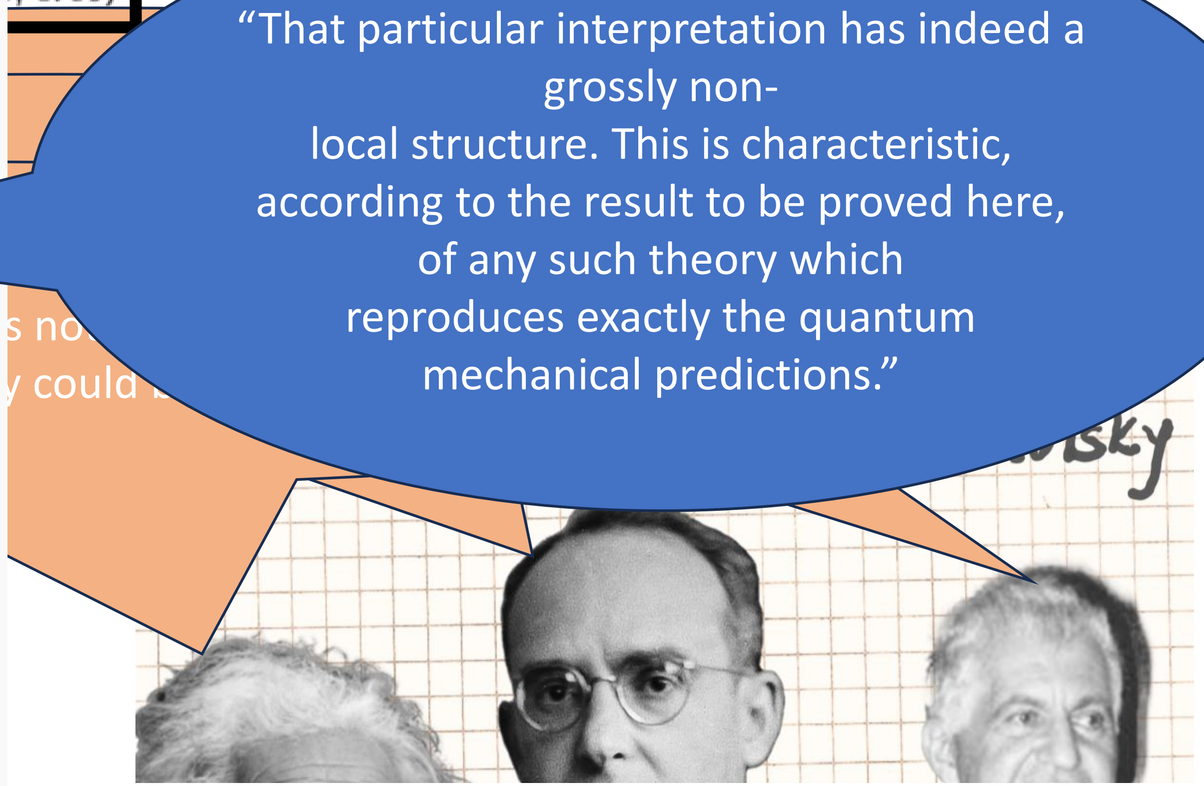



ON THE EINSTEIN PODOLSKY ROSEN PARADOX*

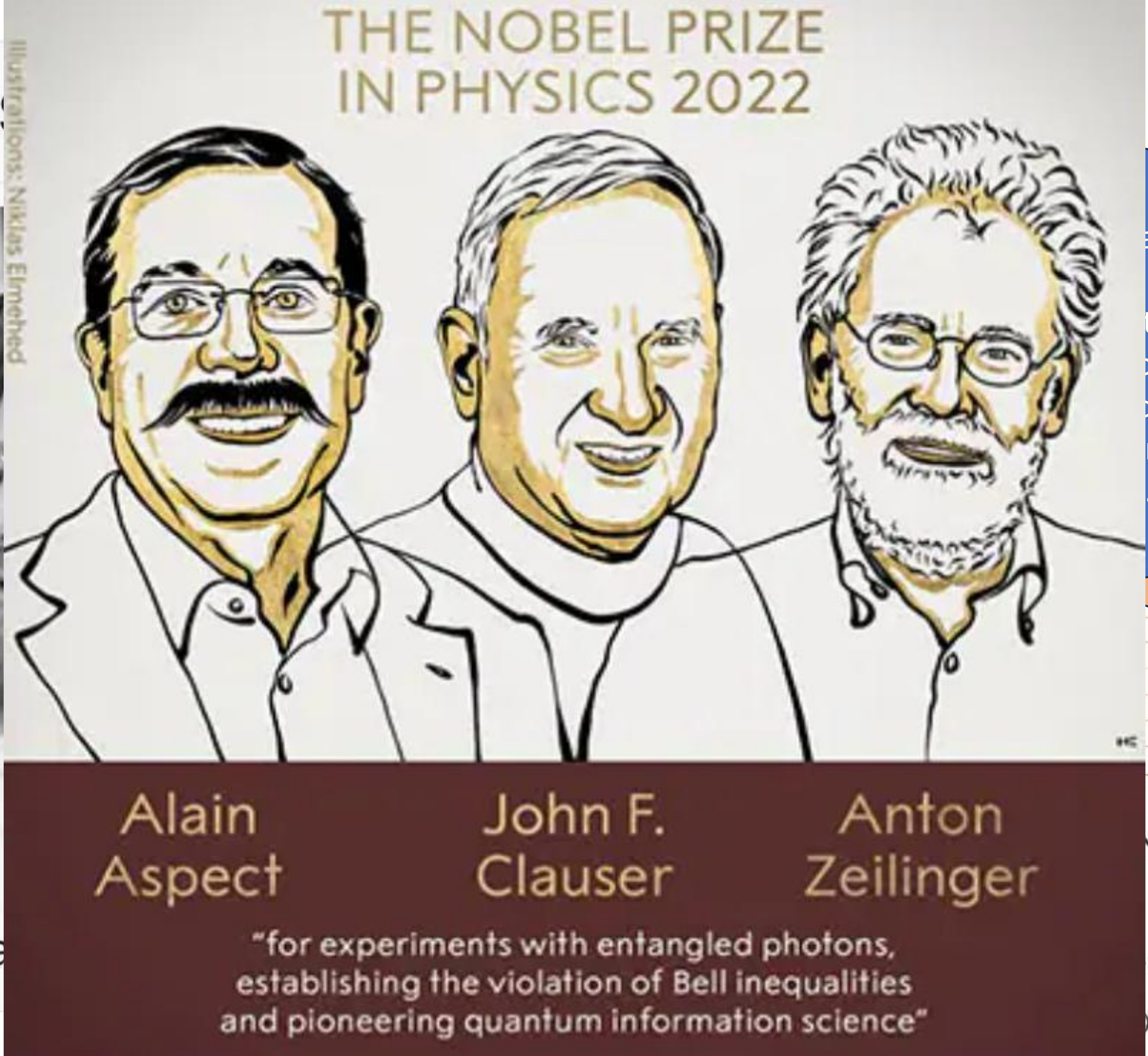

J. S. BELL†

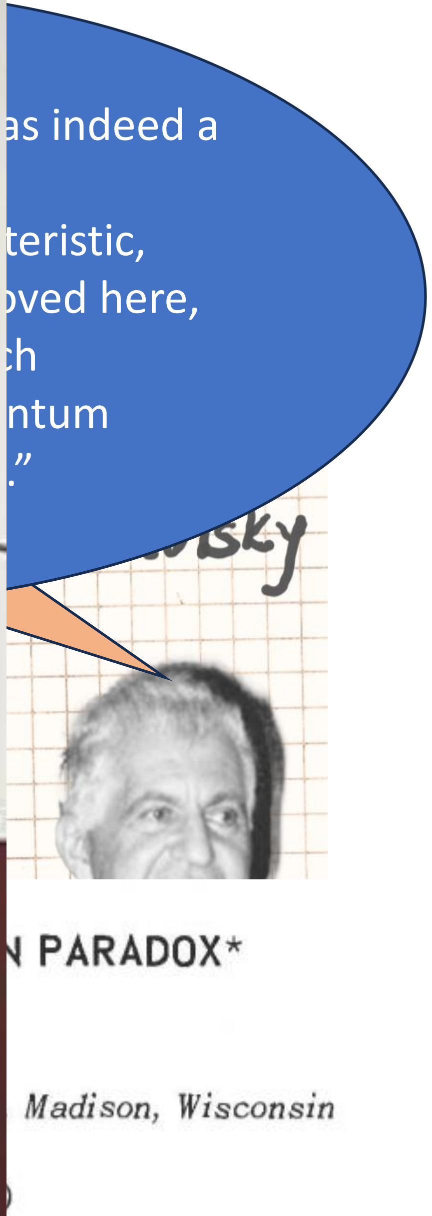
*Department of Physics, University of Wisconsin, Madison, Wisconsin*



(*Received* 4 *November* 1964)


John
John Stewa


THE NOBEL PRIZE
IN PHYSICS 2022
Illustrations: Niklas Elmehed
Alain Aspect
John F. Clauser
Anton Zeilinger
"for experiments with entangled photons,
establishing the violation of Bell inequalities
and pioneering quantum information science"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VIEW VOLUME 47


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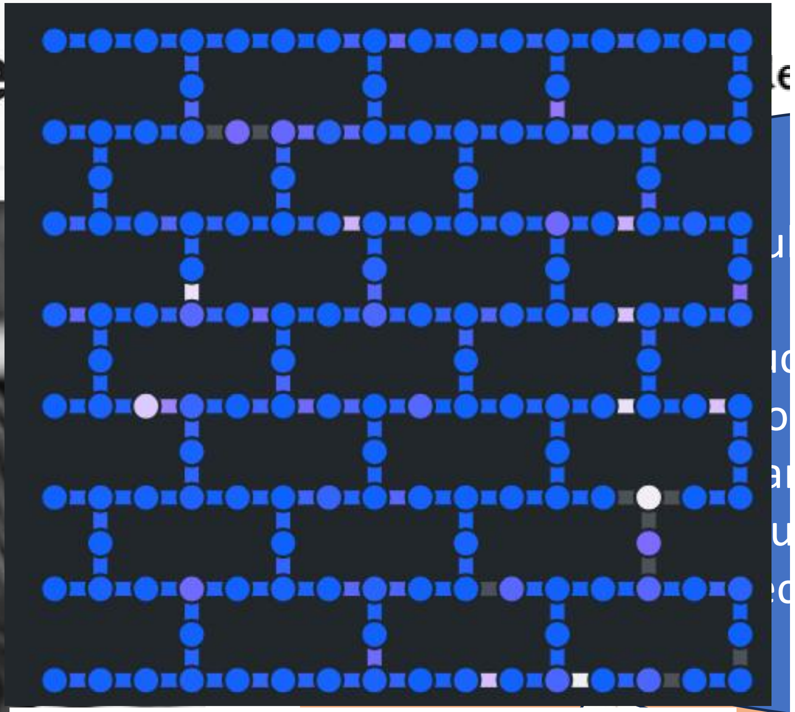
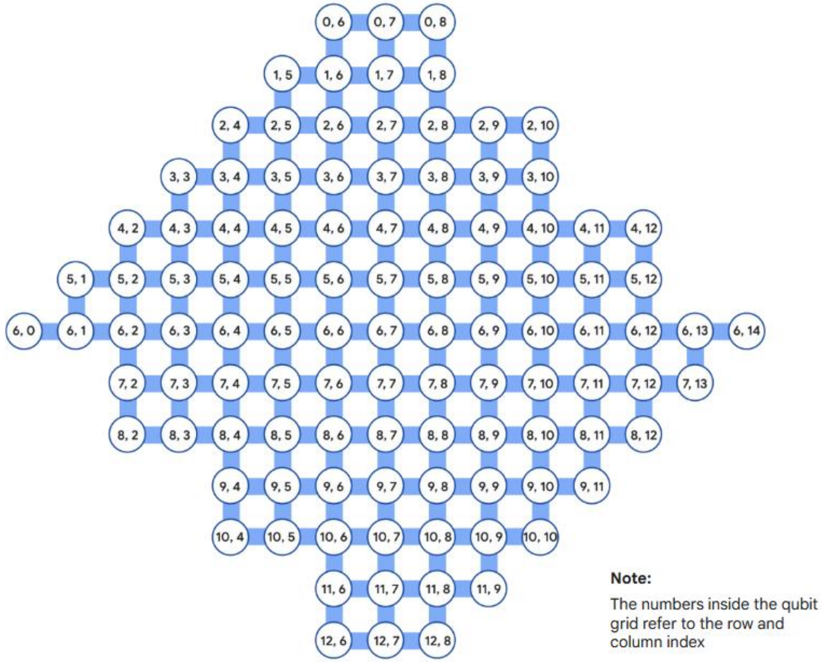


IBM Marrakesh QC

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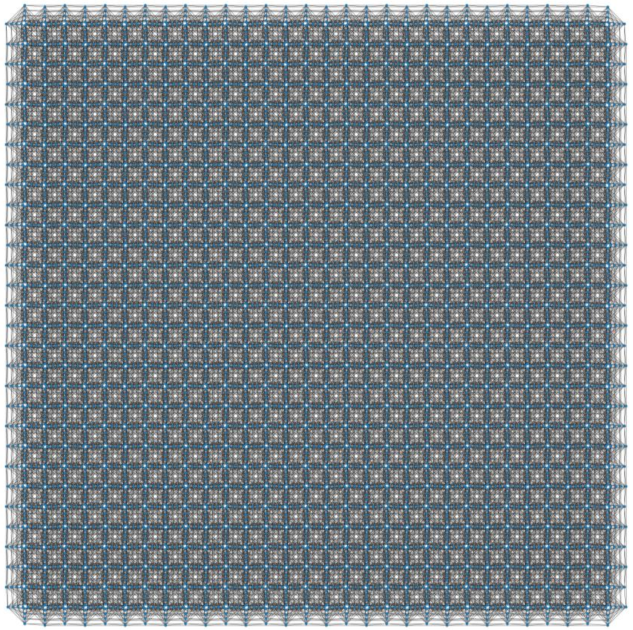
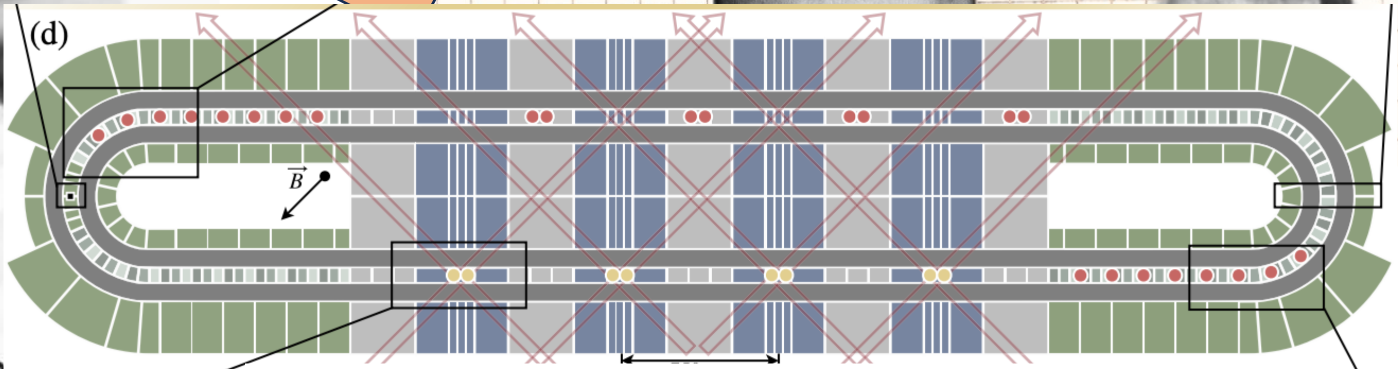


D-Wave Advantage 2 QA



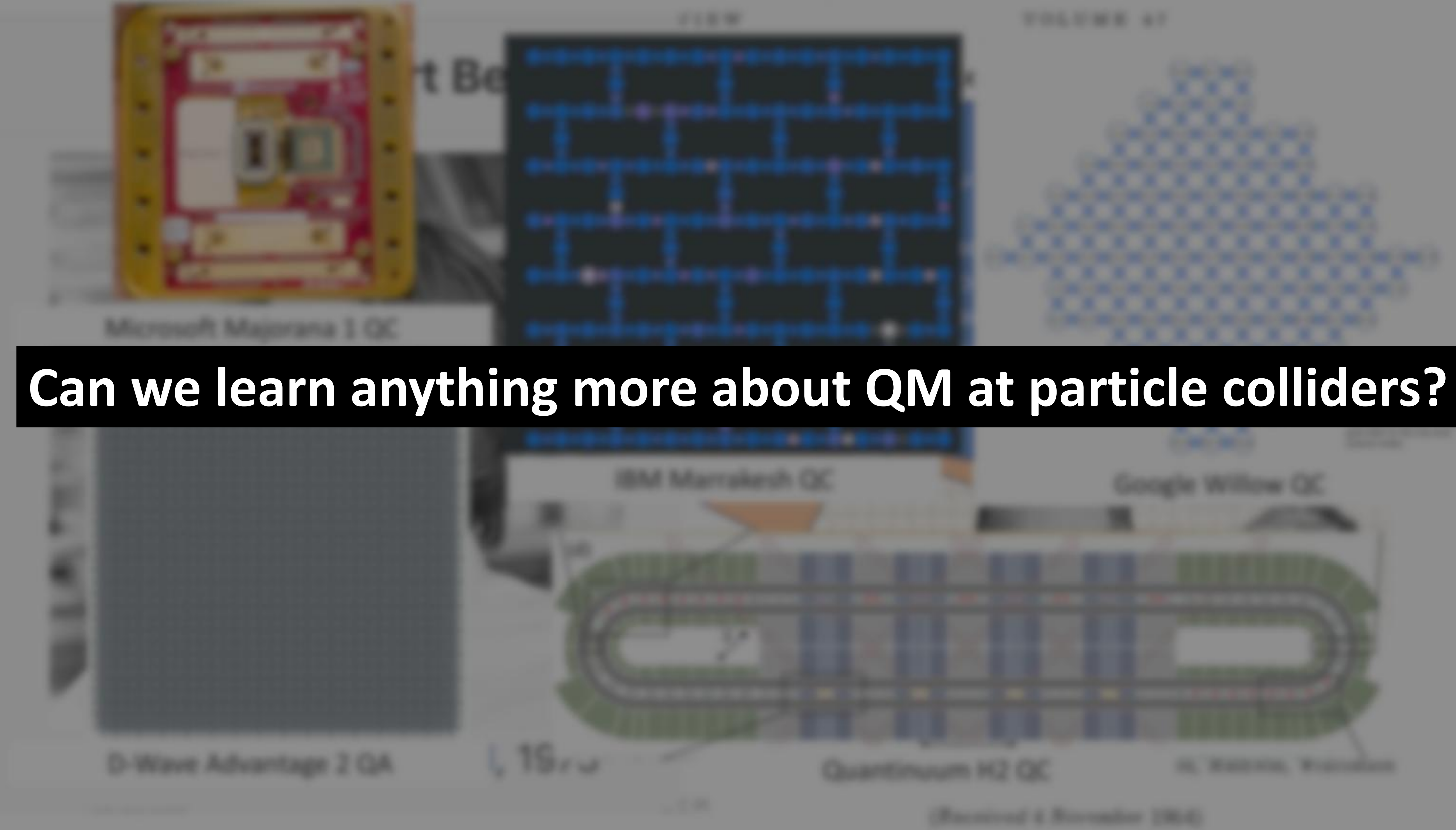

Quantinuum H2 QC

in, Madison, Wisconsin

arXiv:1903.08879

(Received 4 November 1964)

# Can we learn anything more about QM at particle colliders?




LHCb
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SPS 7 km
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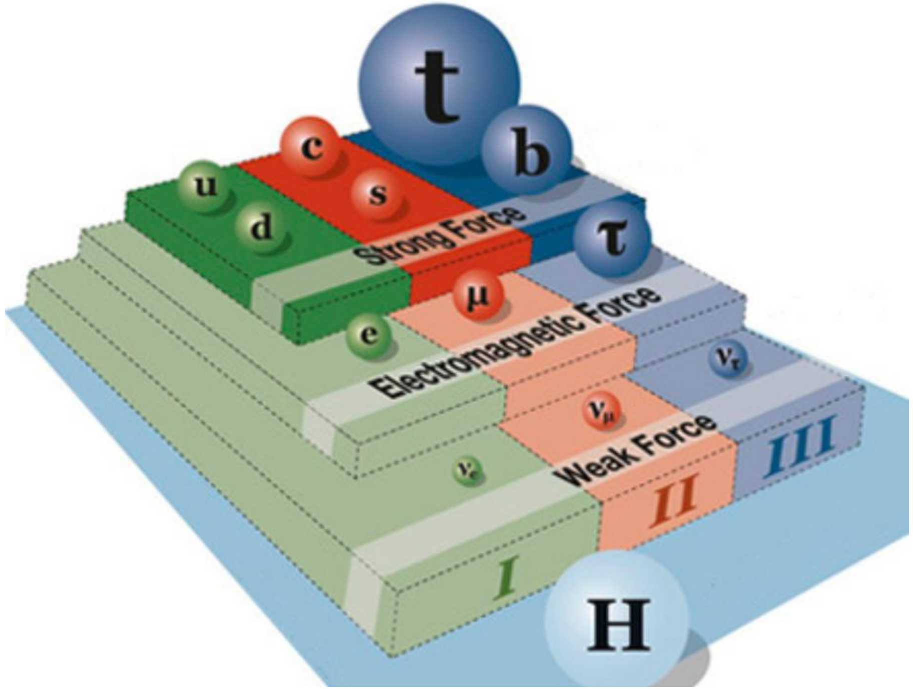
# Top Quark Physics

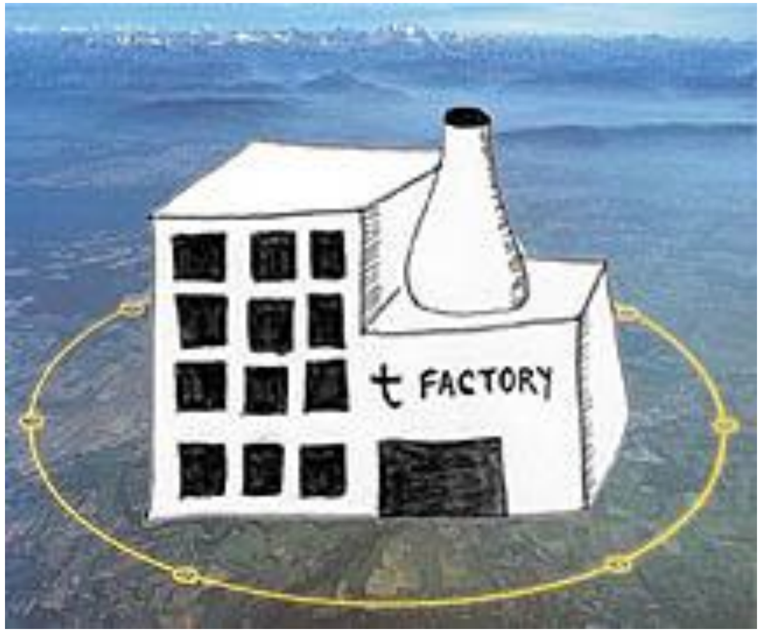
- Top quark is the heaviest fundamental particle discovered thus far: $m_t$ =172.52±0.33 GeV
- Unique:

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

[arXiv:2402.08713]

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

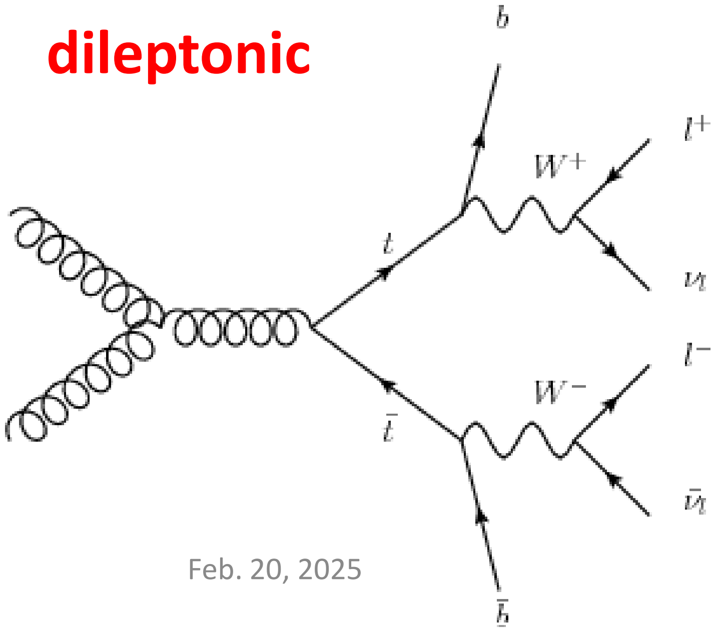


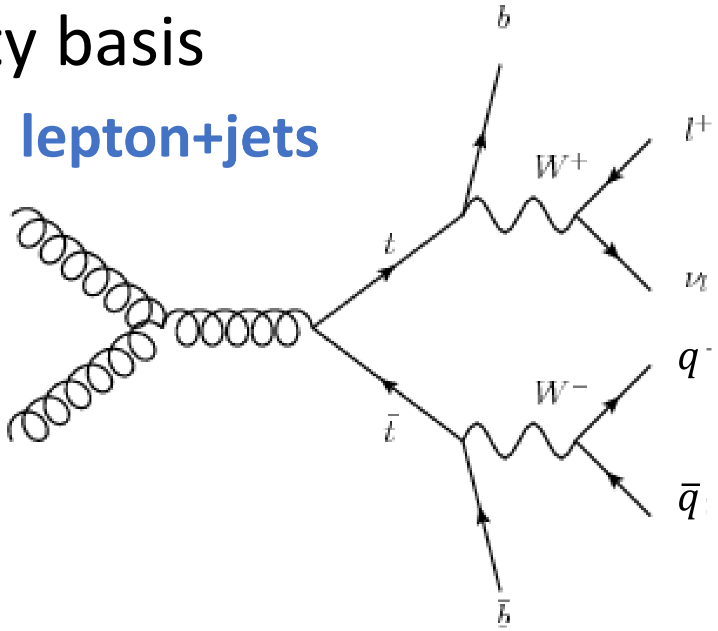
# Top Quark Spin Correlations

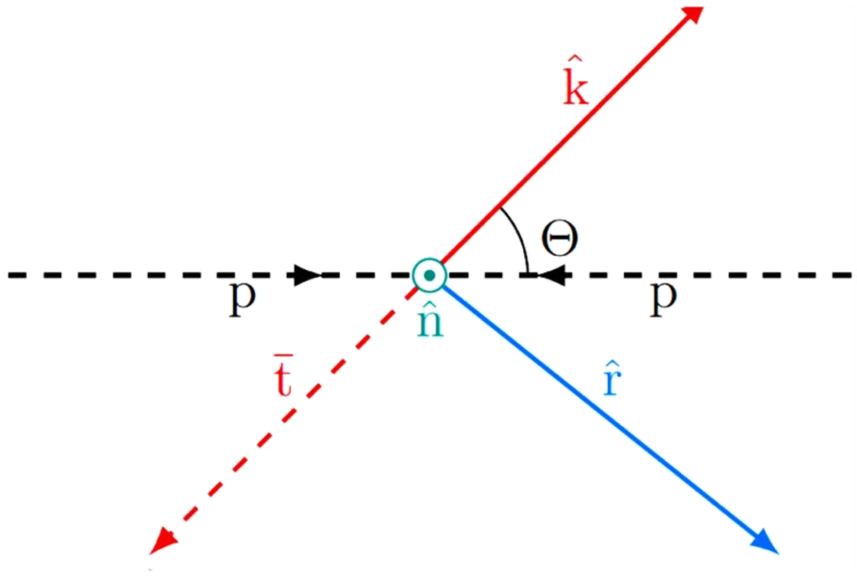
- Spin correlations are dependent on **production mode** ($gg\ vs.\ q\bar{q}$) and higher orbital momenta → function of e.g. $\boldsymbol{\Theta_t, m(t\bar{t})}$
- Top quark spin cannot be measured directly
- Fully preserved in charged leptonic and down-type quark decays of W boson
- Measured in the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

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

- Spin Polarization $\mathbf{B}/\bar{\mathbf{B}} = \begin{pmatrix} B_k \\ B_r \\ B_n \end{pmatrix}$ 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

$$\int \frac{d^4\sigma}{d\Omega d\bar{\Omega}} \rightarrow \frac{1}{\sigma}\frac{d\sigma}{d\mathrm{x}} = \frac{1}{2}(1 + [\mathrm{Coef.}]x)f(x)$$

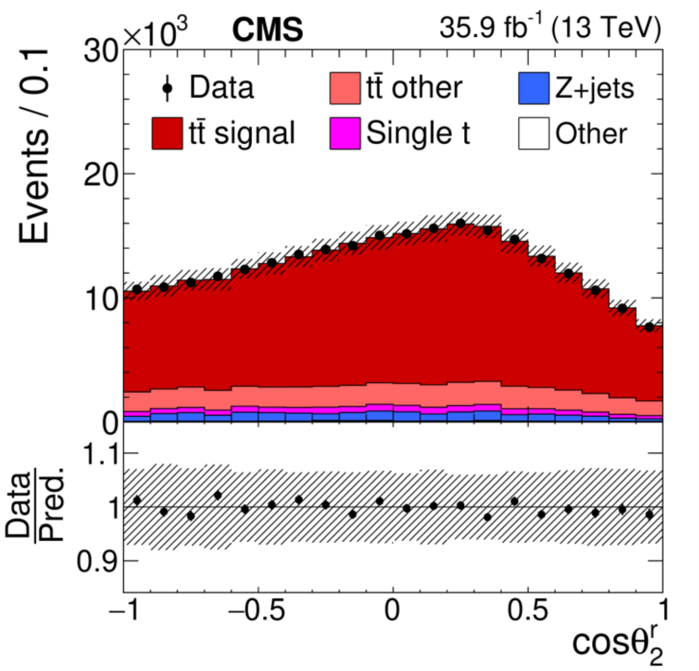
[PRD 100 (2019) 072002]

# Measurement of Top Quark Spin Density Matrix in dilepton

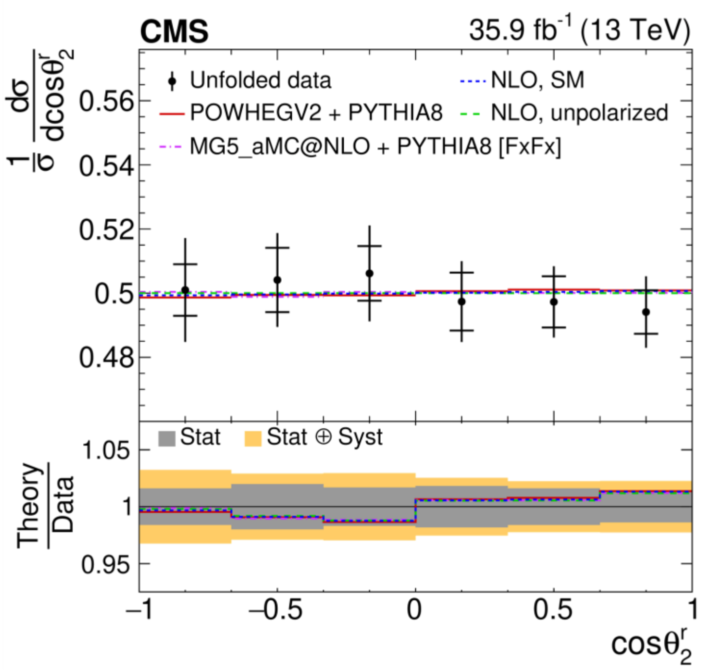
- SM predicts zero polarization for $t\bar{t}$ ($< 10^{-2}$) – QCD is CP even
  - Zero polarization → zero slope at parton level

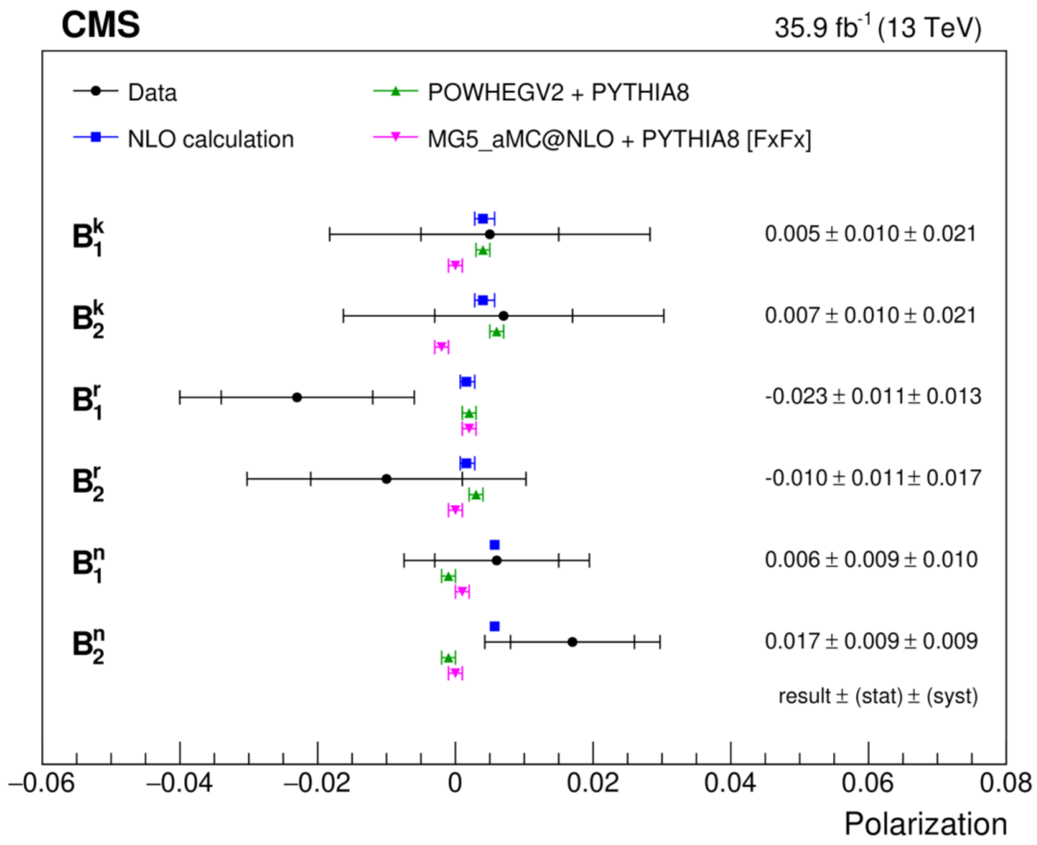
$$\frac{1}{\sigma}\frac{d\sigma}{d\cos\theta^{i}_{1/2}} = \frac{1}{2}\left(1 + B_i \cos\theta^{i}_{1/2}\right)$$

## Reconstruction Level




## Parton level



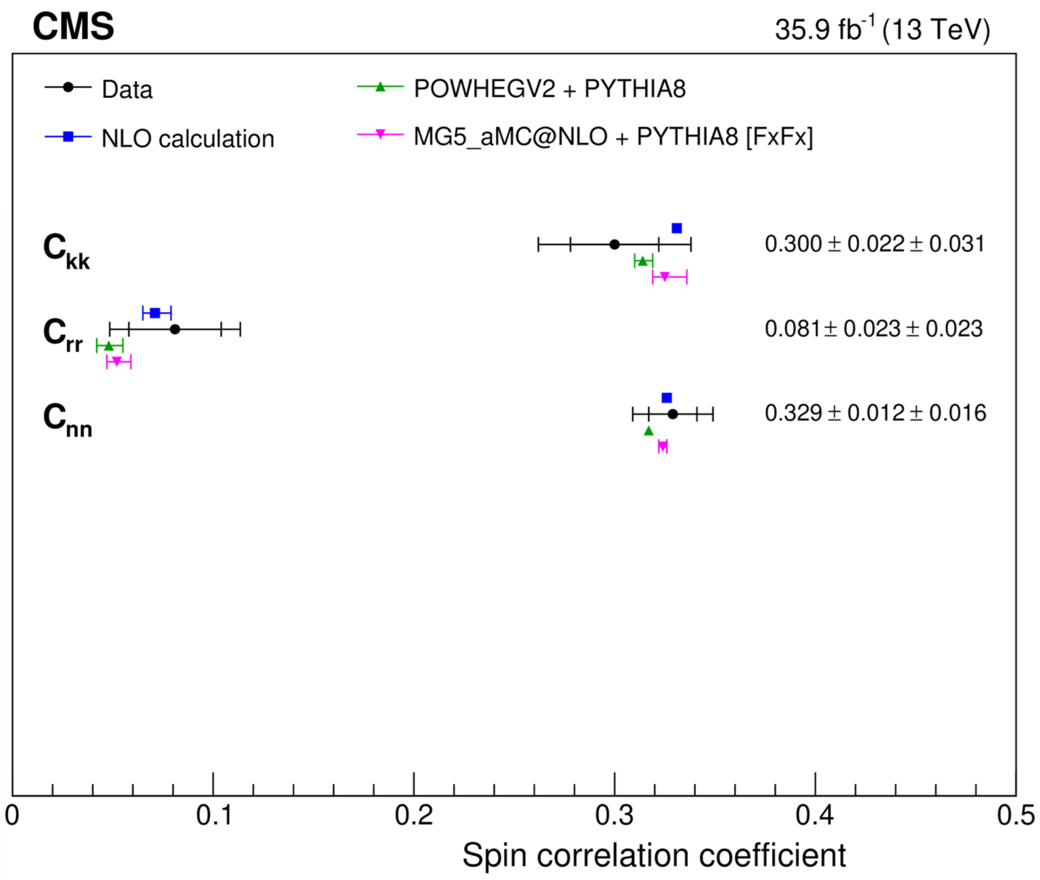



[PRD 100 (2019) 072002]

# 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

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

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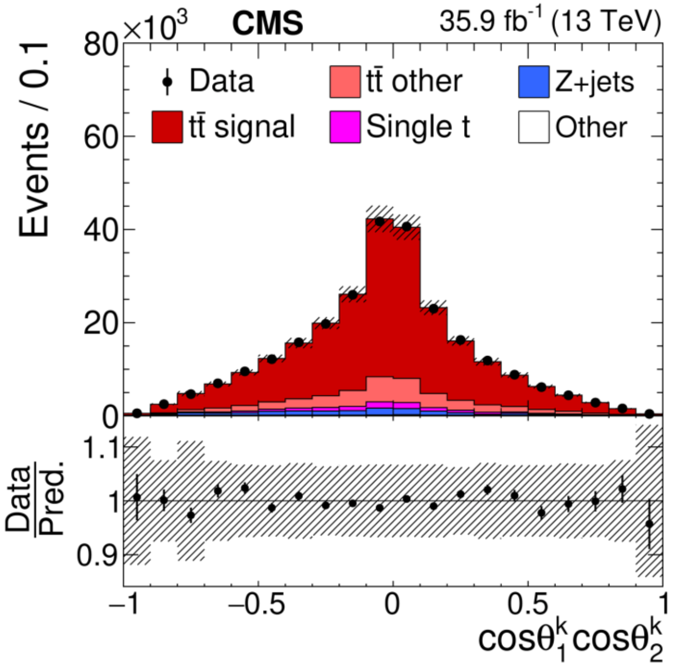


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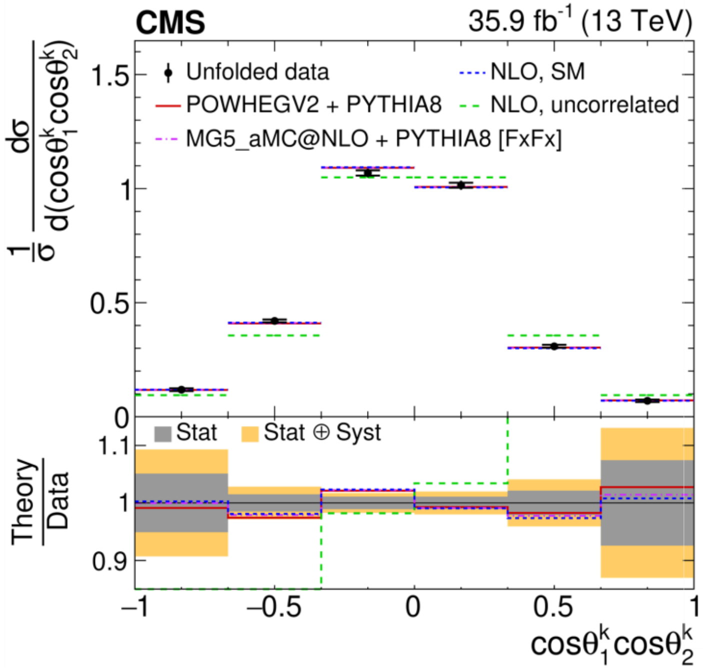


# How to probe entanglement

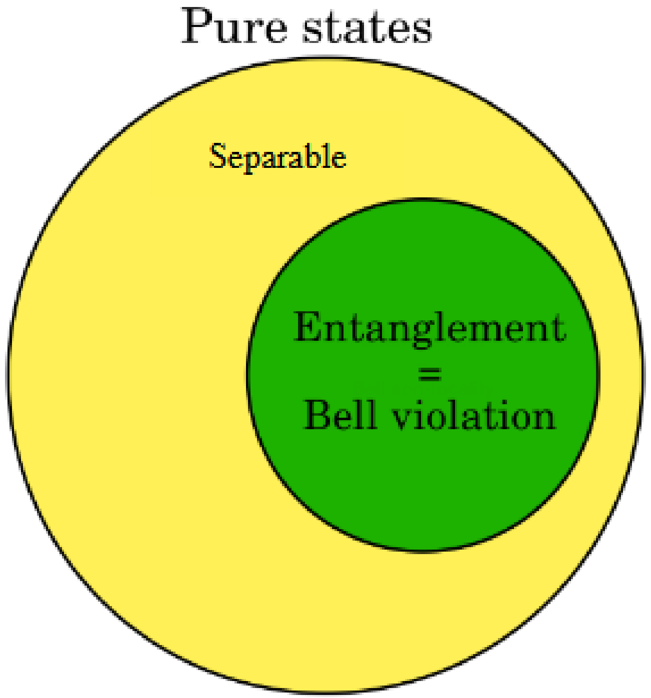
- What does it mean to be **not** entangled? **Separable**!

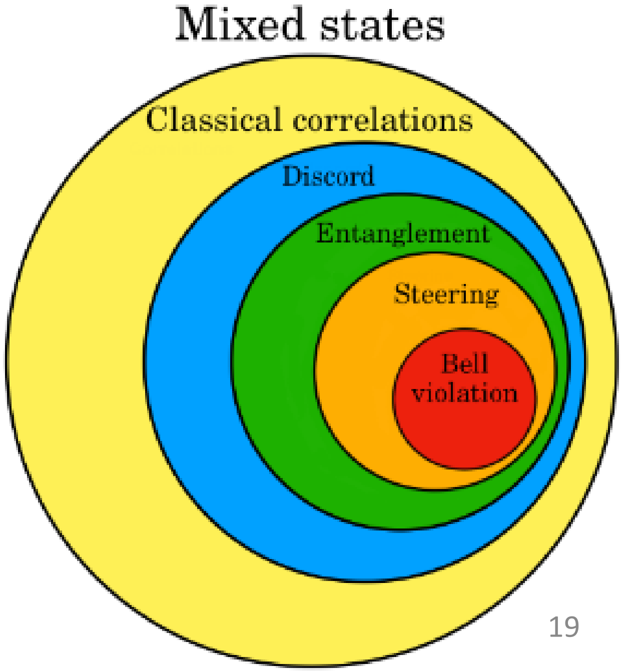
$$|\psi\rangle = |a\rangle_A \otimes |b\rangle_B$$

- 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

- Perform operation (anti-unitary) on subspace (e.g. A)
- 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, $\rho$
- 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** $m(t\bar{t})$

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

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

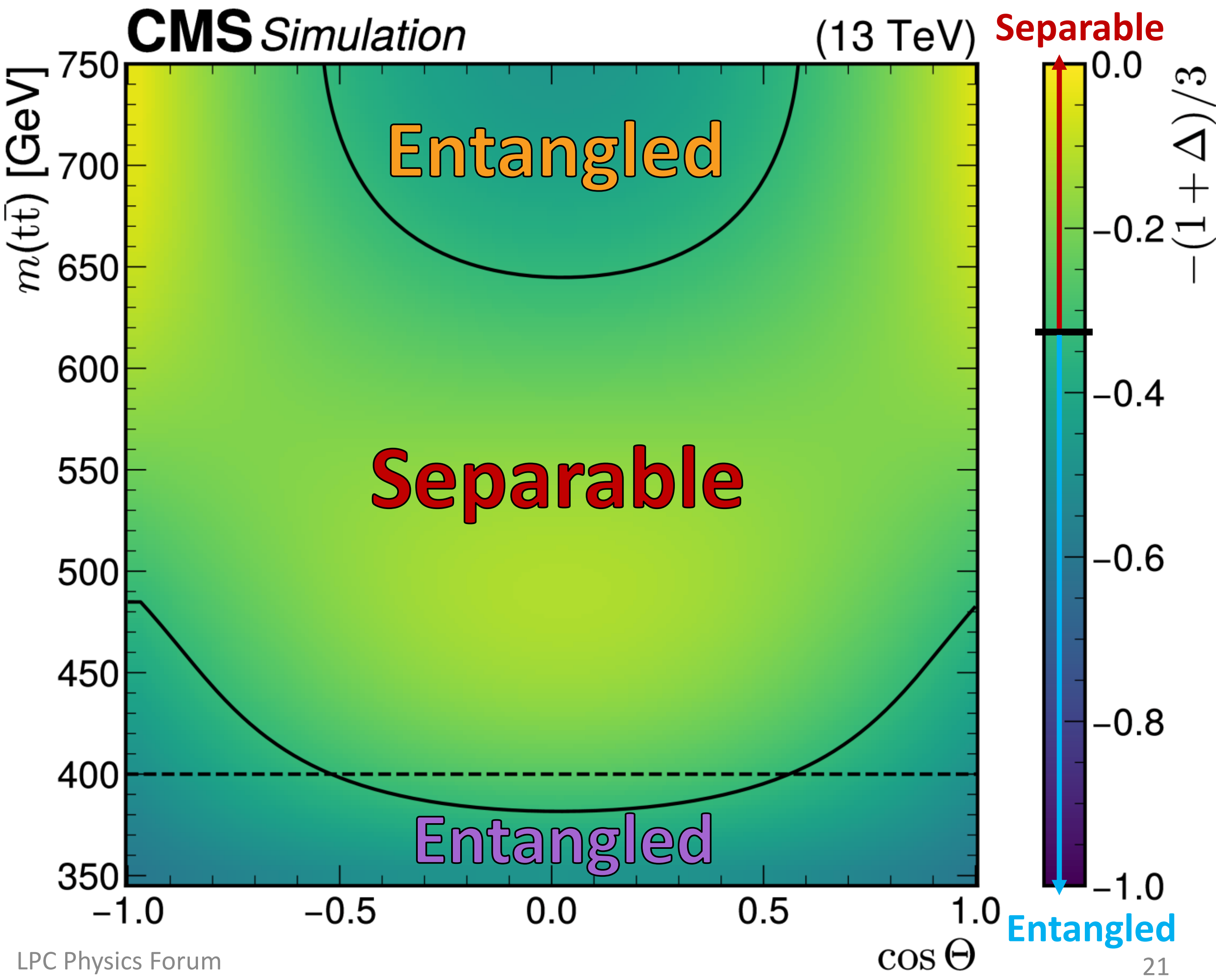
$$D < -\frac{1}{3} \rightarrow \textbf{entangled!}$$

**Measure $D$ to access entanglement information!**

Rep. Prog. Phys. **87** 117801

# How to discover entangled top quarks

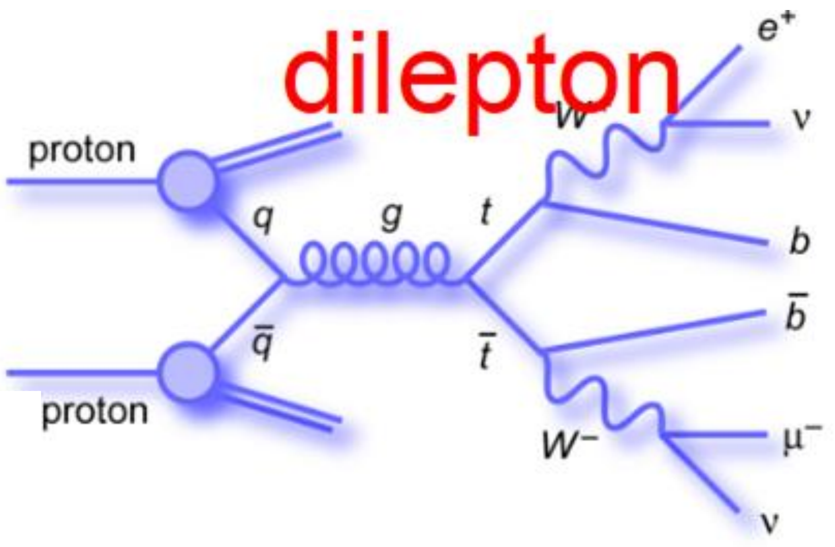
- CMS probed the **production threshold region** for entanglement
- Mostly **timelike** (**spacelike**) separated decays in **production threshold** (**boosted**) region

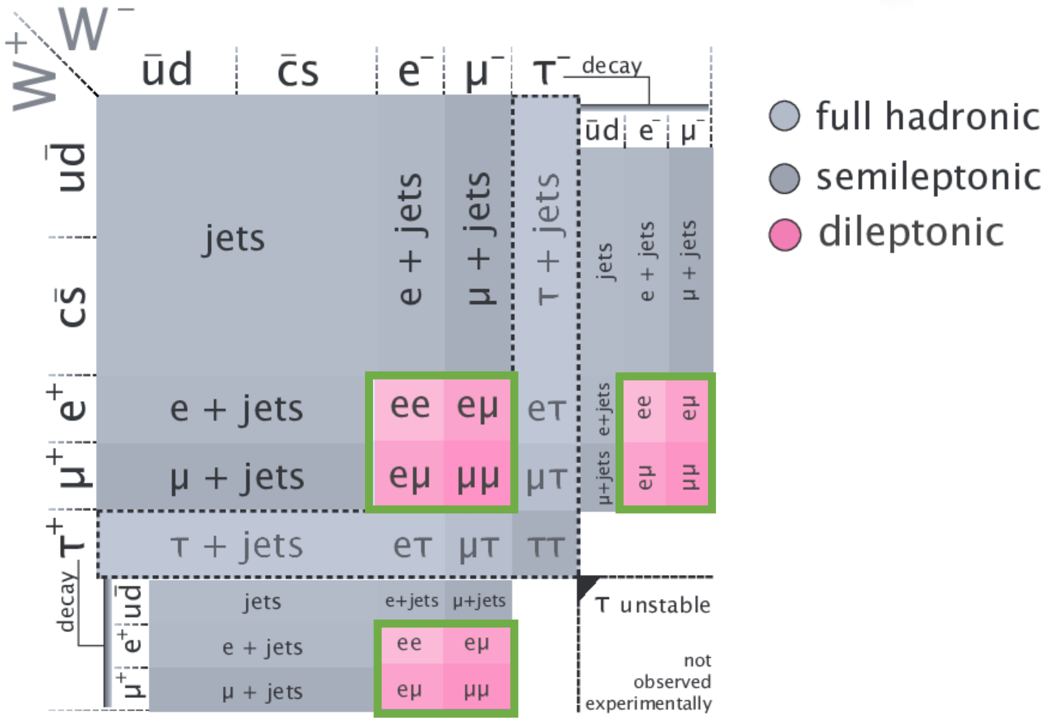


[Rep. Prog. Phys. **87** 117801]

# Event selection

- Dileptonic channel ($ee/\mu\mu/e\mu$) w/ 2016 data
- 2 oppositely charged isolated leptons (ee, eμ and μμ)
  - Leptonic decays of taus included in signal
  - $p_{\mathrm{T}}$ &|η| cuts applied to tight electrons & muons
  - Veto events with more than two leptons
- Low $m_{l\bar{l}}$ events rejected
- ≥ 2 anti-$k_t$ jets (R=0.4)
  - $p_{\mathrm{T}}$ & |η| cuts applied
  - Jet cleaning & iCSVv2 loose working point
- ee, μμ channels have additional selection criteria applied to reduce Drell-Yan background
- Reject events failing kinematic reconstruction constraints



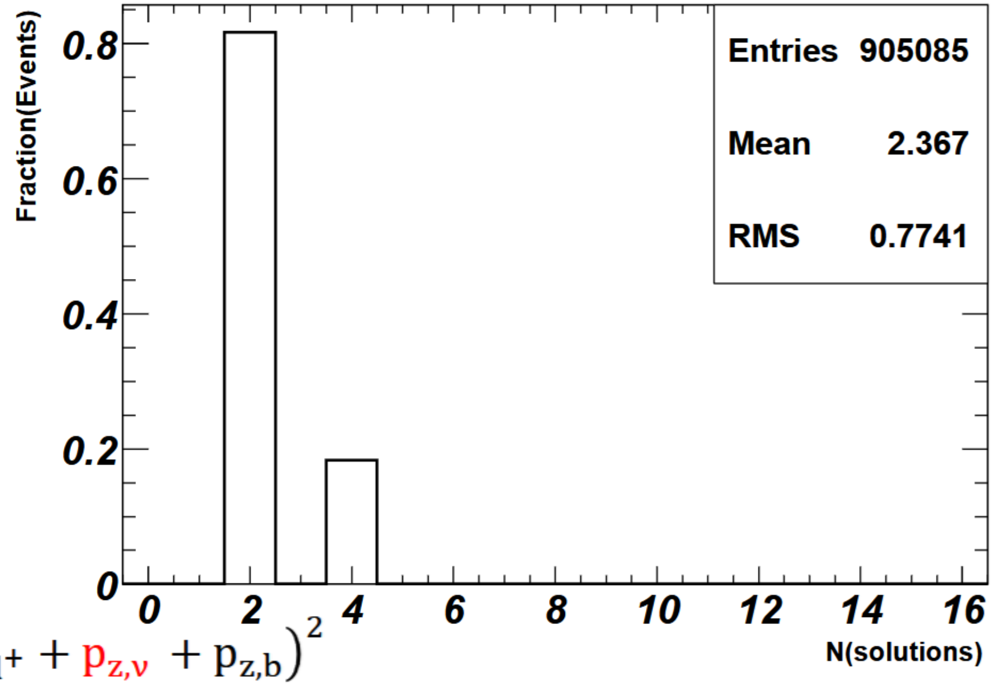
# Dileptonic Top Quark Reconstruction

[Phys. Rev. D **73**, 054015](#)

- Use algebraic method to solve for neutrino 3-vectors
- Results in quartic equation for neutrino momenta

$$0 = \sum_{i=0}^{4} c_i(m_t, p_{\ell^+}, p_{\ell^-}, p_b, p_{\bar{b}})\, p_x(\bar{\nu})^i$$

- Pick solution that has lowest $m(t\bar{t})$




$$m_t^2 = (E_{l^+} + E_\nu + E_b)^2 - (p_{x,l^+} + p_{x,\nu} + p_{x,b})^2 - (p_{y,l^+} + p_{y,\nu} + p_{y,b})^2 - (p_{z,l^+} + p_{z,\nu} + p_{z,b})^2$$

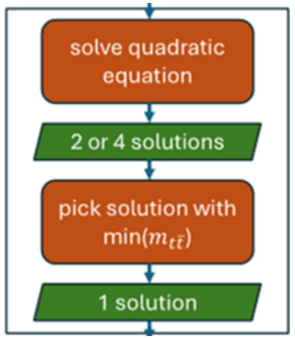
$$m_{\bar{t}}^2 = (E_{l^-} + E_{\bar{\nu}} + E_{\bar{b}})^2 - (p_{x,l^-} + p_{x,\bar{\nu}} + p_{x,\bar{b}})^2 - (p_{y,l^-} + p_{y,\bar{\nu}} + p_{y,\bar{b}})^2 - (p_{z,l^-} + p_{z,\bar{\nu}} + p_{z,\bar{b}})^2$$

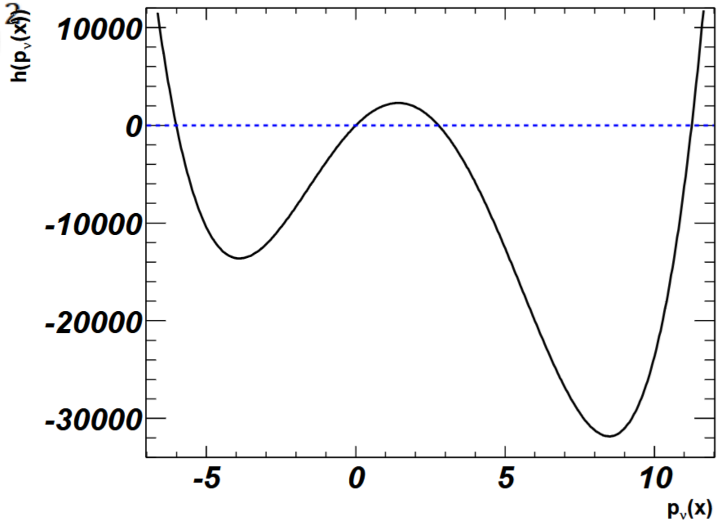
$$m_{W^+}^2 = (E_{l^+} + E_\nu)^2 - (p_{x,l^+} + p_{x,\nu})^2 - (p_{y,l^+} + p_{y,\nu})^2 - (p_{z,l^+} + p_{z,\nu})^2$$

$$m_{W^-}^2 = (E_{l^-} + E_{\bar{\nu}})^2 - (p_{x,l^-} + p_{x,\bar{\nu}})^2 - (p_{y,l^-} + p_{y,\bar{\nu}})^2 - (p_{z,l^-} + p_{z,\bar{\nu}})^2$$

$$E_x^{MET} = p_{x,\nu} + p_{x,\bar{\nu}}$$

$$E_y^{MET} = p_{y,\nu} + p_{y,\bar{\nu}}$$

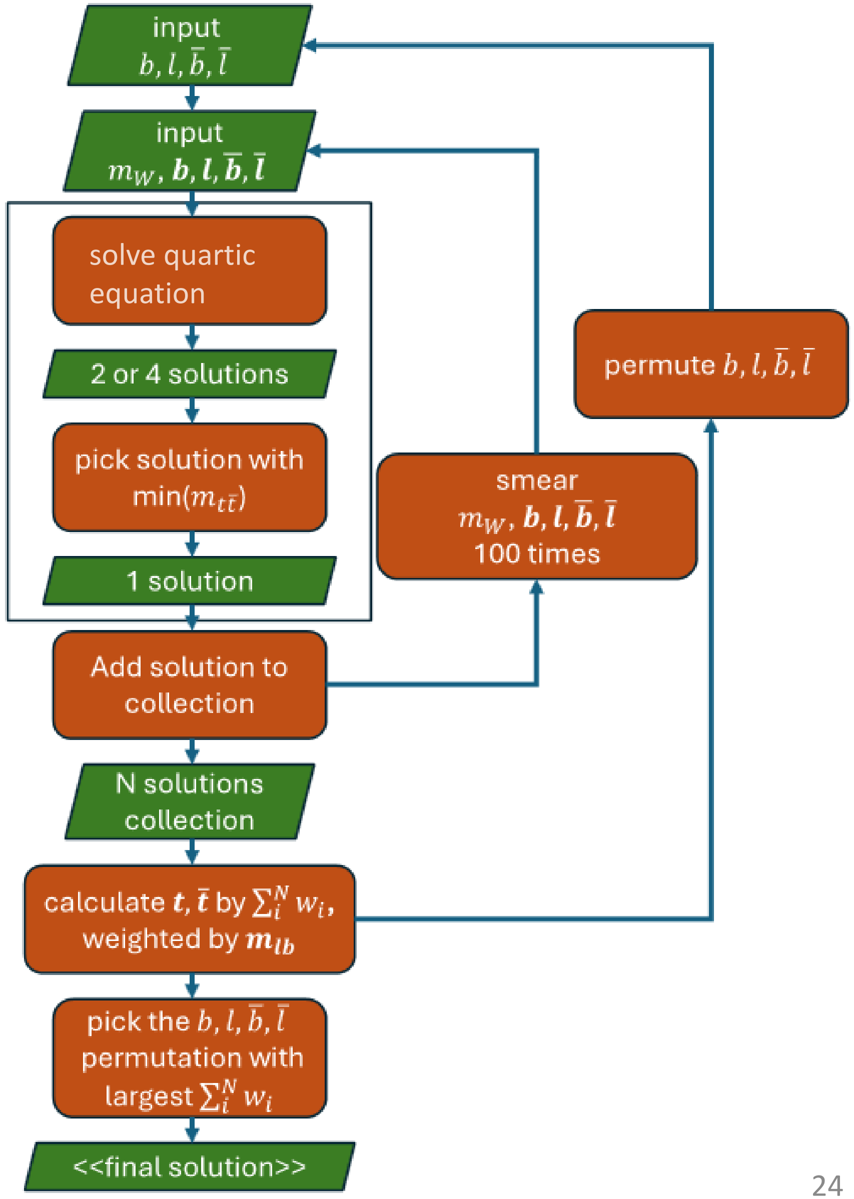


# Top Quark Reconstruction – $m_{\ell b}$ method

TOP-23-006, TOP-23-001, TOP-20-006, TOP-18-006, TOP-18-004, TOP-17-014, TOP-16-011, TOP-16-007, TOP-15-010, TOP-12-028

1. Sample W boson mass from Breit-Wigner
2. Solve quartic equation and pick solution that has lowest $\mathrm{m}(\mathrm{t}\bar{\mathrm{t}})$
3. Repeat process 100x smearing leptons & b jets within resolution & resampling W mass
4. Compute solution as weighted sum from smears weighted by true $m_{\ell b}$ distribution
5. Pick jet-parton assignment that maximizes sum of weights



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# Bumblebee: Foundation Model for Particle Physics Discovery

arXiv:2412.07867v1


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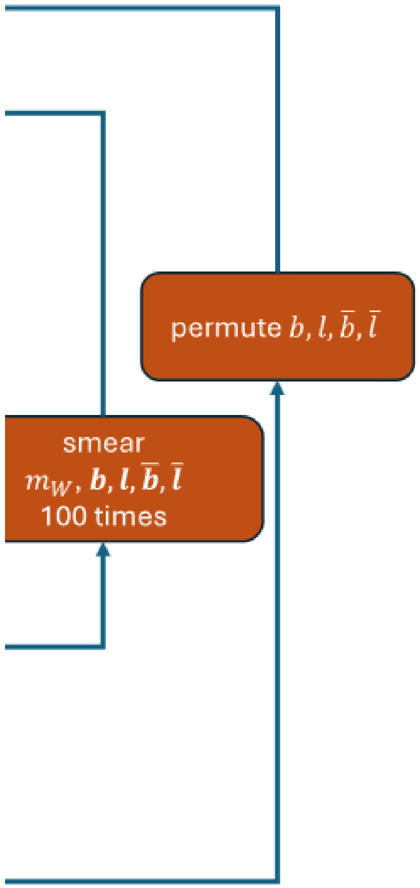

# Top Quar

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**Bumblebee: Foundation Model for Particle Physics Discovery**

[arXiv:2412.07867v1](https://arxiv.org/abs/2412.07867v1)


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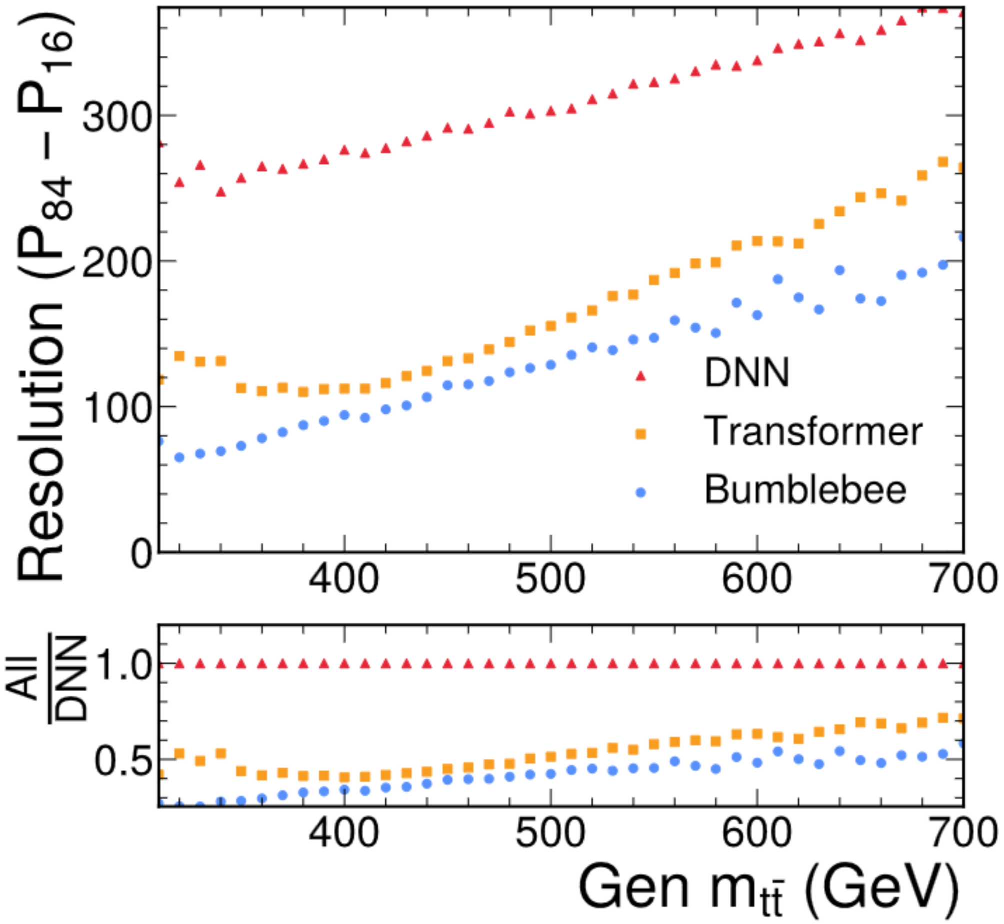
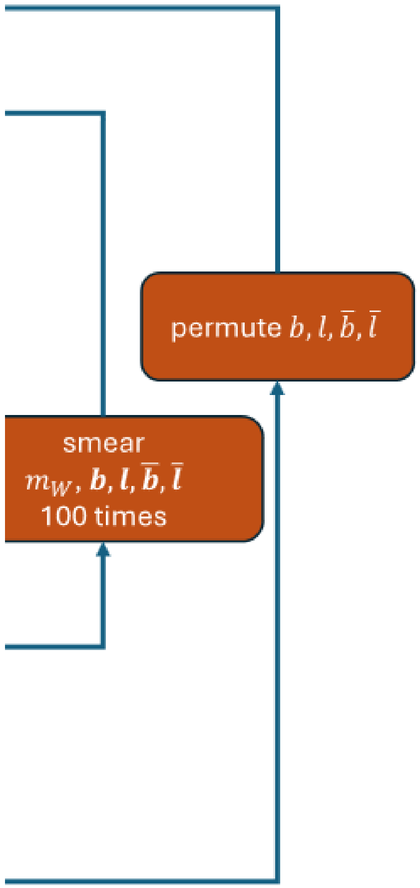
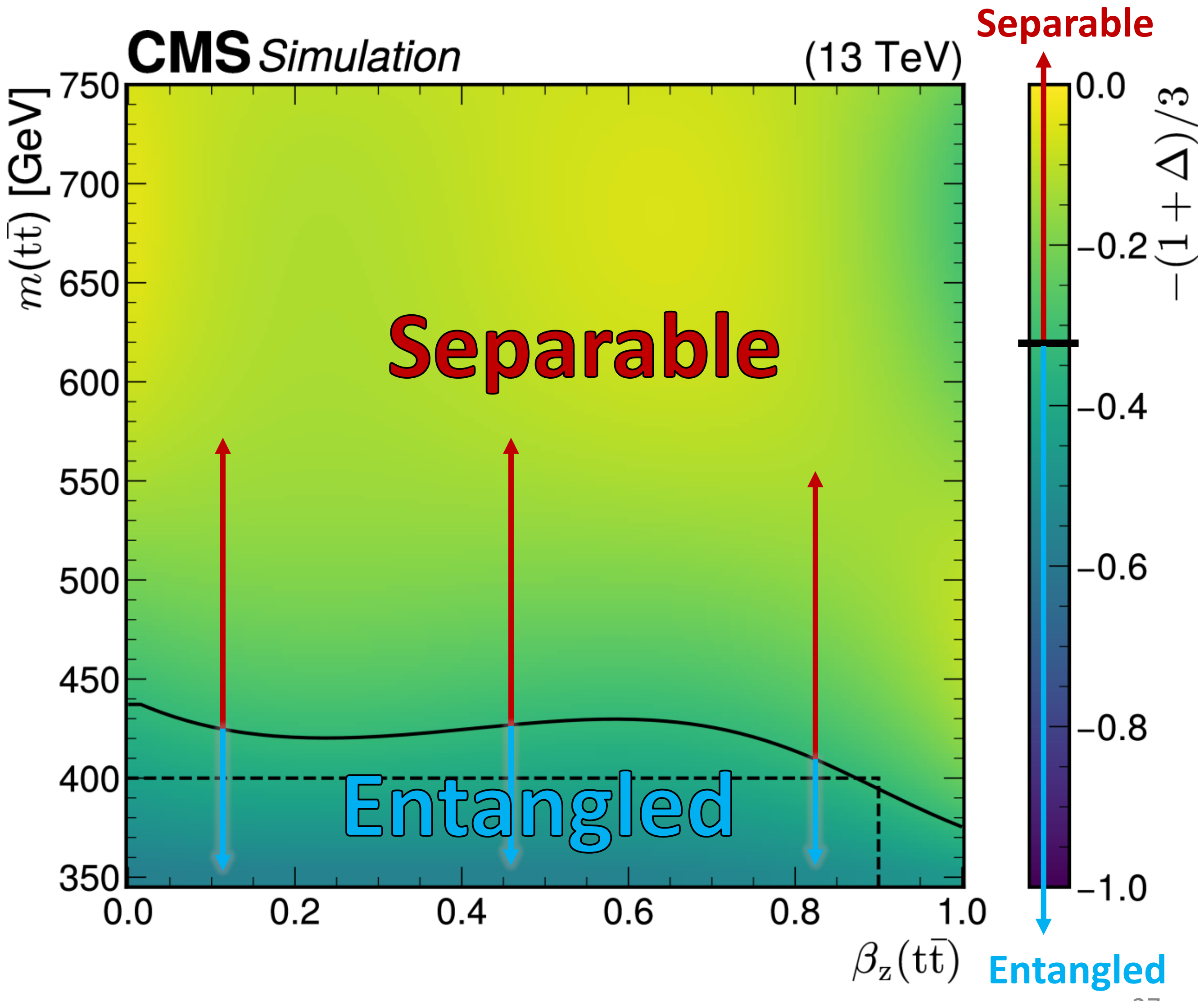


# Measurement of Entanglement in Threshold Region - Method

- 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 &
    $\beta_z(\mathrm{t\bar{t}}) < 0.9$

Rep. Prog. Phys. **87** 117801



Comp. Softw. Big Sci. 8 (2024) 19

# Profile Maximum Likelihood fit - COMBINE

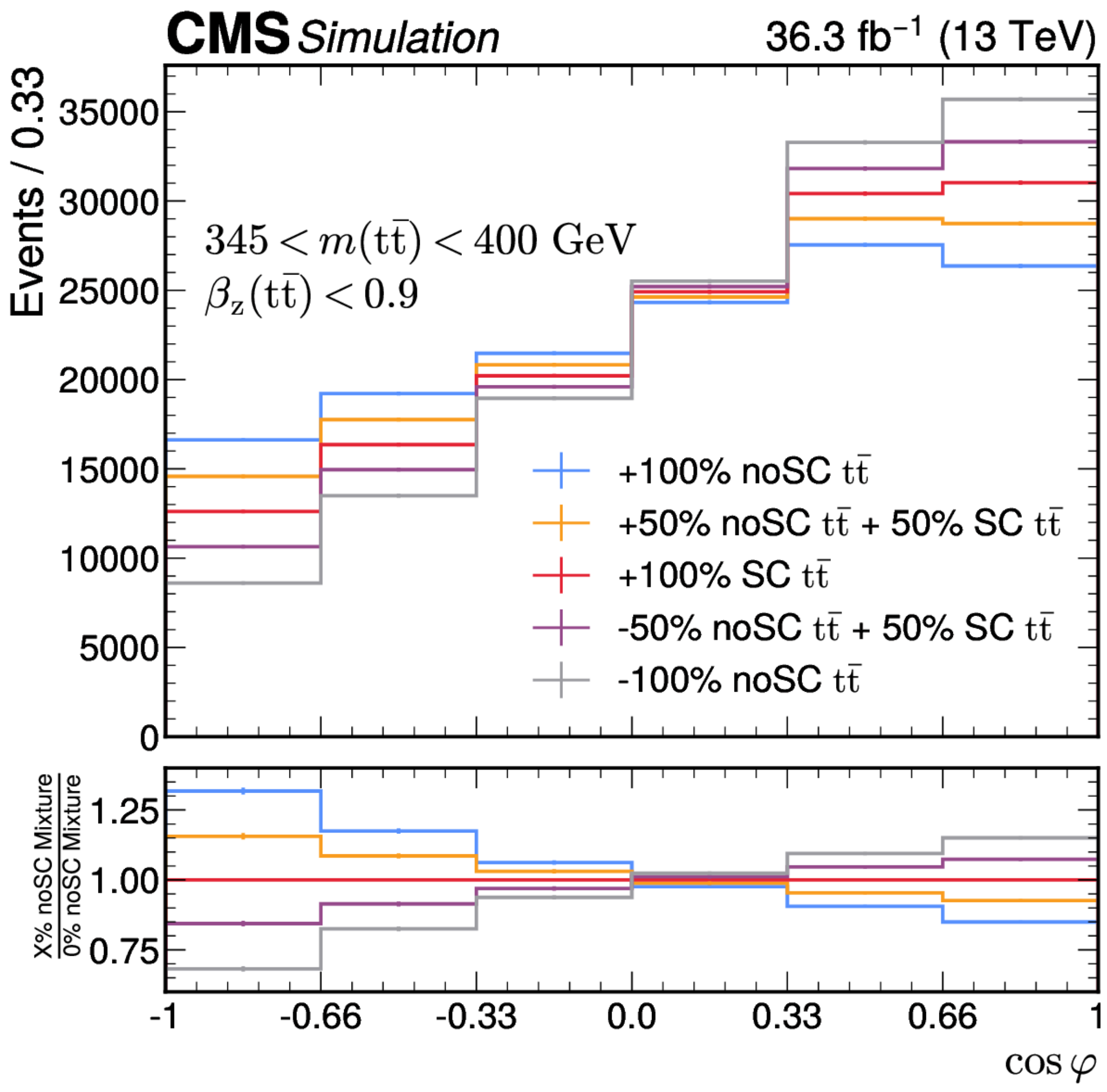
$$\mathcal{L} = \prod_{c\in channels} \prod_{b\in bins_c} Pois(n_{cb}|\nu_{cb}(\mathrm{H},\mathrm{X})) \prod_{\chi\in\mathbf{X}} p_\chi(a_\chi|\chi)$$

- Channels are statistically independent "channels". Can be decay topology for example (ee vs. e$\mu$ vs. $\mu\mu$)
  - We only performed the fit in a single channel – "combined"
- $n_{cb}$ is number of observed events
- $\nu_{cb}$ is number of expected events
- $\eta \in \mathrm{H}$ are unconstrained nuisance parameters meaning they have no prior
  - Signal strength modifier is typically an unconstrained nuisance
  - D is also unconstrained in our fit and we freeze signal strength modifier
- $\chi \in \mathrm{X}$ are constrained nuisance parameters meaning we know/can estimate their prior probability distribution
  - $a_\chi$ are parameters/inputs for the prior (auxiliary measurements)
  - All of our priors are either log normal or shape-based

# Measurement of Entanglement in Threshold Region - Method

- Need to fit POI $\mathrm{D}$
  - Q: How to create variations of $\mathrm{D}$?
  - 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 $[-1, \mathrm{D_{SM}}]$

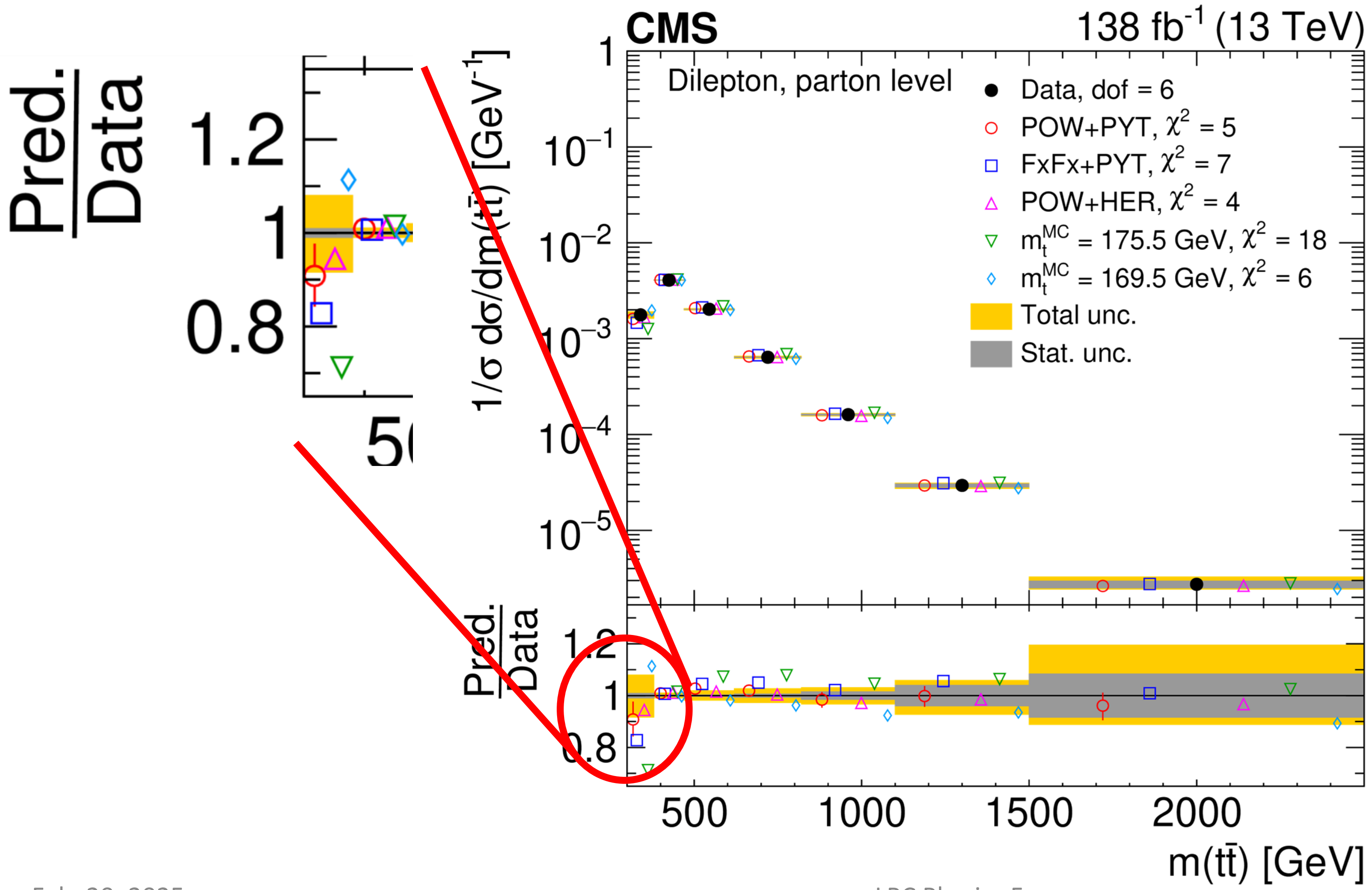
*Rep. Prog. Phys.* **87** 117801



# Measurement of Entanglement in Threshold Region

- Large mismodeling seen for $m(t\bar{t}) \approx 345$ GeV

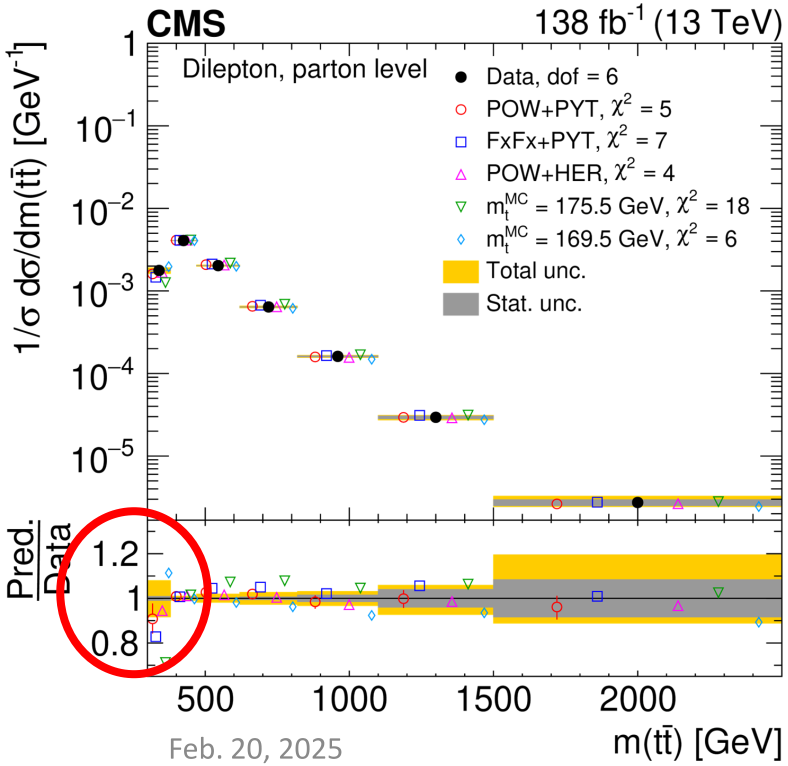
[JHEP (2025), 64]



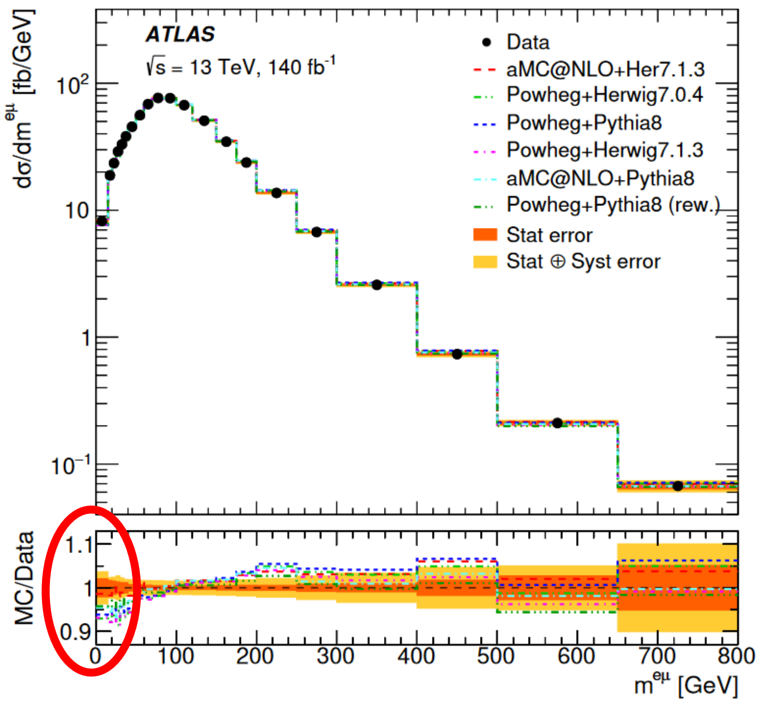
# Measurement of Entanglement in Threshold Region

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

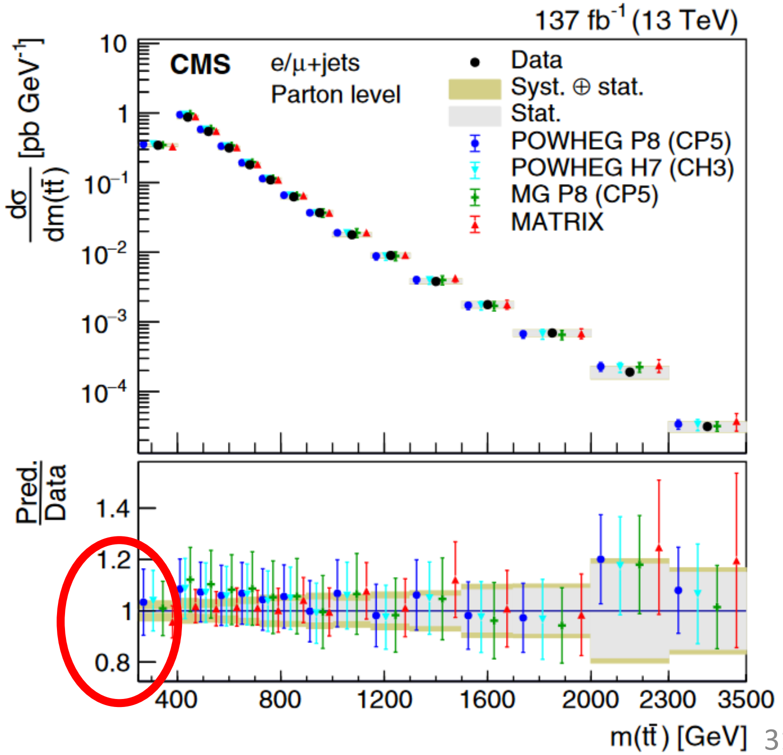
JHEP (**2025**), 64




JHEP 07 (2023) 141



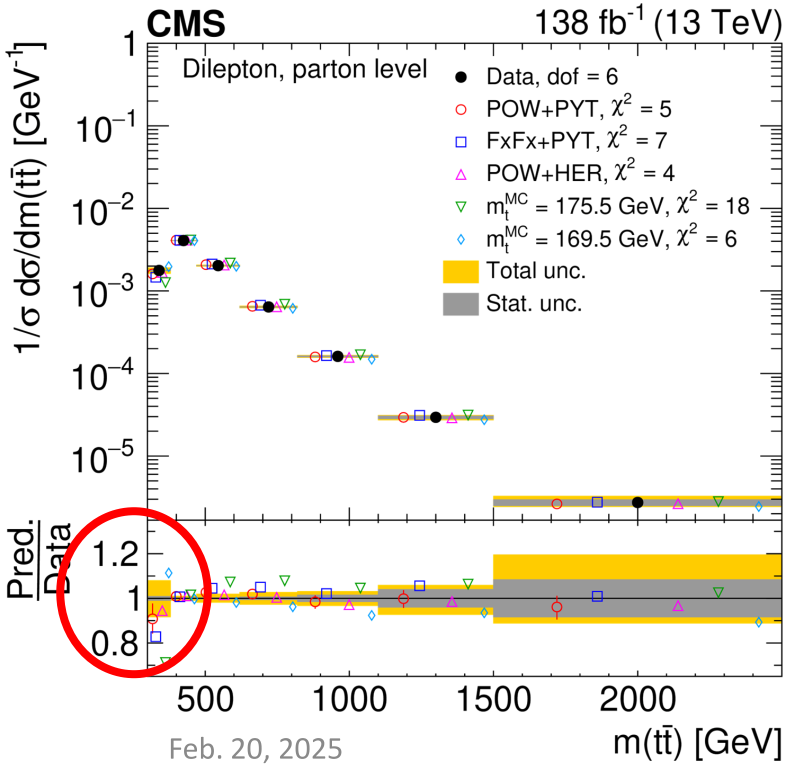

Phys. Rev. D 104, 092013



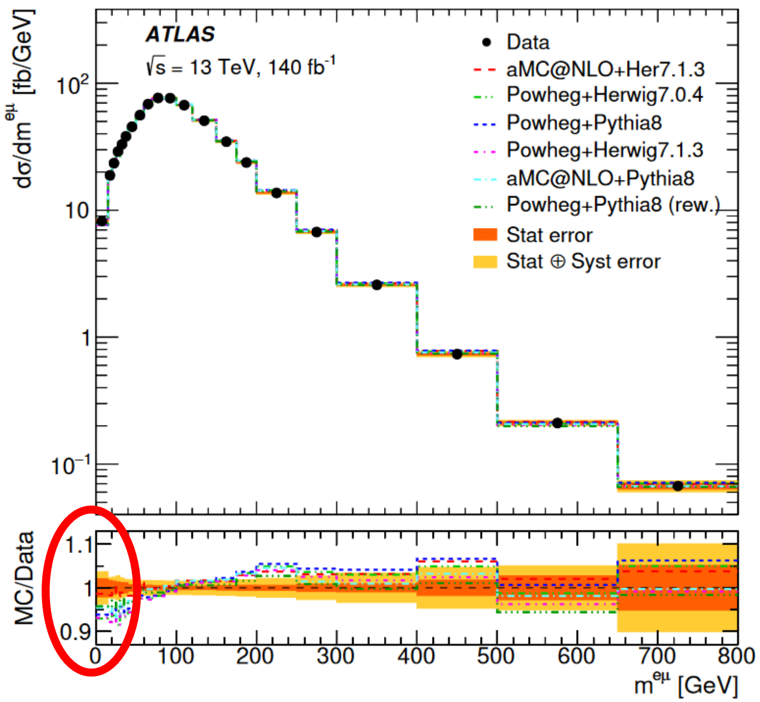
# Measurement of Entanglement in Threshold Region

- 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 $^1S_0^{[1]}$

JHEP (**2025**), 64

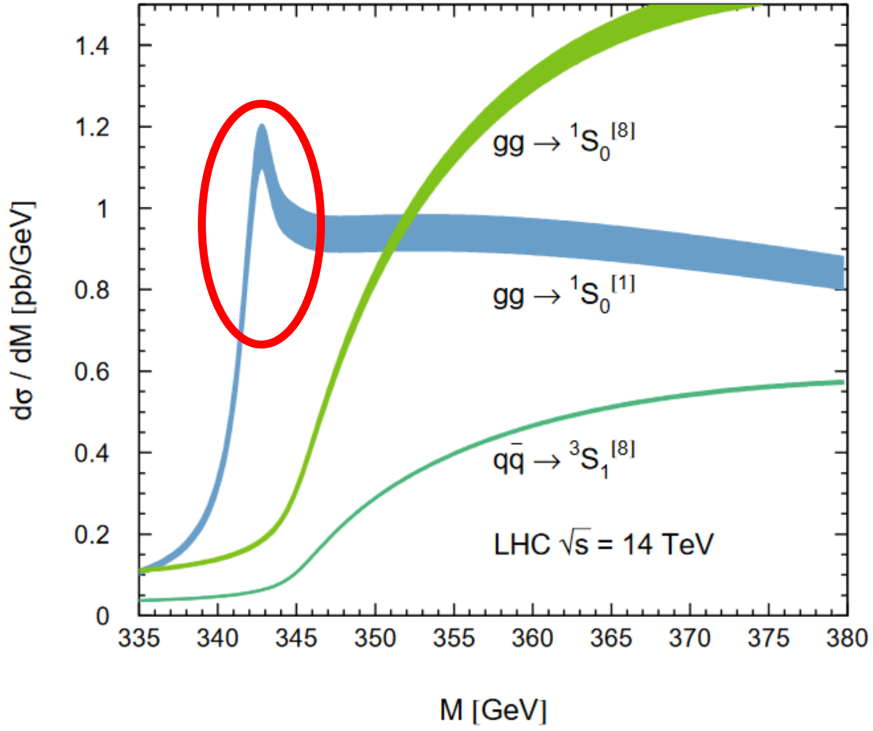



JHEP 07 (2023) 141




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

EPJC 60, 375 (2009)



# 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 → $D = 0$
- Can create new samples with mixtures of SM and no spin corr.
- These mixtures only probe $[D_{SM}, 0]$→ ~~Mirror to probe $[-1, D_{SM}]$~~

- For $\eta_t$ we cannot mirror templates →
- Performed the fit both including & excluding the ground state of **toponium, $\eta_t$**

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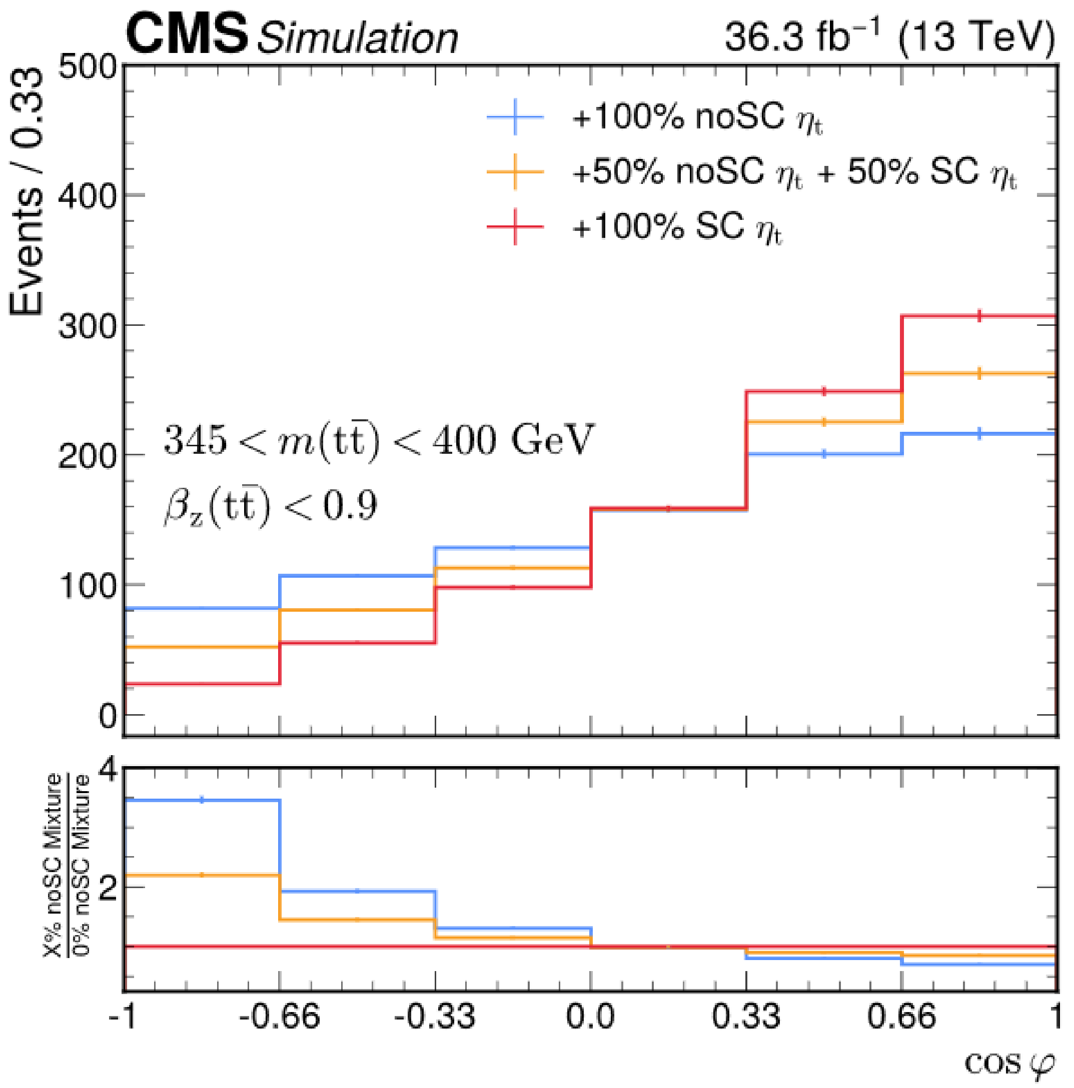
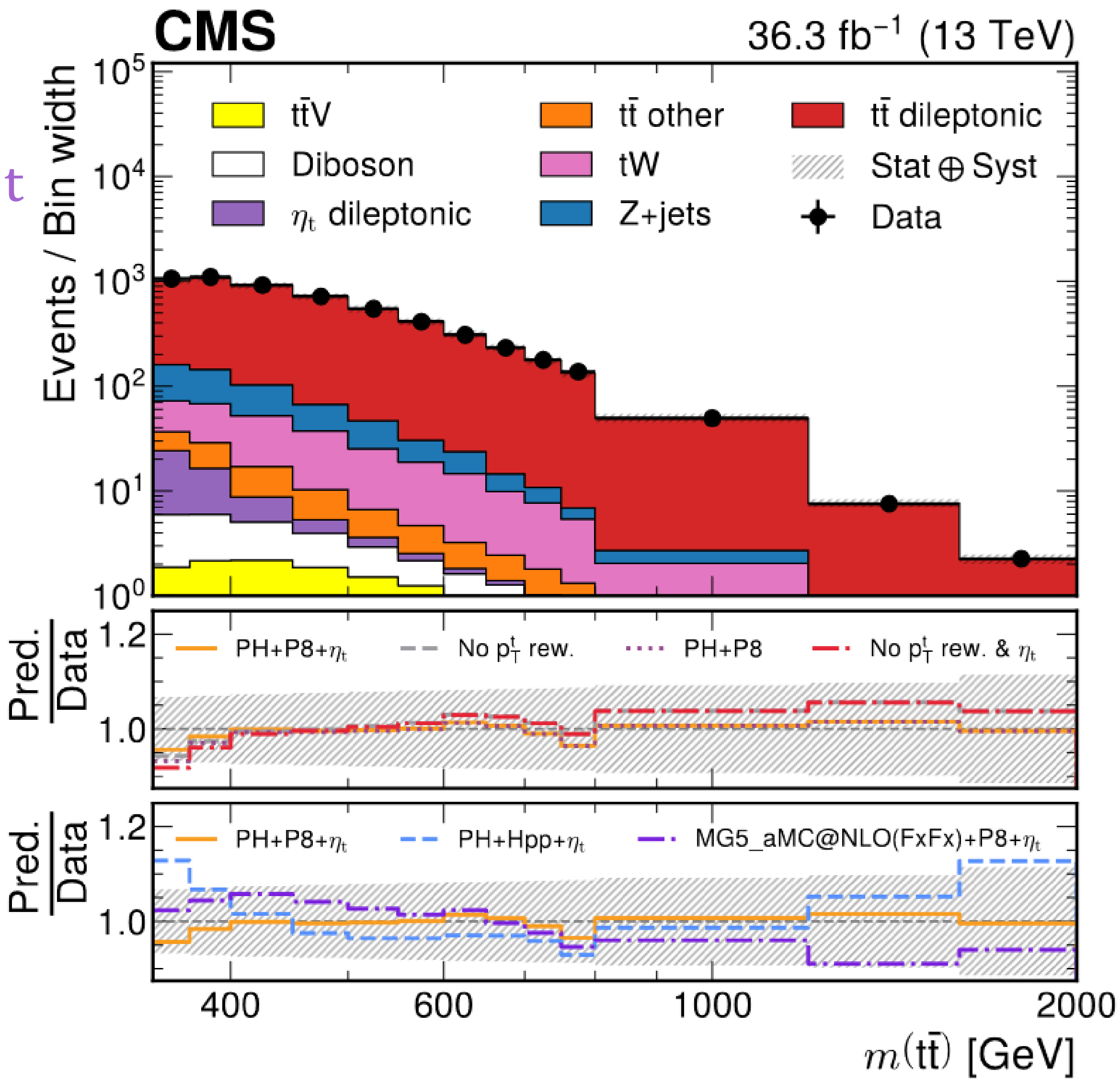


# Pre-fit Distributions

Rep. Prog. Phys. **87** 117801

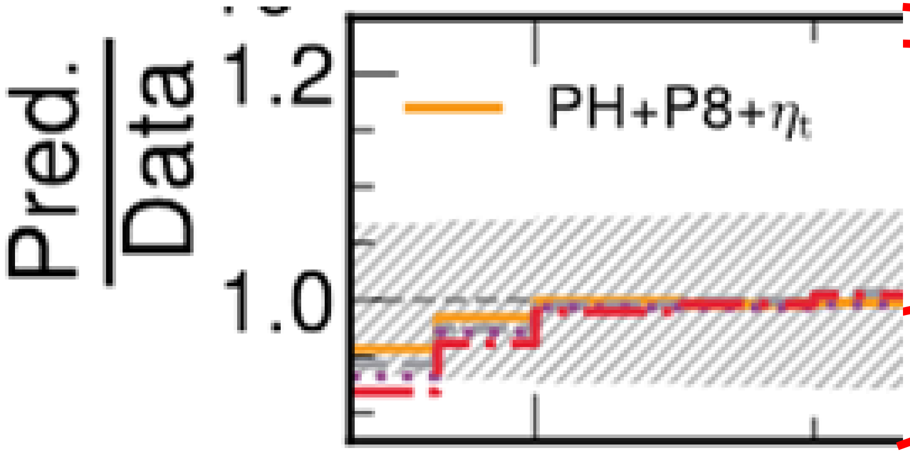
- Better agreement when including $\eta_t$

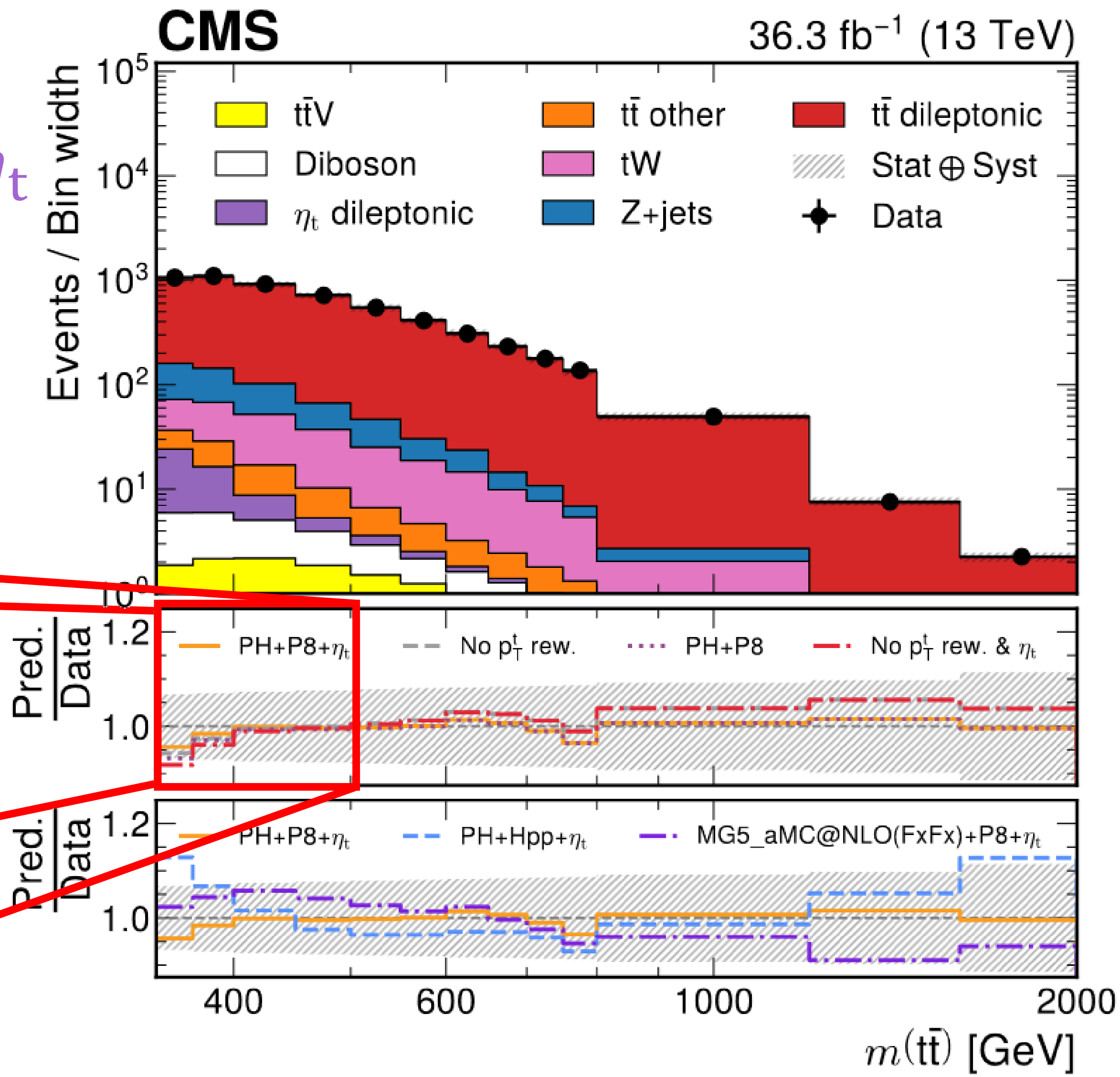


# Pre-fit Distributions

[Rep. Prog. Phys. **87** 117801]

- Better agreement when including $\eta_t$

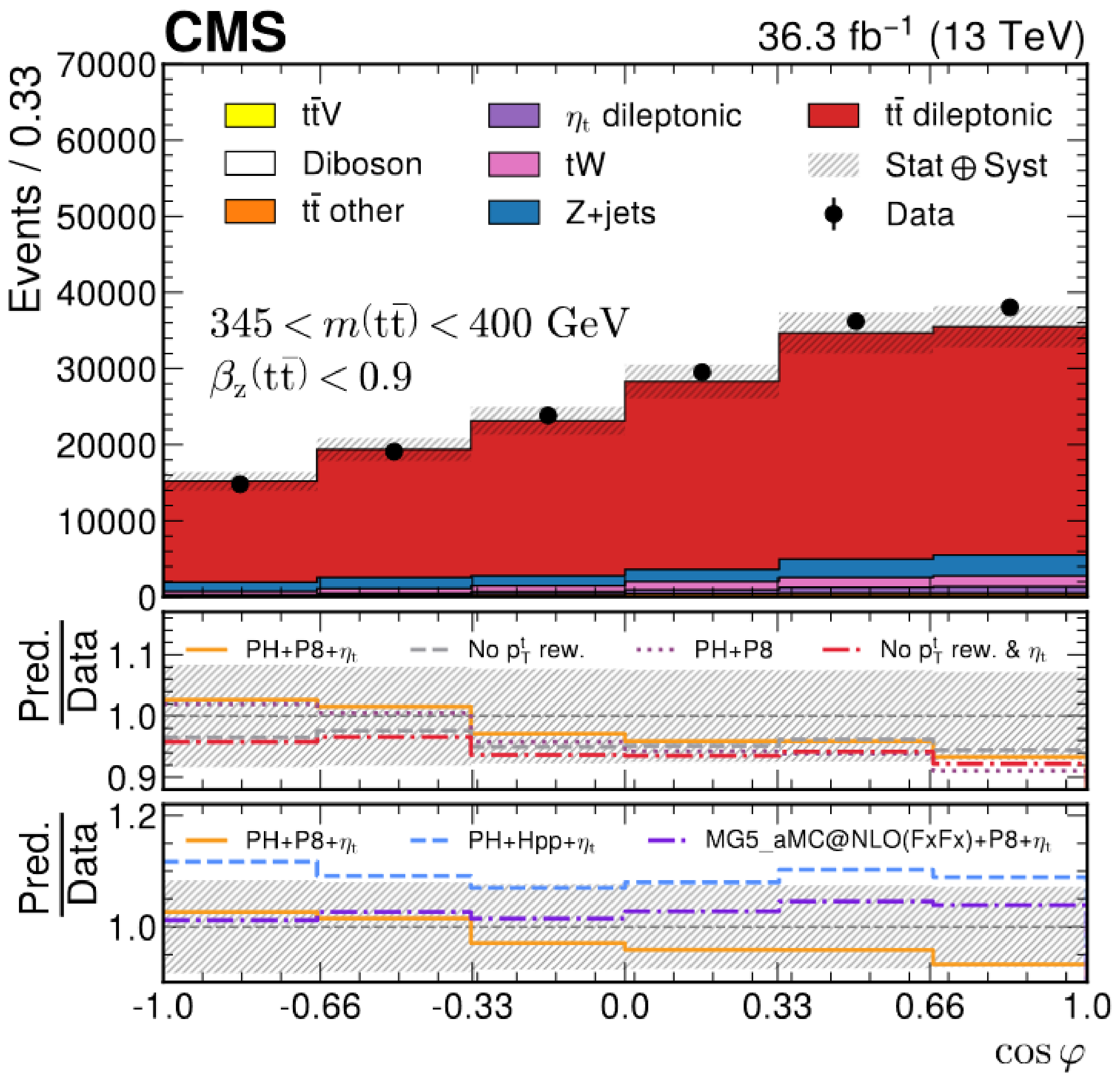


# Pre-fit Distributions

[Rep. Prog. Phys. **87** 117801]

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



# Corrections and Uncertainties

[Rep. Prog. Phys. **87** 117801]

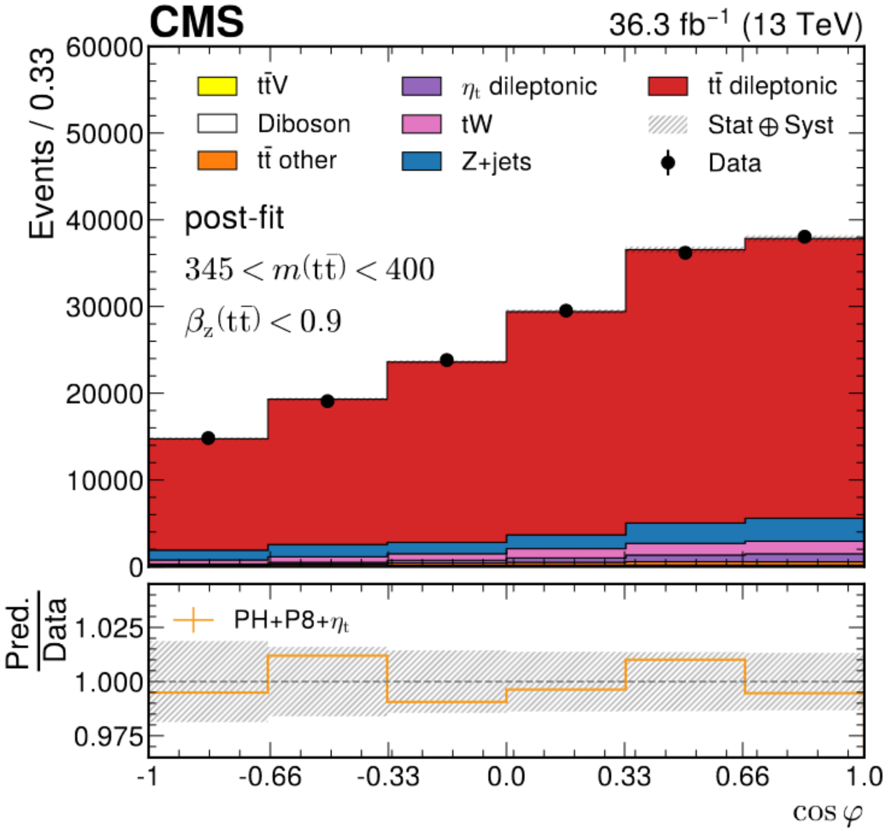
- Entanglement observed via slope parameter ***D*** → shape of $cos\varphi$ is important
- Leading systematics
  - Jet Energy Scale (JES)
  - $\eta_{\mathrm{t}}$ normalization
  - Parton shower Initial state radiation (ISR)/Final state radiation (FSR)
  - Top quark mass
  - NNLO QCD reweighting
  - EWK corrections
  - Z+jets normalization

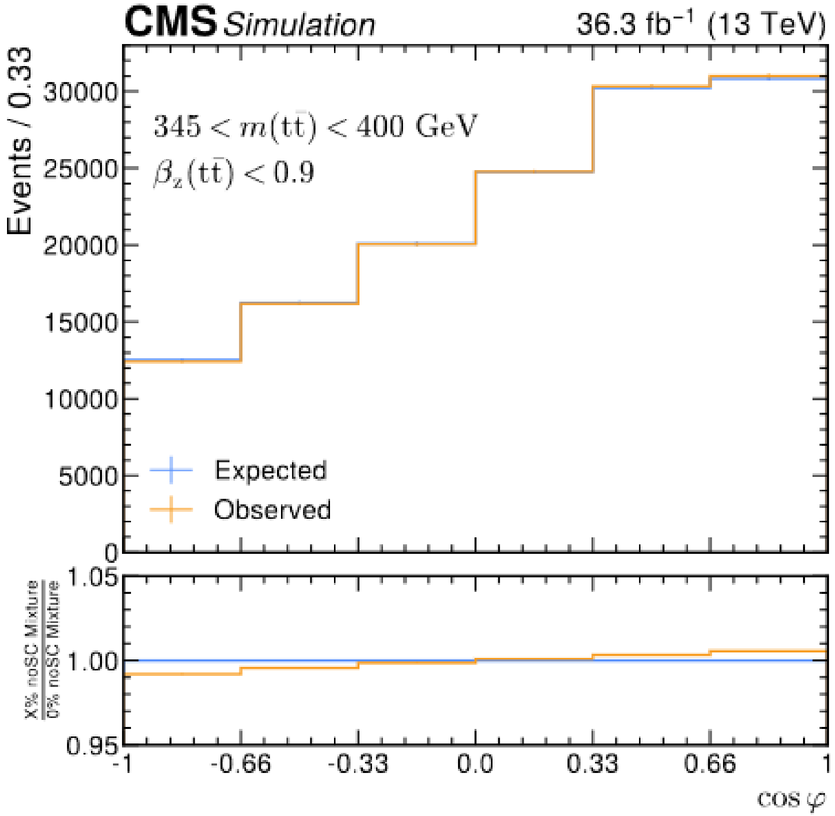
| Uncertainty category | Type | Effect on yield | Effect on shape |
|---|---|---|---|
| *Experimental uncertainties* | | | |
| Trigger efficiency | Shape | 0.5% | 0.2% |
| Lepton ident./isolation | Shape | 3.0% | 0.2% |
| b tagging (heavy) | Shape | 0.6% | 0.1% |
| b tagging (light) | Shape | 0.3% | 0.2% |
| Kinematic reconstruction | Shape | 0.3% | 0.1% |
| JES: Absolute | Shape | 0.9% | 0.3% |
| JES: Absolute (stat) | Shape | 0.4% | 0.2% |
| JES: Pileup | Shape | 0.5% | 0.2% |
| JES: Flavor QCD | Shape | 0.7% | 0.2% |
| JES: Relative balance | Shape | 0.4% | 0.8% |
| JER | Shape | 0.3% | 0.3% |
| Unclustered energy | Shape | 0.2% | 0.3% |
| Pileup | Shape | 0.4% | 0.1% |
| $\mathrm{t\bar{t}}$ normalization | Norm. | 4.4% | 0.3% |
| Z+jets normalization | Norm. | 1.6% | 0.4% |
| Z+jets shape | Shape | 0.2% | 0.2% |
| Luminosity | Norm. | 1.2% | <0.1% |
| *Model uncertainties* | | | |
| Matrix-elem. renorm. scale variation | Shape | 0.4% | 0.3% |
| Matrix-elem. fact. scale variation | Shape | 0.6% | 0.2% |
| Parton shower: Initial-state radiation | Shape | 0.8% | 0.7% |
| Parton shower: Final-state radiation | Shape | 2.1% | 0.4% |
| Top quark mass | Shape | 2.4% | 0.5% |
| ME/parton shower matching | Norm. | 0.8% | <0.1% |
| Underlying event | Norm. | 0.8% | <0.1% |
| PDF | Shape | 0.9% | 0.1% |
| Color reconnection | Norm. | 0.8% | <0.1% |
| b quark fragmentation | Shape | 0.7% | 0.4% |
| B hadron semilept. decays | Shape | 0.3% | 0.2% |
| Branching fraction | Norm. | 1.9% | <0.1% |
| NNLO QCD reweighting | Shape | 0.6% | 0.4% |
| EWK corrections | Shape | 0.6% | 0.4% |
| $\eta_{\mathrm{t}}$ normalization | Norm. | 0.7% | 0.8% |
| $\eta_{\mathrm{t}}$ binding energy | Shape | 0.2% | 0.1% |

# Post-fit Distribution

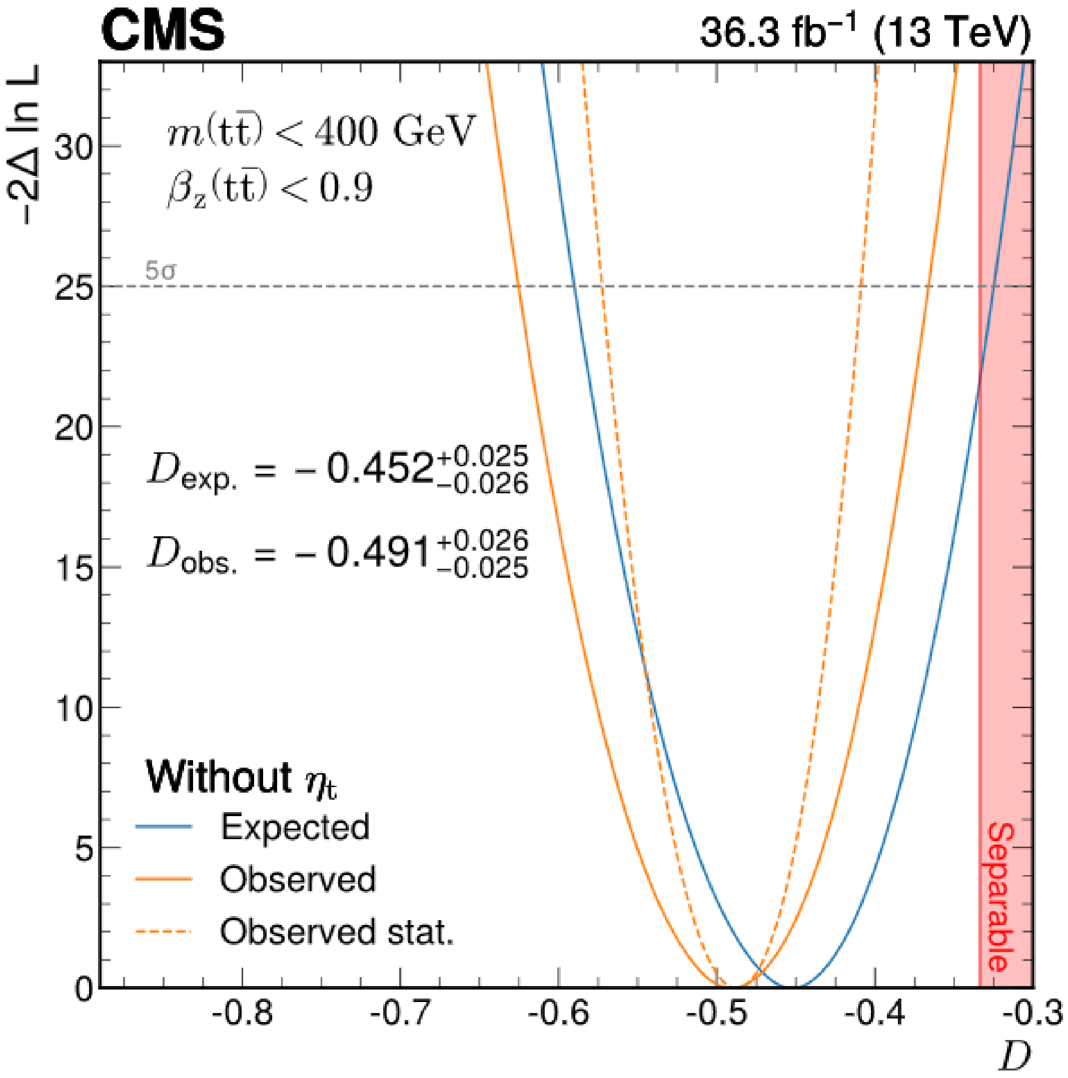
*Rep. Prog. Phys.* **87** 117801

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



# Measurement of Entanglement in Threshold Region - Results

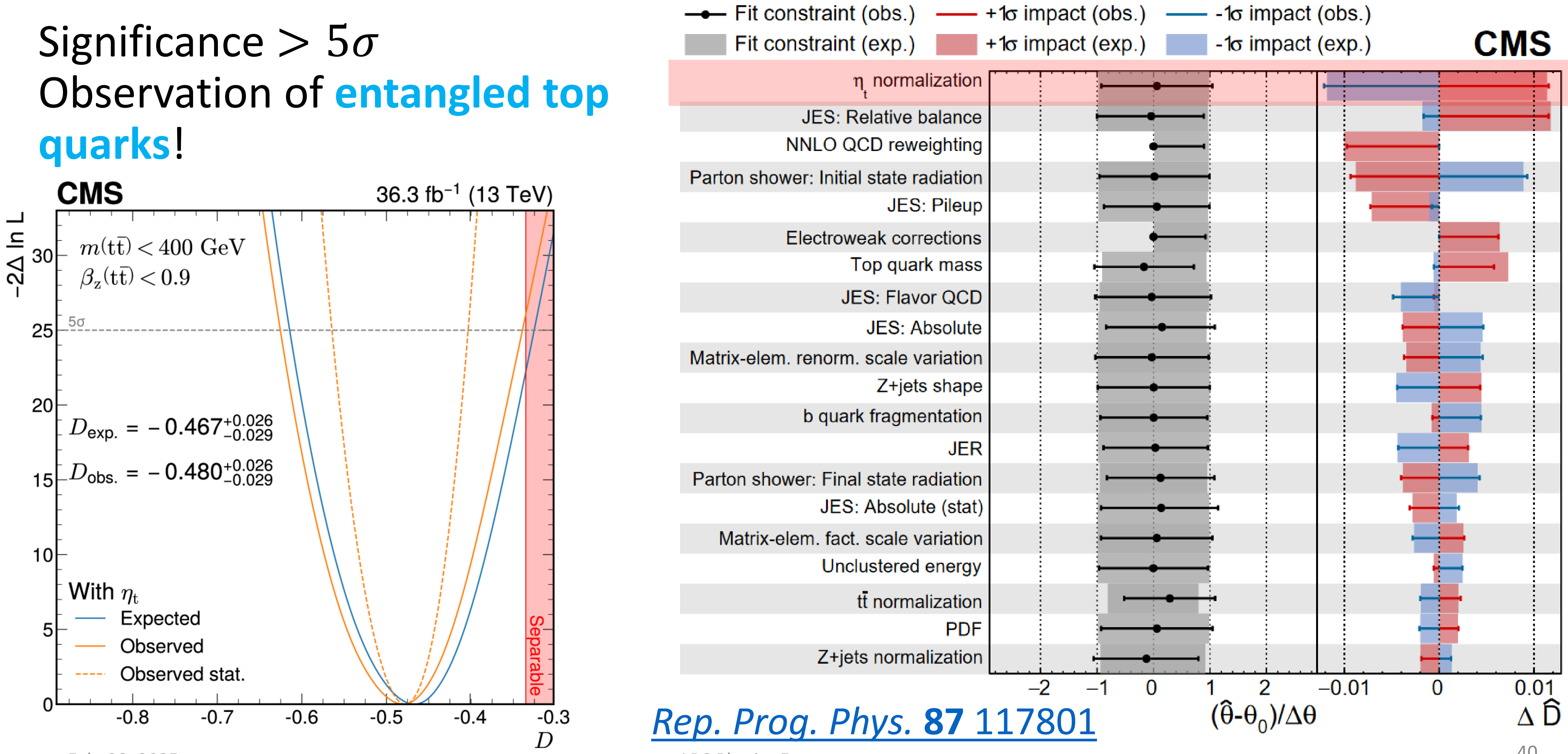



- Significance $> 5\sigma$ when not including uncertainty and effect of $\eta_t$
- Although $\eta_t$ existence hasn't been confirmed experimentally, important to know possible bias & reduction of significance of measurement

*Rep. Prog. Phys.* **87** 117801

# Measurement of Entanglement in Threshold Region - Results

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




[Rep. Prog. Phys. **87** 117801]

# Conclusion

- Top quarks are **entangled**
    - Spins are correlated in a non-classical manner
- First inclusion of bound-state effects in the production threshold region via $\eta_t$
- Start of quantum information studies in high energy physics at the LHC
- New door into "old" physics

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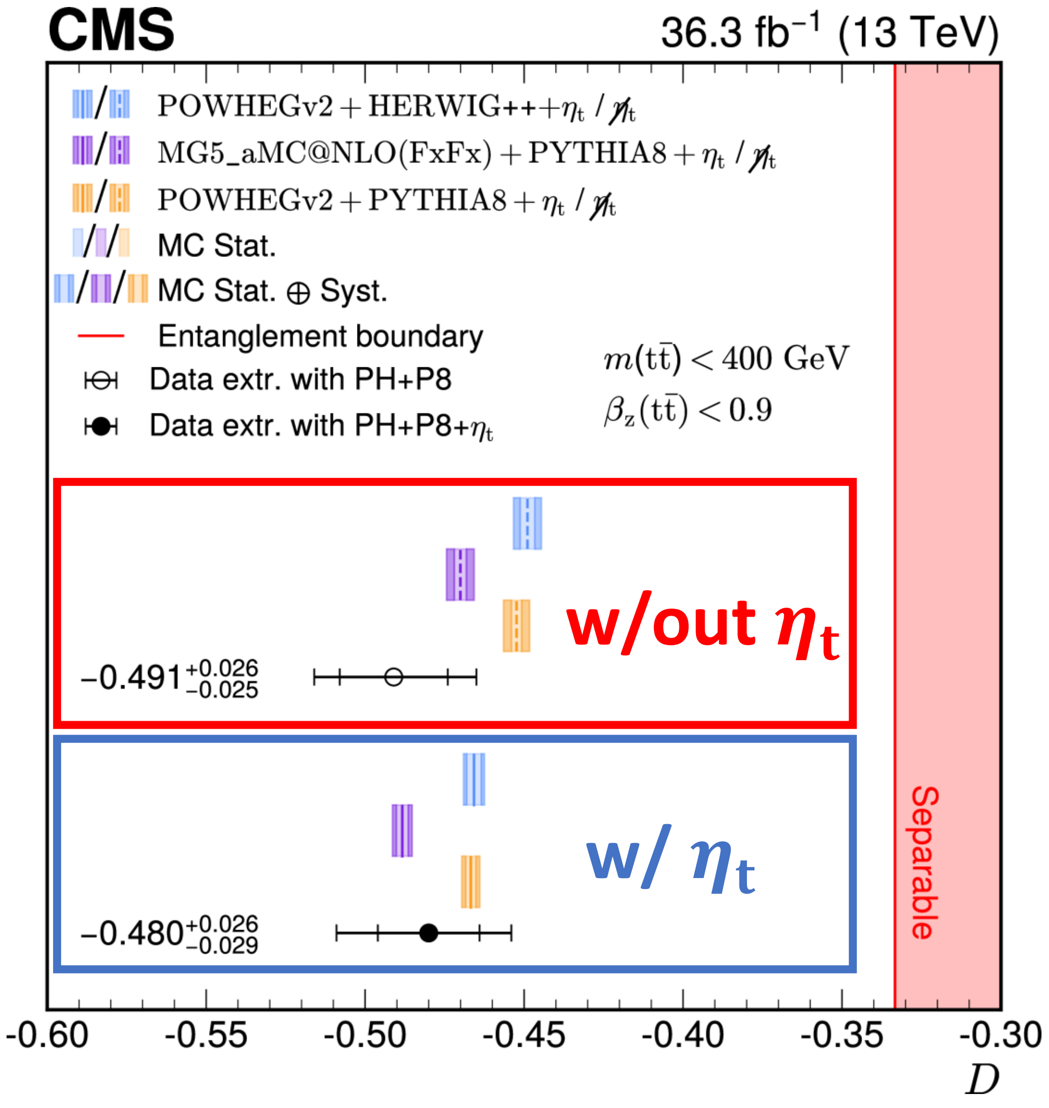

# Conclusion

- Top quarks are **enta**
  - Spins are correlate manner
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- Start of quantum inf high energy physics
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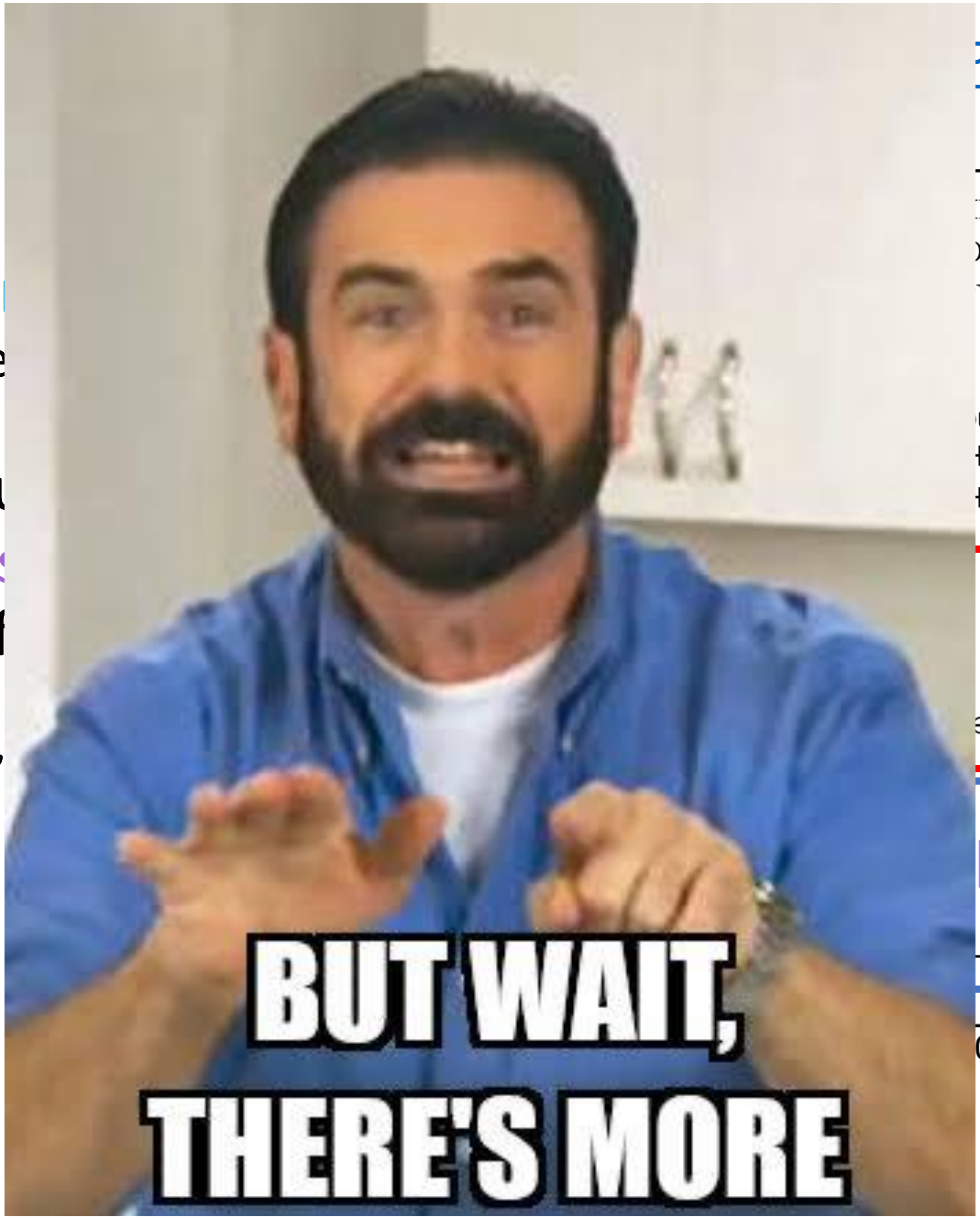
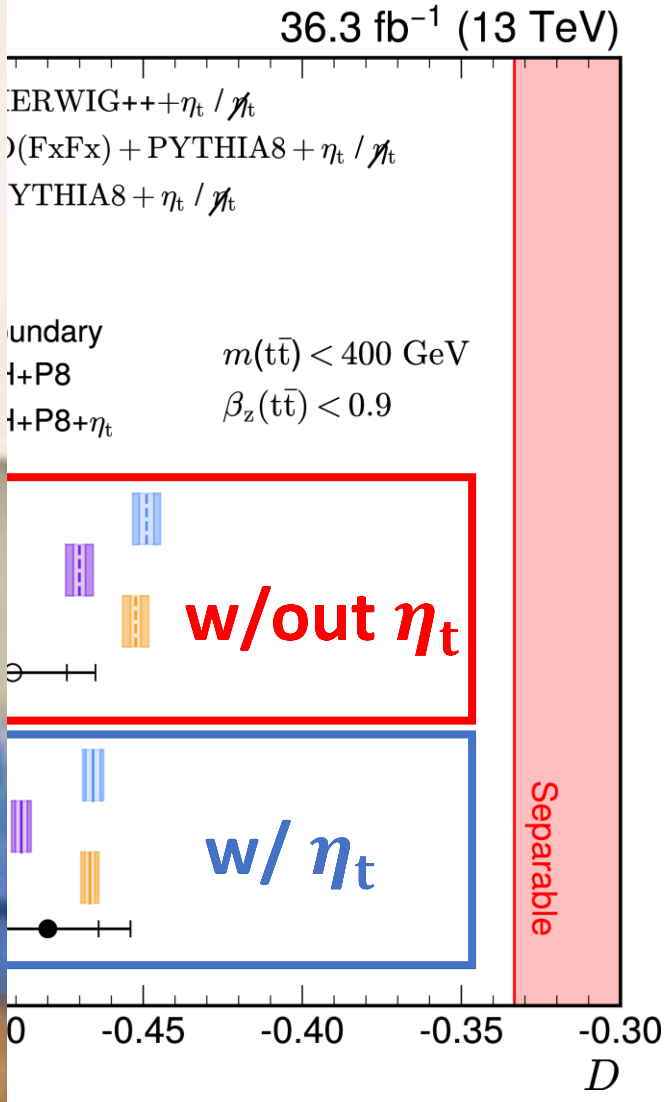


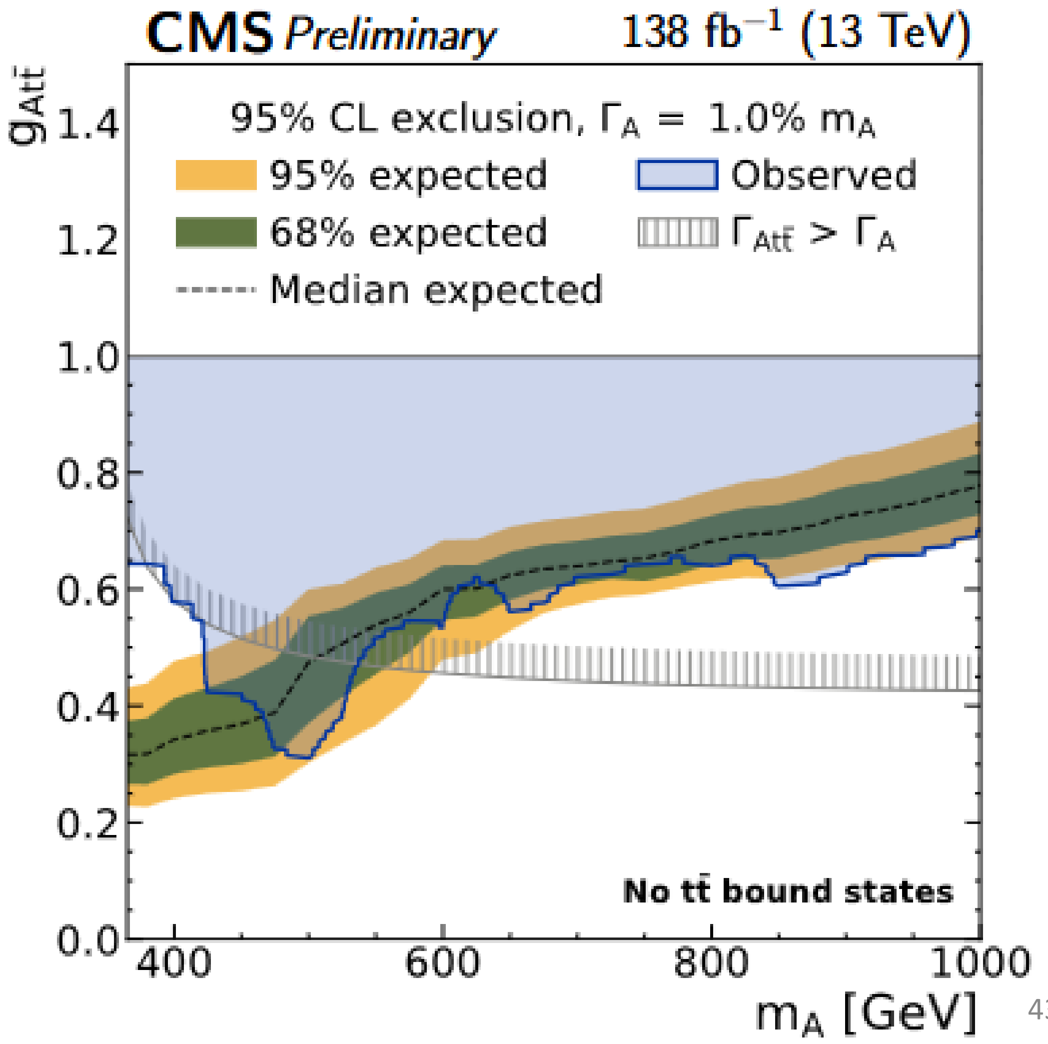

Phys. **87** 117801



# Discovery of a Pseudoscalar Structure

HIG-22-013 PAS

- CMS has now published a separate paper recognizing there is a pseudoscalar structure in the $m(\mathrm{t\bar{t}})$ spectrum in the threshold region
- Consistent with ${}^{1}S_{0}^{[1]}$ and fit $\sigma(\eta_t)$ of 7.1 pb $\pm$ 11%
- Further investigations by both the experimental and theoretical communities are necessary to elucidate the nature of this excess



# What's next? – My personal viewpoint

Phys. Rev. D **108**, 076025 Phys. Rev. D **109**, 096027

- Does the wave function "collapse" after the top quarks decay?
  - Decoherence studied in a high energy environment – only @LHC!!

Phys. Rev. Lett. **127**, 161801 EPJC **82**, 666 Phys. Rev. D **109**, 115023

- Do top quarks violate Bell's inequality?
  - Cannot perform direct Bell test PLB **280**, 3–4
  - Measure expectation value of Bell operator

- What quantum observables are sensitive to new physics?
  - Entanglement witness has shown to give orthogonal directions JHEP (2023)148
  - Magic? – non-linear combination of correlations Phys. Rev. D **110**, 116016
  - Maybe something still new entirely

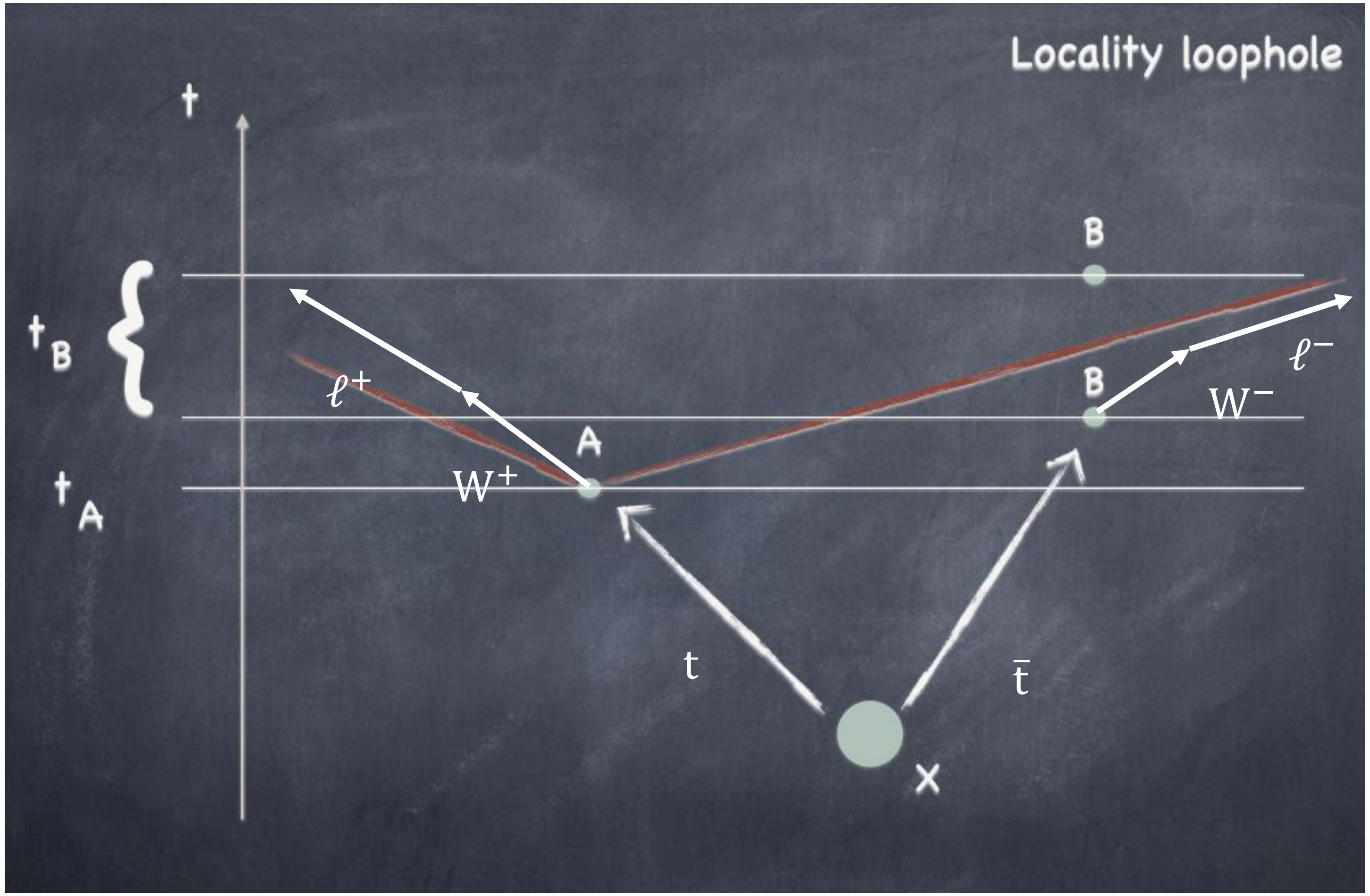
- Qutrit entanglement
  - $H \to WW$, $H \to ZZ$ Phys. Rev. D **109**, 113004
  - Double slit-like experiment arXiv:2411.13464

# 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 $\{\hat{\mathbf{k}}, \hat{\mathbf{n}}, \hat{\mathbf{r}}\}$

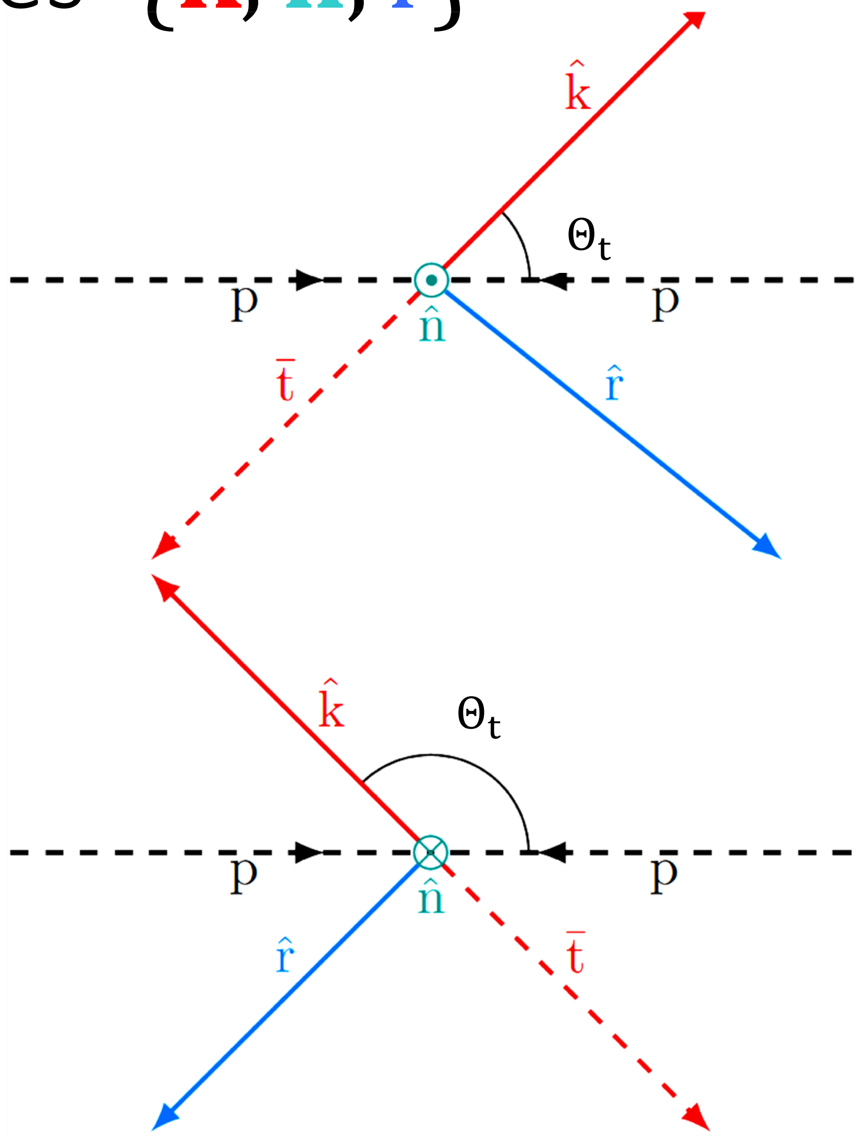
- Helicity $\hat{\mathbf{k}}$-axis: top quark direction in $t\bar{t}$ rest frame
- Transverse $\hat{\mathbf{n}}$-axis: transverse to production plane

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

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

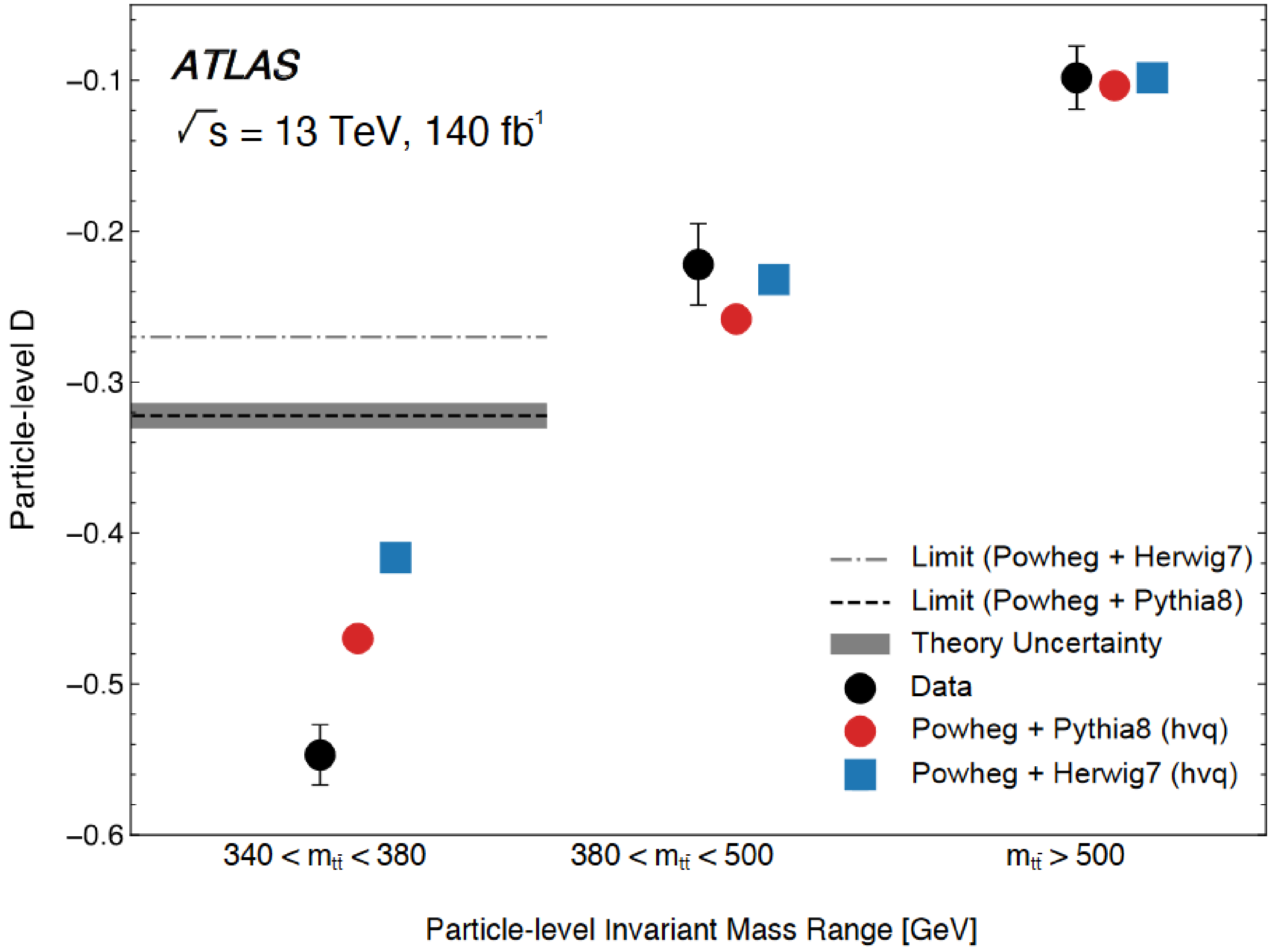
$$\hat{\mathbf{r}} = \frac{\mathrm{sign}(\cos\Theta_t)}{\sin\Theta_t}(\hat{\mathrm{p}} - \hat{\mathbf{k}}\cos\Theta_t)$$

- $\hat{\mathrm{p}}$: direction of the incoming parton, i.e. the direction of the proton beam (z-direction in the laboratory frame)
- $\Theta_t$: 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



# Electroweak Corrections

- NLO EWK differential cross-section calculated using Hathor
- LO QCD for uncertainty generated with MadGraph5
- Uncertainty in EWK correction is taken as difference between multiplicative and additive approaches

$$\kappa_{NLO}^{EWK}(m_{t\bar{t}}, cos\theta^*) = \frac{\left.\frac{d\sigma(m_{t\bar{t}})}{dcos\theta}_{NLO}^{EWK}\right|_{cos\theta^*} + \left.\frac{d\sigma(m_{t\bar{t}})}{dcos\theta}_{LO}^{QCD}\right|_{cos\theta^*}}{\left.\frac{d\sigma(m_{t\bar{t}})}{dcos\theta}_{LO}^{QCD}\right|_{cos\theta^*}}$$

$$n_{bin}^{NLO\ QCD \times EWK} = \kappa_{NLO}^{EWK} n_{bin}^{POWHEG}$$

$$n_{bin}^{NLO\ QCD+EWK} = n_{bin}^{LO\ QCD} + n_{bin}^{NLO\ QCD} + n_{bin}^{NLO\ EWK}$$

# Electroweak Corrections

- Scale factors used to correct Powheg NLO MC
- Use generator level m(ttbar) and cos(theta) to look-up scale factor per event