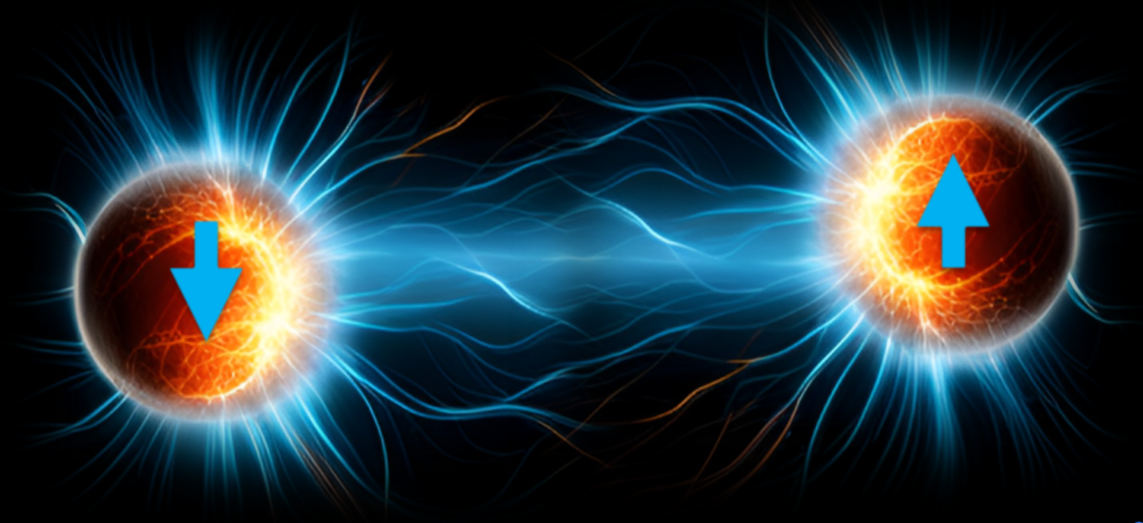
Entanglement of top quarks in CMS



Didar Dobur

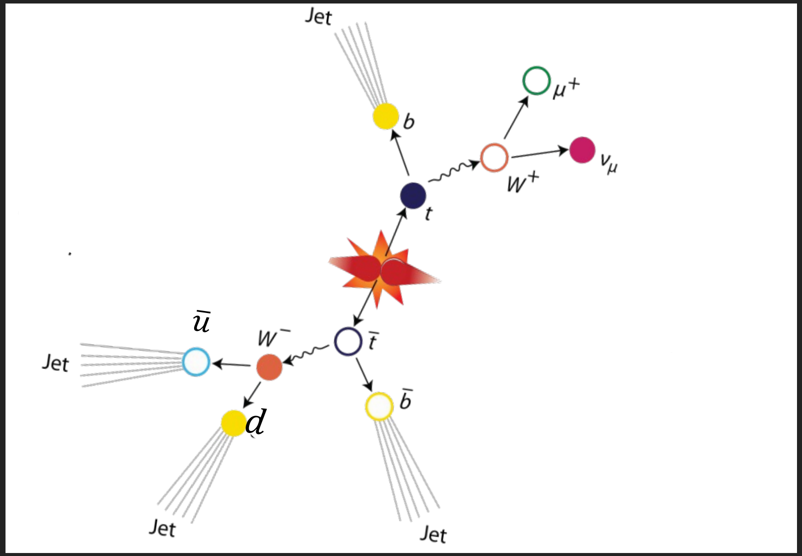
On behalf of the CMS experiment

GHENT UNIVERSITY

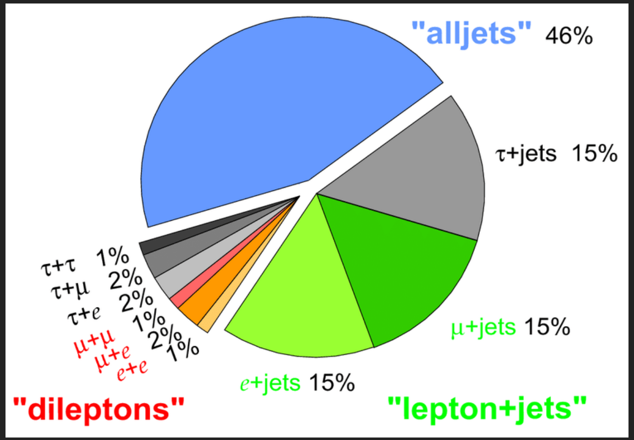
The 43rd International Symposium on Physics in Collision
October 2024, Athens

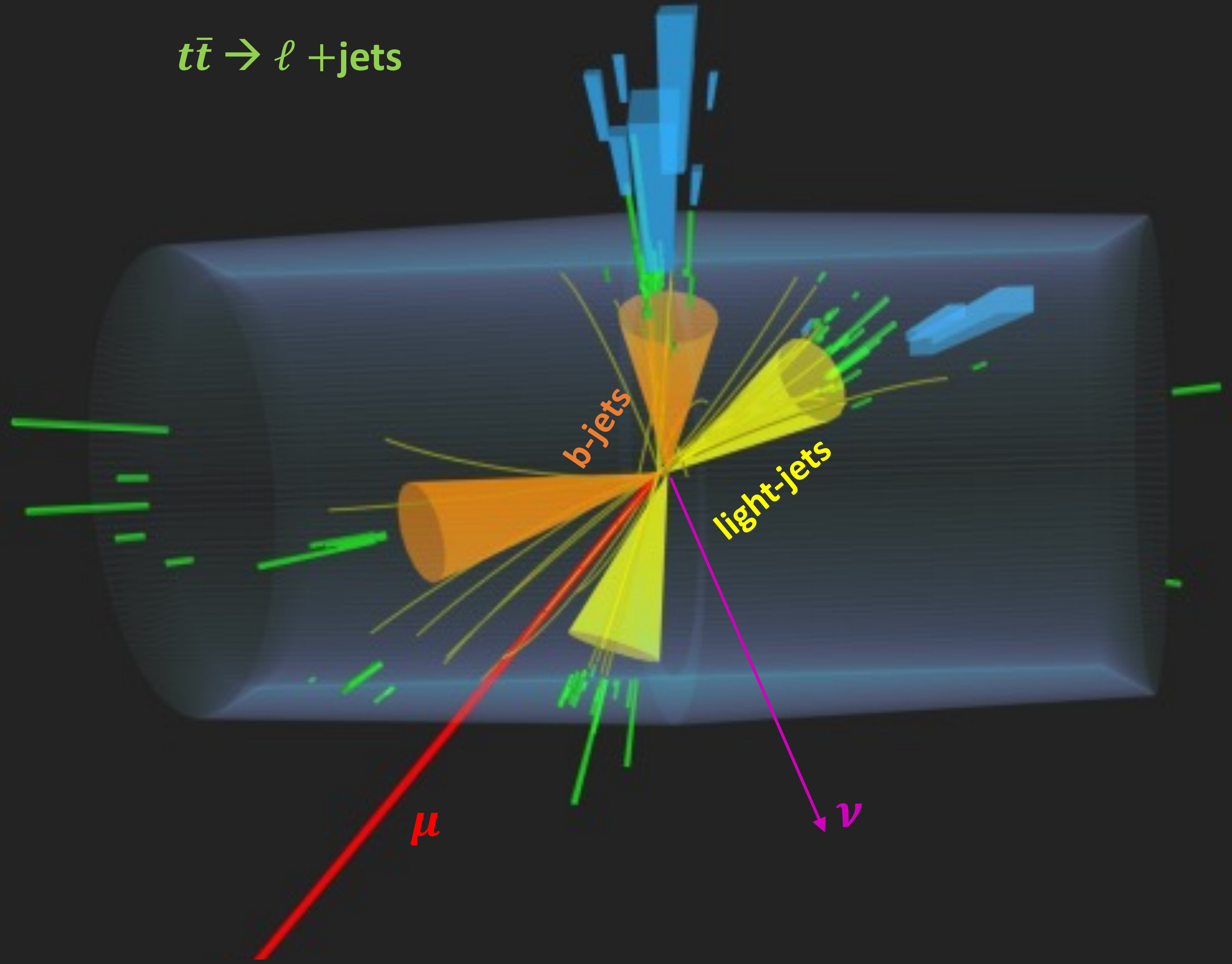
Top quark production at LHC

Top quarks mainly produced in pairs



$\mathcal{B}(t \to Wb) \sim 100\%$





80-90% efficiency to correctly assign the top-decay products using m_W and m_{top}

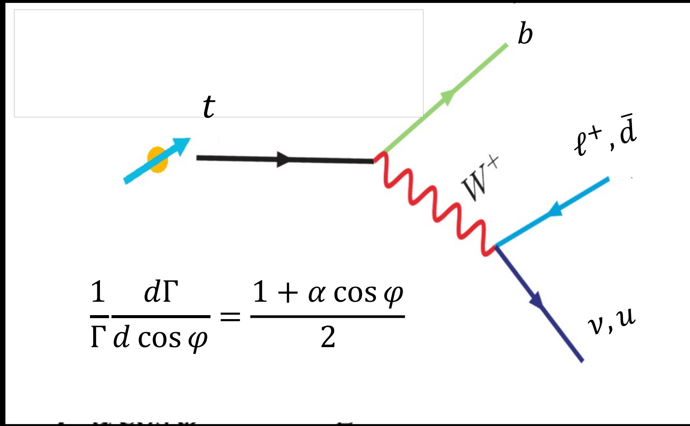
Top quark polarization and spin correlation

- Top-pairs @LHC are mainly unpolarized (parity invariance of QCD)
- Their spins are strongly correlated

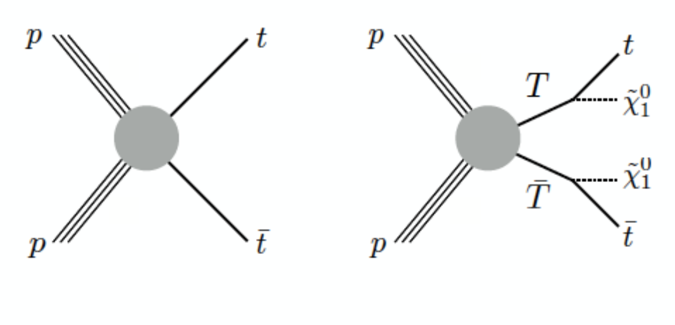
lifetime	$<$	QCD timescale	$\ll$	Spin-flip timescale
10^{-25}s	$<$	10^{-24}s	$\ll$	10^{-21}s

- Spin information is passed onto $\ell^{\pm}$ *and* d-quark

  → preferentially radiated in the top spin direction



- Many NP models modify spin polarization and correlation of top quarks
  - New mediator ?
  - New particles decaying to tops ?



...but also interesting for testing the foundations of Quantum physics

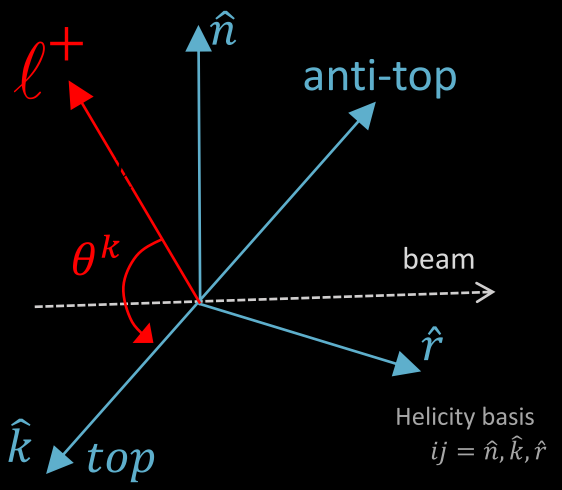
Top quark polarization and spin correlation

PRD 100 (2019) 072002

$t\bar{t}$ production cross section parametrized vs polarization & spin correlation coefficients

$$\frac{1}{\sigma}\frac{d\sigma}{d\cos\theta_+^i \, d\cos\theta_-^j} = \frac{1}{2}\left(1 + \boldsymbol{B_+^i}\cos\theta_+^i + \boldsymbol{B_-^j}\cos\theta_-^j - \boldsymbol{C_{ij}}\cos\theta_+^i\cos\theta_-^j\right)$$

$$B_\pm = \begin{pmatrix} \times \\ \times \\ \times \end{pmatrix} \qquad C = \begin{pmatrix} \times & \times & \times \\ \times & \times & \times \\ \times & \times & \times \end{pmatrix}$$



6 polarization and 9 spin correlation coefficients can be extracted from differential measurements

$\hat{k}$: top-quark direction in $t\bar{t}$ CMF ("helicity")

$\hat{n}$ = normal to $t\bar{t}$ scattering plane ("transverse")

$\hat{r}$ = normal to $\hat{k}$ in $t\bar{t}$ scattering plane

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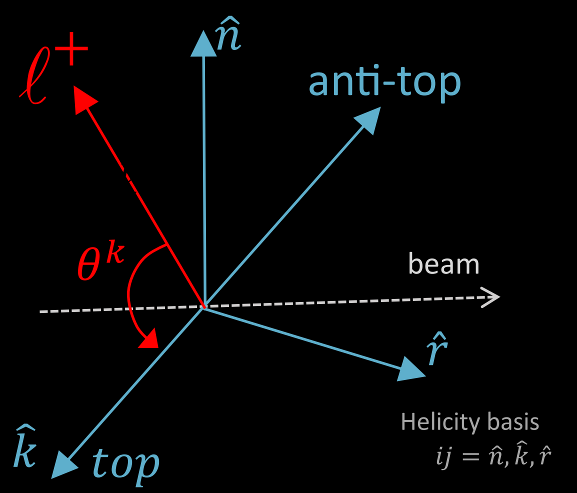

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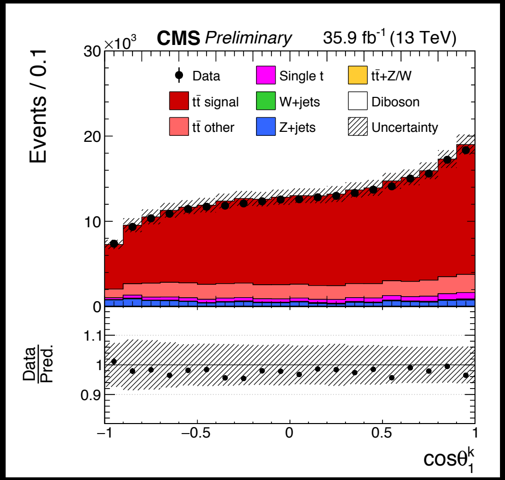
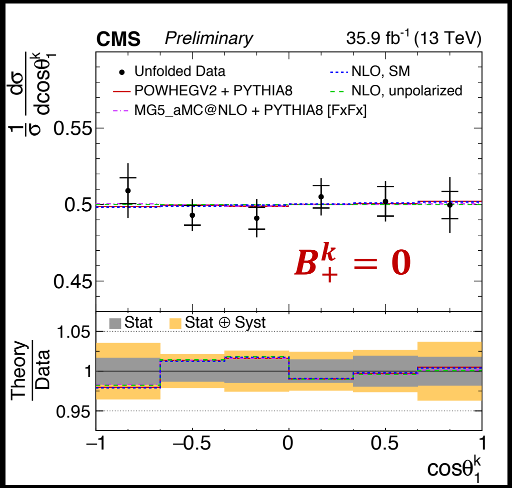


Unfolded to parton level



Published in Nature
arXiv:2311.07288

EUROPEAN ORGANISATION FOR NUCLEAR RESEARCH (CERN)

ATLAS EXPERIMENT

Submitted to: Nature

CERN-EP-2023-230
November 20, 2023

Observation of quantum entanglement in top-quark pairs using the ATLAS detector

The ATLAS Collaboration

We report the highest-energy observation of entanglement, in top–antitop quark events produced at the Large Hadron Collider, using a proton–proton collision data set with a center-of-mass energy of $\sqrt{s} = 13$ TeV and an integrated luminosity of 140 fb^{-1} recorded with the ATLAS experiment. Spin entanglement is detected from the measurement of a single observable D, inferred from the angle between the charged leptons in their parent top- and antitop-quark rest frames. The observable is measured in a narrow interval around the top–antitop quark production threshold, where the entanglement detection is expected to be significant. It is reported in a fiducial phase space defined with stable particles to minimize the uncertainties that stem from limitations of the Monte Carlo event generators and the parton shower model in modelling top-quark pair production. The entanglement marker is measured to be $D = -0.547 \pm 0.002$ (stat.) $\pm$ 0.021 (syst.) for $340 < m_{t\bar{t}} < 380$ GeV. The observed result is more than five standard deviations from a scenario without entanglement and hence constitutes both the first observation of entanglement in a pair of quarks and the highest-energy observation of entanglement to date.

Accepted by *Rep. on Prog. in Phys.*
arXiv:2406.03976

EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH (CERN)

CMS-TOP-23-001

CERN-EP-2024-137
2024/06/07

Observation of quantum entanglement in top quark pair production in proton-proton collisions at $\sqrt{s} = 13$ TeV

The CMS Collaboration*

Abstract

Entanglement is an intrinsic property of quantum mechanics and is predicted to be exhibited in the particles produced at the Large Hadron Collider. A measurement of the extent of entanglement in top quark-antiquark ($t\bar{t}$) events produced in proton-proton collisions at a center-of-mass energy of 13 TeV is performed with the data recorded by the CMS experiment at the CERN LHC in 2016, and corresponding to an integrated luminosity of 36.3 fb^{-1}. The events are selected based on the presence of two leptons with opposite charges and high transverse momentum. An entanglement-sensitive observable D is derived from the top quark spin-dependent parts of the $t\bar{t}$ production density matrix and measured in the region of the $t\bar{t}$ production threshold. Values of $D < -1/3$ are evidence of entanglement and D is observed (expected) to be $-0.480^{+0.026}_{-0.029}$ ($-0.467^{+0.026}_{-0.029}$) at the parton level. With an observed significance of 5.1 standard deviations with respect to the non-entangled hypothesis, this provides observation of quantum mechanical entanglement within $t\bar{t}$ pairs in this phase space. This measurement provides a new probe of quantum mechanics at the highest energies ever produced.

Accepted by Phys. Rev. D
arXiv:2409.11067

DRAFT
CMS Physics Analysis Summary

The content of this note is intended for CMS internal use and distribution only

2024/06/10
Archive Hash: 982a1b8-D
Archive Date: 2024/06/10

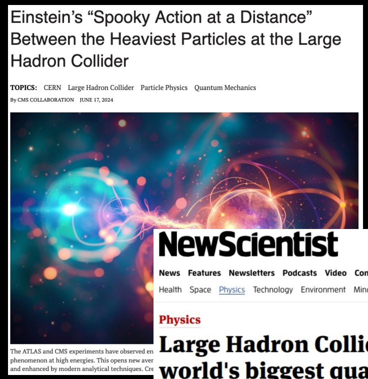
Measurements of polarization, spin correlations, and entanglement in top quark pairs using lepton+jets events from pp collisions at $\sqrt{s} = 13$ TeV

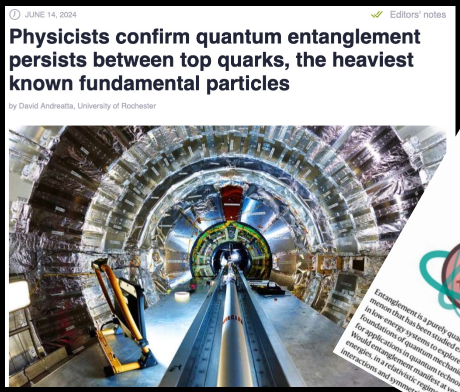
The CMS Collaboration

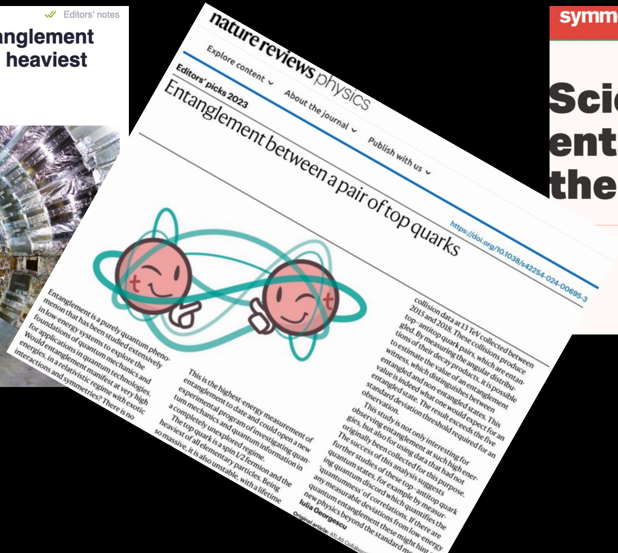
Abstract

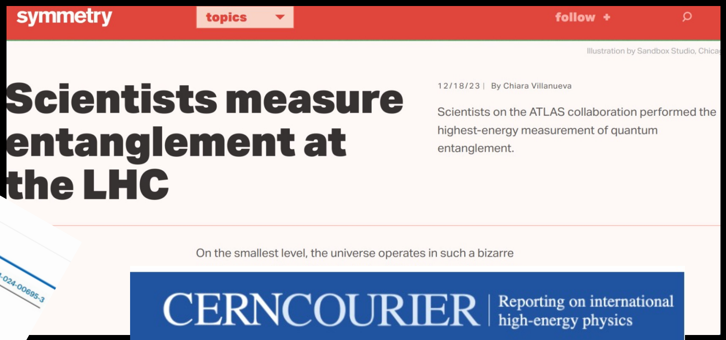
Measurements of the polarization and spin correlations in top quark pairs ($t\bar{t}$) are presented using events with a single electron or muon and jets in the final state. The measurements are based on proton-proton collision data from the LHC at $\sqrt{s} = 13$ TeV collected by the CMS experiment, corresponding to an integrated luminosity of 138 fb^{-1}. All coefficients of the polarization vectors and the spin correlation matrix are extracted simultaneously by performing a binned likelihood fit to the data. The measurement is performed in bins of additional observables such as the mass of the $t\bar{t}$ system and the top quark scattering angle. Inclusive coefficients are obtained by combining the results of all fitted bins. From the measured spin correlations, conclusions on the $t\bar{t}$ spin entanglement are drawn. The standard model predicts entangled spin $t\bar{t}$ states at the production threshold and at high masses of the $t\bar{t}$ system. Entanglement is observed for the first time in events with high $t\bar{t}$ mass, with an observed (expected) significance of 6.7 (5.6) standard deviations. The observed level of entanglement cannot be explained by classical exchange of information between the two particles alone. The observed (expected) significance for entanglement attributable to space-like separated $t\bar{t}$ pairs is 5.4 (4.1) standard deviations.

This talk



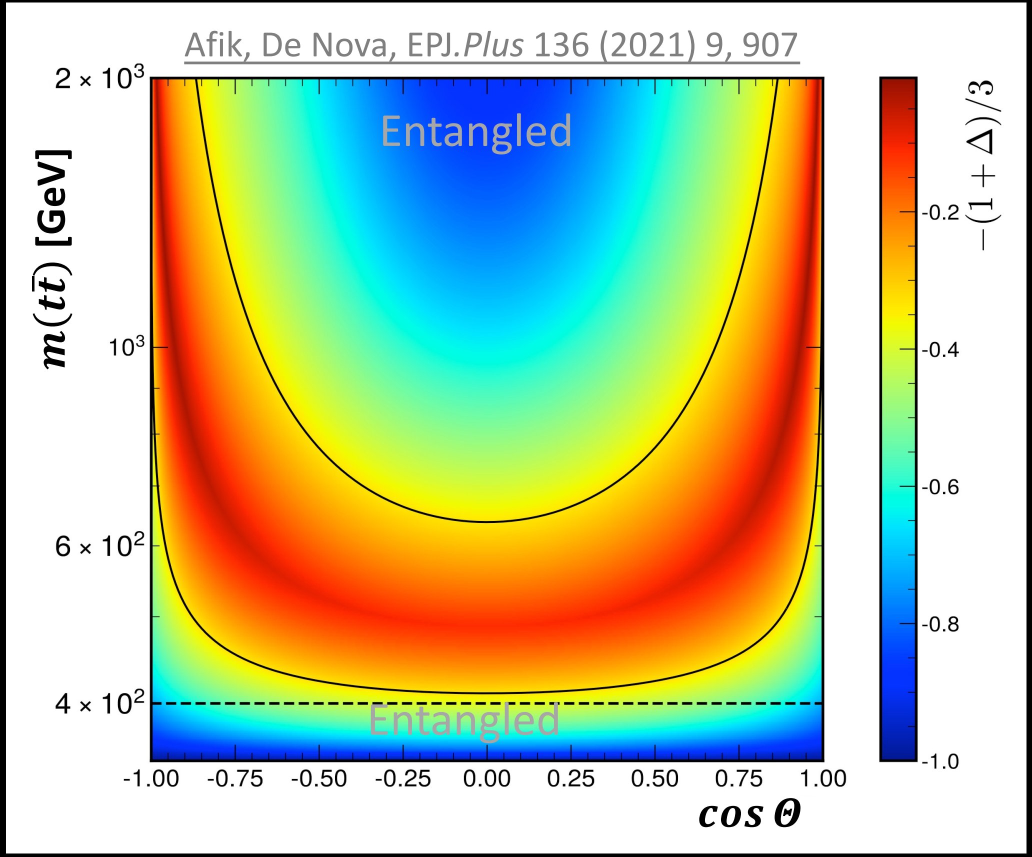


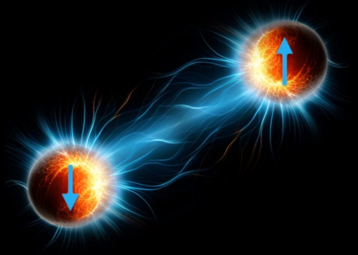


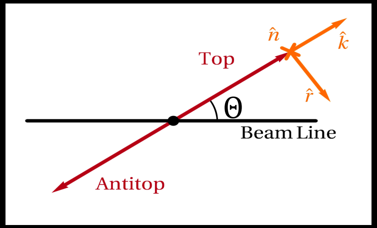


Entanglement in $t\bar{t}$

- Spin correlation is $m(t\bar{t})$ and $\cos\Theta$ dependent
  → Entanglement in some phase-space regions

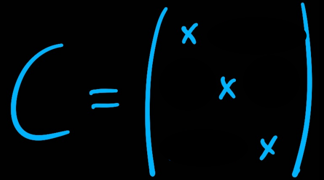






- $t\bar{t}$ in mixed states (eg. $|\Psi\rangle = \frac{1}{\sqrt{2}}(|\uparrow\downarrow\rangle - |\downarrow\uparrow\rangle)$) → two qubit system
- Peres–Horodecki criterion for entanglement

$$\Delta_E = C_{nn} + |C_{rr} + C_{kk}| > 1$$



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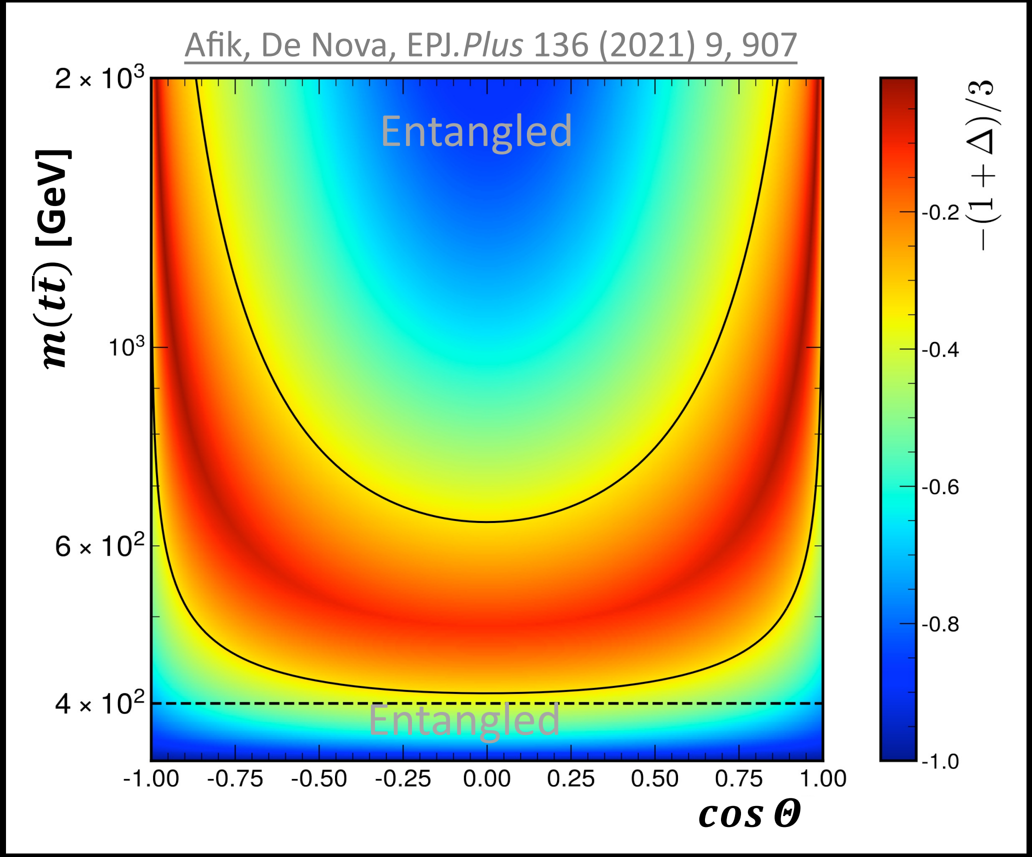

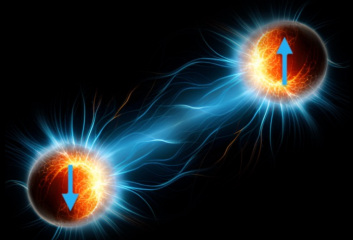

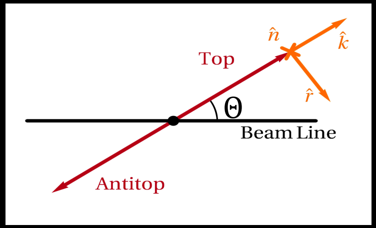

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$$\Delta_E = C_{nn} + |C_{rr} + C_{kk}| > 1$$

Low m($t\bar{t}$): $D = -\frac{\Delta_E}{3} < -\frac{1}{3}$

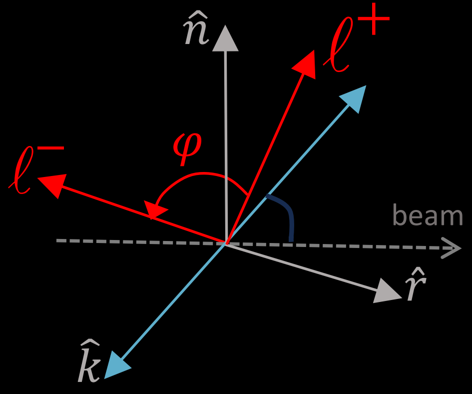
$gg \to t\bar{t}\ (^1S_0)$

High m($t\bar{t}$): $\widetilde{D} = \frac{\Delta_E}{3} > \frac{1}{3}$

$gg/qq \to t\bar{t}\ (^3S_1)$

Extract D and $\widetilde{D}$ from single differential measurement

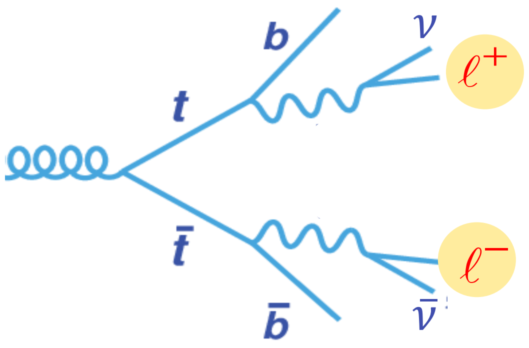
$$\frac{1}{\sigma}\frac{d\sigma}{d\cos\varphi} = \frac{1}{2}(1 + D\cos\varphi)$$



$\cos\varphi = \hat{\ell}^+ \cdot \hat{\ell}^-$

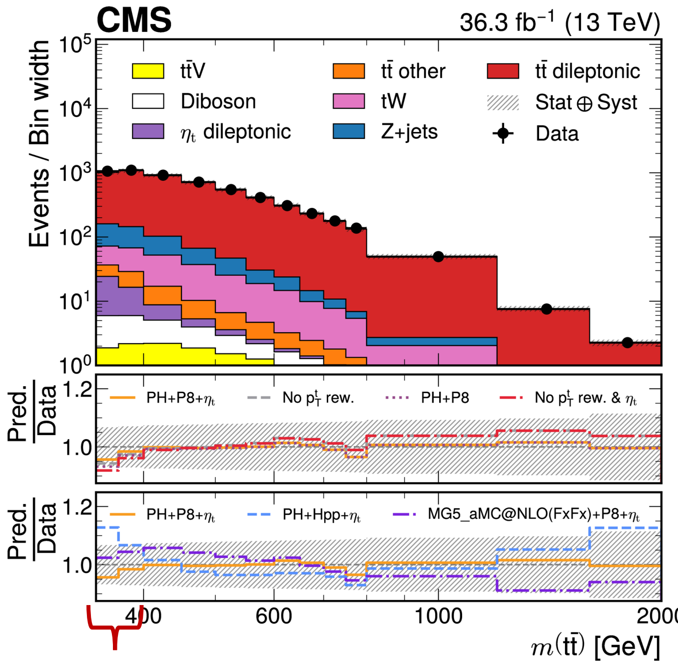
$\hat{\ell}$: unit vector in top rest frame

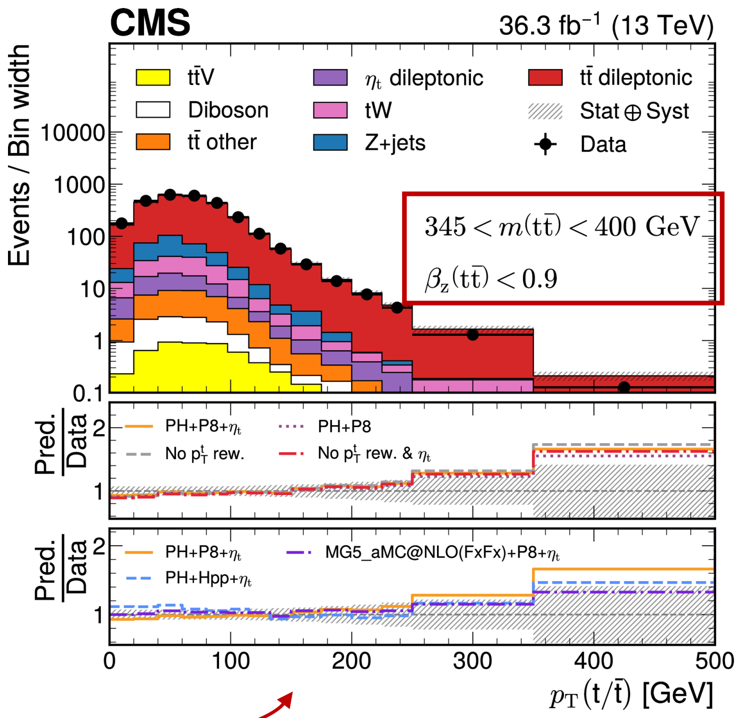
Entanglement in $t\bar{t}$ (dilepton channel)

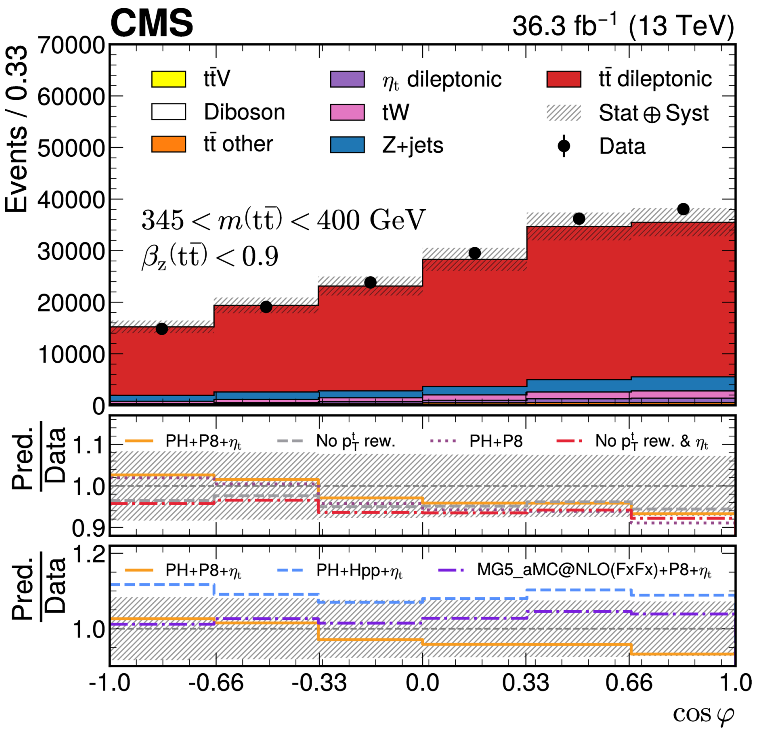


- 2016 data
- $e\mu, ee, \mu\mu$ channels, 2 jets >=1 bjet
- Top reconstruction assuming $p_T^{miss} = p_T^{\nu 1} + p_T^{\nu 2}$, m_W and m_t
- Solution with lowest m_{tt} is taken, 90% efficiency
- $m_{tt} < 400$ GeV, $\beta_z(t\bar{t}) < 0.9$ to enhance $\frac{gg}{qq}$

$$\cos\varphi = \hat{\ell}^{+} \cdot \hat{\ell}^{-}$$

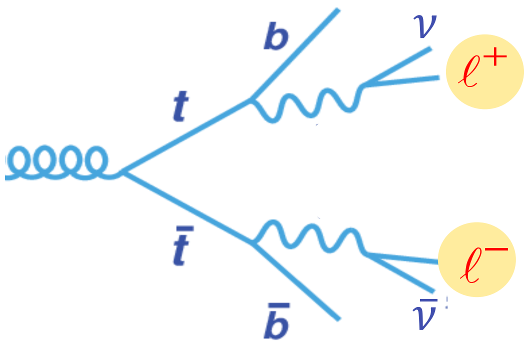




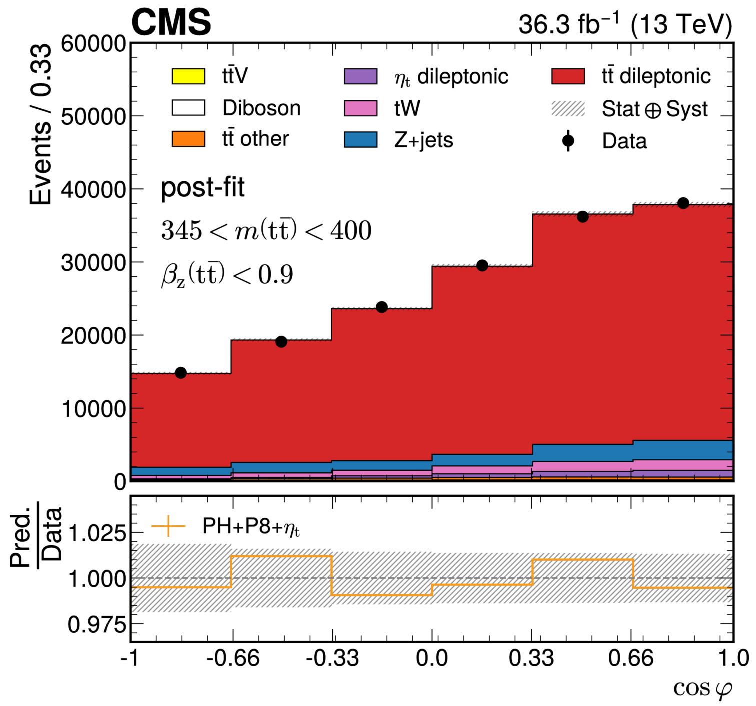


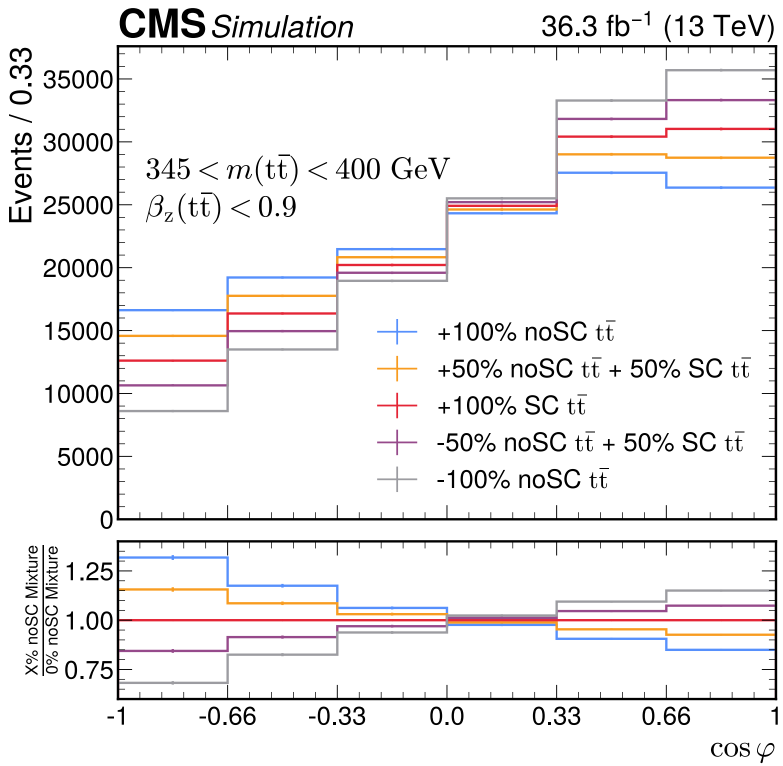
Focus on low m_{tt}

Entanglement in $t\bar{t}$ (dilepton channel)



$$\cos\varphi = \hat{\ell}^+ \cdot \hat{\ell}^-$$



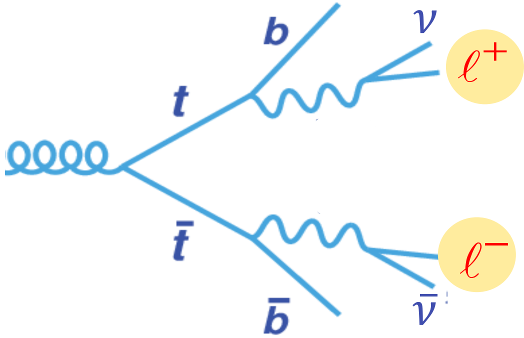


Signal simulation

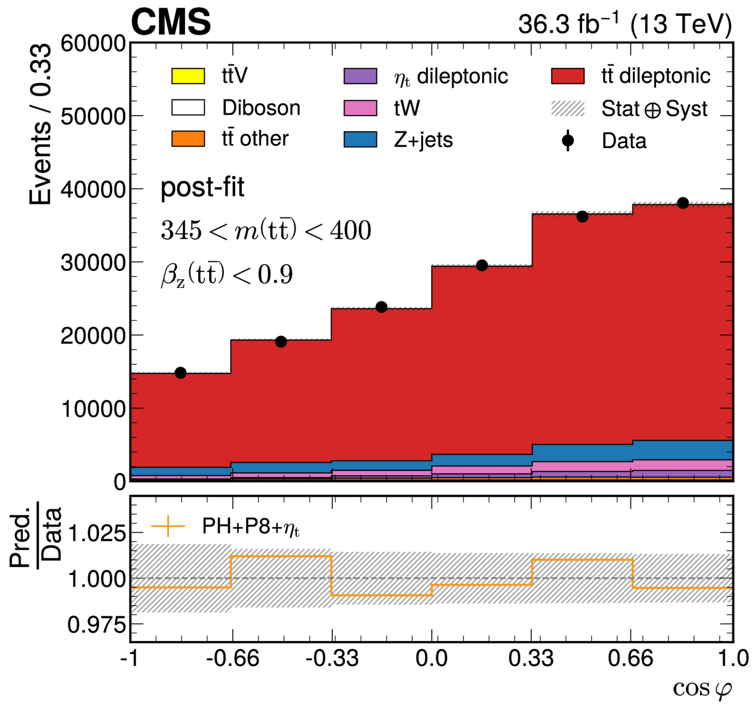
- POWHEG+Pythia8 @NLO QCD
- TOP++ for x-section @NNLO QCD
- EWK corrections @NLO with Higgs exchange
- $p_T(top)$ reweighting to match the top quark p_T spectrum from a fixed order ME calculation at NNLO

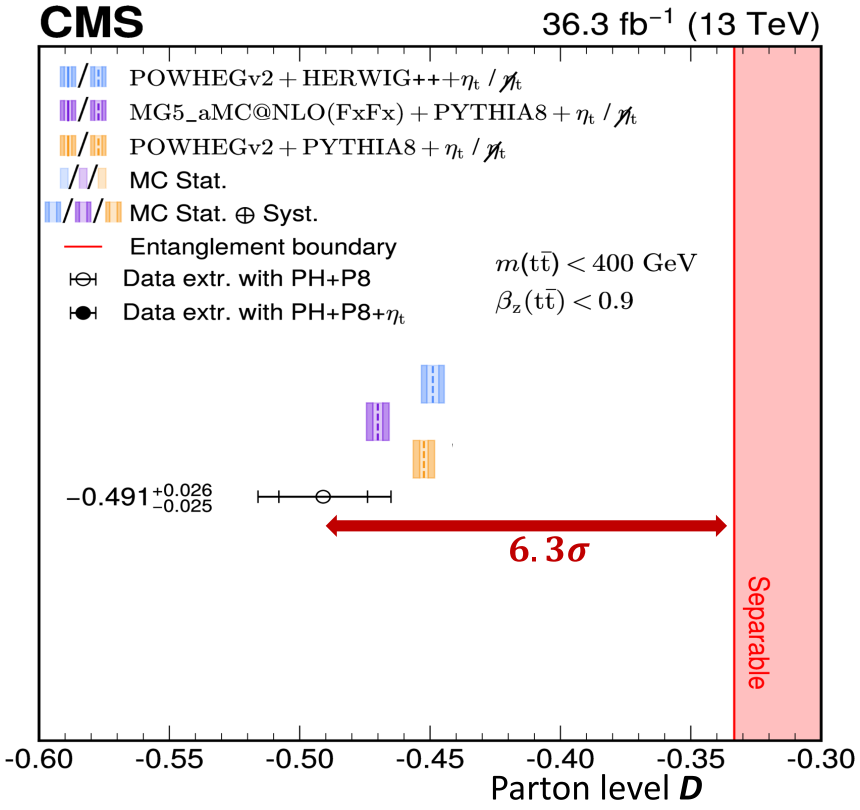
- Different degrees of spin-correlation via mixture of samples with/without SC
- Binned likelihood fit to $\cos\varphi$ to extract D at parton evel

Entanglement in $t\bar{t}$ (dilepton channel)



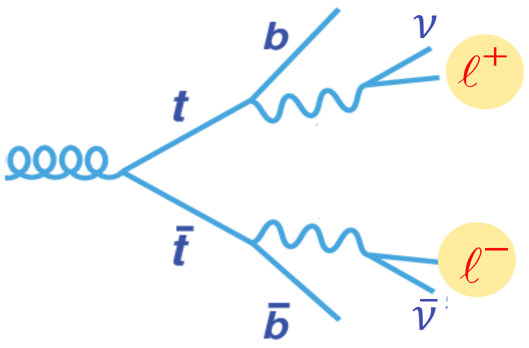
$$\cos\varphi = \hat{\ell}^+ \cdot \hat{\ell}^-$$





Entanglement in $t\bar{t}$ is observed with >5σ at low m_{tt}

Entanglement in $t\bar{t}$ (dilepton channel)



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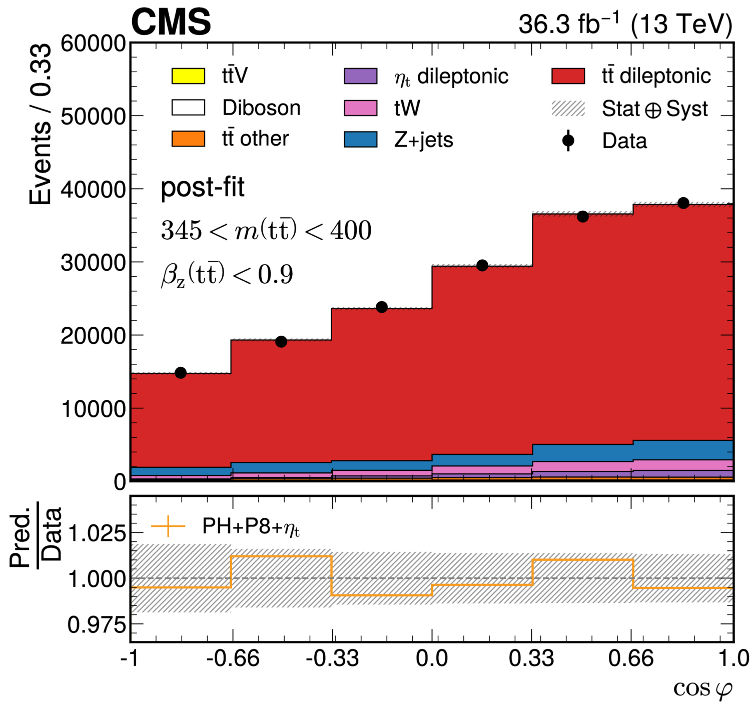
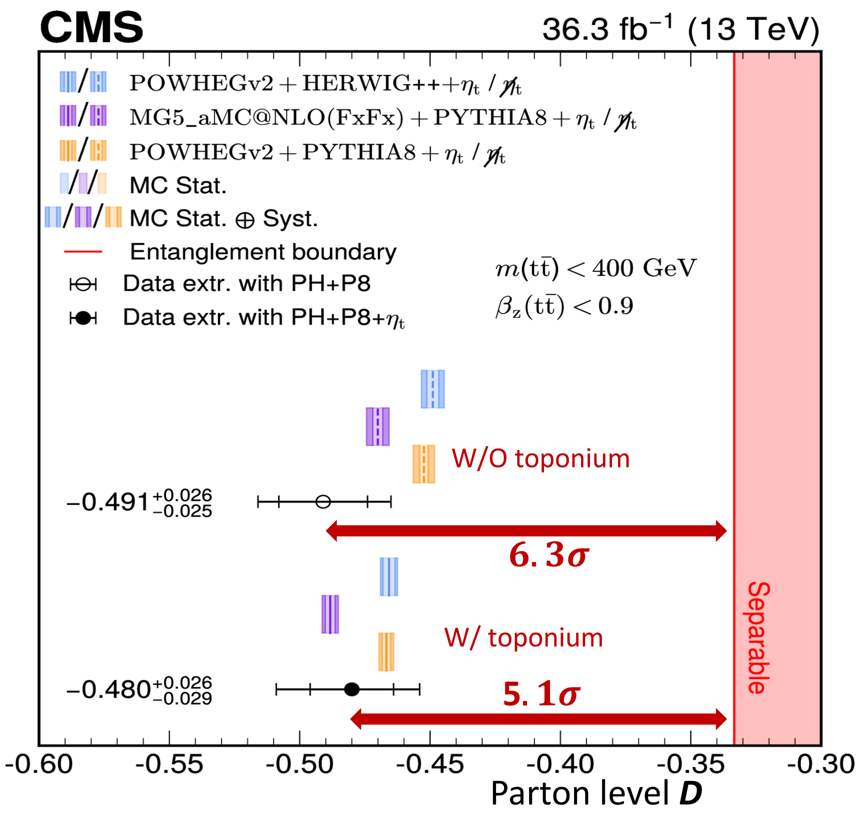
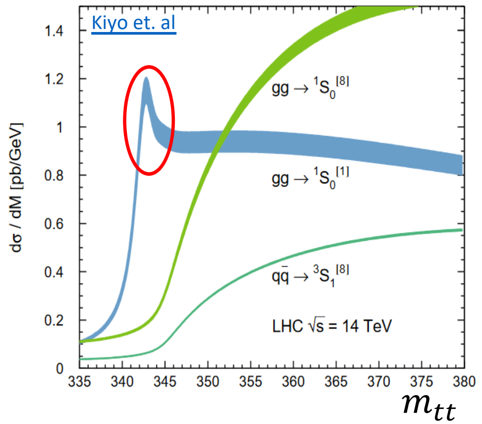
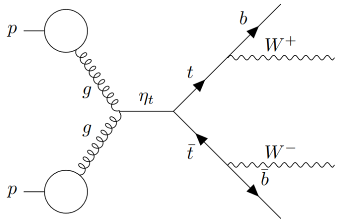




Include $t\bar{t}$ bound-state: toponium (η_t)*

- Pseudoscalar & maximally entangled
- $m(\eta_t) = 343\ GeV$
- $\sigma(pp \to \eta_t) = 6.43 \pm 0.90$ pb





Entanglement in $t\bar{t}$ is observed with >5σ at low m_{tt}

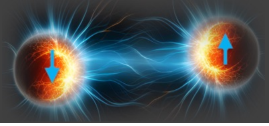
Main uncertainties:

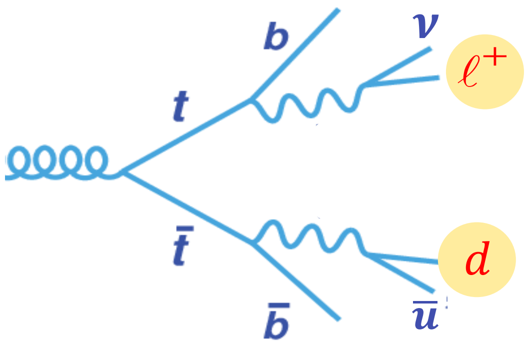
- η_t normalization
- Jet energy calibrations
- Statistical
- Modeling of $t\bar{t}$ production/decay

See E. Gallo's talk for more on toponium

[*] Sumino, Fujii, Hagiwara, Murayama & Ng (PRD`93)
Jezabek, Kuhn & Teubner (Z.Phys.C`92)
B. Fuks et al. (PRD 104 (2021) 034023), F. Maltoni et al. JHEP03(2024)099

Entanglement in $t\bar{t}$ ($\ell + jets$ channel)

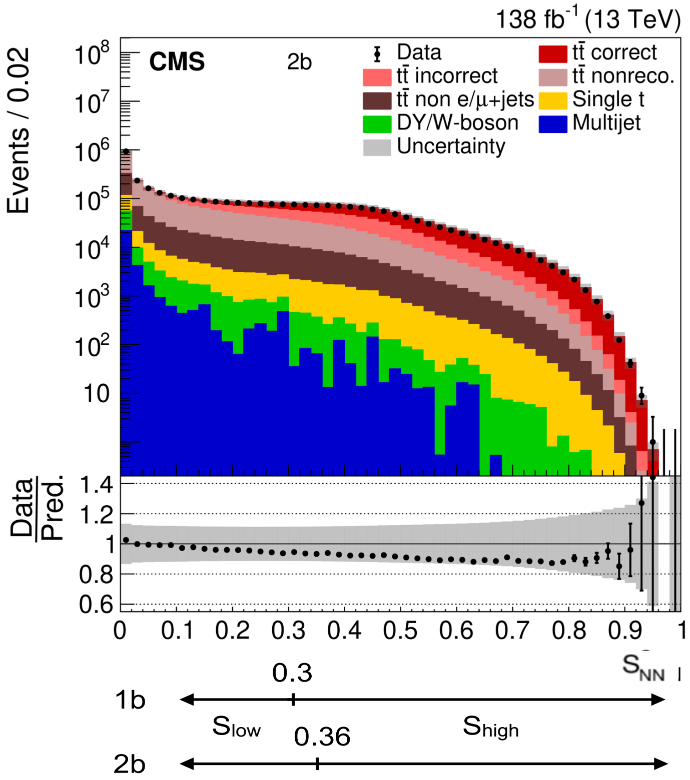


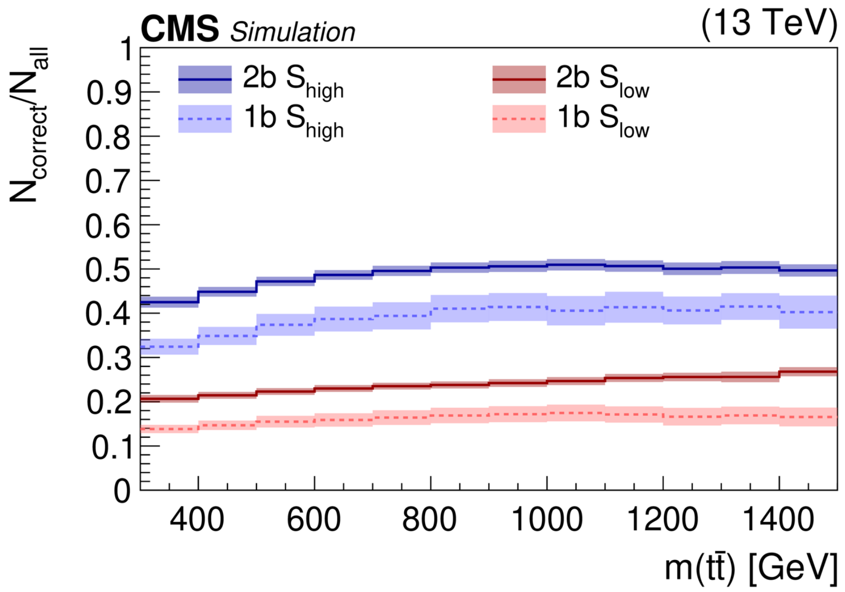


- e/μ + 4 jets, ≥1 bjets
- Better sensitivity at **high $m_{t\bar{t}}$**
- Spin information via ℓ/d-quark

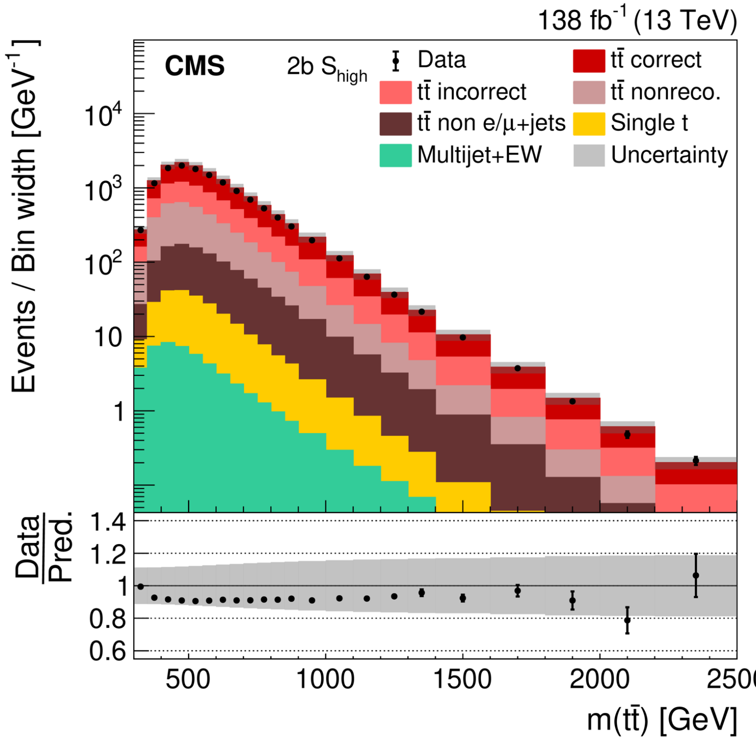
$$\cos\varphi = \hat{\ell} \cdot \hat{d}$$

- NN for correct assignment of top decay products (**up to 50% correct assignment including d-type quark jet**)

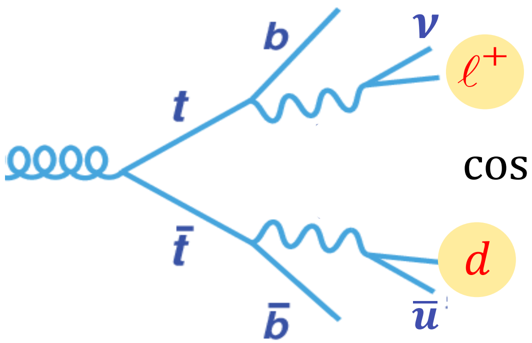




Fraction of correctly reconstructed events including d-quark



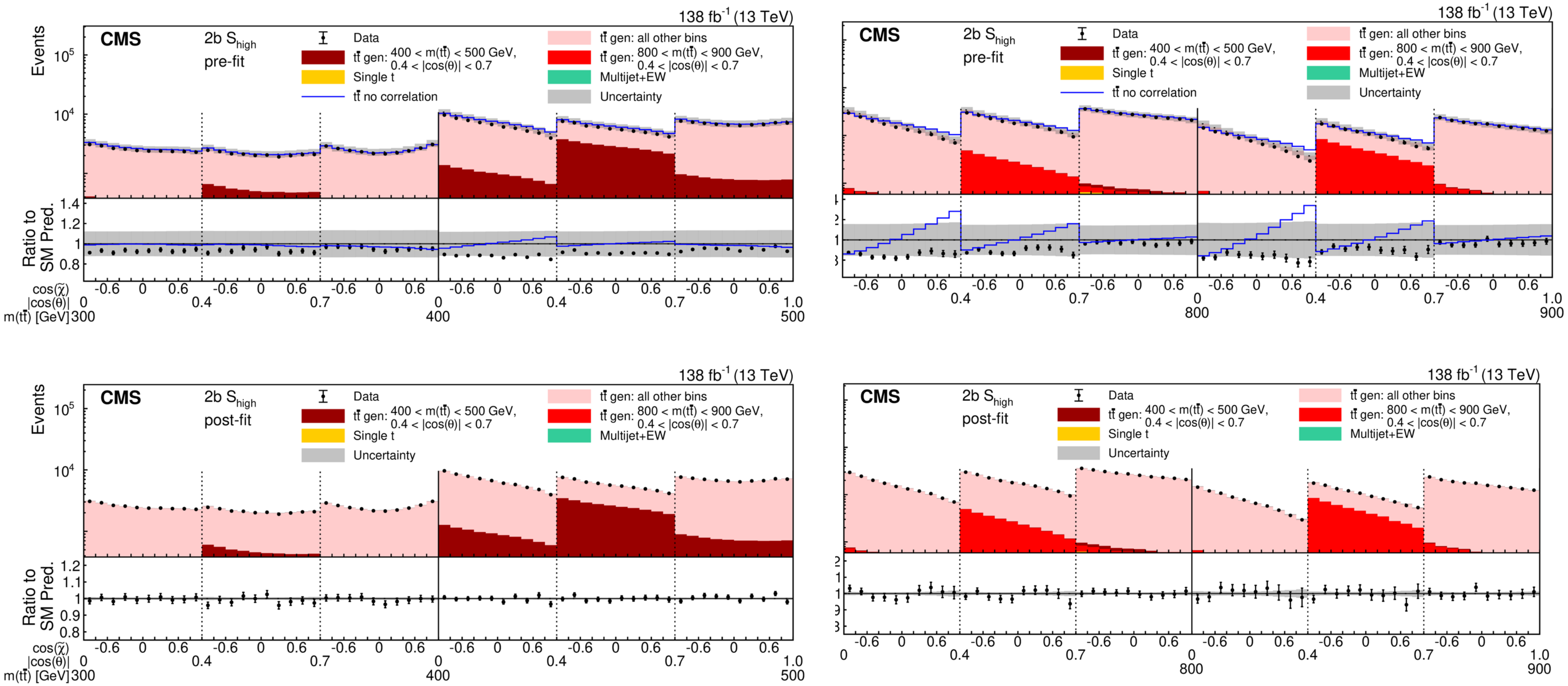
Entanglement in $t\bar{t}$ ($\ell + jets$ channel)



$$\cos\varphi = \hat{\ell} \cdot \hat{d}$$

- Events are categorized according to e/m, Nbjets, and NN score
- Profile likelihood fits to $\cos\varphi$ in bins of $m(t\bar{t})$ and $|\cos\theta|$ in each event cathegory

Extract the coefficients for polarisation vectors ($B^i_\pm$), spin correlation matrix (C_{ij}) as well as $\mathbf{D}$ and $\widetilde{D}$

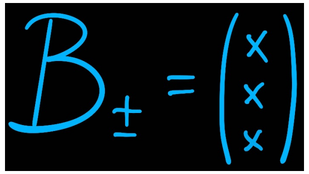


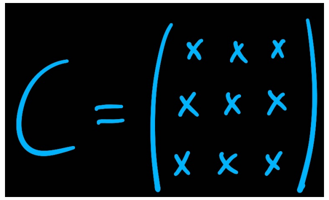
Pre-fit

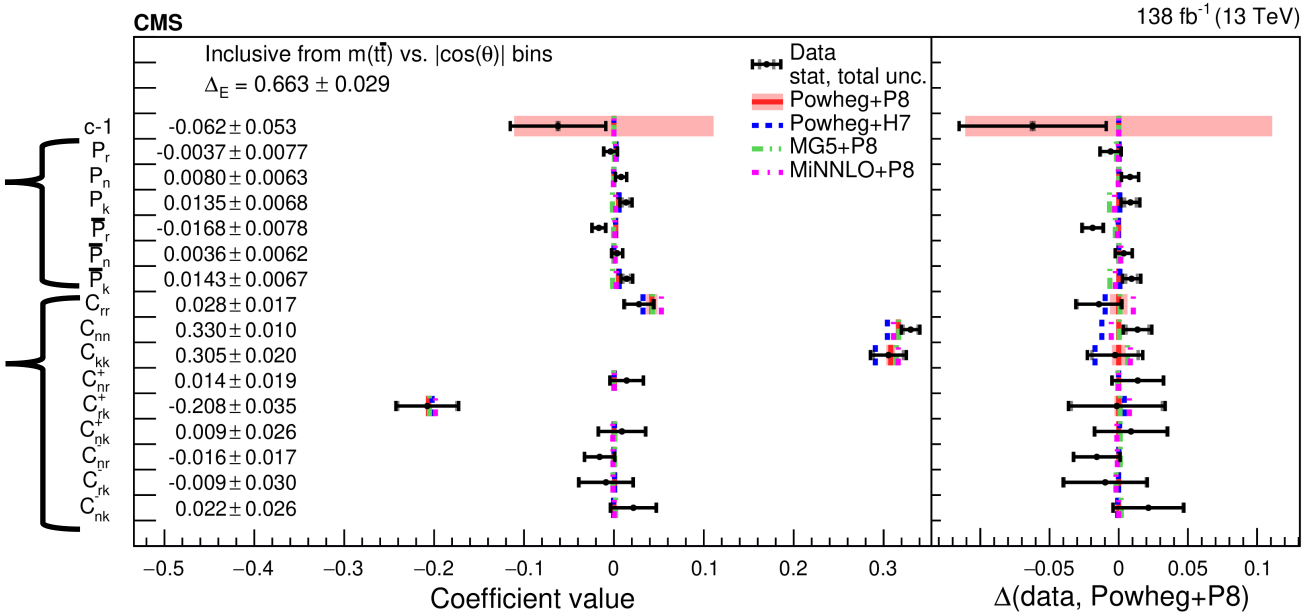
Post-fit

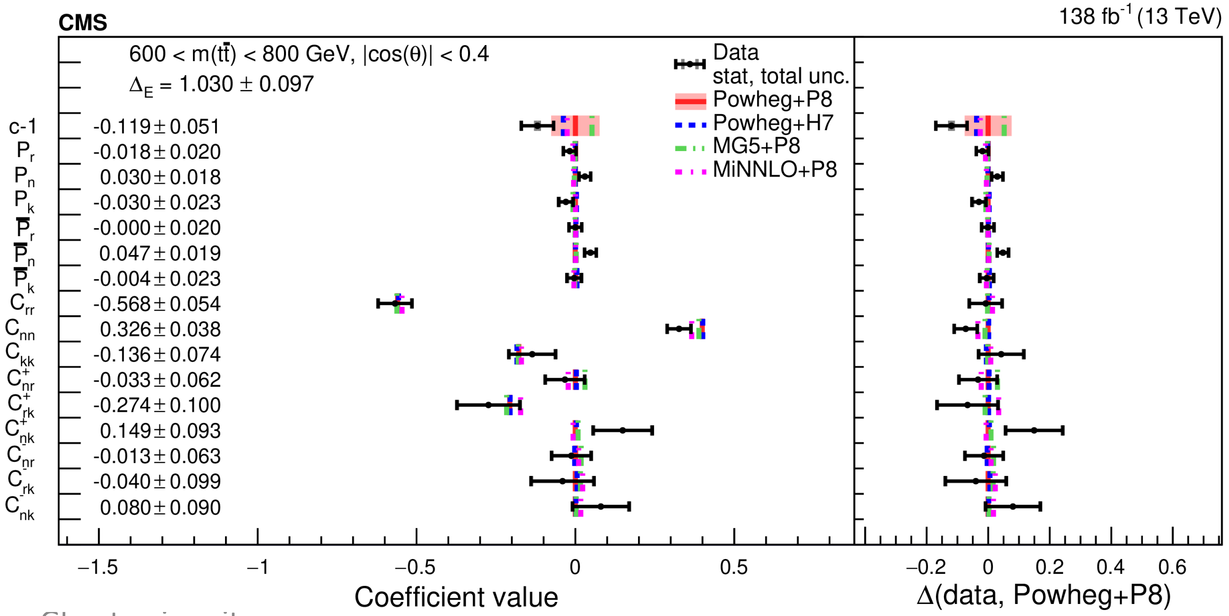
Low $m(t\bar{t})$ → High $m(t\bar{t})$

Polarization and Spin Correlation coefficients





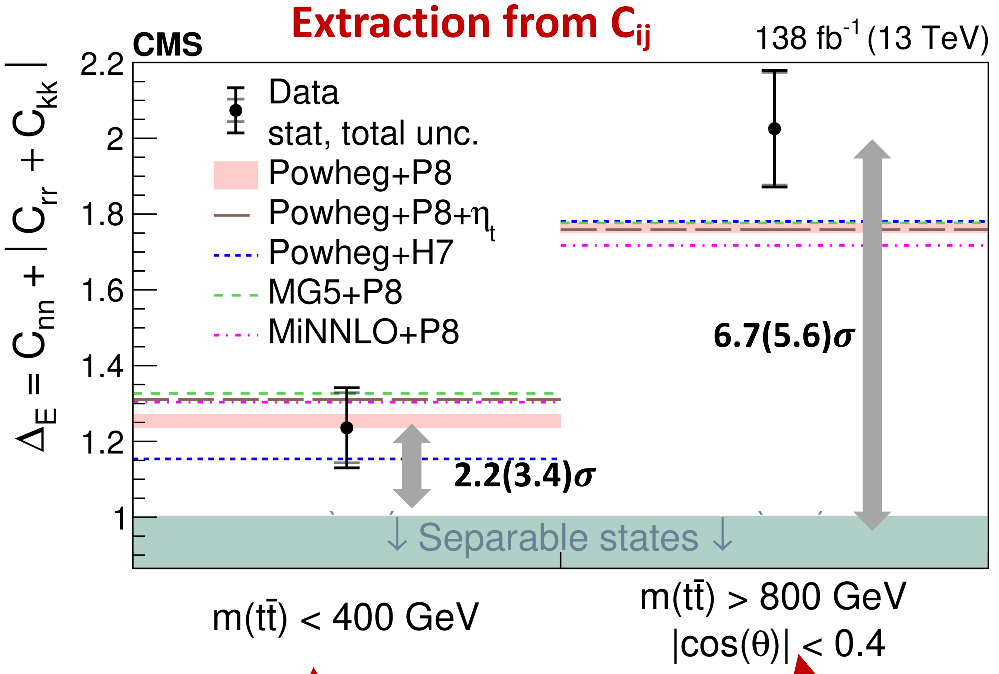


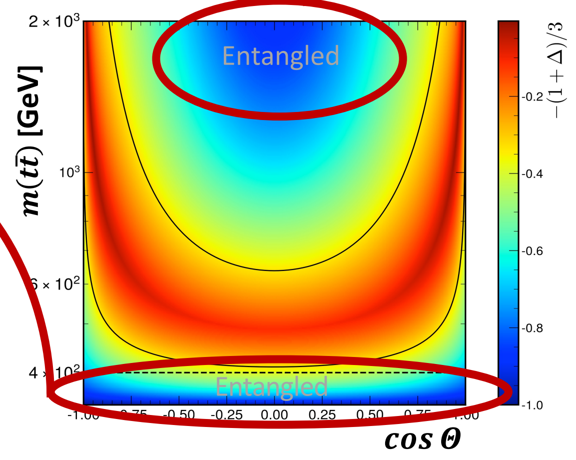


- Measured the coefficients for polarization and spin-correlation in inclusive and various kinematic phase-space
- So far measurements agree with the SM predictions

Entanglement in $t\bar{t}$ ($\ell + jets$ channel)

- Entanglement is established at **high m($t\bar{t}$) for the first time with >5σ**
- Complementarity wrt. dilepton channel





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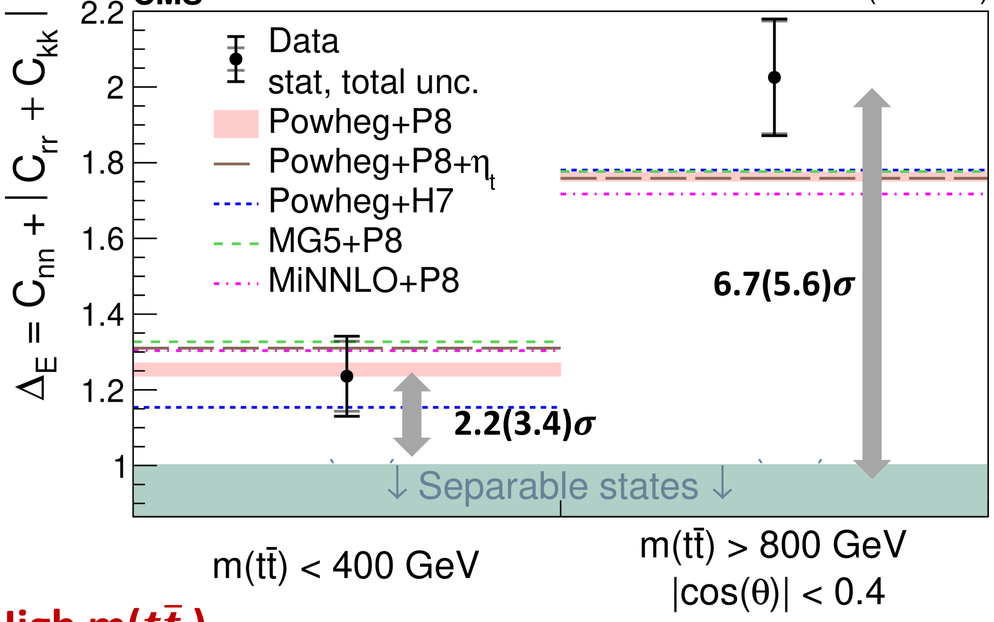
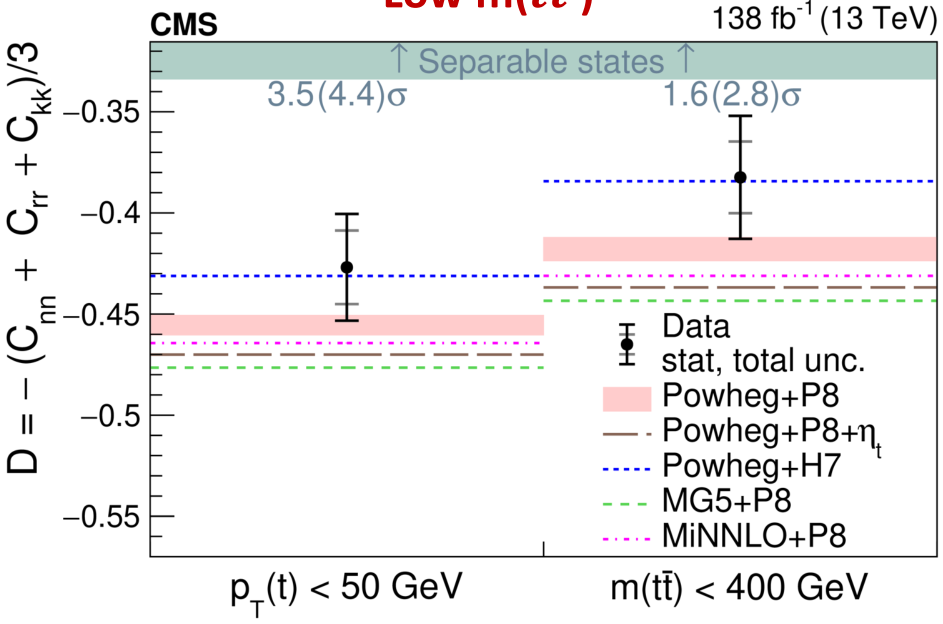
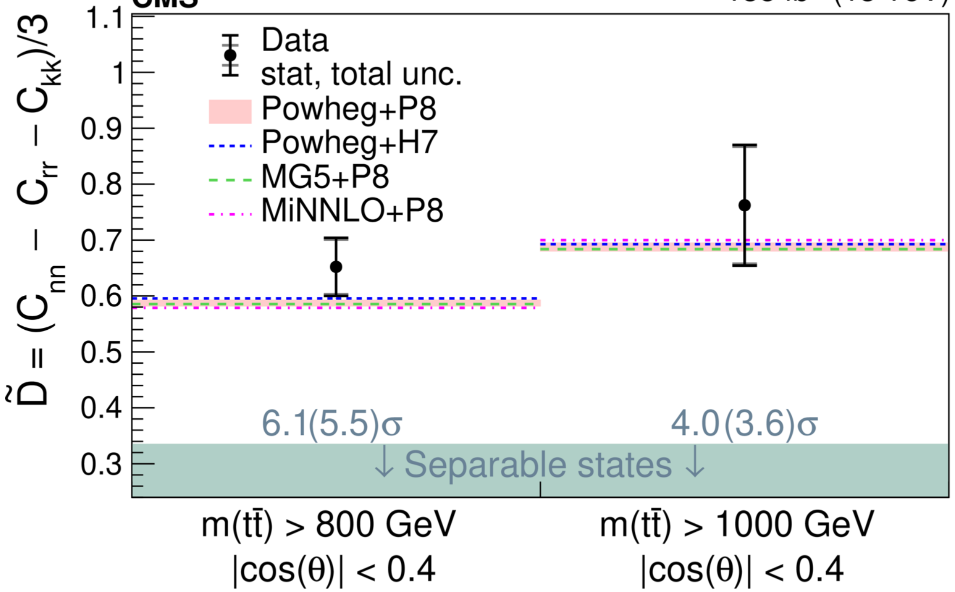
Extraction from C_{ij}



Low m($t\bar{t}$)



High m($t\bar{t}$)



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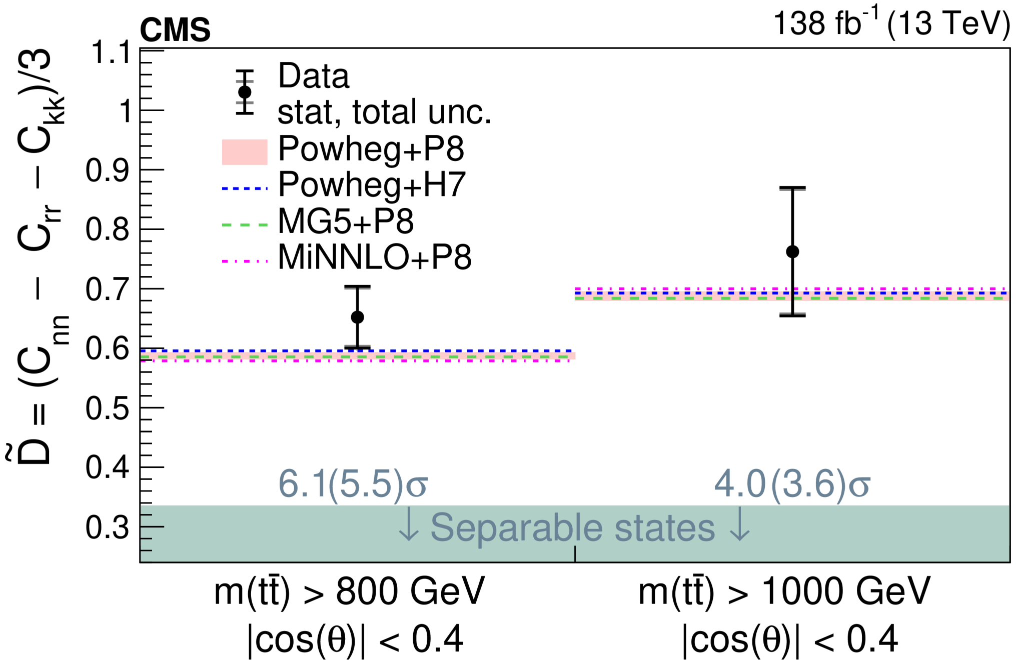
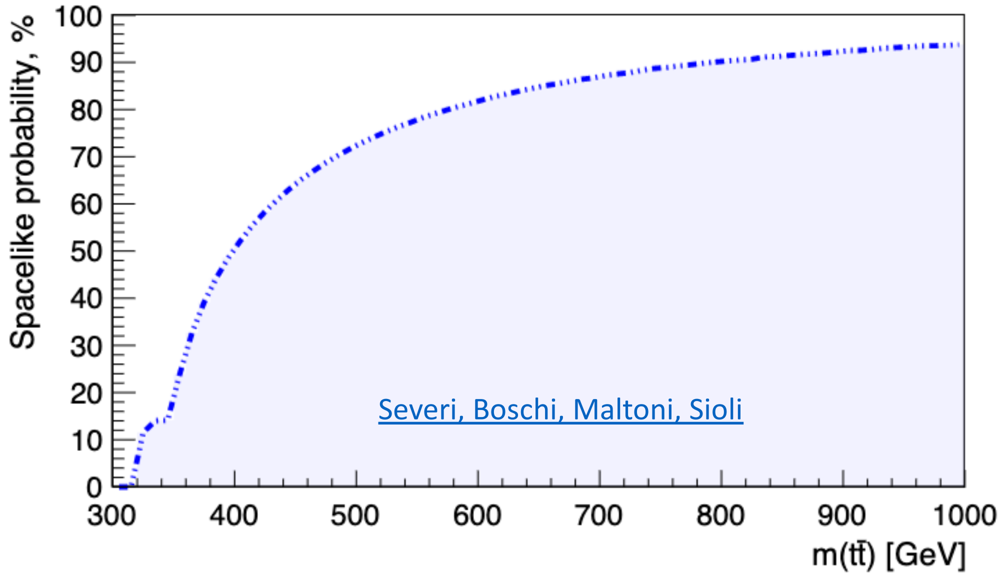


Fraction of events with space-like separation increases with m($t\bar{t}$)



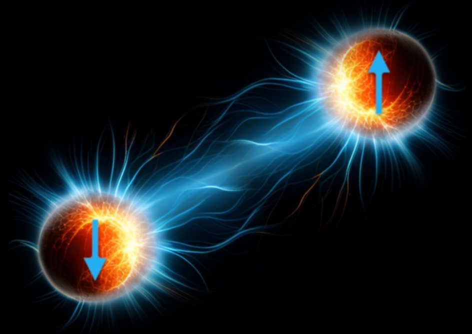
Entanglement at high m($t\bar{t}$)
→ space-like separated region
→ prospects for Bell inequality tests

Demina, et al. 2407.15223

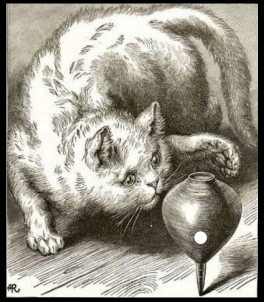
A new window to look for new physics effects

Severi, et al 2210.09330

Summary

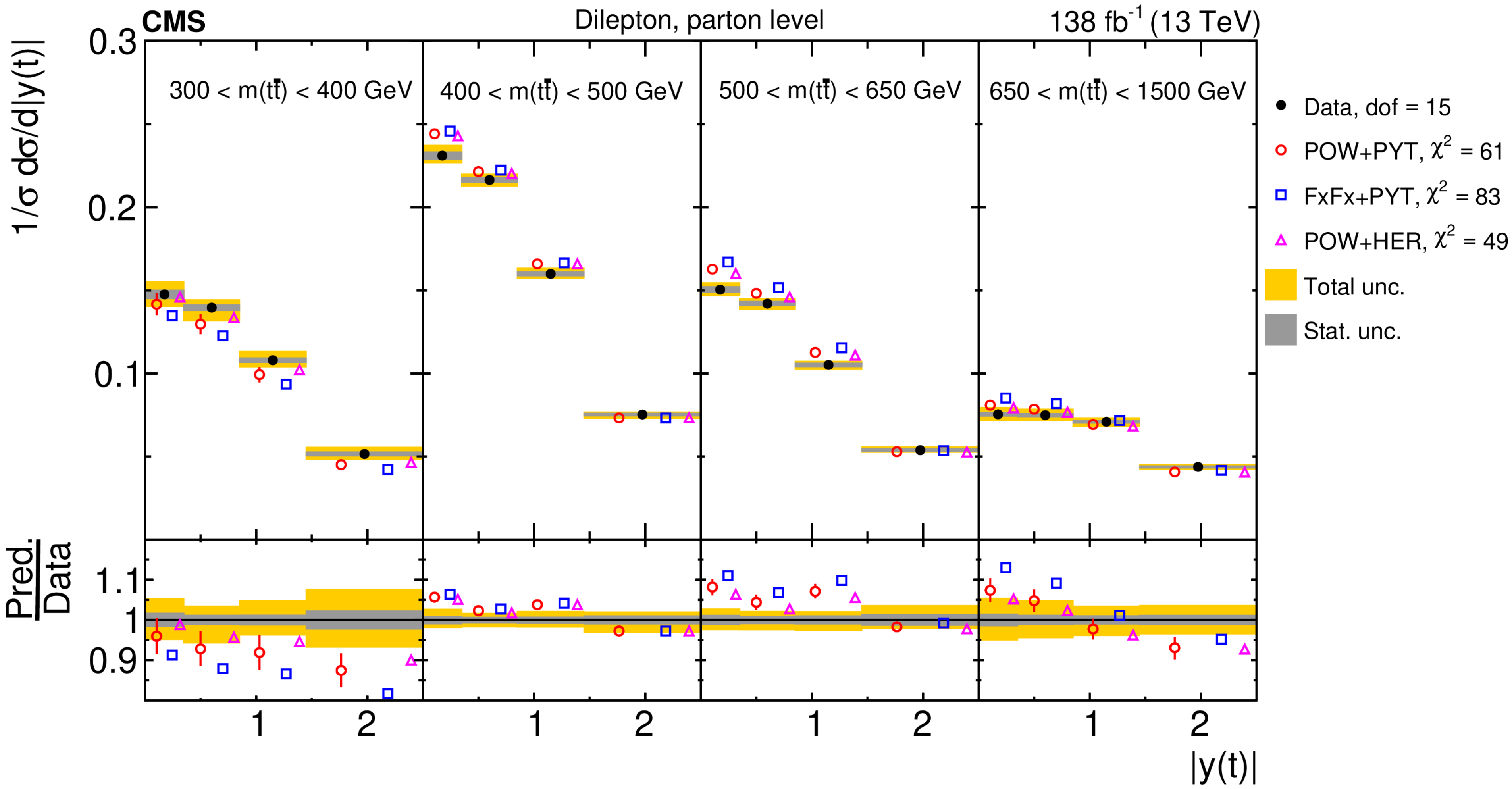


- Entanglement in top quark pairs is observed with $> 5\sigma$
    - Multiple analyses in different phase-space regions!
    - Detailed measurements of polarization coefficients and spin density matrix
- Exciting sensitivity to toponium state!
- A new experimental tool to search for new physics!

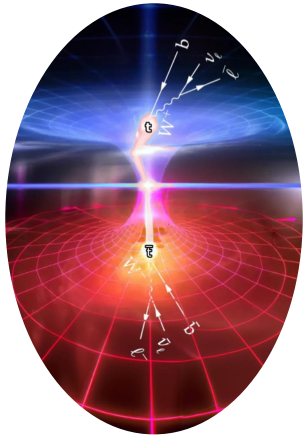


Differential cross sections

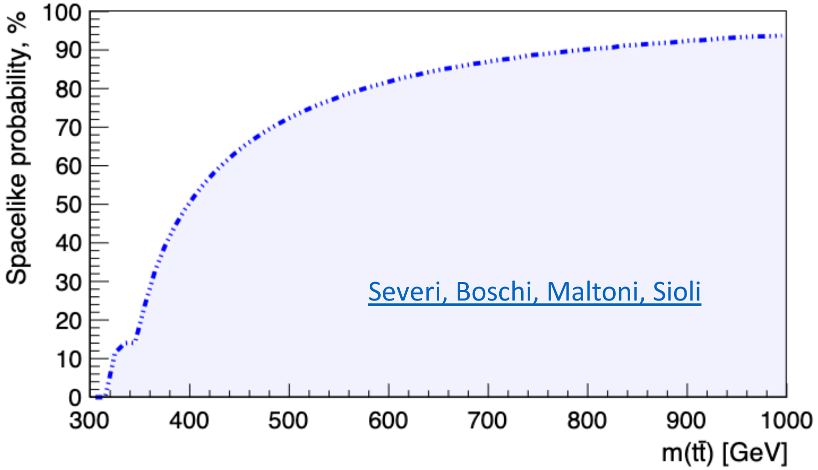
2402.08486



Excluding classical explanation ?

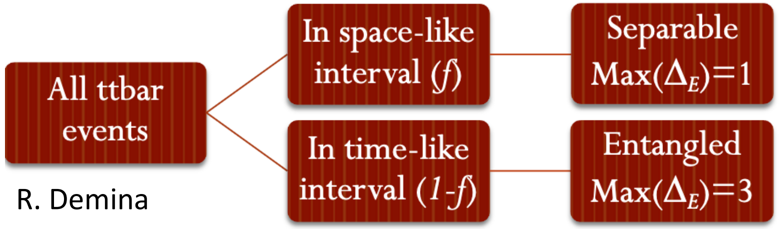


- What is the maximum value of ΔE that can still be explained by the non-quantum communication $(v \leq c)$?
- In this case only t and $\bar{t}$ decays separated by a time-like interval are entangled
- The rest of the events must be separable



- $t\bar{t}$ decay vertices are not observed, the fraction of space-like events, f, can only be determined statistically

→ Form a new Δ_E threshold



R. Demina

$$Max(|C_{ii}|) = 1$$

$$\Delta_{Ecritical} = f(\Delta_E = 1) + (1-f)(\Delta_E = 3)$$