Spin, entanglement, magic and forming bonds in the world of elementary particles?

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The world of elementary particles

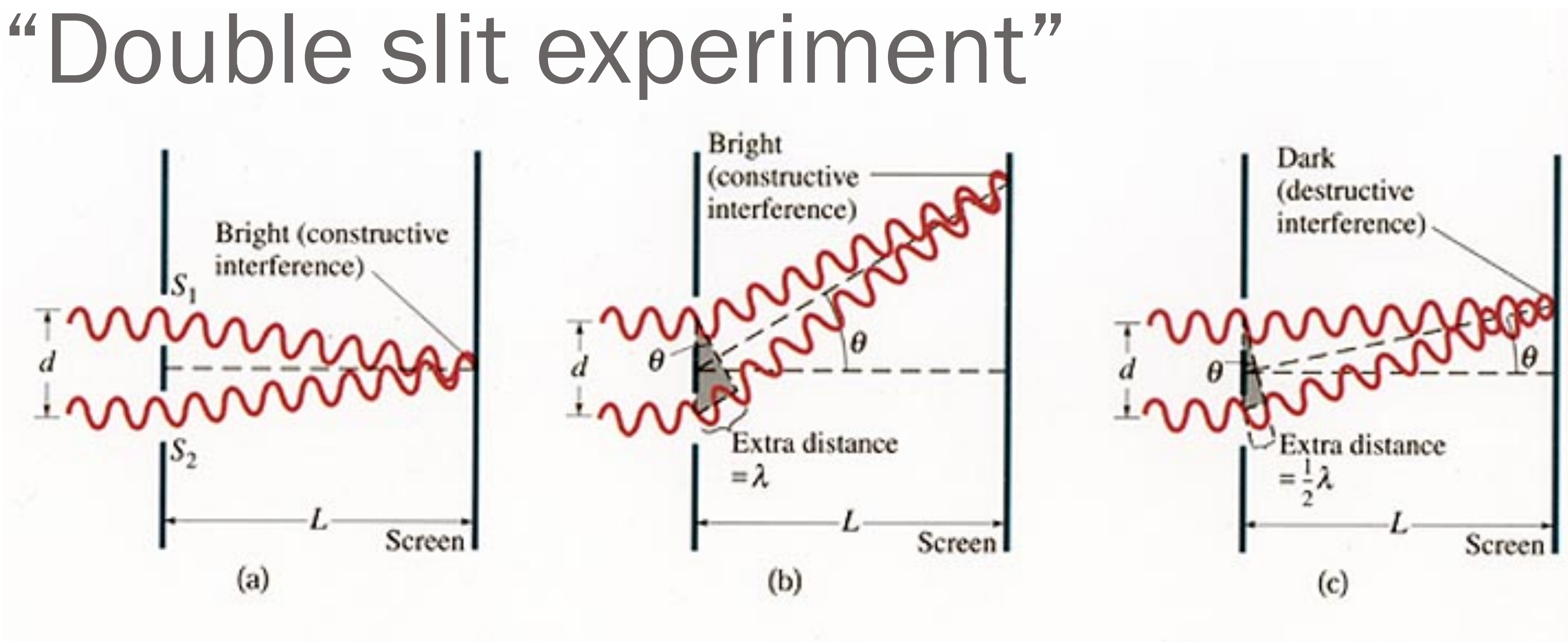
- The behavior of the elementary particles is described by quantum field theories: QED and QCD
- Quantumness should be engrained in their behavior
- Yet, it is not so easy to observe
- For a typical momentum of 100 GeV/c the precision of measurement is ~1GeV/c, typical position precision is 100 um

$$\Delta x \cdot \Delta p > h / 2\pi$$

$$\Delta t \cdot \Delta E > h / 2\pi$$

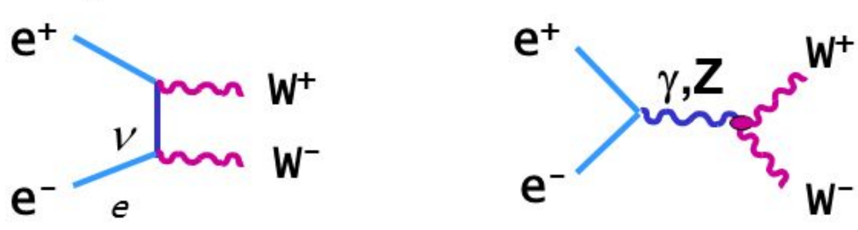
- We are ~10 orders of magnitude away from the uncertainty principle

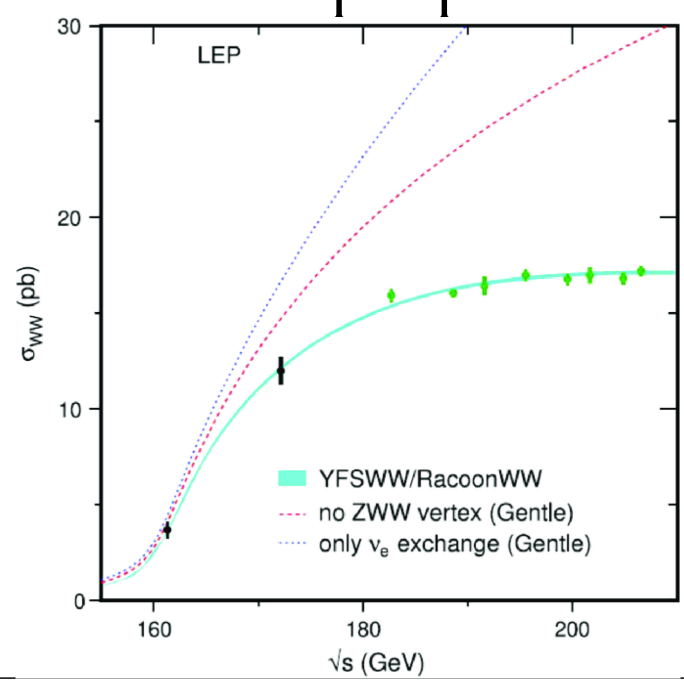
“Double slit experiment”



- Effects of amplitude interference are observed in multiple processes

W pair production at LEPII:

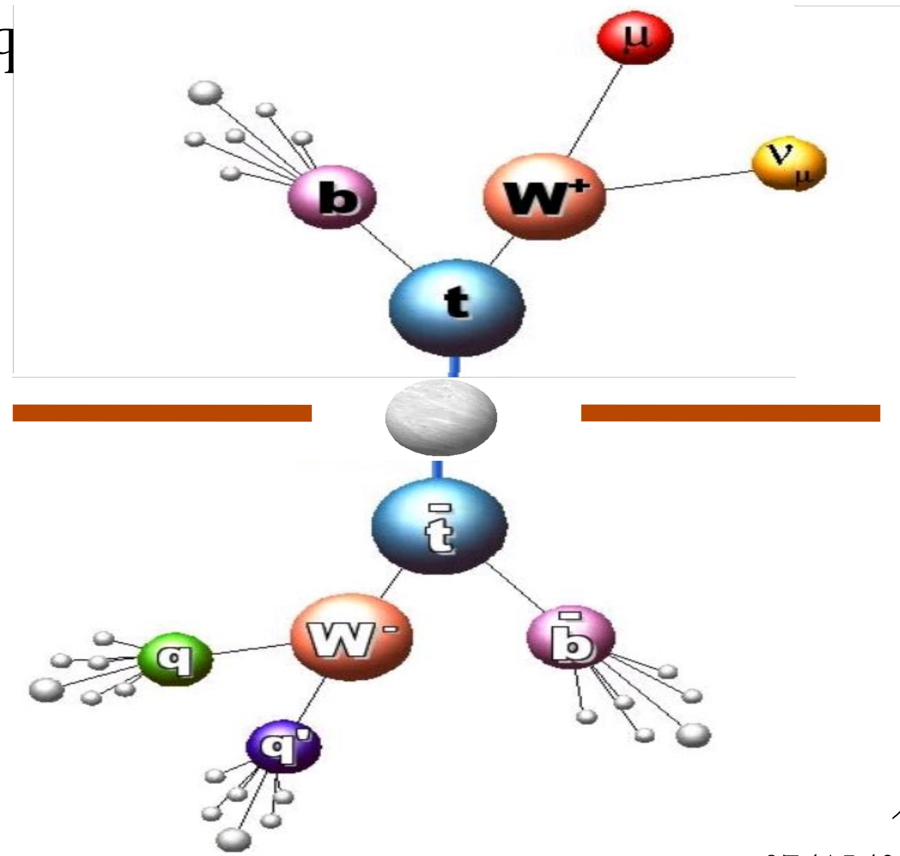




- **And then there is spin**

Top-antitop quark pair is a two qubit system

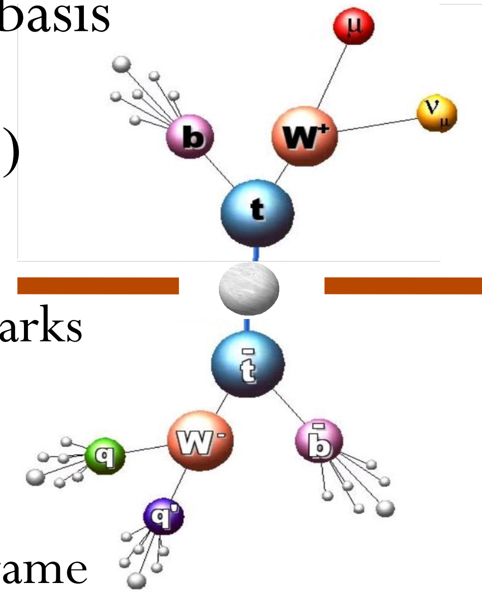
- Top quark has s=1/2, it is a **qubit**
- Top-antitop quark pair is a two-qubit system
- Top quark is very short-lived O(10^{-25}s)< hadronization time O(10^{-24}s), so it decays unlike other quarks before hadronizing (picking up a light quark from “vacuum” to form a bound state – a hadron)
- Top quark spin information is preserved in the angular correlation of its decay products t→Wb, W→lν – or – qq
- When both W bosons decay leptonically – dilepton channel
- When one W boson decays leptonically and the other one hadronically – lepton+jets channel



Spin correlation and entanglement

Polarization, P and spin correlation matrix, C determines the angular distribution of the decay products in the helicity basis as in [1212.4888]

$$\frac{d\sigma}{d\Omega d\bar{\Omega}} = \sigma_{norm}(1+\kappa\vec{P}\cdot\Omega+\bar{\kappa}\vec{\bar{P}}\cdot\bar{\Omega}-\kappa\bar{\kappa}\Omega\cdot C\cdot\bar{\Omega})$$



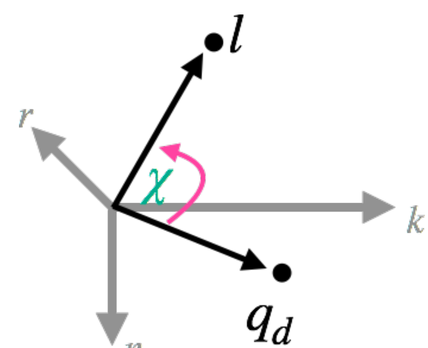
κ - spin analyzing power of top/antitop decay products – leptons or quarks

Ω – unit vector in the direction of the decay product

2×3(P)+3×3(C) =**15 coefficients Q_m**

Or use χ –opening angle between the two decay products in rotated tt frame (a.k.a helicity angle)

$$\frac{d\sigma}{d\cos\chi} = A(1+D\kappa\bar{\kappa}\cos\chi)$$



and $\tilde{\chi}$, where the sign of n-component in one of the decay products is inverted:

$$\frac{d\sigma}{d\cos\tilde{\chi}} = A(1+\tilde{D}\kappa\bar{\kappa}\cos\tilde{\chi})$$

Spin correlation and entanglement in ttbar system

The system is considered **separable** if its density matrix can be factored into individual states

$$\rho = \sum_n p_n \rho_n^t \rho_n^{\bar{t}}$$

Otherwise, it is considered **entangled** → **Peres-Horodecki criterion** [2003.02280]

A. Peres, Phys. Rev. Lett. 77, 1413 (1996).
P. Horodecki, Physics Letters A 232, 333 (1997)

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

Entanglement is a result of spin correlation.

There are four pure maximally entangled (Bell) states:

$$|\Phi^{\pm}\rangle = \frac{1}{\sqrt{2}}\left(|\uparrow\uparrow\rangle \pm |\downarrow\downarrow\rangle\right),$$

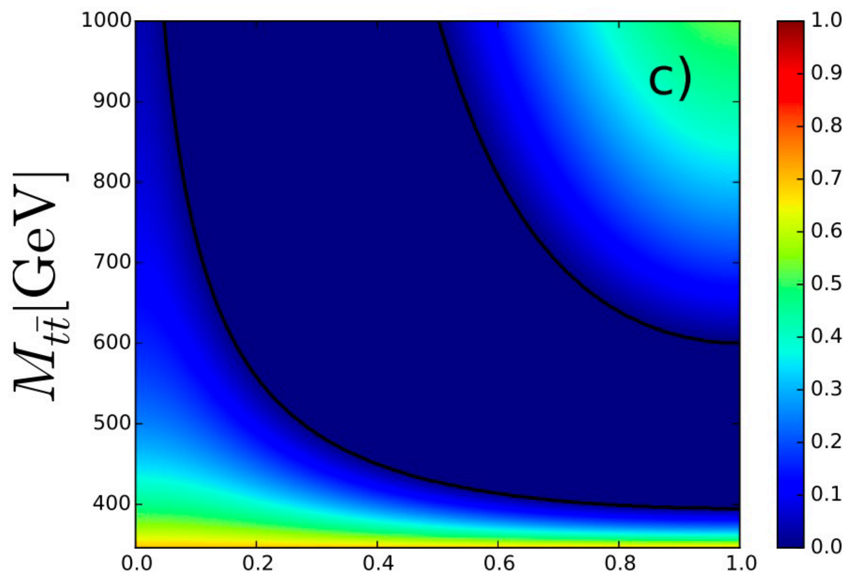
$$|\Psi^{\pm}\rangle = \frac{1}{\sqrt{2}}\left(|\uparrow\downarrow\rangle \pm |\downarrow\uparrow\rangle\right).$$

at low singlet pseudoscalar state Ψ^-

Peres-Horodecki criterion

$$\Delta_E = Tr(C) = -3D > 1$$

$$D < -\frac{1}{3}$$



$\frac{2\Theta}{\pi}$ Top angle with the beam axis

at high triplet vector state ($\Phi^+ - \Phi^-$, Ψ^+, $\Phi^+ + \Phi^-$)

Peres-Horodecki criterion

$$\Delta_E = C_{nn} - C_{rr} - C_{kk} = 3\tilde{D} > 1$$

$$\tilde{D} > \frac{1}{3}$$

Plot from Afik, De Nova EPJP136(2021)9,907 hep-ph:2003.02280

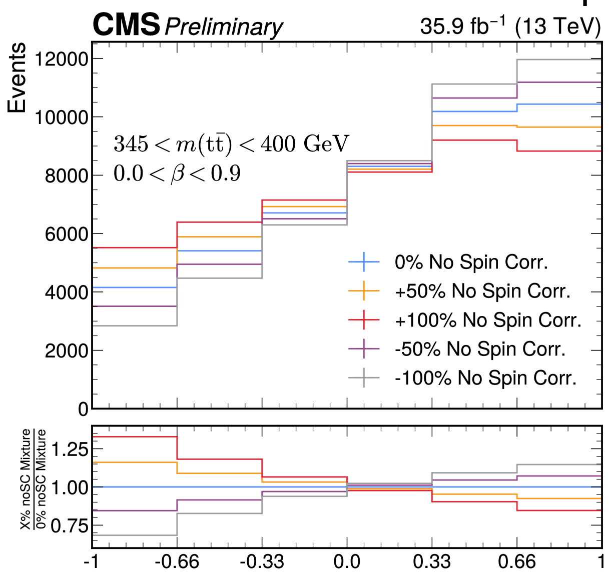
Dilepton channel ROPP 87 (2024) 117801

To extract D we measure the distribution in the sensitive variable – $\cos\chi$

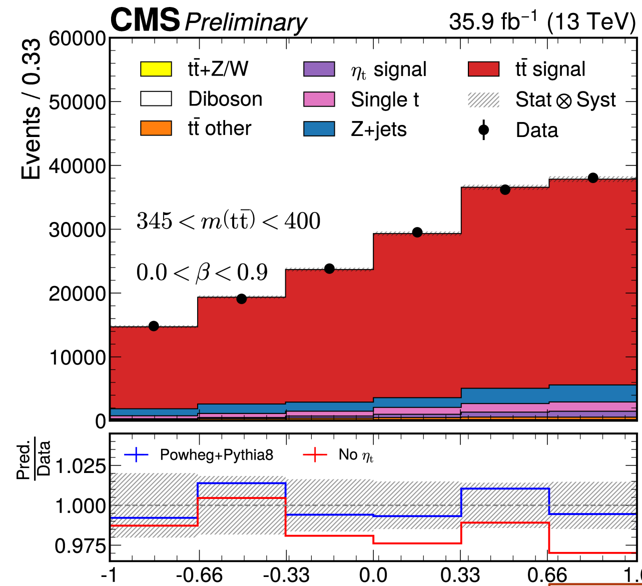
$$\frac{d\sigma}{d\cos\chi} = A(1 + D\kappa\bar{\kappa}\cos\chi)$$

Optimize M_{tt} cut to maximize sensitivity to entanglement

Determine the effect of acceptance and efficiency by comparing $D_{reco}(M_{reco})$ vs D_{gen} (M_{gen} *full phase space*)



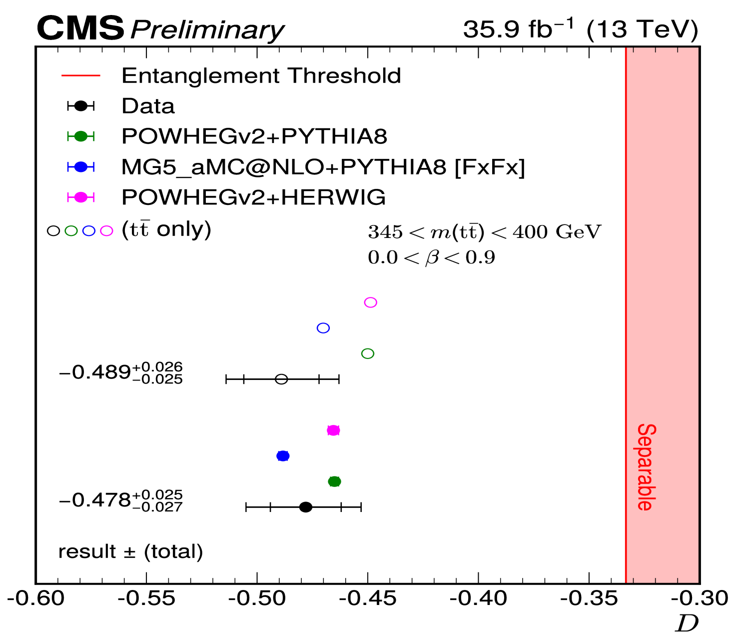
The ttbar entanglement is observed (expected) at the 5.0(4.7)σ level for 345<Mtt<400 GeV, β<0.9



Apparent disagreement with the prediction is reduced once top-antitop bound state is included:

without **Toponium**

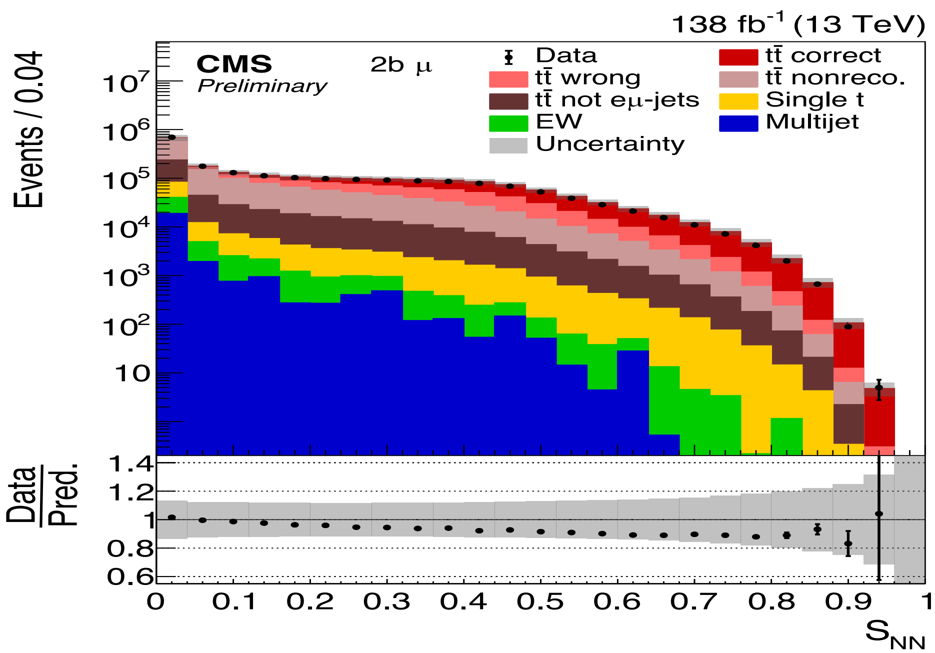
with **Toponium**



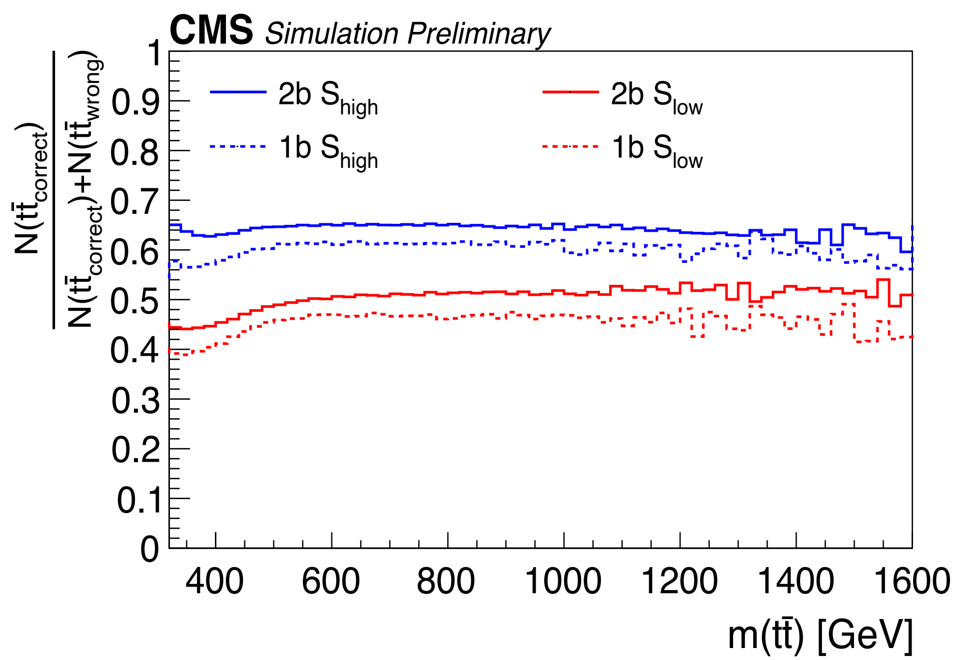
~1.5σ tension with the expectation if toponium is not included

Event reconstruction in l+jets channel

- Highest spin analyzing power is that of charged leptons – electrons and muons (easy to identify) and d-type quarks (extremely hard to distinguish from other light quarks)
- Event reconstruction (jet-parton assignment) is performed using NN
- **Major challenge – identify *d*-type jets from W boson decay**
- Divide events into categories based on lepton flavor, number of b-tags, and NN score



Fraction of *tt* events with correctly assigned jets to partons including *d*-type quark



PRD 110 (2024) 112016

Extraction of spin correlation

- We observe the angular distribution of top decay products, encoded in unit vectors Ω:

$$\frac{d\sigma}{d\Omega d\bar{\Omega}} = \sigma_{norm}(1+\kappa\vec{P}\cdot\Omega+\bar{\kappa}\vec{\bar{P}}\cdot\bar{\Omega}-\kappa\bar{\kappa}\Omega\cdot C\cdot\bar{\Omega})$$

- The cross section depends on 15 known angular functions

$$\Sigma_m = \{\kappa\sin\theta_p\cos\phi_p, \ldots - \kappa\bar{\kappa}\cos\theta_p\cos\theta_{\bar{p}}\}$$

- The total cross section is a linear combination of these functions with coefficients Q_m that are the components of P and C

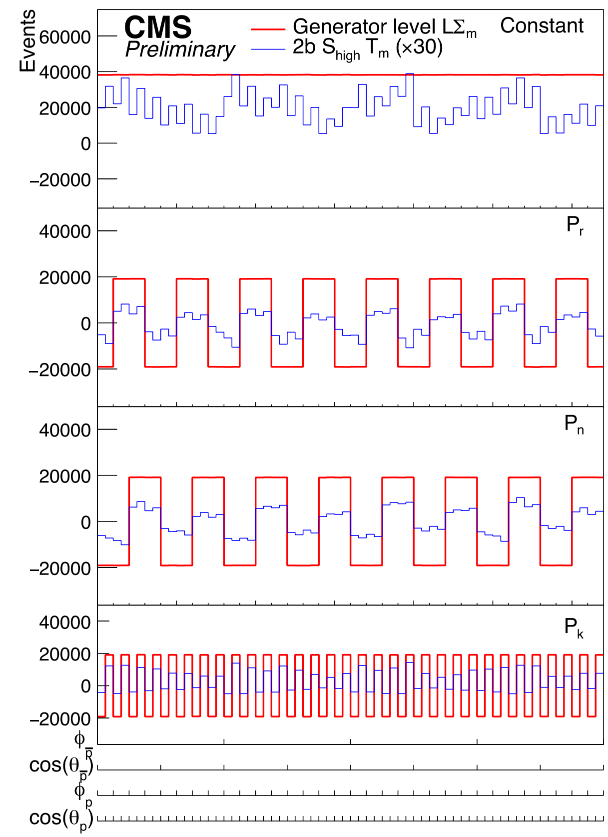
$$\Sigma_{tot} = \Sigma_0 + \sum_{m=1}^{15} Q_m\Sigma_m$$

Σ_m Theoretically predicted distributions in angles of decay products

T_m Reconstruction level distributions, which take into the account selection criteria , efficiency and resolution of the detector.

In other words, encode the effects of the environment

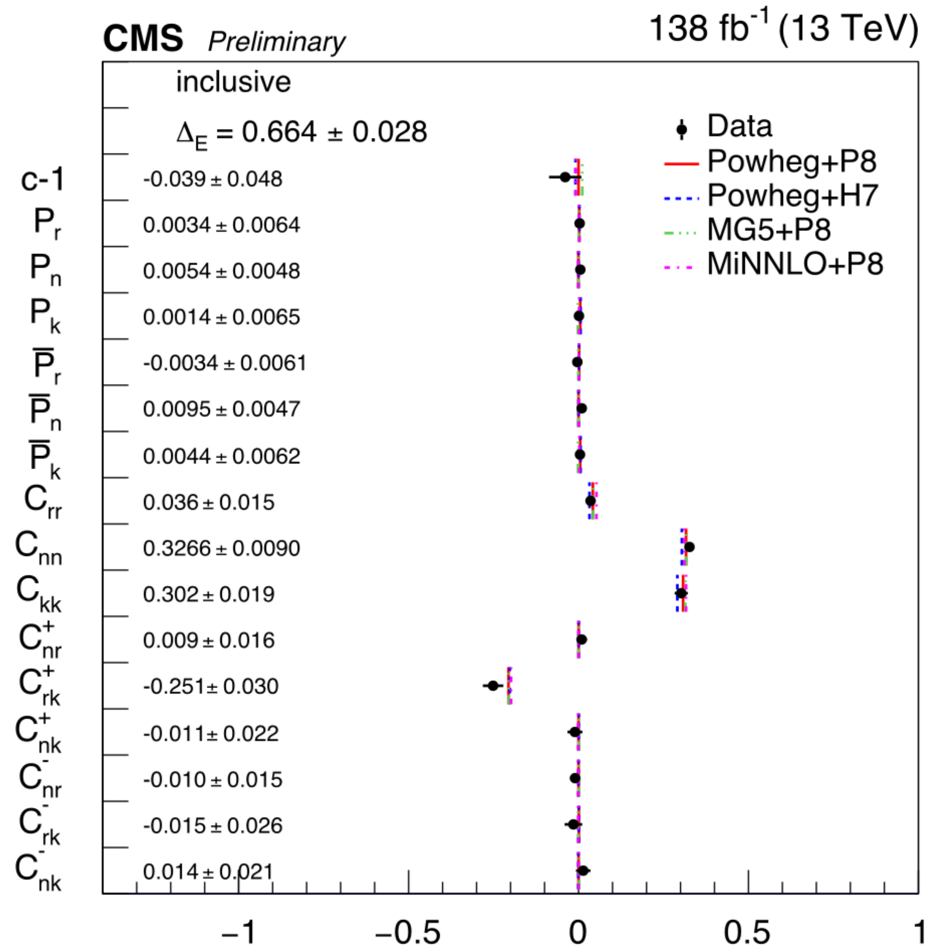
Data distribution is fit the sum of T_m with free coefficients – P_i and C_{ij}



PRD 110 (2024) 112016

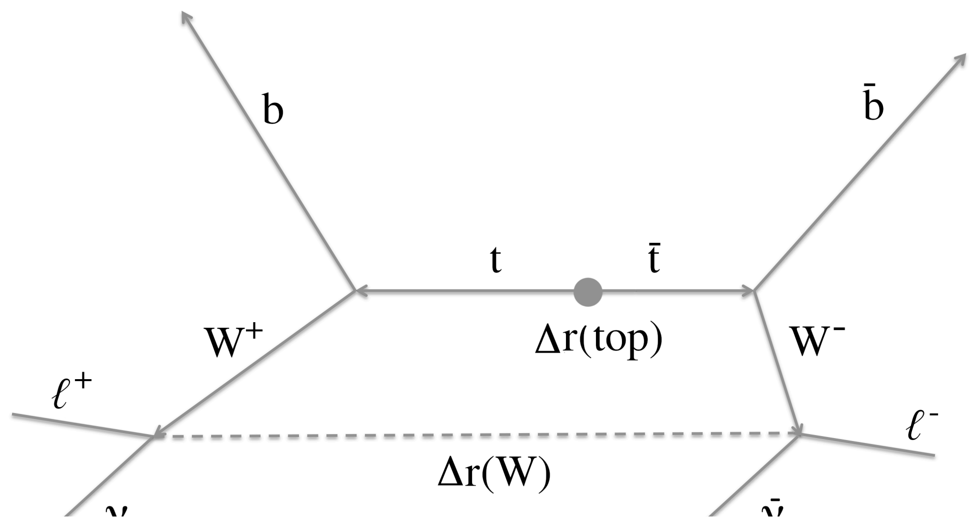
Spin correlation matrix measurement

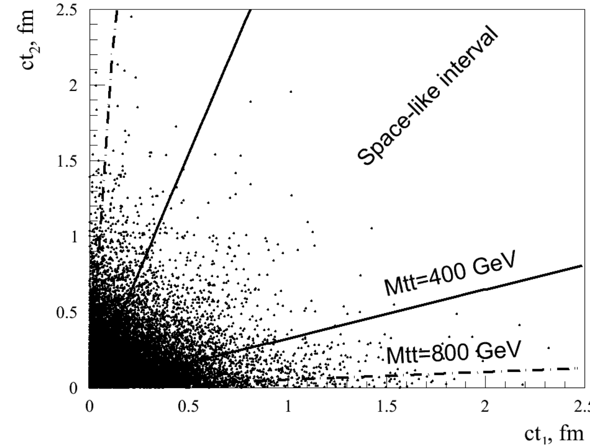
- Full measurement of the P and C is performed inclusively and differentially in bins of M_{tt}, $cos\theta$ and top p_T
- Full covariance matrix is provided with the published result
- A good agreement with the SM prediction is observed
- Measurement performed in the helicity and beam bases

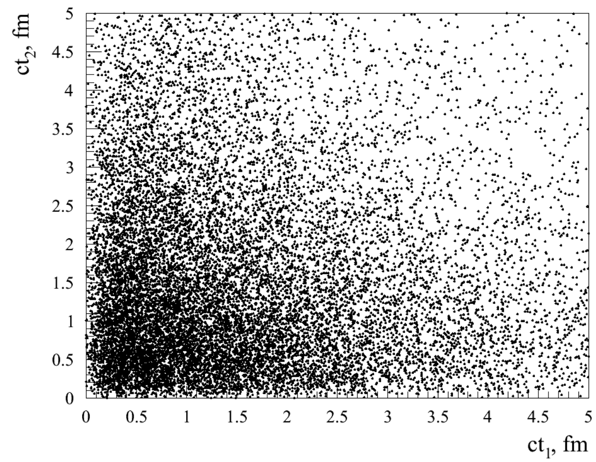


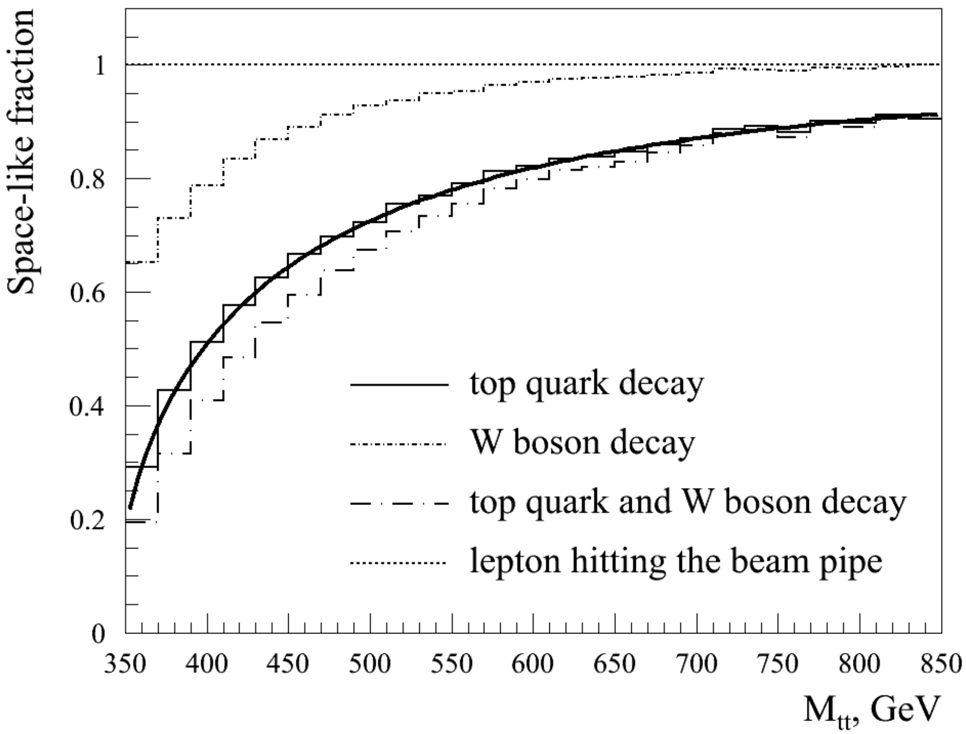
Towards excluding classical explanation

Phys.Rev.D 111 (2025) 1, 012013







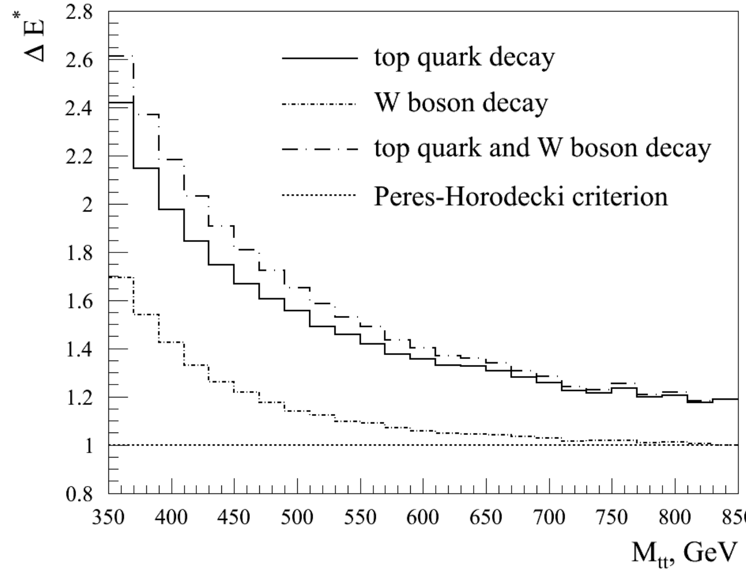


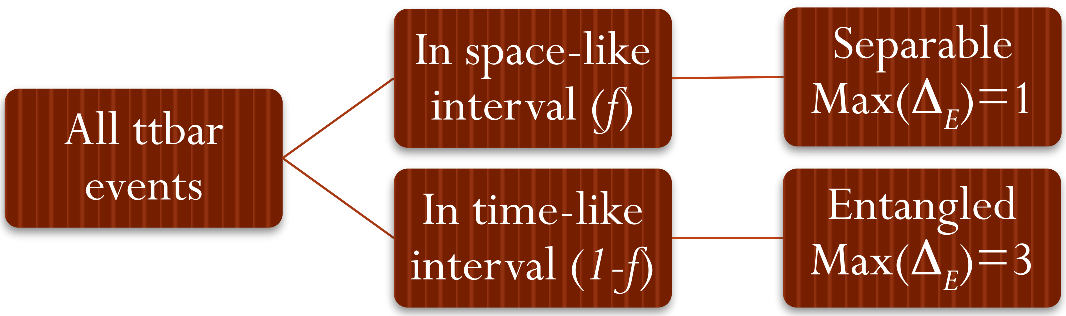
Exclude causal connections between

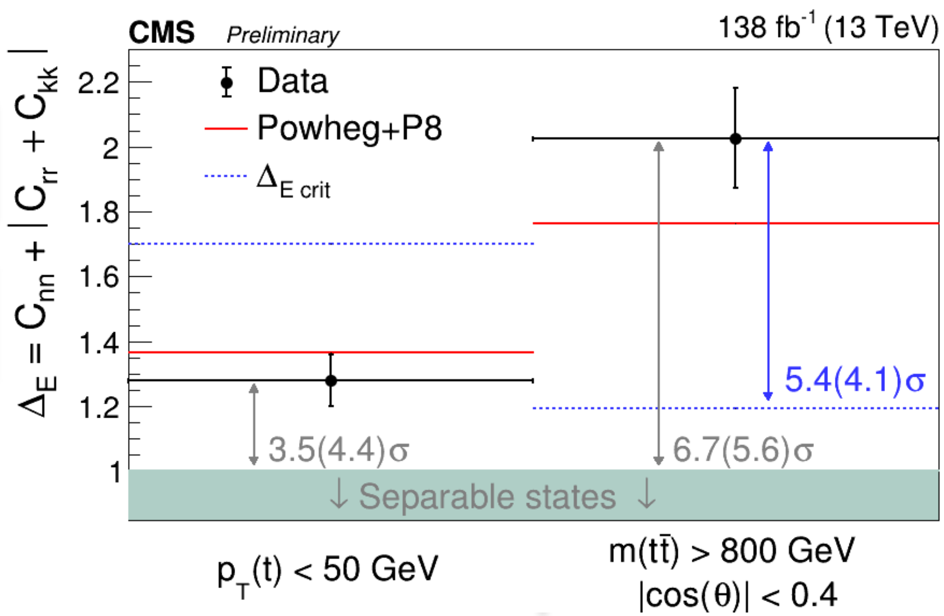
- Top and antitop decays
- W+ and W- decays
- Lepton contact with the macroscopic apparatus
- (beam pipe)

Excluding classical explanation

- What is the maximum value of Δ_E that can still be explained by the non-quantum communication ($v<=c$)?
- In this case only top and antitop decays separated by a **time-like interval** are entangled
- The rest of the events must be separable
- Since top and antitop decay vertices are not observed, the fraction of space-like events, f, can only be determined statistically







- Max(Cij)=1

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

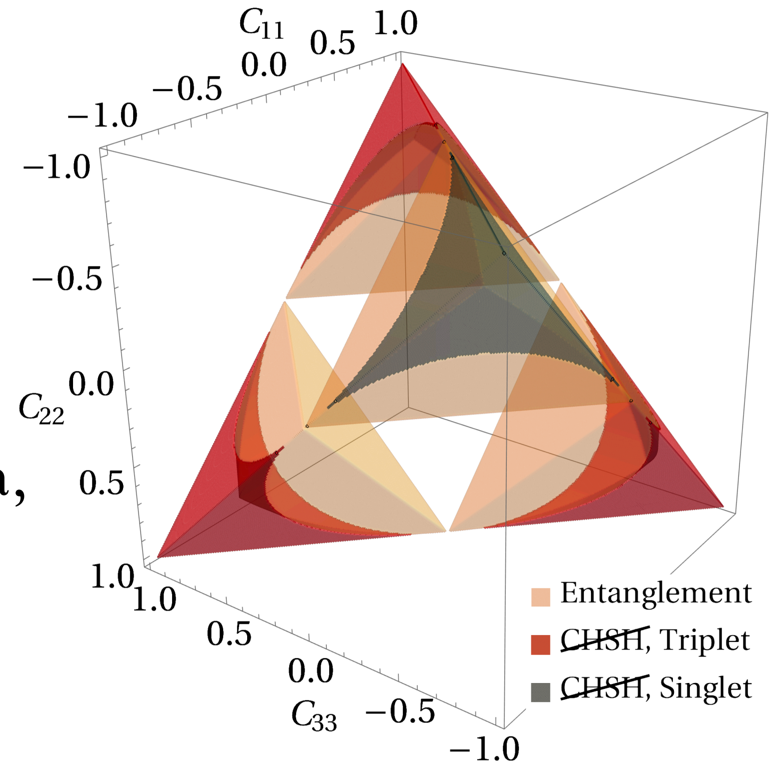
Observed Δ_E exceeds $\Delta_{Ecritical}$ by >5σ excluding classical explanation

Bell inequality

C Severi et al. arXiv:2110.10112v2 [hep-ph]

- **Bell inequality** is formulated based on conventional logic, which is violated in QM
- **Entanglement is a necessary but not sufficient condition for Bell inequality violation**
- It can be phrased in terms of Clauser, Horne, Shimony, and Holt (CHSH) inequality [PRL, 23(15), 1969] which states that measurements a, a' and b, b' on subsystems A and B, respectively (with absolute values <=1) classically must satisfy:

$$\left|\langle ab\rangle - \langle ab'\rangle + \langle a'b\rangle + \langle a'b'\rangle\right| \leq 2$$



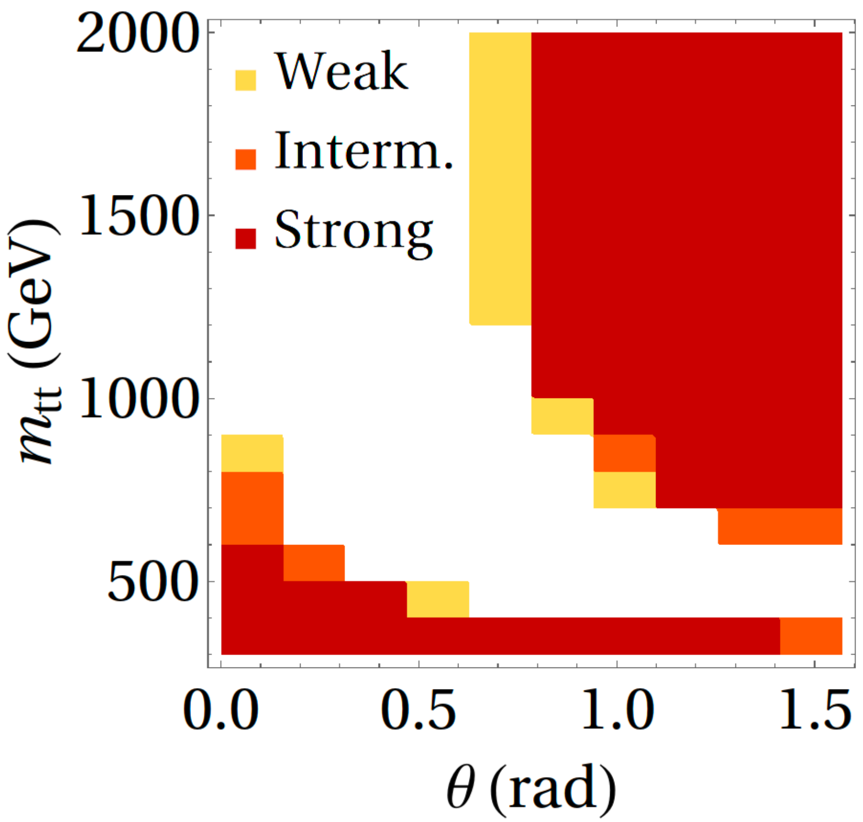
- For ttbar system the CHSH can formatted as

2 leading conditions for CHSH violation

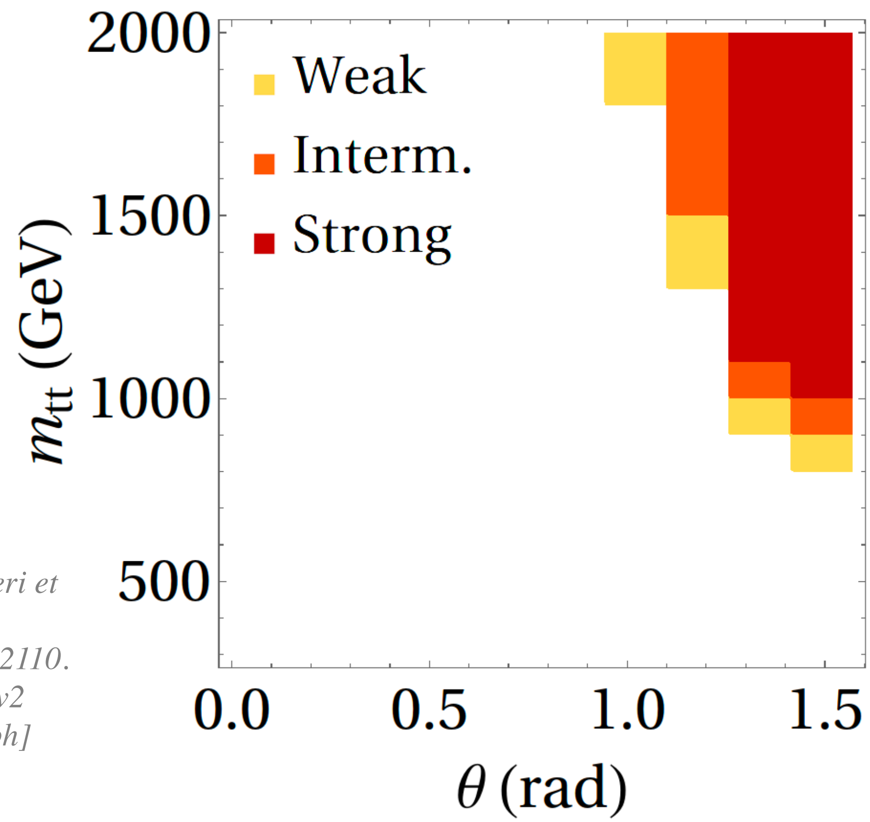
$$B_1 = |C_{rr} - C_{nn}| > \sqrt{2}$$

$$B_2 = |C_{rr} + C_{kk}| > \sqrt{2}$$

Entanglement Bell inequality violation



C Severi et al. arXiv:2110.10112v2 [hep-ph]



While entanglement can be observed at the threshold (singlet) and in high Mtt regions, for the observation of Bell inequality violation we must go to even higher Mtt (>1TeV), central production

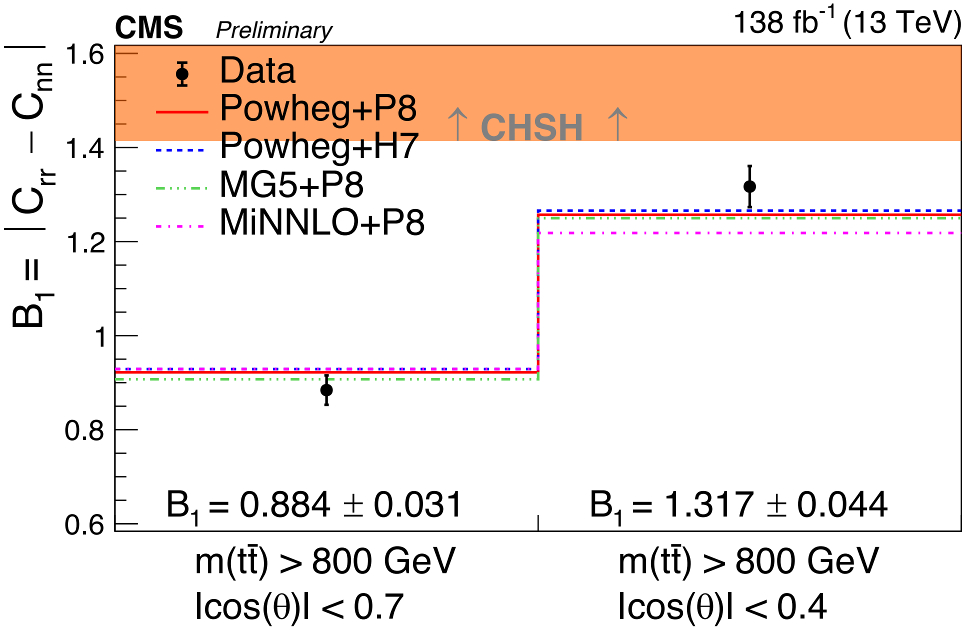
Results in l+jets – reaching for Bell inequality

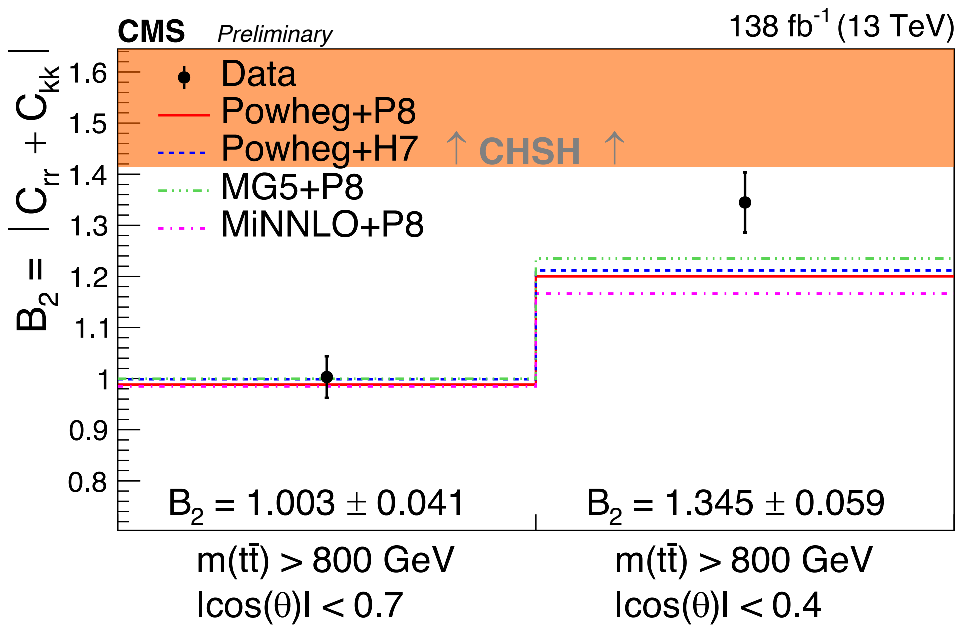
- Criteria for Bell inequality violation (in CHSH definition) are shown in orange

$$B_1 = |C_{rr} - C_{nn}| > \sqrt{2}$$

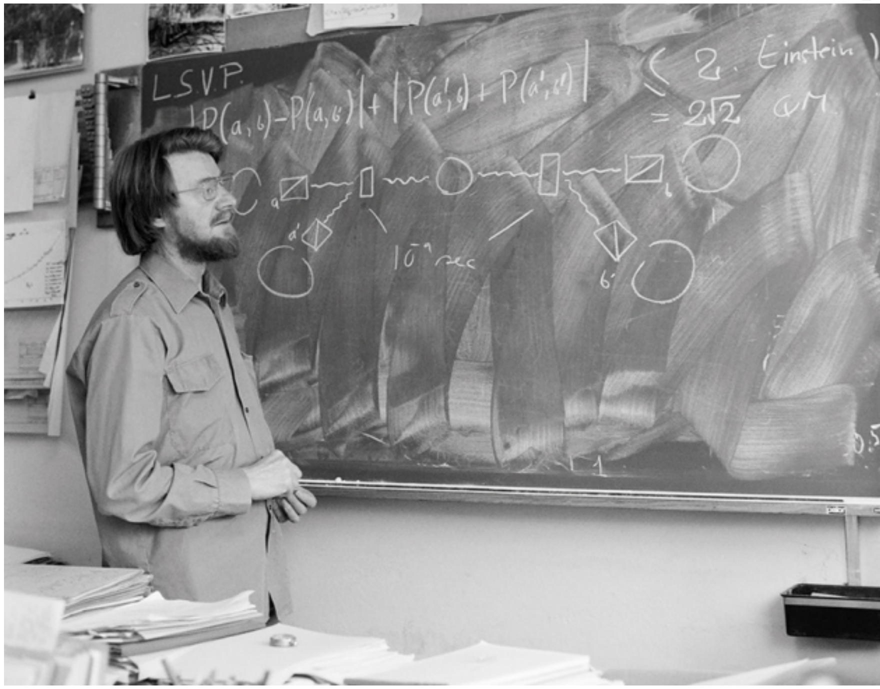
$$B_2 = |C_{rr} + C_{kk}| > \sqrt{2}$$

- We are not there yet
- Need more data to go to higher Mtt



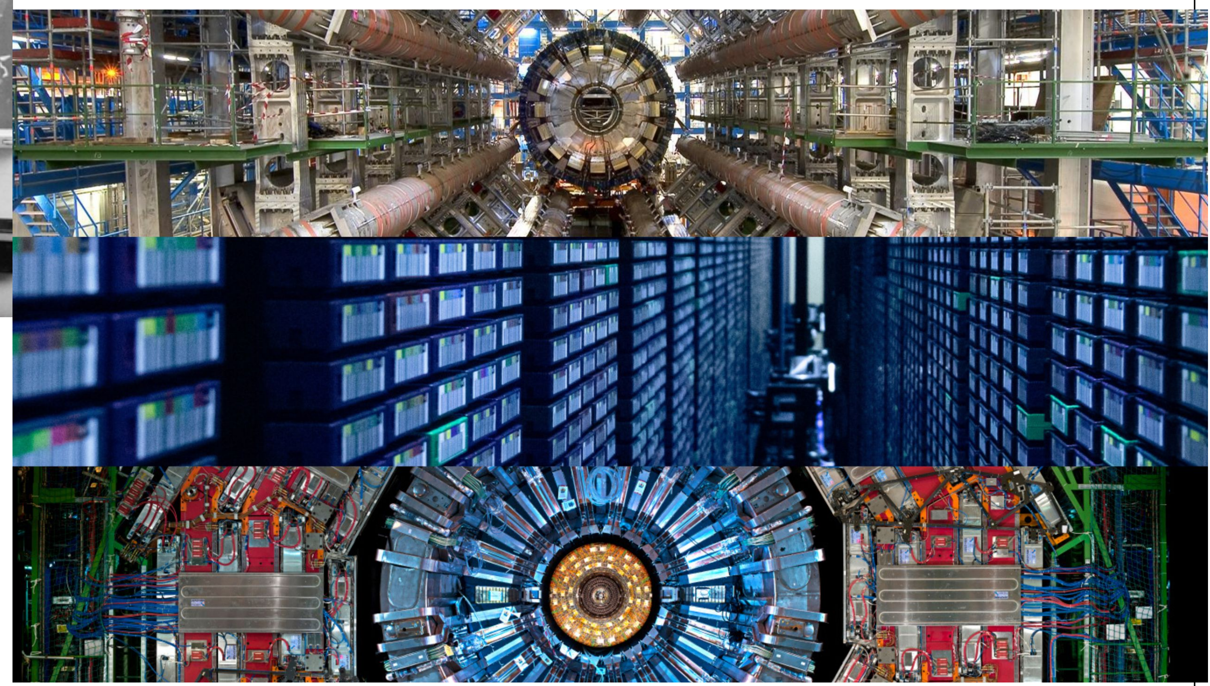


Bell's inequality – full circle



John Stewart Bell

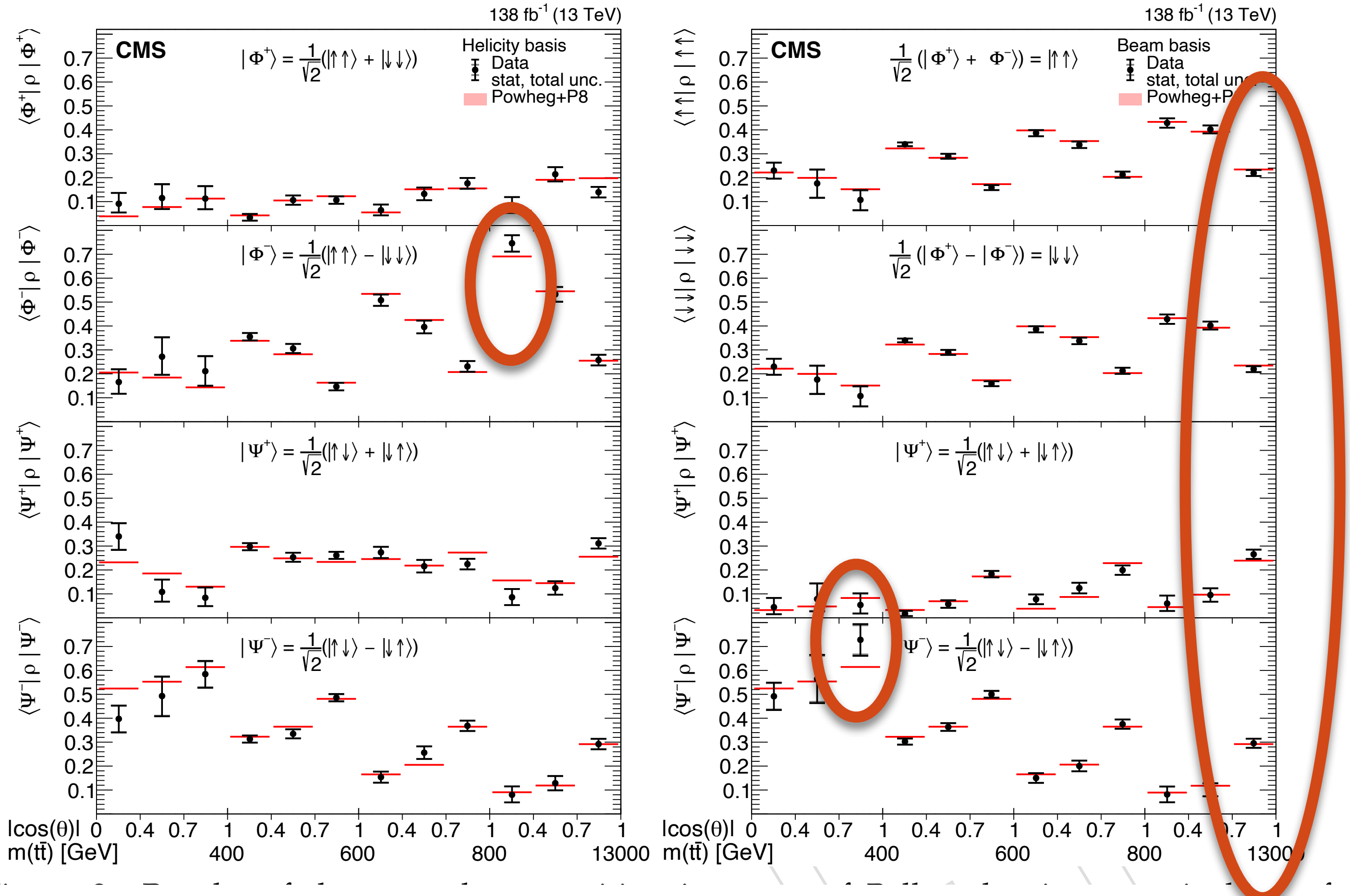
https://home.cern/news/press-release/physics/lhc-experiments-cern-observe-quantum-entanglement-highest-energy-yet



It is symbolic that the test of Bell inequality is coming back to CERN, where the original idea was developed

Decomposition into eigenstates

- Decomposition into the eigenstates in the helicity (Bell states) and beam (pseudoscalar and vector) bases.
- At the threshold (M_{tt}<400 GeV) 70% in the pseudo scalar state and 30% in vector state
- At high M_{tt}, low $cos\theta$ - >70% Φ- (pure Bell state)
- At high M_{tt}, high $cos\theta$ in beam basis maximally mixed state

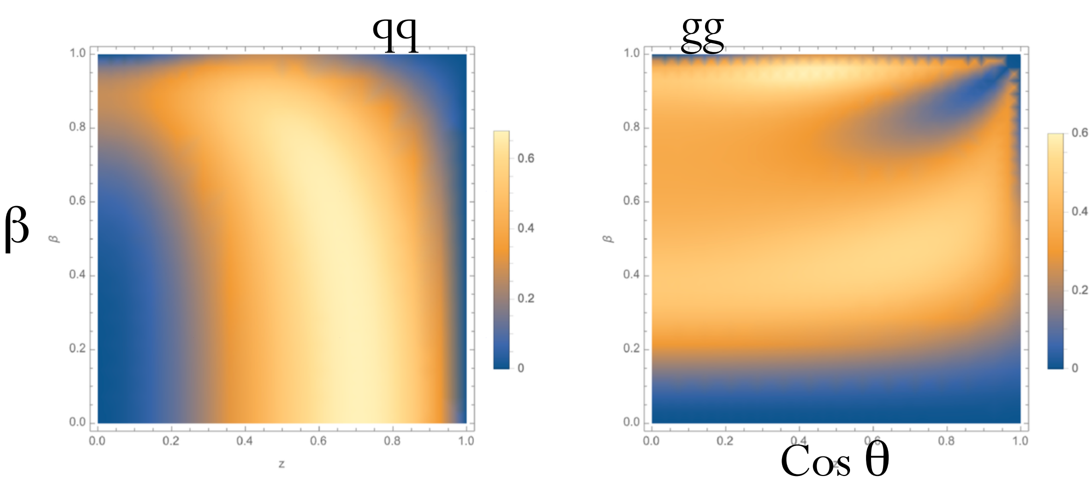


Connecting to QIS: Quantum magic

- Quantum computers are expected to vastly outperform classical computers.
- Naïvely, this is due to quantum *superposition* and *entanglement*.
- However, this not quite true.

- To see why, we need the concept of a *stabiliser state*
- *Gottesman-Knill theorem*: For every quantum computer containing stabiliser states only, there is a classical computer that is just as efficient!
- Need quantum magic - *Stabilizer Rényi Entropies*

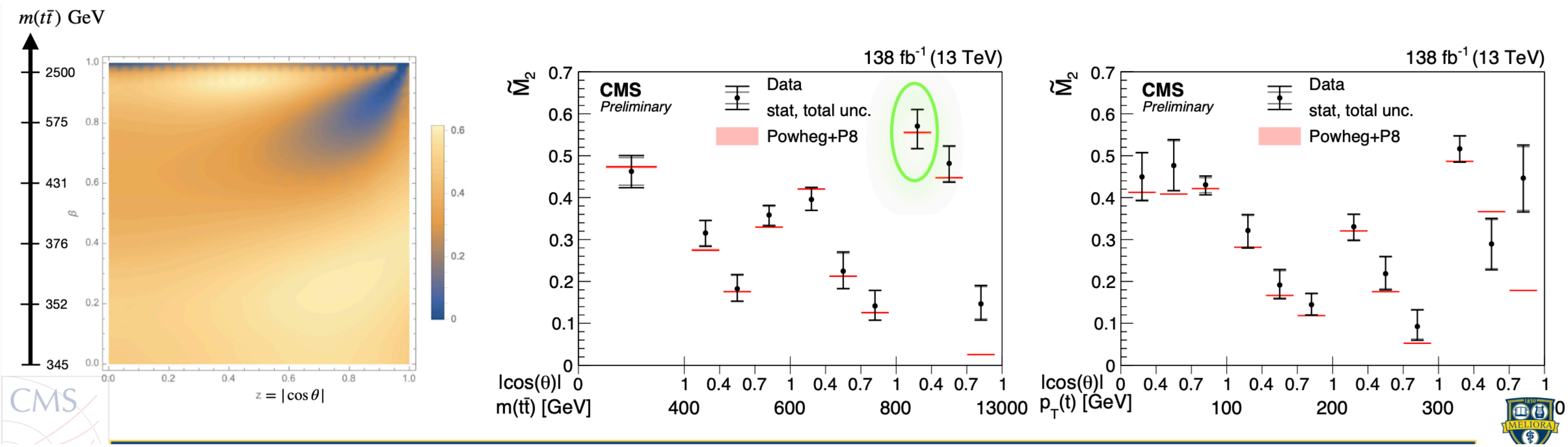
C. White, M. White



Phys.Rev.D 110 (2024) 11, 116016

Magic in top events – results on data

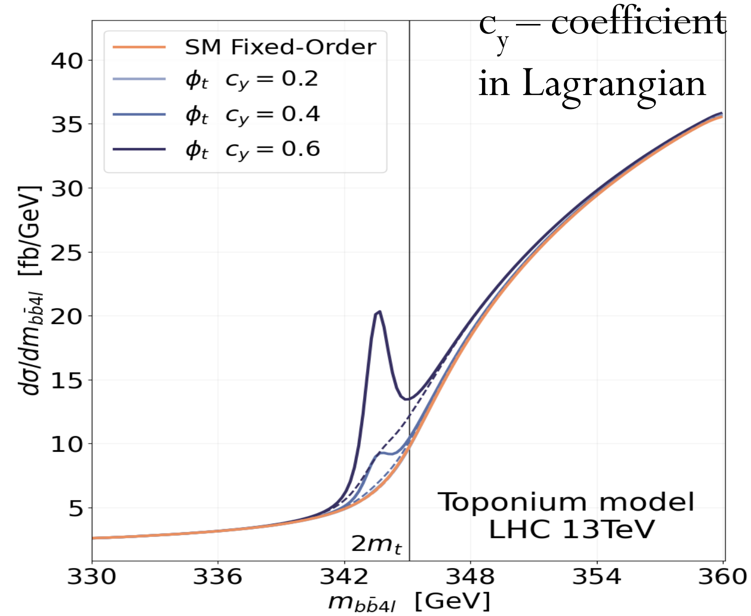
- Magic is quite easy to evaluate based on the spin correlation matrix.
- Preliminary result CMS Top-25-001. Paper in preparation.
- The plan of cause is not to use LHC as a quantum computer, but to establish a common language between QIS and HEP, or at least have a "dictionary"

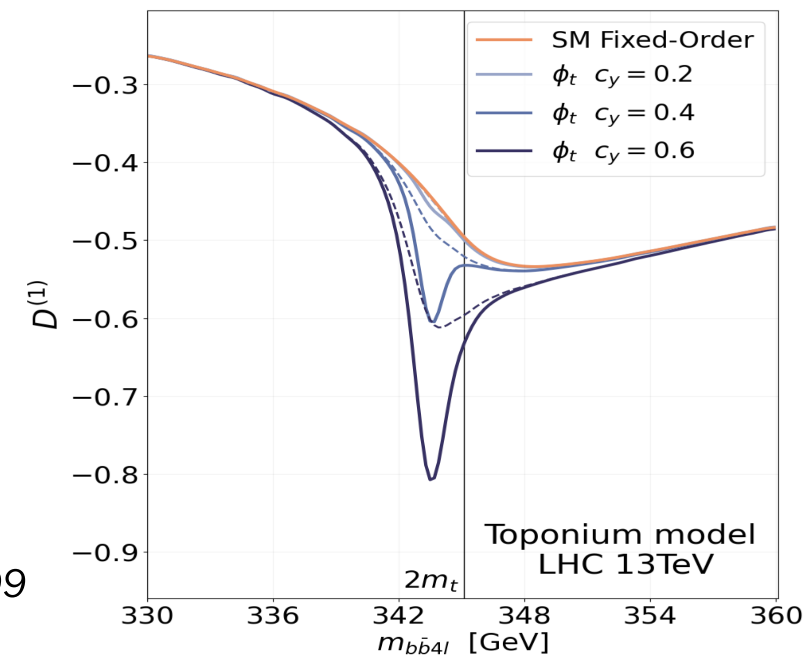


Toponium and entanglement

- Toponium (pseudo-scalar color singlet predicted by non-relativistic QCD)
  - M(toponium)-344 GeV, σ=~6.5pb
    - Sumino, Fujii, Hagiwara, Murayama & Ng (PRD`93)
    - Jezabek, Kuhn & Teubner (Z.Phys.C`92)
    - B. Fuks et al. (PRD 104 (2021) 034023)
  - Toponium affects both the invariant mass distribution and entanglement at the threshold, but
  - **Full spin correlations provide better sensitivity, than one compound property – entanglement**

c_y – coefficient in Lagrangian

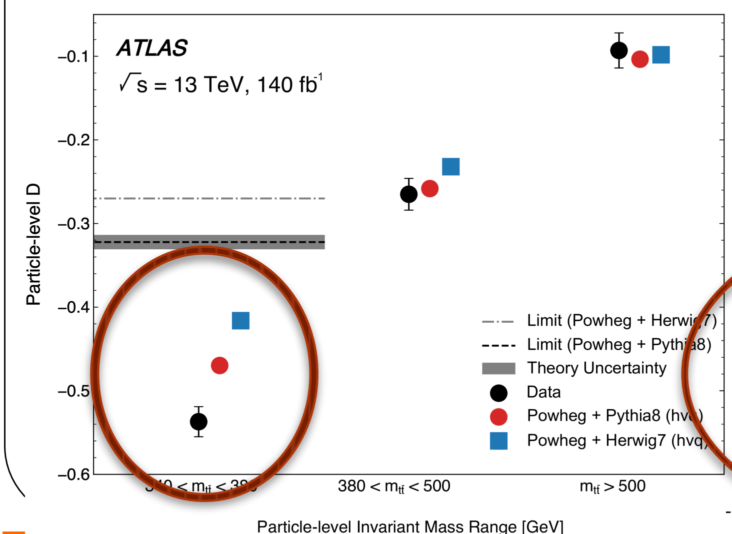


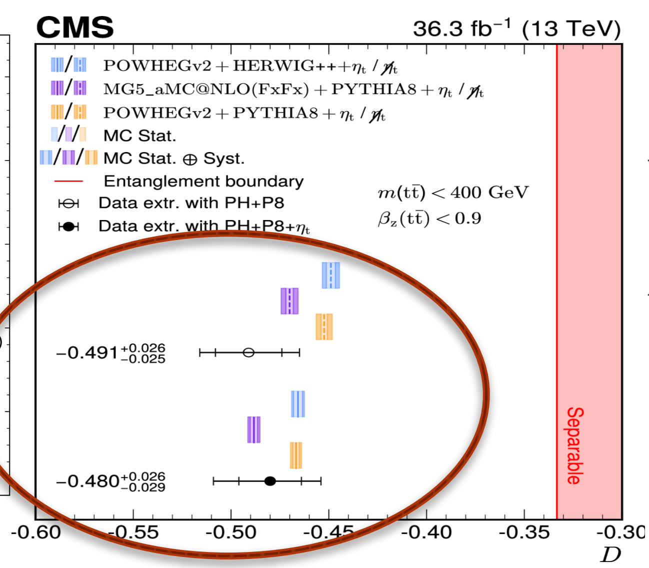


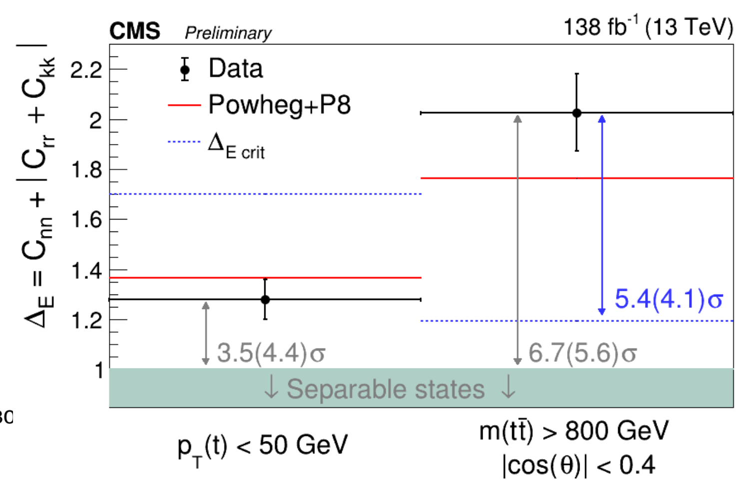
F. Maltoni et al. JHEP03(2024)099

Experimental observations – ttbar

- Atlas sees higher entanglement than predicted by SM without accounting for EW correction, toponium: $D=-0.547\pm0.002$ (stat.)±0.021 (syst.) for $340<m_{t\bar{t}}<380$ GeV
- CMS result is in agreement with SM, considers both (with η_t) and (no η_t) cases
- Even without η_t top and antitop are predicted to have high entanglement at the threshold
- The effect of η_t (with max entanglement of D=-1, but small cross section) on the value of D (Mtt<400GeV, no β cut) is small
  - ΔD(with η_t-no η_t)=0.017, compared to σD=0.025(CMS), 0.021(Atlas)
- These are the measurements of the spin correlations, which rely on the angular correlations of the top decay products, Mtt is only used as a selection, not as a discriminating variable
- <u>Spin correlations alone are not sufficient to establish the presence of η_t signal</u>



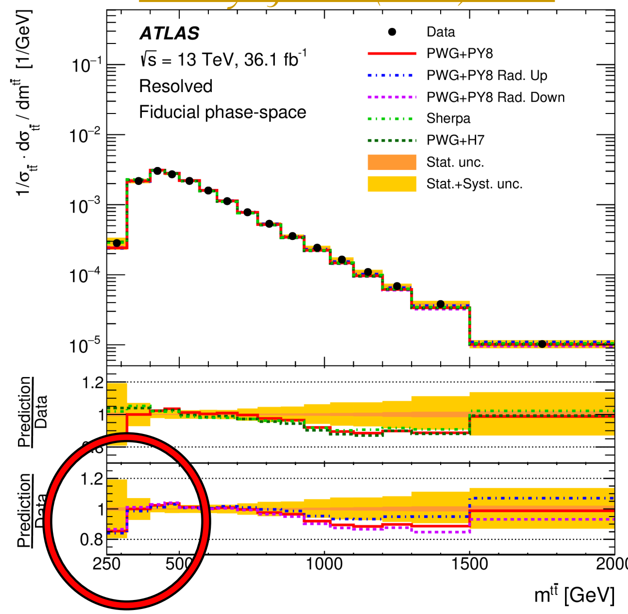




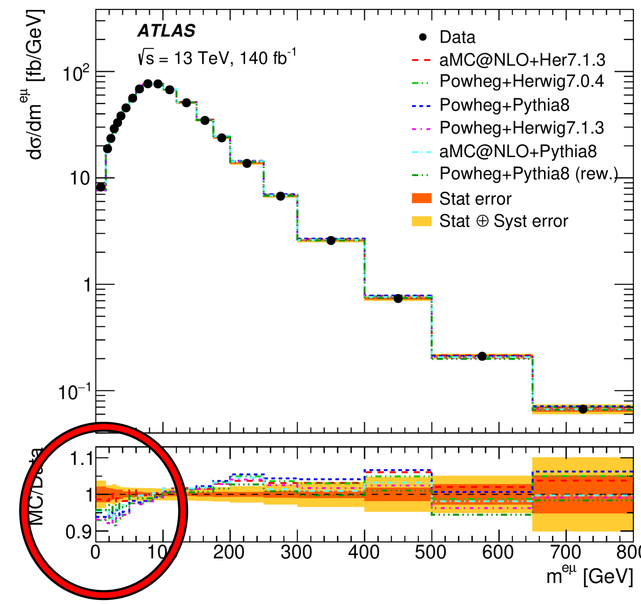
Mtt spectrum

- Both Atlas and CMS have already made their data public in the context of differential ttbar cross section measurement
- Excesses of events at the threshold over the prediction is observed by both Atlas and CMS, in both lepton+jets and dilepton channel

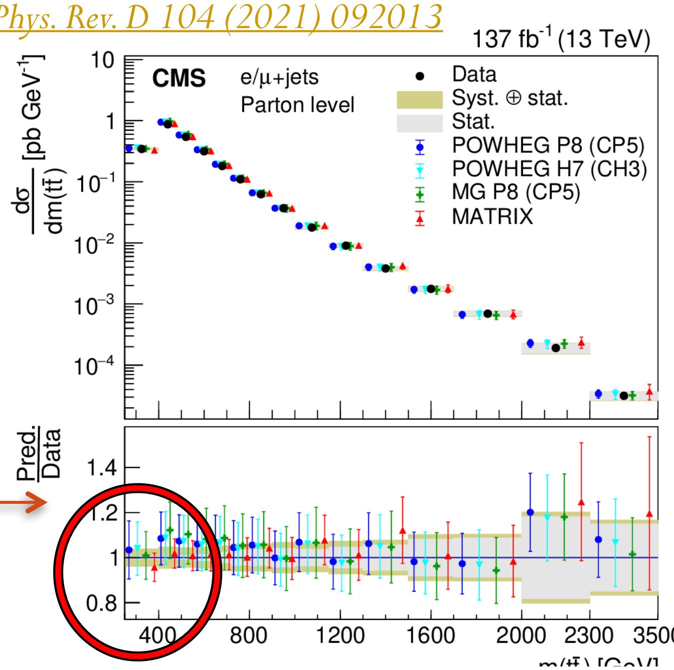
Eur. Phys. J. C 79 (2019) 1028

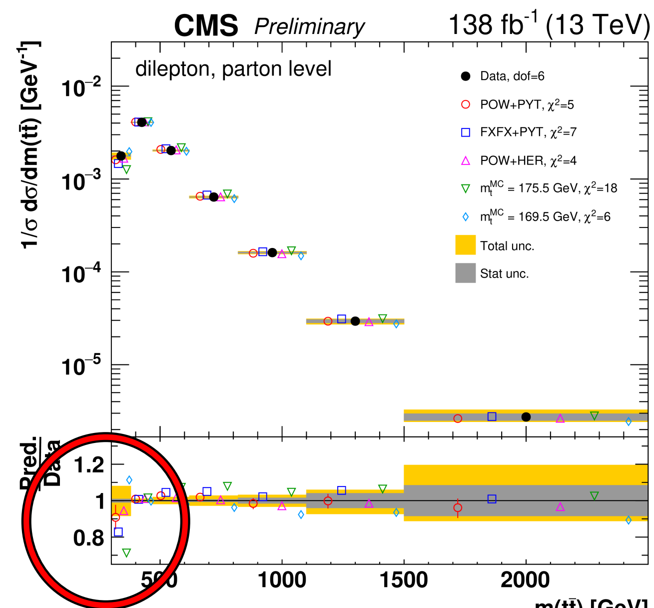


JHEP 07 (2023) 141



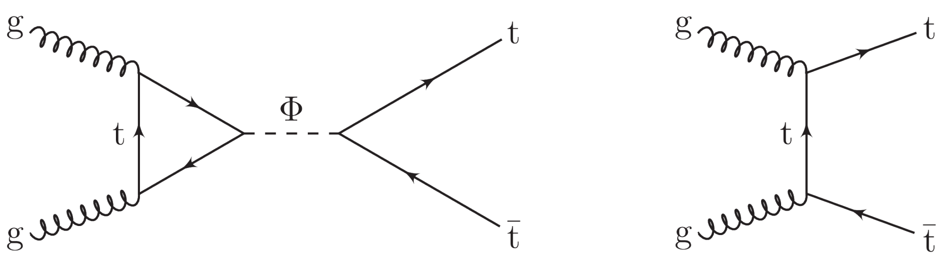
Phys. Rev. D 104 (2021) 092013





CMS-TOP-20-006
Submitted to J. High Energy Phys.

Search for A/H→ tt



- Heavy resonances pseudoscalar A and scalar H if massive enough will decay into a top-antitop pair.
- Interference with the tt continuum → peak-dip structure in Mtt
- Angular correlation of the decay products is determined by the quantum numbers of the resonance.

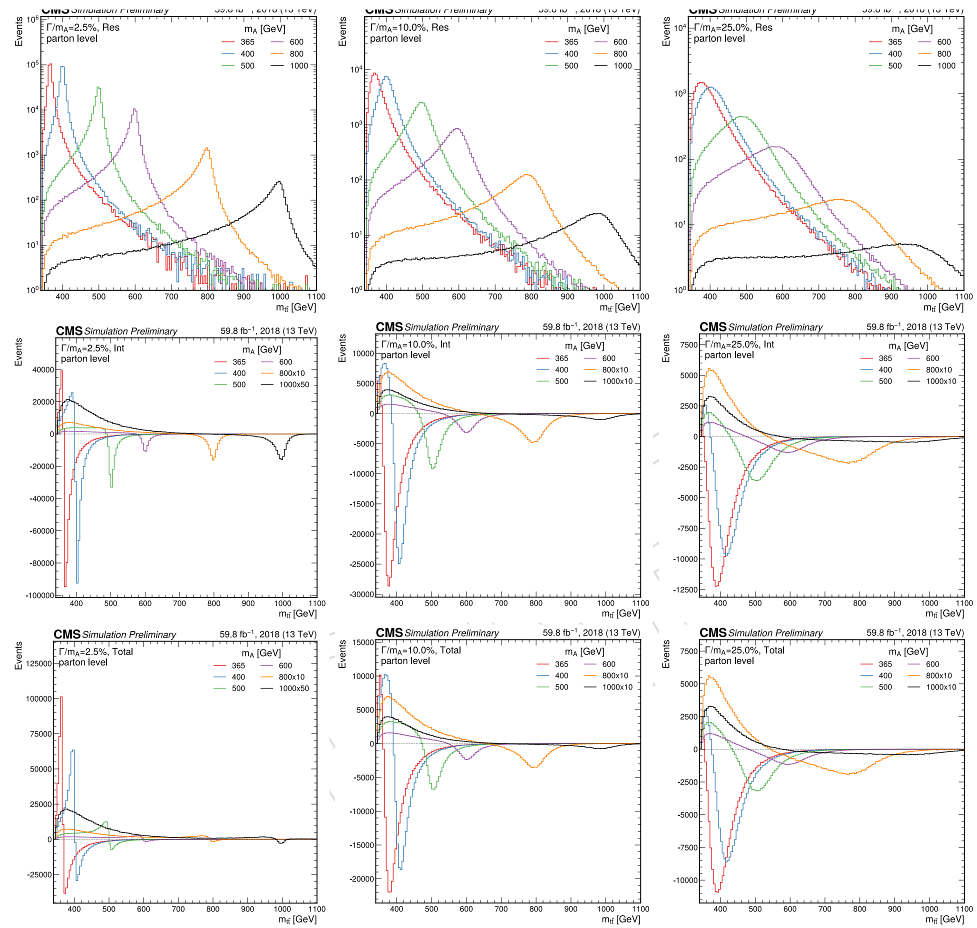
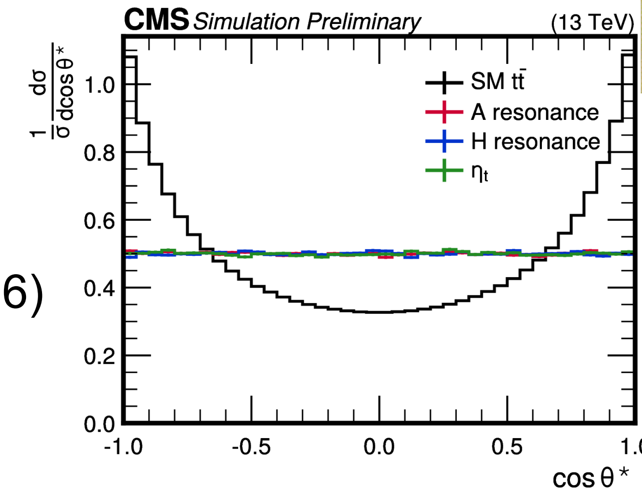
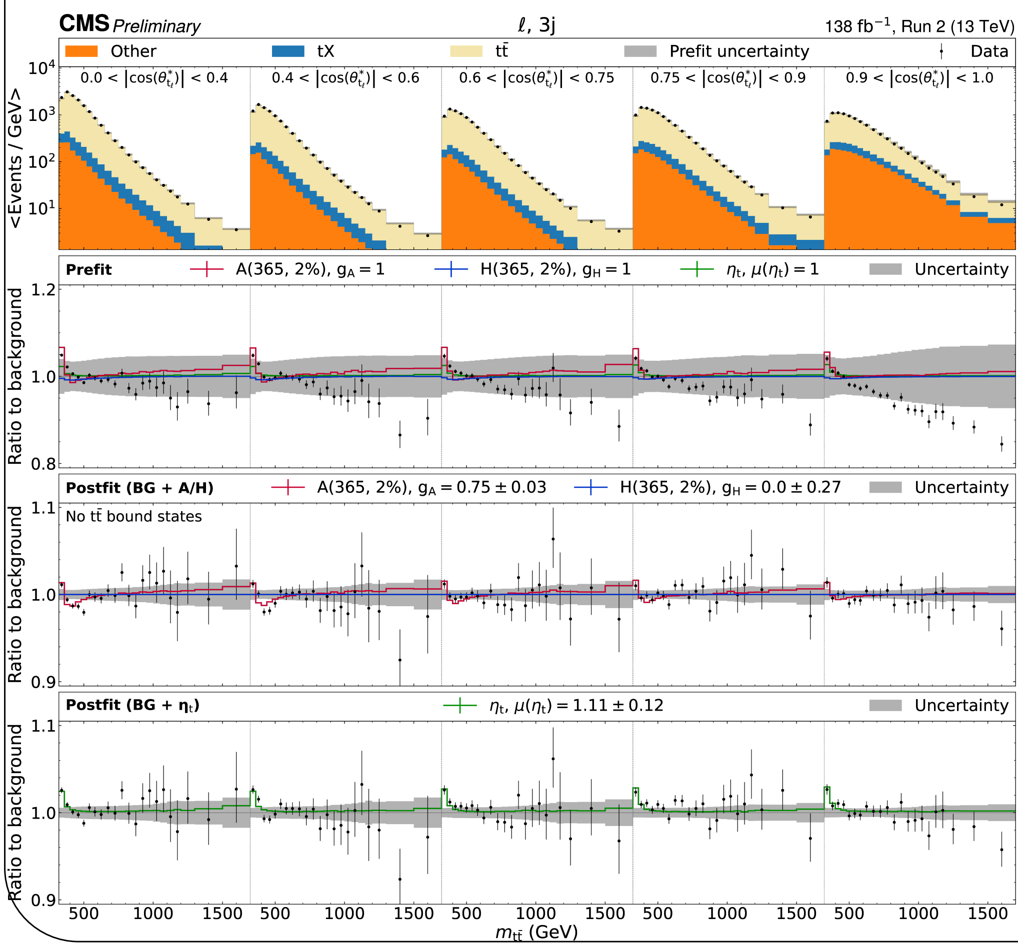


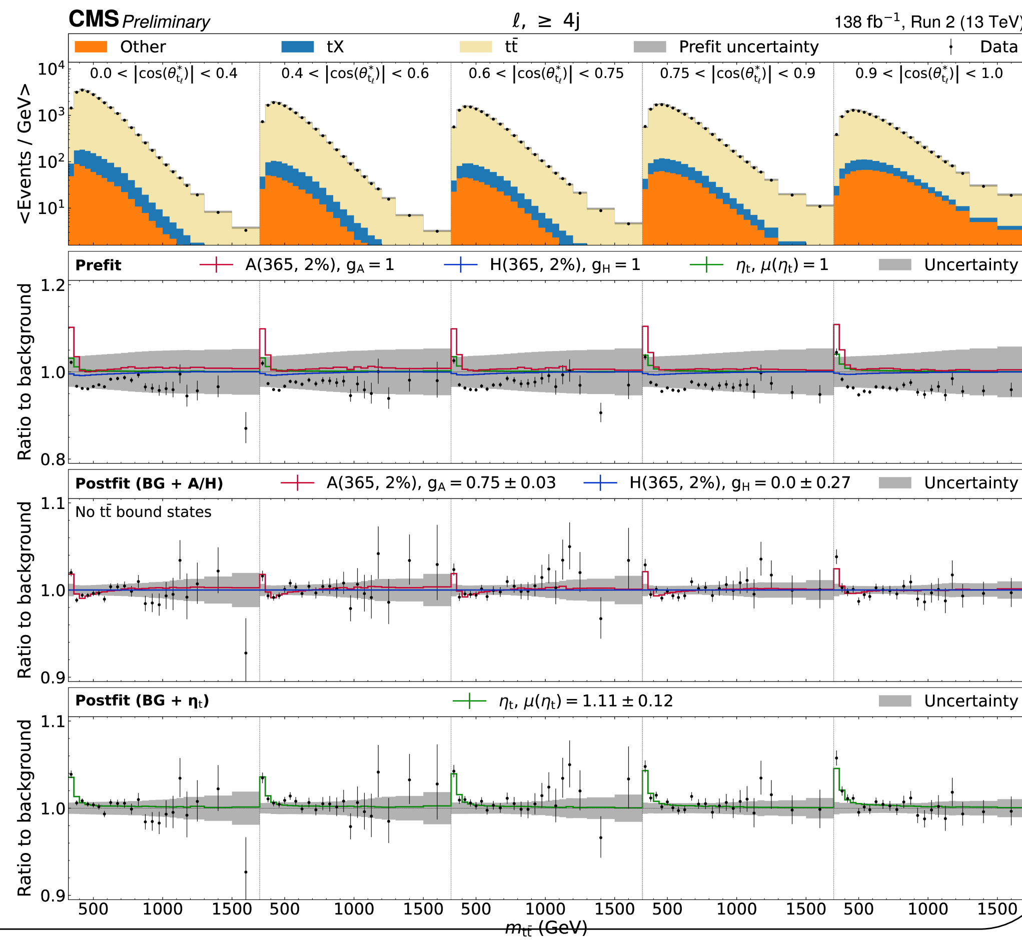
Figure 2: The parton-level expected yield distributions, taken from 2018 simulation, of the reso nant component (top row), the interference component (middle row), and the combined signa (bottom row) of various signal hypotheses are shown, setting the coupling $g_{A_{t\bar{t}}} = 1$. In eac plot, different masses of the pseudoscalar A are presented for $\Gamma_A/m_A = 2.5\%$ (left column 10.0% (middle column), and 25.0% (right column). The distributions of the $m_A \geq 800$ GeV sig nal models are scaled by a factor of either 10 or 50 in the interference and combined signa plots so that their contributions become more visible when compared to other masses, whic are denoted by 'x10' or 'x50' in the labels.

L+jets channel

- Lepton+3, or 4 or more jets, at least 2 b-tags
- Solve for neutrino momentum (NIM A 736 (2014) 169-178)
- Correct for lost jet in 3 jet channel (NIM A 788 (2015) 128-136)
- *Cos*θ* - cosine of scattering angle in the tt rest frame.

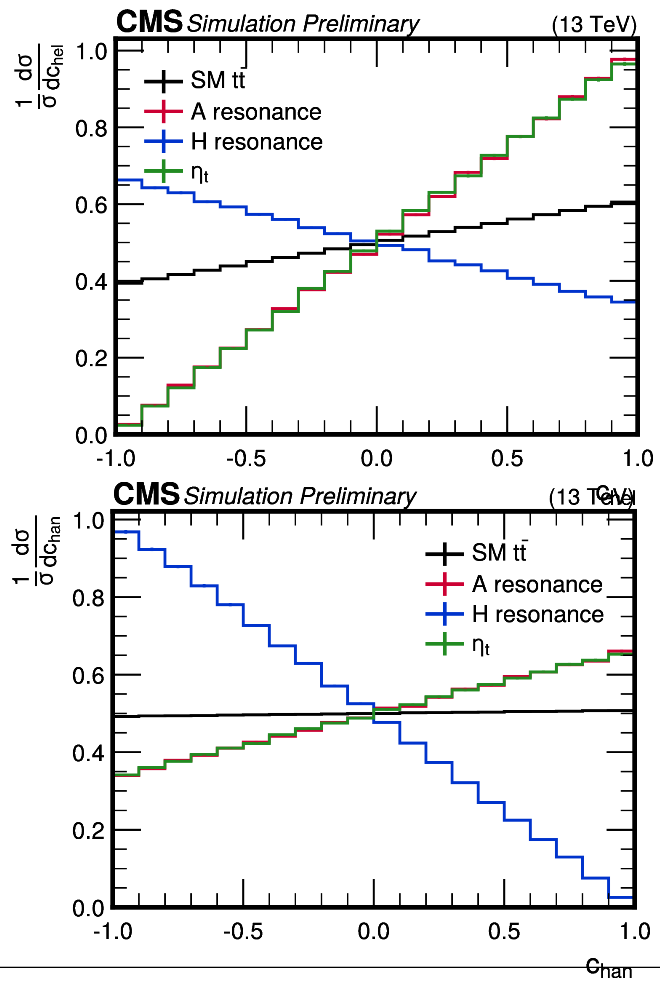


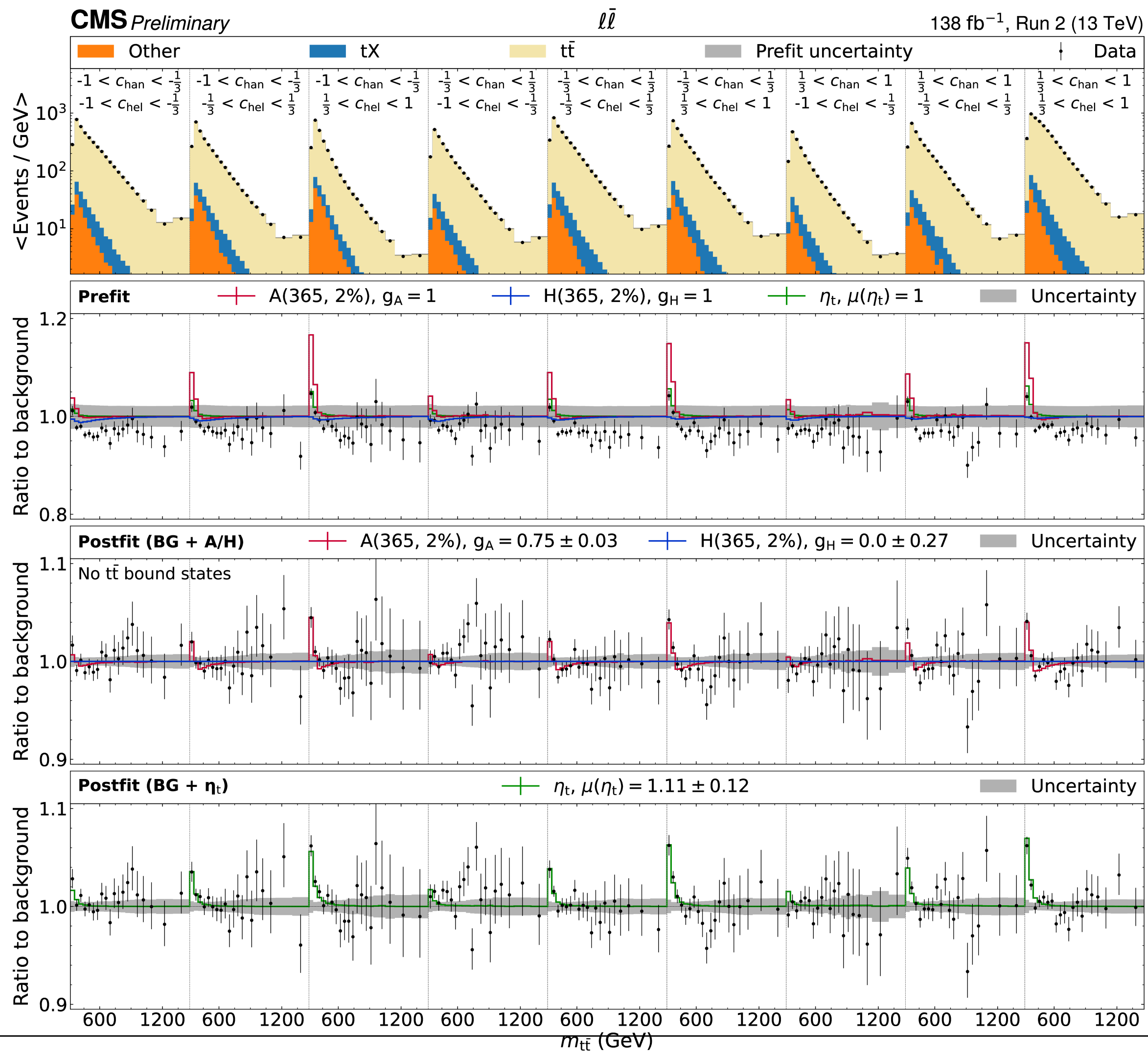




Dilepton channel

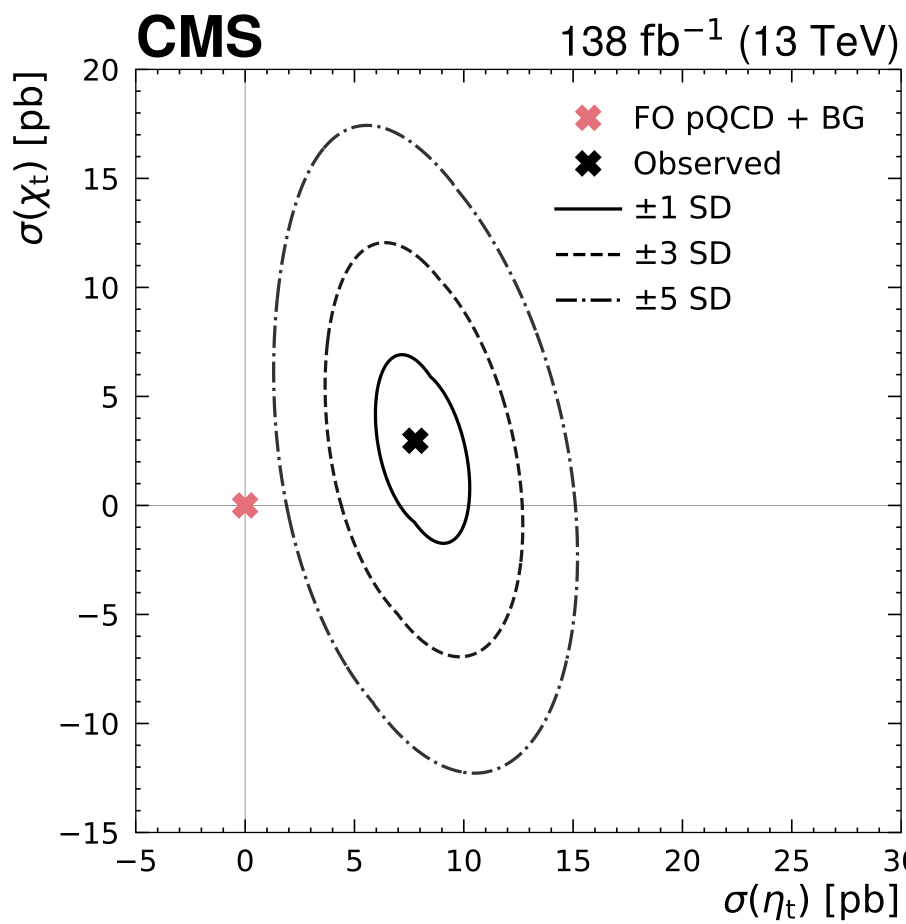
- 2 oppositely charged leptons, at least 2 jets, at least 1 b-tag
- Analytic reconstruction of tt system: Assumptions: all $p_T$miss from νν, tops and Ws on-shell
- Assign b jets using likelihood based on mlb
- Finite detector resolution: repeat reconstruction 100 times with randomly smeared inputs, take weighted average





Characterization of the excess

- The cross section of the toponium signal from the fit: $\sigma(\eta_t)$=7.1+-0.8 pb
- Theoretical prediction 6.43 pb
- Dilepton: $\sigma(\eta_t)$= 8.8 +1.2–1.4 pb
- The excess looks more like pseudoscalar than scalar.
- A word of caution – continuum ttbar is also produced predominantly in the pseudoscalar mode at the threshold.

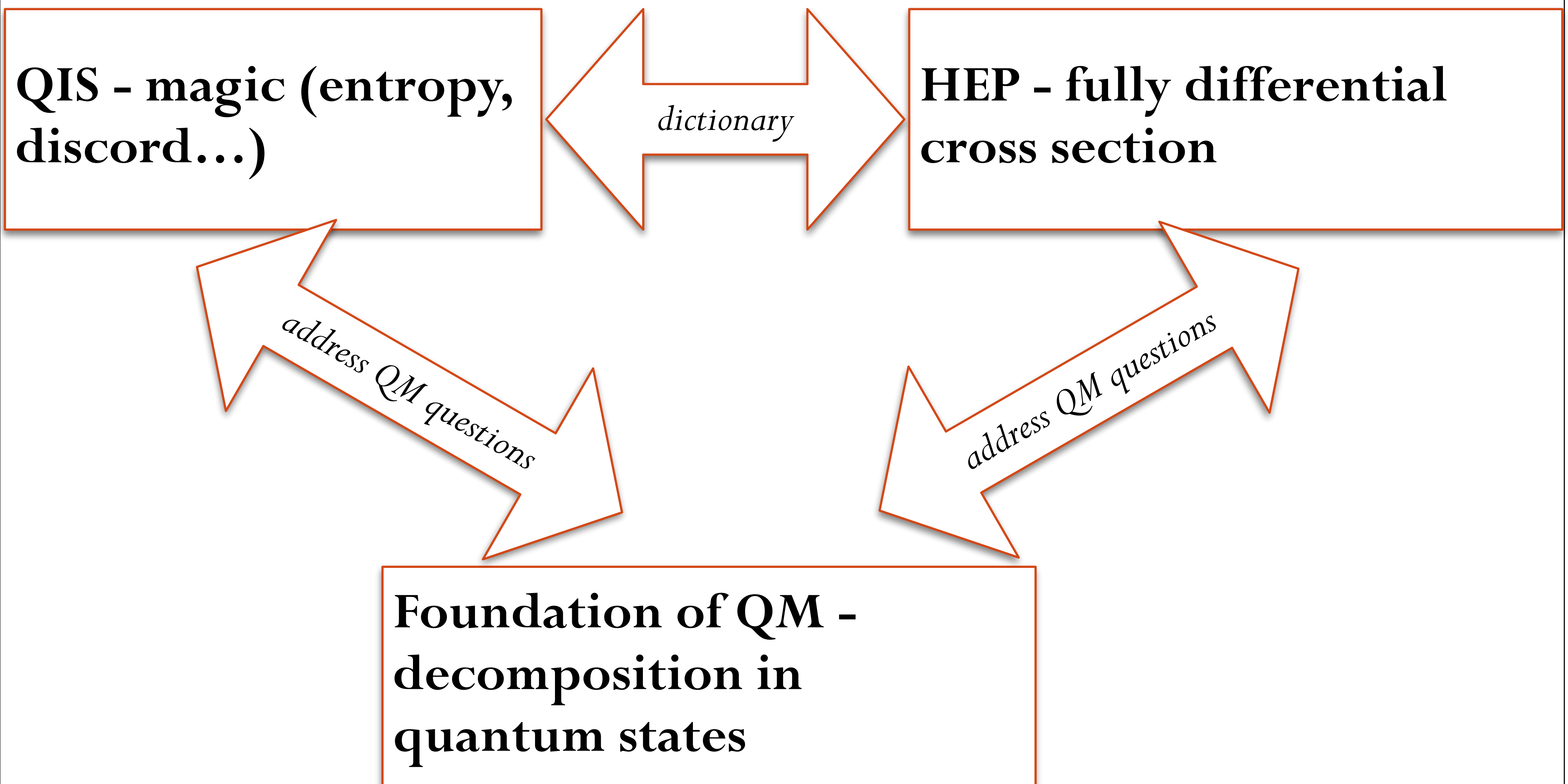


CMS-TOP-24-007, Accepted by Reports on Progress in Physics

Have we discovered toponium?

- Toponium, a.k.a η_t – a pseudo scalar ttbar state predicted by non-relativistic QCD with a mass of 343 GeV
- In 2002, a team of Russian and American scientists created the first ever atom of oganesson (Og), which is the heaviest chemical element ever recorded to date. This nucleus, which consists of 118 protons and 161 neutrons, has a mass number of 279
- If confirmed toponium would be the heaviest particle ever observed
- The existing evidence is tantalizing
- Entanglement and spin correlation play an important role in this observation

QIS and HEP stem from QM



QIS x HEP - Discussion

- *Advantages/ opportunities*
- Probe quantum mechanics at higher energy (smaller distance) - it is always important to test the proven theory at new frontiers
- Work with unstable particles
  - can study how entanglement is passed on to daughter particles, e.g. entanglement between the top quark (a fermion) and W-boson, which is a decay product of antitop quark
  - in some cases the lifetime can be measured on event-by-event basis, for several particles participating in the decay chain, providing multiple (and truly quantum) internal clocks
  - can study entanglement within time-like vs space-like intervals
- Effect of the environment in the form of EM, weak and strong fields, which manifest themselves as quantized emission of the corresponding gauge bosons
- *Disadvantages/challenges*
- Measurements are statistical in nature - true in QIS as well
- No control over conditions —> post selection

Conclusion

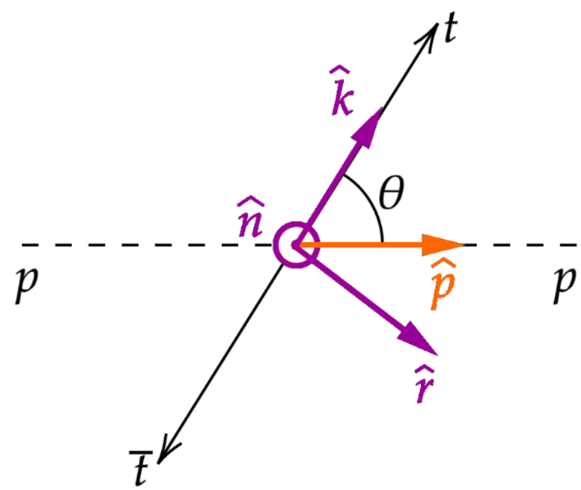
- Entanglement is established between top quarks – unstable elementary particles
- Probing the fundamentals of quantum mechanics at higher energies/shorter distances
- A new field with exciting new opportunities is emerging at the intersection of particle physics and quantum informatics
- Quantum tests at colliders are in their infancy
- Input from QIS community is welcome with open arms

Definition of c_{hel} and c_{han}

- Start in $t\bar{t}$ rest frame, boost leptons into rest frames of their parent tops
- Define lepton three-momenta $\hat{\ell}^+$ and $\hat{\ell}^-$ w.r.t $\{\hat{k}, \hat{r}, \hat{n}\}$ basis:
  - $\hat{k}$: direction of flight of the top quark
  - $\hat{r}$: orthogonal to $\hat{k}$ in the scattering plane
  - $\hat{n}$: orthogonal to $\hat{k}$ and $\hat{r}$

$$c_{\mathrm{hel}} = -(\hat{\ell}^+)_k(\hat{\ell}^-)_k - (\hat{\ell}^+)_r(\hat{\ell}^-)_r - (\hat{\ell}^+)_n(\hat{\ell}^-)_n$$

$$c_{\mathrm{han}} = +(\hat{\ell}^+)_k(\hat{\ell}^-)_k - (\hat{\ell}^+)_r(\hat{\ell}^-)_r - (\hat{\ell}^+)_n(\hat{\ell}^-)_n$$



- It can be shown that they follow a straight line with

$$\frac{1}{\sigma}\frac{d\sigma}{dc_{\mathrm{hel}}} = \frac{1}{2}(1 - D\, c_{\mathrm{hel}}) \qquad \frac{1}{\sigma}\frac{d\sigma}{dc_{\mathrm{han}}} = \frac{1}{2}\left(1 + D^{(k)}\, c_{\mathrm{han}}\right)$$

(JHEP 03 (2024) 099)

L+jets: Example of the fit

- In each (M_{tt}, $cos\theta$) bin $cos\chi$ distribution is fit to the reco-level templates