Quantum tests in collider physics workshop at Merton college, Oxford

R. Demina, University of Rochester

11/12/2024

https://conference.ippp.dur.ac.uk/event/1300/overview

“Black magic and its exposé” or “The revenge of Schrodinger’s cat”

- The most intellectually stimulating workshop that I have attended
- I will present a biased summary guided by my personal question: “Can we at colliders (and if yes then how) probe the fundamentals of quantum mechanics?”

Analogies to the séance of black magic from “Master and Margarita” by M. Bulgakov

Regina Demina, University of Rochester

Show us some simple little trick to begin with

Spin correlation and entanglement in ttbar system

The system is considered **separable** if its density matrix can be factored into that of individual states $\rho = \sum_n p_n \rho_n^t \rho_n^{\bar{t}}$

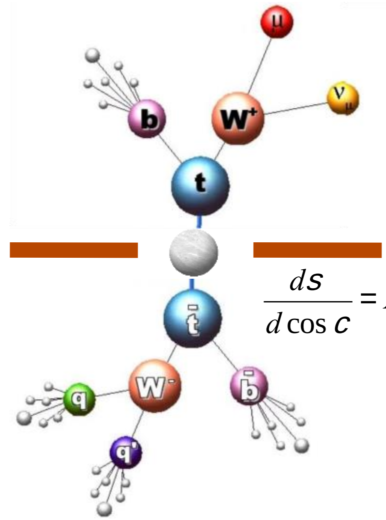
Otherwise, it is considered **entangled** → **Peres-Horodecki criterion** [2003.02280] $\Delta_E = C_{nn} + |C_{rr} + C_{kk}| > 1$

Entanglement is a result of spin correlation.

There are four maximally entangled states

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

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

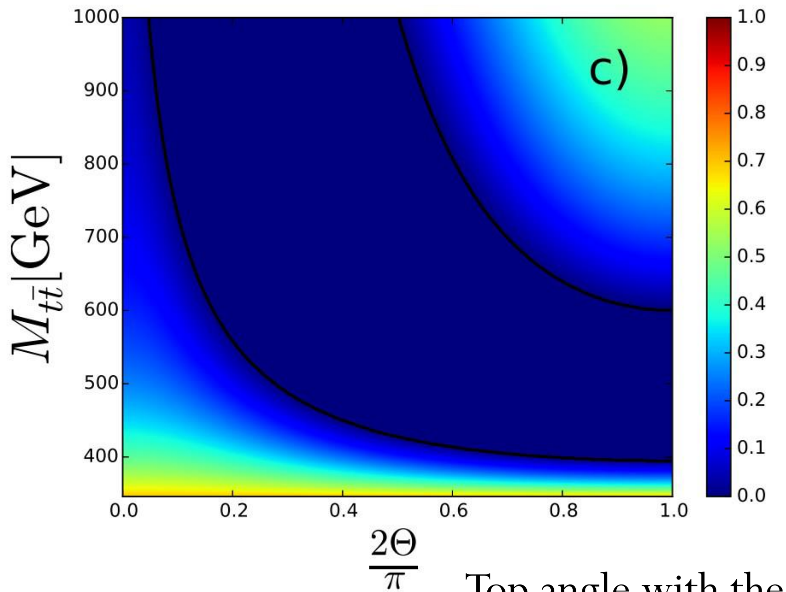


$$\frac{d\sigma}{d\cos\chi} = A(1 + D k\bar{k}\cos\chi)$$

at low $M_{t\bar{t}}$ singlet pseudoscalar state Ψ^- Peres-Horodecki criterion

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

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



Top angle with the beam axis

at high $M_{t\bar{t}}$ triplet vector state ($\Phi^+ - \Phi^-$, Ψ^+, $\Phi^+ + \Phi^-$) Peres-Horodecki criterion

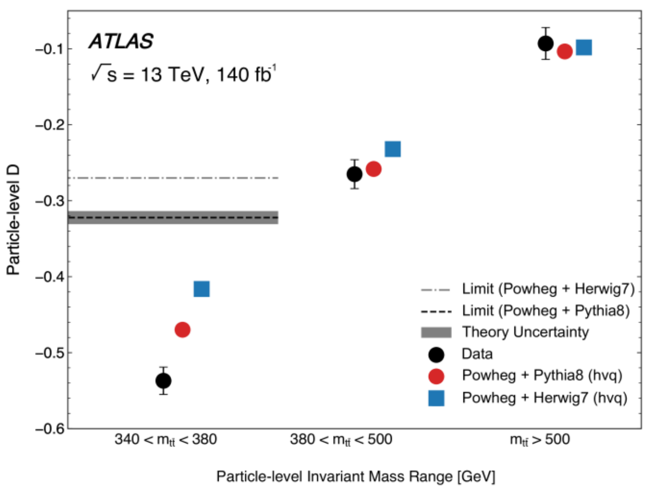
$$\Delta_E = C_{nn} - C_{rr} - C_{kk} = 3\tilde{D} > 1$$

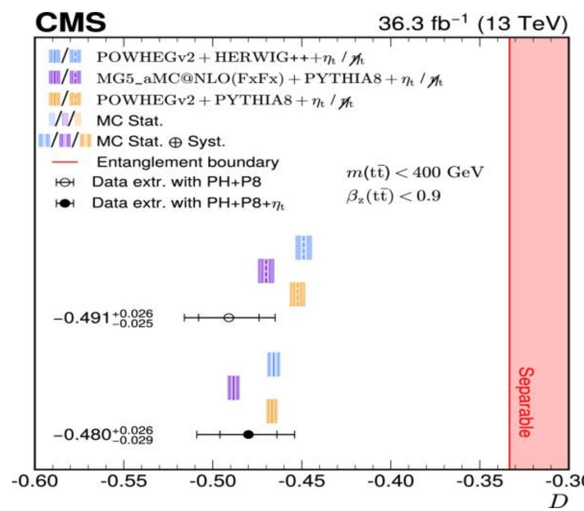
$$\tilde{D} > \frac{1}{3}$$

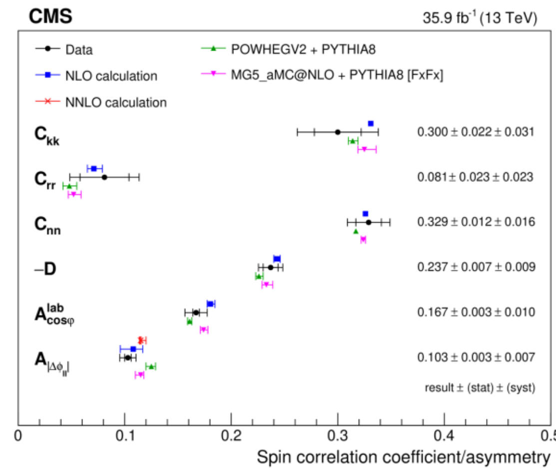
Plot from Afik, De Nova EPJP136(2021)9,907 hep-ph:2003.02280

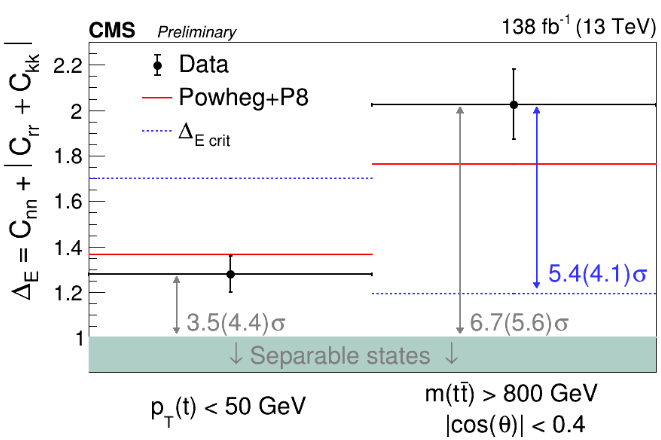
Experimental observations – ttbar

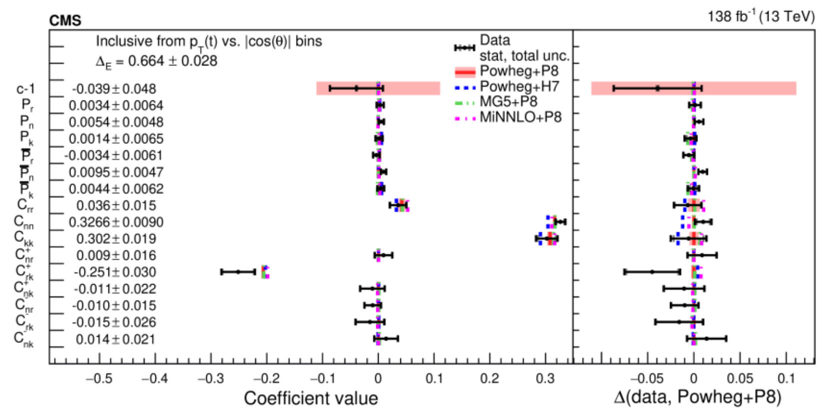
- Ttbar system – Atlas, CMS (dilepton, threshold), CMS(l+jets, high Mtt) reported by J. Howarth, A.J.Wildridge, RD











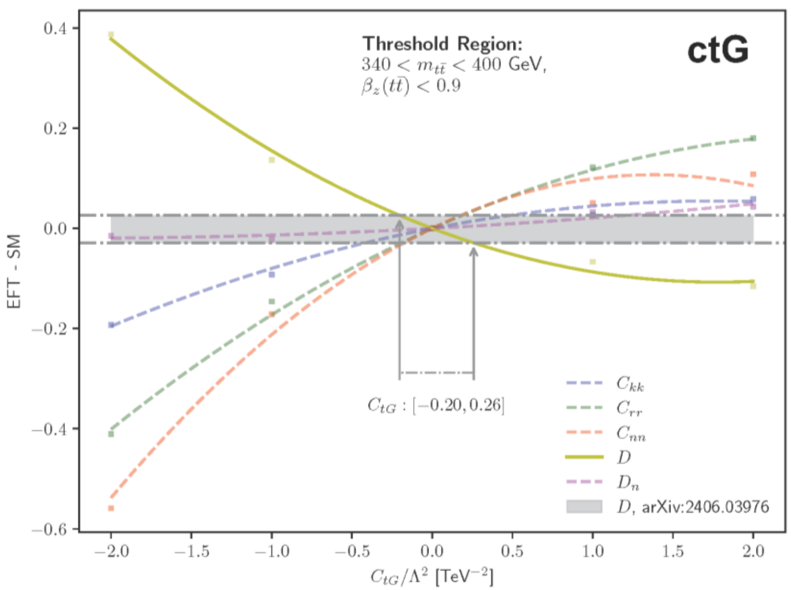
Full tomography is most powerful in constraining new physics

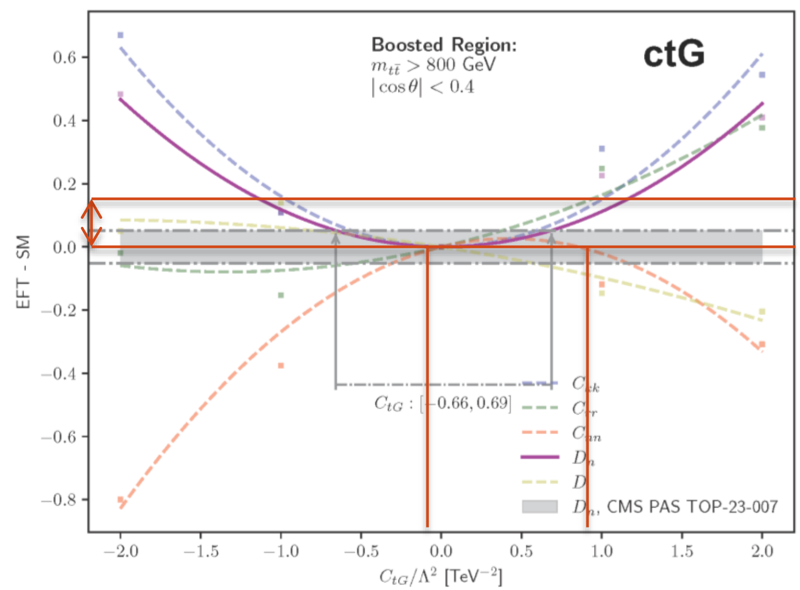
Experimental observations – ttbar

- Use spin correlations in ttbar system to probe SMEFT – Maria Moreno Llacer
- It is essential to provide results at parton level
- CMS l+jets full matrix measurements in various regions of the phase-space

$$X = X_{SM} + \underbrace{\frac{1}{\Lambda^2}\sum_i C_i X_i^{(1)}}_{\text{Linear Terms}} + \underbrace{\frac{1}{\Lambda^4}\sum_{ij} C_i C_j X_{ij}^{(2)}}_{\text{Quadratic Terms}} + \mathcal{O}(\Lambda^{-4})$$

Dependence derived with **MadGraph5_aMC@NLO & SMEFT@NLO**





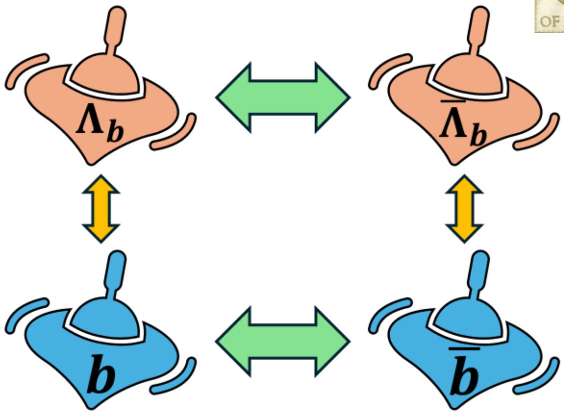
RD:
Based on C_{nn}

- From D → $c_{tG}/\Lambda^2 \in [-0.20, 0.26]$ TeV^{-2} @ 68%CL
- C_{nn} seems also sensitive in threshold regime

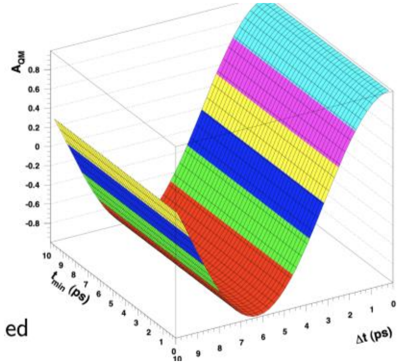
- From D_n → $c_{tG}/\Lambda^2 \in [-0.66, 0.69]$ TeV^{-2} @ 68%CL
- C_{kk} and C_{nn} also sensitive in boosted regime

Experimental observations – bbbar

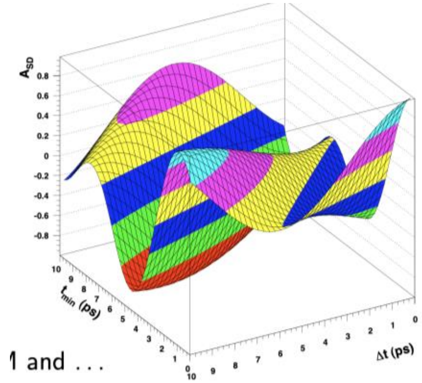
- Bottom quark – spin correlations –Y. Afik
- Unlike **top**, **bottom quarks** hadronize!
- **There is hope: In Λ_b b-quark carries the baryon spin**



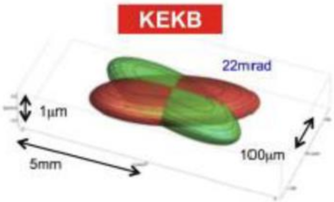
- Use **B0-B0 mixing at Belle** to probe quantum information flow/loss – S. Vahsen
- Production → entanglement → decoherence

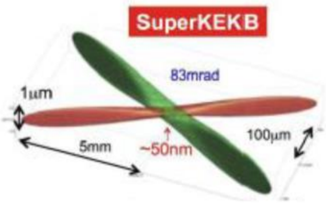


Entanglement: depends only on Δt



Disentanglement and decoherence depends on Δt and $\mathbf{t_1}$



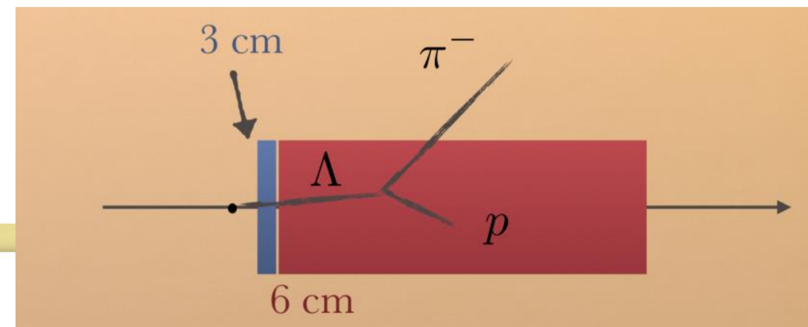


Crucial – resolution on the beam spot

RD: Can we probe decoherence in ttbar system at LHC?

Experimental observations: Charmonium system

- M. Fabbrichesi: Cahrminium system produced at BESIII
- Examples: qubits ($\eta_c/\chi_c \rightarrow \Lambda\ \Lambda^{bar}$) and qutrits ($\chi_c \rightarrow \phi\phi$)
- Entanglement and Bell inequality have been observed with high significance
- Λ is very long lived – observed entanglement is preserved when a particle is inside the material



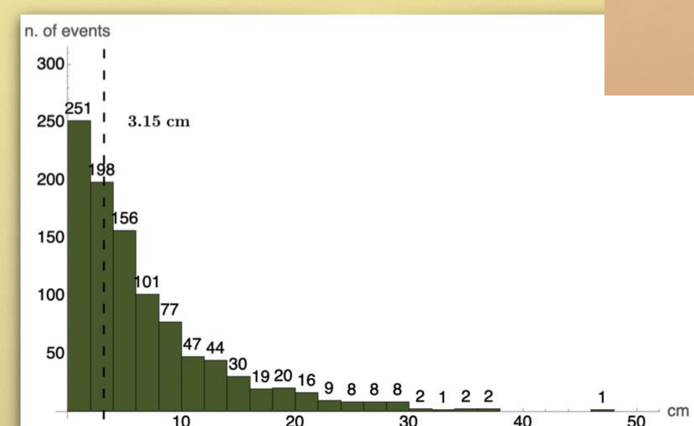
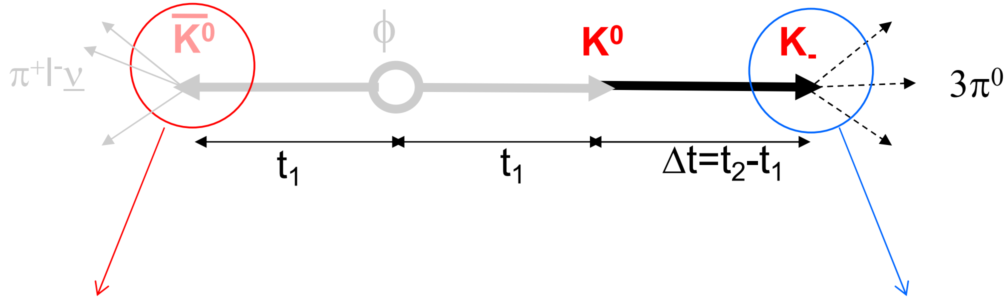


Figure 6.1: Decay $\eta_c \rightarrow \Lambda\bar{\Lambda}$: Fraction (out of 1000) of Λ baryons decaying at different lengths from the primary vertex. The Vertical dashed line stands for the inner surface of the beam pipe (3.15 cm from the primary vertex).

Theoretical work: Can future post-tag the past?

- Time reversal in neutral kaon system (or B-Bbar) – A. Di Domenico, J. Bernabeu



PAST

FUTURE

The future (kaon decay at t_2) post-tags the past partner kaon state at t_1,before the decay, when it was entangled !

If past tags the future, the t_1 , t_2 symmetry of the correlated state in the LY approach demands the exploration of the question: can future post-tag the past?

$$
\begin{aligned}
|K^{(1)}(t=t_1)\rangle =& \langle f_2|T|i_{t_1,t_2}\rangle \\
=& \frac{\mathcal{N}}{\sqrt{2}}\{\langle f_2|T|\mathrm{K_L}\rangle e^{-i\lambda_L t_2} e^{-i\lambda_S t_1}|\mathrm{K_S}\rangle - \langle f_2|T|\mathrm{K_S}\rangle e^{-i\lambda_S t_2} e^{-i\lambda_L t_1}|\mathrm{K_L}\rangle\} \\
=& \frac{\mathcal{N}}{\sqrt{2}}\langle f_2|T|\mathrm{K_S}\rangle\{e^{-i\lambda_S t_1}\left[\eta_2\, e^{-i\lambda_L t_2}|\mathrm{K_S}\rangle\right] - e^{-i\lambda_L t_1}\left[e^{-i\lambda_S t_2}|\mathrm{K_L}\rangle\right]\}\ .
\end{aligned}
$$

PAST

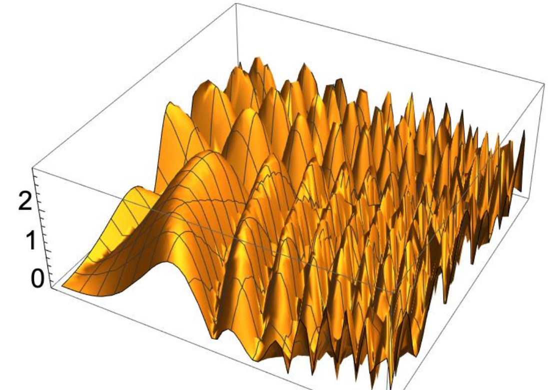
FUTURE

RD: Is it really spooky action to the past, or just a post-selection?

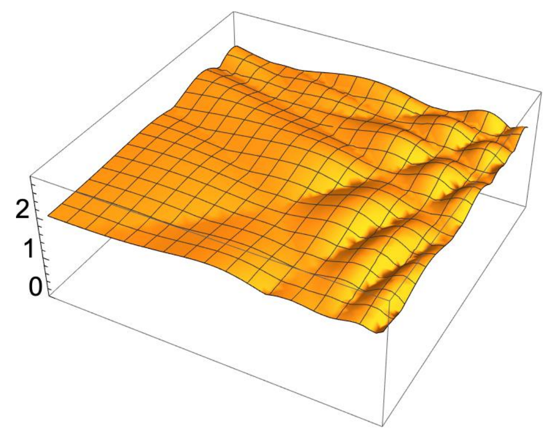
Theoretical work

- Jesús Moreno
- Fermion – to – boson (qubit-to-qudit system)
- Necessary and sufficient condition for Bell in qubit-qubit systems
- Quantum non locality in the tW system at the LHC
  - T – to – W in top decay - Post-decay entanglement (J.A. Aguillar-Saavedra)
- Entanglement and post-selection JAAS 2307.06991; JAAS, Casas 2401.06854; JAAS 2401.10988; JAAS 2308.07412
- **Potentially 7 σ effect for entanglement at the threshold and 5 σ in boosted regime based on Run 2 data!**

Numeric: Wide range of $\mathcal{O}$(Bell) values, many local extrema when increasing *d*



Analytic: Narrow range of $\mathcal{O}$(Bell) values when increasing *d*



Theoretical work

- P. Caban, F. Fabbri, M. Javurkova: Boson-boson (qudit-to- qudit system)
- Examples H→ ZZ, WW
- Helicity correlations of vector bosons,
  - Include BSM couplings, allowing for CP violation (pseudoscalar state)
- Strong bounds from CMS Collaboration, "*Measurements of the Higgs boson width and anomalous HVV couplings from on-shell and off-shell production in the four-lepton final state*" Phys. Rev. D 99,112003 (2019)
- A. Bernal: Quantum tomography of helicity states for general scattering process
- Connection (reformulation) with Quantum Information perspective (Weyl-Wigner-Moyal formalism) () Phys Rev D (2024), 11, 116007
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Entanglement

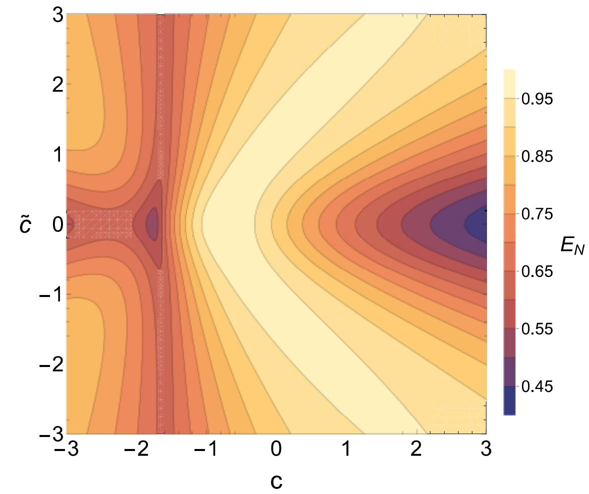


Figure: The logarithmic negativity of the state $\rho_{ZZ}(c, \tilde{c})$ as a function of c, $\tilde{c}$.

The violation of the CGLMP inequality

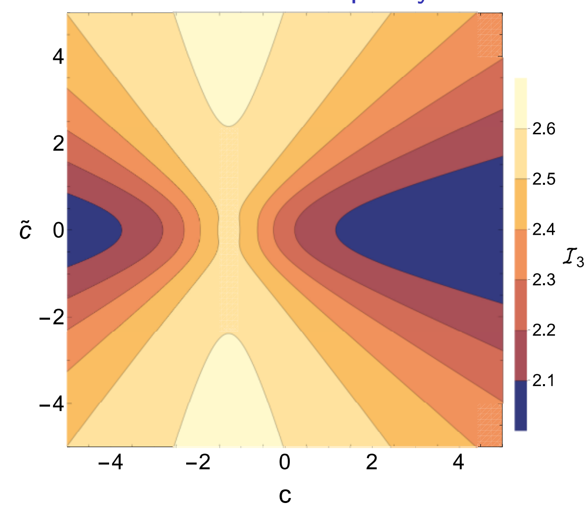


Figure: The maximal value of $\mathcal{I}_3$ in the state $\rho_{ZZ}(c, \tilde{c})$ as a function of c, $\tilde{c}$.

"An exposé is absolutely imperative"

- **Physics Letters B** Volume 280, Issues 3–4, 30 April 1992, Pages 304-312
- **"Testing locality at colliders via Bell's inequality?"**
- S.A. Abel [a], M. Dittmar [b], H. Dreiner [a]
- For all experiments where the correlated observables **commute** we can construct an LHVT using the QM function, which exactly reproduces the data.
- In collider experiments we measure 4-momenta. These all commute. Ergo: all results can be reproduced by an LHVT.
- "Thus you have simply chosen a poor set-up to test locality.
- **So: you are NOT testing locality, at all!"**

Herbi Dreiner

What can we do then at colliders?

- Tao Han: within the framework of QFT, in the HE regime at colliders,

We lay out the QM predictions/information.

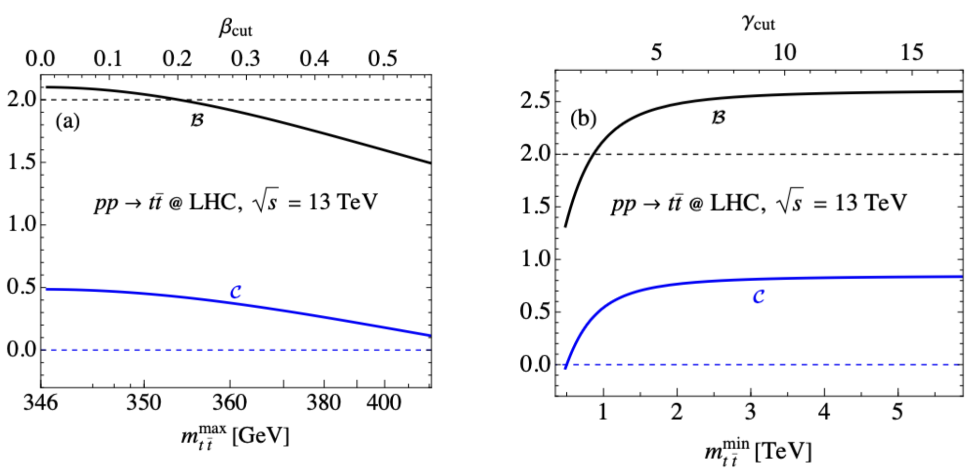
We calculate the QM correlations/entanglement

Hope to establish the quantum tomography.

Understand quantum nature & seek for BSM effects

Tao Han suggested a new approach: **Quantum Entanglement from production without decay measurement**

EPR :

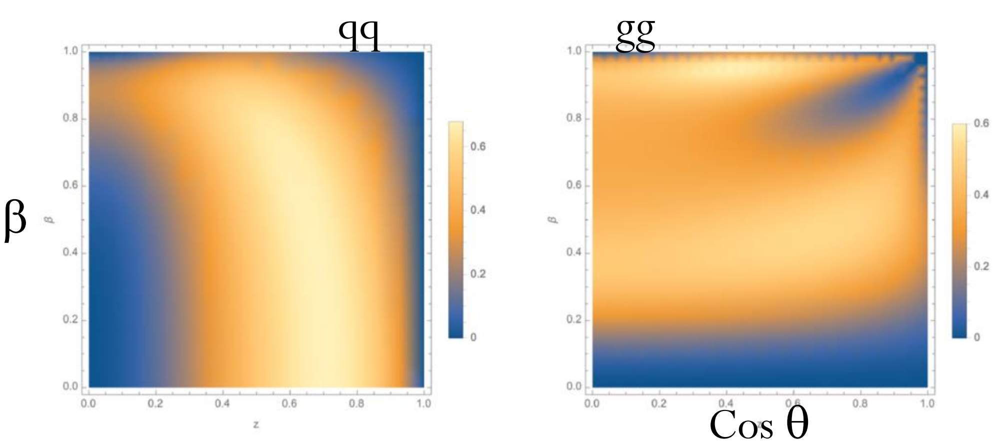


RD: Does this have more information than differential cross section measurement?

Quantum magic

C. White, M. White

- 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*

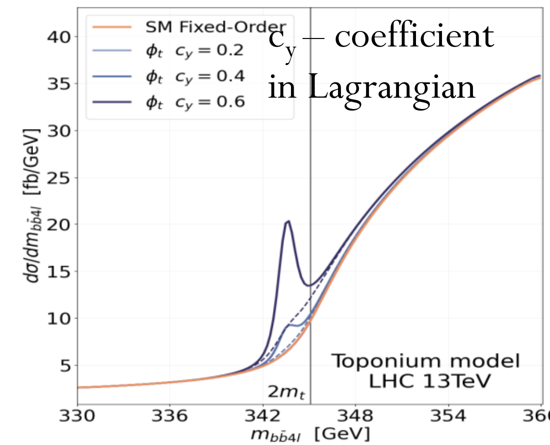


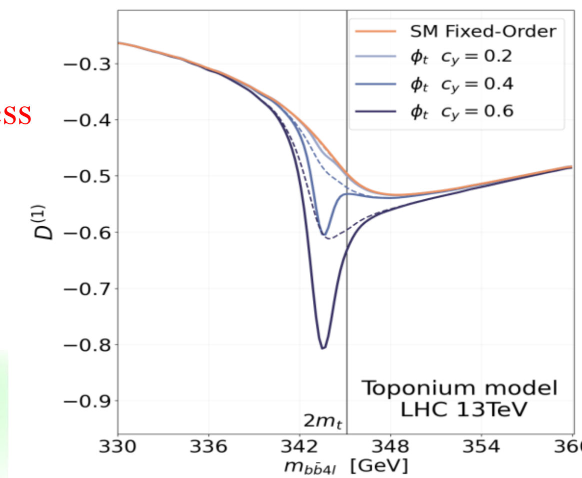
RD: Magic is apparently quite easy to evaluate based on the full spin correlation matrix.

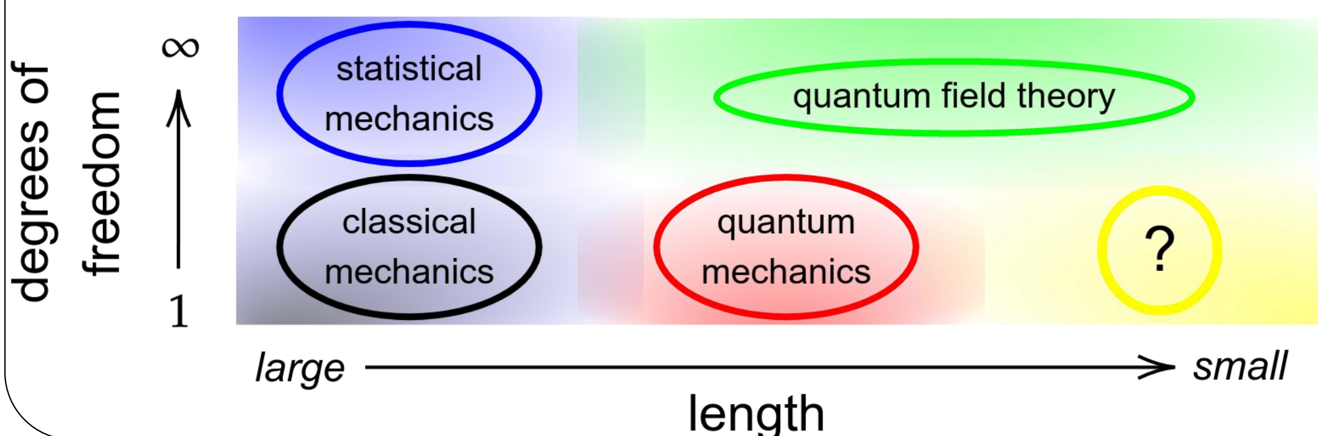
Search for new physics

F. Maltoni et al. JHEP03(2024)099

- "Hot example" - 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)
  - affects the invariant mass distribution and entanglement at the threshold, but
  - **RD: Full spin correlations provide better sensitivity, than one compound property – entanglement**
- Differential cross section are the best way to probe for new physics, unless this physics goes beyond QM
  - A. Valentini: Testing Born rule
- Michał Eckstein: Beyond quantum mechanics and where to find it







Regina Demina, University of Rochester

“Maestro, hack us a march”

- Fictitious States and Optimizing Measurements – M. Low
- An Area Law for Entanglement Entropy in Particle Scattering -I. Low
- Entanglement in gravitational systems – Balasubramanian
- Bell inequality violations: the QBist view – R. Schack

The mainstream approach:
Quantum mechanics is a theory of the world. It is concerned with properties of physical systems.
QBism:
Quantum mechanics is a decision theory. It guides agents in their actions. (But its mathematical form tells us about the character of the world. QBism is a form of “participatory realism”.)

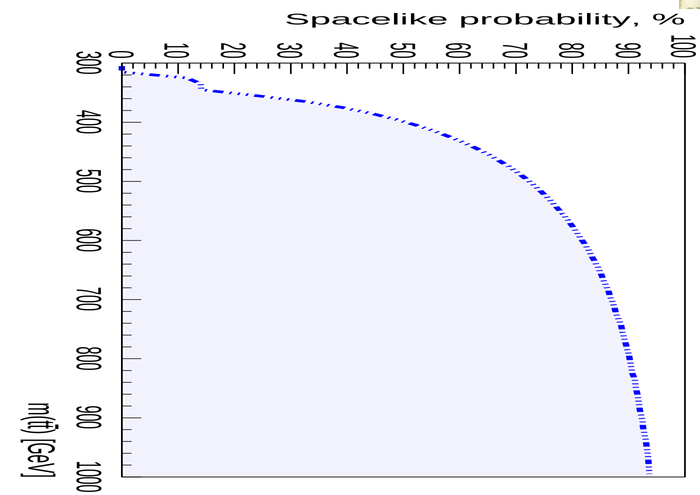
Final thoughts

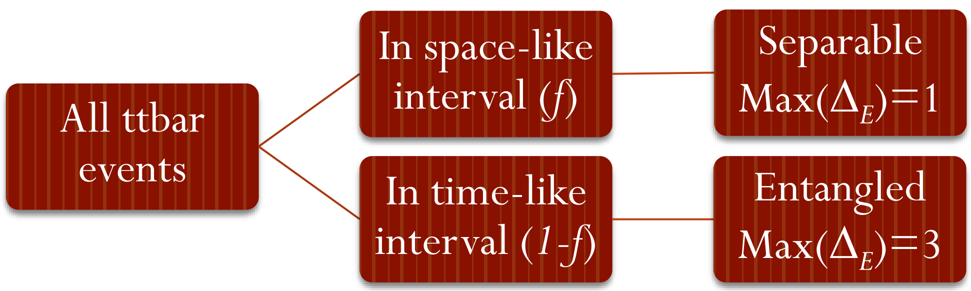
- At LHC we just started observing the effects of quantum behavior, but other collider experiments (Belle, Daphne, BessIII…) have been successfully probing the fundamentals of quantum mechanics for quite some time – we have a lot to learn
  - Decoherence, time reversal…
- Can we exclude the Local Hidden Variable Theories?
  - Probably no, but
  - Do we need to?
- Can we contribute to probing QM fundamentals
  - Probably yes, especially since we probe the highest energy
  - Magic states, qubit-qudit, qudit-qudit entanglement…
- Can we use entanglement to search for BSM?
  - Yes,
    - but differential measurements are more powerful

Back up slides

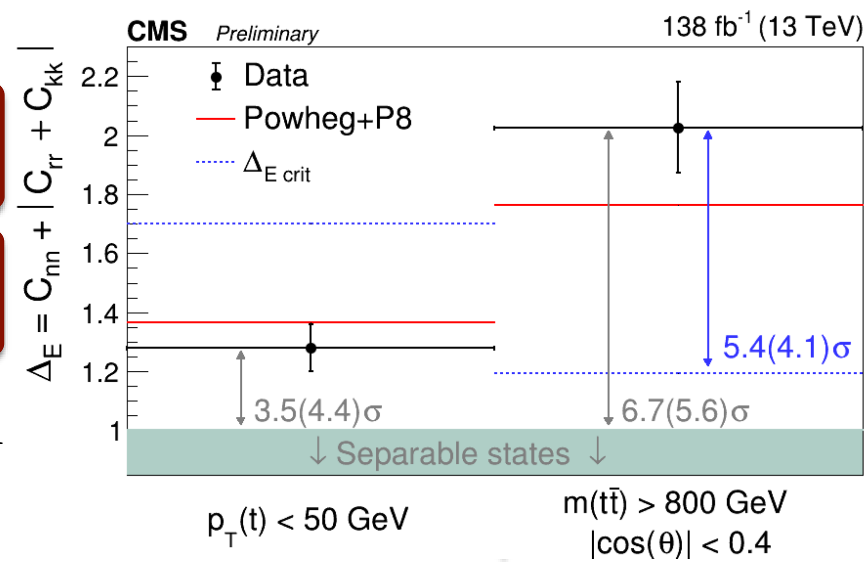
Excluding classical explanation

- 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





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



- Thus,

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

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