Spin Correlation & Entanglement at Colliders

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K. Cheng, TH, M. Low, A. Wu: arXiv: 2311.09166; 2407.01672; 2410.08303; 2507.12513

I. Introduction

unesco

INTERNATIONAL YEAR OF
Quantum Science
and Technology

2025

1925: Werner Heisenberg revolutionized the understanding of the sub-atomic world.

On the quantum-theoretical reinterpretation of kinematical and mechanical relationships

By **W. Heisenberg** in Göttingen

(Received on 29 July 1925)

1926: Ervin Schroedinger established the wave equation, coined "quantum entanglement"

Quantisation as a Problem of Proper Values (Part I)

(*Annalen der Physik* (4), vol. 79, 1926)

§ 1. In this paper I wish to consider, first, the simple case of the hydrogen atom (non-relativistic and unperturbed), and show that the customary quantum conditions can be replaced by another postulate, in which the notion of "whole numbers", merely as such, is not introduced. Rather when integralness does appear, it arises in the same natural way as it does in the case of the *node-numbers* of a vibrating string. The new conception is capable of generalisation, and strikes, I believe, very deeply at the true nature of the quantum rules.

The usual form of the latter is connected with the Hamilton-Jacobi differential equation,

$$H\left(q, \frac{\partial S}{\partial q}\right) = E. \tag{1}$$

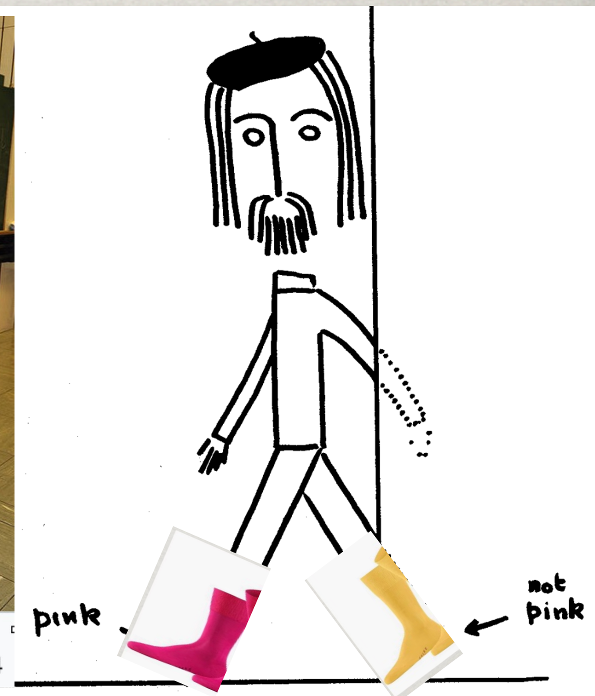
Quantum Entanglement

Prof. Bertlmann's socks:
pink or non-pink

(00) (11) (01) (10)

Classical correlation, local, probabilistic, mutual info.

David Mermin und Reinhold Bertlmann zeigen ihre Socken, 2014



QM superposition: For a bipartite system, *i.e.*, $\frac{1}{2} \otimes \frac{1}{2} = 1 \oplus 0$:

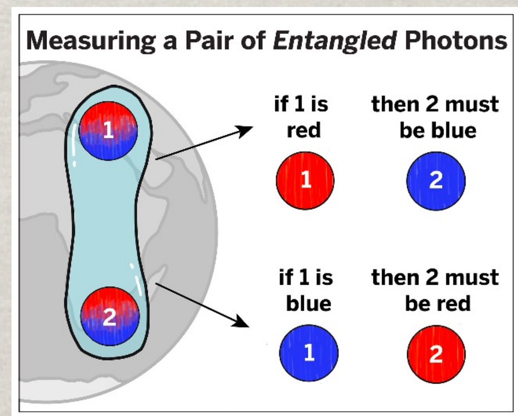
Singlet:

$$|0,0\rangle = \frac{1}{\sqrt{2}}(\uparrow\downarrow - \downarrow\uparrow)$$

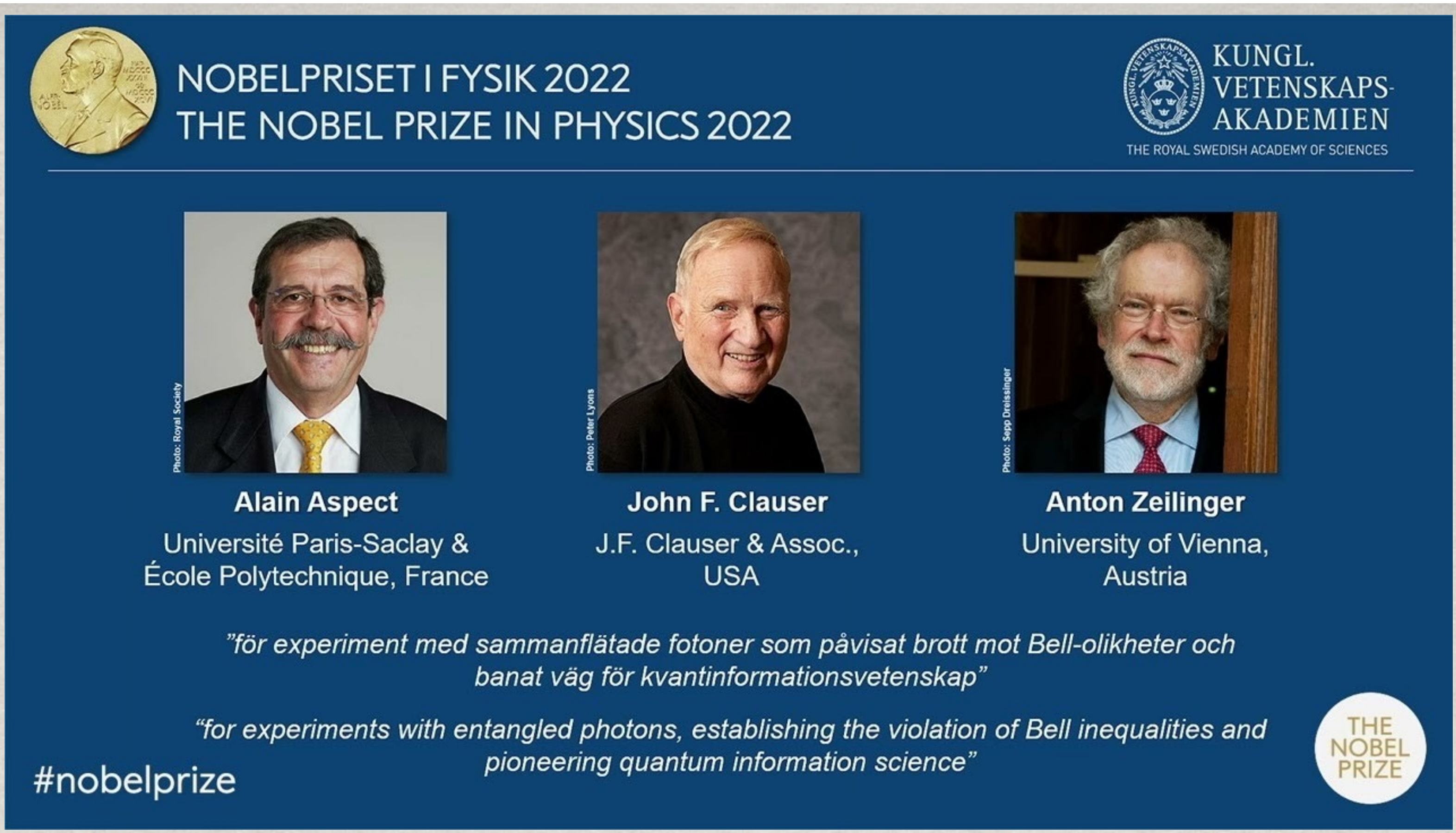
Triplet:

$$\begin{aligned} |1,1\rangle &= \uparrow\uparrow \\ |1,0\rangle &= \frac{1}{\sqrt{2}}(\uparrow\downarrow + \downarrow\uparrow) \\ |1,-1\rangle &= \downarrow\downarrow \end{aligned}$$

Entangled



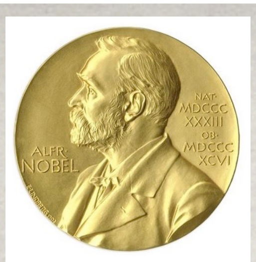
Quantum entanglement →
sub-systems inseparable, even in a space-like separation.



The 2022 Nobel Prize in Physics was awarded to Alain Aspect, John Clauser, and Anton Zeilinger for their groundbreaking experiments in quantum mechanics, specifically for their work with entangled quantum states. These experiments established the violation of Bell inequalities and pioneered quantum information science.

Einstein-Podolsky-Rosen Paradox (EPR)

→ Second Quantum Revolution: QIS



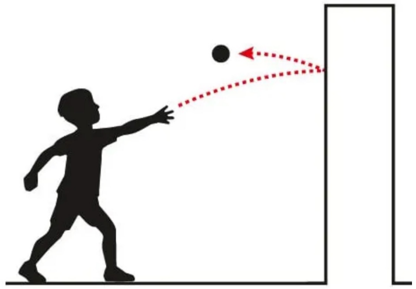
Nobel Prize in Physics 2025

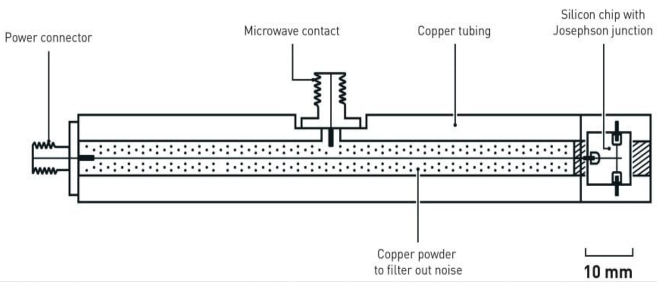
John Clarke
University of California, Berkeley, USA

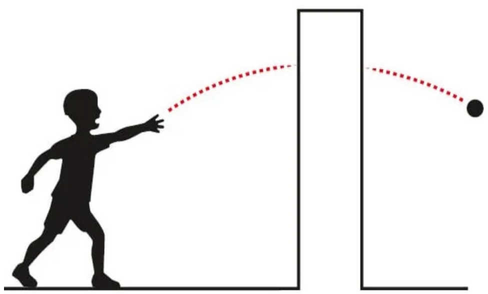
Michel H. Devoret
Yale University, New Haven, CT and
University of California, Santa Barbara, USA

John M. Martinis
University of California, Santa Barbara,

"for the discovery of macroscopic quantum mechanical tunnelling and energy quantisation in an electric circuit"







→ Quantum computer?

"Quantum mechanics describes nature as absurd from the point of view of common sense And yet it fully agrees with experiment. So I hope you can accept nature as She is - absurd."

-- Richard Feynman

Macroscopic Quantum Phenomena:

- Superconductivity, superfluidity
- Bose-einstein condensation

Quantum technology:

- MRI, NMR, Laser
- Semiconductors, fast electronics, computers

"Second Quantum Revolution":

- Quantum sensors, quantum communication
- Quantum simulations, quantum computer

Quantum Mechanics / QFT continues to push the boundary of human knowledge!

II. Setting the Stage: Quantum Tomography

For a state vector $|\phi_i\rangle$

Density matrix

a state

$$\rho = \sum_i n_i |\phi_i\rangle \langle\phi_i|$$

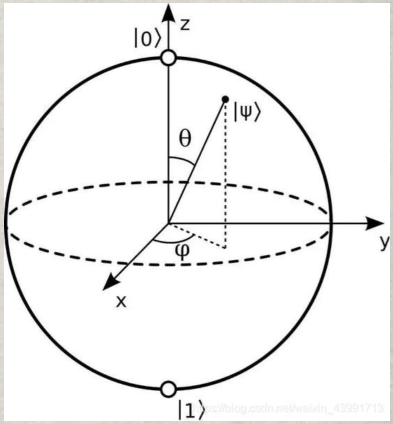
an observable

$$\langle\mathcal{O}\rangle = \mathrm{Tr}(\mathcal{O}\rho)$$

For a **pure state:** $n_i = 1$; for a **mixed state:** $\boldsymbol{\Sigma}_i n_i = 1$.

For a **single qubit** (*i.e.*, a doublet of spin, iso-spin etc.):

in terms of Bloch vector $\mathbf{B_i}$: $\rho = \frac{1}{2}\left(\mathbb{I}_2 + \sum_i B_i\sigma_i\right)$



For a **bipartite system** (*i.e.*, ½⊗½)

$$\rho = \frac{1}{4}\Big(\mathbb{I}_4 + \sum_i \left(B_i^{\mathcal{A}}\left(\sigma_i \otimes \mathbb{I}_2\right) + B_i^{\mathcal{B}}\left(\mathbb{I}_2 \otimes \sigma_i\right)\right) + \sum_{i,j} C_{ij}\left(\sigma_i \otimes \sigma_j\right)\Big)$$

$B_i^{A,B}$ the polarizations, C_{ij} the spin-correlation matrix.

The 15 coefficients for the bipartite → **Quantum Tomography**

which encodes the full quantum information.

Straightforward to generalize to qu-trits, qu-dits …

Quantum Entanglement

Peres-Horodecki Criterion: the concurrence, that can be written in C_i, the eigenvalues of C_{ij}:

$$\mathcal{C}(\rho) = \frac{1}{2}(C_{11} + C_{33} - C_{22} - 1)$$

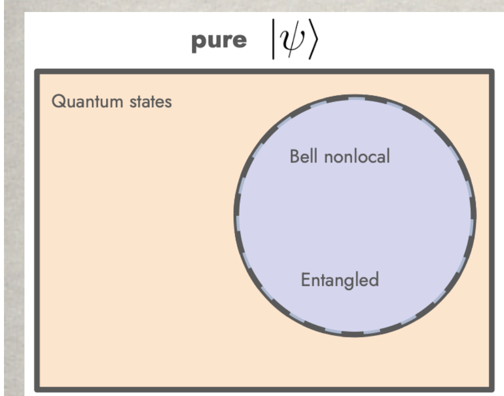
$$0 \le \mathcal{C}(\rho) \le 1$$

No entanglement

Maximumly entangled

John Bell's Inequality

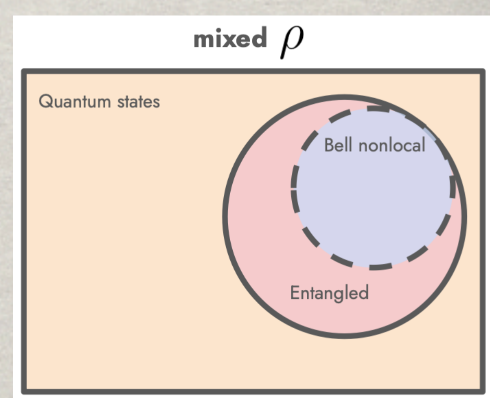
Alice & Bob's two correlated measurements can be cast to Clauser-Horne-Shimony-Holt form, that classical/LHVT satisfies:



$$\langle A_1B_1\rangle - \langle A_1B_2\rangle + \langle A_2B_1\rangle + \langle A_2B_2\rangle \le 2$$

Or: $$\left|\vec{a}_1 \cdot C \cdot (\vec{b}_1 - \vec{b}_2) + \vec{a}_2 \cdot C \cdot (\vec{b}_1 + \vec{b}_2)\right| \le 2$$

$$\mathcal{B} = \sqrt{2}(C_{33} - C_{22})$$



Bell non-local: $2 < \mathcal{B}(\rho) < 2\sqrt{2}$

Quantum Information Observables

With the quantum tomography C_{ij} :

→ much more quantum information.

- Entropy → "randomness"

  Classically: Shannon entropy

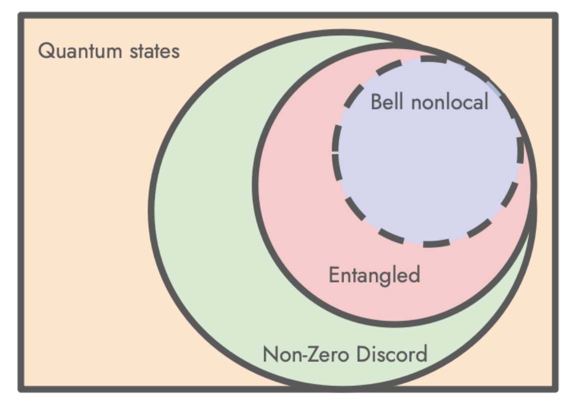
  QIS: Von Neumann entropy

$$H(X) = -\sum_{x\in X} p(x)\log_2(p(x))$$

$$S(\rho) = -\mathrm{tr}(\rho\log_2(\rho))$$

- "Discord": the difference between the total mutual information $I(\rho)$ and the classical mutual information $J(\rho_A)$

$$0 < D(\rho_A) = I(\rho) - J(\rho_A) < 1$$



- "Magic": non-stabilizerness for quantum computing (a stabilizer state can be effectively simulated classically)

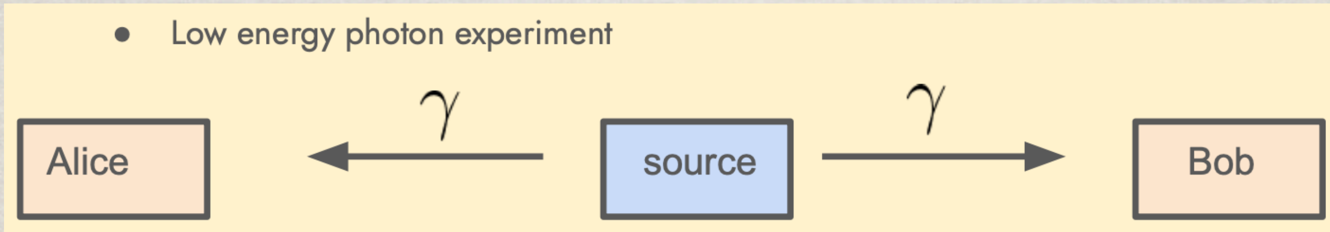
The second stabilizer Renyi entropy:

$$\mathcal{M}_2 = -\log_2 \frac{\sum_{P\in\mathcal{P}_n} \mathrm{Tr}(\rho P)^4}{\sum_{P\in\mathcal{P}_n} \mathrm{Tr}(\rho P)^2} = -\log_2 \frac{1+\sum_i (B_i^+)^4 + \sum_j (B_j^-)^4 + \sum_{ij} (C_{ij})^4}{1+\sum_i (B_i^+)^2 + \sum_j (B_j^-)^2 + \sum_{ij} (C_{ij})^2}.$$

… …

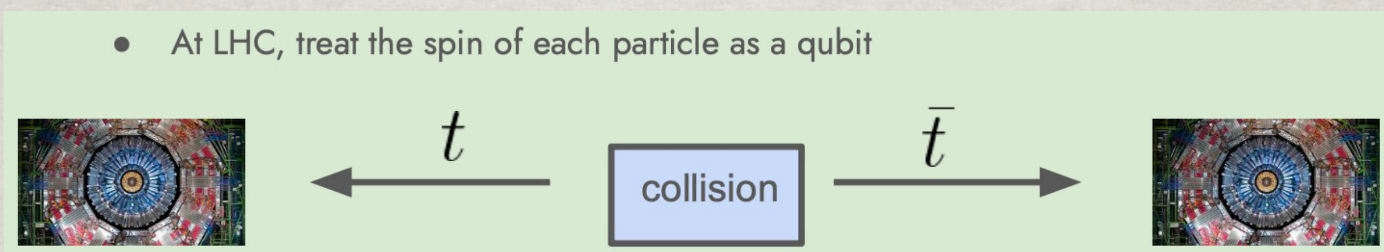
Disclaimer:
We Do Not Set up to Exclude LHVT

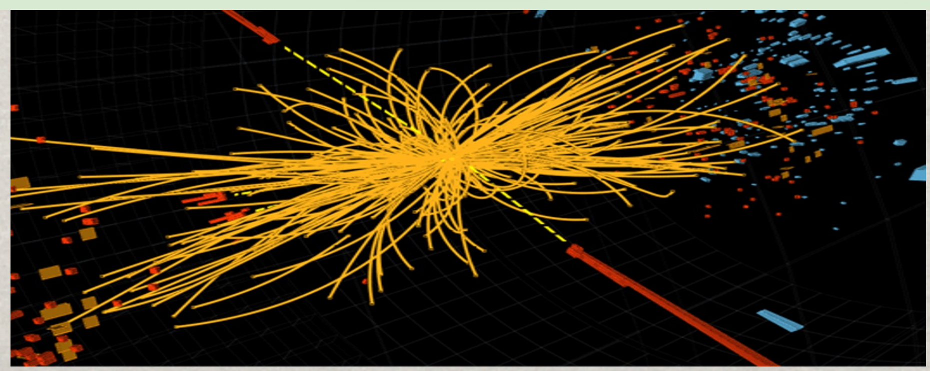
John Bell’s setting: Alice & Bob free will experiments



HEP experiments: intrinsically QM!

- Probabilistic distribution in space-time (not by Alice & Bob)
- Classical observables: E, p, tracks, angles …



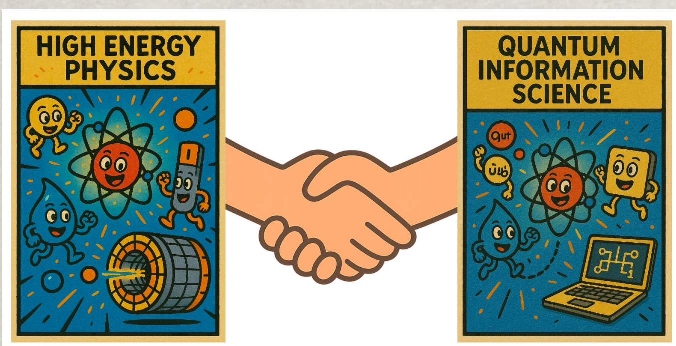


III. QIS in Collider Experiments

Our goals:

In the framework of QFT,
unprecedented relativistic regime at colliders:

- We lay out the QM predictions
- Perform quantum tomography
- Construct quantum information obsrvables:
  Entanglement, Bell variables, Discord, Magic …
- Understand deep quantum nature
  at this unprecedented regime & seek for BSM effects.



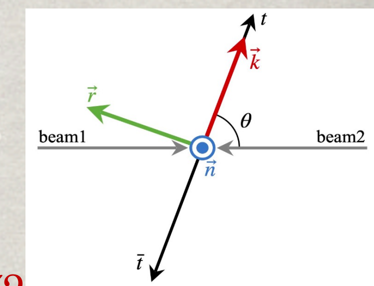
Afik and Munoz de Nova, arXiv:2003.02280;
M. Fabbrichesi et al., arXiv:2102.11883;
A. J. Bar et al., arXiv:2106.01377 … …

Much recent enthusiasm & interests!

Quantum Tomography @ Colliders

- All "classical observables": energy, angles …
- Random events in space-time.
- Follow QM production/decay prediction.

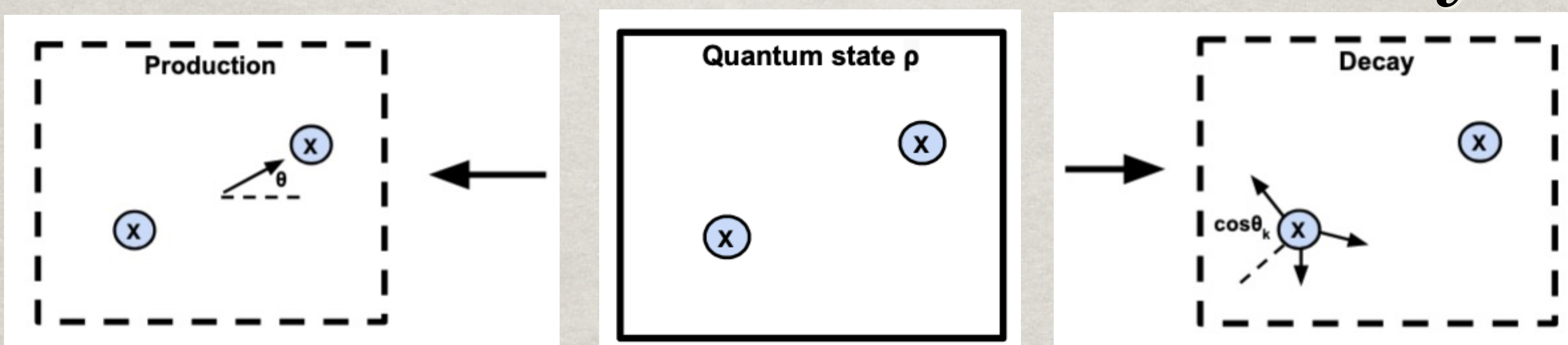
thus statistically: "**fictitious states**"!



Y. Afik, J. de Nova, arXiv:2003.02280; K. Cheng, TH, M. Low, arXiv:2407.01672.

Two paths to proceed to quantum tomography;

Kinematics: **Decay:**



$$\rho = \frac{1}{4}\Big(\mathbb{I}_4 + \sum_i \left(B_i^{\mathcal{A}}\,(\sigma_i \otimes \mathbb{I}_2) + B_i^{\mathcal{B}}\,(\mathbb{I}_2 \otimes \sigma_i)\right) + \sum_{i,j} C_{ij}\,(\sigma_i \otimes \sigma_j)\Big)$$

Both inherit the SAME quantum information!

(1). Top-pair & spin correlation

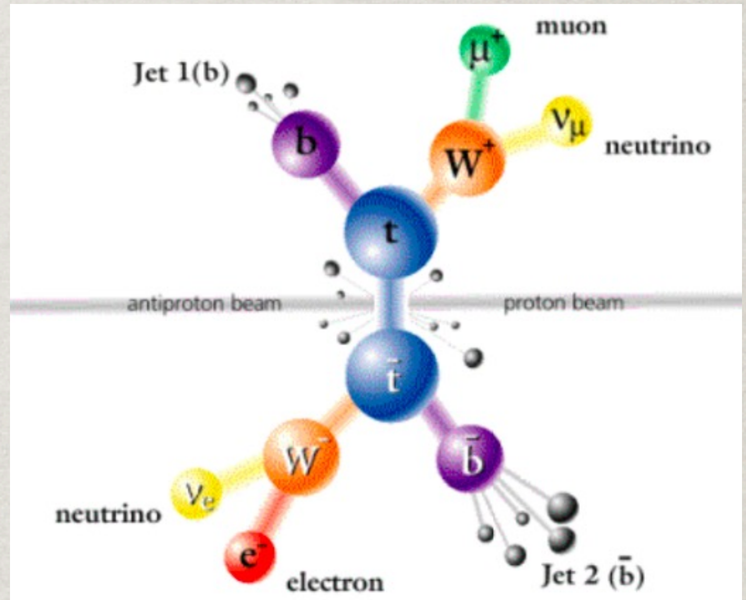
decaying to $A_{1,2,3}$, $B_{1,2,3}$

$$\sigma(XY \to t\bar{t} \to (A_1A_2A_3)(B_1B_2B_3)) =$$

$$\int d\Omega^A d\Omega^B \left(\frac{d\Gamma_{ab}}{d\Omega^A}\right) R_{ab,\bar{a}\bar{b}} \left(\frac{d\bar{\Gamma}_{\bar{a}\bar{b}}}{d\Omega^B}\right)$$

$$\frac{d\Gamma_{ab}}{d\Omega} \propto \delta_{ab} + \kappa\, \sigma^i_{ab}\, \Omega^i$$

Spin analyzing power



$$\Rightarrow \quad \frac{1}{\sigma}\frac{d\sigma}{d\Omega^A d\Omega^B} = \frac{1}{(4\pi)^2}\left(1 + \kappa^A P^A_i \Omega^A_i + \kappa^B P^B_i \Omega^B_i + \kappa^A\kappa^B\, \Omega^A_i C_{ij} \Omega^B_j\right)$$

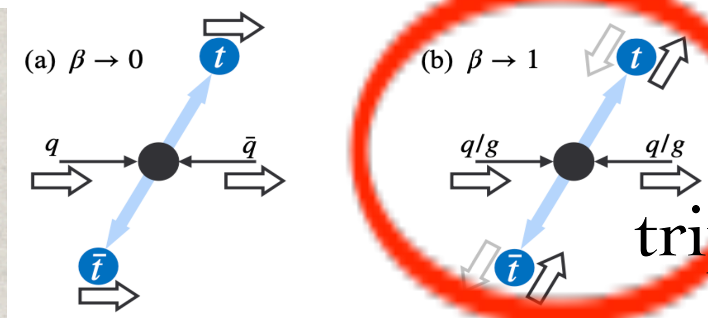
Direction of A, B

$$\Rightarrow \quad C_{ij} = \frac{4}{\kappa^A\kappa^B}\, \frac{N\left(\cos\theta^A_i \cos\theta^B_j > 0\right) - N\left(\cos\theta^A_i \cos\theta^B_j < 0\right)}{N\left(\cos\theta^A_i \cos\theta^B_j > 0\right) + N\left(\cos\theta^A_i \cos\theta^B_j < 0\right)}$$

performing top-pair tomography!

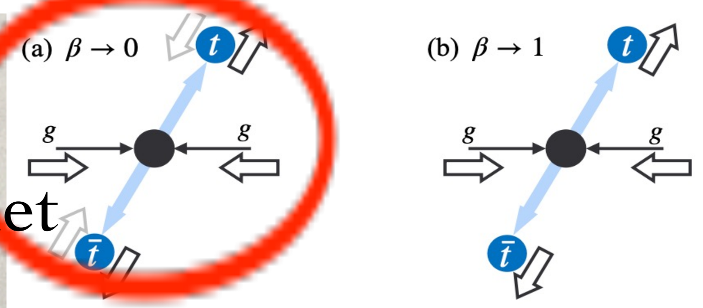
(2). Kinematic Approach for 2 → 2 Production

QCD production	$\overline{\sum}\lvert\mathcal{M}\rvert^2$	spin correlation matrix C_{ij}	ξ
$q\bar{q} \to t\bar{t}$	$\kappa_q\left(2-\beta^2 s_\theta^2\right)$	$\begin{pmatrix} \frac{(2-\beta^2)s_\theta^2}{2-\beta^2 s_\theta^2} & 0 & -\frac{2c_\theta s_\theta\sqrt{1-\beta^2}}{2-\beta^2 s_\theta^2} \\ 0 & \frac{-\beta^2 s_\theta^2}{2-\beta^2 s_\theta^2} & 0 \\ -\frac{2c_\theta s_\theta\sqrt{1-\beta^2}}{2-\beta^2 s_\theta^2} & 0 & \frac{2c_\theta^2+\beta^2 s_\theta^2}{2-\beta^2 s_\theta^2} \end{pmatrix}$	$\tan\xi = \frac{1}{\gamma}\tan\theta$
$g_L g_R \to t\bar{t}$	$\kappa_g \beta^2 s_\theta^2(2-\beta^2 s_\theta^2)$		$\tan\xi = \frac{1}{\gamma}\tan\theta$
$g_L g_L/g_R g_R \to t\bar{t}$	$\kappa_g(1-\beta^4)$	$\begin{pmatrix} \frac{\beta^2-1}{\beta^2+1} & 0 & 0 \\ 0 & \frac{\beta^2-1}{\beta^2+1} & 0 \\ 0 & 0 & -1 \end{pmatrix}$	$\xi = 0$



triplet

All C_{ij} encoded in the production kinematics:
θ & **β**$=(1-4m_t^2/m_{tt}^2)^{1/2}$



singlet

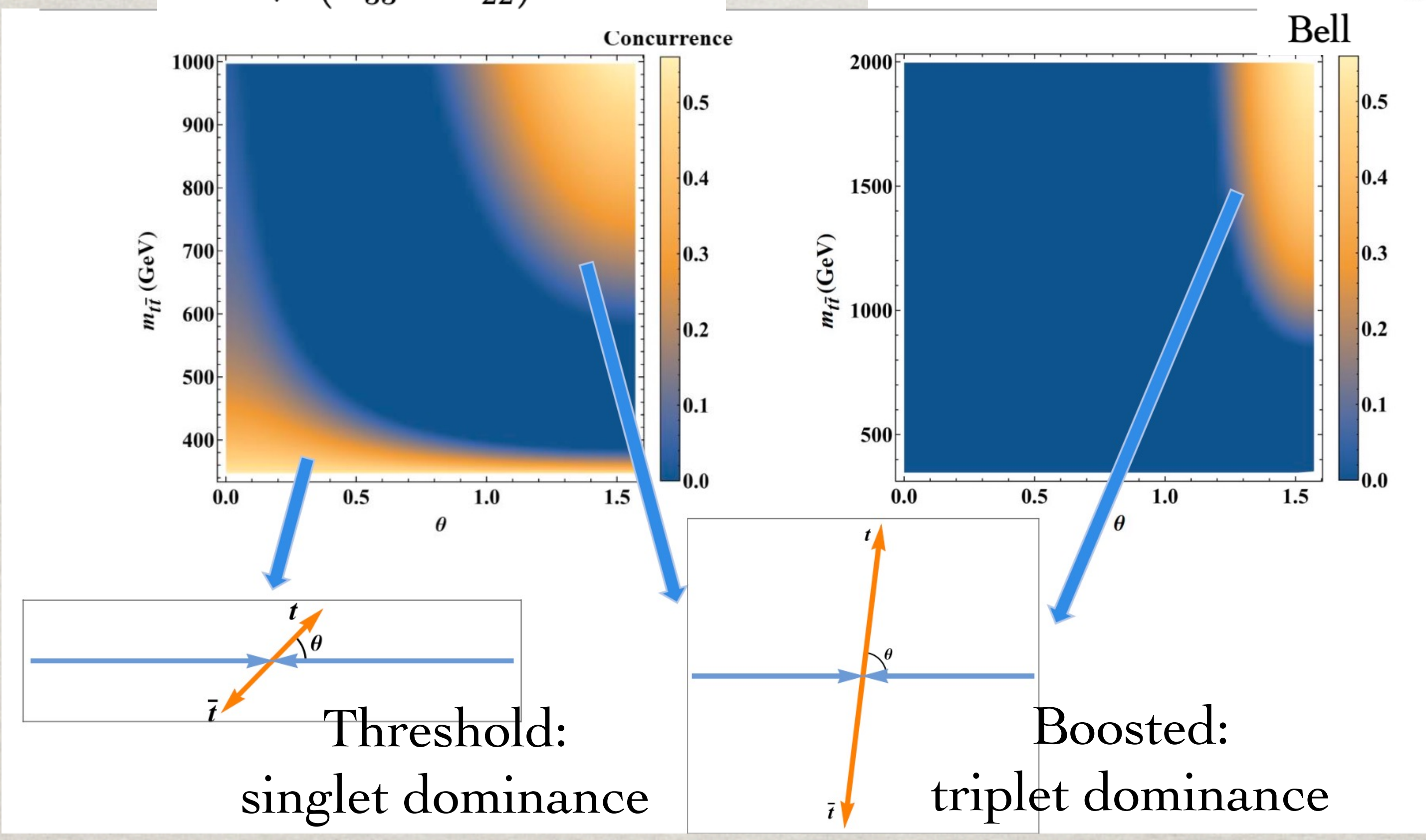
K. Cheng, TH, M. Low, 2410.08303.

Theory & Observation:

(Many theory papers; ATLAS & CMS publications.)

$$\mathcal{C} = \frac{1}{2}(C_{11} + C_{33} - C_{22} - 1),$$
$$\mathcal{B} = \sqrt{2}(C_{33} - C_{22}).$$

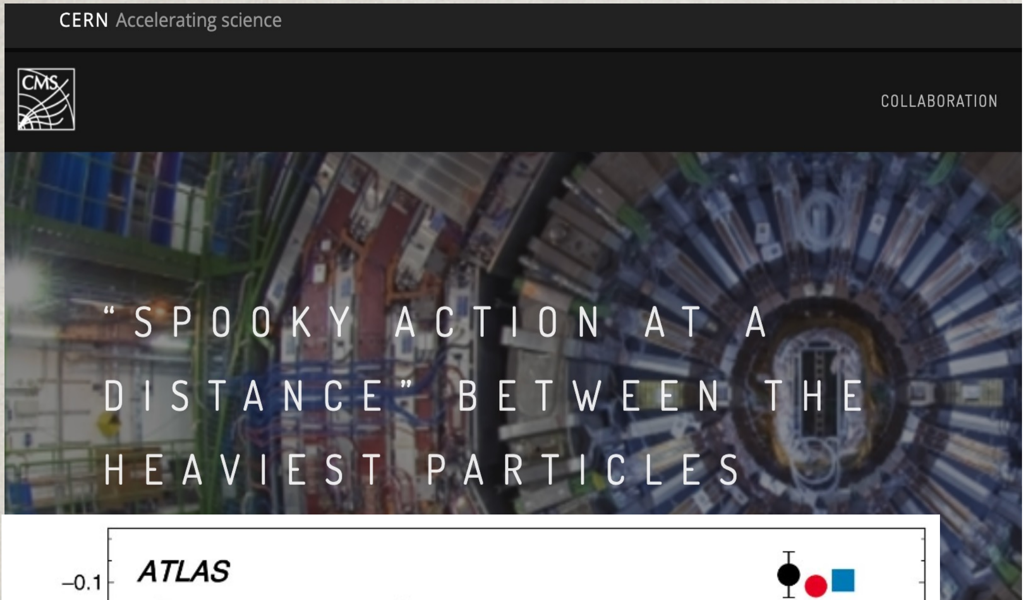
$\mathcal{C} > 0, \qquad \mathcal{B} > 2,$
for entanglement

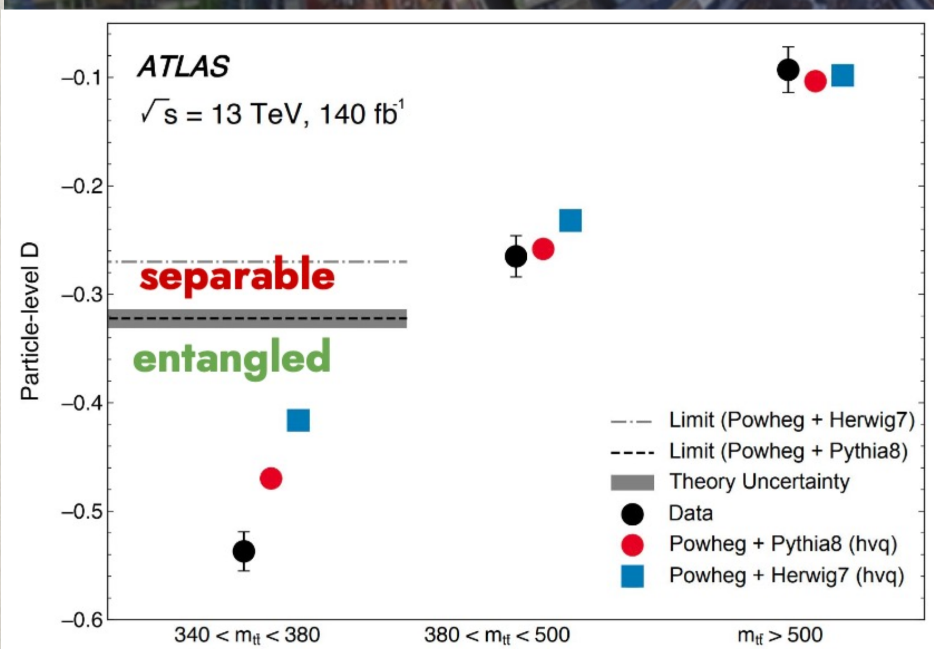


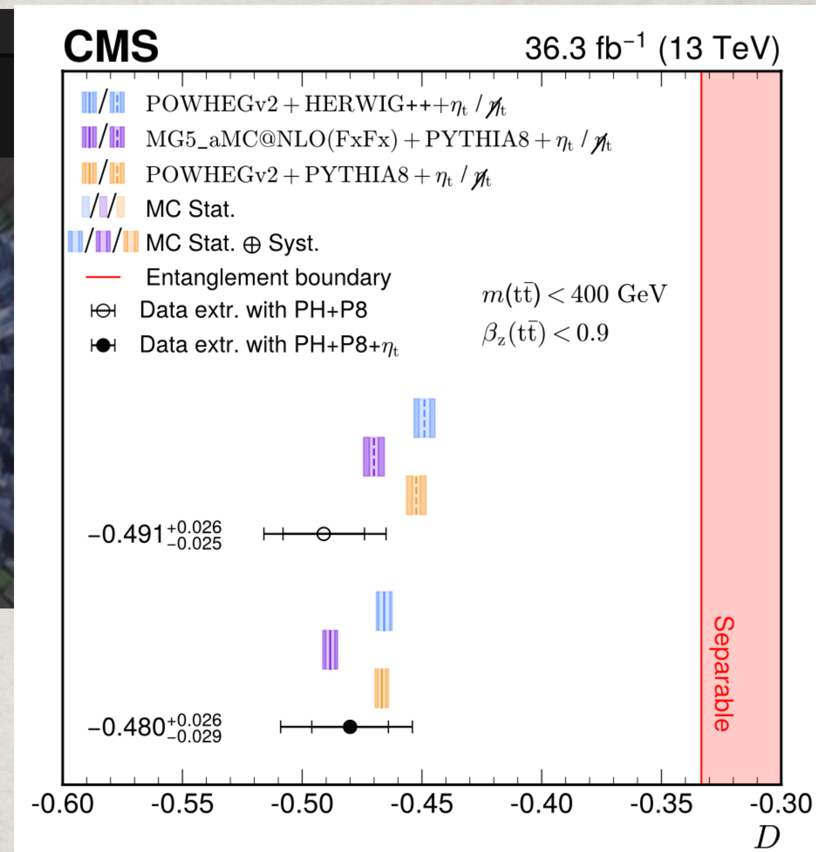
- Threshold:
high rate, low sensitivity

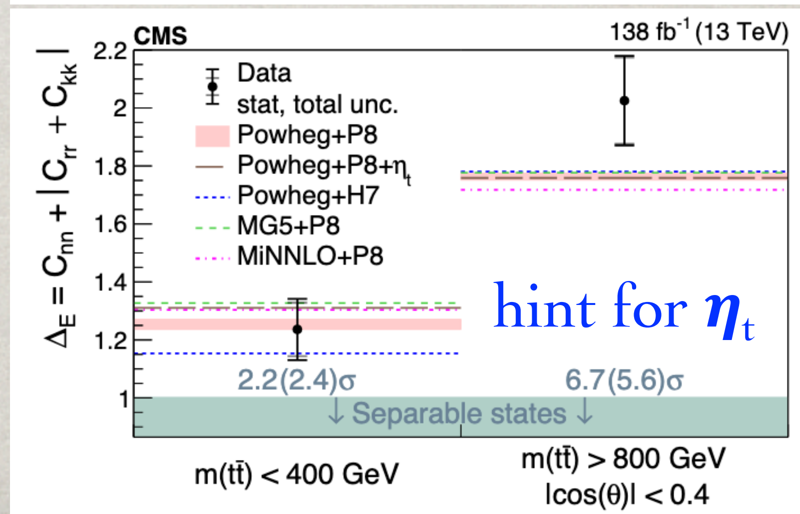
- Highly boosted:
Low rate, high sensitivity

CERN press release on Sept. 19, 2024









$$D = -\frac{1+C}{3}$$

ATLAS 2311.07288

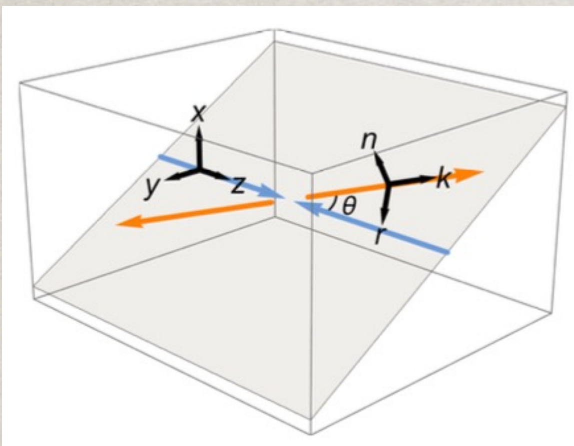
CMS 2406.03976

Rep. Prog. Physics 87 (2024) 117801

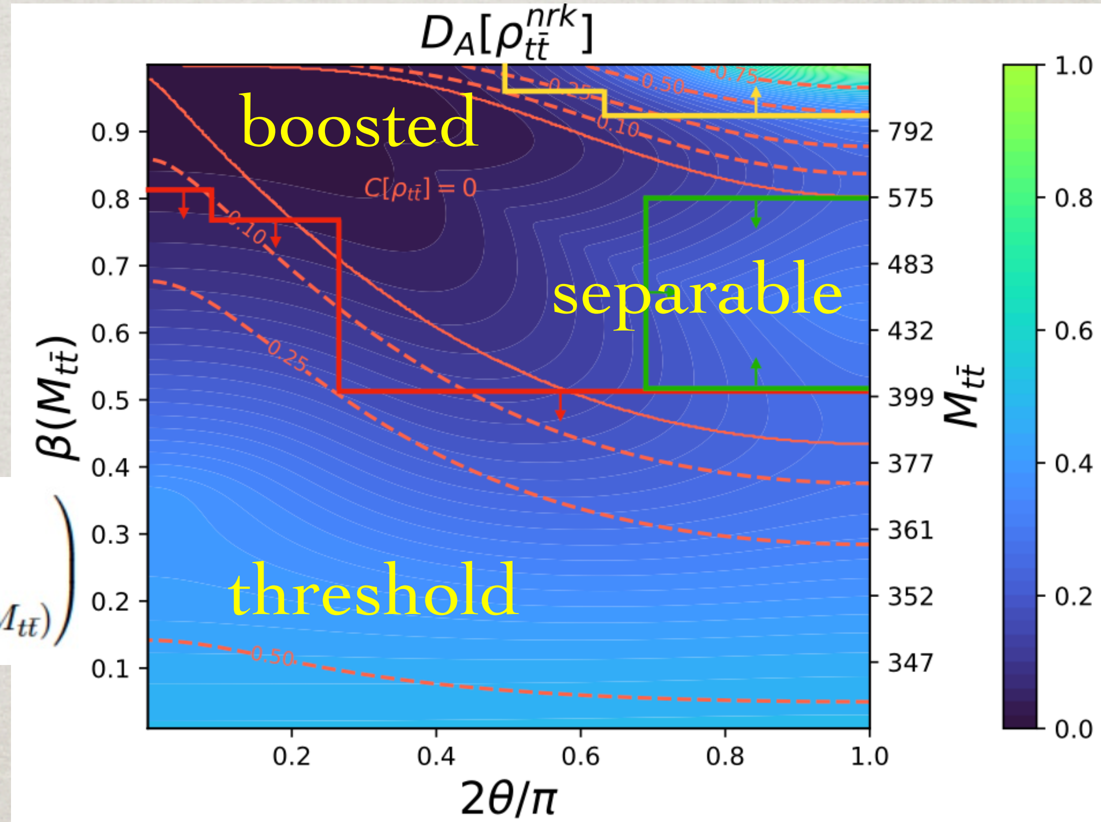
Quantum Discord in top pairs

(beyond the classical mutual information)

$0 < D(\rho_A) = I(\rho) - J(\rho_A) < 1$



$$C_{ij}^{\text{helicity}} = \begin{pmatrix} C_k(\theta, M_{t\bar{t}}) & C_{kr}(\theta, M_{t\bar{t}}) & 0 \\ C_{kr}(\theta, M_{t\bar{t}}) & C_r(\theta, M_{t\bar{t}}) & 0 \\ 0 & 0 & C_n(\theta, M_{t\bar{t}}) \end{pmatrix}$$



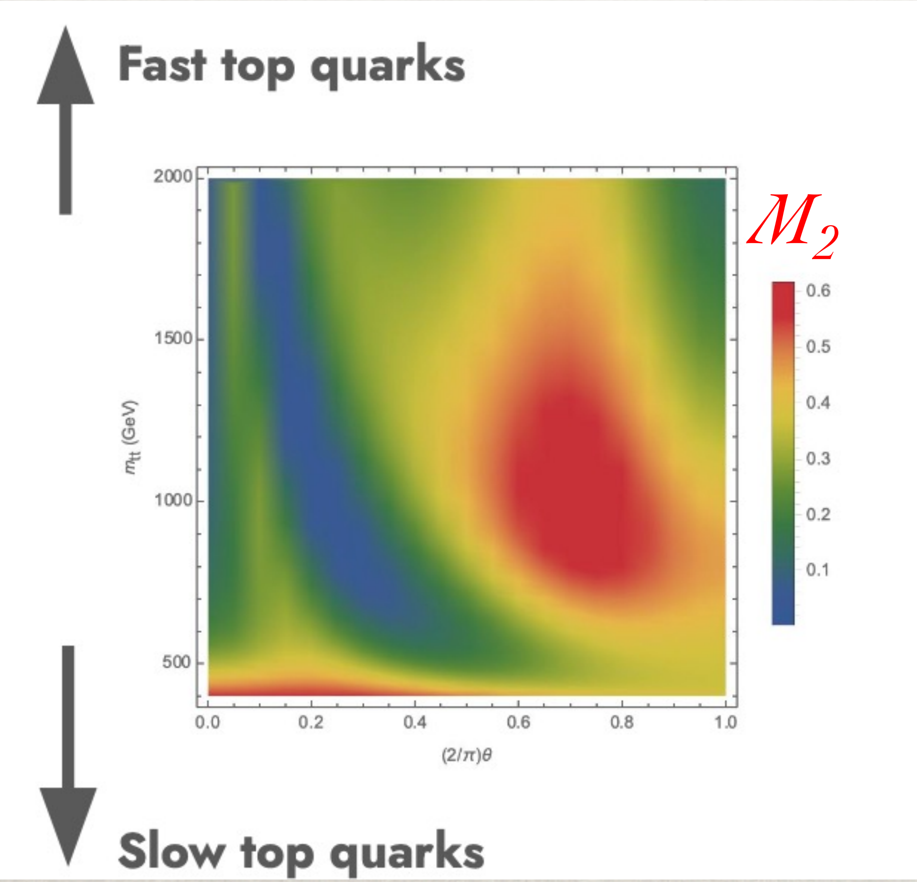
	Threshold Region		Separable Region		Boosted Region	
	$\langle\epsilon_{rec}\rangle$	$D_A(\rho_{t\bar{t}})$	$\langle\epsilon_{rec}\rangle$	$D_A(\rho_{t\bar{t}})$	$\langle\epsilon_{rec}\rangle$	$D_A(\rho_{t\bar{t}})$
Parton		0.200 ± 0.003		0.255 ± 0.008		0.197 ± 0.003
Reconstructed	0.10	0.23 ± 0.04	0.28	0.18 ± 0.05	0.08	0.20 ± 0.05
		5.7σ		**3.6σ**		**4.2σ**

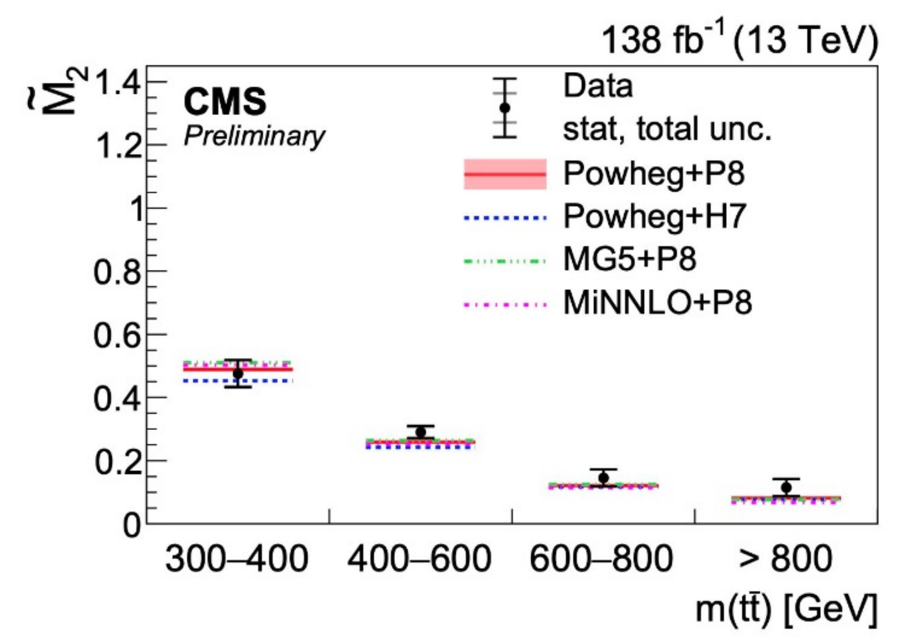
TH, M. Low, S. Su, arXiv:2407.01672.

“Magic” in top pairs

Computational advantage a quantum computer over a classical computer:

$$\mathcal{M}_2 = -\log_2 \frac{\sum_{P\in\mathcal{P}_n} \mathrm{Tr}(\rho P)^4}{\sum_{P\in\mathcal{P}_n} \mathrm{Tr}(\rho P)^2}.$$





Entanglement doesn’t dictate Magic!

White, White, arXiv:2406.07321

BSM Contributions: SMEFT

$$\rho^I = \frac{R^{I,\mathrm{SM}} + R^{I,\mathrm{EFT}}}{\mathrm{Tr}(R^{I,\mathrm{SM}}) + \mathrm{Tr}(R^{I,\mathrm{EFT}})}$$

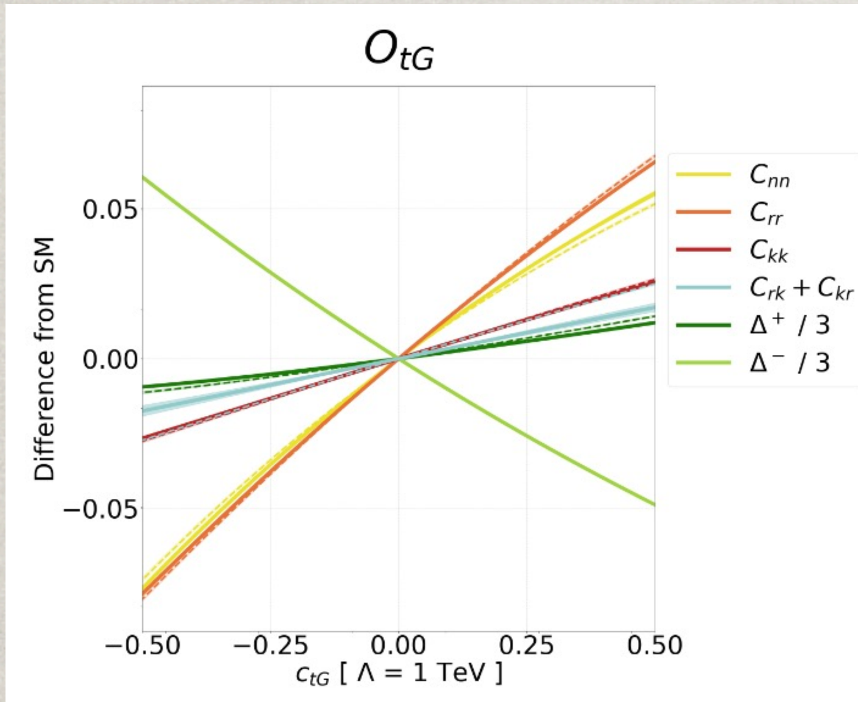
$$\mathcal{O}_{tG} = g_s \left(\bar{Q}\sigma^{\mu\nu}T^A t\right) \tilde{\phi}\, G^A_{\mu\nu} + \mathrm{h.c.}$$

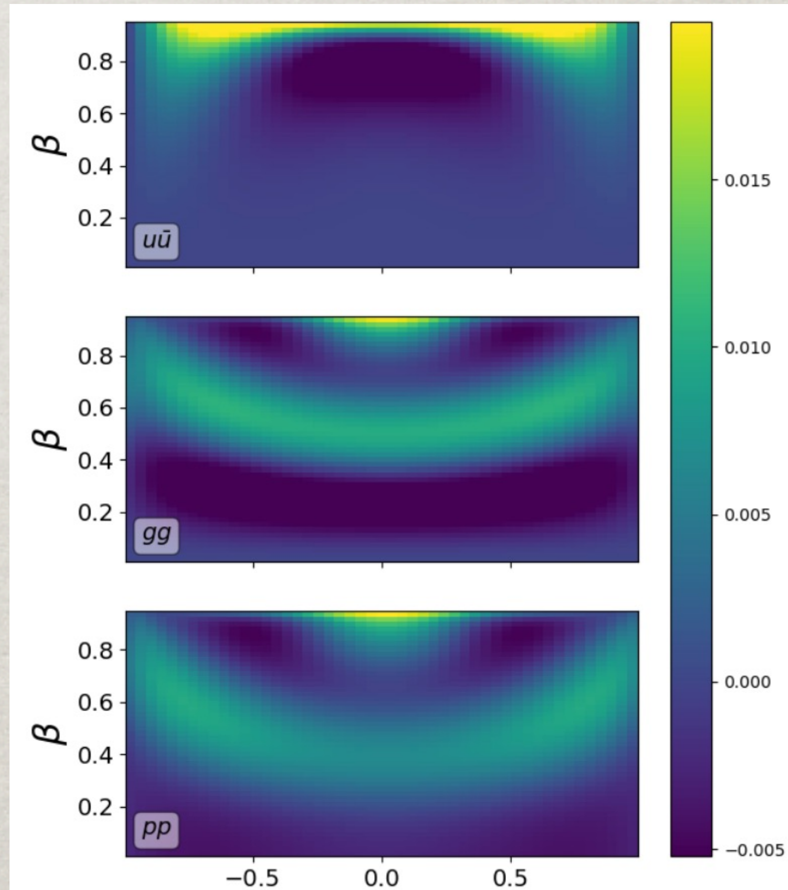
C. Severi, E. Vryonidou
arXiv:2210.09330

R. Aoude et al. ,
arXiv:2505.12522

Quantum tomography

$M_2(\mathrm{SMEFT}\ c_{tG}) - M_2(\mathrm{SM})$





$\cos\theta$

Percentage
Modifications feasible

IV. Quantum Tomography of a Fermion Pair in Polarized $e^+e^- \to f\bar{f}$

Y.—C. Guo, TH, M. Low, Y. Su, arXiv:2602.02719.

Effective couplings for polarized beam RL, LR:

$$f_V^L = Q_e Q_f + \frac{g_L^e(g_L^f + g_R^f)}{2c_W^2 s_W^2}\frac{s}{s - m_Z^2 + i\Gamma_Z m_Z},$$
$$f_A^L = -\frac{g_L^e(g_L^f - g_R^f)}{2c_W^2 s_W^2}\frac{s}{s - m_Z^2 + i\Gamma_Z m_Z},$$
$$f_V^R = Q_e Q_f + \frac{g_R^e(g_L^f + g_R^f)}{2c_W^2 s_W^2}\frac{s}{s - m_Z^2 + i\Gamma_Z m_Z},$$
$$f_A^R = -\frac{g_R^e(g_L^f - g_R^f)}{2c_W^2 s_W^2}\frac{s}{s - m_Z^2 + i\Gamma_Z m_Z},$$

Spin correlation:

$$C_{ij} = \frac{1}{\mathcal{D}}\begin{pmatrix} s_\theta^2\left(f_V^2(2-\beta^2) - f_A^2\beta^2\right) & 0 & -2(f_V^2 c_\theta \pm f_V f_A \beta) s_\theta\sqrt{1-\beta^2} \\ 0 & (f_A^2 - f_V^2)\beta^2 s_\theta^2 & 0 \\ -2(f_V^2 c_\theta \pm f_V f_A\beta)s_\theta\sqrt{1-\beta^2} & 0 & f_V^2(2c_\theta^2 + \beta^2 s_\theta^2) + f_A^2\beta^2(1+c_\theta^2) \pm 4 f_V f_A \beta \end{pmatrix}$$

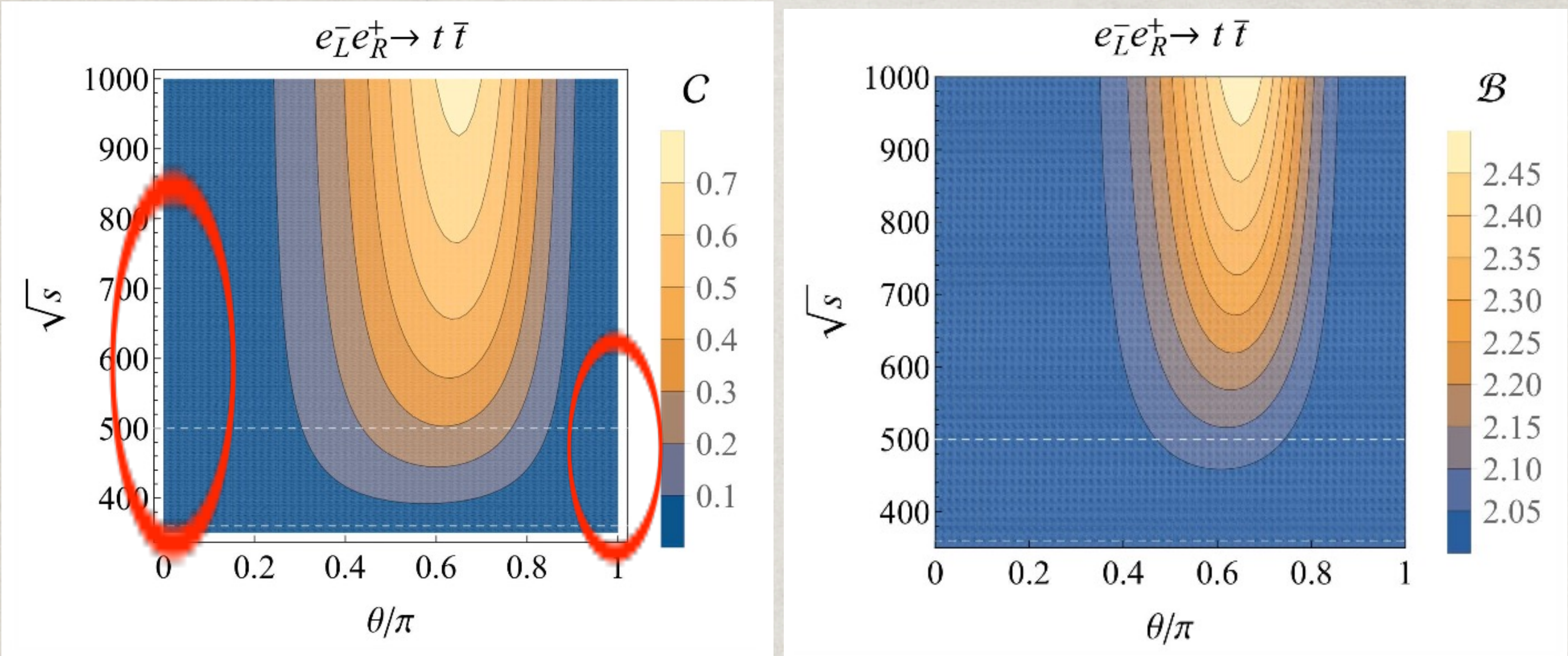
ff polarizations: $$B_k^\pm = \frac{2(f_V \pm f_A c_\theta)(f_A \pm f_V c_\theta)}{(f_V^2 + f_A^2)(1+c_\theta^2) \pm 4 f_V f_A c_\theta},$$

Concurrence $\mathcal{C} = \frac{\beta^2 s_\theta^2 (f_V^2 - f_A^2)}{\mathcal{D}}$, & Bell: $\mathcal{B} = 2\sqrt{1+\mathcal{C}^2}$.

reaching the maximum $\mathcal{C} \to 1$, $\mathcal{B} \to 2\sqrt{2}$ at $\cos\theta = \mp f_A/f_V$.

Magic: $$\mathcal{M}_2 = -\log_2 \frac{1 + \sum_i (B_i^+)^4 + \sum_j (B_j^-)^4 + \sum_{ij}(C_{ij})^4}{1 + \sum_i (B_i^+)^2 + \sum_j (B_j^-)^2 + \sum_{ij}(C_{ij})^2}.$$

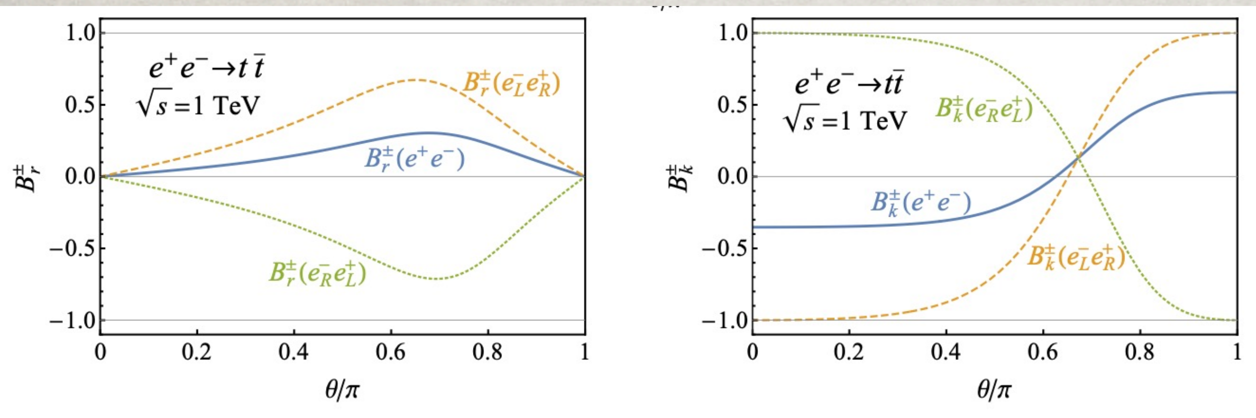
(1). $e^+e^- \to t\bar{t}$ the threshold and well above

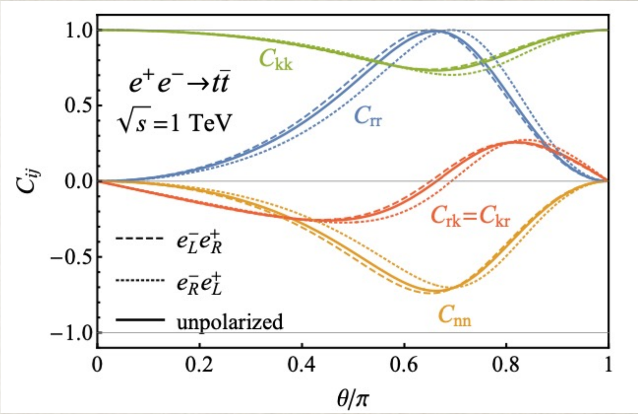


- No entanglement near threshold, nor in backward/forward scattering
- Maximum at

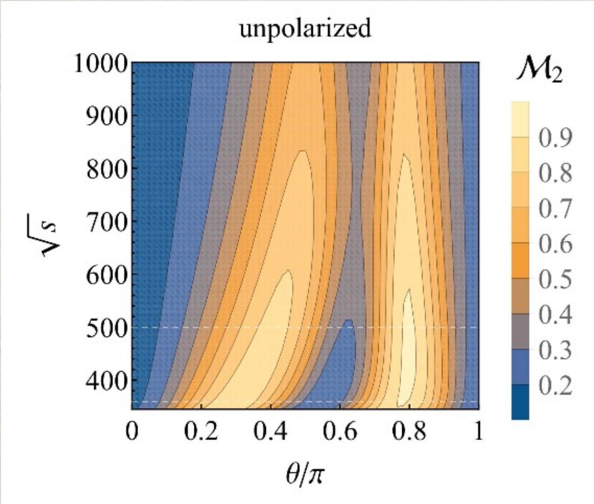
with $f^R_A/f^R_V \approx 0.6$ and $f^L_A/f^L_V \approx -0.5$.

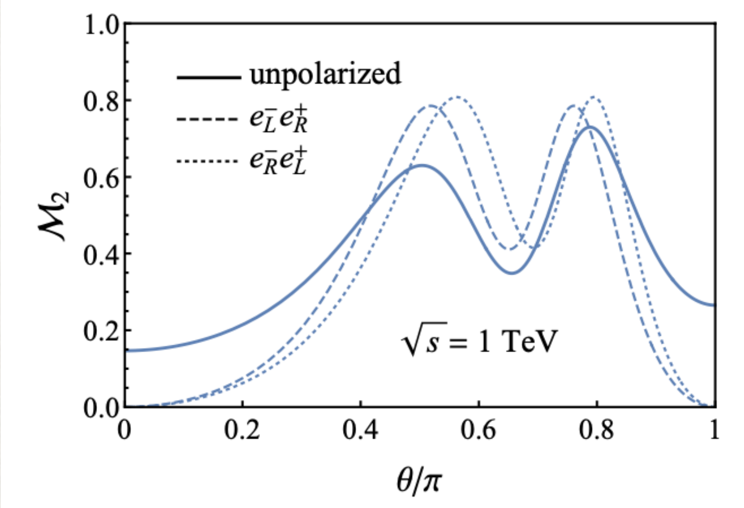
Full tomography in $e^+e^- \to t\bar{t}$





RL ←→ LR flip f-polarization B; Cij insensitive to RL



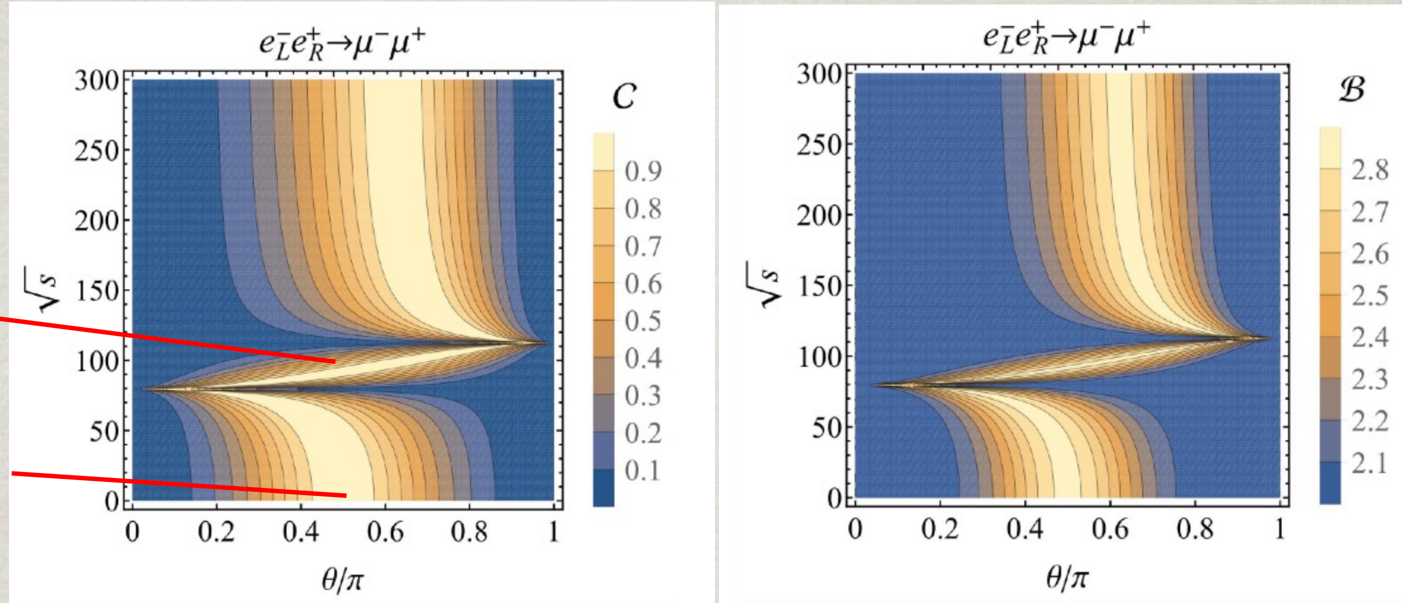


- Entanglement local max → Magic local min!
- Magic twin-peak around local min
- Zero entanglement may have non-zero magic!

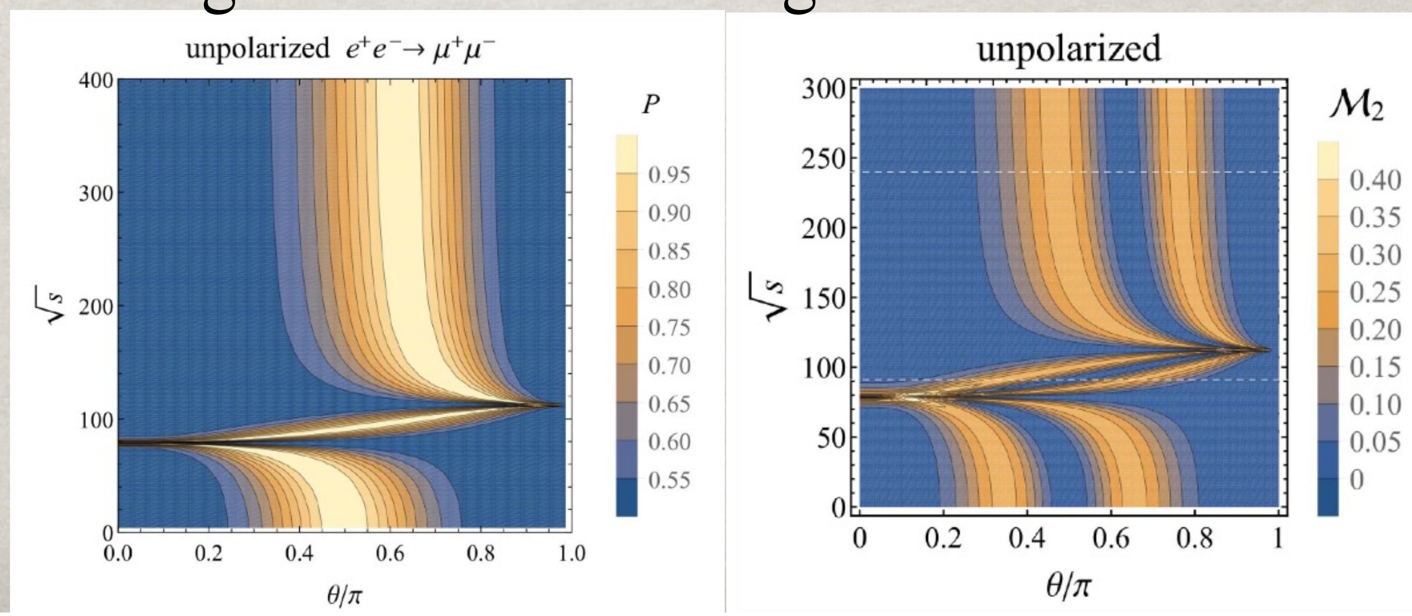
(2). $e^+e^- \to \gamma, Z \to \mu^+\mu^-$ at the Z pole & beyond

EW chiral, asymmetric

QED symmetric



- **μ⁺μ⁻** polarizations correlated w. entanglement
- Max entanglement → low magic



V. Quantum Tomography in flavor space

K. Cheng, TH, M. Low, A. Wu, arXiv:2507.12513

For a neutral meson – anti-meson system: $|M^0\rangle - |\bar{M}^0\rangle$
such as $|B^0\rangle - |\bar{B}^0\rangle,\ |D^0\rangle - |\bar{D}^0\rangle,\ |K^0\rangle - |\bar{K}^0\rangle$

we can treat them as 2-qubit systems:

$$|M_1\rangle = p|M\rangle + q|\bar{M}\rangle, \quad \text{with } (m_1, \Gamma_1),$$
$$|M_2\rangle = p|M\rangle - q|\bar{M}\rangle, \quad \text{with } (m_2, \Gamma_2),$$

$$\mathcal{H} = \begin{pmatrix} m - i\frac{\Gamma}{2} & H_{12} \\ H_{21} & m - i\frac{\Gamma}{2} \end{pmatrix}$$

- The density matrix for a flavor-qubit: $\rho_{_M} = \dfrac{\mathbb{1}_2 + R_i \sigma_i}{2}$

  Flavor eigen-states $|M^0\rangle, |\bar{M}^0\rangle$ by Bloch vectors $R^{init} = (0,0,\pm 1)$

  so that: $\sigma_z |M\rangle = +|M\rangle \qquad \sigma_z |\bar{M}\rangle = -|\bar{M}\rangle$

  Mass eigen-states $|M_1\rangle, |M_2\rangle$ by Bloch vectors $R^{init} = (\pm 1,0,0)$

- The density matrix for a 2-qubit system:

$$\rho_{_{MM}} = \frac{\mathbb{1}_4 + R_i^{\mathcal{A}} \sigma_i \otimes \mathbb{1}_2 + R_i^{\mathcal{B}} \mathbb{1}_2 \otimes \sigma_i + C_{ij} \sigma_i \otimes \sigma_j}{4}$$

Bloch vectors $R_i^{A,B}$ correlation C_{ij} specify quantum tomography.

- $|M^0\rangle, |\bar{M}^0\rangle$ State evolution: $\frac{d\vec{R}(t)}{dt} = -\vec{X} \times \vec{R}(t)$, $\vec{X} = (\Delta m, 0, 0)$

Oscillatory Precession solution: (like an LC circuit)

$$R_x(t) = R_x,$$
$$R_y(t) = R_y c_t + R_z s_t,$$
$$R_z(t) = R_z c_t - R_y s_t,$$

$$c_t = \cos(\Delta m t),\ s_t = \sin(\Delta m t)$$

Thus: $R_y^{init}(0)$ or $R_z^{init}(0)$ → $R_{y,z}(t)$, but not $R_x(t)$.

- Decaying to CP eigen-states (e.g., $B^0 \to J/\psi\ K_S$):

$$\Gamma_{M(t)\to f_+} = \frac{1+R_x(t)}{2}\Gamma_{M_1\to f_+} = (1+R_x(t))\Gamma_{M\to f_+}$$

$$\frac{d(N_f + N_{\bar{f}})}{dt} = N(t)\Gamma_{M\to f} = N_0\, e^{-\Gamma t}(\mathrm{ch}_t - R_x \mathrm{sh}_t)\Gamma_{M\to f}$$

(like an RC circuit)

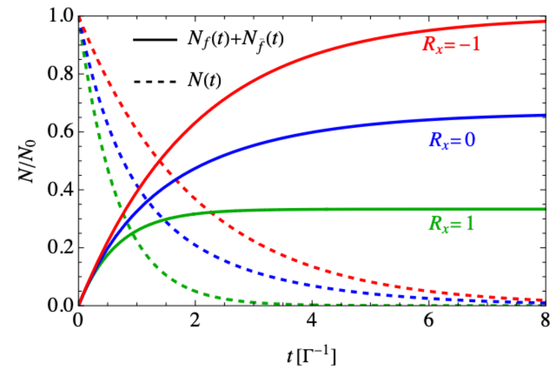
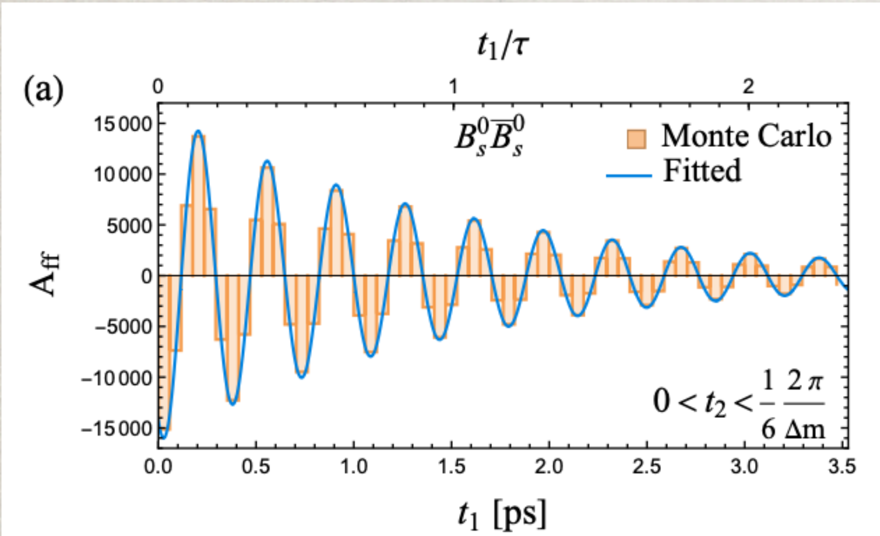
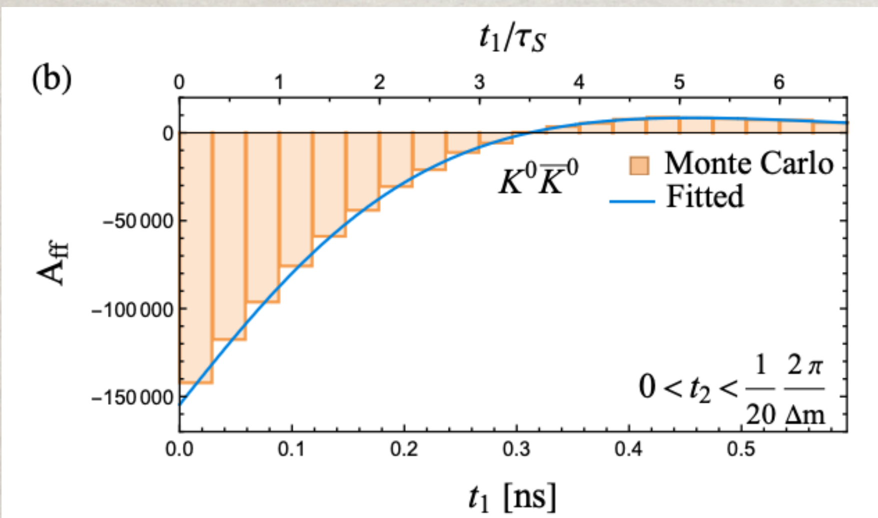


FIG. 1. In percentage, the total number of mesons (dashed lines) and decay products (solid lines) as a function of time, with different Bloch vectors at $t = 0$. Calculated in a toy example with $\Gamma_f = \Gamma_{f_+}$

Thus $R_x(t)$ determined → full quantum tomography $R_i(t)$!

Reconstruction of quantum tomography





	$B_s^0\bar{B}_s^0$ fitted ρ_{Bell} (ρ_κ)	$K^0\bar{K}^0$ fitted ρ_{Bell} (ρ_κ)	Obs.
$b_x^{\mathcal{A}}$	0 ± 0.02 (0 ± 0.017)	0 ± 0.0015 (0 ± 0.0018)	N_{tot}
$b_x^{\mathcal{B}}$	0 ± 0.02 (0 ± 0.016)	0 ± 0.0017 (0 ± 0.0018)	
$b_y^{\mathcal{A}}$	0 ± 0.001 (0 ± 0.0010)	0 ± 0.0019 (0 ± 0.0021)	$A_f^{\mathcal{A}}$
$b_z^{\mathcal{A}}$	0 ± 0.001 (0 ± 0.0009)	0 ± 0.0014 (0 ± 0.0016)	
$b_y^{\mathcal{B}}$	0 ± 0.001 (0 ± 0.0008)	0 ± 0.0020 (0 ± 0.0023)	$A_f^{\mathcal{B}}$
$b^{\mathcal{B}}$	0 ± 0.001 (0 ± 0.0008)	0 ± 0.0015 (0 ± 0.0016)	
C_{xx}	-1 ± 0.3 (-0.8 ± 0.29)	-1 ± 0.0031 (-0.8 ± 0.0032)	N_{tot}
C_{yx}	0 ± 0.02 (0 ± 0.018)	0 ± 0.0023 (0 ± 0.0026)	$A_f^{\mathcal{A}}$
C_{zx}	0 ± 0.02 (0 ± 0.017)	0 ± 0.0017 (0 ± 0.0019)	
C_{xy}	0 ± 0.02 (0 ± 0.015)	0 ± 0.0025 (0 ± 0.0029)	$A_f^{\mathcal{B}}$
C_{xz}	0 ± 0.02 (0 ± 0.016)	0 ± 0.0018 (0 ± 0.0020)	
C_{yy}	-1 ± 0.001 (-0.8 ± 0.0010)	-1 ± 0.0027 (-0.8 ± 0.0023)	A_{ff}
C_{yz}	0 ± 0.001 (0 ± 0.0008)	0 ± 0.0022 (0 ± 0.0020)	
C_{zy}	0 ± 0.001 (0 ± 0.0008)	0 ± 0.0021 (0 ± 0.0017)	
C_{zz}	-1 ± 0.0011 (-0.8 ± 0.0009)	-1 ± 0.0010 (-0.8 ± 0.0011)	

TABLE I. The central values and statistical uncertainties of the Fano coefficients in the $B_s^0\bar{B}_s^0$ system and in the $K^0\bar{K}^0$ system, using the initial states ρ_{Bell} and ρ_κ with $\kappa = 0.2$. Each system uses 10^7 events and 40 pseudo-experiments. The statistical uncertainties scale as $1/\sqrt{N}$.

K. Cheng, TH, M. Low, A. Wu, arXiv:2507.12513

Quantum Information in $M\bar{M}$ system

Quantum tomography C_{ij} → much more quantum information:

	$B_s^0 \bar{B}_s^0$	$K^0 \bar{K}^0$
Concurrence	0.69 ± 0.14	0.702 ± 0.002
Bell Variable	0.1854 ± 0.0014	0.188 ± 0.003
Quantum Discord	0.58 ± 0.10	0.617 ± 0.002
Steerability	9.4 ± 1.3	9.52 ± 0.03
Conditional Entropy	-0.15 ± 0.29	-0.157 ± 0.005
SSRE	0.38 ± 0.15	0.388 ± 0.003

"Concurrence": (entanglement CHSH): $0 < C(\boldsymbol{\rho}) < 1$

Bell inequality violation in QM: $\mathcal{B} = |C_{yy} + C_{zz}| - \sqrt{2}.$

$-\sqrt{2} < \mathcal{B} \leq 0$ indicates a Bell local state and $0 < \mathcal{B} < 2 - \sqrt{2}$ indicates a Bell nonlocal state.

"Discord": the difference between the total mutual information and the classical mutual information

(Shannon entropy vs Von Neumann entropy) $0 < D(\boldsymbol{\rho}_A) < 1$

"Magic">0: non-stabilizerness for quantum computing

(stabilizer Renyi entropy) : $M = -\log_2[\boldsymbol{\zeta}(\boldsymbol{\rho})]$

A lot more to do

At the LHC:

- Higgs → $\tau^+\tau^-$, W^+W^{-*}, ZZ^*, … (J=0)
- Drell-Yan Z → $\mu^+ \mu^-$, $\tau^+ \tau^-$ … (J=1)
- Qutrits: WWZ, WWγ, … 4 tops …

At lepton colliders:

- e+ e- → $\mu^+ \mu^-$, $\tau^+ \tau^-$, t t, W^+W^-, ZZ, …
- $e^\pm$ p → $e^\pm$ p and $e^\pm$ q (EIC, LHeC)
- tau-charm factory
- Polarizations help → transverse unique!

Flavor oscillations: (CP violation)

- Kaon factory
- B-factories

And more QI variable to construct!

Explore the nature of decoherence / BSM.

VI. Conclusions

- Collider experiments produce a large number of quantum states at the unprecedented energy regime.
- Perform the quantum tomography & QI: Entanglement, Bell variables, Discord, Magic …
- **Two paths** to quantum tomography @ colliders: → Decay & without decay
- Flavor oscillations/decays new avenue to QI.
- Understand quantum & seek for BSM effects.

Quantum Information meets High-Energy Physics: Input to the update of the European Strategy for Particle Physics

arXiv:2504.00086

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QIS @ colliders → New observables & rich physics!