Foundational Quantum Tests with Higgs Bosons

Alan Barr

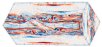
University of Oxford

ICHEP2024, Prague, 20$^{\mathrm{th}}$ July, 2024

AJB, Phys.Lett.B 825 (2022) 136866 — 2106.01377 [hep-ph]
AJB, P. Caban, J.Rembieliński — 2204.11063 [quant-ph]
R.Ashby-Pickering, AJB, A.Wierzchucka — 2209.13990 [quant-ph]
C.Altomonte, AJB, 2312.02242 [hep-ph]

Review article: AJB, M.Fabbrichesi, R.Floreanini, E.Gabrielli, L.Marzola — 2402.07972, Prog.Part.Nucl.Phys.

Interesting physics ≠ 'new' physics ≠ beyond-SM physics

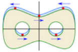


ON THE COVER

Heating of Magnetically Dominated Plasma by Alfvén-Wave Turbulence
February 14, 2022
Three-dimensional kinetic simulation of the onset of relativistic wave turbulence in the collision of two magnetic shear waves. Selected for a Viewpoint in *Physics*.

Joonas Nättilä and Andrei M. Beloborodov
Phys. Rev. Lett. **128**, 075101 (2022)

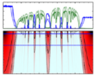
Issue 7 Table of Contents | More Covers



Physics NEWS AND COMMENTARY

A Quantized Surprise from Fermi Surface Topology
February 16, 2022
The quantized conductance of a two-dimensional electron gas can reflect its Fermi surface topology.

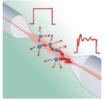
Synopsis on:
C. L. Kane
Phys. Rev. Lett. **128**, 076801 (2022)



EDITORS' SUGGESTION

Chaotic Diffusion in Delay Systems: Giant Enhancement by Time Lag Modulation
Laminar chaotic diffusion is found in systems with delayed nonlinearity, accompanied by a reduction of the effective dimensionality.

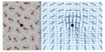
Tony Albers, David Müller-Bender, Lukas Hille, and Günter Radons
Phys. Rev. Lett. **128**, 074101 (2022)



EDITORS' SUGGESTION

Collective Radiative Dynamics of an Ensemble of Cold Atoms Coupled to an Optical Waveguide
An ensemble of cold atoms is coherently coupled in a controlled way to a tapered optical fiber, demonstrating collective effects in this system.

Riccardo Pennetta *et al.*
Phys. Rev. Lett. **128**, 073601 (2022)

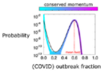


Physics NEWS AND COMMENTARY

Extending and Contracting Cells
February 15, 2022
Cell-substrate interactions explain a difference in behavior between individual cells and tissues on a surface.

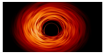
Synopsis on:
Andrew Killeen, Thibault Bertrand, and Chiu Fan Lee
Phys. Rev. Lett. **128**, 078001 (2022)

EDITORS' SUGGESTION



Outbreak Size Distribution in Stochastic Epidemic Models
An analytical approach to stochastic epidemic models shows that the statistics of extreme outbreaks depend on an infinite number of minimum-action paths, and that extreme outbreaks define a new class of rare processes for discrete-state stochastic systems.

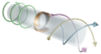
Jason Hindes, Michael Assaf, and Ira B. Schwartz
Phys. Rev. Lett. **128**, 078301 (2022)



Physics NEWS AND COMMENTARY

Illuminating Black Holes through Turbulent Heating
February 14, 2022
Predictions indicate that it should be possible to directly identify how turbulence heats a given black hole's plasma from the spectrum of that plasma's radiation.

Viewpoint on:
Joonas Nättilä and Andrei M. Beloborodov
Phys. Rev. Lett. **128**, 075101 (2022)

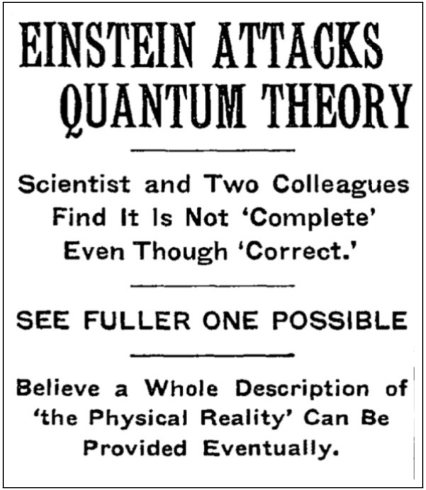


Physics NEWS AND COMMENTARY

Waves in a Solid Imitate Twisted Light
February 11, 2022
Waves of vibration moving through the walls of a pipe can carry orbital angular momentum that could be used for several purposes, according to new theoretical work.

Focus story on:
G. J. Chaplain, J. M. De Ponti, and R. V. Craster
Phys. Rev. Lett. **128**, 064301 (2022)

Some of the old problems are amongst the deepest. . .



EINSTEIN ATTACKS QUANTUM THEORY

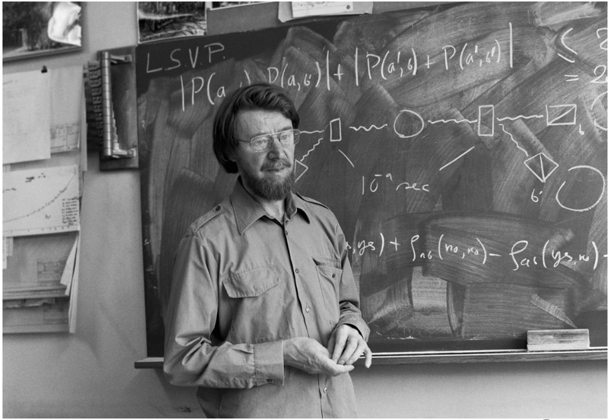
Scientist and Two Colleagues Find It Is Not 'Complete' Even Though 'Correct.'

SEE FULLER ONE POSSIBLE

Believe a Whole Description of 'the Physical Reality' Can Be Provided Eventually.

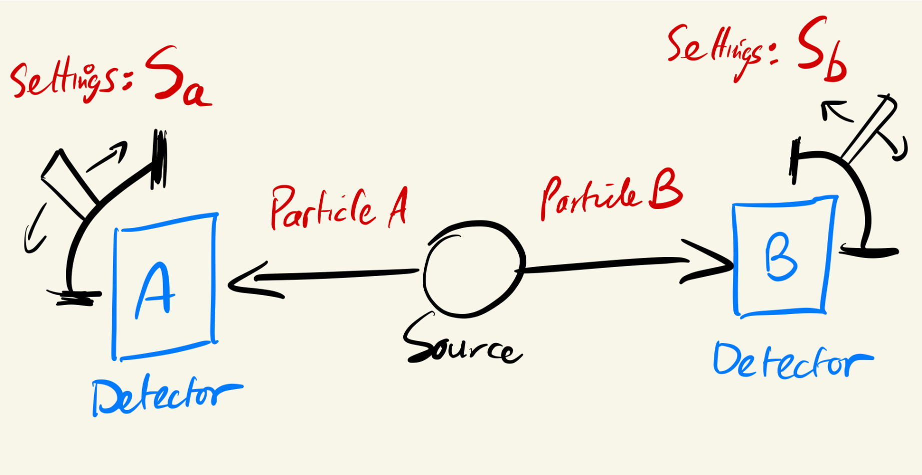
New York Times, May 4 **1935**, reporting on Einstein-Podolsky-Rosen paper,
"*Can Quantum-Mechanical Description of Physical Reality Be Considered Complete*"

. . . and they are experimentally accessible

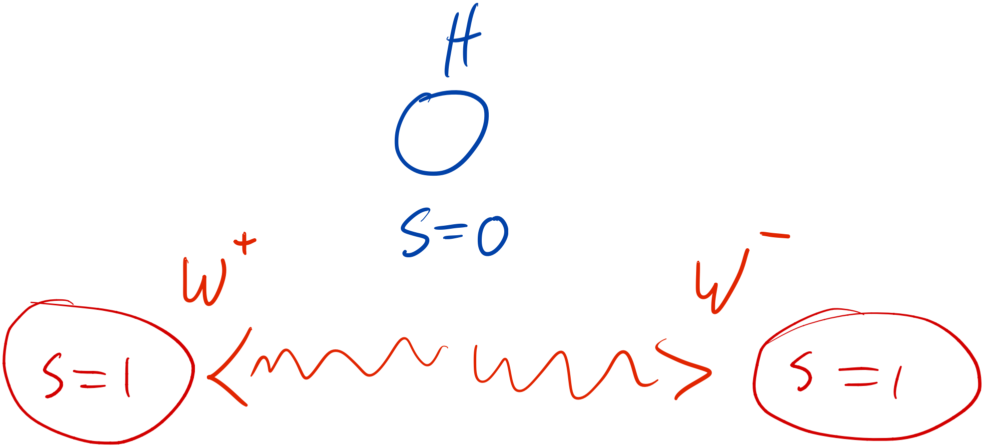


J.S. Bell *'On the Einstein Podolsky Rosen paradox'* (1964)

The textbook case – apparatus



(Ensemble of similarly-prepared systems)


H
S=0
W+
W−
S=1
S=1

Spin in the $H \to W^+W^-$ decay

The Higgs boson is a scalar, while $W^\pm$ bosons are vector bosons.

- $H \to W^+W^-$ decays produce pairs of W bosons in a singlet spin state
- In the narrow-width and non-relativistic approximations:

$$|\psi_s\rangle = \frac{1}{\sqrt{3}}\big(|+\rangle\,|-\rangle - |0\rangle\,|0\rangle + |-\rangle\,|+\rangle \big)$$

This is a Bell state of a pair of qutrits

W bosons are their own polarimeters

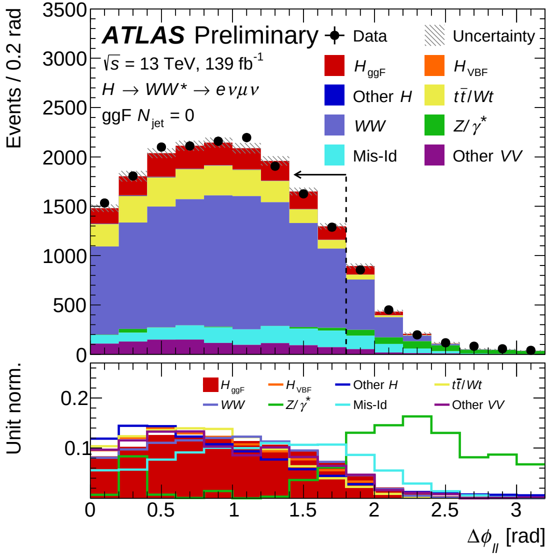
$V - A$ decays

SU(2) weak force is chiral

$$W^+ \rightarrow \ell_R^+ + \nu_L$$
$$W^- \rightarrow \ell_L^- + \bar{\nu}_R$$

Decay of a $W^\pm$ boson is equivalent to a measurement of its spin along the axis of the emitted lepton

$\ell^+\ell^-$ azimuthal correlations in $H \to W^+W^-$



- Higgs signal concentrated at small $\Delta\phi_{\ell\ell}$
- Used e.g. in discovery searches

Quantum tests?

The density matrix ρ

A fully-characterised quantum system is described by a ket $|\psi\rangle$

A more general, not-fully-characterised, quantum system is described by a **density matrix** ρ

$$\rho = \sum_i p_i \, |\psi\rangle_i \, \langle\psi|_i$$

each p_i is a classical probability

Entanglement

For some density matrix

$$\rho = \sum_i p_i \, |\psi_i\rangle \langle\psi_i|$$

p_i is a classical probability

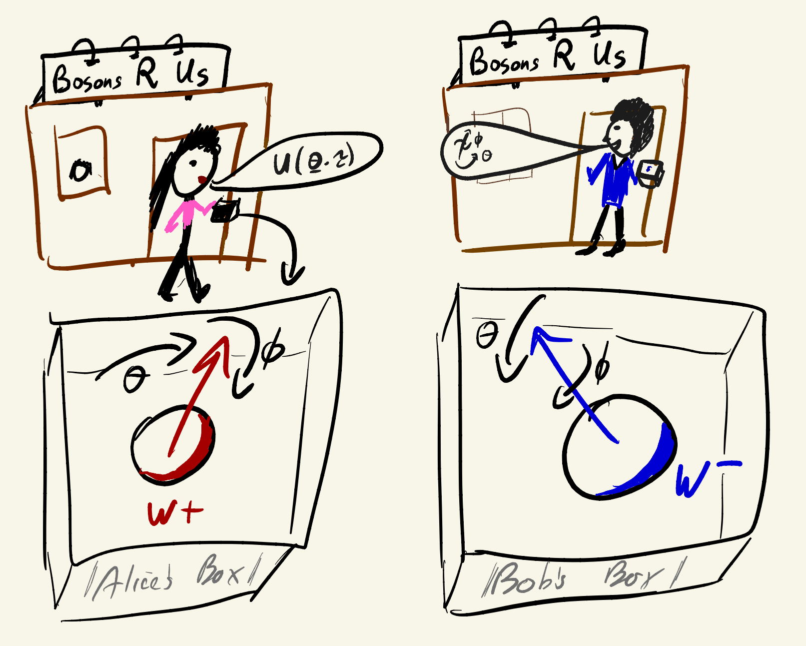
Q: Can we write:

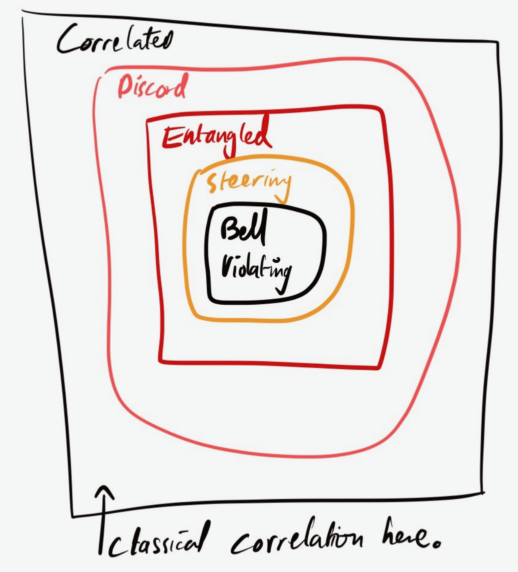
$$\rho \stackrel{?}{=} \sum_i p_i \; \rho_A \otimes \rho_B \qquad p_i \geq 0, \sum p_i = 1$$

i.e. as a convex sum of product states?

- Yes $\implies$ separable
- No $\implies$ entangled

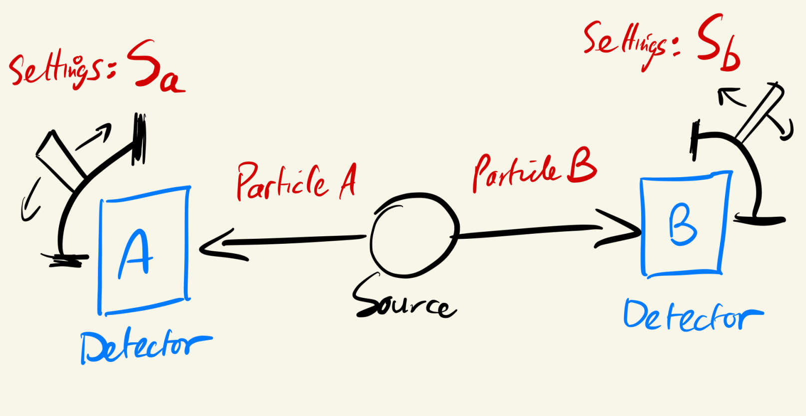
For general ρ (i.e. not pure states) this is a very different statement from just being correlated


Bosons R Us
U(θ,φ)
θ
φ
W+
Alice's Box
Bosons R Us
θ
φ
W−
Bob's Box



For steering, discord see e.g. Y. Afik, J. de Nova 2209.03969

Bell inequality tests



The local realism formalism

Assume that there is a well-defined correlation function for the pair of measurement outcomes:

$$P(S_A, S_B) \equiv \int \mathrm{d}\vec{\lambda} \;\; a(S_A, \vec{\lambda}) \;\; b(S_B, \vec{\lambda}) \;\; P(\vec{\lambda})$$

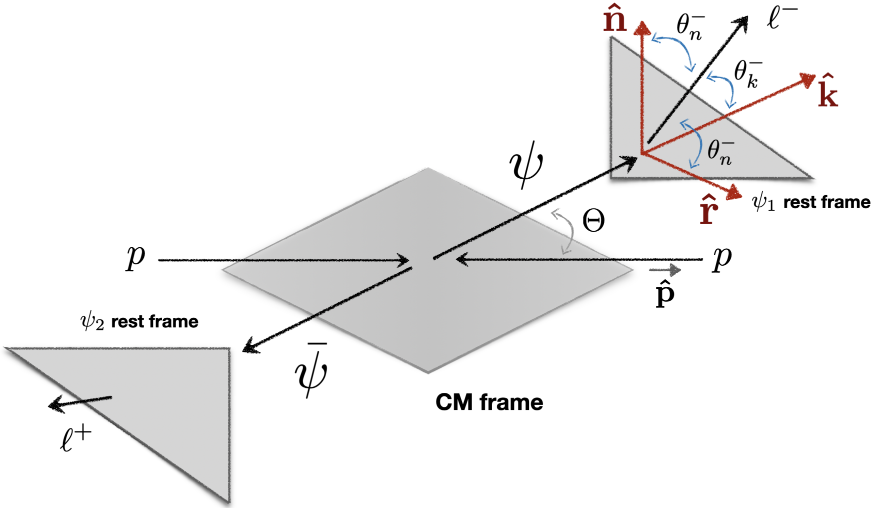
May depend on 'hidden' variables $\vec{\lambda}$ which have a PDF $P(\vec{\lambda})$

Assumptions

- $a(S_A, \vec{\lambda})$ does **not** depend on S_B
- $b(S_B, \vec{\lambda})$ does **not** depend on S_A
- $P(\vec{\lambda})$ does **not** depend on S_A nor on S_B

Demand that marginal probabilities for measurements of A and B are non-negative

Geometry



$\hat{\mathbf{n}}$
θ_n^-
ℓ^-
θ_k^-
$\hat{\mathbf{k}}$
ψ
θ_n^-
$\hat{\mathbf{r}}$
ψ_1 rest frame
Θ
p
p
$\hat{\mathbf{p}}$
ψ_2 rest frame
$\bar{\psi}$
ℓ^+
CM frame

Parameterise ρ – bipartite system

Symmetrically for qutrits in terms of the Gell-Mann matrices λ_i

Single vector boson

$$\rho = \frac{1}{3} I_3 + \sum_{i=1}^{8} a_i \lambda_i,$$

a_i : 8 real parameters $(3^2 - 1)$

Two vector bosons

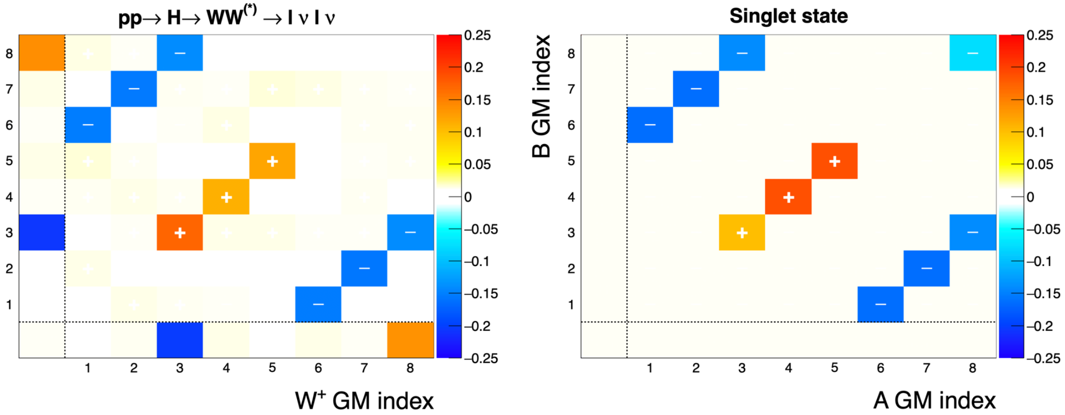
$$\rho = \frac{1}{9} I_3 \otimes I_3 + \sum_{i=1}^{8} a_i \lambda_i \otimes \frac{1}{3} I_3 + \sum_{j=1}^{8} b_j \frac{1}{3} I_3 \otimes \lambda_j + \sum_{i,j=1}^{8} c_{ij} \lambda_i \otimes \lambda_j,$$

$8+8+64 = 80$ real parameters $(9^2 - 1)$

Quantum State Tomography

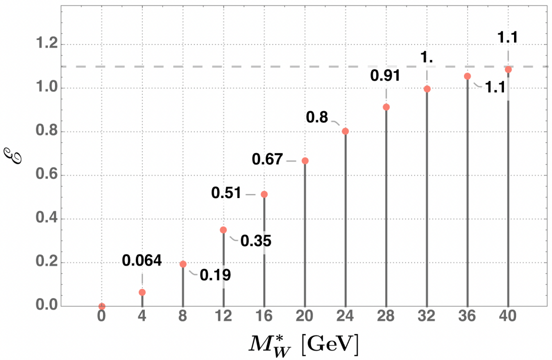
$H \to WW^*$ decays – qutrit pair

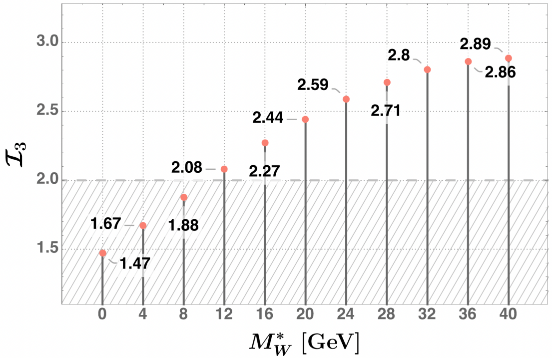
2209.13990



Density matrix parameters from simulated Higgs boson decays to vector bosons (Madgraph, no background)

$H \longrightarrow WW^*$



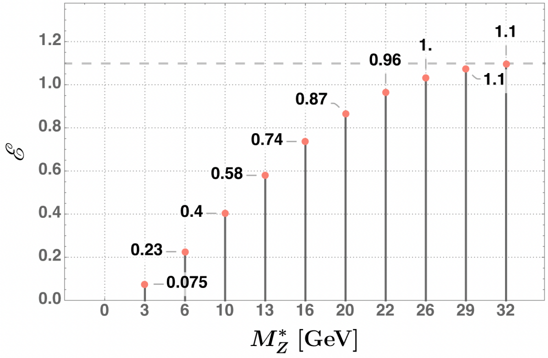


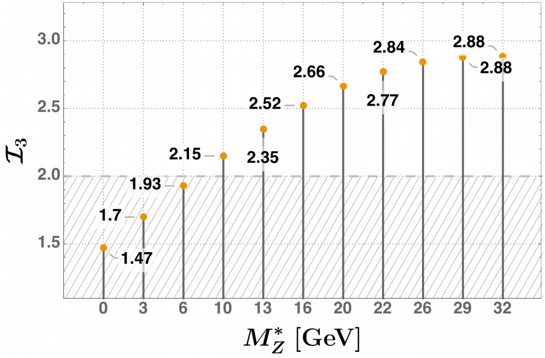
Entangled? Bell Violating?

> 0 > 2

Fabbrichesi et al. 2302.00683

H$\longrightarrow ZZ^*$





Entangled? Bell Violating?

> 0 > 2

Fabbrichesi et al. 2302.00683

Many systems of interest

Qubit systems

$\eta_c \to \Lambda + \bar{\Lambda}$

$pp \to t\bar{t}$

$e^+e^- \to \gamma^*/Z \to \tau^+\tau^-$

$h \to \tau^+\tau^-$

$h \to \gamma\gamma$

Qutrit systems

$B^0 \to J/\psi\, K^{*0}$

$B_s \to \phi\phi$

$pp \to WW\,/\,ZZ$

$h \to WW^*\,/\,ZZ^*$

Prospects at flavour factories, LHC, future e^+e^-, ...

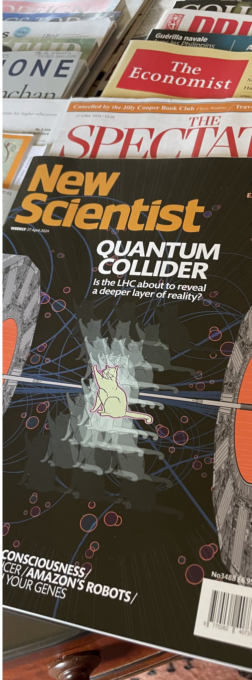
A broad new programme for collider physics

Testing the **foundations** of quantum theory (and beyond?)

- 12 orders of magnitude higher energy that existing tests (shorter time scale, shorter length scale. . .)
- In 'self-measuring' quantum system
- Deep in the realm of quantum field theory (virtual particles)
- in qubit and qutrit systems
- in bipartite and tripartite systems
- in systems with orbital angular momentum

[It's also a good way to find new fields]

Review: AJB, M.Fabbrichesi, R.Floreanini, E.Gabrielli, L.Marzola
2402.07972 Prog.Part.Nucl.Phys.



EXTRAS

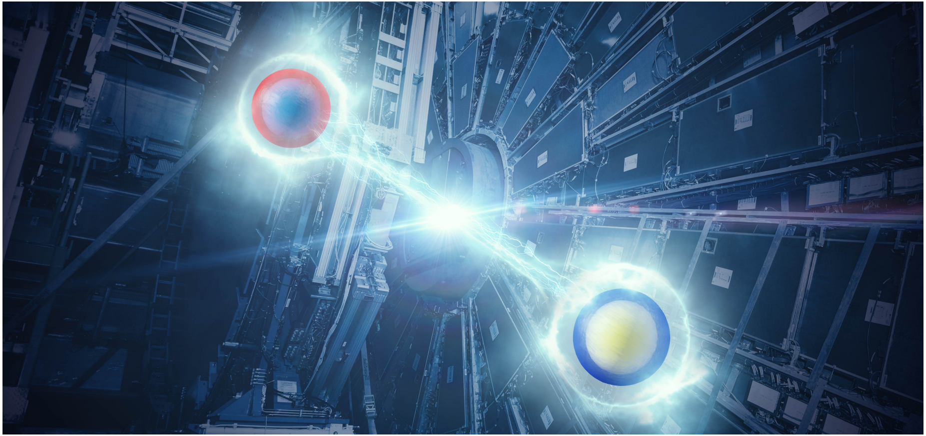


Image from ATLAS physics briefing

Parameterise ρ – bipartite system of qubits

in terms of the Pauli matrices σ_i

Single qubit

$$\rho = \frac{1}{2} I_2 + \sum_{i=1}^{3} a_i \sigma_i,$$

a_i : 3 real parameters $(2^2 - 1)$

Two qubits

$$\rho = \frac{1}{4} I_2 \otimes I_2 + \sum_{i=1}^{3} a_i\, \sigma_i \otimes \frac{1}{2} I_2 + \sum_{j=1}^{3} b_j\, \frac{1}{2} I_2 \otimes \sigma_j + \sum_{i,j=1}^{3} c_{ij}\, \sigma_i \otimes \sigma_j,$$

3+3+9 = 15 real parameters $(4^2 - 1)$

Measure the parameters $(a_i\ b_j, c_{ij})$ and test properties of bipartite ρ

Aside on pure states

Pure states are those for which ρ can be written:

$$\rho = |\psi\rangle\langle\psi|$$

These idealised states have very particular properties. Consider, for example:

$$|\psi\rangle = \alpha\,|\uparrow_A\rangle \otimes |\uparrow_B\rangle + \beta\,|\downarrow_A\rangle \otimes |\downarrow_B\rangle$$

This is both entangled and correlated for $(\alpha,\ \beta) \neq 0$

But for a general ρ correlated $\neq$ entangled

Alice and Bob can make states like

$$\rho_{\text{corr}} = \frac{1}{2}\Big(\rho_A(\uparrow) \otimes \rho_B(\uparrow) + \rho_A(\downarrow) \otimes \rho_B(\downarrow)\Big)$$

where

$$\rho_A(\uparrow) \equiv |\uparrow_A\rangle \langle\uparrow_A|$$

etc.

This is classically correlated, but not entangled
– it can be written as a sum of products (as it is above)

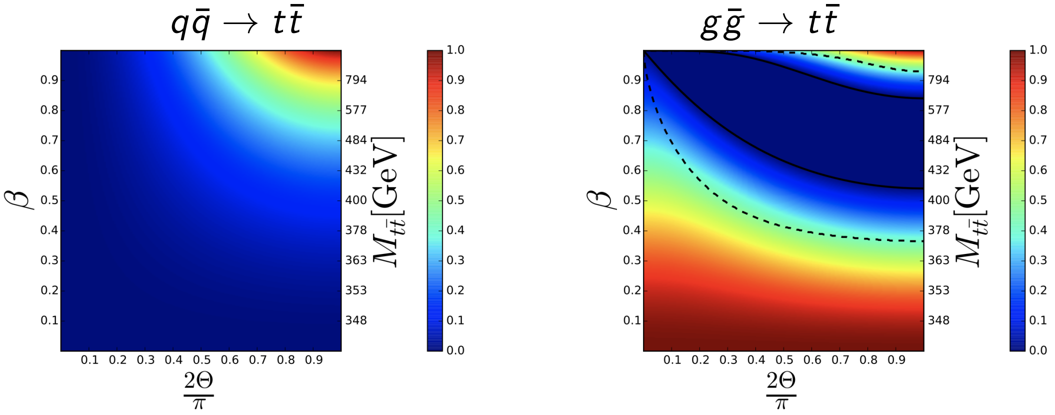
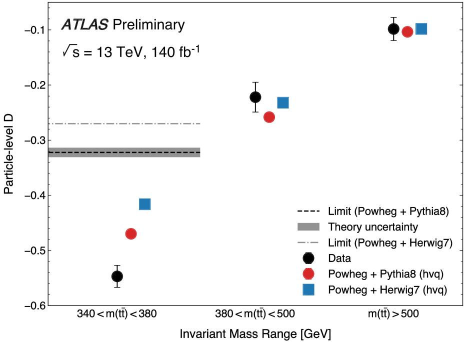


Figure 3: Concurrence of the spin density matrix $\rho^I(\beta, \hat{k})$ resulting from an initial state $I = q\bar{q}, gg$ as a function of the top velocity β and the production angle Θ in the $t\bar{t}$ c.m. frame. All plots are symmetric under the transformation $\Theta \to \pi - \Theta$. Left: $q\bar{q} \to t\bar{t}$. Right: $gg \to t\bar{t}$. Solid black lines represent the critical boundaries between separability and entanglement $\beta^{\mathrm{PH}}_{c1,c2}(\Theta)$, while dashed black lines represent the critical boundaries for the violation of the CHSH inequality, $\beta^{\mathrm{CH}}_{c1,c2}(\Theta)$.

Expect $t\bar{t}$ are entangled near threshold and at high p_T

ATLAS observation of quantum entanglement

- $t\bar{t}$ spin-qubit pair
- Decay before hadronisation
- Leptons measure top spin
- $D = -\,tr[C]/3$
- $\exists$ no separable states with $D < -\frac{1}{3}$

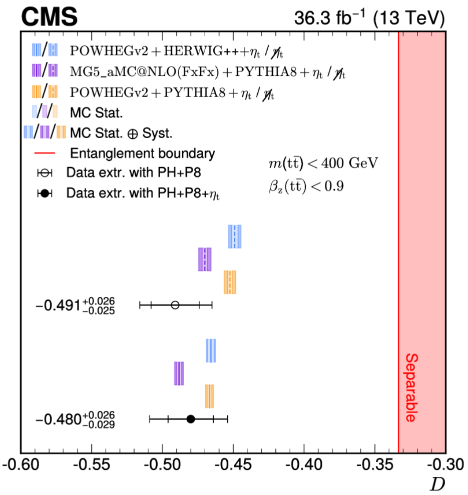


ATLAS result

$$D_{\rm obs} = -0.547 \pm 0.002\,[\rm stat.] \pm 0.021\,[\rm syst.] \qquad (> 5\sigma)$$

ATLAS: Briefing / ATLAS-CONF-2023-069 / 2311.07288

Recent CMS result

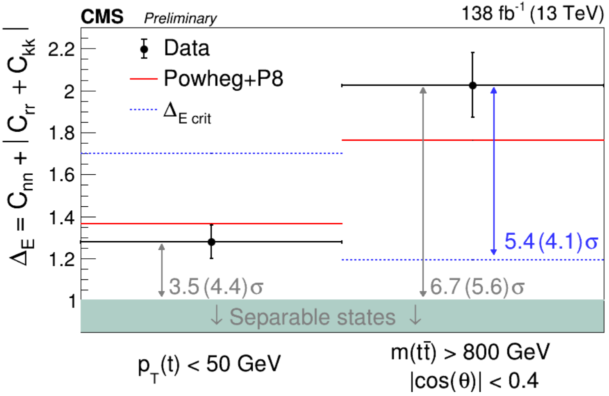


- Includes colour singlet toponium model
- $D = -0.478^{+0.025}_{-0.027}$
- 5.1 obs (4.7 exp) σ

CMS: Briefing / CMS-PAS-TOP-23-001 / 2406.03976

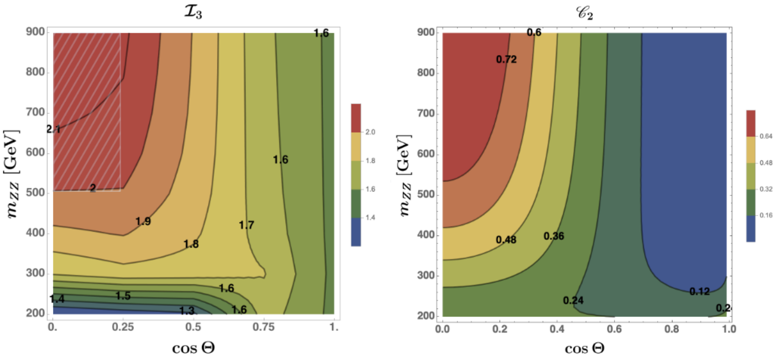
High-m_{tt} CMS result

- Semi-leptonic channel
- High invariant mass region
- Space-like separated decays dominate
- Δ_{Ecrit} corrected on statistical basis for time-like separated events



CMS: Briefing LHCP talk Link to the PAS

pp$\longrightarrow ZZ$

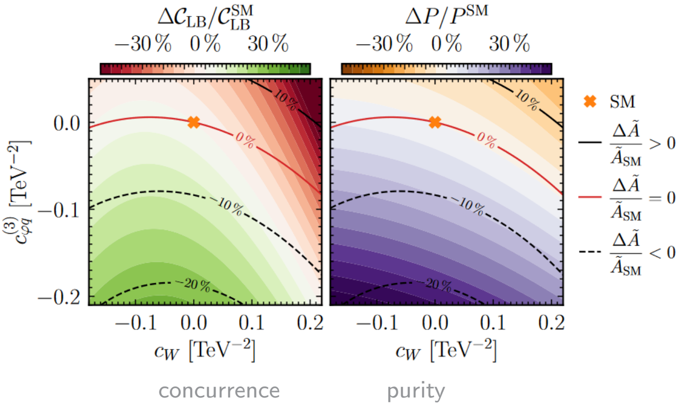


Optimised Bell Operator
$> 2?$

Bound on the concurrence
$> 0?$

Fabbrichesi et al. 2302.00683

Searching Beyond the Standard Model?



- Production of $W\pm/Z$ pairs at pp, e^+e^-
- Quantum spin observables complementary probes of Wilson coefficients/EFT
- Offer increased sensitivity to certain operators

Aoude, Madge, Maltoni, Mantani *Probing new physics through entanglement in diboson production* 2307.09675

The CGLMP Qutrit inequality

Collins Gisin Linden Massar Popescu (2002)

The optimal Bell inequality for pairs of **qutrits**

CGLMP function

$$\mathcal{I}_3 = P(A_1 = B_1) + P(B_1 = A_2 + 1) + P(A_2 = B_2) + P(B_2 = A_1) - P(A_1 = B_1 - 1) - P(B_1 = A_2) - P(A_2 = B_2 - 1) - P(B_2 = A_1 - 1).$$

$P(A_i = B_j + k)$ is the probability that A_i and B_j differ by k mod 3

CGLMP limits?

In a local realist theory

$$\mathcal{I}_3 \leq 2$$

In QM

$$\mathcal{I}_3^{\mathrm{QM}} \leq 1 + \sqrt{11/3} \approx 2.9149$$

In QM for a maximally entangled state

$$\mathcal{I}_3^{\mathrm{QM,singlet}} \leq 4/(6\sqrt{3} - 9) \approx 2.8729$$

Testing the CGLMP inequality

Knowing elements of ρ calculate

$$\mathcal{I}_3 = \mathrm{tr}(\rho\, \mathcal{B}^{xy}_{\mathrm{CGLMP}})$$

where the CGLMP operator is

$$\mathcal{B}^{xy}_{\mathrm{CGLMP}} = -\frac{2}{\sqrt{3}}\left(S_x \otimes S_x + S_y \otimes S_y\right) + \lambda_4 \otimes \lambda_4 + \lambda_5 \otimes \lambda_5$$

where

$$S_x = \frac{1}{\sqrt{2}}(\lambda_1 + \lambda_6) \quad \text{and} \quad S_y = \frac{1}{\sqrt{2}}(\lambda_2 + \lambda_7).$$