Not Testing ``Locality via Bell's Inequality" or``Entanglement" at Colliders

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Papers:

S.~A.~Abel, M.~Dittmar and HKD,
``Testing locality at colliders via Bell's inequality?,''
Phys. Lett. B \textbf{280} (1992), 304-312

S.~A.~Abel, HKD, R.~Sengupta and L.~Ubaldi,
``Colliders are Testing neither Locality via Bell's Inequality nor Entanglement versus Non-Entanglement,''
JHEP 08 (2026) 067, [arXiv:2507.15949 [hep-ph]].

P.~Bechtle, C.~Breuning, HKD, and C.~Duhr,
``A critical appraisal of tests of locality and of entanglement versus non-entanglement at colliders,''
[arXiv:2507.15947 [hep-ph]].

Outline

- Review Bell's 1964 paper - entangled spin-½ pair
- Consider (1992): $e^+e^- \to Z^0 \to \tau^+\tau^- \to (\pi^+\bar{\nu}_\tau)(\pi^-\nu_\tau)$
- 2025: consider other collider signatures
- top quark production, $t\bar{t}$, at the LHC, $t \longrightarrow b + \ell^+ + \nu_\ell$
- (Connection spin- and angular-correlations)
- Summary and Conclusion

Physics Vol. 1, No. 3, pp. 195–200, 1964 Physics Publishing Co. Printed in the United States

I completed my PhD there 25 years later

ON THE EINSTEIN PODOLSKY ROSEN PARADOX*

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(*Received* 4 *November* 1964)

My birthday

I. Introduction

THE paradox of Einstein, Podolsky and Rosen [1] was advanced as an argument that quantum mechanics could not be a complete theory but should be supplemented by additional variables. These additional variables were to restore to the theory causality and locality [2]. In this note that idea will be formulated mathematically and shown to be incompatible with the statistical predictions of quantum mechanics. It is the requirement of locality, or more precisely that the result of a measurement on one system be unaffected by operations on a distant system with which it has interacted in the past, that creates the essential difficulty. There have been attempts [3] to show that even without such a separability or locality requirement no "hidden variable" interpretation of quantum mechanics is possible. These attempts have been examined elsewhere [4] and found wanting. Moreover, a hidden variable interpretation of elementary quantum theory [5] has been explicitly constructed. That particular interpretation has indeed a grossly nonlocal structure. This is characteristic, according to the result to be proved here, of any such theory which reproduces exactly the quantum mechanical predictions.

II. Formulation

With the example advocated by Bohm and Aharonov [6], the EPR argument is the following. Consider a pair of spin one-half particles formed somehow in the singlet spin state and moving freely in opposite directions. Measurements can be made, say by Stern-Gerlach magnets, on selected components of the spins $\vec{\sigma}_1$ and $\vec{\sigma}_2$. If measurement of the component $\vec{\sigma}_1 \cdot \vec{a}$, where $\vec{a}$ is some unit vector, yields the value

What did Bell say?



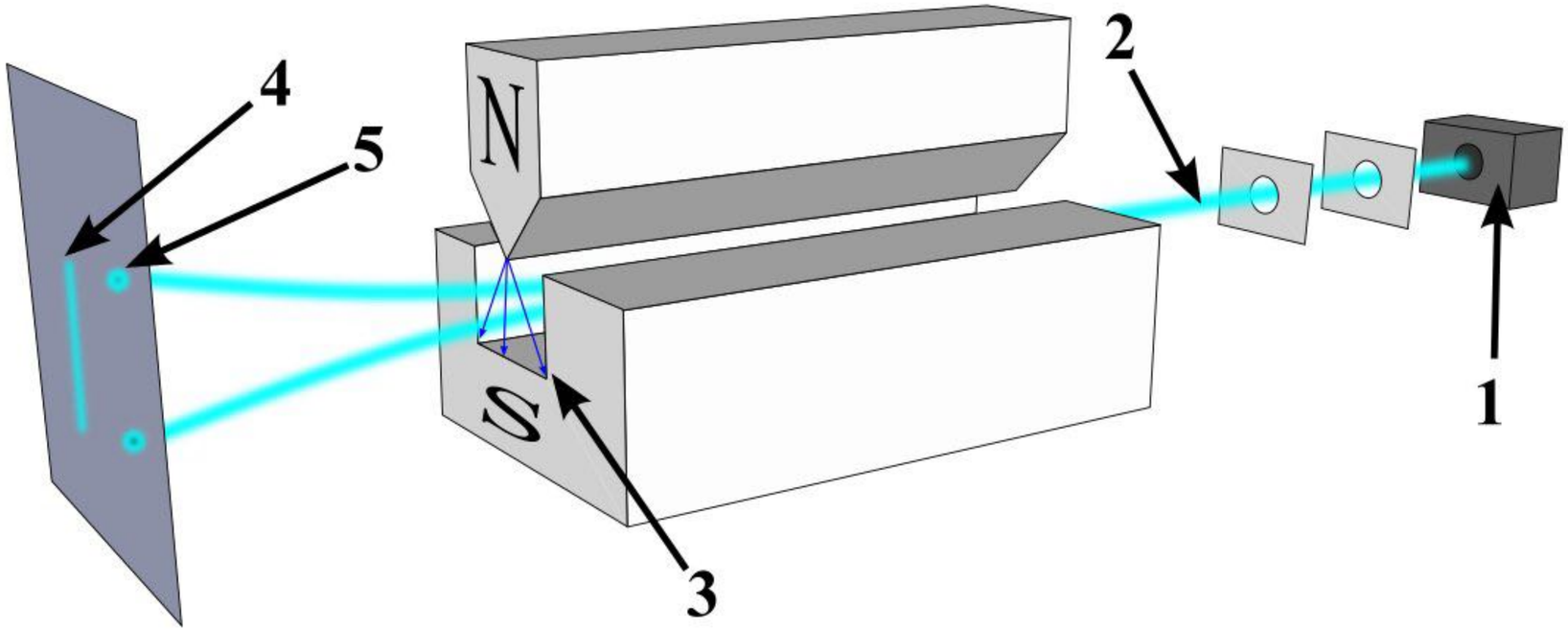
$$\mathrm{A}(\vec{a},\lambda) = \pm 1 \qquad \mathrm{B}(\vec{b},\lambda) = \pm 1$$

- Consider two spin-½ particles flying apart, spins anti-correlated

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

- QM measurement of component: $\vec{\sigma}_A \cdot \vec{a}, \quad \pm 1 \overset{\vec{b}=\vec{a}}{\Longrightarrow} \vec{\sigma}_B \cdot \vec{a}, \quad \mp 1$

Stern-Gerlach



But does not work for electrons!

By Tatoute - Own work, CC BY-SA 4.0, https://commons.wikimedia.org/w/index.php?curid=34095239

Note on History

- Spin singlet state: $$|\psi\rangle = \frac{1}{\sqrt{2}}(\,|\uparrow,\downarrow\rangle - |\downarrow,\uparrow\rangle)$$

- Sometimes denoted “Bell state”, why?

- Spin singlet state first considered in 1926 bei Heisenberg when discussing spectrum of Helium.

- Introduced by Bohm & Aharonov into locality discussion.

QM Expectation

$$|\vec{a}| = |\vec{b}| = 1$$

- QM expectation value: $\langle \vec{\sigma}_1 \cdot \vec{a} \;\; \vec{\sigma}_2 \cdot \vec{b} \rangle = -\vec{a} \cdot \vec{b} = -\cos\theta$

- States are **entangled** — information connected despite separation

- non-separable

- Specific state on the left is only determined AFTER measurement on the right and vice versa.

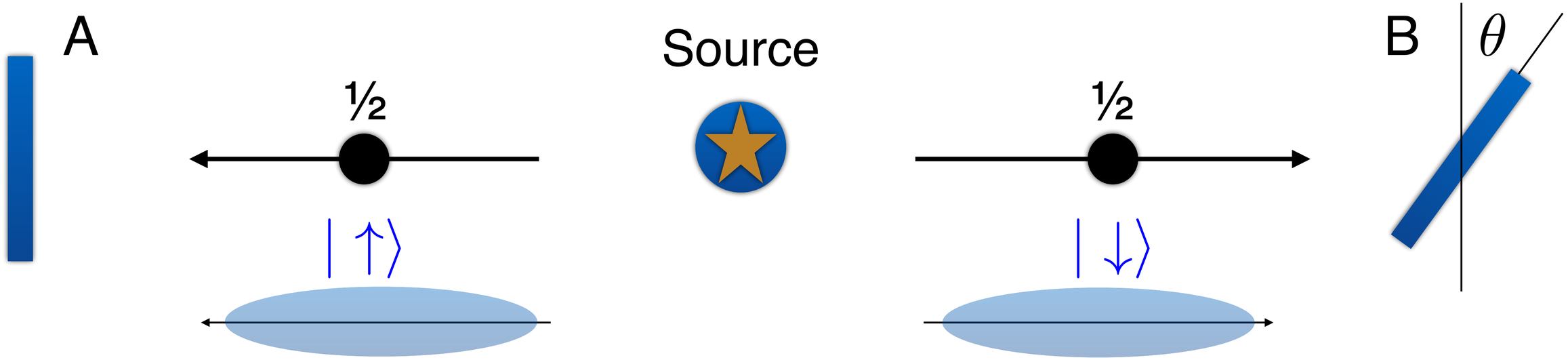
What was Bell interested in?



$$\mathrm{A}(\vec{a},\lambda) = \pm 1$$

$$\mathrm{B}(\vec{b},\lambda) = \pm 1$$

- Can this be described by a local hidden variable theory (LHVT)?
- What is an LHVT? - “Common sense” (once emitted, particles are independent, **separable**)
- Measurements at A and B are independent of each other



- Emitted at source with **definite** spin, just spins are anti-correlated
  (angular mom. conserv.)
- If results are independent: a person or a machine can sit at source and toss out the pairs
- Definite results are achieved through additional, unknown, hidden variables

$\lambda_i \to \lambda,$ $\rho(\lambda)$ prob. dist.

- Local Hidden Variable Theory (LHVT) expectation value:

$$P(\vec{a},\vec{b}) = \int d\lambda\, \rho(\lambda)\, A(\vec{a},\lambda) B(\vec{b},\lambda)$$

prob. dist.

$$\int \rho(\lambda) d\lambda = 1$$

- Local Hidden Variable Theory (LHVT) expectation value:

$$P(\vec{a},\vec{b}) = \int d\lambda\, \rho(\lambda)\, A(\vec{a},\lambda) B(\vec{b},\lambda)$$

factorized, i.e. separable,
"not entangled"

$$\int \rho(\lambda) d\lambda = 1$$

Hidden Variable Theory of Spin (Bell 1964)

- No problem for LHVT to reproduce several special cases

1) Spin measurement on a single particle $\vec{\sigma} \cdot \vec{a} \longrightarrow \mathrm{sign}(\vec{\lambda} \cdot \vec{a}')$

2) Using this in $P(\vec{a}, \vec{b})$ can easily reproduce simple cases

$$P(\vec{a}, \vec{a}) = -P(\vec{a}, -\vec{a}) = -1$$

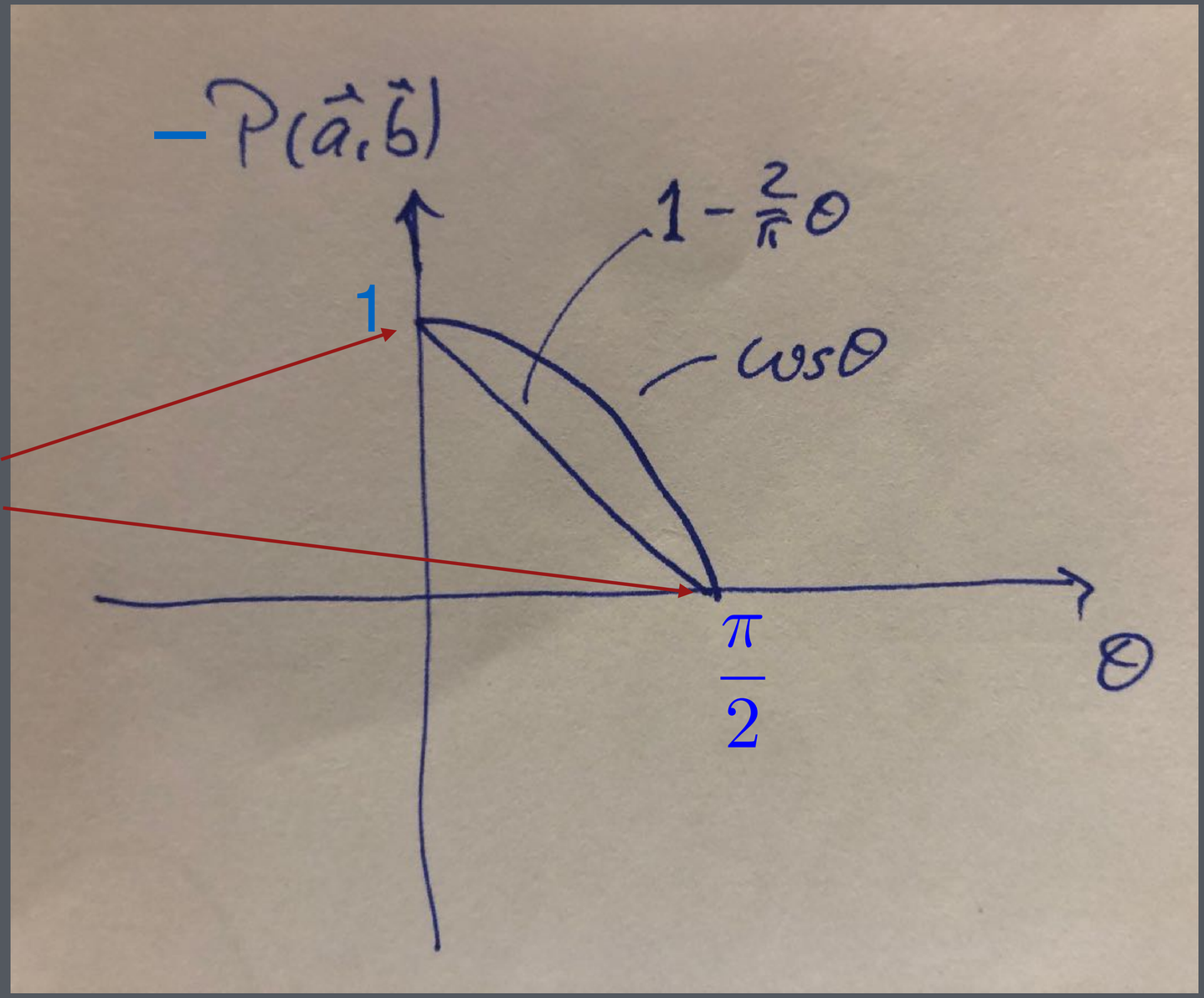
$$P(\vec{a}, \vec{b}) = 0, \quad \text{if} \quad \vec{a} \cdot \vec{b} = 0$$

3) The most general case results in

linear function

$$P(\vec{a}, \vec{b}) = -1 + \frac{2}{\pi}\theta\,, \qquad \vec{a} \cdot \vec{b} = \cos\theta$$

LHVT agrees with QM here by construction



- You need 3 measurements to distinguish the 2 curves

Bell's Inequality

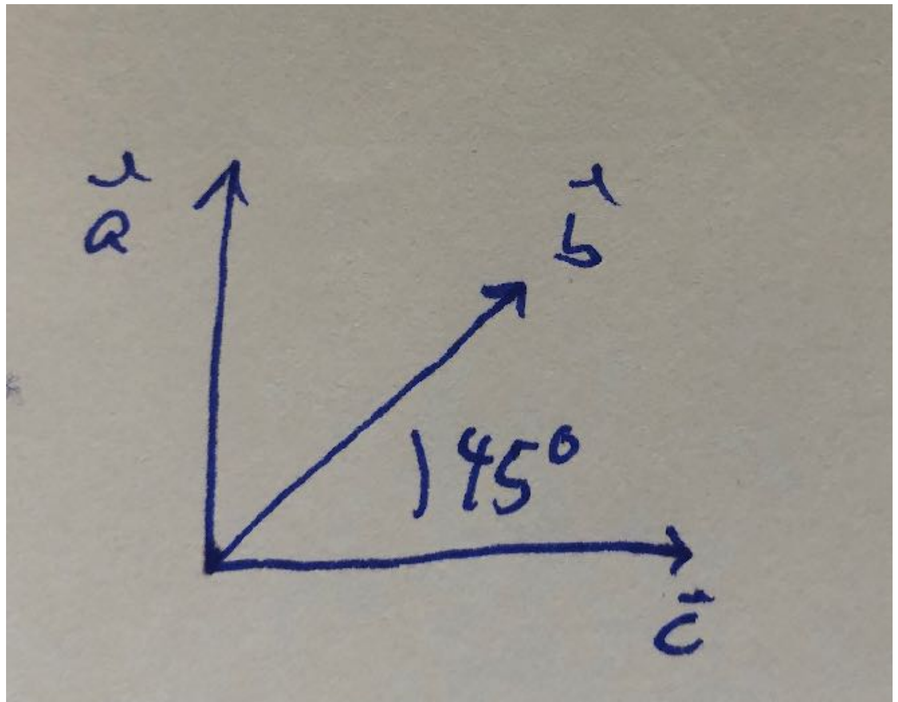
- Bell proved for all LHVT's

$$1 + P(\vec{b}, \vec{c}) \geq |P(\vec{a}, \vec{b}) - P(\vec{a}, \vec{c})|$$

- Note you need 3 settings

- QM expectation value violates this!

$$1 - \frac{1}{\sqrt{2}} \geq \frac{1}{\sqrt{2}}$$



Bell's Inequality: experiments

- All successful experimental tests of locality via Bell's inequality are with low-energy photons.

- Measure 3 settings related to 2 independent spin components using polarimeters (Alain Aspect et al)

$$S_x, \quad S_y, \qquad\qquad [S_x, S_y] = i\hbar S_Z$$

- Would like to test this idea also at high energy and/or with fermions

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North-Holland

PHYSICS LETTERS B

Testing locality at colliders via Bell's inequality?

Oxford

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(1992)

Spin-correlations

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We consider a measurement of correlated spins at LEP and show that it does *not* constitute a *general* test of local-realistic theories via Bell's inequality. The central point of the argument is that such tests, where the spins of two particles are inferred from a scattering distribution, can be described by a local hidden variable theory. We conclude that with present experimental techniques it is not possible to test locality via Bell's inequality at a collider experiment. Finally we suggest an improved fixed-target experiment as a viable test of Bell's inequality.

PHYSICAL REVIEW D VOLUME 55, NUMBER 1 1 JANUARY 1997

How to find a Higgs boson with a mass between 155 and 180 GeV at the CERN LHC

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(1996)

(Received 13 August 1996)

$$H \to W^+W^- \to (\ell^+\nu_\ell)(\ell'^-\bar{\nu}_{\ell'})$$

We reconsider the signature of events with two charged leptons and missing energy as a signal for the detection of the standard model Higgs boson in the mass region $M(\text{Higgs})=155$–180 GeV. It is shown that a few simple experimental criteria allow us to distinguish events originating from the Higgs boson decaying to $H\to W^+W^-$ from the nonresonant production of W^+W^-X at the CERN LHC. With this set of cuts, signal to background ratios of about one to one are obtained, allowing a 5–10σ detection with about 5 fb^{-1} of luminosity. This corresponds to less than one year of running at the initial lower luminosity $\mathcal{L}=10^{33}$ cm^{-2}s^{-1}. This is significantly better than for the hitherto considered Higgs boson detection mode $H\to Z^0Z^{0*}\to 2\ell^+2\ell^-$, where in this mass range about 100 fb^{-1} of integrated luminosity are required for a 5σ signal. [S0556-2821(97)02701-X]

Abel, Dittmar, HKD (1992)

- Our idea: at LEP use the decay

$$Z^0 \longrightarrow \tau^+ + \tau^- \longrightarrow (\pi^+ + \bar{\nu}_\tau) + (\pi^- + \nu_\tau)$$

tau-spins are correlated

self-analyzing weak decay of tau, pion momentum correlated with tau spin

- Consider: $P(\hat{p}_{\pi^-}, \hat{p}_{\pi^+})$; $\hat{p}_{\pi^\pm}$ unit $\pi^\pm$ momenta in $\tau^\pm$ rest frame

- Compute in SM:

$$\frac{d\sigma}{d\cos\theta_{\pi\pi}}(e^+e^- \to \pi^+\pi^-\nu_\tau\bar{\nu}_\tau) = A(1 - \frac{1}{3}\cos\theta_{\pi\pi})$$

$$P_{\rm QM}(\cos\theta_{\pi\pi}) = \frac{d\sigma/d\cos\theta_{\pi\pi}(e^+e^- \to \pi^+\pi^-\nu_\tau\bar{\nu}_\tau)}{\sigma(e^+e^- \to \pi^+\pi^-\nu_\tau\bar{\nu}_\tau)}$$

$$= \frac{1}{2}(1 - \frac{1}{3}\cos\theta_{\pi\pi})$$

- Insert into Bell's inequality: satisfies it for all angles!!!

- Actually should use CHSH inequality (Clauser, Horne, Shimony, Holt)

CHSH Inequality (1969)

- More general inequality. Requires 4 settings. Also valid for more general spin states.

$$|P(\vec{a},\vec{b}) - P(\vec{a},\vec{b}') + P(\vec{a}',\vec{b}) + P(\vec{a}',\vec{b})| \leq 2$$

- Always also always satisfied for our reaction for all angles

$$Z^0 \longrightarrow \tau^+ + \tau^- \longrightarrow (\pi^+ + \bar{\nu}_\tau) + (\pi^- + \nu_\tau)$$

Recall the Logic

- All LHVT's satisfy Bell's inequality or CHSH. Mathematical theorem.

LHVT —> Bell's inequality satisfied

- QM **can** or **can not** satisfy Bell's inequality

- The art is to find a setup where QM violates Bell's inequality

¬(Bell's inequality) —> ¬(LHVT)

Why does it fail as a test of locality, despite correlated spins?

- In decay $\tau^- \to \pi^- + \nu_\tau$ only measure τ-helicity

(not surprising, as just measuring commuting operator)

- This is just one component of spin: $(\vec{S}_\tau)_z$

$$P(S_z^+ = \uparrow, S_z^- = \uparrow) \quad \text{parallel}$$

$$P(S_z^+ = \uparrow, S_z^- = \downarrow) \quad \text{anti-parallel}$$

- According to Bell's analysis can maybe reproduce experiment with LHVT.

- This is in fact the case!

Kasday (1971)

- Consider

SM diff. X-Section

$$\frac{d\sigma}{d\Omega_+ d\Omega_-}(e^+e^- \to \tau^+\tau^- \to \pi^+\nu_\tau\pi^-\bar{\nu}_\tau) = f(\hat{p}_{\pi+}, \hat{p}_{\pi-})$$

- Now let the hidden variables for each τ be a set of unit vectors

$$\{\hat{\lambda}_e,\ \hat{\lambda}_\mu,\ \hat{\lambda}_\pi,\ \hat{\lambda}_\rho,\ ...\}$$

- If tau decays as $\tau^- \to \pi^- + \nu_\tau$ then $\hat{\lambda}_\pi$ tells it to decay such that

$$\hat{p}_\pi = \hat{\lambda}_\pi$$

- Let $F(\hat{\lambda}_{\pi+}, \hat{\lambda}_{\pi-})$ be original prob. distribution of hidden variables for decay to pions

- Identify $F(\hat{\lambda}_{\pi+}, \hat{\lambda}_{\pi-}) \stackrel{!}{=} f(\hat{\lambda}_{\pi+}, \hat{\lambda}_{\pi-})$ $\left(= \dfrac{d\sigma}{d\Omega_+ d\Omega_-}\right)$

- Have an LHVT which **exactly** reproduces **all** experimental results.

- Essential that $[(\hat{p}_{\pi+})_i, (\hat{p}_{\pi-})_j] = 0$

  $[(\hat{p}_{\pi\pm})_i, (\hat{p}_{\pi\pm})_j] = 0$ $\quad \forall i, j$

- Only then does QM provide the function $f(\hat{\lambda}_{\pi+}, \hat{\lambda}_{\pi-})$

- For non-commuting spins (2 photon case), QM does **not** provide function

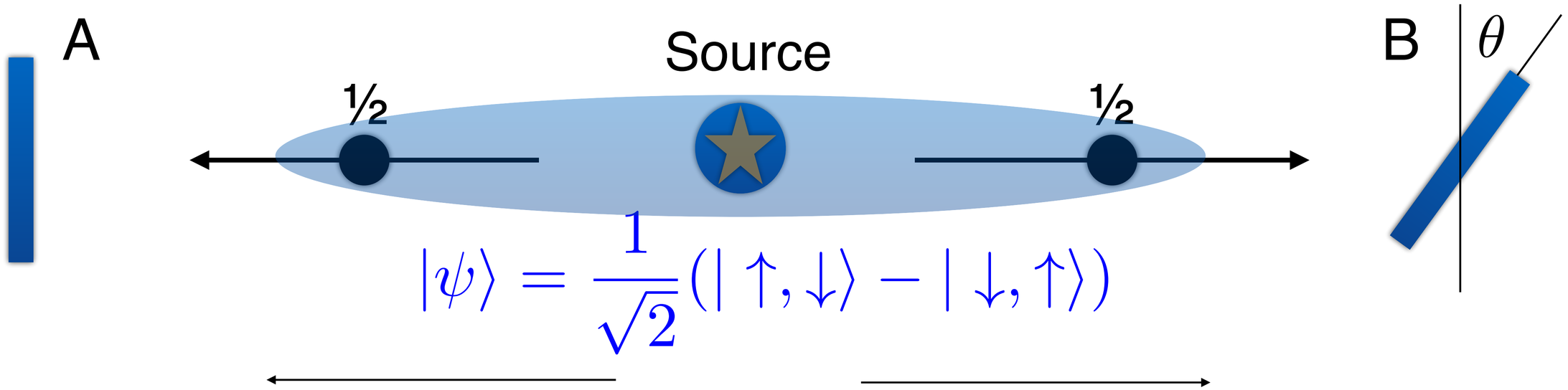
$$\cancel{f(S_x^i, S_y^i, \ldots)}$$

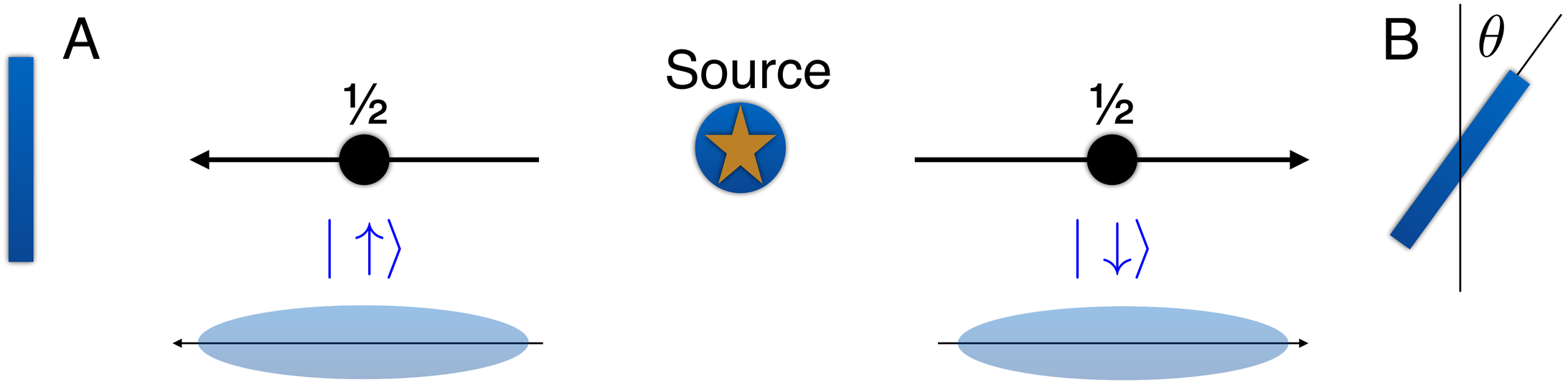
Main Statement — Theorem

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.

A Word on Logic: entanglement/non-separability vs local realism





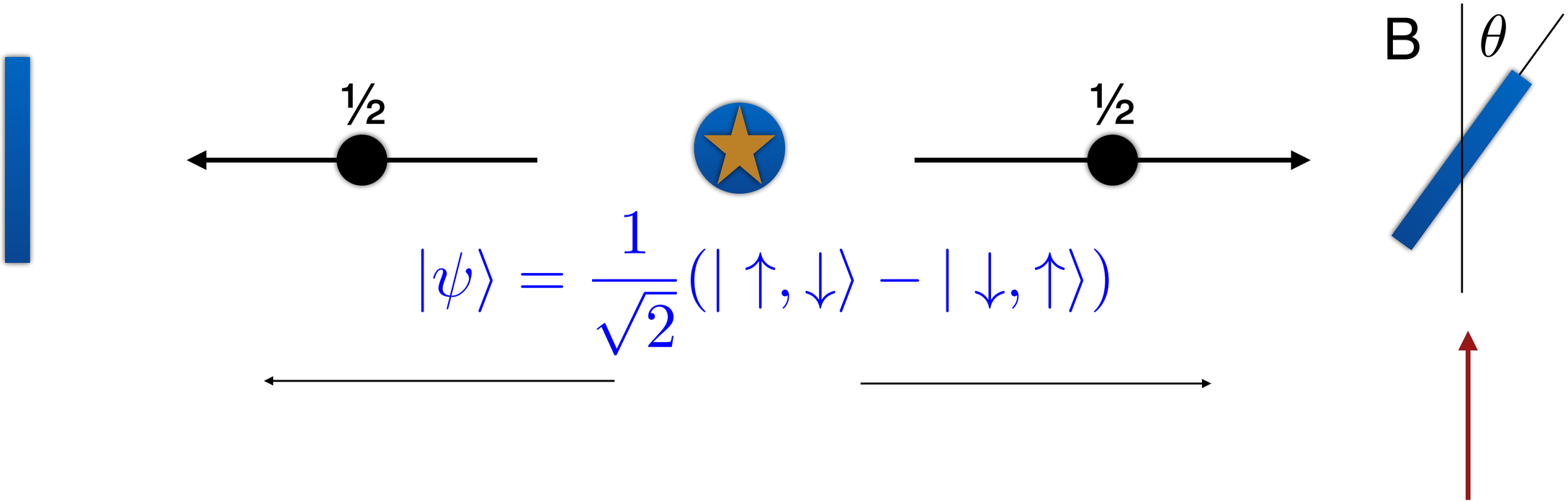
- Can describe the data exactly with an LHVT, i.e. with a **separable** state! I call this **non-entangled.**

- Thus have simply chosen a poor set-up to test locality.

- So: NOT testing locality, at all!

- Also NOT testing entangled (non-separable), versus non-entangled as you can describe the data with a separable (non-entangled) function.

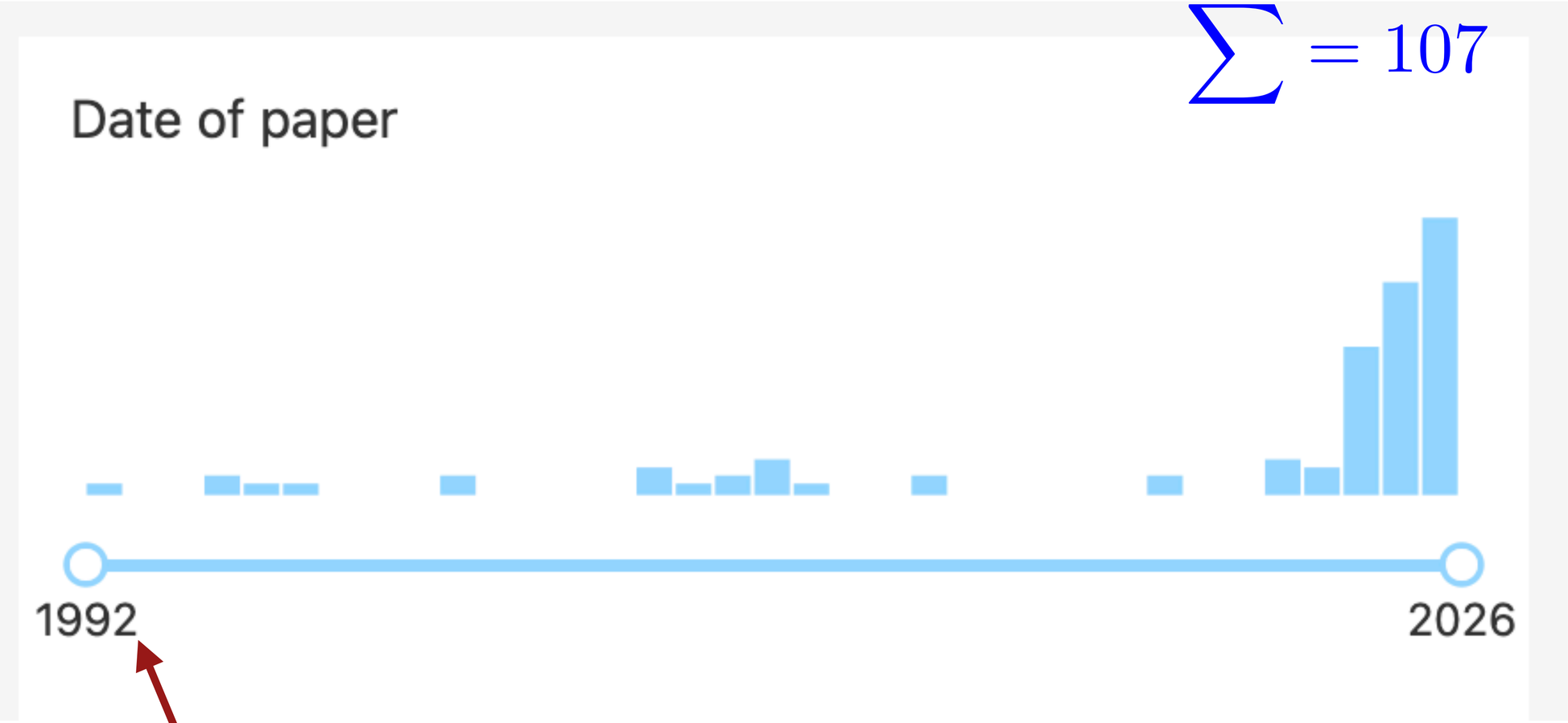
Freedom of Choice



Collapse of wave function by choosing θ and performing **measurement**

- At a collider never have this possibility.

1992 —> Recent Developments



our paper came out

Examples at the LHC from the Recent Literature (ADRS-25)

$$gg \to H^0 \to W^+W^- , \quad W^+ \to \ell^+ + \nu_\ell$$

$$gg \to H^0 \to Z^0 Z^0 , \qquad Z^0 \to \ell^+ + \ell^-$$

$$gg,\, q\bar{q} \to t\bar{t} , \qquad t \to W^+ + b \to (\ell^+ + \nu_\ell) + b$$

$$gg,\, q\bar{q} \to \tau^+\tau^- , \quad \tau^\pm \to \pi^\pm + \nu_\tau$$

- In all cases measure final state momenta, i.e. can write an LHVT reproducing the data using the SM diff. X-section.
- Considered several cases numerically. All satisfy Bell or CHSH.

No Tests of Locality via Bell's Inequality at the LHC

- It should be clear, given all these examples that it is NOT possible to test locality via Bell's or the CHSH inequality at colliders.

- With commuting observables, always have an LHVT which completely reproduces the data. Kasday construction - 1971.

- Numerous papers in the last 5 years claiming the opposite.

Testing Bell Inequalities at the LHC with Top-Quark Pairs

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Correlations between the spins of top-quark pairs produced at a collider can be used to probe quantum entanglement at energies never explored so far. We show how the measurement of a single observable can provide a test of the violation of a Bell inequality at the 98% C.L. with the statistical uncertainty of the data already collected at the Large Hadron Collider, and at the 99.99% C.L. with the higher luminosity of the next run. Detector acceptance, efficiency, and migration effects are taken into account. The test relies on the spin correlations alone and does not require the determination of probabilities—in contrast to all other tests of Bell inequalities.

DOI: 10.1103/PhysRevLett.127.161801

Introduction.—A characteristic property of a quantum system is the presence of quantum correlations (entanglement) among its constituents not accounted for by classical physics (for a review, see [1]), leading to the violation of specific constraints, the so-called Bell inequalities [2,3]. The violation of Bell inequalities requires the presence of the strongest version of quantum nonlocality; although neutrino oscillations [19]. No test has so far been performed at the high energies made available by the LHC—even though some preliminary work has been done in [5,6] and more recently in [20]. In particular, we build on the results of [20] in which the entanglement of the top-quark pairs and the kinematical regions where it could be maximal were identified and explicitly discussed.

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THE EUROPEAN PHYSICAL JOURNAL C

Regular Article - Theoretical Physics

Quantum tops at the LHC: from entanglement to Bell inequalities

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Abstract We present the prospects of detecting quantum entanglement and the violation of Bell inequalities in $t\bar{t}$ events at the LHC. We introduce a unique set of observables suitable for both measurements, and then perform the

ter of experiment. In 1964, Bell proved [1] classical theories obey correlation limits, i.e., Bell Inequalities (BIs), that QM can violate. In the last decades, several experiments have been performed and all results so far agree with QM predic-

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THE EUROPEAN PHYSICAL JOURNAL C

Regular Article - Theoretical Physics

Improved tests of entanglement and Bell inequalities with LHC tops

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Abstract We discuss quantum entanglement in top pair production at the LHC. Near the $t\bar{t}$ threshold, entanglement observables are enhanced by suppressing the contribution of $q\bar{q}$ subprocesses, which is achieved by a simple cut on the velocity of the $t\bar{t}$ system in the laboratory frame. Furthermore, we design new observables that directly measure the relevant combinations of $t\bar{t}$ spin correlation coefficients involved in the measurement of entanglement and Bell inequalities. As a result, the statistical sensitivity is enhanced, up to a factor of 7 for Bell inequalities near threshold.

the qubits associated to the spin states of $t\bar{t}$ pairs produced at the LHC provide a suitable arena to investigate these matters since top quarks decay before their spins are randomised by strong radiation and the spin of the lepton produced in semileptonic decays $t \to \ell\nu b$ ($\ell = e, \mu$) is completely correlated to that of the mother top. Besides, owing to the large cross section, $\sigma = 832$ pb at 13 TeV [11] there is a good amount of statistics on $t\bar{t}$ production already at Run 2 with 139 fb^{-1} of collected data, and there will be much more in the future at its high luminosity upgrade (HL-LHC). In Refs. [6–10] certain sufficient conditions for entanglement and CHSH

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Quantum entanglement and Bell inequality violation in semi-leptonic top decays

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Abstract: Quantum entanglement is a fundamental property of quantum mechanics. Recently, studies have explored entanglement in the $t\bar{t}$ system at the Large Hadron Collider (LHC) when both the top quark and anti-top quark decay leptonically. Entanglement is detected via correlations between the polarizations of the top and anti-top and these polarizations are measured through the angles of the decay products of the top and anti-top. In this work, we propose searching for evidence of quantum entanglement in the semi-leptonic decay channel where the final state includes one lepton, one neutrino, two b-flavor tagged jets, and two light jets from the W decay. We find that this channel is both easier to reconstruct and has a larger effective quantity of data than the fully leptonic channel. As a result, the semi-leptonic channel is 60% more sensitive to quantum entanglement and a factor of 3 more sensitive to Bell inequality violation, compared to the leptonic channel. In 139 fb^{-1} (3 ab^{-1}) of data at the LHC (HL-LHC), it should be feasible to measure entanglement at a precision of $\lesssim 3\%$ (0.7%). Detecting Bell inequality violation, on the other hand, is more challenging. With 300 fb^{-1} (3 ab^{-1}) of integrated luminosity at the LHC Run-3 (HL-LHC),

JHEP07(2024)192

Optimizing entanglement and Bell inequality violation in top antitop events

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A top quark and an antitop quark produced together at colliders have correlated spins. These spins constitute a quantum state that can exhibit entanglement and violate Bell's inequality. In realistic collider experiments, most analyses allow the axes, as well the Lorentz frame, to vary event by event, thus introducing a dependence on the choice of event-dependent basis leading us to adopt "fictitious states," rather than genuine quantum states. The basis dependence of fictitious states allows for an optimization procedure, which makes the usage of fictitious states advantageous in measuring entanglement and Bell inequality violation. In this work, we show analytically that the basis that diagonalizes the spin-spin correlations is optimal for maximizing spin correlations, entanglement, and Bell inequality violation. We show that the optimal basis is approximately the same as the fixed beam basis (or the rotated beam basis) near the $t\bar{t}$ production threshold, while it approaches the helicity basis far above threshold. Using this basis, we present the sensitivity for entanglement and Bell inequality violation in $t\bar{t}$ events at the Large Hadron Collider (LHC) and a future e^+e^- collider. Since observing Bell inequality violation appears to be quite challenging experimentally, and requires a large dataset in collider experiments, choosing the optimal basis is crucially important to observe Bell inequality violation. Our method and general approach are equally applicable to other systems beyond $t\bar{t}$, including interactions beyond the Standard Model.

DOI: 10.1103/PhysRevD.111.033004

Letter

Entanglement and Bell nonlocality with bottom-quark pairs at hadron colliders

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It has been shown that entanglement and Bell nonlocality, which are key concepts in quantum mechanics, can be probed in high-energy colliders via processes of fundamental particle scattering. In fact, the ATLAS and CMS Collaborations have measured entanglement using top-quark pairs produced in proton-proton collisions at the LHC. Recently, it was shown that spin correlations can be measured in pairs of bottom quarks at the LHC, despite the fact that bottom quarks, unlike top quarks, hadronize before decaying. Here, we demonstrate that quantum correlations can also be studied using bottom-quark pairs, and analyze the feasibility of the observation of entanglement and Bell nonlocality in several collider experiments. Given the low mass of the bottom quark relative to typical energies accessible at the LHC, many of the bottom-quark pairs are in the ultrarelativistic regime, where they can exhibit strong spin entanglement. We find that entanglement of bottom-quark pairs may be measurable even with the LHC Run 2 data, especially with the CMS *B* parking dataset, while observation of Bell nonlocality may become feasible at the high-luminosity phase of the LHC.

DOI: 10.1103/fhkc-kfhr

Unfolding quantum entanglement from $h \to ZZ^* \to jj\ell\ell$ at a muon collider

Dec. 2025

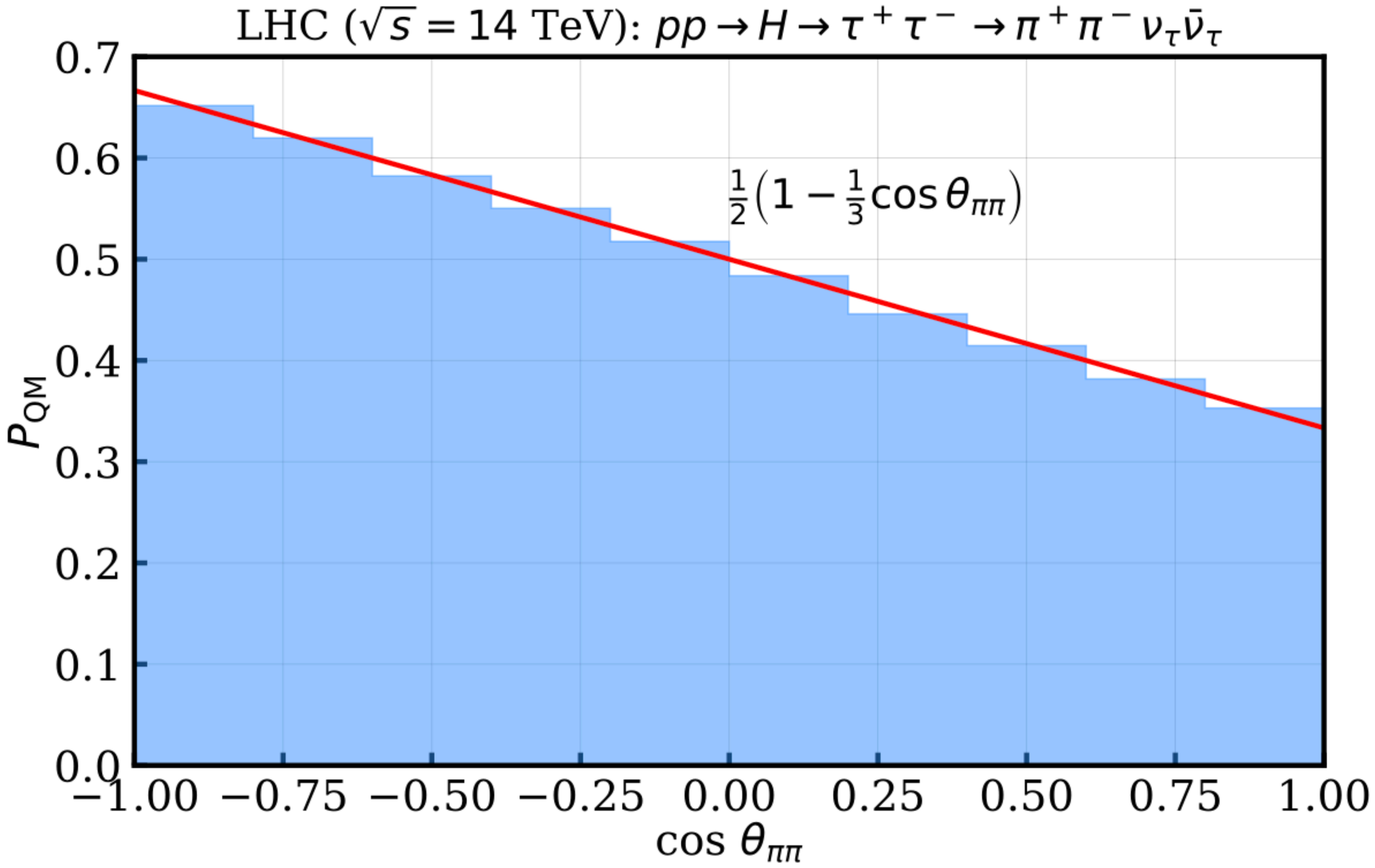
arXiv:2512.09121v1 [hep-ph] 9 Dec 2025

Songshaptak De [a] **Atri Dey** [b] **Tousik Samui** [c]

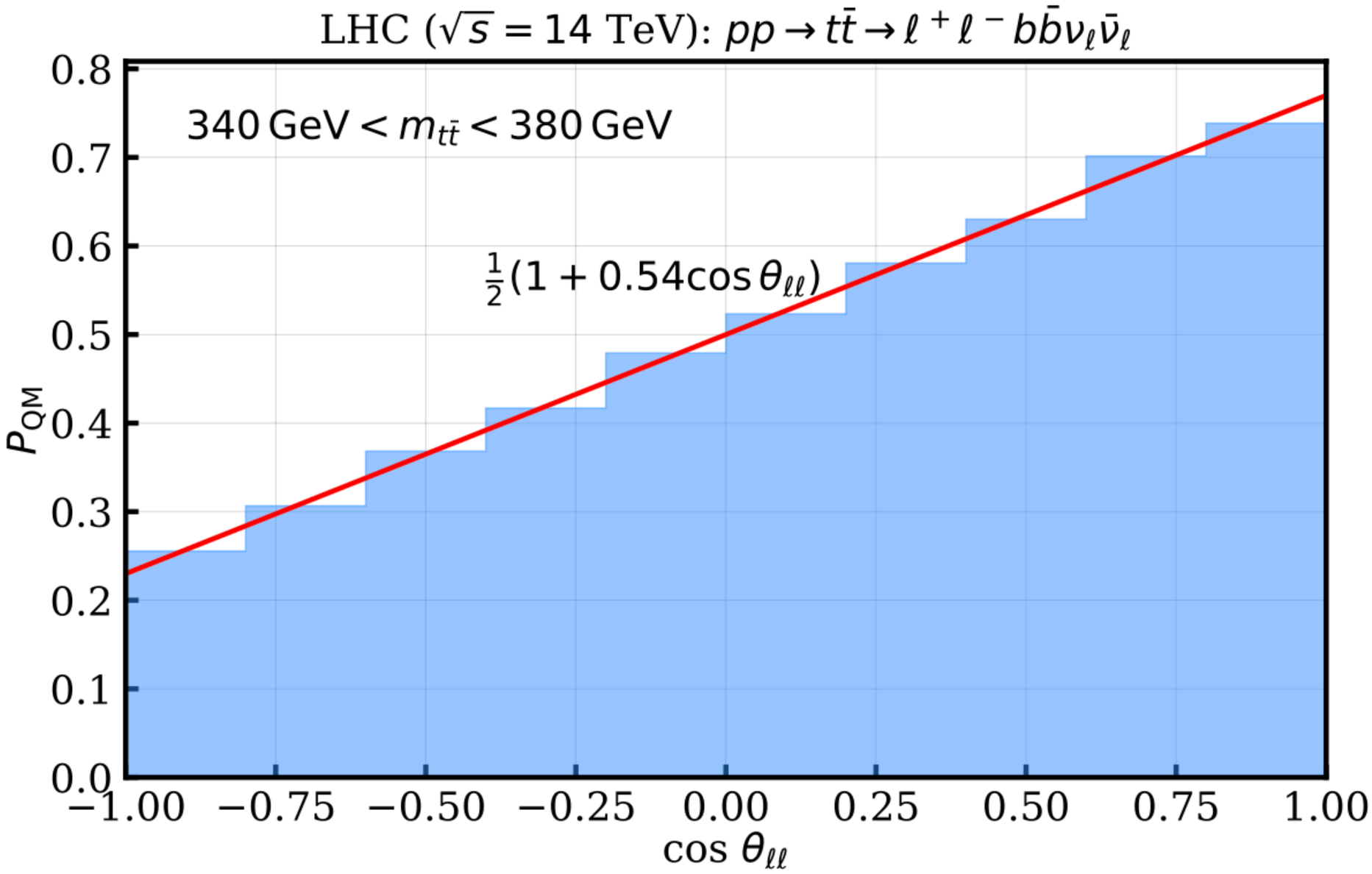
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Abstract: We explore the potential to study quantum entanglement through Bell-type inequalities in Higgs boson decays at a future muon collider. Our analysis focuses on the channel $\mu^+\mu^- \to \nu\bar{\nu}h \to \nu\bar{\nu}ZZ^*$, with one Z decaying to charged leptons and the other decaying hadronically into jets. We study the violation of the CGLMP inequality using the optimal Bell operator for the bipartite qutrit system from $h \to ZZ^*$. The entanglement measure $\mathcal{I}_3$ is constructed from spin-correlated angular observables of the Z decay products. An unfolding method on the angular variables is applied to correct for hadronization and detector effects, recovering the advantage of the hadronic mode with higher event yield and reduced uncertainty. The study is performed at 1, 3, and 10 TeV centre-of-mass energies, assuming 10 ab^{-1} integrated luminosity for each case. At 1 TeV, we use a boosted decision tree for signal isolation, while at higher energies, simple cut-based analyses are sufficient. We find clear Bell inequality violation with the expected values $\mathcal{I}_3 = 2.625 \pm 0.012$, 2.623 ± 0.004, and 2.582 ± 0.010 for the 1, 3, and 10 TeV machines, respectively. Overall, a strong level of entanglement close to the maximum achievable value of 2.9149 for a two-qutrit system can be measured with very small uncertainties due to the large event yield in the hadronic mode.



always satisfies Bell's inequality



always satisfies CHSH inequality

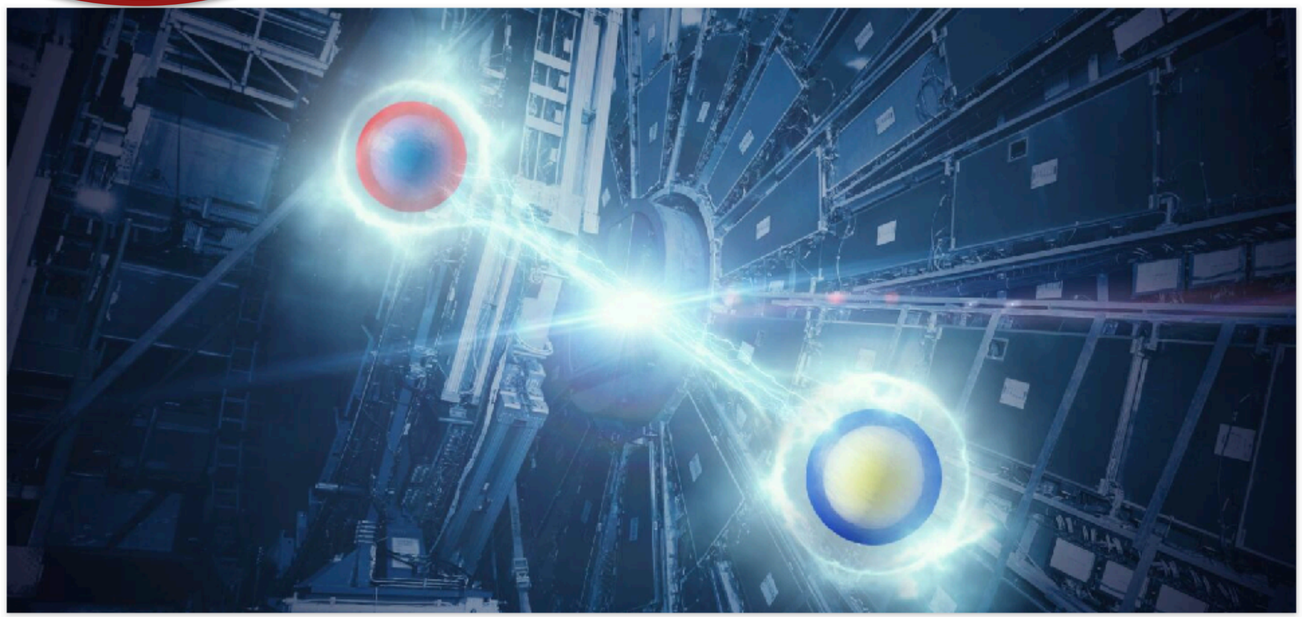
Voir en français

LHC experiments at CERN observe quantum entanglement at the highest energy yet

18.9.2024

The results open up a new perspective on the complex world of quantum physics

18 SEPTEMBER, 2024



Artist's impression of a quantum-entangled pair of top quarks. (Image: CERN)

Quantum entanglement is a fascinating feature of quantum physics – the theory of the very small. If two particles are quantum-entangled, the state of one particle is tied to that of the other, no matter how far apart the particles are. This mind-bending phenomenon, which has no analogue in classical physics, has been observed in a wide variety of systems and has found several important applications, such as quantum cryptography and quantum computing. In 2022, the Nobel Prize in Physics was awarded to Alain Aspect, John F. Clauser and Anton Zeilinger for groundbreaking experiments with entangled photons. These experiments

Atlas, *Nature* 633 (2024) 8030, 542

- $t\bar{t}$ -production at LHC, with: $t \to b\ell^+\nu_\ell \ , \ \bar{t} \to \bar{b}\ell^-\bar{\nu}_\ell$

- Spin density Matrix:

top spins (correlated)

$$\rho = \frac{1}{4}\left[I_4 + \sum_i \left(B_i^+ \sigma^i \otimes I_2 + B_i^- I_2 \otimes \sigma^i\right) + \sum_{i,j} C_{ij}\sigma^i \otimes \sigma^j \right].$$

- Parametrization of the experimental final state:

$$(4\pi)^2 \frac{1}{\sigma}\frac{d\sigma}{d\Omega_+ d\Omega_-} = 1 + \overline{\mathbf{B}}^+ \cdot \hat{\mathbf{q}}_+ - \overline{\mathbf{B}}^- \cdot \hat{\mathbf{q}}_- - \hat{\mathbf{q}}_+ \overline{\mathbf{C}} \cdot \hat{\mathbf{q}}_+$$

QM $\rho = \frac{1}{4}\left[I_4 + \sum_i (B_i^+ \sigma^i \otimes I_2 + B_i^- I_2 \otimes \sigma^i) + \sum_{i,j} C_{ij} \sigma^i \otimes \sigma^j \right].$

different notation

Exp. $(4\pi)^2 \frac{1}{\sigma} \frac{d\sigma}{d\Omega_+ d\Omega_-} = 1 + \overline{\mathbf{B}}^+ \cdot \hat{\mathbf{q}}_+ - \overline{\mathbf{B}}^- \cdot \hat{\mathbf{q}}_- - \hat{\mathbf{q}}_+ \overline{\mathbf{C}} \cdot \hat{\mathbf{q}}_+$

(compute)

QM ⟶ EXP can identify: $\{B_i^+, B_i^-, C_{ij}\} \longrightarrow \{\bar{B}_i^+, \bar{B}_i^-, \bar{C}_{ij}\}$

- But this explicitly assumes QM
- QM includes entanglement automatically

Atlas, *Nature* 633 (2024) 8030, 542

- Spin density matrix: $$\rho = \frac{1}{4}\left[I_4 + \sum_i \left(B_i^+ \sigma^i \otimes I_2 + B_i^- I_2 \otimes \sigma^i\right) + \sum_{i,j} C_{ij}\sigma^i \otimes \sigma^j\right].$$

- ``entanglement identifier": $$D \equiv \frac{1}{3} Tr[\mathbf{C}]$$

- entanglement limit: $$D < -\frac{1}{3} \qquad (\text{not } \bar{D}!)$$

  Peres ('96), Horodecki ('97)

- From differential X-sect.: $$\overline{D} \equiv \frac{1}{3}\mathrm{Tr}[\overline{C}] = -3\langle \cos\phi \rangle$$

angle between lepton momenta in their parent top rest frames

Atlas, *Nature* 633 (2024) 8030, 542

- Atlas measurement:

$$\overline{D} = -0.537 \pm 0.002\,(\text{stat.}) \pm 0.019\,(\text{syst.}) < -\frac{1}{3}$$

- Does this prove entanglement? —NO!

$$(4\pi)^2 \frac{1}{\sigma} \frac{d\sigma}{d\Omega_+ d\Omega_-} = 1 + \overline{\mathbf{B}}^{+} \cdot \hat{\mathbf{q}}_+ - \overline{\mathbf{B}}^{-} \cdot \hat{\mathbf{q}}_- - \hat{\mathbf{q}}_+ \overline{\mathbf{C}} \cdot \hat{\mathbf{q}}_+$$



LHVT! Inherently separable, NOT entangled.

Angular vs Spin-Correlations

Bechtle, Breuning, Duhr, HD (2025)

- At collider measure angular correlation between final state particles

$$Q_{ij} = \langle \hat{\mathbf{p}}_{\pi^+} \hat{\mathbf{p}}_{\pi^+} \rangle$$

- For entanglement etc need the spin correlation of the tau's

$$C_{ij} = \langle \sigma_{\tau^+} \sigma_{\tau^-} \rangle$$

- We proved these are only relatable via theory: QM & LHVT!!

$$\boxed{Q_{ij} = \frac{\alpha_\tau \, \bar{\alpha}_{\bar{\tau}}}{9} C_{ij}}$$

$$\frac{1}{\Gamma} \frac{d\Gamma}{d\Omega} = \frac{1 + \alpha \cos\theta}{4\pi}$$

Summary

- In a collider experiment when measuring momenta always possible to construct an LHVT which explains the data
- LHVT by Bell's proof satisfies Bell's inequality. Also LHVT inherently NOT entangled.
- Thus one is NOT testing locality via Bell's inequality
- Thus NOT testing for entanglement vs non-entanglement. It's a measurement of spin-correlations within the framework of the SM.

KP **Kiran Pothare**

Inbox - Uni-Bonn 25. July 2025 at 0

Colliders are Testing neither Locality via Bell's Inequality nor Entanglement versus Non-Entanglement

To: Herbert Dreiner,

Reply-To: inquiry@info.psychosocialworld.com,

Resent-From: Herbert Dreiner

inquiry@info.psychosocialworld.com 1

Dear Dreiner Herbi K ,

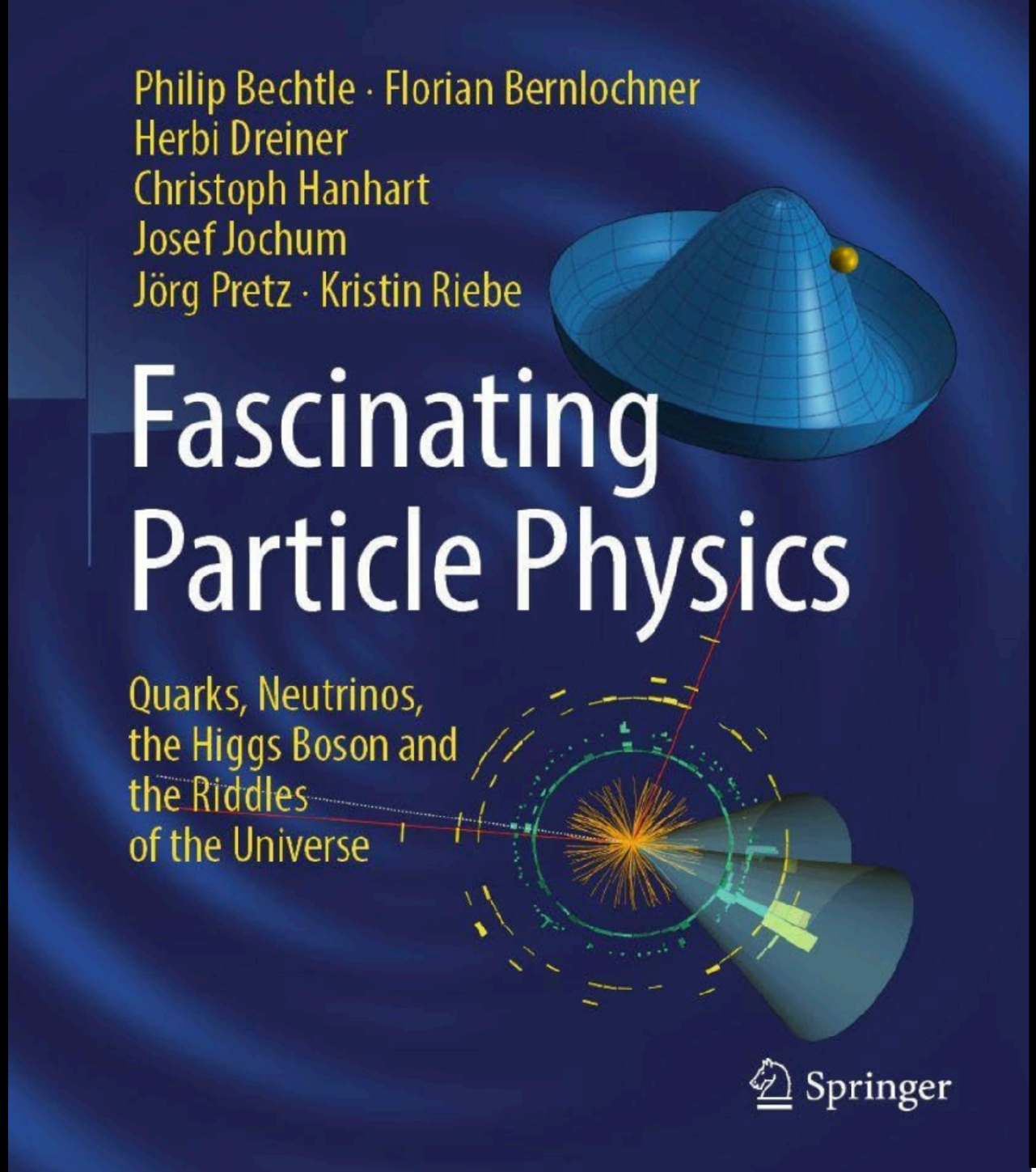
We invite you to submit your research entitled "Colliders are Testing neither Locality via Bell's Inequality nor Entanglement versus Non-Entanglement" for our "**international journal of psychosocial rehabilitation**". Since 2015, we have been dedicated to advancing knowledge through open access publishing under the Creative Commons CC BY 4.0 license.

For more information on how to **submit your article**, please visit our website or contact us directly at editor@psychosocial.com.

We look forward to your submission!

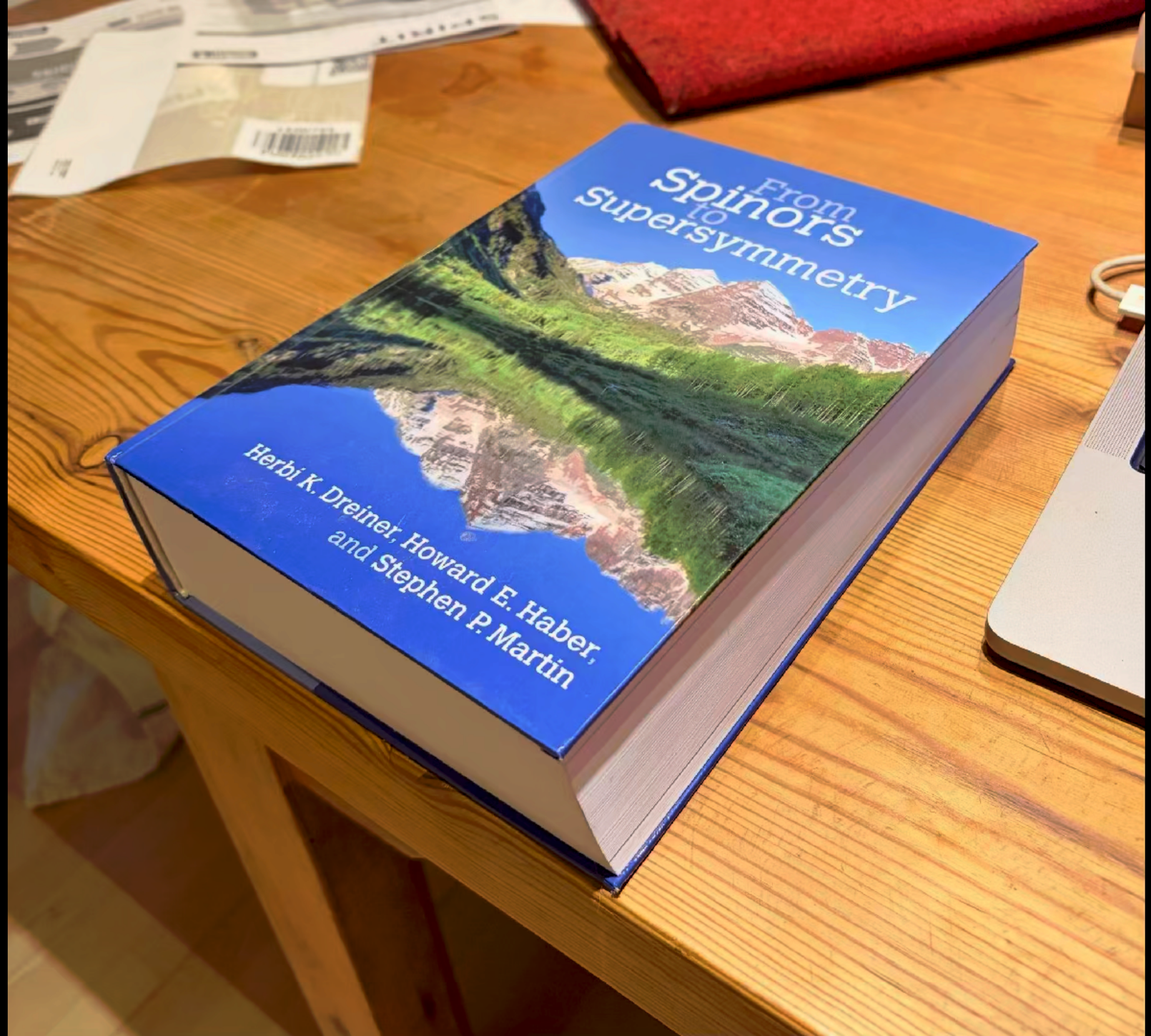
Thanks & regards,

Editorial Team
International journal of psychosocial rehabilitation
ISSN 1475-7192


Philip Bechtle · Florian Bernlochner
Herbi Dreiner
Christoph Hanhart
Josef Jochum
Jörg Pretz · Kristin Riebe
Fascinating Particle Physics
Quarks, Neutrinos, the Higgs Boson and the Riddles of the Universe
Springer

Nov. 2025

June 2023


From
Spinors
to
Supersymmetry
Herbi K. Dreiner, Howard E. Haber,
and Stephen P. Martin

Zurich

Inbox - Uni-Bonn 27. July 2026 at 12:44

Invitation to Feature

To: dreiner@th.physik.uni-bonn.de

Dear Herbi K. Dreiner

My name is Zurich, and I serve as the organizer of Eclectic Charlotte, a Charlotte, North Carolina based community of more than 1,100 active members who share a passion for exploring books, ideas, and diverse cultural perspectives.

Our members recently identified your book, "[From Spinors to Supersymmetry }," as a title of particular interest, and we would be honored to feature it in an upcoming book club discussion. We believe your work would spark meaningful conversations and resonate with the broad interests and values of our community.

As part of our discussions, members frequently exchange insights, reflections, and recommendations, helping to create authentic engagement and increased word of mouth awareness for the books we feature.

We would be delighted to include your book in our upcoming reading schedule and would appreciate your confirmation that you are comfortable with us featuring it as part of our discussion program.

Thank you for your time and consideration. We look forward to hearing from you.

Kind regards,

Zurich
Organizer, Eclectic Charlotte
Charlotte, NC, USA

The End

Backup Slides

Nature

Article

Observation of quantum entanglement with top quarks at the ATLAS detector

https://doi.org/10.1038/s41586-024-07824-z

Received: 14 November 2023

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Published online: 18 September 2024

Open access

Check for updates

The ATLAS Collaboration*

Entanglement is a key feature of quantum mechanics[1–3], with applications in fields such as metrology, cryptography, quantum information and quantum computation[4–8]. It has been observed in a wide variety of systems and length scales, ranging from the microscopic[9–13] to the macroscopic[14–16]. However, entanglement remains largely unexplored at the highest accessible energy scales. Here we report the highest-energy observation of entanglement, in top–antitop quark events produced at the Large Hadron Collider, using a proton–proton collision dataset with a centre-of-mass energy of $\sqrt{s} = 13$ TeV and an integrated luminosity of 140 inverse femtobarns $(\text{fb})^{-1}$ 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, at which 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 the 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 $D = -0.537 \pm 0.002\,(\text{stat.}) \pm 0.019\,(\text{syst.})$ for $340\ \text{GeV} < m_{t\bar{t}} < 380\ \text{GeV}$. The observed result is more than five standard deviations from a scenario without entanglement and hence constitutes the first observation of entanglement in a pair of quarks and the highest-energy observation of entanglement so far.

Particle colliders, such as the Large Hadron Collider (LHC) at CERN, probe fundamental particles and their interactions at the highest energies accessible in a laboratory, exceeded only by astrophysical

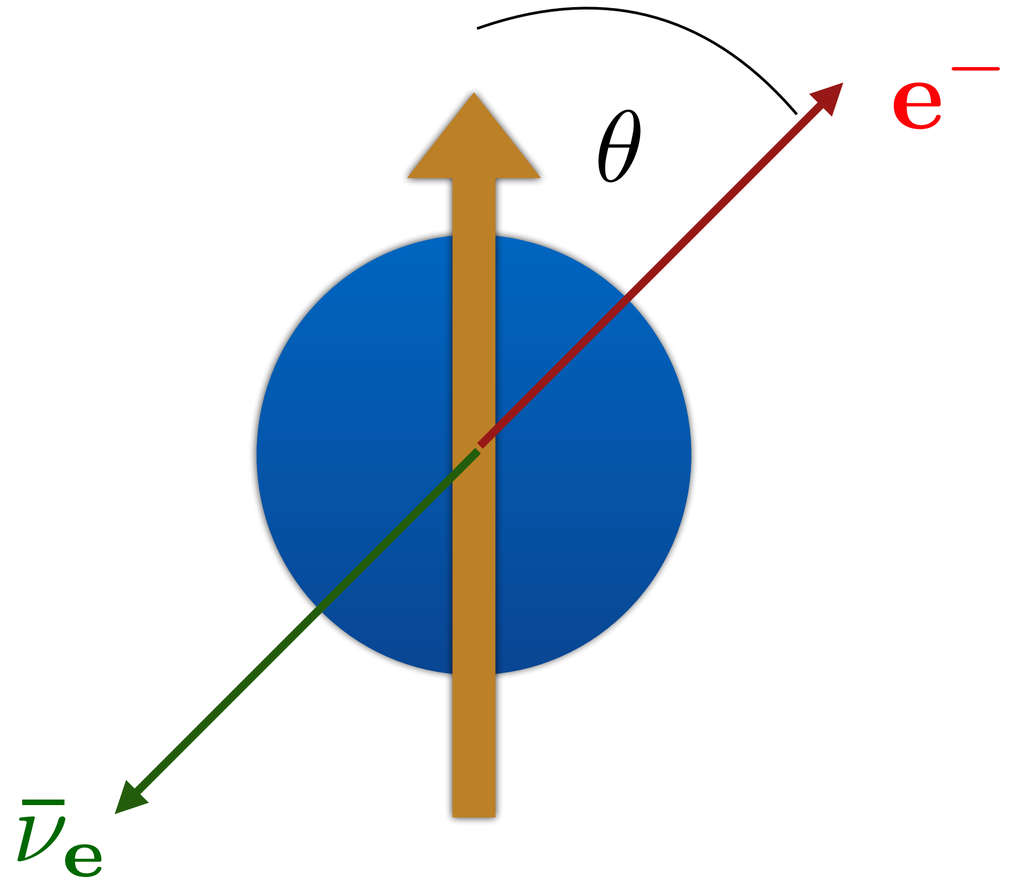
of quantum information about two particles in the same quantum state that exist in superposition. The spin quantum number of a fundamental fermion, a particle that can take spin values of ±1/2, is one of

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, at which 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 the 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 $D = -0.537 \pm 0.002\,(\text{stat.}) \pm 0.019\,(\text{syst.})$ for $340\ \text{GeV} < m_{t\bar{t}} < 380\ \text{GeV}$. The observed result is more than five standard deviations from a scenario without entanglement and hence constitutes the first observation of entanglement in a pair of quarks and the highest-energy observation of entanglement so far.

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of quantum information about two particles in the same quantum state that exist in superposition. The spin quantum number of a fundamental fermion, a particle that can take spin values of ±1/2, is one of the simplest and most fundamental examples of a qubit. Among the fundamental fermions of the standard model of particle physics, the top

Polarized Nucleon - Beta Decay



spin analyzing power

$$4\pi \frac{1}{\Gamma} \frac{d\Gamma}{d\Omega} = 1 + \alpha \cos\theta$$

(I) QFT

$$\frac{1}{\sigma}\frac{\mathrm{d}\sigma}{\mathrm{d}\Omega_+\mathrm{d}\Omega_-} = \frac{1+\alpha_1\,\mathbf{B}_+\cdot\mathbf{q}_+ + \bar{\alpha}_1\,\mathbf{B}_-\cdot\mathbf{q}_- + \alpha_1\bar{\alpha}_1\,\mathbf{q}_+^T\mathbf{C}\mathbf{q}_-}{16\pi^2}$$

$$Q_{ij} = \langle q_+^i\, q_-^j\rangle = \int_{S^2\times S^2}\mathrm{d}\Omega_+\,\mathrm{d}\Omega_-\,\frac{1}{\sigma}\frac{\mathrm{d}\sigma}{\mathrm{d}\Omega_+\mathrm{d}\Omega_-}\,q_+^i\,q_-^j = \frac{\alpha_1\bar{\alpha}_1}{9}\,C_{ij}$$

angular-corr. spin-corr.

$$\boxed{Q_{ij} = \frac{\alpha_1\bar{\alpha}_1}{9}\,C_{ij}}$$

- On to entanglement

- It should be clear that an LHVT is not entangled, i.e. separable

$$P(\vec{a},\vec{b}) = \int d\lambda\, \rho(\lambda)\, A(\vec{a},\lambda) B(\vec{b},\lambda)$$

not entangled,
factorized

A further Note on Separability

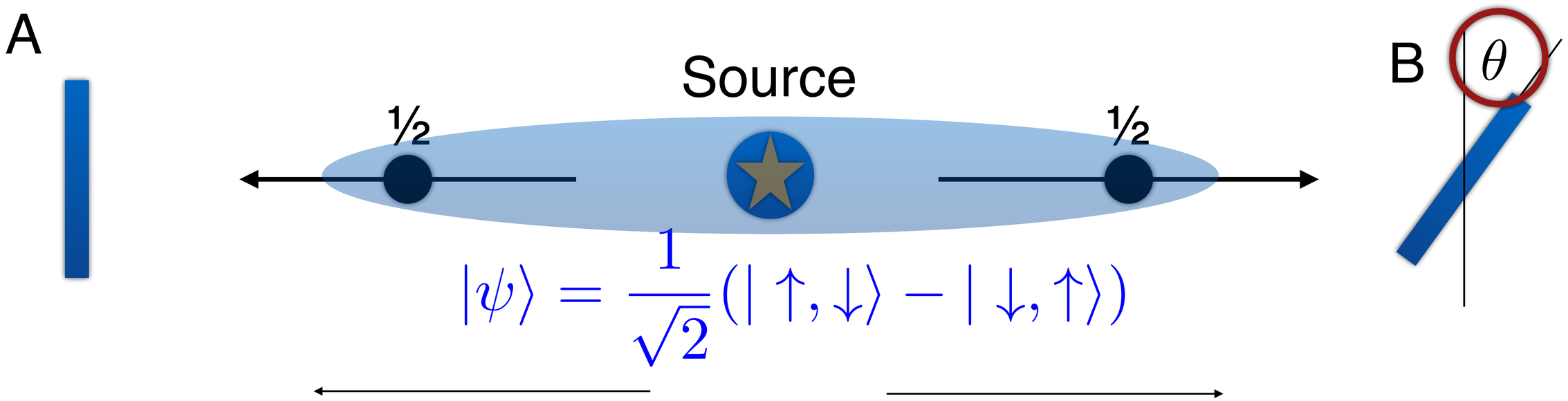
$$\Psi = \sum_{m,n} a_{mn} \Psi_m \otimes \Phi_n \,. \qquad \text{assume} \;\; \Psi_m, \, \Phi_n \;\; \text{pure}$$

$$a_{mn} = b_m c_n \,, \qquad \text{separable}$$

$$\Psi = \left(\sum_m b_m \Psi_m \right) \otimes \left(\sum_n c_n \Phi_n \right) \equiv \tilde{\Psi}_m \otimes \tilde{\Phi}_n \,,$$

$$\langle \Psi | A(m) B(n) | \Psi \rangle = \langle \tilde{\Psi}_m | A(m) | \tilde{\Psi}_m \rangle \cdot \langle \tilde{\Phi}_n | B(n) | \tilde{\Phi}_n \rangle \,,$$

otherwise entangled



Rendering of: “entanglement” - non-separable

Contrast: separable

Bell's LHVTs: $$P(\vec{a},\vec{b}) = \int d\lambda\, \rho(\lambda) A(\vec{a},\lambda) B(\vec{b},\lambda)\,.$$

At Colliders:

$$\frac{1}{\sigma}\frac{d^6\sigma}{d^3p_+ d^3p_-}\left[pp \to t\bar{t} \to (b\ell^+\nu_\ell)(\bar{b}\ell'^-\bar{\nu}_{\ell'-})\right] = F_{+-}(p_+,\, p_-)$$

Expectations for momenta separate:

$$\int d^3p_- \frac{1}{\sigma}\frac{d^2\sigma}{d\Omega_+ d\Omega_-}\left[pp \to t\bar{t} \to (b\ell^+\nu_\ell)(\bar{b}\ell'^-\bar{\nu}_{\ell'-})\right] \equiv f_+(p_+)$$