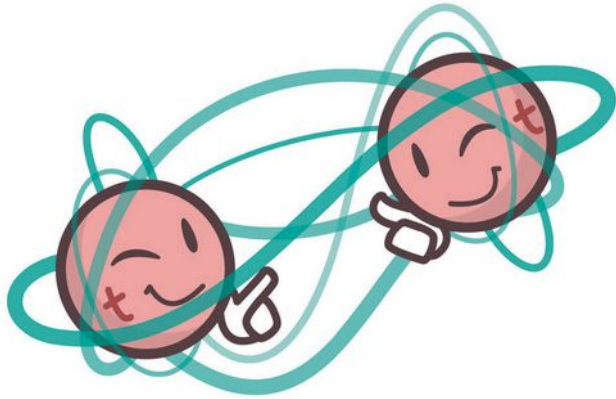
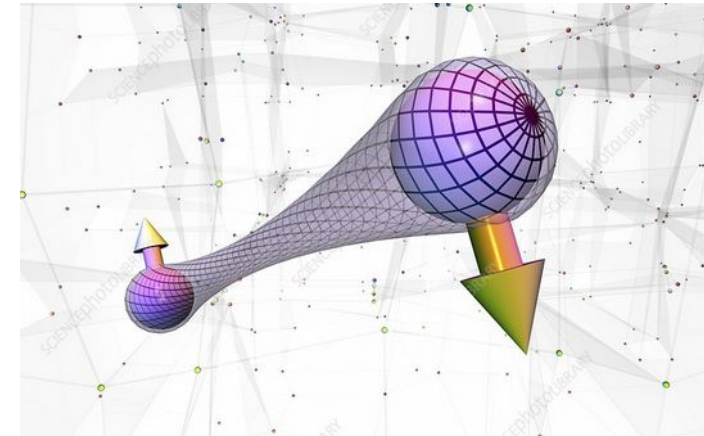


Violazione delle disuguaglianze di Bell ad alte energie



Emidio Gabrielli

PA (FIS/02)



Research Area: Theoretical Particle Physics

Department of Physics, Theoretical Section
University of Trieste

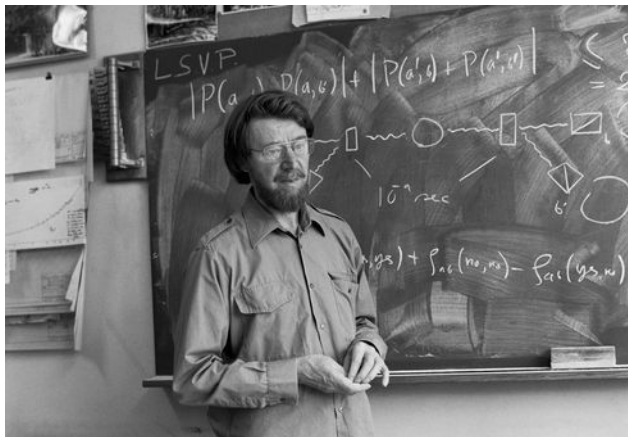
Leonardo Building, Strada Costiera 11, 34151 Trieste

■ “Entanglement” between two systems is a pure quantum phenomena

■ Expected to violates **Bell inequalities** (1964): a set of correlation measurements from “Alice” (**A**) and “Bob” (**B**) observers

$(\hat{A}_1, \hat{A}_2)$ $(\hat{B}_1, \hat{B}_2)$ → example qubits (spin 1/2)

John Bell, CERN (1980)



$$\mathcal{I}_2 = \langle \hat{A}_1 \hat{B}_1 \rangle + \langle \hat{A}_1 \hat{B}_2 \rangle + \langle \hat{A}_2 \hat{B}_1 \rangle - \langle \hat{A}_2 \hat{B}_2 \rangle$$

$$\mathcal{I}_2 \leq 2$$

■ Violations incompatible with classical physics based on causality and local realism (locality) (**Einstein-Podolski-Rosen paradox, hidden variables theories**)

■ **QM is a non-local theory**

measurements in **A** affects what will be measured in **B**, even if **A** and **B** are **space-like** separated apart, and no causal exchange of information between them is possible

Violation of Bell inequality has been observed for the first time in (qubits) optical experiments using **entangled photons** ($\sim$ eV energy range)



The Nobel Prize in Physics 2022 was awarded jointly to Alain Aspect, John F. Clauser and Anton Zeilinger "for experiments with entangled photons, establishing the violation of Bell inequalities and pioneering quantum information science"

[2] A. Zeilinger *et al.*, Nature **433**, 230 (2005)

[3] S.J. Freedman and J.F. Clauser, Phys. Rev. Lett. **28**, 938 (1972).
<https://journals.aps.org/prl/abstract/10.1103/PhysRevLett.28.938>

[4] A. Aspect, J. Dalibard, and G. Roger, Phys. Rev. Lett. **49**, 1804 (1982). A. Aspect, P. Grangier, and G. Roger, Phys. Rev. Lett. **49**, **91** (1982)

[5] G. Weihs, T. Jennewein, C. Simon, H. Weinfurter, A. Zeilinger, Phys. Rev. Lett. **81**, 5039 (1998). D. Bouwmeester, J. W. Pan, K. Mattle, M. Eibl, H. Weinfurter, A. Zeilinger, Nature **390**, 575 (1997)

[6] A. Aspect, Physics **8**, 123. (2015)

ruling out local deterministic theories of Nature (local realism, hidden variables)

- **The new challenge:** measuring Bell inequality violation at **high energy** $\gg$ eV
- and in presence of other fundamental forces: **strong** and **weak** interactions
- require measuring polarization of **massive** (unstable) **particles** with spin
- polarizations can be reconstructed from their decay products

- **first observation of Bell violation** at high energy in B meson decays and in the presence of **WEAK** and **STRONG** interactions and for **qutrit systems** (spin-1) !
- work based on data from LHCb experiment at CERN [Phys. Rev. D 88, 052002 (2013)]

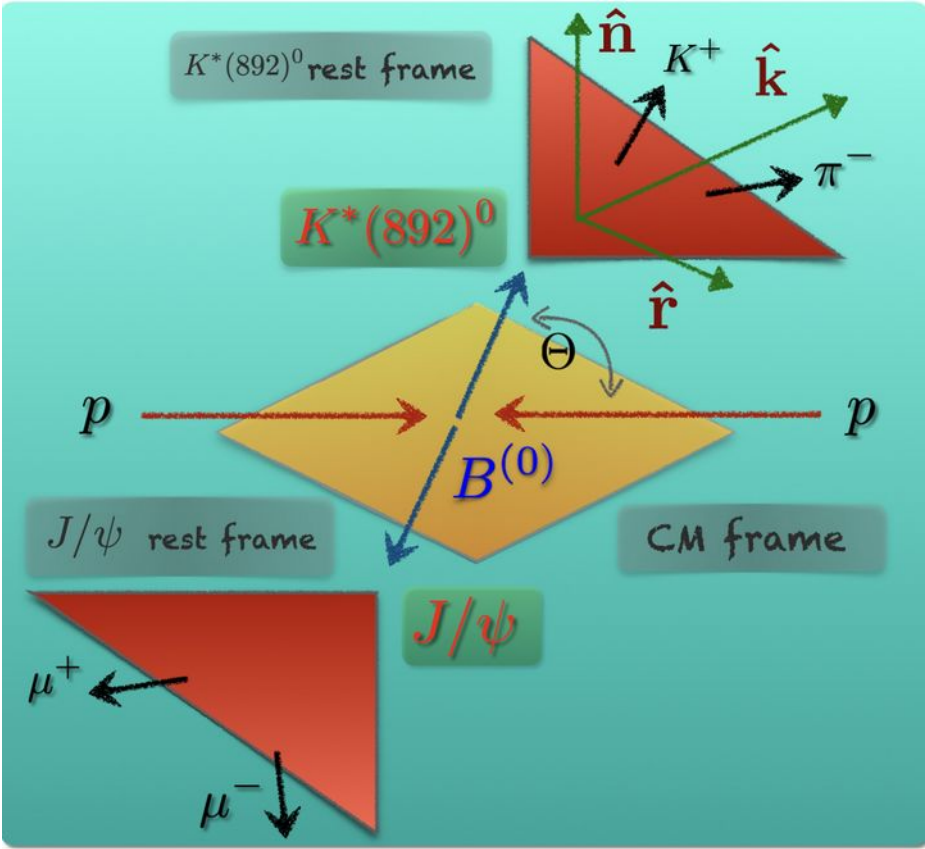
PHYSICAL REVIEW D 109, L031104 (2024)

Letter

Editors' Suggestion

Bell inequality is violated in $B^0 \rightarrow J/\psi K^{*}(892)^0$ decays

M. Fabbrichesi¹, R. Floreanini¹, E. Gabrielli^{2,1,3,4} and L. Marzola⁴



CGLMP inequality
 $\mathcal{I}_3 < 2$

(for qutrits)

$\mathcal{I}_3 = 2.548 \pm 0.015,$

Significance (to reject the null hypothesis)

Entanglement (Entropy): **86 σ**

Bell inequality violation: **36 σ**

Testing entanglement and Bell inequality at colliders

Collaboration Institutes: Oxford University (UK), NICPB (Estonia), INFN (Trieste)

2021-2024

Review : Quantum Entanglement and
Bell inequality violation at colliders

heavy Quarks and Leptons

– **top-quark pair**

– **tau-lepton pair**

● A. Barr, M. Fabbrichesi, EG, L. Marzola, R. Floreanini, [arXiv:2402.07972](https://arxiv.org/abs/2402.07972)

● M. Fabbrichesi, R. Floreanini, G. Panizzo, [PRL 127 \(2021\) 16](#)

● M. Fabbrichesi, EG, R. Floreanini, [EPJC 83 \(2023\) 2, 162](#)

● K. Ehataht, M. Fabbrichesi, L. Marzola, C. Veelken, [PRD 109 \(2024\) 3, 032005](#)

● M. Fabbrichesi, L. Marzola, [PRD 109 \(2024\) 9, 095026](#)

Weak gauge bosons

– **WW, ZZ, WZ**

– **H $\rightarrow$ WW*, ZZ***

● M. Fabbrichesi, R. Floreanini, EG, Marzola, [EPJC 83 \(2023\) 9, 823](#)

● M. Fabbrichesi, R. Floreanini, EG, Marzola, [JHEP 09 \(2023\) 195](#)

Mesons and Barions

– **B-meson ($\rightarrow$ 2 spin1)**

● M. Fabbrichesi, R. Floreanini, EG, Marzola, [PRD 109 \(2024\) 3, L031104](#)

– **Λ hyperons ($\rightarrow$ spin0 + spin1)**

● M. Fabbrichesi, R. Floreanini, EG, L. Marzola (in preparation)

Possibili future linee di ricerca (tesi)

Entanglement ad alte energie

- Entanglement in sistemi (polarizzati) a 3 particelle ad LHC e futuri acceleratori
- **Correzioni radiative elettrodeboli** ad entanglement e disuguaglianze di Bell nei processi di decadimento dell'Higgs boson in $H \rightarrow W W^*$ e $H \rightarrow Z Z^*$
- Violazione delle disuguaglianze di Bell nei sistemi con barioni

Fisica oltre il Modello Standard

- Ricerca di particelle leggere del settore oscuro (materia oscura) ad LHC e oltre