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quantumTANGO

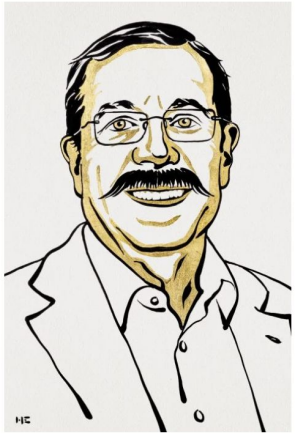
Quantum Information with Top Quarks and Higgs Bosons

Dr James Howarth (Glasgow)
Dr Baptiste Ravina (Göttingen)

THE ROYAL SOCIETY

University of Glasgow
VIA VERITAS VITA

JOINT FORUM
SCOTLAND × LOWER SAXONY



Ill. Niklas Elmehed © Nobel Prize Outreach

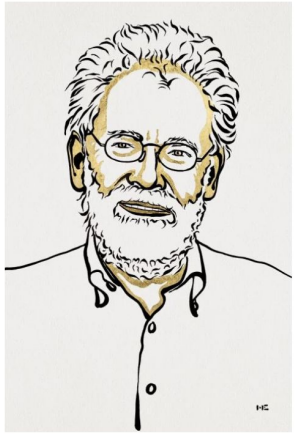
Alain Aspect

Prize share: 1/3

Ill. Niklas Elmehed © Nobel Prize Outreach

John F. Clauser

Prize share: 1/3



Ill. Niklas Elmehed © Nobel Prize Outreach

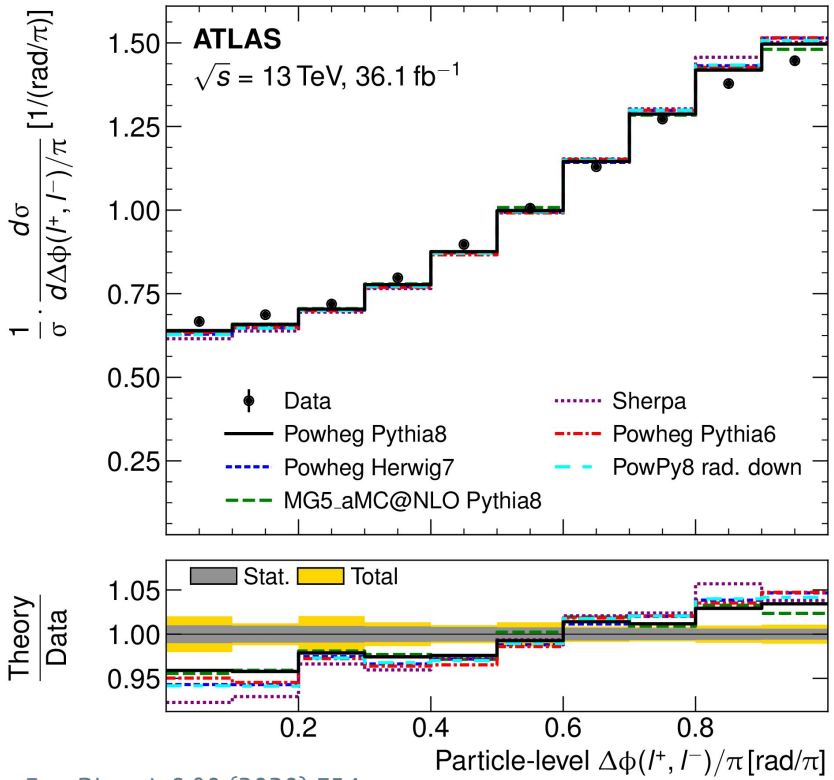
Anton Zeilinger

Prize share: 1/3

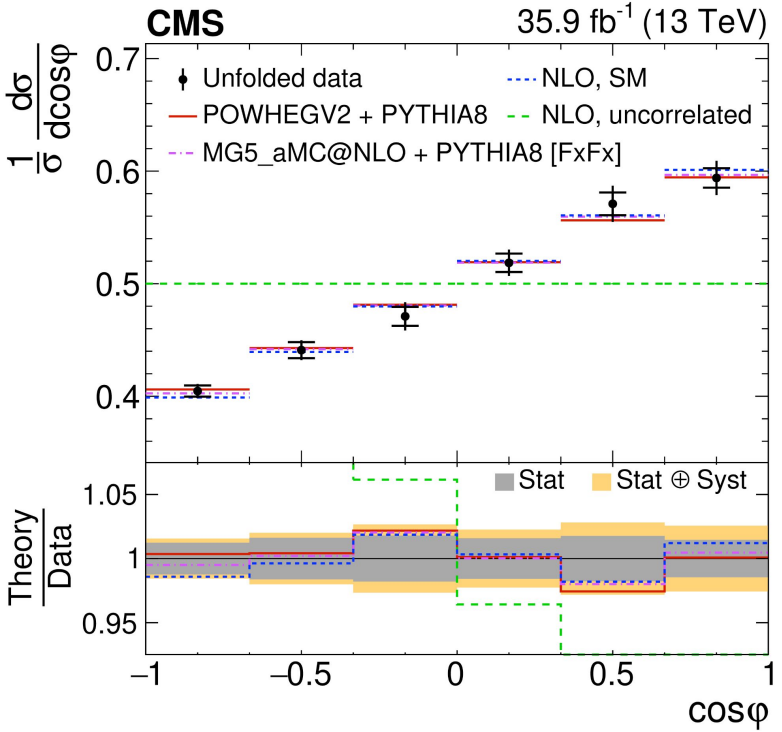
The Nobel Prize in Physics 2022 was awarded jointly to Alain Aspect, John F. Clauser and Anton Zeilinger "for experiments with entangled photons, establishing the violation of Bell inequalities and pioneering quantum information science"

A timely discussion...

From spin correlations to quantum entanglement



Eur. Phys. J. C 80 (2020) 754



PRD 100 (2019) 072002

SIGNIFICANT interest from the THEORY community

[Submitted on 10 Mar 2022 (v1), last revised 20 Sep 2022 (this version, v2)]

Quantum information with top quarks in QCD

Yoav Afik, Juan Ramón Muñoz de Nova

Top quarks represent unique high-energy systems since their spin correlations can be
high-energy colliders. We present here the general framework of the quantum state of
energy collider. We argue that, in general, the total quantum state that can be probed
rise to a mixed state. We compute the quantum state of a $t\bar{t}$ pair produced from the m
different regions of phase space. We show that any realistic hadronic production of a $t\bar{t}$
experimentally relevant cases of proton-proton and proton-antiproton collisions, perfo
energy of the collisions. We provide experimental observables for entanglement and Cl
single observable, which in the case of entanglement represents the violation of a Cauc
pair proposed in the literature to more general quantum states, and for any production
form of violation of Bell's theorem, necessarily containing a number of loopholes.

Comments: 36 pages, 10 figures, 1 table. Accepted version of the manuscript
Subjects: **Quantum Physics (quant-ph)**; High Energy Physics - Phenomenology (hep-ph); High
Cite as: arXiv:2203.05582 **[quant-ph]**
(or arXiv:2203.05582v2 **[quant-ph]** for this version)
https://doi.org/10.48550/arXiv.2203.05582
Journal reference: Quantum 6, 820 (2022)
Related DOI: https://doi.org/10.22331/q-2022-09-29-820

[Submitted on 8 Sep 2022]

Quantum discord and steering in top quarks at the LHC

Yoav Afik, Juan Ramón Muñoz de Nova

Top quarks have been recently shown to be a promising system to study quantum information problems at the hi
discuss topics such as entanglement, Bell nonlocality or quantum tomography. Here, we provide the full picture o
discord and steering. We find that both phenomena are present at the LHC. In particular, quantum discord in a se
statistical significance. Interestingly, due to the singular nature of the measurement process, quantum discord ca
ellipsoid can be experimentally reconstructed, both highly-demanding measurements in conventional setups. In
discord and steering can provide witnesses of new physics beyond the Standard Model.

Comments: 6 pages, 3 figures
Subjects: **Quantum Physics (quant-ph)**; High Energy Physics - Experiment (hep-ex); High Energy Physics - Phenomenology (hep-p
Cite as: arXiv:2209.03969 **[quant-ph]**
(or arXiv:2209.03969v1 **[quant-ph]** for this version)
https://doi.org/10.48550/arXiv.2209.03969

[Submitted on 4 Mar 2020 (v1), last revised 6 Sep 2021 (this version, v3)]

Entanglement and quantum tomography with top quarks at the LHC

Yoav Afik, Juan Ramón Muñoz de Nova

Entanglement is a central subject in quantum mechanics. Due to its genuine relativistic behavior and fundamental nature, high-energy colliders are attractive systems for the experimental study of fundamental aspects of quantum mechanics. We propose the detection of entanglement between the spins of top-antitop-quark pairs at the LHC, representing the first proposal of entanglement detection in a pair of quarks, and also the entanglement observation at the highest energy scale so far. We show that entanglement can be observed by direct measurement of the angular separation between the leptons arising from the decay of the top-antitop pair. The detection can be achieved with high statistical significance, using the current data recorded during Run 2 at the LHC. In addition, we develop a simple protocol for the quantum tomography of the top-antitop pair. This
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Comments: 15
Subjects: Qu
Cite as: ar
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Journal reference: Eu
Related DOI: ht

[Submitted on 28 Sep 2022 (v1), last revised 11 Oct 2022 (this version, v2)]

Quantum state tomography, entanglement detection and Bell violation prospects in weak decays of massive particles

Rachel Ashby-Pickering, Alan J. Barr, Agnieszka Wierzchucka

A rather general method for determining the spin density matrix of a multi-particle system from angular decay data is presented. The method is based on a Bloch parameterisation of the d-dimensional generali
spin density matrix can b
non-projective decays are des
Monte Carlo simulations of pp
$H \to ZZ^*$. Measurements are

Comments: v2: additional references
Subjects: **Quantum Physics (quan**

[Submitted on 10 Mar 2022 (v1), last revised 30 Aug 2022 (this version, v2)]

Quantum SMEFT tomography: top quark pair production at the LHC

Rafael Aoude, Eric Madge, Fabio Maltoni, Luca Mantani

Quantum information observables, such as entanglement measures, provide a powerful way to characterize the properties of quantum states. We propose to use them
structure of fundamental interactions and to search for new physics at high energy. Inspired by recent proposals to measure entanglement of top quark pairs produced
we examine how higher-dimensional operators in the framework of the SMEFT modify the Standard Model expectations. We explore two regions of interest in the phas
the Standard Model produces maximally entangled states: at threshold and in the high-energy limit. We unveil a non-trivial pattern of effects, which depend on the init
partons, $q\bar{q}$ or gg, on whether only linear or up to quadratic SMEFT contributions are included, and on the phase space region. In general, we find that higher-dimensio
lower the entanglement predicted in the Standard Model.

[Submitted on 2 Jun 2021 (v1), last revised 26 Jul 2022 (this version, v4)]

Testing Bell inequalities in Higgs boson decays

Alan Barr

Higgs boson decays produce
of the $W^{\pm}$ pair may be recon
determined. Numerical simul
near-maximally violated. Exp
controlled then statistically s

Comments: Sign corrections t
Subjects: **High Energy Phy**
Cite as: arXiv:2106.01377
(or arXiv:2106.01
https://doi.org/1
Journal reference: Physics Letters B
Related DOI: https://doi.org/1

[Submitted on 28 Sep 2022]

Laboratory-frame tests of quantum entanglement in $H \to WW$

J. A. Aguilar-Saavedra

Quantum entanglement between
frame observables that only involv
be used to observe the quantum
dimensional) angular distribution

Comments: LaTeX 6 pages
Subjects: **High Energy Physics -**
Report number: IFT-UAM/CSIC-22-119
Cite as: arXiv:2209.14033 **[hep-**
(or arXiv:2209.14033v1
https://doi.org/10.4855

[Submitted on 27 Sep 2022]

Testing entanglement and Bell inequalities in $H \to ZZ$

J. A. Aguilar-Saavedra, A. Bernal, J. A. Casas, J. M. Moreno

We discuss quantum entanglement and violation of Bell inequalities in the $H \to ZZ$ decay, in particular when the two $Z-$bosons decay into light leptons. Although such pr
implies an important suppression of the statistics, this is traded by clean signals from a "quasi maximally-entangled" system, which makes it very promising to check thes
phenomena at high energy. In this paper we devise a novel framework to extract from $H \to ZZ$ data all significant information related to this goal, in particular spin correl
observables. In this context we derive sufficient and necessary conditions for entanglement in terms of only two parameters. Likewise, we obtain a sufficient and improved
for the violation of Bell-type inequalities. The numerical analysis shows that with a luminosity of $L = 300\text{fb}^{-1}$ entanglement can be probed at $> 3\sigma$ level. For $L = 3\text{ab}^{-1}$ (
entanglement can be probed beyond the 5σ level, while the sensitivity to a violation of the Bell inequalities is at the 4.5σ level

[Submitted on 1 May 2022 (v1), last revised 1 Aug 2022 (this version, v2)]

Improved tests of entanglement and Bell inequalities with LHC tops

J. A. Aguilar-Saavedra, J. A. Casas

We discuss quantum entanglement in top pair production at the LHC. Near the $t\bar{t}$ threshold, entanglement observ
subprocesses, which is achieved by a simple cut on the velocity of the $t\bar{t}$ system in the laboratory frame. Furtherm
combinations of $t\bar{t}$ spin correlation coefficients involved in the measurement of entanglement and Bell inequalitie
2 for Bell inequalities near threshold

heory (hep-th); Quantum Physics (quant-ph)

[Submitted on 19 Oct 2021 (v1), last revised 25 Mar 2022 (this version, v2)]

Quantum tops at the LHC: from entanglement to Bell inequalities

Claudio Severi, Cristian Degli Esposti Boschi, Fabio Maltoni, Maximiliano Sioli

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 fo
measurements, and then perform the corresponding analyses using simulated events in the dilepton final state, reconstructing up to the unfolded level. We find that entanglem
only very high-p_T events are sensitive to a vio
different unfolding methods and independent
he high luminosity LHC run.

[Submitted on 24 Aug 2022]

Constraining new physics in entangled two-qubit systems: top-quark, tau-lepton and photon pairs

Marco Fabbrichesi, Roberto Floreanini, Emidio Gabrielli

The measurement of quantum entanglement can provide a new and most sensitive probe to physics beyond the Standard Model. We use the concurrence of the top-quark pairs spi
states produced at colliders to constrain the magnetic dipole term in the coupling between top quark and gluons, that of τ-lepton pairs spin states to bound contact interactions an
that of τ-lepton pairs or two photons spin states from the decay of the Higgs boson to try distinguishing between CP-even and odd couplings. These four examples show the powe
of the new approach as well as its limitations. We show that differences in the entanglement in the top-quark and τ-lepton pairs production cross sections can provide constraints
better than those previously estimated from total cross sections or classical correlations. Instead, the final states in the decays of the Higgs boson remain maximally entangled even
in the presence of CP-odd couplings and cannot be used to set bounds on new physics. We discuss the violation of Bell inequalities featured in all four processes and find that the
decays of the Higgs boson into τ-lepton pairs or two photons constitute the best instances to observe such violations.

Comments: 31 pages, 16 Figures
Subjects: **High Energy Physics - Phenomenology (hep-ph)**; High Energy Physics - Experiment (hep-ex)
Cite as: arXiv:2208.11723 **[hep-ph]**
(or arXiv:2208.11723v1 **[hep-ph]** for this version)
https://doi.org/10.48550/arXiv.2208.11723

[Submitted on 23 Feb 2021 (v1), last revised 27 Oct 2021 (this version, v2)]

Testing Bell inequalities at the LHC with top-quark pairs

M. Fabbrichesi, R. Floreanini, G. Panizzo

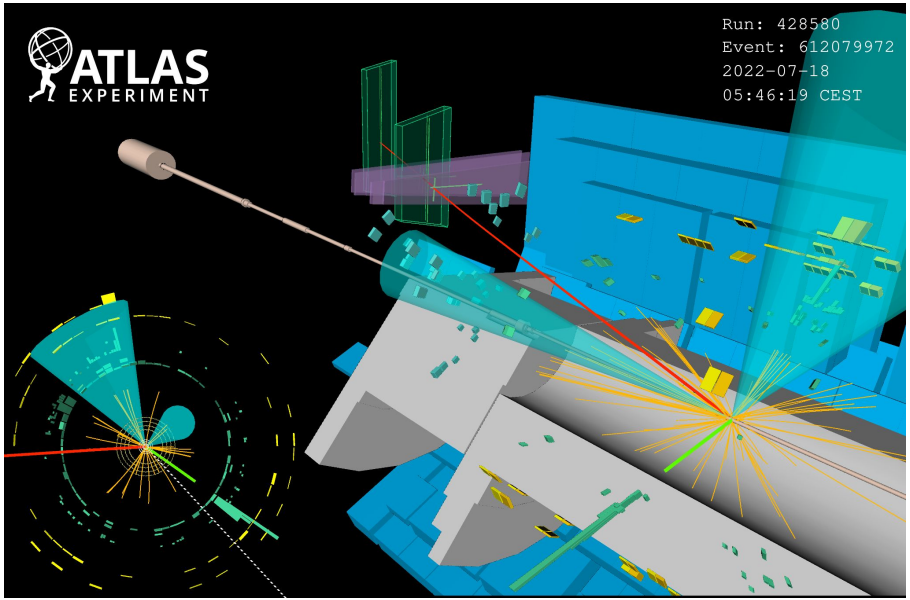
Entanglement between the spins of top-quark pairs produced at a collider can be used to test a (generalized) Bell inequality at energies never explored so far. We show how the measurement of a single observable can provide a test of the violation of the Bell inequality at the 98% CL with the data already collected at the Large Hadron Collider and at the 99.99% CL with the higher luminosity of the next run.

Comments: 4 pages, 1 figure
Subjects: **High Energy Physics - Phenomenology (hep-ph)**; High Energy Physics - Experiment (hep-ex); Quantum Physics (quant-ph)
Cite as: arXiv:2102.11883 **[hep-ph]**
(or arXiv:2102.11883v2 **[hep-ph]** for this version)
https://doi.org/10.48550/arXiv.2102.11883
Journal reference: Phys.Rev.Lett. 127 (2021) 16, 161801
Related DOI: https://doi.org/10.1103/PhysRevLett.127.161801

This Workshop

- bring experimentalists and theorists **together**
- start developing a **coherent analysis strategy**
- kick-start **common funding** projects

What would we like to find out?



From the theory side...

- entanglement, tomography, discord, Bell's inequalities... **— what are the options?**
- phase-space(s) of interest?
- what information is needed for reinterpretation?

Experimentally...

- different final states, processes, reconstruction techniques... **— what kind of resolution?**
- current challenges?
- timeline and combinations?

Before we start...

- The slides and the agenda are available on Indico: https://indico.cern.ch/event/1223483/
- The session will be moderated – please be considerate and respectful of others.
- **Questions** can be asked **after** each talk: please “raise your hand” on Zoom or type them in the chat
- You’re welcome to turn on your camera (but don’t have to!)
- There will be a **short coffee break** halfway through

After the workshop...

- Feel free to **share the results** of this discussion with your colleagues!
- We’d be happy to hear your **feedback** / **ideas to move forward**, by email
- We’d be particularly interested in setting up **new collaborations**
  - *strengthen* and *diversify* analysis teams
  - more **ambitious funding initiatives**
  - *training network* for MSc / PhD students
  - **international scope of the research**