Quantum Observables for Collider Physics 2025

Report of Abstracts

https://agenda.infn.it/e/44563

Abstract ID : **39**

A first test on spooky actions between free-traveling charged lepton pairs

Content

Quantum entanglement is a cornerstone of quantum mechanics. While entanglement between confined electron pairs is well-studied, free-traveling lepton pairs remain largely unexplored due to significant challenges in spin measurement. We hereby propose a novel theory-assisted quantum entanglement test for free-traveling electron-positron pairs through polarization correlation measurements. The entangled pairs are generated in a GeV-scale positron on-target experiment, approaching a Bell state theoretically. Then their polarization correlation is measured at two secondary scattering targets, where a high event rate can be achieved and the unique behavior of the Bell state theoretically known in prior helps verify the entanglement.

Primary authors: Mr GAO, Leyun (Peking University); ET AL.,

Presenter: Mr GAO, Leyun (Peking University)

Status: ACCEPTED

Submitted by **Mr GAO, Leyun** on **Thursday, February 20, 2025**

Abstract ID : **42**

Measurement of quantum correlations in the WZ system at the LHC

Content

The study of heavy vector bosons has been fundamental both for understanding and testing the predictions of the Standard Model and for exploring the potential existence of new physics. In recent years, a new approach to study particle physics is quickly developing using quantum information principle and inspired observables to investigate relations between particles created at colliders. This work analyzes the bipartite qutrit system arising from the process $pp \to W^{\pm}Z$, where the resulting bosons decay into leptonic final states. The spin density matrix of the process has been derived by applying a quantum tomography approach to the simulated final state. This procedure allows to derive information on the heavy bosons' spin by exploiting the angular distribution of the decay products. The key measurement in this work is the lower bound of the concurrence, which is a quantum observable sensitive to the entanglement between the WZ spin. During the analysis, realistic selections and reconstruction procedures were included to estimate the realistic effects that would affect such measurements performed in collider experiments. Moreover, a dedicated statistical analysis is employed to recover the observable of interest and estimate the corresponding statistical uncertainties expected to be achievable at the LHC. Additionally, a study on missing transverse energy is conducted to achieve a more realistic measurement of quantum observables detectable at colliders. The analysis results indicate that measuring entanglement between the W and Z bosons is feasible, though it would be highly challenging with the current Run 3 dataset.

Primary authors: FABBRI, Federica (University of Bologna and INFN); FORTI, Nicola (Istituto Nazionale di Fisica Nucleare); MALTONI, fabio (Université catholique de Louvain)

Presenter: FORTI, Nicola (Istituto Nazionale di Fisica Nucleare)

Status: ACCEPTED

Submitted by **FORTI, Nicola** on **Friday, March 7, 2025**

Abstract ID : **44**

Prospects for quantum process tomography at high energies.

Content

In quantum information theory, the evolution of an open quantum system - a unitary evolution followed by a measurement - is described by a quantum channel or, more generally, a quantum instrument. In this work, we formulate spin and flavour measurements in collider experiments as a quantum instrument. We demonstrate that the Choi matrix, which completely determines input-output transitions, can be both theoretically computed from a given model and experimentally reconstructed from a set of final state measurements (quantum state tomography) using varied input states. The reconstruction of the Choi matrix, known as quantum process tomography, offers a powerful new approach for probing potential extensions of the Standard Model within the quantum field theory framework and also provides a fundamental test of quantum mechanics itself. As an example, we outline a quantum process tomography approach applied to the $e^+e^- \to t\bar{t}$ process at a polarized lepton collider.

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Presenter: ALTOMONTE, Clelia (King's College London)

Comments:

poster session on 7th April

Status: ACCEPTED

Submitted by **ALTOMONTE, Clelia** on **Wednesday, March 19, 2025**

Abstract ID : **45**

Search for decoherence of $B\bar{B}$ flavor entanglement at Belle II

Content

We report on searches for quantum decoherence with the Belle II experiment at the SuperKEKB electron-positron collider, located in Tsukuba, Japan. SuperKEKB operates at a nominal collision energy of 10.58 GeV to produce the $\Upsilon\,(4S)$ bottomonium state, which decays predominantly into flavor-entangled pairs of neutral B mesons. The flavor entanglement is usually assumed to be perfect in analyses carried out at Belle II and the predecessor experiment, Belle. However, environmental effects or new physics could lead to the decoherence of the entanglement of the two B mesons. We will discuss past work by Belle and our ongoing work to search for Lindblad type decoherence using Belle II data. The nanobeam scheme employed by SuperKEKB leads to a smaller beam spot at Belle II compared to Belle. This enables a new event-based measurement of the absolute lifetime of the entangled $B\bar{B}$ state, which improves the sensitivity to decoherence.

Primary authors: MAHOOD, Timothy (University of Hawaii at Manoa); STOETZER, Lucas (University of Hawaii at Manoa)

Presenters: MAHOOD, Timothy (University of Hawaii at Manoa); STOETZER, Lucas (University of Hawaii at Manoa)

Status: ACCEPTED

Submitted by **STOETZER, Lucas** on **Friday, March 21, 2025**

Abstract ID : **46**

Quantum properties of H ⟶ VV: precise predictions in the SM and sensitivity to new physics

Content

We study the quantum properties of Higgs-boson decays into vector bosons and their sensitivity to new physics. We consider four-fermion final states, focusing on the H ⟶ ZZ decay leading to four lepton in the final states, and compute quantum observables within the standard model up to next-to-leading order (NLO) accuracy in electroweak couplings and strong coupling. We find that NLO effects can in some specific cases significantly alter the extraction of the parameters controlling the quantum correlations. We identify the observables that are robust and can be used to extract reliable information.
Finally, we provide a rather extensive analysis of possible resonant and non-resonant new physics effects in the Higgs sector and study their signatures on quantum observables.

Primary authors: DEL GRATTA, Morgan; FABBRI, Federica (University of Bologna and INFN); LAMBA, Priyanka (Faculty of Physics, University of Warsaw); PAGANI, Davide (INFN Bologna); MALTONI, fabio (Université catholique de Louvain)

Presenter: DEL GRATTA, Morgan

Status: ACCEPTED

Submitted by **DEL GRATTA, Morgan** on **Sunday, March 23, 2025**

Abstract ID : **47**

Quantum channels and operations at high energies

Content

High energy scattering processes can be described within the framework of quantum information theory using quantum operations and the corresponding Choi matrices. A general quantum operation consists of a unitary evolution followed by a (partially) selective measurement. In the context of high energy scattering, the unitary part is modelled by the S-matrix, and the measurement is performed on the outgoing projectiles. The experimental reconstruction of the Choi matrix provides a new tool for probing the beyond standard model physics and testing the foundations of quantum theory itself. In this poster, we present a brief overview of these techniques, illustrated by a polarized $e^+e^- \to t\bar{t}$ scattering. We also discuss how potential beyond quantum effects, such as violation of the Tsirelson bound, may occur in the quantum channel framework.

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Presenter: GRZELKA, Łukasz (Jagiellonian University)

Comments:

Poster

Status: ACCEPTED

Submitted by **GRZELKA, Łukasz** on **Tuesday, April 1, 2025**

Abstract ID : **48**

An improved Bell-CHSH observable for gauge boson pairs

Content

For particles decaying without parity violation, it is impossible to reconstruct the full spin-density matrix from the velocities of their decay products. In this work, we consider Bell inequalities based on squares of spin operators. The corresponding Bell operators probe only the part of the density matrix that can be reconstructed from any gauge boson decay or splitting to fermions, which is accessible regardless of whether parity is violated. We find that our new choice of Bell operator has promising properties regarding states seen at colliders. In particular, it substantially outperforms the inequality previously used for the $pp \to ZZ$ process at the LHC in terms of the phase space volume in which it is violated. We also conduct the first investigation of Bell violation in a system involving gauge bosons mediating different interactions, namely the W boson and gluon in the $pp \to W(g \to b\bar{b})$ process.

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Presenter: GRABARCZYK, Radoslaw (University of Oxford)

Status: ACCEPTED

Submitted by **GRABARCZYK, Radoslaw** on **Wednesday, April 2, 2025**