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Probing quantum entanglement using HZZ at the ATLAS experiment

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Quantum entanglement, a fundamental feature of quantum mechanics, has emerged as a powerful tool that has significantly impacted various areas of physics. Notably, the quantification of entanglement through entanglement entropy has played a crucial role in advancing our understanding of diverse phenomena. In this study, we investigate the presence of quantum entanglement within the HZZ interaction. Utilizing quantum tomography techniques, we extract the complete spin density matrix characterizing the HZZ interaction from Monte Carlo simulation data. Subsequently, we employ the derived spin density matrix to evaluate whether there is quantum entanglement in the system. Our investigation sheds light on the potential entanglement properties within the HZZ interaction and offers valuable insights into its quantum characteristics.

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1. Introduction

Quantum entanglement, famously described by Schrödinger as 'the characteristic trait of quantum mechanics [1],' has recently transitioned from being a tool primarily used in low-energy atomic physics to an important subject of study at the higher energies of the LHC. In 2023, both ATLAS and CMS found evidence of quantum entanglement between top quarks, marking the highest energy example of quantum entanglement to date [2], [3]. This raises the question of whether other processes at the LHC, specifically at ATLAS, exhibit detectable quantum entanglement. This work discusses the use of a quantum tomography procedure, originally proposed in Ref. [4], to reconstruct the full spin density matrix for Higgs $\rightarrow ZZ^* \rightarrow 4\ell$. The unique scalar nature of the Higgs boson is paramount, as it implies that the initial state of the Higgs boson is in a maximally entangled state (pure state).

2. Background

Within the framework of quantum information theory, the density matrix is expressed as:

$$\rho = \frac{1}{9}\mathbb{I}_3 \otimes \mathbb{I}_3 + \sum_{i=1}^{8} a_i \lambda_i \otimes \frac{1}{3}\mathbb{I}_3 + \sum_{j=1}^{8} b_j \frac{1}{3}\mathbb{I}_3 \otimes \lambda_j + \sum_{i,j=1}^{8} c_{ij} \lambda_i \otimes \lambda_j, \tag{1}$$

where $\mathbb{I}_3$ is the 3×3 identity matrix, λ_i are the Gell-Mann matrices for a spin-1 system, a_i (b_j) is the coefficient describing particle 1 (2) and c_{ij} describes correlations between the two particles. The coefficients a_i, b_j and c_{ij} are given by:

$$a_i = b_i = \frac{1}{8}\left\langle \phi_i^P(\hat{n}_1) + \phi_i^P(\hat{n}_2)\right\rangle_{\text{avg}}, \tag{2}$$

where a_i and b_j are symmetrized due to the indistinguishability of the two Z bosons. The coefficient c_{ij} is given by:

$$c_{ij} = c_{ji} = \frac{1}{16}\left\langle \phi_i^P(\hat{n}_1)\phi_j^P(\hat{n}_2) + \phi_j^P(\hat{n}_1)\phi_i^P(\hat{n}_2)\right\rangle_{\text{avg}}. \tag{3}$$

In the above relations, $\hat{n}_1$ ($\hat{n}_2$) is the unit vector representing the decay of the daughter lepton from the first (second) Z boson, defined in the Higgs rest frame.

Φ_i^P are the eight components of the Wigner P functions, which depend solely on the azimuthal (ϕ) and polar angles (θ) of the Z and Z* bosons.

To quantify entanglement, we use the lower bound of the three state analog of concurrence, proposed in Ref. [5]:

$$c_{MB}^2 = -\frac{4}{9} - \frac{2}{3}\sum_{i=1}^{8} a_i^2 - \frac{2}{3}\sum_{j=1}^{8} b_j^2 + 8\sum_{i,j=1}^{8} c_{ij}^2, \tag{4}$$

where a value of 0 indicates no entanglement and a value of 1 indicates maximal entanglement. Anything outside this range is inconclusive.

We expect the lower bound of concurrence to be close to one for ggH, since it is approximately a maximally entangled state. For qqZZ, we expect some degree of entanglement but since it is not a maximally entangling state, the degree of entanglement is expected to be lower.

3. Datasets Used

In this study, the following datasets were used, specifically analyzing events within the 4-lepton invariant mass range of 115-130 GeV:

- MC16.345060.PowhegPythia8EvtGen_ NNLOPS_ nnlo_ 30_ ggH125_ ZZ4l,
- MC16.364251.Sherpa_ 222_ NNPDF30NNLO_ llll_ m4l100_ 300_ filt100_ 150,

where DSID 345060 (gluon-gluon fusion Higgs production) served as the primary signal process, and DSID 364251 ($q\bar{q} \rightarrow ZZ^*$) was used as the main background.

The following event selection criteria were applied:

1. Transverse momentum p_T of each lepton ≥ 5 GeV and absolute pseudo-rapidity $|\eta| \leq 2.7$
2. Additional p_T requirements:

   At least one lepton with $p_T \leq 20$ GeV

   At least two leptons with $p_T \leq 15$ GeV

   At least three leptons with $p_T \leq 10$ GeV
3. Invariant mass windows:

   $50 \leq m_{Z1} \leq 106$ GeV

   $12 \leq m_{Z2} \leq 115$ GeV

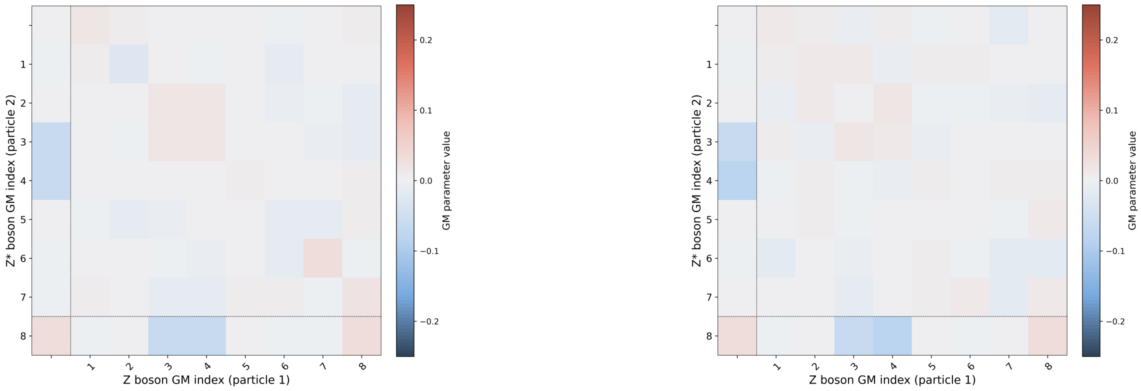
   $115 \leq m_{4\ell} \leq 130$ GeV
4. Minimum invariant mass $m_{\ell\ell}$ of any lepton pair ≥ 5 GeV
5. Minimum angular separation ΔR between lepton pairs ≥ 0.1

4. Results

Our analysis showed a lower than expected correlation for both the signal (ggH) to the background (qqZZ) processes, suggesting that our analysis was unable to capture the full spin correlations for the processes (Fig. 1). Figures 1 present visualizations of the reconstructed Gell-Mann (GM) parameters for the ggH and qqZZ processes, providing insight into the structure of the reconstructed density matrices.

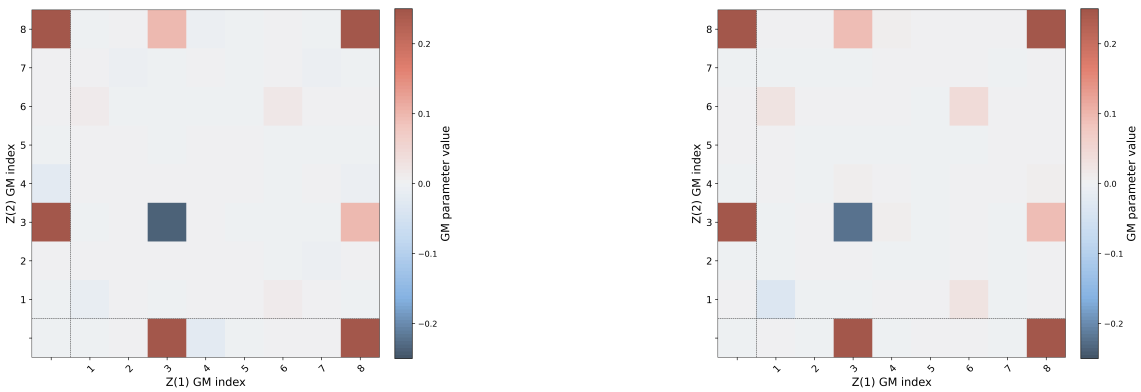
This is can be explained by the observation that the correlations along the diagonal in both GM parameter plots are minimal. Additionally, when the concurrence was calculated, which was supposed to be between zero and one, the following values were obtained, which suggest our process is unphysical:

- For ggH: c^2_{MB} = -0.4205 < 0
- For qqZZ: c^2_{MB} = -0.4068 < 0



(a) ggH GM parameter plot **(b)** qqZZ GM parameter plot

Figure 1: GM Parameter Plots with selection criteria applied. (a) ggH GM parameter plot, (b) qqZZ GM parameter plot. The bottom row represents the values of the coefficients a_i. The leftmost column represents the values of the coefficients b_j ($a_i = b_j$ due to the symmetrization procedure applied). The rest of the plot shows the coefficients of the two-particle correlations, c_{ij}.



(a) ggH GM parameter plot (no cuts) **(b)** qqZZ GM parameter plot (no cuts)

Figure 2: GM Parameter Plots with selection criteria applied. (a) ggH GM parameter plot (no cuts), (b) qqZZ GM parameter plot (no cuts). The bottom row represents the values of the coefficients a_i. The rows and columns are defined as they were in Fig. 1.

We hypothesized that using truth-level data without cuts could reveal stronger correlations. Fig. 2 depicts the GM parameter plots for the subsequent analysis done with zero cuts.

In this case, the spin correlations along the diagonal are indeed much stronger than the case where cuts were placed.

Additionally, the values of concurrence are now physical:

In the above relation, we have the concurrence for ggH close to one, as expected, and the concurrence for qqZZ suggesting that entanglement is present however to a lower degree than with ggH.

- For ggH (no cuts): $0 < c^2_{MB} = 0.916866 < 1$
- For qqZZ (no cuts): $0 < c^2_{MB} = 0.627143 < 1$

5. Conclusion

This proceeding discusses the application of quantum tomography on Higgs to ZZ to 4 lepton data. We present results for the full spin density matrix and concurrence for the cases of the standard ATLAS selection criteria applied as well as the case of no cuts. With no cuts applied, the concurrence of the ggH was close to one, confirming our hypothesis that this is a maximally entangled state. For qqZZ, the concurrence was substantially lower than for ggH, but still non zero, indicating that entanglement is present, however to a lesser degree. This study lays the groundwork for future research on quantifying entanglement in ATLAS collisions. The next step of this work is to calculate the Bell operators and test for Bell's inequality violation.

References

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