PROBING QUANTUM ENTANGLEMENT USING H→ ZZ AT THE ATLAS EXPERIMENT

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1 ABSTRACT/INTRO

❖ Use quantum tomography to reconstruct the full spin density matrix ρ for HZZ and qqZZ.

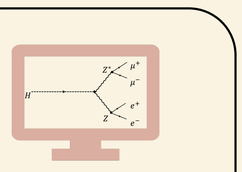
❖ Allows us to: visualize quantum correlations between Z bosons & search for signs of new physics

❖ Use spin-1 GM matrices as basis

❖ Assume massless leptons

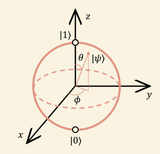
❖ Kraus operator is diagonal:
$K_{total} = diag(c_L, 0, c_R) \otimes diag(c_L, 0, c_R)$

2 OVERVIEW OF PROCESS & DEFINITION OF ρ



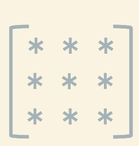
Use e- and μ- as proxy for Z boson spin states

Boost to rest frame of parent particles



Calculate coefficients of ρ using quantum tomography

Symmetrize Z bosons



Consistency check:

$0 < det\rho < 1$

$Tr(\rho) = 1$

$0 < Eigenvalues < 1$

Calculate concurrence and Bell operator

$I_3^{max} > 2$

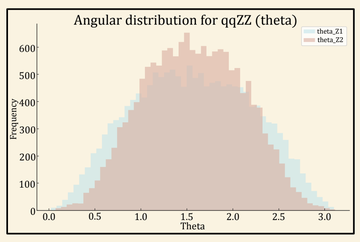
$c_{MB}^2 < 0$

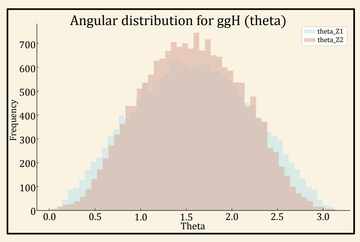
$$\rho = \frac{1}{9}\mathbb{I}_3 \otimes \mathbb{I}_3 + \sum_{i=1}^{8} a_i \lambda_i \otimes \frac{1}{3}\mathbb{I}_3 + \sum_{j=1}^{8} b_j \frac{1}{3}\mathbb{I}_3 \otimes \lambda_j + \sum_{i,j=1}^{8} c_{ij} \lambda_i \otimes \lambda_j$$

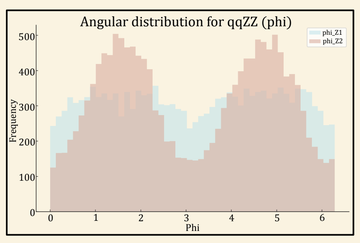
$$\hat{a}_i = \hat{b}_i = \frac{1}{16}\langle \phi_i^P(\hat{n}_1) + \phi_i^P(\hat{n}_2) \rangle_{avg}$$

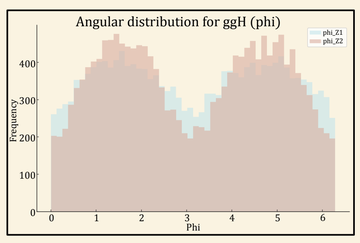
$$\hat{c}_{ij} = \hat{c}_{ji} = \frac{1}{16}\langle \phi_i^P((\hat{n}_1))\phi_j^P(\hat{n}_2) + \phi_j^P(\hat{n}_1)\phi_i^P(\hat{n}_2) \rangle_{avg}$$

3 ANGULAR INFO









All angles are defined in the rest frame of the parent particle.

$0 \leq \theta \leq \pi$ and $0 \leq \phi \leq 2\pi$

4 INTERPRETATION/KEY INSIGHTS

❖ For qqZZ, we **do not** expect entanglement

❖ For ggH, we **do** expect entanglement

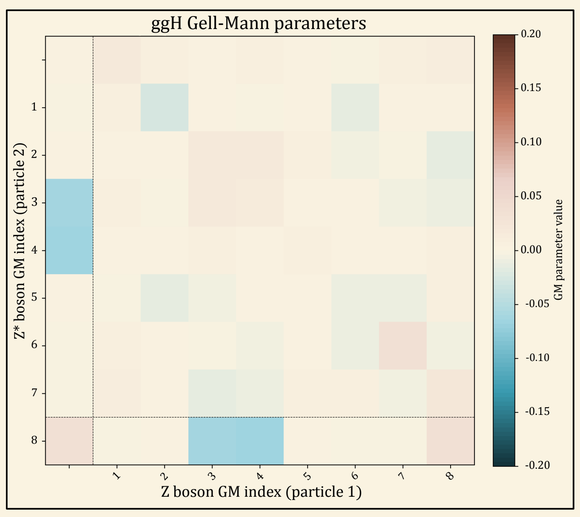
❖ Doesn't seem to be much of a difference between the two processes
★ Why are we unable to fully capture spin correlations in ggH?

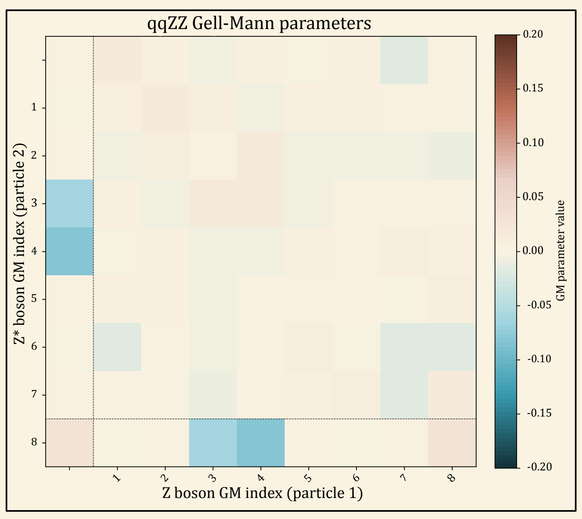
❖ qqZZ, concurrence is: $c_{MB}^2 = -0.4205 < 0$

❖ ggH, concurrence is: $c_{MB}^2 = -0.4068 < 0$

inconclusive result

5 GM PARAMETER COLOR PLOTS





Mass cut applied to both: $\mathrm{abs(m4l\_fsr-122.5)} < 7.51$

6 CONCLUSION & OUTLOOK

❖ Complete analysis of ggH(200 GeV) sample for comparison

❖ Compute Bell operator to test for Bell inequality violation

❖ Understand why current study isn't showing entanglement (improper symmeterization of bosons?)

❖ Promising proof-of-concept for applying quantum tomography to LHC data

References:
Ashby-Pickering, R., Barr, A.J. & Wierzchucka, A. Quantum state tomography, entanglement detection and Bell violation prospects in weak decays of massive particles. J. High Energ. Phys. 2023, 20 (2023). https://doi.org/10.1007/JHEP05(2023)020

Datasets used:
mc16_13TeV.345060.PowhegPythia8EvtGen_NNLOPS_nnlo_30_ggH125_ZZ4l.root
mc16_13TeV.364250.Sherpa_222_NNPDF30NNLO_llll.root

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ATLAS EXPERIMENT

Yale