Probing Quantum Information through Higgs Boson Decays: Experimental Opportunities at the LHC and Beyond

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Focus of the Talk

- A forward-looking strategy to explore how Higgs boson decays—especially the channel $H \to ZZ^* \to 4\ell$ can be used to probe fundamental quantum information observables with an emphasis on methodological ideas and future experimental prospects.

Outline of the Talk

- I. ***Motivation & Strategic Framing***
  – QI meets HEP; Higgs as a probe; HL-LHC to FCC-hh

  II. ***Theoretical Framework: Spin & Angular Tools***
  – SDM formalism; qutrit basis; spherical harmonics

  III. ***Methodology: Entanglement Tests & Systematics***
  – Null hypothesis; CP tests; likelihood fits

  IV. ***Experimental Reach & Observable Classification***
  – HL-LHC reach; BSM sensitivity; observable types

  V. ***Collider Comparison & Extensions***
  – ZZ* vs other channels; FCC-hh vs Muon Collider

  VI. ***Vision, Strategy & Conclusions***
  – Strategic role of QI; roadmap to tomography

Quantum Information Science Meets High-Energy Physics

- QIS: Entanglement, coherence, non-locality
- HEP: Clean, relativistic quantum systems
- Colliders as testbeds for quantum structure
- 2025 European Strategy supports QI–HEP synergy

Strategic Framing

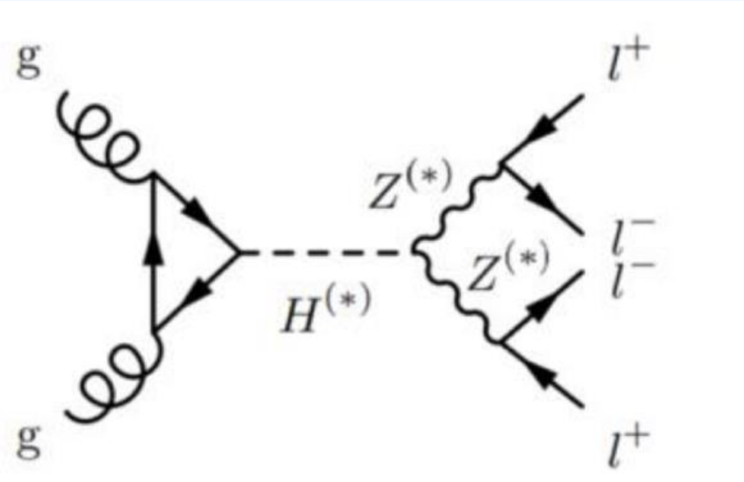
- HL-LHC: 50k H → ZZ* → 4ℓ events by 2040
- FCC-hh: 100 x stats, boosted Higgs
- Muon Collider: cleanest lab for QI tests
- Strategic opportunity for foundational QI studies

Higgs Decays as Quantum Probes

- Higgs: spin-0, no initial polarization
- $H \to ZZ^* \to 4\ell$: probing entanglement, coherence, and non-locality
- Each Z boson acts as a qutrit
- EPR-like entangled system from scalar decay

Why H → ZZ* → 4ℓ?

- Golden channel for spin correlations: clean, fully reconstructable final state
- Low background and excellent resolution
- No missing energy, all angles reconstructable
- Full kinematic and angular information accessible
- Sensitive to spin, CP, and entanglement structure



Spin Density Matrix Framework

- ρ_{ZZ}: 9×9 for spin-1 ⊗ spin-1
- Encodes polarization, coherence, entanglement
- Reconstructed via angular distributions
- Key for observable design and tomography

Qutrit Basis and Angular Momentum

- Z bosons: spin-1 → qutrits
- Basis: $|+1\rangle$, $|0\rangle$, $|-1\rangle$
- Total angular momentum conservation
- Tensor decomposition: spherical harmonics Y_{JM}

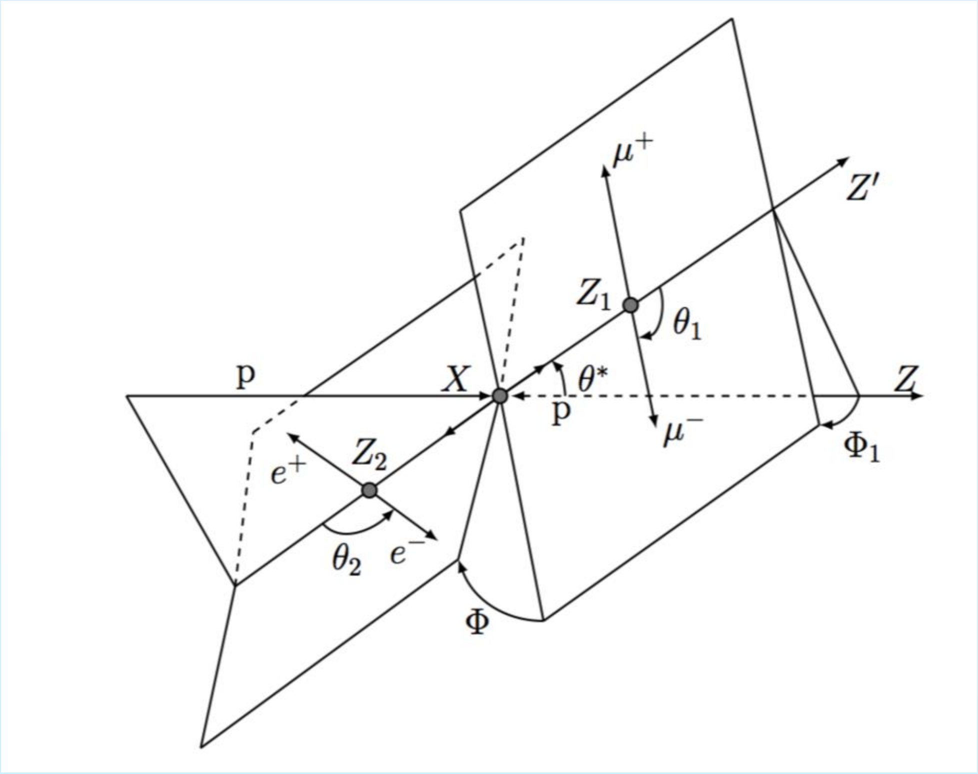
Observable Design from SDM

- Coefficients $C_{J_1M_1J_2M_2} \leftrightarrow$ entanglement
- Separable: only diagonal entries non-zero
- Non-zero off-diagonals → quantum interference
- Extract via spherical harmonic projections

Constructing the Observables

- Input: angles θ_1, θ_2, ϕ
- Expand distribution: $d^3\sigma/d\cos\theta_1 \, d\cos\theta_2 \, d\phi = \Sigma \, C_{ijk} \, Y_i \, Y_j \, e^{ik\phi}$
- Extract SDM elements C_{ijk}
- Angular analysis → QI observables

- Five angles describe the 4ℓ system: θ_1, θ_2, φ, Φ, θ^*
- Sensitive to helicity interference and CP violation
- Standard in spin-parity studies of Higgs boson
- Basis for extracting spherical harmonic moments



Entanglement Witnesses

- Specific SDM elements = witnesses
- $C_{2,1,2,-1}$, $C_{2,2,2,-2}$: vanish if separable
- Non-zero ⇒ entangled state
- Simple, robust, and testable

Null Hypothesis: Non-Entangled States

- Construct separable benchmark: $|0,0\rangle$
- Fully longitudinal Z bosons = no entanglement
- Use as null hypothesis for tests
- Compare data to this state statistically

Systematic Effects and Realistic Distortions

- Lepton miss-pairing smears angular distributions
- Detector acceptance: uneven ϕ, θ coverage
- QCD/EW corrections modify SDM structure
- Must propagate all uncertainties into observables

Sensitivity to CP Violation and BSM

- Off-diagonal SDM ↔ CP-sensitive observables
- Interference terms → imaginary components
- Observable $C_{2,2,2,-2}$ sensitive to CP-odd phases
- Access to new physics beyond SM Higgs couplings

Frame Dependence and Basis Choices

- Some observables frame-invariant, others not
- Must match theory and experiment consistently
- Frame choice impacts interpretation of SDM

Likelihood-Based Hypothesis Tests

- Define test statistic: $q = -2 \log(L_{null} / L_{alt})$
- Use toy MC for distribution under each hypothesis
- Compare separable (null) vs entangled (data)
- Extract significance of QE observation

Entanglement Signatures in SDM

- SDM off-diagonals ⇒ interference
- Measure: purity, concurrence, negativity
- Bell inequality–inspired constraints
- Geometry of spin space encodes quantum structure

Tomography Strategy: Long-Term Goal

- Goal: reconstruct full SDM (81 components)
- Requires full angular distribution + mass correlations
- Similar to quantum optics tomography
- Challenging, but feasible at FCC or muon collider

HL-LHC Sensitivity

- ~50k events expected in 4ℓ by HL-LHC
- Statistical reach for entanglement observables
- Needs angular efficiency unfolding
- First test of QI observables at energy frontier

Classification of Observables

- ① Entanglement witnesses
- ② Bell-type (non-locality-sensitive)
- ③ CP-sensitive interference terms
- ④ Frame-invariant structure coefficients
- ⑤ Tomographic full SDM components

Summary of Observable Flow

- Extract angular distributions
- Project onto spherical harmonics
- Derive SDM elements
- Test QE vs separable hypothesis
- Classify by symmetry and sensitivity

BSM Sensitivity via QE Observables

- Some BSM models modify Z boson polarizations
- Deviations in SDM structure signal new physics
- Effective Field Theory: anomalous couplings shift observables
- QE observables complement traditional fits

Alternative Higgs Decay Channels: Comparison

- $H \rightarrow \gamma\gamma$: clean but no spin analysis
- $H \rightarrow WW^*$: missing energy
- $H \rightarrow \tau\tau$: poor resolution
- $H \rightarrow ZZ^* \rightarrow 4\ell$: best angular access

Collider Comparisons: QE Potential

- HL-LHC: first reach, but limited by stats and systematics
- FCC-hh: x100 more events; access to high-pT Higgs
- Muon Collider: low-background, clean lepton reconstruction
- Each collider complements the others for QI goals

Quantum Coherence Beyond Entanglement

- Coherence: basis-dependent but experimentally observable
- Quantum Discord: partial quantumness without entanglement
- Steering and contextuality: advanced diagnostics
- All encoded in SDM and angular correlations

CP Violation and Interference

- CP-odd observables from interference terms
- Imaginary SDM components → absorptive phases
- Complementary to triple-product asymmetries
- Potential to probe loop-level CPV in Higgs sector

Frame-Invariant Observables

- Some observables invariant under boosts/rotations
- Robust against detector effects
- Good for comparisons between experiments
- Examples: traces, purities, diagonal SDM entries

Systematic Effects and Realistic Distortions

- Angular resolution → smearing of harmonics
- Lepton miss-pairing → smears angular distributions
- Detector acceptance effects → distort spherical projections
- Need full detector simulation or unfolding
- QCD/EW corrections modify SDM structure
- Must propagate all uncertainties into observables

Strategic Opportunity for QI at Colliders

- QI tools apply naturally to collider data
- Spin correlations $\leftrightarrow$ quantum observables
- Entanglement tests are within experimental reach
- A new avenue for foundational tests in HEP

Summary & Conclusions

- Higgs decays offer clean quantum systems
- QI observables from angular analysis
- Entanglement, CP, and BSM sensitivity
- HL-LHC is first step; future colliders essential
- A new paradigm for collider-based quantum tests

Additional Slides

Comparison of Higgs Decay Channels

- $H \to ZZ^* \to 4\ell$: full spin access, clean
- $H \to WW^*$: missing neutrinos, incomplete kinematics
- $H \to \gamma\gamma$: no angular correlations
- $H \to \tau\tau$: spin info diluted by decays
- $H \to b\bar{b}$: large QCD background

Future Collider Potential for QE Studies

- HL-LHC: sufficient statistics to initiate QE studies
- FCC-hh: 20–30 ab^{-1} → precision SDM reconstruction
- Muon collider: optimal angular resolution, no pileup
- Each brings unique capabilities for entanglement tests

BSM and CP Sensitivity in Entanglement Observables

- CP-odd operators → imaginary SDM elements
- Effective couplings shift off-diagonal C coefficients
- Quantum observables = precision probes for loop-level BSM
- Complementarity with EFT, angular asymmetries

Exotic Higgs Decays & Detector Innovations

- Higgs decays to hidden sectors could show quantum patterns
- Displaced vertices may retain angular correlations
- Timing layers, tracking upgrades help preserve spin info
- Quantum-aware detector design as long-term strategy

Frame-Invariant SDM Structures

- Observable classes based on transformation properties
- CP-even, CP-odd, boost-invariant structures
- Basis choice impacts interpretation, not measurement
- Map observables to EFT coefficients in any frame

Classification of Quantum Observables

- Bell inequalities → non-locality
- Entanglement witnesses → separability
- Coherence measures → basis-dependent quantum structure
- Steering & discord: operational diagnostics

Quantum Tomography Summary

- Goal: reconstruct full 81-component SDM
- Use: full angular and mass distributions
- Requires: detector unfolding, acceptance correction
- Application: benchmark full quantum state of ZZ system

Strategy Flowchart

- Input: 4-lepton kinematics
- Step 1: Compute angular variables
- Step 2: Project onto harmonics
- Step 3: Extract SDM
- Step 4: Null hypothesis test
- Step 5: BSM and QI interpretations

Angular Conventions & Basis Definitions

- Gottfried-Jackson vs. Helicity basis
- Polar and azimuthal angles θ, ϕ in Z rest frames
- Consistency essential across theory and experiment

References

- [1] arXiv:2504.00086 – Afik et al. (2025)
- [2] arXiv:2209.13441 – Aguilar-Saavedra et al. (2022)
- [3] arXiv:2402.07972 – Barr et al. (2024)
- [4] arXiv:2505.11870 – Spin diagnostics in H → VV
- [5] arXiv:2504.03841 – SM predictions and entanglement
- [6] arXiv:2411.13464 – Entanglement witness construction
- [7] arXiv:2409.16731 – Frame-invariant observables
- [8] arXiv:2504.12382 – BSM benchmark scenarios