Quantum Entanglement Is Quantum: Insights from Diboson Systems at LHC

based on JHEP12(2025)122, JHEP11(2025)158, arXiv.2604.16218

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1. Motivation
2. $pp \to 4\ell$
3. Higgs decay $h \to VV^\star$
4. Summary

Outline

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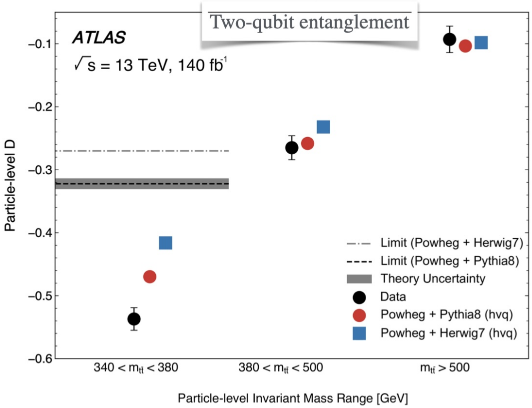
Introduction

- Observation of entanglement at highest energies



EUROPEAN ORGANISATION FOR NUCLEAR RESEARCH (CERN)

Two-qutrit entanglement

Submitted to: PRL

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March 30, 2026

Measurements of Z-boson pair entanglement in decays of Higgs bosons at the ATLAS experiment

The ATLAS Collaboration

Entanglement is a key property of quantum systems. In this Letter the first measurements of quantum entanglement between spins in pairs of Z bosons are reported, using proton–proton collision data from the Large Hadron Collider (LHC) at center-of-mass energies of 13 TeV and 13.6 TeV, recorded with the ATLAS detector. Measurements of angular observables sensitive to ZZ^* spin-density-matrix elements in the $H \to ZZ^* \to \ell^+\ell^-\ell^+\ell^-$ process yield coefficients $C_{2,1,2,-1} = -0.71 \pm 0.45$ and $C_{2,2,2,-2} = 0.08 \pm 0.44$, consistent with their Standard Model predictions. A complementary hypothesis test using the full angular distribution, and relying on several Standard Model assumptions in the decays, provides substantially higher sensitivity to quantum correlations and disfavors the separable-state hypothesis at a significance of 4.7 standard deviations (expected 4.9σ) relative to the entangled Standard Model hypothesis. These results provide strong evidence of quantum entanglement between massive bosons (spin qutrits) at the electroweak scale.

(Nature 633 (2024) 542, CERN-EP-2026-061)

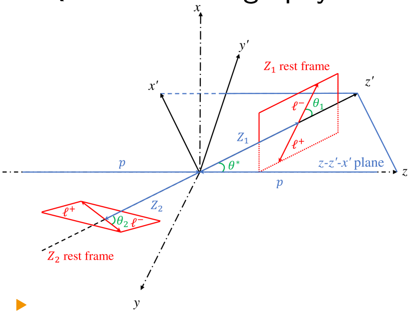
- Interplay of quantum information theory, precision physics, and BSM searches
- $h \to VV^*$ one of the most prominent channels to probe quantum phenomena between two qutrits and new physics at colliders.

Diboson as a two-qutrit system

- The most general two-qutrit system can be represented by

$$\rho = \frac{1}{9}\left(\mathbb{I}_3 \otimes \mathbb{I}_3 + A^1_{LM} T^L_M \otimes \mathbb{I}_3 + A^2_{LM} \mathbb{I}_3 \otimes T^L_M + C_{L_1 M_1 L_2 M_2} T^{L_1}_{M_1} \otimes T^{L_2}_{M_2}\right),$$

- Quantum tomography: Consider $h \to ZZ \to \ell_1^+ \ell_1^- \ell_2^+ \ell_2^+$



$$\frac{1}{\sigma}\frac{d\sigma}{d\Omega_1 d\Omega_2} = \left(\frac{3}{4\pi}\right)^2 \mathrm{Tr}\left\{\rho\left(\Gamma_1(\theta_1,\phi_1)\otimes\Gamma_2(\theta_2,\phi_2)\right)^{\mathrm{T}}\right\}$$

$$= \frac{1}{(4\pi)^2}\Bigg[1 + A^1_{LM} B_L Y^M_L(\Omega_1) + A^2_{LM} B_L Y^M_L(\Omega_2)$$

$$+ C_{L_1 M_1 L_2 M_2} B_{L_1} B_{L_2} Y^{M_1}_{L_1}(\Omega_1) Y^{M_2}_{L_2}(\Omega_2)\Bigg].$$

-

$$\frac{1}{\sigma}\int \frac{d\sigma}{d\Omega_1 d\Omega_2} Y^M_L(\Omega_i)^* \, d\Omega_1 d\Omega_2 = \frac{B_L}{4\pi} A^i_{LM}$$

$$\frac{1}{\sigma}\int \frac{d\sigma}{d\Omega_1 d\Omega_2} Y^{M_1}_{L_1}(\Omega_1)^* Y^{M_2}_{L_2}(\Omega_2)^* \, d\Omega_1 d\Omega_2 = \frac{B_{L_1} B_{L_2}}{(4\pi)^2} C_{L_1 M_1 L_2 M_2}$$

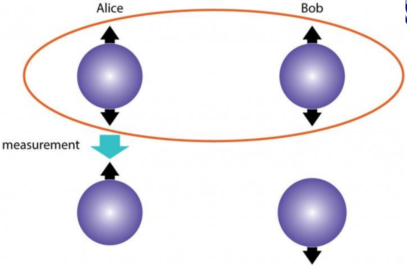
$$\boxed{\begin{aligned} B_1 &= -\sqrt{2\pi}\,\eta_\ell \\ B_2 &= \sqrt{2\pi/5} \end{aligned}}$$

Quantum Entanglement

- Quantum state of two subsystems A and B is separable if its density matrix ρ can be written as a convex sum:

$$\rho = \sum_i p_i \rho_A^i \otimes \rho_B^i ,$$

- If the state is not separable, it is entangled.



- Measurement in one subsystem immediately affect the other, even if they are causally disconnected
- Concurrence C a convenient measure of entanglement, with $C \neq 0$ for entangled systems.

$$(\mathcal{C}(\rho))^2 \geqslant 2\max\left\{0,\ [\rho^2]-[(\rho_A)^2],\ [\rho^2]-[(\rho_B)^2]\right\} \equiv C_{\rm LB}^2 ,$$

$$(\mathcal{C}(\rho))^2 \leqslant 2\min\left\{1-[(\rho_A)^2],\ 1-[(\rho_B)^2]\right\} \equiv C_{\rm UB}^2 .$$

- $C_{\rm UB} = 0$ separable states and $C_{\rm LB} > 0$ entangled states

(Mintert, Buchleitner 2007)

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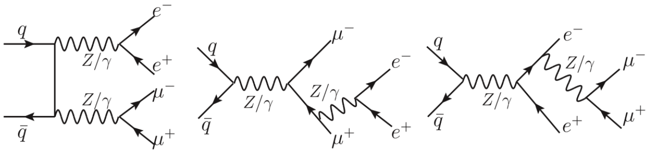
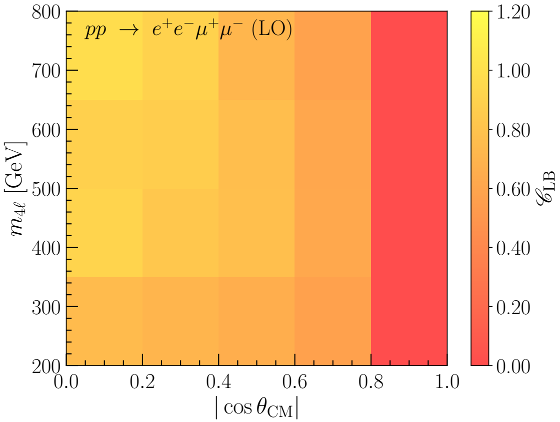
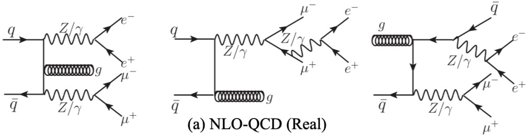
$pp \to 4\ell$: Leading Order



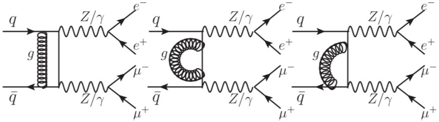


- 81 GeV $< m_{\ell^+\ell^-} <$ 101 GeV.
- Central Z bosons (small $|\cos\theta_{\text{CM}}|$) exhibit stronger entanglement. (Gonçalves, **AK**, Krauss, Navarro '25) See also: Barr 2106.01377, Saavedra et al 2209.13441, Maltoni et al 2307.09675, Fabbrichesi et al 2302.00683, Fabbri et al 2307.13783...

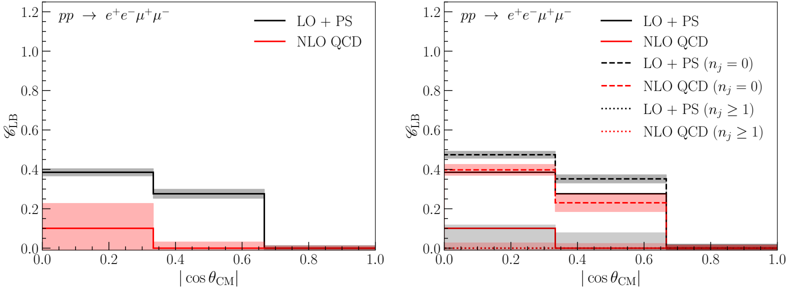
$pp \to 4\ell$: NLO QCD



(a) NLO-QCD (Real)

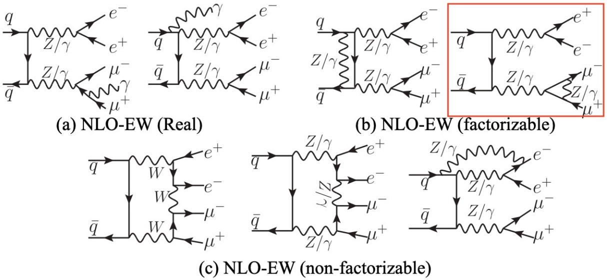


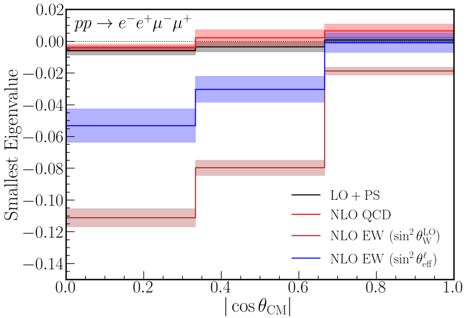
(b) NLO-QCD (Virtual)



(Gonçalves, **AK**, Krauss, Navarro 2025)

$pp \to 4\ell$: NLO EW





- Density matrix must satisfy:
  1. Unit Trace: $\mathrm{Tr}(\rho) = 1$
  2. Hermitian: $\rho^\dagger = \rho$
  3. Positive semi-definite: $\psi\rho\psi \geqslant 0$
- Spin analyzing factor η_ℓ

$$\eta_\ell = \frac{1 - 4\sin^2\theta_W}{1 - 4\sin^2\theta_W + 8\sin^4\theta_W}.$$

- 4% shift in $\sin^2\theta_W$ can induce $\frac{\eta_\ell^{\mathrm{NLO}}}{\eta_\ell^{\mathrm{LO}}} \approx 0.66$
- NLO-EW effects can be partially absorbed into $\sin^2\theta_{\mathrm{eff}}^{\ell}$

(Gonçalves, **AK**, Krauss, Navarro 2025)

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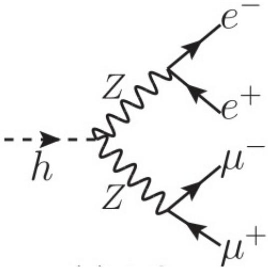
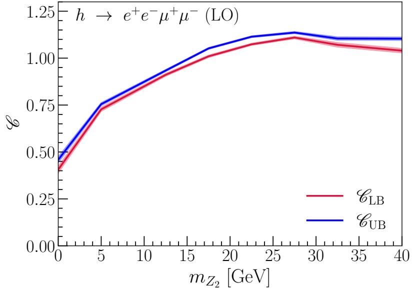
$h \to e^+e^-\mu^+\mu^-$ at leading order



- Density matrix strongly constrained by symmetries of decay (spin 0 Higgs boson)
- Due to conservation of angular momentum and parity only two independent parameters
- $C_{2,2,2,-2} \neq 0$ or $C_{2,1,2,-1} \neq 0$ implies entanglement

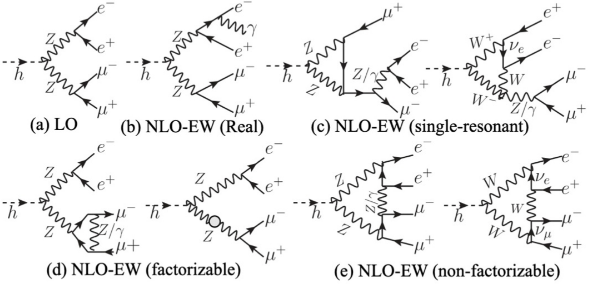
$$\rho_{\mathrm{LO}} = \begin{pmatrix} 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & \frac{1}{3}C_{2,2,2,-2} & 0 & \frac{1}{3}C_{2,1,2,-1} & 0 & \frac{1}{3}C_{2,2,2,-2} & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & \frac{1}{3}C_{2,1,2,-1} & 0 & \frac{1}{3}\left(3 - 2C_{2,2,2,-2}\right) & 0 & \frac{1}{3}C_{2,1,2,-1} & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & \frac{1}{3}C_{2,2,2,-2} & 0 & \frac{1}{3}C_{2,1,2,-1} & 0 & \frac{1}{3}C_{2,2,2,-2} & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \end{pmatrix}$$



(Saavedra, Bernal, Casas, Moreno '22, Gonçalves, **AK**, Krauss, Navarro '25)

$h \to e^+e^-\mu^+\mu^-$ at NLO-EW

- While NLO EW corrections on partial width are only 1.4%, there are sizable effects on angular coefficients



(a) LO (b) NLO-EW (Real) (c) NLO-EW (single-resonant)

(d) NLO-EW (factorizable) (e) NLO-EW (non-factorizable)

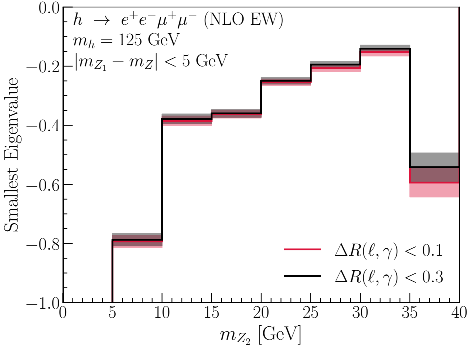
Coefficient	LO	NLO	NLO/LO
$A^1_{2,0}$	$-0.4910(8)$	$-0.486(1)$	0.989
$A^2_{2,0}$	$-0.4915(8)$	$-0.471(1)$	0.958
$C_{1,0,1,0}$	$-0.65(1)$	$0.42(3)$	-0.646
$C_{1,1,1,-1}$	$1.008(9)$	$-0.37(3)$	-0.279
$C_{2,1,2,-1}$	$-0.993(2)$	$-0.985(3)$	0.992
$C_{2,0,2,0}$	$1.335(2)$	$1.328(4)$	0.995
$C_{2,2,2,-2}$	$0.646(2)$	$0.635(3)$	0.983

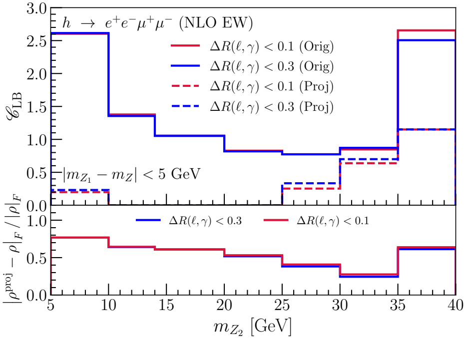
$|m_{Z_1} - m_Z| < 5\,\mathrm{GeV}$ and $m_{Z_2} > 10\,\mathrm{GeV}$

$$\rho^{\mathrm{LO}}_{ZZ} = \begin{pmatrix} 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0.193(1) & 0 & -0.313(1) & 0 & 0.192(1) & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & -0.313(1) & 0 & 0.611(1) & 0 & -0.311(1) & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0.192(1) & 0 & -0.311(1) & 0 & 0.193(1) & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \end{pmatrix} \quad \rho^{\mathrm{NLO}}_{ZZ} = \begin{pmatrix} 0.102(4) & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0.103(4) & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0.100(4) & 0 & -0.207(4) & 0 & 0.188(1) & 0 & 0 \\ 0 & 0.103(4) & 0 & 0.003(1) & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & -0.207(4) & 0 & 0.591(1) & 0 & -0.199(4) & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0.004(1) & 0 & 0.109(4) & 0 \\ 0 & 0 & 0.188(1) & 0 & -0.199(4) & 0 & 0.100(4) & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0.109(4) & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0.098(4) \end{pmatrix}$$

(Gonçalves, **AK**, Krauss, Navarro 2025)

$h \to e^+e^-\mu^+\mu^-$ at NLO-EW



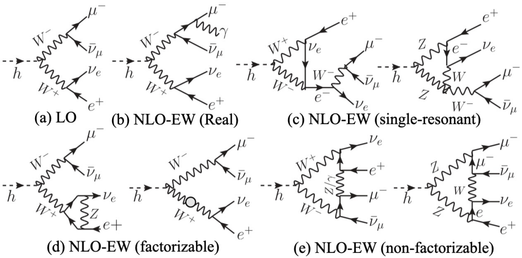


- Projecting original density matrix to a nearest positive semi-definite Hermitian matrix with unit trace $\rho^{\rm proj}$,

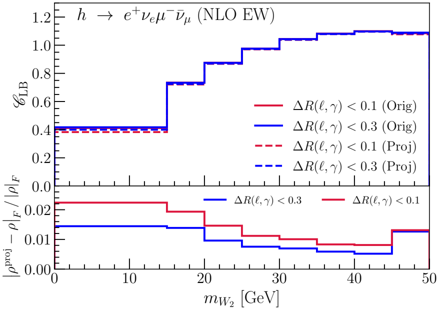
$$\left|\rho^{\rm proj} - \rho\right|_F \equiv \sqrt{\sum_{i,j}\left|\rho_{ij}^{\rm proj} - \rho_{ij}\right|^2}.$$

(Gonçalves, **AK**, Navarro 2025)

$h \to e^+\nu_e\mu^-\bar{\nu}_\mu$ at NLO-EW



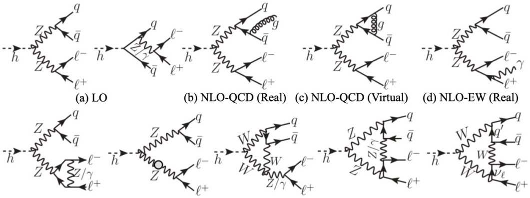
Coefficient	LO	NLO EW	NLO/LO
$A^1_{2,0}$	$-0.5769(6)$	$-0.550(1)$	0.953
$A^2_{2,0}$	$-0.5763(6)$	$-0.550(1)$	0.954
$C_{1,0,1,0}$	$-0.5917(3)$	$-0.6034(4)$	1.0198
$C_{1,1,1,-1}$	0.9439(3)	0.9429(3)	0.9989
$C_{2,1,2,-1}$	$-0.939(1)$	$-0.949(2)$	0.989
$C_{2,0,2,0}$	1.401(2)	1.383(2)	0.987
$C_{2,2,2,-2}$	0.5885(5)	0.590(1)	1.002
$A^1_{1,0}$	0	$-0.0122(3)$	–
$A^2_{1,0}$	0	$-0.0115(3)$	–
$C_{1,-1,2,1}$	0	$-0.0153(6)$	–
$C_{1,0,2,0}$	0	0.0244(7)	–
$C_{2,-1,1,1}$	0	$-0.0169(6)$	–
$C_{2,0,1,0}$	0	0.0232(7)	–



- $|m_{W_1} - m_W| \lesssim 10$ GeV and 10 GeV $\lesssim m_{W_2} \lesssim 40$ GeV.
- New angular coefficients acquire nonzero value
- Mild corrections to angular coefficients of upto 5%

(Gonçalves, **AK**, Navarro 2025)

$h \to \ell^+\ell^- q\bar{q}$



(a) LO (b) NLO-QCD (Real) (c) NLO-QCD (Virtual) (d) NLO-EW (Real)

(e) NLO-EW (Virtual)

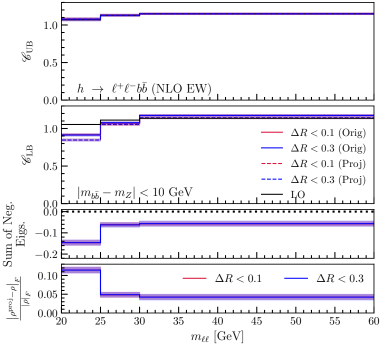
- In $h \to VV^*$, the off-shell V have a scalar component to its propagator:

$$-g^{\mu\nu} + \frac{q^\mu q^\nu}{m_V^2} = \underbrace{\left(-g^{\mu\nu} + \frac{q^\mu q^\nu}{q^2}\right)}_{\text{spin-1 component}} + \underbrace{\left(\frac{q^\mu q^\nu}{q^2} - \frac{q^\mu q^\nu}{m_V^2}\right)}_{\text{spin-0 component}}$$

  When coupled to fermions, the contribution of scalar component is $\mathcal{O}(m_f^2/m_V^2)$.
- Requiring the hadronic bosons to be on-shell $|m_{V_{\text{had}}} - m_V| < 10\,\text{GeV}$
- To suppress diagrams with quarks from Yukawa couplings and leptons from Z/γ radiation, we require $m_{\ell\ell} > 20\ \text{GeV}$.

$h \to \ell^+\ell^- q\bar{q}$ at NLO EW

	LO	NLO$_{\Delta R<0.1}$	NLO$_{\Delta R<0.1}$/LO	NLO$_{\Delta R<0.3}$	NLO$_{\Delta R<0.3}$/LO
	$h \to \ell^+\ell^- c\bar{c}$				
$A^1_{2,0}$	$-0.329(1)$	$-0.320(3)$	$0.97(1)$	$-0.324(2)$	$0.985(7)$
$A^2_{2,0}$	$-0.328(2)$	$-0.323(2)$	$0.985(9)$	$-0.326(2)$	$0.994(9)$
$C_{1,1,1,-1}$	$1.047(4)$	$1.01(1)$	$0.96(1)$	$1.02(1)$	$0.97(1)$
$C_{2,1,2,-1}$	$-1.041(3)$	$-1.043(9)$	$1.002(9)$	$-1.043(9)$	$1.002(9)$
$C_{1,0,1,0}$	$-0.766(4)$	$-0.66(8)$	$0.9(1)$	$-0.67(8)$	$0.9(1)$
$C_{2,0,2,0}$	$1.233(3)$	$1.23(1)$	$0.997(8)$	$1.23(1)$	$0.997(8)$
$C_{2,2,2,-2}$	$0.764(3)$	$0.758(8)$	$0.99(1)$	$0.758(7)$	$0.99(1)$
	$h \to \ell^+\ell^- b\bar{b}$				
	LO	NLO$_{\Delta R<0.1}$	NLO$_{\Delta R<0.1}$/LO	NLO$_{\Delta R<0.3}$	NLO$_{\Delta R<0.3}$/LO
$A^1_{2,0}$	$-0.329(1)$	$-0.318(4)$	$0.96(1)$	$-0.322(4)$	$0.98(1)$
$A^2_{2,0}$	$-0.328(1)$	$-0.323(5)$	$0.98(2)$	$-0.325(5)$	$0.99(2)$
$C_{1,1,1,-1}$	$1.046(3)$	$0.945(8)$	$0.903(8)$	$0.950(7)$	$0.908(7)$
$C_{2,1,2,-1}$	$-1.035(3)$	$-1.041(6)$	$1.006(6)$	$-1.041(6)$	$1.006(6)$
$C_{1,0,1,0}$	$-0.764(3)$	$-0.60(2)$	$0.79(3)$	$-0.61(1)$	$0.79(1)$
$C_{2,0,2,0}$	$1.218(4)$	$1.22(1)$	$1.002(9)$	$1.22(1)$	$1.002(9)$
$C_{2,2,2,-2}$	$0.763(3)$	$0.762(5)$	$0.999(8)$	$0.762(4)$	$0.999(7)$



- NLO-EW contribution can reach upto $\mathcal{O}(20\%)$.
- No sign flip for the $L = 1$ coefficients.
- Reconstructed density matrix is more stable than fully-leptonic.

(Gonçalves, **AK**, Navarro 2026)

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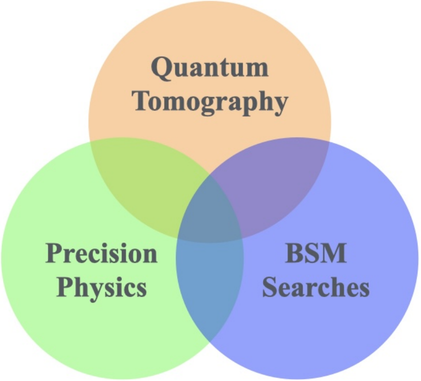
Summary

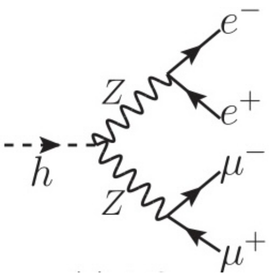
- Higher-order effects can challenge the two-qutrit interpretation of $h \to e^+e^-\mu^+\mu^-$; however, fully leptonic $h \to WW^*$ and semi-leptonic $h \to ZZ^*, WW^*$ channels remain well described by an effective two-qutrit state.
- Quantum tomography serve as powerful tool for precision measurements and searches for new physics



Thank You

Backup slides

$h \to e^+e^-\mu^+\mu^-$ at leading order



- Density matrix strongly constrained by symmetries of decay (spin 0 Higgs boson)

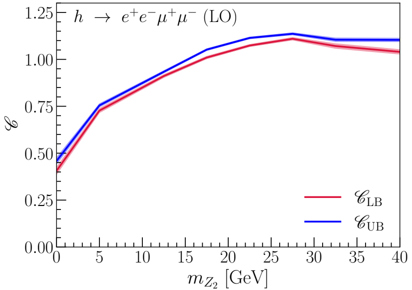
$$A^1_{20} = A^2_{20} \neq 0,$$

$$C_{1,1,1-1} = C_{1,-1,1,1} = -C_{2,1,2,-1} = -C_{2,-1,2,1} \neq 0,$$

$$C_{2,2,2,-2} = C_{2,-2,2,2} = -C_{1,0,1,0} = 2 - C_{2,0,2,0} \neq 0,$$

$$\frac{A^{2,1}_{20}}{\sqrt{2}} + 1 = C_{2,2,2,-2},$$

$$\rho_{\mathrm{LO}} = \begin{pmatrix} 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & \frac{1}{3}C_{2,2,2,-2} & 0 & \frac{1}{3}C_{2,1,2,-1} & 0 & \frac{1}{3}C_{2,2,2,-2} & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & \frac{1}{3}C_{2,1,2,-1} & 0 & \frac{1}{3}\left(3 - 2C_{2,2,2,-2}\right) & 0 & \frac{1}{3}C_{2,1,2,-1} & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & \frac{1}{3}C_{2,2,2,-2} & 0 & \frac{1}{3}C_{2,1,2,-1} & 0 & \frac{1}{3}C_{2,2,2,-2} & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \end{pmatrix}$$

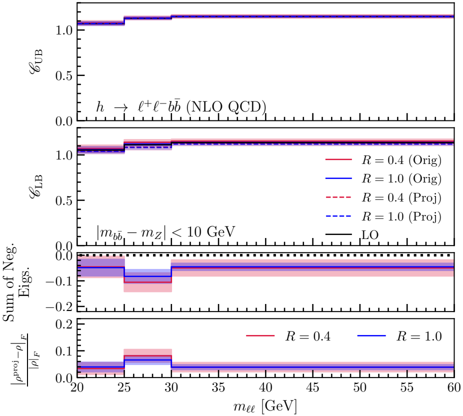


- $C_{2,2,2,-2} \neq 0$ or $C_{2,1,2,-1} \neq 0$ implies entanglement

(Saavedra, Bernal, Casas, Moreno '22, Gonçalves, **AK**, Krauss, Navarro '25)

$h \to \ell^+\ell^- q\bar{q}$ at NLO QCD

	$h \to \ell^+\ell^- c\bar{c}$				
	LO	$\mathrm{NLO}_{R=0.4}$	$\mathrm{NLO}_{R=0.4}/\mathrm{LO}$	$\mathrm{NLO}_{R=1}$	$\mathrm{NLO}_{R=1}/\mathrm{LO}$
$A^1_{2,0}$	$-0.329(1)$	$-0.316(8)$	$0.96(2)$	$-0.326(4)$	$0.99(1)$
$A^2_{2,0}$	$-0.328(1)$	$-0.29(1)$	$0.88(3)$	$-0.315(4)$	$0.96(2)$
$C_{1,1,1,-1}$	$1.047(4)$	$1.07(3)$	$1.02(3)$	$1.07(2)$	$1.02(2)$
$C_{2,1,2,-1}$	$-1.041(3)$	$-1.05(2)$	$1.01(2)$	$-1.04(1)$	$1.00(1)$
$C_{1,0,1,0}$	$-0.766(4)$	$-0.81(3)$	$1.06(4)$	$-0.79(1)$	$1.03(1)$
$C_{2,0,2,0}$	$1.233(3)$	$1.22(2)$	$0.99(2)$	$1.22(1)$	$0.989(8)$
$C_{2,2,2,-2}$	$0.764(3)$	$0.76(2)$	$0.99(2)$	$0.76(1)$	$0.99(1)$
$A^2_{2,1}$	0	$0.19(3)$	–	$0.14(2)$	–
$A^2_{2,2}$	0	$-0.21(3)$	–	$-0.16(2)$	–
$C_{2,0,2,2}$	0	$0.11(3)$	–	$0.08(2)$	–
	$h \to \ell^+\ell^- b\bar{b}$				
	LO	$\mathrm{NLO}_{R=0.4}$	$\mathrm{NLO}_{R=0.4}/\mathrm{LO}$	$\mathrm{NLO}_{R=1}$	$\mathrm{NLO}_{R=1}/\mathrm{LO}$
$A^1_{2,0}$	$-0.329(1)$	$-0.314(8)$	$0.95(2)$	$-0.321(5)$	$0.98(1)$
$A^2_{2,0}$	$-0.328(1)$	$-0.294(7)$	$0.90(2)$	$-0.313(4)$	$0.95(1)$
$C_{1,1,1,-1}$	$1.046(3)$	$1.04(2)$	$0.99(2)$	$1.03(2)$	$0.98(2)$
$C_{2,1,2,-1}$	$-1.035(3)$	$-1.05(3)$	$1.01(3)$	$-1.04(2)$	$1.00(2)$
$C_{1,0,1,0}$	$-0.764(3)$	$-0.80(2)$	$1.05(3)$	$-0.78(1)$	$1.02(1)$
$C_{2,0,2,0}$	$1.218(4)$	$1.22(2)$	$1.00(2)$	$1.22(1)$	$1.00(1)$
$C_{2,2,2,-2}$	$0.763(3)$	$0.77(2)$	$1.01(3)$	$0.76(2)$	$1.00(3)$
$A^2_{2,1}$	0	$0.06(1)$	–	$0.09(1)$	–
$A^2_{2,2}$	0	$-0.07(1)$	–	$-0.10(1)$	–
$C_{2,0,2,2}$	0	$0.03(2)$	–	$0.05(2)$	–



- Effects only hadronic side
- New nonzero coefficients.
- Sensitivity to the choice of jet radius.

(Gonçalves, **AK**, Navarro 2026)