Quantum Observables and Higher-Order Effects in Leptonic $h \to VV^*$ Decays

DG, Kaladharan, Krauss, Navarro '25
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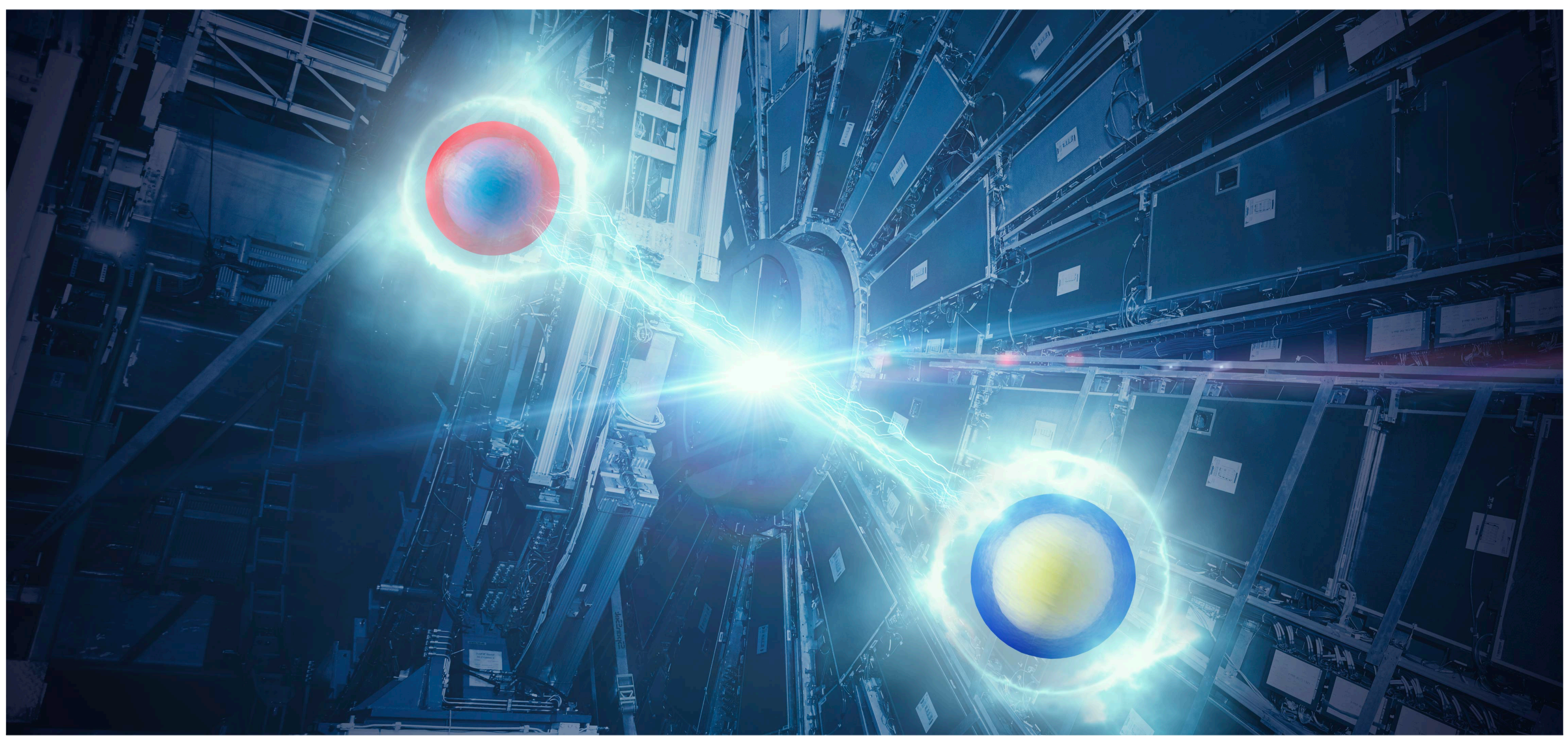
Pheno - 05.12.2026

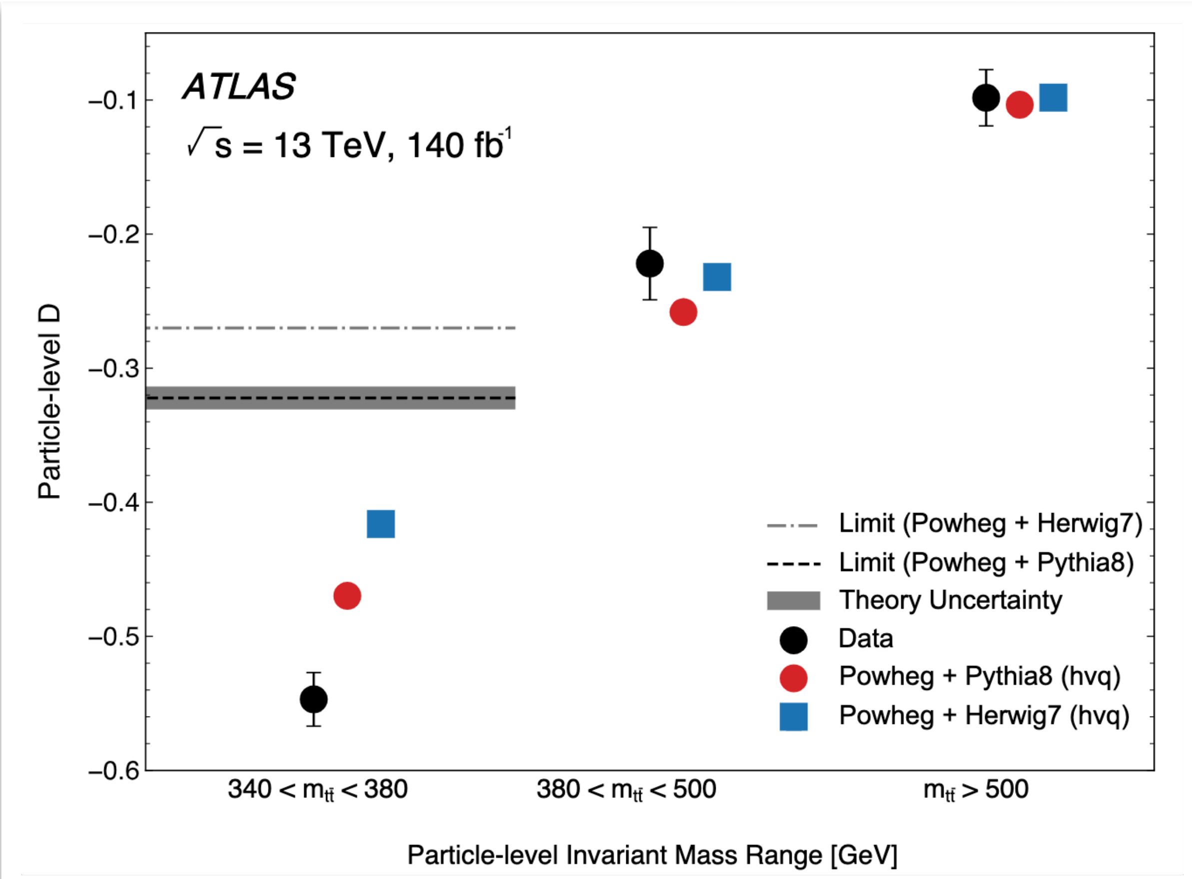
Dorival Gonçalves



Experimental Observation

Two-qubit entanglement:

First observation of entanglement in a pair of quarks and the highest-energy observation



Two-qutrit entanglement:

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.

Barr ’21, ATLAS arXiv:2603.26463, CMS-PAS-HIG-25-011

- Dilepton channel at tt threshold

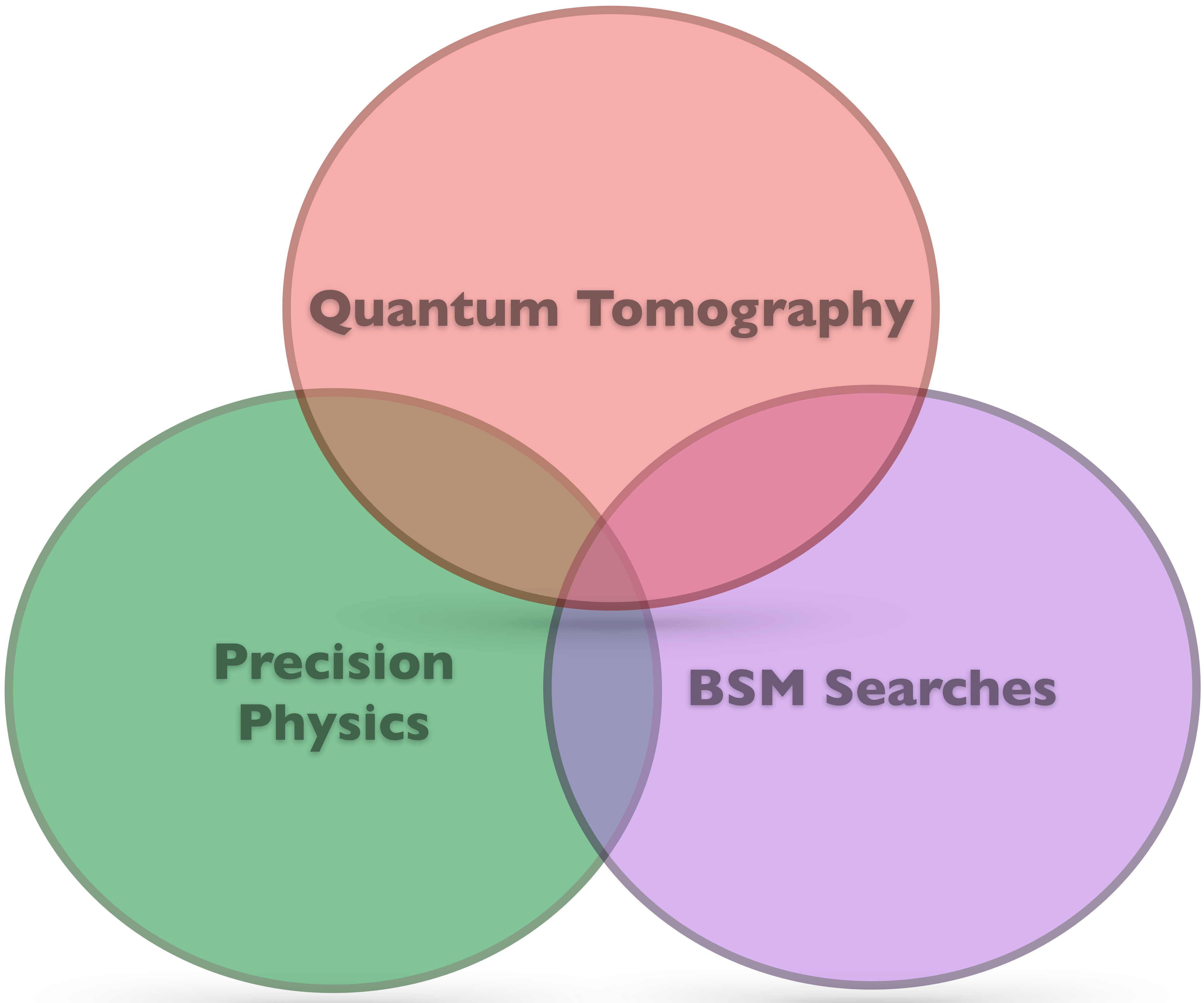
  Afik, Nova ’21; ATLAS Nature vol 633, 542-547 (2024), CMS 2406.03976

- Lepton+jets channel at boosted regime: CMS 2409.11067

  Entanglement above 5σ level, in agreement with theory expectations:

  Dong, **DG**, Kong, Navarro 2305.07075; Han, Low Wu 2310.17696

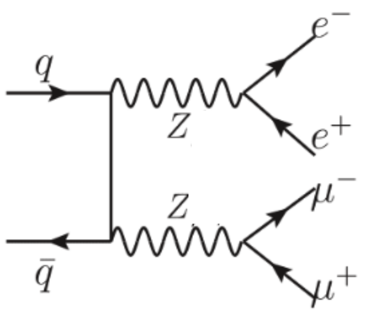
See talks by F. Maltoni & R. Demina


Quantum Tomography
Precision Physics
BSM Searches

Diboson as a two-qutrit system

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

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



ρ is fully characterized by 80 independent real parameters

- Quantum tomography

$$ZZ \to \ell_1^+ \ell_1^- \ell_2^+ \ell_2^- \qquad \frac{1}{\sigma}\frac{d\sigma}{d\Omega_1 d\Omega_2} = \left(\frac{3}{4\pi}\right)^2 \mathrm{Tr}\left\{\rho(\Gamma_1 \otimes \Gamma_2)^T\right\}$$

$$\frac{1}{\sigma}\frac{d\sigma}{d\Omega_1 d\Omega_2} = \frac{1}{(4\pi)^2}\left[1 + A^1_{LM} B_L Y^M_L(\theta_1,\varphi_1) + A^2_{LM} B_L Y^M_L(\theta_2,\varphi_2) + C_{L_1 M_1 L_2 M_2} B_{L_1} B_{L_2} Y^{M_1}_{L_1}(\theta_1,\varphi_1) Y^{M_2}_{L_2}(\theta_2,\varphi_2)\right]$$

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

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

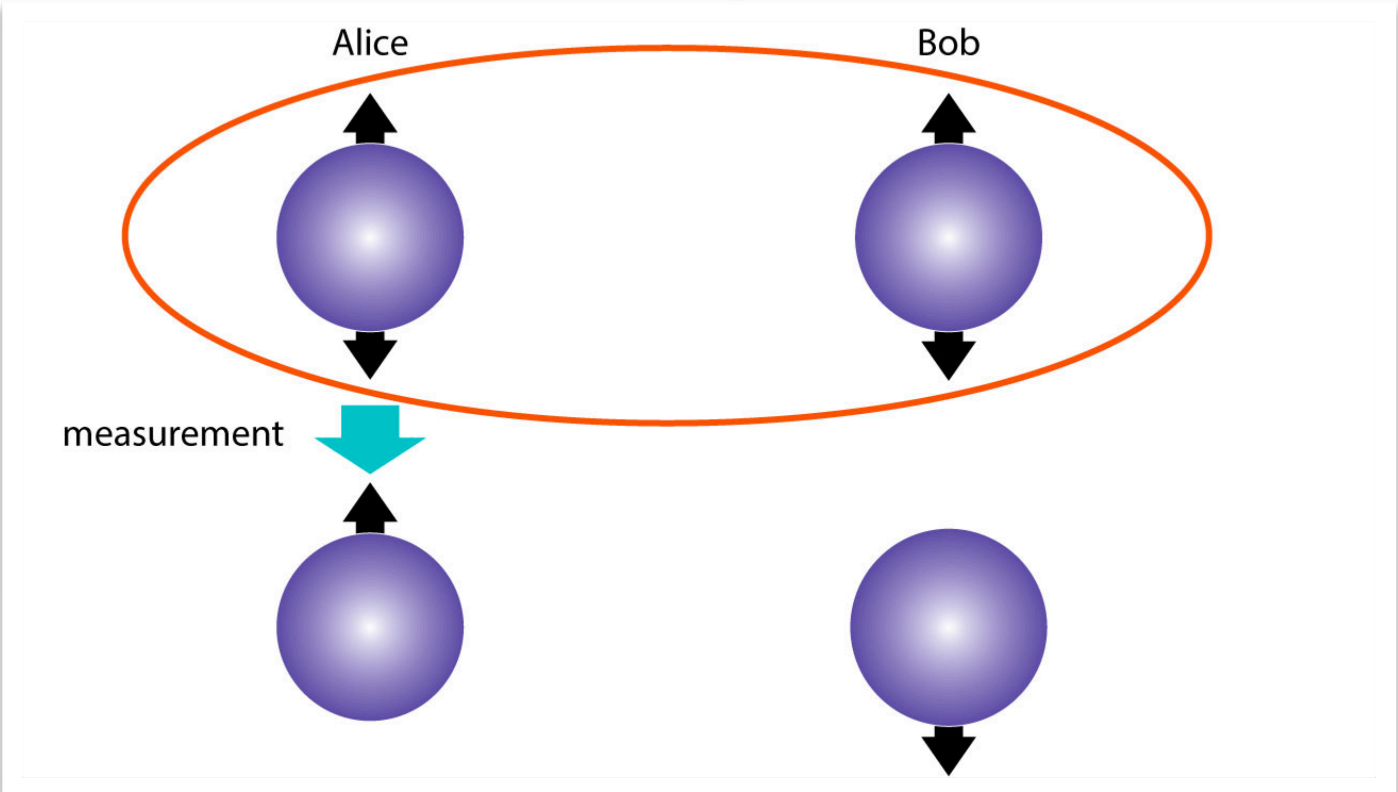
$B_1 = -\sqrt{2\pi}\eta_\ell$ and $B_2 = \sqrt{2\pi/5}$.

Quantum Entanglement

- A quantum state of two subsystems A and B is separable when its density matrix ρ can be expressed as a convex sum

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

→ If the state is not separable, it is named *entangled*



Measurement in one subsystem immediately affect the other, even if they are causally disconnected

Quantum Entanglement

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- A convenient metric for entanglement is Concurrence (C≠0 is entangled)

Bounds on C(ρ) can be employed to estimate entanglement:

$$\begin{aligned}
(\mathcal{C}(\rho))^2 &\geq 2\max\left\{0,\ \mathrm{Tr}\left[\rho^2\right] - \mathrm{Tr}\left[(\rho_A)^2\right],\ \mathrm{Tr}\left[\rho^2\right] - \mathrm{Tr}\left[(\rho_B)^2\right]\right\} \equiv \mathscr{C}^2_{\mathrm{LB}} \\
(\mathcal{C}(\rho))^2 &\leq 2\min\left\{1 - \mathrm{Tr}\left[(\rho_A)^2\right],\ 1 - \mathrm{Tr}\left[(\rho_B)^2\right]\right\} \equiv \mathscr{C}^2_{\mathrm{UB}}\,.
\end{aligned}$$

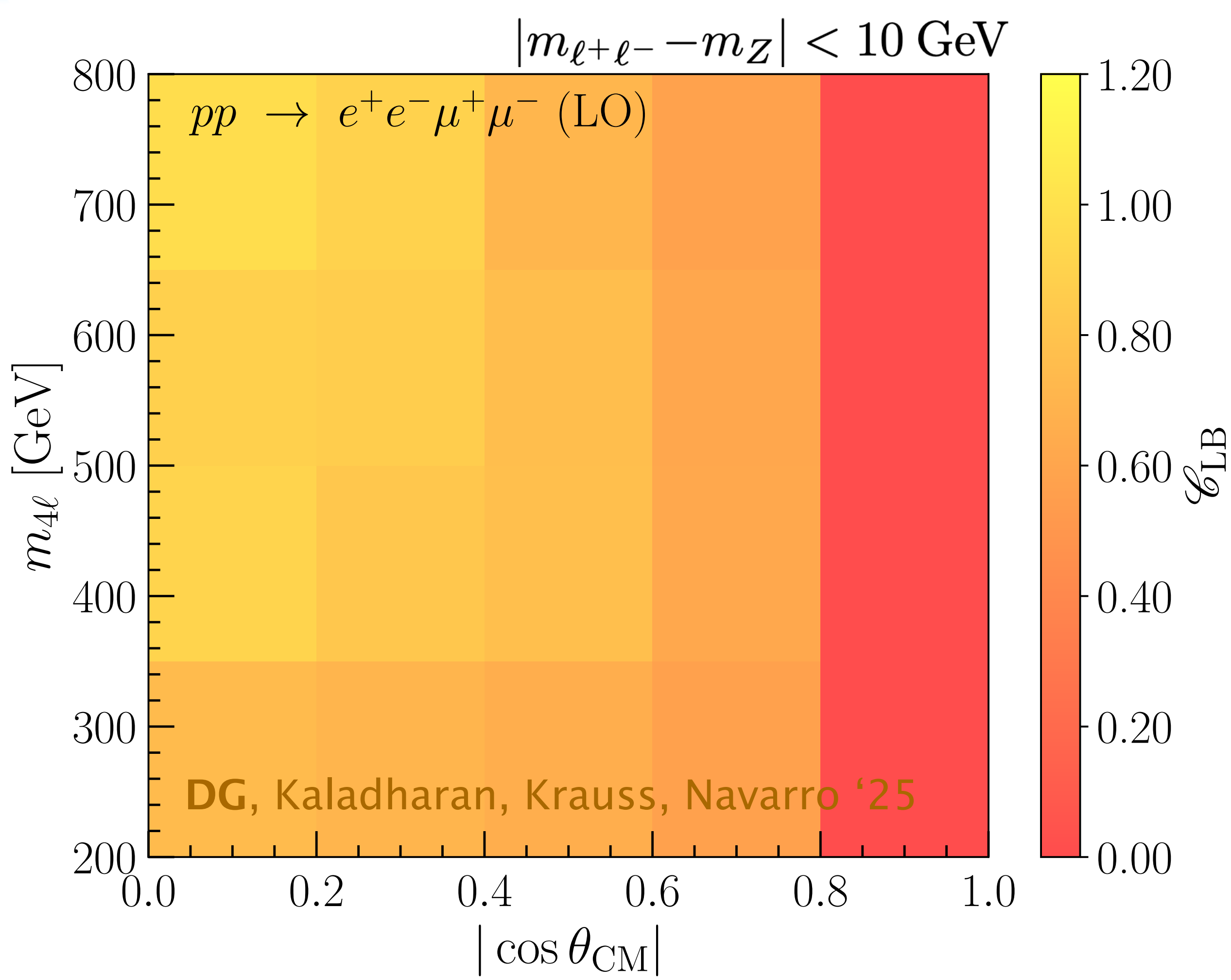
Mintert, Buchleitner (PRL, 2007)

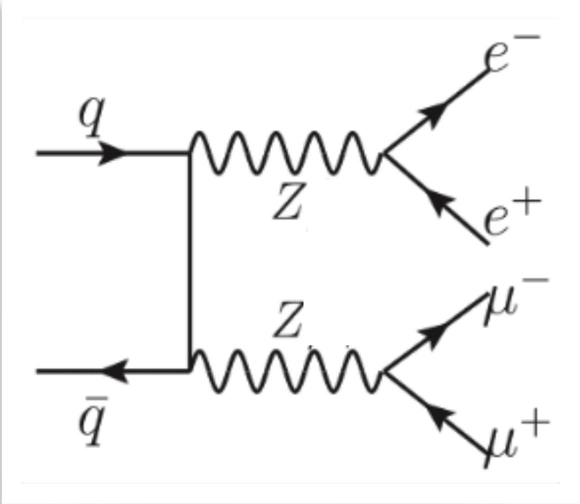
→ $C_{LB}>0$: entangled states

→ $C_{UB}=0$: separable states

Diboson as a two-qutrit system

- Entanglement estimates @LO:

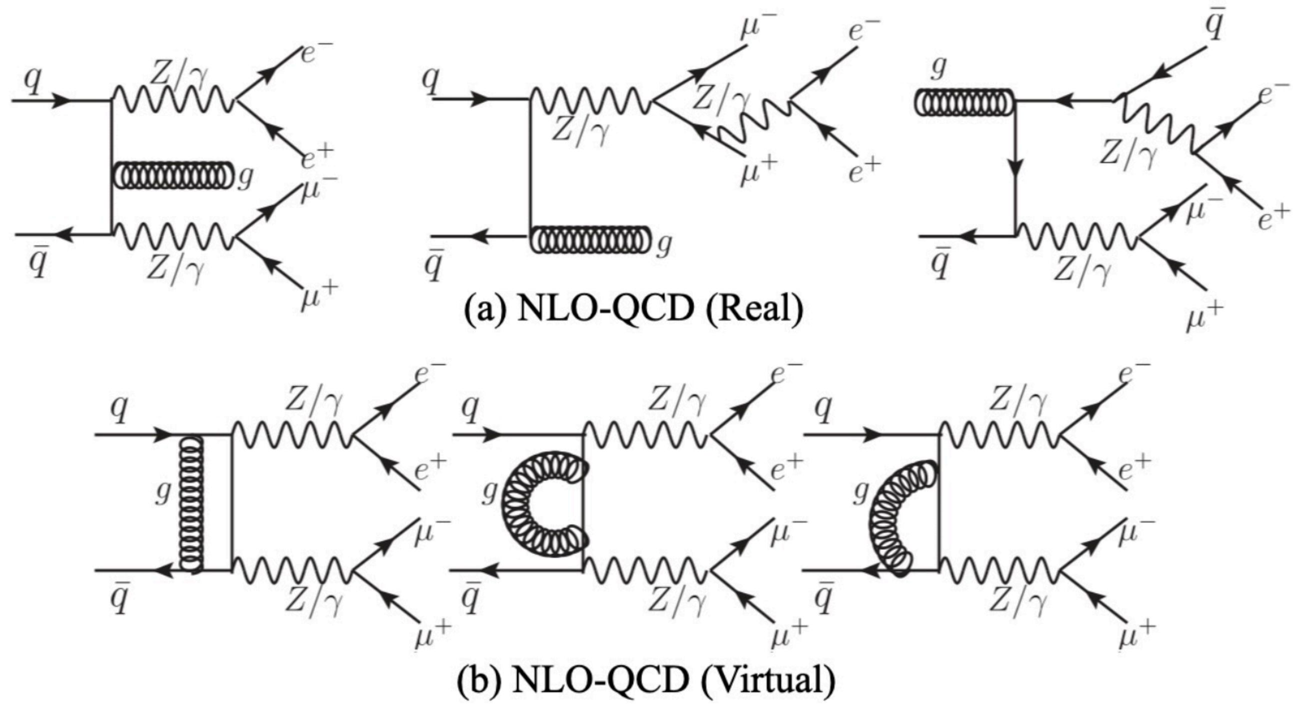




See also: Barr 2106.01377
Saavedra et al 2209.13441
Maltoni et al 2307.09675
Fabbrichesi et al 2302.00683
Fabbri et al 2307.13783
Bernal et al 2307.13496
Saavedra 2403.13942
Sullivan 2410.10980
Pelliccioli et al 2409.16731
Gratta et al 2504.03841
…

Quantum Entanglement is Quantum

- NLO QCD:



- Angular coefficients work as analyzers of the underlying production dynamics

→ Sizable NLO QCD corrections

→ Crucial effects for precision measurements and new physics studies (EFT analyses,…)

$|m_{\ell^+\ell^-} - m_Z| < 10$ GeV

Coefficient	LO+PS	NLO QCD	NLO/LO
$A^1_{1,0}$	$-0.008(2)$	$-0.035(3)$	4.37
$A^1_{2,0}$	0.3224(9)	0.301(1)	0.93
$A^1_{2,1}$	0.0758(6)	0.1023(7)	1.35
$C_{1,0,1,0}$	0.94(1)	0.75(1)	0.80
$C_{2,0,2,0}$	0.221(2)	0.198(3)	0.89
$C_{2,1,2,0}$	0.005(2)	0.024(2)	4.80

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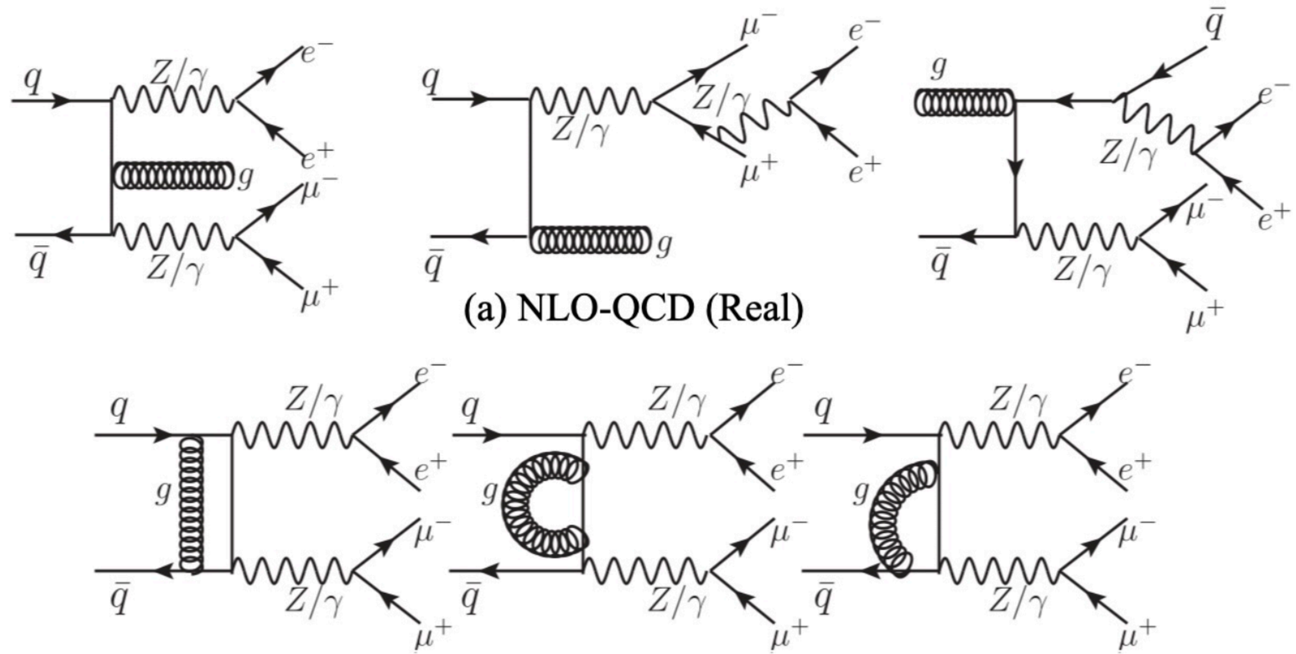
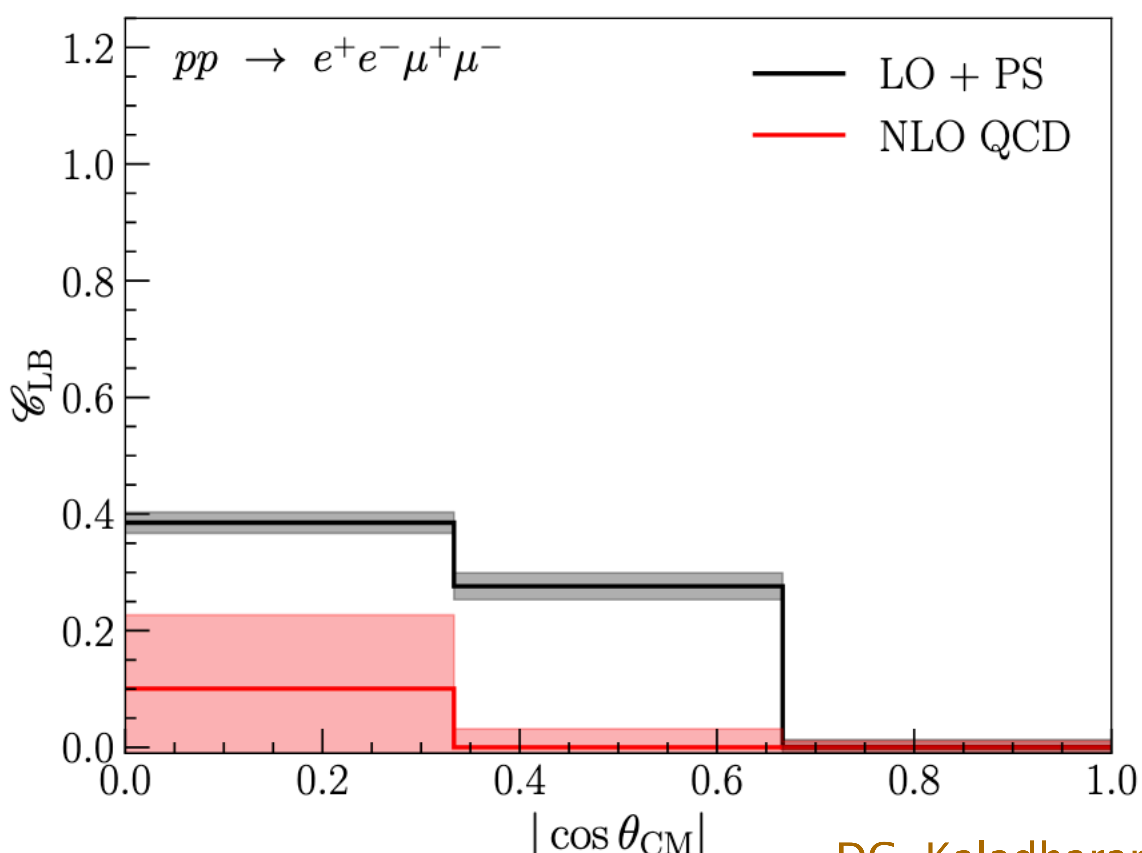
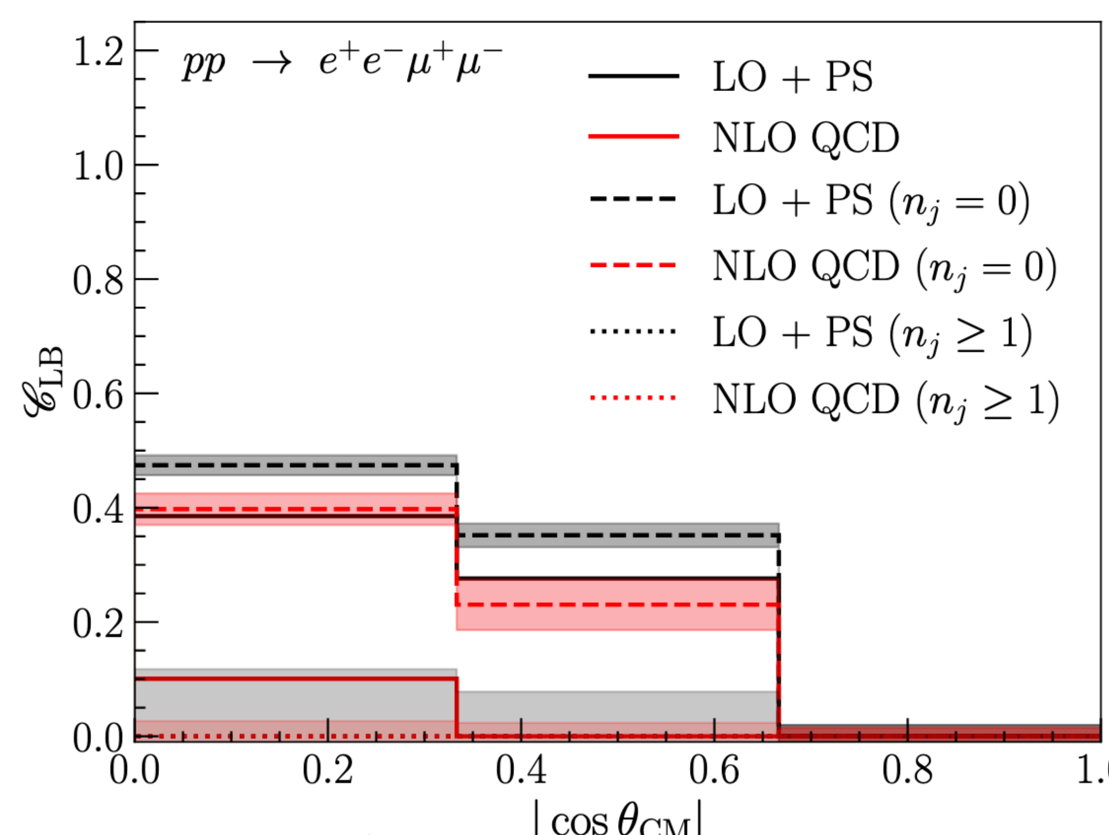
Grossi, Pellicciolo, Vicini '24

Quantum Entanglement is Quantum

- NLO QCD:







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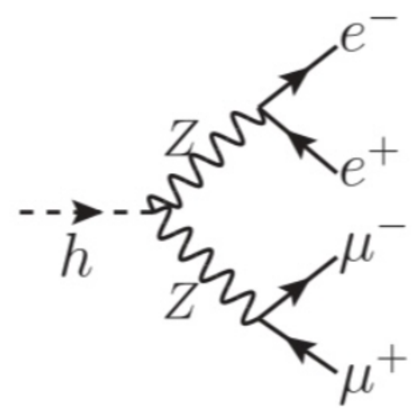
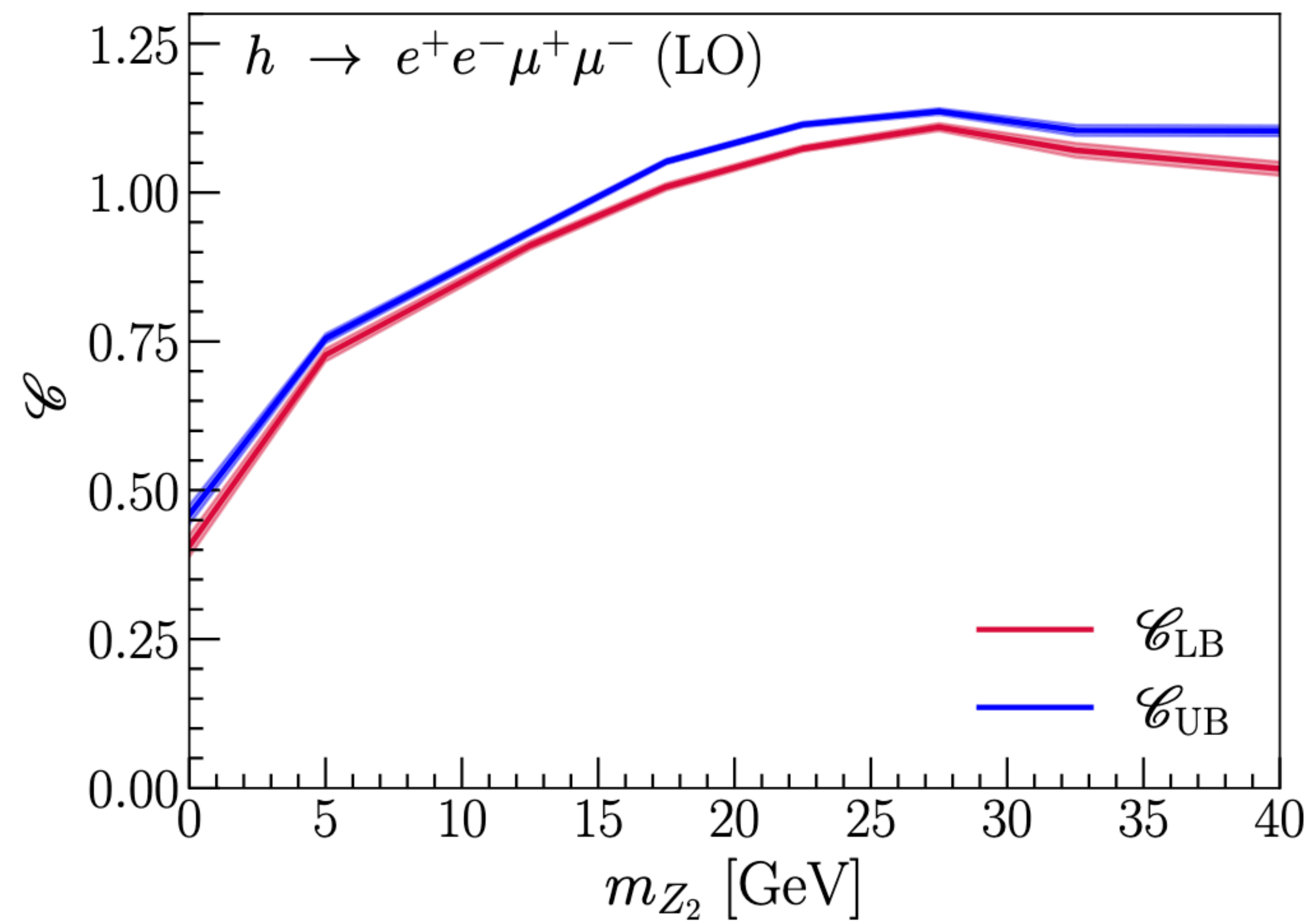
$h \to e^+e^-\mu^+\mu^-$ at LO



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

matrix depend on just two independent parameters

Saavedra, Bernal, Casas, Moreno 22'



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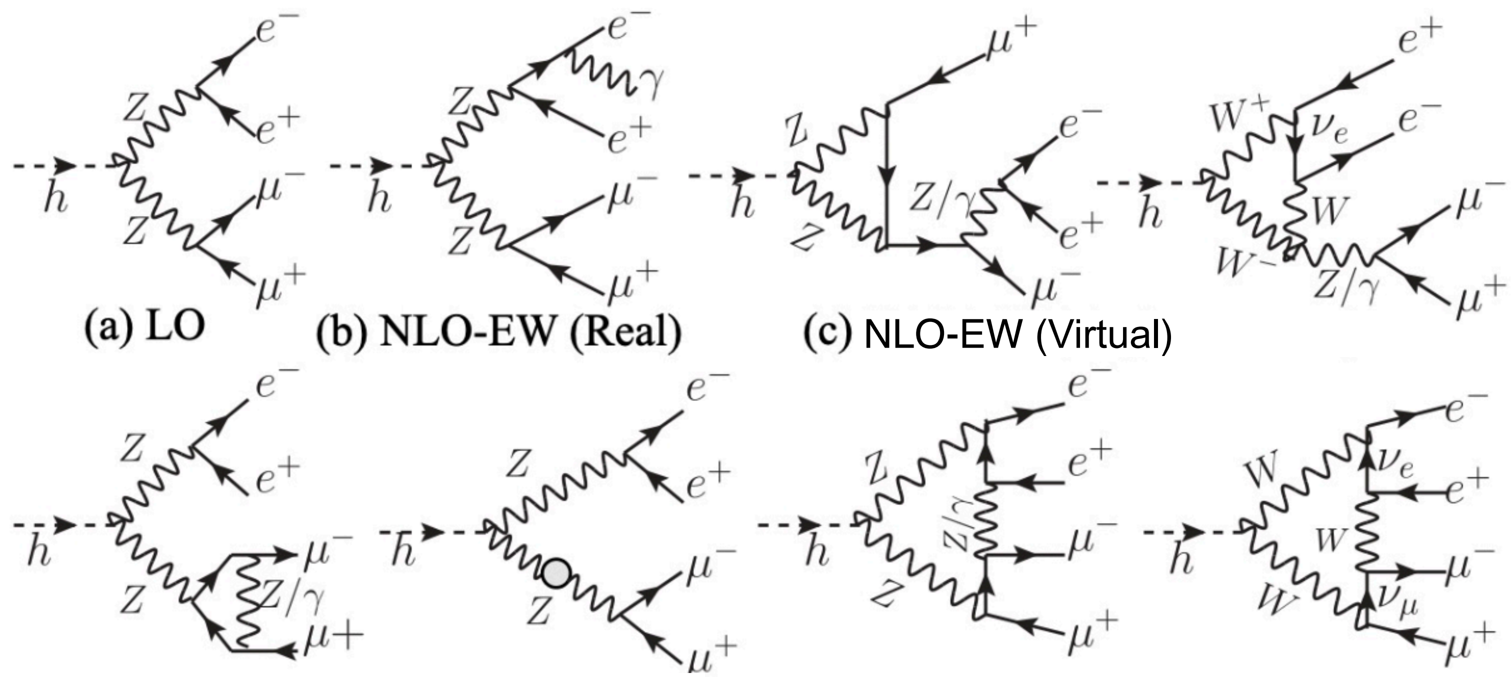
$h \to e^+e^-\mu^+\mu^-$: NLO EW Corrections



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

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

$|m_{Z_1} - m_Z| < 5$ GeV

$m_{Z_2} > 10$ GeV

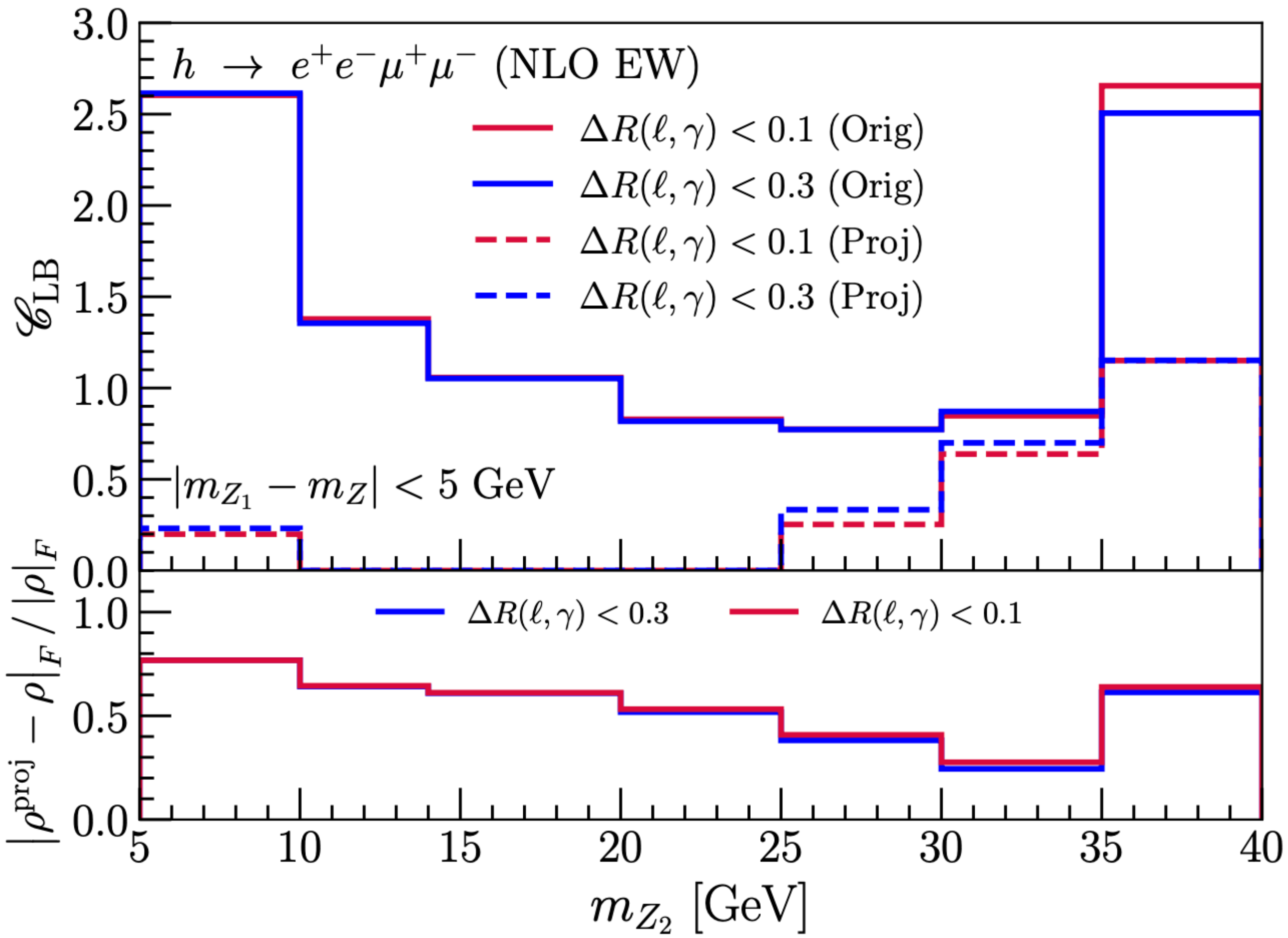
→ NLO EW is crucial for a robust BSM analysis

DG, Kaladharan, Krauss, Navarro '25; see also Gratta, Fabbri, Lamba, Maltoni, Pagani 25'; Saavedra, Giardino 26'

$h \to ZZ^*$ vs $h \to WW^*$

- Projecting the original matrix to a well defined state (unit trace, hermitian, and positive eigenvalues) minimizing the Frobenius norm:

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



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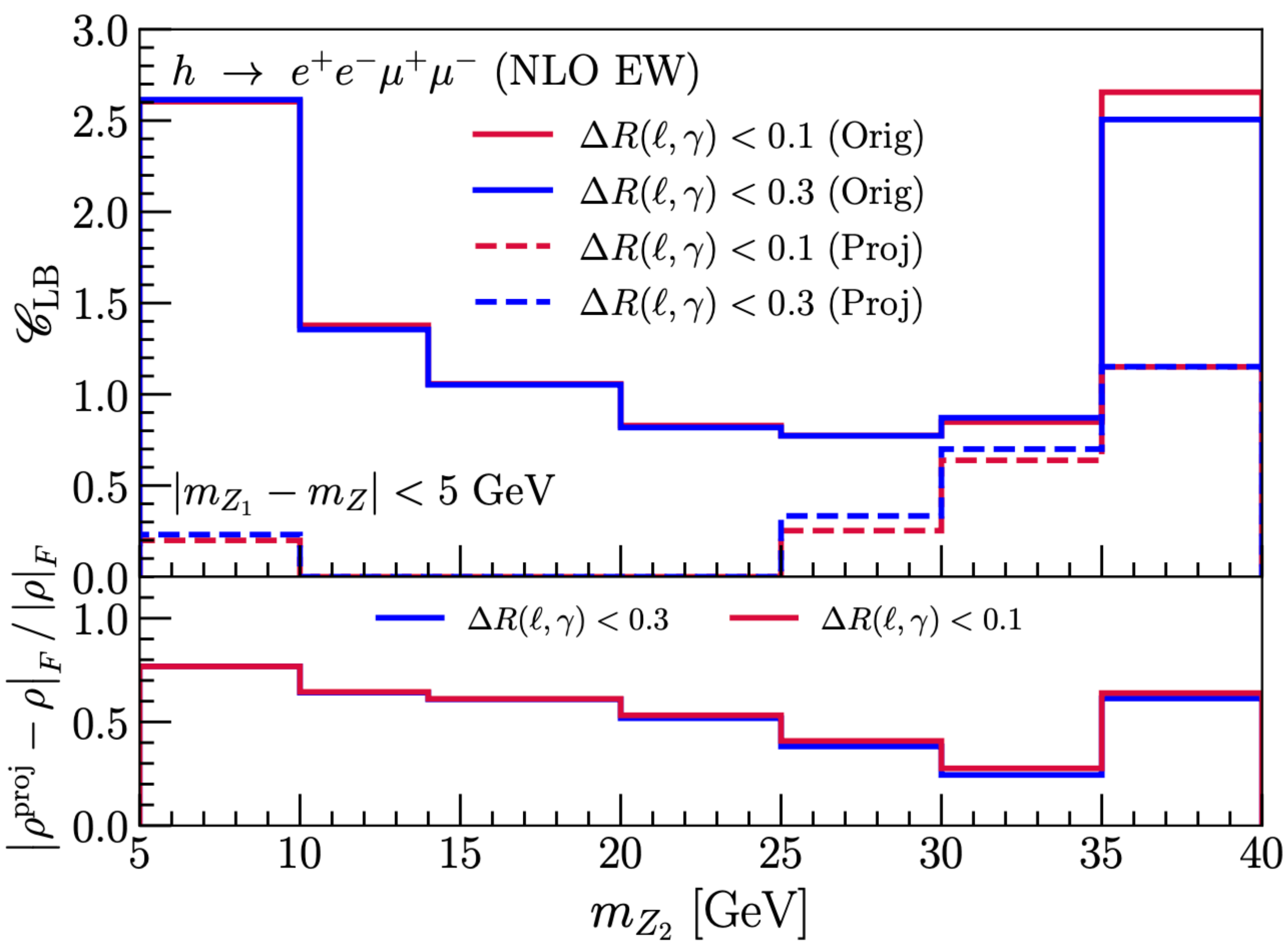

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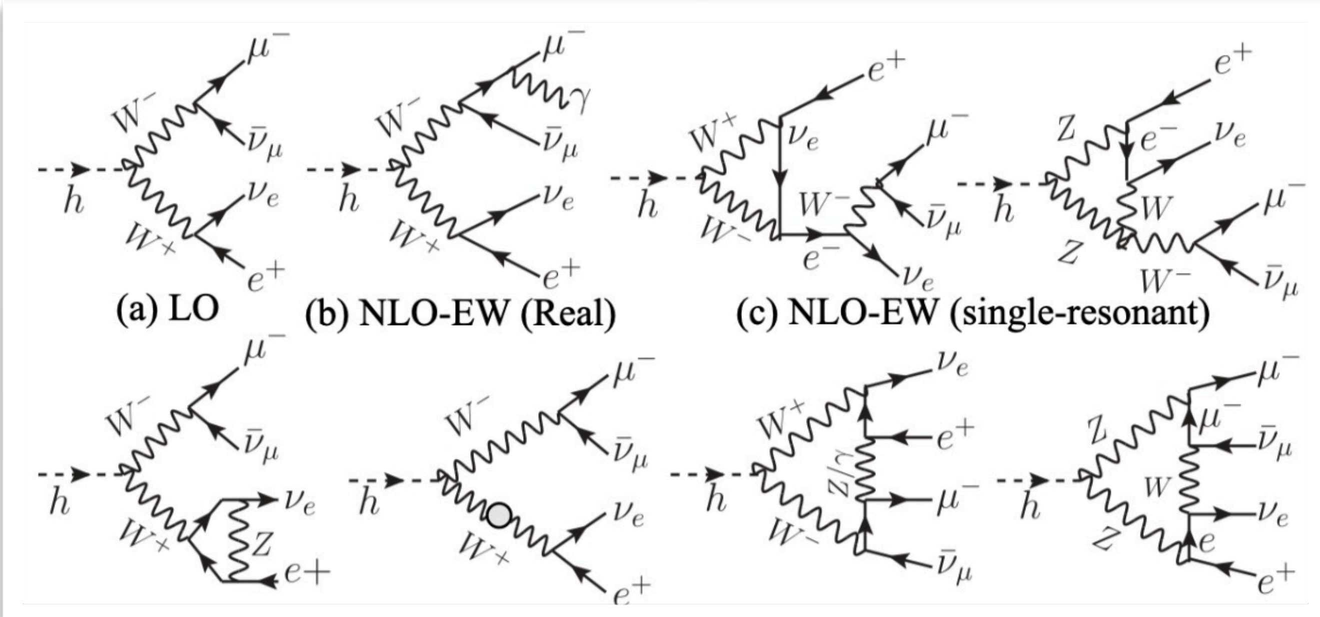
Higher-order corrections are channel dependent. What about the other relevant Higgs decays?



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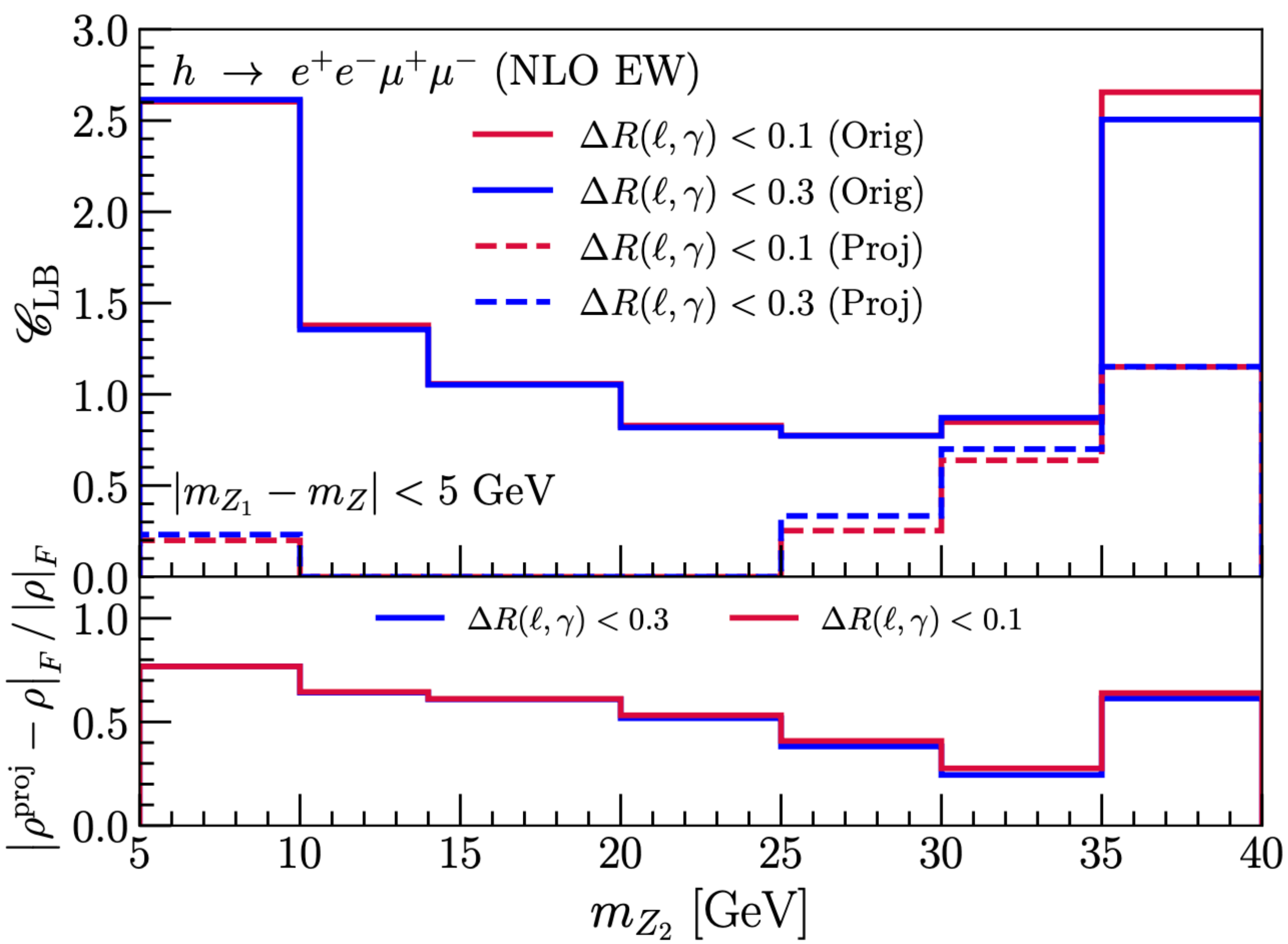

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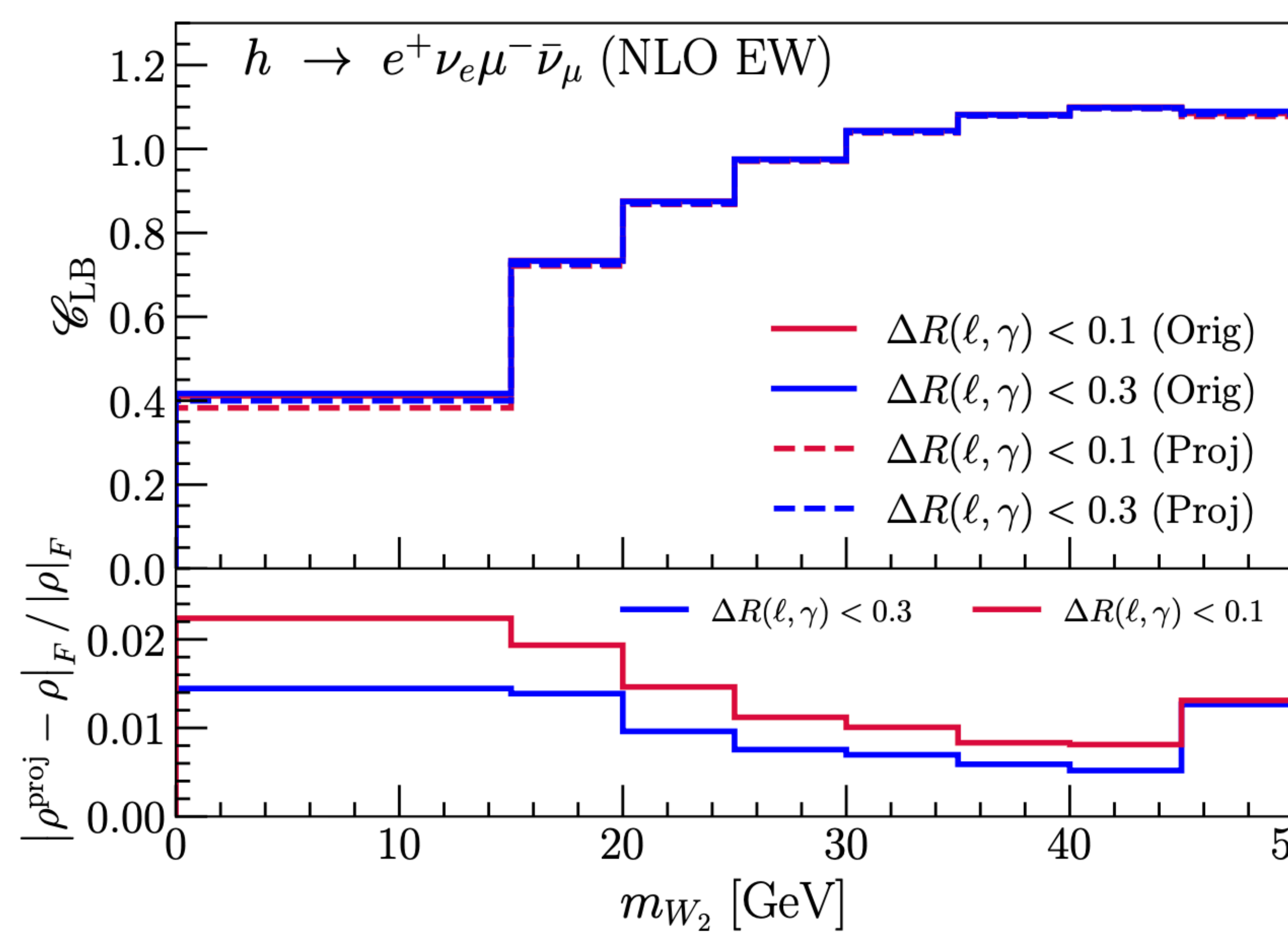

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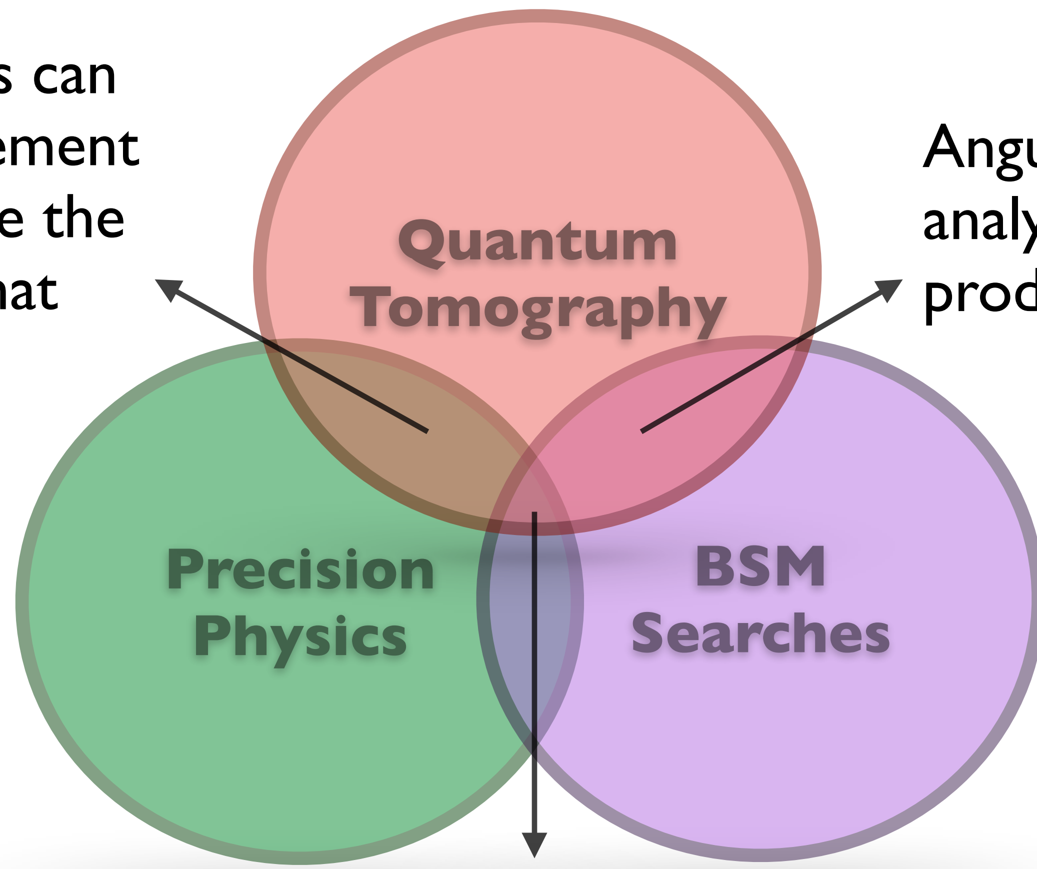
See A. Navarro's talk for study of semi-leptonic $h \to ZZ^*, WW^*$ decays

Summary

- Quantum tomography serve as powerful tool for precision measurements and searches for new physics

Sizable radiative corrections can significantly modify entanglement indicators and may challenge the interpretation of systems that appear well-defined at LO

Angular coefficients work as analyzers of the underlying production dynamics



Higher-order (QCD and EW) corrections to angular coefficients are crucial for precision measurements and new physics studies (EFT analyses,…)

Work in collaboration with

Ajay Kaladharan (ICPT-AP)

Alberto Navarro (SeoulTech)

Frank Krauss (IPPP-Durham)