From spin correlations to quantum observables in di-boson systems

Giovanni Pelliccioli
University and INFN of Milano-Bicocca

mostly based on Grossi GP Vicini 2409.16731

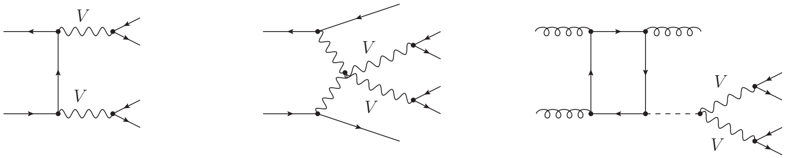
Introduction

Motivations

Precise measurements of multi-boson processes with Run-3 & High-Lumi LHC data.

Spin correlations of EW bosons

- are non trivial to extract
- probe interplay between gauge and scalar SM sectors
- discriminate power between SM and new physics
- allow to construct for entanglement/ Bell non-locality probes



Di-boson: simplest, non-trivial spin correlations with EW bosons

Experimental results

We cannot directly measure the spin state of EW bosons but we can:

⋆ Extract spin-sensitive coefficients from angular distributions

Run-1 analyses mostly relied on angular-coefficient extraction:

- W/Z+jets [CMS 1104.3829, 1504.03512, 2008.04174, ATLAS 1203.2165, 1606.00689]
- $t\bar{t}$ [CMS 1605.09047, ATLAS 1612.02577, 2005.03799]

⋆ Perform fits of LHC data with polarised templates

Run-2 analyses mostly rely fits with polarised templates:

- WZ/ZZ [ATLAS 1902.05759, CMS 2110.11231, ATLAS 2211.09435, 2402.16365, 2310.04350]
- $W^\pm W^\pm$ scattering [CMS 2009.09429]

What about theory?

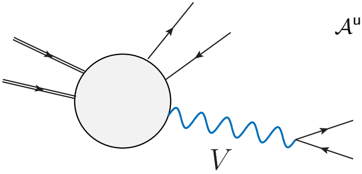
Need proper understanding, precise predictions and new ideas to extract polarisations and spin correlations.

This talk:
spin correlations and quantum observables in $h \to 4\ell$ with radiative corrections.

General framework

Amplitude structure

Tree-level structure for single resonant boson (in pole/narrow-width approximation):



$$\mathcal{A}^{\text{unpol}} = \mathcal{P}_\mu \frac{-g^{\mu\nu}}{k^2 - M_V^2 + iM_V\Gamma_V} \mathcal{D}_\nu$$

$$= \mathcal{P}_\mu \frac{\sum_{\lambda'} \varepsilon^\mu_{\lambda'} \varepsilon^{*\nu}_{\lambda'}}{k^2 - M_V^2 + iM_V\Gamma_V} \mathcal{D}_\nu$$

$$= \sum_{\lambda'} \mathcal{P}_\mu \frac{\varepsilon^\mu_{\lambda'} \varepsilon^{*\nu}_{\lambda'}}{k^2 - M_V^2 + iM_V\Gamma_V} \mathcal{D}_\nu = \sum_{\lambda'} \mathcal{A}_{\lambda'}$$

At the cross section level:

$$|\mathcal{A}^{\text{unpol}}|^2 = \underbrace{\sum_{\lambda} |\mathcal{A}_\lambda|^2}_{\text{incoherent sum}} + \underbrace{\sum_{\lambda \neq \lambda'} \mathcal{A}^*_\lambda \mathcal{A}_{\lambda'}}_{\text{interference terms}}$$

Polarisation vectors are defined in a specific Lorenzt frame.

Decay-product angular distributions reflect polarisation state of the decayed V boson [Bern et al. 1103.5445, Stirling et al. 1204.6427, Belyaev et al. 1303.3297].

Angular dependence for one boson

At tree-level, decay of a single resonant boson (θ^*, ϕ^* are ℓ^+ angles in V rest frame, w.r.t. V direction in some Lorentz frame) [Bern et al. 1103.5445, Stirling Vryonidou 1204.6427]:

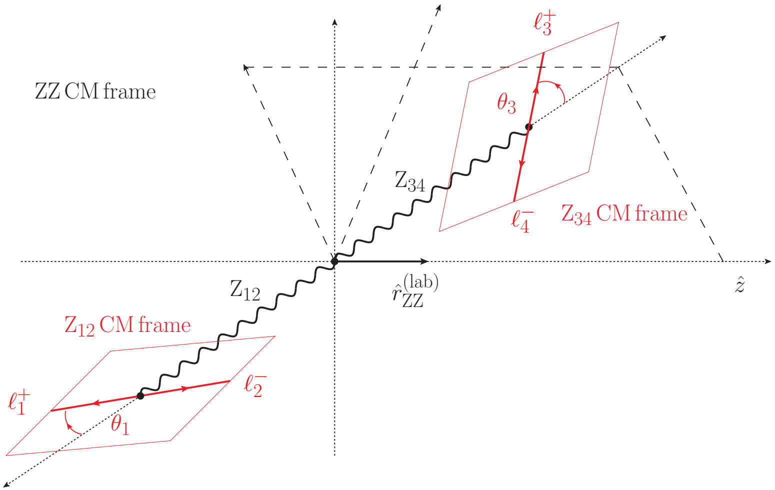
$$\frac{d\sigma}{d\cos\theta^* d\phi^* dX} = \frac{d\sigma}{dX}\frac{3}{16\pi}\Big[(1+\cos^2\theta^*) + (A_0/2)(1-3\cos^2\theta^*) + A_1 \sin 2\theta^* \cos\phi^* + (A_2/2)\sin^2\theta^* \cos 2\phi^* + A_3 \sin\theta^* \cos\phi^* + A_4\cos\theta^* + A_5 \sin\theta^* \sin\phi^* + A_6 \sin 2\theta^* \sin\phi^* + A_7 \sin^2\theta^* \sin 2\phi^*\Big]$$

$$= \frac{d\sigma}{dX}\left[\frac{1}{4\pi} + \sum_{\ell=1}^{2}\sum_{m=-\ell}^{\ell} \alpha_{\ell m}\, Y_{\ell m}(\theta^*, \phi^*)\right] \quad (1)$$

8 independent coefficients ($\{A_i\}$ or $\{\alpha_{\ell,m}\}$) extracted through projections [Bern et al. 1103.5445, Stirling Vryonidou 1204.6427, Ballestrero Maina GP 1710.09339, Baglio et al. 1910.13746, Frederix Vitos 2007.08867] or asymmetries [Boudjema Singh 0903.4705] *e.g.*:

$$\int_{-1}^{1} d\cos\theta^* \int_0^{2\pi} d\phi^*\, Y_{\ell m}(\theta^*, \phi^*)\frac{d\sigma}{d\cos\theta^* d\phi^* dX} = \alpha_{\ell m} = \alpha_{\ell m}(X) \quad (2)$$

Two bosons: geometric visualisation



Angular dependence for boson pairs

Two resonant bosons (θ_1, ϕ_1, and θ_3, ϕ_3) are ℓ_1^+ and ℓ_3^+ angles in each V rest frame, w.r.t. V direction in some Lorentz frame (typical choice: VV-CM frame):

$$\frac{d\sigma}{\mathrm{d}\cos\theta_1\,\mathrm{d}\phi_1\,\mathrm{d}\cos\theta_3\,\mathrm{d}\phi_3\,\mathrm{d}X} = \frac{d\sigma}{\mathrm{d}X}\Bigg[\frac{1}{(4\pi)^2} + \tag{3}$$

$$+\frac{1}{4\pi}\sum_{\ell=1}^{2}\sum_{m=-\ell}^{\ell}\alpha^{(1)}_{\ell m}(X)\,Y_{\ell m}(\theta_1,\phi_1)$$

$$+\frac{1}{4\pi}\sum_{\ell=1}^{2}\sum_{m=-\ell}^{\ell}\alpha^{(3)}_{\ell m}(X)\,Y_{\ell m}(\theta_3,\phi_3)$$

$$+\sum_{\ell_1=1}^{2}\sum_{\ell_3=1}^{2}\sum_{m_1=-\ell_1}^{\ell_1}\sum_{m_3=-\ell_3}^{\ell_3}\gamma_{\ell_1 m_1 \ell_3 m_3}(X)\,Y_{\ell_1 m_1}(\theta_1,\phi_1)\,Y_{\ell_3 m_3}(\theta_3,\phi_3)\Bigg]$$

80 independent coefficients [Rahaman Singh 2109.09345, Aguilar-Saavedra et al. 2209.13441], extracted similarly to the single-boson case.

Remark: the two bosons are correlated if $\alpha^{(1)}_{\ell_1,m_1}\alpha^{(3)}_{\ell_3,m_3} \neq \gamma_{\ell_1 m_1 \ell_3 m_3}$.

Issues in angular-coefficient extraction

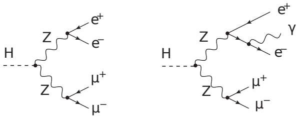
In principle, coefficients extracted directly from data through projections up to $\ell_{1,3} = 2$ of the angular distributions $d\sigma/d\Omega_1 d\Omega_3$.

In practice, the analytic structure of $d\sigma/d\Omega_1 d\Omega_3$ in eq. (3):

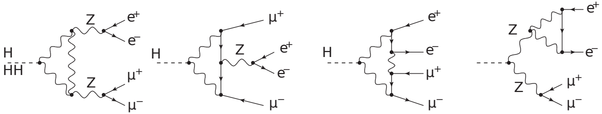
1. assumes two spin-1 resonances, and subsequent two-body decays,
2. its coefficient values not invariant under Lorentz boosts,
3. is not described by $\ell_{1,3} \leq 2$ if selection cuts/ν-reconstruction applied,
4. is not fully model independent (if NP in both production and decay)

Radiative corrections

LO, NLO EW real:



NLO EW virt.:



$h \to 4\ell(\gamma)$: one Z boson necessarily off-shell.

Non-factorisable virtual and real-photon corrections lead to higher-rank contributions: tricky interpretation of LO-like angular structure [Grossi GP Vicini 2409.16731].

$M_{\ell^+\ell^-} > 10$ GeV	LO	NLO EW (H-rest)	$\delta_{\rm EW}$
$\alpha^{(1)}_{2,0}$	$-0.04792(4)$	$-0.04215(6)$	-12.0%
$\alpha^{(3)}_{2,0}$	$-0.04792(4)$	$-0.04224(6)$	-11.9%
$\gamma_{1,0,1,0}$	0.00117(1)	0.00011(2)	-91%
$\gamma_{2,0,2,0}$	0.01097(1)	0.01019(2)	-7.1%
$\gamma_{1,1,1,-1}$	$-0.00185(2)$	$-0.00047(2)$	-75%
$\gamma_{2,1,2,-1}$	$-0.00776(1)$	$-0.00715(2)$	-7.9%
$\gamma_{2,2,2,-2}$	0.00493(2)	0.00481(2)	-2.4%

Frame dependence and real-photon corrections in h $\rightarrow 4\ell$

h $\rightarrow 4\ell + \gamma$ real corrections to (integrated) partial decay rate typically small.

Massless charged leptons dressed with real photons to construct IR-safe observables.

Quantum tomography can be carried out in Higgs rest frame (H-rest) or in dressed four-lepton CM frame (4ℓ-CM) [Grossi GP Vicini 2409.16731]:

$M_{\ell^+\ell^-} > 10$ GeV	LO	NLO EW (4ℓ-CM)	$\delta_{\rm EW}$	NLO EW (H-rest)	$\delta_{\rm EW}$
$\alpha^{(1)}_{2,0}$	$-0.04792(4)$	$-0.04498(6)$	-6.1%	$-0.04215(6)$	-12.0%
$\alpha^{(3)}_{2,0}$	$-0.04792(4)$	$-0.04506(6)$	-6.0%	$-0.04224(6)$	-11.9%
$\gamma_{1,0,1,0}$	0.00117(1)	0.00012(2)	-90%	0.00011(2)	-91%
$\gamma_{2,0,2,0}$	0.01097(1)	0.01079(2)	-1.6%	0.01019(2)	-7.1%
$\gamma_{1,1,1,-1}$	$-0.00185(2)$	$-0.00048(2)$	-74%	$-0.00047(2)$	-75%
$\gamma_{2,1,2,-1}$	$-0.00776(1)$	$-0.00779(2)$	$+0.4\%$	$-0.00715(2)$	-7.9%
$\gamma_{2,2,2,-2}$	0.00493(2)	0.00489(2)	-0.8%	0.00481(2)	-2.4%

NLO EW corrections to $\ell = 2$ coeff.'s smaller in the 4ℓ-CM definition.

Dramatic effects on $\ell = 1$ coeff.'s persists in both definitions: one-loop weak effects.

NLO EW effects on LO relations amongst coefficients

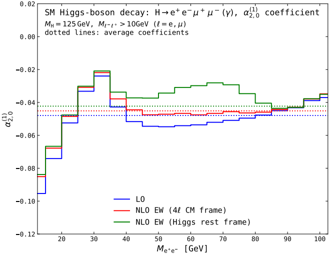
$M_{\ell^+\ell^-} > 10\,\text{GeV}$: NLO EW changes tree structure of the (CP-even) SM amplitude [Grossi GP Vicini 2409.16731].

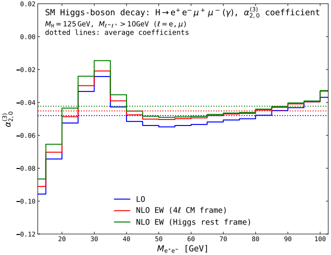
	LO	NLO (4ℓ-CM)	NLO (H-rest)
$\alpha^{(1)}_{2,0}$	$-0.04792(4)$	$-0.04498(6)$	$-0.04215(6)$
$\alpha^{(3)}_{2,0}$	$-0.04792(4)$	$-0.04506(6)$	$-0.04224(6)$
$\gamma_{1,0,1,0}$	$0.00117(1)$	$0.00012(2)$	$0.00011(2)$
$\gamma_{2,0,2,0}$	$0.01097(1)$	$0.01079(2)$	$0.01019(2)$
$\gamma_{1,1,1,-1}$	$-0.00185(2)$	$-0.00048(2)$	$-0.00047(2)$
$\gamma_{1,-1,1,1}$	$-0.00186(2)$	$-0.00047(2)$	$-0.00047(2)$
$\gamma_{2,1,2,-1}$	$-0.00776(1)$	$-0.00779(2)$	$-0.00715(2)$
$\gamma_{2,-1,2,1}$	$-0.00778(1)$	$-0.00783(2)$	$-0.00709(2)$
$\gamma_{2,2,2,-2}$	$0.00493(2)$	$0.00489(2)$	$0.00481(2)$
$\gamma_{2,-2,2,2}$	$0.00494(2)$	$0.00488(2)$	$0.00479(2)$

- ⋆ $\alpha^{(1)}_{2,0} = \alpha^{(3)}_{2,0}$
- ⋆ $\gamma_{2,m,2,-m} = \gamma_{2,-m,2,m}$ for $m = 1, 2$
- ⋆ $\gamma_{1,1,1,-1} = \gamma_{1,-1,1,1}$
- ⋆ $20\pi\left(\gamma_{2,2,2,-2} + \gamma_{2,0,2,0}\right) = 1$
- ⋆ $40\pi\gamma_{2,2,2,-2} = \sqrt{20\pi}\alpha^{(1)}_{2,0} + 1$
- ⋆ $5\eta_\ell^2\,\gamma_{2,1,2,-1} = \gamma_{1,1,1,-1}$
- ⋆ $\eta_\ell^2\left(1 - 20\pi\,\gamma_{2,0,2,0}\right) = 4\pi\gamma_{1,0,1,0}$

More on off-shell effects $\mathrm{h} \to 4\ell$

Dependence of coefficients on $M_{\ell^+\ell^-}$ [Grossi GP Vicini 2409.16731]. $\alpha_{(2,0)}$ in figure.
Setup: $M_{\mathrm{e}^+\mathrm{e}^-}, M_{\mu^+\mu^-} > 10\mathrm{GeV}$.





Strong dependence of coefficients on off-shell-ness already at LO. 4ℓ-CM definition better behaved at NLO EW.

$\alpha^{(1)}_{2,0} = \alpha^{(3)}_{2,0}$ relation broken at NLO EW if unequal cuts applied on $M_{\ell\ell}$.

Spin-correlations change value with tighter $M_{\ell\ell}$ cuts but preserve symmetric charachter ($\gamma_{2,+2,2,-2} = \gamma_{2,-2,2,+2}$).

Quantum observables

A fast-growing business

Quantum entanglement between top-quarks (two-qubit system) measured at LHC [ATLAS 2311.07288, CMS 2406.03976, 2409.11067]

Measuring entanglement and Bell non-locality at colliders possible also for two-qutrit systems $\rightarrow$ two massive weak bosons.

Di-boson EW production at LHC and lepton colliders (generic $\mathbf{1} \otimes \mathbf{1}$) [Barr et al. 2204.11063, Ashby-Pickering et al. 2209.13990, Fabbrichesi et al. 2302.00683, Morales 2306.17247, Aoude et al. 2307.09675, Bernal et al. 2307.13496, Bernal 2310.10838, Barr et al. 2402.07972, Grossi GP Vicini 2409.16731, Grabarczyk 2410.18022]

Di-boson in spin-0 decays ($\mathbf{0} \rightarrow \mathbf{1} \otimes \mathbf{1}$) [Barr 2106.01377, Aguilar-Saavedra et al. 2209.13441, 2209.14033, Ashby-Pickering et al. 2209.13990, Fabbrichesi et al. 2302.00683, 2304.02403, Fabbri et al. 2307.13783, Bernal et al. 2307.13496, Barr et al. 2402.07972, Aguilar-Saavedra 2403.13942, 2411.13464, Bernal et al. 2405.16525, Grossi GP Vicini 2409.16731, Sullivan 2410.10980, Subba Singh 2411.19171]

Entanglement witnesses

For generic mixed states of two subsystems A & B,

$$\rho = \sum_{i,j,l,k} p_{ij} p^*_{kl} \, |a_i\rangle \otimes |b_j\rangle\langle a_k| \otimes \langle b_l| \longrightarrow \rho^{\mathrm{T_B}} = \sum_{i,j,l,k} p_{il} p^*_{kj} \, |a_i\rangle\langle a_k| \otimes |b_j\rangle\langle b_l|$$

Peres-Horodecki criterion [Peres 9604005, Horodecki 9703004]: if $\rho^{\mathrm{T_B}}$ has a negative eigenvalue, then the system is entangled.

At LO two spin-1 bosons from decay of a spin-0 state are entangled if and only if $\gamma_{2,1,2,-1} \neq 0$ or $\gamma_{2,2,2,-2} \neq 0$ [Aguilar-Saavedra 2209.13441]. What about NLO EW?

$M_{\ell^+\ell^-} > 10$ GeV	LO	NLO EW (4ℓ-CM)	δ_{EW}	NLO EW (H-rest)	δ_{EW}
$\gamma_{2,1,2,-1}$	−0.00776(1)	−0.00779(2)	+0.4%	−0.00715(2)	−7.9%
$\gamma_{2,2,2,-2}$	0.00493(2)	0.00489(2)	−0.8%	0.00481(2)	−2.4%

NLO EW corr. small, many zeros in ρ_{LO} compatible with zero at NLO [Grossi GP Vicini 2409.16731], some get non-zero values.

A priori, no guarantee $\gamma_{2,1,2,-1} \neq 0$ or $\gamma_{2,2,2,-2} \neq 0$ still sufficient and necessary conditions: full NLO spin-density matrix needed, then apply Peres-Horodecki

Bell-inequality violation

Quantum state close to maximal entanglement: Bell non-locality can be probed.

CGLMP inequality [Collins et al. 0106024] suitable for two qutrits: violated if

$$\mathcal{I}_3 = \langle \mathcal{O}_{\rm Bell} \rangle = {\rm Tr}\left(\rho\, \mathcal{O}_{\rm Bell}\right) > 2\,.$$

For a scalar decaying into two spin-1,

$$\mathcal{I}_3 = \frac{1}{2} + \frac{4\sqrt{3}}{9} - \sqrt{5\pi}\left(1 - \frac{8\sqrt{3}}{9}\right)\alpha_{2,0} - 40\pi\left(\frac{2}{3} + \frac{4\sqrt{3}}{9}\right)\gamma_{2,1,2,-1} + \frac{20\pi}{3}\gamma_{2,2,2,-2}\,.$$

In our inclusive setup ($M_{\ell^+\ell^-} > 10{\rm GeV}$) [Grossi GP Vicini 2409.16731]

$$\mathcal{I}_3^{\rm (LO)} = 2.671(2)\,, \qquad \mathcal{I}_3^{\rm (NLO\,EW,4\ell)} = 2.682(4)\,, \qquad \mathcal{I}_3^{\rm (NLO\,EW,H)} = 2.571(4)\,.$$

$\mathcal{I}_3$ robust under EW corrections (not guaranteed a priori).

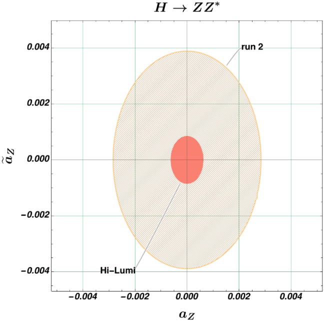
LO spin-density matrix seems sufficient at LHC [Aguilar-Saavedra et al. 2209.13441].

Importance of reference-frame choice for the spin quantisation.

Quantum observables and new physics in Higgs decays

Quantum observables with new-physics in $h \to 4\ell$ decay:

- ⋆ anomalous couplings [Bernal et al. 2307.13496, Fabbrichesi et al. 2304.02403]



$$\begin{aligned}\mathcal{L}_{hVV} \quad = \quad & g_W M_W W^+_\mu W^{-\mu} h + \frac{g_W}{2\cos\theta_W} M_Z Z_\mu Z^\mu h \\ & - \frac{g_W}{M_W}\left[\frac{a_W}{2} W^+_{\mu\nu} W^{-\mu\nu} + \frac{\tilde{a}_W}{2} W^+_{\mu\nu} \widetilde{W}^{-\mu\nu}\right] h \\ & - \frac{g_W}{M_W}\left[\frac{a_Z}{4} Z_{\mu\nu} Z^{\mu\nu} + \frac{\tilde{a}_Z}{4} Z_{\mu\nu} \tilde{Z}^{\mu\nu}\right] h\end{aligned}$$

Obtained limits on anomalous couplings at HL-LHC, through 3 entanglement witnesses ($\mathcal{E}_{\text{entropy}} = \text{Tr}(\rho_A \log \rho_A)$, $\mathcal{C}[\rho] \geq \mathcal{C}_2$, $\mathcal{C}_{\text{odd}} = \frac{1}{2}\sum_{i<j} |\rho^{\text{off}}_{ij} - \rho^{\text{off}}_{ji}|$)

- ⋆ SMEFT [Sullivan 2410.10980, Subba Singh 2411.19171]: determining $c_{VH}, c_{V\tilde{H}}$ challenging also at HL-LHC.

Conclusion

Conclusions

Rich phenomenology from decay angles in di-boson (or two-qutrit) systems at LHC.

Aimed at measuring polarisation properties to pin down the EWSB mechanism realised in nature, and accessing quantum entanglement at high energies.

Several aspects discussed for $h \to 4\ell$:

- ⋆ off-shell effects and radiative decays have strong impact
- ⋆ NLO corrections sizeably change the angular coefficients
- ⋆ important to choose suitable Lorentz frame, especially with rad. corr.
- ⋆ LO picture may be enough for some entanglement/Bell non-locality witnesses
- ⋆ better to scrutinise NLO effects

Backup

Two-qutrit formalism

Generic spin-density matrix:

$$\rho = \frac{1}{9}\left[(\mathbb{I}_3 \otimes \mathbb{I}_3) + A^{(1)}_{l_1,m_1}\left(T^{l_1}_{m_1} \otimes \mathbb{I}_3\right) + A^{(3)}_{l_3,m_3}\left(\mathbb{I}_3 \otimes T^{l_3}_{m_3}\right) + C_{l_1,m_1,l_3,m_3}\left(T^{l_1}_{m_1} \otimes T^{l_3}_{m_3}\right)\right]$$

T^l_m: irreducible tensor representations of the boson spin.

Our original, fully decayed formula is nothing but:

$$\frac{1}{\sigma}\frac{d\sigma}{d\Omega_1 d\Omega_3} = \left(\frac{3}{4\pi}\right)^2 \mathrm{Tr}\left\{\rho\left(\Gamma^{(1)} \otimes \Gamma^{(3)}\right)^{\mathsf{T}}\right\}.$$

$\Gamma^{(1,3)}$: decay matrices.

$$\sqrt{40\pi}\alpha^{(i)}_{2,m_i} = A^{(i)}_{2,m_i}\,, \qquad 40\pi\gamma_{2,m_1,2,m_3} = C_{2,m_1,2,m_3}\,, \qquad 8\pi\gamma_{1,m_1,1,m_3}/\eta_\ell^2 = C_{1,m_1,1,m_3}\,.$$

$$\mathrm{Tr}\left(\mathbb{I}_3\Gamma^{\mathsf{T}}\right) \propto Y_{00}(\theta,\phi)\,, \qquad \mathrm{Tr}\left(T^l_m\Gamma^{\mathsf{T}}\right) \propto Y_{lm}(\theta,\phi)$$

$$\begin{aligned}\mathcal{O}_{\mathrm{Bell}} &= \frac{2}{3\sqrt{3}}(T^1_1 \otimes T^1_1 - T^1_0 \otimes T^1_0 + T^1_1 \otimes T^1_{-1}) + \frac{1}{12}(T^2_2 \otimes T^2_2 + T^2_2 \otimes T^2_{-2}) \\ &+ \frac{1}{2\sqrt{6}}(T^2_2 \otimes T^2_0 + T^2_0 \otimes T^2_2) - \frac{1}{3}(T^2_1 \otimes T^2_1 + T^2_1 \otimes T^2_{-1}) + \frac{1}{4}T^2_0 \otimes T^2_0\,, +\mathrm{h.c.}\end{aligned}$$

Polar-angle correlations

$$\alpha^{(i)}_{1,0} = \frac{1}{4}\sqrt{\frac{3}{\pi}}\,\eta_i\left(f^{(i)}_{+} - f^{(i)}_{-}\right)\,,$$

$$\alpha^{(i)}_{2,0} = \frac{1-3\,f^{(i)}_{\mathrm{L}}}{4\sqrt{5\pi}}\,,$$

$$\gamma_{1,0,1,0} = 3\,\eta_1\eta_3\,\frac{f_{--}+f_{++}-f_{-+}-f_{+-}}{16\pi}\,,$$

$$\gamma_{2,0,2,0} = \frac{1-3f^{(1)}_{\mathrm{L}}-3f^{(3)}_{\mathrm{L}}+9f_{\mathrm{L\,L}}}{80\pi}\,,$$

$$\gamma_{1,0,2,0} = \sqrt{\frac{3}{5}}\,\eta_1\,\frac{3\left(f_{-\,\mathrm{L}}-f_{+\,\mathrm{L}}\right)-\left(f^{(1)}_{-}-f^{(1)}_{+}\right)}{16\pi}\,,$$

$$\gamma_{2,0,1,0} = \sqrt{\frac{3}{5}}\,\eta_3\,\frac{3\left(f_{\mathrm{L}-}-f_{\mathrm{L}+}\right)-\left(f^{(3)}_{-}-f^{(3)}_{+}\right)}{16\pi}\,.$$

The 4ℓ channel: EW production and Higgs decays

Four-charged-lepton is promising channel to measure entanglement and Bell-inequality violation at hadron/lepton colliders [Ashby-Pickering et al. 2209.13990, Aguilar-Saavedra et al. 2209.13441, Fabbrichesi et al. 2302.00683, Aoude et al. 2307.09675, Aguilar-Saavedra 2403.13942, 2411.13464, Bernal et al. 2405.16525, Grossi GP Vicini 2409.16731, Sullivan 2410.10980, Grabarczyk 2410.18022, Subba Singh 2411.19171]:

- clean signature, no ν reconstruction
- ZZ CM frame precisely reconstructed
- EW production has lower sensitivity to NP than WZ/WW
- off-shell bosons make two-boson angular structure not well defined in Higgs-boson decays
- fiducial cuts disrupt angular integration
- higher-order corrections

Goodness of *entanglement witnesses* (sufficient conditions for system to be entangled) depend on how well we extract spin-density-matrix entries from (LHC) data.