STUDIES ON QUANTUM CORRELATIONS IN (H→)VV FINAL STATES

F. Fabbri, with several contributions.

OUTLINE

Impact of higher order electroweak and new physics on the spin density matrix in H→4l

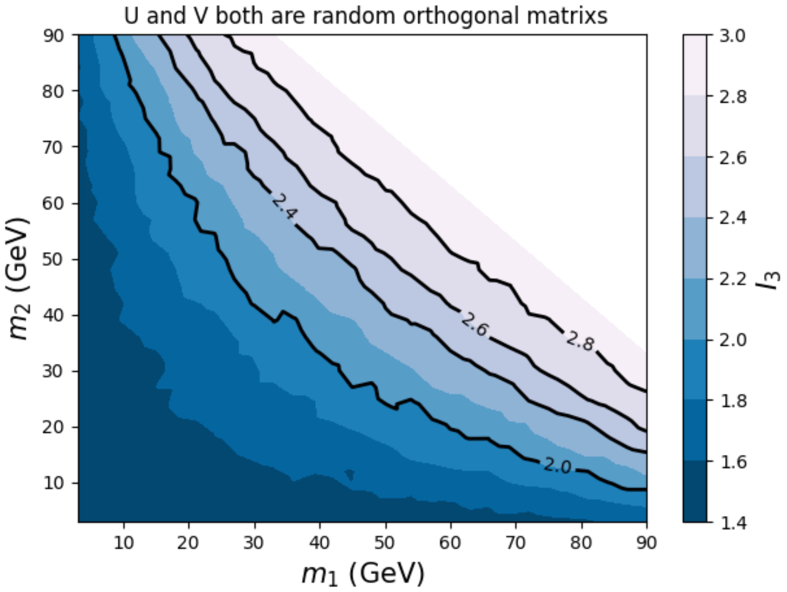
Feasibility study for observing entanglement in WZ final states at LHC

Both works are in preparation and should be on arxiv soon.

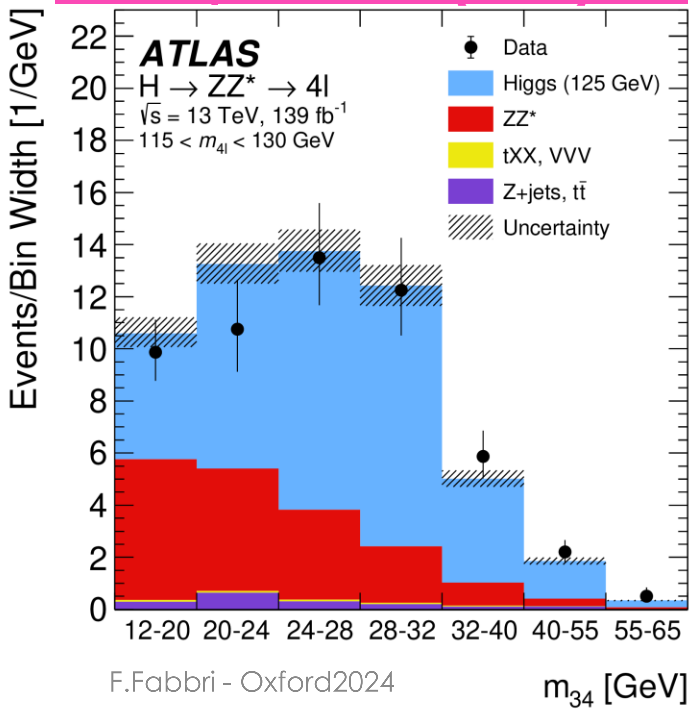
IMPACT OF HIGHER ORDER ELECTROWEAK AND NEW PHYSICS ON THE SPIN DENSITY MATRIX IN H→4L

03/10/2024

M. Del Gratta, F. Fabbri, D. Pagani, F. Maltoni, P. Lamba



Eur. Phys. J. C 80 (2020) 942



INTRODUCTION

- H->ZZ* highly studied in several paper on QI at LHC.
  - Including several studies on constraints on new physics
- Higgs characteristic make the ZZ highly entangled on the whole phase space
  - Violation of Bell's Inequality ($I_3 > 2$)
  - The level of entanglement depend on the masses of the two bosons
- Experimental advantage:
  - Pure signal
  - Fully re-constructable final state (no neutrinos)
  - Disadvantage: small statistics

BASIC FORMALISM-I

- Assuming the SM and H→ZZ*→4l the form of the spin density matrix is driven by the possible helicity states in the final state.
- The existence of superposition between the helicity state implies entanglement
  - Non zero non-diagonal elements [Saavedra, Bernal, Moreno, Casas]
    - Easy criteria for entanglement

$$|\psi\rangle = a_+|+-\rangle + a_0|0\,0\rangle + a_-|-+\rangle$$

The a depends on the mass of the bosons.
ZZ produced at rest → a0 == 1
→ Bell state

$$\rho = \begin{pmatrix} 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & a_+a_+ & 0 & a_+a_0 & 0 & a_+a_- & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & a_0a_+ & 0 & a_0a & 0 & a_0a_- & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & a_-a_+ & 0 & a_-a_0 & 0 & a_-a_- & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \end{pmatrix}$$

BASIC FORMALISM-II

- "Easy" quantum tomography approach:
  - Based on the measurement of θ and ϕ in parent boson rest frame (passing by the H rest frame)
  - Averages of the products (or single) spheric harmonics
  - Weighted by the "spin analysing power"

$$\frac{1}{\sigma}\frac{d\sigma}{d\Omega_a d\Omega_b} = \frac{1}{(4\pi)^2}[1 + A^a_{LM} B^a_L Y^M_L(\theta_a,\phi_a) + A^b_{LM} B^b_L Y^M_L(\theta_b,\phi_b) + C_{L_1M_1L_2M_2} B^a_{L_1} B^b_{L_2} Y^{M_1}_{L_1}(\theta_a,\phi_a) Y^{M_2}_{L_2}(\theta_b,\phi_b)]$$

$$\int \frac{1}{\sigma}\frac{d\sigma}{d\Omega_a d\Omega_b} Y^{*M}_L(\Omega_j)\, d\Omega_a d\Omega_b = \frac{B^j_L}{4\pi} A^j_{LM} \quad j = a, b$$

$$\int \frac{1}{\sigma}\frac{d\sigma}{d\Omega_a d\Omega_b} Y^{*M_1}_{L_1}(\Omega_a) Y^{*M_2}_{L_2}(\Omega_b)\, d\Omega_a d\Omega_b = \frac{B^a_{L_1} B^b_{L_2}}{(4\pi)^2} C_{L_1M_1L_2M_2}$$

BASIC FORMALISM-II

- "Easy" quantum tomography approach:
  - Based on the measurement of θ and ϕ in parent boson rest frame (passing by the H rest frame)
  - Averages of the p
  - Weighted by the "

$$\frac{1}{\sigma}\frac{d\sigma}{d\Omega_a d\Omega_b} = \frac{1}{(4\pi)}$$

$$\ldots{}_b, \phi_b)]$$

$$\int$$

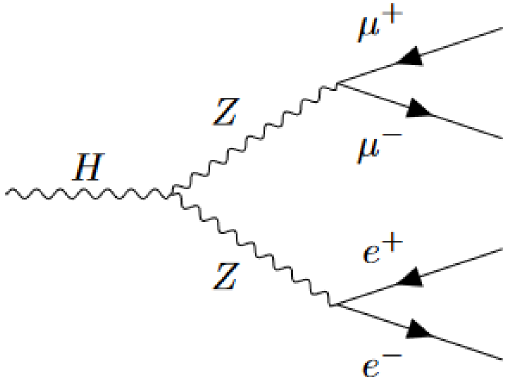
Putting together the this and last slides we obtain the following relations:

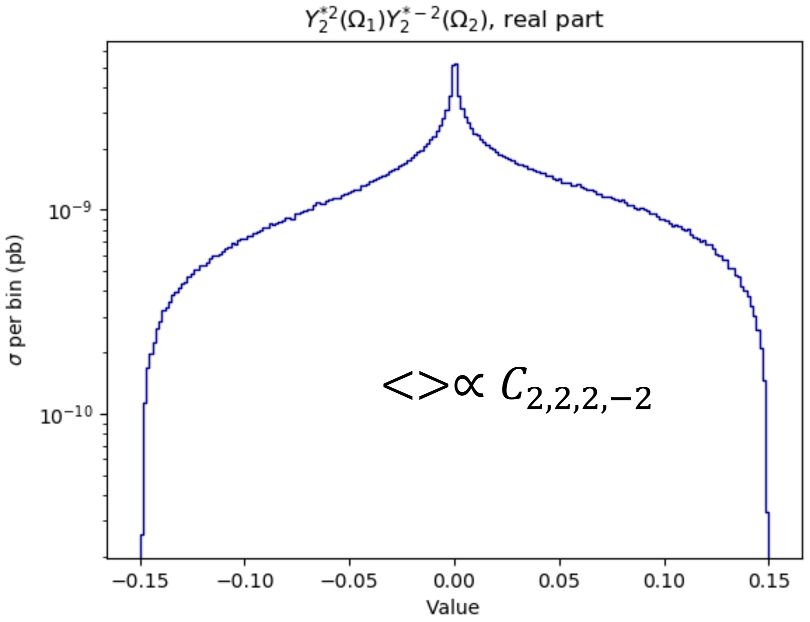
$$A^a_{2,0} = A^b_{2,0} \neq 0$$
$$\frac{A^a_{2,0}}{\sqrt{2}} + 1 = C_{2,2,2,-2} \neq 0$$
$$C_{1,-1,1,1} = C_{1,1,1,-1} = -C_{2,-1,2,1} = -C_{2,1,2,-1} \neq 0$$
$$C_{2,2,2,-2} = -C_{1,0,1,0} = 2 - C_{2,0,2,0} \neq 0$$

With the entanglement condition that is reduced to:

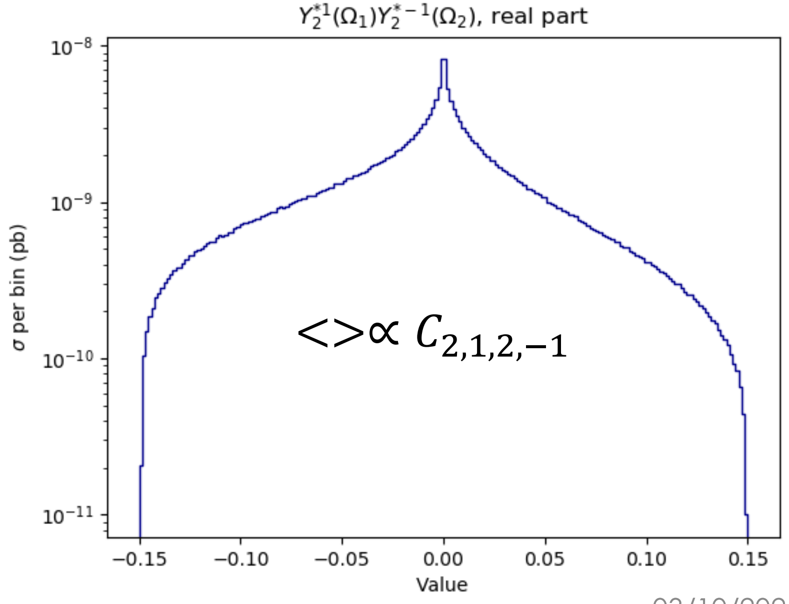
$$C_{2,2,2,-2} \neq 0, \qquad \text{or} \qquad C_{2,1,2,-1} \neq 0$$

ANALYSIS



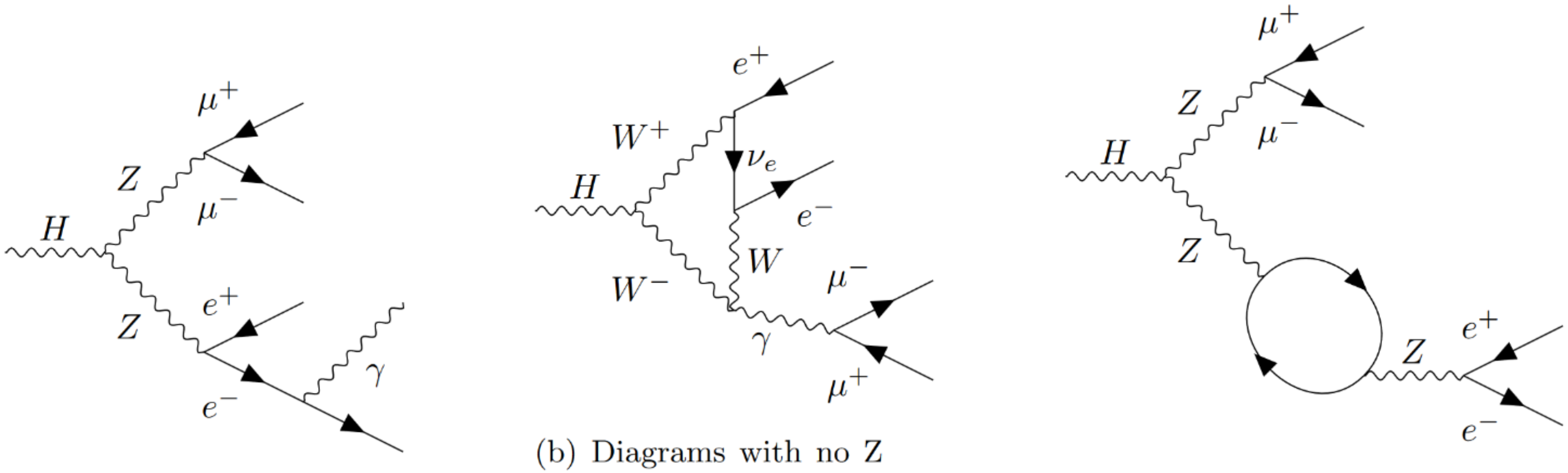


- Simulated H→$e^-e^+\mu^+\mu$
- Histograms generated with MG5@NLO (no showering)
- Z reconstructed combining same-flavour leptons
- Matrix extracted by averaging on the harmonics histograms
  - (0,0,1) direction assumed for the proton in the Higgs rest frame
- Excellent agreement with literature at LO.



REAL LIFE: NLO EW

- The same *kind* of analysis will be performed at LHC (plus all other complications)
  - There is no way to enforce the presence of two Z between the Higgs and the 4 leptons
- This opens the floor to a much more complex structure:
  - The contribution on the total xs is small, but what is the effect of the observables of interest? And the structure of the matrix?



(a) Real photon radiated (b) Diagrams with no Z bosons (c) Diagrams with loops

- Lepton definition: merging with photons in a cone 0.1
- Same approach employed for the quantum tomography
  - We are able to reconstruct all the elements of the spin density matrix

NLO EFFECTS SPIN DENSITY MATRIX-I

LO

$$\begin{pmatrix} 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0.195 & 0 & -0.313 & 0 & 0.194 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & -0.313 & 0 & 0.6121 & 0 & -0.313 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0.194 & 0 & -0.313 & 0 & 0.195 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \end{pmatrix}$$

NLO

$$\begin{pmatrix} 0.099 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0.004 & 0 & 0.131 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0.111 & 0 & -0.183 & 0 & 0.189 & 0 & 0 \\ 0 & 0.131 & 0 & -0.009 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & -0.183 & 0 & 0.591 & 0 & -0.183 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & -0.009 & 0 & 0.131 & 0 \\ 0 & 0 & 0.189 & 0 & -0.183 & 0 & 0.110 & 0 & 0 \\ 0 & 0 & 0 & 0.01 & 0 & 0.131 & 0 & 0.004 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0.099 \end{pmatrix}$$

- Different values of the coefficients
- Different structure of the matrix:
  - Some relations are broken
  - Some terms that used to be 0 have the same size of the other terms

NLO EFFECTS SPIN DENSITY MATRIX-I

LO

$$\begin{pmatrix} 0 & 0 & 0 & 0 & 0 & \cdots \\ 0 & 0 & 0 & 0 & 0 & \cdots \\ 0 & 0 & 0.195 & 0 & -0.31\ldots & \cdots \\ 0 & 0 & 0 & 0 & 0 & \cdots \\ 0 & 0 & -0.313 & 0 & 0.612 & \cdots \\ 0 & 0 & 0 & 0 & 0 & \cdots \\ 0 & 0 & 0.194 & 0 & -0.31\ldots & \cdots \\ 0 & 0 & 0 & 0 & 0 & \cdots \\ 0 & 0 & 0 & 0 & 0 & \cdots \end{pmatrix}$$

NLO

$$\begin{pmatrix} \cdots & 0 & 0 & 0 & 0 \\ \cdots & 0 & 0 & 0 & 0 \\ \cdots & 0 & 0.189 & 0 & 0 \\ \cdots & 0 & 0 & 0 & 0 \\ \cdots & 0 & -0.183 & 0 & 0 \\ \cdots & \ldots.009 & 0 & 0.131 & 0 \\ \cdots & 0 & 0.110 & 0 & 0 \\ \cdots & \ldots.131 & 0 & 0.004 & 0 \\ \cdots & 0 & 0 & 0 & 0.099 \end{pmatrix}$$

Looking at the relations existing at LO

$A^a_{2,0} = A^b_{2,0} \neq 0$	NLO → Sort of valid
$\frac{A^a_{2,0}}{\sqrt{2}} + 1 = C_{2,2,2,-2} \neq 0$	NLO → Broken
$C_{1,-1,1,1} = C_{1,1,1,-1} = -C_{2,-1,2,1} = -C_{2,1,2,-1} \neq 0$	NLO → Broken
$C_{2,2,2,-2} = -C_{1,0,1,0} = 2 - C_{2,0,2,0} \neq 0$	NLO → Broken

- Now it is very complicated to interpret the matrix only in terms of the helicities of the vector bosons.
  - What about the entanglement conditions? Is the condition itself valid?
- The NLO effect can be diminished in some specific regions of the phase space

- Different values of th...
- Different structure of...
  - Some relations c...
  - Some terms that...

REAL LIFE: NEW PHYSICS?

- We can only measure H→4leptons
  - We can write this as a generic current with this kind of interaction (EFT):

$$\mathcal{L}^7_{\rm EFT} = \frac{h}{\Lambda^3}\sum_i a_i \bar{\psi}_1 \Gamma^i \psi_2 \, \bar{\psi}_3 \Gamma^i \psi_4, \qquad \text{with} \qquad \begin{aligned} \Gamma^i &= \{1, \gamma_5, \sigma_{\mu\nu}, \gamma_\mu, \gamma_\mu\gamma_5\}, \\ a_i &= \{a_S, a_5, a_T, a_V, a_A\} \end{aligned}$$

  - We can use simplified models with intermediate resonances (tensors, scalar, vectors)
- Then we can investigate how these effects would modify the spin density matrix structure

EXAMPLE: TENSOR-TENSOR

- The amplitude can be expressed in terms of the four-momenta of the final state leptons
- Then the spin density matrix can be estimated analytically calculating the squared amplitudes

$$\sum_s \mathcal{A}_S^* \mathcal{A}_S = 16|c_S|^2 \Pi_0 \left(a^2 + b^2\right)\left(a'^2 + b'^2\right)$$

$$\sum_s \mathcal{A}_V^* \mathcal{A}_V = 16|c_V|^2 \left[\left(c_L^2 d_L^2 + c_R^2 d_R^2\right)\Pi_1 + \left(c_L^2 d_R^2 + c_R^2 d_L^2\right)\Pi_2\right]$$

$$\sum_s \mathcal{A}_T^* \mathcal{A}_T = 128|c_T|^2 (2\Pi_1 + 2\Pi_2 - \Pi_0)$$

$$\sum_s \mathcal{A}_S^* \mathcal{A}_T + \mathcal{A}_S \mathcal{A}_T^* = -64\mathrm{Re}(c_S c_T^*)\left[(ab' + a'b)\Pi_\epsilon + (aa' - bb')(\Pi_1 - \Pi_2)\right]$$

$$\sum_s \mathcal{A}_V^* \mathcal{A}_T = 0$$

$$\sum_s \mathcal{A}_V^* \mathcal{A}_S = 0$$

$\Pi_0 = (p_1 \cdot p_2)\,(p_3 \cdot p_4)$

$\Pi_1 = (p_1 \cdot p_3)(p_2 \cdot p_4)$

$\Pi_2 = (p_1 \cdot p_4)\,(p_2 \cdot p_3)$

$\Pi_\epsilon = \epsilon^{p1p2p3p4}$

EXAMPLE: TENSOR-TENSOR

VV

$$\rho = \begin{pmatrix} 0&0&0&0&0&0&0&0&0\\ 0&0&0&0&0&0&0&0&0\\ 0&0&x&0&y&0&x&0&0\\ 0&0&0&0&0&0&0&0&0\\ 0&0&y&0&z&0&y&0&0\\ 0&0&0&0&0&0&0&0&0\\ 0&0&x&0&y&0&x&0&0\\ 0&0&0&0&0&0&0&0&0\\ 0&0&0&0&0&0&0&0&0 \end{pmatrix}$$

TT

$$\rho = \begin{pmatrix} x_1&0&0&0&0&0&0&0&0\\ 0&-x_1&0&-y_1&0&0&0&0&0\\ 0&0&x_1&0&y_1&0&4x_1&0&0\\ 0&-y_1&0&-x_1&0&0&0&0&0\\ 0&0&y_1&0&1&0&y_1&0&0\\ 0&0&0&0&0&-x_1&0&-y_1&0\\ 0&0&4x_1&0&y_1&0&x_1&0&0\\ 0&0&0&0&0&-y_1&0&-x_1&0\\ 0&0&0&0&0&0&0&0&x_1 \end{pmatrix}$$

Part of the structure of the tensor-tensor case resemble the structure of the matrix obtained for the NLO

EXAMPLE: TENSOR-TENSOR

VV | **TT**

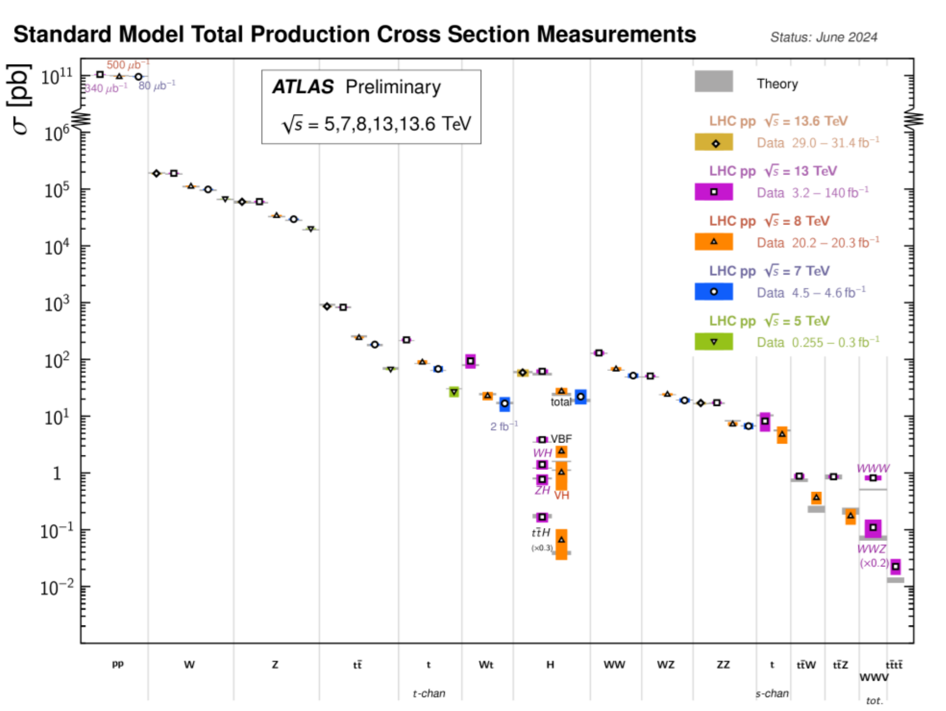
- The NLO corrections modify the structure of the spin density matrix for H→4l
  - Break symmetries, modified some coefficients 0 at LO
  - The same effects can be obtained assuming different intermediate resonances (e.g. TT)
- The measurement of the spin density matrix has been presented as a tool to search for new physics
  - Need to disentangle possible new physics effects from NLO effects

Part of the structure of the tensor-tensor case resemble the structure of the matrix obtained for the NLO

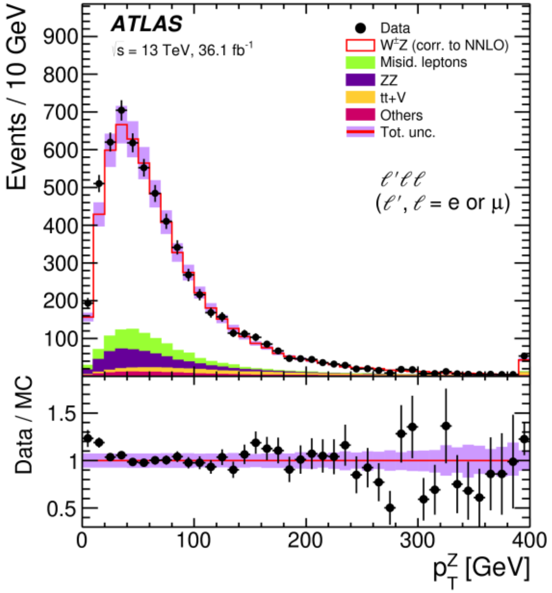
MEASURING QUANTUM CORRELATIONS IN WZ FINAL STATE AT LHC

03/10/2024

N. Forti, F. Maltoni, F. Fabbri



Eur. Phys. J. C 79 (2019) 535



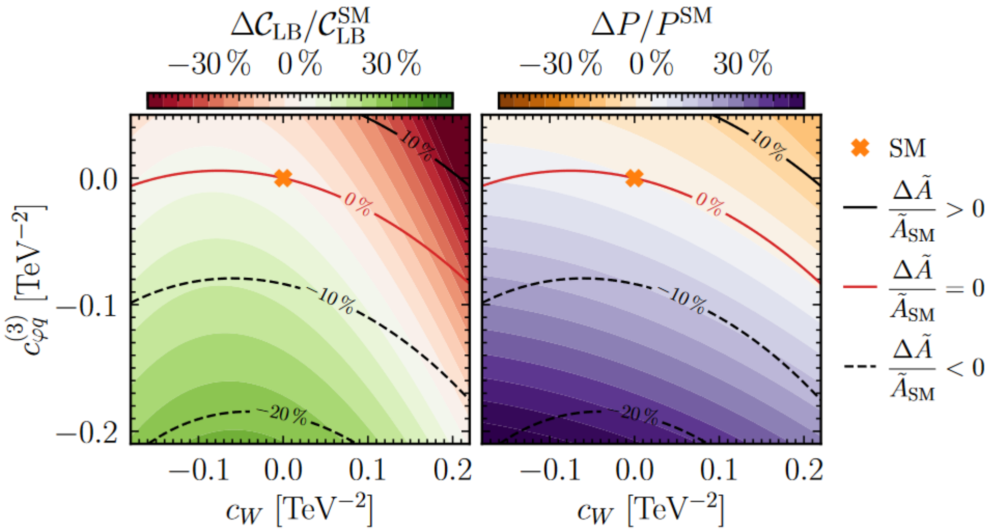
WHY WZ FINAL STATE?

Experimental advantages:

- Among diboson channels has more statistics than ZZ
- The final state is "easy" to reconstruct (it contains only a single neutrino)
- There is a small amount of background

Process	c^2_{MB}
$pp \to W^+W^- \to \ell^+\nu\ell^-\bar{\nu}$	-0.147
$H(125) \to WW^{(*)} \to \ell^+\nu_\ell\ell^-\bar{\nu}_\ell$	0.973
$H(200) \to WW \to \ell^+\nu_\ell\tau^-(30)\bar{\nu}_\tau$	0.946
$pp \to ZZ \to e^+e^-\mu^+\mu^-$	-0.21
$H(125) \to ZZ^{(*)} \to e^+e^-\mu^+\mu^-$	0.53
$pp \to W^+Z \to e^+\nu_e\mu^+\mu^-$	0.10

- 10.1007/JHEP05(2023)020



10.1007/JHEP12(2023)017

WHY WZ FINAL STATE?

Experimental advantages:

- Among diboson channels has more statistics than ZZ
- The final state is "easy" to reconstruct (it contains only a single neutrino)
- There is a small amount of background

QI perspective :

- Only process that is expected to be slightly entangled (on average) in the inclusive phase space
- Sensitive to new physics effects

ANALYSIS STRATEGY

- Based the quantum tomography approach described in R. Ashby-Pickering, A. J. Barr, A. Wierzchucka
  - Gell-Mann matrices parametrization
  - Quantum tomography based on the Weyl-Wigner P symbols

$$\rho = \frac{1}{9} I_9 + \frac{1}{3}\sum_{i=1}^{8} a_i \lambda_i \otimes I_3 + \frac{1}{3}\sum_{j=1}^{8} b_j I_3 \otimes \lambda_j + \sum_{i=1}^{8}\sum_{j=1}^{8} c_{ij} \lambda_i \otimes \lambda_j$$

W boson (a_i) | Z boson (b_j) | Correlation (c_{ij})

- Events simulated at LO (MG5 + Pythia8), processed through Rivet
  - Charged leptons dressed with photons $p_T > 7$ GeV, $|\eta| < 2.5$
  - Neutrinos reconstructed as MET
- Implemented a realistic selection (trigger, == 3l, |total charge| = 1)
- Final state reconstructed imposing W mass
- Statistical uncertainty assuming 450 fb^{-1}

LOWER BOUND ON THE CONCURRANCE

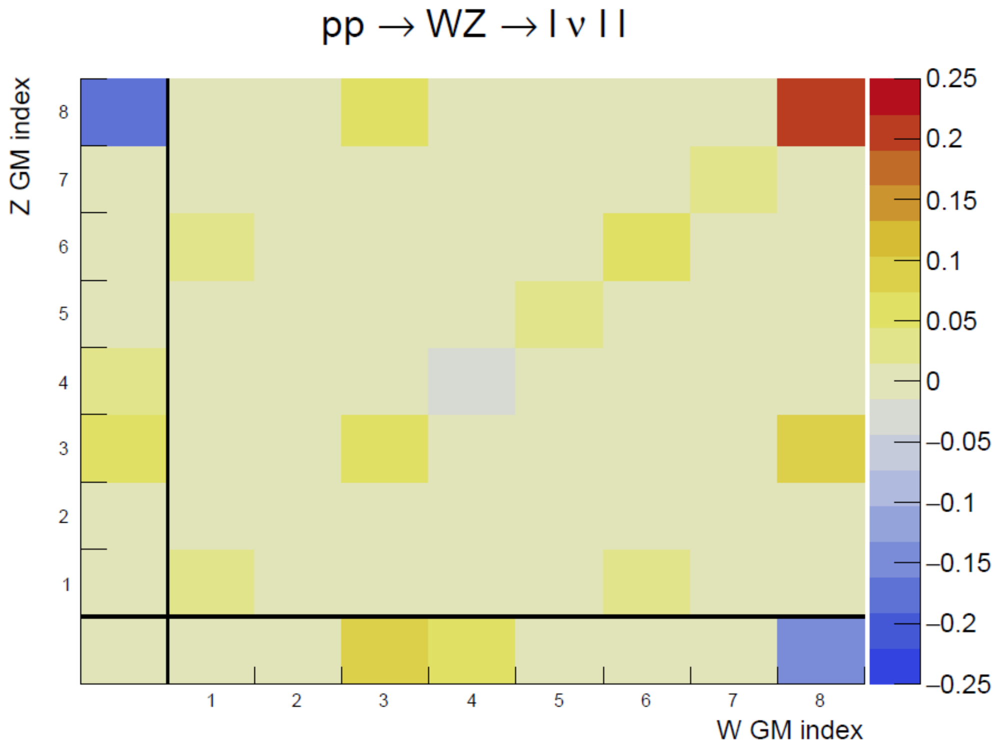
- Reconstructed all 80 histograms corresponding to the coefficients of the spin density matrix
- Extracted the concurrence using the lower bound

$$\left(c(\rho)\right)^2 \geq c_{MB}^2 = -\frac{4}{9} - \frac{2}{3}\sum_{i=1}^{8} a_i^2 - \frac{2}{3}\sum_{j=1}^{8} b_j^2 + 8\sum_{i,j=1}^{8} c_{ij}^2$$

- Value barely above the entanglement limit, considering the uncertainty difficult to observe entanglement

$$c_{MB}^2 = 0.036 \pm 0.018$$

- Using bootstrap method to propagate the statistical uncertainty and preserve the correlations
  - Statistical uncertainty based on Run2 + Run3 data



RECONSTRUCTED LEVEL

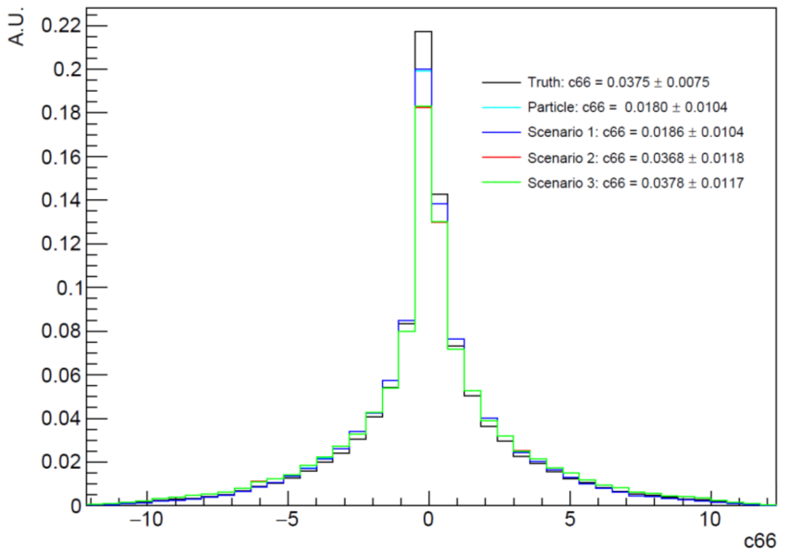
- Unfolded each distribution from reconstructed to "truth" level:
  - Using IBU
  - Identified a large limitation for the analyses: some values are extremely sensitive to the binning
- Expected concurrence:

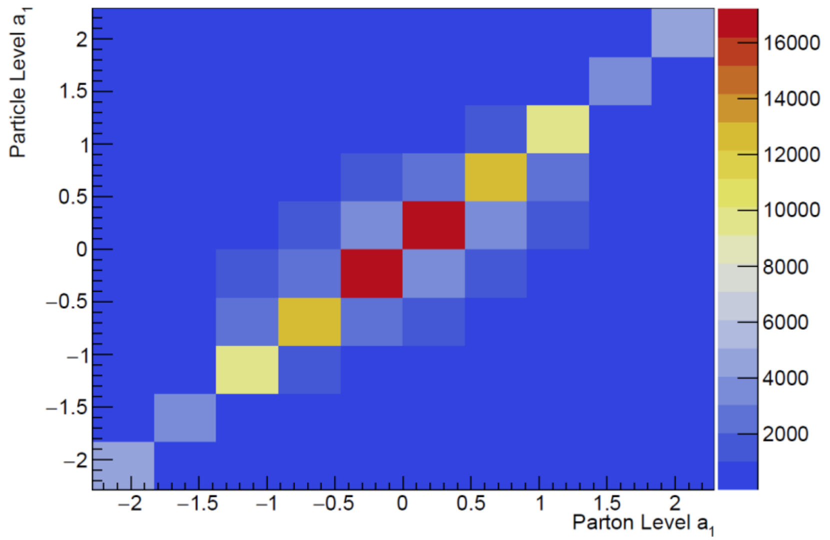
$$c^2_{MB} = 0.046 \pm 0.031$$

- Compatible with parton level (method works!)
- Inclusively not possible to observe entanglement
- Studied several regions of the phase space to identify the optimal region:

  cos | θ | > 0.5, pT(WZ) < 40 GeV:

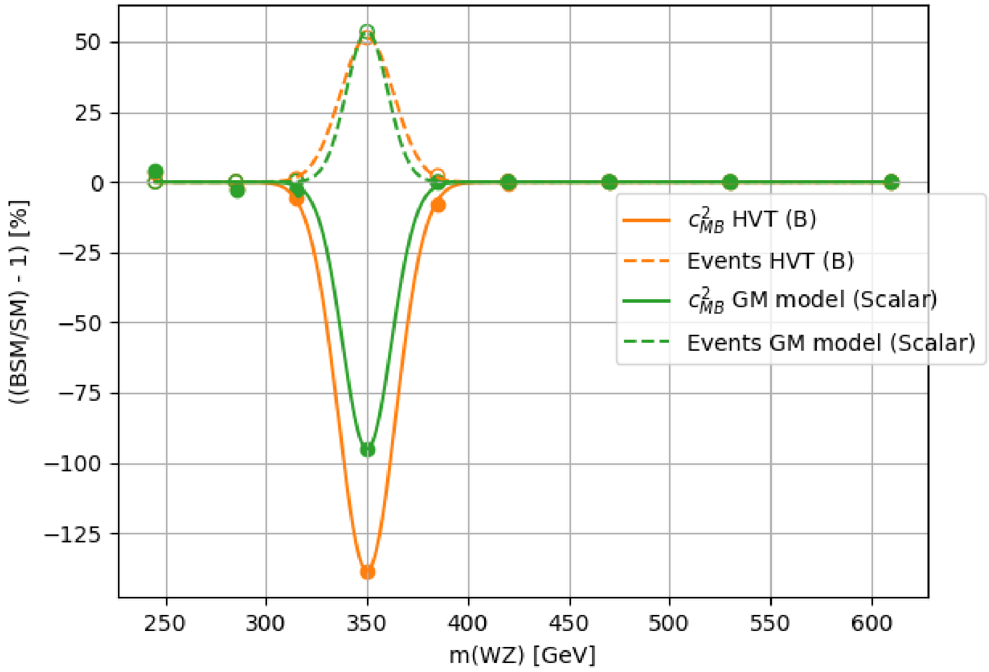
$$c^2_{MB} = 0.19 \pm 0.05\ (3.5\sigma)$$





IMPACT ON NEW PHYSICS SEARCHES

- Observing entanglement is not necessary the only interesting point in measuring c_{MB}^2
- Could be used to set constraints for new physics searches
  - As in $t\bar{t}$ where the presence of new physics had a larger impact on the entanglement markers than xs
- For now tested in direct searches with scalar and vector resonances decaying in $W^{+/-}Z$
  - Heavy vector model (https://arxiv.org/abs/1402.4431)
  - GM model (https://arxiv.org/abs/1404.2640)



CONCLUSIONS

- Presented 2 studies in the context of the diboson final state
  - We have investigated the effects of NLO EW on the structure of the spin density matrix for H→4l
    - NLO effects heavily modify the matrix (not just the values) but also the structure, with effects that can mimic new physics presence
  - We have performed a feasibility study for measuring the entanglement between WZ bosons at LHC (before HL)
    - Possible only in specific regions of the phase space to reach > 3 σ
    - Assumptions:
      - No MET smearing → in progress
      - No systematic uncertainties, no background
      - Sub-optimal neutrino reconstruction and statistical interpretation
    - Even if entanglement is not observed, the lower bound on the concurrence may be interesting in putting constraints on the existence of new physics.