Polarisation for multi-boson LHC processes

1st COMETA WG1 meeting

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Motivations

LHC luminosities accumulated in Run 2 ($\approx 150\,\text{fb}^{-1}$) and foreseen in next runs ($300\,\text{fb}^{-1}$ in Run 3, and $3000\,\text{fb}^{-1}$ in High-Lumi) at 13/14 TeV CoM energy enable

$\rightarrow$ precise measurements of EW processes: multi-boson production.

Polarisations of EW bosons

- are non trivial to disentangle
- are important probes of SM gauge and Higgs sectors,
- provide discrimination power between SM and BSM physics.

Polarisation within COMETA

COMETA: COmprehensive Multiboson Experiment-Theory Action

Polarisation of EW bosons is one main focus!

From the Memorandum of Understanding:

a) optimal definition of polarised-boson signals:
   comparison and validation of tools for the MC simulation
b) polarisation taggers:
   impact of kinematic selections, performance stability against higher orders
c) higher-order perturbative corrections to the SM predictions with polarised bosons
d) matching parton-level polarised predictions to parton-shower and hadronisation

Experimental results

Run-1 (angular-coefficient extraction):

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

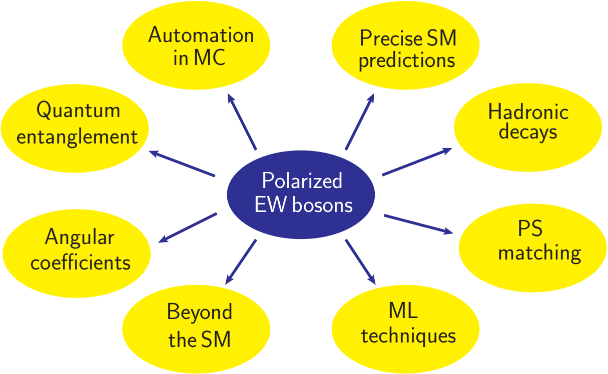
Run-2 (fits with polarised templates):

- WZ, singly polarised [ATLAS 1902.05759, CMS 2110.11231],
- $W^\pm W^\pm$ scattering [CMS 2009.09429],
- WZ, doubly polarised [ATLAS 2211.09435],
- ZZ, doubly longitudinal [ATLAS 2310.04350].

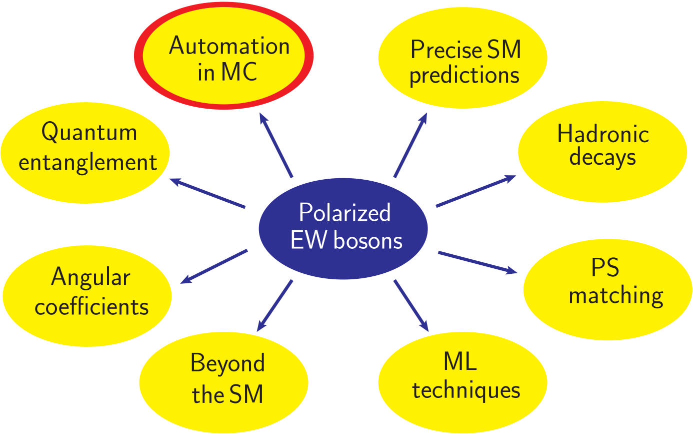
More ongoing analyses and promising sensitivity studies at High-Lumi
[CMS-PAS-FTR-18-014, CERN-LPCC-2018-03, Roloff et al. 2108.00324].

What's needed from the theory side?

Proper understanding, precise predictions and new ideas to extract polarisations.



COMETA is an opportunity not to be missed.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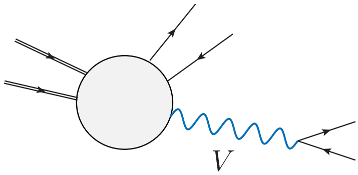
Separating polarisations in amplitudes

A natural definition for resonant diagrams (in pole/narrow-width approximation):



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

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

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

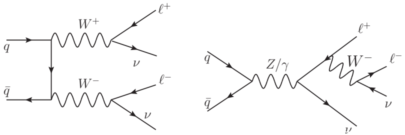
At the cross section level:

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

Polarisation states are not Lorentz invariant: defined in a specific frame. ★

Selecting resonant diagrams

To define polarisations, we need a factorized amplitude (production $\otimes$ propagator $\otimes$ decay): not possible for all contributions. *E.g.* diboson (fully leptonic):



Non-resonant diagrams regarded as non-resonant background.

Resonant diagrams treated with ★

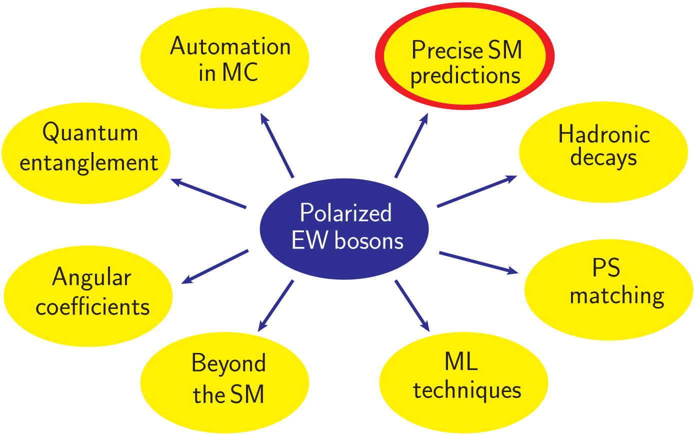
- DPA: double-pole approximation [Denner et al. 0006307]
- NWA: spin-correlated narrow-width approximation [Artoisenet et al. 1212.3460, Richardson 0110108].

→ separating polarisations is then straightforward.

Flexible and generalisable approach for numerical simulation and event generation.

Possible COMETA tasks

- agree on the best reference-frame choice to define polarisation (depending on the process)
- technical comparison between NWA/DPA approaches in defining multiboson signals in the *on-shell region*
- agree on the best choice of off-shell smearing (for NWA) and of on-shell projection (for DPA)



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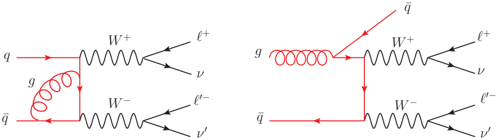
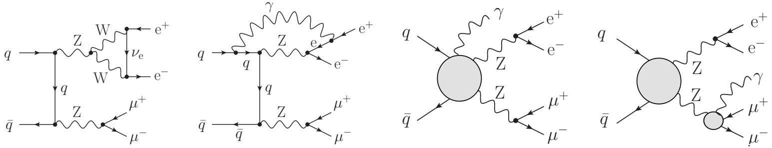
Going beyond leading-order: N(N)LO corrections



Corrections only affect production of resonance(s) $\longrightarrow$ conceptually straightforward.
N(N)LO QCD corr. with leptonic decays [Denner GP 2006.14867, Poncelet Popescu 2102.13583].



Corrections affect both production and decays of resonance(s).
NLO EW (QCD) corrections to Z/ W bosons with leptonic (hadronic) decays. [Denner GP 2107.06579, 2211.09040, Le Baglio 2203.01470, 2208.09232]

Missing ingredients, *i.e.* subtraction dipoles for complicated processes.

SM results at N(N)LO

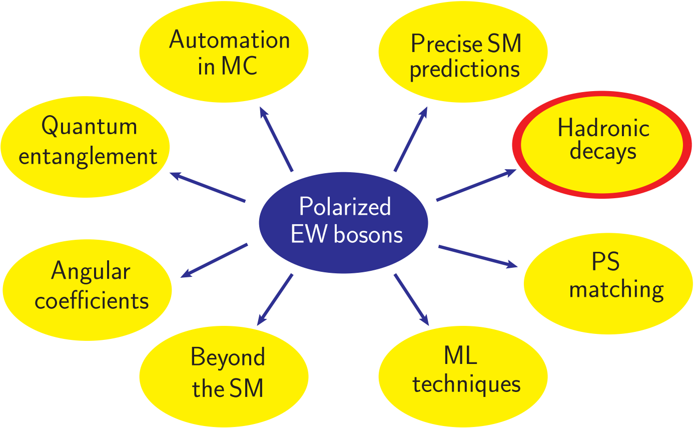
Recent precise predictions mostly target inclusive di-boson and V+jet production:

- → $\mathrm{W}^+(\ell^+\nu_\ell)\,\mathrm{W}^-(\ell'^-\bar{\nu}_{\ell'})$: NLO QCD + loop-ind. in the DPA [Denner GP 2006.14867], NNLO QCD + loop-ind. in the DPA and NWA [Poncelet Popescu 2102.13583];
- → $\mathrm{W}^\pm(\ell^\pm\nu_\ell)\,\mathrm{Z}(\ell'^+\ell'^-)$: NLO QCD [Denner GP 2010.07149] and NLO QCD+EW [Le Baglio 2203.01470, 2208.09232, Dao Le 2302.03324] in the DPA;
- → $\mathrm{Z}(\ell^+\ell^-)\,\mathrm{Z}(\ell'^+\ell'^-)$: NLO EW+QCD + loop-ind in the DPA [Denner GP 2107.06579];
- → $\mathrm{W}^\pm(\ell^\pm\nu_\ell)\,\mathrm{j}$: NNLO QCD in the NWA [Pellen et al. 2109.14336];
- → $\mathrm{W}^\pm(\mathrm{jets})\,\mathrm{Z}(\ell'^+\ell'^-)$: NLO QCD in the DPA [Denner Haitz GP 2211.09040].

Missing combination of NNLO QCD and NLO EW corrections in diboson ★
as well as NLO corrections to polarised VBS processes.

Possible COMETA tasks

- precise predictions for WZ inclusive production, combination of NNLO QCD and NLO EW:
  - NLO QCD (2 literature results: Denner-Haitz-GP, Baglio-Le-Dao)
  - NLO EW (1 literature result: Baglio-Le-Dao, code ready: Denner-Haitz-GP)
  - NNLO QCD (no literature results, code ready: Poncelet-Pellen)
- NLO QCD for $gg \to W^+W^-, ZZ$ for polarised states:
  - exchange with di-Higgs community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Hadronic decays of weak bosons

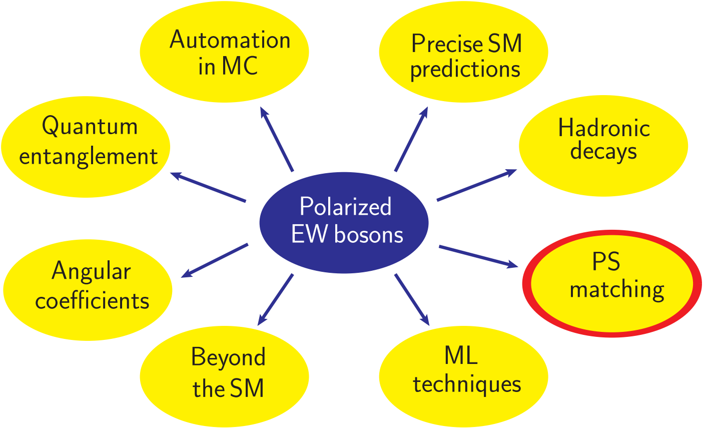
Higher statistics, but larger backgrounds: polarisation studies benefit from know-how developed for new-resonance searches and boosted-topology analyses.

Semi-leptonic di-boson channels (inclusive, VBS) investigated with: ★

- jet-substructure observables [De et al. 2008.04318, Dey Samui 2110.02773]
- energy correlators [Ricci Riembau 2207.03511]
- machine-learning methods [Grossi et al. 2008.05316, Kim Martin 2102.05124]
- polarised-template approach [Denner Haitz GP 2211.09040]

Possible COMETA tasks

★ detailed review of state-of-the-art tools, interplay with WG2 & WG3 activities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Matching to parton shower

Usual assumption: factorisation of PS effects from spin-structure of the multi-boson system → not true already with one real emission.

MC codes simulating intermediate polarised bosons (public or soon-to-be-published):

1. PHANTOM (v1.7): LO, 2 → 6 processes in the DPA, interfaced to PS [Ballestrero Maina GP 1710.09339, 1907.04722, 2007.07133, Maina GP 2105.07972].
2. MG5_aMC@NLO (v2.7): LO, any process in the NWA, multi-jet merging and PS matching, UFO models for BSM/EFT [Buarque-Franzosi et al. 1912.01725].
3. SHERPA: nLO (approx.), any process in the NWA, multi-jet merging and PS matching, UFO models for BSM/EFT [Hoppe et al. 2310.14803]
4. POWHEG-BOX-RES: NLO, diboson processes in the DPA, PS matching [GP Zanderighi 2311.05220].

First efforts towards a public unweighted-event generators capable to treat intermediate polarised bosons beyond LO in SHERPA [Hoppe et al. 2310.14803] and POWHEG-BOX-RES [GP Zanderighi 2311.05220].

Ongoing efforts towards NLO+PS in SHERPA and MG5_aMC@NLO ★

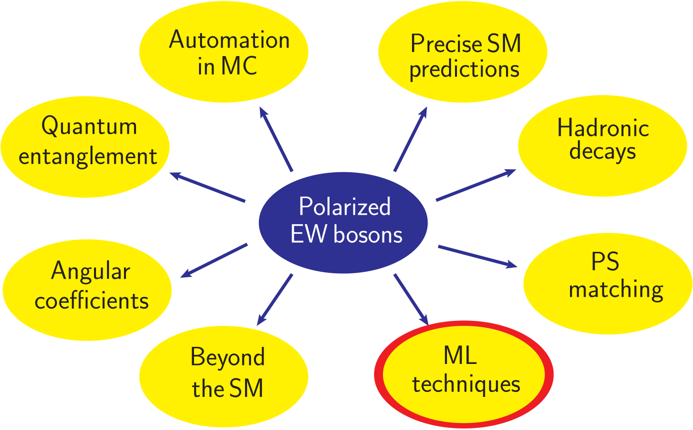
Effort needed to incorporate EW and spin-dependent effects in PS.

Possible COMETA tasks

★ Monte Carlo comparison (*à la* VBSCan) for diboson at (N)LO QCD + PS:

- MG5_aMC@NLO (LO available, NLO work in progress)
- Sherpa (nLO & multi-jet merging available, NLO work in progress)
- Powheg-Box-Res (NLO available)

→ foster implementation in other frameworks: Whizard? VBFNLO?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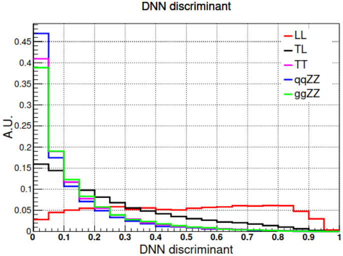
Machine learning for polarisation extraction

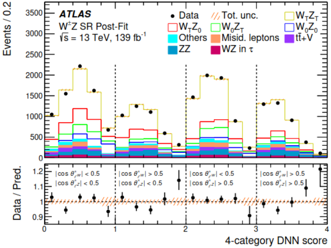
Various neural-network strategies used for polarisation extraction from leptonic decays in VBS events [Searcy et al. 1510.01691, Lee et al. 1812.07591, 1908.05196, Grossi et al. 2008.05316, Li et al. 2010.13281, 2109.09924] ★

ML approaches used to extract polarisations from hadronic decays [Kim Martin 2102.05124].

Mostly use kinematical features to reconstruct polarisation-sensitive angles or directly extract polarisation fractions with DNN score (figure from Ref. [Lee et al. 1908.05196])



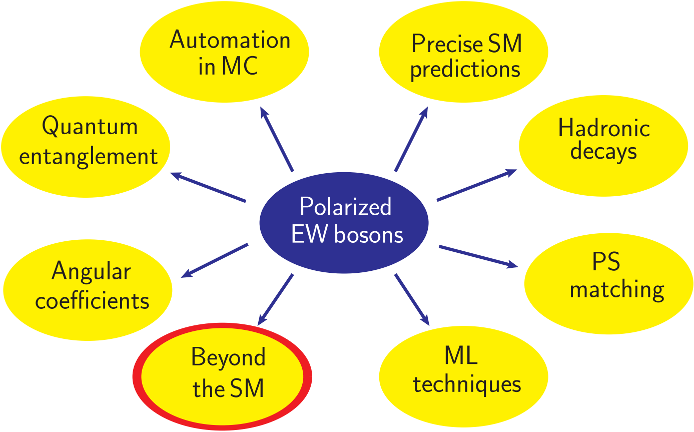
DNN output crucial for doubly-polarised $W^{\pm}Z$ measurement with Run-2 data [ATLAS 2211.09435]: enhanced sensitivity, evaluation for polarised signals at NLO QCD.



Recent proposal [Grossi et al. 2306.07726]: combine kinematic input (exp) with amplitudes (theory) to train NN tagging longitudinal bosons.

Possible COMETA tasks

- ★ detailed review of state-of-the-art tools, interplay with WG2 activities: merge forces and come up with a *COMETA polarisation tagger*?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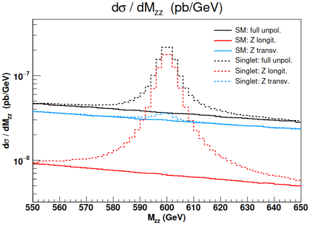
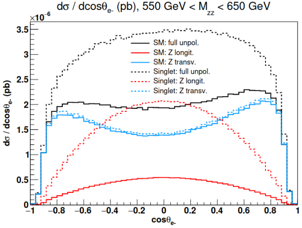
Extended Higgs sectors

A few VBS studies with polarised templates in presence of extended Higgs sectors:

- Higgsless SM, $\mathcal{Z}_2$-symmetric Singlet extension [Ballestrero Maina GP 1907.04722]





- composite-Higgs models [Buarque-Franzosi et al. 1912.01725]

	p-CM SM ($a=1$)		p-CM CH ($a=0.8$)			p-CM CH ($a=0.9$)		
Process	σ [fb]	$f_{\lambda\lambda'}$	σ [fb]	$f_{\lambda\lambda'}$	σ^{CH}/σ^{SM}	σ [fb]	$f_{\lambda\lambda'}$	σ^{CH}/σ^{SM}
jjW^+W^-	171	...	173	...	1.00	172	...	1.00
$jjW^+_TW^-_T$	119	70%	116	69%	0.98	115	69%	0.96
$jjW^+_0W^-_T$	20.6	12%	21.5	13%	1.05	22.0	13%	1.07
$jjW^+_TW^-_0$	23.8	14%	24.1	14%	1.01	23.9	14%	1.01
$jjW^+_0W^-_0$	5.45	3%	7.17	4%	1.31	6.01	4%	1.10

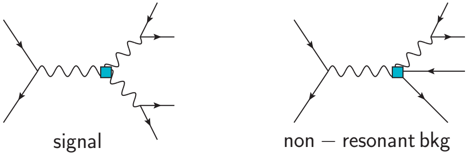
Anomalous couplings studied also in $H \to VV$ [Brehmer et al. 1404.5951].
Limits on anomalous couplings or Wilson coefficients through angular-coefficient methods [Rahaman Singh 1810.11657, 1911.03111, 2109.09345].

EFT: some thoughts

• Polarization observables in di-boson have been studied in SMEFT at NLO QCD [Baglio, Dawson, Lewis 1812.00214, 2003.07862, Franceschini et al. 1712.01310].

• Angular observables and NLO QCD to resurrect dim-6 SMEFT-SM interference [Azatov et al. 1707.08060, Panico et al. 1708.07823, Franceschini et al. 1712.01310]. Including decays and off-shell effects could play a relevant role in the results.

• Polarised-template approach relies on the separation between a resonant signal (treated with NWA/DPA) and a non-resonant background (the missing off-shell effects). It can be applied with any underlying dynamics, for example SMEFT: some effective insertions will affect the non-resonant background, some will affect the signal.

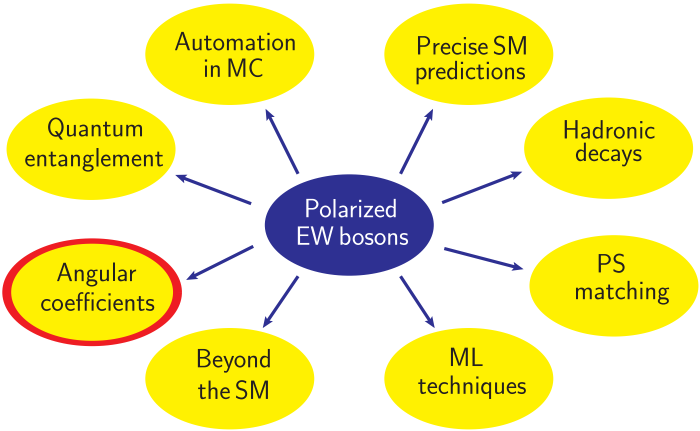


Simulation with BSM/SMEFT effects in production × decay is only LO accurate: MG5_aMC@NLO and Sherpa. ★

Possible COMETA tasks

★ cross topic amongst WG1 “sub-groups”, input from WG3 (analyses) needed:

- polarisation structure
- precision physics
- EFT frameworks
- BSM models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Angular coefficients: polarisation and spin correlations

Extraction from single-boson unpolarised decay rate in finite-p_T Drell-Yan [Frederix Vitos 2007.08867, Pellen et al. 2204.12394]

Generalised strategy for two-weak-boson systems at colliders [Rahaman Singh 2109.09345, Ashby-Pickering et al. 2209.13990]: 80 indep. coeffs $= (2s_1+1)^2(2s_2+1)^2 - 1$ $(s_1, s_2 = 1)$

$$\rho(\lambda_1, \lambda_1', \lambda_2, \lambda_2') = \left(\frac{1}{9}\left[\mathbb{1}\otimes\mathbb{1}\right] + \sum_a f_a \left[T^a \otimes \mathbb{1}\right] + \sum_a g_a \left[\mathbb{1}\otimes T^a\right] + \sum_{ab} h_{ab} \left[T^a \otimes T^b\right]\right)_{\lambda_1\lambda_1',\lambda_2\lambda_2'}.$$

$$\frac{1}{\sigma}\frac{\mathrm{d}\sigma}{\mathrm{d}\Omega^+\,\mathrm{d}\Omega^-} = \left(\frac{3}{4\pi}\right)^2 \mathrm{Tr}\left[\rho_{V_1V_2}\left(\Pi_+\otimes\Pi_-\right)\right]$$

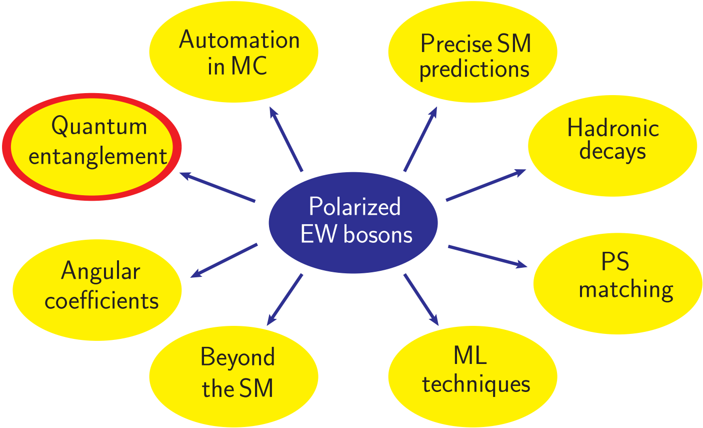
Based on Wigner-Weyl method [Jacob '58, Wigner '59, Jacob Wick '59], often dubbed quantum tomography [Martens et al. 1707.01638]. Used with EFT operators [Rahaman Singh 2109.09345].

1. radiative corrections: spin-density matrix modified, possible 3-body decays;
2. cuts on decay products: angular coefficients do not describe properly polarisation fractions and spin-correlations [Stirling et al.1204.6427, Belyaev et al.1303.3297].

Assessment of selection-cut effects only done for DY [Frederix Vitos 2007.08867] and WZ production [Baglio et al. 1810.11034], not yet for other diboson channels nor with BSM. ★

Possible COMETA tasks

- Impact of selections, higher orders, and BSM effects on angular coefficients
  - involve people in the business
  - bridge needed between the precision/full-simulation and the quantum-tomography/angular-coefficient communities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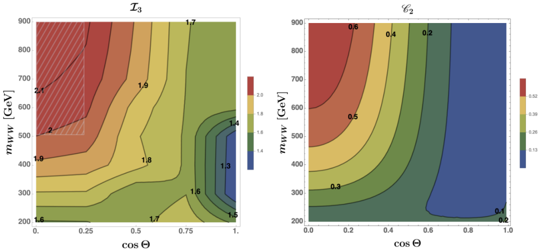
Quantum entanglement with di-boson systems

Test Bell inequalities and quantum entanglement in relativistic boson-pair systems.

Applied to $H \to VV$ [Barr 2106.01377, Aguilar-Saavedra et al. 2209.13441] and in general ZZ/W^+W^- systems [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, Bi et al. 2307.14895].

Idea: full access to the spin-density matrix $\to$ quantum-entanglement observables.

HL-LHC sensitivity: $H \to ZZ$ very promising ($\mathcal{I}_3 \leq 2$ rejected with up to 5.6σ), less sensitvity in $pp \to W^+W^-$ (figure from [Fabbrichesi et al. 2302.00683])

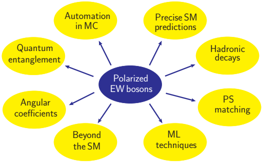


Missing assessment of higher-order corrections on quantum observables. ★

Possible COMETA tasks

- review state-of-the-art, find connections and involve people in the business
  - bridge needed between the polarisation-simulation and the quantum-entanglement communities

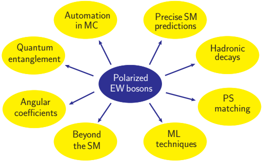
Conclusions



Much effort invested in past few years:

- **automation** of MC simulations within the SM
- calculation of **higher-order** corrections
- study of **polarisation observables**

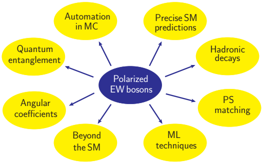
Conclusions



Started new efforts, recently:

- matching to **parton shower** and hadronisation
- **higher-order** predictions for **complicated processes**
- polarisation observables with **SMEFT** effects
- usage of **ML techniques**
- interplay with **quantum entanglement**

Conclusions



Missing, but crucial:

- **common** recommendations and **Monte Carlo** comparisons
- **public** codes to ease experimental effort
- **workforce**

Conclusions

An opportunity to improve our understanding of polarisation in multi-boson processes

Precision SM and BSM/EFT predictions for polarised signals, as well as spin-sensitive observables, lead to a deeper understanding of the EWSB.

Several links to other WG1 ($\rightarrow$ precision, EFT, BSM), WG2 ($\rightarrow$ ML-based tagging) and WG3 goals ($\rightarrow$ analyses and measurements).