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Theory predictions and event generation for polarisation measurements

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In order to perform template fits of data and enhance the sensitivity to new-physics effects, precise and accurate theoretical predictions are needed for polarised weak bosons in LHC processes. We have proposed a strategy to compute polarised cross-sections including radiative corrections to the production and decay of bosons, relying on the pole approximation and the separation of polarisation states at amplitude level. After showing some details of the theoretical definition, we present results relevant for di-boson polarisation analyses with semi-leptonic decays.

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Introduction The LHC luminosities accumulated in Run 2 and foreseen in the upcoming runs will enable precise measurements of electroweak (EW) processes with one or more weak bosons ($W^\pm$, Z). Accessing the polarisation state of weak bosons represents a crucial step towards a better understanding of the electroweak-symmetry-breaking mechanism realised in nature, providing us with important probes of the Standard Model (SM) gauge and Higgs sectors, as well as high discrimination power between SM and beyond-the-SM (BSM) dynamics. Unfortunately, extracting EW-boson polarisation states is hampered by the unstable nature of massive gauge bosons, making it impossible to directly detect polarised bosons. However, the polarisation mode of W and Z bosons leaves trace in the kinematic distributions of the decay products. A template-fit approach was introduced by ATLAS and CMS in the analysis programme of Run 2, leading to polarisation measurements in di-boson inclusive production [1] and scattering [2]. Sensitivity studies for polarisation measurements in the High-Lumi and High-Energy stages of the LHC are promising [3]. In order to enable fits of LHC data with polarised templates, we need: (i) proper control on the theoretical definition of polarised signals, (ii) high accuracy in the perturbative and non-perturbative predictions, and (iii) smart ideas to enhance the sensitivity to polarisation.

Definition of polarised signals A natural definition of polarised signals can be identified for rocesses that are described by resonant diagrams (in a certain on-shell approximation, with a given gauge choice). In the ‘t Hooft-Feynman gauge, the (unpolarised) amplitude for topologies like the

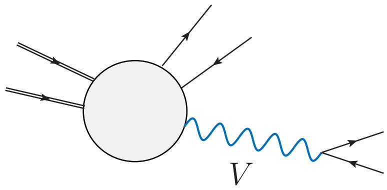

Figure 1: Generic resonant contribution to EW-boson production and decay.

one in Fig. 1 reads,

$$\mathcal{A}^{\mathrm{unp}} = \mathcal{P}_\mu \, \frac{-g^{\mu\nu}}{k^2 - M_V^2 + iM_V\Gamma_V} \, \mathcal{D}_\nu = \mathcal{P}_\mu \, \frac{\sum_{\lambda'} \varepsilon^\mu_{\lambda'} \varepsilon^{*\nu}_{\lambda'}}{k^2 - M_V^2 + iM_V\Gamma_V} \, \mathcal{D}_\nu \,. \tag{1}$$

The sum runs over physical polarisation modes as unphysical modes are canceled by Goldstone-boson contributions. Replacing the sum with a single term we obtain a polarised amplitude,

$$\mathcal{A}_\lambda = \mathcal{P}_\mu \, \frac{\varepsilon^\mu_\lambda \varepsilon^{*\nu}_\lambda}{k^2 - M_V^2 + iM_V\Gamma_V} \, \mathcal{D}_\nu \,, \qquad \text{for polarisation } \lambda = \mathrm{L}, +, -. \tag{2}$$

Therefore, the squared unpolarised amplitude is written an incoherent sum of squared polarised amplitudes plus interference terms:

$$|\mathcal{A}^{\mathrm{unpol}}|^2 = \sum_\lambda |\mathcal{A}_\lambda|^2 + \sum_{\lambda \neq \lambda'} \mathcal{A}^*_\lambda \mathcal{A}_{\lambda'} \tag{3}$$

Up to flux, symmetry and phase-space factors, we obtain a natural definition of *polarised cross section* proportional to $|\mathcal{A}_\lambda|^2$ [5]. Note that polarisation vectors (and therefore polarised signals) are defined in a specific Lorentz frame. As mentioned above the decay-product distributions reflect the polarisation state of the decayed boson, thus the polarisation fractions (f_{L}, $f_{\pm}$) can be extracted from the unpolarised decay-angle distribution [4],

$$\frac{\mathrm{d}\sigma}{\mathrm{d}\cos\theta^*}\frac{1}{\sigma} = \frac{3f_{\mathrm{L}}}{4}(1-\cos^2\theta^*)+\frac{3f_+}{8}(1+\cos^2\theta^*+2c_{\mathrm{RL}}\cos\theta^*)+\frac{3f_-}{8}(1+\cos^2\theta^*-2c_{\mathrm{RL}}\cos\theta^*)\,, \quad (4)$$

by means of projections onto suitable spherical harmonics. However, this strategy is not viable with more than one bosons, with radiative corrections modifying the decay structure, and in the presence of cuts on decay products [4, 5]. On the contrary, the polarised-signal definition of Eq. 3 can be systematically applied in the presence of more bosons and including such realistic effects.

Since both resonant and non resonant diagrams contribute to LHC process already at leading order (LO), only resonant diagrams must be selected, recovering gauge invariance by means of a narrow-width or pole approximation [6]. Then, separating polarised amplitudes is straightforward. This strategy can be applied to processes with any number of EW bosons and a general method was proposed [7, 8] to extend it also to the presence of next-to-leading-order (NLO) corrections (both to production and to decay). This has been applied to all di-boson processes in the fully leptonic decay channel up to NNLO QCD and NLO EW accuracy [7–9]. The extension of the method to the NLO matching to parton showers has been achieved in the Powheg-Box-Res framework [10].

Polarised boson-pair production with semi-leptonic decays Very recently, the first calculation of di-boson inclusive production in the semi-leptonic decay channel has been carried out at NLO QCD in the presence of polarised bosons [11]. This was done in the MoCaNLO Monte Carlo code with tree-level and one-loop SM amplitudes calculated with Recola [12] and Collier[13] libraries. The considered process is $\mathrm{p\,p} \to \mathrm{Z}(\to \mathrm{e}^+\mathrm{e}^-)\,\mathrm{W}^+(\to \mathrm{jets})$ at $\sqrt{s} = 13.6\mathrm{TeV}$, with fiducial selections that mimic those of a recent CMS analysis [14]. Two setups are studied, depending on the two-light-jet (resolved) or one-fat-jet (unresolved) hadronic decay of the W boson. A boosted regime for both bosons is considered ($p_{\mathrm{T},V} > 200\mathrm{GeV}$). Polarisation states (L=longitudinal, T=transverse) are defined in the centre-of-mass frame of the di-boson system. The integrated cross sections are shown in Table 1. The large NLO QCD corrections mostly come from gluon-initiated real contributions. A large LL fraction characterises the boosted regime, compared to inclusive setups. The longitudinal state is unsuppressed, due to the presence of the triple-gauge coupling. Sizeable differences are found between the two setups at LO, owing to jet recombination, while they become smaller at NLO. Interference contributions are very small, especially at NLO (less than 0.5% of the total).

It is essential to study the differential distributions for (doubly) polarised signals, which typically feature an enhanced discrimination power between longitudinal and transverse states. In Fig. 2 the transverse momentum of the positron is considered for the two setups and for the various polarisation states. There is a clear sensitivity to the Z-boson polarisation in the low-transverse-momentum range. The faster decrease of the curves in the high-$p_{\mathrm{T,e^+}}$ regime at LO in the resolved setup gives larger K-factors than in the unresolved setup. A number of other observables have very strong discrimination power amongst the doubly polarised states [11].

Summary The extraction of polarised-boson signals is of high interest for the LHC community. So far most of the theoretical effort has been devoted to SM fixed-order predictions, to the automation in Monte Carlo codes, and to the search for polarisation-sensitive observables, with special focus

state	$\sigma_{\rm LO}$ [fb]	$f_{\rm LO}$ [%]	$\sigma_{\rm NLO}$ [fb]	$f_{\rm NLO}$ [%]	$K_{\rm NLO}$	$K_{\rm NLO}^{(\rm no\,g)}$
resolved setup, $\rm Z(e^+e^-)W^+(jj)$						
unpol.	$1.8567(2)^{+1.2\%}_{-1.4\%}$	100	$3.036(2)^{+6.8\%}_{-5.3\%}$	100	1.635	1.033
$\rm Z_L W^+_L$	$0.64603(5)^{+0.2\%}_{-0.6\%}$	34.8	$0.6127(4)^{+0.9\%}_{-0.7\%}$	20.2	0.948	1.031
$\rm Z_L W^+_T$	$0.08687(1)^{+0.2\%}_{-0.6\%}$	4.7	$0.17012(6)^{+8.6\%}_{-6.8\%}$	5.6	1.958	0.967
$\rm Z_T W^+_L$	$0.08710(1)^{+0.1\%}_{-0.6\%}$	4.7	$0.24307(7)^{+10.2\%}_{-8.2\%}$	8.0	2.791	1.017
$\rm Z_T W^+_T$	$0.97678(7)^{+2.0\%}_{-2.2\%}$	52.6	$2.0008(7)^{+8.9\%}_{-7.1\%}$	65.8	2.048	1.059
interf.	0.0595(1)	3.2	0.009(2)	0.4	–	–
unresolved setup, $\rm Z(e^+e^-)W^+(J)$						
unpol.	$1.6879(2)^{+1.9\%}_{-2.1\%}$	100	$3.112(2)^{+7.6\%}_{-6.1\%}$	100	1.843	1.193
$\rm Z_L W^+_L$	$0.61653(5)^{+1.0\%}_{-1.3\%}$	36.5	$0.6799(5)^{+0.9\%}_{-0.7\%}$	21.9	1.103	1.170
$\rm Z_L W^+_T$	$0.06444(1)^{+0.7\%}_{-1.0\%}$	3.8	$0.17584(6)^{+10.8\%}_{-8.6\%}$	5.7	2.729	1.158
$\rm Z_T W^+_L$	$0.07437(1)^{+0.6\%}_{-0.9\%}$	4.4	$0.24742(8)^{+11.0\%}_{-8.9\%}$	8.0	3.327	1.193
$\rm Z_T W^+_T$	$0.88233(9)^{+2.9\%}_{-2.9\%}$	52.3	$2.0041(8)^{+9.6\%}_{-7.7\%}$	64.3	2.271	1.227
interf.	0.0503(3)	3.0	0.004(2)	0.1	–	–

Table 1: Fiducial cross sections and fractions for (un)polarised $\rm ZW^+$ production with semi-leptonic decays. Monte Carlo errors (in parentheses) and QCD-scale uncertainties (in percentage) are shown.

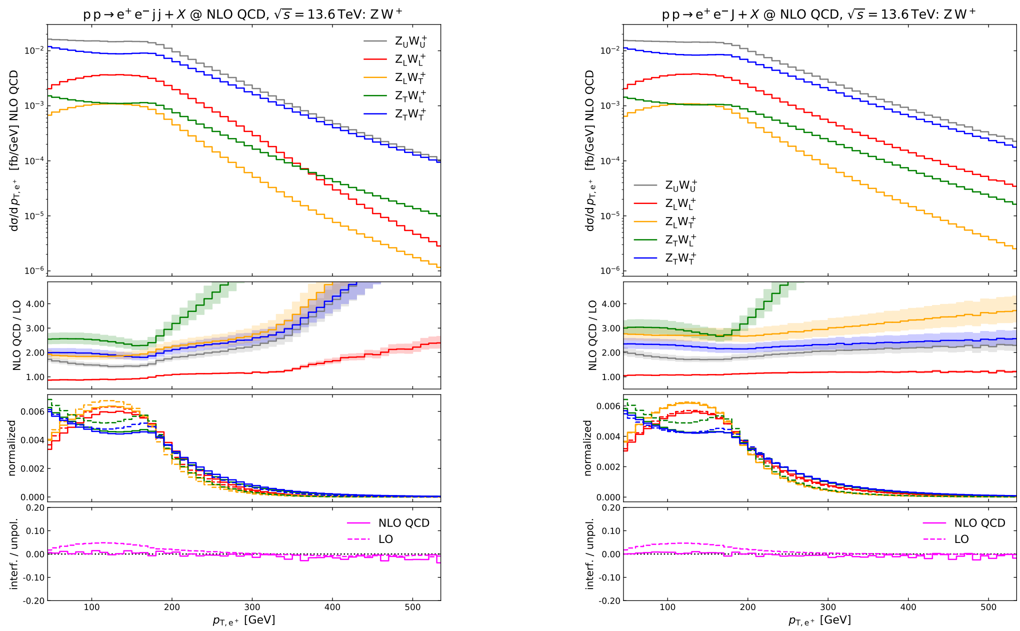

Figure 2: Distributions in the positron transverse momentum for polarised and unpolarised $\rm ZW^+$ production in the semi-leptonic decay channel, for the resolved (left) and unresolved (right) setups. From top down: differential cross sections, NLO QCD K-factors, normalised distributions, relative interference contribution.

on di-boson production. The calculation of polarised predictions matched to parton-shower is ongoing. In the coming years, it will be desirable to achieve accurate SM predictions for polarised vector-boson scattering (the *golden channel* for polarisation) and to study new-physics effects in the production and the decay of polarised bosons.

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