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NNLO QCD study of polarised W^+W^- production at the LHC

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We perform a polarisation study [1] of the diboson production in the pp $\to e^+\nu_e\mu^-\bar{\nu}_\mu$ process at next-to-next-to-leading order (NNLO) QCD in the fiducial setup inspired by experimental measurements at ATLAS. This is the first polarisation study at NNLO. We employ the double pole approximation framework for the polarised calculation, and investigate NNLO effects arising in differential distributions.

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1. Introduction

The idea to isolate and scrutinise the longitudinal mode of the Standard Model weak boson comes from the fact, that it originates from the electro-weak (EW) symmetry breaking mechanism, and is thus sensitive to new physics at the EW scale.

The leptonic decay of $pp \to W^+W^-$ is one of the most convenient experimental signatures for the polarisation study. It is clean and has the largest cross-section among other diboson processes. It also adds interesting spin-correlation effects. W-bosons couple only to left-handed chiral currents which gives them an advantage over Z-bosons in separating left and right polarisations [2]. The statistics of Run 2-3 will allow for a precise measurement in EW boson production processes [3].

Seminal papers first pointed out that W-bosons are produced primarily left-handed at the LHC [2, 4]. This was confirmed by experiments [5, 6]. Theoretical studies regarding the diboson production were performed at NLO in the framework of double-pole approximation (DPA). They also explored the effects of the fiducial setup [7] and the choice of the polarisation frame [8].

Experiments studied polarisation in various processes such as: $W + j$ [9], $W^\pm Z$ [10] and top-quark pair production [11].

2. Calculational details

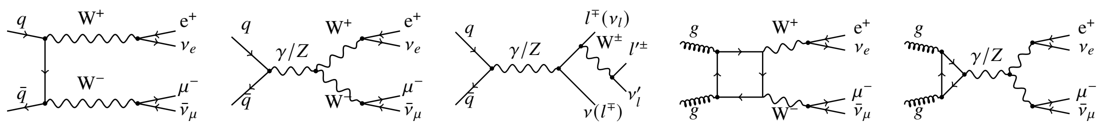

Figure 1: Leading order (LO) diagrams for pp $\to$ e$^+\nu_e\mu^-\bar{\nu}_\mu$ process. Born contributions are represented by (a-c), and loop-induced – by (d-e).

Polarisation is physical only for on-shell bosons, so single resonant diagrams in figure 1(c) present an irreducible background. Since bosons are not detected directly, mixing of differently polarised amplitudes takes place, leading to *interference* effects. Finally, the *Loop-induced* (LI) gluon channel appears at $O(\alpha_s^2)$ but is a LO contribution. We explore its effects separately from NNLO.

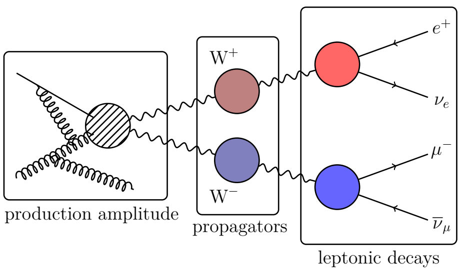

Figure 2: Diboson production from the view of the double-pole approximation.

DPA is a special case of pole approximations in general [12]. The unpolarised off-shell amplitude is approximated by on-shell sub-amplitudes and the off-shell propagators:

$$A \approx \sum_{\alpha,\beta} A^{pp\to W^+W^-}_{\alpha\beta,\mu\nu} \frac{A^{\mu}_{\alpha}(W^+ \to l^+\nu) \cdot A^{\nu}_{\beta}(W^- \to l^-\overline{\nu})}{(p_+^2 - M^2)\cdot(p_-^2 - M^2)},$$

where α, β are boson polarisations, and the colouring of the terms identifies their position in figure 2.

Sub-amplitudes use on-shell kinematics, defined by a chosen *on-shell projection*. In this study we preserve the leptonic angles in their corresponding decay frames, and also boson angles in the diboson frame.

Cross-term amplitude contributions coming from $A^\dagger_\alpha A_{\alpha'}$ terms create interferences on the cross section level. They happen to cancel out in the inclusive setup for the total cross section and in observables that do not restrict the leptonic phase space integration.

The fiducial setup used in our calculation is inspired by ATLAS measurements [13].

Experimental cut	Description
$p_{T\,miss} > 20\,\mathrm{GeV}$	to avoid D-Y background
$M_{e^+\mu^-} > 55\,\mathrm{GeV}$	to avoid Higgs background
perfect b-quark jet veto	to avoid $t\bar{t}$ background
$p_{T,l} > 27\,\mathrm{GeV}, \quad \lvert y_l \rvert < 2.5,$	detector cuts
jet veto: $\lvert\eta_j\rvert < 4.5,\ p_{T,j} > 35\,\mathrm{GeV}$	to reduce QCD corrections

Another implicit cut comes from on-shell projection in DPA: $M_{WW} > 2M_W$. The central scale choice is fixed: $\mu_{0,R,F} = M_W$. Theoretical uncertainty is estimated through the standard 7-point variation $1/2 < \mu_{R,F}/\mu_0 < 2$. Boson polarisations are defined in Lab frame. Further details about input parameters and the definition of the boson polarisations can be found in [1].

3. Results

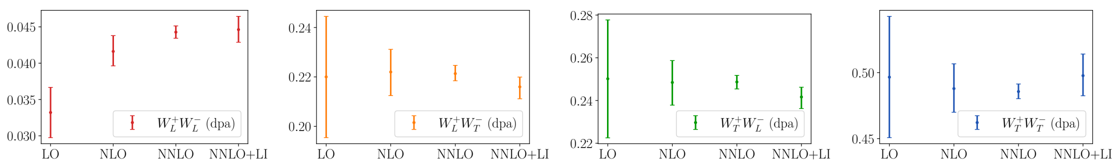

Figure 3: Polarisation fractions defined as $\sigma_{pol}/\Sigma\sigma_{pol}$ for doubly-polarised setups with the fiducial cuts. The errors are estimated using independent combination of scale variation uncertainties.

Of particular interest are the (differential) polarisation fractions $f_L = \sigma_L/\Sigma\sigma_{pol}$, $f_T = \sigma_T/\Sigma\sigma_{pol}$ and their logical extensions to the diboson case f_{LL}, f_{TT}, f_{TL} and f_{LT}. In the fiducial setup, the polarisation fractions are presented in figure 3. They are very stable w.r.t QCD corrections with the exception of $W_L^+W_L^-$ setup. Loop-induced channel presents significant effects in all setups.

NNLO corrections are 2-3% of σ_{total} for all setups except $W_L^+W_L^-$ where it is 9%. The scale uncertainty is reduced by a factor of 3 w.r.t NLO. A differential distribution with respect to the positron rapidity is showcased in figure 4. The upper pane shows absolute distributions for the various polarisation configurations. The middle pane presents their ratio to the off shell differential cross section. The ratio between the unpolarised DPA and off-shell calculation is flat and close to 1, implying negligible off-shell effects. The shape difference between the summed polarised and the unpolarised DPA cross section indicates interference effects. The last pane shows the ratio of NNLO/NLO highlighting the large corrections in the $W_L^+W_L^-$ setup.

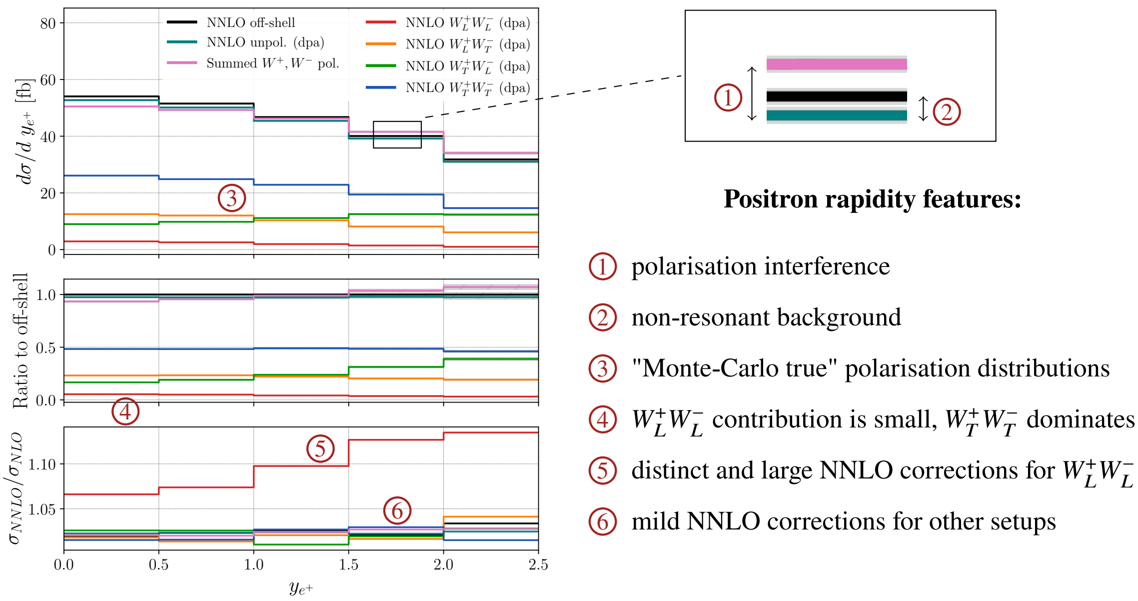

Figure 4: NNLO positron rapidity distribution with relevant features highlighted.

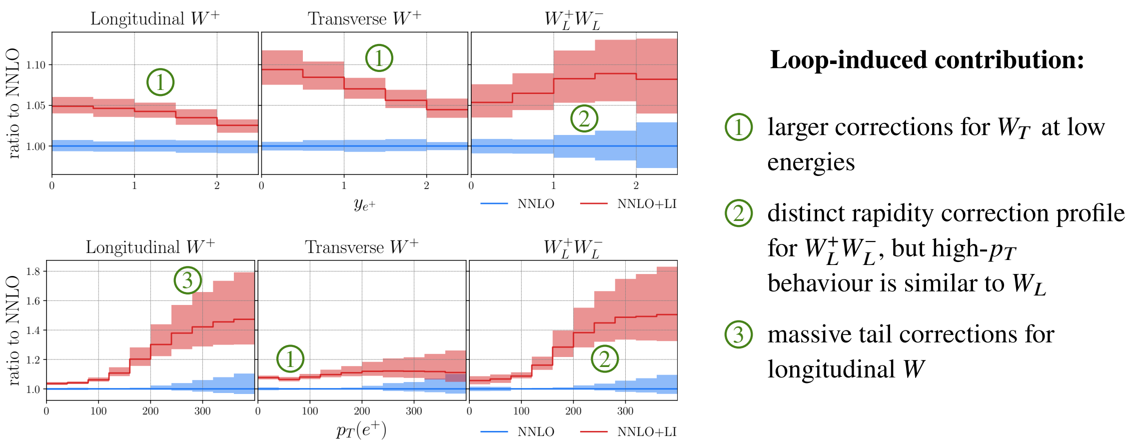

Figure 5: Loop-induced corrections at positron rapidity and p_T with relevant features highlighted.

Loop-induced channel corrections are 6-9% contribution to σ_{total} increasing its uncertainty by a factor of 2 w.r.t NNLO. Its differential effects are shown in figure 5.

4. Conclusions

We performed the first weak boson polarisation study at NNLO QCD for pp $\rightarrow e^+\nu_e\mu^-\bar{\nu}_\mu$ process in the DPA framework. We found that NNLO corrections show a reliable perturbative convergence and sizeable reduction in scale dependence. Large QCD effects are found only in $W_L^+W_L^-$ setup, the origin of which is left to further investigation. The loop induced channel significantly affects the results and scale uncertainty, implying NLO corrections of order $O(\alpha_s^3)$ to the loop-induced channel would be instrumental to reduce the scale uncertainty.

References

[1] R. Poncelet and A. Popescu, *NNLO QCD study of polarised W^+W^- production at the LHC*, arXiv:2102.13583.

[2] W. J. Stirling and E. Vryonidou, *Electroweak gauge boson polarisation at the LHC*, *JHEP* **07** (2012) 124, [arXiv:1204.6427].

[3] P. Azzi et al., *Report from Working Group 1: Standard Model Physics at the HL-LHC and HE-LHC*, in *Report on the Physics at the HL-LHC,and Perspectives for the HE-LHC* (A. Dainese, et al., eds.), vol. 7, pp. 1–220. CERN, 12, 2019. arXiv:1902.04070.

[4] Z. Bern et al., *Left-Handed W Bosons at the LHC*, *Phys. Rev.* **D84** (2011) 034008, [arXiv:1103.5445].

[5] **CMS** Collaboration, S. Chatrchyan et al., *Measurement of the Polarization of W Bosons with Large Transverse Momenta in W+Jets Events at the LHC*, *Phys. Rev. Lett.* **107** (2011) 021802, [arXiv:1104.3829].

[6] **ATLAS** Collaboration, G. Aad et al., *Measurement of the polarisation of W bosons produced with large transverse momentum in pp collisions at $\sqrt{s}$ = 7 TeV with the ATLAS experiment*, *Eur. Phys. J.* **C72** (2012) 2001, [arXiv:1203.2165].

[7] A. Denner and G. Pelliccioli, *Polarized electroweak bosons in W^+W^- production at the LHC including NLO QCD effects*, *JHEP* **09** (2020) 164, [arXiv:2006.14867].

[8] S. Dittmaier and C. Schwan, *Non-factorizable photonic corrections to resonant production and decay of many unstable particles*, *Eur. Phys. J. C* **76** (2016) 144, [arXiv:1511.01698].

[9] CMS Collaboration, *Measurements of the W Boson Rapidity, Helicity, Double-Differential Cross Sections, and Charge Asymmetry in Pp Collisions at $\sqrt{s} =$ 13 TeV*, *Physical Review D* **102** (Nov., 2020) 092012, [arXiv:2008.04174].

[10] **ATLAS** Collaboration, M. Aaboud et al., *Measurement of $W^\pm Z$ production cross sections and gauge boson polarisation in pp collisions at $\sqrt{s}$ = 13 TeV with the ATLAS detector*, *Eur. Phys. J. C* **79** (2019) 535, [arXiv:1902.05759].

[11] **CMS, ATLAS** Collaboration, G. Aad et al., *Combination of the W boson polarization measurements in top quark decays using ATLAS and CMS data at $\sqrt{s}$ = 8 TeV*, arXiv:2005.03799.

[12] A. Denner and S. Dittmaier, *Electroweak Radiative Corrections for Collider Physics*, *Phys. Rept.* **864** (2020) 1–163, [arXiv:1912.06823].

[13] **ATLAS** Collaboration, M. Aaboud et al., *Measurement of fiducial and differential W^+W^- production cross-sections at $\sqrt{s}$ = 13 TeV with the ATLAS detector*, *Eur. Phys. J.* **C79** (2019) 884, [arXiv:1905.04242].