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Abstract: We perform a polarisation study^[1] of the diboson production in the $pp \rightarrow e^+ \nu_e \mu^- \bar{\nu}_\mu$ 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.

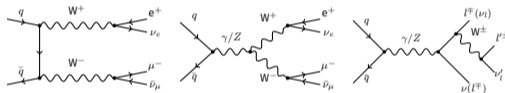
Motivation

- ✓ **Longitudinal** polarisation originates from the electro-weak symmetry breaking mechanism \implies idea to isolate and scrutinise it.
- ✓ Why $W^+ W^- \rightarrow 4$ leptons:
 - leptons are a clean experimental signature;
 - interesting spin-correlation effects;
 - largest cross-section among diboson processes;
 - W -bosons couple only to left chiral currents.
- ✓ Statistics in Run 2/3 will allow for precise measurement.

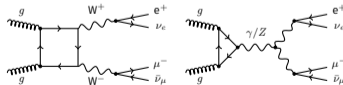
Literature overview

- 📖 W-bosons are produced primarily left-handed at the LHC^[2, 3].
- 📖 Fiducial setup and other effects explored in WW, WZ at NLO^[4, 5].
- 📖 Experiments studied polarisation in processes such as: $W + j$ ^[6], $W^\pm Z$ production^[7], top-quark pair production^[8].
- 📖 Pole approximation approaches^[9].

Leading Order Contributions

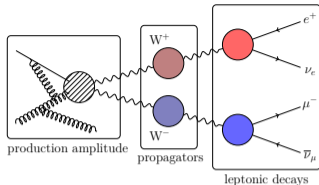


- Polarisation is physical only for **on-shell** bosons, so single resonant diagrams present an irreducible background.
- Bosons are not detected directly, so mixing of differently polarised amplitudes takes place – **interference** effects.



- **Loop-induced (LI)** gluon channel appears at $\mathcal{O}(\alpha_s^2)$ but is a LO contribution. We explore its effects separately from NNLO.

Method – Double Pole Approximation



The unpolarised off-shell amplitude is approximated by on-shell sub-amplitudes and the off-shell propagators:

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

where α, β are boson polarisations.

- Sub-amplitudes use on-shell kinematics, defined by a selected on-shell projection. We choose to preserve leptonic angles in the decay frames, and boson angles in the diboson frame.
- Cross-term amplitude contributions coming from $A_{\alpha} A_{\bar{\alpha}}$ terms create interferences for cross sections.

For inclusive setup the leptonic angle of emission distribution θ^* for each boson is described analytically by:

$$\frac{1}{\sigma} \frac{d\sigma}{d \cos \theta^*} = \frac{3}{4} (1 + \cos^2 \theta^*) f_T + \frac{3}{8} \sin^2 \theta^* f_L,$$

with f_T, f_L polarisation fractions for **transverse** and **longitudinal** W .

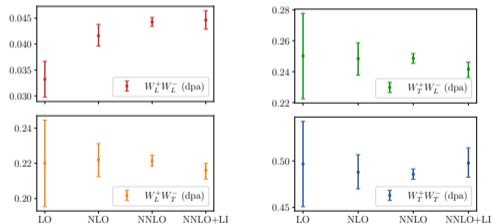
Fiducial Setup

Inspired by ATLAS measurements^[1] of unpolarised $W^+ W^-$:

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

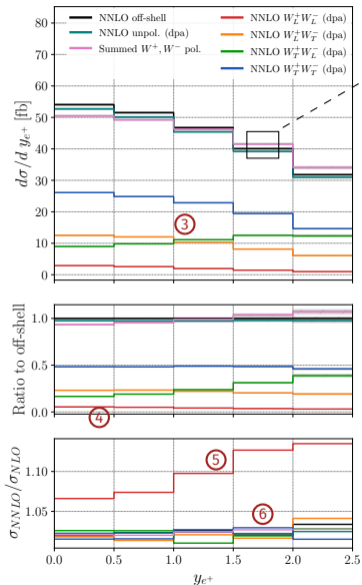
Another implicit cut comes from on-shell projection: $M_{WW} > 2M_W$.
Scale choice: $\mu_R = \mu_F = M_W$. Polarisations defined in Lab frame.

Polarisation fractions



- Polarisation fractions are presented for doubly-polarised setups and are defined as $\sigma_{pol} / \Sigma \sigma_{pol}$.
- Fractions are stable w.r.t QCD corrections, except $W_L^+ W_L^-$ setup.
- Significant effects by the loop-induced channel.

Distribution at NNLO

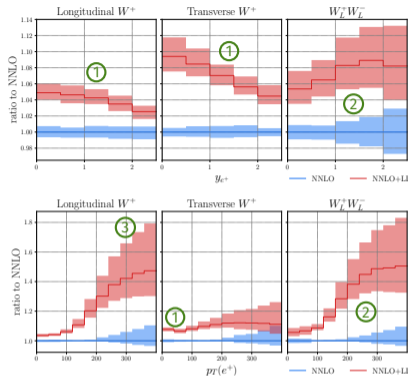


Positron rapidity features:

- ① polarisation interference
- ② non-resonant background
- ③ "Monte-Carlo true" polarisation distributions
- ④ $W_L^+ W_L^-$ contribution is small, $W_T^+ W_T^-$ dominates
- ⑤ distinct and large NNLO corrections for $W_L^+ W_L^-$
- ⑥ mild NNLO corrections for other setups

- NNLO effects are 2-3% of σ_{tot} for all setups except $W_L^+ W_L^-$ where it is 9%.
- Scale uncertainty is reduced by a factor of 3 w.r.t NLO.

Loop-induced channel effects



- ① larger corrections for W_T at low energies
- ② distinct rapidity correction profile for $W_L^+ W_L^-$, but high- p_T behaviour is similar to W_L
- ③ massive tail corrections for longitudinal W

- Loop-induced channel has a 6-9% contribution to σ_{tot} and increases uncertainty by a factor of 2 w.r.t NNLO.

Summary

- 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.
- Smooth NNLO corrections \Rightarrow reliable perturbative convergence.
- NNLO corrections reduce the scale uncertainty by a factor of 3.
- Large QCD corrections only in $W_L^+ W_L^-$ setup.
- Loop induced channel significantly affects results and scale uncertainty.

Outlook

- NLO corrections of order $\mathcal{O}(\alpha_s^3)$ to the loop-induced channel would be instrumental to reduce scale uncertainty.
- Investigate other processes with polarised weak bosons at NNLO, e.g. V +jet, vector boson scattering (VBS), top-quark pair + decay.

References

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