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Theory of Diboson Production - Polarized & Unpolarized

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The measurement of diboson production processes serves as an excellent probe to test the electroweak sector of the Standard Model. Moreover, it allows for studying cross sections in dependence of the vector boson polarization, which is of particular interest due to the direct connection between the longitudinal polarization and the electroweak symmetry breaking mechanism. The increasing luminosity of the Large Hadron Collider necessitates precise theoretical predictions for these processes to compare with. This contribution provides an overview over state-of-the-art and new calculations for both unpolarized and polarized diboson production processes. For polarized cross sections, this includes the presentation of two new Monte Carlo codes that, for the first time, allow for the simulation of fully realistic, polarized events including higher-order QCD effects.

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The increasing luminosity of the Large Hadron Collider (LHC) allows for increasingly precise measurements of a wide variety of processes over an impressive range of cross sections. So far, no significant deviations from the Standard Model (SM) have been found. However, there are many fundamental questions that cannot be addressed by the SM, such as the nature of dark matter, the baryon-antibaryon asymmetry, or the incorporation of gravity into the SM. The least known part of the SM is the electroweak (EW) sector, making it a promising candidate for new physics that could explain one or several of these open questions. In particular, the concrete mechanism of electroweak symmetry breaking (EWSB), the number of Higgs bosons, the nature of the SM Higgs boson itself, and the form of the Higgs potential outside the minimum are not yet known.

Inclusive diboson production and vector boson scattering (VBS) are promising process groups for deepening our understanding of the EW sector. For the purpose of this contribution, inclusive diboson production is understood as the production of two vector bosons (VBs) without any final state jets at the leading order (LO) $O(\alpha^4)$. It provides an opportunity to test triple gauge couplings. In addition, inclusive diboson production processes are important background contributions to many experimental analyses such as Higgs production. VBS denotes the production of two VBs in association with two final state jets at LO, corresponding to $O(\alpha^6)$ at LO. Precise measurements of VBS processes are of particular interest since they allow us to probe both the electroweak gauge sector, including quartic gauge couplings and the HVV coupling, and the mechanism of EWSB.

In this work, we give an overview of state-of-the-art and new fixed-order as well as parton shower (PS) matched calculations both for unpolarized and polarized diboson production processes. For the latter, we also review new tools for the simulation of polarization templates supporting NLO QCD matching to PS.

Due to the limited scope of this contribution, not all topics regarding diboson production can be covered; specifically, massless VBs, BSM studies, quantum entanglement, and new results from analytical resummation are not reviewed. Unless stated otherwise, the leptonic decay modes of the VBs are assumed.

1. Unpolarized cross sections for diboson production

1.1 State-of-the-art predictions

Inclusive diboson production has been extensively studied in the literature. The fixed-order cross section for all three fully leptonic, inclusive diboson production processes is known up to NNLO QCD [1–8] and NLO EW [9–14] for the quark-quark initial states, and up to NLO QCD for the gluon-gluon initial state [15–19]. Combined NNLO QCD and NLO EW calculations have been performed for all massive, inclusive diboson production processes [20]. These calculations are already well established; hence, public tools MATRIX [21] and MCFM [22–24] are available, supporting both higher-order QCD and EW or at least higher-order QCD calculations.

NLO calculations for VBS are much more involved compared to their inclusive counterparts, not only due to the larger coupling order but especially due to different Born contributions with the same final state that mix at NLO. Nonetheless, every order of this NLO tower has been calculated at least once [25–34], besides $O(\alpha_S^2\alpha^5)$ for $W^\pm Z$ and W^+W^- scattering, which have NLO EW contributions from the QCD-induced and NLO QCD contributions from the QCD-EW-interference term.

Predictions matched to PS are available for all inclusive diboson production processes with at least one of the state-of-the-art NNLO matching algorithms [35–40]. For the gg-induced channel, NLO QCD predictions matched to PS exist in the $4l$ channel [41]. Combined matched NLO QCD+NLO EW+PS calculations can be performed with RECOLA2+COLLIER+POWHEG-BOX-RES+PYTHIA8 [42]. Matched NLO QCD predictions including approximate NLO EW effects and contributions from up to three additional jets are presented by the SHERPA collaboration [43, 44]. For VBS processes, PS matched predictions are currently only available for the EW- and the QCD-induced process at NLO QCD [45–53] and at NLO EW for the EW-induced component [54]. Usually, the VBS approximation is applied in these calculations.

1.2 Desired calculations and recent progress

According to the most recent Les Houches wishlist containing diboson processes from 2021 [55], NLO QCD predictions for the gg-induced channel including massive quark loop effects and $\mathrm{N}^{(1,1)}_{\mathrm{QCD}\times\mathrm{EW}}$ predictions in the case of inclusive diboson production, as well as predictions for the whole NLO tower in the case of VBS processes, are necessary to fulfill current precision goals of the LHC. Having these predictions matched to PS would be even more helpful for experimental analyses.

Until recently, the complete calculation of the NLO QCD contribution of gg-induced channels in inclusive diboson production was not possible due to missing massive top loop calculations. This changed recently when the corresponding loop corrections in gg-induced ZZ production became available [56], allowing for the first complete NLO QCD calculation of the gg-induced channel in this process, including top mass effects [57]. Very good agreement with the previously available calculation including approximate mass effects [16] was found for the studied observables. The difference in the integrated cross section between calculations with and without massive quark loop contributions amounts to about -2%.

Regarding the completion of the NLO tower in VBS processes or their matching to PS, no progress has been achieved since the publication of [55]. Instead, a first calculation of semi- and fully-hadronic WZ scattering [57] and a first independent recalculation of the NLO tower in $\mathrm{W}^+\mathrm{W}^+$jj using BONSAY+OPENLOOPS have been done [58]. All former complete calculations of the VBS NLO tower were performed using MOCANLO+RECOLA. Very good agreement between the leading contributions was found between the two calculations. In addition, common approximations in the VBS context, namely the VBS and the effective VB approximation, were studied in comparison with the full calculation. Only the VBS approximation combined with a double-pole approximation for virtual corrections delivered sufficient agreement with the full calculation suitable for some LHC applications while being ten times faster.

2. Polarized cross sections for diboson production

Investigating VB polarization can provide even deeper insights into the EW gauge sector and the EWSB than the study of unpolarized processes alone, since impacts of new physics influencing only single polarization states might be overlooked in unpolarized measurements.

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2.1 Measurement strategies

Measuring VB polarization, however, is not trivial since VBs cannot be observed directly. At tree-level, with polarization defined in the helicity basis, the differential cross section of the VB decay as a function of the lepton decay angle θ^* can be formulated as a sum of terms each depending only on one polarization fraction [59, 60]. This formulation allows extraction of polarization information from measurable unpolarized distributions via fits or projections onto Legendre polynomials This method was applied in LHC Run 1 and early Run 2 analyses [61–64].

Besides its limitation to a certain set of observables, this method loses its validity if lepton selection criteria or higher-order corrections to the VB decay are applied, as they spoil the connection between the angular distributions and the polarization fractions.

Hence, the polarization measurement strategy changed for more recent LHC Run 2 analyses, where fully exclusive polarized events from Monte-Carlo event generators are used to build fitting templates to extract polarization information from unpolarized distributions [65–68].

2.2 Definition of polarization for intermediate states

Fully exclusive polarized events can be calculated by replacing the numerator of the VB propagator by the corresponding sum over polarization vectors via the completeness relation:

$$-g^{\mu\nu} + \frac{q^\mu q^\nu}{q^2} = \sum_{\lambda=1}^{4} \varepsilon^\mu_\lambda(q) \varepsilon^{*\nu}_\lambda(q), \tag{1}$$

with q denoting the four-momentum of the intermediate VB.

The polarization vectors ε can be defined in different bases. The typical basis for polarization measurements is the helicity basis, where the spin axis is aligned with the particle's momentum, and the polarization vectors take the form:

$$\begin{aligned} \varepsilon^\mu_\pm(q) &= \frac{e^{\pm i\phi}}{\sqrt{2}}(0. - \cos\theta\cos\phi \pm i\sin\phi, -\cos\theta\sin\phi \mp i\cos\phi, \sin\theta)\,, \\ \varepsilon^\mu_0(q) &= \frac{q^0}{m}\left(\frac{|\vec{q}|}{q^0}, \cos\phi\sin\theta, \sin\phi\sin\theta, \cos\theta\right), \end{aligned} \tag{2}$$

with m denoting the mass of the VB and θ, ϕ being the polar and azimuthal angles of $\vec{q}$. VBs with helicity + or - are called transversely polarized or right-handed (+) and left-handed (-), respectively, those with helicity 0 are called longitudinally polarized. Polarized cross sections in the helicity basis are not Lorentz-invariant; they vary depending on the frame in which q is measured.

After squaring the matrix elements, the replacement in Eq. 1 leads to two different types of polarized matrix elements obtained by omitting the sum over polarization states:

$$\underbrace{|\mathcal{M}|^2}_{\text{coherent sum}} = \underbrace{\sum_\lambda |\mathcal{M}^\mathcal{F}_\lambda|^2}_{\text{polarized contributions, incoherent sum}} + \underbrace{\sum_{\lambda\neq\lambda'} \mathcal{M}^\mathcal{F}_\lambda \mathcal{M}^{*\mathcal{F}}_{\lambda'}}_{\text{interference}}, \tag{3}$$

i.e., matrix elements where $\mathcal{M}$ and $\mathcal{M}^*$ depend on the same (pure polarization contributions) or different polarization states (interference contributions) for the intermediate particles.

In order to allow for the separation of polarized matrix elements from the unpolarized amplitudes, only diagrams where the bosons of interest are resonant can be considered. Simple diagram selection, however, would break gauge invariance. Hence, appropriate on-shell approximations like the Double-Pole- or the Narrow-Width Approximation (DPA/NWA) are used to remove the non-resonant diagrams in a gauge-invariant manner.

2.3 Fixed-order phenomenological landscape

All fixed-order calculations published so far are based on the DPA and were done with private tools. Polarized cross sections for all inclusive, fully leptonic diboson production processes are known up to NLO QCD and NLO EW [69–76] in at least either the laboratory (lab) or the VB pair center-of-mass frame (com). For inclusive W^+W^- production, results up to NNLO QCD are available in the lab [77]. Semi-leptonic VB production is studied for inclusive W^+Z production [78] in the W^+Z com.

Polarized cross sections for fully leptonic VBS are mostly known only at LO [60, 79, 80]. They are computed in the lab, except for W^+W^+ scattering in Ref. [80], where the W^+W^+ com is investigated. Very recently, NLO QCD and NLO EW corrections for polarized W^+W^+ scattering were studied in the W^+W^+ com for the first time [81].

2.4 Generator landscape

Fixed-order calculations cannot be applied directly in experimental analyses and always require a reweighting of a fully-realistic simulation result of less fixed-order perturbative accuracy, including PS and non-perturbative contributions, to the fixed-order result. This leads to higher systematic uncertainties than if fully-realistic calculations of the same fixed-order accuracy were available.

For many years, fully-realistic polarization templates could only be provided at LO accuracy by PHANTOM [45, 82] and MadGraph [83, 84], using either the DPA or the truncated propagator method. The latter consists of a simple diagram selection allowing only diagrams with resonant intermediate bosons without any on-shell projection. Gauge-dependent effects are suppressed by applying a selection criterion that ensures the intermediate bosons are close to on-shell.

Recently, implementations in SHERPA [85] and POWHEG-BOX-RES [86] have become available, which are capable of including polarized fixed-order, higher-order QCD effects in a fully-realistic event simulation. This development allows for a significant reduction of modeling uncertainties in future LHC analyses compared to their Run 2 predecessors. Subsequently, these new implementations are introduced in greater detail.

2.4.1 SHERPA

In SHERPA, polarized cross sections are calculated on top of an otherwise unpolarized simulation run in a spin-correlated NWA. Off-shell effects are retained by a mass-smearing of the on-shell VBs according to the Breit-Wigner distribution. The whole amplitude tensor of the process of interest is computed. Hence, fully differential polarization fractions can be provided for all VB polarization combinations and the interference between different VB polarization states in a single simulation run. In addition, different polarization definitions can be investigated in one simulation run.

In order to match higher-order QCD corrections to the PS simulation, SHERPA uses the MC@NLO algorithm [87]. It distinguishes three event types: $\mathbb{H}$-events, resolved and unresolved $\mathbb{S}$-events. Polarized NLO QCD calculations require the calculation of an amplitude tensor according to the event type. For $\mathbb{H}$- and resolved $\mathbb{S}$-events, the amplitude tensor is reconstructed from the real emission amplitude. The amplitude tensor for unresolved $\mathbb{S}$-events relies on the Born amplitude. This leads to overall NLO-accurate results for $\mathbb{H}$- and resolved $\mathbb{S}$-events. For unresolved $\mathbb{S}$-events, however, corrections from virtual, ultra-soft, and ultra-collinear corrections on per-event polarization fractions are neglected. As the number of events in this category is generally small, and this construction is only used to determine the polarization fractions in the otherwise fully NLO-accurate unpolarized simulation, the error introduced in this way is expected to be small.

Besides matching of polarized fixed-order NLO QCD calculations to PS, SHERPA also supports multi-leg merging for polarized predictions.

As the implementation can be applied for arbitrary processes with intermediate VBs, it allowed for a first study of higher-order QCD corrections matched to PS for VBS processes. In the VBS approximation, only subpercent level effects of NLO QCD corrections on integrated as well as differential polarization fractions were found.

2.4.2 POWHEG-BOX-RES

The polarization framework in POWHEG-BOX-RES is built on RECOLA 1 [88, 89] polarized matrix elements in DPA and applies the POWHEG matching prescription. It can provide polarization templates for inclusive diboson production at NLO QCD + PS. The framework is first applied in a detailed phenomenological analysis of PS effects on polarization predictions in inclusive diboson production processes at NLO QCD. Sizeable effects on polarization fractions are only found for boosted setups and if jet-activity vetoes are applied. The QED shower leads to the overall largest PS effect.

3. Conclusion and future prospects

In this work, the current status of fixed-order and PS matched predictions for both unpolarized and polarized diboson production processes was reviewed.

Despite significant progress in recent years, there are still many open tasks to reach the precision targets of upcoming LHC runs. The fixed-order VBS NLO tower is not yet completely known for both polarized and unpolarized processes. PS matched predictions are still missing for VBS processes in general, as well as for polarized NLO EW and NNLO QCD contributions for inclusive diboson processes. Precise predictions for semi- and fully hadronic diboson production, as well as for BSM models, are barely available yet. Top mass effects are not yet known for all loop-induced contributions in inclusive diboson production, and NLO EW predictions for these processes still need to be included in available NNLO QCD calculations. Moreover, there are ideas on how to improve the measurement of VB polarization beyond increasing the precision of polarization templates, such as using polarization taggers or adopting more model-independent approaches than the current template method that could not be reviewed here.

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