NNLO QCD event generation for ZZ production matched to parton shower

Alessandro Gavardi

Università degli Studi di Milano-Bicocca

Cortona Young 2021 — June 9^{th}-11^{th}, 2021

based on arXiv:2103.01214 [hep-ph] (S. Alioli, A. Broggio, AG, S. Kallweit, M. A. Lim, R. Nagar, D. Napoletano)

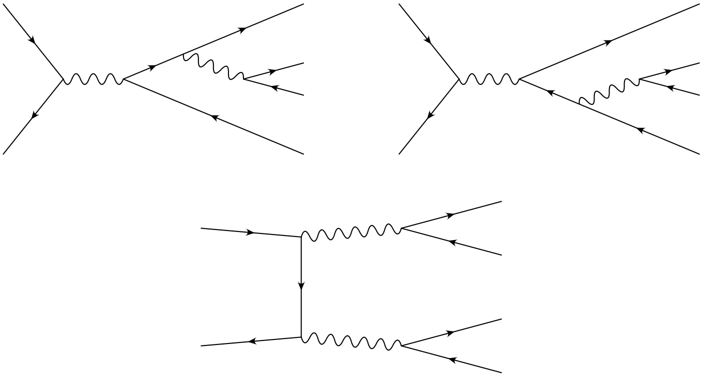
Why studying diboson production at NNLO?

- The production of on-shell and off-shell vector boson pairs at high-energy hadron colliders are very relevant processes in phenomenology since they allow **precision studies of the electroweak interactions**, with the aim of looking for **new physics**.
- NLO theoretical predictions for diboson production have been available for a long time. However, in order to match the experimental precision that will be reached at the LHC in the next years, we need event generators that are **NNLO accurate**.

Diboson production

We study proton-proton scattering processes with four final-state leptons

$$p\,p \to \ell_1\,\bar{\ell}_2\,\ell_3\,\bar{\ell}_4 + X$$



Diboson production

In particular we focus on

$$p\,p \to e^+\,e^-\,\mu^+\,\mu^- + X$$

where the exchanged bosons can be either **Z bosons** or **off-shell photons** γ^*, and we apply the following cuts

$$m_{\mathrm{V}}^{\mathrm{min}} < m_{e^+e^-}, m_{\mu^+\mu^-} < m_{\mathrm{V}}^{\mathrm{max}}$$

The entire calculation has been implemented within the GENEVA framework in order to obtain

- Fully differential results up to **NNLO**
- **NNLL' resummation** of the zero-jettiness (beam thrust) $\mathcal{T}_0$ spectrum
- Matching to a **parton shower**

Event generation

When generating events the phase space is sliced into regions with 0, 1 and 2 resolved partons in the final state, using **0**- and **1-jettiness** as **resolution parameters**

- **2-parton events** with $\mathcal{T}_1 > \mathcal{T}_1^{\mathrm{cut}}$ are generated according to $\dfrac{d\sigma_2}{d\Phi_2}$
- **1-parton events** with $\mathcal{T}_0 > \mathcal{T}_0^{\mathrm{cut}}$ are generated according to $\dfrac{d\sigma_1}{d\Phi_1}(\mathcal{T}_1^{\mathrm{cut}})$, which takes contributions from 1-parton phase-space points and 2-parton phase-space points with $\mathcal{T}_1 < \mathcal{T}_1^{\mathrm{cut}}$
- **0-parton events** are generated according to $\dfrac{d\sigma_0}{d\Phi_0}(\mathcal{T}_0^{\mathrm{cut}})$, which takes contributions from 0-parton phase-space points and 1- or 2-parton phase-space points with $\mathcal{T}_0 < \mathcal{T}_0^{\mathrm{cut}}$

Zero-jettiness

The resolution parameter used to distinguish between 0- and 1-parton phase-space points is the **zero-jettiness** (or beam thrust) $\mathcal{T}_0$. Given a process with two incoming partons of momenta

$$p_\pm = \frac{\sqrt{s}}{2}\, e^{\pm y}\,(1, 0, 0, \pm 1)$$

and n outgoing partons, the zero-jettiness is defined as

$$\mathcal{T}_0 = \sum_{i=1}^{n} \min_{j=\pm}\left(\frac{2p_i \cdot p_j}{\sqrt{s}}\right) = \sum_{i=1}^{n} \min\left(p_i^+ e^{y}, p_i^- e^{-y}\right)$$

with

$$p_i^\pm = p_i^0 \mp p_i^3$$

0-jet exclusive differential cross section

The GENEVA **0-jet exclusive differential cross section** at NNLO accuracy and resummed up to NNLL' precision in $\mathcal{T}_0$ is

$$\frac{d\sigma_0}{d\Phi_0}(\mathcal{T}_0^{\mathrm{cut}}) = \frac{d\sigma^{\mathrm{NNLL}'}}{d\Phi_0}(\mathcal{T}_0^{\mathrm{cut}}) + \frac{d\sigma_0^{\mathrm{NNLO}}}{d\Phi_0}(\mathcal{T}_0^{\mathrm{cut}}) - \frac{d\sigma^{\mathrm{NNLL}'}}{d\Phi_0}(\mathcal{T}_0^{\mathrm{cut}})\bigg|_{\mathrm{NNLO}}$$

We define

$$\frac{d\sigma_0^{\mathrm{nonsing}}}{d\Phi_0}(\mathcal{T}_0^{\mathrm{cut}}) = \frac{d\sigma_0^{\mathrm{NNLO}}}{d\Phi_0}(\mathcal{T}_0^{\mathrm{cut}}) - \frac{d\sigma^{\mathrm{NNLL}'}}{d\Phi_0}(\mathcal{T}_0^{\mathrm{cut}})\bigg|_{\mathrm{NNLO}}$$

1-jet inclusive differential cross section

The GENEVA **1-jet inclusive differential cross section** at NLO accuracy is

$$\frac{d\sigma_{\geq 1}}{d\Phi_1} = \frac{d\sigma_{\geq 1}^{\mathrm{NNLL}'}}{d\Phi_1} + \frac{d\sigma_{\geq 1}^{\mathrm{nonsing}}}{d\Phi_1}$$

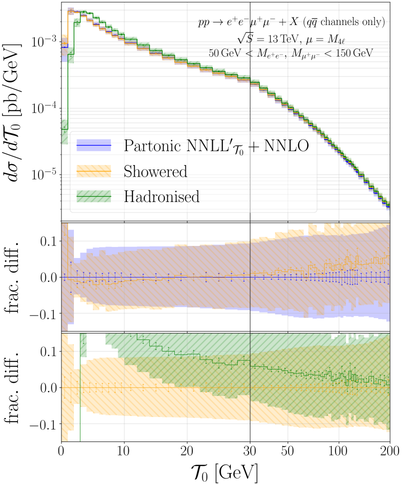
The resummed spectrum $d\sigma^{\mathrm{NNLL}'}/d\Phi_0 d\mathcal{T}_0$ is spreaded over the Φ_1 phase space through a normalized splitting probability P

$$\frac{d\sigma_{\geq 1}^{\mathrm{NNLL}'}}{d\Phi_1} = \frac{d\sigma^{\mathrm{NNLL}'}}{d\Phi_0 d\mathcal{T}_0} P(z,\phi)$$

so that

$$\int dz\, d\phi\, P(z,\phi) = 1$$

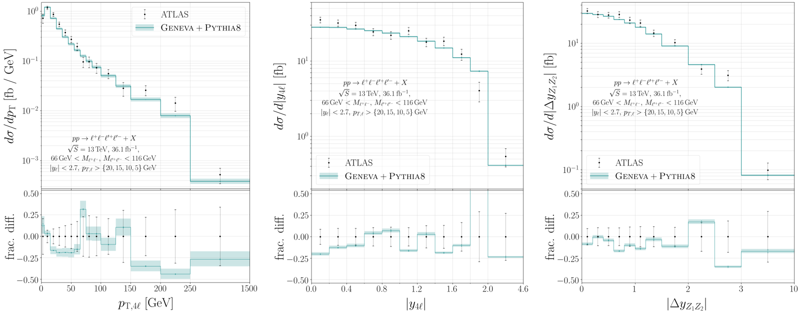
Parton shower and hadronization



Effects of the PYTHIA8 parton shower and hadronization on the $\mathcal{T}_0$ distribution

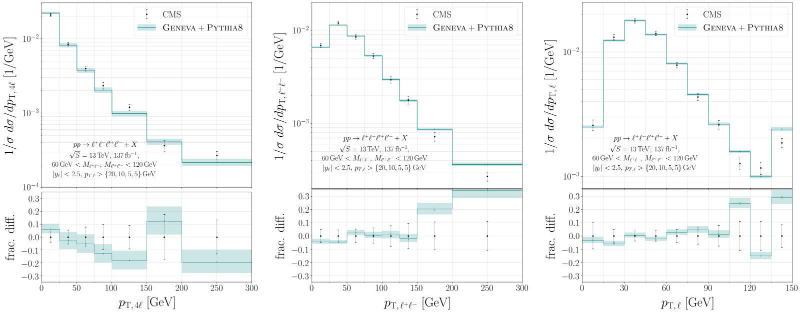
- The parton shower effects are $\mathcal{O}(2\%)$ on most of the $\mathcal{T}_0$ range
- The hadronization effect is large for small values of $\mathcal{T}_0$

Phenomenological results (ATLAS)



ATLAS measurements at 13 TeV from arXiv:1709.07703 [hep-ex]

Phenomenological results (CMS)



CMS measurements at 13 TeV from arXiv:2009.01186 [hep-ex]

Some information

- The 0- and 1-loop matrix elements have been taken from OpenLoops (`ppvv` and `ppvvj`)
- The two-loop virtual has been implemented starting from the public code `qqvvamp` (Gehrmann, von Manteuffel, Tancredi JHEP09(2015)128)
- The paper has been accepted for publication in Physics Letters B (preprint arXiv:2103.01214 [hep-ph])
- The code is available upon request to the authors and will be made public in a future release of Geneva

Some information

- The 0- and 1-loop matrix elements have been taken from OpenLoops (ppvv and ppvvj)
- The two-loop virtual has been implemented starting from the public code qqvvamp (Gehrmann, von Manteuffel, Tancredi JHEP09(2015)128)
- The paper has been accepted for publication in Physics Letters B (preprint arXiv:2103.01214 [hep-ph])
- The code is available upon request to the authors and will be made public in a future release of Geneva

Thanks for your attention!