Next-to-next-to-leading order predictions for diboson production in hadronic scattering combined with parton showers

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Standard Model at the LHC

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NNLO Monte Carlo event generators

Why Monte Carlo event generators?

- The **fully differential events** are the closest simulations of the scattering processes observed at colliders
- They combine
  - **Multi-loop matrix elements** → perturbative accuracy
  - (**Analytic resummation** → logarithmic accuracy)
  - **Parton showers** → multiplicity of the final state
  - **Hadronization models** → from colored partons to colorless hadrons

Why NNLO?

- LHC is turning into a precision machine

  → More and more accurate theoretical predictions are needed

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The Geneva framework

Geneva is a **Monte Carlo event generator** that provides

- Fully differential **events** up to **NNLO QCD** accuracy
- **NNLL′ resummation** of the 0-jet resolution variable (e.g. the zero-jettiness $\mathcal{T}_0$ or the color-singlet transverse momentum q_T for the case of color singlet production)
- **NLL′ resummation** of the 1-jet resolution variable (e.g. the one-jettiness $\mathcal{T}_1$ for the case of color singlet production)
- Interface to **parton showers**

Examples of 0-jet resolution variables

Given a process of production of a color singlet

$$p\,p \to \mathrm{CS}(q) + X$$

the phase space regions where the matrix elements present QCD infrared divergences at NLO can be equivalently identified as those with low

- **Color-singlet transverse momentum** q_T
- **Zero-jettiness** $\mathcal{T}_0$
- **Hardest-jet transverse momentum** $p_\mathrm{T}^\mathrm{jet}$

0-jet resolution variables

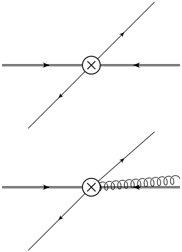
We can equivalently use q_T, $\mathcal{T}_0$ and $p_\mathrm{T}^\mathrm{jet}$ as **0-jet resolution variables**

If X is a massless parton of momentum p

$$q_\mathrm{T} = \sqrt{q_x^2 + q_y^2} \qquad \mathcal{T}_0 = \min(\hat{p}_0 - \hat{p}_z,\ \hat{p}_0 + \hat{p}_z) \qquad p_\mathrm{T}^\mathrm{jet} = \sqrt{p_x^2 + p_y^2}$$

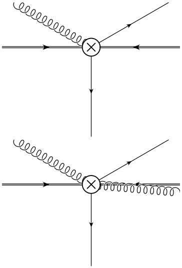
Slicing of the phase space

$\mathcal{T}_0 < \mathcal{T}_0^{\mathrm{cut}}$



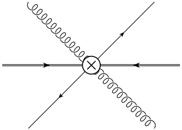
No resolved partons in the final state

$\mathcal{T}_0 > \mathcal{T}_0^{\mathrm{cut}}$
$\mathcal{T}_1 < \mathcal{T}_1^{\mathrm{cut}}$



One resolved parton in the final state

$\mathcal{T}_0 > \mathcal{T}_0^{\mathrm{cut}}$
$\mathcal{T}_1 > \mathcal{T}_1^{\mathrm{cut}}$

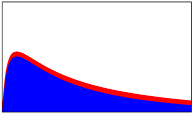


Two resolved partons in the final state

Matching the resummation and the fixed order calculation

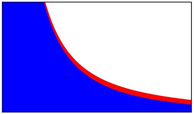
We write the **NNLO differential $\mathcal{T}_0$ spectrum** as the sum of a **resummed singular** and **non-singular** spectrum

$$\frac{d\sigma_{\rm CS}^{\rm NNLO}}{d\Phi_0\, d\mathcal{T}_0} = \frac{d\sigma^{\rm NNLL'}}{d\Phi_0\, d\mathcal{T}_0} + \frac{d\sigma_{\rm CS}^{\rm nonsing}}{d\Phi_0\, d\mathcal{T}_0}$$



where the **non-singular** spectrum is given by the difference between the **fixed-order** and the $\alpha_{\rm S}$ **expansion of the resummed singular** spectrum

$$\frac{d\sigma_{\rm CS}^{\rm nonsing}}{d\Phi_0\, d\mathcal{T}_0} = \int \frac{d\Phi_1}{d\Phi_0\, d\mathcal{T}_0} \frac{d\sigma_{\rm CS+jet}^{\rm NLO_1}}{d\Phi_1} - \frac{d\sigma^{\rm NNLL'}}{d\Phi_0\, d\mathcal{T}_0}\bigg|_{\rm NLO_1}$$



0-jet exclusive and 1-jet inclusive differential cross sections

- The phase space points with $\mathcal{T}_0 < \mathcal{T}_0^{\rm cut}$ contribute to the **NNLO 0-jet exclusive differential cross section**

$$\frac{d\sigma_{\rm CS}^{(0)}}{d\Phi_0}(\mathcal{T}_0^{\rm cut}) = \frac{d\sigma^{\rm NNLL'}}{d\Phi_0}(\mathcal{T}_0^{\rm cut}) + \frac{d\sigma_{\rm CS}^{\rm nonsing}}{d\Phi_0}(\mathcal{T}_0^{\rm cut})$$

- The phase space points with $\mathcal{T}_0 > \mathcal{T}_0^{\rm cut}$ contribute to the **NLO$_1$ 1-jet inclusive differential spectrum**

$$\frac{d\sigma_{\rm CS}^{(\geq 1)}}{d\Phi_0\, d\mathcal{T}_0} = \frac{d\sigma^{\rm NNLL'}}{d\Phi_0\, d\mathcal{T}_0} + \frac{d\sigma_{\rm CS}^{\rm nonsing}}{d\Phi_0\, d\mathcal{T}_0}$$

- The integration recovers the total **NNLO differential cross section**

$$\frac{d\sigma_{\rm CS}^{\rm NNLO}}{d\Phi_0} = \frac{d\sigma_{\rm CS}^{(0)}}{d\Phi_0}(\mathcal{T}_0^{\rm cut}) + \int d\mathcal{T}_0\, \frac{d\sigma_{\rm CS}^{(\geq 1)}}{d\Phi_0\, d\mathcal{T}_0}\, \theta(\mathcal{T}_0 - \mathcal{T}_0^{\rm cut})$$

The splitting functions

To generate Φ_1 events, we need to spread the **1-jet inclusive differential spectrum** over the entire Φ_1 phase space

$$\frac{d\sigma_{\mathrm{CS}}^{(\geq 1)}}{d\Phi_1} = \left(\frac{d\sigma^{\mathrm{NNLL}'}}{d\Phi_0\, d\mathcal{T}_0} - \frac{d\sigma^{\mathrm{NNLL}'}}{d\Phi_0\, d\mathcal{T}_0}\bigg|_{\mathrm{NLO}_1} \right) P_{0\to 1}(\Phi_1) + \frac{d\sigma_{\mathrm{CS+jet}}^{\mathrm{NLO}_1}}{d\Phi_1}$$

- The **fixed-order contribution** has a natural Φ_1 dependence
- We multiply the **resummed contributions** by a **splitting function** $P_{0\to 1}(\Phi_1)$ defined so that, for every function $f(\Phi_0, \mathcal{T}_0)$ of the underlying phase space Φ_0 and the resolution variable $\mathcal{T}_0$,

$$\int d\Phi_1\, f(\Phi_0, \mathcal{T}_0)\, P_{0\to 1}(\Phi_1) = \int d\Phi_0 \int d\mathcal{T}_0\, f(\Phi_0, \mathcal{T}_0)$$

Combination with the parton shower

- Ideally, we would like to feed in the generated NNLO events to a **$\mathcal{T}_N$-ordered shower** where

$$\mathcal{T}_1(\Phi_2) > \mathcal{T}_2(\Phi_3) > \ldots > \mathcal{T}_n(\Phi_{n+1}) > \ldots$$

- If that is not available, we simulate it by mean of a **vetoed p_{T}-ordered shower**

Vetoed shower

- We compute the p_{T} starting scale of the shower
- We pass the event to the shower and let it generate the additional QCD (and QED) radiation
  - $\rightarrow$ If $\mathcal{T}_2(\Phi_n) > \mathcal{T}_1(\Phi_2)$, we re-shower the event (**veto**)
  - $\rightarrow$ Otherwise, we add MPI and hadronization effects

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The MiNNLO$_{\rm PS}$ method in a nutshell

In the MiNNLO$_{\rm PS}$ formalism, the **$q_{\rm T}$ spectrum** of the differential cross section for the $p\,p \to \mathrm{CS} + X$ process is written as

$$\frac{d\sigma^{\rm MiNNLO}_{\rm CS}}{d\Phi_{\rm CS}\, dp_{\rm T}} = e^{-\tilde{S}} D + R_f$$

- The term $e^{-\tilde{S}} D$ provides the **$q_{\rm T}$ resummation**
- The term R_f contains non-singular (i.e. integrable in the $q_{\rm T} \to 0$ limit) contributions to the $p\,p \to \mathrm{CS} + \mathrm{jet}$ process

The non-singular contribution is set to

$$R_f = e^{-\tilde{S}} \left[\frac{d\sigma^{\rm NLO}_{\rm CS+jet}}{d\Phi_{\rm CS}\, dq_{\rm T}} - e^{-\tilde{S}} D \Big|_{\rm NNLO} + \tilde{S}^{(1)} \left(\frac{d\sigma^{\rm LO}_{\rm CS+jet}}{d\Phi_{\rm CS}\, dq_{\rm T}} - D^{(1)} \right) \right]_{\mu = q_{\rm T}}$$

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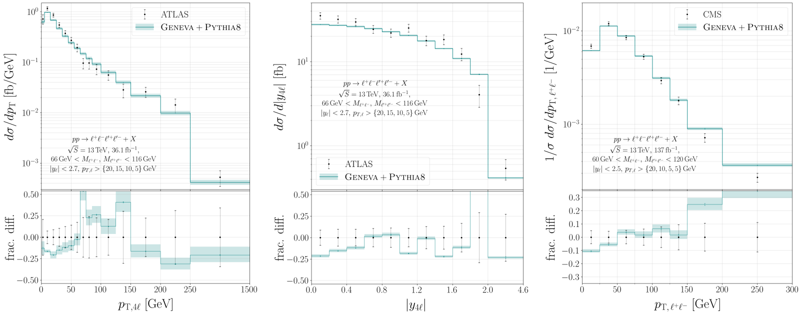
ZZ distributions in Geneva



- Geneva predictions from S. Alioli, A. Broggio, AG, S. Kallweit, M. A. Lim, R. Nagar, D. Napoletano Phys.Lett.B 818 (2021) 136380
- ATLAS and CMS data at 13 TeV from Phys.Rev.D 97 (2018) 3, 032005 and Eur.Phys.J.C 81 (2021) 3, 200
- See also L. Buonocore, G. Koole, D. Lombardi, L. Rottoli, M. Wiesemann, G. Zanderighi JHEP 01 (2022) 072 for MiNNLOPS predictions

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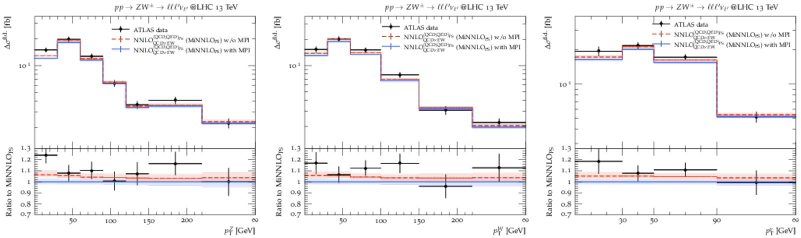
WZ distributions in MiNNLO$_{PS}$

Comparison for the transvsrse momenta of the reconstraucted Z boson, W boson and neutrino (missing energy)



- MiNNLO$_{PS}$ predictions at **(NNLO QCD x NLO EW) + PS** from J. M. Lindert, D. Lombardi, M. Wiesemann, G. Zanderighi, S. Zanoli JHEP 11 (2022) 036
- ATLAS data at 13 TeV from Eur. Phys. J. C 79 (2019) 535

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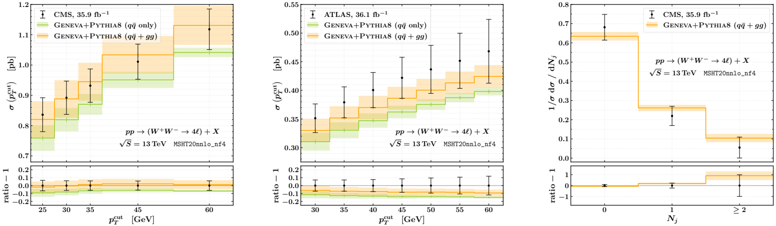
WW distributions in Geneva

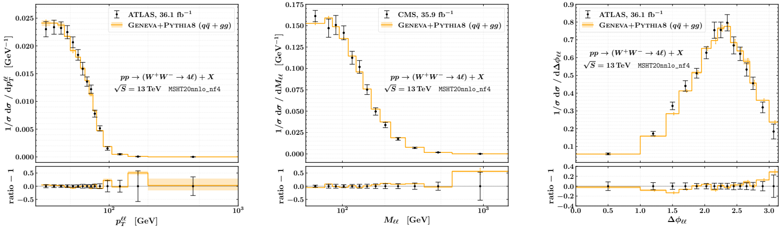
Comparison for the exclusive zero-jet cross section as a function of the jet transverse momentum veto and the jet multiplicity



- Geneva predictions with **hardest-jet transverse momentum resummation** from AG, M. A. Lim, S. Alioli, F. Tackmann JHEP 12 (2023) 069
- ATLAS and CMS data at 13 TeV from Eur. Phys. J. C 79 (2019) 884 and Phys. Rev. D 102, 092001 (2020)

WW distributions in Geneva

Comparison for the transverse momentum, mass and azimuthal separation of the charged lepton pair



- GENEVA predictions with **hardest-jet transverse momentum resummation** from AG, M. A. Lim, S. Alioli, F. Tackmann JHEP 12 (2023) 069
- ATLAS and CMS data at 13 TeV from Eur. Phys. J. C 79 (2019) 884 and Phys. Rev. D 102, 092001 (2020)
- See also D. Lombardi, M. Wiesemann, G. Zanderighi JHEP 11 (2021) 230 for MINNLO$_{PS}$ predictions

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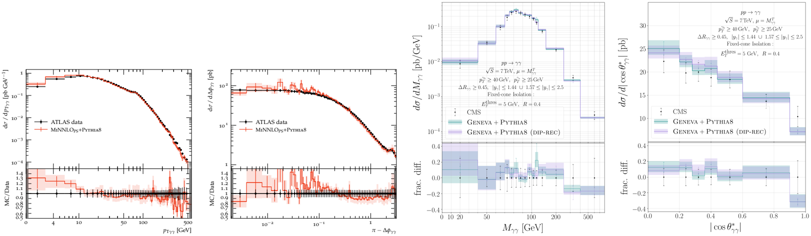
$\gamma\gamma$ distributions in MiNNLO$_{\mathrm{PS}}$ and Geneva



- MiNNLO$_{\mathrm{PS}}$ predictions from AG, C. Oleari, E. Re JHEP 09 (2022) 061
- GENEVA predictions from S. Alioli, A. Broggio, AG, S. Kallweit, M. A. Lim, R. Nagar, D. Napoletano, L. Rottoli JHEP 04 (2021) 041
- ATLAS data (at 13 TeV) and CMS data (at 7 TeV) from JHEP 11 (2021) 169 and Eur. Phys. J. C 74 (2014) 3129
- Check out also D. Lombardi, M. Wiesemann, G. Zanderighi JHEP 06 (2021) 095 for $Z\gamma$ predictions in MiNNLO$_{\mathrm{PS}}$ and S. Alioli, G. Billis, A. Broggio, AG, S. Kallweit, M. A. Lim, G. Marinelli, R. Nagar, D. Napoletano JHEP 06 (2023) 205 ffor *HH* production in GENEVA

Thanks for your attention!

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