

Extending GENEVA to New Resolution Variables for Precise NNLO+PS Event Generation

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based on

AG, Lim, Alioli, Tackmann – arXiv:2308.11577

AG, von Kuk, Lim – arXiv:2505.14773



Monte Carlo event generators

Why event generators?

- The **fully differential events** are the most realistic simulations of the scattering processes observed at colliders

What do they provide?

- They combine
 - **Multi-loop matrix elements**
 - Perturbative accuracy of inclusive distributions
 - **(Analytic resummation)**
 - Logarithmic accuracy of the resummation variable
 - **Parton showers**
 - Fully differential events
 - **MPI, hadronization models, detector simulation, ...**

Monte Carlo event generators at NNLO+PS

Why NNLO+PS?

- **LHC** is progressively turning into a precision machine
- Higher accuracy is needed both for **Standard Model validation** and **Beyond-Standard-Model searches**
 - NNLO+PS event generators provide state-of-the-art predictions in both **inclusive** and **fiducial** phase spaces

Two main implementations

- **GENEVA**
Alioli, Bauer, Berggren, Tackmann, Walsh – arXiv:1508.01475
- **MINNLO_{PS}**
Monni, Nason, Re, Wieseemann, Zanderighi – arXiv:1908.06987
Monni, Re, Wieseemann – arXiv:2006.04133

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The Geneva framework

GENEVA is a Monte Carlo event generator that provides

- Fully differential **events** up to **NNLO QCD** accuracy
→ Interface to external matrix element providers like **OPENLOOPS** and **VVAMP**
- **NNLL' resummation** of the 0-jet resolution variable
→ e.g. the zero-jettiness $\mathcal{T}_0$ or the color-singlet transverse momentum q_T
- **NLL' resummation** of the 1-jet resolution variable
→ e.g. the one-jettiness $\mathcal{T}_1$
- Interface to **parton showers**
→ Default interface to **PYTHIA8**

Alioli, Bauer, Berggren, Tackmann, Walsh – arXiv:1508.01475

Examples of 0-jet resolution variables

Given a color singlet production process

$$p p \rightarrow \text{CS}(q) + X$$

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_T^{jet}

0-jet resolution variables

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

If X is a massless parton of momentum p

$$q_T = \sqrt{q_x^2 + q_y^2} \quad \mathcal{T}_0 = \min(\hat{p}_0 - \hat{p}_z, \hat{p}_0 + \hat{p}_z) \quad p_T^{\text{jet}} = \sqrt{p_x^2 + p_y^2}$$

The Geneva method in a nutshell

Building blocks

The GENEVA method at its core can be summarized by three schematic steps

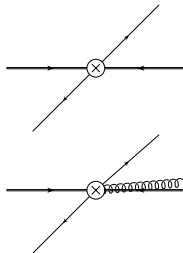
- **Slicing** of the phase space into resolution bins
- **Matching** between the analytic resummation and the fixed-order calculation
- **Splitting** of the resummed contributions to make them more differential and usable to generate events

Beyond NLO

This procedure is **iterated** every time a new order in the perturbative expansion is added

Slicing of phase space

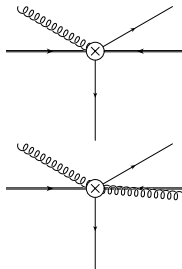
$$r_0 < r_0^{\text{cut}}$$



No resolved partons
in the final state

$$r_0 > r_0^{\text{cut}}$$

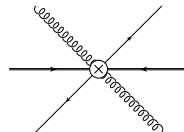
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One resolved parton
in the final state

$$r_0 > r_0^{\text{cut}}$$

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Two resolved partons
in the final state

Matching between resummation and fixed order calculation

We write the **NNLO differential** r_0 **spectrum** as the sum of a **resummed singular** spectrum and a **non-singular** spectrum

$$\frac{d\sigma_{\text{MC}}^{\text{NNLO}}}{d\Phi_0 dr_0} = \frac{d\sigma^{\text{NNLL}'}}{d\Phi_0 dr_0} + \frac{d\sigma_{\text{CS}}^{\text{nonsing}}}{d\Phi_0 dr_0}$$



where the **non-singular** spectrum is given by the difference between the **fixed-order** and the α_s **expansion of the resummed singular** spectrum

$$\frac{d\sigma_{\text{CS}}^{\text{nonsing}}}{d\Phi_0 dr_0} = \int \frac{d\Phi_1}{d\Phi_0 dr_0} \frac{d\sigma_{\text{CS+jet}}^{\text{NLO}_1}}{d\Phi_1} - \left. \frac{d\sigma^{\text{NNLL}'}}{d\Phi_0 dr_0} \right|_{\text{NLO}_1}$$



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

- The phase space points with $r_0 < r_0^{\text{cut}}$ contribute to the **NNLO 0-jet exclusive differential cross section**

$$\frac{d\sigma_{\text{MC}}^{(0)}}{d\Phi_0}(r_0^{\text{cut}}) = \frac{d\sigma^{\text{NNLL}'}}{d\Phi_0}(r_0^{\text{cut}}) + \frac{d\sigma_{\text{CS}}^{\text{nonsing}}}{d\Phi_0}(r_0^{\text{cut}})$$

- The phase space points with $r_0 > r_0^{\text{cut}}$ contribute to the **NLO₁ 1-jet inclusive differential spectrum**

$$\frac{d\sigma_{\text{MC}}^{(\geq 1)}}{d\Phi_0 dr_0} = \frac{d\sigma^{\text{NNLL}'}}{d\Phi_0 dr_0} + \frac{d\sigma_{\text{CS}}^{\text{nonsing}}}{d\Phi_0 dr_0}$$

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

$$\frac{d\sigma_{\text{MC}}^{\text{NNLO}}}{d\Phi_0} = \frac{d\sigma_{\text{MC}}^{(0)}}{d\Phi_0}(r_0^{\text{cut}}) + \int dr_0 \frac{d\sigma_{\text{MC}}^{(\geq 1)}}{d\Phi_0 dr_0} \theta(r_0 - r_0^{\text{cut}})$$

Splitting of resummed contributions

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

$$\frac{d\sigma_{\text{MC}}^{(\geq 1)}}{d\Phi_1} = \left(\frac{d\sigma^{\text{NNLL}'}}{d\Phi_0 dr_0} - \frac{d\sigma^{\text{NNLL}'}}{d\Phi_0 dr_0} \Big|_{\text{NLO}_1} \right) P_{0 \rightarrow 1}(\Phi_1) + \frac{d\sigma_{\text{CS+jet}}^{\text{NLO}_1}}{d\Phi_1}$$

- The **fixed-order contribution** has a natural Φ_1 dependence
- We multiply the **resummed contributions** by a **splitting function** $P_{0 \rightarrow 1}(\Phi_1)$ defined so that, for every function $f(\Phi_0, r_0)$ of the underlying phase space Φ_0 and the resolution variable r_0 ,

$$\int d\Phi_1 f(\Phi_0, r_0) P_{0 \rightarrow 1}(\Phi_1) = \int d\Phi_0 \int dr_0 f(\Phi_0, r_0)$$

0- and 1-jet Monte Carlo differential cross sections

After combining the **fixed order**, **resummed** and **resummed expanded** contributions the **0-** and **1-jet Monte Carlo differential cross sections** read

$$\begin{aligned}\frac{d\sigma_{\text{MC}}^{(0)}}{d\Phi_0} &= \frac{d\sigma^{\text{NNLL}'}}{d\Phi_0}(r_0^{\text{cut}}) - \frac{d\sigma^{\text{NNLL}'}}{d\Phi_0}(r_0^{\text{cut}}) \Big|_{\text{NLO}_0} + \frac{d\sigma^{\text{NLO}_0}}{d\Phi_0}(r_0^{\text{cut}}) \\ \frac{d\sigma_{\text{MC}}^{(\geq 1)}}{d\Phi_1} &= \left\{ \left[\frac{d\sigma^{\text{NNLL}'}}{d\Phi_0 dr_0} - \frac{d\sigma^{\text{NNLL}'}}{d\Phi_0 dr_0} \Big|_{\text{NLO}_1} \right] \mathcal{P}_{0 \rightarrow 1}(\Phi_1) \right. \\ &\quad \left. + \frac{d\sigma^{\text{NLO}_1}}{d\Phi_1} \right\} \theta(r_0 - r_0^{\text{cut}}) \\ &\quad + \frac{d\sigma^{\text{LO}_1}_{\text{nonproj}}}{d\Phi_1} \theta(r_0^{\text{cut}} - r_0)\end{aligned}$$

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$$\frac{d\sigma_{\text{MC}}^{(\geq 1)}}{d\Phi_1} = \left\{ \left[\frac{d\sigma^{\text{NNLL}'}}{d\Phi_0 dr_0} - \frac{d\sigma^{\text{NNLL}'}}{d\Phi_0 dr_0} \Big|_{\text{NLO}_1} \right] \mathcal{P}_{0 \rightarrow 1}(\Phi_1) + \frac{d\sigma^{\text{NLO}_1}}{d\Phi_1} \right\} \theta(r_0 - r_0^{\text{cut}}) + \frac{d\sigma^{\text{LO}_1}_{\text{nonproj}}}{d\Phi_1} \theta(r_0^{\text{cut}} - r_0)$$

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$$\begin{aligned}
 \frac{d\sigma_{\text{MC}}^{(1)}}{d\Phi_1} &= \left\{ \left[\frac{d\sigma^{\text{NNLL}'}}{d\Phi_0 dr_0} - \frac{d\sigma^{\text{NNLL}'}}{d\Phi_0 dr_0} \Big|_{\text{NLO}_1} \right] \mathcal{P}_{0 \rightarrow 1}(\Phi_1) U_1(\Phi_1, r_1^{\text{cut}}) \right. \\
 &\quad \left. + \frac{d\sigma^{\text{NLO}_1}}{d\Phi_1}(r_1^{\text{cut}}) + \frac{d\sigma^{\text{NLL}'}}{d\Phi_1}(r_1^{\text{cut}}) - \frac{d\sigma^{\text{NLL}'}}{d\Phi_1}(r_1^{\text{cut}}) \Big|_{\text{NLO}_1} \right\} \theta(r_0 - r_0^{\text{cut}}) \\
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 \end{aligned}$$

Combination with the parton shower

- Ideally we would like to feed the generated NNLO events into an **r_N -ordered shower** where

$$r_1(\Phi_2) > r_2(\Phi_3) > \dots > r_n(\Phi_{n+1}) > \dots$$

- If that is not available we simulate it by means 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
 - If $r_2(\Phi_n) > r_1(\Phi_2)$ we re-shower the event (**veto**)
 - Otherwise we add MPI and hadronization effects

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$W^- W^+$ production

- **Fully differential** $W^- W^+$ production

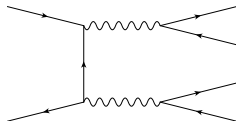
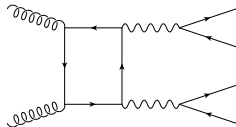
$$p p \rightarrow W^- W^+ \rightarrow \ell^- \bar{\nu}_\ell \ell'^+ \nu_{\ell'}$$

at **NNLO QCD** with leptonically decaying W bosons

- Experimentally relevant **jet veto** resummed at **NNLL'**
- **Transverse momentum** of the **second jet** resummed at **NLL'**
- **Loop-induced channel**

$$g g \rightarrow W^- W^+ \rightarrow \ell^- \bar{\nu}_\ell \ell'^+ \nu_{\ell'}$$

included at **LO**



AG, Lim, Alioli, Tackmann – arXiv:2308.11577

Tools and validation

Matrix elements

- **OPENLOOPS** for tree-level and one-loop amplitudes (including the loop-induced channel)
- **VVAMP** for the two-loop amplitudes

Resummation and shower

- **SCETLIB** for the jet-veto resummation at NNLL' and second-jet p_T resummation at NLL'
- **PYTHIA8** for the shower

Validation

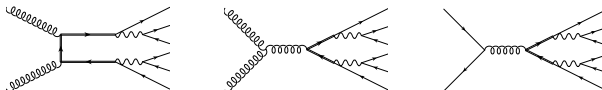
- **MATRIX** for the fixed-order NNLO predictions
- **MCFM** for the jet-veto resummation

Why use the jet veto as resolution variable?

- $W^- W^+$ analyses typically apply a **jet veto**

$$p_T^{\text{jet}} < p_T^{\text{veto}}$$

to suppress the $t\bar{t}$ background (arXiv:1905.04242, arXiv:2009.00119)

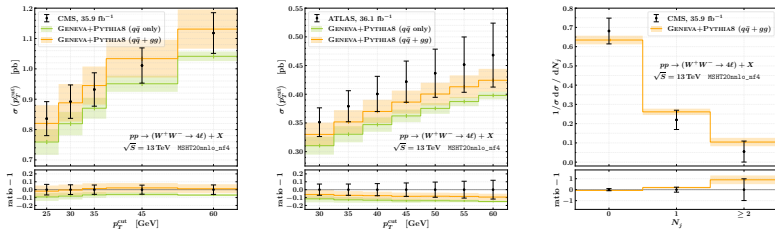


- For $p_T^{\text{veto}} \ll Q \sim M_{WW}$ the fiducial cross section is plagued by **large logarithms**

$$\log\left(\frac{p_T^{\text{veto}}}{Q}\right)$$

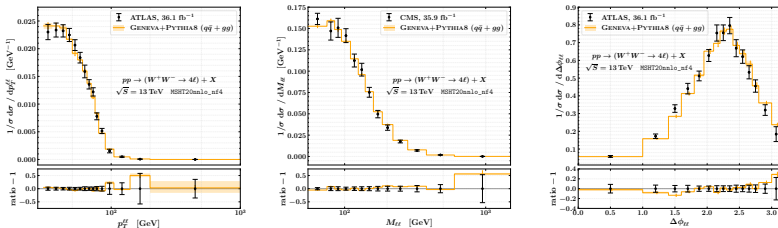
- Choosing the hardest-jet transverse momentum $p_{T,1}^{\text{jet}}$ as the GENEVA resolution variable allows for the **resummation of such logarithms**

Comparison with data



- Comparison with ATLAS data from [arXiv:1905.04242](#) and CMS data from [arXiv:2009.00119](#)
- **Left and Centre:** Fiducial cross section at increasing values of p_T^{veto} compared with CMS and ATLAS data
- **Right:** Number of jets compared with CMS data

Comparison with data



- Comparison with ATLAS data from [arXiv:1905.04242](#) and CMS data from [arXiv:2009.00119](#)
- **From Left to Right:** lepton-antilepton transverse momentum, mass and azimuthal difference

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$b\bar{b} \rightarrow H$ production

- **Higgs boson production** through heavy-quark annihilation

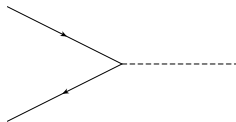
$$b\bar{b} \rightarrow H$$

at **NNLO QCD**

- **Transverse momentum** of the Higgs boson resummed at **N³LL**

$$q_T = p_T^H$$

- **Generalized (p_T -like) one-jettiness** $\mathcal{T}_1^{p_T}$ arXiv:1704.08262 resummed at **NLL'**
- The use of **transverse resolution variables** facilitates the matching to **p_T -ordered parton showers**



AG, von Kuk, Lim – arXiv:2505.14773

Tools and validation

Matrix elements

- OPENLOOPS for tree-level and one-loop amplitudes

Resummation and shower

- SCETLIB for the q_T resummation at N³LL and $\mathcal{T}_1^{pT}$ resummation at NLL'
- PYTHIA8 for the shower

Validation

- MCFM for the NNLO Higgs rapidity spectrum
- SCETLIB for the N³LL Higgs transverse momentum spectrum

The N -jettiness resolution variable

Given a configuration with m final-state partons of momenta $p_1, \dots, p_m$ we define the **N -jettiness** as

$$\mathcal{T}_N = \min_{\substack{n_1, \dots, n_N \\ \text{lightlike with } n_i^0 = 1}} T_N \quad T_N = \sum_{i=1}^m \min(n_a \cdot \hat{p}_i, n_b \cdot \hat{p}_i, n_1 \cdot \hat{p}_i, \dots, n_N \cdot \hat{p}_i)$$

Jet directions and momenta

- $n_a = (1, 0, 0, 1)$ and $n_b = (1, 0, 0, -1)$ are the beam directions
- $n_1, \dots, n_N$ can be any lightlike vector with $n_i^0 = 1$
- $\hat{p}_1, \dots, \hat{p}_m$ are the parton momenta after a longitudinal boost from the laboratory to the frame where the color singlet has zero rapidity

The N -jettiness resolution variable

Given a configuration with m final-state partons of momenta $p_1, \dots, p_m$ we define the **N -jettiness** as

$$\mathcal{T}_N = \min_{\substack{n_1, \dots, n_N \\ \text{lightlike with } n_i^0 = 1}} T_N \quad T_N = \sum_{i=1}^m \min(n_a \cdot \hat{p}_i, n_b \cdot \hat{p}_i, n_1 \cdot \hat{p}_i, \dots, n_N \cdot \hat{p}_i)$$

Physical properties

- The N -jettiness measures how close the configuration is to having N or fewer jets
- A configuration with N or fewer final-state partons has $\mathcal{T}_N = 0$
- The N -jettiness of a configuration with $N + 1$ final-state partons approaches 0 when any of the partons approaches its soft or collinear limit

The generalized (p_T -like) N -jettiness

- **Standard N -jettiness** uses and **invariant-mass-like** measure (and distance) for each beam/jet region i

$$\mathcal{T}_N = \sum_k \min_i n_i \cdot p_k$$

which does not interface naturally with parton showers ordered in transverse momentum

- The original N -jettiness paper already noted that distances and measures could be **generalized to functions $d_i(p_k)$ and $f_i(p_k)$**
- **In this work** we choose p_T -like distances and measures built from $(p_{T,k}, \eta_k, \phi_k)$ relative to each beam/jet direction
- **First resummation** of this generalized one-jettiness beyond LL (achieved here at **NLL'**)

The p_T -like one-jettiness

■ Step 1 – region assignment

$$d_0(p_k) = 1 \text{ (beam region)} \quad d_J(p_k) = \frac{R_{kJ}^2}{R^2} \text{ (jet region)}$$

$$R_{kJ} = \sqrt{(\eta_k - \eta_J)^2 + (\phi_k - \phi_J)^2}$$

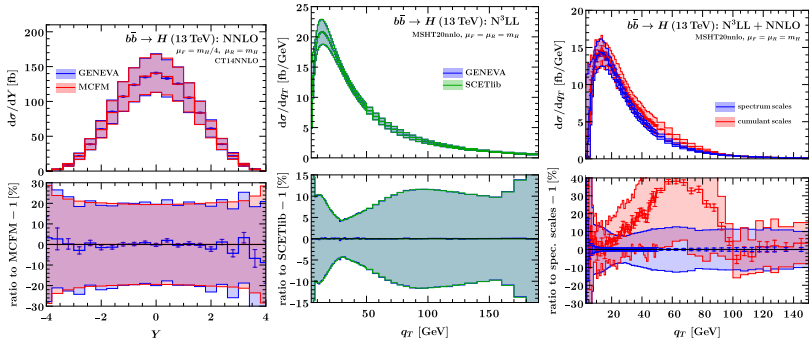
particle k assigned to beam or jet region by $\min\{d_0(p_k), d_J(p_k)\}$

■ Step 2 – observable value

$$\mathcal{T}_1^{p_T} = \sum_k \begin{cases} f_B(p_k) & \text{if } k \in \text{beam region} \\ f_J(p_k) & \text{if } k \in \text{jet region} \end{cases} \quad \begin{aligned} f_B(p_k) &= p_{T,k} \\ f_J(p_k) &= p_{T,k} \mathcal{R}_{kJ} \end{aligned}$$

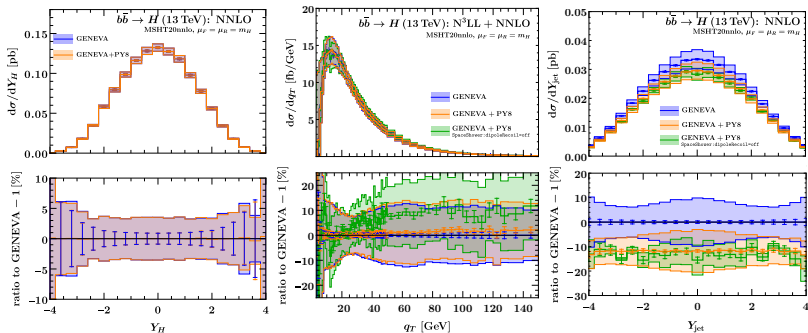
$$\mathcal{R}_{kJ} = \sqrt{2 \cosh(\eta_k - \eta_J) - 2 \cos(\phi_k - \phi_J)}$$

Validation against fixed order and resummation



- **Left:** GENEVA vs. MCFM Higgs rapidity distribution
- **Centre:** GENEVA vs. SCETlib Higgs transverse momentum distribution
- **Right:** Cumulant vs. spectrum scale choice effect

Effects of the parton shower



- GENEVA predictions before and after the PYTHIA8 shower
- **From Left to Right:** Higgs rapidity Y_H , Higgs transverse momentum q_T and leading-jet rapidity Y_{jet}

Thanks for your attention!

Acknowledgements



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