NNLO event generation matched to parton showers in the GENEVA Monte Carlo

http://geneva.physics.lbl.gov

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Theory Seminar

DESY - Zeuthen
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SA, C. Bauer, C. Berggren, F. Tackmann, J. Walsh, Phys.Rev. D92 (2015) 9

SA, C. Bauer, F. Tackmann, S. Guns, Eur.Phys.J. C76 (2016) 614

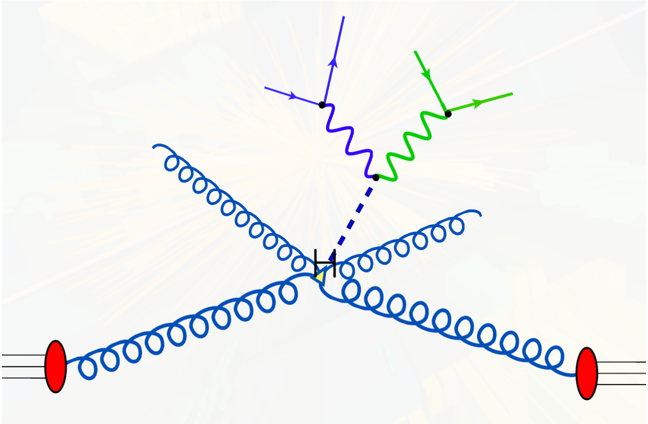
SA, A. Broggio, M. Lim, S. Kallweit, L. Rottoli Phys.Rev.D 100 (2019)

SA, A. Broggio, A. Gavardi, M. Lim, R. Nagar, D. Napoletano, S. Kallweit, L. Rottoli (2020-2021)

T. Cridge, M. Lim, R. Nagar (2021)

Motivation

- Shower Monte Carlo are essential tools for particle physics phenomenology.
- They start from a perturbative description of the hard-interaction at $\mathcal{O}(100)$ GeV and predict the evolution of the event at ever small scales, down to the nonperturbative domain $\mathcal{O}(1)$ GeV



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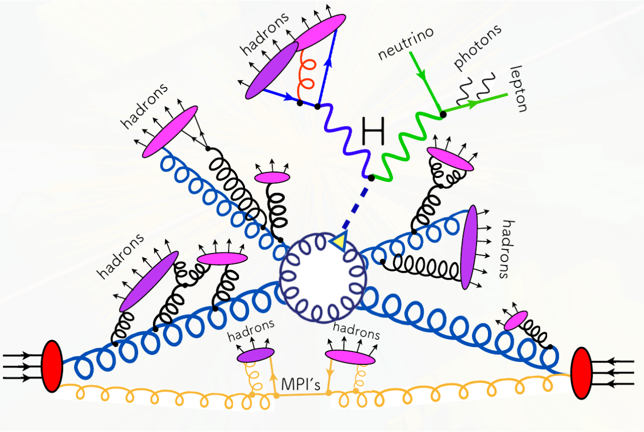

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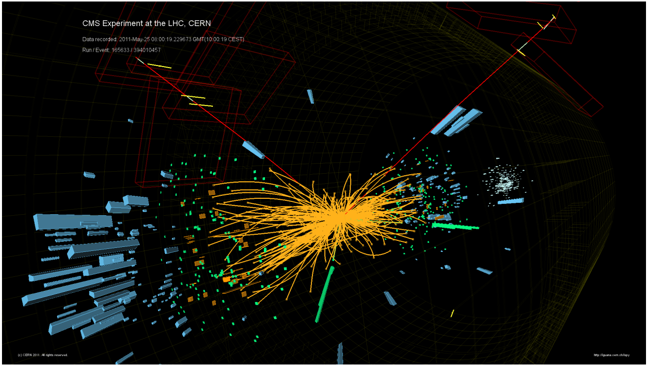
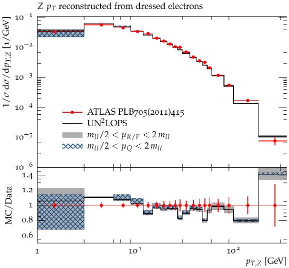


- They are ubiquitous in LHC analyses

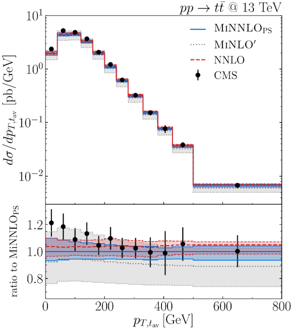
Motivation

- The increasing experimental precision of LHC measurements challenges existing generators, pushing the request for higher accuracy
- The state-of-the-art is the inclusion of NNLO corrections into parton-shower Monte Carlo
- Three main approach to the problem:

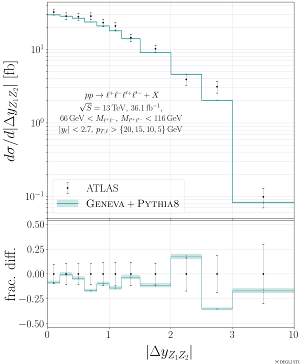
UNNLOPS



MiNNLOPS



GENEVA



Introduction

GENEVA combines the 3 theoretical tools we use for QCD predictions into a single framework:

1) Fully differential fixed-order calculations

- up to NNLO via *N*-jettiness or q_T-subtraction

2) Higher-logarithmic resummation

- up to NNLL$'$ or N3LL via SCET or RadISH

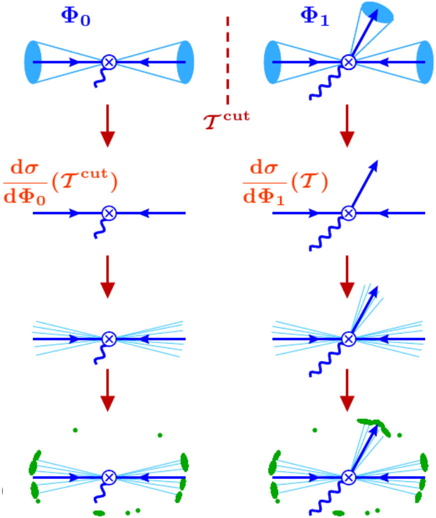
3) Parton showering, hadronization and MPI

- recycling standard SMC. Using PYTHIA8 now, any SMC supporting LHEF and user-hook vetoes is OK

Resulting Monte Carlo event generator has many advantages:

- consistently improves perturbative accuracy away from FO regions
- provides event-by-event systematic estimate of theoretical perturbative uncertainties and correlations
- gives a direct interface to SMC hadronization, MPI modeling and detector simulations.

The four steps of GENEVA:



1. Choose the resolution parameters, e.g. $\mathcal{T}_0^{\rm cut}$ or $p_T^{\rm cut}$, for an IR-finite definition of the events.

2. Associate differential cross-sections to events such that events are (N)NLO accurate and the resolution parameter is resummed at high-enough accuracy.

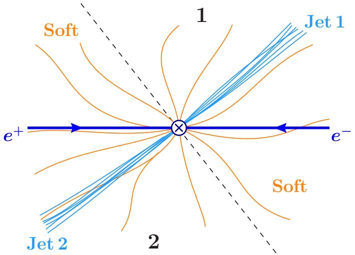
3. Shower the events imposing conditions trying to avoid spoiling the resummation accuracy reached at step 2.

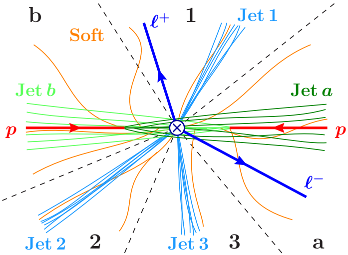
4. Hadronize, add multi-parton interactions (MPI) and decay without further restrictions.

N-jettiness as jet-resolution variable

- N-jettiness is a good resolution parameter. Global physical observable with straightforward definitions for hadronic colliders, in terms of beams $q_{a,b}$ and jet-directions q_j

$$\mathcal{T}_N = \frac{2}{Q}\sum_k \min\{q_1 \cdot p_k, \ldots, q_N \cdot p_k\} \Rightarrow \mathcal{T}_N = \frac{2}{Q}\sum_k \min\{q_a \cdot p_k, q_b \cdot p_k, q_1 \cdot p_k, \ldots, q_N \cdot p_k\}$$

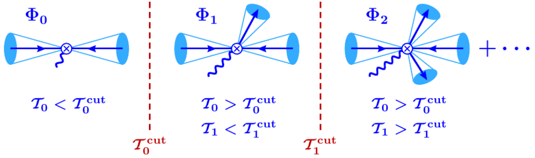


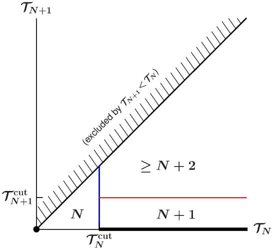


- N-jettiness has good factorization properties, IR safe and resummable at all orders. Resummation known at NNLL for any N in SCET [Stewart et al. 1004.2489, 1102.4344]
- $\mathcal{T}_N \to 0$ for N pencil-like jets, $\mathcal{T}_N \gg 0$ spherical limit.
- $\mathcal{T}_N < \mathcal{T}_N^{\text{cut}}$ limits the activity outside the jets

Step 1: IR-safe definitions of events beyond LO

At NNLO one needs a 0-jet and a 1-jet resolution parameters. Iterating the procedure, the phase space is sliced into jet-bins





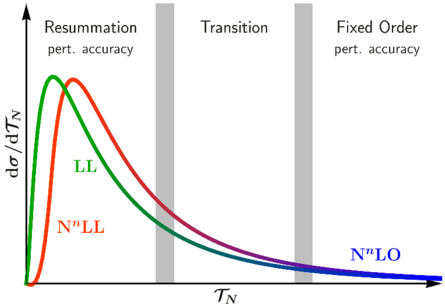
Different choices are possible for the resolution parameters, but one always has:

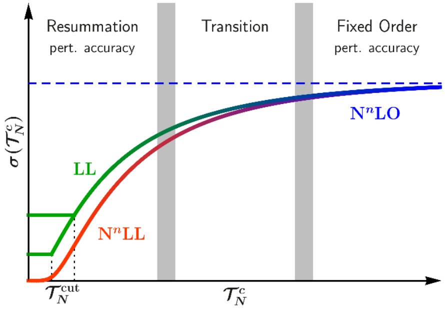
- Emissions below $\mathcal{T}_N^{\rm cut}$ are unresolved (i.e. integrated over) and the kinematic considered is the one of the event before the extra emission(s).
- Emissions above $\mathcal{T}_N^{\rm cut}$ are retained and the kinematics is fully specified.

An M-parton event is considered a N-jet event, $N \leq M$, fully differential in Φ_N

- Price to pay: power corrections in $\mathcal{T}_N^{\rm cut}$ due to PS projection.
- Advantage: vanish for IR-safe observables as $\mathcal{T}_N^{\rm cut} \to 0$

Step 2: Combining resummation with fixed-order in GENEVA





- The inclusion of the higher-order resummation is key to improve the accuracy of the predictions across the whole spectrum.
- Assuming a counting in which $\alpha_s L \sim 1$, the first "next-to-leading-order" correction to the spectrum enters at NNLL.
- To correctly match this to fixed-predictions one needs to include all singular α_s^2 terms, hence the NNLL$^{'}$, and match to NNLO.
- These conditions set the minimum accuracy requirement for GENEVA.

Step 2: Combining resummation with fixed-order in GENEVA

For color-singlet at NNLO provide partonic formulae for up to 2 extra partons.

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For color-singlet at NNLO provide partonic formulae for up to 2 extra partons.

- $0-$jet exclusive cross section

$$\frac{\mathrm{d}\sigma_0^{\mathrm{MC}}}{\mathrm{d}\Phi_0}(\mathcal{T}_0^{\mathrm{cut}}) = \frac{\mathrm{d}\sigma_0^{\mathrm{NNLL}'}}{\mathrm{d}\Phi_0}(\mathcal{T}_0^{\mathrm{cut}}) + \frac{\mathrm{d}\sigma_0^{\mathrm{nons}}}{\mathrm{d}\Phi_0}(\mathcal{T}_0^{\mathrm{cut}})$$

$$\frac{\mathrm{d}\sigma^{\mathrm{NNLL}'}}{\mathrm{d}\Phi_0}(\mathcal{T}_0^{\mathrm{cut}}) = \int_0^{\mathcal{T}_0^{\mathrm{cut}}} \mathrm{d}\mathcal{T}_0 \sum_{ij} \frac{\mathrm{d}\sigma_{ij}^B}{\mathrm{d}\Phi_0} H_{ij}(Q^2, \mu_H)\, U_H(\mu_H, \mu)$$
$$\times \left[B_i(x_a, \mu_B) \otimes U_B(\mu_B, \mu)\right] \times \left[B_j(x_b, \mu_B) \otimes U_B(\mu_B, \mu)\right]$$
$$\otimes \left[S(\mu_S) \otimes U_S(\mu_S, \mu)\right],$$

- Originally done exploiting SCET factorization: hard, beam and soft function depend on a single scale. No large logarithms present when scales are at their characteristic values:

$$\mu_H = Q, \quad \mu_B = \sqrt{Q\mathcal{T}_0}, \quad \mu_S = \mathcal{T}_0$$

- Resummation performed via RGE evolution factors U to a common scale μ.
- At NNLL' all singular contributions to $\mathcal{O}\left(\alpha_s^2\right)$ already included by definition.
- Two-loop virtual corrections properly spread to nonzero $\mathcal{T}_0$ by resummation.

Any other resummation formalism that provides the cumulant at this level of accuracy is equally applicable (e.g. RadISH) .

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For color-singlet at NNLO provide partonic formulae for up to 2 extra partons.

- $0-$jet exclusive cross section

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$$\frac{\mathrm{d}\sigma_0^{\mathrm{nons}}}{\mathrm{d}\Phi_0}(\mathcal{T}_0^{\mathrm{cut}}) = \frac{\mathrm{d}\sigma_0^{\mathrm{NNLO}_0}}{\mathrm{d}\Phi_0}(\mathcal{T}_0^{\mathrm{cut}}) - \left[\frac{\mathrm{d}\sigma^{\mathrm{NNLL}'}}{\mathrm{d}\Phi_0}(\mathcal{T}_0^{\mathrm{cut}})\right]_{\mathrm{NNLO}_0}$$

- Nonsingular matching constrained by requirement of NNLO_0 accuracy.

Step 2: Combining resummation with fixed-order in GENEVA

For color-singlet at NNLO provide partonic formulae for up to 2 extra partons.

- $1-$jet inclusive cross section

$$\frac{\mathrm{d}\sigma^{\mathsf{MC}}_{\geq 1}}{\mathrm{d}\Phi_1}(\mathcal{T}_0 > \mathcal{T}_0^{\mathrm{cut}}) = \frac{\mathrm{d}\sigma^{\mathrm{NNLL}'}_{\geq 1}}{\mathrm{d}\Phi_1}\,\theta(\mathcal{T}_0 > \mathcal{T}_0^{\mathrm{cut}}) + \frac{\mathrm{d}\sigma^{\mathrm{nons}}_{\geq 1}}{\mathrm{d}\Phi_1}(\mathcal{T}_0 > \mathcal{T}_0^{\mathrm{cut}})$$

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$$\frac{d\sigma^{\mathrm{NNLL'}}_{\geq 1}}{d\Phi_1}\,\theta(\mathcal{T}_0 > \mathcal{T}_0^{\mathrm{cut}}) = \frac{d\sigma^{\mathrm{NNLL'}}}{d\Phi_0 d\mathcal{T}_0}\,\mathcal{P}(\Phi_1)\,\theta(\mathcal{T}_0 > \mathcal{T}_0^{\mathrm{cut}})$$

- Resummed formula only differential in $\Phi_0, \mathcal{T}_0$. Need to make it differential in 2 more variables, e.g. energy ratio $z = E_M/E_S$ and azimuthal angle ϕ
- We use a normalized splitting probability to make the resummation differential in Φ_1.

$$\mathcal{P}(\Phi_1) = \frac{p_{\mathrm{sp}}(z,\phi)}{\sum_{\mathrm{sp}} \int_{z_{\min}(\Phi_0,\mathcal{T}_0)}^{z_{\max}(\Phi_0,\mathcal{T}_0)} dz d\phi\, p_{\mathrm{sp}}(z,\phi)}\,\frac{d\Phi_0 d\mathcal{T}_0 dz d\phi}{d\Phi_1}, \qquad \int \frac{d\Phi_1}{d\Phi_0 d\mathcal{T}_0}\,\mathcal{P}(\Phi_1) = 1$$

- p_{sp} are based on AP splittings for FSR, weighted by PDF ratio for ISR.
- All singular $\mathcal{O}(\alpha_s^2)$ terms again included at NNLL' by definition.

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$$\frac{\mathrm{d}\sigma^{\mathrm{nons}}_{\geq 1}}{\mathrm{d}\Phi_1}(\mathcal{T}_0 > \mathcal{T}_0^{\mathrm{cut}}) = \frac{\mathrm{d}\sigma^{\mathrm{NLO}_1}_{\geq 1}}{\mathrm{d}\Phi_1}(\mathcal{T}_0 > \mathcal{T}_0^{\mathrm{cut}}) - \left[\frac{\mathrm{d}\sigma^{\mathrm{NNLL}'}}{\mathrm{d}\Phi_0 \mathrm{d}\mathcal{T}_0}\,\mathcal{P}(\Phi_1)\right]_{\mathrm{NLO}_1} \theta(\mathcal{T}_0 > \mathcal{T}_0^{\mathrm{cut}})$$

  - Nonsingular matching fixed by NLO_1 requirement

Step 2: Combining resummation with fixed-order in GENEVA

For color-singlet at NNLO provide partonic formulae for up to 2 extra partons.

- $1-$jet inclusive cross section
- The separation between 1 and 2 jets is determined by the NLL resummation of $\mathcal{T}_1^{\mathrm{cut}}$
  - Include both the $\mathcal{T}_0$ and $\mathcal{T}_1$ resummations in a unitarity-based approach for $\mathcal{T}_1 \ll \mathcal{T}_0$. See arXiv: 1508.01475 and arXiv: 1605.07192 for derivation.

$$\frac{\mathrm{d}\sigma_1^{\mathsf{MC}}}{\mathrm{d}\Phi_1}(\mathcal{T}_0 > \mathcal{T}_0^{\mathrm{cut}}; \mathcal{T}_1^{\mathrm{cut}}) = \frac{\mathrm{d}\sigma_{\geq 1}^C}{\mathrm{d}\Phi_1} U_1(\Phi_1, \mathcal{T}_1^{\mathrm{cut}})\, \theta(\mathcal{T}_0 > \mathcal{T}_0^{\mathrm{cut}}) + \frac{\mathrm{d}\sigma_1^{\mathrm{match}}}{\mathrm{d}\Phi_1}(\mathcal{T}_0 > \mathcal{T}_0^{\mathrm{cut}}; \mathcal{T}_1^{\mathrm{cut}})$$

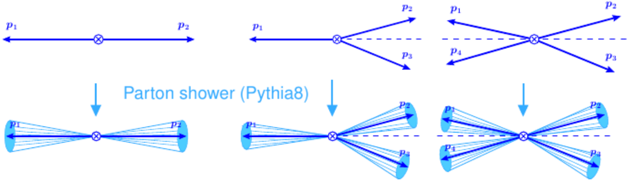
$$\frac{\mathrm{d}\sigma_{\geq 2}^{\mathsf{MC}}}{\mathrm{d}\Phi_2}(\mathcal{T}_0 > \mathcal{T}_0^{\mathrm{cut}}, \mathcal{T}_1 > \mathcal{T}_1^{\mathrm{cut}}) = \frac{\mathrm{d}\sigma_{\geq 1}^C}{\mathrm{d}\Phi_1} U_1'(\Phi_1, \mathcal{T}_1)\, \theta(\mathcal{T}_0 > \mathcal{T}_0^{\mathrm{cut}})\Big|_{\Phi_1 = \Phi_1^{\mathcal{T}}(\Phi_2)} \times \mathcal{P}(\Phi_2)\, \theta(\mathcal{T}_1 > \mathcal{T}_1^{\mathrm{cut}}) + \frac{\mathrm{d}\sigma_{\geq 2}^{\mathrm{match}}}{\mathrm{d}\Phi_2}(\mathcal{T}_0 > \mathcal{T}_0^{\mathrm{cut}}, \mathcal{T}_1 > \mathcal{T}_1^{\mathrm{cut}})$$

$$\frac{\mathrm{d}\sigma_{\geq 1}^C}{\mathrm{d}\Phi_1} = \frac{\mathrm{d}\sigma_{\geq 1}^{\mathrm{NNLL}'}}{\mathrm{d}\Phi_1} + (B_1 + V_1^C)(\Phi_1) - \left[\frac{\mathrm{d}\sigma_{\geq 1}^{\mathrm{NNLL}'}}{\mathrm{d}\Phi_1}\right]_{\mathrm{NLO}_1}$$

  - The fully differential $\mathcal{T}_0$ information is contained trough $\frac{\mathrm{d}\sigma_{\geq 1}^{\mathrm{NNLL}'}}{\mathrm{d}\Phi_1}$

Step 3: Adding the parton shower.

- Purpose of the parton shower is to fill the $0-$ and $1-$jet exclusive bins with radiation and add more emissions to the inclusive $2-$jet bin



- Ideally it should not change accuracy reached at partonic level.
- If the shower is ordered in resolution variable, setting SCALUP would be enough.
- For different ordering variable, jet-boundaries constraints $\mathcal{T}_k^{\mathrm{cut}}$ need to be imposed on hardest radiation (largest jet resolution scale)
- Impose the first emission has the largest jet resolution scale, by performing a splitting by hand using a NLL Sudakov and the $\mathcal{T}_k$-preserving map.

$$\frac{\mathrm{d}\sigma_1^{\mathrm{MC}}}{\mathrm{d}\Phi_1}(\mathcal{T}_0 > \mathcal{T}_0^{\mathrm{cut}}, \mathcal{T}_1^{\mathrm{cut}}, \Lambda_1) = \frac{\mathrm{d}\sigma_1^{\mathrm{MC}}}{\mathrm{d}\Phi_1}(\mathcal{T}_0 > \mathcal{T}_0^{\mathrm{cut}}, \mathcal{T}_1^{\mathrm{cut}})\, U_1(\mathcal{T}_1^{\mathrm{cut}}, \Lambda_1)\,,$$

$$\begin{aligned}\frac{\mathrm{d}\sigma_{\geq 2}^{\mathrm{MC}}}{\mathrm{d}\Phi_2}(\mathcal{T}_0 > \mathcal{T}_0^{\mathrm{cut}}, \mathcal{T}_1^{\mathrm{cut}}, \mathcal{T}_1 > \Lambda_1) &= \frac{\mathrm{d}\sigma_{\geq 2}^{\mathrm{MC}}}{\mathrm{d}\Phi_2}(\mathcal{T}_0 > \mathcal{T}_0^{\mathrm{cut}}, \mathcal{T}_1 > \mathcal{T}_1^{\mathrm{cut}}) \\ &+ \frac{\mathrm{d}}{\mathrm{d}\mathcal{T}_1}\frac{\mathrm{d}\sigma_1^{\mathrm{MC}}}{\mathrm{d}\Phi_1}(\mathcal{T}_0 > \mathcal{T}_0^{\mathrm{cut}}, \mathcal{T}_1^{\mathrm{cut}}, \mathcal{T}_1) \\ &\times \mathcal{P}(\Phi_2)\,\theta(\Lambda_1 < \mathcal{T}_1 < \mathcal{T}_1^{\mathrm{max}})\,.\end{aligned}$$

Step 3: more details about the interface to PYTHIA8.

Each event multiplicity is treated differently:

Φ_0 events below $\mathcal{T}_0^{\rm cut}$ ($\mathcal{O}(1\%)$ of total xsec)

- All events have $\mathcal{T}_0 = 0$. Here the shower should restore the emissions which were integrated over. Only constrain is on normalization, shape entirely given by PYTHIA.
- Events are showered starting from SCALUP $\sim \sqrt{Q\mathcal{T}_0^{\rm cut}}$ and re-showered until $\mathcal{T}_0^{PY} < \mathcal{T}_0^{\rm cut}$. Small 5% spillover allowed to avoid hard border.

Φ_1 events made negligible by splitting down to $\Lambda_1 \lesssim 100$ MeV ($\mathcal{O}(0.1\%)$ of total xsec)

- Events have a non-zero value of $\mathcal{T}_0$ while $\mathcal{T}_1 = 0$.
- Showered starting from SCALUP $k_{T,max} \sim \sqrt{Q\mathcal{T}_1^{\rm cut}}$ and re-showered until $\mathcal{T}_1^{PY} < \mathcal{T}_1^{\rm cut}$.

Φ_2 events ($\mathcal{O}(99\%)$ of total xsec)

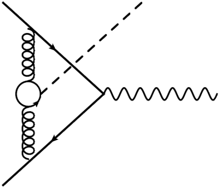
- Bulk of events, with nonzero values of $\mathcal{T}_0$ and $\mathcal{T}_1$
- Starting scale set to $k_{T,2nd} \sim \sqrt{Q\mathcal{T}_1}$, re-shower events until $\mathcal{T}_2^{PY} < \mathcal{T}_1$
- PYTHIA first emission can be shown to shift $\mathcal{T}_0$ distribution starting from order $\alpha_s^3/\mathcal{T}_0$ on average (term beyond NNLL')

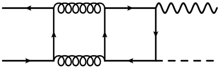
RESULTS

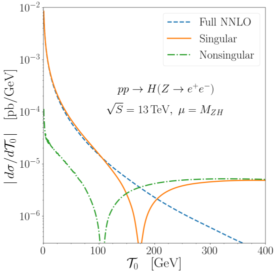
HiggsStrahlung

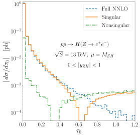
SA et al. Phys.Rev.D 100 (2019)

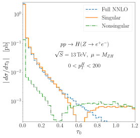
- Third largest Higgs boson production channel. Observed recently by ATLAS and CMS.
- Allows possibility to study VVH vertex, $Hb\bar{b}$ when also considering decay
- Similar to DY production, complications coming from diagrams with top-quark loops
- Including all top-quark mass effects at 1 loop, currently neglecting top-quark mass diagrams V_I and V_{II} only known in top-quark mass expansion.











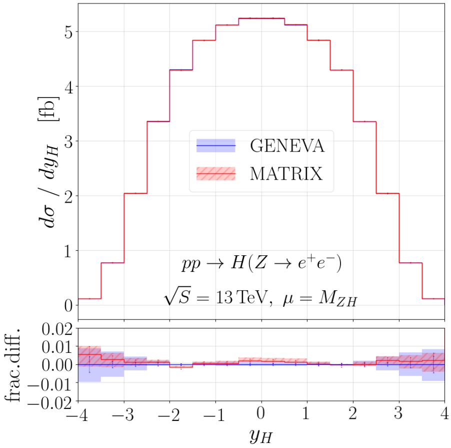
- Beam-thrust resummation at NNLL' matched to NNLO$_0$ via SCET
- Scale profiles adapted to the process, not extremely dependent on leading-order kinematics

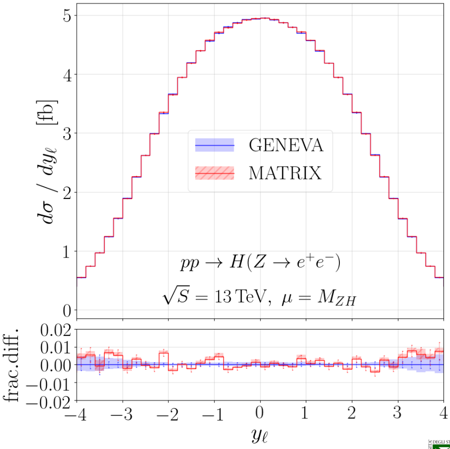
NNLO validation

- NNLO cross-section and inclusive distributions validated against MATRIX

Kallweit et al. Eur.Phys.J. C78 (2018).

- Non-trivial correlations for scales variations, dedicated profiled used to reproduce fixed-order variations for inclusive quantities.
- Smallness of scale variations makes it numerically very challenging.





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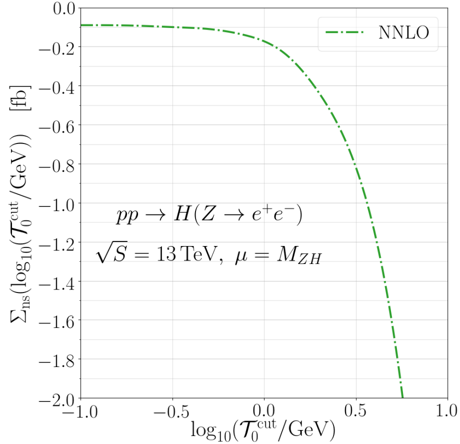
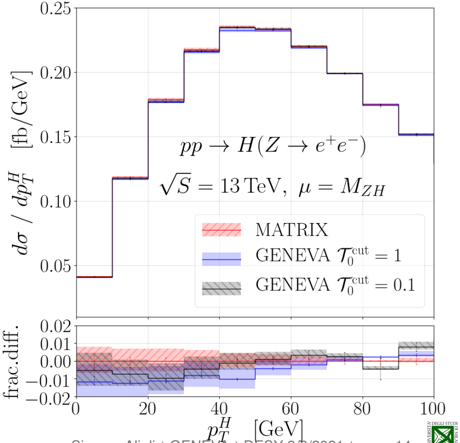
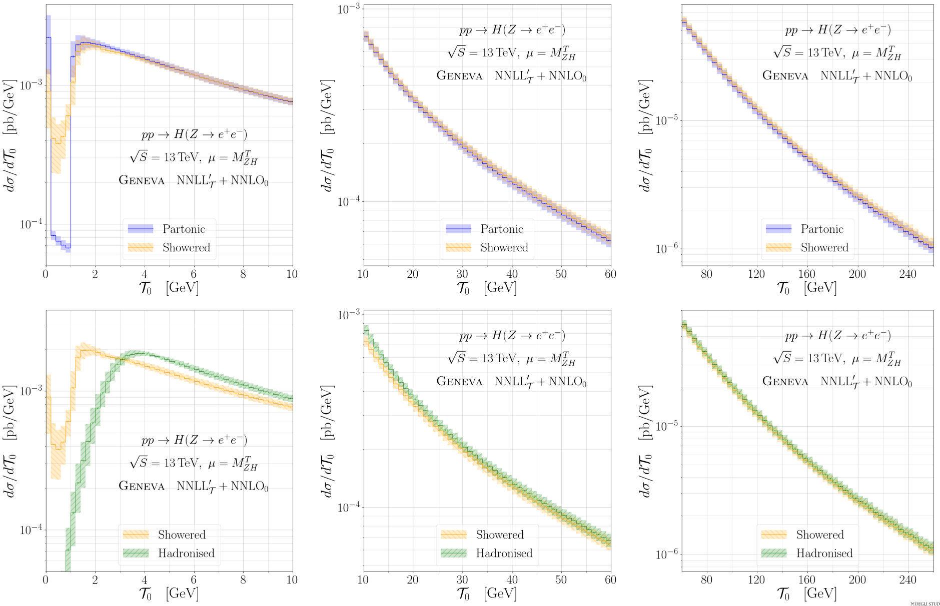
- Non-trivial correlations for scales variations, dedicated profiled used to reproduce fixed-order variations for inclusive quantities.
- Smallness of scale variations makes it numerically very challenging.
- Power-suppressed corrections effects on distributions small.



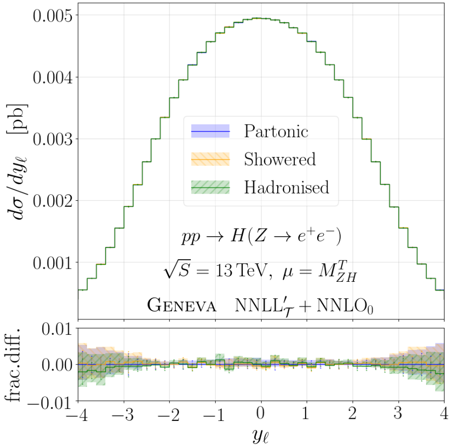


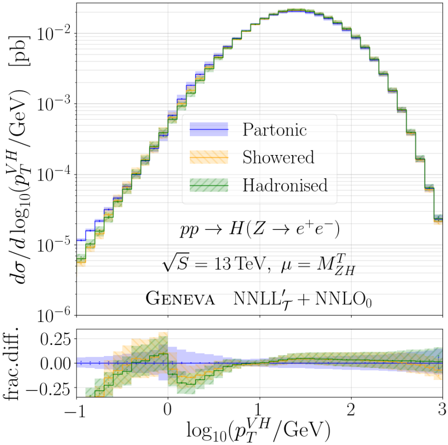
Showered and hadronized results for HiggsStrahlung



Showered and hadronized results for HiggsStrahlung

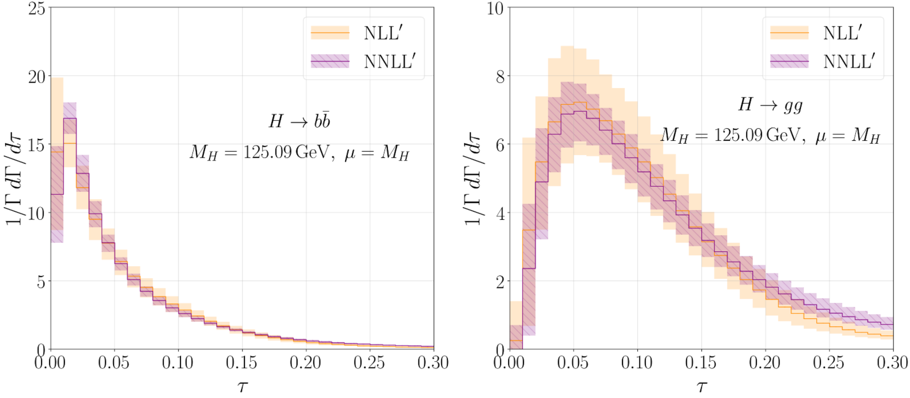
- Inclusive quantities not modified, expected changes in exclusive ones.





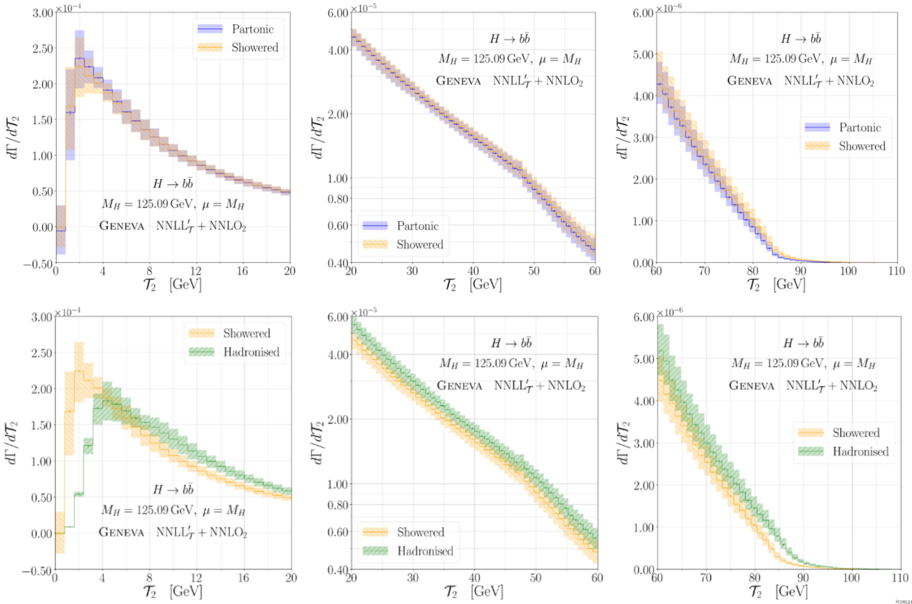
Adding the Higgs boson hadronic decay at NNLO

- 2-jettiness (thrust) τ_2^{dec} used as resolution parameter for decay
- Many ingredients recycled from original e^+e^- GENEVA calculation. Only hard function computed anew. Total decay rate know analytically at NNLO, but $\mathcal{O}(\alpha_s^2)$ nonsingular contributions still needs to be computed numerically.



- Also included the $H \to gg$ channel, which shows larger corrections.

Adding the Higgs boson decay at NNLO



Production and decay at NNLO

- In the NWA it is possible to factorize production from decay and correctly match two GENEVA implementations.
- Beam-thrust $\mathcal{T}_0$ resolution parameter for production, 2-jettiness (thrust) $\tau_2^{\rm dec}$ for decay
- The new $0-$jets cross section is

$$
\begin{aligned}
\overbrace{\frac{d\sigma_0^{\rm MC}}{d\Phi_{\ell^+\ell^- b\bar b}}(\mathcal{T}_0^{\rm cut};\tau_2^{\rm cut})}^{(\rm NNLL+NNLO_0)\otimes(\rm NNLL+NNLO_2)}
&= \overbrace{\frac{d\sigma_0^{\rm MC}}{d\Phi_{\ell^+\ell^- H}}(\mathcal{T}_0^{\rm cut})}^{\rm NNLL+NNLO_0} \times \frac{d\Gamma^{(0)}_{H\to b\bar b}}{d\Phi_{H\to b\bar b}} + \frac{d\sigma^{(0)}_{\ell^+\ell^- H}}{d\Phi_{\ell^+\ell^- H}} \times \overbrace{\frac{d\Gamma_2^{\rm MC}}{d\Phi_{H\to b\bar b}}(\tau_2^{\rm cut})}^{\rm NNLL+NNLO_2} \\
&\quad - \frac{d\sigma^{(0)}_{\ell^+\ell^- H}}{d\Phi_{\ell^+\ell^- H}} \times \frac{d\Gamma^{(0)}_{H\to b\bar b}}{d\Phi_{H\to b\bar b}} \\
&\quad + \left(\frac{d\sigma^{\rm NLL}}{d\Phi_{\ell^+\ell^- H}}(\mathcal{T}_0^{\rm cut}) + \frac{d\sigma^{\overline{\rm NLO}}_{\ell^+\ell^- H}}{d\Phi_{\ell^+\ell^- H}}(\mathcal{T}_0^{\rm cut}) - \left[\frac{d\sigma^{\rm NLL}}{d\Phi_{\ell^+\ell^- H}}(\mathcal{T}_0^{\rm cut})\right]_{\overline{\rm NLO}} \right) \\
&\quad \times \left(\frac{d\Gamma^{\rm NLL}}{d\Phi_{H\to b\bar b}}(\tau_2^{\rm cut}) + \frac{d\Gamma^{\overline{\rm NLO}}_{H\to b\bar b}}{d\Phi_{H\to b\bar b}}(\tau_2^{\rm cut}) - \left[\frac{d\Gamma^{\rm NLL}}{d\Phi_{H\to b\bar b}}(\tau_2^{\rm cut})\right]_{\overline{\rm NLO}} \right)
\end{aligned}
$$

- Care must be taken in adding the fixed-order NLO x NLO terms, they can't just be added at fixed-order, need to be properly resummed as well.

Production and decay at NNLO

- In the NWA it is possible to factorize production from decay and correctly match two GENEVA implementations.
- Beam-thrust $\mathcal{T}_0$ resolution parameter for production, 2-jettiness (thrust) $\tau_2^{\rm dec}$ for decay
- There are now 2 contributions to the 1-jet bin, coming from production or decay

$$\overbrace{\frac{d\sigma_1^{\rm MC}}{d\Phi_{\ell^+\ell^- b\bar{b}j}}(\mathcal{T}_0>\mathcal{T}_0^{\rm cut};\mathcal{T}_1^{\rm cut};\tau_2^{\rm cut})}^{({\rm NNLL+NLO}_1)\otimes({\rm NLL+NLO}_2)} = \overbrace{\frac{d\sigma_1^{\rm MC}}{d\Phi_{\ell^+\ell^- Hj}}(\mathcal{T}_0>\mathcal{T}_0^{\rm cut};\mathcal{T}_1^{\rm cut})}^{\rm NNLL+NLO_1} \times \frac{d\Gamma^{(0)}_{H\to b\bar{b}}}{d\Phi_{H\to b\bar{b}}} +$$

$$\overbrace{\frac{d\sigma_1^{\rm MC}}{d\Phi_{\ell^+\ell^- Hj}}(\mathcal{T}_0>\mathcal{T}_0^{\rm cut};\mathcal{T}_1^{\rm cut})}^{\rm NLL+LO_1}$$

$$\times\left(\frac{d\Gamma^{\rm NLL}}{d\Phi_{H\to b\bar{b}}}(\tau_2^{\rm cut}) + \frac{d\Gamma^{\overline{\rm NLO}}_{H\to b\bar{b}}}{d\Phi_{H\to b\bar{b}}}(\tau_2^{\rm cut}) - \left[\frac{d\Gamma^{\rm NLL}}{d\Phi_{H\to b\bar{b}}}(\tau_2^{\rm cut})\right]_{\overline{\rm NLO}}\right)$$

Production and decay at NNLO

- In the NWA it is possible to factorize production from decay and correctly match two GENEVA implementations.
- Beam-thrust $\mathcal{T}_0$ resolution parameter for production, 2-jettiness (thrust) $\tau_2^{\rm dec}$ for decay
- There are now 2 contributions to the 1-jet bin, coming from production or decay

$$\overbrace{\frac{d\sigma_1^{\rm MC}}{d\Phi_{\ell^+\ell^- b\bar{b}j}}(\mathcal{T}_0^{\rm cut};\tau_2^{\rm dec}>\tau_2^{\rm cut};\tau_3^{\rm cut})}^{({\rm NLL+NLO_0})\otimes({\rm NNLL+NLO_3})} = \frac{d\sigma^{(0)}_{\ell^+\ell^- H}}{d\Phi_{\ell^+\ell^- H}} \times \overbrace{\frac{d\Gamma_3^{\rm MC}}{d\Phi_{H\to b\bar{b}j}}(\tau_2^{\rm dec}>\tau_2^{\rm cut};\tau_3^{\rm cut})}^{\rm NNLL+NLO_3} +$$

$$\left(\frac{d\sigma^{\rm NLL}}{d\Phi_{\ell^+\ell^- H}}(\mathcal{T}_0^{\rm cut}) + \frac{d\sigma^{\overline{\rm NLO}}_{\ell^+\ell^- H}}{d\Phi_{\ell^+\ell^- H}}(\mathcal{T}_0^{\rm cut}) - \left[\frac{d\sigma^{\rm NLL}}{d\Phi_{\ell^+\ell^- H}}(\mathcal{T}_0^{\rm cut})\right]_{\overline{\rm NLO}}\right)$$

$$\times \overbrace{\frac{d\Gamma_3^{\rm MC}}{d\Phi_{H\to b\bar{b}j}}(\tau_2^{\rm dec}>\tau_2^{\rm cut};\tau_3^{\rm cut})}^{\rm NLL+LO_3}$$

Production and decay at NNLO

- In the NWA it is possible to factorize production from decay and correctly match two GENEVA implementations.
- Beam-thrust $\mathcal{T}_0$ resolution parameter for production, 2-jettiness (thrust) τ_2^{dec} for decay
- And 3 contributions to the 2-jets bin, coming from production, decay or both

$$\overbrace{\frac{d\sigma_2^{\mathrm{MC}}}{d\Phi_{\ell^+\ell^- b\bar{b}jj}}(\mathcal{T}_0 > \mathcal{T}_0^{\mathrm{cut}}; \mathcal{T}_1 > \mathcal{T}_1^{\mathrm{cut}}; \tau_2^{\mathrm{cut}})}^{(\mathrm{NNLL}+\mathrm{LO}_2)\otimes\mathrm{LO}_2} =$$

$$\overbrace{\frac{d\sigma_2^{\mathrm{MC}}}{d\Phi_{\ell^+\ell^- Hjj}}(\mathcal{T}_0 > \mathcal{T}_0^{\mathrm{cut}}; \mathcal{T}_1 > \mathcal{T}_1^{\mathrm{cut}})}^{\mathrm{NNLL}+\mathrm{LO}_2} \times \frac{d\Gamma^{(0)}_{H\to b\bar{b}}}{d\Phi_{H\to b\bar{b}}}$$

Production and decay at NNLO

- In the NWA it is possible to factorize production from decay and correctly match two GENEVA implementations.
- Beam-thrust $\mathcal{T}_0$ resolution parameter for production, 2-jettiness (thrust) τ_2^{dec} for decay
- And 3 contributions to the 2-jets bin, coming from production, decay or both

$$\overbrace{\frac{d\sigma_2^{\mathrm{MC}}}{d\Phi_{\ell^+\ell^- b\bar{b}jj}}(\mathcal{T}_0 > \mathcal{T}_0^{\mathrm{cut}}; \mathcal{T}_1^{\mathrm{cut}}; \tau_2^{\mathrm{dec}} > \tau_2^{\mathrm{cut}}; \tau_3^{\mathrm{cut}})}^{(\mathrm{NLL+LO_1})\otimes(\mathrm{NLL+LO_3})} =$$

$$\overbrace{\frac{d\sigma_1^{\mathrm{MC}}}{d\Phi_{\ell^+\ell^- Hj}}(\mathcal{T}_0 > \mathcal{T}_0^{\mathrm{cut}}; \mathcal{T}_1^{\mathrm{cut}})}^{\mathrm{NLL+LO_1}} \times \overbrace{\frac{d\Gamma_1^{\mathrm{MC}}}{d\Phi_{H\to b\bar{b}j}}(\tau_2^{\mathrm{dec}} > \tau_2^{\mathrm{cut}}; \tau_3^{\mathrm{cut}})}^{\mathrm{NLL+LO_3}}$$

Production and decay at NNLO

- In the NWA it is possible to factorize production from decay and correctly match two GENEVA implementations.
- Beam-thrust $\mathcal{T}_0$ resolution parameter for production, 2-jettiness (thrust) $\tau_2^{\rm dec}$ for decay
- And 3 contributions to the 2-jets bin, coming from production, decay or both

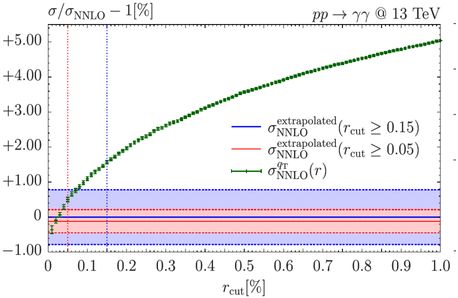
$$\overbrace{\frac{d\sigma_2^{\rm MC}}{d\Phi_{\ell^+\ell^- b\bar{b}jj}}(\mathcal{T}_0^{\rm cut};\mathcal{T}_1^{\rm cut};\tau_2^{\rm dec}>\tau_2^{\rm cut};\tau_3>\tau_3^{\rm cut})}^{\rm LO_0\otimes(NNLL+LO_4)} =$$

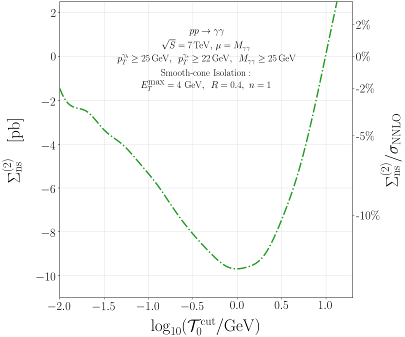
$$\frac{d\sigma^{(0)}_{\ell^+\ell^- H}}{d\Phi_{\ell^+\ell^- H}} \times \overbrace{\frac{d\Gamma_2^{\rm MC}}{d\Phi_{H\to b\bar{b}jj}}(\tau_2^{\rm dec}>\tau_2^{\rm cut};\tau_3>\tau_3^{\rm cut})}^{\rm NNLL+LO_4}$$

- We now have all the ingredients, next step is to combine them. This is work in progress.
- In principle this approach can be extended beyond scalars, but one needs to keep track of spin correlations.

Diphoton production

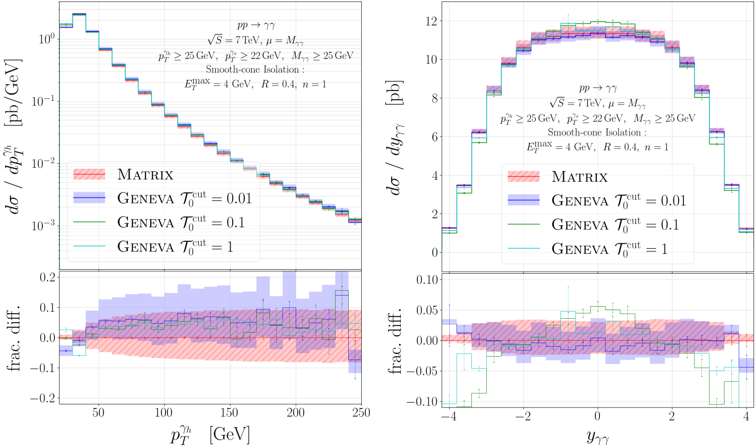
- Important background to Higgs boson production and NP searches
- Similar to DY and VH production, complications from process definition due to QED divergencies
- Requires introduction of photon-isolation procedure, to remove huge background from secondary photons
- Using dynamic-cone (Frixione) isolation in generation. Final analysis can be performed with dynamic or fixed-cone isolation.
- Size of power-corrections very challenging, both in q_T and $\mathcal{T}_0$



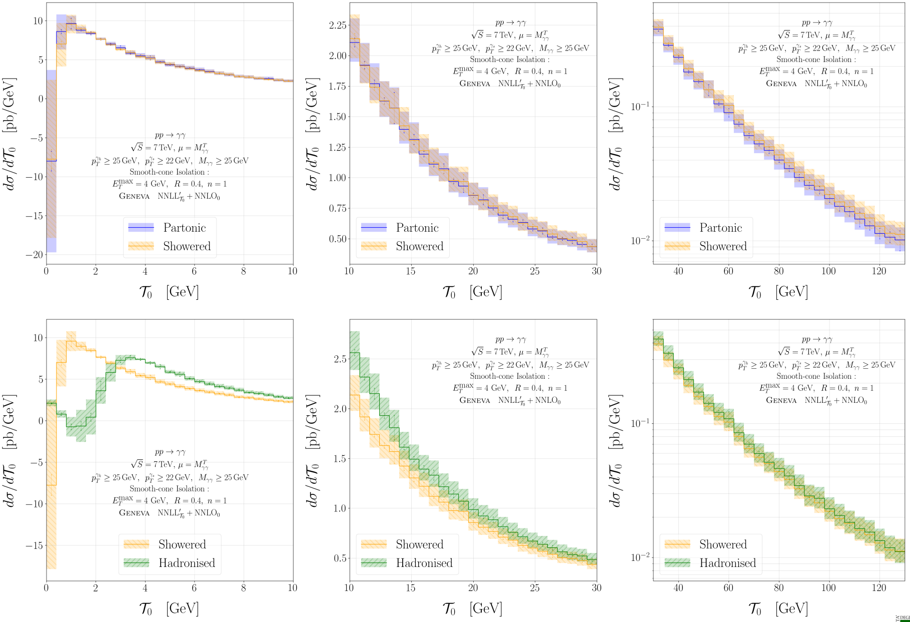


GENEVA for diphoton production

- NNLO comparison for 13 TeV LHC, $p_{T,\gamma_h} > 25$ GeV , $p_{T,\gamma_s} > 22$ GeV, Frixione isolation R=0.4
- Only $q\bar{q}$-channel included in comparison, gg loop-induced can be added as nonsingular contribution.
- Kinematical-effects at subleading power at order $\mathcal{O}(\alpha_S^2)$ can no longer be neglected.

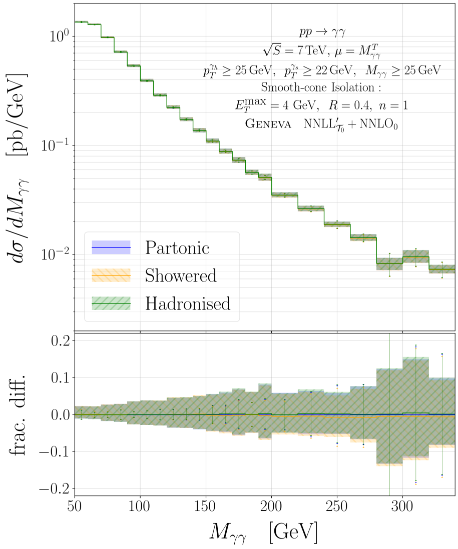


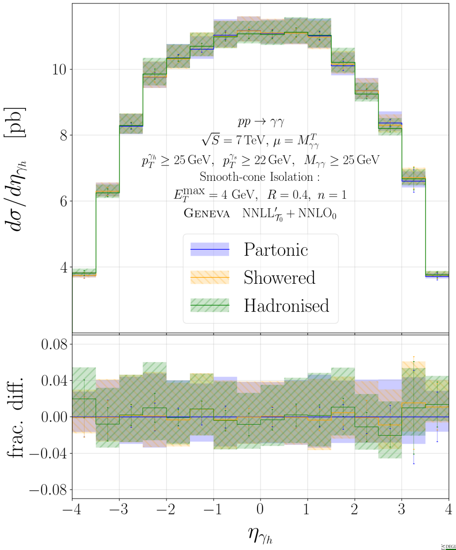
Showered and hadronized results for Diphoton



Showered and hadronized results for Diphoton

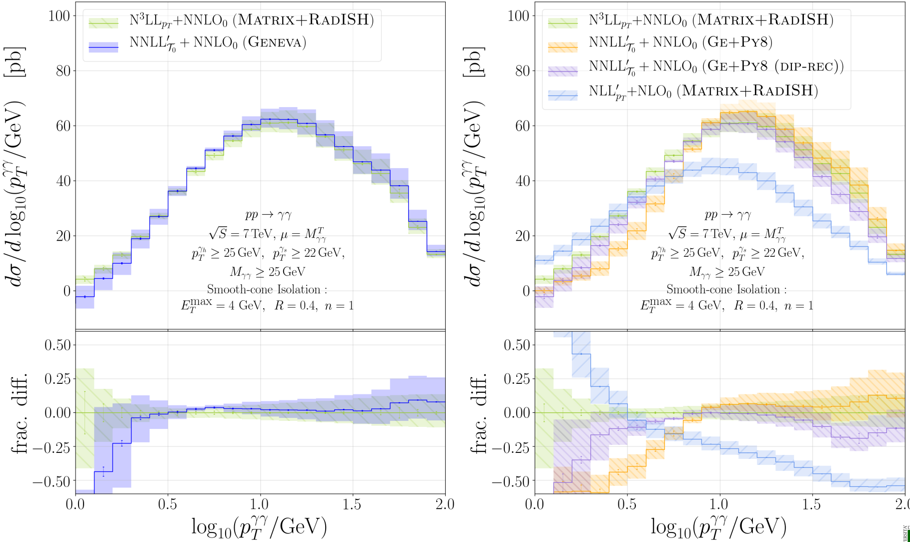
- Inclusive quantities not modified, expected changes in exclusive ones.





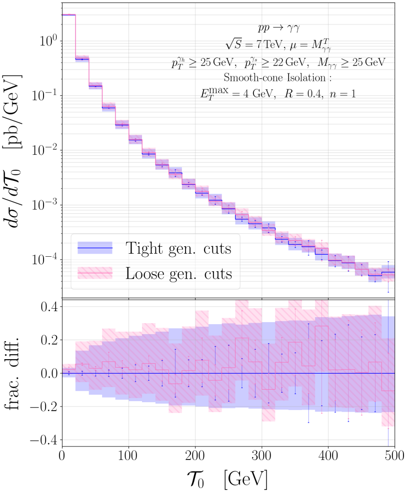
Showered and hadronized results for Diphoton

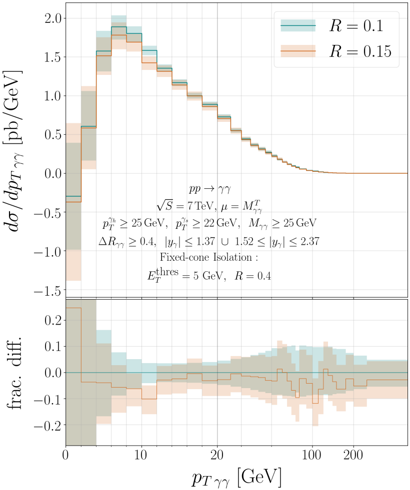
- Inclusive quantities not modified, expected changes in exclusive ones.
- Shower recoil scheme has large impact in prediction of color singlet p_T



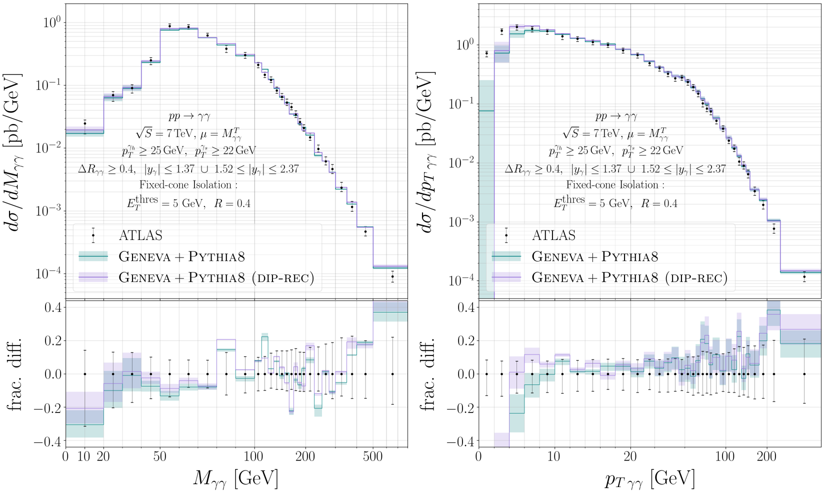
Showered and hadronized results for Diphoton

- Inclusive quantities not modified, expected changes in exclusive ones.
- Shower recoil scheme has large impact in prediction of color singlet p_T
- Important to assess independence of final results from generation cuts.

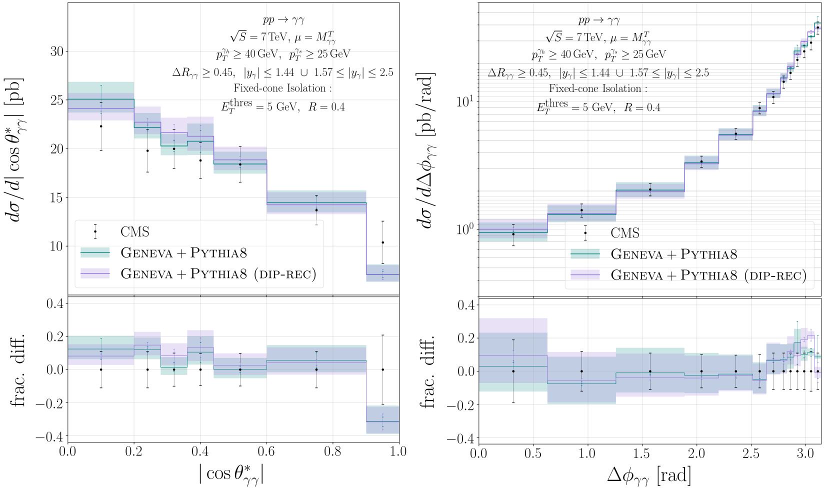




Diphoton: comparison with data

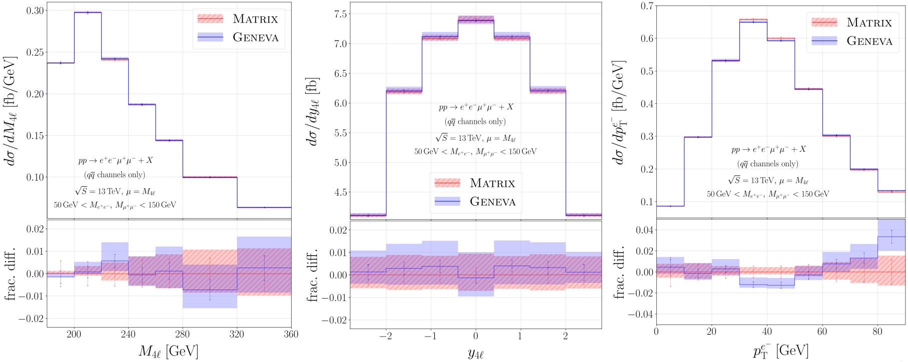


Diphoton: comparison with data



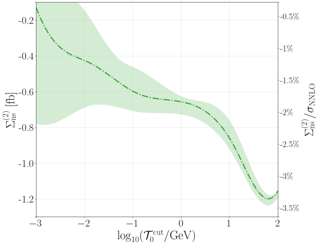
Diboson production: $ZZ \to \ell^+\ell^-\ell'^+\ell'^-$

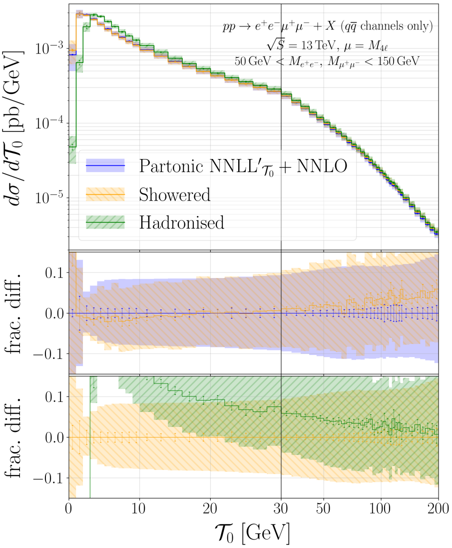
- Experimentally very clean signature.
- Precision needed for costraining anomalous couplings and Higgs boson width.
- Numerically challenging 2-loop corrections taken from VVAMP
- Complex kinematics dependence, validated against MATRIX



Diboson production: $ZZ \to \ell^+\ell^-\ell'^+\ell'^-$

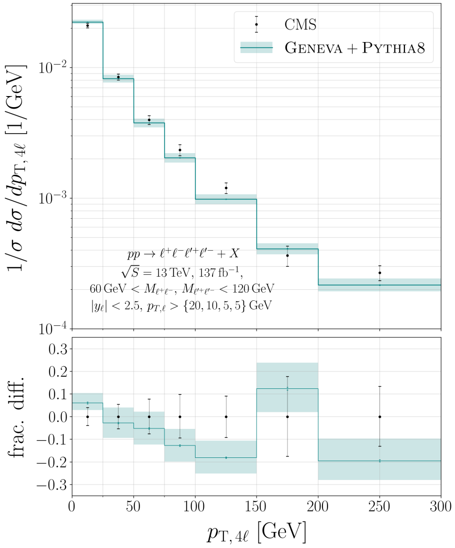
- Experimentally very clean signature.
- Precision needed for costraining anomalous couplings and Higgs boson width.
- Numerically challenging 2-loop corrections taken from VVAMP
- Complex kinematics dependence, validated against MATRIX
- After showering, expected behaviour for inclusive as well as for exclusive quantities.

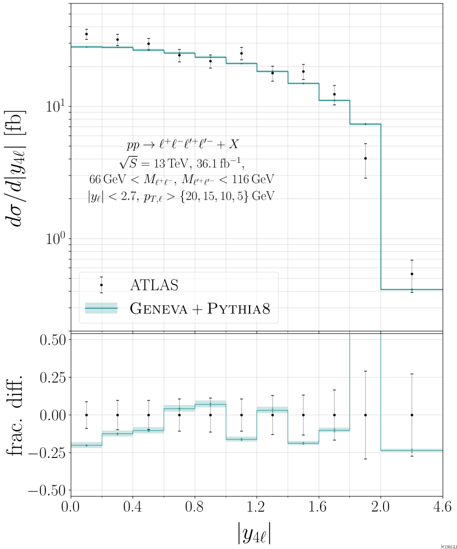




Diboson: comparison with data

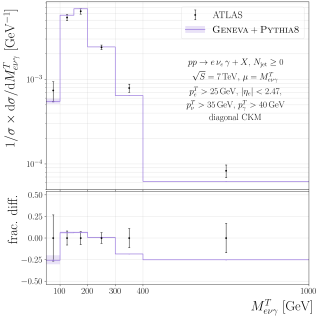
- After inclusion of gg-channel at LO we compared to ATLAS and CMS

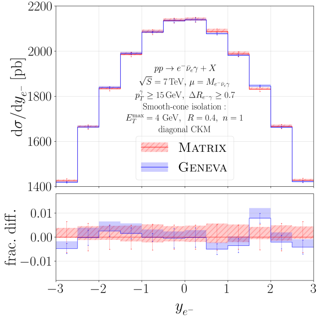


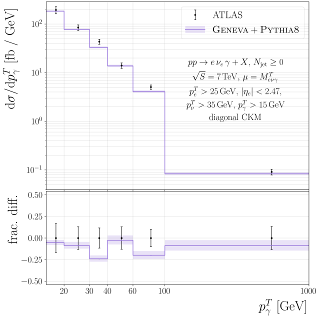


Diboson production: $W\gamma \to \ell\nu\gamma$

- NLO corrections artificially large due to the presence of a radiation zero at LO
- High sensititivity to non Abelian gauge couplings.
- Can be used to constrain the effects of higher-dimensional operator in the SMEFT
- Complex kinematics dependence, validated against MATRIX

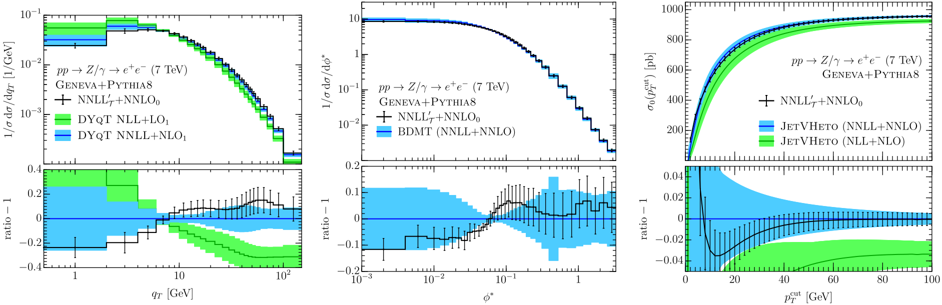






Accuracy for other observables : q_T, ϕ^* and jet-veto

- For DY one can compare with dedicated tools DYqT Bozzi et al. arXiv:1007.2351 , BDMT Banfi et al. arXiv:1205.4760 and JetVHeto Banfi et al. 1308.4634
- Analytic NNLL predictions formally higher log accuracy than GENEVA

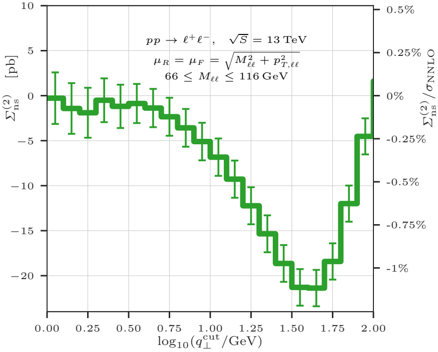


- Results are in better agreement with higher-order resummation, despite lack of perturbative ingredients.
- Difficult to formally quantify the accuracy achieved after the parton shower stage, despite starting from a higher-order logarithmic accuracy. Numerical tests are possible, very computationally demanding.
- Recently NLL accurate showers begin to appear. It will be interesting to study how to interface GENEVA to them. Dasgupta et al. 2002.11114

Changing resolution parameter: Drell-Yan using q_T

Using q_T as 0-jet resolution parameter allows for target N3LL$_{q_T}$+NNLO$_0$ accuracy

- RadISH performs q_T resummation up to N3LL directly in q_T space
  Bizon et al. arXiv:1905.05171
- Its internal structure requiring Monte Carlo generation of unphysical events makes it hard to directly link.
- We proceeded building interpolating grids with Chebyshev polynomials and calling these interpolating grids from Geneva.
- Usage of Chebyshev polynomials is key in easily obtaining spectrum from cumulant.



- Results are in good agreement with dedicated RadISH+NNLOJET N3LL+NNLO$_0$ control runs.

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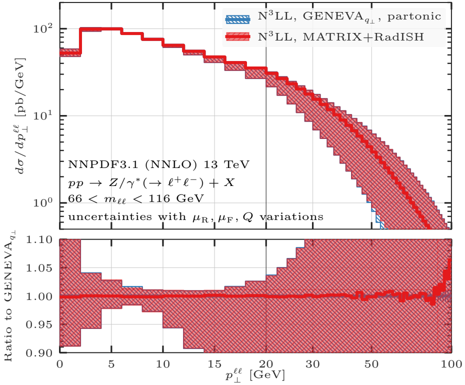

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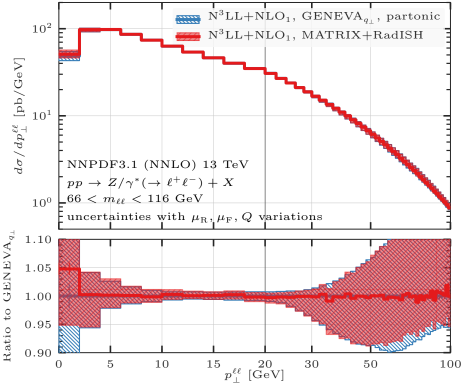
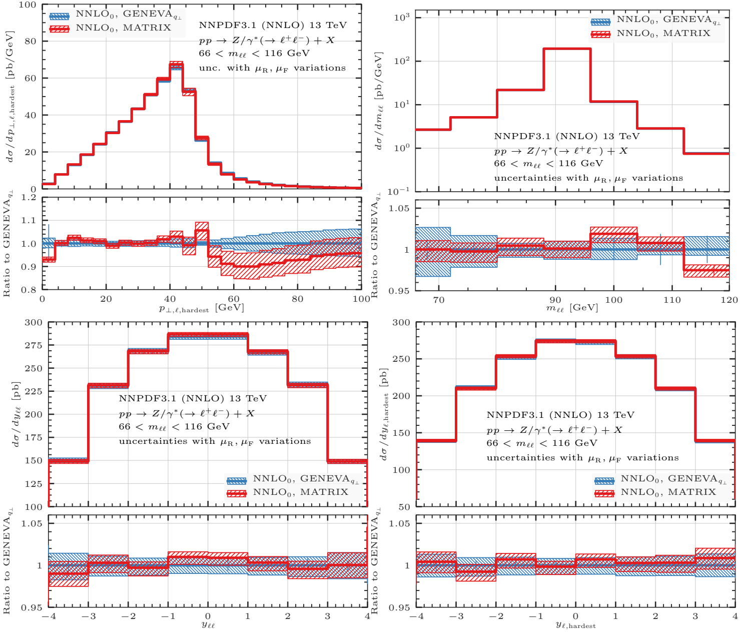
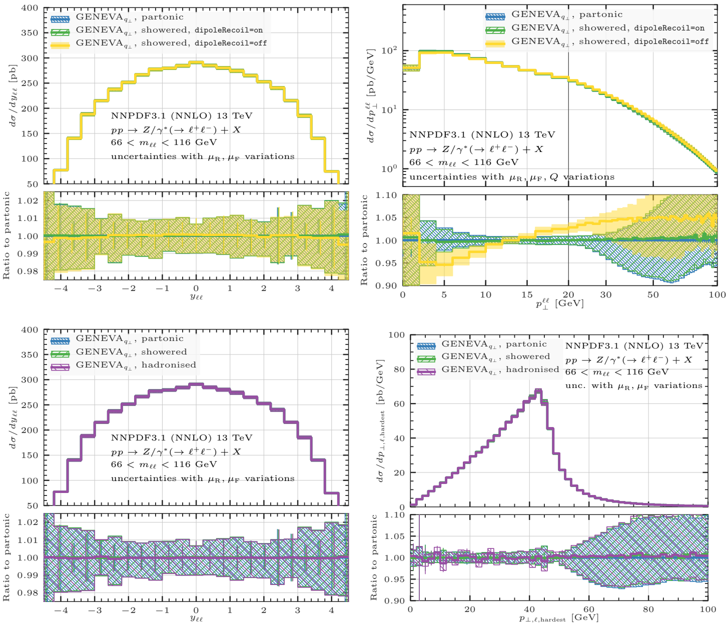


- Results are in good agreement with dedicated RadISH+NNLOJET N3LL+NNLO$_0$ control runs.
- Shower interface slightly more complicated than $\mathcal{T}_0$ case. N3LL accuracy cannot be achieved formally, but numerically still OK.

Drell-Yan using q_T : NNLO validation

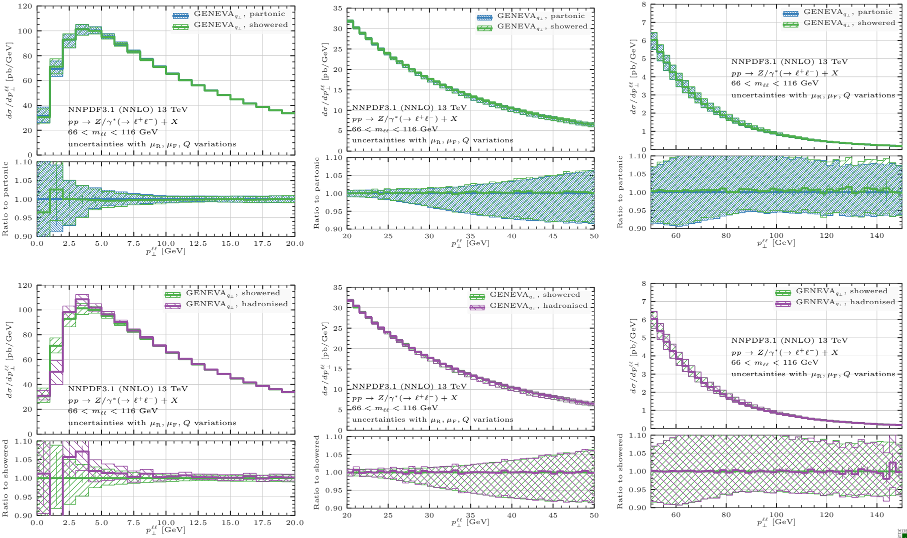


Drell-Yan using q_T : shower and hadronization



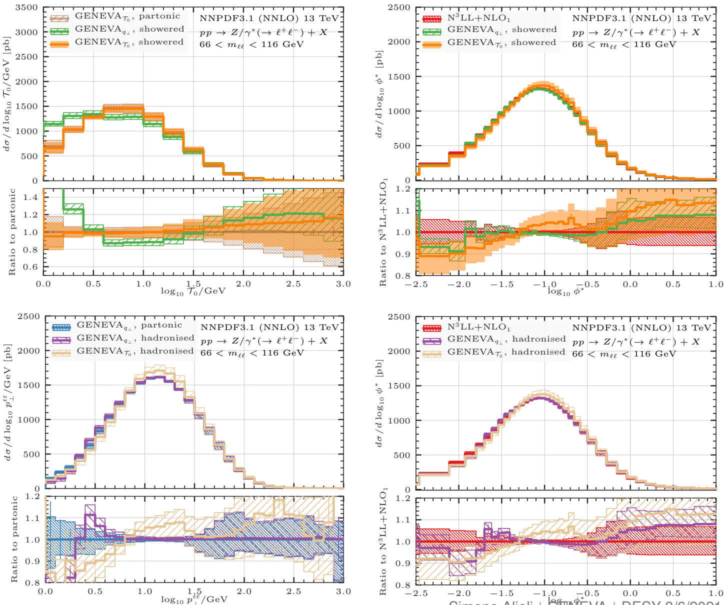
Drell-Yan using q_T : shower and hadronization

- Predictions for transverse momentum almost unchanged from parton-level to final hadronized events.



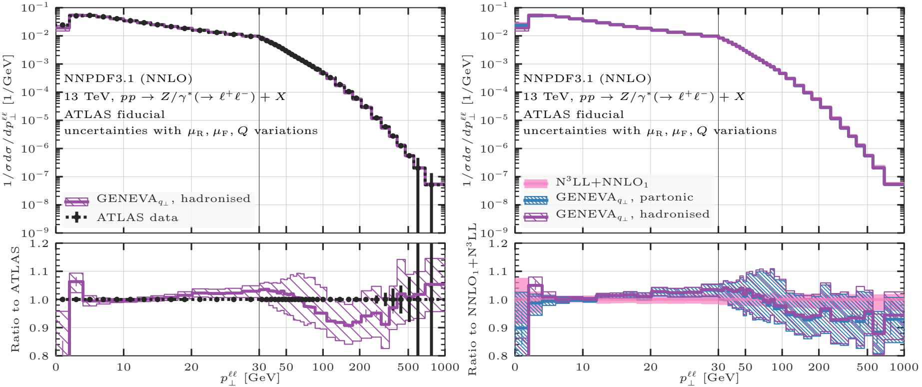
Drell-Yan comparing GENEVA$_{q_T}$ and GENEVA$_{\mathcal{T}_0}$

- Unique opportunity to study interplay between different higher-order resummations.



Comparison with data

- Agreement with precise LHC data vastly improved



- Small differences in transition region due to missing higher-order effects.
- The description of the ϕ^* spectrum shows a similar improvement.

Summary and Outlook

GENEVA **performs matching of NNLO calculations with higher-log resummation and parton showers.**

- Higher-order resummation of resolution parameters provides a natural link between NNLO and PS.
- Provides theoretical perturbative uncertainties coming from both fixed-order and resummation on a event-by-event basis.
- Allows for realistic event simulation and interface to detectors.

Current status:

Several processes have been implemented

- $pp \to V$, $pp \to VH$, $pp \to \gamma\gamma$, $pp \to ZZ$ and $pp \to W\gamma$
- Decay $H \to b\bar{b}$ and $H \to gg$ also done. Next step merging with $pp \to VH$.
- Usage of different resolution parameter (q_T) up via RadISH at N3LL now available.

Outlook:

- Other color-singlet processes (Higgs, remaining VV, etc.) in the pipeline.
- Inclusion of EW corrections.
- Investigate formal accuracy after showering.
- ...

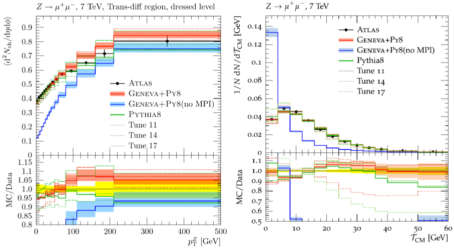
Thank you for your attention!

BACKUP

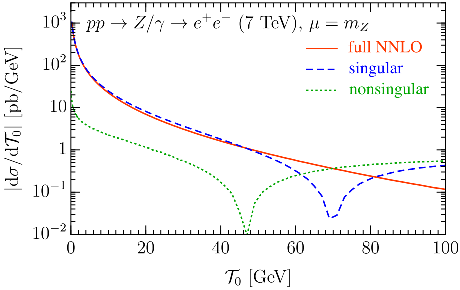
Step 4: Hadronization and MPI.

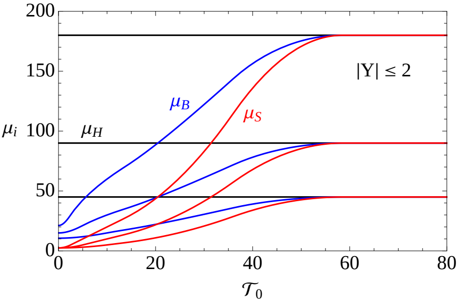
- GENEVA is not improving this stage, which should entirely be taken from the Shower Monte Carlo
- Care must be taken to appropriately re-tune parameters, due to the increased accuracy of perturbative ingredients.
- If the only tunable parameters in SMC were truly nonperturbative this re-tuning would not be necessary. Unfortunately this is not case: many times perturbative parameters are tuned to make up for the lack of higher order ingredients, e.g. increasing $\alpha_s(M_z)$ to enhance emissions in the tails.

- MPI is more problematic, especially when evolution is interleaved. The shower conditions must be applied on the event stripped off by MPI. It can only be done before hadronization, afterwards shower history is mixed up.



Scale profiles and theoretical uncertainties





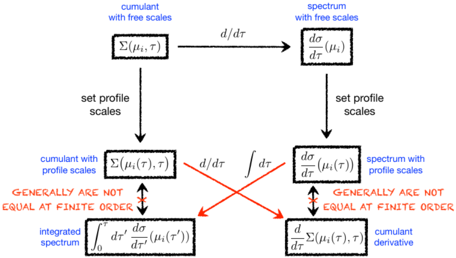
- Theoretical uncertainties in resum. are evaluated by independently varying each μ.
- Range of variations is tuned to turn off the resummation before the nonsingular dominates and to respect SCET scaling $\mu_H \gtrsim \mu_B \gtrsim \mu_S$
- FO unc. are usual $\{2\mu_H, \mu_H/2\}$ variations.
- Final results added in quadrature.

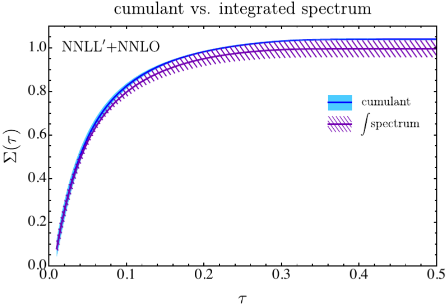
$$\mu_H = \mu_{\rm FO} = M_{\ell^+\ell^-}\,,$$
$$\mu_S(\mathcal{T}_0) = \mu_{\rm FO} f_{\rm run}(\mathcal{T}_0/Q)\,,$$
$$\mu_B(\mathcal{T}_0) = \mu_{\rm FO}\sqrt{f_{\rm run}(\mathcal{T}_0/Q)}$$

- $f_{\rm run}(x)$ common profile function: strict canonical scaling $x \to 0$ and switches off resummation $x \sim 1$

Scale profiles that preserve the total cross-section

- Different advantages in resumming the cumulant (better cross-section and correlated unc.) or the spectrum (better profiles in trans and tail region and better point-by-point unc.)
- The two approaches only agree at all order. Numerical differences when truncating are a problem for NNLO precision.
- Enforcing equivalence by taking derivative or integrating results in unreliable uncertainties.
- Similar problem in preserving total xsec in matched QCD resummation solved with ad-hoc smoother.
- We add higher-order term to the spectrum such that the total NNLO XS is preserved.
- Correlations now enforced by hand for up/down scales





Scale profiles that preserve the total cross-section

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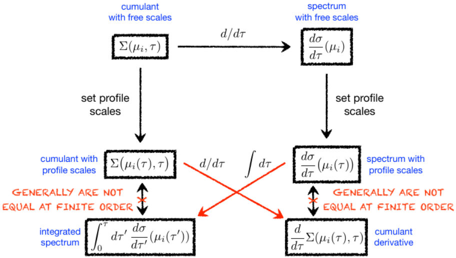
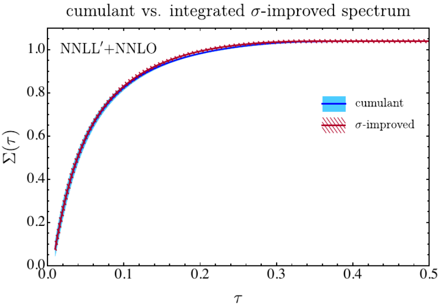




NNLO accuracy in GENEVA: nonsingular rescaling

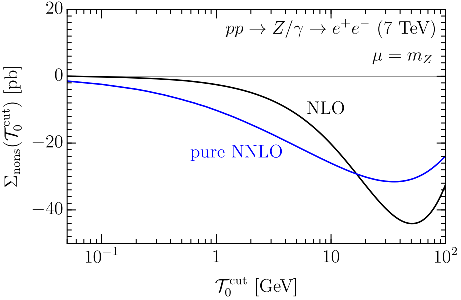
- Resum. expanded result in $\mathrm{d}\sigma^{\mathrm{nons}}_{\geq 1}/\mathrm{d}\Phi_1$ acts as a differential NNLO $\mathcal{T}_0$-subtraction

$$\frac{\mathrm{d}\sigma^{\mathrm{NLO}_1}_{\geq 1}}{\mathrm{d}\Phi_1} - \left[\frac{\mathrm{d}\sigma^{\mathrm{NNLL}'}}{\mathrm{d}\Phi_0 \mathrm{d}\mathcal{T}_0}\,\mathcal{P}(\Phi_1)\right]_{\mathrm{NLO}_1}$$

- Nonlocal cancellation in Φ_1, after averaging over $\mathrm{d}\Phi_1/\mathrm{d}\Phi_0\mathrm{d}\mathcal{T}_0$ gives finite result.
- To be local in $\mathcal{T}_0$ has to reproduce the right singular $\mathcal{T}_0$-dependence when projected onto $\mathrm{d}\mathcal{T}_0\mathrm{d}\Phi_0$.

$$\frac{\mathrm{d}\sigma^{\mathrm{nons}}_0}{\mathrm{d}\Phi_0}(\mathcal{T}_0^{\mathrm{cut}}) = \left[\alpha_s f_1(\mathcal{T}_0^{\mathrm{cut}}, \Phi_0) + \alpha_s^2 f_2(\mathcal{T}_0^{\mathrm{cut}}, \Phi_0)\right]\mathcal{T}_0^{\mathrm{cut}}$$

$$\Sigma_{\mathrm{nons}}(\mathcal{T}_0^{\mathrm{cut}}) = \int \mathrm{d}\Phi_0\, \frac{\mathrm{d}\sigma^{\mathrm{nons}}_0}{\mathrm{d}\Phi_0}(\mathcal{T}_0^{\mathrm{cut}})$$



- At $\mathcal{T}_0^{\mathrm{cut}} = 1\,\mathrm{GeV}$ gives $\sim 1\%$ xsec. Small but not negligible, can be lowered further. Tradeoff with speed/stability.
- $f_1(\Phi_0, \mathcal{T}_0^{\mathrm{cut}})$ included exactly by doing NLO$_0$ on-the-fly.
- For pure NNLO$_0$, we currently neglect the Φ_0 dependence below $\mathcal{T}_0^{\mathrm{cut}}$ and include total integral via simple rescaling of $\mathrm{d}\sigma_0^{\mathrm{MC}}/\mathrm{d}\Phi_0(\mathcal{T}_0^{\mathrm{cut}})$.

GENEVA for diphoton production

- Introduction of isolation cuts requires particular attention to definition of resummed component.
- Differences arise due to treatment of nonsingular phase-space points which might fail isolation cuts after the projection.