Status and perspectives on NNLO + parton shower matching

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Introduction

Motivations:

- NNLO predictions and the corresponding reduced theory uncertainties are nowadays required for the level of precisions reached by experiments (few percent)
- NNLO calculations are becoming increasingly available. Different subtractions approaches have proven to be effective and the list of calculated processes is steadily increasing.
- Fixed-order perturbative expansion is often not a sufficient description of the phsyics, especially for exclusive quantities.
- Resumation must be included (either explicitly or via parton showers) to account for all-order effects, which can become the dominant ones.
- Experiments need fully-exclusive many-particle final states event generators that are reliable across all phase-space and that can be interfaced to detectors.

Outline of the talk:

- Merging NLO+PS and extension to NNLO
- Rewiew of available NNLO+PS methods:
  - UNNLOPS
  - MINLO/NNLOPS + recent extension
  - Geneva
- Conclusions and outlook

Merging different multplicities in NLO+PS samples

- When merging NLO$_N$ and NLO$_{N+1}$ samples separated by a $\mathcal{T}_{\rm cut}$ cut, the unphysical dependence manifests itself in $\sigma^{\rm tot}$ as $\log(\mathcal{T}_{\rm cut}/Q)$.

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Different solutions have been proposed :

- choose merging scale wisely, by using a jet-algo to determine it – FxFx [Frederix&Frixione, 1209.6215]
- remove need of a merging scale, by making the NLO$_{N+1}$ predictions NLO$_N$ accurate – MiNLO [Hamilton et al. 1212.4504]
- enforce unitarity by subtracting back the new terms that have been added – UNLOPS [Lonnblad&Prestel 1211.7278, Plätzer 1211.5467]
- include higher-order resummation contributions, multiple NLO merging comes as by-product – GENEVA [SA et al. 1211.7049]

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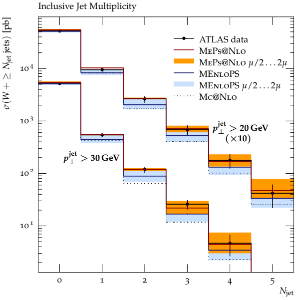
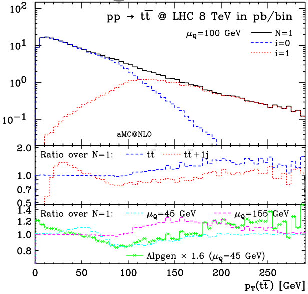
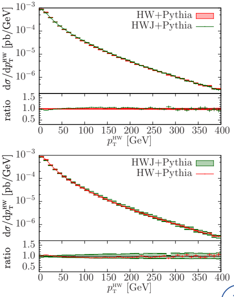
SHERPA



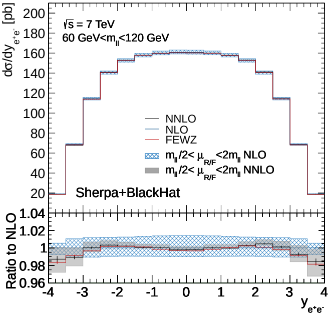
MC@NLO/FxFx

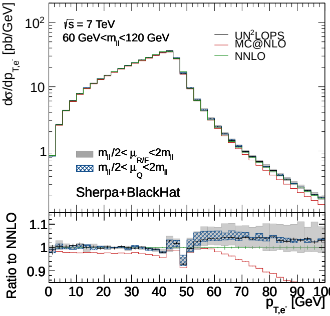


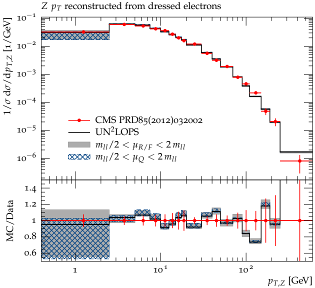
MiNLO



Extending NLO+PS to NNLO accuracy: UNNLOPS.



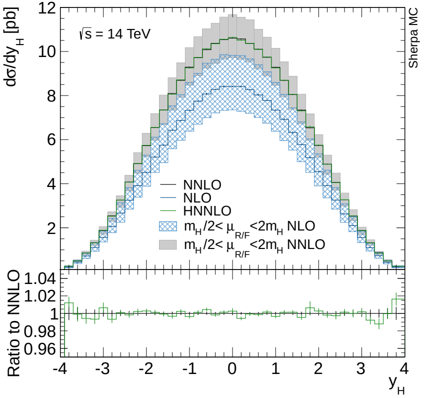


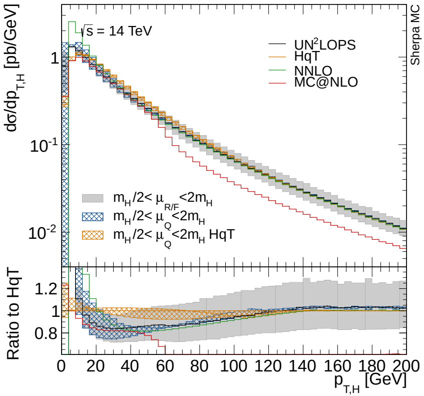


- Results for V presented in [1405.3607]
- NLO accuracy of $V + j$ is maintained by imposing unitarity: "subtracts-what-you-add" UNLOPS approach.
- Dependence on merging scale cancel by construction for sufficently inclusive quantities.
- NNLO is obtained using q_T-slicing for $0-$jet (never showered!)

UNNLOPS in Sherpa

- Also available for Higgs production [Hoeche,Li,Prestel 1407.3773]





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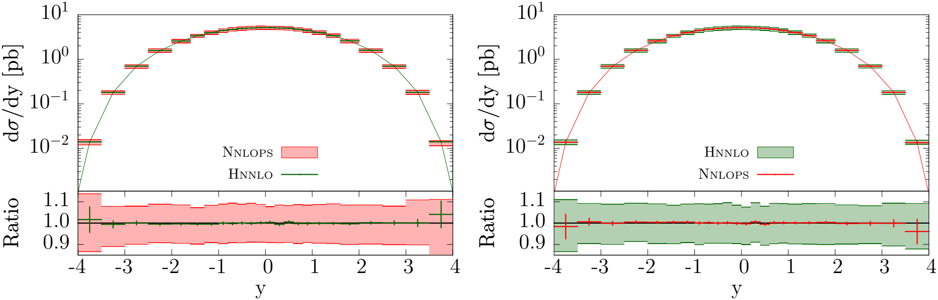
- For simple processes (e.g. $gg \to H$), using HNNLO [Catani et al. 0801.3232] for event-by-event reweighting results in a NNLO+PS [Hamilton,Nason,Re,Zanderighi 1309.0017]

$$\mathcal{W}(y) = \frac{\left(\frac{d\sigma}{dy}\right)_{\mathrm{HNNLO}}}{\left(\frac{d\sigma}{dy}\right)_{\mathrm{HJ-MiNLO}}} = \frac{c_2\alpha_{\mathrm{S}}^2 + c_3\alpha_{\mathrm{S}}^3 + c_4\alpha_{\mathrm{S}}^4}{c_2\alpha_{\mathrm{S}}^2 + c_3\alpha_{\mathrm{S}}^3 + c_4'\alpha_{\mathrm{S}}^4 + \ldots} = 1 + \frac{c_4 - c_4'}{c_2}\,\alpha_{\mathrm{S}}^2 + \ldots$$

  - Integrates back to the total NNLO cross-section
  - NLO accuracy of Hj not spoiled
  - Need to reweight after generation

MiNLO′ NNLO+PS.

- Hj-MiNLO NNLO+PS results [Hamilton,Nason,Re,Zanderighi 1309.0017]



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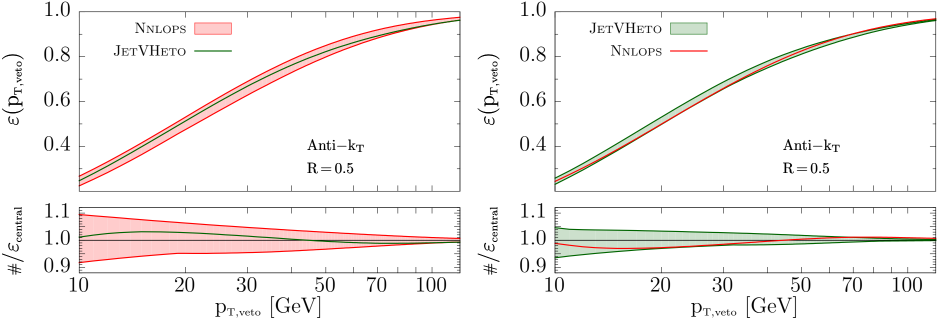
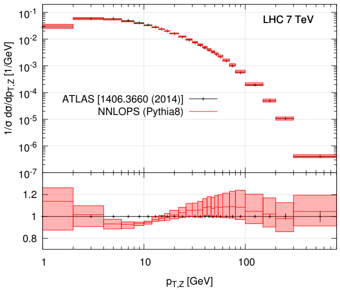
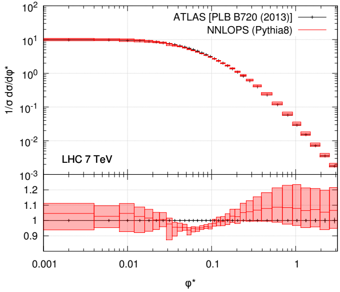
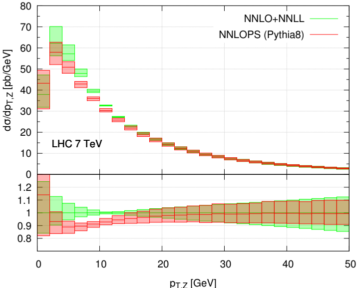


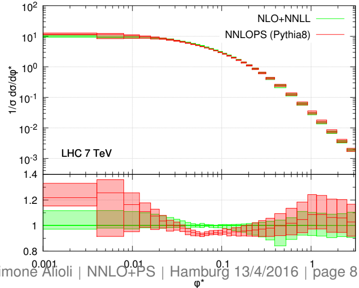
MiNLO′ NNLO+PS.

- Also available for Z and W production [Karlberg et al. 1407.2949]









MINLO′/NNLOPS for HW

- Recently added HW, W leptonic decay [Astill et al. 1603.01620]
- Avoids $6D$-reweighting by employing parametrization in Collins-Soper angles

$$\begin{aligned}\frac{d\sigma}{d\Phi_B} &= \frac{d^6\sigma}{dy_{\texttt{HW}}\, d\Delta y_{\texttt{HW}}\, dp_{t,\mathrm{H}}\, dm_{\ell\nu}\, d\cos\theta^* d\phi^*} \\ &= \frac{3}{16\pi}\left(\frac{d\sigma}{d\Phi_{\texttt{HW}^*}}(1+\cos^2\theta^*) + \sum_{i=0}^{7} A_i(\Phi_{\texttt{HW}^*}) f_i(\theta^*,\phi^*)\right)\end{aligned}$$

- Spreads NNLO K-factor away from $p_T = 0$ via

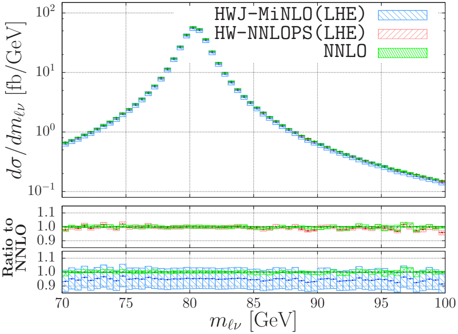
$$h(p_T) = \frac{(M_H+M_W)^2}{(M_H+M_W)^2+p_T^2}\,,$$

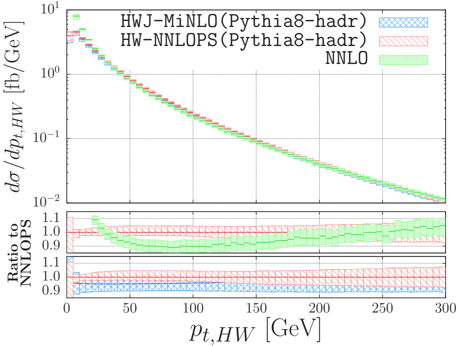
- and reweights with

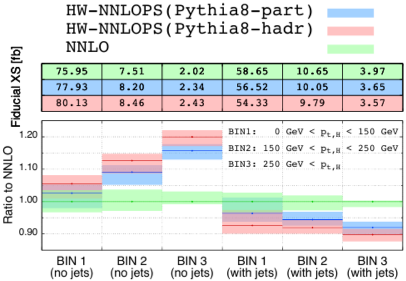
$$\begin{aligned}\mathcal{W}(\Phi_{\texttt{HW}}, p_{\mathrm{T}}) &= h(p_{\mathrm{T}})\,\frac{\int d\sigma^{\mathrm{NNLO}}\ \delta(\Phi_{\texttt{HW}} - \Phi_{\texttt{HW}}(\Phi)) - \int d\sigma_B\, \delta(\Phi_{\texttt{HW}} - \Phi_{\texttt{HW}}(\Phi))}{\int d\sigma_A\, \delta(\Phi_{\texttt{HW}} - \Phi_{\texttt{HW}}(\Phi))} \\ &+ (1 - h(p_{\mathrm{T}}))\end{aligned}$$

$$d\sigma_A = d\sigma\, h(p_T)\,, \qquad d\sigma_B = d\sigma\,(1 - h(p_T))$$

MINLO′/NNLOPS for HW



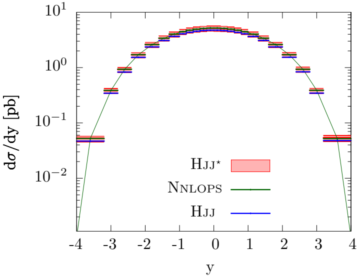


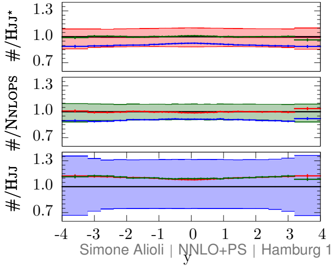


- Reweighting via angular coefficient proved to work
- Sizable differences (15%) found with NNLO after jet-veto and boosted-Higgs cuts
- These regions are problematic for FO calculations so NNLOPS shuld give a better description.

Extending MINLO′

- Recent reformulation and extension of MINLO' [Frederix and Hamilton. 1512.02663].
- MINLO' can be reached with limited knowledge of resummation (NLL_σ). Imposing the condition that the XS is unchanged wrt NLO allows to numerically extract B_2
- The MINLO' process can be iterated by imposing that MINLO' Bj XS is preserved in the first step. This allows Bjj NLO simulation to be NLO accurate for B inclusive observables.
- The NNLOPS reweighting can be applied as before, but now gives NNLO B, NLO Bj and NLO Bjj.
- Applied to Higgs production
  - Formulated as plugin to existing H NNLOPS and Hjj MINLO′ events, no changes required in the code. Reweights Hjj MINLO′ event such that Hj distributions becomes equal to H NNLOPS ones, without spoiling accuracy.
  - Smoothly interpolates between H NNLOPS results for H and Hj inclusive distributions and Hjj MINLO′ for Hjj ones.





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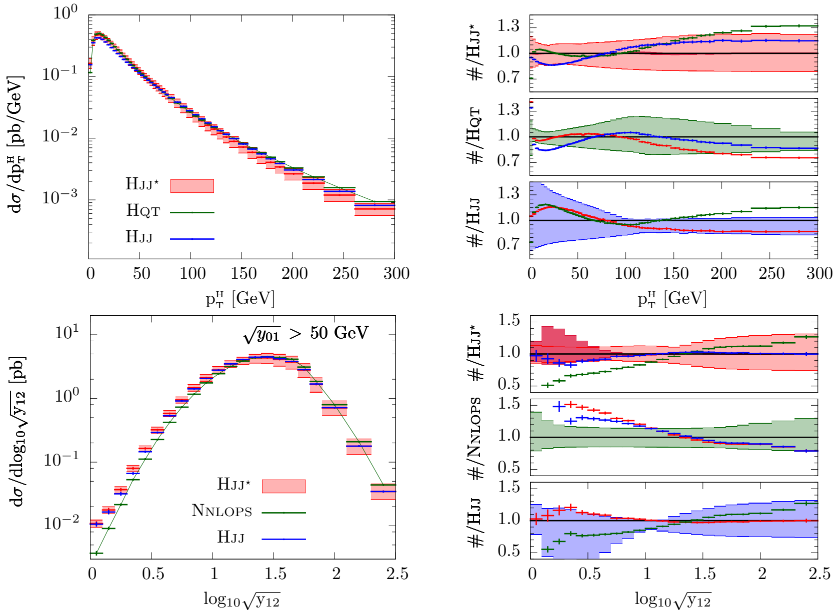
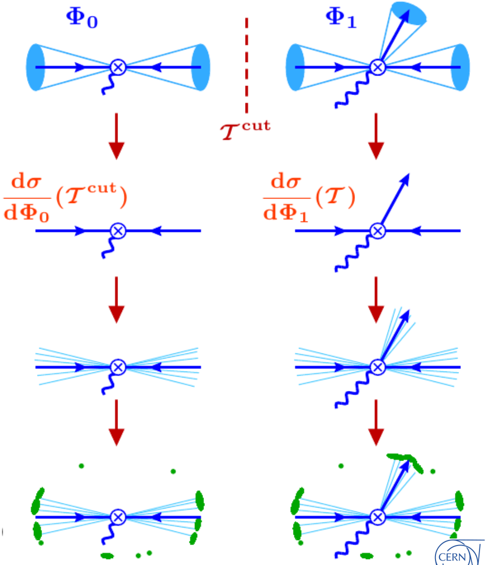


GENEVA

- Resolves mergin problem by employing high enough resummation.

1. Start from an IR-finite NLO definition of events, based on resolution parameters $\mathcal{T}_N^{\rm cut}$.
2. Associate differential cross-sections to events such that inclusive jet bins are (N)NLO accurate and jet resolution is resummed at NNLL'$_{\mathcal{T}}$
3. Shower events imposing conditions to avoid spoiling higher order logarithmic accuracy reached at step 2
4. Hadronize, add MPI and decay without restrictions



GENEVA main formulae [SA et al. 1508.01475]

- For Drell-Yan at NNLO need to provide partonic formulae for up to 2 extra partons.
- $0-$jet exclusive cross section

$$\frac{d\sigma_0^{\mathrm{MC}}}{d\Phi_0}(\mathcal{T}_0^{\mathrm{cut}}) = \frac{d\sigma_0^{\mathrm{resum}}}{d\Phi_0}(\mathcal{T}_0^{\mathrm{cut}}) + \frac{d\sigma_0^{\mathrm{sing\ match}}}{d\Phi_0}(\mathcal{T}_0^{\mathrm{cut}}) + \frac{d\sigma_0^{\mathrm{nons}}}{d\Phi_0}(\mathcal{T}_0^{\mathrm{cut}})$$

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

- 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.

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$$\frac{d\sigma_0^{\mathrm{sing\,match}}}{d\Phi_0}(\mathcal{T}_0^{\mathrm{cut}}) = 0$$

- At NNLL' all singular contributions to $\mathcal{O}\left(\alpha_s^2\right)$ already included in $\frac{d\sigma^{\mathrm{NNLL}'}}{d\Phi_0}(\mathcal{T}_0^{\mathrm{cut}})$ by definition. Singular matching vanishes.
- Two-loop virtual corrections properly spread to nonzero $\mathcal{T}_0$ as resummation dictates.

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

- Nonsingular matching constrained by requirement of NNLO_0 accuracy.

GENEVA main formulae [SA et al. 1508.01475]

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- $1-$jet inclusive cross section

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

- 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.

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

- p_{sp} are based on AP splittings for FSR, weighted by PDF ratio for ISR.

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

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

- Singular matching vanishes again at NNLL'
- Nonsingular matching fixed by NLO_1 requirement

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- $1-$jet inclusive cross section

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

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

- Singular matching vanishes again at NNLL'
- Nonsingular matching fixed by NLO_1 requirement

- Also performs a Sudakov-like NLL resummation of $\mathcal{T}_1^{\mathrm{cut}}$ to obtain a sensible separation between 1 and 2 jets, always enforcing unitarity.

NNLO accuracy in GENEVA

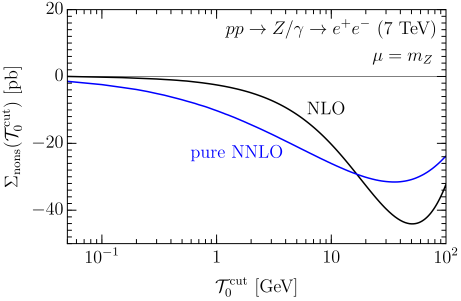
- Resum. expanded result in $\mathrm{d}\sigma^{\mathrm{nons}}_{\geq 1}/\mathrm{d}\Phi_1$ acts as a differential NNLO $\mathcal{T}_0$-subtraction

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

- 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 $\mathrm{d}\mathcal{T}_0\mathrm{d}\Phi_0$.

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

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

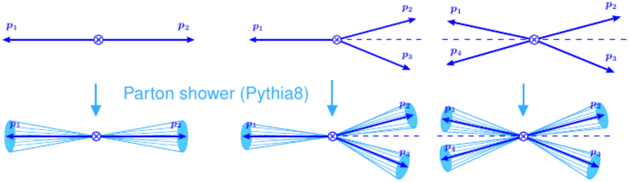


- At $\mathcal{T}_0^{\mathrm{cut}} = 1\,\mathrm{GeV}$ gives $\sim 1\%$ xsec. Small but not negligible, can be lowered further. Tradeoff with speed/stability.

- $f_1(\Phi_0, \mathcal{T}_0^{\mathrm{cut}})$ 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 $\mathrm{d}\sigma_0^{\mathrm{MC}}/\mathrm{d}\Phi_0(\mathcal{T}_0^{\mathrm{cut}})$.

Adding the parton shower.

- Purpose of the parton shower is to make the partonic calculation differential in the higher multiplicities.
- Not allowed to affect jet xsec at accuracy reached at partonic.
- Can be viewed as filling the $0-$ and $1-$jet exclusive bins with radiations and adding more to the inclusive $2-$jet bin

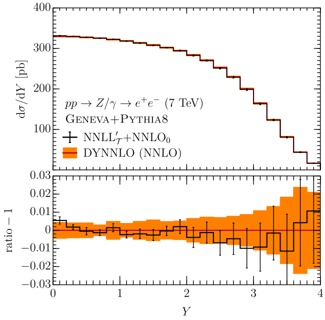


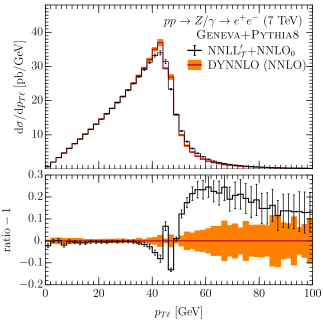
- For ordering variable $! = \mathcal{T}$ constraints need to be imposed on hardest radiation (largest jet resolution scale), rather than the first. Can happen much later.

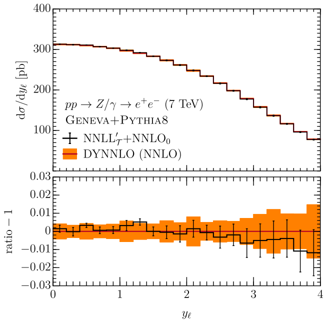
Do first emission and shower starting from $\mathcal{T}_k^{\mathrm{cut}}$. Does not spoil NNLL'+NNLO accuracy:

- Φ_0 events only constrained by normalization, shape given by PYTHIA
- Φ_1 events vanish for $\Lambda_1 \lesssim 100$ MeV (sub per mille ot total xsec).
- Φ_2 events: PYTHIA showering can be shown to shift $\mathcal{T}_0$ distribution at the same $\alpha_s^3/\mathcal{T}_0$ order of the dominant term beyond NNLL'. Beyond claimed accuracy.

NNLO validation







- NNLO xsec and inclusive distributions validated against DYNNLO

  Catani, Grazzini et al. [hep-ph/0703012, 0903.2120]

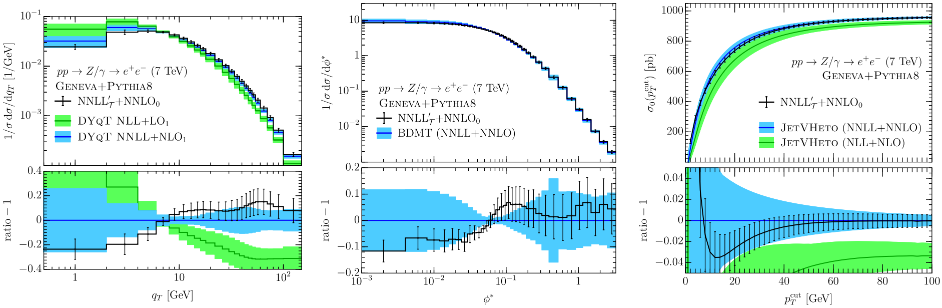
  Also checked against VRAP.

  Anastasiou, Dixon et al. [hep-ph/0312266]

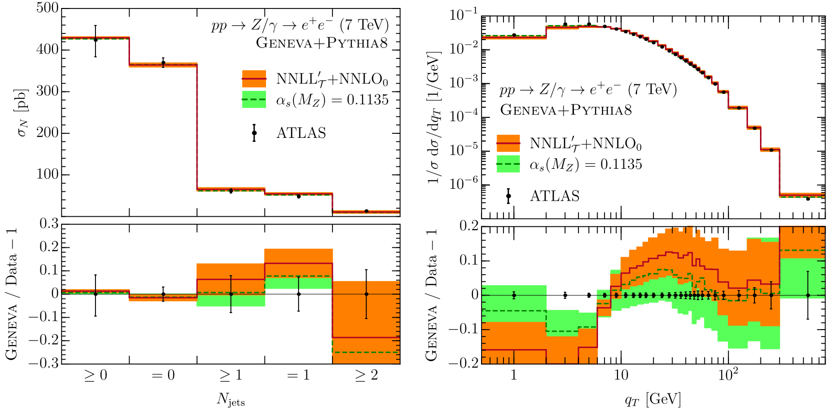
- Only scale variations shown as error bands, statistical fluctuations show up at large rapidities.

Predictions for q_T , ϕ^* and jet-veto acceptance

- Comparison with 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, but in better agreement than NLL
- Very low end highly sensitive to non-pertub. effects, k_{T} smearing (PYTHIA8).
- Smaller unc. in GENEVA there not necessarily an indication of higher precision.
- No sistematic tuning attempt, nor inclusion of shower uncert. yet.

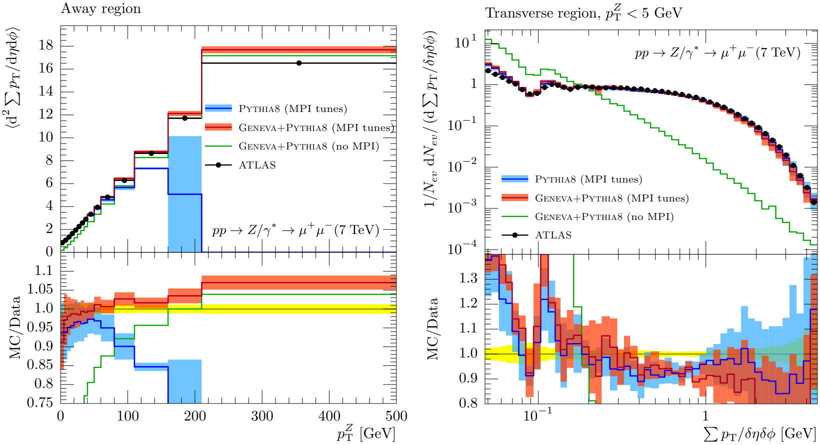


Comparisons with data



- Used RIVET [Buckley et al. 1003.0694] analyses to ensure full compliance with exp. selection.
- Also showing results for $\alpha_s(M_Z) = 0.1135$ in GENEVA perturbative calculation.
- Good agreement for both inclusive and exclusive jet cross sections.

Addition of MPI



- MPI effects provided by the PYTHIA8 interleaved evolution.
- We apply shower constraints independently from MPI.
- Less sensitivity to MPI tune model compared to standalone PYTHIA 8
- Good agreement with data, improves standalone PYTHIA8 in hard regions.

Conclusions

- Three independent methods have been proposed to match NNLO calculation to Parton Showers.
- They are based on different ways of solving the merging of “NLO+PS” simulations, and then extended to NNLO accuracy.
- All have been proved to work for color-singlet NNLO productions. UNNLOPS has been applied to Higgs and DrellYan, MINLO/NNLOPS to Higgs, DrellYan, HW and Geneva to DrellYan
- Recent proposal to extend MINLO/NNLOPS one further unit of multiplicity yield to improved H NNLOPS which is NLO accurate for Hjj
- Extensions to more complex processes is under investigation. In “extended” MINLO/NNLOPS this is facilitated by the possibility to extract B_2 numerically only knowing NLL resummation (or even LL). Needs to be verified in implementations.
- In Geneva, more complicated processes require the NNLL’ resummation of $\mathcal{T}_N, N > 0$. The method remains unchanged.

Thank you for your attention!