GENEVA Monte Carlo: status and new developments

http://geneva.physics.lbl.gov

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Theory Seminar

Vienna University
19 May 2020

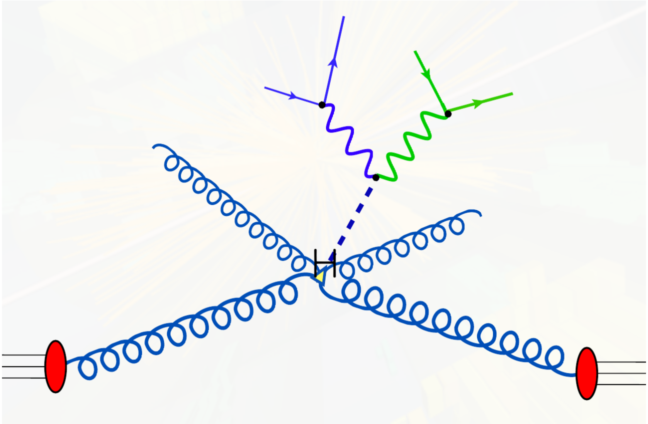
SA, C. Bauer, C. Berggren, F. Tackmann, J. Walsh, Phys.Rev. D92 (2015) 9

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)

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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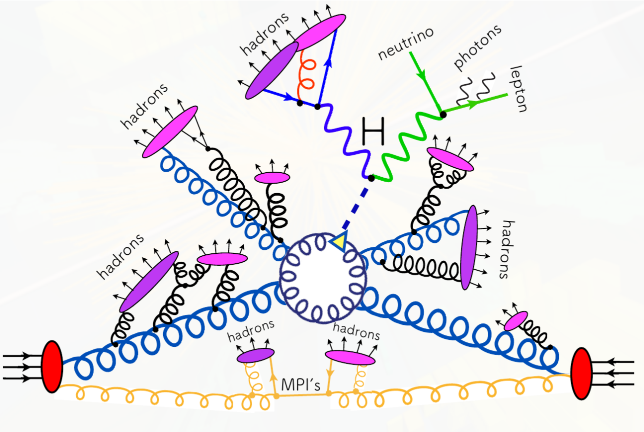

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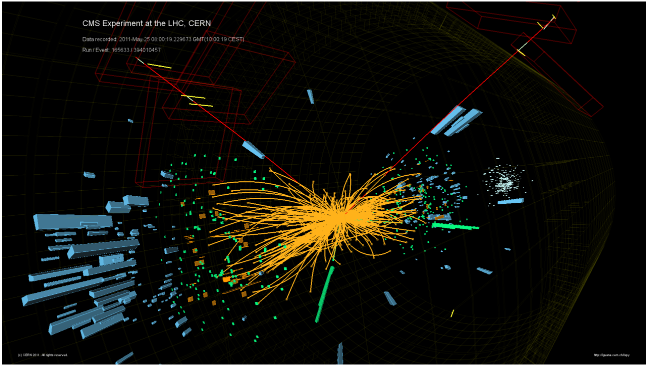

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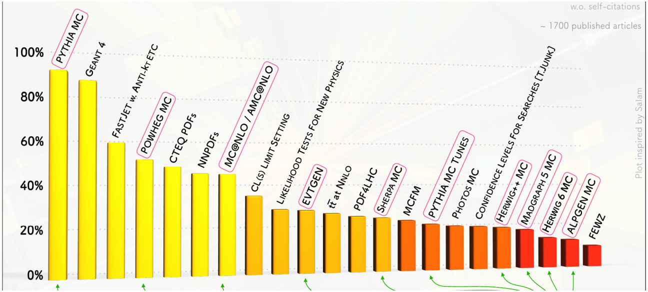


- They are ubiquitous in LHC analyses

graphics from K. Hamilton

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′ via SCET or more traditional QCD approaches (*e.g.* RadISH)

3) Parton showering, hadronization and MPI

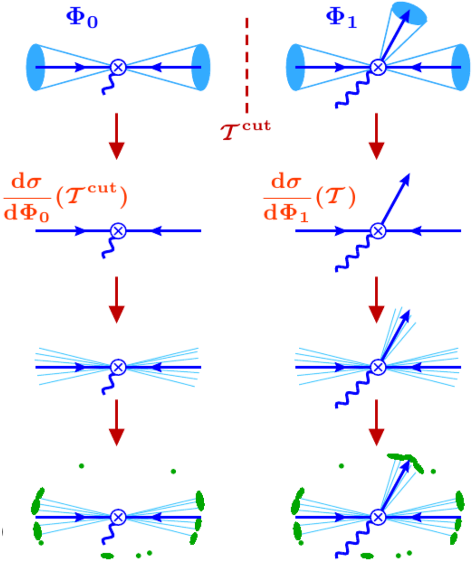
- recycling standard SMC. Using PYTHIA8 now, any SMC supporting LHEF and user-hook vetoes is OK

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.

GENEVA in a nutshell: color singlet production

1. Design IR-finite definition of events, based e.g. on resolution parameters $\mathcal{T}_0^{\mathrm{cut}}$ (or p_T^{cut}).
2. Associate differential cross-sections to events such that 0-jet events are (N)NLO accurate and $\mathcal{T}_0$ is resummed at NNLL' accuracy
3. Shower events imposing conditions to avoid spoiling NNLL' accuracy reached at step 2
4. Hadronize, add multi-parton interactions (MPI) and decay without further restrictions



IR-safe definitions of events beyond LO

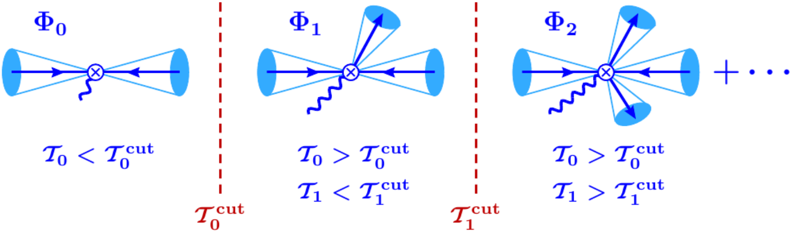
Using 0- and 1-jettiness an IR safe definition of color-single events with any number of extra emissions can be devised:

- 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 interpreted as an N-jet event, $N \leq M$, fully differential in Φ_N, without using a standard “jet-algo”

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

Iterating the procedure, the phase space is sliced into jet-bins



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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- $0-$jet exclusive cross section

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

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

- 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.

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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.

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

- 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.

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

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

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

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

$$\frac{d\sigma^{\rm nons}_{\geq 1}}{d\Phi_1}(\mathcal{T}_0 > \mathcal{T}_0^{\rm cut}) = \frac{d\sigma^{\rm NLO_1}_{\geq 1}}{d\Phi_1}(\mathcal{T}_0 > \mathcal{T}_0^{\rm cut}) - \left[\frac{d\sigma^{\rm NNLL'}}{d\Phi_0 d\mathcal{T}_0}\,\mathcal{P}(\Phi_1)\right]_{\rm NLO_1}\theta(\mathcal{T}_0 > \mathcal{T}_0^{\rm cut})$$

- Nonsingular matching fixed by NLO_1 requirement

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.

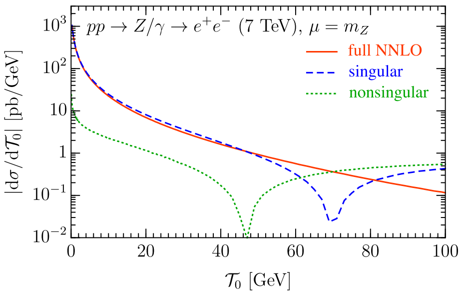
$$\frac{\mathrm{d}\sigma_1^{\mathrm{MC}}}{\mathrm{d}\Phi_1}(\mathcal{T}_0 > \mathcal{T}_0^{\mathrm{cut}}; \mathcal{T}_1^{\mathrm{cut}}) = \frac{\mathrm{d}\sigma_{\geq 1}^{C}}{\mathrm{d}\Phi_1} U_1(\Phi_1, \mathcal{T}_1^{\mathrm{cut}})\, \theta(\mathcal{T}_0 > \mathcal{T}_0^{\mathrm{cut}}) + \frac{\mathrm{d}\sigma_1^{\mathrm{match}}}{\mathrm{d}\Phi_1}(\mathcal{T}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

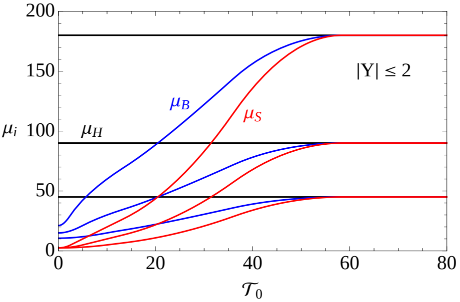
$$\frac{\mathrm{d}\sigma_{\geq 2}^{\mathrm{MC}}}{\mathrm{d}\Phi_2}(\mathcal{T}_0 > \mathcal{T}_0^{\mathrm{cut}}, \mathcal{T}_1 > \mathcal{T}_1^{\mathrm{cut}}) = \frac{\mathrm{d}\sigma_{\geq 1}^{C}}{\mathrm{d}\Phi_1} U_1'(\Phi_1, \mathcal{T}_1)\, \theta(\mathcal{T}_0 > \mathcal{T}_0^{\mathrm{cut}})\Big|_{\Phi_1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

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

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

Scale profiles and theoretical uncertainties





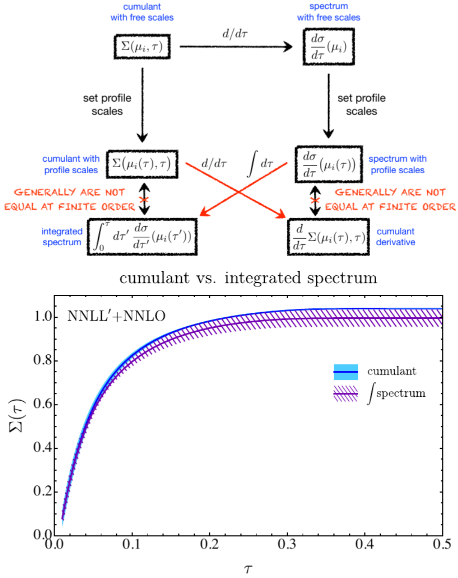
- Theoretical uncertainties in resum. are evaluated by independently varying each μ.
- Range of variations is tuned to turn off the resummation before the nonsingular dominates and to respect SCET scaling $\mu_H \gtrsim \mu_B \gtrsim \mu_S$
- FO unc. are usual $\{2\mu_H, \mu_H/2\}$ variations.
- Final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



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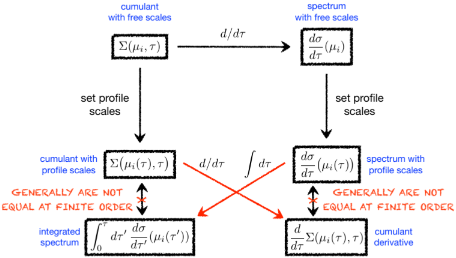
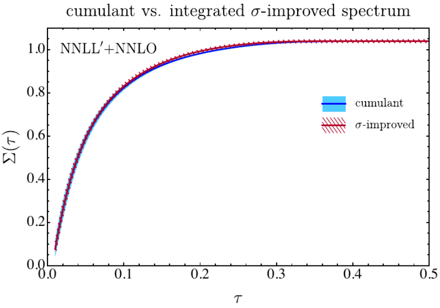




NNLO accuracy in GENEVA: Drell-Yan

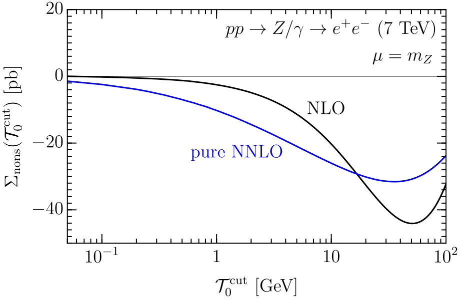
- Resum. expanded result in $\mathrm{d}\sigma^{\mathrm{nons}}_{\geq 1}/\mathrm{d}\Phi_1$ acts as a differential NNLO $\mathcal{T}_0$-subtraction

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

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

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

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

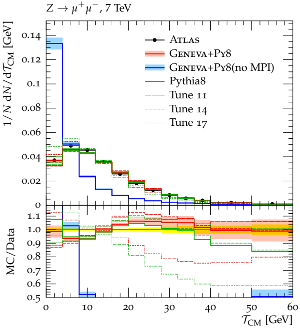


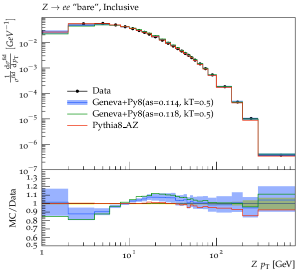
- At $\mathcal{T}_0^{\mathrm{cut}} = 1\,\mathrm{GeV}$ gives $\sim 1\%$ xsec. Small but not negligible, can be lowered further. Tradeoff with speed/stability.

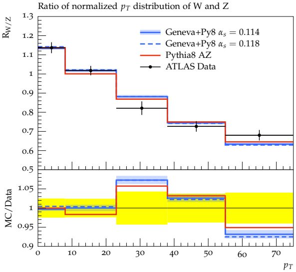
- $f_1(\Phi_0, \mathcal{T}_0^{\mathrm{cut}})$ included exactly by doing NLO$_0$ on-the-fly.
- For pure NNLO$_0$, we currently neglect the Φ_0 dependence below $\mathcal{T}_0^{\mathrm{cut}}$ and include total integral via simple rescaling of $\mathrm{d}\sigma_0^{\mathrm{MC}}/\mathrm{d}\Phi_0(\mathcal{T}_0^{\mathrm{cut}})$.

Results for Drell-Yan production

- Both NC and, more recently, CC contributions included [Phys.Rev. D92 (2015) 9]
- Interface to the parton showers, hadronization and MPI carefully studied [Eur.Phys.J. C76 (2016) 614]
- Used to study the W/Z transverse distribution ratio.







Public code release candidate http://geneva.physics.lbl.gov

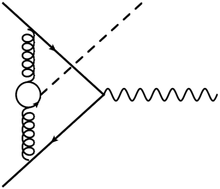
- Release candidate version is publicly available since 2016 at DESY git repo or LBNL mirror. Please report back issues to geneva@lbl.gov.
- Installation by CMake, external packages either found or automatically installed.
- As most NNLO codes, GENEVA needs reasonable parallelization and runtime to produce accurate results.
- Python interface available to steer the running on several systems (own laptop, clusters, etc.). Can also just provide the list of commands to be run and their grouping, to extend it to other systems.
- Running is best organized into 4 separate stages: setup, generate, reweight and shower. All accessible and managed through the Python interface

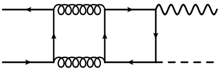
```
✓ alioli@woland:~/GENEVA/geneva/bin/python [release-RC1| …81]> ./geneva -h
usage: geneva [-h] {setup,run,reweight,analyze_lhef,shower,rivet} ...

Run the Geneva event generator

positional arguments:
  {setup,run,reweight,analyze_lhef,shower,rivet}
                        Available stages:
    setup               Sets up Geneva to start generating events
    run                 Runs the main Calculation
    reweight            Reweights the LHEF events
    analyze_lhef        Analyze the LHEF events
    shower              Shower LHEF events using Pythia8
    rivet               Analyze (compressed) HepMC files using Rivet

optional arguments:
  -h, --help            show this help message and exit
```

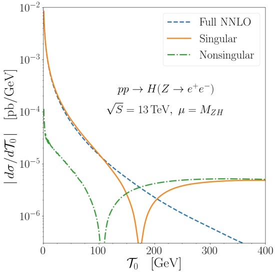
New implementations: HiggsStrahlung

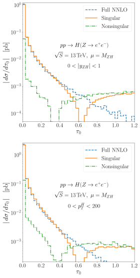
SA et al. Phys.Rev.D 100 (2019)

- 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.





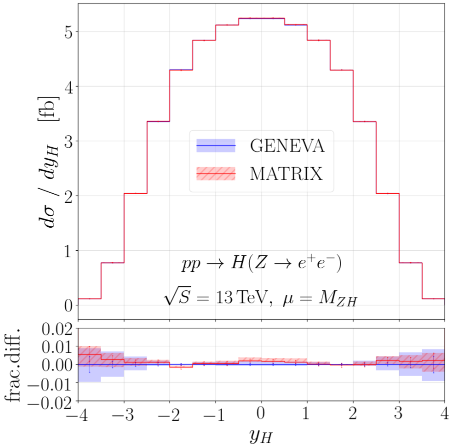


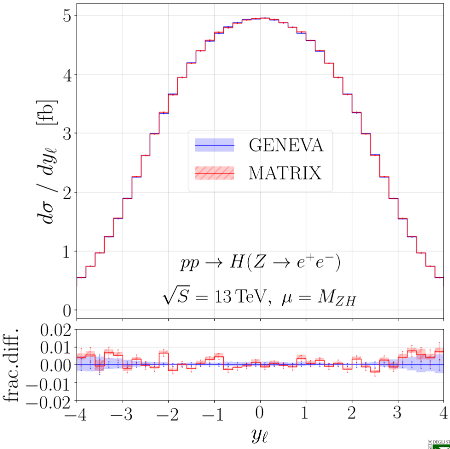


- Beam-thrust resummation at NNLL' matched to NNLO_0 via SCET
- Scale profiles adapted to the process, not extremely dependent on leading-order kinematics

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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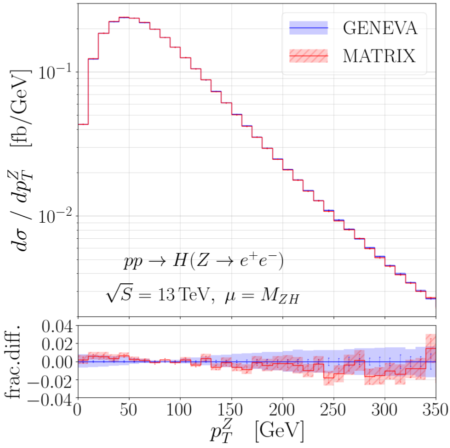

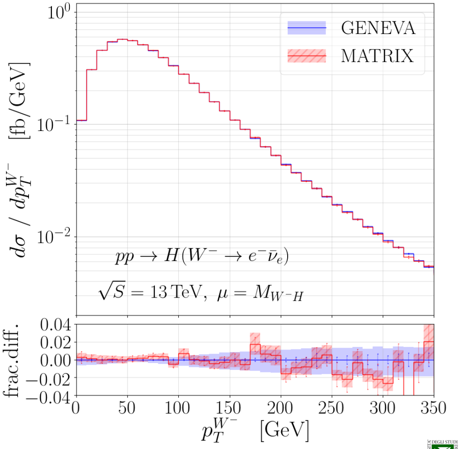

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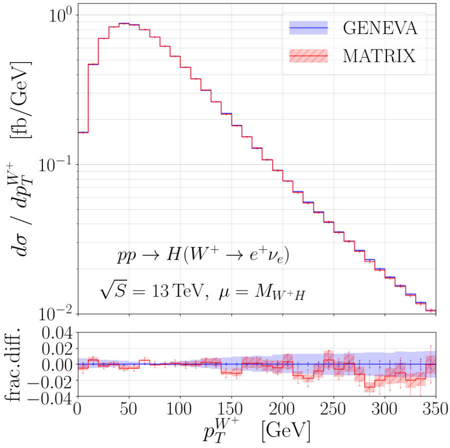

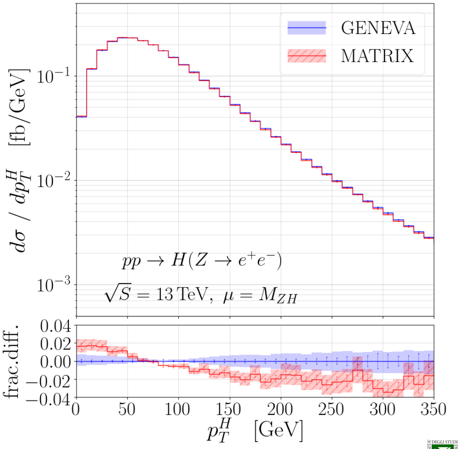

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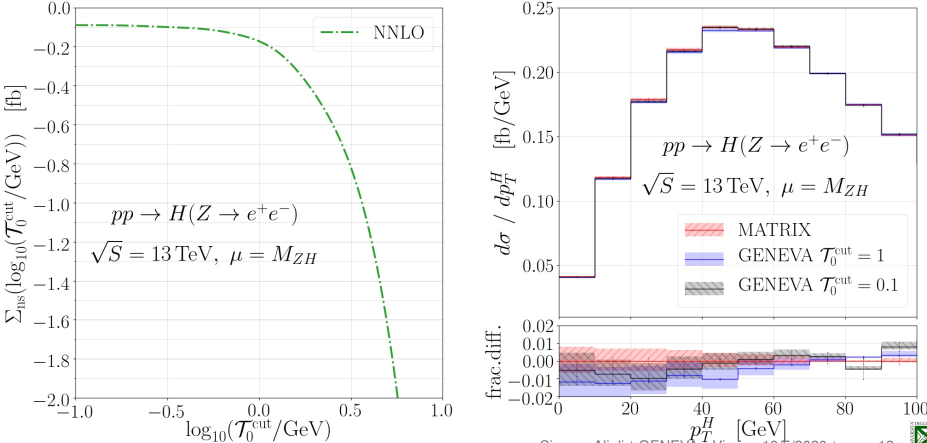
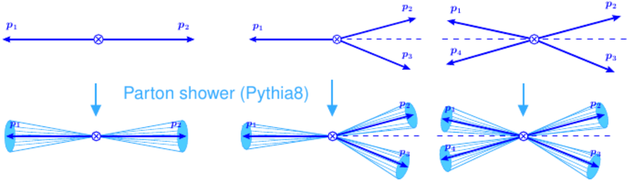
- NNLO cross-section and inclusive distributions validated against MATRIX
  Kallweit et al. Eur.Phys.J. C78 (2018).
- Non-trivial correlations for scales variations, dedicated profiled used to reproduce fixed-order variations for inclusive quantities.
- Smallness of scale variations makes it numerically very challenging.
- Power-suppressed corrections effects on distributions small.



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

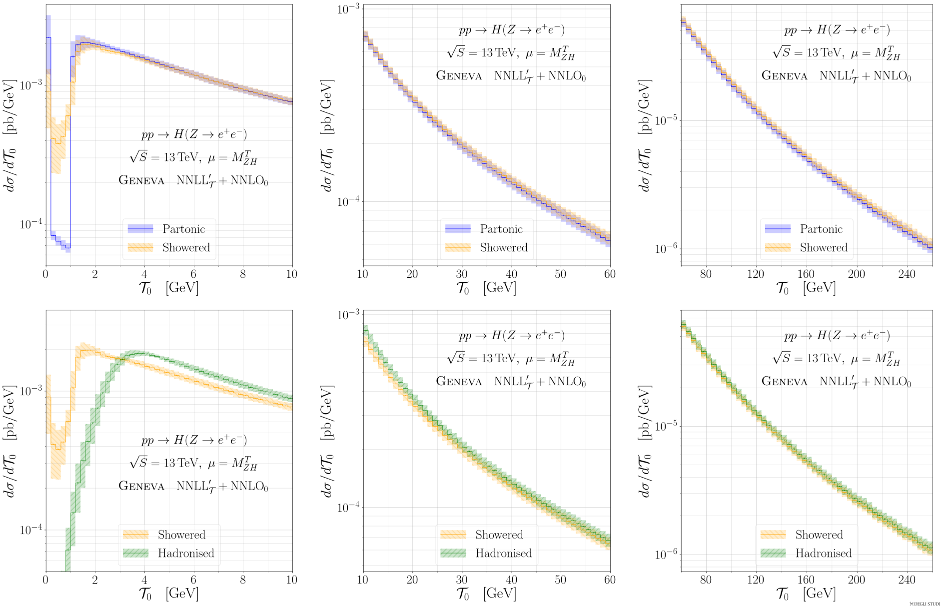


- Not allowed to change accuracy reached at partonic level.
- If shower ordered in N-jettiness setting starting scales is enough.
- For different ordering variable (i.e. any real shower), jet-boundaries constraints $\mathcal{T}_k^{\rm cut}$ need to be imposed on hardest radiation (largest jet resolution 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.

Showering setting starting scales $\mathcal{T}_k^{\rm cut}$:

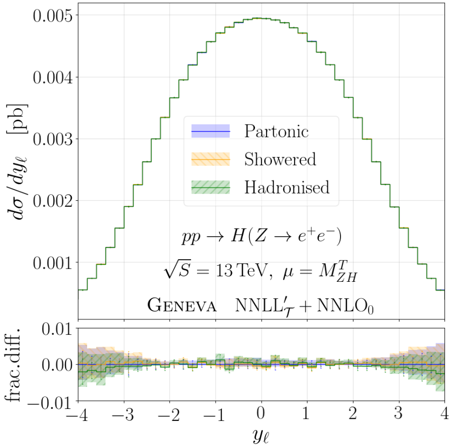
- Φ_0 events only constrained by normalization, shape given by PYTHIA
- Φ_1 events vanish forced to vanish by splitting down to $\Lambda_1 \lesssim 100$ MeV.
- Φ_2 events: PYTHIA showering can be shown to shift $\mathcal{T}_0$ distribution at the same $\alpha_{\rm s}^3/\mathcal{T}_0$ order of the dominant term beyond NNLL'.

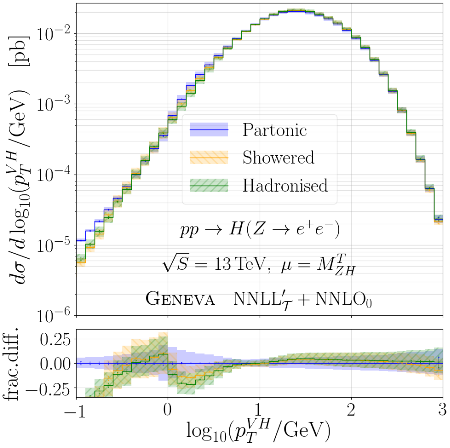
Showered and hadronized results for HiggsStrahlung



Showered and hadronized results for HiggsStrahlung

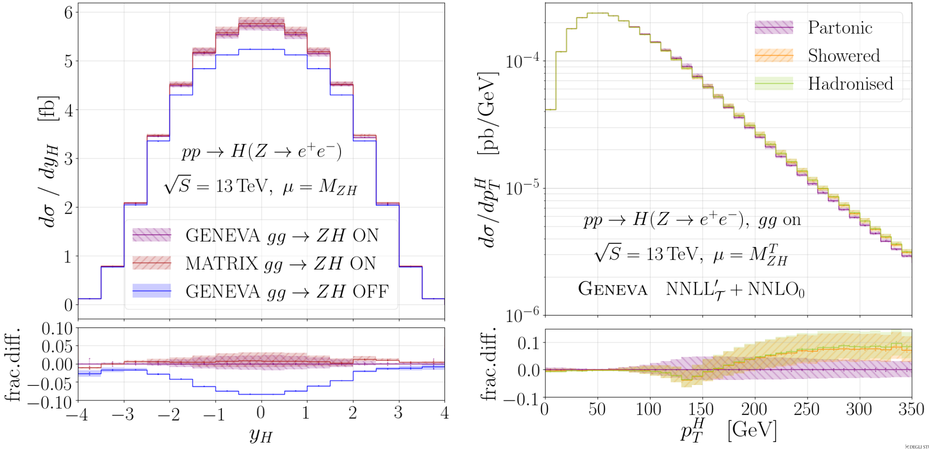
- Inclusive quantities not modified, expected changes in exclusive ones.





Including the gluon-fusion channel

- Sizeable contribution due to gluon luminosity. Loop-induced nonsingular contribution added at fixed-order only.
- Scale unc. dominated by gg channel, desirable to have NLO corrections.
- Shower effects more marked, as already seen in other gg-initiated processes.



Handling the 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

$$
\overbrace{\frac{d\sigma_0^{\rm MC}}{d\Phi_{\ell^+\ell^- b\bar{b}}}(\mathcal{T}_0^{\rm cut};\tau_2^{\rm cut})}^{(\rm NNLL+NNLO_0)\otimes(\rm NNLL+NNLO_2)} = \overbrace{\frac{d\sigma_0^{\rm MC}}{d\Phi_{\ell^+\ell^- H}}(\mathcal{T}_0^{\rm cut})}^{\rm NNLL+NNLO_0} \times \frac{d\Gamma^{(0)}_{H\to b\bar{b}}}{d\Phi_{H\to b\bar{b}}} + \frac{d\sigma^{(0)}_{\ell^+\ell^- H}}{d\Phi_{\ell^+\ell^- H}} \times \overbrace{\frac{d\Gamma_2^{\rm MC}}{d\Phi_{H\to b\bar{b}}}(\tau_2^{\rm cut})}^{\rm NNLL+NNLO_2}
$$

$$
- \frac{d\sigma^{(0)}_{\ell^+\ell^- H}}{d\Phi_{\ell^+\ell^- H}} \times \frac{d\Gamma^{(0)}_{H\to b\bar{b}}}{d\Phi_{H\to b\bar{b}}}
$$

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

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

- 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.

Handling the 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

$$\overbrace{\frac{d\sigma_1^{\rm MC}}{d\Phi_{\ell^+\ell^- b\bar{b}j}}(\mathcal{T}_0 > \mathcal{T}_0^{\rm cut}; \mathcal{T}_1^{\rm cut}; \tau_2^{\rm cut})}^{(\rm NNLL+NLO_1)\otimes(\rm NLL+NLO_2)} = \overbrace{\frac{d\sigma_1^{\rm MC}}{d\Phi_{\ell^+\ell^- Hj}}(\mathcal{T}_0 > \mathcal{T}_0^{\rm cut}; \mathcal{T}_1^{\rm cut})}^{\rm NNLL+NLO_1} \times \frac{d\Gamma^{(0)}_{H\to b\bar{b}}}{d\Phi_{H\to b\bar{b}}} +$$

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

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

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

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

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

Handling the 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

$$\overbrace{\frac{d\sigma_2^{\mathrm{MC}}}{d\Phi_{\ell^+\ell^- b\bar{b}jj}}(\mathcal{T}_0 > \mathcal{T}_0^{\mathrm{cut}}; \mathcal{T}_1 > \mathcal{T}_1^{\mathrm{cut}}; \tau_2^{\mathrm{cut}})}^{(\mathrm{NNLL+LO_2})\otimes\mathrm{LO_2}} =$$

$$\overbrace{\frac{d\sigma_2^{\mathrm{MC}}}{d\Phi_{\ell^+\ell^- Hjj}}(\mathcal{T}_0 > \mathcal{T}_0^{\mathrm{cut}}; \mathcal{T}_1 > \mathcal{T}_1^{\mathrm{cut}})}^{\mathrm{NNLL+LO_2}} \times \frac{d\Gamma^{(0)}_{H\to b\bar{b}}}{d\Phi_{H\to b\bar{b}}}$$

Handling the decay at NNLO

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- Beam-thrust $\mathcal{T}_0$ resolution parameter for production, 2-jettiness (thrust) $\tau_2^{\rm dec}$ for decay
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$$\overbrace{\frac{d\sigma_2^{\rm MC}}{d\Phi_{\ell^+\ell^- b\bar{b}jj}}(\mathcal{T}_0 > \mathcal{T}_0^{\rm cut}; \mathcal{T}_1^{\rm cut}; \tau_2^{\rm dec} > \tau_2^{\rm cut}; \tau_3^{\rm cut})}^{(\mathrm{NLL+LO}_1)\otimes(\mathrm{NLL+LO}_3)} =$$

$$\overbrace{\frac{d\sigma_1^{\rm MC}}{d\Phi_{\ell^+\ell^- Hj}}(\mathcal{T}_0 > \mathcal{T}_0^{\rm cut}; \mathcal{T}_1^{\rm cut})}^{\mathrm{NLL+LO}_1} \times \overbrace{\frac{d\Gamma_1^{\rm MC}}{d\Phi_{H\to b\bar{b}j}}(\tau_2^{\rm dec} > \tau_2^{\rm cut}; \tau_3^{\rm cut})}^{\mathrm{NLL+LO}_3}$$

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- Beam-thrust $\mathcal{T}_0$ resolution parameter for production, 2-jettiness (thrust) τ_2^{dec} for decay
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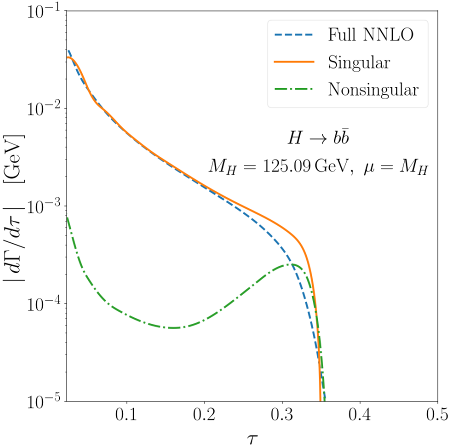
$$\overbrace{\frac{d\sigma_2^{\mathrm{MC}}}{d\Phi_{\ell^+\ell^- b\bar{b}jj}}(\mathcal{T}_0^{\mathrm{cut}};\mathcal{T}_1^{\mathrm{cut}};\tau_2^{\mathrm{dec}}>\tau_2^{\mathrm{cut}};\tau_3>\tau_3^{\mathrm{cut}})}^{\mathrm{LO}_0\otimes(\mathrm{NNLL+LO}_4)} =$$

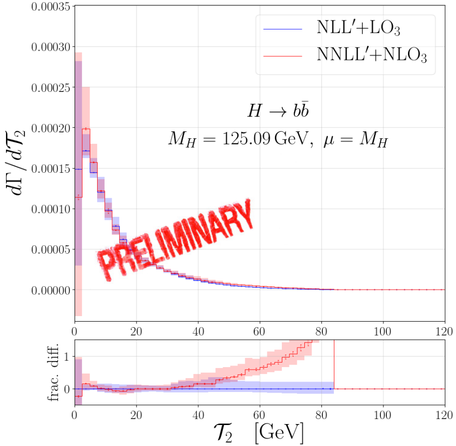
$$\frac{d\sigma^{(0)}_{\ell^+\ell^- H}}{d\Phi_{\ell^+\ell^- H}} \times \overbrace{\frac{d\Gamma_2^{\mathrm{MC}}}{d\Phi_{H\to b\bar{b}jj}}(\tau_2^{\mathrm{dec}}>\tau_2^{\mathrm{cut}};\tau_3>\tau_3^{\mathrm{cut}})}^{\mathrm{NNLL+LO}_4}$$

- Having obtained a final formula, we started constructing the missing ingredients

GENEVA for NNLO $\mathrm{H} \to \mathrm{b}\bar{\mathrm{b}}$ 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

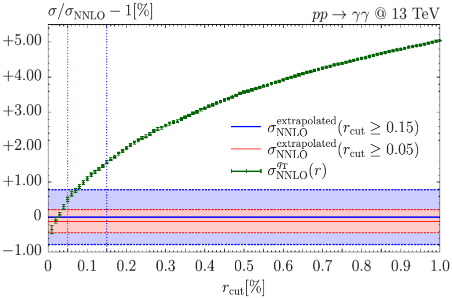


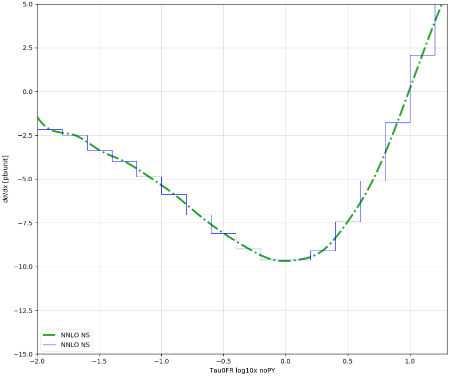


- All ingredients now available, production+decay is work in progress

New implementation: Diphoton production

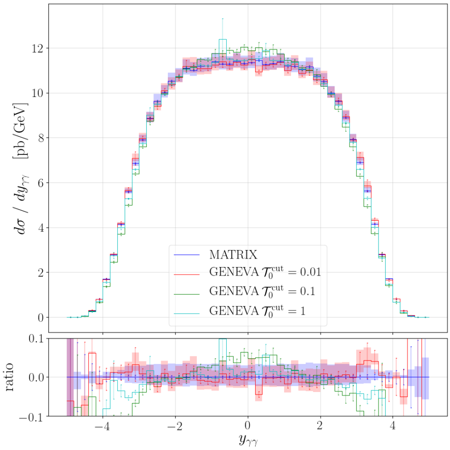
- Important background to Higgs boson production and NP searches
- Similar to DY and VH production, complications coming from QED divergencies
- Requires introduction of photon-isolation procedure, to remove huge background from secondary photons
- Using dynamic-cone (Frixione) isolation for now, more experimental-friendly alternatives available and under study.
- Size of power-corrections very challenging, both in q_T and $\mathcal{T}_0$

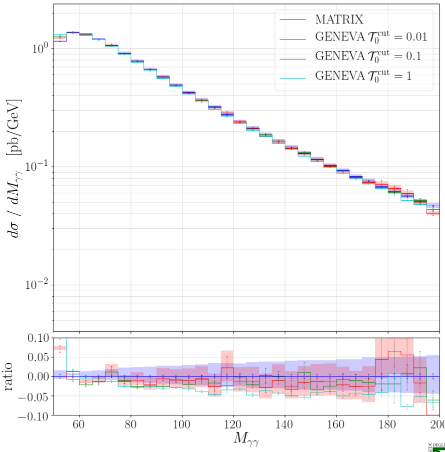




GENEVA for diphoton production

- 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.





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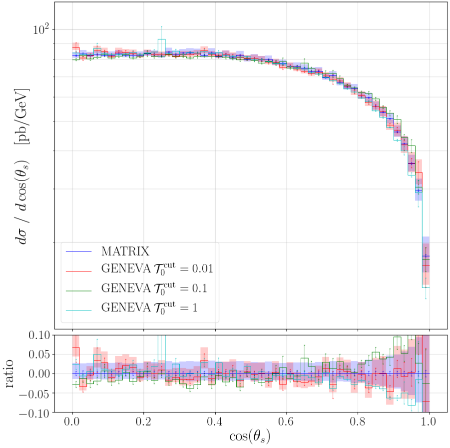
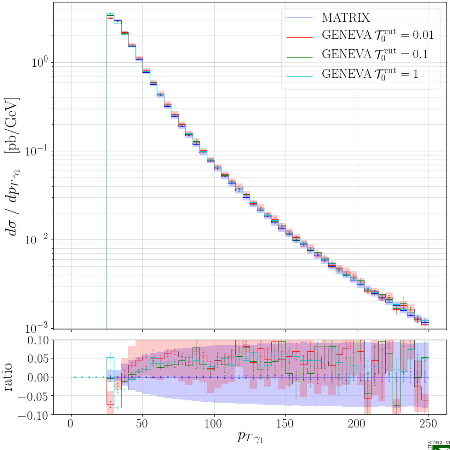
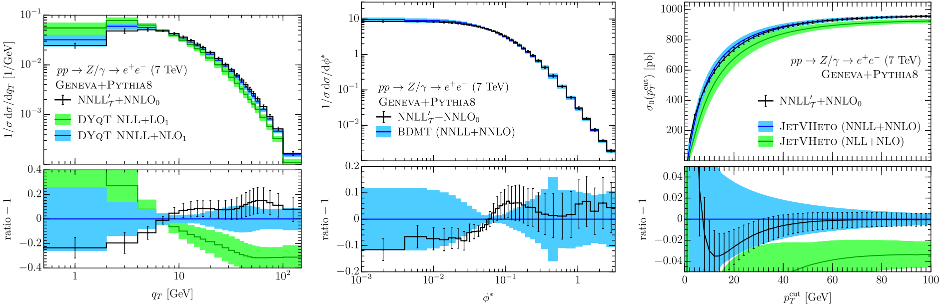




Accuracy for other observables : q_T, ϕ^* and jet-veto

- 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

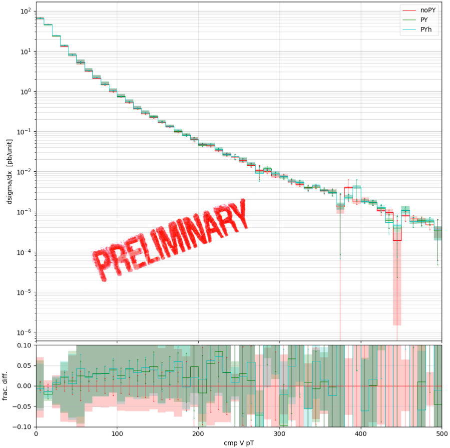


- Results are in better agreement with higher-order resummation, despite lack of perturbative ingredients.
- Difficult to formally quantify the accuracy achieved due to parton shower.
- Recently NLL accurate showers started to appear. It will be interesting to study how to interface to them and how they will perform.

Changing the resolution parameter: q_T

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

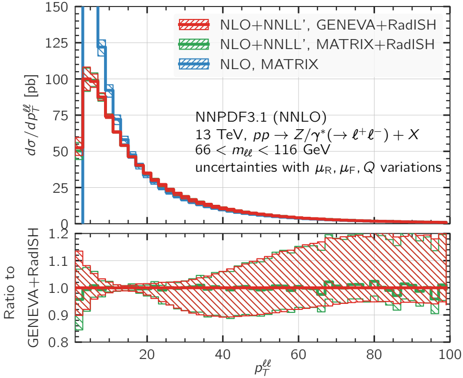
- RadISH performs q_T resummation up to N3LL directly in q_T space
  Bizon et al. arXiv:1905.05171
- Its internal structure requiring Monte Carlo generation of unphysical events makes it hard to directly link.
- We proceeded building interpolating grids with Chebyshev polynomials and calling these interpolating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

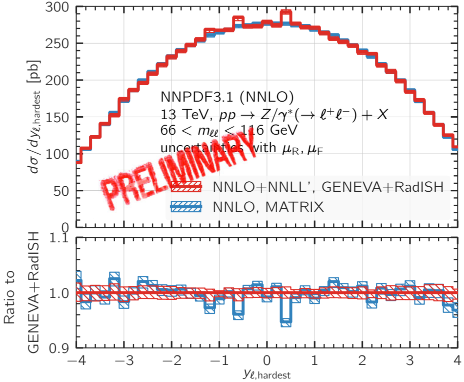


- Results are in good agreement with dedicated RadISH+NNLOJET NNLL'+NNLO$_0$ control runs.
- Shower interface slightly simplified compared to $\mathcal{T}_0$, currently under testing ...

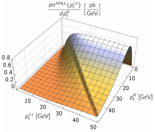
Changing the resolution parameter: q_T

- Validation of NNLO results and NNLL resummation performed





- Exploring possibility of changing $1/2$-jet resolution variable to simplify interface with the shower.



- Interface to RadISH opens up possibility to use even more resolution parameters like $p_{T,\mathrm{jet}}$ and also multiple resummations, *e.g* p_T resummation with a jet-veto

P. Monni et al. 1909.04704

Summary and Outlook

GENEVA **performs matching of NNLO+NNLL$'$+PS.**

- 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:

- $pp \to V$ is publicly available.
- $pp \to VH$ including NNLO $H \to b\bar{b}$ is almost ready.
- $pp \to \gamma\gamma$ is also at an advanced stage.
- Usage of different resolution parameter (q_T) is also almost ready

Outlook:

- Other color-singlet processes (Higgs, VV, etc.) in the pipeline.
- Investigate multi-differential resummations.
- Start tackling the $1-$jettiness challenge to do V+1-jet at NNLO+PS.

Thank you for your attention!