Accurate Monte Carlo event generators for LHC processes

NNLOPS in the GENEVA convention

Matthew Lim, on behalf of GENEVA@Bicocca

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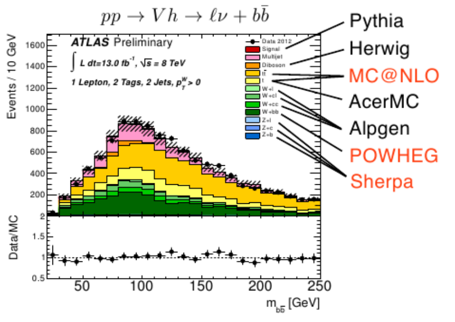
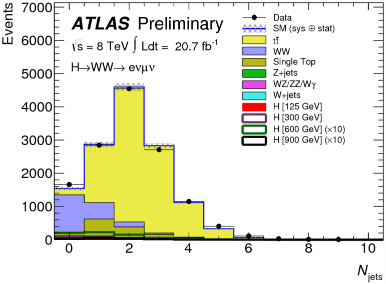
Motivation

- MC event generators aim to provide a realistic simulation of what actually happens in a collider experiment





- First principles QFT calculations are combined with parton shower and hadronisation modelling, detector simulation
- Experimental precision in measurement demands equally precise theory predictions

Overview of talk

- Introduction to Geneva as a MC event generator
- Application to colour singlet production and decay processes
- Future directions and applications

The GENEVA method

The Geneva method

The Three Jewels:

- Geneva produces fully differential fixed order calculations at NNLO;
- By resumming large logarithms at NNLL′, it provides precise predictions over the whole phase space;
- These are matched to a parton shower to produce realistic events (which can further be hadronised, MPI effects included).

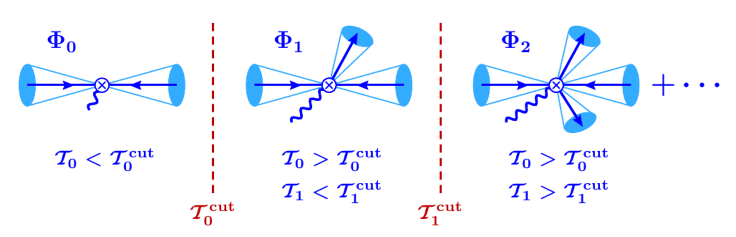
The method is fully general.

Constructing IR-finite events

Work with IR-finite events to which a finite cross section can be assigned:

- Introduce a resolution parameter $\mathcal{T}_N$, $\mathcal{T}_N \to 0$ in the IR region. Emissions below $\mathcal{T}_N^{\mathrm{cut}}$ are unresolved (i.e. integrated over) and the kinematic configuration considered is the one of the event before the emission.
- An M-parton event is thus translated to an N-jet event, $N \leq M$, fully differential in Φ_N (no jet-algorithm needed).
  - Price to pay: power corrections in $\mathcal{T}_N^{\mathrm{cut}}$ due to PS projection.
  - Advantage: vanish for IR-safe observables as $\mathcal{T}_N^{\mathrm{cut}} \to 0$
- Iterating the procedure, the phase space is sliced into jet-bins.

Constructing IR-finite events



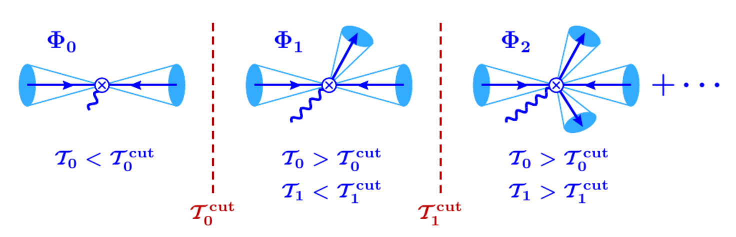
Exclusive N-jet bin

$$\frac{d\sigma_N^{\rm MC}}{d\Phi_N}(\mathcal{T}_N^{\rm cut})$$

Inclusive $(N+1)$-jet bin

$$\frac{d\sigma_{\geq N+1}^{\rm MC}}{d\Phi_{N+1}}(\mathcal{T}_N > \mathcal{T}_N^{\rm cut})$$

Constructing IR-finite events



Excl. N-jet bin

$$\frac{\mathrm{d}\sigma_N^{\rm MC}}{\mathrm{d}\Phi_N}(\mathcal{T}_N^{\rm cut})$$

Excl. $(N+1)$-jet

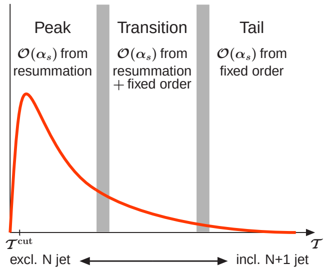
$$\frac{\mathrm{d}\sigma_{N+1}^{\rm MC}}{\mathrm{d}\Phi_{N+1}}(\mathcal{T}_N > \mathcal{T}_N^{\rm cut}; \mathcal{T}_{N+1}^{\rm cut})$$

Inclusive $(N+2)$-jet bin

$$\frac{\mathrm{d}\sigma_{\geq N+2}^{\rm MC}}{\mathrm{d}\Phi_{N+2}}(\mathcal{T}_N > \mathcal{T}_N^{\rm cut}, \mathcal{T}_{N+1} > \mathcal{T}_{N+1}^{\rm cut})$$

Resummation

- As we take $\mathcal{T}_N^{\mathrm{cut}} \to 0$, large logarithms of $\mathcal{T}_N^{\mathrm{cut}}, \mathcal{T}_N$ appear which must be resummed to prevent perturbative convergence being spoiled.



- In the region where $\tau \equiv \mathcal{T}/Q \ll 1$, $\alpha_s \log^2(\tau) \sim 1$ and logs must be resummed.
- Resummation of $\mathcal{T}_N$ must be at NNLL′ to ensure $\mathcal{O}(\alpha_s^2)$ accuracy over the whole spectrum.

Combining resummed and fixed order calculations

Consider colour singlet production at NNLO. We need events with $0, 1$ and 2 additional QCD partons in the final state.
Exclusive 0-jet cross section:

$$\frac{\mathrm{d}\sigma_0^{\mathit{MC}}}{\mathrm{d}\Phi_0}(\mathcal{T}_0^{\mathrm{cut}}) = \frac{\mathrm{d}\sigma_0^{\mathit{NNLL}'}}{\mathrm{d}\Phi_0}(\mathcal{T}_0^{\mathrm{cut}}) + \overbrace{\frac{\mathrm{d}\sigma_0^{\mathit{sing\ match}}}{\mathrm{d}\Phi_0}(\mathcal{T}_0^{\mathrm{cut}})}^{=0} + \frac{\mathrm{d}\sigma_0^{\mathit{nons}}}{\mathrm{d}\Phi_0}(\mathcal{T}_0^{\mathrm{cut}})$$

- At NNLL′, all singular terms included to $\mathcal{O}(\alpha_s^2)$ by definition – singular matching term vanishes.
- Nonsingular matching term determined by requirement of FO NNLO accuracy:

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

Combining resummed and fixed order calculations

Inclusive 1-jet cross section:

$$\frac{\mathrm{d}\sigma^{\mathsf{MC}}_{\geq 1}}{\mathrm{d}\Phi_1}(\mathcal{T}_0 > \mathcal{T}_0^{\mathrm{cut}}) = \frac{\mathrm{d}\sigma^{\mathit{resum}}_{\geq 1}}{\mathrm{d}\Phi_1}\,\theta(\mathcal{T}_0 > \mathcal{T}_0^{\mathrm{cut}}) + \frac{\mathrm{d}\sigma^{\mathit{sing\ match}}_{\geq 1}}{\mathrm{d}\Phi_1}(\mathcal{T}_0 > \mathcal{T}_0^{\mathrm{cut}}) + \frac{\mathrm{d}\sigma^{\mathit{nons}}_{\geq 1}}{\mathrm{d}\Phi_1}(\mathcal{T}_0 > \mathcal{T}_0^{\mathrm{cut}})$$

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

- 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 normalised splitting probability to make the resummation differential in Φ_1.

Combining resummed and fixed order calculations

Inclusive 1-jet cross section:

$$\frac{\mathrm{d}\sigma^{\mathrm{MC}}_{\geq 1}}{\mathrm{d}\Phi_1}(\mathcal{T}_0 > \mathcal{T}_0^{\mathrm{cut}}) = \frac{\mathrm{d}\sigma^{resum}_{\geq 1}}{\mathrm{d}\Phi_1}\,\theta(\mathcal{T}_0 > \mathcal{T}_0^{\mathrm{cut}}) + \frac{\mathrm{d}\sigma^{sing\ match}_{\geq 1}}{\mathrm{d}\Phi_1}(\mathcal{T}_0 > \mathcal{T}_0^{\mathrm{cut}}) + \frac{\mathrm{d}\sigma^{nons}_{\geq 1}}{\mathrm{d}\Phi_1}(\mathcal{T}_0 > \mathcal{T}_0^{\mathrm{cut}})$$

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

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

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

Combining resummed and fixed order calculations

Inclusive 1-jet cross section:

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

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

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

Combining resummed and fixed order calculations

- We also split the inclusive 1-jet cross section into exclusive 1-jet and inclusive 2-jet cross sections, using $\mathcal{T}_1$ as the resolution variable
- Resummation of $\mathcal{T}_1$ is performed at NLL accuracy.

$$\begin{aligned}
\frac{\mathrm{d}\sigma_1^{\mathrm{MC}}}{\mathrm{d}\Phi_1}(\mathcal{T}_0 > \mathcal{T}_0^{\mathrm{cut}}; \mathcal{T}_1^{\mathrm{cut}}) &= \frac{\mathrm{d}\sigma_1^{resum}}{\mathrm{d}\Phi_1}(\mathcal{T}_0 > \mathcal{T}_0^{\mathrm{cut}}; \mathcal{T}_1^{\mathrm{cut}}) \\
&\quad + \frac{\mathrm{d}\sigma_1^{match}}{\mathrm{d}\Phi_1}(\mathcal{T}_0 > \mathcal{T}_0^{\mathrm{cut}}; \mathcal{T}_1^{\mathrm{cut}}) \\
\frac{\mathrm{d}\sigma_{\geq 2}^{\mathrm{MC}}}{\mathrm{d}\Phi_2}(\mathcal{T}_0 > \mathcal{T}_0^{\mathrm{cut}}, \mathcal{T}_1 > \mathcal{T}_1^{\mathrm{cut}}) &= \frac{\mathrm{d}\sigma_{\geq 2}^{resum}}{\mathrm{d}\Phi_2}(\mathcal{T}_0 > \mathcal{T}_0^{\mathrm{cut}})\, \theta(\mathcal{T}_1 > \mathcal{T}_1^{\mathrm{cut}}) \\
&\quad + \frac{\mathrm{d}\sigma_{\geq 2}^{match}}{\mathrm{d}\Phi_2}(\mathcal{T}_0 > \mathcal{T}_0^{\mathrm{cut}}, \mathcal{T}_1 > \mathcal{T}_1^{\mathrm{cut}})
\end{aligned}$$

Combining resummed and fixed order calculations

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

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

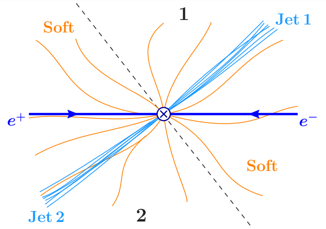
$$\frac{d\sigma_{\geq 1}^{C}}{d\Phi_1} = \frac{d\sigma_{\geq 1}^{resum}}{d\Phi_1} + (B_1 + V_1^C)(\Phi_1) - \left[\frac{d\sigma_{\geq 1}^{resum}}{d\Phi_1}\right]_{NLO_1}$$

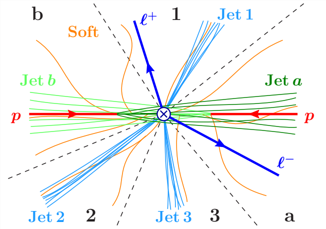
- The fully differential $\mathcal{T}_0$ resummation is contained within $\frac{d\sigma_{\geq 1}^{resum}}{d\Phi_1}$.

Choice of the jet resolution variable

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

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





- N-jettiness has good factorisation properties, IR safe and resummable at all orders. Resummation known at NNLL for any N in Soft-Collinear Effective Theory
- $\mathcal{T}_N \to 0$ for N pencil-like jets, $\mathcal{T}_N \gg 0$ spherical limit.

NNLL′ resummation from SCET

The spectrum in $\mathcal{T}_0$ can be factorised at all-orders as

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

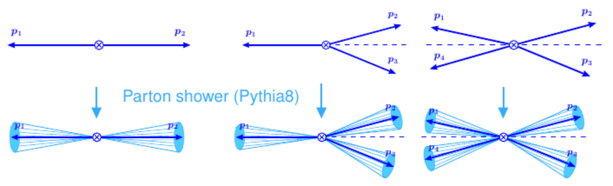
- Hard, Beam and Soft functions are each evaluated at their own scale ⇒ no large logarithms,

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

- RGE kernels U_X evolve functions to a common scale μ and in so doing resum logarithms.

Matching to a parton shower

- Parton shower makes calculation differential in higher multiplicities by adding radiation.
- Fills the 0- and 1-jet bins with radiation, adds more to the inclusive 2-jet bin.



- Not allowed to affect the accuracy of the cross section reached at partonic level.
- $\mathcal{T}_i^{\rm cut}$ constraints must be respected.

Matching to a parton shower

We want to ensure preservation of NNLO+NNLL′ accuracy as far as possible. Take each class of event in turn:

- For Φ_0 events, cumulant below $\mathcal{T}_0^{\mathrm{cut}}$ must not be modified. Emissions generated must have $\mathcal{T}_0(\Phi_N) < \mathcal{T}_0^{\mathrm{cut}}$; for single emissions must be projectable onto Φ_0.
- Achieve first goal due to unitarity, latter by choice of starting scale.
- For Φ_2 events, can show that first emission of shower only alters accuracy of $\mathcal{T}_0$ distribution beyond NNLL′.
- What about Φ_1 events?

Matching to a parton shower

- For Φ_1 events, the resulting Φ_2 events must be projectable back onto the Φ_1 (while preserving the value of $\mathcal{T}_0$).
- Constraint from $\mathcal{T}_1(\Phi_N) < \mathcal{T}_1^{\mathrm{cut}}$ must be applied on hardest radiation, not necessarily first (real showers are not ordered in N-jettiness).
- Force this by using an NLL Sudakov and the $\mathcal{T}_0$-preserving map.

$$\frac{\mathrm{d}\sigma^{\mathsf{MC}}_{N\to N}}{\mathrm{d}\Phi_N}(\mathcal{T}_N^{\mathrm{cut}};\Lambda_N) = \frac{\mathrm{d}\sigma^{\mathsf{MC}}_{N}}{\mathrm{d}\Phi_N}(\mathcal{T}_N^{\mathrm{cut}})\, U_N(\mathcal{T}_N^{\mathrm{cut}},\Lambda_N)$$

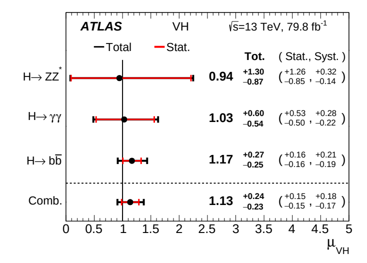
$$\frac{\mathrm{d}\sigma^{\mathsf{MC}}_{N\to N+1}}{\mathrm{d}\Phi_{N+1}}(\mathcal{T}_N > \Lambda_N, \mathcal{T}_N^{\mathrm{cut}}) = \frac{\mathrm{d}}{\mathrm{d}\mathcal{T}_N}\left[\frac{\mathrm{d}\sigma^{\mathsf{MC}}_{N\to N}}{\mathrm{d}\Phi_N}(\mathcal{T}_N^{\mathrm{cut}};\mathcal{T}_N)\right]\mathcal{P}(\Phi_{N+1}) \times \theta(\mathcal{T}_N^{\mathrm{cut}} > \mathcal{T}_N > \Lambda_N)$$

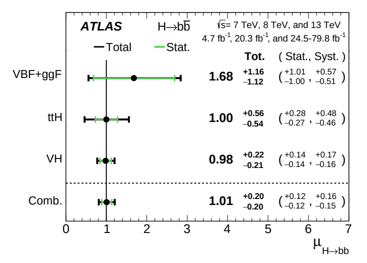
- Λ_N is a shower cutoff, much lower than $\mathcal{T}_N^{\mathrm{cut}}$.
- Since we have no control over the showering of Φ_1 events, we choose $\Lambda_1 \sim \Lambda_{QCD}$, thus reducing the contribution to $\sim 0.1\%$ of the total cross section.

Applications to colour singlet production and decay

The Higgsstrahlung process

- The VH production process is experimentally important.

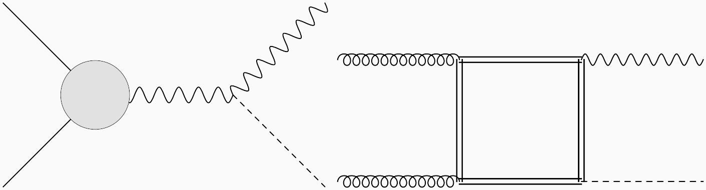




- Observation of both VH production and $H \to b\bar{b}$ – leading significance comes from $VH, H \to b\bar{b}$ analysis.

The Higgsstrahlung process

- Similar to Drell-Yan, but a Higgs is radiated off the vector boson – can recycle hard function in factorisation theorem from DY case.
- At NNLO and for ZH, gluon-initiated channel appears as well – we include this at fixed order.



- Neglect 2-loop contributions with heavy quarks in the loops ($\mathcal{O}(1\%)$ effect).

Scale choices and profile scales

What do we choose for the scales μ_X?

- Must switch off resummation in FO region to obtain correct cancellation between singular and nonsingular terms.
- Switch off happens when all resummation scales are chosen equal to each other,

$$\mu_{NS} = \mu_H = \mu_S = \mu_B$$

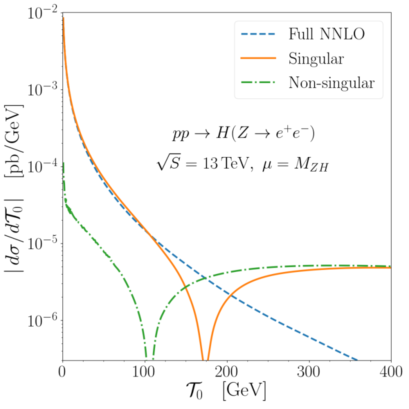
- Choose functional forms of scales ('profile scales') that interpolate smoothly from resummation to FO region,

$$\begin{aligned} \mu_H &= \mu_{\mathrm{NS}}\,, \\ \mu_S(\mathcal{T}_0) &= \mu_{\mathrm{NS}} f_{run}(\mathcal{T}_0/Q)\,, \\ \mu_B(\mathcal{T}_0) &= \mu_{\mathrm{NS}} \sqrt{f_{run}(\mathcal{T}_0/Q)}\,. \end{aligned}$$

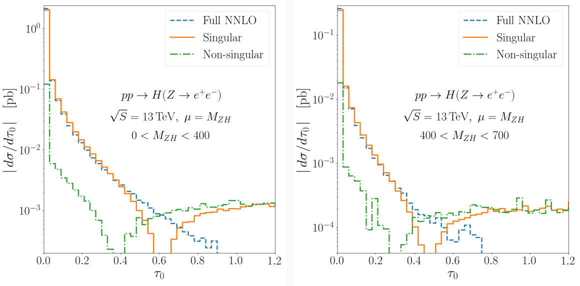
Scale choices and profile scales

- The f_{run} must switch off the resummation when nonsingular and singular terms are similar in magnitude. When does this happen?

- For full spectrum integrated over all Born kinematics, happens $\sim$ 150 GeV.
- Choose functional form of f_{run} accordingly.



- The f_{run} must switch off the resummation when nonsingular and singular terms are similar in magnitude. When does this happen?
- Can check that there is only a weak dependence on the exact kinematic regime:



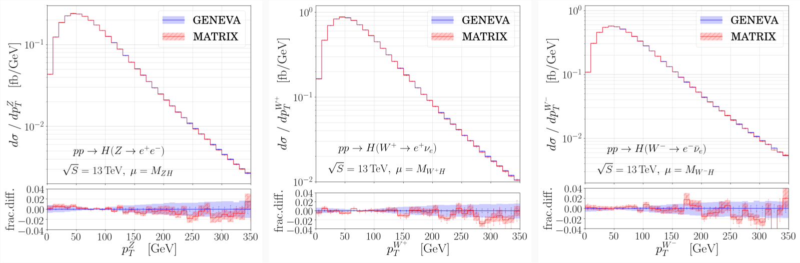
- We can therefore use same profile scales for all distributions.

Scale choices and profile scales

- In resummation region, μ_{NS} must be $\sim Q$.
- In FO region, can be an arbitrary fixed or dynamic scale μ_{FO}.
- Estimate FO uncertainties by varying μ_{NS} up and down by factor 2, preserving ratios of all scales.
- Estimate resummation uncertainties by varying profile scales about central profiles while keeping μ_H fixed. Arguments of resummed logs are varied in order to estimate the size of corrections in resummed series, but scale hierarchy is maintained.
- Finally, include two more profiles where transition points between regions are varied with scales at their central values.
- Take quadrature sum of FO and resummation uncertainties as total uncertainty.

Fixed order validation

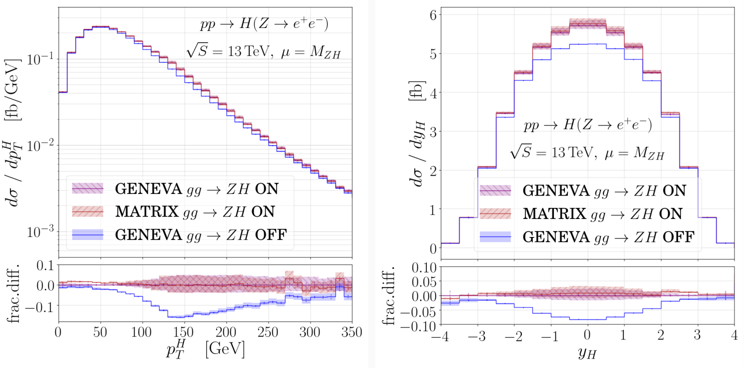
- Fixed order results for total cross section and inclusive distributions checked against a private version of the code MATRIX, which implements q_T subtraction.
- Comparison for 13 TeV LHC with $\mathcal{T}_0^{\mathrm{cut}} = 1$. Good agreement for central values and scale uncertainties.



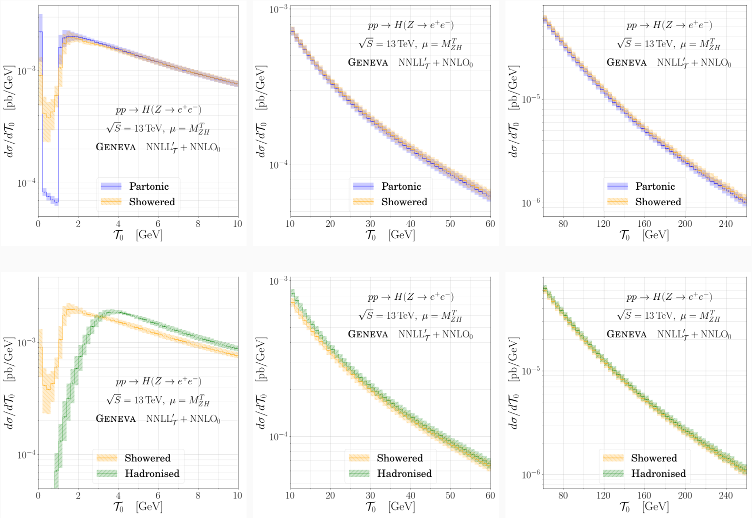
arXiv:1909.02026

Fixed order validation

- We include the gluon fusion channel only at fixed order.
- Important at the LHC – up to 20% effect on differential distributions.
- Large scale uncertainties as process is included effectively only at LO.

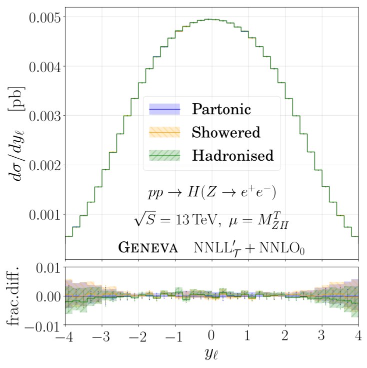


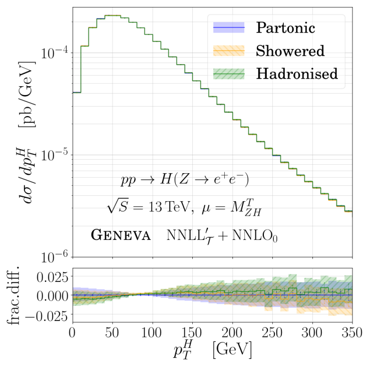
- Shower with PYTHIA8, which also takes care of hadronisation effects and MPI.



Results – inclusive distributions

- Shower changes shape of distributions very little for inclusive distributions.





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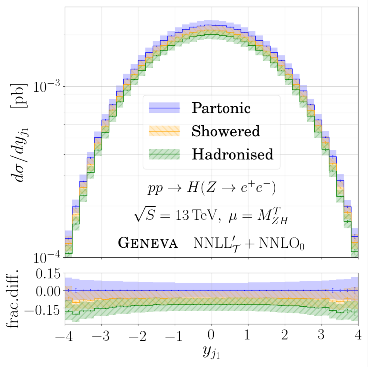
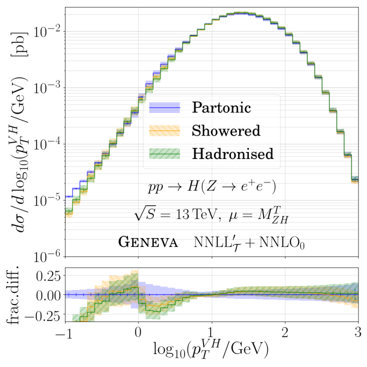
Results – exclusive distributions

- Larger changes in exclusive cases (sensitive to resummation).
- Resummation only being provided at (N)LL by shower.





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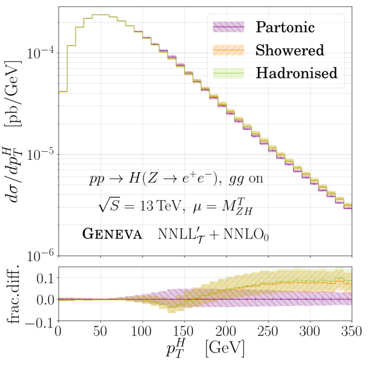
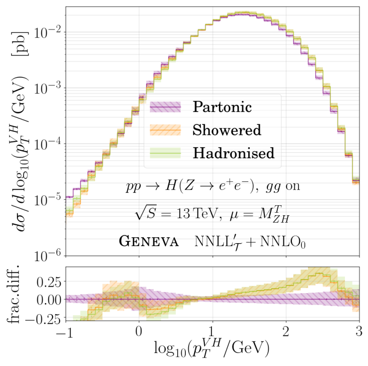
Results – gg channel

- gg channel more sensitive to parton shower (colour effect).
- Effects on Hp_T begin at $\sim$ 100 GeV.





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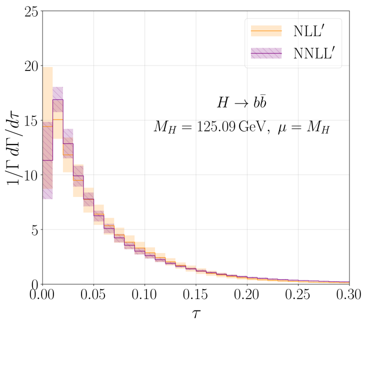
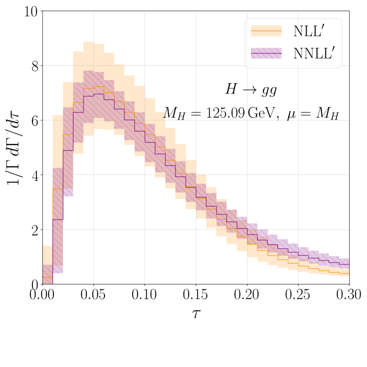
Hadronic Higgs decays

- Most important Higgs decay channel for *VH* production is $H \to b\bar{b}$.
- Given GENEVA implementations for both production and decay, one can combine both in the narrow width approximation.
- Colour singlet in the initial state, coloured particles in the final state – relevant resolution variables at NNLO are now $\mathcal{T}_2$,$\mathcal{T}_3$.





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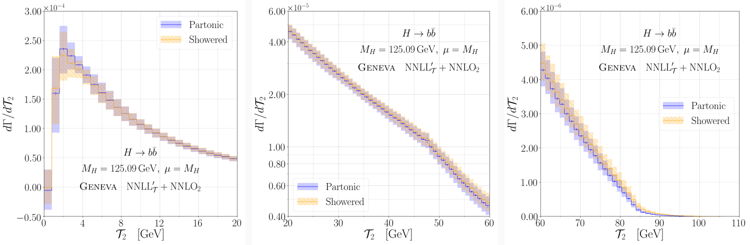
- Given Geneva implementations for both production and decay, one can combine both in the narrow width approximation.
- Colour singlet in the initial state, coloured particles in the final state – relevant resolution variables at NNLO are now $\mathcal{T}_2$,$\mathcal{T}_3$.

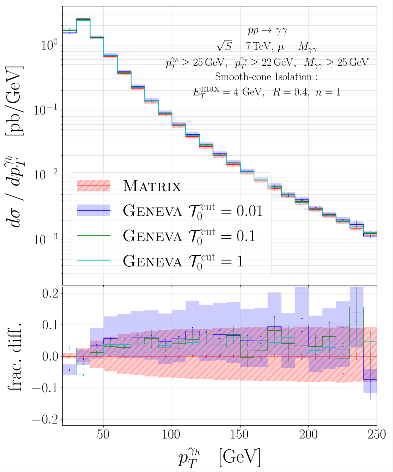


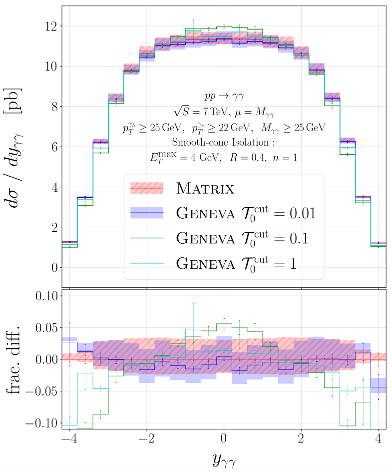
arXiv:2009.13533

Diphoton production

- Diphoton production is an important process at a hadron collider.
- Conceptually, introduces a new problem – process is undefined at Born level, need to introduce isolation criteria to prevent QED/QCD divergences.
- We use Frixione isolation for comparison with FO calculations, hybrid procedure to compare with data.
- Compared predictions to ATLAS and CMS data collected at $\sqrt{s} = 7$ TeV.

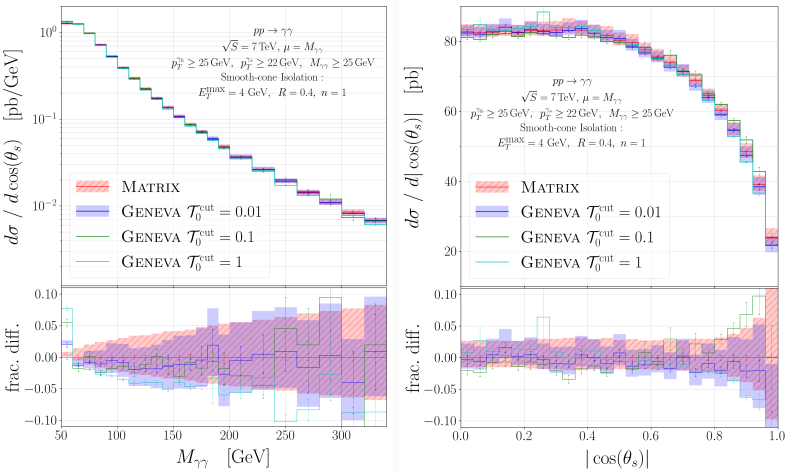
NNLO validation





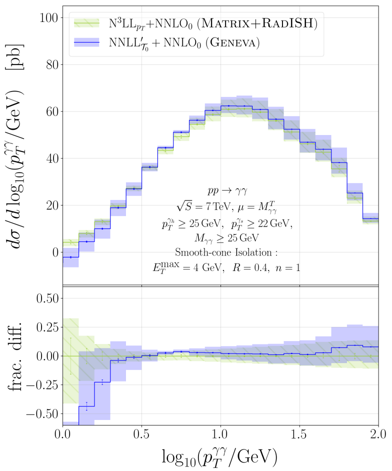
arXiv:2010.10498

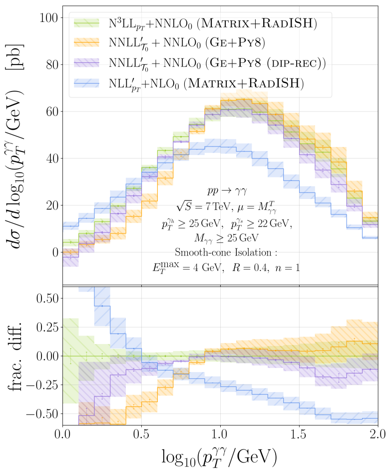
NNLO validation



arXiv:2010.10498

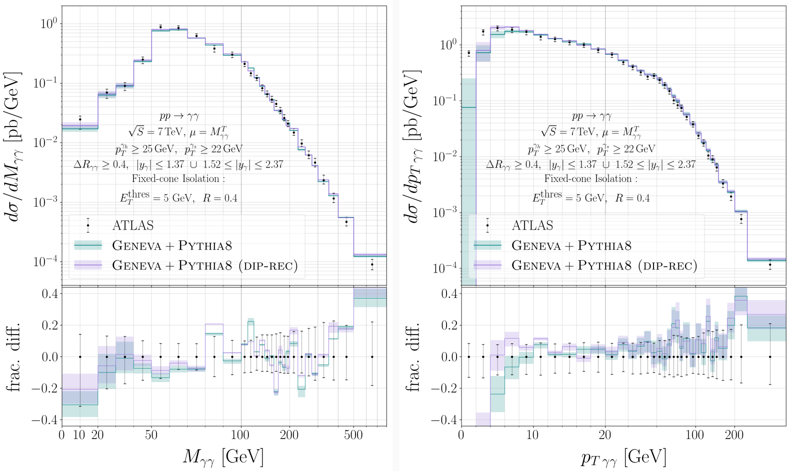
Comparison with dedicated p_T resummation





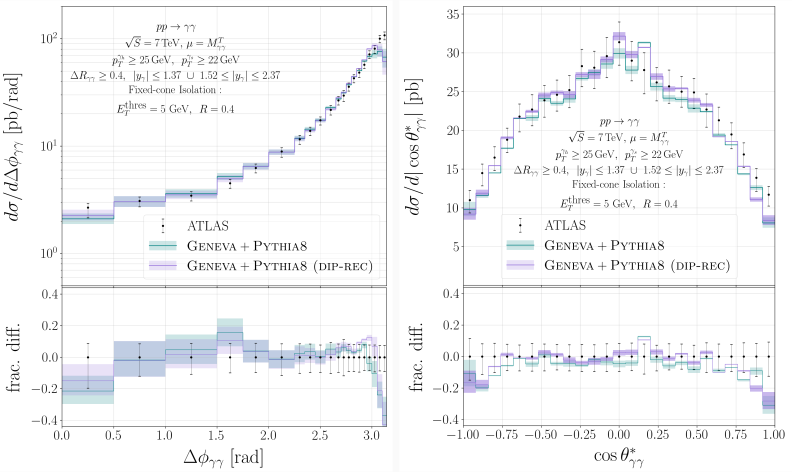
arXiv:2010.10498

Diphoton production – ATLAS 7 TeV



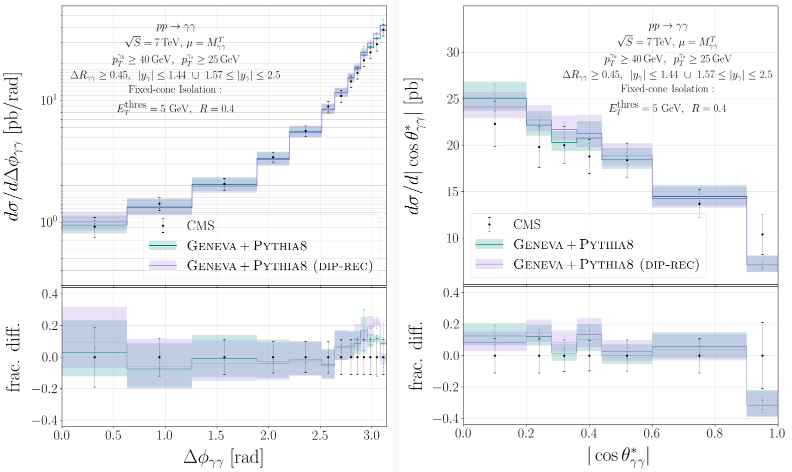
arXiv:2010.10498

Diphoton production – ATLAS 7 TeV



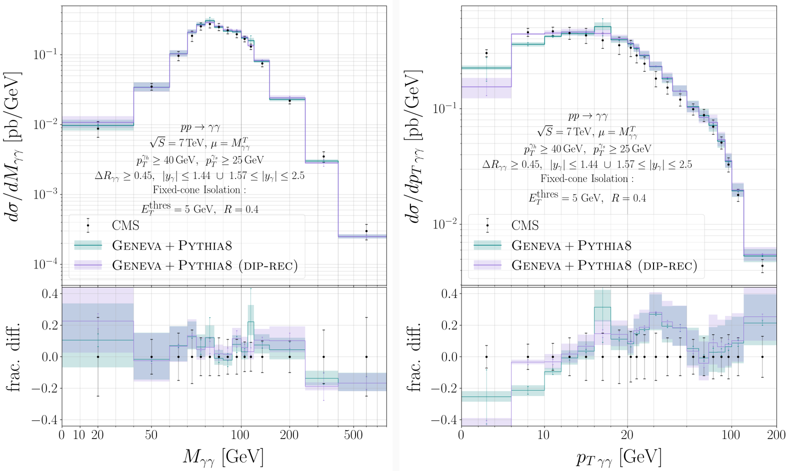
arXiv:2010.10498

Diphoton production – CMS 7 TeV



arXiv:2010.10498

Diphoton production – CMS 7 TeV



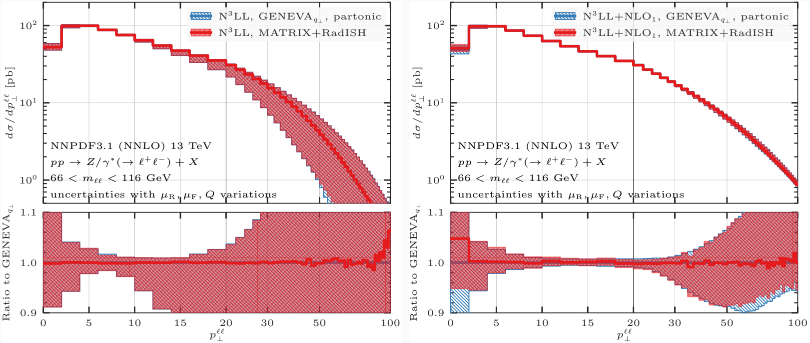
arXiv:2010.10498

Changing the resolution variable

- The GENEVA approach is not specific to a particular resolution variable.
- In particular, as long as a suitable resummed calculation is available, any appropriate variable can be used.
- An obvious candidate is the q_T of the colour singlet system – in this case, we can obtain resummed predictions at N^3LL from RadISH.

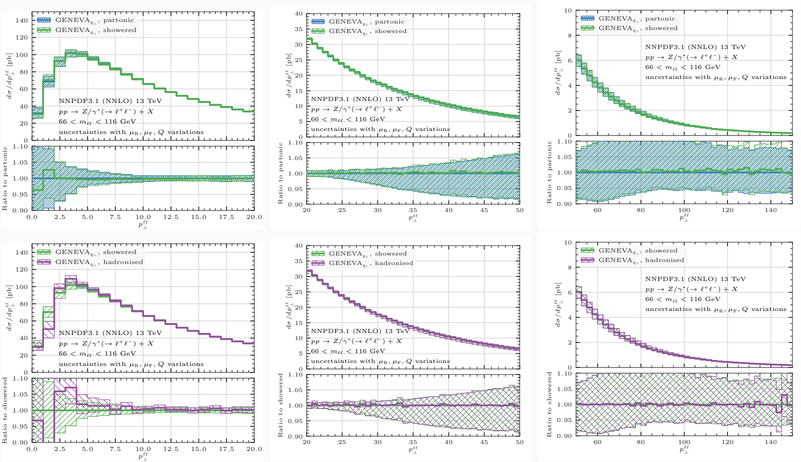
GENEVA+RadISH for Drell-Yan

- N^3LL accuracy maintained in GENEVA compared to matching of RadISH with MATRIX.



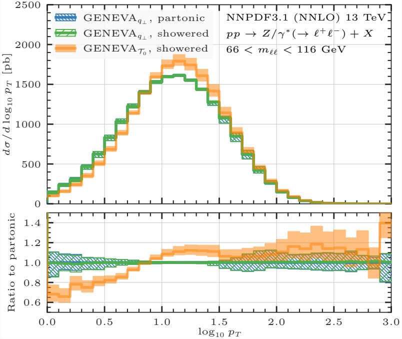
arXiv:21XX.XXXXX

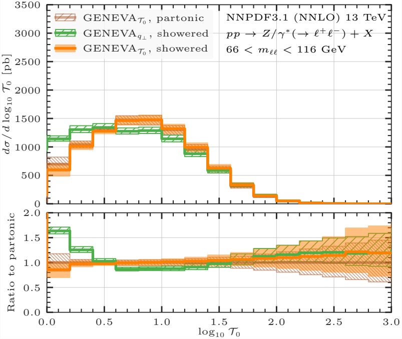
GENEVA+RadISH for Drell-Yan



arXiv:21XX.XXXXX

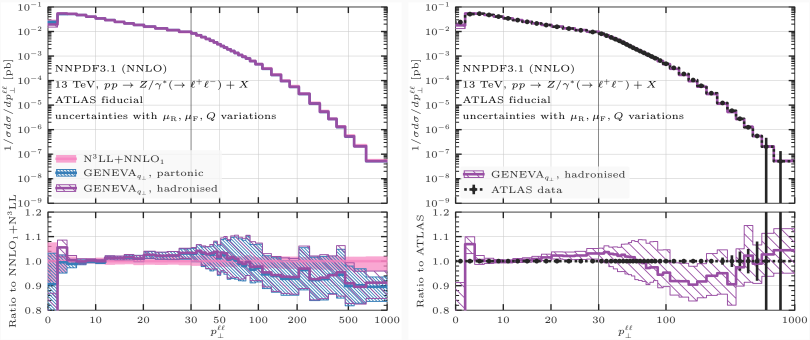
GENEVA+RadISH for Drell-Yan





arXiv:21XX.XXXXX

GENEVA+RadISH for Drell-Yan



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Future directions

Future work

- Matching of Higgs decay to *VH* production is in the pipeline.
- Implementation of other colour-singlet processes also ongoing (Higgs, diboson,...)
- Nothing restricts the application of the Geneva approach to colour-singlet processes - the only bottlenecks are the availability of the relevant perturbative ingredients.

Conclusion

- GENEVA allows resummed, fixed order and parton shower calculations to be combined in order to provide an event generator which makes accurate predictions over the full range of relevant energy scales.
- Flexibility in terms of resolution variable and in how the resummation is accomplished.
- Several applications to colour singlet production already achieved, more forthcoming.
- Double differential resummation also possible in principle ($\mathcal{T}_0$ and p_T), future avenue to explore.
- Future exploration of coloured final states possible.

Backup slides

Power-suppressed contributions to the nonsingular cumulant

- The definition of the Φ_0 events depends on a projective map from higher multiplicity partonic events.
- This means observables dependent on the Φ_0 kinematics are correct at $\mathcal{O}(\alpha_s^2)$ only up to power corrections in $\mathcal{T}_0^{\mathrm{cut}}$.
- We can use this limitation to simplify the expression for the 0-jet formula and write:

$$\frac{\widetilde{\mathrm{d}\sigma_0^{MC}}}{\mathrm{d}\Phi_0}(\mathcal{T}_0^{\mathrm{cut}}) = \frac{\mathrm{d}\sigma^{NNLL'}}{\mathrm{d}\Phi_0}(\mathcal{T}_0^{\mathrm{cut}}) - \left[\frac{\mathrm{d}\sigma^{NNLL'}}{\mathrm{d}\Phi_0}(\mathcal{T}_0^{\mathrm{cut}})\right]_{NLO_0} + B_0(\Phi_0) + V_0(\Phi_0) + \int \frac{\mathrm{d}\Phi_1}{\mathrm{d}\Phi_0} B_1(\Phi_1)\,\theta\left(\mathcal{T}_0(\Phi_1) < \mathcal{T}_0^{\mathrm{cut}}\right) ,$$

- The double virtual and real virtual contributions have been dropped, resulting in a missing nonsingular contribution which is also a power correction in $\mathcal{T}_0^{\mathrm{cut}}$.

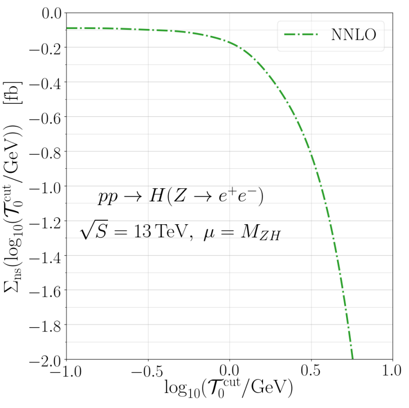
Power-suppressed contributions to the nonsingular cumulant

The missing nonsingular contribution is:

$$\frac{\mathrm{d}\sigma_0^{\mathrm{nons}}}{\mathrm{d}\Phi_0}(\mathcal{T}_0^{\mathrm{cut}}) = \left[\alpha_s f_1(\mathcal{T}_0^{\mathrm{cut}}, \Phi_0) + \alpha_s^2 f_2(\mathcal{T}_0^{\mathrm{cut}}, \Phi_0)\right] \mathcal{T}_0^{\mathrm{cut}}$$

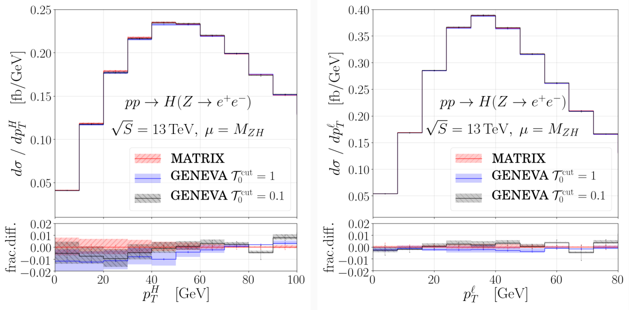
We include the first term fully but neglect the f_2 piece. How big is this effect?

For ZH, this is rather small for $\mathcal{T}_0^{\mathrm{cut}} = 1$ – about 0.7% of the total cross section.



Power-suppressed contributions to the nonsingular cumulant

- We include the effects of the integral of the f_2 term by reweighting the Φ_0 events such that the correct total cross section is obtained.
- Full NNLO cross section provided by MATRIX in this case.
- Missing $\mathcal{O}(\alpha_s^2)$ dependence on Φ_0 variables is of the same order as that missing due to the projective map, even if a full NNLO fixed order calculation were included.



Is NNLL′ accuracy maintained by the shower?

There are two cases to consider: Φ_0 and Φ_2 events (we can say nothing about Φ_1 events and restrict their size by our choice of Λ_1).

- In the Φ_0 case, GENEVA predicts only the normalisation and not the shape of the distribution below $\mathcal{T}_0^{\mathrm{cut}}$ – the shape is filled in completely by the shower and unitarity prevents modification of the NNLL′+NNLO cross section constructed by GENEVA .
- In the Φ_2 case, any difference can only be due to the fact that the PS map does not preserve $\mathcal{T}_0$. We make the ansatz

$$\mathcal{T}_0(\Phi_2) - \mathcal{T}_0(\Phi_3) = a(\Phi_3)\mathcal{T}_2(\Phi_3)$$

- $a(\Phi_3)$ is well behaved in the singular limit, all singular behaviour encoded in $\mathcal{T}_2$.

Is NNLL$'$ accuracy maintained by the shower?

- After the first emission, we have

$$\frac{\mathrm{d}\sigma^S}{\mathrm{d}\mathcal{T}_0} = \int \mathrm{d}\Phi_2 \, \frac{\mathrm{d}\sigma_2}{\mathrm{d}\Phi_2} \, U_2(\mathcal{T}_1^{max}, \Lambda_2) \, \delta[\mathcal{T}_0(\Phi_2) - \mathcal{T}_0] + \int \mathrm{d}\Phi_3 \, \frac{\mathrm{d}\sigma_3^S}{\mathrm{d}\Phi_3} \, \delta[\mathcal{T}_0(\Phi_2) - \mathcal{T}_0 + a\, \mathcal{T}_2(\Phi_3)] \, .$$

- Integrating over the radiation variables and Taylor expanding, the difference before and after the shower is

$$\frac{\mathrm{d}\sigma}{\mathrm{d}\mathcal{T}_0} - \frac{\mathrm{d}\sigma^S}{\mathrm{d}\mathcal{T}_0} = -a \frac{\mathrm{d}}{\mathrm{d}\mathcal{T}_0} \left[\frac{\mathrm{d}\sigma}{\mathrm{d}\mathcal{T}_0} \, \langle \mathcal{T}_2 \rangle \, (\mathcal{T}_0) \right] ,$$

where the average $\mathcal{T}_2$ value is

$$\langle \mathcal{T}_2 \rangle \equiv \int_{\Lambda_2}^{\mathcal{T}_2^{\mathrm{max}}} \mathrm{d}\mathcal{T}_2 \, \mathcal{T}_2 \, U_2'(\mathcal{T}_2^{max}, \mathcal{T}_2) \, .$$

Is NNLL′ accuracy maintained by the shower?

- What is the $\mathcal{T}_0$ dependence of $\langle\mathcal{T}_2\rangle$?
- Consider a LL Sudakov for a single emission:

$$U(\mathcal{T}^{\mathrm{max}},\mathcal{T}) \sim \exp\left[-C\,\frac{\alpha_s}{\pi}\ln^2\frac{\mathcal{T}}{\mathcal{T}^{\mathrm{max}}}\right]$$

- Then we have that

$$\begin{aligned}\langle\mathcal{T}\rangle &\equiv \int_0^{\mathcal{T}^{\mathrm{max}}} \mathrm{d}\mathcal{T}\,\mathcal{T}\,U'(\mathcal{T}^{\mathrm{max}},\mathcal{T}) \\ &\sim\ \mathcal{T}^{\mathrm{max}}\left[1-\frac{e^{\pi/(4\alpha_s C)}\pi\,Erfc\left(\frac{\sqrt{\pi}}{2\sqrt{\alpha_s C}}\right)}{2\sqrt{\alpha_s C}}\right] \\ &\sim 2\,\frac{C\,\alpha_s}{\pi}\,\mathcal{T}^{\mathrm{max}}+\mathcal{O}(\alpha_s^2)\,. \end{aligned} \qquad (1)$$

Is NNLL′ accuracy maintained by the shower?

- Iterated over two emissions, this is

$$\begin{aligned}\langle \mathcal{T}_2 \rangle &= \int_0^{\mathcal{T}_0} \mathrm{d}\mathcal{T}_1 \, U_1'(\mathcal{T}_0, \mathcal{T}_1) \int_0^{\mathcal{T}_1} \mathrm{d}\mathcal{T}_2 \, \mathcal{T}_2 \, U_2'(\mathcal{T}_1, \mathcal{T}_2) \\ &\sim 2 \, \frac{C_2 \alpha_s}{\pi} \int_0^{\mathcal{T}_0} \mathrm{d}\mathcal{T}_1 \, \mathcal{T}_1 \, U'(\mathcal{T}_0, \mathcal{T}_1) \\ &\sim 4 \, \frac{C_1 C_2 \, \alpha_s^2}{\pi^2} \, \mathcal{T}_0 + \mathcal{O}(\alpha_s^3)\end{aligned}$$

- Using this and rewriting, we have that

$$\frac{\frac{\mathrm{d}\sigma}{\mathrm{d}\mathcal{T}_0} - \frac{\mathrm{d}\sigma^S}{\mathrm{d}\mathcal{T}_0}}{\frac{\mathrm{d}\sigma}{\mathrm{d}\mathcal{T}_0}} = f(\mathcal{T}_0) \frac{\langle \mathcal{T}_2 \rangle}{\mathcal{T}_0} \, ,$$

where

$$f(\mathcal{T}_0) \equiv -a \, \frac{\mathrm{d}}{\mathrm{d} \ln \mathcal{T}_0} \ln \left[\frac{\mathrm{d}\sigma}{\mathrm{d} \ln \mathcal{T}_0} \right] \, .$$

Is NNLL′ accuracy maintained by the shower?

- The dominant contribution to the spectrum is

$$\frac{\mathrm{d}\sigma}{\mathrm{d}\ln\mathcal{T}_0} \sim -\alpha_s \ln\mathcal{T}_0\, e^{-\alpha_s \ln^2\mathcal{T}_0}\,,$$

so that

$$f(\mathcal{T}_0) \sim \frac{1}{\ln\mathcal{T}_0}\,.$$

- Then the change of the spectrum after the first emission is

$$\frac{\frac{\mathrm{d}\sigma}{\mathrm{d}\mathcal{T}_0} - \frac{\mathrm{d}\sigma^S}{\mathrm{d}\mathcal{T}_0}}{\frac{\mathrm{d}\sigma}{\mathrm{d}\mathcal{T}_0}} \sim \frac{1}{\ln\mathcal{T}_0}\frac{\langle\mathcal{T}_2\rangle}{\mathcal{T}_0} \sim \frac{\alpha_s^2}{\ln\mathcal{T}_0}\,.$$

- Comparing the dominant term that we omit to the dominant NNLL′ term, we have

$$\frac{\Delta\frac{\mathrm{d}\sigma^{NNLL'}}{\mathrm{d}\mathcal{T}_0}}{\frac{\mathrm{d}\sigma^{NNLL'}}{\mathrm{d}\mathcal{T}_0}} \sim \frac{\alpha_s^3/\mathcal{T}_0}{\alpha_s\ln\mathcal{T}_0/\mathcal{T}_0} \sim \frac{\alpha_s^2}{\ln\mathcal{T}_0}$$

so the effect of first emission of shower on the spectrum is beyond NNLL′ accuracy.

What about the cumulant?

- Above discussion holds for the $\mathcal{T}_0$ spectrum $\mathrm{d}\sigma^{NNLL'}/\mathrm{d}\mathcal{T}_0$, but not necessarily the cumulant $\mathrm{d}\sigma^{NNLL'}(\mathcal{T}_0^{\mathrm{cut}})$.
- Since profile scales have a functional dependence on $\mathcal{T}_0$, choosing scales and integrating over $\mathcal{T}_0$ do not commute – difference is $\mathcal{O}(N^3LL)$. Inclusive FO cross section not recovered exactly!
- Solution: add term to spectrum so that
  1. The integral of the modified spectrum gives the correct FO cross section;
  2. Term only contributes in region of $\mathcal{T}_0$ where missing N^3LL terms are large;
  3. Term is itself $\mathcal{O}(N^3LL)$ to prevent spoiling $NNLL'$ accuracy.

What about the cumulant?

Add the term:

$$\kappa(\mathcal{T}_0)\left[\frac{\mathrm{d}}{\mathrm{d}\mathcal{T}_0}\frac{\mathrm{d}\sigma^{NNLL'}}{\mathrm{d}\Phi_0}(\mathcal{T}_0,\mu_h(\mathcal{T}_0)) - \frac{\mathrm{d}\sigma^{NNLL'}}{\mathrm{d}\Phi_0\mathrm{d}\mathcal{T}_0}(\mu_h(\mathcal{T}_0))\right]$$

- Of higher order (by construction);
- In FO region, $\mu_h = Q$ and difference between terms is zero (scales are constant) – term vanishes;
- Tune $\kappa(\mathcal{T}_0 \to 0)$ so that correct inclusive cross section is obtained on integration.

Including the Higgs decay at NNLO

$$
\overbrace{\frac{d\sigma_0^{MC}}{d\Phi_{\ell^+\ell^- b\bar{b}}}(\mathcal{T}_0^{cut};\tau_2^{cut})}^{(\mathrm{NNLL'+NNLO_0})\otimes(\mathrm{NNLL'+NNLO_0})} =
$$

$$
\overbrace{\frac{d\sigma_0^{MC}}{d\Phi_{\ell^+\ell^- H}}(\mathcal{T}_0^{cut})}^{\mathrm{NNLL'+NNLO_0}} \times \frac{d\Gamma^{(0)}_{H\to b\bar{b}}}{d\Phi_{H\to b\bar{b}}} + \frac{d\sigma^{(0)}_{\ell^+\ell^- H}}{d\Phi_{\ell^+\ell^- H}} \times \overbrace{\frac{d\Gamma_0^{MC}}{d\Phi_{H\to b\bar{b}}}(\tau_2^{cut})}^{\mathrm{NNLL'+NNLO_0}}
$$

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

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

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

Including the Higgs decay at NNLO

$$\overbrace{\frac{d\sigma_1^{MC}}{d\Phi_{\ell^+\ell^- b\bar{b}j}}(\mathcal{T}_0 > \mathcal{T}_0^{cut}; \mathcal{T}_1^{cut}; \tau_2^{cut})}^{(\mathrm{NNLL'+NLO_1})\otimes(\mathrm{NLL+NLO_0})} =$$

$$\overbrace{\frac{d\sigma_1^{MC}}{d\Phi_{\ell^+\ell^- Hj}}(\mathcal{T}_0 > \mathcal{T}_0^{cut}; \mathcal{T}_1^{cut})}^{\mathrm{NNLL'+NLO_1}} \times \frac{d\Gamma^{(0)}_{H\to b\bar{b}}}{d\Phi_{H\to b\bar{b}}} +$$

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

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

Including the Higgs decay at NNLO

$$\overbrace{\frac{d\sigma_1^{MC}}{d\Phi_{\ell^+\ell^- b\bar{b}j}}(\mathcal{T}_0^{cut};\tau_2^{dec}>\tau_2^{cut};\tau_3^{cut})}^{(\mathrm{NLL+NLO_0})\otimes(\mathrm{NNLL'+NLO_1})} =$$

$$\frac{d\sigma^{(0)}_{\ell^+\ell^- H}}{d\Phi_{\ell^+\ell^- H}} \times \overbrace{\frac{d\Gamma_1^{MC}}{d\Phi_{H\to b\bar{b}j}}(\tau_2^{dec}>\tau_2^{cut};\tau_3^{cut})}^{\mathrm{NNLL'+NLO_1}} +$$

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

$$\times \overbrace{\frac{d\Gamma_1^{MC}}{d\Phi_{H\to b\bar{b}j}}(\tau_2^{dec}>\tau_2^{cut};\tau_3^{cut})}^{\mathrm{NLL+LO_1}}.$$

Including the Higgs decay at NNLO

$$\overbrace{\frac{d\sigma_2^{MC}}{d\Phi_{\ell^+\ell^- b\bar{b}jj}}(\mathcal{T}_0 > \mathcal{T}_0^{cut}; \mathcal{T}_1 > \mathcal{T}_1^{cut}; \tau_2^{cut})}^{(\mathrm{NNLL}'+\mathrm{LO}_2)\otimes\mathrm{LO}_0} = \overbrace{\frac{d\sigma_2^{MC}}{d\Phi_{\ell^+\ell^- Hjj}}(\mathcal{T}_0 > \mathcal{T}_0^{cut}; \mathcal{T}_1 > \mathcal{T}_1^{cut})}^{\mathrm{NNLL}'+\mathrm{LO}_2} \times \frac{d\Gamma^{(0)}_{H\to b\bar{b}}}{d\Phi_{H\to b\bar{b}}}$$

$$\overbrace{\frac{d\sigma_2^{MC}}{d\Phi_{\ell^+\ell^- b\bar{b}jj}}(\mathcal{T}_0 > \mathcal{T}_0^{cut}; \mathcal{T}_1^{cut}; \tau_2^{dec} > \tau_2^{cut}; \tau_3^{cut})}^{(\mathrm{NLL}+\mathrm{LO}_1)\otimes(\mathrm{NLL}+\mathrm{LO}_1)} = \overbrace{\frac{d\sigma_1^{MC}}{d\Phi_{\ell^+\ell^- Hj}}(\mathcal{T}_0 > \mathcal{T}_0^{cut}; \mathcal{T}_1^{cut})}^{\mathrm{NLL}+\mathrm{LO}_1} \times \overbrace{\frac{d\Gamma_1^{MC}}{d\Phi_{H\to b\bar{b}j}}(\tau_2^{dec} > \tau_2^{cut}; \tau_3^{cut})}^{\mathrm{NLL}+\mathrm{LO}_1}$$

Including the Higgs decay at NNLO

$$\overbrace{\frac{d\sigma_2^{MC}}{d\Phi_{\ell^+\ell^- b\bar{b}jj}}(\mathcal{T}_0^{cut};\mathcal{T}_1^{cut};\tau_2^{dec} > \tau_2^{cut};\tau_3 > \tau_3^{cut})}^{\mathrm{LO}_0\otimes(\mathrm{NNLL}'+\mathrm{LO}_2)} =$$

$$\frac{d\sigma^{(0)}_{\ell^+\ell^- H}}{d\Phi_{\ell^+\ell^- H}} \times \overbrace{\frac{d\Gamma_2^{MC}}{d\Phi_{H\to b\bar{b}jj}}(\tau_2^{dec} > \tau_2^{cut};\tau_3 > \tau_3^{cut})}^{\mathrm{NNLL}'+\mathrm{LO}_2}$$

Photon isolation procedures

- We are interested only in prompt photon production, where the photons are produced in the hard scattering interaction
- Need to remove contribution from fragmentation process, where photons are radiated off final-state jets.
- A fixed-cone algorithm restricts the amount of hadronic energy allowed to lie within a cone around the jet, BUT
- This is not IR-safe – forbids soft emissions inside the cone.
- Still sensitive to fragmentation, since collinear configurations are still allowed.

Frixione isolation

- An IR-safe method to isolate photons has been provided by Frixione.
- Consider a series of sub-cones with radius $r < R_{\rm iso}$ where $R_{\rm iso}$ is the outer cone radius. We then require

$$E_T^{\rm had}(r) \leq E_T^{\rm max} \chi(r; R_{\rm iso})$$

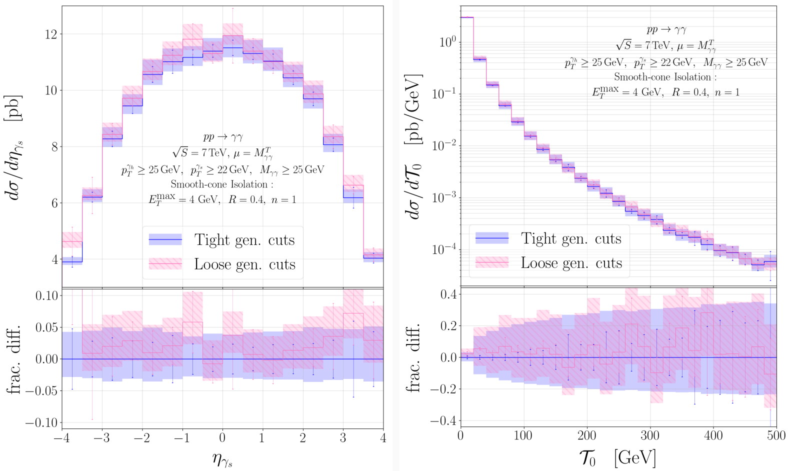
  where the isolation function χ is smooth and monotonic.
- This reduces hadronic activity in a smooth way when approaching the photon direction.
- Standard choice is

$$\chi(r; R_{\rm iso}) = \left(\frac{1 - \cos r}{1 - \cos R_{\rm iso}} \right)^n$$

Hybrid isolation

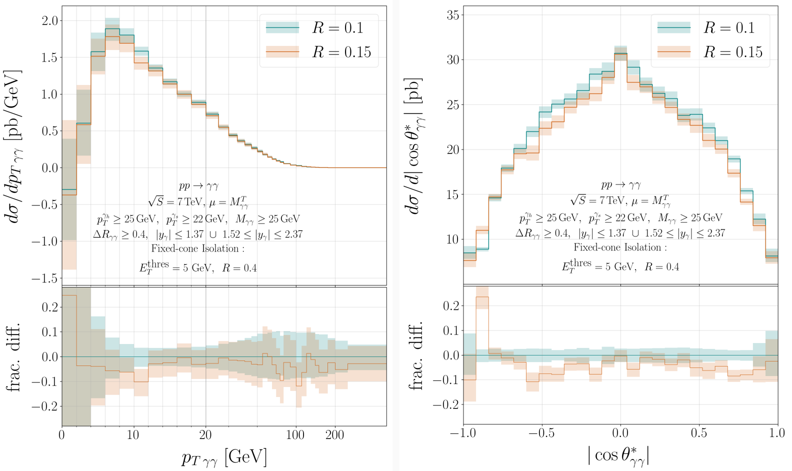
- Frixione isolation complicates comparison with experimental analyses, which always use a fixed-cone approach.
- A hybrid-cone procedure uses Frixione isolation with a very small R_{iso} to remove a tiny slice of phase space around the photon.
- A fixed-cone procedure with a larger radius $R \gg R_{\mathrm{iso}}$ is then applied to events passing the first isolation step.

Isolation dependence



arXiv:2010.10498

Isolation dependence



arXiv:2010.10498