Current status of the GENEVA event generator and recent improvements

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on behalf of the GENEVA collaboration

Overview of GENEVA

GENEVA consistently combines three theoretical ingredients of QCD calculations

1. **fully differential fixed-order calculation**
   - up to **NNLO** through N-jettiness ($\mathcal{T}_N$) subtraction
2. **higher-order resummation**
   - up to **NNLL′** in $\mathcal{T}_0$ using SCET
   - not limited to SCET nor to $\mathcal{T}_N$ (we have p_T at **N^{3}LL** via RadISH)
3. **parton shower, hadronization and MPI**
   - provided by a shower MC (currently PYTHIA8 or SHERPA)

⇒ **produce a NNLO+NNLL′+PS event generator**

Advantages of higher-order resummation

- link between **NNLO** and **PS**
- consistently improve perturbative accuracy over full spectrum
- provide event-by-event systematic estimate of theory uncertainties

Overview of GENEVA

1. slice the phase space into jet bins using a **resolution parameter** (like $\mathcal{T}_0$ or p_T)
2. compute FO + resummed **matched cross section** up to NNLO+NNLL′
3. fill in additional radiation by **matching to a parton shower**, in a way that avoids spoiling the resummed accuracy
4. include **hadronization and MPI**

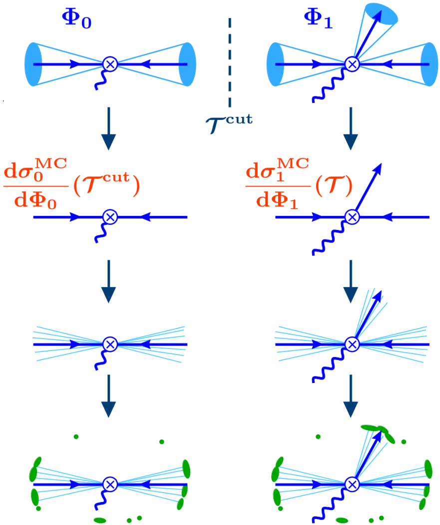


figure by F. Tackmann

N-jettiness as resolution parameter

Separate phase space Φ into jet bins Φ_N, then let $\mathcal{T}_N^{\mathrm{cut}} \to 0$

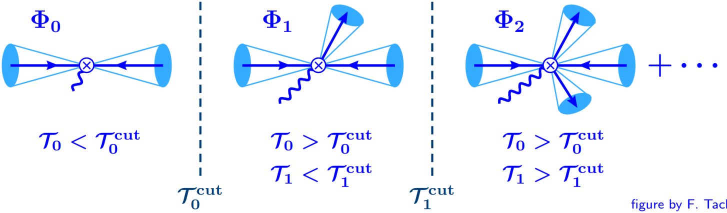


figure by F. Tackmann

$$\frac{d\sigma_0}{d\Phi_0}(\mathcal{T}_0^{\mathrm{cut}}) \qquad \frac{d\sigma_1}{d\Phi_1}(\mathcal{T}_0 > \mathcal{T}_0^{\mathrm{cut}}) \qquad \frac{d\sigma_2}{d\Phi_2}(\mathcal{T}_1 > \mathcal{T}_1^{\mathrm{cut}})$$

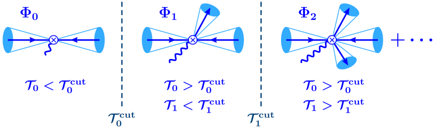
Advantages of $\mathcal{T}_N$

Most GENEVA applications use **N-jettiness $\mathcal{T}_N$** [Stewart, Tackmann, Waalewijn '09, '10] as resolution parameter

- classify jet observables in an **IR-safe** way, can take $\mathcal{T}_N \to 0$
- **resummation** of large $\mathcal{T}_N$ logarithms **known** up to *at least* NNLL′ in SCET for color-singlet final state

other possible res. variable p_T [Alioli, Bauer, Broggio, Gavardi, Kallweit, Lim, RN, Napoletano, Rottoli 2102.08390]
but also p_T^{jet}, k_T-ness, ...

Matching fixed-order and resummed calculations



At NNLO needed:

- $\mathbf{0/1}$-jet res. parameter
- $\mathbf{1/2}$-jet res. parameter

Jet-bin cross sections (simplified)

$$\frac{d\sigma_0}{d\Phi_0}(\mathcal{T}_0^{\rm cut}) = \frac{d\sigma^{\rm NNLL'}}{d\Phi_0} + \overbrace{\frac{d\sigma_0^{\rm FO}}{d\Phi_0} - \frac{d\sigma^{\rm NNLL'}}{d\Phi_0}\bigg|_{\alpha_s^2}}^{d\sigma^{\rm nons}}$$

$$\frac{d\sigma_1}{d\Phi_1}(\mathcal{T}_0 > \mathcal{T}_0^{\rm cut}) = \left[\frac{d\sigma^{\rm NNLL'}}{d\Phi_0 d\mathcal{T}_0} - \frac{d\sigma^{\rm NNLL'}}{d\Phi_0 d\mathcal{T}_0}\bigg|_{\alpha_s^2}\right]\mathcal{P}(\Phi_1) + \frac{d\sigma_1^{\rm FO}}{d\Phi_1}$$

$$\frac{d\sigma_2}{d\Phi_2}(\mathcal{T}_1 > \mathcal{T}_1^{\rm cut}) = \left[\frac{d\sigma^{\rm NNLL'}}{d\Phi_0 d\mathcal{T}_0} - \frac{d\sigma^{\rm NNLL'}}{d\Phi_0 d\mathcal{T}_0}\bigg|_{\alpha_s^2}\right]\mathcal{P}(\tilde{\Phi}_1)\,\mathcal{P}(\Phi_2) + \frac{d\sigma_2^{\rm FO}}{d\Phi_2}$$

1. splitting functions $\mathcal{P}$ make resummed piece differential in Φ_N
   $\hookrightarrow$ new treatment of functions $\mathcal{P}$
2. usually also resum $\mathbf{1/2}$-jet res. variable with $\mathcal{T}_1$ **NLL Sudakov**

$\mathcal{T}_0$ resummation in SCET

For color singlet final state, the $\mathcal{T}_0$ spectrum is factorized in SCET

[Stewart, Tackmann, Waalewijn '09]

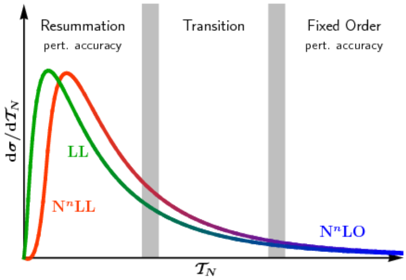
$$\frac{d\sigma}{d\mathcal{T}_0} = \sum_{ij} H_{ij}(\mu) \int dt_a dt_b \, B_i(t_a, \mu) \, B_j(t_b, \mu) \, S_{ij}\left(\mathcal{T}_0 - \frac{t_a + t_b}{Q}, \mu\right)$$

- **hard function** H_{ij} is process dependent, at NNLO contains the 2-loop virtual corrections
- **beam functions** B_i known up to N^{3}LO
- **soft function** S_{ij} is process dependent, only perturbative part included

Resummation

- compute each at its typical scale $\mu_H \sim Q$, $\mu_B \sim \sqrt{Q\mathcal{T}_0}$ and $\mu_S \sim \mathcal{T}_0$
- resum by **RGE evolution** $\mu_i \to \mu$
- **New:** we take the resummed results from `scetlib` [Ebert, Michel, Tackmann, et al.]
- similar factorization formulae for resummation in other variables (like p_T)

$\mathcal{T}_0$ spectrum and profile scales



- **peak region**: nonsingulars are power-suppressed; pert. accuracy determined by **resummation**
- **transition region**: smooth connection; scale choice generates ambiguity
- **tail region**: power expansion breaks down, must turn off resummation; pert. accuracy determined by **fixed order**

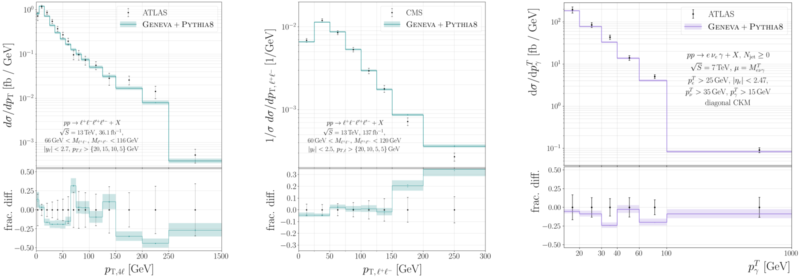
Profile scales

This is achieved by appropriate choice of $\mathcal{T}_N$-dependent **profile scales** $\mu_i(\mathcal{T}_N)$ so that while approaching the FO region, all scales $\mu_i \to \mu_{\mathrm{FO}}$

- profile scale variations **isolate different sources of pert. uncertainties**
- total theoretical uncertainty **combining FO and resummation** scale variations
- cross section evaluated at all sets of scales, so that pert. uncertainty are **provided event-by-event**

List of available NNLO processes in GENEVA

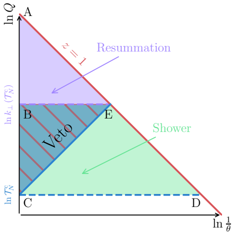
- Drell-Yan ($\mathcal{T}_0$) [Alioli, Bauer, Berggren, Tackmann, Walsch 1508.01475]
- Higgsstrahlung [Alioli, Broggio, Kallweit, Lim, Rottoli 1909.02026]
- Higgs decays (gg, $b\bar{b}$) [Alioli, Broggio, Gavardi, Kallweit, Lim, RN, Napoletano, Rottoli 2009.13533]
- $\gamma\gamma$ [Alioli, Broggio, Gavardi, Kallweit, Lim, RN, Napoletano, Rottoli 2010.10498]
- Drell-Yan (p_T) [Alioli, Bauer, Broggio, Gavardi, Kallweit, Lim, RN, Napoletano, Rottoli 2102.08390]
- ZZ [Alioli, Broggio, Gavardi, Kallweit, Lim, RN, Napoletano, Rottoli 2103.01214]
- $W^\pm\gamma$ [Cridge, Lim, RN 2105.13214]
- **New:** $gg \to HH$ [Alioli, Billis, Broggio, Gavardi, Kallweit, Lim, Marinelli, RN, Napoletano 2212.10489]
- **New:** $gg \to H$ [Alioli, Billis, Broggio, Gavardi, Kallweit, Lim, Marinelli, RN, Napoletano 2301.11875]



Parton shower interface

Two challenges

- **avoid impacting pert. accuracy** of $\mathcal{T}_0$ spectrum
- **avoid double counting** between resummation in $\mathcal{T}_0$ and PS (usually not $\mathcal{T}$-ordered)



Matching to a parton shower in Geneva

- impose veto **discarding showered events with $\mathcal{T}_N > \mathcal{T}_N^{\mathrm{cut}}$**
- all **Φ_0 events** are showered with the only requirement $\mathcal{T}_0 < \mathcal{T}_0^{\mathrm{cut}}$
- **first shower emission $\Phi_1 \to \Phi_2$** performed by hand in Geneva using $\mathcal{T}_0$-preserving mapping
- starting from **Φ_2 events**, PS affects $\mathcal{T}_0$ spectrum only beyond NNLL′

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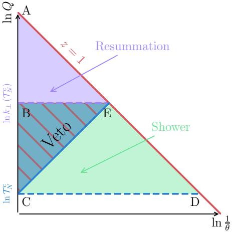
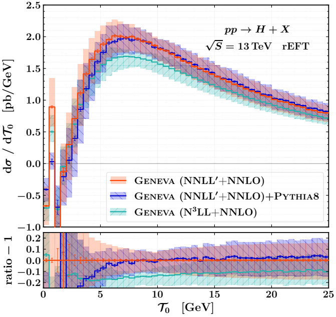
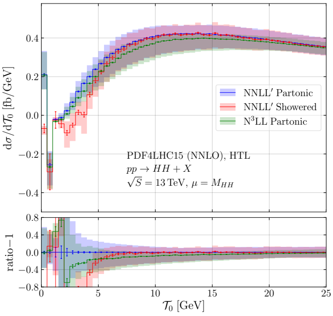
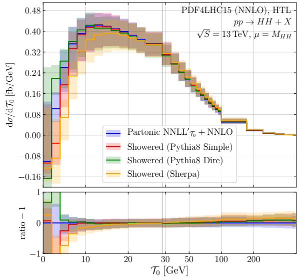


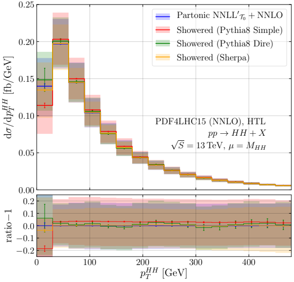


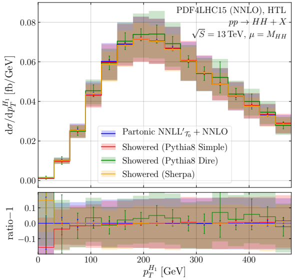


New: interface with different parton shower MCs

- study effects of different **PS evolution variables**
- estimate shower matching uncertainty
- currently possible to interface
  - PYTHIA8
  - **New:** DIRE (in PYTHIA8)
  - **New:** SHERPA
- applied to $gg \to HH$ process





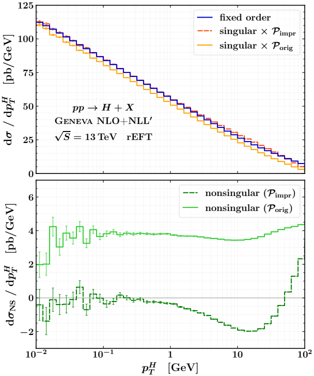


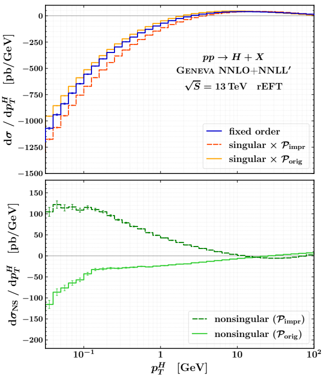
Improved treatment of splitting functions $\mathcal{P}$

Reproduce higher-multiplicity phase space

$$\frac{d\sigma_1}{d\Phi_1}(\mathcal{T}_0 > \mathcal{T}_0^{\rm cut}) = \left[\frac{d\sigma^{\rm NNLL'}}{d\Phi_0 d\mathcal{T}_0} - \frac{d\sigma^{\rm NNLL'}}{d\Phi_0 d\mathcal{T}_0}\bigg|_{\alpha_s^2}\right]\mathcal{P}(\Phi_1) + \frac{d\sigma_1^{\rm FO}}{d\Phi_1}$$

- soft and collinear limit in $\mathcal{P}_{0\to 1}$ $\Rightarrow$ now correctly reproduced
- soft and collinear limit in $\mathcal{P}_{1\to 2}$ $\Rightarrow$ improved, now only miss single log
- **New:** tested on $gg \to H$ and Drell-Yan





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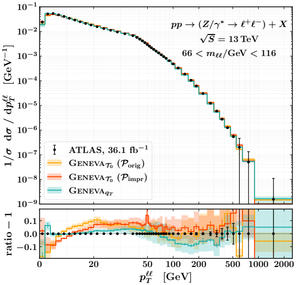
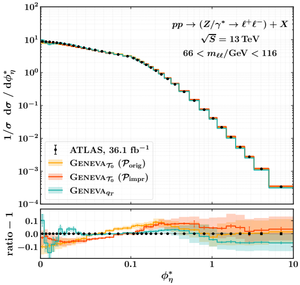




Complex scale prescription

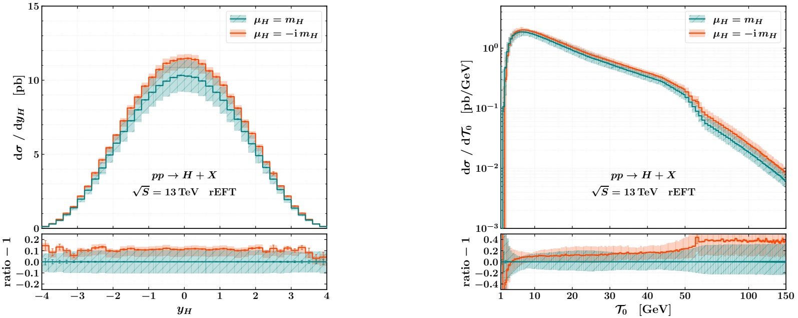
- allow choice of **complex hard scale** μ_H in resummed cross section

$$\mu_H = Q \quad \to \quad \mu_H = -i\,Q$$

- include **additional source of theory uncertainty** ϕ

$$\mu_H = Q\,e^{i\phi}, \qquad \phi \in [\pi/4, 3\pi/4]$$

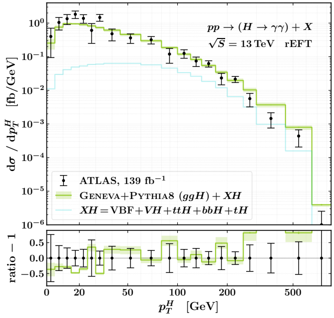
- **"resumming" large π^2 terms** arising from $\log^k(-q^2/\mu^2)$, effectively reducing overall theory uncertainty
- **New:** implemented for $gg \to H$ production

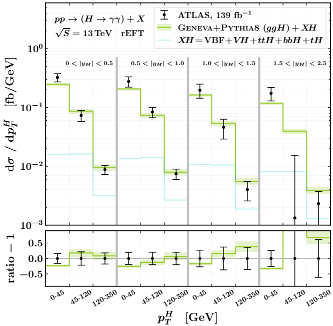


Comparison to ATLAS and CMS Higgs data

Comparing to latest ATLAS [CERN-EP-2021-227] and CMS [CERN-EP-2022-142] data sets for Higgs differential cross sections in the **diphoton decay channel**

- $gg \to H$ computed at **NNLO+NNLL$'_0$+NLL$_1$+PS** in GENEVA, in the **rescaled EFT scheme**
  $\hookrightarrow m_t \to \infty$, rescaled by exact overall LO m_t dependence
- $H \to \gamma\gamma$ inserted by PYTHIA8 at LO in QCD
- include VBF, VH, ttH, etc. taken from experimental simulations
- **New:** include **7 point scale variations**, nondiagonal in $\{\mu_R, \mu_F\}$





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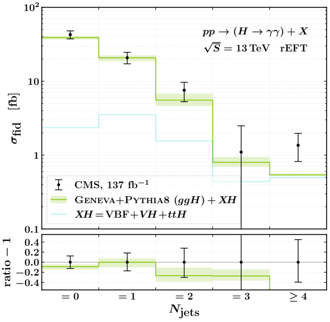
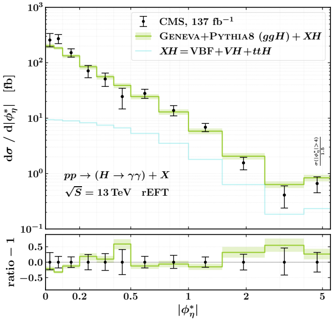




WIP: $pp \to Z + j$ at NNLO in GENEVA

1-jet final state

- $Z + j$ needs **process-defining cuts** (e.g. $\mathcal{T}_0$ or p_T cut)
- relevant Φ_1/Φ_2 resolution variable is $\mathcal{T}_1$
- at NNLO need a $\mathcal{T}_1$-preserving **phase-space mapping** $\Rightarrow$ **still WIP!**

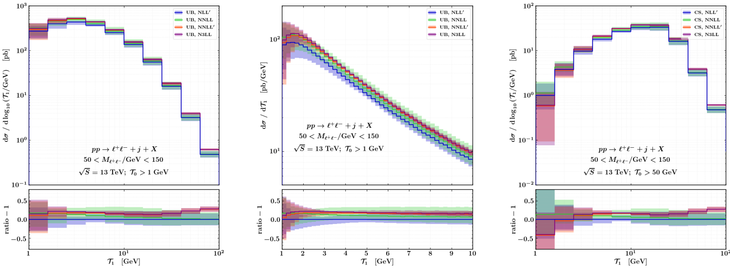
$Z + j$ in GENEVA

- only $\mathcal{T}_1$ spectra computed, with **resummation up to N^{3}LL**
- $\mathcal{T}_1$ definition introduces **frame dependence**
  - underlying Born frame (**UB**)
  - colour singlet frame (**CS**)
  - laboratory frame (**LAB**)
- factorization formula in SCET (showing explicit frame dependence)

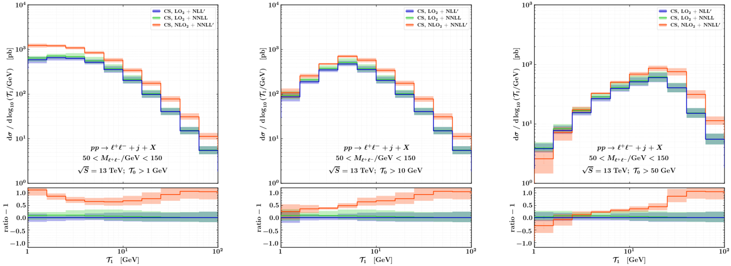
$$\frac{d\sigma}{d\mathcal{T}_1} = \sum_{\kappa} H_\kappa \int dt_a dt_b ds_J \, B_{\kappa_a}(t_a)\, B_{\kappa_b}(t_b)\, J_{\kappa_J}(s_J)$$
$$\times\, S_\kappa\left(n_{a,b}\cdot n_J, \mathcal{T}_1 - \frac{t_a}{Q_a} - \frac{t_b}{Q_b} - \frac{s_J}{Q_J}\right)$$

WIP: Resummed and matched $\mathcal{T}_1$ spectrum

Resummed spectra:



Matched results:



Outlook

More processes

- $Z + j$ ($\mathcal{T}_1$-preserving $1 \to 2$ mapping is WIP)
- $t\bar{t}$, $t\bar{t}V$ ($\mathcal{T}_0$ resummation for $t\bar{t}$ already done [Alioli, Broggio, Lim 2111.03632])
- $Z\gamma$ ($\dots W\gamma$ already there)
- $gg \to (H)H$ with exact m_t dependence

More features

- implement different 0-jet resolution variable, e.g. p_T, for more processes
- include EW corrections to Drell-Yan
- revamp $e^+e^- \to X$ generator

Conclusions

- **GENEVA** performs matching of NNLO calculations with higher-order resummation and parton shower MCs
- versatile framework:
  - freedom to choose jet-resolution variables ($\mathcal{T}_0$, p_T mappings tested)
  - freedom to choose resummation formalism (SCET, RadISH implemented)
  - interface to **different parton showers** (PYTHIA8, DIRE, SHERPA already in)
- implemented for several processes, **latest:** $gg \to H$, HH
- covered a few technical improvements:
  - **better accuracy** of differential distributions **in the soft & collinear limits**
  - consolidated theory uncertainty by allowing **7-point scale variations**
  - included π^2 **resummation** through new `scetlib` interface
- first steps towards NNLO+NNLL′+PS for **coloured final states**: stay tuned!

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Thank you!

Backup: N-jettiness

General definition

For a phase space point with M final state particles ($M > N$)

$$\mathcal{T}_N(\Phi_M) = \sum_k \min\{\hat{q}_a \cdot p_k, \hat{q}_b \cdot p_k, \hat{q}_1 \cdot p_k, \ldots, \hat{q}_N \cdot p_k\}$$

where $\hat{q}_{a,b}$ are **beam directions** and $\hat{q}_i$ are **jet direction** 4-vectors

[Stewart, Tackmann, Waalewijn '09, '10]

- physical meaning: as $\mathcal{T}_N \to 0$ the final state looks more like a N-jet final state, i.e. **unresolved emissions** are **either soft or collinear** to one of the beam or jet directions
- $\mathcal{T}_0$ definition corresponds to **beam thrust**, happens to be boost invariant

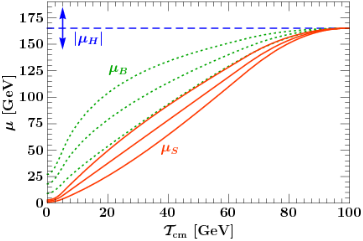
$$\mathcal{T}_0 = \sum_k |p_k^\perp| e^{-|\eta_k - Y|}$$

- $\mathcal{T}_1$ is **not boost invariant**, frame dependence through Q_a, Q_b, Q_J

$$\mathcal{T}_1 = \sum_k \min\left\{\frac{2q_a \cdot p_k}{Q_a}, \frac{2q_b \cdot p_k}{Q_b}, \frac{2q_J \cdot p_k}{Q_J}\right\}$$

Backup: Profile scales

- $\mathcal{T}_0$ resummation is performed by RGE-evolving each piece H, B_i, S from their typical scales μ_H, μ_B, μ_S to the common μ
- when $\sigma^{\text{nons}} \sim \sigma^{\text{sing}}$, resummation must be switched off



- achieve this via smooth $\mathcal{T}_0$-dependent profile scales

$$\mu_H(\mathcal{T}_0) = \mu_{\rm FO}$$
$$\mu_B(\mathcal{T}_0) = \mu_{\rm FO}\sqrt{f(\mathcal{T}_0/Q)}$$
$$\mu_S(\mathcal{T}_0) = \mu_{\rm FO}\, f(\mathcal{T}_0/Q)$$

- for $\mathcal{T}_0$ in the resummation region $f(\mathcal{T}_0/Q) = \mathcal{T}_0/Q$
- for $\mathcal{T}_0$ in the fixed-order region $f(\mathcal{T}_0/Q) = 1$

  $\Rightarrow \mu_H = \mu_B = \mu_S = \mu_{\rm FO}$
- in nonperturbative region $f(\mathcal{T}_0/Q)$ freezes all scales to a minimum value
- scale uncertainty estimated by independently varying $\mu_F O$, μ_S, μ_B, and varying the functions $f(\mathcal{T}_0/Q)$ themselves

Backup: Ingredients of N^{3}LL $\mathcal{T}_1$ resummation

Hard, beam, jet, and soft functions

- **hard function** known analytically up to two loops [Gehrmann, Tancredi, et al. '11, '22]
- at NNLL′ include one-loop squared $gg \to Zg$

- **beam and jet functions** known at N^{3}LO [Ebert, Mistlberger, Vita '20] [Bruser, Liu, Stahlhofen '18]
- only NNLO beam [Gaunt, Stahlhofen, Tackmann '14] and jet [Becher, Neubert '06; Becher, Bell '11] are needed for our purpose

- **soft function** at NLO implemented as on-the-fly integrals using [Jouttenus, Stewart, Tackmann, Waalewijn '13]
- NNLO boundary terms provided by interpolation over `SoftSERVE` grids [Bell, Rahn, Talbert '18, '20]

- NLO results validated in all frames
- NNLO results validated in underlying Born frame against MCFM [Campbell, Ellis, Mondini, Williams '17]; for other frames ours are first results