GENEVA Monte Carlo: status and new developments

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Istituto Nazionale di Fisica Nucleare

UNIVERSITA' DEGLI STUDI DI MILANO BICOCCA

Outline

- Theoretical framework:
  - **GENEVA** method;
  - $\mathcal{T}_0$ and $\mathcal{T}_1$ resummation;
  - Interface to parton shower;
- Recent applications
- Future plans

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GENEVA: GENerate EVents Analytically

Fully differential fixed order calculations

up to NNLO through N-jettiness ($\mathcal{T}_N$) subtraction,

Higher-logarithmic resummation

up to N3LL through SCET or pT-resummation
for colour singlet production,

Parton showering, hadronization and MPI

GENEVA method

resolution parameter ⟶ N-jettiness $\mathcal{T}_N$

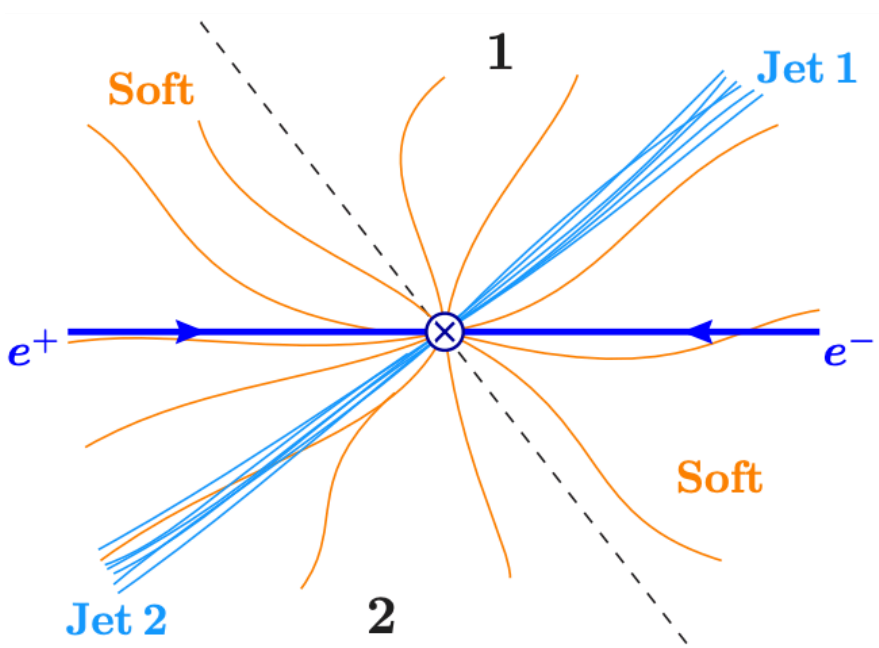
$$\mathcal{T}_N = \min_k\{q_a \cdot p_k, q_b \cdot p_k, q_1 \cdot p_k, \ldots, q_N \cdot p_k\}$$

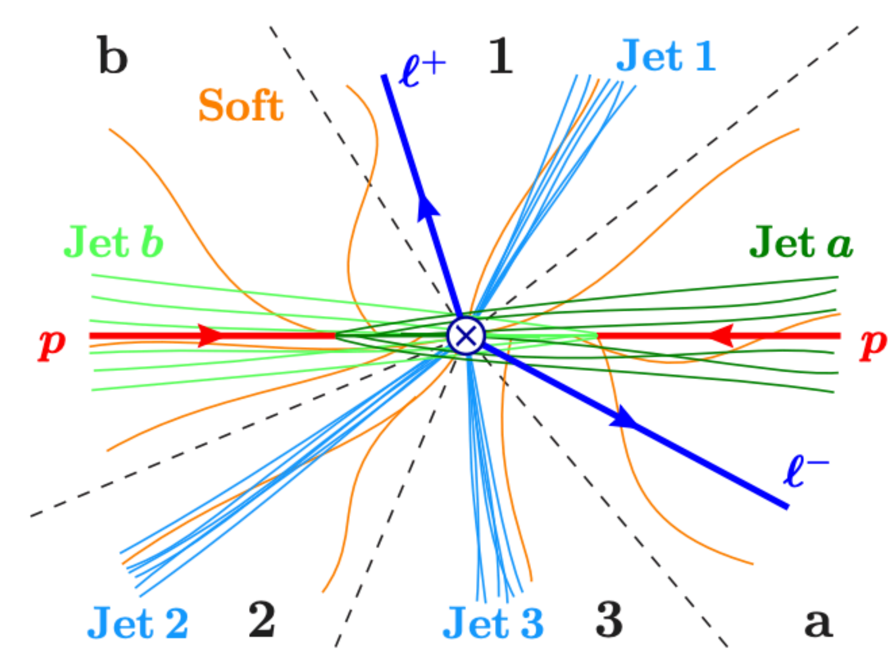
$q_{a,b}$ beam and $q_{1,\ldots,N}$ jet direction

Why N-jettiness?

* Infrared-safe variable: $\mathcal{T}_N \to 0$ in the IR region;

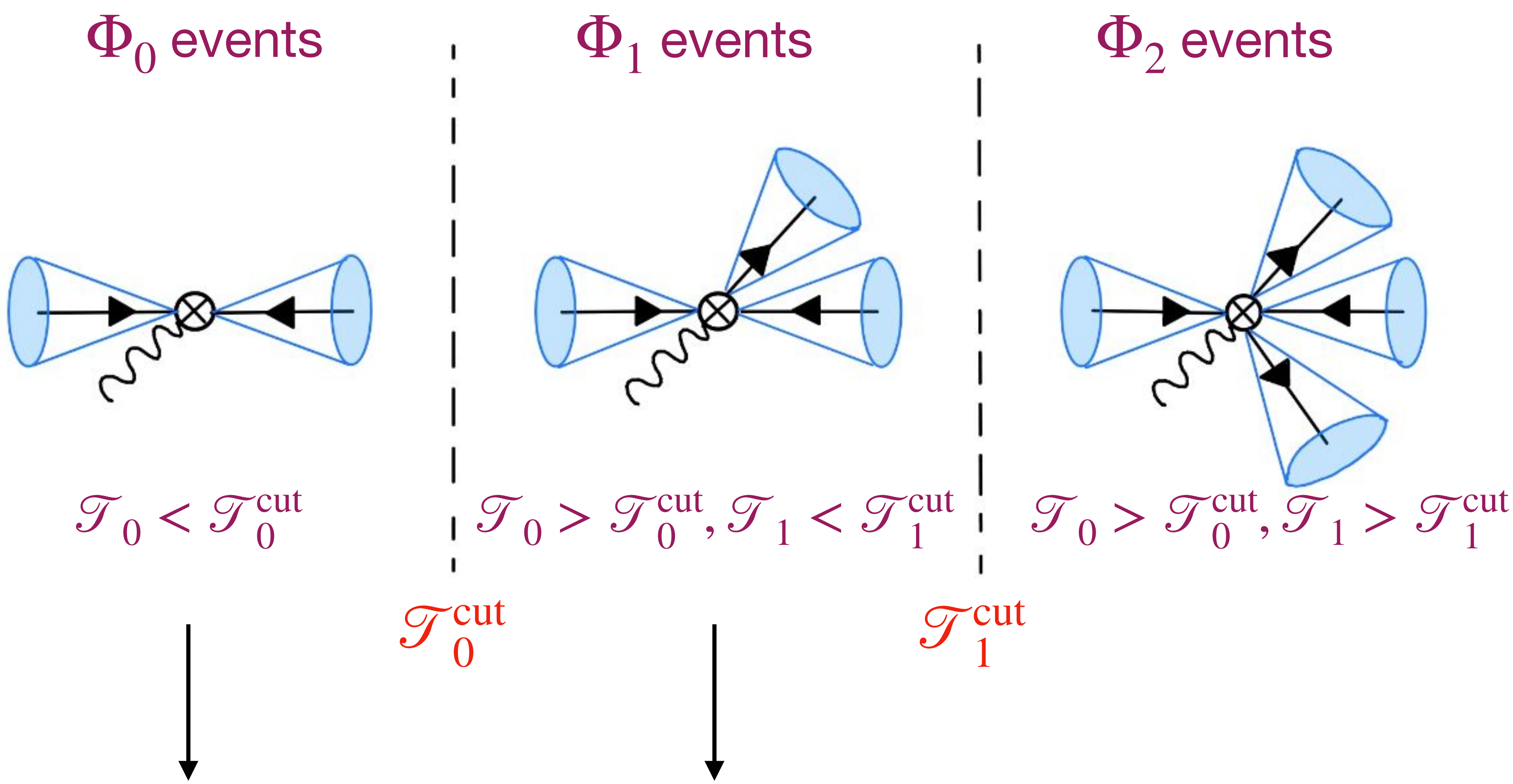
* Resummation know up to NNLL for each N in SCET.





GENEVA method

Phase space sliced into jet-bins:



from 0-,1- and 2-
parton phase space points

from 1- and 2-
parton phase space points

GENEVA method

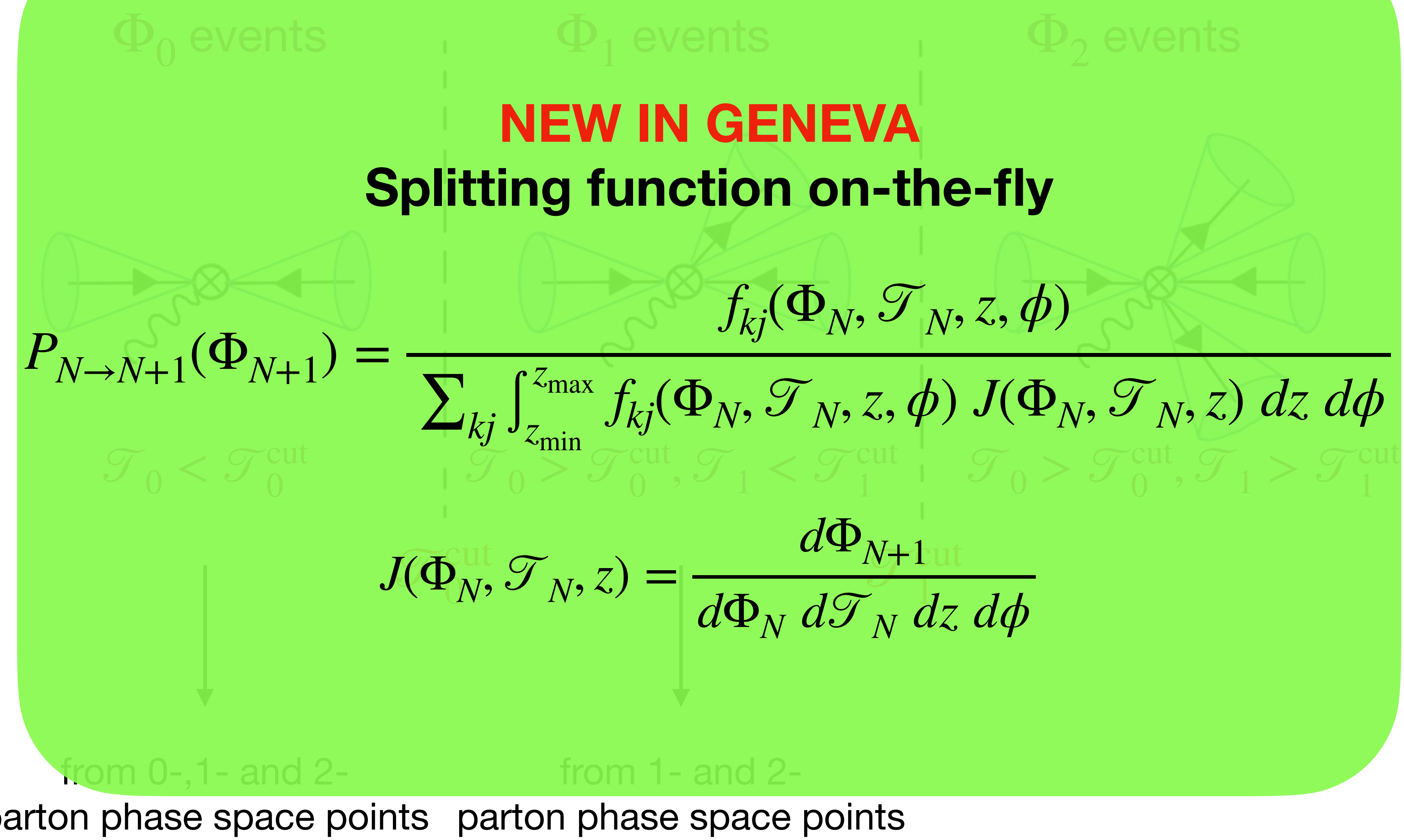
Phase space sliced into jet-bins:

NEW IN GENEVA

Splitting function on-the-fly

$$P_{N\to N+1}(\Phi_{N+1}) = \frac{f_{kj}(\Phi_N, \mathcal{T}_N, z, \phi)}{\sum_{kj}\int_{z_{\min}}^{z_{\max}} f_{kj}(\Phi_N, \mathcal{T}_N, z, \phi)\; J(\Phi_N, \mathcal{T}_N, z)\; dz\; d\phi}$$

$$J(\Phi_N, \mathcal{T}_N, z) = \frac{d\Phi_{N+1}}{d\Phi_N\; d\mathcal{T}_N\; dz\; d\phi}$$



$\mathcal{T}_{0,1}$ resummation

- $\mathcal{T}_0$ **case (NNLL')**:

$$\frac{d\sigma^{\rm SCET}}{d\Phi_0\, d\mathcal{T}_0} = H_\kappa(Q^2,\mu_H)\, U_H(\mu_H,\mu)$$

Hard function → two-loop virtual corrections calculation

$$\times \int [B_{\kappa_a}(t_a,x_a,\mu_B) \otimes U_B(\mu_B,\mu)] \times [B_{\kappa_b}(t_b,x_b,\mu_B) \otimes U_B(\mu_B,\mu)]$$

Beam functions → **SCETlib**

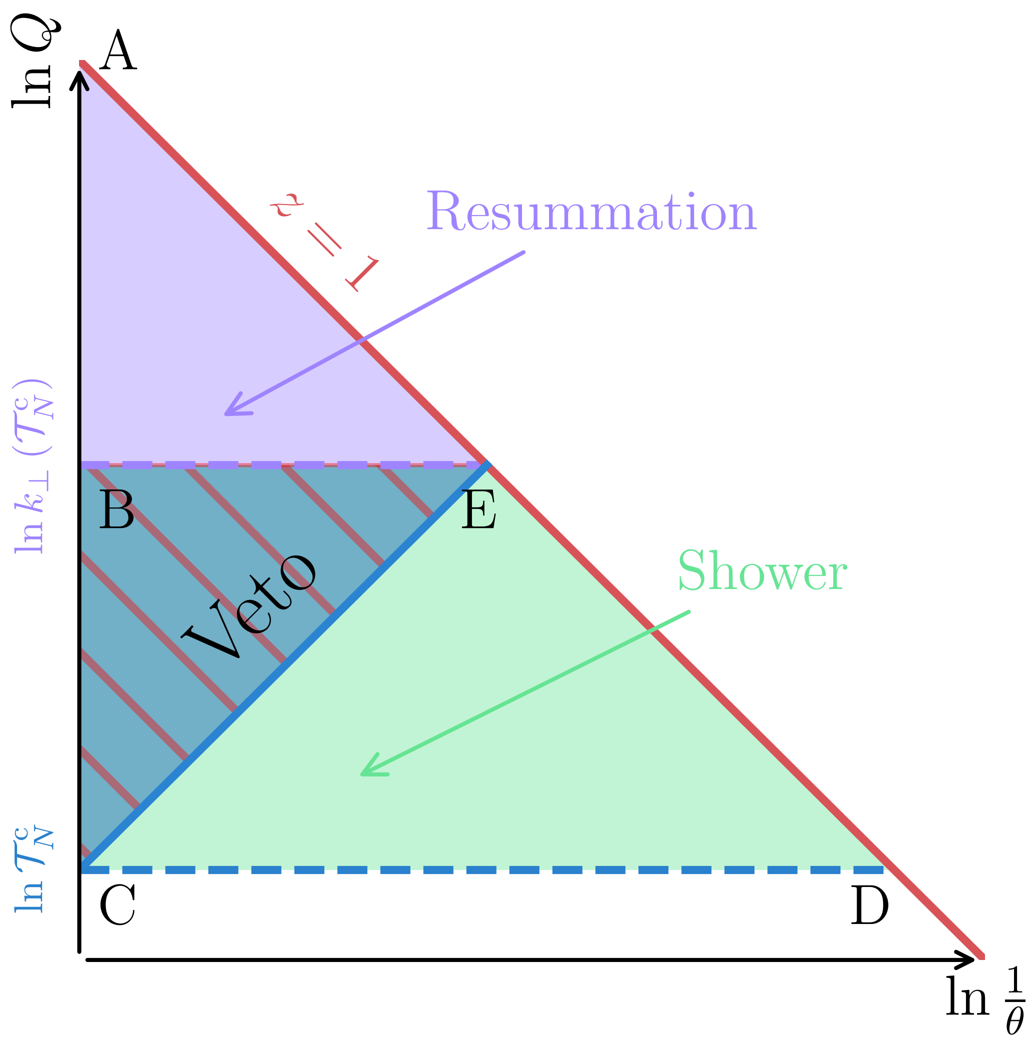
$$\times \left[S_\kappa\left(\mathcal{T}_0 - \frac{t_a+t_b}{Q}\right) \otimes U_S(\mu_S,\mu) \right] dt_a\, dt_b$$

Soft function

$U_{H,B,S}$ renormalization group evolution factors

- $\mathcal{T}_1$ **case (NLL)**

Interface to parton shower



Starting Scale:

resummation performed in $\mathcal{T}_N^{\mathrm{cut}} \leq \mathcal{T}_N \leq Q$ (hard scale)

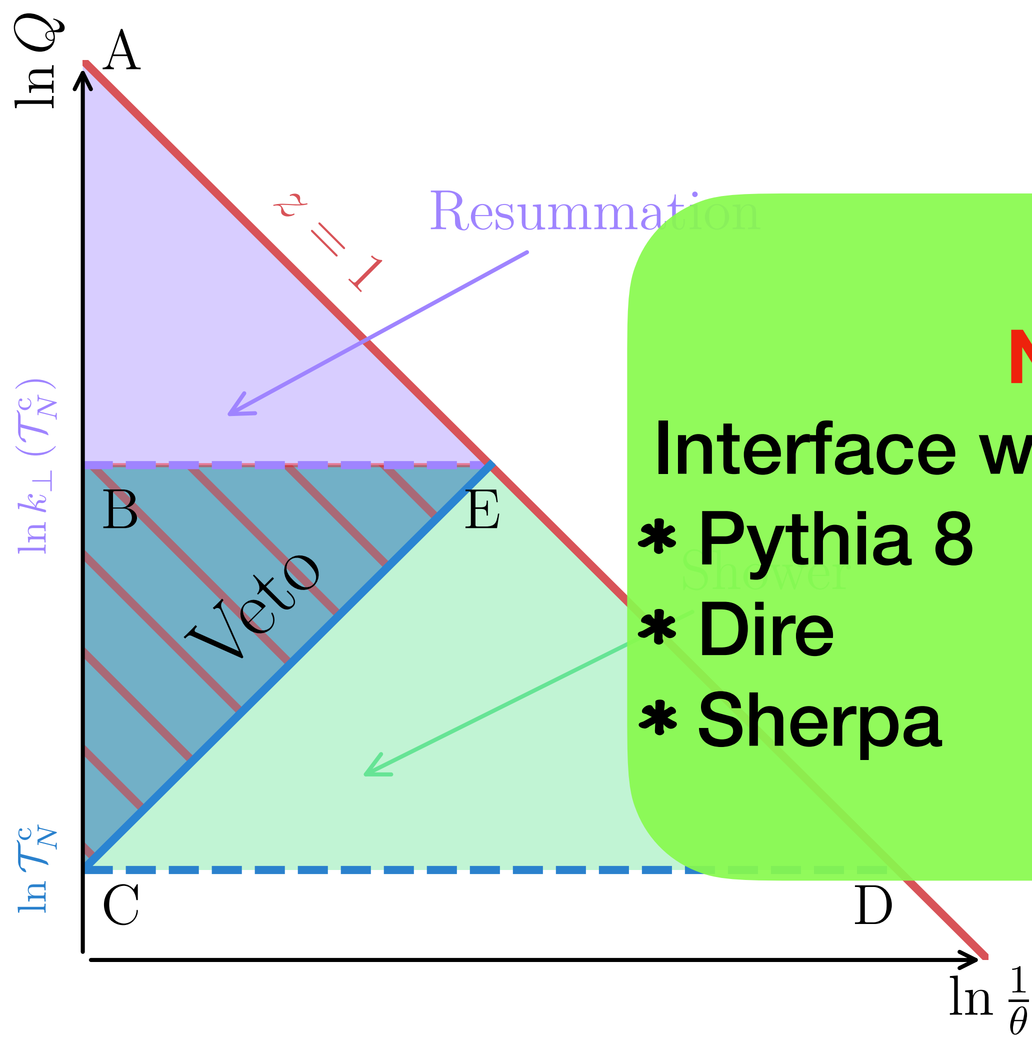
- 0-parton phase space points $\rightarrow \mathcal{T}_N^{\mathrm{cut}} = \mathcal{T}_0^{\mathrm{cut}}$
- 1-parton phase space points $\rightarrow \mathcal{T}_N^{\mathrm{cut}} = \mathcal{T}_1^{\mathrm{cut}}$
- 2-parton phase space points $\rightarrow \mathcal{T}_N^{\mathrm{cut}} = \mathcal{T}_1(\Phi_2)$

Veto Step (after M emission):

$$\mathcal{T}_N(\Phi_{N+M}) > \mathcal{T}_N$$

Accuracy on any observable computed with this matching is *at least* as accurate as the PS is

Interface to parton shower



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NEW IN GENEVA

Interface with three different showers:

- **Pythia 8**
- **Dire**
- **Sherpa**

Veto Step (after M emission):

$$\mathcal{T}_N(\Phi_{N+M}) > \mathcal{T}_N$$

Accuracy on any observable computed with this matching is *at least* as accurate as the PS is

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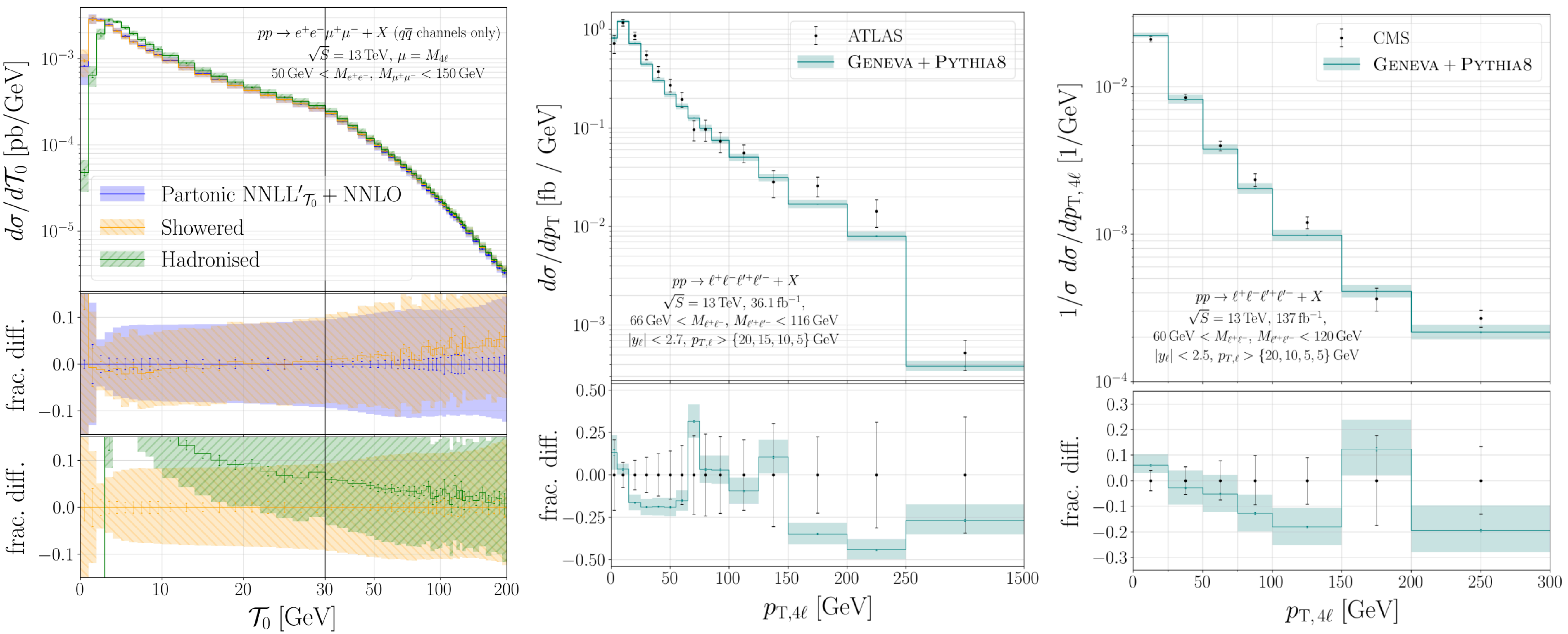
Processes in GENEVA

- Drell-Yan: PhysRevD 92.094020
- Higgsstrahlung: PhysRevD 100.096016
- Higgs boson decays: JHEP 04 (2021) 254
- Photon pair production: JHEP 04 (2021) 041
- pT-resummation: Phys.Rev.D 104 (2021) 9
- $W\gamma$ production: j.physletb.2022.136918

Recent developments

Colour singlet production

- Z boson pair production: 10.1016/j.physletb.2021.136380



Recent developments

Colour singlet production

- Higgs boson production via gluon fusion: arXiv: 2301.11875

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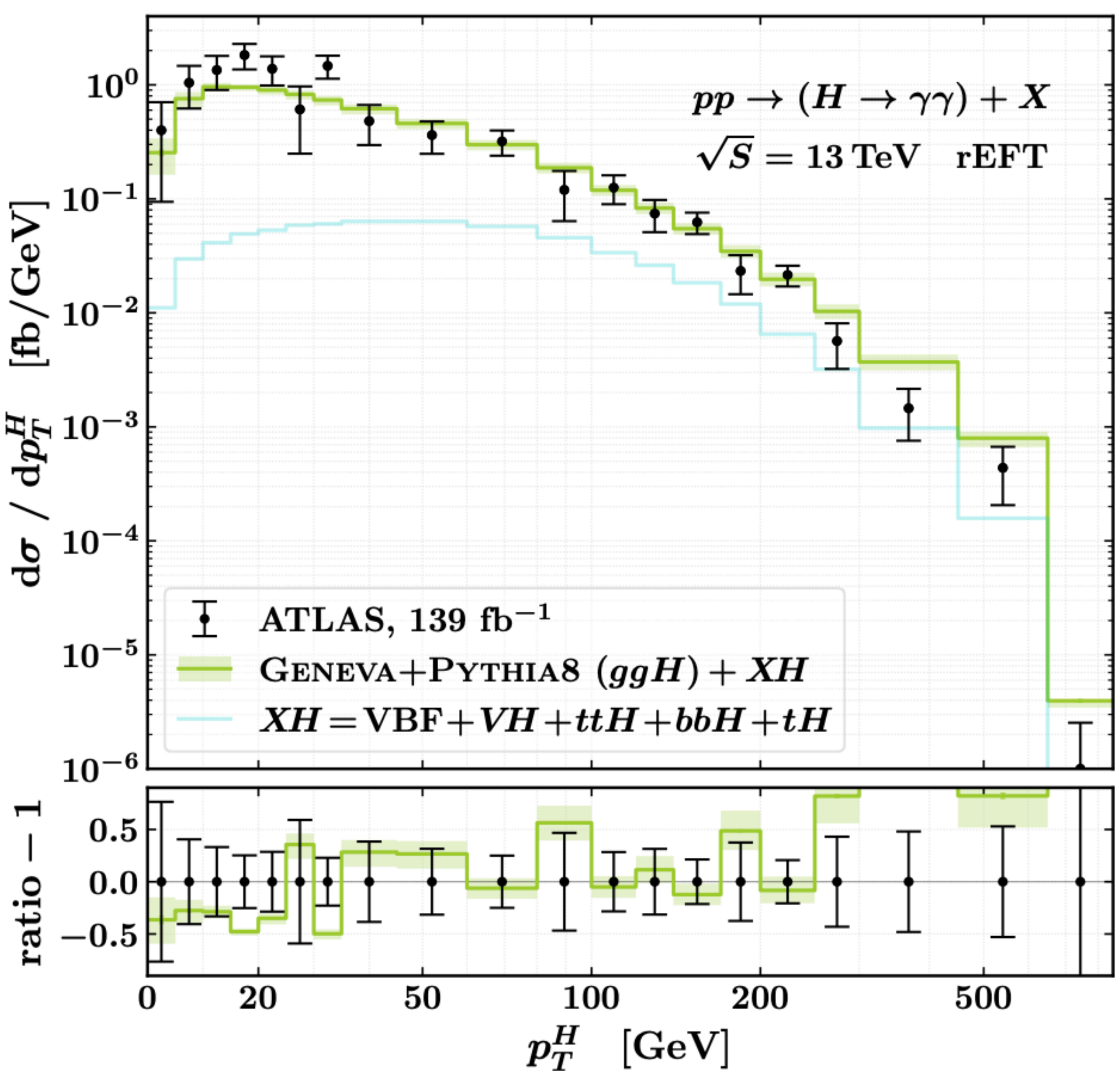

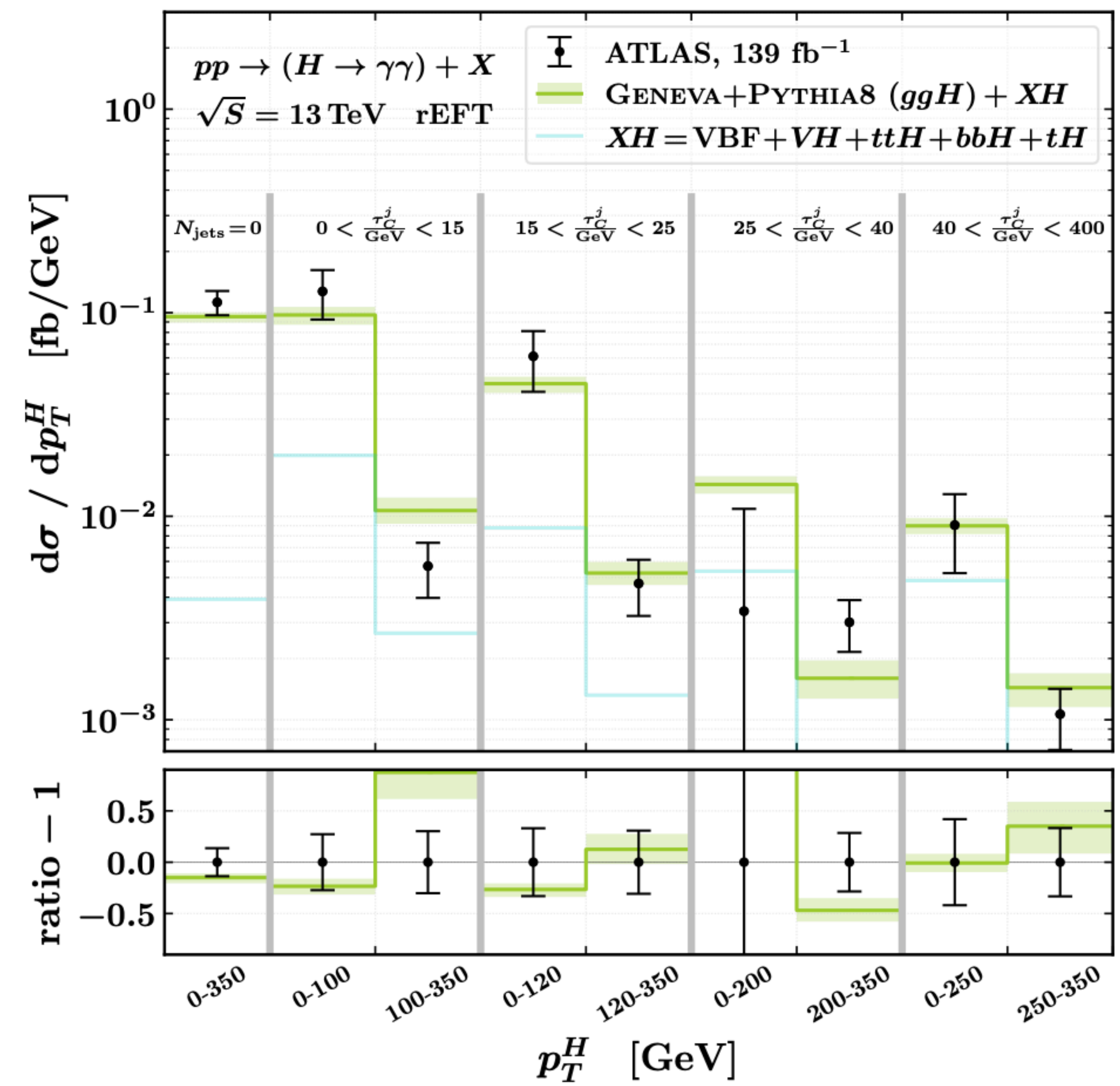

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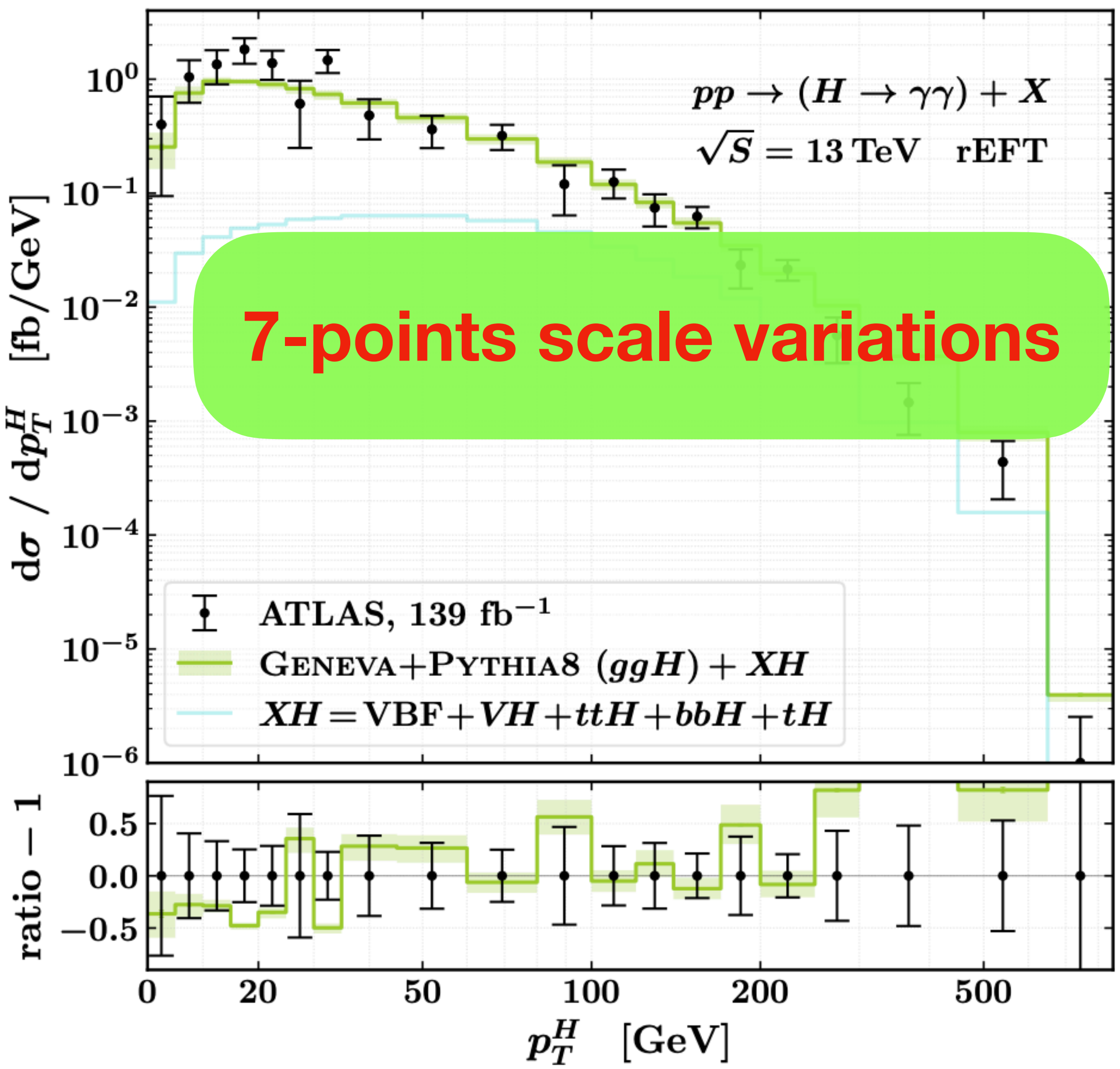

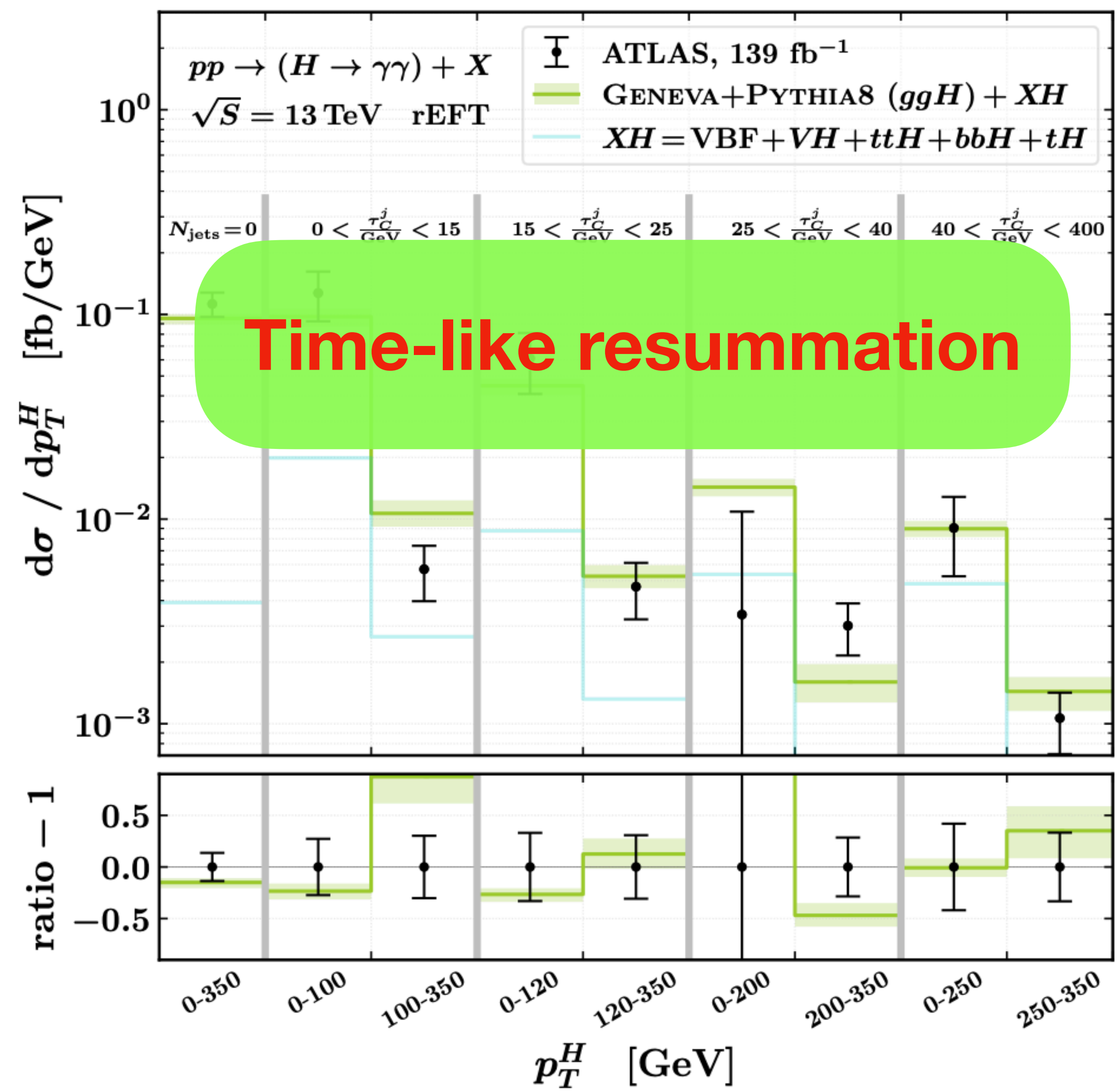

Recent developments

Colour singlet production

- Double Higgs production via gluon fusion: arXiv: 2212.10489

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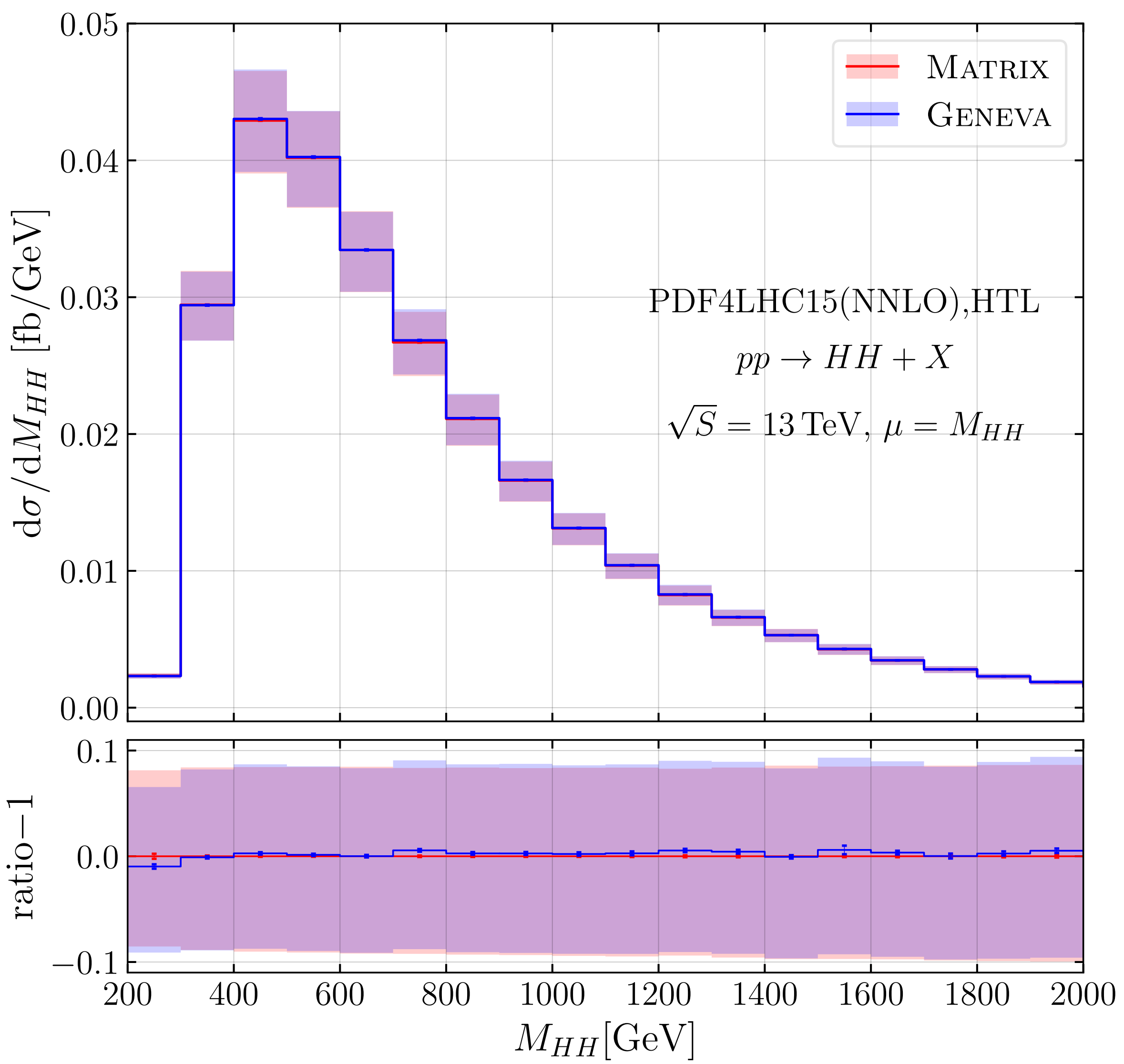
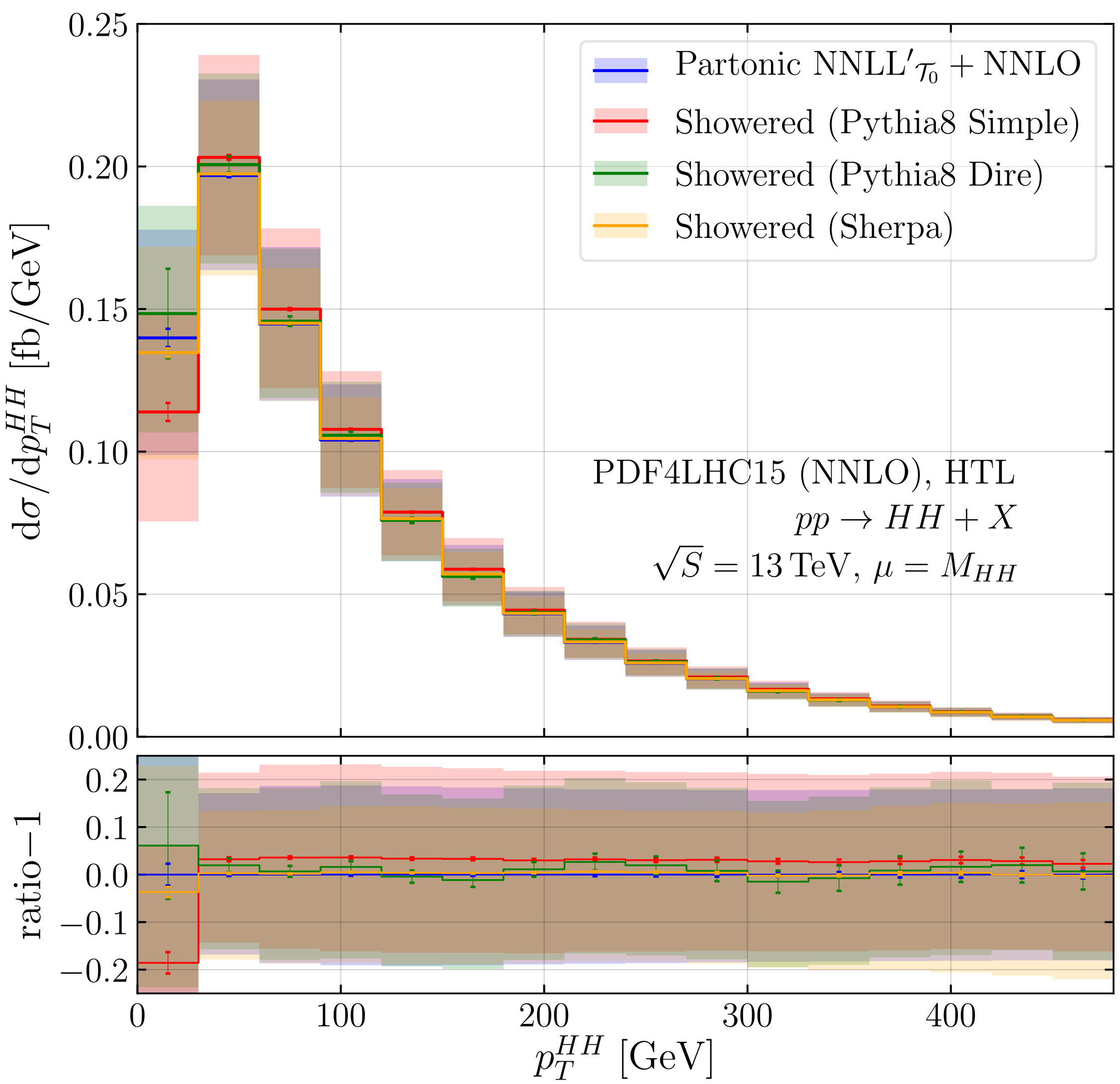
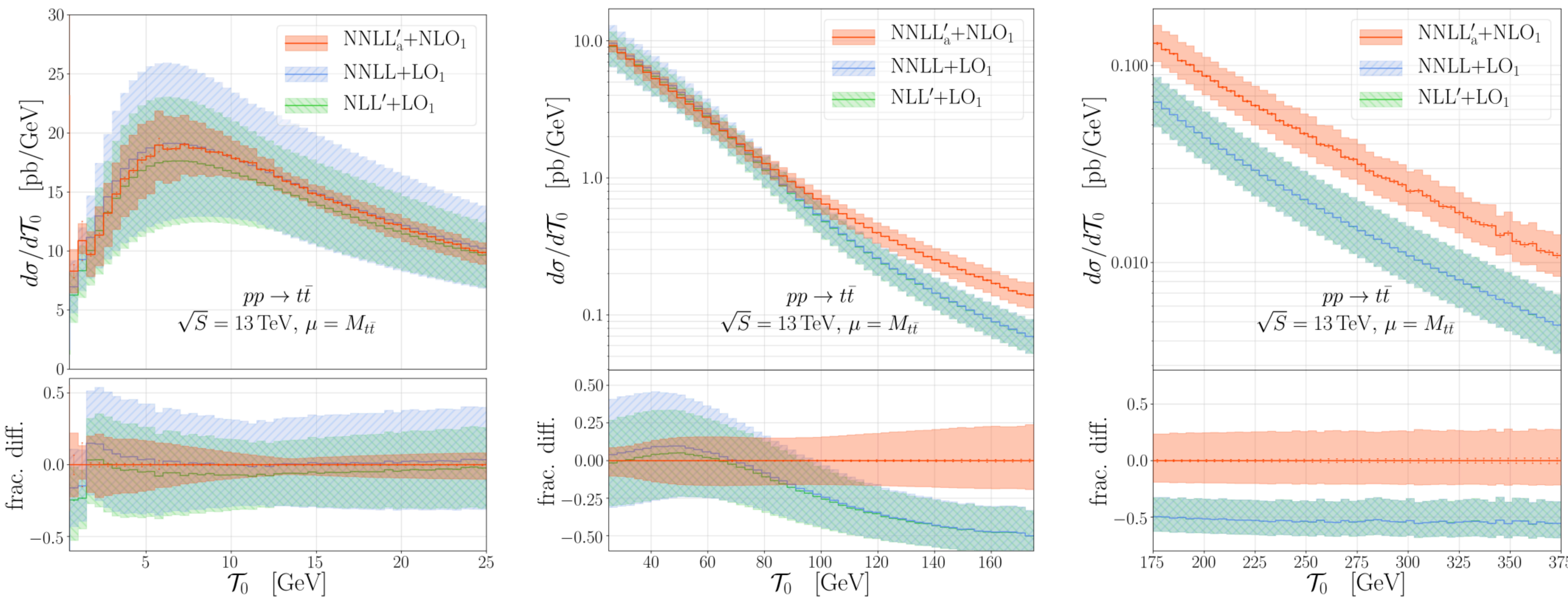




Recent developments

Final states with heavy coloured partons and jets

- $\mathscr{T}_0$ resummation for top-quark pair production: JHEP 01 (2022) 066



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Future plans

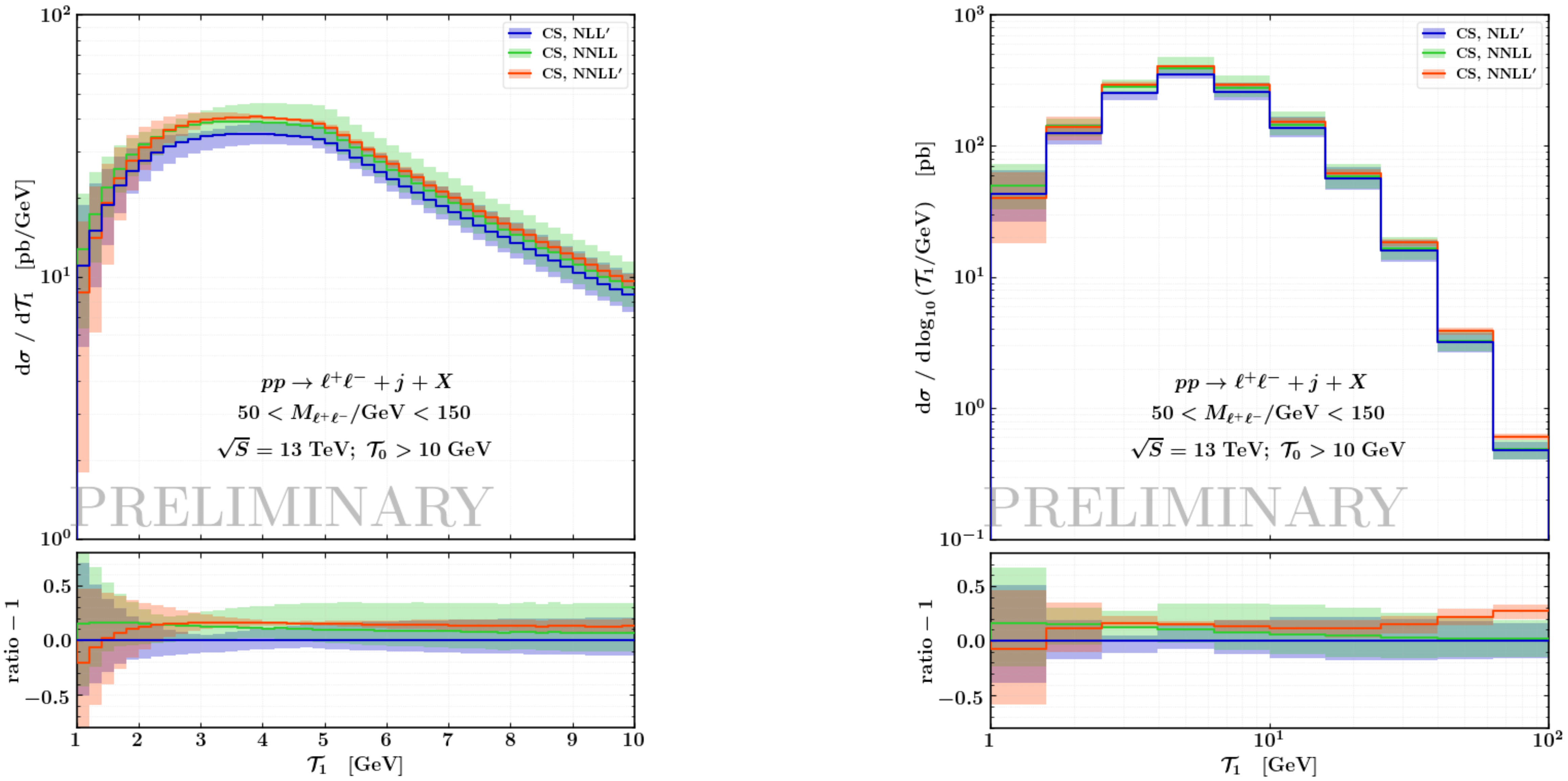
For colour singlet production:

- Including top-quark mass corrections to single and double Higgs production;
- Implementing many other processes;

Future plans

For final states with heavy coloured partons and jets:

- One-jettiness resummation (NNLL’)
- NNLO+PS for V+jet production



Backup slides

Backup slides

Time-like resummation: $q^2 = Q^2 > 0$

$$H(q^2, \mu) \propto L \equiv \ln\left(\frac{-q^2 - i0}{\mu^2}\right) = 2\ln\left(\frac{-iQ}{\mu}\right) = -i\pi + 2\ln\left(\frac{Q}{\mu}\right)$$

$\mu = Q$ classical choice

$\mu = -iQ = Qe^{-i\phi}$ time-like resummation

- $\phi = 0$ central value of FO prediction (no resummation)
- $\phi = \frac{\pi}{2}$ central value of resummed prediction
- $\phi \in \left[\frac{\pi}{4}, \frac{3}{4}\pi\right]$ phase variation of $\pm\frac{\pi}{4}$

Backup slides

Resumed $\mathscr{T}_0$ distribution:

Hard Function: 1-loop (some 2-loop ingredients known but not included)
Soft Function: 1-loop, with logarithmic 2-loop terms
Beam Function: 2-loops

↓

NNLL accuracy

Including know 2-loop terms of the soft function: NNLL'_a accuracy

missing only terms in the hard and soft at 2-loop $\propto \delta(\mathscr{T}_0)$

Backup slides

One-jettiness definition:

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

$q_{a,b}$ beam and q_J jet direction

$Q_{a,b,J}$ directions that minimizes the N-jettiness

NNLL' resummation:

3-loop cusp anomalous dimension

2-loop non cusp anomalous dimension

2-loop boundary terms (hard, soft, beam, jet)