0- and 1-jettiness resummation for processes with coloured final states at the LHC

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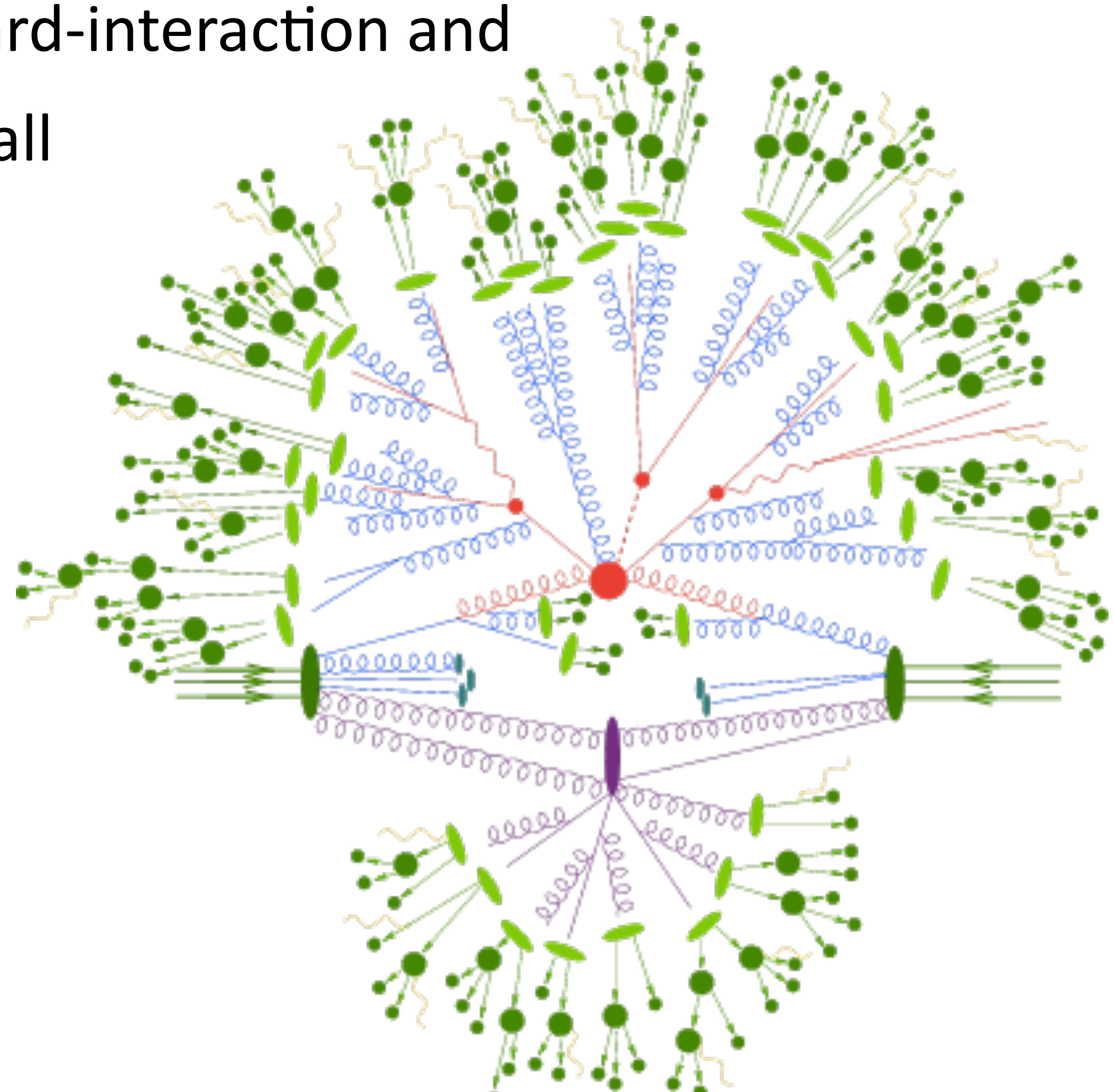
Overview of the talk

- Motivation
- Geneva Monte Carlo GENEVA http://geneva.physics.lbl.gov
- Zero-jettiness resummation for top-quark pair production at the LHC
- One-jettiness resummation for Z+jet production at the LHC
- Conclusions & Outlook

Motivation

- MC event generators are essential tools for particle physics phenomenology
- They provide realistic simulations: first principles QFT calculations are combined with parton showers and hadronization modelling
- They start from a perturbative description of the hard-interaction and predict the evolution of the event down to very small (nonperturbative) scales $\mathcal{O}(1)$ GeV
- State-of-the-art is the inclusion of partonic NNLO corrections. Several methods are available for colour-singlet processes (UNNLOPS, MiNNLOPS, GENEVA)

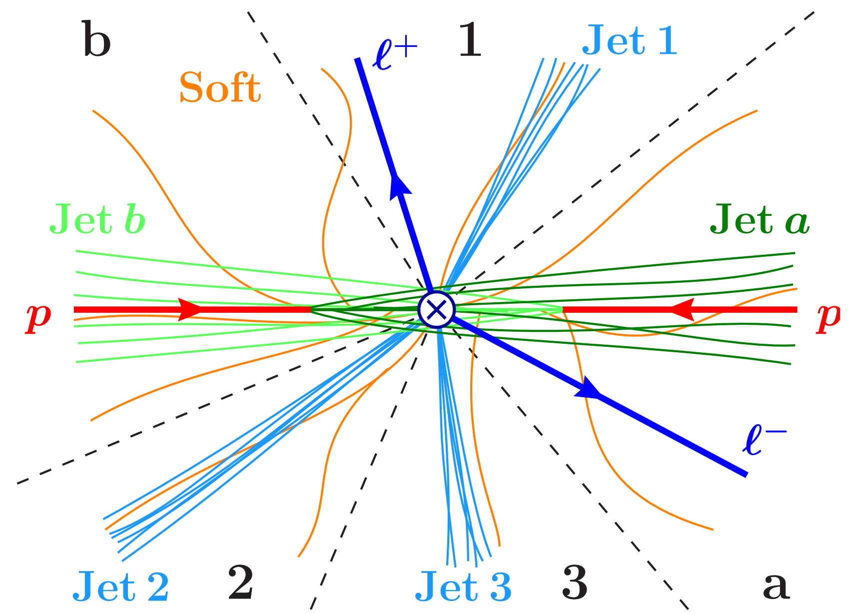


N-Jettiness and Factorization

- N-jettiness resolution variables: given an M-particle phase space point with $M \geq N$

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

- The limit $\mathcal{T}_N \to 0$ describes a N-jet event where the unresolved emissions can be either soft or collinear to the final state jets or initial state beams



- Color singlet final state, relevant variable is 0-jettiness aka "beam thrust" [Stewart, Tackmann,Waalewijn `09,`10]

$$\mathcal{T}_0 = \sum_k |\vec{p}_{kT}|\, e^{-|\eta_k - Y|}$$

- When an extra jet is present the relevant jet resolution variable is 1-jettiness

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

- Class of geometric measures $Q_i = \rho_i\, 2\, E_i$ (ρ_i dimensionless parameter), remove the dependence on the energies E_i and only depends on the directions $\hat{q}_i$. Introduce frame dependence.

- Choice of the ρ_i determines the frame in which the 1-jettiness is evaluated. We focus on 3 choices: Laboratory frame, Underlying Born (UB) frame ($Y_{Vj} = 0$), Color Singlet (CS) frame ($Y_V = 0$).

Monte Carlo implementation

- GENEVA [Alioli,Bauer,Berggren,Tackmann, Walsh `15], [Alioli,Bauer,Tackmann,Guns `16], [Alioli,Broggio,Lim, Kallweit,Rottoli `19],[Alioli,Broggio,Gavardi,Lim,Nagar,Napoletano,Kallweit,Rottoli `20-`21] combines 3 theoretical tools that are important for QCD predictions into a single framework

  - fully differential fixed-order calculations, up to NNLO via 0-jettiness or q_T subtraction

  - up to NNLL` resummation for 0-jettiness in SCET or N^{3}LL for q_T via RadISH for colour singlet processes

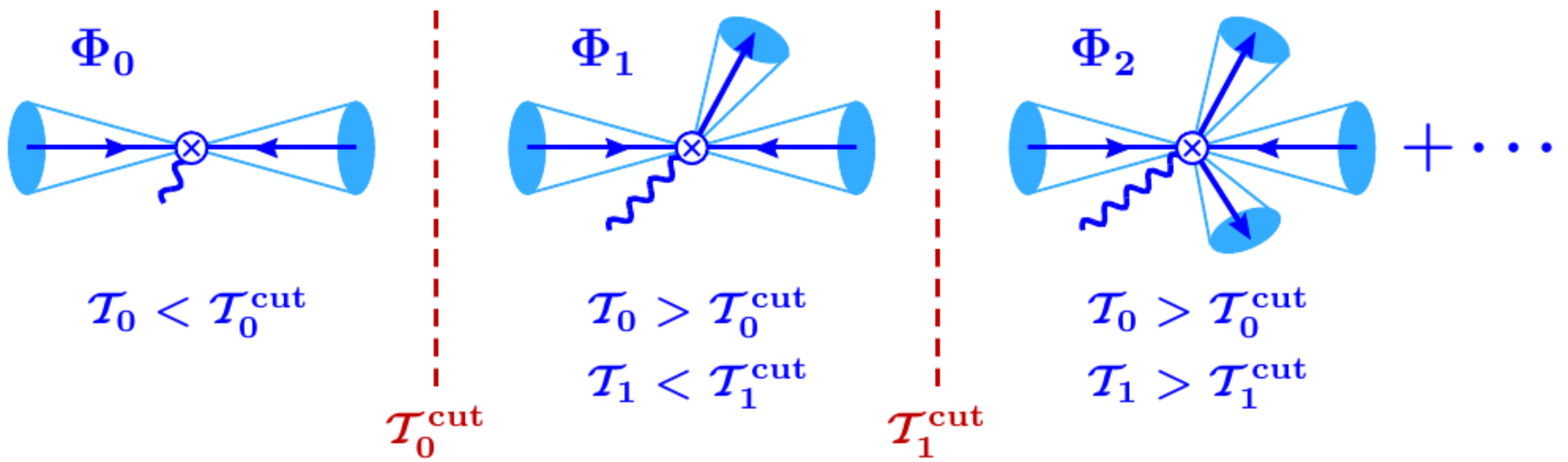
  - shower and hadronize events (PYTHIA8)

- IR-finite definition of events based on resolution parameters $\mathcal{T}_0^{\rm cut}$ and $\mathcal{T}_1^{\rm cut}$

$$\Phi_0 \text{ events:} \qquad \frac{d\sigma_0^{\rm MC}}{d\Phi_0}(\mathcal{T}_0^{\rm cut}),$$

$$\Phi_1 \text{ events:} \qquad \frac{d\sigma_1^{\rm MC}}{d\Phi_1}(\mathcal{T}_0 > \mathcal{T}_0^{\rm cut}; \mathcal{T}_1^{\rm cut}),$$

$$\Phi_2 \text{ events:} \qquad \frac{d\sigma_{\geq 2}^{\rm MC}}{d\Phi_2}(\mathcal{T}_0 > \mathcal{T}_0^{\rm cut}, \mathcal{T}_1 > \mathcal{T}_1^{\rm cut})$$



- When we take $\mathcal{T}_N^{\rm cut} \to 0$, large logarithms of $\mathcal{T}_N^{\rm cut}$, $\mathcal{T}_N$ appear and need to be resummed

- Including the higher-order resummation will improve the accuracy of the predictions across the whole spectrum

Zero-jettiness resummation for top-quark pair production at the LHC

Based on arXiv:2111.03632, S. Alioli, AB, M.A. Lim

0-jettiness resummation for $t\bar{t}$ production

- Top-quark properties are very interesting, interplay with the Higgs sector
- It is desirable to have a NNLO+PS calculation. Extrapolation from fiducial to inclusive phase space is done using NLO event generators [Behring, Czakon, Mitov, Papanastasiou, Poncelet `19]
- NNLO+PS for $t\bar{t}$ production available in MINNLOPS framework [Mazzitelli, Monni, Nason, Re, Wiesemann, Zanderighi `20, `21]
- Including higher-order resummation can improve the description of observables (this is the case of the GENEVA generator)

0-jettiness resummation for $t\bar{t}$ production

- To reach NNLO+PS accuracy in GENEVA
  - NLO calculations for $t\bar{t}$ and $t\bar{t}$+jet
  - Resummed calculation at NNLL` in the resolution variable $\mathcal{T}_0$
  - q_T resummation via SCET (NNLL in [1307.2464]) or direct QCD [1408.4564], [1806.01601] NNLL' ingredients (soft functions) in [S. Catani, S. Devoto, M. Grazzini, J. Mazzitelli 2301.11786], [Angeles-Martinez, Czakon, Sapeta 1809.01459]
  - 0-jettines resummation is used for colour-singlet in GENEVA, has to be extended for $t\bar{t}$ production
  - Definition of 0-jettiness has to be adapted with *top-quarks* in the final state, we choose to *treat them like EW particles* and exclude them from the sum over radiation
  - We first need to develop the resummation framework

Factorization

We derived a factorization formula (see 2111.03632 Appendix A) using SCET+HQET in the region $\mathcal{T}_0 \to 0$ when $M_{t\bar{t}} \sim m_t \sim \sqrt{\hat{s}}$ are all hard scales (in case of boosted regime $M_{t\bar{t}} \gg m_t$ situation similar to [Fleming, Hoang,Mantry,Stewart `07][Bachu,Hoang,Mateu,Pathak,Stewart `21])

Three different scales arise $\mu_H = M_{t\bar{t}}, \quad \mu_B = \sqrt{\mathcal{T}_0 M_{t\bar{t}}}, \quad \mu_S = \mathcal{T}_0$

Hard functions (color matrices) known to NLO

$$\frac{d\sigma}{d\Phi_0 d\tau_B} = M \sum_{ij=\{q\bar{q},\bar{q}q,gg\}} \int dt_a\, dt_b\, \boxed{B_i(t_a, z_a, \mu)\, B_j(t_b, z_b, \mu)}\, \mathrm{Tr}\left[\boxed{\mathbf{H}_{ij}(\Phi_0, \mu)}\, \boxed{\mathbf{S}_{ij}\left(M\tau_B - \frac{t_a + t_b}{M}, \Phi_0, \mu\right)}\right]$$

Beam functions [Stewart, Tackmann, Waalewijn, [1002.2213], known up to N^{3}LO

Soft functions (color matrices) known to NLO

It is convenient to transform the soft and beam functions in Laplace space to solve the RG equations, the factorization formula is turn into a product of functions

$$\mathscr{L}\left[\frac{d\sigma}{d\Phi_0 d\tau_B}\right] = M \sum_{ij=\{q\bar{q},\bar{q}q,gg\}} \tilde{B}_i\left(\ln\frac{M\kappa}{\mu^2}, z_a\right) \tilde{B}_j\left(\ln\frac{M\kappa}{\mu^2}, z_b\right) \mathrm{Tr}\left[\mathbf{H}_{ij}\left(\ln\frac{M^2}{\mu^2}, \Phi_0\right) \tilde{\mathbf{S}}_{ij}\left(\ln\frac{\mu^2}{\kappa^2}, \Phi_0\right)\right]$$

Hard functions

The hard functions arise from matching the full theory onto the EFT, they can be extracted from colour decomposed loop amplitudes. At NLO it was first computed in [Ahrens, Ferroglia, Neubert, Pecjak, Yang, 1003.5827]. They satisfy the RG equations

$$\frac{\mathrm{d}}{\mathrm{d}\ln\mu}\mathbf{H}(M,\beta_t,\theta,\mu) = \mathbf{\Gamma}_H(M,\beta_t,\theta,\mu)\,\mathbf{H}(M,\beta_t,\theta,\mu) + \mathbf{H}(M,\beta_t,\theta,\mu)\,\mathbf{\Gamma}_H^\dagger(M,\beta_t,\theta,\mu)$$

Solution:

$$\mathbf{H}(M,\beta_t,\theta,\mu) = \mathbf{U}(M,\beta_t,\theta,\mu_h,\mu)\mathbf{H}(M,\beta_t,\theta,\mu_h)\mathbf{U}^\dagger(M,\beta_t,\theta,\mu_h,\mu)$$

$$\boxed{\mathbf{U}(M,\beta_t,\theta,\mu_h,\mu) = \exp\left[2S(\mu_h,\mu) - a_\Gamma(\mu_h,\mu)\left(\ln\frac{M^2}{\mu_h^2} - i\pi\right)\right]\mathbf{u}(M,\beta_t,\theta,\mu_h,\mu)}$$

We have split the anomalous dimension into a cusp (diagonal in colour space) and non-cusp (not diagonal) part

$$\mathbf{\Gamma}_H(M,\beta_t,\theta,\mu) = \Gamma_{\mathrm{cusp}}(\alpha_s)\left(\ln\frac{M^2}{\mu^2} - i\pi\right) + \boldsymbol{\gamma}^h(M,\beta_t,\theta,\alpha_s)$$ [Ferroglia, Neubert, Pecjak, Yang,`09]

$$\mathbf{u}(M,\beta_t,\theta,\mu_h,\mu) = \mathcal{P}\exp\int_{\alpha_s(\mu_h)}^{\alpha_s(\mu)}\frac{\mathrm{d}\alpha}{\beta(\alpha)}\boldsymbol{\gamma}^h(M,\beta_t,\theta,\alpha)$$

We evaluate the matrix exponential **u** as a series expansion in α_s [1003.5827], [Buchalla,Buras,Lautenbacher `96]

Beam functions

The beam functions are given by convolutions of perturbative kernels with the standard PDFs $f_i(x,\mu)$

$$B_i(t,z,\mu) = \sum_j \int_z^1 \frac{d\xi}{\xi} I_{ij}(t,z/\xi,\mu) f_j(\xi,\mu)$$

I_{ij} kernels are known up to N^{3}LO, process independent

RG equation in Laplace space is given by

$$\frac{\mathrm{d}}{\mathrm{d}\ln\mu}\tilde{B}_i(L_c,z,\mu) = \Big[-2\,\Gamma_{\rm cusp}(\alpha_s)\,L_c + \gamma_i^B(\alpha_s)\Big]\tilde{B}_i(L_c,z,\mu)$$

with solution in momentum space

$$B(t,z,\mu) = \exp\left[-4S(\mu_B,\mu) - a_{\gamma^B}(\mu_B,\mu)\right] \tilde{B}(\partial_{\eta_B},z,\mu_B)\frac{1}{t}\left(\frac{t}{\mu_B^2}\right)^{\eta_B} \frac{e^{-\gamma_E\eta_B}}{\Gamma(\eta_B)}$$

where $\eta_B \equiv 2a_\Gamma(\mu_B,\mu)$ and the collinear log is given by $L_c = \ln\left(M\kappa/\mu^2\right)$

Soft functions

We computed the soft functions matrices at NLO which were unknown for this observable

$$\mathbf{S}^{(1)}_{\text{bare},\,ij}(k_a^+, k_b^+, \beta_t, \theta, \epsilon, \mu) = \sum_{\alpha,\,\beta} \boldsymbol{w}_{ij}^{\alpha\beta}\, \hat{\mathcal{I}}_{\alpha\beta}(k_a^+, k_b^+, \beta_t, \theta, \epsilon, \mu)$$

$$\hat{\mathcal{I}}_{\alpha\beta}(k_a^+, k_b^+, \beta_t, \theta, \epsilon, \mu) = -\frac{2(\mu^2 e^{\gamma_E})^\epsilon}{\pi^{1-\epsilon}} \int \mathrm{d}^d k \frac{v_\alpha \cdot v_\beta}{v_\alpha \cdot k\, v_\beta \cdot k}\, \delta(k^2)\Theta(k^0)$$
$$\times \left[\delta(k_a^+ - k\cdot n_a)\Theta(k\cdot n_b - k\cdot n_a)\,\delta(k_b^+) + \delta(k_b^+ - k\cdot n_b)\Theta(k\cdot n_a - k\cdot n_b)\,\delta(k_a^+)\right]$$

One can average over the two hemisphere momenta, the soft function satisfies the RG equation in Laplace space

$$\frac{\mathrm{d}}{\mathrm{d}\ln\mu}\tilde{\mathbf{S}}_B(L, \beta_t, \theta, \mu) = \left[\Gamma_{\text{cusp}} L - \boldsymbol{\gamma}^{s\dagger}\right] \tilde{\mathbf{S}}_B(L, \beta_t, \theta, \mu) + \tilde{\mathbf{S}}_B(L, \beta_t, \theta, \mu) \left[\Gamma_{\text{cusp}} L - \boldsymbol{\gamma}^{s}\right]$$

Solution in momentum space, where we used the consistency relation among anomalous dimensions $\boldsymbol{\gamma}^s = \boldsymbol{\gamma}^h + \gamma^B\,\mathbf{1}$

$$\mathbf{S}_B(l^+, \beta_t, \theta, \mu) = \exp\left[4S(\mu_s, \mu) + 2a_{\gamma^B}(\mu_s, \mu)\right]$$
$$\times\ \mathbf{u}^\dagger(\beta_t, \theta, \mu, \mu_s)\, \tilde{\mathbf{S}}_B(\partial_{\eta_s}, \beta_t, \theta, \mu_s)\, \mathbf{u}(\beta_t, \theta, \mu, \mu_s)\, \frac{1}{l^+}\left(\frac{l^+}{\mu_s}\right)^{2\eta_s} \frac{e^{-2\gamma_E \eta_s}}{\Gamma(2\eta_s)}$$

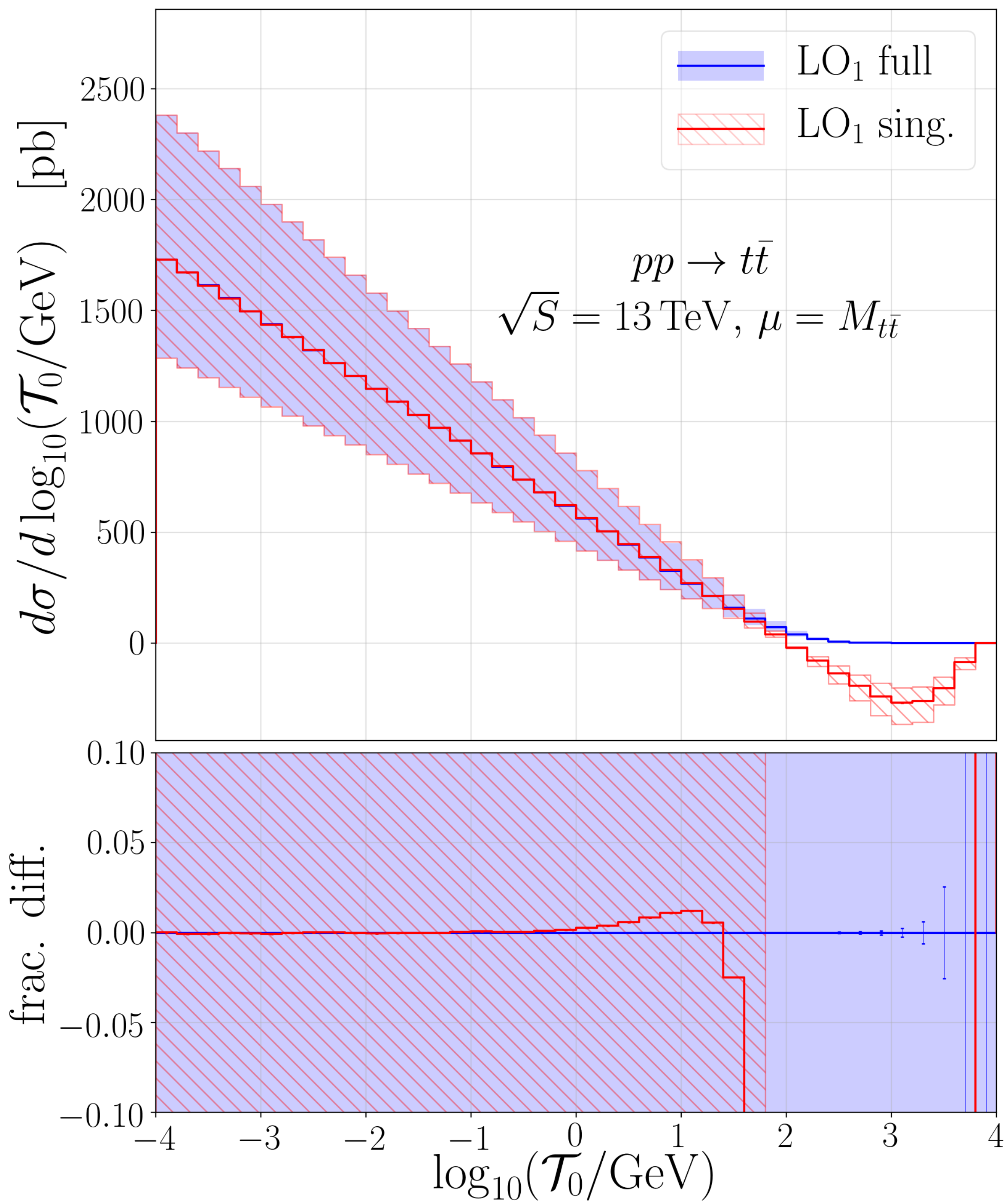
$$\eta_s \equiv -2a_\Gamma(\mu_s, \mu)$$

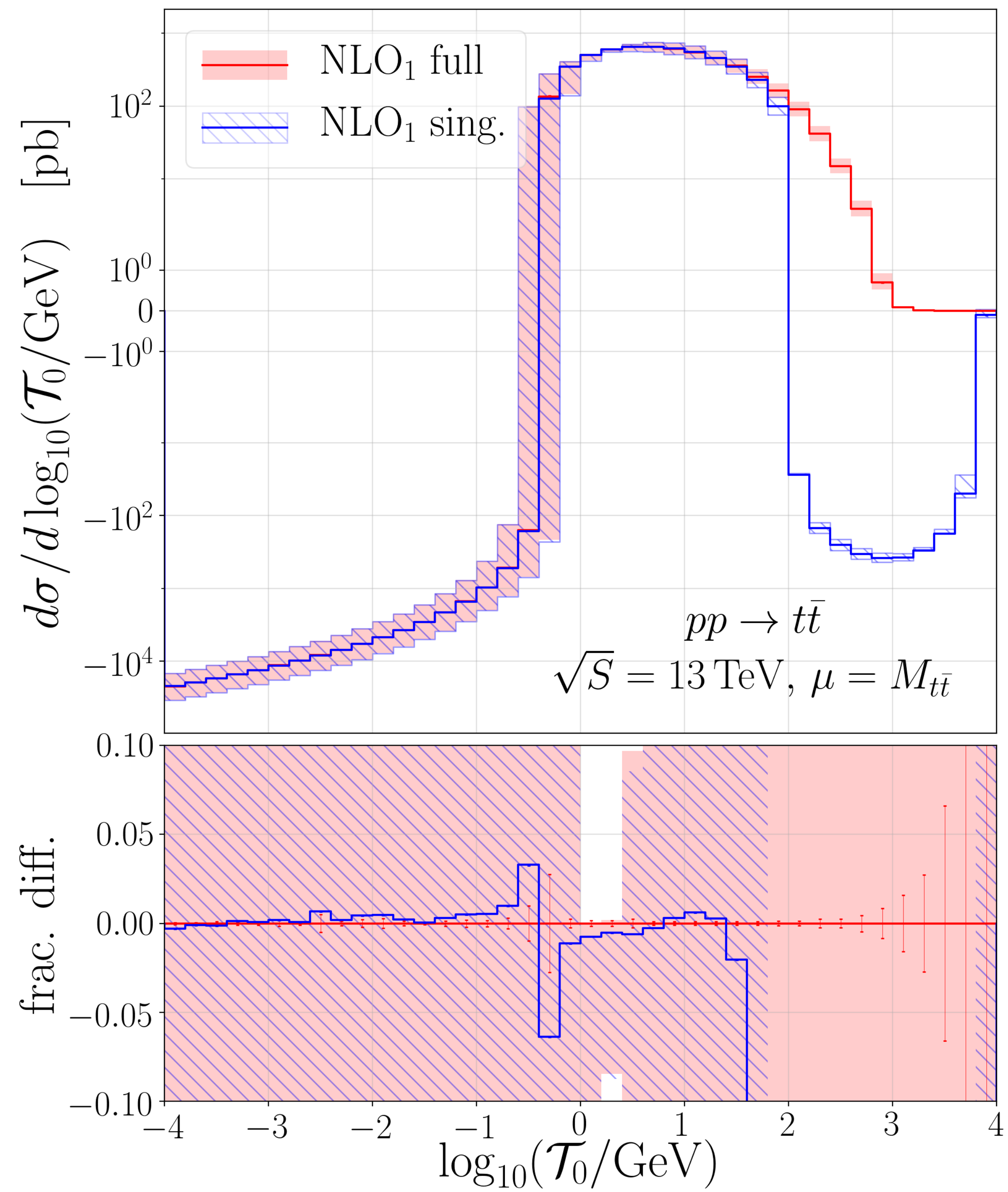
Resummed result for the cross section

- We have
  - hard functions at NLO
  - soft functions at NLO, by knowing the two-loop soft anomalous dimensions we can solve the RG equations order by order and obtain all the NNLO logarithmic contributions, we miss $\delta(\mathcal{T}_0)$ terms at NNLO
  - beam functions at NNLO (both for $q\bar{q}$ and gg channels)
  - two-loop anomalous dimensions
- We can resum to NNLL. We are missing $\delta(\mathcal{T}_0)$ terms (NNLO hard functions and NNLO soft). If we include everything we know we obtain a NNLL$'_{\mathrm{a}}$ result
- We construct an approximate (N)NLO formula which reproduces the fixed-order behaviour of the spectrum (for $\mathcal{T}_0 > 0$)

Singular vs Fixed-order

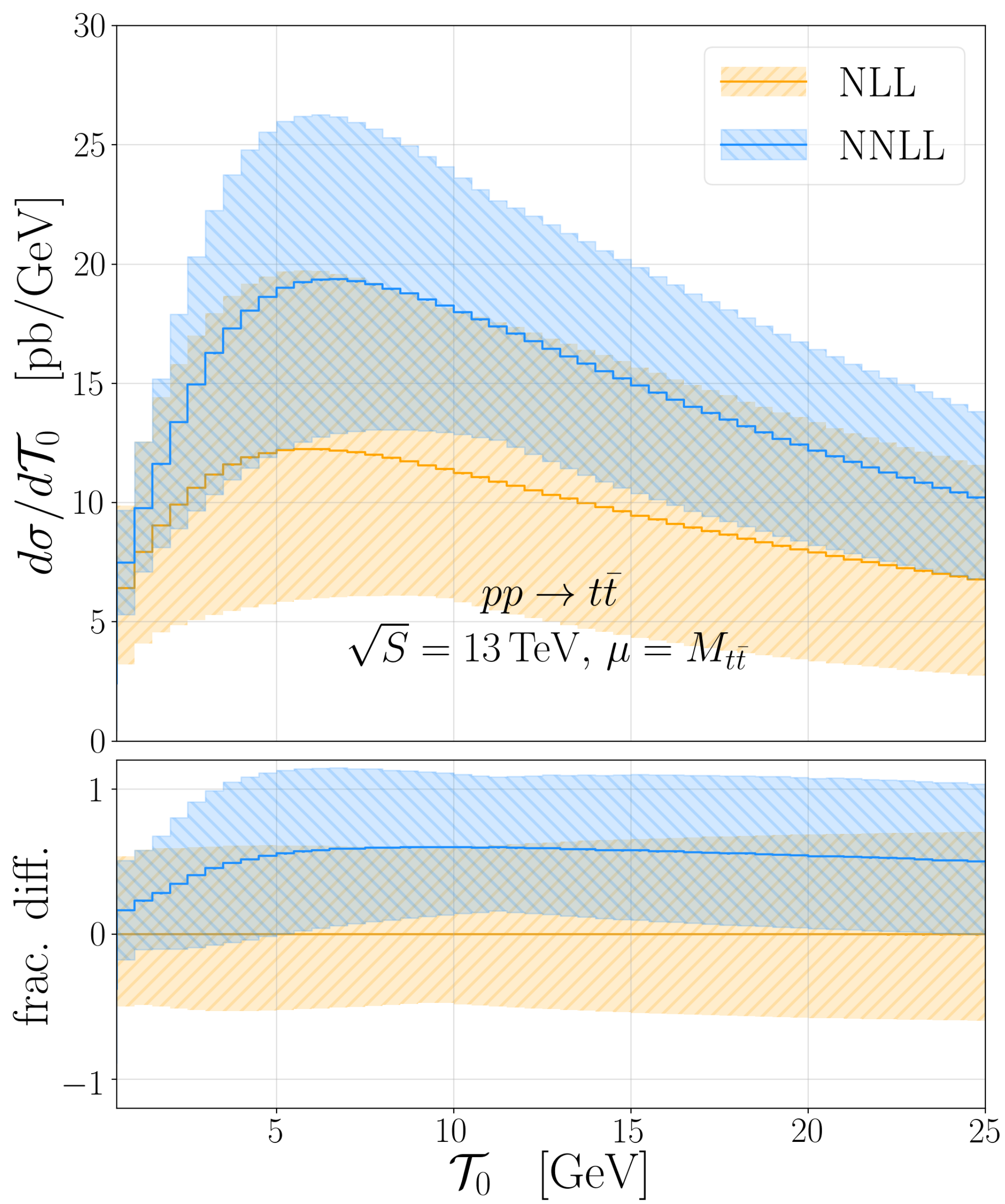
Fixed-order comparisons, approximate NLO and approximate NNLO vs LO_1 and NLO_1

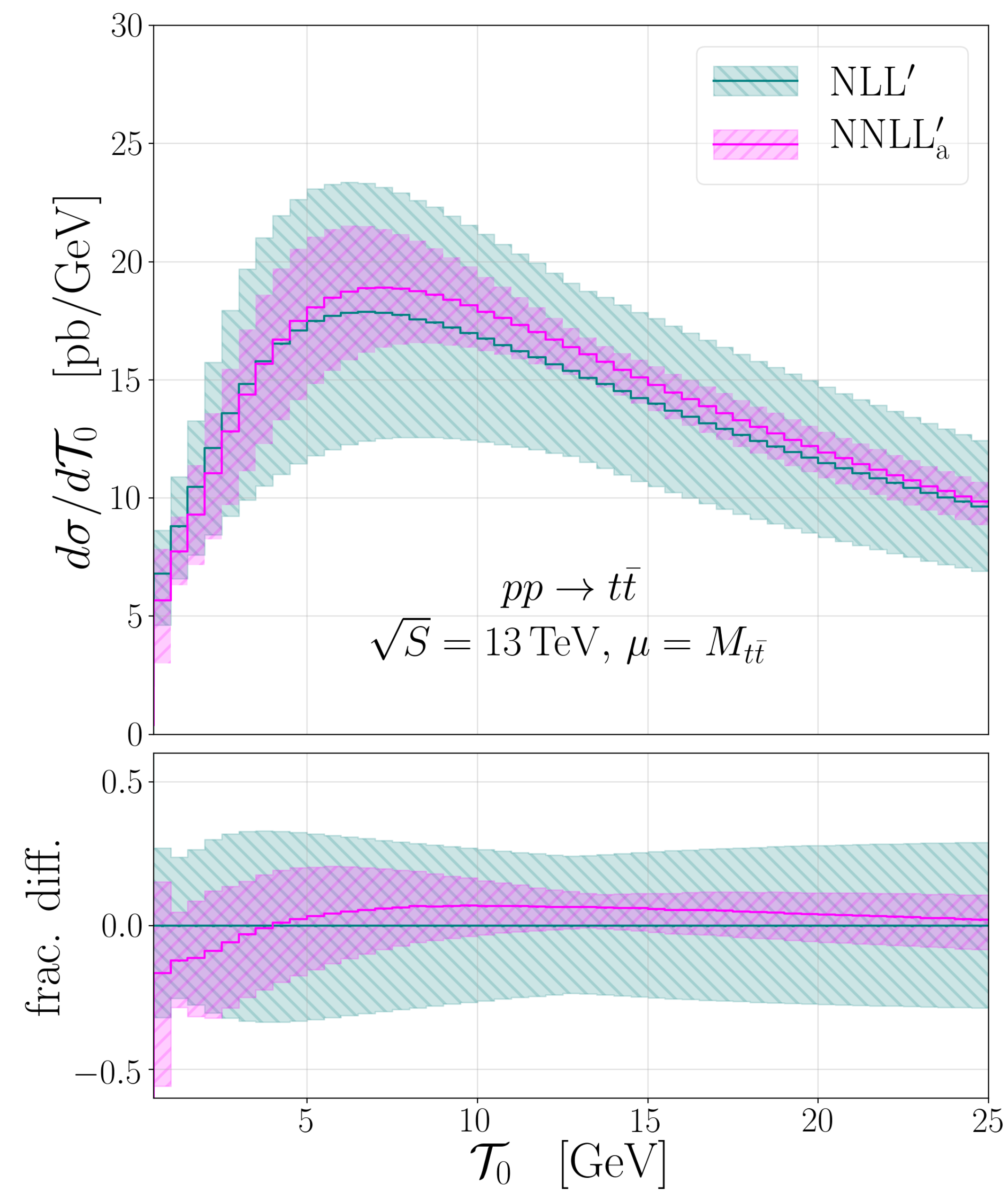




Resummed results

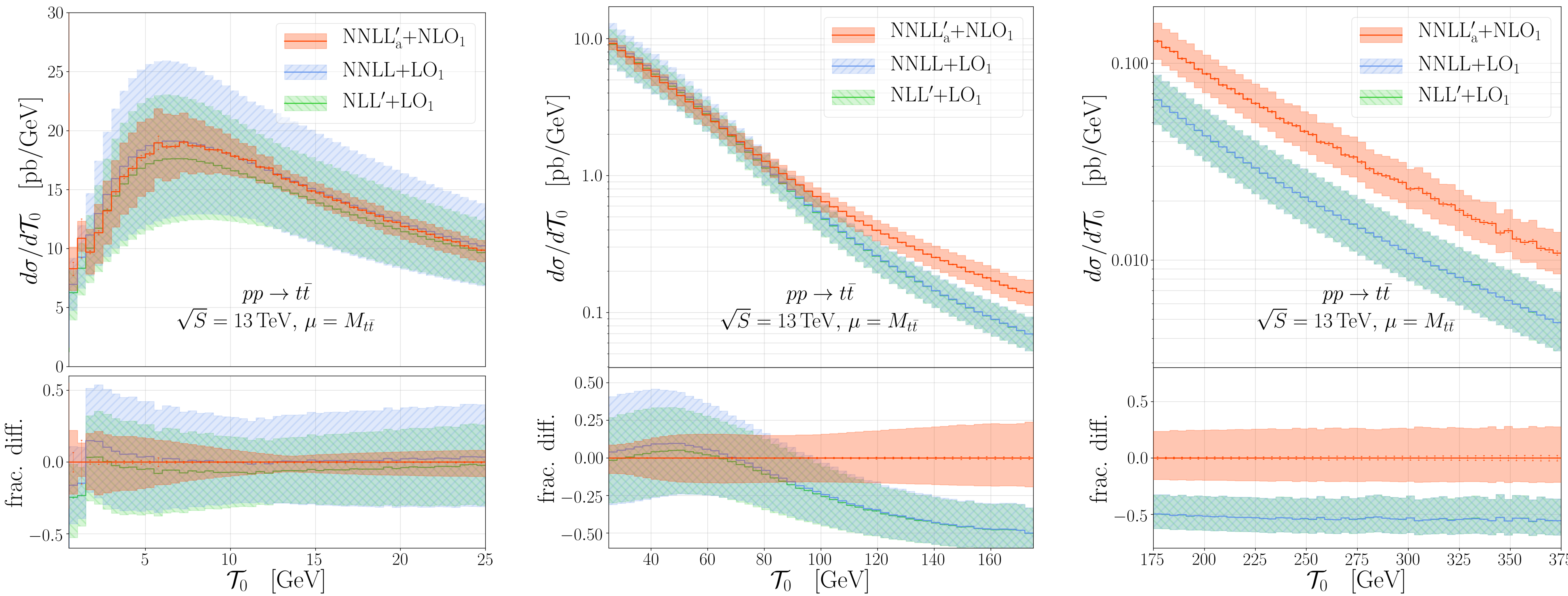
NNLL'_a is our best prediction, it includes NNLO beam functions, all mixed NLO x NLO terms, NNLL evolution matrices, all NNLO soft logarithmic terms. Resummation is switched off via profile scales





Matched results to fixed-order

$$\frac{\mathrm{d}\sigma^{\mathrm{match}}}{\mathrm{d}\mathcal{T}_0} = \frac{\mathrm{d}\sigma^{\mathrm{resum}}}{\mathrm{d}\mathcal{T}_0} + \frac{\mathrm{d}\sigma^{\mathrm{FO}}}{\mathrm{d}\mathcal{T}_0} - \left[\frac{\mathrm{d}\sigma^{\mathrm{resum}}}{\mathrm{d}\mathcal{T}_0}\right]_{\mathrm{FO}}$$



One-jettiness resummation for Z+jet production at the LHC

work in progress…

1-jettiness

- Start from expression for 1-jettiness in the Born frame, where $\rho_i = 1$

$$\hat{\mathcal{T}}_1 = \sum_k \min\{\frac{\hat{q}_a \cdot \hat{p}_k}{\rho_a}, \frac{\hat{q}_b \cdot \hat{p}_k}{\rho_b}, \frac{\hat{q}_J \cdot \hat{p}_J}{\rho_J}\}$$

- 1-jettiness in the color singlet frame by making a different choice of the ρ_i's (similar way to go to the laboratory frame)

$$\rho_a = e^{\hat{Y}_V}\,,$$
$$\rho_b = e^{-\hat{Y}_V}\,,$$
$$\rho_J = \frac{e^{-\hat{Y}_V}(\hat{p}_J)_+ + e^{\hat{Y}_V}(\hat{p}_J)_-}{2\hat{E}_J}$$

- We also employ a Fully-Recursive (FR) version of one-jettiness which is used in the fixed order calculations. Closest particles in the one-jettiness metric are merged together.

- Factorization formula in the region $\mathcal{T}_1 \ll M_{ll} \sim \sqrt{s} \sim M_{T,ll}$ [Stewart, Tackmann,Waalewijn \`09,\`10]

$$\frac{d\sigma}{d\Phi_1 d\mathcal{T}_1} = \sum_{\kappa=\{q\bar{q}g,qgq,ggg\}} \boxed{H_\kappa(\Phi_1)} \int dt_a dt_b ds_J \boxed{B_{\kappa_a}(t_a) B_{\kappa_b}(t_b) J_{\kappa_J}(s_J)}$$
$$\times \boxed{S_\kappa\left(n_{a,b} \cdot n_J, \mathcal{T}_1 - \frac{t_a}{Q_a} - \frac{t_b}{Q_b} - \frac{s_J}{Q_J}\right)}$$

Dependence on the frame

Hard, Soft, Beam and Jet functions

- Hard functions: two-loop amplitudes for $q\bar{q} \to Zg$ known from [T. Gehrmann and L. Tancredi 1112.1531]. Recently available also the axial vector couplings [T. Gehrmann,T. Peraro,L. Tancredi 2211.13596] *but not-included yet*. IR-finite functions taken from [T. Becher, G. Bell, C. Lorentzen, S. Marti 1309.3245]. $\gamma^*/Z^* \to l^+l^-$ added, squared amplitude complete analytic result. At NNLL` accuracy included the 1loop squared $gg \to Zg$.

- Beam and quark Jet functions known up to N^{3}LO [M. Ebert, B. Mistlberger, G. Vita 2006.03056] and [R. Bruser, Z.L. Liu, M. Stahlhofen 1804.09722], only needed up to NNLO here Beams [J.R. Gaunt, M. Stahlhofen, F. Tackmann 1401.5478, 1405.1044] and Jets [T. Becher and M. Neubert 0603140], [T. Becher and G. Bell 1104.4108].

- Soft function boundary terms at NLO implemented as on-the-fly integrals using results in [T.T. Jouttenus, I.W. Stewart, F. Tackmann, W. Waalewijn 1302.0846], kept full dependence on $\mathcal{T}_1$ frame dependence.

- Frame dependent NNLO soft function boundary contribution is provided by using the SoftSERVE [G. Bell, R. Rahn, J. Talbert 1812.08690, 2004.08396] method (thanks to Bahman Dehnadi, Guido Bell, Rudi Rahn) in the form of an interpolation grid over the parameters $\{\cos\theta_J, 1/\rho_a, 1/\rho_J\}$

- Validation against NLO result in different frames, at NNLO validated in UB frame against the interpolation in MCFM [J. Campbell, K. Ellis, R. Mondini, C. Williams, 1711.09984]. In CS and Lab frames new results.

Resummation formula

Combine the solutions to the RG equations for the hard, soft, beam and jet functions to obtain

$$
\begin{aligned}
\frac{\mathrm{d}\sigma}{\mathrm{d}\Phi_1 \mathrm{d}\mathcal{T}_1} = \sum_\kappa \exp\Big\{ & 4(C_{\kappa_a}+C_{\kappa_b})K_{\Gamma_{\rm cusp}}(\mu_B,\mu_H) + 4C_{\kappa_J}K_{\Gamma_{\rm cusp}}(\mu_J,\mu_H) \\
& - 2(C_{\kappa_a}+C_{\kappa_b}+C_{\kappa_J})K_{\Gamma_{\rm cusp}}(\mu_S,\mu_H) - 2C_{\kappa_J}L_J\,\eta_{\Gamma_{\rm cusp}}(\mu_J,\mu_H) \\
& - 2(C_{\kappa_a}L_B + C_{\kappa_b}L_B')\eta_{\Gamma_{\rm cusp}}(\mu_B,\mu_H) + \Big[C_{\kappa_a}\ln\left(\frac{Q_a^2 u}{st}\right) + C_{\kappa_b}\ln\left(\frac{Q_b^2 t}{su}\right) \\
& \quad + C_{\kappa_j}\ln\left(\frac{Q_J^2 s}{tu}\right) + (C_{\kappa_a}+C_{\kappa_b}+C_{\kappa_J})L_S\Big]\eta_{\Gamma_{\rm cusp}}(\mu_S,\mu_H) + K_{\gamma_{\rm tot}}\Big\} \\
& \times \tilde{B}_{\kappa_a}(\partial_{\eta_B}+L_B, x_a,\mu_B)\tilde{B}_{\kappa_b}(\partial_{\eta_B'}+L_B', x_b,\mu_B)\,\tilde{J}_{\kappa_J}(\partial_{\eta_J}+L_J,\mu_J) \\
& \times H_\kappa(\Phi_1,\mu_H)\tilde{S}^{\kappa}_{\mathcal{T}_1}\left(\partial_{\eta_S}+L_S,\mu_S\right)\frac{Q^{-\eta_{\rm tot}}}{\mathcal{T}_1^{1-\eta_{\rm tot}}}\frac{\eta_{\rm tot}\,e^{-\gamma_E\eta_{\rm tot}}}{\Gamma(1+\eta_{\rm tot})} + \mathcal{O}\left(\frac{\mathcal{T}_1}{Q}\right)
\end{aligned}
$$

where we defined

$$
L_H = \ln\left(\frac{Q^2}{\mu_H^2}\right) \qquad L_B = \ln\left(\frac{Q_a Q}{\mu_B^2}\right), \qquad L_B' = \ln\left(\frac{Q_b Q}{\mu_B^2}\right)
$$

$$
L_J = \ln\left(\frac{Q_J Q}{\mu_J^2}\right) \qquad L_S = \ln\left(\frac{Q^2}{\mu_S^2}\right)
$$

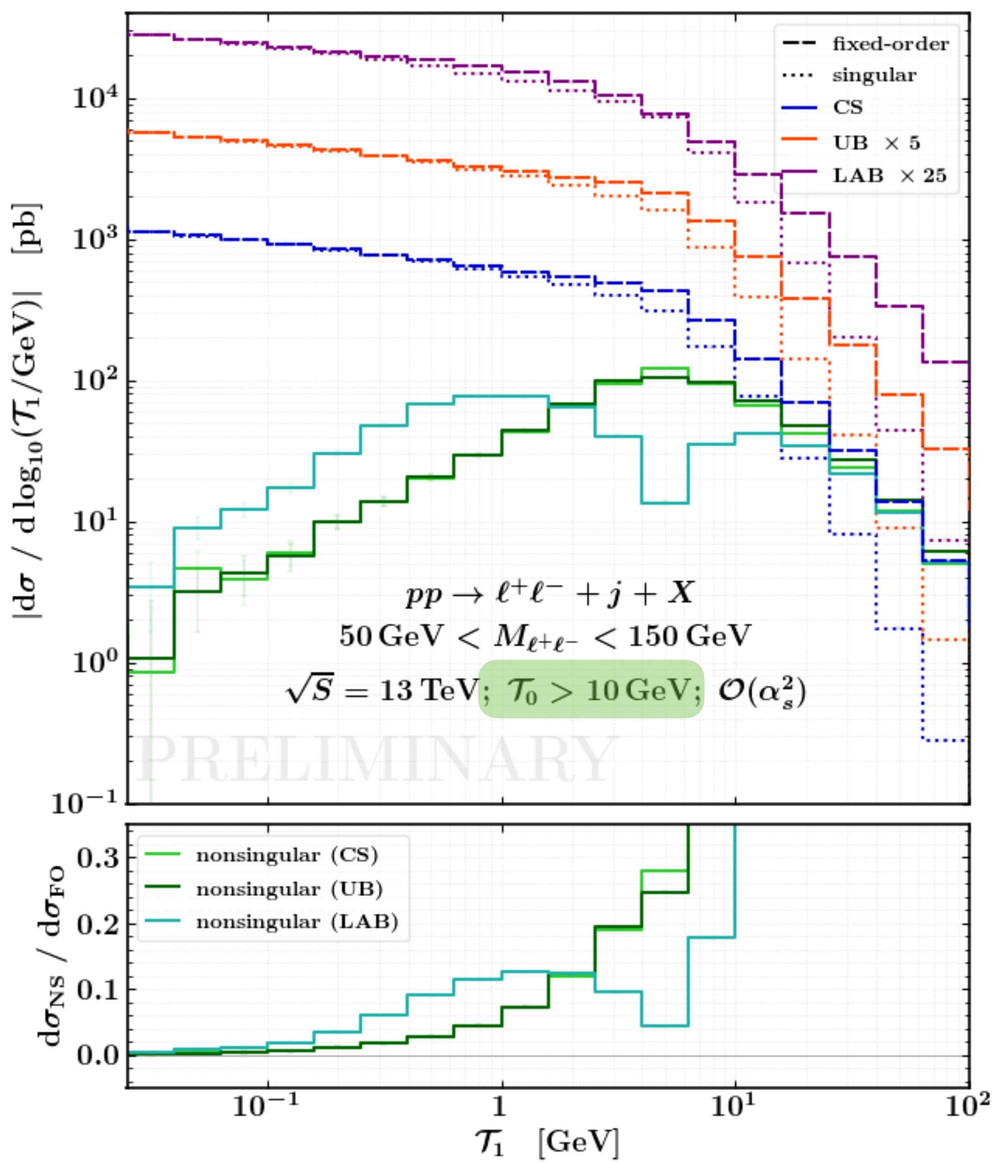
$$
\begin{aligned}
K_{\gamma_{\rm tot}} = & -2n_g K_{\gamma_C^g}(\mu_S,\mu_H) + 2(n_g-3)K_{\gamma_C^q}(\mu_S,\mu_H) \\
& - (n_g - n_g^{\kappa_J})K_{\gamma_J^g}(\mu_J,\mu_B) - n_g K_{\gamma_J^g}(\mu_S,\mu_J) \\
& + (n_g - 2 - n_g^{\kappa_J})K_{\gamma_J^q}(\mu_J,\mu_B) + (n_g-3)K_{\gamma_J^q}(\mu_S,\mu_J)
\end{aligned}
$$

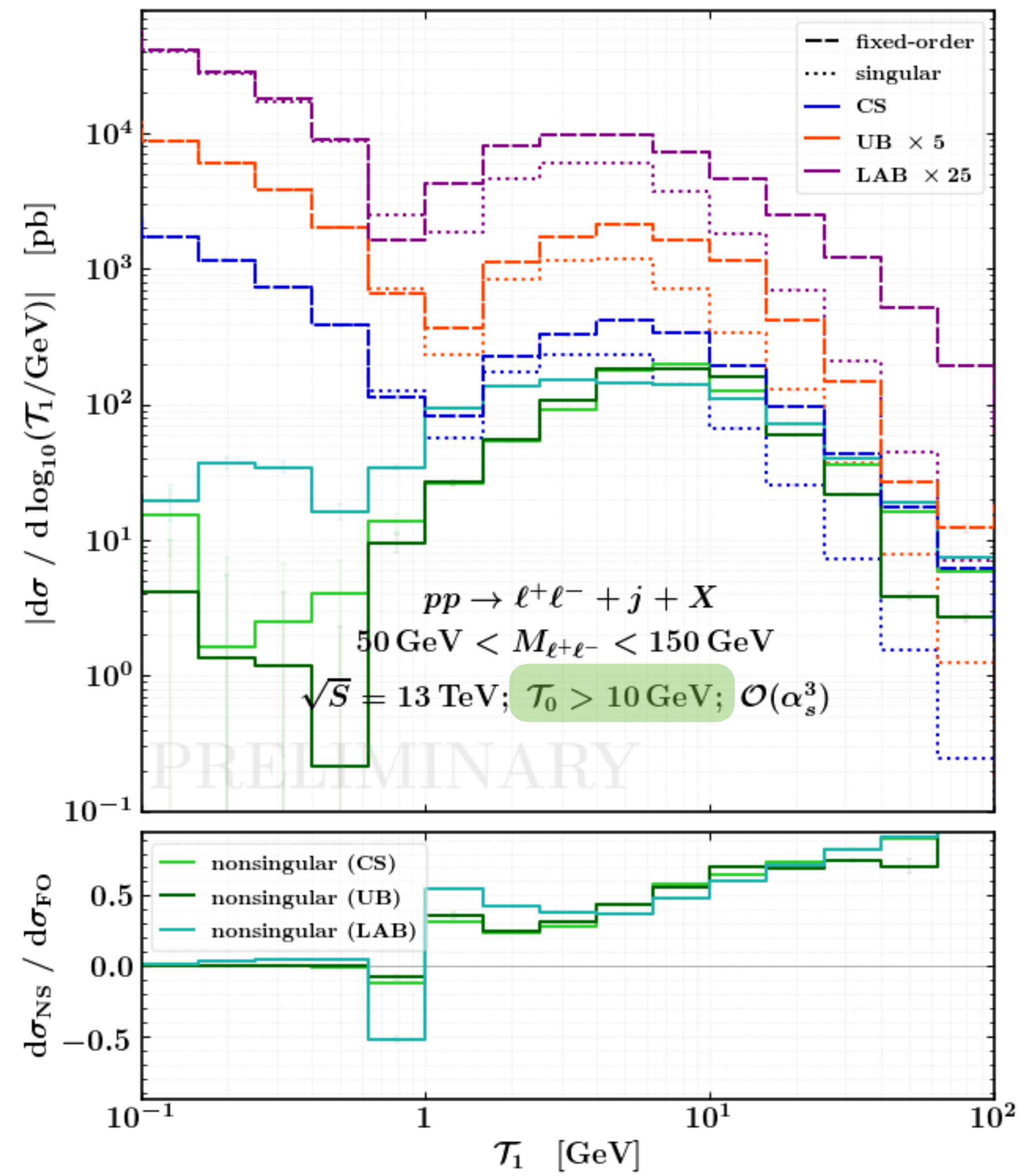
$$
\eta_{\rm tot} = -2(C_{\kappa_a}+C_{\kappa_b})\eta_{\Gamma_{\rm cusp}}(\mu_B,\mu_J) + 2(C_{\kappa_a}+C_{\kappa_b}+C_{\kappa_J})\eta_{\Gamma_{\rm cusp}}(\mu_S,\mu_J)
$$

Singular vs Nonsingular

- Different frame choices for one-jettiness definition have different sizes of power corrections (fully-recursive results below, only fixed-order is different for $\mathcal{T}_1 > 0$)

- CS frame as good as UB frame for different cuts, Lab. frame is worse

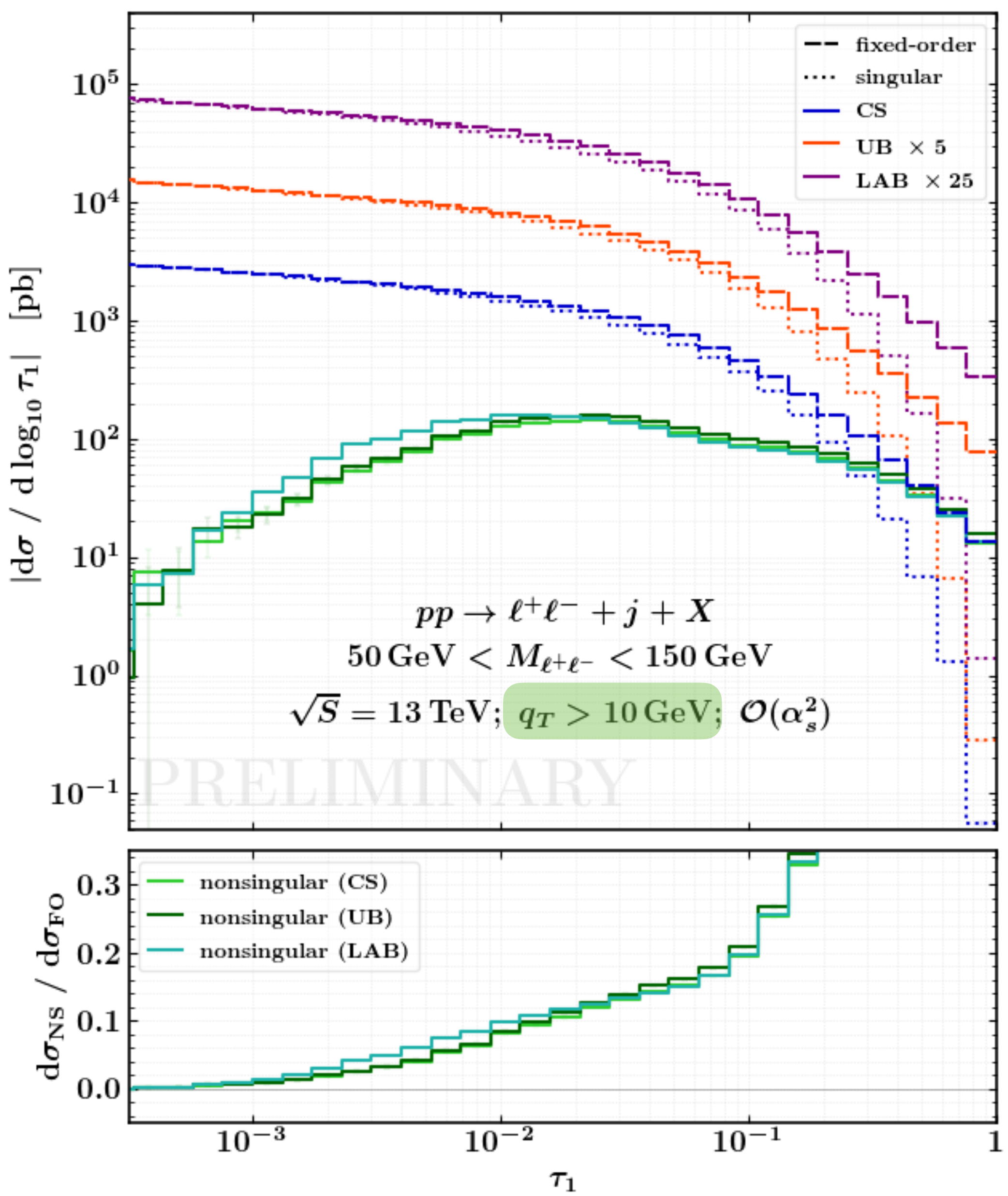


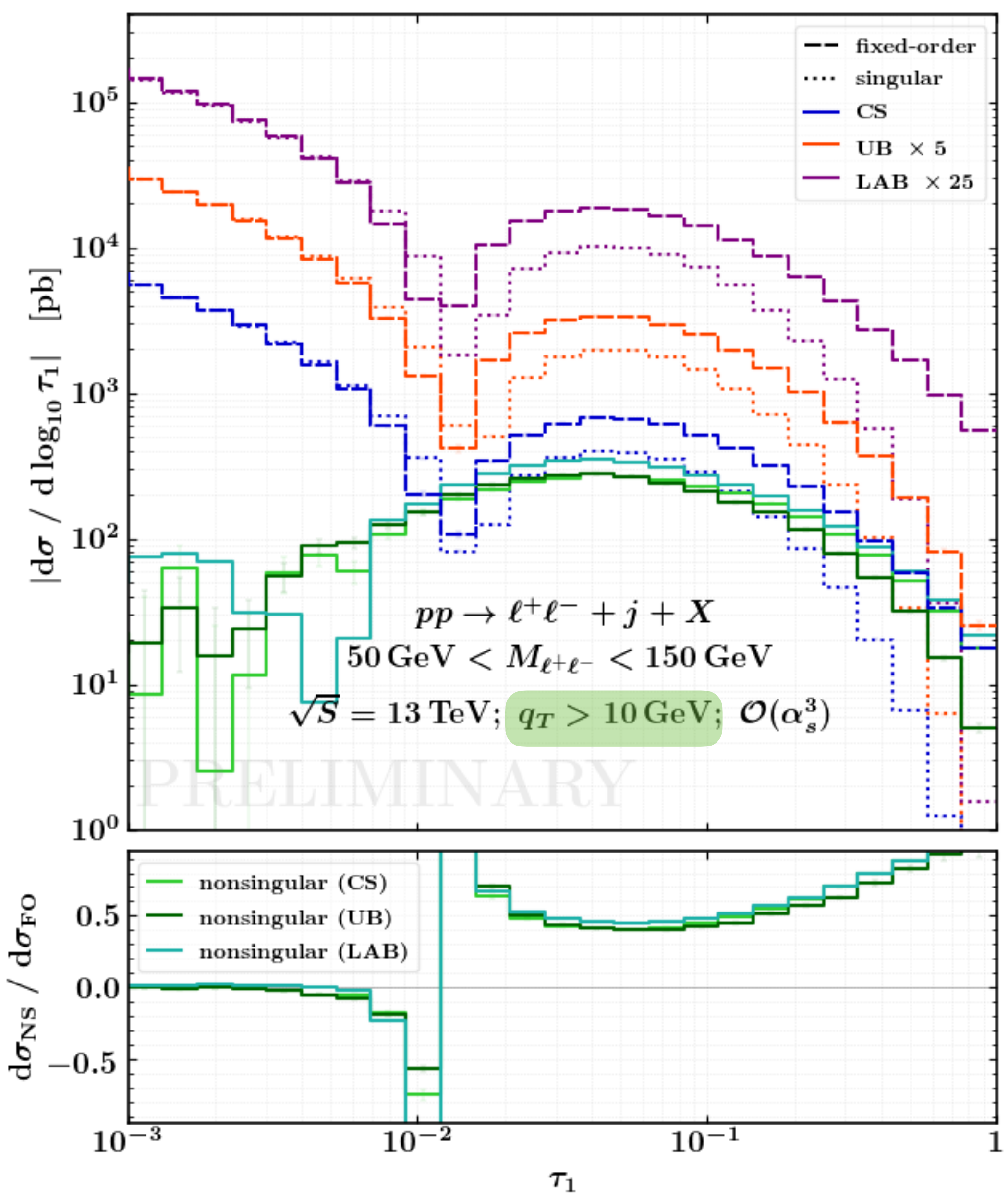


Singular vs Nonsingular

- Reduced definition $\tau_1 = 2\,\mathcal{T}_1/\sqrt{M^2_{l^+l^-} + q_T^2}$

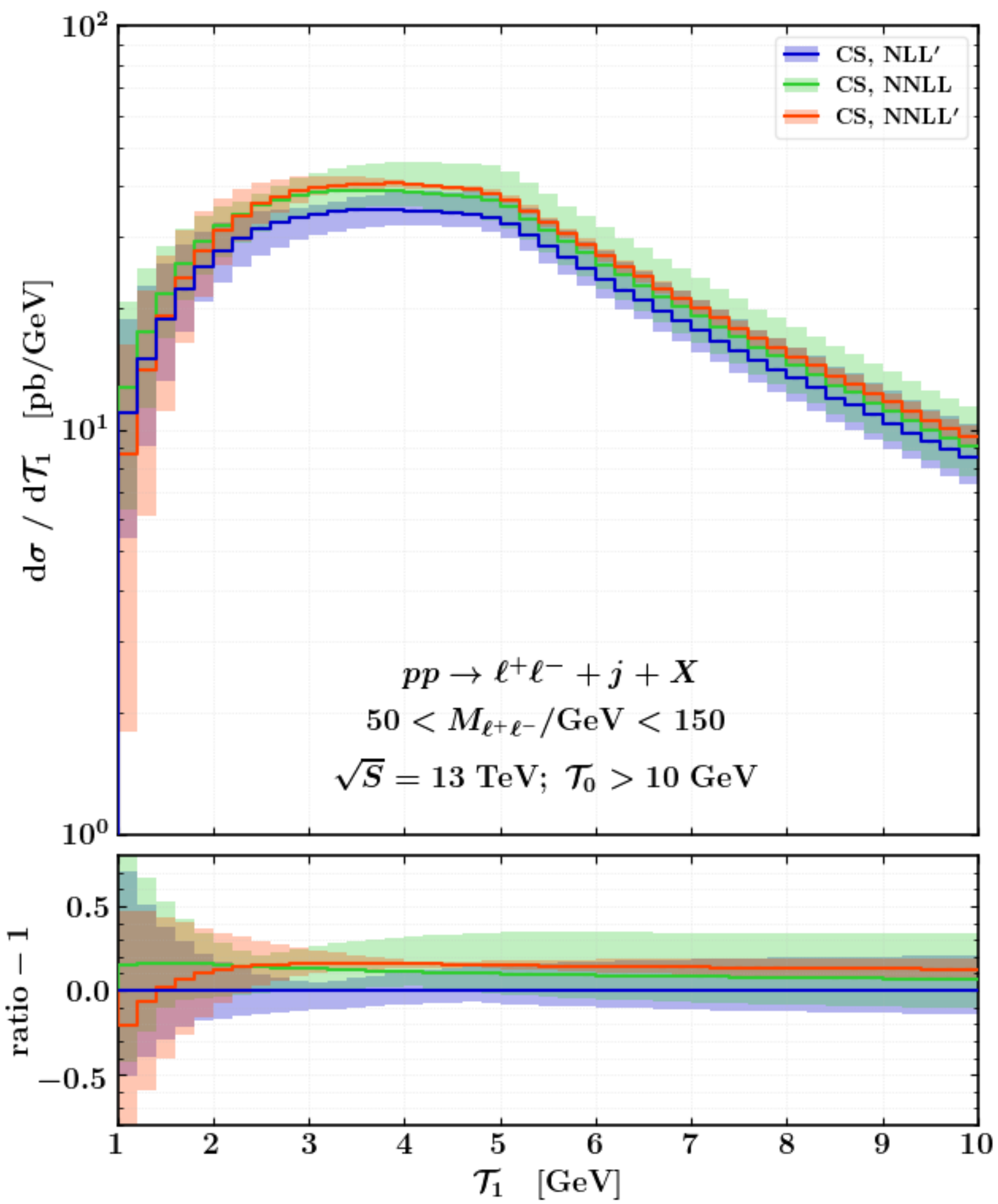
- When we use as born defining cut the Z boson transverse momentum q_T, differences in power corrections among definitions are reduced

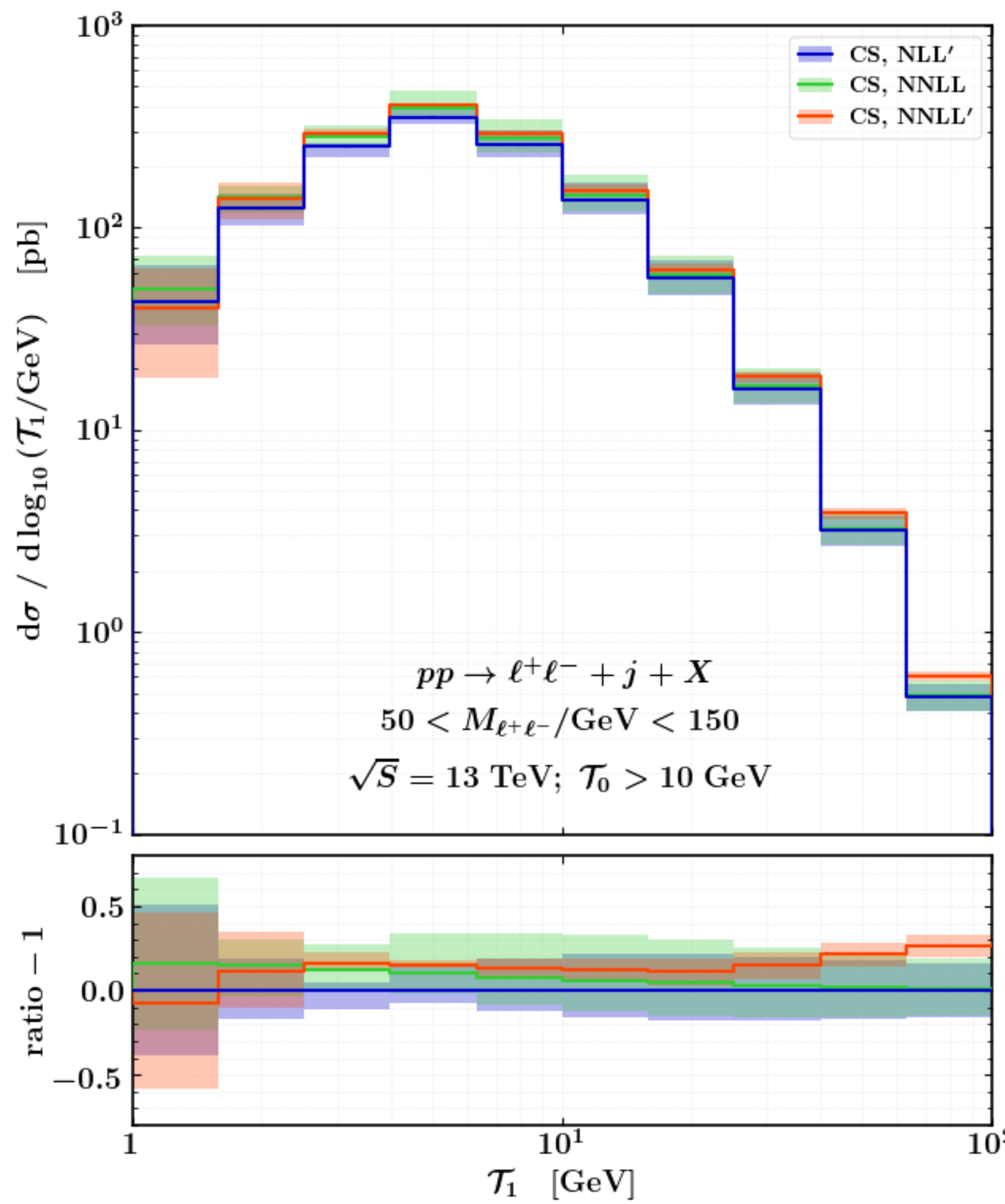




Resummed results

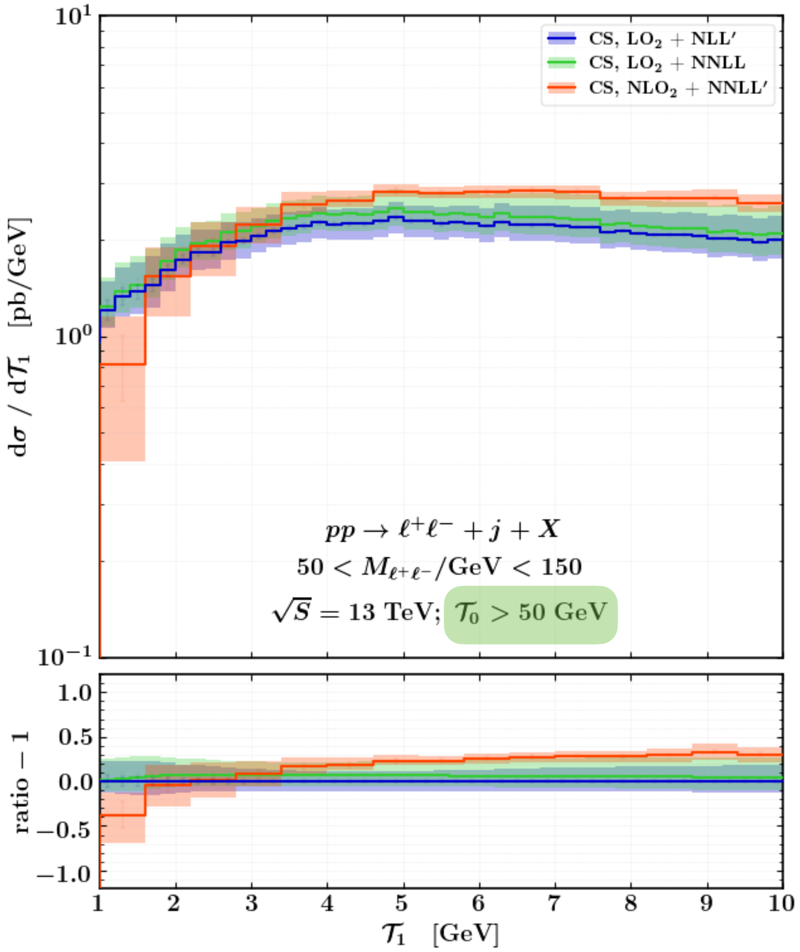
- We use profile scales to switch off resummation at $\mu_H = \sqrt{M_{l^+l^-}^2 + q_T^2}$

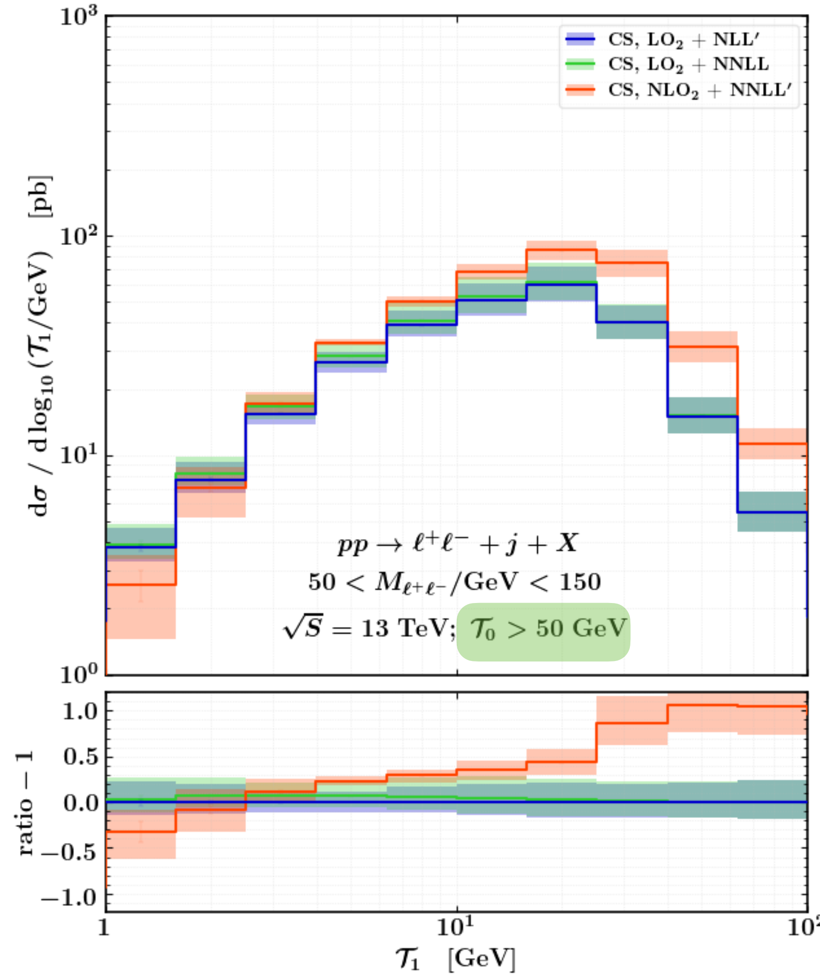


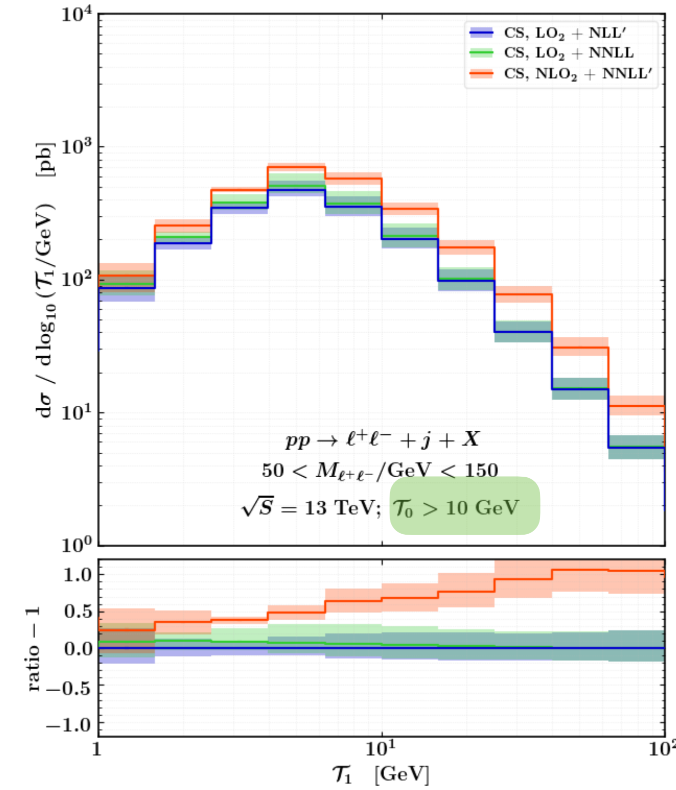


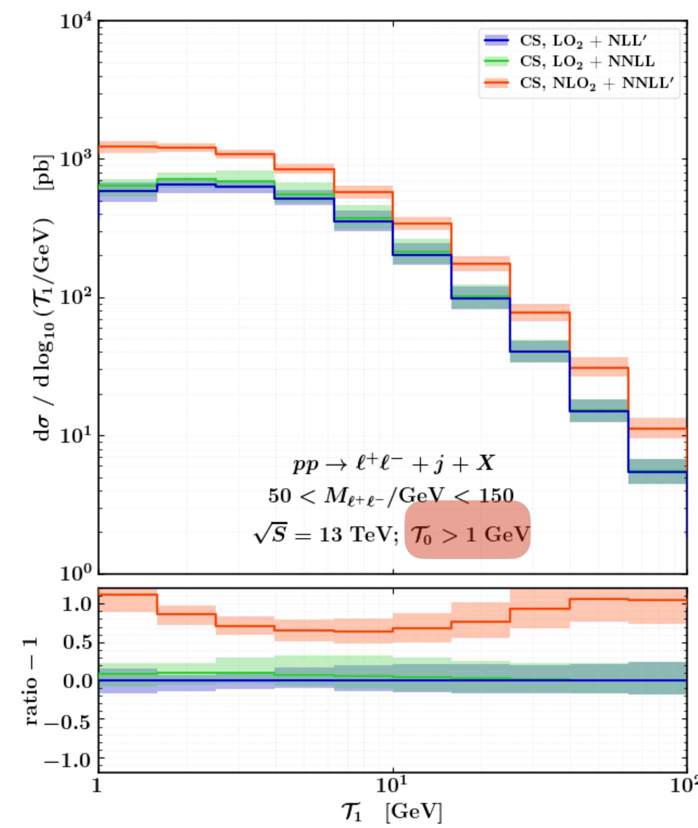
Matched results

$$\frac{d\sigma^{\text{match}}}{d\mathcal{T}_1} = \frac{d\sigma^{\text{resum}}}{d\mathcal{T}_1} + \frac{d\sigma^{\text{FO}}}{d\mathcal{T}_1} - \left[\frac{d\sigma^{\text{resum}}}{d\mathcal{T}_1}\right]_{\text{FO}}$$









- $\mathcal{O}(\alpha_s^3)$ large corrections especially for small values of $\mathcal{T}_0^{\text{cut}}$
- We know that nonsingular in $\mathcal{T}_1$ is divergent for $\mathcal{T}_0 \to 0$
- We sum in quadrature profile scales variations and fixed-order scale variations

Outlook

- Calculate and extract all the missing ingredients to reach NNLL$'$ accuracy for the top-quark pair production process (hard and soft functions). Implement in GENEVA event generator

- Extend top-quark pair to study associated production of a top-pair and a heavy boson $t\bar{t}V$ $(V = H, W^{\pm}, Z)$ [AB,Ferroglia,Pecjak,Signer, Yang `15], [AB,Ferroglia,Pecjak,Ossola `16], [AB,Ferroglia,Pecjak,Yang `16],[AB,Ferroglia,Pecjak,Ossola,Sameshima `17],[AB,Ferroglia,Frederix, Pagani,Pecjak,Tsinikos `19]

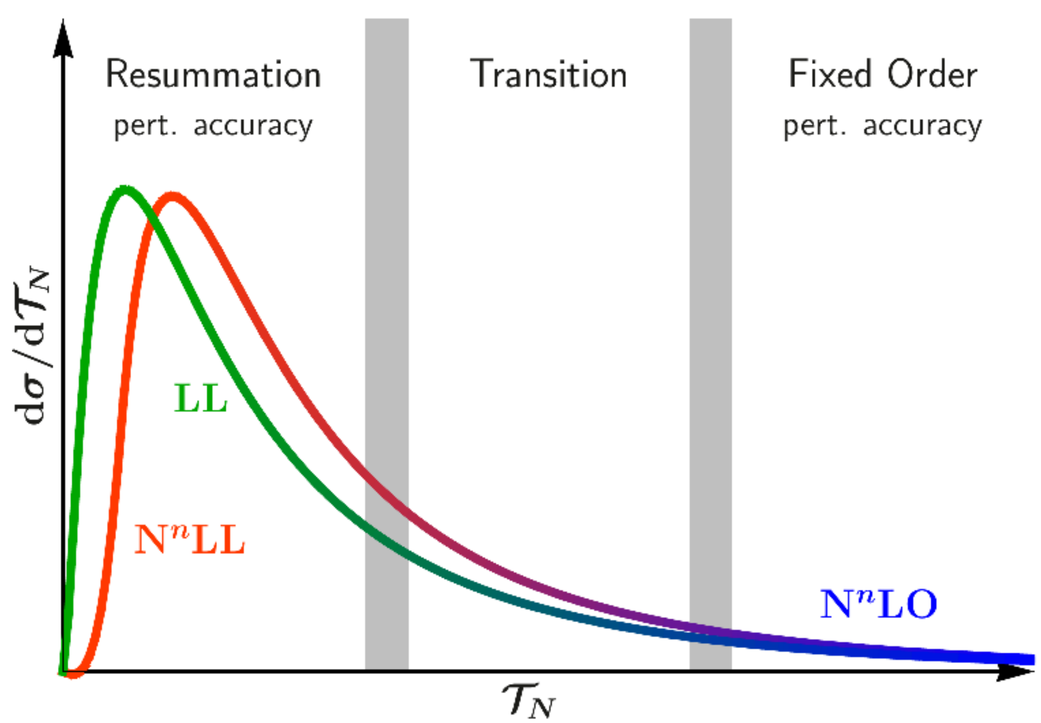
- Extend resummation to N^{3}LL for Z+jet production. Implementation in Monte Carlo event generator

Thank you!

Backup slides

N-Jettiness and Resummation

- At NNLO one needs a 0-jet and a 1-jet (for Z+j also 2-jet) resolution parameters
- Emissions below $\mathcal{T}_N^{\rm cut}$ are unresolved (integrated over) and the kinematic considered is the one of the event before extra emissions
- Emissions above $\mathcal{T}_N^{\rm cut}$ are kept and the full kinematics is considered
- When we take $\mathcal{T}_N^{\rm cut} \to 0$, large logarithms of $\mathcal{T}_N^{\rm cut}$, $\mathcal{T}_N$ appear and need to be resummed
- Including the higher-order resummation will improve the accuracy of the predictions across the whole spectrum



Resummed result for the cross section

We can combine the solutions for the hard, soft and beam functions to obtain

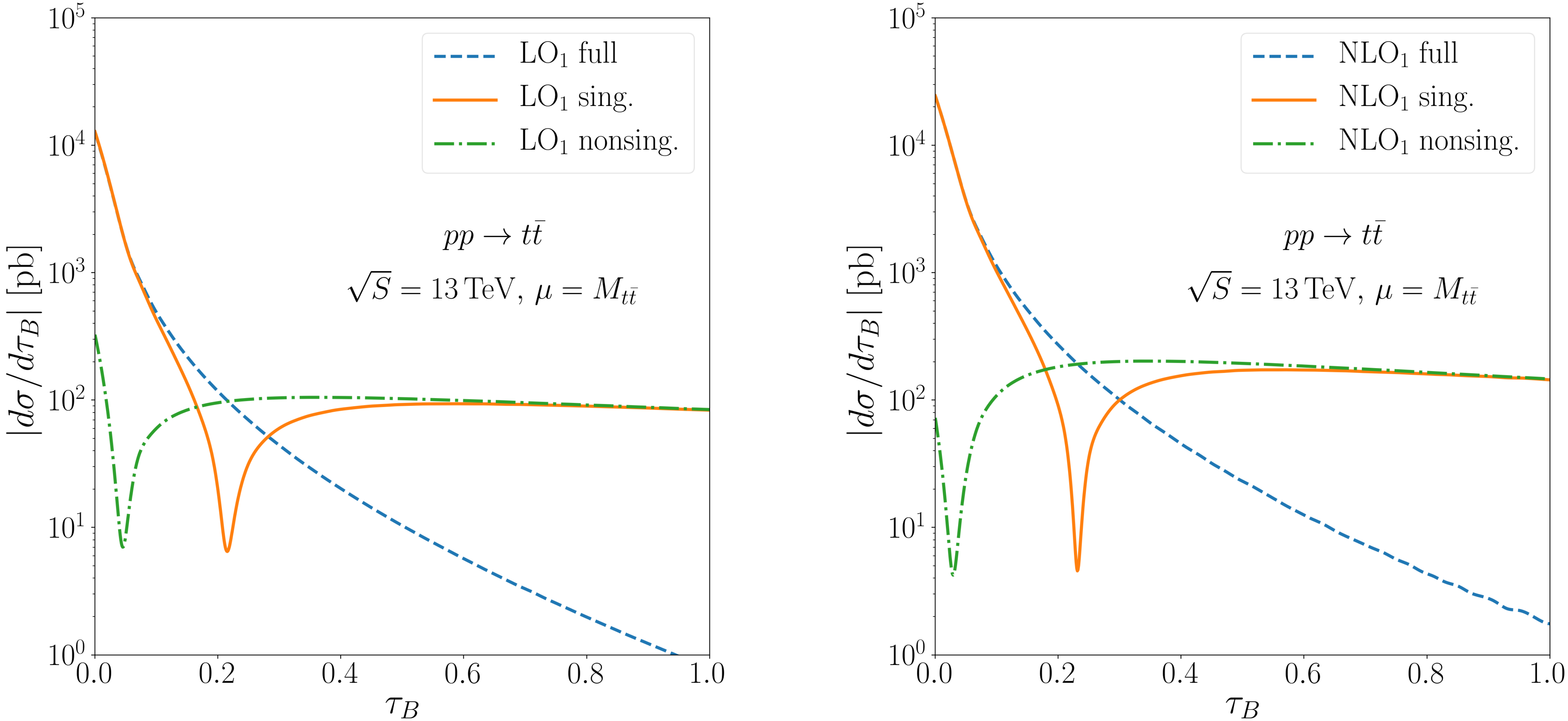
$$\frac{\mathrm{d}\sigma}{\mathrm{d}\Phi_0 \mathrm{d}\tau_B} = U(\mu_h, \mu_B, \mu_s, L_h, L_s)$$
$$\times \operatorname{Tr}\left\{ \mathbf{u}(\beta_t, \theta, \mu_h, \mu_s) \boxed{\mathbf{H}(M, \beta_t, \theta, \mu_h)} \mathbf{u}^\dagger(\beta_t, \theta, \mu_h, \mu_s) \boxed{\tilde{\mathbf{S}}_B(\partial_{\eta_s} + L_s, \beta_t, \theta, \mu_s)} \right\}$$
$$\times \boxed{\tilde{B}_a(\partial_{\eta_B} + L_B, z_a, \mu_B) \tilde{B}_b(\partial_{\eta'_B} + L_B, z_b, \mu_B)} \frac{1}{\tau_B^{1-\eta_{\text{tot}}}} \frac{e^{-\gamma_E \eta_{\text{tot}}}}{\Gamma(\eta_{\text{tot}})}$$

where

$$U(\mu_h, \mu_B, \mu_s, L_h, L_s) =$$
$$\exp\left[4S(\mu_h, \mu_B) + 4S(\mu_s, \mu_B) + 2a_{\gamma^B}(\mu_s, \mu_B) - 2a_\Gamma(\mu_h, \mu_B) L_h - 2a_\Gamma(\mu_s, \mu_B) L_s \right]$$

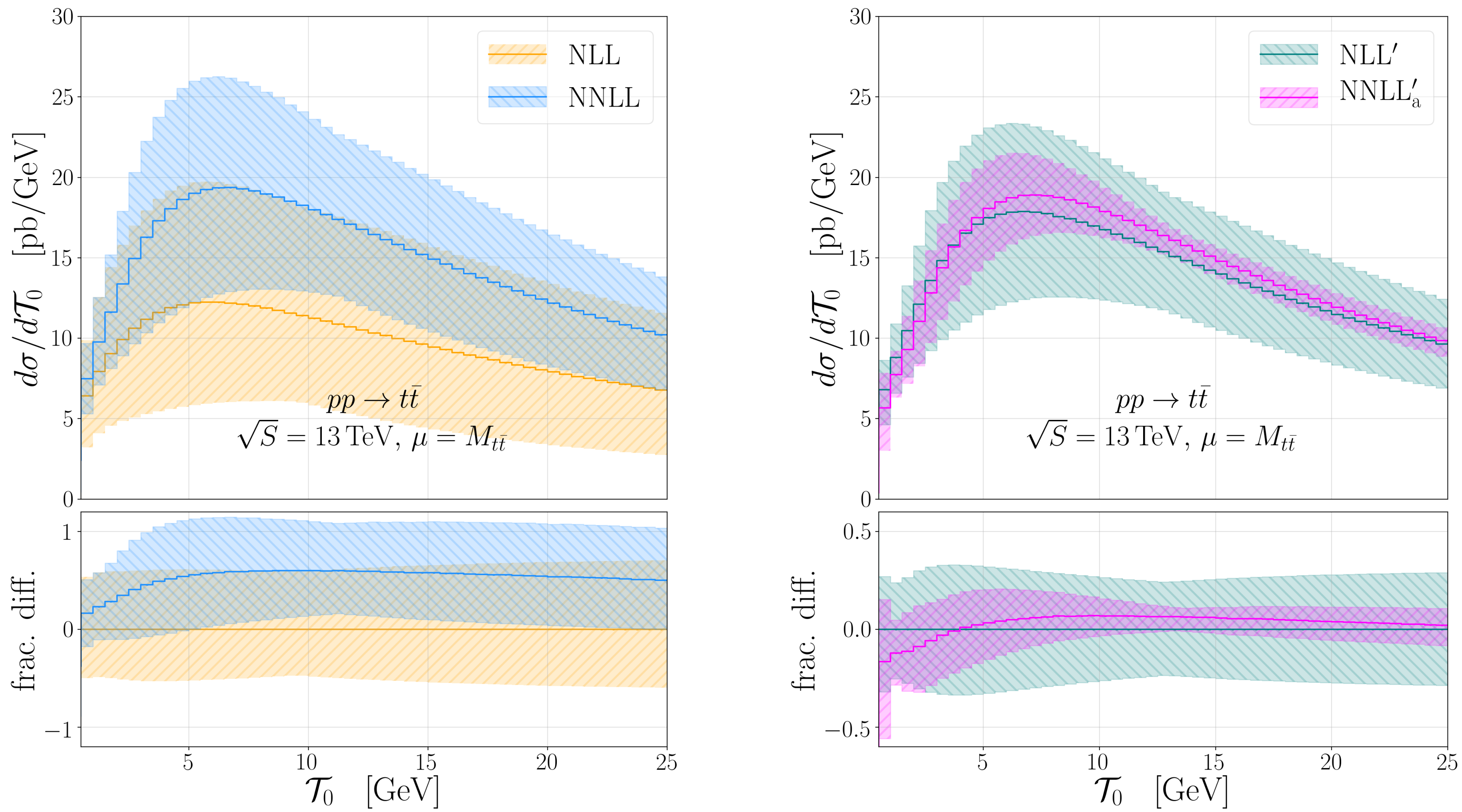
and $L_s = \ln(M^2/\mu_s^2)$, $L_h = \ln(M^2/\mu_h^2)$, $L_B = \ln(M^2/\mu_B^2)$ and $\eta_{\text{tot}} = 2\eta_S + \eta_B + \eta_{B'}$

Singular vs Nonsingular contributions



Resummed results

NNLL′ is our best prediction, it includes NNLO beam functions, all mixed NLO x NLO terms, NNLL evolution matrices, all NNLO soft logarithmic terms. Resummation is switched off via profile scales



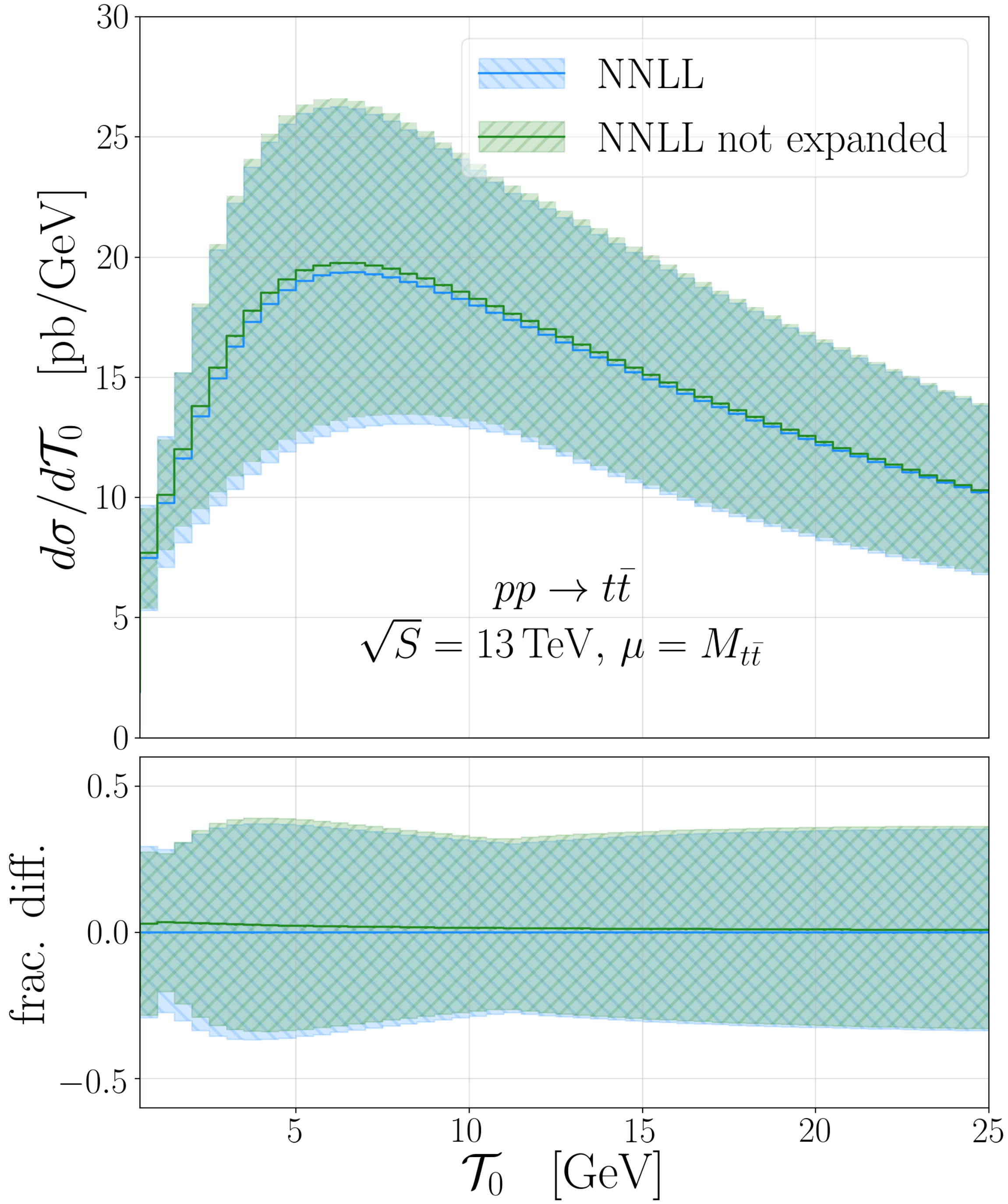
$$\mu_H = \mu_{\rm NS}\,,$$
$$\mu_S(\mathcal{T}_0) = \mu_{\rm NS}\ f_{\rm run}(\mathcal{T}_0/M)\,,$$
$$\mu_B(\mathcal{T}_0) = \mu_{\rm NS}\ \sqrt{f_{\rm run}(\mathcal{T}_0/M)}$$

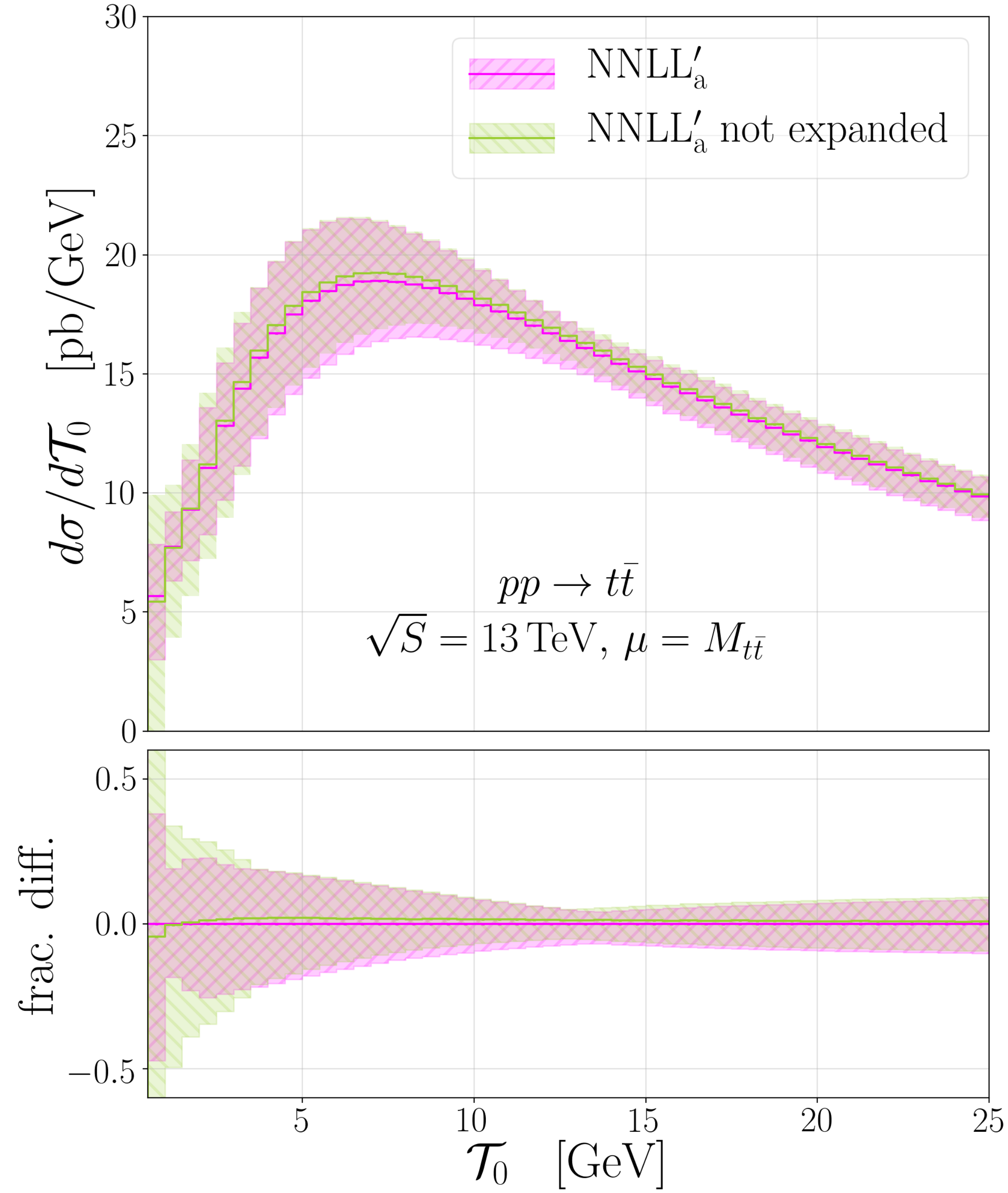
$$f_{\rm run}(y) = \begin{cases} y_0\big[1+(y/y_0)^2/4\big] & y \le 2y_0\,, \\ y & 2y_0 \le y \le y_1\,, \\ y + \frac{(2-y_2-y_3)(y-y_1)^2}{2(y_2-y_1)(y_3-y_1)} & y_1 \le y \le y_2\,, \\ 1 - \frac{(2-y_1-y_2)(y-y_3)^2}{2(y_3-y_1)(y_3-y_2)} & y_2 \le y \le y_3\,, \\ 1 & y_3 \le y\,. \end{cases}$$

$$y_0 = 1.0\,\mathrm{GeV}/M\,, \quad \{y_1,y_2,y_3\} = \{0.1, 0.175, 0.25\}$$

Resummed results

The evolution matrix **u** is evaluated in α_s expansion, we can choose to expand or not expand U, the difference is quite small





Singular vs Nonsingular

- Result for *exact* one-jettiness in CS frame, very similar results to FR