Resummation benchmark: status report

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On behalf of the resummation precision sub-group

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Main purpose of the benchmark

- We are now in the **precision phase** of the LHC.
- The present **accuracy** for *W*/*Z* production now is such that:
  - electroweak corrections become relevant,
  - **QCD** has to be pushed to its limits.
- **Resummation** allows us to include corrections to all orders in α_s:
  - necessary in the presence of large logs (typical in multiscale problems),
  - production of a *W*/*Z* with small q_T but large invariant mass Q **($q_T \ll Q$)** is a typical example.
- Different **formalisms** provide resummation of $\log(q_T/Q)$:
  - need to understand **similarities/differences** and **uncertainties**.
- This will *eventually* allow for a **sensible comparison** to data:
  - reliable determination of the *W* mass through *W*/*Z* ratio.

Resummation formalisms

- Different formulations of the q_T spectrum:

$$\left(\frac{d\sigma}{dq_T}\right)_{\text{res.}} \propto \begin{cases} e^{2S}\left[f_1 \otimes \mathcal{H} \otimes f_2\right] & : \textbf{Resum.} \\ H \times F_1 \times F_2 & : \textbf{TMD} \\ H \times B_1 \times B_2 \times S & : \textbf{SCET} \end{cases} + \mathcal{O}\left[\left(\frac{q_T}{Q}\right)^m\right]$$

- Dictionary:

$$\mathcal{H} = H C_1 C_2$$

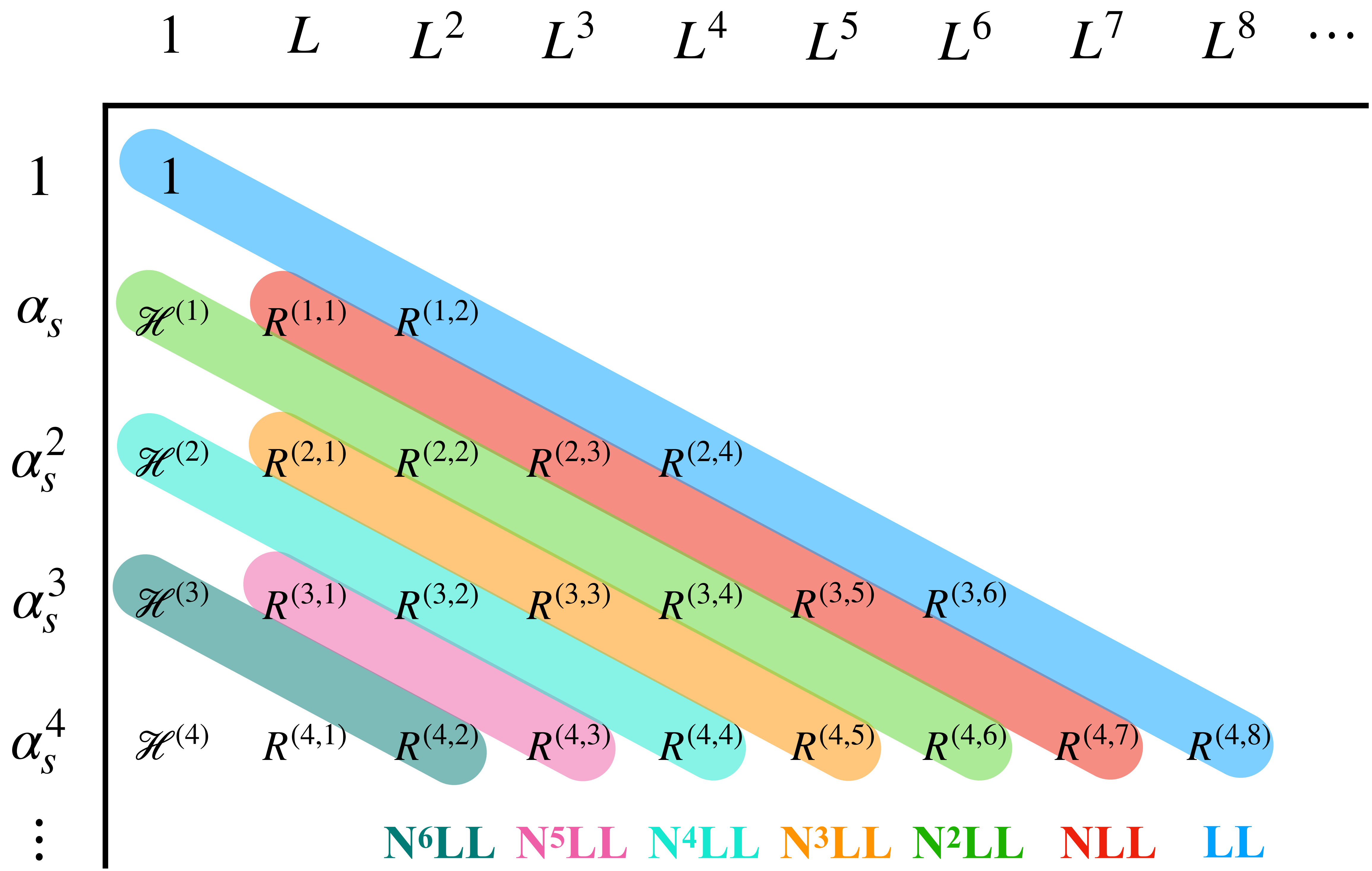
$$F_i = e^S C_i \otimes f_i$$

$$F_i = \sqrt{S} \times B_i$$

- All **equivalent** for *exponentiating* processes such as inclusive Drell-Yan.

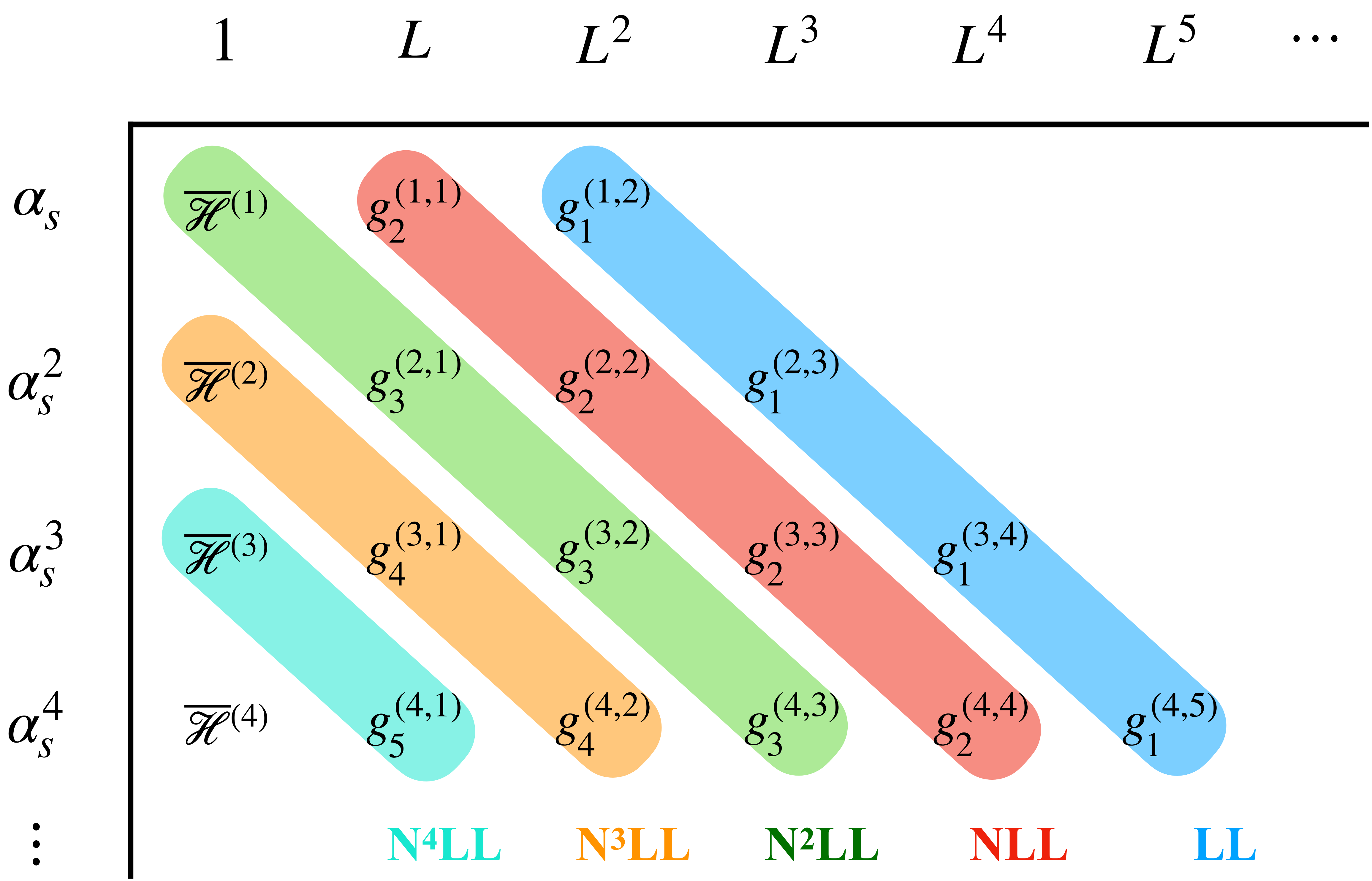
Logarithmic counting (1)

$$\frac{d\sigma}{dq_T} \propto \left(1 + \sum_{m=1}^{\infty} \alpha_s^m \mathcal{H}^{(m)}\right)\left(1 + \sum_{n=1}^{\infty} \alpha_s^n \sum_{k=1}^{2n} R^{(n,k)} L^k\right) \qquad \alpha_S L^2 \sim 1$$



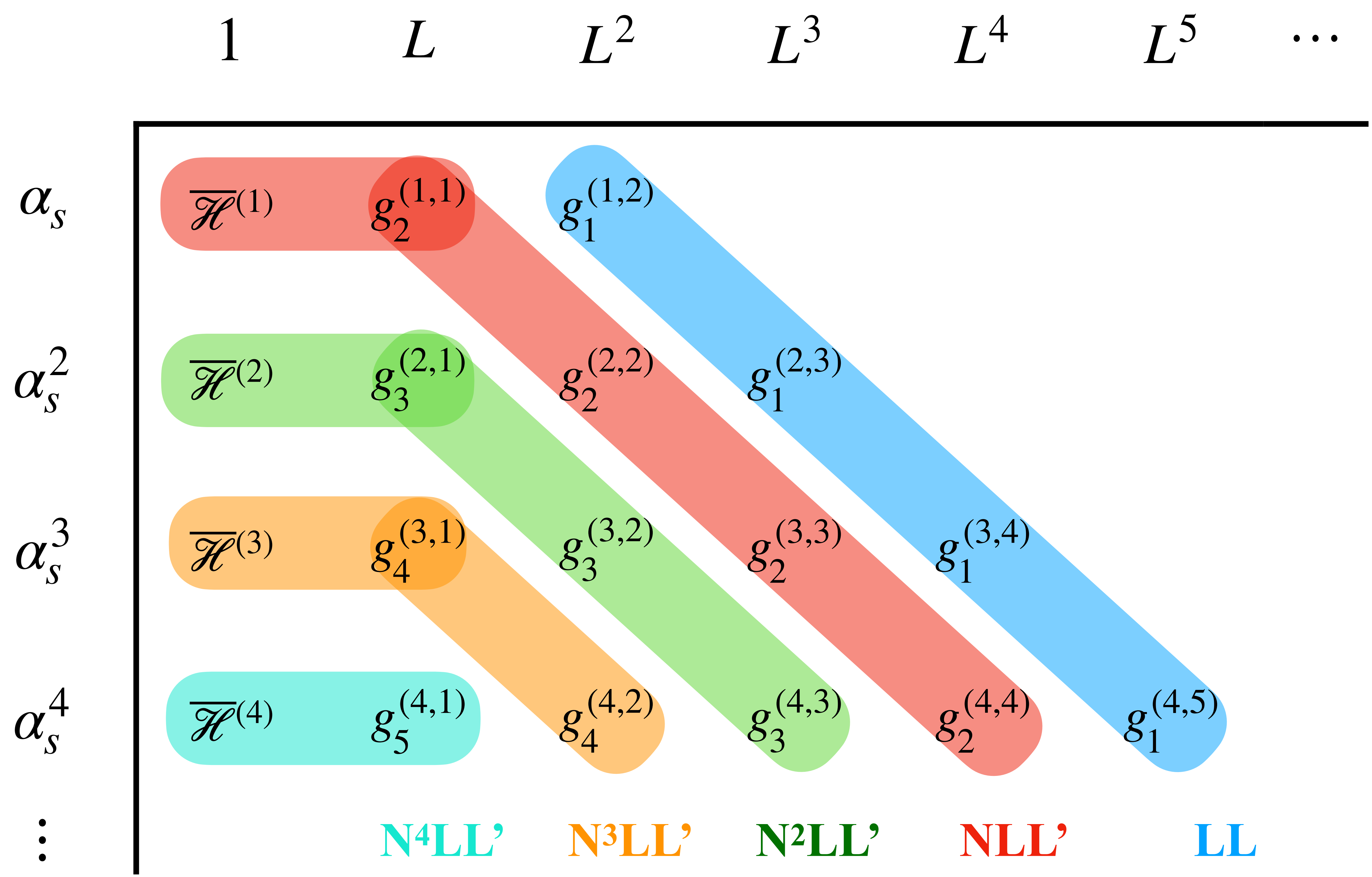
Logarithmic counting (2)

$$\ln\left(\frac{d\sigma}{dq_T}\right) \propto \ln\left(1 + \sum_{m=1}^{\infty} \alpha_s^m \mathcal{H}^{(m)}\right) + \sum_{n=1}^{\infty} \alpha_s^n \sum_{k=1}^{n+1} g^{(n,k)} L^k \qquad \alpha_S L \sim 1$$



Logarithmic counting (3)

$$\ln\left(\frac{d\sigma}{dq_T}\right) \propto \ln\left(1 + \sum_{m=1}^{\infty} \alpha_s^m \mathcal{H}^{(m)}\right) + \sum_{n=1}^{\infty} \alpha_s^n \sum_{k=1}^{n+1} g^{(n,k)} L^k \qquad \alpha_S L \sim 1$$



Logarithmic counting

$$\left(\frac{d\sigma}{dq_T}\right)_{\text{res.}} \overset{\text{TMD}}{=} \sigma_0 H(Q) \int d^2\mathrm{b}_T e^{i\mathrm{b}_T\cdot \mathrm{q}_T} F_1(x_1, \mathrm{b}_T, Q, Q^2) F_2(x_2, \mathrm{b}_T, Q, Q^2)$$

$$F_f(x, \mathrm{b}_T, \mu, \zeta) = \sum_j C_{f/j}(c, b_T; \mu_b, \zeta) \otimes f_j(x, \mu_b) \times \exp\left\{ K(b_T, \mu_b) \ln \frac{\sqrt{\zeta}}{\mu_b} + \int_{\mu_b}^{\mu} \frac{d\mu'}{\mu'} \left[\gamma_F - \gamma_K \ln \frac{\sqrt{\zeta}}{\mu'} \right] \right\}$$

Accuracy	γ_K	γ_F	K	$C_{f/j}$	H
LL	α_s	-	-	1	1
NLL	α_s^2	α_s	α_s	1	1
NLL'	α_s^2	α_s	α_s	α_s	α_s
N²LL	α_s^3	α_s^2	α_s^2	α_s	α_s
N²LL'	α_s^3	α_s^2	α_s^2	α_s^2	α_s^2
N³LL	α_s^4	α_s^3	α_s^3	α_s^2	α_s^2
N³LL'	α_s^4	α_s^3	α_s^3	α_s^3	α_s^3

Additive matching and counting

- Accurate predictions for all q_T's by **additive matching**, order by order in perturbation theory, of collinear and TMD calculations:

$$\left(\frac{d\sigma}{dq_T}\right)_{\text{add.match.}} = \left(\frac{d\sigma}{dq_T}\right)_{\text{res.}} + \left(\frac{d\sigma}{dq_T}\right)_{\text{f.o.}} - \left(\frac{d\sigma}{dq_T}\right)_{\text{d.c.}}$$

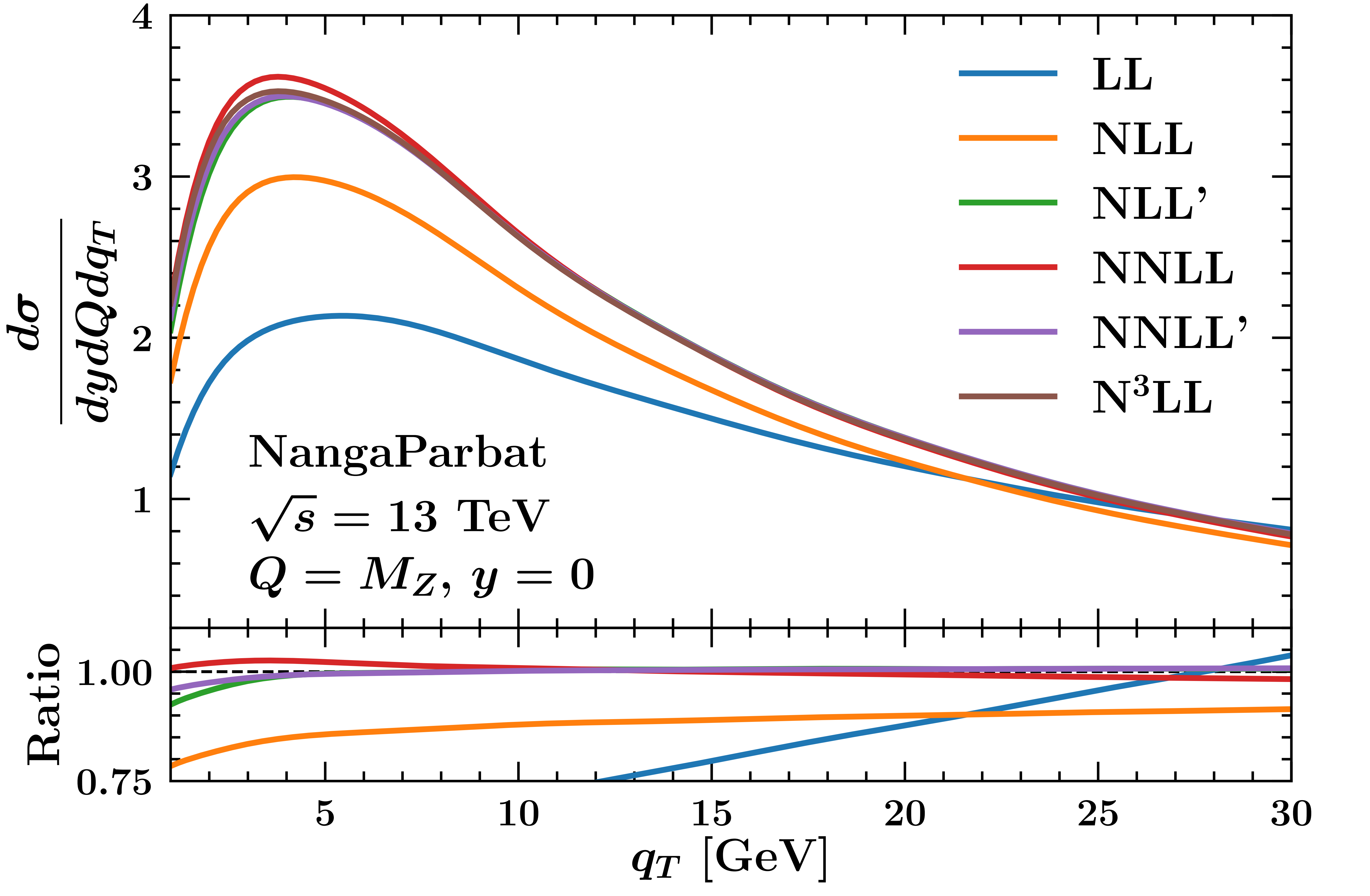
- In order for the match to actually take place:

$$\left(\frac{d\sigma}{dq_T}\right)_{\text{res.}} \xrightarrow[\text{f.o.}]{} \left(\frac{d\sigma}{dq_T}\right)_{\text{d.c.}} \xleftarrow[q_T \ll Q]{} \left(\frac{d\sigma}{dq_T}\right)_{\text{f.o.}}$$

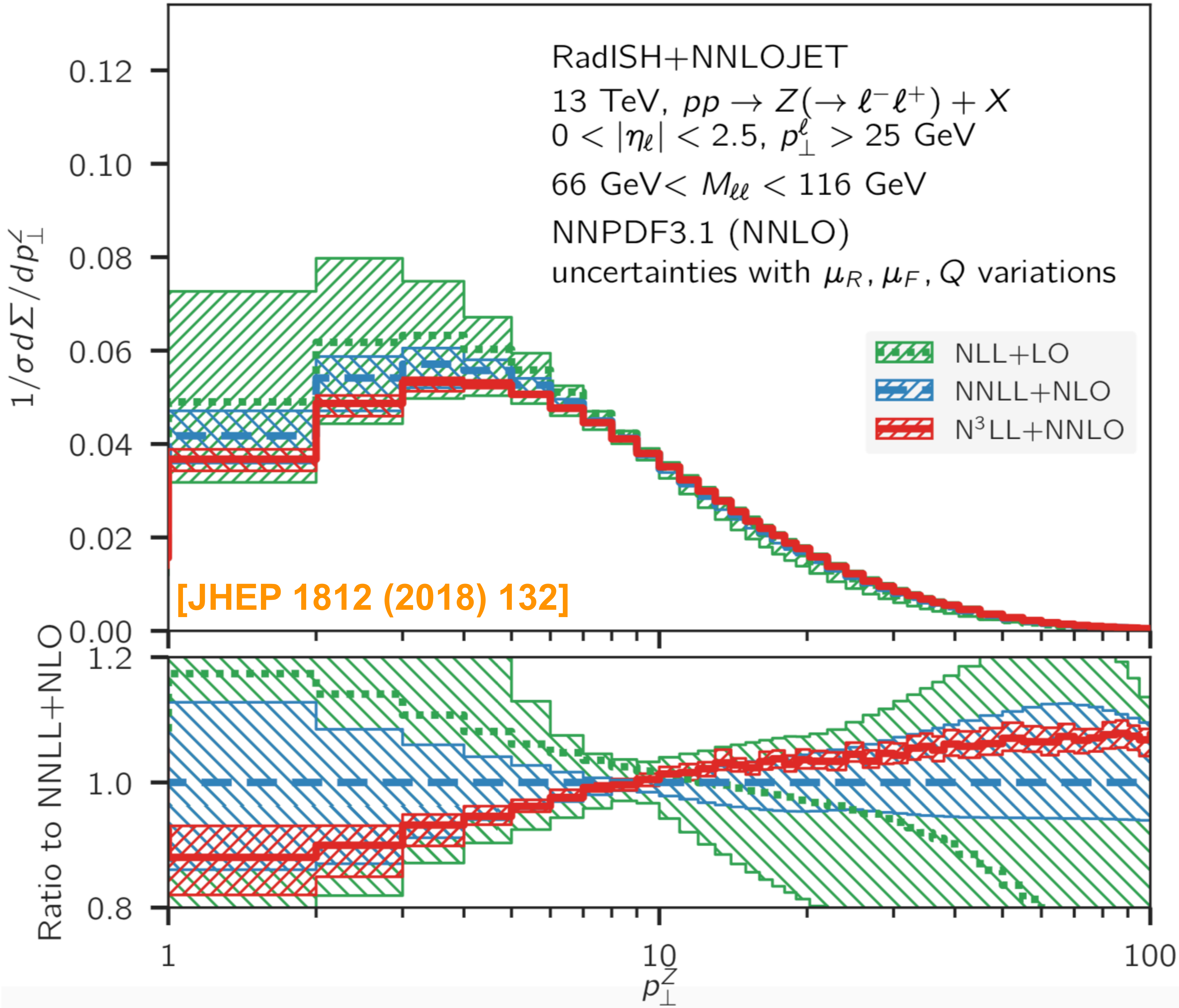
- Therefore, the "fixed-order" parts have to match in the relevant limits:

Log Accuracy	Minimal f.o. accuracy
NLL'	α_s (LO)
N^2LL	α_s (LO)
N^2LL'	α_s^2 (NLO)
N^3LL	α_s^2 (NLO)
N^3LL'	α_s^3 (NNLO)

Perturbative convergence

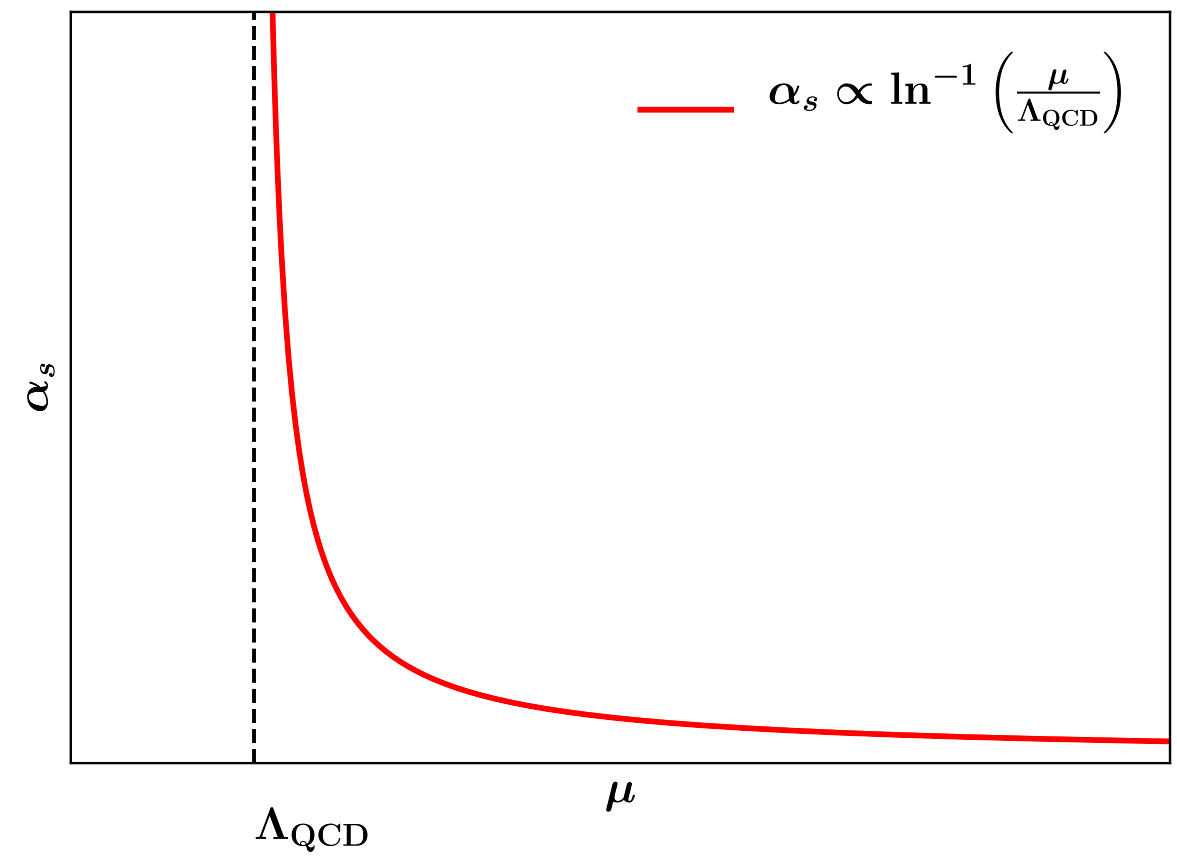


Perturbative convergence



Landau pole regularisation

$$\sigma \propto \int_0^\infty db_\mathrm{T}\, \alpha_s^p\left(\frac{1}{b_\mathrm{T}}\right)\cdots \sim \int_0^Q dk_\mathrm{T}\, \alpha_s^p\,(k_\mathrm{T})\ldots$$



- Integrating over the full phase space would give a **divergent** result.
- **Prescriptions** to avoid integrating over the **Landau pole**:
    - $\boldsymbol{b^*}$ (global or local) or $\boldsymbol{k_\mathrm{T}}^*$ prescription or a sharp cutoff,
    - minimal prescription,
- Non-perturbative effects are thus ***intrinsically present***:
    - whether large or small depends on the experimental/theoretical uncertainties.

Landau pole regularisation

- In b_T space the ***unregularised*** (diverging) cross section looks like this:

$$\frac{d\sigma}{dq_T} = \int_0^\infty db_T\, b_T J_0(b_T q_T) \left[\sum_{n=0}^{\infty} \alpha_s^n \left(\frac{1}{b_T}\right) \sum_{k=0}^{2n} \ln^k(Q^2 b_T^2) \frac{d\bar{\sigma}^{[n,k]}}{dq_T} \right] \otimes \mathcal{L}\left(\frac{1}{b_T}\right)$$

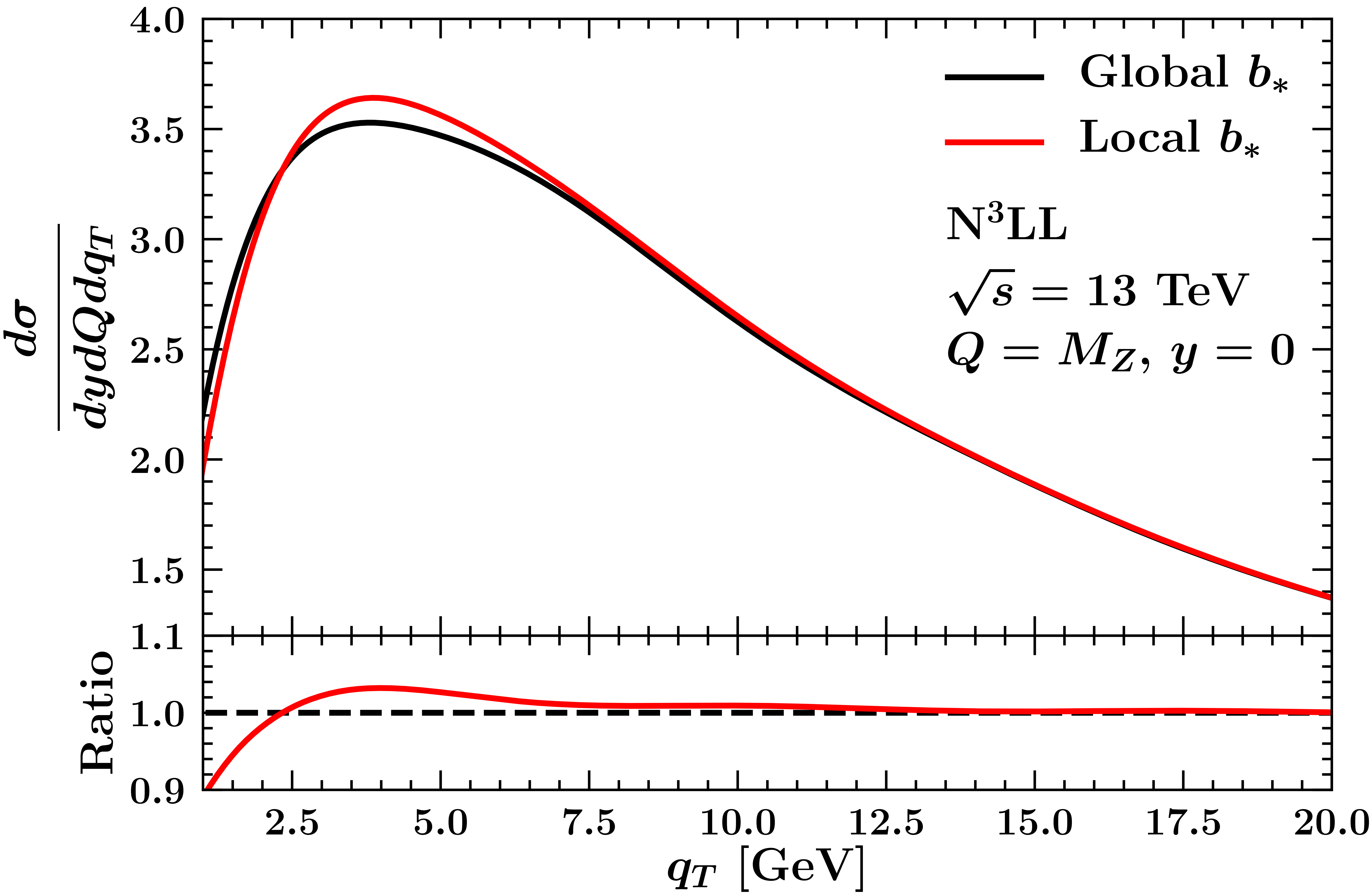
- The **global** b* prescription is:

$$\frac{d\sigma}{dq_T} = \int_0^\infty db_T\, b_T J_0(b_T q_T) \left[\sum_{n=0}^{\infty} \alpha_s^n \left(\frac{1}{b_*(b_T)}\right) \sum_{k=0}^{2n} \underline{\ln^k(Q^2 b_*^2(b_T))} \frac{d\bar{\sigma}^{[n,k]}}{dq_T} \right] \otimes \mathcal{L}\left(\frac{1}{b_*(b_T)}\right)$$

- The **local** b* prescription is:

$$\frac{d\sigma}{dq_T} = \int_0^\infty db_T\, b_T J_0(b_T q_T) \left[\sum_{n=0}^{\infty} \alpha_s^n \left(\frac{1}{b_*(b_T)}\right) \sum_{k=0}^{2n} \underline{\ln^k(Q^2 b_T^2)} \frac{d\bar{\sigma}^{[n,k]}}{dq_T} \right] \otimes \mathcal{L}\left(\frac{1}{b_*(b_T)}\right)$$

Landau pole regularisation



Codes taking part

- SCETlib [https://confluence.desy.de/display/scetlib]
- CuTe [https://cute.hepforge.org]

} SCET

- DYRes/DYTURBO [https://gitlab.cern.ch/DYdevel/DYTURBO]
- ReSolve [https://github.com/fkhorad/reSolve]

} q_T-res.

- RadISH [https://arxiv.org/pdf/1705.09127.pdf]
- PB-TMD [https://arxiv.org/pdf/1906.00919.pdf]

} PB

- NangaParbat [https://github.com/vbertone/NangaParbat]
- arTeMiDe [https://teorica.fis.ucm.es/artemide/]

} TMD

Differences

- **NP-physics (1): Landau pole regularisation**
  - q_T-space: low-q_T cutoff or k_*,
  - b_T-space: b^* or “minimal prescription” (complex plane).
- **NP-physics (2): intrinsic-k_T**
  - fits to data (in principle, *x* and flavour dependent).
- **matching to fixed order**
  - multiplicative or additive,
  - damping function to switch off resummation/evolution,
  - unitarity enforcing, *i.e.*, modified logs.

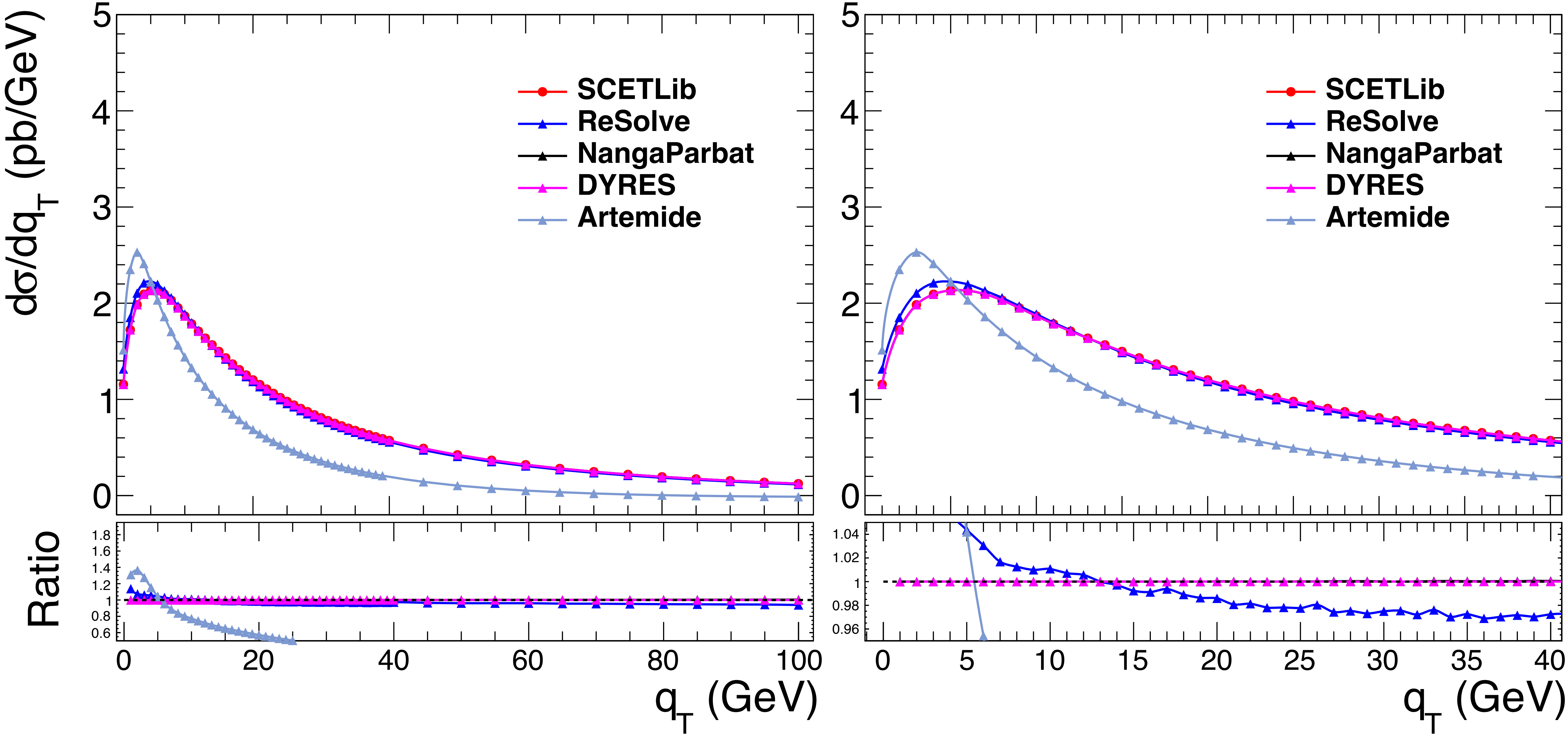
Benchmark settings: step 1

- Z/γ^* production at $\sqrt{s} = 13$ TeV,
- **Resummation only** (no matching to fixed order yet),
- A number of values of Q and y:
  - we will mostly show results at $Q = M_Z$ and $y = 0$.
- Consider **all possible logarithmic orders**:
  - up to N^3LL.
- Favourite **Landau-pole regularisation** procedure:
  - b^*/k_T^* or "minimal prescription",
  - this is one of the main sources of (understood) differences at low q_T.
- Only **standard logs**:
  - no modified logs to enforce unitarity.
- **q_T distribution from 1 to 100 GeV**:
  - we are aware that for resummation breaks down well before,
  - benchmark exercise aimed at checking the consistency of codes/formalisms.

Benchmark settings: next steps

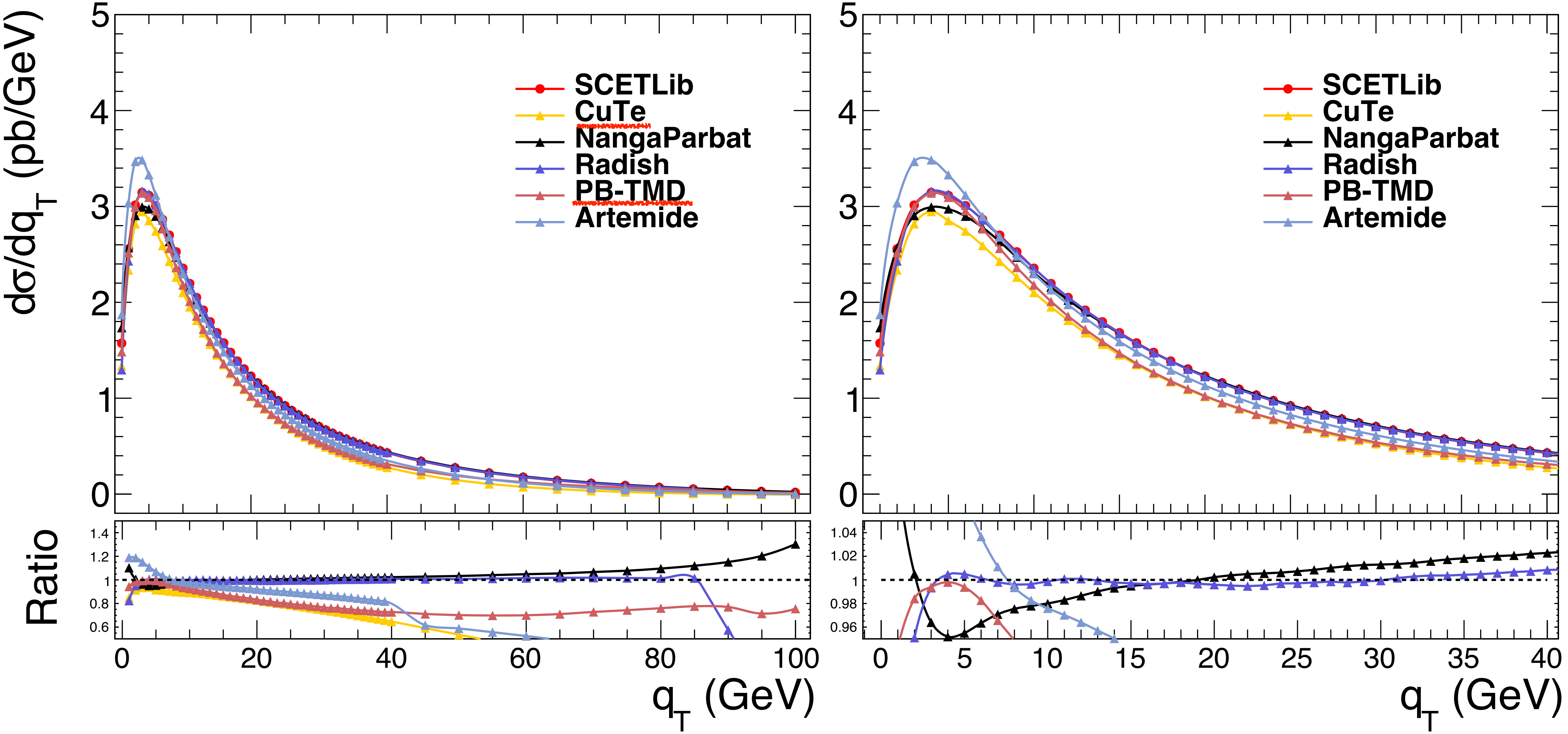
- **Step-2** benchmarking:
  - inclusion of **modified logs**,
  - different codes use their **“nominal” settings**:
    - For example: favorite Landau pole regularisation
- **Systematic uncertainties** become relevant for this step:
  - perturbative uncertainties (μ_R/μ_F and resummation scales),
  - profile/matching scales, modified logarithms, etc.
  - …
- Aiming at completing Step-2 pithing the next 2-3 months.
  - optimistic but involved groups are all working actively.
- **Step-3** benchmarking:
  - full **quantitative** understanding of the resummation formalisms,
  - **matching** to fixed-order.
- **Documenting** the three steps:
  - material for the next **yellow report**.

LL



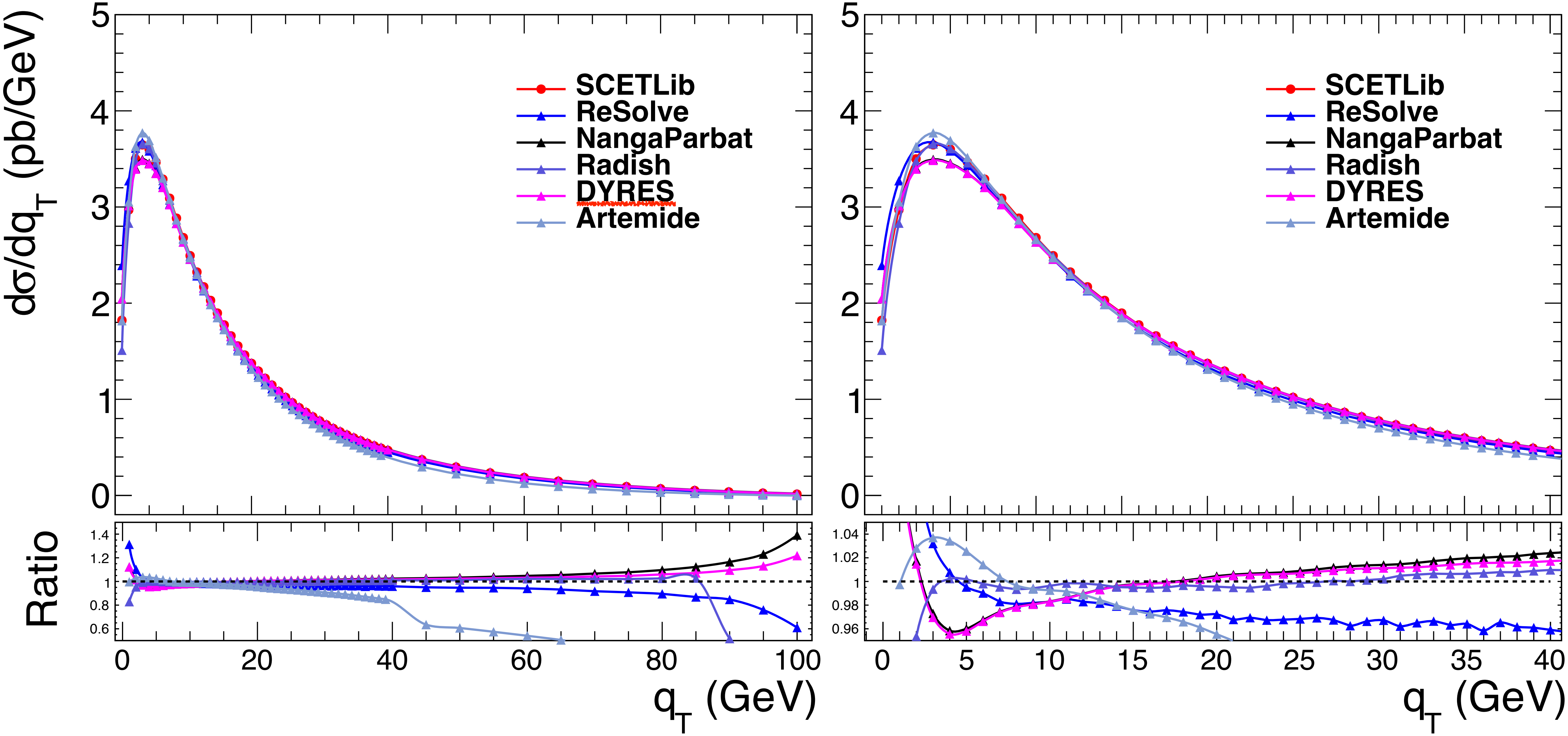
SCETLib
ReSolve
NangaParbat
DYRES
Artemide
dσ/dq_T (pb/GeV)
Ratio
q_T (GeV)

NLL



dσ/dq_T (pb/GeV)
Ratio
q_T (GeV)
SCETLib
CuTe
NangaParbat
Radish
PB-TMD
Artemide

NLL'



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dσ/dq_T (pb/GeV)
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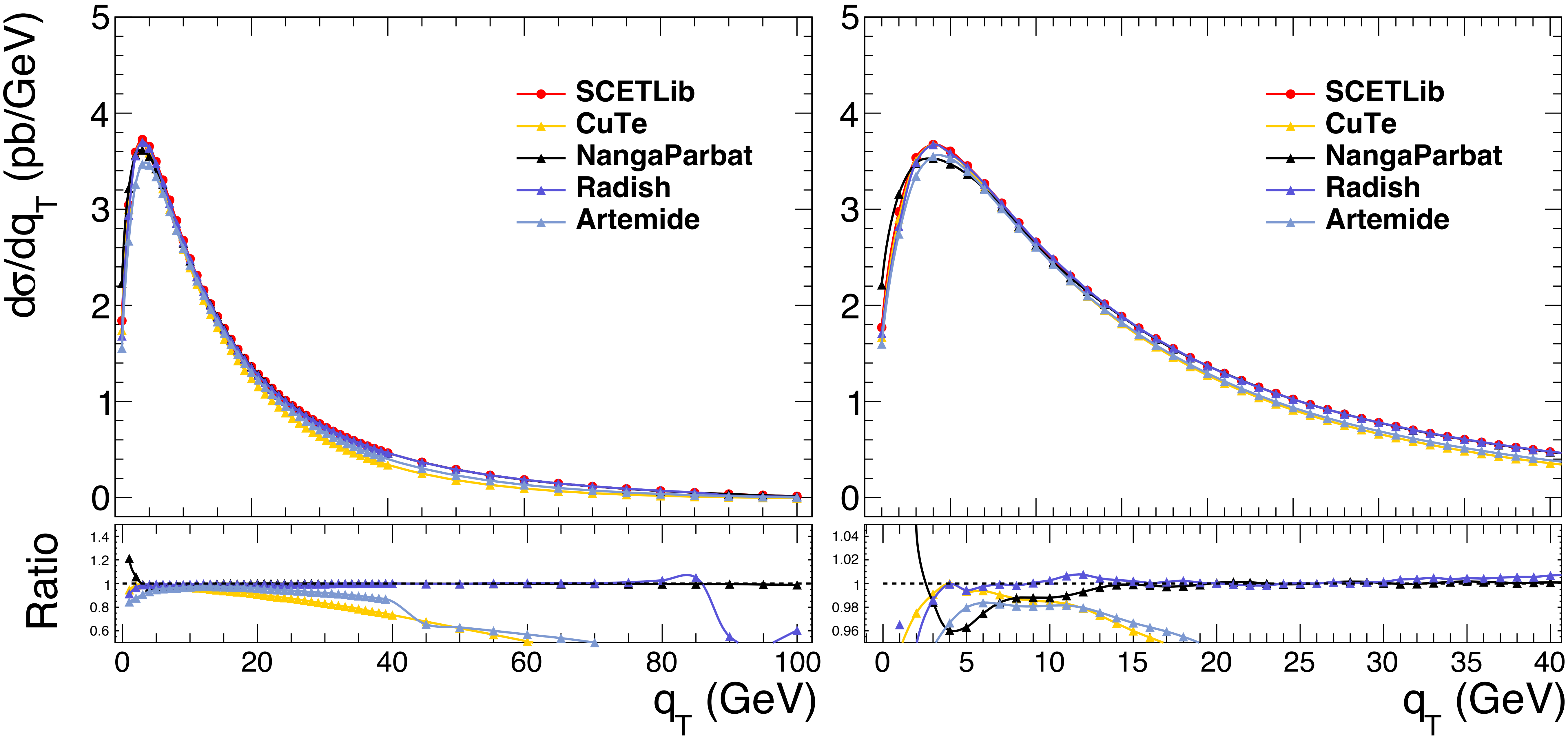
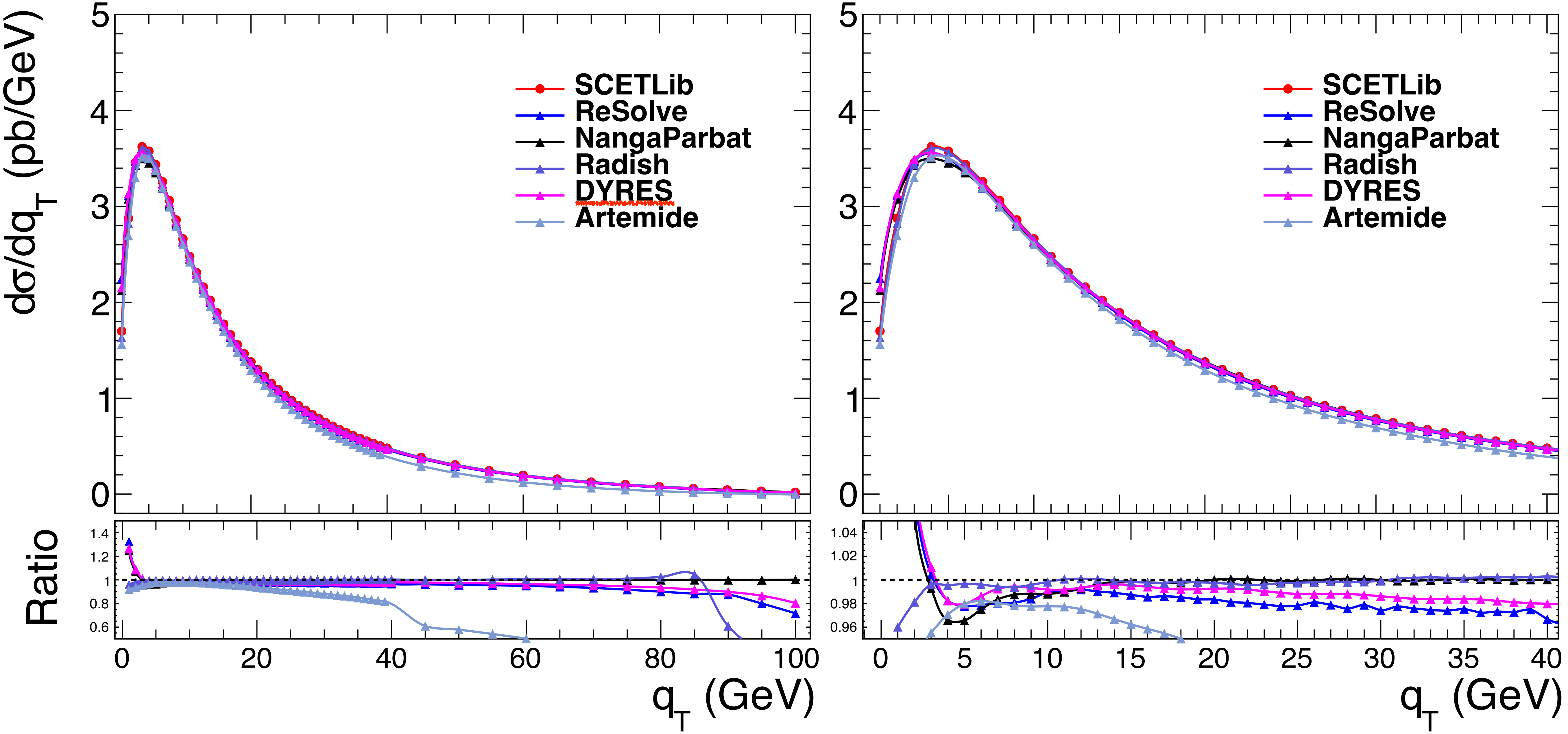
NNLL



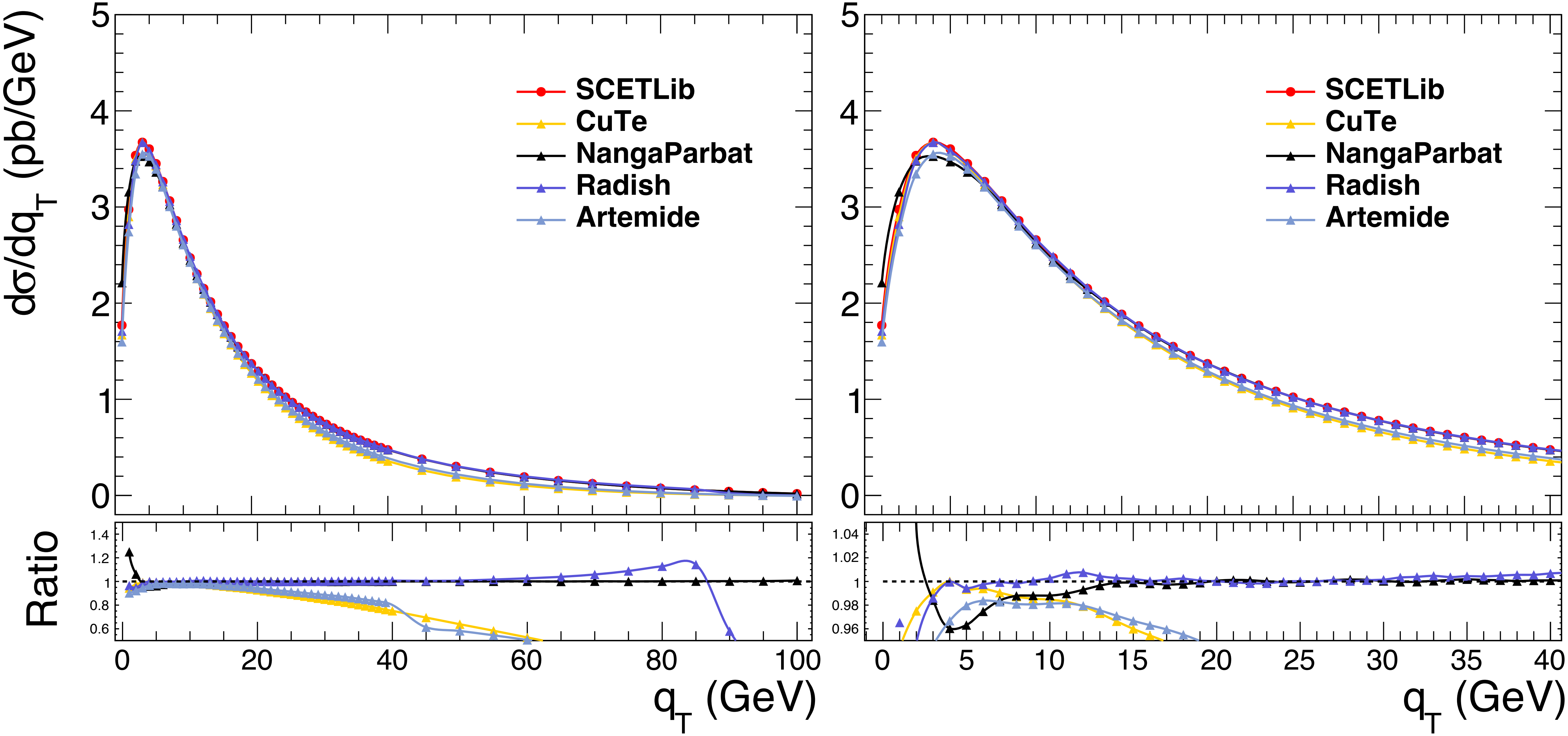
dσ/dq_T (pb/GeV)
Ratio
SCETLib
CuTe
NangaParbat
Radish
Artemide
q_T (GeV)

NNLL'



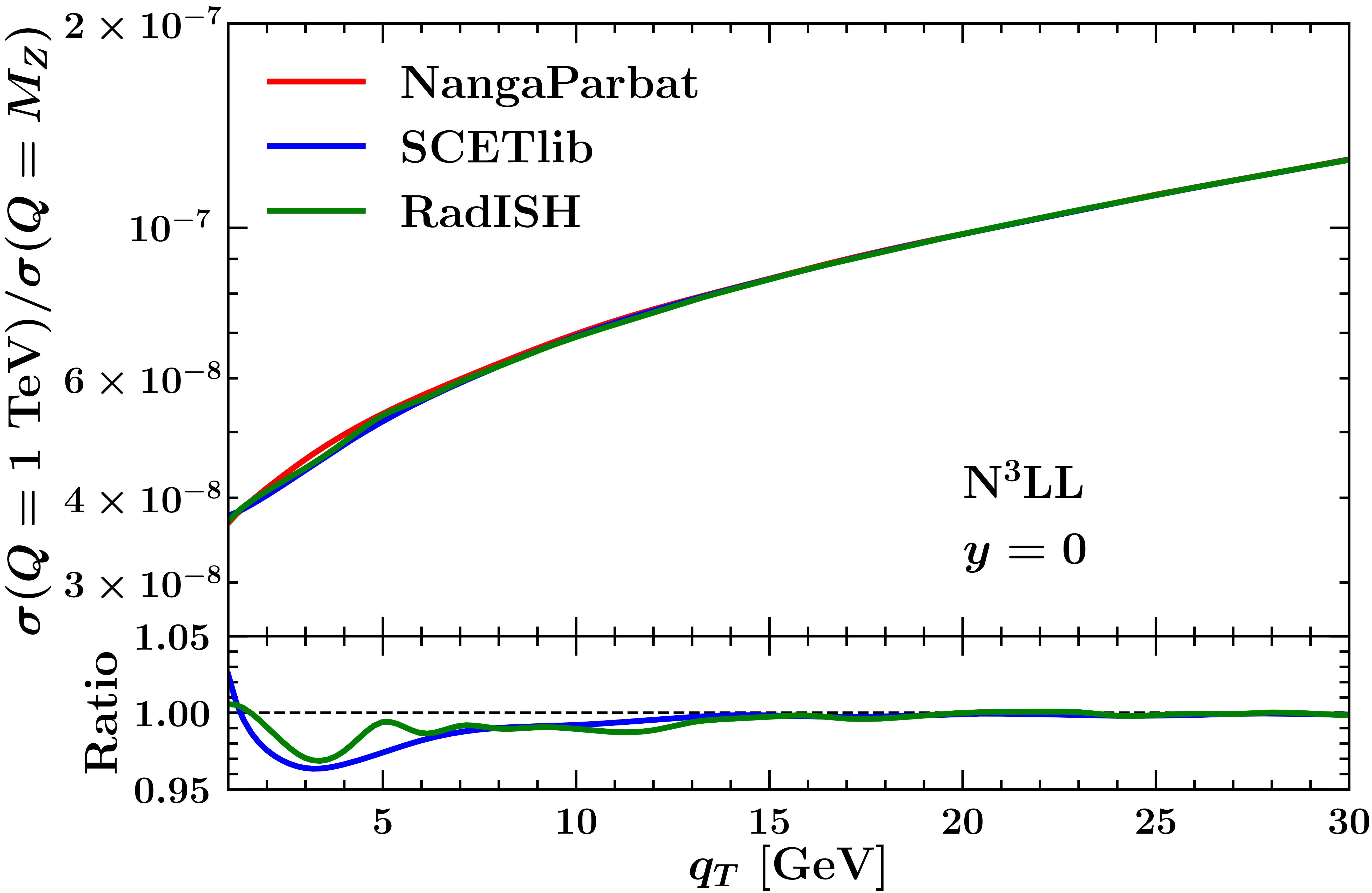
dσ/dq_T (pb/GeV)
Ratio
SCETLib
ReSolve
NangaParbat
Radish
DYRES
Artemide
q_T (GeV)

N³LL

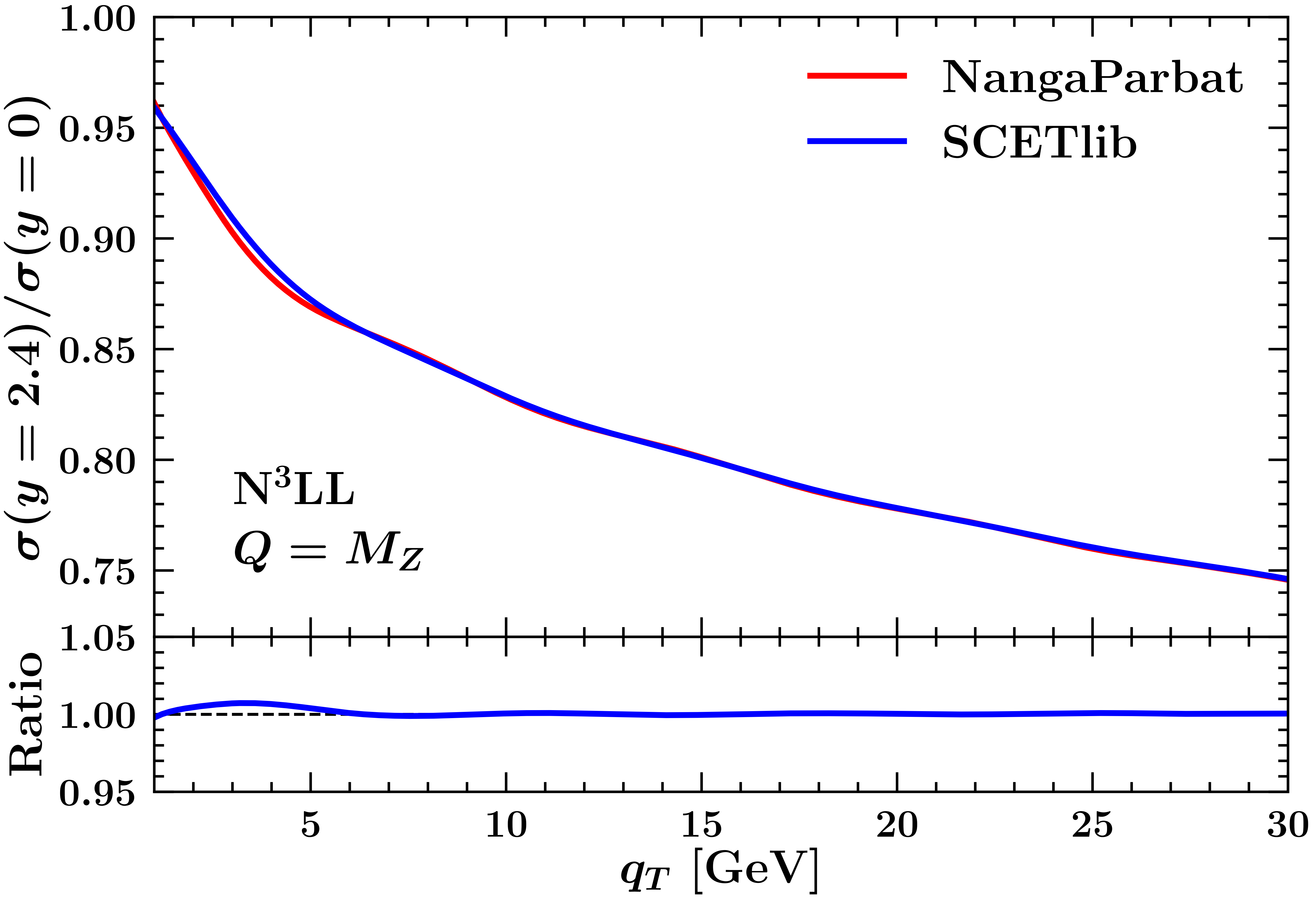


SCETLib
CuTe
NangaParbat
Radish
Artemide
dσ/dq_T (pb/GeV)
Ratio
q_T (GeV)

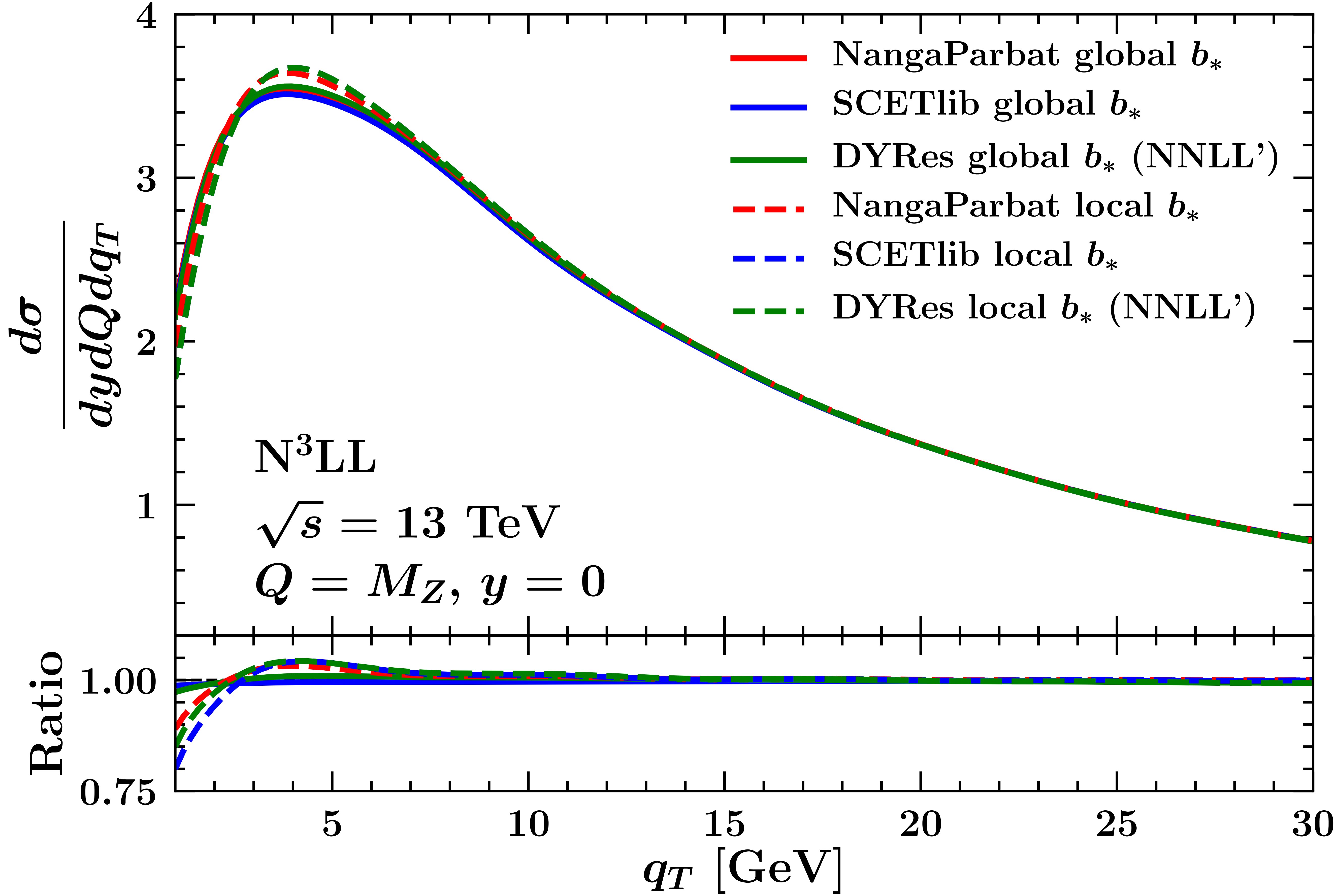
Kinematic evolution



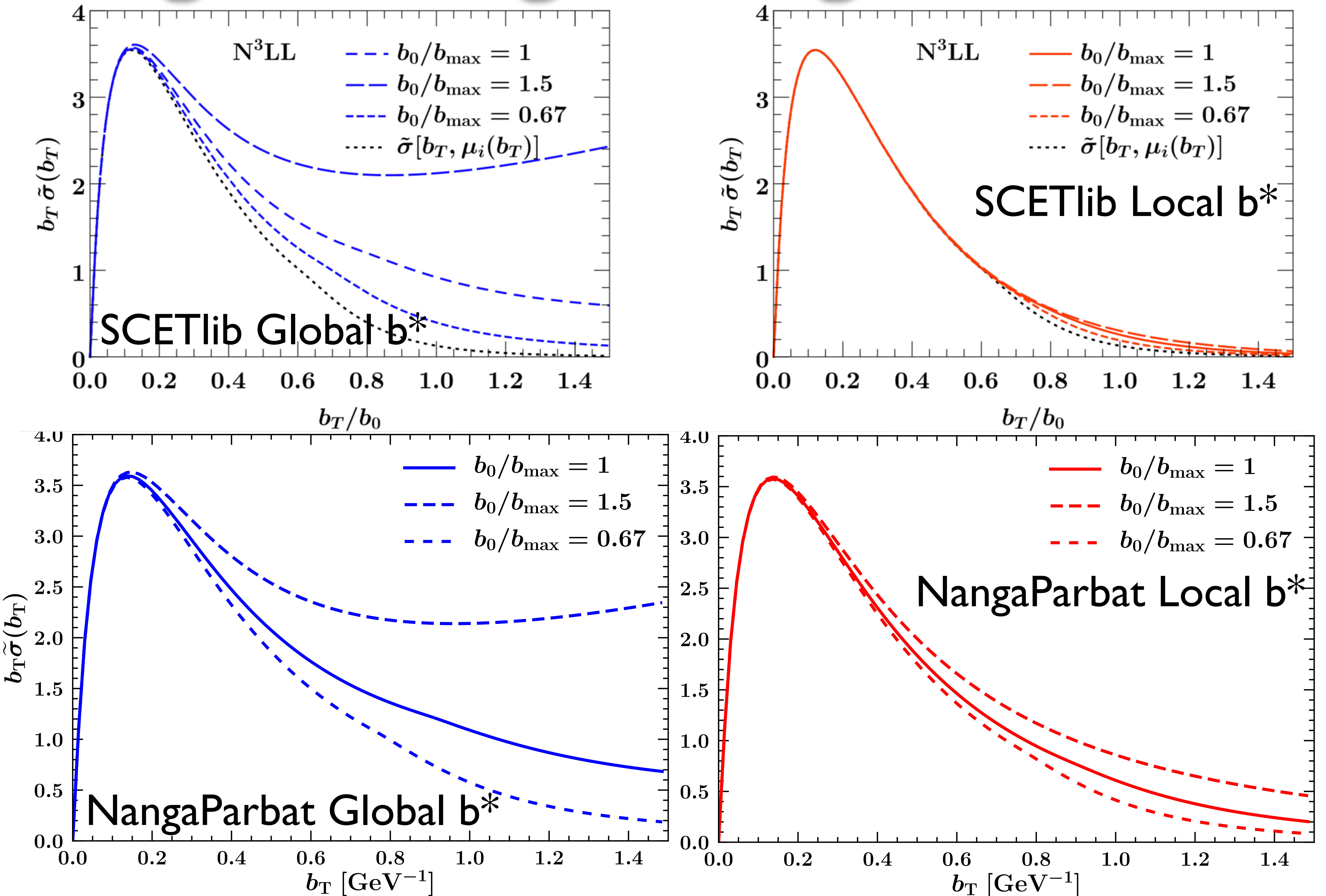
Kinematic evolution



Regularising strategies



Regularising strategies



Conclusions

- There has been very good progress within the resummation subgroup:
  - many collaborations/codes involved (not easy to coordinate, many thanks to **Daniel** and **Aram**),
  - despite **intrinsic differences** we managed to get an encouraging agreement at step 1,
  - some of the main **differences** are being **understood**,
- Ready to go through **steps 2** and **3**:
  - these will give us a clearer general picture concerning "**resummation accuracy**",
  - aiming at reporting all this progress in the next **Yellow Report**,
  - the very final goal is **precise but reliable predictions** to extract relevant quantities such as the ***W* mass** through *W/Z ratio*.