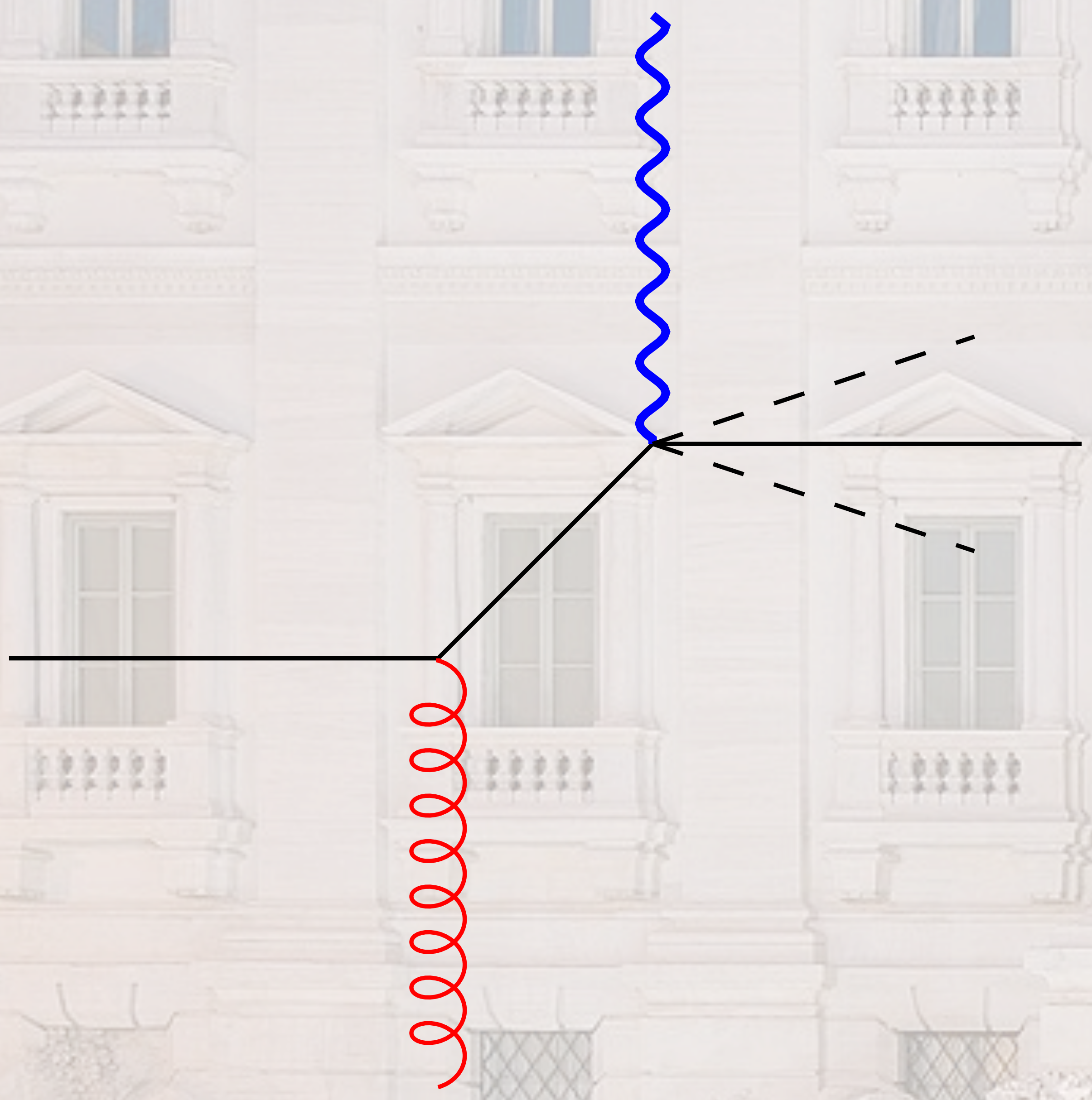
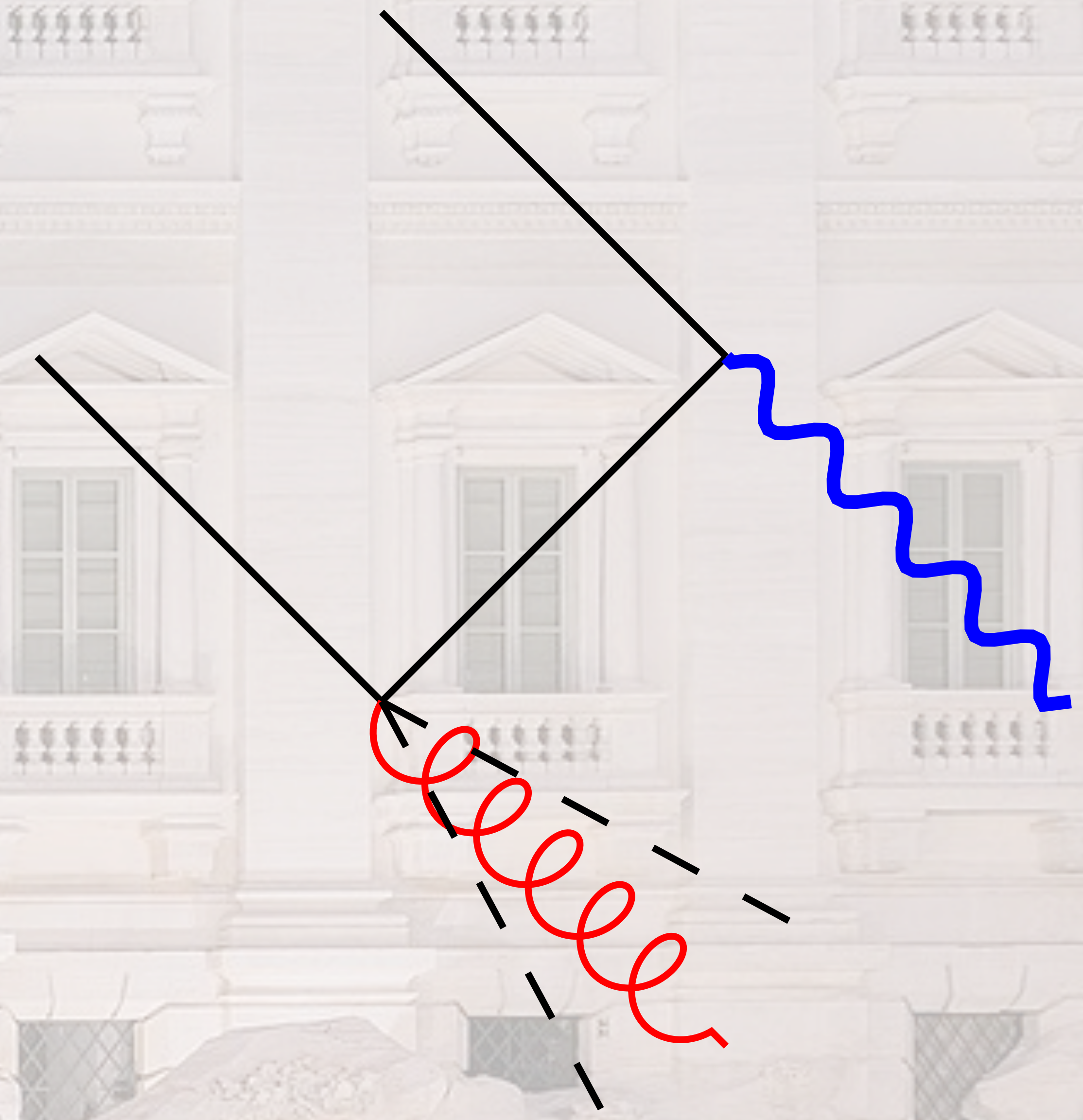
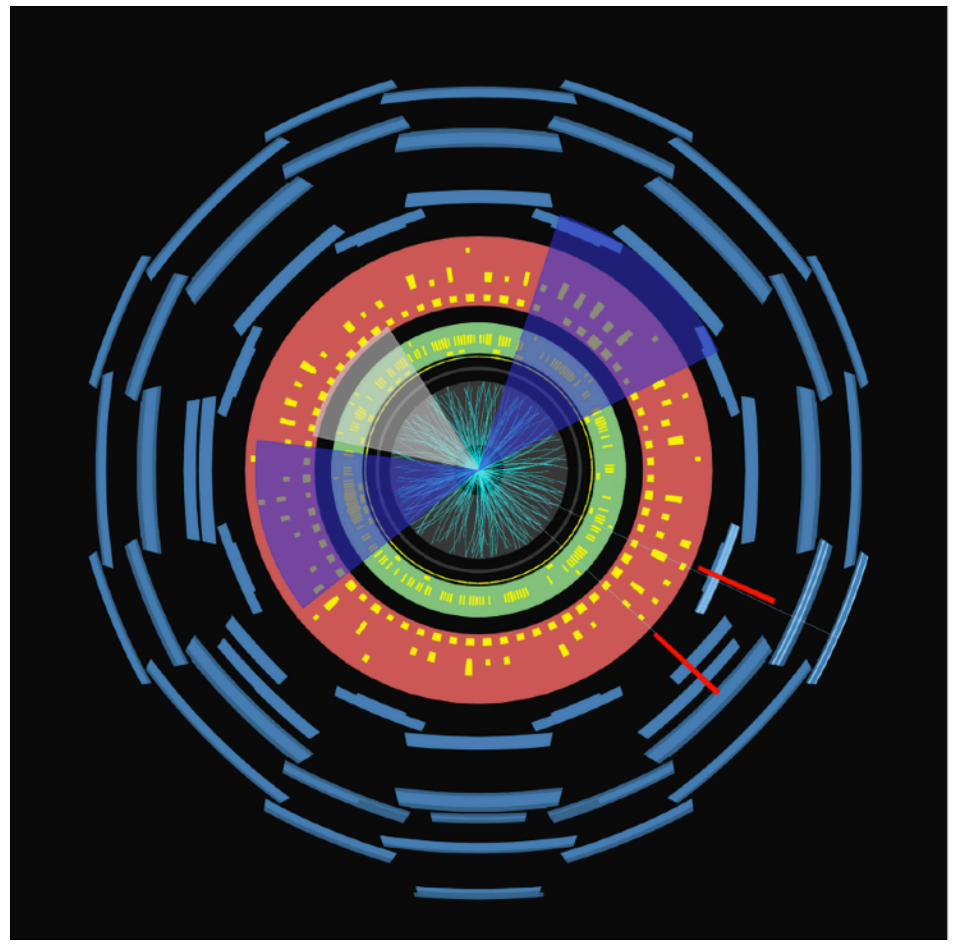


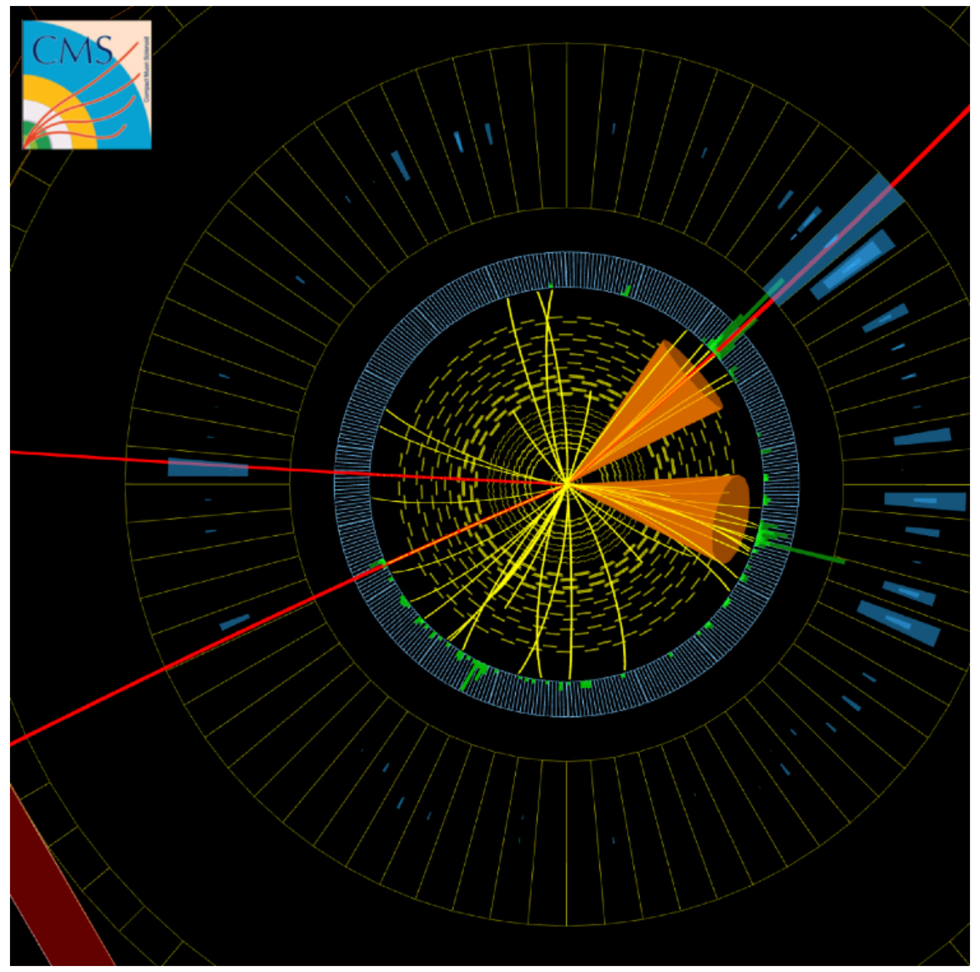
Precise predictions for V+jet production

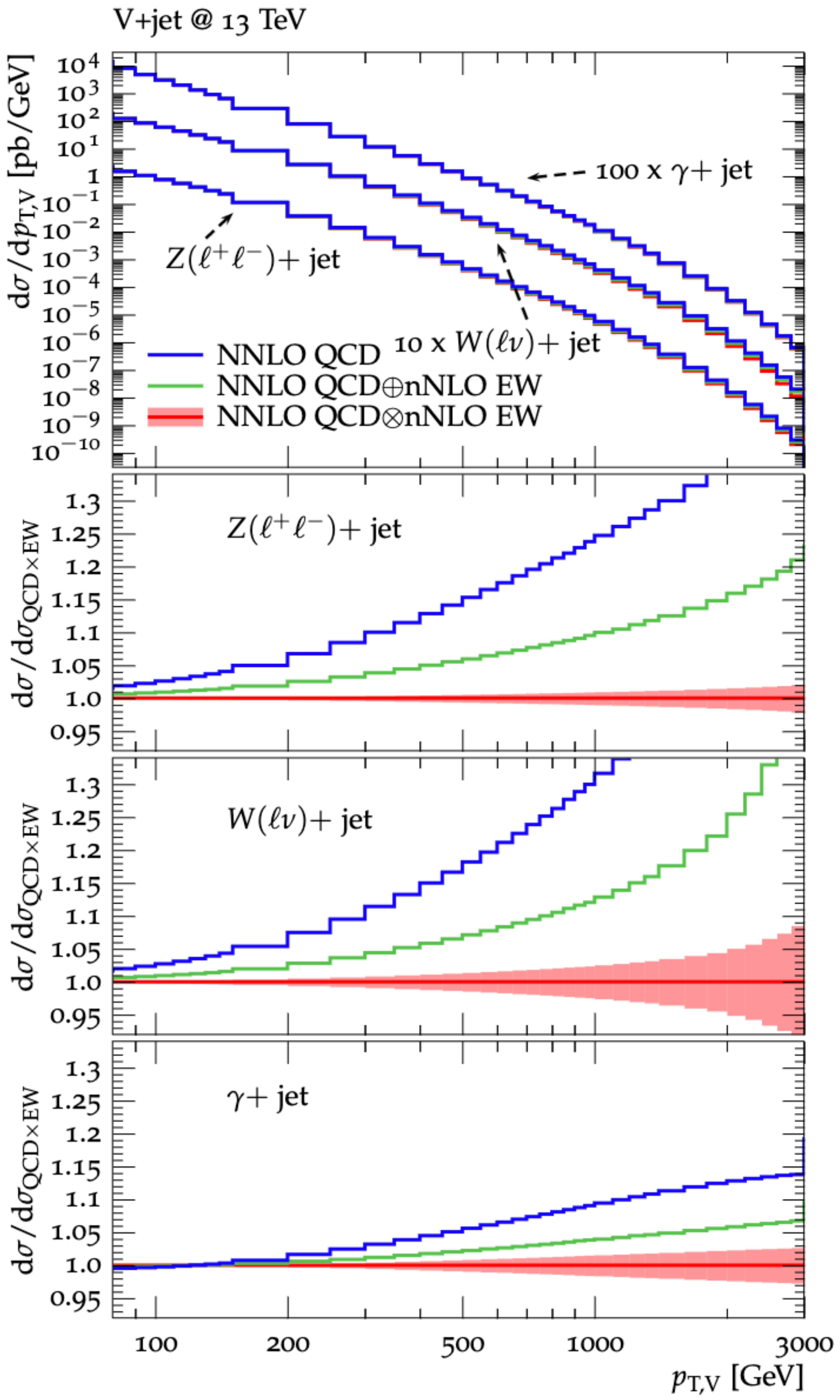


Giovanni Stagnitto
(Milano Bicocca University & INFN)



SM@LHC 2777 *ab Urbe condita*



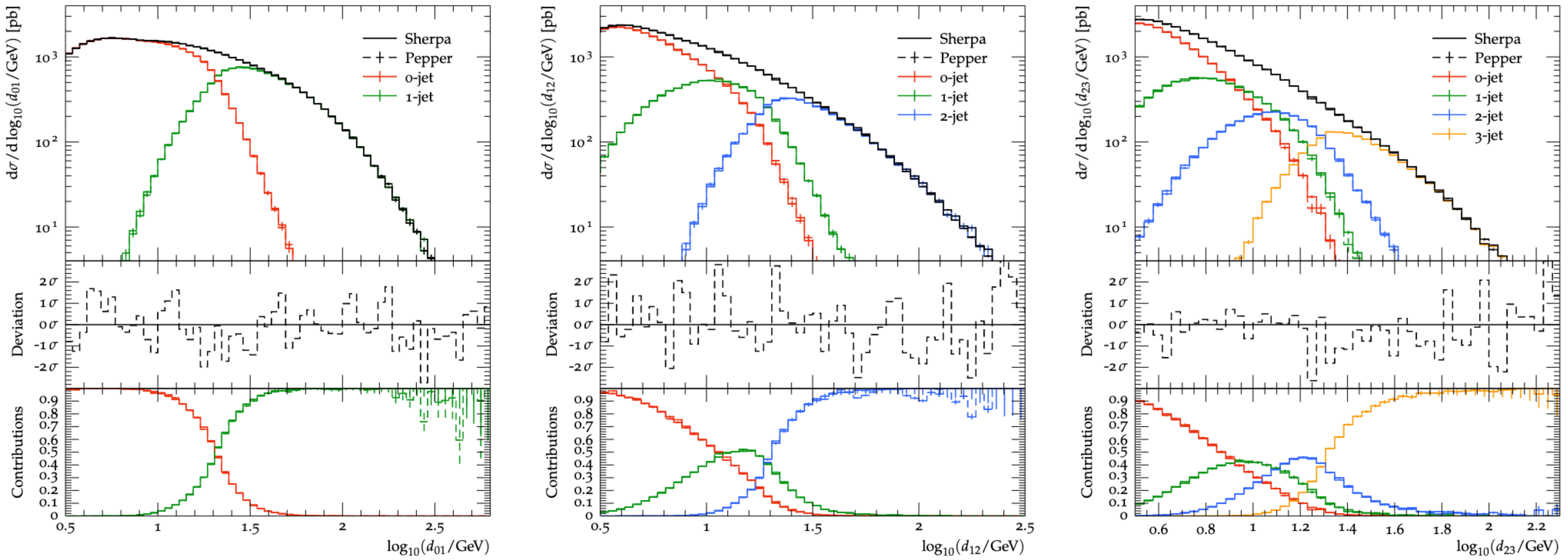


[Lindert et al. ’17]

V+jets ($V = \gamma/Z, W^{\pm}$) events:
ideal probe for testing QCD and EW interactions
major source of backgrounds for new physics searches

V+jet fixed-order: NNLO QCD + NLO EW

V+jets MC samples: multi-jet merging at LO/NLO QCD



Progress towards new parton-level event generators
capable of utilising modern hardware [Bothmann et al. ’23]

Outlook of this talk

1. Two recent phenomenological results related to γ+jet(s):

- Realistic photon isolation in photon-plus-jet events at NNLO
  [Chen, Gehrmann, Glover, Höfer, Huss, Schürmann ’22]

- Isolated photon plus two jets at NNLO
  [Badger, Czakon, Hartanto, Moodie, Peraro, Poncelet, Zoia ’23]

2. Progress towards NNLO+PS for V+jet

3. Progress towards N^{3}LO fixed-order for V+jet

Personal selection of recent results that are representative for on-going progress.
Apologies for any relevant omission of references

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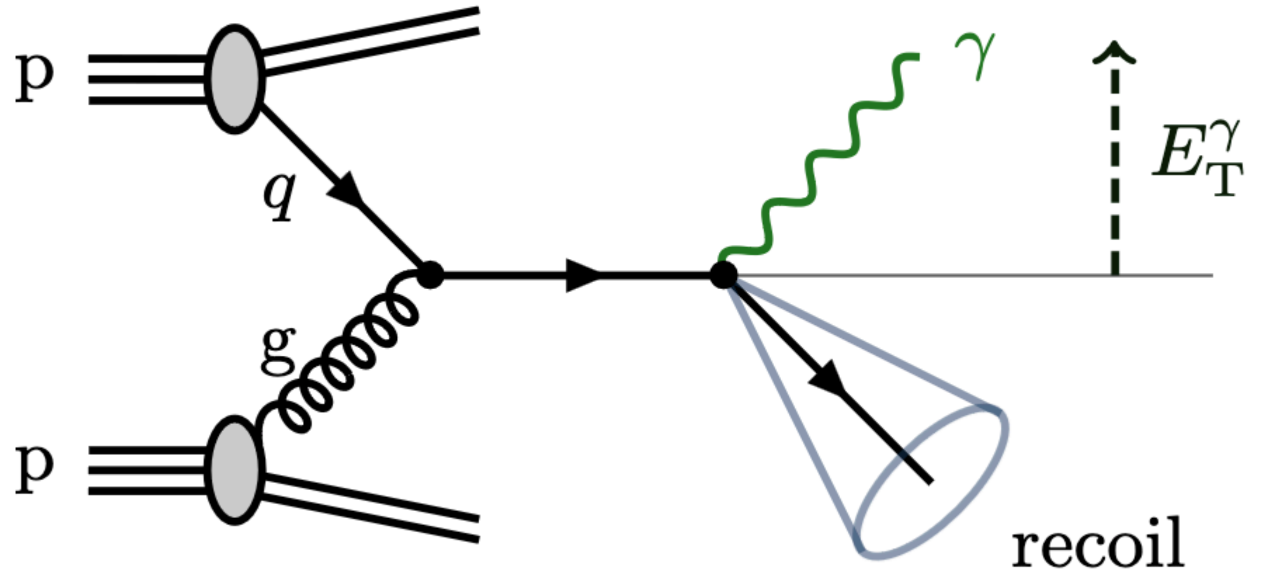

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Realistic photon isolation in photon-plus-jet events at NNLO

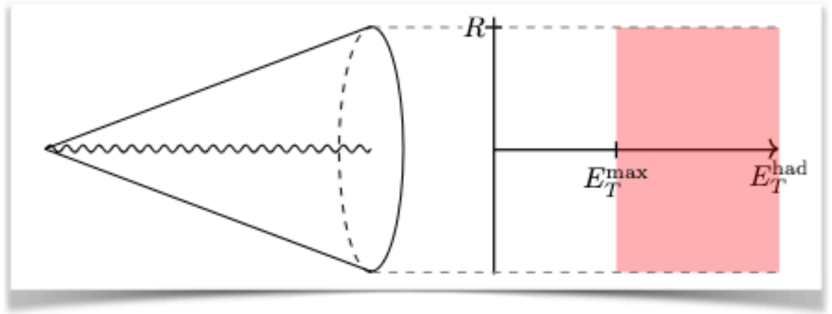
[Chen, Gehrmann, Glover, Höfer, Huss, Schürmann ’22]

How to define an isolated photon?

Fixed-cone vs. dynamic-cone isolation has long been a systematic difference between theory and experiment

Hybrid-cone partially alleviate this inconsistency (correct R-dependence)

Inclusion of photon fragmentation [with $D_{p\to\gamma}(z)$] in theory predictions solve the mismatch: theory predictions with fixed-cone!



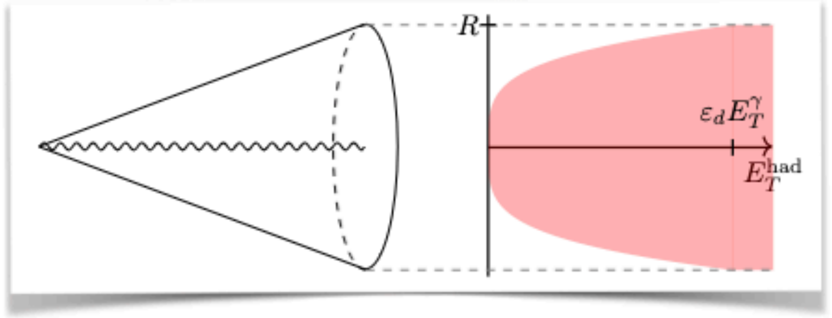
Fixed cone isolation

can choose simple linear dependence:

$$E_{\mathrm{T}}^{\mathrm{had.}}(R) < E_{\mathrm{T}}^{\max} = \epsilon E_{\mathrm{T}}^{\gamma} + E_{\mathrm{T}}^{\mathrm{thresh.}}$$

✓ used in experiments

✗ sensitivity to fragmentation



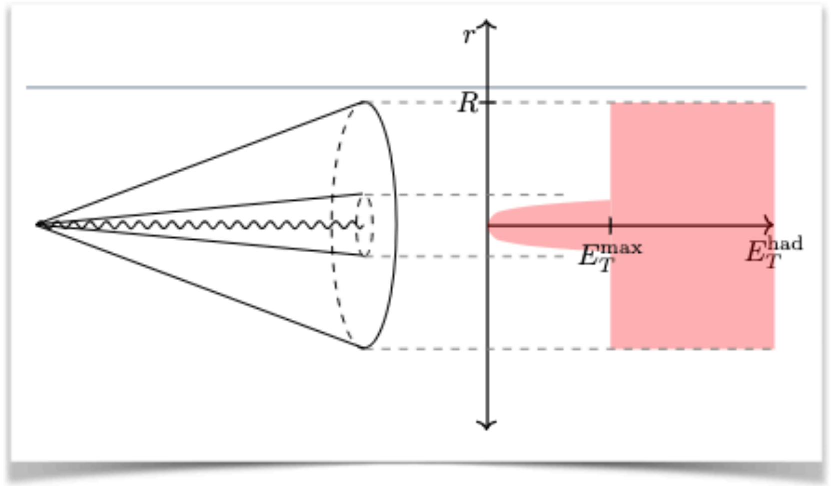
Dynamic cone isolation [Frixione ’98]

smoothly get rid of collinear radiation:

$$E_{\mathrm{T}}^{\mathrm{had.}}(r) < \epsilon E_{\mathrm{T}}^{\gamma}\left(\frac{1-\cos r}{1-\cos R}\right)^{n} \qquad \forall r < R$$

✓ eliminates fragmentation part

✗ no direct analogue in experiment



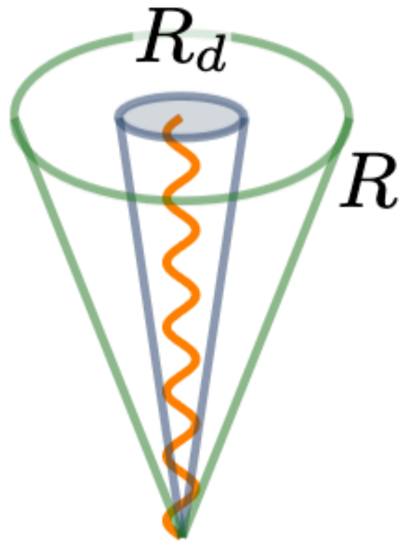
Hybrid cone isolation [Siegert ’17]

1. *narrow* dynamic cone $R_d < R$ (0.1)
2. *wider* fixed cone R (0.4)

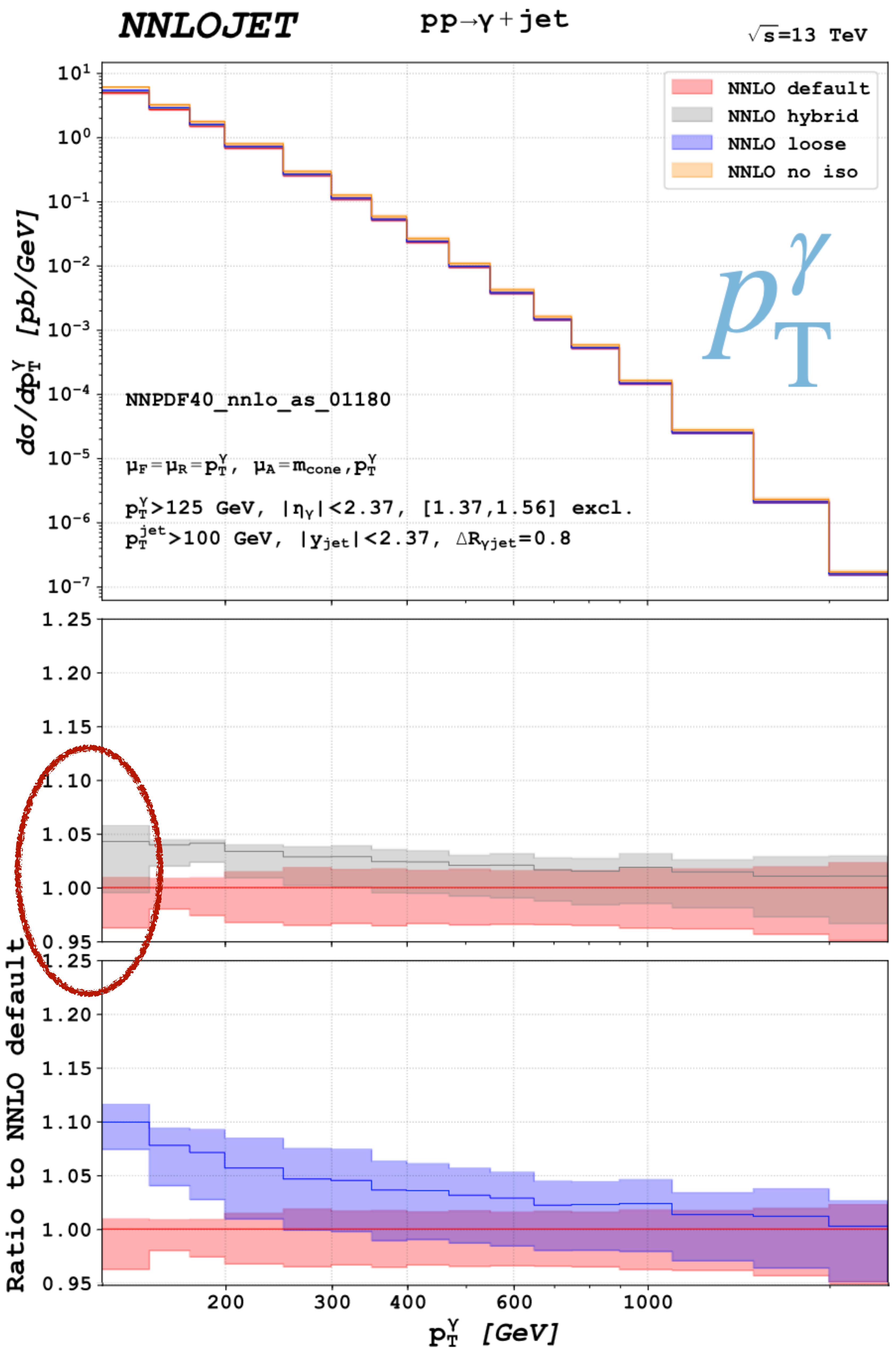
✓ eliminates fragmentation part

✓ reduces mismatch to experiment

✓ *correct* R dependence



@ A. Huss



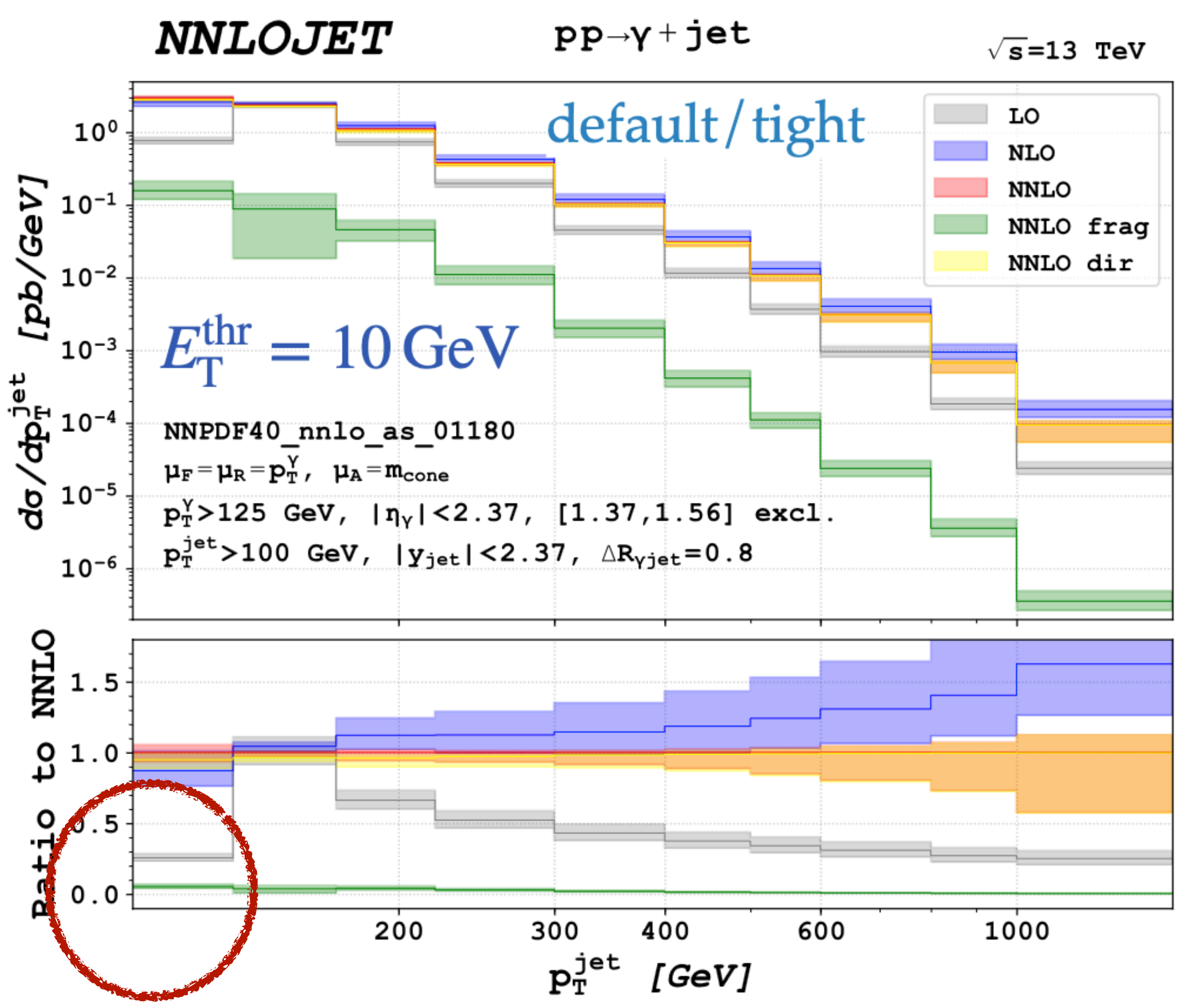
Fixed-cone with $R = 0.4$, $\epsilon = 0.0042$:

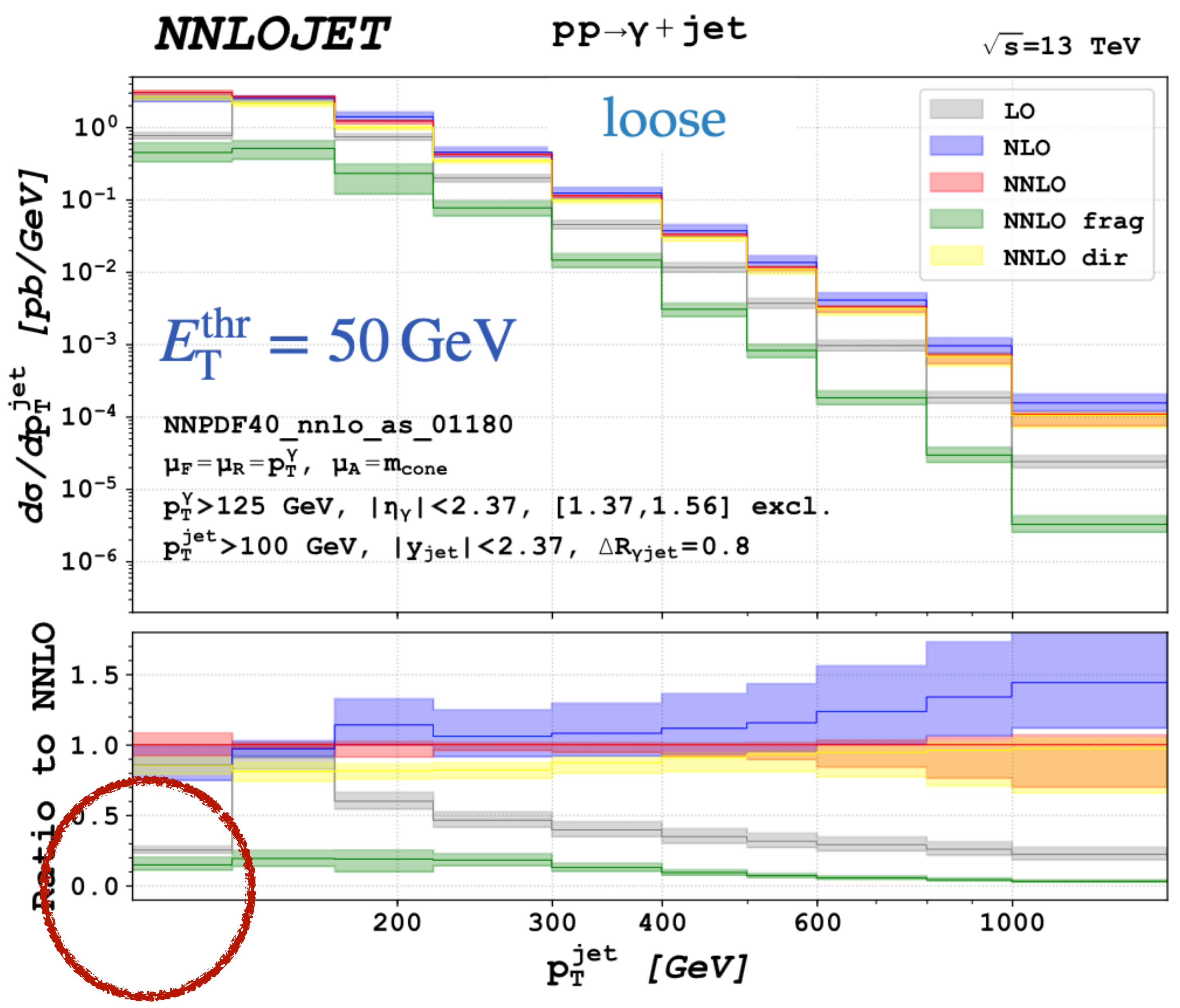
$E_T^{\rm thrs.} = 10\,\mathrm{GeV}$ (*default*), $E_T^{\rm thrs.} = 50\,\mathrm{GeV}$ (*loose*)

Hybrid-cone with $R_d = 0.1$, $R = 0.4$ and $\epsilon = 0.0042$

Hybrid vs. Fixed: 5% effect in the small-$p_T^{\gamma/\rm jet}$ region

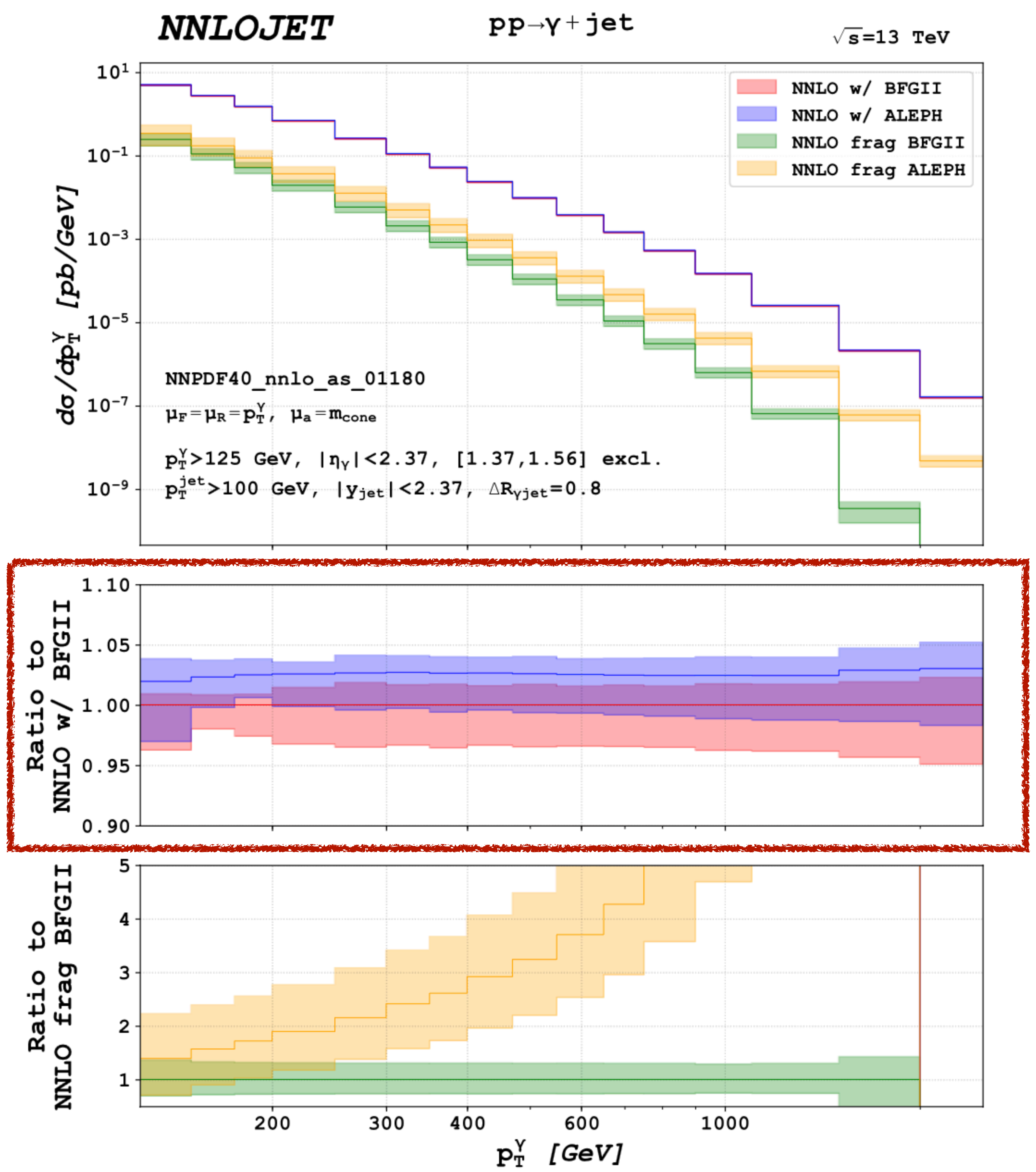
Fragmentation component larger with looser isolation

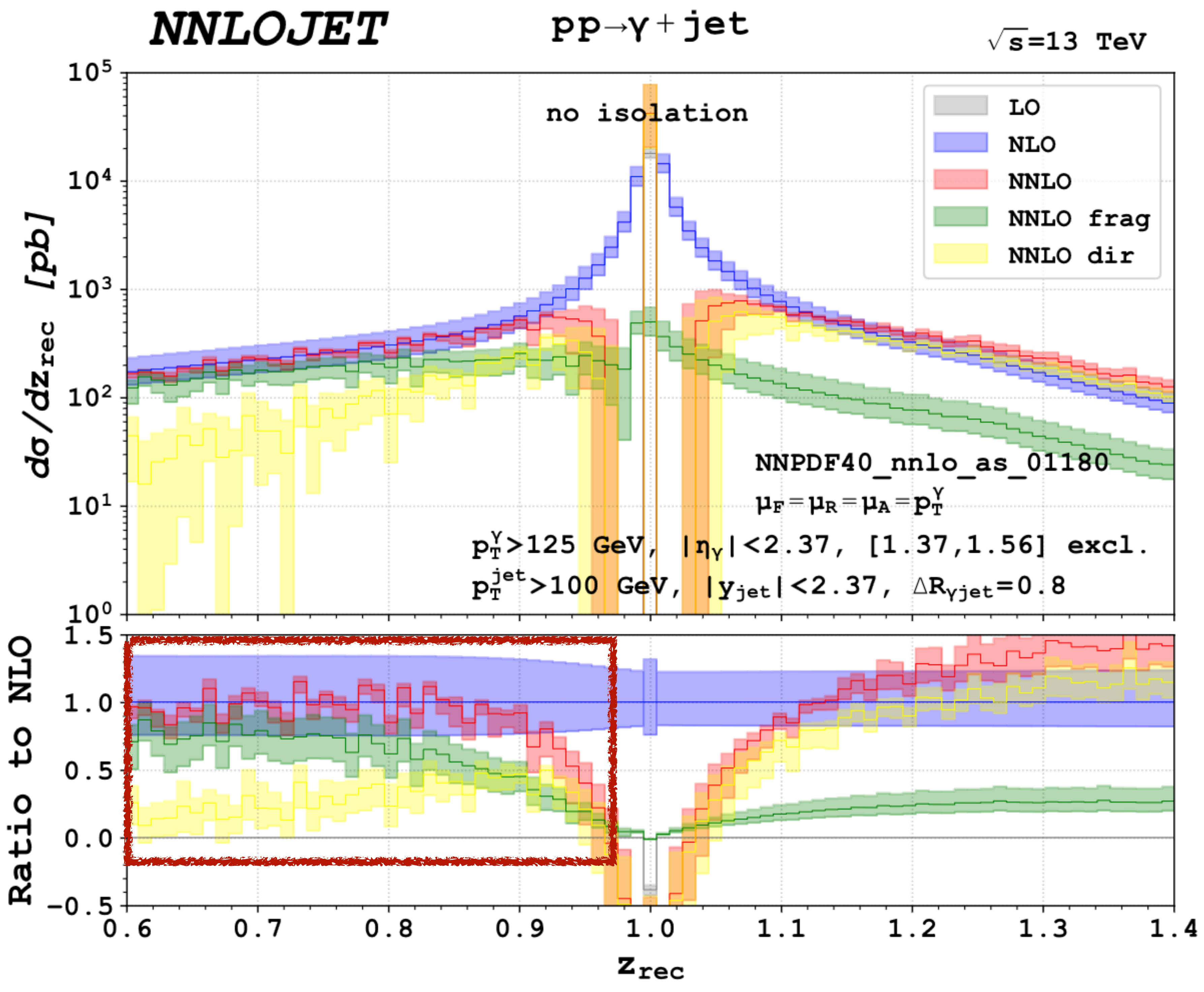


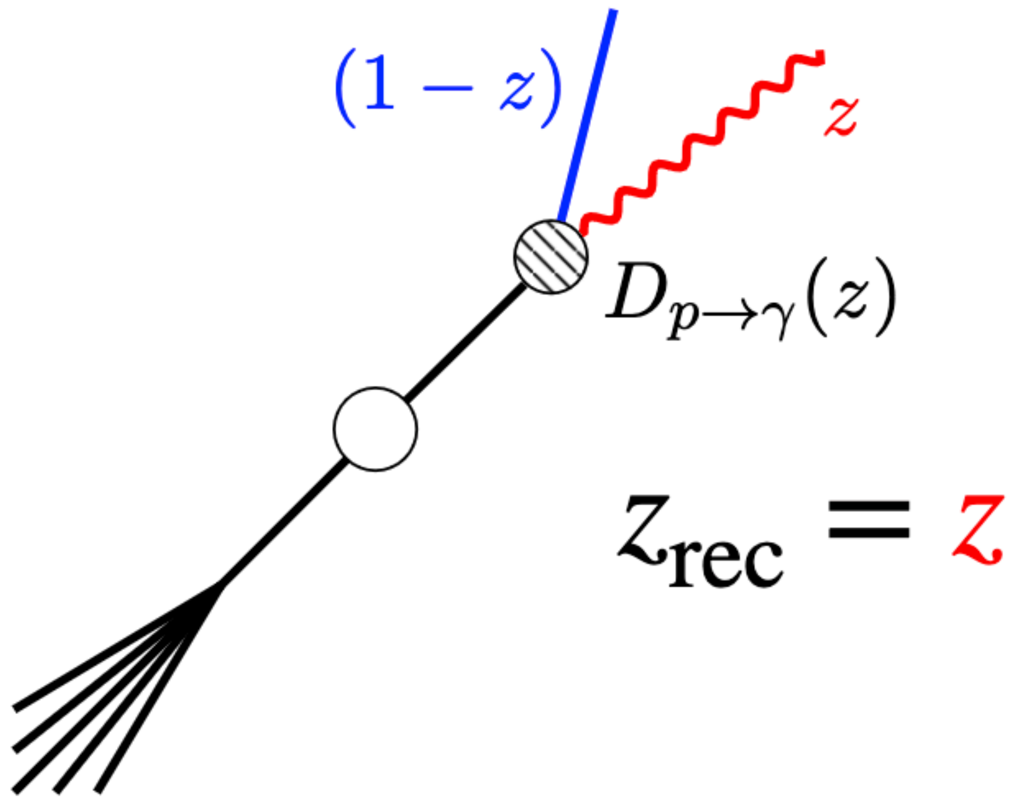


Isolated photons at the LHC probe high-z ($z \gtrsim 0.93$), where $D_{p\to\gamma}(z)$ is poorly constrained

New observable $z_{\text{rec}} = p_T^\gamma / p_T^{\text{jet}}$ (= z at LO) to extract $D_{p\to\gamma}(z)$ at the LHC







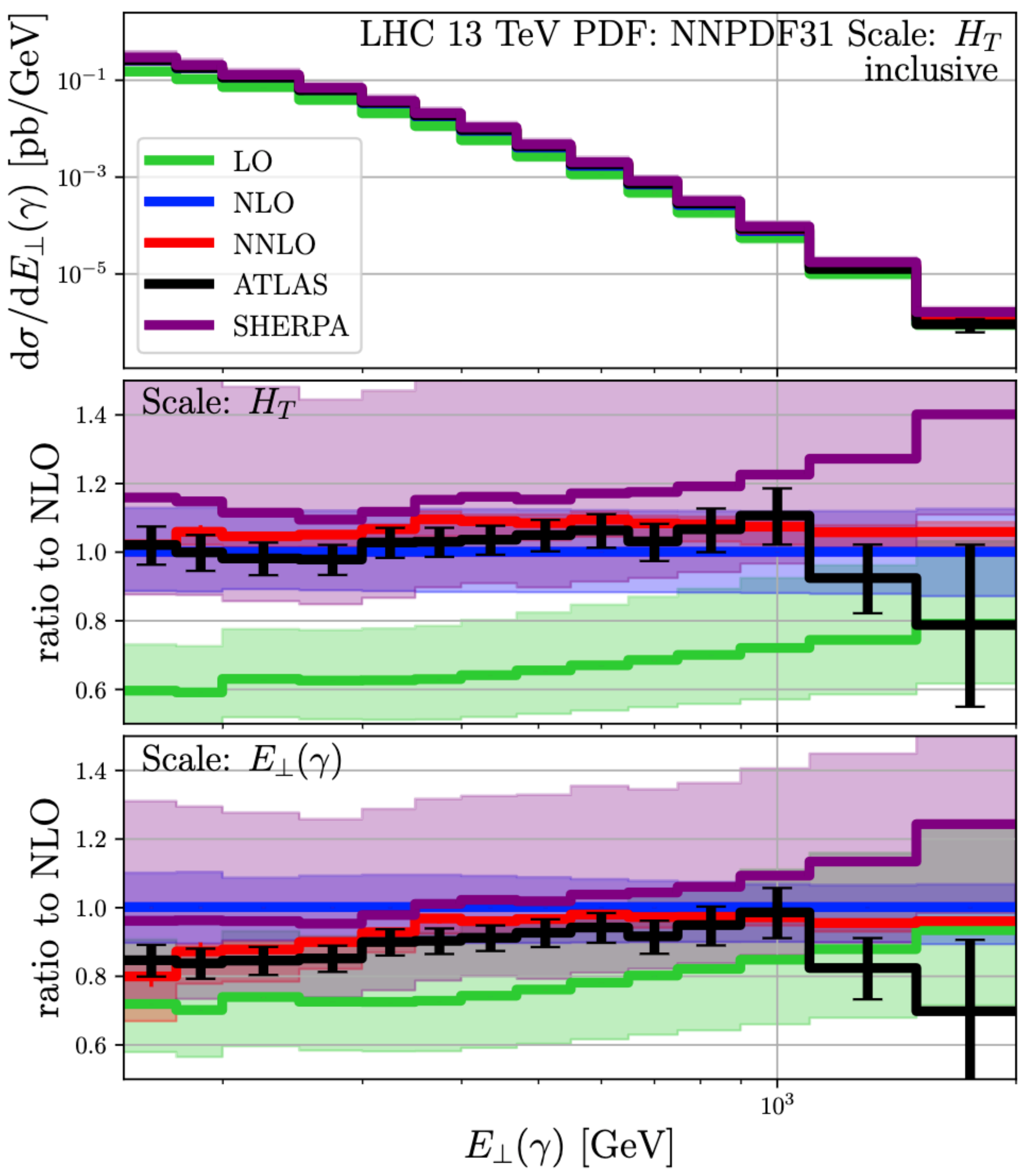
Best sensitivity to fragmentation component with no isolation (but experimentally challenging)

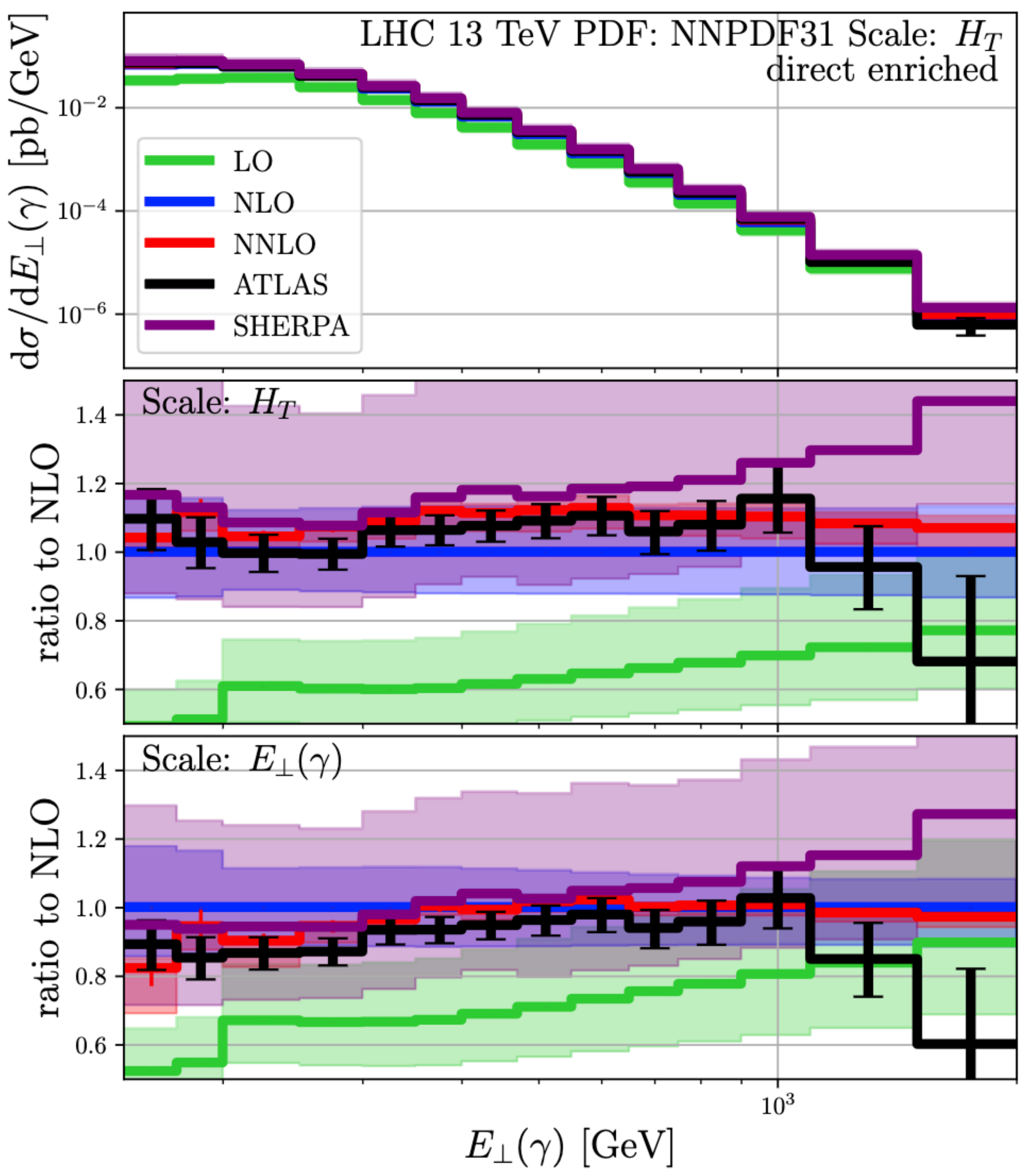
Isolated photon plus two jets at NNLO

[Badger, Czakon, Hartanto, Moodie, Peraro, Poncelet, Zoia ’23]

Interesting process: access angular correlations between the photon and jets.

Hierarchy between $E_\perp(\gamma)$, $p_T(j_1)$ and $p_T(j_2)$: relative size of direct and fragmentation contributions e.g. *direct-enriched*: $E_\perp(\gamma) > p_T(j_1)$





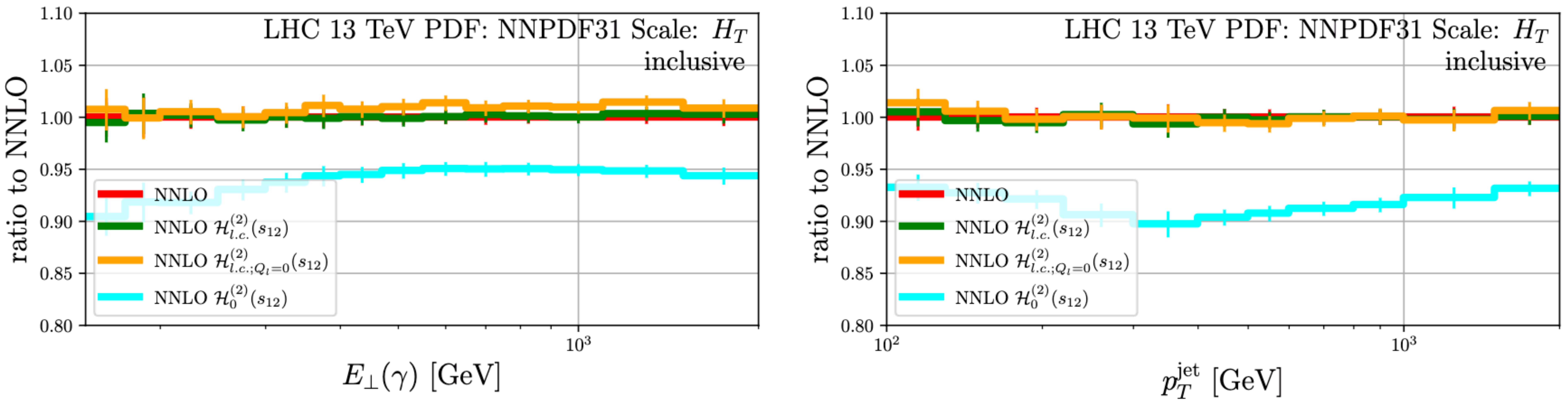
Good perturbative convergence
Improved agreement with ATLAS data

No fragmentation included, but expected to be small with hybrid-cone and in the direct-enriched region

In the tail, missing EW corrections, expected to be large and negative

First calculation for a $2 \to 3$ process with exact full colour 2-loop amplitude

Comparison of full NNLO, NNLO with two-loop finite-remainder at leading colour ("NNLO $\mathscr{H}^{(2)}_{l.c.}$") and NNLO no two-loop finite-remainder ("NNLO $\mathscr{H}^{(2)}_{0}$")



While the inclusion of finite-remainder is important (5-10% effect), the leading colour approximation seems to be good at cross section level

Similar observations in $pp \to \gamma\gamma\gamma$ [Abreu, De Laurentis, Ita, Klinkert, Page, Sotnikov '23]: differences between $\mathscr{H}^{(2)}$ and $\mathscr{H}^{(2)}_{l.c.}$ expected to be small at cross section level

N.B. process-dependent statement! Knowledge of full colour is generally important

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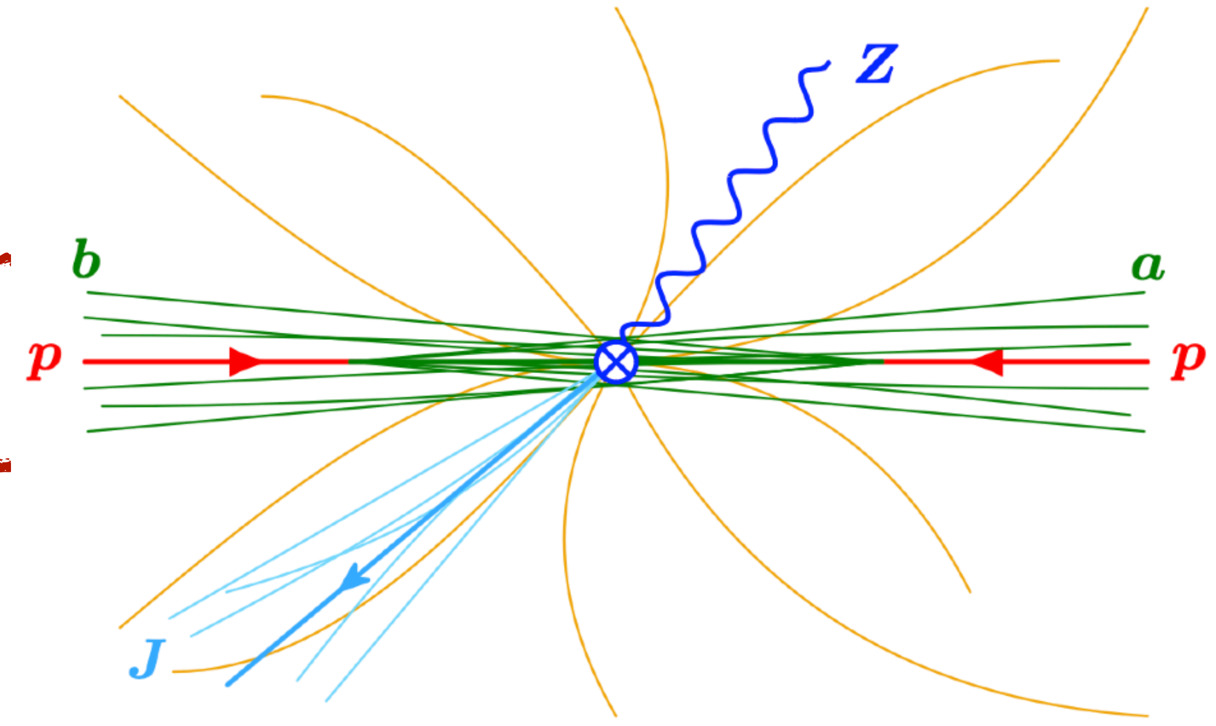

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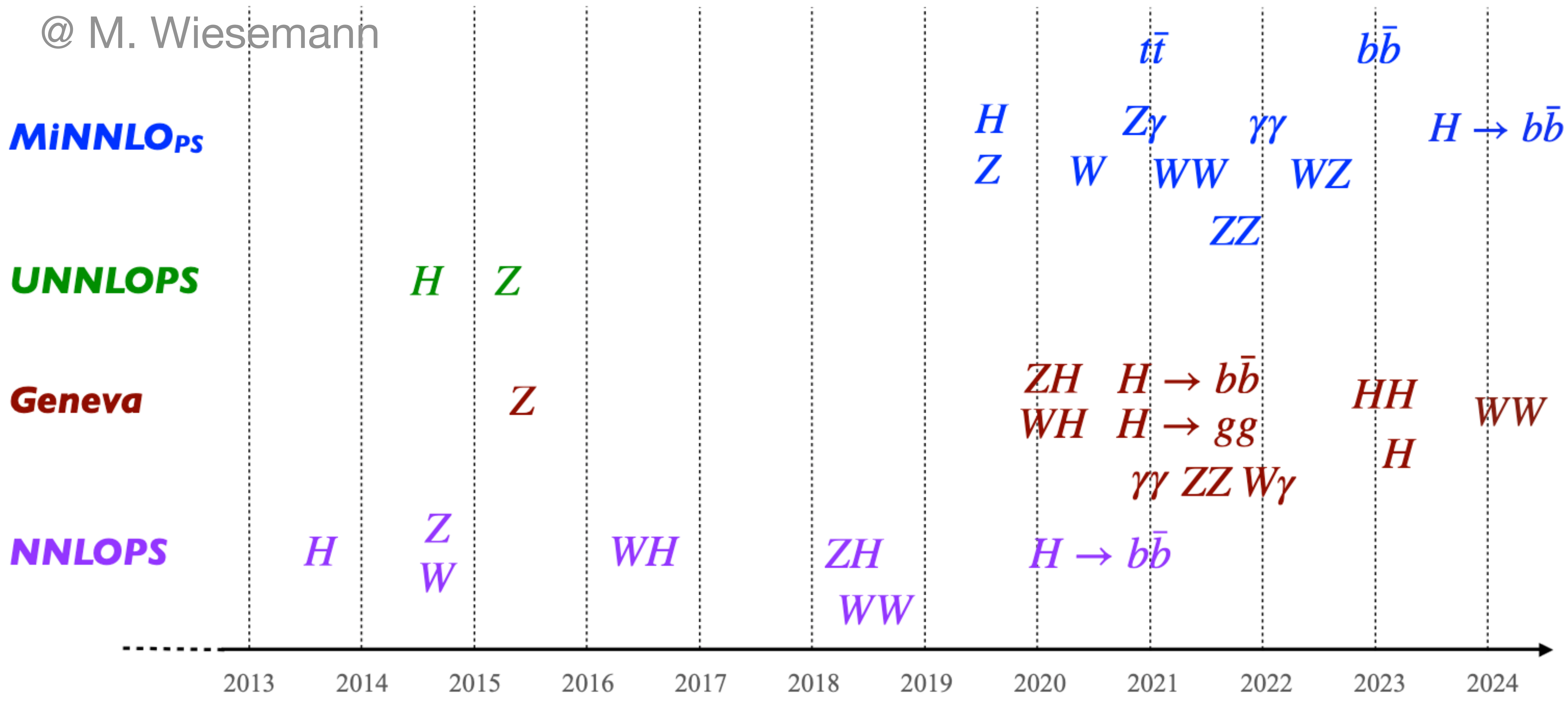
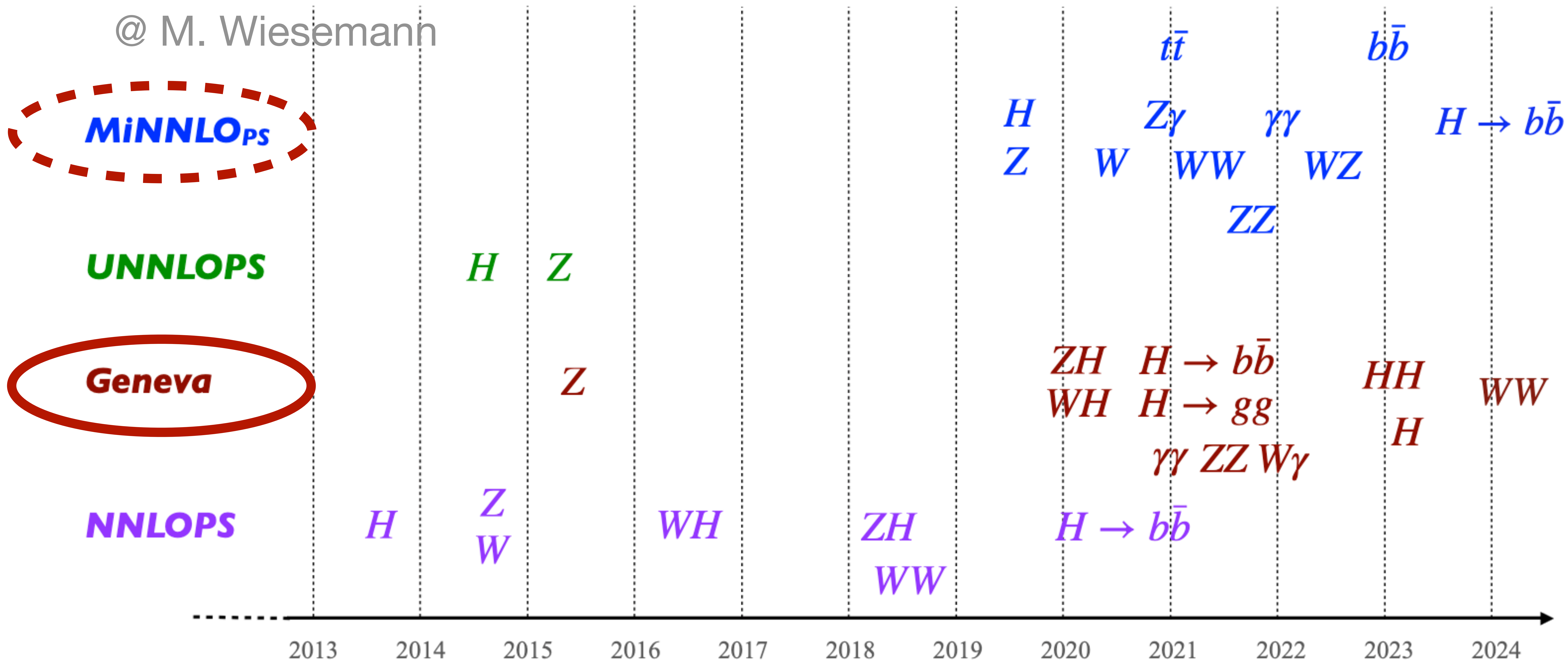
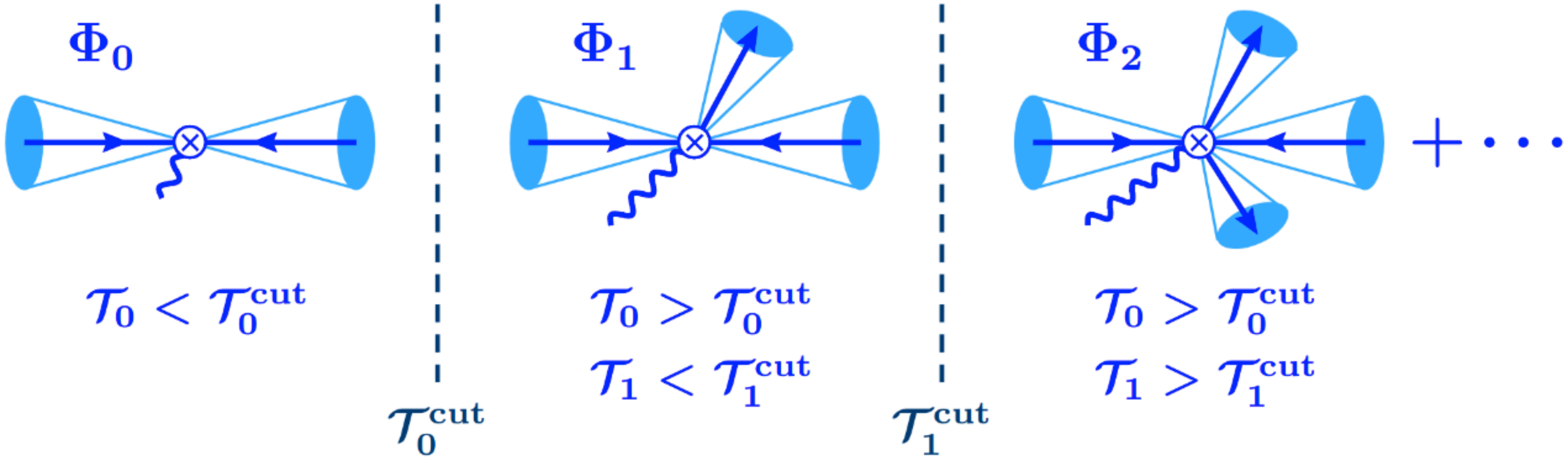


Impressive results in the recent years, but so far limited to processes with colour-singlets or heavy quarks in the final state



Impressive results in the recent years, but so far limited to processes with colour-singlets or heavy quarks in the final state

GENEVA in a nutshell (for colour-singlet production)



Division into 0/1/2-jet events dictated by resolution variable(s) $\mathscr{T}_N$

Originally developed for N-jettiness $\mathscr{T}_N$, but later extended to colour-singlet q_T [Alioli, Bauer et al. '21] and leading-jet p_T [Gavardi, Lim et al. '23]

As $\mathscr{T}_N$s regulate IR divergences, large logarithms appear: resummation is required!

$\mathscr{T}_0$ resummed up to NNLL', $\mathscr{T}_1$ up to NLL

GENEVA in a nutshell (for colour-singlet production)

Example: 0/1-jet separation, dictated by $\mathscr{T}_0^{\mathrm{cut}}$

$$\frac{\mathrm{d}\sigma_0^{\mathrm{MC}}}{\mathrm{d}\Phi_0}(\mathcal{T}_0^{\mathrm{cut}}) = \frac{\mathrm{d}\sigma^{\mathrm{NNLL}'}}{\mathrm{d}\Phi_0}(\mathcal{T}_0^{\mathrm{cut}}) + \frac{\mathrm{d}\sigma_0^{\mathrm{nons}}}{\mathrm{d}\Phi_0}(\mathcal{T}_0^{\mathrm{cut}})\,,$$

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

<u>Below the cut</u>, one adopts the *integrated* resummed cross section, with additive matching to fixed-order result (by requiring $\mathscr{T}_0 < \mathscr{T}_0^{\mathrm{cut}}$)

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

<u>Above the cut</u>, one adopts the *differential* resummed cross section, with additive matching to fixed-order result (by requiring $\mathscr{T}_0 > \mathscr{T}_0^{\mathrm{cut}}$)

$$\int \frac{\mathrm{d}\Phi_1}{\mathrm{d}\Phi_0\mathrm{d}\mathcal{T}_0}\,\mathcal{P}(\Phi_1) = 1$$

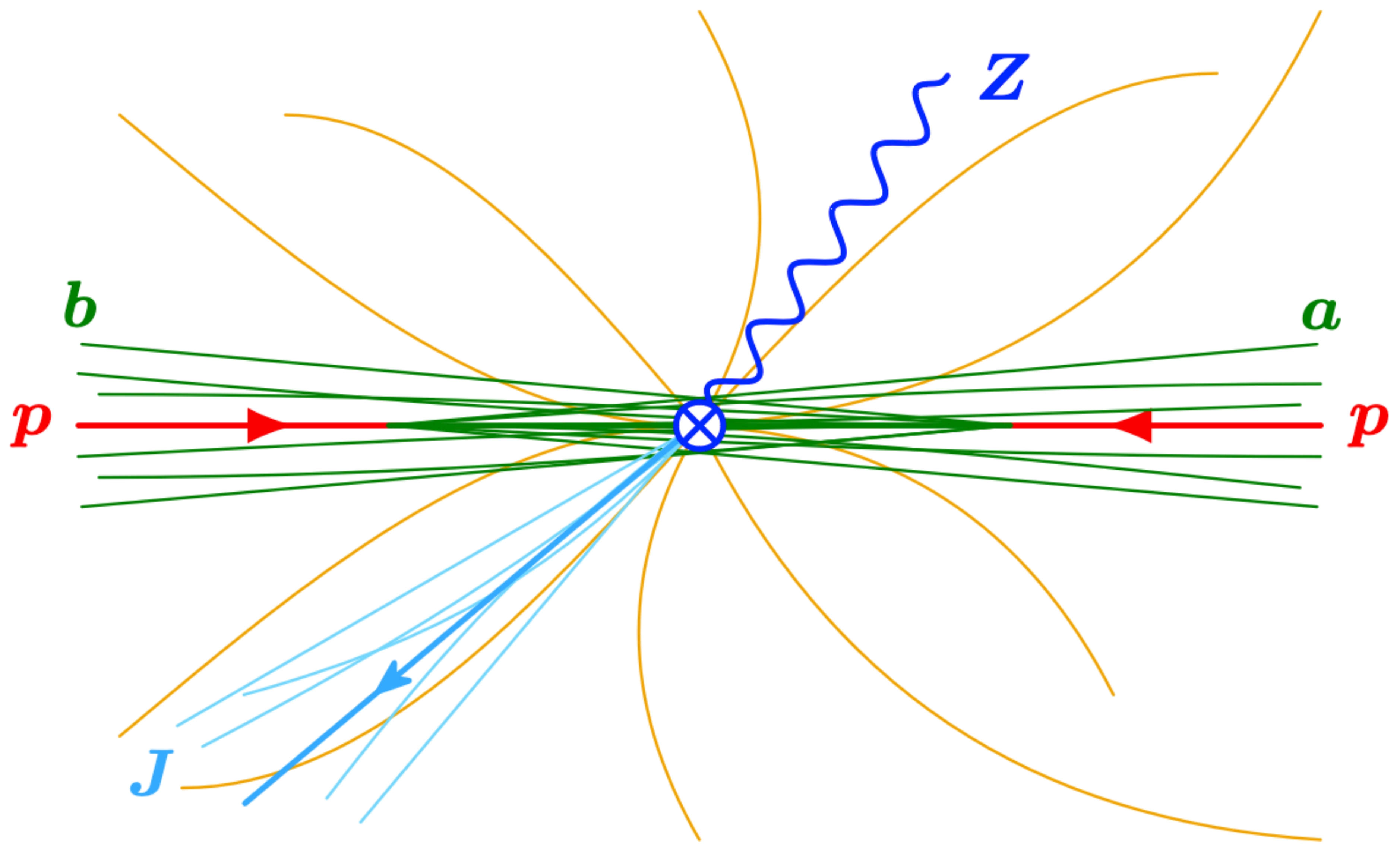
Normalised “splitting” function $\mathscr{P}(\Phi_1)$ to make the resummed cross section differential in the higher multiplicity phase space

How to extend GENEVA to vector boson plus jet production?

First step: resummation of one-jettiness $\mathcal{T}_1$, performed up to N3LL
[Alioli, Bell, Billis, Broggio, Dehnadi, Lim, Marinelli, Nagar, Napoletano, Rahn ’23]

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

$$Q_i = 2\rho_i E_i$$



Freedom in precise definition of $\mathcal{T}_1$:
dependence on reference frame;
dependence on definition of jet axis
(e.g. obtained recursively with exclusive clustering or a priori with inclusive clustering)

frames	$\rho_{a,b}$	ρ_J
Lab	1	1
Color Singlet (CS)	$e^{\pm Y_V}$	$(e^{Y_V} p_J^- + e^{-Y_V} p_J^+)/E_J$
Underlying Born (UB)	$e^{\pm Y_{VJ}}$	$(e^{Y_{VJ}} p_J^- + e^{-Y_{VJ}} p_J^+)/E_J$

@ G. Billis

Resummation of one-jettiness $\mathscr{T}_1$ in SCET: analytical ingredients

Beam function: known up to N3LO for any $\mathscr{T}_N$
[Ebert, Mistlberger, Vita '20]

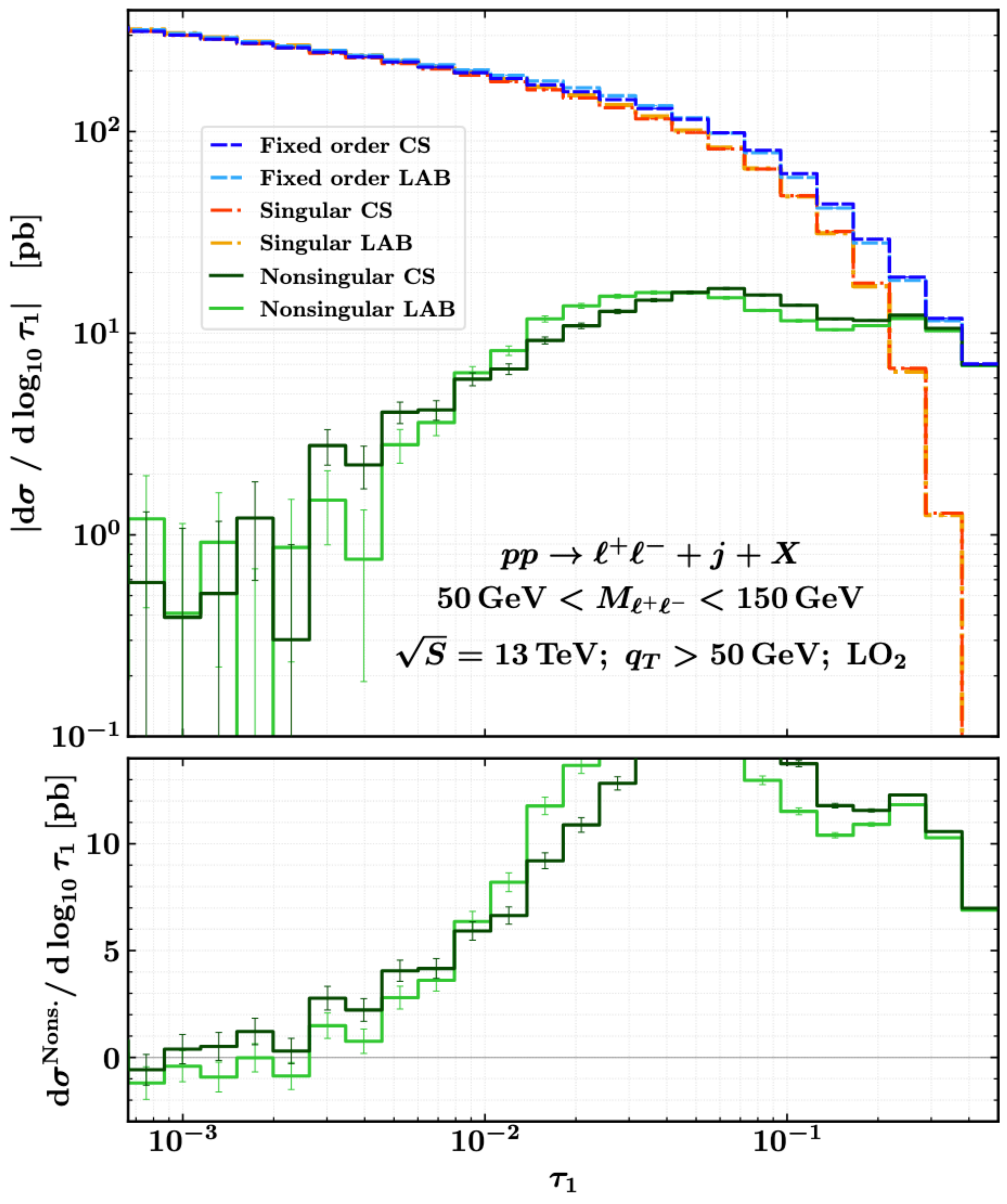
Jet function (universal): known up to N3LO
[Brüser, Liu, Stahlhofen '18]
[Banerjee, Dhani, Ravindran '18]

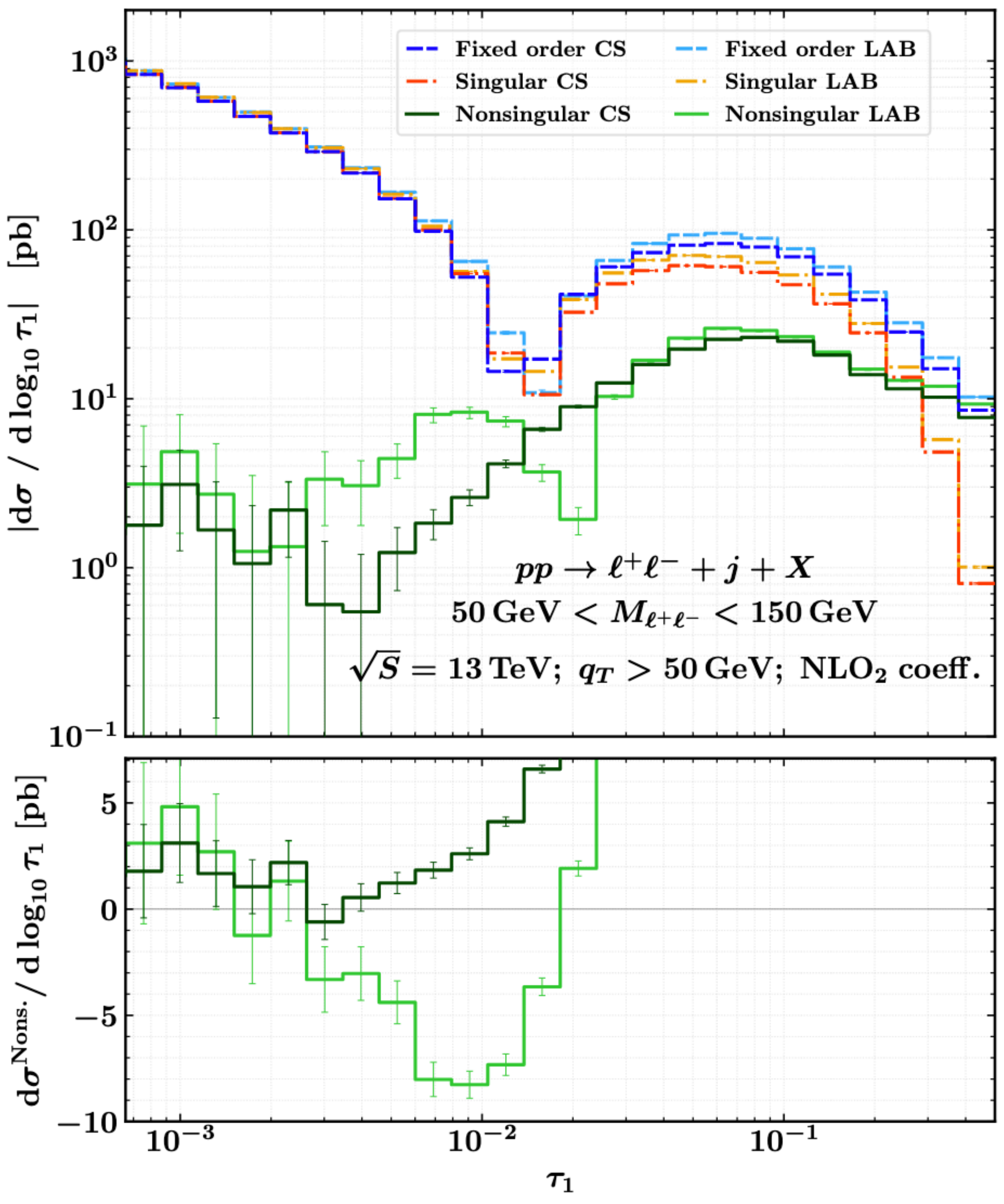
$$\frac{d\sigma}{d\mathcal{T}_1} = H_\kappa(\mu) \int dt_a dt_b ds_J \, B_a(t_a,\mu) B_b(t_b,\mu) J_c(s_J,\mu) \times S_\kappa(\mathcal{T}_1 - t_a/Q_a - t_b/Q_b - s_J/Q_J, \mu)$$

Hard function: extracted from two-loop amplitudes
[Gehrmann, Tancredi et al. '12, '22]

Soft function: known for $\mathscr{T}_1$ up to NNLO [Campbell, Ellis, Mondini, Williams '17],
but novel NNLO evaluations for any $\mathscr{T}_N$
[Bell, Dehnadi, Mohrmann, Rahn '23] [Agarwal, Melnikov, Pedron '24]

Matching the resummation to fixed order: size of nonsingular





$$\frac{d\sigma^{\mathrm{N^3LL+NLO_2}}}{d\Phi_1 d\mathcal{T}_1} = \frac{d\sigma^{\mathrm{N^3LL}}}{d\Phi_1 d\mathcal{T}_1} + \frac{d\sigma^{\mathrm{Nons.}}}{d\Phi_1 d\mathcal{T}_1}\,,$$

$$\frac{d\sigma^{\mathrm{Nons.}}}{d\Phi_1 d\mathcal{T}_1} = \left(\frac{d\sigma^{\mathrm{NLO_2}}}{d\Phi_1 d\mathcal{T}_1} - \left.\frac{d\sigma^{\mathrm{N^3LL}}}{d\Phi_1 d\mathcal{T}_1}\right|_{\mathcal{O}(\alpha_s^2)} \right) \theta(\mathcal{T}_1)$$

Nonsingular = Fixed order - Singular

In order to have a finite Born for Z+jet, one adopts a cut on q_T (or on $\mathscr{T}_0$, see backup)

$$\tau_1 = \mathcal{T}_1 / m_T$$

$$m_T \equiv \sqrt{M^2_{\ell^+\ell^-} + q_T^2}$$

Fixed-order approaches singular as $\tau_1 \to 0$ (as expected)
Power corrections seem to behave better in the CS frame

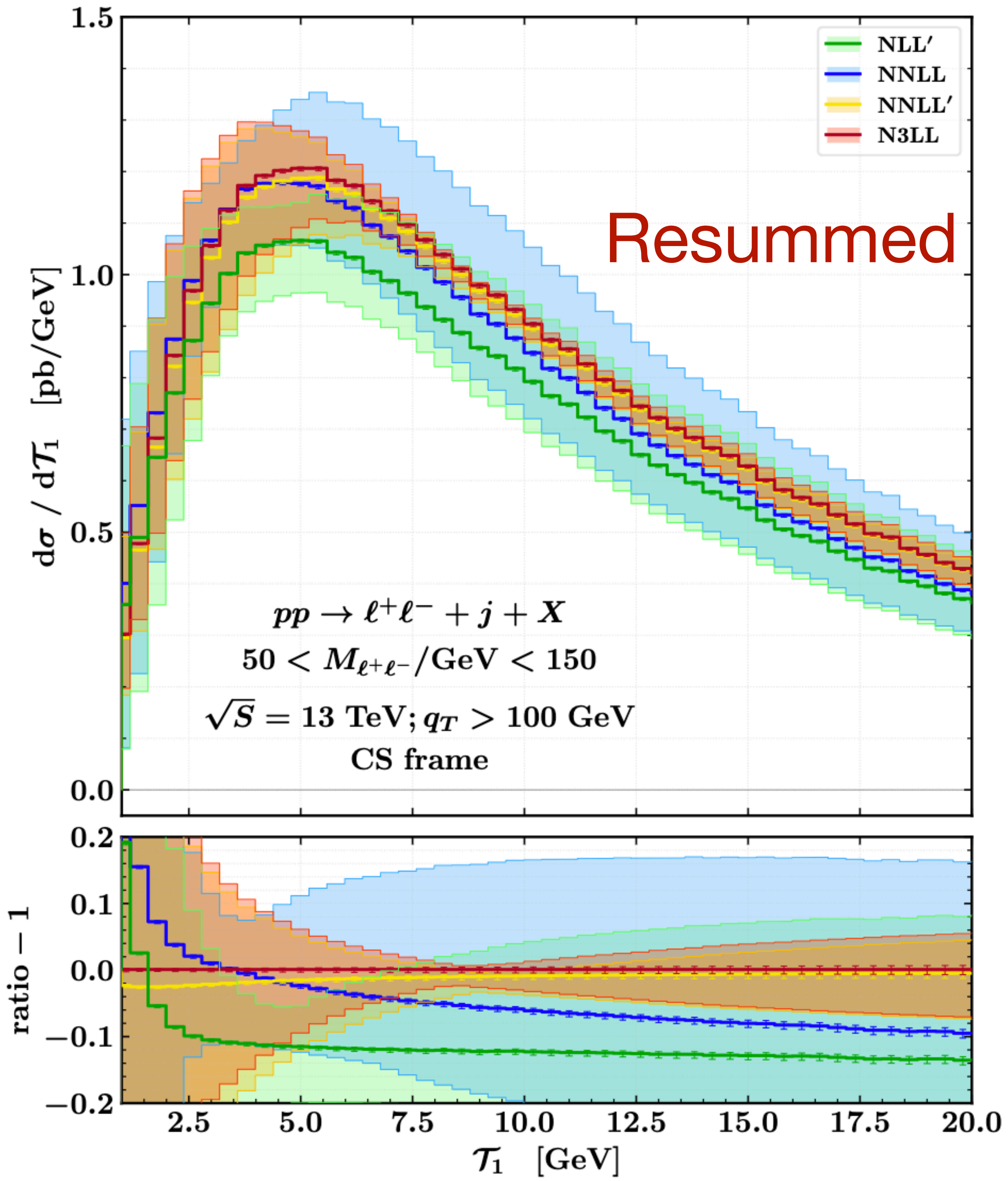
Results for resummed and matched result

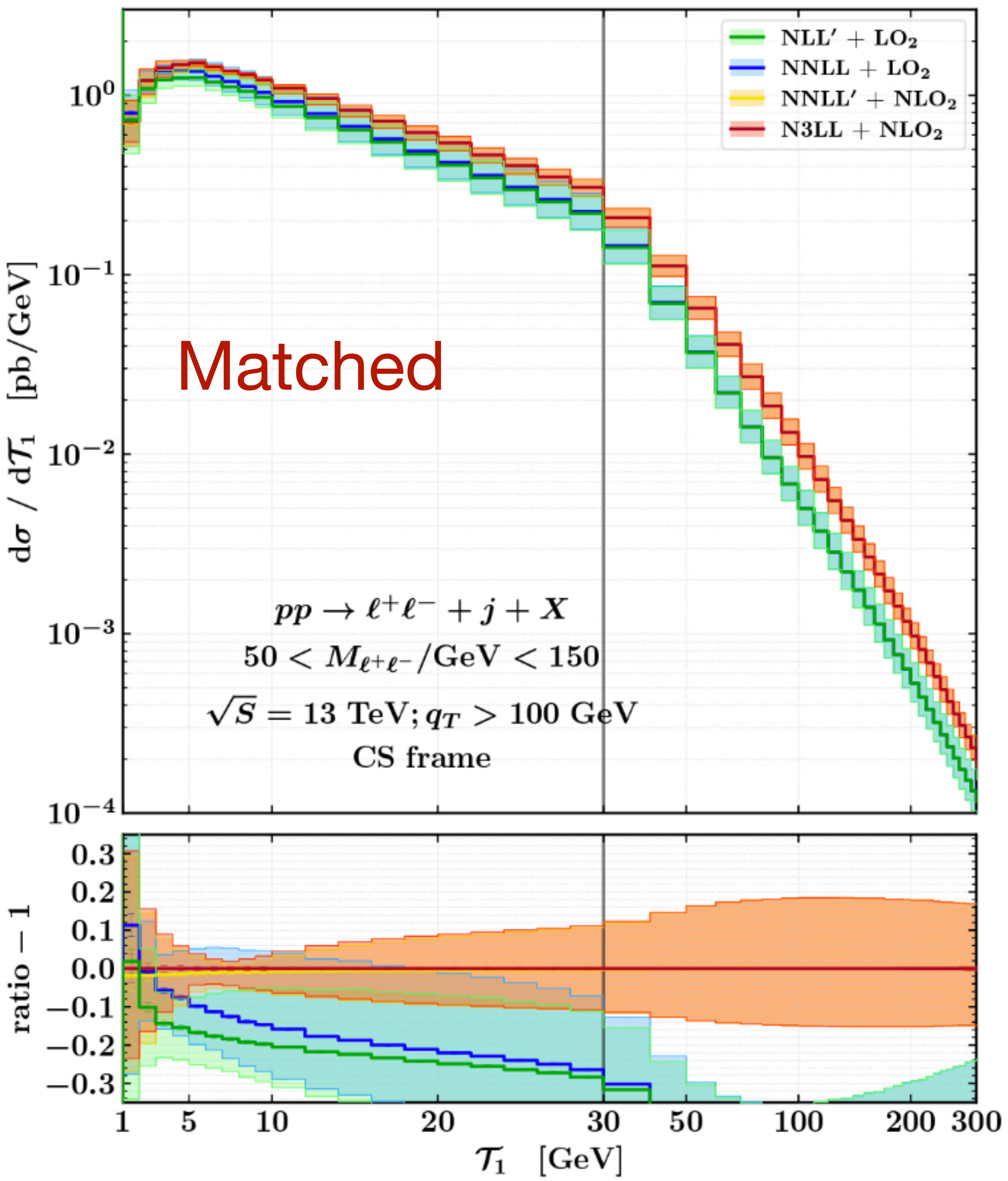
NLL’ → NNLL → NNLL’ sizeable

NNLL’ → N³LL minor effect

Large effect from NLO_2 fixed-order (not surprising)

When decreasing q_T, larger differences between curves. Joint resummation would be required in that case.



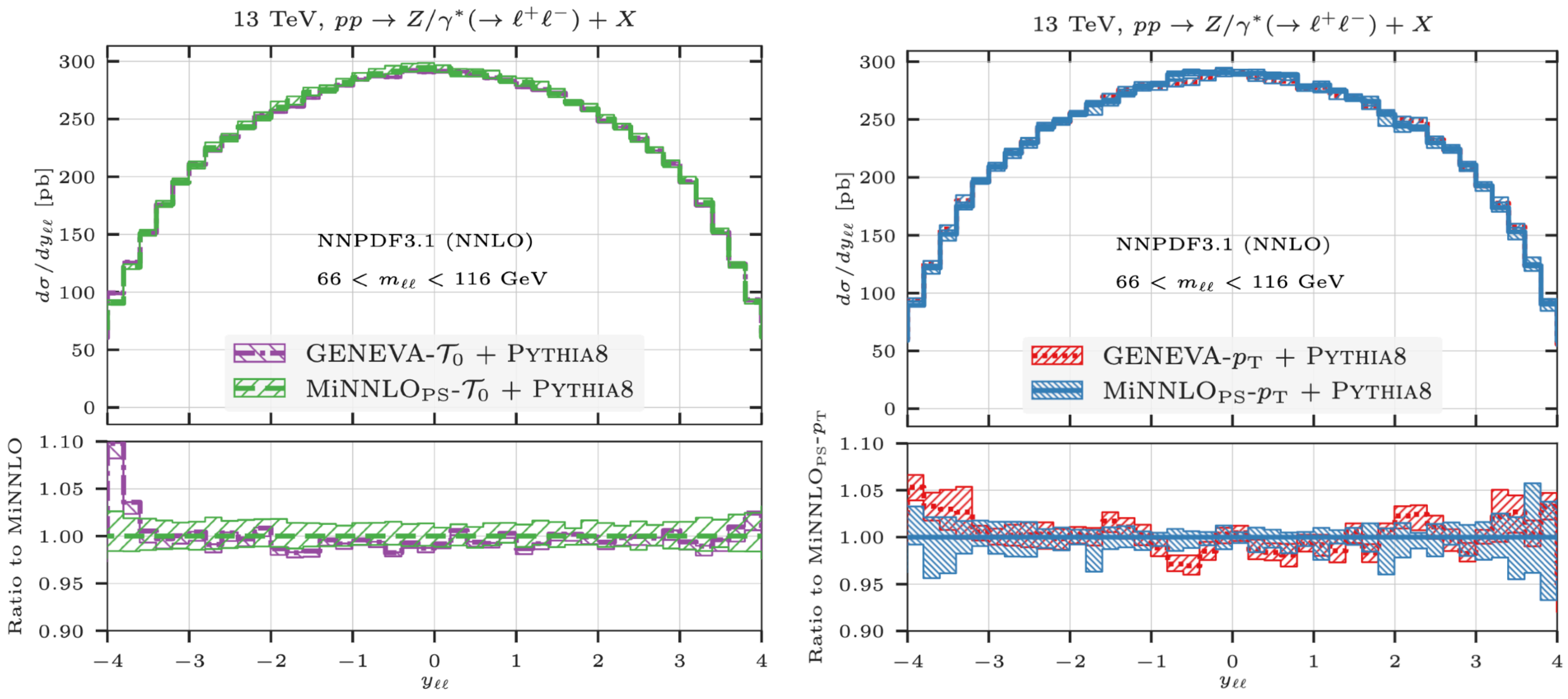


Next steps towards NNLO+PS: $\mathscr{T}_1$-preserving mapping, splitting functions $\mathscr{P}_{2\to3}(\Phi_2)$, interface to PS, better understanding of different definitions of $\mathscr{T}_1$ …

Jettiness-like variables in MiNNLO$_{PS}$

MiNNLO$_{PS}$ is another powerful method to achieve NNLO+PS accuracy based on Sudakov factors to resum logarithmic dependence on resolution parameters and to a multiplicative-like matching to reach NNLO accuracy

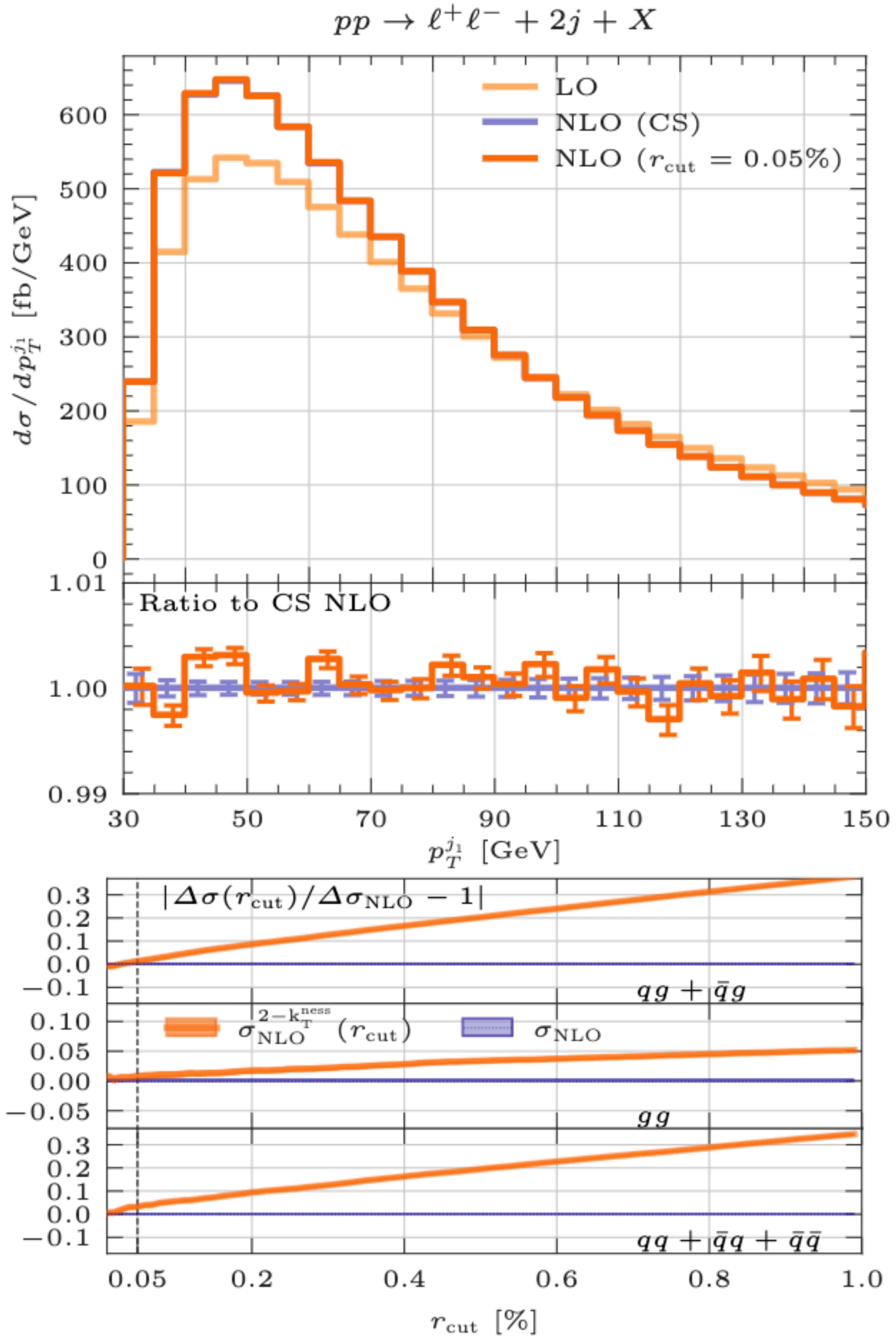
Originally developed using q_T-like observables, it has been recently extended to use jettiness-like variables [Ebert, Rottoli, Wiesemann, Zanderighi, Zanoli '24]



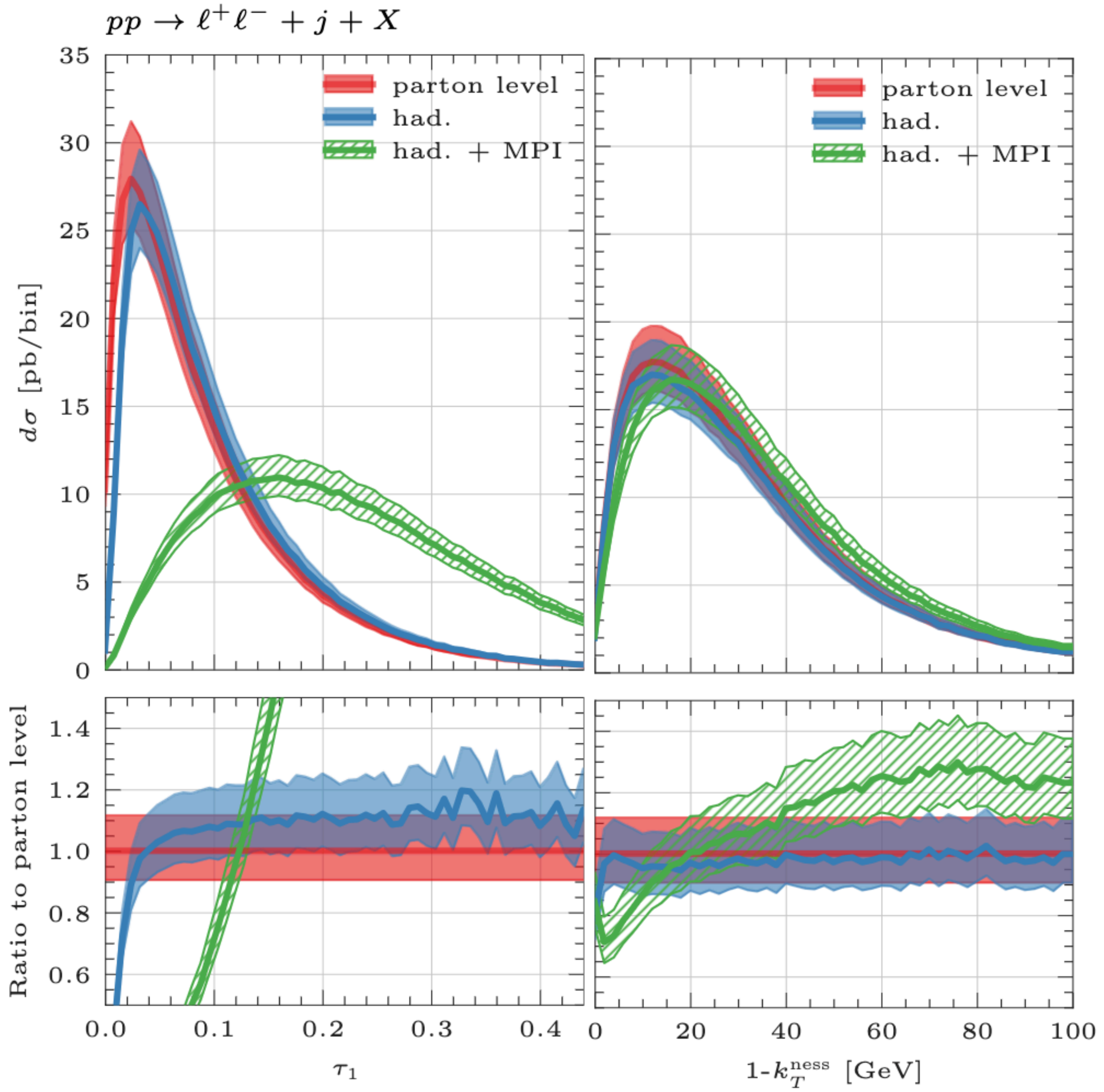
Formalism for $\mathscr{T}_0$ and $\mathscr{T}_1$, phenomenological results for $\mathscr{T}_0$

Implementation of different resolution variables in different frameworks important to assess systematic uncertainties

Transverse-momentum like observables for processes with final-state jets?



e.g. $k_T^{\rm ness}$, based on exclusive k_T-clustering algorithm
[Buonocore, Grazzini, Haag, Rottoli, C. Savoini ’22,’23]



More stable than $\mathcal{T}_1$
under had. and MPI effects

All ingredients at NLO,
extension to NNLO in progress

Resummation up to NNLL’
would also allow for usage in
NNLO+PS frameworks

Outlook of this talk

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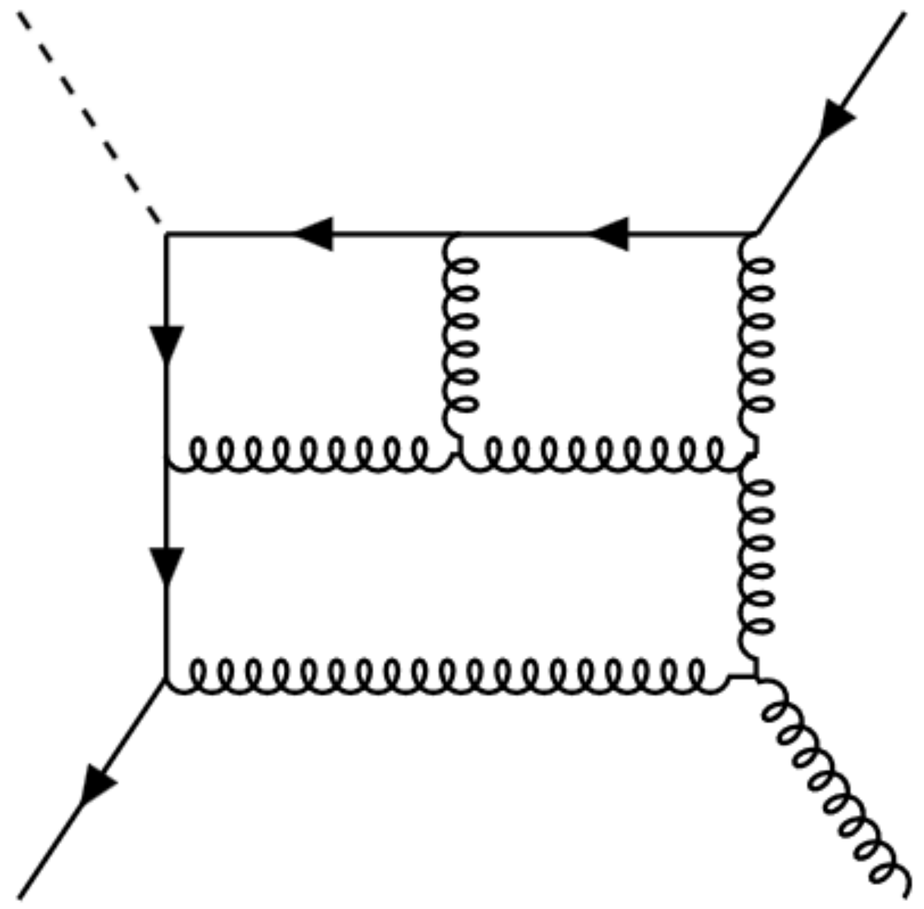

Personal selection of recent results that are representative for on-going progress.
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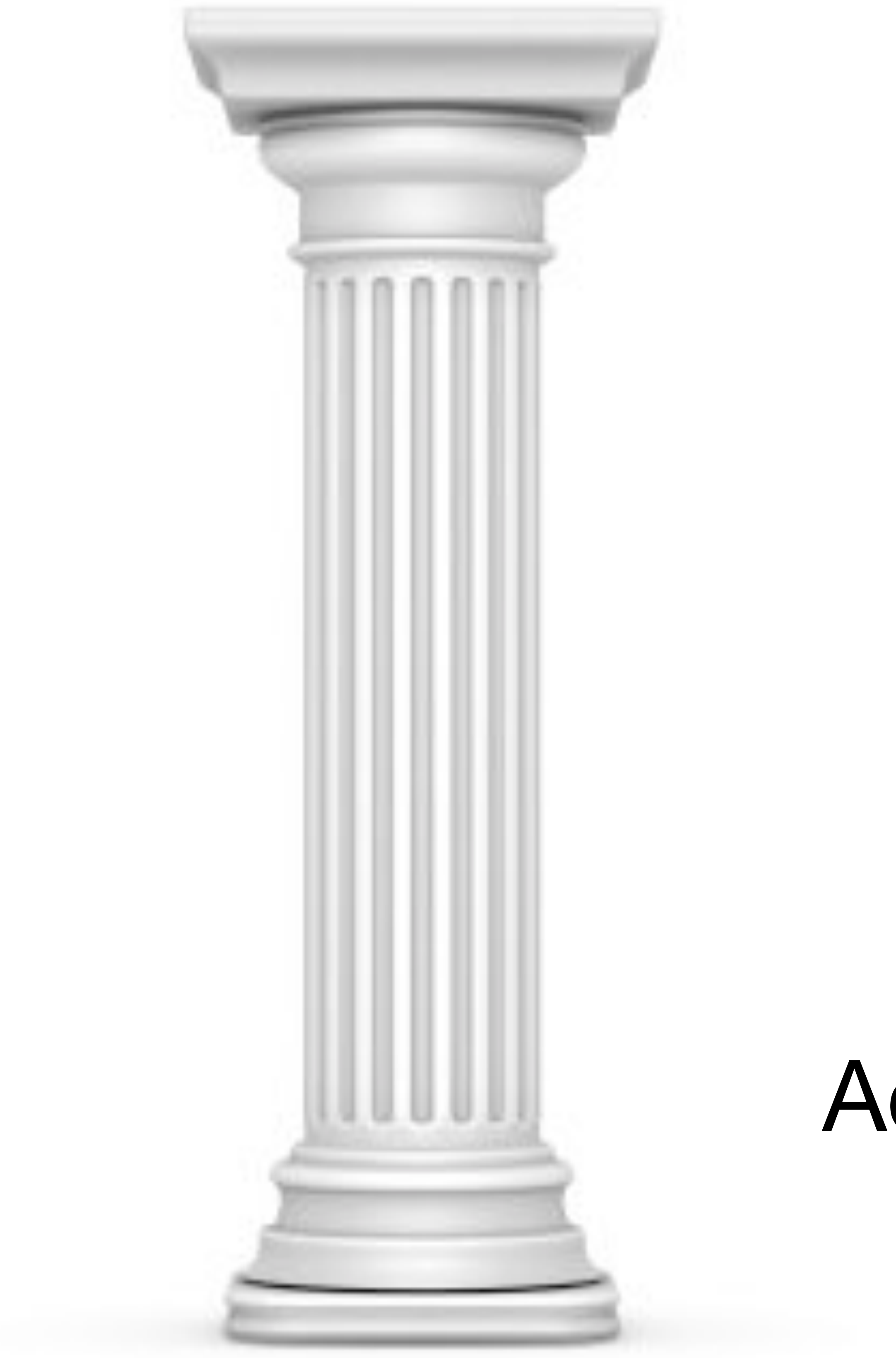
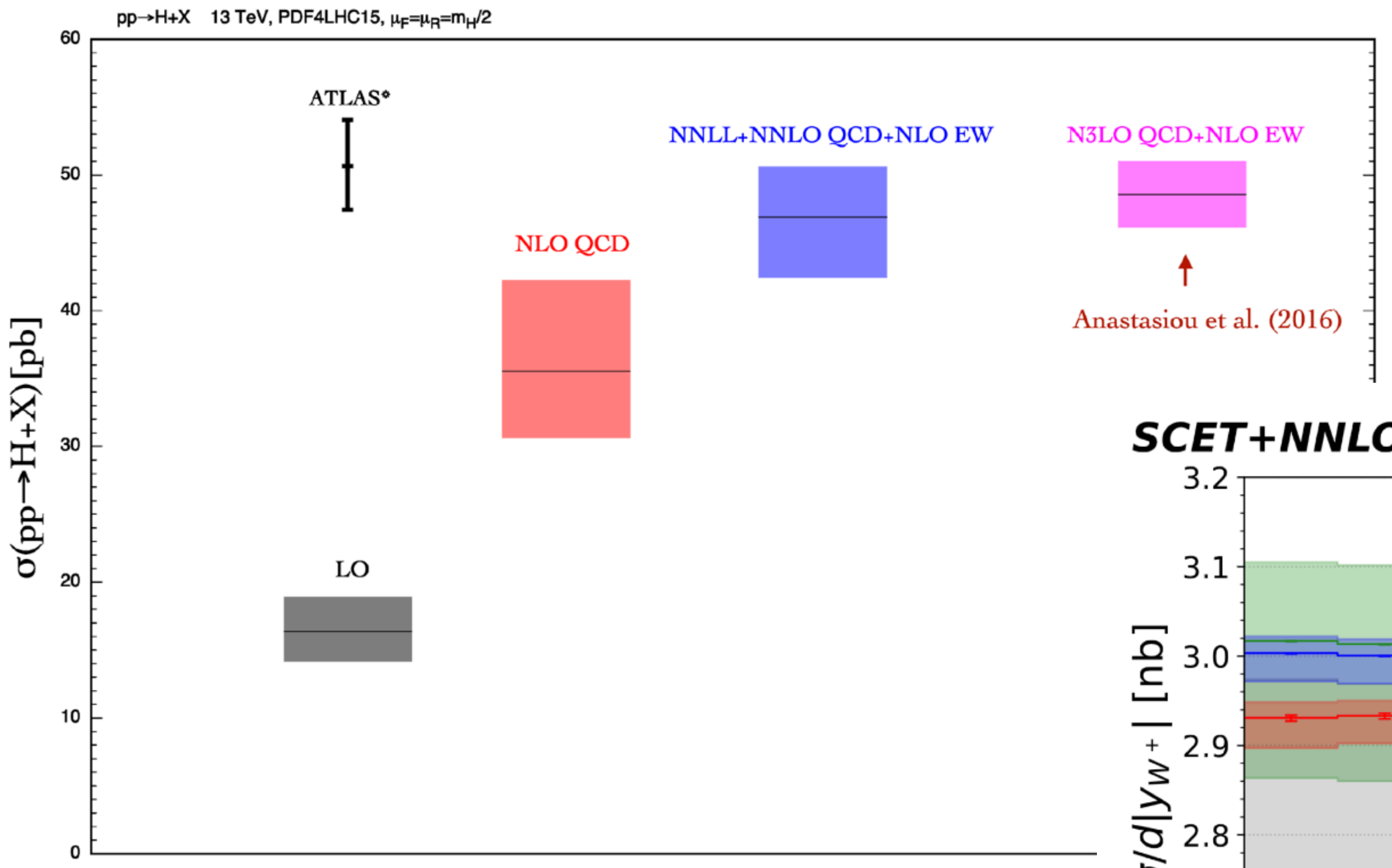
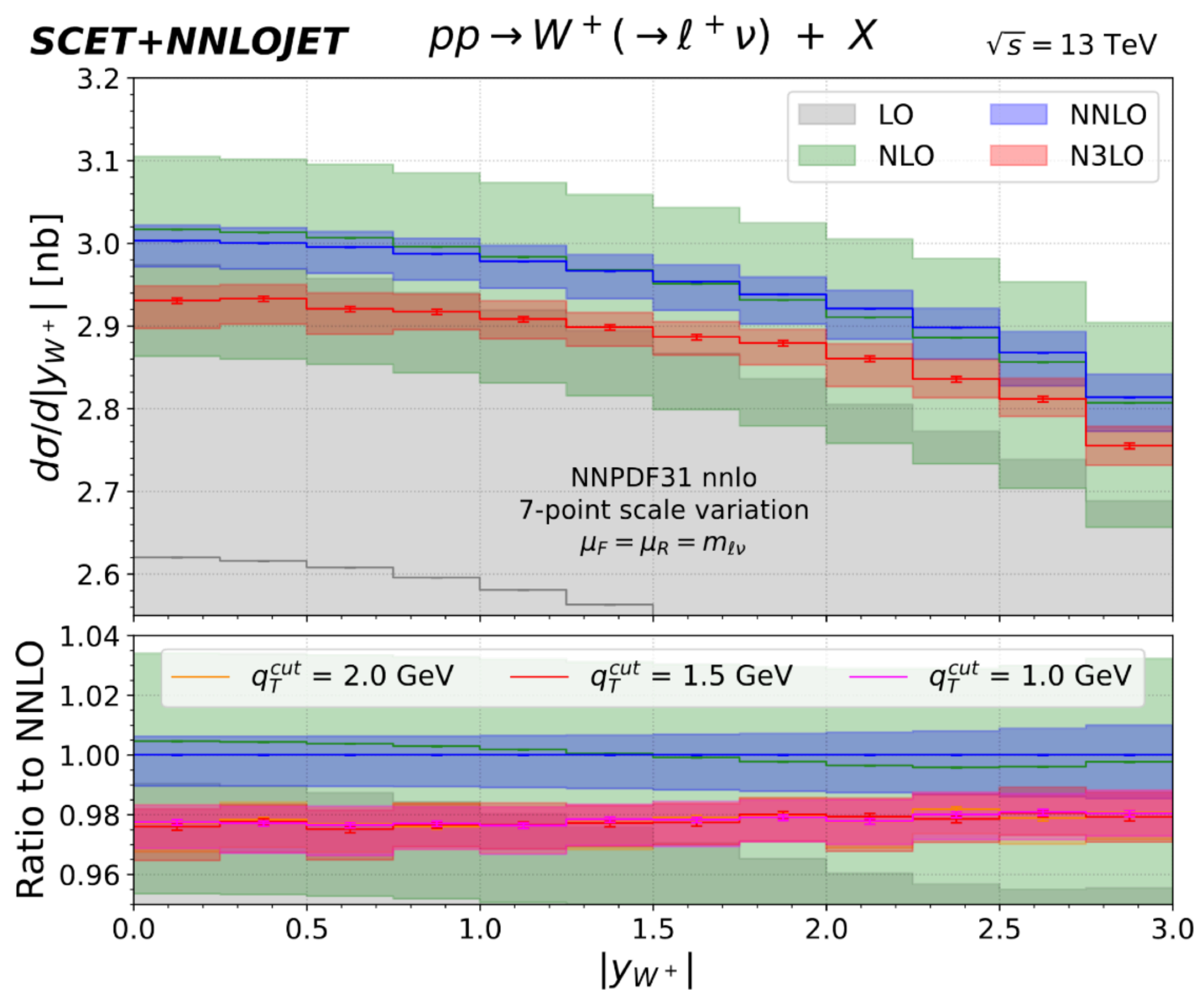
The two pillars of fixed-order calculations

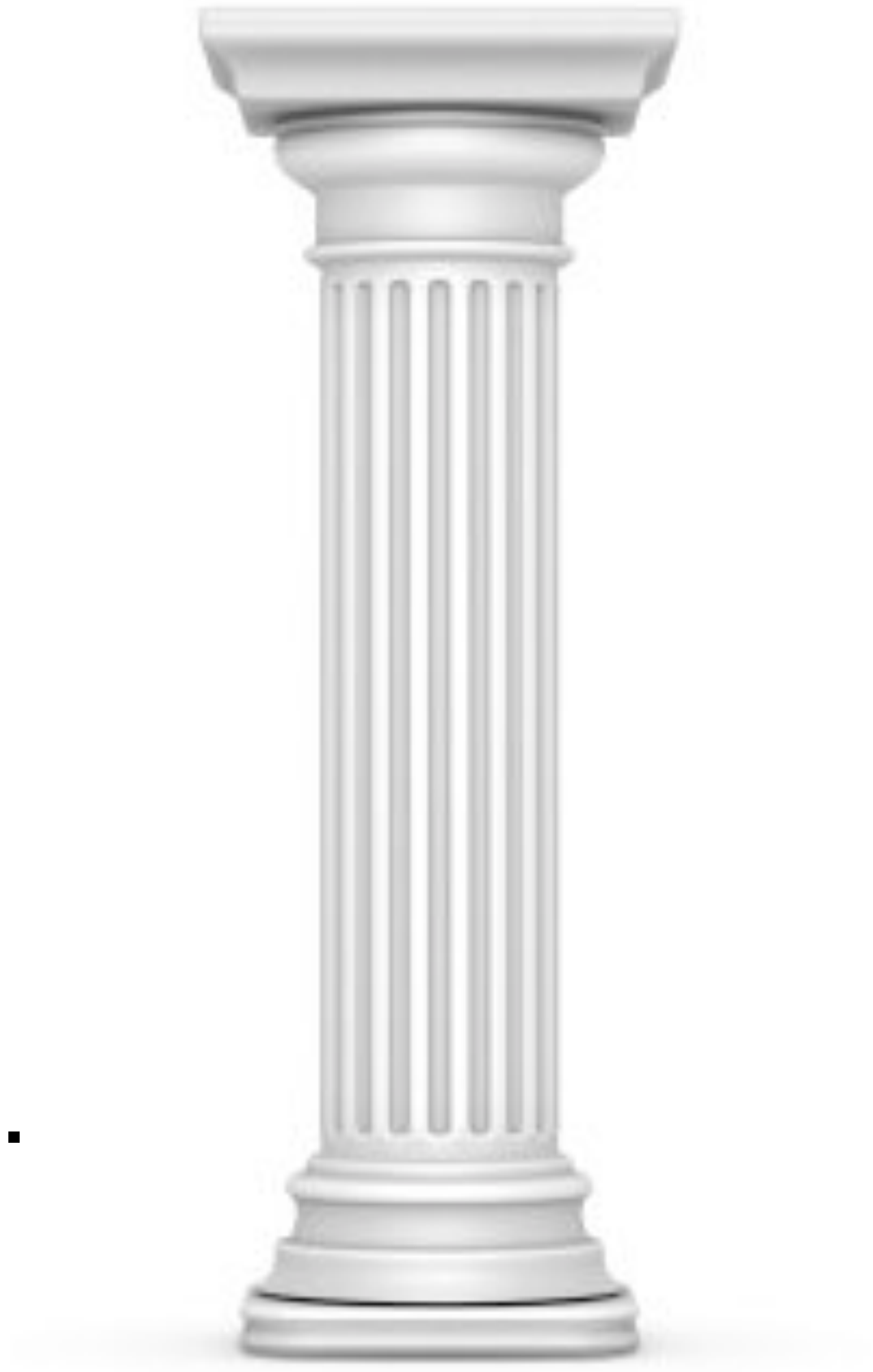
AMPLITUDES







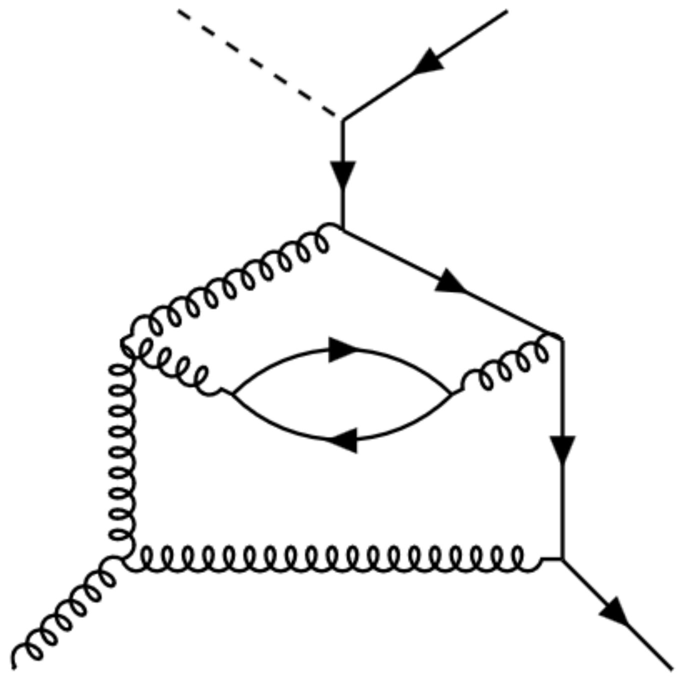
SUBTRACTION



Accuracy for standard candle processes at LHC (e.g. Higgs and DY) pushed to (fully differential) N^{3}LO

→ see talk by P. Torrielli

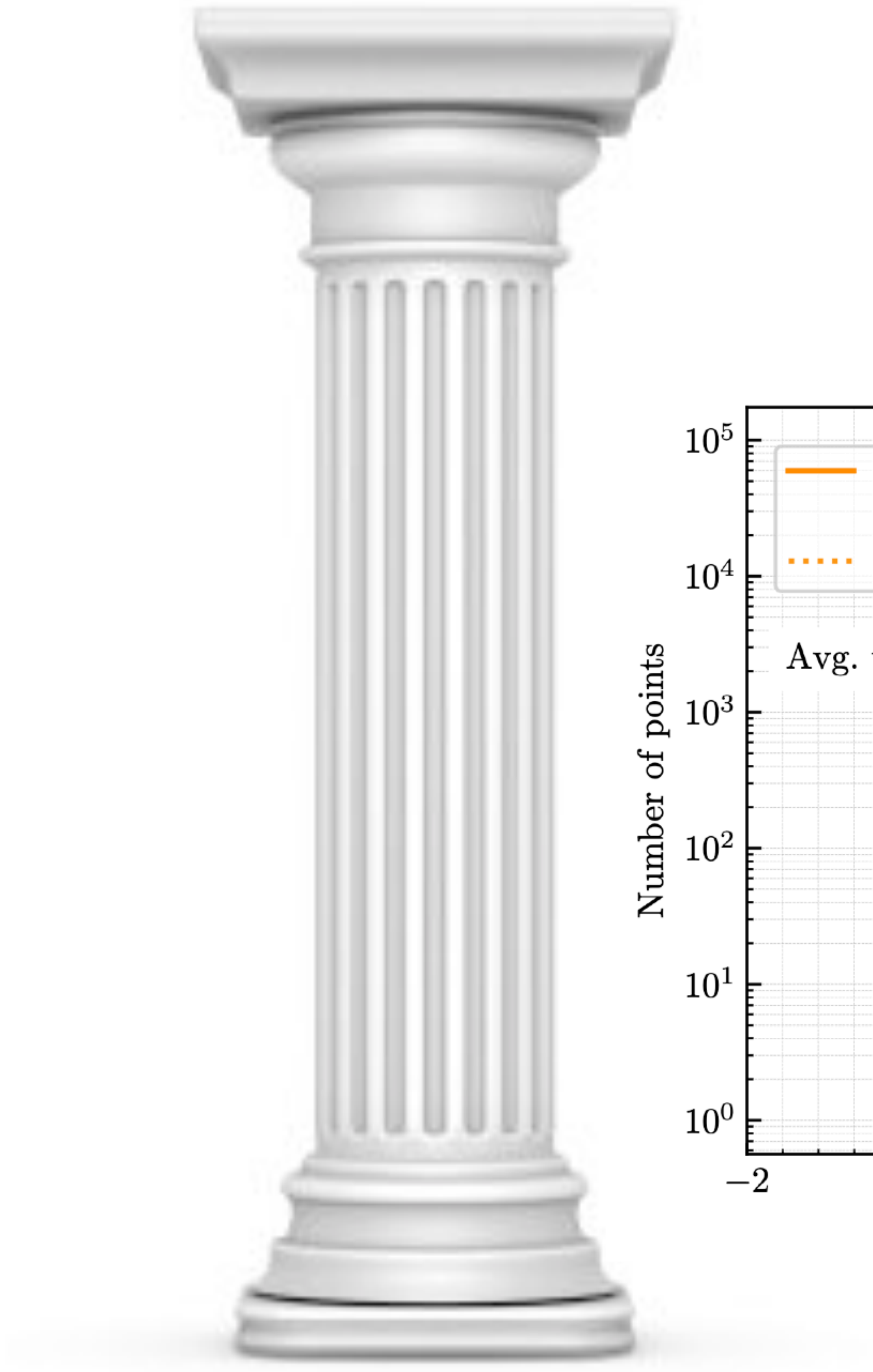
Amplitudes

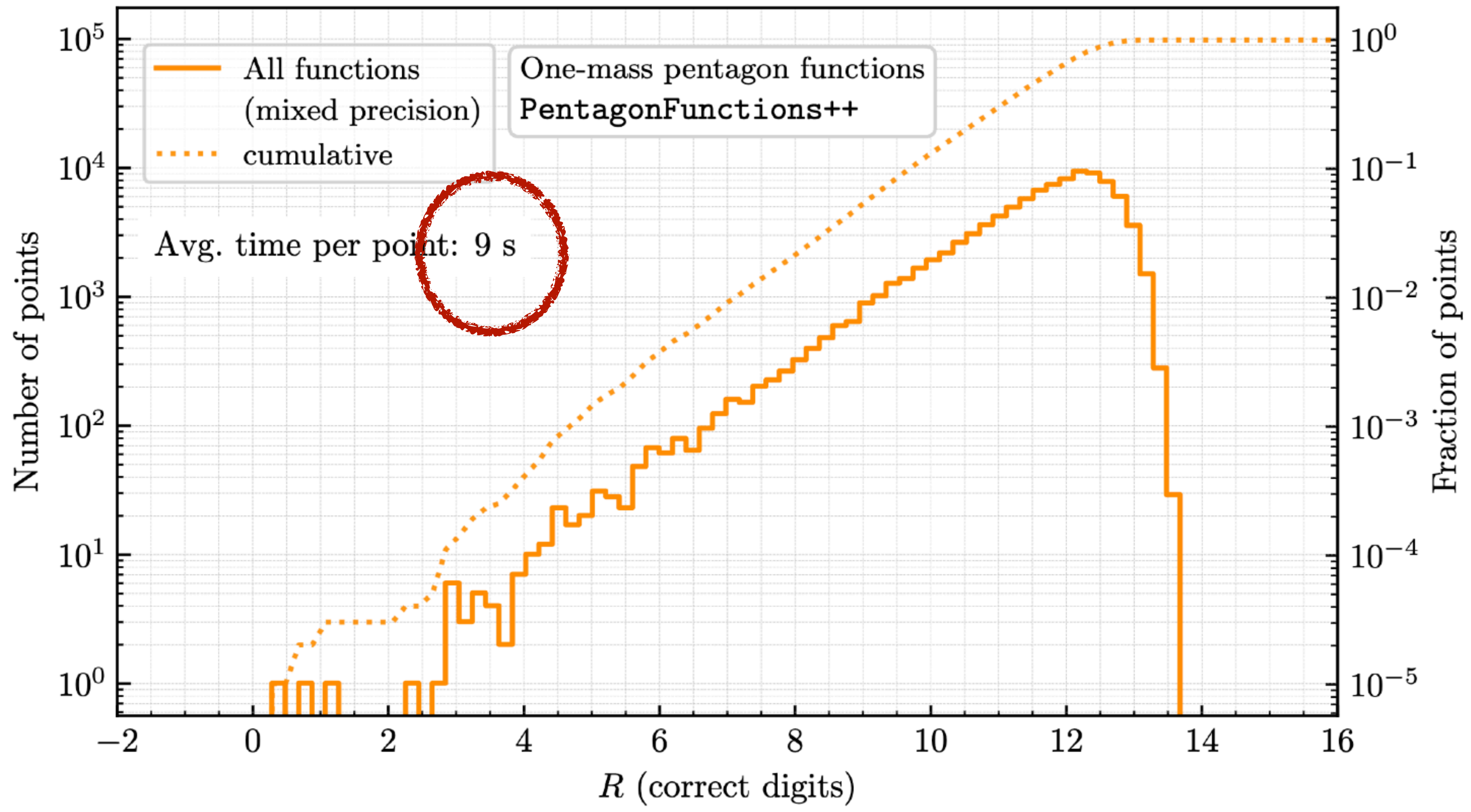


V+3 partons at three-loop (and two-loop to higher orders in ϵ)
[Gehrmann, Jakubcik, Mella, Syrrakos, Tancredi '22,'23]
(Planar) amplitudes in terms of GHPLs with simple alphabet:

$$\{x, y, 1-x-y, 1-x, 1-y, x+y\},\ x = s_{12}/m^2,\ y = s_{13}/m^2$$

Fast to evaluate





V+4 partons at two-loop [Abreu, Chicherin, Febres Cordero, Ita, Klinkert, Page, Sotnikov, Tschernow, Zoia '21,'23]
Amplitudes in terms of
"(one-mass) pentagon functions"
Lot of recent progress
to evaluate them efficiently

Subtraction

$$\mathrm{d}\sigma^V_{\mathrm{N^3LO}} = \mathrm{d}\sigma^V_{\mathrm{N^3LO}}\Big|_{q_T<q_T^{\mathrm{cut}}} + \mathrm{d}\sigma^V_{\mathrm{N^3LO}}\Big|_{q_T>q_T^{\mathrm{cut}}}$$
$$= \mathscr{H}^V_{\mathrm{N^3LO}} \otimes \mathrm{d}\sigma^V_{\mathrm{LO}} + \left[\mathrm{d}\sigma^{V+\mathrm{jet}}_{\mathrm{NNLO}} - \mathrm{d}\sigma^{V,\mathrm{CT}}_{\mathrm{N^3LO}}\right]_{q_T>q_T^{\mathrm{cut}}}$$

Non-local (slicing) schemes : used for differential N^{3}LO colour-singlet

For V+jet, one could use N-jettiness subtraction with $\mathscr{T}_1$

Beam, hard and jet functions are known (see above)

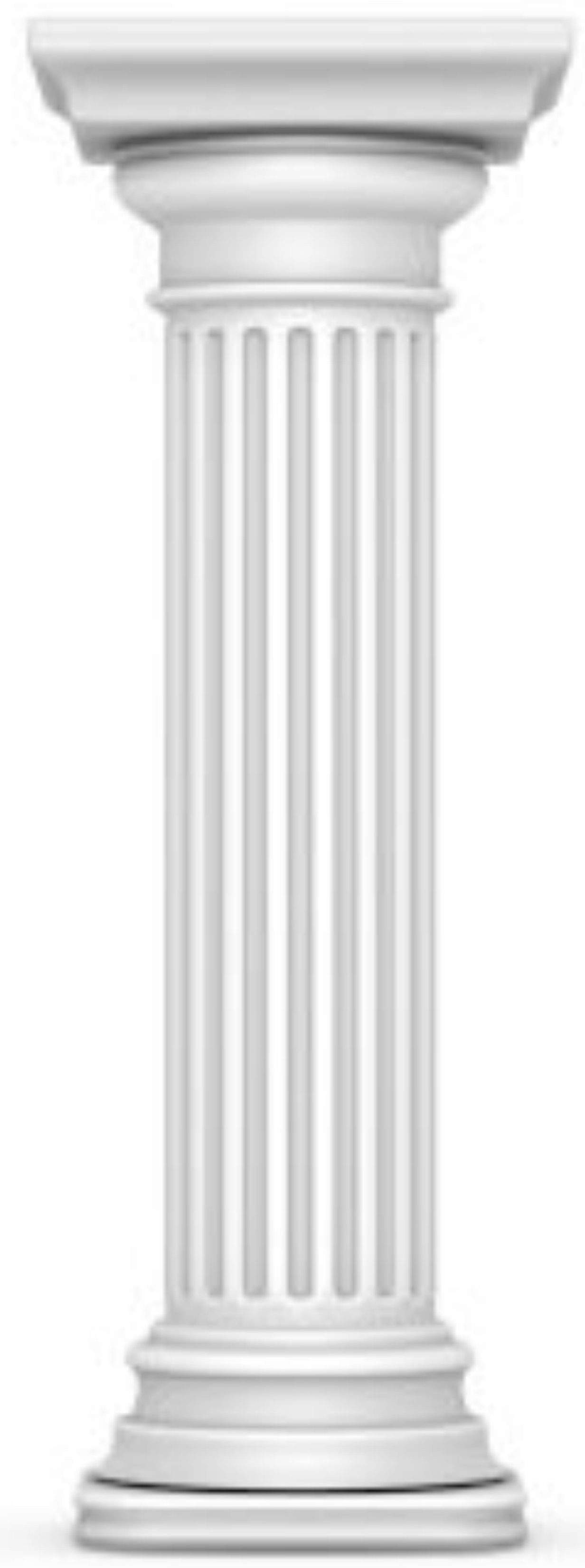
Missing ingredient: N^{3}LO soft function for $\mathscr{T}_1$, currently beyond reach

Calculation of N^{3}LO soft function for $\mathscr{T}_0$ in progress
[Baranowski, Delto, Melnikov, Pikelner, Wang]

Local schemes : still in their infancy

Analytical ingredients for N^{3}LO antenna subtraction in e^+e^- collisions
[Chen, Jakubcik, Marcoli, GS '22,'23]

Ideas for the N^{3}LO extension of the local analytic subtraction method
[Magnea, Milloy, Signorile-Signorile, Torrielli '24]



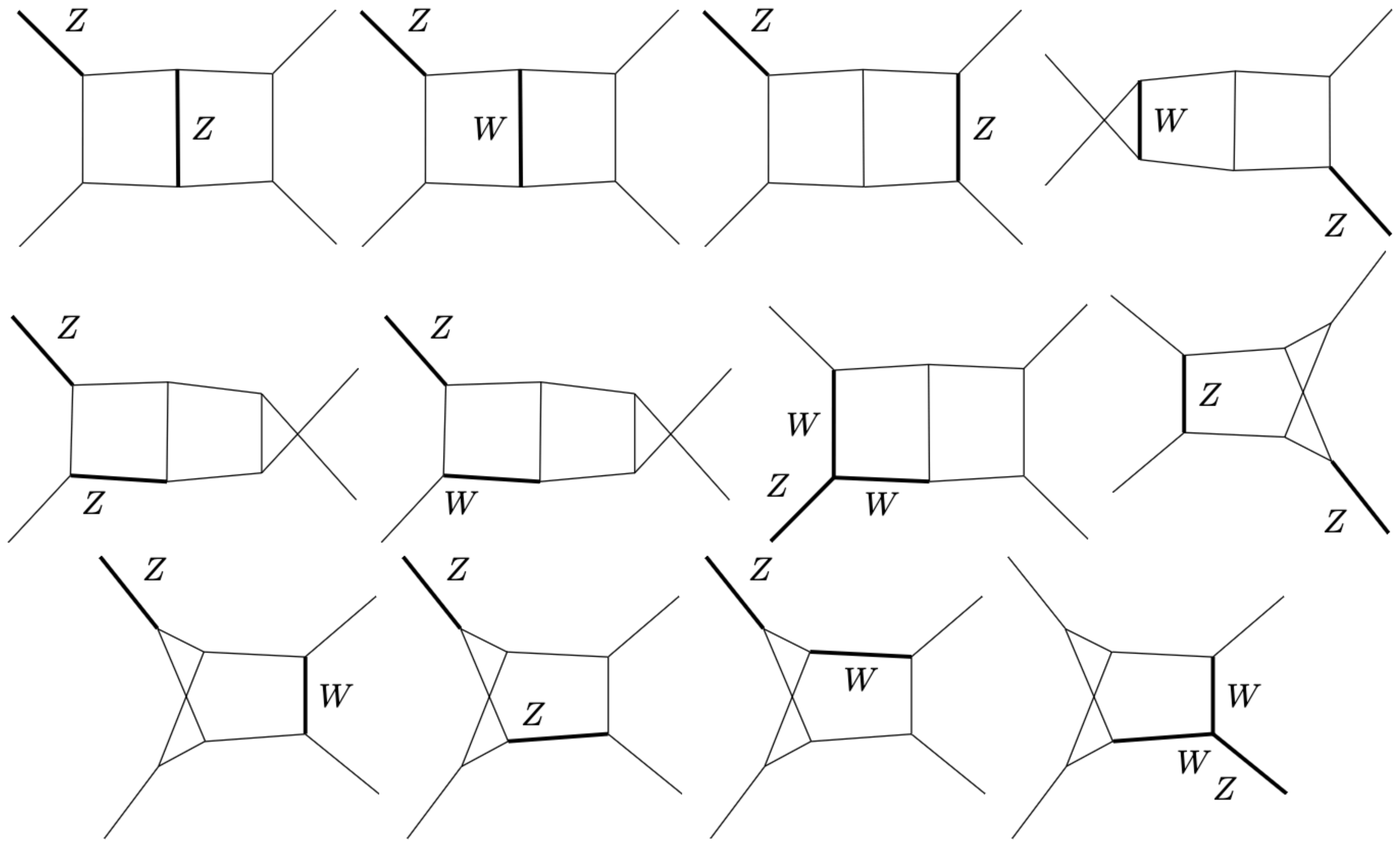
Mixed $\mathcal{O}(\alpha_s \alpha)$ effects?

Full $\mathcal{O}(\alpha_s \alpha)$ corrections known for Drell-Yan
[Bonciani et al. ’21] [Buccioni et al. ’22] → see talk by A. Vicini

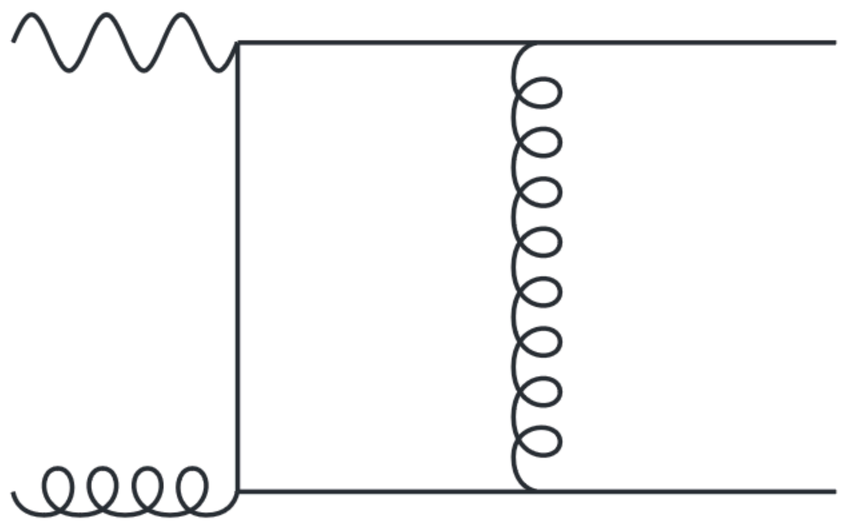
Still not known for V+jet. Estimation of size in [Lindert et al. ’17]:
on multiplicative combination of NNLO QCD and NLO EW,
uncertainty of 10-20% for W/Z+jet and 40% for γ+jet

First step: bosonic (neglecting closed fermion loops) contribution to the two-loop mixed QCD-EW amplitudes for Z+jet
[Bargiela, Caola, Chawdhry, Liu ’23]

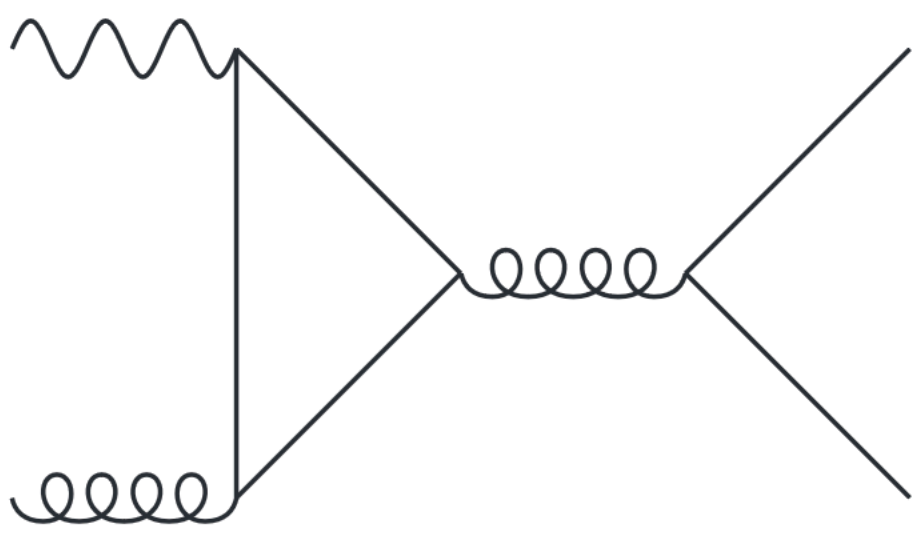
Appropriate IR subtraction schemes for mixed QCD-QED real-emission would be required



Axial-vector contributions?



Non-singlet



Pure-singlet
(vanishes for $W^{\pm}$)

Known exactly at one-loop

Non-singlet: vector = axial-vector

Pure-singlet: missing two-loop axial-vector contributions computed recently (with large m_t) [Gehrmann, Peraro, Tancredi '22]

Phenomenological impact to be assessed: expected to be very small (per-mille correction) for sufficiently inclusive observable, but may be sizeable in e.g. angular correlations between leptons and jet

Related calculation is the three-loop quark form factor, entering NC DY @ N3LO:
exact top quark mass dependence in [Chen, Czakon, Niggetiedt '21]
Effect of exact axial-vector on total cross section is negligible [Duhr, Mistlberger '21]

Conclusions

Work to improve the theoretical description of V+jet well inserted in the overall effort of the community towards better SM predictions:

- push predictions for multi-leg final states to NNLO

- consider more exclusive final states e.g. with identified photons/hadrons (or flavoured jets $\rightarrow$ see talks by H. B. Hartanto and A. Mitov)

- improve generators (including accuracy of PS and matching to fixed-order)

- go to N^{3}LO (likely with non-local subtraction methods in a first phase)

- start thinking about formally sub-dominant effects that may become relevant

I am grateful to S. Alioli, X. Chen, P. Jakubcik, A. Huss and L. Rottoli for discussions

BACKUP

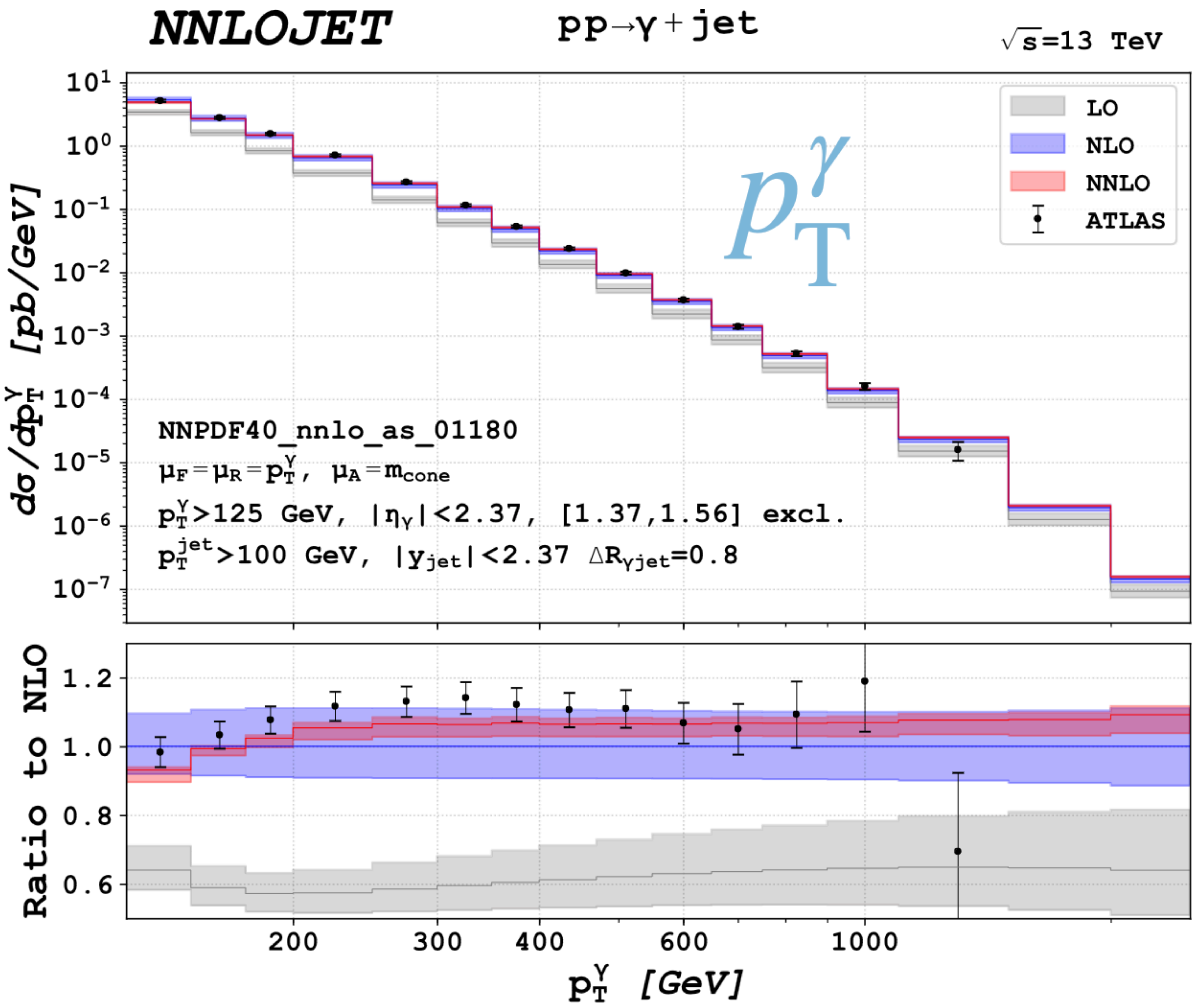
$$\frac{\mathrm{d}\sigma_0^{\mathrm{MC}}}{\mathrm{d}\Phi_0}(\mathcal{T}_0^{\mathrm{cut}}) = \frac{\mathrm{d}\sigma^{\mathrm{NNLL}'}}{\mathrm{d}\Phi_0}(\mathcal{T}_0^{\mathrm{cut}}) + \frac{\mathrm{d}\sigma_0^{\mathrm{nons}}}{\mathrm{d}\Phi_0}(\mathcal{T}_0^{\mathrm{cut}}),$$

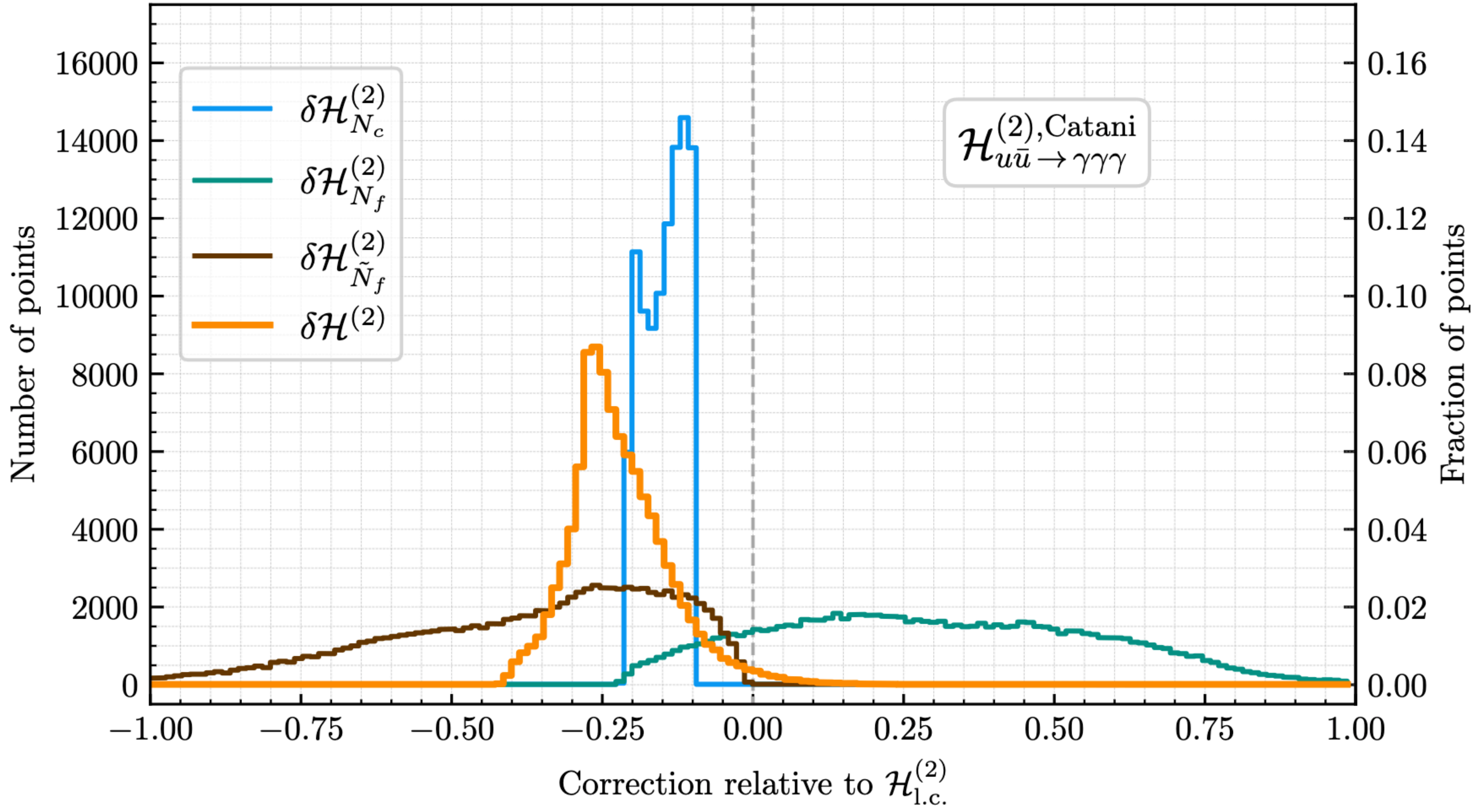
$$\begin{aligned}\frac{\mathrm{d}\sigma_{\geq 1}^{\mathrm{MC}}}{\mathrm{d}\Phi_1}(\mathcal{T}_0 > \mathcal{T}_0^{\mathrm{cut}}) &= \frac{\mathrm{d}\sigma^{\mathrm{NNLL}'}}{\mathrm{d}\Phi_0 \mathrm{d}\mathcal{T}_0}\,\mathcal{P}(\Phi_1)\theta\left(\mathcal{T}_0 > \mathcal{T}_0^{\mathrm{cut}}\right) \\ &\quad + \frac{\mathrm{d}\sigma_{\geq 1}^{\mathrm{nons}}}{\mathrm{d}\Phi_1}(\mathcal{T}_0 > \mathcal{T}_0^{\mathrm{cut}}),\end{aligned}$$

$$\begin{aligned}\frac{\mathrm{d}\sigma_{\geq 1}^{\mathrm{MC}}}{\mathrm{d}\Phi_1}(\mathcal{T}_0 > \mathcal{T}_0^{\mathrm{cut}}) &= \frac{\mathrm{d}\sigma^{\mathrm{NNLL}'}}{\mathrm{d}\Phi_0 \mathrm{d}\mathcal{T}_0}\,\mathcal{P}(\Phi_1)\;\theta\left(\mathcal{T}_0 > \mathcal{T}_0^{\mathrm{cut}}\right) \\ &\quad - \left[\frac{\mathrm{d}\sigma^{\mathrm{NNLL}'}}{\mathrm{d}\Phi_0 \mathrm{d}\mathcal{T}_0}\mathcal{P}(\Phi_1)\right]_{\mathrm{NLO}_1}\theta\left(\mathcal{T}_0 > \mathcal{T}_0^{\mathrm{cut}}\right) \\ &\quad + (B_1 + V_1)(\Phi_1)\,\theta\left(\mathcal{T}_0(\Phi_1) > \mathcal{T}_0^{\mathrm{cut}}\right) \\ &\quad + \int \frac{\mathrm{d}\Phi_2}{\mathrm{d}\Phi_1^{\mathcal{T}}}\,B_2(\Phi_2)\,\theta\left(\mathcal{T}_0(\Phi_2) > \mathcal{T}_0^{\mathrm{cut}}\right)\end{aligned}$$

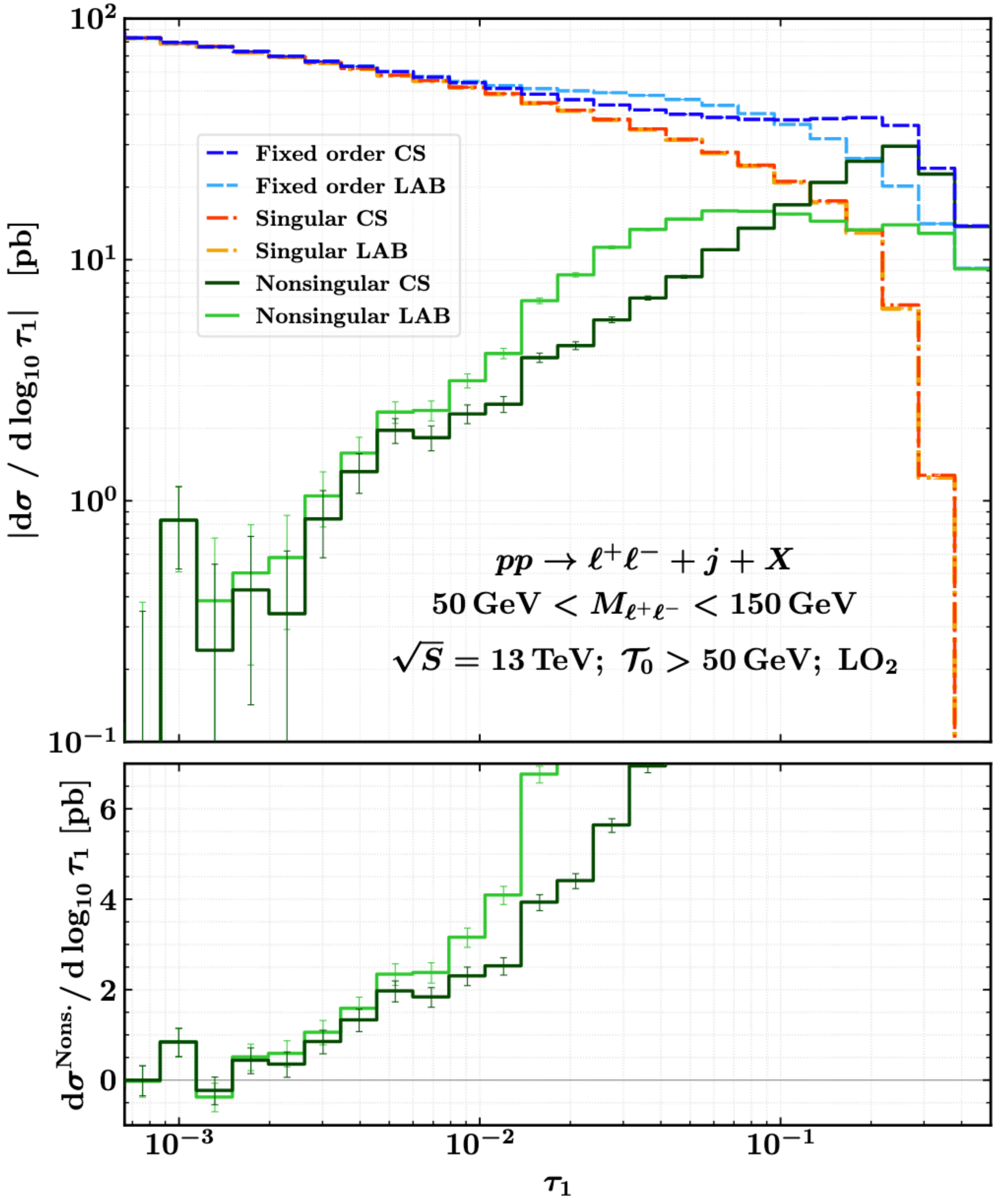
$$\int \frac{\mathrm{d}\Phi_1}{\mathrm{d}\Phi_0 \mathrm{d}\mathcal{T}_0}\,\mathcal{P}(\Phi_1) = 1$$

$$\mathcal{T}_0(\Phi_1^{\mathcal{T}}(\Phi_2)) = \mathcal{T}_0(\Phi_2)$$

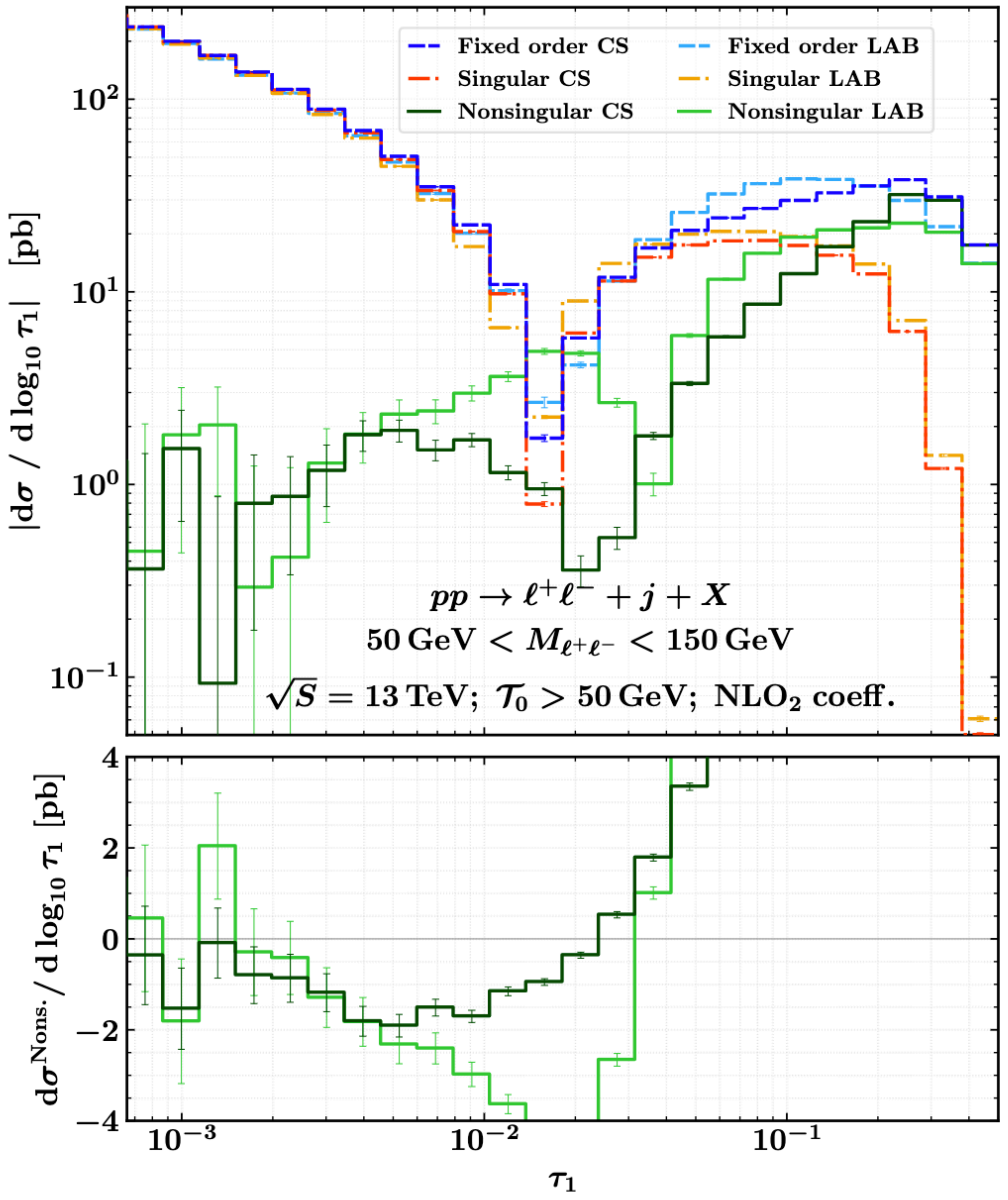

NNLOJET
pp→γ+jet
√s=13 TeV
LO
NLO
NNLO
ATLAS
p_T^γ
NNPDF40_nnlo_as_01180
$\mu_F=\mu_R=p_T^\gamma$, $\mu_A=m_{cone}$
p_T^γ>125 GeV, $|\eta_\gamma|$<2.37, [1.37,1.56] excl.
p_T^{jet}>100 GeV, $|y_{jet}|$<2.37 $\Delta R_{\gamma jet}$=0.8
$d\sigma/dp_T^\gamma$ [pb/GeV]
Ratio to NLO
p_T^γ [GeV]



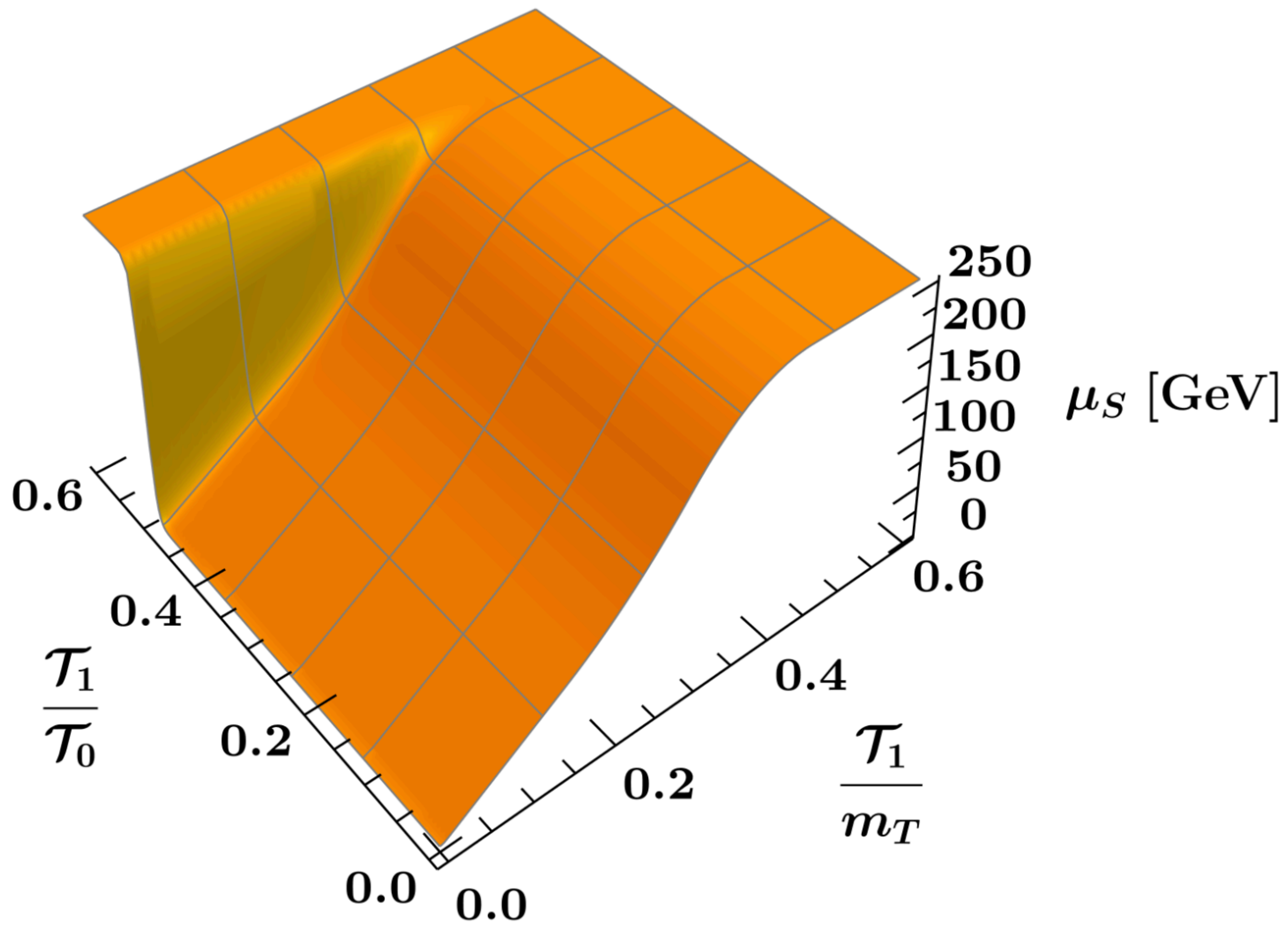
$\delta\mathcal{H}^{(2)}_{N_c}$
$\delta\mathcal{H}^{(2)}_{N_f}$
$\delta\mathcal{H}^{(2)}_{\tilde{N}_f}$
$\delta\mathcal{H}^{(2)}$
$\mathcal{H}^{(2),\text{Catani}}_{u\bar{u}\to\gamma\gamma\gamma}$
Number of points
Fraction of points
Correction relative to $\mathcal{H}^{(2)}_{\text{l.c.}}$
16000
14000
12000
10000
8000
6000
4000
2000
0
0.16
0.14
0.12
0.10
0.08
0.06
0.04
0.02
0.00
−1.00
−0.75
−0.50
−0.25
0.00
0.25
0.50
0.75
1.00



Fixed order CS
Fixed order LAB
Singular CS
Singular LAB
Nonsingular CS
Nonsingular LAB
$pp \to \ell^+\ell^- + j + X$
$50\,\mathrm{GeV} < M_{\ell^+\ell^-} < 150\,\mathrm{GeV}$
$\sqrt{S} = 13\,\mathrm{TeV};\ \mathcal{T}_0 > 50\,\mathrm{GeV};\ \mathrm{LO}_2$
$|\mathrm{d}\sigma\ /\ \mathrm{d}\log_{10}\tau_1|\quad[\mathrm{pb}]$
$\mathrm{d}\sigma^{\mathrm{Nons.}}/\,\mathrm{d}\log_{10}\tau_1\ [\mathrm{pb}]$
τ_1



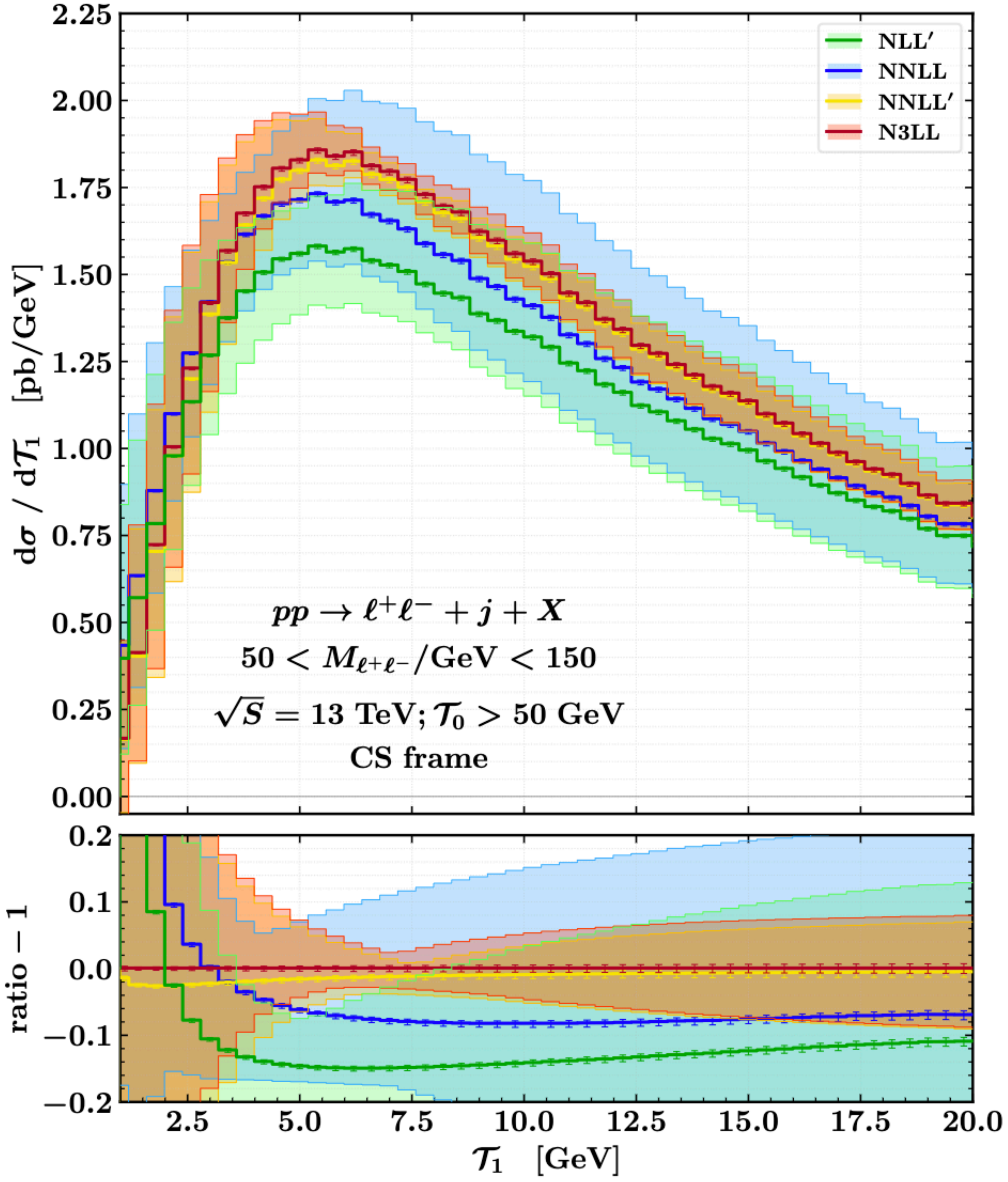
Fixed order CS
Singular CS
Nonsingular CS
Fixed order LAB
Singular LAB
Nonsingular LAB
$pp \to \ell^+\ell^- + j + X$
$50\,\mathrm{GeV} < M_{\ell^+\ell^-} < 150\,\mathrm{GeV}$
$\sqrt{S} = 13\,\mathrm{TeV};\ \mathcal{T}_0 > 50\,\mathrm{GeV};\ \mathrm{NLO}_2\ \mathrm{coeff.}$
$|\mathrm{d}\sigma\ /\ \mathrm{d}\log_{10}\tau_1|\quad[\mathrm{pb}]$
$\mathrm{d}\sigma^{\mathrm{Nons.}}/\,\mathrm{d}\log_{10}\tau_1\ [\mathrm{pb}]$
τ_1

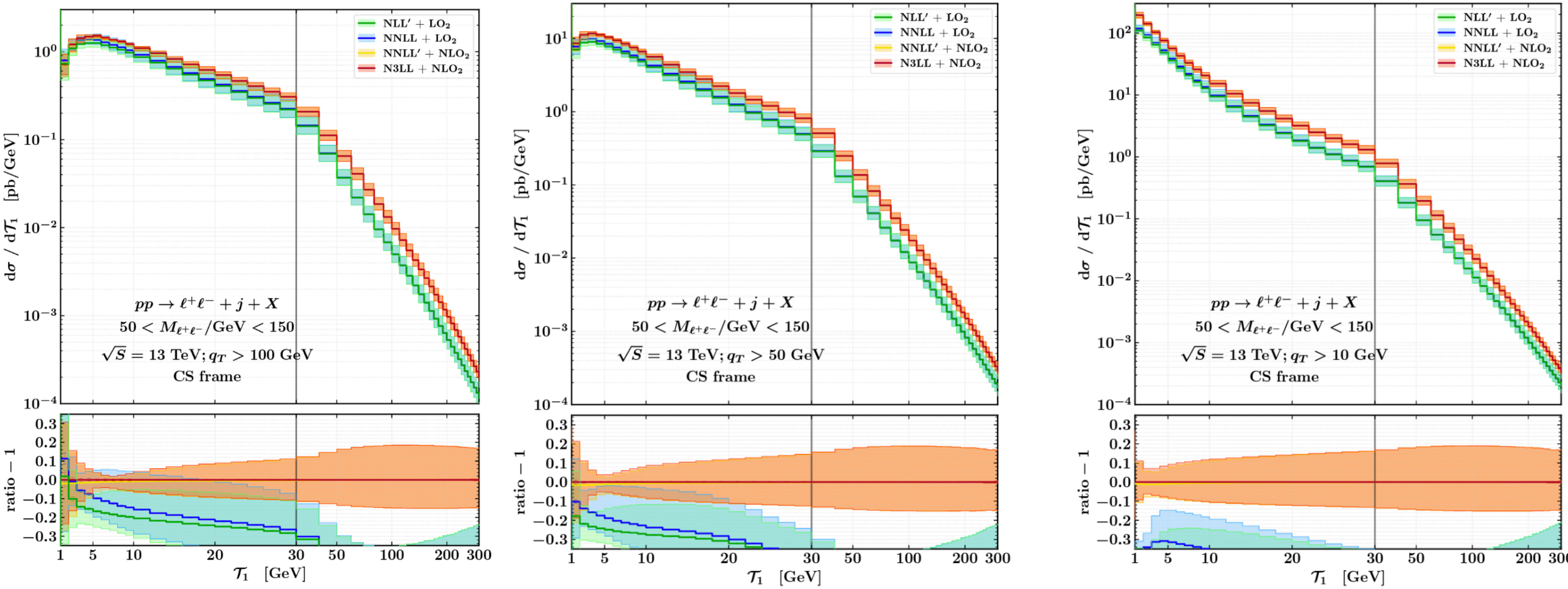


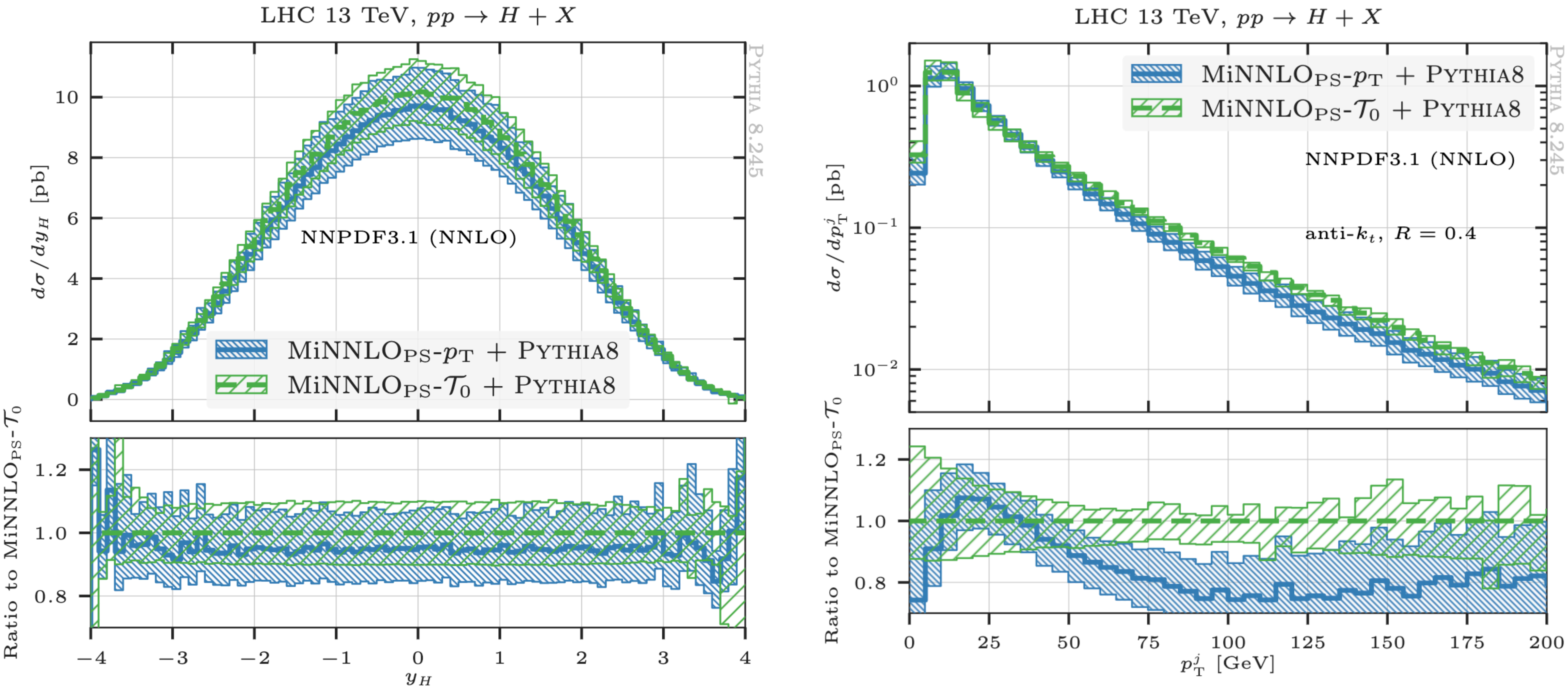
$$\frac{\mathcal{T}_1(\Phi_N)}{\mathcal{T}_0(\Phi_N)} \leq \frac{N-1}{N} = \begin{cases} 1/2\,, & N=2 \\ 2/3\,, & N=3 \end{cases}$$

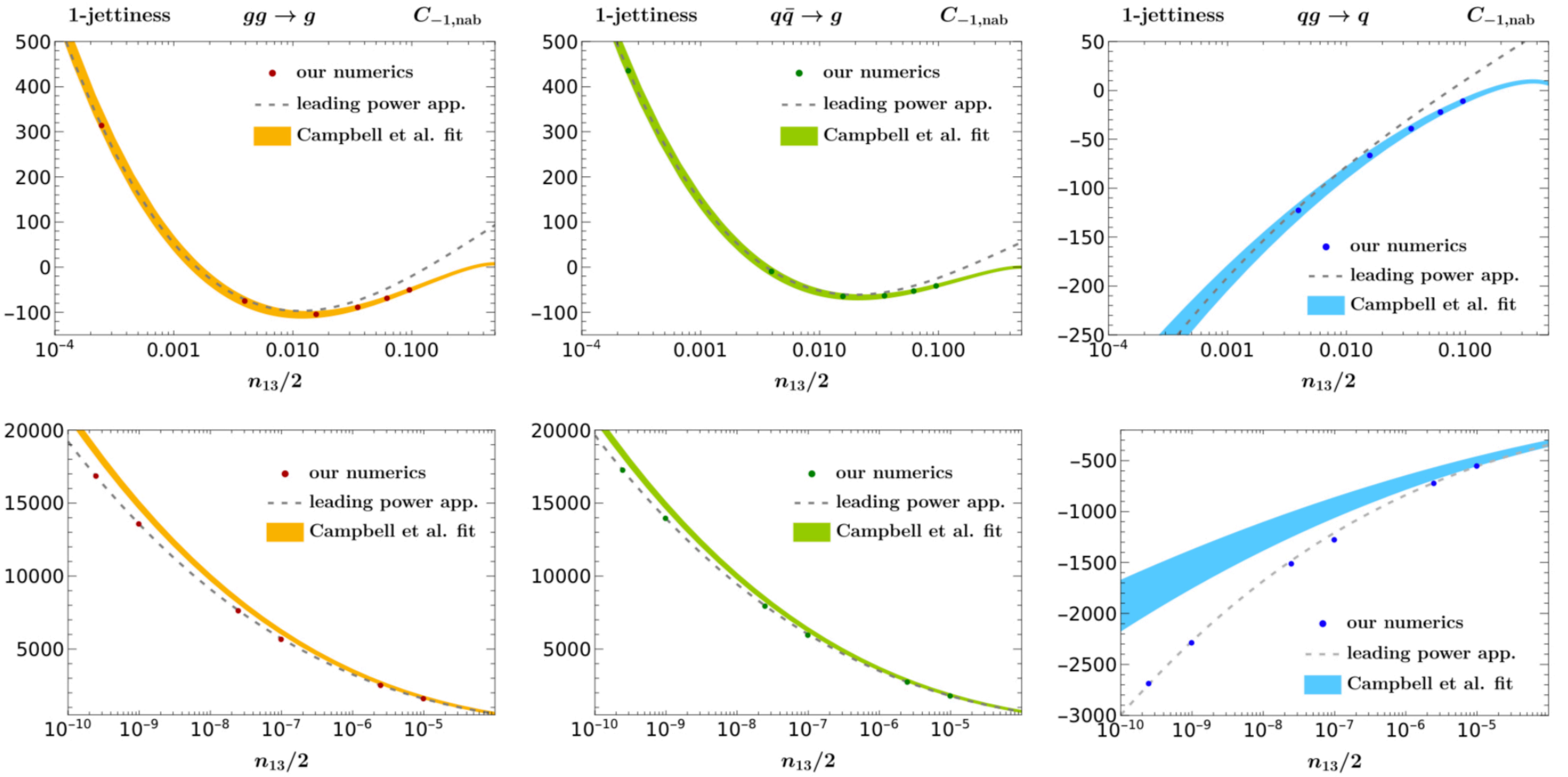
$$\mu_S(\mathcal{T}_1 \ll \mu_{\rm FO}) \sim \mathcal{T}_1\,,$$
$$\mu_S(\mathcal{T}_1 \sim \mu_{\rm FO}) \sim \mu_{\rm FO}\,,$$
$$\mu_S\big(\mathcal{T}_1/\mathcal{T}_0 \sim (N-1)/N\big) \sim \mu_{\rm FO}\,.$$

$$\mu_B(\mathcal{T}_1/\mu_{\rm FO}, \mathcal{T}_1/\mathcal{T}_0) = \sqrt{\mu_{\rm FO}\mu_S(\mathcal{T}_1/\mu_{\rm FO}, \mathcal{T}_1/\mathcal{T}_0)}\,,$$
$$\mu_J(\mathcal{T}_1/\mu_{\rm FO}, \mathcal{T}_1/\mathcal{T}_0) = \sqrt{\mu_{\rm FO}\mu_S(\mathcal{T}_1/\mu_{\rm FO}, \mathcal{T}_1/\mathcal{T}_0)}\,,$$
$$\mu_H = \mu_{\rm FO} = m_T \equiv \sqrt{m^2_{\ell^+\ell^-} + q_T^2}\,.$$


NLL′
NNLL
NNLL′
N3LL
$pp \to \ell^+\ell^- + j + X$
$50 < M_{\ell^+\ell^-}/\text{GeV} < 150$
$\sqrt{S} = 13$ TeV; $\mathcal{T}_0 > 50$ GeV
CS frame
$d\sigma / d\mathcal{T}_1$ [pb/GeV]
ratio − 1
$\mathcal{T}_1$ [GeV]


NLL′ + LO₂
NNLL + LO₂
NNLL′ + NLO₂
N3LL + NLO₂
$pp \to \ell^+\ell^- + j + X$
$50 < M_{\ell^+\ell^-}/\text{GeV} < 150$
$\sqrt{S} = 13$ TeV; $q_T > 100$ GeV
CS frame
$d\sigma / d\mathcal{T}_1$ [pb/GeV]
ratio − 1
$\mathcal{T}_1$ [GeV]
$\sqrt{S} = 13$ TeV; $q_T > 50$ GeV
$\sqrt{S} = 13$ TeV; $q_T > 10$ GeV


LHC 13 TeV, $pp \to H + X$
NNPDF3.1 (NNLO)
MiNNLO$_{PS}$-p_T + PYTHIA8
MiNNLO$_{PS}$-$\mathcal{T}_0$ + PYTHIA8
PYTHIA 8.245
$d\sigma/dy_H$ [pb]
Ratio to MiNNLO$_{PS}$-$\mathcal{T}_0$
y_H
LHC 13 TeV, $pp \to H + X$
anti-k_t, $R = 0.4$
$d\sigma/dp_T^j$ [pb]
p_T^j [GeV]


1-jettiness
$gg \to g$
$C_{-1,\text{nab}}$
1-jettiness
$q\bar{q} \to g$
$C_{-1,\text{nab}}$
1-jettiness
$qg \to q$
$C_{-1,\text{nab}}$
our numerics
leading power app.
Campbell et al. fit
$n_{13}/2$