Power corrections for jet processes

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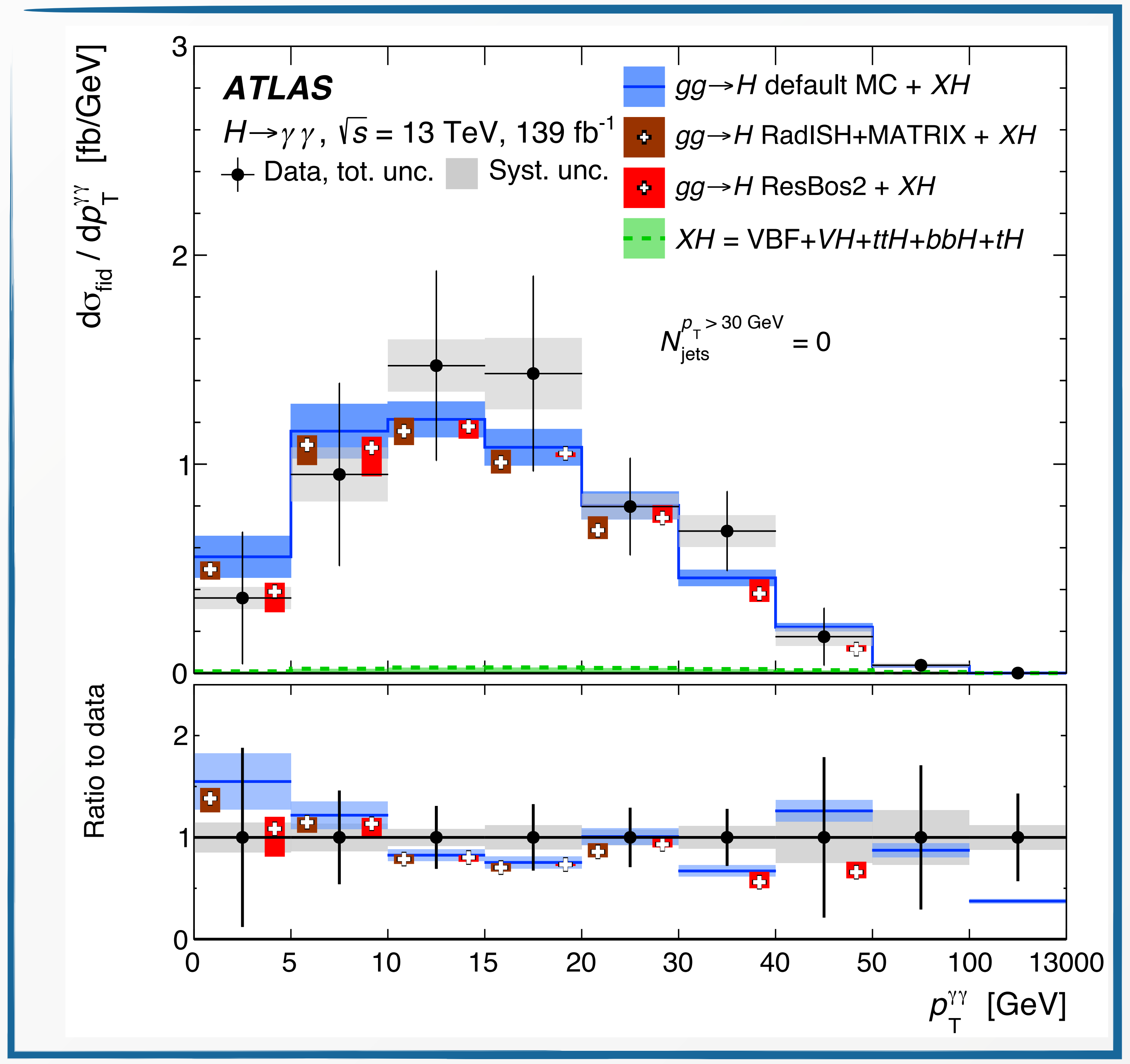
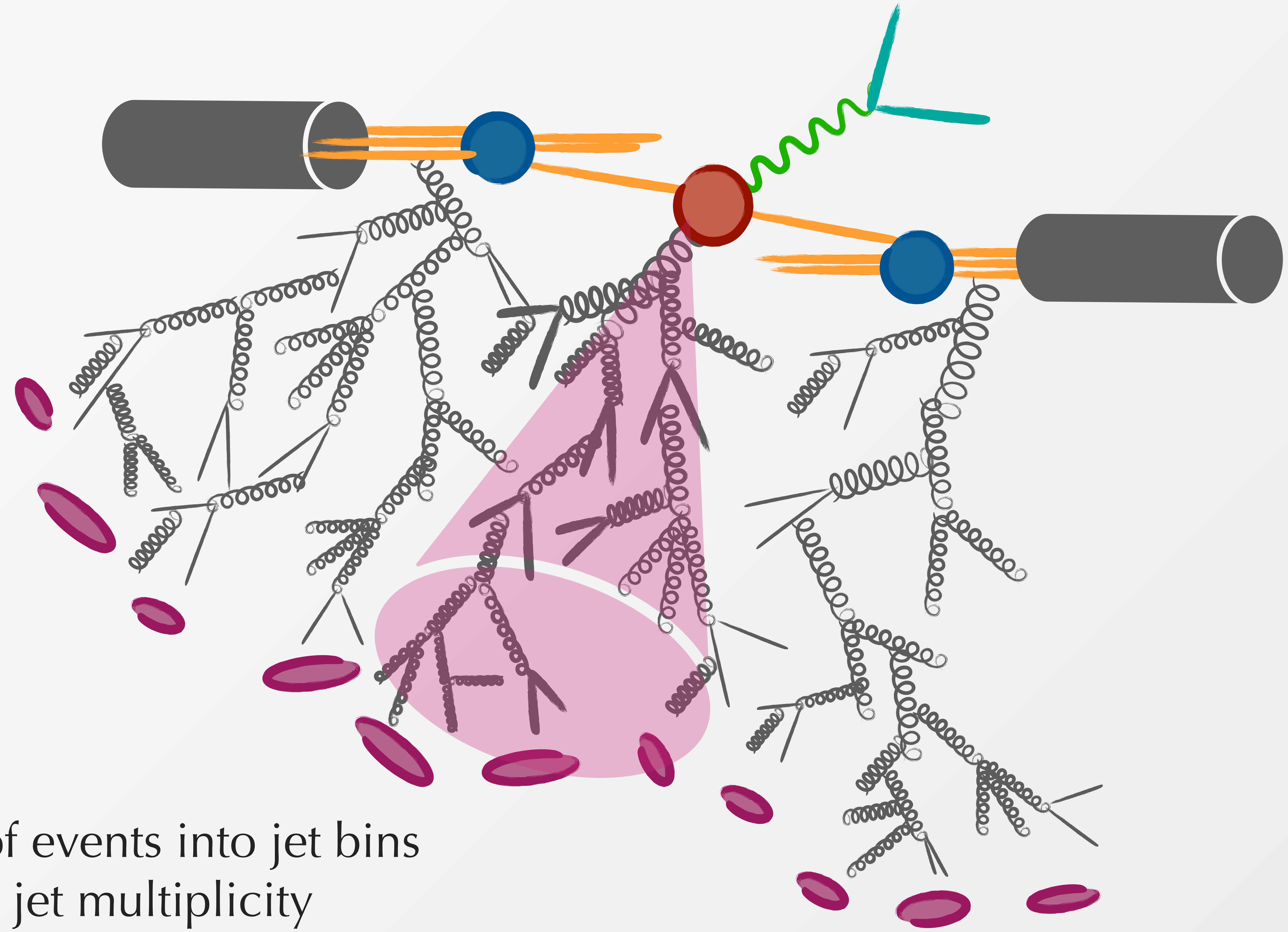
Precision physics at the LHC

- Precise description of LHC collisions requires a profound understanding of QCD needed across a **wide range of energy scales** and **kinematic domains**

- Processes with **jets at lowest order**: **essential** for LHC physics (more differential information), but **much more complex**



[ATLAS 2202.00487]



Categorization of events into jet bins according to the jet multiplicity

E.g. $pp \to H + X$: **enhanced sensitivity** to Higgs boson kinematics, spin-CP properties, BSM effects…

Fixed-order calculations

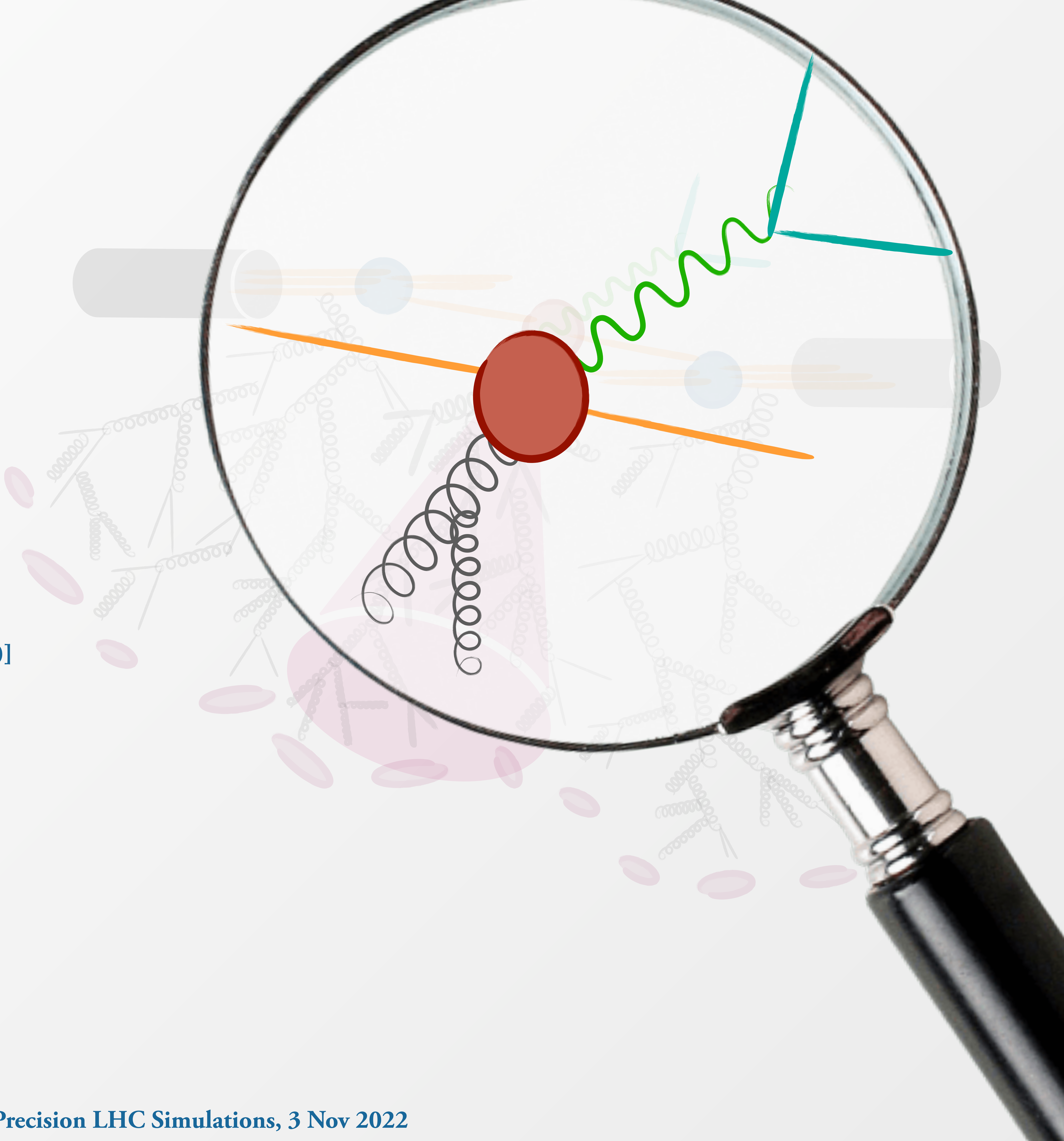
- **Complex singularity structure** for processes with one or more jets

- Fixed order calculations at NNLO accuracy require efficient subtraction methods to extract and cancel virtual and real singularities

- $V + j$ NNLO calculations available with local and non-local subtraction methods
  [Caola, Melnikov, Schulze]
  [Chen, Gehrmann, Gehrmann-De Ridder, Glover, Huss + others (NNLOJET)]
  [Boughezal, Campbell, Ellis, Focke, Giele, Liu, Petriello, Williams]

- $pp \to 2j$ and even $pp \to 3j$ recently computed
  [H.Chawdhry, M.Czakon, A.Mitov, R.Poncelet] ($pp \to 2j$ and $pp \to 3j$)
  [NNLOJET] ($pp \to 2j$)

- **Computationally expensive** (100k-1M CPU hours); **no public code** available (yet)

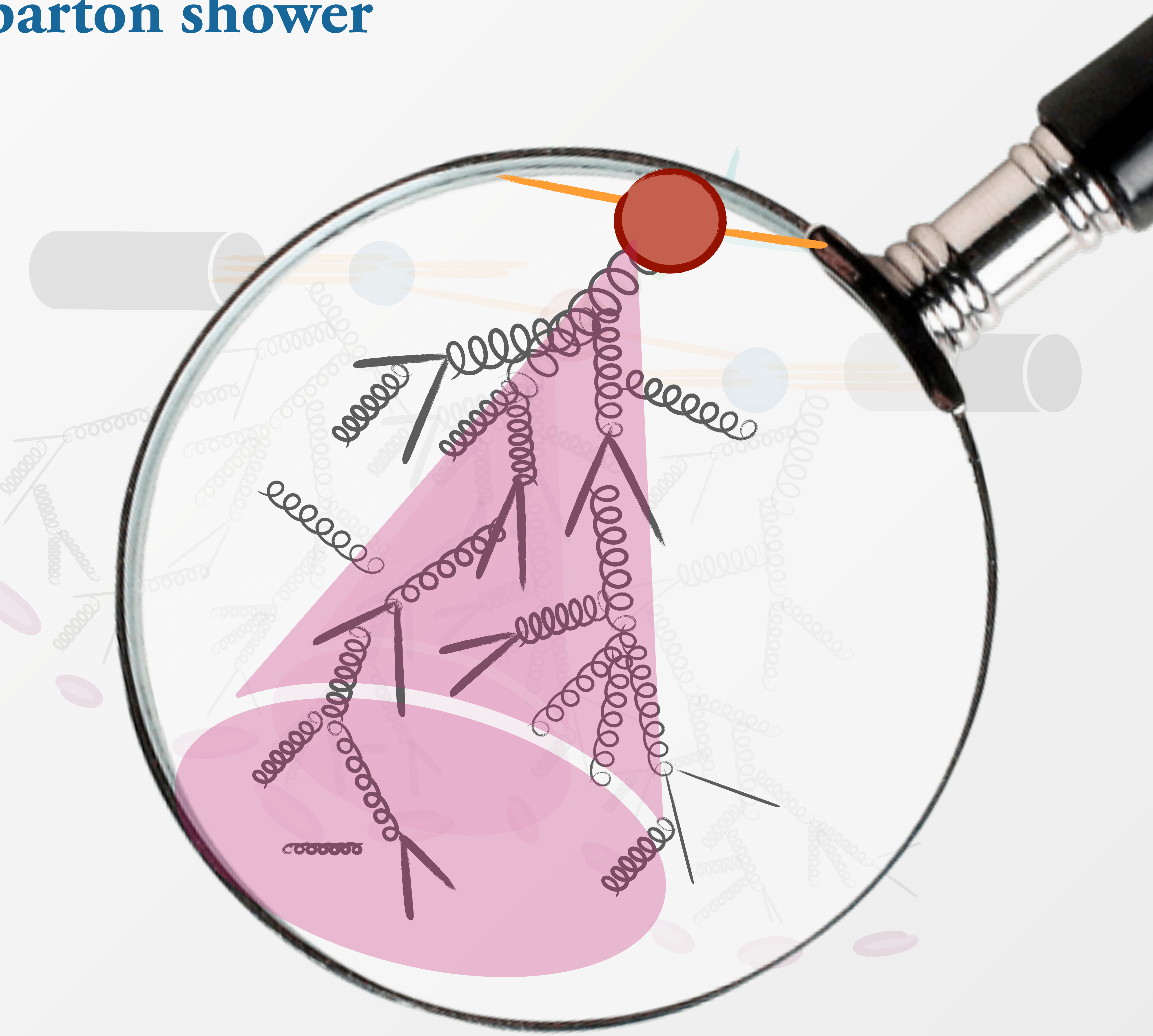


All-order calculations and matching to parton shower

- Resummation structure for jet observables complicated by the presence of **multiple emitters**

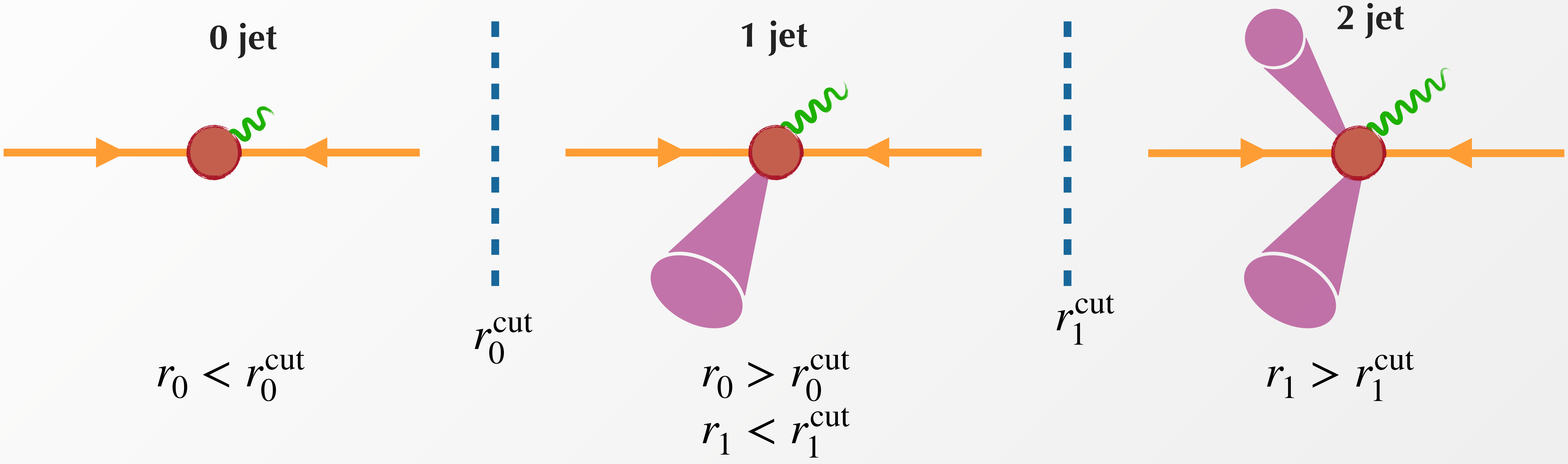
- Ingredients to reach NNLL accuracy available only for a few selected observables with three or more coloured legs
  [Bonciani, Catani, Grazzini, Sargsyan, Torre, Devoto, Mazzitelli, Kallweit]($t\bar{t}$)
  [Arpino, Banfi, El-Menoufi](three jet rate)
  [Jouttenus, Stewart, Tackmann, Waalewijn](jet mass)
  [Becher, Garcia I Tormo, Piclum](transverse thrust in pp collisions)
  [Chien, Rahn, Schrijnder van Velzen, Shao, Waalewijn, Wu]

- Matching of NNLO calculations with parton shower requires the knowledge of the same ingredients entering at NNLL′ for a **suitable resolution variable** which captures the singularities of the $N \to N+1$ (partonic) jet transition



Jet resolution variables

Resolution variable r smoothly captures the transition from N to $N+1$ configurations



$0 \to 1$ jet transition: p_T^{veto}, q_T, 0-jettiness τ_0

$1 \to 2$ jet transition: two-jet resolution parameter y_{12}, 1-jettiness τ_1

Caveat: the definition of the resolution variable may or may not depend on the jet definition

Jet resolution variables and slicing

Resolution variable r can be used to discriminate a region with **1-resolved emission** from an **unresolved** region

$$\sigma_{\mathrm{N^kLO}} = \int d\sigma_{\mathrm{N^kLO}} \Theta(r_{\mathrm{cut}} - r) + \int d\sigma^{R}_{\mathrm{N^{k-1}LO}} \Theta(r - r_{\mathrm{cut}})$$

In the unresolved region the cross section can be approximated by an expansion in the soft-collinear limits (**factorisation theorems** in EFT, expansion of a **resummed computation**)

$$\int d\sigma_{\mathrm{N^kLO}} \Theta(r_{\mathrm{cut}} - r) = \int d\sigma^{\mathrm{sing}}_{\mathrm{N^kLO}} \Theta(r_{\mathrm{cut}} - r) + \mathcal{O}(r^{\ell}_{\mathrm{cut}}) = \mathcal{H} \otimes d\sigma_{LO} - \int d\sigma^{CT}_{\mathrm{N^kLO}} \Theta(r - r_{\mathrm{cut}}) + \mathcal{O}(r^{\ell}_{\mathrm{cut}})$$

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Virtual correction after subtraction of IR singularities and contribution of soft/collinear origin **(beam, soft, jet functions)**

$$\int d\sigma_{\mathrm{N^kLO}} = \mathscr{H} \otimes d\sigma_{LO} + \int \left[d\sigma^{R}_{\mathrm{N^{k-1}LO}} - d\sigma^{CT}_{\mathrm{N^kLO}} \right]_{r > r_{\mathrm{cut}}} + \mathcal{O}(r^{\ell}_{\mathrm{cut}})$$

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Counterterm cancels the infrared behaviour of the real calculation in the limit $X_{\mathrm{cut}} \to 0$

$$\int d\sigma_{\mathrm{N^kLO}} = \mathscr{H} \otimes d\sigma_{LO} + \int \left[d\sigma^{R}_{\mathrm{N^{k-1}LO}} - d\sigma^{CT}_{\mathrm{N^kLO}} \right]_{r > r_{\mathrm{cut}}} + \mathcal{O}(r^{\ell}_{\mathrm{cut}})$$

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Missing **power corrections** below the slicing cut-off

$$\int d\sigma_{\mathrm{N^kLO}} = \mathcal{H} \otimes d\sigma_{LO} + \int \left[d\sigma^{R}_{\mathrm{N^{k-1}LO}} - d\sigma^{CT}_{\mathrm{N^kLO}} \right]_{r > r_{\mathrm{cut}}} + \mathcal{O}(r^{\ell}_{\mathrm{cut}})$$

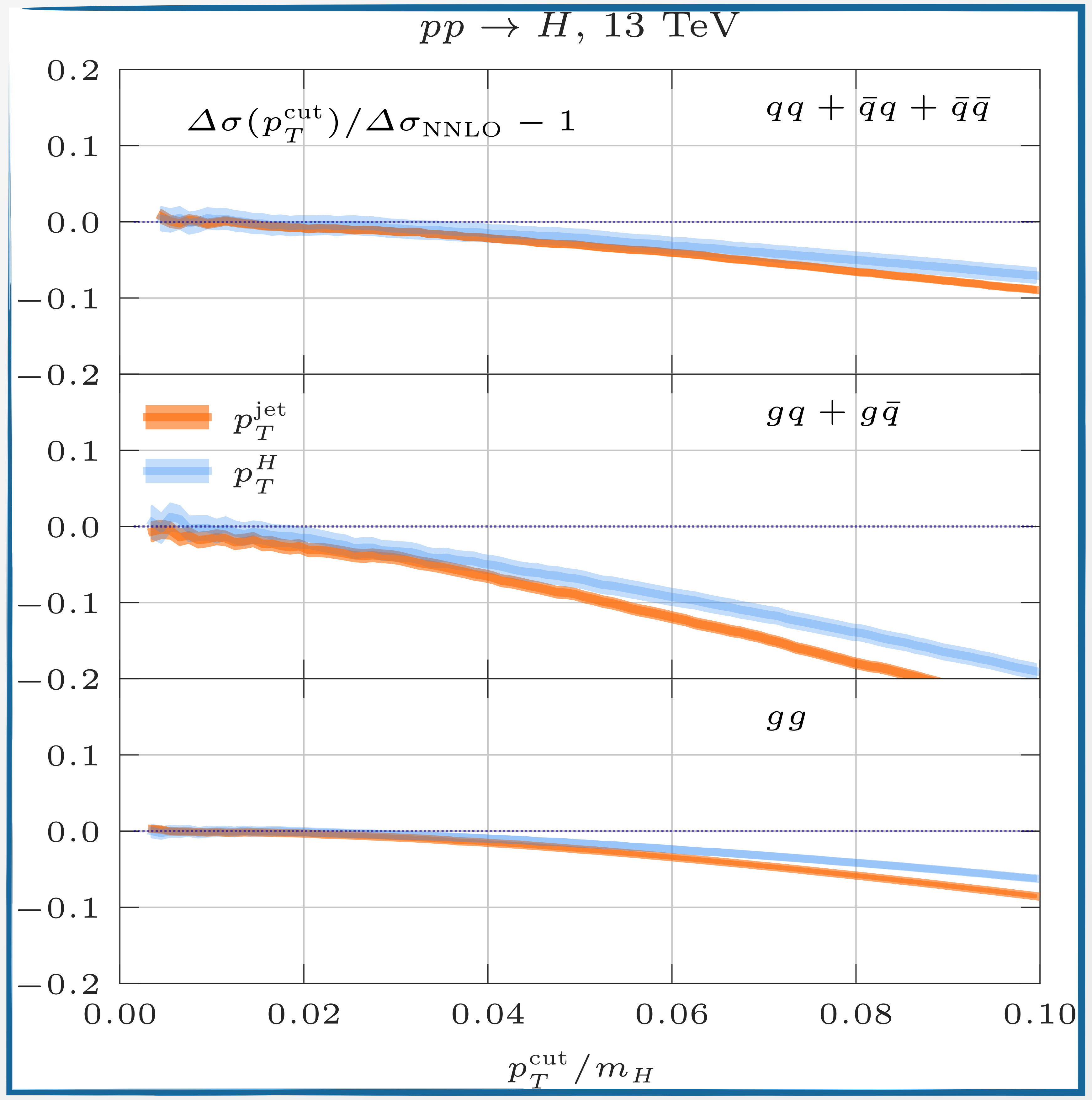
Jet resolution variables and higher-order computations

- p_T^{veto}, q_T, τ_0 are three well known variables able to **inclusively describe initial-state radiation**
- The knowledge of all $\mathcal{O}(\alpha_s^k)$ ingredients (anomalous dimensions and constant terms) allows for the formulation of non-local subtraction methods for QCD calculations at NNLO

[Catani, Grazzini][Gaunt, Stahlhofen, Tackmann, Walsh]

Ingredients at $\mathcal{O}(\alpha_s^2)$ have been known since some time for q_T, τ_0. Recently, also the $\mathcal{O}(\alpha_s^2)$ constant terms (**soft and beam functions**) for p_T^{veto} have been computed, allowing for the formulation of a slicing scheme based on p_T^{veto}

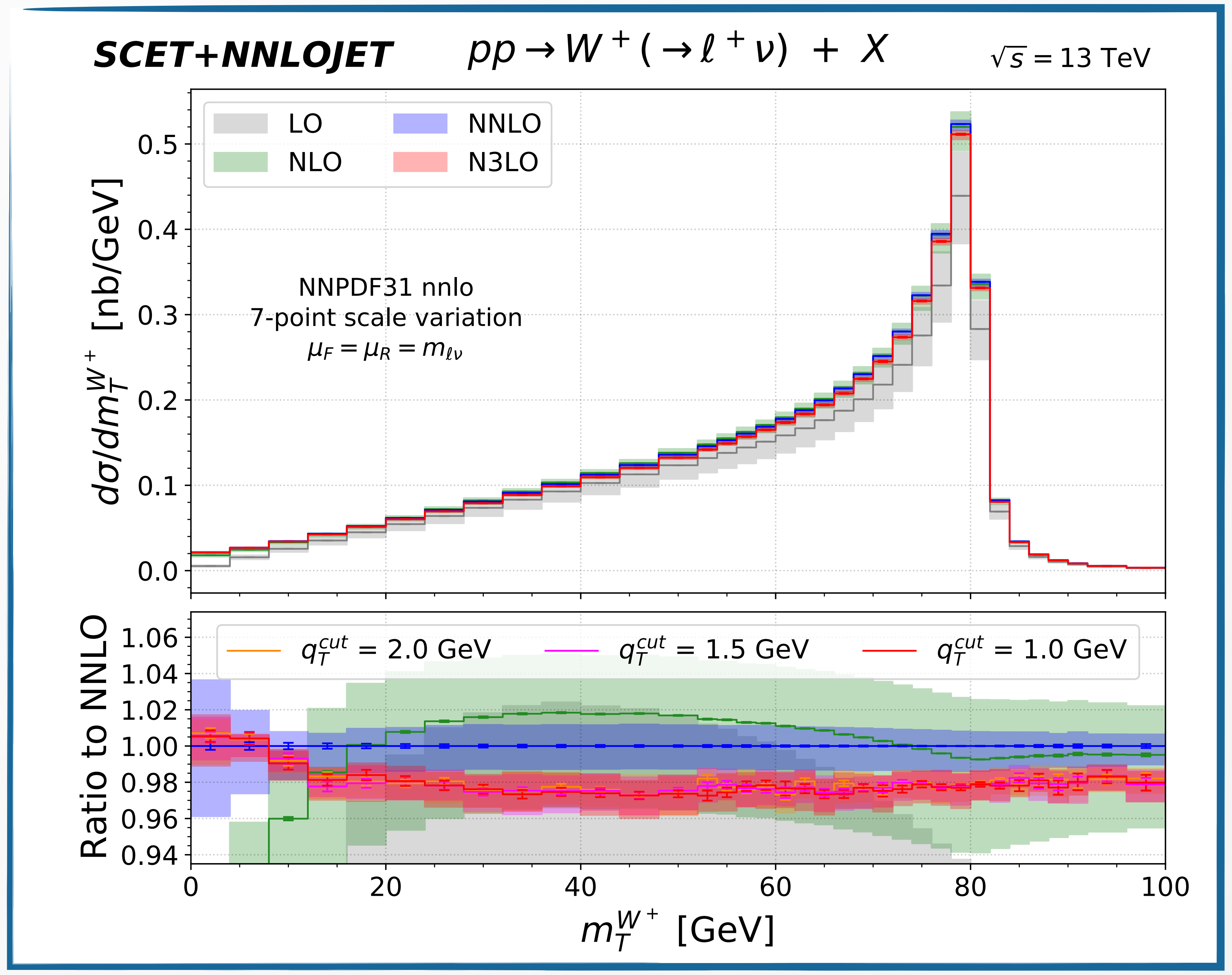
[Abreu, Gaunt, Monni, LR, Szafron]



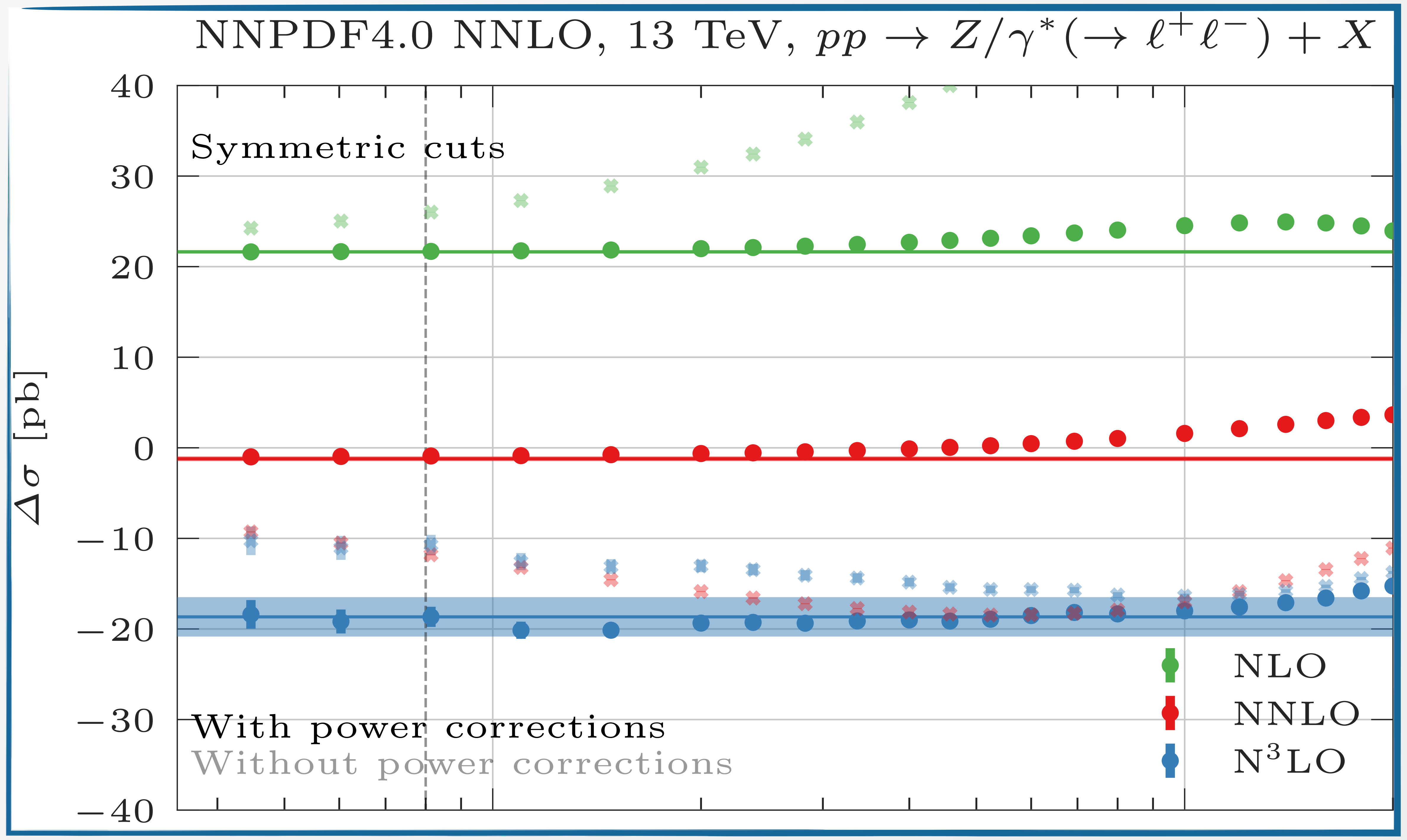
Jet resolution variables and higher-order computations

- Sensitivity to power corrections below the cut-off **depends on the observable** and affects the **performance** of the method

- q_T displays a **faster convergence** and generally guarantees a better performance. This (together with the availability of all $\mathcal{O}(\alpha_s^3)$ ingredients) allowed for pushing the q_T subtraction method at N³LO
[Billis, Dehnadi, Ebert, Michel, Tackmann '21][Chen, Gehrmann, Glover, Huss, Yang, Zhu '21, 22][Chen, Gehrmann, Glover, Huss, Monni, Re, LR, Torrielli '22][Camarda, Cieri, Ferrera '22][Neumann, Campbell '22]
- To reach higher accuracy it is fundamental to have **excellent control** of the relative size of the **power corrections**



[Chen, Gehrmann, Glover, Huss, Yang, Zhu '22]



[Chen, Gehrmann, Glover, Huss, Monni, Re, LR, Torrielli '22]

Slicing and power corrections

Naive counting of power corrections at order α_s

$$\int \frac{dr}{r}(A \log r + B) r^k \sim A_k r^k \log r + B_k r^k \qquad k \geq 1$$

Linear power corrections expected, with a **single logarithmic enhancement**

$$\mathcal{O}(r_{\text{cut}}^k \ln r_{\text{cut}}) \qquad\qquad \mathcal{O}(r_{\text{cut}}^k \ln^{2m-1} r_{\text{cut}})$$

NLO **N^{m}LO**

$$r = \tau_n, q_T/Q, p_T^{\text{veto}}/Q, \ldots$$

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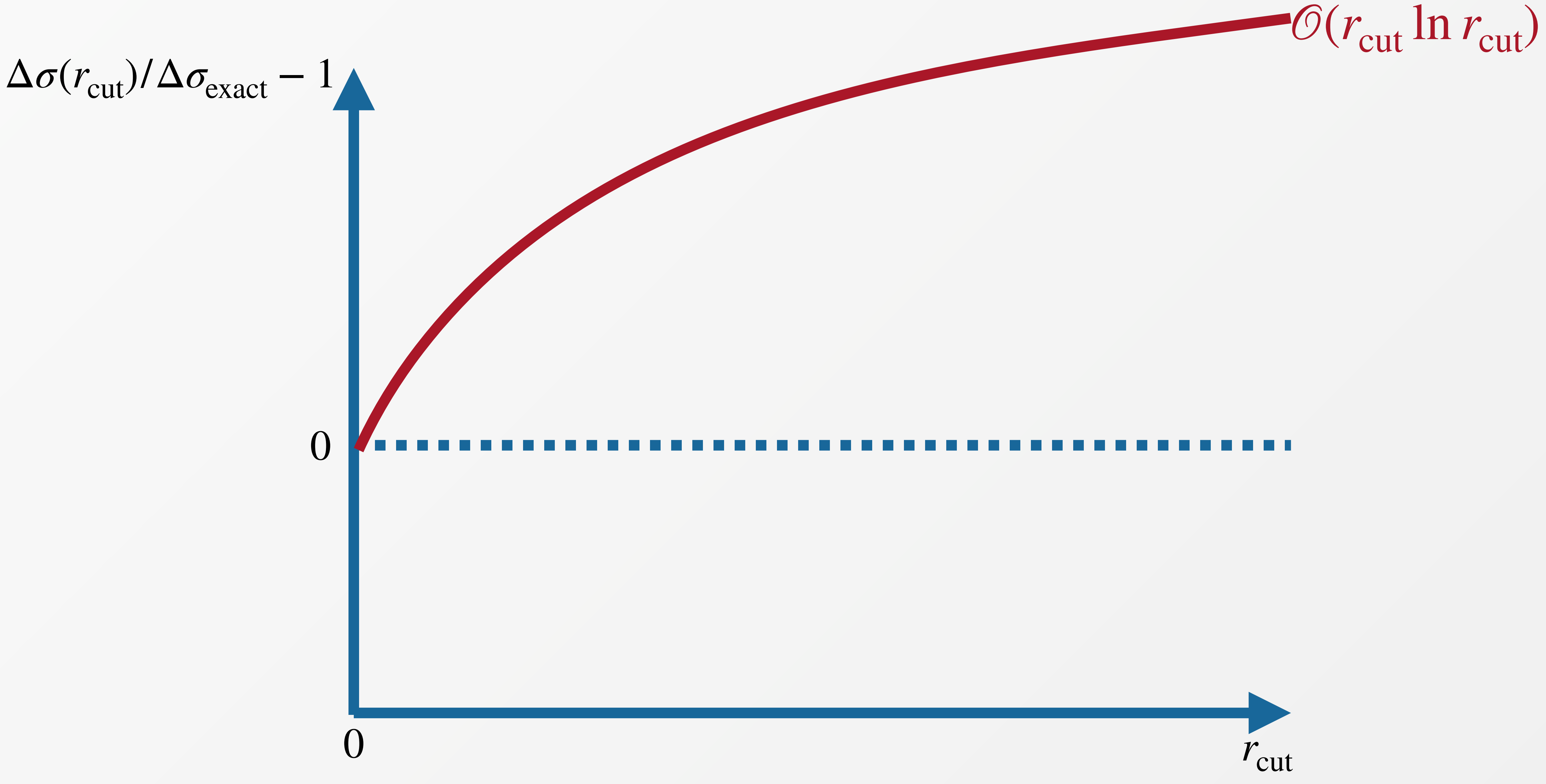
$\mathcal{O}(\alpha_s)$ correction

τ_n-subtraction



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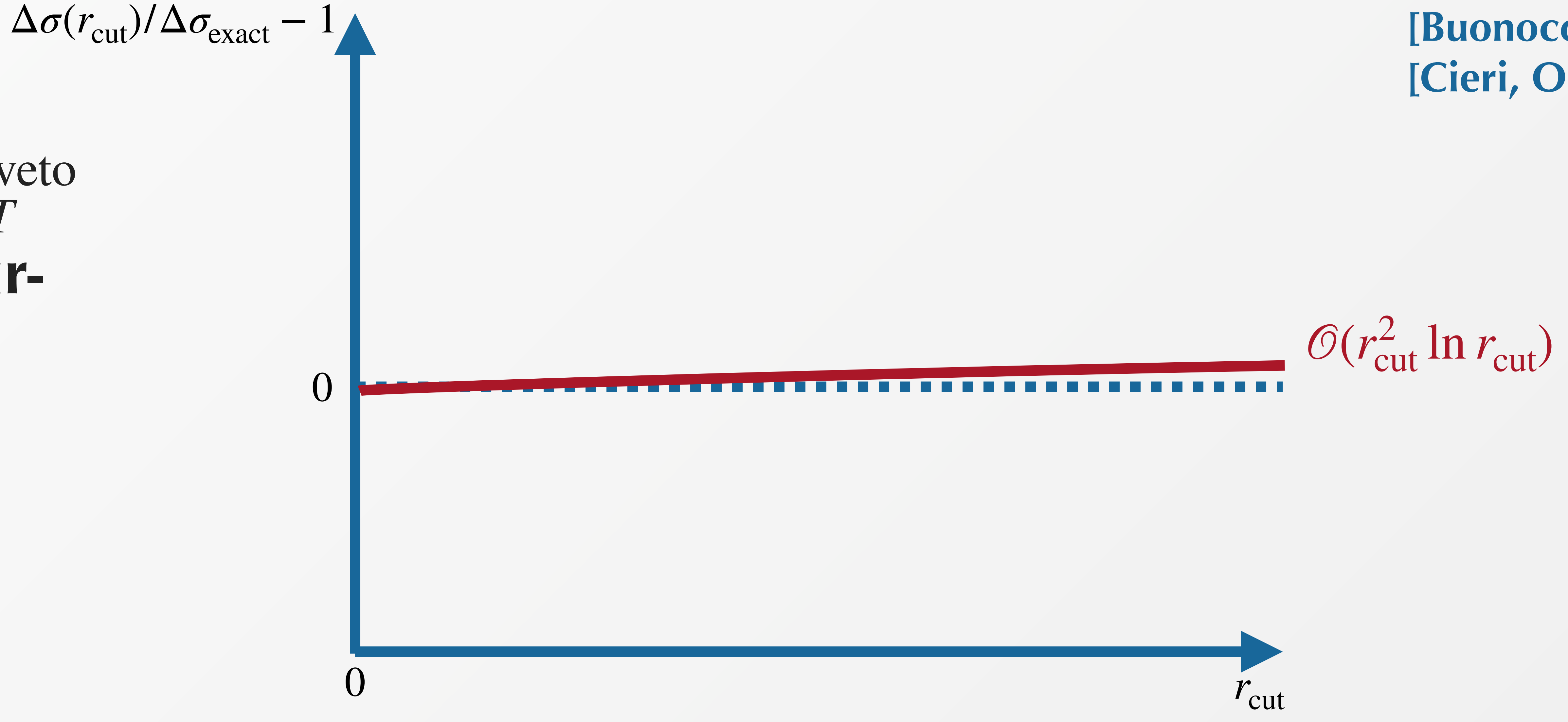
Naive counting of power corrections at order α_s

$$\int \frac{dr}{r}(A \log r + B) r^k \sim A_k r^k \log r + B_k r^k \qquad k \geq 1 \quad \Rightarrow \quad \begin{array}{c} A_k = 0, \quad B_k = 0 \\ k = 1,3,\ldots \end{array}$$

$\mathcal{O}(\alpha_s)$ correction



Odd powers are zero thanks to **azimuthal symmetry**

[Ebert, Moult, Stewart, Tackmann, Vita, Zhu]
[Buonocore, Grazzini, Tramontano]
[Cieri, Oleari, Rocco]

q_T-subtraction and p_T^{veto} subtraction for colour-singlet processes (no photons, no fiducial cuts)

Slicing and power corrections

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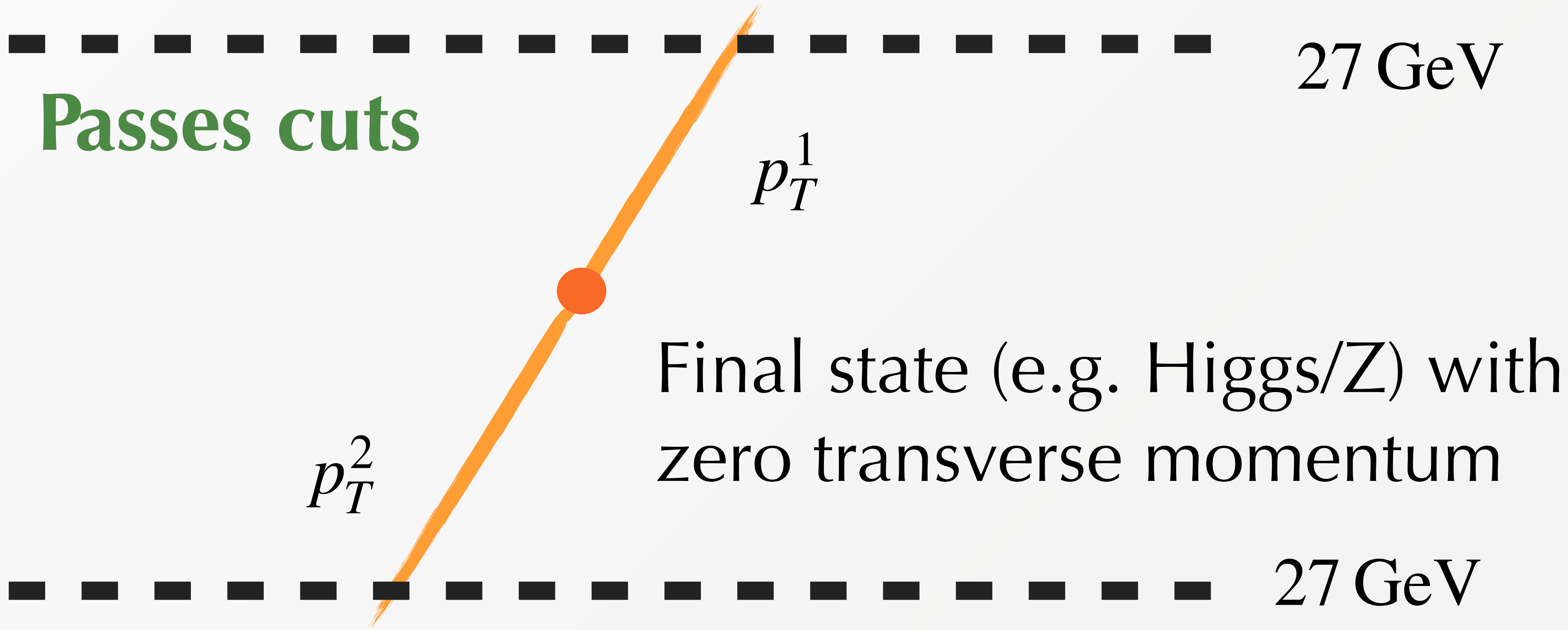
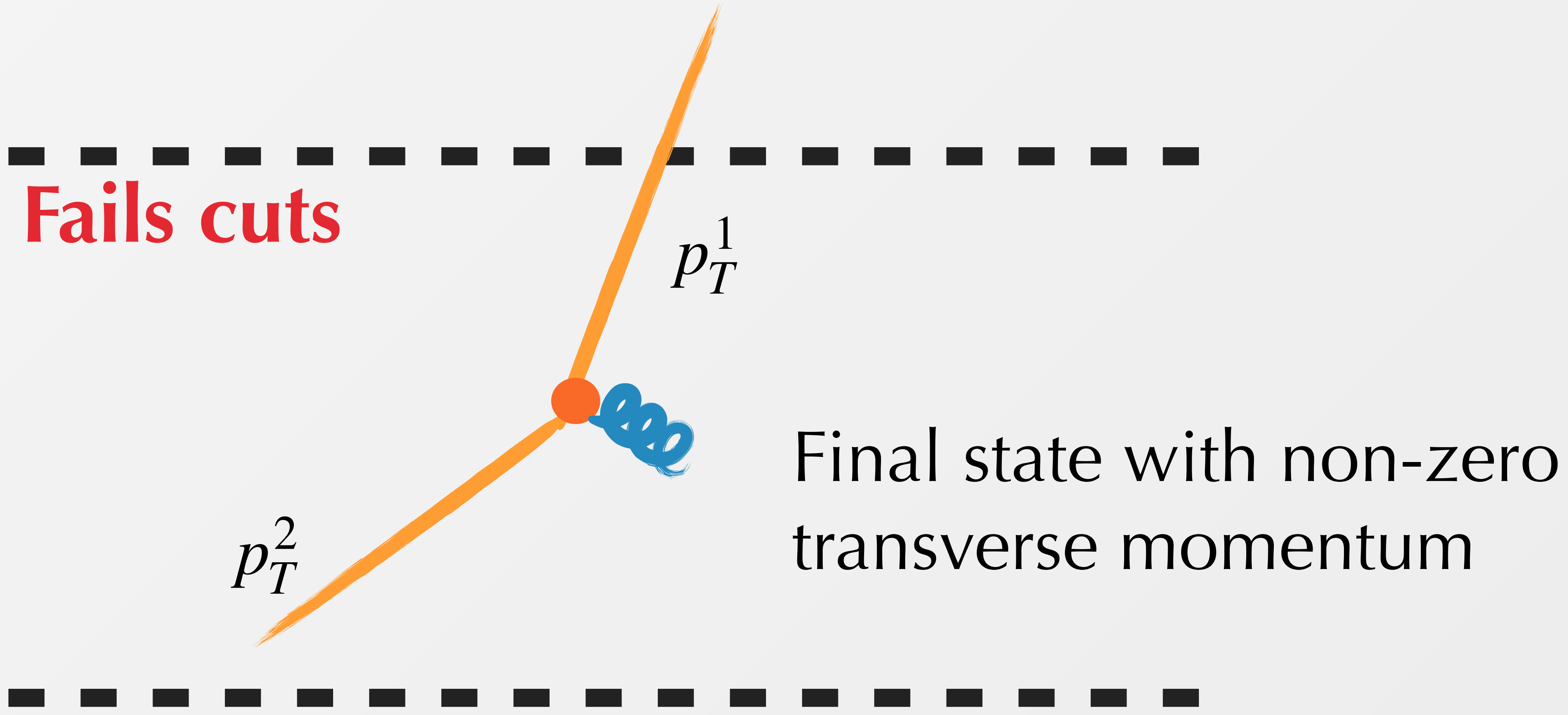
Definition of **fiducial cuts** can alter the behaviour of power corrections

Perturbative instability induced by sensitivity to **soft** radiation in configurations close to the back-to-back limit
[Klasen, Kramen '96][Harris, Owen '97][Frixione, Ridolfi '97]





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Definition of **fiducial cuts** can alter the behaviour of power corrections

$\mathcal{O}(\alpha_s)$ correction

q_T-subtraction for processes with symmetric/ asymmetric cuts on two-body final states

NB: These linear power corrections have a **purely kinematical origin** and can **be predicted by factorisation**

[Ebert, Michel, Stewart, Tackmann '20]

Slicing and power corrections

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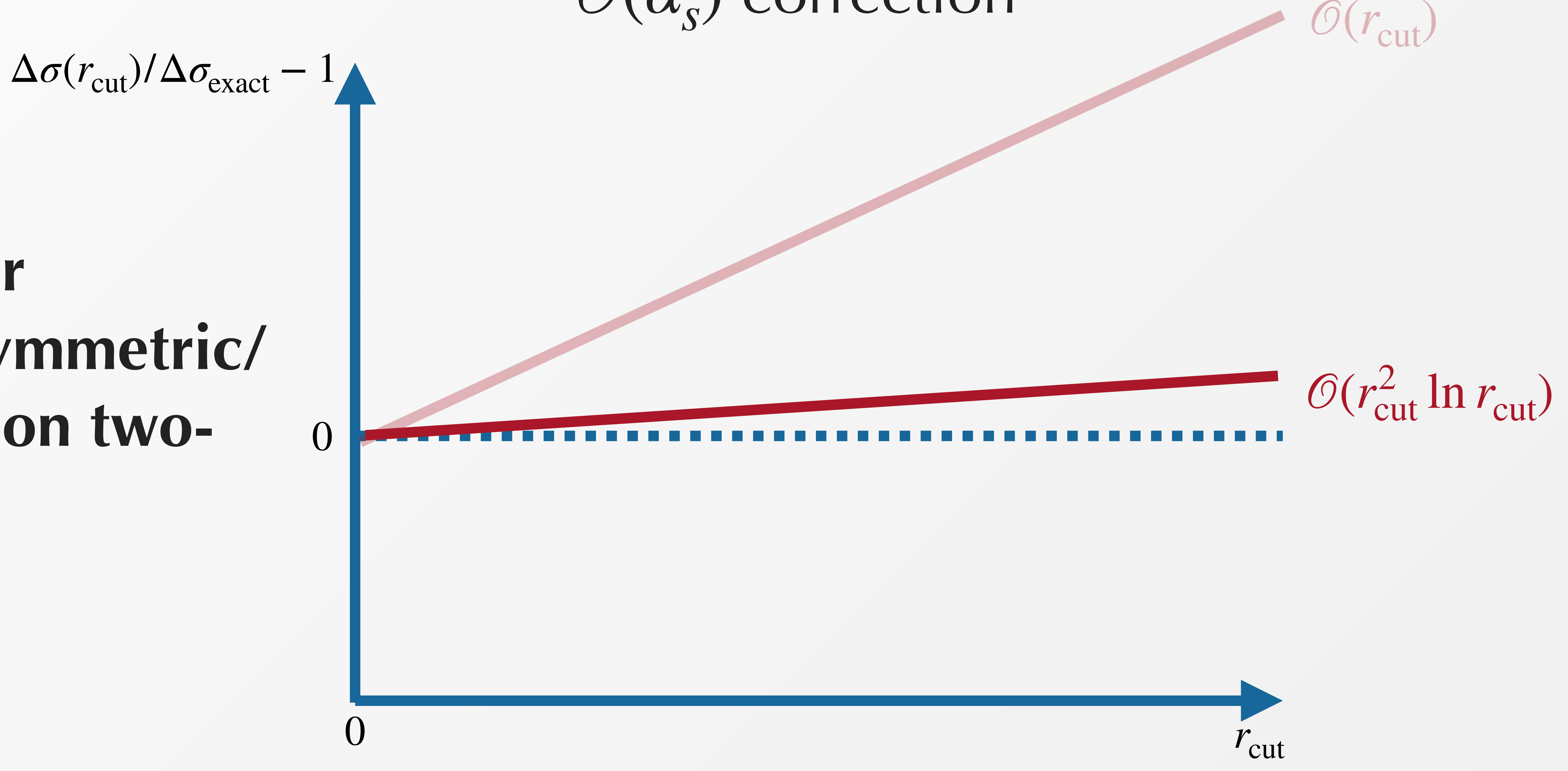


NB: These linear power corrections have a **purely kinematical origin** and can **be predicted by factorisation**

[Ebert, Michel, Stewart, Tackmann '20]

As such, they can be easily computed and taken care of

[Buonocore, Kallweit, LR, Wiesemann'21]
[Camarda, Cieri, Ferrera '21]

Slicing and power corrections

Naive counting of power corrections at order α_s

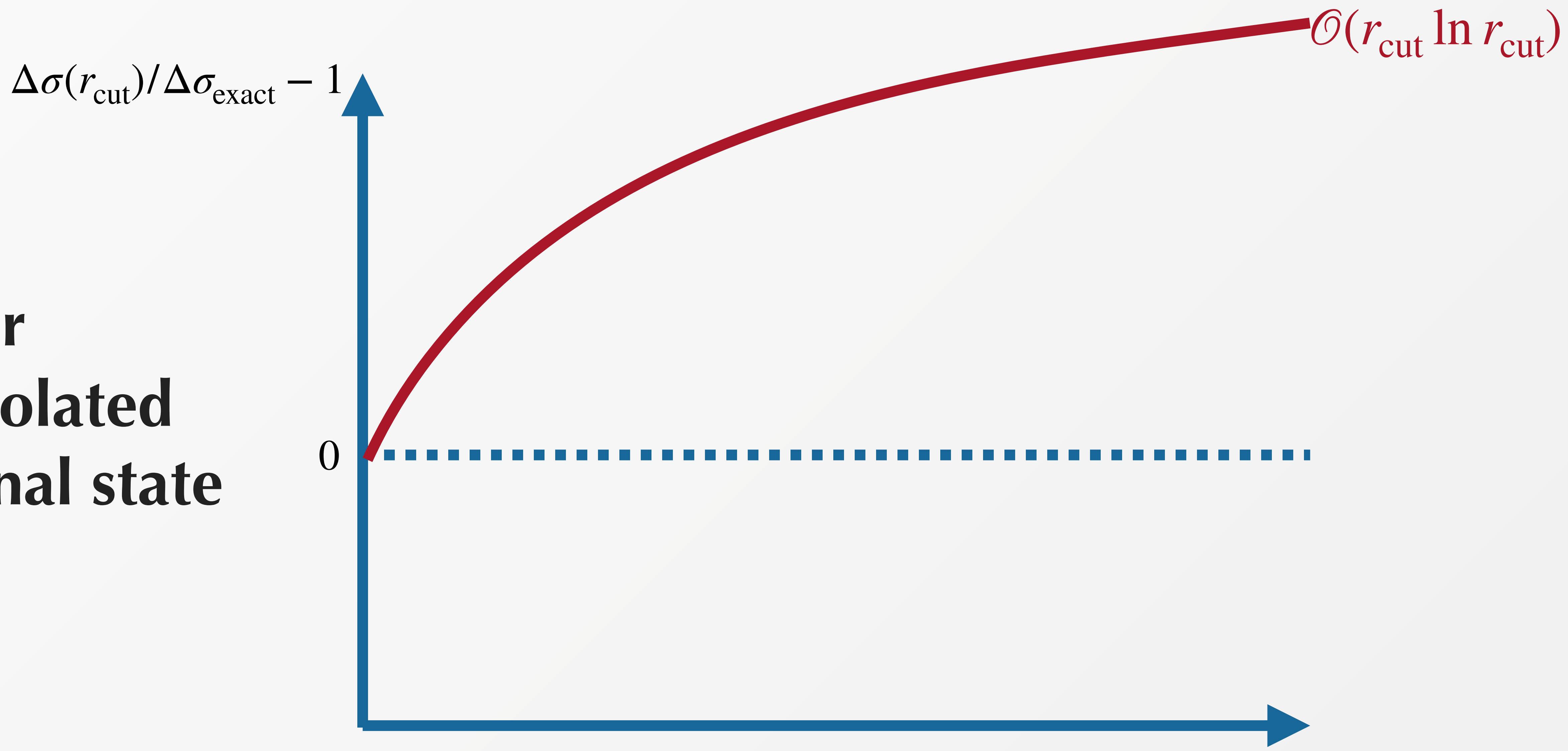
$$\int \frac{dr}{r}(A \log r + B) r^k \sim A_k r^k \log r + B_k r^k \qquad k \geq 1$$

$\rightarrow$ $\cancel{A_k = 0}, \quad \cancel{B_k = 0}$

$k = 1,3,\ldots$

Isolation requirements (processes with photons) can alter the behaviour of power corrections

q_T-subtraction for processes with isolated photons in the final state



Transverse observables for processes with jets

N-jettiness has proved a successful resolution variable for processes with 1 jet, but so far is essentially the only player in the game [Boughezal, Campbell, Ellis, Focke, Giele, Liu, Petriello, Williams]

It may prove worthwhile to explore other resolution variables which may have

- **smaller power corrections** → Applications to NNLO subtraction and beyond
- more **direct experimental relevance** → Comparison of resummed prediction with data
- simpler relation with parton shower ordering variables → Improved NNLO+PS matching

$k_T^{\rm ness}$: definition

[Buonocore, Grazzini, Haag, LR, Savoini]

Looking for a variable capable of capturing the $N \to N+1$ jet transition and such that

- is sensitive also to radiation emitted **collinear to any final state parton**
- for one emission, it reduces to an effective transverse momentum relative to the emitter parton in any collinear limit
- longitudinal boost invariant by inspection

The $k_T^{\rm ness}$ variable takes its name from the k_T clustering algorithm and is defined via a **recursive procedure**

For one extra emission, we define $k_T^{\rm ness}$ as

$$k_T^{\rm ness} = \min_{i,j \in \mathcal{J}_{N+1}} \{d_{iB}, d_{ij}\}, \quad d_{iB} = k_T^i, \quad d_{ij} = \min(k_T^i, k_T^i)\Delta R_{ij}/D$$

according to the distances of the k_T **jet algorithm**.

We can generalise the definition **to all-order emissions in a recursive way**:

1. run the k_T-algorithm up to a configuration $\mathcal{J}_{N+1}$ with N+1 jets
2. apply the above definition of $k_T^{\rm ness}$

$k_T^{\rm ness}$: definition

[Buonocore, Grazzini, Haag, LR, Savoini]

$k_T^{\rm ness}$ is by construction **infrared safe** and **global** and in the **0-jet case it is similar to the p_T^J observable.**

Its definition can be modified in a such way that in **the 0-jet case $k_T^{\rm ness}$ is similar to q_T**, i.e. an observable which displays azimuthal cancellation. In order to do so, **the recoil of the beam** must be taken into account

We have computed the singular structure in the limit $k_T^{\rm ness} \to 0$ at NLO to construct a **non-local subtraction**

$$d\hat{\sigma}^{\rm F+N\,jets+X}_{\rm NLO} = \mathscr{H}^{\rm F+N\,jets}_{\rm NLO} \otimes d\hat{\sigma}^{\rm F+N\,jets}_{\rm LO} + \left[d\hat{\sigma}^{\rm F+(N+1)\,jets}_{\rm LO} - d\hat{\sigma}^{\rm CT,F+Njets}_{\rm NLO} \right]$$

Computation of the relevant coefficients proceeds by identifying singular regions and removing the double counting

Structure of the counterterm **remarkably simple**

Radius used to define k_t-distances

$$\hat{\sigma}^{\rm CT,F+Njets}_{{\rm NLO}\,ab} = \frac{\alpha_s}{\pi} \frac{dk_t^{\rm ness}}{k_t^{\rm ness}} \Bigg\{ \left[\ln \frac{Q^2}{(k_t^{\rm ness})^2} \sum_\alpha C_\alpha - \sum_\alpha \gamma_\alpha - \sum_i C_i \ln\left(D^2\right) - \sum_{\alpha \neq \beta} \mathbf{T}_\alpha \cdot \mathbf{T}_\beta \ln \left(\frac{2p_\alpha \cdot p_\beta}{Q^2} \right) \right] \times$$

$$\delta_{ac}\delta_{bd}\delta(1-z_1)\delta(1-z_2) + 2\delta(1-z_2)\delta_{bd}P^{(1)}_{ca}(z_1) + 2\delta(1-z_1)\delta_{ac}P^{(1)}_{db}(z_2) \Bigg\} \otimes d\hat{\sigma}^{\rm F+N\,jets}_{{\rm LO}\,cd}$$

$$\gamma_q = 3C_F/2$$

$$\gamma_g = (11C_A - 2n_F)/6$$

$\mathscr{H}$ contains **the finite remainder from the cancellation of singularities of real and virtual origin**, and the finite contributions embedded in **beam** (same as those of p_T^J or q_T), **jet** and **soft** functions (which we computed)

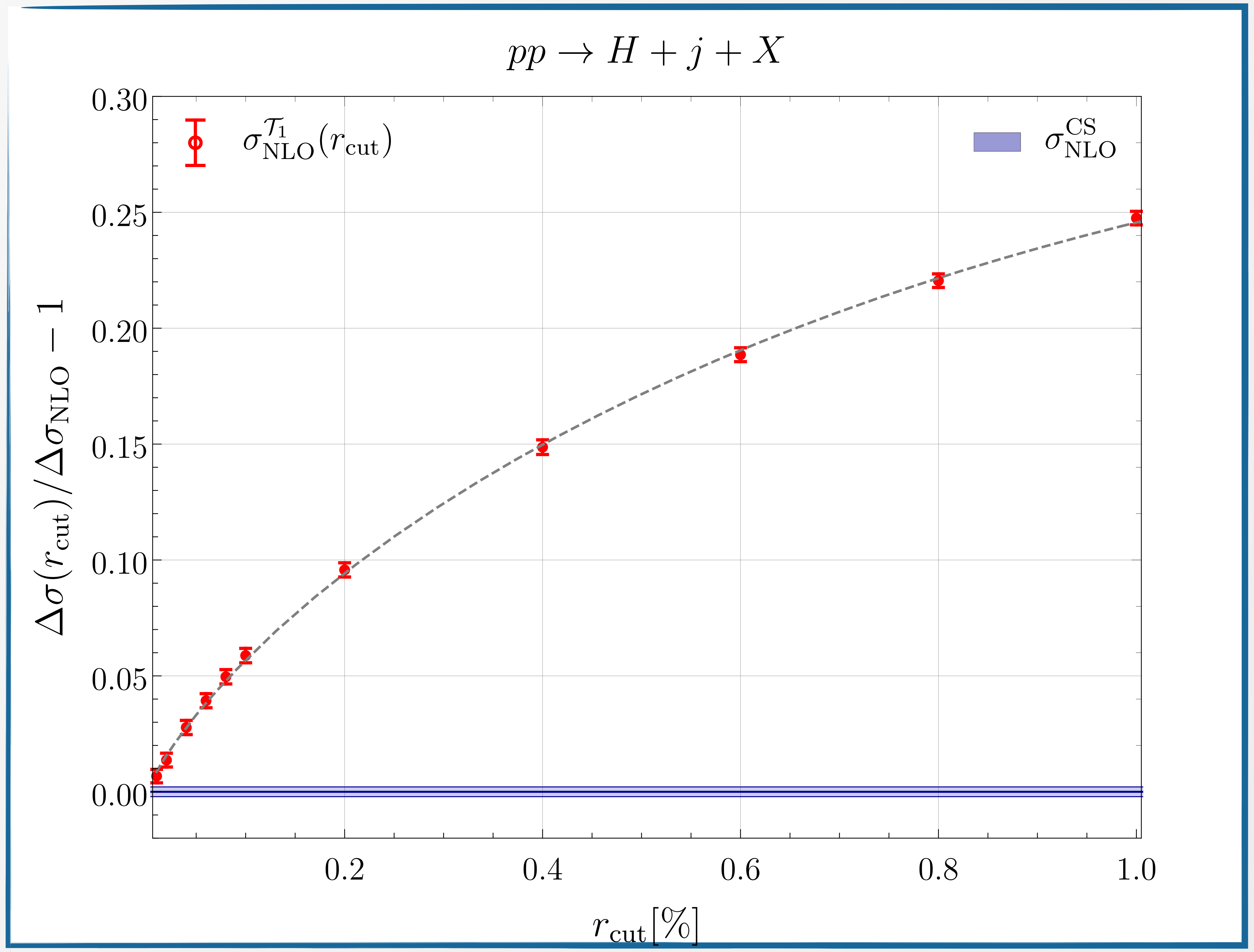
Phenomenological application: $H + j$ production

We have implemented our calculation first to $H + j$ production. Amplitudes from MCFM

We set the parameter D=1 and we require $p_T^j > 30$ GeV.

We compare our result with a **1-jettiness** calculation for the same process, which we implemented in MCFM

$$r = \mathcal{T}_1 / \sqrt{m_H^2 + (p_T^j)^2} \qquad r = k_T^{\mathrm{ness}} / \sqrt{m_H^2 + (p_T^j)^2}$$



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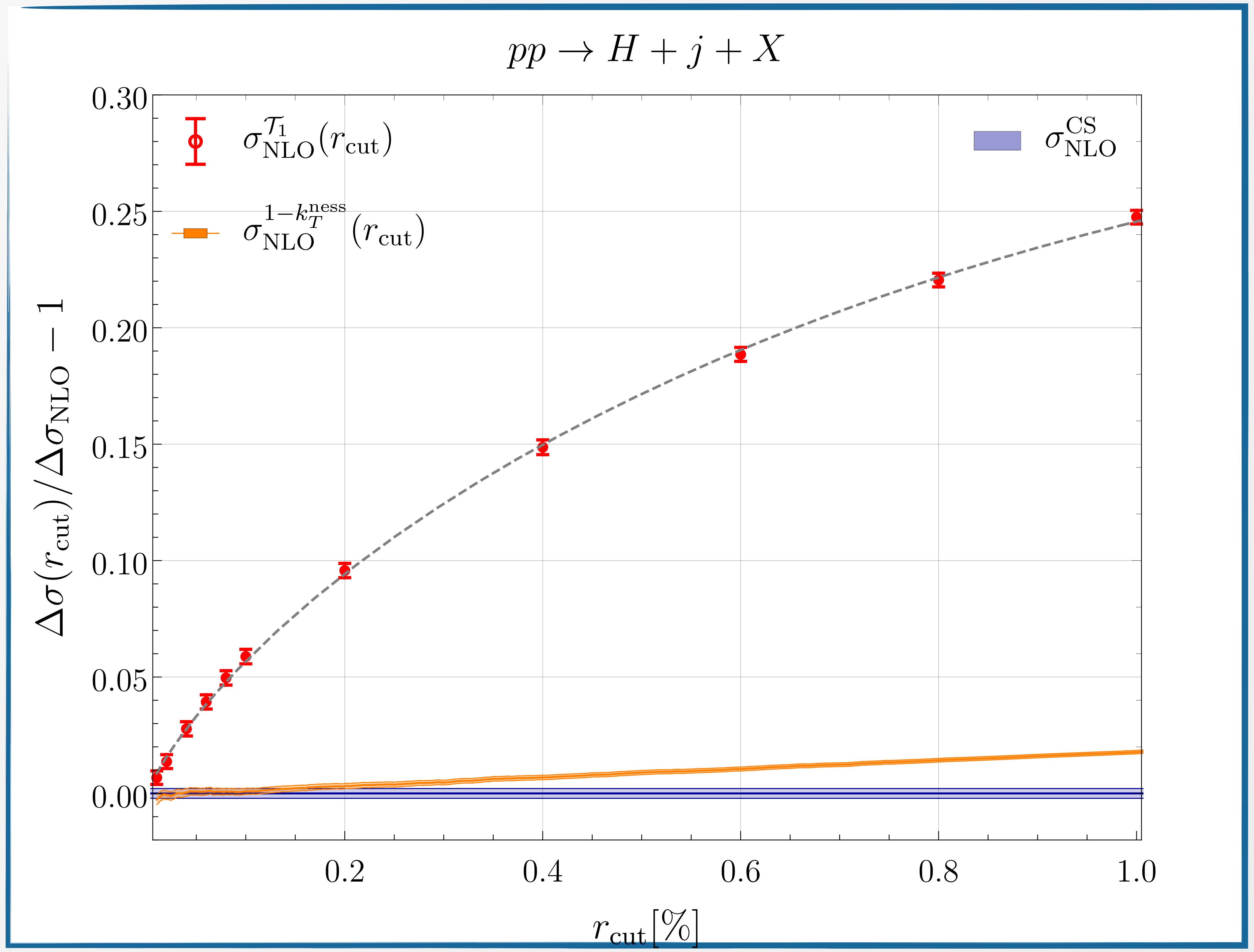
Faster convergence, power corrections compatible with **purely linear behaviour**

Excellent control of the NLO correction

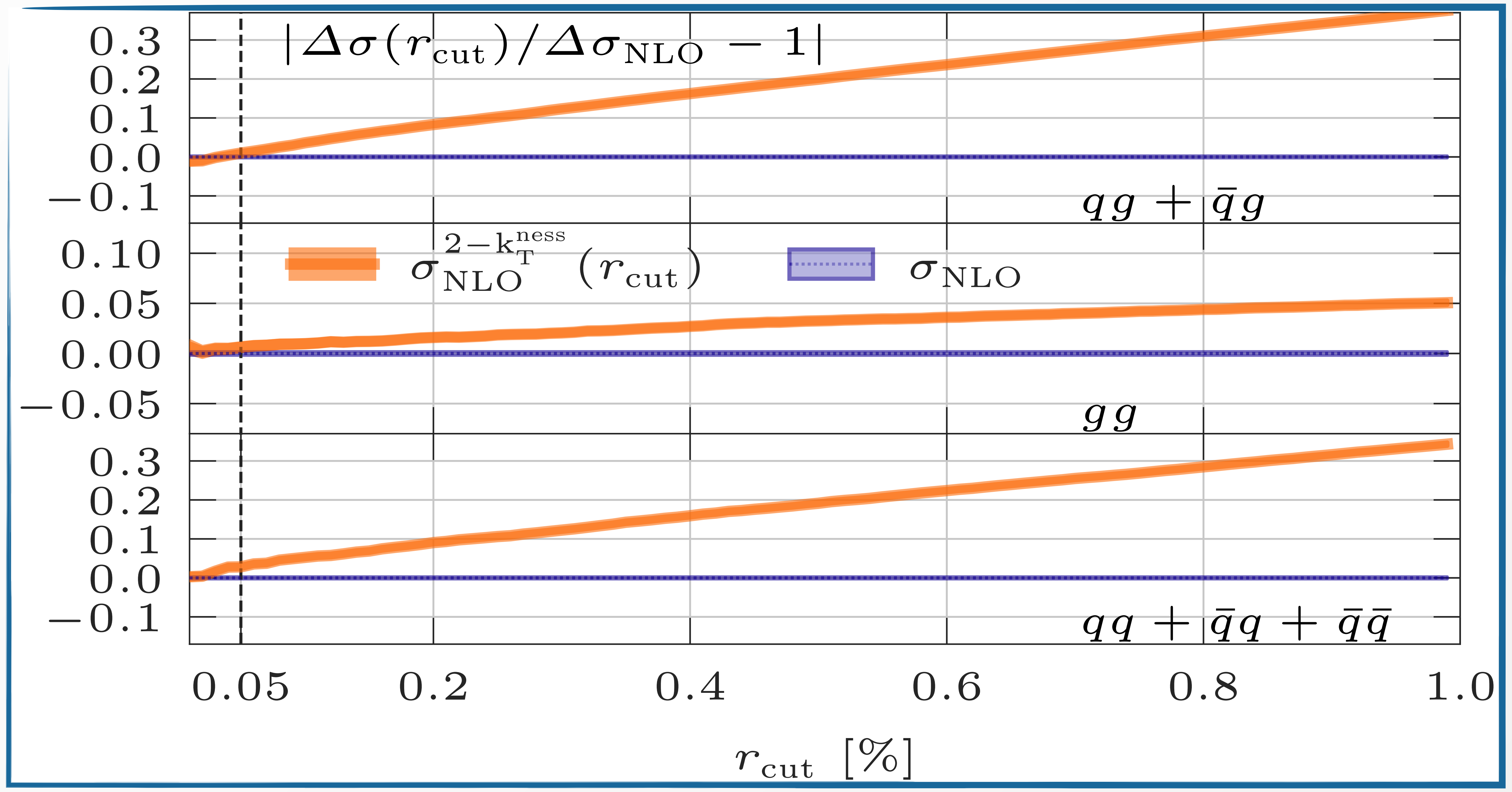


Phenomenological application: $Z + 2j$ production

We also considered a process with a more complex final state with a non-trivial colour structure

Our implementation uses colour-correlated amplitudes from OL
[Buccioni, Lang, Lindert, Maierhöfer, Pozzorini, Zhang, Zoller]

In this case we set the parameter D=0.1 and we require $p_T^j > 30$ GeV.



Power corrections exhibit **linear behaviour** in all partonic channels

Control of the NLO correction at the few **percent level**

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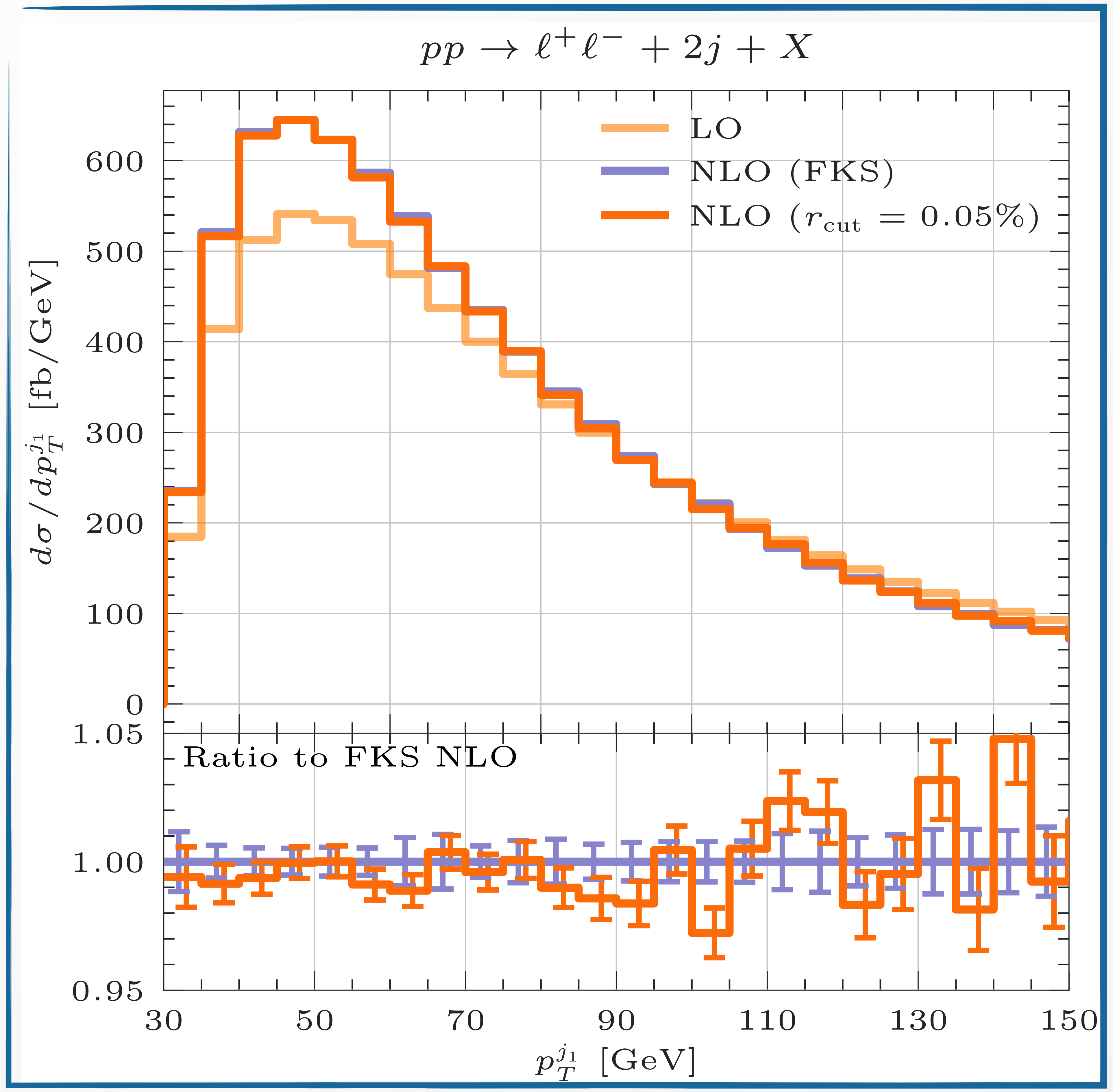
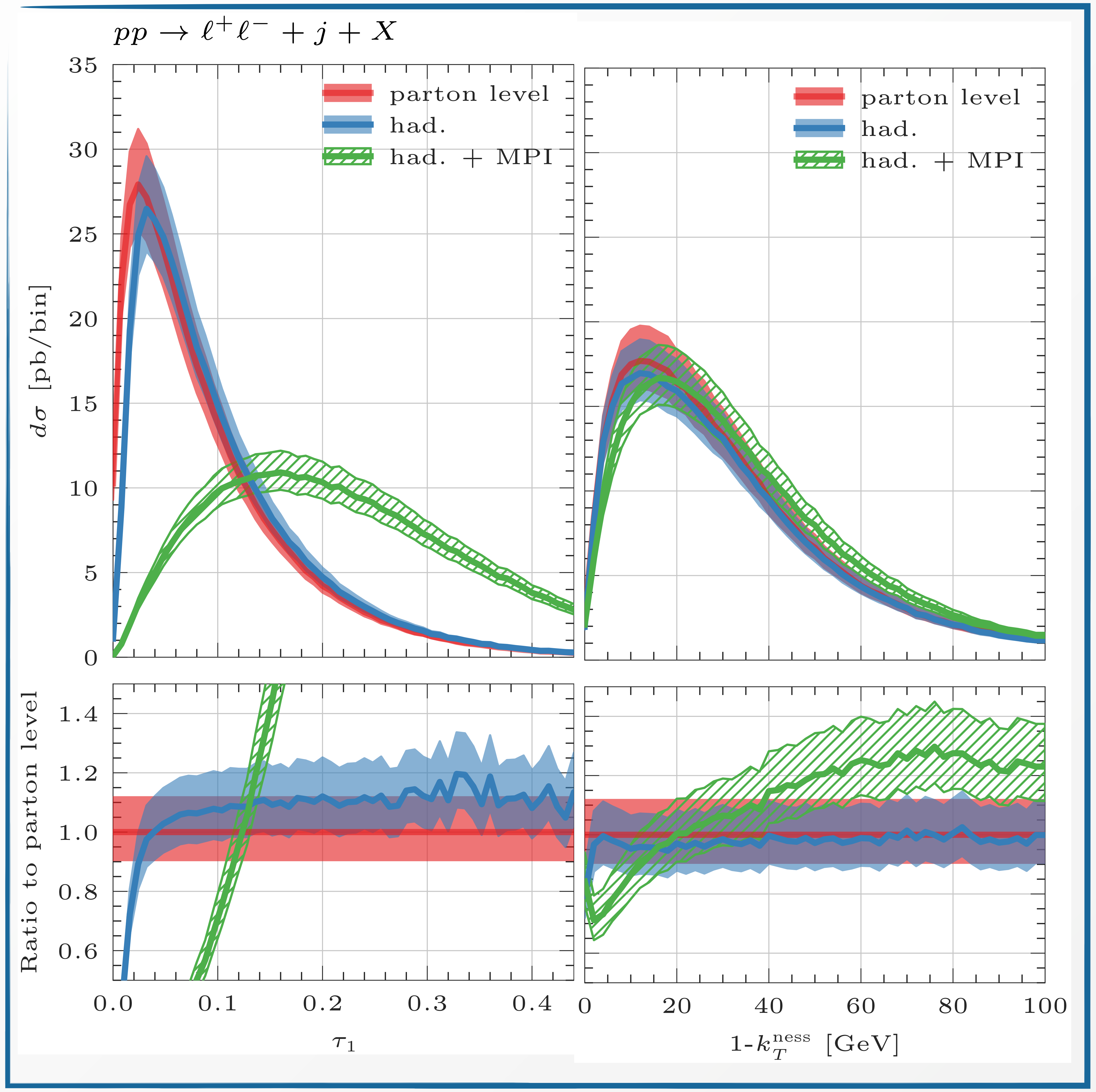


Nice agreement with results obtained with FKS subtraction (from POWHEG) for a variety of observables

Stability with respect to hadronisation and MPI



We have generated a sample of LO events for $Z + j$ with the POWHEG and showered them with PYTHIA8

We compare the impact of **hadronisation** and **MPI** on $k_T^{\rm ness}$

The distribution has a peak at ~ 15 GeV, which remain **stable** upon hadronisation and MPI

Effect of hadronisation marginal, MPI makes the distribution somewhat harder

Compared to 1-jettiness, effects are much reduced

k_T^{ness}: NNLO

Extending the calculation beyond NLO requires the availability of new ingredients:

- Two-loop beam functions
- Two-loop jet function
- Two loop soft function

k_T^{ness}: NNLO

Extending the calculation beyond NLO requires the availability of new ingredients:

- Two-loop beam functions — Available from p_T^J / q_T resummation
- Two-loop jet function
- Two loop soft function

k_T^{ness}: NNLO

Extending the calculation beyond NLO requires the availability of new ingredients:

- Two-loop beam functions
- Two-loop jet function
- Two loop soft function

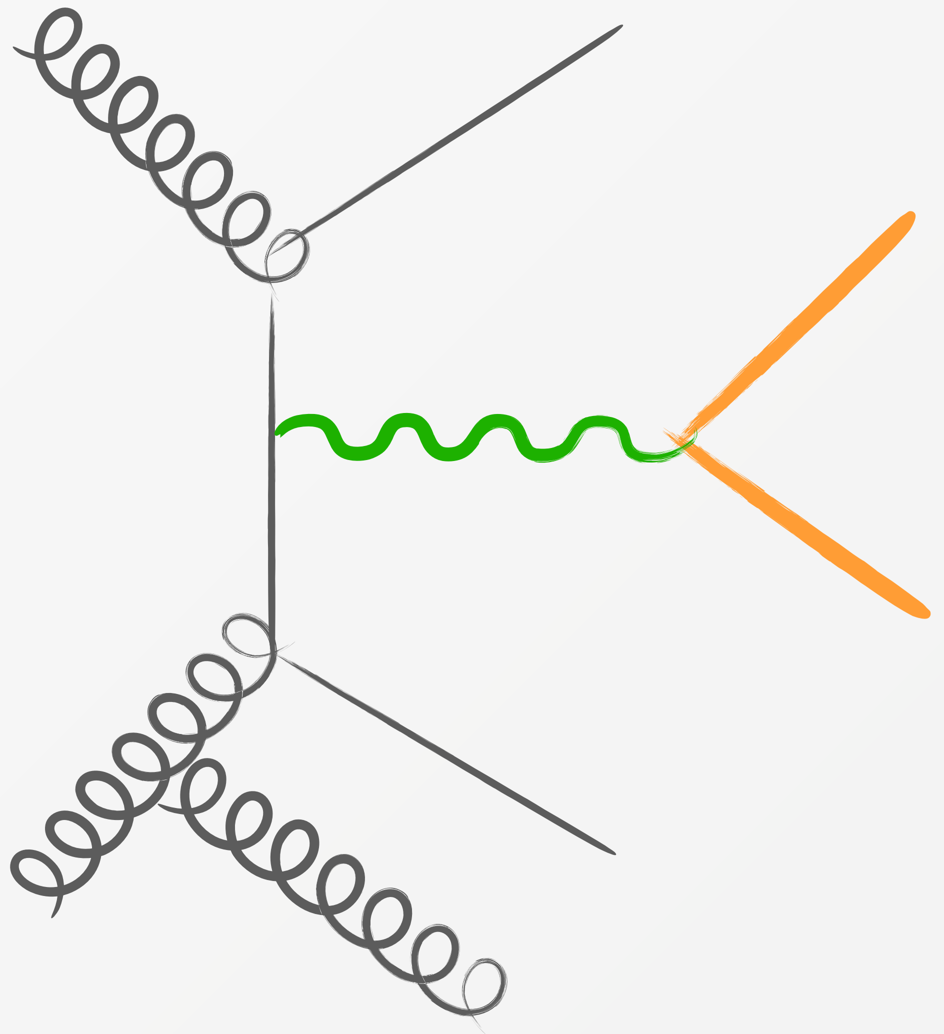
Need to be computed for our observable

k_T^{ness}: NNLO

Extending the calculation beyond NLO requires the availability of new ingredients:

- Two-loop beam functions
- Two-loop jet function
- Two loop soft function

First channel that can be checked is gg channel in $Z+j$, $W+j$ production at NNLO

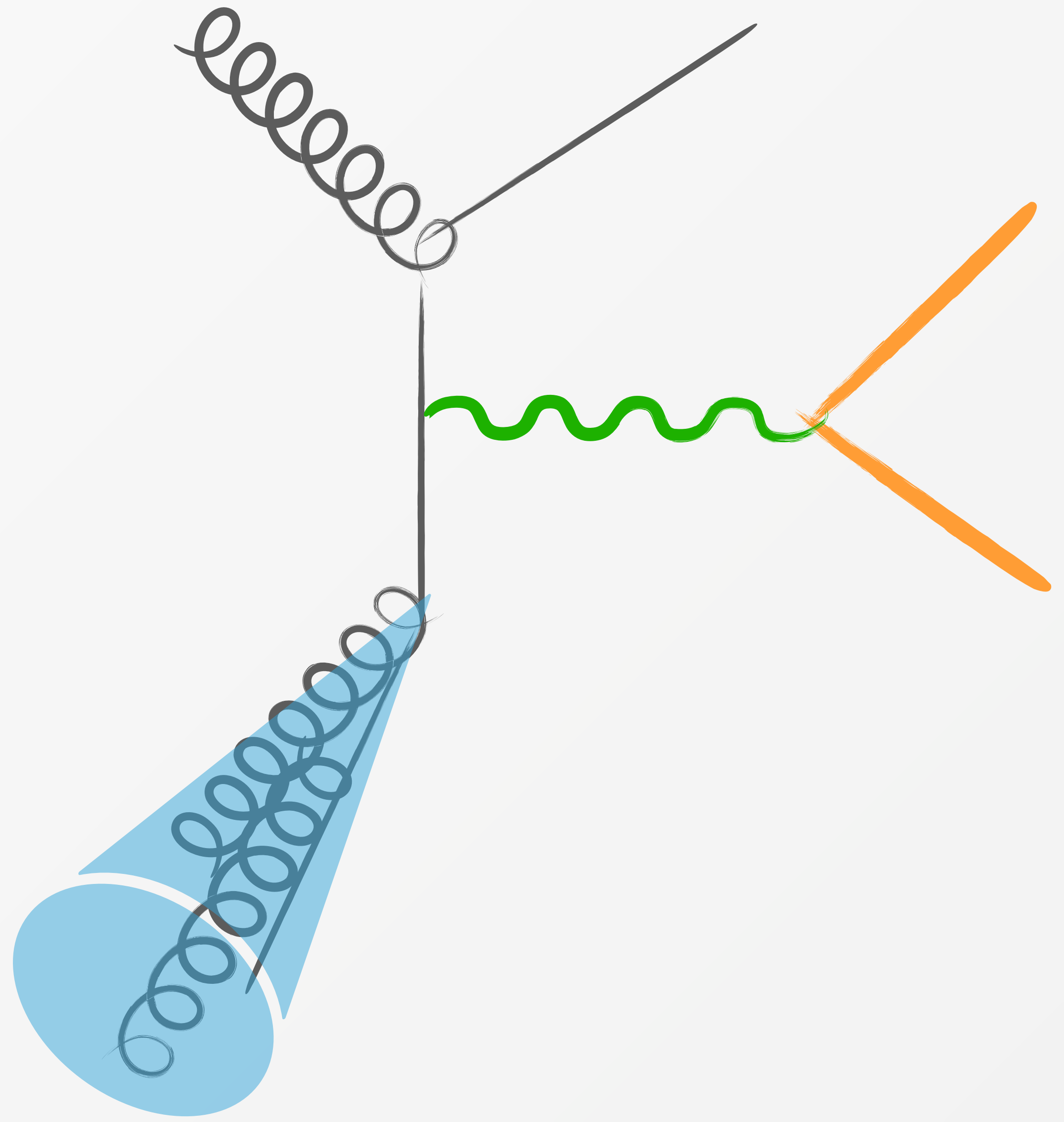


k_T^{ness}: NNLO

Extending the calculation beyond NLO requires the availability of new ingredients:

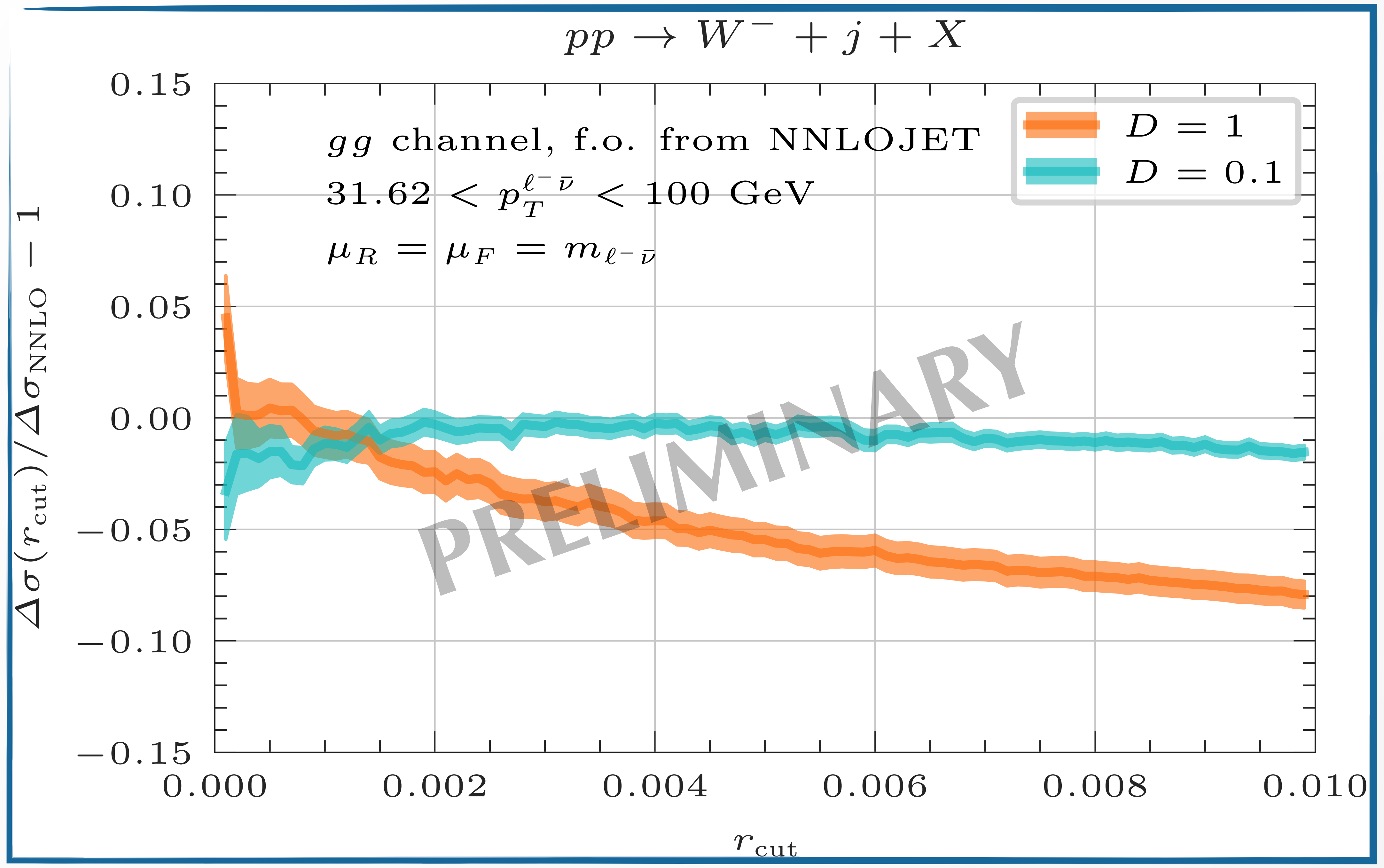
- Two-loop beam functions
- Two-loop jet function
- Two loop soft function

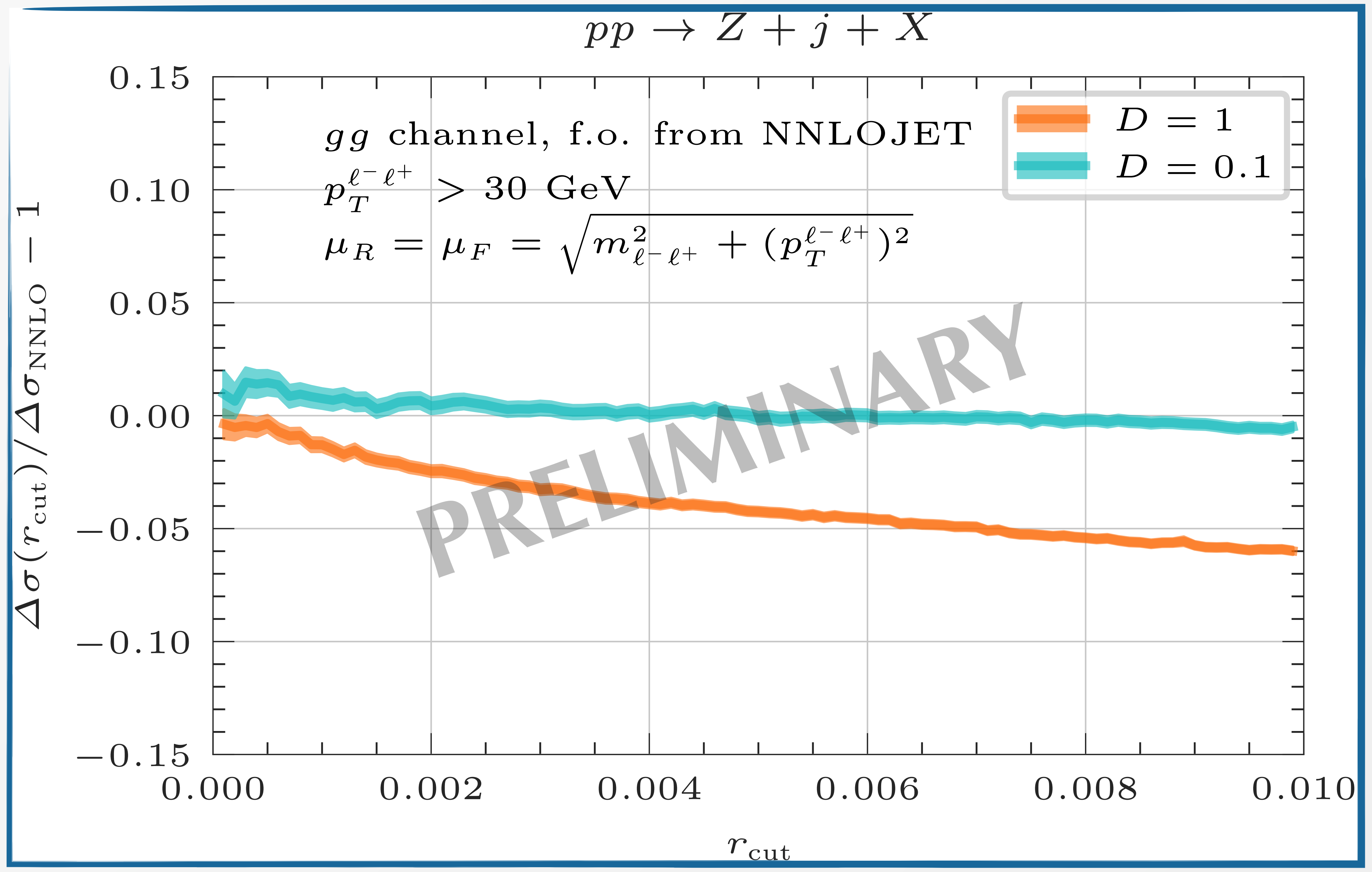
First channel that can be checked is gg channel in $Z+j$, $W+j$ production at NNLO



Only two-loop ingredient required for this process should be the two-loop beam functions

k_T^{ness}: NNLO





Excellent agreement with a local NNLO calculation (thanks Xuan Chen & NNLOJET for providing results)

Non trivial check of the **factorization properties** of the observable and hints on its all-order structure

Non-trivial dependence of the power corrections as a function of the radius parameter *D*

Case study: $e^+e^- \to 2j + X$

[Buonocore, Grazzini, Guadagni, LR in preparation]

Simplest possible process with only one FSR dipole configuration at the Born level (FSR analog of the q_T for color singlet production)

Consider resolution variables with different scalings in the soft/collinear limit

$$X \sim k_T^a e^{-b|\eta|}$$

Study behaviour of power corrections for different choices of a, b

Case study: $e^+e^- \to 2j + X$

$$X \sim k_T^a e^{-b|\eta|}$$

- Case $a = 1, b = 1$: thrust τ_2 is a viable resolution variable

By an analytical computation we find a logarithmic power correction (as expected)

$$\sigma_{\text{LPC}} = \frac{\alpha_s}{2\pi} C_F \sigma_{\text{LO}} (4 r_{\text{cut}} \log(r_{\text{cut}}) + 14 r_{\text{cut}})$$

Case study: $e^+e^- \to 2j + X$

$$X \sim k_T^a e^{-b|\eta|}$$

- Case $a = 1, b = 0$: y_{23} is a viable resolution variable

  Naively, one may expect a quadratic leading power correction as for q_T

  Instead, by an analytical computation for the inclusive y_{23} jet rate we find that it is **linear** (but not log-enhanced)

$$\sigma_{\mathrm{LPC}} = \frac{\alpha_s}{2\pi} C_F \sigma_{\mathrm{LO}} 4 \left[2 \sinh^{-1}(1) - 4\sqrt{2} \right] r_{\mathrm{cut}}$$

Case study: $e^+e^- \to 2j + X$

$$X \sim k_T^a e^{-b|\eta|}$$

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$$\sigma_{\mathrm{LPC}} = \frac{\alpha_s}{2\pi} C_F \sigma_{\mathrm{LO}} 4 \left[2 \sinh^{-1}(1) - 4\sqrt{2} \right] r_{\mathrm{cut}}$$

Origin can be traced to a soft-wide angle contribution which does not completely cancel for color conservation and color coherence

soft end point of
collinear splitting

Define a **subtracted current** which embeds the pure **soft-wide angle** contribution

$$J^2_{\mathrm{sub}} = -T_1 \cdot T_2 \frac{p_1 \cdot p_2}{p_1 \cdot k \, p_2 \cdot k} \Theta(r_{\mathrm{cut}} - \min(d_{1k}, d_{2k})) - T_1^2 \frac{p_1 \cdot p_2}{p_1 \cdot k \, (p_1 + p_2) \cdot k} \Theta(r_{\mathrm{cut}} - d_{1k}) - T_2^2 \frac{p_1 \cdot p_2}{p_2 \cdot k \, (p_1 + p_2) \cdot k} \Theta(r_{\mathrm{cut}} - d_{2k})$$

$$\equiv -T_1 \cdot T_2 \, \omega_{12} \, \Theta(r_{\mathrm{cut}} - \min(d_{1k}, d_{2k})) - T_1^2 \, \omega_1 \, \Theta(r_{\mathrm{cut}} - d_{1k}) - T_2^2 \, \omega_2 \, \Theta(r_{\mathrm{cut}} - d_{2k}) \neq 0$$

despite the fact that $\omega_{12} = \omega_1 + \omega_2$ and $2T_1 \cdot T_2 = -(T_1^2 + T_2^2)$

Case study: $e^+e^- \to 2j + X$

$$X \sim k_T^a e^{-b|\eta|}$$

- Case $a = 1, b = 0$

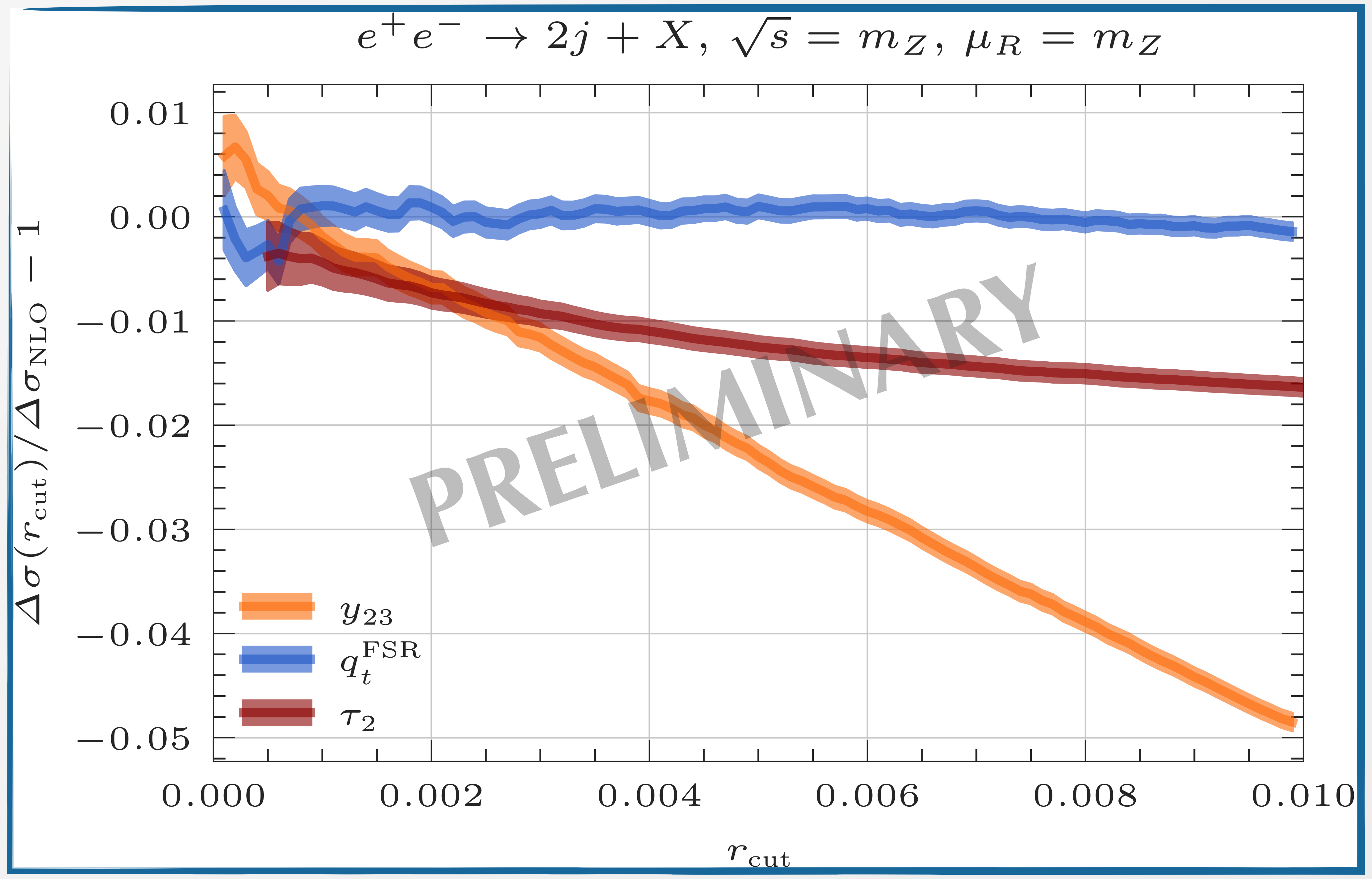
We can however define a variable that is symmetric with respect to the two collinear directions, as q_T for IS collinear radiation. At NLO, we can introduce

$$q_T^{FSR} = \sqrt{2\frac{p_1 \cdot k \, p_2 \cdot k}{p_1 \cdot p_2}}$$

which corresponds to the relative transverse momentum of the radiation k with respect to the quark-anti quark axis in the frame in which they are back-to-back

Leading power correction becomes quadratic

$$\sigma_{\text{LPC}} = \frac{\alpha_s}{2\pi} C_F \sigma_{\text{LO}} \mathcal{O}(r_{\text{cut}}^2)$$



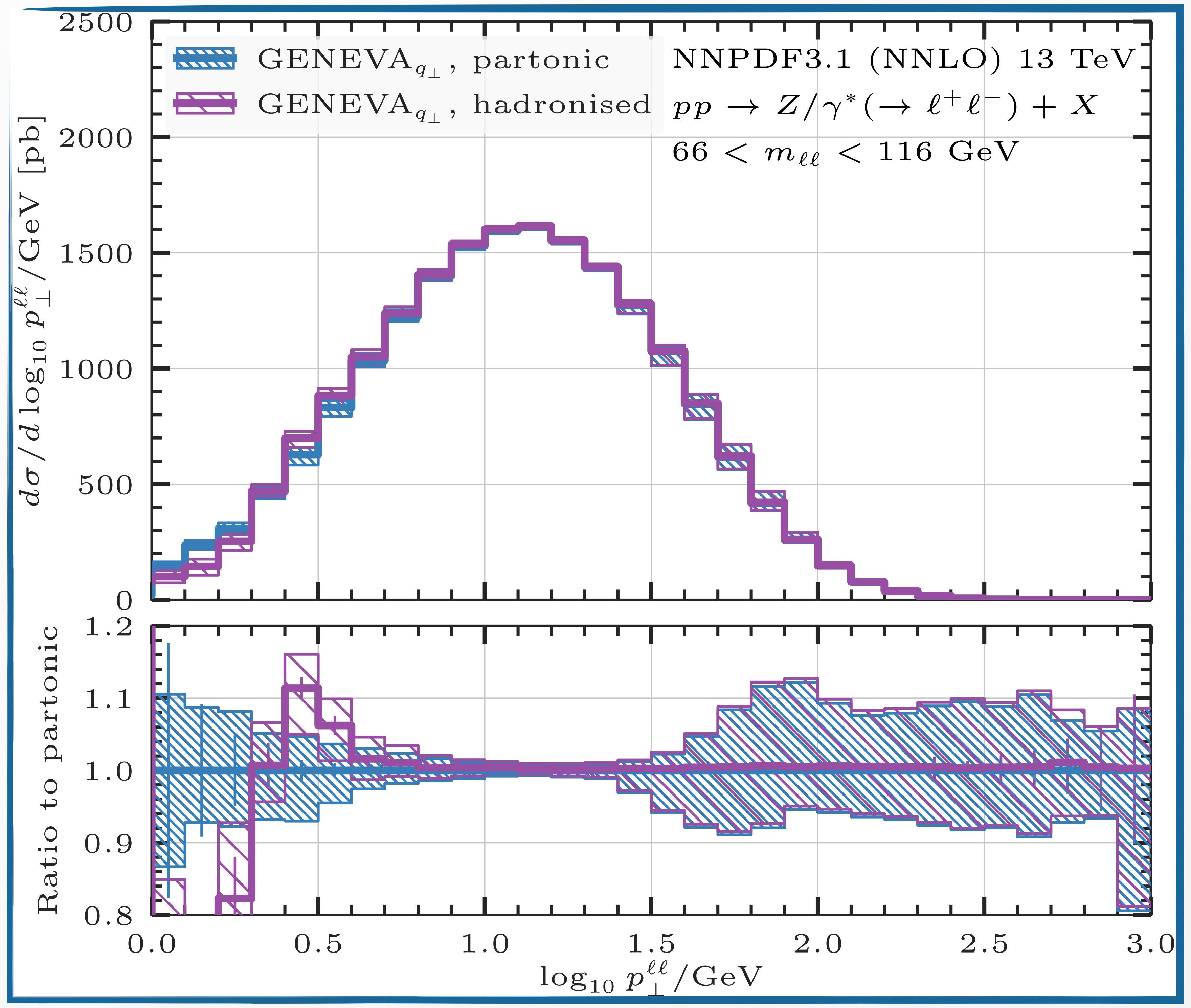
Conclusions

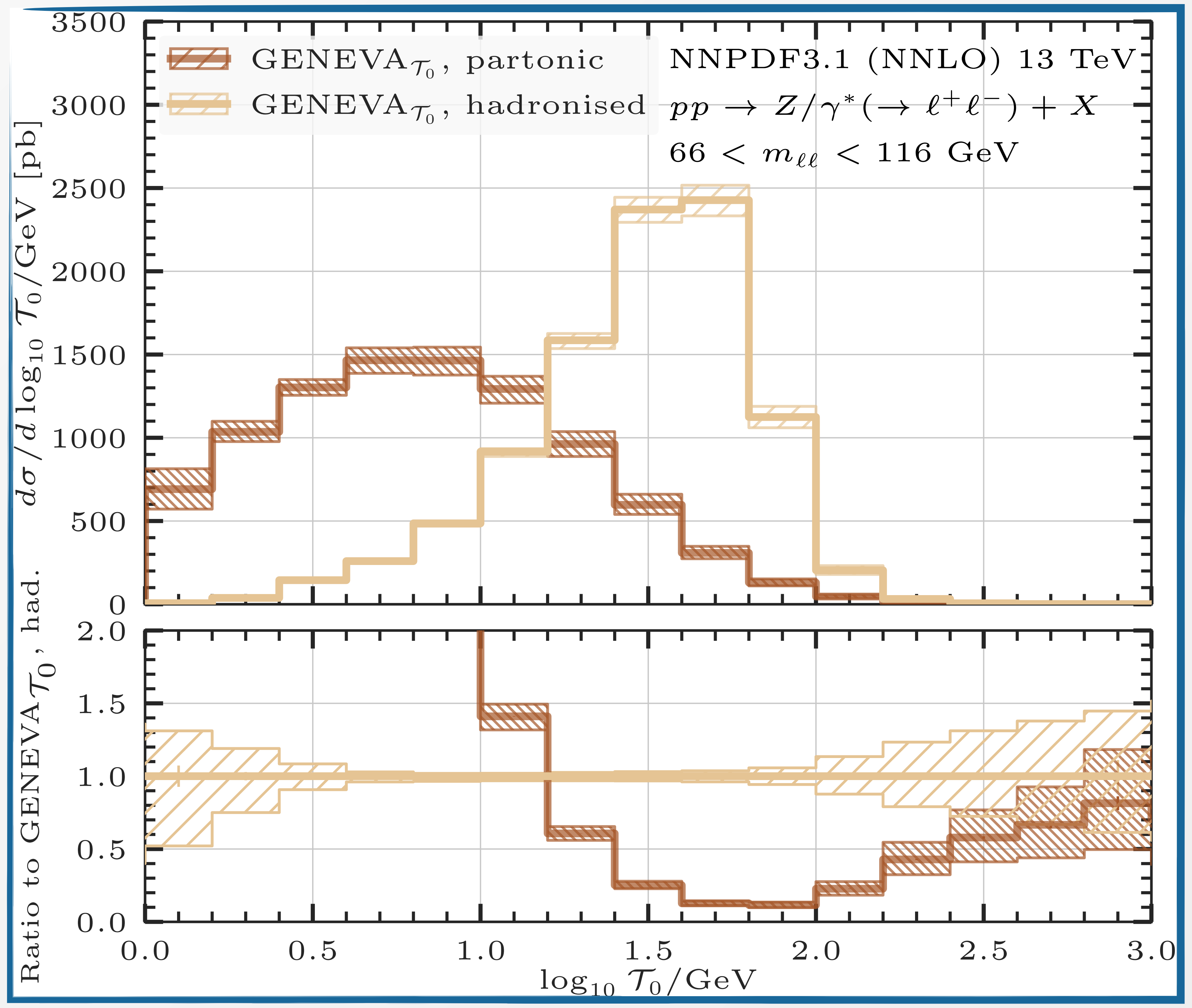
- Factorisation and resummation properties of the observables used in non-local subtraction methods provide a systematic path to reach higher-order accuracy in fixed-order computations
- The size of the residual power corrections below the slicing cutoff constitute a challenge in non-local subtraction methods
- The use of transverse observables in slicing approaches appears advantageous due to good scaling properties of the power corrections and to facilitate NNLO+PS matching thanks to the relation with the shower ordering variable
- We explored transverse variables in multi jet production. We defined a new variables, k_T-ness, which captures the singular structure of processes with jets and we computed the relevant ingredients to construct a subtraction at NLO for processes with N jets
- Computation of α_s^2 ingredients (jet, soft functions) required to reach NNLO accuracy
- We studied transverse variables in $e^+e^- \to 2$ jets $+ X$ at NLO and we investigated their scaling properties

Backup

Jet resolution variables and NNLO+PS

- p_T^{veto}, q_T, τ_0 are three well known variables able to **inclusively describe initial-state radiation**
- The knowledge of the all-order structure of resolution variables makes them suitable for **NNLO+PS event generators**
  - q_T: UNNLOPS, [Höche, Li, Prestel] MiNNLO$_{\text{PS}}$ [Nason, Monni, Re, Wiesemann, Zanderighi]
  - τ_0: GENEVA [Alioli, Bauer, Berggren, Tackmann, Walsh] recently extended to q_T [Alioli, Bauer, Broggio, Gavardi, Kallweit, Lim, Nagar, Napoletano, LR]





Predictiveness of resummed predictions affected by corrections of NP origin (hadronisation, MPI). Spectrum in q_T **mildly affected**, **large corrections** due to MPI in the case of τ_0