Power Corrections in transverse observables

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University of Zurich[UZH]

Outline

- Intro&Motivations
- Transverse observables for jet cross sections: q_T imbalance
- Transverse observables for jet cross sections: $k_T^{\rm ness}$
- Case study: $e^+e^- \to 2$ jets $+ X$ detour
- Conclusions&Outlook

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Intro&Motivations

Precise predictions for collider observables are based on **collinear factorisation,** systematically improved by the inclusion of **higher-order radiative corrections**

$$\sigma = \int dx_1 dx_2 f_{a/h_1}(x_1, \mu_F) f_{b/h_2}(x_2, \mu_F) \hat{\sigma}_{ab}(\hat{s}, \mu_R, \mu_F) + \mathcal{O}\left((\Lambda/Q)^k\right)$$

power corrections to factorisation are not the focus of this talk!

$$\hat{\sigma}_{ab} = \hat{\sigma}^{(0,0)}_{ab} + \hat{\sigma}^{(1,0)}_{ab} + \hat{\sigma}^{(2,0)}_{ab} + \hat{\sigma}^{(3,0)}_{ab} + \ldots \qquad \text{QCD}$$

$$+ \hat{\sigma}^{(0,1)}_{ab} + \ldots \qquad \text{EW}$$

$$+ \hat{\sigma}^{(1,1)}_{ab} + \ldots \qquad \text{QCD-EW}$$

Nowadays, there are general and flexible methods for computing **NLO cross sections**

Going to higher orders, the situation is **less established.** Technical problems:

- computation of **multi-loop virtual amplitudes**
- **subtraction scheme** for handling infrared divergences at intermediate steps of the calculation

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Intro&Motivations

Different subtraction schemes available on the market

Antenna, ColorFull, Nested, Sector, Local, projection to Born, q_T and jettiness slicing …

We consider slicing/non local subtractions

CONs

- large global cancellation
- residual power corrections

PROs

- usually simpler (allowed to reach N^{3}LO for color singlet production)
- connection with **factorisation** theorems and **resummation**
- implications for higher-order matching (MiNNLO/GENEVA)

Intro&Motivations: slicing formalism

Introduce a **resolution variable** X that discriminates a region with **1-resolved emission** from an **unresolved** region

$$\sigma_{N^kLO} = \int d\sigma_{N^kLO}\Theta(X_{\rm cut} - X) + \int d\sigma^{R}_{N^{k-1}LO}\Theta(X - X_{\rm cut})$$

In the unresolved region, approximate the cross section by an expansion in the soft-collinear limits (factorisation theorems in EFT, resummation formula)

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

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

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Real contribution: $N^{k-1}LO$ calculation, **divergent** in the limit $X_{\rm cut} \to 0$

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

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

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

Intro&Motivations: slicing formalism

REMARKs

The computation can be carried out only for a **finite value of the cut-off!**
Size of power corrections crucial for the **performance** of the method

Systematic improvement is difficult, it requires **going beyond soft and/or collinear factorisation**

We consider the **power scaling behaviour** as the main qualitative criterium

Numerical efficiency of the actual implementation may be a different story.
For example, a simple LL argument suggests that the efficiency ϵ should scales as

$$X \sim k_T^a e^{-b|\eta|} \quad \rightarrow \quad \epsilon \sim X^{\frac{1}{a+b}}$$

Scaling of the leading power correction determined at NLO

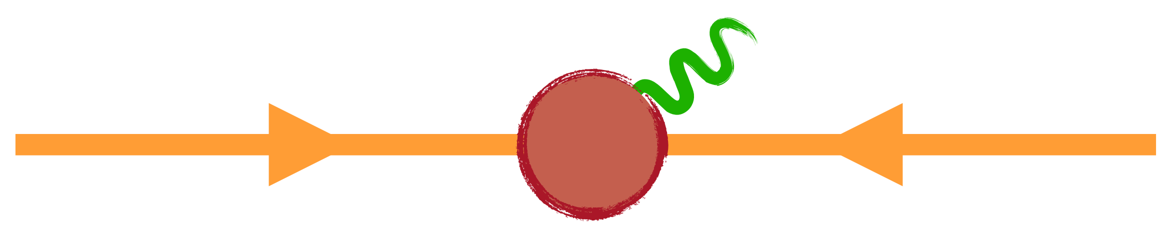
$$\mathcal{O}(X_{\rm cut}^{\ell}) \quad \text{at NLO} \quad \rightarrow \quad \mathcal{O}(X_{\rm cut}^{\ell} \ln^{2(k-1)} X_{\rm cut}) \quad \text{at N}^k\text{LO}$$

0-jet case: inclusive color singlet production

The simplest case is provided by color singlet production
Prominent examples of variables able to discriminate the $0 \to 1$ transition are

- p_T^{jet}, q_T, τ_0 which **inclusively describe initial-state radiation**

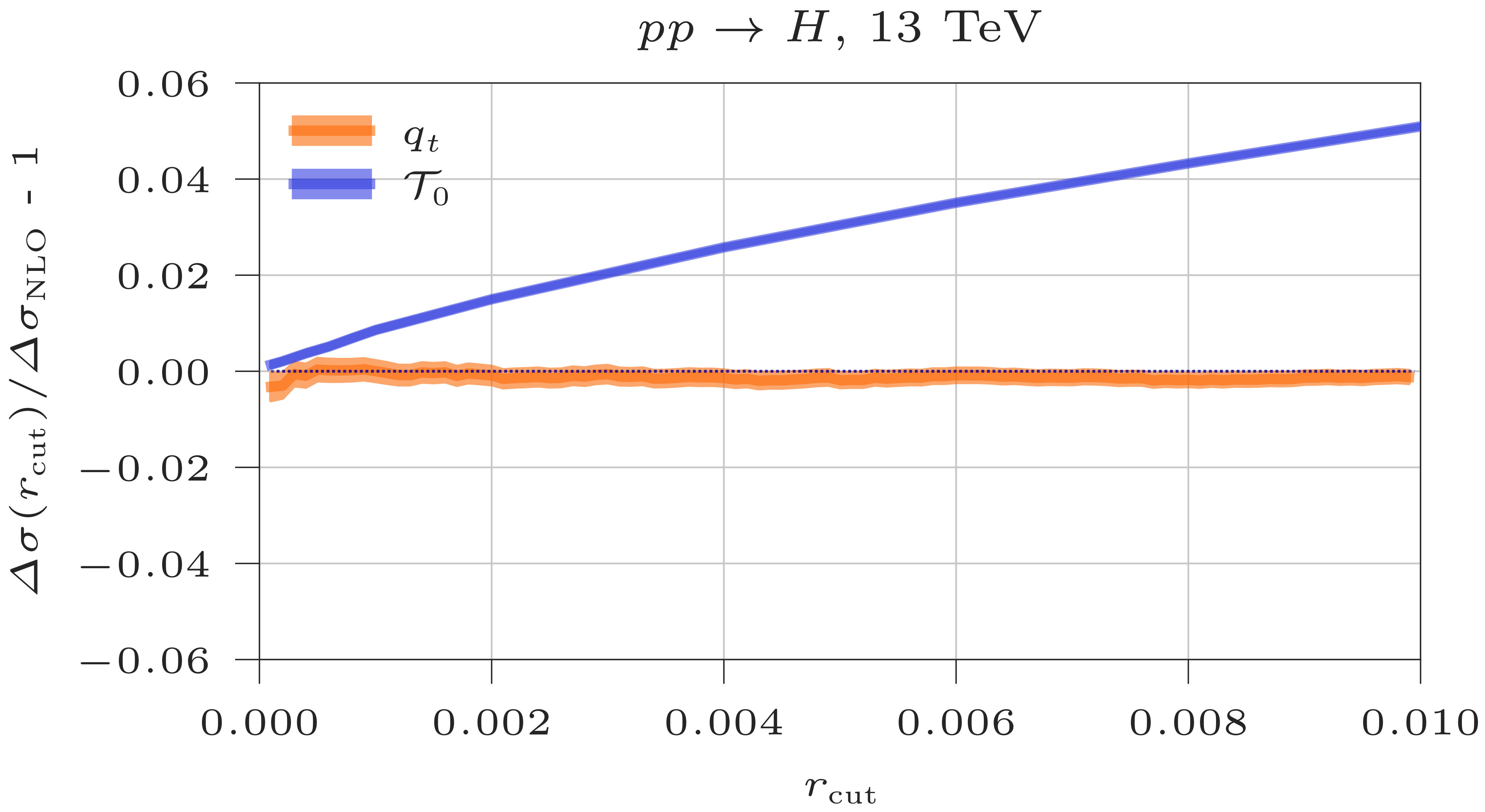
0 jet



one emission resolved for $X/Q > r_{\text{cut}}$

In the case of q_T, τ_0, the knowledge of all $\mathcal{O}(\alpha_s^2)$ 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]



Scaling of power corrections
(confirmed by various analytical calculations)

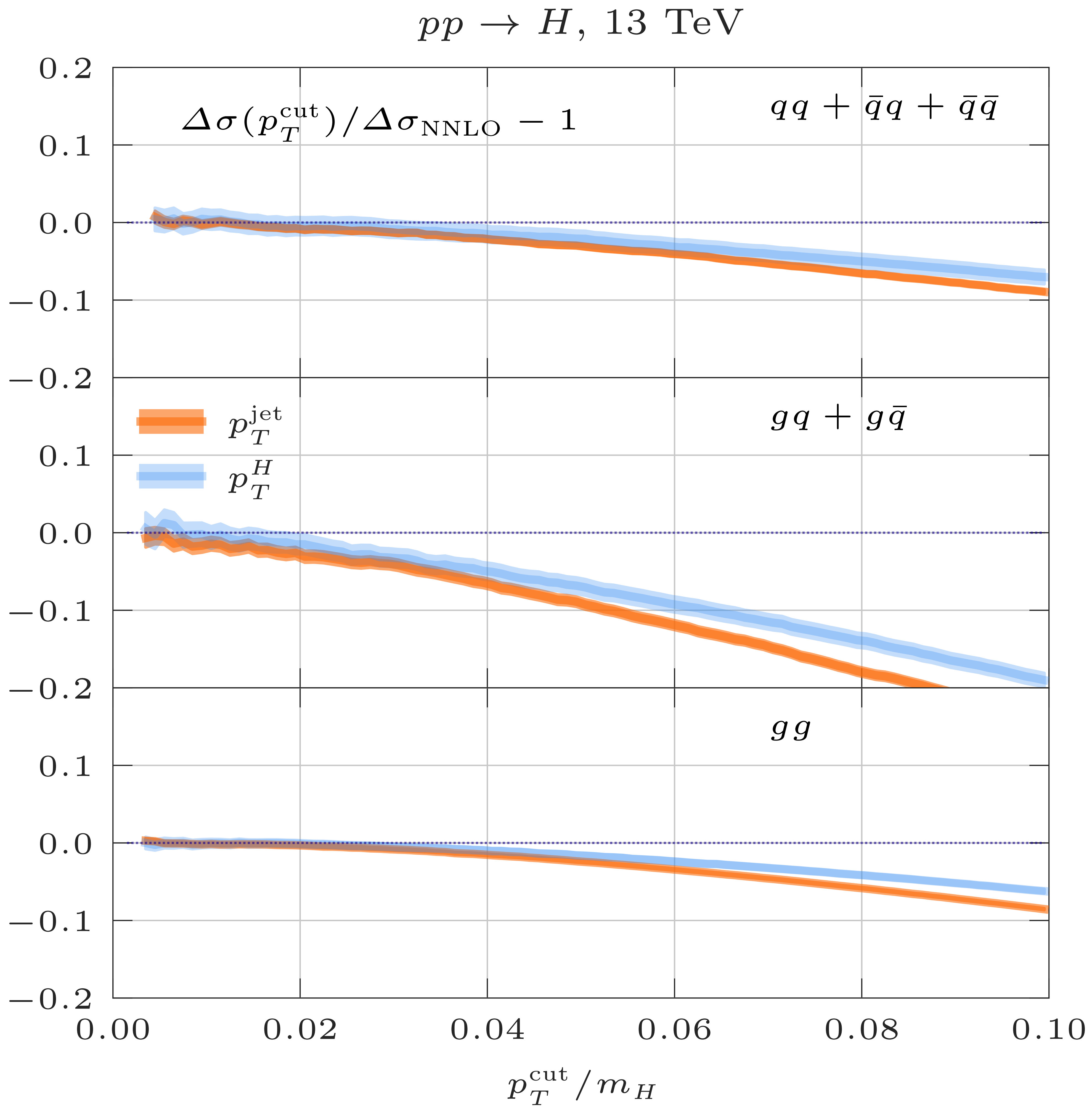
- q_T : quadratic $\quad r_{\text{cut}}^2 \ln r_{\text{cut}}$
- τ_0 : linear $\quad r_{\text{cut}} \ln r_{\text{cut}}$

q_T displays a faster convergence and so better performance

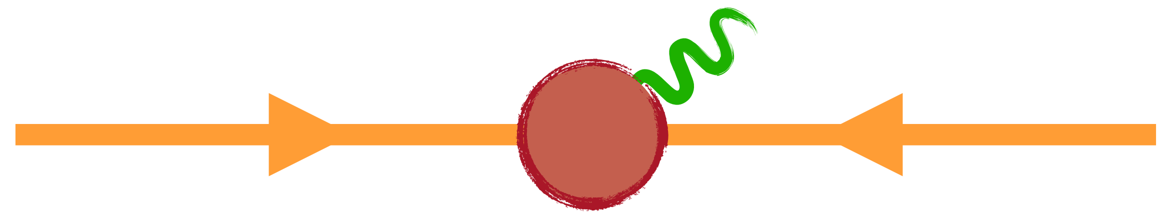
Very efficient for (N)NNLO calculation

0-jet case: inclusive color singlet production

Very recently, also the $\mathcal{O}(\alpha_s^2)$ constant terms (**soft and beam functions**) for p_T^{jet} have been computed [Abreu, Gaunt, Monni, Rottoli, Szafron]



0 jet



one emission resolved for $X/Q > r_{\text{cut}}$

Power corrections in p_T^{jet} display a **quadratic scaling** as expected from the fact that $p_T^{\text{jet}} \sim q_T$ at NLO

0-jet case: beyond inclusive color singlet production

As usual, life is not that simple…
The power corrections in q_T subtraction **may get worse** when **fiducial cuts** and/or emission off a **massive final state emitter** are considered

2-body fiducial cuts

Examples: symmetric cuts on Drell-Yan and Higgs 2-body decay products

Kinematical origin

- q_T : linear $\quad r_{\rm cut}$

Photon isolation

Examples: vector bosons pair production involving photons, tri-photon

Kinematical and Dynamical origin

- q_T : linear $\quad r_{\rm cut} \ln r_{\rm cut}$

Massive final state emitters

Examples: heavy quarks, NLO EW and mixed QCD-EW corrections to Drell-Yan

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Kinematical and Dynamical origin

- q_T : linear r_{cut}

Linear power corrections can be efficiently computed numerically and the quadratic scaling restored!

Wait for Luca's Talk

Transverse observables for the N-jet case

Beyond the 0-jet case, **N-jettiness** is the most studied resolution variable

NNLO calculations for $V + 1$ jet using 1-jettines subtraction have been performed

[Boughezal, Campbell, Ellis, Focke, Giele, Liu, Petriello, Williams]

Soft-function for 2-jettiness at NNLO also available, allows for potential computation of dijet at NNLO

[Jin, Liu]

It may prove worthwhile to consider other classes of **transverse observables** which may have

- a **better power corrections scaling** → for **NNLO subtraction** (and beyond)
- a more **direct experimental relevance** → for comparison of resummed prediction with data
- a simpler relation with parton shower ordering variables → for **NNLO+PS matching**

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q_T imbalance: definition

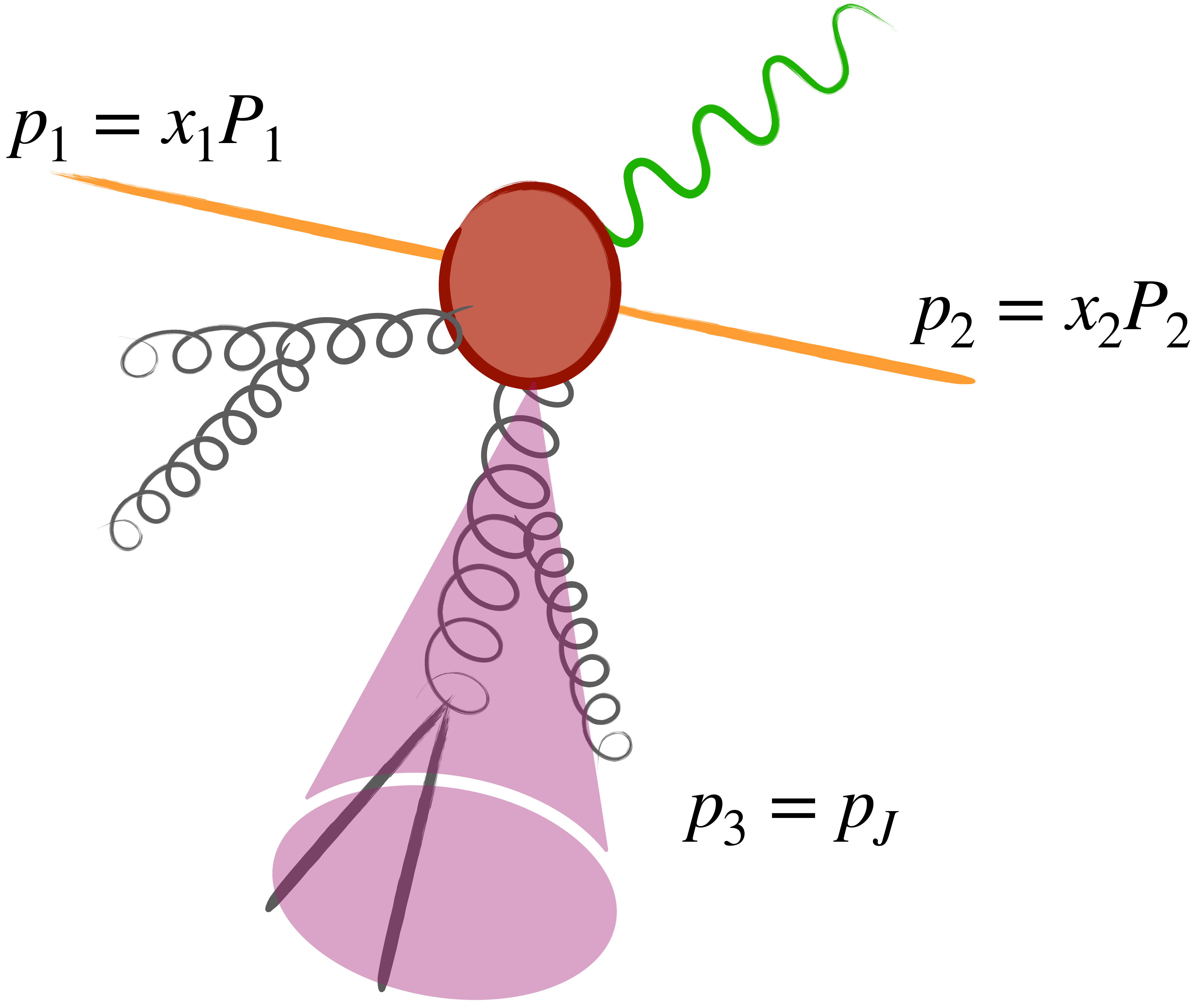
Consider production of boson V in association with a jet

$$h_1(P_1) + h_2(P_2) \to V(p_V) + j(p_j) + X$$

Define q_T**-imbalance** as

$$\vec{q}_T = (\vec{p}_V + \vec{p}_J)_T$$

Variable depends on the **jet definition**: jet defined through anti-k_t algorithm with a **finite jet radius** R



Fixed-order calculation develops **large logarithms** of $\ln(q_T)^2/Q^2$ in the limit $q_T \to 0$.

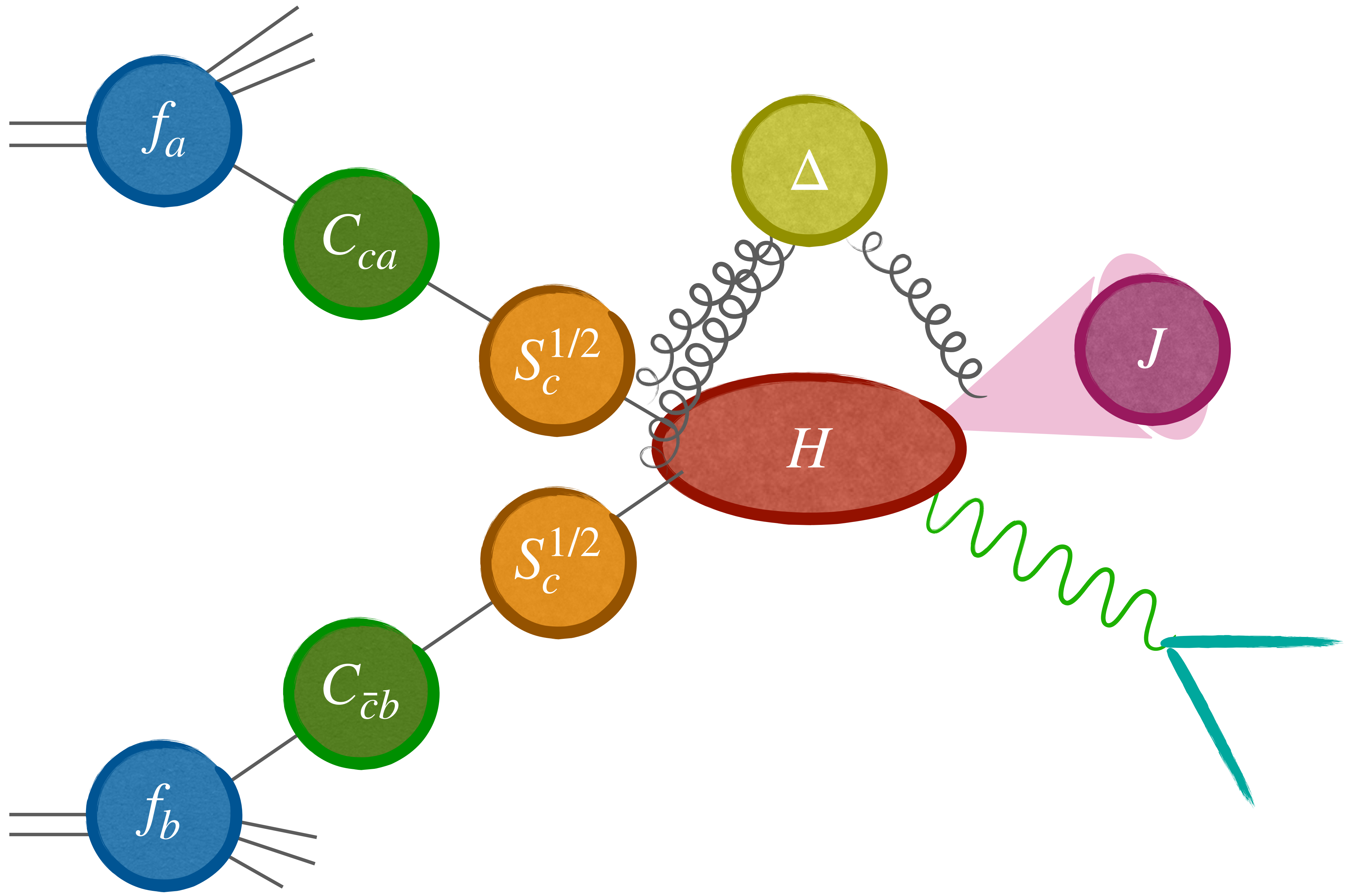
Perturbative expansion rescued by the **all-order resummation** of logarithmically enhanced terms

q_T imbalance: resummation

Resummation already considered both in direct QCD and in SCET, but performed in the **narrow jet approximation**

[Sung, Yan, Yuan, Yuan][Chien, Shao, Wu]

[LB, Haag, Grazzini, Rottoli]



In view of potential applications for e.g. subtraction scheme, it is important to assess the impact of such an approximation

In our calculation:

- Full R **dependence** in the anomalous dimensions
- Full **azimuthal dependence**
- Inclusion of all finite contributions (**NLL′ accuracy**)

q_T imbalance: fixed order analysis at 1-loop

Decompose in contribution **inside/outside** the jet cone of radius R

$$d\sigma = d\sigma^{\text{out}} + d\sigma^{\text{in}} = d\sigma^{\text{out}}\Theta(r_{\text{cut}} - q_T/Q) + d\sigma^{\text{out}}\Theta(q_T/Q - r_{\text{cut}}) + d\sigma^{\text{in}}\delta(q_T)$$

real contribution above the cut

By construction, the contribution inside the jet cone lives at $q_T = 0$

Approximate the matrix element and the phase space in collinear and soft limits and remove double counting

$$d\sigma^{\text{out}}\Theta(r_{\text{cut}} - q_T/Q) \sim \left[d\sigma^{\text{out}}_{\text{coll},1} + d\sigma^{\text{out}}_{\text{coll},1} + d\sigma^{\text{out}}_{\text{soft}} - \lim_{z_1 -> 1} d\sigma^{\text{out}}_{\text{coll},1} - \lim_{z_2 -> 1} d\sigma^{\text{out}}_{\text{coll},2} \right] \Theta(r_{\text{cut}} - q_T/Q)$$

$$\sim \left[d\sigma_{\text{coll},1} + d\sigma_{\text{coll},1} + d\sigma^{\text{out}}_{\text{soft}} - \lim_{z_1 -> 1} d\sigma_{\text{coll},1} - \lim_{z_2 -> 1} d\sigma_{\text{coll},2} \right] \Theta(r_{\text{cut}} - q_T/Q) + \ldots$$

pure soft wide-angle contribution

regular terms in the limit $q_T = 0$

q_T imbalance: fixed order analysis at 1-loop

One-Loop subtracted current, k is the momentum of soft gluon

$$J^2_{\text{sub}} = \sum_{i<j} T_i \cdot T_j \frac{p_i \cdot p_j}{p_i \cdot k \, p_j \cdot k} \Theta^{out} - \sum_{i=1,2} (-T_i^2) \frac{p_1 \cdot p_2}{p_i \cdot k \, (p_1 + p_2) \cdot k} \times 1$$

eikonal current outside the cone — soft end point of collinear splitting

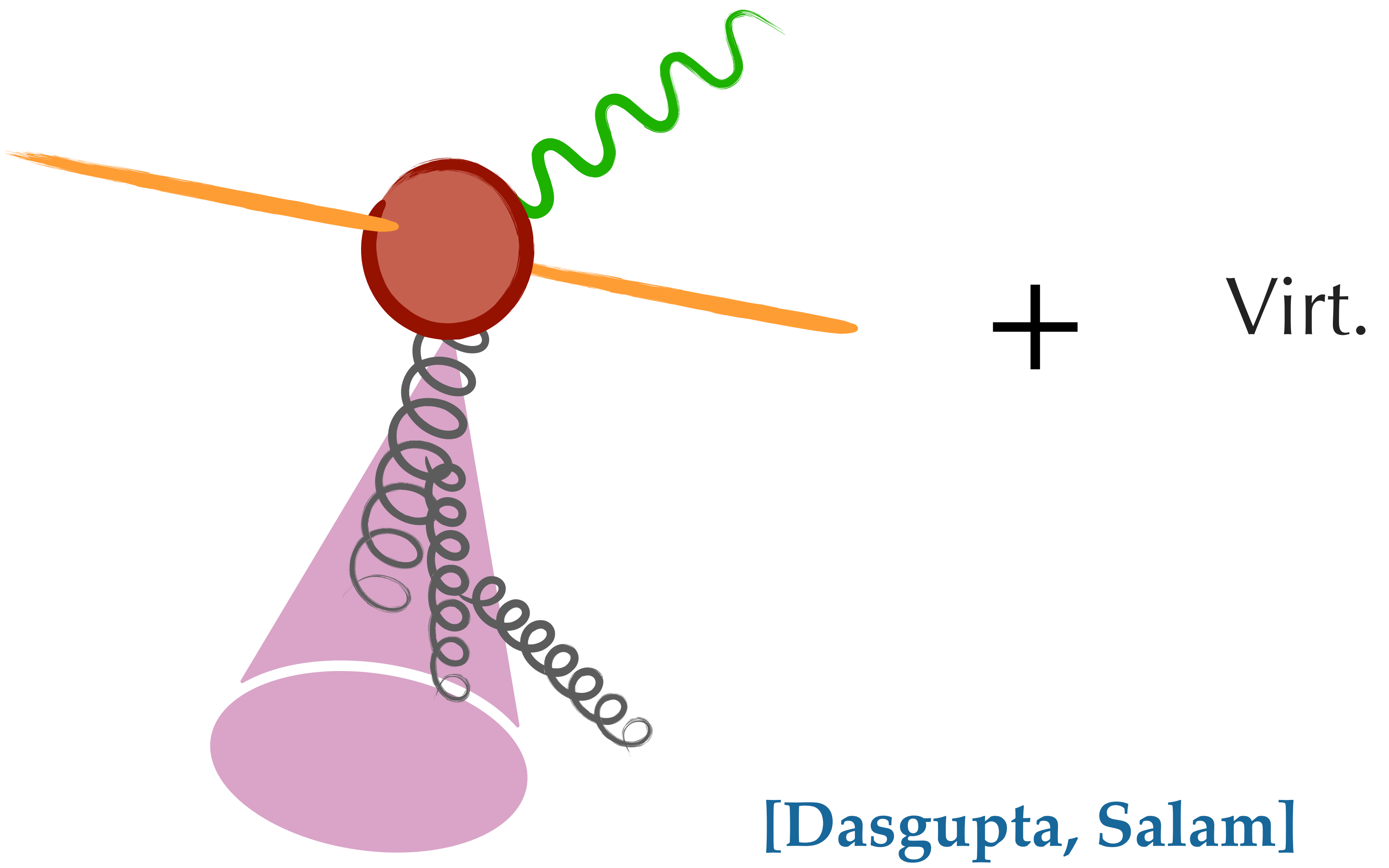
It is **free of any collinear divergence** due to the **end points subtraction** and the constraint of the **jet radius** R

It can be integrated in d-dimensions and **develops large logarithms of the jet radius**

Main drawbacks

The jet radius R acts as a **second cut-off variable** but exact calculation in the jet radius may be difficult

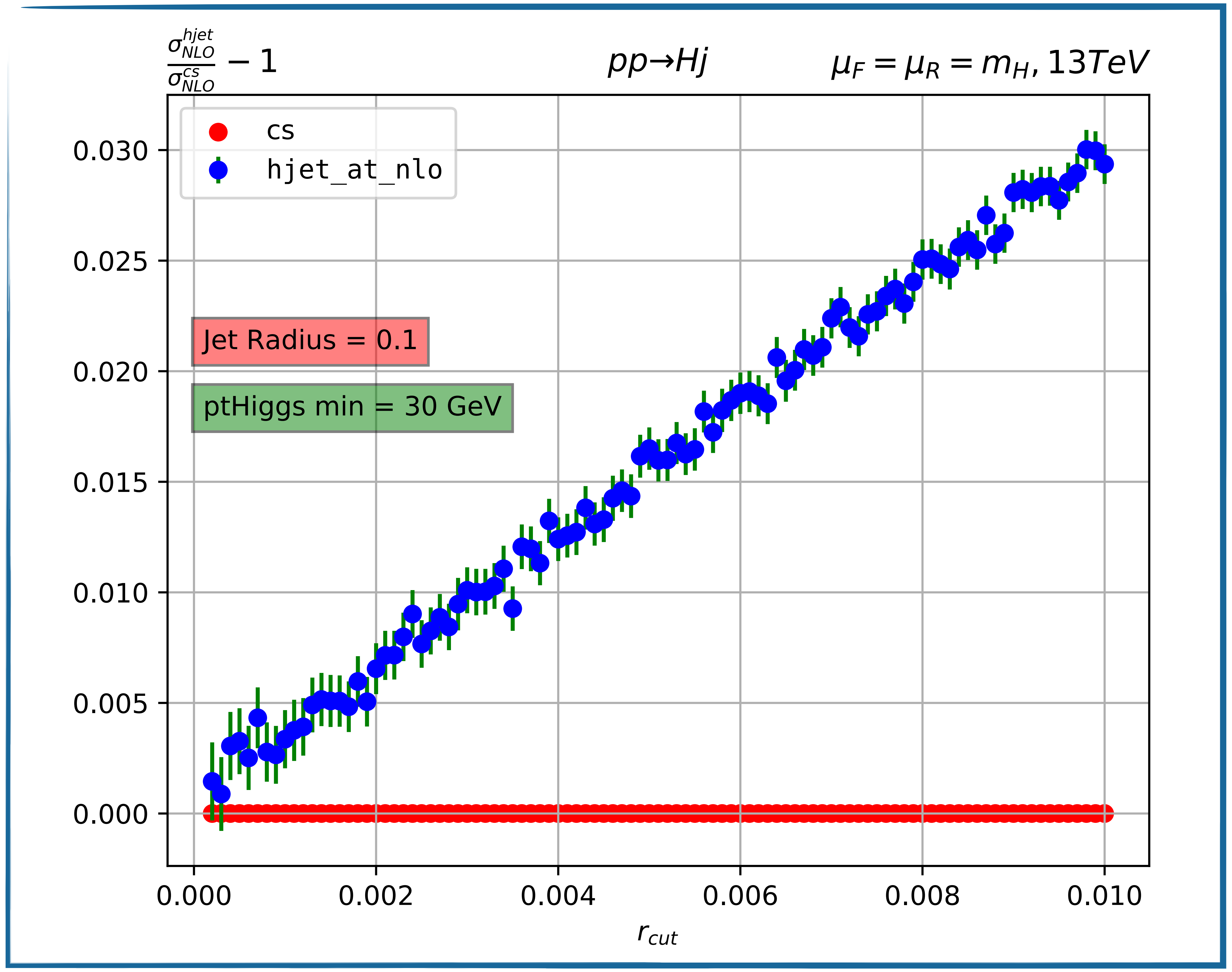
The observable is insensitive to soft radiation entering the jet cone. At two loops, **non-global** contributions enter the resummation formula already at the NLL $\alpha_s^2 \ln q_t^2/Q^2$ level (in the strongly ordered soft limit)



[Dasgupta, Salam]

q_T imbalance: power corrections (numerical study)

[M. Costantini Master's thesis, UZH]



Scaling of power corrections

- q_T : linear r_{cut}

Nice convergence towards the exact result

NLO [pb]	$\mu_F = \mu_R = m_H$
q_T subtraction	13.256 ± 0.034
mcfm	13.250 ± 0.007
LO [pb]	7.758 ± 0.007

q_T imbalance: take home message

q_T-imbalance has nice convergence properties but has some limitations, which makes the extension at higher orders more complex:

- The observable is defined through a jet algorithm, which induces a dependence on an additional cutting variable (the jet radius R)

- The resummation of q_T-imbalance involves additional difficulties such as NGL entering at $\mathcal{O}(\alpha_s^2)$

We look for a variable which has:

- Same convergence properties of q_T-imbalance: **linear scaling** (or better)
- Does not feature NGL
- Can be easily extended to an **arbitrary number of jets**

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k_T-ness: operative definition

We look for a observable that discriminates the transition $N+1 \to N$ jets 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

For one extra emission, the above list is easily fulfilled if we define

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

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^{ness}

k_T-ness: non-local subtraction

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

We can modify its definition in a such way that in **the 0-jet case k_T^{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

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

All the perturbative ingredients at one-loop for building a NLO non-local subtraction scheme can be worked out in a way similar to what done for q_T imbalance. The structure of the counterterm is **remarkably simple**

$$\hat{\sigma}_{\text{NLO}\,ab}^{\text{CT,F+Njets}} = \frac{\alpha_s}{\pi}\frac{dk_t^{\text{ness}}}{k_t^{\text{ness}}}\left\{\left[\ln\frac{Q^2}{(k_t^{\text{ness}})^2}\sum_\alpha C_\alpha - \sum_\alpha \gamma_\alpha - \sum_i C_i \ln\left(D^2\right) - \sum_{\alpha\neq\beta}\mathbf{T}_\alpha\cdot\mathbf{T}_\beta \ln\left(\frac{2p_\alpha\cdot p_\beta}{Q^2}\right)\right]\times\right.$$
$$\left.\delta_{ac}\delta_{bd}\delta(1-z_1)\delta(1-z_2) + 2\delta(1-z_2)\delta_{bd}P_{ca}^{(1)}(z_1) + 2\delta(1-z_1)\delta_{ac}P_{db}^{(1)}(z_2)\right\}\otimes d\hat{\sigma}_{\text{LO}\,cd}^{\text{F+N jets}}$$

$$\gamma_q = 3C_F/2$$

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

$\mathscr{H}$ 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 q_T), **jet** and **soft** functions (which we computed)

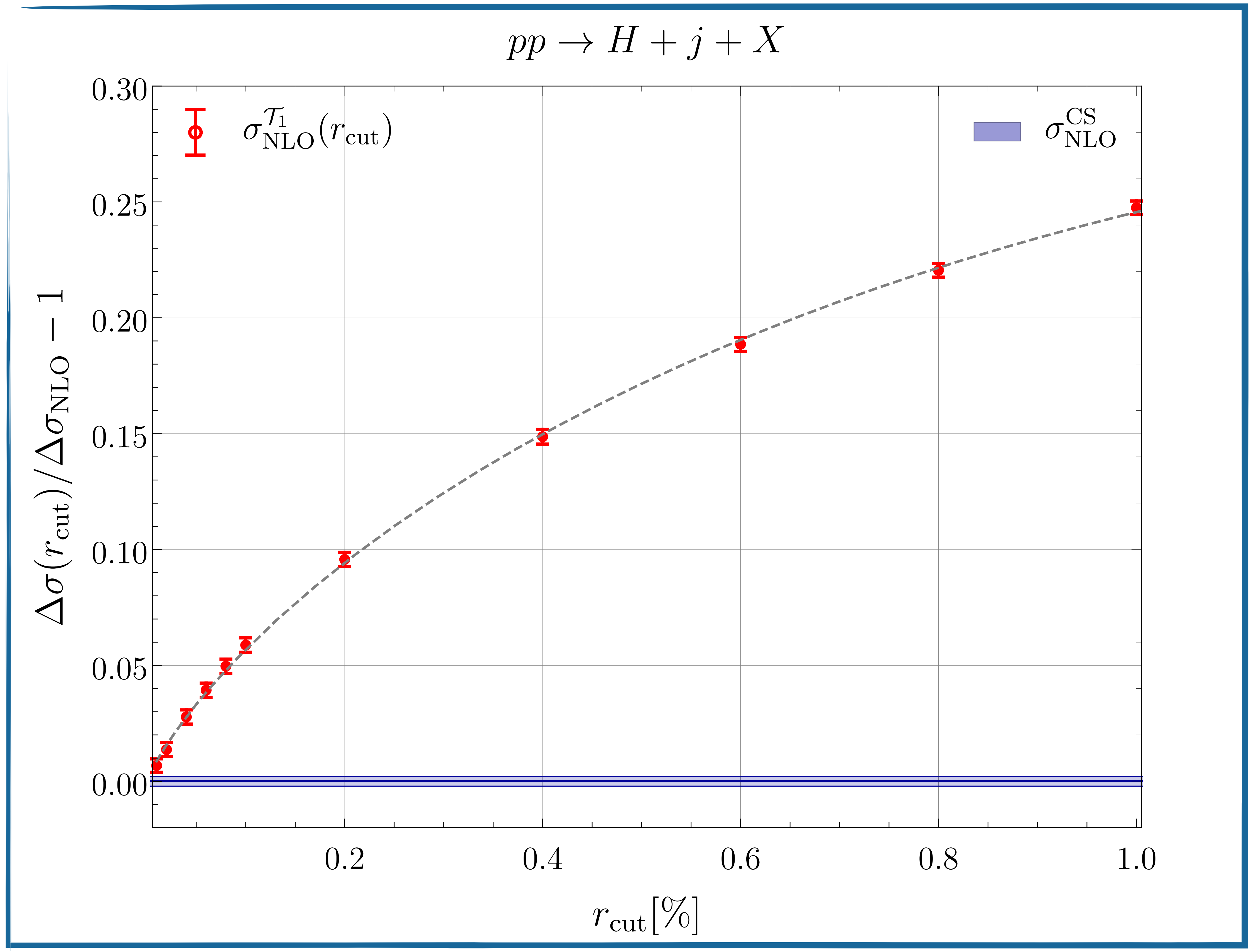
k_T-ness: power corrections (numerical analysis)

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

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



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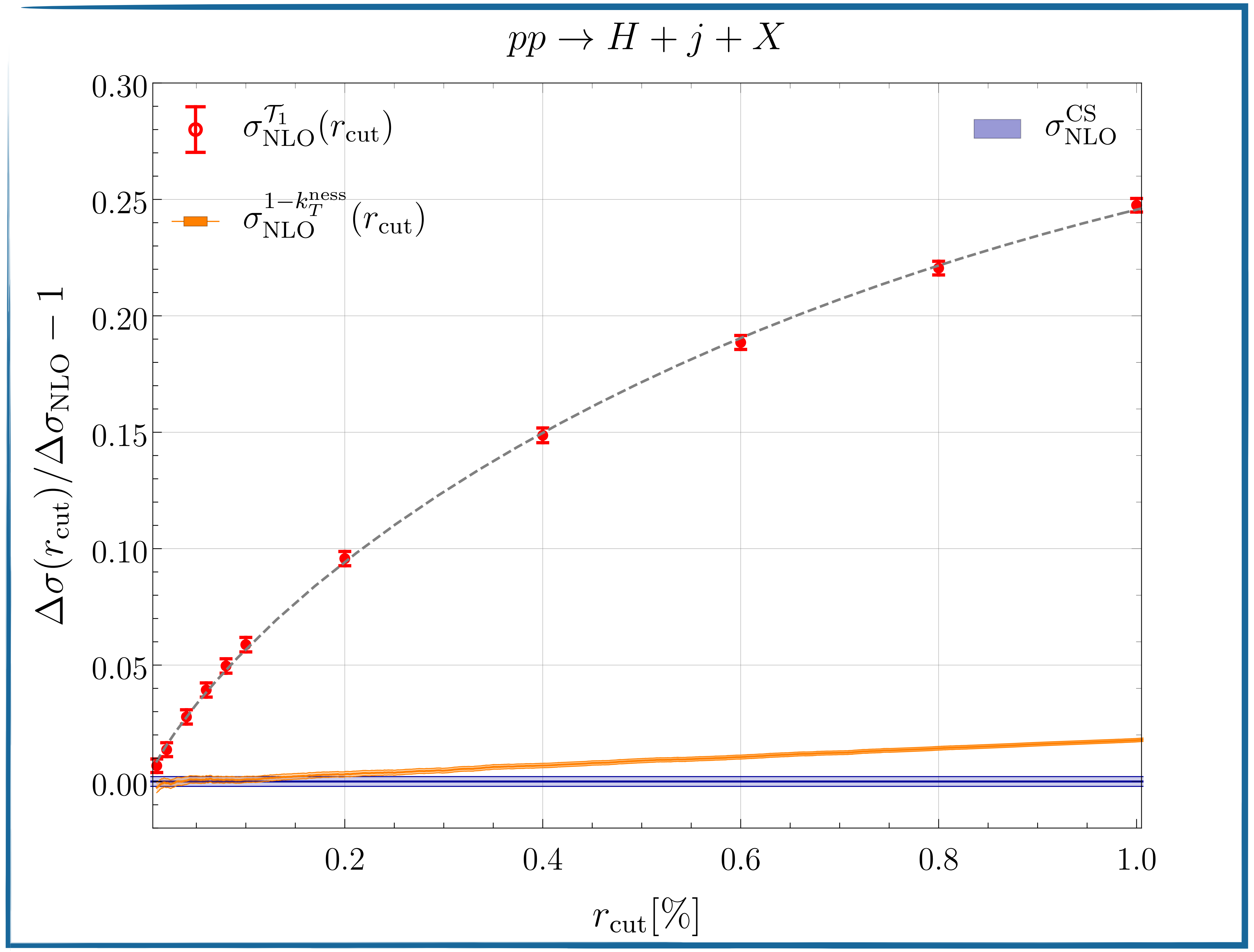


Faster convergence, power corrections compatible with **purely linear behaviour**

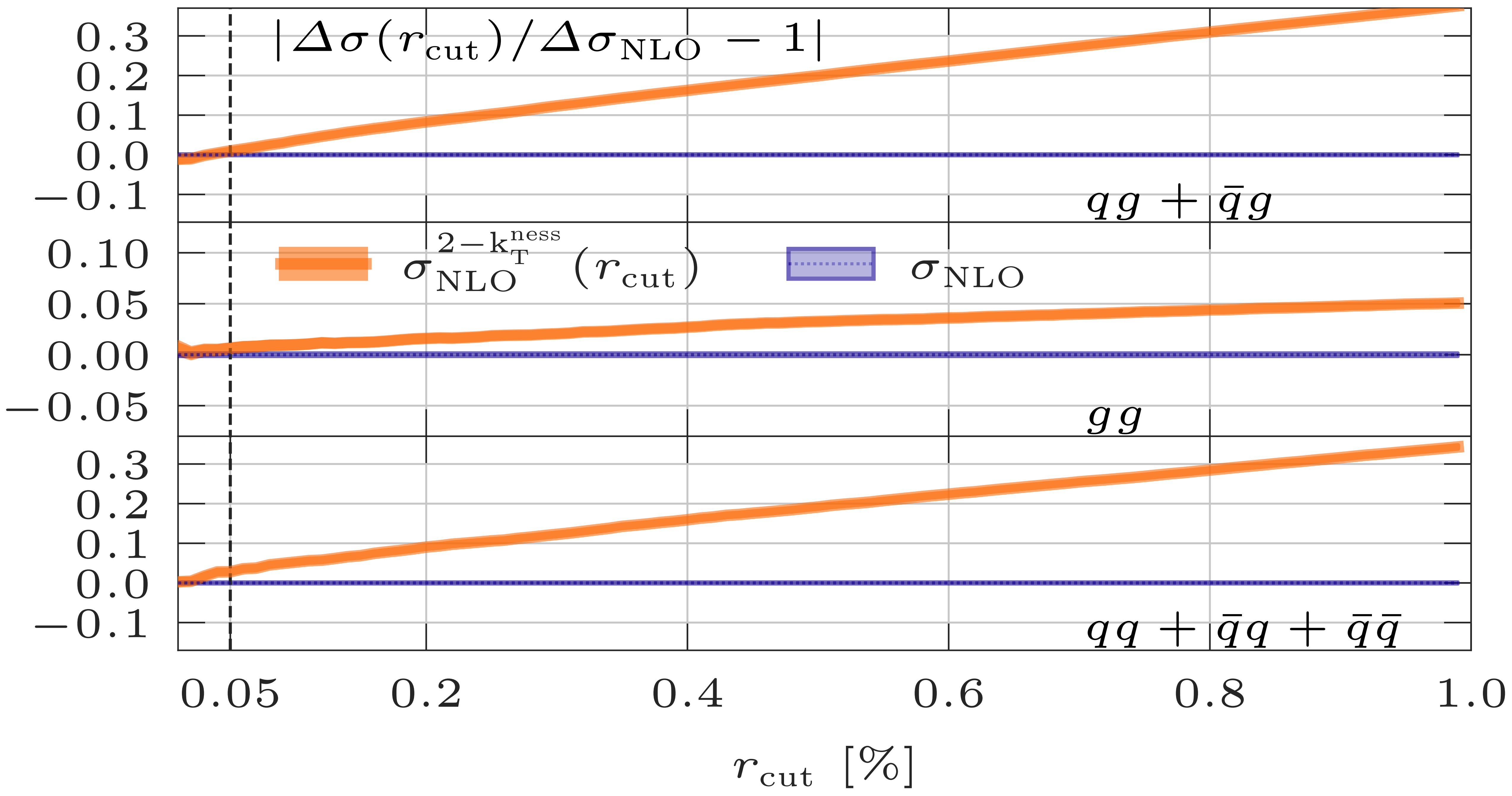
Excellent control of the NLO correction

k_T-ness: power corrections (numerical analysis)

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

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

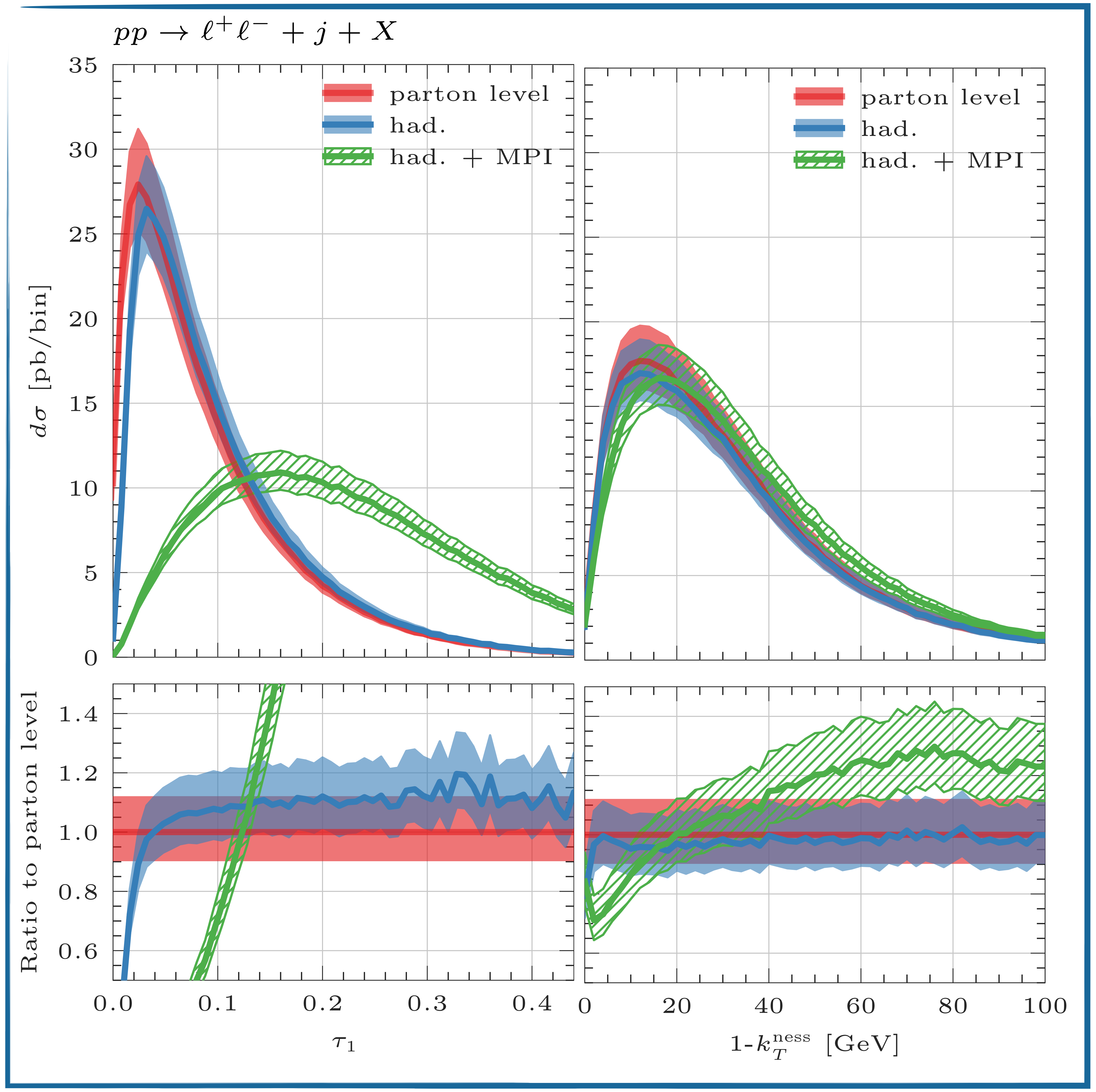
We set the parameter D=0.1 and we require $p_T^j > 30$ GeV.



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

Excellent control of the NLO correction

k_T-ness: all-order analysis



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^{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

Outline

- Intro&Motivations
- Transverse observables for jet cross sections: q_T imbalance
- Transverse observables for jet cross sections: k_T^{ness}
- Case study: $e^+e^- \to 2$ jets $+ X$ detour
- Conclusions&Outlook

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

[LB, Grazzini, Guadagni, Rottoli in preparation]

Consider dijet production in electron-positron collisions. We observe that

- $k_T^{\rm ness}$ reduces to a y_{23}-like variable, defined with the k_T jet algorithm. In this case, we can consider also the original y_{23} as a viable resolution variable
- it is the simplest possible process with only one FSR dipole configuration at the Born level (FSR analog of the q_T for color singlet production)

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**

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

Origin: by comparing with q_T, we argue that there is a "soft-wide angle" contribution which does not completely cancel for color conservation and color coherence

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

[LB, Grazzini, Guadagni, Rottoli in preparation]

The subtracted current is indeed

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

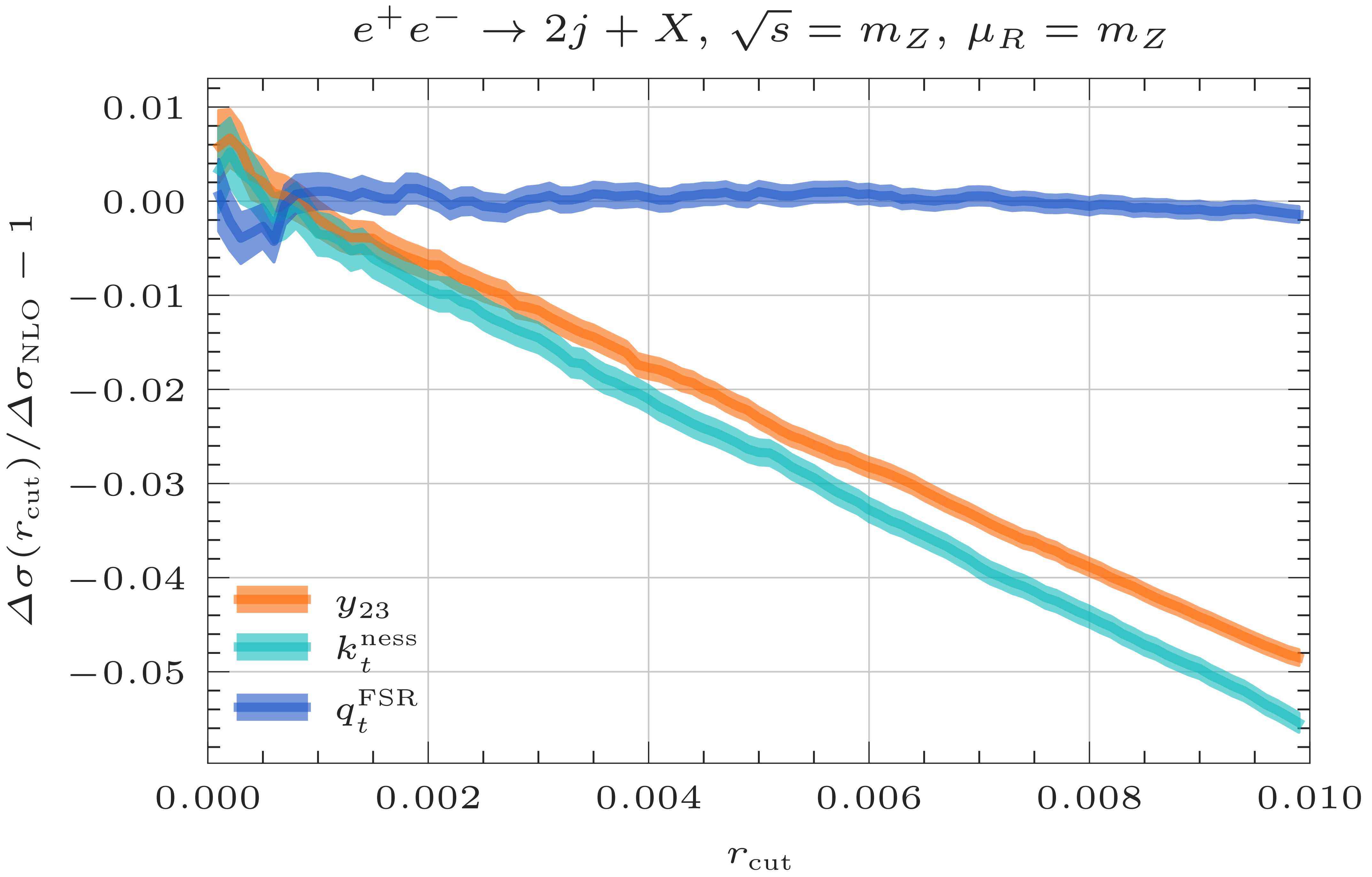
$$\equiv -\,T_1\cdot T_2\;\omega_{12}\;\Theta(r_{\rm cut}-\min(d_{1k},d_{2k})) - T_1^2\;\omega_1\;\Theta(r_{\rm cut}-d_{1k}) - T_2^2\;\omega_2\;\Theta(r_{\rm cut}-d_{2k}) \neq 0$$

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

As a counter-example, we can 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



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Conclusions&Outlook

- 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
- We studied transverse variables in $e^+e^- \to 2$ jets $+ X$ at NLO and we investigated their scaling properties
- Computation of α_s^2 ingredients (jet, soft functions) required to reach NNLO accuracy

BACKUPS

q_T imbalance: resummation

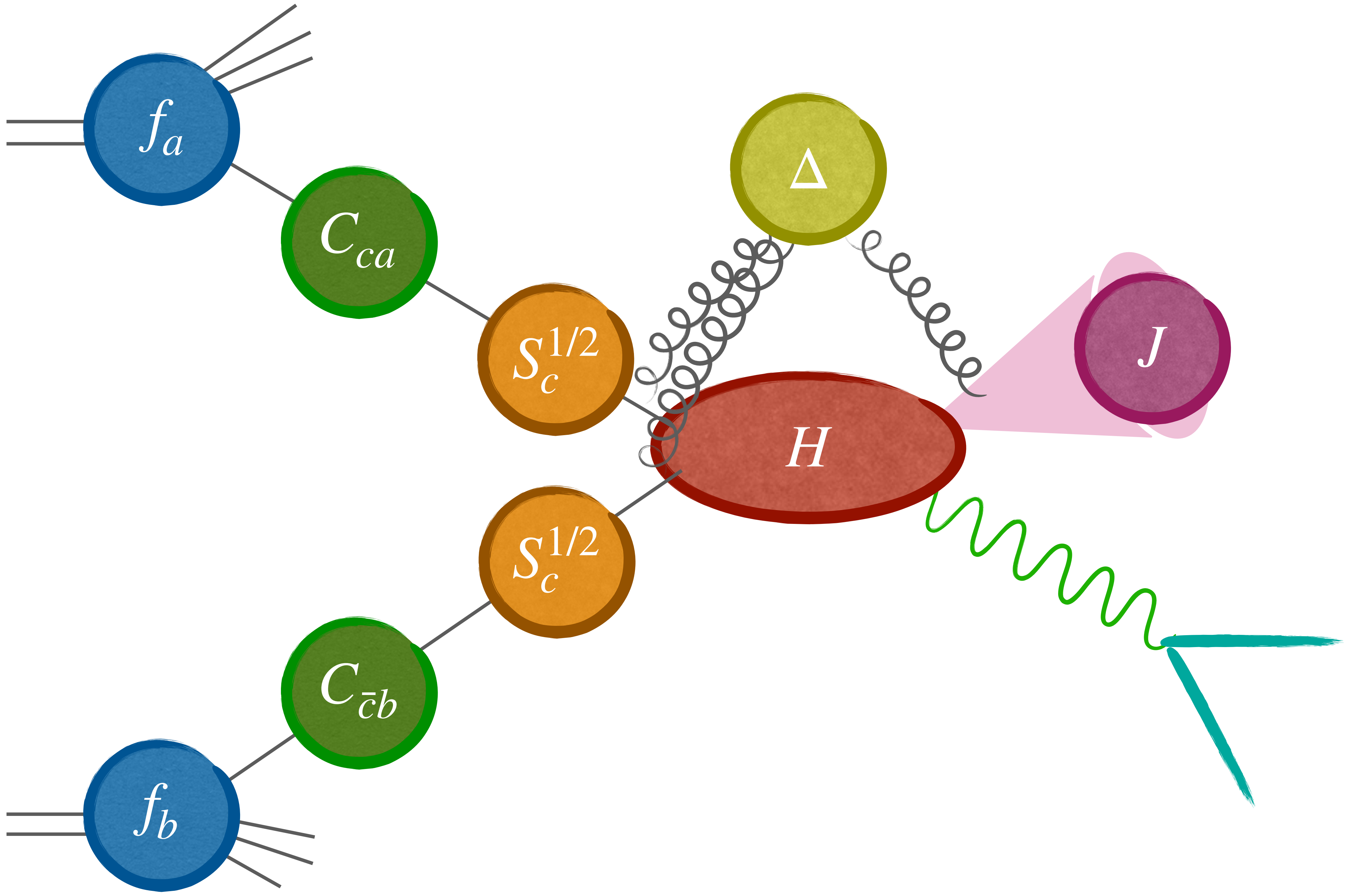
Fully differential resummation formula at NLL (for **global** contribution) in **impact parameter b-space**

$$\frac{d\sigma}{d^2\mathbf{q_T}dQ^2dy\,d\boldsymbol{\Omega}} = \frac{Q^2}{2P_1\cdot P_2}\sum_{(a,c)\in\mathcal{I}}[d\sigma^{(0)}_{ac}]\int\frac{d^2\mathbf{b}}{(2\pi)^2}e^{i\mathbf{b}\cdot\mathbf{q_T}}\mathcal{S}_{ac}(Q,b)$$

$$\times\sum_{a_1,a_2}\int_{x_1}^1\frac{dz_1}{z_1}\int_{x_2}^1\frac{dz_2}{z_2}[(\mathbf{H\Delta})C_1C_2]_{ac;a_1a_2}f_{a_1/h_1}(x_1/z_1,b_0^2/b^2)f_{a_2/h_2}(x_2/z_2,b_0^2/b^2)$$

$$\mathcal{S}_{ac}(Q,b) = \exp\left\{-\int_{b_0^2/b^2}^{Q^2}\frac{dq^2}{q^2}\left[A_{ac}(\alpha_s(q^2))\ln\frac{Q^2}{q^2}+B_{ac}(\alpha_s(q^2))\right]\right\}$$

$[(\mathbf{H\Delta})C_1C_2]_{ac;a_1a_2}$ Contains additional contribution which starts at NLL accuracy and describes QCD radiation of **soft-wide angle radiation** (colour singlet: $\boldsymbol{\Delta}=1$)



q_T imbalance: non-local subtraction

[M. Costantini Master's thesis, UZH]

Exact dependence on the jet radius crucial to ensure the cancellation of logarithmic enhanced terms