

Effective transverse momentum in multijet production at hadron colliders

Chíara Savoíní

University of Zürich

(based on the paper **2201.11519**, in collaboration with *L. Buonocore, M. Grazzini, J. Haag, L. Rottoli*)

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**Universität
Zürich^{UZH}**

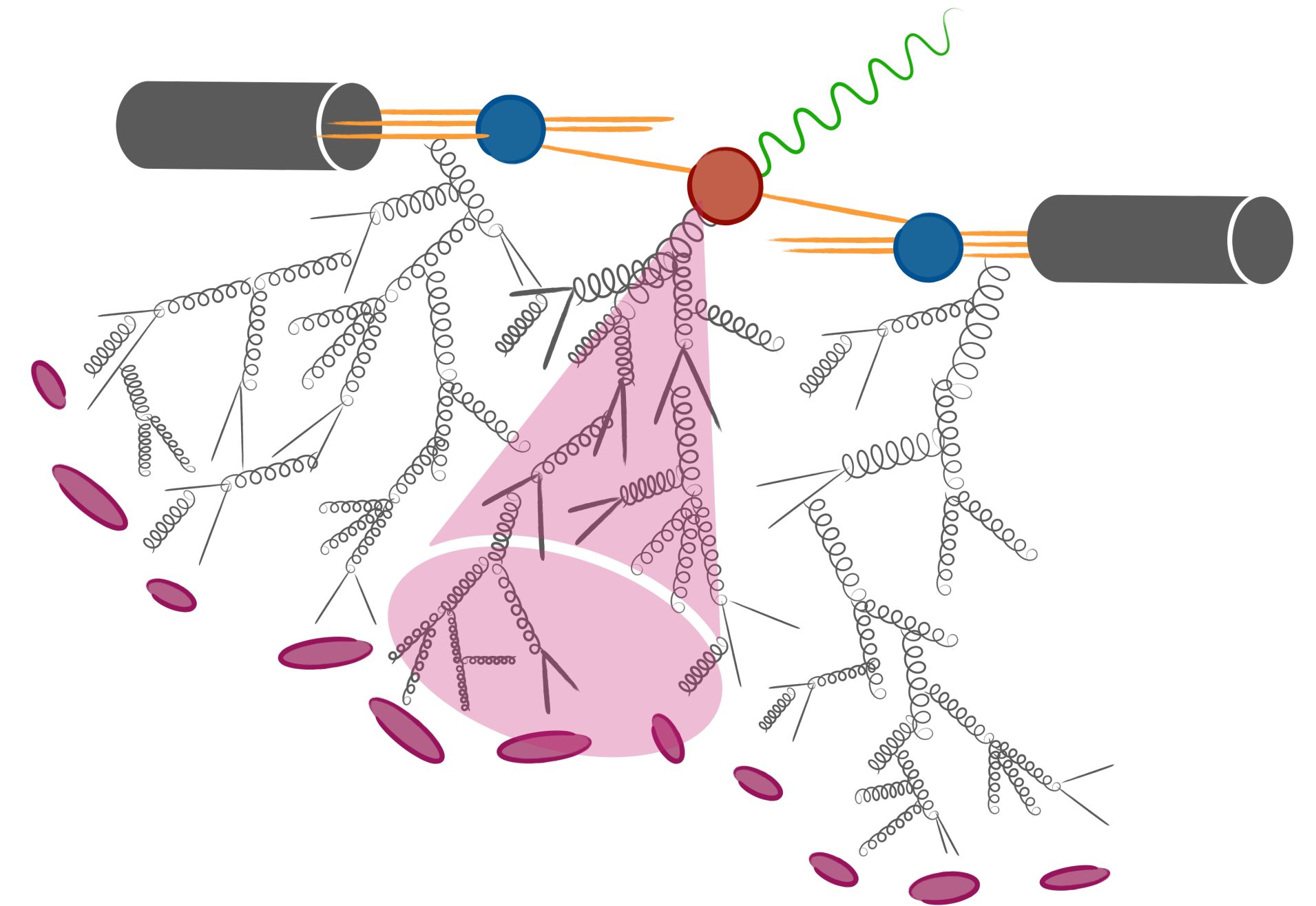
Introduction

Jet physics @ LHC :

- ▶ jets are **collimated bunches** of hadrons that represent the **fingerprints** of the high-energy partons produced in the hard-scattering interaction
- ▶ jets are **ubiquitous** at the LHC
- ▶ experimental analyses categorise events into **jet bins** according to jet multiplicity
(*BSM searches, signal-background discrimination*)
- ▶ undesired additional radiation is vetoed by cutting on

jet resolution variables:

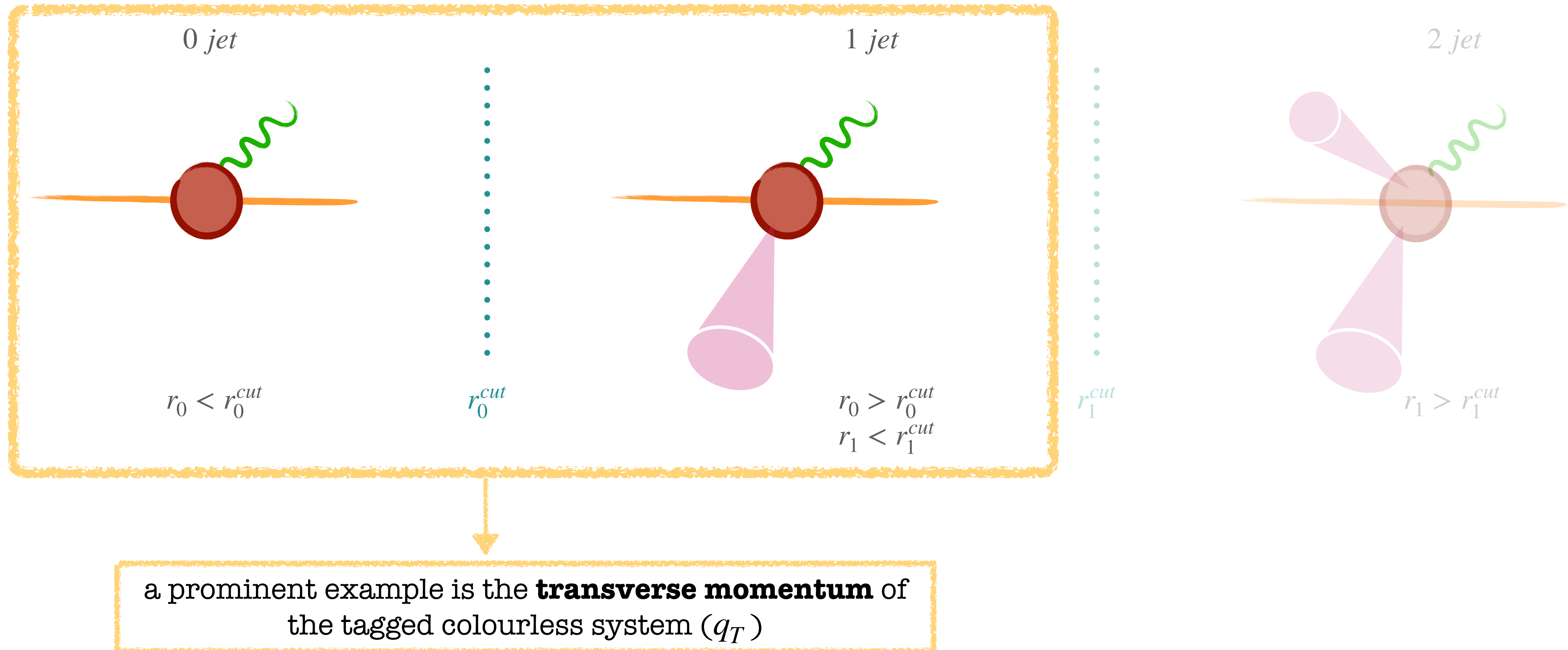
observables capable to capture the deviation from the LO energy flow, which characterises the bulk of the events



Introduction

Jet resolution variables (0-jet case):

- 0-jet resolution variables should smoothly capture the transition from 0 to 1 jet configuration



Introduction

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q_T -subtraction (0-jet case):

- q_T is a good resolution variable for processes that do **not** involve **jets at Born level** [Catani, Grazzini (2007)]
- it captures the $0 \rightarrow 1$ jet transition ($q_T = 0$ if no hard jets are found, $q_T > 0$ if at least one hard jet is tagged)
- it can be used as a **slicing variable**, to regularise IR-singularities, for colour-singlet and heavy-quark production
(for $q_T > 0$, only $N^{n-1}LO$ -type singularities can appear @ N^nLO)

[in MATRIX, NNLO computations publicly available for $pp \rightarrow V, H, VV, HH, \gamma\gamma, \gamma\gamma\gamma, V\gamma, t\bar{t}$]

[Grazzini, Kallweit, Wieseemann (2017)] [Catani, Devoto, Grazzini, Kallweit, Mazzitelli (2019,2020)]

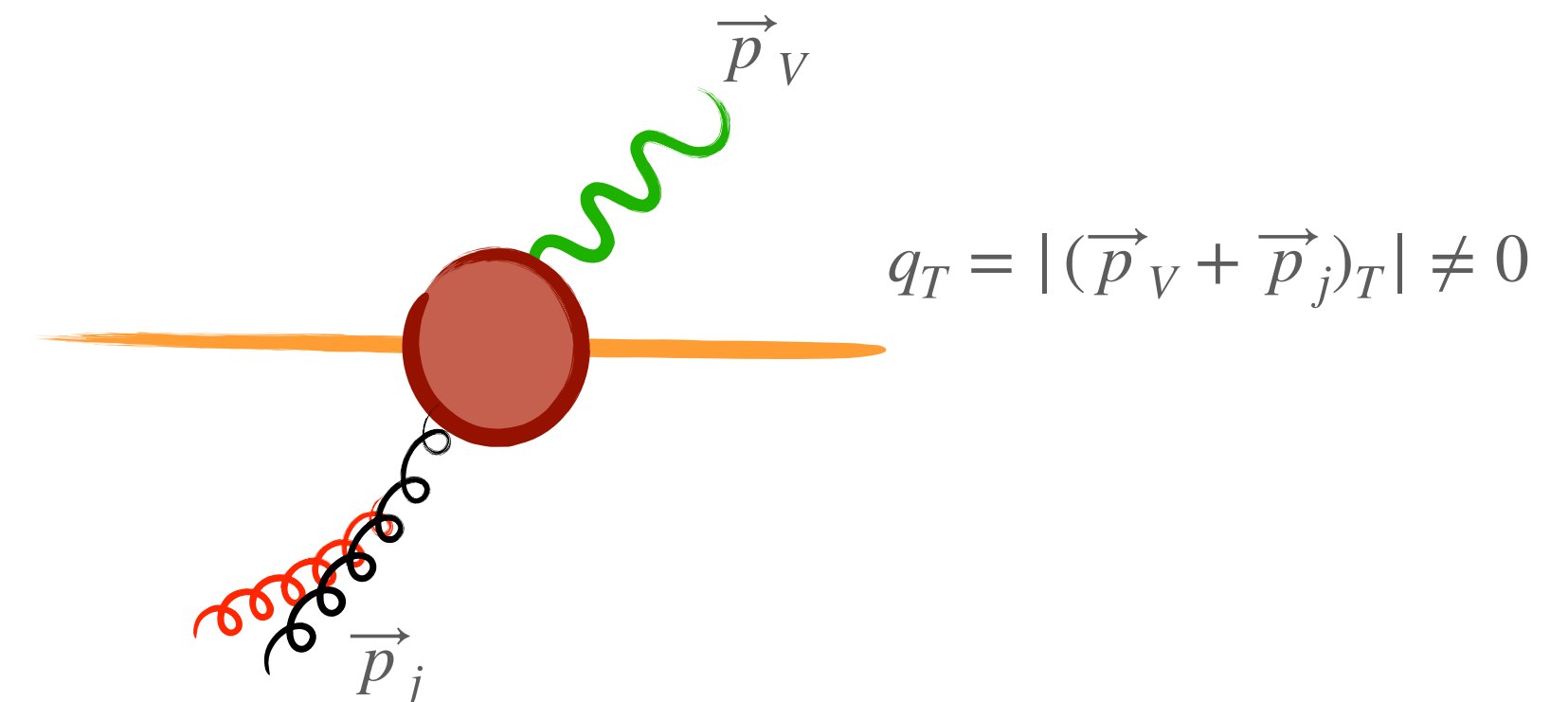
- it has been used @ N^3LO for DY

[Chen, Gehrmann, Glover, Huss, Yang and Zhu (2021)] [Chen, Gehrmann, Glover, Huss, Monni, Rottoli, Re, Torrielli (2022)] [Camarda, Cieri, Ferrera (2022)]

and Higgs production [Billis, Dehnadi, Ebert, Michel, Tackmann (2021)]

drawback:

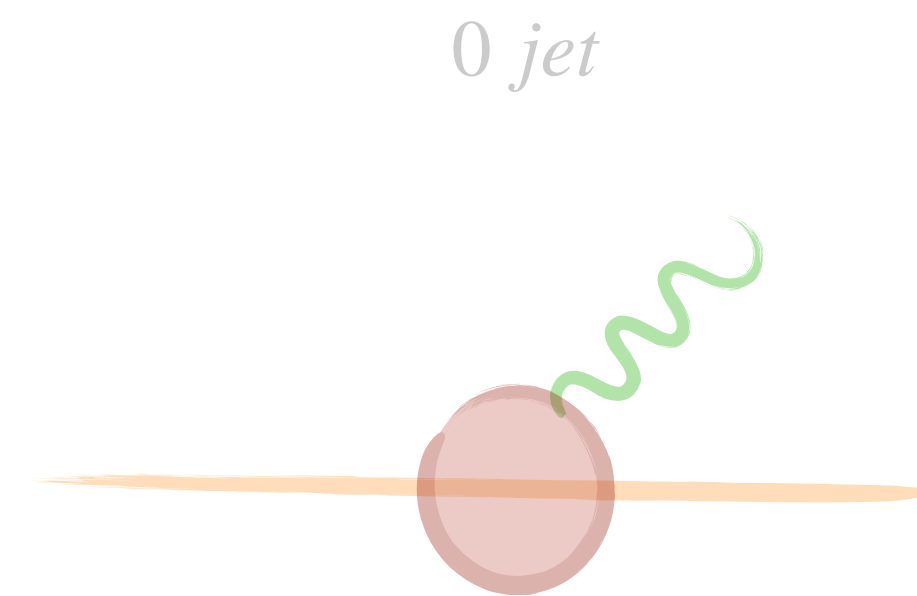
- it cannot regularise **final-state collinear** singularities (FSR)



Introduction

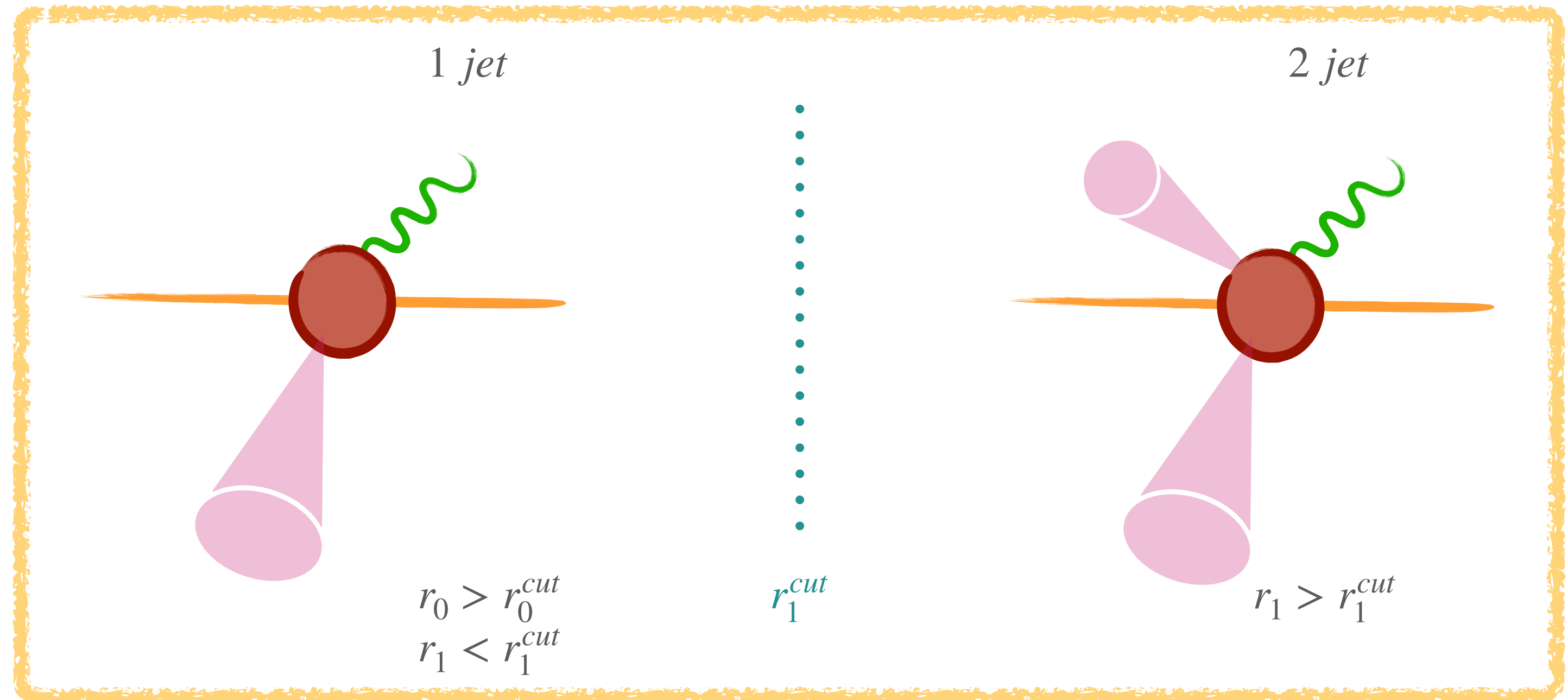
Jet resolution variables (beyond 0-jet case):

- N-jet resolution variables should smoothly capture the transition from N to $N + 1$ jet configuration



$$r_0 < r_0^{cut}$$

r_0^{cut}



Introduction

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\mathcal{N} -jettiness (beyond 0-jet case):

- ▶ N -jettiness (τ_N) [Stewart, Tackmann, Waalewijn (2010)] is so far the **only player in the game!**
- ▶ it measures how **N-jet like** the event looks
- ▶ it has proved a successful resolution variable for processes with 1 *jet* up to NNLO
[$H + jet$: Boughezal, Focke, Giele, Liu, Petriello (2015)], [$Z + jet$: Boughezal, Campbell, Ellis, Focke, Giele, Liu, Petriello (2016)],
[$W + jet$: Boughezal, Liu, Petriello (2016)]
- ▶ no full computation available for 2-jettiness

drawbacks:

- ▶ **large missing power corrections** (logarithmically enhanced already @NLO)
- ▶ instabilities under hadronisation and multiple-parton interactions (MPI)

it may prove worthwhile to **explore other resolution variables** which overcome some of the shortcomings of jettiness:

- smaller power corrections
- more direct experimental evidence

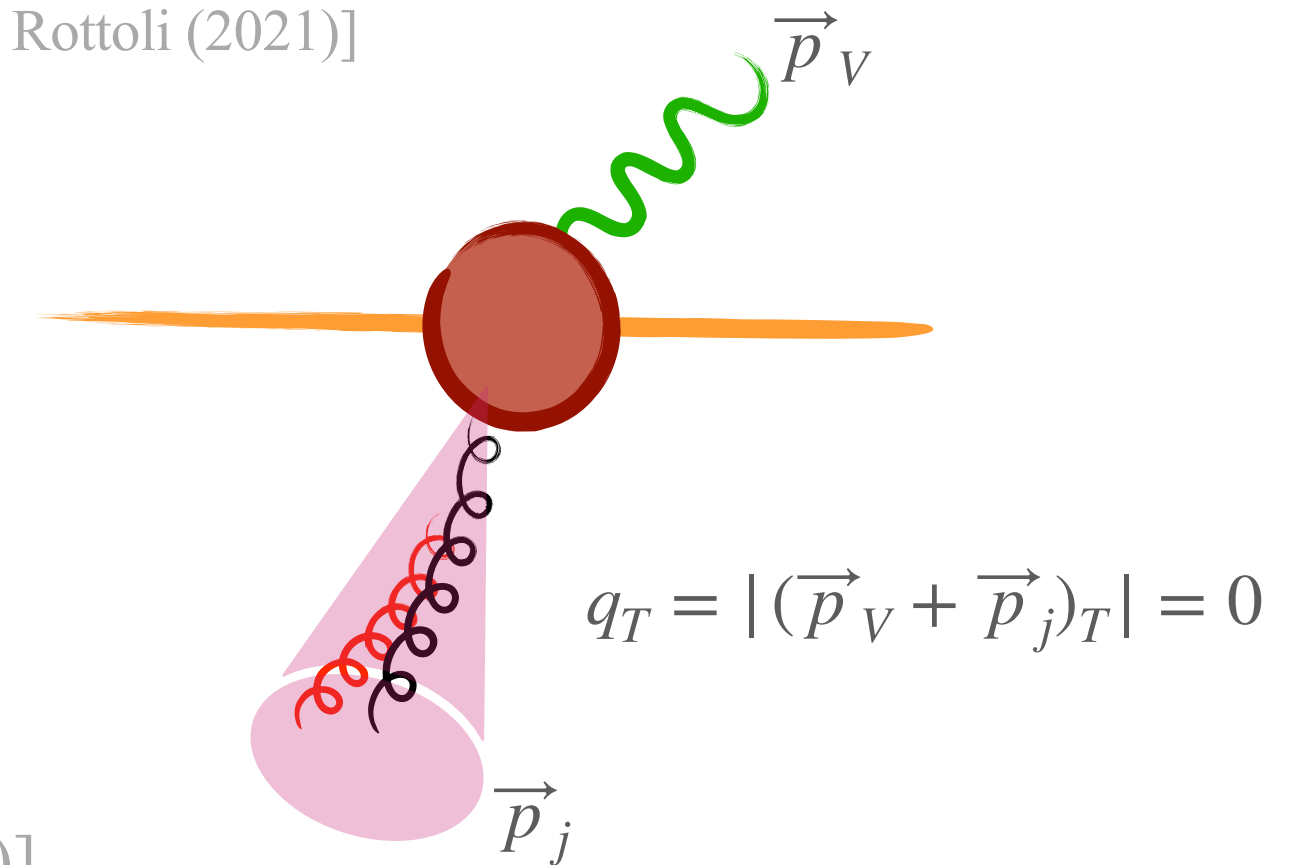
Exploring jet resolution variables

q_T -imbalance (for $V + 1jet$ processes):

[Buonocore, Grazzini, Haag, Rottoli (2021)]

- ▶ it is the **natural extension** of the transverse momentum used in the colour-singlet case
- ▶ it is defined as the transverse momentum of the $V + 1jet$ system after applying a **clustering algorithm** (anti- k_T with radius R)
- ▶ resummation formula up to NLL'
- ▶ it was applied as a slicing parameter @NLO for $H + 1jet$ [M.Costantini, Master thesis, UZH (2021)]

→ linear power corrections



drawbacks:

- ▶ dependence of the observable on the additional cutting variable R (the extension to higher orders is more complicated)
- ▶ presence of **non-global logarithms** starting @NNLO

Exploring jet resolution variables

main goal: find an “IDEAL” jet resolution variable with the following properties

- ▶ dimensional variable able to capture the $N \rightarrow N + 1$ jet transition
- ▶ global
- ▶ extendable to any number of jets
- ▶ variable that reduces to q_T in the 0-jet case and for ISC radiation
- ▶ nice convergence properties (linear scaling or better)
- ▶ stable under hadronisation and MPI

does such a
variable exist ?



Our proposal: k_T^{ness}

- we consider a process with **N -jets at Born level**, possibly accompanied by a generic colourless system F

$$h_1(P_1) + h_2(P_2) \rightarrow j(p_1) + \dots + j(p_N) + F(p_F) + X$$

- we introduce the usual distances between partons

$$d_{ij} = \min(p_{T,i}, p_{T,j}) \frac{\Delta R_{ij}}{D} \quad \text{with} \quad \Delta R_{ij} = \sqrt{(y_i - y_j)^2 + (\phi_i - \phi_j)^2} \quad \text{and} \quad d_{iB} = p_{T,i}$$

- we can define N - k_T^{ness} via a **recursive procedure** by applying an exclusive k_T clustering algorithm until $N+1$ jets remain
- physically, the variable represents an **effective transverse momentum**:
 - if the unresolved radiation is close to the beams (ISR), k_T^{ness} is the transverse momentum of the hard system
 - if the unresolved radiation is collinear to one of the final-state jets (FSR), k_T^{ness} describes the relative transverse momentum of the hard system wrt the jet direction

Handling of IR-singularities

k_T^{ness} -subtraction:

- we consider the NLO cross section, at the partonic level, $d\hat{\sigma}_{NLO} = d\sigma_V + d\sigma_R$ and we introduce a slicing cut r_{cut} on the variable $r = k_T^{\text{ness}}/M$:

$$d\hat{\sigma}_{NLO} = (d\sigma_V + d\sigma_R)\Theta(r_{\text{cut}} - r) + d\sigma_R\Theta(r - r_{\text{cut}})$$

jet resolution scale

- the **master formula** for NLO subtraction is

$$d\hat{\sigma}_{NLO}^{F+Njets+X} = \mathcal{H}_{NLO}^{F+Njets} \otimes d\hat{\sigma}_{LO}^{F+Njets} + [d\hat{\sigma}_{LO}^{F+(N+1)jets} - d\hat{\sigma}_{NLO}^{CT,F+Njets}]_{r>r_{\text{cut}}}$$

where the **counterterm** is

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

with $\gamma_q = \frac{3}{2}C_F$ and $\gamma_g = \frac{11C_A - 2n_f}{6}$

Numerical results

Setup and implementation

- we implemented k_T^{ness} -subtraction @NLO, for processes with 1 and 2 jets, in a **private Fortran code**. The subtraction is now implemented, for an arbitrary number of jets, also in the **MATRIX** framework [work done by J.Haag and S.Kallweit]
- we consider **proton-proton collisions** @ LHC with $\sqrt{s} = 13$ TeV
- the parameters common to all studied processes are:

- $G_F = 1.16639 \times 10^{-5} \text{ GeV}^{-2}$ (G_μ scheme to treat the EW input parameters)
- $m_W = 80.385 \text{ GeV}$
- $m_Z = 91.1876 \text{ GeV}$ $\Gamma_Z = 2.4952 \text{ GeV}$
- $m_H = 125 \text{ GeV}$
- anti- k_T algorithm with $R = 0.4$
- NNPDF_nlo_as_0118 with $\alpha_s(m_Z) = 0.118$

Numerical results

$Z + 1\text{jet}$ production: hadronisation and MPI effects

$$p_T^j > 30 \text{ GeV}$$

$$|y^j| < 2.5$$

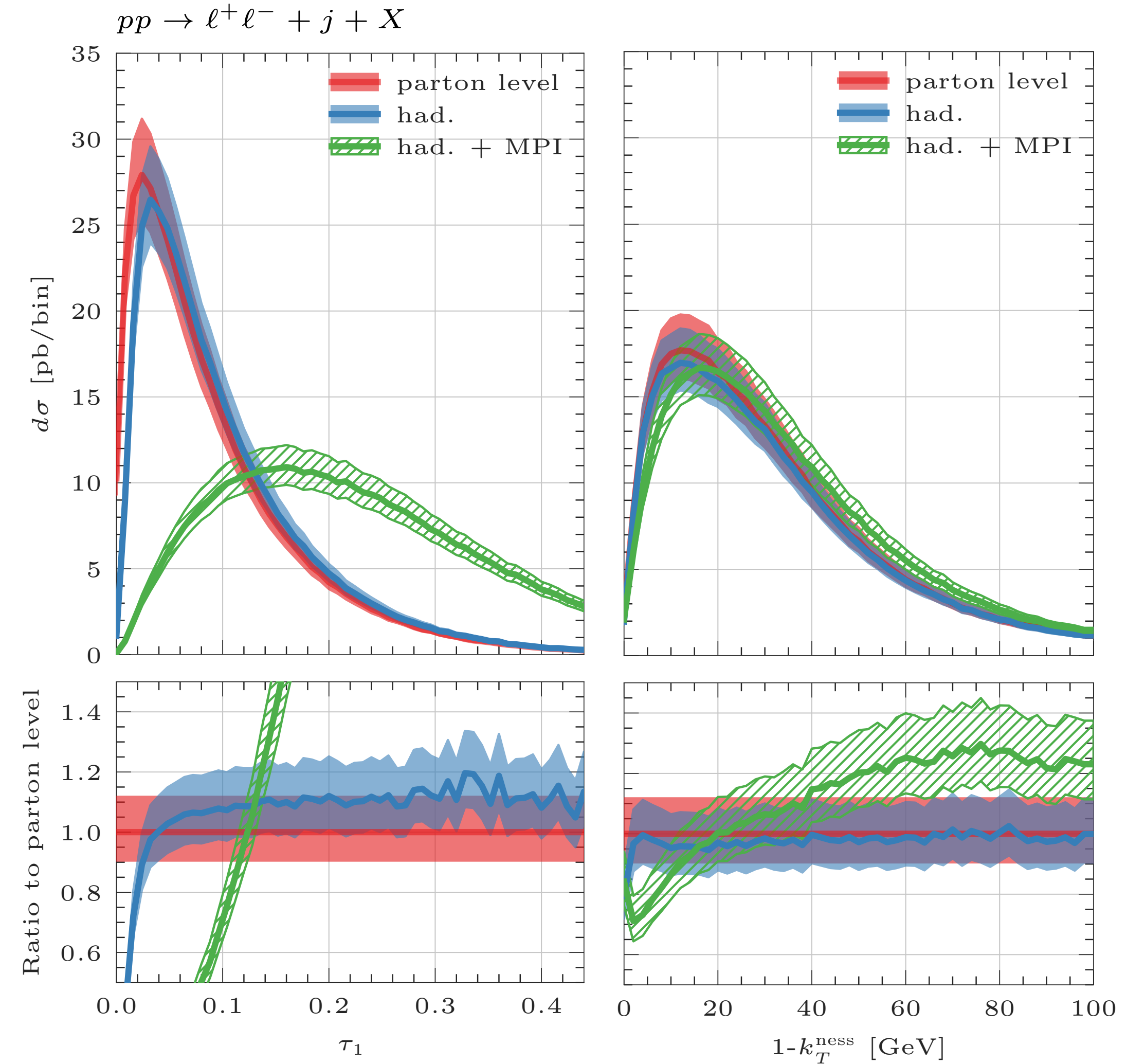
$$D = 1$$

$$\mu_R = \mu_F = m_Z$$

- comparison between the results obtained with $1-k_T^{\text{ness}}$ and 1-jettiness (treated as **event shape variables**)

$$\tau_1 = \mathcal{T}_1/Q \quad \mathcal{T}_1 = \sum_i \min_l \left\{ \frac{2q_l \cdot p_i}{Q} \right\}$$

- $1-k_T^{\text{ness}}$ shows a peak at $\sim 15 \text{ GeV}$ which remains stable under hadronisation and MPI
- $1-k_T^{\text{ness}}$ is overall much **more stable** than 1-jettiness



LO events obtained with POWHEG and showered with PYTHIA8 (A14 tune).
FASTJET was used to reconstruct the leading jet and to define k_T^{ness} .

Numerical results

$H + 1jet$ production @NLO

$$p_T^j > 30 \text{ GeV}$$

$$D = 1$$

$$\mu_R = \mu_F = m_H$$

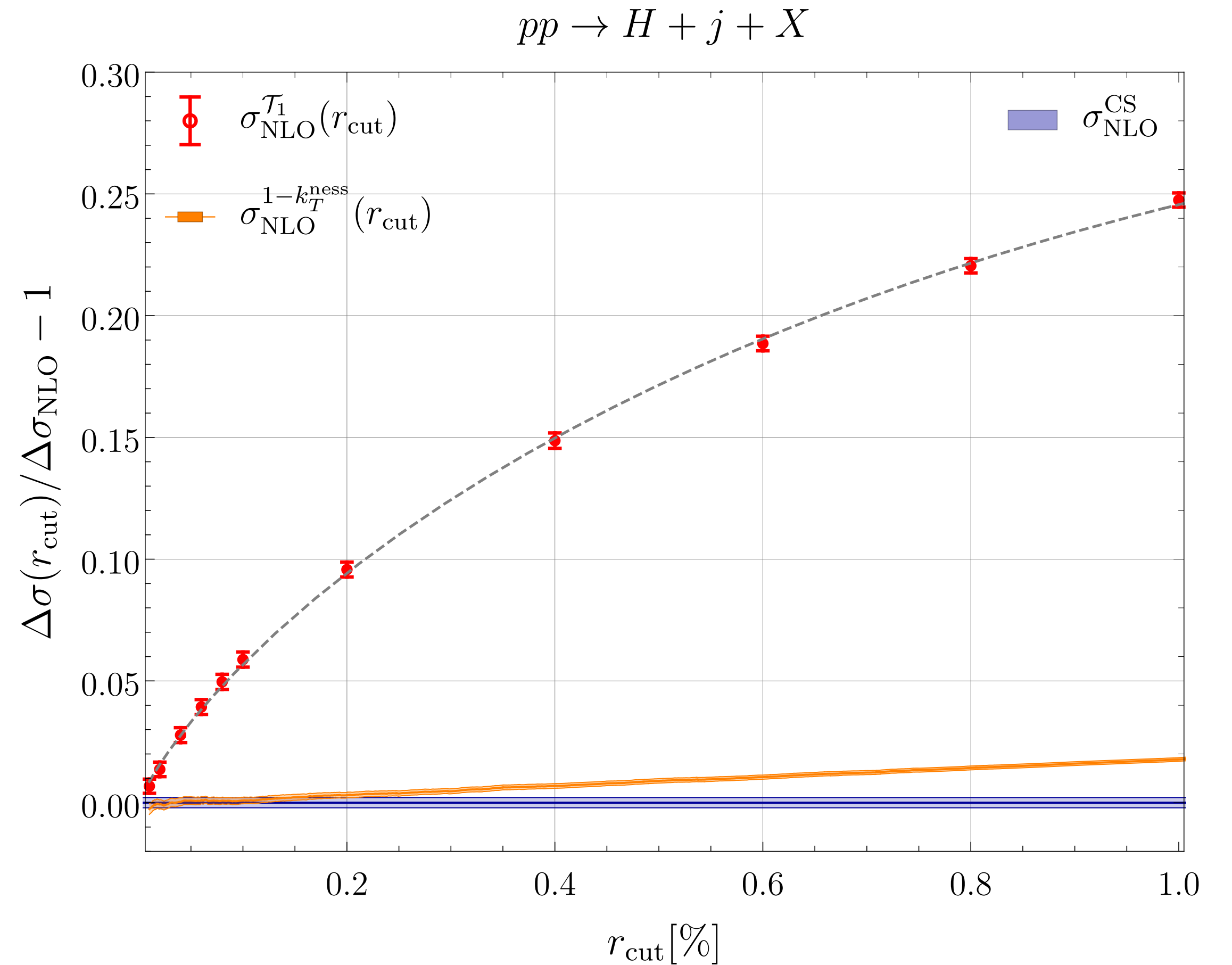
- comparison between the results obtained with $1-k_T^{ness}$ and 1-jettiness.

- the cut is applied on the dimensionless variable

$$r = \mathcal{T}_1 / \sqrt{m_H^2 + (p_T^j)^2} \quad \text{with} \quad \mathcal{T}_1 = \sum_i \min_l \left\{ \frac{2q_l \cdot p_i}{Q_l} \right\}$$

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

- linear** missing power corrections vs logarithmically-enhanced ones



1-jettiness results obtained from a suitably modified version of MCFM

Numerical results

$Z + 2\text{jets production @NLO}$

$$p_T^j > 30 \text{ GeV} \quad |\eta^j| < 4.5$$

$$p_T^l > 20 \text{ GeV} \quad |\eta^l| < 2.5$$

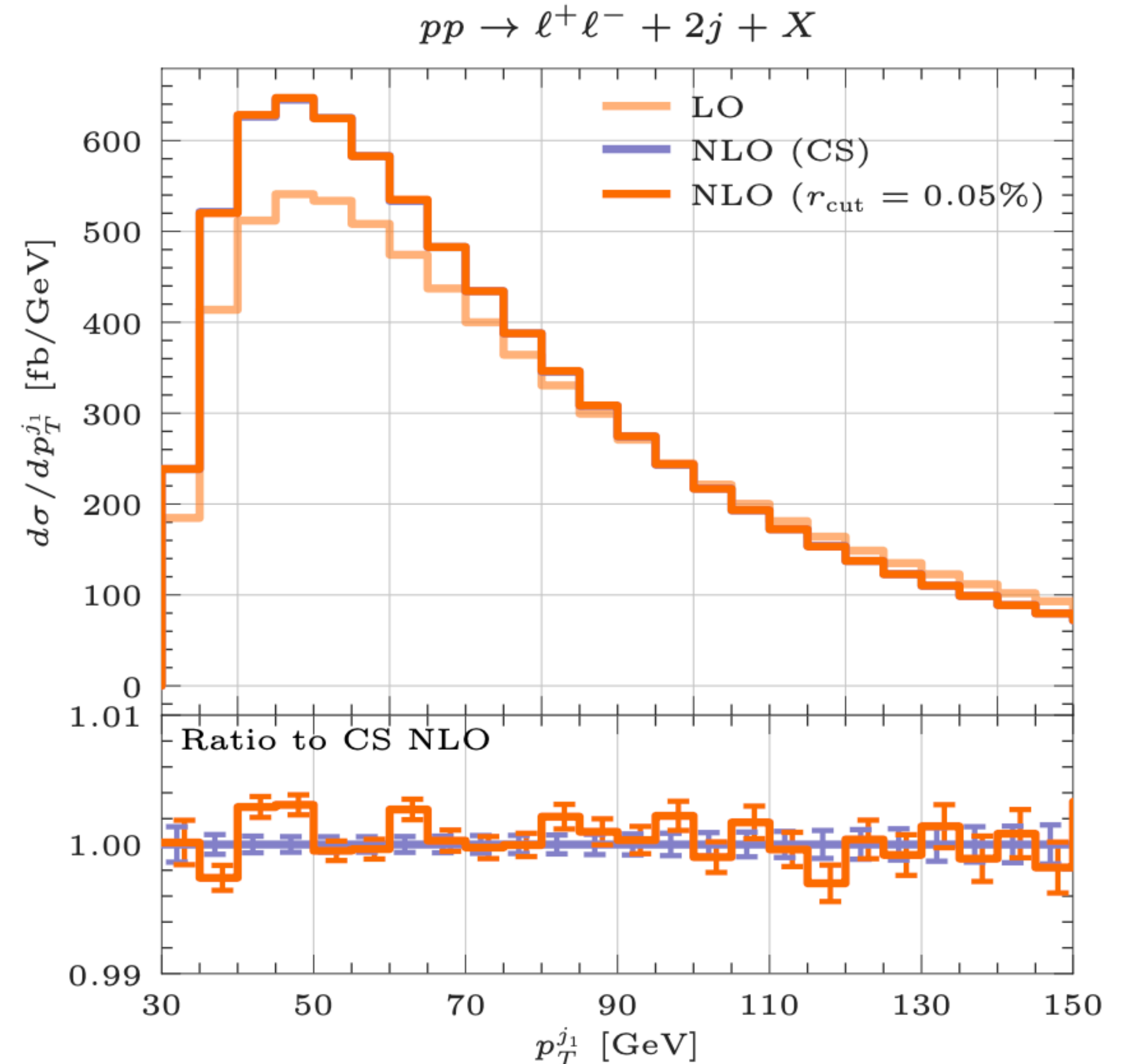
$$66 \text{ GeV} < m_{ll} < 116 \text{ GeV}$$

$$\Delta R_{lj} > 0.5 \quad \Delta R_{ll} > 0.2$$

$$D = 0.1$$

$$\mu_R = \mu_F = m_Z$$

- comparison between the results obtained with $2\text{-}k_T^{\text{ness}}$ and CS local subtraction, at the level of the **differential distributions**
- the cut is applied on k_T^{ness} normalised over the hard scale M which is the transverse mass of the di-lepton system (fixed $r_{\text{cut}} = 0.05 \%$)
- **nice agreement** in all range within uncertainties



The reference NLO result is obtained with MCFM (CS local subtraction).

Conclusions

- ▶ we introduced a new variable k_T^{ness} able to capture the $N \rightarrow N + 1$ jet transition
- ▶ we computed all relevant ingredients necessary for the construction of a subtraction formula @NLO
- ▶ we showed that k_T^{ness} has promising properties: pure linear power corrections, stability under NP effects

- ▶ future goals:
 - extension of the subtraction method @NNLO [ongoing work on Z+1jet]
 - inclusion of processes with heavy quarks plus jets
 - resummation (factorisation in b-space ?)
 - implementation in MATRIX framework

Conclusions

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- ▶ future goals:

- extension of the subtraction method @NNLO [ongoing work on Z+1jet, mainly by J Haag]
- inclusion of processes with heavy quarks plus jets
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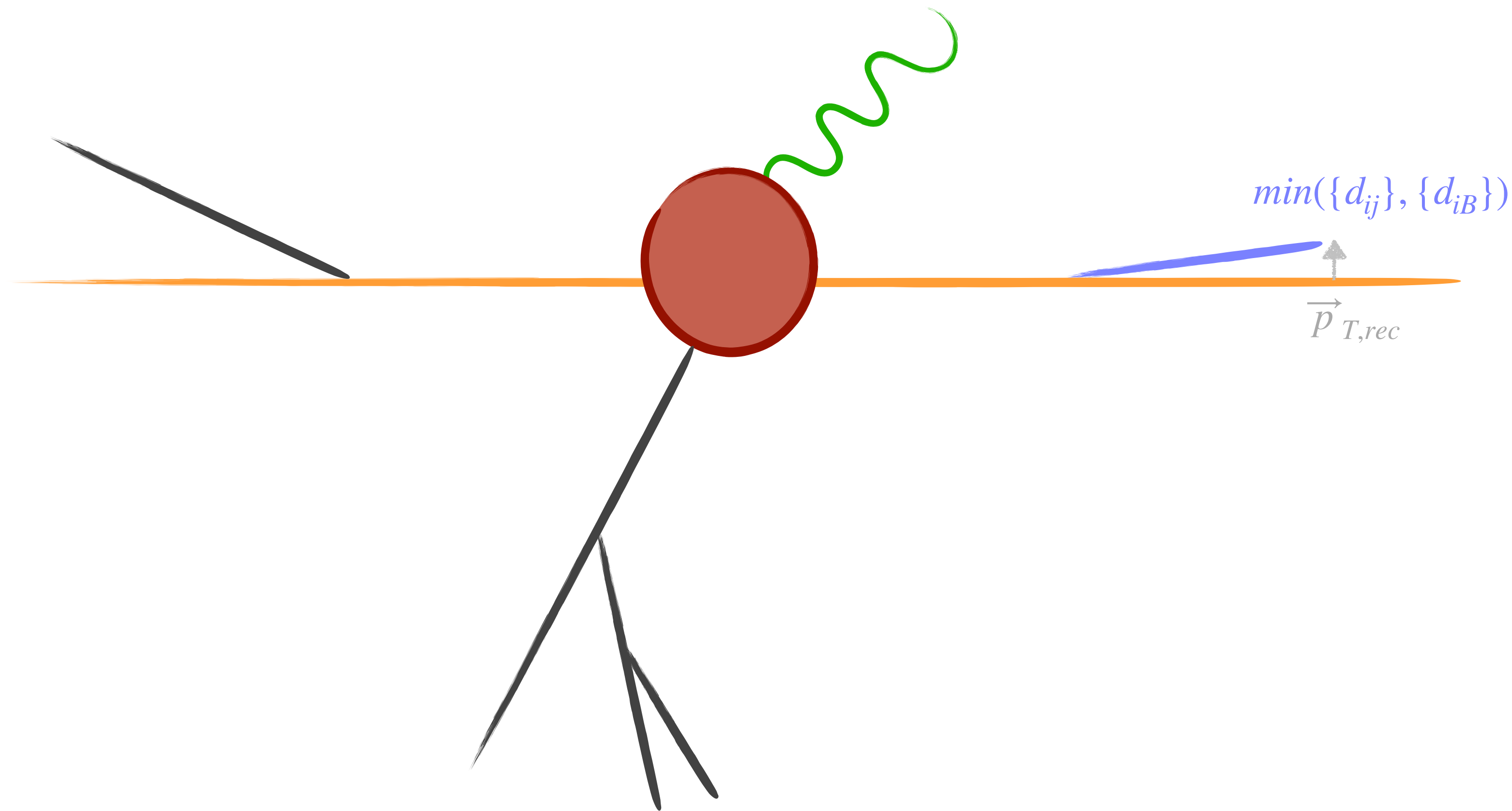
THANKS !

BACKUP SLIDES

Our proposal: k_T^{ness}

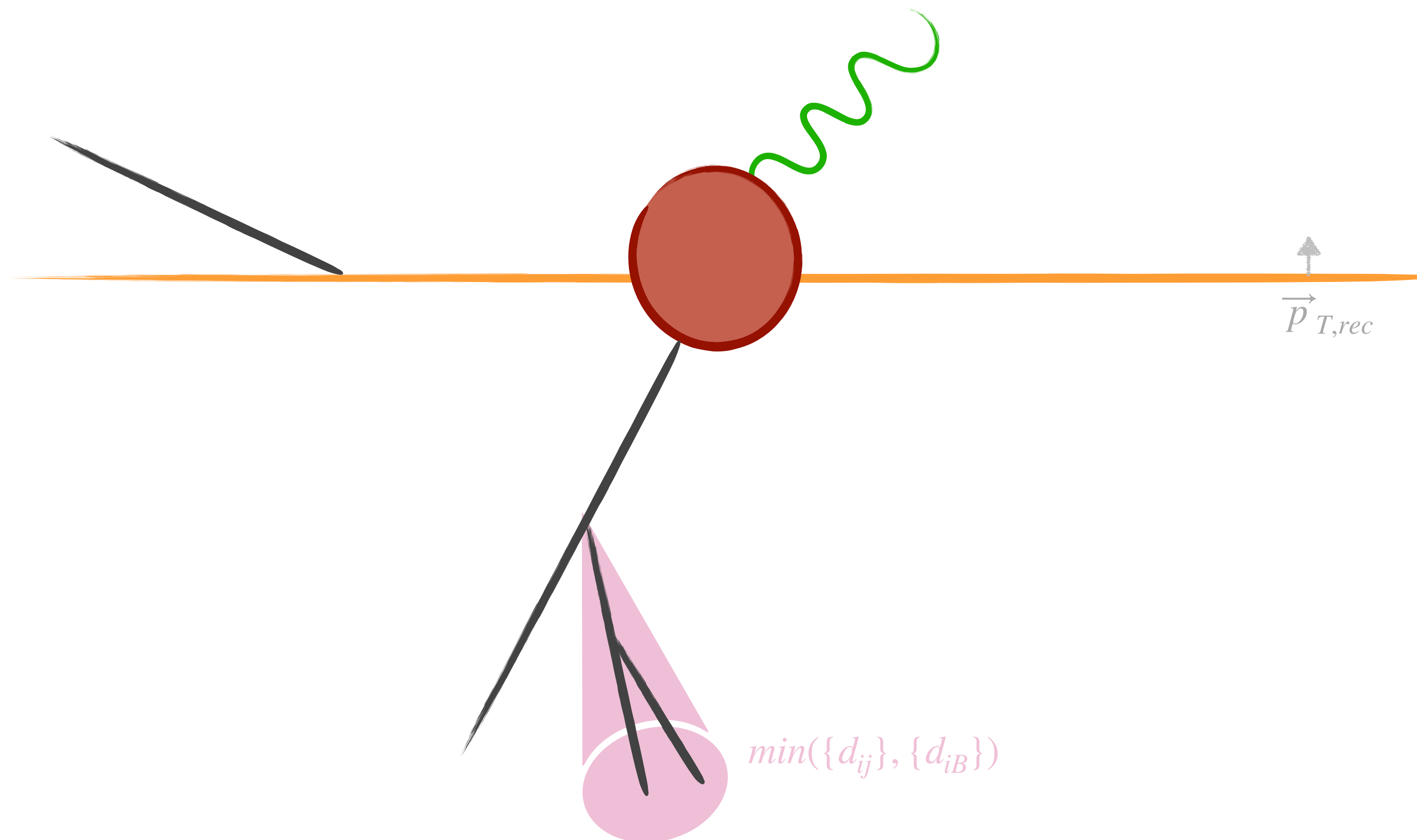
definition: run the exclusive k_T -algorithm till $N + 1$ proto-jets are left

example of $1-k_T^{ness}$



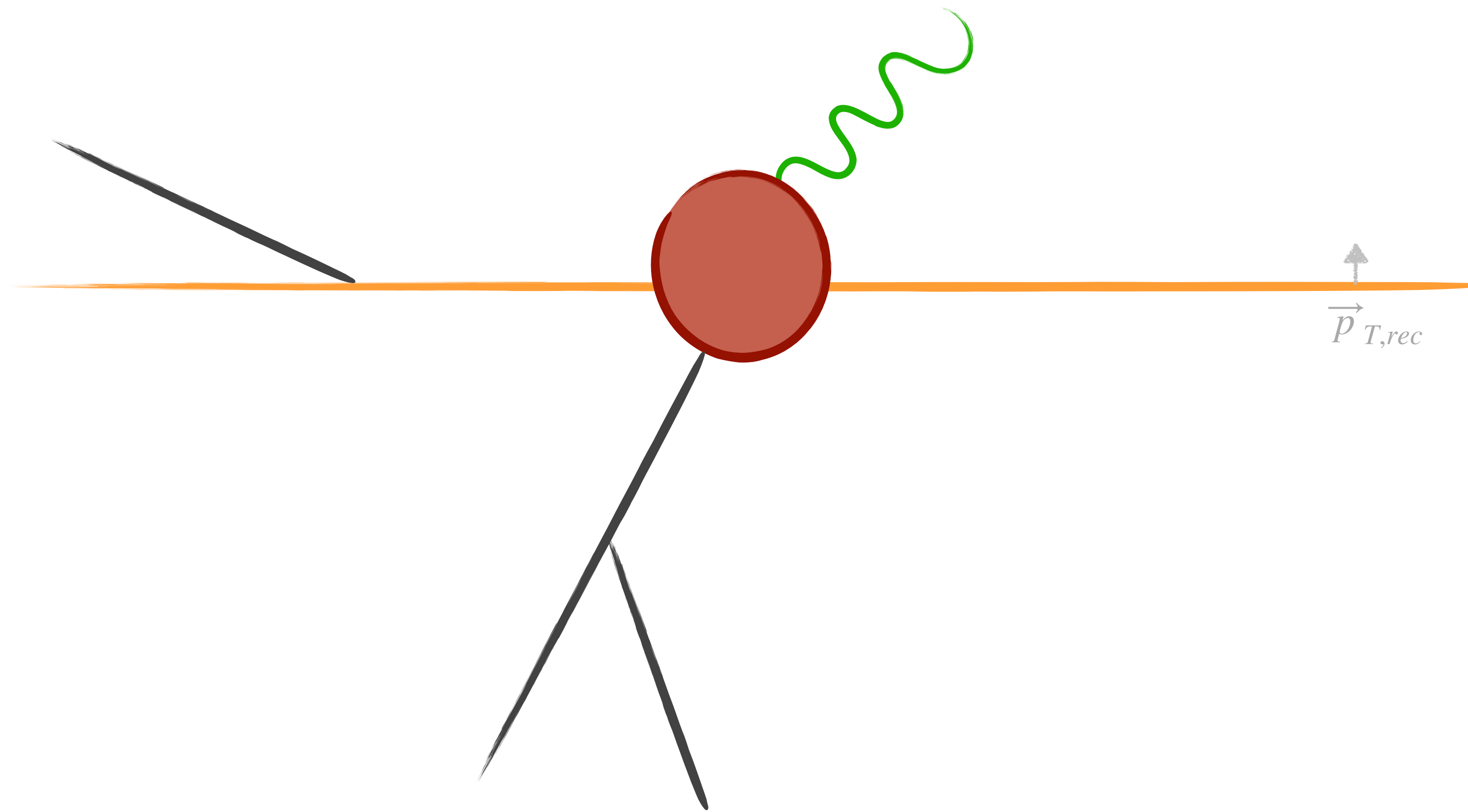
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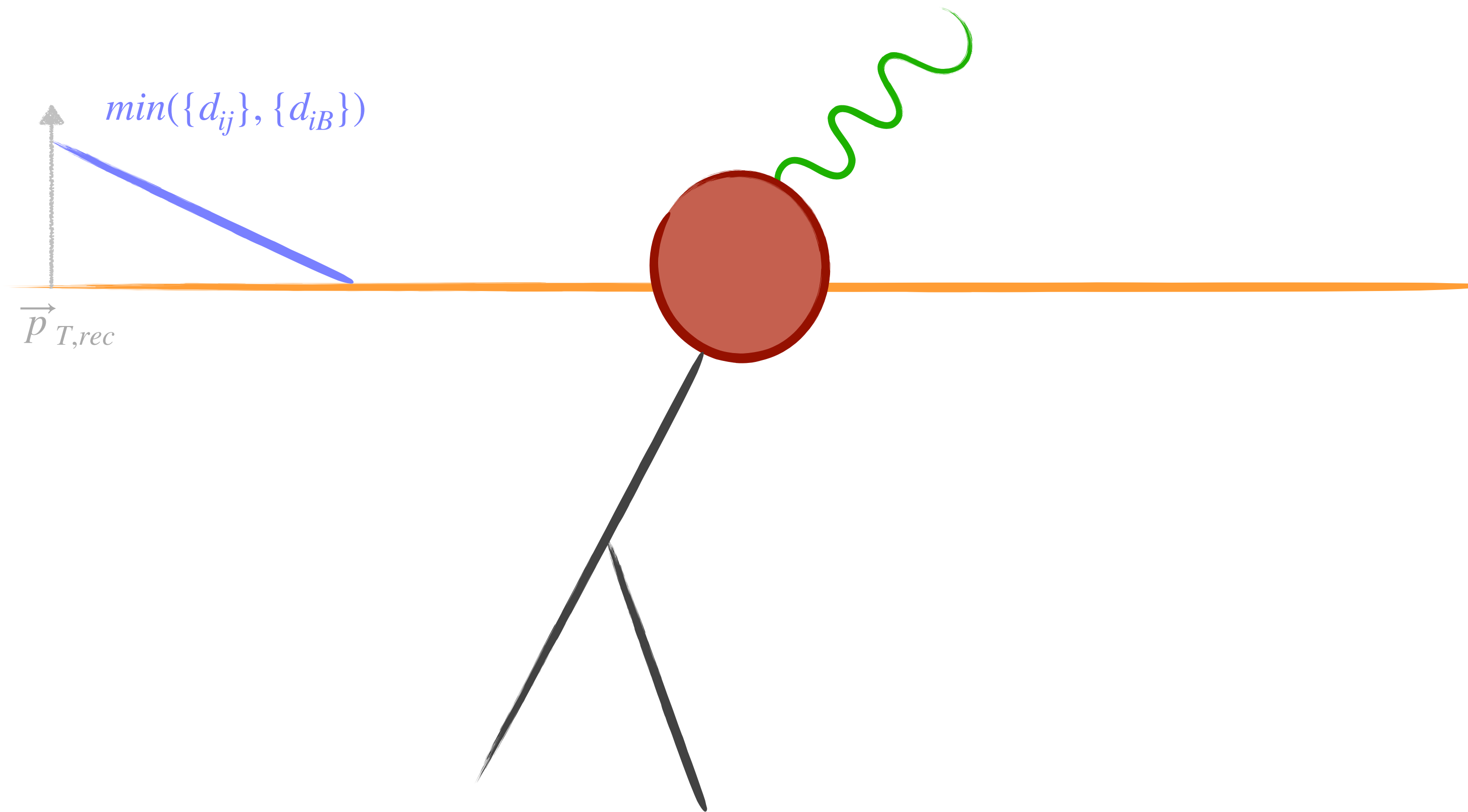
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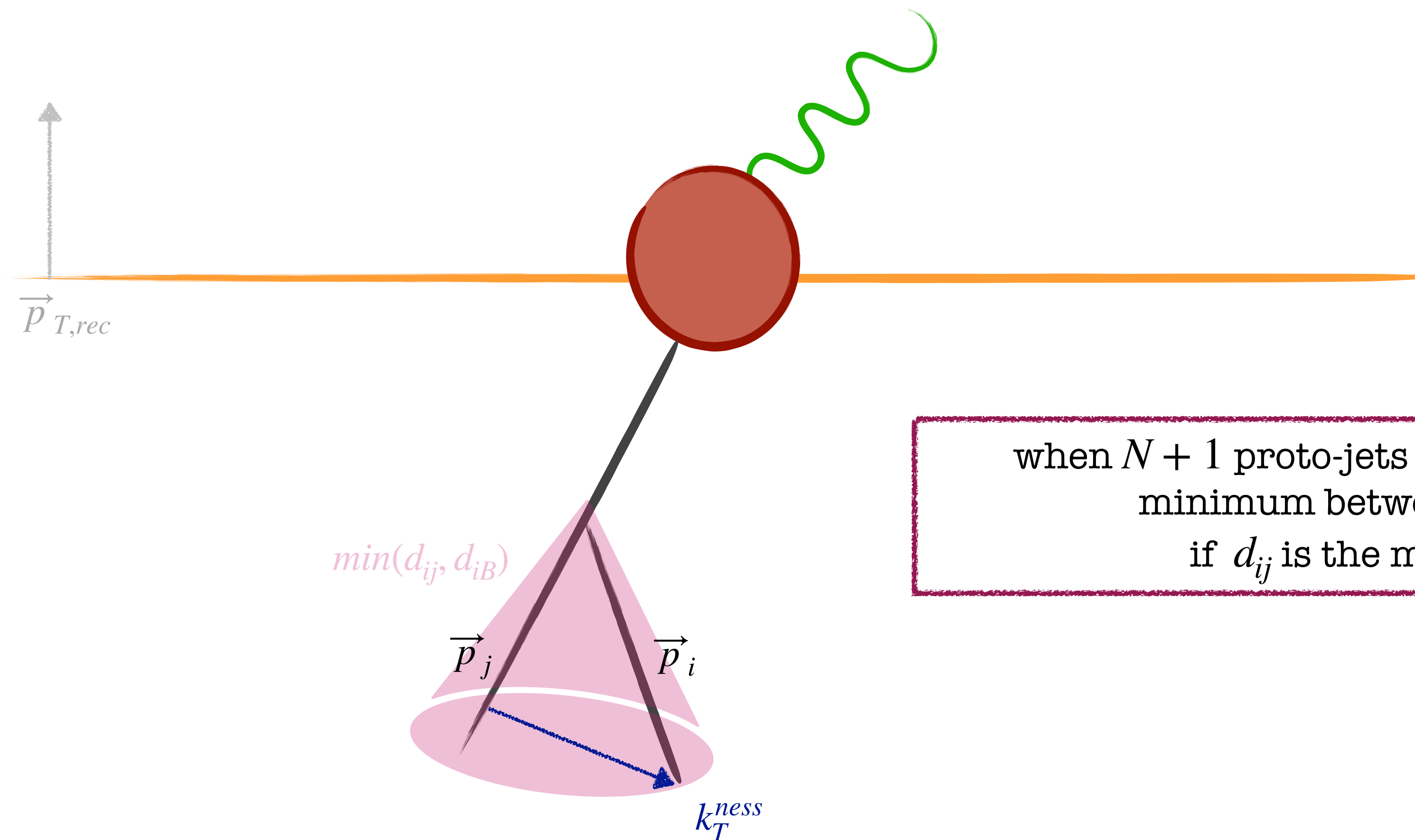
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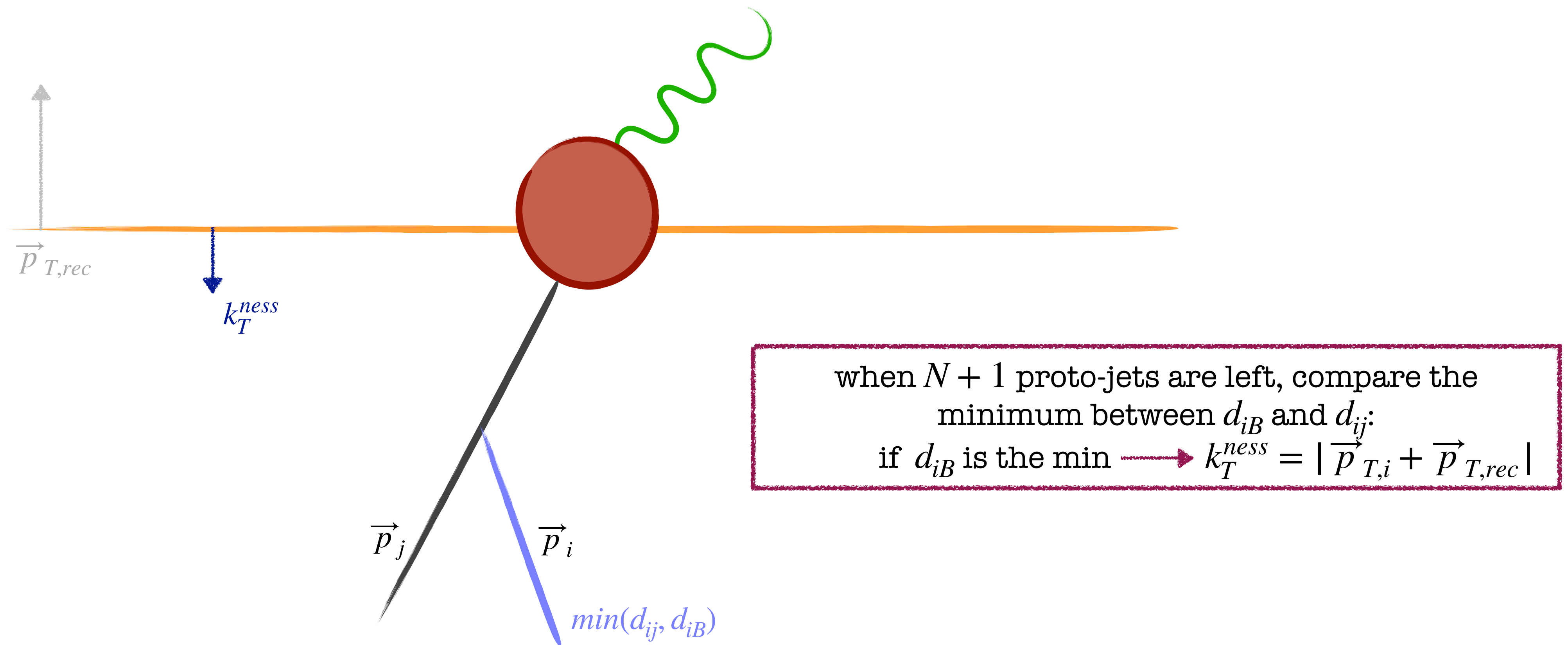
definition: run the k_T -algorithm till $N + 1$ proto-jets are left



when $N + 1$ proto-jets are left, compare the minimum between d_{iB} and d_{ij} :
if d_{ij} is the min $\longrightarrow k_T^{ness} = d_{ij}$

Our proposal: k_T^{ness}

definition: run the k_T -algorithm till $N + 1$ proto-jets are left



k_T^{ness} -subtraction

finite piece :

► the **master formula** for NLO subtraction is

$$d\hat{\sigma}_{NLO}^{F+Njets+X} = \mathcal{H}_{NLO}^{F+Njets} \otimes d\hat{\sigma}_{LO}^{F+Njets} + [d\hat{\sigma}_{LO}^{F+(N+1)jets} - d\hat{\sigma}_{NLO}^{CT,F+Njets}]_{r>r_{cut}}$$

where the **finite piece** is

$$\mathcal{H}_{cd;ab}^{F+Njets} = (\mathbf{HS})_{cd} C_{ca} C_{db} \prod_{i=1}^N J_i$$

with jet function

$$J_i^f = \begin{cases} 1 + \frac{\alpha_S(\mu_R)}{\pi} \left\{ C_A \left[\frac{131}{72} - \frac{\pi^2}{4} - \frac{11}{6} \ln(2D) - \ln(D) \ln\left(\frac{Q^2 D}{4E_i^2}\right) \right] \right. \\ \quad \left. + T_R n_f \left[-\frac{17}{36} + \frac{2}{3} \ln(2D) \right] \right\} + \mathcal{O}(\alpha_S^2) & \text{if } f = g \\ 1 + \frac{\alpha_S(\mu_R)}{\pi} C_F \left[\frac{7}{4} - \frac{\pi^2}{4} - \frac{3}{2} \ln(2D) - \ln(D) \ln\left(\frac{Q^2}{4E_i^2}\right) - \ln^2(D) \right] + \mathcal{O}(\alpha_S^2) & \text{if } f = q, \bar{q} \end{cases}$$

k_T^{ness} -subtraction

finite piece :

► the **master formula** for NLO subtraction is

$$d\hat{\sigma}_{NLO}^{F+Njets+X} = \mathcal{H}_{NLO}^{F+Njets} \otimes d\hat{\sigma}_{LO}^{F+Njets} + [d\hat{\sigma}_{LO}^{F+(N+1)jets} - d\hat{\sigma}_{NLO}^{CT,F+Njets}]_{r>r_{cut}}$$

where the **finite piece** is

$$\mathcal{H}_{cd;ab}^{F+Njets} = (\mathbf{HS})_{cd} C_{ca} C_{db} \prod_{i=1}^N J_i$$

with soft factor

$$(\mathbf{HS})_{cd} = \frac{\langle \mathcal{M}_{cd} | \mathbf{S} | \mathcal{M}_{cd} \rangle}{|\mathcal{M}_{cd}^{(0)}|^2} \quad \mathbf{S} = 1 + \frac{\alpha_S(\mu_R)}{\pi} \mathbf{S}^{(1)} + \mathcal{O}(\alpha_S^2)$$

► the soft factor $\mathbf{S}^{(1)}$ is an operator in colour space and it is related to the integral, over the radiation phase space, of the soft-subtracted current

$$\begin{aligned} \mathbf{J}_{\text{sub}}^2 = & \left(-\mathbf{T}_c \cdot \mathbf{T}_d \omega_{cd} - \sum_i (\mathbf{T}_c \cdot \mathbf{T}_i \omega_{ci} + (c \leftrightarrow d)) - \sum_{i \neq j} \mathbf{T}_i \cdot \mathbf{T}_j \omega_{ij} \right) \Theta(r_{\text{cut}} - k_{T,S}^{\text{ness}}/Q) \\ & - \left(\mathbf{T}_c^2 \omega_d^c + (c \leftrightarrow d) \right) \Theta(r_{\text{cut}} - k_t/Q) - \sum_i \mathbf{T}_i^2 \omega_{CS,i} \Theta(r_{\text{cut}} - k_{T,CS_i}^{\text{ness}}/Q) \end{aligned}$$

other numerical results

$Z + 2\text{jets production @NLO}$

$$p_T^j > 30 \text{ GeV} \quad |\eta^j| < 4.5$$

$$p_T^l > 20 \text{ GeV} \quad |\eta^l| < 2.5$$

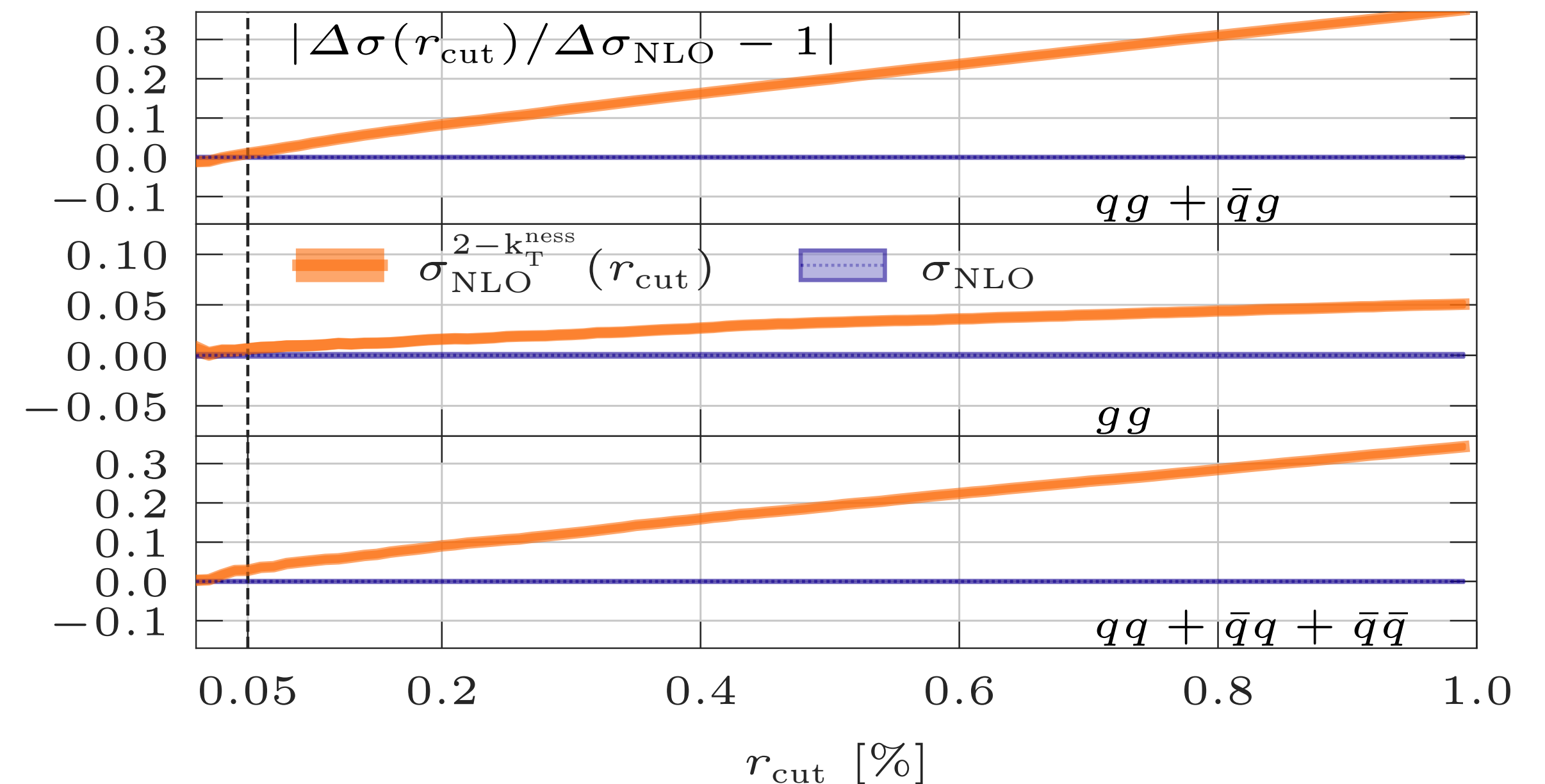
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$$\Delta R_{lj} > 0.5 \quad \Delta R_{ll} > 0.2$$

$$D = 0.1$$

$$\mu_R = \mu_F = m_Z$$

- comparison between the results obtained with $2-k_T^{\text{ness}}$ and CS local subtraction, at the level of the **total cross section**
- the cut is applied on k_T^{ness} normalised over the hard scale M which is the transverse mass of the dilepton system
- **linear** power behaviour in all channels
- control of the NLO correction ($r_{\text{cut}} \rightarrow 0$) at the **percent level**



The reference NLO result is obtained with MCFM (CS local subtraction).

other numerical results

Dijet production @NLO

$$p_T^j > 30 \text{ GeV}$$

$$D = 1$$

$$\mu_R = \mu_F = m_Z$$

- ▶ comparison between the results obtained with $2-k_T^{\text{ness}}$ and CS local subtraction, at the level of the **total cross section**
- ▶ the cut is applied on k_T^{ness} normalised over the hard scale M which is the invariant mass of the dijet system
- ▶ **linear** power behaviour

