

# Effective transverse momentum for processes with jets at the LHC

Based on work with L. Buonocore, M. Grazzini, L. Rottoli, C. Savoini ([2201.11519](#))



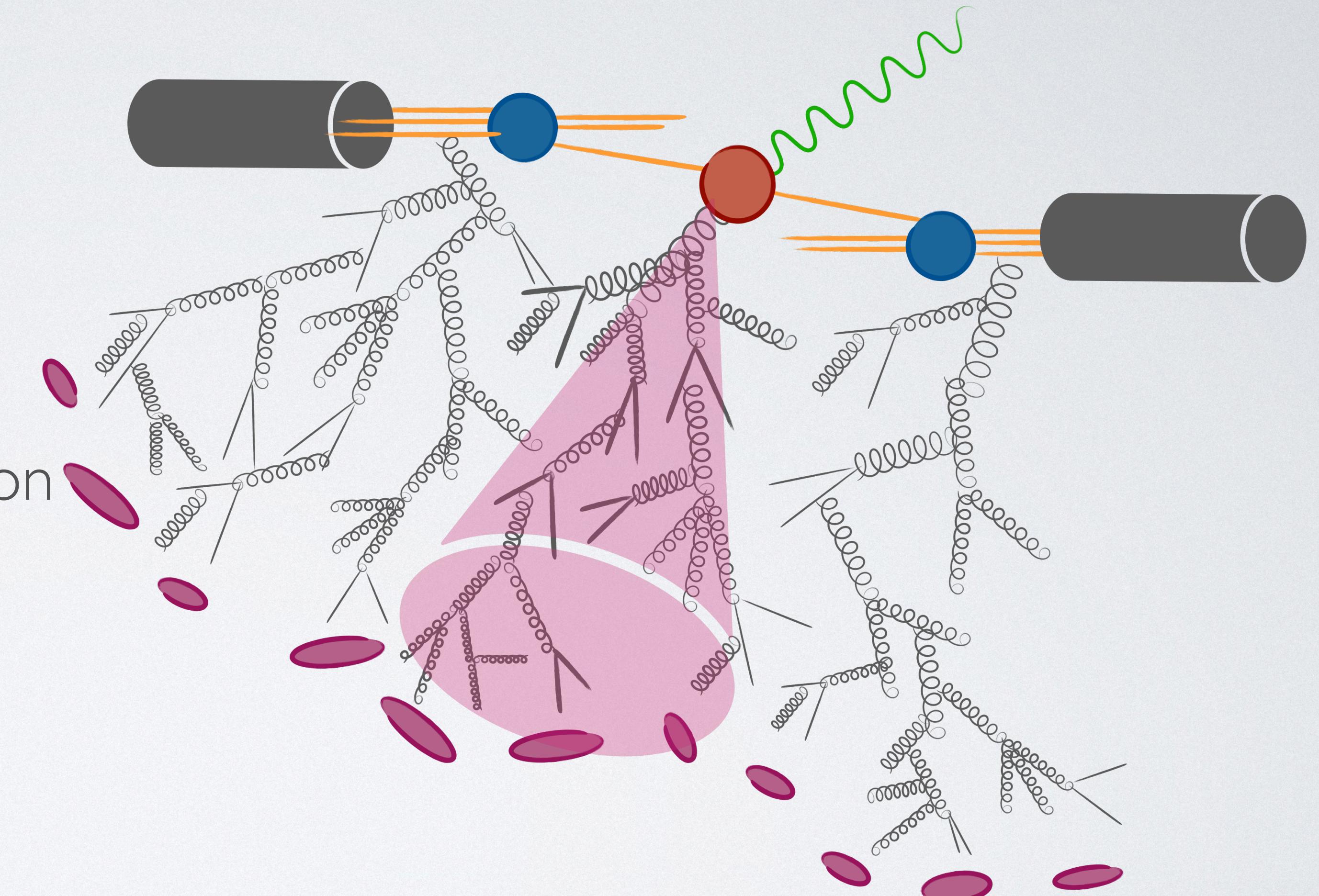
**Universität  
Zürich<sup>UZH</sup>**

HP2 2022

Jürg Haag

# Introduction

Goal: Generalisation of  $q_T$ -subtraction  
for processes with jets.



# Outline

- $q_T$  - subtraction and resummation
- Generalising  $q_T$  to processes involving jets
- Definition of  $N - k_T^{\text{ness}}$
- $k_T^{\text{ness}}$  as a slicing variable
- All order and non-perturbative behaviour of  $k_T^{\text{ness}}$

# $q_T$ - Subtraction And Resummation

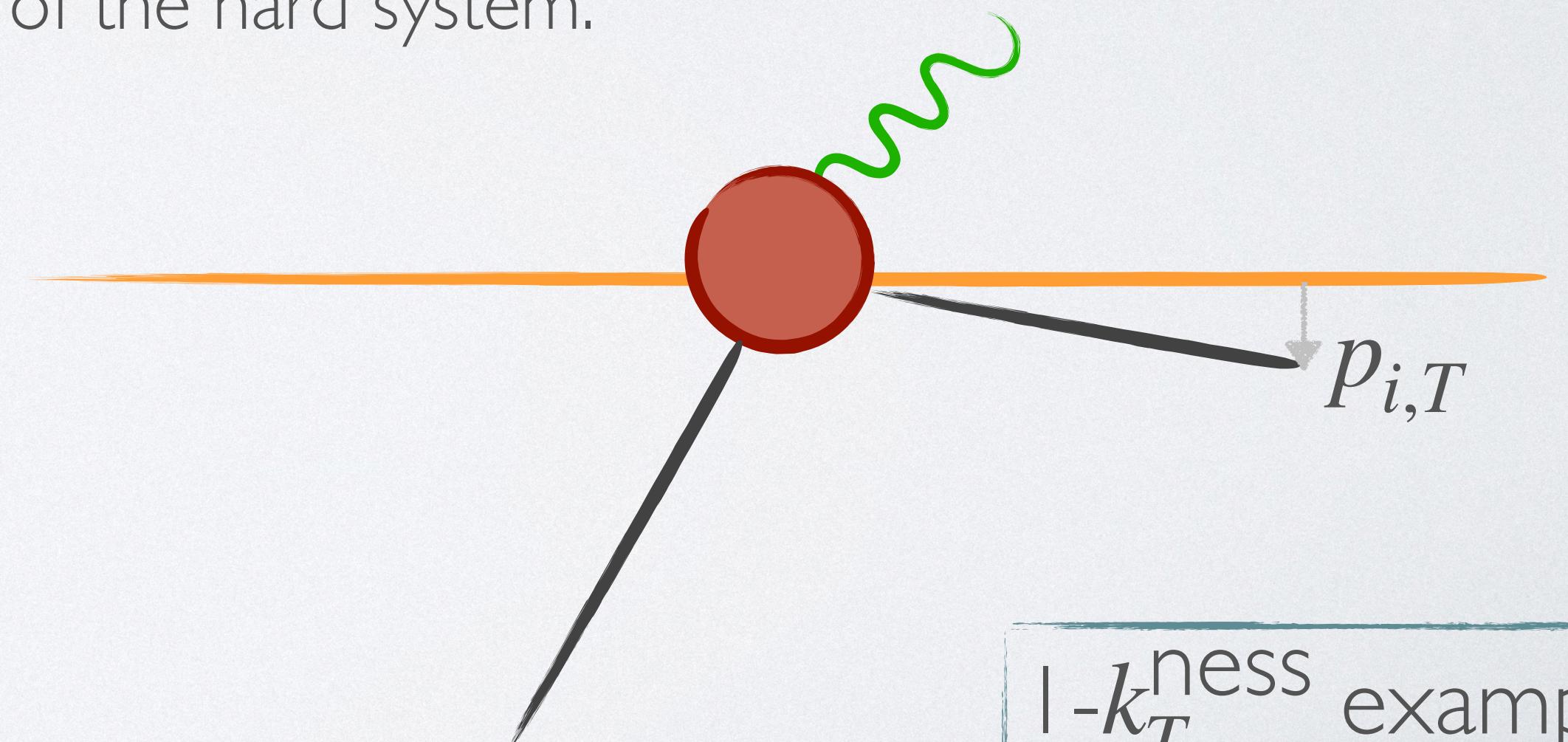
- $q_T$  = transverse momentum of resolved system (system already present at LO)
- If no jets are present at LO then  $q_T > 0$  ensures that at  $N^nLO$  only IR divergences of  $N^{n-1}LO$ -type appear
- Thus,  $q_T$  can be used as a slicing variable at NNLO. (Catani, Grazzini (2007) [[0703012](#)])
- MATRI✗:  $pp \rightarrow V, H, \gamma\gamma, V\gamma, VV, t\bar{t}, \gamma\gamma\gamma, HH, b\bar{b}$  (Grazzini, Kallweit, Wiesemann (2017) [[1711.06631](#)])
- Has been used at N3LO for Higgs production (Billis, Dehnadi, Ebert, Michel, Tackmann (2021) and Drell-Yan [[2102.08039](#)])  
(Chen, Gehrmann, Glover, Huss, Yang, Zhu (2021)[[2107.09085](#)])(Chen, Gehrmann, Glover, Huss, Monni, Re, Rottoli, Torrielli [[2203.01565](#)])  
(Camarda, Cieri, Ferrera [[2103.04974](#)])
- BUT, if there are jets,  $q_T$  no longer regulates all NLO type IR-divergences!

# How To Deal With Jets

- We want something that smoothly captures the N to N+1 jet transition.
- We want a variable that is  $q_T$  for the 0 jet case and for ISC radiation
- We want the variable to scale like relative transverse momentum in all soft collinear regions
- We want something (continuously) global
- N-jettiness (Stewart, Tackmann, Waalewijn (2010)[\[1004.2489\]](#)) is the only well-studied player in the game, but 0-jettiness is not  $q_T$  and does not scale as a transverse momentum.
- N-jettiness-subtraction at NNLO (Gaunt, Stahlhofen, Tackmann, Walsh (2015)[\[1505.04794\]](#))
- 1-jettiness at NNLO for V+jet (Boughezal, Focke, Liu, Petriello (2015) [\[1504.02131\]](#))(Boughezal, Campbell, Ellis, Focke, Giele, Liu, Petriello (2016)[\[1512.01291\]](#))

# Defining $k_T^{\text{ness}}$

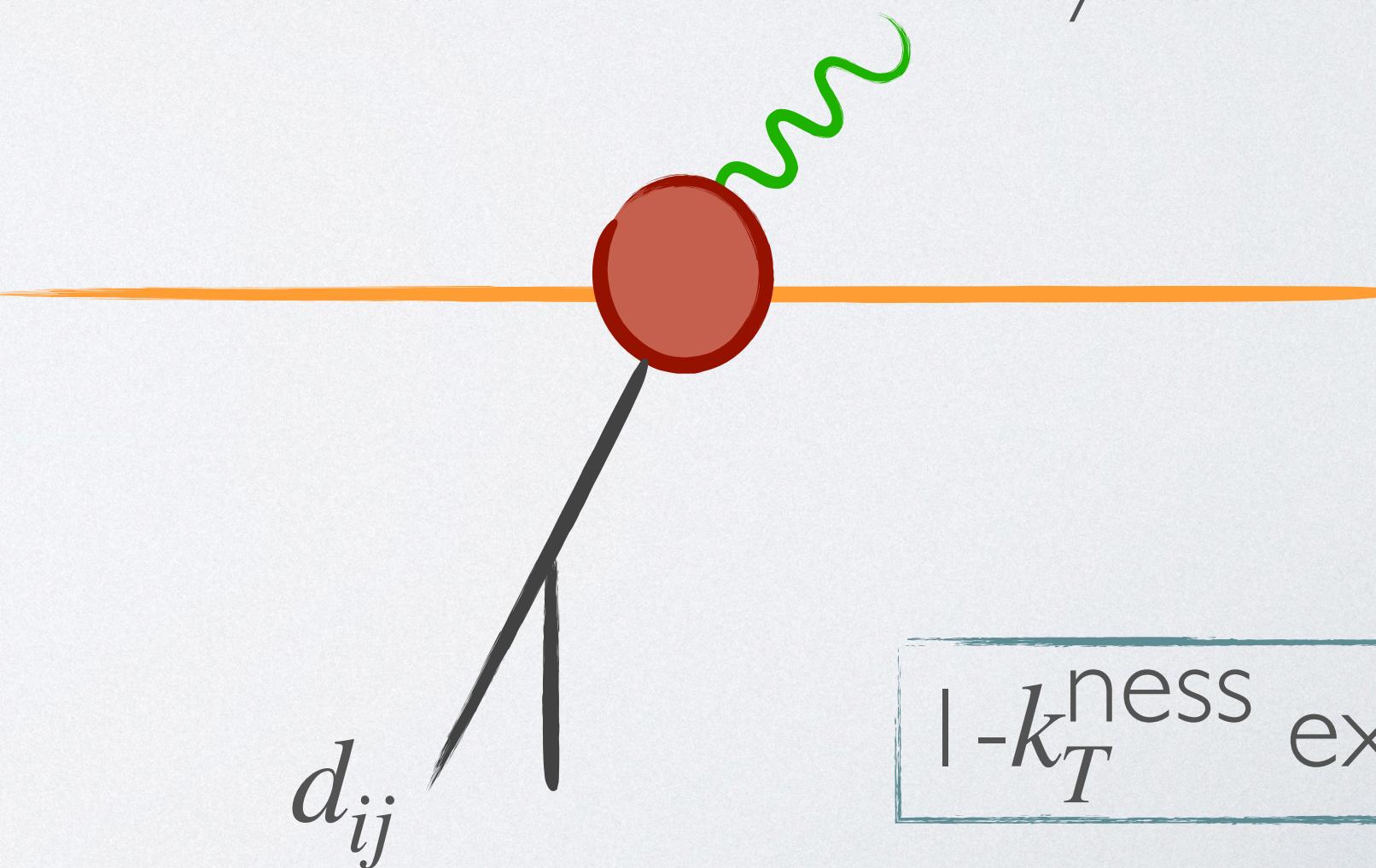
- Remember the  $k_T$  - jet clustering algorithm:  $d_{ij} = \min(p_{i,T}, p_{j,T})\sqrt{\Delta y^2 + \Delta\phi^2} \approx \tilde{k}_T$
- For a process where we require  $N$  or more jets we can define  $N - k_T^{\text{ness}}$  as follows:
- For a configuration of  $N + 1$  massless coloured partons we can define  $N - k_T^{\text{ness}} = \min(\{p_{i,T}\}, \frac{\{d_{ij}\}}{D})$
- For ISC radiation  $N - k_T^{\text{ness}}$  is the transverse momentum of the hard system.



$| - k_T^{\text{ness}}$  example

# Defining $k_T^{\text{ness}}$

- Remember the  $k_T$  - jet clustering algorithm:  $d_{ij} = \min(p_{i,T}, p_{j,T})\sqrt{\Delta y^2 + \Delta\phi^2} \approx \tilde{k}_T$
- For a process where we require  $N$  or more jets we can define  $N - k_T^{\text{ness}}$  as follows:
- For a configuration of  $N + 1$  massless coloured partons we can define  $N - k_T^{\text{ness}} = \min(\{p_{i,T}\}, \frac{\{d_{ij}\}}{D})$
- For FSC radiation along a jet,  $N - k_T^{\text{ness}}$  is the relative transverse momentum of the hard system wrt that jet



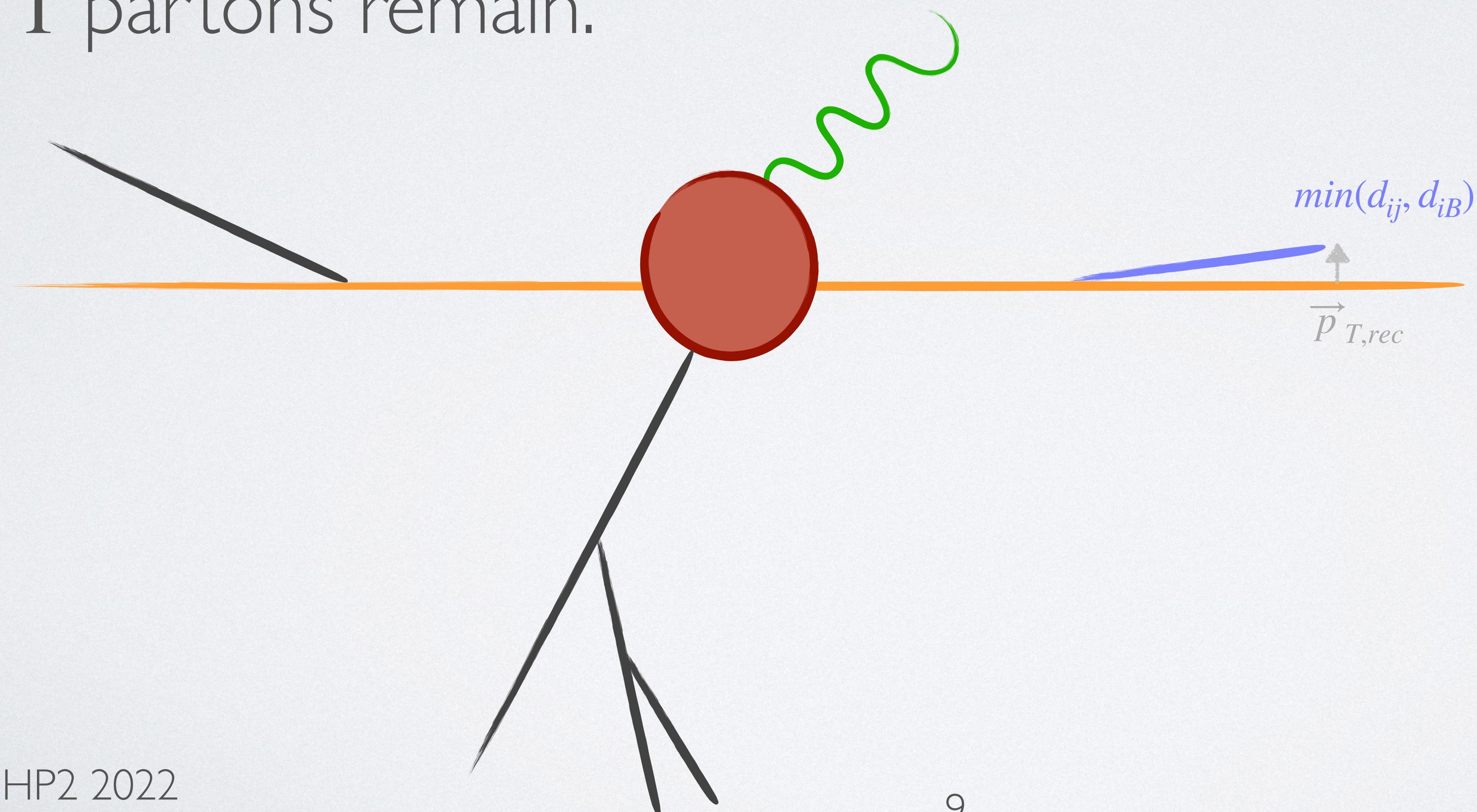
$| - k_T^{\text{ness}}$  example

# Defining $k_T^{\text{ness}}$

- Remember the  $k_T$  - jet clustering algorithm:  $d_{ij} = \min(p_{i,T}, p_{j,T})\sqrt{\Delta y^2 + \Delta\phi^2} \approx \tilde{k}_T$
- For a process where we require  $N$  or more jets we can define  $N - k_T^{\text{ness}}$  as follows:
- For a configuration of  $N + 1$  massless coloured partons we can define  $N - k_T^{\text{ness}} = \min(\{p_{i,T}\}, \frac{\{d_{ij}\}}{D})$
- For ISC radiation  $N - k_T^{\text{ness}}$  is the transverse momentum of the hard system.
- For FSC radiation along a jet,  $N - k_T^{\text{ness}}$  is the relative transverse momentum of the hard system wrt that jet
- For soft radiation the situation is more involved

# Defining $k_T^{\text{ness}}$

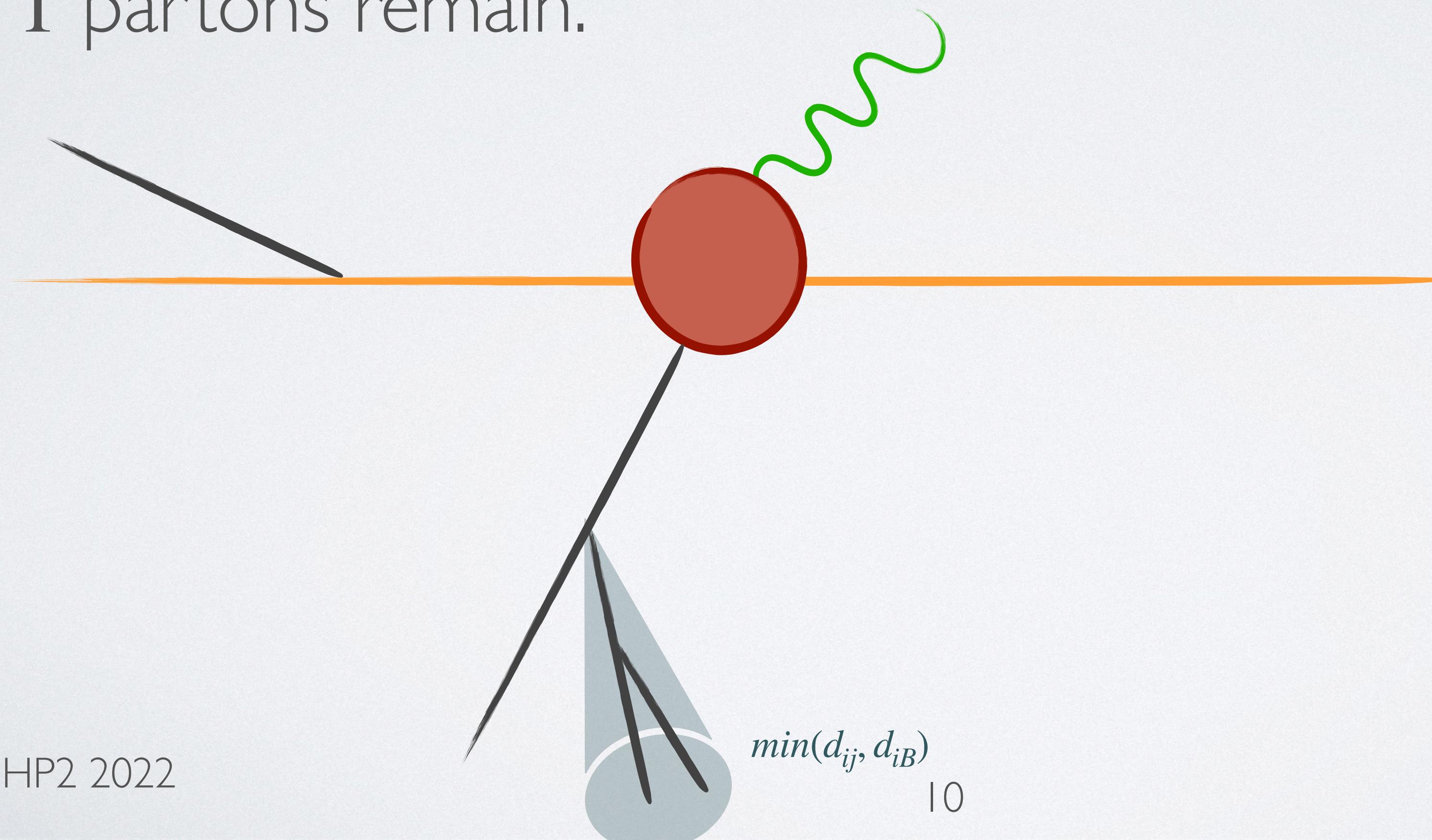
- For a configuration of  $N + k$  partons, one runs the kt-algorithm until  $N + 1$  partons remain.



$| -k_T^{\text{ness}}$  example

# Defining $k_T^{\text{ness}}$

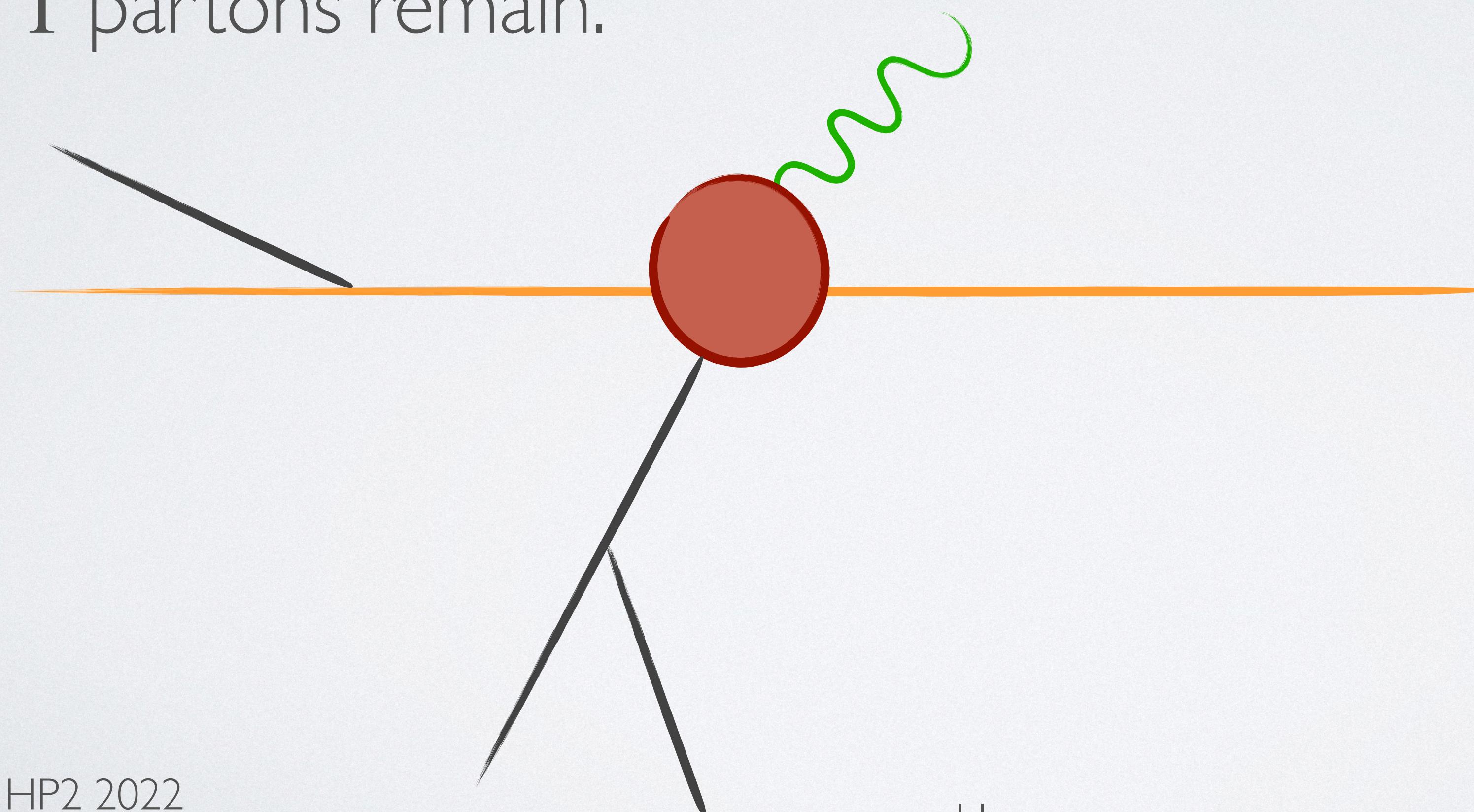
- For a configuration of  $N + k$  partons, one runs the kt-algorithm until  $N + 1$  partons remain.



$| - k_T^{\text{ness}}$  example

# Defining $k_T^{\text{ness}}$

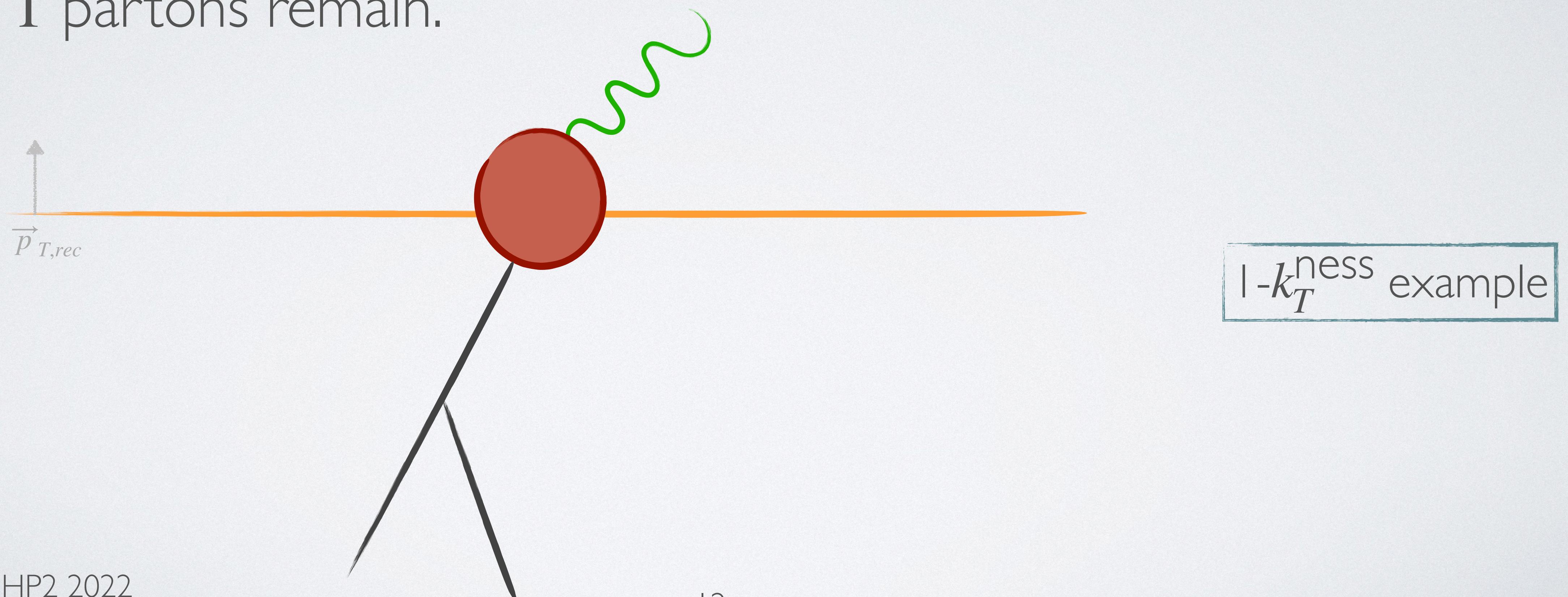
- For a configuration of  $N + k$  partons, one runs the kt-algorithm until  $N + 1$  partons remain.



$1 - k_T^{\text{ness}}$  example

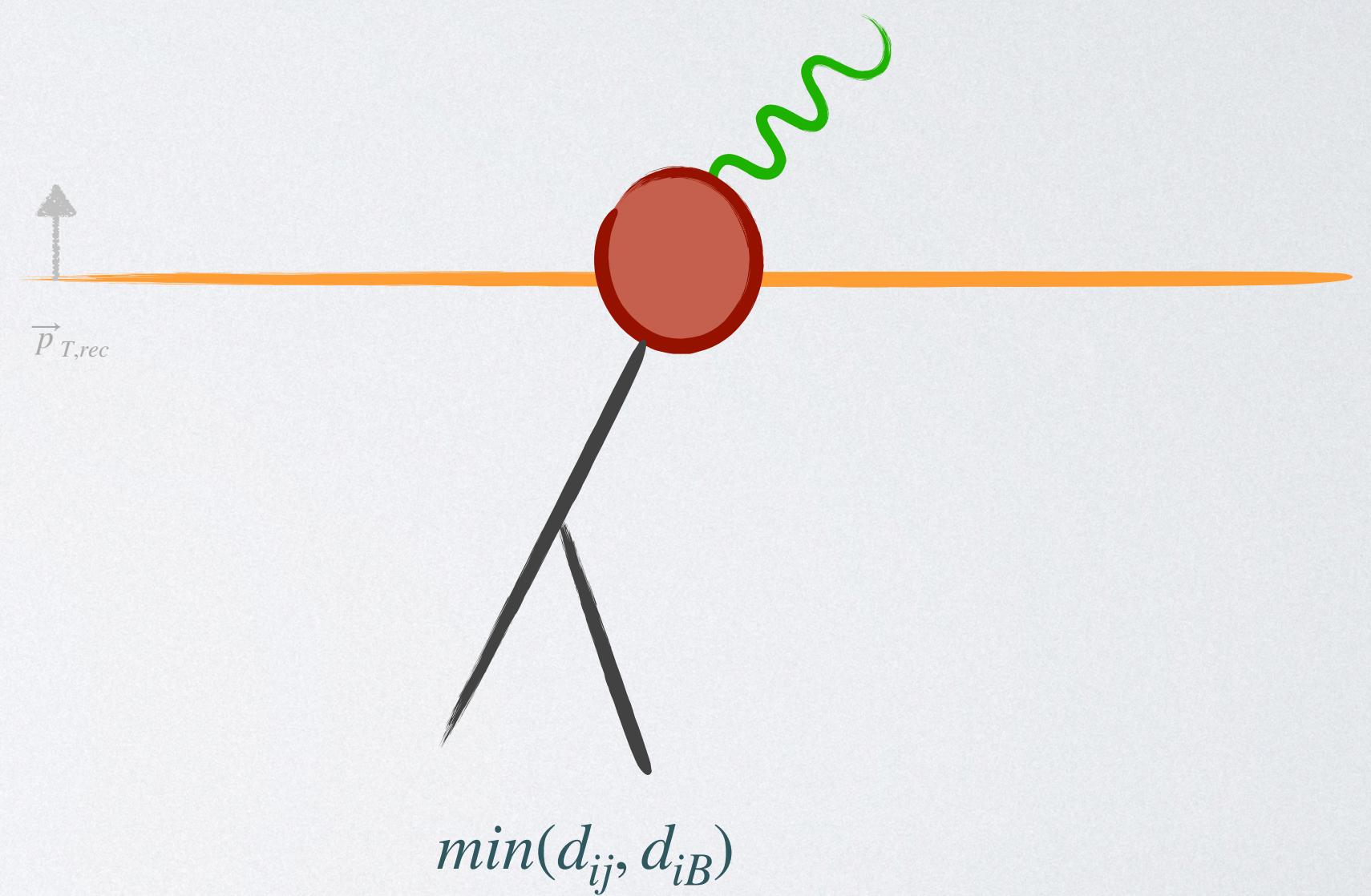
# Defining $k_T^{\text{ness}}$

- For a configuration of  $N + k$  partons, one runs the kt-algorithm until  $N + 1$  partons remain.



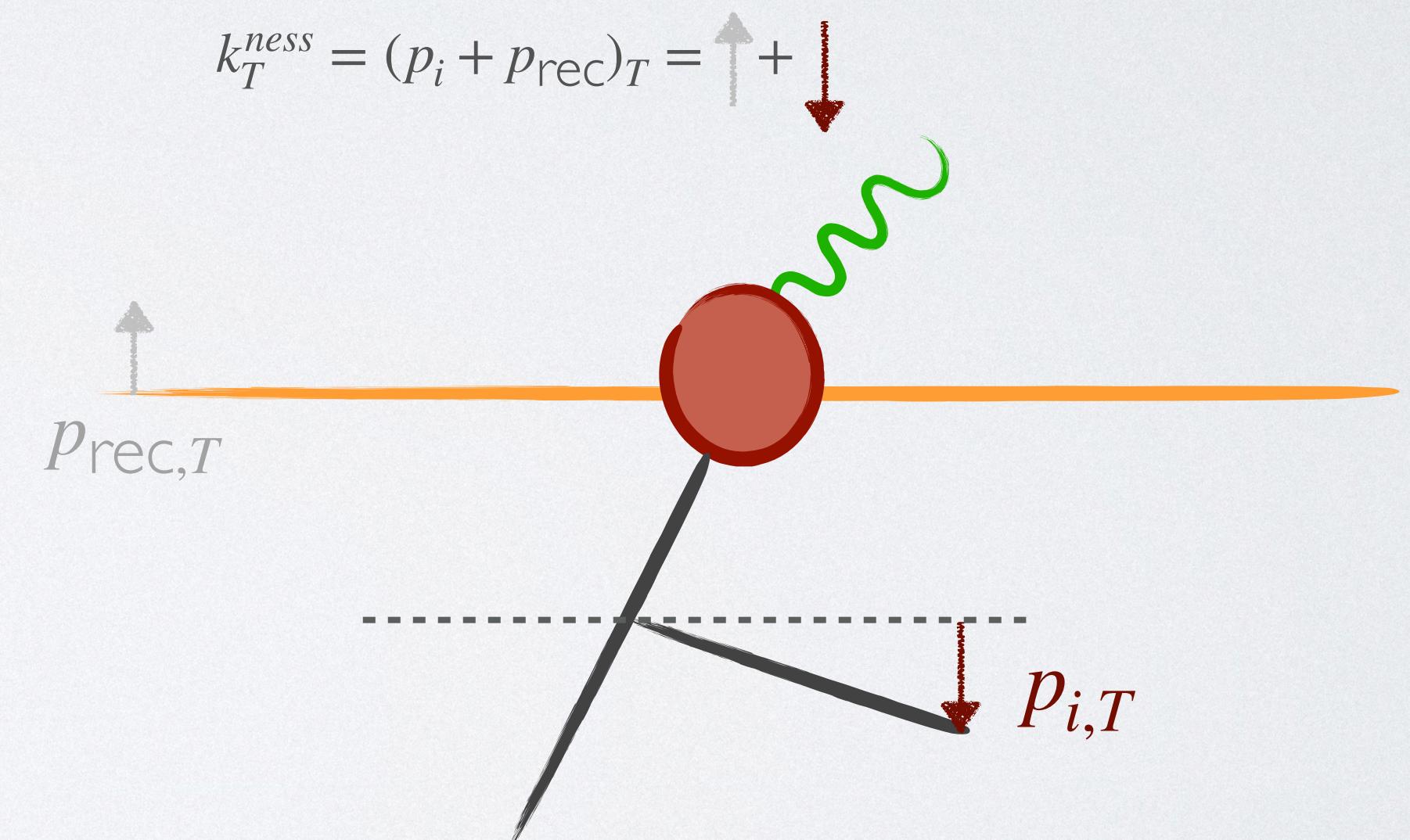
# Defining $k_T^{\text{ness}}$

- For a configuration of  $N + k$  partons, one runs the kt-algorithm until  $N + 1$  partons remain.
- We again determine  $\min(\{p_{i,T}\}, \frac{\{d_{ij}\}}{D})$
- If it is a  $\frac{d_{ij}}{D}$ , define  $k_T^{\text{ness}} = \frac{d_{ij}}{D}$



# Defining $k_T^{\text{ness}}$

- For a configuration of  $N + k$  partons, one runs the kt-algorithm until  $N + 1$  partons remain.
- We again determine  $\min(\{p_{i,T}\}, \frac{\{d_{ij}\}}{D})$
- If it is a  $p_{i,t}$  define  $k_T^{\text{ness}} = (p_i + p_{\text{rec}})_T$   
( $p_{\text{rec}}$  is the total momentum of the particles clustered with the beam)



# Defining $k_T^{\text{ness}}$

- For a configuration of  $N + k$  partons, one runs the kt-algorithm until  $N + 1$  partons remain.
- We again determine  $\min(\{p_{i,T}\}, \frac{\{d_{ij}\}}{D})$
- If it is a  $\frac{d_{ij}}{D}$ , define  $k_T^{\text{ness}} = \frac{d_{ij}}{D}$
- If it is a  $p_{i,t}$  define  $k_T^{\text{ness}} = (p_i + p_{\text{rec}})_T$  ( $p_{\text{rec}}$  is the total momentum of the particles clustered with the beam)
- Note: If all emissions are ISC,  $k_T^{\text{ness}}$  is again the  $|q_T|$  of the hard system!

# $k_T^{\text{ness}}$ as a slicing variable

- We have analysed the small  $r$  behaviour of  $\int d\Pi_R d\sigma_R \Theta(r - \frac{k_T^{\text{ness}}}{Q})$  for general processes of the type  $pp \rightarrow N \text{ jets} + \text{colorless}$
- The pieces containing powers of  $\log(r)$  give rise to the  $k_T^{\text{ness}}$ -slicing counter-terms

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

$$\gamma_g = \frac{(11C_A - 2n_F)}{6}, \gamma_q = \frac{3C_F}{2}$$

# $k_T^{\text{ness}}$ as a slicing variable

- We calculated the constant pieces in terms of two-fold integrals
- We have implemented  $k_T^{\text{ness}}$  - slicing at NLO for general  $pp \rightarrow N \text{ jets} + \text{colorless processes}$  in MATRIX

# NLO Results

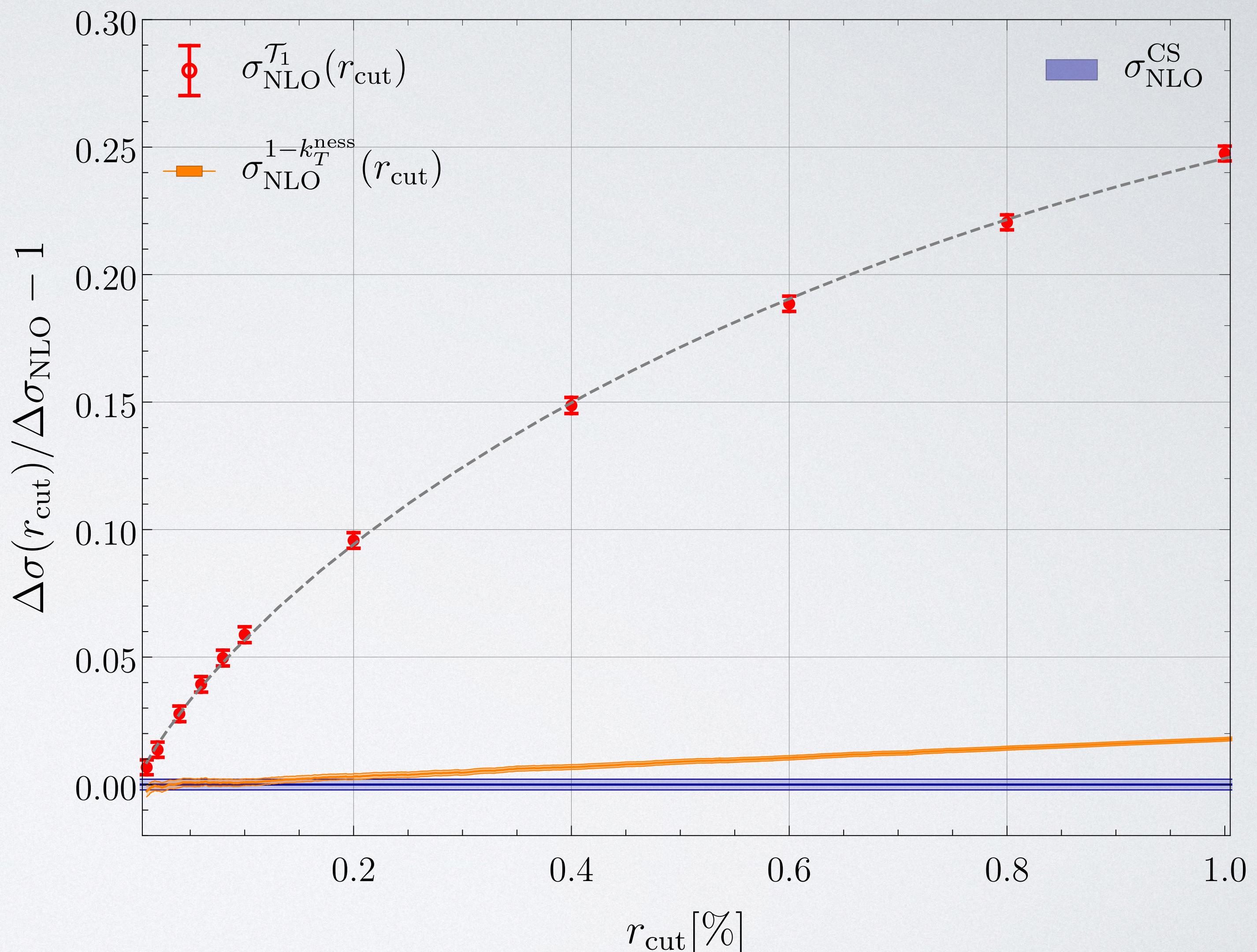
$pp \rightarrow H + j + X$

Higgs + jet

$r_{\text{cut}}$ -dependence of  $\tau_1$  and

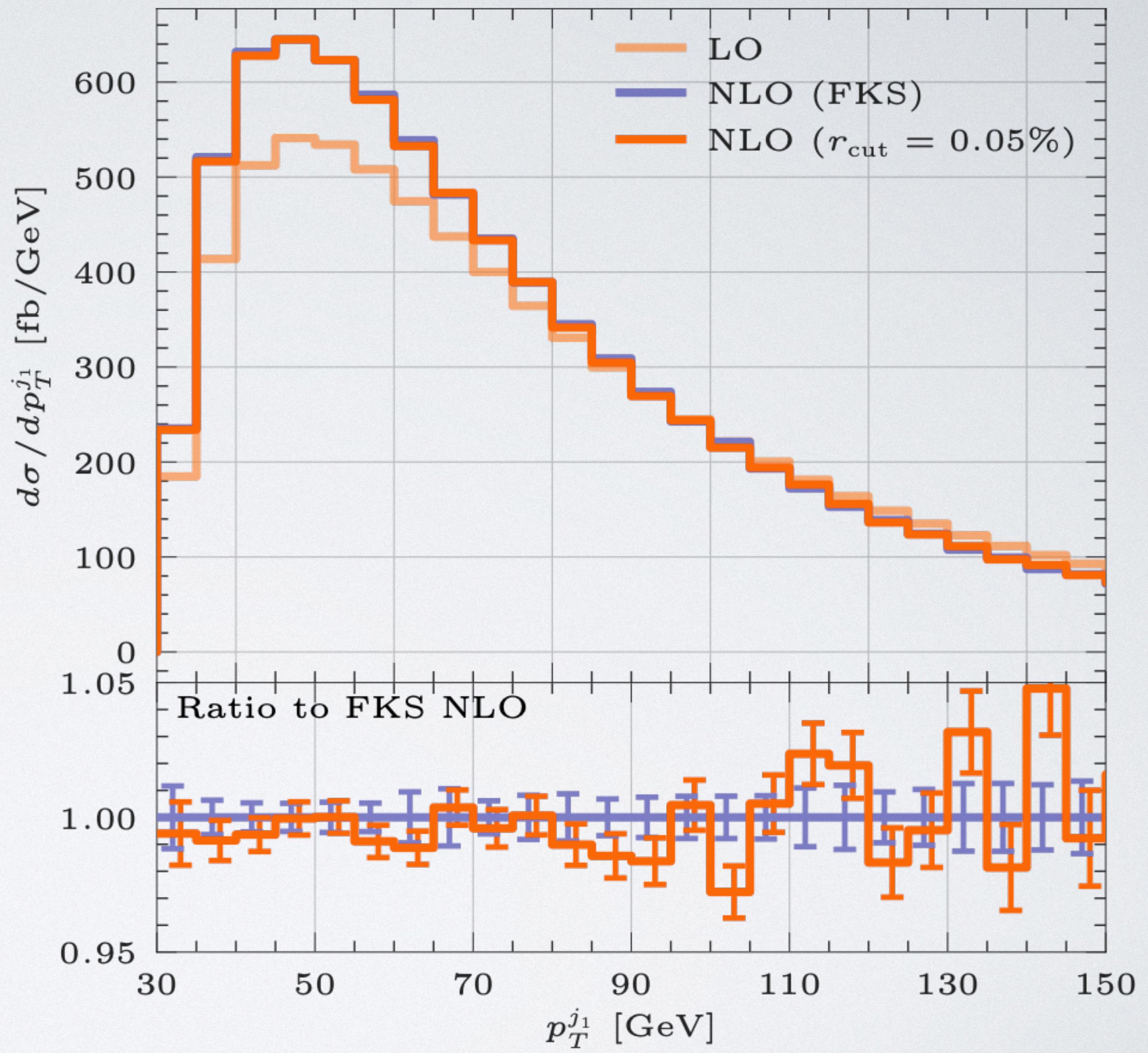
$$r = \frac{\tau_1}{\sqrt{m_H^2 + (p_T^j)^2}} \quad \text{and}$$

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

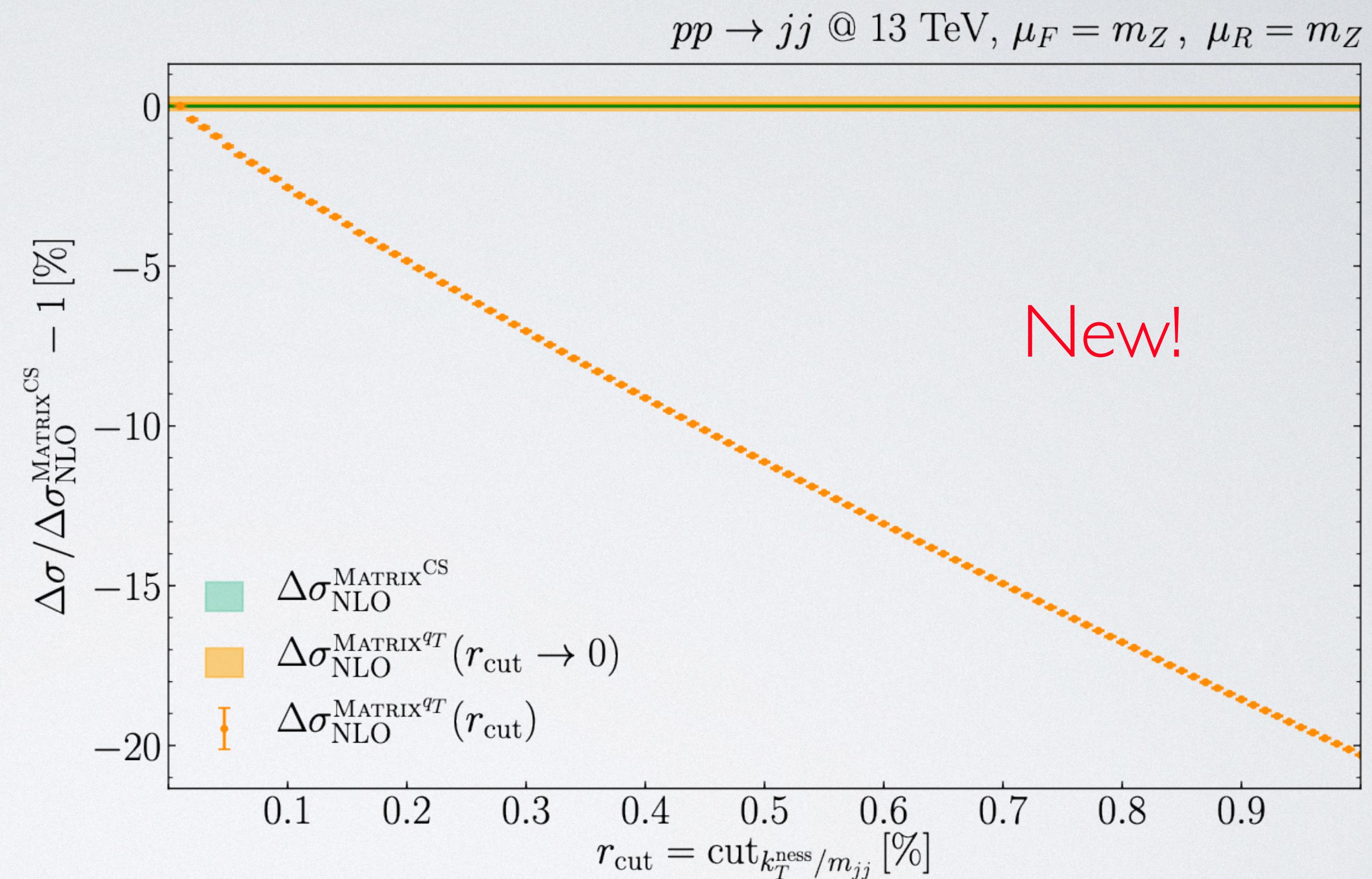


CS and 1-jettiness obtained with MCFM (Campbell, Neumann 1909.09117)

Z+2 jets  
 $p_T$  - distribution of leading jet



# Di-jet (in MATRIX)

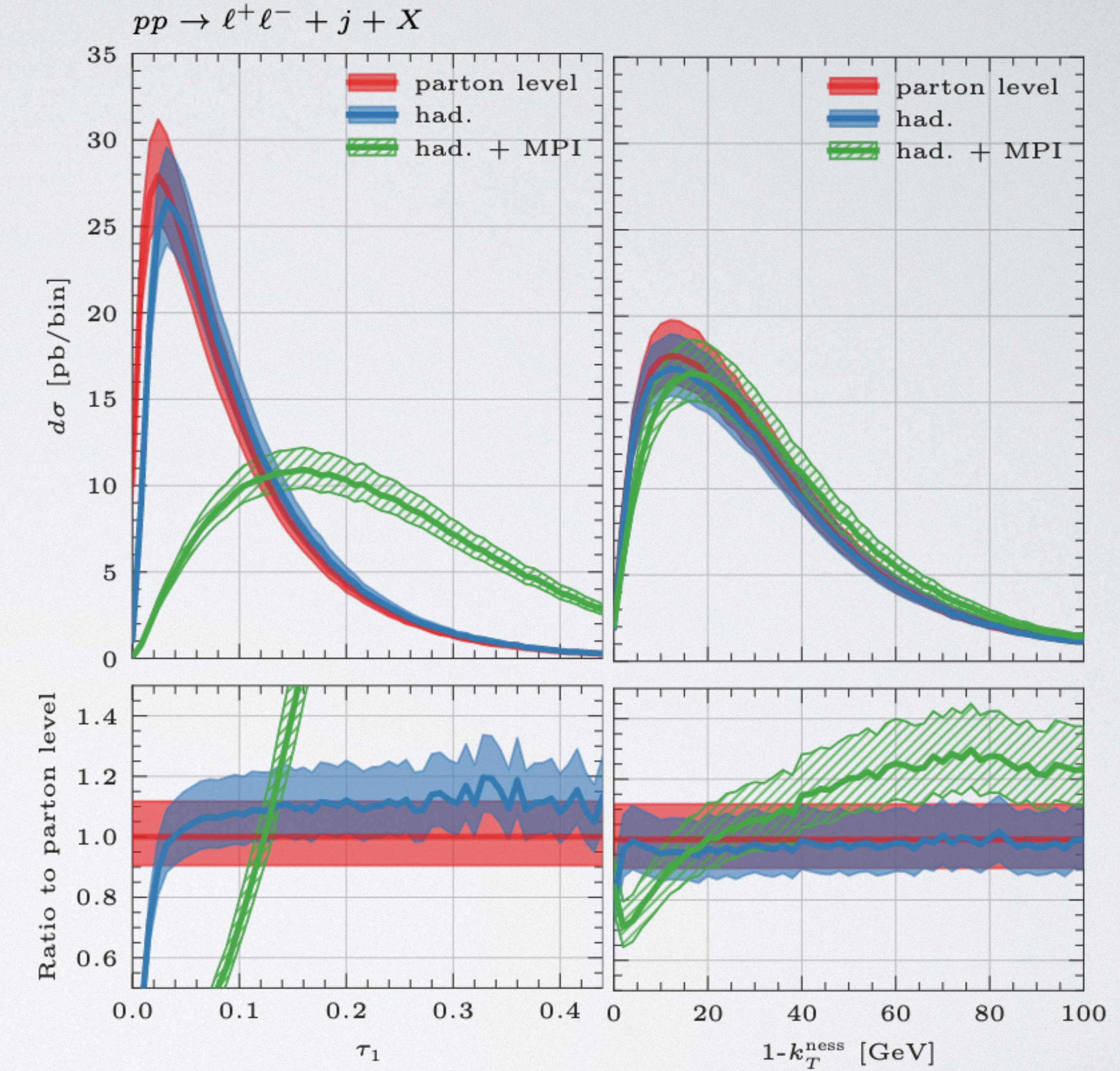


Beyond NLO

# Hadronisation and MPI

$k_T$ -like variables behave well under hadronisation and MPI

(see also Banfi, Salam and Zanderighi [1001.4082])



LO events generated with POWHEG [0709.2092] and showered with PYTHIA8 [1410.3012] using the A14 tune. Jets and  $k_T^{\text{ness}}$  defined with FASTJET [1111.6097]

# Outlook

- NLO:  $k_T^{\text{ness}}$ -subtraction will soon work in MATRIX for general NLO QCD corrections.
- Resummation: Some technicalities need to be understood: b-space for IS radiation?  
Clustering logarithms (especially beyond NLL)?
- Currently working on Z+j at NNLO
- Ultimate long term goal: Make MATRIX a general NNLO provider for QCD corrections  
(and mixed corrections)

Thank You!

# Backup

# Setups for NLO calculations

- Higgs + jet:  
 $\mu_R = \mu_F = m_H$   
 $p_T^j > 30\text{GeV}$   
 $D = 1$
  - $Z + 2\text{jets}$ :  
 $p_T^j > 30\text{GeV}, \eta_j < 4.5$   
 $p_T^l > 20\text{GeV}, \eta_l < 2.5, 66\text{GeV} < m_{ll} < 116\text{GeV}, R_{jl} > 0.5, R_{ll} > 0.2$   
 $D = 0.1$
  - Dijet:  
 $p_T^j > 30\text{GeV}$   
 $D = 1$
- $\sqrt{s_{\text{had}}} = 13\text{TeV}$   
 $NNPDF31\_nlo\_as\_0118$   
with  $\alpha_S(m_z) = 0.118$   
 $G_\mu$  – scheme  
 $G_F = 1.16639 \times 10^{-5}\text{GeV}^{-2}$   
 $m_W = 80.386\text{GeV}$   
 $m_Z = 91.1876\text{GeV}$   
 $\Gamma_Z = 2.4952\text{GeV}$   
anti- $k_T$ -clustering with  $R = 0.4$

# The Finite Piece

$$J_g = 1 + \frac{\alpha_s(\mu_R)}{\pi} \left\{ C_A \left[ \frac{131}{72} - \frac{\pi^2}{4} - \frac{11}{6} \log(2) - \log(D) \left( \frac{11}{6} + \log \left( \frac{Q^2}{4p_i^2} \right) \right) - \log^2(D) \right] + T_R n_f \left[ -\frac{17}{36} + \frac{2}{3} \log(2D) \right] \right\} + O(\alpha_s^2)$$

$$J_q = 1 + \frac{\alpha_s(\mu_R)}{\pi} C_F \left[ \frac{7}{4} - \frac{\pi^2}{4} - \frac{3}{2} \log(2) - \log(D) \left( \frac{3}{2} + \log \left( \frac{Q^2}{4p_i^2} \right) \right) - \log^2(D) \right] + O(\alpha_s^2)$$

$$\begin{aligned} J_{sub}^2 &= \left( -T_1 \cdot T_2 \omega_{12} - \sum_i (T_1 \cdot T_i \omega_{1i} + (1 \leftrightarrow 2)) - \sum_{i \neq j} T_i \cdot T_j \omega_{ij} \right) \Theta(r_{cut} - k_T^{ness,soft}/Q) \\ &\quad - (T_1^2 \omega_2^1 + (1 \leftrightarrow 2)) \Theta(r_{cut} - k_t/Q) - \sum_i T_i^2 \omega_{FS \rightarrow S}^i \Theta(r_{cut} - q_{t,ik}/Q) \end{aligned}$$