Effective Transverse Momentum For Multi-Jet Events At The LHC

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

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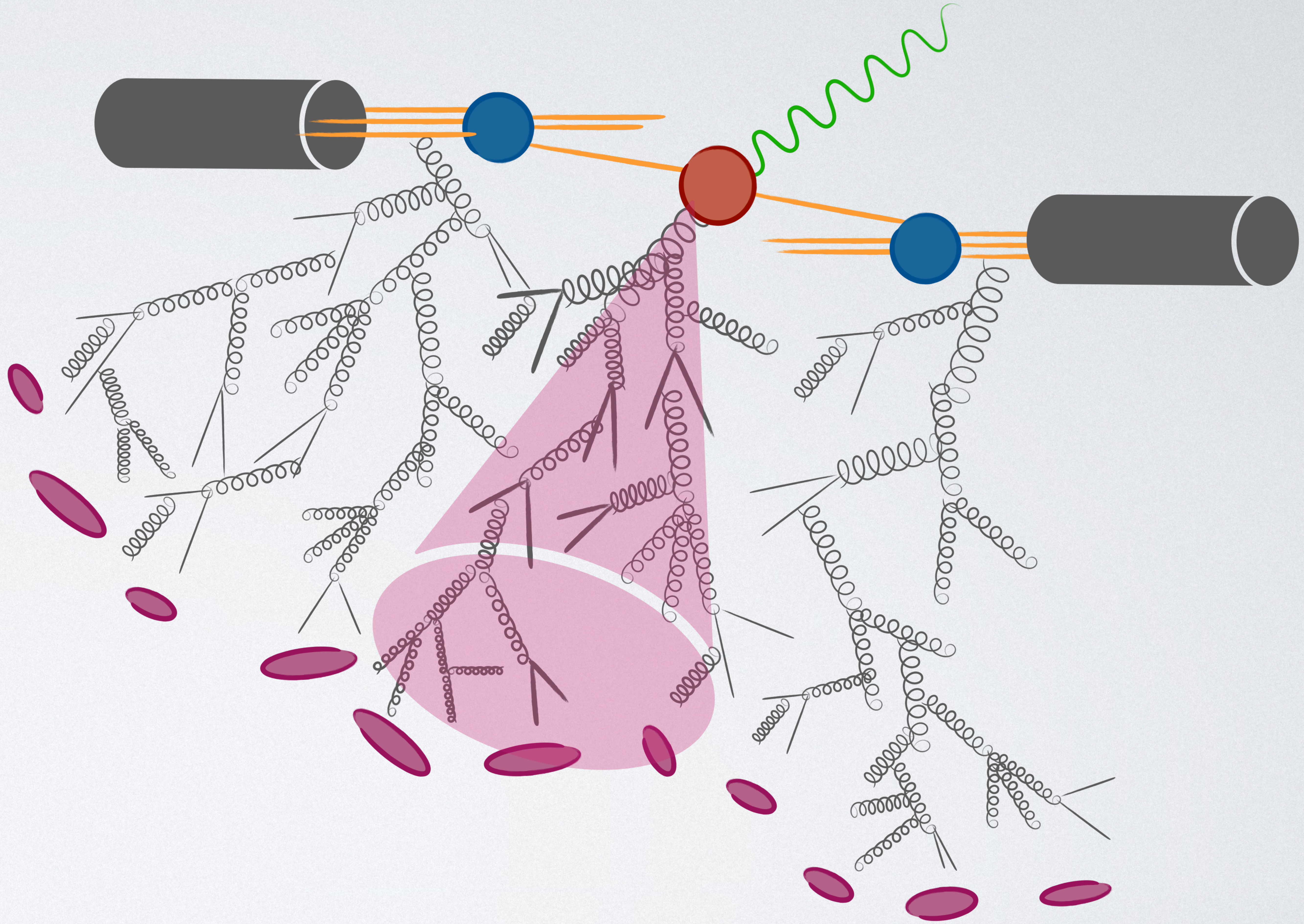
Introduction

Goal: Extending q_T - subtraction to 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^{ness} as a slicing variable
- All order and non-perturbative behaviour of k_T^{ness}

q_T - Subtraction And Resummation

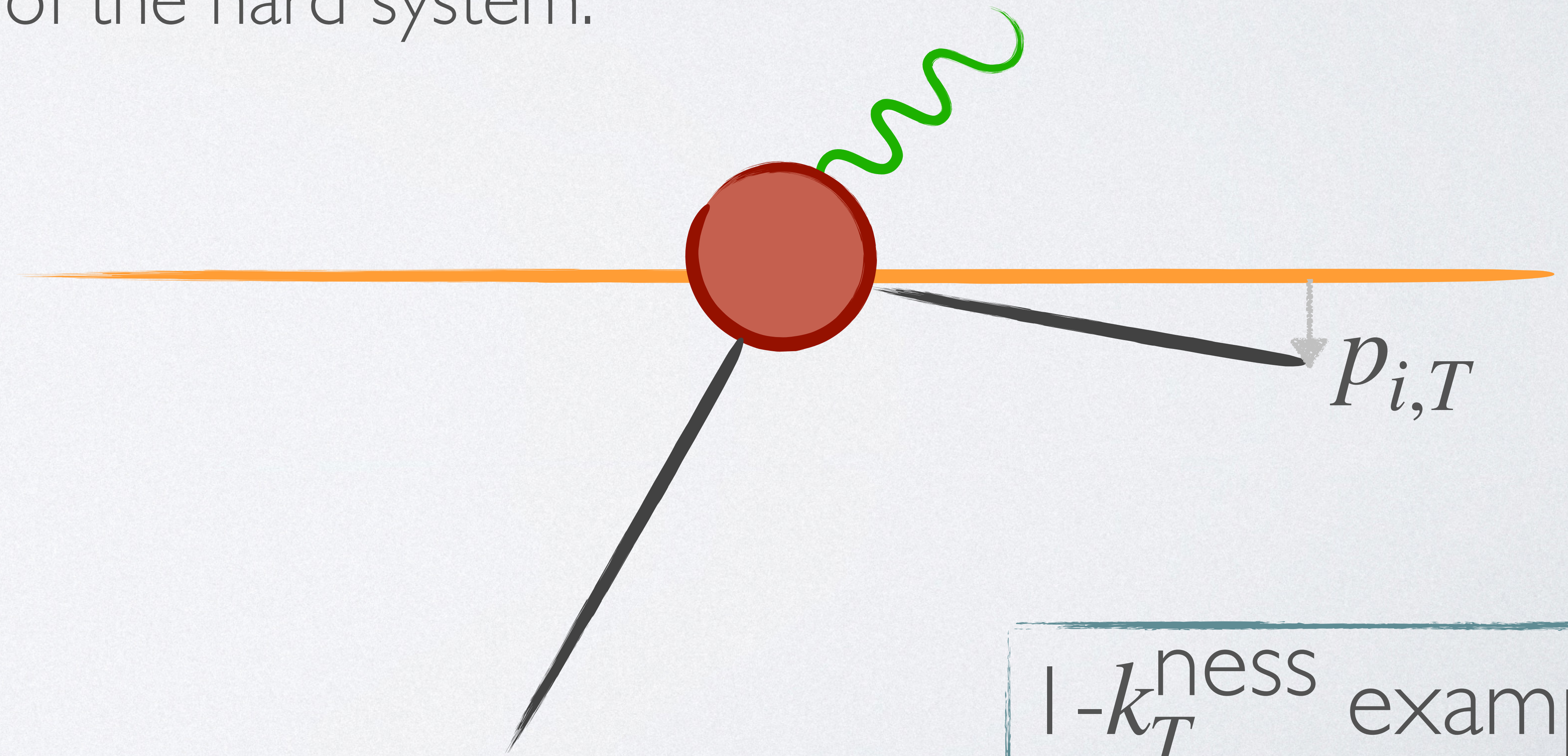
- $q_T =$ transverse momentum of resolved system (system already present at LO)
- If no jets are present at LO then $q_T > 0$ ensures that at N^{n}LO only IR divergences of N^{n-1}LO-type appear
- Thus, q_T can be used as a slicing variable at NNLO. (Catani, Grazzini (2007) [0703012])
- MATRIX: $pp \to V, H, \gamma\gamma, V\gamma, VV, t\bar{t}, \gamma\gamma\gamma, HH, b\bar{b}$ (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^{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.



1-k_T^{ness} example

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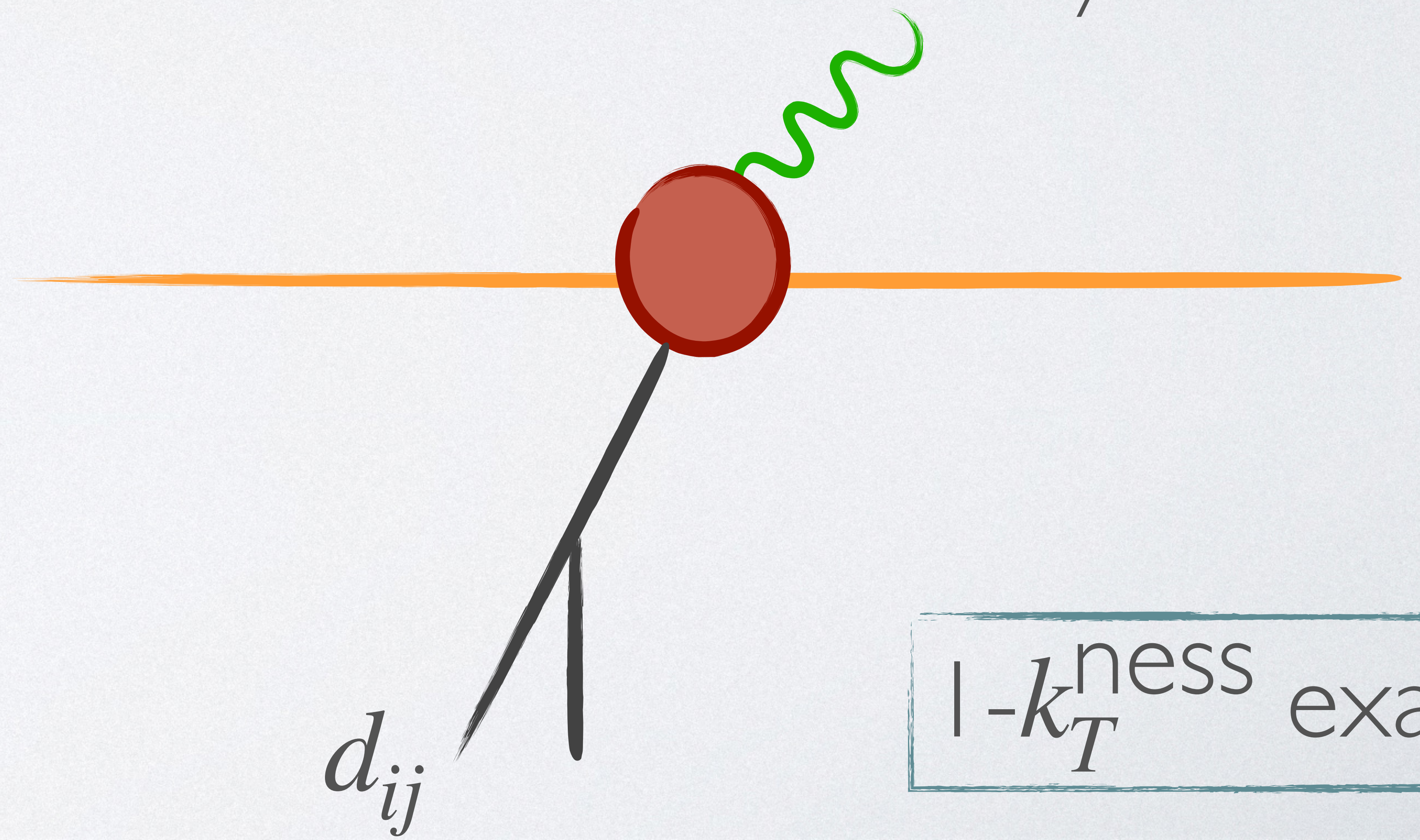

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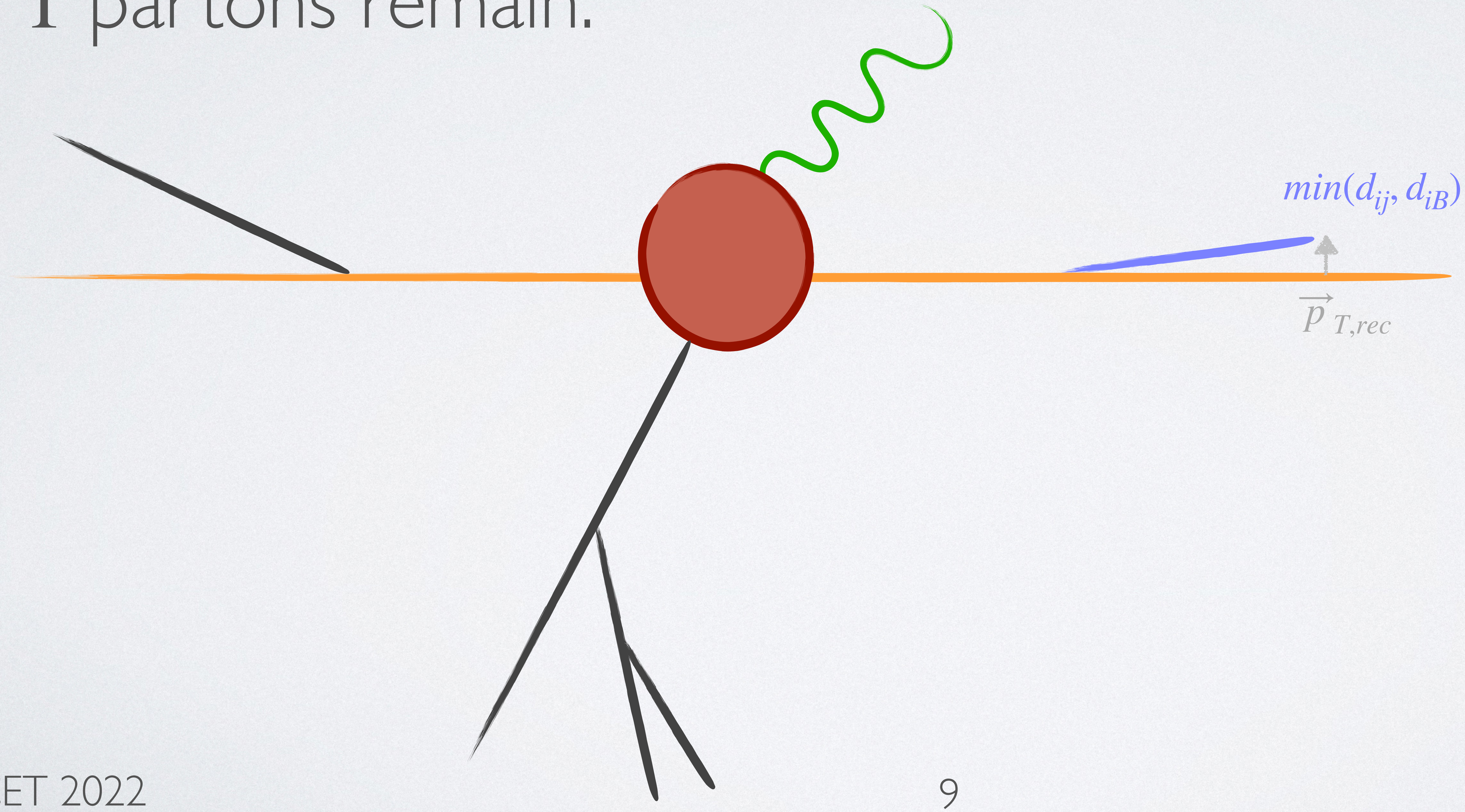
- For ISC radiation $N - k_T^{\text{ness}}$ is the transverse momentum of the hard system.
- For FSC radiation along a jet, $N - k_T^{\text{ness}}$ is the relative transverse momentum of the hard system wrt that jet
- For soft radiation the situation is more involved

Defining k_T^{ness}

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



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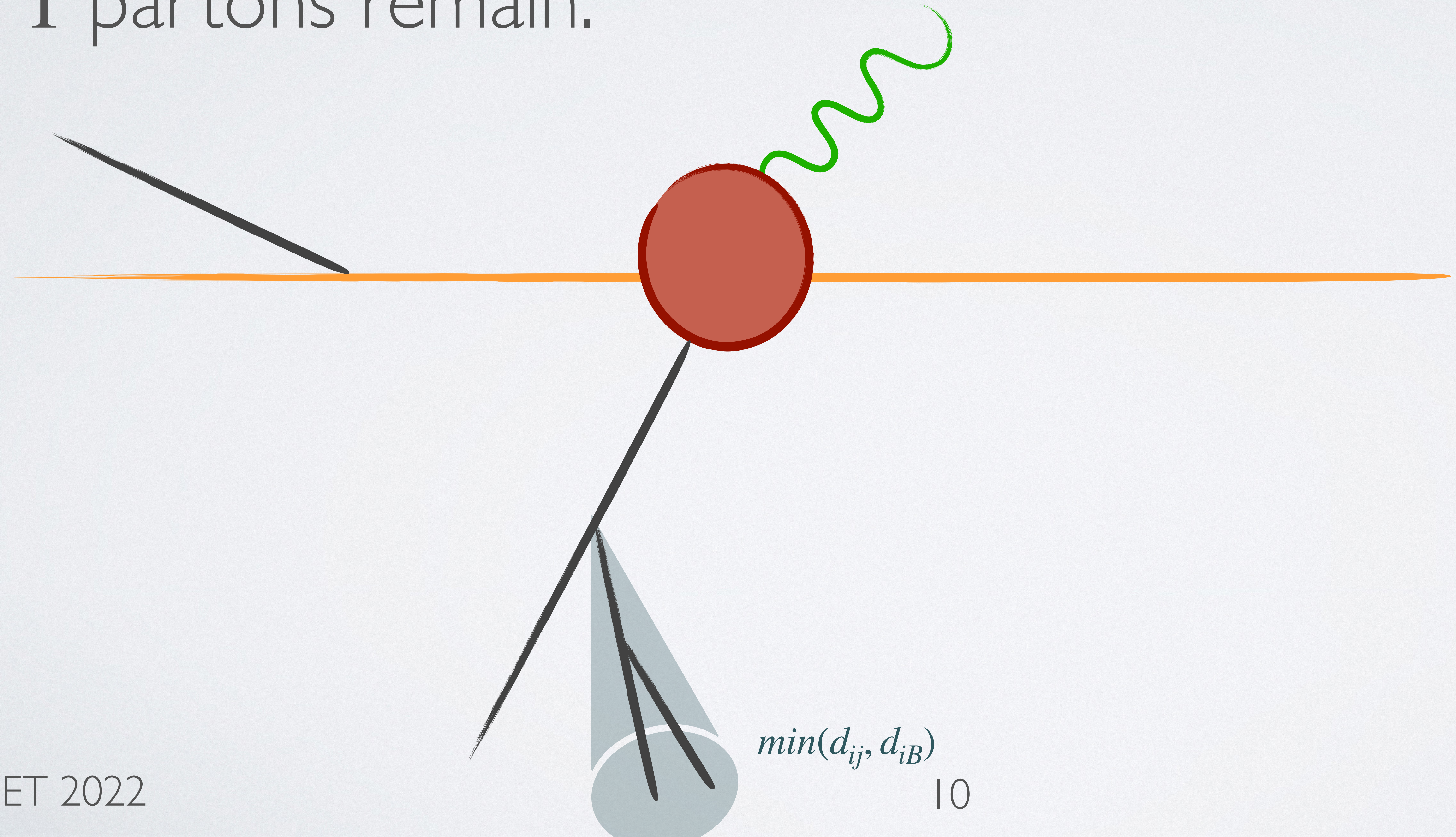

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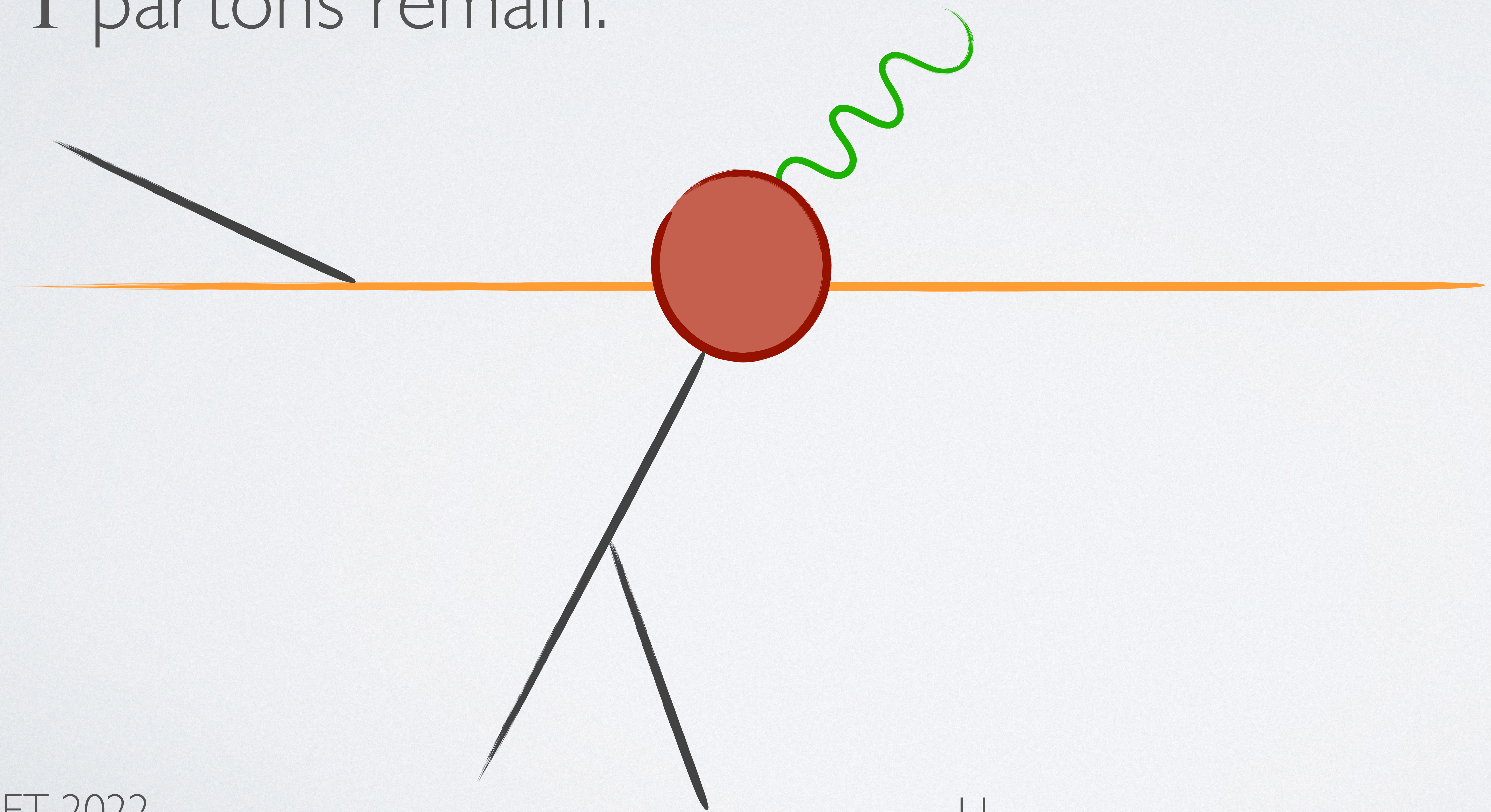

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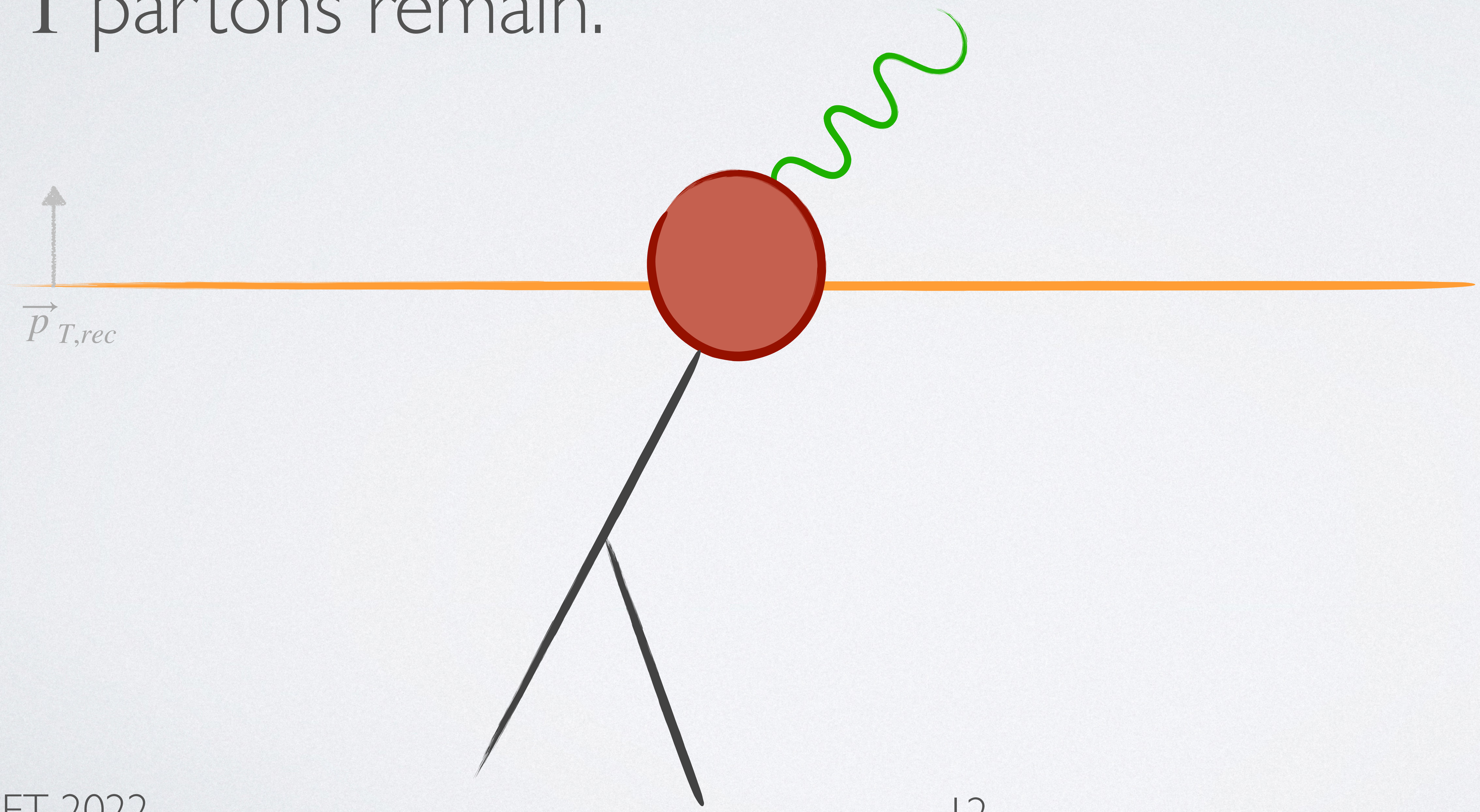

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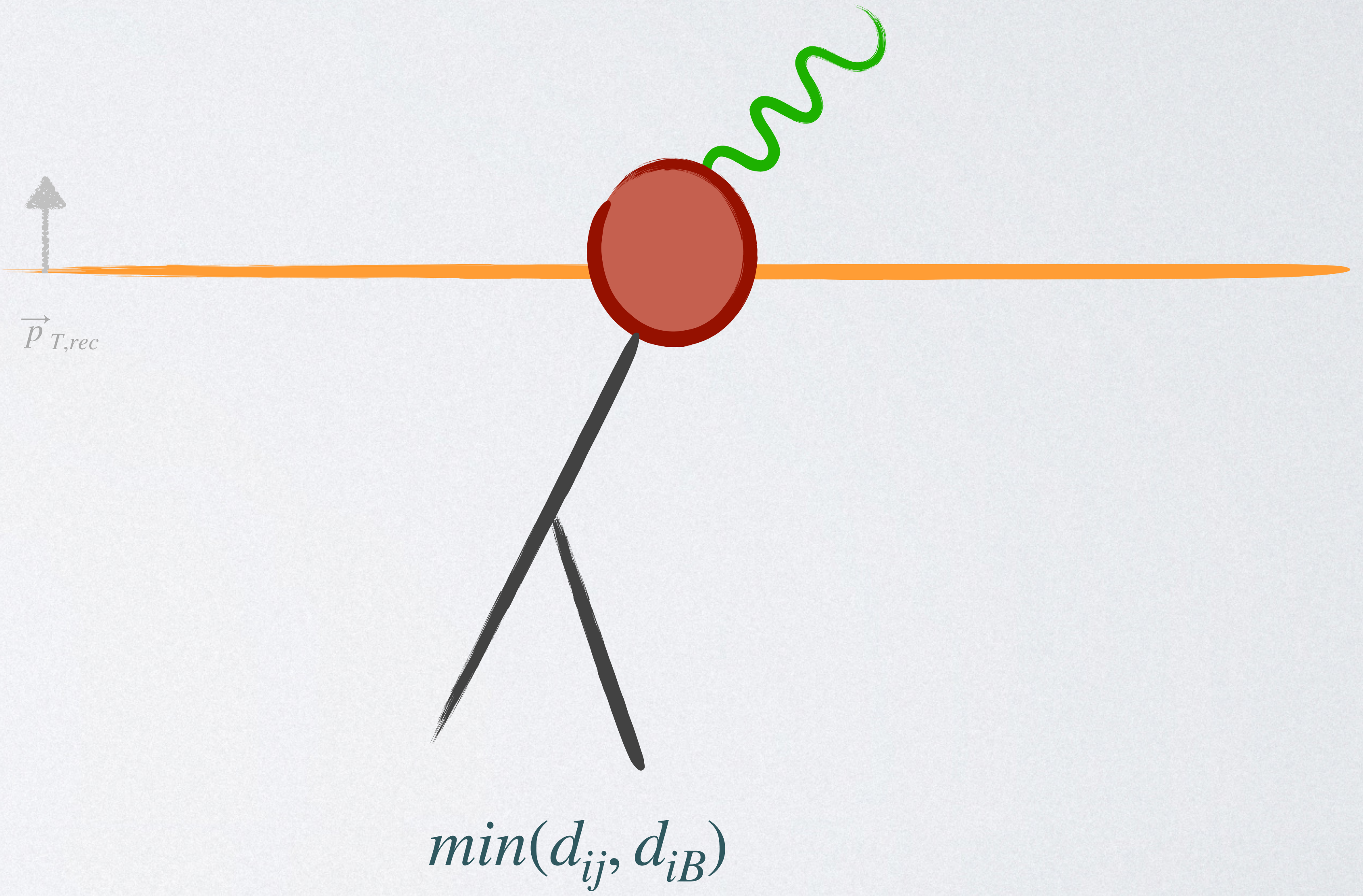
- We again determine $\mathbf{min}(\{p_{i,T}\}, \frac{\{d_{ij}\}}{D})$

- If it is a $\frac{d_{ij}}{D}$, define $k_T^{\text{ness}} = \frac{d_{ij}}{D}$



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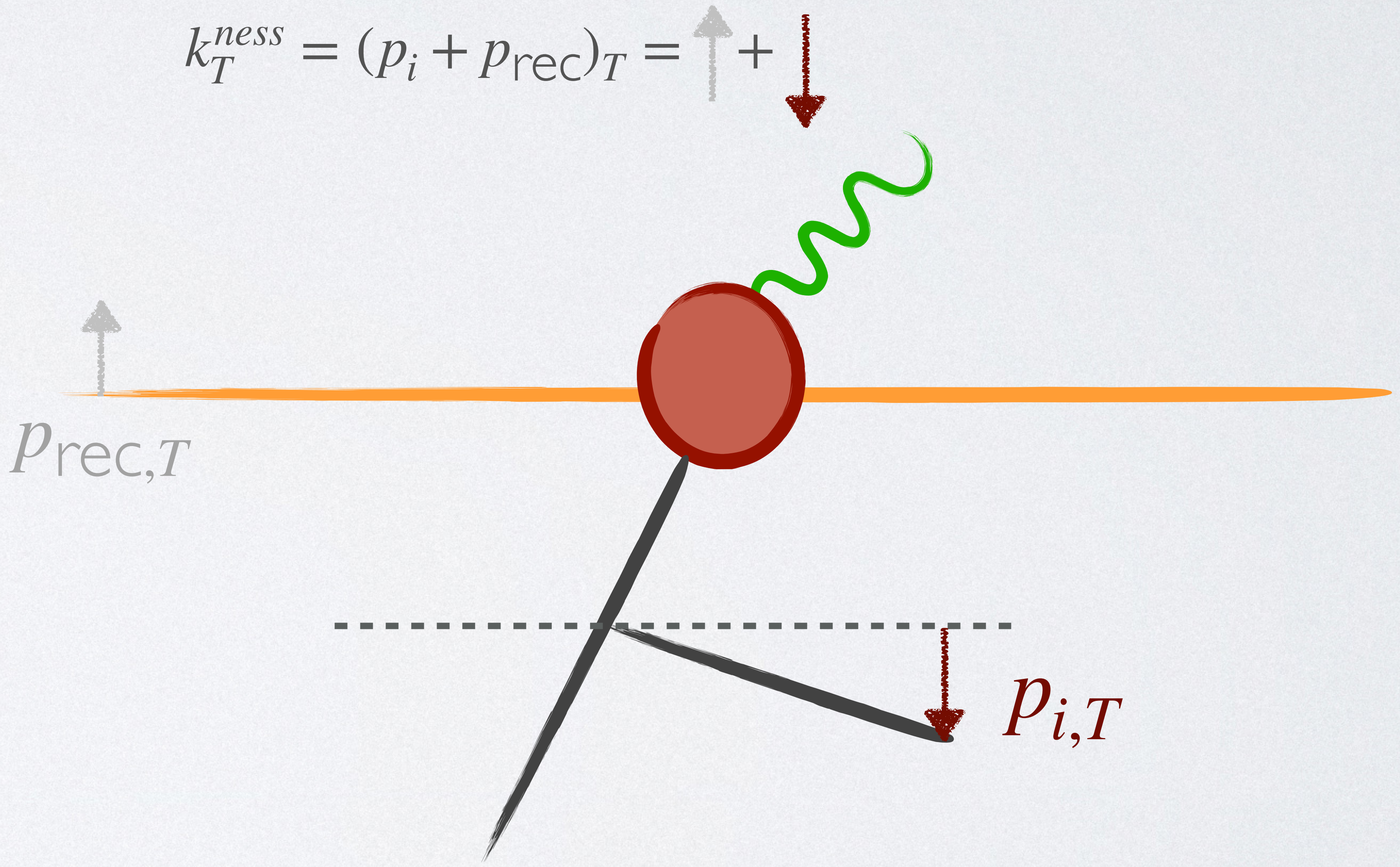
- If it is a $p_{i,t}$ define $k_T^{ness} = (p_i + p_{\text{rec}})_T$ (p_{rec} is the total momentum of the particles clustered with the beam)



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

k_T^{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 $pp \to N$ jets + colorless

- The pieces containing powers of $\log(r)$ give rise to the k_T^{ness}-slicing counter-terms

$$d\hat{\sigma}^{\text{CT,F+Njets}}_{\text{NLO}ab} = \frac{\alpha_S}{\pi}\frac{dk_T^{\text{ness}}}{k_T^{\text{ness}}}\text{Tr}\Bigg\{\Bigg[\ln\frac{Q^2}{\left(k_T^{\text{ness}}\right)^2}\sum_\alpha C_\alpha - \sum_\alpha \gamma_\alpha - \sum_i C_i \ln\left(D^2\right) - \sum_{\alpha\neq\beta}\mathbf{T}_\alpha\cdot\mathbf{T}_\beta \ln\left(\frac{2p_\alpha\cdot p_\beta}{Q^2}\right)\Bigg]$$

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

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

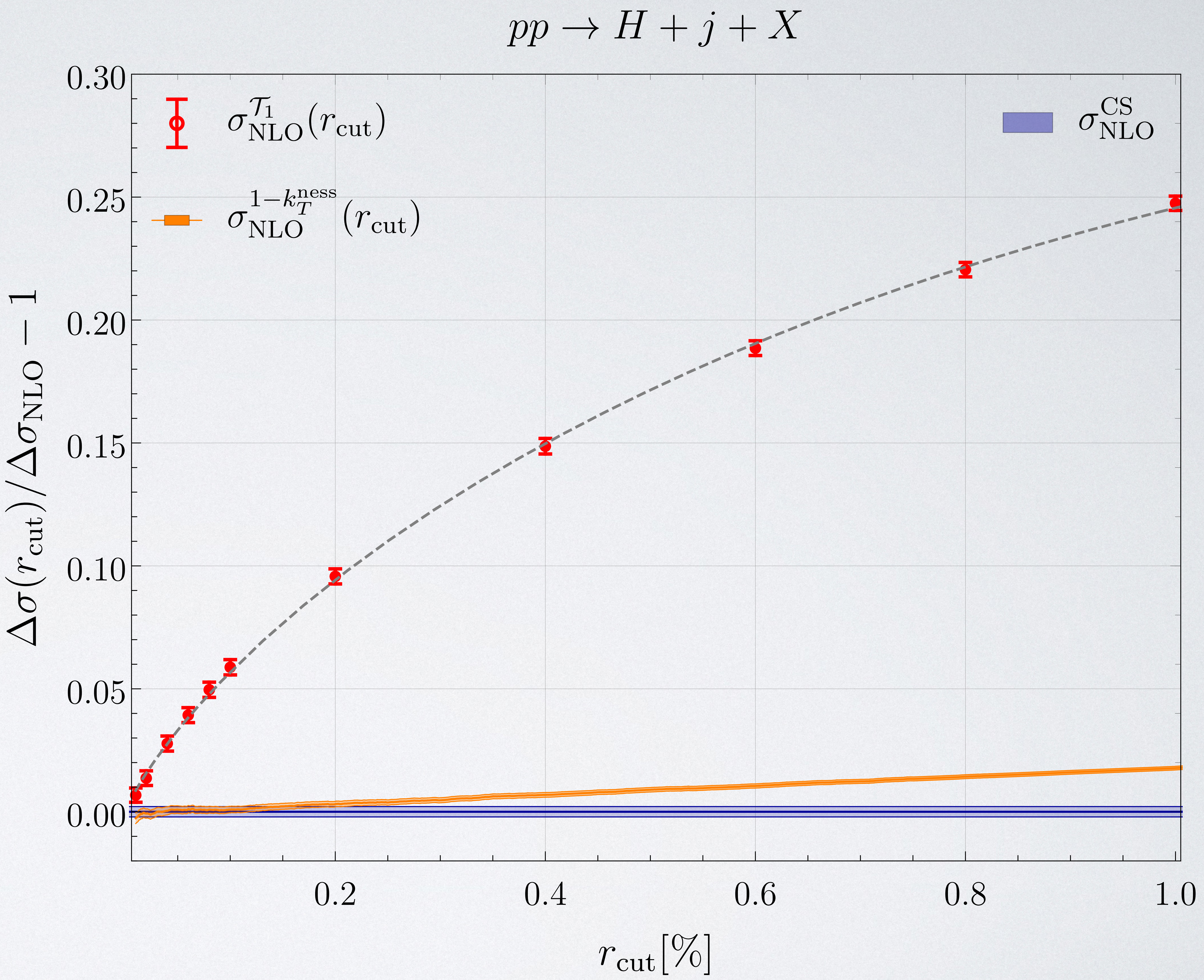
k_T^{ness} as a slicing variable

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

NLO Results

Higgs + jet

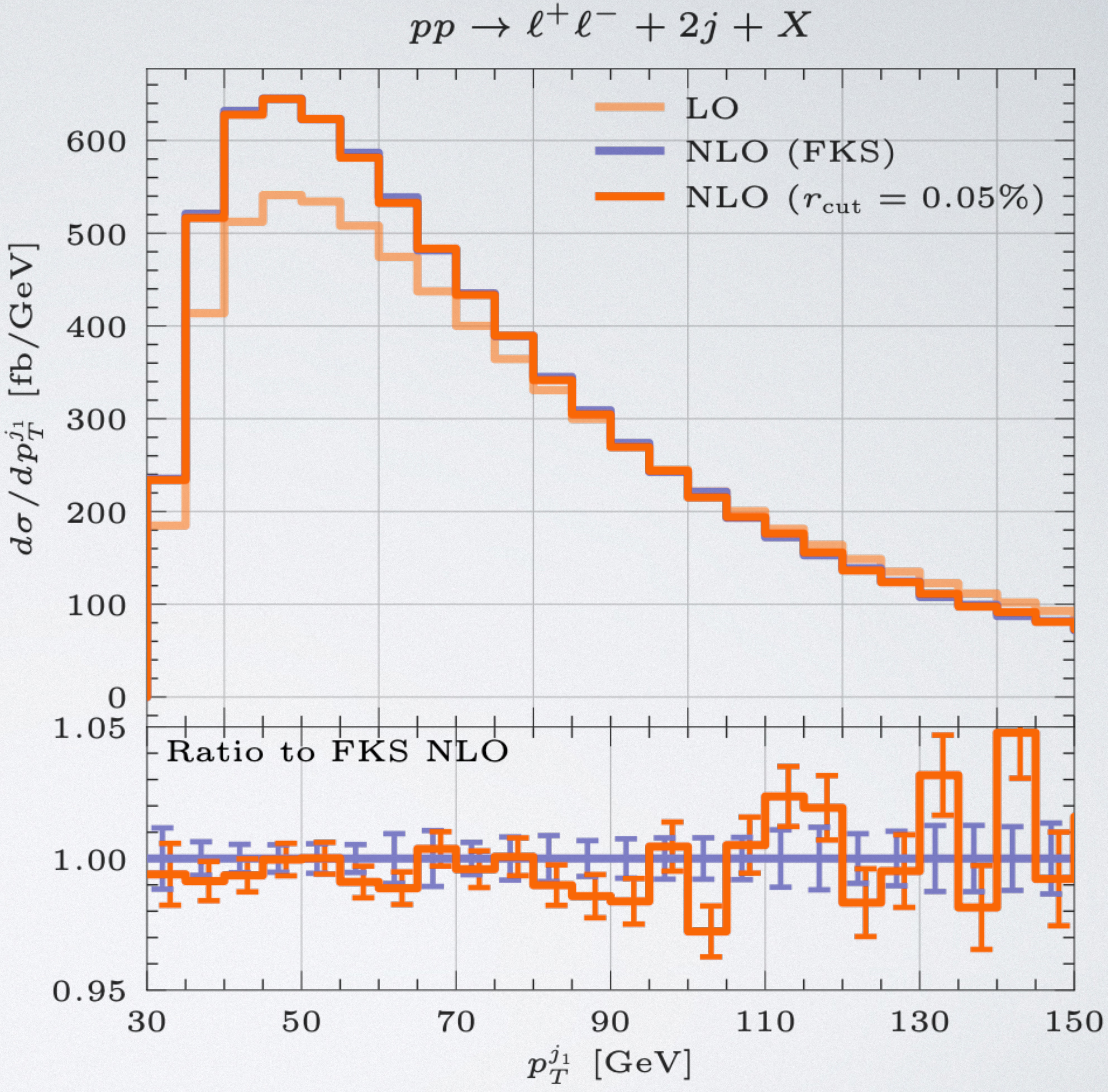
r_{cut}-dependence of $r = \frac{\tau_1}{\sqrt{m_H^2 + (p_T^j)^2}}$ and $r = \frac{k_T^{\text{ness}}}{\sqrt{m_H^2 + (p_T^j)^2}}$



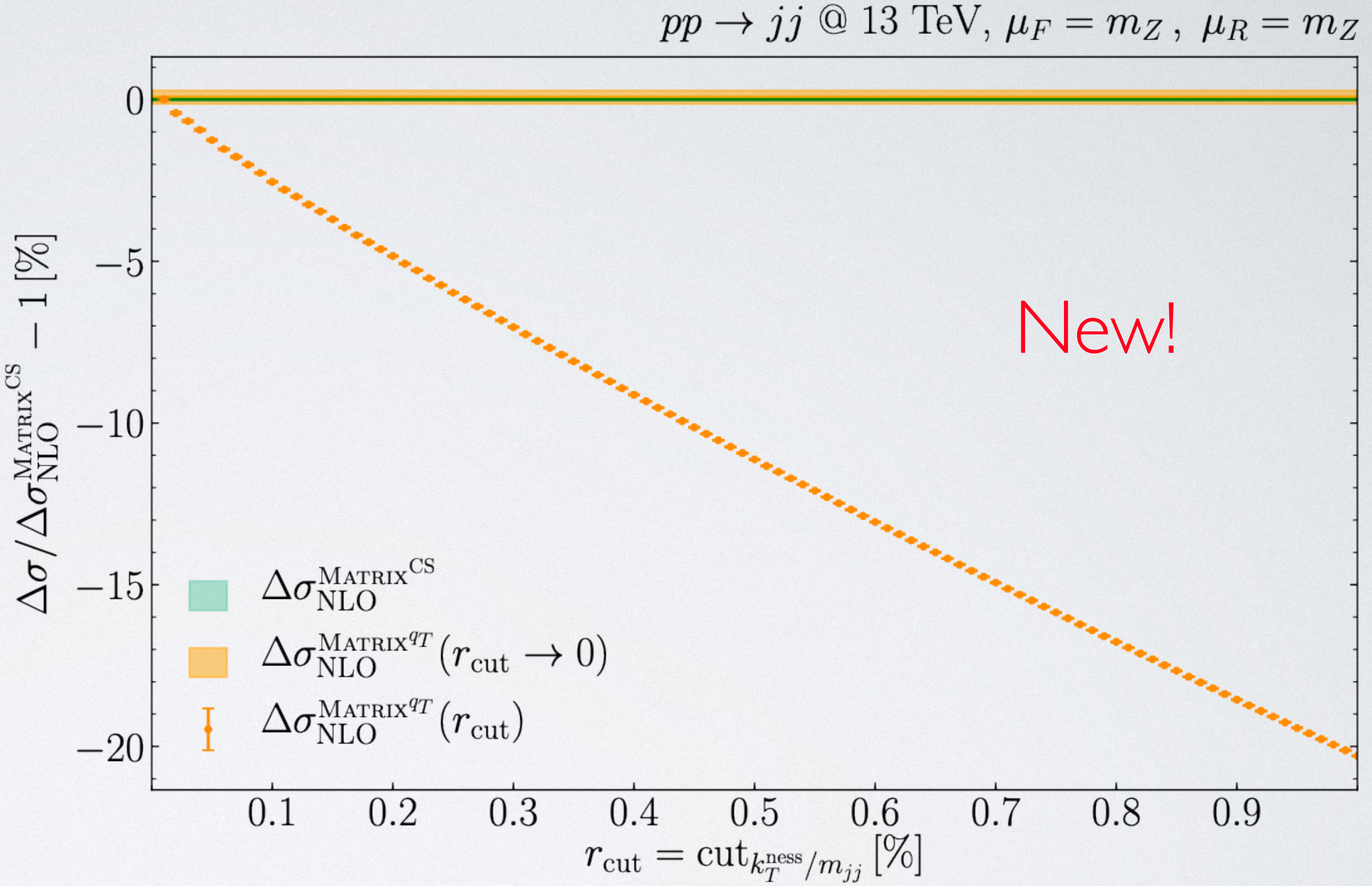
CS and 1-jettiness obtained with MCFM (Campbell, Neumann 1909.09117)

Z+2 jets

p_T - distribution of leading jet



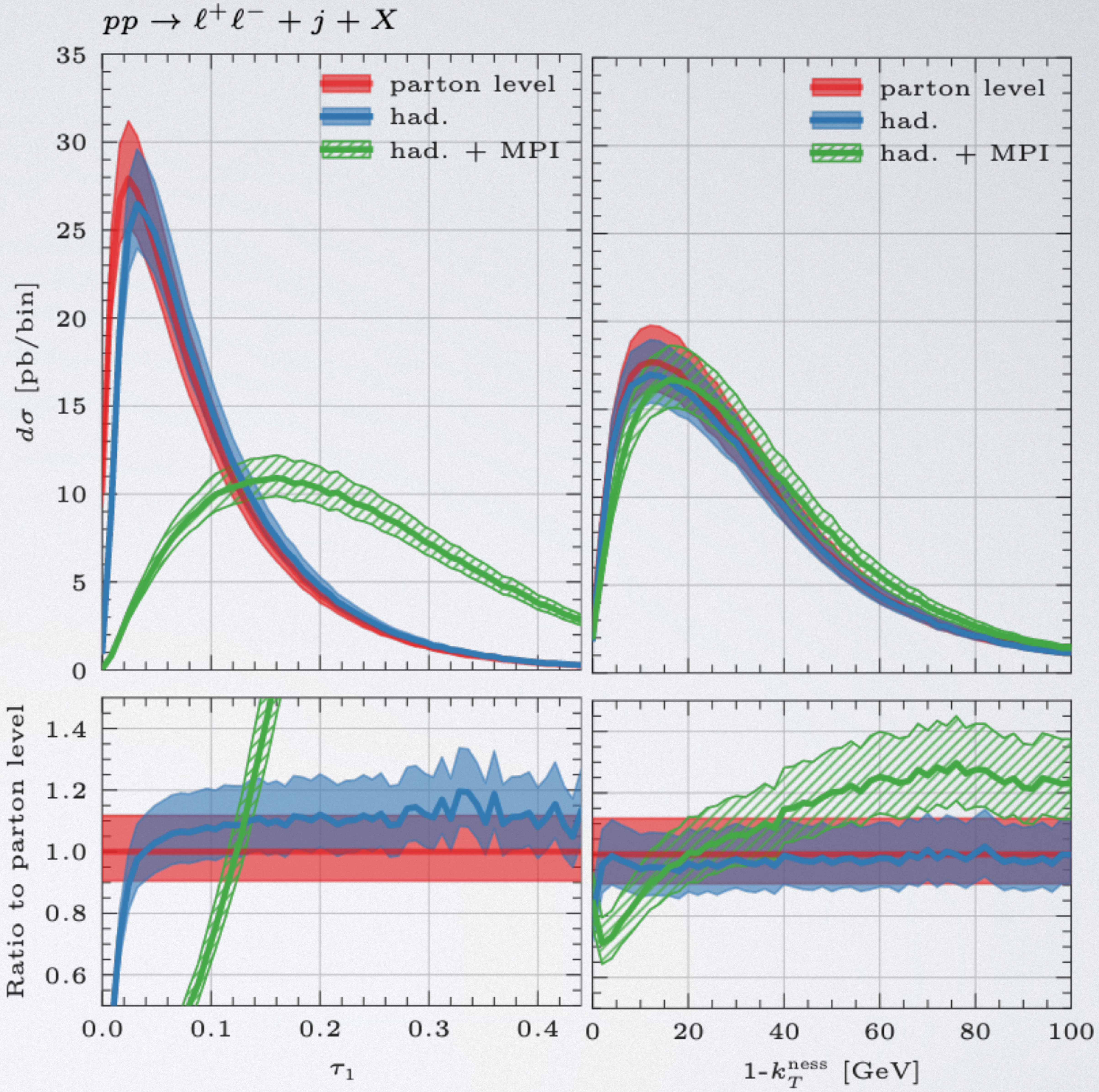
Di-jet (in MATRIX)



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^{ness} defined with FASTJET [1111.6097]

Outlook

- NLO: k_T^{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: $\mu_R = \mu_F = m_H$
  $p_T^j > 30GeV$
  $D = 1$
- Z+2jets: $p_T^j > 30GeV, \eta_j < 4.5$
  $p_T^l > 20\text{GeV}, \eta_l < 2.5, 66\,\text{GeV} < m_{ll} < 116\,\text{GeV}, R_{jl} > 0.5, R_{ll} > 0.2$
  $D = 0.1$
- Dijet: $p_T^j > 30GeV$
  $D = 1$

$\sqrt{s_{\text{had}}} = 13\text{TeV}$

$NNPDF31\_nlo\_as\_0118$

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

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

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

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