

# Flavour sensitive observables at NNLO

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HP2 - 22 Sept. 2022

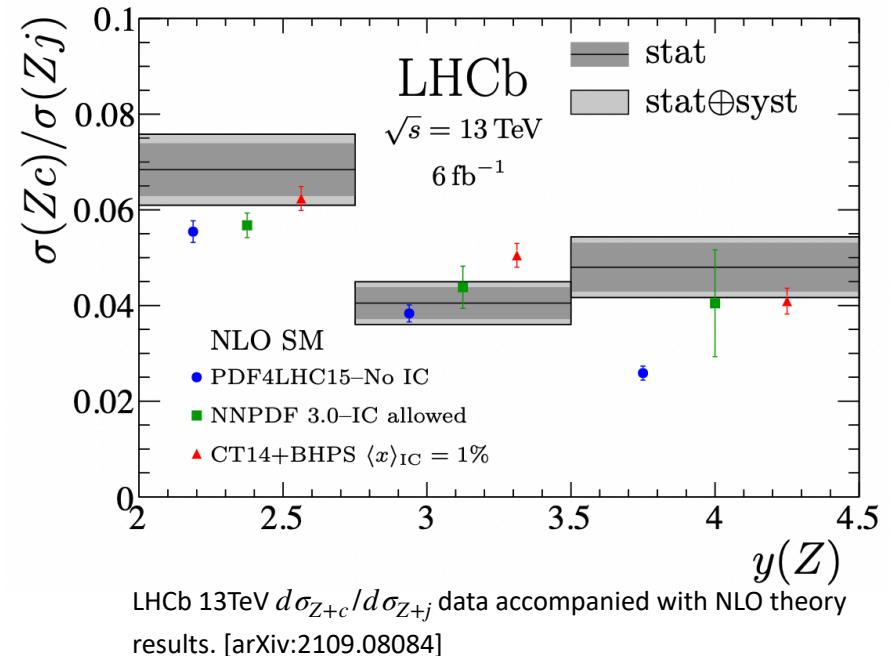
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# Overview

- Why use  $Z + c\text{-jet}$  process with LHCb set up?
- Flavour tagging: Experiment vs Theory and IRC safety
- Presentation of three IRC flavour safe jet algorithms
- Theoretical predictions for  $Z + c\text{-jet}$  observables at NNLO for LHCb 13TeV

# Intrinsic charm (IC): probed at LHCb 13TeV

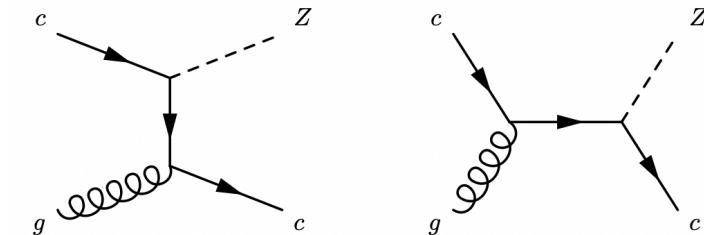
- Charm quarks appear only perturbatively via PDF evolution (DGLAP)
- Intrinsic Charm: allow charm content in the proton PDF at low scale ( $Q \approx 1\text{GeV}$ )
- Predictions appear to do better when including IC component
- Currently probed at NLO only
- First goal: NNLO predictions for  $c$ -jet observables with the LHCb set up



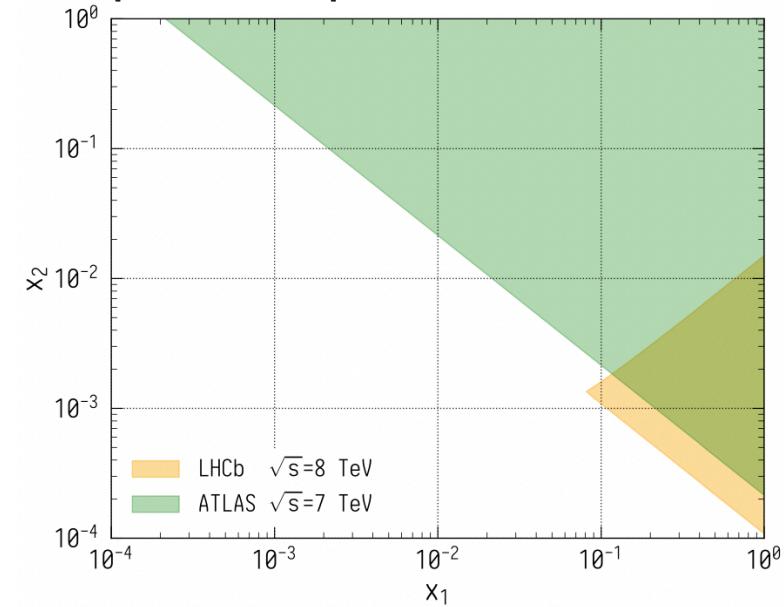
# Why Z+c-jet at LHCb?

- The dominant contribution to  $p\ p \rightarrow Z + c$  arises from the  $cg$ -channel
- LHCb suited to probe highly asymmetric parton momentum fractions  $x_1, x_2$   
⇒ Abundant low  $x$  gluons and high  $x$  valence quarks including possibly the charm quark

Diagrams of the leading order contribution to  $p\ p \rightarrow Z + c$



Z+jet LHCb experimental  $(x_1, x_2)$  coverage at LO.  
[arXiv:1901.11041]



# Our focus

- Compute precise predictions for flavour sensitive  $Z + c\text{-jet}$  observables at NNLO ( $\alpha_s^3$ )
- Using the  $Z + c\text{-jet}$  at LHCb 13TeV set up

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$Z$ bosons	$p_T(\mu) > 20 \text{ GeV}, 2.0 < \eta(\mu) < 4.5, 60 < m(\mu^+\mu^-) < 120 \text{ GeV}$
Jets	$20 < p_T(j) < 100 \text{ GeV}, 2.2 < \eta(j) < 4.2$
Charm jets	$p_T(c \text{ hadron}) > 5 \text{ GeV}, \Delta R(j, c \text{ hadron}) < 0.5$
Events	$\Delta R(\mu, j) > 0.5$

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Table with LHCb 13TeV fiducial region. [arXiv:2109.08084]

- Investigate flavour sensitive jet algorithms.

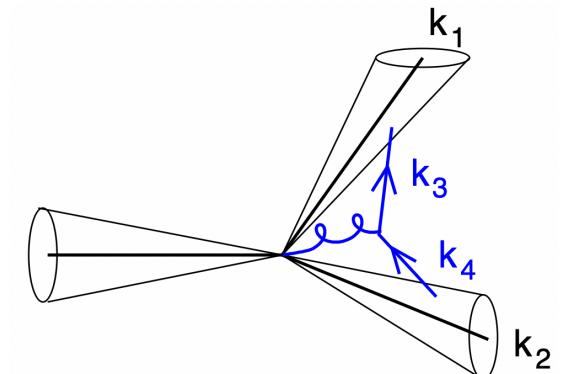
# Flavoured jet definition: experiments vs theory

- Jet flavour is defined by the number of flavoured particles inside a jet
  - If  $\#[p_f] - \#[\bar{p}_f] \neq 0 \Rightarrow$  jet is flavoured
  - If zero, the jet is considered a flavourless gluon jet
- Experimental jet definition: associate flavour to already generated flavourless jets (with the anti- $k_T$  jet algorithm)
- Use vertex + track reconstruction tools to find D-hadron (if tagging c-quarks) decay products

# Flavoured jet definition: experiments vs theory

- In theory the steps are reversed: flavour information comes from partons and then a jet algorithm defining flavourless and flavoured jets is applied
- Anti- $k_T$  jet algorithm is **flavour IR unsafe** for massless quarks at NNLO

- Large angle splitting into a  $q\bar{q}$  pair ( $k_3, k_4$ ) of gluon can alter the flavour of a hard jet



⇒ Need for a different jet algorithm than anti- $k_T$

# Flavour safe jet algorithms (selection)

## 1. Flavour- $k_T$

([arXiv:hep-ph/0601139]: A. Banfi, G.P. Salam, G. Zanderighi)

## 2. Infrared-safe flavoured anti- $k_T$ jets

([arXiv:2205.11879]: M. Czakon, A. Mitov, R. Poncelet)

## 3. Flavour dressing suiting any jet definition

([arXiv:2208.11138]: R. Gauld, A. Huss, G. Stagnitto)

This work focused on these three algorithms; more exist:

([arXiv:2205.01109]: D. Reichelt et al., ... )

# 1. Flavour- $k_T$ jet algorithm

([arXiv:hep-ph/0601139]: A. Banfi, G.P. Salam, G. Zanderighi)

- Uses the distance measures of the  $k_T$  algorithm but modified in case flavour particles are involved

$$d_{ij}^{(F,\alpha)} = (\Delta\eta_{ij}^2 + \Delta\phi_{ij}^2) \times \begin{cases} \max(k_{ti}, k_{tj})^\alpha \min(k_{ti}, k_{tj})^{2-\alpha}, & \text{softer of } i, j \text{ is flavoured,} \\ \min(k_{ti}^2, k_{tj}^2), & \text{softer of } i, j \text{ is flavourless,} \end{cases}$$

$$d_{iB}^{(F,\alpha)} = \begin{cases} \max(k_{ti}, k_{tB}(\eta_i))^\alpha \min(k_{ti}, k_{tB}(\eta_i))^{2-\alpha}, & i \text{ is flavoured,} \\ \min(k_{ti}^2, k_{tB}^2(\eta_i)), & i \text{ is flavourless,} \end{cases}$$

(+): Works for theory computations. Benchmark to beat

(-): It generates  $k_T$ -like jets  $\Rightarrow$  no one to one comparison with data yet

# 2. Flavour anti- $k_T$ jet algorithm

([arXiv:2205.11879]: M. Czakon, A. Mitov, R. Poncelet)

- Uses the distance measures of anti- $k_T$  but modified in case flavour particles are involved

$$d_{ij} = R^2 \min(k_{T,i}^{-2}, k_{T,j}^{-2}) \cdot S_{ij}^a \quad \text{and} \quad d_{iB} = k_{T,i}^{-2}$$

- $S_{ij}^a \neq 1$  only in the case  $i$  and  $j$  are of opposite flavour

$$S_{ij}^a \equiv 1 - \theta(1 - \kappa) \cos\left(\frac{\pi}{2}\kappa\right) \quad \text{with} \quad \kappa \equiv \frac{1}{a} \frac{k_{T,i}^2 + k_{T,j}^2}{2k_{T,max}^2}$$

(+): Generates anti- $k_T$  jets but only in the  $a \rightarrow 0$  limit

(-): Therefore not exactly anti- $k_T$  jets

# 3. Flavour dressing to suit any jet definition

([arXiv:2208.11138]: R. Gauld, A. Huss, G. Stagnitto)

- Inputs:
    - Previously defined flavour agnostic jets
    - Flavoured clusters
  - Construction of a **flavoured cluster**: the algorithm finds a flavoured particle and clusters it with collinearly radiated gluons.  
    ⇒ Ensures collinear safety
  - Flavour- $k_T$  distance measures assign the flavour clusters to the flavour agnostic jets
- (+): Can be applied on anti- $k_T$  (or any jet definition)
- (+?): Method replicable in experiments?

# NNLO predictions

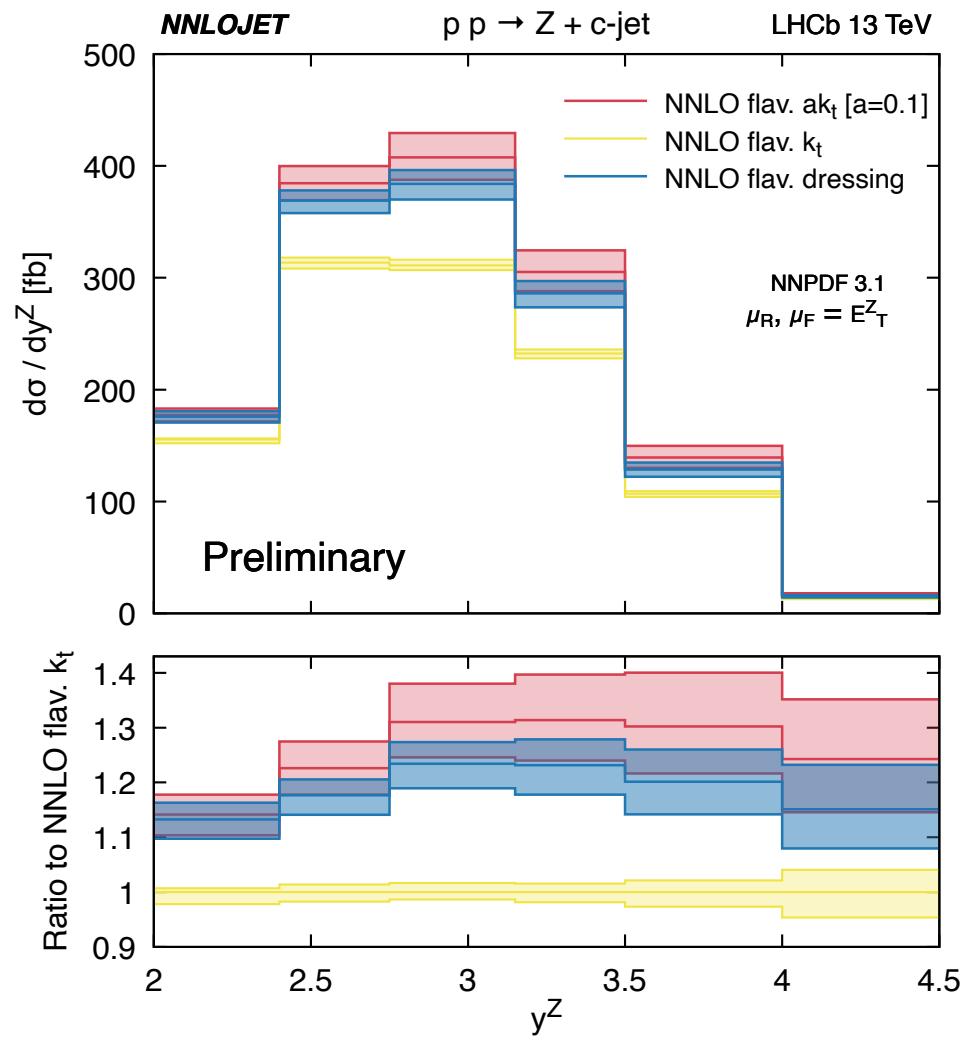
Z+c-jet LHCb 13TeV

# NNLOJET implementation

- Calculation performed on NNLOJET
  - Parton-level event generator
  - Antenna subtraction method to handle infrared singular real radiation
- Use existing Z+jet flavour-blind computation on top of which we add and trace the flavour information
- Flavoured jets: flavour- $k_t$ , flavour anti- $k_t$  and flavour dressing algorithms ( $\Delta R = 0.5$ )
- Theoretical uncertainty is shown with the 7-point scale variation using  $E_T^Z$  as the central scale

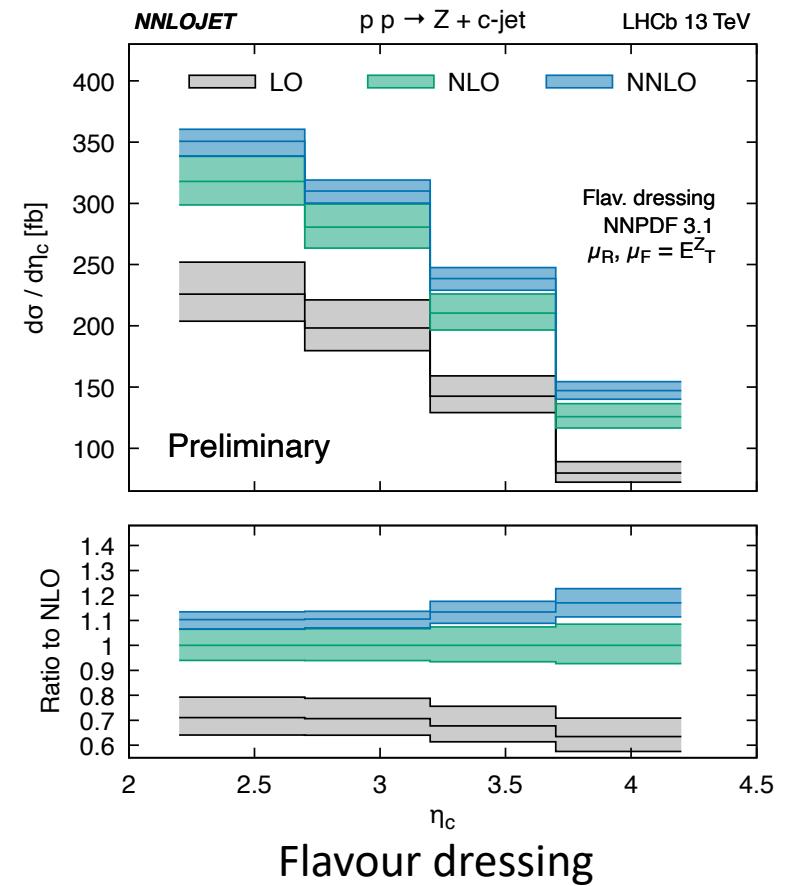
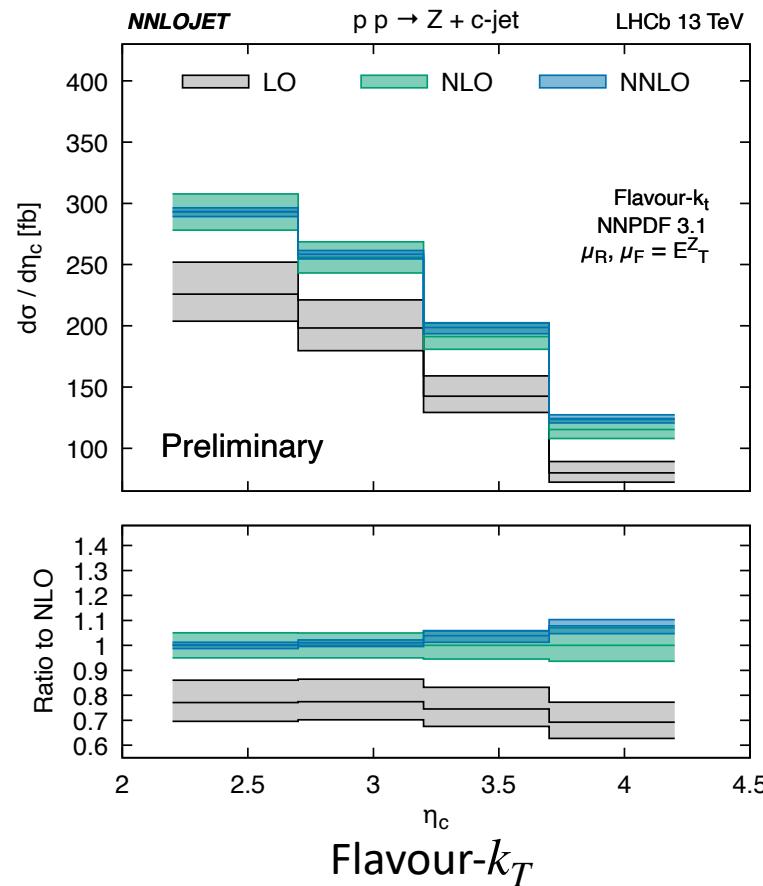
# Algorithm comparison: $y^Z$ distribution at NNLO

- Flavour anti- $k_T$  and flavour dressing show similar shape, and higher values and uncertainties than flavour- $k_T$
- Flavour anti- $k_T$  has higher uncertainties than flavour dressing



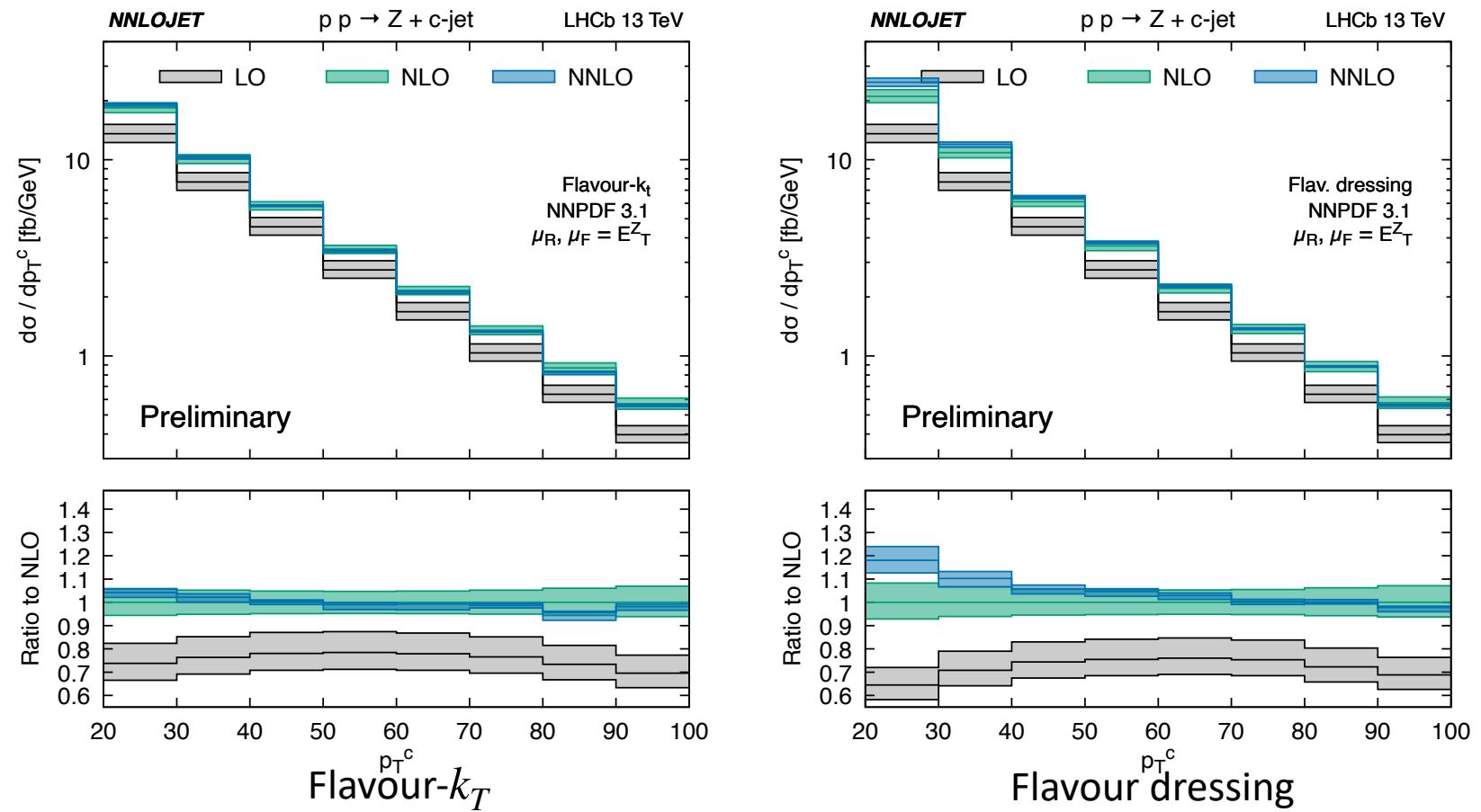
# $\eta_c$ distribution up to NNLO: flavour- $k_T$ vs flavour dressing

- Larger corrections and uncertainties for flavour dressing
- Perturbative convergence seems better for flavour- $k_T$



# $p_T^c$ distribution up to NNLO: flavour- $k_T$ vs flavour dressing

- Higher values for flavour dressing (already at NLO)
- For  $p_T^c > 40 \text{ GeV}$ :
  - Similar ratio NNLO/NLO
  - Good perturbative convergence for both algorithms
  - Comparable theoretical uncertainties at NNLO



# Conclusions

- We presented NNLO ( $\alpha_s^3$ ) predictions for  $Z + c\text{-jet}$  observables
- We discussed and compared the results obtained with three different flavoured jet definitions by analysing the impact of higher order corrections
- Phenomenology is still in progress, more to come!

Thank you!

# Backup slides

# 3. Flavour dressing: flavoured clusters

([arXiv:2208.11138]: R. Gauld, A. Huss, G. Stagnitto)

- Construction of the flavoured clusters
  - Take a set with the objects used as input to the flavour agnostic jet algorithm
  - Find pair  $a, b$  with smallest  $\Delta R_{ab}^2 = (y_a - y_b)^2 + (\varphi_a - \varphi_b)^2$ . If  $\Delta R_{ab}^2 > R_{cut}$ :
    - $a, b$  flavourless: replace  $a, b$  by a single flavourless object with momenta  $p_{T,a} + p_{T,b}$
    - $a \text{ or } b$  flavoured: remove the unflavoured one, if  $\frac{\min(p_{T,a}, p_{T,b})}{(p_{T,a} + p_{T,b})} > z_{cut} \left( \frac{\Delta R_{ab}}{R_{cut}} \right)^\beta$  update the momentum of the flavoured one
    - $a \text{ and } b$  flavoured:  $a$  and  $b$  are already flavour clusters

# 3. Flavour dressing distance measures

([arXiv:2208.11138]: R. Gauld, A. Huss, G. Stagnitto)

- The distance measures used are inspired from the flavour- $k_T$  algorithm:
  - For  $i, j$  flavoured clusters or jets:
    - $d_{ij} = \Delta R_{ij}^2 \max(p_{T,i}^\alpha, p_{T,j}^\alpha) \min(p_{T,i}^{2-\alpha}, p_{T,j}^{2-\alpha})$
  - For beam distance:
    - $d_{\hat{a}B_\pm} = \max(p_{T,\hat{a}}^\alpha, p_{T,B_\pm}^\alpha(y_{\hat{a}})) \min(p_{T,\hat{a}}^{2-\alpha}, p_{T,B_\pm}^{2-\alpha}(y_{\hat{a}}))$
    - with  $p_{T,B_\pm}(y) = \sum_{k=1}^m p_{T,j_k} \left[ \Theta(\pm \Delta y_{j_k}) + \Theta(\mp \Delta y_{j_k}) e^{\pm \Delta y_{j_k}} \right]$

# $\eta_c$ distribution up to NNLO: flavour anti- $k_T$

([arXiv:2205.11879]: M. Czakon, A. Mitov, R. Poncelet)

- Large NNLO corrections and uncertainties over the whole  $\eta_c$  range
- No overlapping of NNLO and NLO uncertainty bands

