The Galileo Galilei Institute
For Theoretical Physics
Centro Nazionale di Studi Avanzati dell'Istituto Nazionale di Fisica Nucleare
Arcetri, Firenze

Flavoured jets at the LHC

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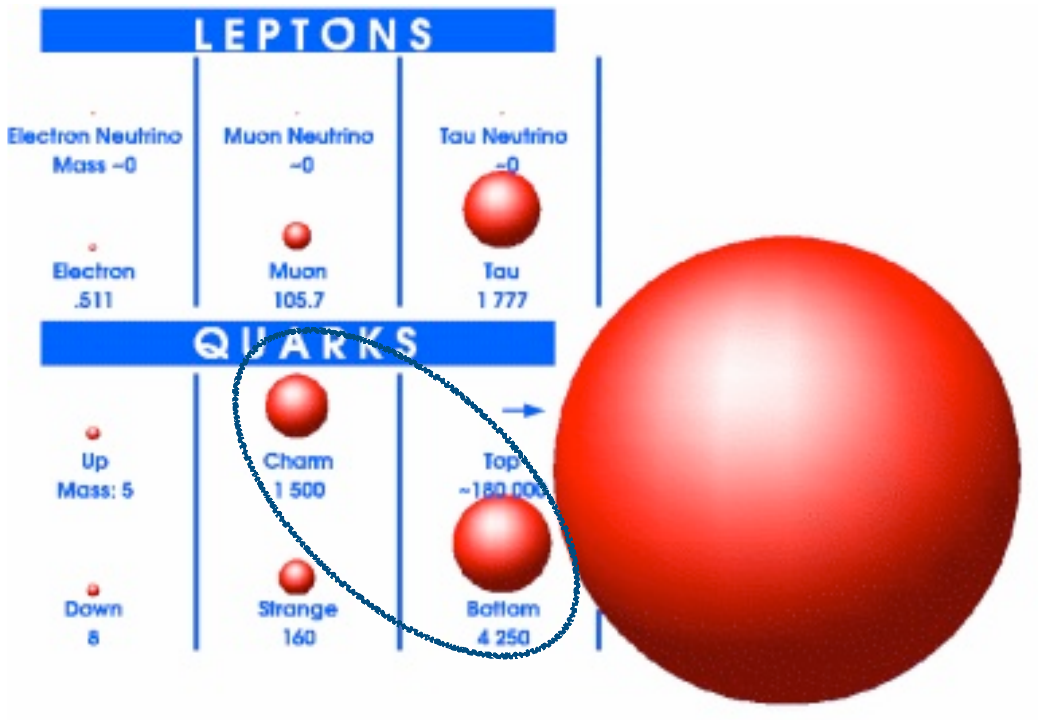
Theory Challenges in the Precision Era of the Large Hadron Collider
GGI Florence, 28.08-01.09.2023

5 years ago

Flavoured (heavy) quarks → Flavoured jets



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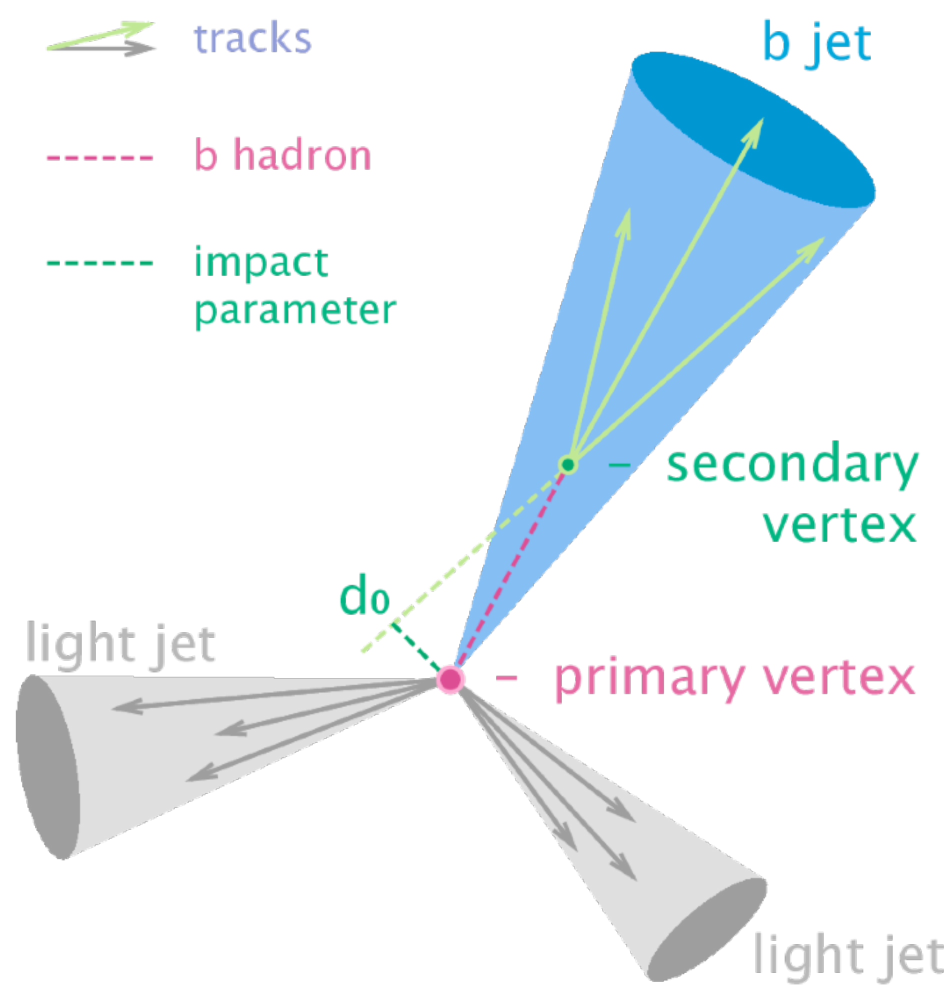
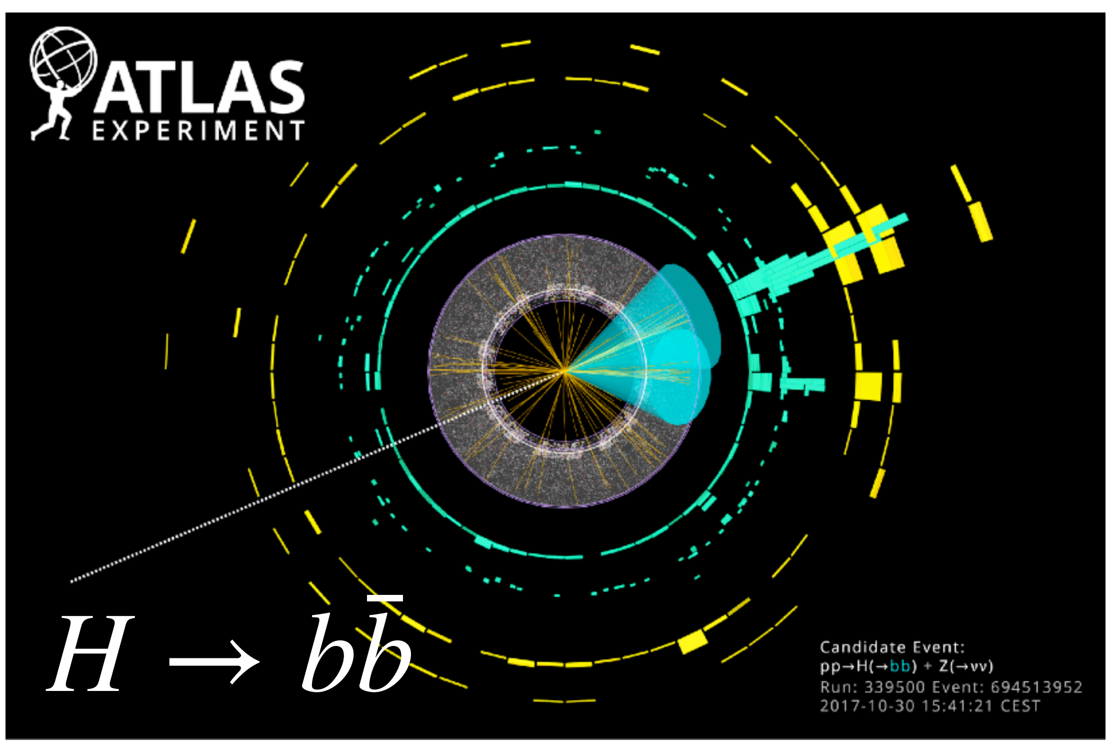
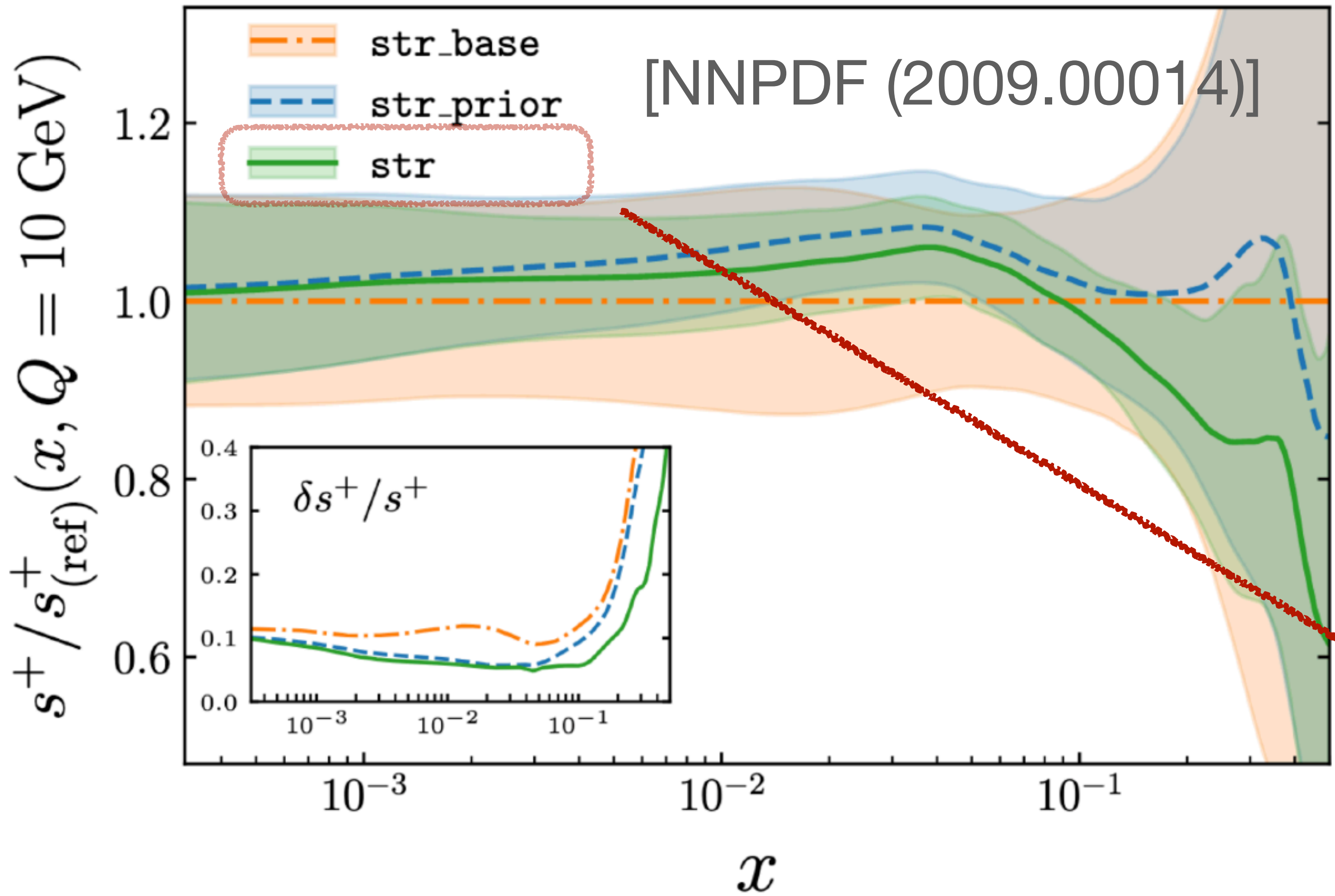


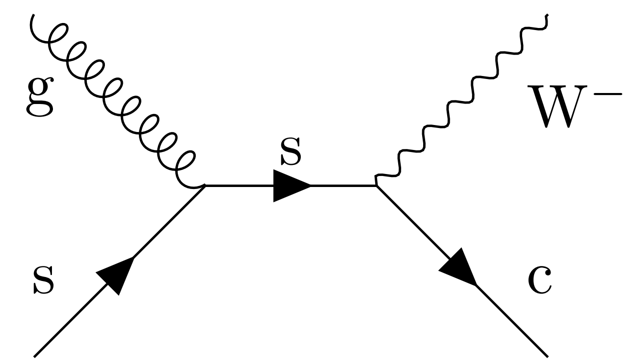


Decay products of B- or D-hadrons as a **proxy** for b or c quarks in the hard scattering process

Why flavoured jets?



An example: W+c-jet
unique probe into the strange PDF



contain [ATLAS (1402.6263)] and [CMS (1310.1138)] 7 TeV data

… but **flavoured jets/particles appear everywhere**:
top, Higgs, new physics searches, …
useful to pinpoint specific scattering processes and reject backgrounds

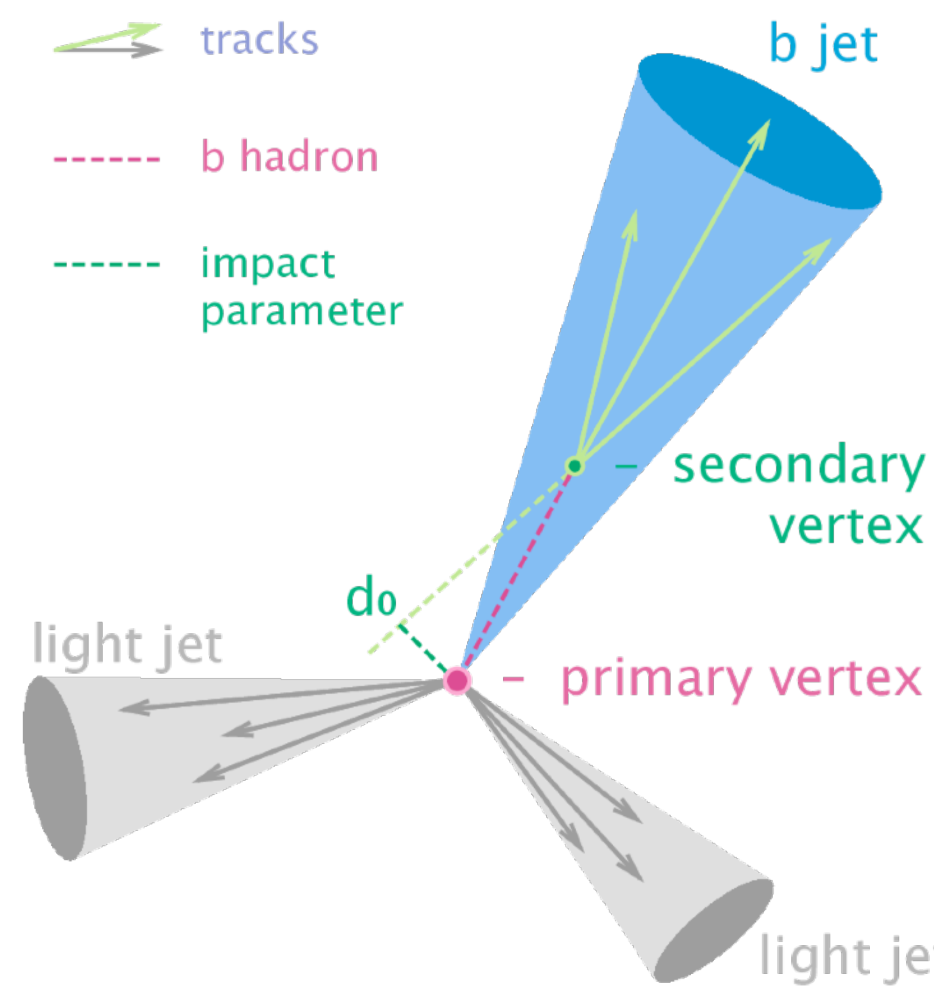
How are flavoured jets defined?

(Usual) experimental definition of flavoured jet

"An (anti-k_t) jet is flavoured if it contains at least one heavy hadron within $\Delta R < R$ with $p_T > p_{T,\mathrm{cut}}$"

This definition is adopted as "true" label in MC samples.

These samples are then used to train ML architectures ("high-level taggers"), which exploit low-level variables as inputs.

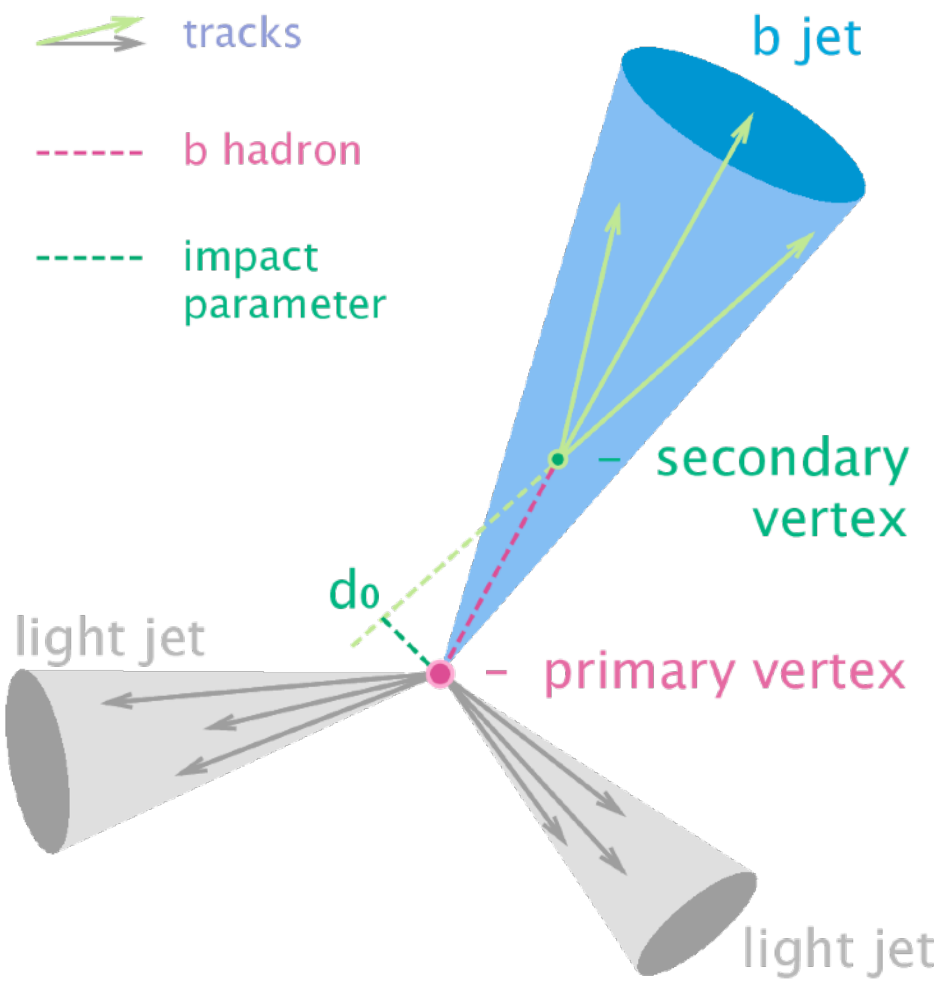


(Usual) experimental definition of flavoured jet

"An (anti-k_t) jet is flavoured if it contains at least one heavy hadron within $\Delta R < R$ with $p_T > p_{T,\mathrm{cut}}$"

This definition is both **soft and collinear (IRC) unsafe**
(in massless perturbative QCD calculations)

i.e. arbitrary soft and/or collinear emissions alter the flavour of jets



Infrared safe jet definitions

Infrared unsafe jet algorithms widely used at the Tevatron
[Infrared unsafe = the structure of the hard jets can be modified by very soft or collinear splittings in QCD]

Things changed at the LHC thanks seminal work which lead to the development of the fast-k_t, the SIScone and anti-kt algorithms

Cacciari & Salam hep-ph/0512210; Salam & Soyez 0704.0292; Cacciari, Salam, Soyez 0802.1189

This progress triggered considerable more work on jet-area, pileup subtraction and paved the way to the field of jet-substructure

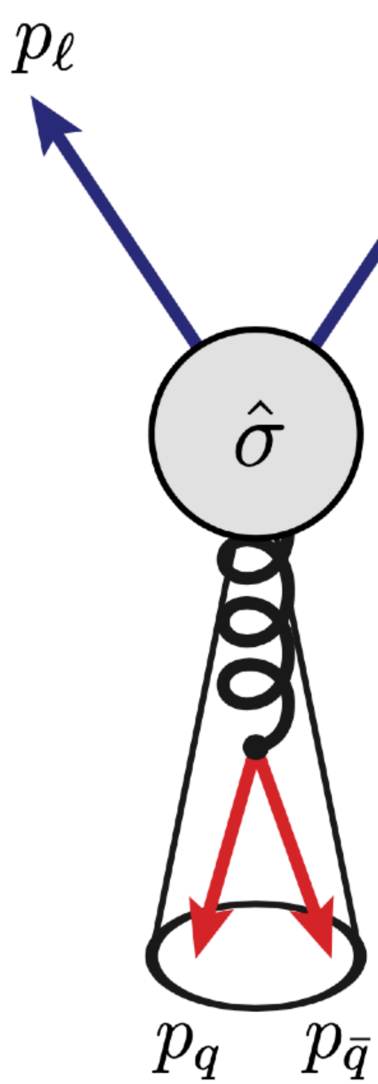
Nobody, today, would use any old infrared unsafe jet-algorithm.
So, you will wonder, why I am talking about this at all here?

Because jet-algorithms specifying the flavour of jets are still a notable exception!

slide from Giulia Zanderighi @ LHCP 2023

(Usual) experimental definition of flavoured jet

"An (anti-k_t) jet is flavoured if it contains at least one heavy hadron within $\Delta R < R$ with $p_T > p_{T,\mathrm{cut}}$"

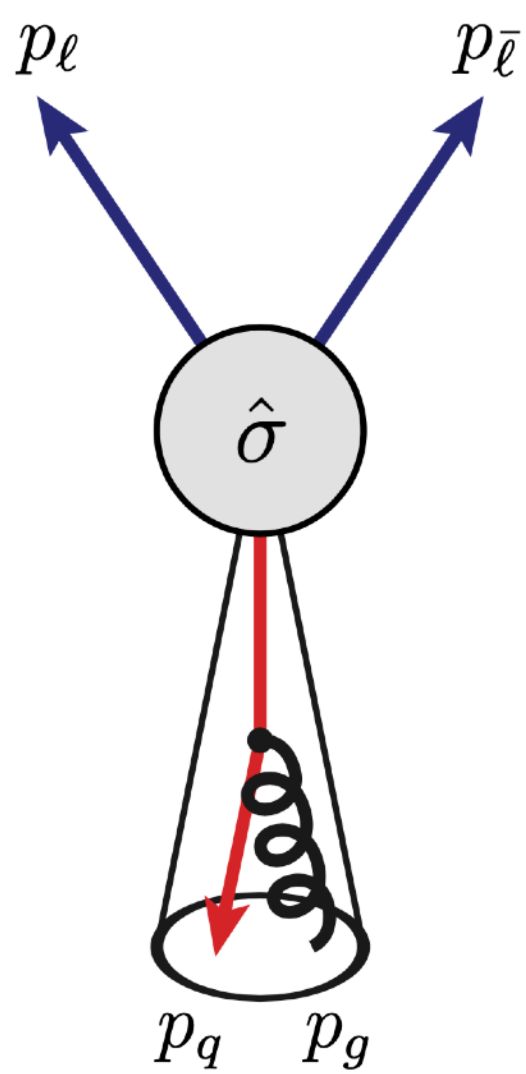


$g \to q\bar{q}$ is always flavoured even in the collinear limit

An *even-tag veto* in calculations is enough to fix this issue

(Usual) experimental definition of flavoured jet

"An (anti-k_t) jet is flavoured if it contains at least one heavy hadron within $\Delta R < R$ with $p_T > p_{T,\text{cut}}$"



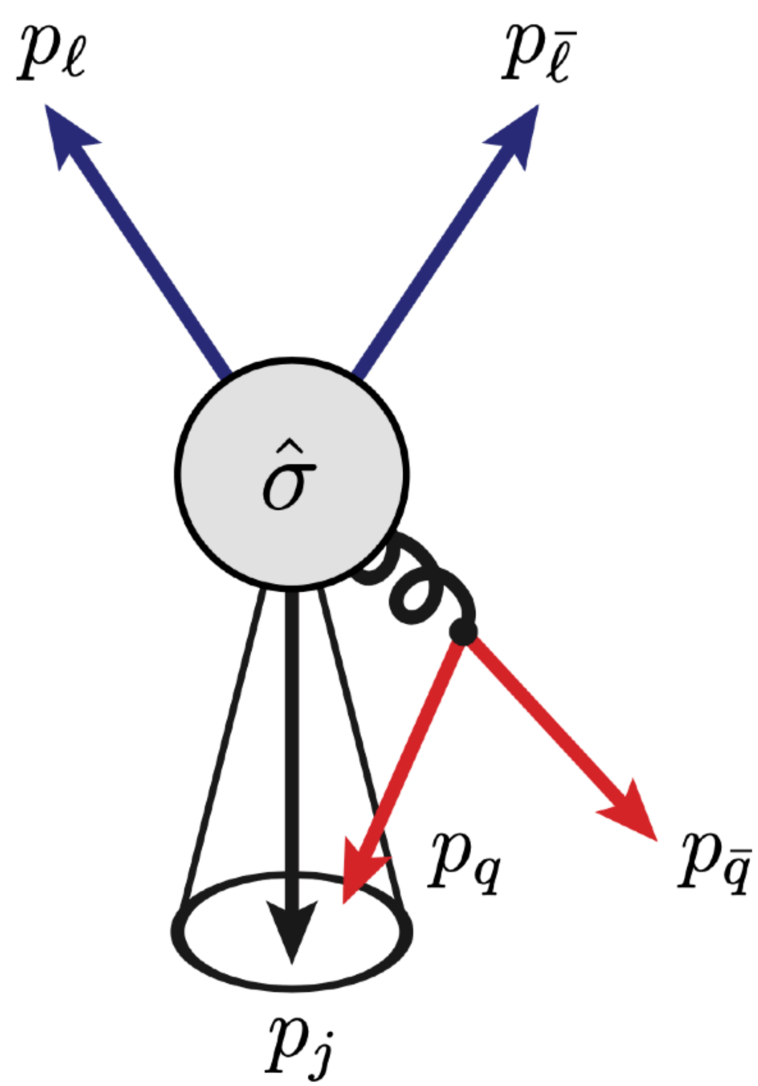
$q \to qg$ collinear with a hard gluon leads to a flavourless jet

With $p_{T,\text{cut}}$, it requires a fragmentation function, as we are identifying a particle

Without $p_{T,\text{cut}}$, any IRC safe flavour-agnostic algorithm will recombine the qg pair

(Usual) experimental definition of flavoured jet

"An (anti-k_t) jet is flavoured if it contains at least one heavy hadron within $\Delta R < R$ with $p_T > p_{T,\mathrm{cut}}$"



Soft large-angle $g \to b\bar{b}$ polluting the flavour of other jets

No way of fixing this issue within a flavour-agnostic jet algorithm!

Theory-friendly flavoured jet algorithms

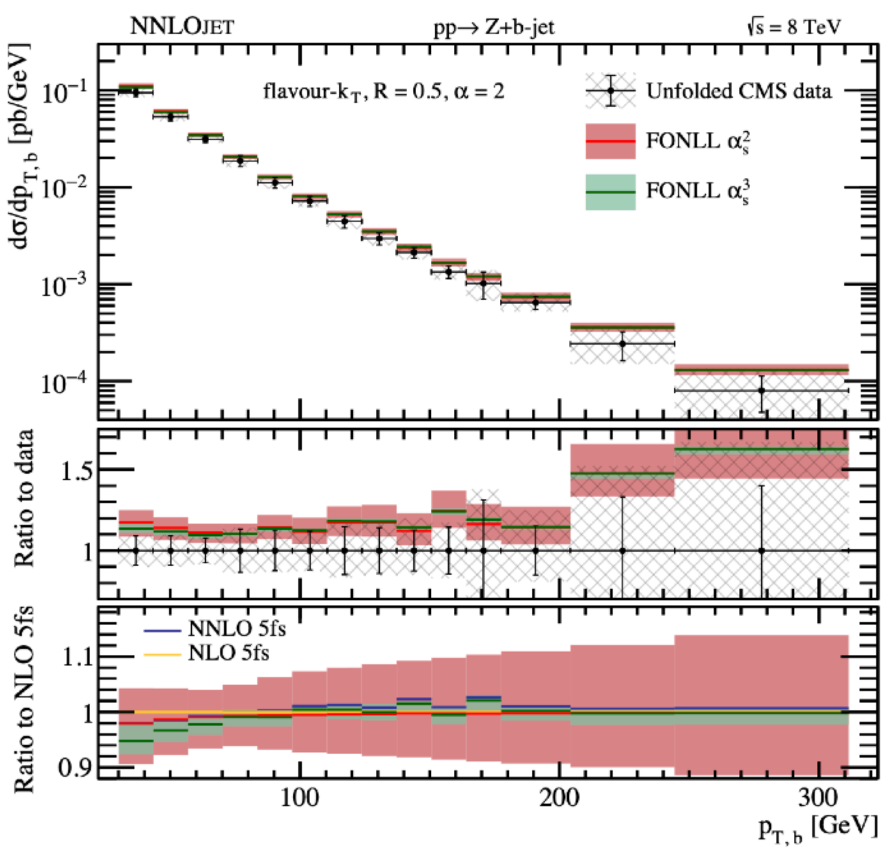
The first proposal: flavour-k_t algorithm

[Banfi, Salam, Zanderighi (hep-ph/0601139)]

Flavour-aware distance:

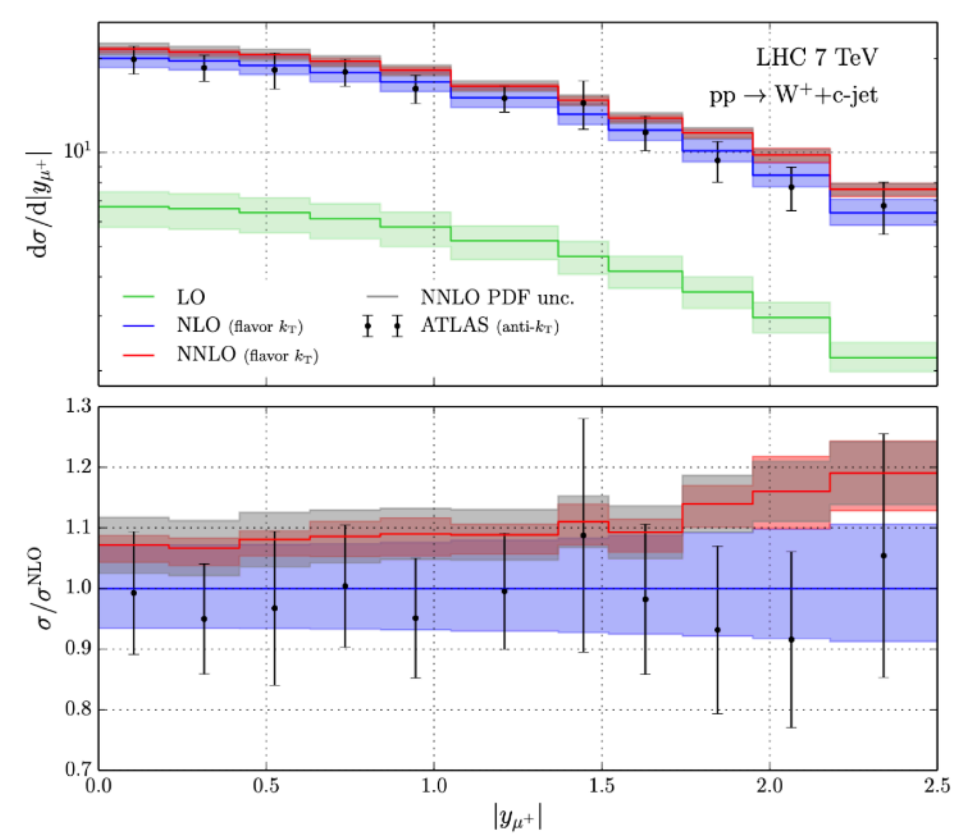
$$d_{ij}^{(F,\alpha)} = \frac{\Delta y_{ij}^2 + \Delta\phi_{ij}^2}{R^2} \times \begin{cases} \max(k_{ti}, k_{tj})^{\alpha} \min(k_{ti}, k_{tj})^{2-\alpha}\,, & \text{softer of } i,j \text{ is flavoured,} \\ \min(k_{ti}^2, k_{tj}^2)\,, & \text{softer of } i,j \text{ is flavourless} \end{cases}$$

at the price of jets with different kinematics i.e. not anti-k_t jets.



[Gauld et al. (2005.03016)]

Comparison with experimental data **not straightforward**



[Czakon et al. (2011.01011)]

After 15 years, many alternative proposals to overcome limitations of flavour-k_t

[Caletti, Larkoski, Marzani, Reichelt (2205.01109)]

[Caletti, Larkoski, Marzani, Reichelt (2205.01117)]

[Czakon, Mitov, Poncelet (2205.11879)]

[Caola, Grabarczyk, Hutt, Salam, Scyboz, Thaler (2306.07314)]

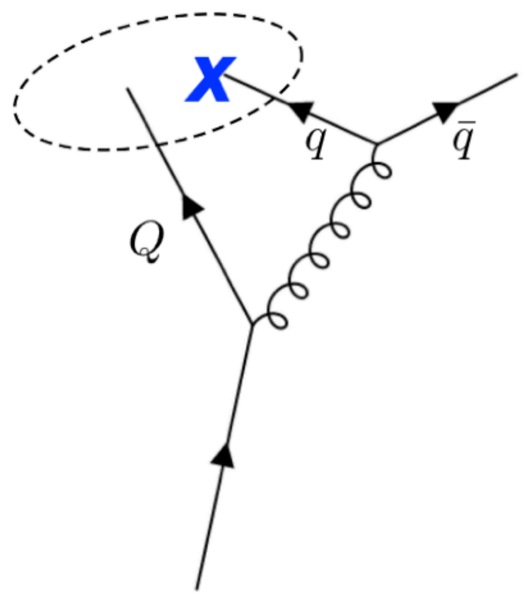
[Gauld, Huss, GS (2208.11138)]

I will now briefly introduce them

[Caletti, Larkoski, Marzani, Reichelt

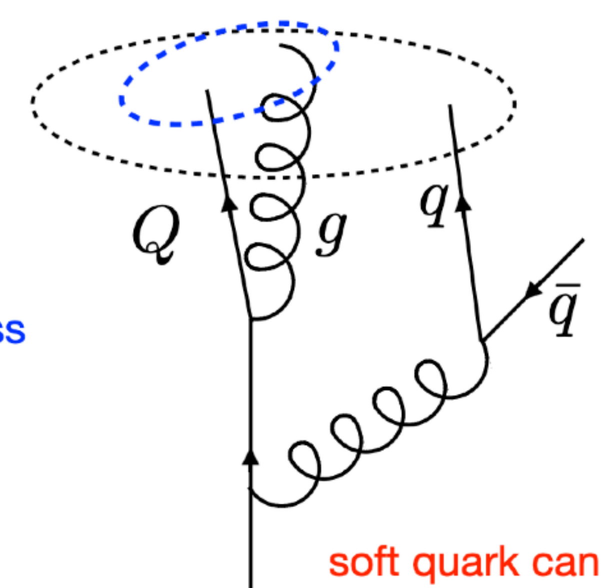
(2205.01109)]

Use Soft Drop to remove soft quarks, by using JADE as reclusters



Known to fail at N3LO

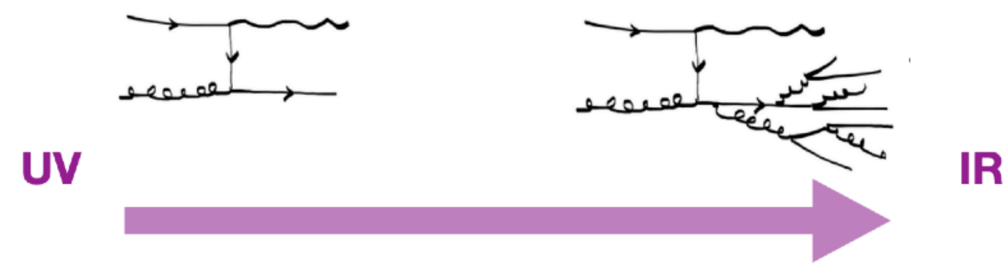
this system has the smallest invariant mass and passes SD



soft quark can alter the flavour

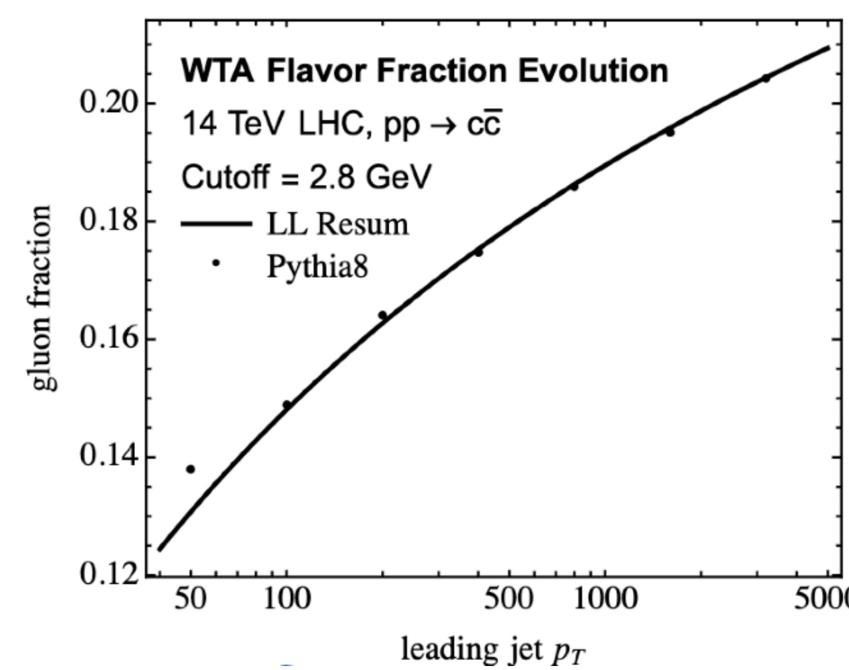
[Caletti, Larkoski, Marzani, Reichelt

(2205.01117)]



Flavour of jet = flavour of particle(s) lying along the Winner-Take-All (WTA) axis

Soft safe, but collinear unsafe: requires usage of suited fragmentation functions



[Czakon, Mitov, Poncelet (2205.11879)]

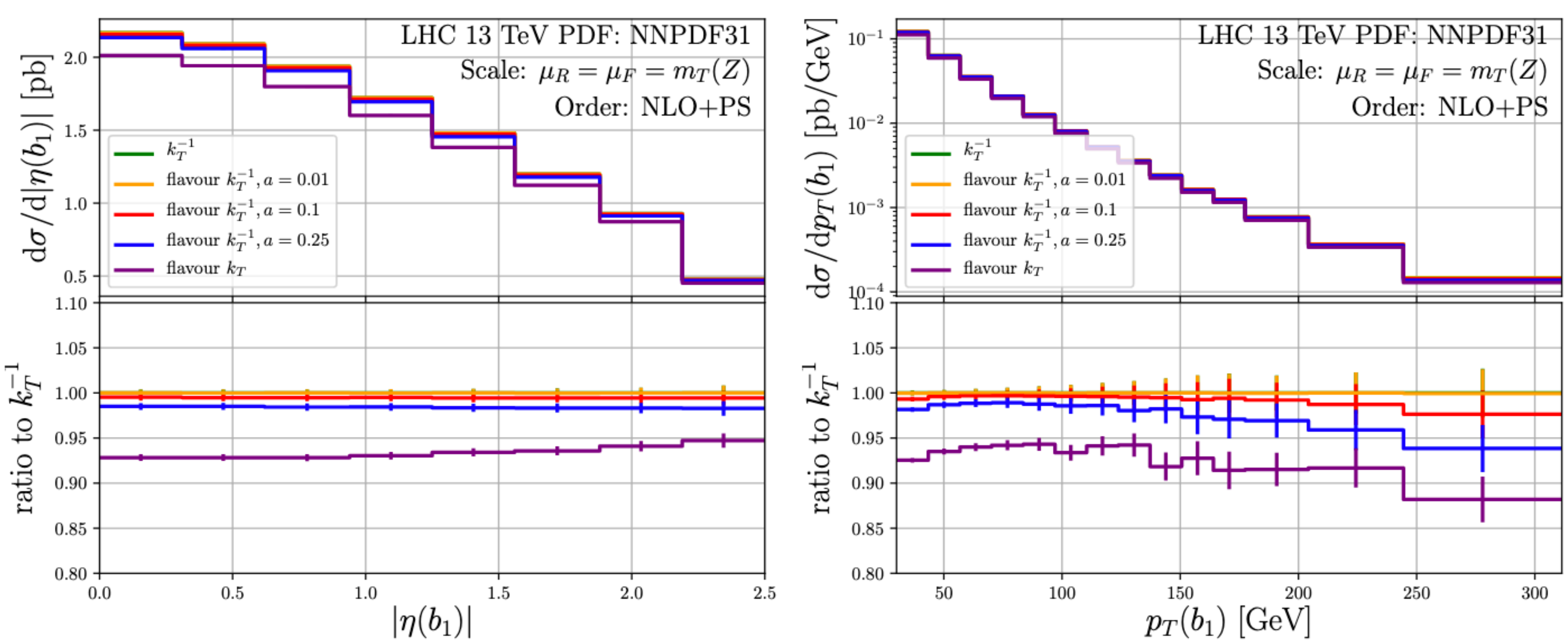
"**Flavour anti-k_t**": modify anti-k_t distance when flavoured particles involved

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

where $S_{ij} \neq 1$ only when i and j are of opposite flavour

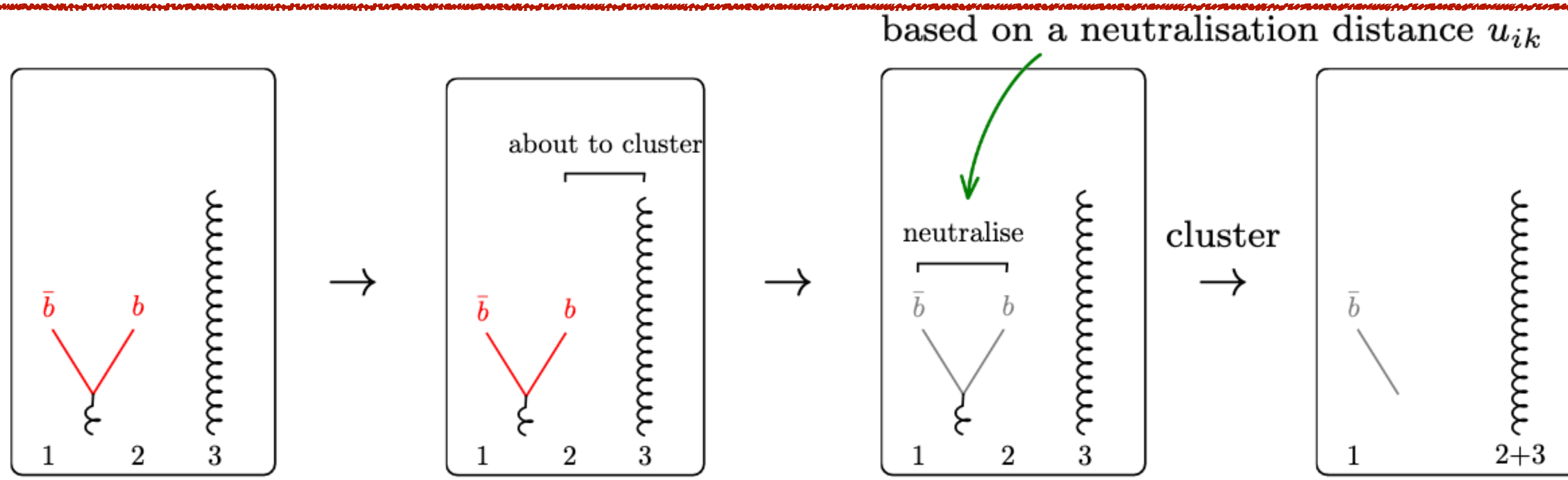
$$S_{ij}^{a} = 1 - \theta(1-\kappa)\cos\left(\frac{\pi}{2}\kappa\right)\,, \quad \kappa = \frac{1}{a}\frac{k_{T,i}^2 + k_{T,j}^2}{2\,k_{T,\max}^2}$$

One recovers (IRC flavour unsafe) anti-k_t jets when $a \to 0$



[Caola, Grabarczyk, Hutt, Salam, Scyboz, Thaler (2306.07314)]

"Flavour neutralisation"



neutralise ≡ remove the (opposite) flavour of both 1 & 2 while maintaining kinematics

- Generic form (with parameters p, q, and a):

$$u_{ik} = \max\left(p_{ti}^2, p_{tk}^2\right)^p \min\left(p_{ti}^2, p_{tk}^2\right)^q \times 2\left[\frac{1}{a^2}\left(\cosh(a\Delta y_{ik}) - 1\right) - \left(\cos\Delta\phi_{ik} - 1\right)\right]$$

from Ludovic Scyboz slides at Moriond QCD 2023

[Gauld, Huss, GS (2208.11138)]

“Flavour dressing”
Flavour assignment *factorised* from jet reconstruction
(exact anti-k_t kinematics by construction)

Inputs: *flavour-agnostic jets* (jets obtained with any IRC safe algorithm) and *flavour inputs* (e.g. b- or c-quarks, stable heavy-flavour hadrons, …)

Preliminary step: we first build flavour clusters to recombine flavour inputs with radiation close in angle, but without touching the soft particles (thanks to a Soft Drop condition [Larkoski, Marzani, Soyez, Thaler 1402.2657]):

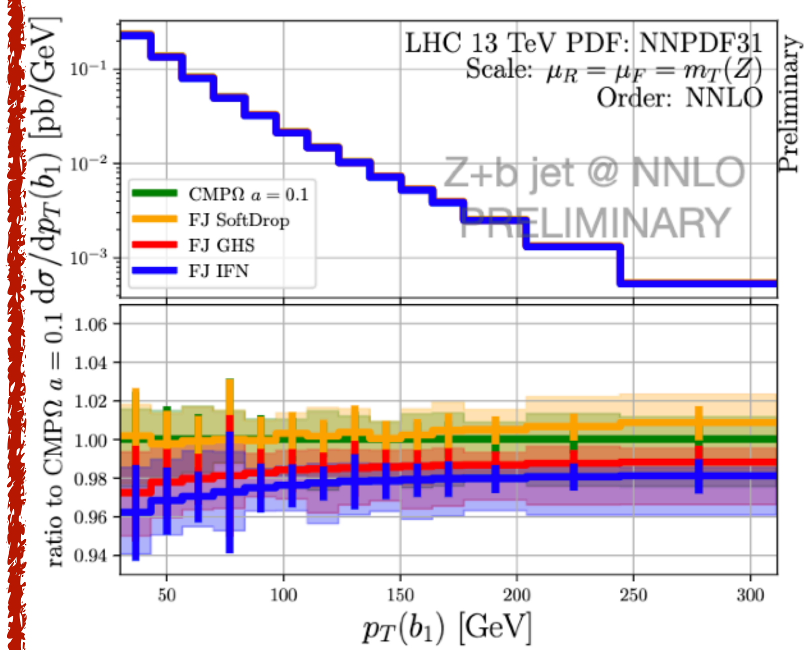
$$\frac{\min(p_{t,a}, p_{t,b})}{(p_{t,a} + p_{t,b})} > z_{\rm cut} \left(\frac{\Delta R_{ab}}{\delta R}\right)^{\beta}$$

Dressing step: in order to assign flavour to jets, we run a sequential recombination algorithm with flavour-k_t-like distances between jets and flavour clusters.

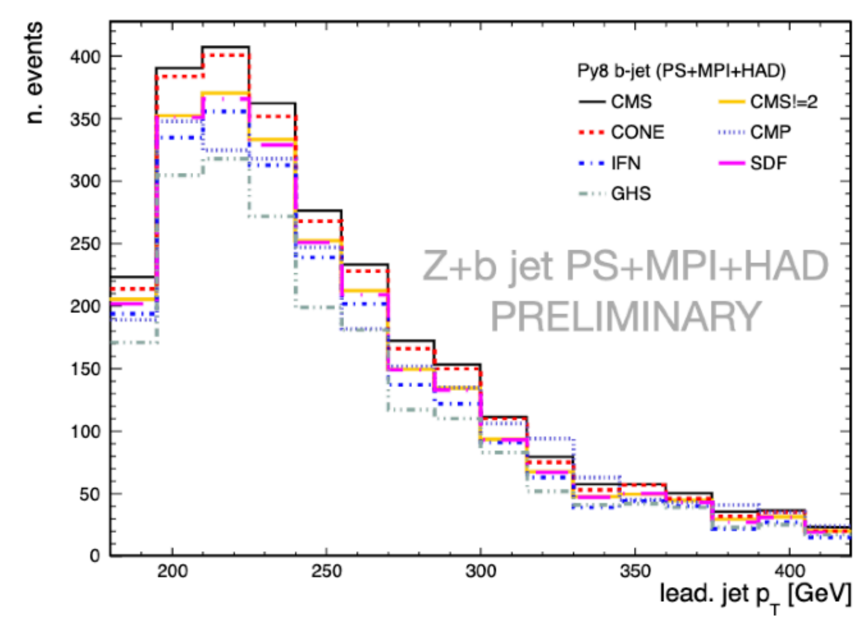
Jet flavour = hot topic in LH

Les Houches 2023 studies

- it is important to investigate IRC safety, resilience against non-perturbative effects and experimental viability of the 4 algorithms
- a detailed comparison of these 4 algorithms was started at Les Houches
- current results are very preliminary, they will be refined and will appear in the proceedings



interesting shape difference at low p_t: it deserves further investigation!



first hadron-level studies show larger differences… something to investigate further

7

slide from Simone Marzani

Public repository with FastJet implementation of the algorithms

jetflav

https://github.com/jetflav

Popular repositories

IFNPlugin Public
Implementation of interleaved flavour neutralisation
C++

SDFlavPlugin Public
C++

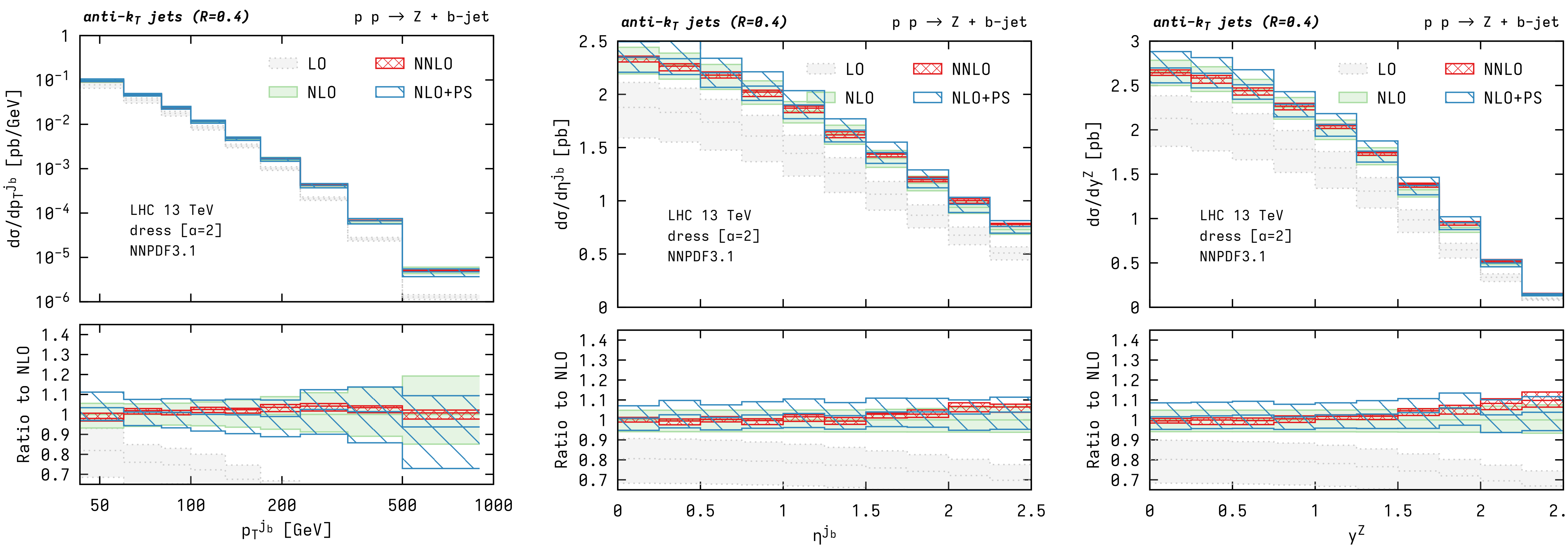
CMPPlugin Public
C++

GHSAlgo Public
C++

[Applications of flavour dressing: Z + b/c-jet]

Test flavour dressing in a realist scenario: $Z + b$-jet

[same setup of Gauld, Gehrmann-De Ridder, Glover, Huss, Majer (2005.03016)]



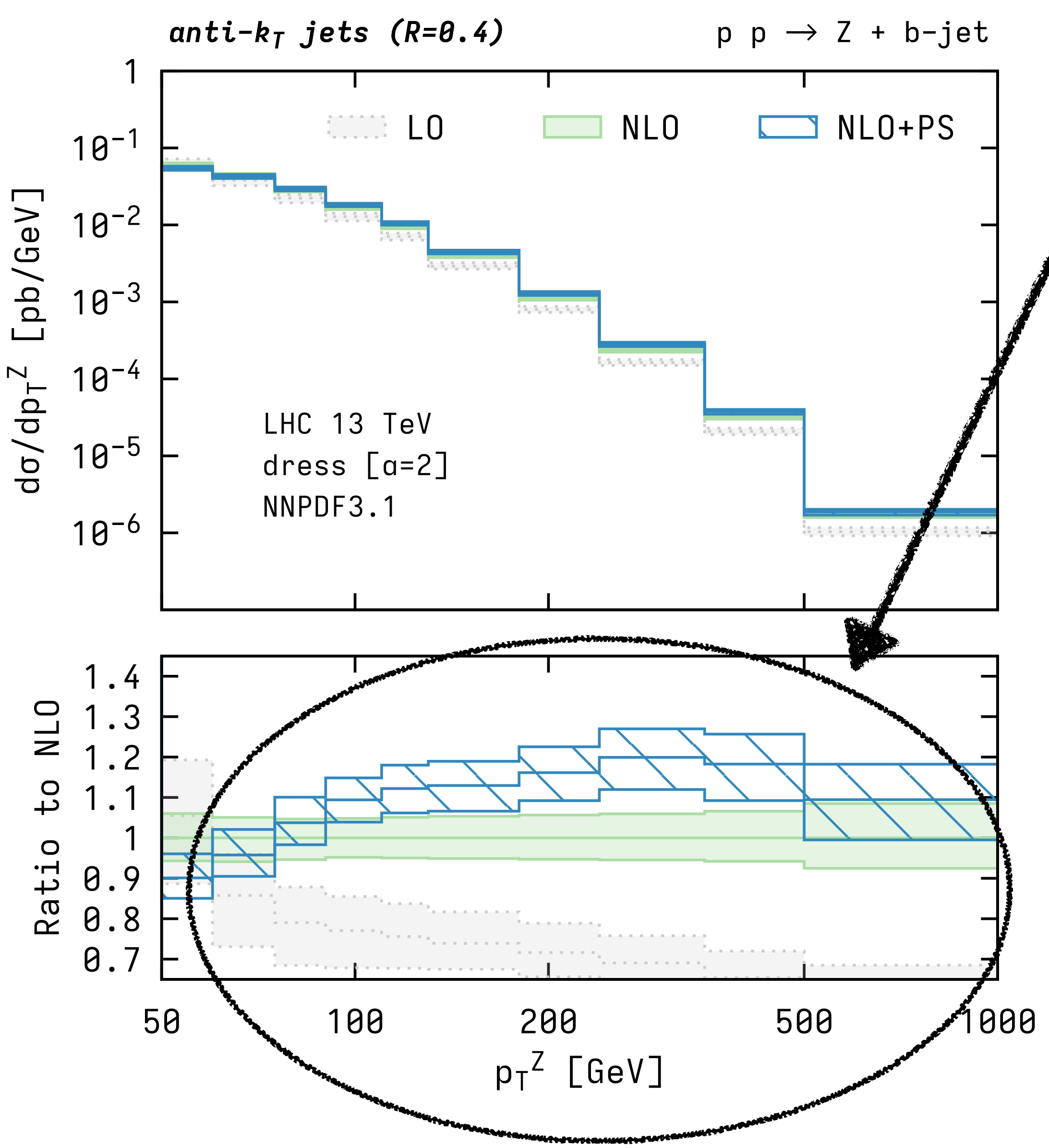
Remarkable agreement between (N)NLO and NLO+PS

→ for most distributions

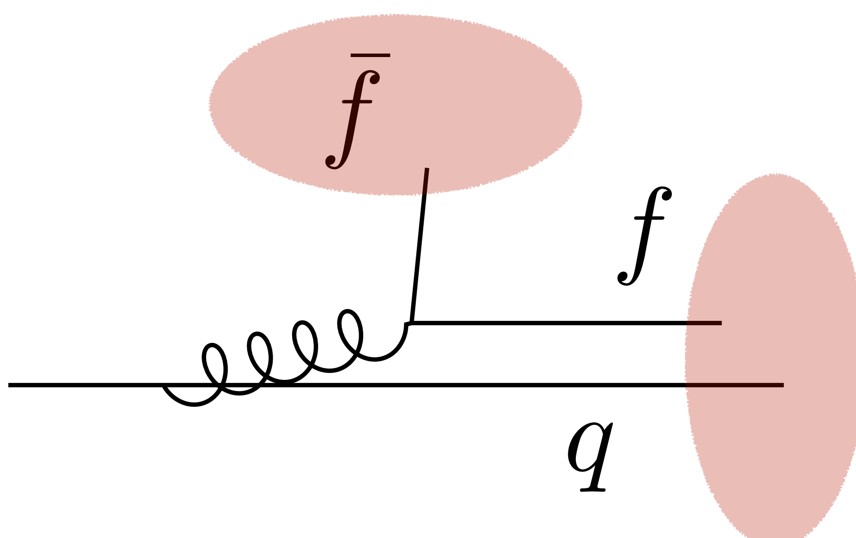
largely insensitive to all-order corrections

Test flavour dressing in a realist scenario: $Z + b$-jet

[same setup of Gauld, Gehrmann-De Ridder, Glover, Huss, Majer (2005.03016)]



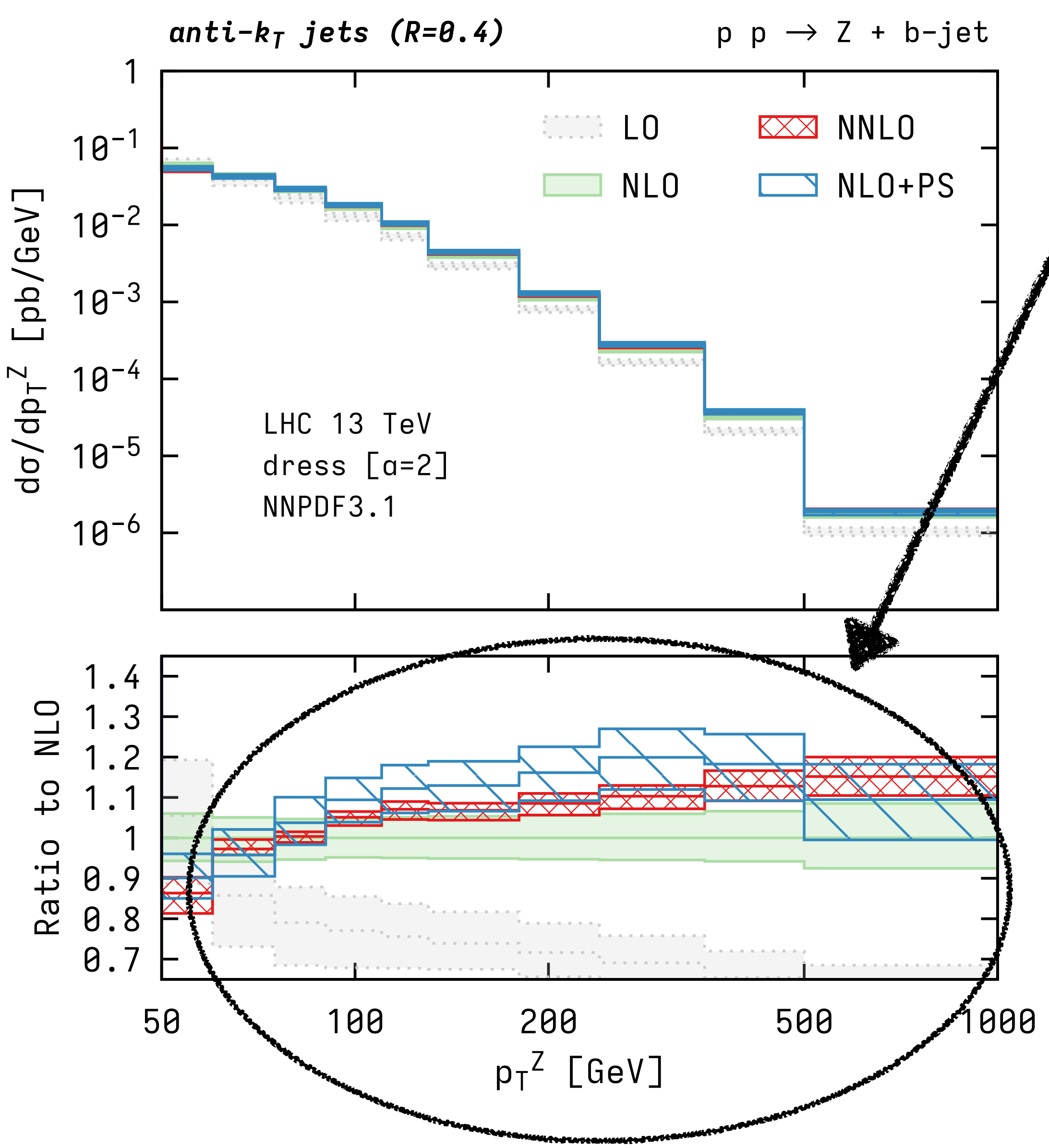
Some sensitivity observed in p_T^Z, likely due to:



Even if IRC finite, it leads to large migration of (unflavoured)-jet into the b-jet sample.

Test flavour dressing in a realist scenario: $Z + b$-jet

[same setup of Gauld, Gehrmann-De Ridder, Glover, Huss, Majer (2005.03016)]



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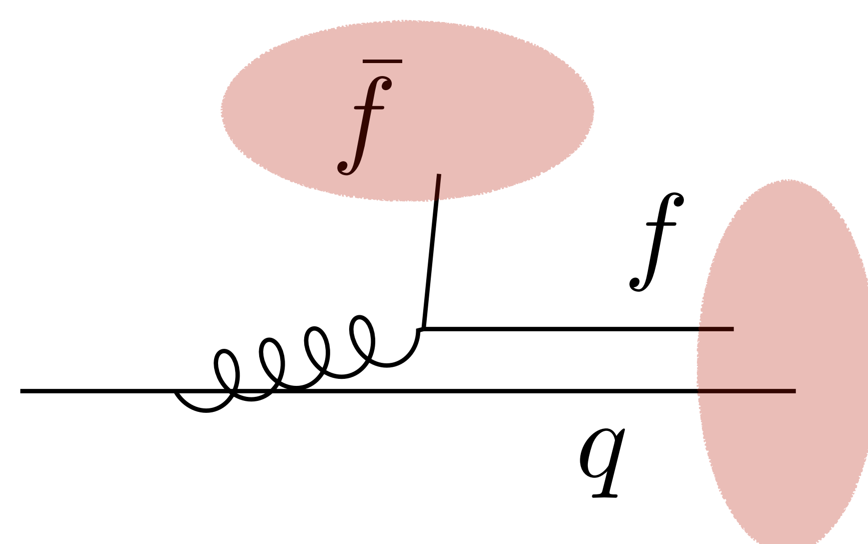
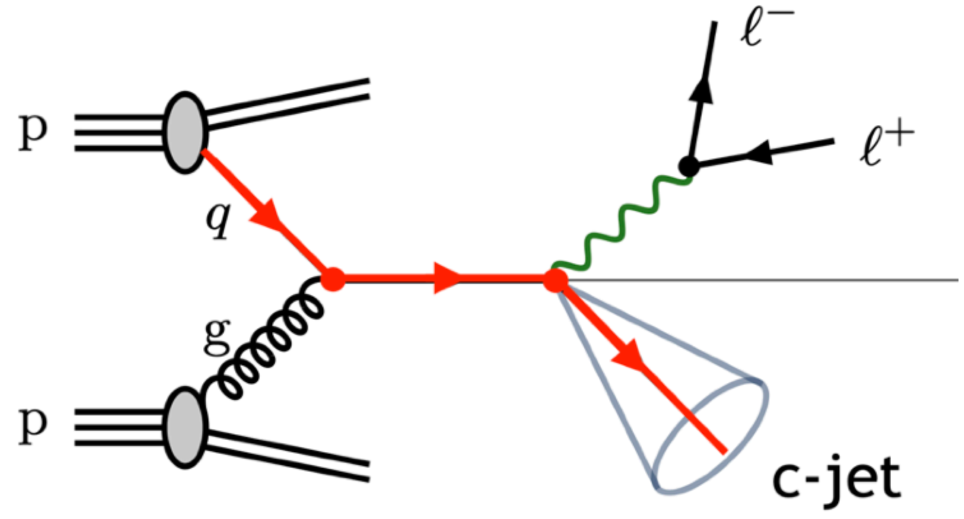
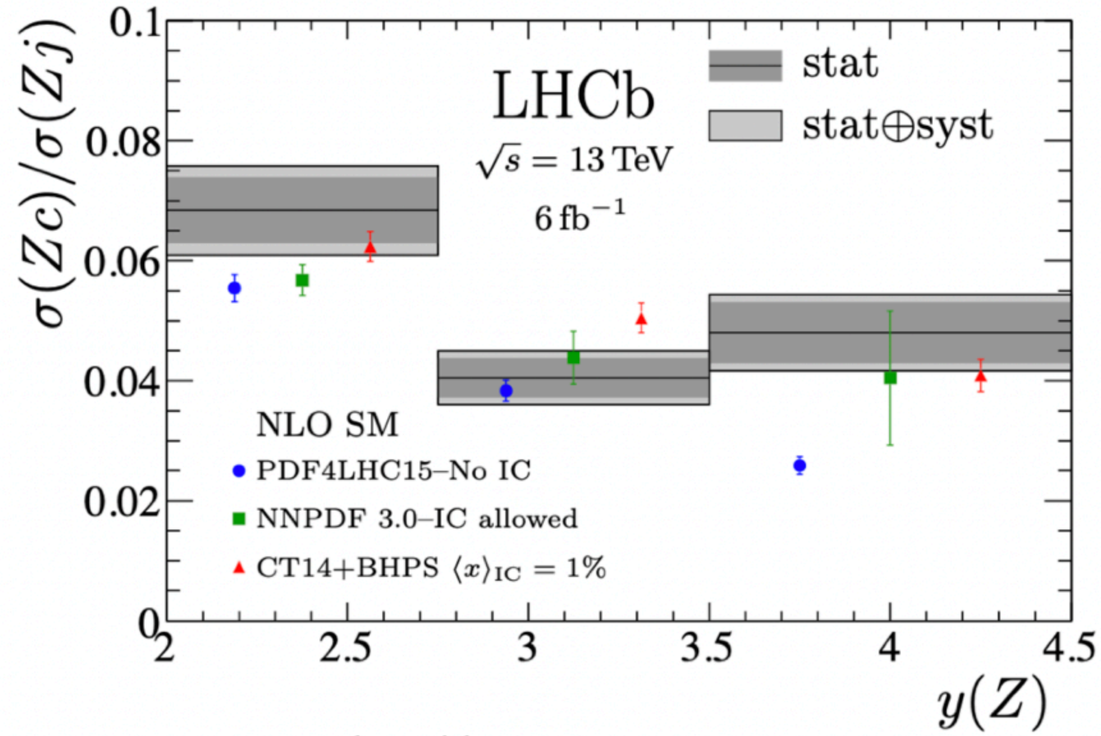


Effect **captured at NNLO**

$Z + c$-jet at LHCb

[Gauld, Gehrmann-De Ridder, Glover, Huss, Rodriguez Garcia, GS (2302.12844)]





Measurement sensitive to **intrinsic charm in the proton**

LHCb data at 13TeV for ratio

$(\mathrm{d}\sigma_{Z+c}/dy_Z)$ / $(\mathrm{d}\sigma_{Z+j}/dy_Z)$ [2109.08084]

(With flavour dressing, both the numerator and the denominator feature the same sample of anti-k_t jets!)

LHCb fiducial cuts

Very unique fiducial region of the measurement:

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

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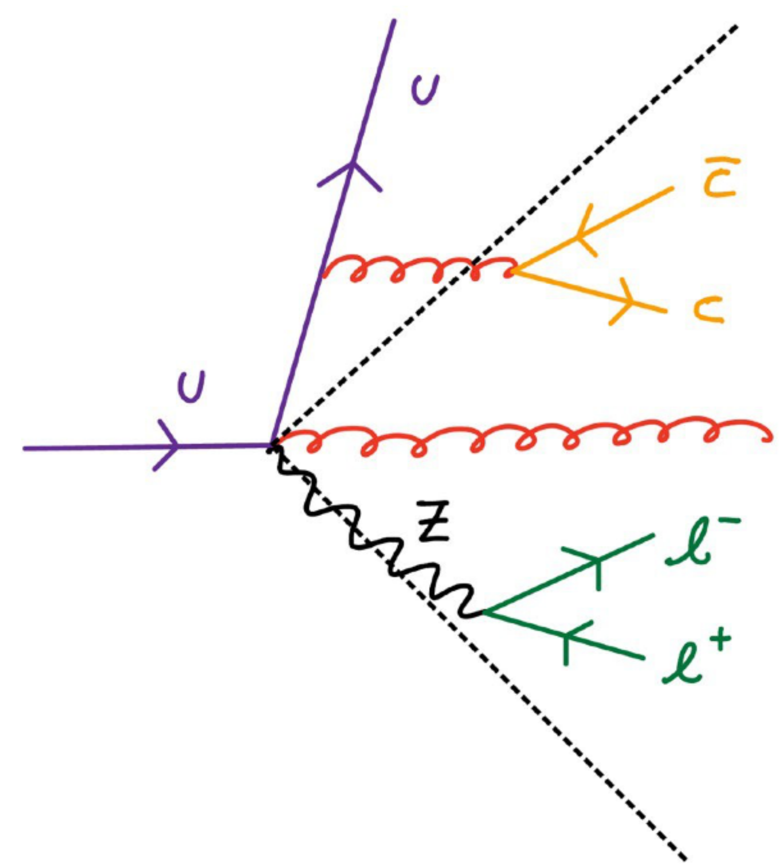
Charm jets	$p_{\mathrm{T}}(c\text{ hadron}) > 5\,\mathrm{GeV}$, $\Delta R(j, c\text{ hadron}) < 0.5$
Events	$\Delta R(\mu, j) > 0.5$

We explore a theory-driven cut:

$$p_{\mathrm{T}}(Z + \mathrm{jet}) < \mathrm{p}_{\mathrm{T,jet}}$$

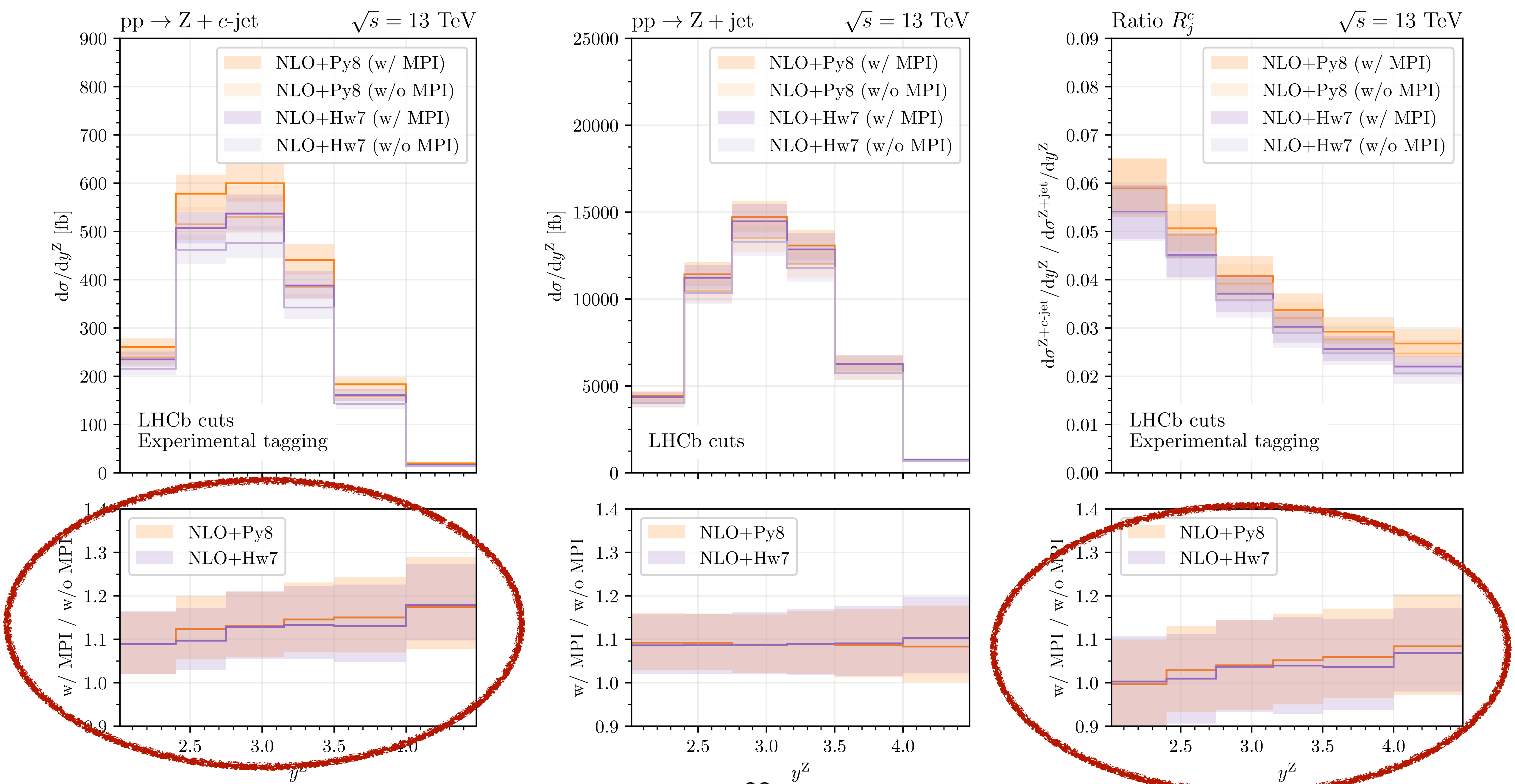
At Born level, the p_{T} of the Z+jet system vanishes, hence the cut limits the hard QCD radiation outside the LHCb acceptance in a dynamical way.



We refrain from making a comparison to the LHCb data

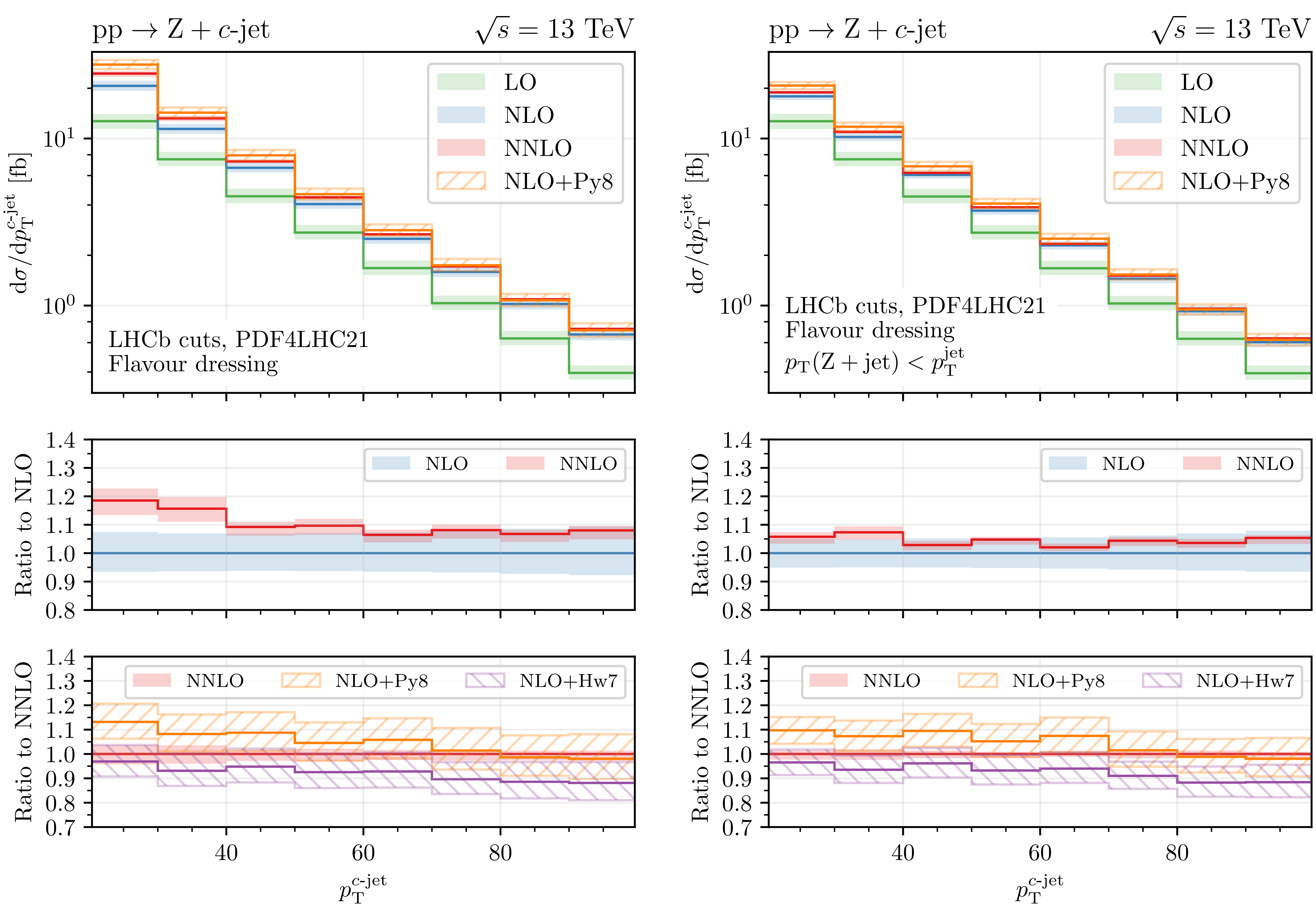
1) definition of flavoured jet not IRC safe

2) significant contamination from MPI



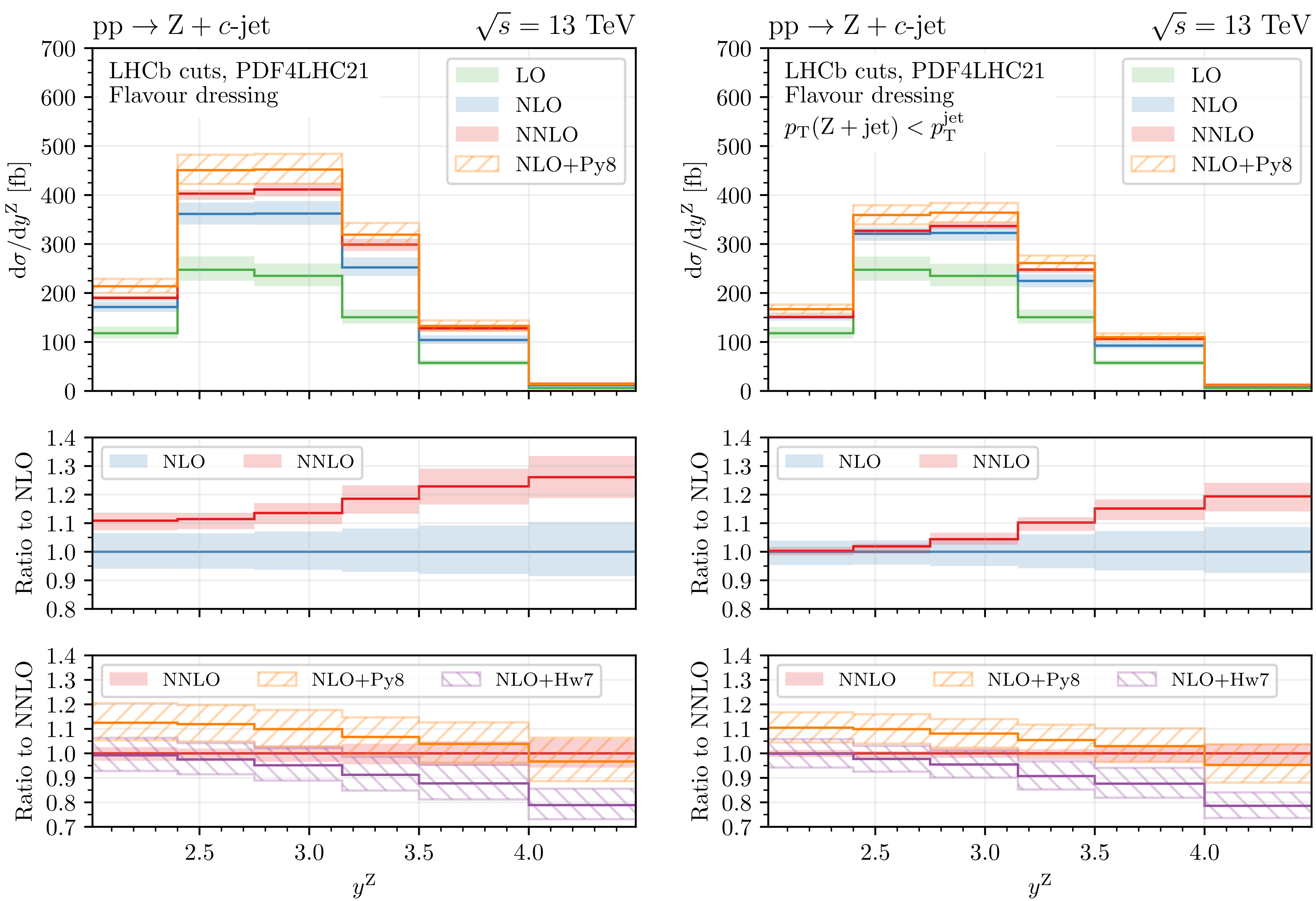
Results: $p_{\mathrm{T}}^{\mathrm{c-jet}}$

[Gauld, Gehrmann-De Ridder, Glover, Huss, Rodriguez Garcia, GS (2302.12844)]



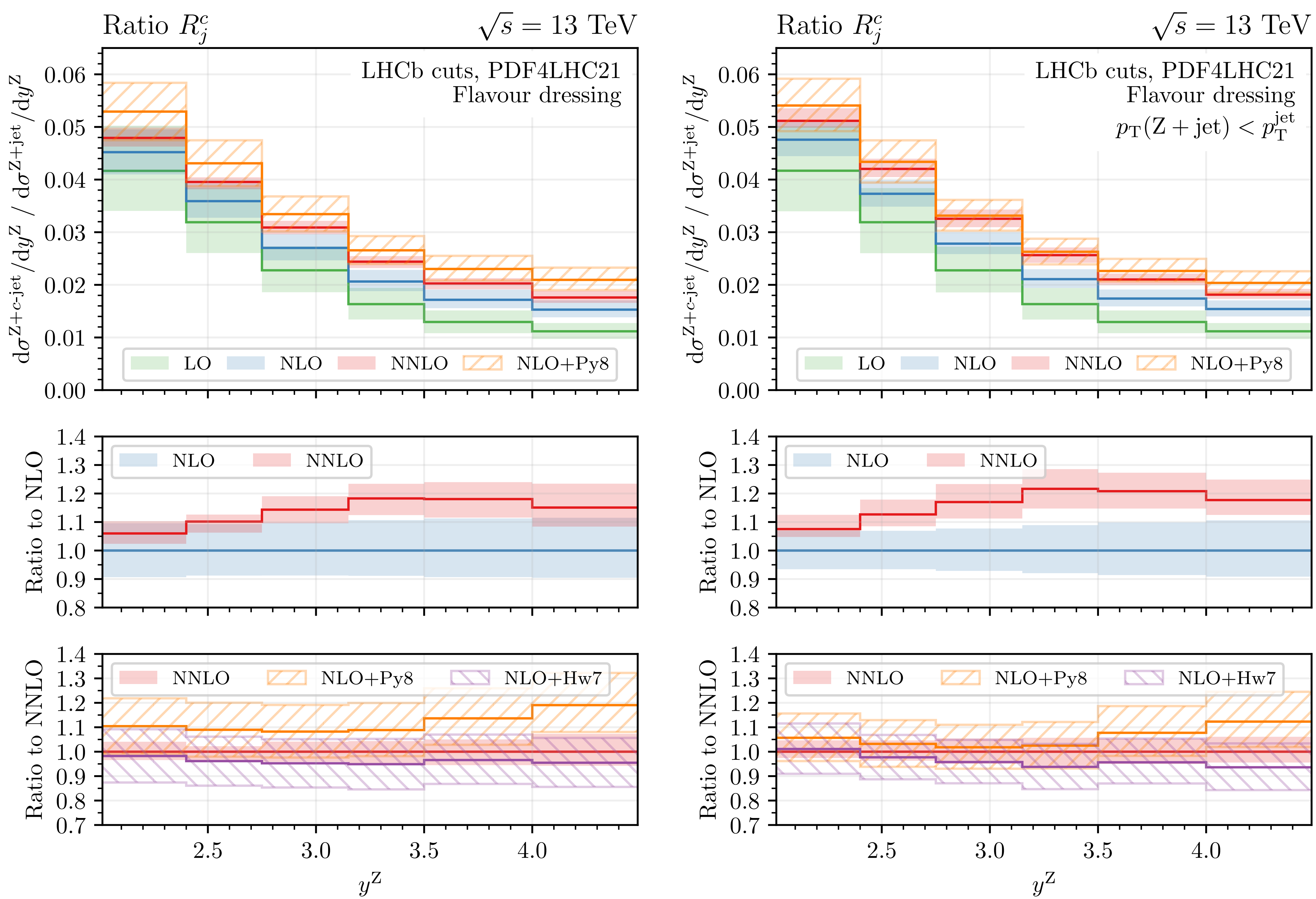
Results: y^Z

[Gauld, Gehrmann-De Ridder, Glover, Huss, Rodriguez Garcia, GS (2302.12844)]



Results: ratio $\sigma(Z + \mathrm{c} - \mathrm{jet})$ / $\sigma(Z + \mathrm{jet})$

[Gauld, Gehrmann-De Ridder, Glover, Huss, Rodriguez Garcia, GS (2302.12844)]

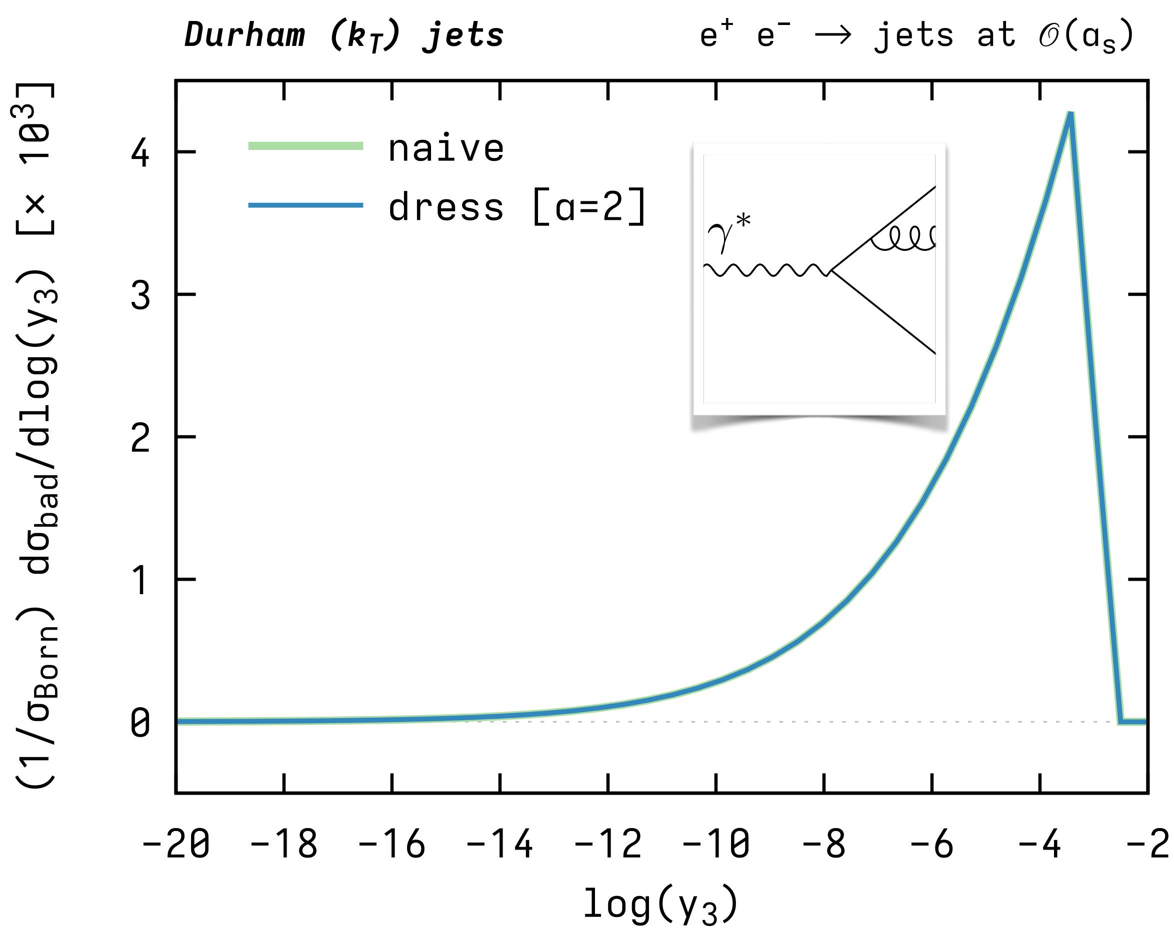


How to test IRC safety?

Flavour dressing IRC safety test in $e^+e^- \to$ jets

= vanishing “bad” identification of flavours
in the fully unresolved regime

only soft and/or collinear radiation



Any gen-k_t algo is safe (no additional flavour in the event)

Flavour dressing IRC safety test in $e^+e^- \to$ jets

= vanishing “bad” identification of flavours
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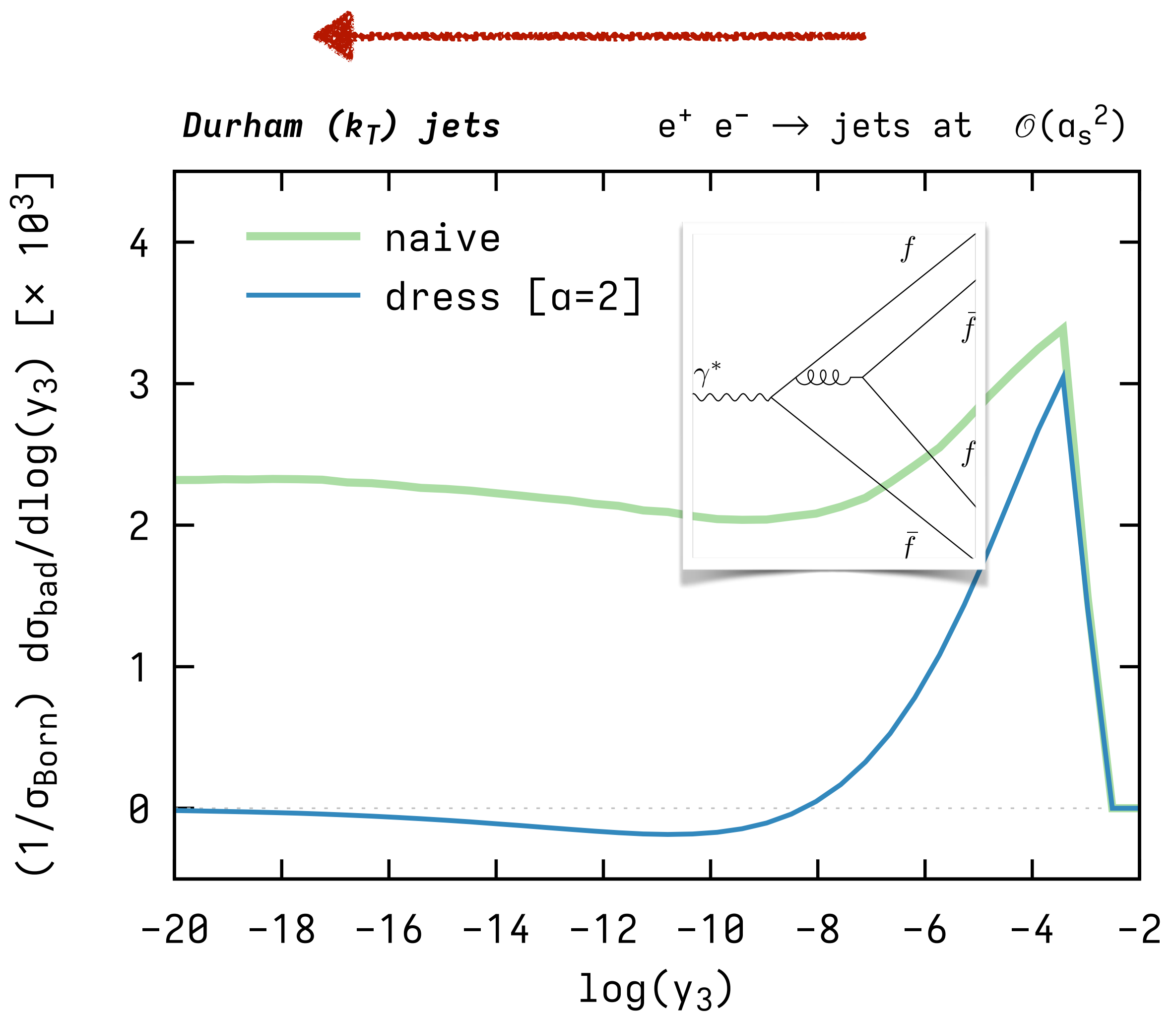
only soft and/or collinear radiation

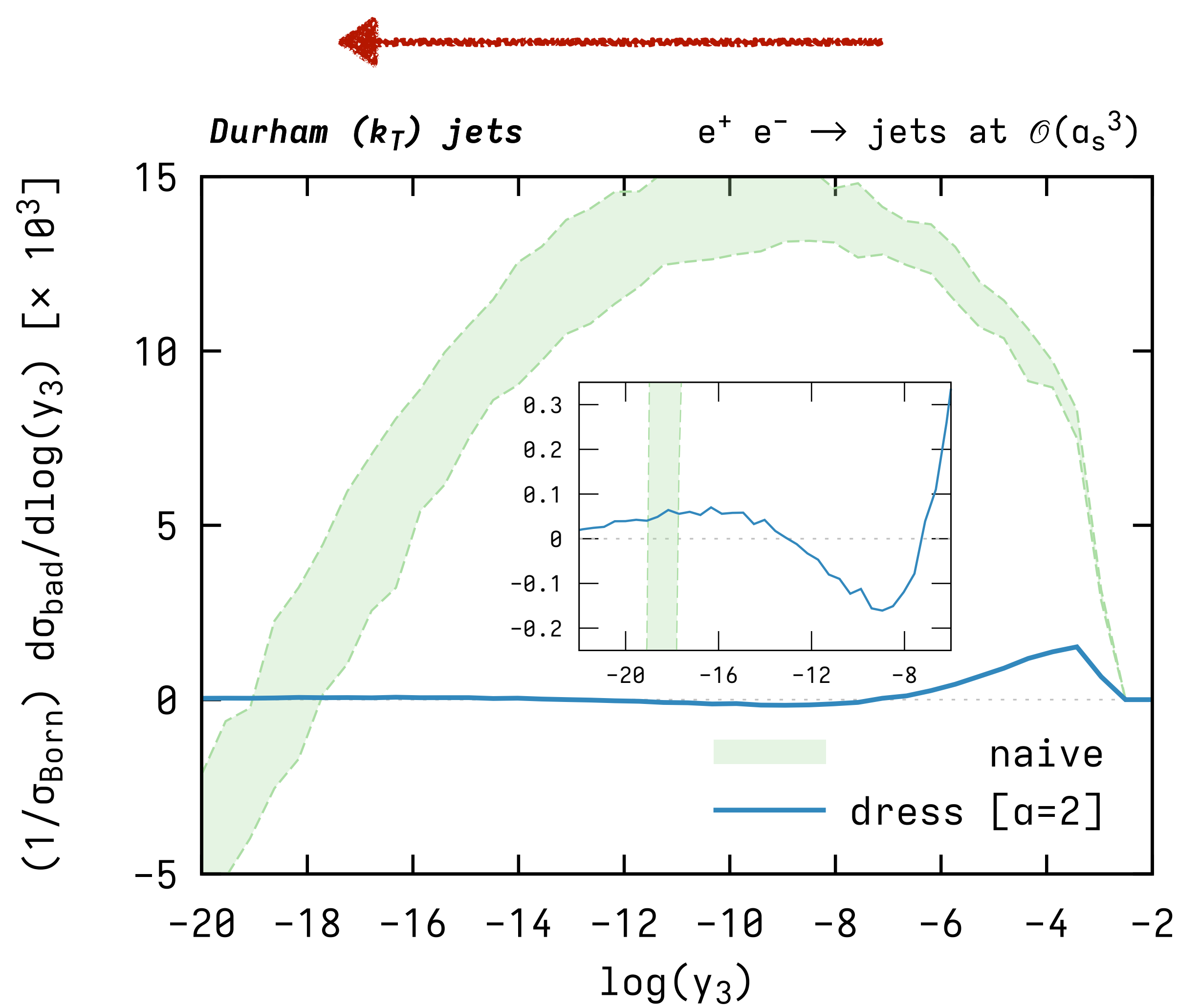


Naive dressing unsafe, flavour dressing safe!

Flavour dressing IRC safety test in $e^+e^- \to$ jets

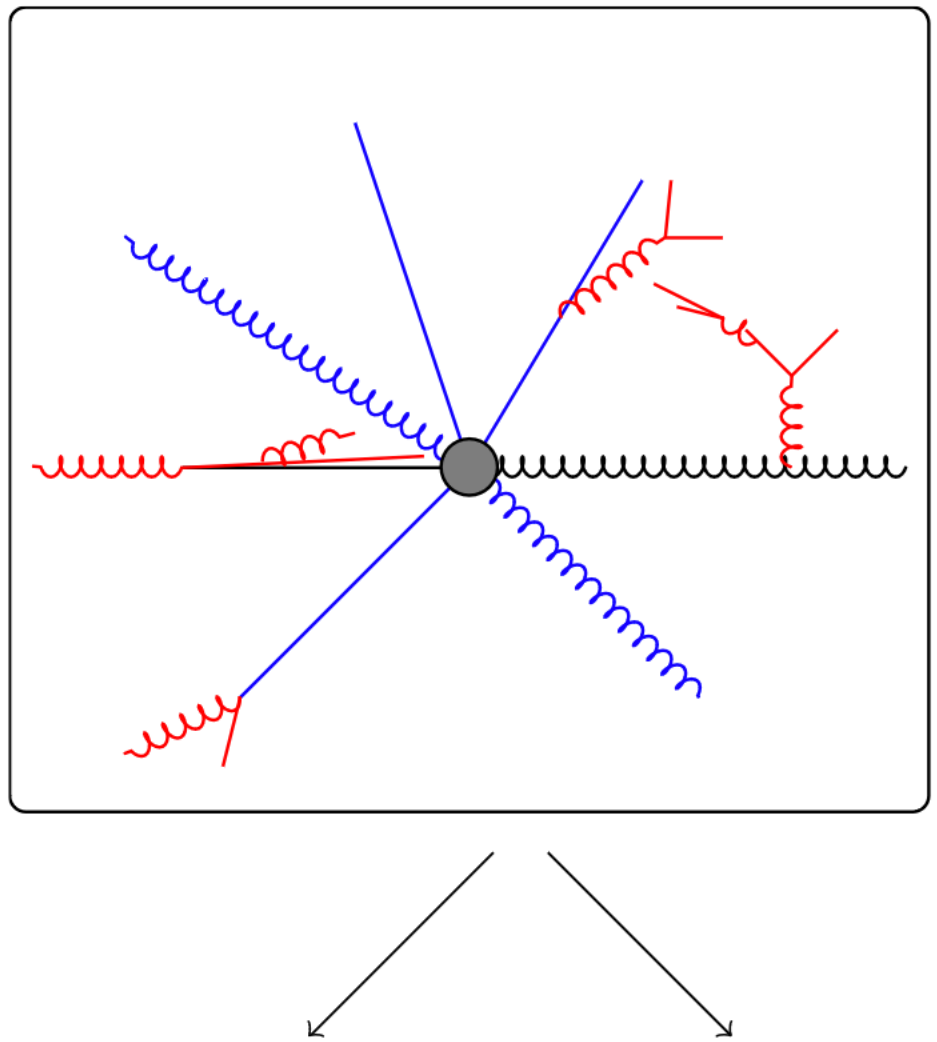
= vanishing “bad” identification of flavours
in the fully unresolved regime

only soft and/or collinear radiation



Naive dressing unsafer, flavour dressing still safe!

Systematic IRC safety tests (2306.07314)



Set of hard jets

$\mathcal{J}_{\text{hard}} = \{(p_1, f_1), \ldots\}$

$\stackrel{!}{=}$

Set of hard+IRC jets

$\mathcal{J}_{\text{hard+IRC}} = \{(\tilde{p}_1, \tilde{f}_1), \ldots\}$

slide from Ludovic Scyboz

Numerical framework has allowed to discover potentially problematic configurations at higher orders (CMP = "flavour anti-k_t"; GHS = "flavour dressing", IFN = "interleaved flavour neutralisation")

order relative to Born		anti-k_t	flav-k_t ($\alpha = 2$)	CMP	GHS$_{\alpha,\beta}$ $(2,2)$	anti-k_t+IFN$_\alpha$	C/A+IFN$_\alpha$
α_s	FHC	✓	✓	✓	✓	✓	✓
	IHC	✓	✓	✓	✓	✓	✓
α_s^2	FDS	× II B	✓	✓	✓	✓	✓
	IDS	× II B	✓	✓	✓	✓	✓
	FHC×IHC	✓	✓	✓	✓	✓	✓
	IHC^2	✓	✓	× C 2	✓	✓	✓
	FHC^2	✓	✓	✓	× C 4	✓	✓
α_s^3	IHC×IDS		∼ C 1	× C 3	∼ C 1	✓	✓
	rest					✓	✓
α_s^4	IDS×FDS				× C 5	✓	✓
	rest					✓	✓
α_s^5						✓	✓
α_s^6						✓	✓

Fix by replacing angular factor in CMP

$$S_{ij} \to \bar{S}_{ij} = S_{ij} \frac{\Omega_{ij}^2}{\Delta R_{ij}^2} \quad \text{with } \omega > 1$$

e.g. $Zb\bar{b}$ @ N4LO

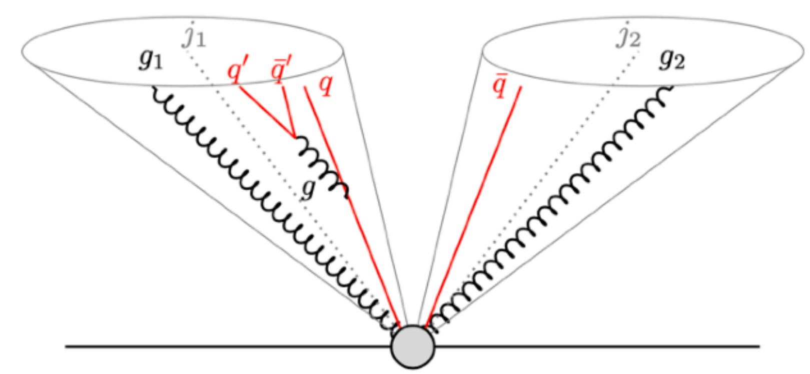
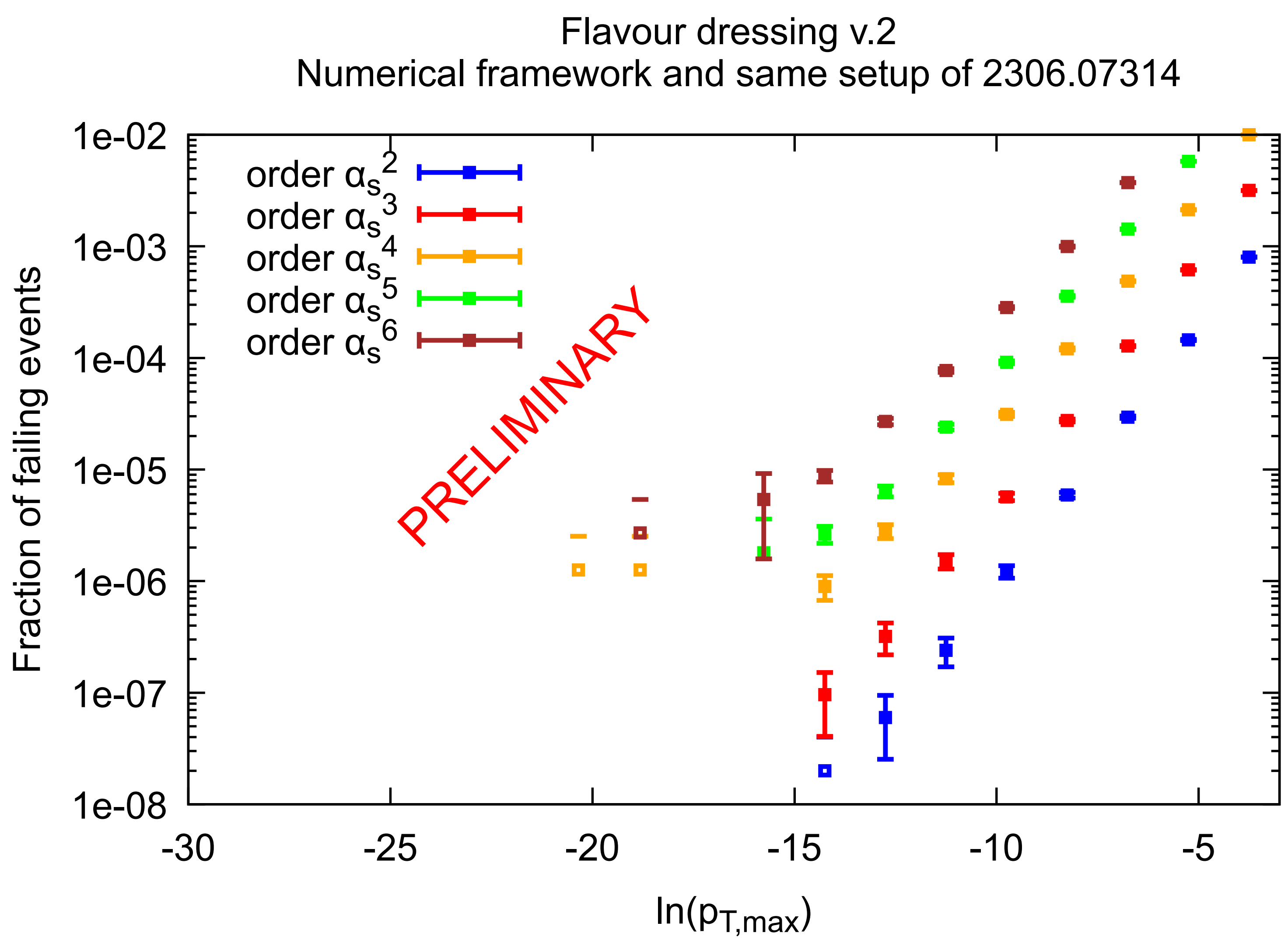


FIG. 20. Example $\mathcal{O}(\alpha_s^2)$ configuration that yields an issue for the GHS algorithm. There are four hard particles (that one can imagine recoiling against a hard gluon or electroweak system on the other side of the event), a collinear emission of a hard gluon g from one of the flavoured particles (the q), which then splits collinearly to a flavoured pair $q'\bar{q}'$.

Fix?

Flavour dressing version 2 (WIP)

Main change: avoid flavour clusters, apply recombination algorithm with flavour-k_t-like distances between anti-k_t jets and all particles in the event



The new version seems to pass the IRC safety tests of 2306.07314
(thanks to the authors for making the code available to us!)

Final remarks

- At lot of recent proposals trying to solve the longstanding issue of a proper definition of flavoured jet

- IRC-safe definition allows for massless fixed-order calculations to be directly compared to experimental data (and a suppressed sensitivity on mass logarithms). Crucial to resume mass logarithms in the initial state.

- A comparison between the different approaches started in Les Houches 2023, and it is currently going on.

- How feasible is the experimental realisation of one of the proposed algorithms?