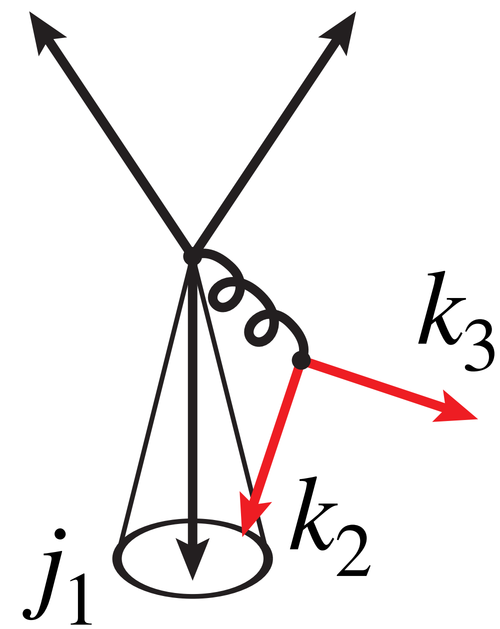


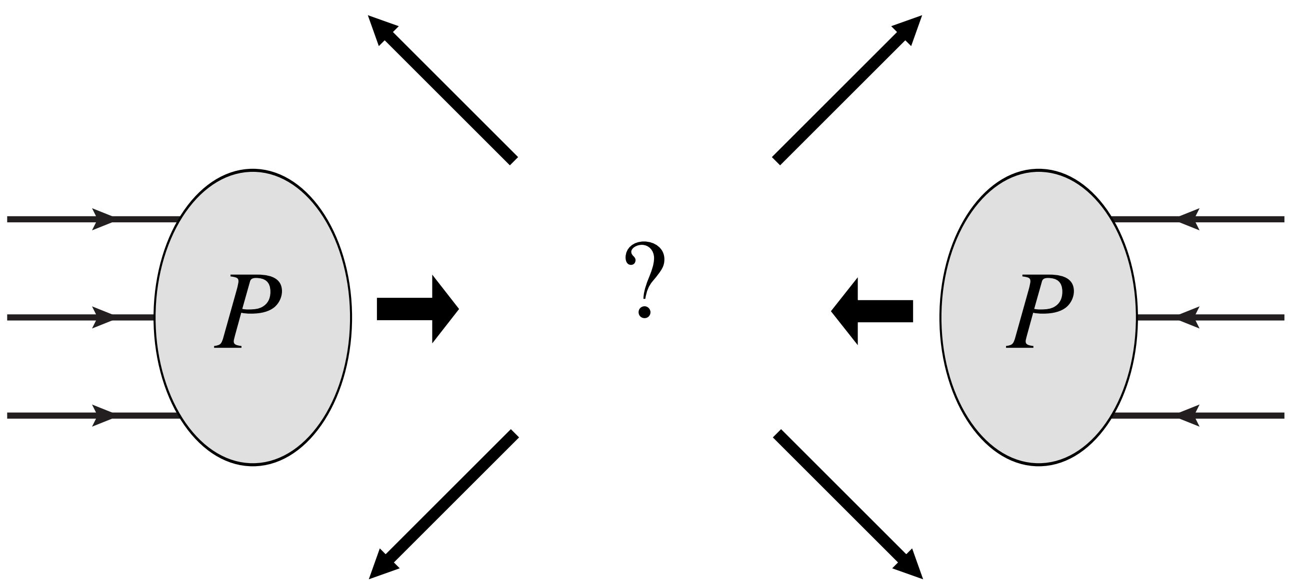
Heavy-flavour jets:

theory progress; and applications

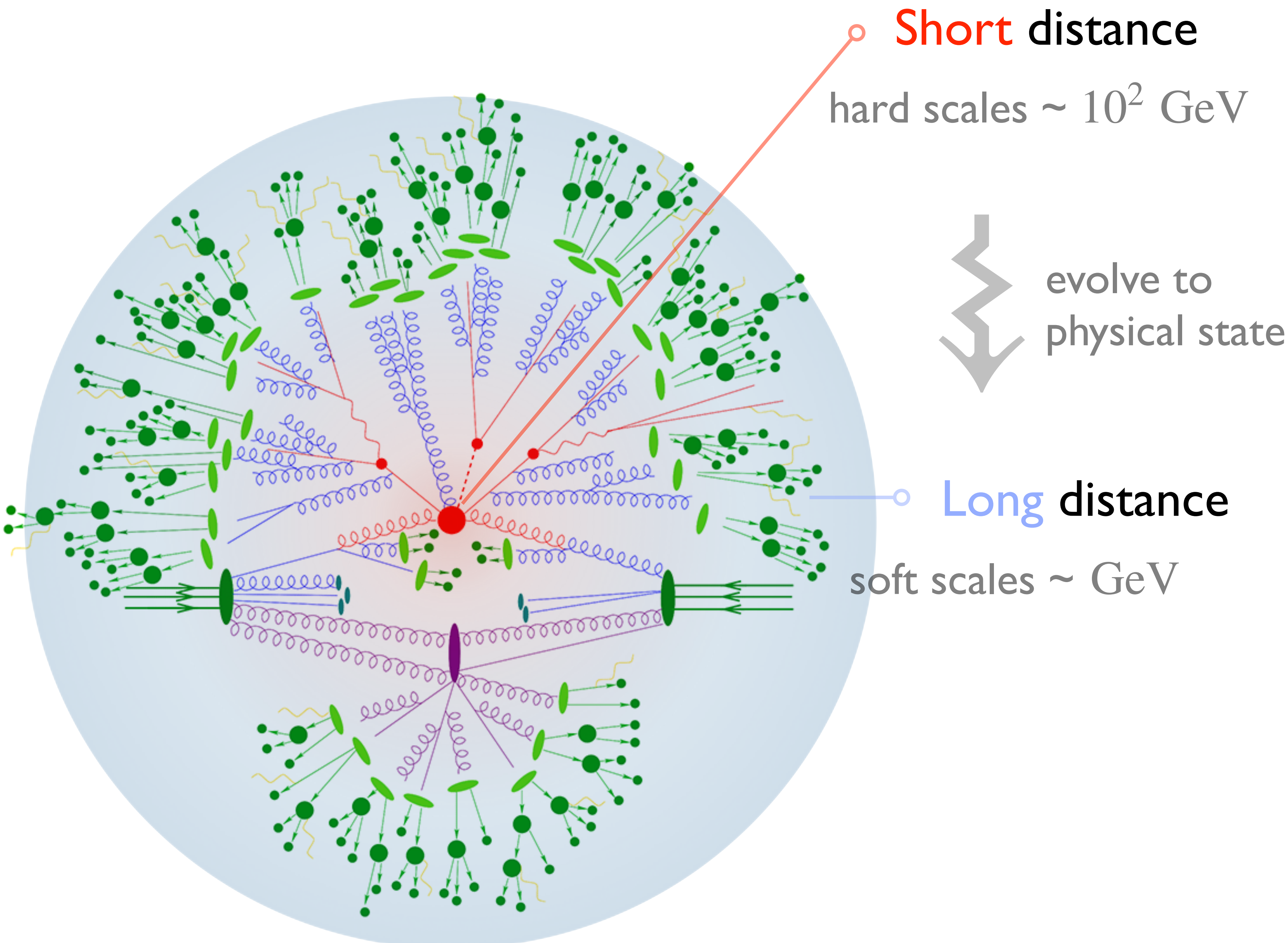
Rhorry Gauld

CERN QCD Seminar (04/04/23)

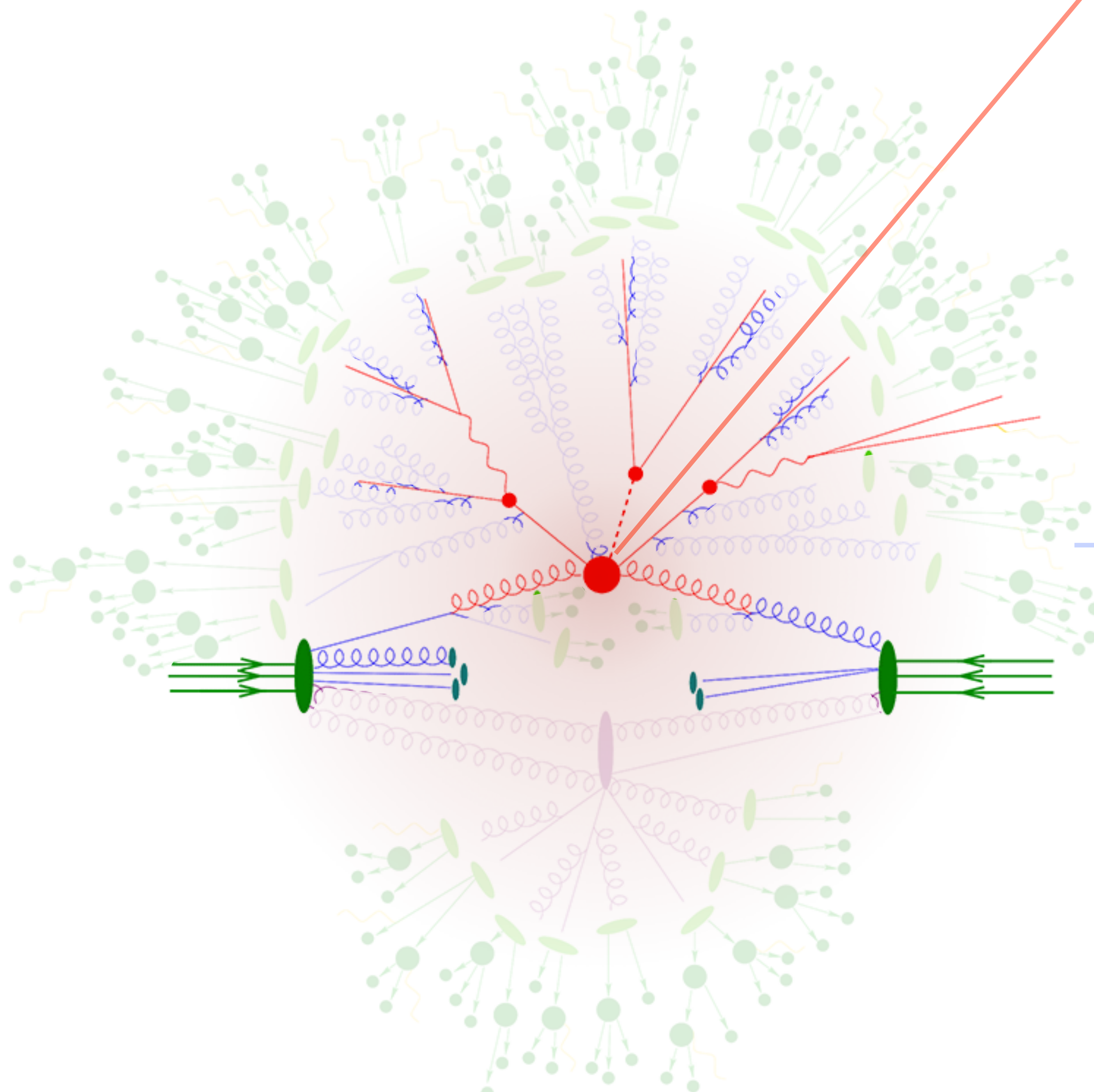
MAX-PLANCK-INSTITUT FÜR PHYSIK



$$PP \to f + X$$


Short distance
hard scales ~ 10^2 GeV
evolve to
physical state
Long distance
soft scales ~ GeV

$$PP \to f + X$$



Short distance

hard scales ~ 10^2 GeV

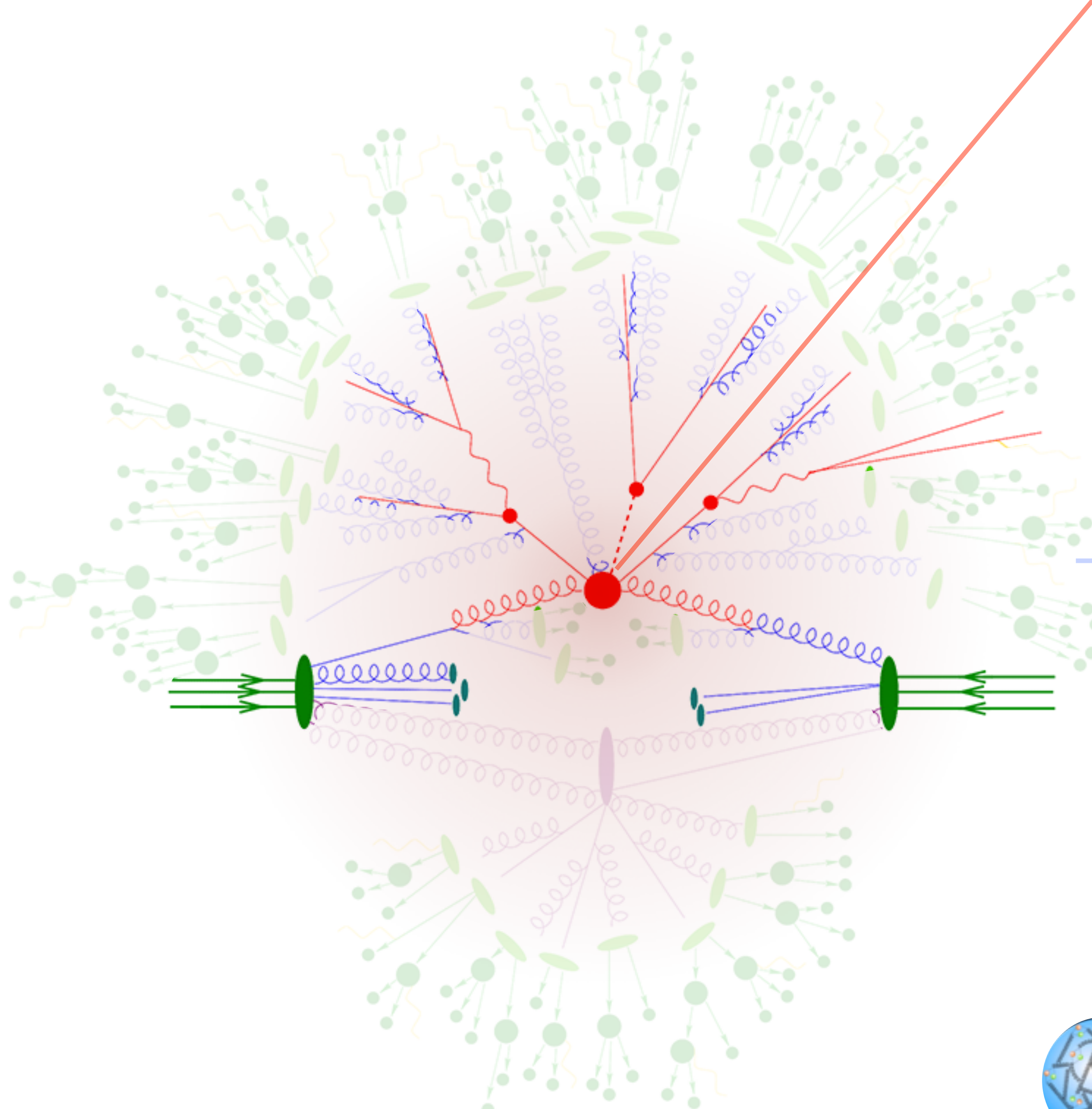
$$\sigma = \sigma_0 \left(1 + \alpha_s c_1 + \alpha_s^2 c_2 + \ldots\right)$$

Long distance

soft scales ~ GeV

(non-perturbative)

$$PP \to f + X$$



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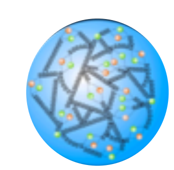
Long distance

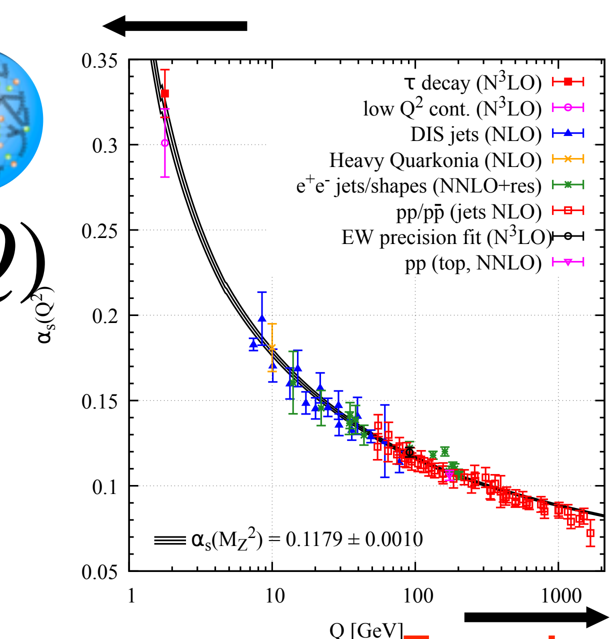
soft scales ~ GeV

(non-perturbative)

Confinement

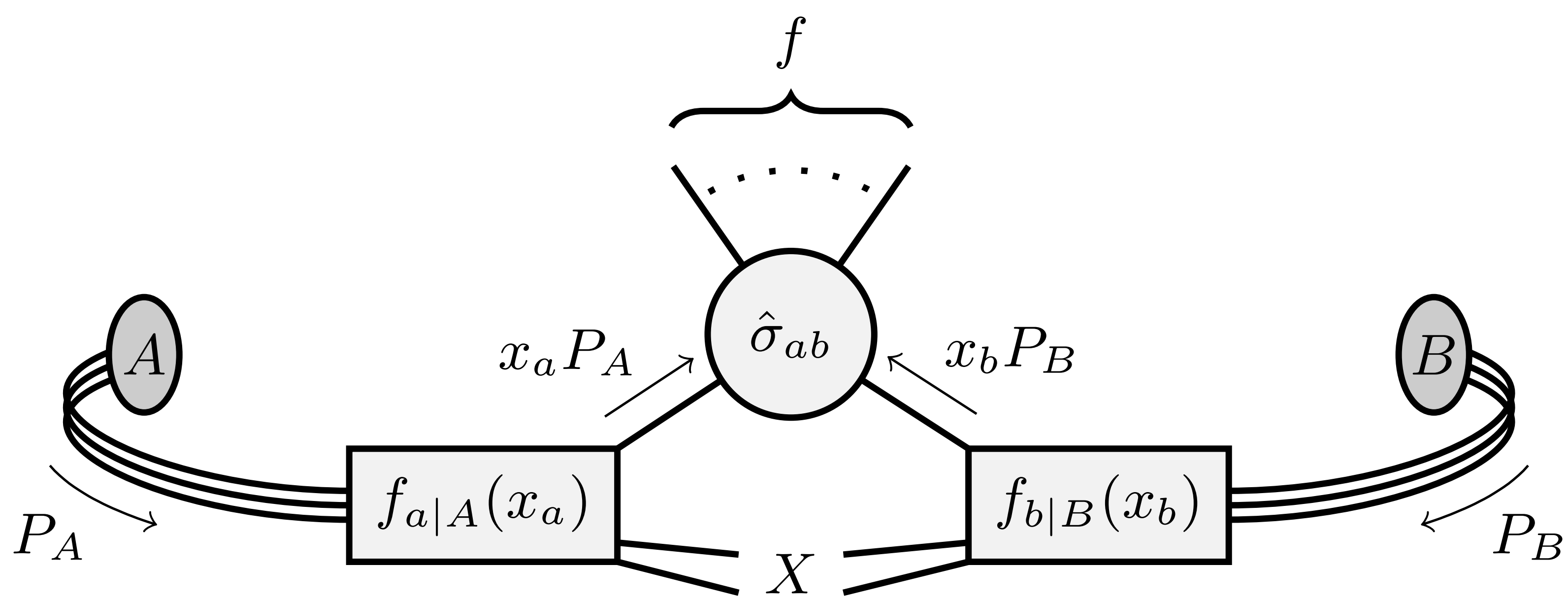


$\alpha_s(Q)$



Freedom

$$PP \to f + X$$



$$\sigma_{AB} = \sum_{ab} \int_0^1 \mathrm{d}x_a \int_0^1 \mathrm{d}x_b \; f_{a|A}(x_a)\; f_{b|B}(x_b)\; \hat{\sigma}_{ab}(x_a, x_b)\; \big(1 + \mathcal{O}(\Lambda_{\mathrm{QCD}}/Q)\big)$$

parton distribution functions (PDFs)

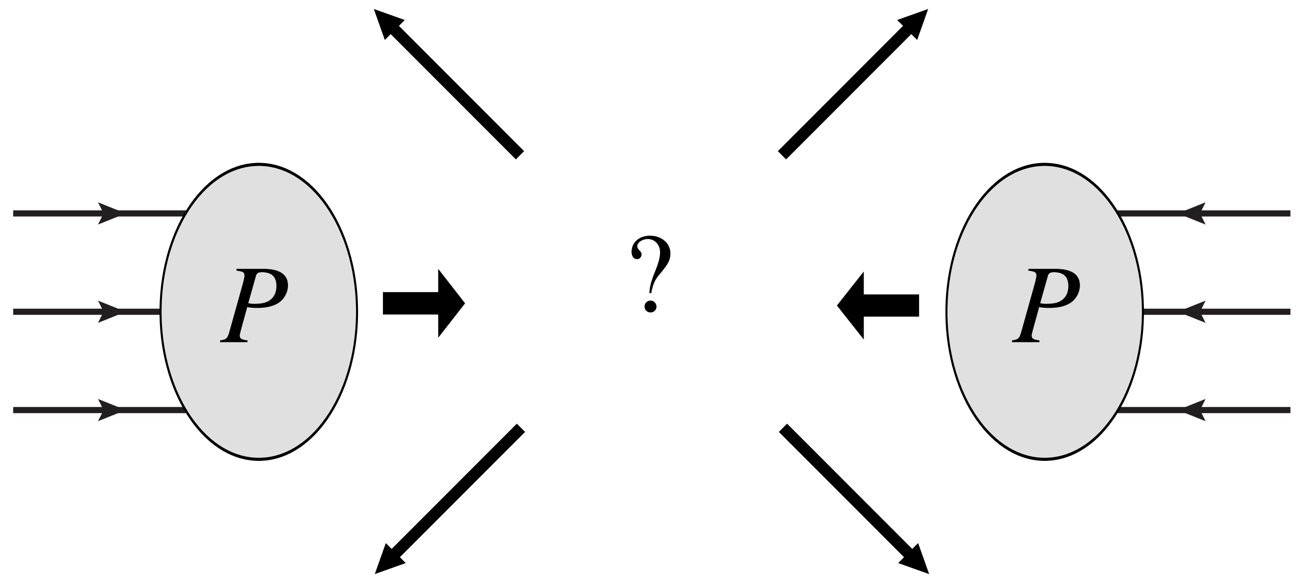
non-perturbative, data-driven

hard scattering

perturbation theory

hadronisation corrections, …

non-perturbative effects



$$PP \to f + X$$

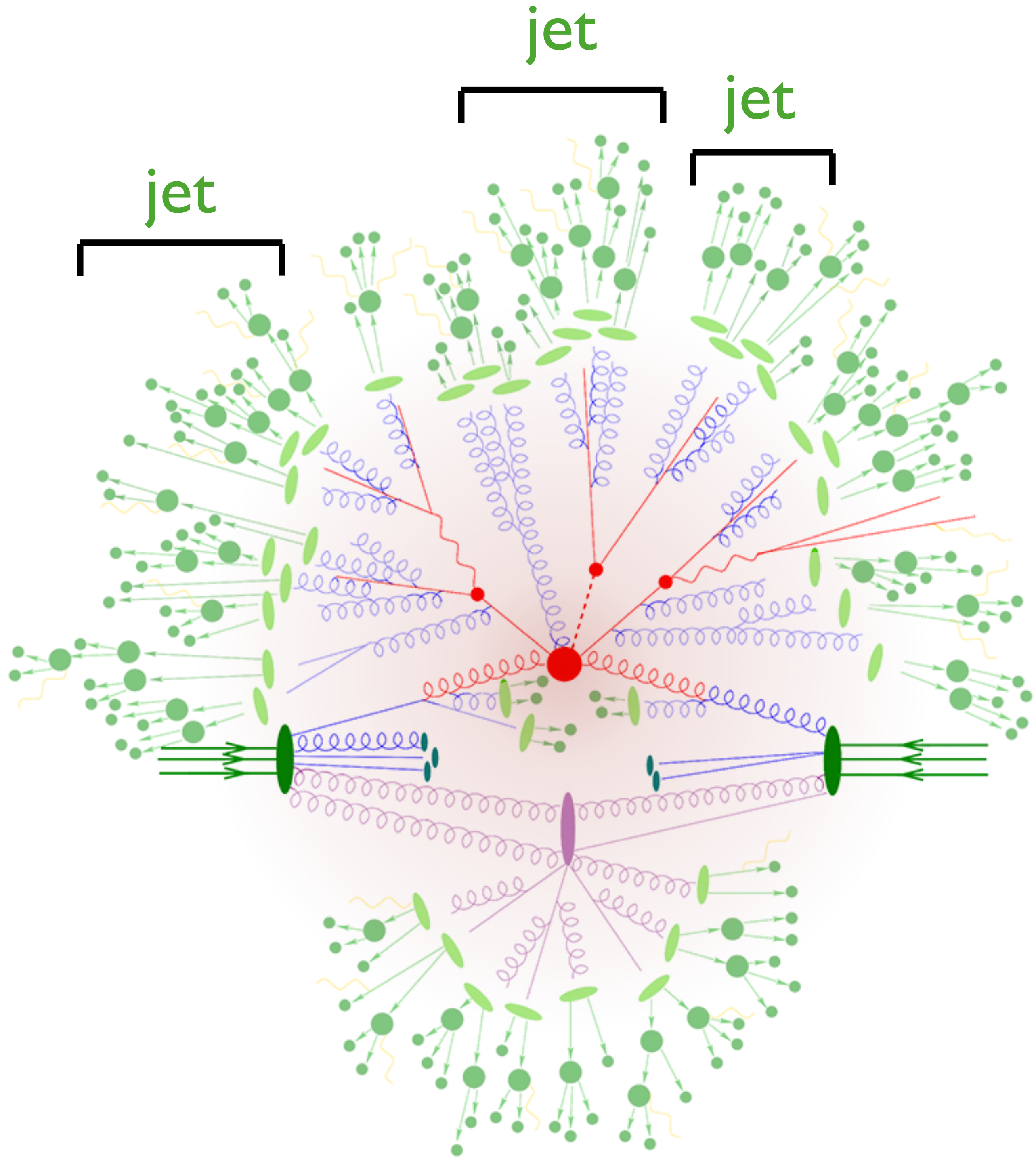
f composed of :

- leptons
- hadrons
- photons
- missing E_T
- jet
- …

critical question: how to define f to best enable this comparison

$$d\sigma^{\text{data (meas.)}}_{PP\to f+X} \quad \text{vs} \quad d\sigma^{\text{theory}}_{PP\to f+X}$$

e.g. flavour = c or b



- leptons
- hadrons
- photons
- missing E_T
- flavoured jet
- …

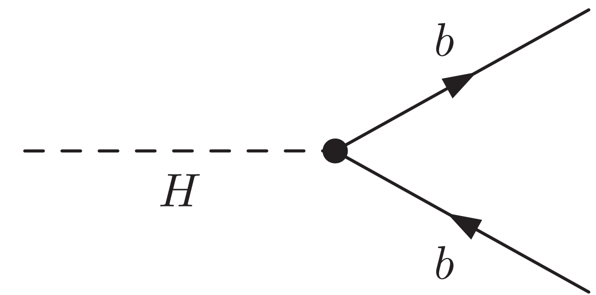
critical question: how to define f to best enable this comparison

$$d\sigma^{\text{data (meas.)}}_{PP\to f+X} \quad \text{vs} \quad d\sigma^{\text{theory}}_{PP\to f+X}$$

e.g. flavour = c or b

… and why the focus on flavoured jets?

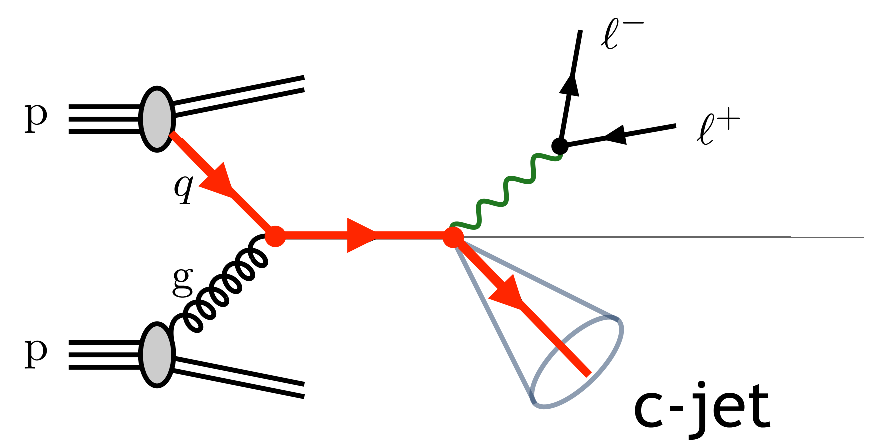
a) Higgs physics (hadronic decays)



b) Top-quark physics ($|V_{tb}| \sim 1$)

c) New physics searches (f-jet $+ E_T^{\rm miss}$)

d) Gauge-boson + heavy-flavour



…

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$$d\sigma^{\rm data\,(meas.)}_{PP\to f+X} \quad \text{vs} \quad d\sigma^{\rm theory}_{PP\to f+X}$$

$$d\sigma^{\text{data (meas.)}}_{\text{PP}\to\text{f}+\text{X}} \quad \text{vs} \quad d\sigma^{\text{theory}}_{\text{PP}\to\text{f}+\text{X}}$$

Focus is on IRC (InfraRed and Collinear) safe observables:

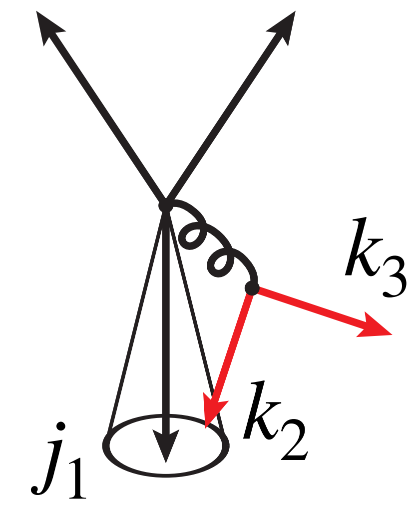
- Those not impacted by collinear splitting(s) or emission(s) of soft particles
- Those calculated in terms of quarks and gluons where the $m_q \to 0$ limit does not introduce singularities (Stermann, Weinberg '77)

➡ Can (reliably) use fixed-order perturbation theory

KLN theorem: (Kinoshita '62, Lee & Nauenberg '64)

- For such observables, a cancellation of IRC divergences between virtual and real emissions is ensured (order-by-order)
- IRC unsafe observables can be defined, all-order-resummation/factorisation theorems typically required (PDF evolution, obs. dependent resummation)

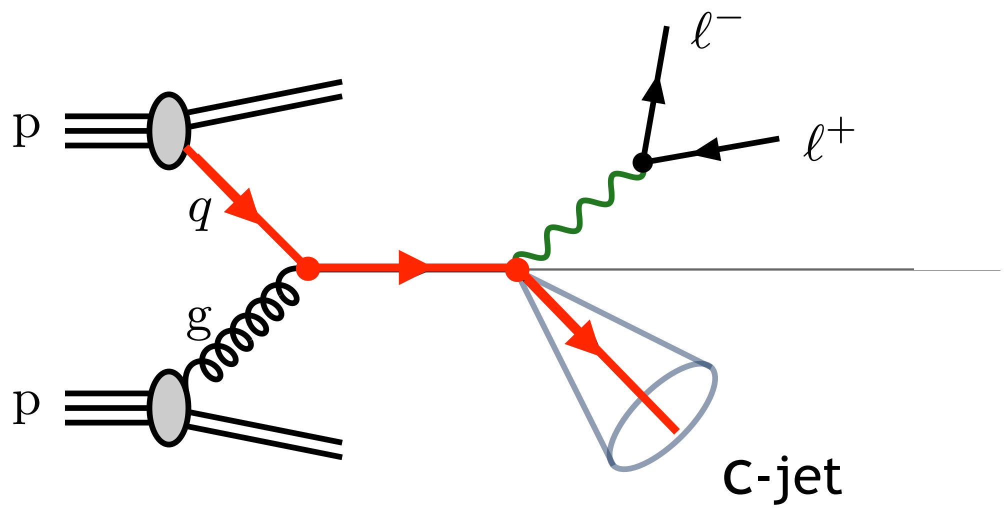
1) The problem of jet flavour (IRC safety)



- Stating the problem
- Recent solutions (algorithms)

2) Application: Z-boson + c-jet production at LHCb

- Motivation and context
- Phenomenological results



3) Experimental feasibility of flavoured jet algorithms

[Time permitting]

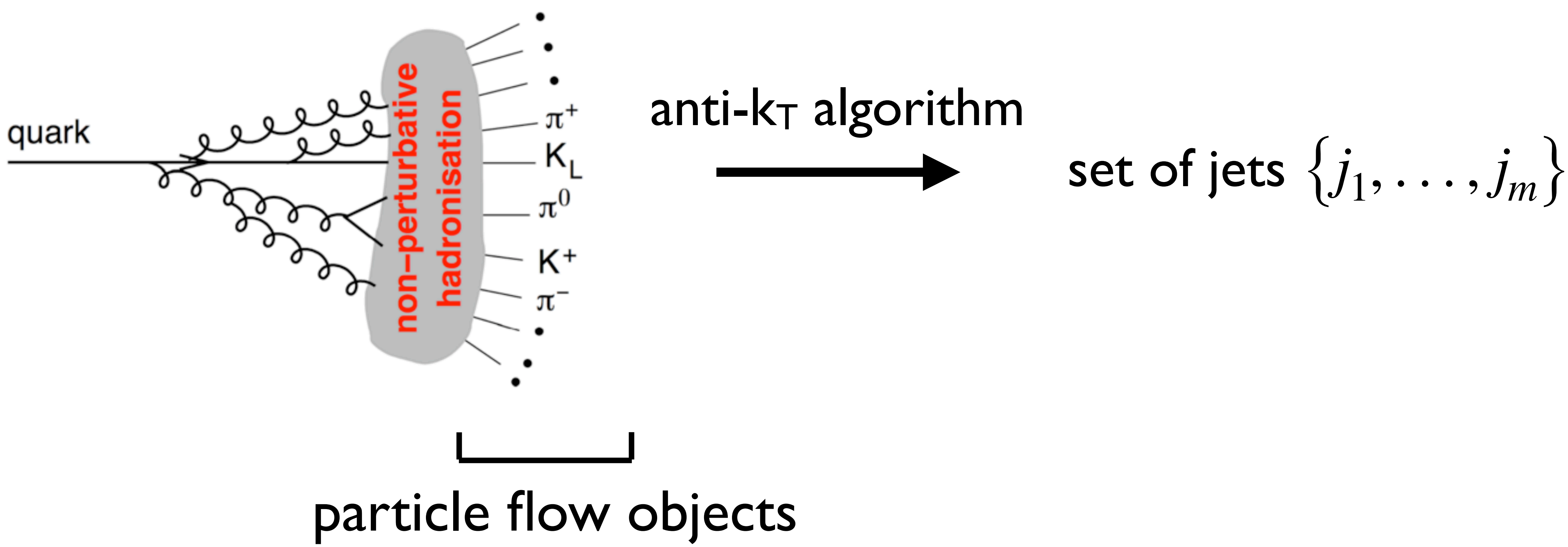
Jets at the LHC

Experimentally: apply an algorithm to particle flow objects (Kaons, Pions,…)
(e.g. ATLAS arXiv:1703.10485, CMS arXiv:1706.04965, LHCb arXiv:1310.8197)

The anti-k_T algorithm (Cacciari, Salam, Soyez arXiv:0802.1189) applied to these objects

Simple version

➡ Reconstruct hadronic jets (~collimations of hadronic radiation)



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Or… initialise a list of particles (pseudo jets) from these objects

Introduce distance measures between particles (pseudo jets) and a Beam:

$$d_{ij} = \min\left(k_{Ti}^{2p}, k_{Tj}^{2p}\right)\frac{\Delta R_{ij}^2}{R^2} \qquad \Delta R_{ij}^2 = (y_i - y_j)^2 + (\phi_i - \phi_j)^2$$

$$d_{iB} = k_{Ti}^{2p}$$

(Inclusive) clustering proceeds by identifying the min. distance:

- If it is d_{ij} combine particles ij (update list to contain combined particle)
- If it is d_{iB} , identify i as a jet and remove from list

[repeat until list is empty]

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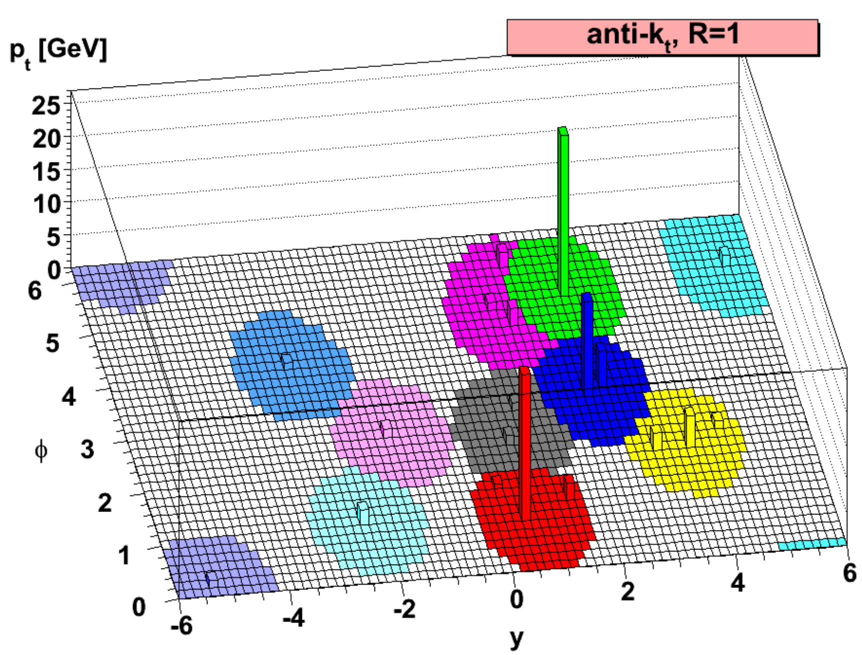
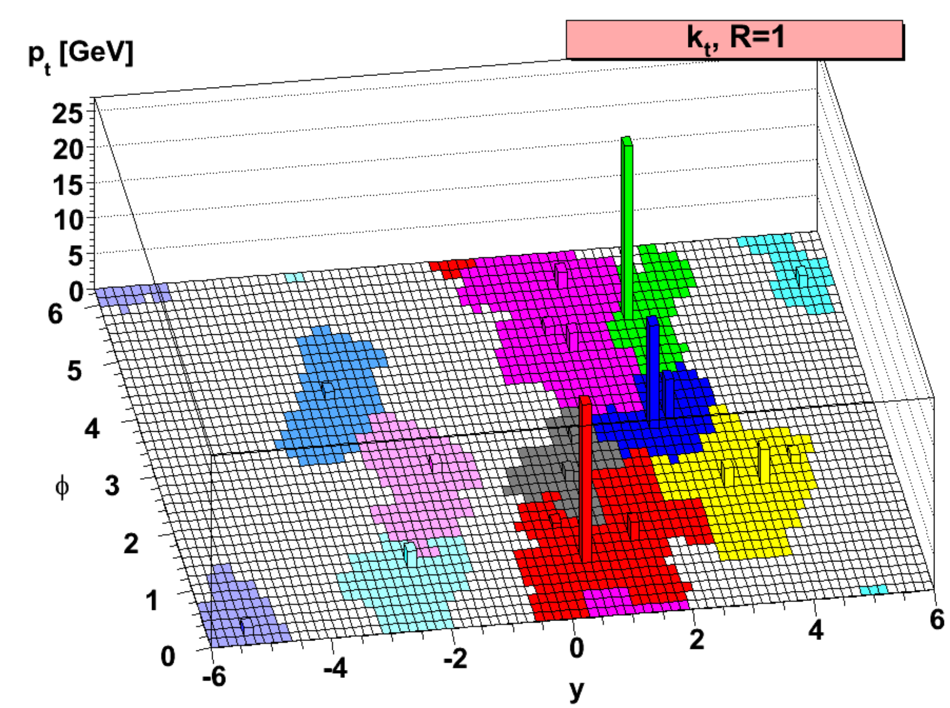
anti-k_T has nice geometrical properties (used in all LHC analyses)





anti-k_T ($p=-1$)

k_T ($p=1$)

Heavy-flavour jets at the LHC

Typical experimental approaches of defining jet flavour (truth/data level):

(ATLAS arXiv:1504.07670, CMS arXiv:1712.07158, LHCb arXiv:1504.07670)

i) First identify flavour-blind anti-k_T jets in a fiducial region

ii) Tag these jets with flavour by the presence of 1 or more D/B hadrons

$$\Delta R(j, D/B) < 0.5$$

iii) [ATLAS/LHCb] Apply p_T requirement to D/B hadron ~ $p_T^{D/B} > 5 \text{ GeV}$

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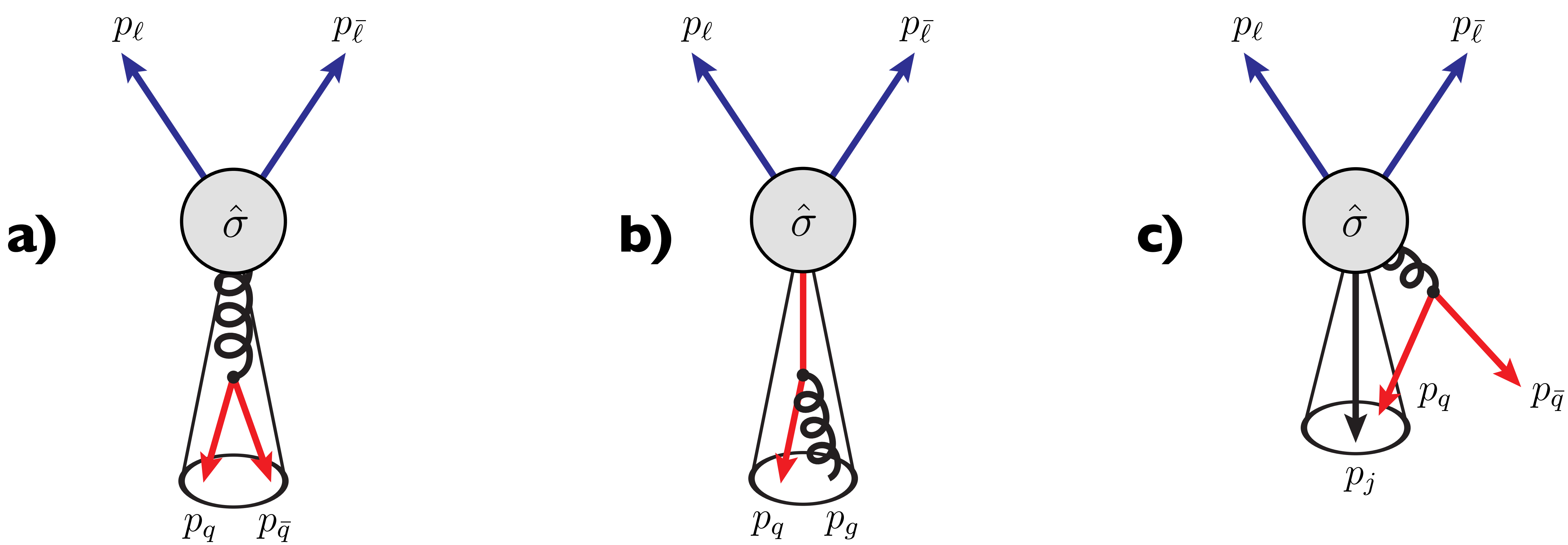

Solutions to this problem

Comments/status

"The Flavour-k_T algorithm"
(Banfi, Salam, Zanderighi: hep-ph/0601139)

k_T jets
all-order IRC safe?

… theory progress on NNLO QCD jet calculations (VH, $t\bar{t}$ w/ decay, $V+j$)

Practical jet flavour through NNLO
(Caletti, Larkoski, Marzani, Reichelt: arXiv:2205.01109)

(substructure based)
Soft unsafe N3LO

Infrared-safe flavoured anti-k_T jets
(Czakon, Mitov, Poncelet: arXiv:2205.11879)

approx. anti-k_T jets
all-order IRC safe?

A dress of flavour to suit any jet
(**RG**, Huss, Stagnitto: arXiv:2208.11138)

Tested at N3LO ($e^+e^- \to$ jets)
all-order IRC safe?

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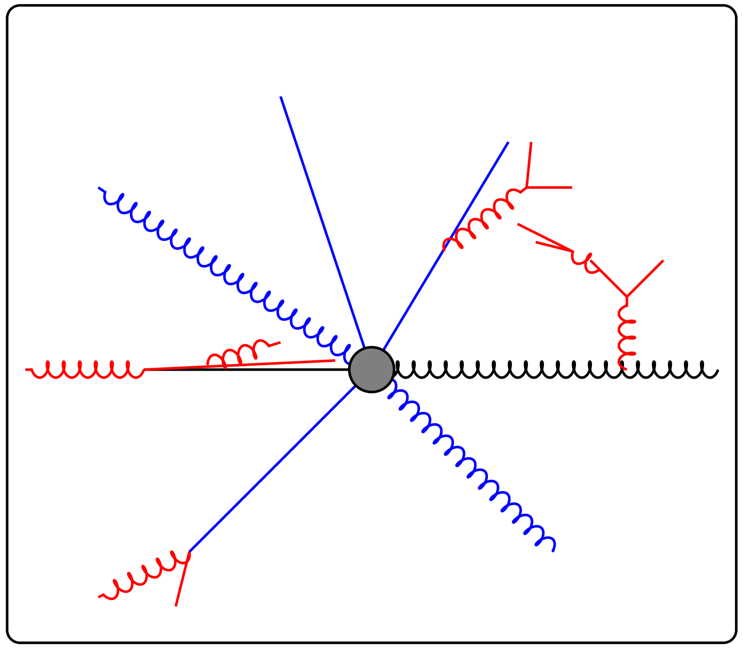
Flavoured jets with exact anti-k_T kinematics
(Caola, Grabarczyk, Hutt, Salam, Scyboz, Thaler: preliminary—Moriond last week)
(substructure based)

em

Systematic framework to test IRC safety
[numerical tests up to $\mathcal{O}(\alpha_s^6)$]



FSR-DS = double-soft
ISR-DS
FC = FS hard-collinear
IC = IS hard-collinear

possibly nested

Set of hard jets
$\mathcal{J}_{\text{hard}} = \{(p_1, f_1), ...\}$ $\stackrel{!}{=}$ Set of hard+IR jets
$\mathcal{J}_{\text{hard+IR}} = \{(\tilde{p}_1, \tilde{f}_1), ...\}$

Comments/status

k_T jets
all-order IRC safe?

H, $t\bar{t}$ w/ decay, $V + j$)

(substructure based)
Soft unsafe N3LO

approx. anti-k_T jets
IC-IC unsafety?

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Tested at N3LO ($e^+e^- \to$ jets)
adjustments required

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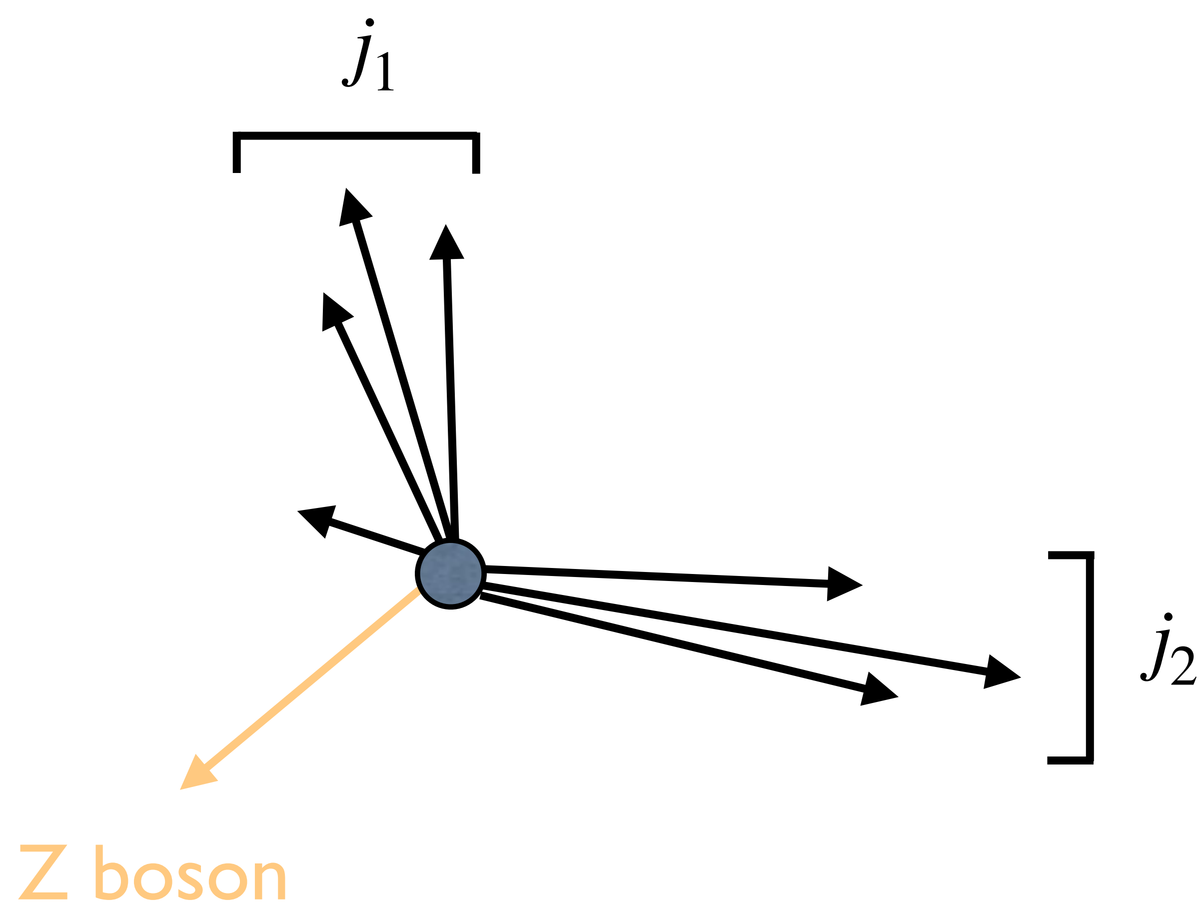
Our motivation: A well defined flavour algorithm applicable to anti-k_T jets

(actually, any jet)

Also, applicable to heavy-flavour tagging in LHC analyses

Toy event



set of jets $\{j_1, \ldots, j_m\}$

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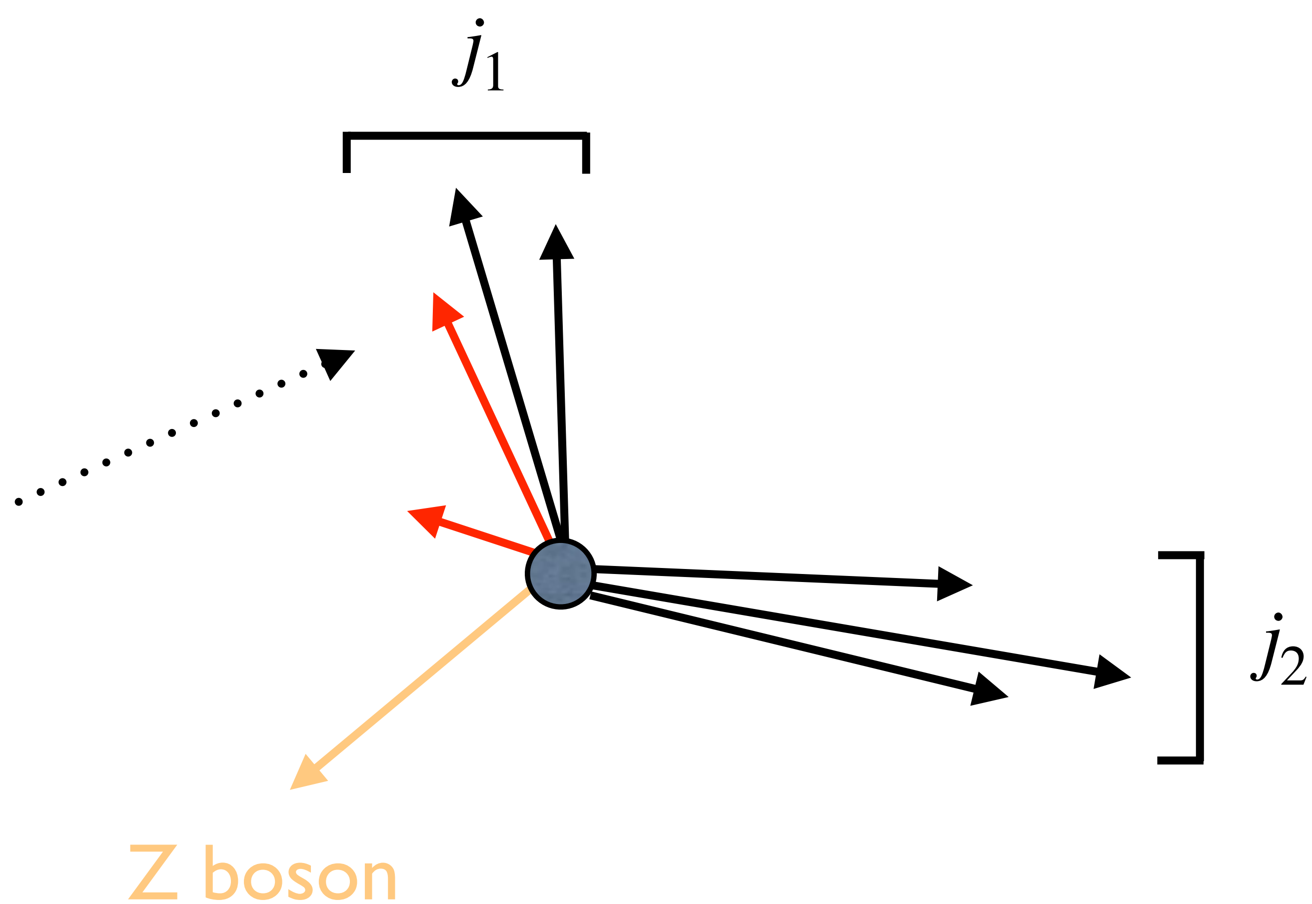
Toy event

Flavoured particles
b-quark (theory)
secondary vertex (exp.)



set of jets $\{j_1, \ldots, j_m\}$ set of flavoured objects $\{\hat{f}_1, \ldots, \hat{f}_n\}$

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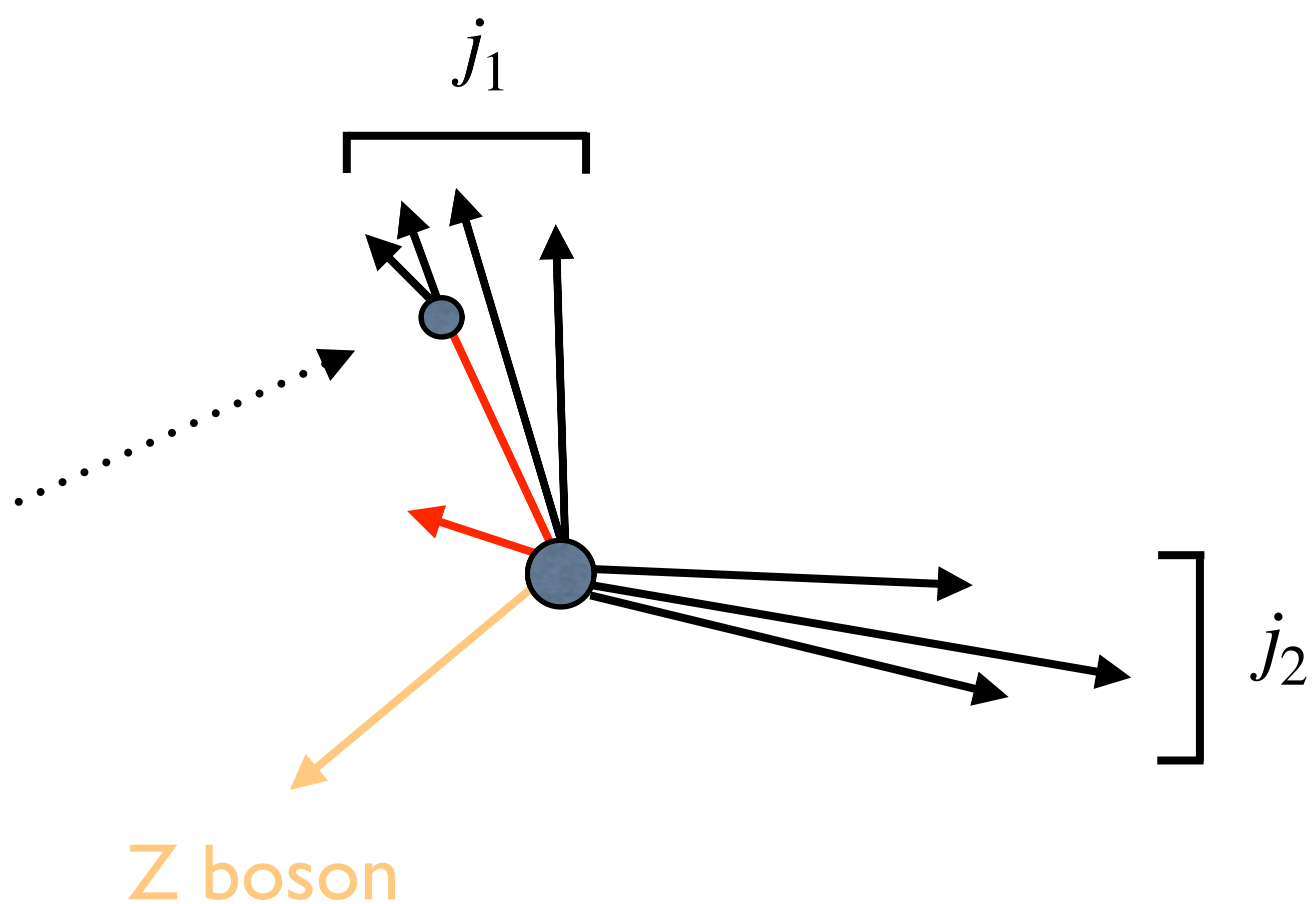

set of jets $\{j_1, \ldots, j_m\}$

set of flavoured objects $\left\{\hat{f}_1, \ldots, \hat{f}_n\right\}$

(flavoured particles not required to be final state!)

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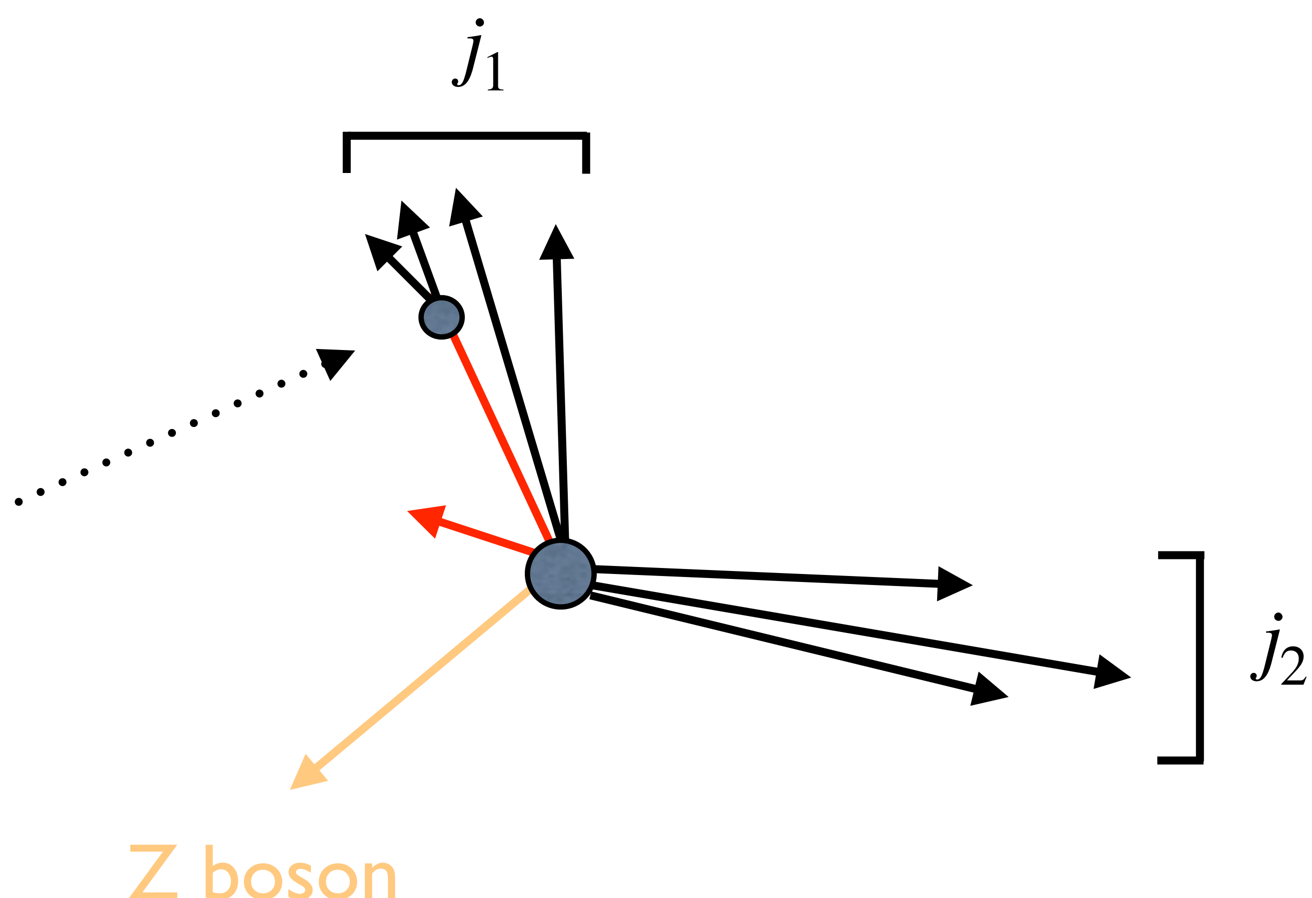

algorithm assigns $\hat{f}_i$ to j_k

set of jets $\{j_1, \ldots, j_m\}$ ⟵ set of flavoured objects $\{\hat{f}_1, \ldots, \hat{f}_n\}$

(flavoured particles not required to be final state!)

(1/3) collinear-safe flavoured objects

(**RG**, Huss, Stagnitto arXiv:2208.11138)

flavoured particles (quarks, hadrons) not collinear safe. Define new objects:

Dress the flavoured particles with collinear radiation

(altering momenta but not flavour)

$$\{f_1, \ldots, f_n\} \to \left\{\hat{f}_1, \ldots, \hat{f}_{n-2m}\right\}$$

flavoured particles → flavoured 'clusters'

(potentially annihilating m collinear $f_i f_j$ pairs)

(1/3) collinear-safe flavoured objects

(**RG**, Huss, Stagnitto arXiv:2208.11138)

flavoured particles (quarks, hadrons) not collinear safe. Define new objects:

i) Initialise a list of all particles

ii) Add to the list all flavoured particles, removing any overlap

iii) Calculate the distances $d_{ij} = \Delta R_{ij}^2$ between all particles

iv) If $d_{ij}^{\min} > \Delta R_{\text{cut}}^2$ terminate the clustering. Otherwise:

1. (i & j flavourless) replace i & j in the list with combined object ij
2. (i or j flavoured) combine i and j if:

$$\frac{\min(p_{T,i}, p_{T,j})}{p_{T,i} + p_{T,j}} > z_{\text{cut}} \left(\frac{\Delta R_{ij}}{R_{\text{cut}}} \right)^{\beta}$$

[Soft-drop]
(Larkoski et al. arXiv:1402.2657)

Otherwise:

(i & j flavoured) remove both from list

(i or j flavourless) remove only flavourless object

[Repeat until list empty, or no flavoured particles left]

(2/3) Association criterion and counting

(**RG**, Huss, Stagnitto arXiv:2208.11138)

We now have have $\{j_1, \ldots, j_m\}, \left\{\hat{f}_1, \ldots, \hat{f}_n\right\}$

We introduce an **Association criterion** for $\hat{f}_a$ with j_b (some possibilities):

- the flavoured particle f_a is a constituent of jet j_b
- or $\Delta R(\hat{f}_a, j_b) < R_{\rm tag}$
- or Ghost association of $\hat{f}_a$ (include direction of $\hat{f}_a$ in anti-k_T clustering)

(association criterion required as not assumed that f_a is a stable particle)

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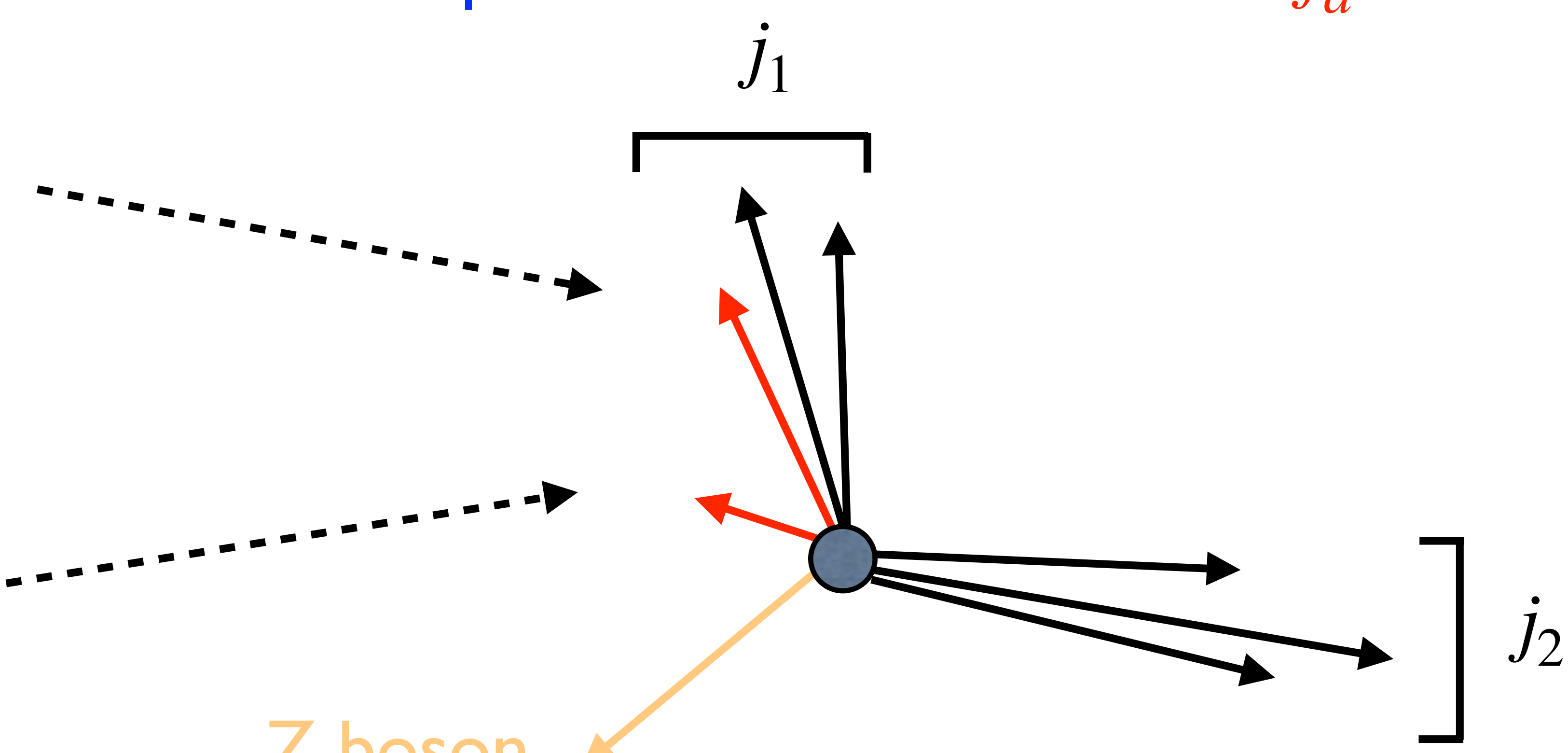
Here, $f \sim j_1$

No association for this f



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Introduce a **Counting** or **Accumulation** for flavour:

- with charge info. (q vs $\bar{q}$), then $q = +1$ and $\bar{q} = -1$ (net flavour is sum)
- if one cannot (e.g. experiment), $q = \bar{q} = 1$ (net flavour is sum modulo 2)
  [i.e. jets with even number of $q_i + \bar{q}_j$ are NOT flavoured]

(3/3) The flavour dressing algorithm

(**RG**, Huss, Stagnitto arXiv:2208.11138)

We now have have $\{j_1, \ldots, j_m\}, \left\{\hat{f}_1, \ldots, \hat{f}_n\right\}$, association, and counting rules

(3/3) The flavour dressing algorithm

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Dressing algorithm:

- Calculate a set of distances between the flavoured objects, jets and beam:
  - [ff] d_{ab} between all all flavoured objects $\hat{f}_a$ and $\hat{f}_b$
    - [fj] d_{ab} between $\hat{f}_a$ and j_b ONLY if there is an association
    - [fB] d_{aB} for all $\hat{f}_a$ without a jet association

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    - [fB] d_{aB} for all $\hat{f}_a$ without a jet association
- Find the minimum distance of all entries in the list
  - if it is an [fj] assign $\hat{f}_a$ to j_b (removing entries involving $\hat{f}_a$ from list)
  - otherwise just remove $\hat{f}_a$ [fB] or $\hat{f}_a$ and $\hat{f}_b$ [ff] from the list

[repeat until list empty]

- The flavour of each jet is then just the accumulation of its flavour

(3/3) The flavour dressing algorithm

(**RG**, Huss, Stagnitto arXiv:2208.11138)

We now have have $\{j_1, \ldots, j_m\}, \left\{\hat{f}_1, \ldots, \hat{f}_n\right\}$, association, and counting rules

Note: Originally we used the distance measures proposed in flavour-k$_T$

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

$$d_{ab} = \Delta R_{ab}^2 \max\left(p_{T,a}^{\alpha}, p_{T,b}^{\alpha}\right) \min\left(p_{T,a}^{2-\alpha}, p_{T,b}^{2-\alpha}\right)$$

$$d_{aB\pm} = \max\left(p_{T,a}^{\alpha}, p_{T,B_\pm}^{\alpha}(y_{\hat{f}_a})\right) \min\left(p_{T,a}^{2-\alpha}, p_{T,B_\pm}^{2-\alpha}(y_{\hat{f}_a})\right)$$

As pointed out by (Caola, Grabarczyk, Hutt, Salam, Scyboz, Thaler) alteration required

[e.g. unsafe configuration “IDS x FDS” encountered at N4LO]

(TBC: addressed with Jade distance and $\beta < 2$) $\quad$ $d_{ab} = 2 p_a \cdot p_b$

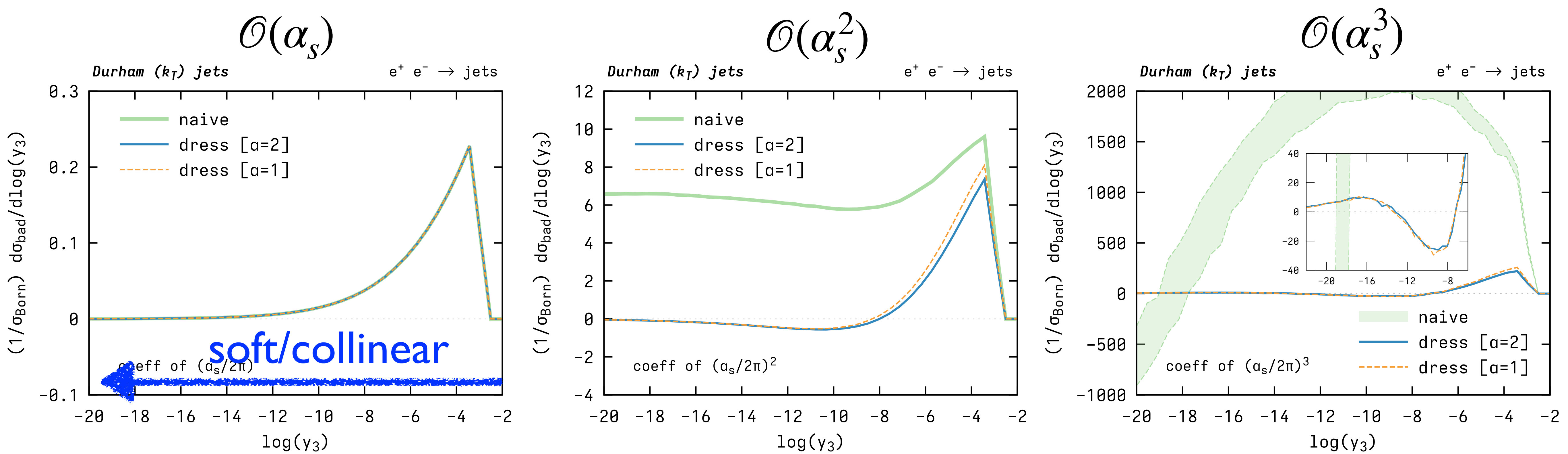
Tests of the algorithm (e^+e^-)

(**RG**, Huss, Stagnitto arXiv:2208.11138)

Consider the process $e^+e^- \to 2$ jets at fixed-order using k_T algorithm

Look at 'bad' events (i.e. where we do not find 2 flavoured jets, $e^+e^- \to q\bar{q}$)

The 'bad' cross-section should vanish in the $y_3 \to 0$ limit
($y_3 \to 0$ corresponds to limit of extremely soft and/or collinear emissions)



These tests originally proposed/shown in the original flavour-k_T study

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

Summary Part (1)

(reminder: I have detailed the "flavour-dressing" approach)

i) Several theory motivated algorithms for jet flavour, with differences:

* Reproduction of exact anti-k_T kinematics (at parton level)

* Fixed-order IRC safety (between N2LO and N6LO+)

* Applicability at truth-level (parton) or measurement (unstable B/D hadrons)

ii) An all-order proof of IRC safety very difficult

* How many orders are needed? Differential N3LO feasible in future…

iii) Experimental feasibility (or dependence on an unfolding correction)

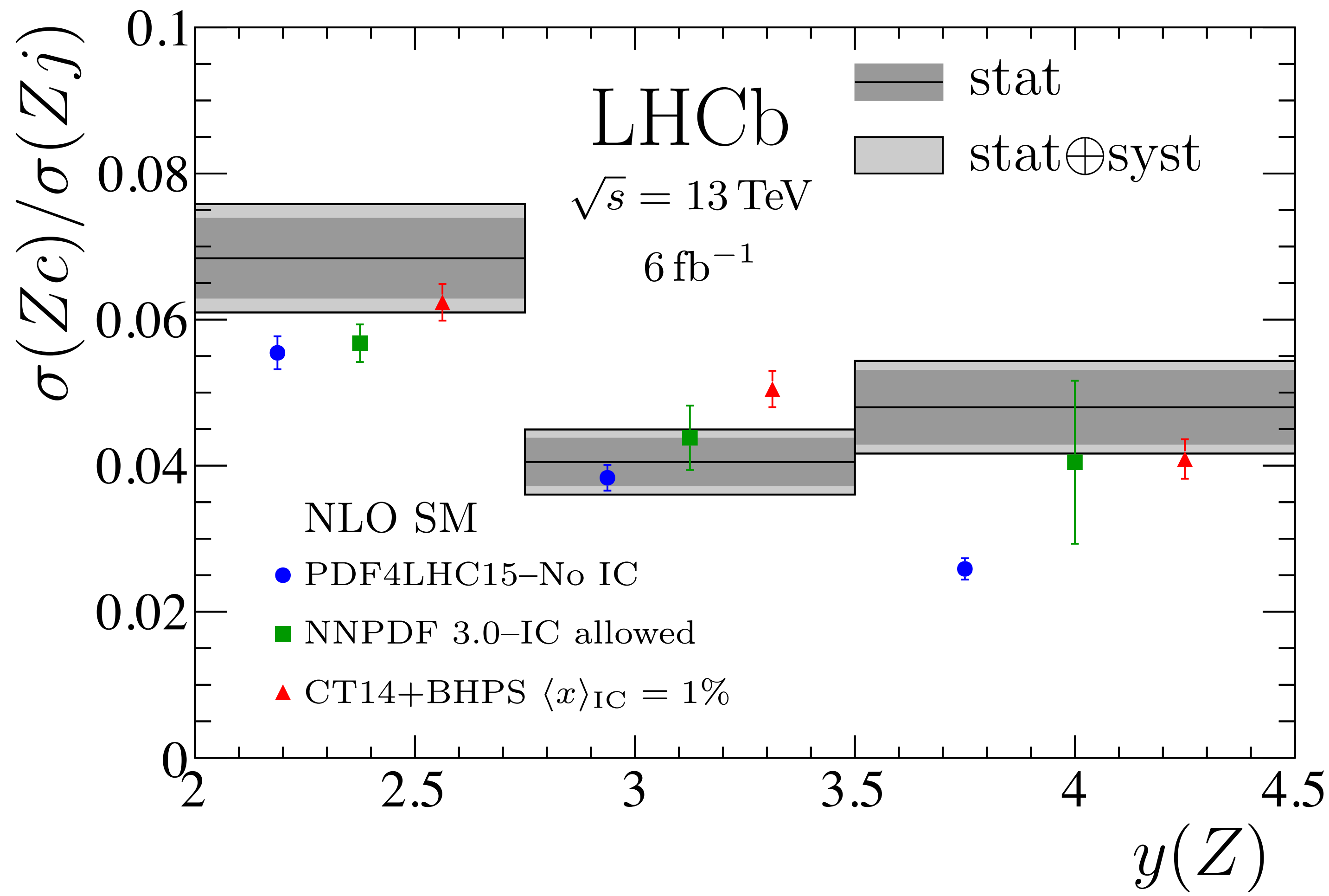
*) Size of this correction may be strongly algorithm/process dependent

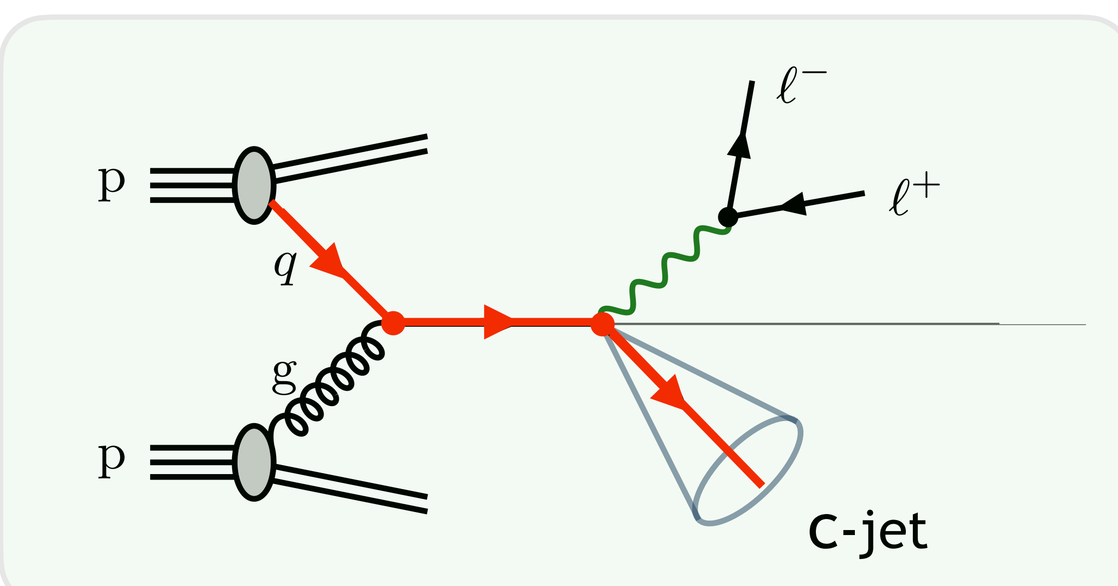
$$d\sigma^{\text{data (meas.)}}_{PP\to f+X} \quad \text{vs} \quad d\sigma^{\text{theory}}_{PP\to f+X}$$

(unclear what is best to achieve this)

Applications: Z+c-jet at LHCb

LHCb measurement (13 TeV), arXiv: 2109.08084





Forward kinematics:

$$x_{1(2)} \sim \frac{1}{\sqrt{s}}\left(m_T^Z e^{+(-)y_Z} + p_T^j e^{+(-)y_j}\right)$$

unique probe of large(small) x

see Boettcher et al., arXiv: 1512.06666

Applications: Z+c-jet at LHCb

LHCb measurement (13 TeV), arXiv: 2109.08084

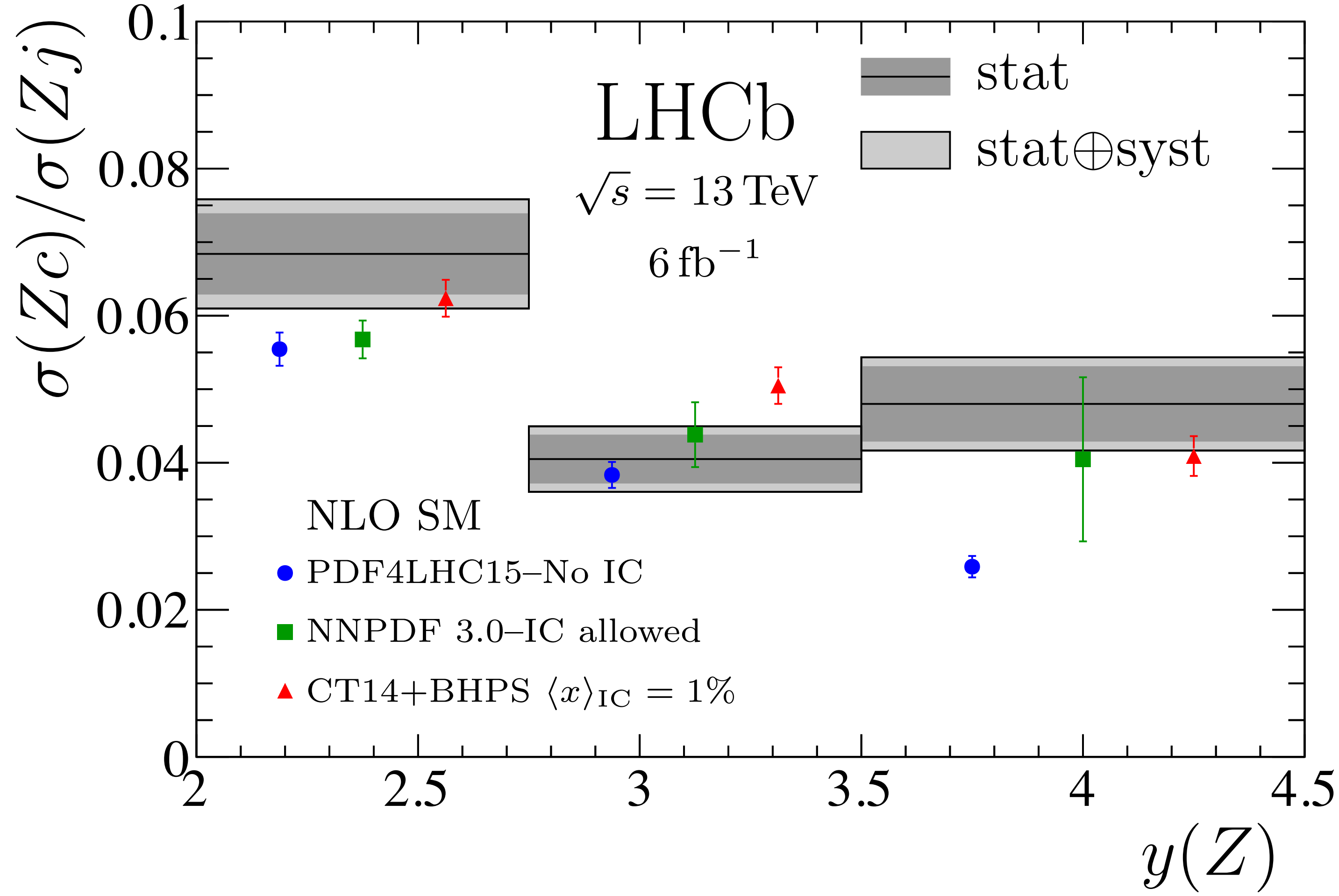


Table 1: Definition of the fiducial region.

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

Applications: Z+c-jet at LHCb

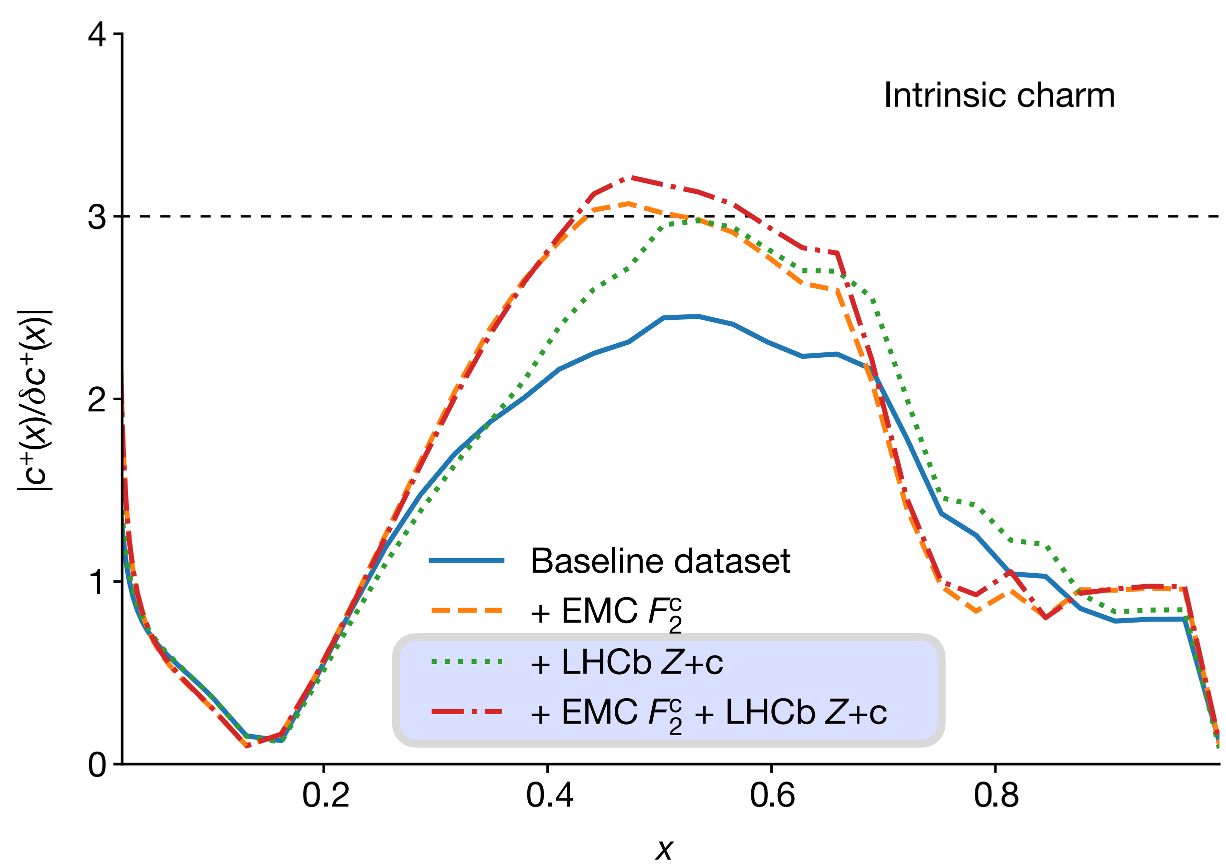
Article | Open Access | Published: 17 August 2022

Evidence for intrinsic charm quarks in the proton

The NNPDF Collaboration

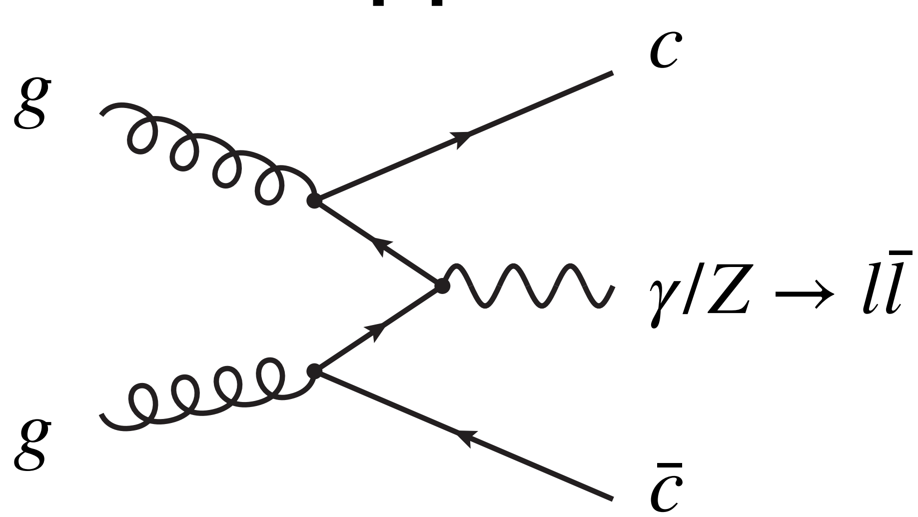
Nature **608**, 483–487 (2022) | Cite this article

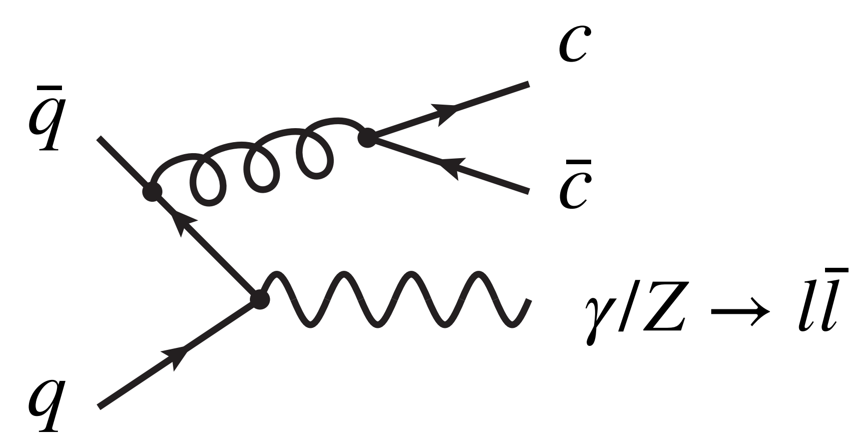
42k Accesses | **7** Citations | **374** Altmetric | Metrics



(not observed by all pdf fitting groups, Guzzi et al. arXiv:2211.01387)

Applications: Z+c-jet at LHCb

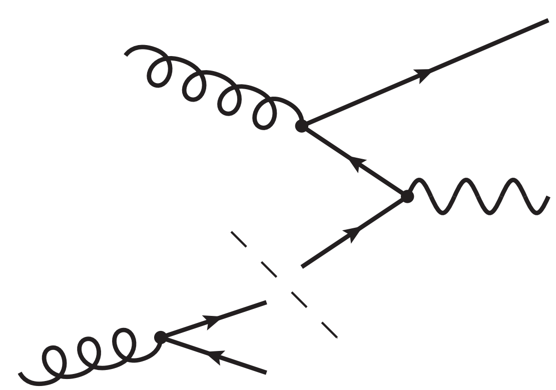




Calculated in the 3fs scheme (i.e. $n_f^{\max} = 3$ in PDFs, and α_s evolution)

$$\mathrm{d}\sigma^{3fs} = \mathrm{d}\sigma^{m_c=0} \quad + \quad \mathrm{d}\sigma^{\ln[m_c]} \quad + \quad \mathrm{d}\sigma^{m_c}$$

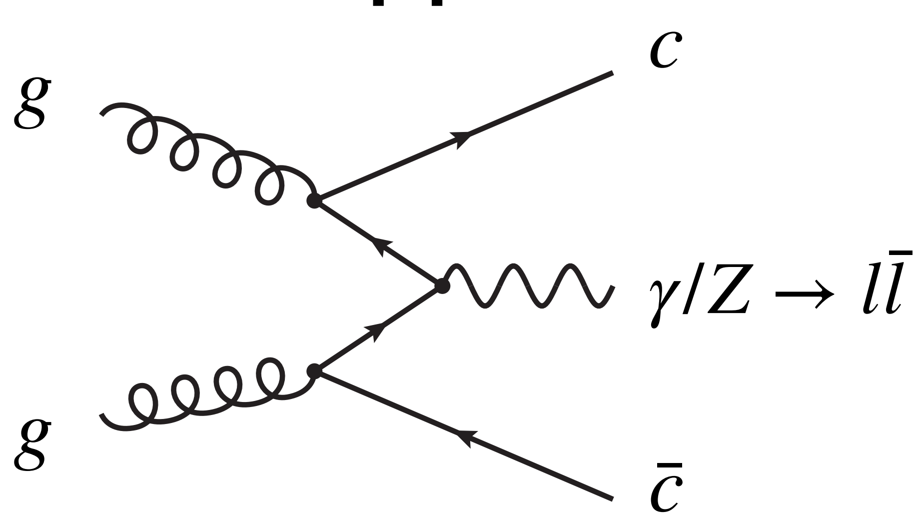
Massless component
$\mathcal{O}(\alpha_s^2 n_f)$ in 4fs

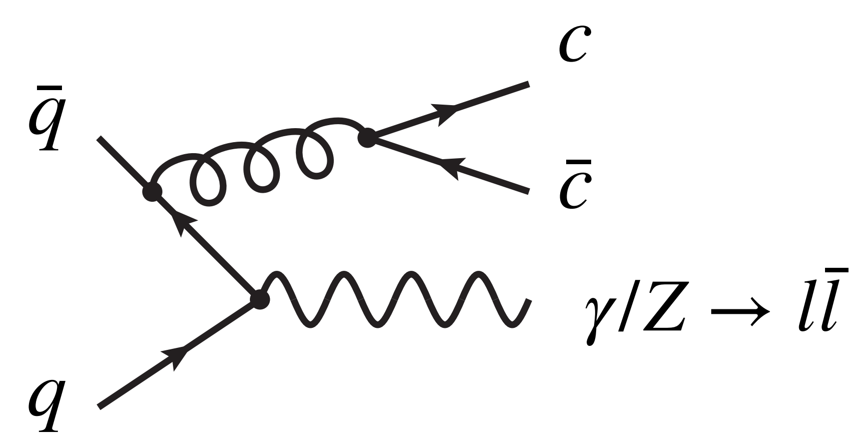


$\mathcal{O}(m_c^2)$ effects
(exact kinematics)

Note, initial-state mass singularities still there (even with IRC safe jet alg.)

Applications: Z+c-jet at LHCb





Calculated in the 3fs scheme (i.e. $n_f^{\max} = 3$ in PDFs, and α_s evolution)

$$\mathrm{d}\sigma^{3fs} = \mathrm{d}\sigma^{m_c=0} \quad + \quad \mathrm{d}\sigma^{\ln[m_c]} \quad + \quad \mathrm{d}\sigma^{m_c}$$

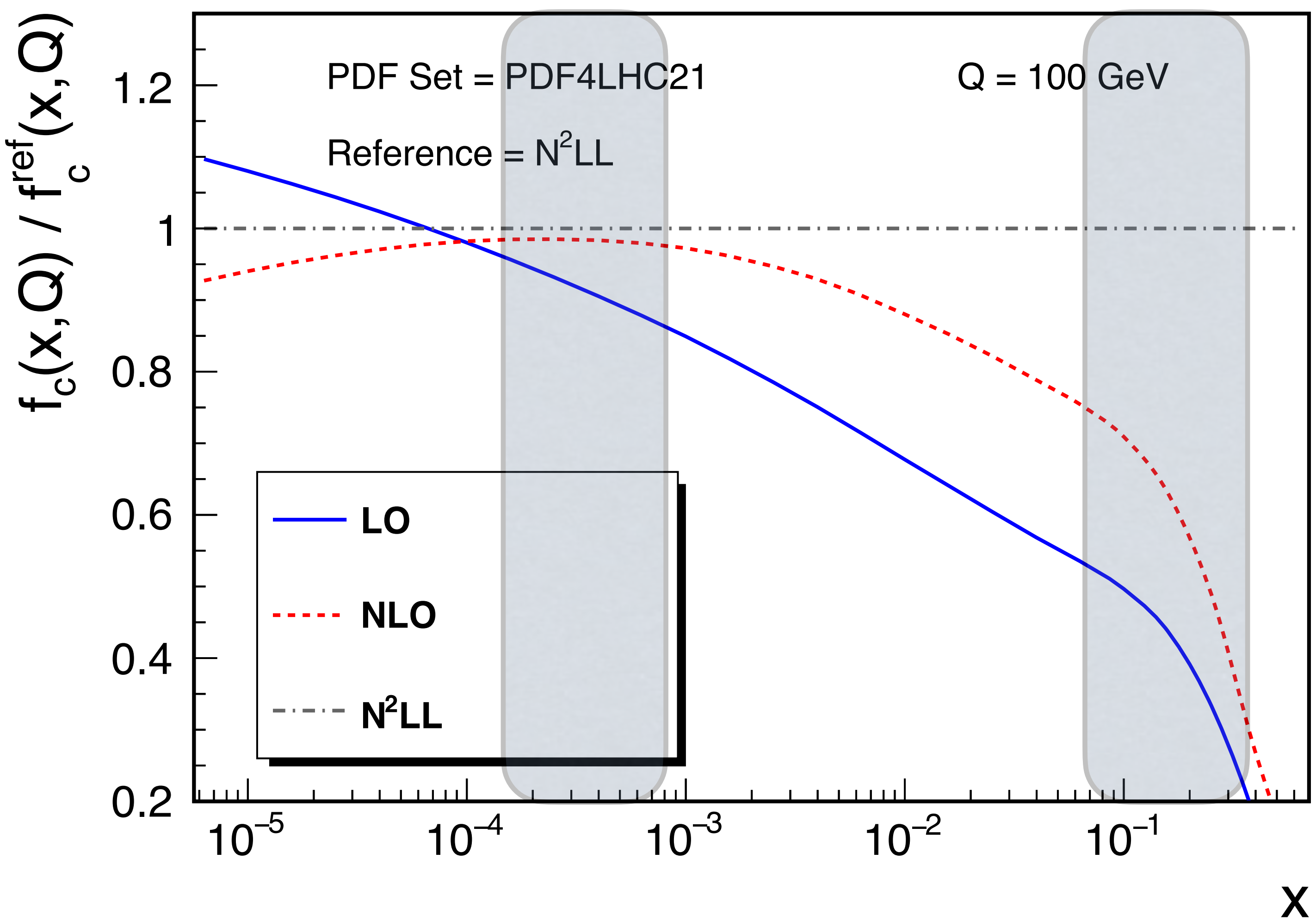
0.220 = +0.0364 +0.203 -0.019 [pb]

100% = +16% +92% -8%

Note, initial-state mass singularities still there (even with IRC safe jet alg.)

Applications: Z+c-jet at LHCb

The perturbative corrections are enormous: resummation critical (this class of logarithm resummed by PDF evolution)



$< x_1 > \sim 0.2$

$< x_2 > \sim 6 \times 10^{-4}$

LHCb cross-section: Leading Log (1st order) = 0.203pb, Leading Log (resumed) = 0.332pb

I am showing fixed-order pdf versus a resummed one (PDF evolution)

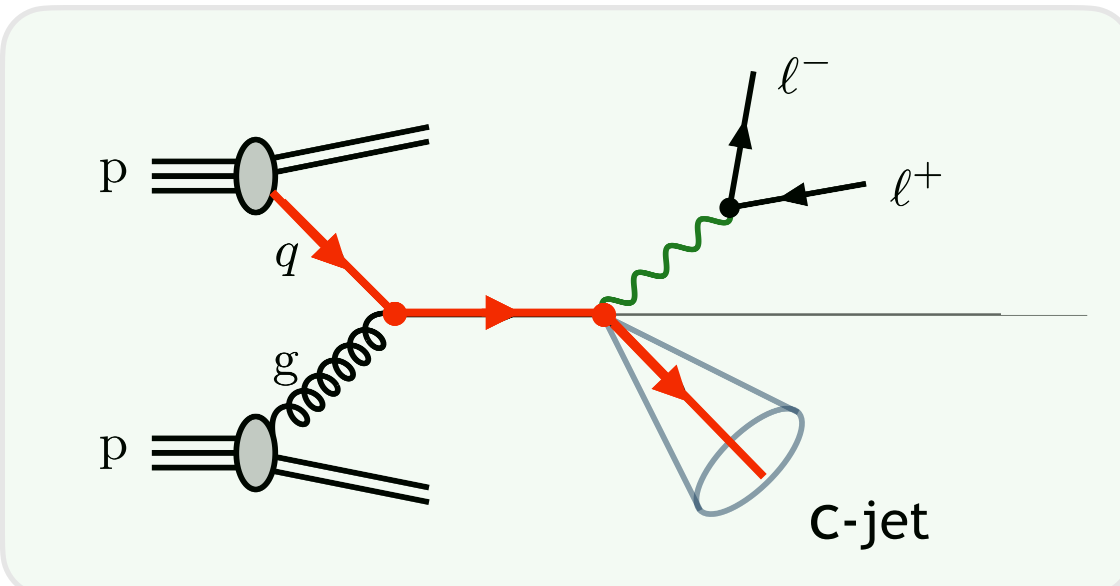
$\alpha_s^m \ln^n[\mu_F^2/m_c^2], \quad m \geq n$

Note! $\alpha_s \ln[m_Z^2/m_c^2] \approx 1.0$

Applications: Z+c-jet at LHCb

RG, Gehrmann-De Ridder, Glover, Huss, Rodriguez Garcia, Stagnitto, arXiv:2302.12844

- Theory study based on SPS predictions (no MPI corrections)
- Consider a fiducial region matching that of the LHCb experiment



Introduce the constraint

$$p_T(Zj_c) \leq p_T(j_c)$$

Predictions are provided in a Massive - Variable Flavour Number Scheme

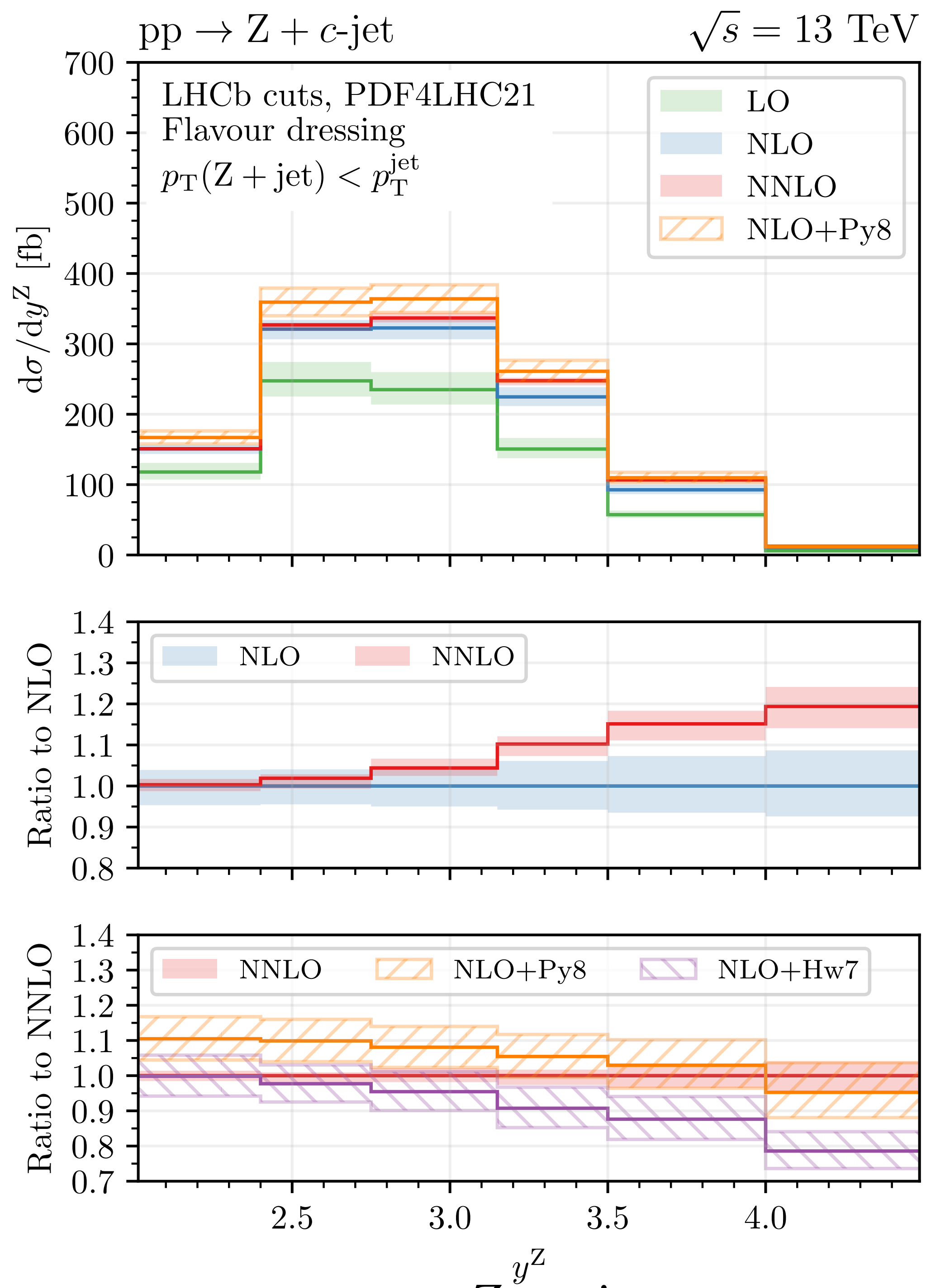
RG, Gehrmann-De Ridder, Glover, Huss, Maier, arXiv:2005.03016, RG, arXiv:2107.01226

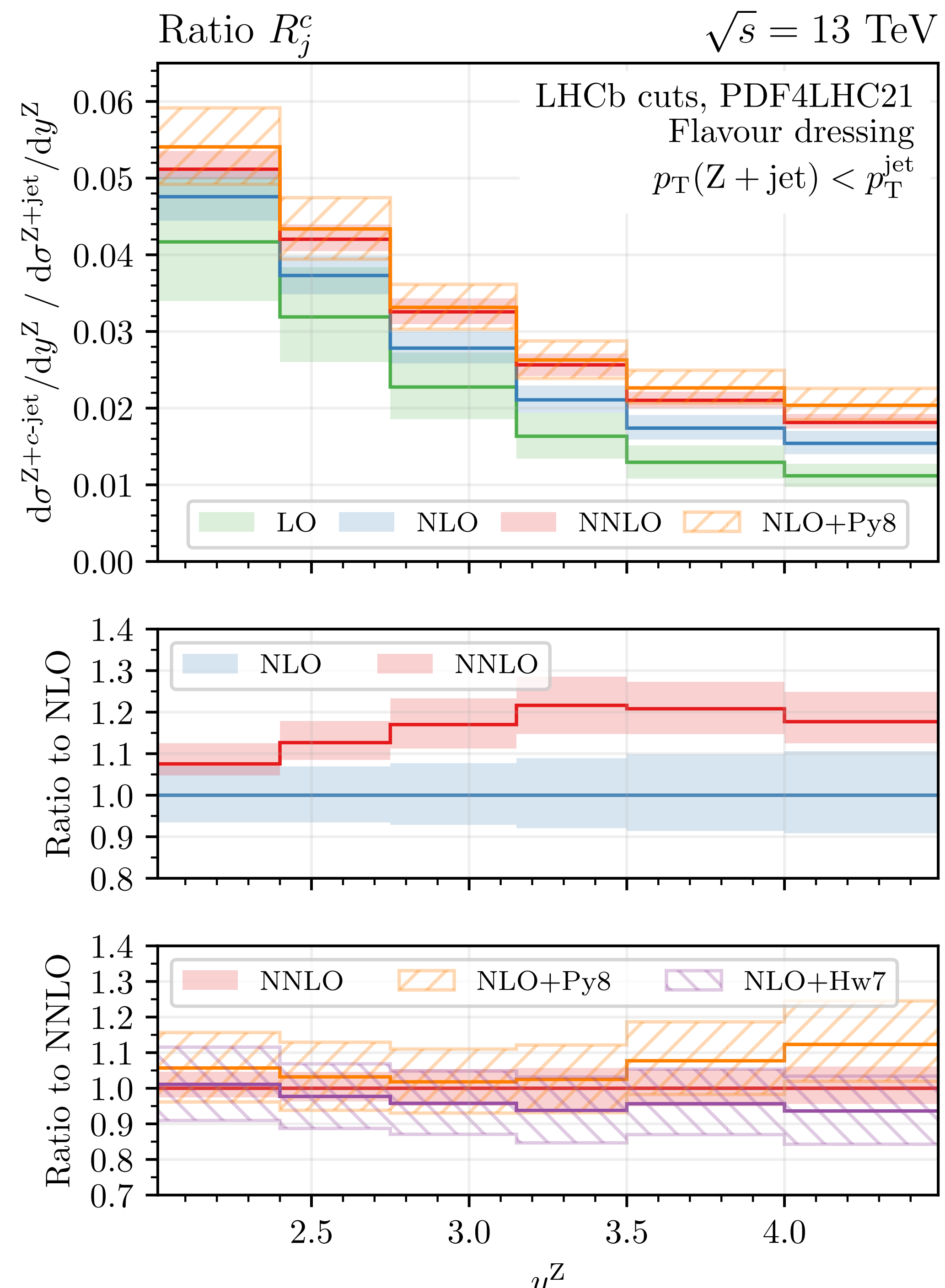
$$\mathrm{d}\sigma^{M-VFNS} = \mathrm{d}\sigma^{ZM-VFNS} + \mathrm{d}\sigma^{pc}$$

NNLO QCD predictions via the Z+jet antenna subtraction calculation
Gehrmann-De Ridder, Gehrmann, Glover, Huss, Morgan, arXiv:1507.02850

α_{G_μ} scheme, 7-point scale variation around $E_{T,Z}$, and the PDF4LHC21 set
arXiv:2203.05506

Applications: Z+c-jet at LHCb





$$\frac{d\sigma^{Z+c-jet}}{dy_Z}$$

$$\frac{d\sigma^{Z+c-jet}}{dy_Z} \Big/ \frac{d\sigma^{jet}}{dy_Z}$$

NNLO QCD corrections positive and grow with y_Z

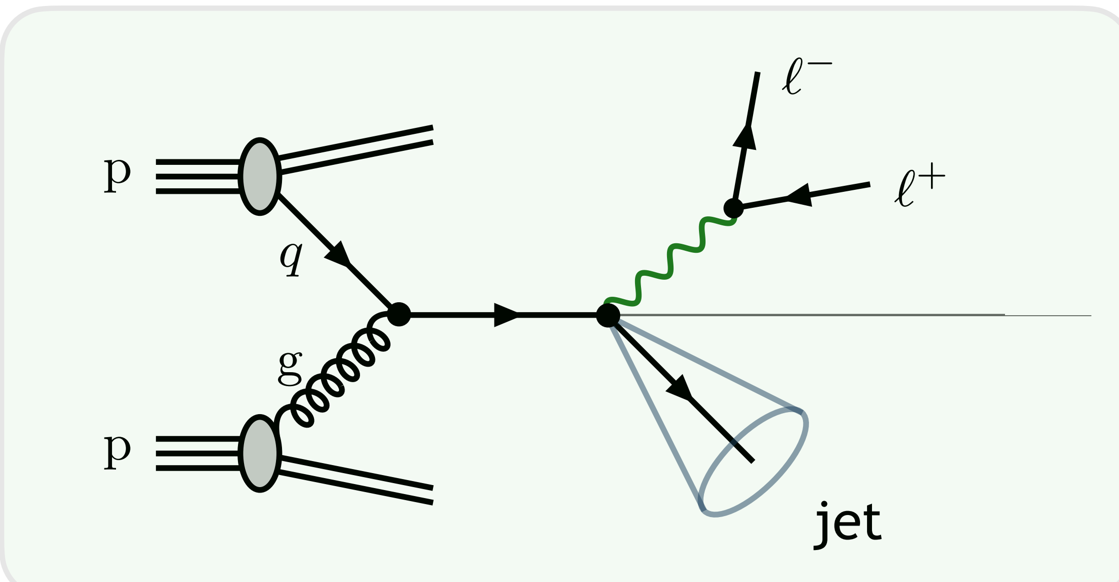
Applications: Z+c-jet at LHCb … MPI

Possibility for multiple hard interactions in a single pp-collision

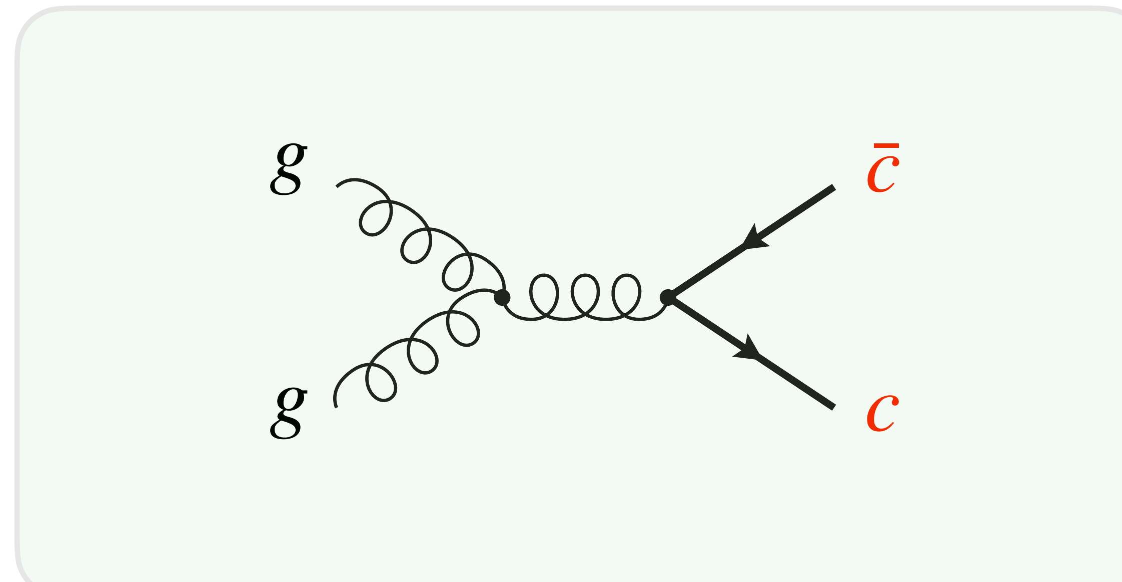
e.g. single-parton-scattering (SPS), double-parton-scattering (DPS), …

Hard Process 1 (HP1) = Z+jet

Hard Process 2 (HP2) = $c\bar{c}$



The jet is flavour inclusive



Large cross-section at LHCb

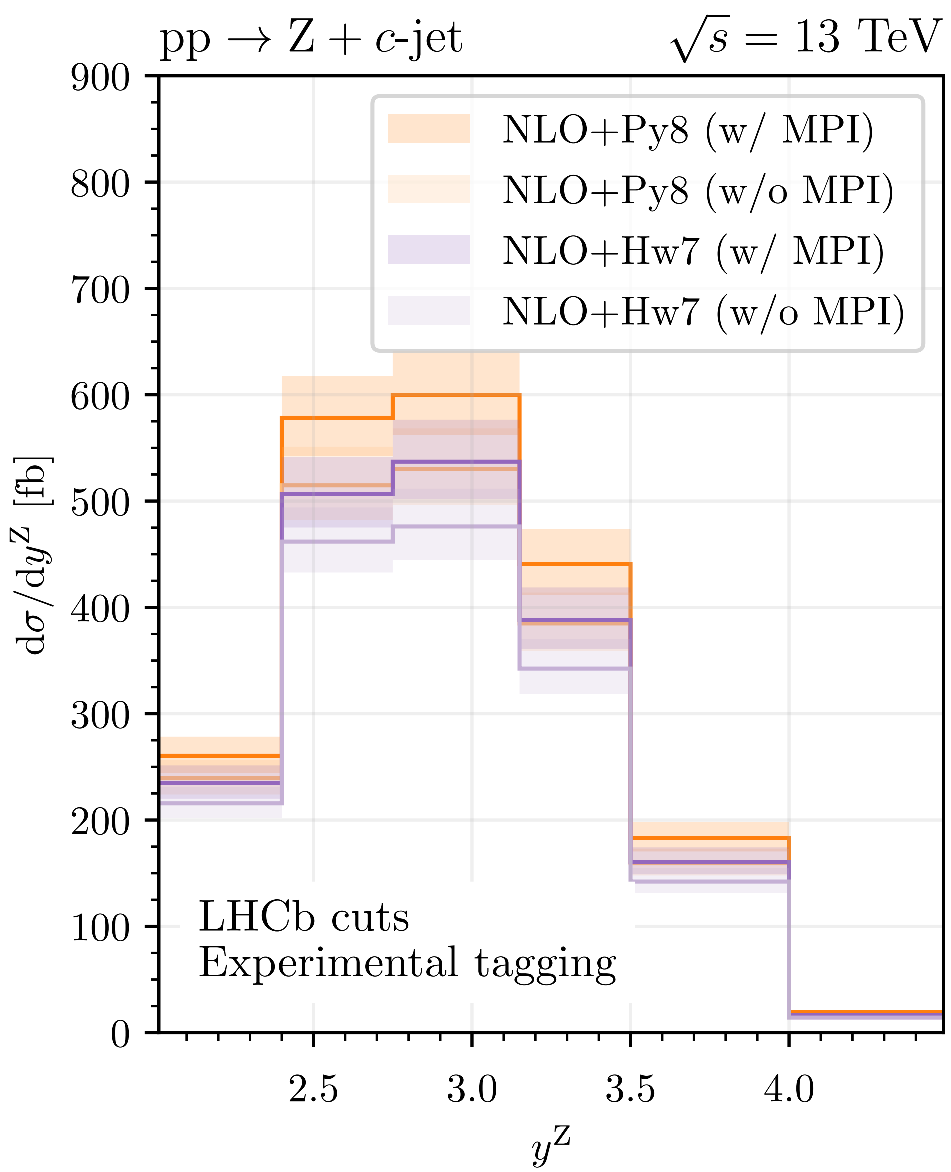
Probability that $\Delta R(j_{HP1}, c_{HP2}) \leq 0.5$ leading to a charm tagged jet

(small phase-space compensated by large $c\bar{c}$ cross-section)

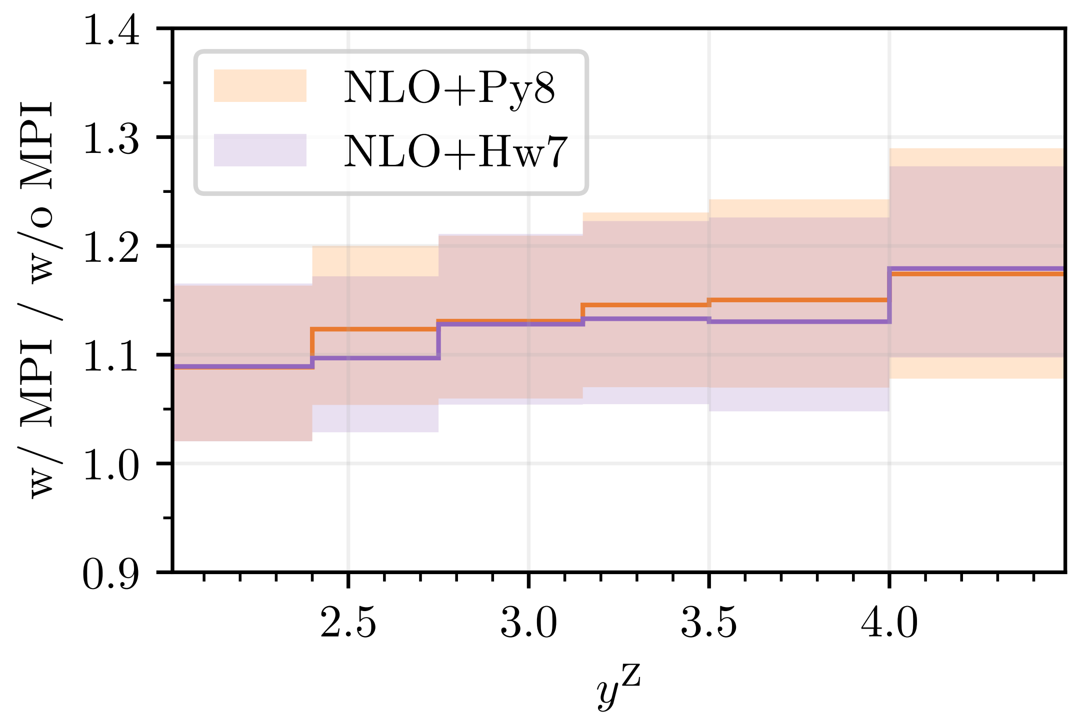
Applications: Z+c-jet at LHCb … MPI

Possibility for multiple hard interactions in a single pp-collision

e.g. single-parton-scattering (SPS), double-parton-scattering (DPS), …



Z+c-jet (MPI on / MPI off)



MPI correction required when the considered observable is sensitive to the <u>combination</u> of H1 and H2 (a genuine physics effect not described by SPS)

Summary Part (2)

i) Precise theory predictions with anti-k_T charm jets available

* NNLO QCD accurate, additionally includes finite charm mass corrections

ii) RE: Use of LHC data in collinear PDF fits

* The data should be IRC safe (necessarily to the considered fixed-order)

* The role of the discussed MPI effects in data must be accounted for

iii) MPI effects in Z+c-jet need careful attention…

* Note that the process $pp \to c\bar{c}$ has theory uncertainties in excess of 50%

* Pythia8 and Herwig MPI models this at LO with a single scale choice

* Theoretically subtracting this component will introduce substantial uncertainty

Further work still required for a careful interpretation of this data…

Closing remarks

... and why the focus on flavoured jets?

a) Higgs physics (hadronic decays)

b) Top-quark physics ($|V_{tb}| \sim 1$)

c) New physics searches (f-jet $+E_T^{\rm miss}$)

d) Gauge-boson + heavy-flavour

...

critical question: how to define f to best enable this comparison

$$d\sigma^{\rm data\,(meas.)}_{\rm PP\to f+X} \quad \text{vs} \quad d\sigma^{\rm theory}_{\rm PP\to f+X}$$

(my opinion) still a lot of exciting work head

Whiteboard

Experimental feasibility of flavoured jet algorithms

Input particles to the jet algorithm are typically particle flow objects (i.e. not unstable B/D-hadron candidates such as secondary vertices)

Heavy-flavour candidates found by reconstructing secondary vertices (with a probability of being a light, charm of beauty object)

Most of these algorithms require the jets be built knowing the flavour of input particles (which for heavy flavours is not known at particle flow level)

Could experimentally consider a new set of inputs: $\{PF\} + \{SV\} - \{\text{overlap}\}$

That would result in modified kinematics to the current anti-k_T jets (that step not necessary for flavour-dressing approach)

Additionally, systematic treatment of flavour probabilities required (different flavour paths lead to different jet kinematics for flavour-[anti-]kT)

Or just rely on an unfolding to “truth level” (where B/D-hadrons stable)

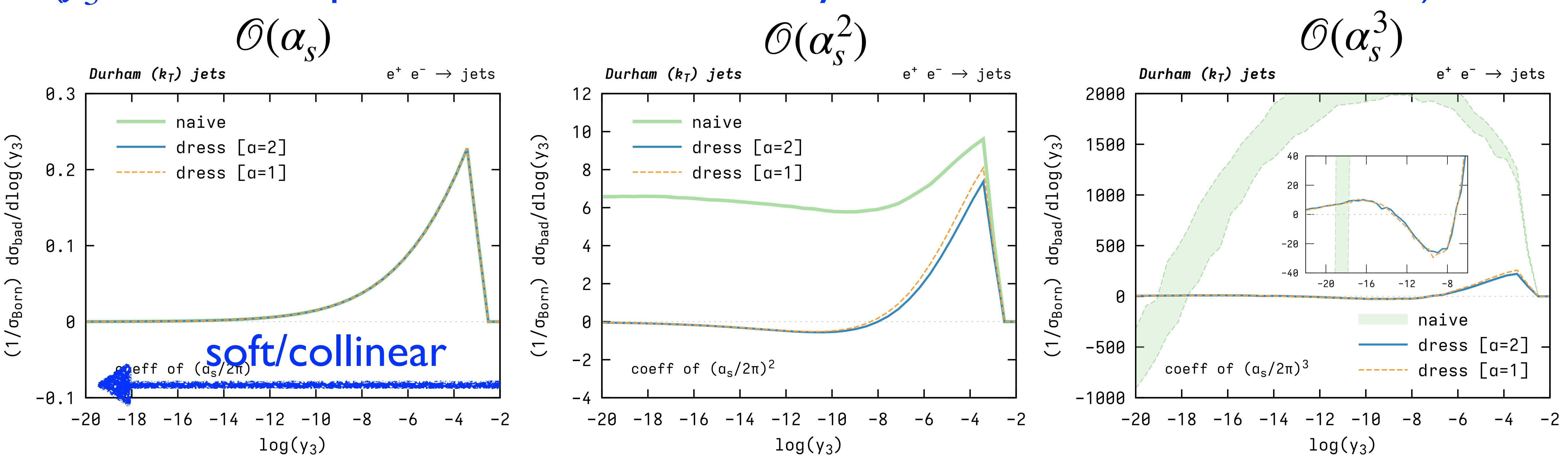
Tests of the algorithm (e^+e^-)

(**RG**, Huss, Stagnitto arXiv:2208.11138)

Consider the process $e^+e^- \to 2$ jets at fixed-order using k$_T$ algorithm

Look at 'bad' events (i.e. where we do not find 2 flavoured jets, $e^+e^- \to q\bar{q}$)

The 'bad' cross-section should vanish in the $y_3 \to 0$ limit
(y_3 defines the distance measure at which the event goes from 2 jet → 3 jet)
($y_3 \to 0$ corresponds to limit of extremely soft and/or collinear emissions)



These tests originally proposed/shown in the original flavour-k$_T$ study

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

Tests of the algorithm (pp)

(**RG**, Huss, Stagnitto arXiv:2208.11138)

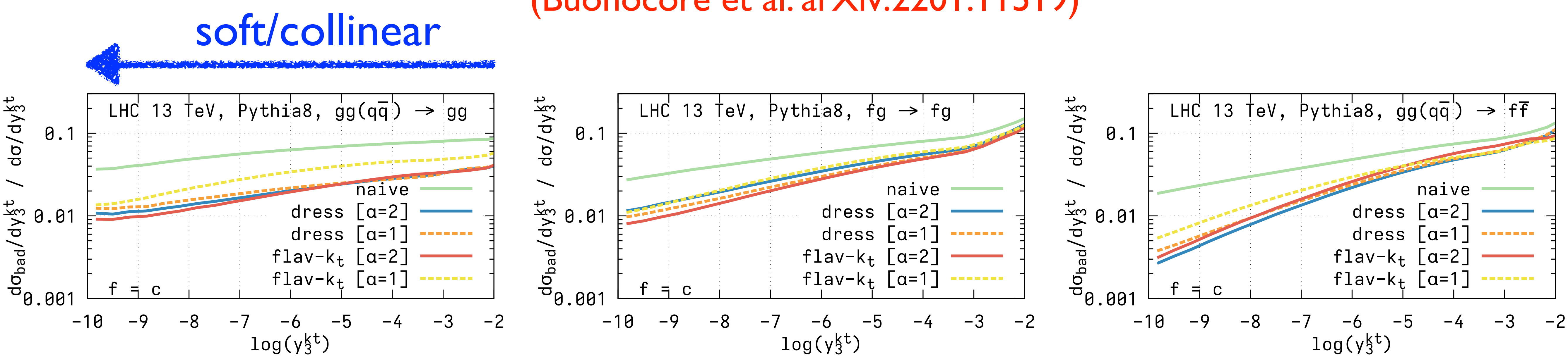
Can also perform all-order 'sensitivity' tests using Parton Shower framework

In this case study, also use resolution variable to probe IRC sensitive regions (here we study the behaviour, rather than the bad cross-section vanishing)

Here consider dijet events (exclusive k_T algorithm) with $E_T \geq 1\ \text{TeV}$

We use the resolution variable: $y_3^{\mathrm{k_T}} = d_3^{\mathrm{k_T}}/(E_{T,1} + E_{T,2})$

(Buonocore et al. arXiv:2201.11519)



These tests originally proposed/shown in the original flavour-k_T study

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

Application of the algorithm (pp)

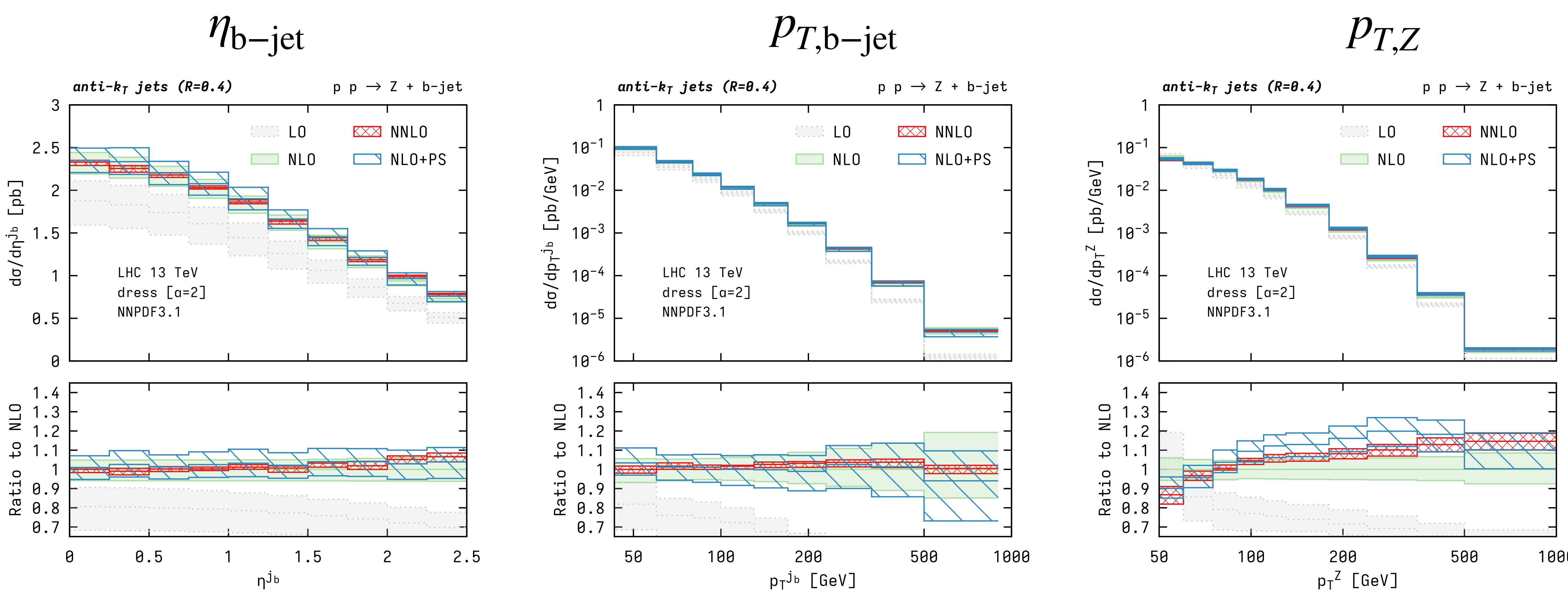
(**RG**, Huss, Stagnitto arXiv:2208.11138)

Now consider the process $pp \to Z + b - \text{jet}$ in Fiducial region (13 TeV, CMS-like)

(N)NLO at fixed-order w/ NNLOJET, **RG** et al. arXiv:2005.03016

NLO+PS Hadron-level with aMC@NLO interfaced to Pythia8

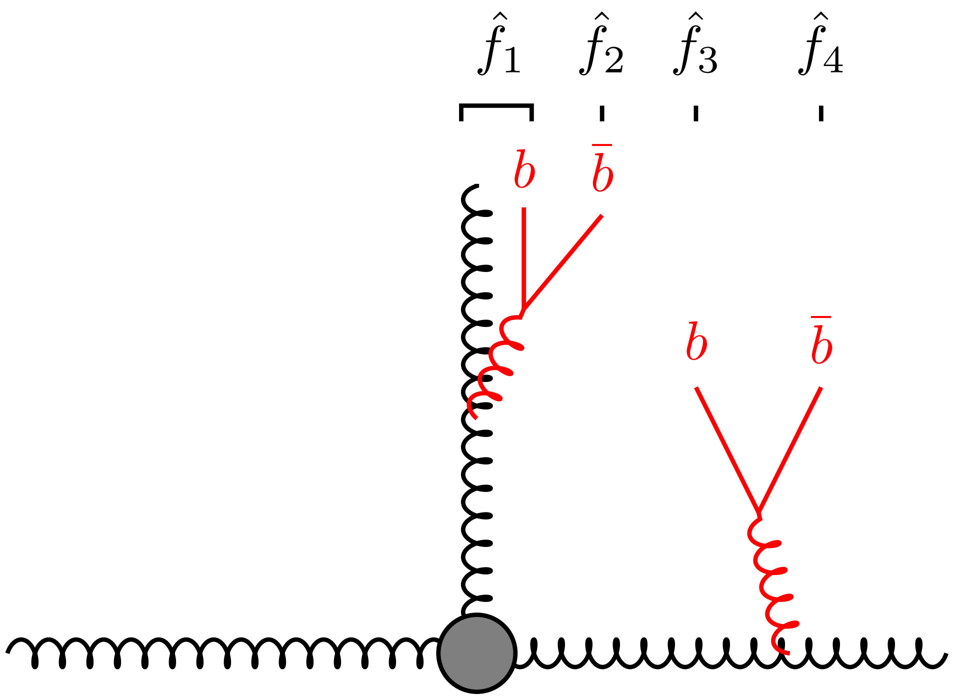
Tests sensitivity to: all-order effects, hadronisation (also FO IRC safety in pp)



Higher-order configurations / pitfalls

(Ludovic Scyboz, Moriond QCD)

Examples of pitfalls / III



Hard event:
$\rightarrow$ 1 flavourless jet

Hard+IR event:

1(b) accumulated into hard g, but not 2($\bar{b}$)

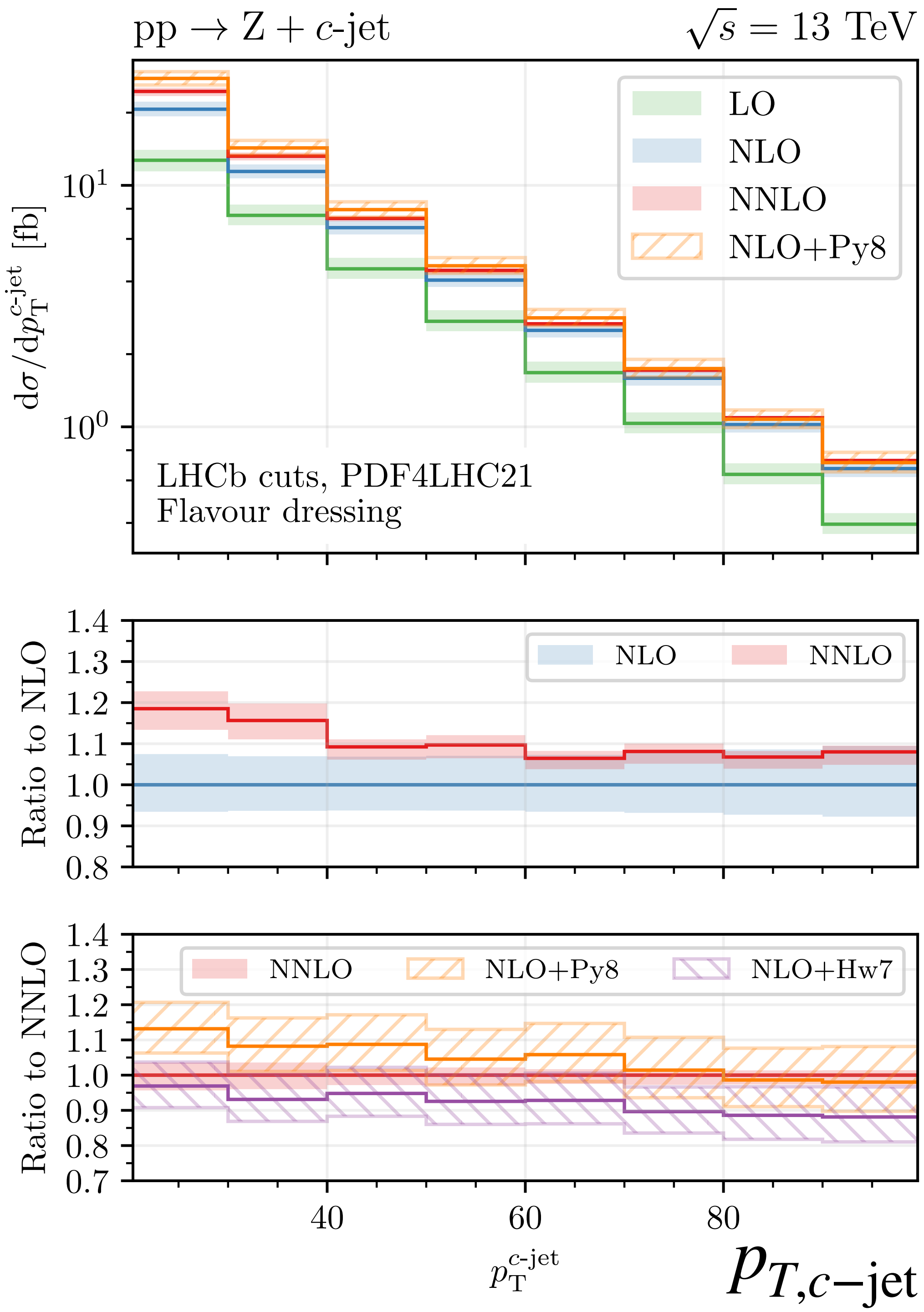
$\hat{f}_2$ and $\hat{f}_3$ annihilate, but $\hat{f}_1$ and $\hat{f}_4$ do not

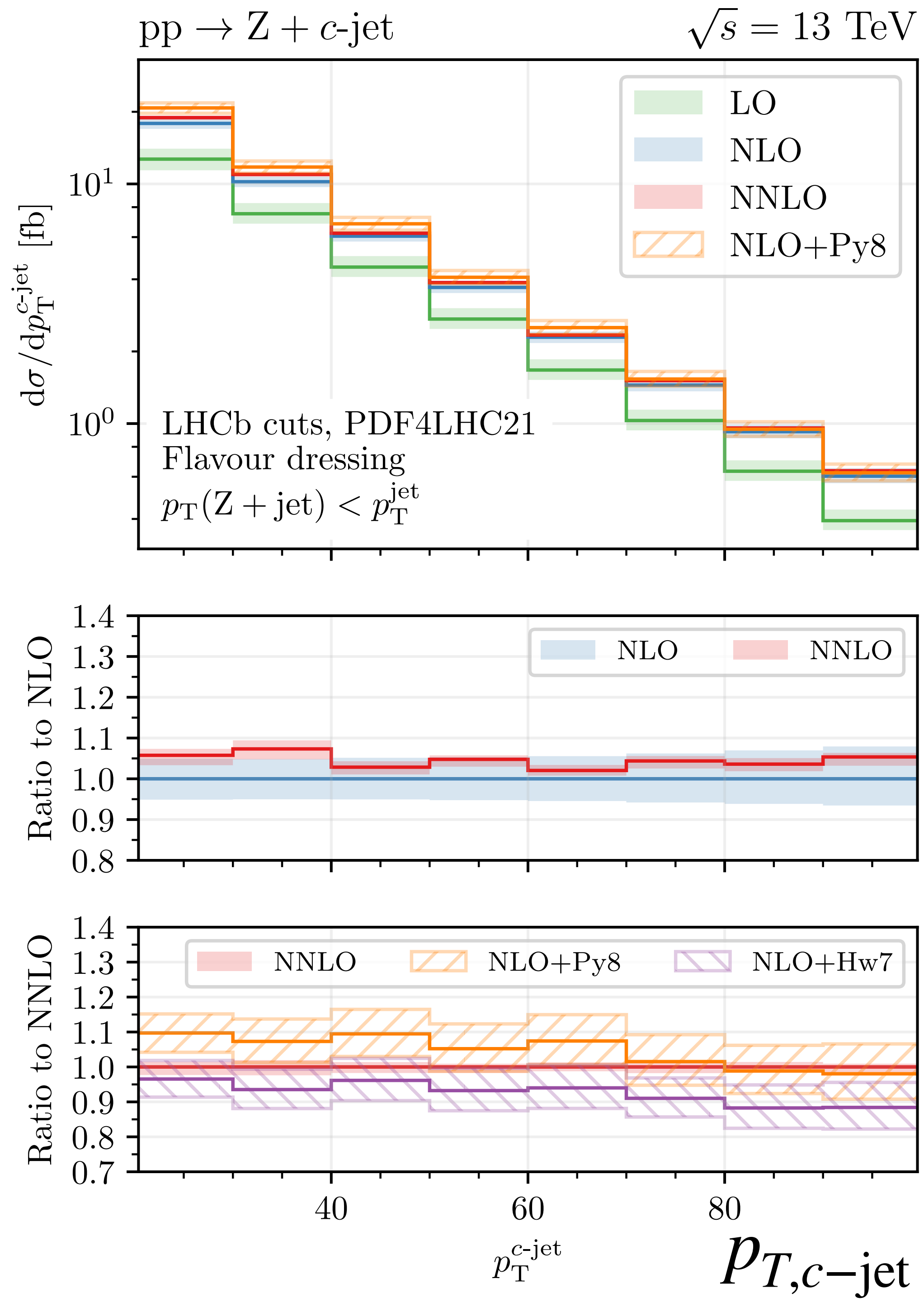
$\rightarrow$ 1 b-jet (+ 1 $\bar{b}$ beam jet)

- Some analytic/numerical understanding of the complicated interplay between distances (as a function of α and β)

  $\rightarrow$ suggests $\alpha \cdot \beta < 2$ is fine for this configuration

NNLO QCD predictions for Z+c-jet production: $p_{T,c-\text{jet}}$

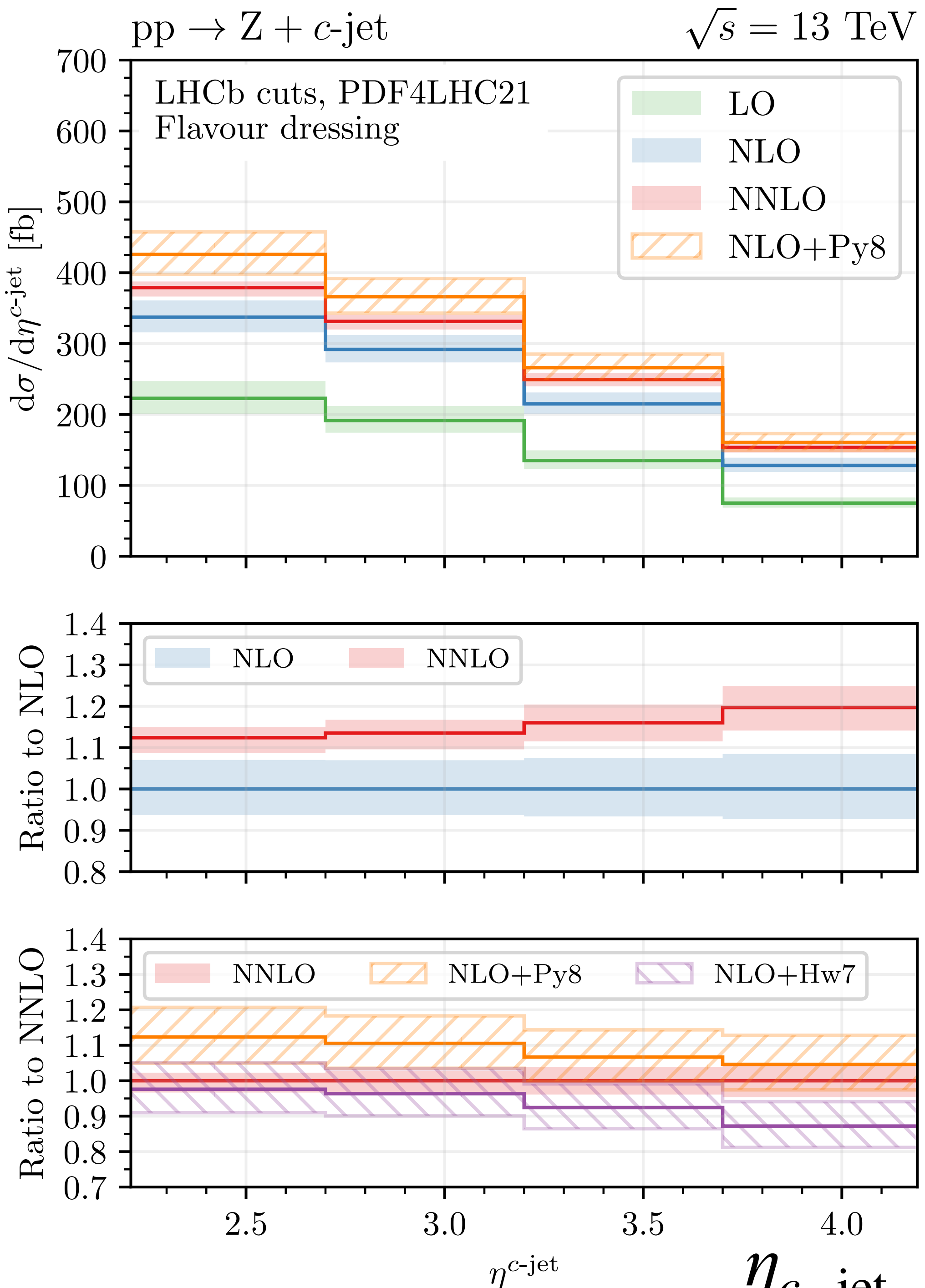


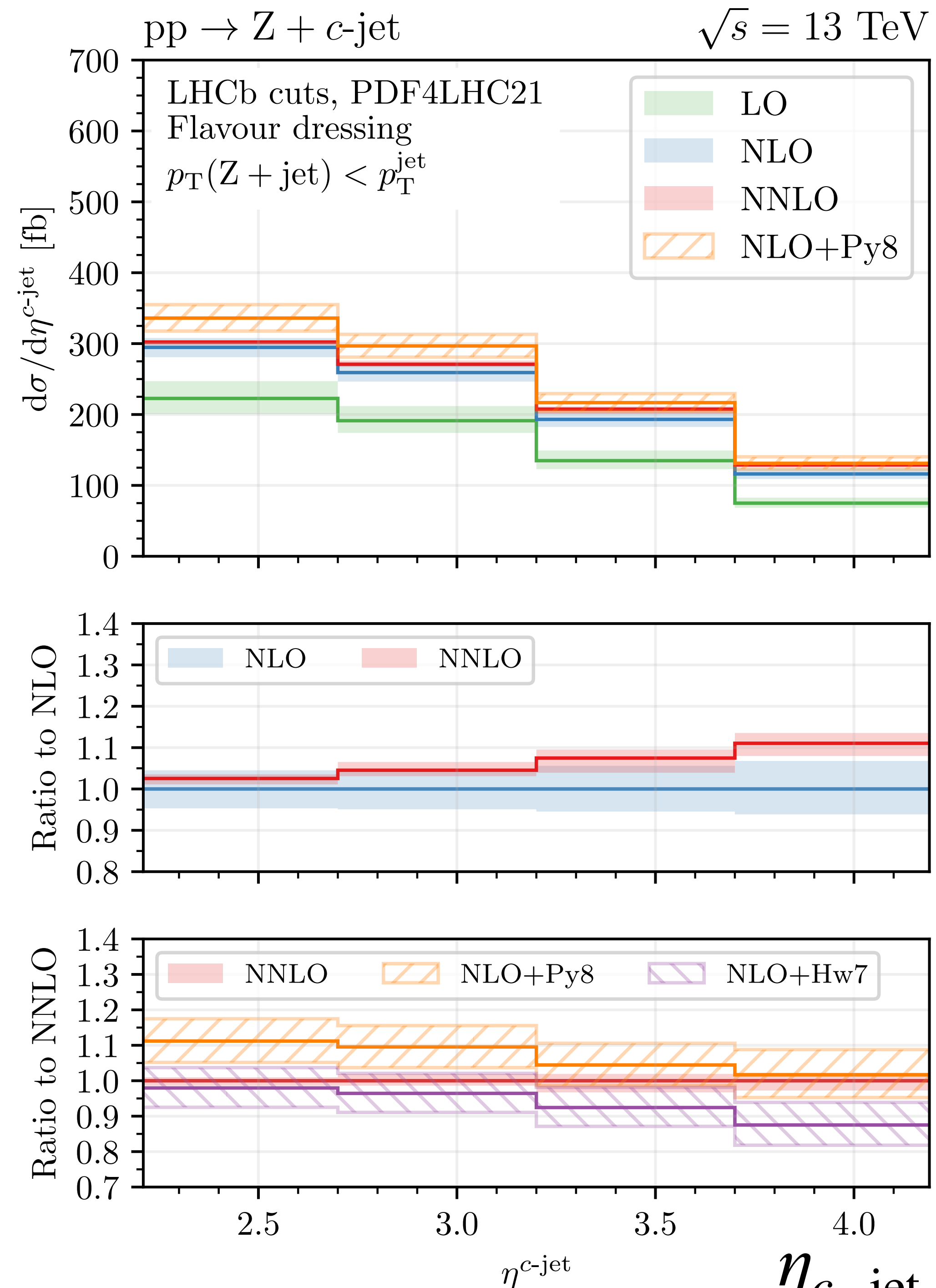


RHS includes: $p_T(Zj_c) \leq p_T(j_c)$

NNLO QCD: reduced uncertainties, and consistent with NLO+PS

NNLO QCD predictions for $\eta_{c-\mathrm{jet}}$



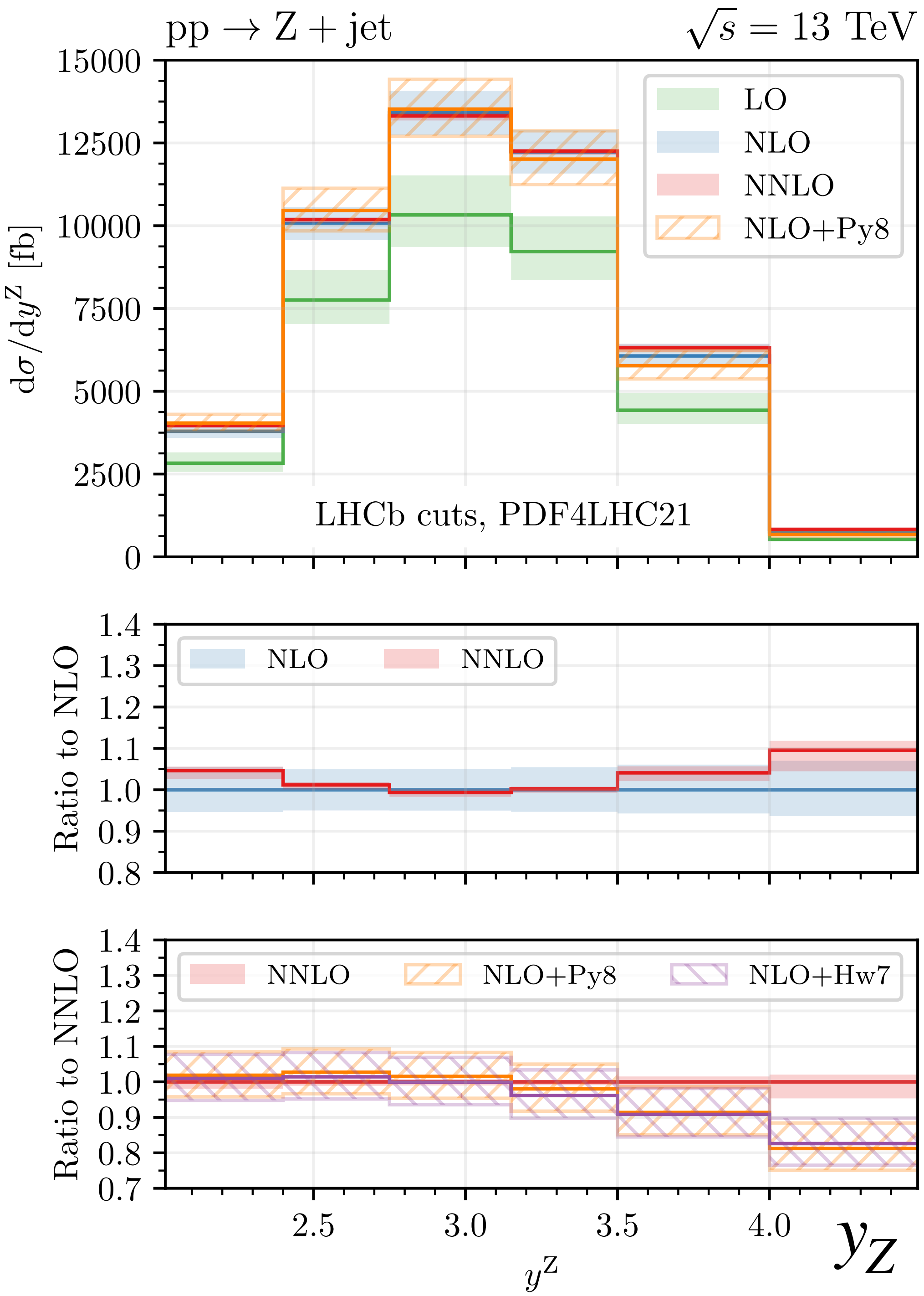


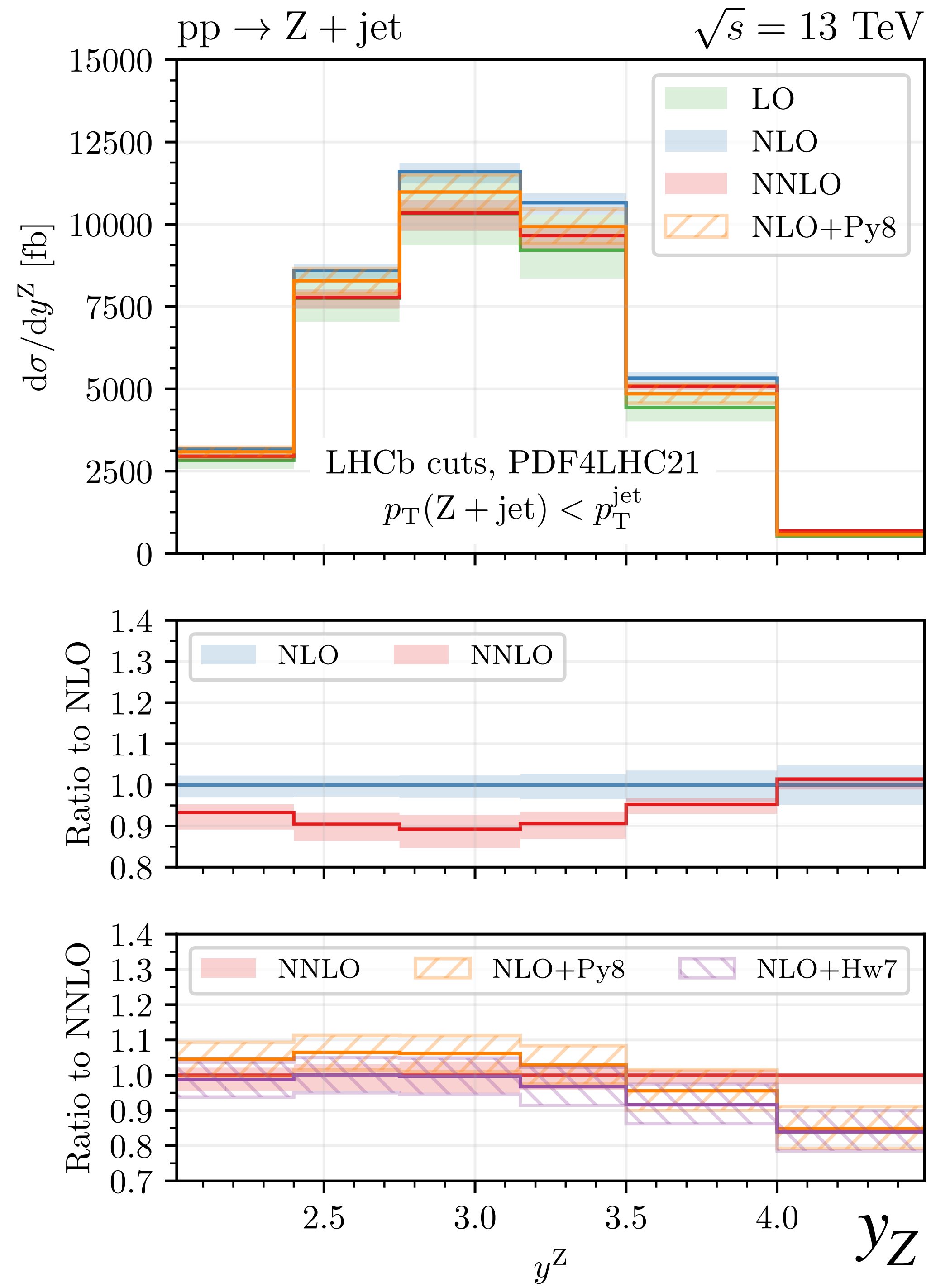
$\eta_{c-\mathrm{jet}}$ $\eta_{c-\mathrm{jet}}$

RHS includes: $p_T(Zj_c) \leq p_T(j_c)$

…

NNLO QCD predictions for flavour inclusive process

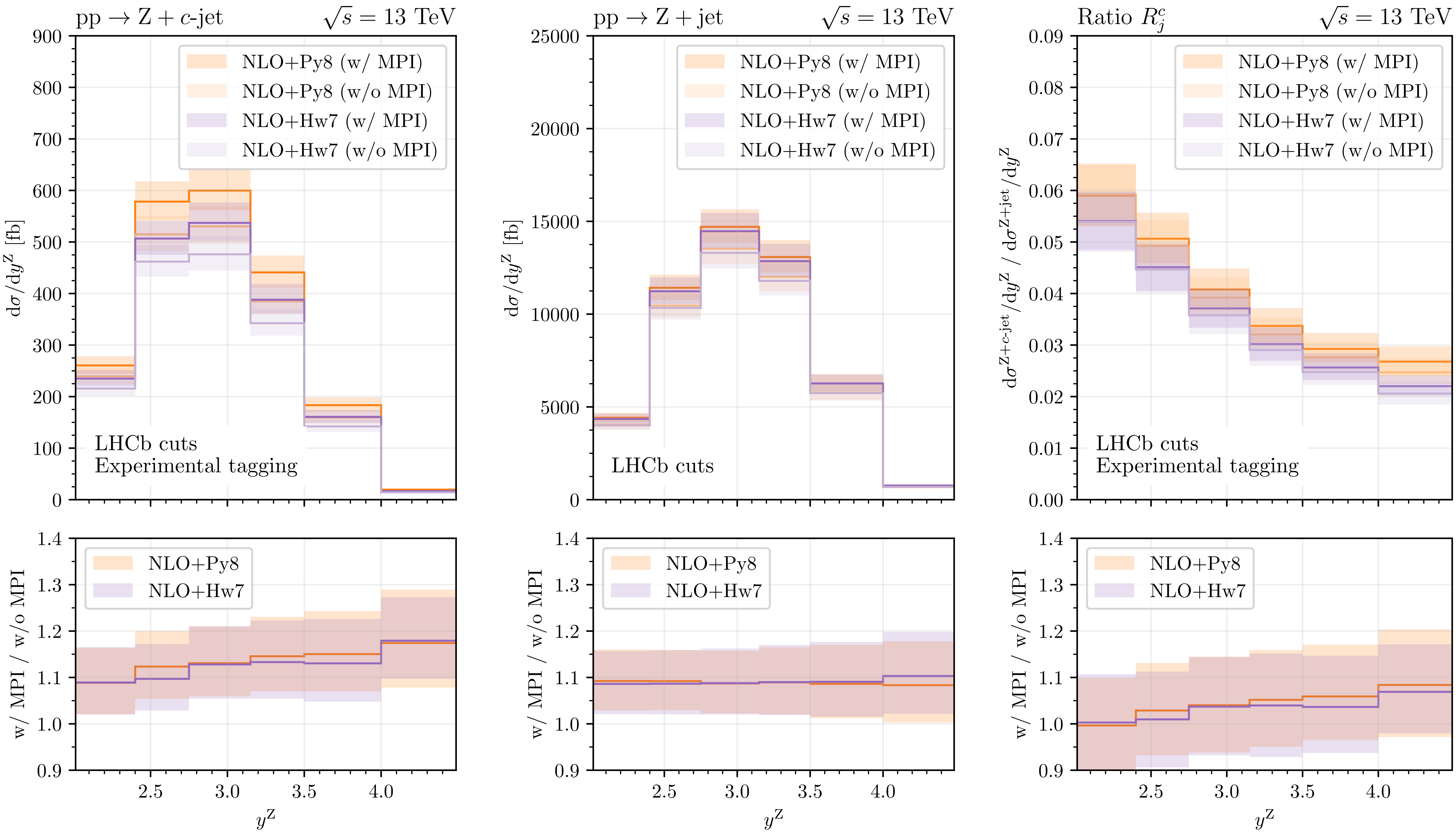




RHS includes: $p_T(Zj_c) \leq p_T(j_c)$

…

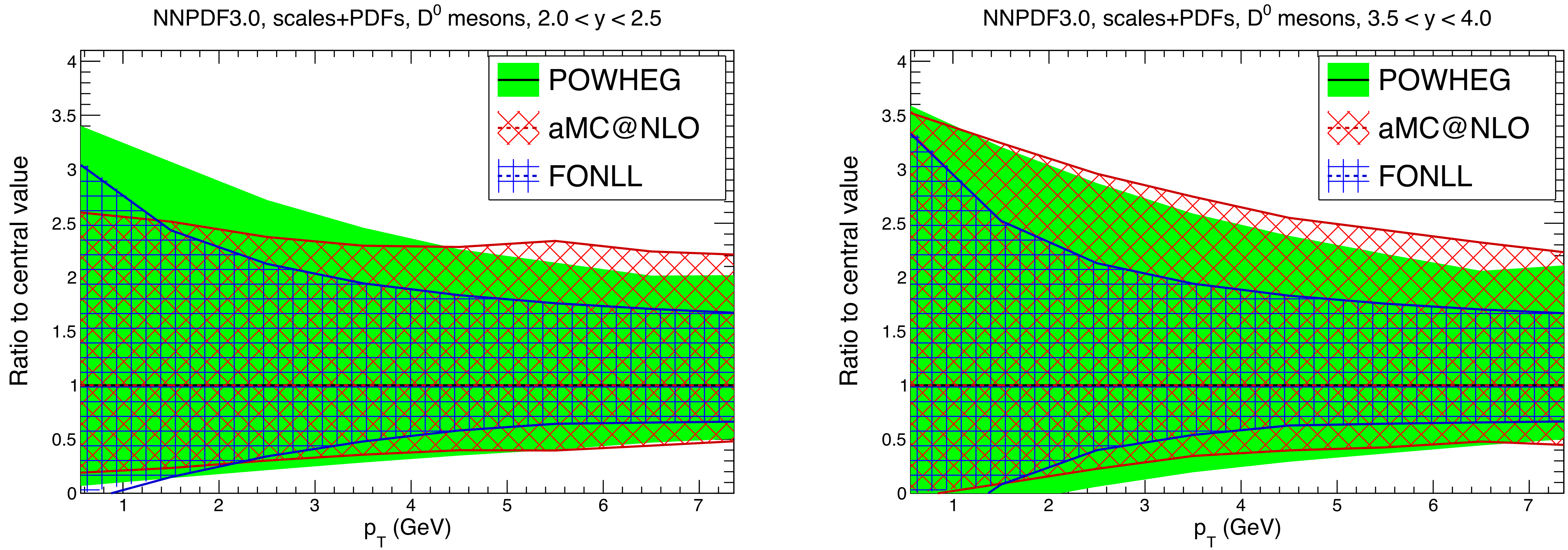
MPI effects



Z+c-jet　　Z+jet　　Ratio

Heavy-quark pair production

(RG et al., arXiv:1506.08025)



These are the theory uncertainties (PDF+scales) for D-cross section at LHCb

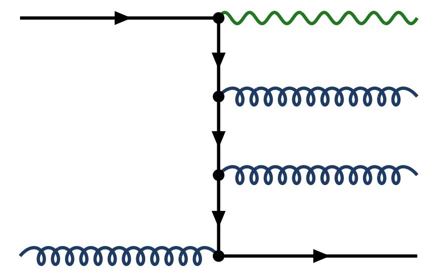
With a requirement of $P_{T,c} > 5$ GeV QCD uncertainties >> 50% (at best)

The charm MPI component generates a ~15% contribution to LHCb Z+c-jet σ

Extracting the SPS component will lead to increased uncertainties (>>7.5%)

Ingredients of an NNLO computation

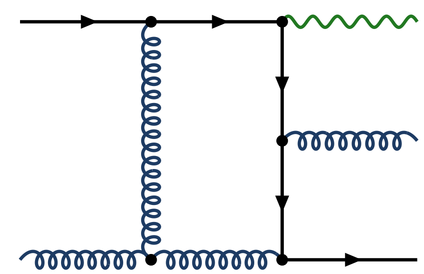
$$\sigma_{\rm NNLO} = \int_{\phi_{n+2}} {\rm d}\sigma^{RR}_{\rm NNLO}$$



Single unresolved

Double unresolved

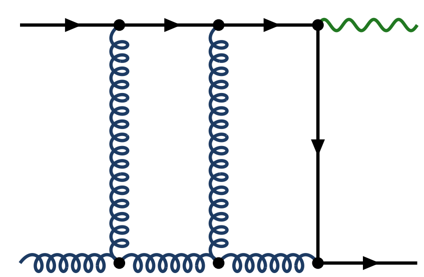
$$+ \int_{\phi_{n+1}} {\rm d}\sigma^{RV}_{\rm NNLO}$$



Single unresolved

$1/\epsilon,\ 1/\epsilon^2$

$$+ \int_{\phi_{n+0}} {\rm d}\sigma^{VV}_{\rm NNLO}$$



$1/\epsilon,\ 1/\epsilon^2,\ 1/\epsilon^3,\ 1/\epsilon^4$

$$\sum = {\rm Finite}$$

Non-trivial cancellation of IR divergences

Ingredients of an NNLO computation

$$\sigma_{\mathrm{NNLO}} = \int_{\phi_{n+2}} \left(\mathrm{d}\sigma^{RR}_{\mathrm{NNLO}} - \mathrm{d}\sigma^{S}_{\mathrm{NNLO}}\right)$$

$$+ \int_{\phi_{n+1}} \left(\mathrm{d}\sigma^{RV}_{\mathrm{NNLO}} - \mathrm{d}\sigma^{T}_{\mathrm{NNLO}}\right)$$

$$+ \int_{\phi_{n+0}} \left(\mathrm{d}\sigma^{VV}_{\mathrm{NNLO}} - \mathrm{d}\sigma^{U}_{\mathrm{NNLO}}\right)$$

mimic unresolved

explicit pole cancellation

$$\sum = \mathrm{Finite} - 0$$

Each line individually finite, can be integrated in 4-d

Ingredients of an NNLO computation (Antenna)

Gehrmann De-Ridder, Gehrmann, Glover '05

Primary challenge: dealing with flavour (see RG et al., arXiv:1907.05836)

$$\mathrm{d}\hat{\sigma}_{ij,\mathrm{NLO}} = \int_{n+1} \left[\mathrm{d}\hat{\sigma}^{R}_{ij,\mathrm{NLO}} - \mathrm{d}\hat{\sigma}^{S}_{ij,\mathrm{NLO}}\right] + \int_{n} \left[\mathrm{d}\hat{\sigma}^{V}_{ij,\mathrm{NLO}} - \mathrm{d}\hat{\sigma}^{T}_{ij,\mathrm{NLO}}\right], \tag{2.1}$$

Jet function acts on flavour and momenta of reduced MEs. In general (i, j, k) → (I, K) (flavour, momentum)

$$\mathrm{d}\hat{\sigma}^{R}_{ij,\mathrm{NLO}} = \mathcal{N}^{R}_{\mathrm{NLO}}\, \mathrm{d}\Phi_{n+1}\left(\{p_3,\ldots,p_{n+3}\};p_1,p_2\right) \frac{1}{S_{n+1}} \times \left[M^0_{n+3}\left(\{p_{n+3}\},\{f_{n+3}\}\right)\; J^{(n+1)}_{n}(\{p_{n+1}\},\{f_{n+1}\})\right]. \tag{2.2}$$

The ~ functions denoted mapped (in soft/collinear limits) momenta/flavour sets

$$\mathrm{d}\hat{\sigma}^{S}_{ij,\mathrm{NLO}} = \mathcal{N}^{R}_{\mathrm{NLO}} \sum_k \mathrm{d}\Phi_{n+1}\left(\{p_3,\ldots,p_{n+3}\};p_1,p_2\right) \frac{1}{S_{n+1}} \times \left[X^0_3(\cdot,k,\cdot)\; M^0_{n+2}\left(\{\tilde{p}_{n+2}\},\{\tilde{f}_{n+2}\}\right)\; J^{(n)}_{n}\left(\{\tilde{p}_{n}\},\{\tilde{f}_{n}\}\right)\right], \tag{2.3}$$

Massive - Variable Flavour Number Scheme

$$\mathrm{d}\sigma^{M-VFNS} = \mathrm{d}\sigma^{m=0} + \left(\mathrm{d}\sigma^{m} - \mathrm{d}\sigma^{m\to 0}\right)$$

Form of massive computation for IRC safe or QCD inclusive observables

RG, arXiv:2107.01226

$$\mathrm{d}\sigma^{m} = \mathrm{d}\sigma^{m=0,n_f} + \mathrm{d}\sigma^{L[m]} + \mathrm{d}\sigma^{\mathcal{O}(m^2)}$$

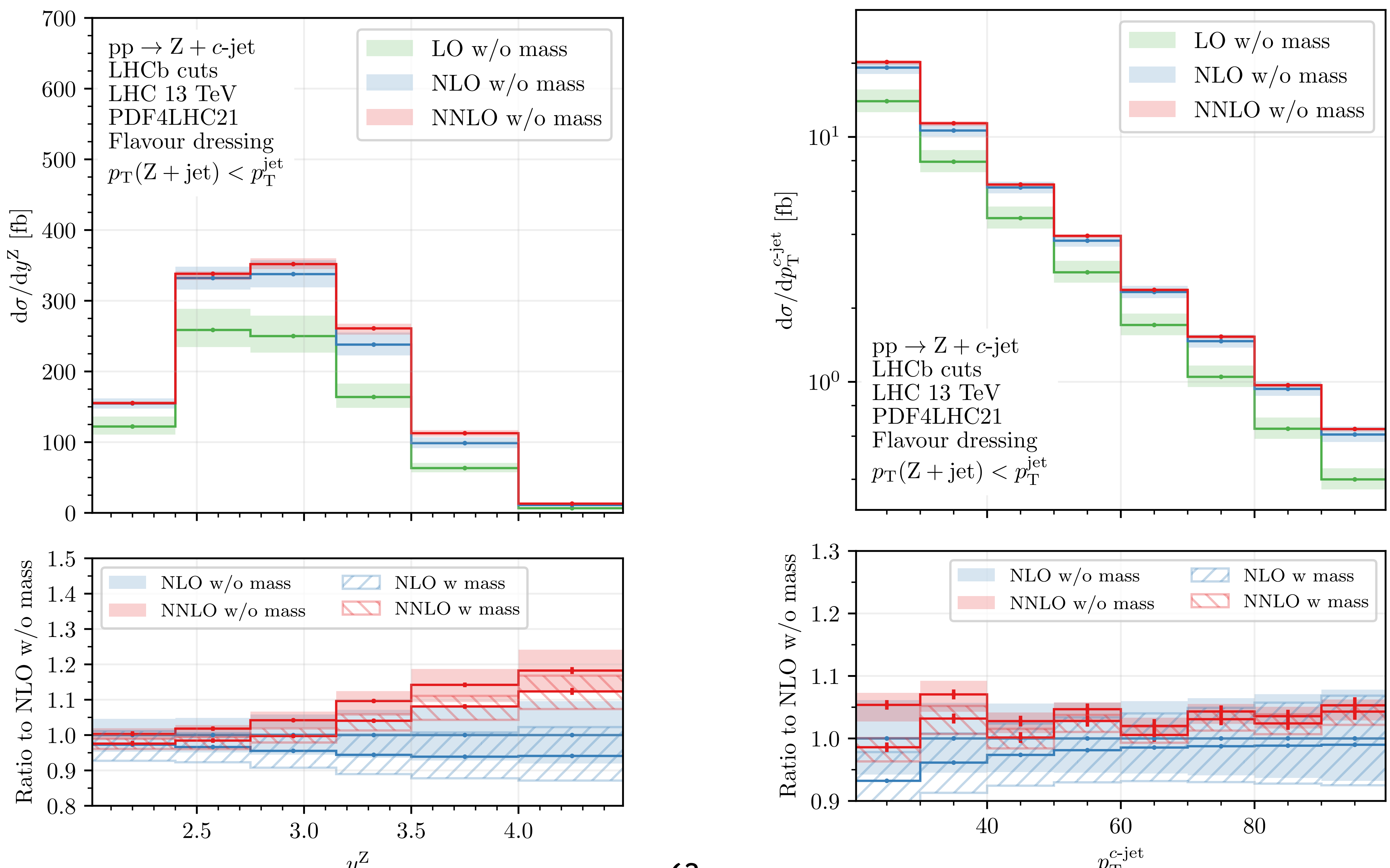
These terms can be directly calculated

(so the last term can be numerically extracted)

$$\mathrm{d}\sigma^{M-VFNS} = \mathrm{d}\sigma^{m=0} + \mathrm{d}\sigma^{\mathcal{O}(m^2)}$$

Massive - Variable Flavour Number Scheme

$$\mathrm{d}\sigma^{M-VFNS} = \mathrm{d}\sigma^{m=0} + \left(\mathrm{d}\sigma^{m} - \mathrm{d}\sigma^{m\to 0}\right)$$



Z+b-jet and unfolding

How to account for theory-experiment mismatch?

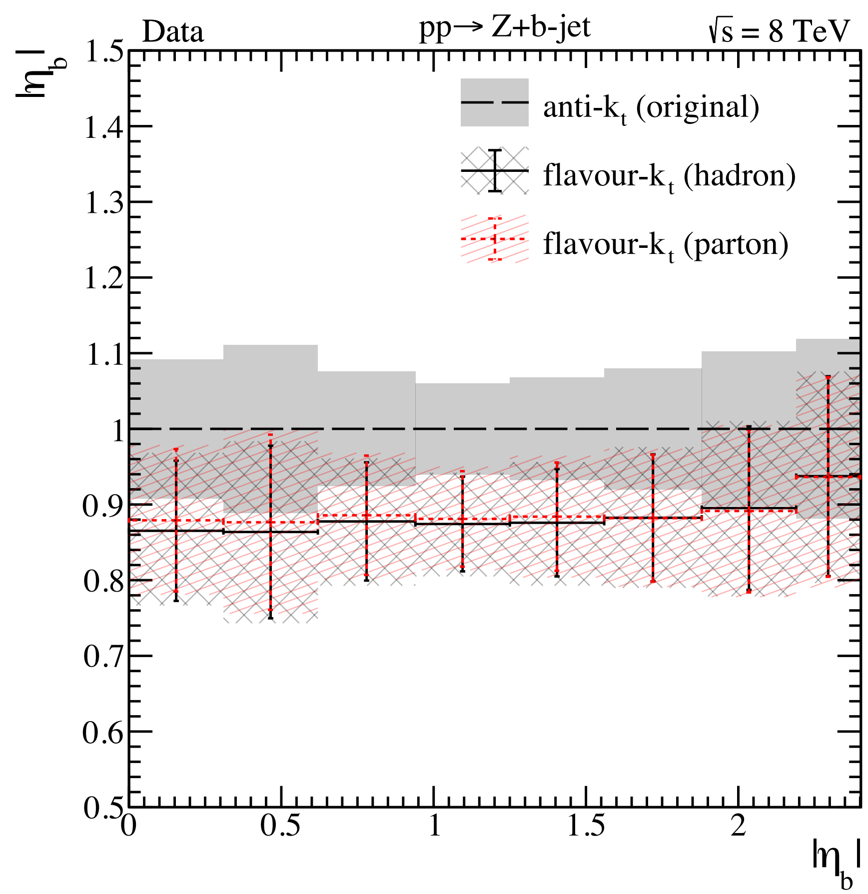
[Gauld, Gehrmann-De Ridder, Glover, Huss, Majer] *PRL* 125 (2020) 22, 222002

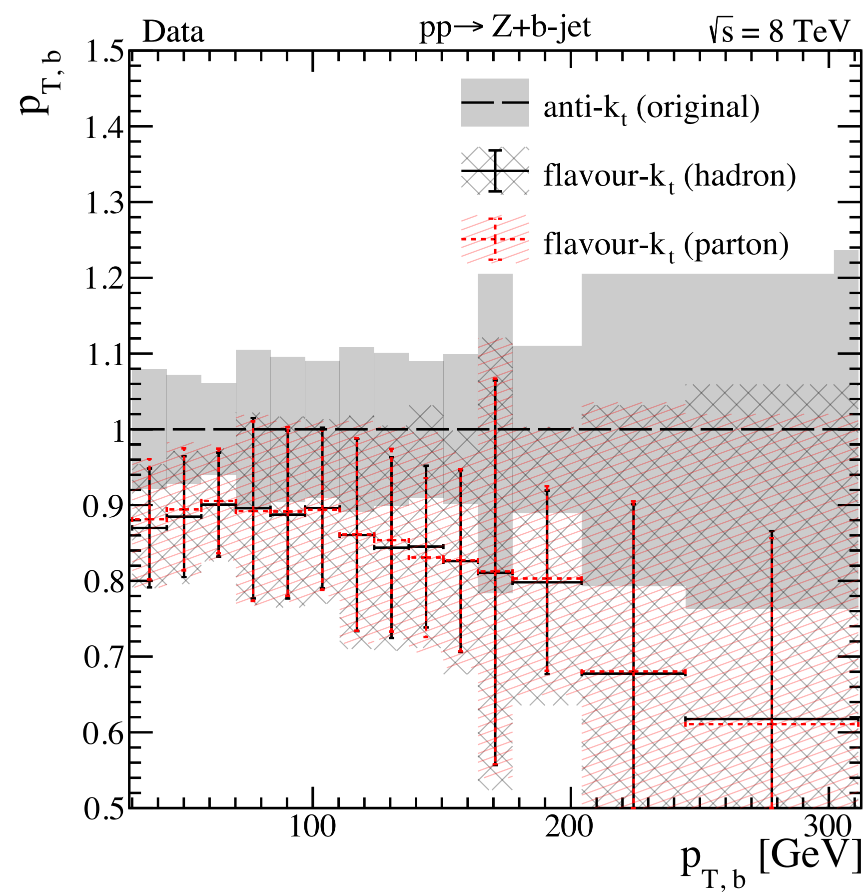
Use an NLO + Parton Shower prediction (which can evaluate both)

1) Prediction at parton-level, flavour-k_T algorithm **(Theory)**

2) Prediction at hadron-level, anti-k_T algorithm **(Experiment)**

Calculate an "Unfolding" correction from 2) Experiment → 1) Theory





We use RooUnfold (following the procedure used in the exp. analyses)

f-jets @ NNLO as of 2021

$$\mathrm{d}\hat{\sigma}_{ij\to\hat{X}} = \mathrm{d}\hat{\sigma}^{\mathrm{LO}}_{ij\to\hat{X}} + \alpha_s\,\mathrm{d}\hat{\sigma}^{\mathrm{NLO}}_{ij\to\hat{X}} + \alpha_s^2\,\mathrm{d}\hat{\sigma}^{\mathrm{NNLO}}_{ij\to\hat{X}} + \ldots$$

$V + (H \to b\bar{b})$ — Ferrera et al. (1705.10304), Caola et al. (1712.06974), Gauld et al. (1907.05836)

$Z + \mathrm{b-jet}$ — Gauld et al. (2005.03016)

$W^{\pm} + \mathrm{c-jet}$ — Czakon et al. (2011.01011)

$t\bar{t}$ with PFF [B-hadrons] — Czakon et al. (2102.08267)

flavoured-jet algorithm applied

anti-k$_T$ algorithm applied (regulated by m_b , a tech. cut, or 'prescription')

$t\bar{t}$ with decay — Behring et al. (1901.05407), Czakon et al. (2008.11133)

$t, \bar{t}$ (t-chan with decay) — Berger et al. (1606.08463,1708.09405), Campbell et al. (2012.01574)

$V + (H \to b\bar{b})$ [4fs] — Behring et al. (2003.08321)