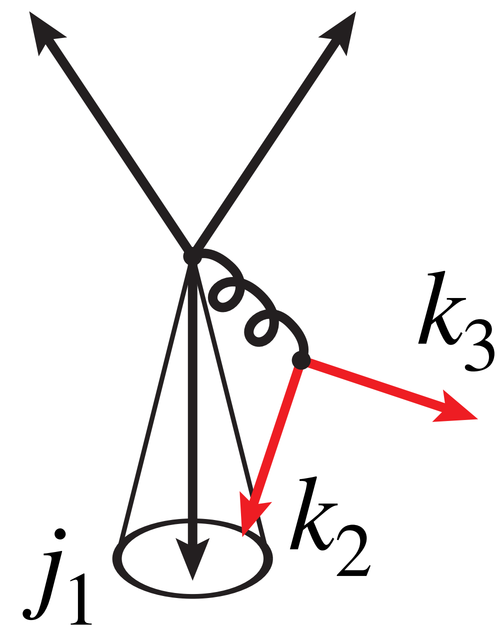


Flavour Identification of Reconstructed Hadronic Jets

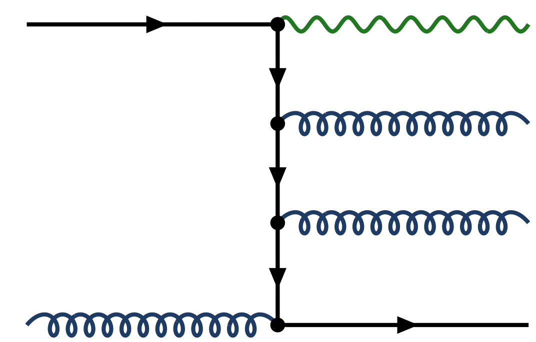
RG, Alexander Huss, Giovanni Stagnitto, PRL 130 (2023) 16

Rhorry Gauld

RADCOR 2023 (30/05/23)

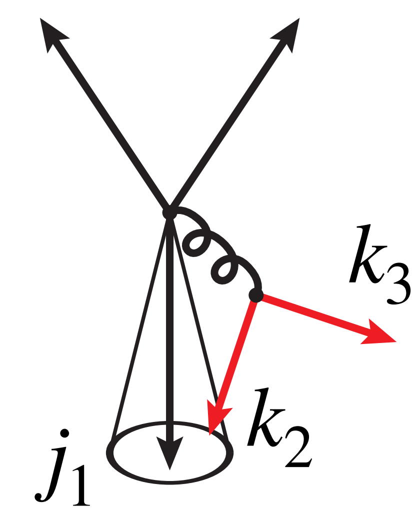
MAX-PLANCK-INSTITUT FÜR PHYSIK

1) General introduction



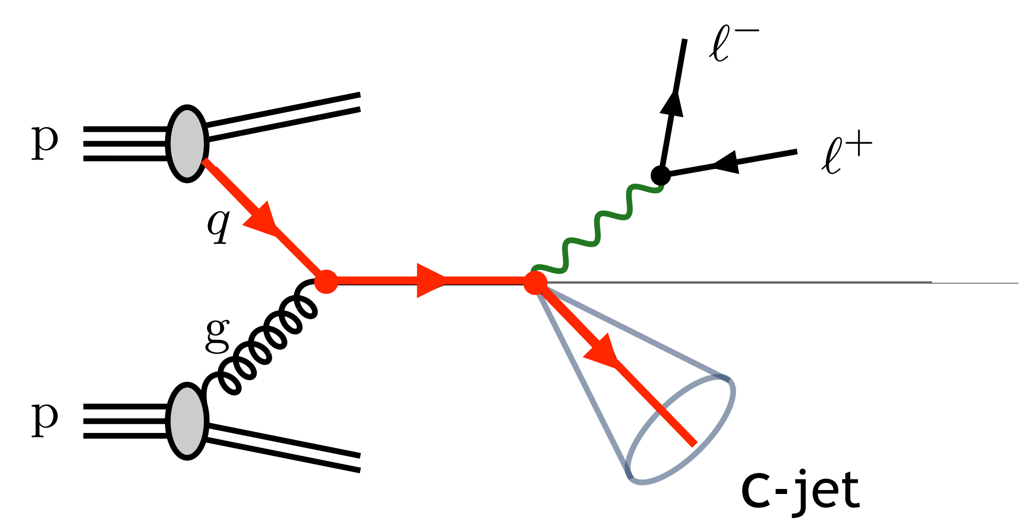
- Final state jets
- Related progress in fixed-order calculations

2) The challenges of jet flavour



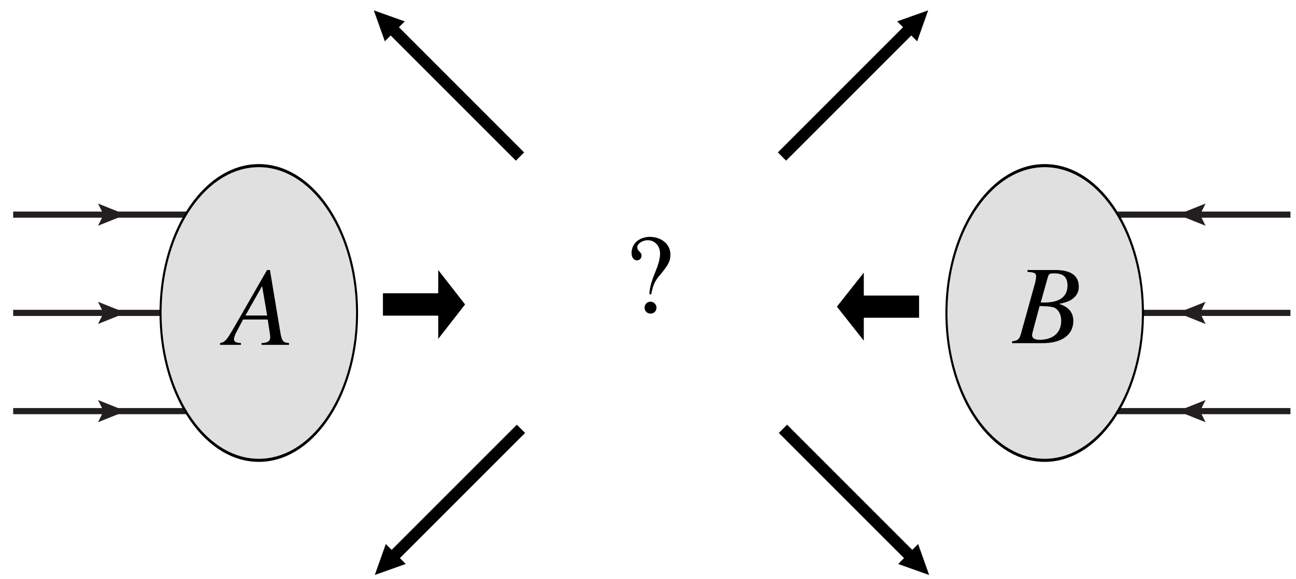
- The problem(s)
- Summary of recent solution(s)

3) The flavour dressing algorithm



- Motivation and context
- Some pheno. results (Z+c-jet)

Generic scattering processes



$$AB \to f + X$$

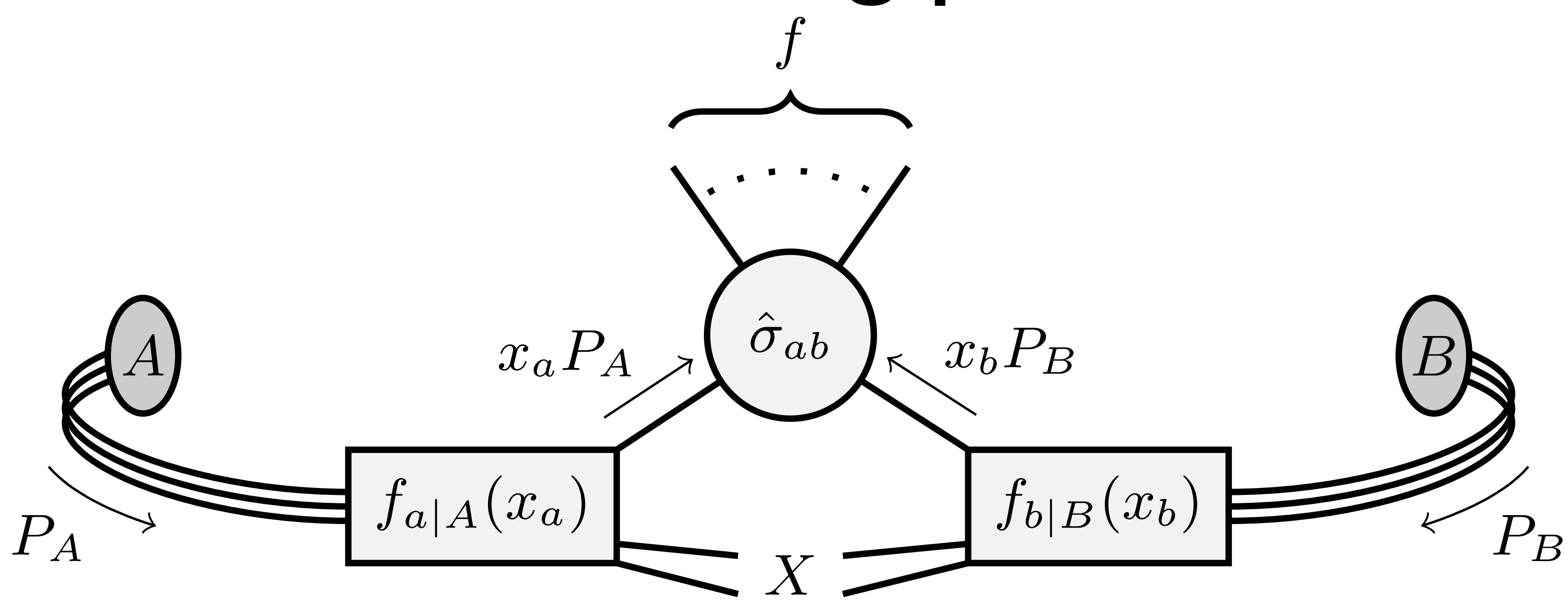
f composed of :

- leptons
- hadrons
- photons
- missing E_T
- jet(s)
- …

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

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

LHC scattering processes



$$\mathrm{d}\sigma_{pp\to f+X} = \sum_{i,j} \int \mathrm{dx}_1 \mathrm{dx}_2\, f_a(x_1)\, f_b(x_2)\, \boxed{\mathrm{d}\hat{\sigma}_{ab\to f+\hat{X}}(\hat{s},\ldots)}\, \Big(1 + \mathcal{O}(\Lambda_{QCD}/Q)\Big)$$

$$\boxed{\mathrm{d}\hat{\sigma}_{ab\to f+..} = \mathrm{d}\hat{\sigma}^{\mathrm{LO}}_{ab\to f+..} + \alpha_s\, \mathrm{d}\hat{\sigma}^{\mathrm{NLO}}_{ab\to f+..} + \alpha_s^2\, \mathrm{d}\hat{\sigma}^{\mathrm{NNLO}}_{ab\to f+..} + \ldots}$$

- (renormalised) amplitudes
- subtracting/slicing
- application of <u>jet algorithm</u>

…

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

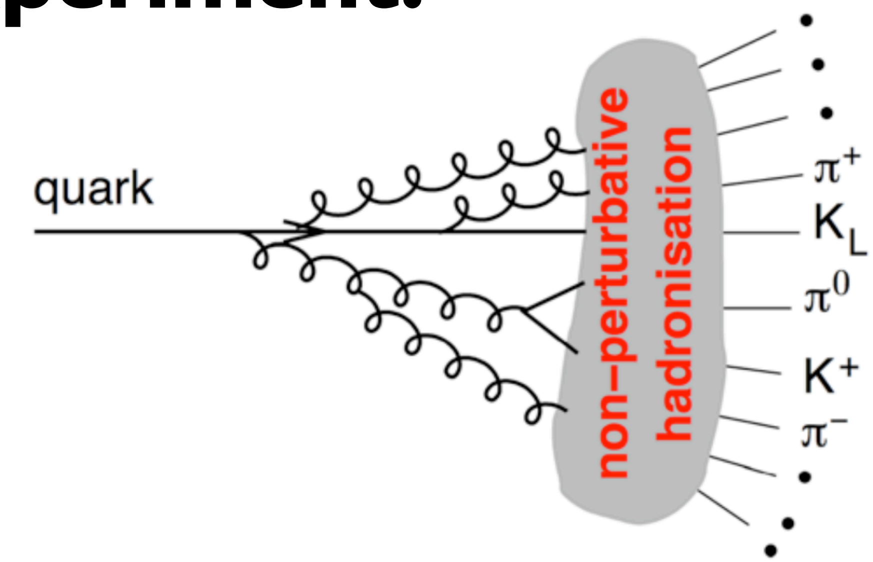
$$\mathrm{d}\sigma^{\mathrm{data\,(meas.)}}_{\mathrm{PP}\to\mathrm{f}+\mathrm{X}} \quad \text{vs} \quad \mathrm{d}\sigma^{\mathrm{fixed-order}}_{\mathrm{PP}\to\mathrm{f}+\mathrm{X}}$$

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)

Final state jets

Experiment:



particle flow objects

jet algorithm $\longrightarrow$ set of hadronic jets $\{j_1, \ldots, j_m\}$

Theory:

parton level (quarks, gluons) $\xrightarrow{\text{jet algorithm}}$ partonic jets $\{j_1, \ldots, j_m\}$

hadron level (e.g. [N]NLO+PS) hadronic jets $\{j_1, \ldots, j_m\}$

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

Final state jets

Experiment:

focus of this talk will be flavour identified (c/b) jets

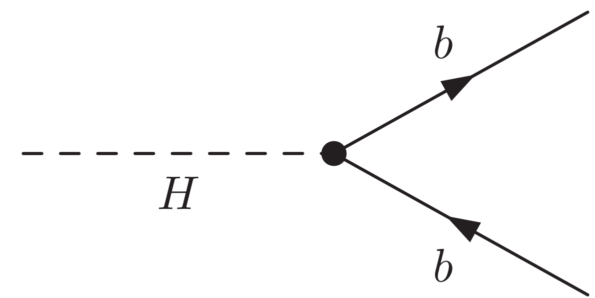
a) Higgs physics (hadronic decays)

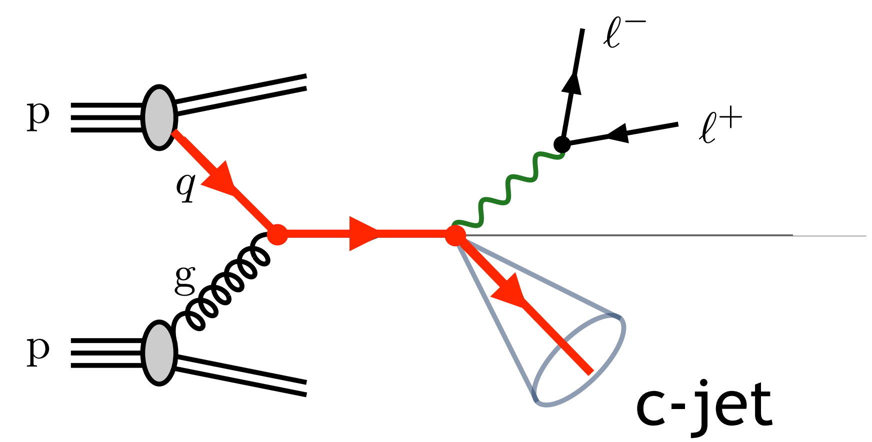
b) Top-quark physics ($|V_{tb}| \sim 1$)

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

d) Gauge-boson + heavy-flavour

…





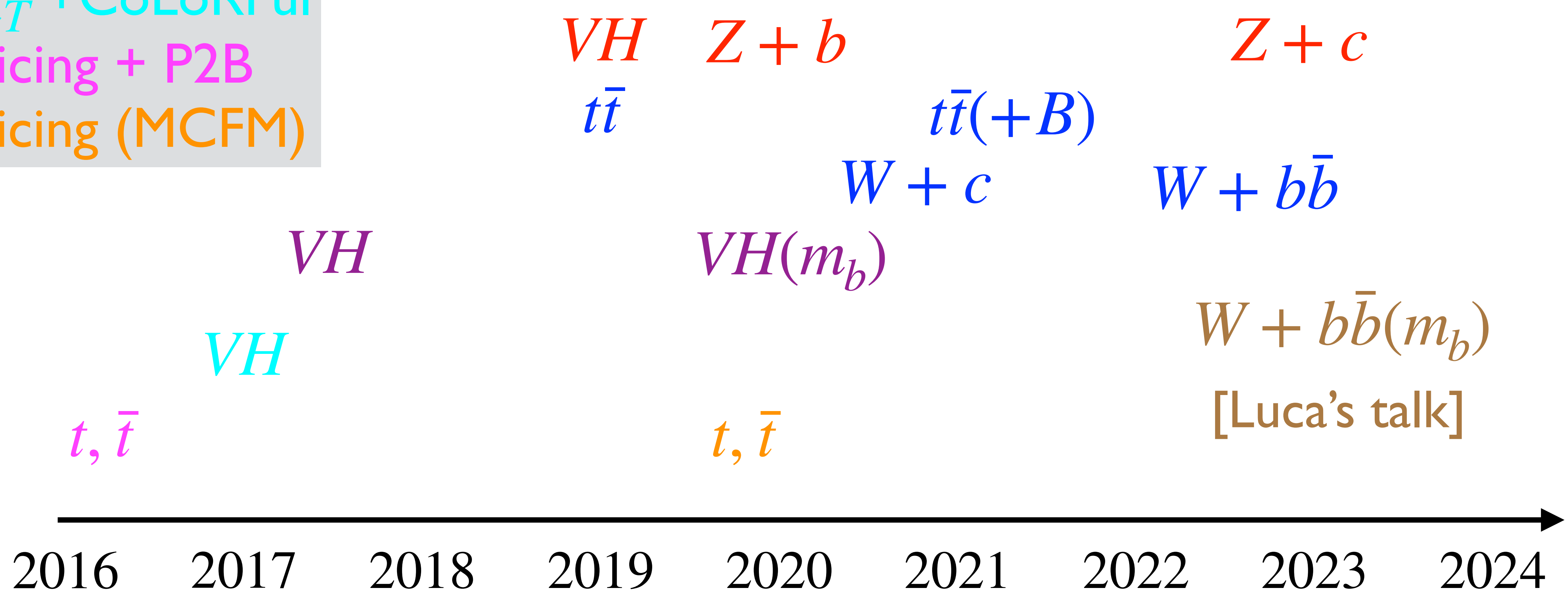
$$d\sigma^{\rm data\,(meas.)}_{PP\to f+X} \quad \text{vs} \quad d\sigma^{\rm theory}_{PP\to f+X}$$

Recent NNLO progress with flavoured jets

Methods

- Antenna
- Stripper
- Nested SC
- Q_T subtraction
- Q_T +CoLoRFul
- Slicing + P2B
- Slicing (MCFM)

All calculations consider flavoured jets



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All calculations consider flavoured jets

… few calculations consistently compared to data
(a mismatch between jet-flavour definitions)

VH $\quad$ $Z+b$ $\quad$ $Z+c$

$t\bar{t}$ $\quad$ $t\bar{t}(+B)$

$W+c$ $\quad$ $W+b\bar{b}$

VH $\quad$ $VH(m_b)$

$W+b\bar{b}(m_b)$

[Luca's talk]

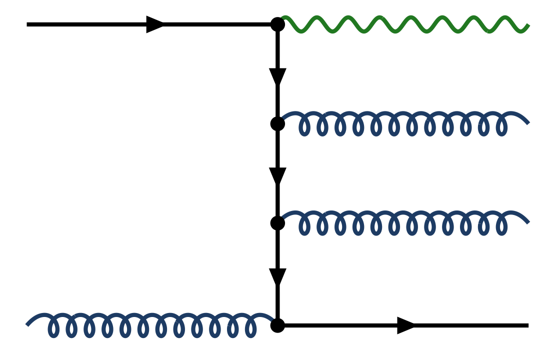
VH

$t,\bar{t}$ $\quad$ $t,\bar{t}$

2016 2017 2018 2019 2020 2021 2022 2023 2024

1) General introduction

- Final state jets
- Related progress in fixed-order calculations



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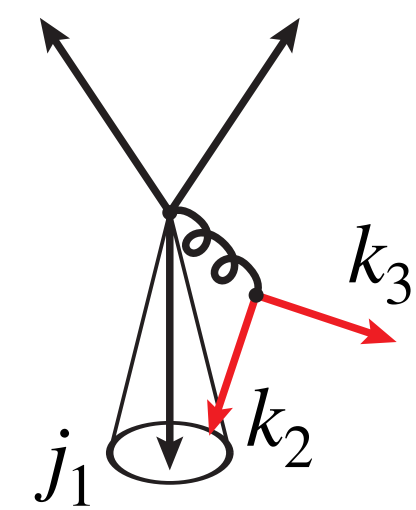

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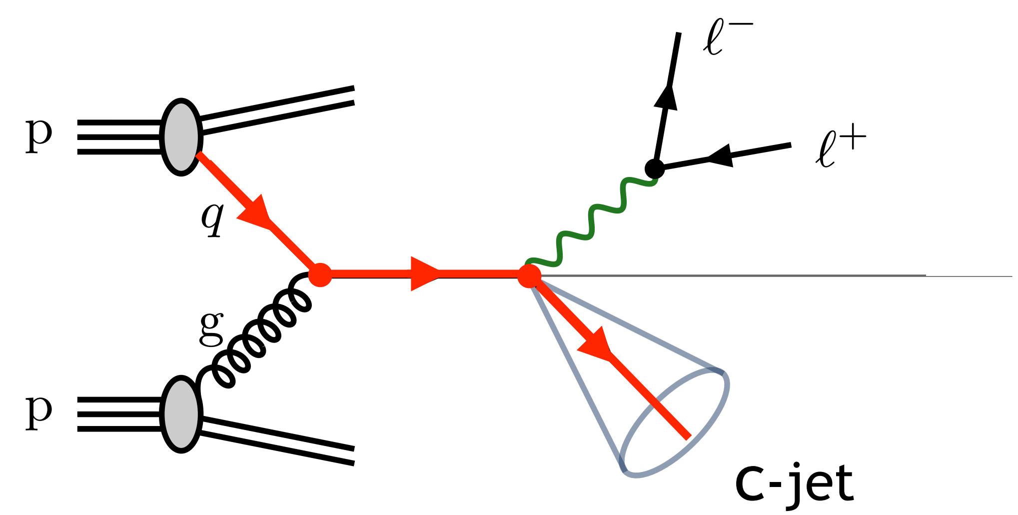

Jets at the LHC

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

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

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

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

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

anti-k_T (p=-1)

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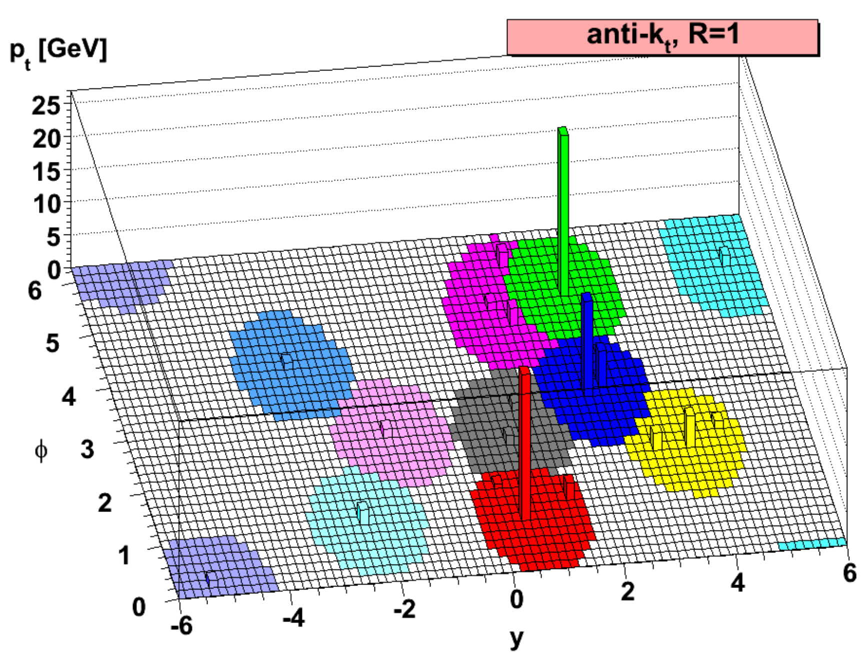
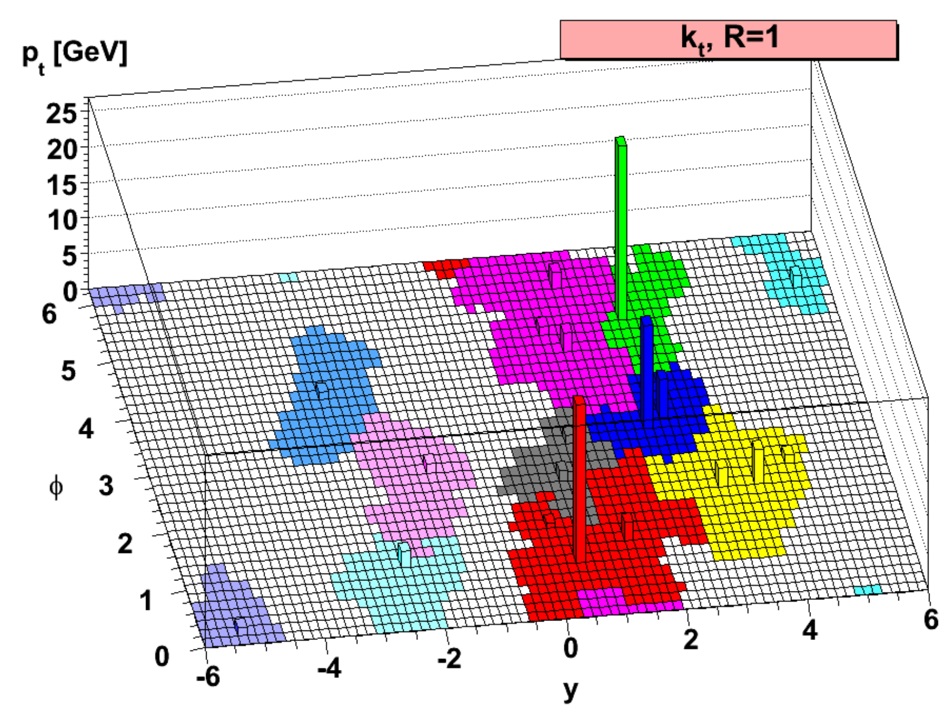
anti-k_T has nice geometrical properties (used in all LHC analyses)



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 ~ $p_T^{D/B} > 5\ \mathrm{GeV}$

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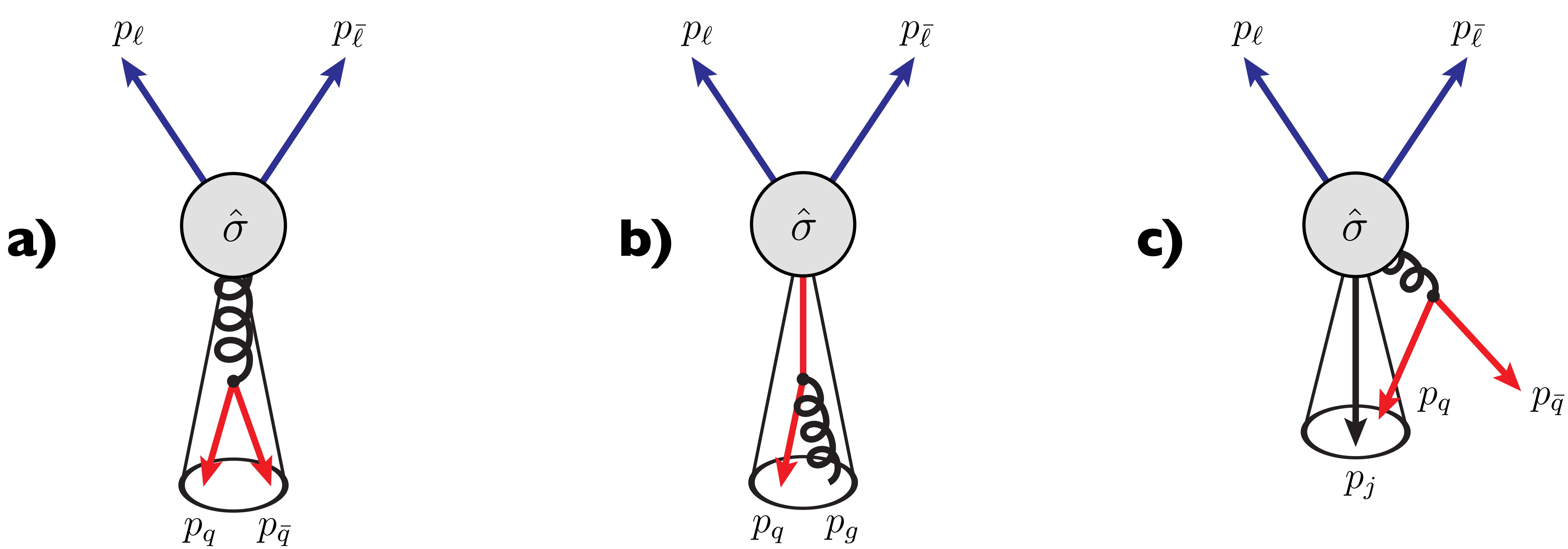

Solutions to this problem

Comments/status

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

k_T jets

Solutions to this problem

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

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

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

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

A dress of flavour to suit any jet — Tested at N3LO ($e^+e^- \to$ jets)
(**RG**, Huss, Stagnitto: arXiv:2208.11138)

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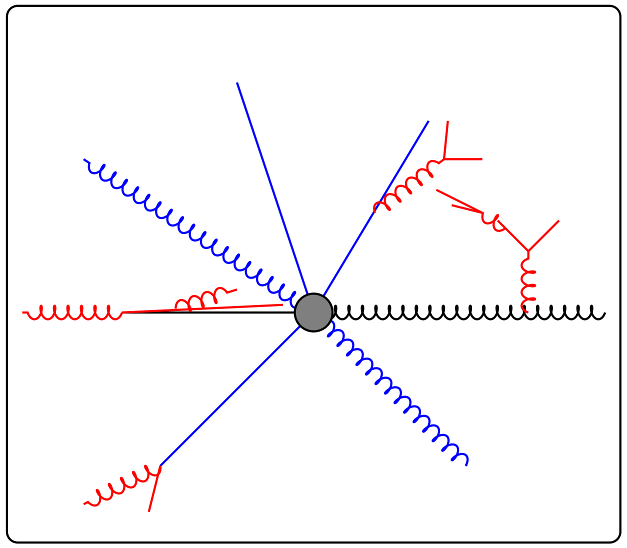
Flavoured jets with exact anti-k_T kinematics — (substructure based)
(Caola, Grabarczyk, Hutt, Salam, Scyboz, Thaler: preliminary—Moriond Mar '23)

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



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

$\underbrace{\hspace{4cm}}_{\text{possibly nested}}$

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

...lem

Comments/status

k$_T$ jets

...VH, $t\bar{t}$ w/ decay, $V+j$) …

(substructure based)
soft unsafe at N3LO

Infrared-safe flavoured anti-k$_T$ jets
(Czakon, Mitov, Poncelet: arXiv:2205.11879)

approx. anti-k$_T$ jets
potential issues with ICIC

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

Tested at N3LO ($e^+e^- \to$ jets)
issues at N4LO [requires changes]

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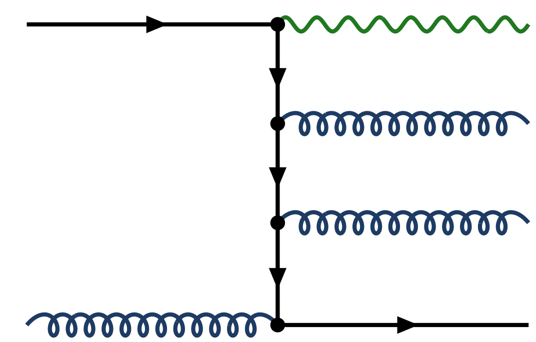

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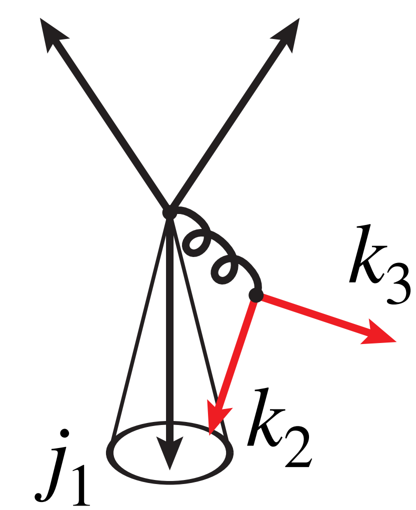

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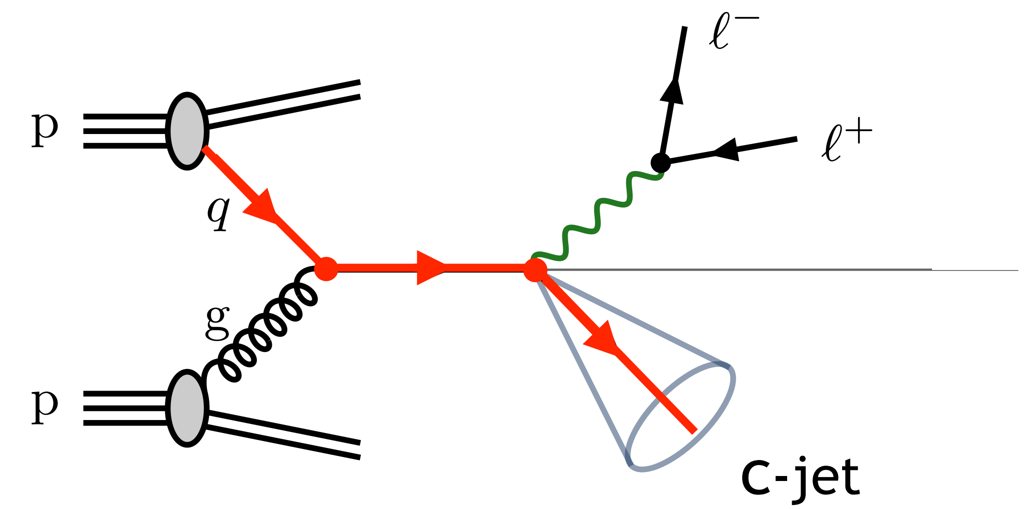


A dress of flavour to suit any jet

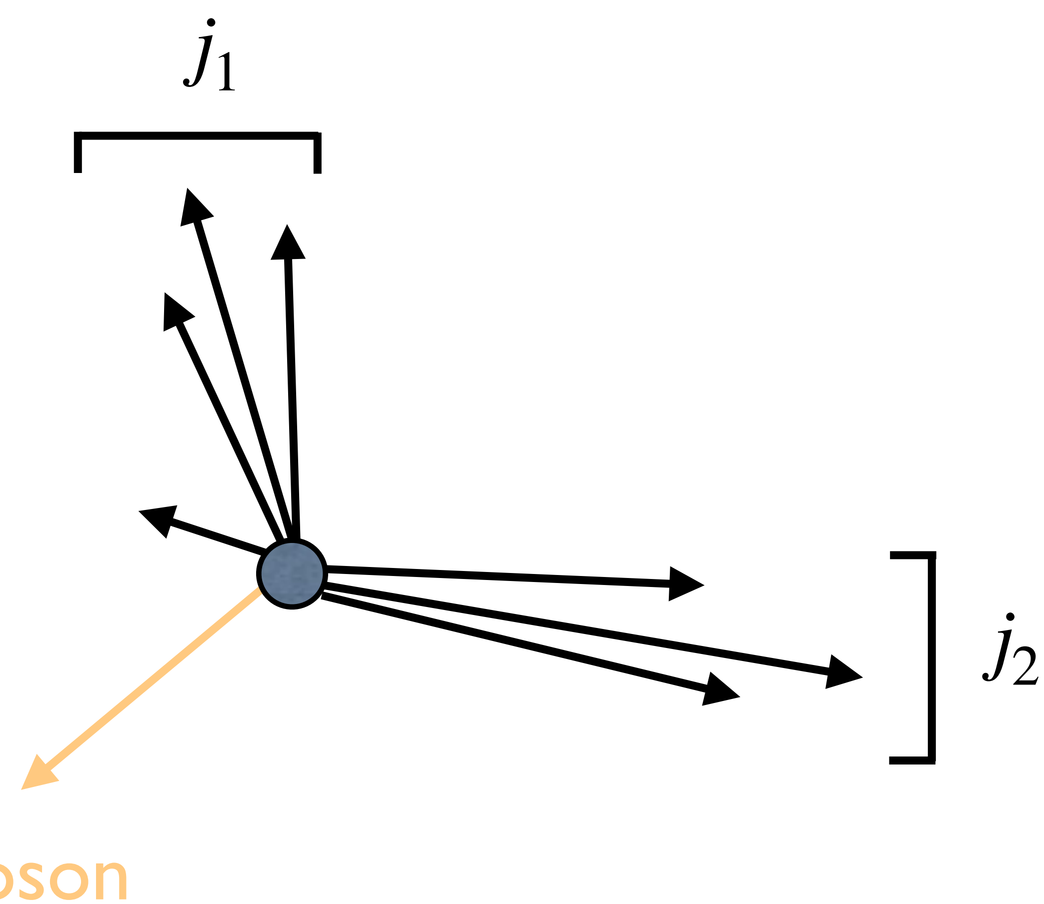
(**RG**, Huss, Stagnitto arXiv:2208.11138)

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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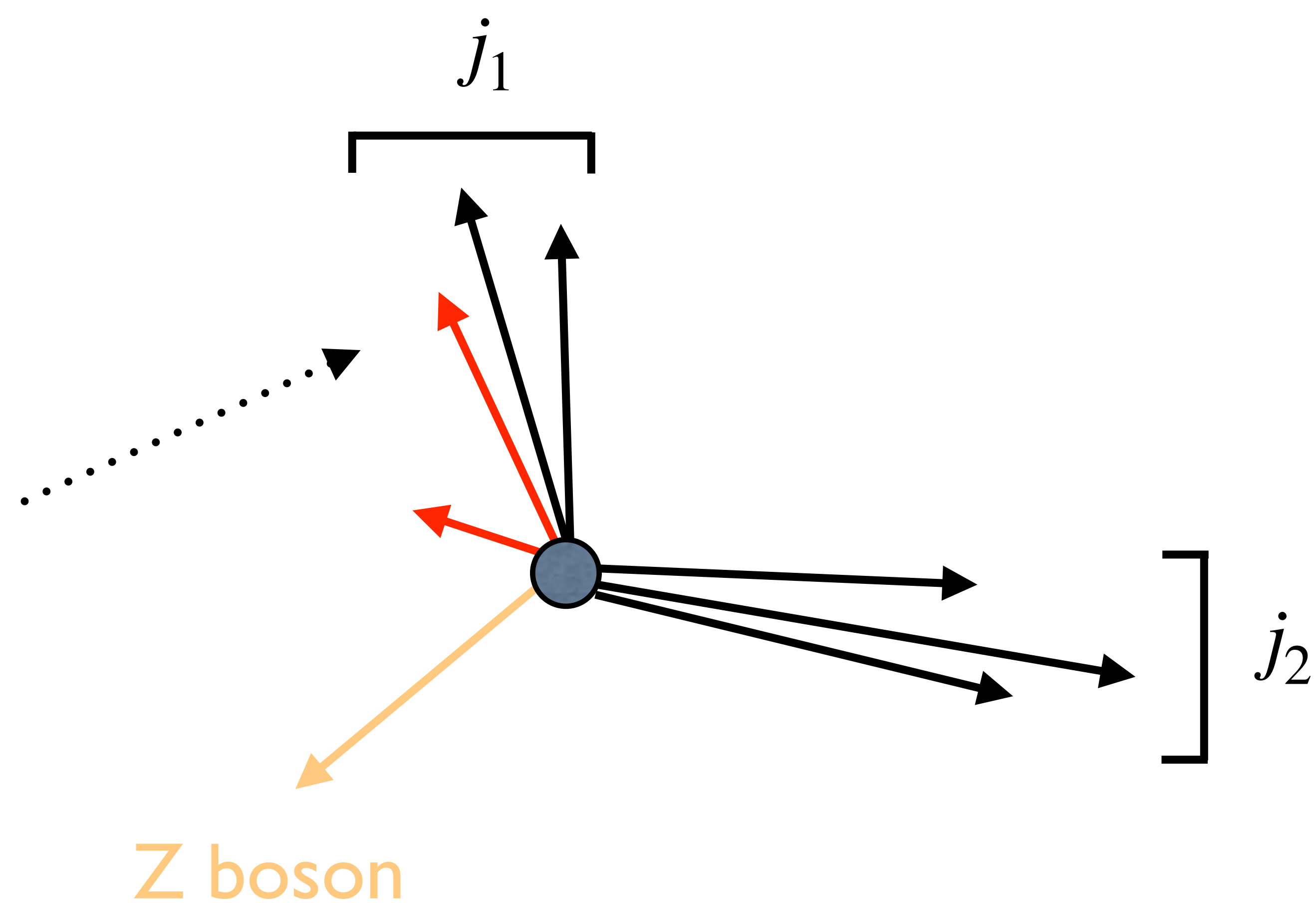
Toy event

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



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

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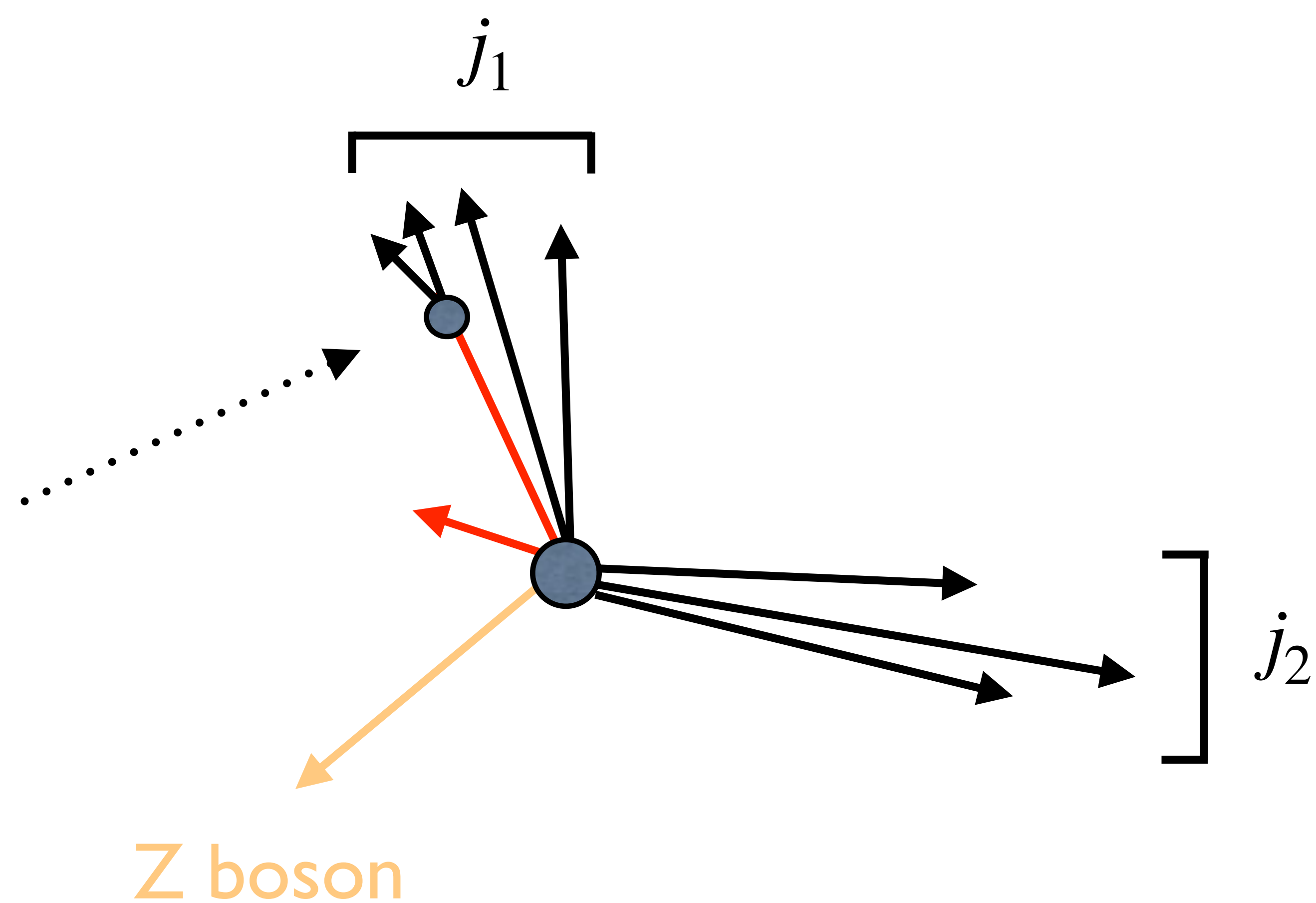

set of jets $\{j_1, \ldots, j_m\}$

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

(flavoured particles not required to be final state!)

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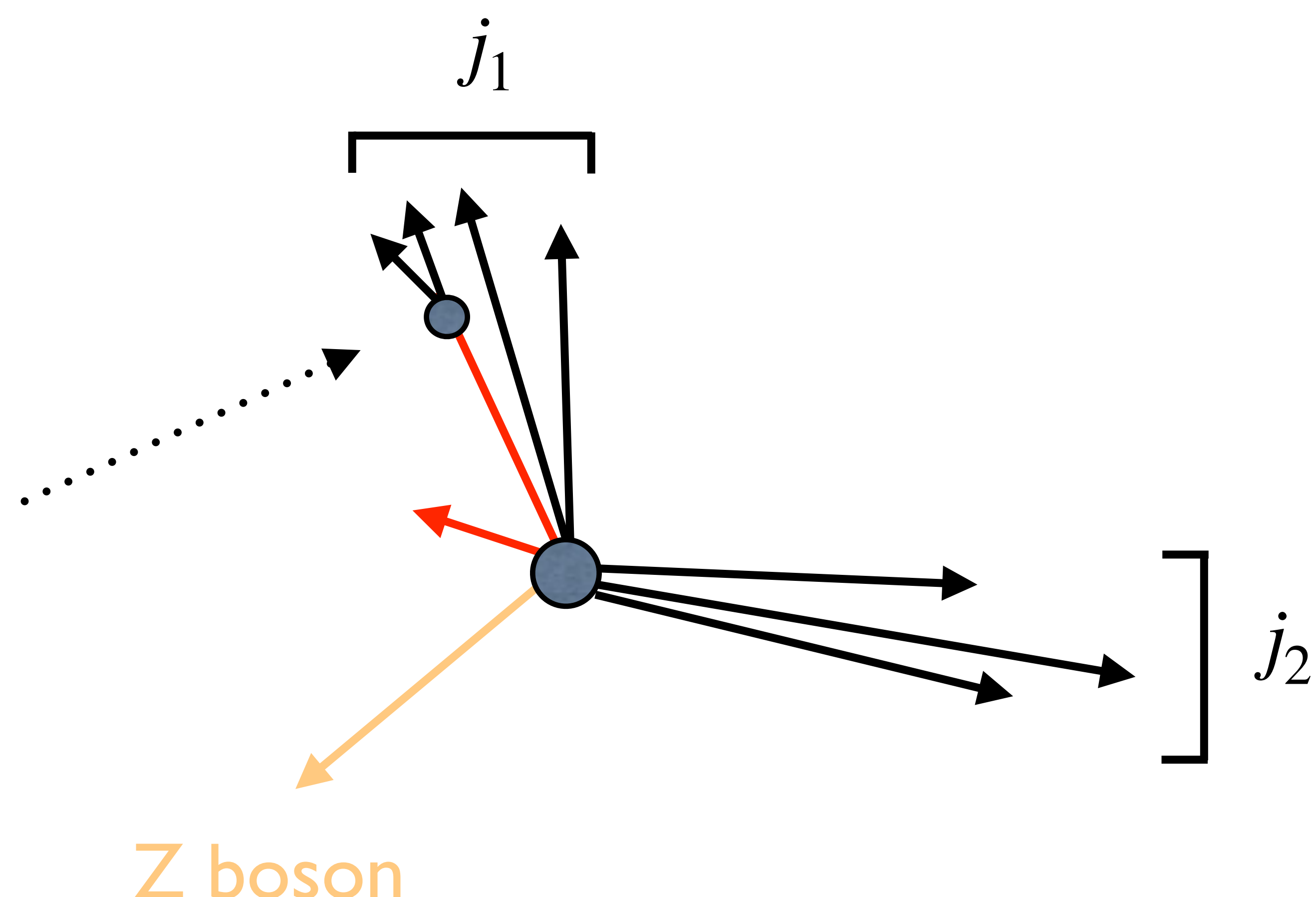

algorithm assigns $\hat{f}_i$ to j_k

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!)

A dress of flavour to suit any jet

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

Stage 1: 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*)

*adjustment of original algorithm

A dress of flavour to suit any jet

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

Stage 2: Calculate d_{ab} for all $\{j_1, \ldots, j_m\}, \left\{\hat{f}_1, \ldots, \hat{f}_n\right\}$

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

(this is the original flavour-k_T distance)

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

(rapidity dependent measure of the Beam)

- If min. is d_{fj} : assign f quantum number to j, [remove f from list]
- If min. is: d_{ff} or d_{fB} , [remove f from list]

[repeat until list is empty]

Note: only evaluate d_{fj} if the f is associated to the jet (e.g. a constituent)

[complete details in back-up slides]

A dress of flavour to suit any jet

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

Stage 2: Calculate d_{ab} for all $\{j_1, \ldots, j_m\}, \left\{\hat{f}_1, \ldots, \hat{f}_n\right\}$

Adjustment required (Caola, Grabarczyk, Hutt, Salam, Scyboz, Thaler)

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

$$d_{ab} = 2p_a \cdot p_b$$

(TBC, simple fix with Jade distance and β<2 in clustering)

- If min. is d_{fj} : assign f quantum number to j, [remove f from list]
- If min. is: d_{ff} or d_{fB} , [remove f from list]

[repeat until list is empty]

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[complete details in back-up slides]

A dress of flavour to suit any jet

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

Stage 3: Count how many flavours assigned to each jet $\{j_1, \ldots, j_m\}$

How to count flavour quantum numbers:

- With charge info. (q vs $\bar{q}$), then $q = +1$ and $\bar{q} = -1$

  (net flavour is sum of the q_i and $\bar{q}_j$ assigned to jet j_n)

- If one cannot (e.g. experiment), $|q| = |\bar{q}| = 1$

  (net flavour is sum [modulo 2] of the q_i and $\bar{q}_j$ assigned to jet j_n)

  [i.e. even tagged jets are NOT flavoured]

Outcome: a set of flavour identified (anti-k$_T$) jets $\left\{j_1^{f_1}, \ldots, j_m^{f_m}\right\}$

This algorithm is applicable at the measurement level in experiments

Summary

(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 or hadron level)

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

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

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

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

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

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

a lot of exciting work: close experiment + theory collaboration still required

Whiteboard

(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 $d_{ij}^{\min} > \Delta R_{\mathrm{cut}}^2$ 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:

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

[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 $\Delta R(\hat{f}_a, j_b) < R_{\text{tag}}$
- 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)

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

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
- 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 $\beta < 2$) $\qquad d_{ab} = 2p_a \cdot p_b$

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

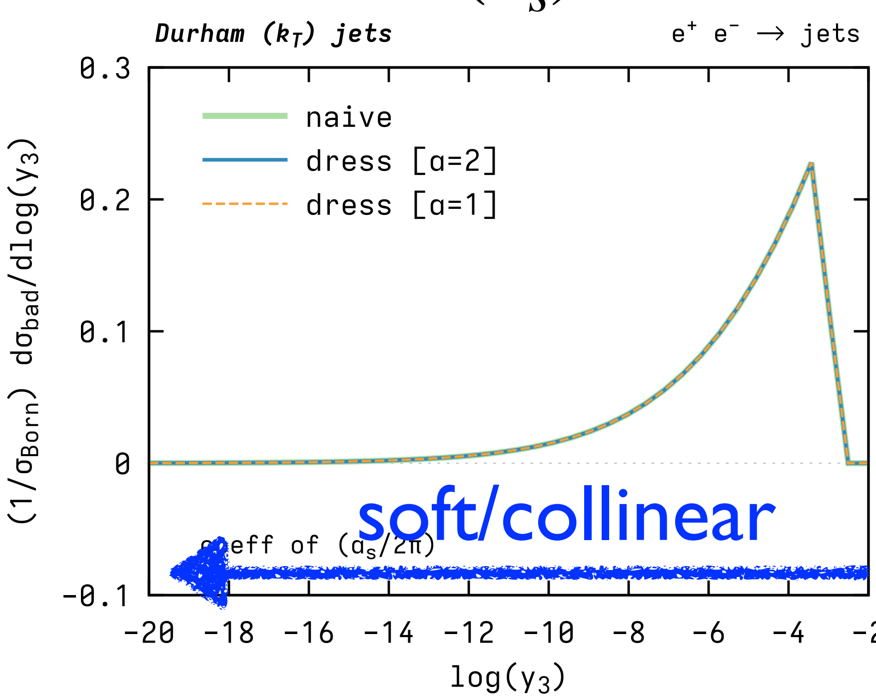
(**RG**, Huss, Stagnitto arXiv:2208.11138)

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

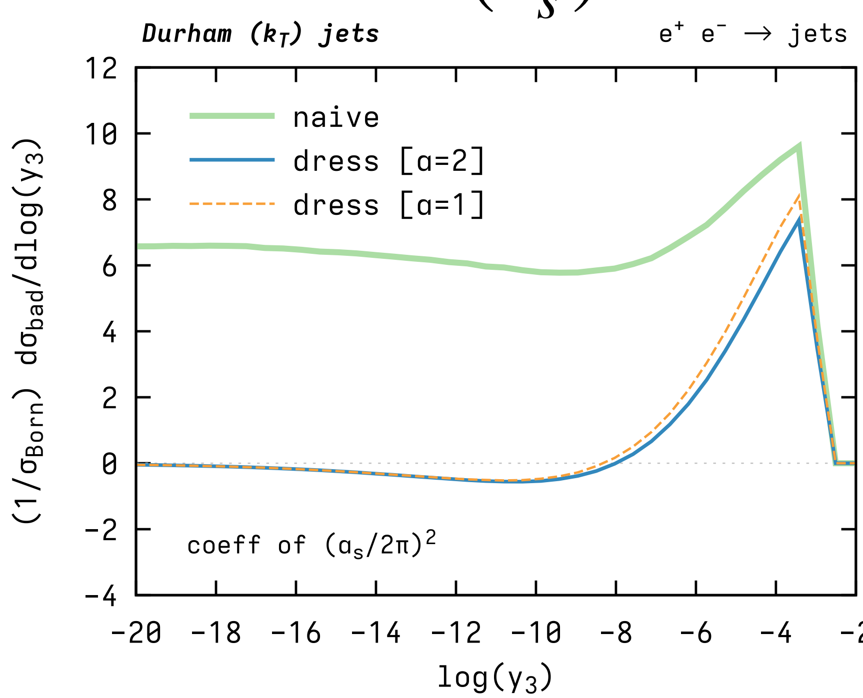
Look at 'bad' events (i.e. where we do not find 2 flavoured jets, $e^+e^- \to q\bar{q}$)

The 'bad' cross-section should vanish in the $y_3 \to 0$ limit
(y_3 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)

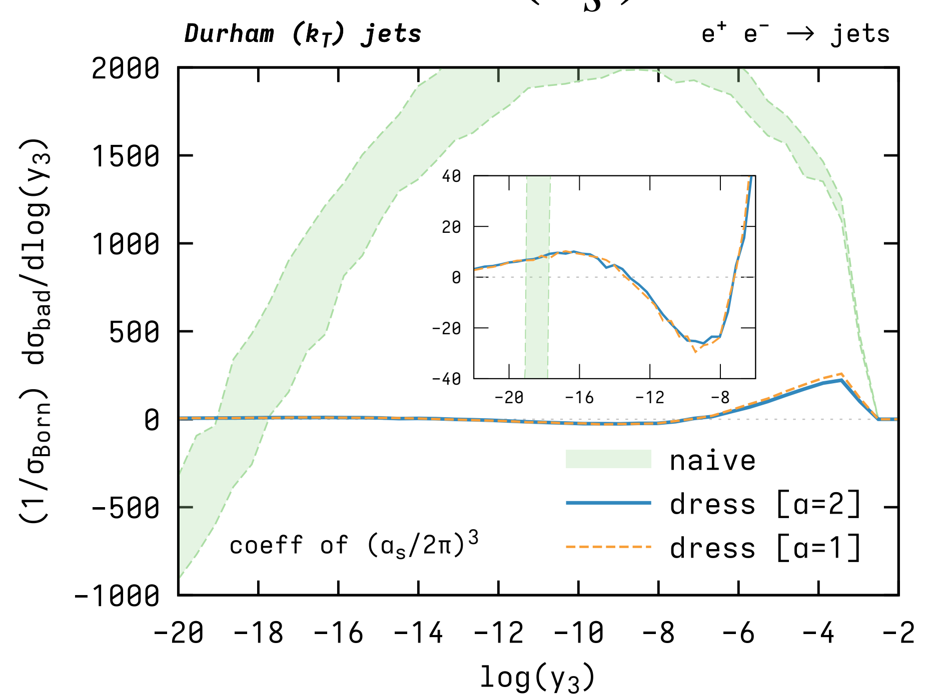
$\mathcal{O}(\alpha_s)$



$\mathcal{O}(\alpha_s^2)$



$\mathcal{O}(\alpha_s^3)$



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

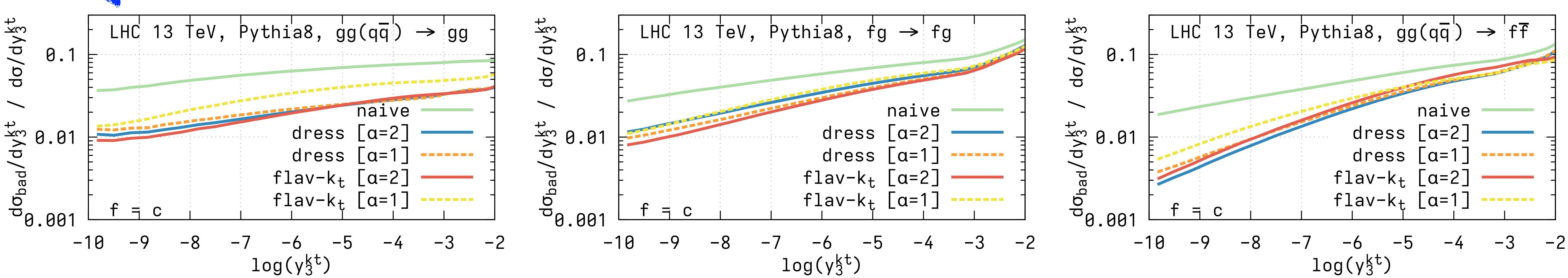
In this case study, also use resolution variable to probe IRC sensitive regions (here we study the behaviour, rather than the bad cross-section vanishing)

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

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

(Buonocore et al. arXiv:2201.11519)

soft/collinear



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)

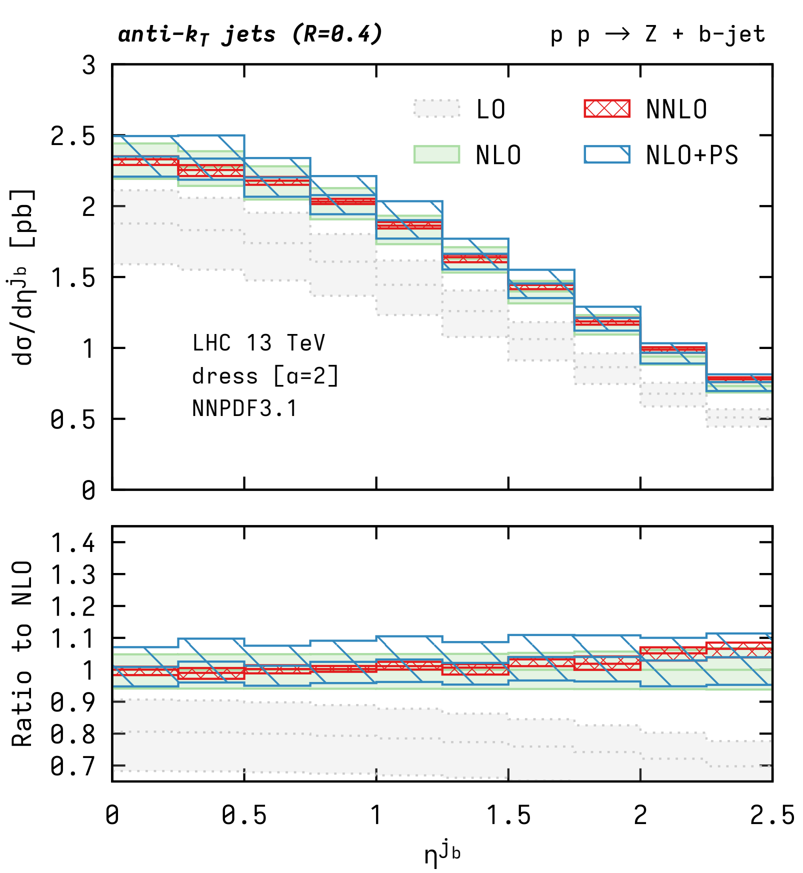
Now consider the process $pp \to Z + b - \mathrm{jet}$ in Fiducial region (13 TeV, CMS-like)

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

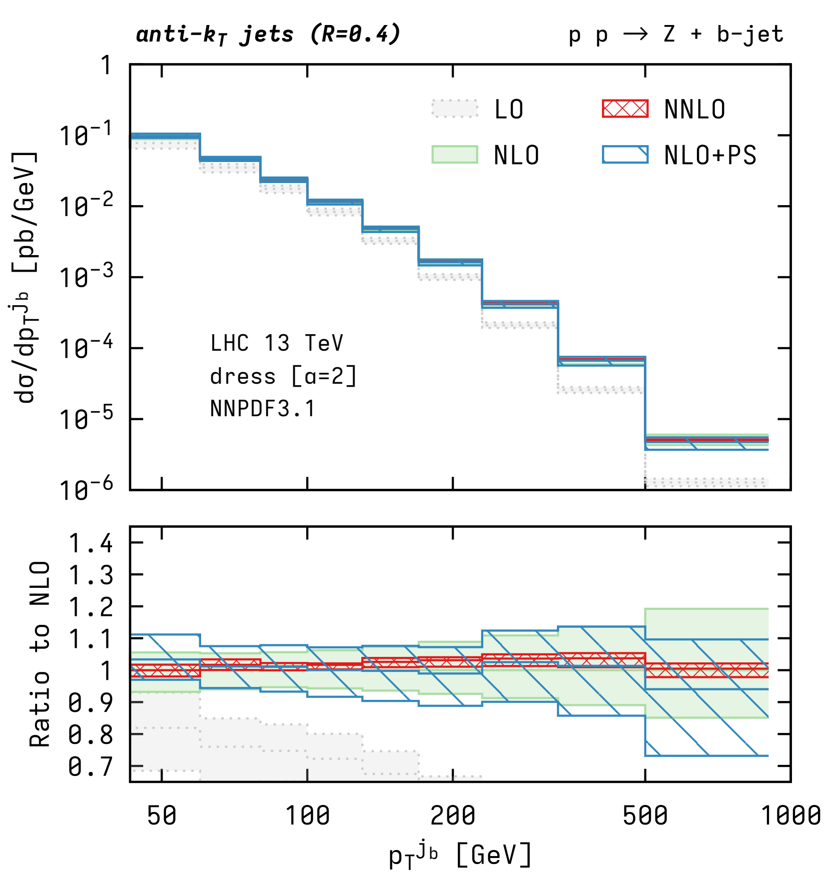
NLO+PS Hadron-level with aMC@NLO interfaced to Pythia8

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

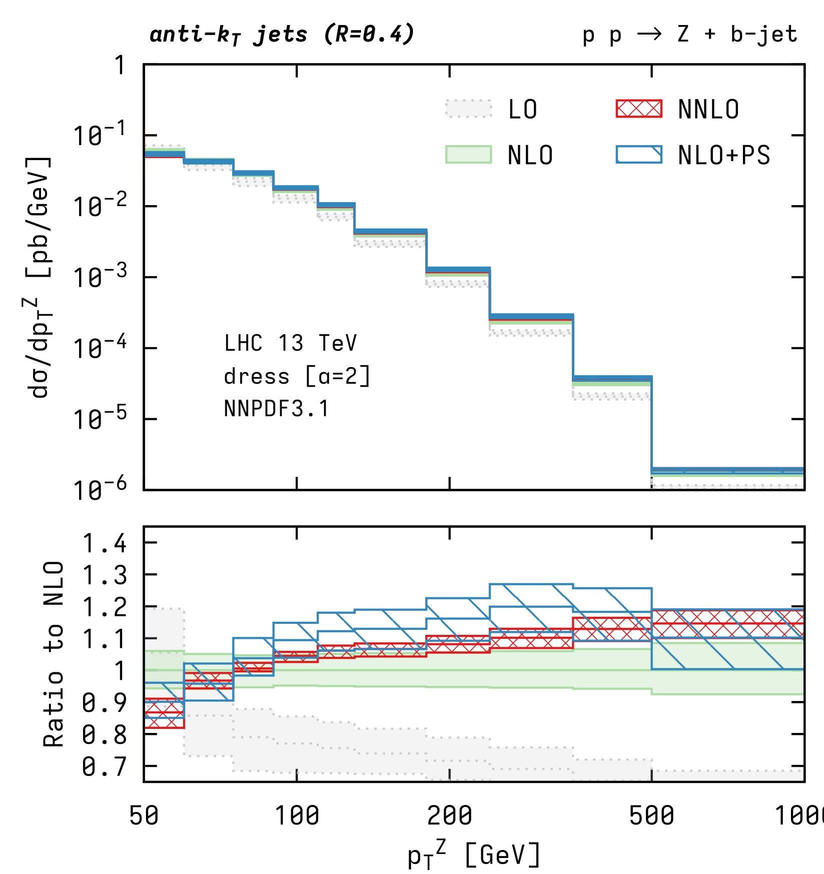
$\eta_{\mathrm{b-jet}}$



$p_{T,\mathrm{b-jet}}$



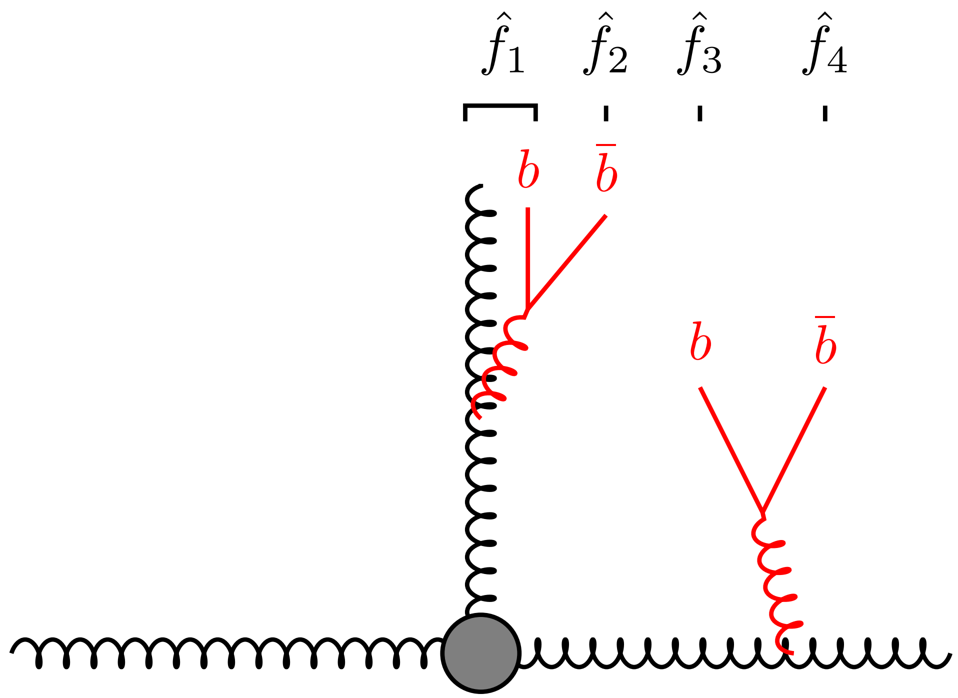
$p_{T,Z}$



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

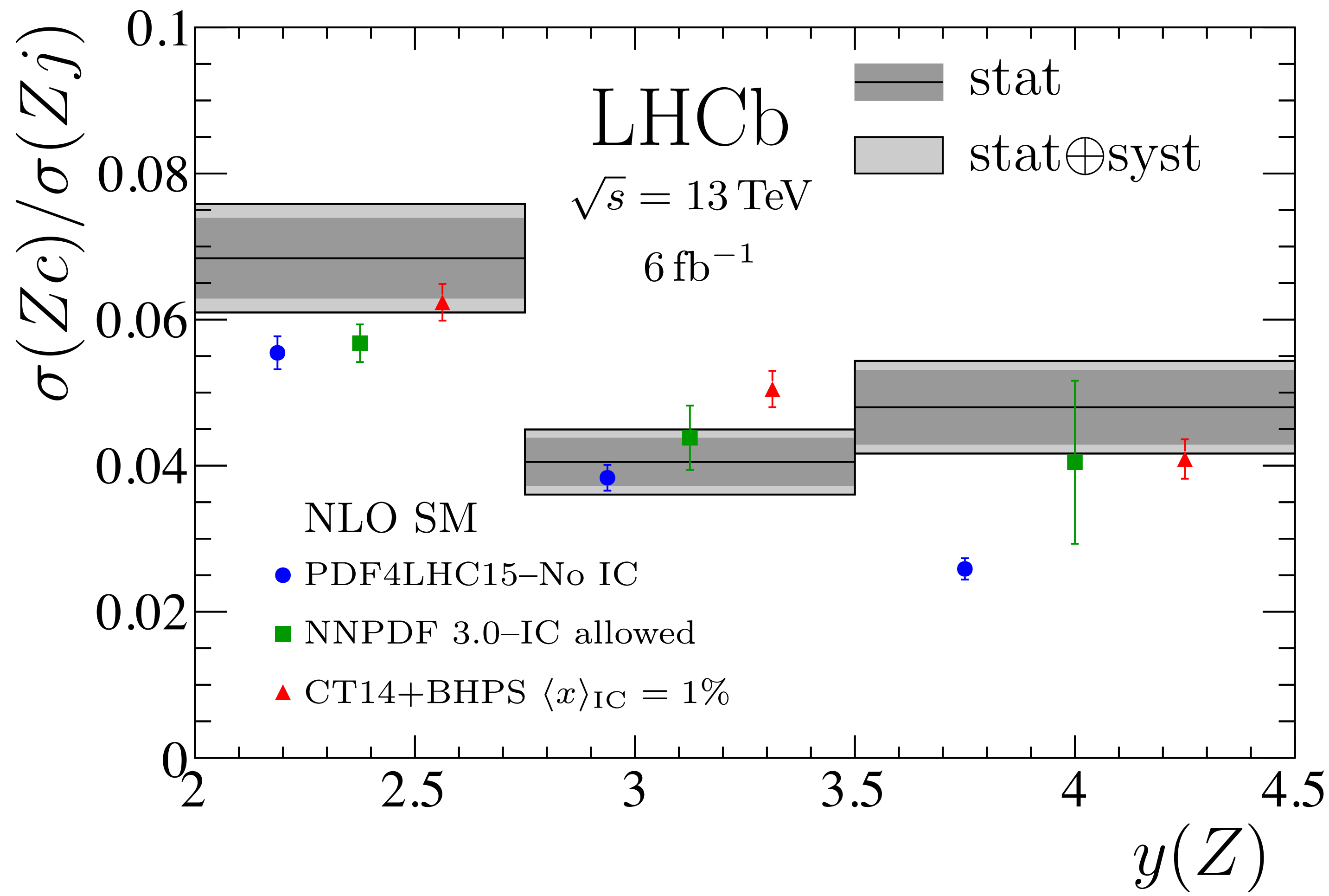
$\rightarrow$ 1 b-jet (+ 1 $\bar{b}$ beam jet)

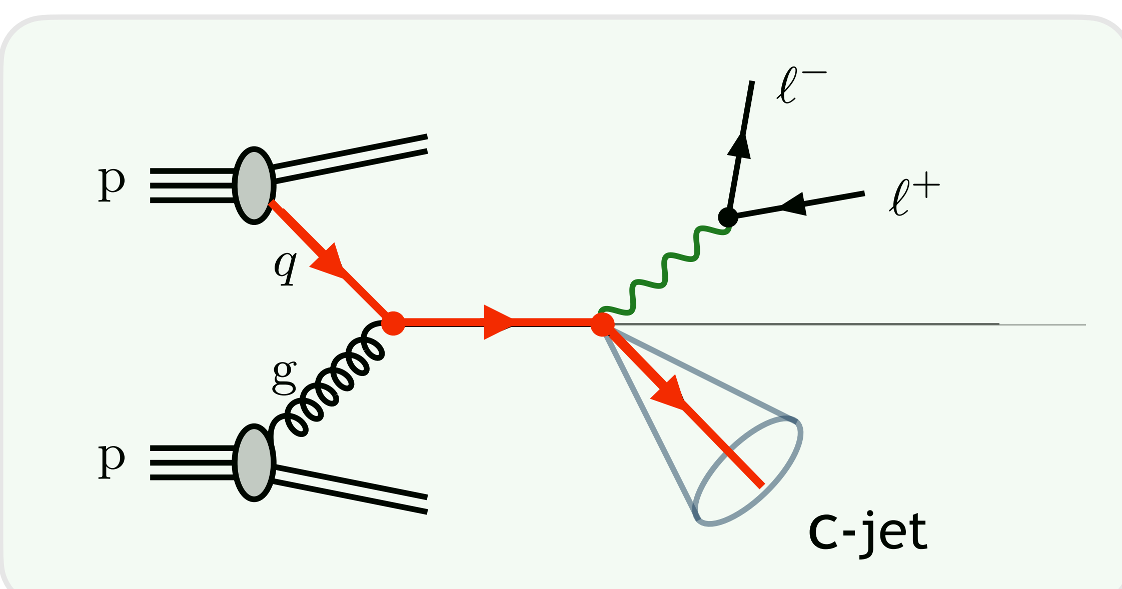
- Some analytic/numerical understanding of the complicated interplay between distances (as a function of α and β)

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

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

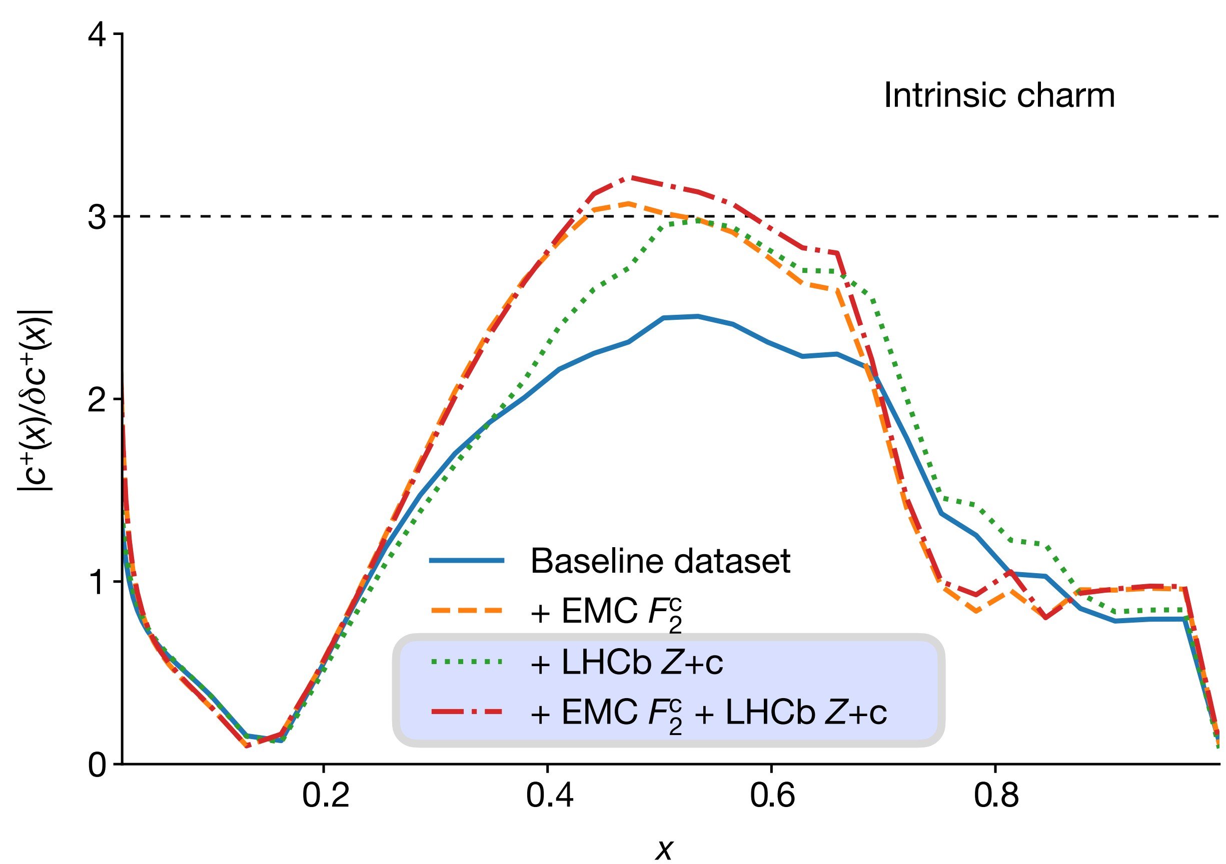
Article | Open Access | Published: 17 August 2022

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, CTEQ-TEA Guzzi et al. arXiv:2211.01387)

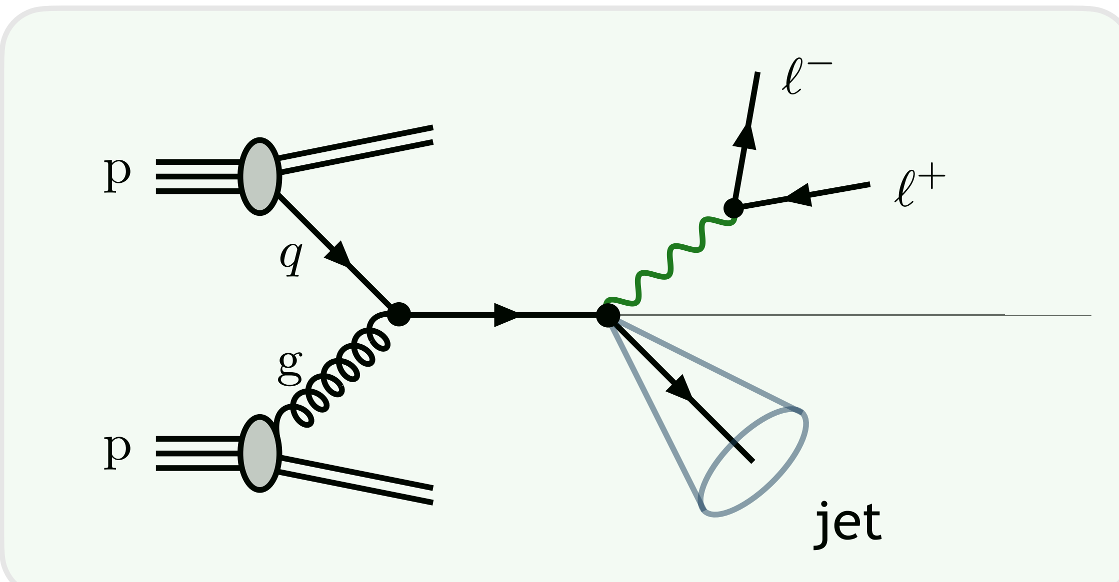
Applications: Z+c-jet at LHCb … MPI

Possibility for multiple hard interactions in a single pp-collision

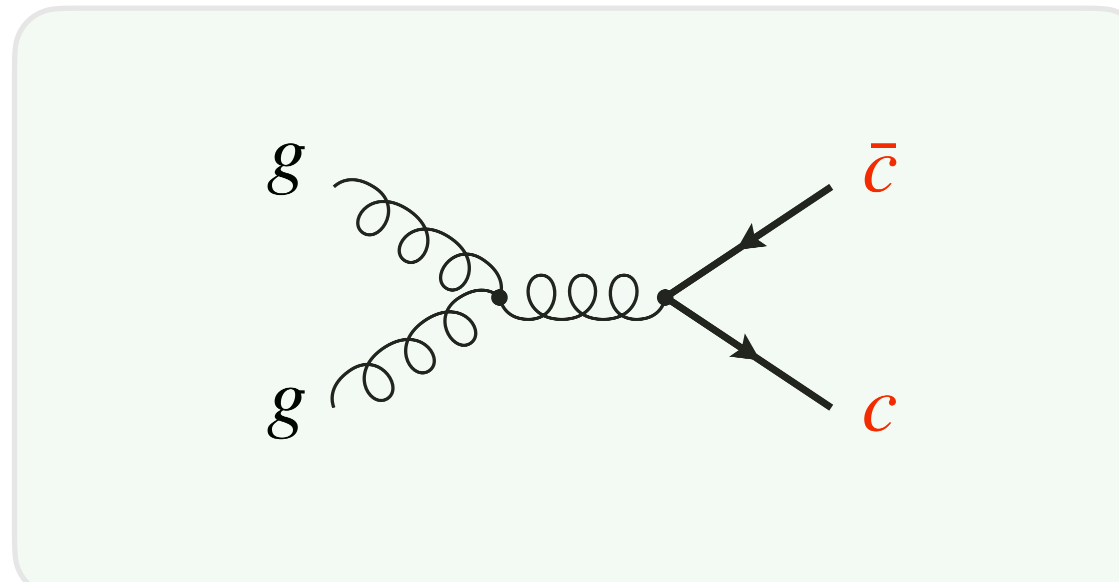
e.g. single-parton-scattering (SPS), double-parton-scattering (DPS), …

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

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

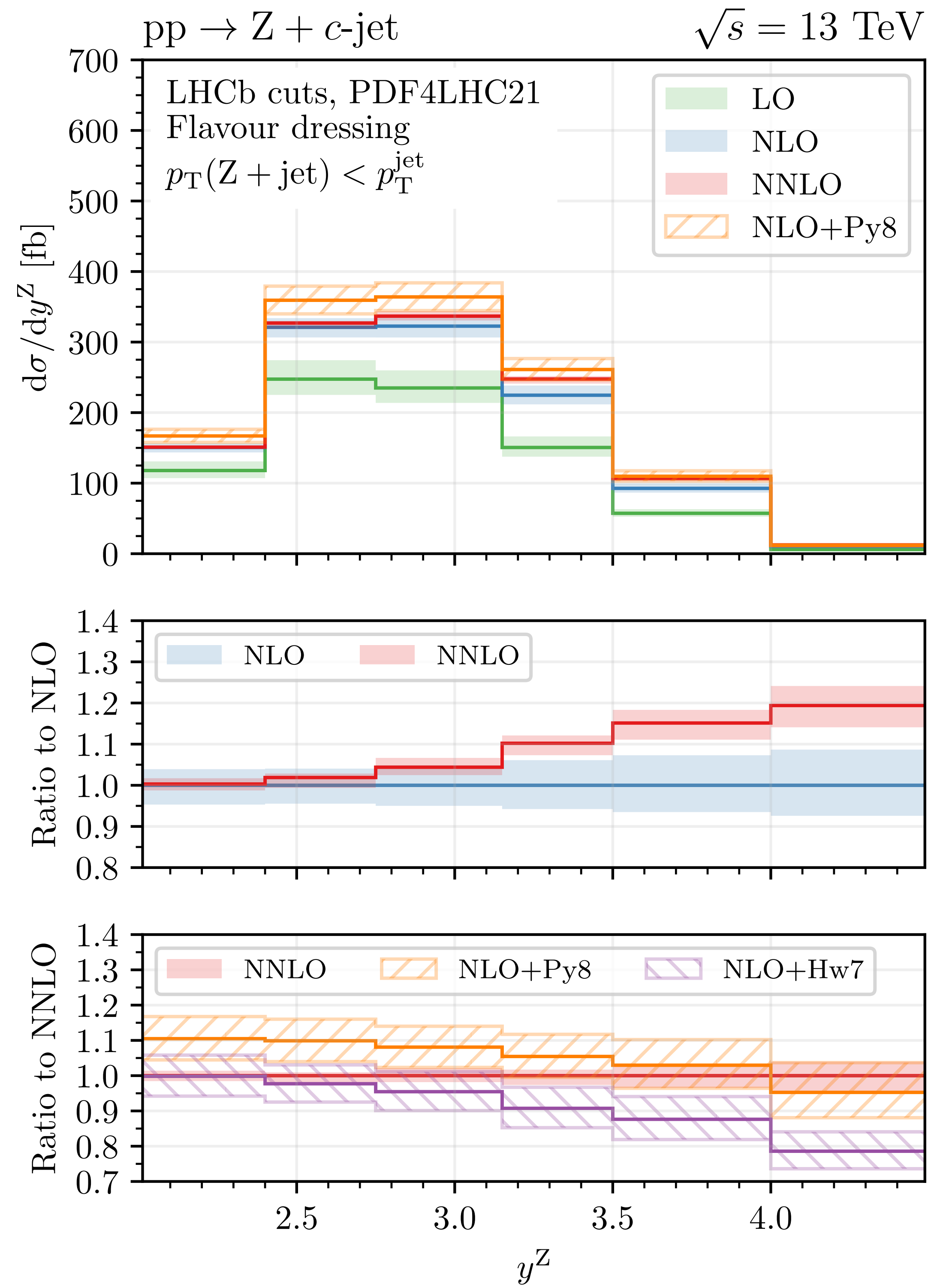
$$\frac{d\sigma^{Z+c-jet}}{dy_Z}$$

Note: no direct comparison to data:

- IRC safe jet algorithm required
(resumming charm PDF critical)

- Data sensitive to MPI contributions
(positive and rapidity dependent)

More details in backups

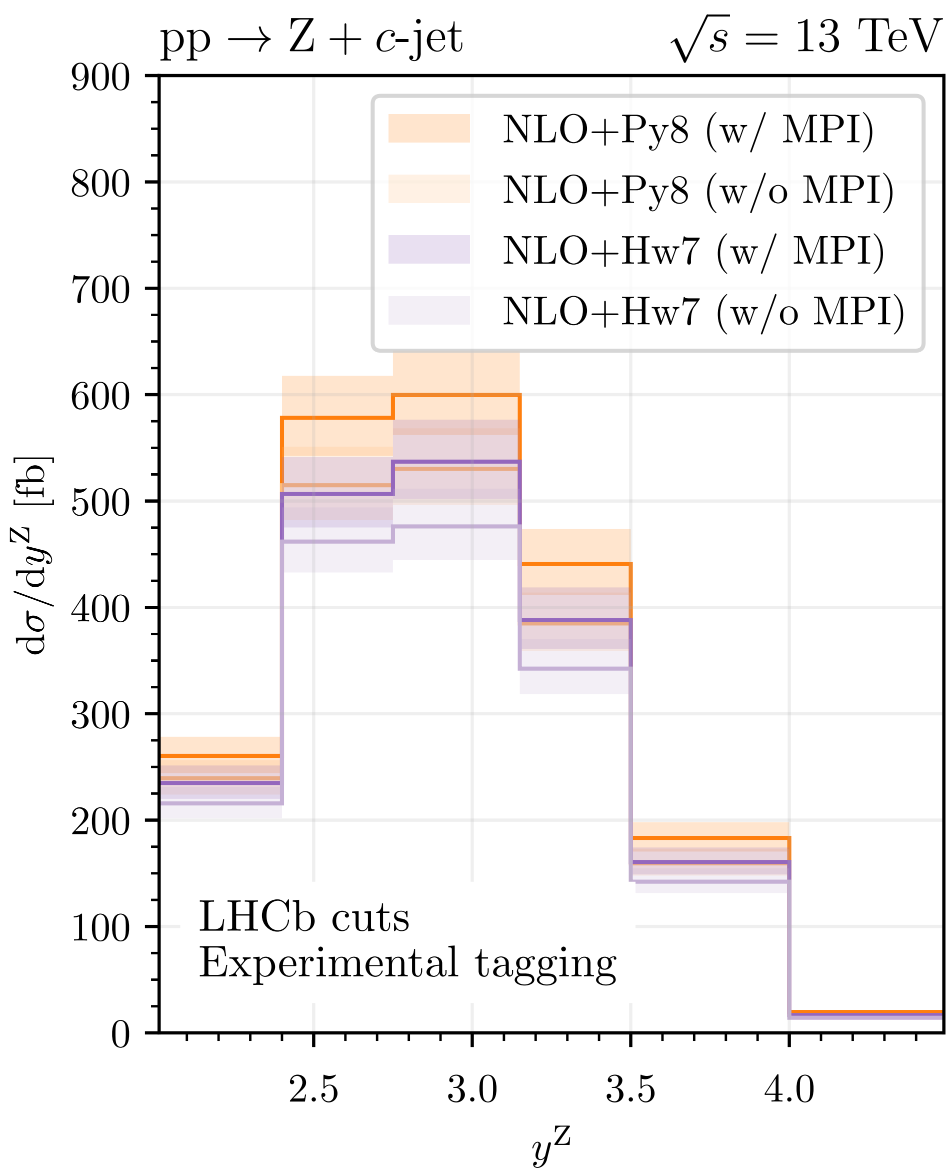


NNLO QCD corrections positive and grow with y_Z (mimicking intrinsic charm)

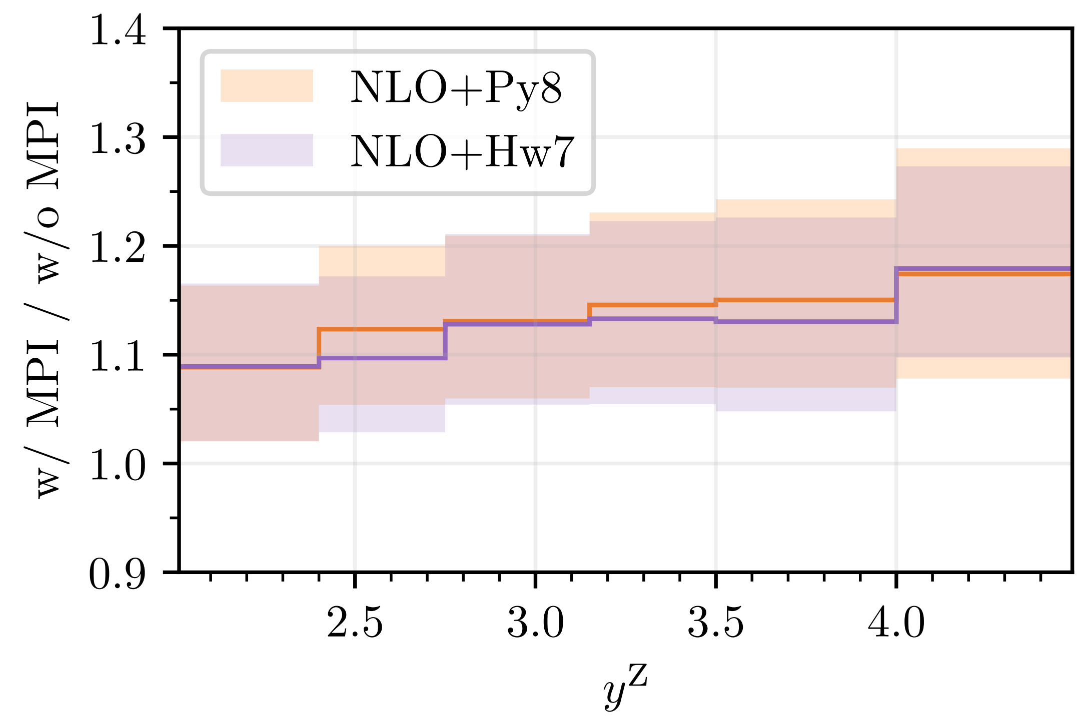
Applications: Z+c-jet at LHCb … MPI

Possibility for multiple hard interactions in a single pp-collision

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

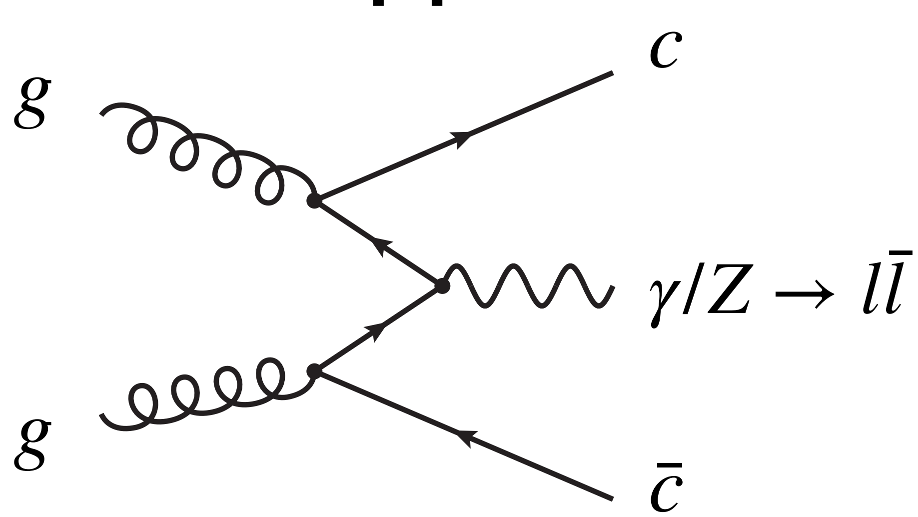


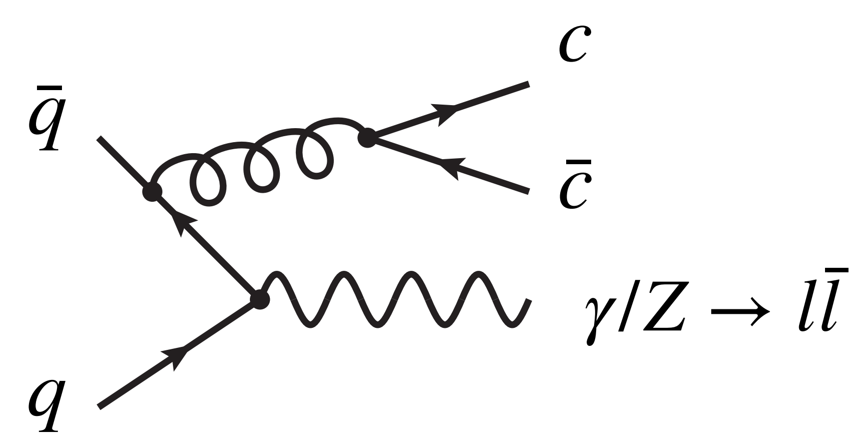
Z+c-jet (MPI on / MPI off)



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)

Applications: Z+c-jet at LHCb

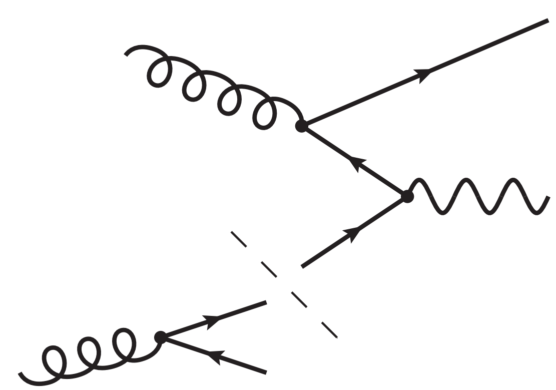




Calculated in the 3fs scheme (i.e. $n_f^{\max} = 3$ in PDFs, and α_s evolution)

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

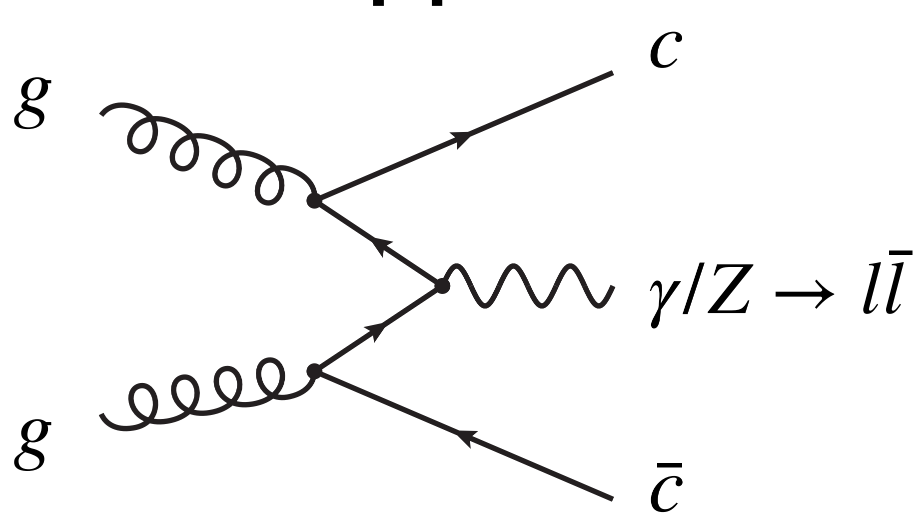
Massless component
$\mathcal{O}(\alpha_s^2 n_f)$ in 4fs

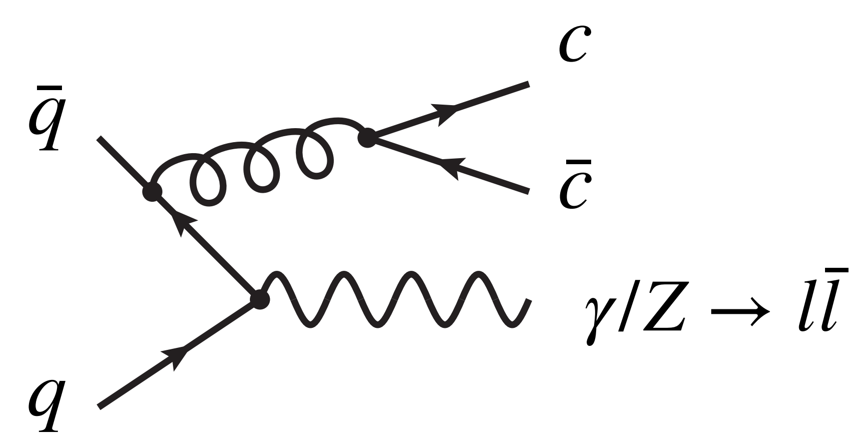


$\mathcal{O}(m_c^2)$ effects
(exact kinematics)

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)

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

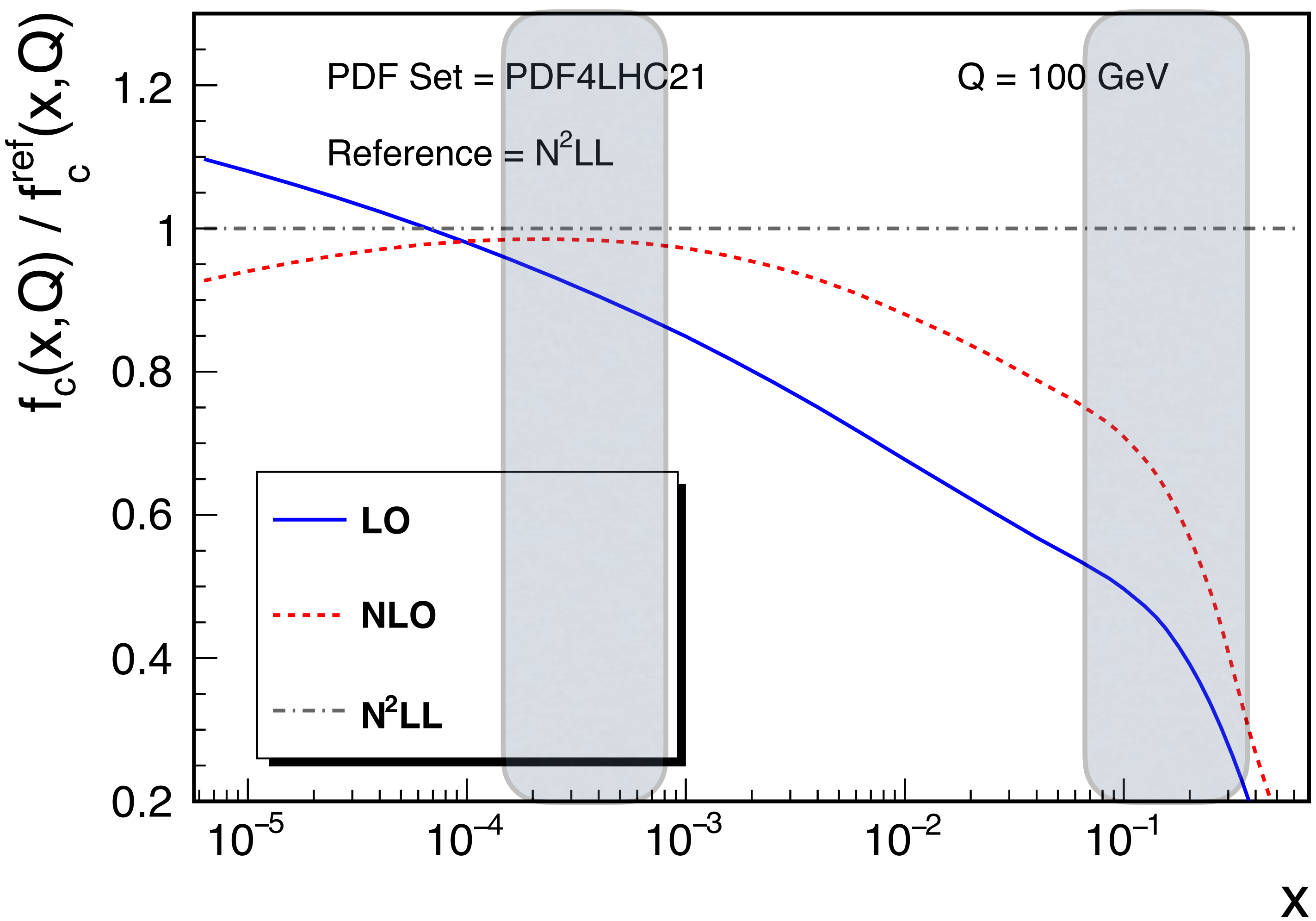
0.220 = +0.0364 +0.203 -0.019 [pb]

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)



$$< x_1 > \sim 0.2$$

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

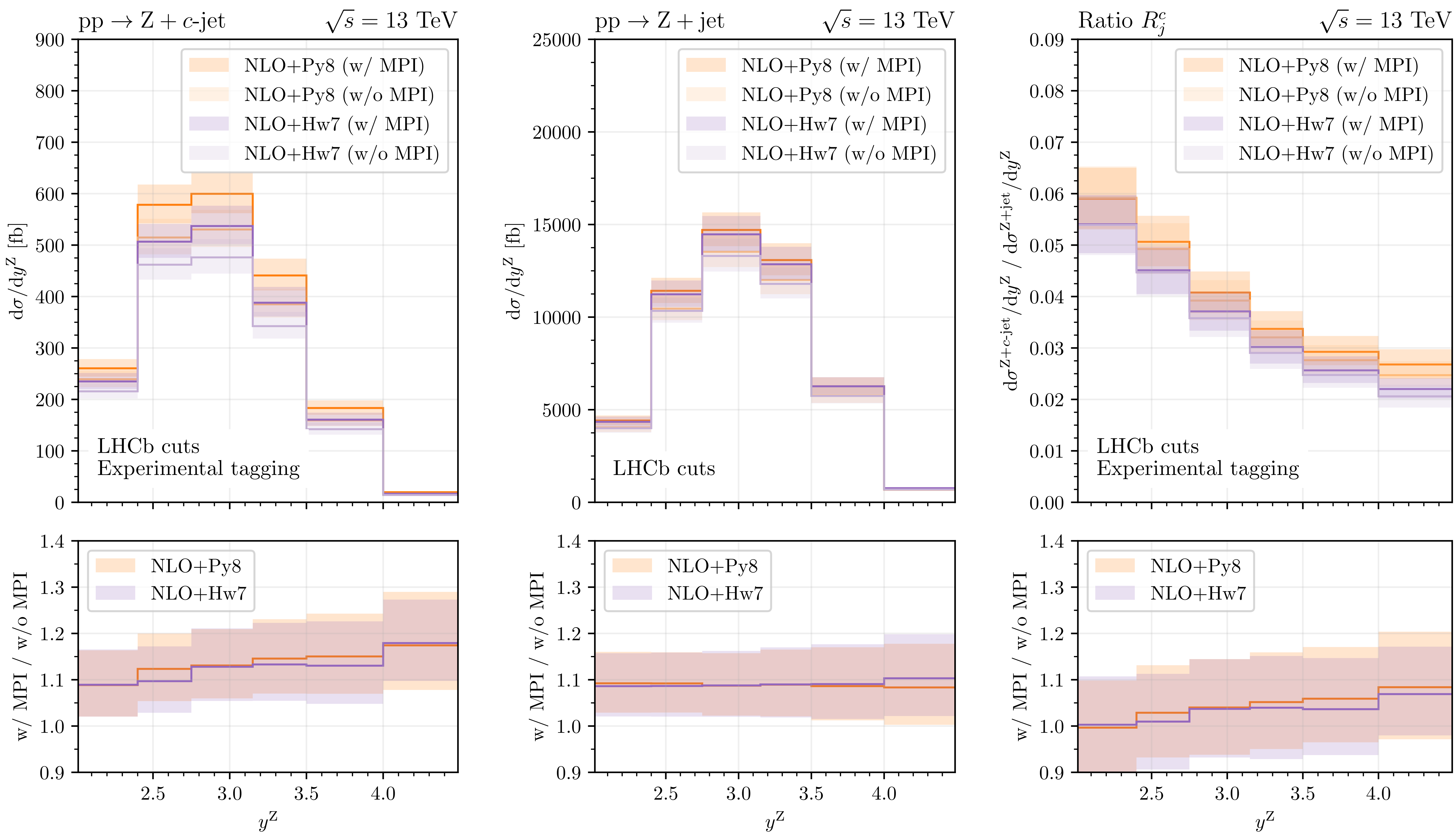
LHCb cross-section: Leading Log (1st order) = 0.203pb, Leading Log (resumed) = 0.332pb

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

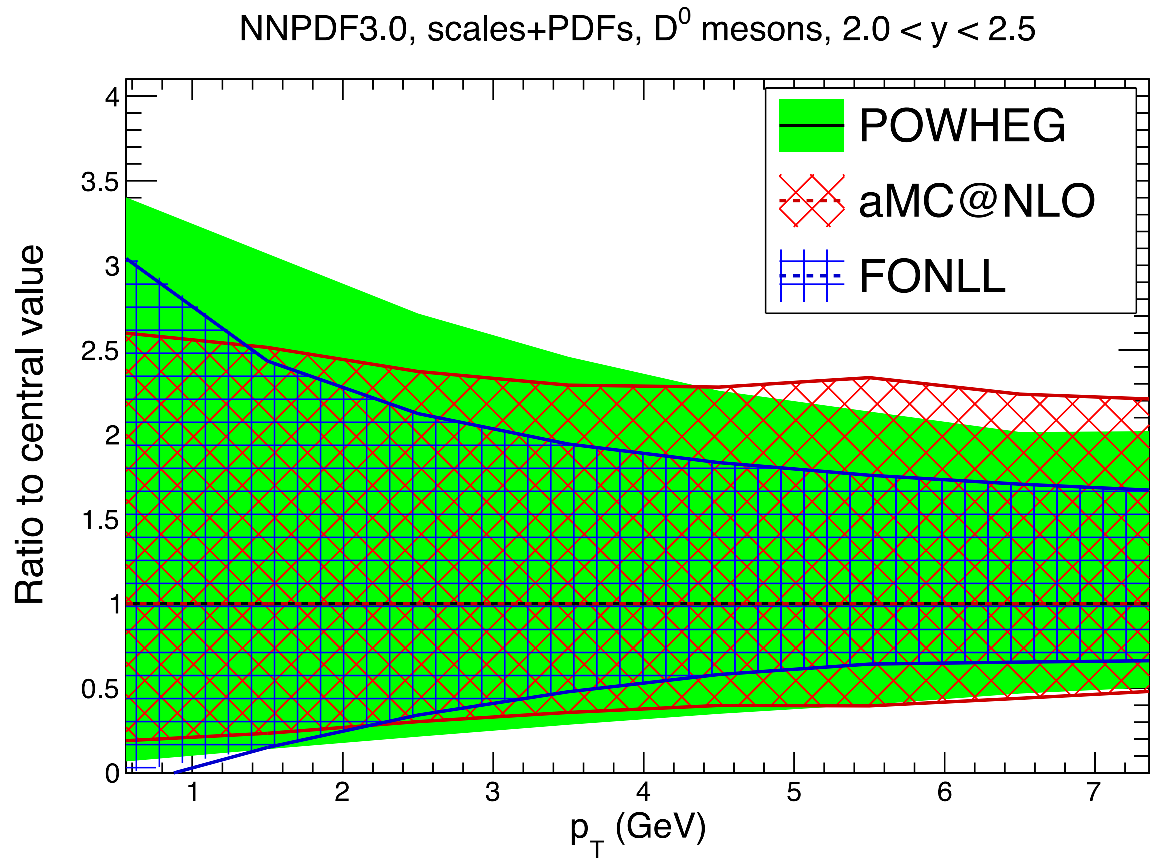
MPI effects

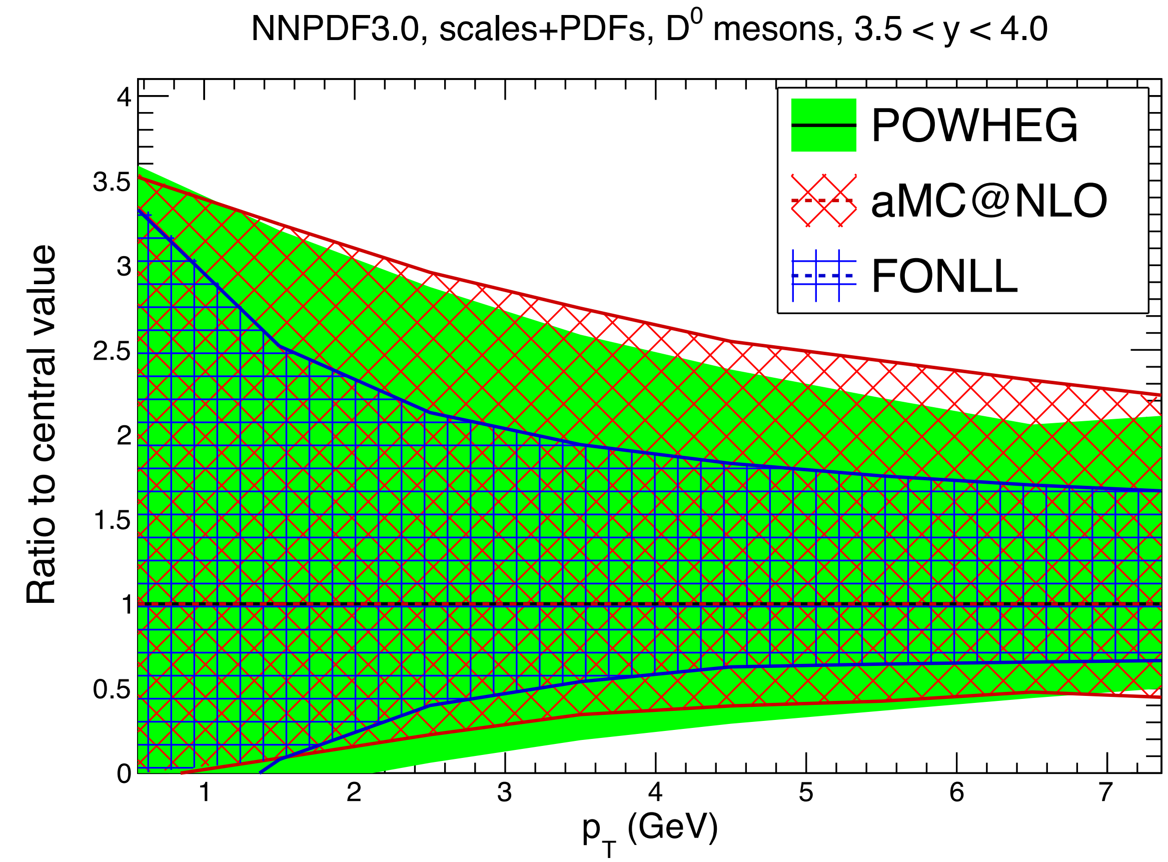


Z+c-jet Z+jet Ratio

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 $P_{T,c} > 5\ \mathrm{GeV}$ 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%)

Z+b-jet and unfolding

How to account for theory-experiment mismatch?

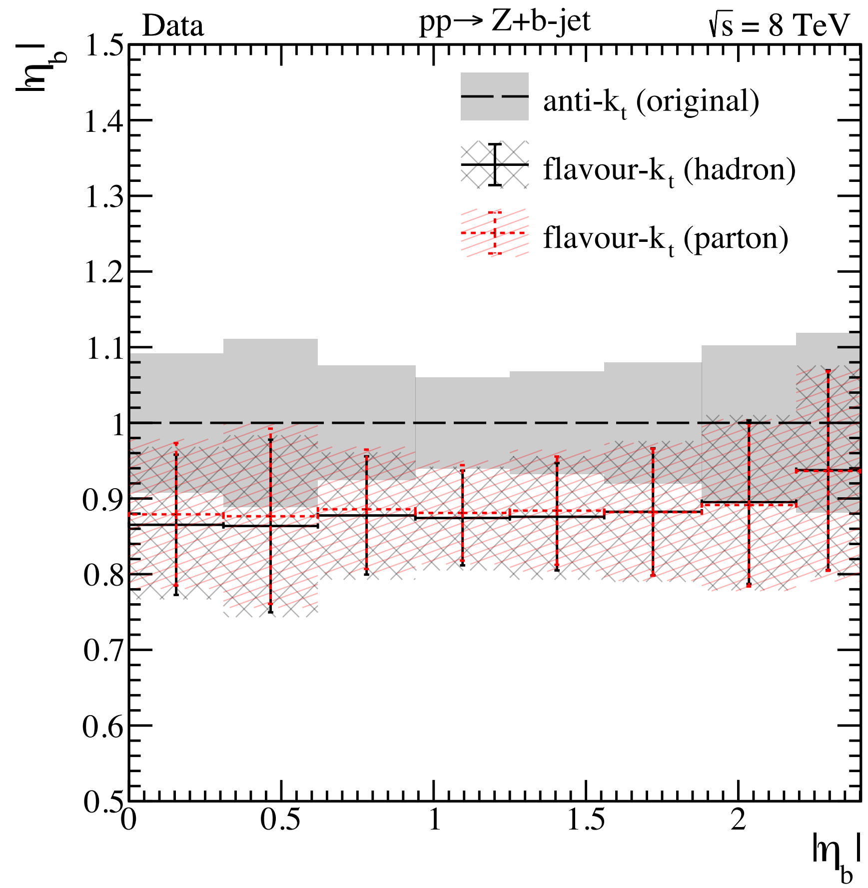
[Gauld, Gehrmann-De Ridder, Glover, Huss, Majer] *PRL* 125 (2020) 22, 222002

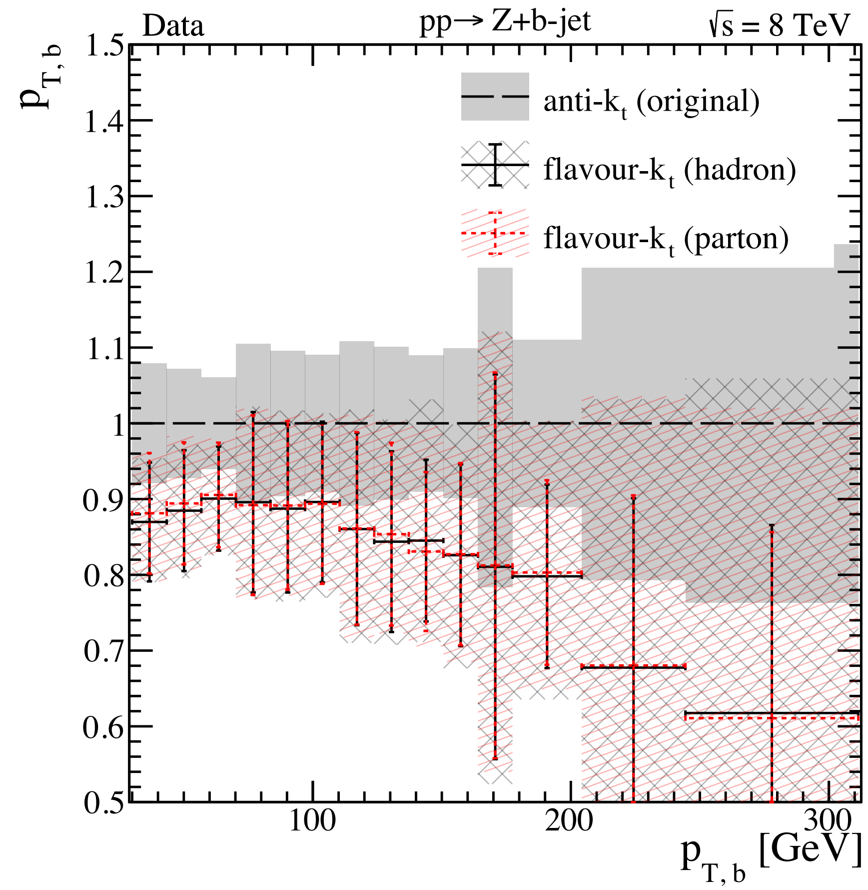
Use an NLO + Parton Shower prediction (which can evaluate both)

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)