Flavoured jets and particles at the LHC

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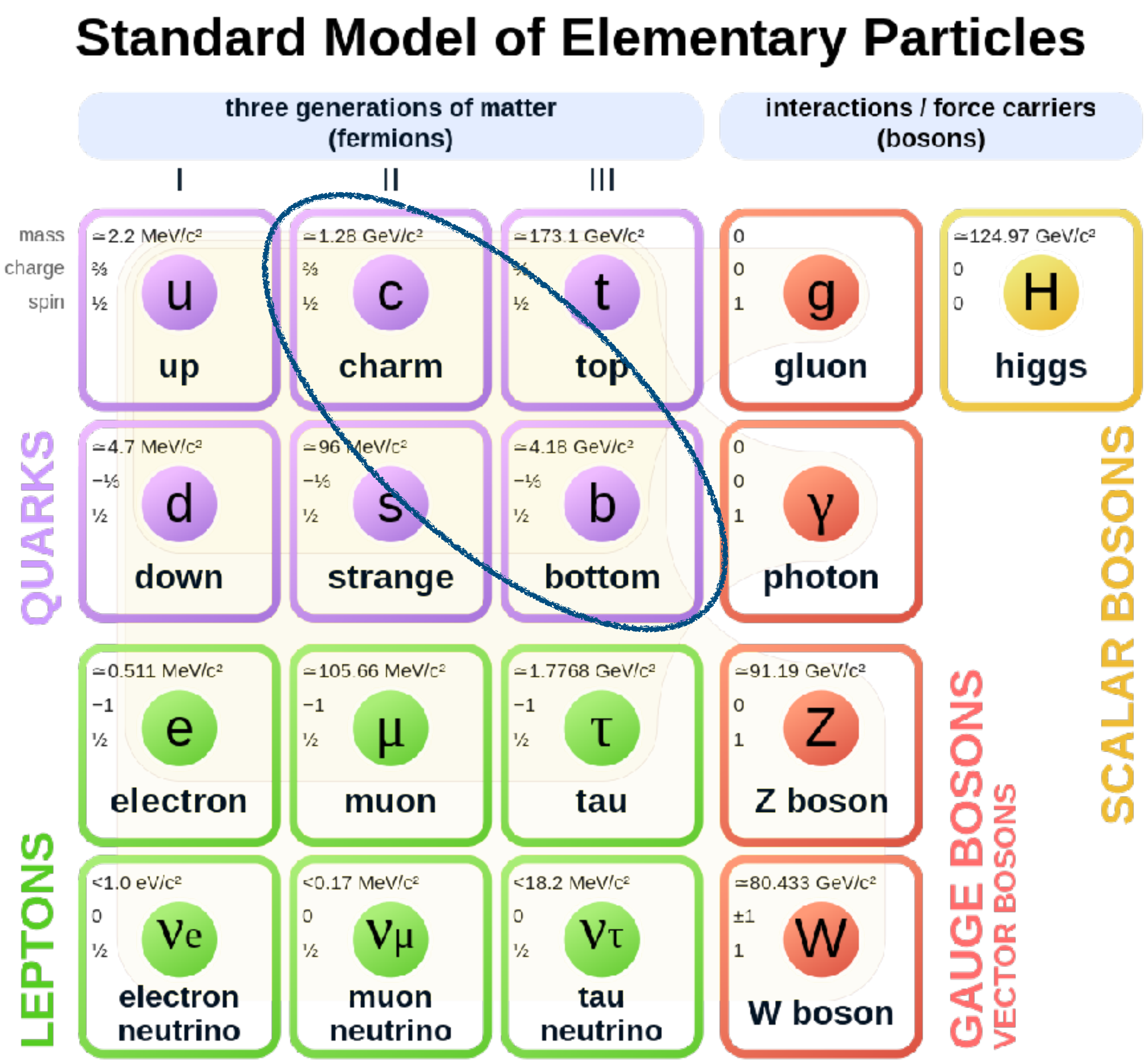
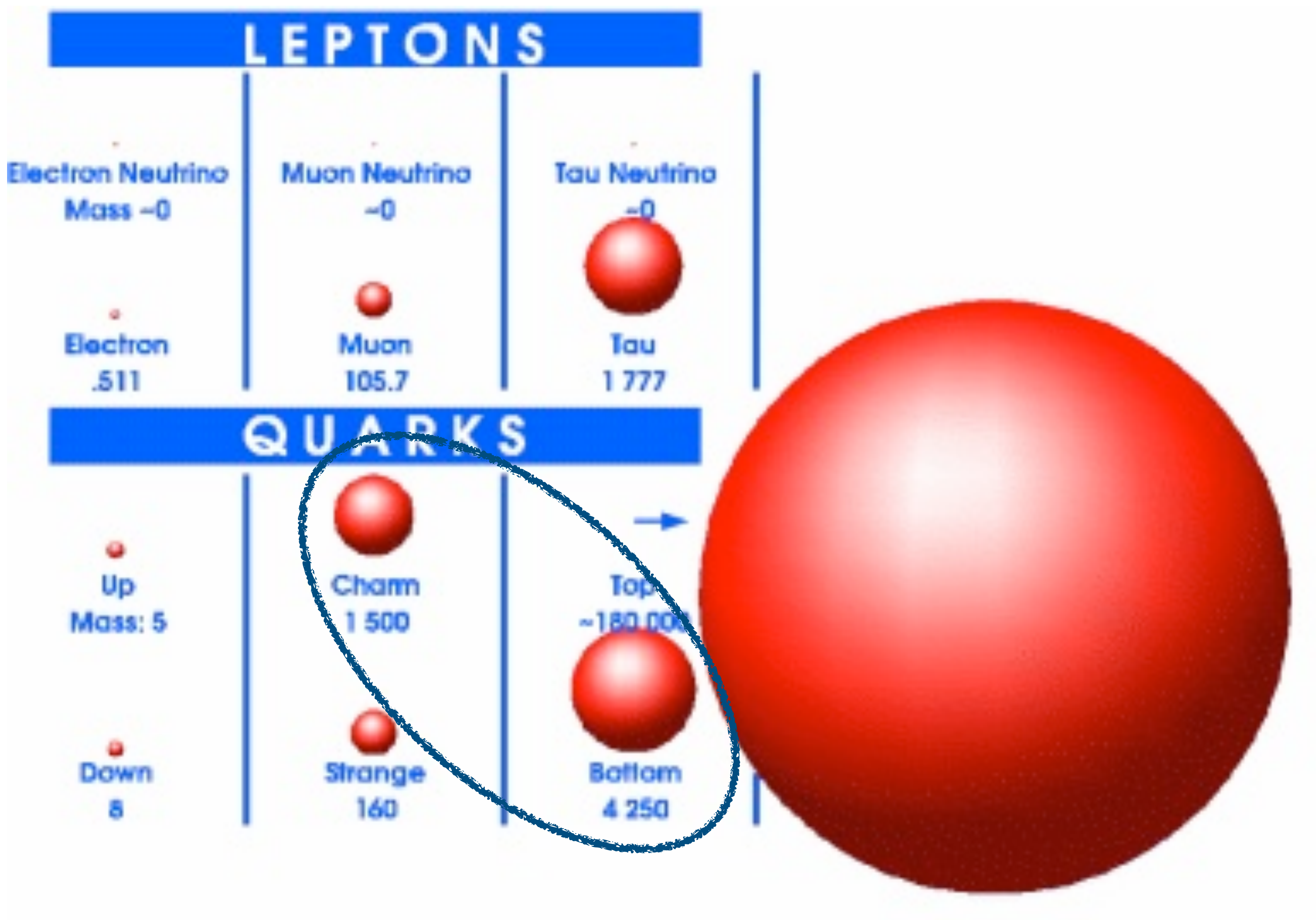
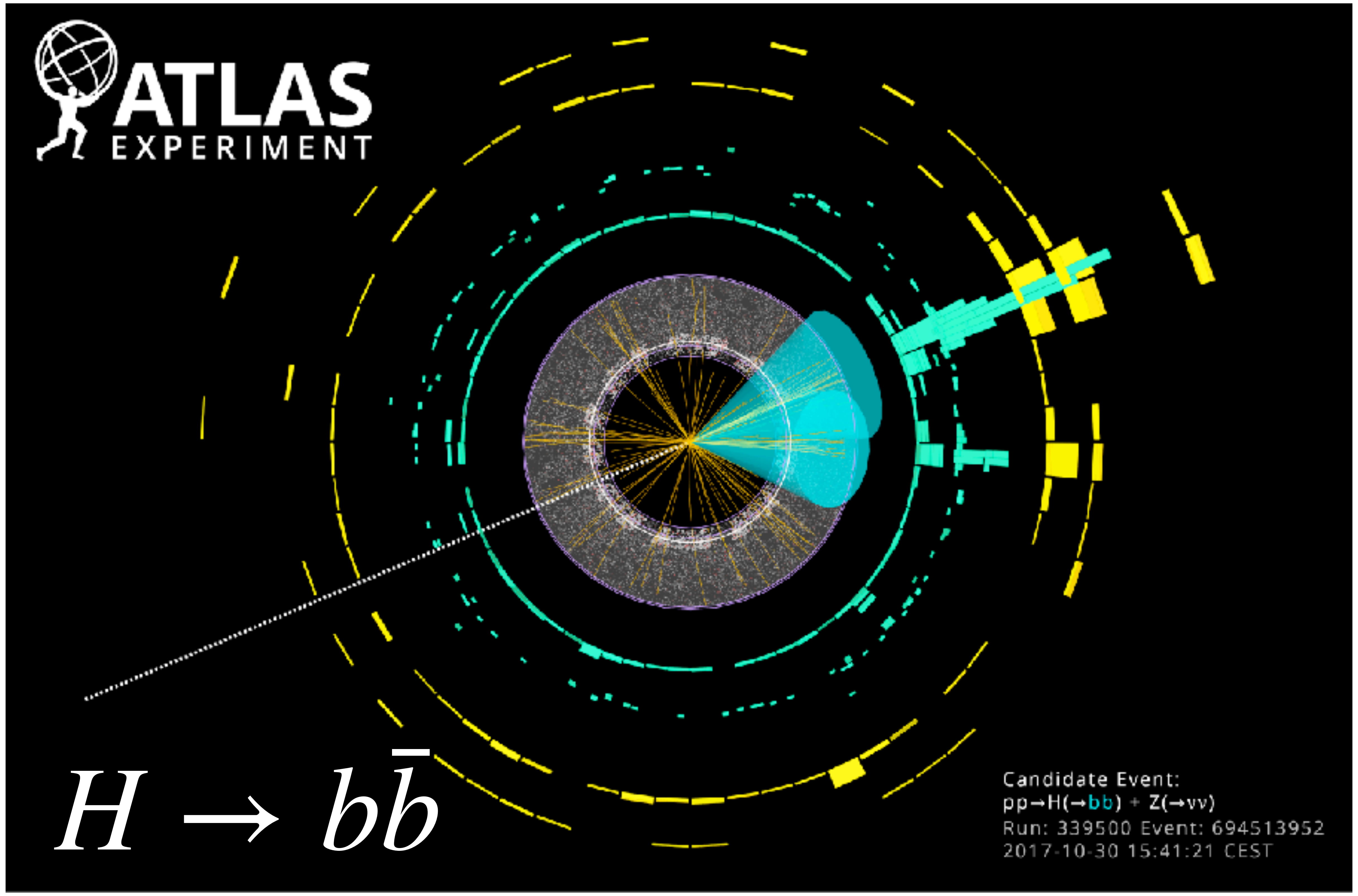
Flavoured (heavy) quarks

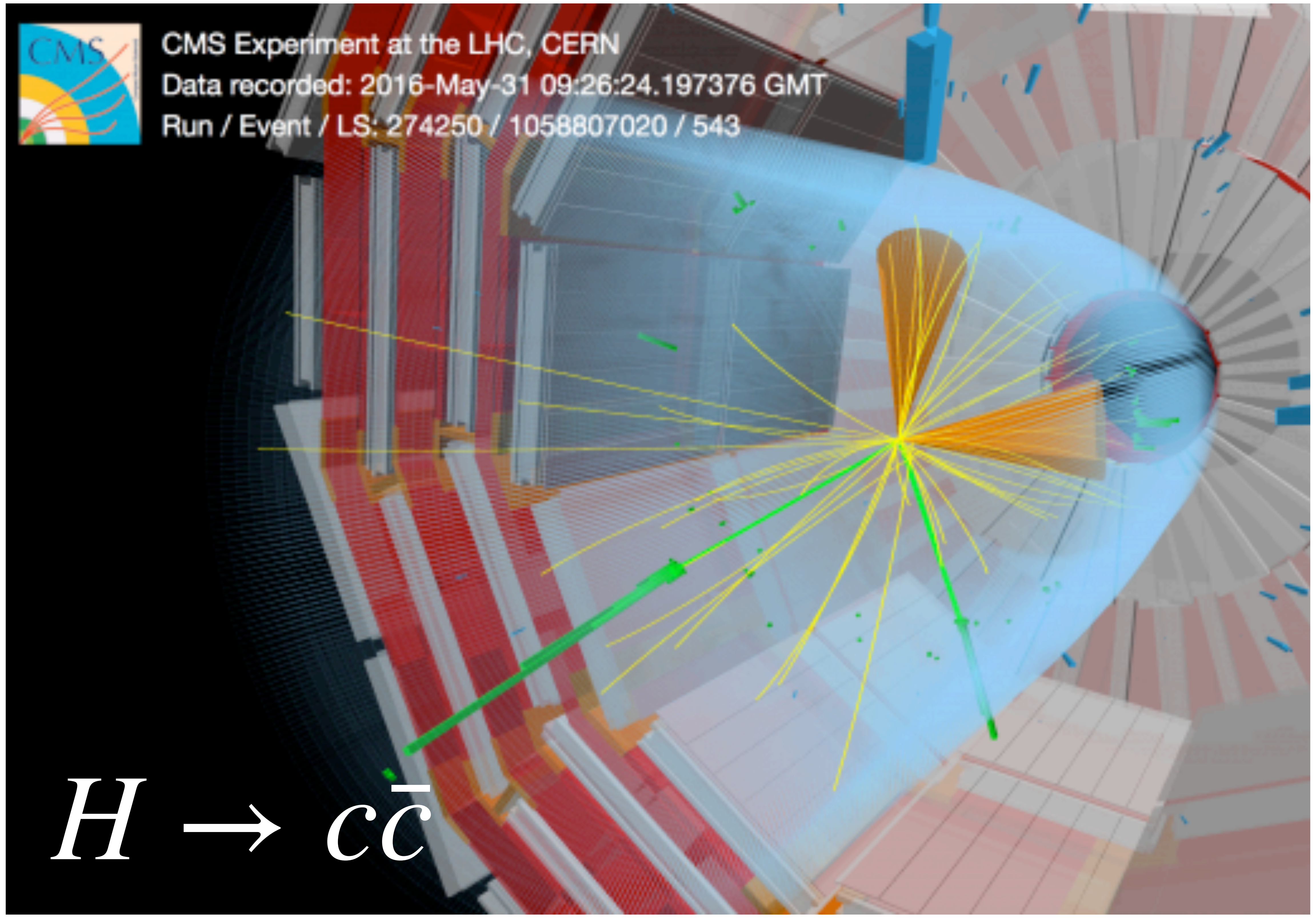




There's a difference between beauty and charm.
A beautiful person/quark is one I notice.
A charming person/quark is one who notices me.
(John Erskine)

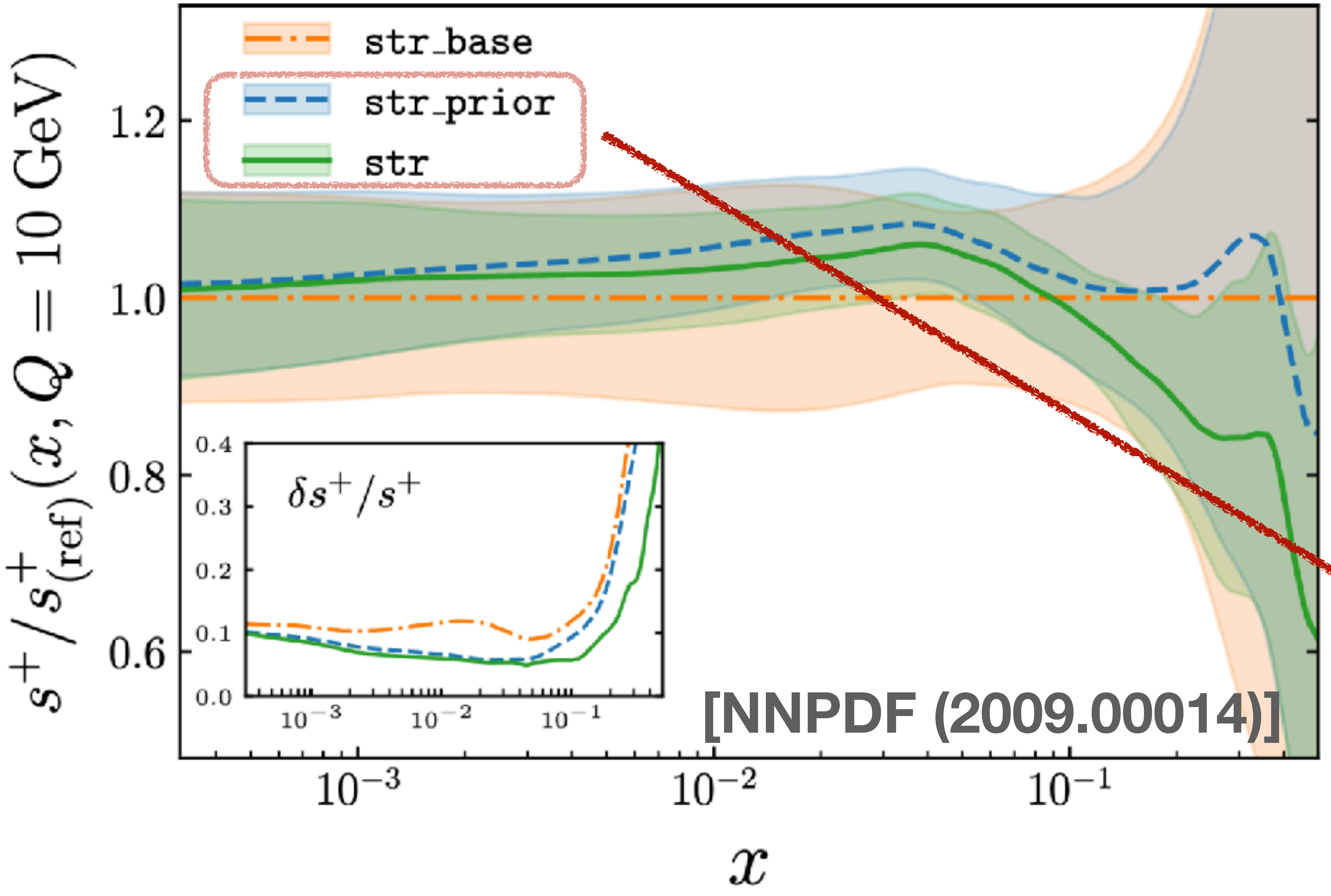
Flavoured objects at the LHC



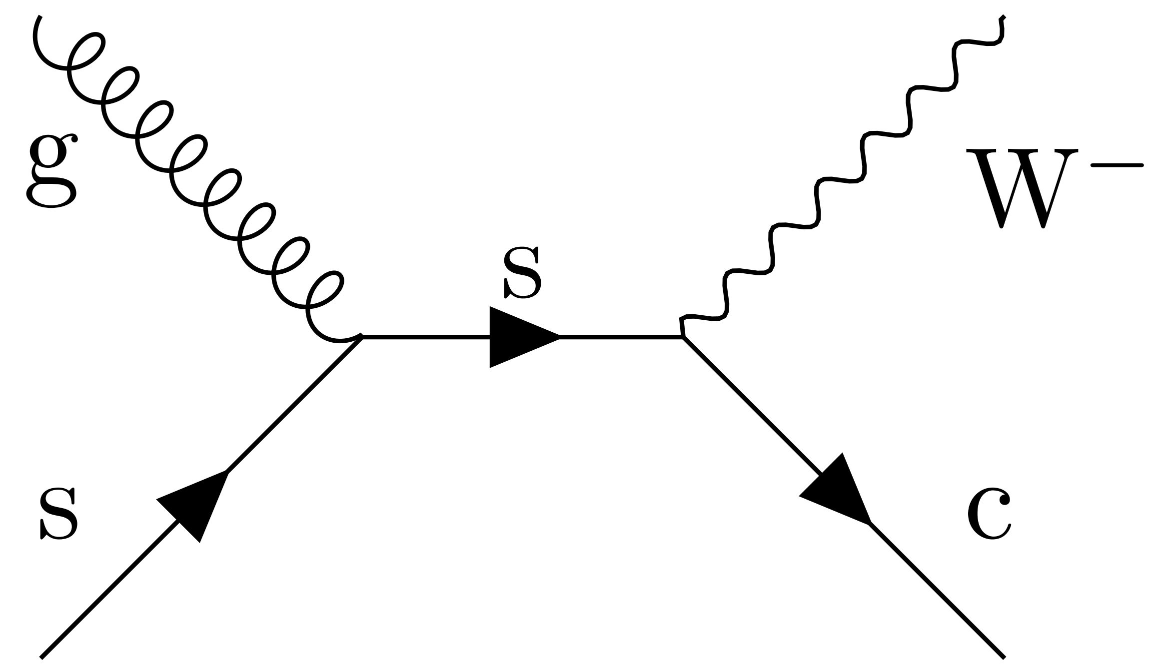


Decay products of B- or D-hadrons
as a **proxy** for b or c quarks in the hard scattering process

Why flavoured objects?



An example: W+D-hadron/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

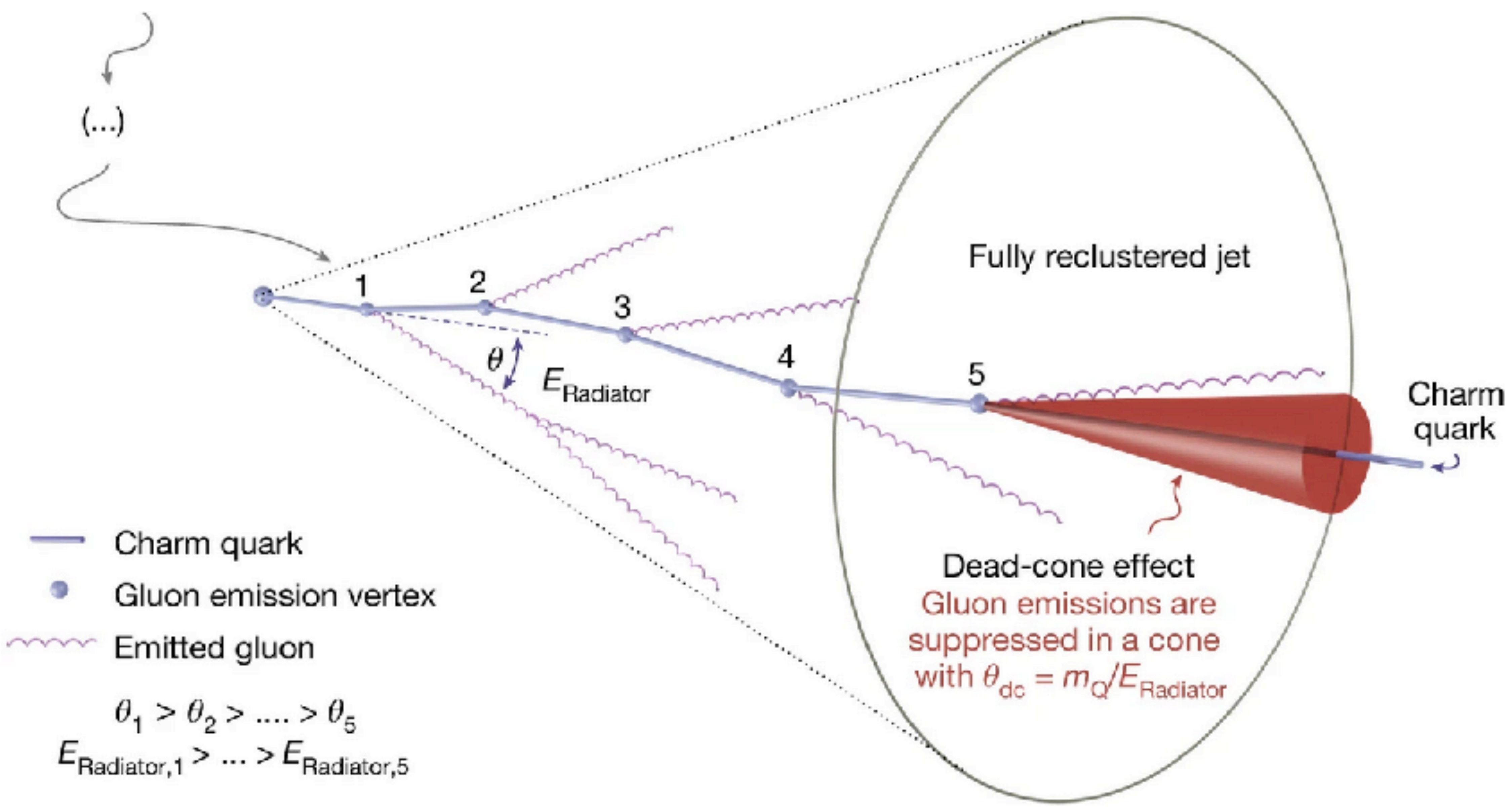
Heavy quarks are *Nature*'s aficionados

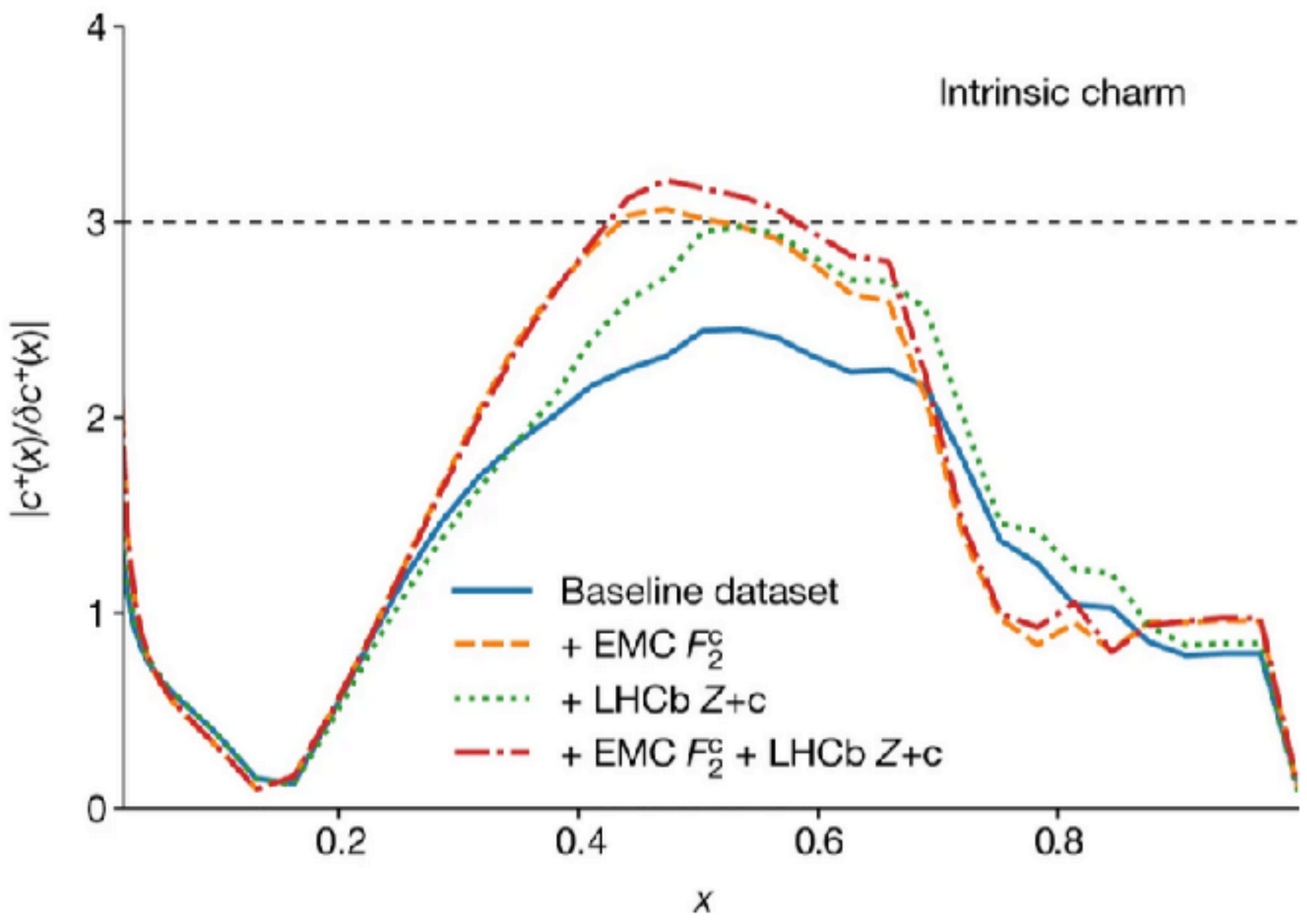
Article | Open Access | Published: 18 May 2022

Direct observation of the dead-cone effect in quantum chromodynamics

ALICE Collaboration

Nature **605**, 440–446 (2022) | Cite this article





Article | Open Access | Published: 17 August 2022

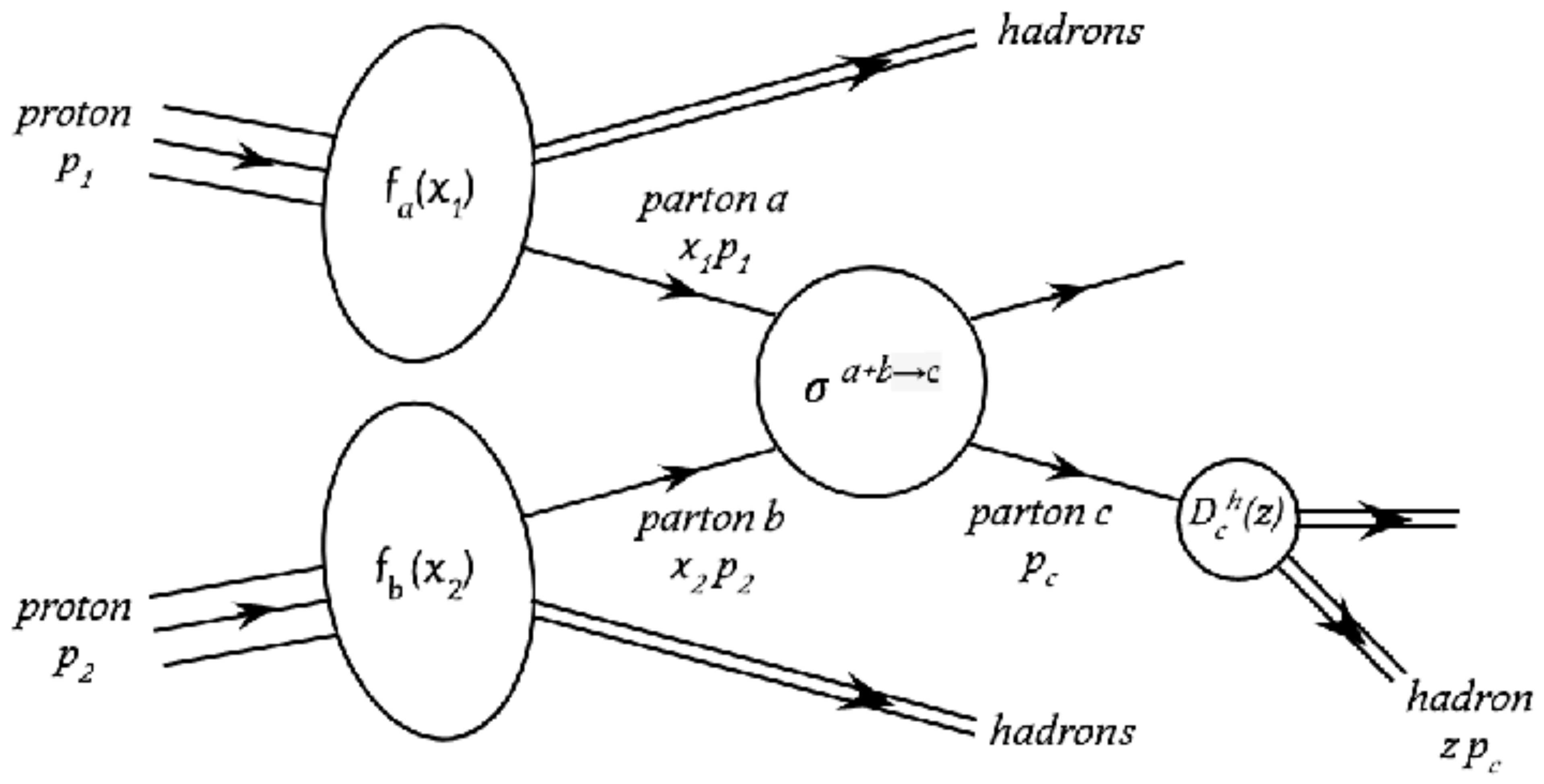
Evidence for intrinsic charm quarks in the proton

The NNPDF Collaboration

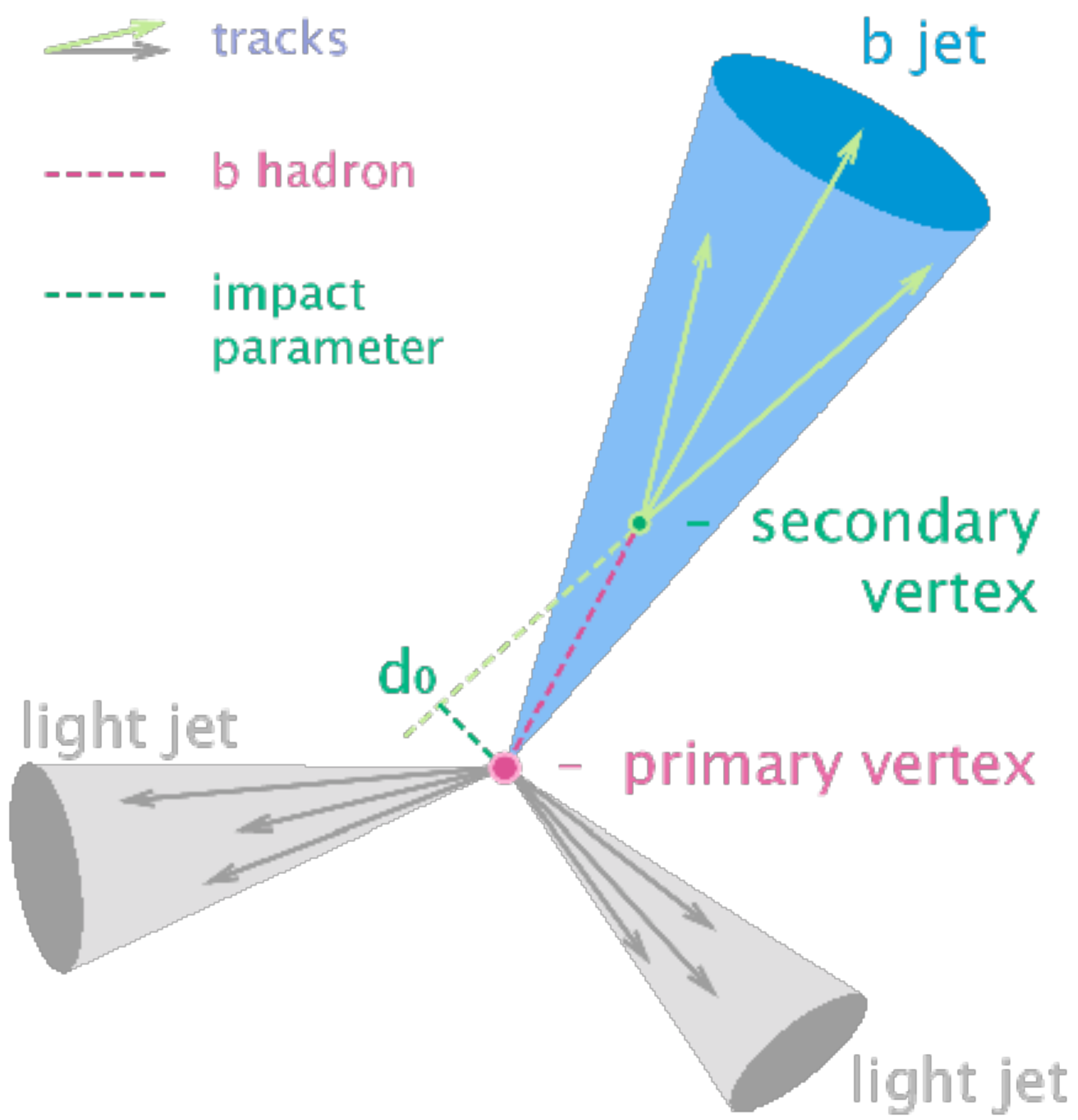
Nature **608**, 483–487 (2022) | Cite this article

Two ways of looking at flavour

*not a review, presentation biased towards my ongoing projects



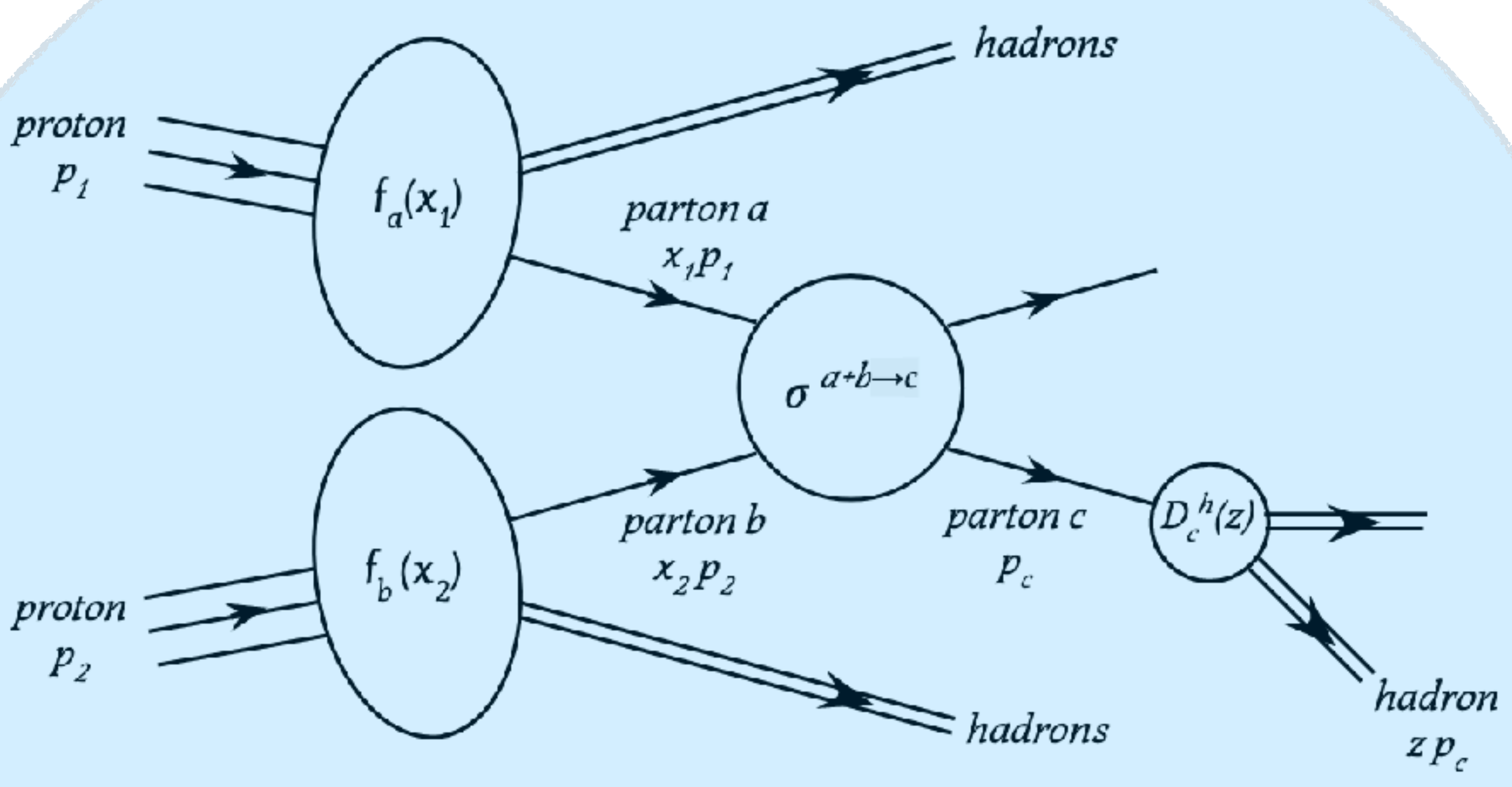
Identified hadrons



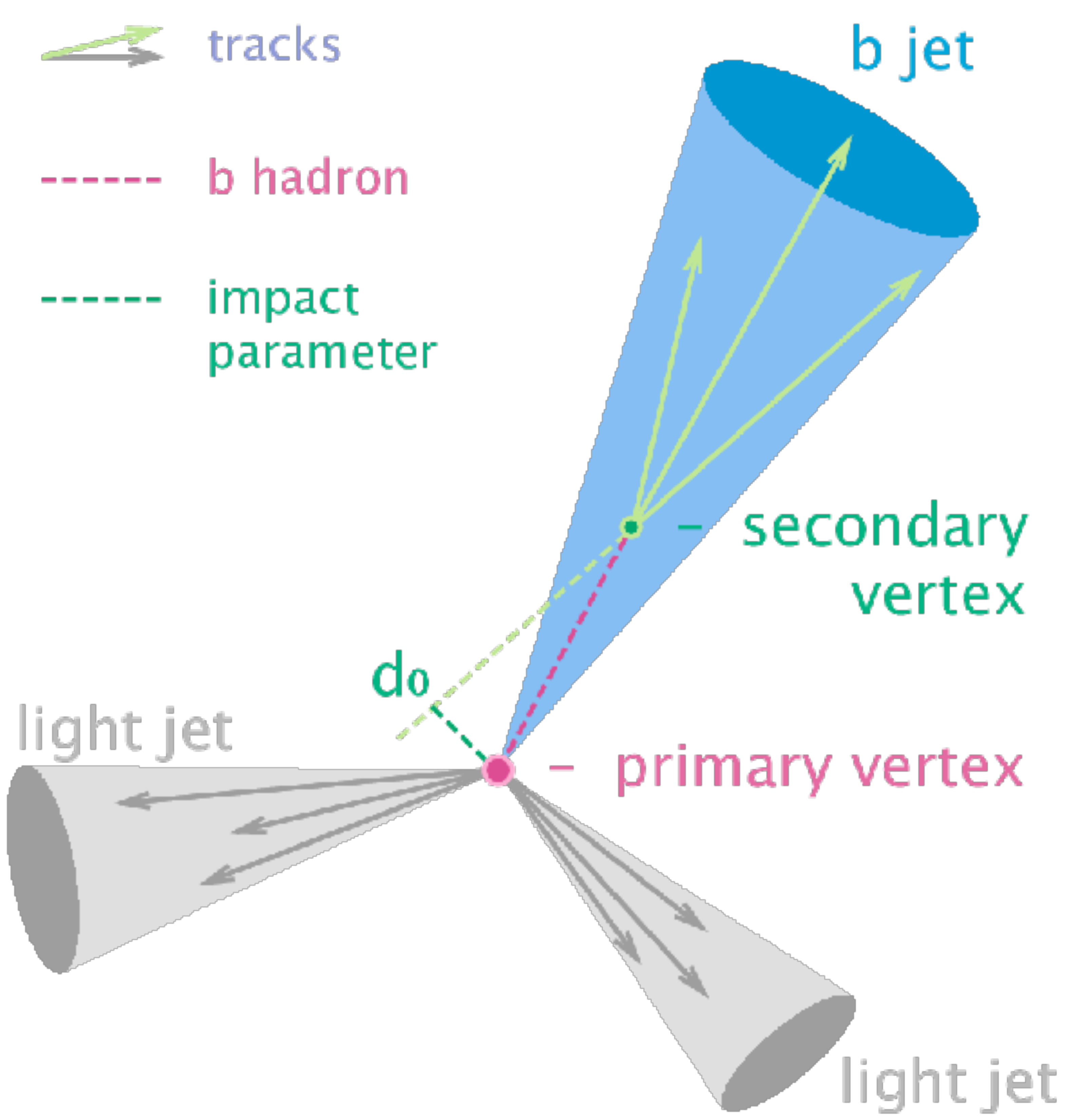
Flavoured jets

Flavoured particles and flavoured jets are **two complementary ways** of looking at the same events

Two ways of looking at flavour



Identified hadrons



Flavoured jets

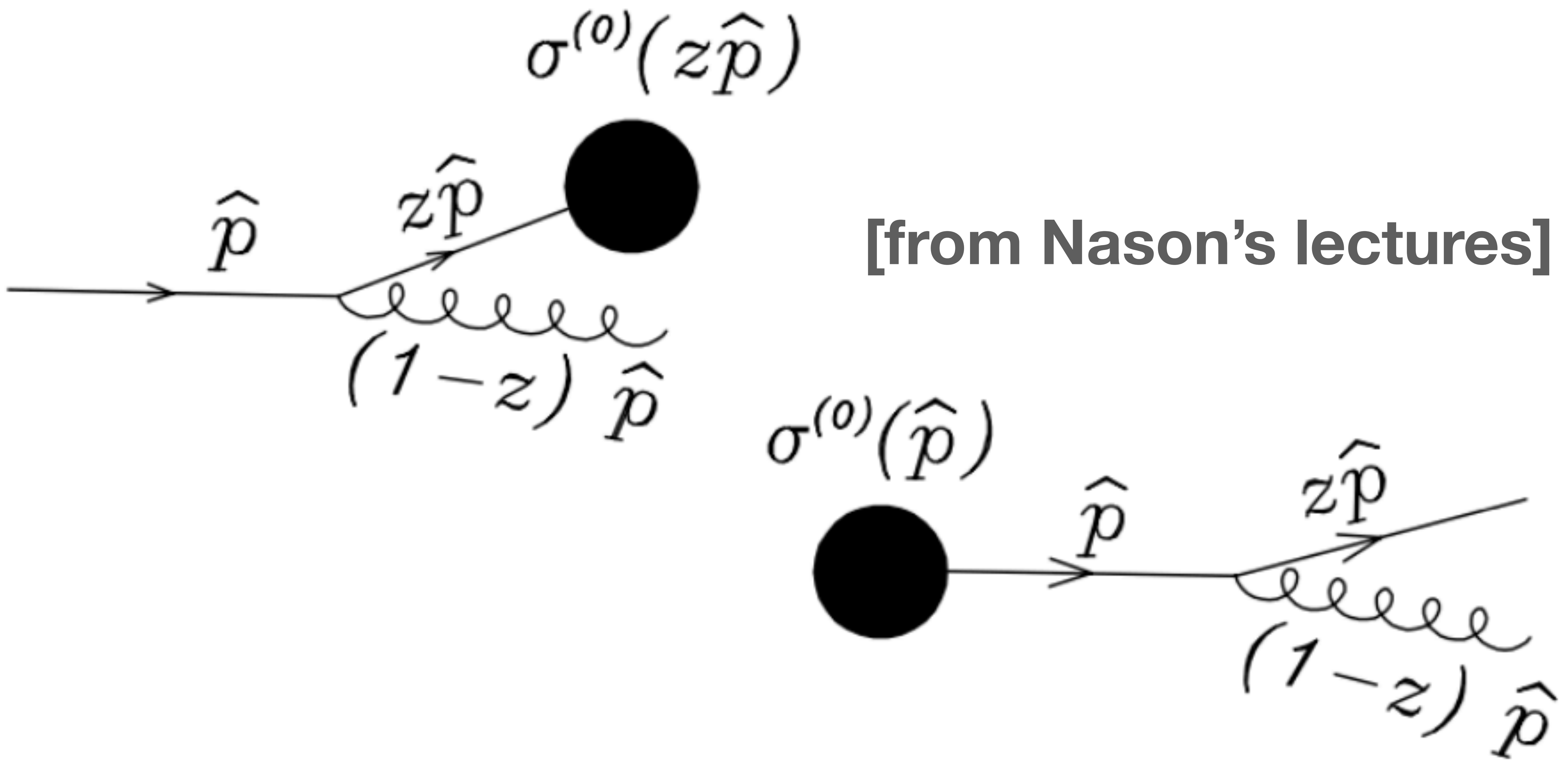
Identified hadrons

$$d\sigma^H = \sum_p \int d\eta\, D_{H\leftarrow p}(\eta, \mu_a^2)\, d\hat{\sigma}_p(\eta, \mu_a^2)$$

Fixed order parton prediction convolved with a non-perturbative **fragmentation function** (FF) to describe transition to hadrons

Whenever we identify a QCD particle, we spoil the cancellation of collinear divergences! FF = "final-state PDF"

We absorb divergences into a bare FF to result in the physical FF



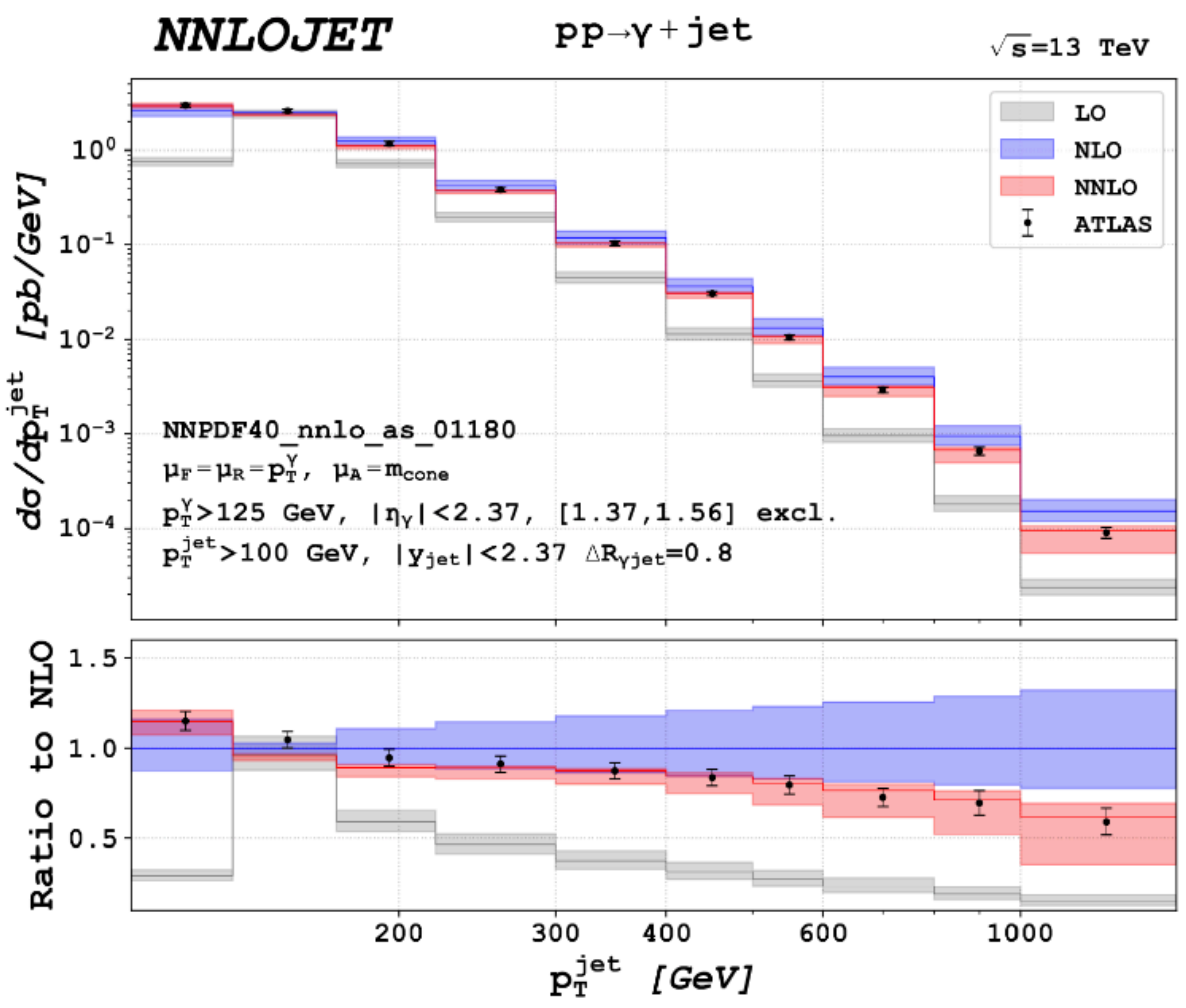
[from Nason's lectures]

NNLO QCD with identified particles

- Parton-to-photon fragmentation processes in the antenna subtraction formalism (photon as the identified particle) → → **[Schürmann, Gehrmann 2022] [Chen et al. 2022]**

- B-hadron production in $t\bar{t}$ events in the sector-improved residue subtraction scheme **[Czakon et al. 2021]**

- Analytic ingredients for **fully exclusive identified hadrons (i.e. possible presence of additional jets)** in e^+e^- in the antenna subtraction formalism **[Gehrmann, GS 2022]**



Antenna subtraction with identified hadrons

[Gehrmann, GS 2022]

$$e^+e^- \to h + X(+\text{jets})$$

$$\mathrm{d}\hat{\sigma} = \mathrm{d}\hat{\sigma}^{\mathrm{LO}} + \left(\frac{\alpha_s}{2\pi}\right) \mathrm{d}\hat{\sigma}^{\mathrm{NLO}} + \left(\frac{\alpha_s}{2\pi}\right)^2 \mathrm{d}\hat{\sigma}^{\mathrm{NNLO}}$$

Deal with infrared divergences in the intermediate steps of the calculations, by introducing subtractions terms and adding them back analytically integrated

$$\mathrm{d}\hat{\sigma}^{\mathrm{LO}} = \int_n \left[\mathrm{d}\hat{\sigma}^{\mathrm{B}}\right]$$

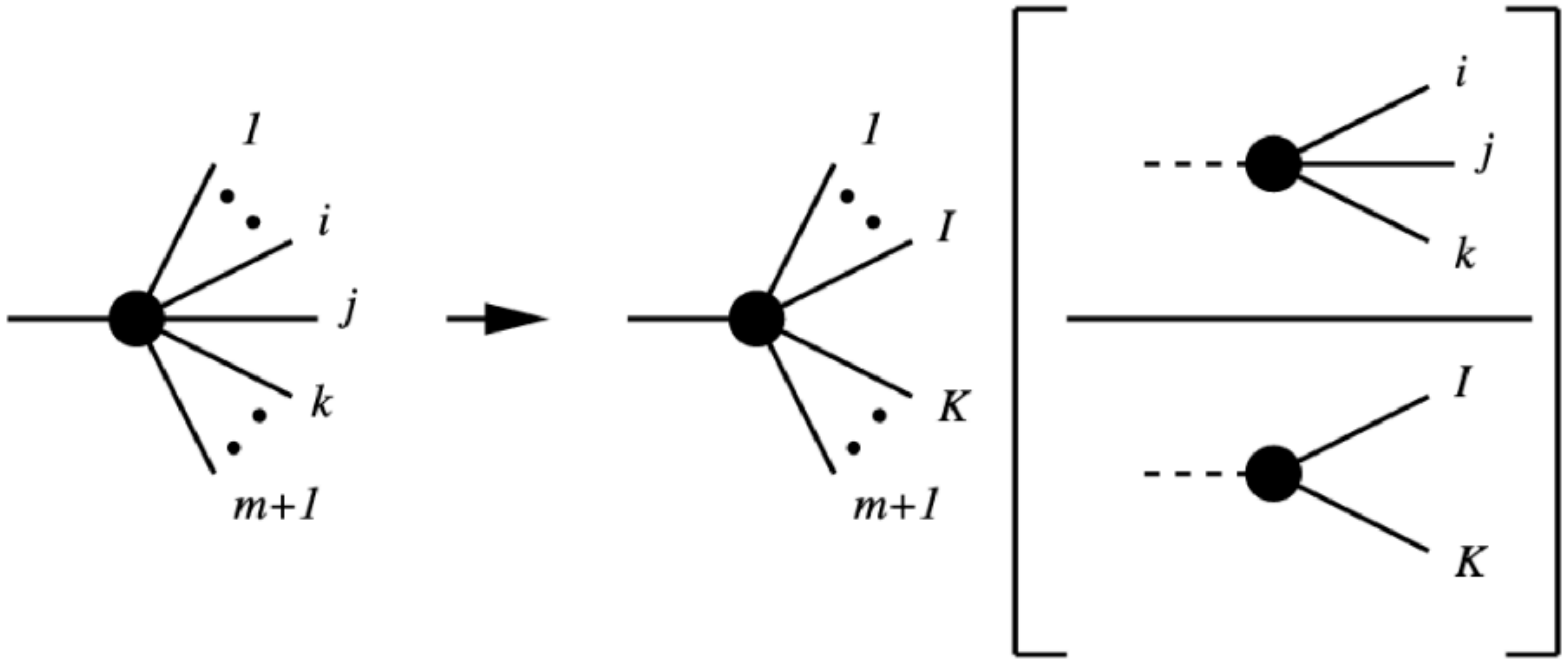
$$\mathrm{d}\hat{\sigma}^{\mathrm{NLO}} = \int_{n+1} \left[\mathrm{d}\hat{\sigma}^{\mathrm{R}} - \mathrm{d}\hat{\sigma}^{\mathrm{S}}\right] + \int_n \left[\mathrm{d}\hat{\sigma}^{\mathrm{V}} - \mathrm{d}\hat{\sigma}^{\mathrm{T}} - \underline{\mathrm{d}\hat{\sigma}^{\mathrm{MF}}}\right]$$

Timelike
mass factorisation

$$\mathrm{d}\hat{\sigma}^{\mathrm{NNLO}} = \int_{n+2} \left[\mathrm{d}\hat{\sigma}^{\mathrm{RR}} - \mathrm{d}\hat{\sigma}^{\mathrm{S}}\right] + \int_{n+1} \left[\mathrm{d}\hat{\sigma}^{\mathrm{RV}} - \mathrm{d}\hat{\sigma}^{\mathrm{T}} - \underline{\mathrm{d}\hat{\sigma}^{\mathrm{MF,RV}}}\right] + \int_n \left[\mathrm{d}\hat{\sigma}^{\mathrm{VV}} - \mathrm{d}\hat{\sigma}^{\mathrm{U}} - \underline{\mathrm{d}\hat{\sigma}^{\mathrm{MF,VV}}}\right]$$

NLO real subtraction term $\mathrm{d}\hat{\sigma}^S$

Antenna functions encapsulate unresolved radiation between a pair of hard emitters



M_{n+1}(original momenta) $\to M_n$(mapped momenta) $\times\, X$(original momenta)

$X(p_i, p_j, p_k)$ = **antenna function**
(basically matrix element
of simple processes,
properly normalised)

$M_n(\ldots, \tilde{p}_{ij}, \tilde{p}_{jk}, \ldots)$ = **reduced matrix element** with **mapped momenta**

If the identified particle not involved in the infrared limit,
just standard momentum mapping **[Gehrmann-De Ridder, Gehrmann, Glover 2005]**

NLO real subtraction term $\mathrm{d}\hat{\sigma}^S$

When the **identified parton** k_p is involved in the antenna, we need a **new mapping**:

$$M(k_1, \ldots, k_p, k_j, k_k, \ldots, k_{1+m}) \to M(k_1, \ldots, K_p, K, \ldots, k_{1+m}) \times X(k_p, k_j, k_k)$$

$$z = \frac{s_{pj} + s_{pk}}{s_{pj} + s_{pk} + s_{jk}}\,, \quad K_p = k_p/z\,, \quad K = k_j + k_k - (1-z)\frac{k_p}{z}$$

The phase space factorises as:

$$\mathrm{d}\Phi_{m+1}(k_1, \ldots, k_p, k_j, k_k, \ldots, k_{m+1}) = \mathrm{d}\Phi_m(k_1, \ldots, K_p, K, \ldots, k_{m+1})\frac{q^2}{2\pi}\mathrm{d}\Phi_2(k_j, k_k; q - k_h)\, z^{1-2\varepsilon}\,\mathrm{d}z$$

$$q = k_j + k_k + k_h$$

NLO virtual subtraction term $\mathrm{d}\hat{\sigma}^{\mathrm{T}}$

We analytically integrate the antenna function, by leaving an **explicit dependence** on z:

$$\mathcal{X}_{30}^{\mathrm{id}.p}(z) = \frac{1}{C(\epsilon)} \int \mathrm{d}\Phi_2 \frac{q^2}{2\pi} z^{1-2\varepsilon} X_{30}^{\mathrm{id}.p}, \quad C(\varepsilon) = (4\pi e^{-\gamma_E})^{\varepsilon}/(8\pi^2)$$

over the two-particle phase space with kinematics

$$q(q^2) + (-k_p) \to k_j + k_k, \quad s_{jk} = (q - k_p)^2 = q^2(1 - z)$$

The **poles** of the integrated antenna function **cancel** against some of the explicit poles of the virtual matrix element; the remaining poles are removed by the mass factorisation terms.

Subtraction at NNLO

- *Double-real subtraction term* $\mathrm{d}\hat{\sigma}^{\mathrm{S}}$: single unresolved subtracted by X_3^0, double unresolved limit subtracted by X_4^0, with product of $X_3^0 X_3^0$ to avoid over-subtraction; large-angle soft subtraction terms. With identified particle, generalisation of NLO mapping:

$$z = \frac{s_{pj} + s_{pk} + s_{pl}}{s_{pj} + s_{pk} + s_{jk} + s_{pl} + s_{jl} + s_{kl}}\,, \quad K_p = k_p/z\,, \quad K = k_j + k_k + k_l - (1-z)\frac{k_p}{z}$$

- *Real-virtual subtraction term* $\mathrm{d}\hat{\sigma}^{\mathrm{V}}$: explicit poles cancel against integration of X_3^0 and mass factorisation terms; single unresolved limit subtracted by $X_3^0 M_n^1 + X_3^1 M_n^0$.

- *Double-virtual subtraction term*: no unresolved limits; all the explicit poles cancel against integrated pieces from the layers above, and mass factorisation terms.

Integration of NNLO antenna functions

$$\mathcal{X}_{40}^{\mathrm{id}.p}(z) = \frac{1}{[C(\varepsilon)]^2} \int \mathrm{d}\Phi_3 \frac{q^2}{2\pi} z^{1-2\varepsilon} X_{40}^{\mathrm{id}.p} \qquad \mathcal{X}_{31}^{\mathrm{id}.p}(z) = \frac{1}{C(\varepsilon)} \int \mathrm{d}\Phi_2 \frac{q^2}{2\pi} z^{1-2\varepsilon} X_{31}^{\mathrm{id}.p}$$

with kinematics: $q(q^2) + (-k_p) \to k_1 + k_2(+k_3),\ s = q^2(1-z)$

Well-known technique: phase space expressed in terms of cut propagators; reduction to master integrals with Reduze **[Manteuffel, Studerus 2012]**; master integrals derived by explicit evaluation or via differential equations **[Gehrmann, Remiddi 2000]** in the canonical form **[Henn 2015]**; solutions in terms of harmonic polylogarithms **[Remiddi, Vermaseren 2000]** with boundary conditions fixed by internal consistency or explicit evaluation at $z = 1$; finally expansion of $(1-z)^{-2\varepsilon}$ in term of distributions.

All analytical ingredients for identified hadron production in e^+e^- available

First application: **hadron-in-jet fragmentation in $e^+e^- \to$ 3 jets**

[work in progress Bonino, GS et al.]

Checks

Since antenna functions are derived from physical matrix elements,
we can check integrated expressions against known analytical results
for **one-particle inclusive coefficient functions** $\mathbb{C}_j$

$$\frac{\mathrm{d}\sigma^H}{\mathrm{d}x} = \sum_{i=q,\bar{q},g} \int_x^1 \frac{\mathrm{d}z}{z} D_i^H\left(\frac{x}{z}\right) \frac{\mathrm{d}\sigma_i^H}{\mathrm{d}z} = \sum_j \sigma_j^{(0)} \int_x^1 \frac{\mathrm{d}z}{z} D_j^H\left(\frac{x}{z}\right) \mathbb{C}_j(z)\,, \quad x = \frac{2E_h}{\sqrt{s}}$$

The coefficient functions can be expressed as a linear combination of:

$e^+e^- \to \gamma^* \to q\bar{q}$ **[Rijken, Van Neerven 1996,1997] [Mitov, Moch, Vogt 2006]**

quark-quark antennae $\mathscr{A}, \mathscr{B}, \mathscr{C}$ + quark form factors

$e^+e^- \to H \to gg$ **[Almasy, Moch, and Vogt 2012]**

gluon-gluon antennae $\mathscr{F}, \mathscr{G}, \mathscr{H}$ + gluon form factors

Moving towards *ep* and *pp* collisions

Missing ingredient: integrated antenna functions for unresolved radiation with **one hard radiator** k_i **in the initial state** and **one identified parton** k_p, already developed in part in the context of photon fragmentation

[Schürmann, Gehrmann 2022]

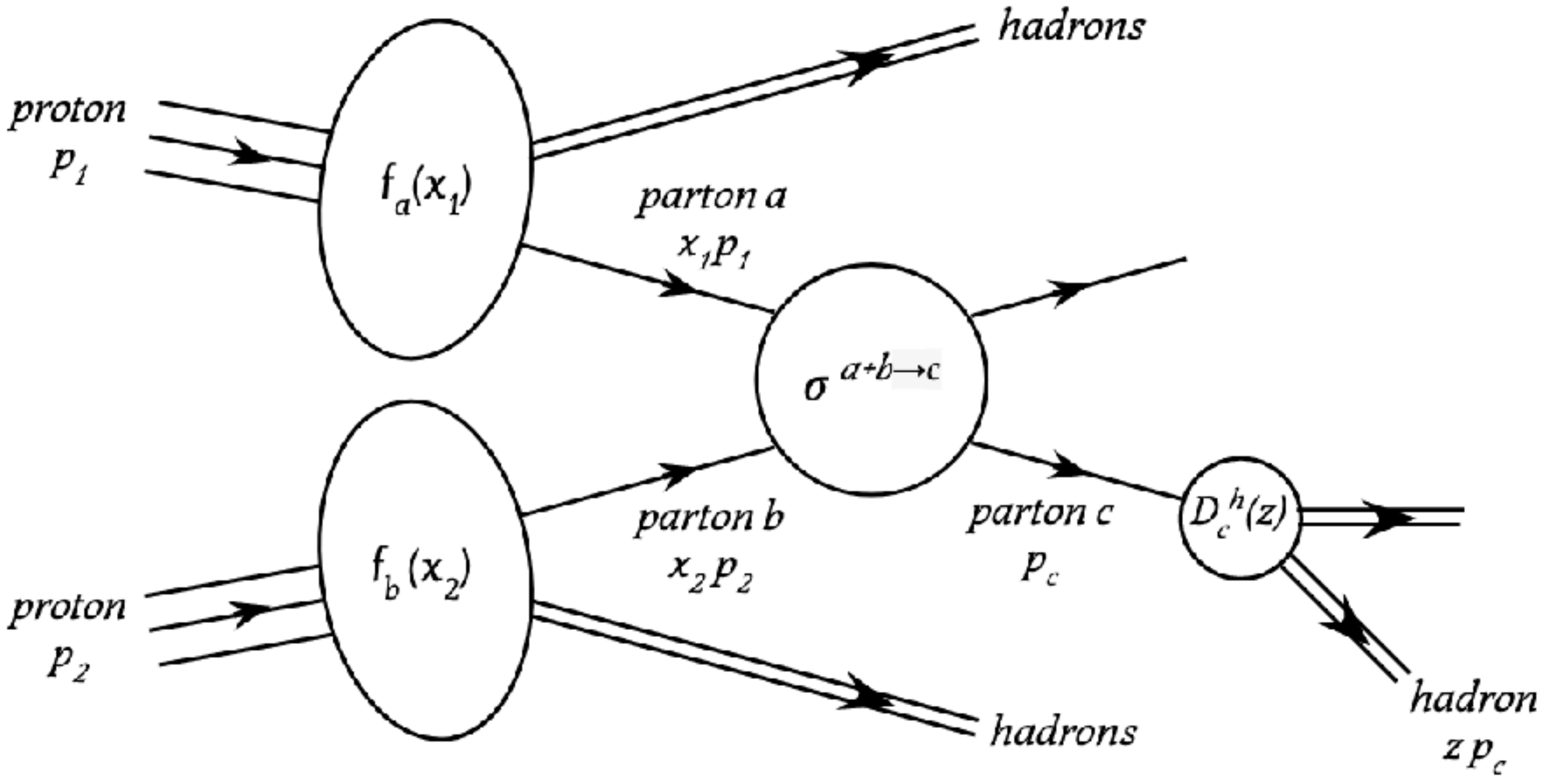
$$\mathcal{X}^{0,\mathrm{id.p}}_{i,pkl} = \frac{1}{C(\varepsilon)^2} \int \mathrm{d}\Phi_3(k_p, k_k, k_l; p_i, q)\,\delta\left(z - x\frac{(k_p+k_i)^2}{Q^2}\right) \frac{Q^2}{2\pi} X^0_{i,pkl}$$

with a different definition of z,where the initial state parton k_i acts as reference momentum

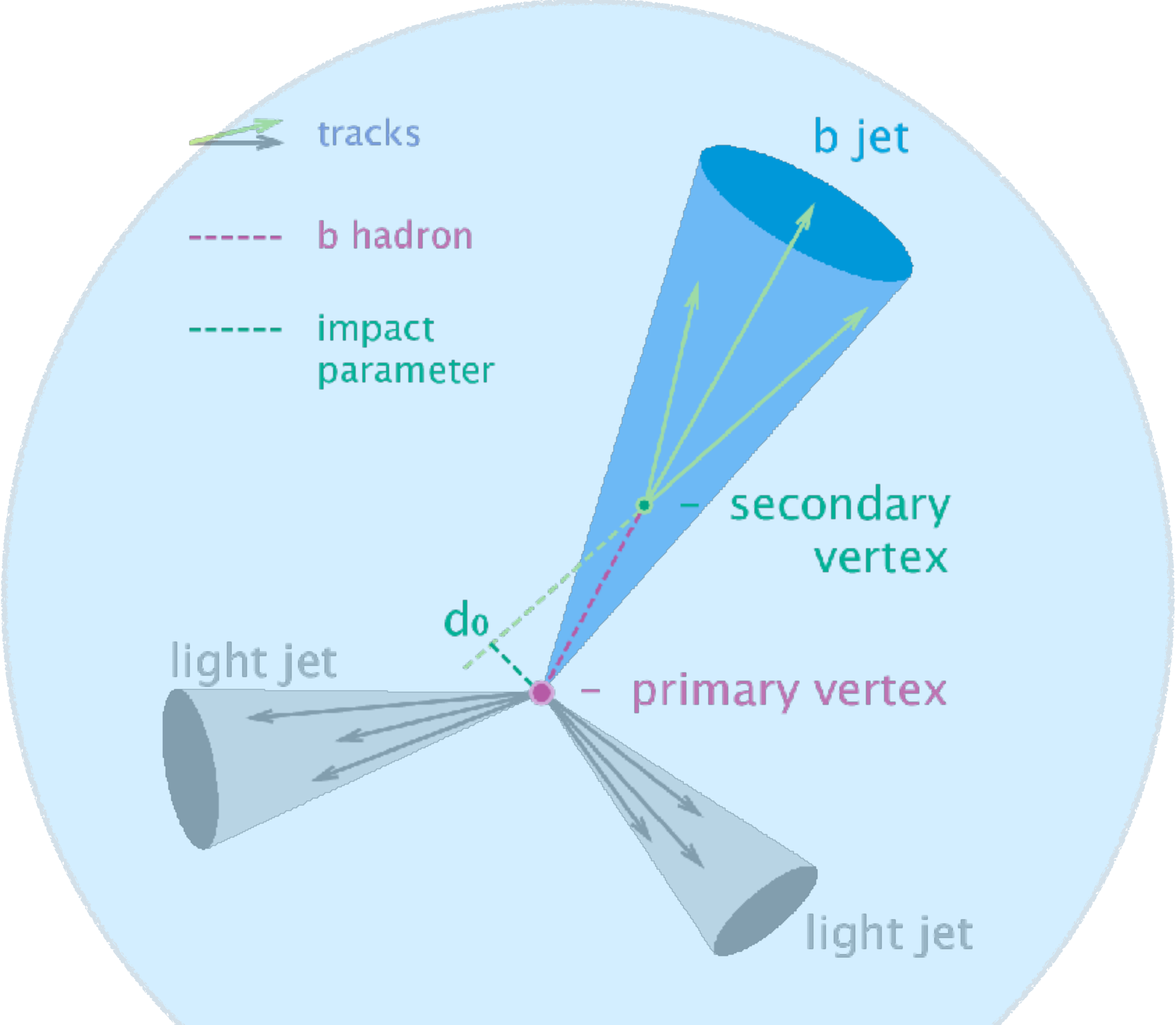
$$z = x\frac{(k_p+k_i)^2}{Q^2} = \frac{s_{pi}}{s_{pi}+s_{ki}+s_{li}} \equiv \frac{k_p \cdot k_i}{q \cdot k_i}$$

Work ongoing, we are integrating the missing antenna functions.
Stay tuned for first applications!

Two ways of looking at flavour



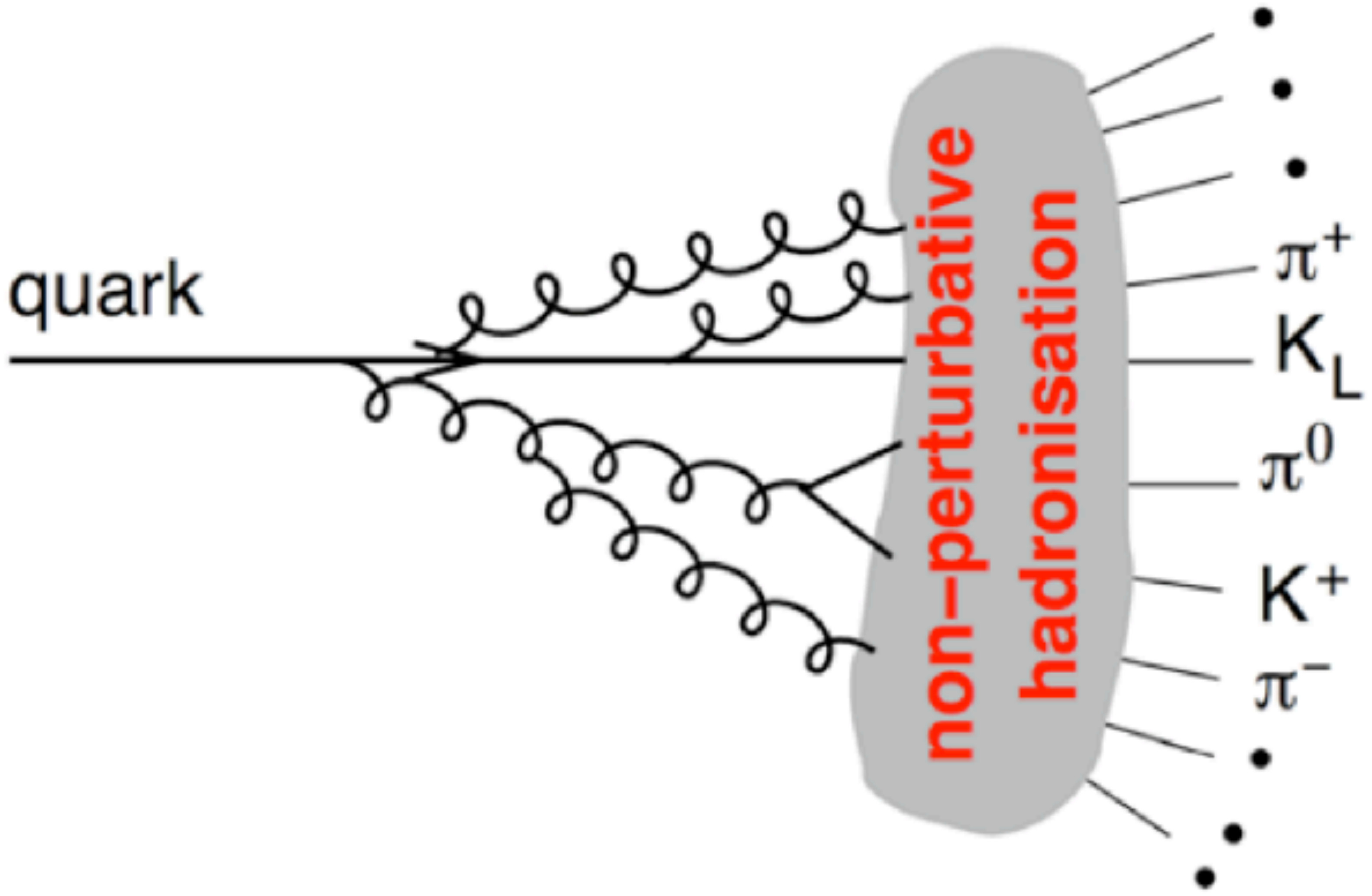
Identified hadrons

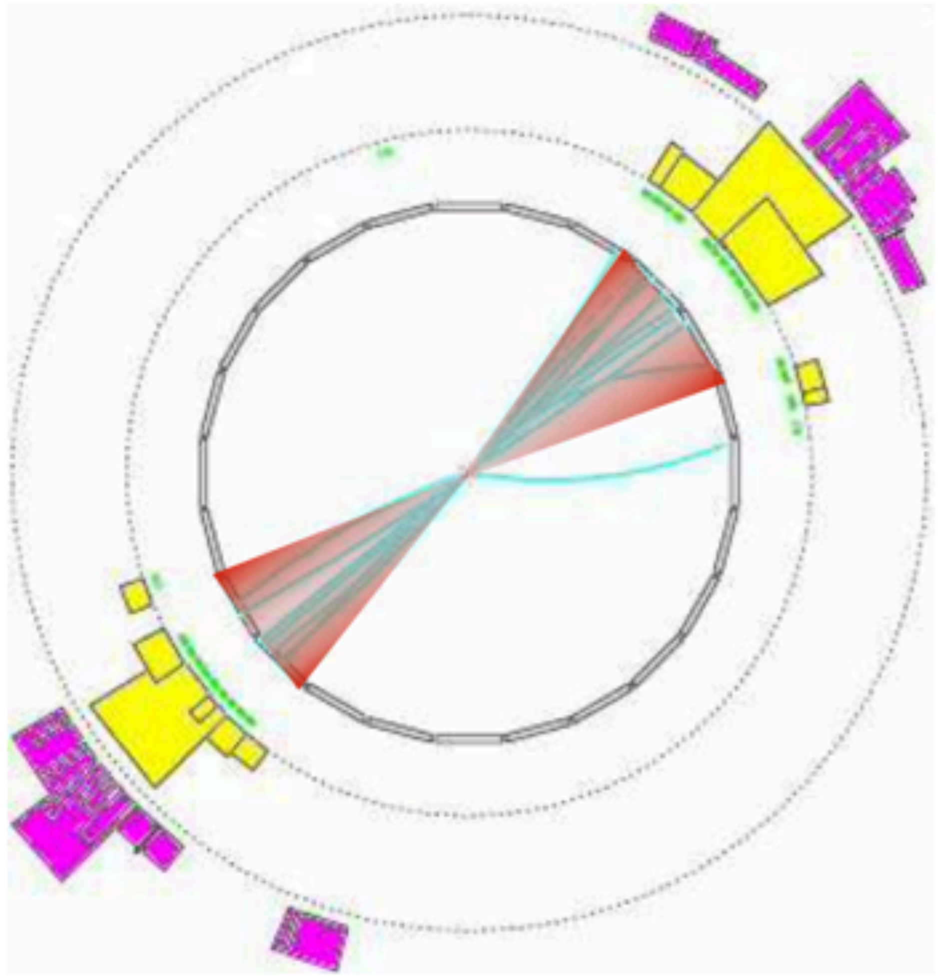


Flavoured jets

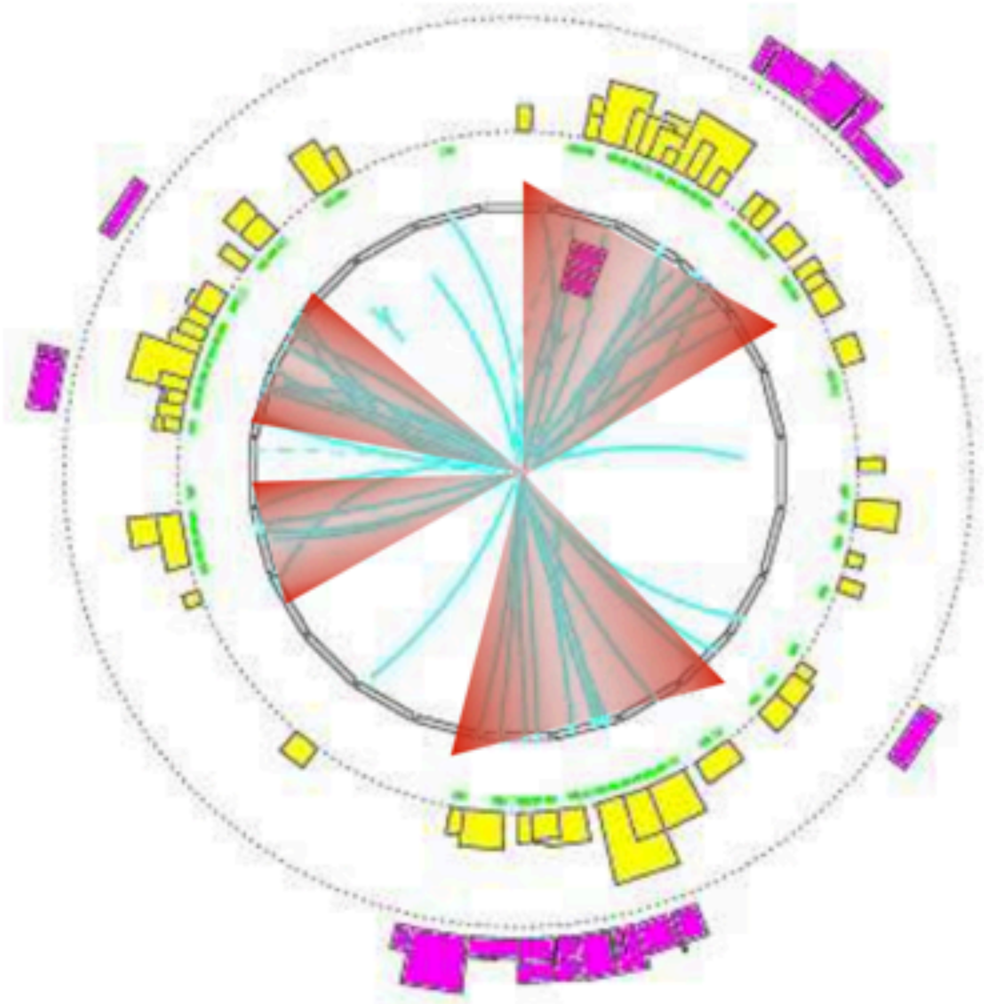
What are jets?

Naive definition: **collimated bunch of hadrons** flying roughly in the same direction





2 clear jets



3 jets?
or 4 jets?

Proper definition: a collection of hadrons defined by means of a **jet algorithm**

"Jet [definitions] are legal contracts between theorists and experimentalists"
MJ Tannenbaum

IRC safety

An observable is **infrared and collinear safe** if, in the limit of a **collinear splitting**, or the **emission of an infinitely soft** particle, the observable remains **unchanged:**

$$O(X; p_1, \ldots, p_n, p_{n+1} \to 0) \to O(X; p_1, \ldots, p_n)$$

$$O(X; p_1, \ldots, p_n \parallel p_{n+1}) \to O(X; p_1, \ldots, p_n + p_{n+1})$$

This property ensures cancellation of **real** and **virtual** divergences in higher order calculations

If we wish to be able to calculate a jet rate in perturbative QCD the jet algorithm that we use must be IRC safe:
soft emissions and collinear splittings must not change the hard jets

slide stolen from Matteo Cacciari

The k_t algorithm and its siblings

$$d_{ij} = \min(p_{ti}^{2p}, p_{tj}^{2p}) \frac{\Delta y^2 + \Delta\phi^2}{R^2} \qquad d_{iB} = p_{ti}^{2p}$$

p = 1 k_t algorithm

S. Catani, Y. Dokshitzer, M. Seymour and B. Webber, Nucl. Phys. B406 (1993) 187
S.D. Ellis and D.E. Soper, Phys. Rev. D48 (1993) 3160

p = 0 Cambridge/Aachen algorithm

Y. Dokshitzer, G. Leder, S.Moretti and B. Webber, JHEP 08 (1997) 001
M. Wobisch and T. Wengler, hep-ph/9907280

p = -1 **anti-k_t algorithm**

MC, G. Salam and G. Soyez, arXiv:0802.1189

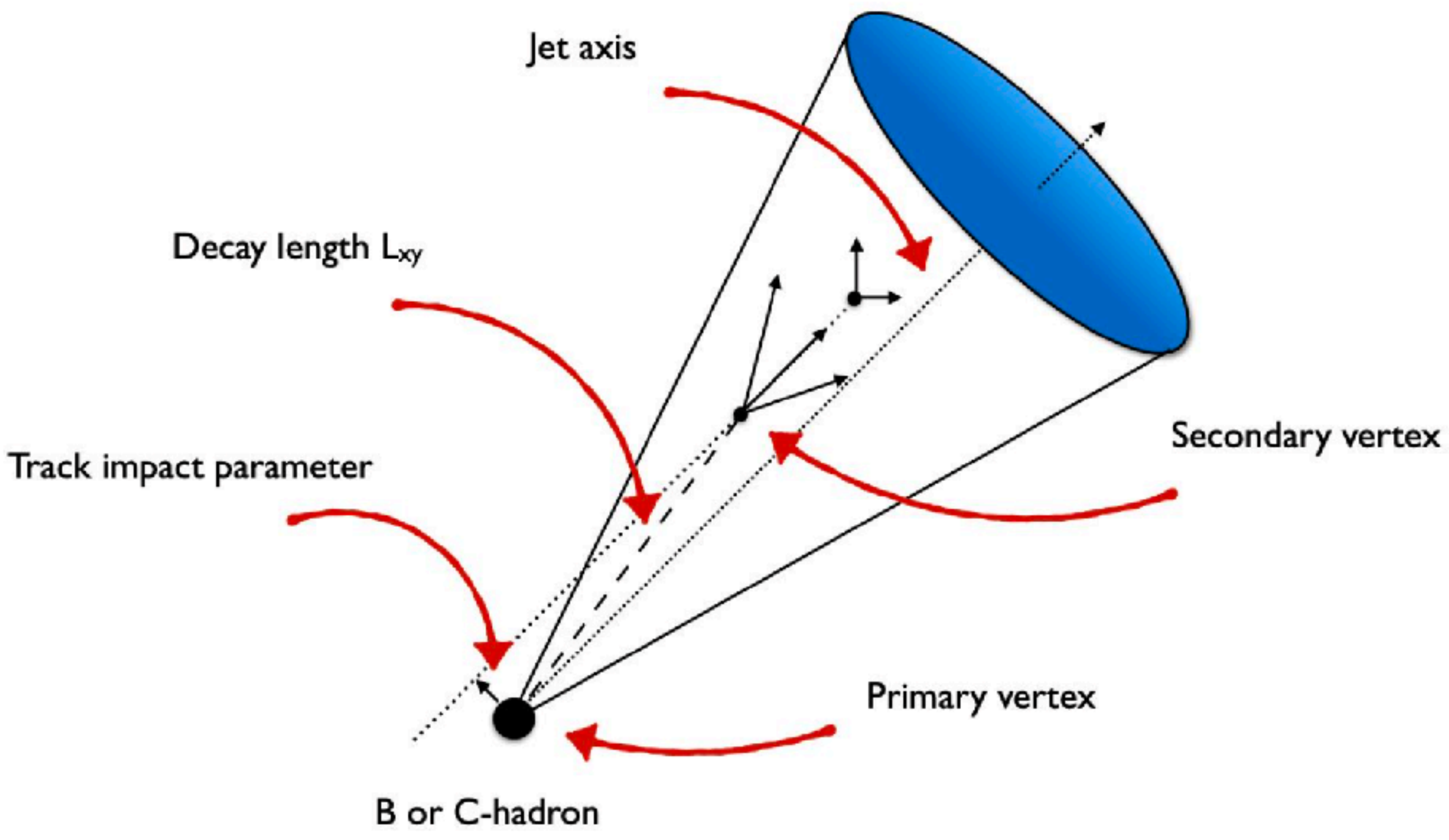
NB: in anti-kt pairs with a **hard** particle will cluster first: if no other hard particles are close by, the algorithm will give **perfect cones**

slide stolen from Matteo Cacciari

(Usual) experimental definition of flavoured jet

A jet is defined as flavoured if it contains at least one heavy hadron within $\Delta R < R$ from the jet axis and with $p_T > p_{T,\mathrm{cut}}$

This is the “truth” labelling used in Monte Carlo samples, used to train a ML architecture (“high-level tagger”) which adopts low-level variables as inputs



IRC flavour safety

The experimental definition is both **collinear and soft unsafe**
(in massless fixed order calculations)

"A jet defined as flavoured if it contains
at least one heavy hadron
within $\Delta R < R$ from the jet axis
and with $p_T > p_{T,\mathrm{cut}}$"

IRC flavour safety

The experimental definition is both **collinear and soft unsafe** (in massless fixed order calculations)

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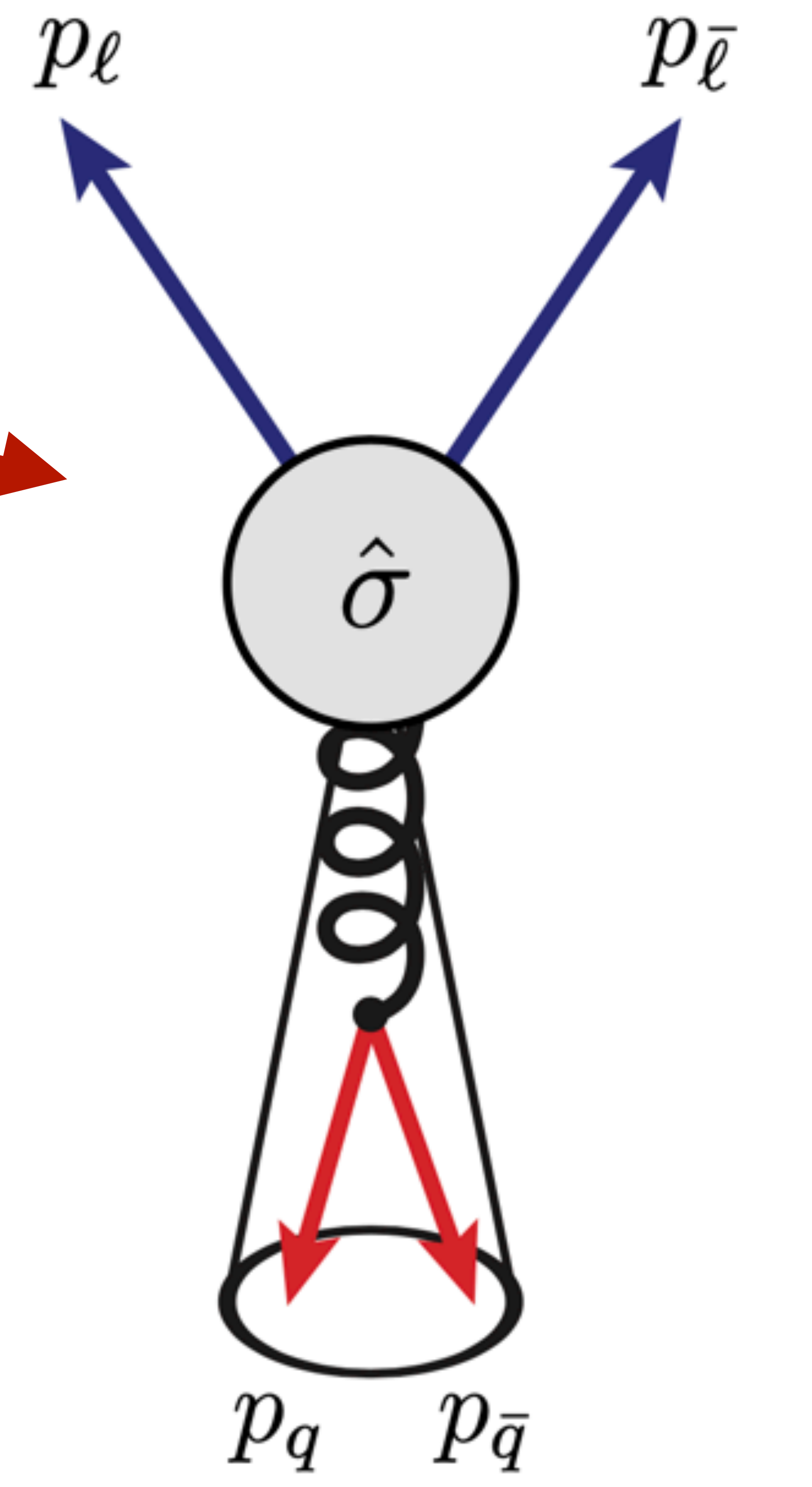
$g \to b\bar{b}$ is always flavoured even in the collinear limit (an "even tag" removal is enough to fix this)



drawing stolen from Rhorry Gauld

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The experimental definition is both **collinear and soft unsafe**
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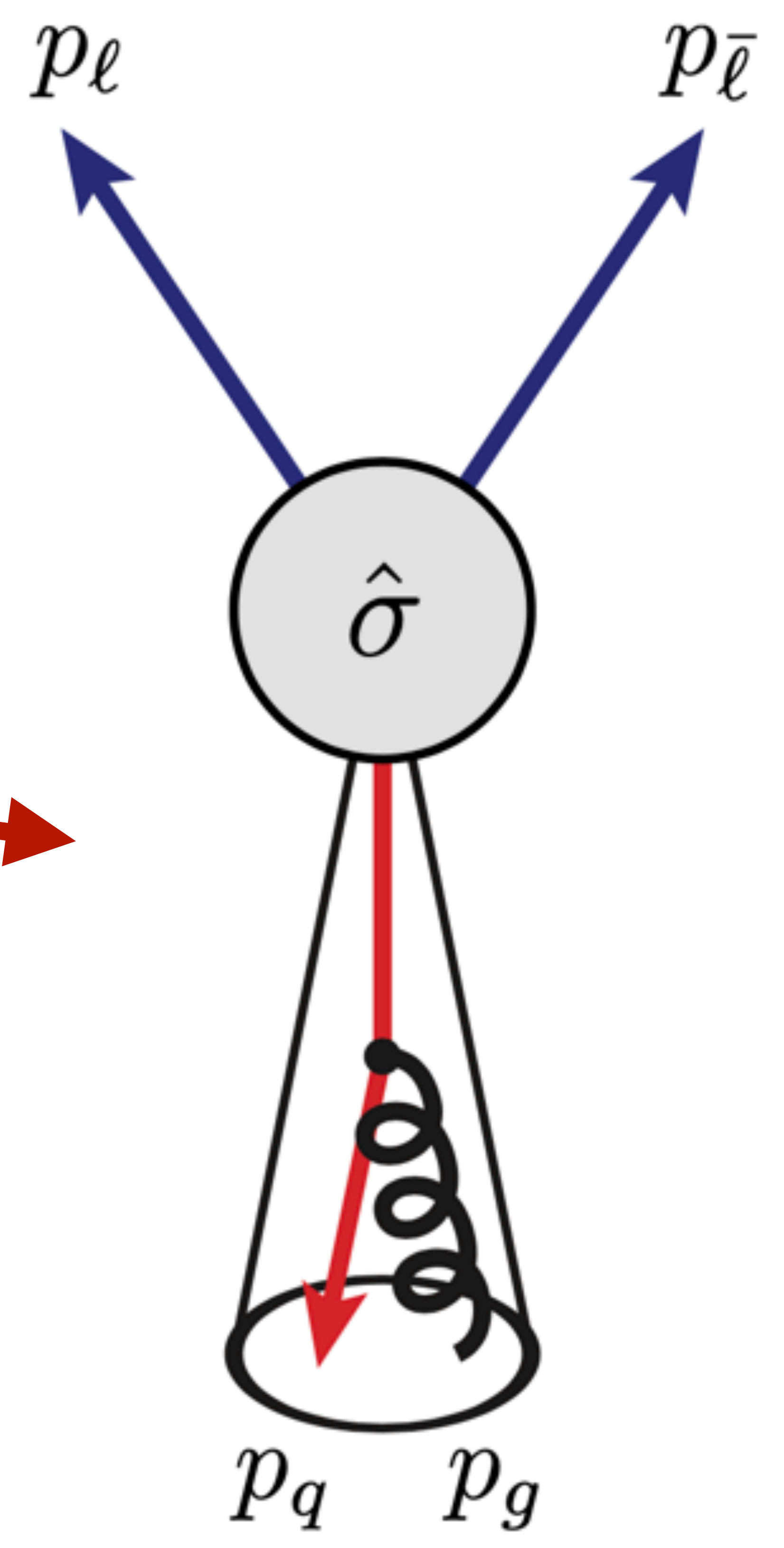
"A jet defined as flavoured if it contains
at least one heavy hadron
within $\Delta R < R$ from the jet axis
and with $p_T > p_{T,\mathrm{cut}}$"

*$b \to bg$ collinear with the gluon carrying
most of the momentum
(would be ok with fragmentation function)*



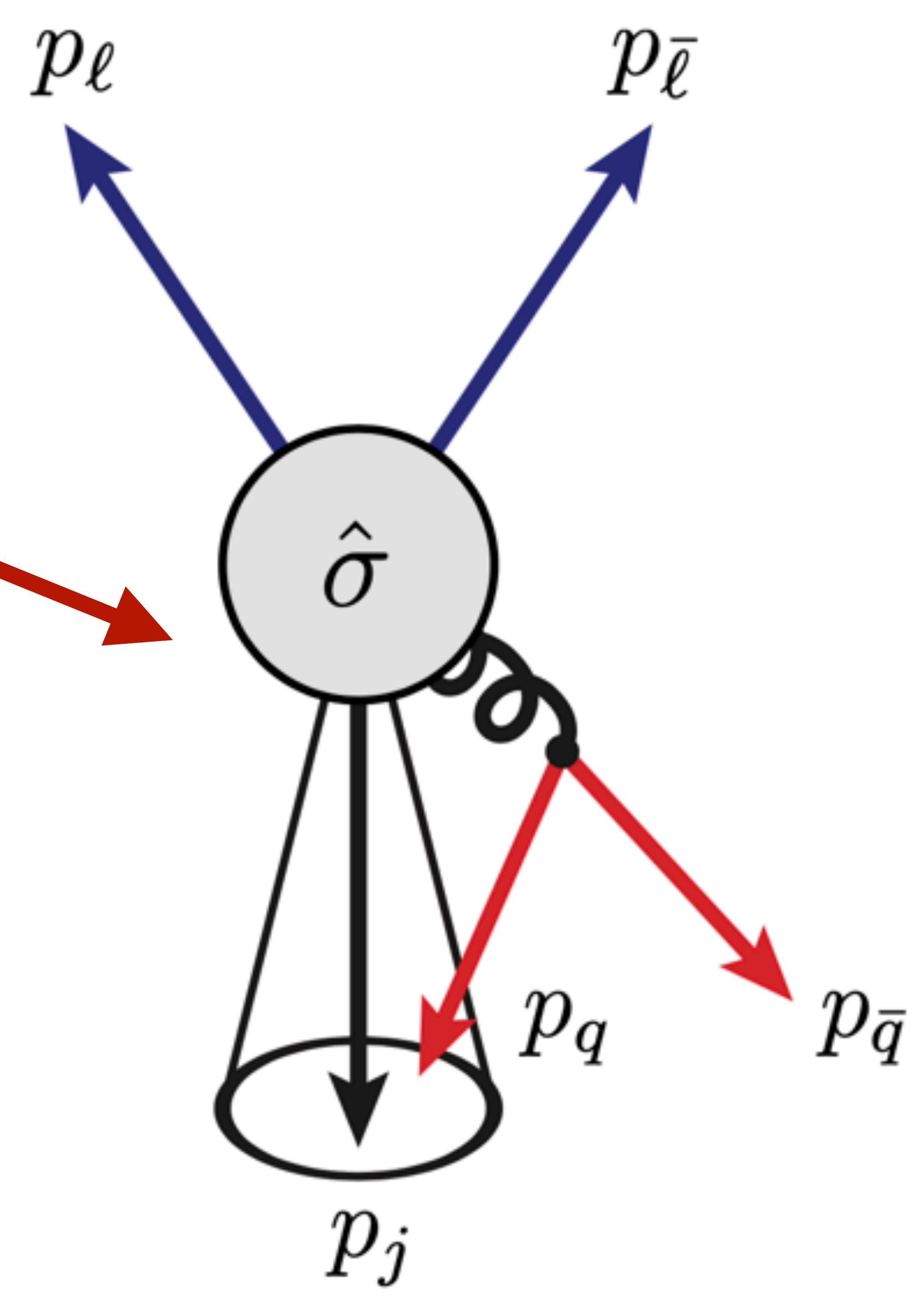
drawing stolen from Rhorry Gauld

IRC flavour safety

The experimental definition is both **collinear and soft unsafe** (in massless fixed order calculations)

"A jet defined as flavoured if it contains at least one heavy hadron within $\Delta R < R$ from the jet axis and with $p_T > p_{T,\text{cut}}$"

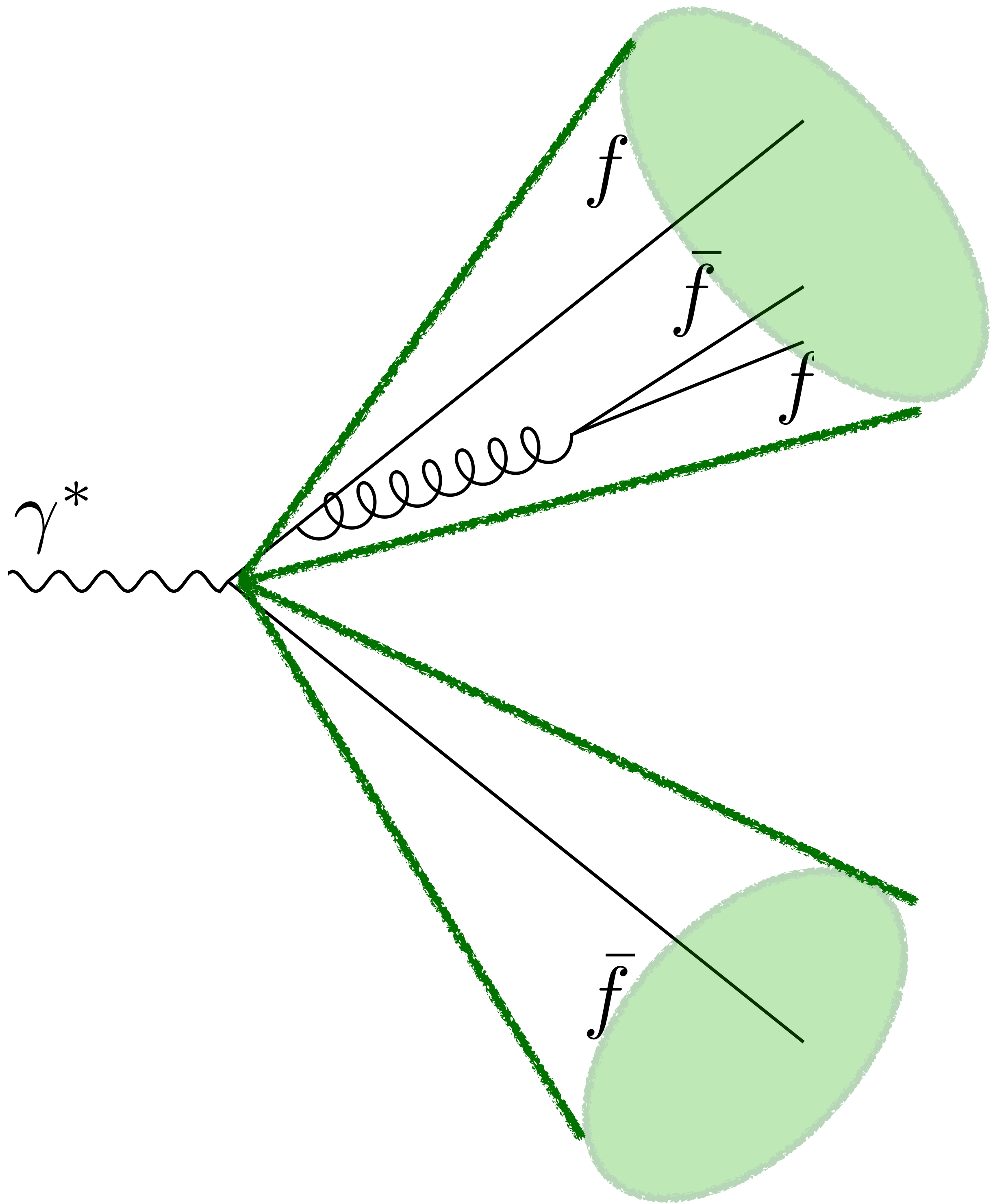
Soft large angle $g \to b\bar{b}$ *polluting different jets*

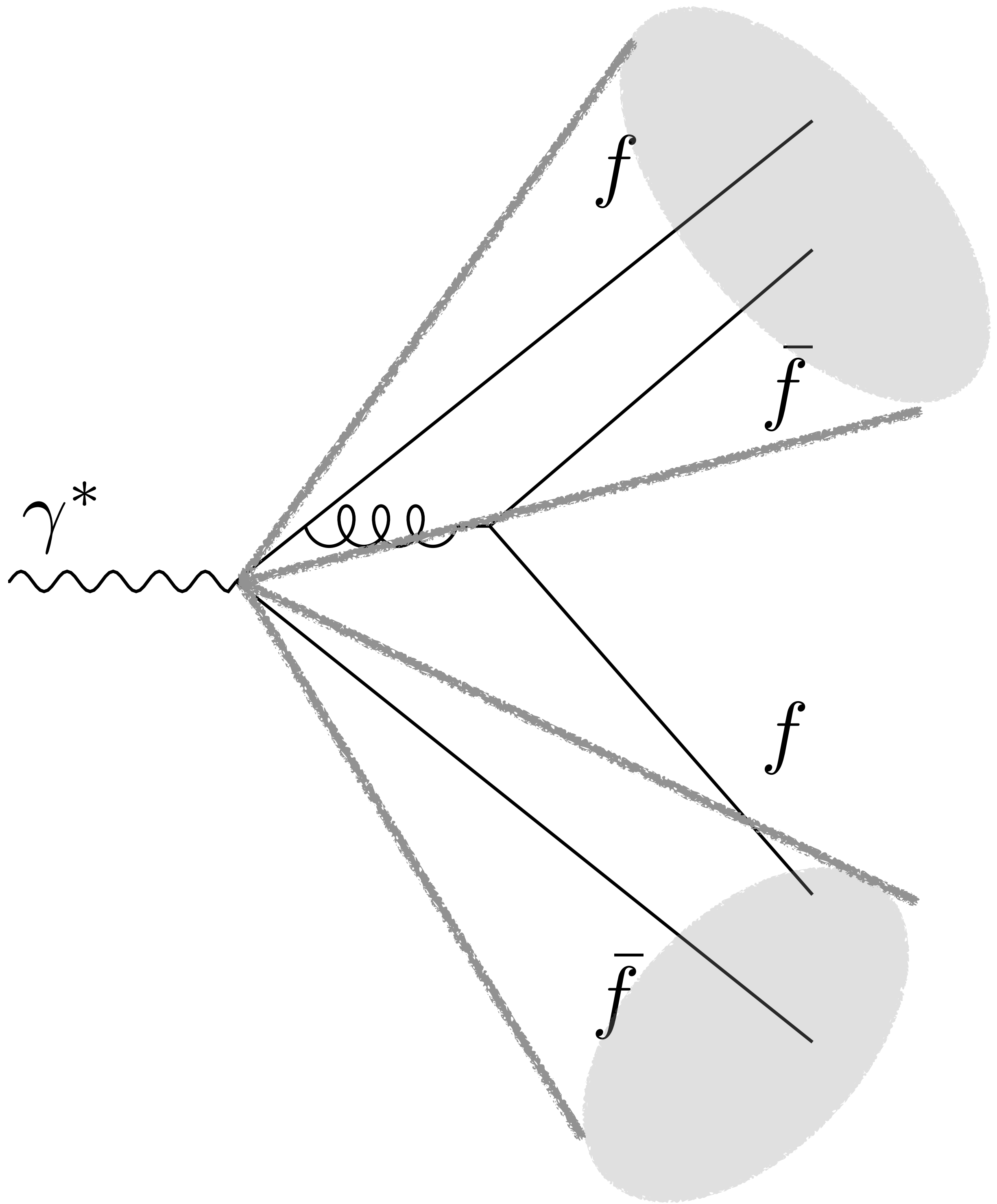


drawing stolen from Rhorry Gauld

Example: e^+e^- to 2 flavoured jets with k_t algorithm

In the soft and collinear limits, we should obtain two flavoured jets





✓ $\mathcal{O}(\alpha_s^2)$ with a $f\bar{f}$ collinear pair: any IRC safe algorithm is OK

✗ $\mathcal{O}(\alpha_s^2)$ with a $f\bar{f}$ soft pair: large-angle polluting issue

The flavour-k_t algorithm

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

1. Introduce a distance measure $d_{ij}^{(F)}$ between every pair of partons i, j:

$$d_{ij}^{(F,\alpha)} = (\Delta\eta_{ij}^2 + \Delta\phi_{ij}^2) \times \begin{cases} \max(k_{ti}, k_{tj})^\alpha \min(k_{ti}, k_{tj})^{2-\alpha}, & \text{softer of } i, j \text{ is flavoured,} \\ \min(k_{ti}^2, k_{tj}^2), & \text{softer of } i, j \text{ is flavourless,} \end{cases} \quad (17)$$

as well as distances to the two beams,

$$d_{iB}^{(F,\alpha)} = \begin{cases} \max(k_{ti}, k_{tB}(\eta_i))^\alpha \min(k_{ti}, k_{tB}(\eta_i))^{2-\alpha}, & i \text{ is flavoured,} \\ \min(k_{ti}^2, k_{tB}^2(\eta_i)), & i \text{ is flavourless,} \end{cases} \quad (18)$$

and an analogous definition of $d_{i\bar{B}}^{(F,\alpha)}$ involving $k_{t\bar{B}}(\eta_i)$ instead of $k_{tB}(\eta_i)$ (both defined as in eqs. (15) and (16)).[9] As in section 2 we have introduced a class of measures, parametrised by $0 < \alpha \leq 2$.

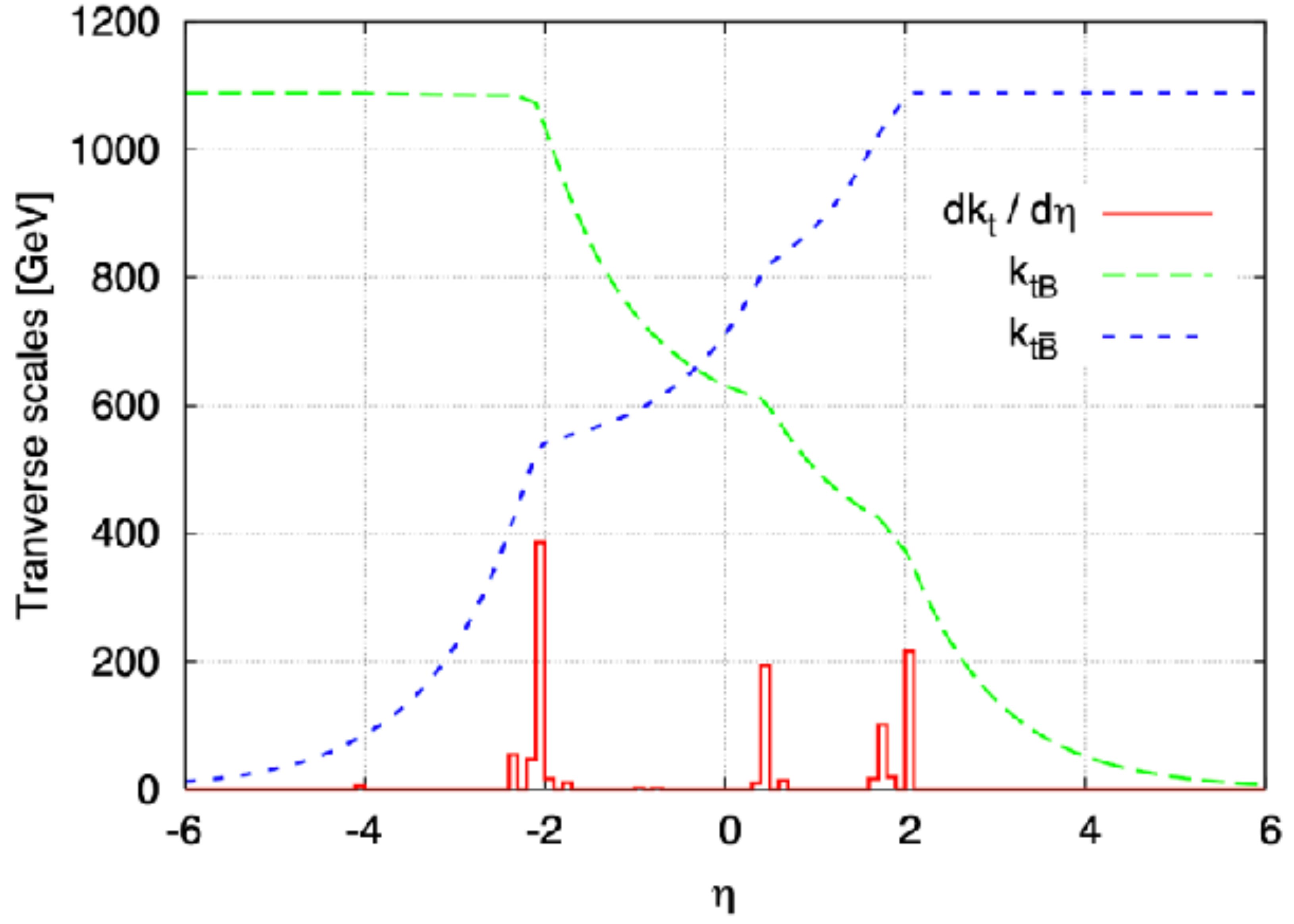
2. Identify the smallest of the distance measures. If it is a $d_{ij}^{(F,\alpha)}$, recombine i and j; if it is a $d_{iB}^{(F,\alpha)}$ ($d_{i\bar{B}}^{(F,\alpha)}$) declare i to be part of beam B ($\bar{B}$) and eliminate i; in the case where the $d_{iB}^{(F,\alpha)}$ and $d_{i\bar{B}}^{(F,\alpha)}$ are equal (which will occur if i is a gluon), recombine with the beam that has the smaller $k_{tB}(\eta_i)$, $k_{t\bar{B}}(\eta_i)$.

3. Repeat the procedure until all the distances are larger than some d_{cut}, or, alternatively, until one reaches a predetermined number of jets.[10,11]

Modified beam distance:

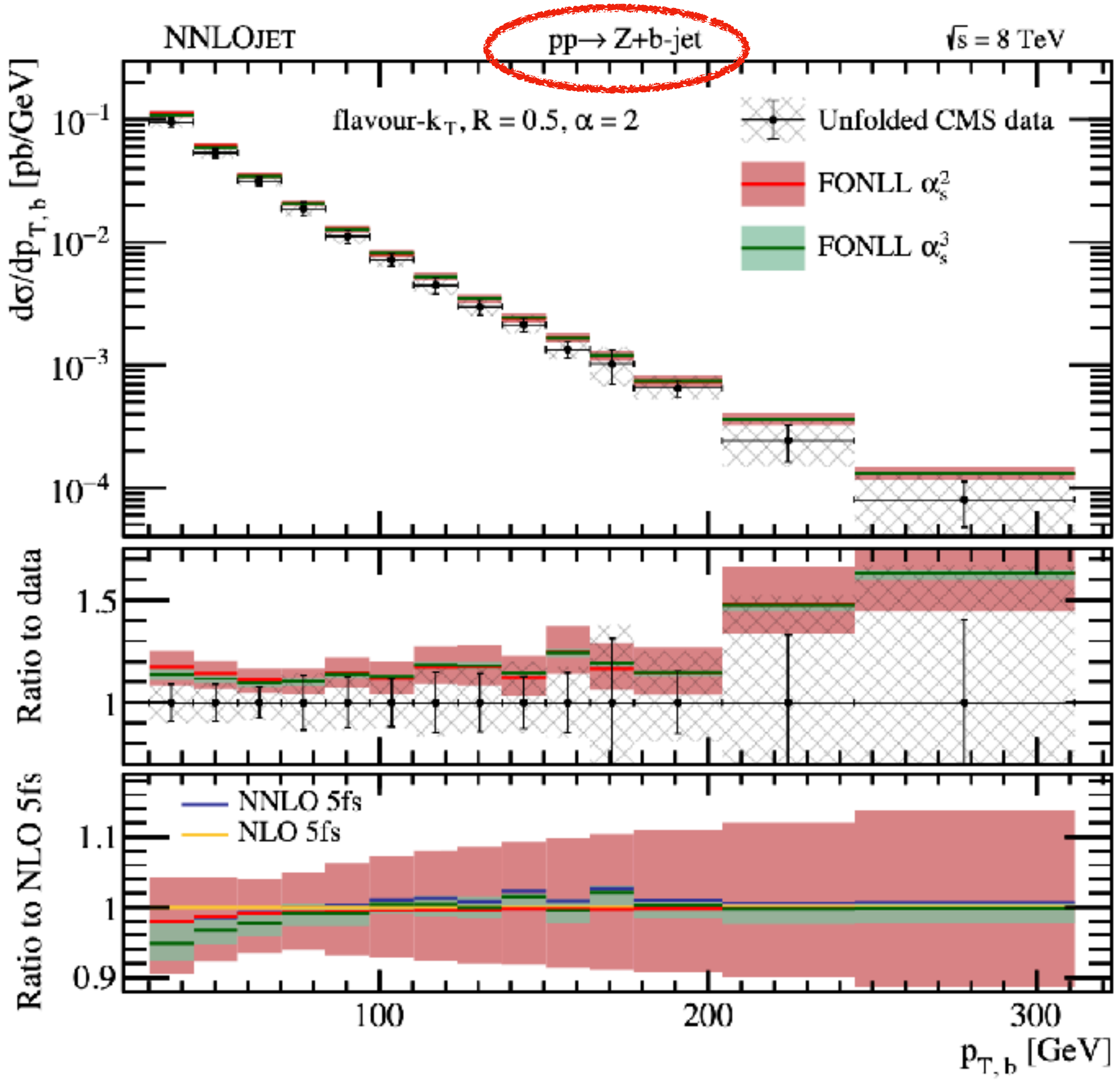
$$k_{tB}(\eta) = \sum_i k_{ti} \left(\Theta(\eta_i - \eta) + \Theta(\eta - \eta_i) e^{\eta_i - \eta}\right)$$

$$k_{t\bar{B}}(\eta) = \sum_i k_{ti} \left(\Theta(\eta - \eta_i) + \Theta(\eta_i - \eta) e^{\eta - \eta_i}\right)$$

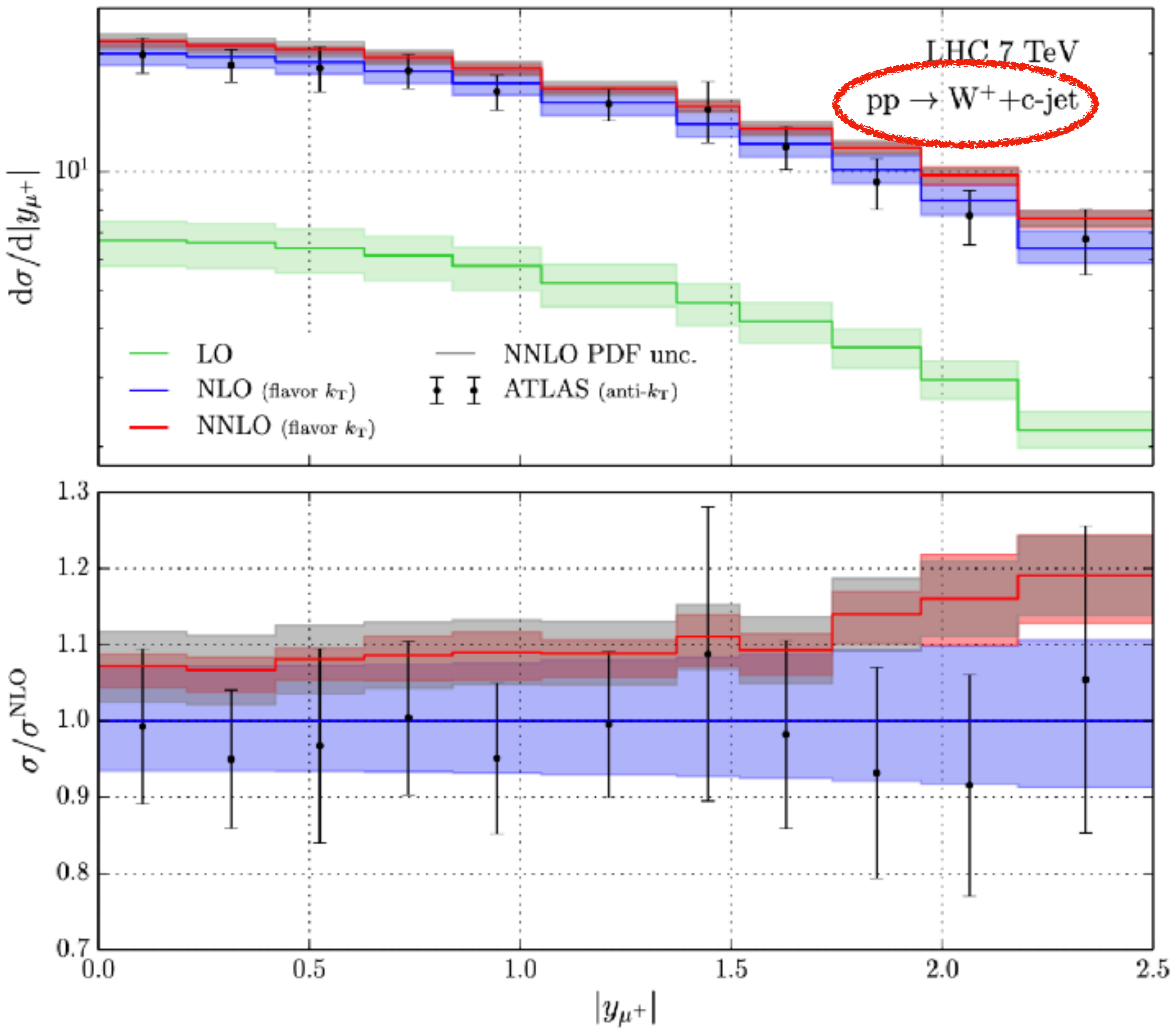


IRC flavour safe to all orders,
but different kinematics
(because new distance)

Recent NNLO predictions with flavour-k_t



[Gauld et al. (2005.03016)]



[Czakon et al. (2011.01011)]

Comparison with experimental data **not straightforward**

A lot of recent alternative proposals!

- based on Soft Drop grooming techniques
  [Caletti, Larkoski, Marzani, Reichelt (2205.01109)]
- through the alignment of particles along the Winner-Take-All axis
  [Caletti, Larkoski, Marzani, Reichelt (2205.01117)]
- through a modification of anti-k_t clustering distance
  [Czakon, Mitov, Poncelet (2205.11879)]
- with successive iterations of flavour-k_t and anti-k_t
  [Caletti, Fedkevych, Marzani, Reichelt (2108.10024)]
- using jet angularities and primary Lund jet plane as discriminants
  [Fedkevych, Khosa, Marzani, Sforza (2202.05082)]

However, none of the above reproduces the same jets as anti-k_t, can be applied to a generic process with one or more jets and it is IRC safe to all orders.

The flavour dressing algorithm

[Gauld, Huss, GS (2208.11138)]

Flavour assignment *factorised* from jet reconstruction:
we assign flavour to flavour-agnostic jets in an IRC safe way

Inputs:
flavour agnostic jets $\{j_k\}$, flavoured clusters $\{\hat{f}_i\}$, association criterion, accumulation criterion

Run a sequential recombination algorithm with flavour-k_t-like distances:
- $d(\hat{f}_i, \hat{f}_j)$ between flavoured clusters;
- $d(\hat{f}_i, \hat{j}_k)$ if flavoured cluster $\hat{f}_i$ *associated* to jet j_k
- $d_B(\hat{f}_i)$ if $\hat{f}_i$ not associated to any jet

Finally, assign flavour to jet j_k according to collected tag_k and *accumulation* criterion

The flavour dressing algorithm: inputs

- *Flavour agnostic jets* $\{j_k\}$*:* set of jets obtained with an IRC safe jet algorithm (e.g. gen-k_t family), possibly after a fiducial selection.
- *Flavoured clusters* $\{\hat{f}_i\}$
- *Association criterion*
- *Accumulation criterion*

The flavour dressing algorithm: inputs

- *Flavour agnostic jets* $\{j_k\}$

- *Flavoured clusters* $\{\hat{f}_i\}$*:* built out of quarks (e.g. c, b) or stable heavy-flavour hadrons (e.g. D, B), by **dressing them with radiation close in angle, but without touching the soft particles.**

  Exploiting the Soft Drop criterion [Larkoski, Marzani, Soyez, Thaler 1402.2657]

  “Naked” flavoured objects are collinear unsafe

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

- *Association criterion*

- *Accumulation criterion*

The flavour dressing algorithm: inputs

- *Flavour agnostic jets* $\{j_k\}$

- *Flavoured clusters* $\{\hat{f}_i\}$

- *Association criterion:* whether $\hat{f}_i$ is “associated” to j_k
  At parton-level simply if $\hat{f}_i$ is a constituent of j_k
  Other options: $\Delta R(\hat{f}_i, j_k) < R_{\text{tag}}$, ghost association, …

  <u>Flavour assignment based only on association is soft unsafe</u>

- *Accumulation criterion*

The flavour dressing algorithm: inputs

- *Flavour agnostic jets* $\{j_k\}$
- *Flavoured clusters* $\{\hat{f}_i\}$
- *Association criterion*
- *Accumulation criterion:* how to "sum" flavours
  - sum flavoured if unequal number of f and $\bar{\mathrm{f}}$ (need charge information)
  - sum flavoured if odd number of f or $\bar{\mathrm{f}}$ (if no charge information)

Definition of flavoured cluster $\hat{f}_i$

1. Initialise a set with all the flavourless objects p_i (particles used as input to jets) and all the flavoured objects f_i (bare flavours), avoiding double counting if necessary.

2. Find the pair with the smallest angular distance ΔR_{ab}:
   — flavourless p_a, p_b: combine p_a and p_b into a flavourless p_{ab};
   — flavoured f_a, f_b: remove both from the set;
   — flavoured f_a, unflavoured p_b: remove p_b from the set and check a Soft Drop criterion

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

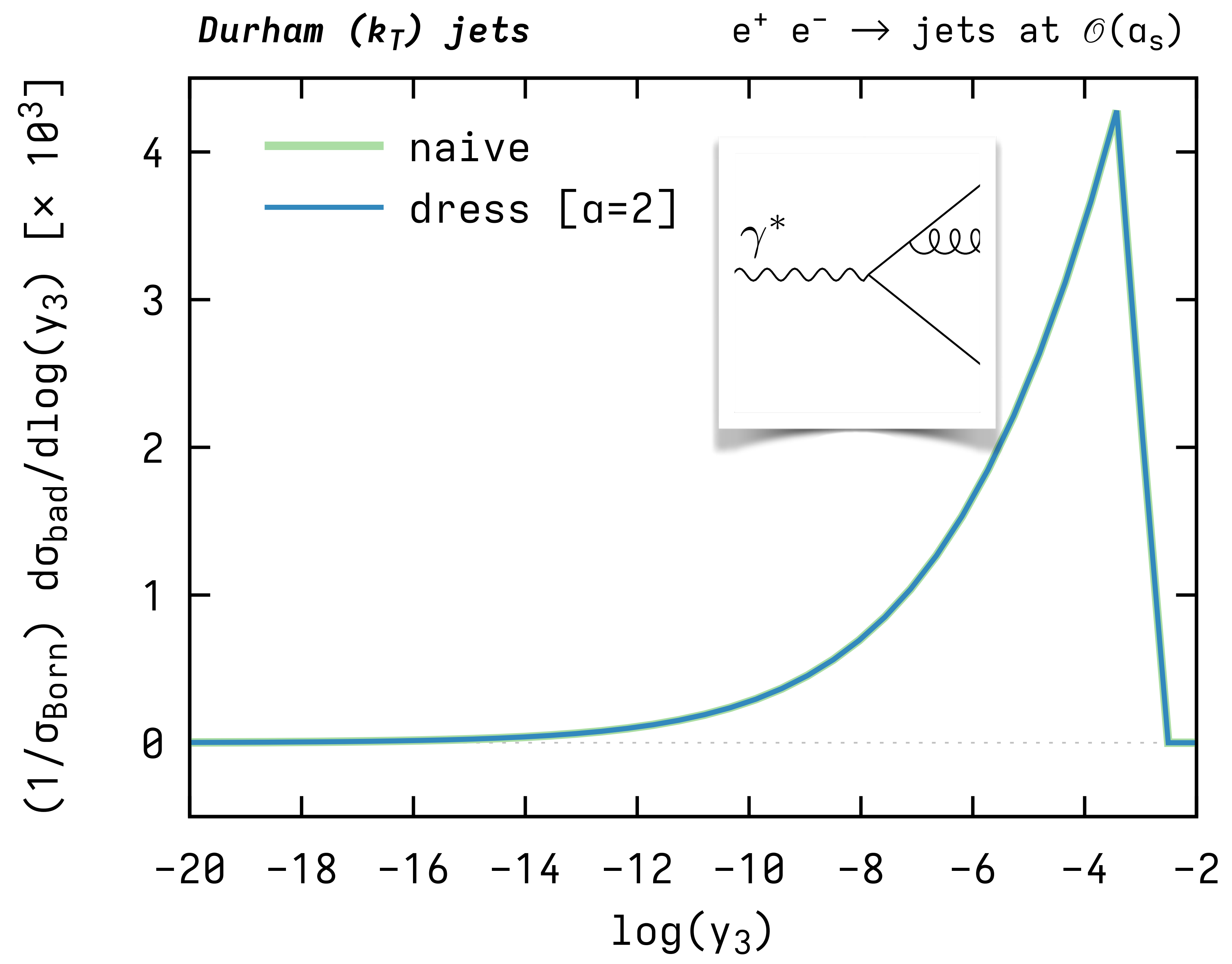
   to **recombine collinear while preserving soft.** [default: $\delta R = 0.1$, $z_{\text{cut}} = 0.1$, $\beta = 2$]
   If satisfied, combine f_a and p_b into a flavoured f_{ab}.

3. Iterate while there are at least two objects in the set until $\Delta R_{ab} > \delta R$.
   The momentum of $\hat{f}_i$ is given by the accumulated momentum into f_i.

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

Vanishing mis-identification of flavours in the fully unresolved regime = IRC safety

only soft and/or collinear radiation



Any gen-k_t algo is safe!

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

Vanishing mis-identification of flavours in the fully unresolved regime = IRC safety

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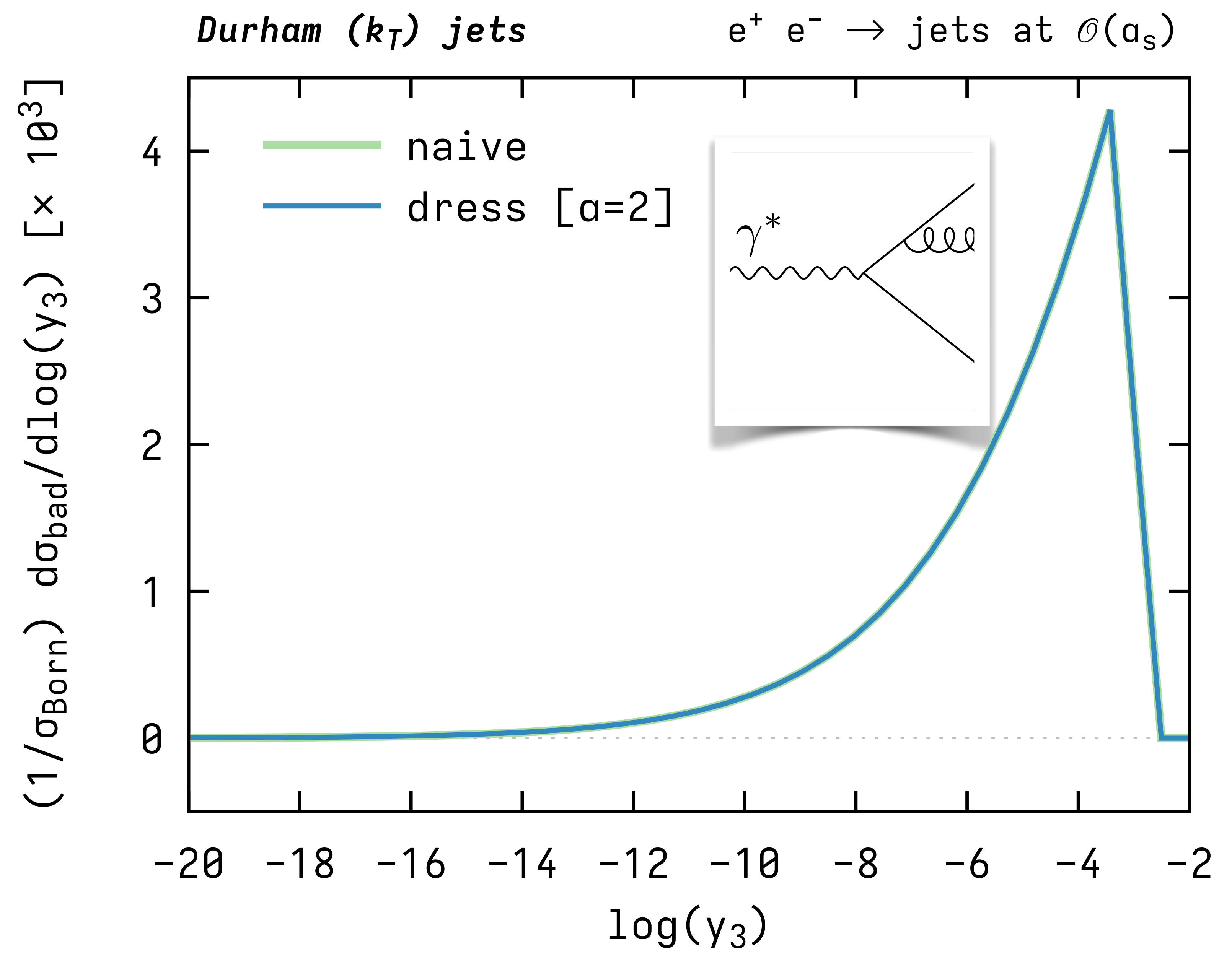

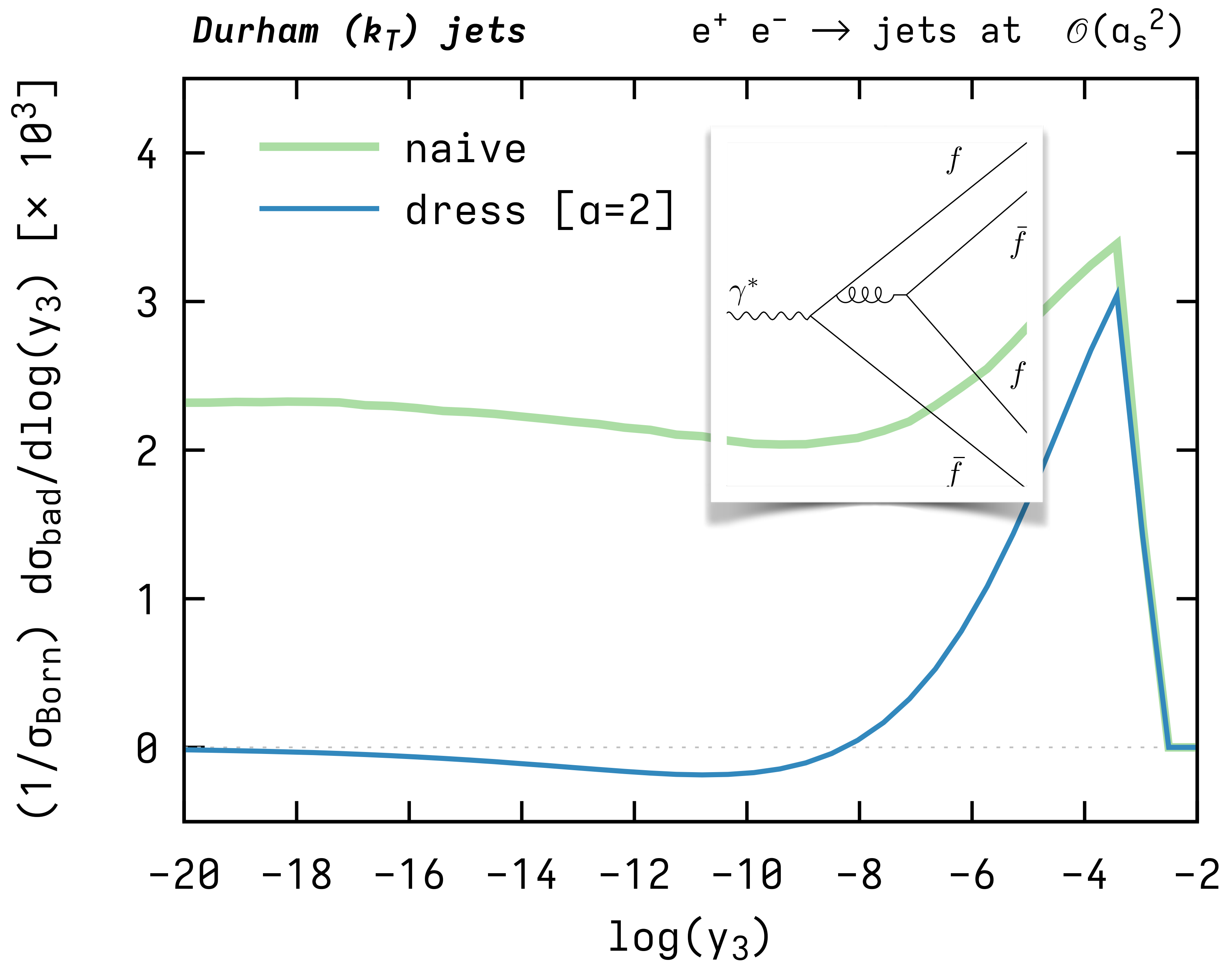

Any gen-k_t algo is safe!

Naive dressing unsafe, flavour dressing safe!

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

Vanishing mis-identification of flavours in the fully unresolved regime = IRC safety

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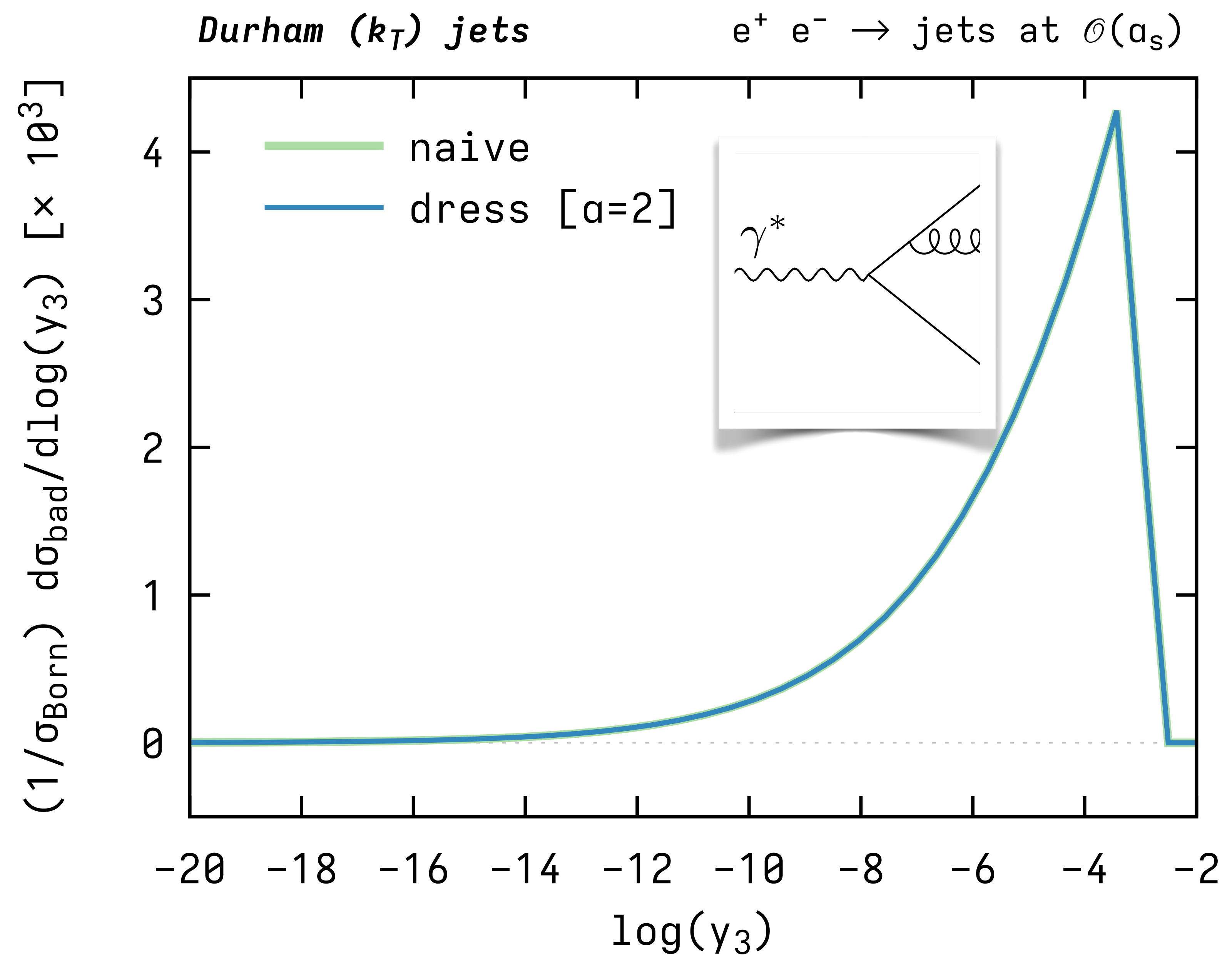
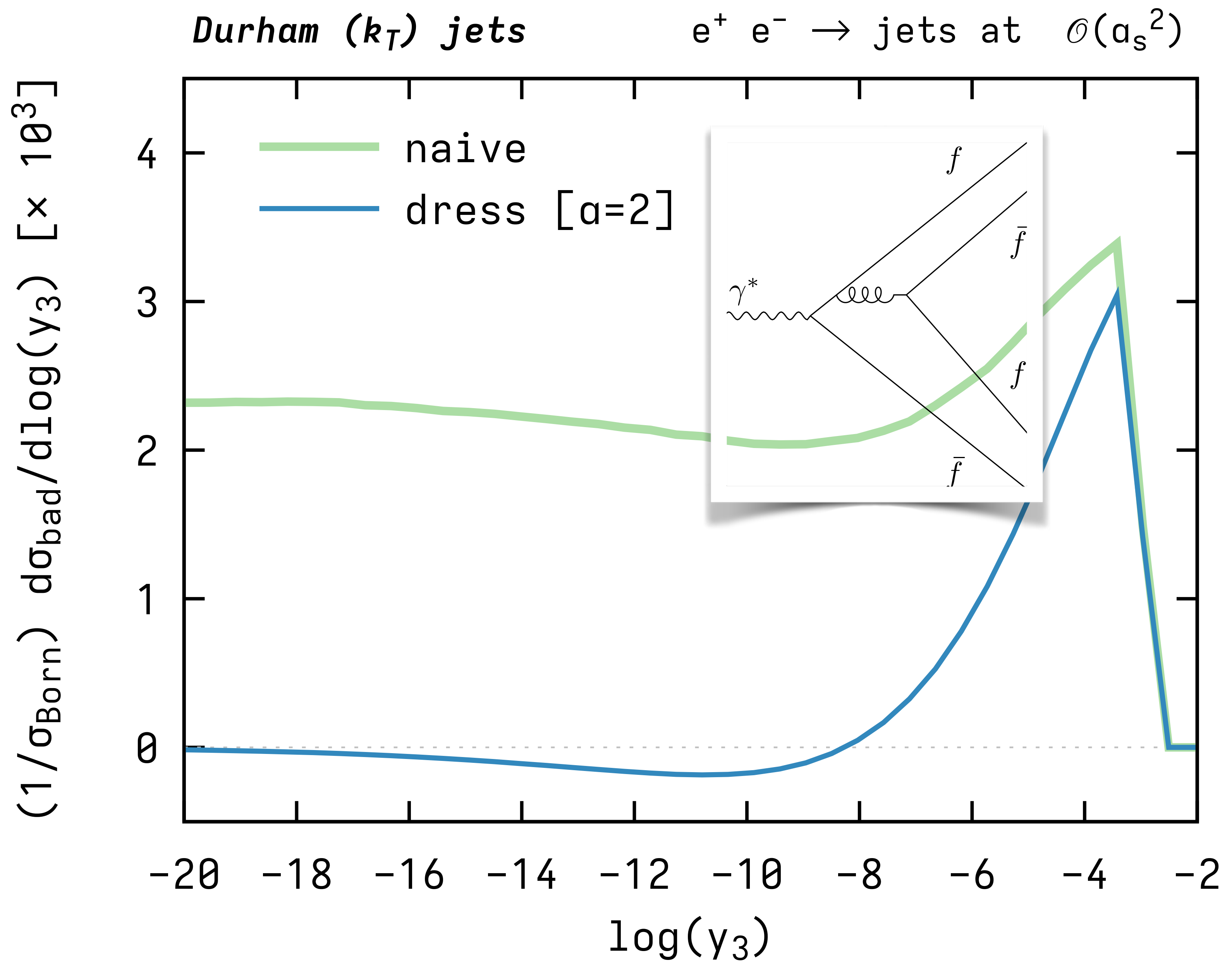
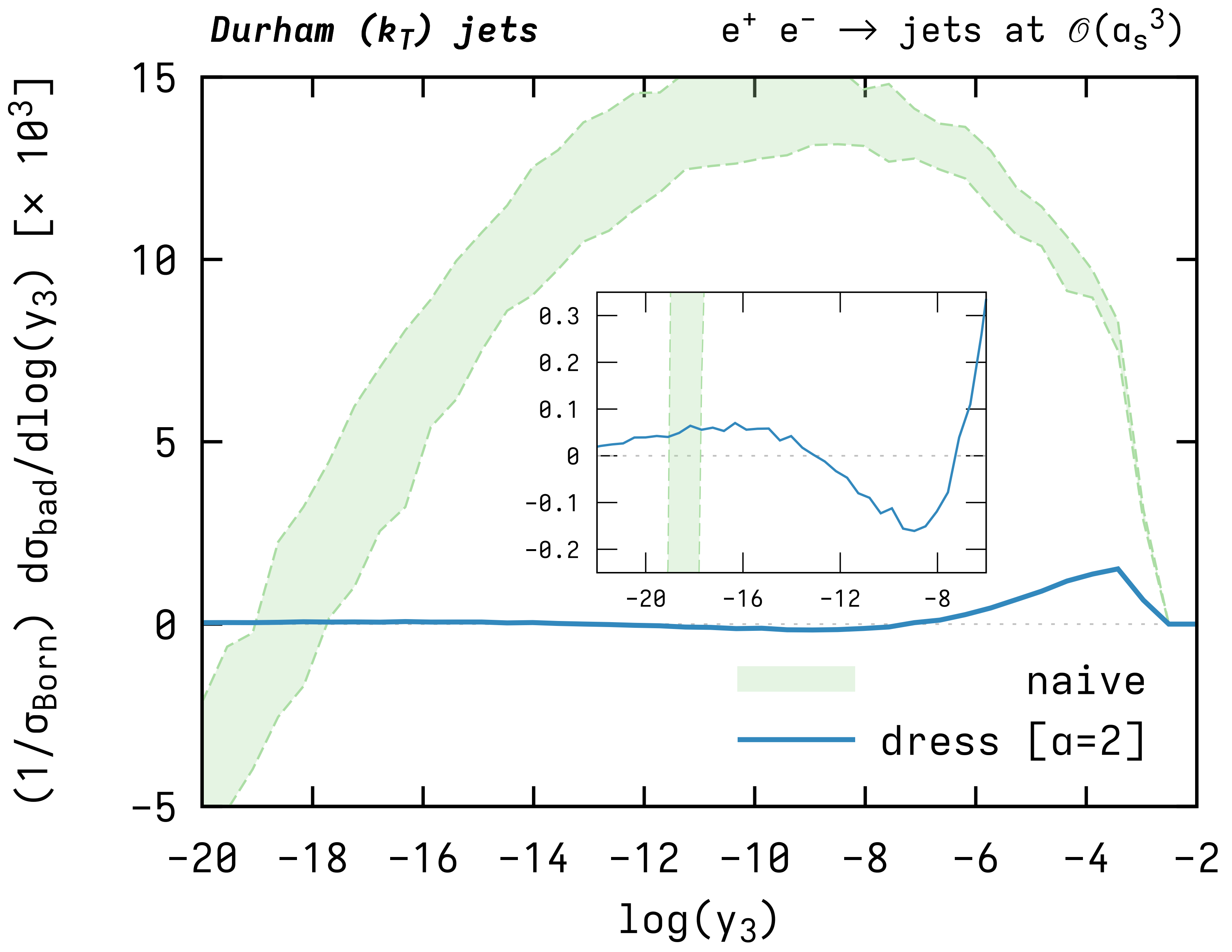




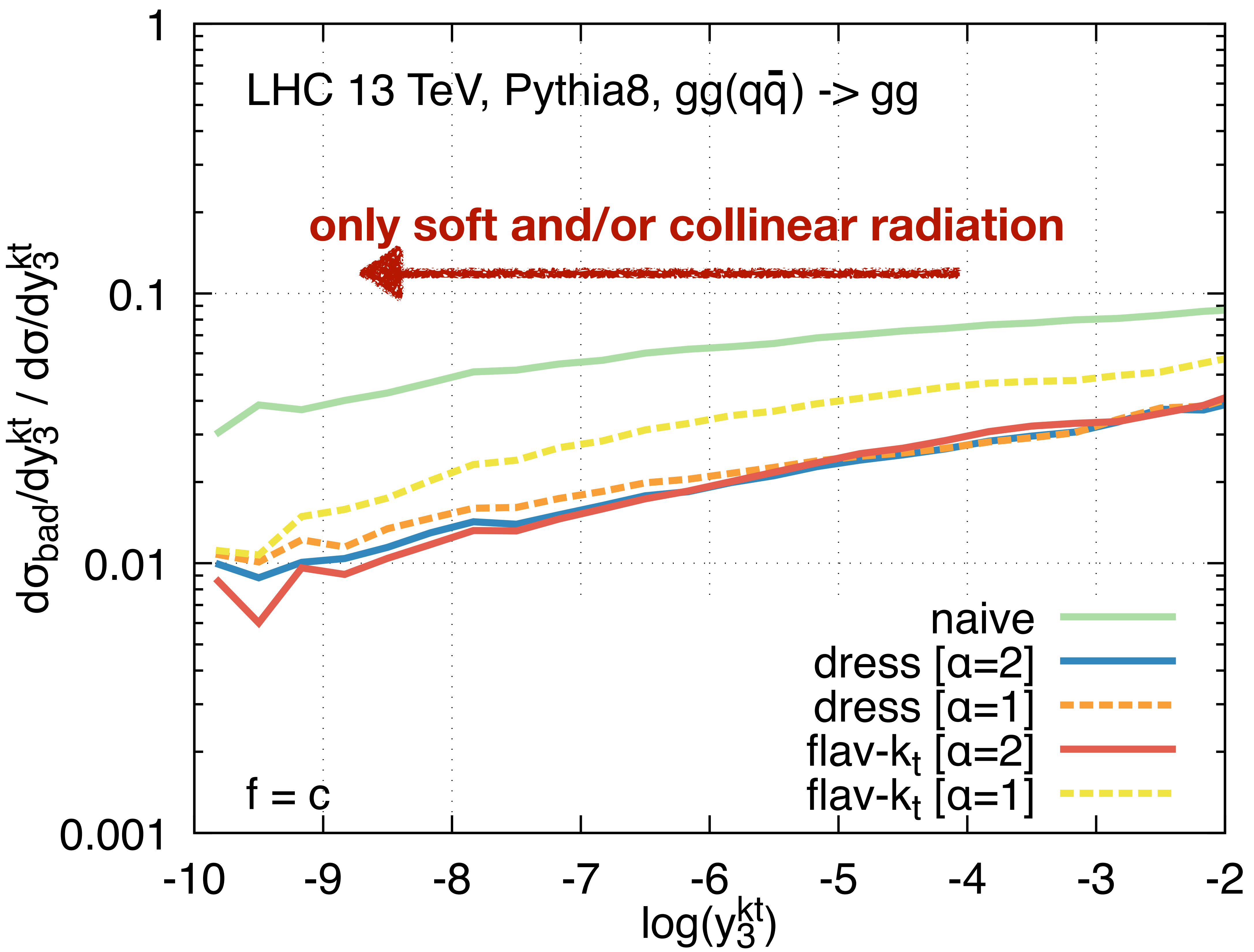


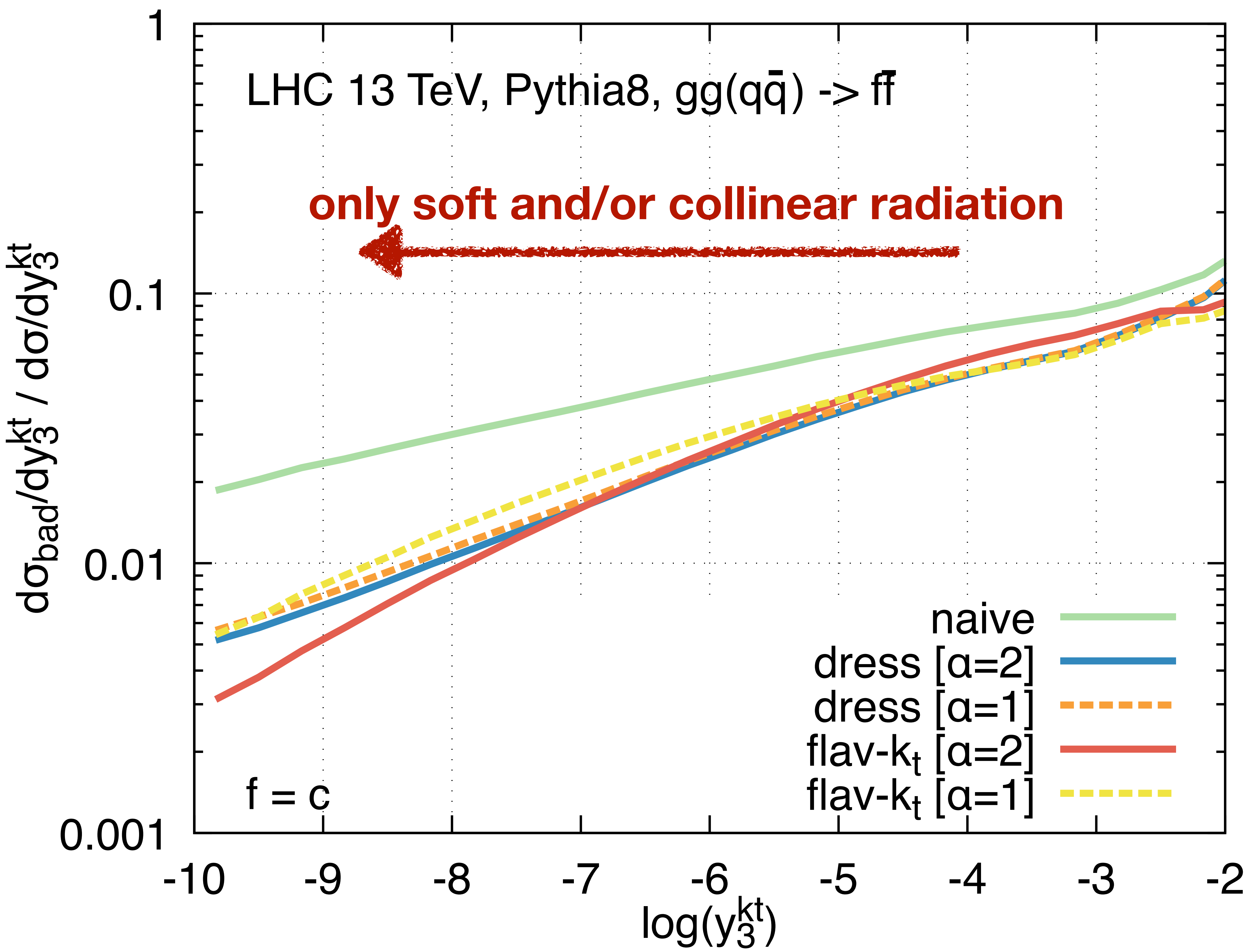
Any gen-k_t algo is safe!

Naive dressing unsafe, flavour dressing safe!

Naive dressing unsafer, flavour dressing still safe!

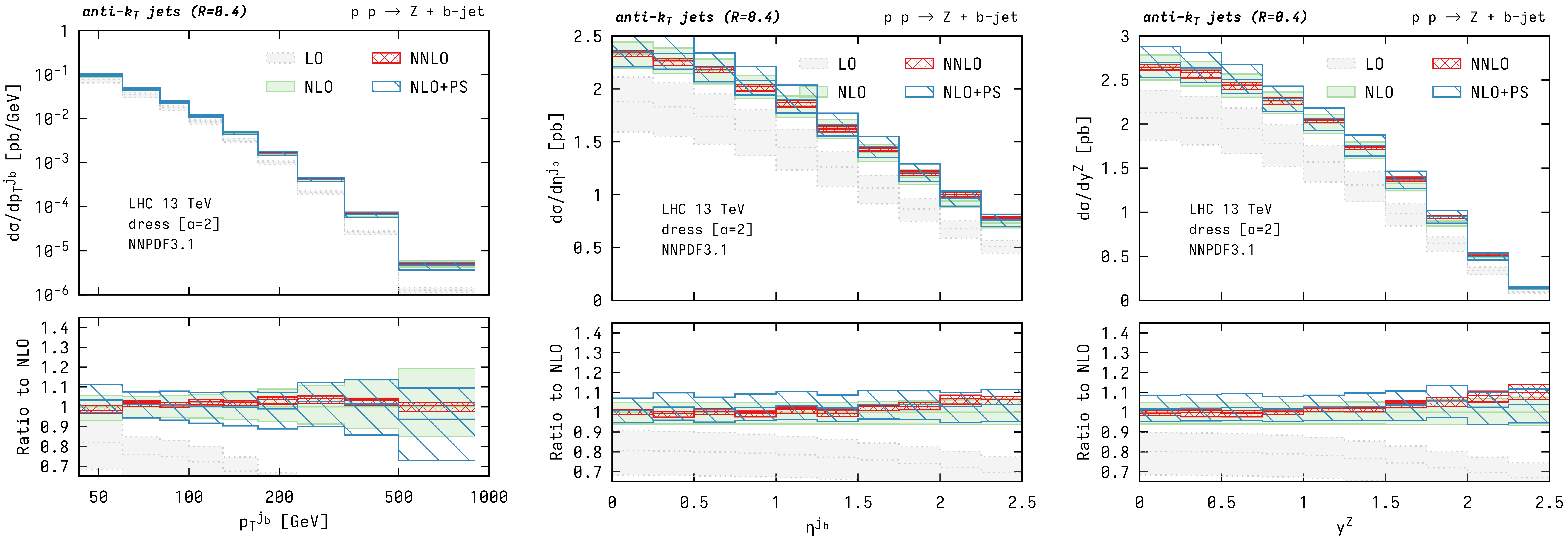
IRC sensitivity in $2 \to 2$ QCD events in pp





Flavour dressing approaches zero faster than a naive flavour tagging as $y_3^{k_t} \to 0$

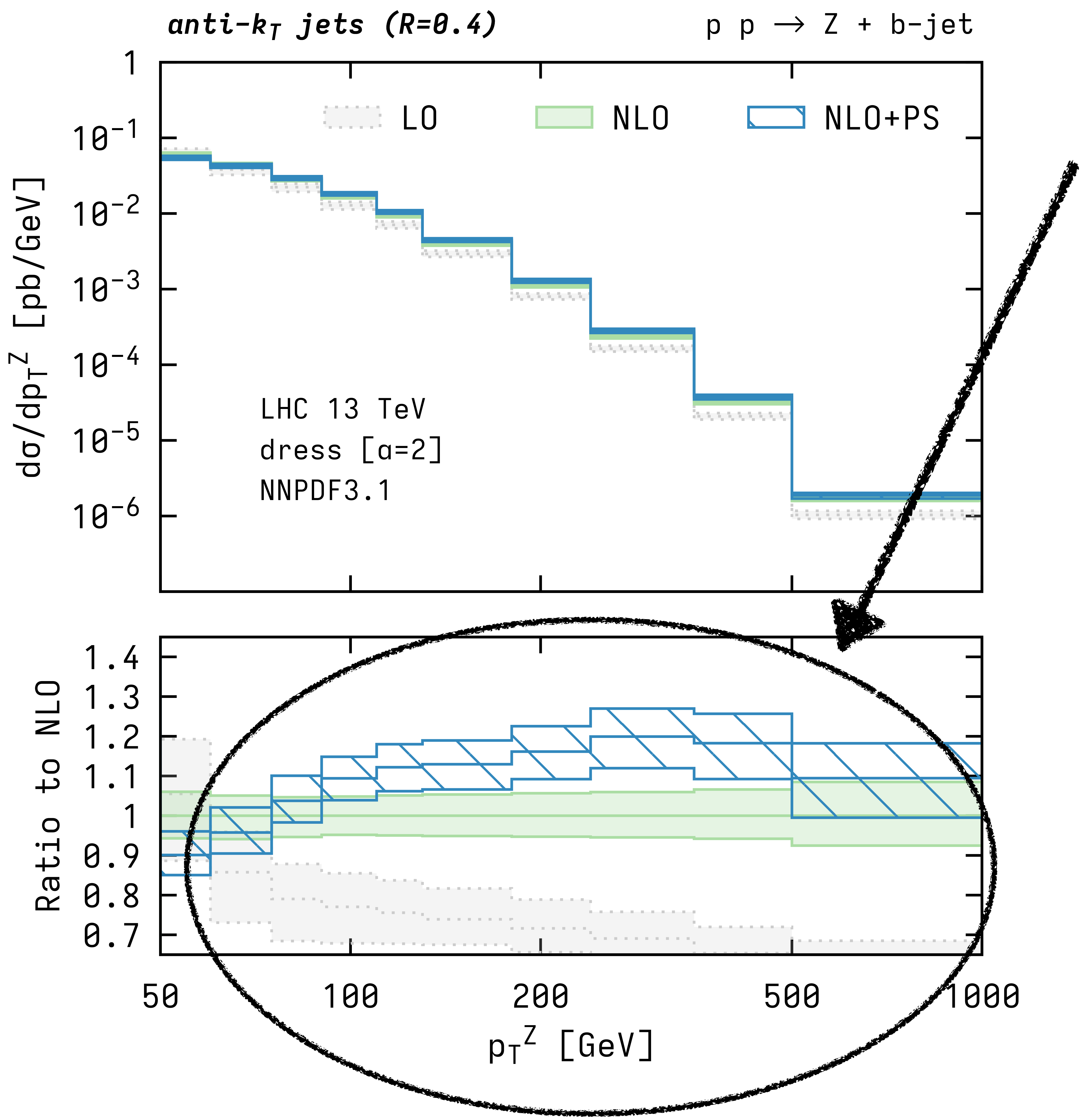
Test in a realist scenario: $Z + b$-jet



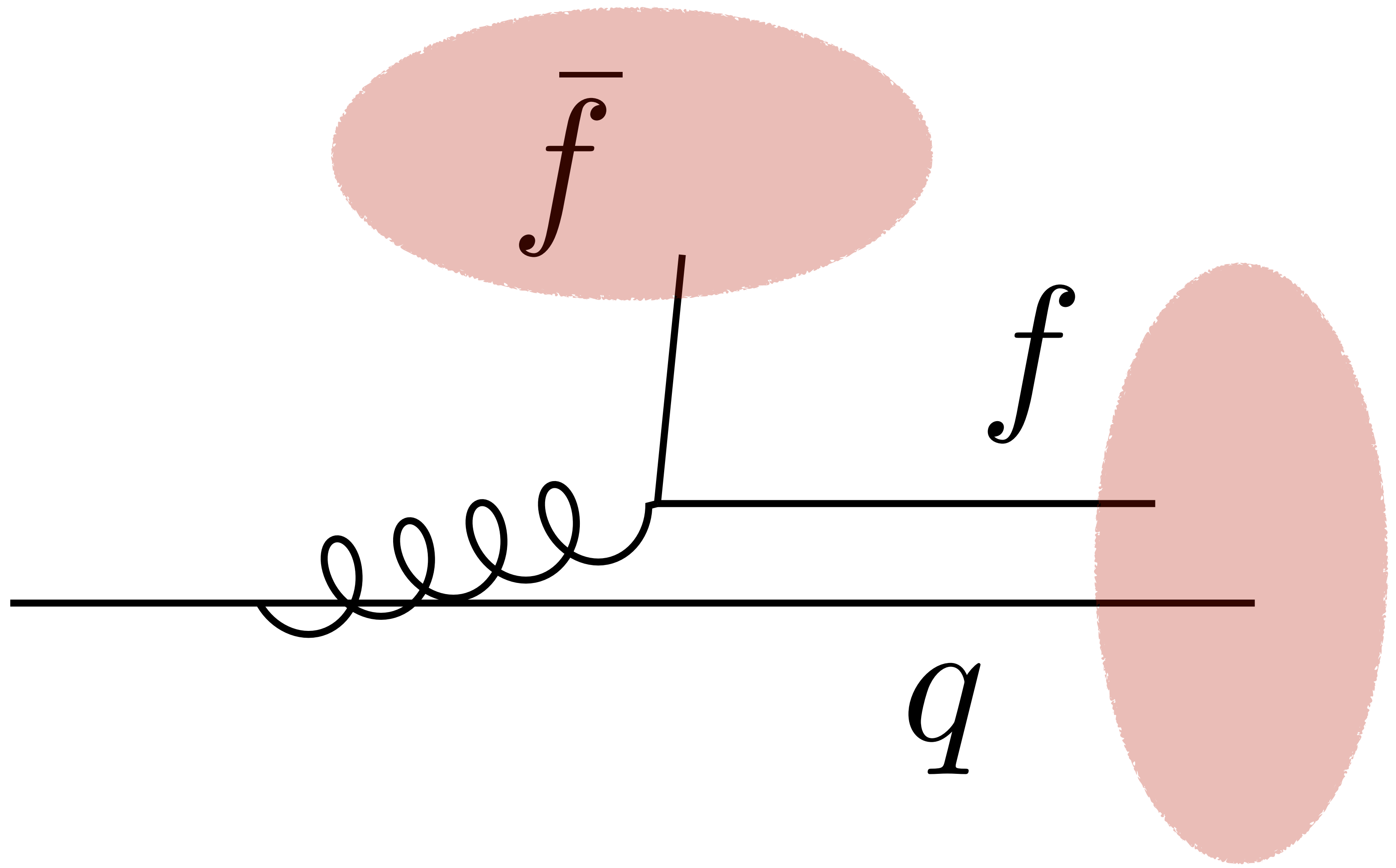
Remarkable agreement between (N)NLO and NLO+PS

→ for most distributions **largely insensitive to all-order corrections**

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

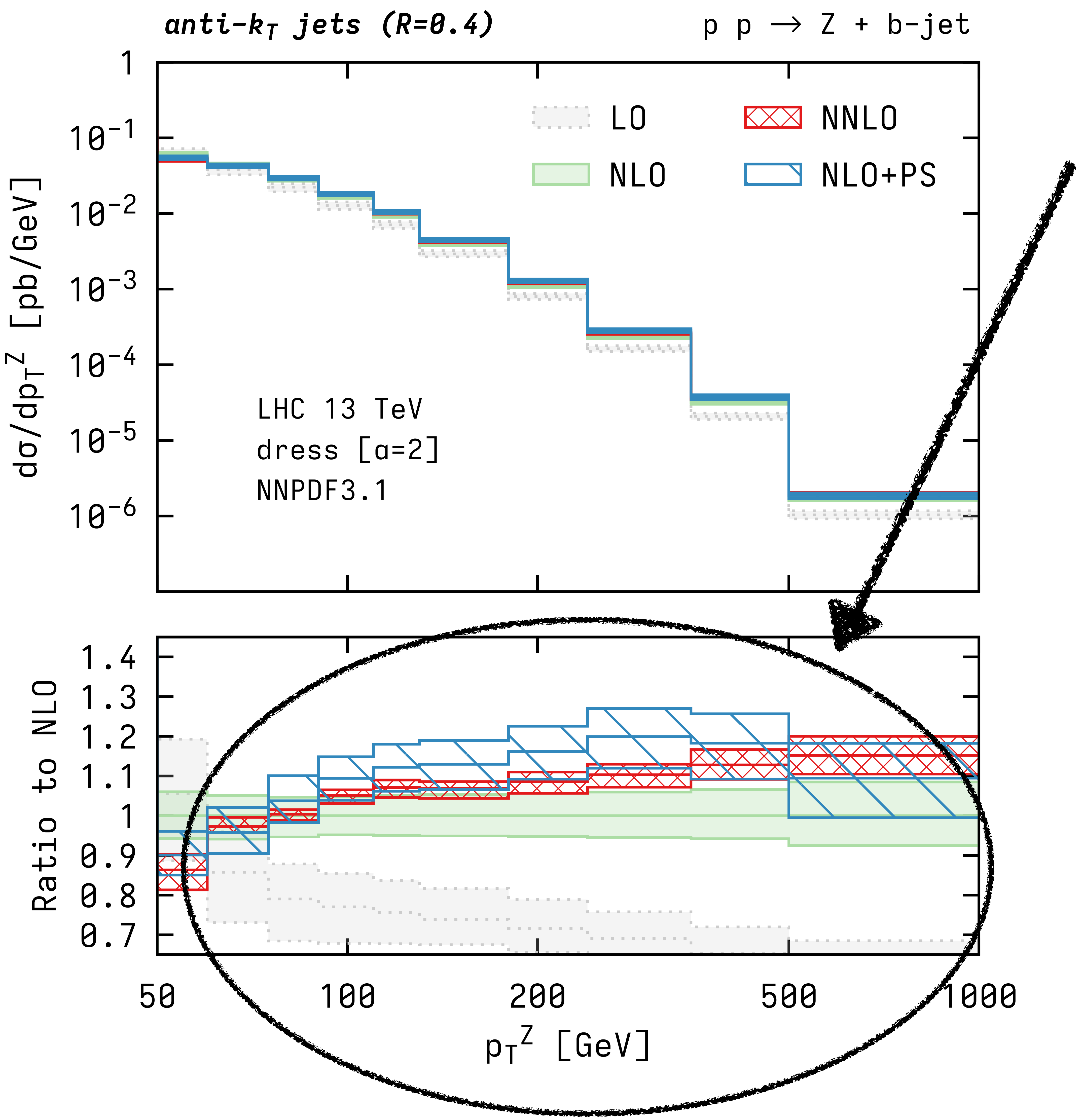


Some sensitivity observed in p_T^Z, likely due to:



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

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



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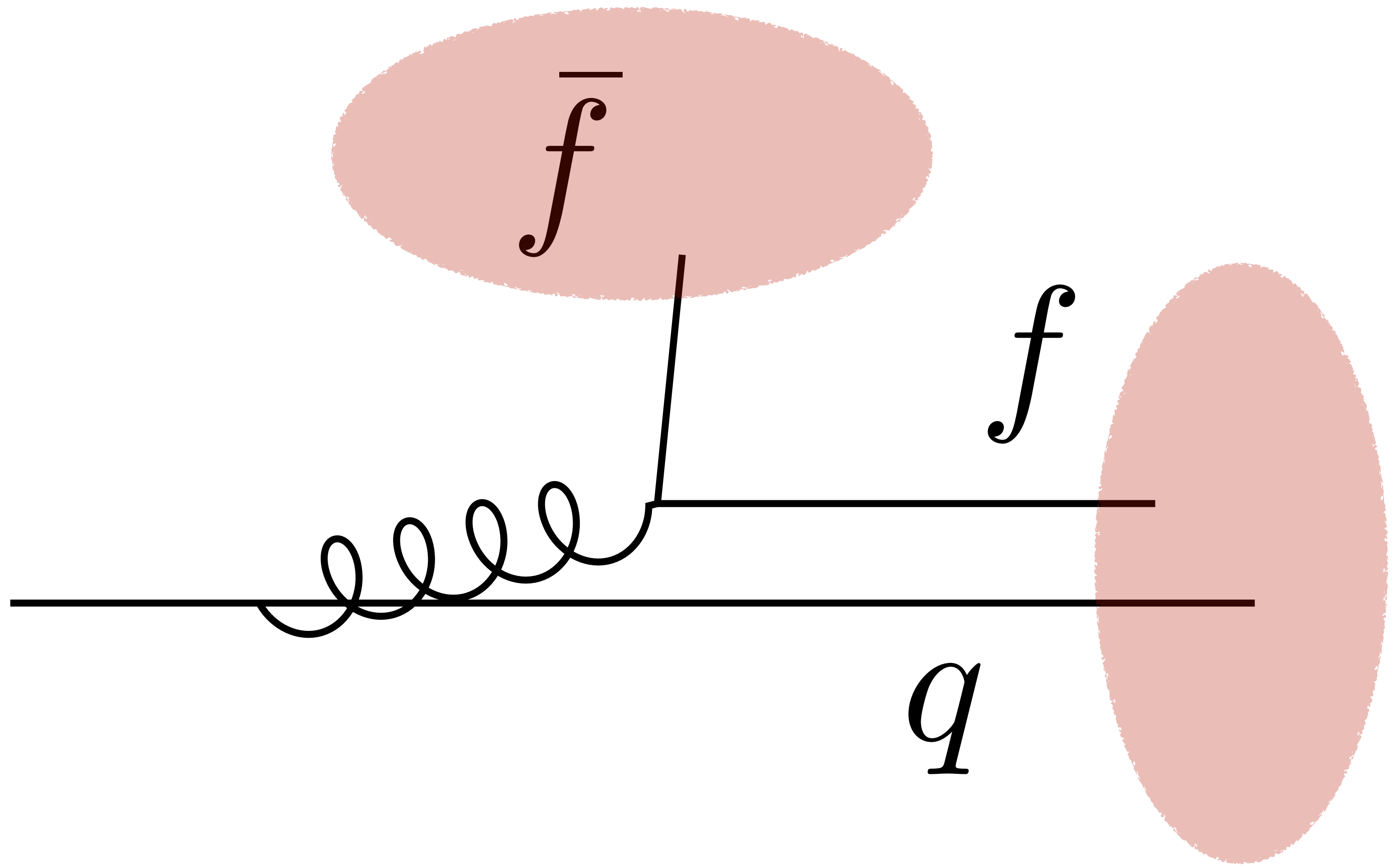
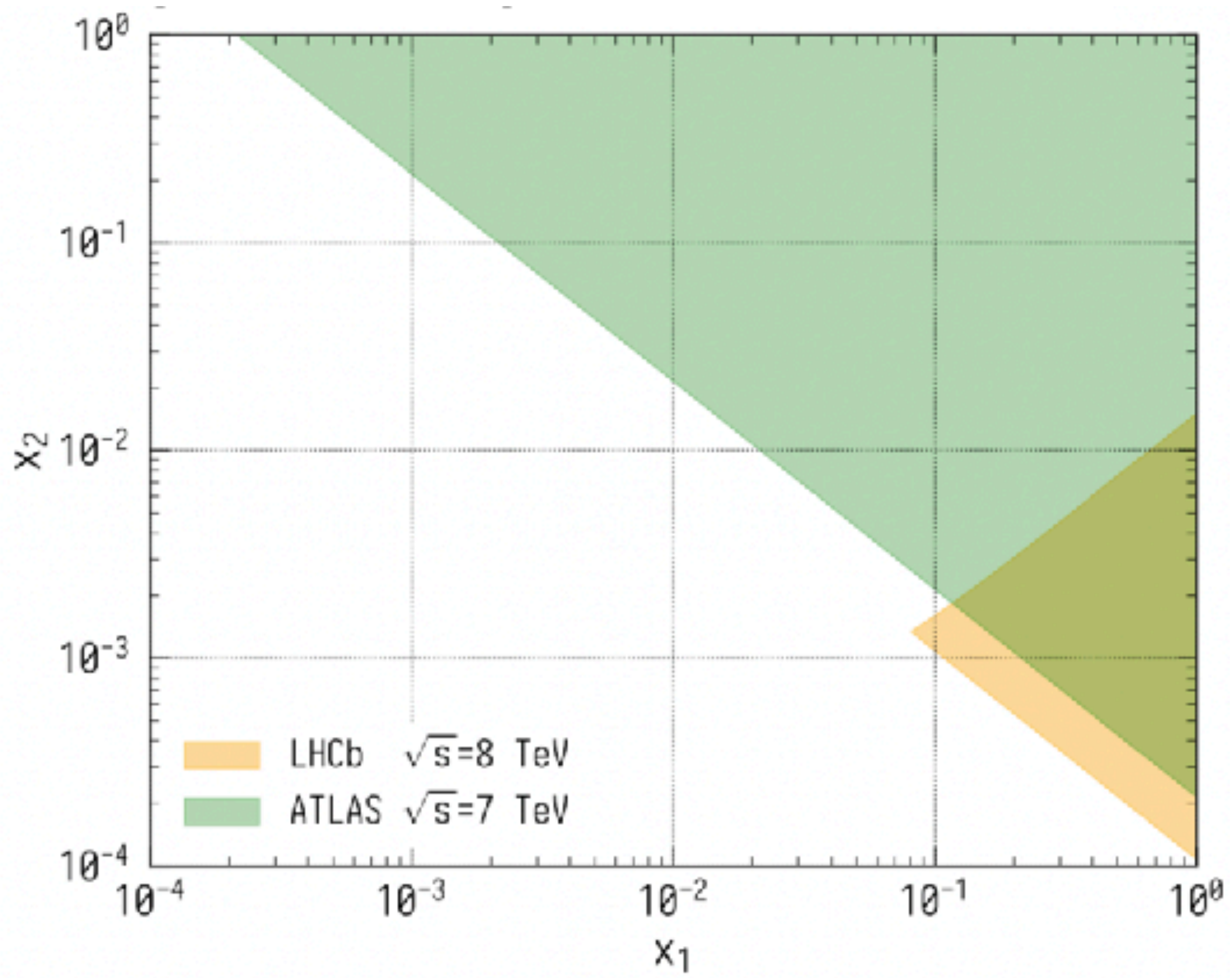
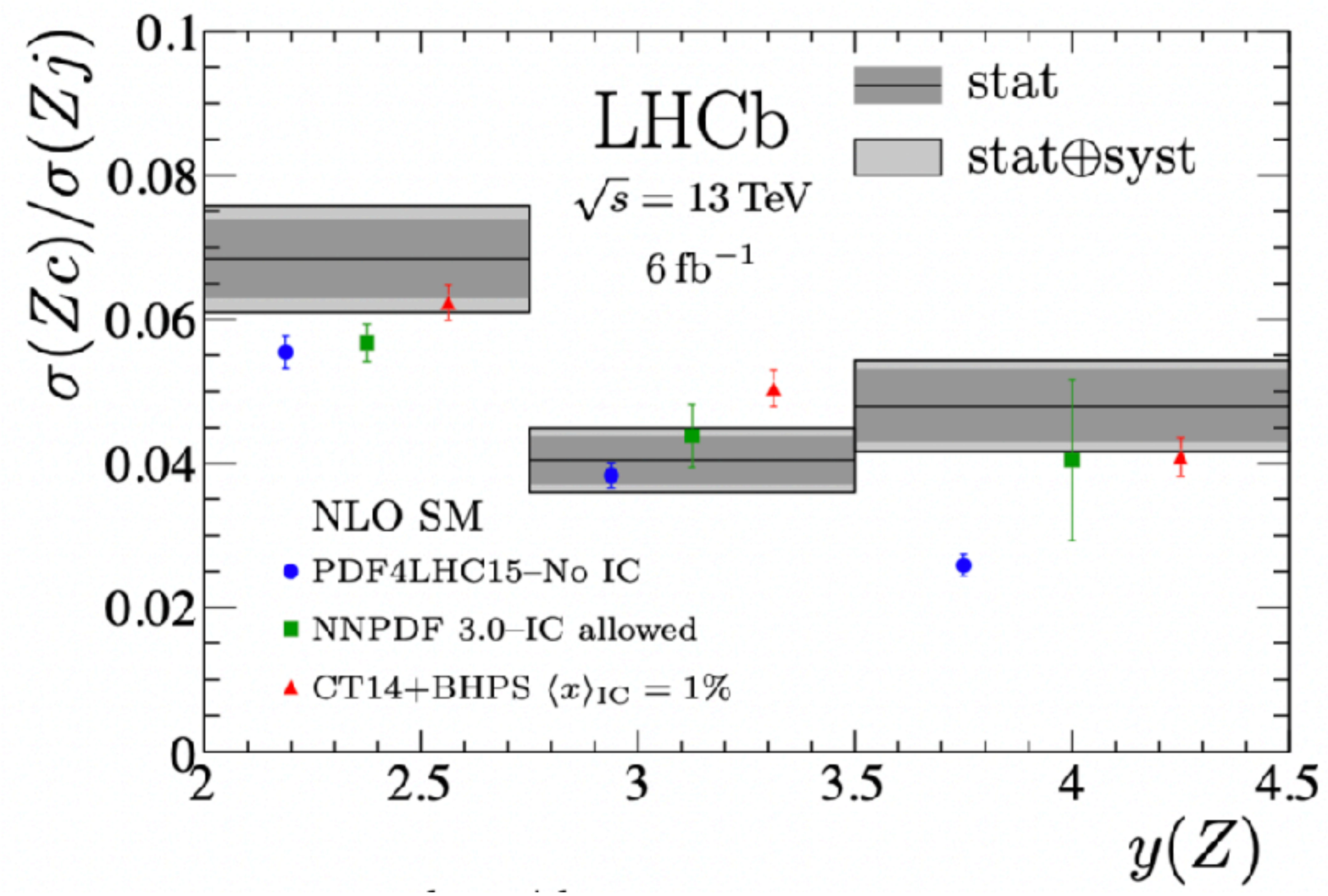


Effect **captured at NNLO**

$Z + c$-jet at LHCb



Sensitive to intrinsic charm in the proton, since LHCb suited to probe highly asymmetric momentum fractions

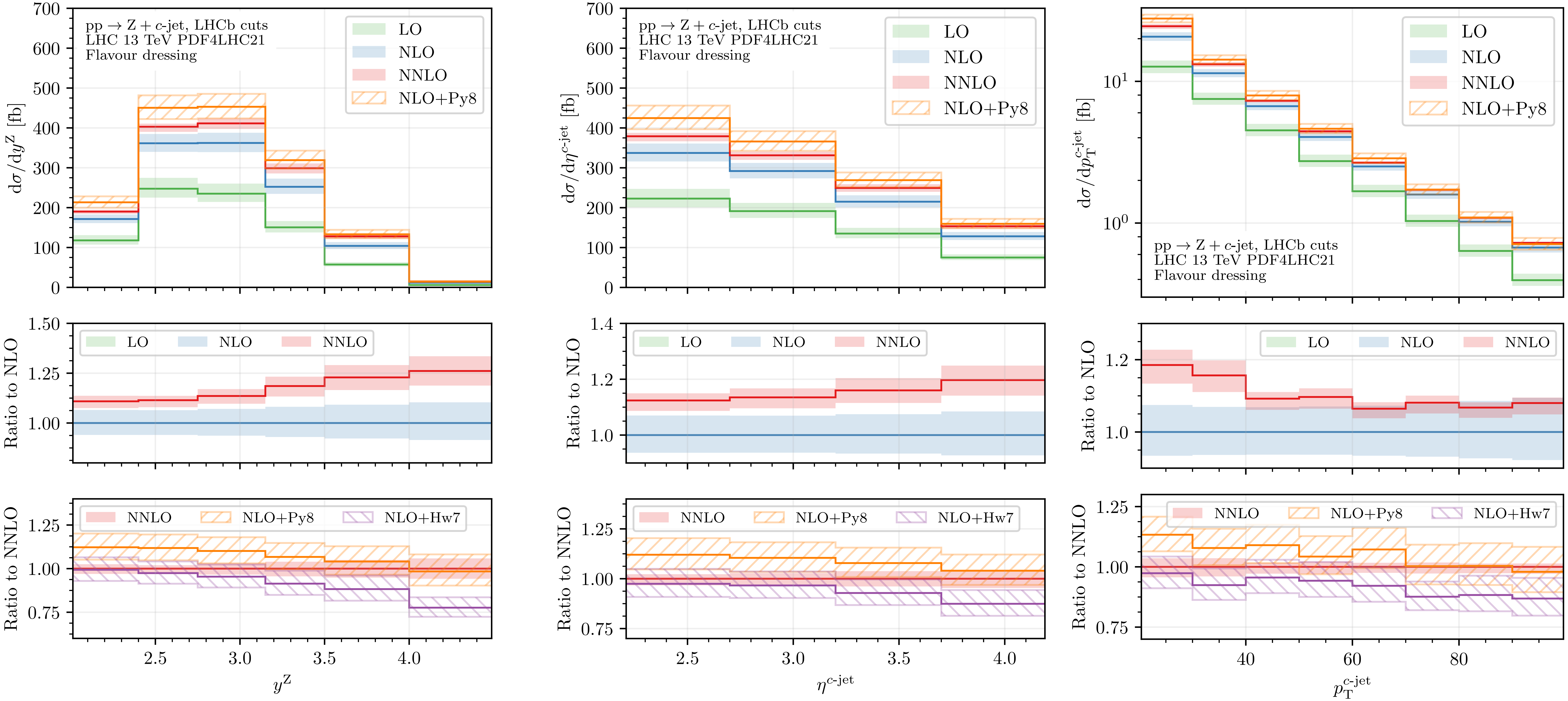


Exp. data at 13TeV for ratio $(d\sigma_{Z+c}/dy_Z)$ / $(d\sigma_{Z+j}/dy_Z)$ available

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

$Z + c$-jet in the forward kinematics

[Gauld, Gehrmann-De Ridder, Glover, Huss, Rodriguez Garcia, GS 2302.xxxxx]



Good agreement between NNLO and p_T-ordered NLO+PS

PRELIMINARY

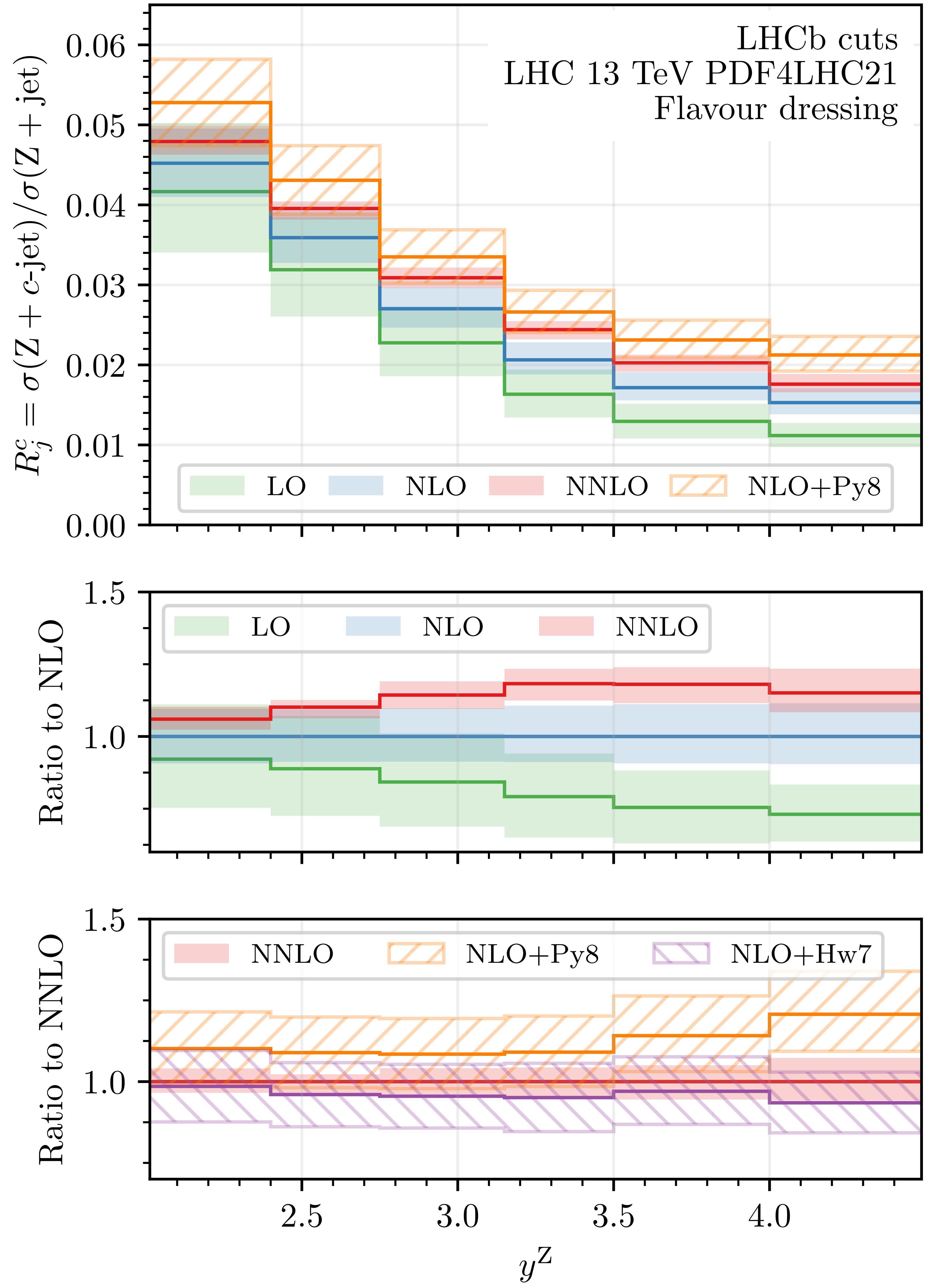
$Z + c$-jet in the forward kinematics

[Gauld, Gehrmann-De Ridder, Glover, Huss, Rodriguez Garcia, GS 2302.xxxxx]

$$R_j^c = (\mathrm{d}\sigma_{Z+c}/dy_Z)\ /\ (\mathrm{d}\sigma_{Z+j}/dy_Z)$$

Thanks to flavour dressing, numerator and denominator both feature the same anti-k_T jets!

However, comparison to available LHCb data not possible… Interesting to explore experimental feasibility of flavour dressing



Final remarks on flavour dressing

With flavour dressing, **flavour assignment *factorised* from the initial jet reconstruction**, hence it can be **combined with any IRC safe definition of a jet**

The IRC safe flavour assignment allows for massless fixed-order predictions, and in the case of massive calculations and/or parton showered events, implies a suppressed sensitivity on $\log(Q^2/m_f)$

A fastjet-contrib (https://fastjet.hepforge.org/contrib/) is in preparation.

Conclusions

Heavy Flavours are of **paramount importance** in particle physics

Flavoured particles and flavoured jets are **two complementary ways** of looking at the same events

Accurate phenomenology requires both precise theory predictions and good (e.g. IRC safe) definitions of objects

Work in progress, stay tuned!