[Jet] Flavour and IRC safety

Gavin Salam,
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Flavoured Jets at the LHC,
Durham, UK, 11–12 June 2024

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Measuring the Fractions of Quark and Gluon Jets in Hardon–Hadron Collisions #1

S.G. Shulha (Dubna, JINR and Gomel State U.), D.V. Budkovskii (Dubna, JINR and Belarus State U.) (Mar 11, 2024)

Published in: *Phys.Part.Nucl.* 55 (2024) 1, 180-182

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Two Types of Gluons in QCD: Re-interpretation of ALEPH and CMS Gluon Jet Data #2

Y.M. Cho (Jan 15, 2024)

e-Print: 2401.08704 [hep-ph]

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New Approach to Measuring Quark–Gluon Jets at the LHC #3

Petr Baroň (Cracow, INP), Michael H. Seymour (Lancaster U. (main)), Andrzej Siódmok (Jagiellonian U.) (2024)

Published in: *Acta Phys.Polon.Supp.* 17 (2024) 2, 2-A9 • Contribution to: MTTD 2023, 2-A9

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The dead cone effect in heavy quark jets observed in momentum space and its QCD explanation #4

Stefan Kluth (Garching, Max Planck Inst.), Wolfgang Ochs (Garching, Max Planck Inst.), Redamy Perez Ramos (Paris, LPTHE) (Dec 29, 2023)

e-Print: 2312.17697 [hep-ph]

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A PARAMETRIZATION OF THE PROPERTIES OF QUARK JETS *

R.D. FIELD and R.P. FEYNMAN
California Institute of Technology, Pasadena, California 91125, USA

Received 11 October 1977

Recent data from ISR[1,2] and Fermilab[3] indicate that the "jets" observed in large $p_\perp$ hadron-hadron collisions are similar to those in processes initiated by leptons (i.e., e^+e^-, ep, and γp processes). The "jets" observed in both cases are thought to arise from quarks that fragment or cascade into a collection of hadrons moving in roughly the direction of the original quark.

[...]

(Some theorists believe that gluon jets will be produced at large $p_\perp$ in hadron-hadron collisions in addition to quark jets.)

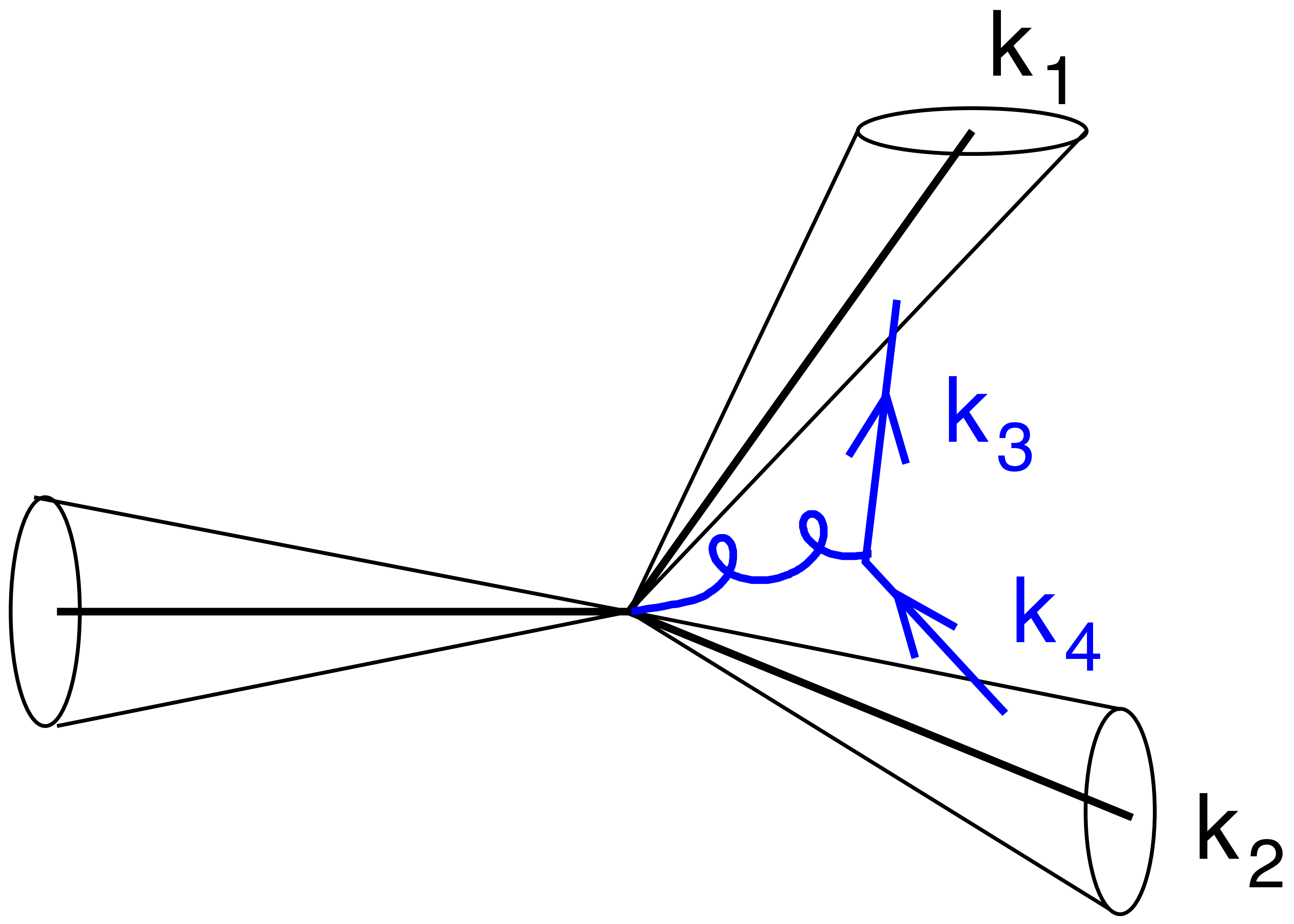
Jet flavour and infrared safety

Physical meaning of quark or gluon jet (jet *flavour*) is "obvious".

[one initiated by a hard quark resp. gluon]

But with normal jet algorithms (k_t, cone), sum of flavours of partons in jet is *infrared unsafe:*

- Soft gluon → large angle $q\bar{q}$ is clustered into different jets and *contaminates* jet flavour.



Can the jet flavour be made infrared safe?

Feynman alleged to have said "no" (but we haven't found ref.)

∃ hints of problems in reconciling IR safety and flavour: *e.g.* Nagy & Soper '05

GPS @DIS 2006

Jet flavour: two broad contexts for infrared and collinear (IRC) safety

light flavour

e.g. is it a quark or gluon-induced jet?

Important conceptual question to be able to answer "in principle" (@N^{k}LO)

Enters when asking about efficiency of quark/gluon tagging —- **what does it even mean to have a quark jet**, what's the level of fundamental ambiguity?

Relevant also in organising matching/merging in resummation & MCs

Systematics of quark/gluon tagging *1704.03878*

Philippe Gras,[a] Stefan Höche,[b] Deepak Kar,[c] Andrew Larkoski,[d] Leif Lönnblad,[e] Simon Plätzer,[f,g] Andrzej Siódmok,[h,i] Peter Skands,[j] Gregory Soyez,[k,†] and Jesse Thaler[l,†]

Abstract: By measuring the substructure of a jet, one can assign it a "quark" or "gluon" tag. In the eikonal (double-logarithmic) limit, quark/gluon discrimination is determined solely by the color factor of the initiating parton (C_F versus C_A). In this paper, we confront the challenges faced when going beyond this leading-order understanding, using both parton-shower generators and first-principles calculations to assess the impact of higher-order perturbative and nonperturbative physics. Working in the idealized context of electron-positron collisions, where one can define a proxy for quark and gluon jets based on the Lorentz structure of the production vertex, we find a fascinating interplay between perturbative shower effects and nonperturbative hadronization effects. Turning to proton-proton collisions, we highlight a core set of measurements that would constrain current uncertainties in quark/gluon tagging and improve the overall modeling of jets at the Large Hadron Collider.

QCD matrix elements and truncated showers

Stefan Höche[1], Frank Krauss[2], Steffen Schumann[3], Frank Siegert[2]

We derive an improved prescription for the merging of matrix elements with parton showers, extending the CKKW approach. A flavour-dependent phase space separation criterion is proposed. We show that this new method preserves the logarithmic accuracy of the shower, and that the original proposal can be [...]

0903.1219

Jet flavour: two broad contexts for infrared and collinear (IRC) safety

light flavour

e.g. is it a **quark** or **gluon**-induced jet?

Important conceptual question to be able to answer "in principle" (@N^{k}LO)

Enters when asking about efficiency of quark/gluon tagging —- **what does it even mean to have a quark jet**, what's the level of fundamental ambiguity?

Can be relevant in organising matching/merging in resummation & MCs

heavy flavour

e.g. is it a ***b*-quark** induced jet or not?

Critical practical question for many experimental measurements

With massive quarks, no IRC safety problem. But IRC unsafe algorithms are more sensitive to log-enhanced contamination ($\alpha_s^n \log^m p_t/m_b$)

Theorists often treat *b*-quarks as massless — IRC safe def^n critical

Logic behind k_t clustering

k_t algorithm clusters closest pair of particles, next closest pair, etc.

cf. talk by Cacciari

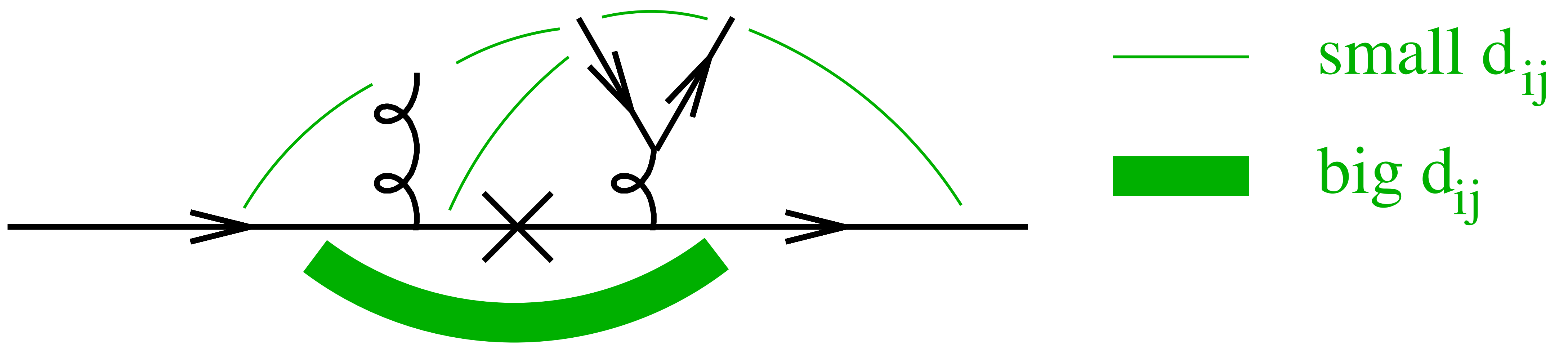
Key issue is *distance measure:*

$$d_{ij}^{(k_t)} = 2\min(E_i^2, E_j^2)\,(1-\cos\theta_{ij})\,,$$

This is a logical generic choice because of structure of divergences in gluon emission:

$$[dk_j]|M^2_{g\to g_i g_j}(k_j)| \simeq \frac{\alpha_s C_A}{\pi}\frac{dE_j}{\min(E_i,E_j)}\frac{d\theta_{ij}^2}{\theta_{ij}^2}\,, \qquad (E_j \ll E_i\,,\;\; \theta_{ij} \ll 1)\,.$$

For each divergent limit, $E_j \to 0$, $\theta_{ij} \to 0$, distance vanishes ($y_{ij} \to 0$).



k_t distance and quarks

Quark production only has collinear divergence, but no soft divergence

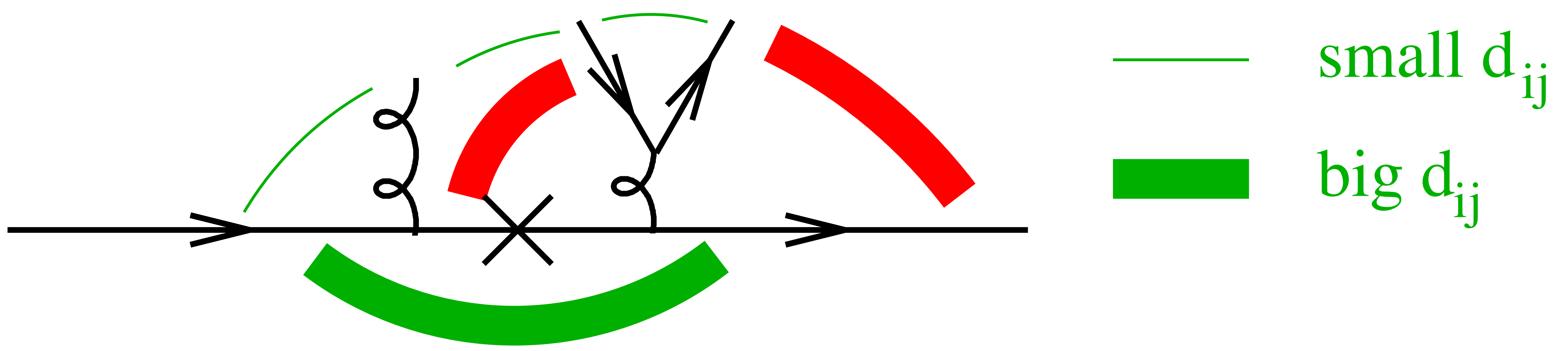
$$[dk_j]|M^2_{g\to q_i\bar{q}_j}(k_j)| \simeq \frac{\alpha_s T_R}{2\pi}\frac{dE_j}{\max(E_i,E_j)}\frac{d\theta_{ij}^2}{\theta_{ij}^2}\,, \qquad (E_j \ll E_i\,,\ \theta_{ij}\ll 1)\,,$$

- k_t distance does not match divergence structure for quark emission
- *fatal* for jet flavour studies because soft large-angle $q, \bar{q}$ from soft gluon are deemed similarly close to all particles in event

Solution: modify distance measure for quarks to reflect divergences

[Banfi, GPS & Zanderighi, hep-ph/0601139]

$$d_{ij}^{(F)} = 2(1-\cos\theta_{ij}) \times \begin{cases} \max(E_i^2, E_j^2)\,, & \text{softer of } i,j \text{ is quark-like,} \\ \min(E_i^2, E_j^2)\,, & \text{softer of } i,j \text{ is gluon-like,} \end{cases}$$



Until recently, choice was between

"Flavour-k_t algorithm" [from 2006],

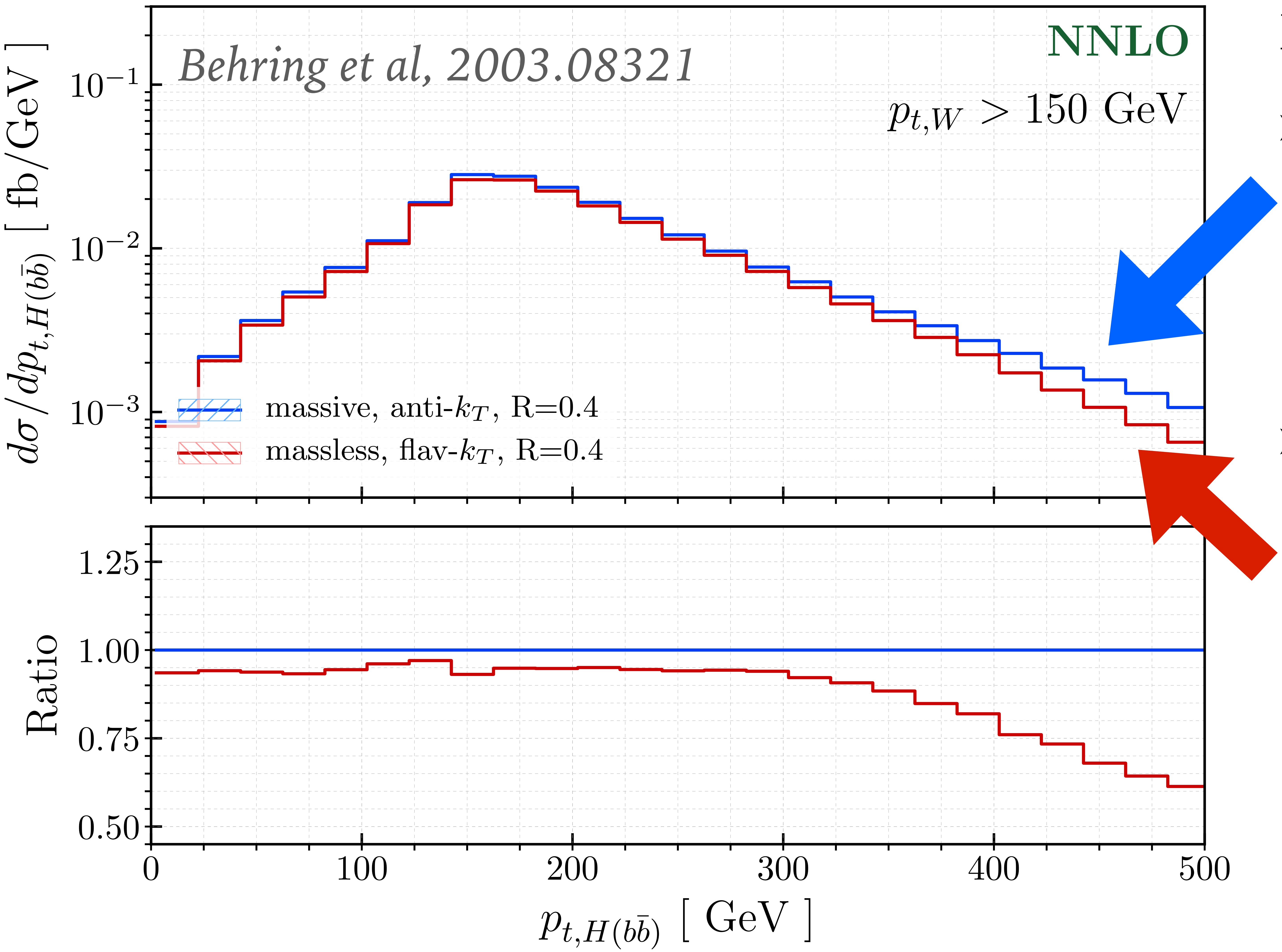
- with Infrared and collinear (IRC) safe† flavour + kinematics

Modern jet finding tools [post 2008] such as

- anti-k_t algorithm
- Cambridge/Aachen (C/A) for jet substructure, incl. Soft-Drop, etc.
- associated software ecosystem (FastJet, FJContrib)

for which flavour is IRC unsafe.

Why a problem? Different algorithms give different jet kinematics



E.g. at NNLO

- Use anti-k_t algorithm (heavy-flavour can only be defined with explicitly massive quarks; unresummed logarithms of p_t/m_b)
- Use flavour-k_t algorithm with massless b-quarks (but kinematics differ wrt anti-k_t and even wrt normal k_t alg.)

Recent approaches

Calculate better the flavour that's there (in MCs or resummation)

Caletti, Larkoski, Marzani, Reichelt, 2205.01117
Caletti, Ghira, Marzani, 2312.11623
Larkoski at May 2024 LHCb meeting
Ferrario Ravasio, Hamilton, Karlberg, GPS, Scyboz, Soyez [PanScales "double soft" paper] 2307.11142

Make jet algorithms IRC safe up to some order (e.g. NNLO)

Caletti, Larkoski, Marzani, Reichelt, 2205.01109

Make jet algs. IRC safe to all orders

→ the next few slides

First: flavour recombination schemes

scheme \ jet contents	b	$b+\bar{b}$	$b+b$	
"any flavour"	b	b	b	simplest experimentally (but collinear unsafe for $m_b \to 0$)
net flavour	b	g	$2b$	theoretically "ideal" definition; but not robust wrt B–Bbar oscillations
flavour modulo 2	b	g	g	theoretically OK; robust wrt B–Bbar oscillations

} All algorithms in the next pages can work with these two

Four IRC safe algorithms († including post-IRC safety test adaptations)

Flav-k_t hep-ph/0601139†	CMP 2205.11879†	Flav-Dressing 2208.11138†	IFN 2306.07314
modified k_t-like distance when quark is softer	modified anti-k_t like distance for low-p_t quark pairs	after-burner on jets above p_t threshold	separates flavour-recomb. from kinematic recomb.
Flavoured jets have different effective radius & kinematics	Jets with flavour ≠ anti-k_t also have ≠ kinematics	Identical kinematics to reference alg.	Identical kinematics to reference alg.
replaces k_t alg	replaces anti-k_t alg	works with anti-k_t, C/A & k_t	works with anti-k_t, C/A (incl. substructure)
Banfi, GPS, Zanderighi	*Czakon, Mitov, Poncelet*	*Gauld, Huss, Stagnitto*	*Caola, Grabarczyk, Hutt, GPS, Scyboz, Thaler*

The CMP algorithm

Infrared-safe flavoured anti-kT jets, Czakon, Mitov, Poncelet 2205.11879

anti-kT: $d_{ij} = \min(k_{T,i}^{-2}, k_{T,j}^{-2}) R_{ij}^2 \qquad d_i = k_{T,i}^{-2}$

Proposed modification:

A soft term designed to modify the distance of flavoured pairs.

$$d_{ij}^{(F)} = d_{ij} \begin{cases} \mathcal{S}_{ij} & \text{i,j is flavoured pair} \\ 1 & \text{else} \end{cases} \qquad \text{where} \quad \mathcal{S}_{ij} \to 0 \quad \text{if } i,j \text{ are soft}$$

Original proposal:

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

Issue when $E_i, E_j \gg 1$ but $p_{T,i}, p_{T,j} \ll 1$

Variant IFN paper [2306.07314]

$$\mathcal{S}_{ij} \to \overline{\mathcal{S}}_{ij} = \mathcal{S}_{ij} \frac{\Omega_{ij}^2}{\Delta R_{ij}^2} \qquad \Omega_{ik}^2 \equiv 2\left[\frac{1}{\omega^2}\left(\cosh(\omega \Delta y_{ik}) - 1\right) - \left(\cos\Delta\phi_{ik} - 1\right)\right]$$

The flavour dressing algorithm: algorithm

The flavour dressing algorithm.—With this information at hand, the flavour dressing algorithm to identify whether a reconstructed jet can be assigned the flavour quantum number $\mathfrak{f}$ proceeds as follows:

1. Initialise empty sets $\text{tag}_k = \varnothing$ for each jet j_k to accumulate all flavoured particles assigned to it.

2. Populate a set $\mathcal{D}$ of distance measures based on all allowed pairings:

   (a) For each unordered pair of particles p_i and p_j, add the distance measure $d_{p_i p_j}$ if either *both particles are flavoured*[1] or *at least one particle is unflavoured and p_i and p_j are associated with the same jet.*

   (b) If the particle p_i is associated to jet j_k, add the distance measure $d_{p_i j_k}$. In a hadron collider environment, the beam distances $d_{p_i B_\pm}$ should be added if p_i is not associated to any jet.

3. While the set $\mathcal{D}$ is non-empty, select the pairing with the smallest distance measure:

   (a) $d_{p_i p_j}$ is the smallest: the two particles merge into a new particle k_{ij} carrying the sum of the four-momenta and flavour. All entries in $\mathcal{D}$ that involve p_i or p_j are removed and new distances for k_{ij} are added.

   (b) $d_{p_i j_k}$ is the smallest: assign the particle p_i to the jet j_k, $\text{tag}_k \to \text{tag}_k \cup \{p_i\}$, and remove all entries in $\mathcal{D}$ that involve p_i.

   (c) $d_{p_i B_\pm}$ is the smallest: discard particle p_i and remove all entries in $\mathcal{D}$ that involve p_i.

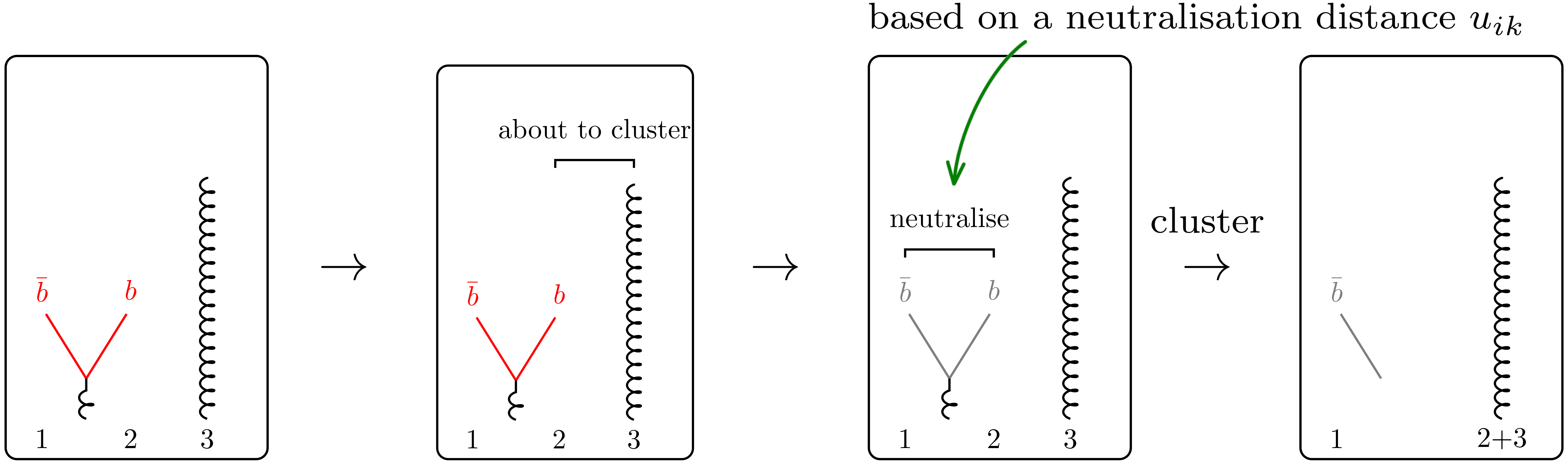
4. The flavour assignment for jet j_k is determined according to the accumulated flavours in tag_k.

Giovanni Stagnitto, LHCb meeting on jet flavour algorithms

Interleaved Flavour Neutralisation (IFN)

- Cluster particles with a generalised-k_t algorithm (e.g. anti-k_t, C/A),

$$d_{ij} = \min\left(p_{ti}^{2p}, p_{tj}^{2p}\right) \frac{\Delta R_{ij}^2}{R^2} \qquad d_{iB} = p_{ti}^{2p}$$



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

→ need to apply this recursively

Ludovic Scyboz, LHCb meeting on jet flavour algorithms

Distance measures for flavoured clusterings in Flavour-k_t, IFN & Flavour Dressing [GHS]

$$u_{ik} = \underbrace{\max\left(p_{ti}, p_{tk}\right)^{\alpha} \min\left(p_{ti}, p_{tk}\right)^{2-\alpha}}_{\text{flavour}-k_t-\text{like}} \cdot \Omega_{ik}^2$$

$$\Omega_{ik}^2 = 2\left[\frac{1}{\omega^2}\left(\cosh(\omega\Delta y_{ik}) - 1\right) - \left(\cos\Delta\phi_{ik} - 1\right)\right]$$

$$\alpha = 1,\ \omega = 2$$
$$\alpha = 2,\ \omega = 1$$

instead of ΔR^2

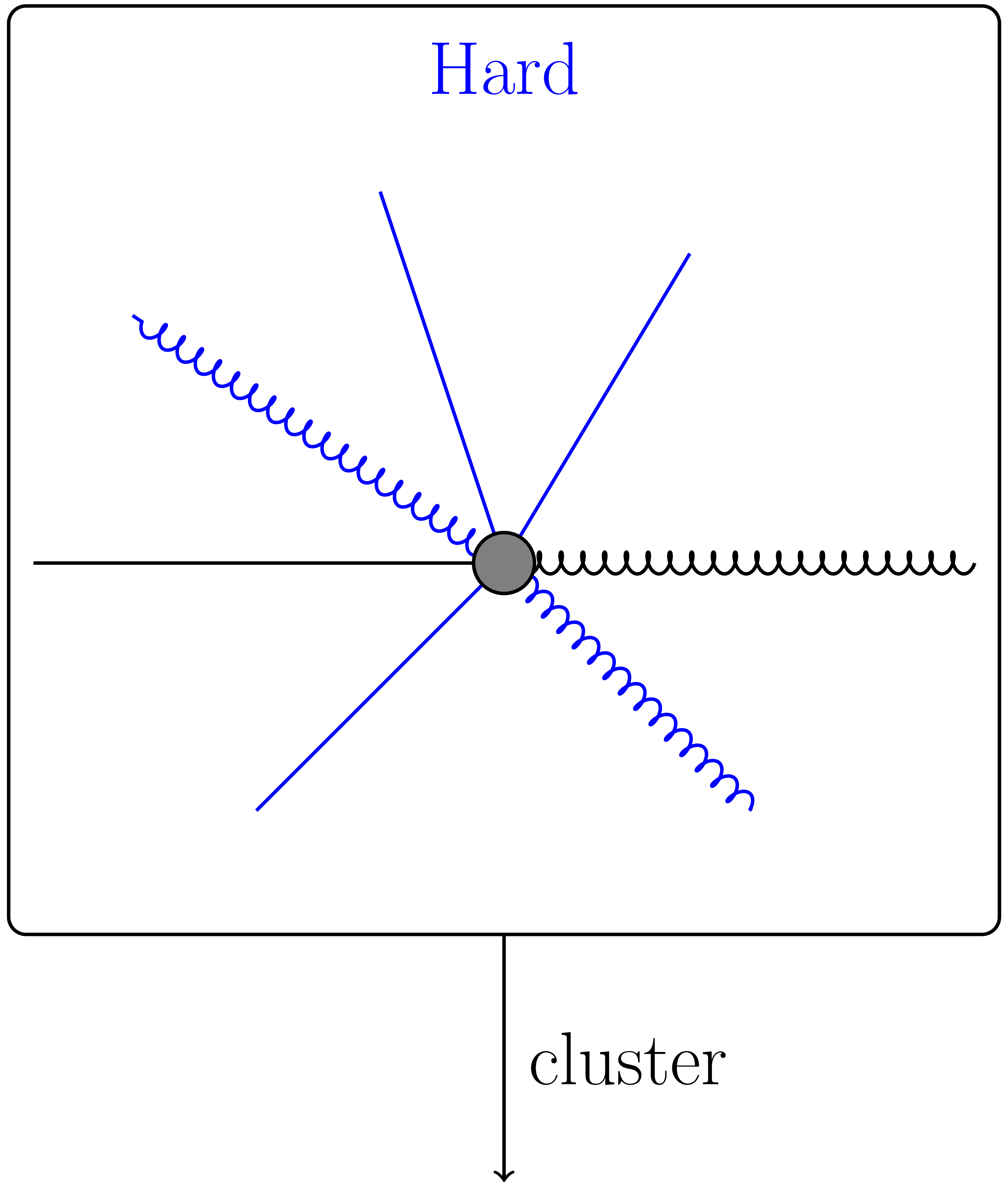
Ω_{ik} needed for IRC safety [initial-state collinear splitting & soft large angle pair]

NB: Flavour-k_t and Flavour Dressing also uses a “beam distance”

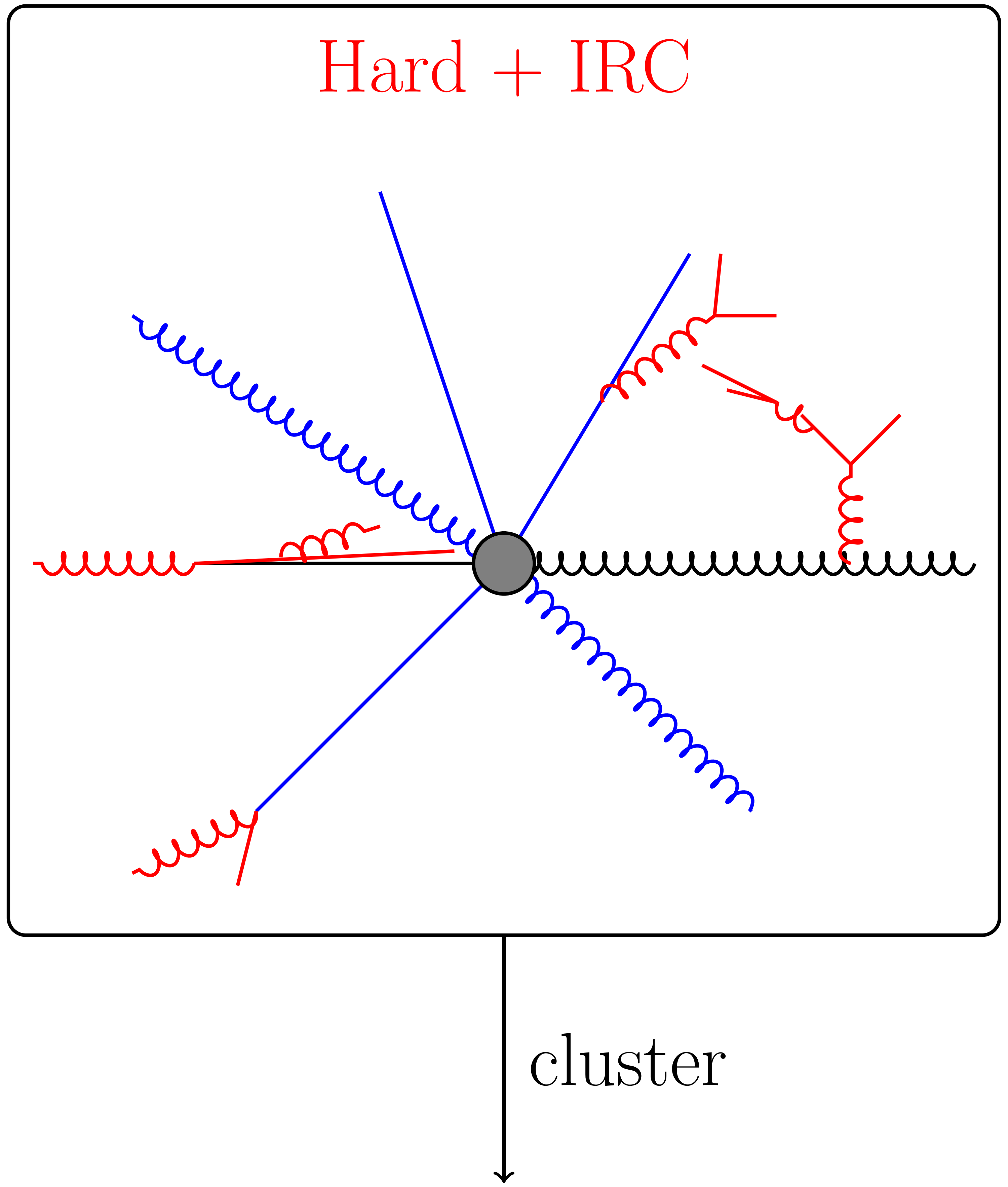
$$d_{p_i B_\pm} = \max\left(p_{\mathrm{T},i}^{\alpha}, p_{\mathrm{T},B_\pm}^{\alpha}(y_i)\right)\ \min\left(p_{\mathrm{T},i}^{2-\alpha}, p_{\mathrm{T},B_\pm}^{2-\alpha}(y_i)\right),$$

$$p_{\mathrm{T},B_\pm}(y) = \sum^{m} p_{\mathrm{T},j_k}\left[\Theta(\pm\Delta y_{j_k}) + \Theta(\mp\Delta y_{j_k})\, e^{\pm\Delta y_{j_k}}\right],$$

Testing IRC safety: analytically & numerically [2306.07314, started in 2020…]



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



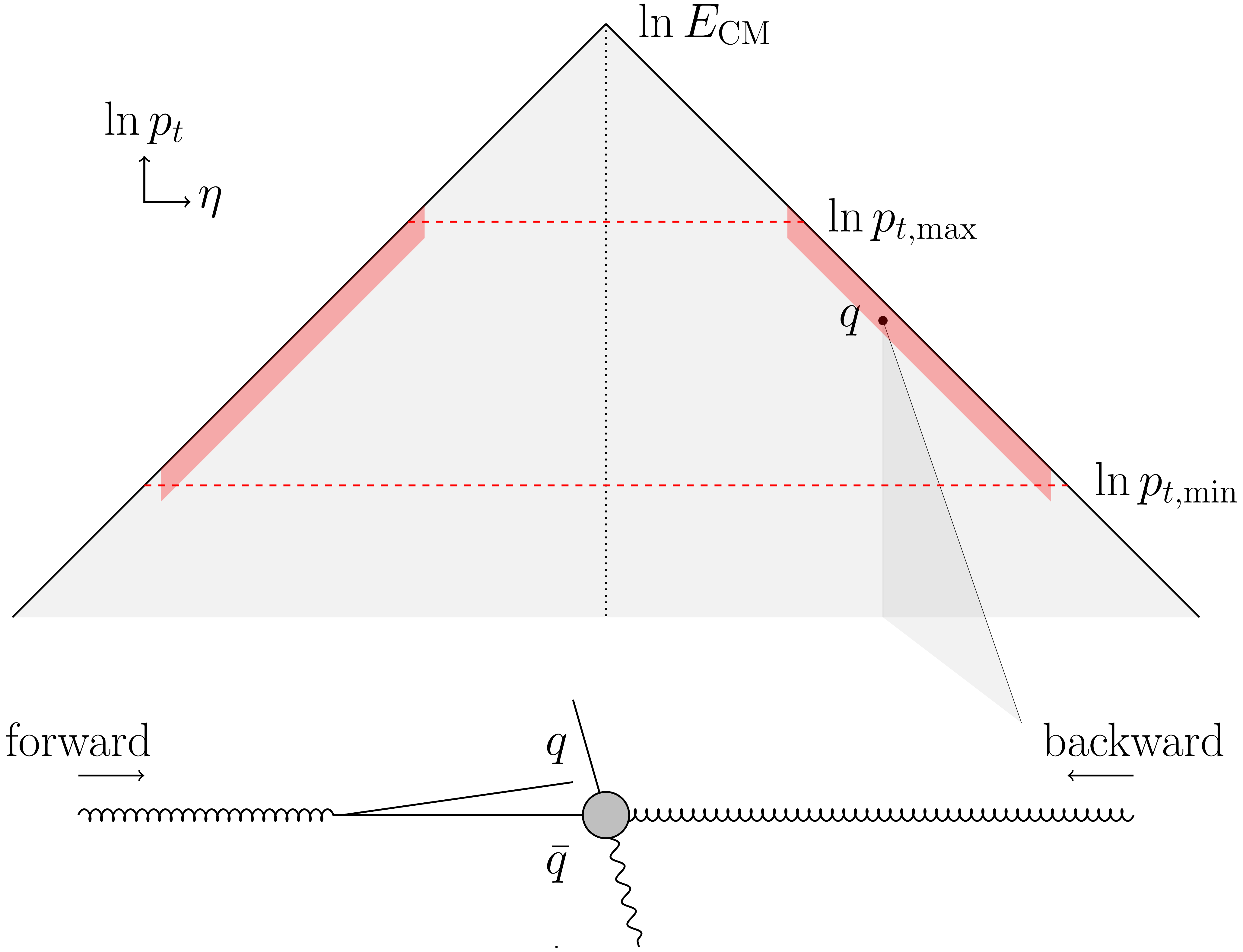
$\mathcal{J}_{\text{hard+IRC}} = \{(\tilde{p}_1, \tilde{f}_1), \ldots, (\tilde{p}_n, \tilde{f}_n)\}$

Supplement random "hard" event with IRC particles/splittings

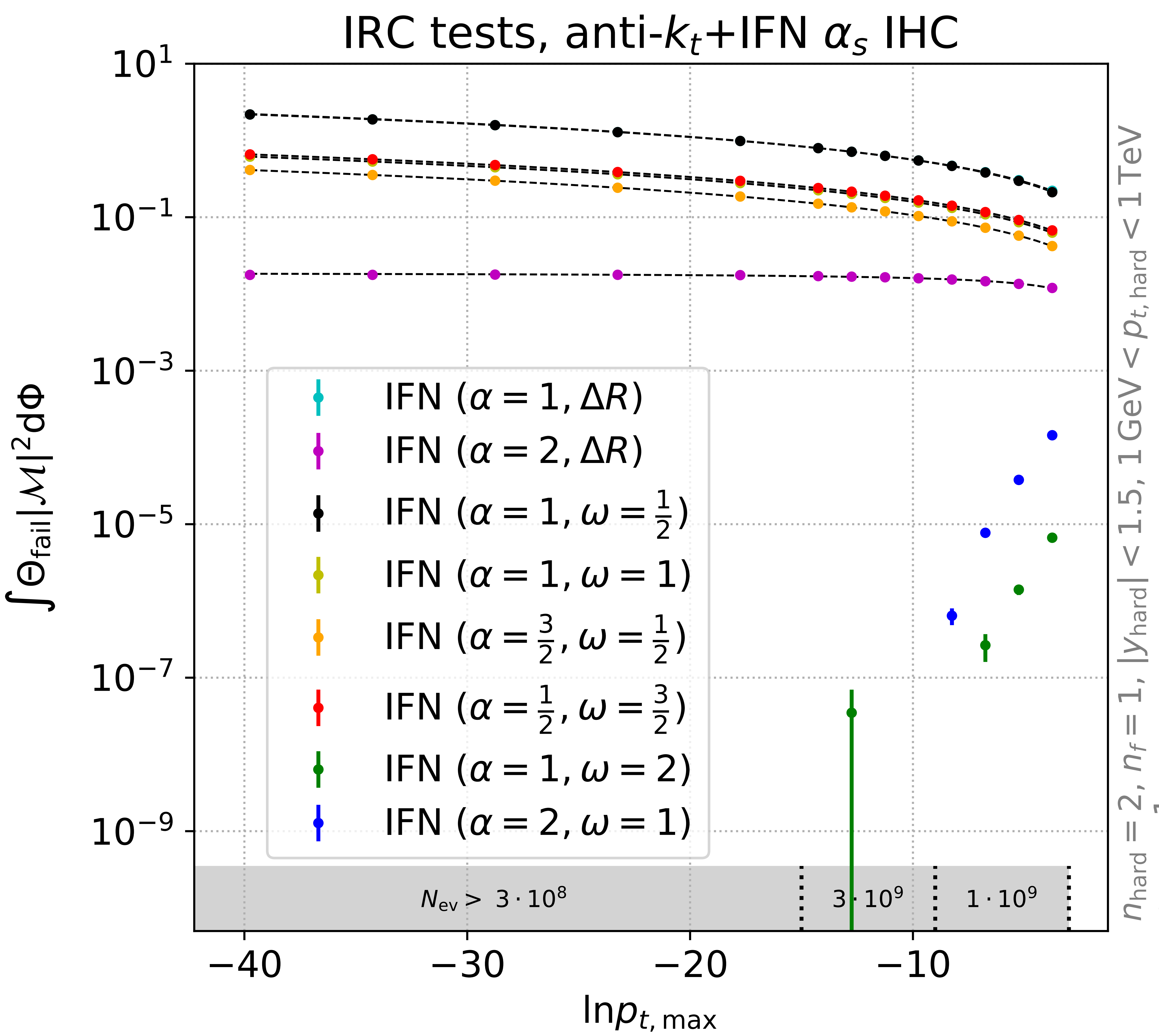
Are the hard jets' flavours the same in the original event and the supplemented one?

very considerably expanded relative to SISCone tests [GPS+Soyez, 0704.0292]

Example: use of Ω distance measure v. ΔR

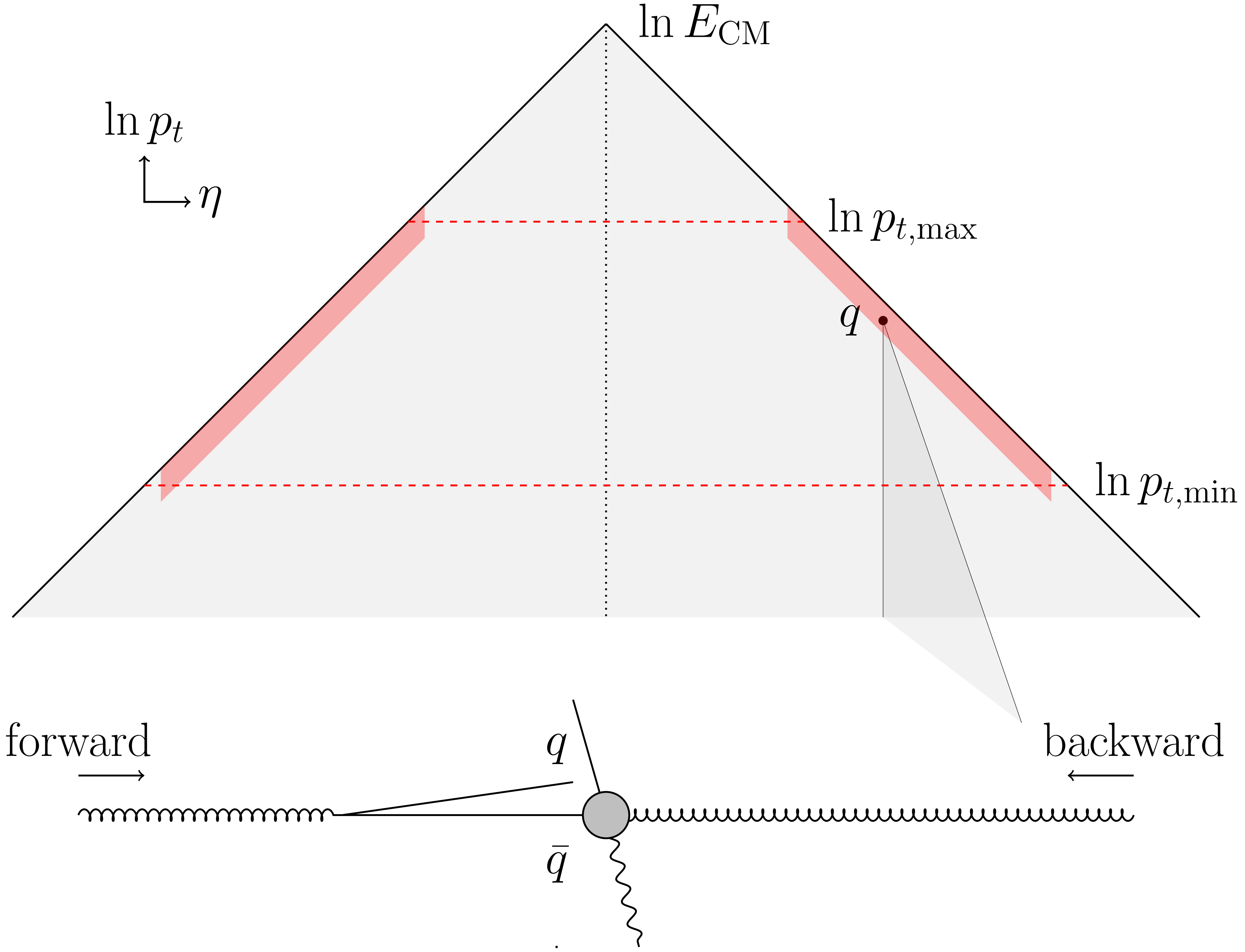


(b) IHC: initial-state hard-collinear

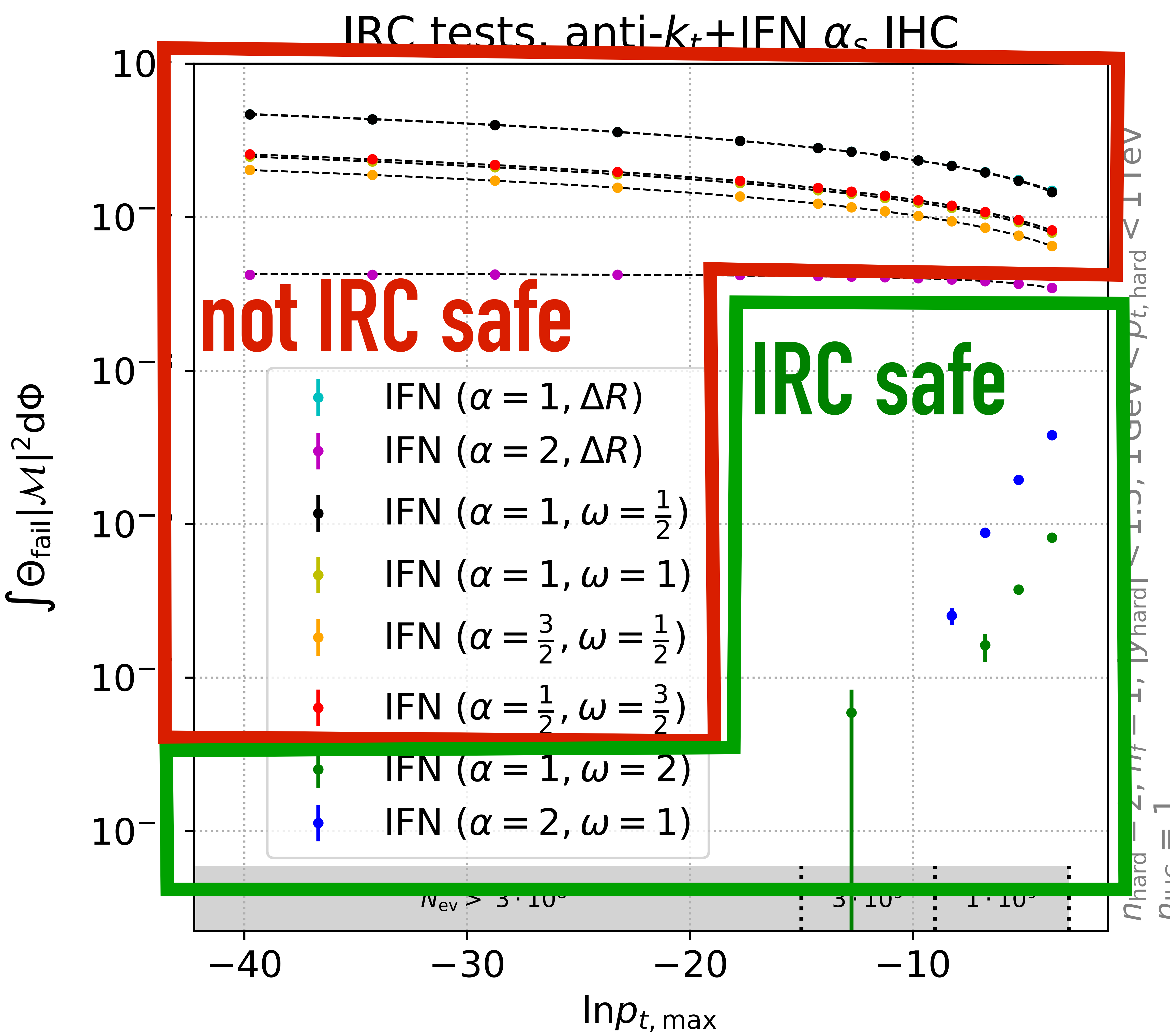


$$\Delta R_{ik}^2 \to \Omega_{ik}^2 = 2\left[\frac{1}{\omega^2}\left(\cosh(\omega \Delta y_{ik}) - 1\right) - \left(\cos\Delta\phi_{ik} - 1\right)\right] \qquad \alpha + \omega > 2$$

Example: use of Ω distance measure v. ΔR

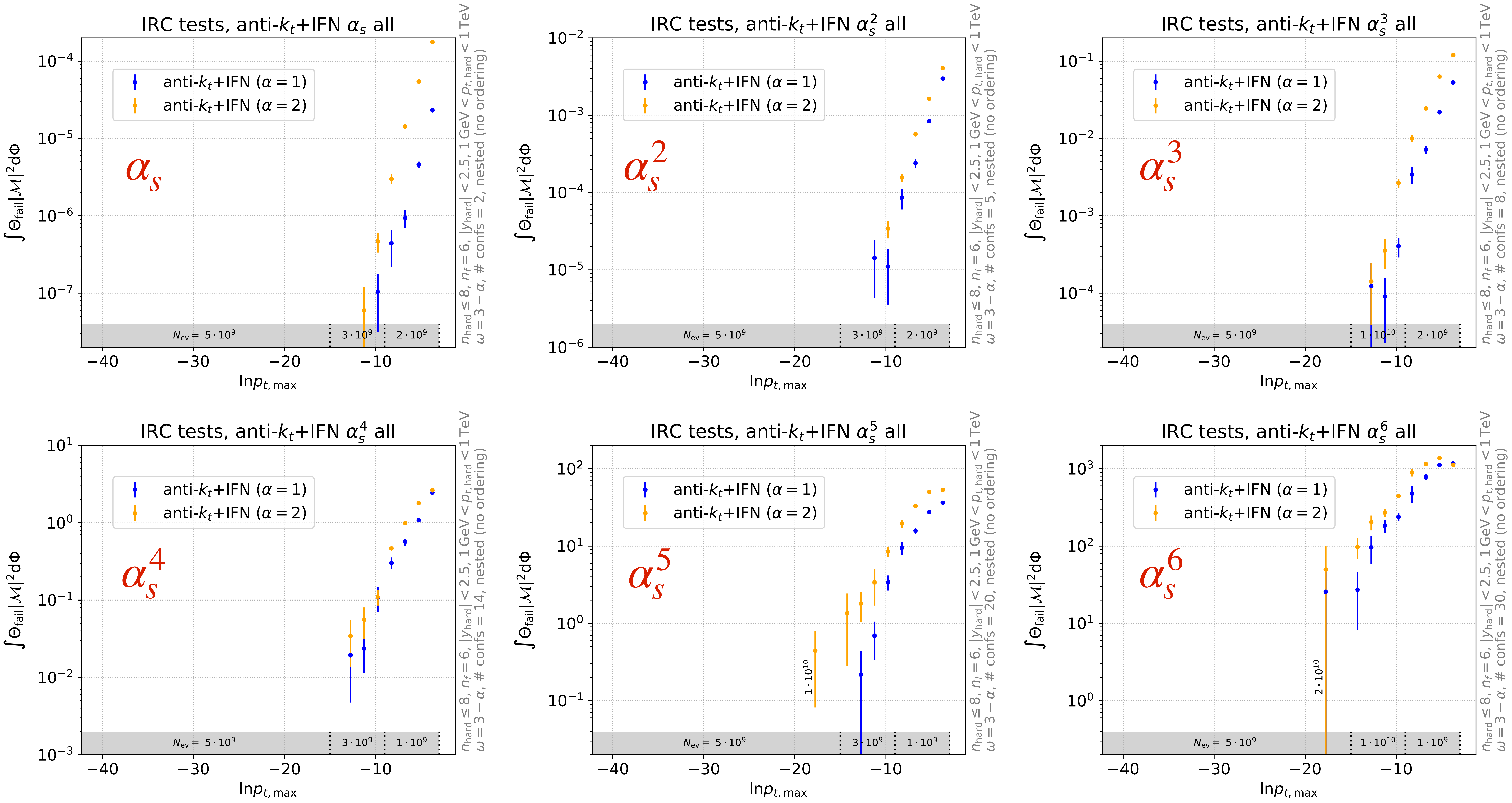


(b) IHC: initial-state hard-collinear

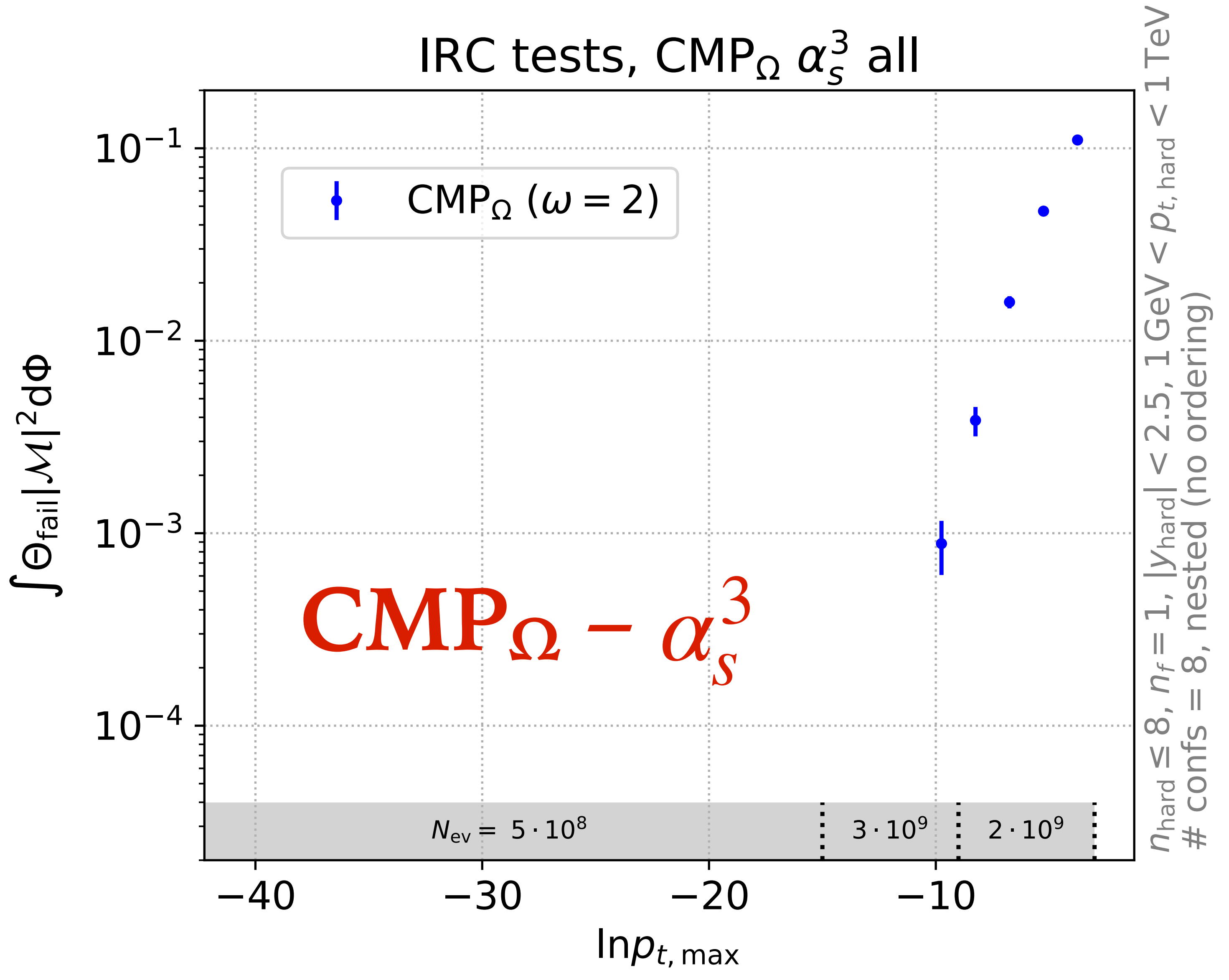


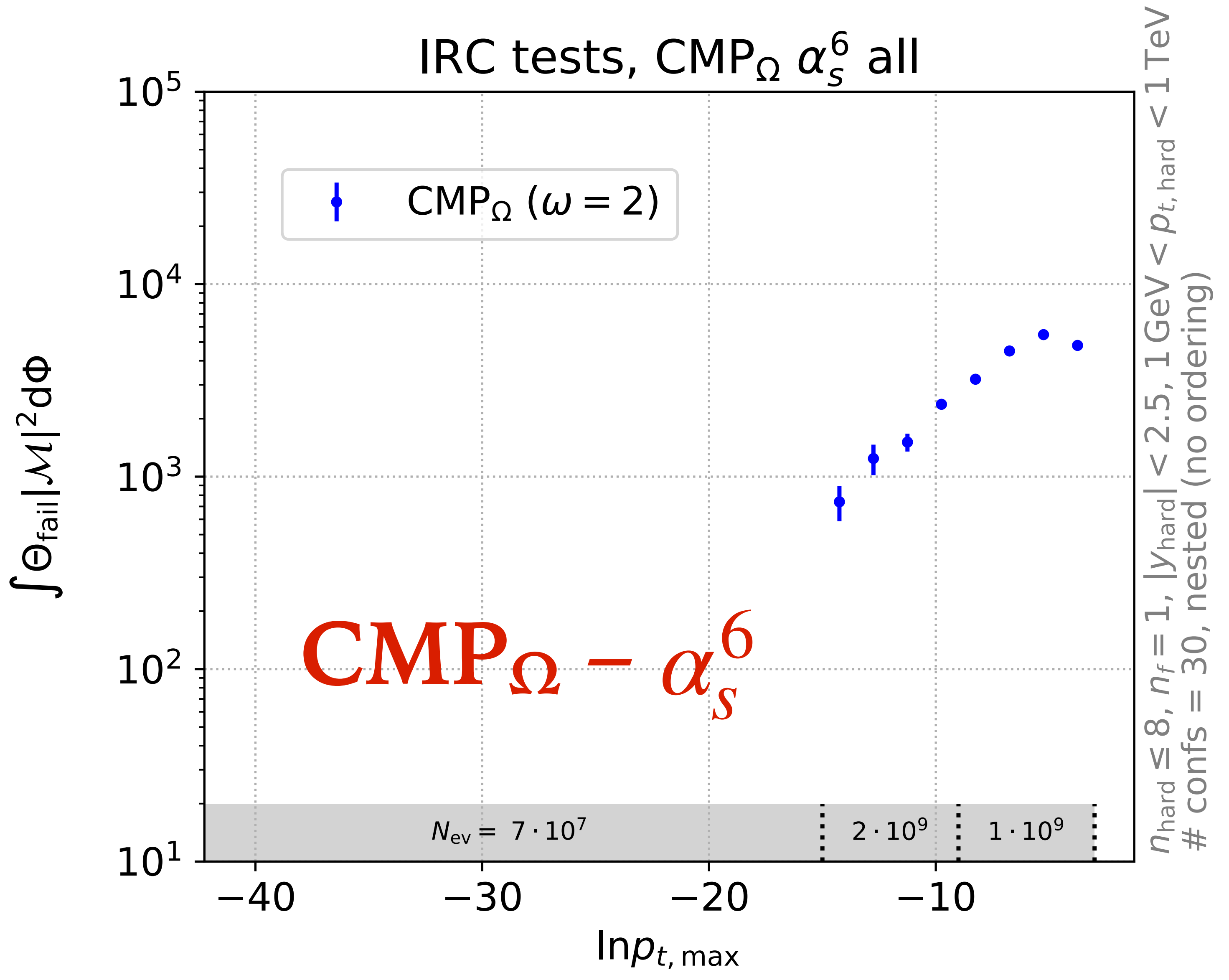
$$\Delta R_{ik}^2 \to \Omega_{ik}^2 = 2\left[\frac{1}{\omega^2}\left(\cosh(\omega \Delta y_{ik}) - 1\right) - \left(\cos \Delta\phi_{ik} - 1\right)\right] \qquad \alpha + \omega > 2$$

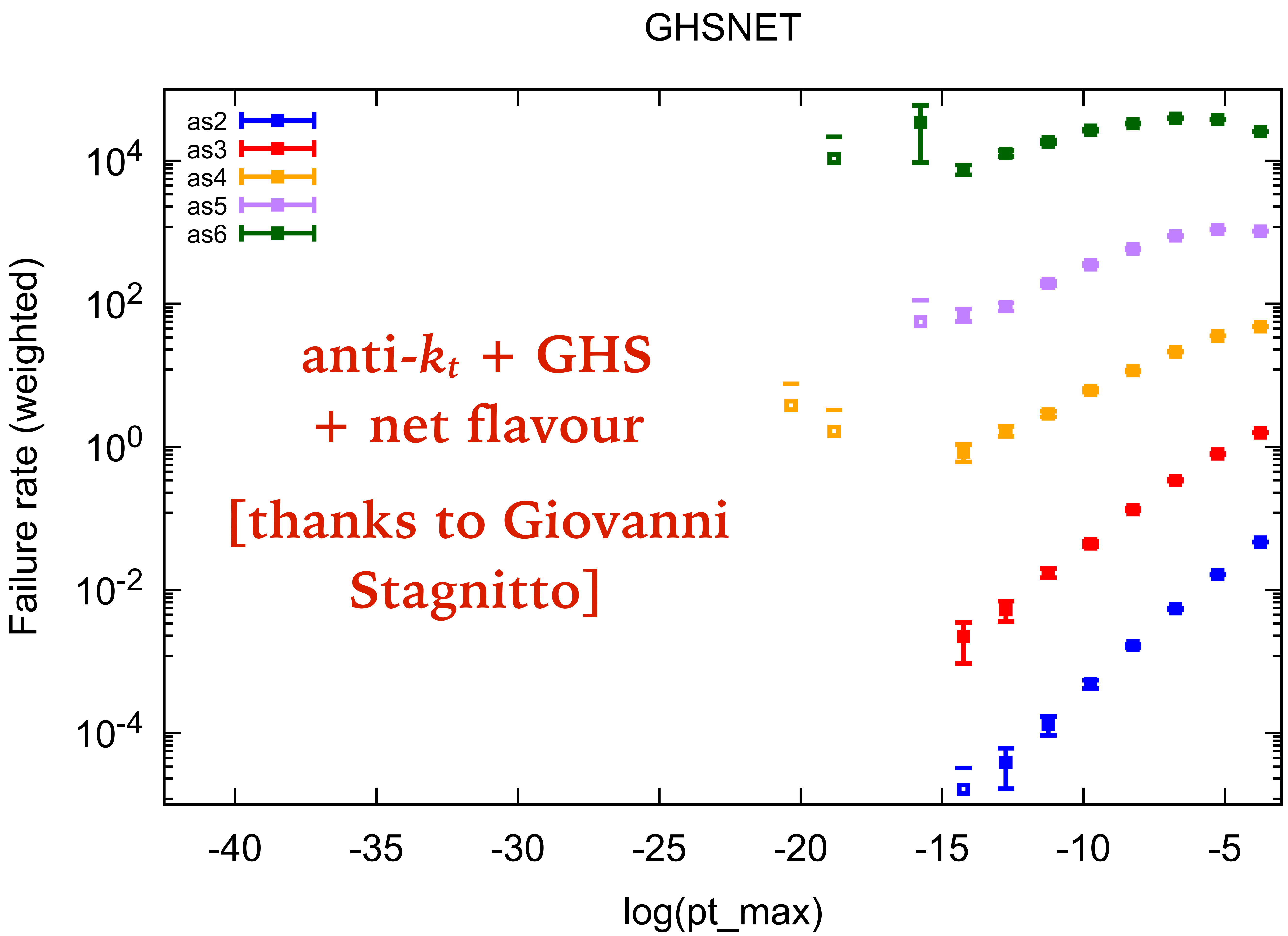
anti-k_t + IFN safety tests to 6th order in α_s



CMP & Flavour-Dressing[GHS] IRC tests







Parameters [aside from jet radius R]: CMP

one main parameter a (plus ω in Ω_{ij}), in factor $\mathcal{S}_{ij}$ that multiplies anti-k_t distance

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

$$\mathcal{S}_{ij} \to \overline{\mathcal{S}}_{ij} = \mathcal{S}_{ij}\,\frac{\Omega_{ij}^2}{\Delta R_{ij}^2}$$

when $a \to 0$, $\mathcal{S}_{ij} = 1$, algorithm becomes anti-k_t

→ so be aware of $\alpha_s^n \ln^m a$ terms if a taken too small

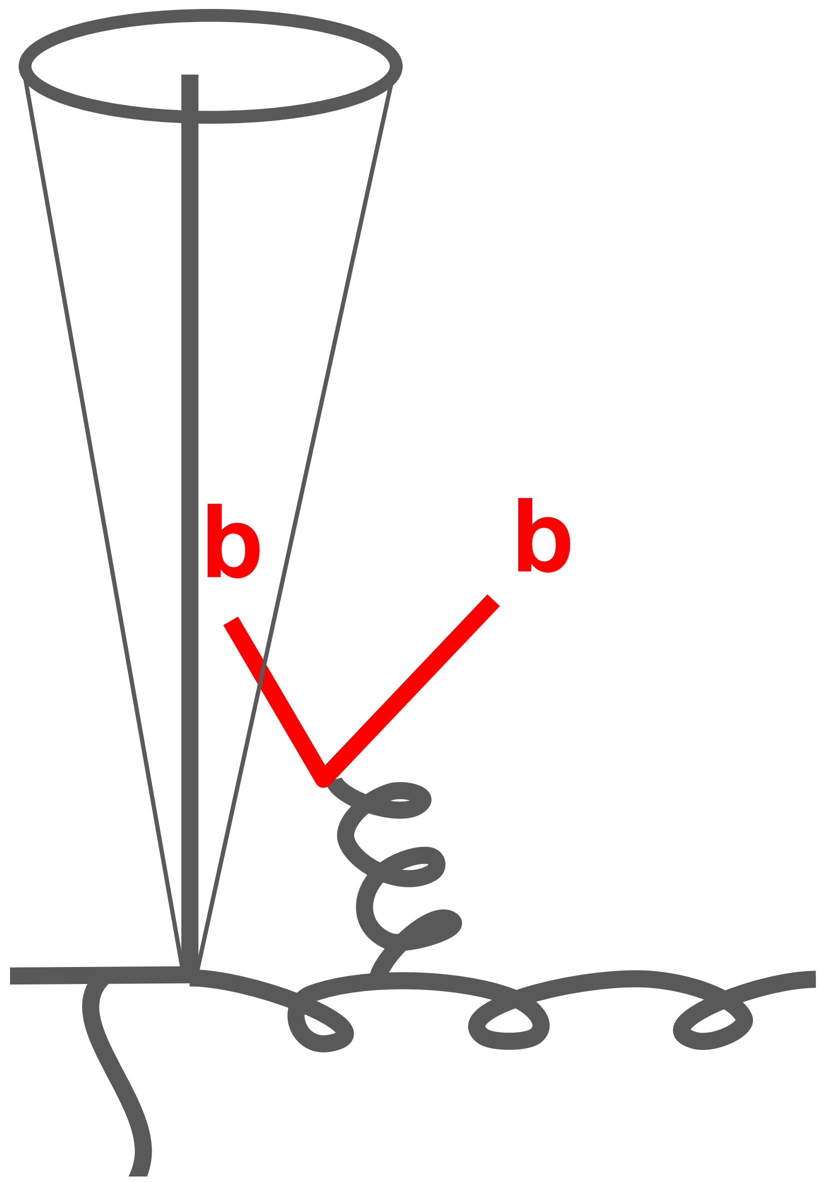
(to be balanced with fact that larger a values bring greater modification of jet kinematics relative to anti-k_t)

Parameters [aside from jet radius R]: Flavour Dressing

usual Flavour-k_t parameters + p_t cut on input “flavour agnostic jets” $\{j_k\}$

any single-particle jet retains its flavour

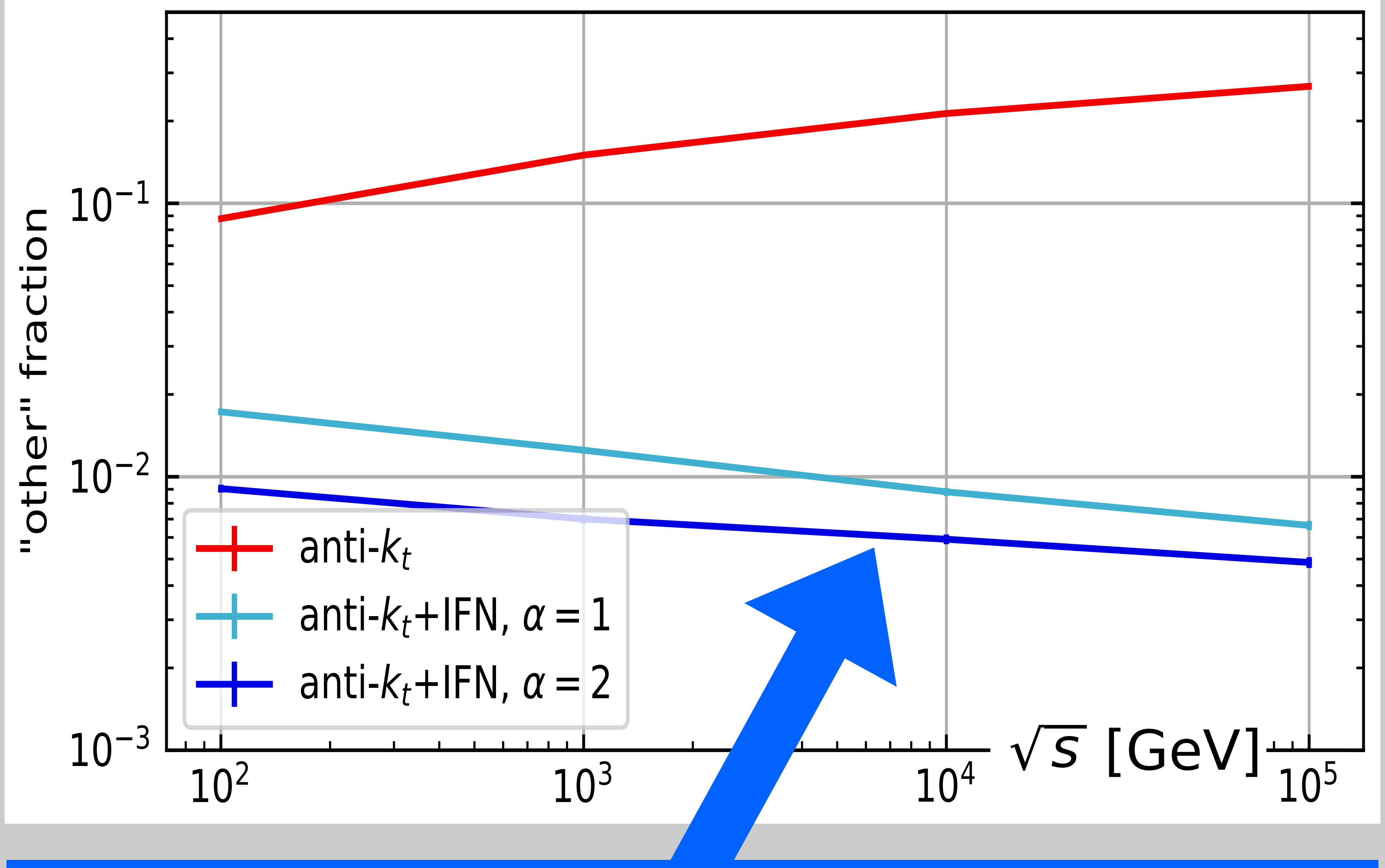
→ means that low-p_t single-parton jet will prevent in-jet soft b from having its flavour cancelled



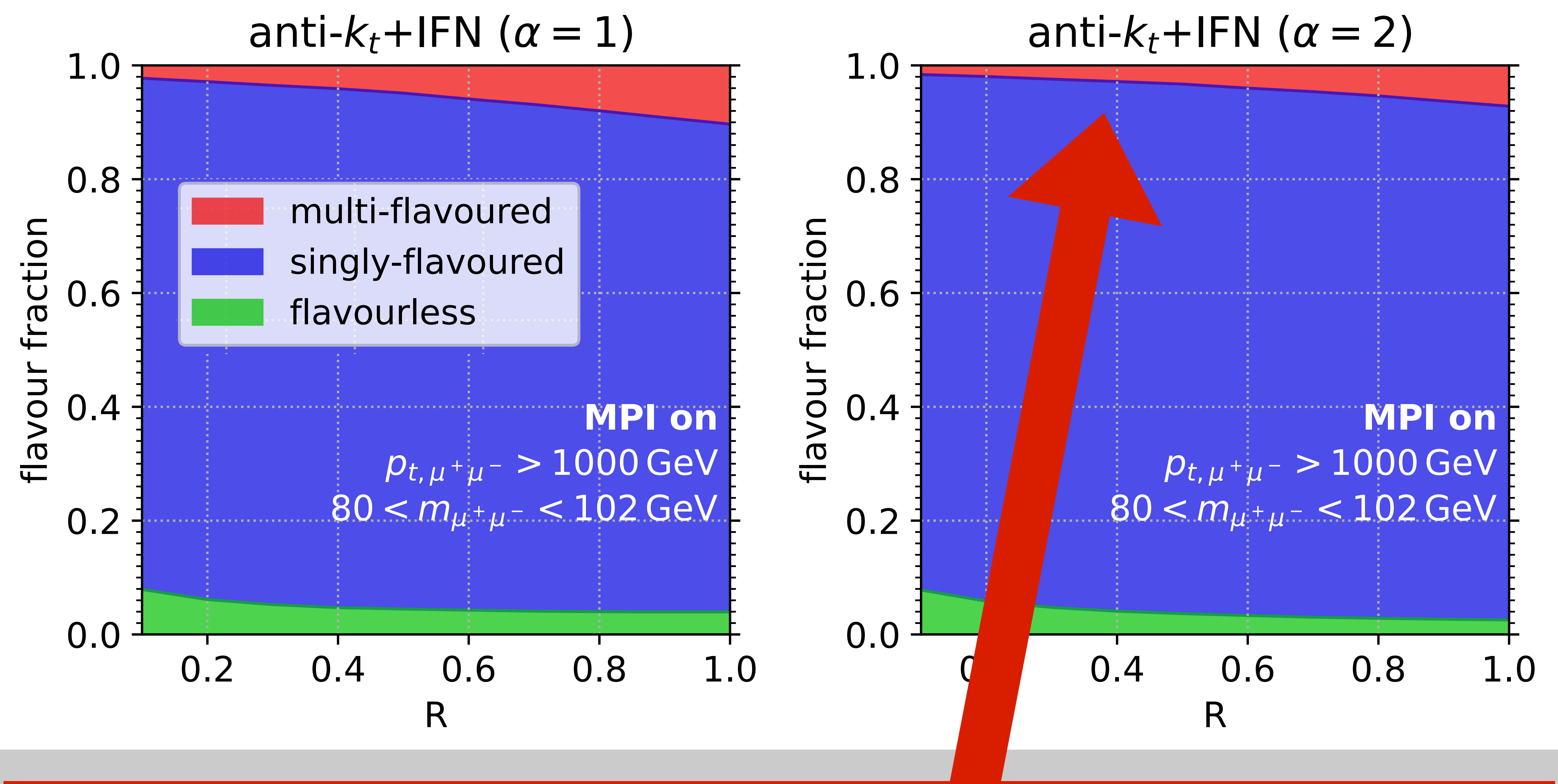
Parameters [aside from jet radius R]: flavour-k_t, IFN & Flav.Dressing [GHS]

α $[k_{t,\max}^{\alpha} k_{t,\min}^{2-\alpha}]$ and ω [in $\Delta R^2 \to \Omega$ distance], typically $\alpha = \{1,2\}$, $\omega = 3 - \alpha$

[some studies suggest slight preference for $\alpha = 2$ — not clear if universal]



fraction of $e^+e^- \to s\bar{s}$ events with two leading jet classified as "other" (non-g) flavour



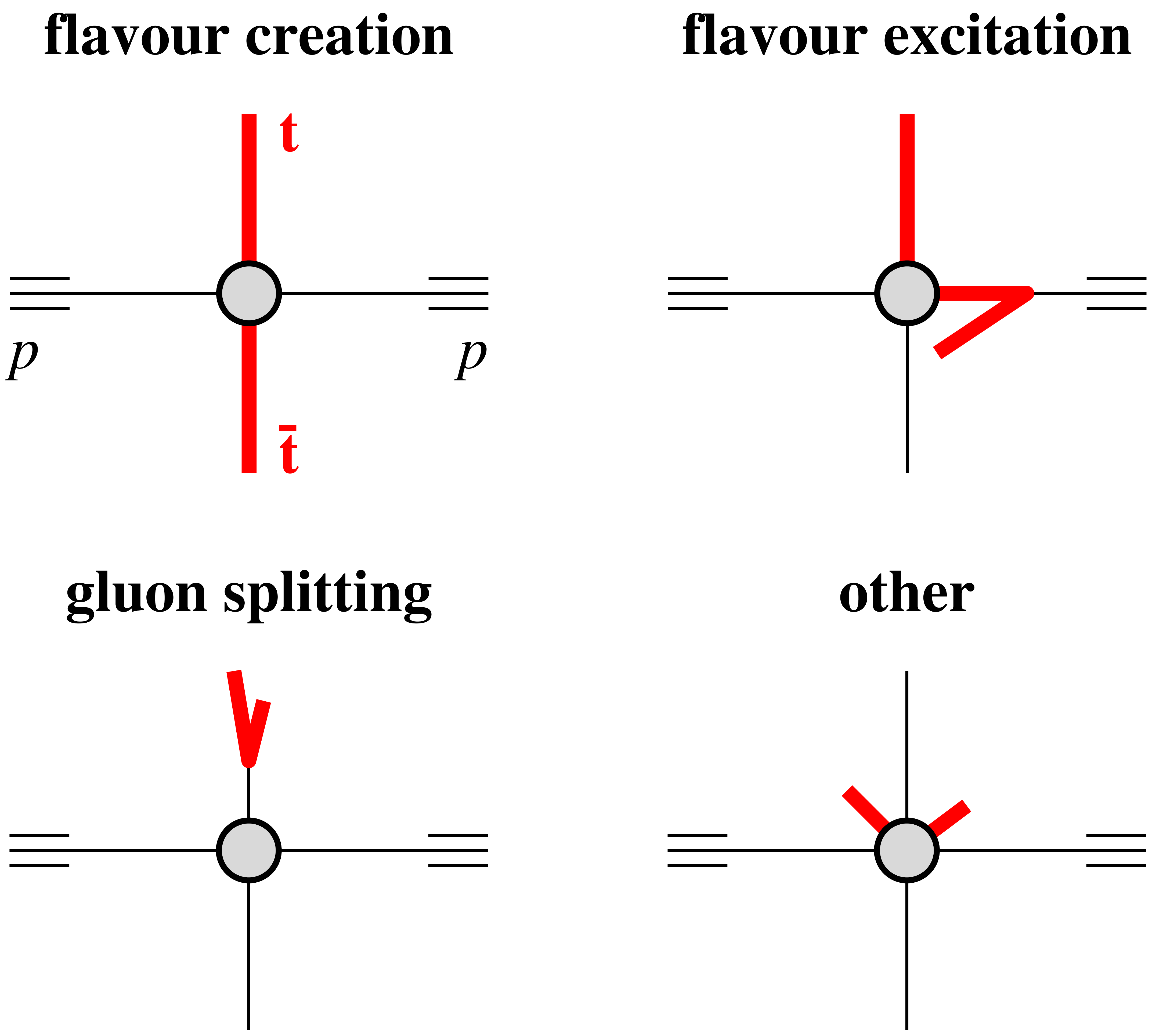
red band = fraction of Z+q, with q-jet mis-classified as multi-flavour (mostly due to MPI)

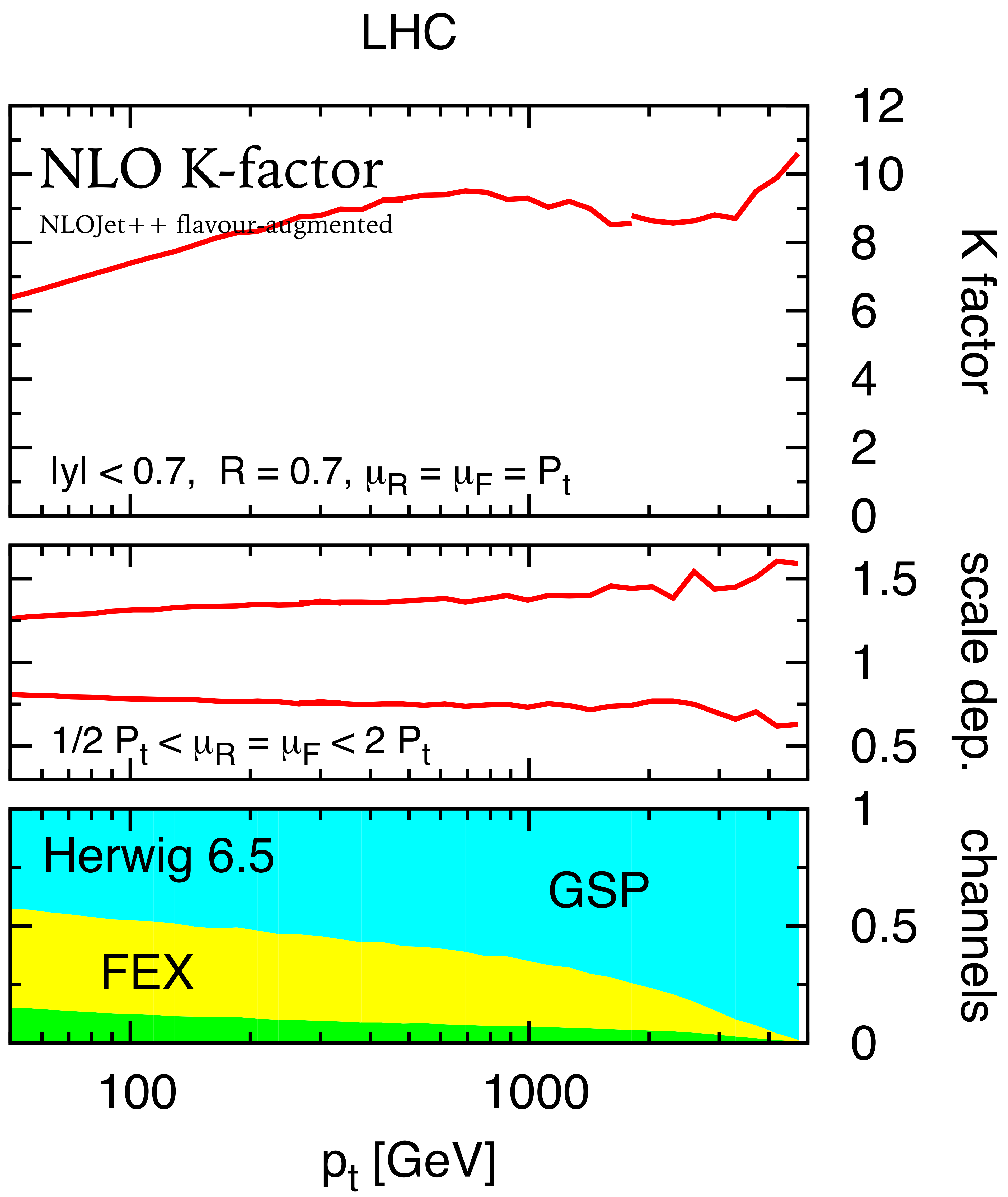
Conclusions

- Degree of precision of LHC physics (and importance of heavy flavour across much of physics programme) brings renewed need to understand jet flavour
- big progress in recent years in defining IRC-safe jet-flavour algorithms
- use in experiment ultimately relies on
  - good measurement of full phase space of heavy-flavour production
  - better theory calculations of full phase space of heavy-flavour production
- We may benefit from critically thinking about some of what we do in both experiment and theory
  - "*b*-hints" — i.e. if you tag one *b*, what's the most likely candidate (if any) for the other one in the detector
  - understanding logs — heavy-flavour sub-leading logs come with big coefficients

backup

Inclusive b-jet spectrum [Banfi, GPS & Zanderighi, 0704.2999]

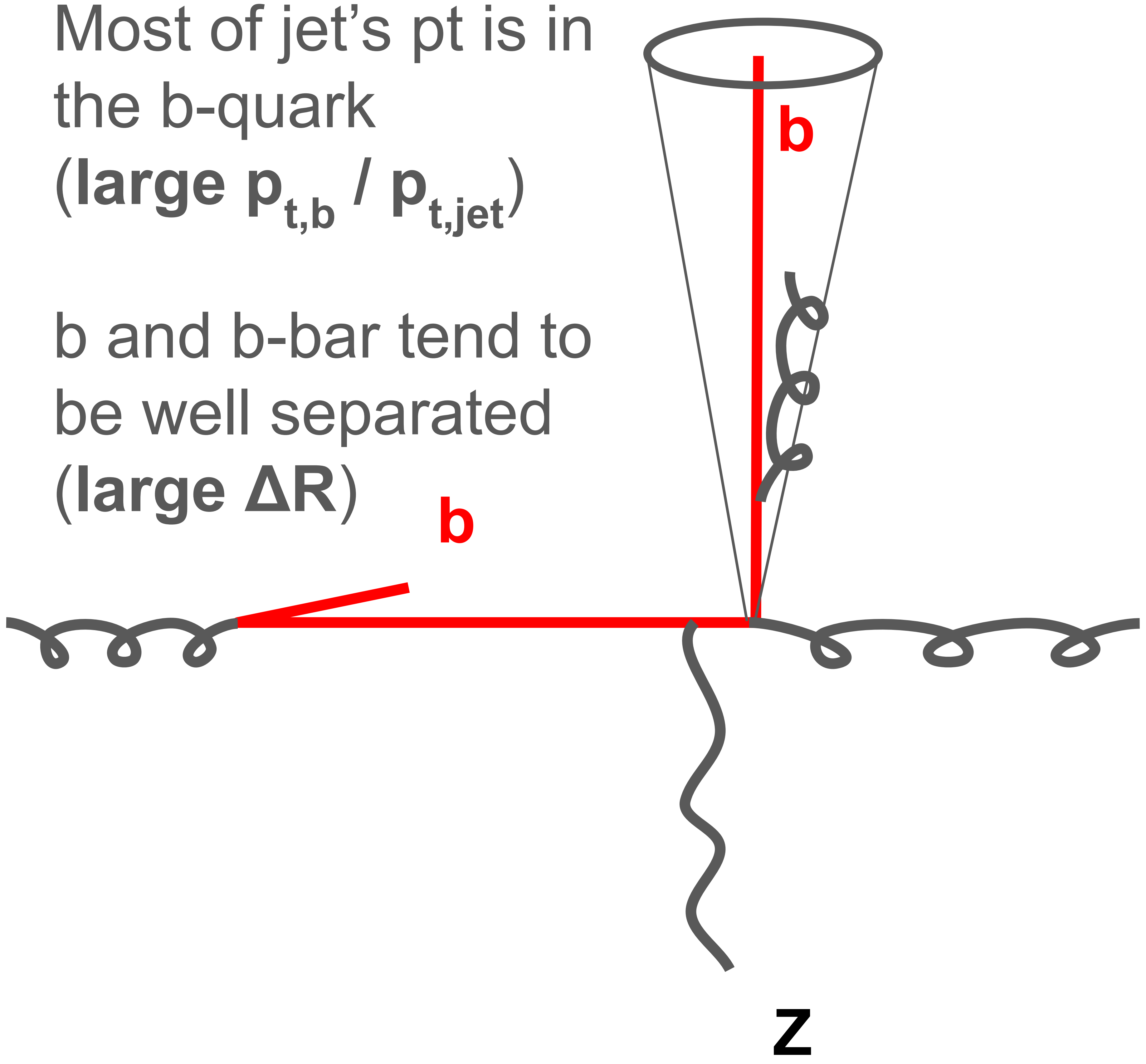




Genuine b-jet

Most of jet's pt is in the b-quark (**large $p_{t,b}$ / $p_{t,jet}$**)

b and b-bar tend to be well separated (**large ΔR**)



Fake b-jet

Little of jet's pt is in the b-quark (**small $p_{t,b}$ / $p_{t,jet}$**)

b and b-bar tend to be separated by **ΔR ~ 1**