Flavour of anti-k_t jets

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[arXiv:2205.01109]

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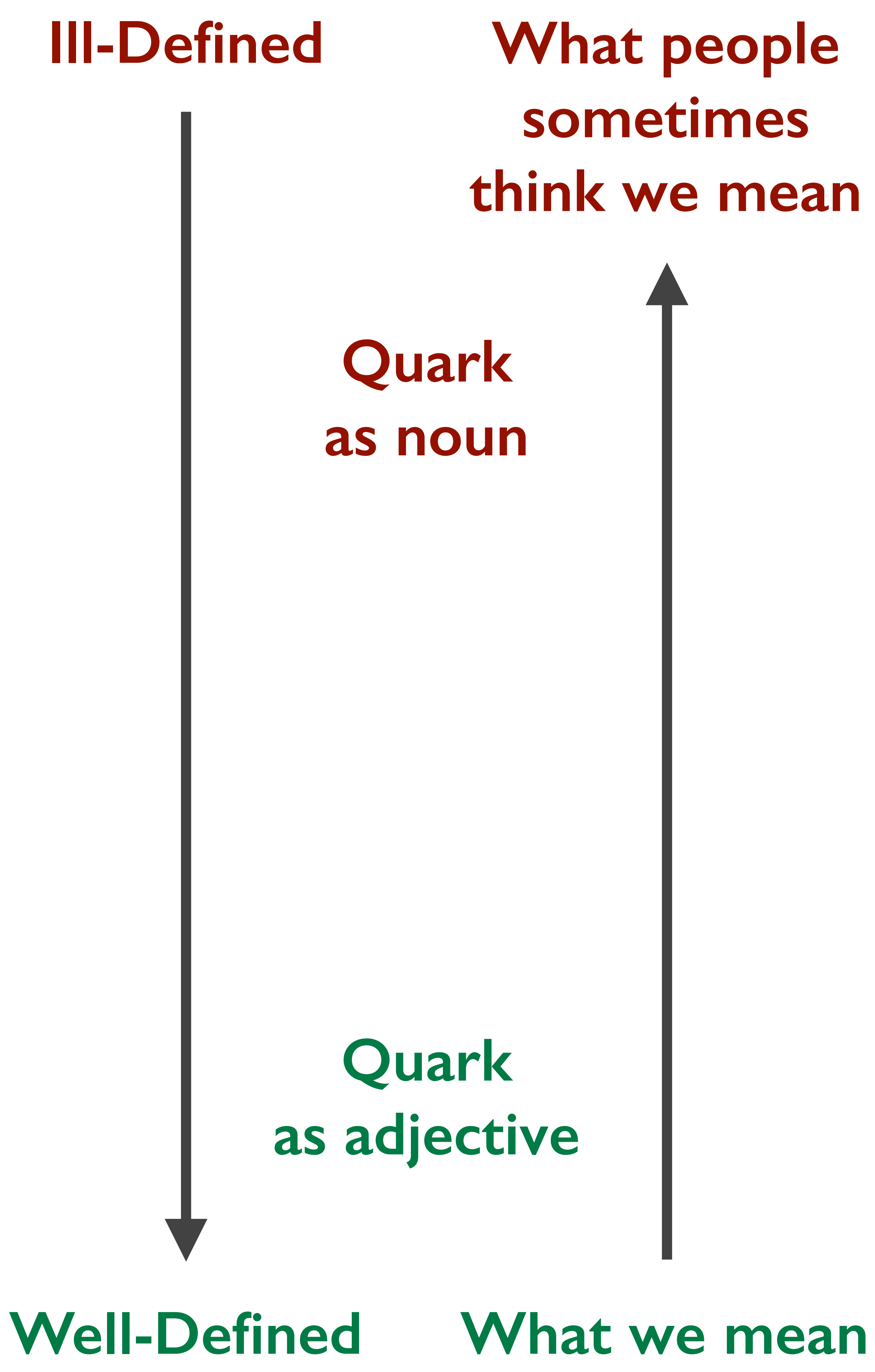
What is a Quark Jet?



A quark parton

A Born-level quark parton

The initiating quark parton in a final state shower

An eikonal line with baryon number 1/3
and carrying triplet color charge

A quark operator appearing in a hard matrix element
in the context of a factorization theorem

A parton-level jet object that has been quark-tagged
using a soft-safe flavored jet algorithm (automatically
collinear safe if you sum constituent flavors)

A phase space region (as defined by an unambiguous
hadronic fiducial cross section measurement) that yields
an enriched sample of quarks (as interpreted by some
suitable, though fundamentally ambiguous, criterion)

from [Les Houches '15]

What is a Quark Jet?

UV

Evolution between scales:

[Caletti, Larkoski, Marzani, DR '22]

IR

Ill-Defined

What people sometimes think we mean

Quark as noun

Quark as adjective

Well-Defined

What we mean

from [Les Houches '15]

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4 new algorithms proposed since then:

[Caletti, Larkoski, Marzani, DR '22]

[Czakon, Mitov, Poncelet '22]

[Gauld, Huss, Stagnitto '22]

[Caola, Grabarczyk, Hutt, Salam, Scyboz '23]

jet and flavour definition

- Jets from (anti-)k_t algorithm → sequential clustering, starting from pair with smallest distance measures $d_{ij} = \min(k_{t,i}^{\pm 2}, k_{t,j}^{\pm 2})\Delta R_{ij}^2/R^2\,, \;\; d_{iB} = k_{t,i}^{\pm 2}$

Flavoured of jets in experiment (theorist's view):

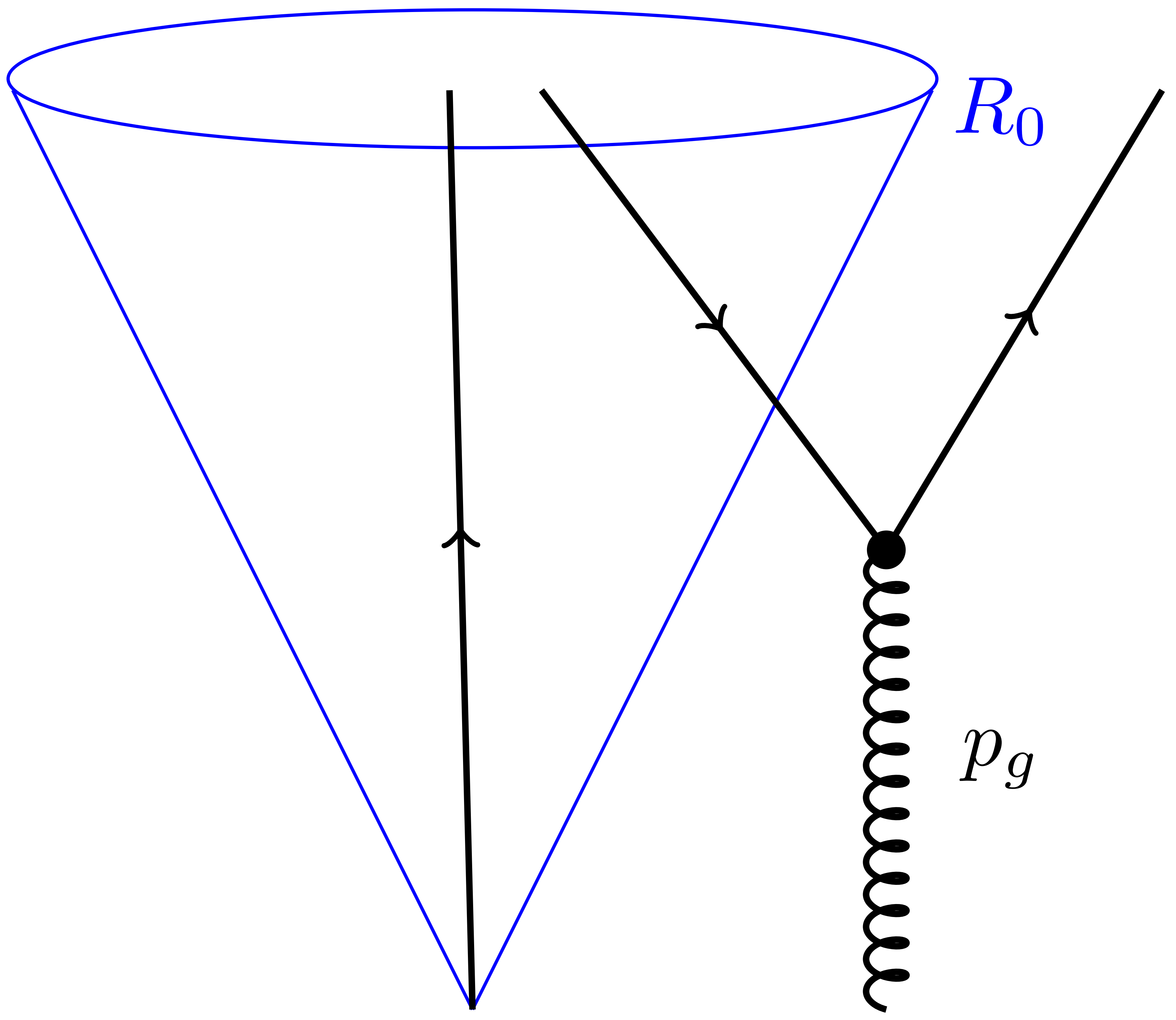
- anti-k_t jets defined based on detector objects
- look for B/D hadron in jet → visible (roughly) by displaced vertex

Flavoured of jets in theory (naive version):

- perturbative calculation on parton level
- apply anti-k_t to raw partons
- look for b-quark in jet? → jet flavour = sum of quark flavours?

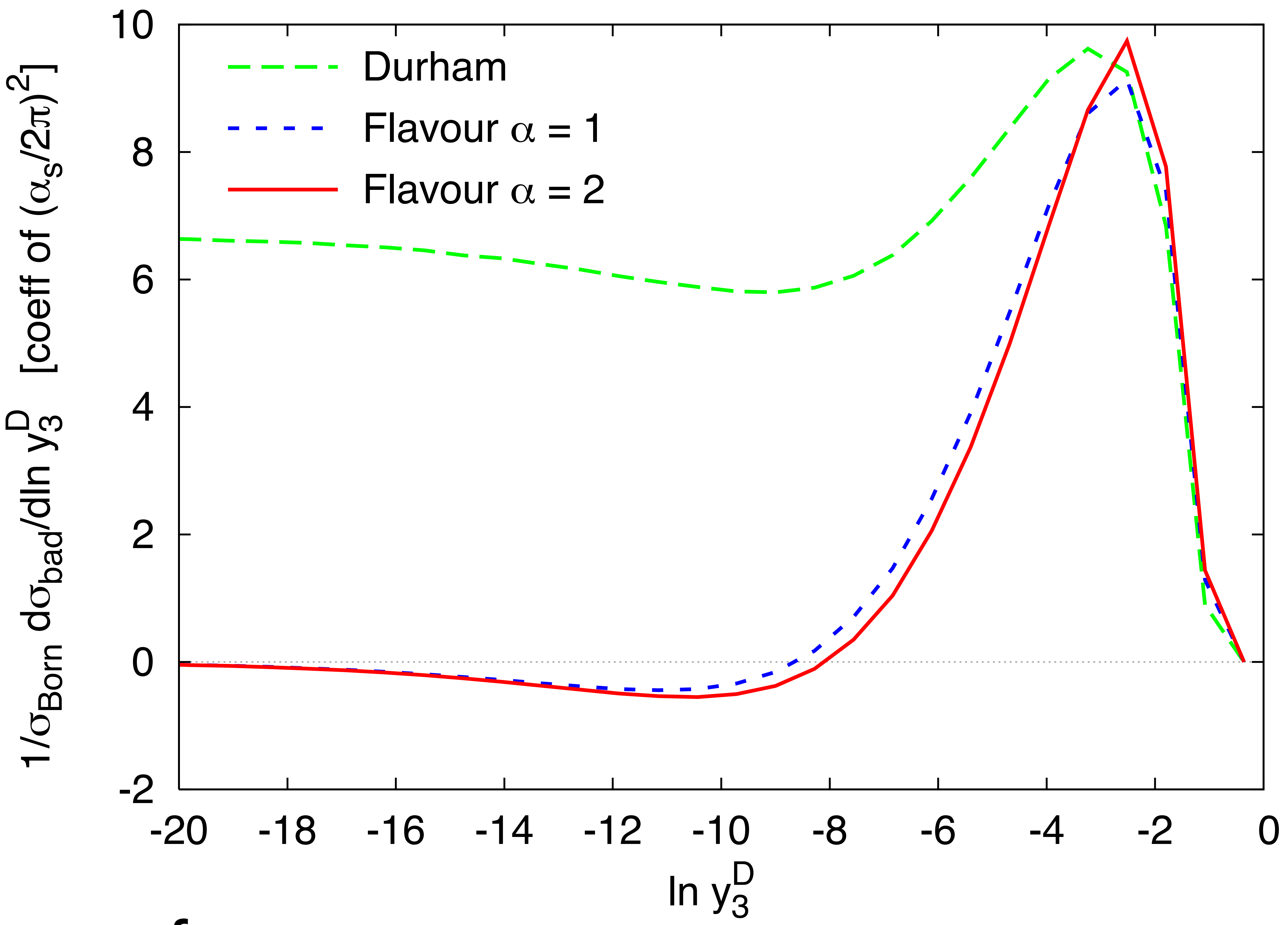
problems in naive theory definition

- starting at NNLO, consider configuration where a soft gluon splits into two quarks
- singularity in limit where $p_q, p_{\bar{q}} \to 0$
- might belong to “gluon-jet” or “quark-jet” phase space depending on clustering
- corresponding virtual correction clearly in “quark-jet” phase space $\Rightarrow$ IRC unsafe



let's see the divergence

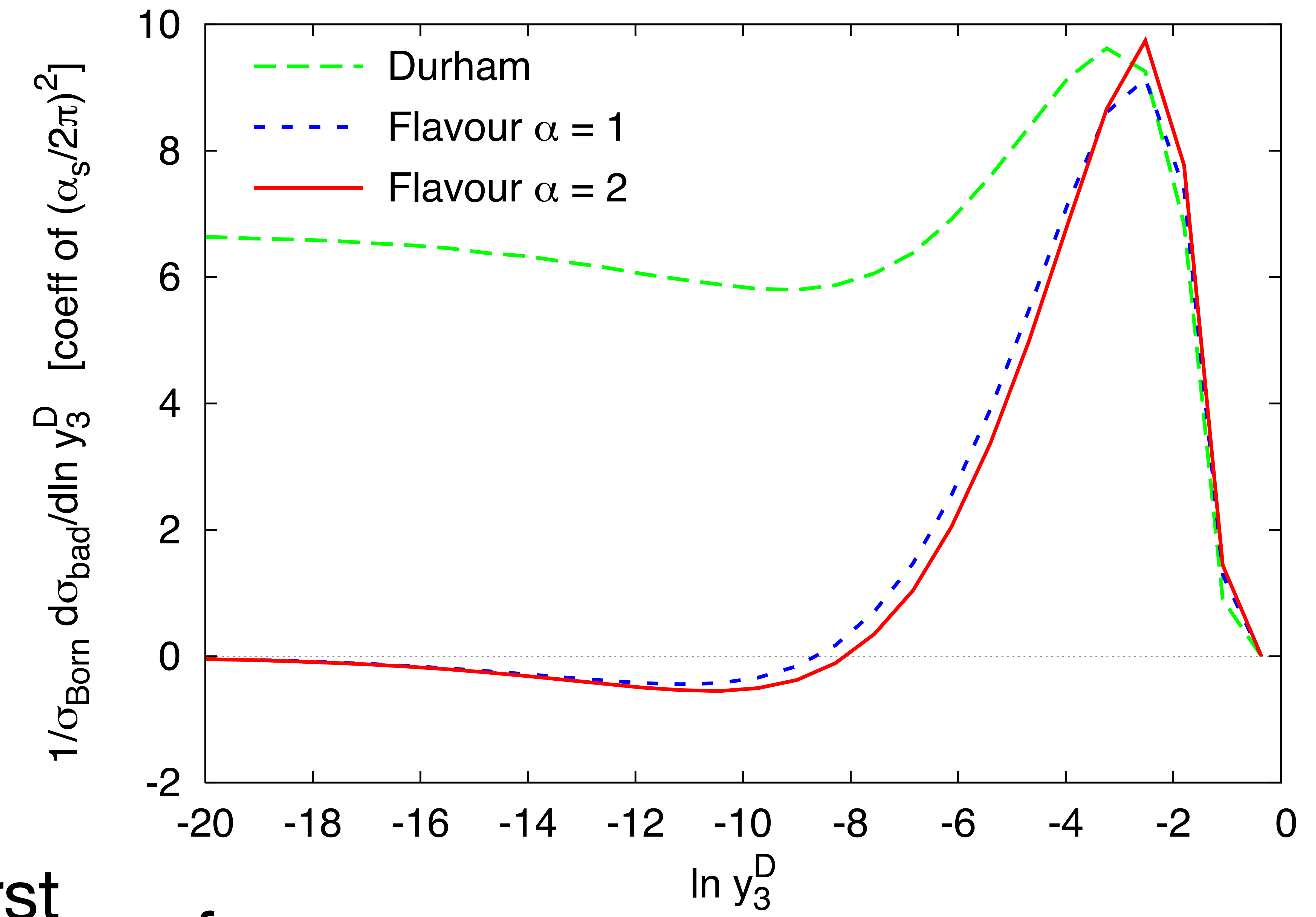
- test for IRC safety (in $e^+e^- \to$ jets):
  - cluster event into two jets, soft limit $\sim y_3 \to 0$
  - only one diagram at Born level $e^+e^- \to q\bar{q} \Rightarrow$ Born and all virtual correction classed as 2 quark jets
  - real corrections $\Rightarrow$ could be identified as gluon jets (or multi-flavoured) in certain phase space regions
  - this has to vanish in the soft limit



from [Banfi, Salam, Zanderighi '06]

first solution - the BSZ algorithm

- known solution
  - use algorithm with well defined flavour
    - achieved by modifying distance measure between flavoured i, j:
      $d_{ij} = \max(k_{t,i}^2, k_{t,j}^2)\Delta R_{ij}^2/R^2$
    - will tend to cluster soft quarks first
- downside: these are evidently not the anti-k_t jets used in experiments, unfolding corrections can be large



from [Banfi, Salam, Zanderighi ’06]

flavour algorithms - summary

1. new jets with well defined flavour

- original BSZ [Banfi, Salam, Zanderighi ’06]
- anti-k_t variant [Czakon, Mitov, Poncelet ’22]

2. flavour of the jets in an event

- iteration of BSZ [Caletti, Fedkevych, Marzani, DR Schumann ‘21]
- dressing of jets [Gauld, Huss, Stagnitto ’22]

3. flavour of an isolated jet

- soft drop groomed jets (to NNLO) [Caletti, Larkoski, Marzani, DR ’22]

- flavour of jets with exact anti-k_t kinematics [Caola, Grabarczyk, Hutt, Salam, Scyboz ’23]

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- flavour of ... exact anti...
  [Caola, Grab... Salam, Scyb...

...solated

...omed
...) [Caletti, ..., DR '22]

- similar to BSZ, introduce new distance measure

- improve by staying closer to anti-k_t (instead of k_t) algorithm

$$d_{ij}^{(F)} = d_{ij} \begin{cases} \mathcal{S}_{ij} & \text{i,j is flavoured pair} \\ 1 & \text{else} \end{cases}$$

$$\mathcal{S}_{ij} \equiv 1 - \theta\left(1 - \kappa_{ij}\right) \cos\left(\frac{\pi}{2}\kappa_{ij}\right)$$

$$\kappa_{ij} \equiv \frac{1}{a} \frac{k_{T,i}^2 + k_{T,j}^2}{2k_{T,\max}^2}$$

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- start with 'normal' jets
- define 'flavoured clusters'
  - recombine collinear particles with soft-drop step
- use 'flavoured' BSZ distances between clusters and jets
- assign flavour of jets based on those

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- ‘normal’ clustering (with anti-k_t)
- when clustering flavoured particle, consider additional ‘neutralisation distances’ to already existing jets
- recursively annihilate flavours according to new distances, after each step of kinematic clustering

+ framework for general testing of IRC safety at given fixed order

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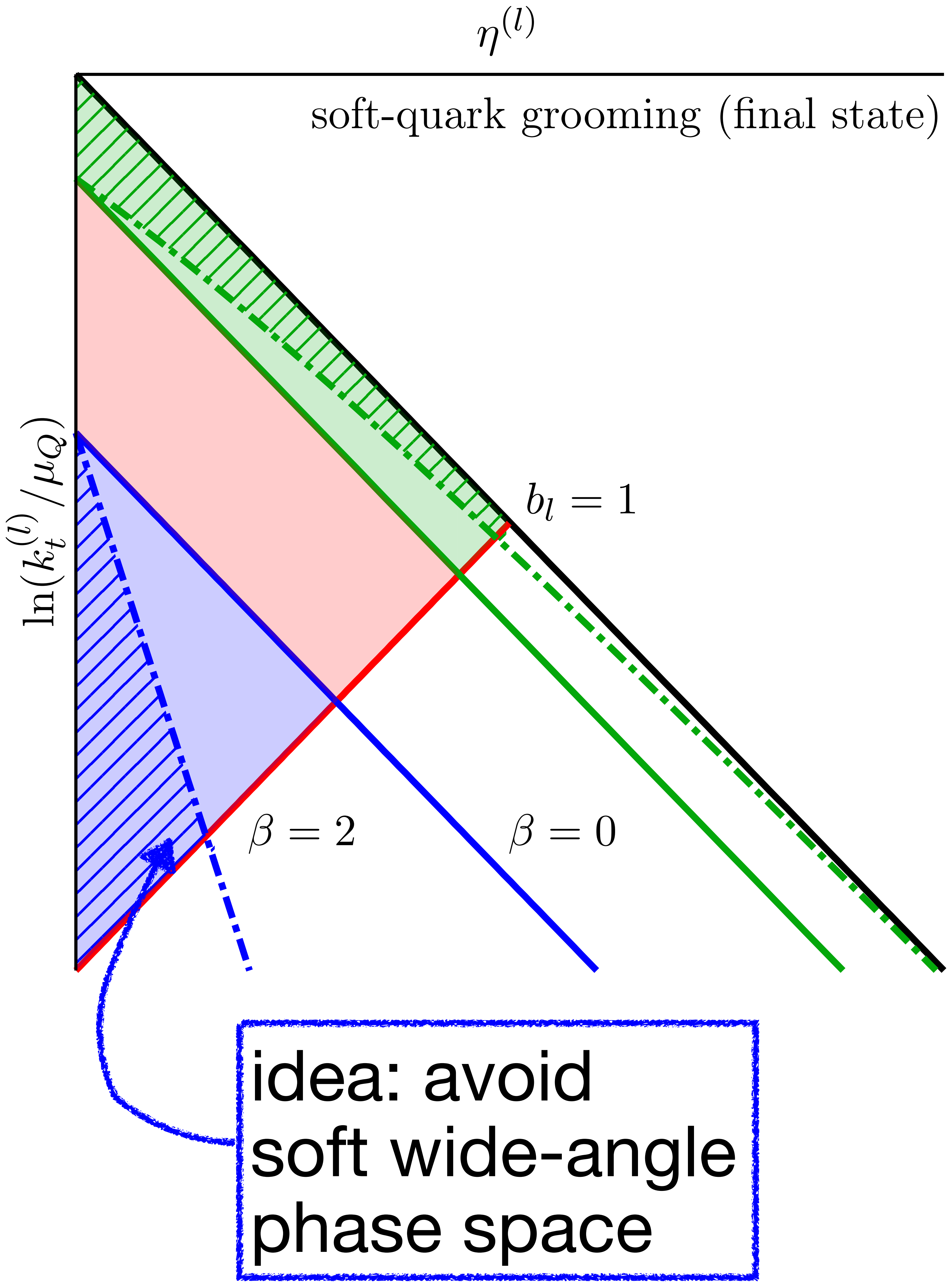
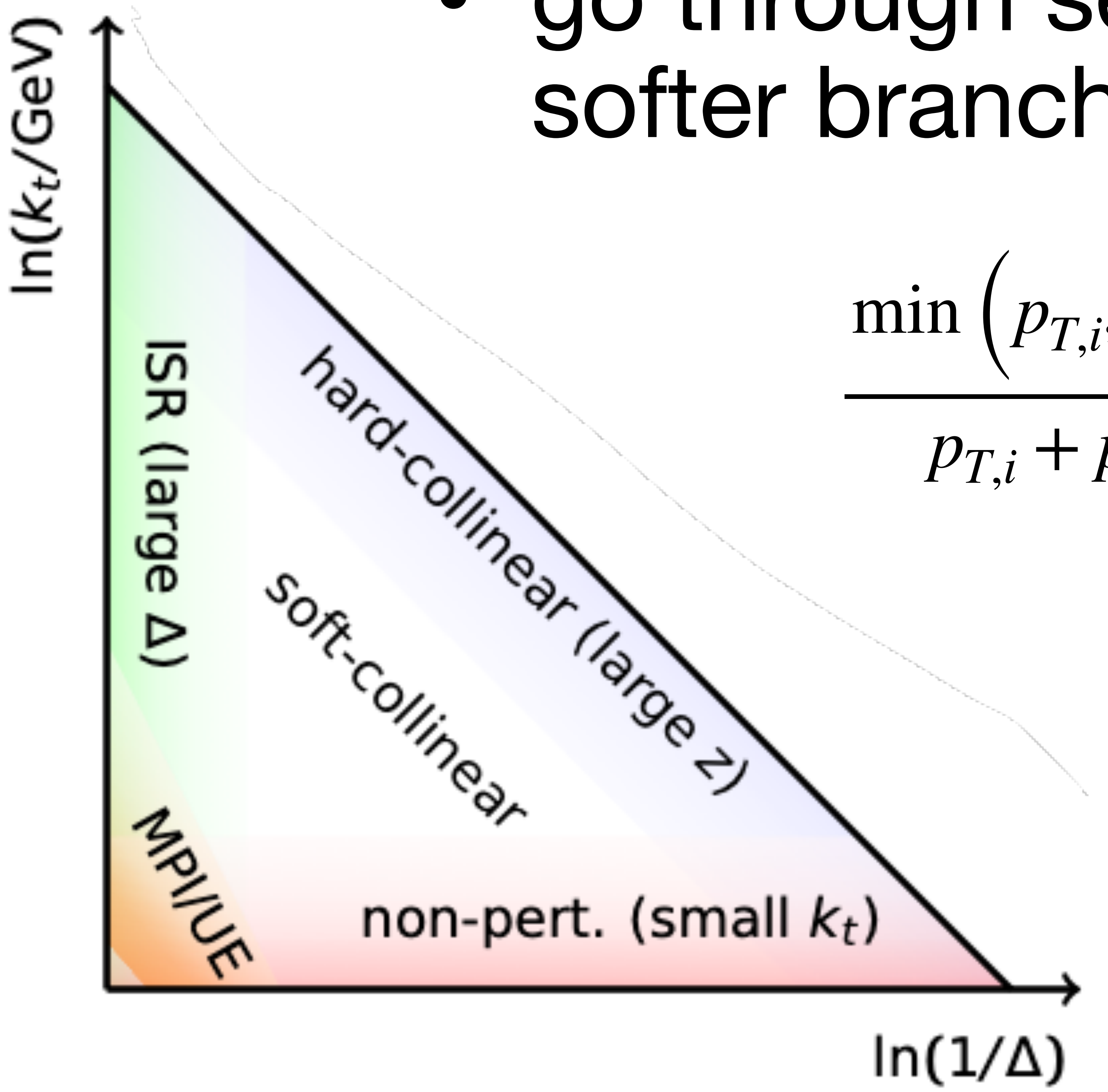
soft drop groomed jets



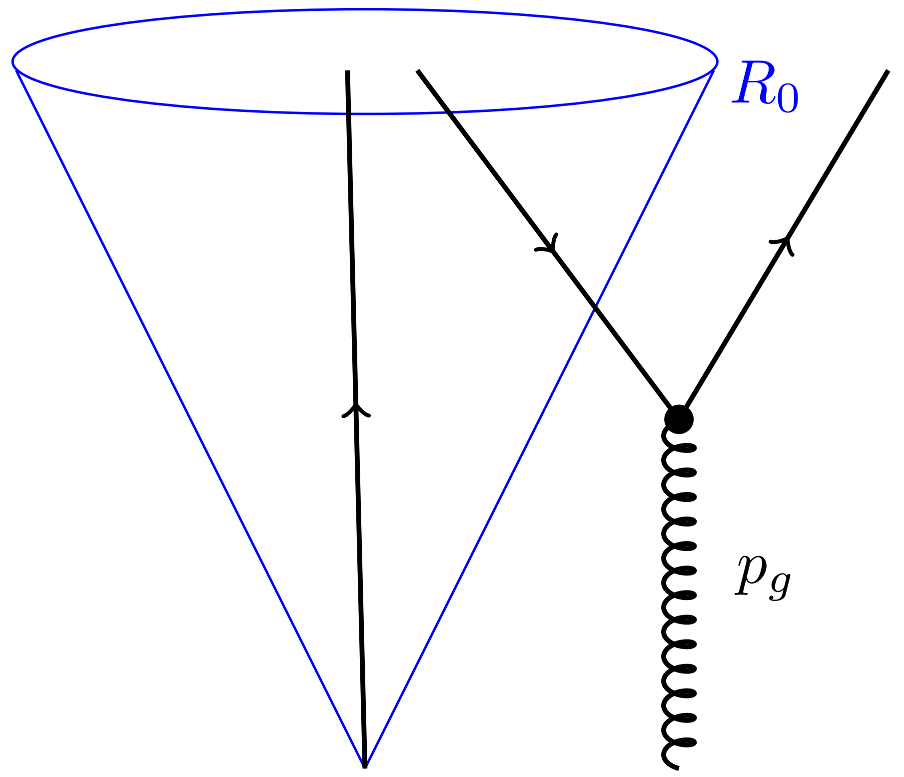
- popular jet substructure technique: [Larkoski, Marzani, Soyez, Thaler ’14]
  - decluster given jet with Cambridge/ Aachen jet measure ⇒ angular ordered splitting sequence
    - go through sequence, remove softer branch if

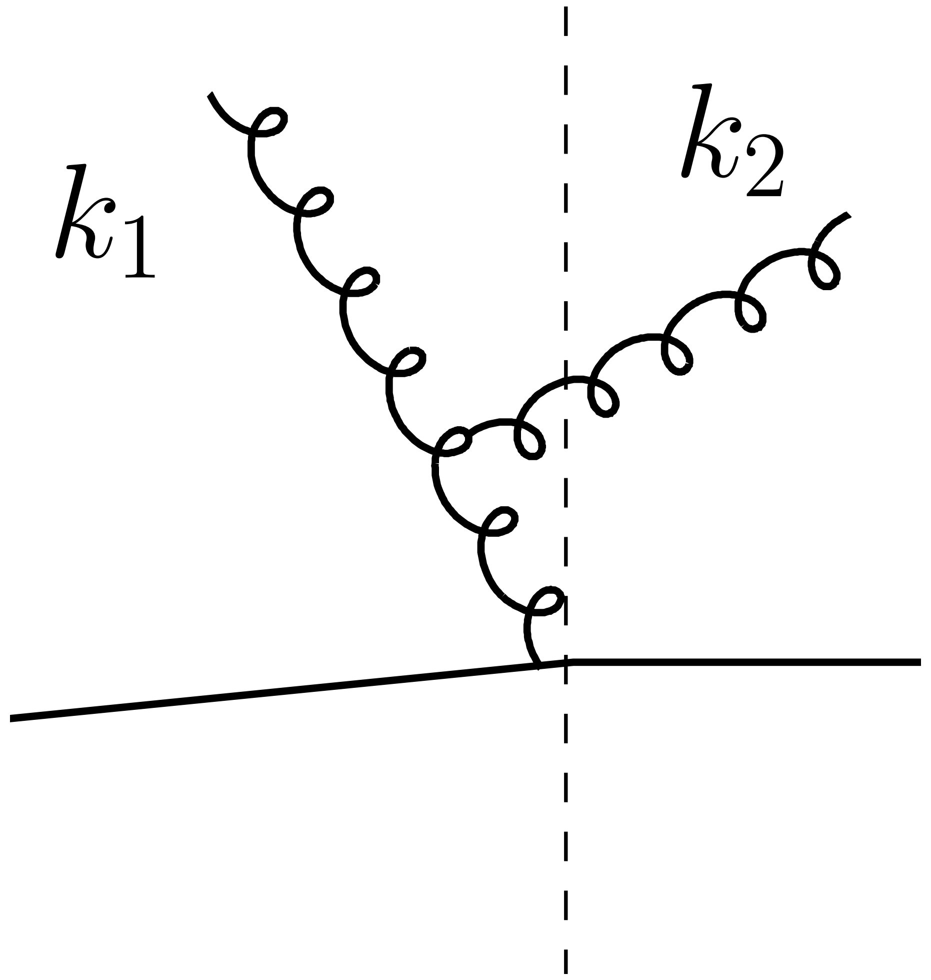
$$\frac{\min\left(p_{T,i}, p_{T,j}\right)}{p_{T,i} + p_{T,j}} > z_{\text{cut}} \left(\frac{\Delta R}{R}\right)^{\beta}$$



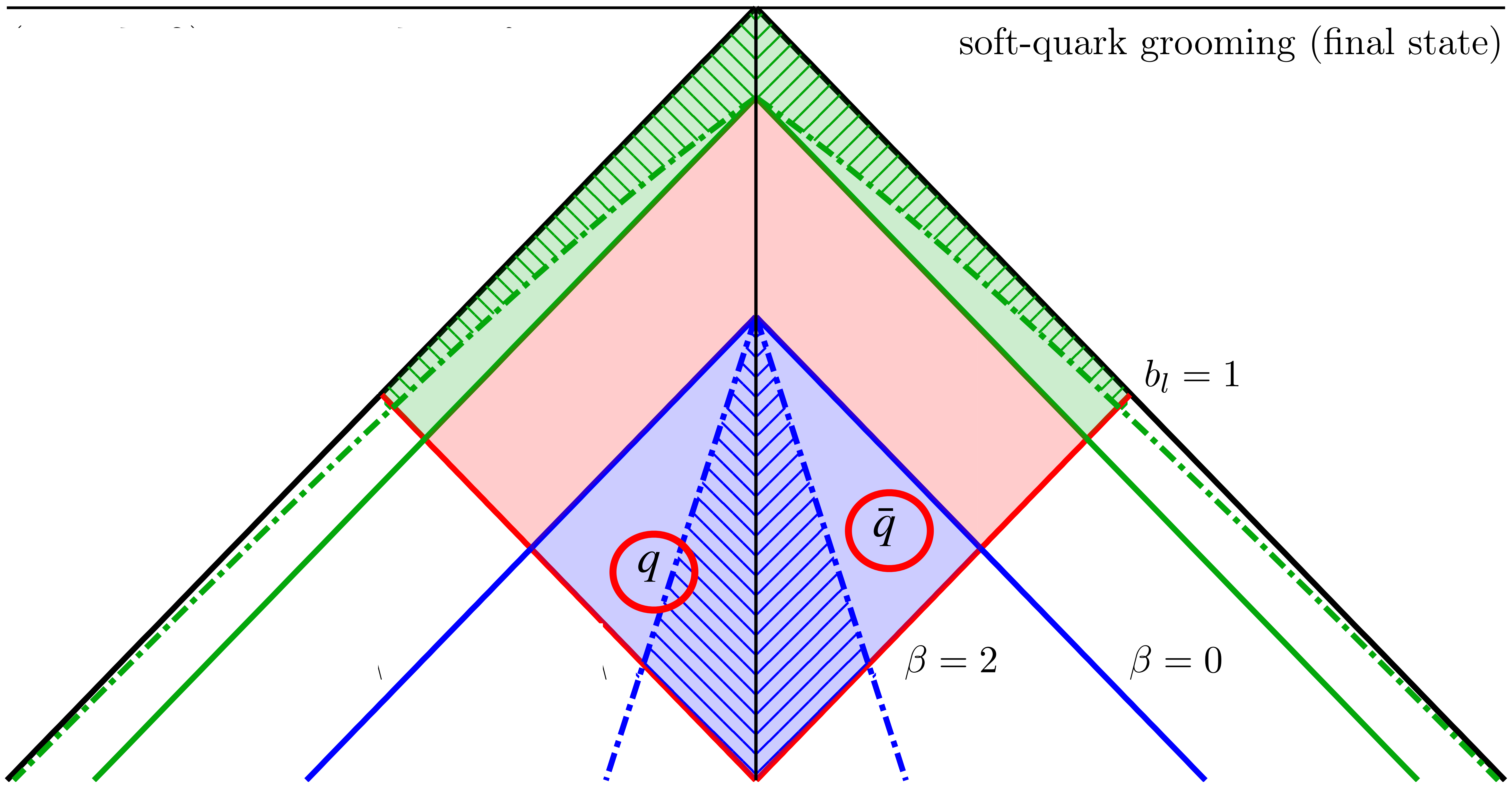
motivation

- Idea: groom jet/hemisphere/object → take flavour from remaining partons
- Why would this work:
  - Intuitively: soft particles should not enter tagging → just need a clean definition excluding soft particles
  - Formally: soft divergencies in “naive” flavour definitions are associated with configurations similar to non-global logs → SD removes non-global logs, should also help here

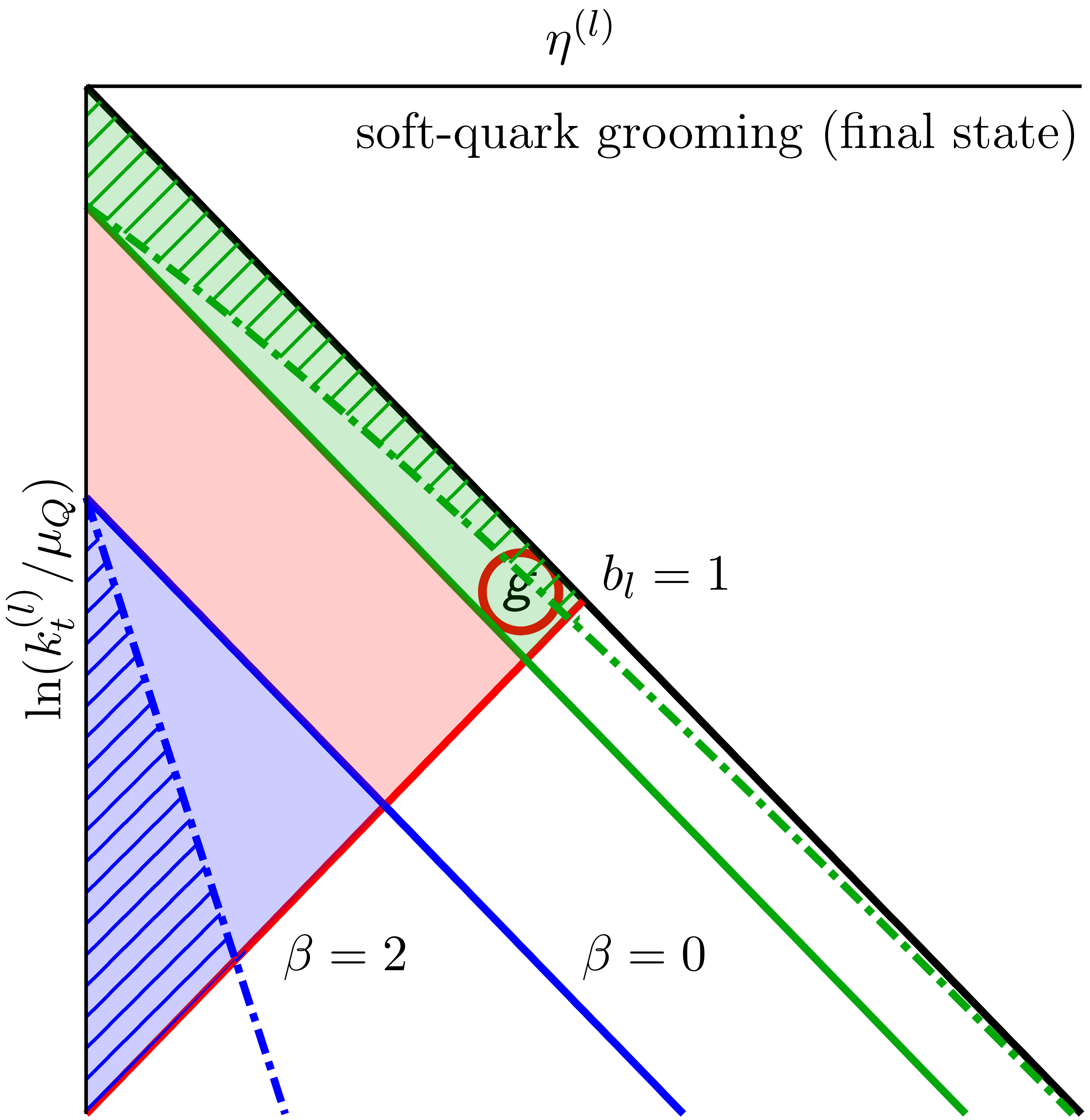




how it should work

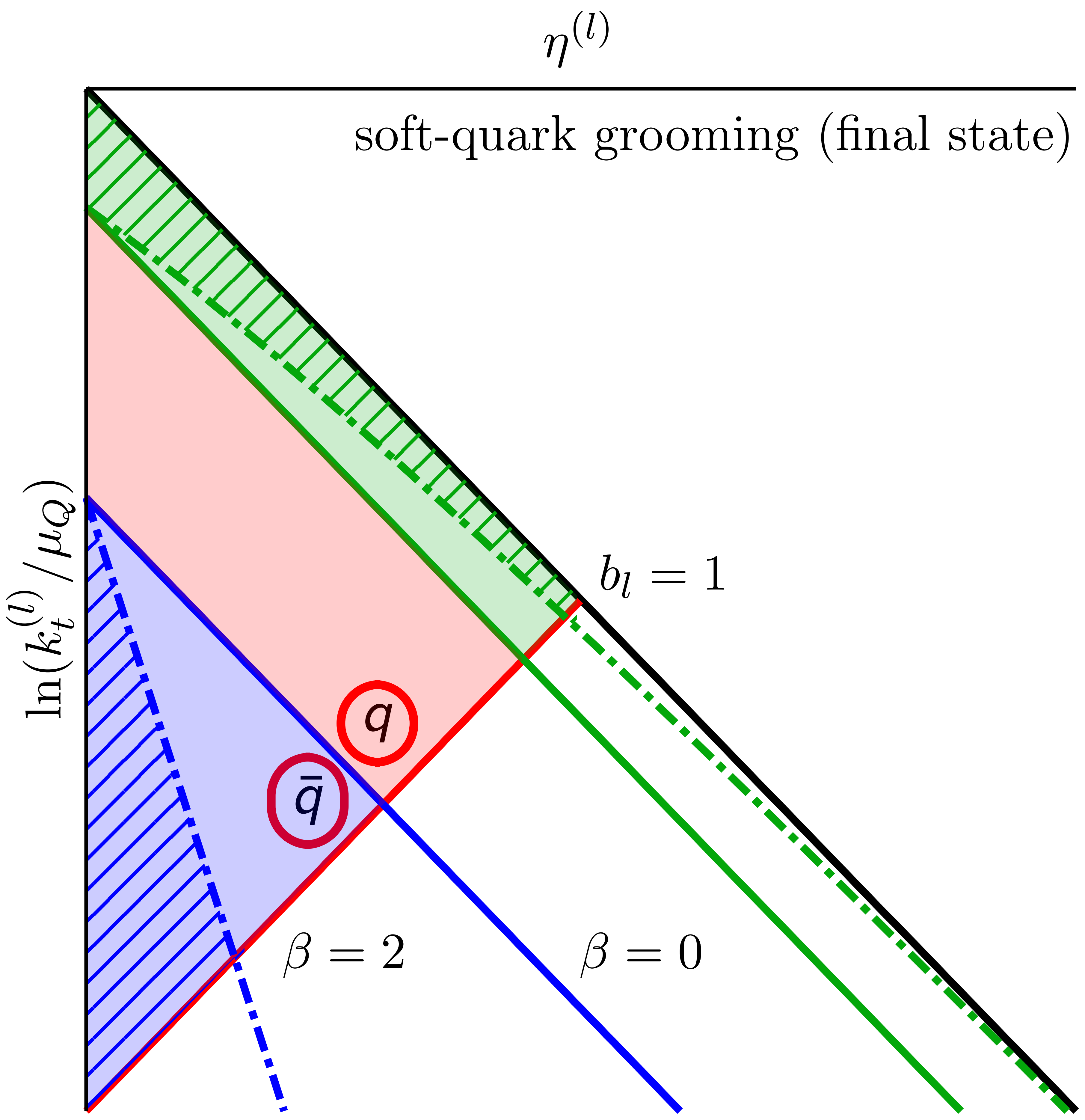


caveats - at $\mathcal{O}(\alpha_s)$



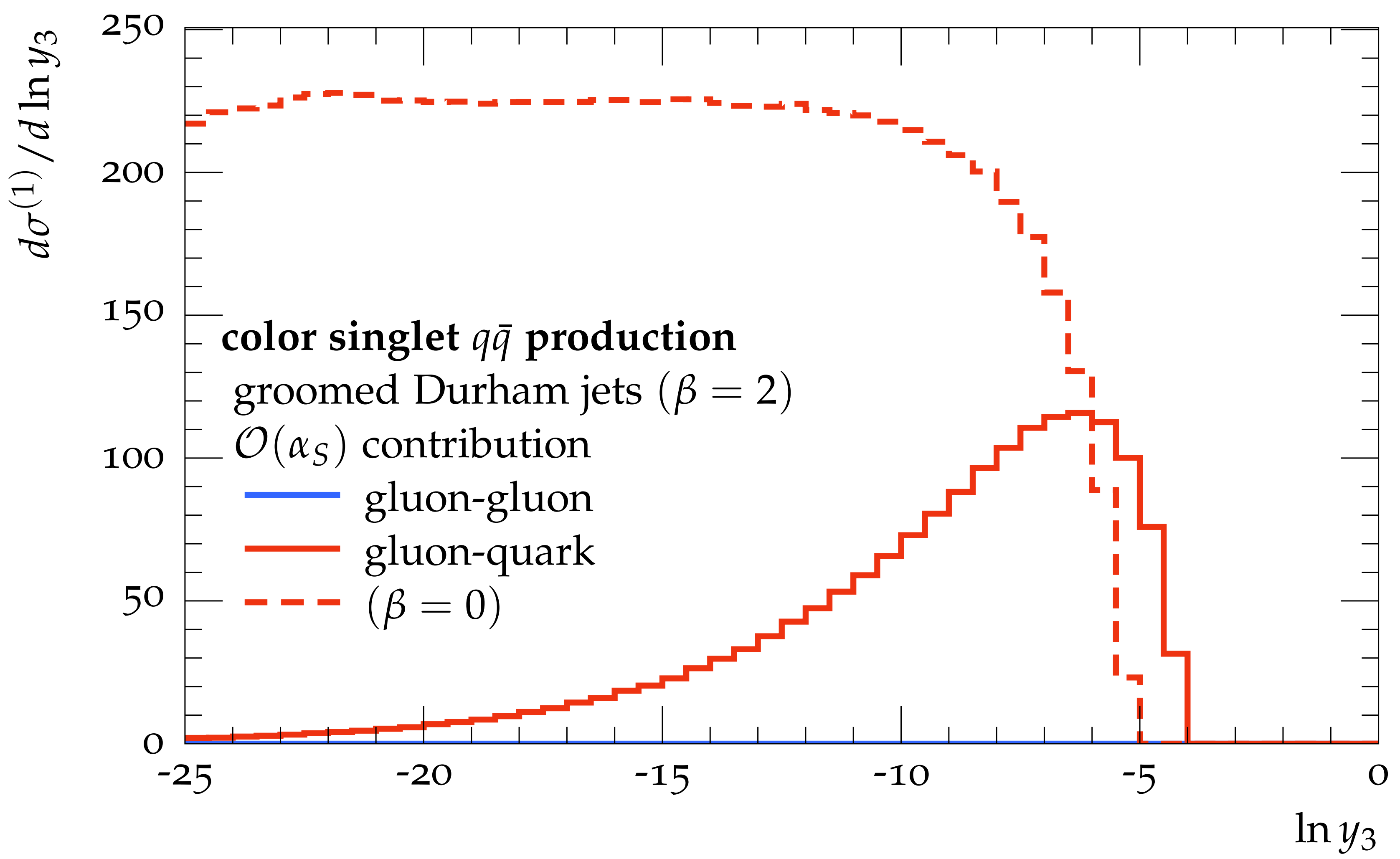
- close to collinear region, might groom away “hard” quark instead of gluon
- logarithmic region for $\beta = 0$, spoils flavour definition already at LO!
- power suppressed for $\beta > 0$, thus requirement for IRC safe soft drop flavour

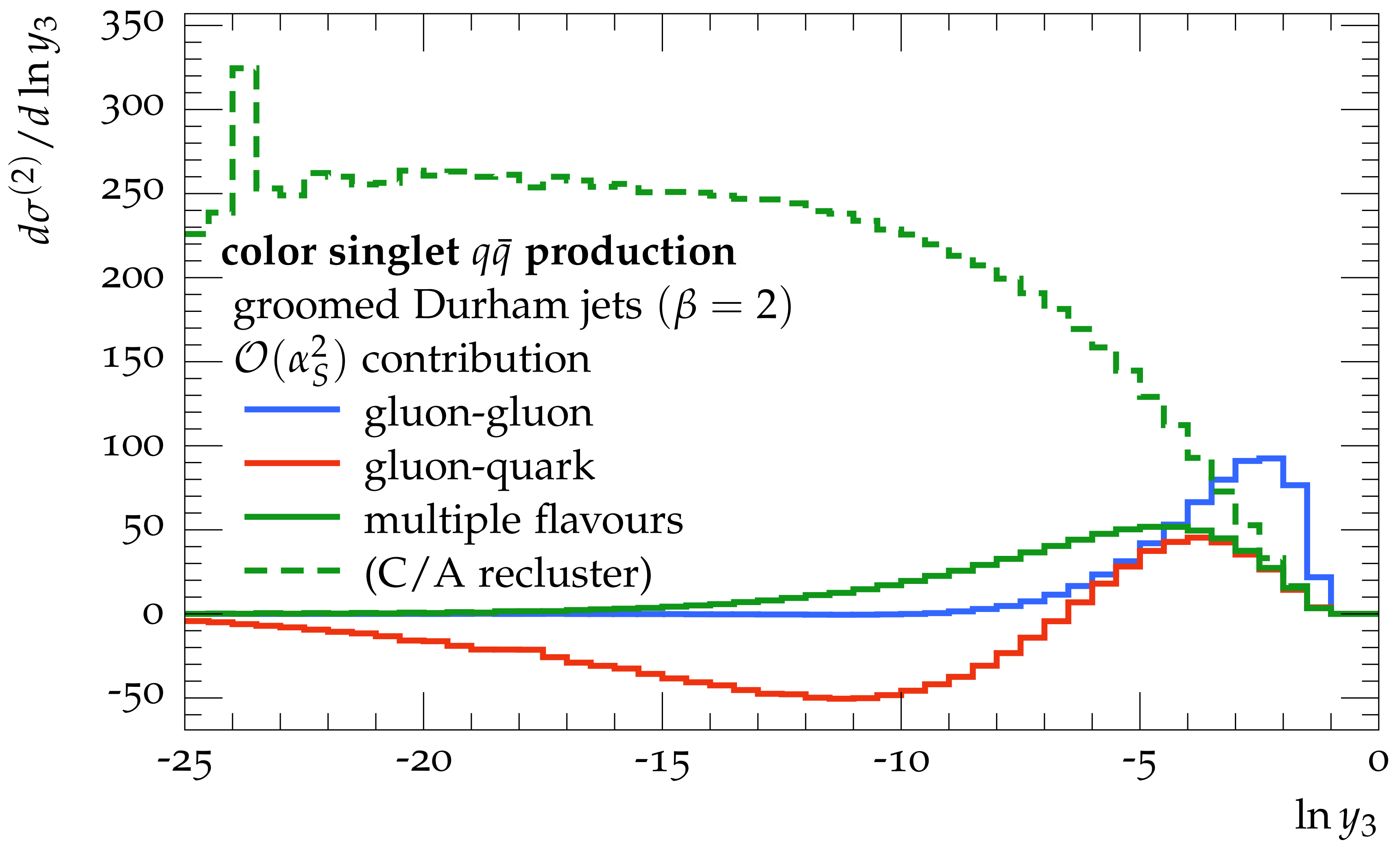
caveats - at $\mathcal{O}(\alpha_s^2)$

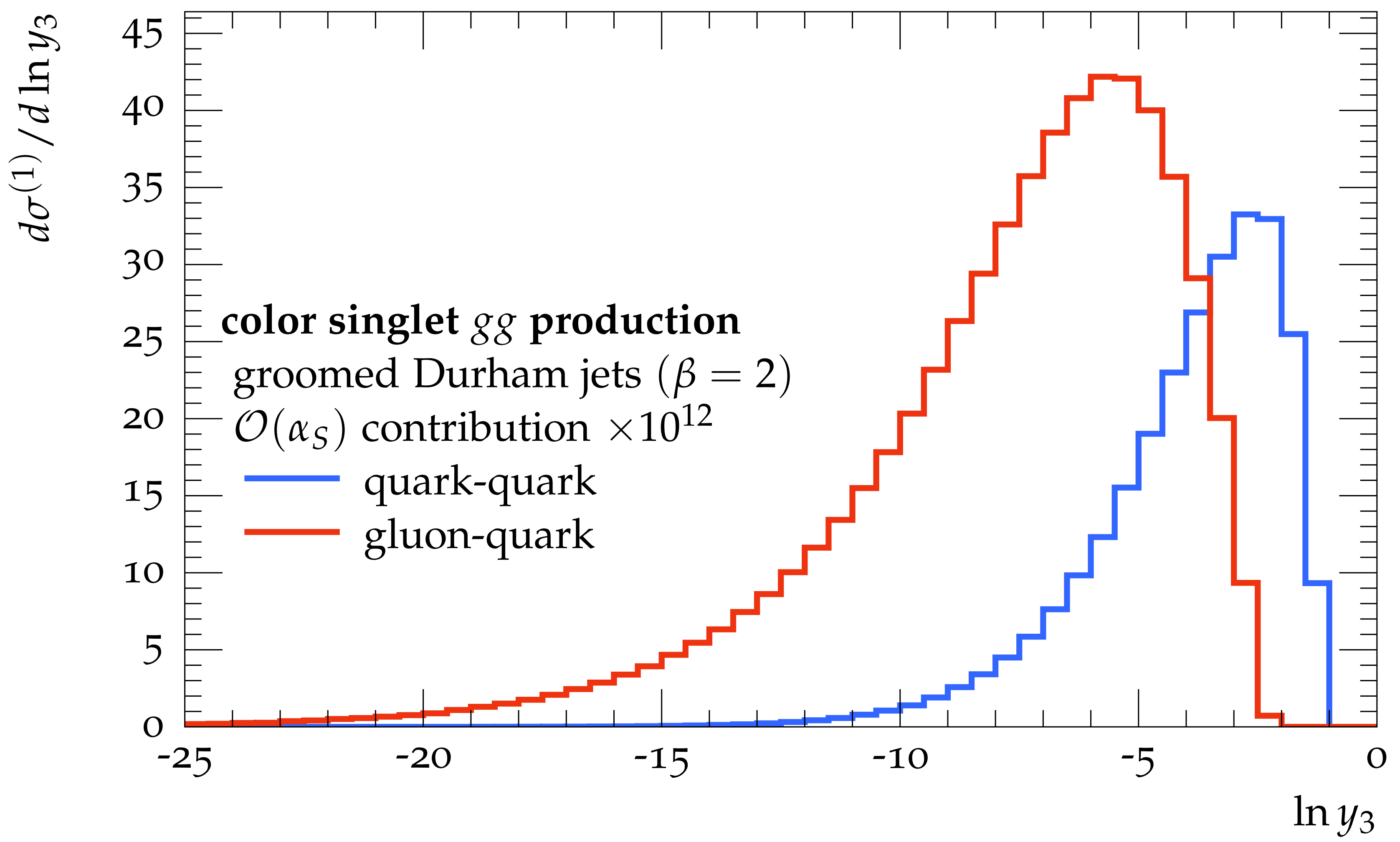


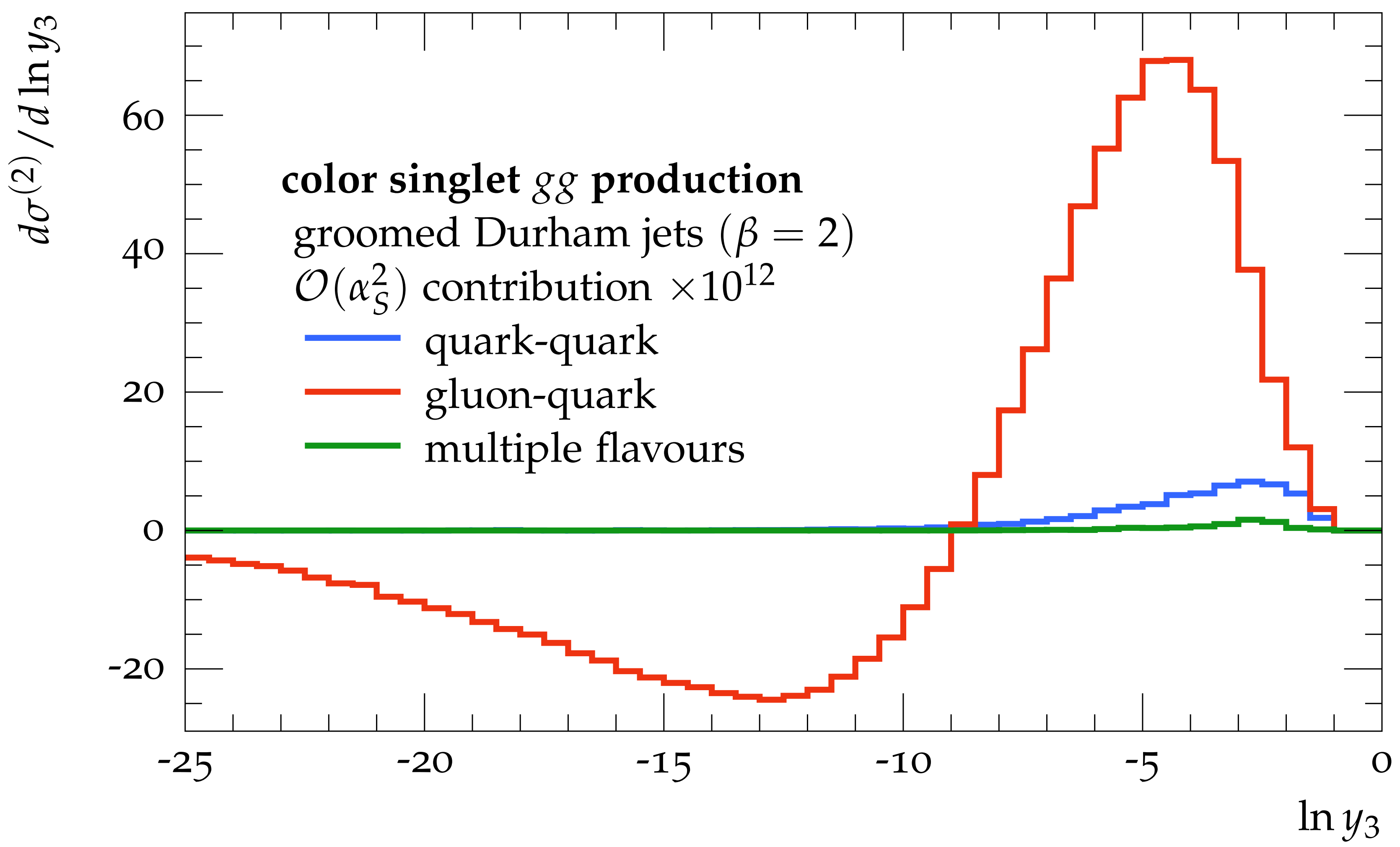
- soft drop involves re-clustering step to establish “splitting sequence”
- traditional: Cambridge/Aachen (angular ordered)
- but: consider jet with 3 particles $(g, q, \bar{q})$ → potentially assign as quark jet, even if both quarks are soft
- need to make sure $q\bar{q}$ pair clustered together first in this case → can be achieved by using JADE (virtuality ordered)

tests of IRC safety to $\mathcal{O}(\alpha_s^2)$









+ analytic check against singularity structure from double soft/ tripple collinear splitting functions

+ fails at next order, when hard gluon can ‘protect’ soft quark in clustering

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- interleaved flavour neutralisation [Caola, Grabarczyk, Hutt, Salam, Scyboz ’23]

Upcoming study from Les Houches 2023, comparing the new proposals in realistic setups, stay tuned!

Backup

WTA flavour

- companion paper [arXiv:2205.01117] suggesting to measure flavour of particle(s) along WTA axis
- soft- but not collinear safe
- similar to fragmentation functions, linear evolution equation ~ DGLAP
- not trivially applicable to fixed order calculation, but could use this as benchmark for MC analyses

1. Cluster and find jets in your collision event with any desired jet algorithm.
2. On a given jet, recluster its constituents with a pairwise, IRC safe, algorithm, using the WTA recombination scheme [50–52]. Specifically:
   (a) For all pairs i, j of particles in your jet, calculate the pairwise metric d_{ij}.
   (b) For the pair i, j that corresponds to the smallest d_{ij}, recombine their momenta into a new massless particle $\widetilde{ij}$ such that $E_{\widetilde{ij}} = E_i + E_j$, and the direction of $\widetilde{ij}$ is along the direction of the harder of i and j.[2]
   (c) Replace particles i and j with their combination $\widetilde{ij}$ in the collection of particles in the jet.
   (d) Repeat clustering until there is a single, combined particle that remains. The direction of this particle corresponds to the direction of the WTA axis of the jet.
3. The sum of the flavors of all particles in the jet whose momenta lie exactly along the WTA axis is defined to be the flavor of the jet.