Heavy Flavours at High p_T

Theory Challenges in the Precision Era of the Large Hadron Collider
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Galileo Galilei Institute, Florence

Simone Marzani
Università di Genova and INFN Sezione di Genova

Outline

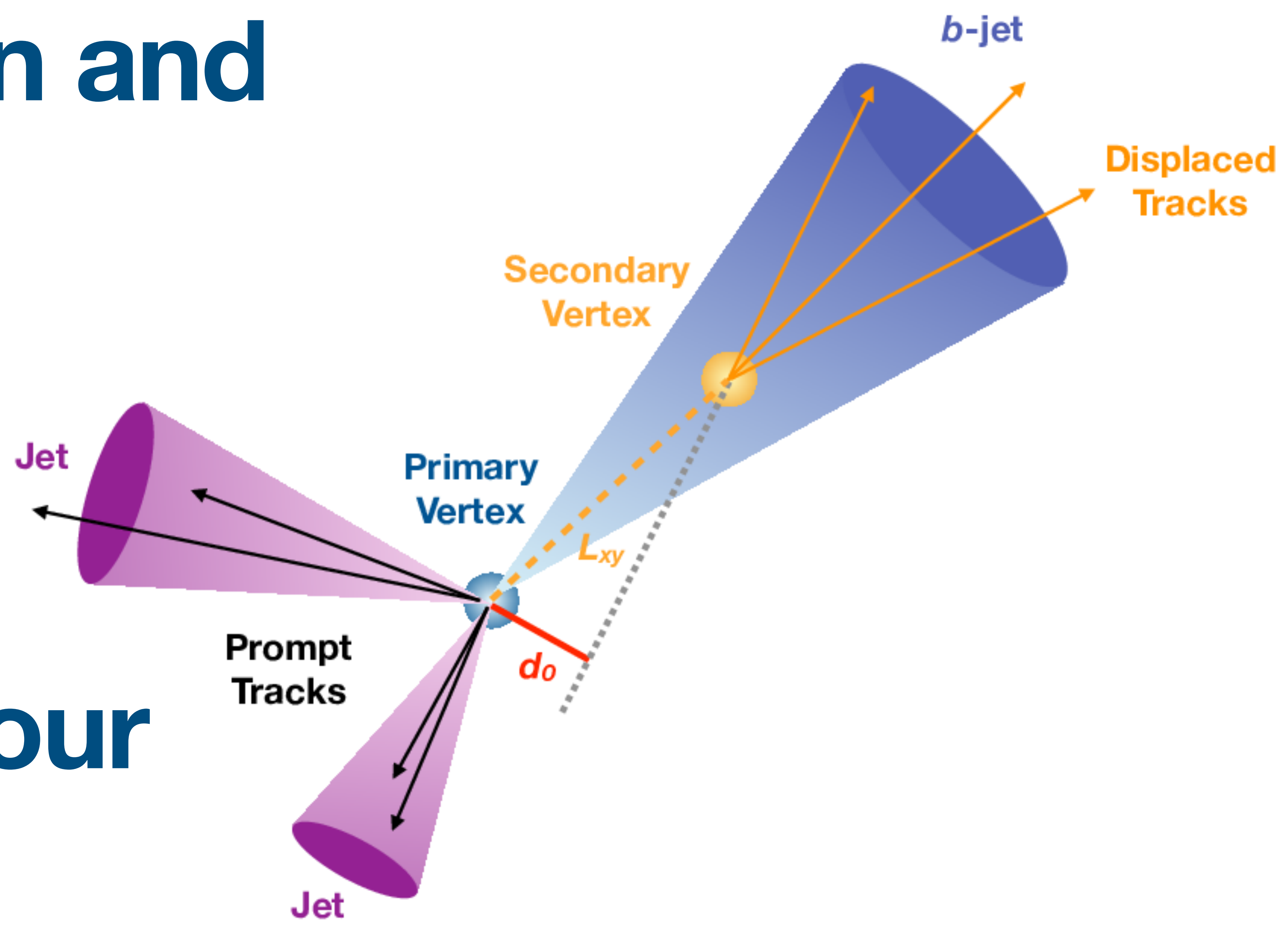
- Introduction and motivation: heavy-flavour at the LHC

- A consistent resummation of mass and soft logarithms

- Outlook: prospects for heavy-flavoured jet substructure

Introduction and motivation:

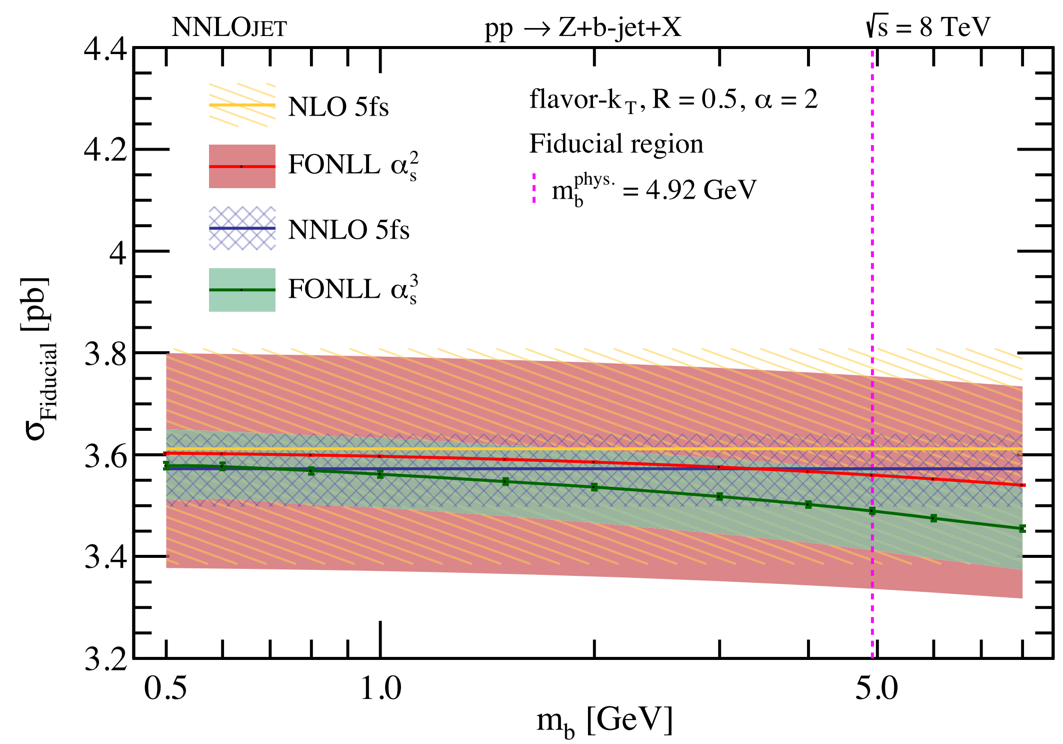
Heavy Flavour at the LHC



https://cds.cern.ch/record/2771727/plots

Heavy Flavours at the LHC

- heavy-flavour processes (charm and beauty) are central to the LHC Higgs program
- important for QCD studies too: PDFs, fragmentation etc.
- they are identified exploiting B (D) hadron lifetime: displaced vertices
- from theory viewpoint, m_b & m_c set perturbative scales: high accuracy (NNLO) QCD calculations Z+b/c (jet) now exist



Gauld et a. (2020)

see Oleksandr Zenaiev's talk

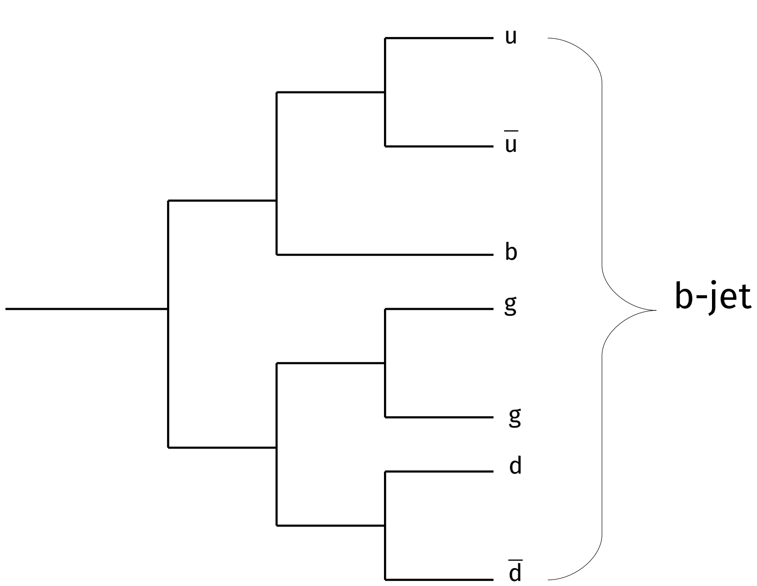
HF jets: experiment vs theory

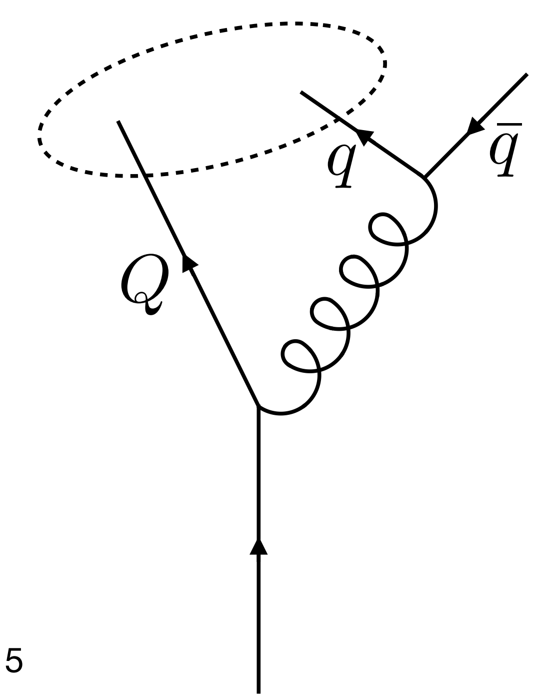
- jets are powerful bridge between theory and experiment
  However jets with identified flavour are not straightforward

- *Experimental procedure:*
  - cluster jets using the anti-k_t algorithm
  - run *b* (*c*)-tagging

- *Theory calculation:*
  - compute real and virtual
  - cluster jets using an IRC safe (flavour) algorithm

BUT counting the flavour of an anti-k_t jet is NOT IRC Safe beyond NLO!





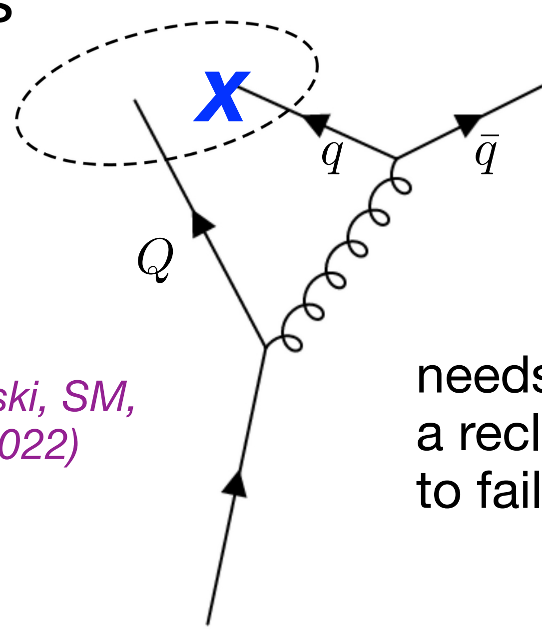
splitting of a soft gluon can affect jet flavour

Banfi Salam Zanderighi (2006)

see Giovanni Stagnitto's talk

4 new ideas in the past year!

1. use Soft Drop to remove soft quarks

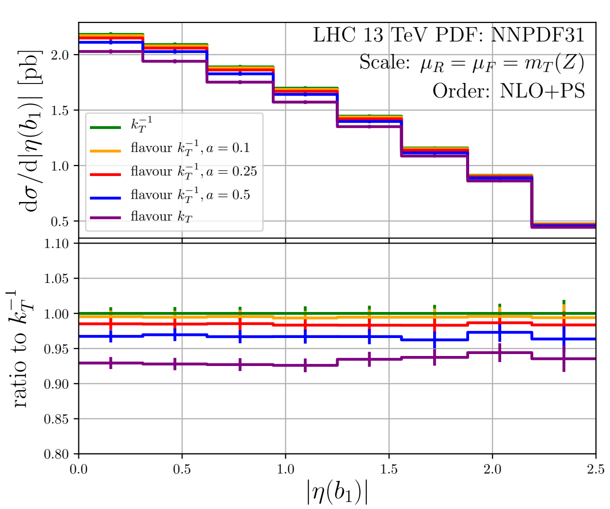


Caletti, Larkoski, SM, Reichelt (2022)

needs JADE as a recluster, know to fail at 3 loops

2. define a flavour algorithm that resembles anti-k_t

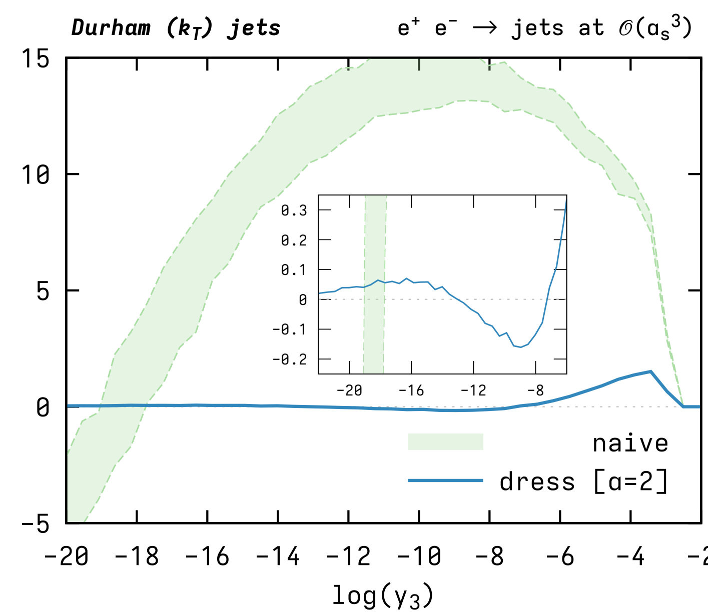
$$d_{ij}^{(F)} \equiv d_{ij} \times \begin{cases} \mathcal{S}_{ij}\,, & \text{if both } i \text{ and } j \text{ have non-zero flavour of opposite sign,} \\ 1\,, & \text{otherwise.} \end{cases}$$



flavour-dependent metric, still needs some (small) unfolding

Czakon, Mitov, Poncelet (2022)

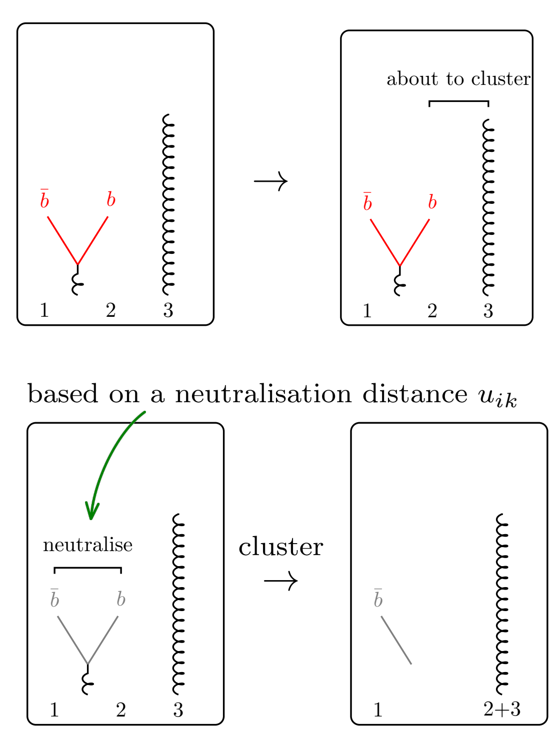
3. construct a flavour dressing for a given jet



needs flavour information of many (all?) particles in an event

Gauld, Huss, Stagnitto (2022)

4. interleaved flavour neutralisation

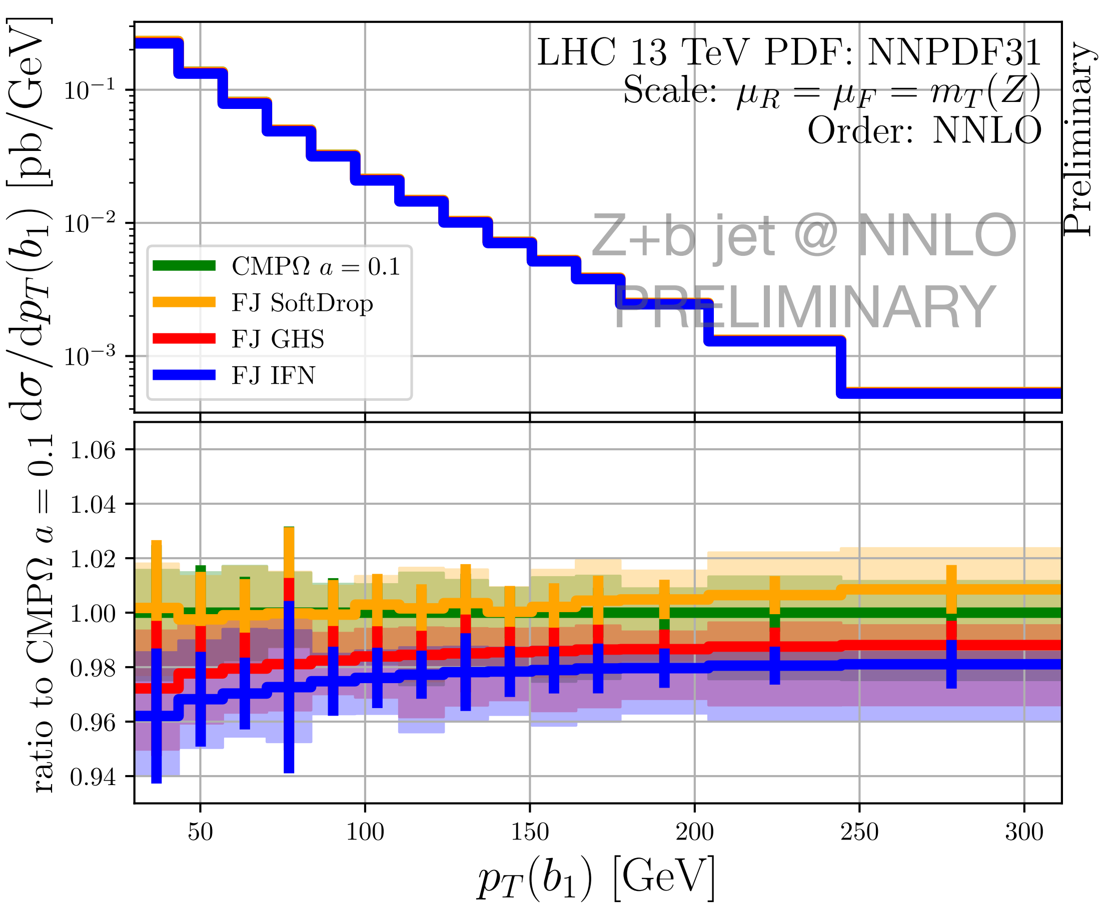


neutralise = remove the (opposite) flavour of both 1 & 2 while maintaining kinematics

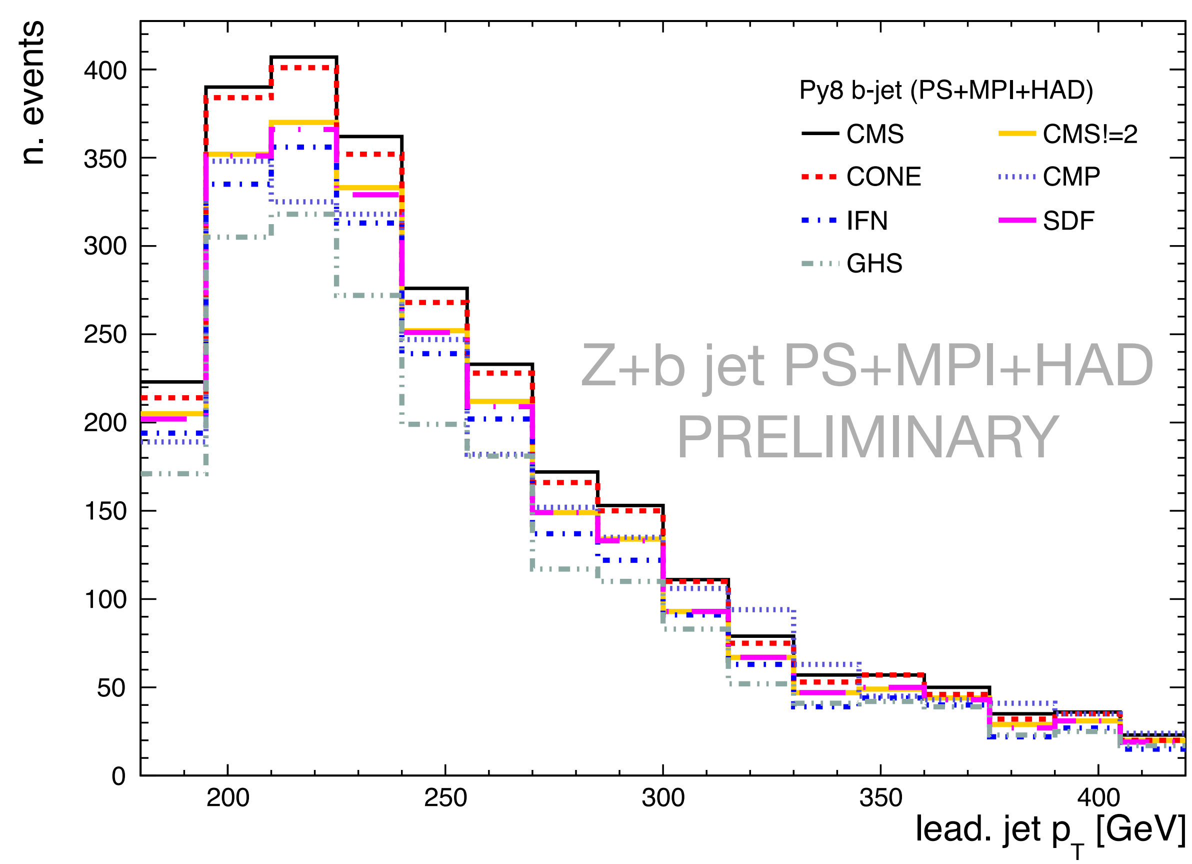
Caola, Grabarczyk, Hutt, Salam, Scyboz, Thaler (2023)

Les Houches 2023 studies

- it is important to investigate IRC safety, resilience against non-perturbative effects and experimental viability of the 4 algorithms
- a detailed comparison of these 4 algorithms was started at Les Houches
- current results are very preliminary, they will be refined and will appear in the proceedings



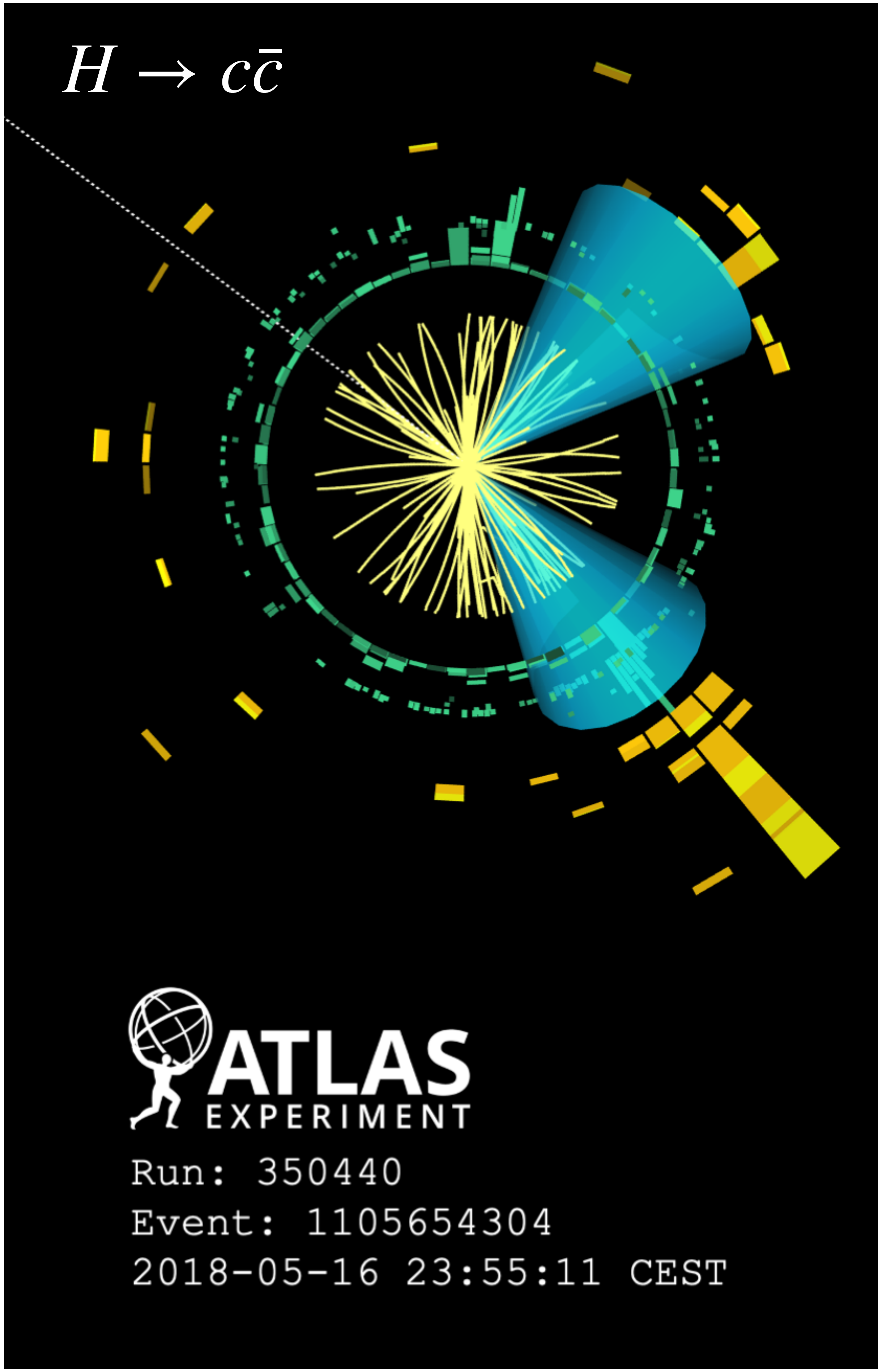
interesting shape difference at low p_t: it deserves further investigation!



first hadron-level studies show larger differences… something to investigate further

A consistent resummation of mass and soft logarithms

in collaboration with (Daniele Gaggero)
Andrea Ghira and Giovanni Ridolfi

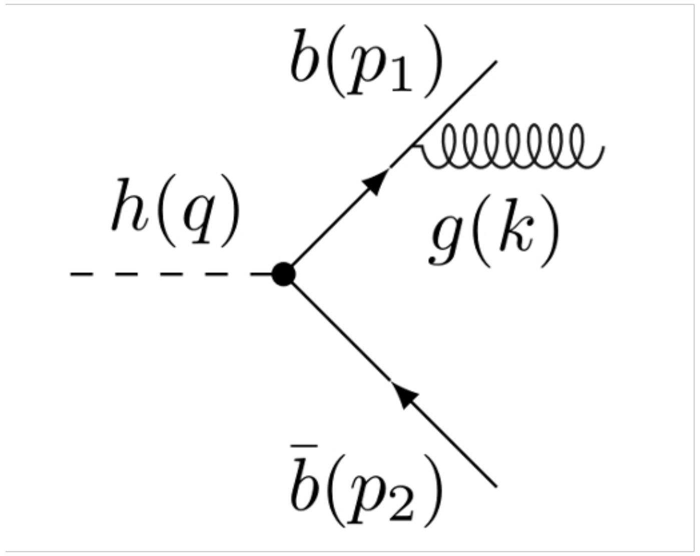


All-orders calculations with HF

- jets are not the only way to investigate HF
- we can study more exclusive processes with an identified B (or D) hadron (plus unmeasured QCD radiation)
- in both cases we face the challenge to describe processes which are characterised by multiple energy scales
    - hard scale of the process *Q* (c.o.m energy, jet p_T, …)
    - heavy flavour mass *m* (much larger than Λ_{QCD})
    - scale *vQ* set by the HF property we want to measure (e.g. its energy or a jet's substructure variable)
- (multiple) resummations become relevant and it is important to understand the hierarchy between the different scales

Heavy Flavour production

- as a toy example we consider the energy spectrum of an identified b-quark produced by a colour-singlet decay
- similar considerations hold for HF decay and HF deep-inelastic scattering



- two dimensionless ratios

$$\xi = \frac{m^2}{q^2}, \quad x = \frac{2p_b \cdot q}{q^2} = \frac{E_b}{E_h/2}$$

- we consider Mellin moments of the differential decay rate

$$\tilde{\Gamma}(N, \xi) = \int_0^1 dx\, x^{N-1} \frac{d\Gamma}{dx}$$

Massless vs Massive scheme

massless scheme (5 flv)

- quark mass used as a regulator
- cross section computed as a convolution of a coefficient function times a fragmentation function
- logs of ξ resummed through DGLAP evolution

massive scheme (4 flv)

- full mass dependence taken into account
- kinematics treated correctly at every order
- large mass logs spoil the convergence of the series

- the two approaches are usually combined (e.g. FONLL)

$$\tilde{\Gamma}^{FONLL}(N,\xi) = \tilde{\Gamma}^{(5)}(N,\xi) + \tilde{\Gamma}^{(4)}(N,\xi) - d\,.\,c\,.$$

Infra-red effects

a lot of recent (NNLL) progress, see Bakar Chargeishvili's talk

- both calculations exhibit large logs in *1-x* (or logs of *N,* in moment space) of soft and/or collinear origin

massless scheme (5 flv)

- double logs of *N* in coefficient function and fragmentation function initial condition

$$
\begin{aligned}
\tilde{\Gamma}^{(5,res)}(N,\xi) &= \tilde{C}^{res}\left(N,\frac{\mu^2}{q^2}\right) e^{\int_{\mu_0^2}^{\mu^2}\frac{d\kappa}{\kappa}\gamma(N,\alpha_s(\kappa))} \\
&\times \tilde{D}^{res}\left(N,\frac{m^2}{\mu_0^2}\right) \\
&\simeq \left(\sum_{k=0}^{\infty}\alpha_s^k c_k \log^{2k} N + \dots\right)\left(\sum_{k=0}^{\infty}\alpha_s^h A^{(h)}\log^h \xi \log N + \dots\right) \\
&\times \left(\sum_{l=0}^{\infty}\alpha_s^l d_l \log^{2l} N + \dots\right)
\end{aligned}
$$

Cacciari, Catani (2001)

massive scheme (4 flv)

- single logs of *N* with mass-dependent coefficients

$$
\begin{aligned}
\tilde{\Gamma}^{(4,res)}(N,\xi) &= \tilde{K}\left(\xi\right) e^{\int_{1/\bar{N}}^{1}\frac{d\kappa}{\kappa}\gamma_{soft}(\xi,\alpha_s(\kappa))} \\
&\simeq \sum_{k=0}^{\infty}\alpha_s^k c_k(\xi)\log^k \bar{N} \\
&\simeq \sum_{k=0}^{\infty}\alpha_s^k\left(\tilde{c}_k \log^k \xi + \dots\right)\log^k \bar{N}
\end{aligned}
$$

Laenen, Oderda, Sterman (1998)

Difficulties with matching

- we would like to combine the two calculations, with their all-order log *N* resummation
- however, they have different log structure and we cannot identify an all-order "double counting" term to subtract
- note that all the contributions of the 5-flv calculation could recombine to give something consistent with the small mass limit of the 4-flv calculation. This happens for instance for DY kinematics (more on the next slide)
- additional oddity

$$K(\xi) \simeq 1 + \frac{\alpha_s C_F}{2\pi} \log^2 \xi + \dots$$

while DGLAP evolution predicts only single logs of the mass

Origin of the mismatch (I)

- in order to better understand, we can look at the NLO calculation

massless scheme (5 flv)

$$\lim_{x\to 1}\lim_{\xi\to 0}\frac{1}{\Gamma_0}\frac{\mathrm{d}\Gamma}{\mathrm{d}x} = -\frac{\alpha_\mathrm{s} C_\mathrm{F}}{\pi}\left[\frac{\log\xi}{1-x} + \frac{\log(1-x)}{1-x} + \frac{7}{4}\frac{1}{1-x} + \ldots\right]$$

massive scheme (4 flv)

$$\lim_{\xi\to 0}\lim_{x\to 1}\frac{1}{\Gamma_0}\frac{\mathrm{d}\Gamma}{\mathrm{d}x} = -\frac{2\alpha_\mathrm{s} C_\mathrm{F}}{\pi}\left[\frac{1+\log\xi}{1-x} + \ldots\right]$$

- the $x \to 1$ and $\xi \to 0$ limits do not commute, one needs to decide what is the hierarchy
- this crucially depends on the observable and on the process we are looking at, e.g. DIS has the same issue, while DY is fine
- issue investigated also in HF decay

Corcella and Mitov (2003), Aglietti et al (2007), Gaggero, Ghira, SM, Ridolfi (2022)

Origin of the mismatch (II)

- at NLL, the 5-flv doubly resummed calculation can be written as the product of two independent jet functions

$$\tilde{\Gamma}^{(5,res)}(N,\xi) = \left(1+\alpha_s C^{(1)}\right)\left(1+\alpha_s D^{(1)}\right)\mathscr{E}^{sub}(N,\xi)$$

$$\times \exp\left[J(N,\xi) + \bar{J}(N)\right] \qquad \mu^2 = q^2, \mu_0^2 = m^2$$

- measured jet function for the b quark

$$J(N,\xi) \simeq -\frac{\alpha_s C_F}{\pi}\left(-\log^2 \bar{N} + \log\xi \log \bar{N} + \log^2 \bar{N}\right) = -\frac{\alpha_s C_F}{\pi}\log\xi\log\bar{N}$$

- unmeasured (recoil) jet function for the $\bar{b}$ quark

$$\bar{J}(N) \simeq -\frac{\alpha_s C_F}{2\pi}\log^2 \bar{N}$$

- double logs of N purely stem from the recoil jet function

Towards a solution

- the calculation of the measured jet function is performed in the quasi-collinear limit in order to account for mass logs

$$k_t^2 \to 0, m^2 \to 0, \quad \text{but} \quad \frac{k_t^2}{m^2} \text{ fixed}$$

- the recoil jet function is instead computed at $m = 0$, while we should compute it too in the quasi-collinear limit

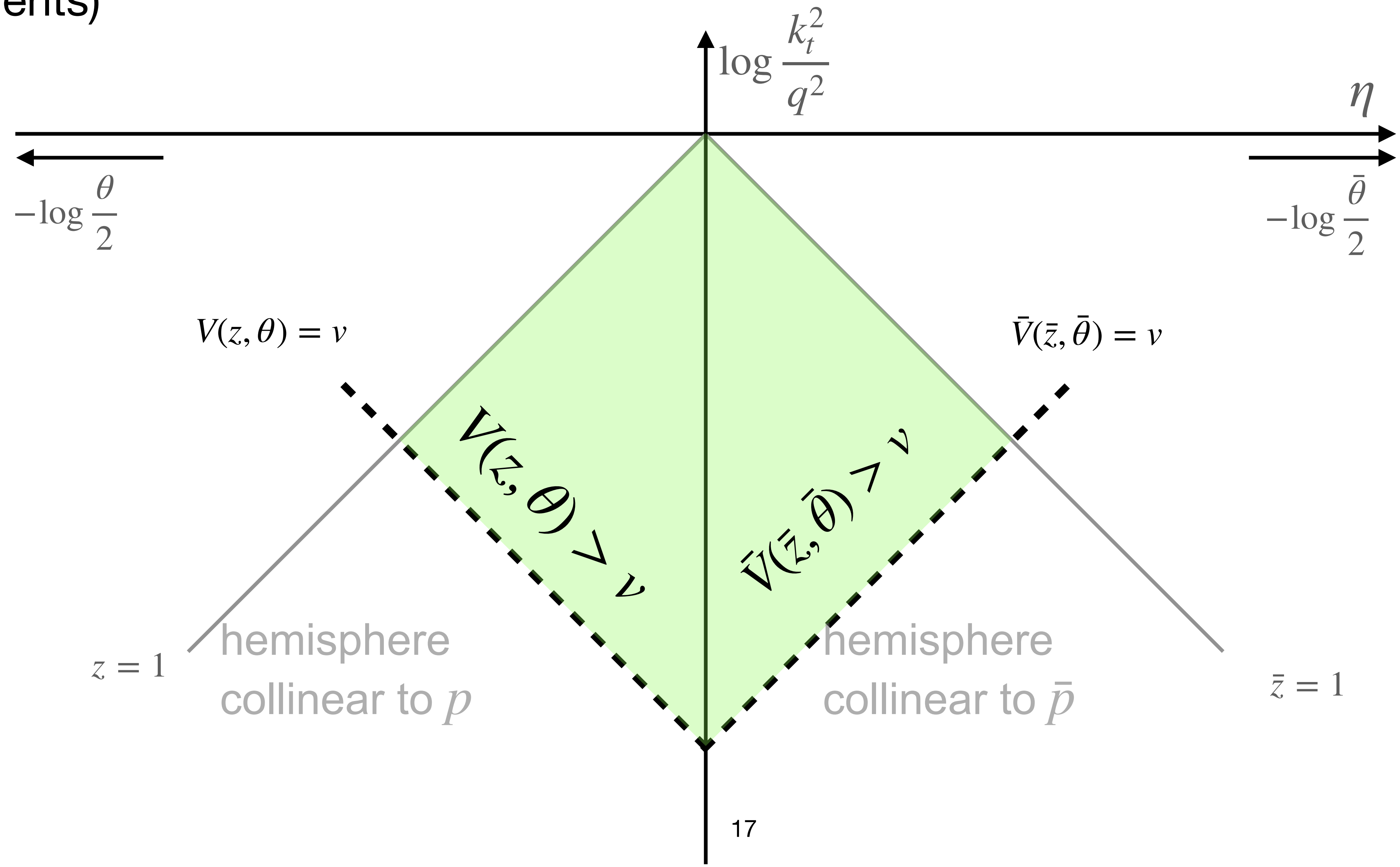
see also Aglietti et al (2007)

- furthermore, because we are matching massive (4 flv) and massless (5 flv) calculation, we should pay attention to the quark mass thresholds when performing integrals over the running coupling

- interpretation of these thresholds not transparent in Mellin space, so we perform a momentum-space analysis

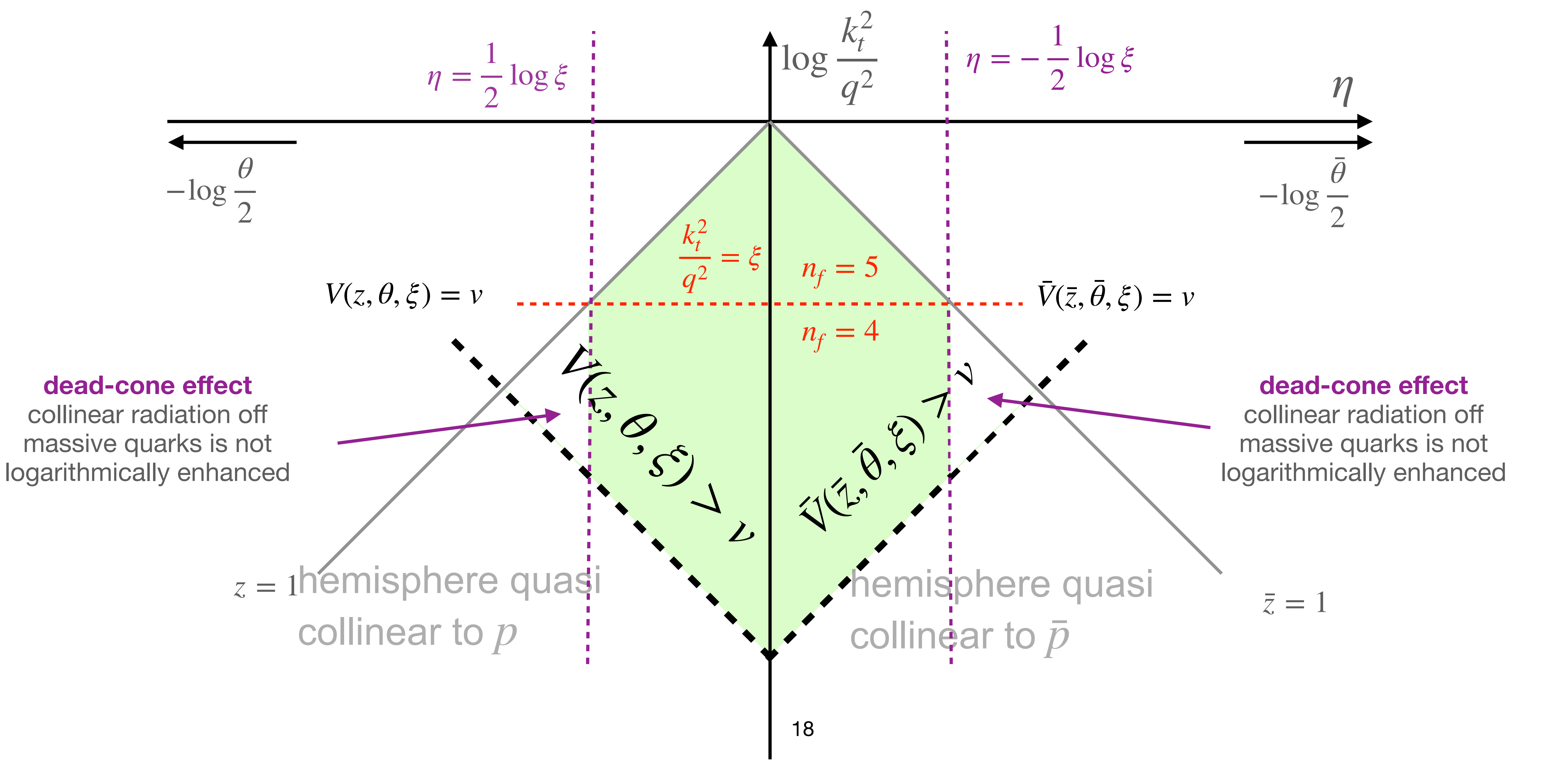
Lund plane - a short review

- Lund planes are a powerful way to visualise the kinematics of soft/collinear emissions
- Observables $\mathscr{V}$ have different parametrisation $(V, \bar{V})$ in the two collinear regions
- Coloured areas represent the NLL Sudakov form factors (i.e. the resummed exponents)



Lund plane with masses

- The presence of masses introduce new vertical (purple) boundaries, the so-called dead-cone effect
- the horizontal (red) line marks the $n_f = 4, 5$ boundary



Behaviour of the observable

- in order to apply this formalism to our case, we have to work out the observable parametrisation in the two quasi-collinear limits

- we have $\mathscr{V} = 1 - x$, which leads to

$$V(z, \theta, \xi) = z$$ energy fraction of the quasi-collinear gluon

$$\bar{V}(z, \theta, \xi) = \bar{z}(\frac{\bar{\theta}^2}{4} + \xi) \simeq \frac{\bar{z}\bar{\theta}^2}{4}$$ invariant mass of the recoil jet

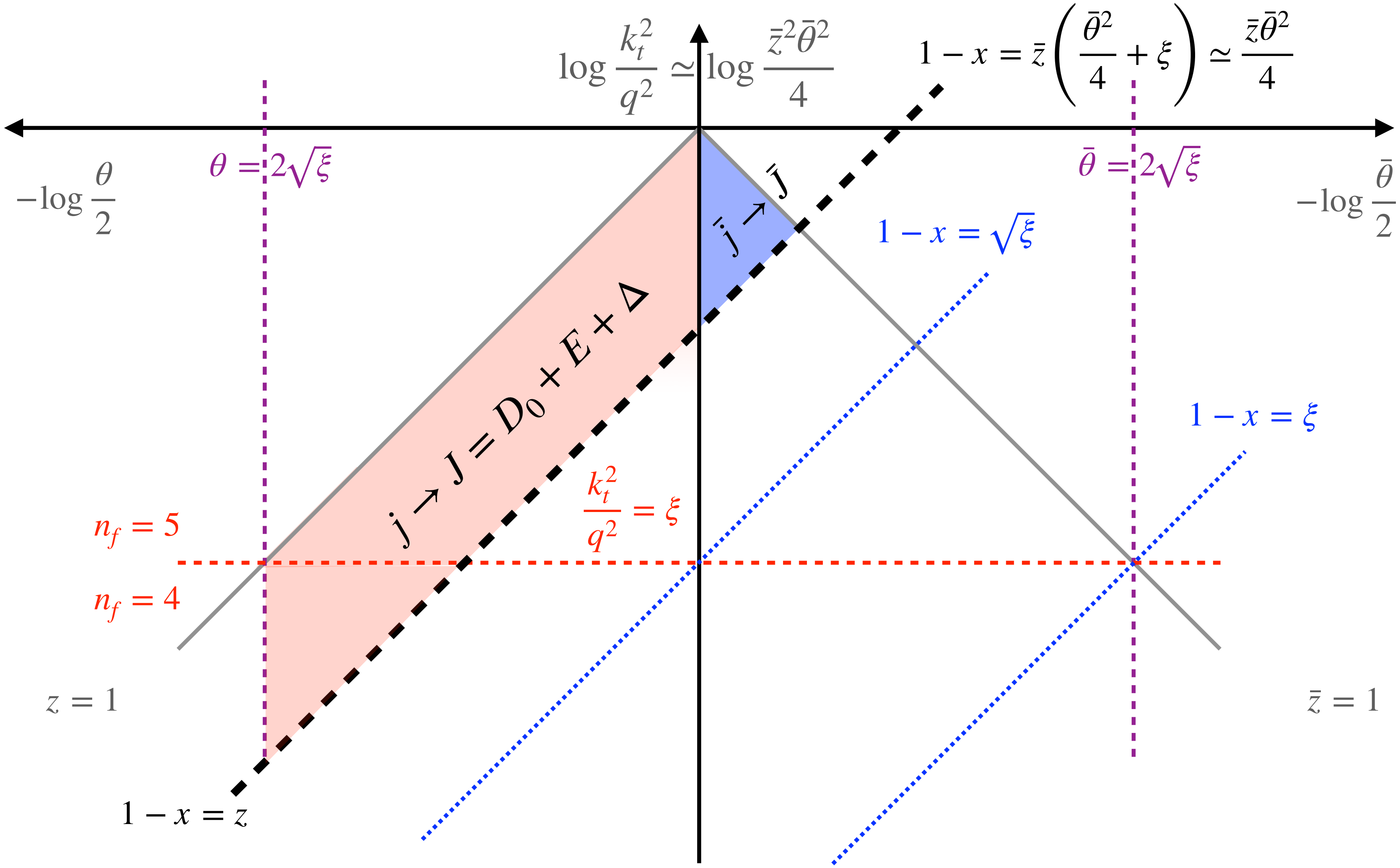
- now we have to turn the crank and compute the two jet functions, taking into account flavour-threshold and dead-cone boundaries on the Lund plane

- this is very similar to what we've been doing for jet substructure observables for the past 10 years

- technical aside: we use the two-loop running coupling in the CMW scheme

Region 1: $1-x>\sqrt{\xi}$

- we find three different regions
- in the first region we recover the known massless result



- in this region we have double logs of *1-x* and single logs of the mass

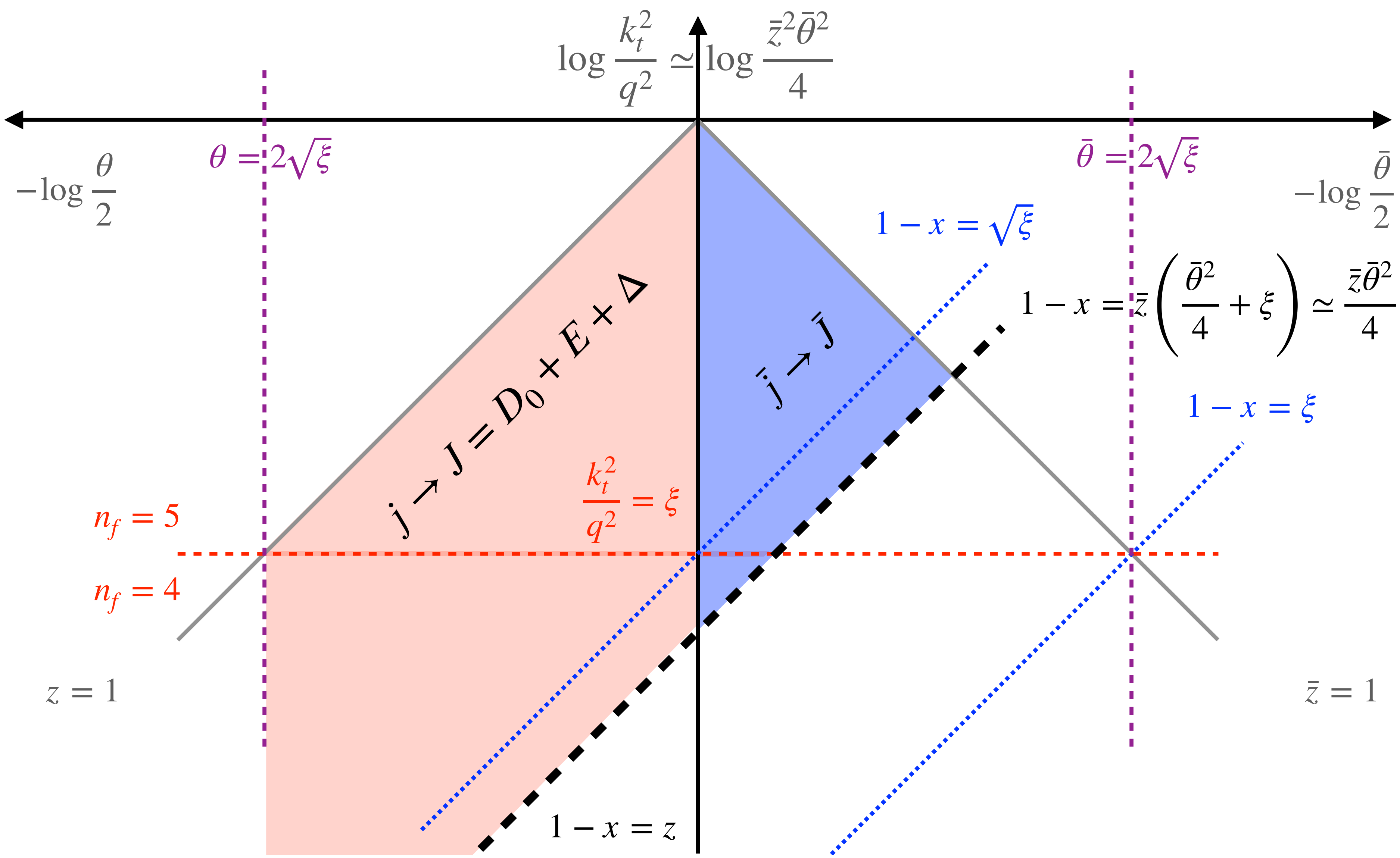
back to Mellin space

$$J^{(1)}(N,\xi)=j^{(1)}(1-x,\xi)\Big|_{1-x=\bar N^{-1}}$$

$$\bar J^{(1)}(N,\xi)=\bar j^{(1)}(1-x,\xi)\Big|_{1-x=\bar N^{-1}}$$

Region 2 : $\xi < 1 - x < \sqrt{\xi}$

- we find three different regions:
- the second region is a smoothly matches $n_f = 5$ to $n_f = 4$



- in this region 5 flv is frozen, while 4 flv continues to evolve

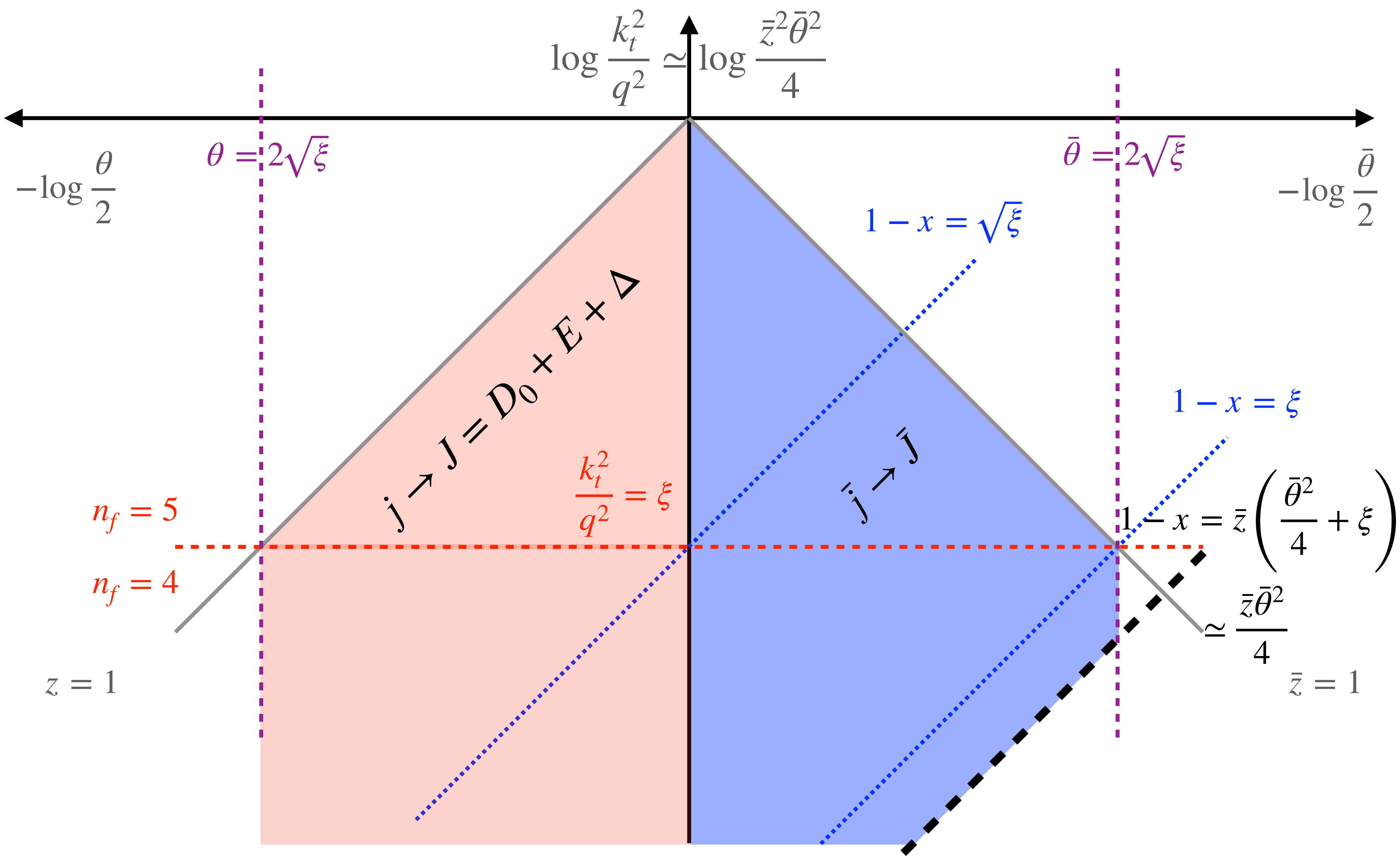
back to Mellin space

$$J^{(2)}(N, \xi) = j^{(2)}(1 - x, \xi)\Big|_{1-x=\bar{N}^{-1}}$$

$$\bar{J}^{(2)}(N, \xi) = \bar{j}^{(2)}(1 - x, \xi)\Big|_{1-x=\bar{N}^{-1}}$$

Region 3 : $1 - x < \xi$

- we find three different regions:
- the third region is consistent with the massive calculations (with mass logs exponentiated)



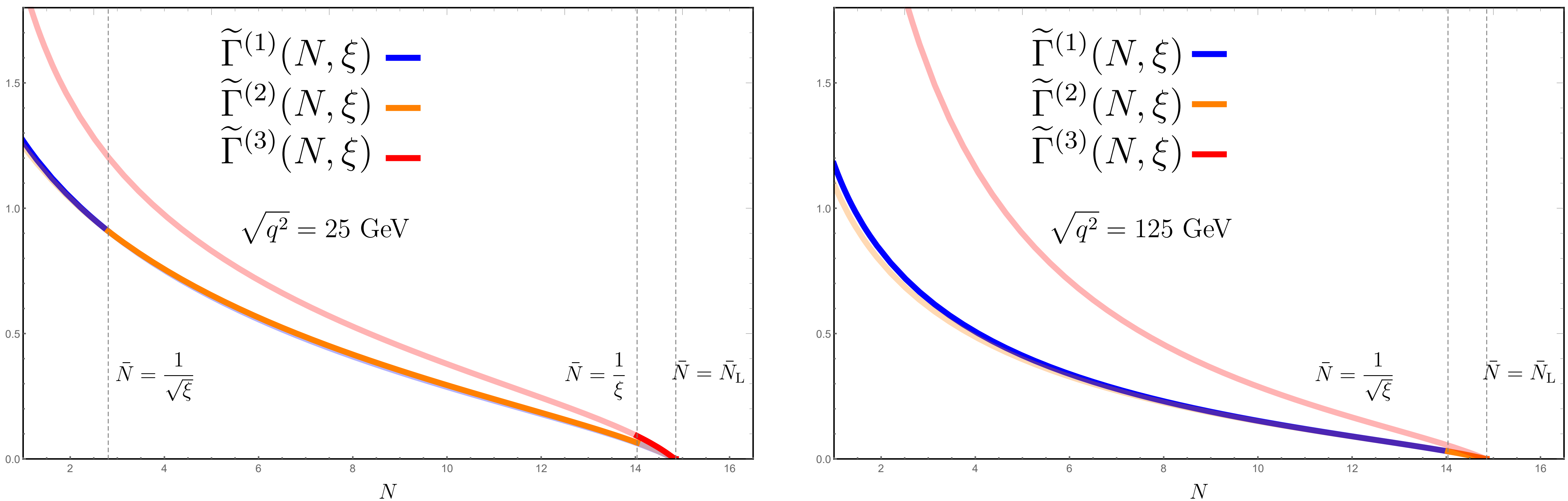
- in this region we have double logs of *m* and single logs of *1-x*

back to Mellin space

$$J^{(2)}(N, \xi) = j^{(2)}(1 - x, \xi)\Big|_{1-x=\bar{N}^{-1}}$$

$$\bar{J}^{(3)}(N, \xi) = \bar{j}^{(3)}(1 - x, \xi)\Big|_{1-x=\bar{N}^{-1}}$$

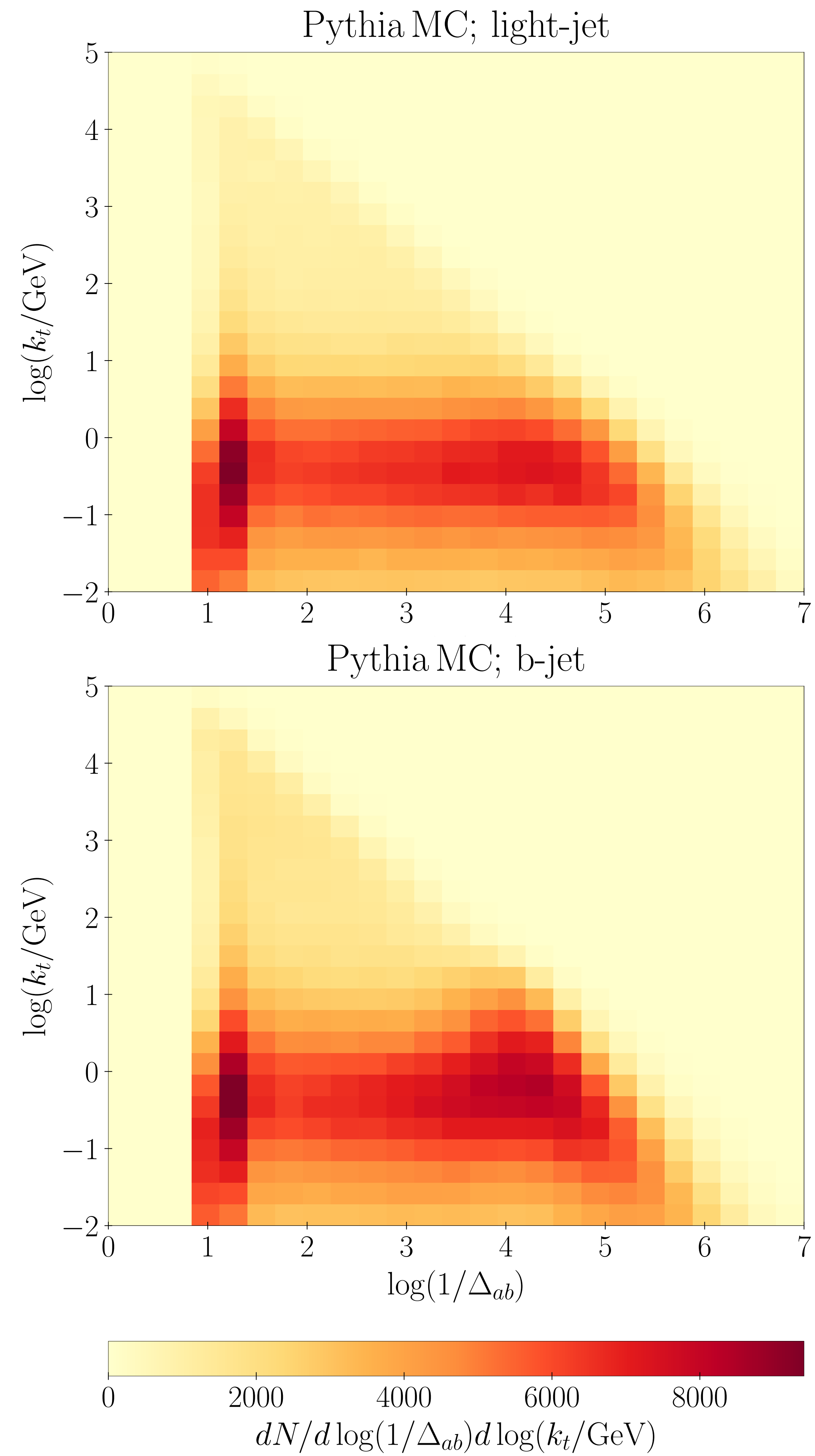
N space results (for real *N*)



- we plot our results on the real-*N* axis for two values of q^2
- curves are shown in solid in the real-*N* intervals corresponding to the *1-x* regions
- region 3 is visible only for small q^2, and the result in region 2 differs very little from the one of region 1
- we have also applied our formalism can be applied also to DIS, for which we have data in a wide Q^2 region (numerics are work in progress)

Outlook:

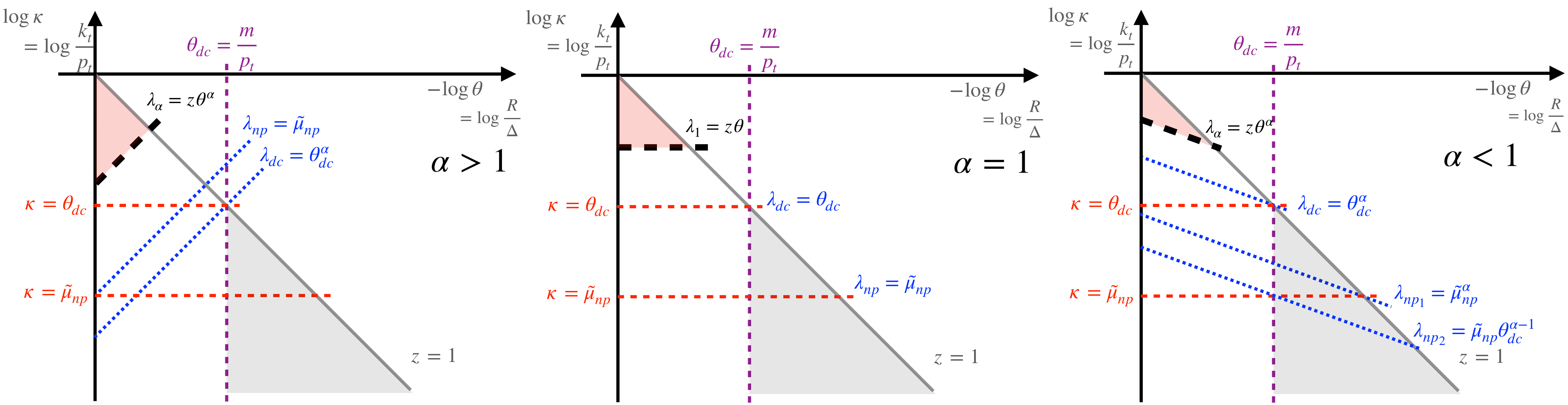
prospects for heavy-flavoured jet substructure



HF-jet substructure

- in order to achieve a consistent resummation of mass and soft logarithms we had to understand jet functions in the quasi-collinear limit
- we can apply this very same formalism to a wide class of jet observables, opening up a novel HF-jet substructure program for LHC Run 3
- for instance jet angularities and energy correlations functions

$$\lambda_\alpha = \sum_{i \in jet} \frac{p_{Ti}}{p_{Tjet}} \left(\frac{\Delta_i}{R} \right)^\alpha$$



jet thrust | jet width | LHA

in collaboration with Prasanna Dhani, Oleh Fedkevych, Andrea Ghira, Gregory Soyez

Grooming to expose the dead-cone

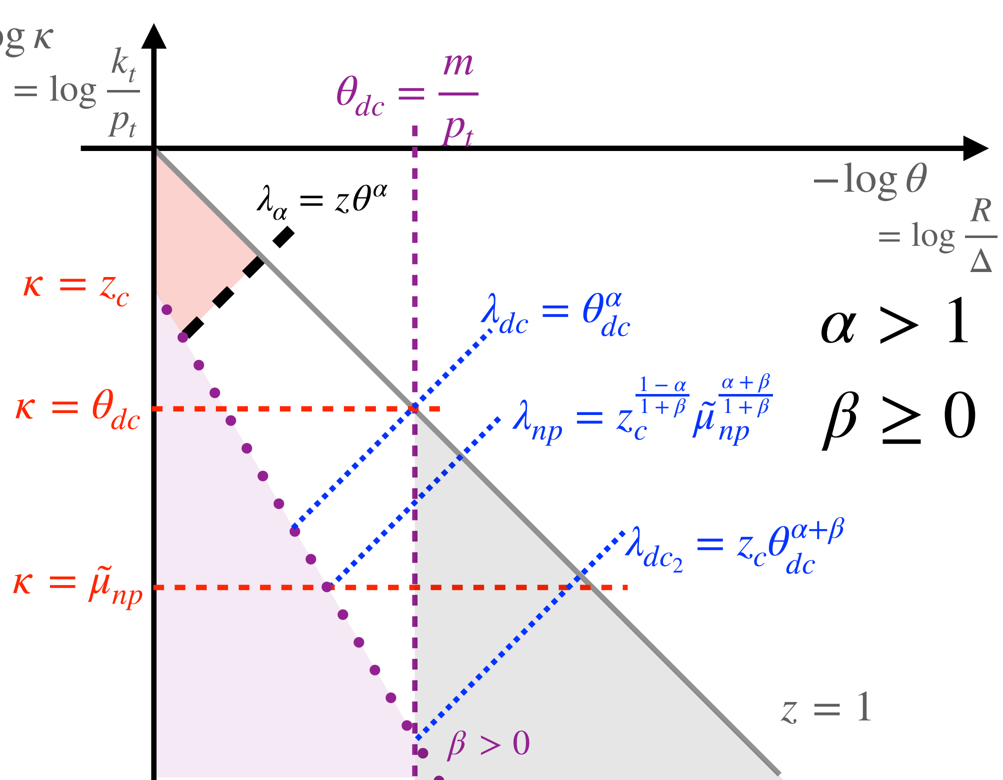
- jet substructure techniques are being exploited to measure the dead-cone effect at the LHC

  ALICE collaboration (2022)

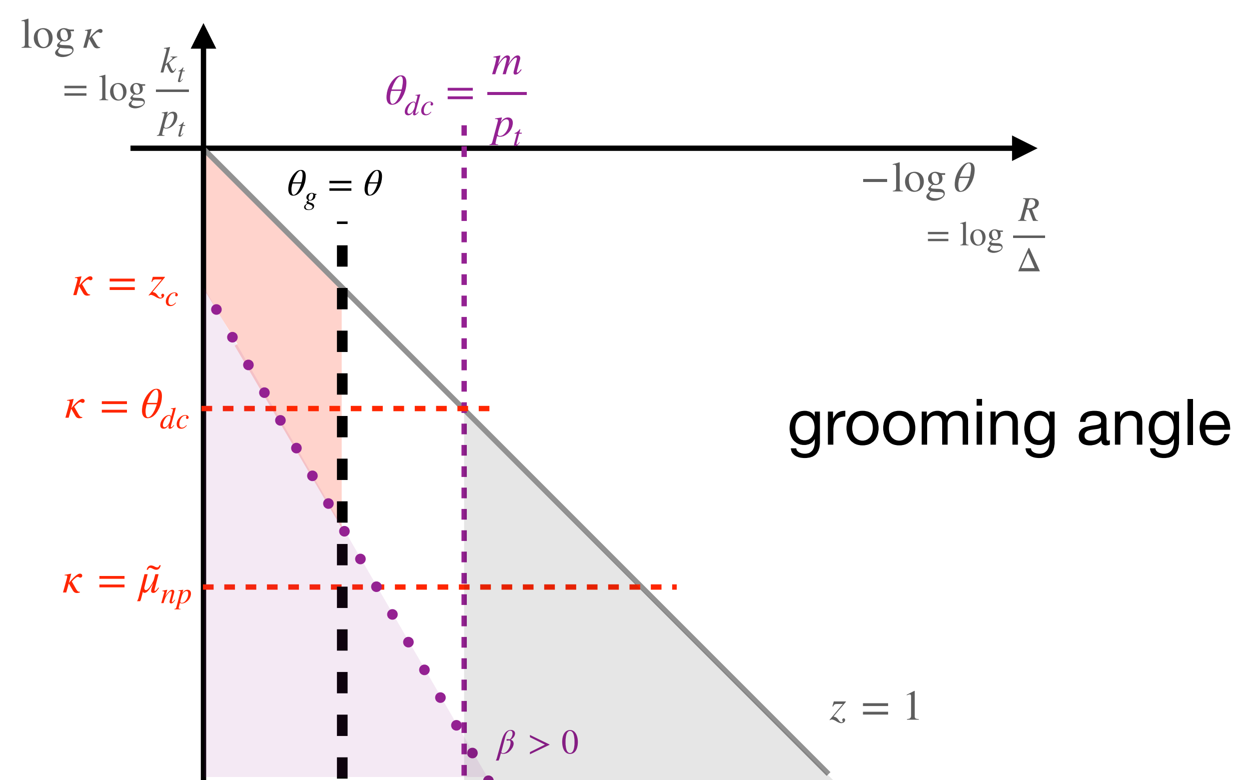
- jet grooming removes soft-wide angle radiation and enables us to expose collinear dynamics giving rising to the dead-cone

  Cunqueiro, Napoletano, Soto-Ontoso (2023)

- Soft Drop is a very-well understood grooming techniques (high-precision calculation, many measurements) and we have recently begun studying the properties of groomed HF jets.



Soft Drop jet thrust



in collaboration with Simone Caletti and Andrea Ghira

Conclusions

- high-p_T processes with identified flavour (hadron or jets) offer a complementary handle to study bottom and charm physics

- the presence of multiple scales often requires (more than one) resummation

- we aim to exploit the past-decade improvement in our understanding of jets and their structure to provide new insights into flavour physics

- Higgs Centre Workshop: *Heavy Flavours at High pT*
  29$^{\text{th}}$ Nov - 1$^{\text{st}}$ Dec 2023, Edinburgh

THANKS FOR YOUR ATTENTION