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Dead-cone searches in heavy-ion collisions using the jet tree

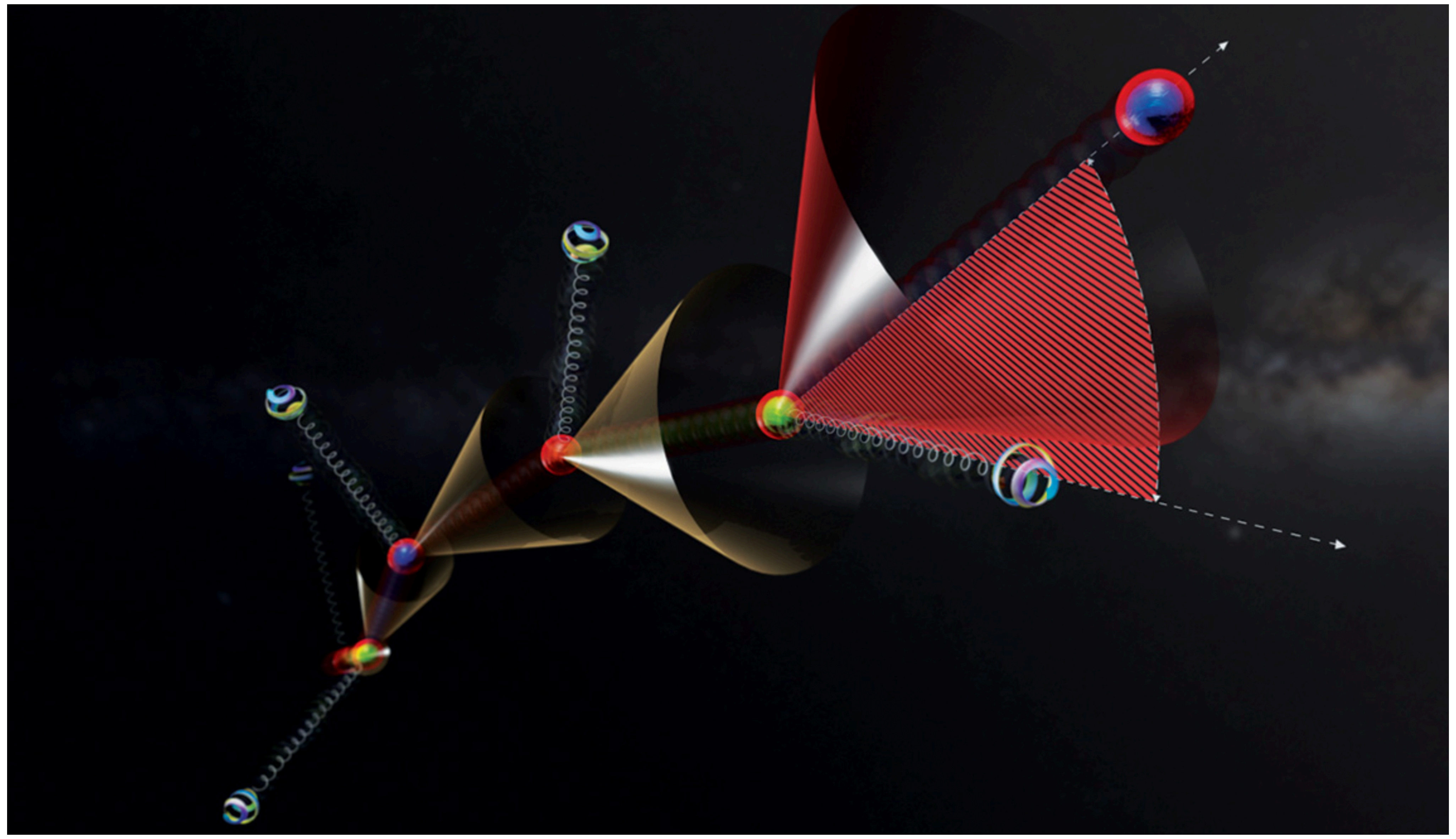
Leticia Cunqueiro Méndez

based on: LCM, Alba Soto-Ontoso, Davide Napoletano https://arxiv.org/pdf/2211.11789.pdf

Hard Probes 2023, Aschaffenburg

The dead-cone effect in QCD

Gluon radiation by a particle of mass m and energy E is suppressed within a cone of angular size m/E around the emitter



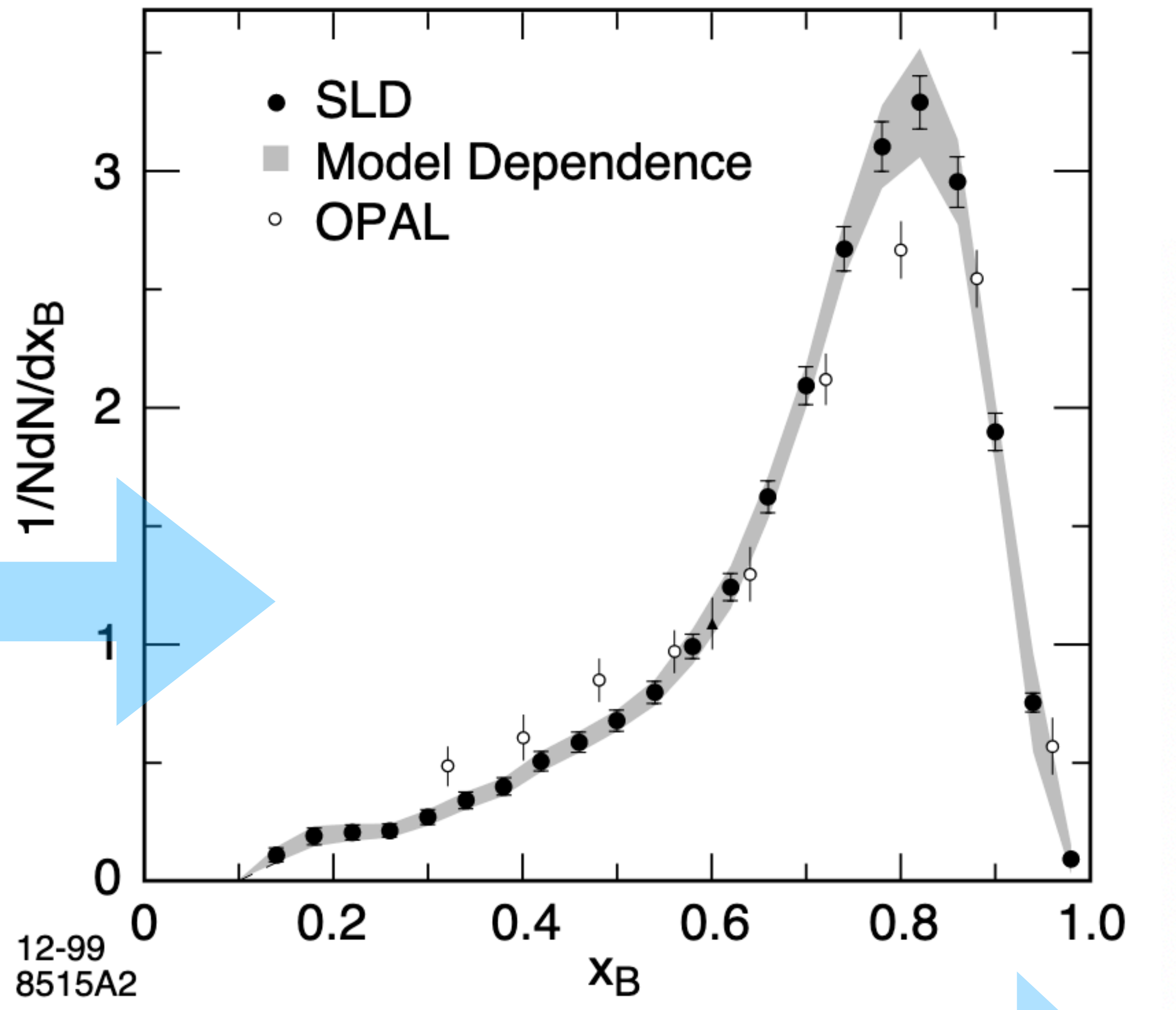
$$\frac{\frac{dN_Q}{d\theta}}{\frac{dN_q}{d\theta}} \propto \frac{\theta^4}{(\theta^2 + \theta_0^2)^2} \qquad \theta_0 = \frac{m_Q}{E_Q}$$

Dokshitzer,V.A.Khoze and S.I.Troyan "On specific QCD properties of heavy quark fragmentation", J. Phys. G 17 (1991)

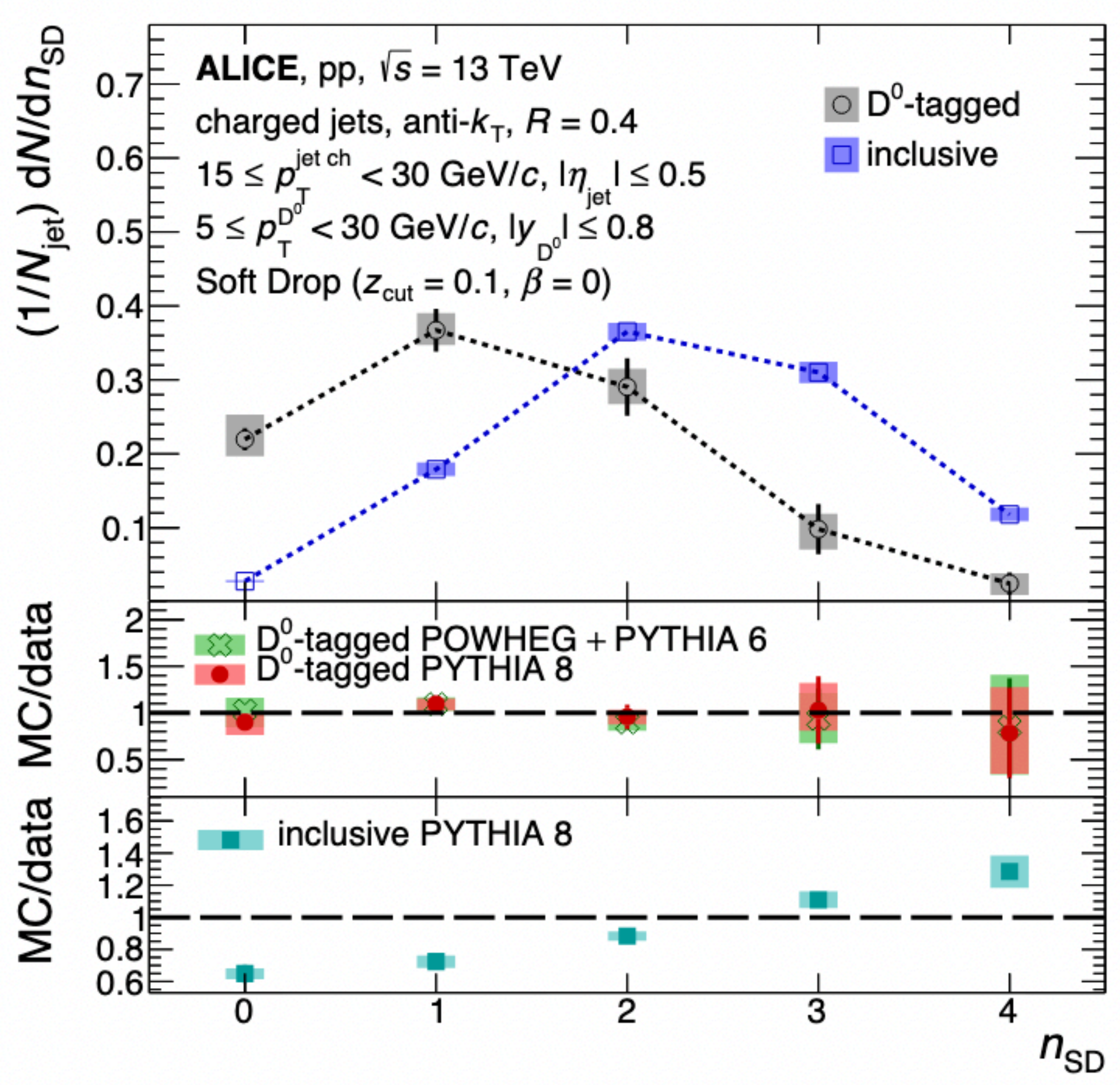
The dead-cone effect

Consequences of the dead cone:

- Restriction of hard gluons with small k_T
  —> reduction of emissions, FF peaked a larger z



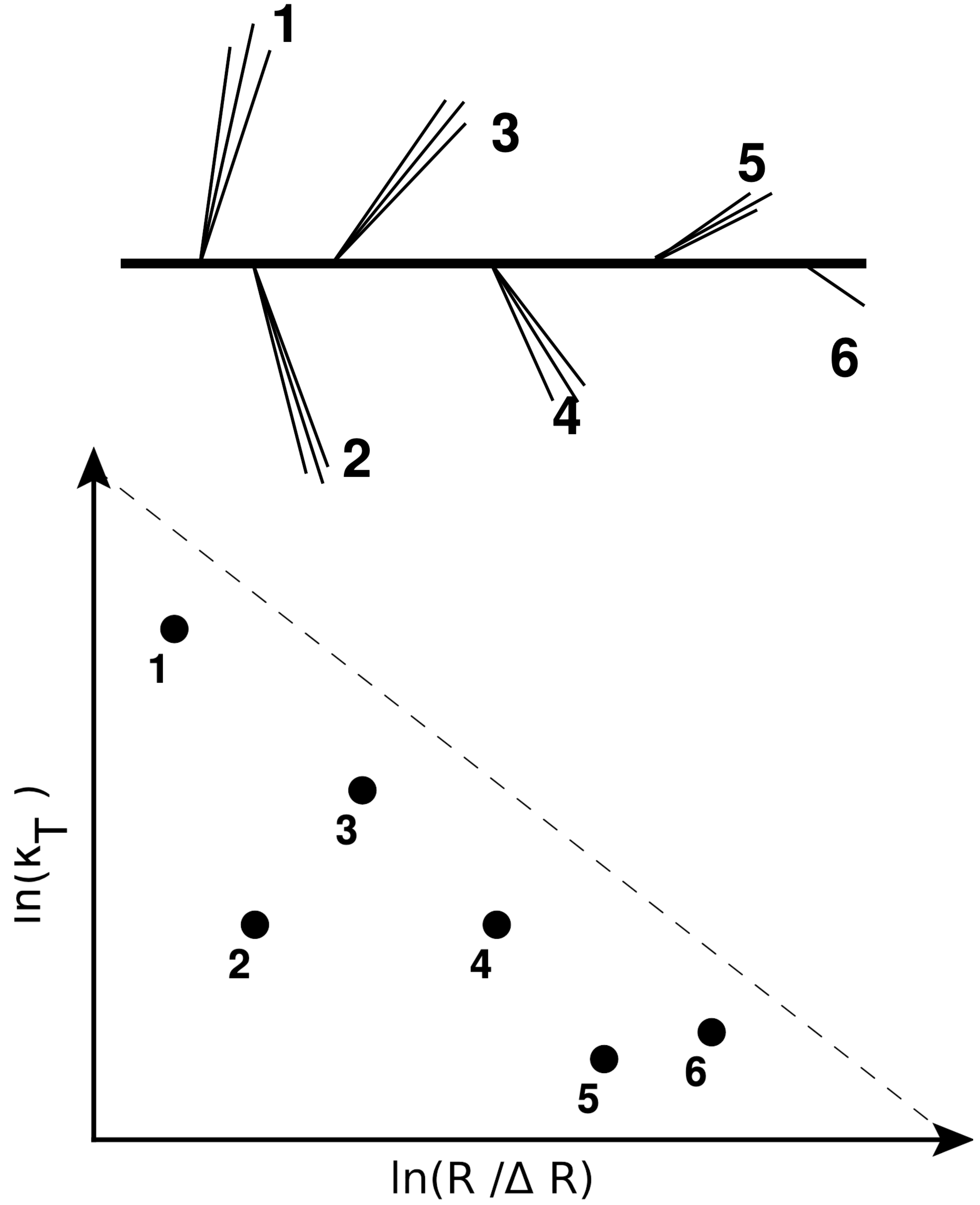
- Lower intrajet multiplicities



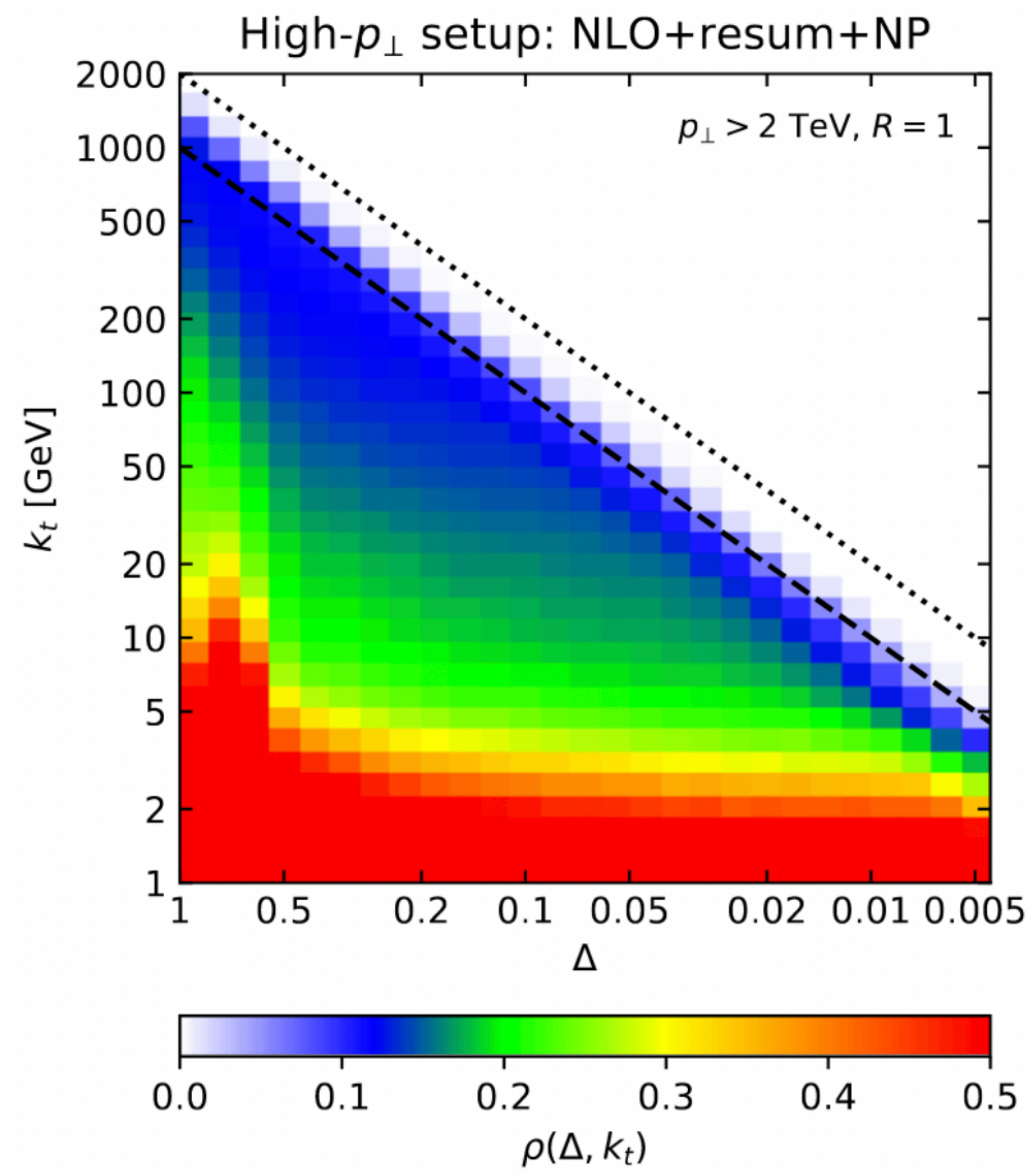
Experimental challenges for a direct measurement

- The decays of the heavy flavour particles happen at similar angular scales and fill the dead cone
- Accurate determination of the dynamically evolving direction of the heavy-flavour particle relative to which radiation is suppressed

The jet tree and the primary Lund plane



- Unwind the Cambridge-Aachen clustering history
- At each step register (k_T, θ) onto the Lund plane
- Follow the leading branch at each step



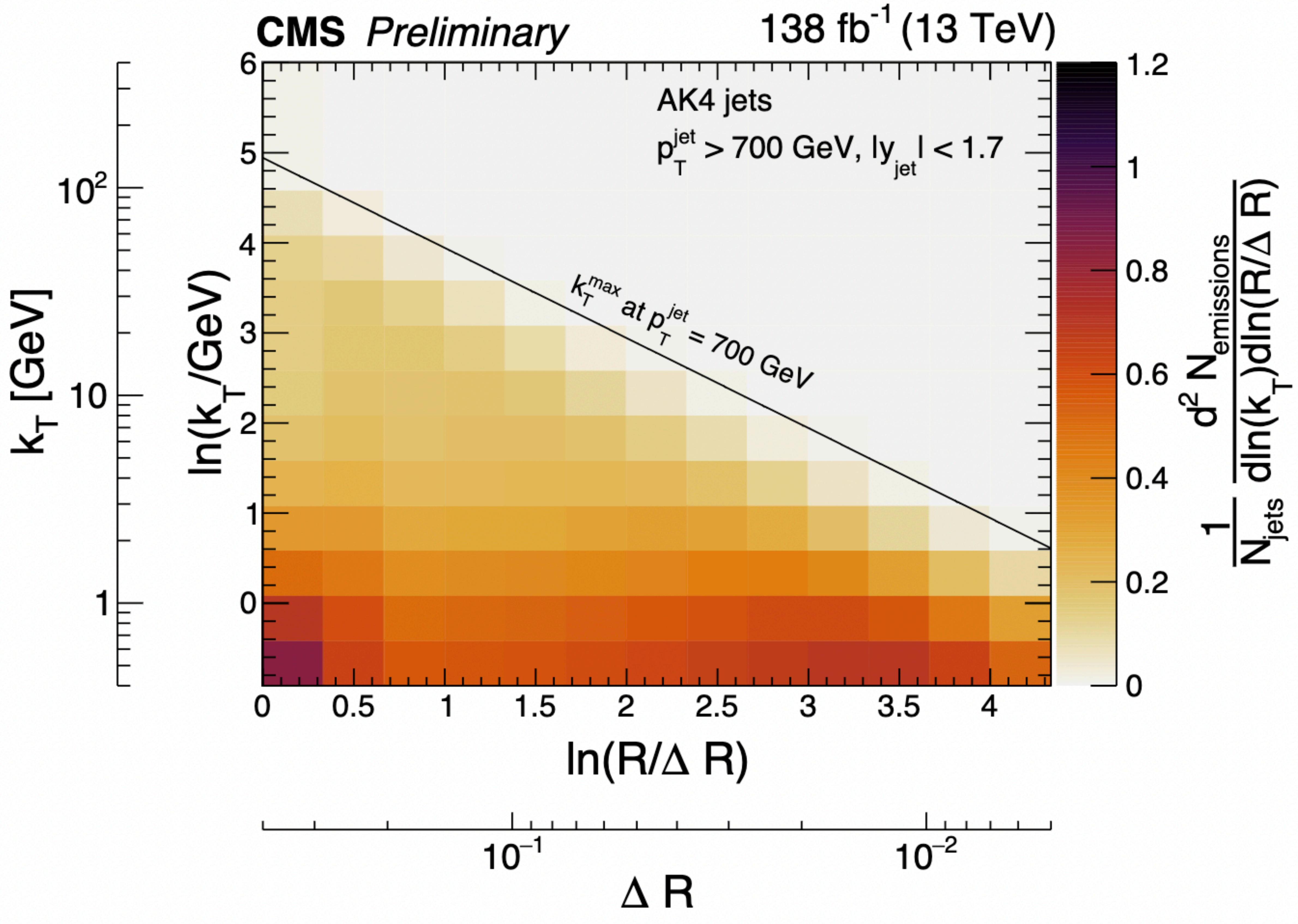
At leading order, emissions populate the plane uniformly and the running of the coupling sculpts the plane

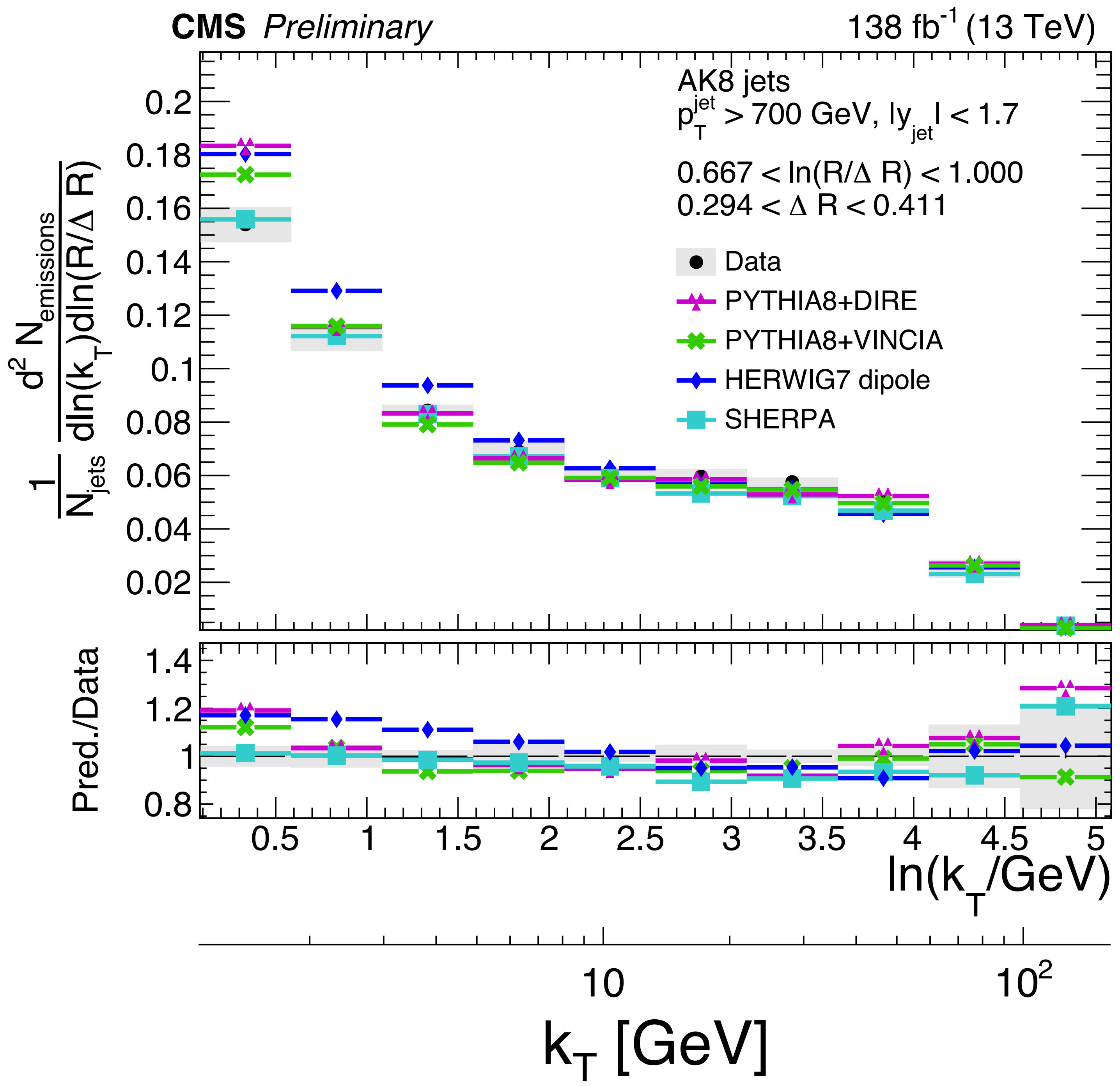
$$d^2P = 2\frac{\alpha_s(k_\perp)C_R}{\pi}dln(z\theta)dln(\frac{1}{\theta})$$

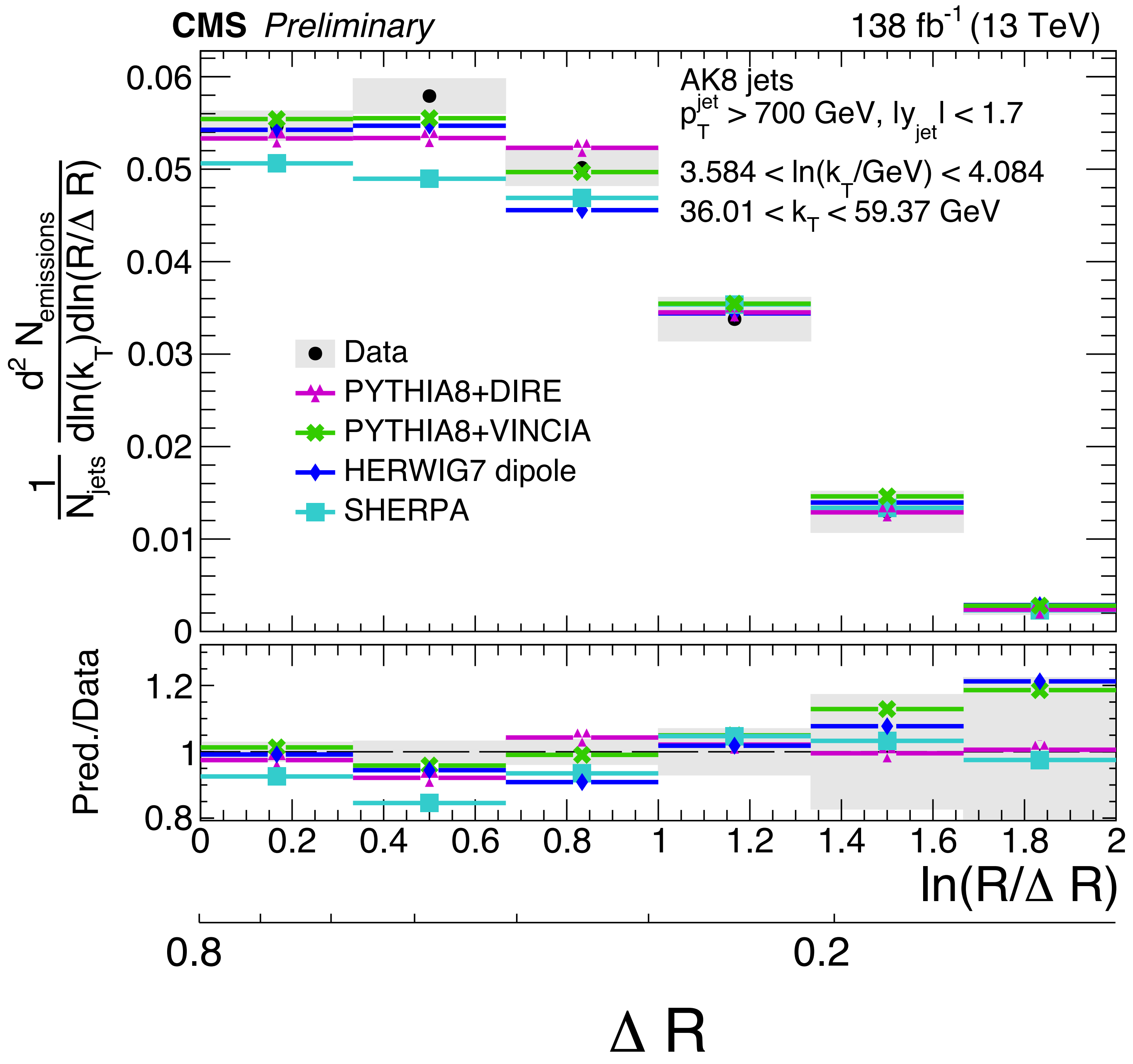
Lifson, Salam, Soyez, JHEP 10 (2020)
Dreyer, Salam, Soyez, JHEP 12 (2018) 064

The jet tree (filling the primary Lund plane)

CMS-PAS-SMP-22-007
and Cristian Baldenegro's talk at Moriond QCD





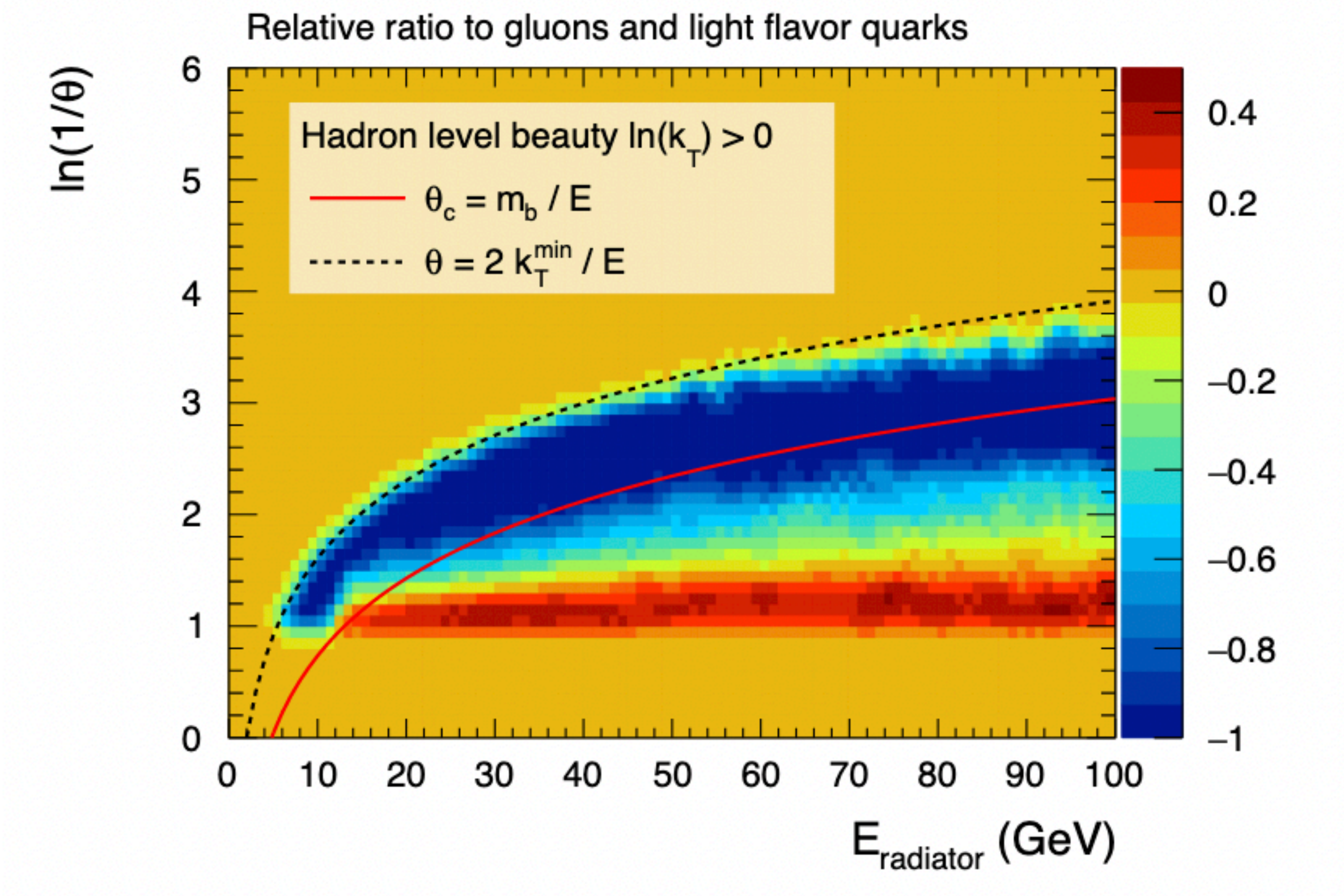


- Multiple physics effects contribute beyond the LO uniformly-filled plane
- However the measurement captures salient features

of the q/g parton shower: the running of the coupling sculpts the plane

The heavy-flavour jet tree and the dead cone

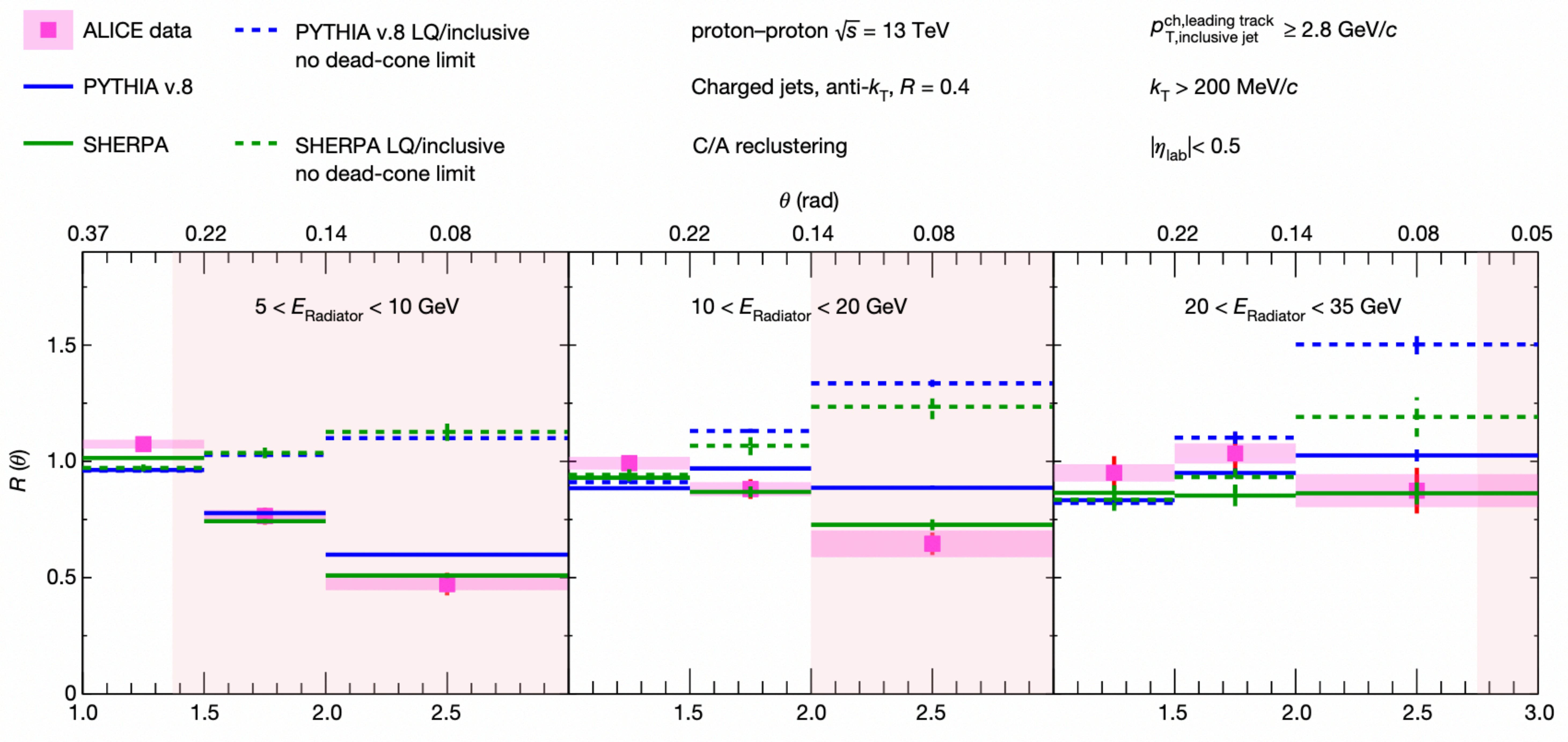
Cunqueiro, Ploskon, Phys.Rev.D 99 (2019) 7, 074027



Strong suppression of splittings relative to inclusive jets

$E_{radiator}$ is the sum energy of the daughter prongs at each node of the jet tree
->proxy for the quark energy

ALICE, Nature 605, 440-446 (2022)

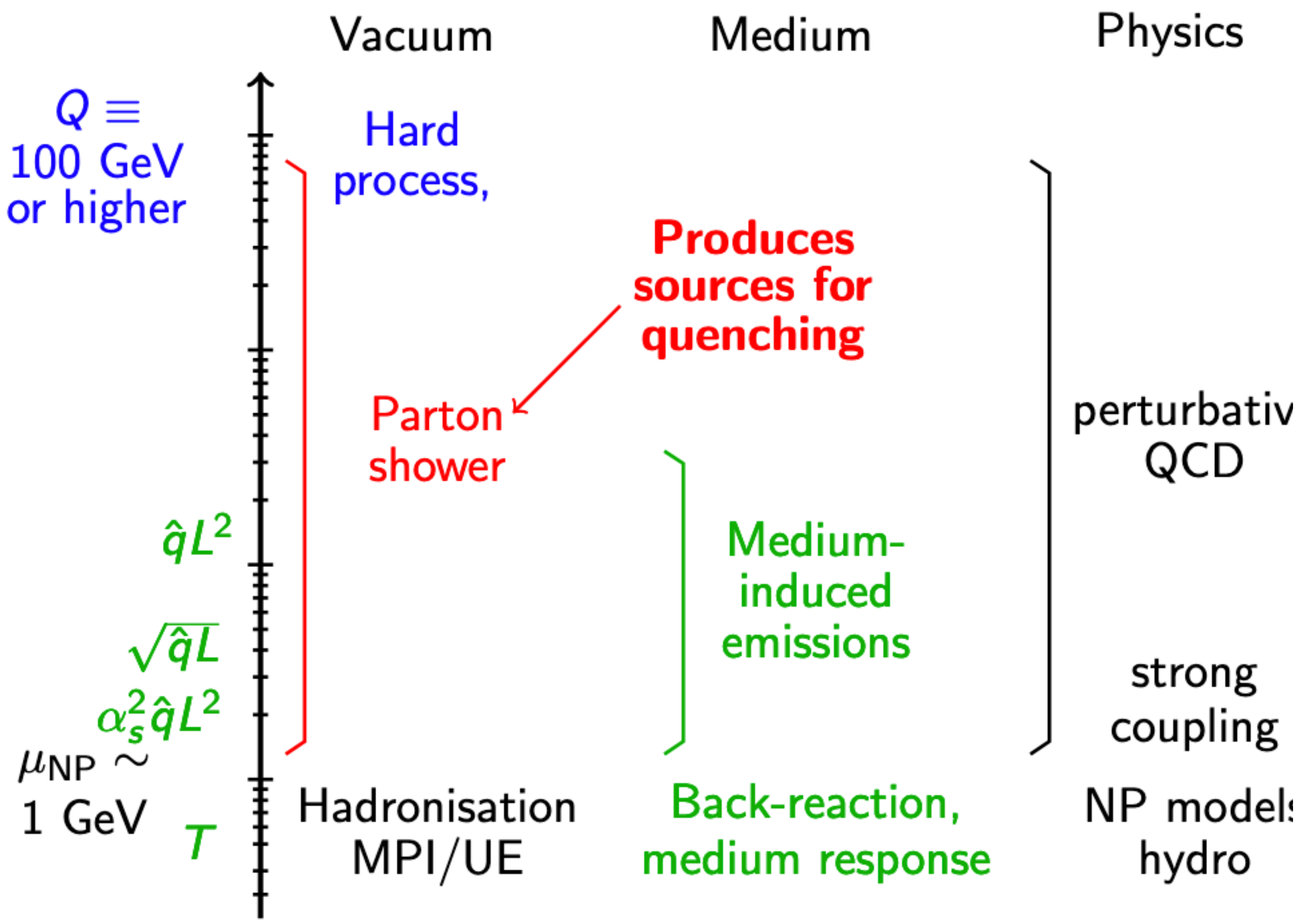


$$R(\theta) = \frac{1}{n^{D^0 \text{jets}}} \frac{dn^{D^0 \text{jets}}}{d\ln(1/\theta)} \Big/ \frac{1}{n^{\text{inclusive jets}}} \frac{dn^{\text{inclusive jets}}}{d\ln(1/\theta)} \Bigg|_{k_T > x\Lambda_{QCD}}.$$

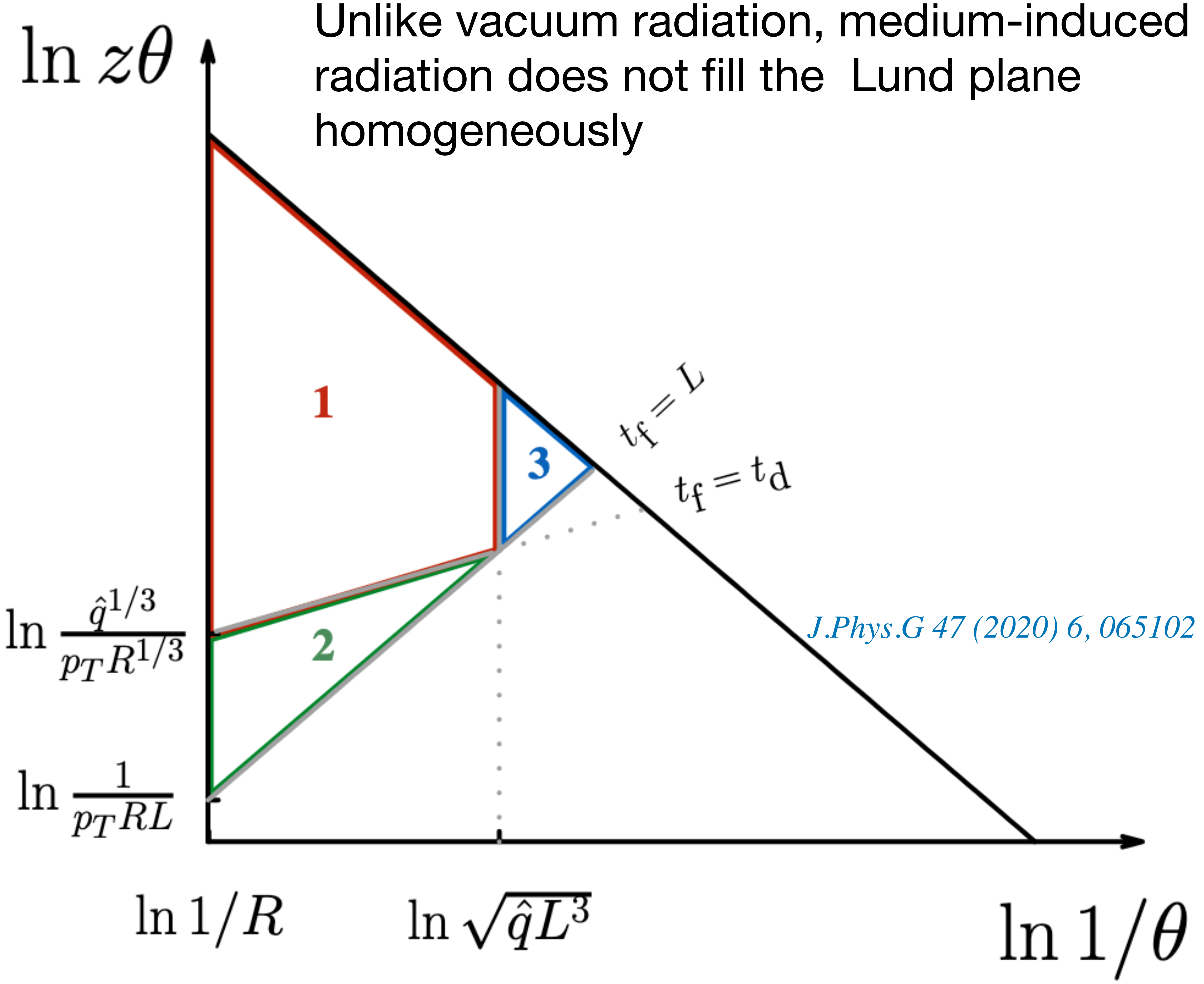
Strong suppression in the lowest $E_{radiator}$ bin

Pink areas represent the vetoed regions given by m_C/E

The heavy-ion case



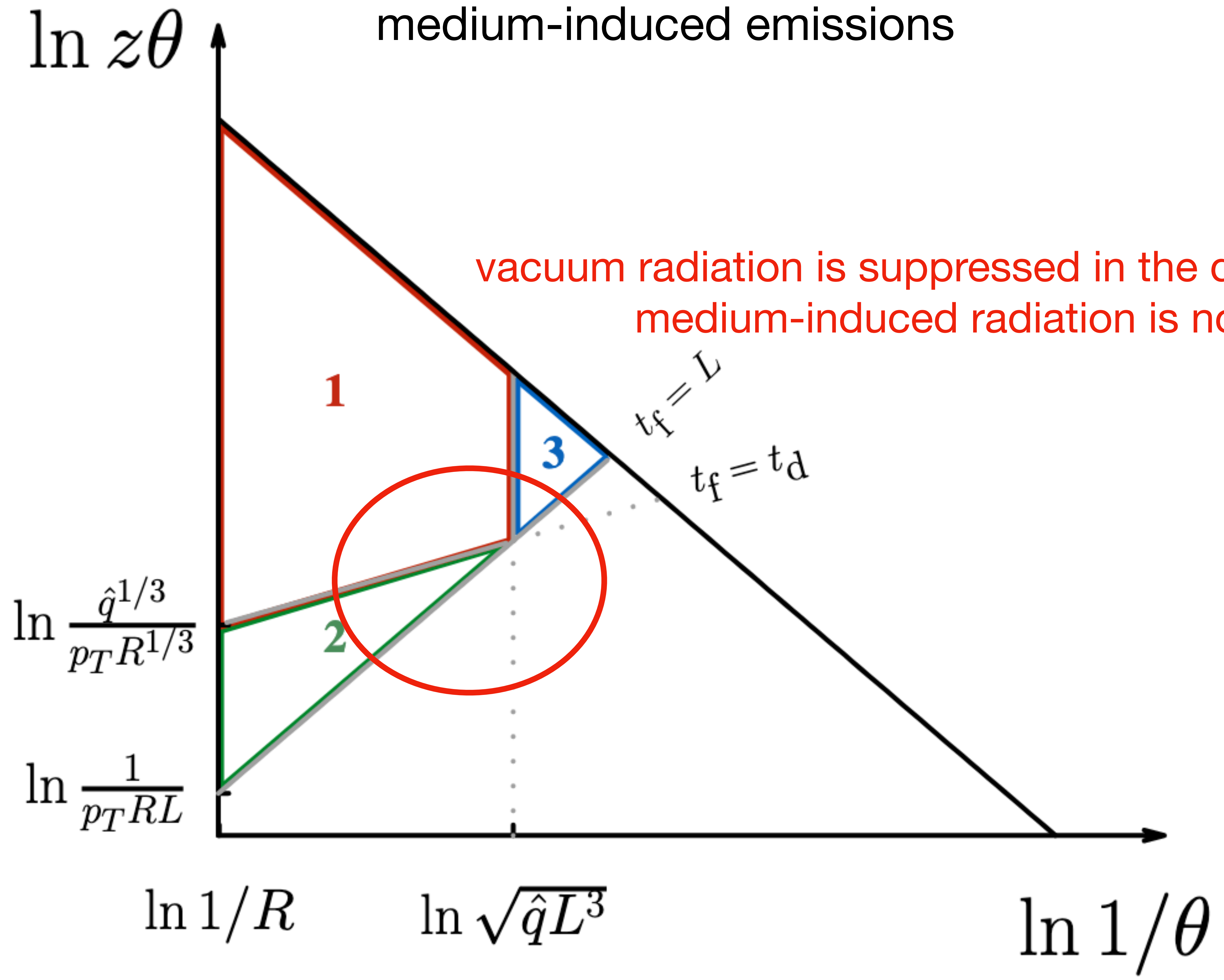
Unlike vacuum radiation, medium-induced radiation does not fill the Lund plane homogeneously



New scales appear, jet evolution embedded into a hot coloured medium of temperature T and length L
Expected dominant mechanism for jet-medium interaction: medium-induced gluon radiation

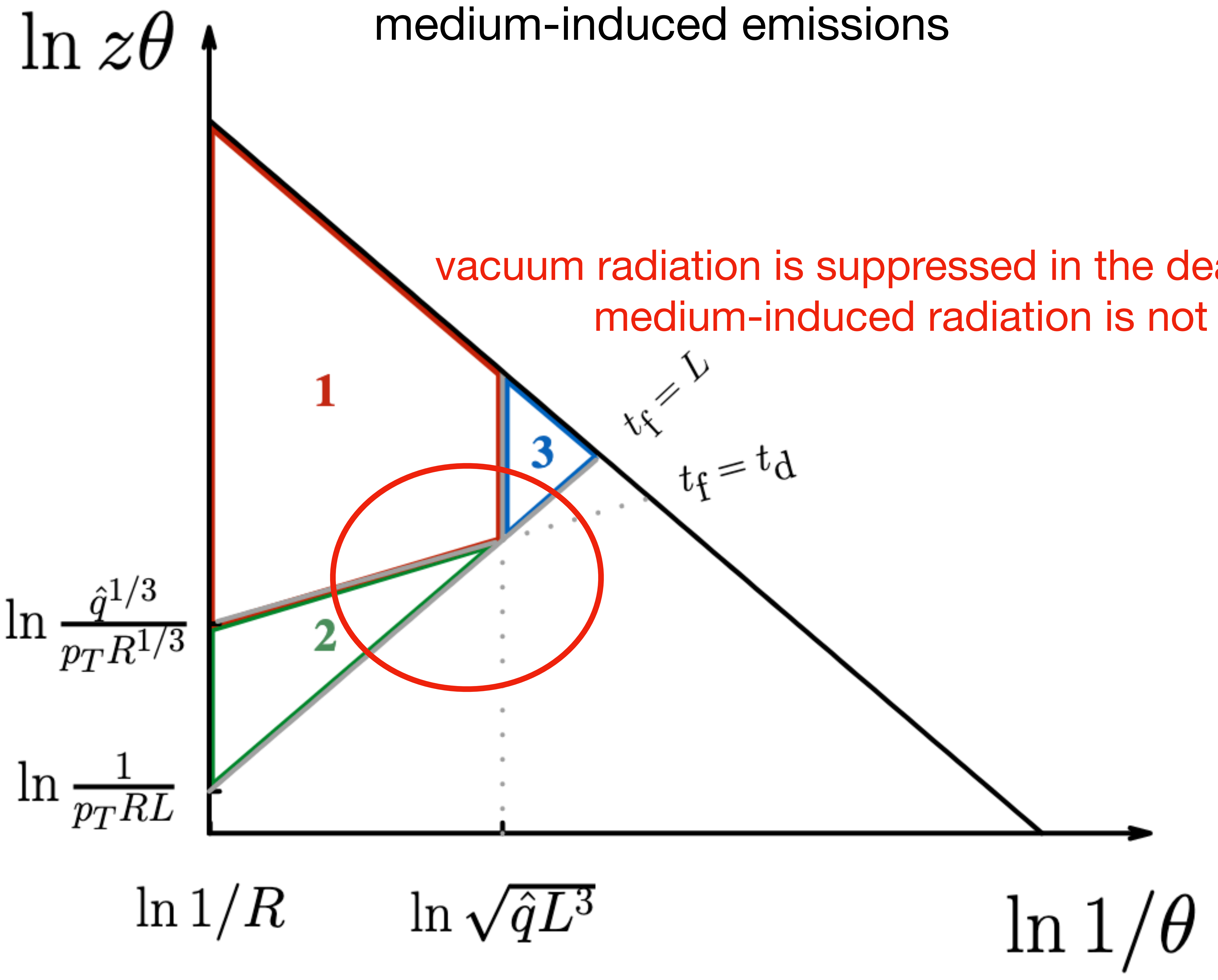
The heavy-ion case

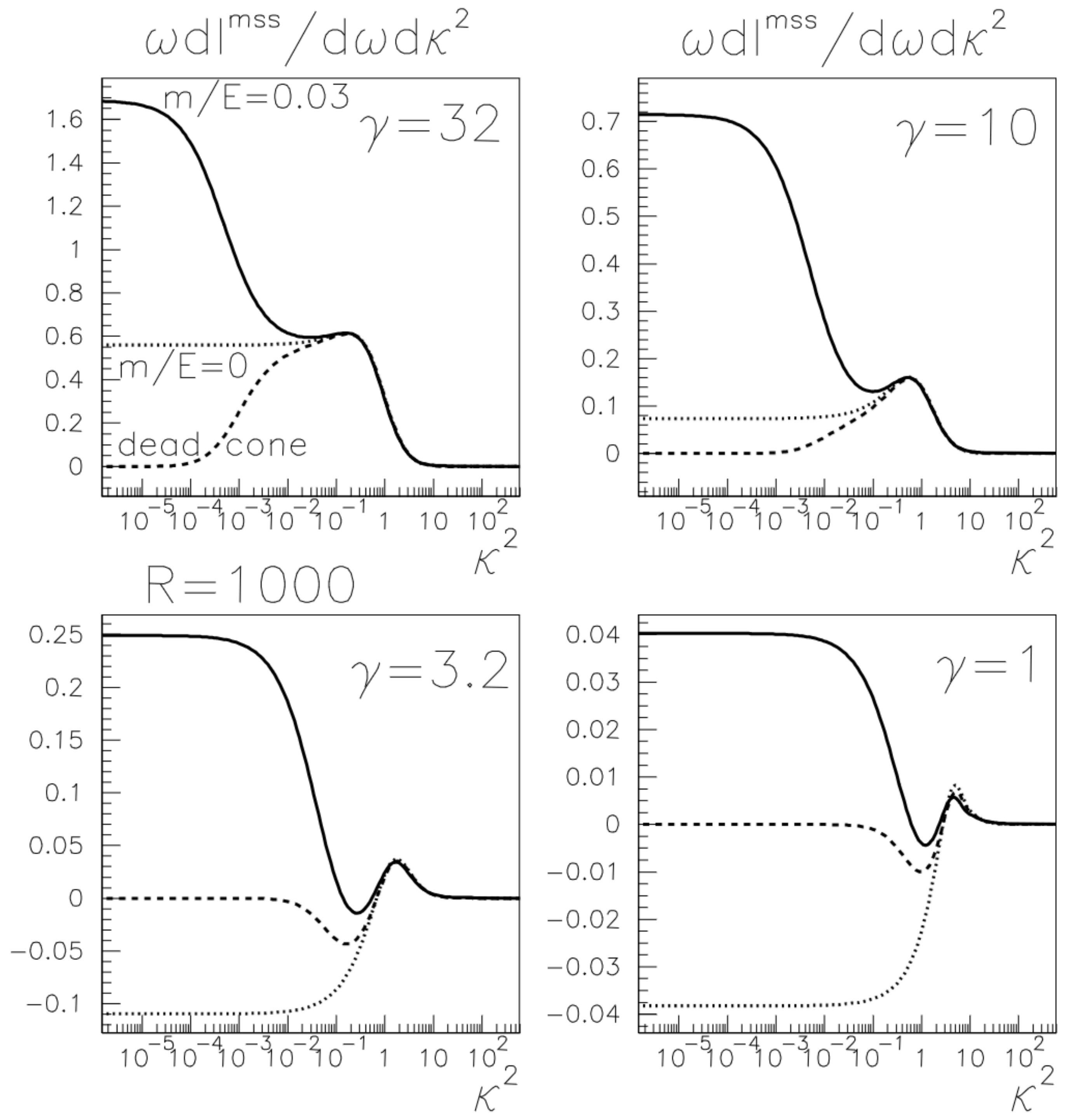
IDEA: Exploit dead-cone suppression of vacuum radiation to access a clean, pQCD regime of medium-induced emissions



The heavy-ion case

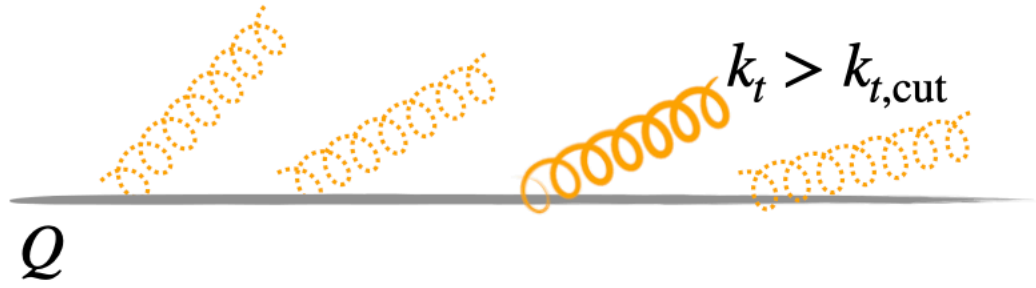
IDEA: Exploit dead-cone suppression of vacuum radiation to access a clean, pQCD regime of medium-induced emissions





Early studies showed that medium-induced gluon radiation is expected to fill the dead cone
Armesto, Salgado, Wiedemann, Phys.Rev.D 69 (2004) 114003

The dead cone in heavy-ion collisions using the jet tree: Late-k_T



In order to be sensitive to mass effects in PbPb:

Look at the region of small angles in the Lund plane
Suppress hadronisation effects
Avoid fake background splittings

Our proposal:

Select the smallest-angle perturbative emission

In practice:

Select the last splitting of the CA tree with k_T above a cutoff

The Late-k_T algorithm:

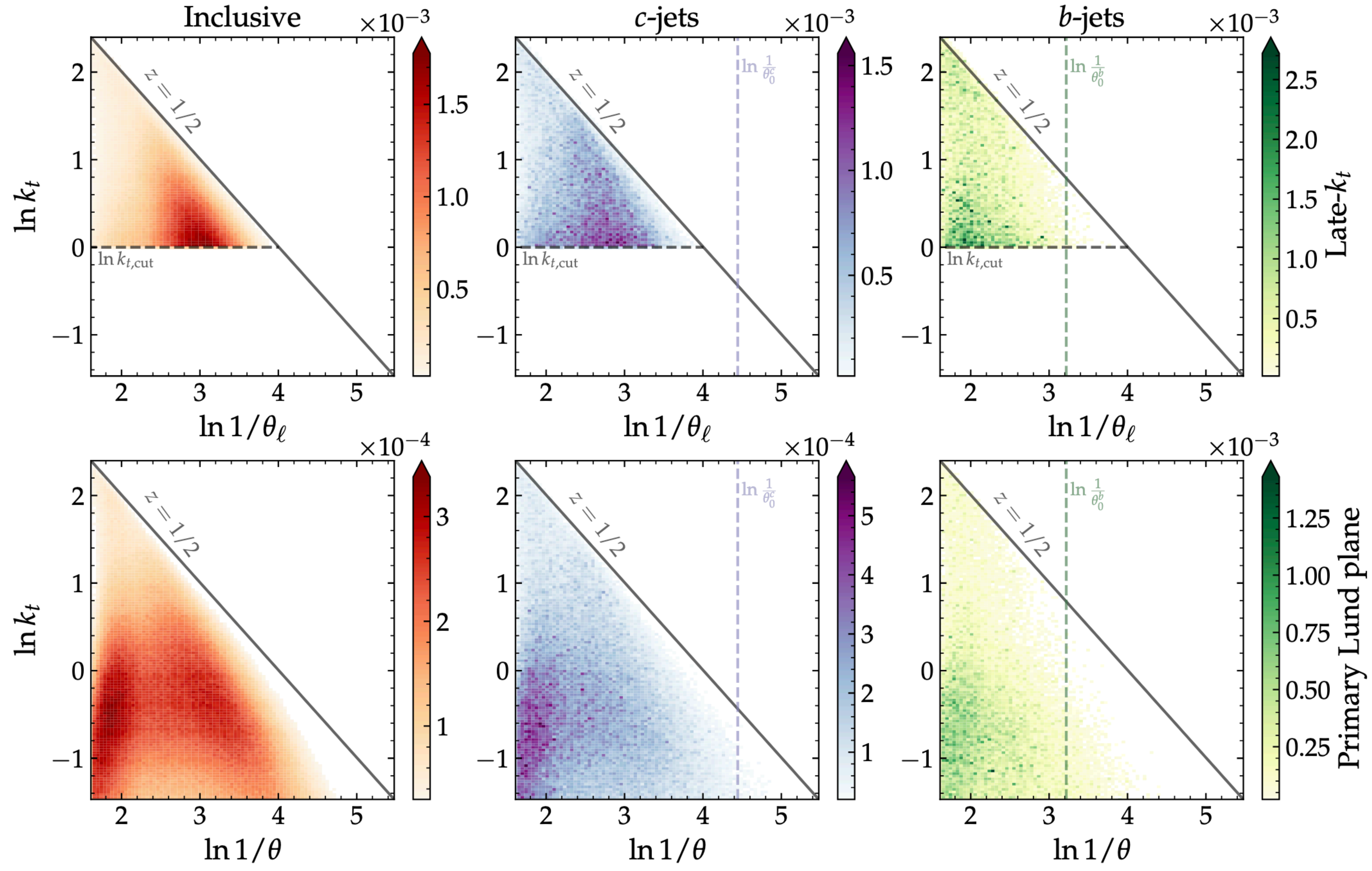
1. Undo the last clustering step in the angular ordered jet to produce two pseudojets with momenta p_a and p_b.
2. Calculate the relative k_t of the pair

$$k_t = \min(p_{t,a}, p_{t,b})\Delta_{ab}, \quad (3)$$

   with Δ^2_{ab} being the relative distance in the rapidity-azimuth plane, i.e. $\Delta^2_{ab} = (y_a - y_b)^2 + (\phi_a - \phi_b)^2$. Note that this definition coincides with the Lund-k_t variable introduced in Ref. [5].
3. Store the value of Δ_{ab} only if $k_t > k_{t,\text{cut}}$, and repeat from step 1 following the hardest branch.
4. Finally, find the minimal value in the list of Δ_{ab} values and drop all branches at larger angles, that is, prior in the C/A sequence.

The dead cone in heavy-ion collisions using the jet tree: Late-k_T

E=100 GeV, Pythia8 at hadron level



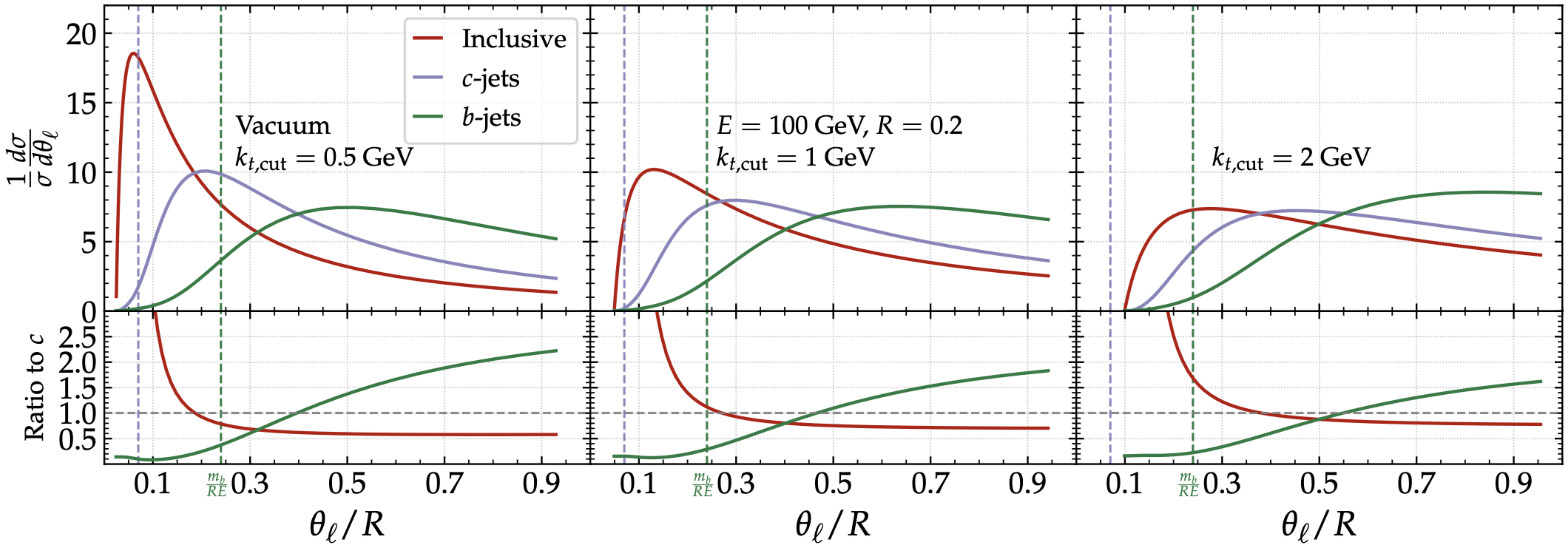
Late-k_T splittings populate the plane at small angles

The differences between the first or the last splitting above cutoff are smaller for the higher quark mass due to the reduced phase space

Dashed lines represent the dead cone of the first splitting in the massive cases (minimum dead cone i the shower)

The dead cone in heavy-ion collisions using the jet tree: Late-k_T

vacuum

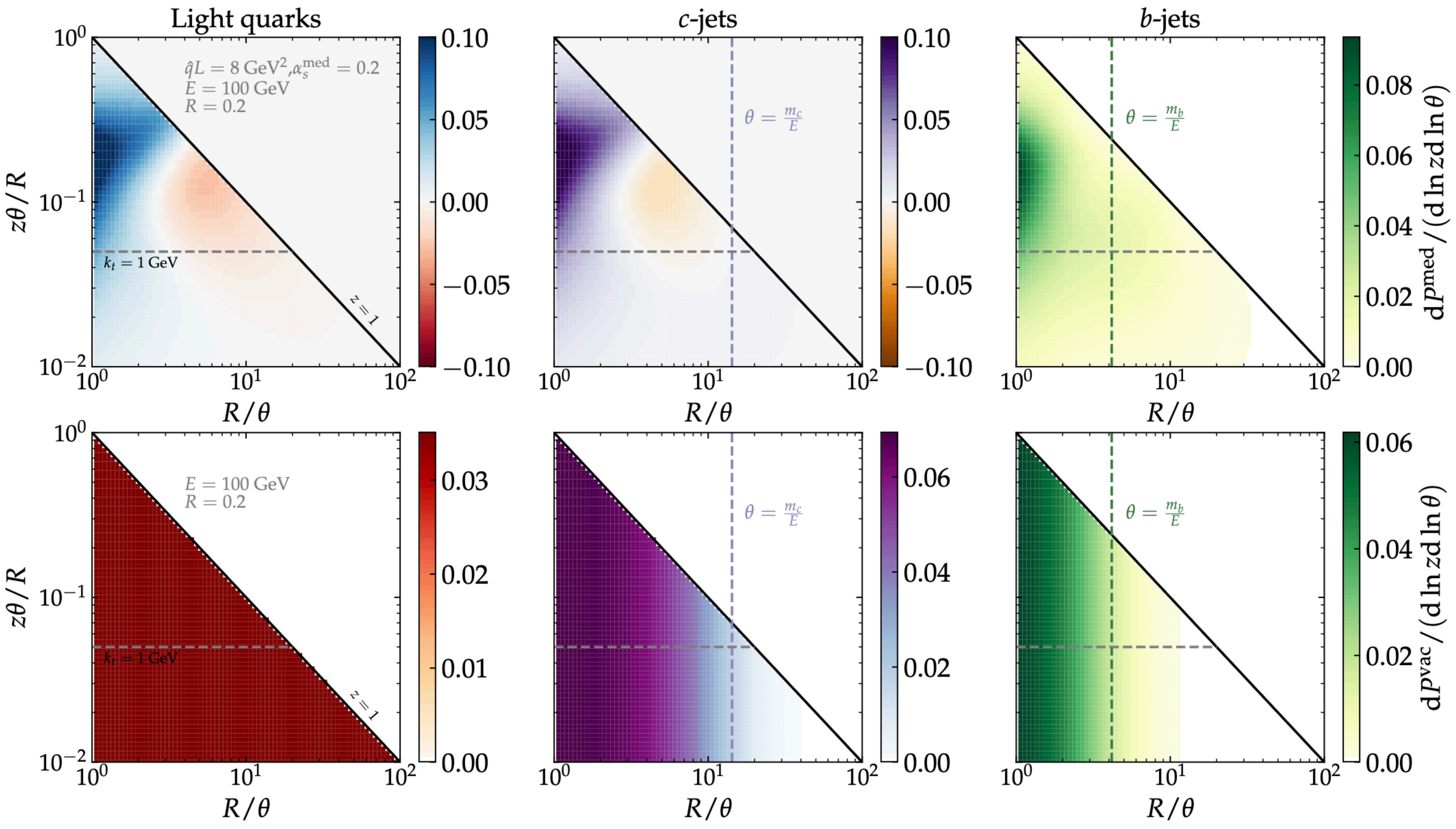


$$\frac{1}{\sigma}\frac{\mathrm{d}\sigma}{\mathrm{d}\theta_\ell} = \frac{1}{1-\Sigma(R)}\int_0^1 \mathrm{d}z \mathcal{P}_i(z,\theta_\ell)\Theta(z\theta_\ell - \bar{k}_{t,\mathrm{cut}})\,\Sigma(\theta_\ell),$$

Proof of principle: analytical vacuum calculation at modified leading log accuracy
Clear separation power for inclusive, c and b jets
k_T,cut can be optimized: separation power vs suppression of hadronisation
Dashed lines indicate position of the dead cone angle of the first splitting of the jet tree

The dead cone in heavy-ion collisions using the jet tree: Late-k_T

Lund plane filled by medium-induced radiation



Radiation clumps around typical transverse momentum scale acquired by diffusion in transverse space $Q_s^2=\hat{q}$ L
(L is the medium length and $\hat{q}$ is the transport coefficient of the QGP)

Medium induced radiation in b-jets is filling region that is empty in vacuum, mostly soft gluons at small angles

Simplified medium model: static brick of length L, difusion parameter $\hat{q}$
multiple soft scattering limit

The dead cone in heavy-ion collisions using the jet tree: Late-k_T

Interesting interplay of scales

$$\theta_C < \theta < \theta_{dead}$$

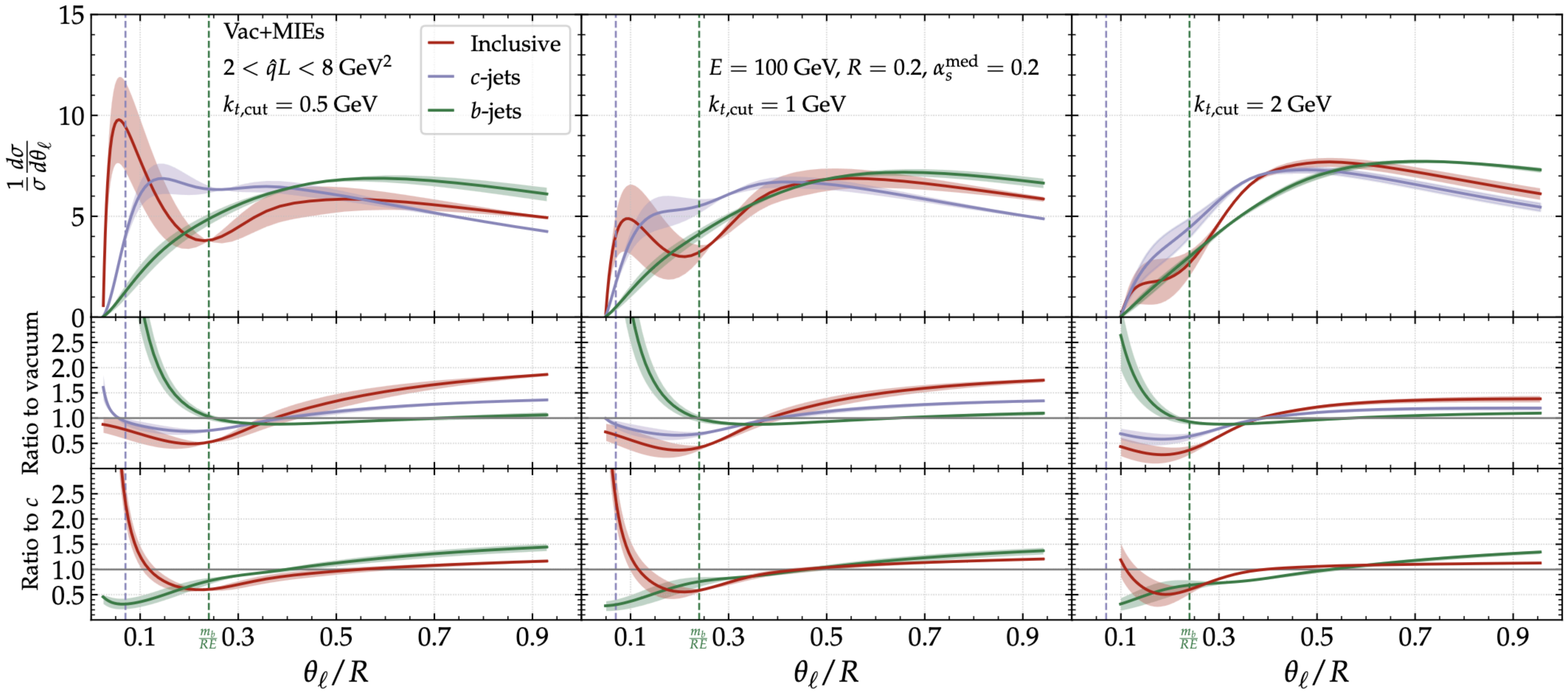
with θ_C the minimal decoherence angle $\theta_C \approx 1/\sqrt{(\hat{q}L^3)}$

The dead cone angle needs to be wider than the decoherence angle for it to be filled with medium emission

For our choice of parameters, kinematic cuts and approximations:

minimum dead cone angle for D remains intact $\theta_{dead}^{charm} < \theta_C$
minimum dead cone angle for B gets filled $\theta_{dead}^{beauty} > \theta_C$

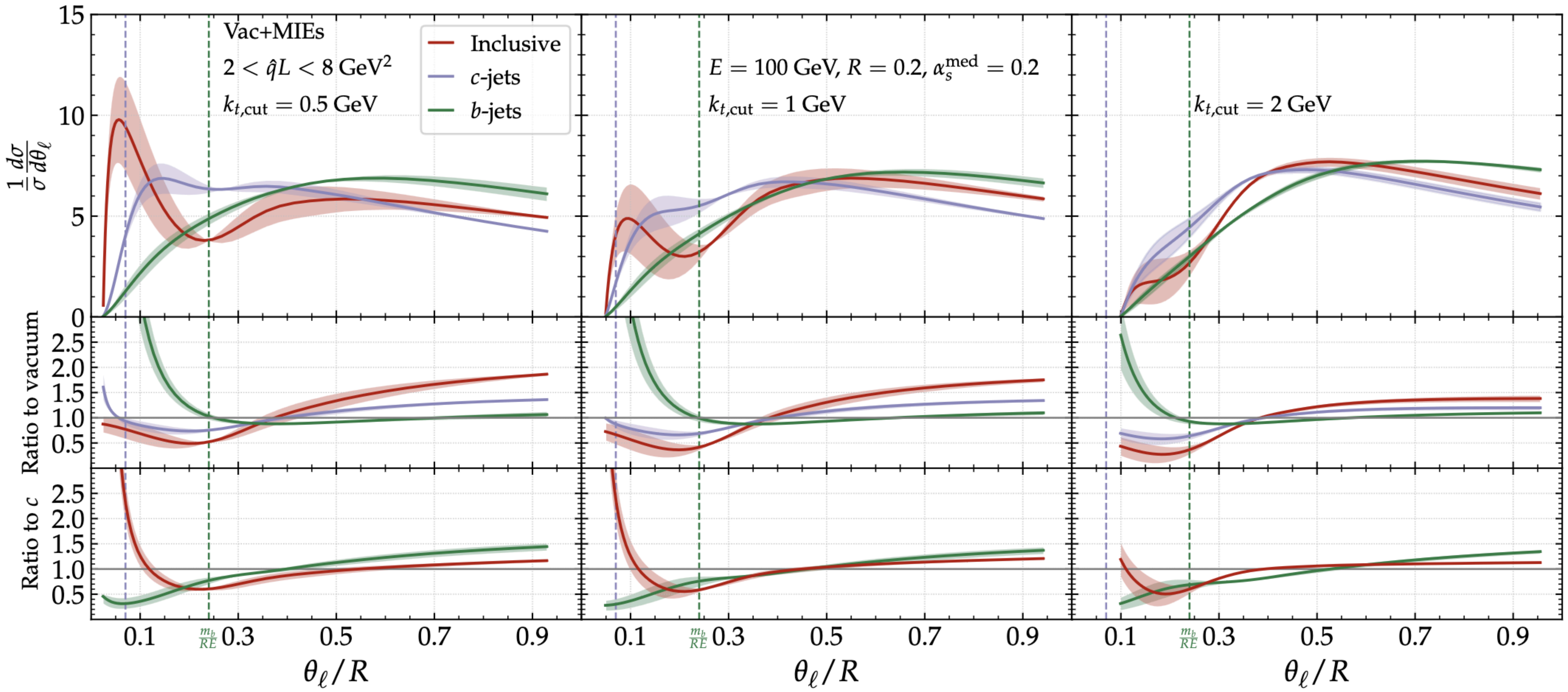
The dead cone in heavy-ion collisions using the jet tree: Late-k_T



The splitting angle selected by late-k_T, θ_l, shows a strong enhancement of medium-induced collinear radiation relative to vacuum at small angles for b-jets. Detectable!

D-jets and inclusive jets show transverse momentum broadening

The dead cone in heavy-ion collisions using the jet tree: Late-k_T

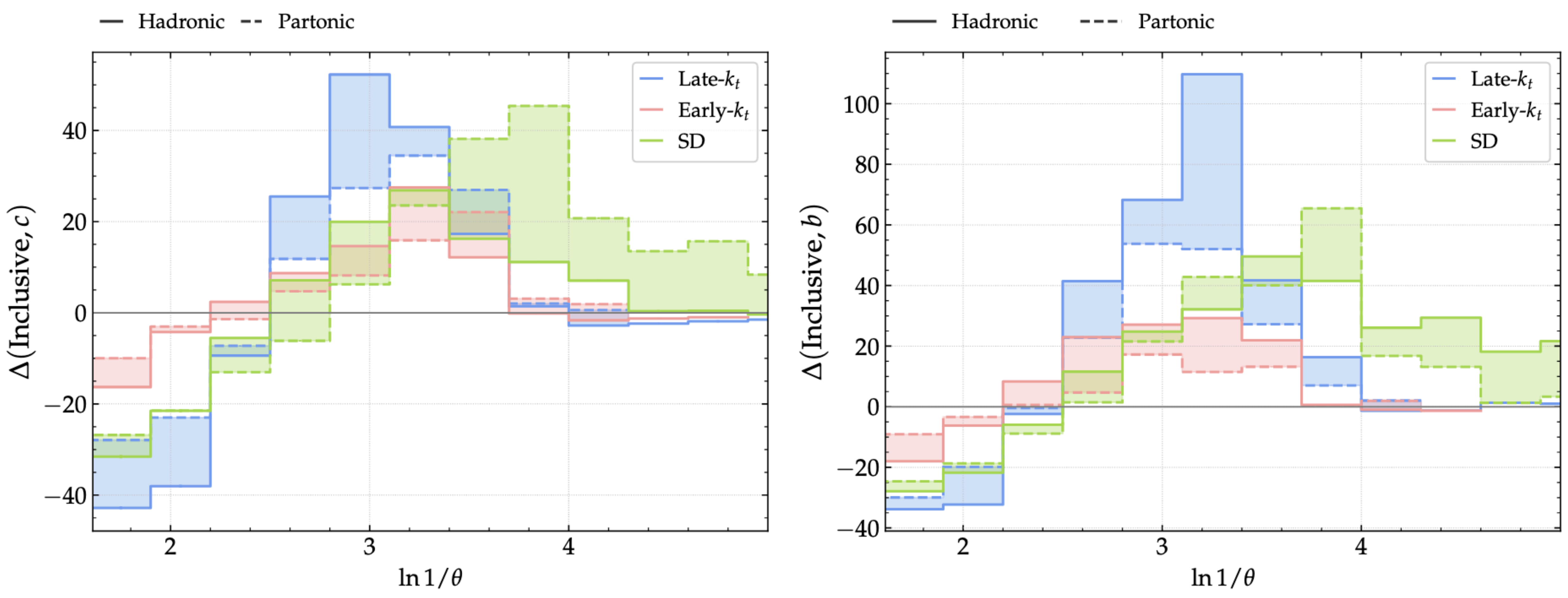


Note: qualitative picture that arises from the interplay of scales

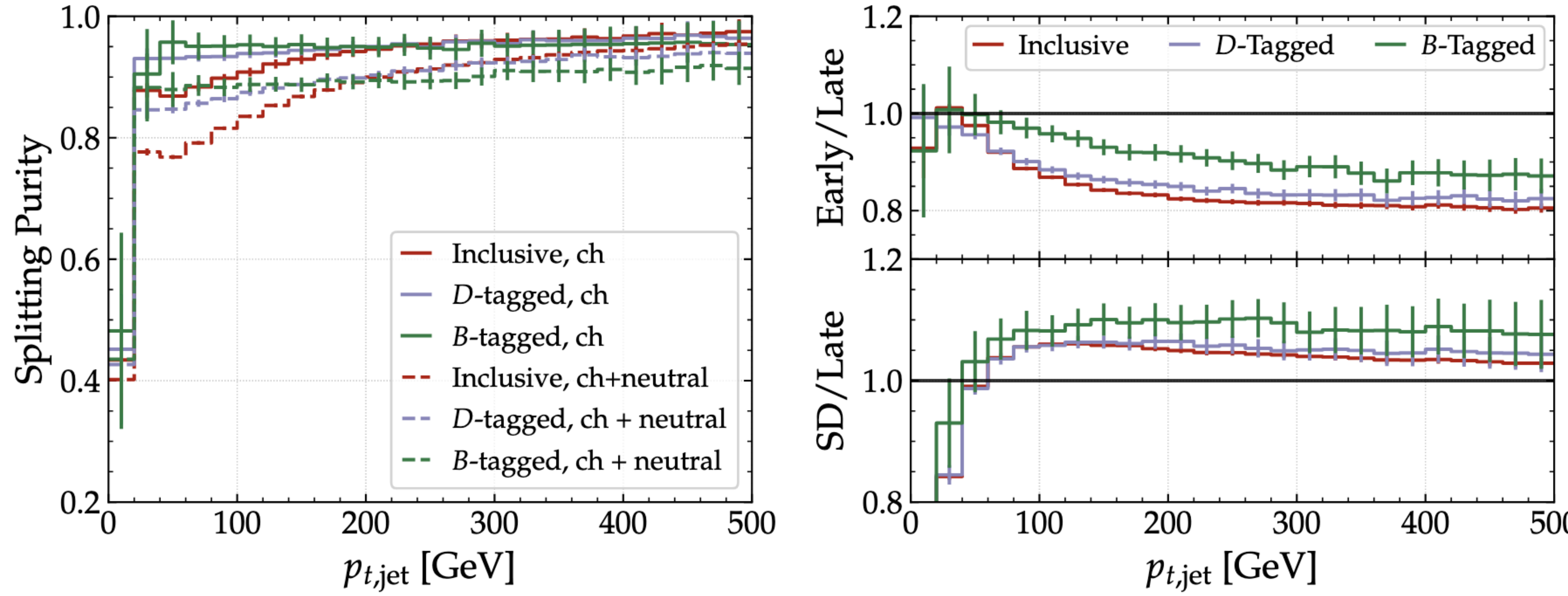
The impact of energy loss not taken into account. Color coherence dynamics can narrow all θ_l distributions!

Separation power and resilience of Late-k_T

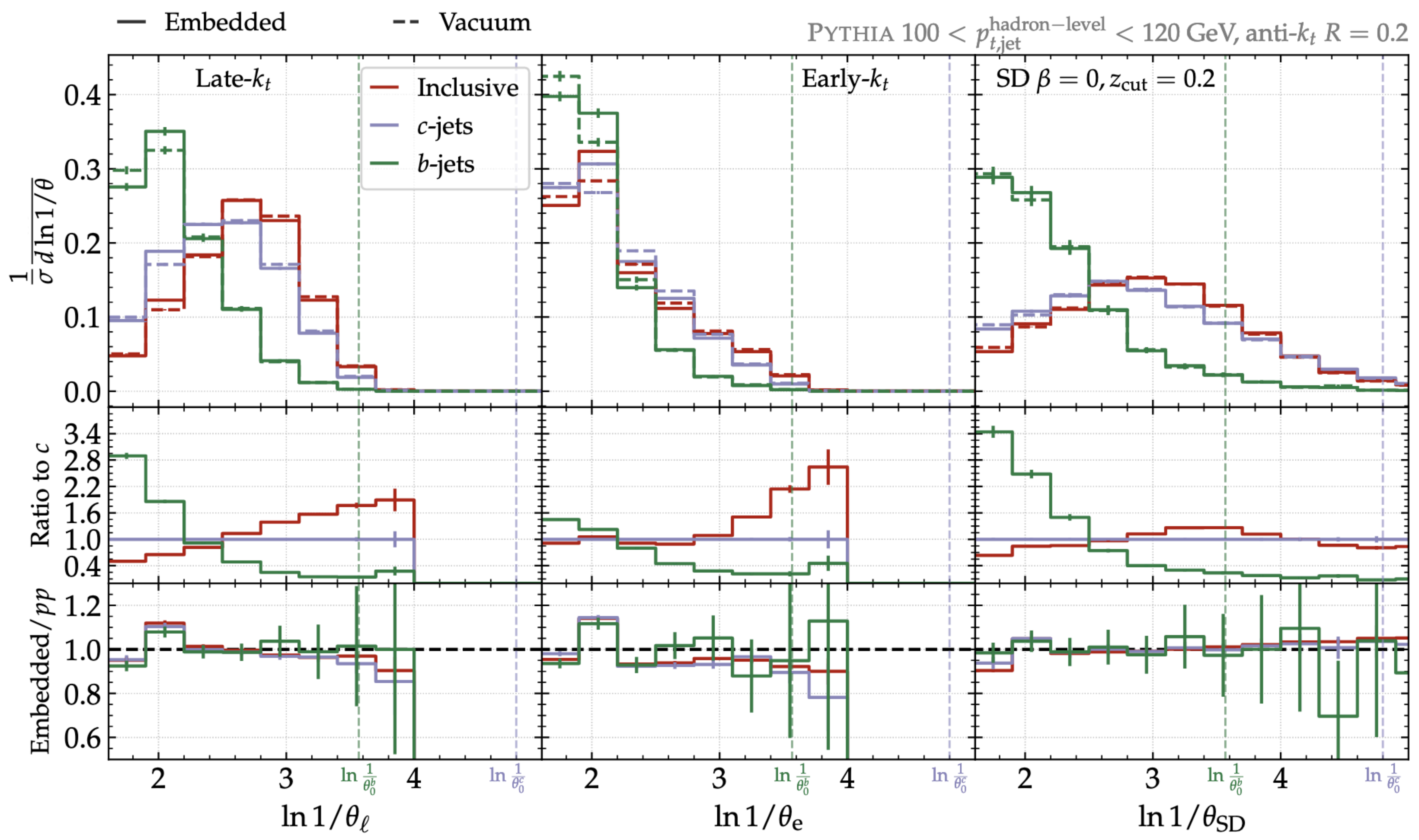
Separation power at parton and hadron level



Splitting purity



Resilience to heavy ion background



The dead-cone effect: Summary

The iterative clustering of the jet tree has given direct access to the dead cone in pp collisions

Fully corrected measurements of the Lund plane of heavy-flavour jets will allow quark mass and quark energy scans of the effect

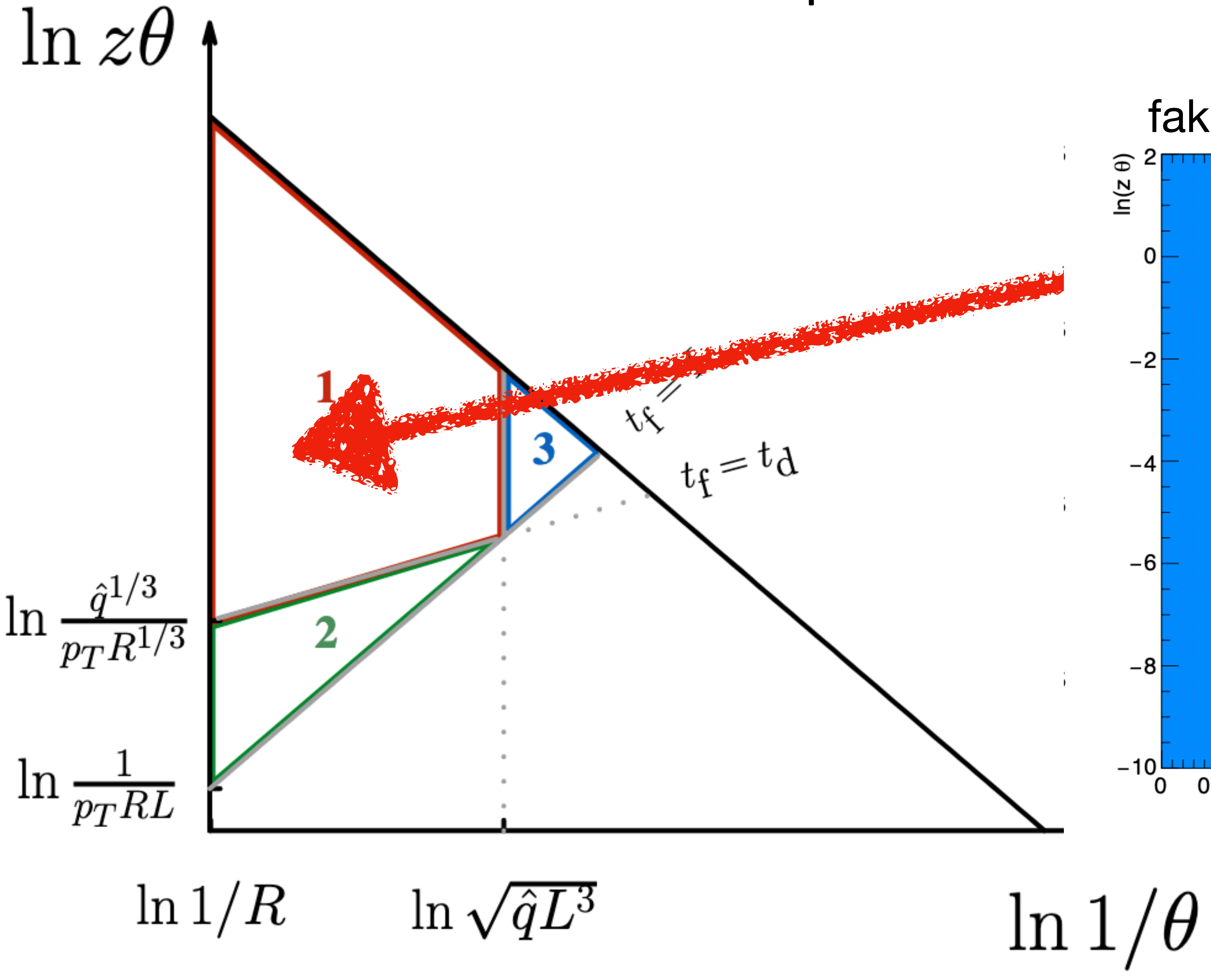
Interesting prospects for heavy ion collisions: use the dead cone as a region to isolate QGP-induced signal

The filling of the D and B dead cones in medium is dictated by the interplay of their dead cone angles and the decoherence angle

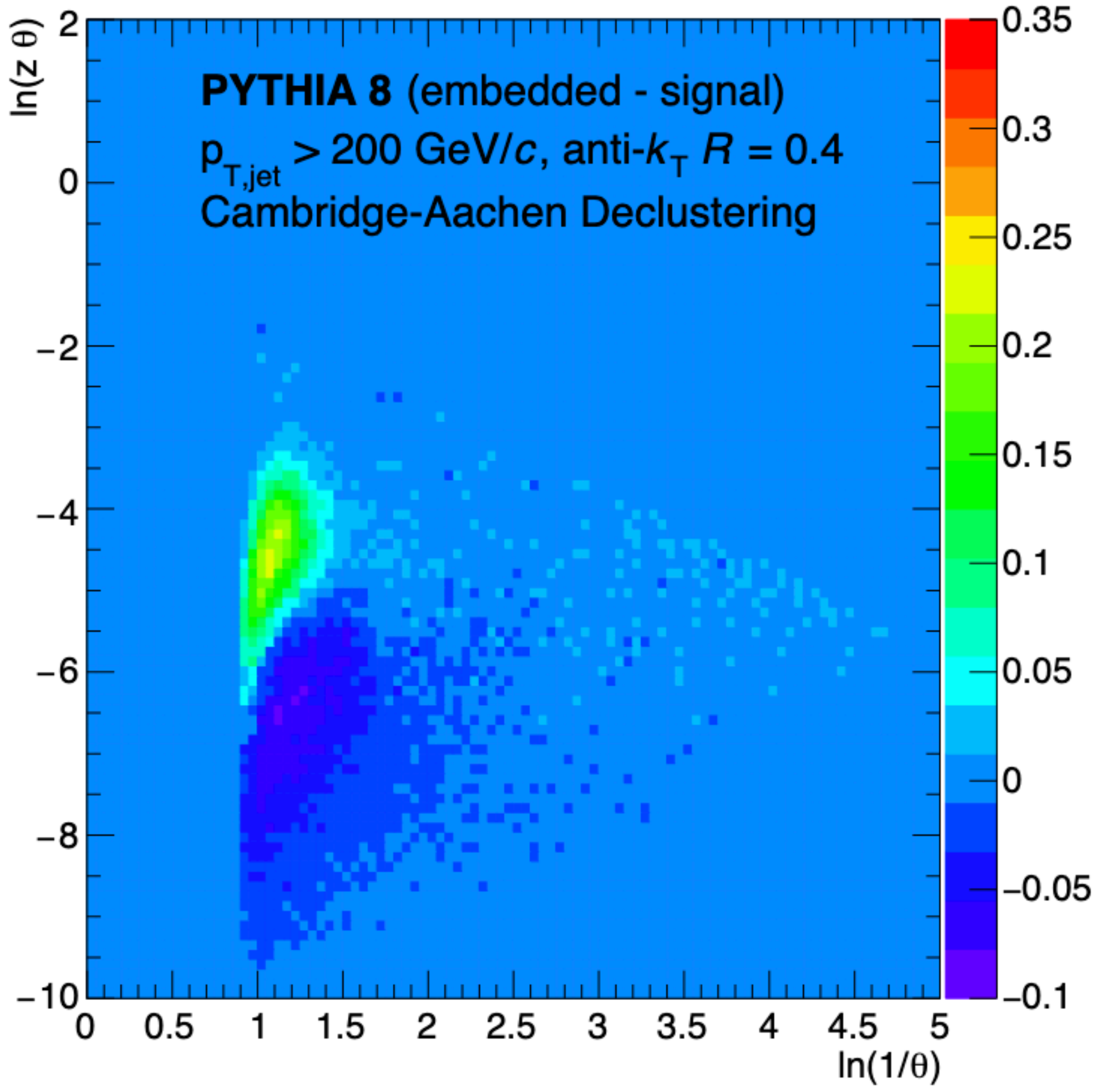
Such interplay is experimentally testable and we have proposed a strategy and an observable

The heavy-ion case: distortion of the jet tree

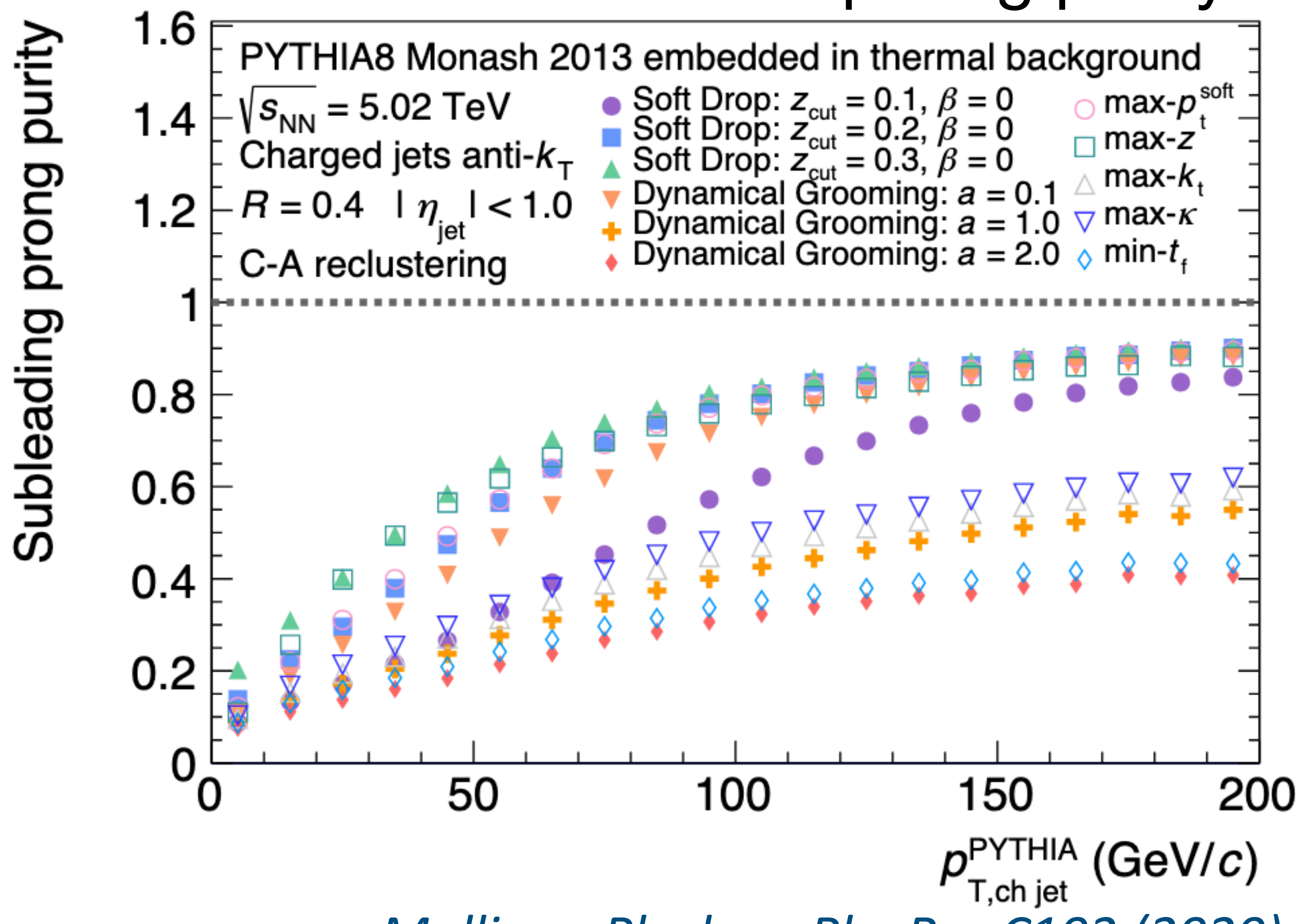
Main problem: combinatorial background from the large underlying event



fake splittings at large angles



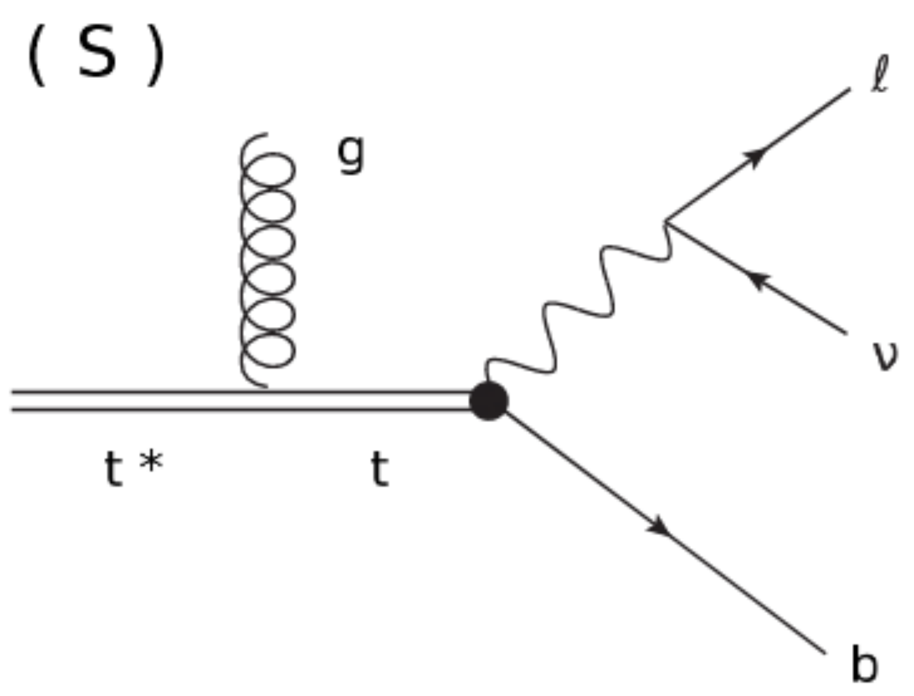
low splitting purity



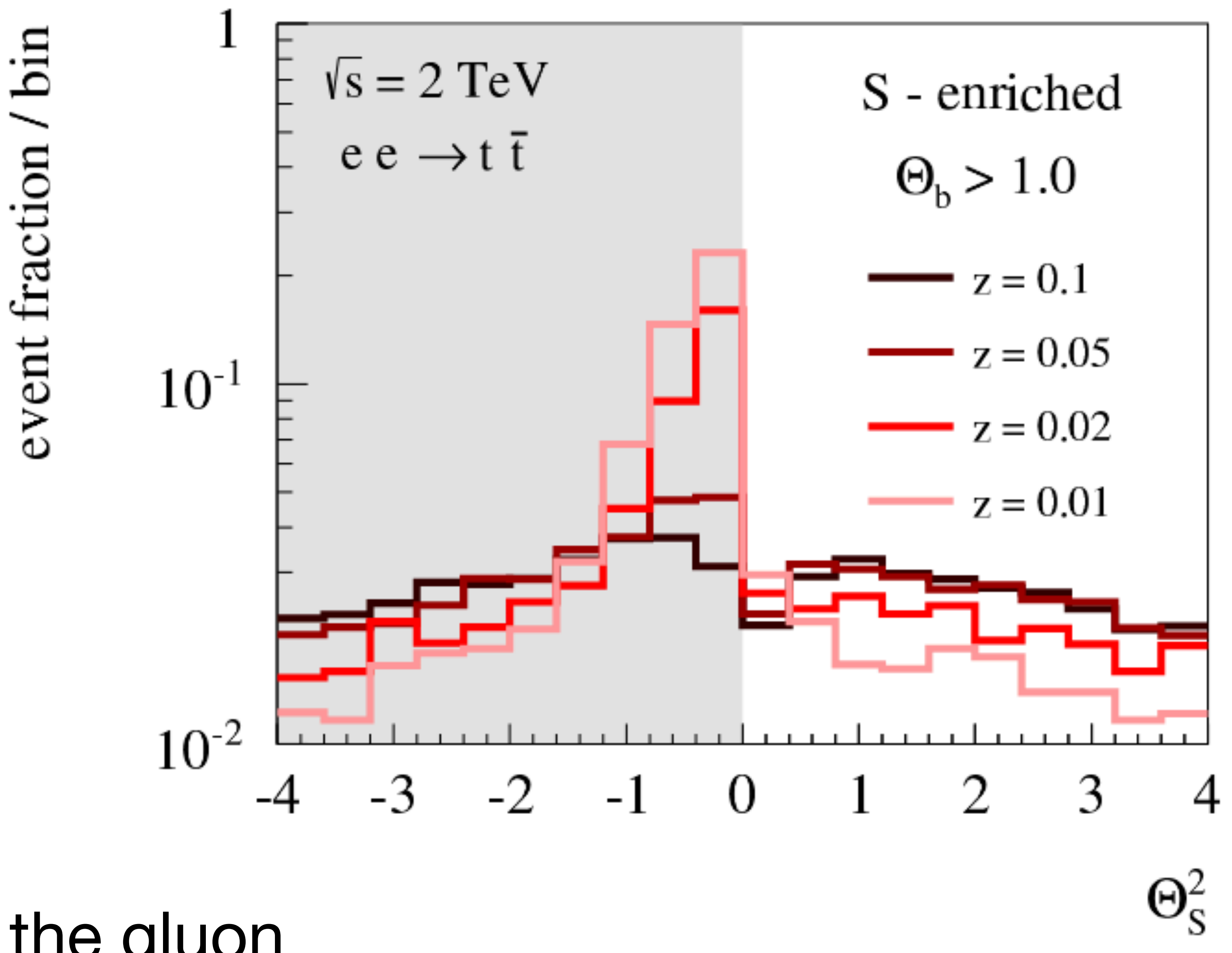
.Mulligan,Ploskon, Phs.Rev.C102 (2020)

The underlying event creates fake subleading prongs at large angles (where area is maximal)
Full measurement of the Lund plane problematic

The dead cone for heavier quarks: top quarks using SoftDrop



Focus on: a top quark can emit a FSR gluon before decaying into a lepton, neutrino and b-jet



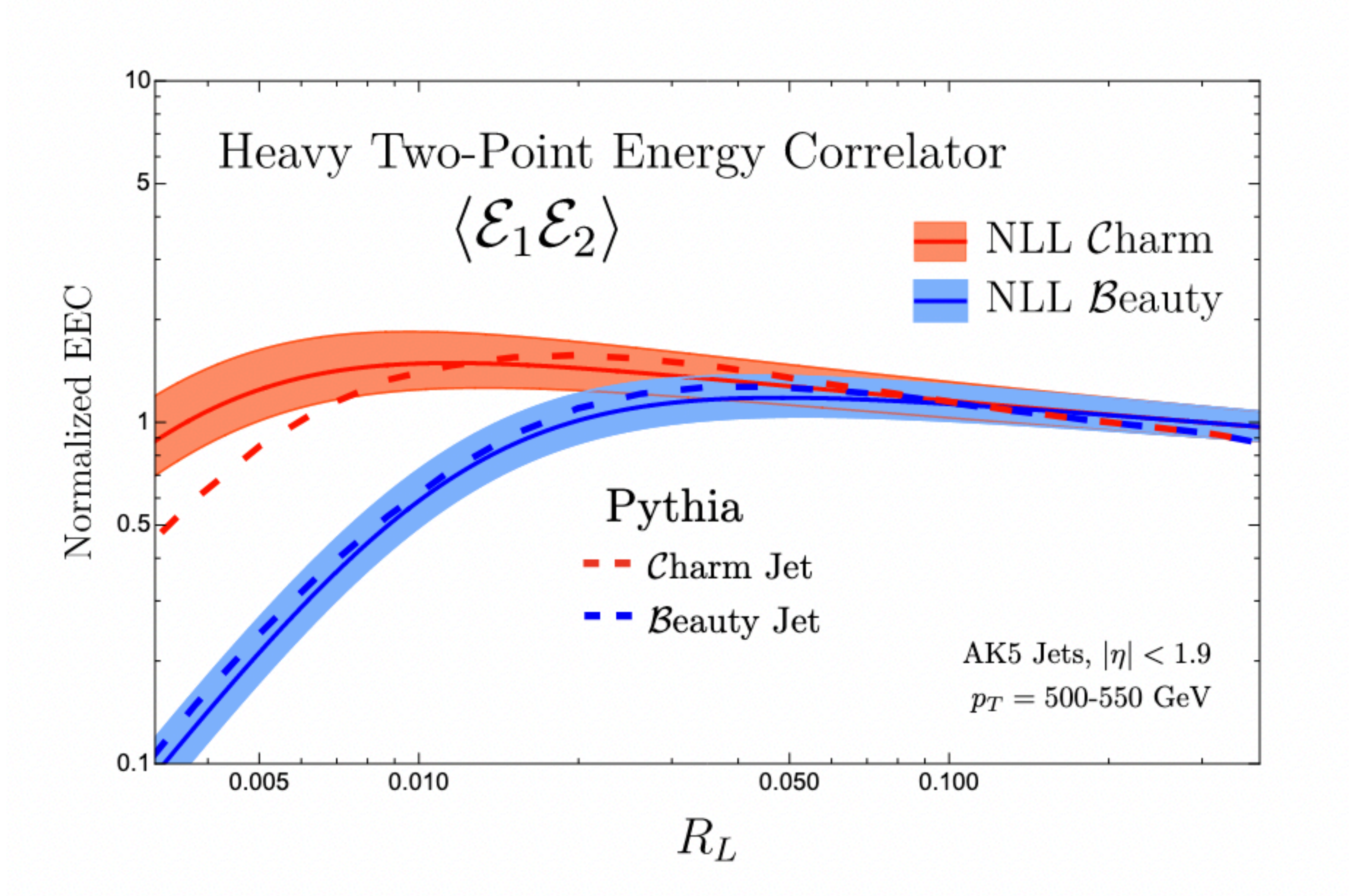
SoftDrop leading prong is b-tagged, subleading prong is proxy for the gluon

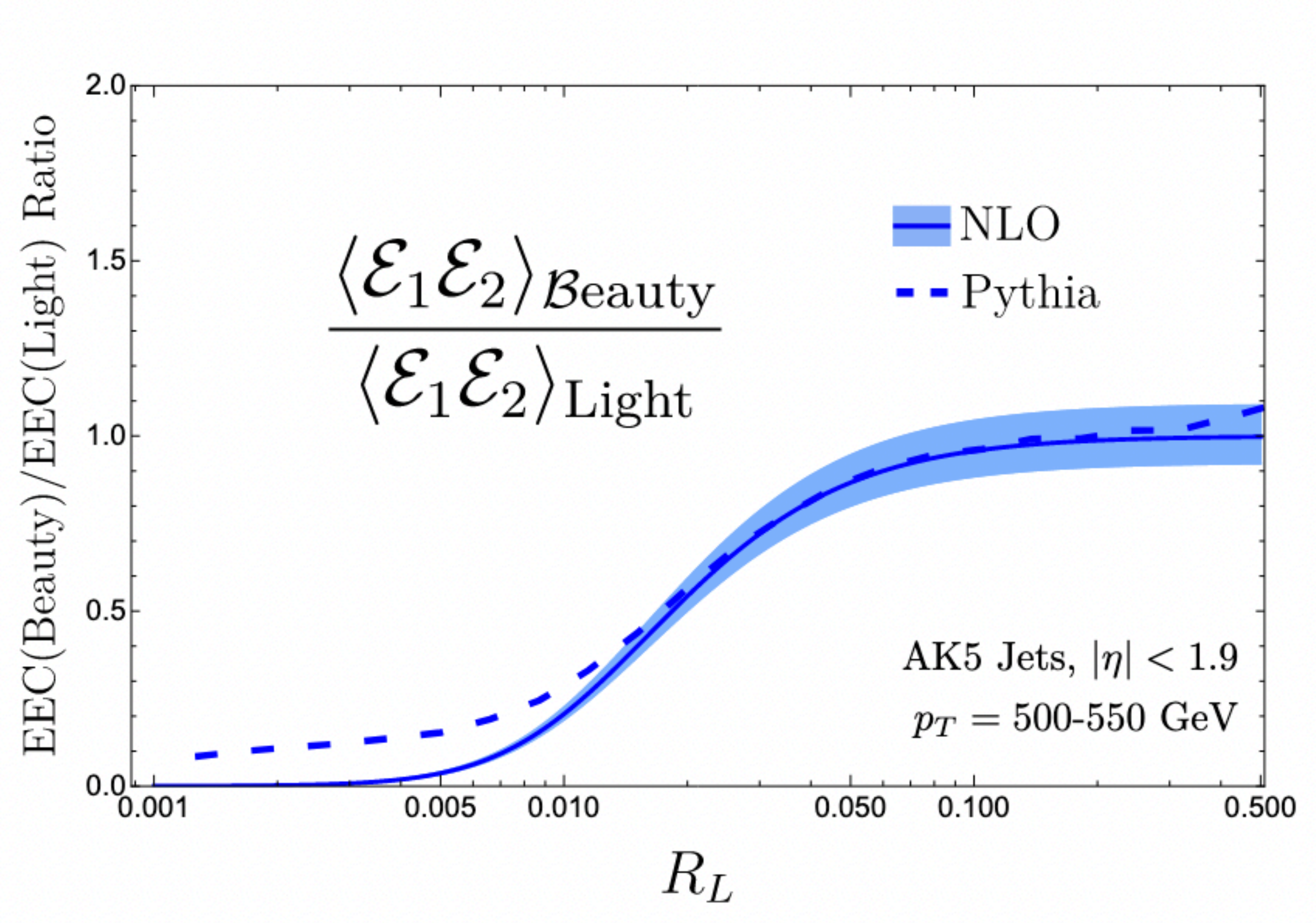
Main difficulty: separating radiation from the b and the top quarks and suppression of the background process where the on-shell top decays

for $z=p_{Tg}/p_{Tt}>0.05$, dead cone suppression in the region of $\Theta_S<1$

Maltoni, Selvaggi, Thaler, Phys.Rev.D 94 (2016) 4, 054-15

The dead-cone effect, searches using the energy-energy correlators



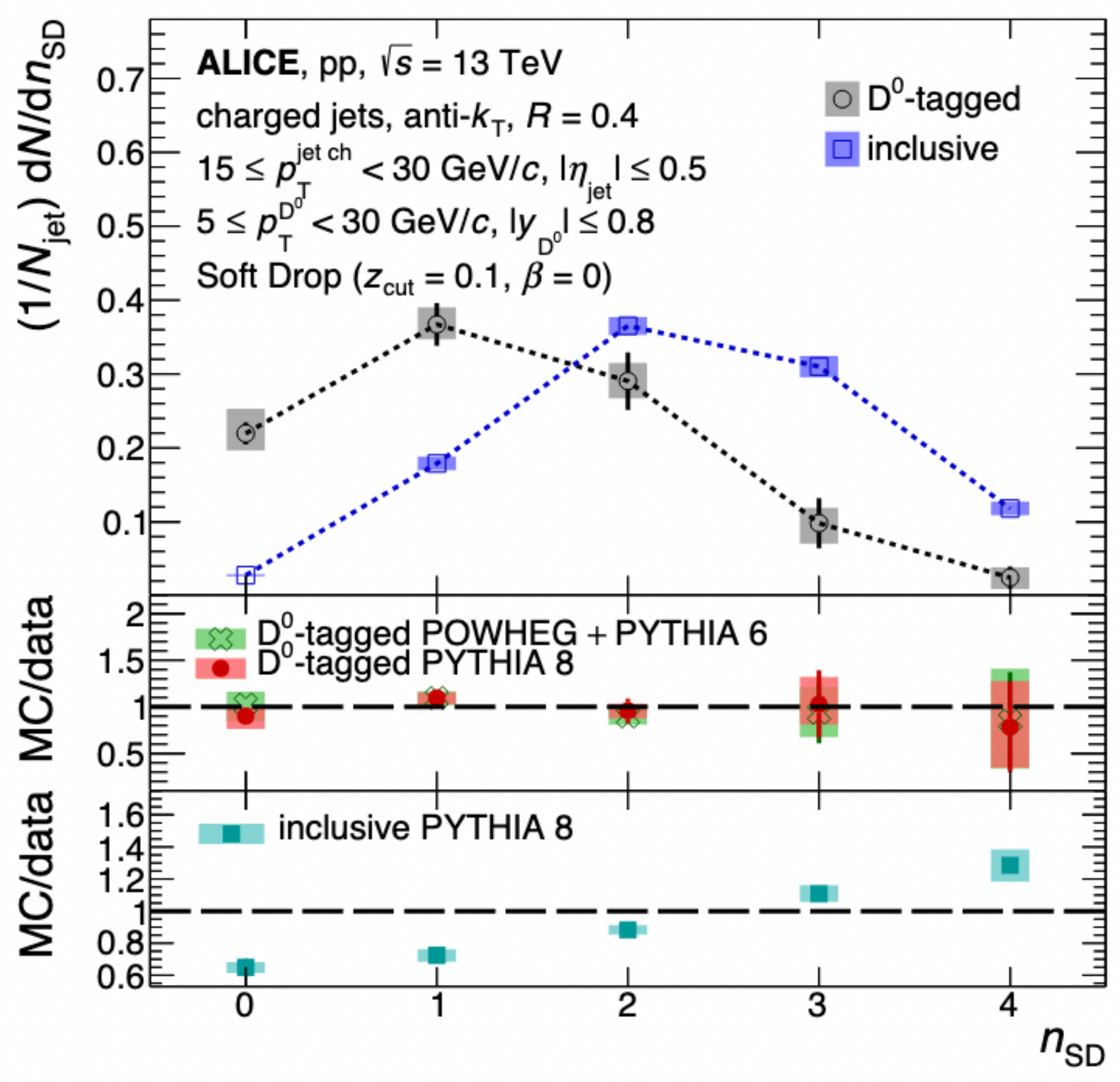


First NLL calculation of a heavy-flavoured jet substructure observable in pp collisions
Clear suppression of small angles for b-jets, same scaling behaviour as massless for large angular scales

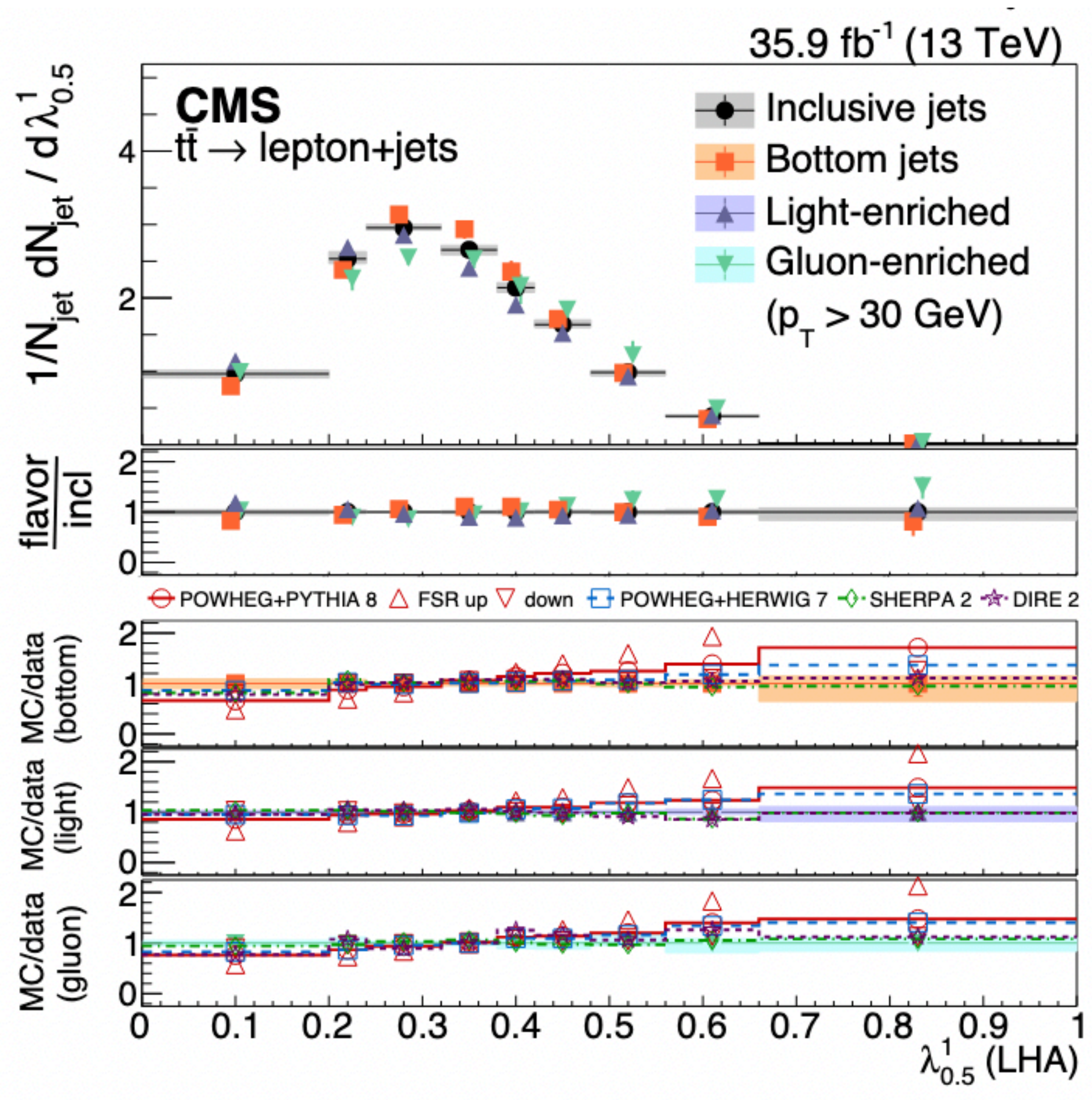
Craft, Lee, Mecca, Moult, [2210.09311]

Indirect measurements of the dead cone: a selection

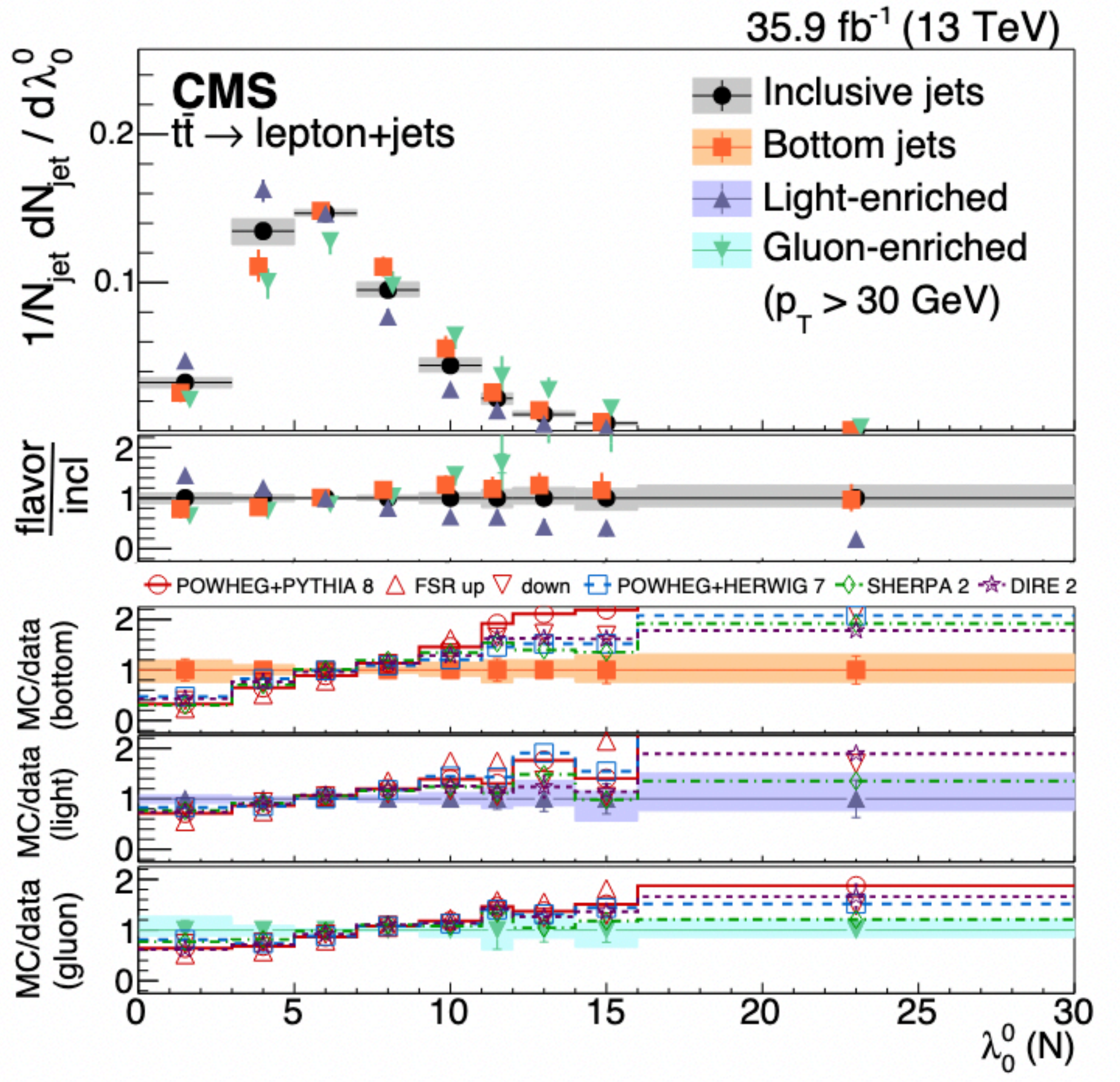
Number of hard prongs



intrajet multiplicity



Angularity



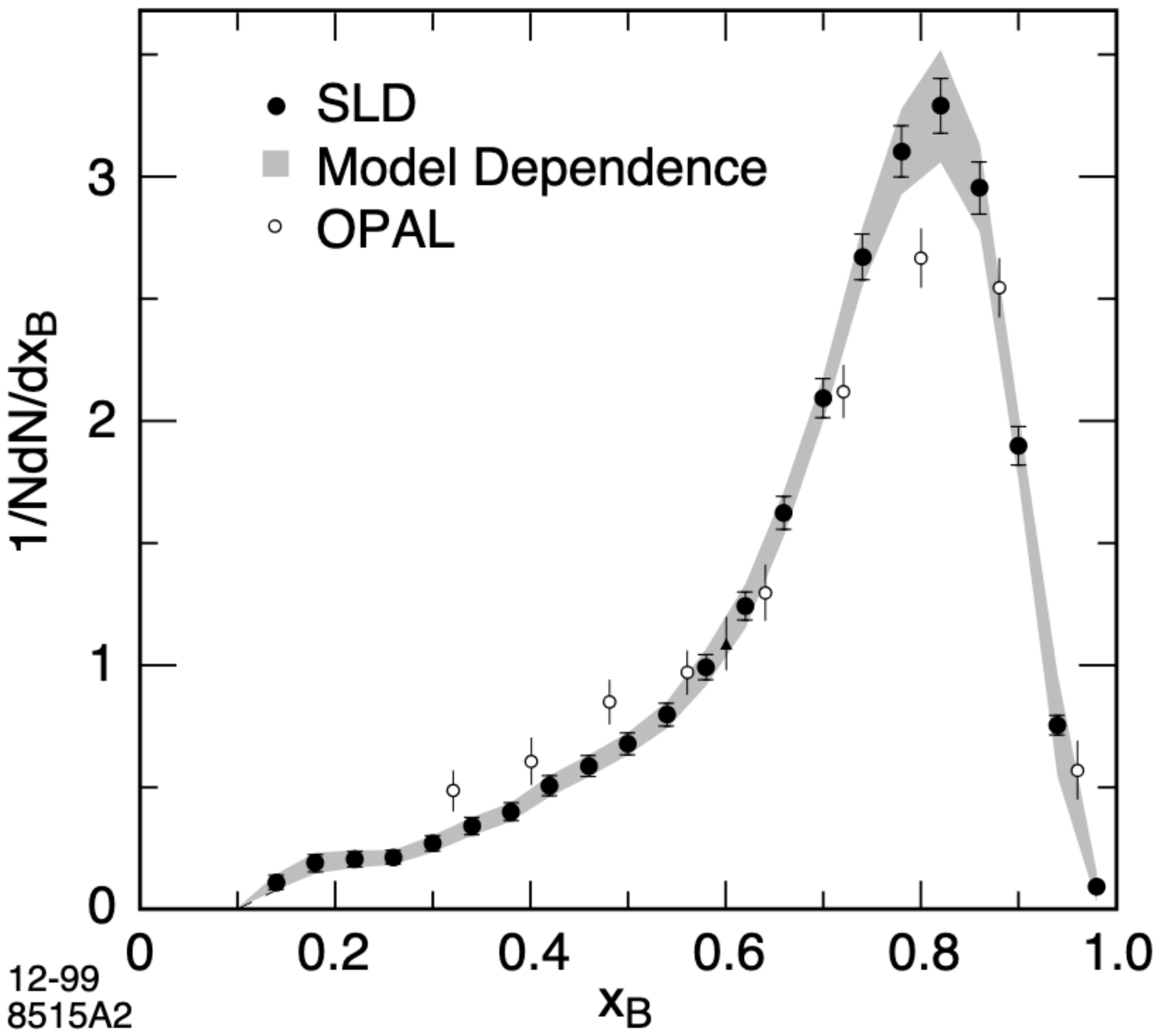
Lower intrajet multiplicities (measured via the number of SoftDrop prongs) in D-jets
Comparison to inclusive includes q/g differences

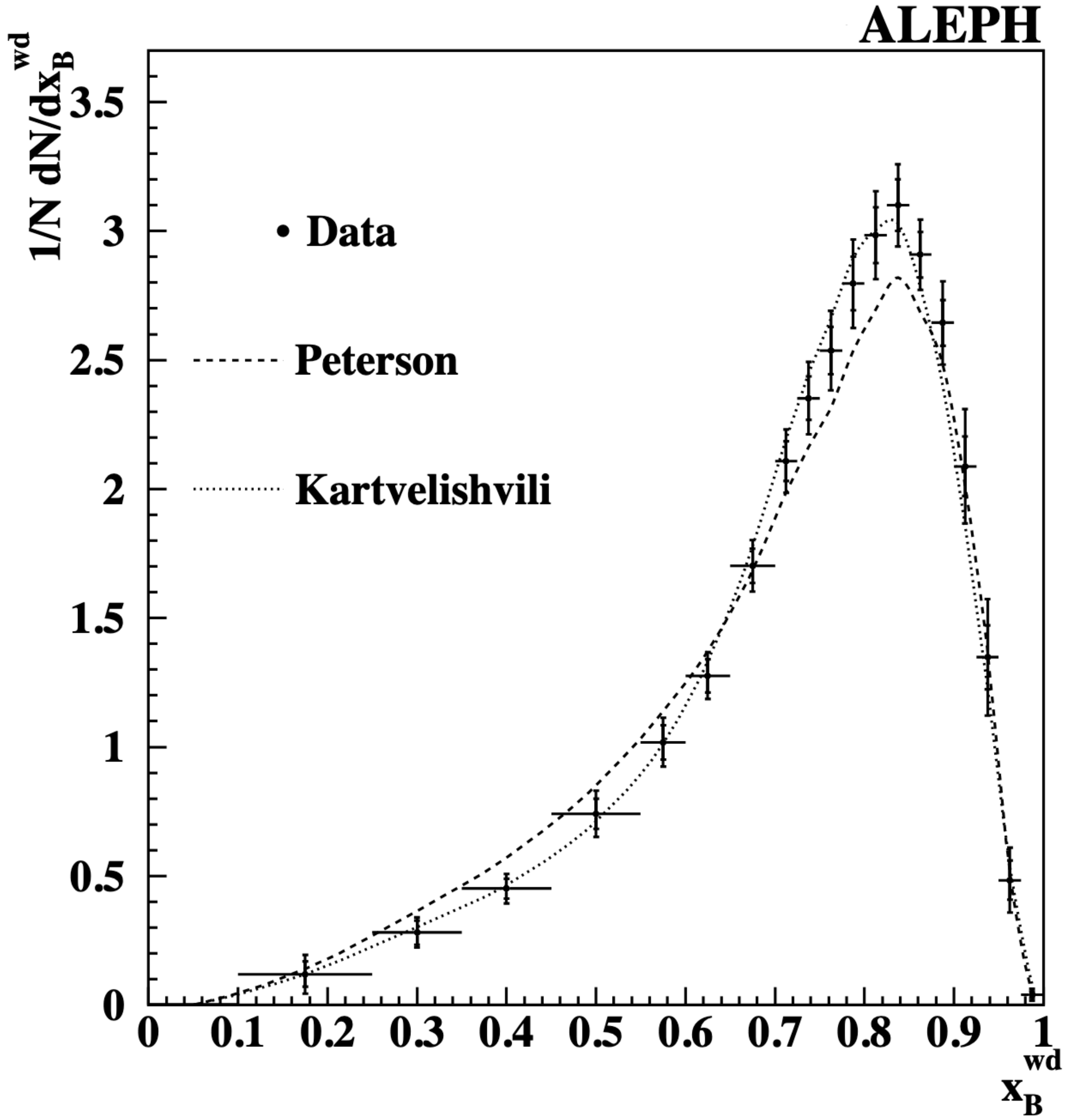
Bottom jet multiplicity and angularity very similar to inclusive's
Light-enriched jets have smaller multiplicities than b-jets
Impact of the heavy flavour hadron decay daughters?

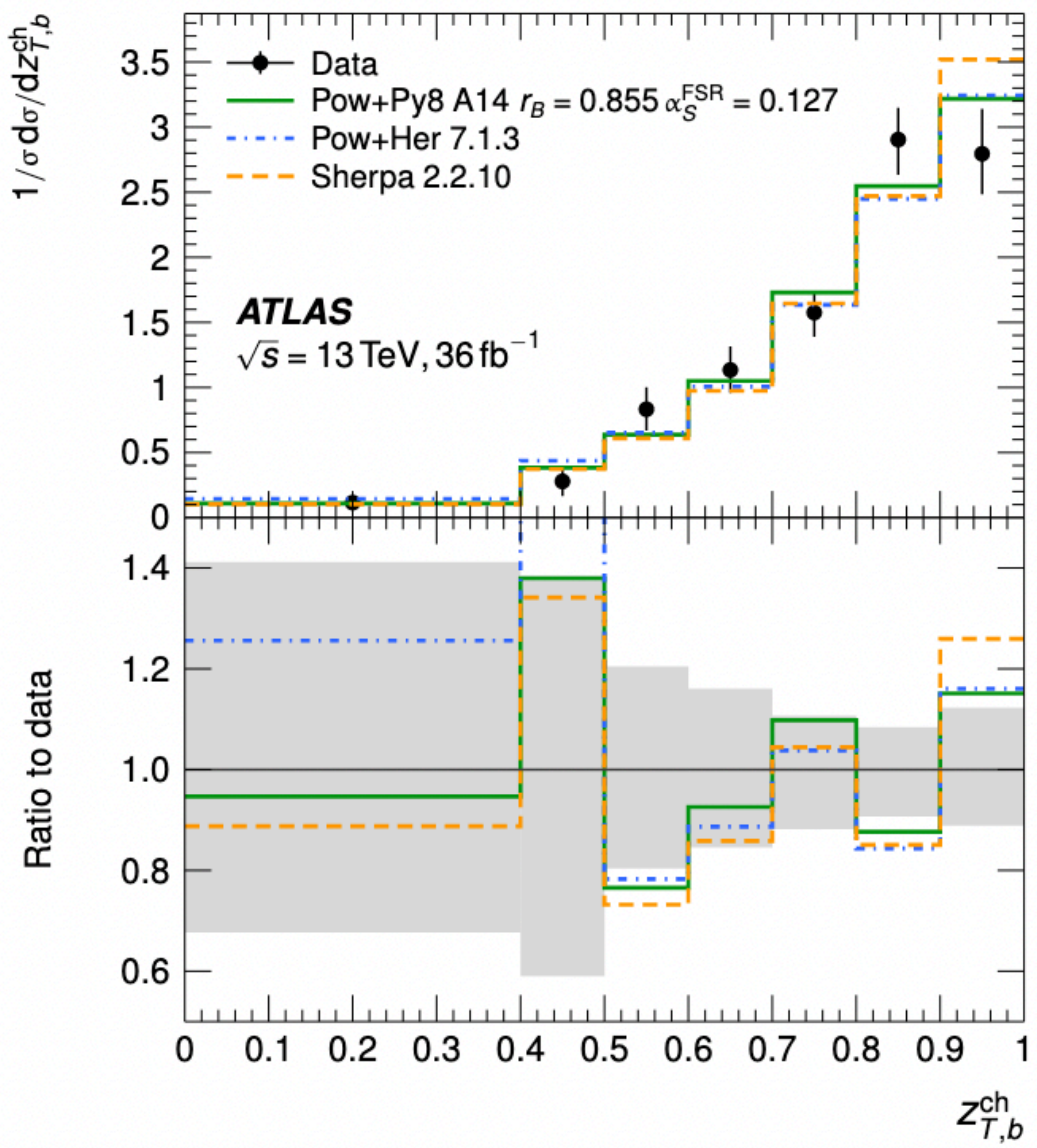
ALICE, [2208.04857]

CMS, Phys.Rev.D.98 09 (2014)

Impact of the dead cone on fragmentation: a selection



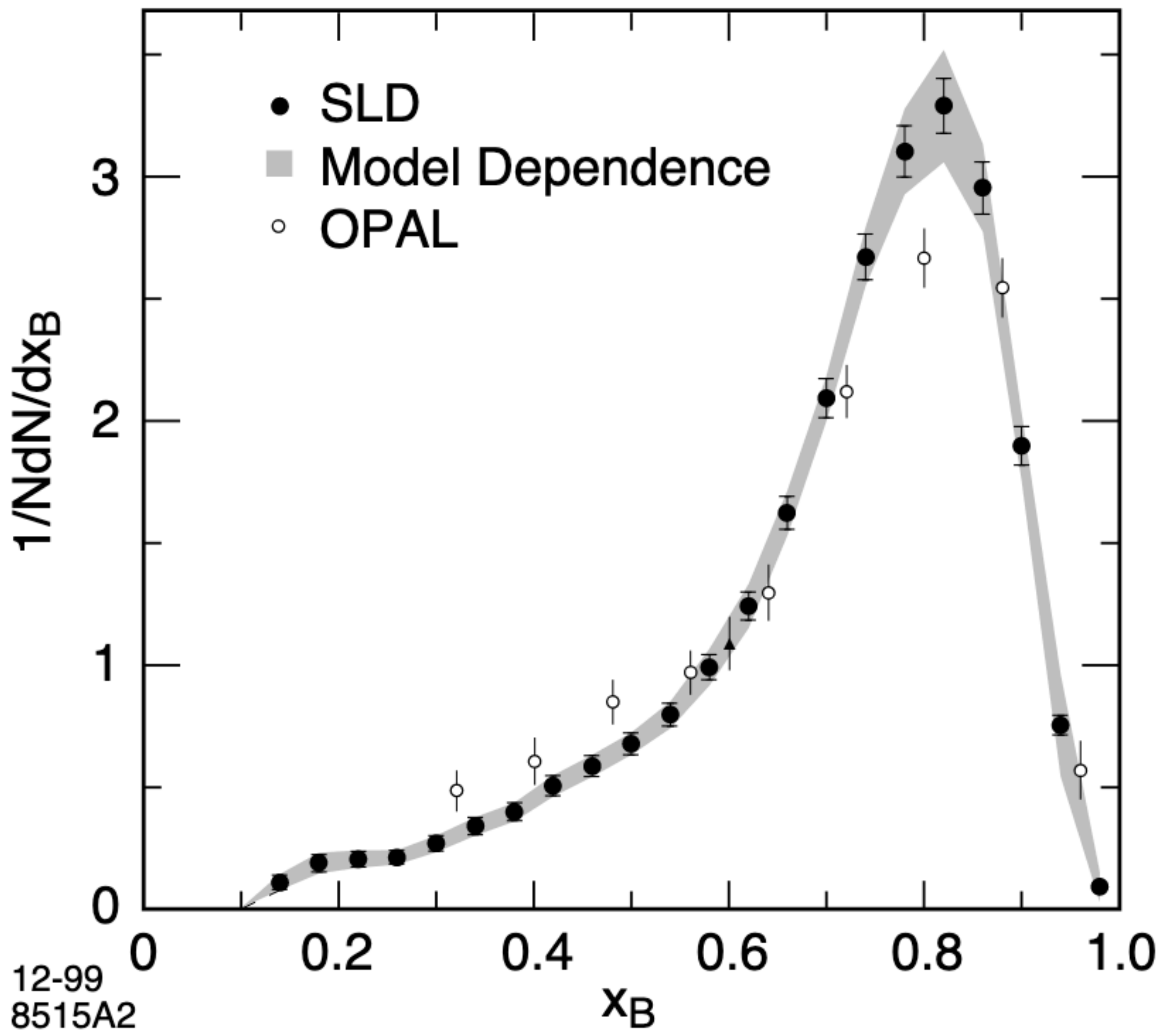


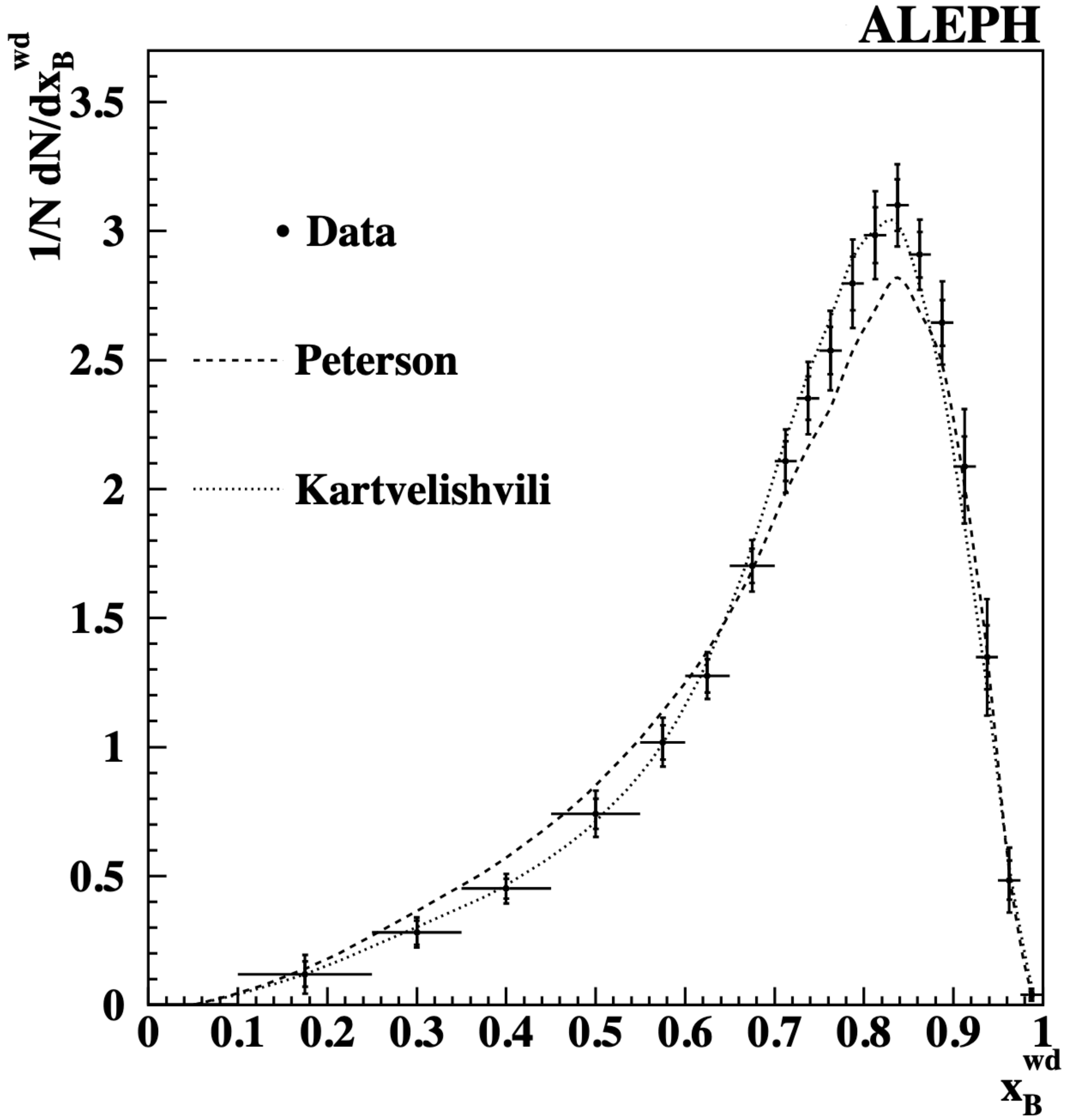


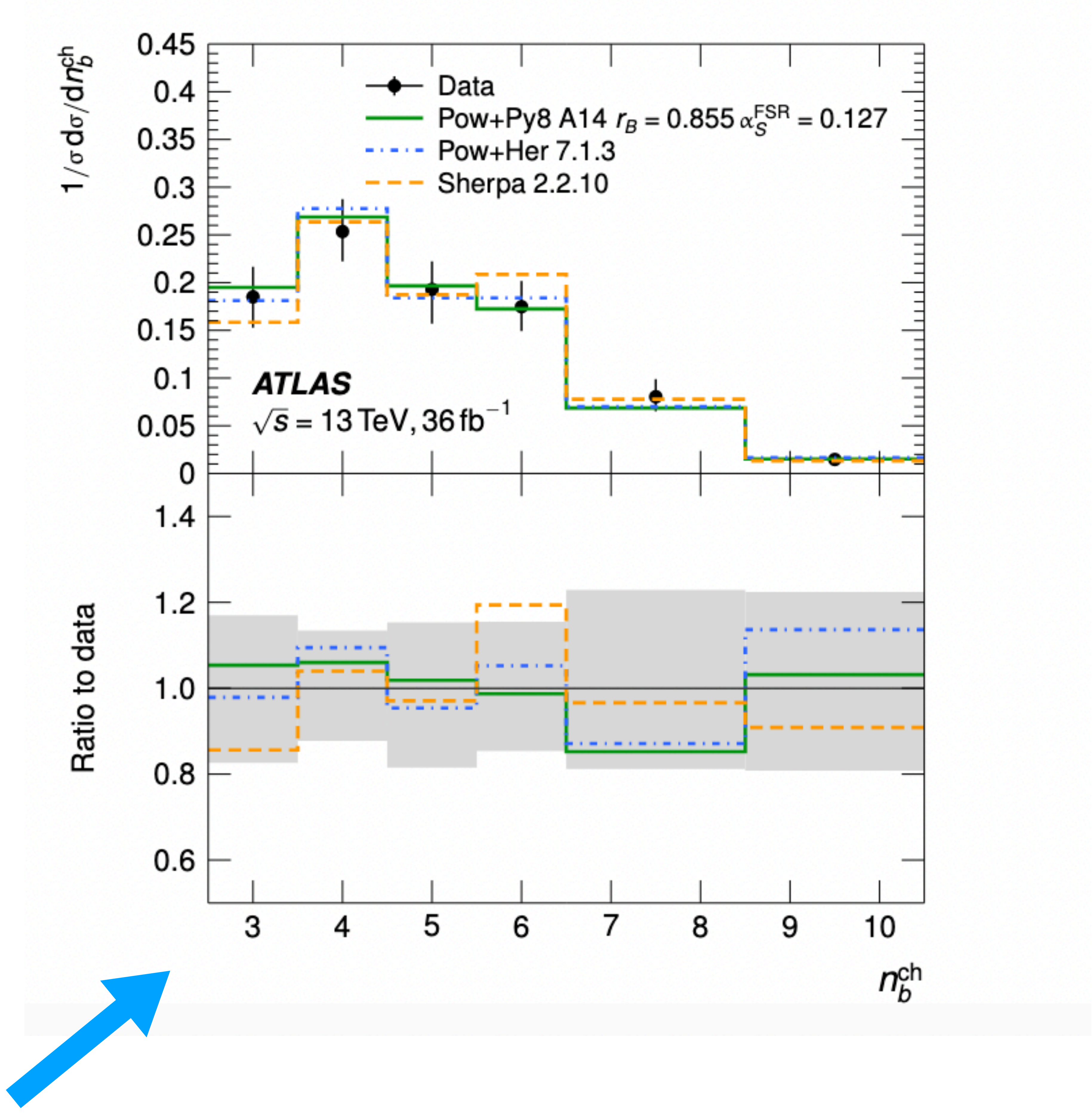
SLD, Phys.Rev.Lett 84, 4300-4304 (2000)
ALPEH, Phys.Lett.B512, 30-40 (2001)
OPAL, Phys.Lett.B 364, 93-106 (1995)
DELPHI, Z.Phys.C57 181-196 (1993)
ATLAS, Phys.Rev.D 106 (2022) 032008

Distinct peak of the fragmentation function at high values of x_B ->hard fragmentation
ATLAS uses b-tagging and aggregates the charged particles from the secondary vertex to access the B-hadron transverse momentum

Impact of the dead cone on fragmentation: a selection







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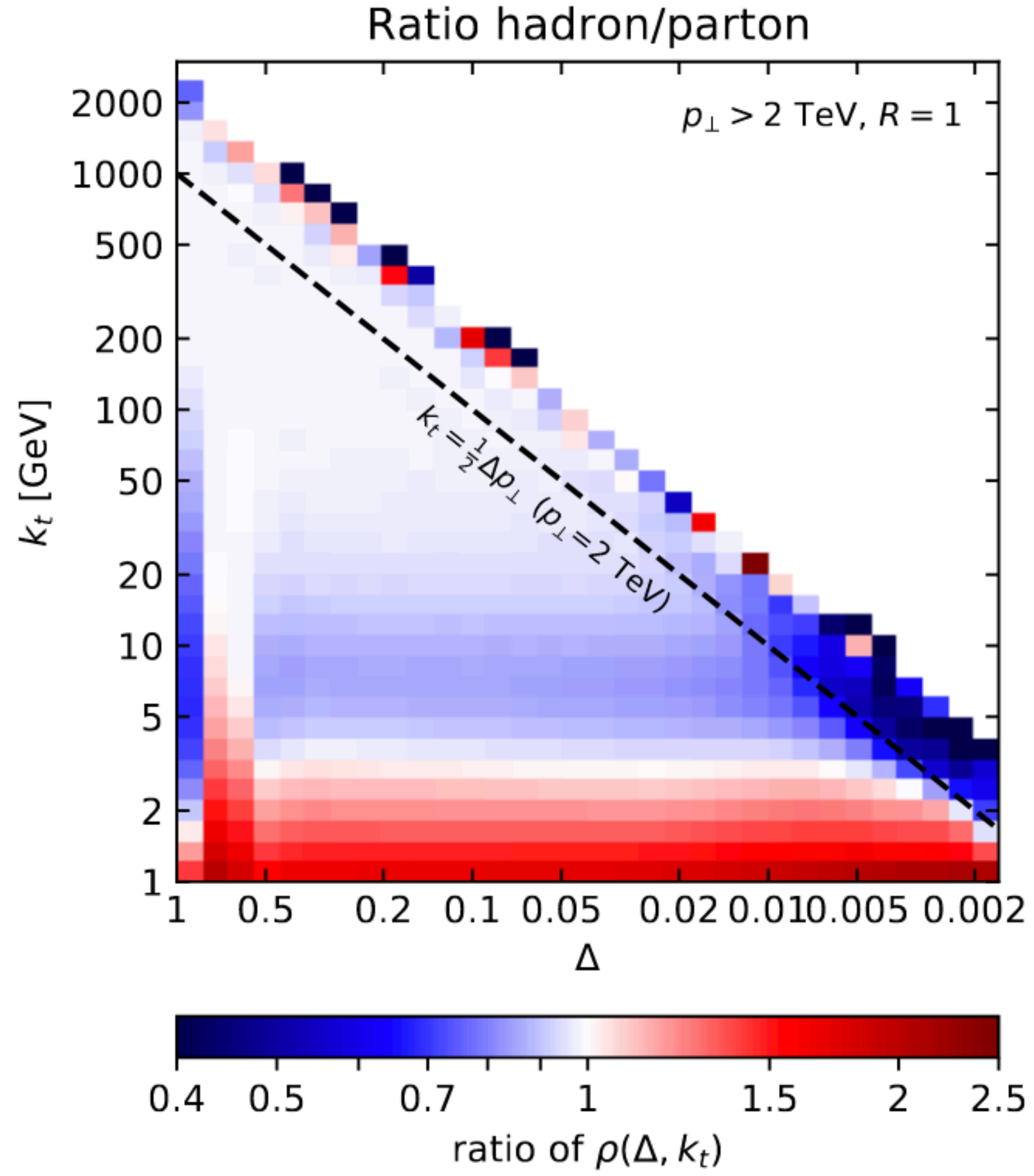
OPAL, Phys.Lett.B 364, 93-106 (1995)
DELPHI, Z.Phys.C57 181-196 (1993)
ATLAS, Phys.Rev.D 106 (2022) 032008

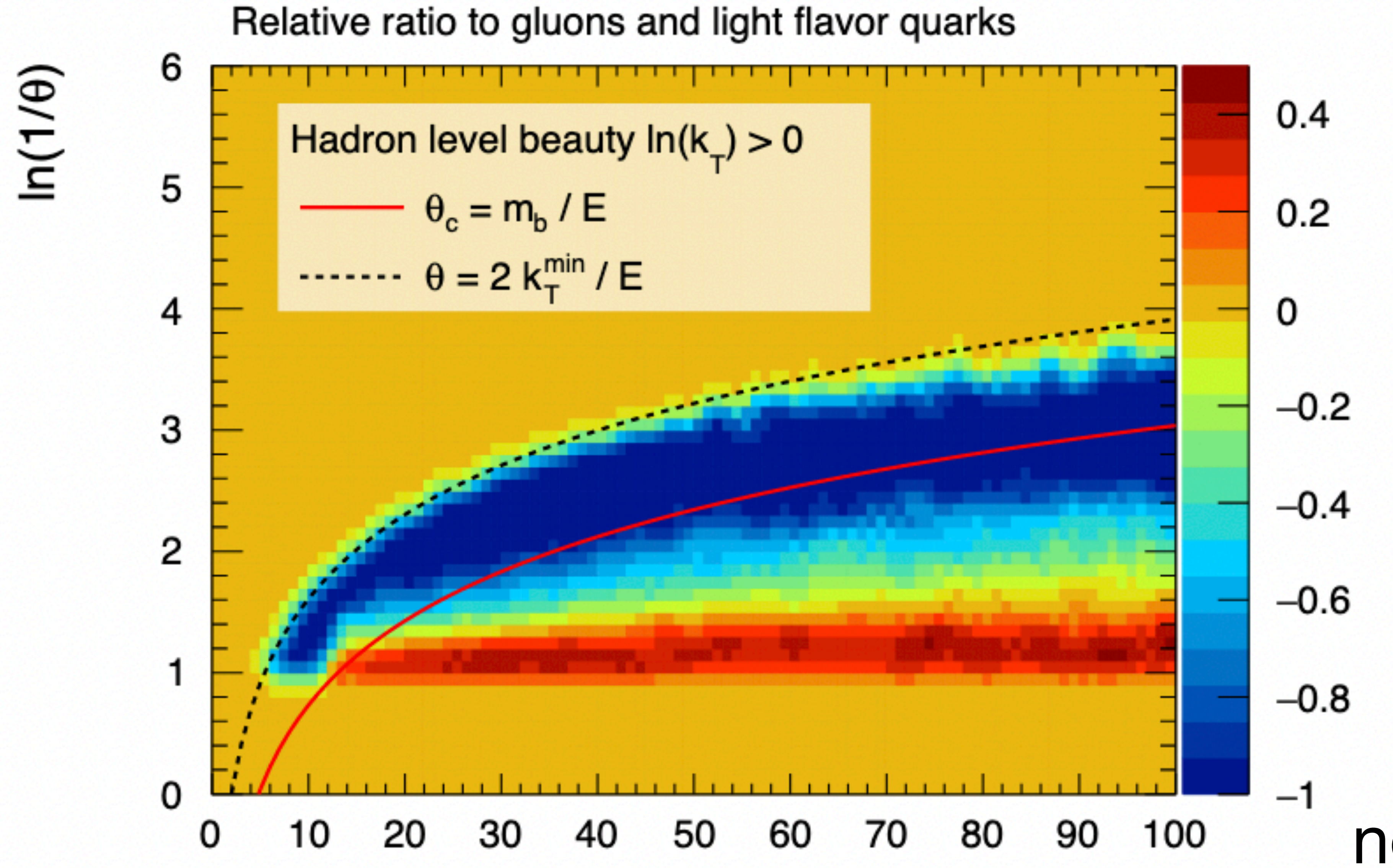
Number of charged aggregated particles in the secondary vertex has a broad distribution that can contaminate the jet tree or the substructure observable if not taken care of

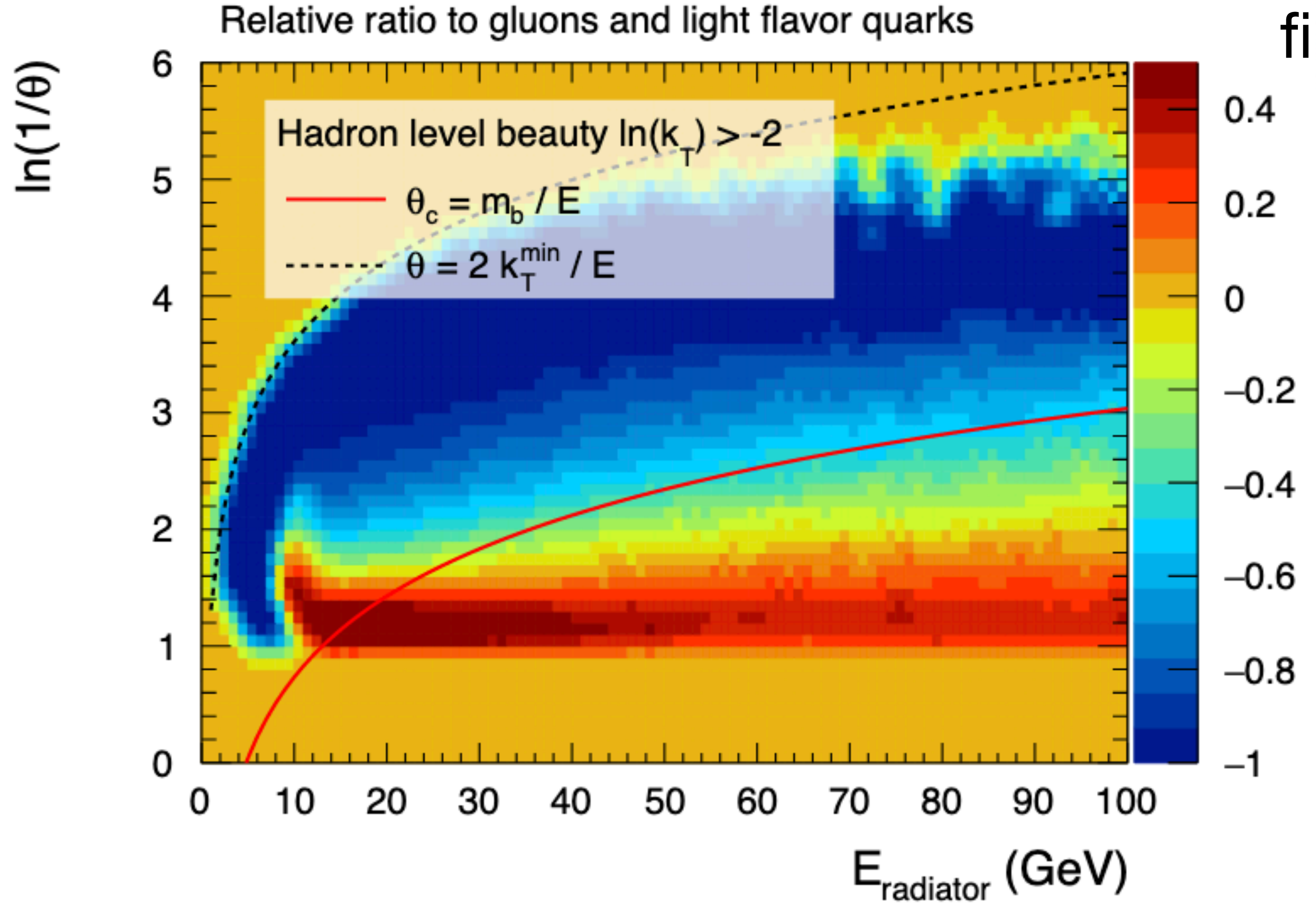
The darkening of the dead cone: hadronisation



Hadronisation naturally dominates the low-k_T region

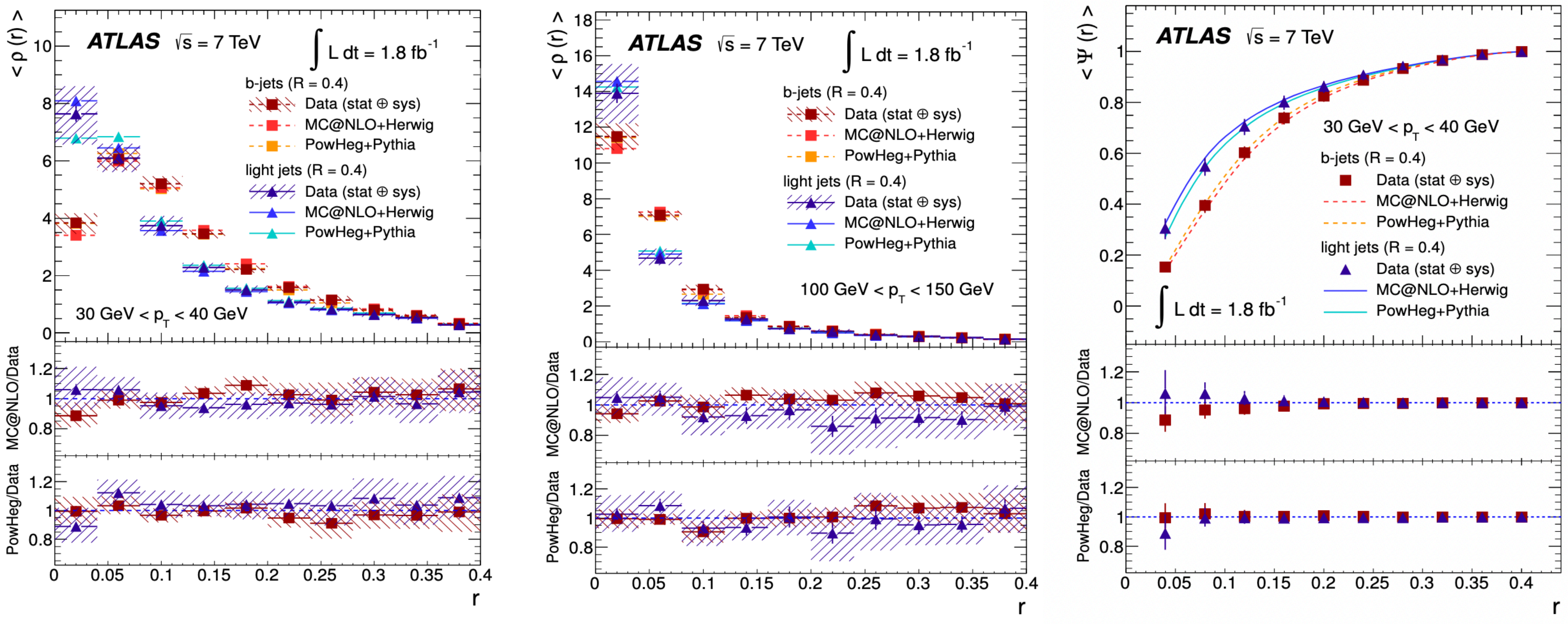
Lifson, Salam, Soyez, JHEP 10 (2020)





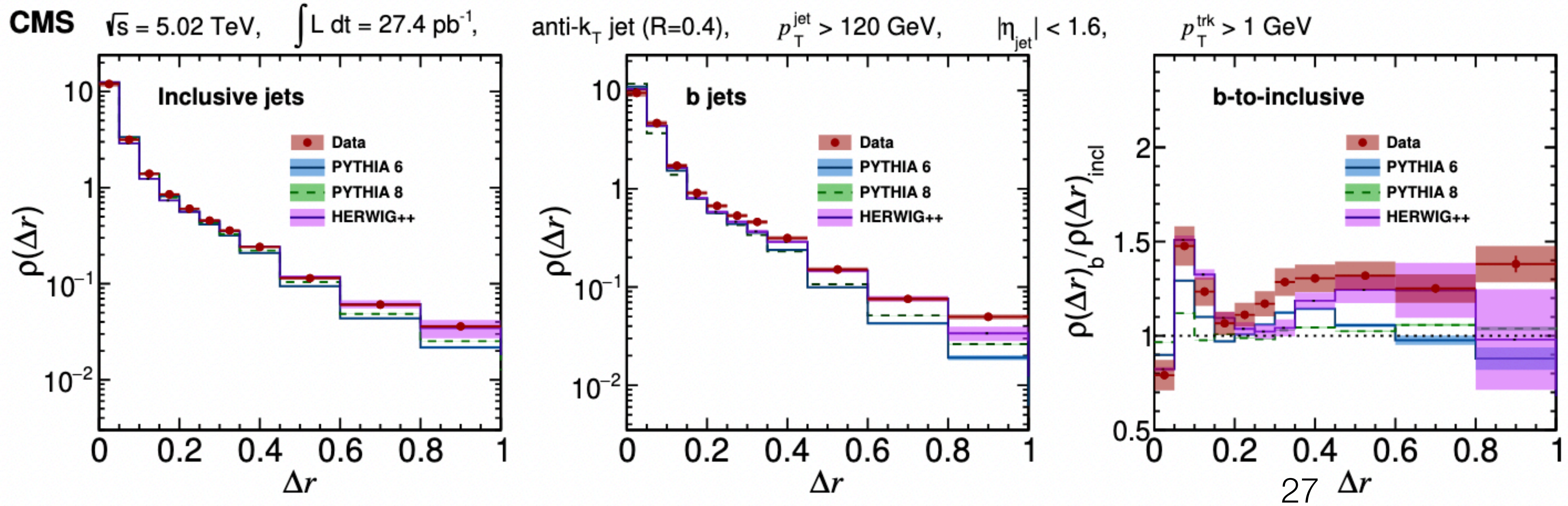
non-perturbative splittings fill the dead cone

Impact of the dead cone on fragmentation: a selection



Jet transverse profiles in top-quark pair events
The cores of light jets have a larger energy density than those of b-jets
Differences are smaller for higher jet transverse momentum as expected for mass effects

ATLAS, Eur.Phys.J.C (2013)73:2676

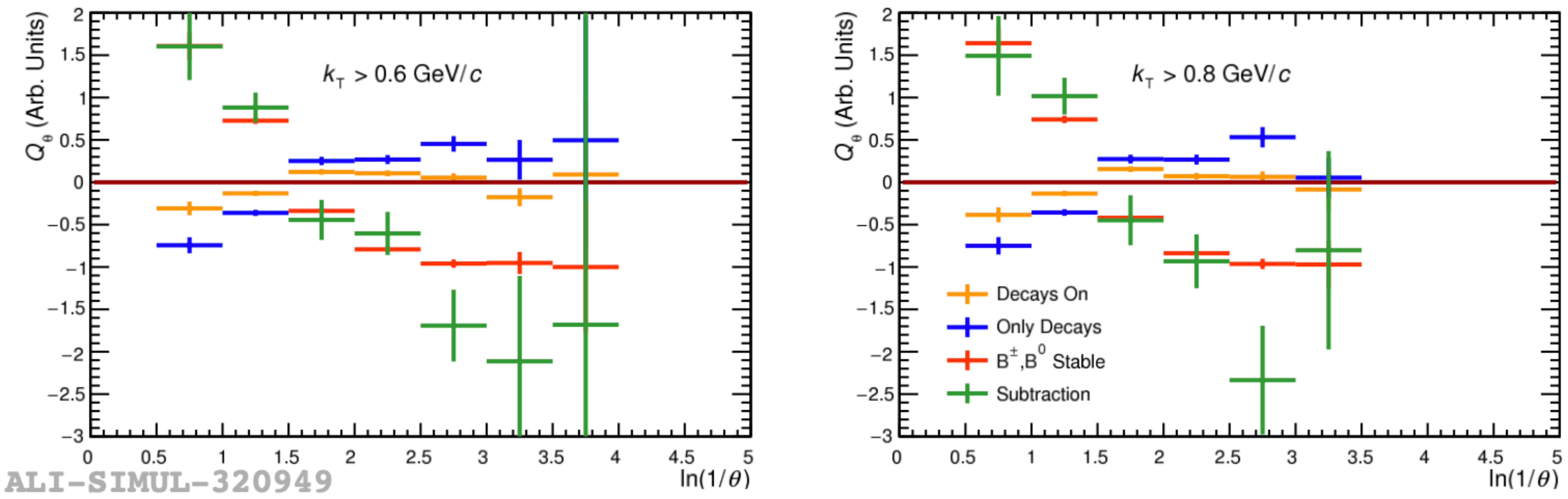


Similar qualitative picture in dijet events and high jet p_T
Reference is inclusive jets (q/g effects)

CMS, JHEP05 (2021) 054

The darkening of the dead cone: decays

K.Garner, QM19



Crucial to fully reconstruct the hevy flavour hadron, otherwise decays create extra splittings in the jet tree
See in the plot: B hadrons are stable vs B hadrons decay
When decays are on, no dead cone is visible!
See the **purely decay splittings in blue**
Full reconstruction of the heavy flavour hadron is statistically painfull, new strategies are needed if b/c-tagging techniques are used