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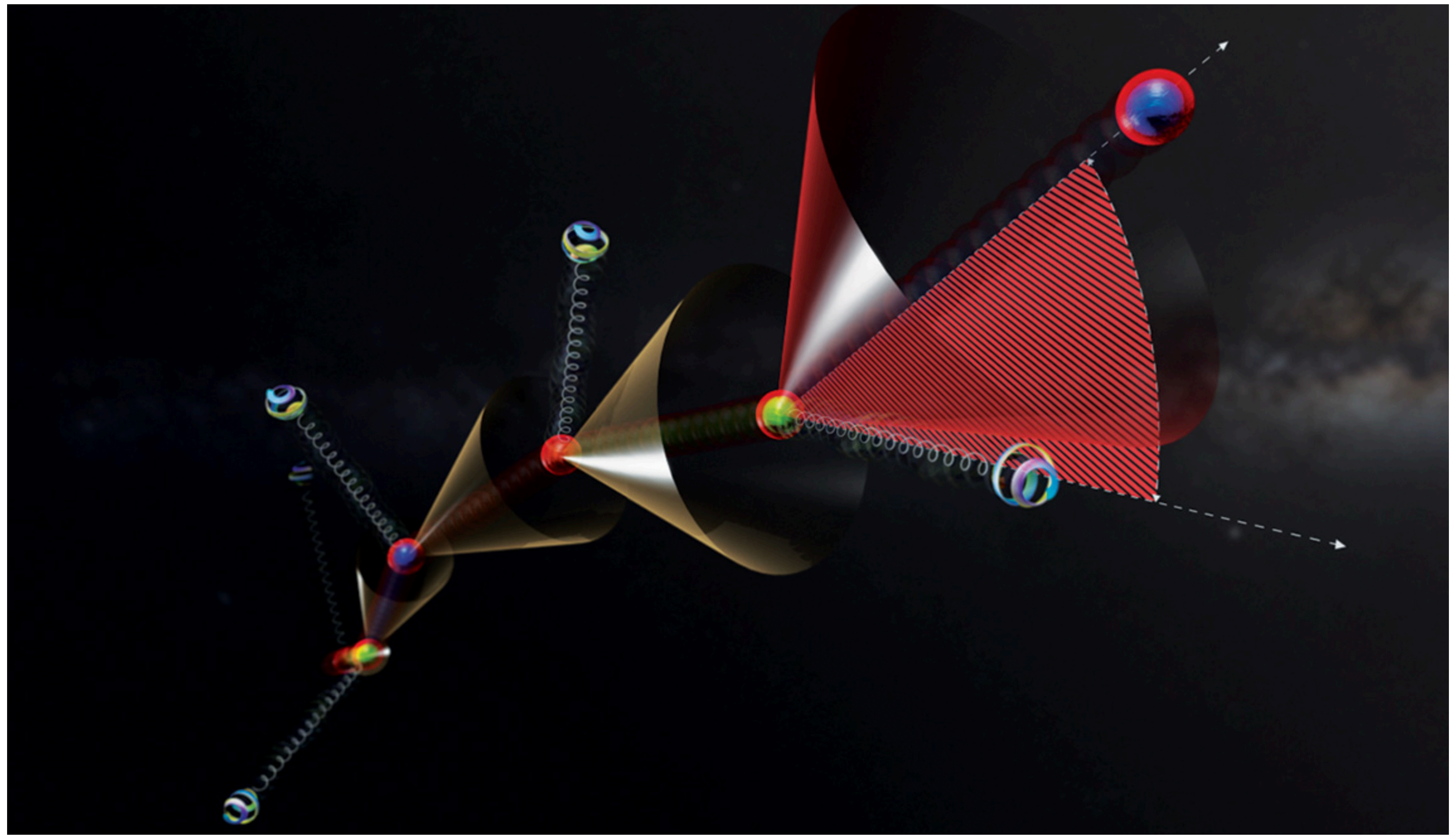
The dead cone: theoretical and experimental approaches in pp and in heavy-ion collisions

Leticia Cunqueiro Mendez



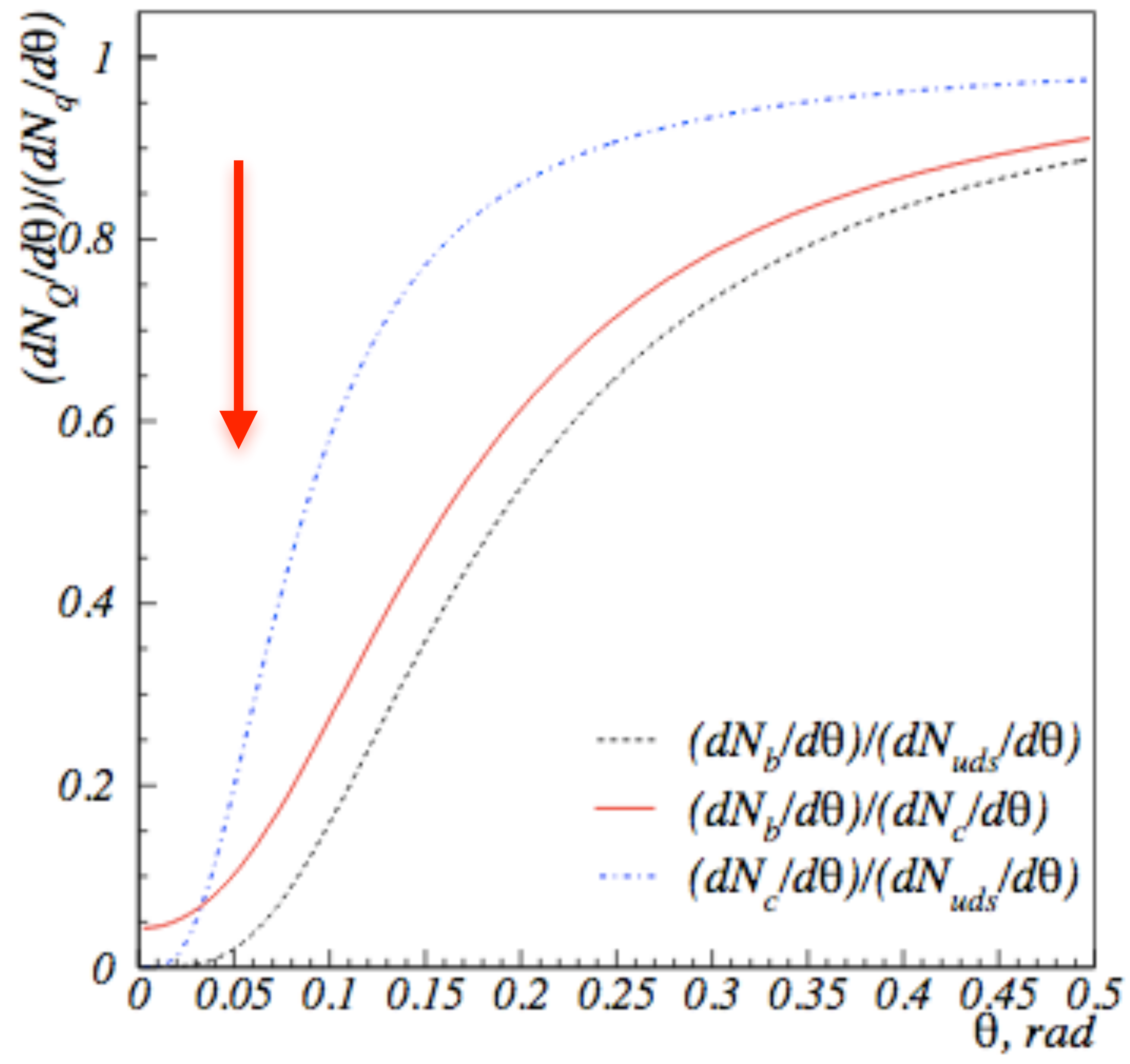
Lund Jet Workshop CERN July 4th

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

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

Parametric dependence of the dead cone effect



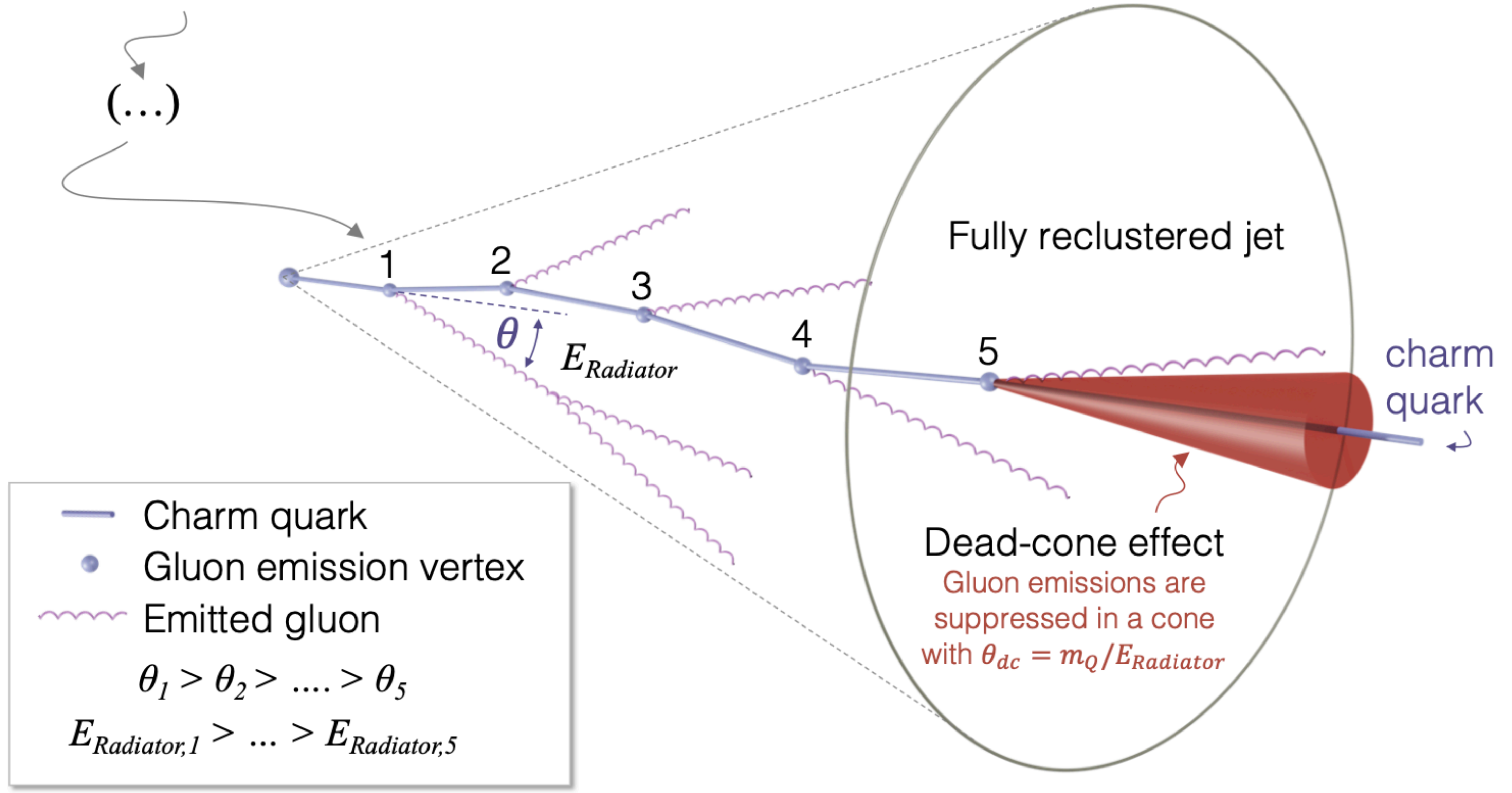
Battaglia et al, DELPHI-2004-037 CONF 712

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

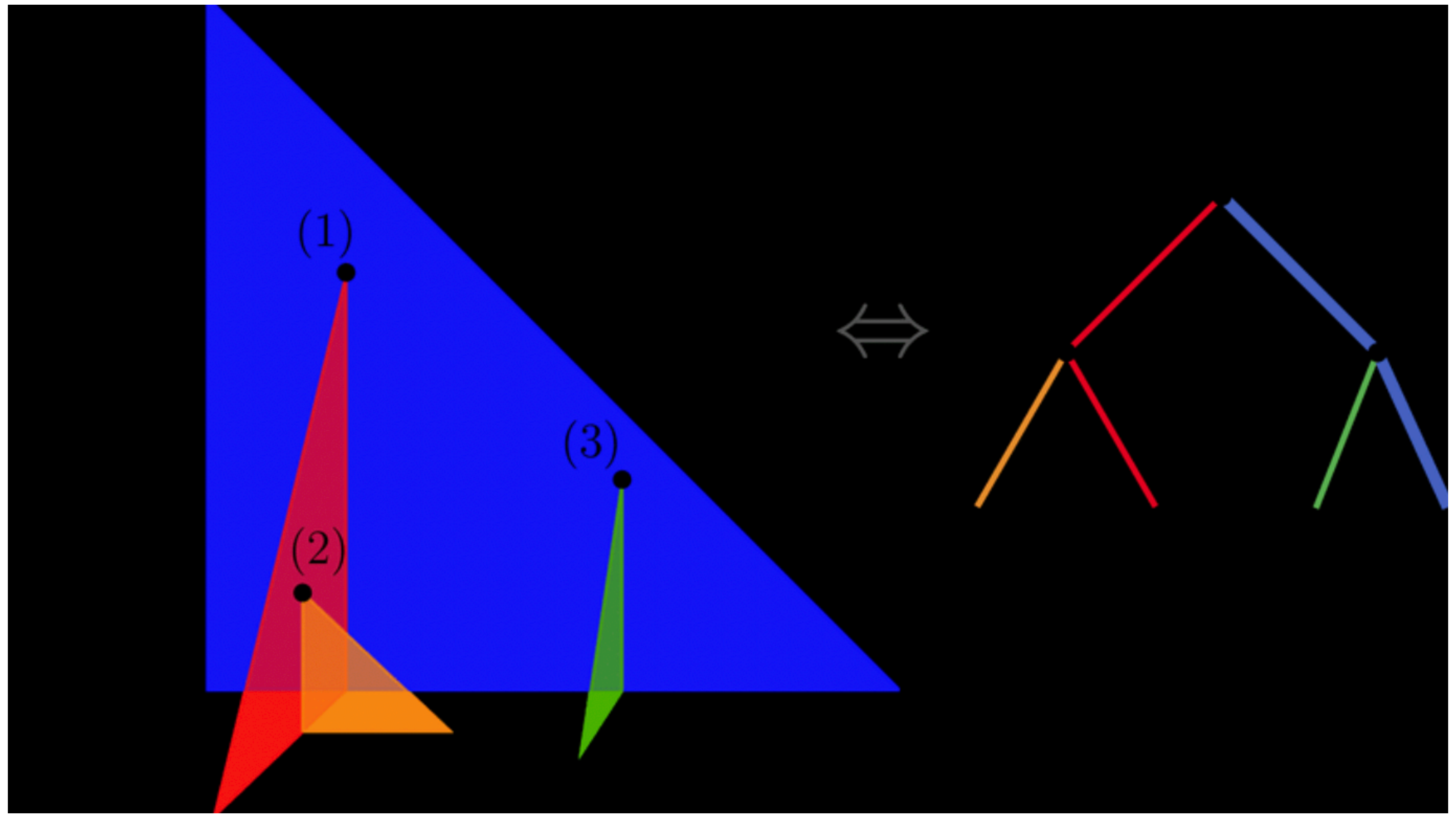


Experimental challenges for a direct measurement

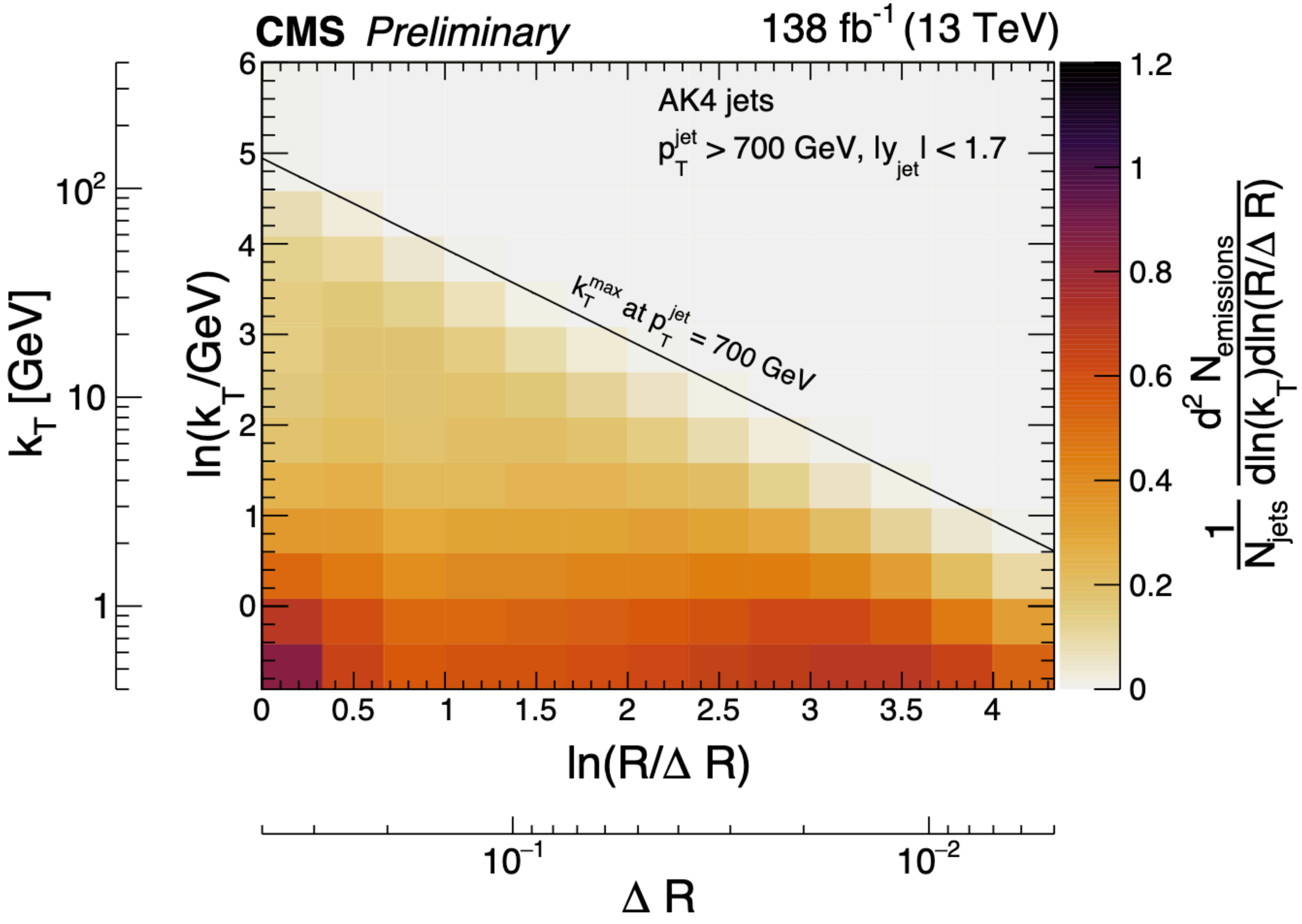
- The decays of the heavy flavour particles happen at similar angular scales and fill the dead cone
- Accurate determination of the dynamically evolving direction of the heavy-flavour particle relative to which radiation is suppressed

The jet tree (filling 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



[CMS-PAS-SMP-22-007]



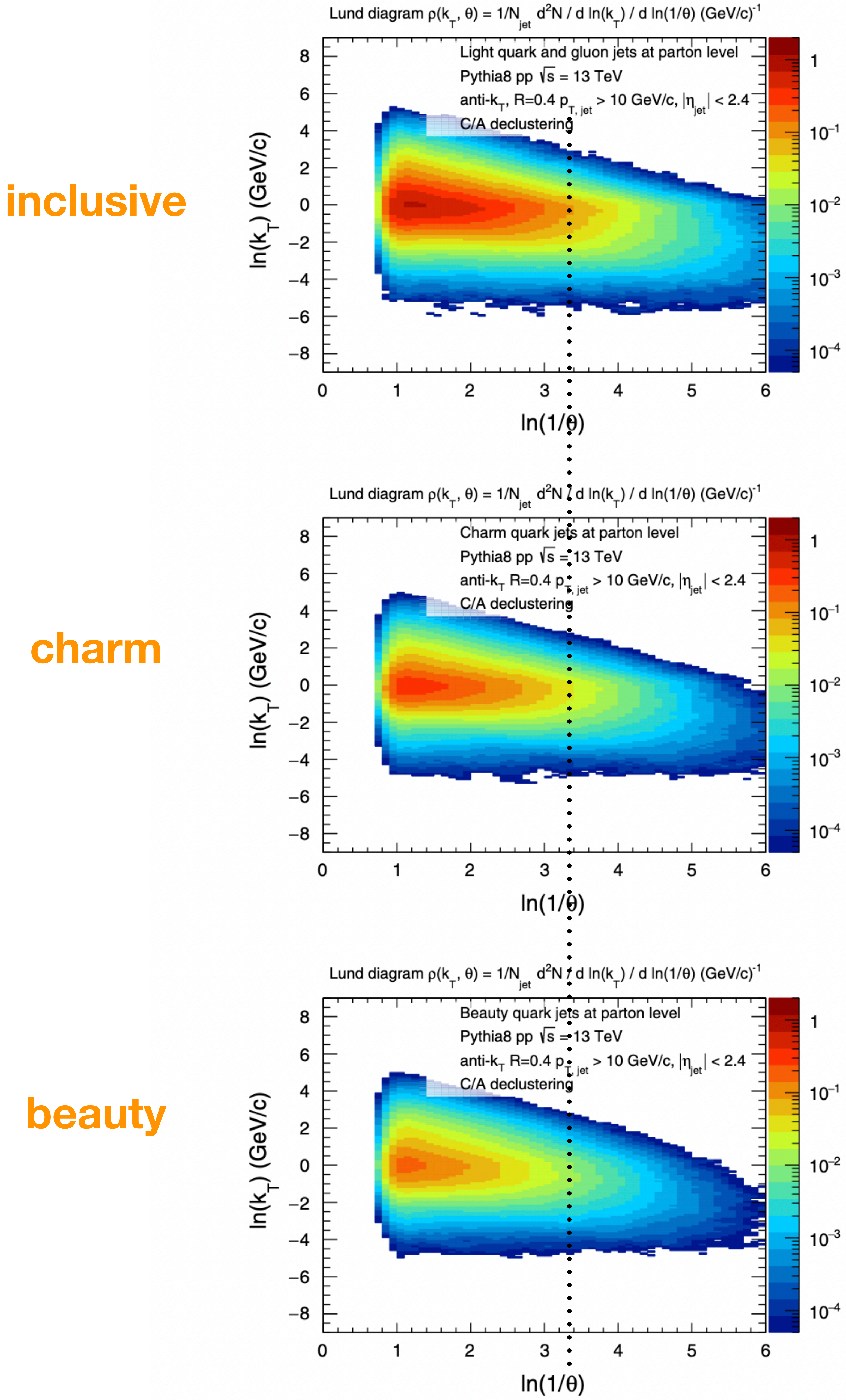
At leading order, emissions populate the plane uniformly and the running of the coupling sculpts the plane

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

See Cristian's and Emily's presentations

The heavy-flavour jet tree

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

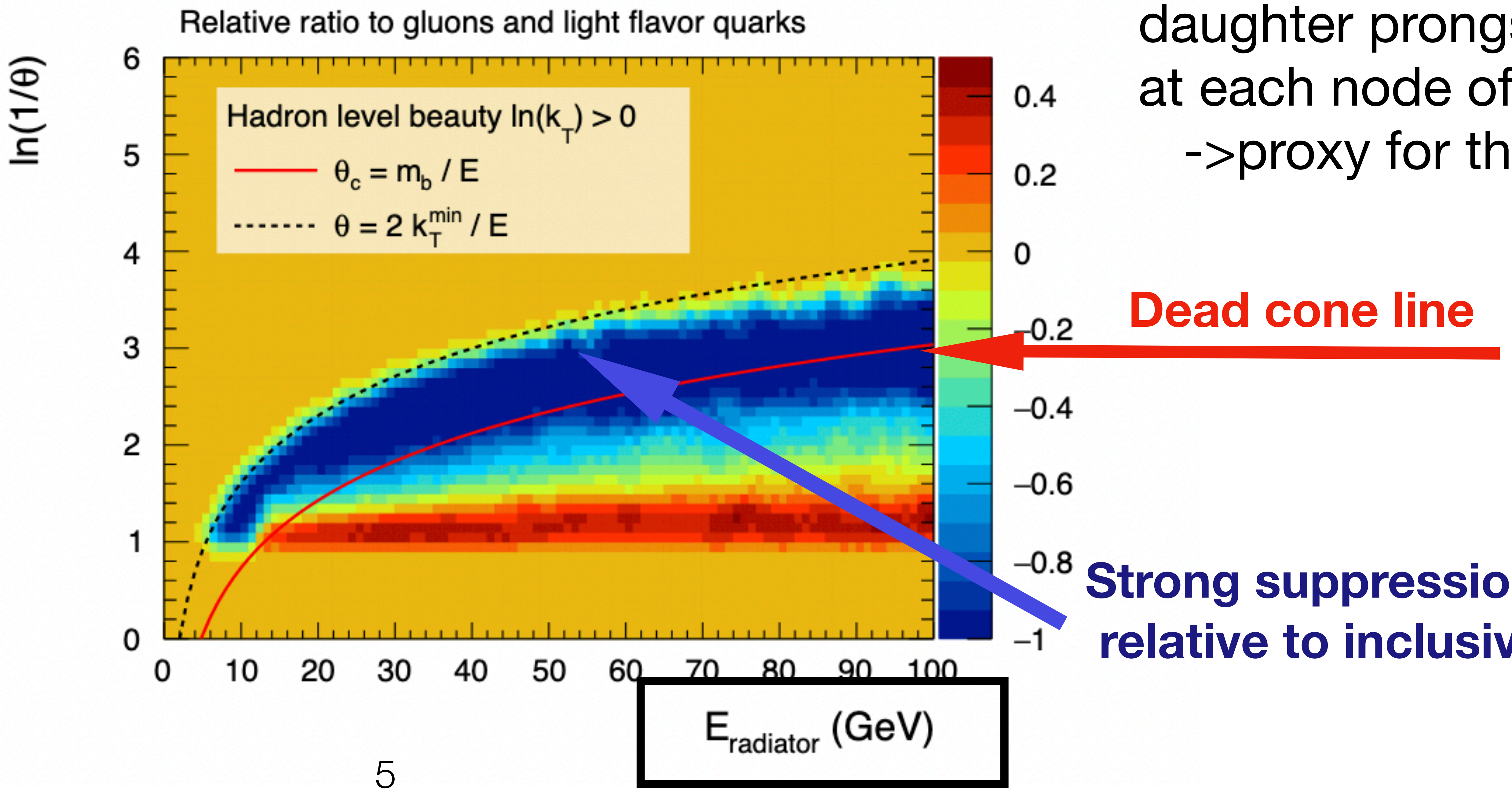


Idea: fill the Lund plane as in the inclusive jet case + follow at each declustering step the branch that contains the heavy flavour particle

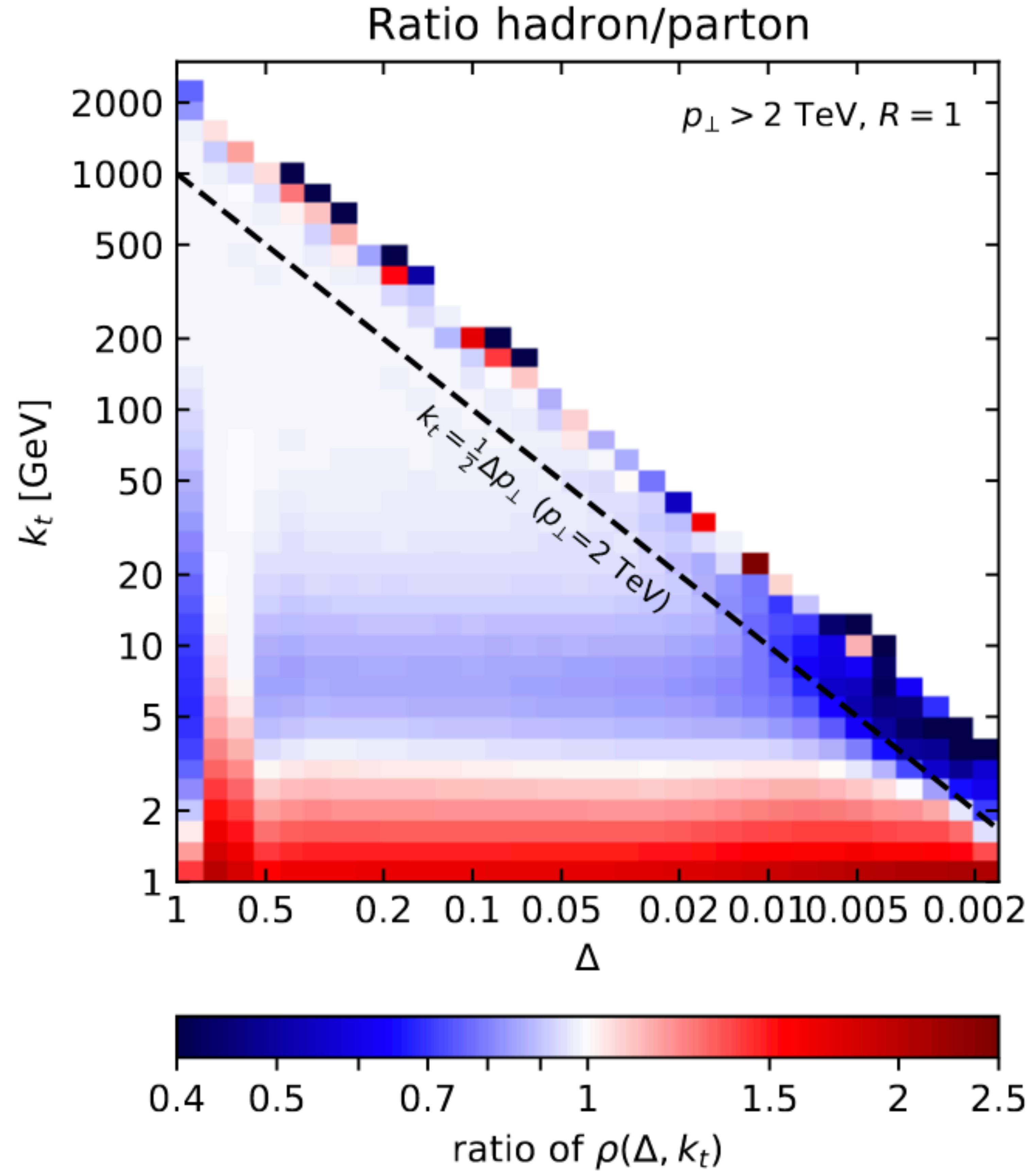
One can see by eye that heavy flavour jet Lund planes are less populated at small angles than the inclusive case

Opportunity to access the smallest-angle splittings in the jet tree that are most sensitive to the quark mass

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

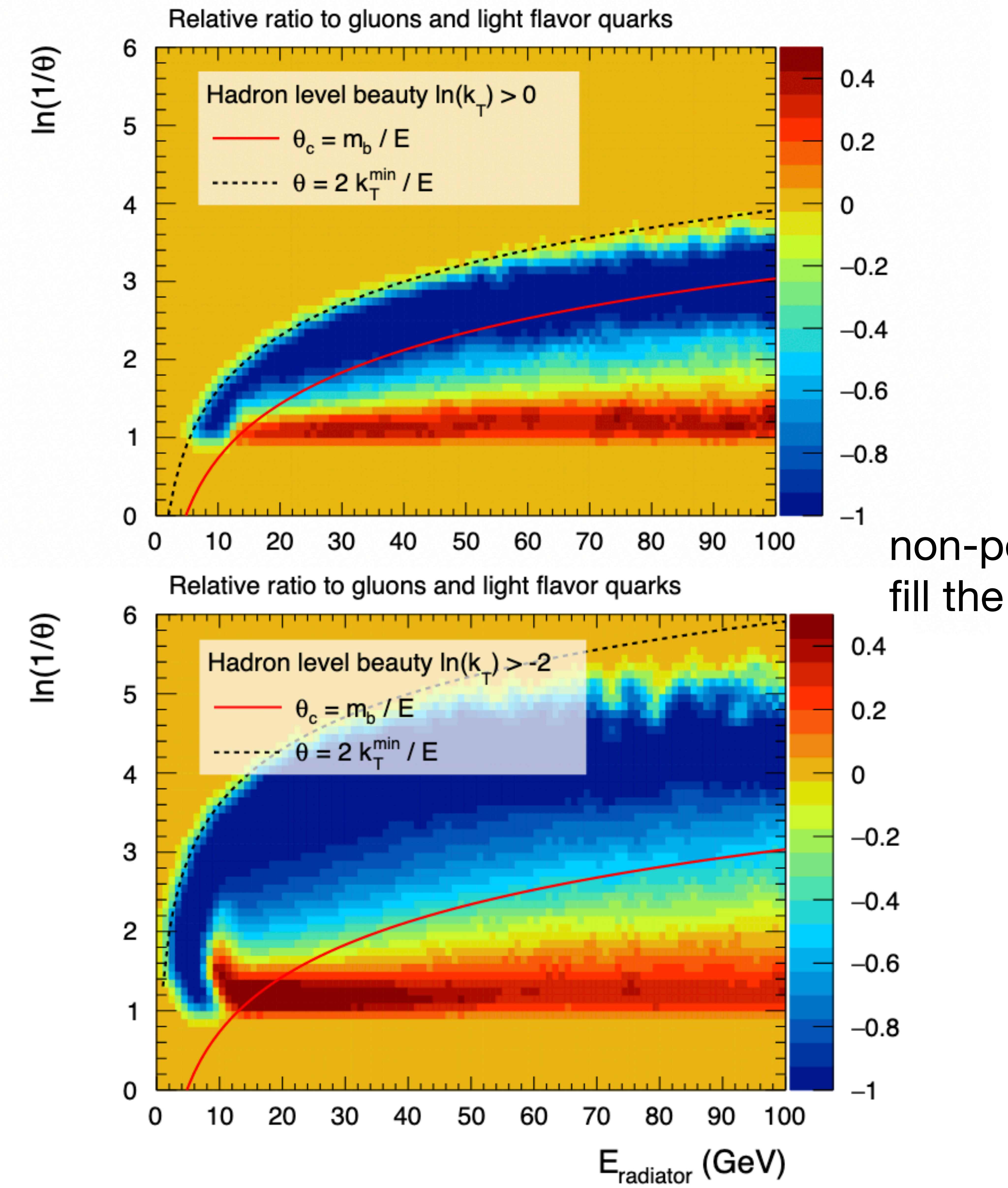


The darkening of the dead cone: hadronisation



Hadronisation naturally dominates the low-k_T region

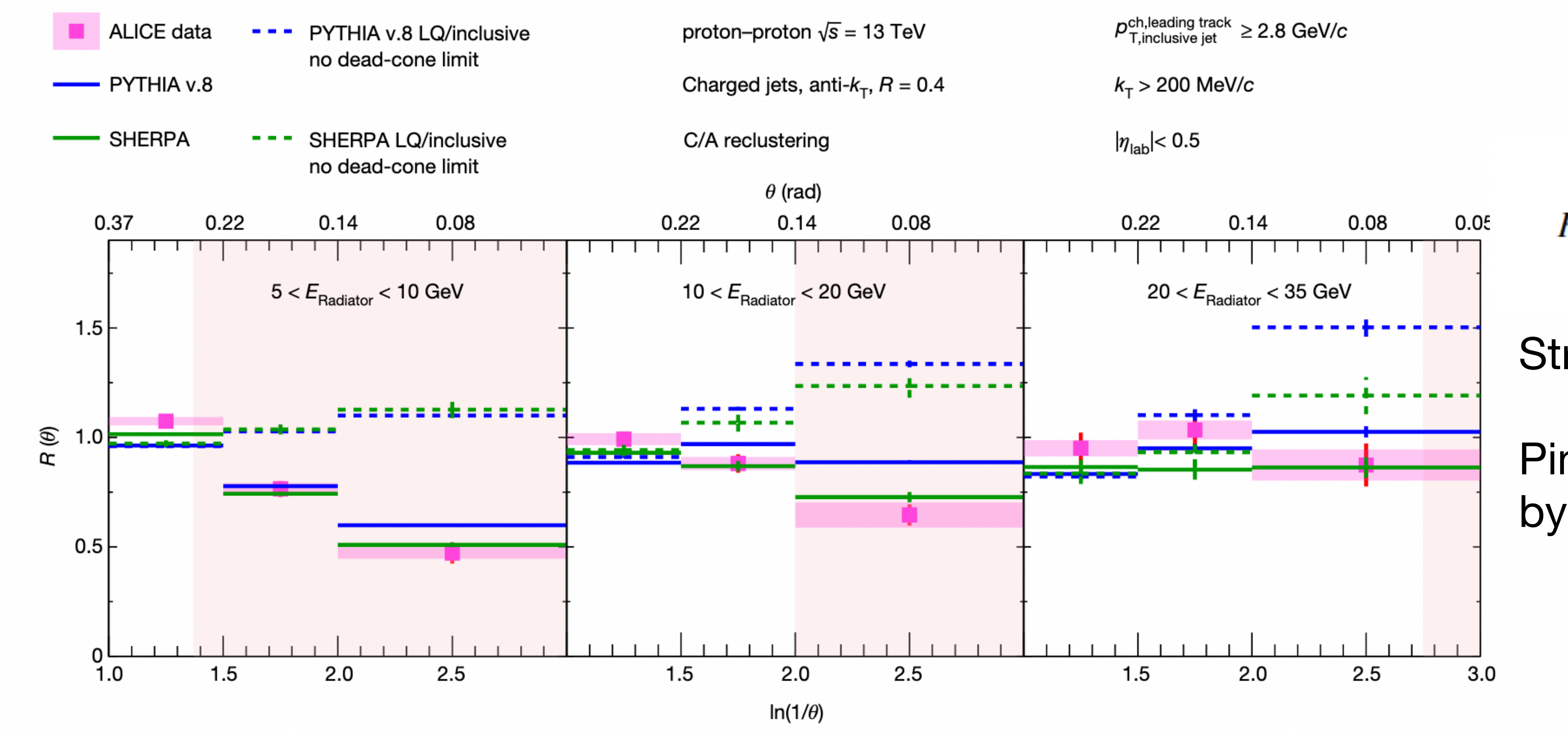
Lifson, Salam, Soyez, JHEP 10 (2020)



non-perturbative splittings fill the dead cone

The first direct observation of the dead cone with D-jets

ALICE, Nature 605, 440-446 (2022)



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

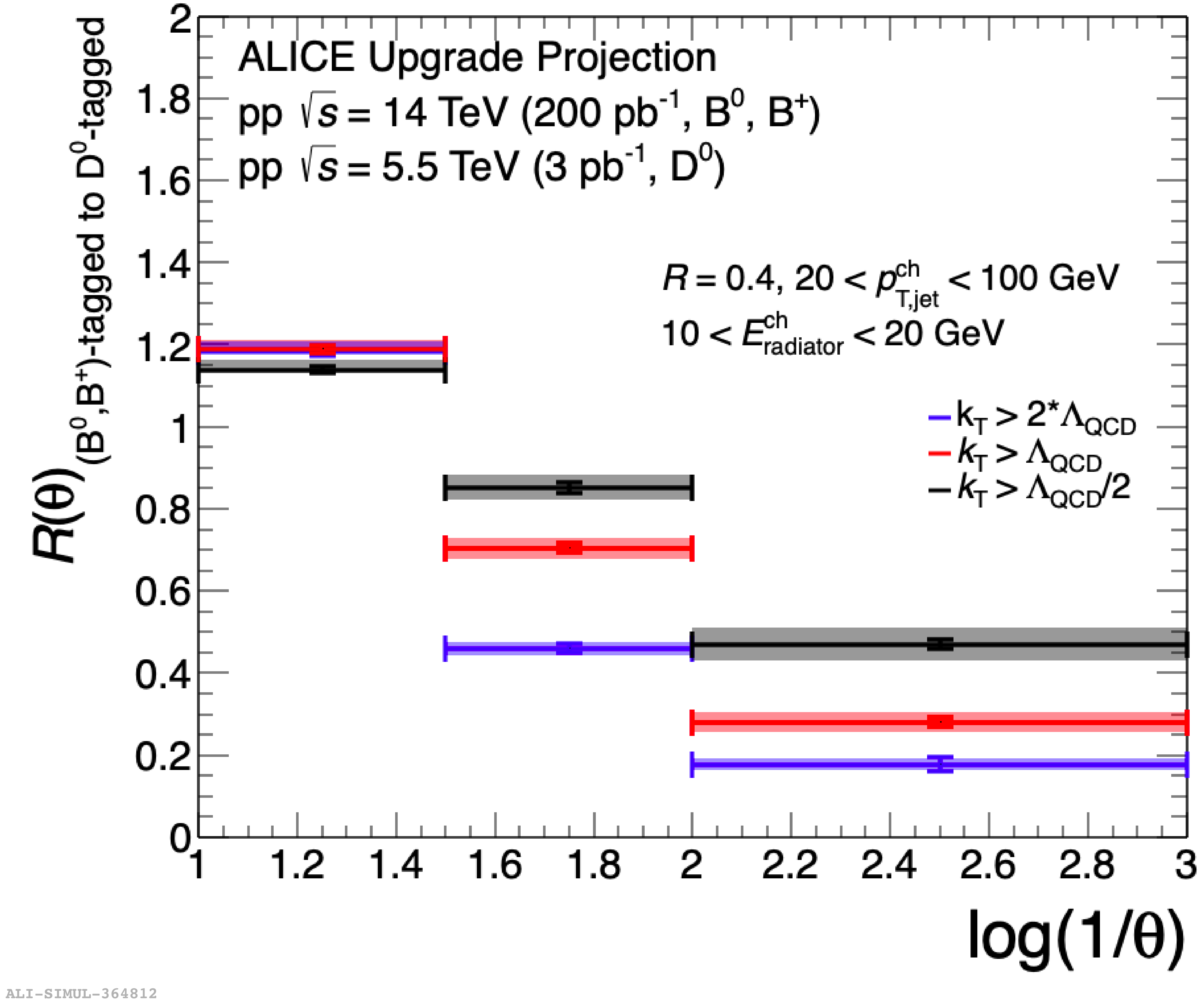
Strong suppression in the lowest $E_{radiator}$ bin

Pink areas represent the vetoed regions given by m_C/E

Accesing the Q->Qg splitting and testing its mass dependence requires:

1. To penetrate the jet tree down to the splittings at the smallest angles
2. To suppress hadronisation effects, by imposing a cut on the hardness of the splittings -on k_T
3. To fully reconstruct the heavy flavour hadron: decay products interfere with the jet tree and create extra splittings at small angles that darken the dead cone

The first direct observation of the dead cone with D-jets



Run3 brings the possibility of a mass scan:

Projections for Lund plane ratios
using fully reconstructed B and D hadron jets

D-jets as reference are ideal ->factor out color effects,
ratio just sensitive to quark mass

Possible to perform a fully corrected $E_{radiator}$ vs θ scan

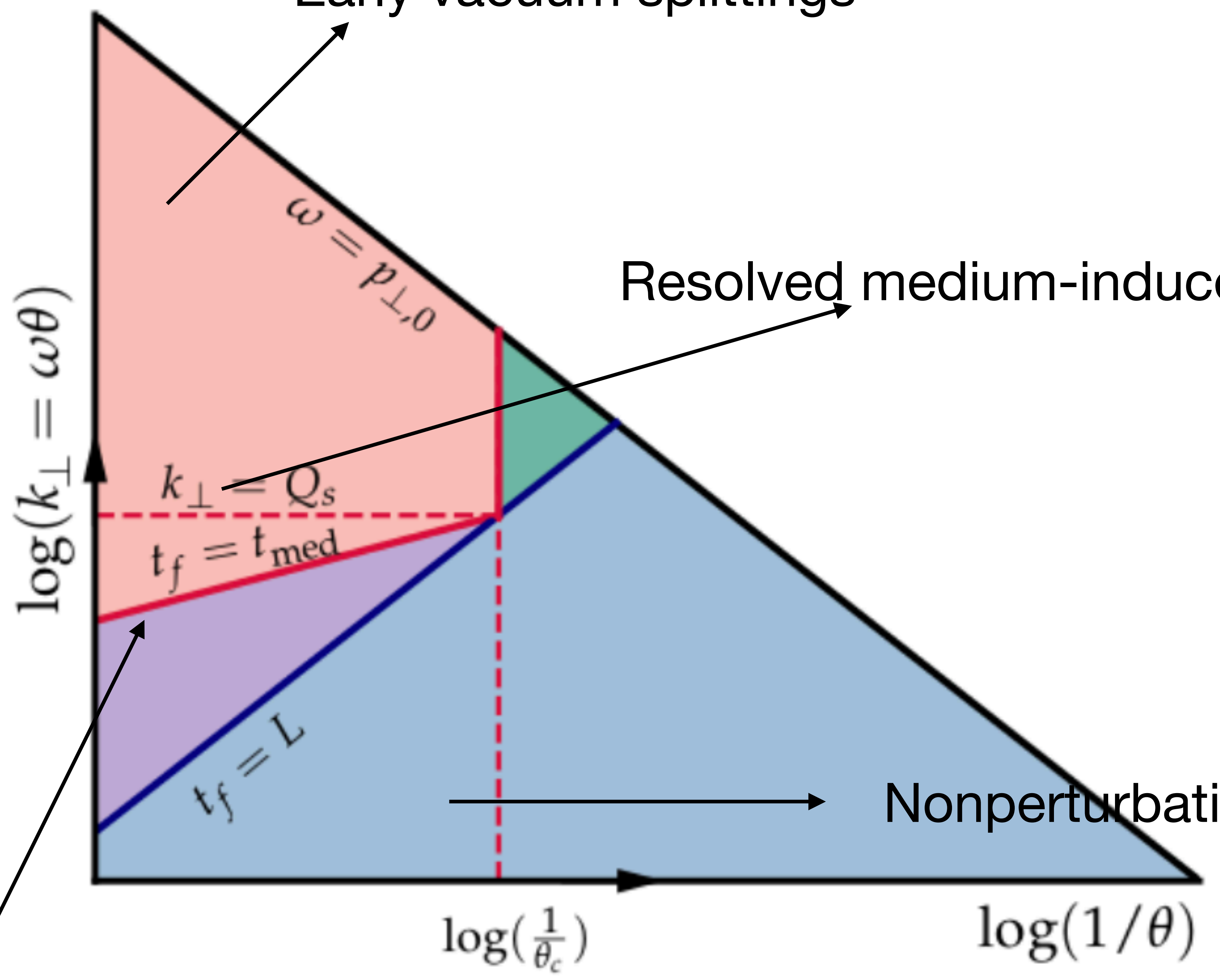
Looking forward to Lund plane analytical calculations for heavy flavours!

The Lund Plane in heavy-ion collisions

The Lund plane density in PbPb is not expected to be filled uniformly at LO like in vacuum

Early vacuum splittings

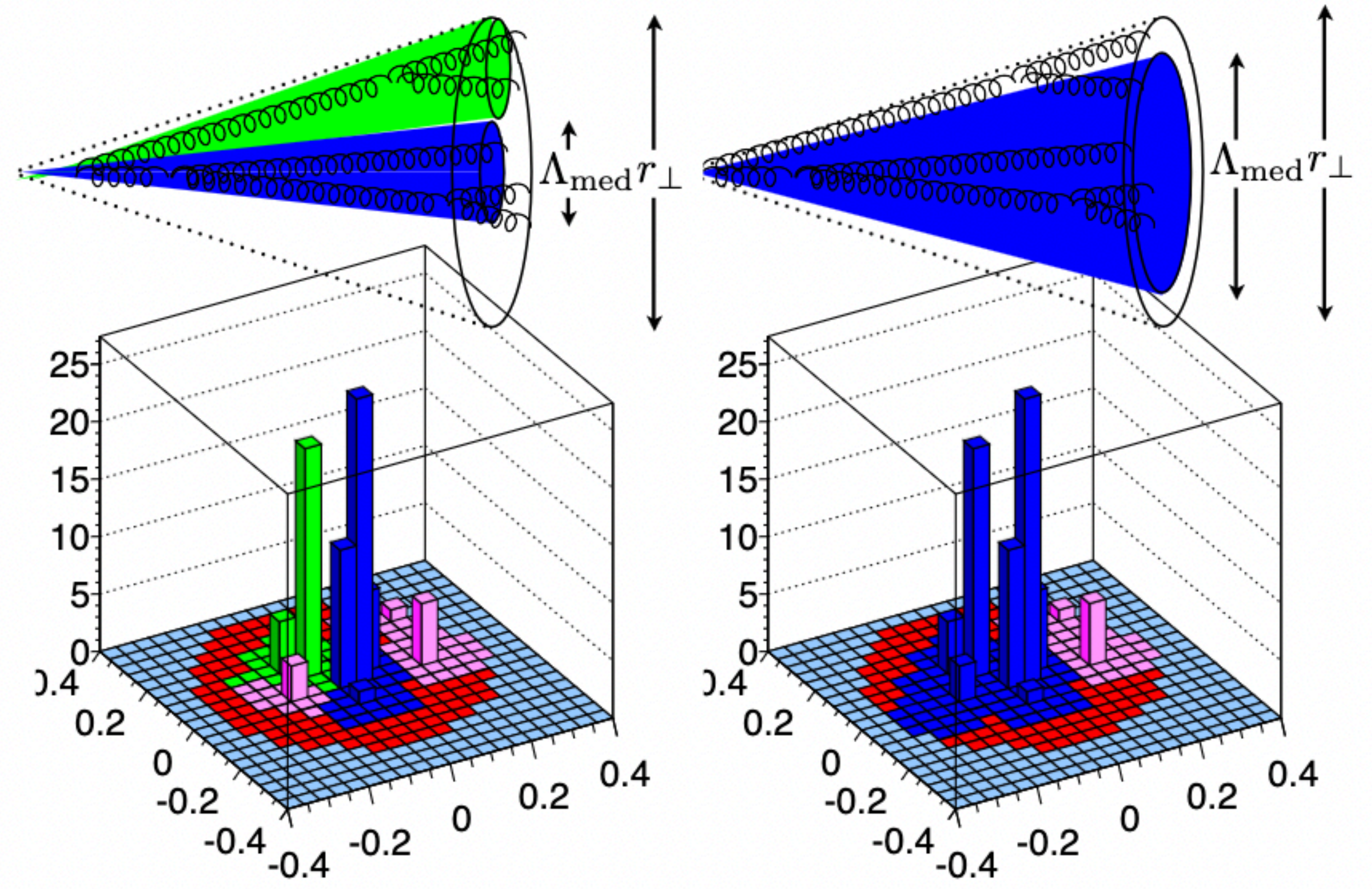
Resolved medium-induced emissions



Nonperturbative effects

Large-angle, soft emissions,
Strong fake contribution

[Casalderrey et al, Phys.Lett.B725 (2013)]

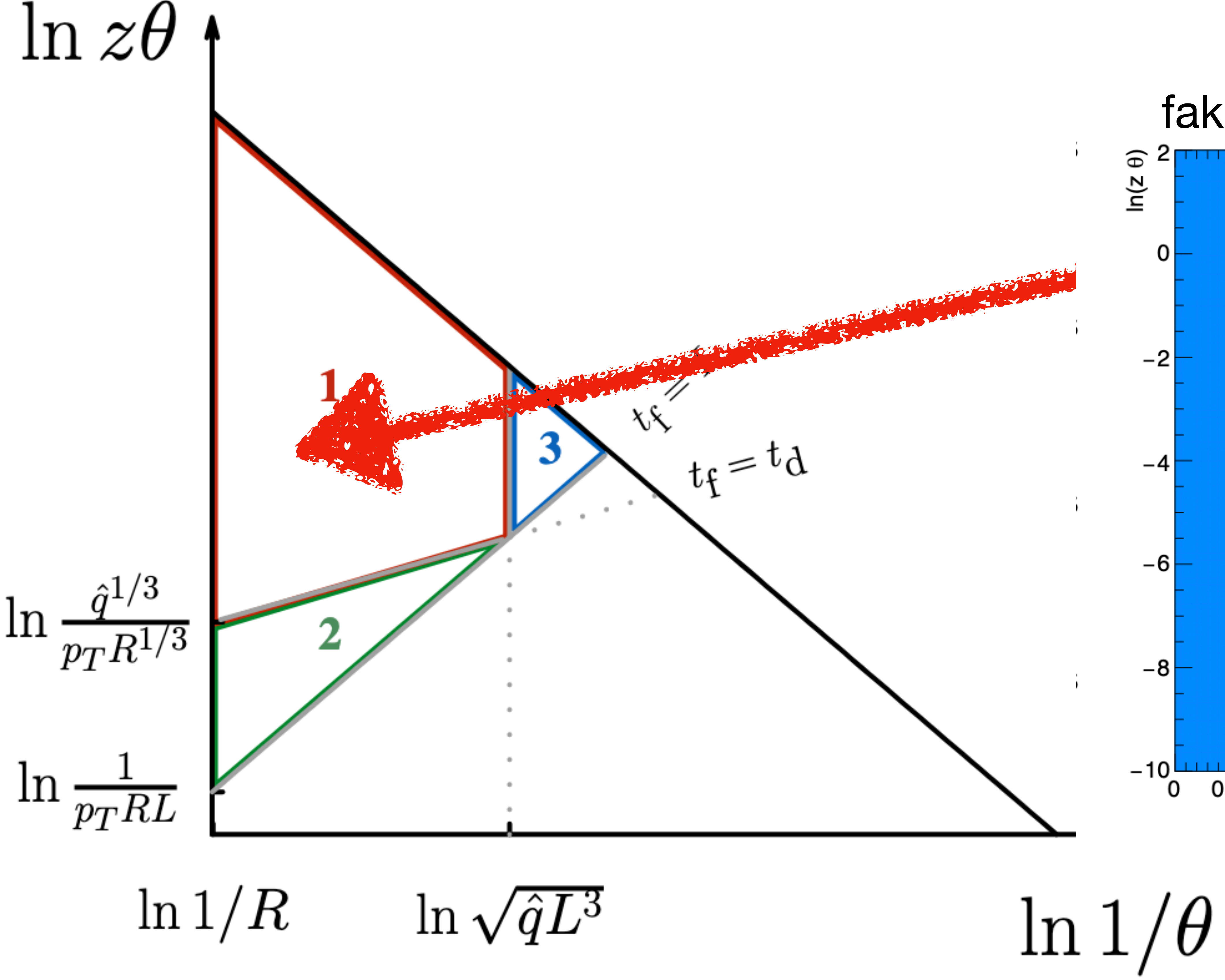


New scales in medium: emissions with $\theta < \theta_C$ are not resolved by the medium

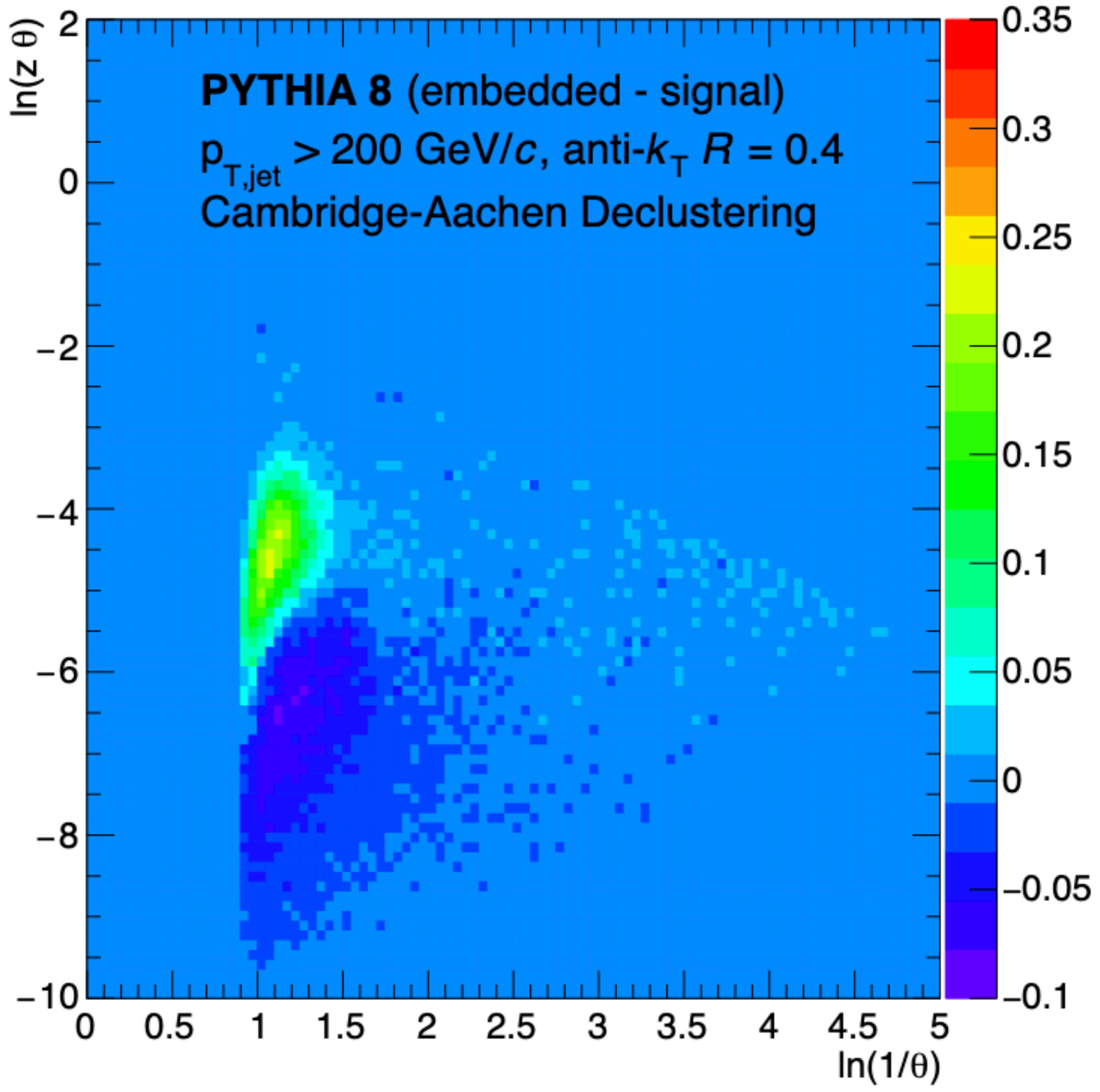
See previous talks by Konrad, Yi, Raymond, Nima

The heavy-ion case: distortion of the jet tree

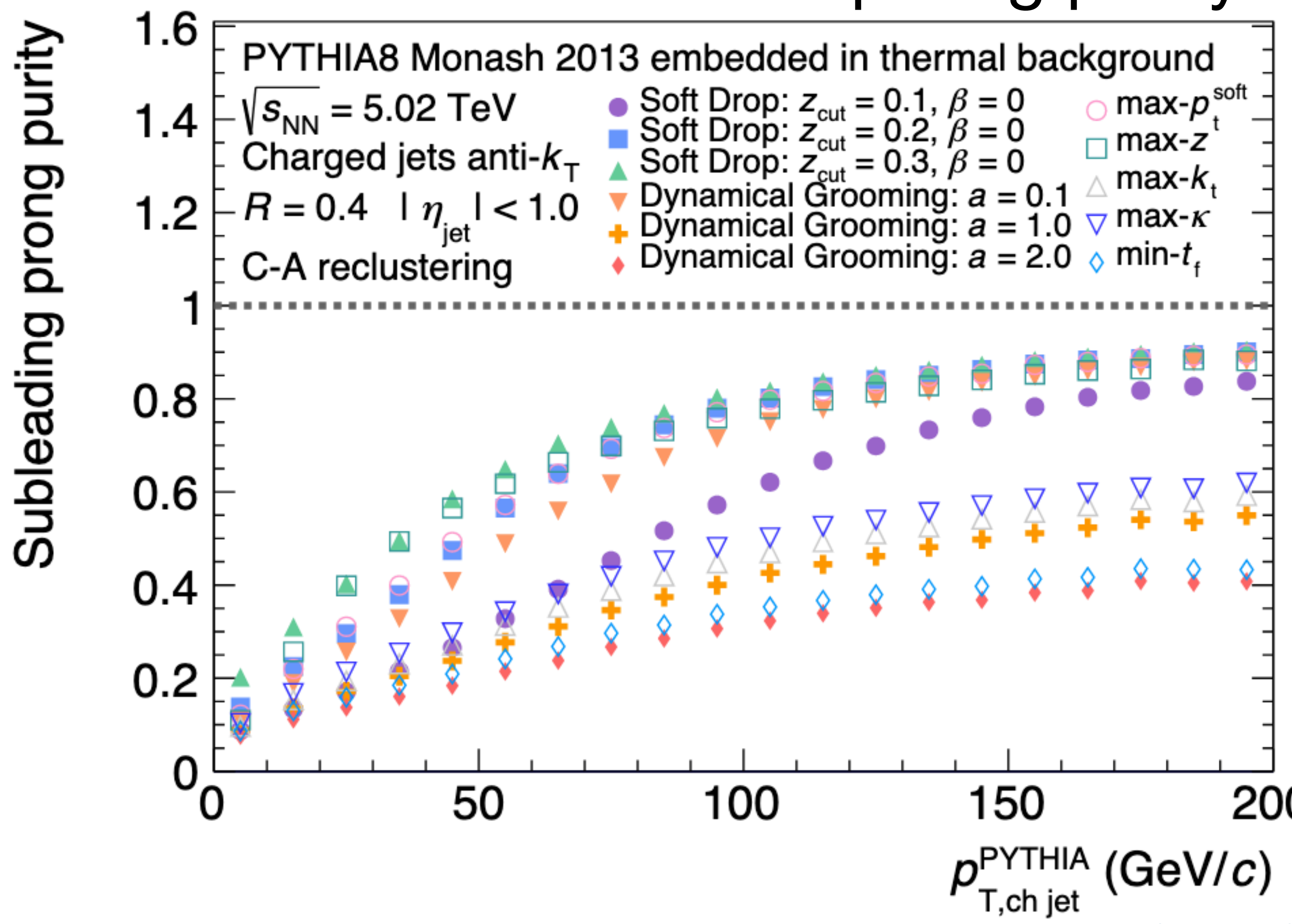
Main problem: combinatorial background from the large underlying event



fake splittings at large angles



low spltting purity



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

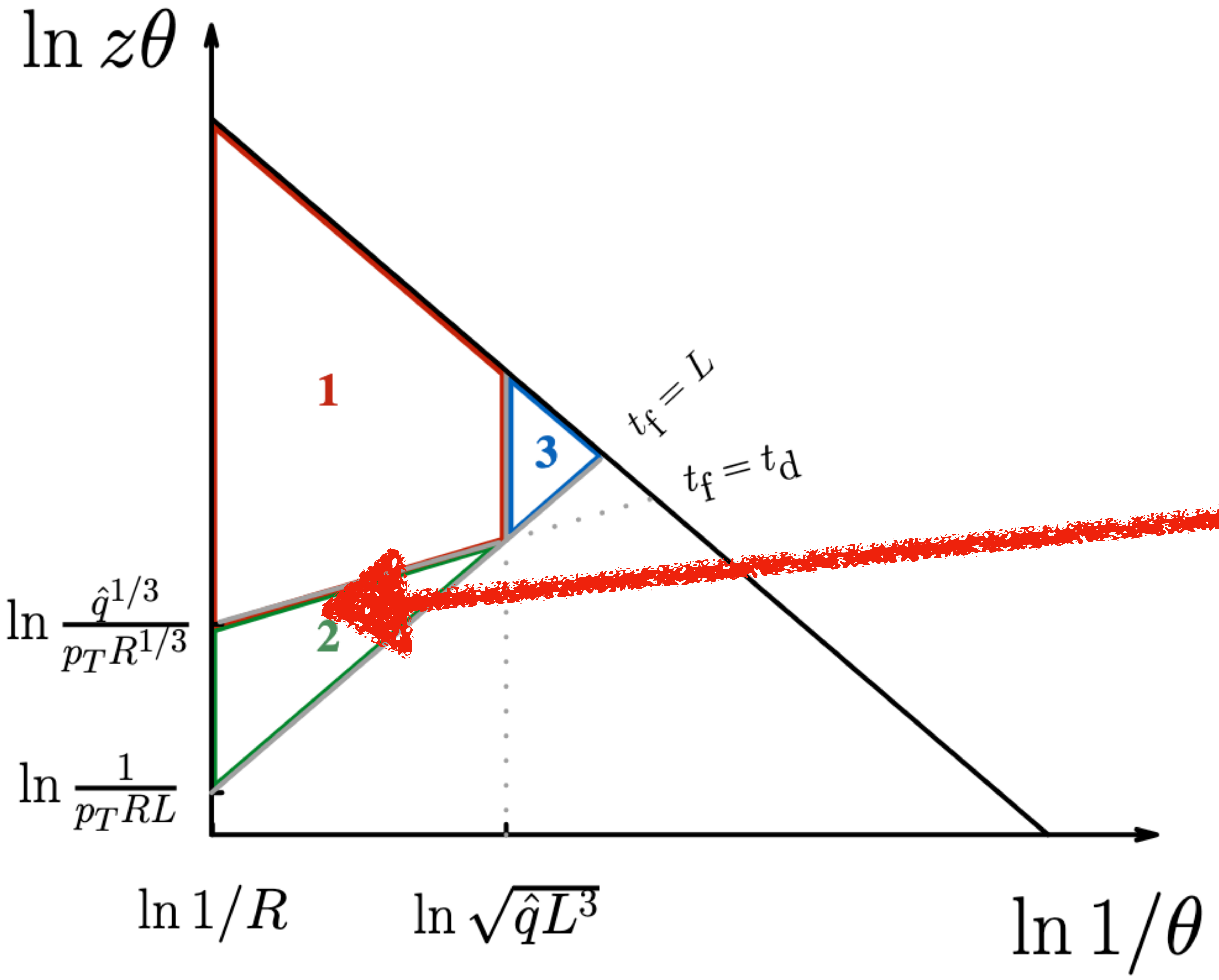
The underlying event creates fake subleading prongs at large angles (where area is maximal)

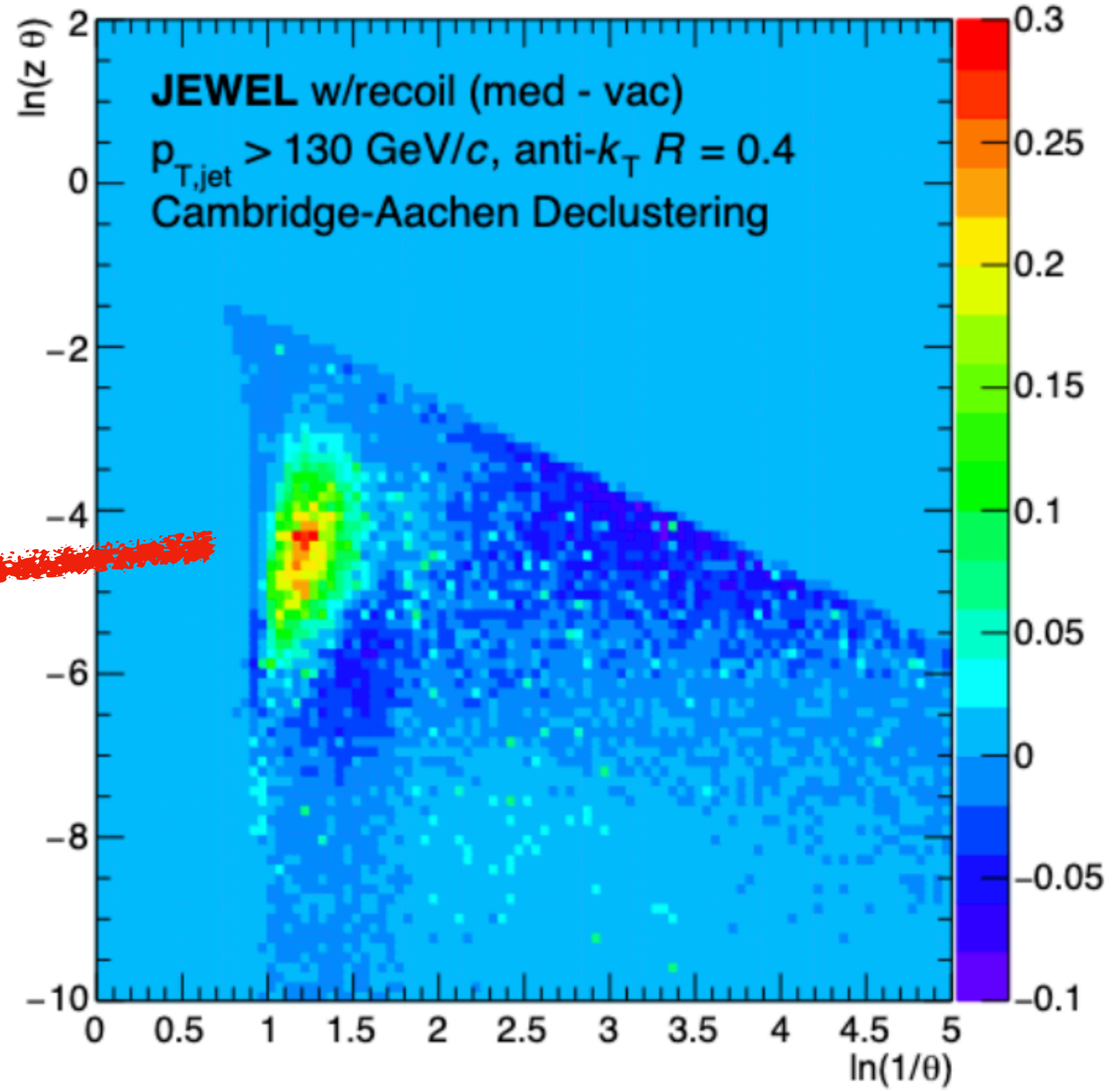
Full measurement of the Lund plane problematic

See Konrad's slides, from 2017 Jet Tools Workshop

The heavy-ion case: distortion of the jet tree

The medium response: particles from the medium that are excited by the jet

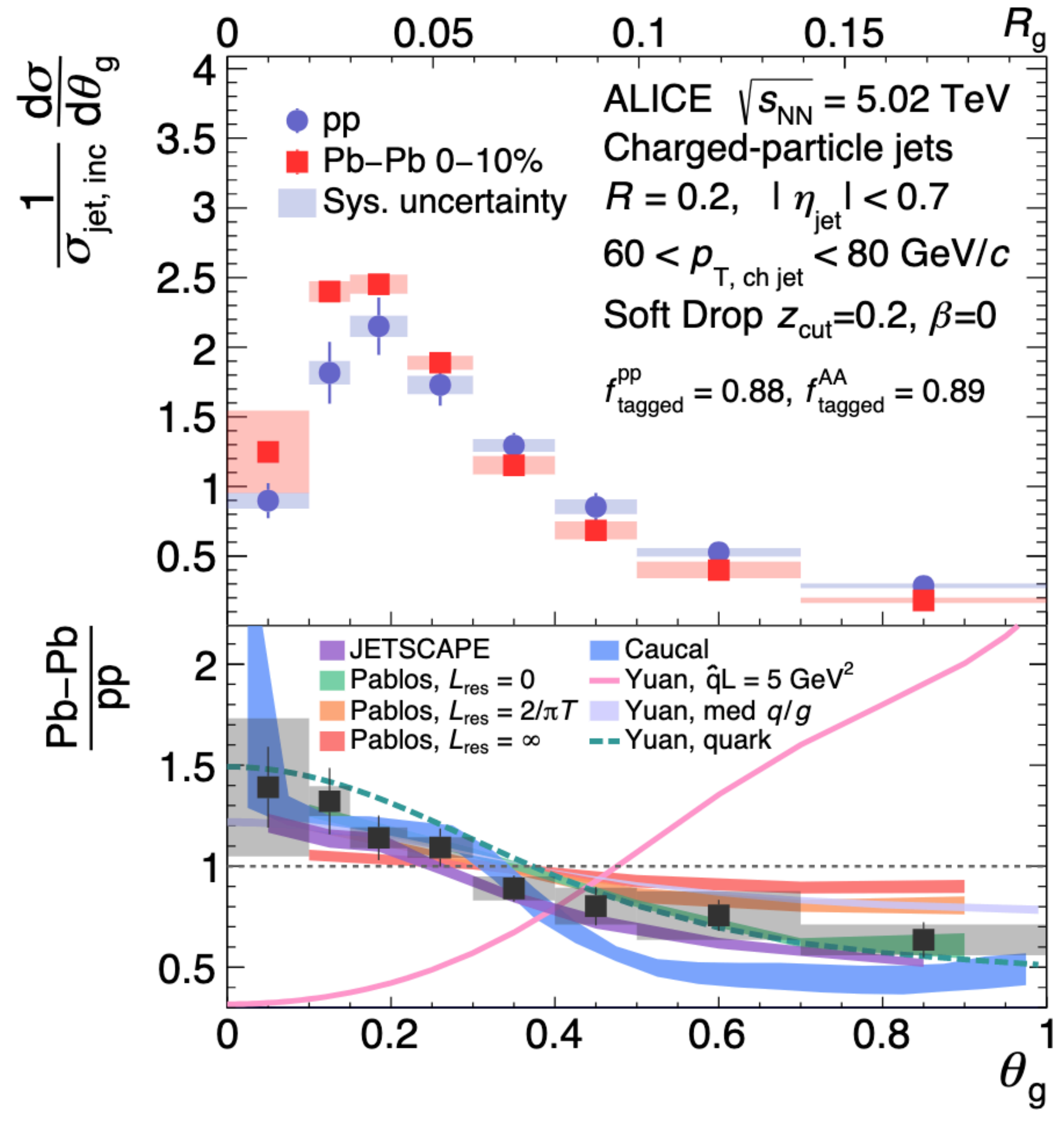




The the medium response acts like a correlated bkg, and is expected to populate the region of large-angle splittings

See Konrad's slides, from 2017 Jet Tools Workshop

The heavy-ion case: searching for signal



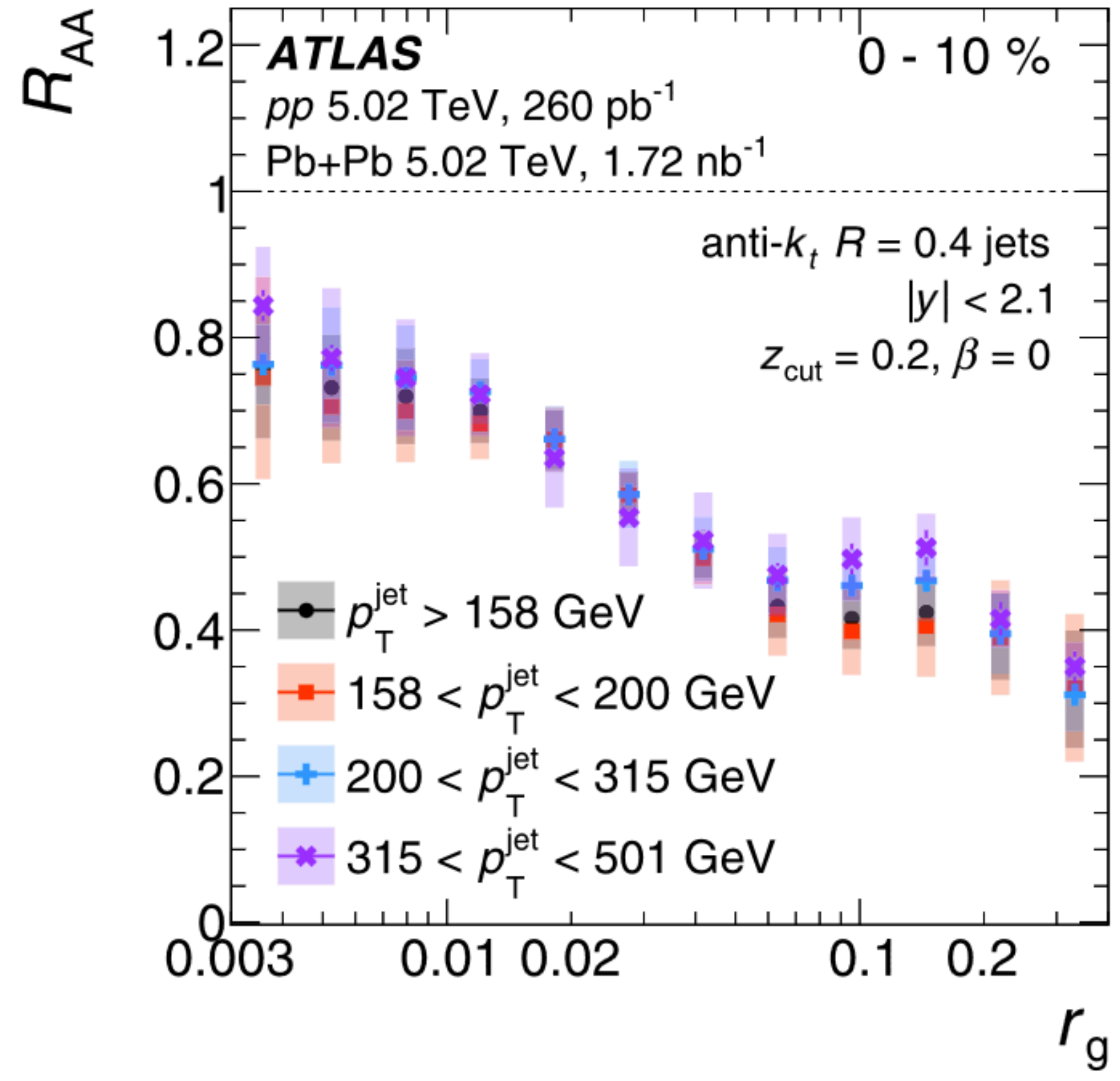
- A full measurement of the Lund plane is challenging in heavy-ion collisions
- Scanning strategies so far are SoftDrop and Dynamical grooming

  Larkoski et al, JHEP 05 (2014) 146

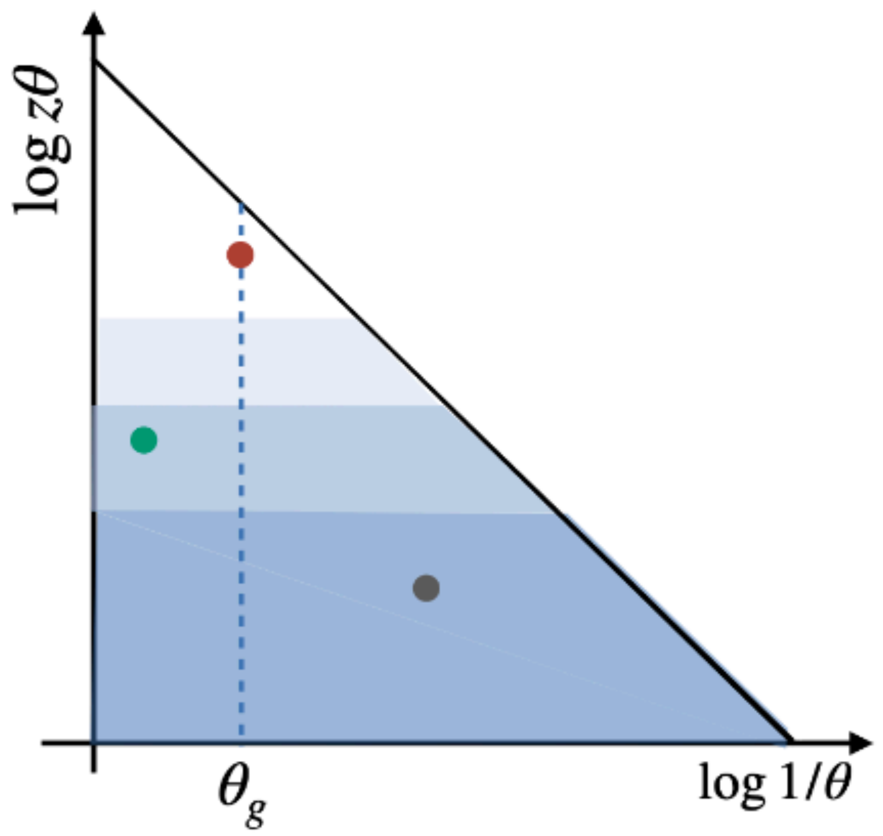
  Butterworth et al, Phys.Rev.Lett. 100 (2008) 242001

  Mehtar-Tani et al, Phys.Rev.D 101(2020) 3, 034004

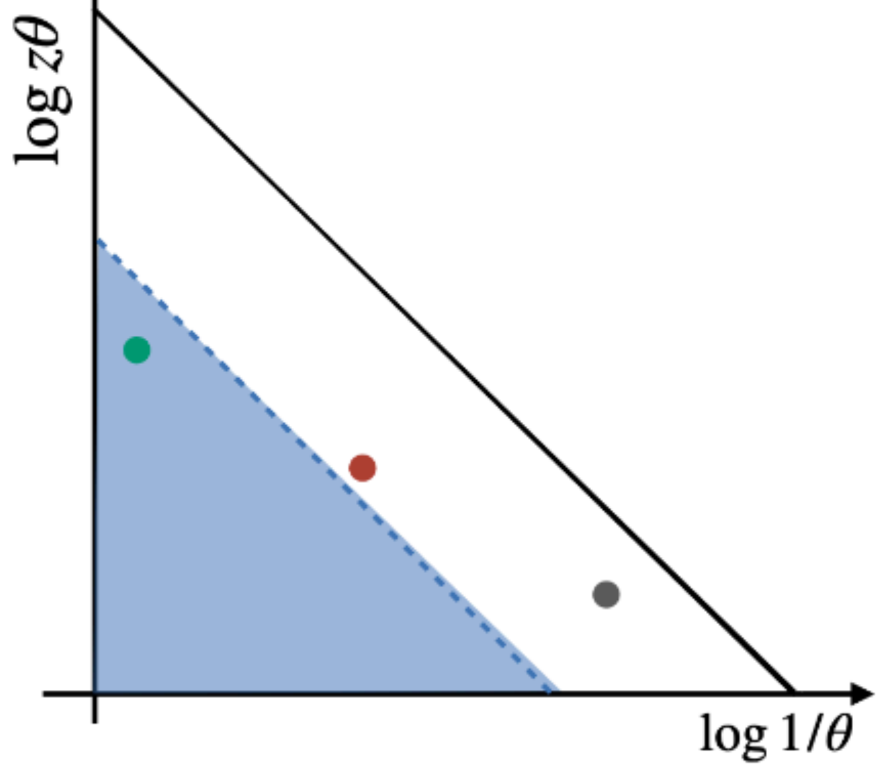
- The observed narrowing is most likely due to a a selection bias by which broad jets are strongly quench and migrate to lower jet p_T EW boson-jet substructure is next step!
- Sensitivity to relevant scales

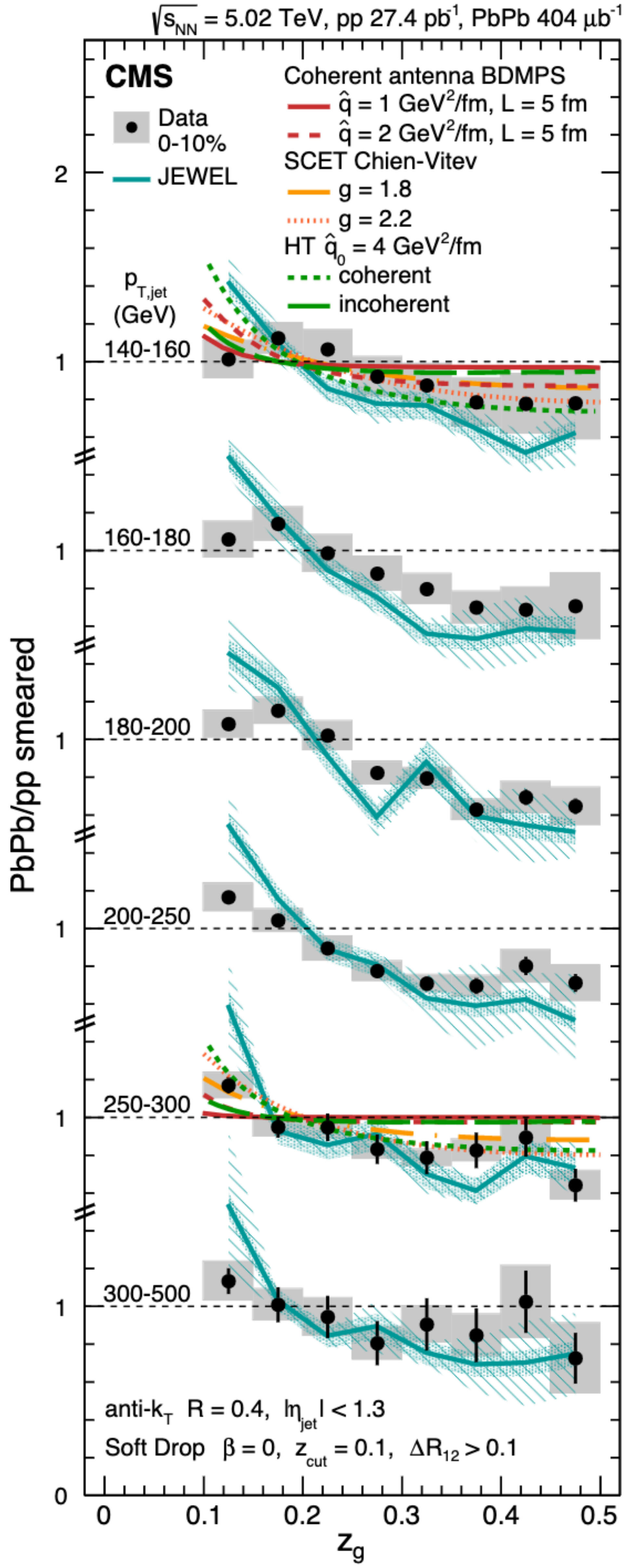


DyG:



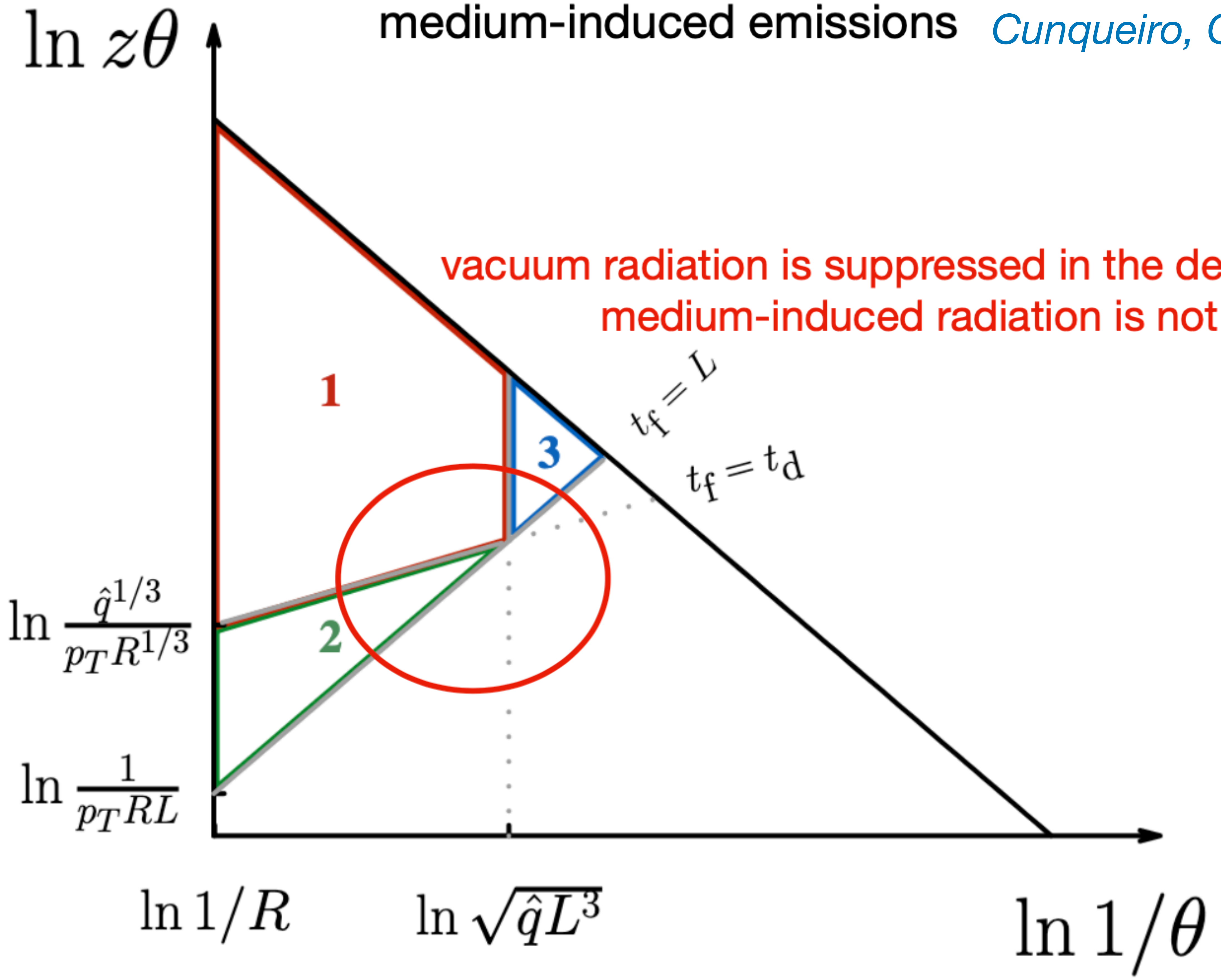
SD:

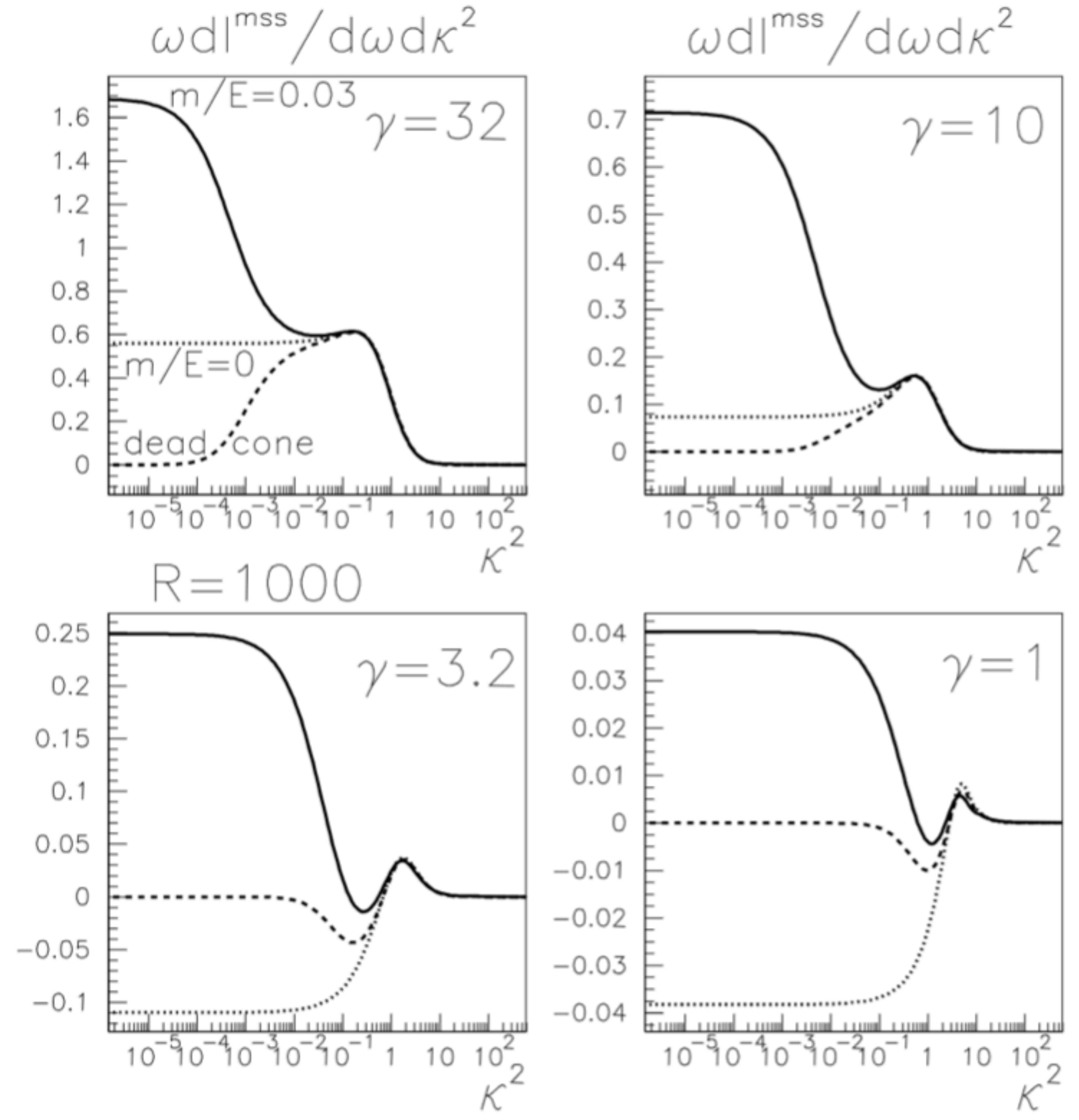




The heavy-ion case: searching for signal in a clean corner of phase space

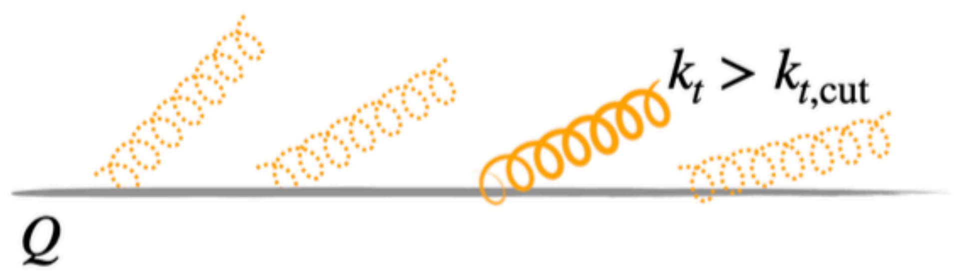
IDEA: Exploit dead-cone suppression of vacuum radiation to access a clean, pQCD regime of medium-induced emissions *Cunqueiro, Ontoso, Napoletano, Phys.Rev.D 107 (2023) 9, 094008*





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



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

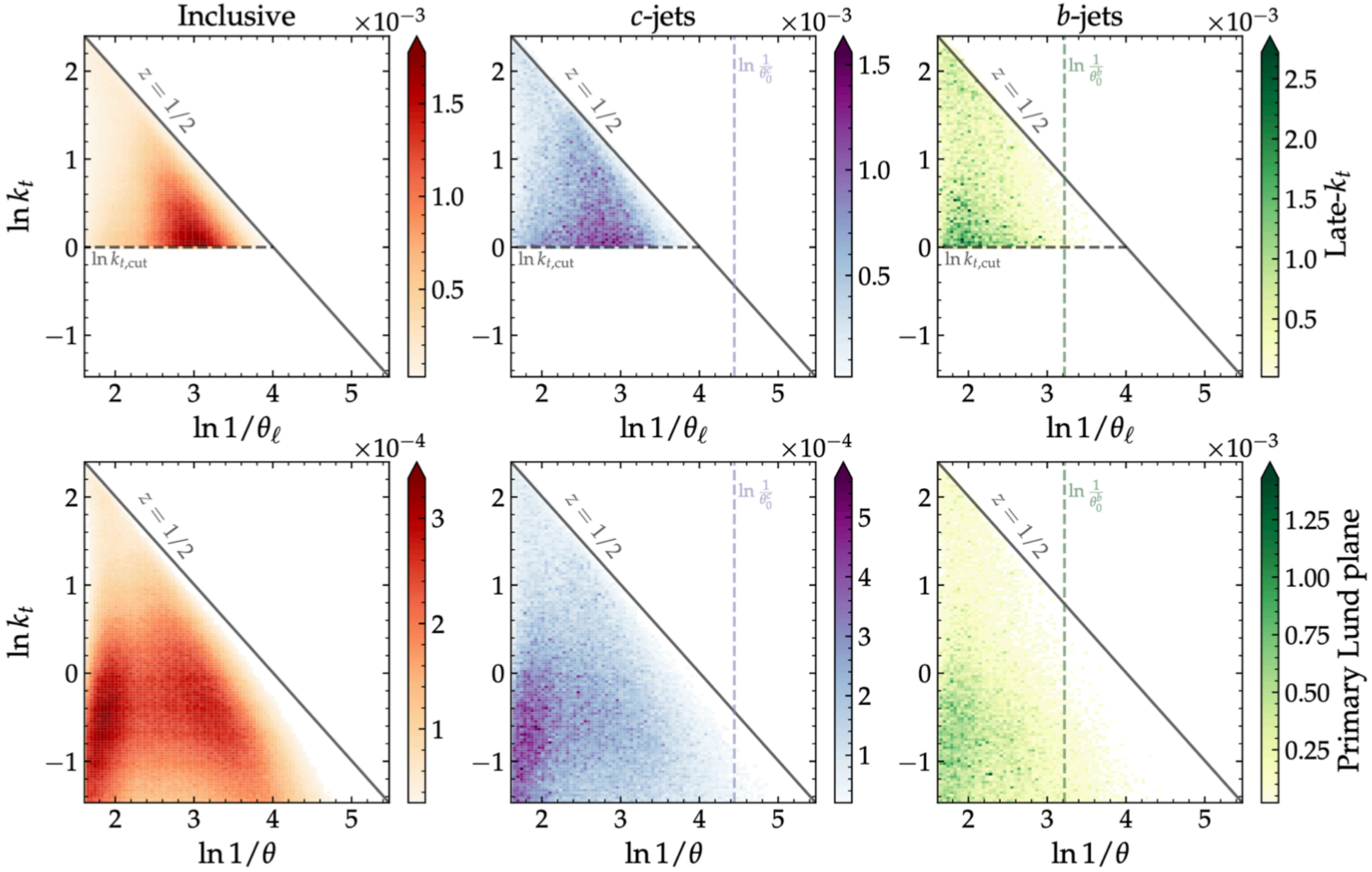
$$k_t = \min(p_{t,a}, p_{t,b})\Delta_{ab}, \quad (3)$$

   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 $k_t > k_{t,\mathrm{cut}}$, 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.

Cunqueiro,Napoletano, Soto-Ontoso, 2211.11789

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

E=100 GeV, Pythia8 at hadron level



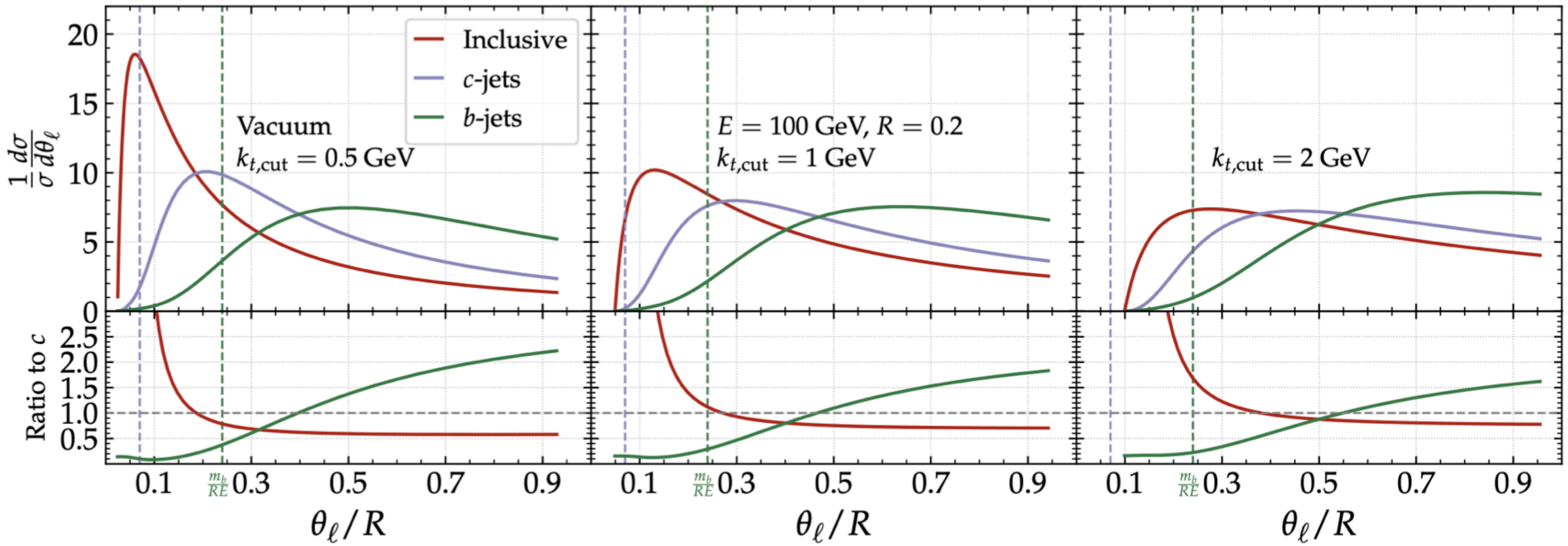
Late-k_T splittings populate the plane at small angles

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

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

Interesting interplay of scales

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

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

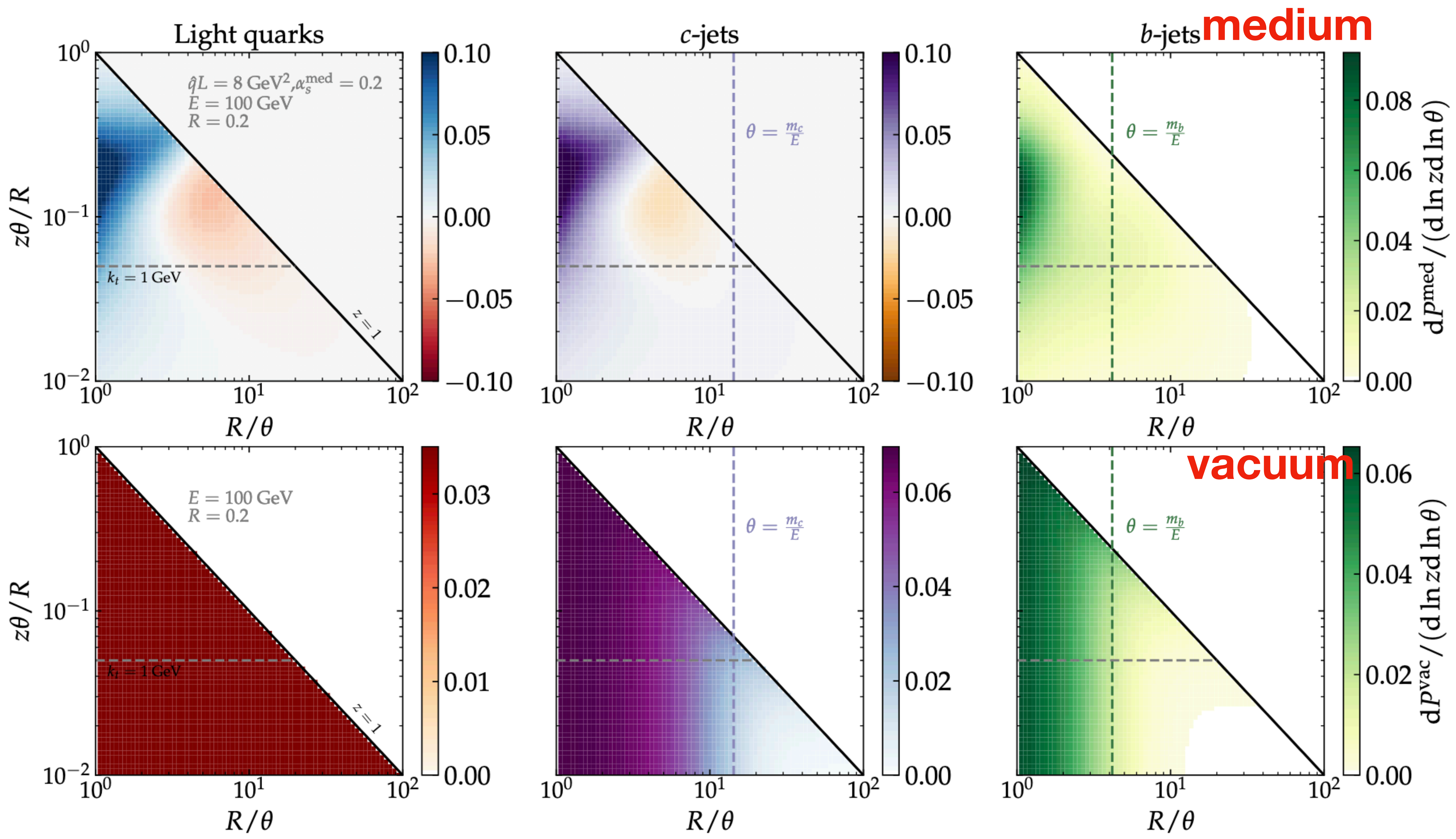
The dead cone angle needs to be wider than the decoherence angle for it to be filled with medium emission

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

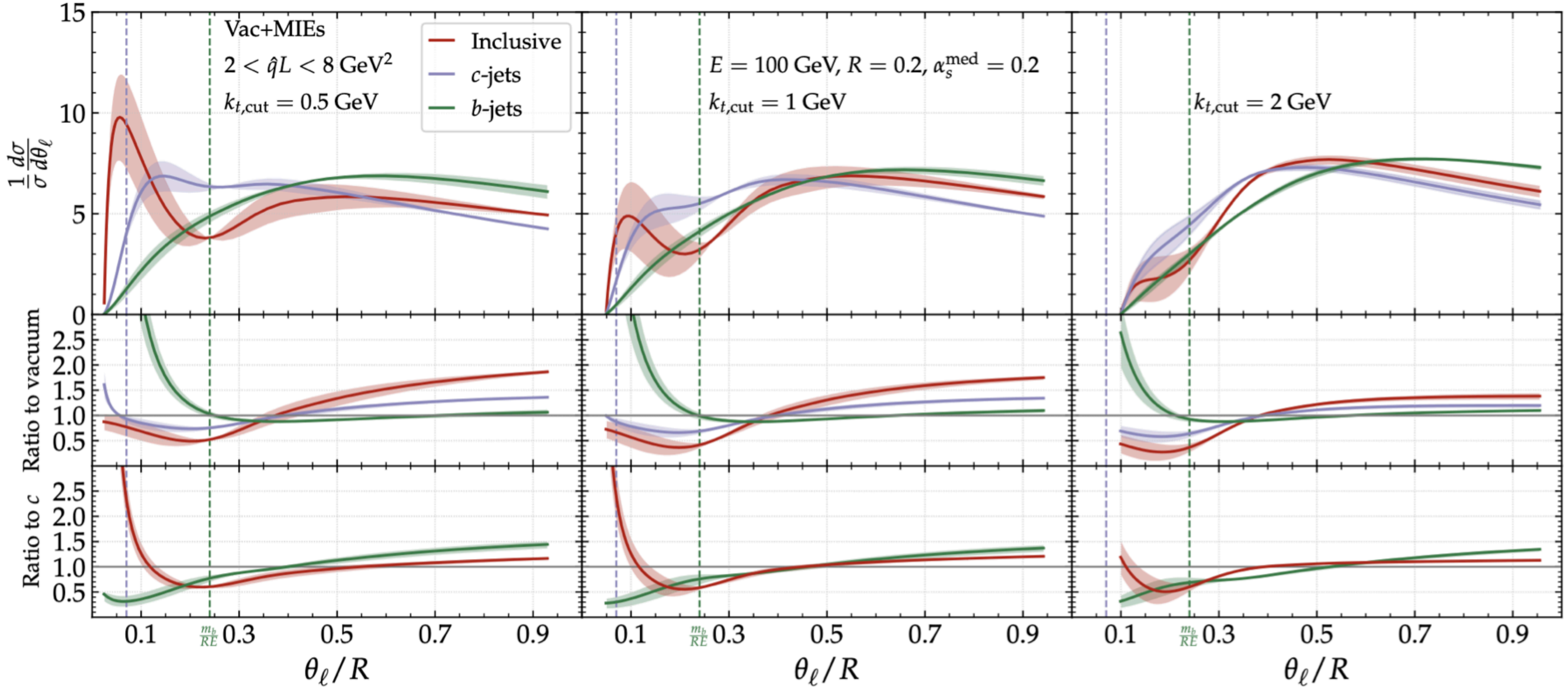


Radiation clumps around typical transverse momentum scale acquired by diffusion in transverse space $Qs^2=\hat{q}$ L

(L is the medium length and $\hat{q}$ is the transport coefficient of the QGP)

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

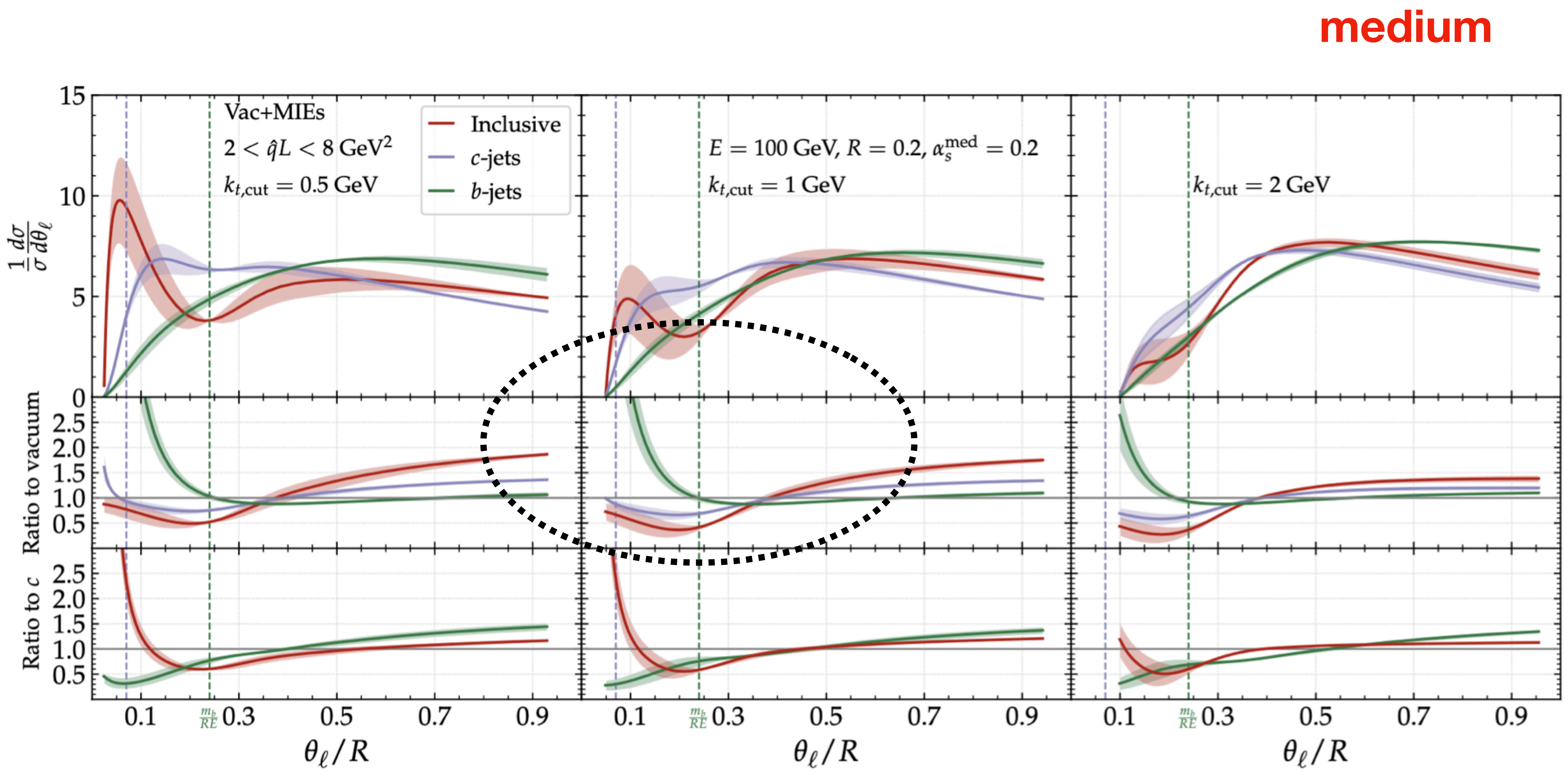
medium



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



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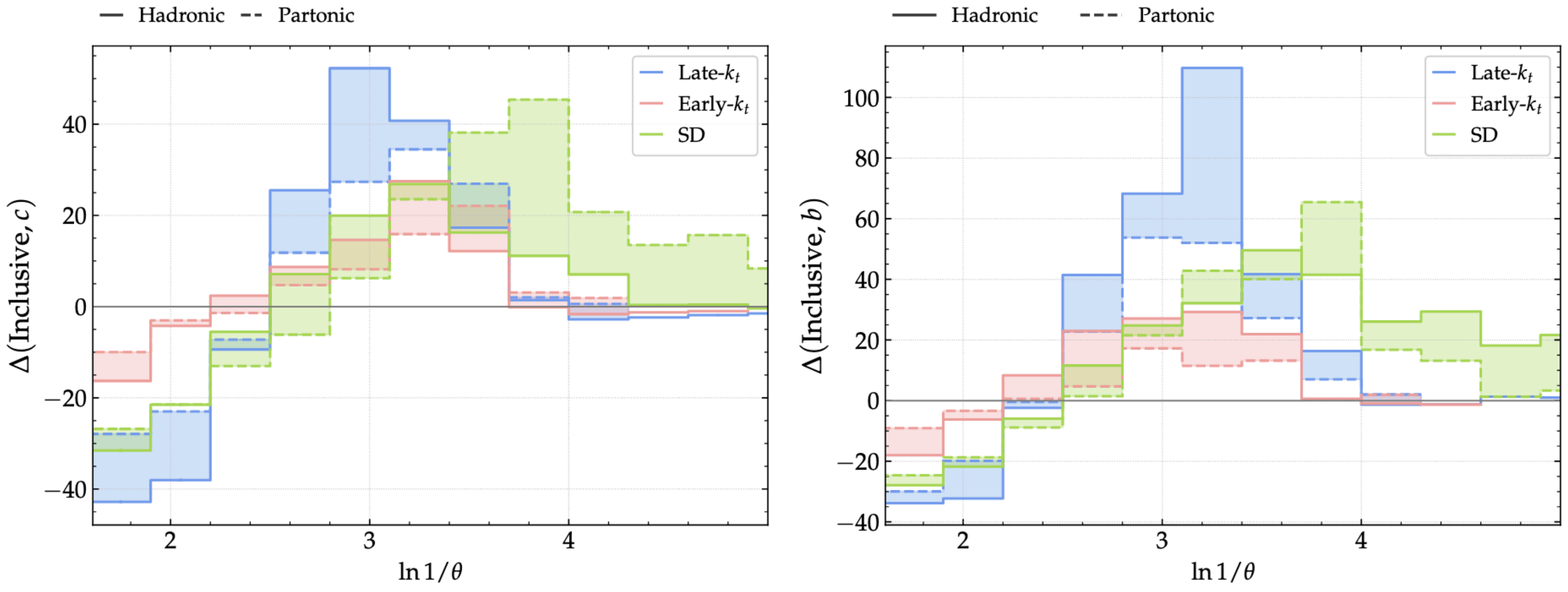
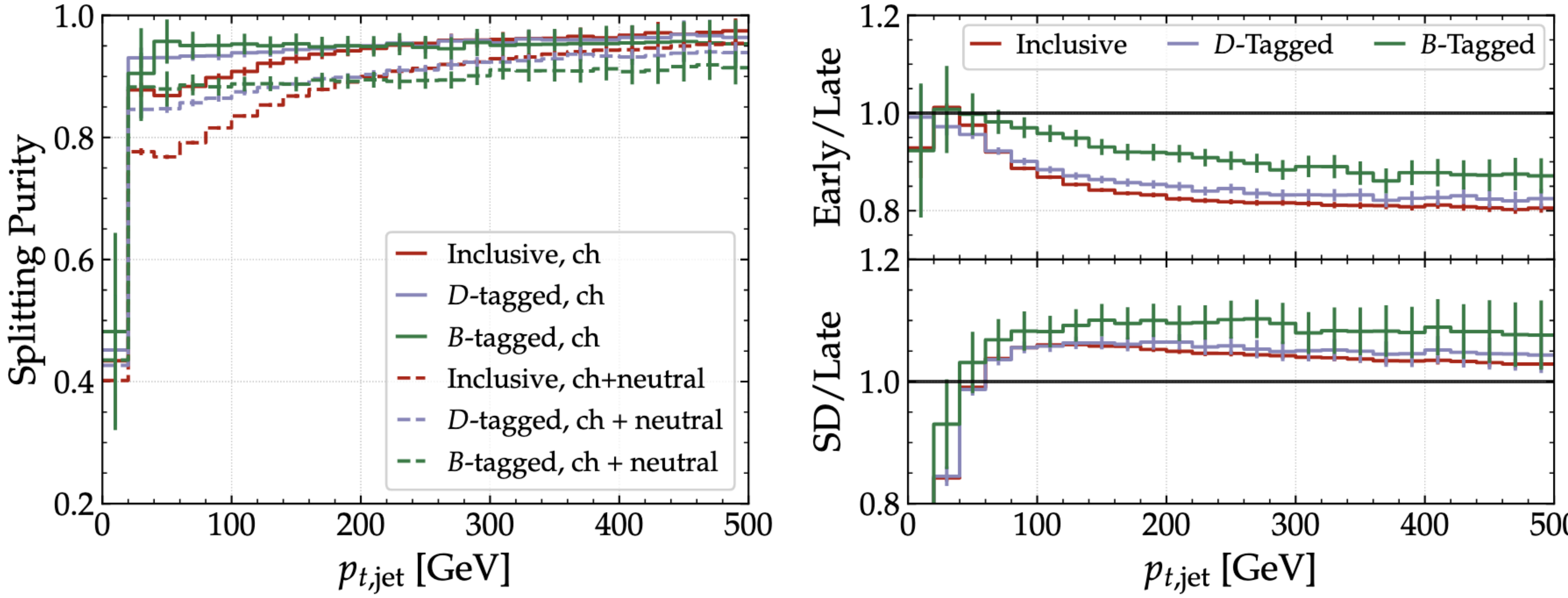
D-jets and inclusive jets show transverse momentum broadening

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

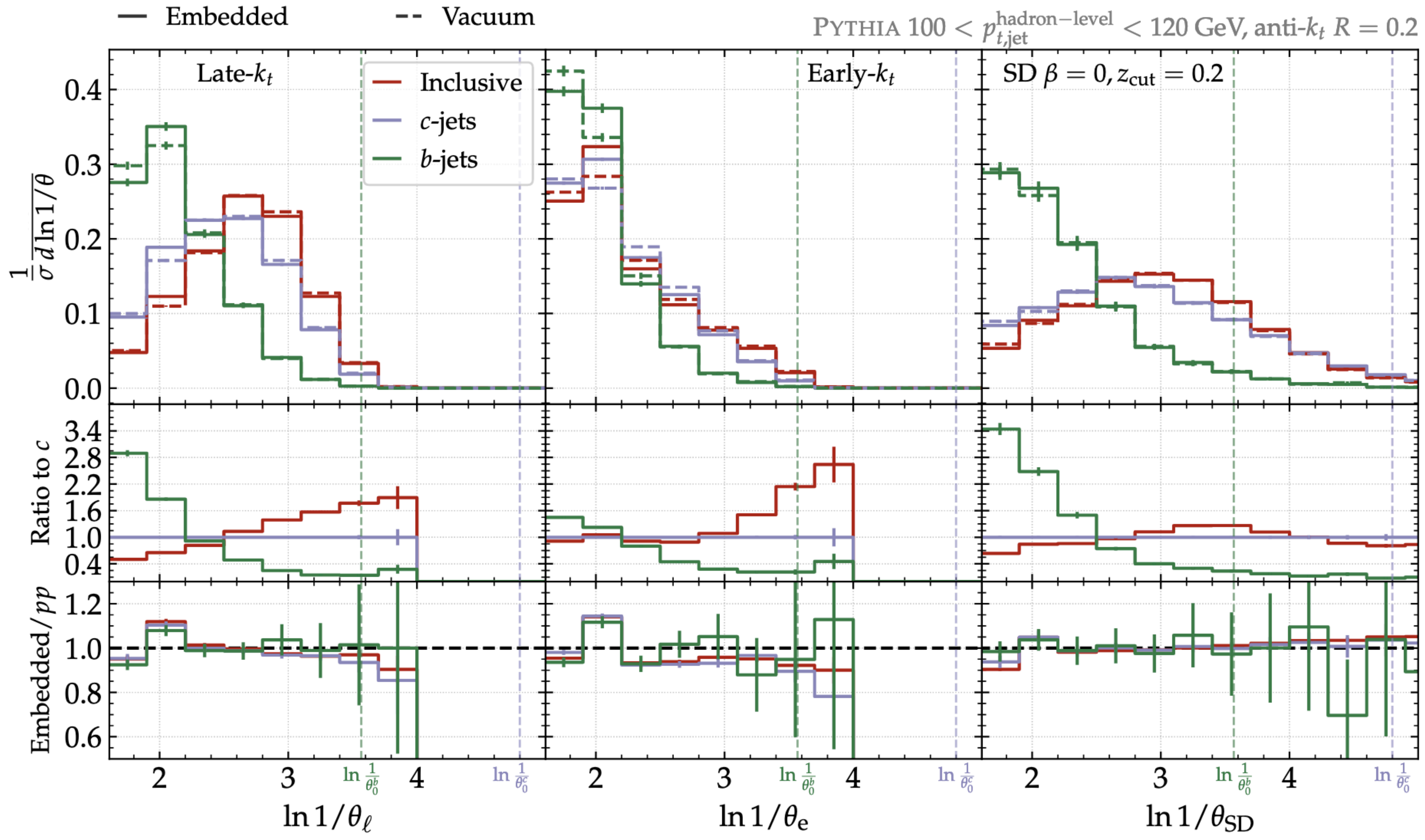
Separation power at parton and hadron level



Splitting purity



Resilience to heavy ion background



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

Methods and calculations alternative to using jet tree based on energy correlators, progressing fast
Would be interesting to understand systematically pros and cons of the two alternative approaches

But….

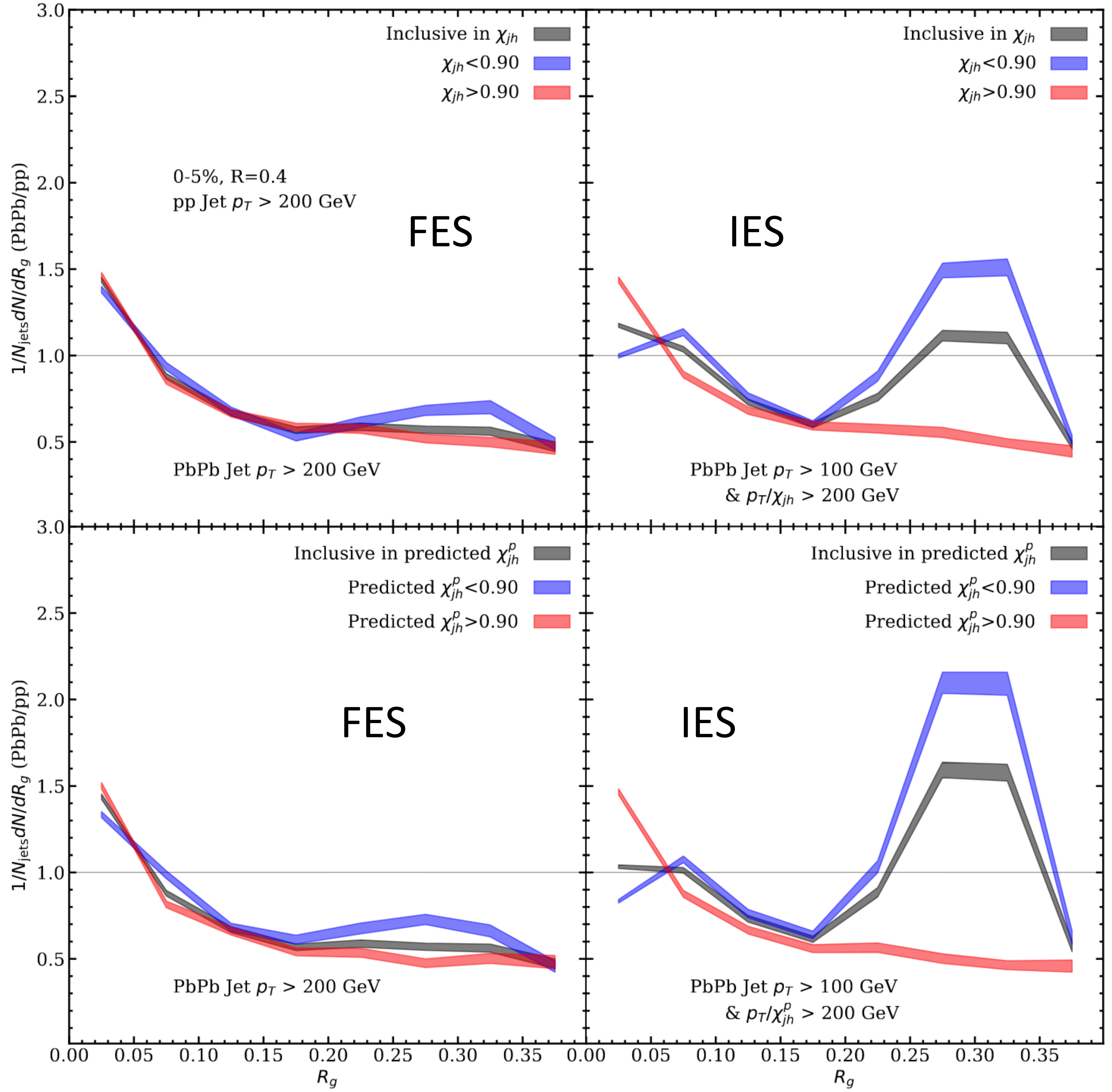
We are comparing pp and PbPb jets at the same reconstructed energy.
That doesn't map to the same scattered parton energy due to energy loss of the latter

Vacuum and medium-modified showers factorize in time to a first approximation[1],
with the harder vacuum part happening earlier. A broader, early vacuum shower
will undergo a more active medium-induced shower due to the larger number of emitters.
This introduces a jet-width dependence of energy loss, interwound with flavour. These effects
coexist with color coherence, which further regulates the number of emitters in medium

Thus the interpretation of the results is ambiguous

[1] Caucal et al, Phys. Rev. Lett. 120 (2018) 232001

Selection bias



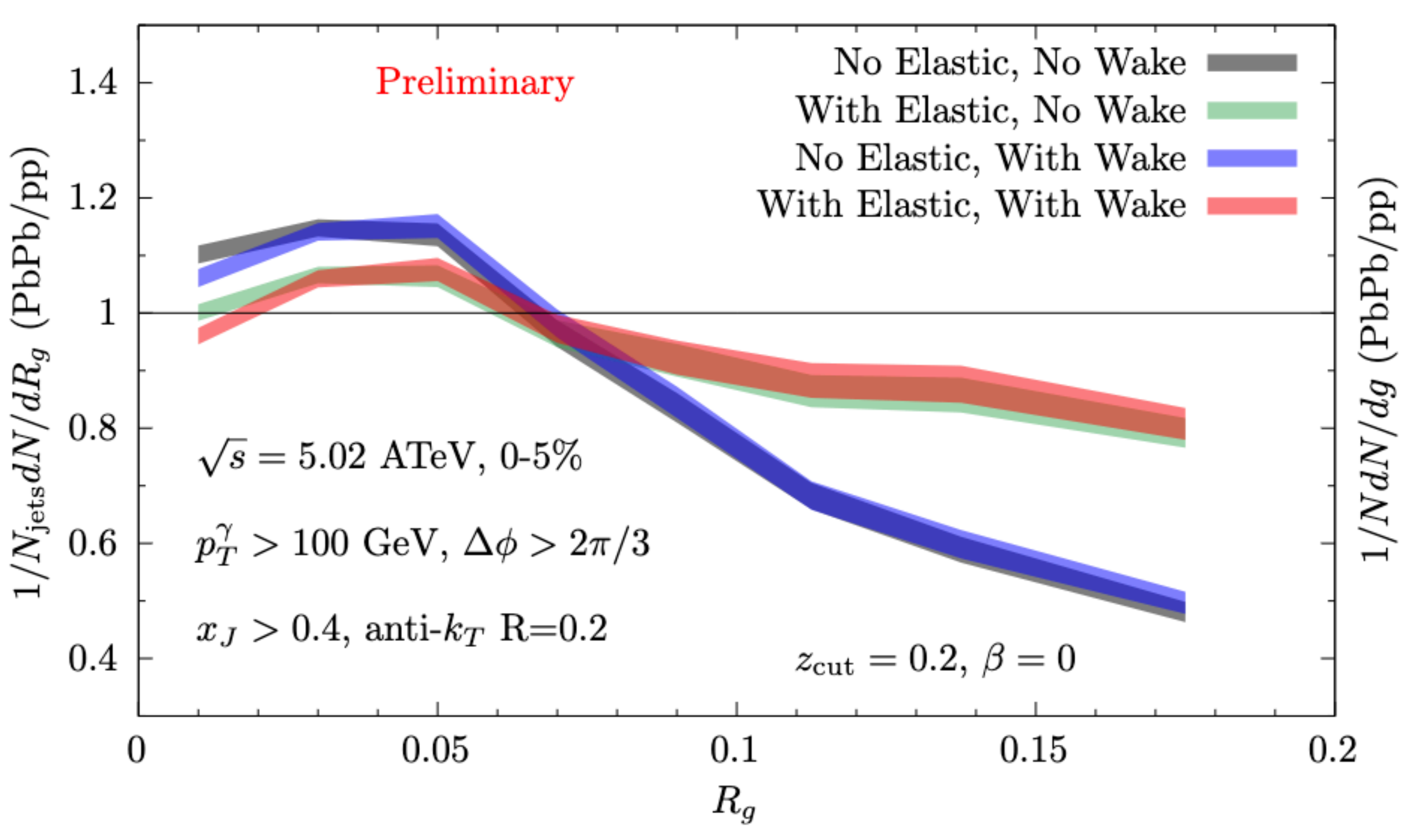
Du et al, 2106.11271, Brewer et al, 2009.03316

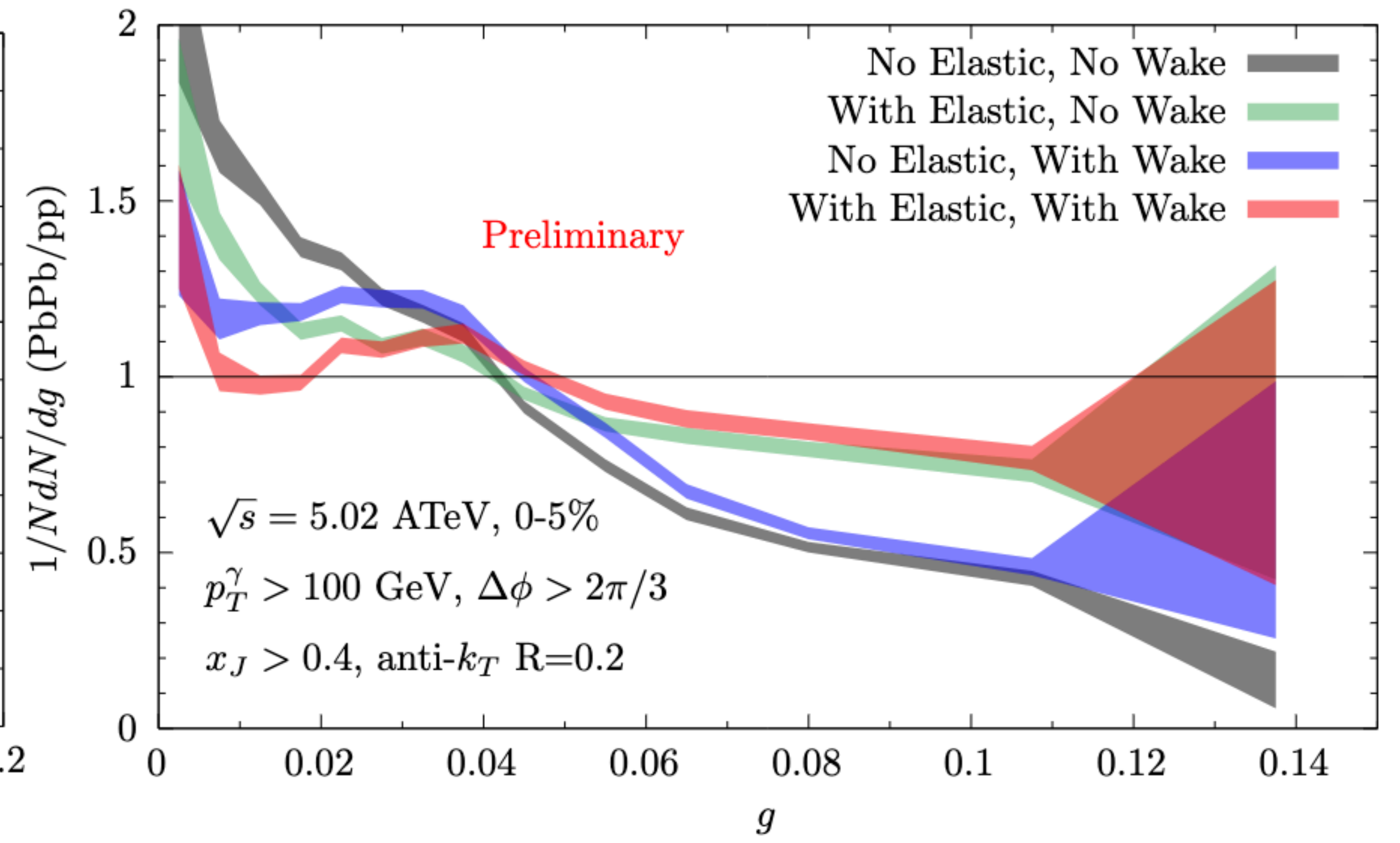
Unquenched class: $\chi > 0.9$

Quenched class: $\chi < 0.9$

Similar conclusion when accessing the true jet energy via ML

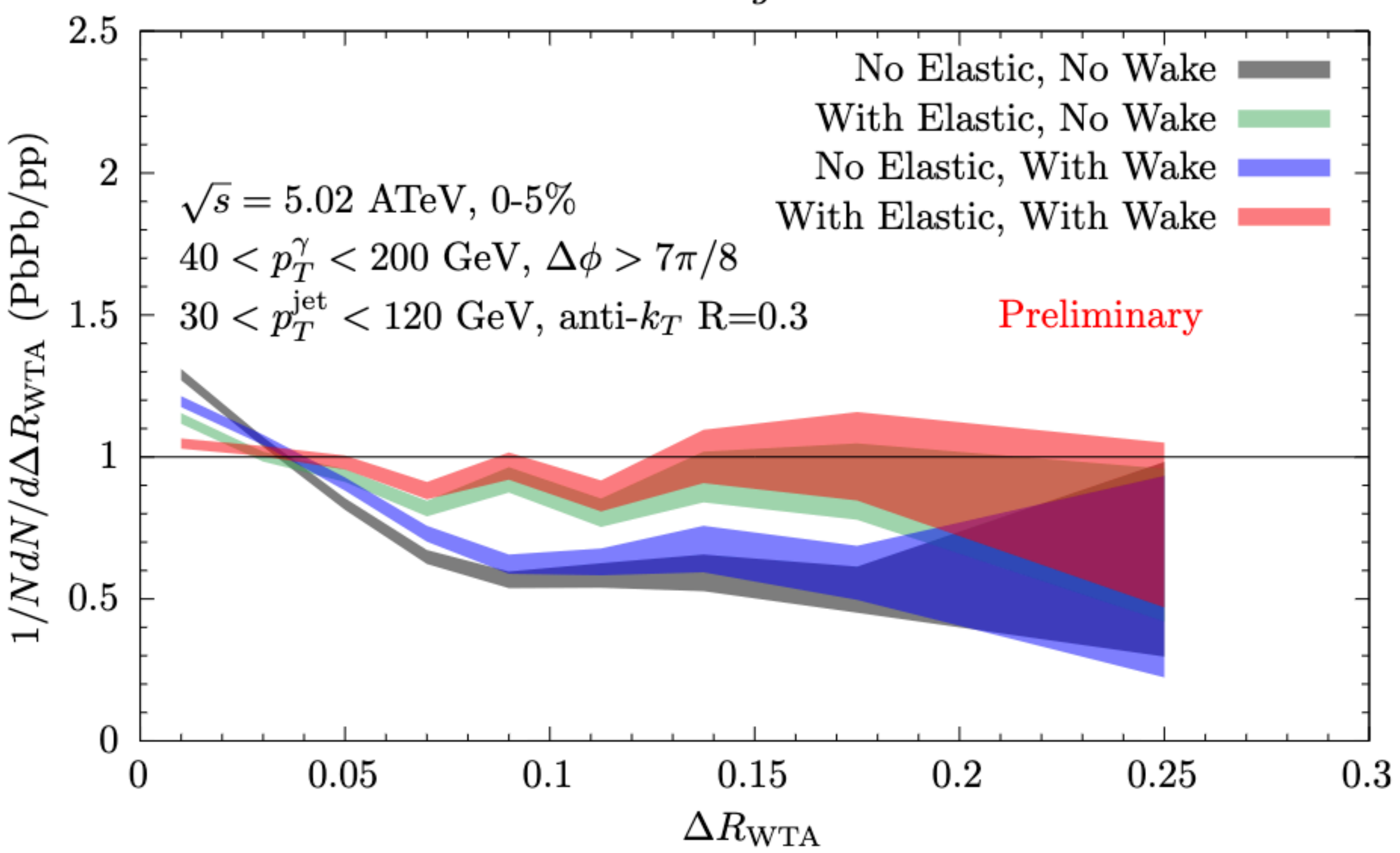
Mitigating the selection bias with γ-jet events





Stay tuned for the upcoming CMS data

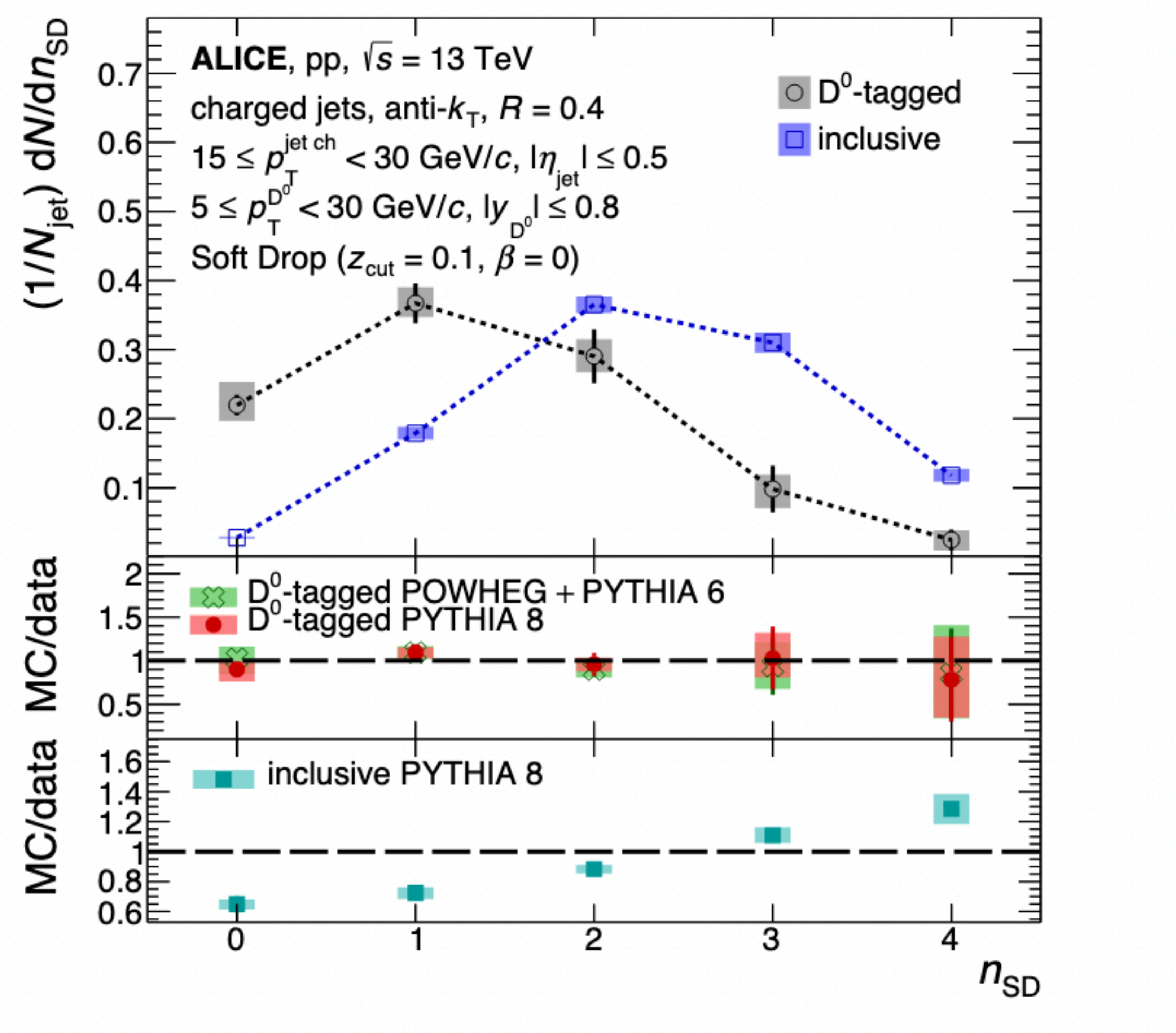
All show much less sensitivity to wake: R=0.2; Moliere scattering shows up; effects of Moliere and wake are again similar in shape, but here effects of Moliere are very much dominant.



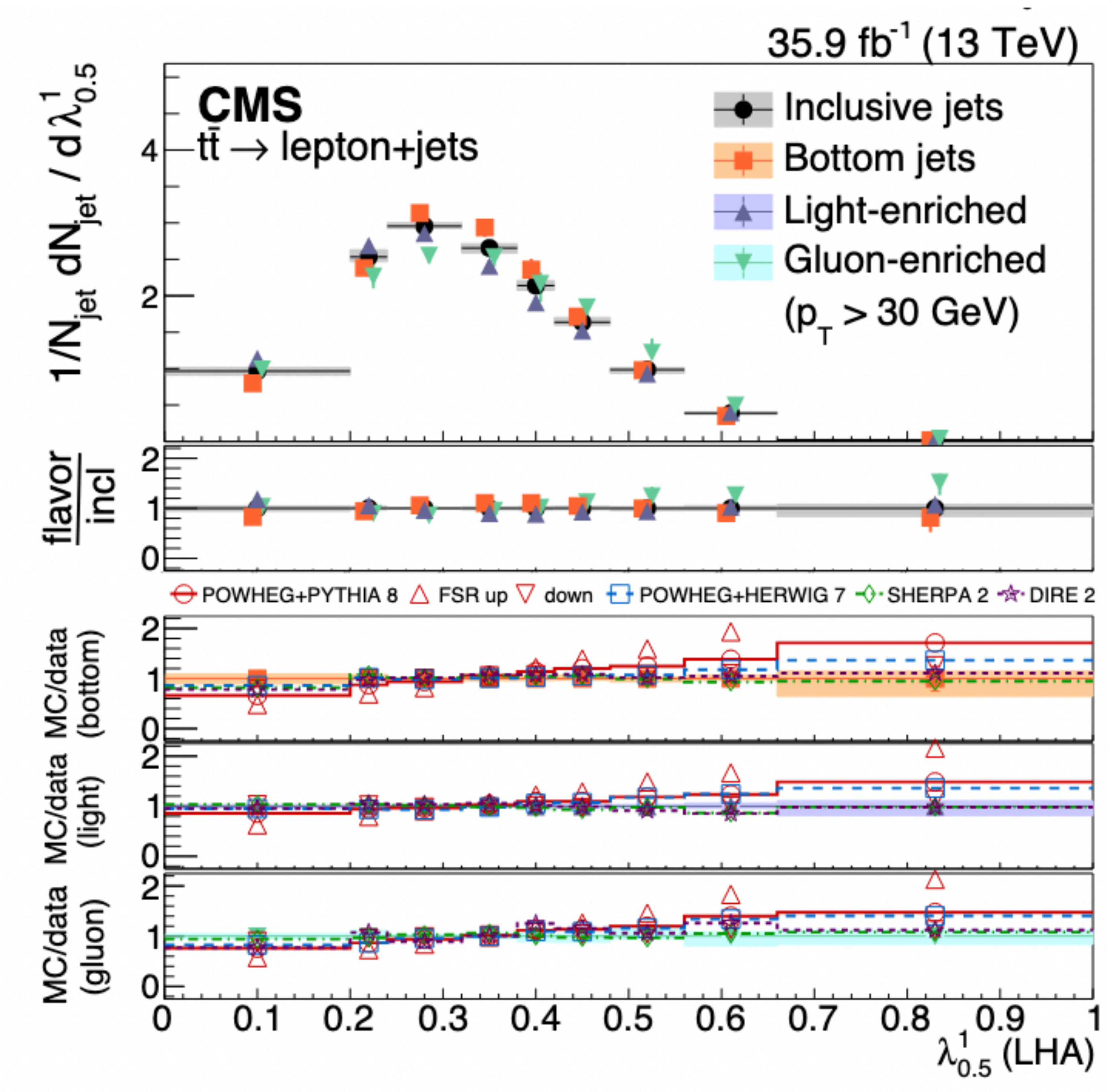
slide from Krishna Rajagopal, Hard Probes 2023

Indirect measurements of the dead cone: a selection

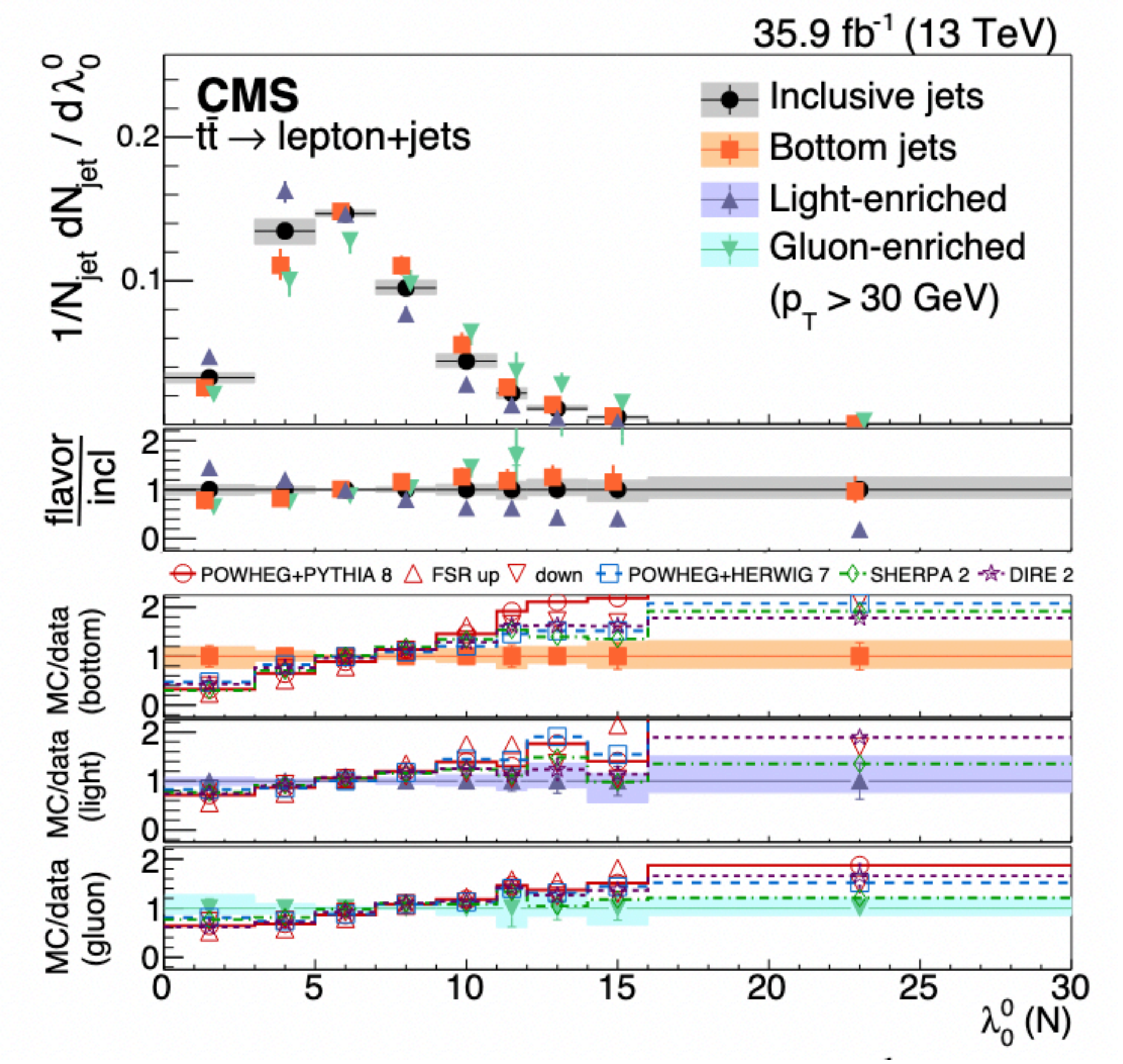
Number of hard prongs



intrajet multiplicity



Angularity



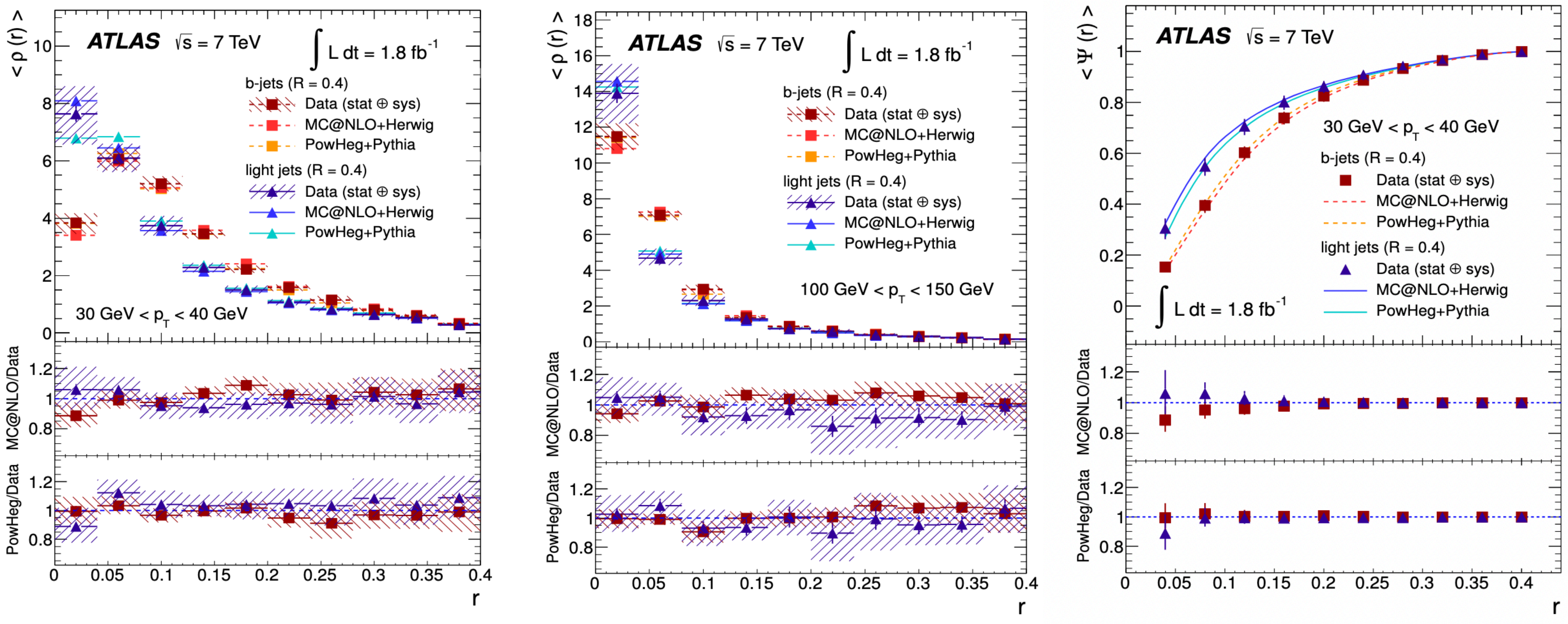
Lower intrajet multiplicities (measured via the number of SoftDrop prongs) in D-jets
Comparison to inclusive includes q/g differences

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

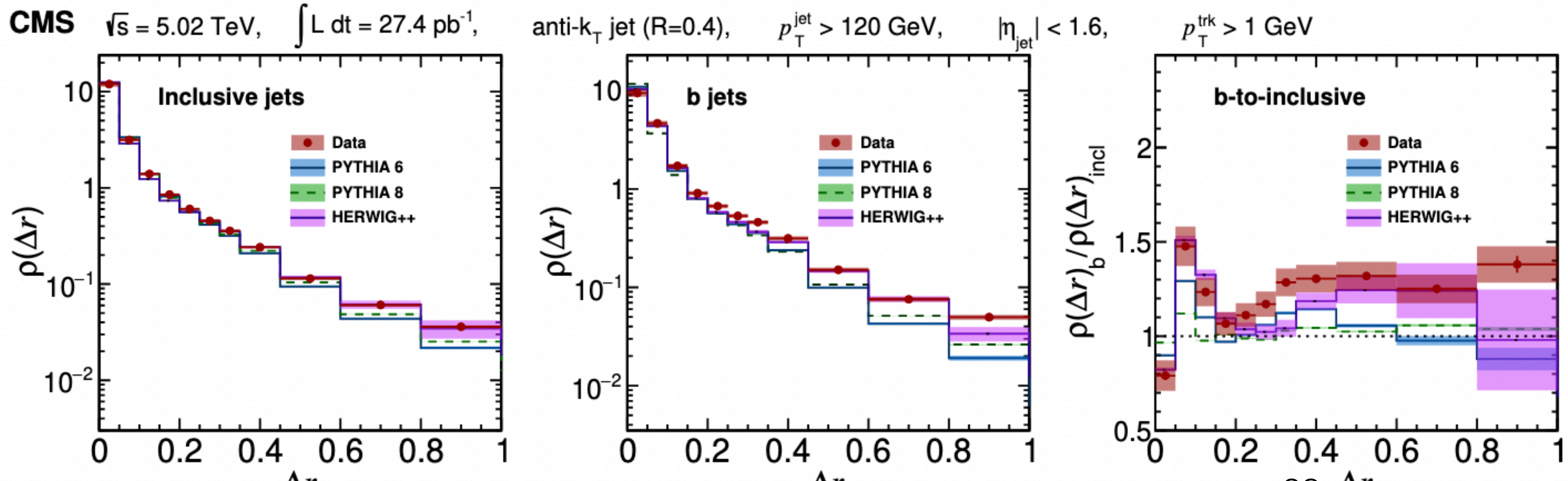


Jet transverse profiles in top-quark pair events

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

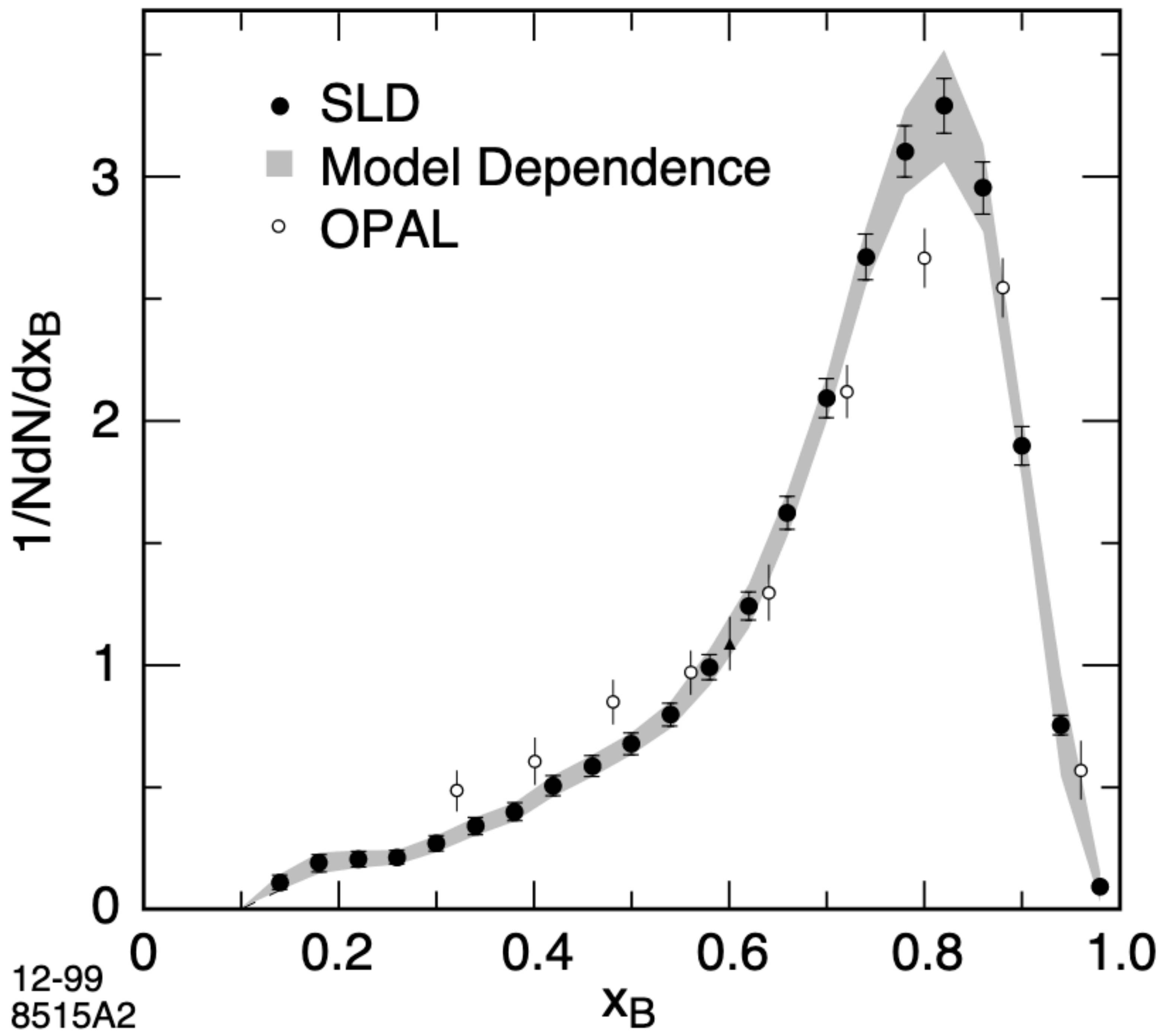


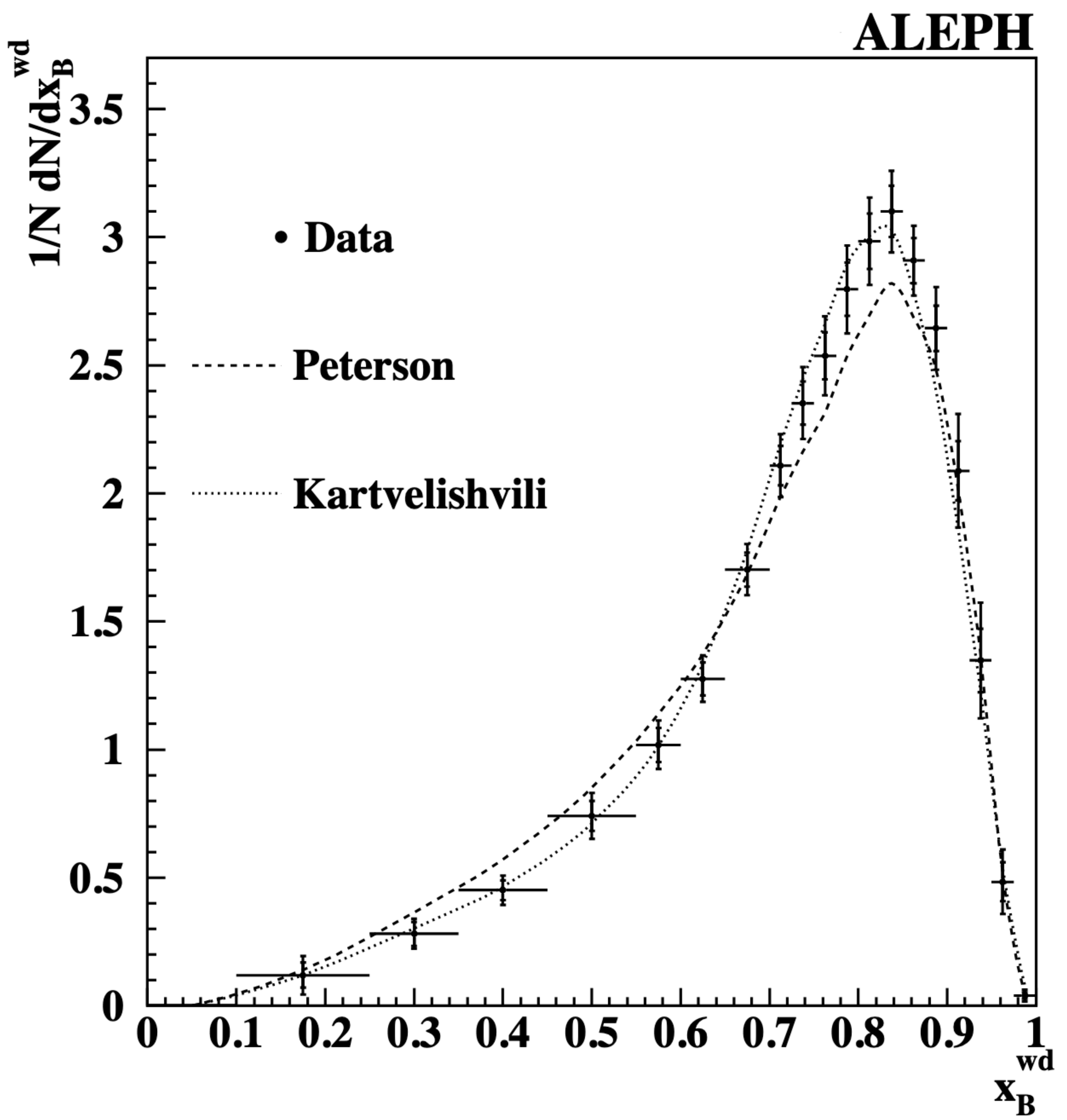
Similar qualitative picture in dijet events and high jet p_T

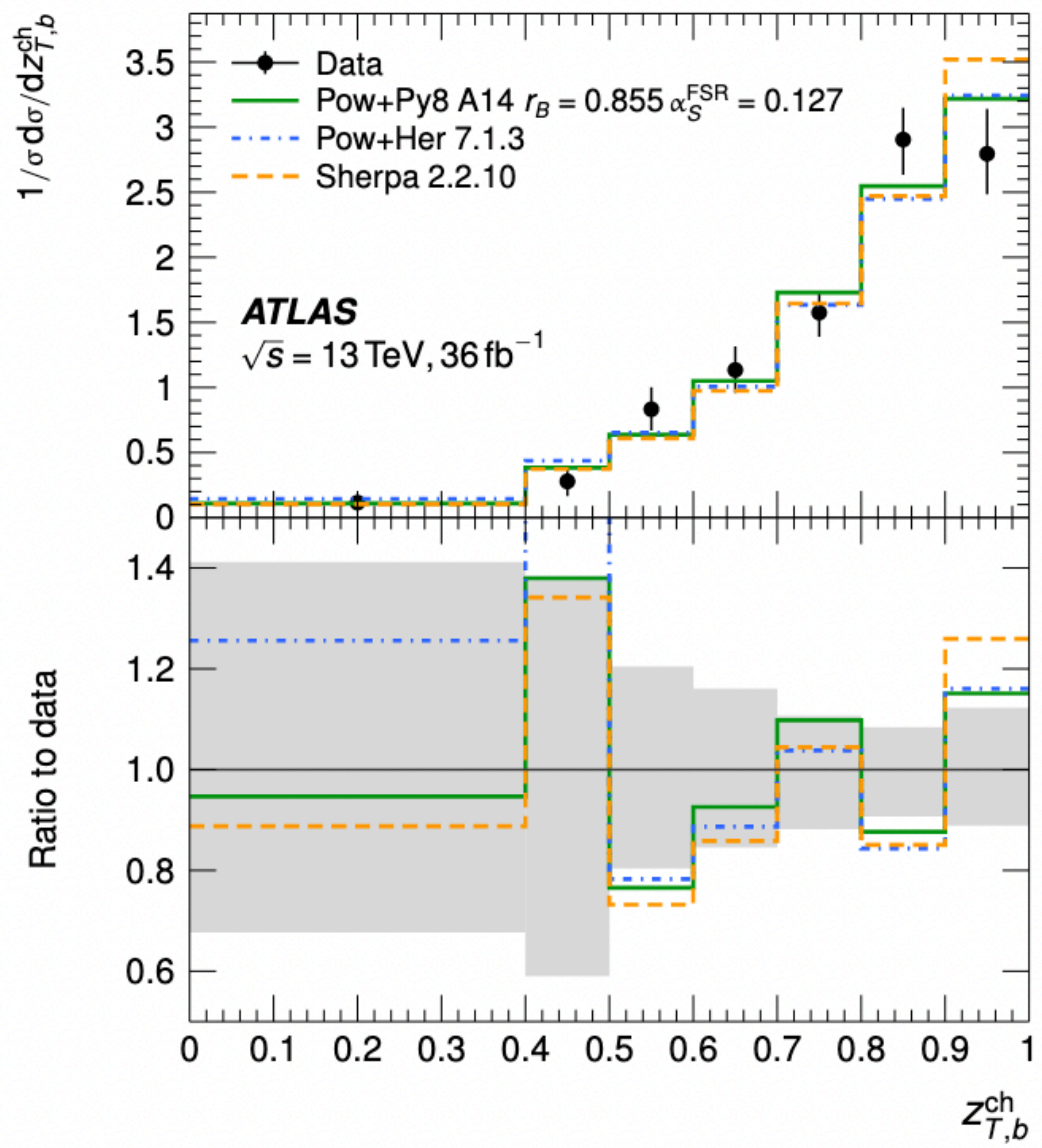
Reference is inclusive jets (q/g effects)

CMS, JHEP05 (2021) 054

Impact of the dead cone on fragmentation: a selection



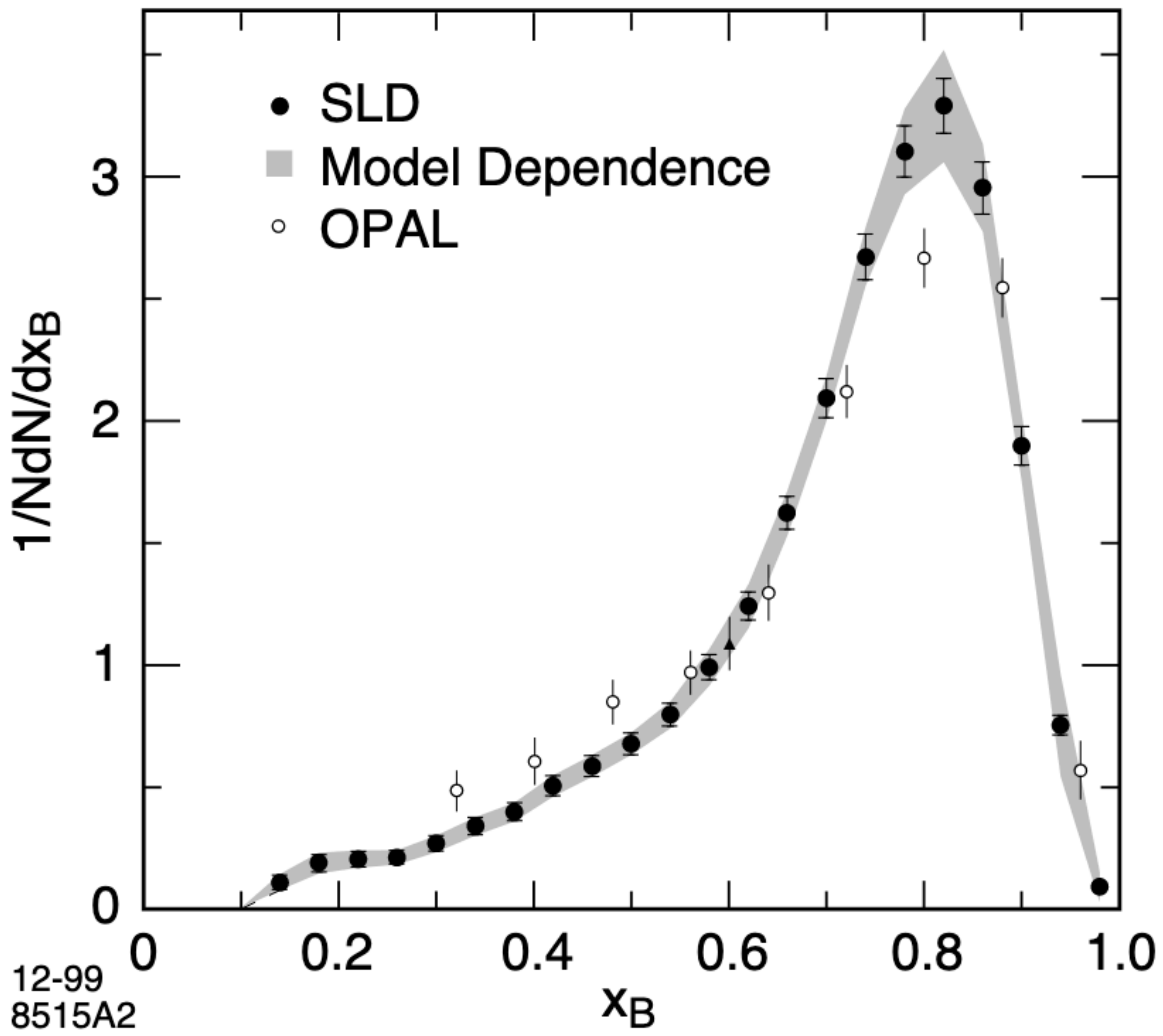


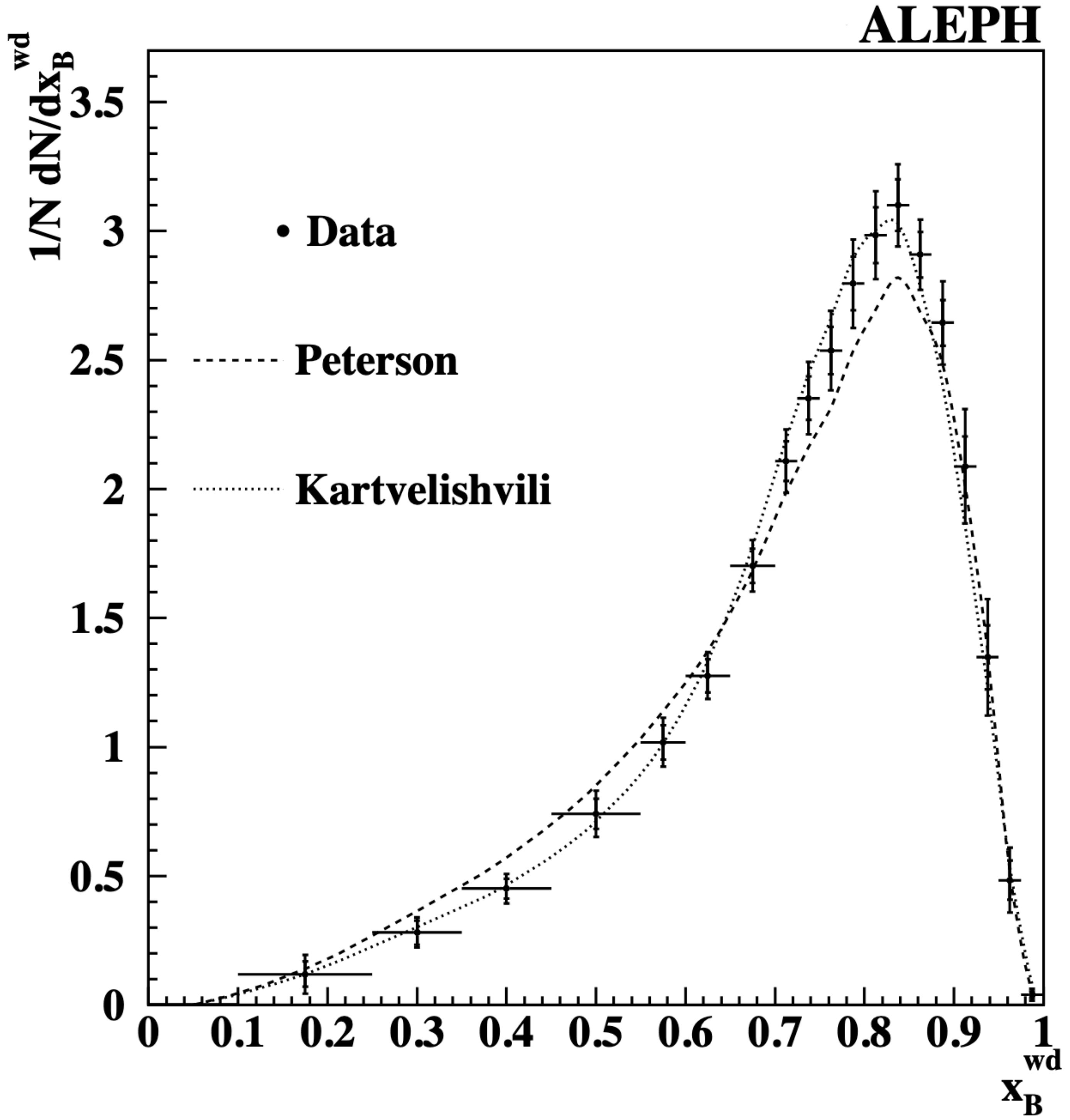


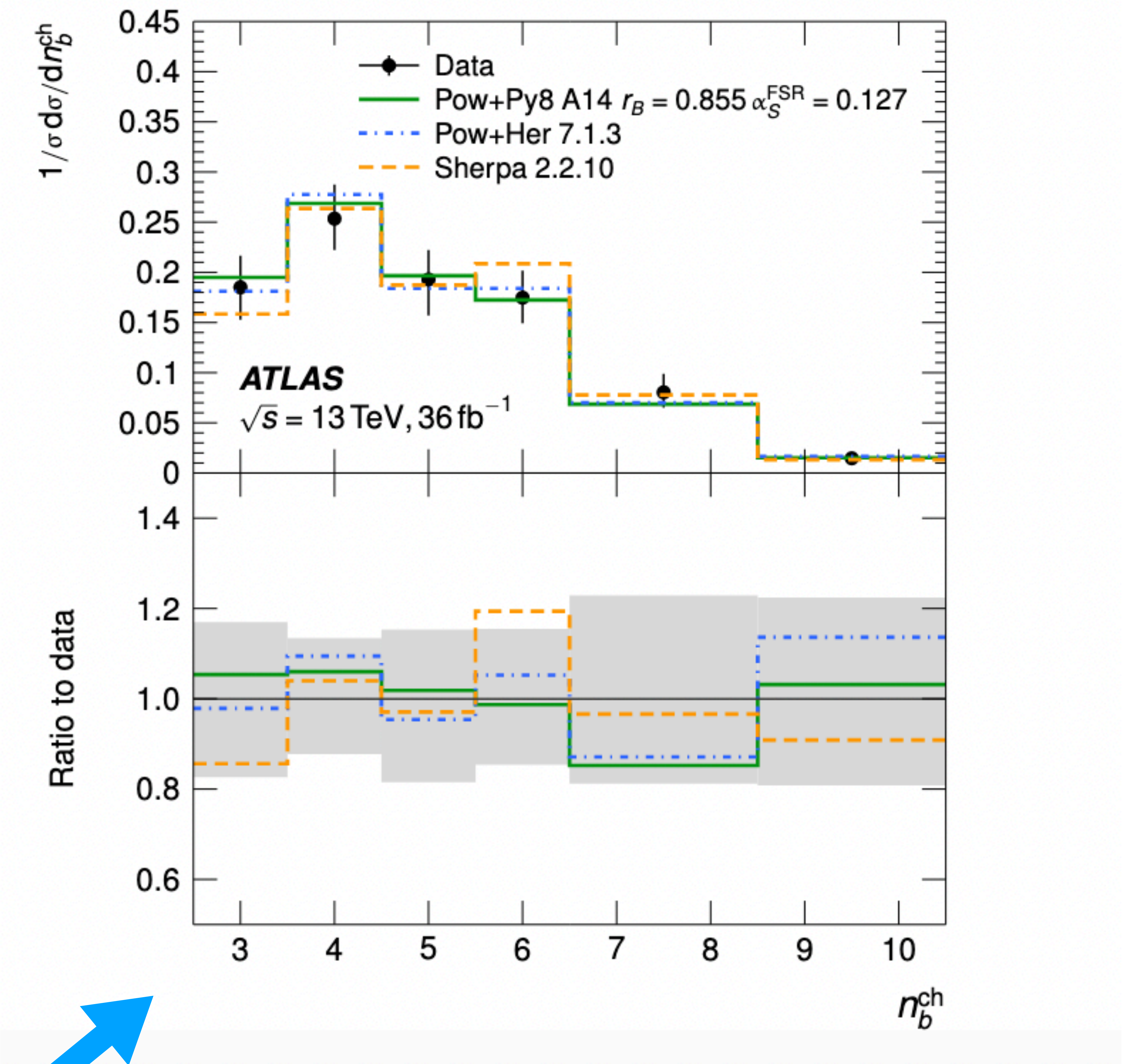
SLD, Phys.Rev.Lett 84, 4300-4304 (2000)
ALPEH, Phys.Lett.B512, 30-40 (2001)
OPAL, Phys.Lett.B 364, 93-106 (1995)
DELPHI, Z.Phys.C57 181-196 (1993)
ATLAS, Phys.Rev.D 106 (2022) 032008

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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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