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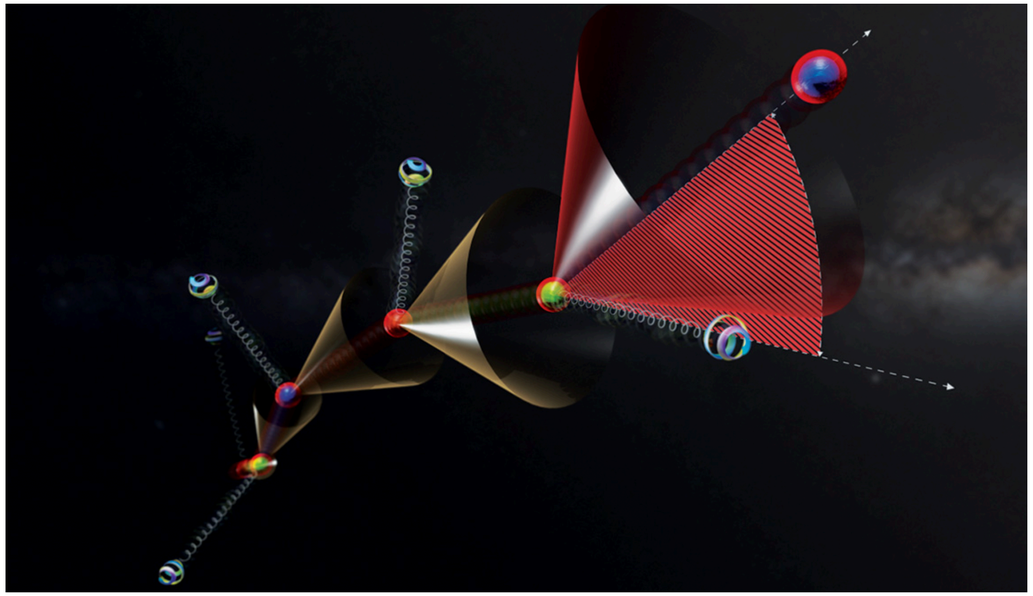
The dead cone: theoretical and experimental approaches in pp and in heavy-ion collisions

Leticia Cunqueiro Mendez



QCD@LHC

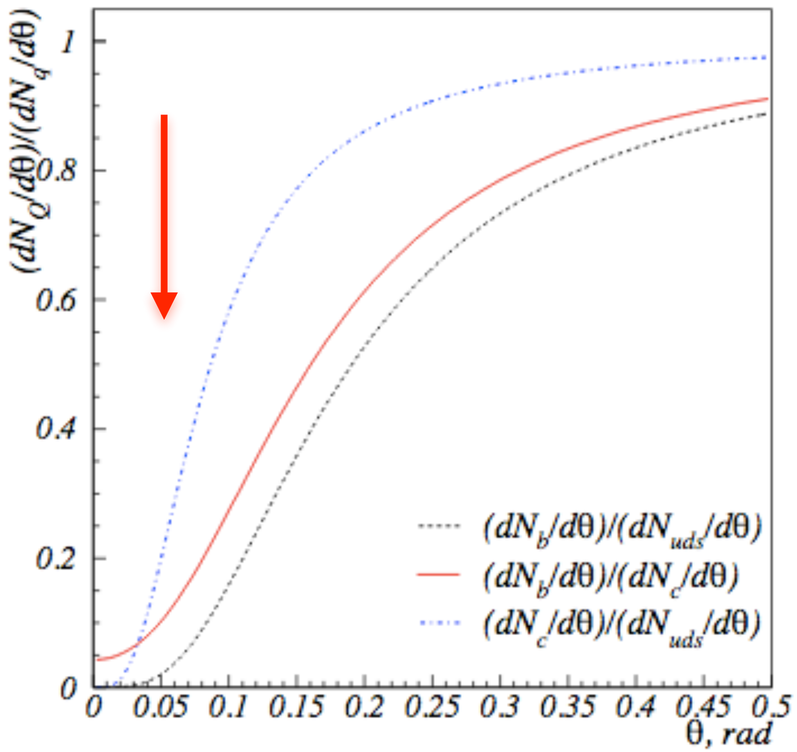
2nd December 2022, Orsay

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



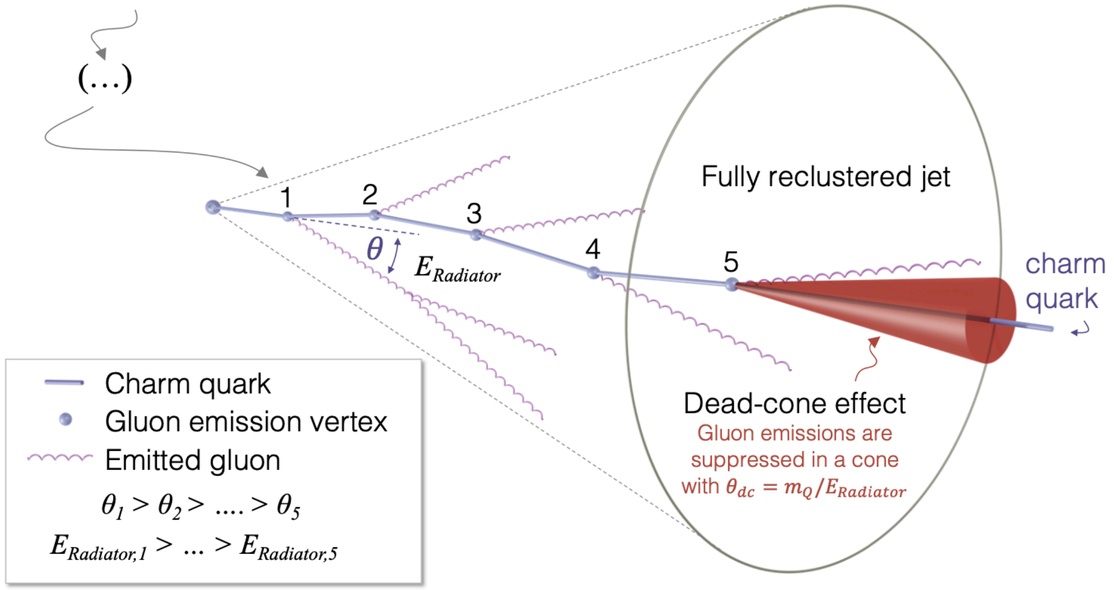
Battaglia et al, DELPHI-2004-037 CONF 712

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 dead-cone effect: recent approaches

In this talk, we'll discuss:

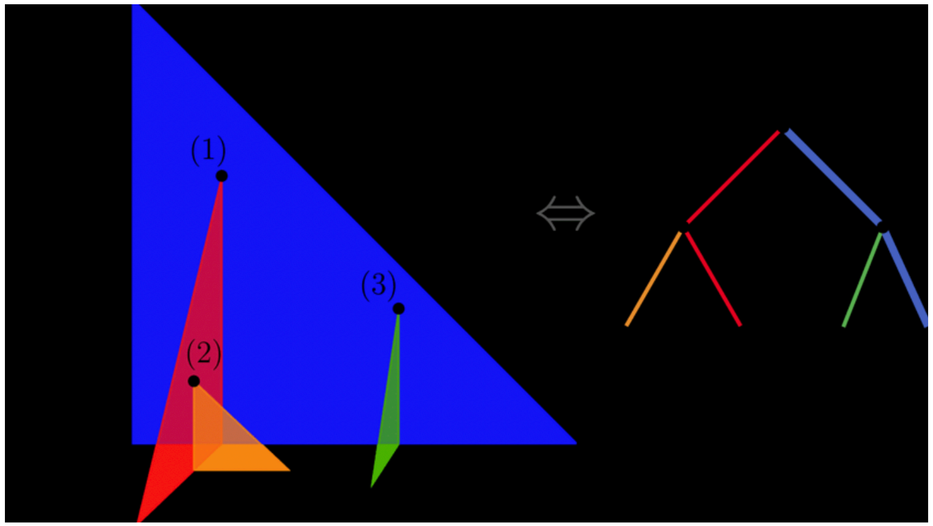
- Recent approaches based on the iterative declustering of the jet tree:
  - including a direct visualization of the dead cone by ALICE
  - including prospects for heavy-ion collisions

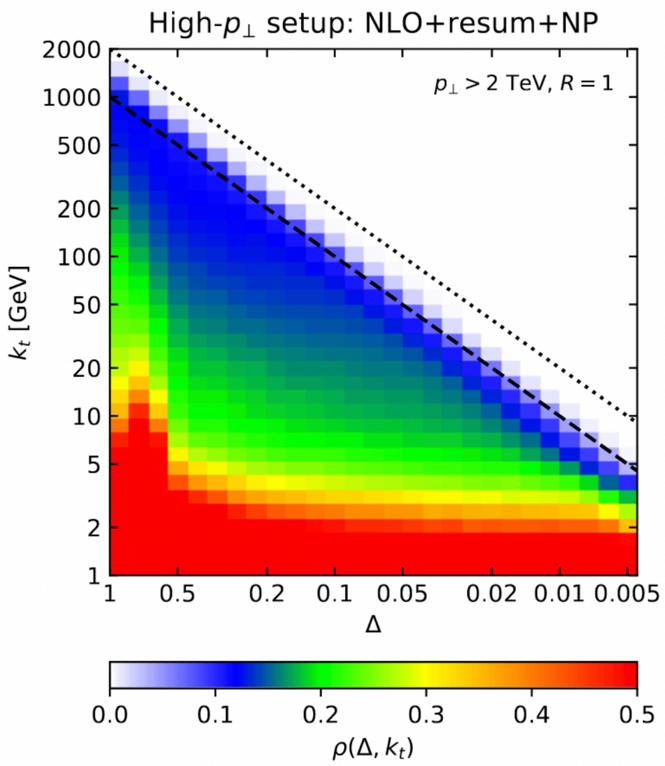
- New proposals concerning energy-energy correlators

- Selection of existing measurements sensitive to the quark mass: mostly fragmentation functions and jet shapes of heavy-flavour jets in e+e- and pp collisions

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





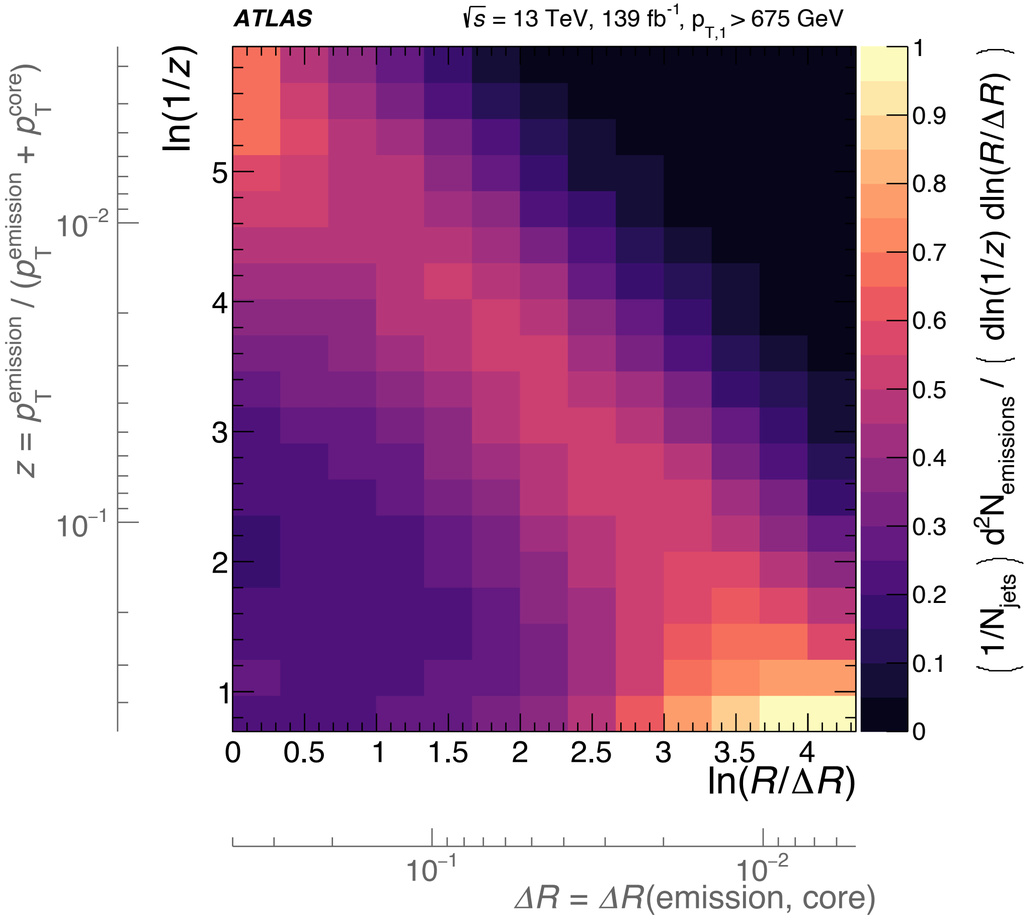
At leading order, emissions populate the plane uniformly and the running of the coupling sculpts the plane

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

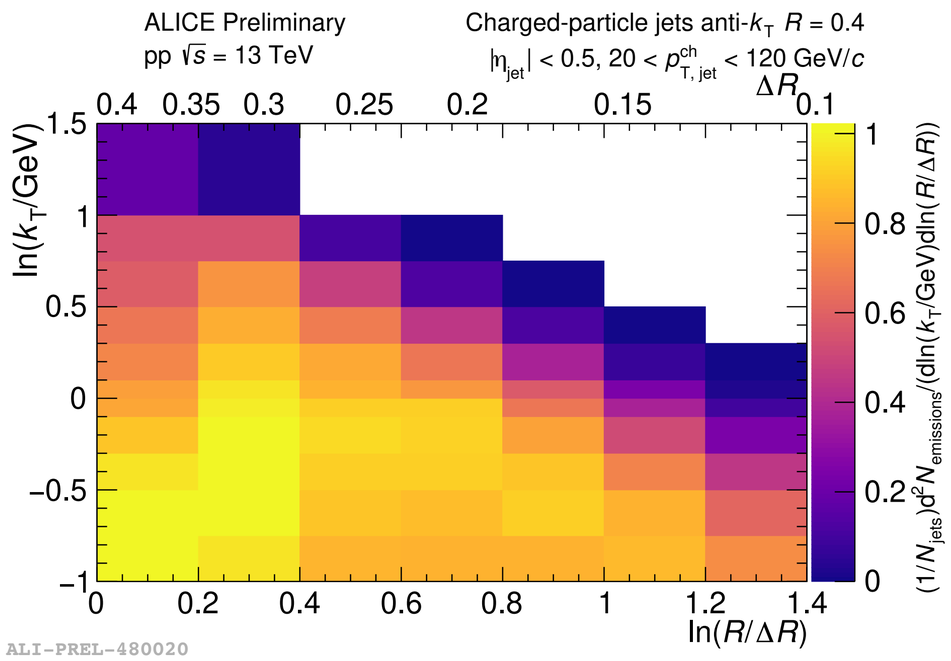
Lifson, Salam, Soyez, JHEP 10 (2020)
Dreyer, Salam, Soyez, JHEP 12 (2018) 064

The jet tree (filling the primary Lund plane)

ATLAS, Phys.Rev.Lett. 124 (2020) 22, 222002



ALICE-PUBLIC-2021-002.



Complementary kinematic ranges

- 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

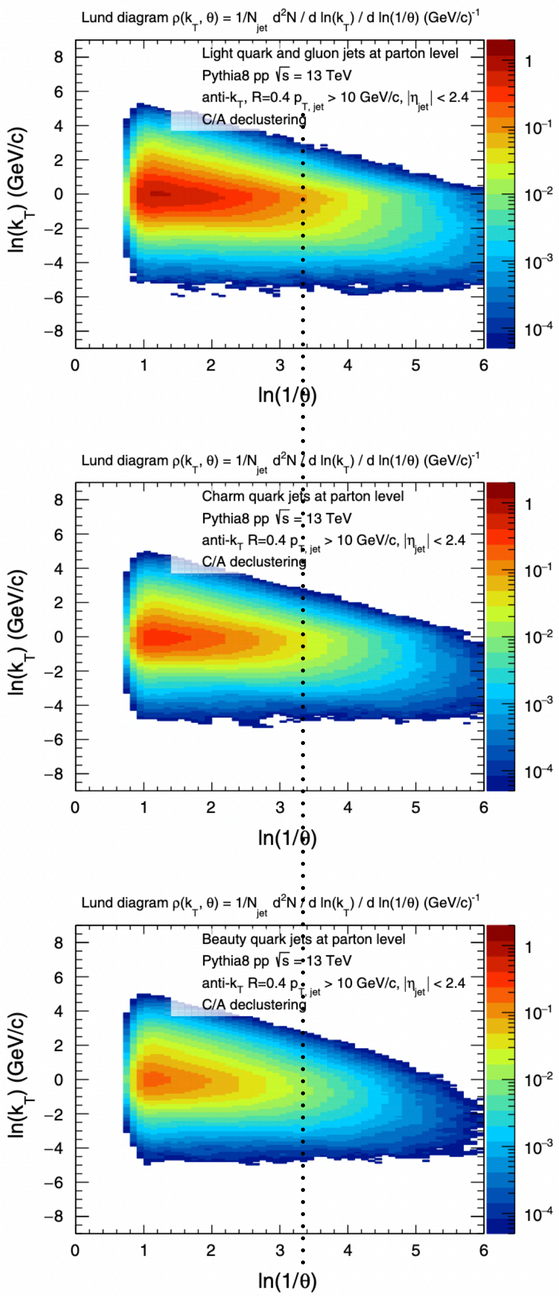
The heavy-flavour jet tree

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

inclusive

charm

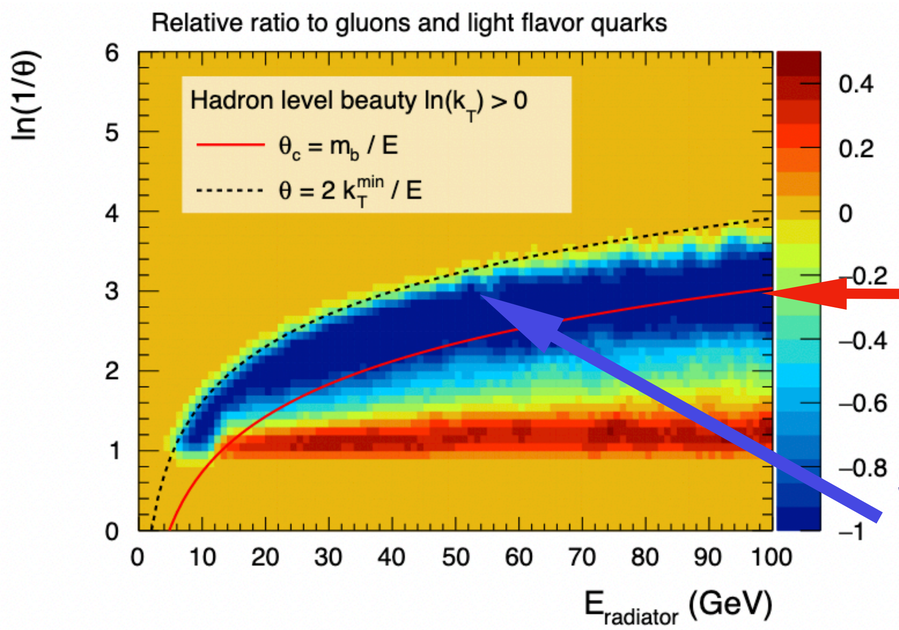
beauty



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

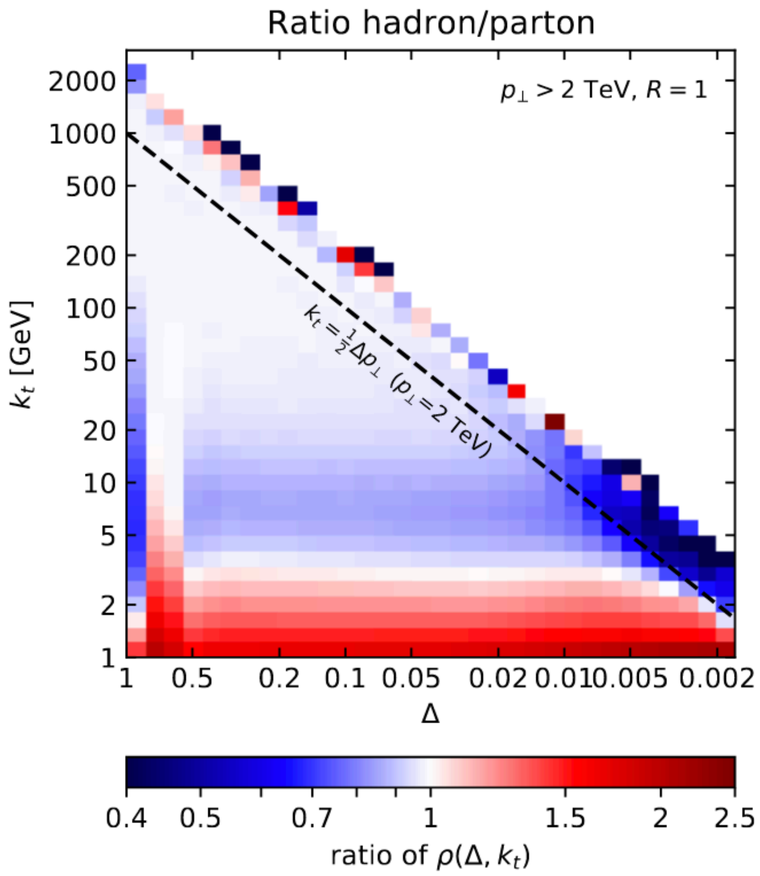


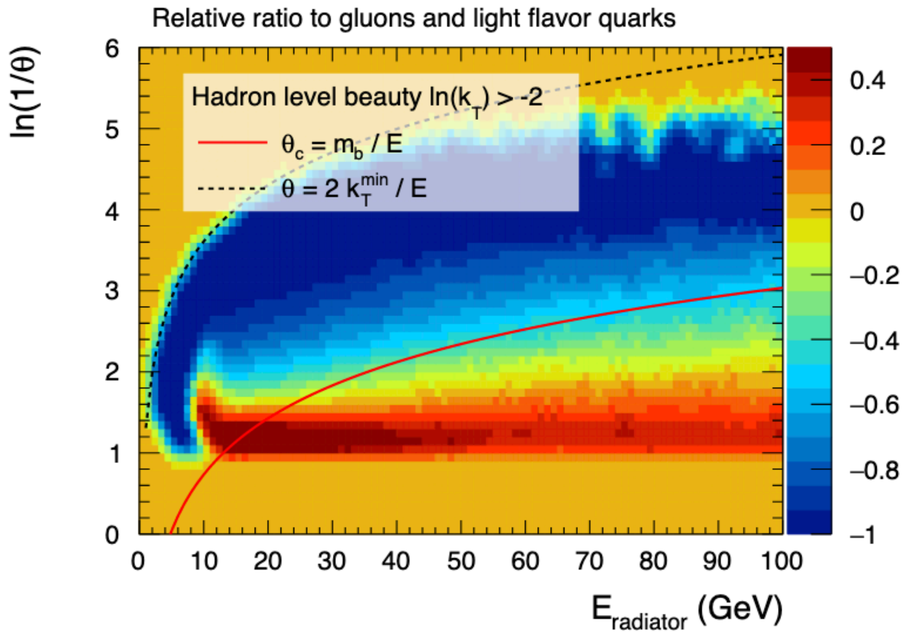
$E_{radiator}$ is the sum energy of the daughter prongs at each node of the jet tree
->proxy for the quark energy

Dead cone line

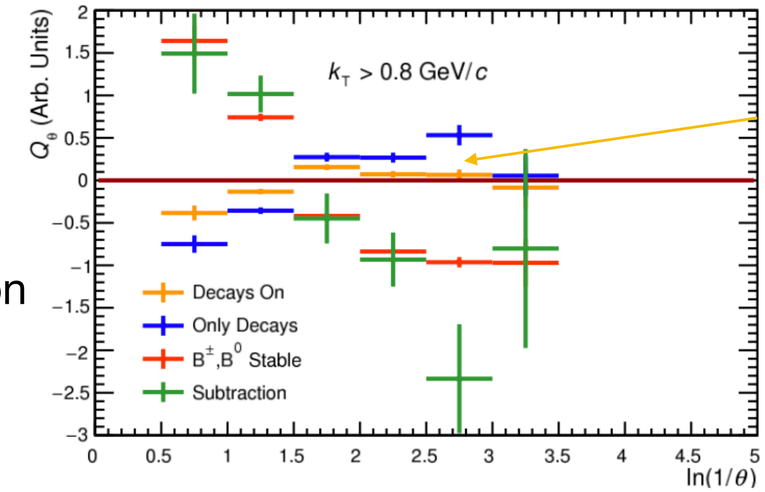
Strong suppression of splittings relative to inclusive jets

The darkening of the dead cone: hadronisation and decays





non-perturbative splittings fill the dead cone



b/inclusive splitting angle

decays fill the dead cone

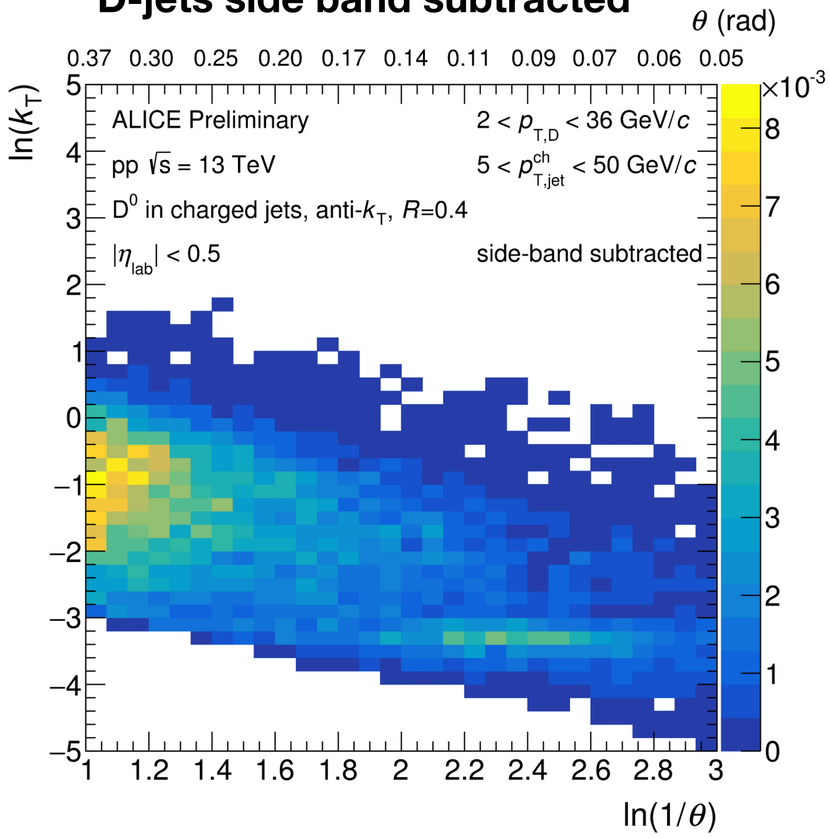
Hadronisation naturally dominates the low-k_T region

Lifson, Salam, Soyez, JHEP 10 (2020)

K.Garner, QM19

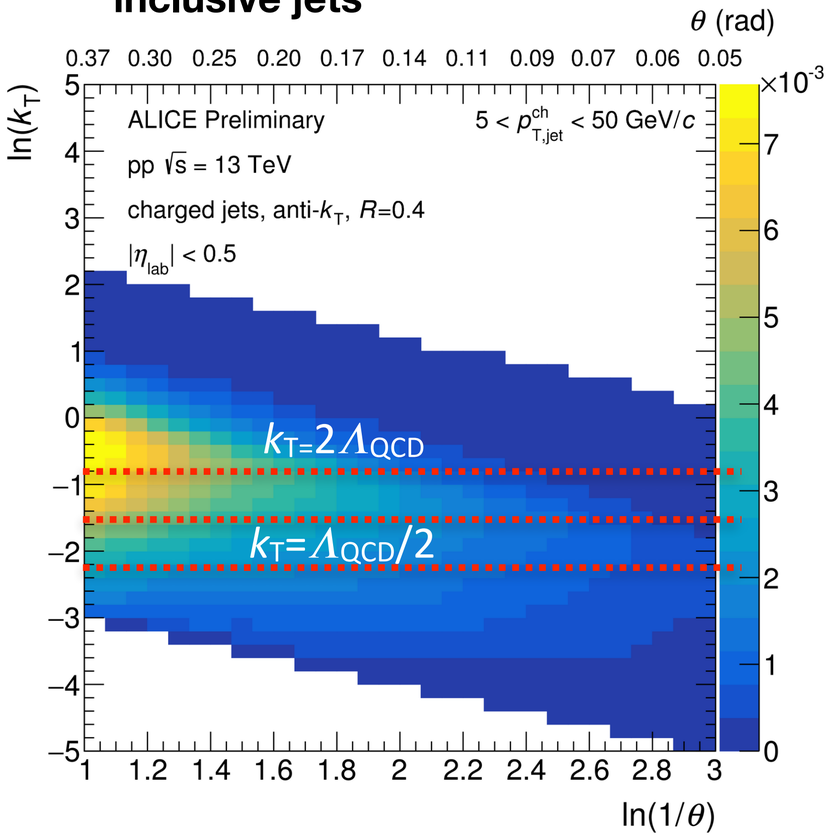
The first direct observation of the dead cone with D-jets

D-jets side band subtracted

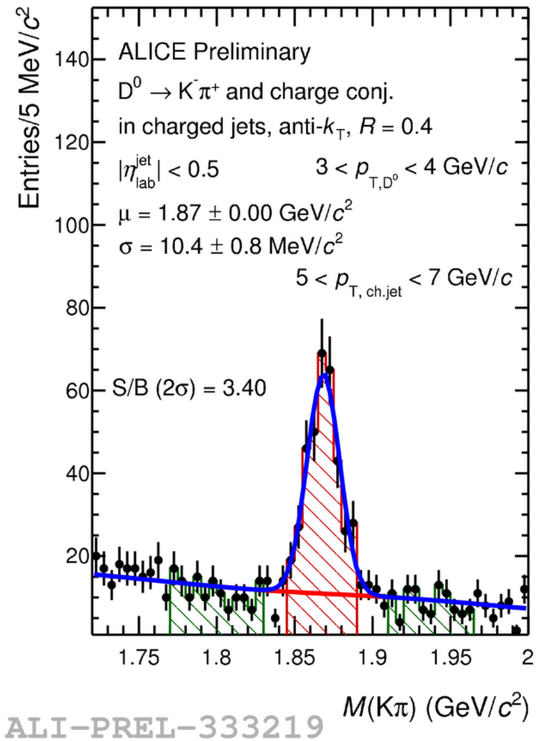


ALI-PREL-339746

inclusive jets



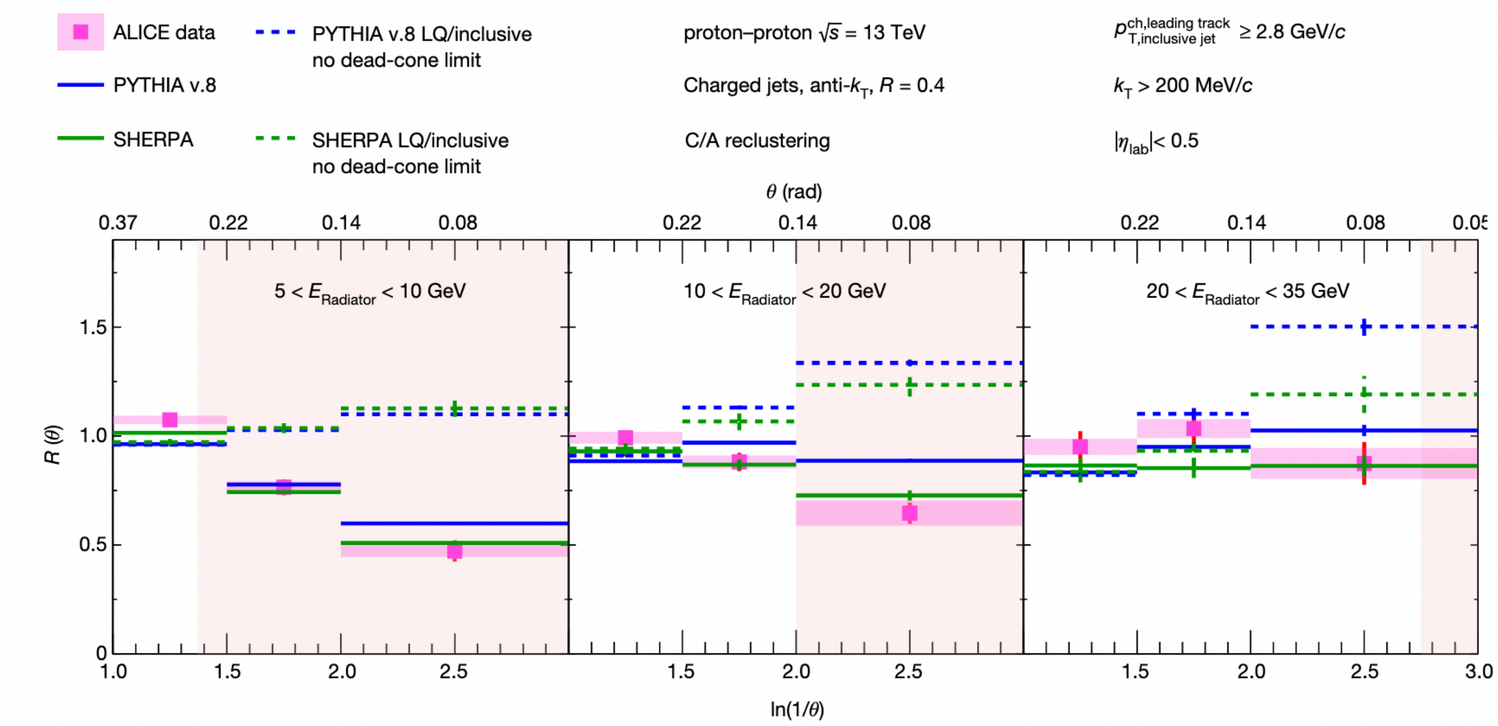
ALI-PREL-339786



ALI-PREL-333219

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

ALICE, Nature 605, 440-446 (2022)



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

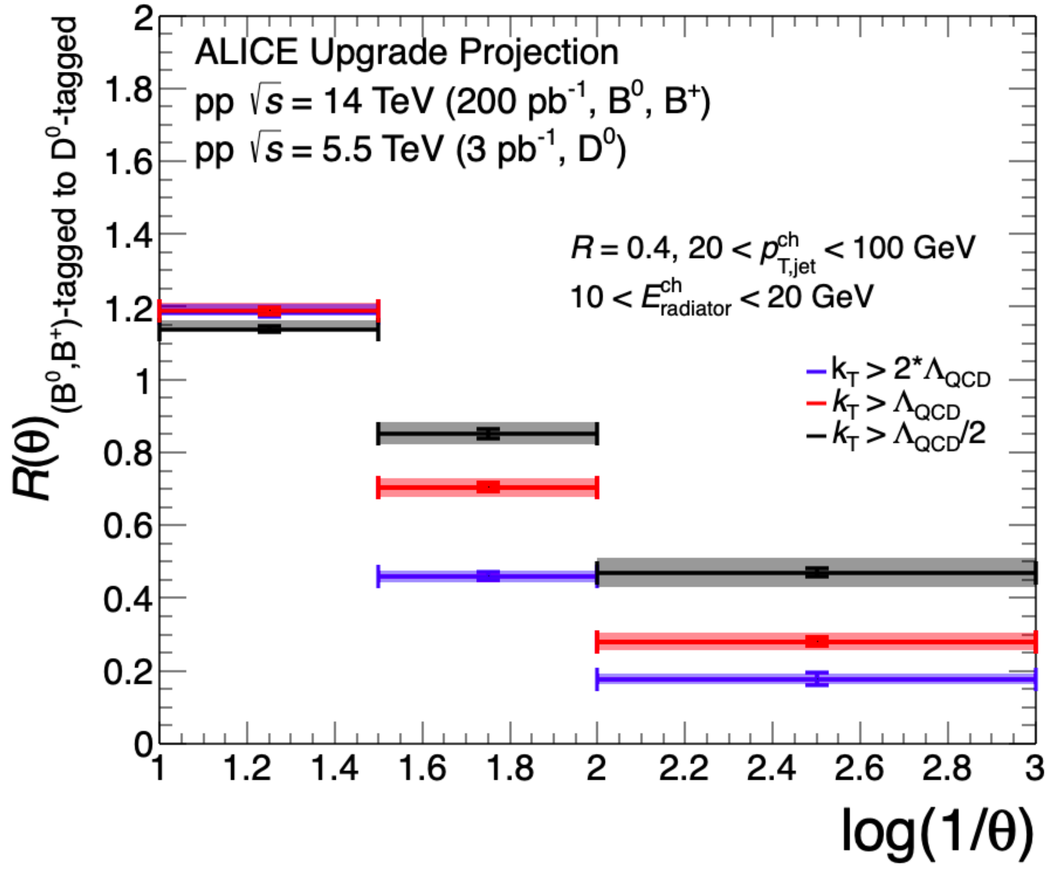
Strong suppression in the lowest $E_{radiator}$ bin

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:

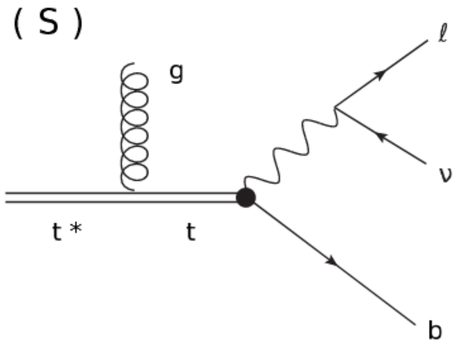
Projections for Lund plane ratios
using fully reconstructed B and D hadron jets

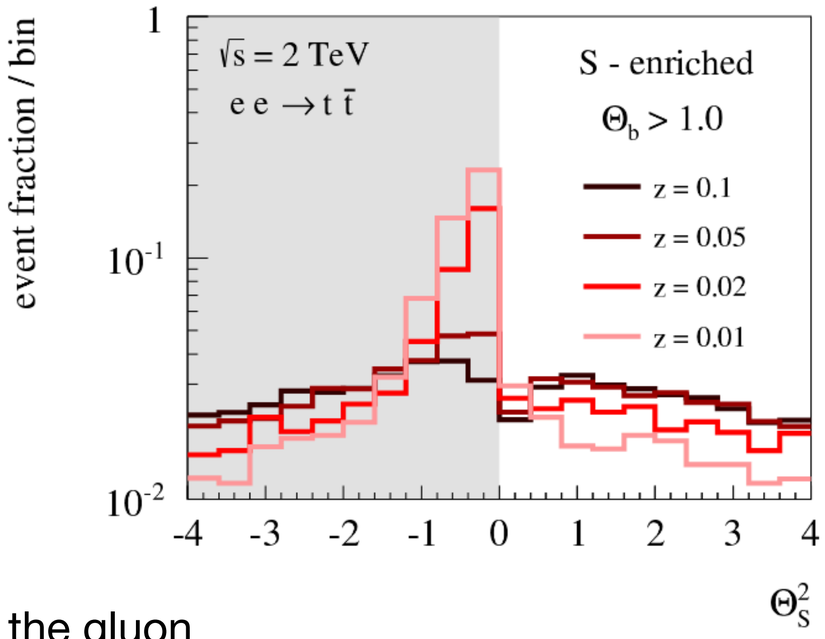
D-jets as reference are ideal ->factor out color effects, ratio just sensitive to quark mass

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

Looking forward to Lund plane analytical calculations for heavy flavours!

The dead cone for top quarks using SoftDrop





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

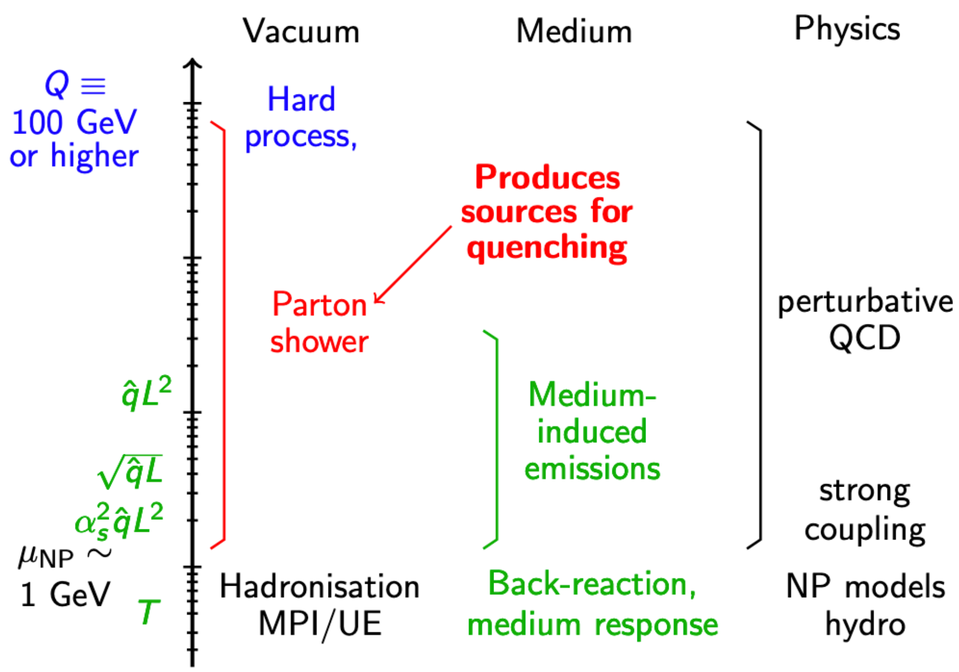
SoftDrop leading prong is b-tagged, subleading prong is proxy for the gluon

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

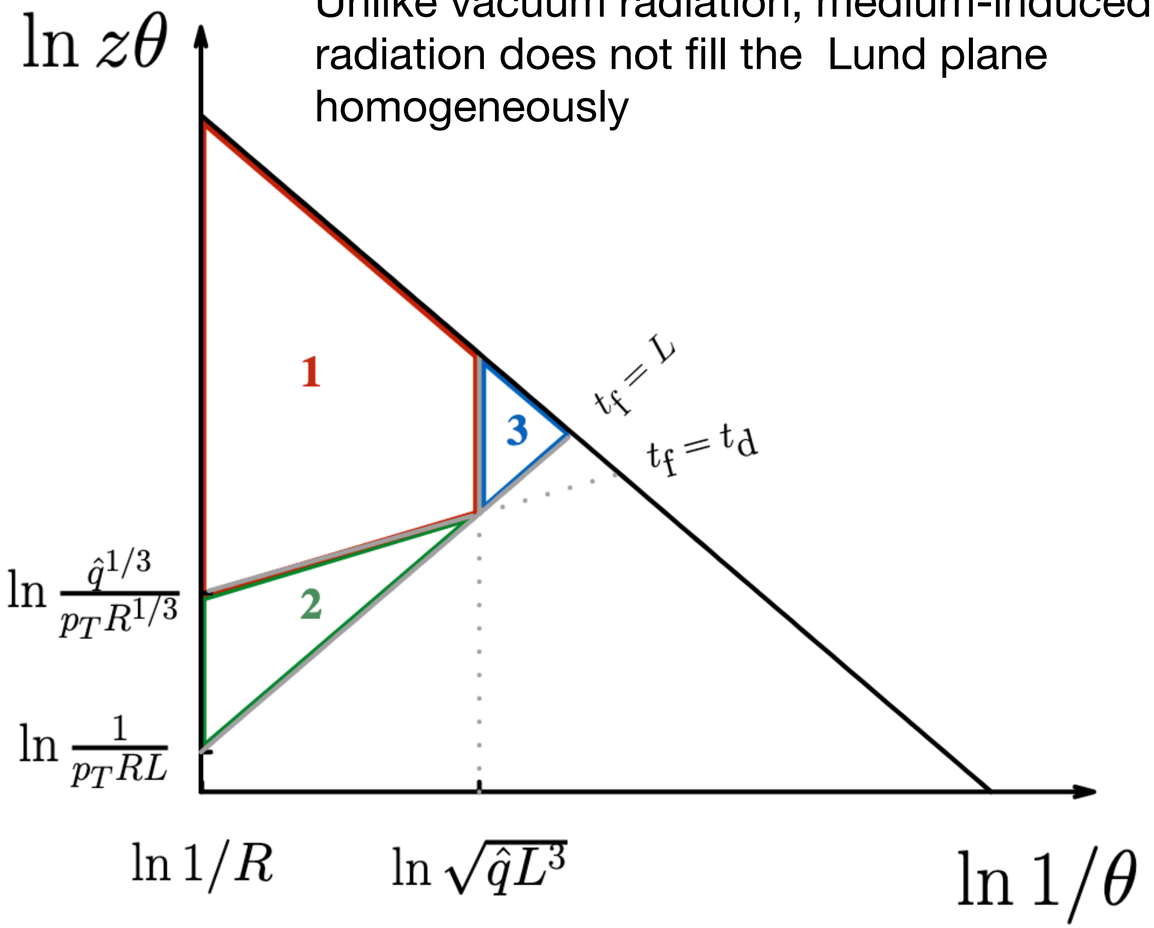
for $z=p_{Tg}/p_{Tt}>0.05$, dead cone suppression in the region of $\Theta_S<1$

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

The heavy-ion case



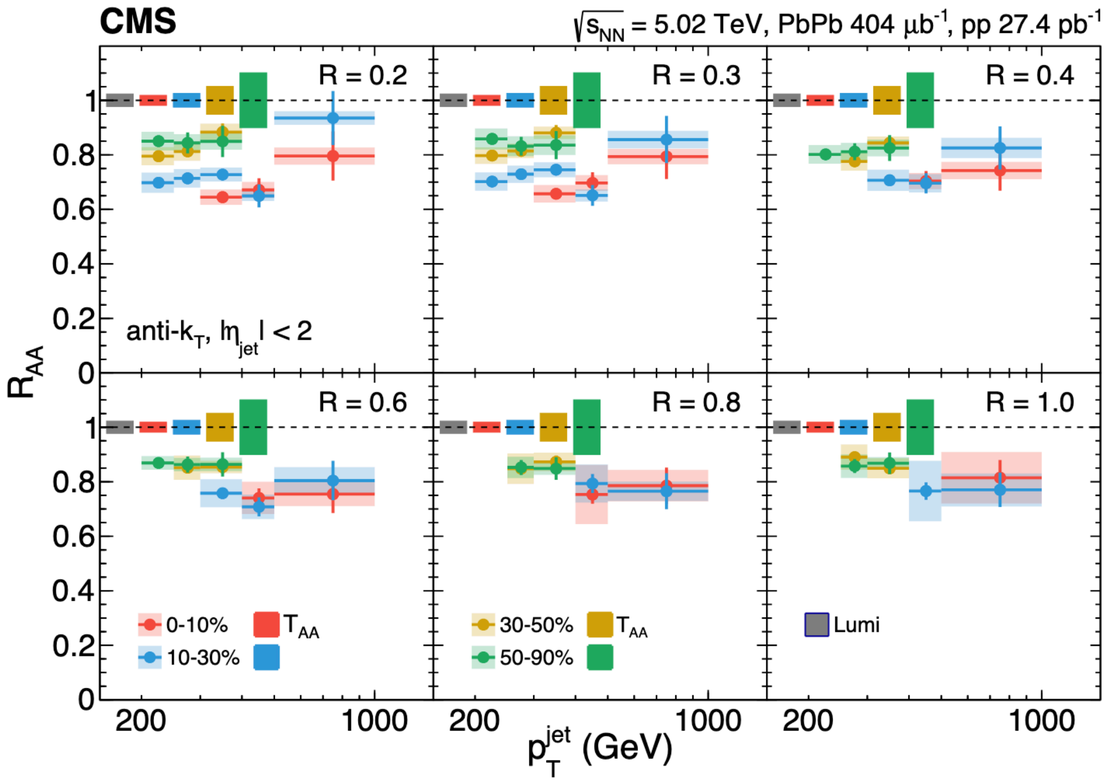
Unlike vacuum radiation, medium-induced radiation does not fill the Lund plane homogeneously



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

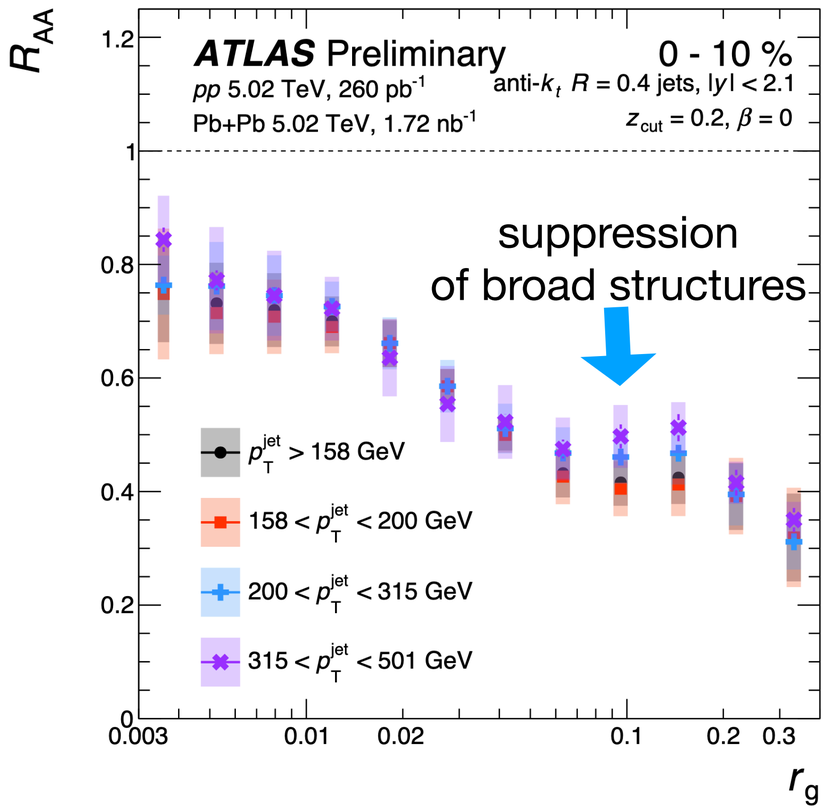
The heavy-ion case

In heavy-ion collisions, jets are stopped by the medium and their radiation pattern is modified



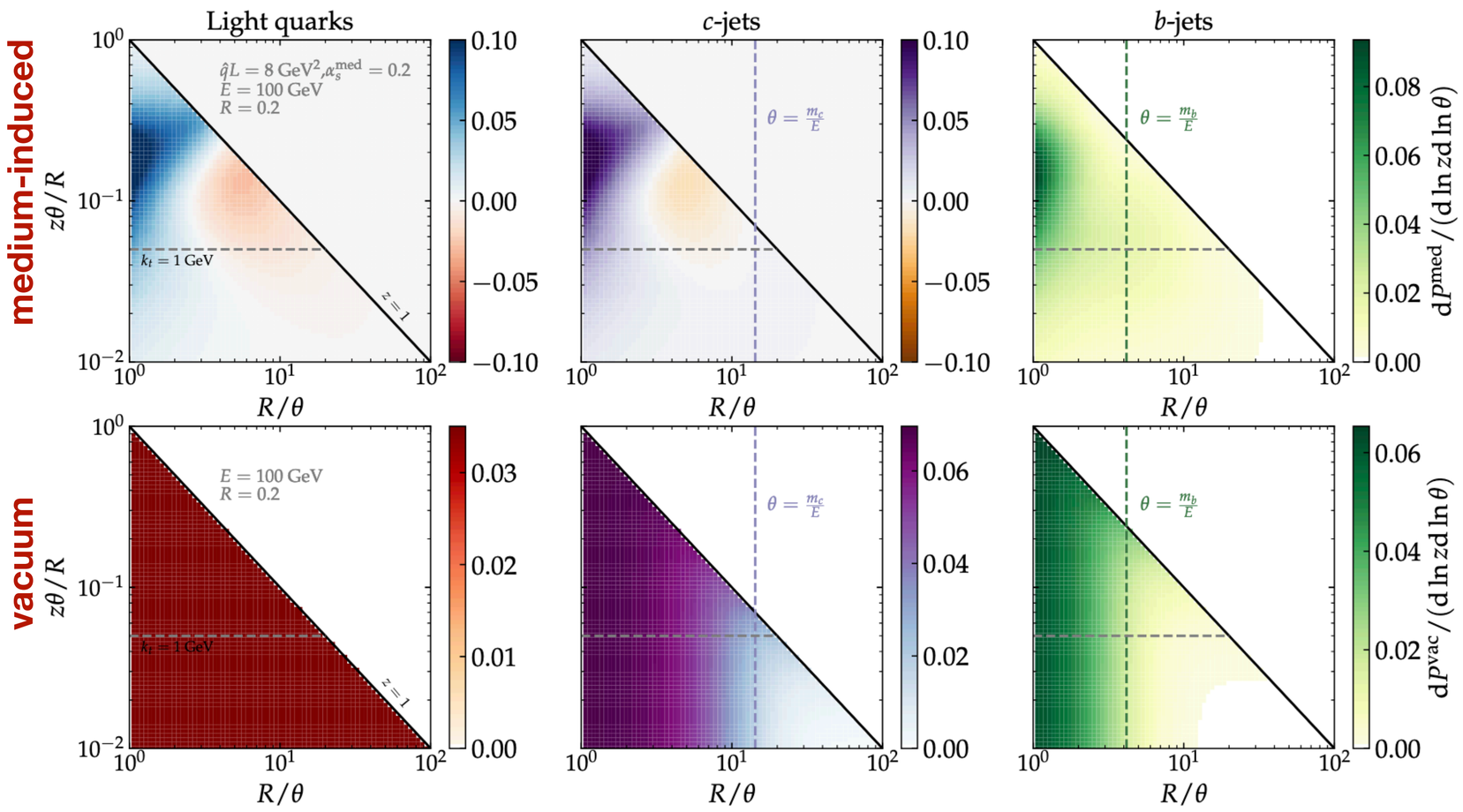
[CMS JHEP 05 (2021) 284]

Ongoing exploration of the modification of the jet substructure in Pb-Pb relative to pp
An example: narrowing of the groomed jet radius.



ATLAS-CONF-2022-026

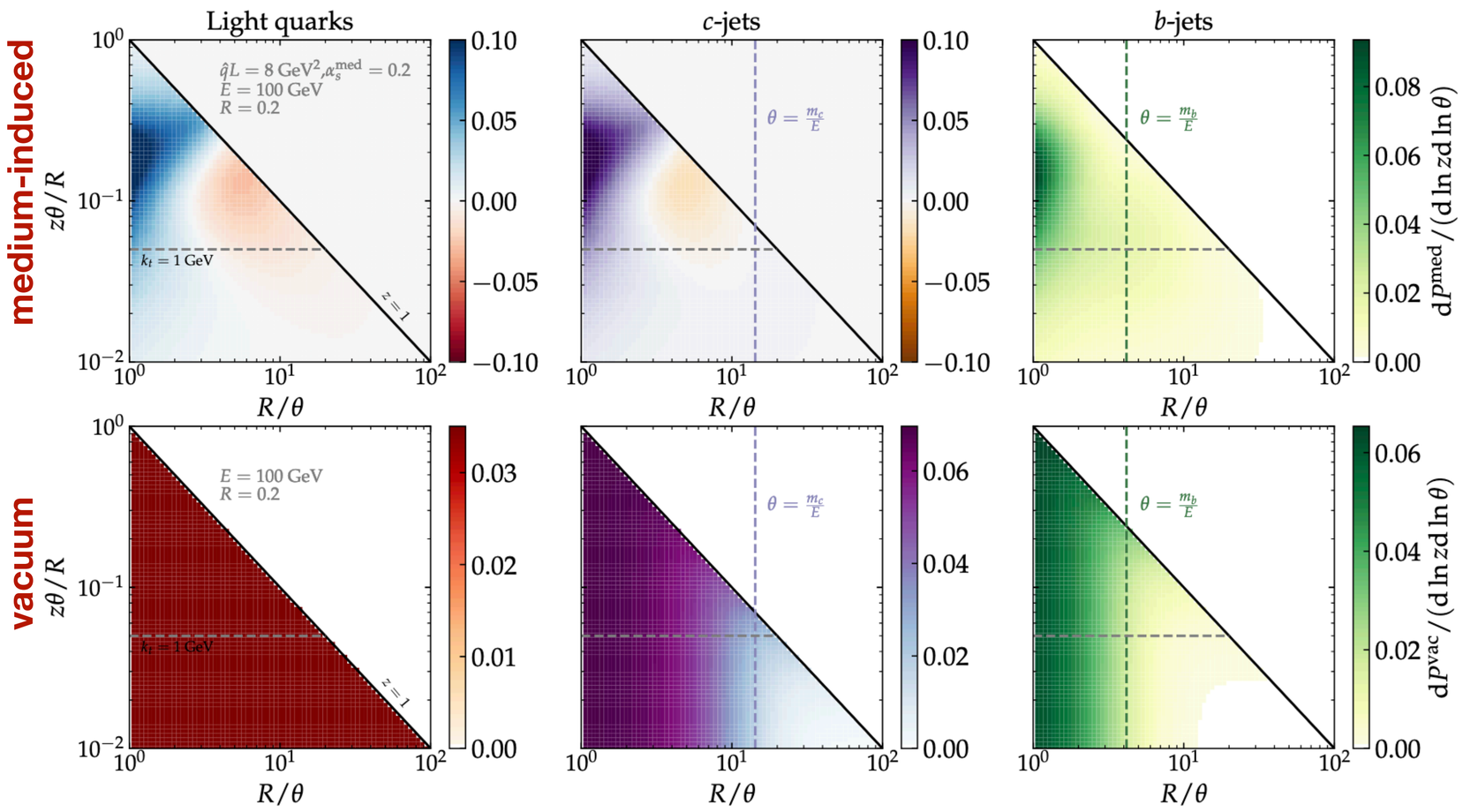
The dead cone in heavy-ion collisions using the jet tree



Idea: use the dead cone as a region of the phase space to isolate medium-induced signal (vacuum radiation is vetoed, only QPG-induced gluons can fill it)

Cunqueiro,Napoletano, Soto-Ontoso, 2211.11789

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



For b-jets, we observed medium-induced gluon radiation with angles $\theta < \theta_0$ where vacuum (DLA) radiation vanishes

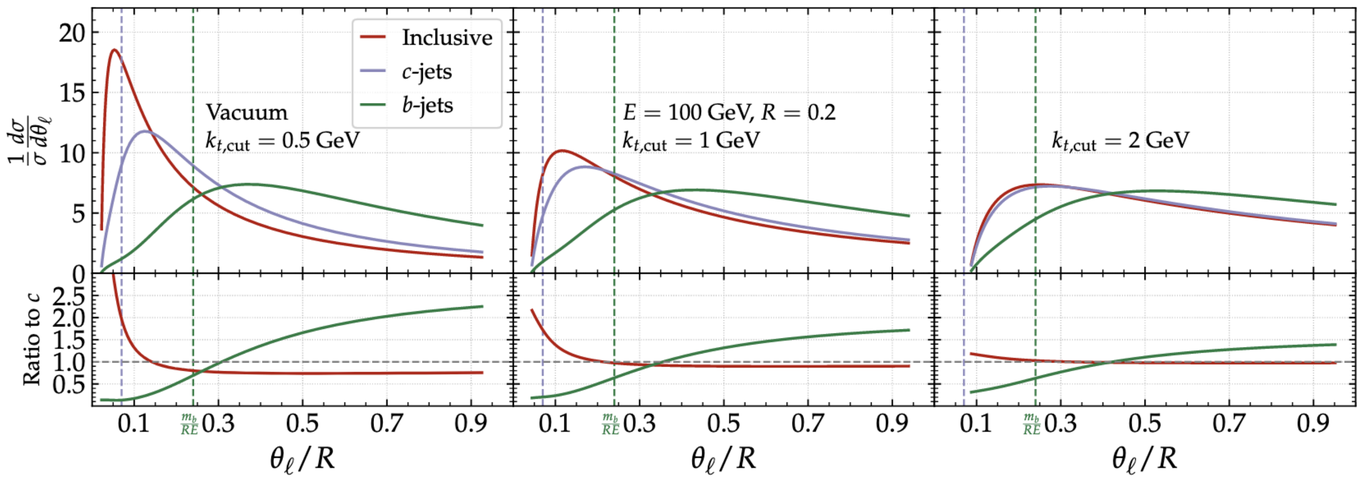
Not the case for c-jets.

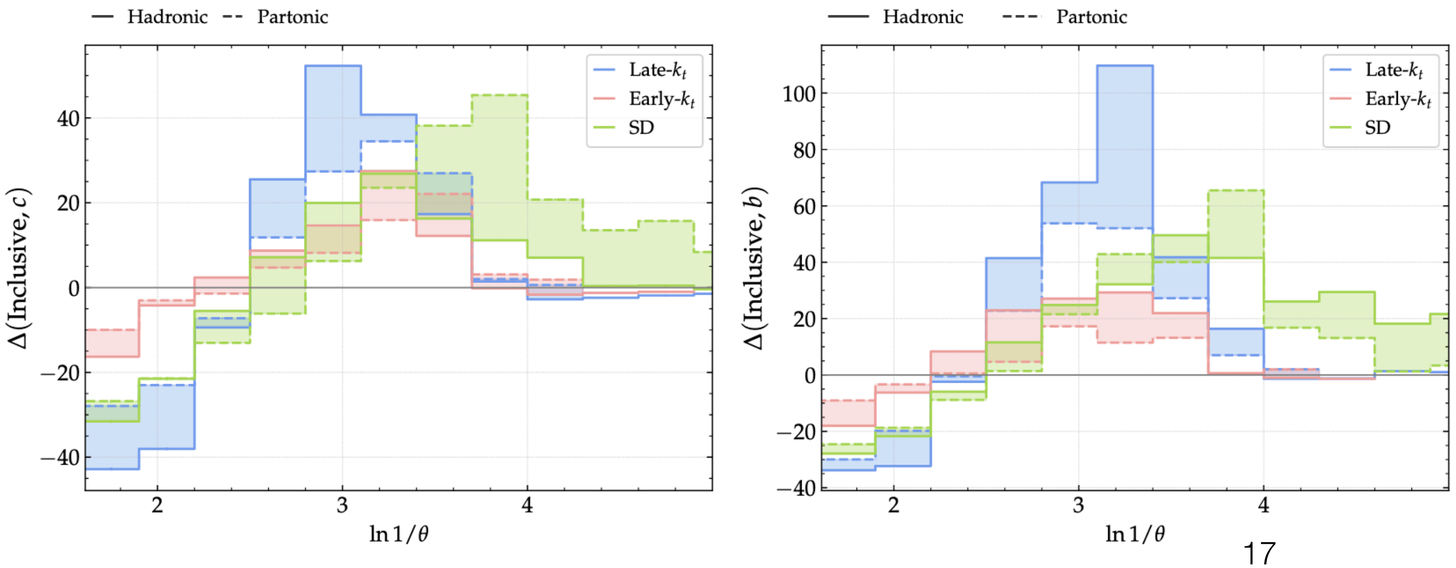
This is the result of the interplay beween two scales: the dead cone angle and the minimum angle a medium-induced emission can have due to transverse broadening.

$$1/\sqrt{(\hat{q}L^3)} < m_Q/E_Q$$

Cunqueiro,Napoletano, Soto-Ontoso, 2211.11789

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





Late-k_T

Since the measurement of the full Lund plane in heavy ion collisions is currently challenging, a new tagger is introduced, late-kT, which selects the last splitting of the CA tree that passes a k_T cut

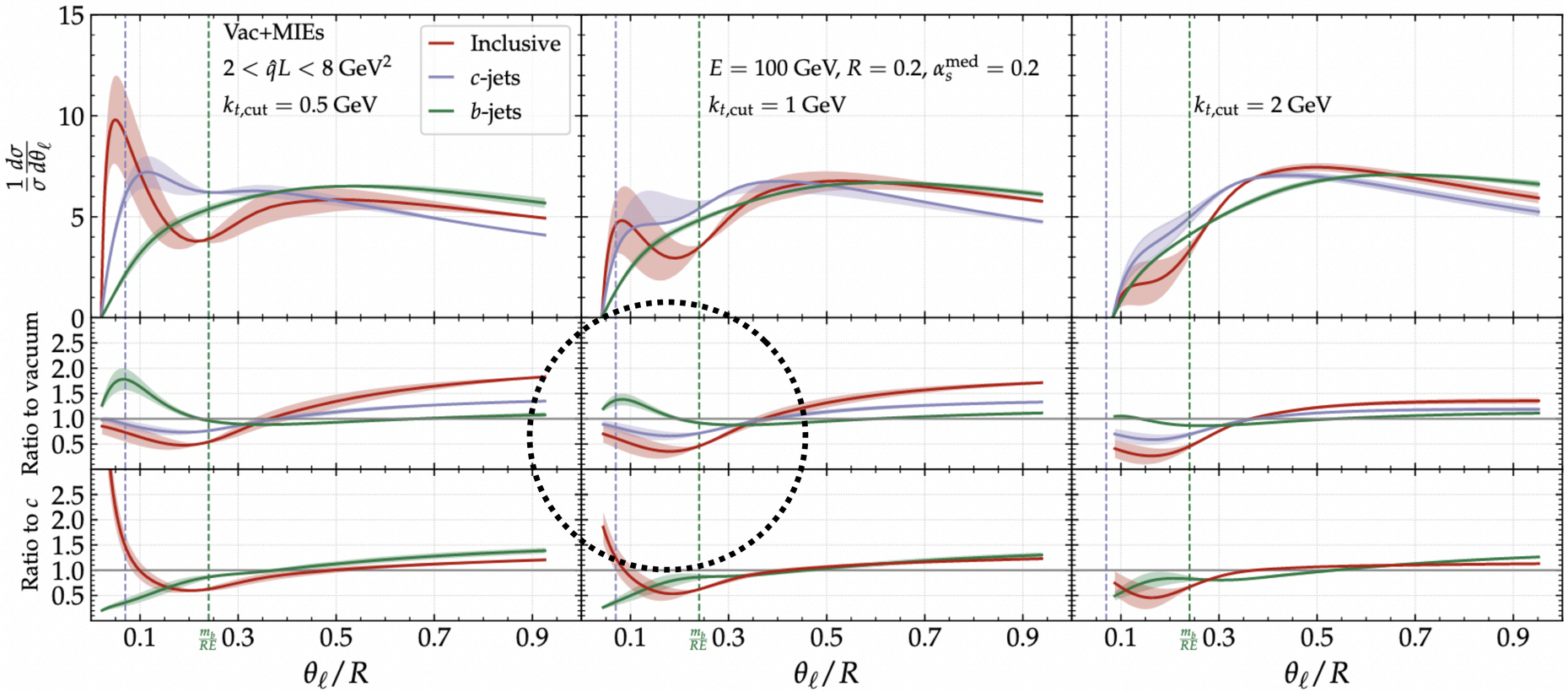
Selection of the most collinear among the perturbative splittings in the tree

Good resilience to hadronisation effects and heavy-ion background

Cunqueiro, Napoletano, Soto-Ontoso, 2211.11789

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

Cunqueiro,Napoletano, Soto-Ontoso, 2211.11789



The splitting angle selected by late-k_T, θ_l, shows an enhancement of medium-induce splittings relative to vacuum at small angles for b-jets. -> opportunity to search experimentally for the filling of the dead cone

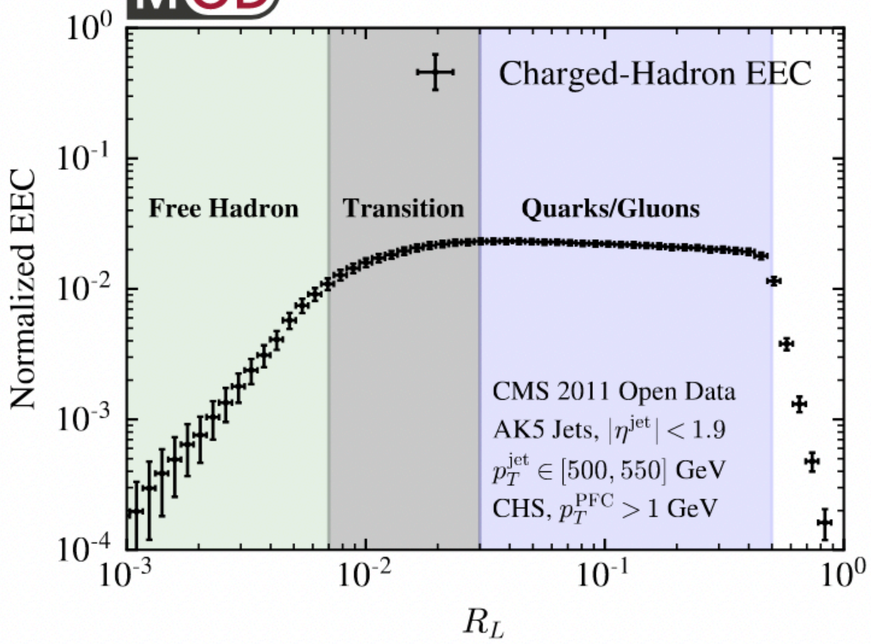
D-jets and inclusive jets show transverse momentum broadening

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

Komiske, Moult, Thaler, XingZhu, 2201.07800

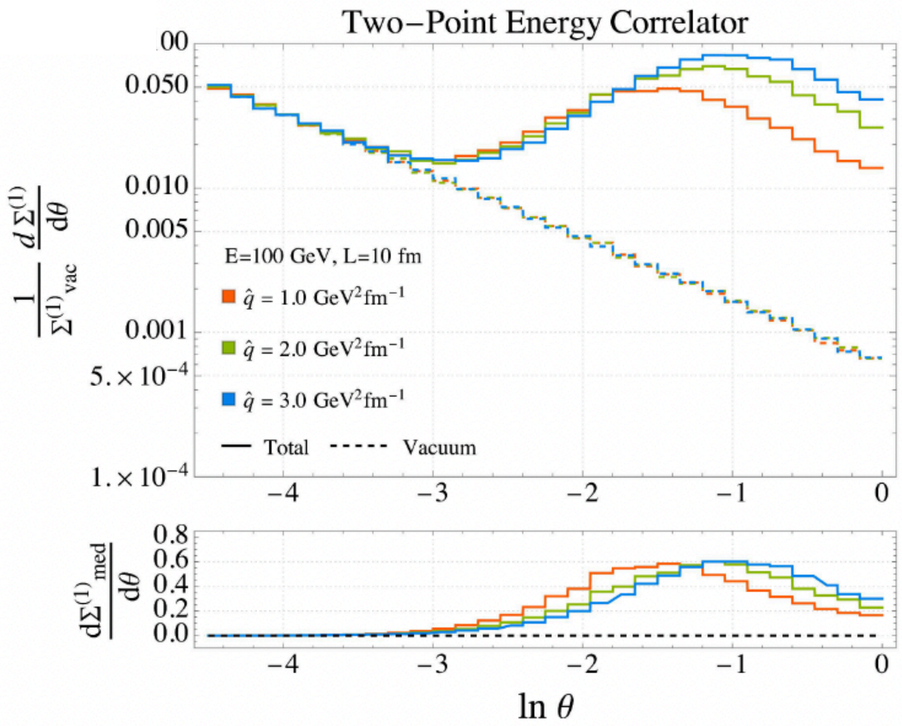
Andres, Dominguez,Kunnawalkam, Holguin, Marquet,Moult 2209.11236

2-point energy correlation



$$\frac{\langle \mathcal{E}^n(\vec{n}_1)\mathcal{E}^n(\vec{n}_2)\rangle}{Q^{2n}} = \frac{1}{\sigma}\sum_{ij}\int \frac{d\sigma_{ij}}{d\vec{n}_i d\vec{n}_j}\frac{E_i^n E_j^n}{Q^{2n}}\delta^{(2)}(\vec{n}_i-\vec{n}_1)\delta^{(2)}(\vec{n}_j-\vec{n}_2)$$

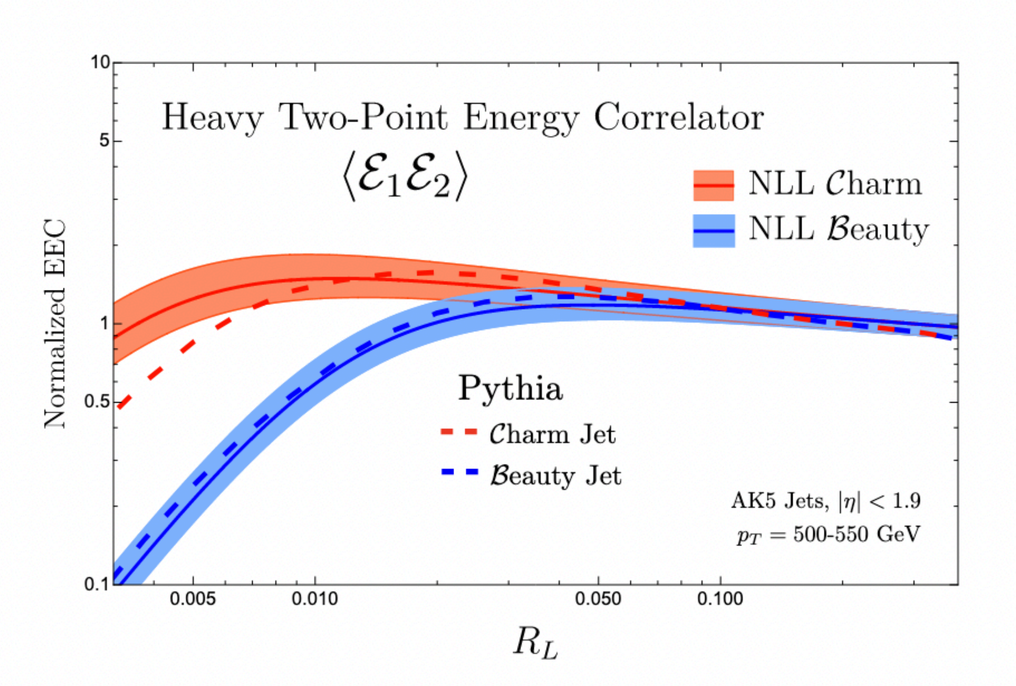
strong broadening signal

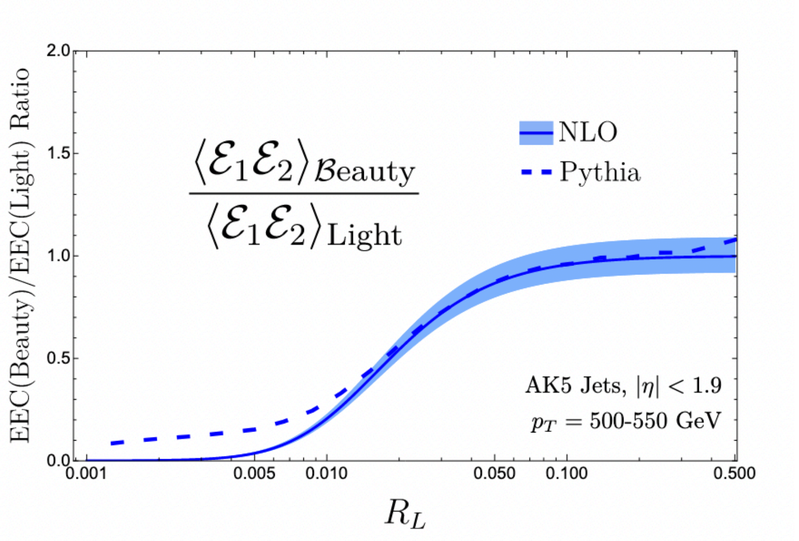


No jet reclustering required
Distinct scaling behaviour associated to quarks and gluons (large angles) and hadrons (small angles)
Reduced sensitivity to q/g fractions and selection biases

The correlations identify the scales defined by the properties of the QGP

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



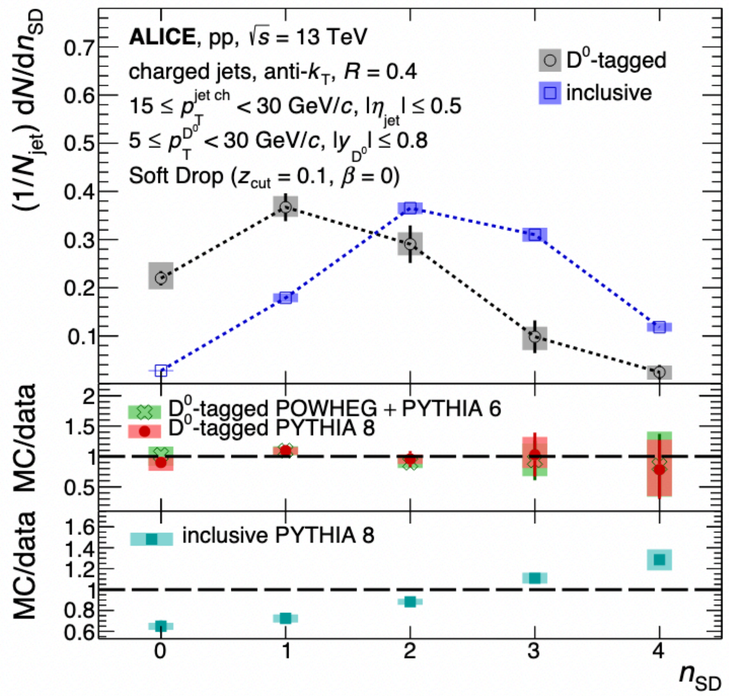


First NLL calculation of a heavy-flavoured jet substructure observable in pp collisions
Clear suppression of small angles for b-jets, same scaling behaviour as massless for large angular scales

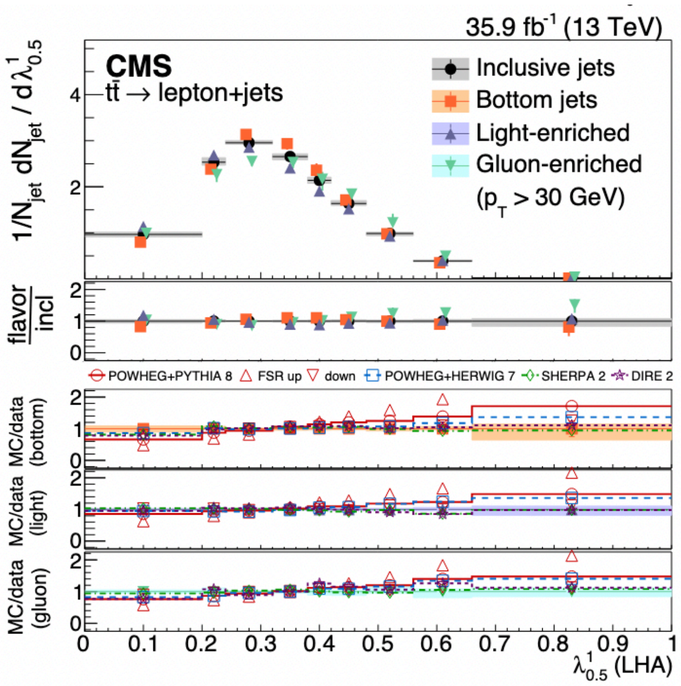
Craft, Lee, Mecca, Moult, 2210.09311

Impact of the dead cone on fragmentation: a selection

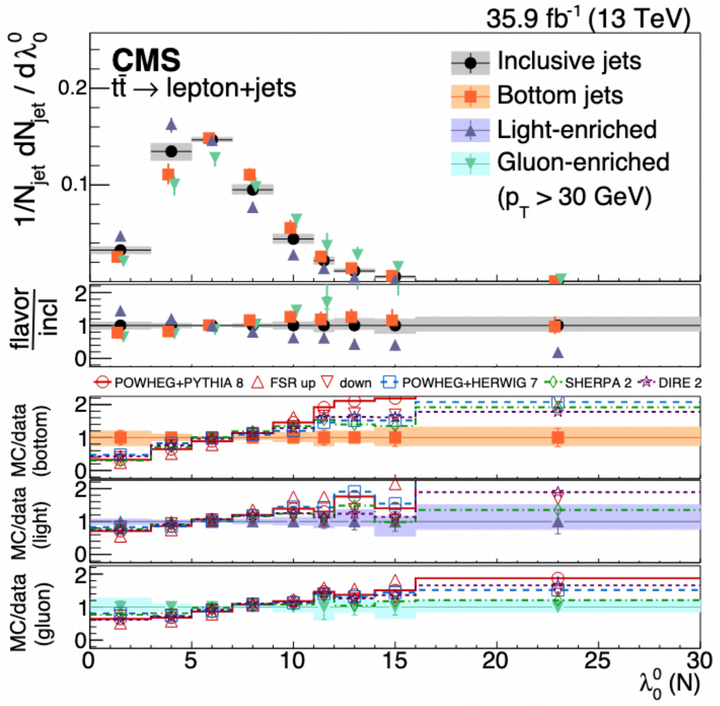
Number of hard prongs



intrajet multiplicity



Angularity



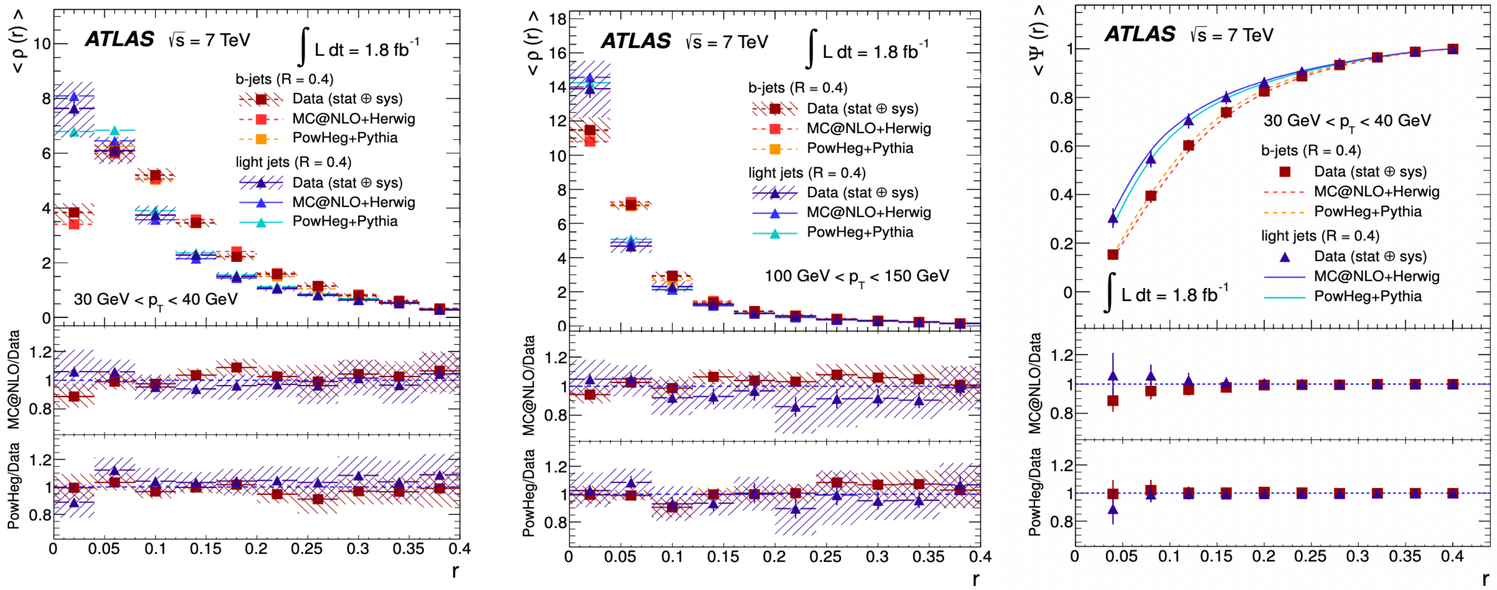
Lower intrajet multiplicities (measured via the number of SoftDrop prongs) in D-jets
Comparison to inclusive includes q/g differences

ALICE, 2208.04857

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?

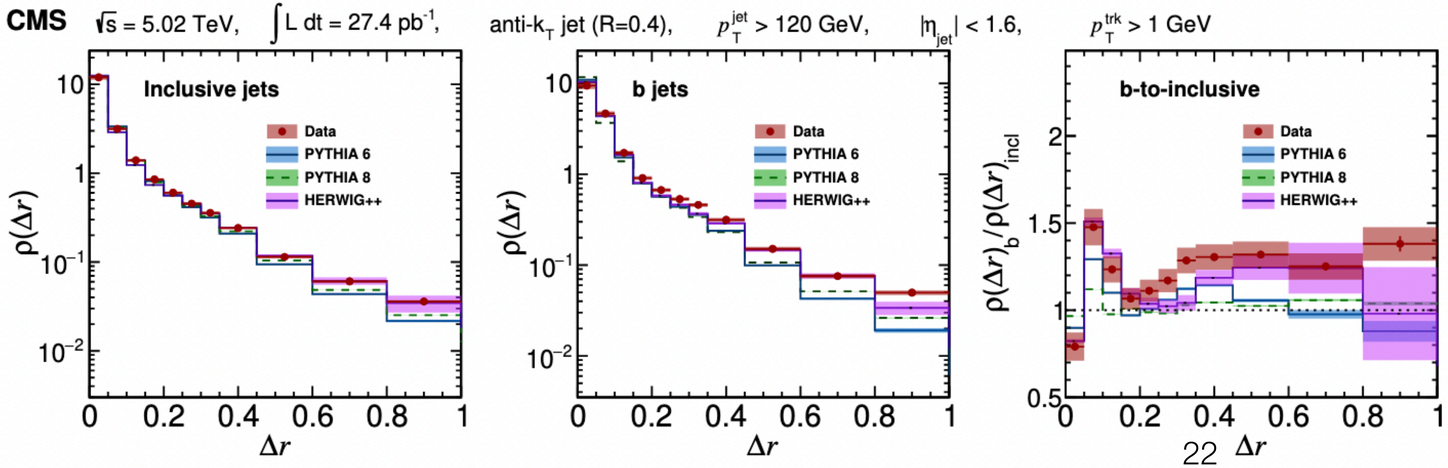
CMS, Phys.Rev.D.98 09 (2014)

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

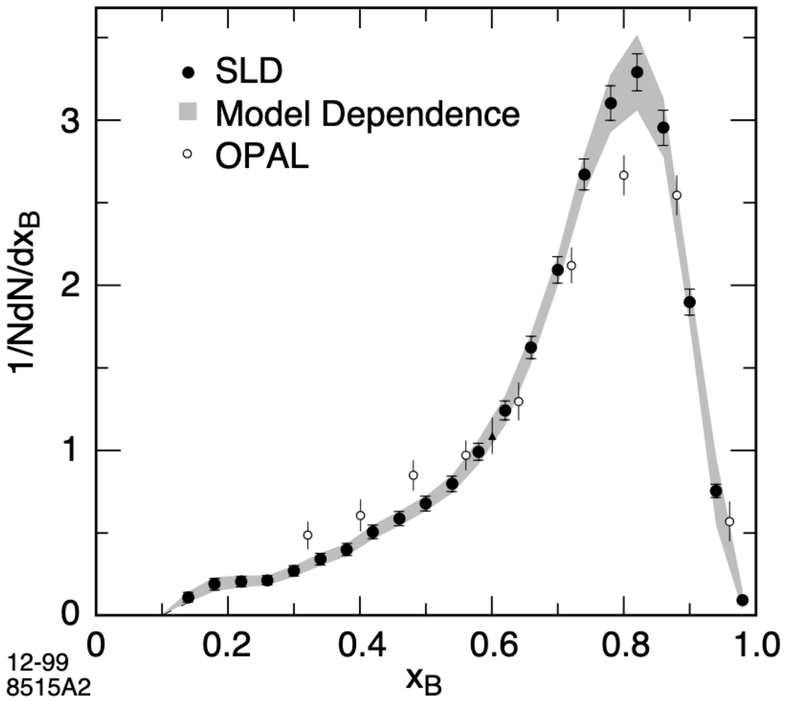
ATLAS, Eur.Phys.J.C (2013)73:2676

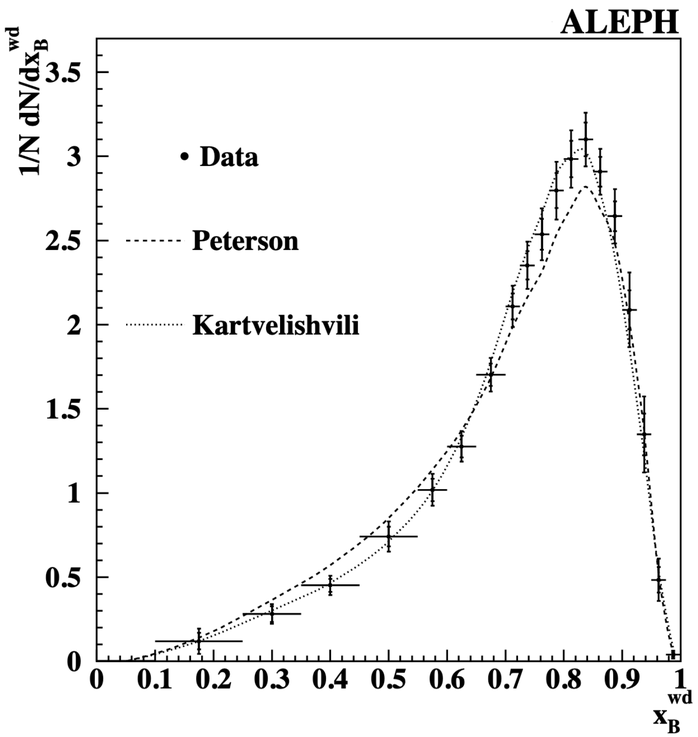


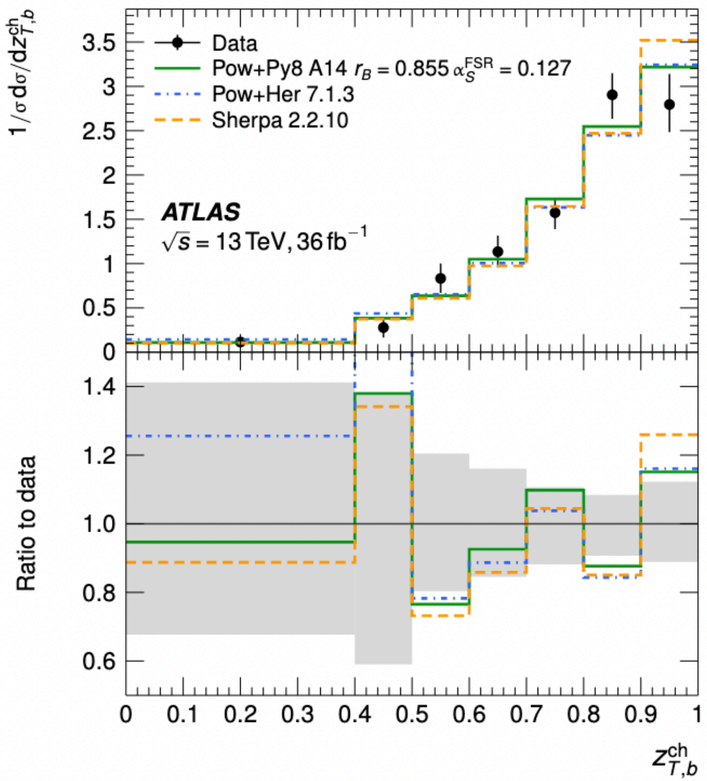
Similar qualitative picture in dijet events and high jet p_T
Reference is inclusive jets (q/g effects)

CMS, JHEP05 (2021) 054

Impact of the dead cone on fragmentation: a selection



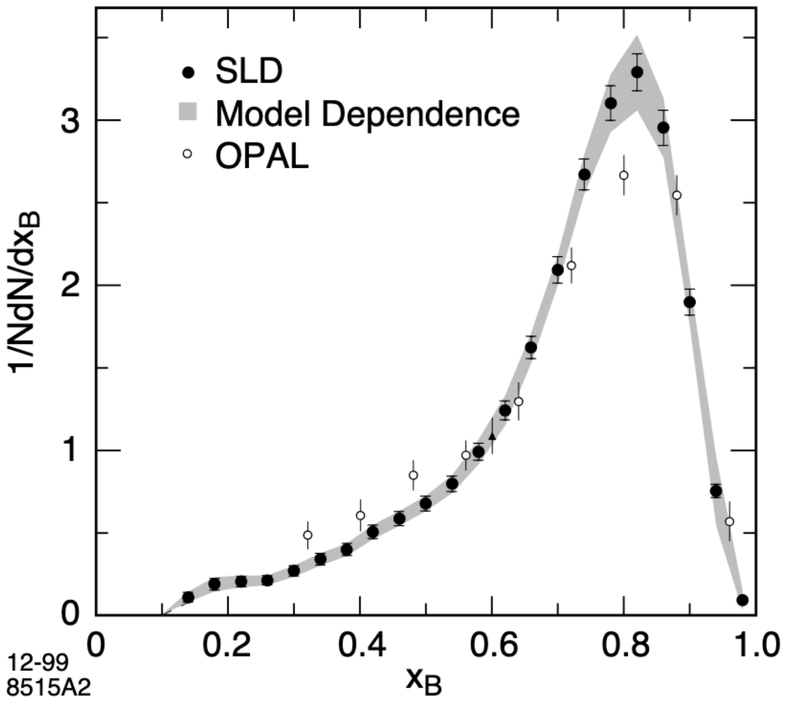


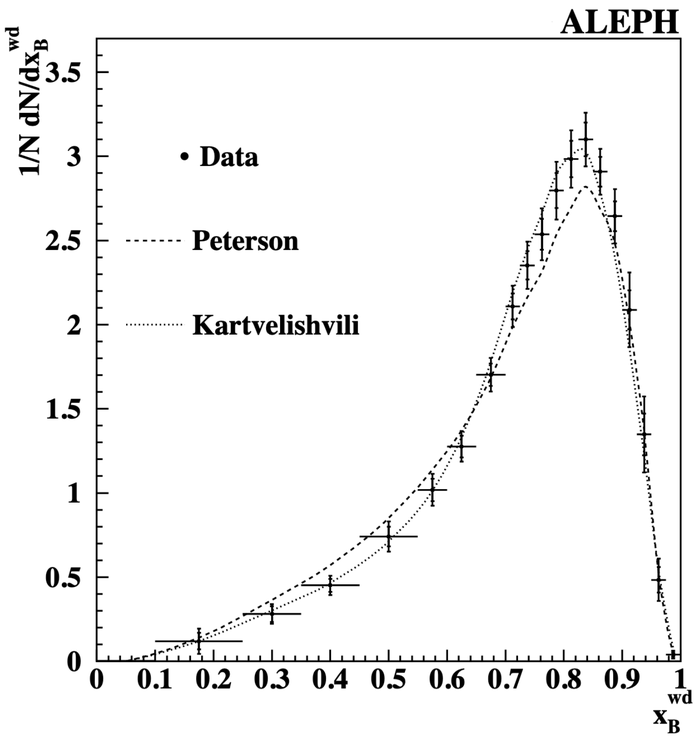


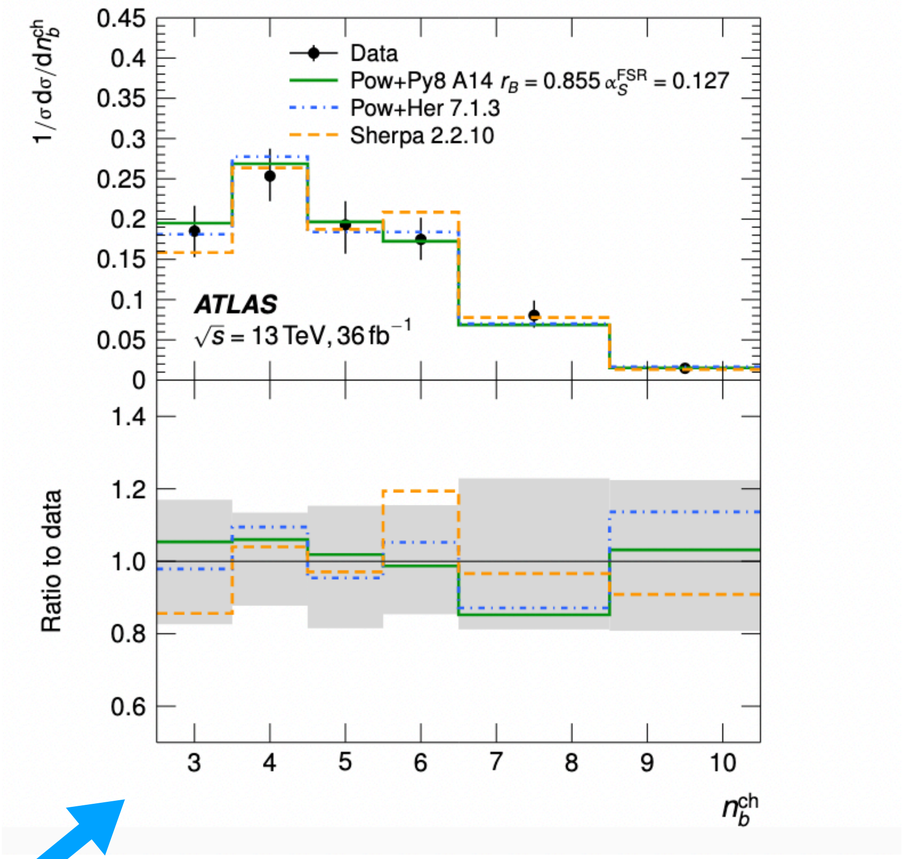
SLD, Phys.Rev.Lett 84, 4300-4304 (2000)
ALPEH, Phys.Lett.B512, 30-40 (2001)
OPAL, Phys.Lett.B 364, 93-106 (1995)
DELPHI, Z.Phys.C57 181-196 (1993)
ATLAS, Phys.Rev.D 106 (2022) 032008

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







SLD, Phys.Rev.Lett 84, 4300-4304 (2000)
ALPEH, Phys.Lett.B512, 30-40 (2001)
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DELPHI, Z.Phys.C57 181-196 (1993)
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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

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

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

Impact of the dead cone on the fragmentation is inspected with measurements of the jet shapes, a selection is discussed

Late versus all