Direct (and indirect) observation of the dead cone with heavy flavour jet substructure

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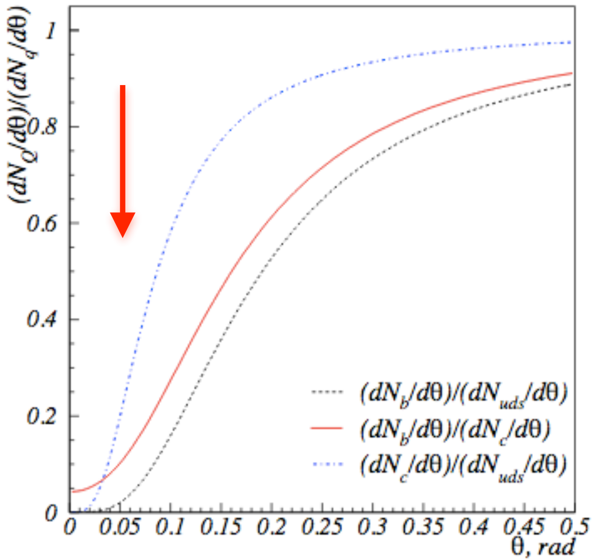
The dead cone effect in QCD

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)

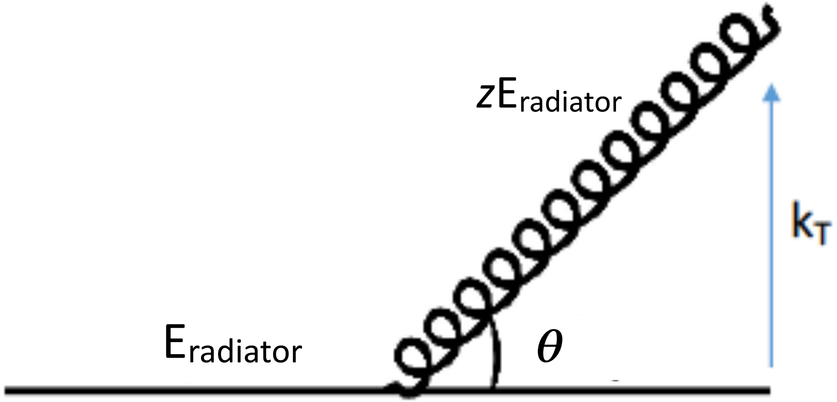
The dead cone effect

Direct consequences of the dead cone:

- Restriction of hard gluons with small k_T

  —> reduction of emissions, FF peaked at larger z

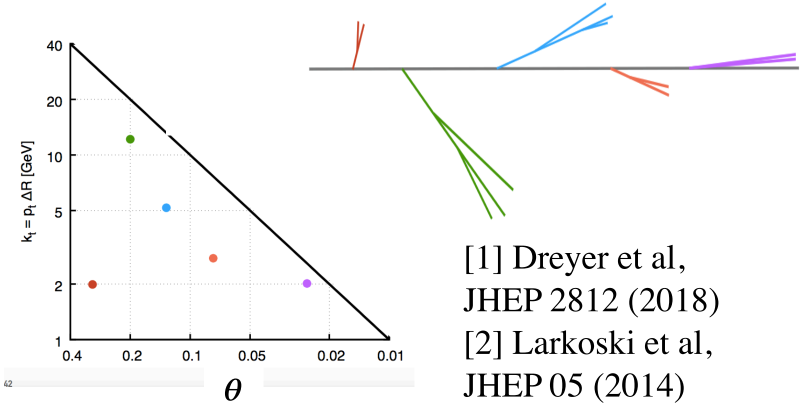
- Lower intrajet multiplicities



Experimental challenges for a direct measurement

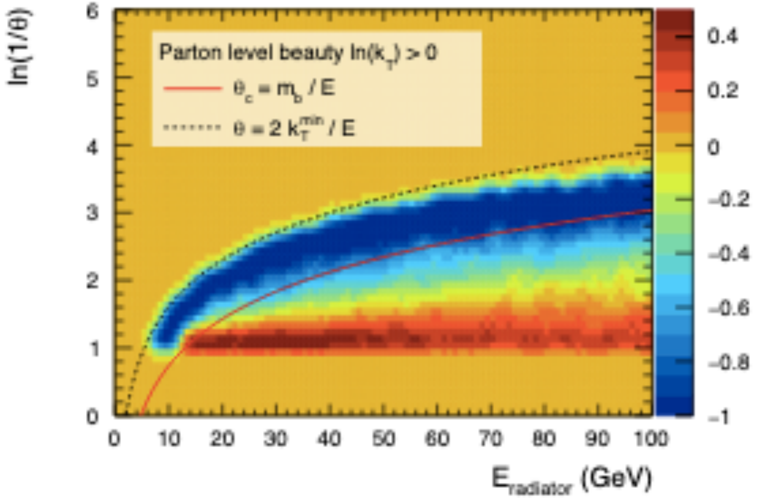
- The decays of the heavy flavour particles happen at similar angular scales and fill the dead cone
- Accurate determination of the dynamically evolving direction of the heavy-flavour particle relative to which radiation is suppressed

Iterative declustering to expose the dead cone effect



[1] Dreyer et al, JHEP 2812 (2018)
[2] Larkoski et al, JHEP 05 (2014)

Relative difference of b and q splitting maps



- Unwind the Cambridge-Aachen clustering history
- At each step register (k_T, θ) onto the Lund plane[1]
- Follow the branch containing the fully reconstructed heavy flavour hadron at each step

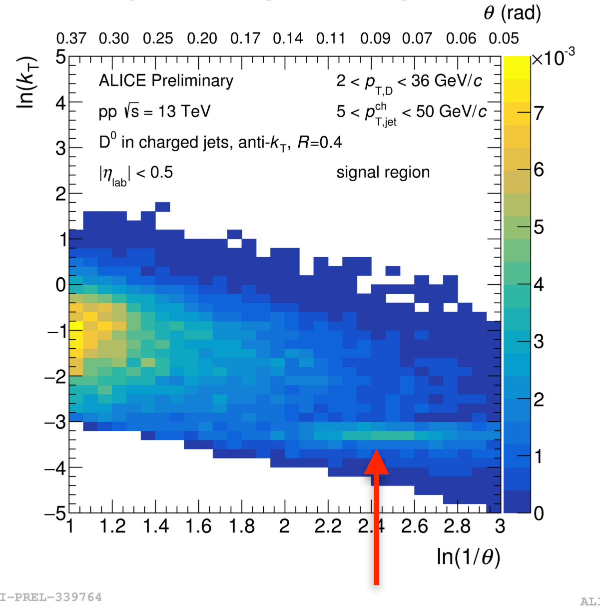
Complementary set of observables: projection of Lund plane onto θ axis, number of splittings satisfying the SD[2] cut, groomed momentum balance z_g

- Penetrate the jet tree deep enough to reach the small-angle splittings that are sensitive to mass effects $\Theta < m_Q/E_{radiator}$

Cunqueiro, Ploskon, *Phys. Rev. D* 99 (2019)

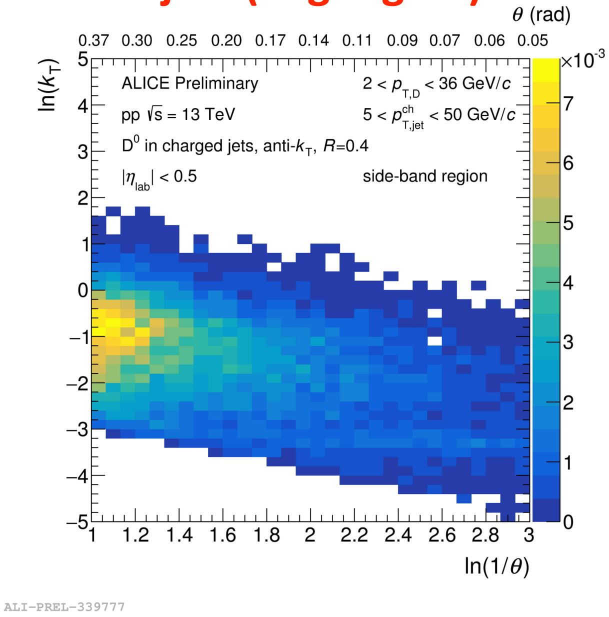
Splitting Lund Map: D^0 signal extraction

D jets (signal region)

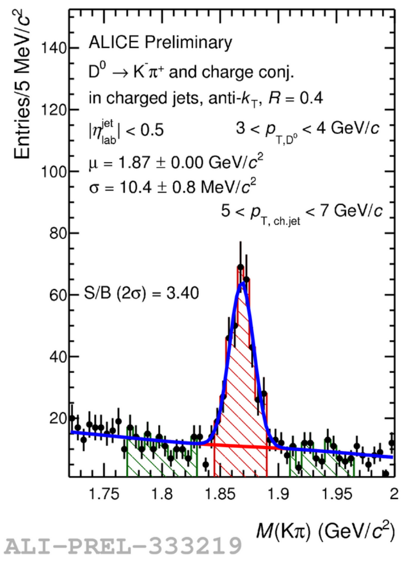


D⁰ from D* decays

D jets (bkg region)



$D^0 \to K^{\pm}\pi^{\mp}$ (BR=3.8%)

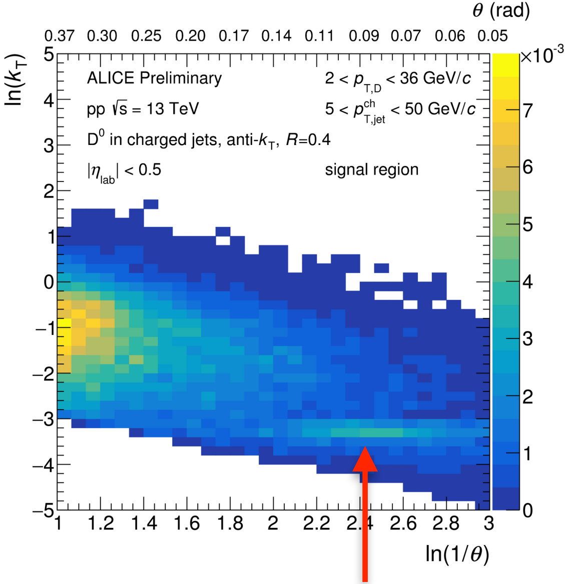


$$\rho^{D^0\text{jet}} = \sum_i \frac{1}{\varepsilon_i}\left(\rho(\theta,E)_S^{D^0\text{jet candidate}} - \frac{A_S}{A_B}\rho(\theta,E)_B^{D^0\text{jet candidate}}\right)$$

- Invariant mass distribution of the $K^{\pm}$, $\pi^{\mp}$ in bins of $p_{T,D}$
- Side-band subtraction procedure in 2D on Lund Maps
- Correction by D^0 reconstruction efficiency

Splitting Lund Map: D^0 signal extraction

D jets (signal region)



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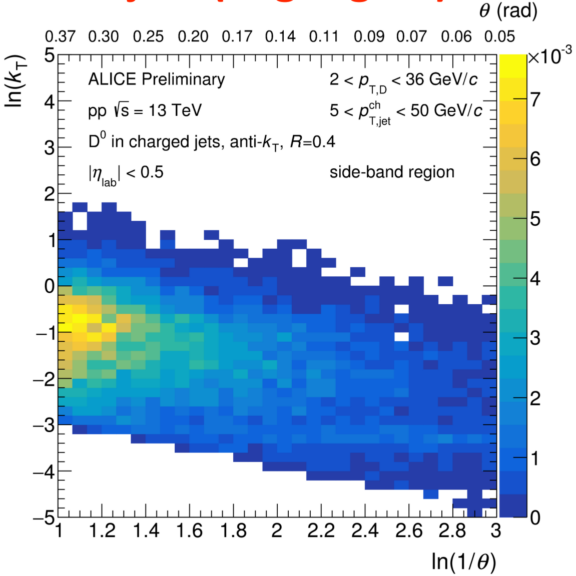
D jets (bkg region)



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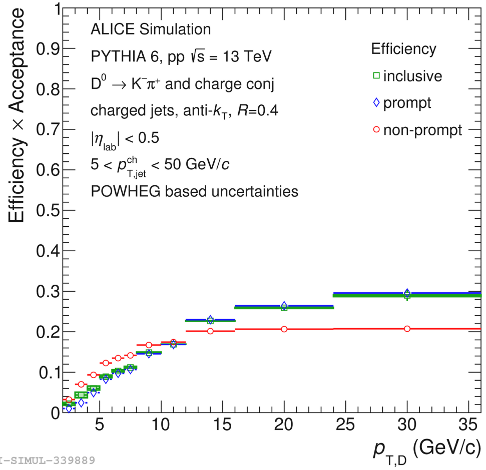
D^0 from D^* decays

$$\rho^{D^0\text{jet}} = \sum_i \frac{1}{\varepsilon_i}\left(\rho(\theta,E)_S^{D^0\text{jet candidate}} - \frac{A_S}{A_B}\rho(\theta,E)_B^{D^0\text{jet candidate}}\right)$$



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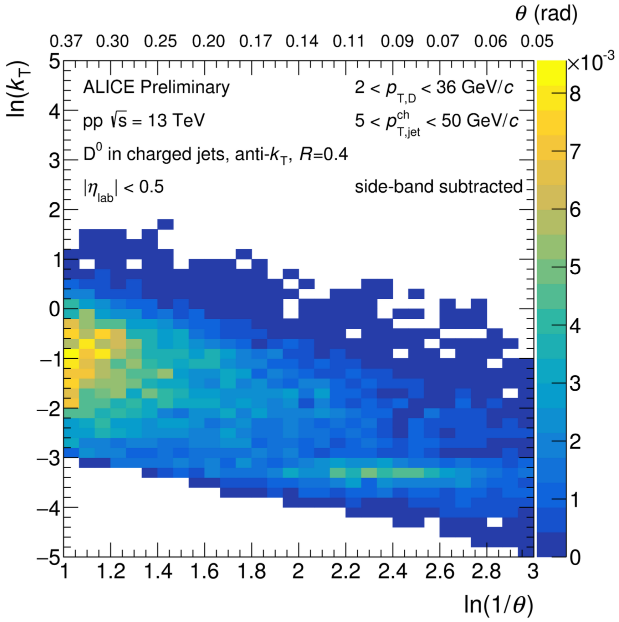
- The topological and PID cuts used for the D candidat selection have finite efficiency
- The prompt and non-prompt fractions at detector level are estimated by weighting POWHEG cross sections with the corresponding experimental efficiencies

Splittings Lund Maps

D jets (side-band subtracted)



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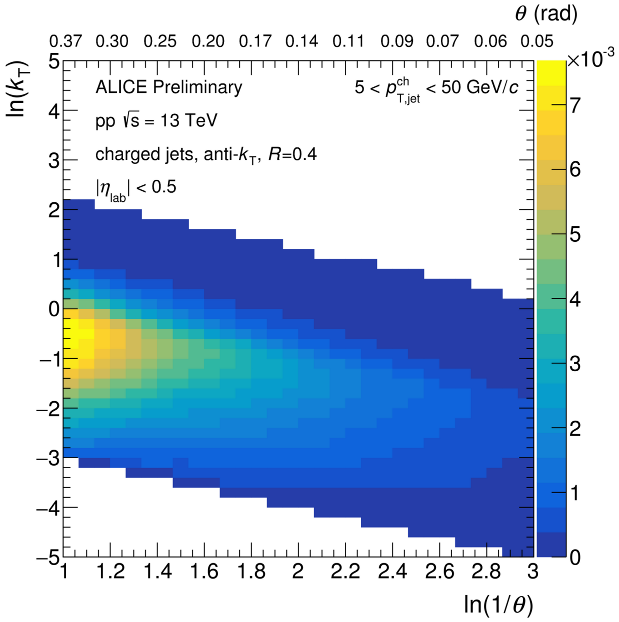
Inclusive jets



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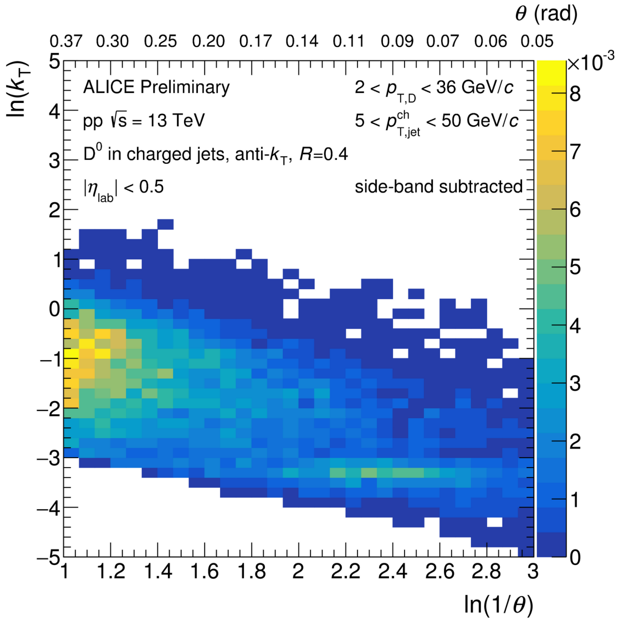
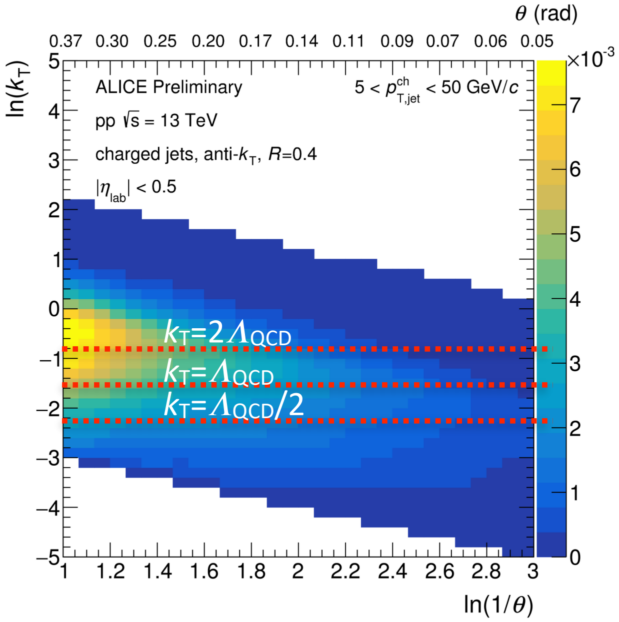
Our main observable is the ratio of projections onto the θ axis for D and inclusive jets

Splittings Lund Maps

D jets (side-band subtracted)



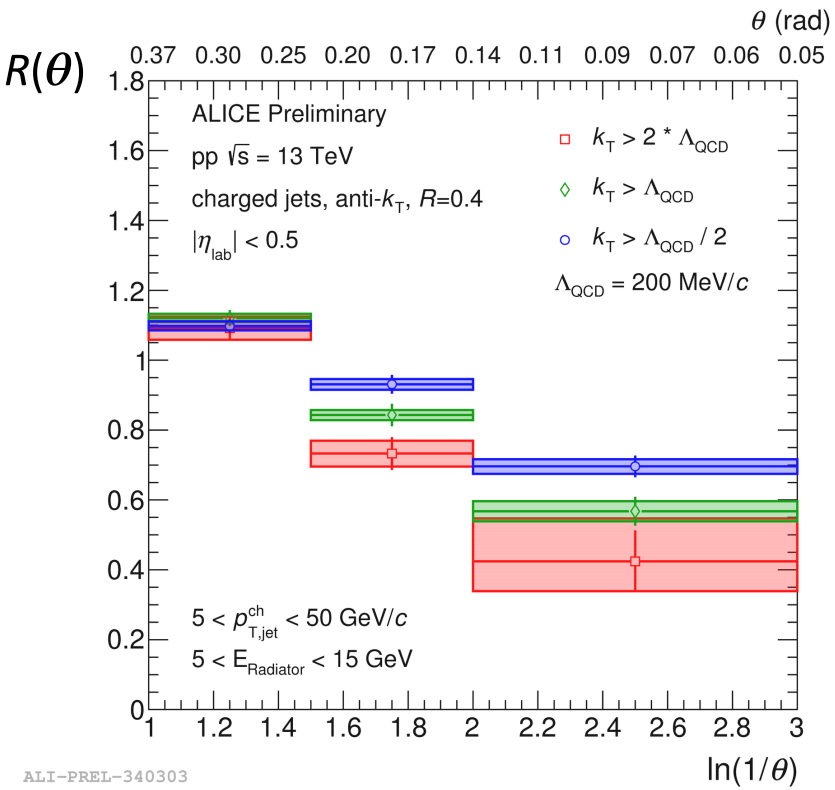
Inclusive jets



k_T cuts are applied to suppress hadronisation effects

Detector effects cancel out in the ratio

Direct observation of the dead cone effect

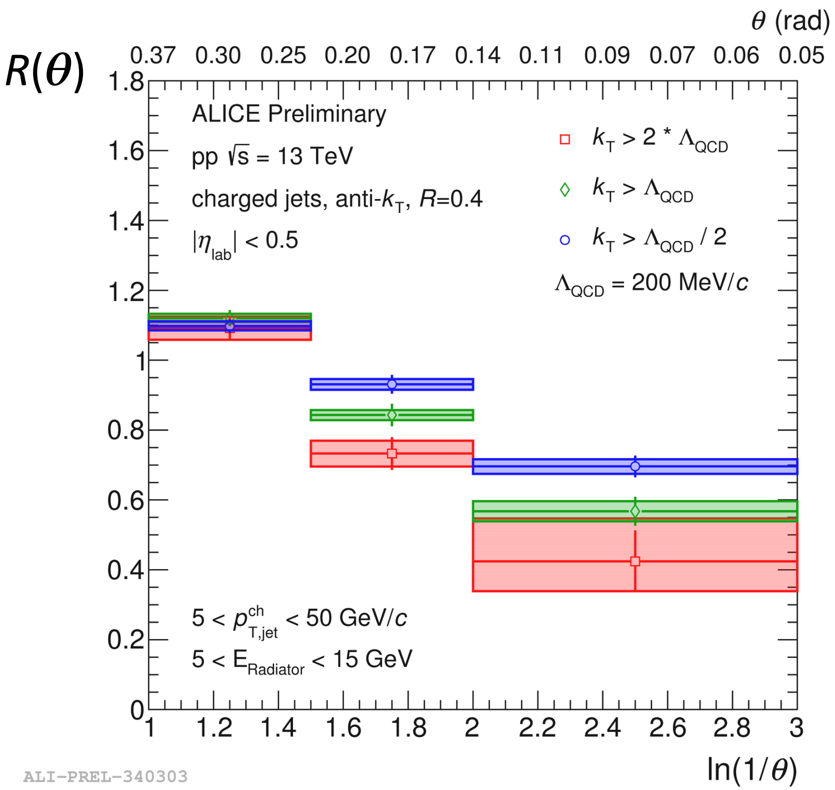


$$R(\theta) = \frac{1}{n^{D^0 \text{jets}}} \frac{dn^{D^0 \text{jets}}}{d\ln(1/\theta)} \Big/ \frac{1}{n^{\text{inclusive,jets}}} \frac{dn^{\text{inclusive,jets}}}{d\ln(1/\theta)} \Bigg|_{k_T > x\Lambda_{QCD}} .$$

Suppression of splittings at small angles in heavy flavour jets due to the dead cone effect

Effect increases with stricter k_T cuts, which suppress hadronisation effects

Direct observation of the dead cone effect



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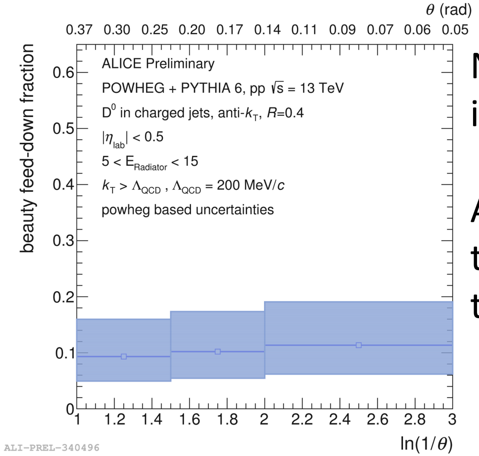
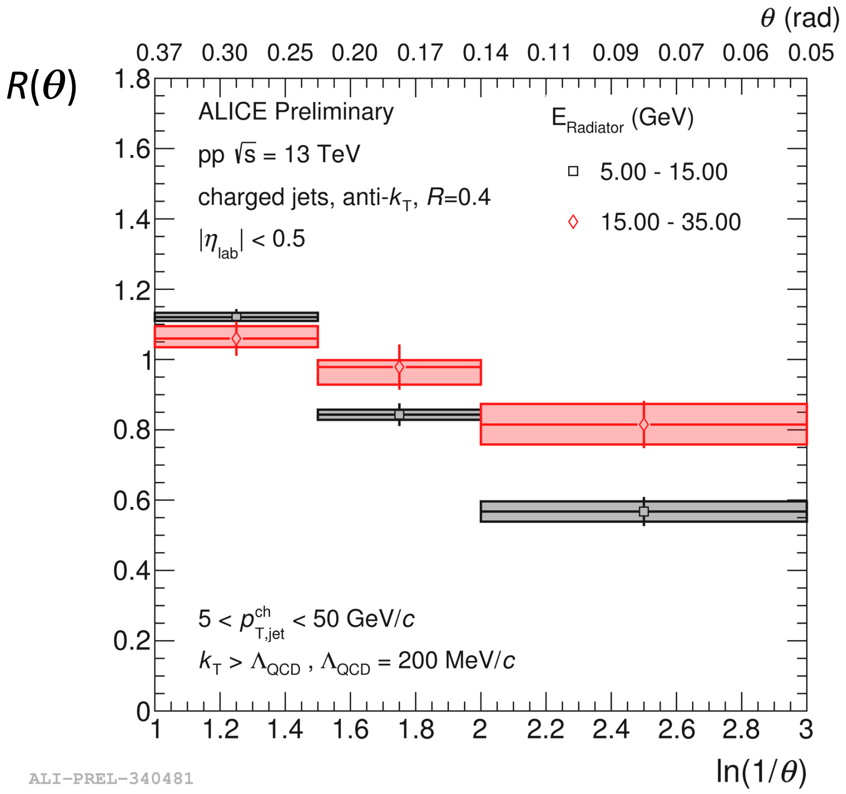


Non-prompt fraction is ~10% for $5 < E_{Radiator} < 15$ GeV

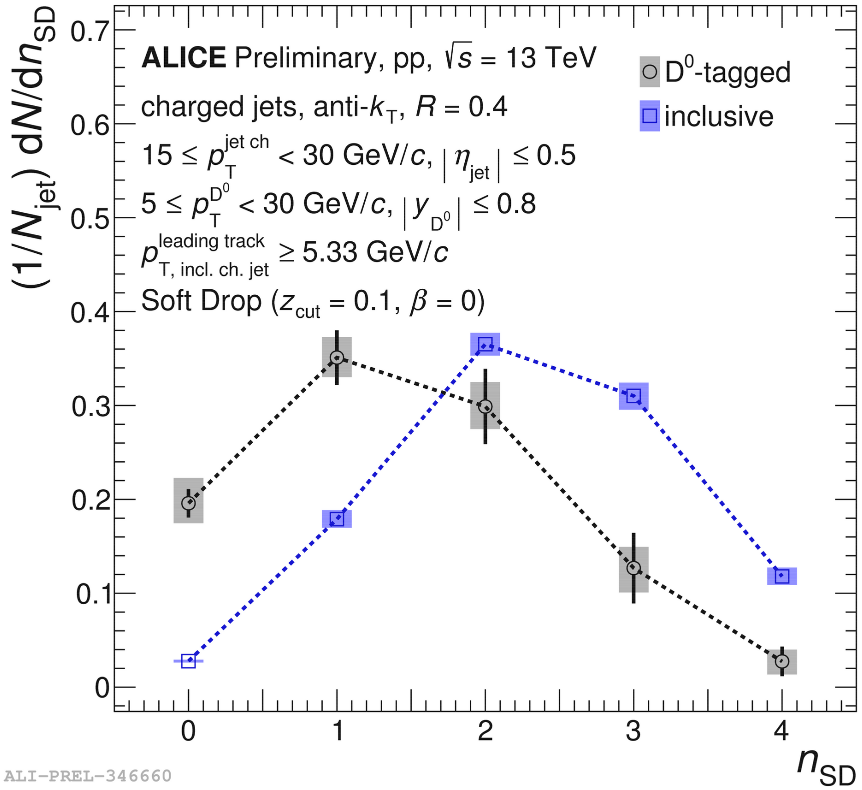
Additional decay products of the beauty hadron can cloud the dead cone effect

Dead cone effect: energy of the radiating prong



The suppression is stronger for lower energy splittings, inline with the dependence of the dead cone angle on the radiator energy

The dead cone leads to a reduced intrajet multiplicity



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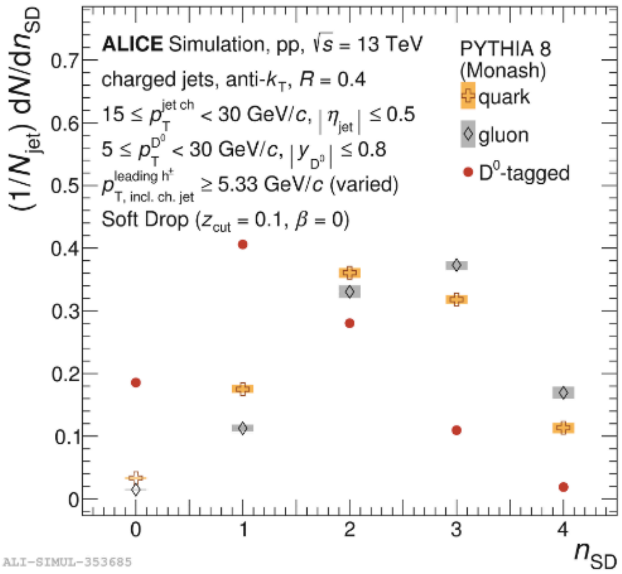
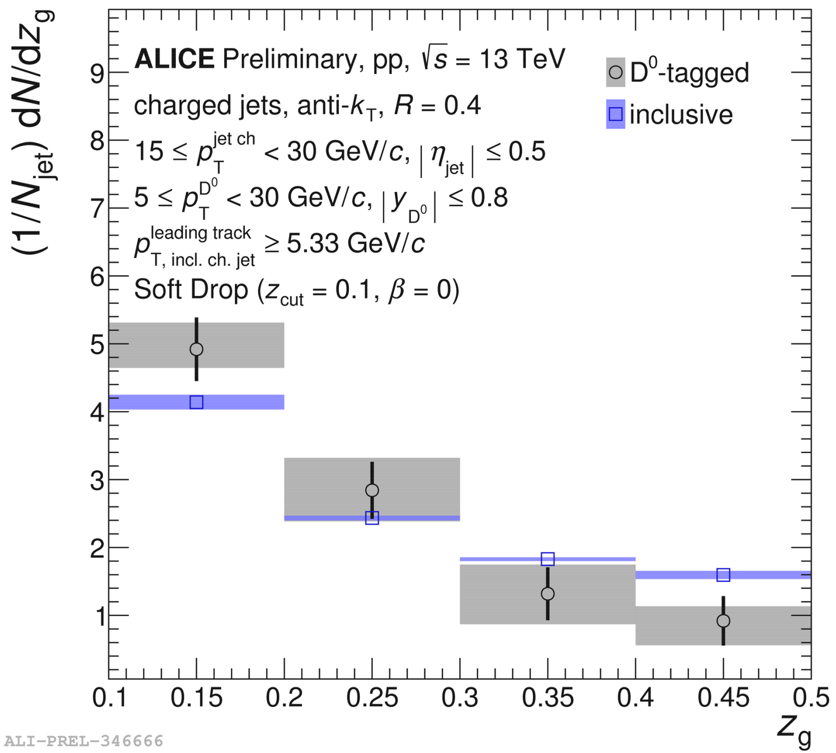
Fewer prongs passing the Soft Drop cut for D-jets than for inclusive jets



Both color factors and mass effects contribute to the difference in Pythia

The dead cone leads to a harder fragmentation



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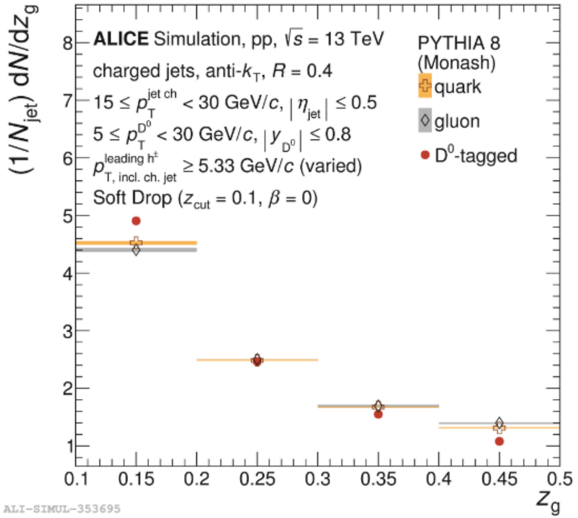
Hint for a more asymmetric groomed momentum balance for D-jets than for inclusive jets

Consistent with a harder fragmentation for heavy quarks

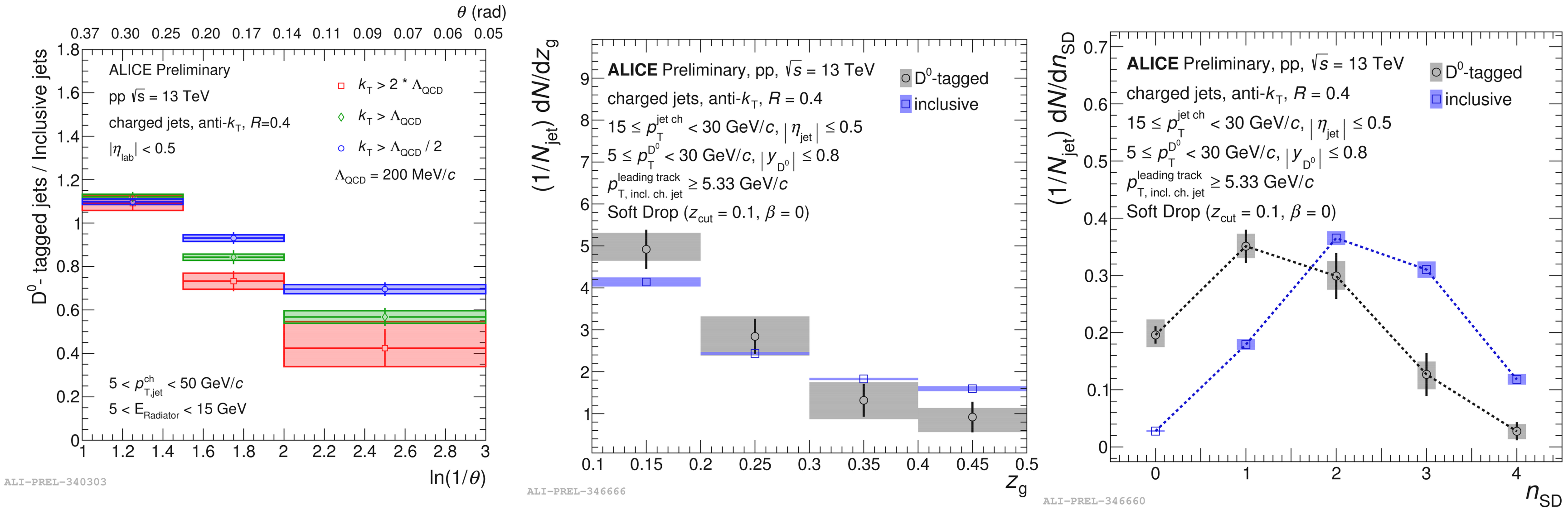


Mass effects are potentially isolated with this observable, since to a good approximation z_g is the same for quark and gluons [1]

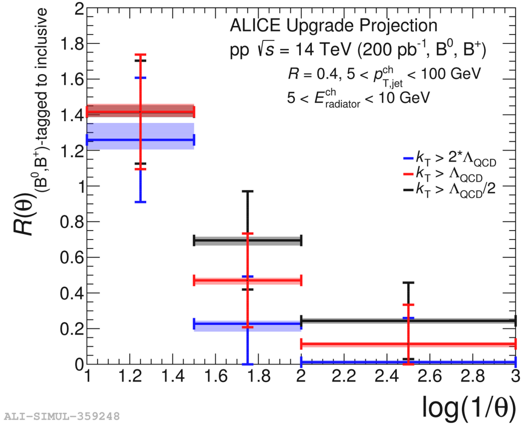
[1] Larkoski et al, *Phys.Rev.Lett*. 119 (2017) 13, 132003

Conclusions

- First direct measurement of the dead cone effect using iterative declustering of fully reconstructed D-jets
- Groomed jet substructure like the momentum balance z_g or the n_{SD} probe consequences of the dead cone effect, ie harder fragmentation and lower intrajet multiplicities for HF jets



Prospects: mass scan and dead cone effect in heavy ion collisions



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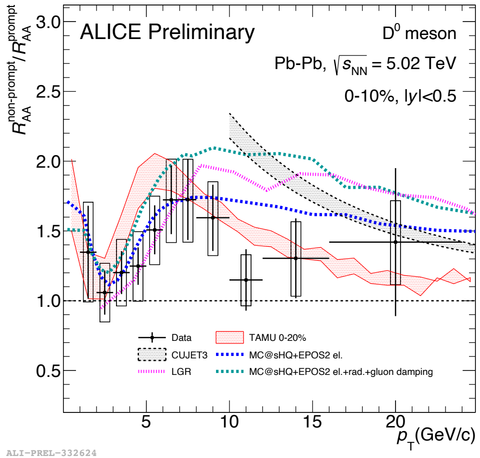


ALI-PREL-332624

Improved HF selection after ALICE upgrade in LS2 will allow to measure the dead cone using iterative declustering of jets containing a fully reconstructed B hadron as constituent

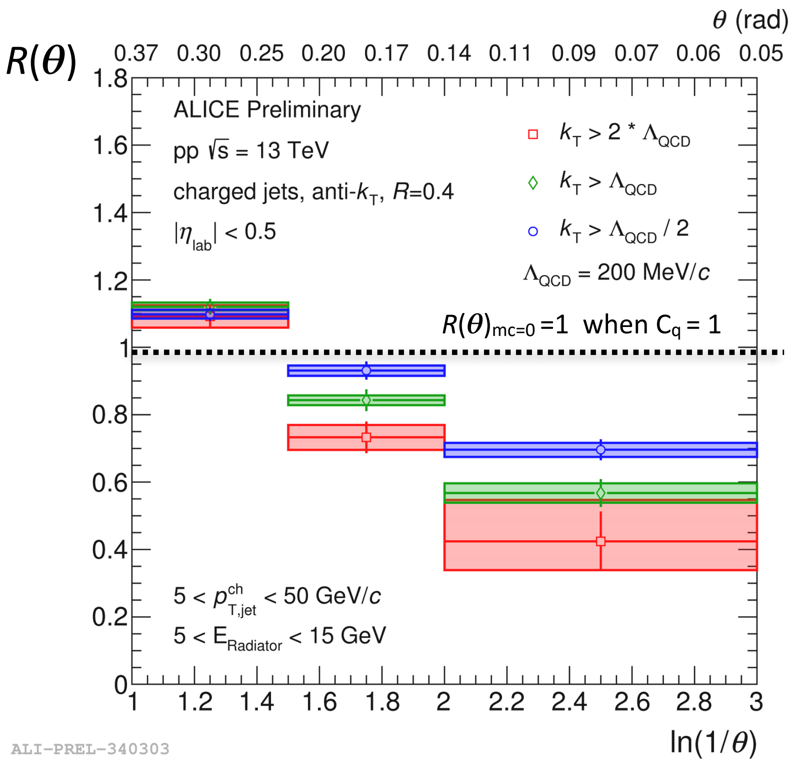
Run 3 projections: possibility to measure the dead cone differentially as function of the mass of the heavy hadron and radiator energy

In heavy ion collisions, medium-induced radiation is expected to fill the dead cone [1]
Opportunity to explore a region of phase space where vacuum radiation is suppressed and medium-induced signal is expected to dominate?

[1]Armesto et al, *Phys.Rev.D* 69 (2004) 114003

EXTRAS

Dead cone: the impact of the inclusive reference



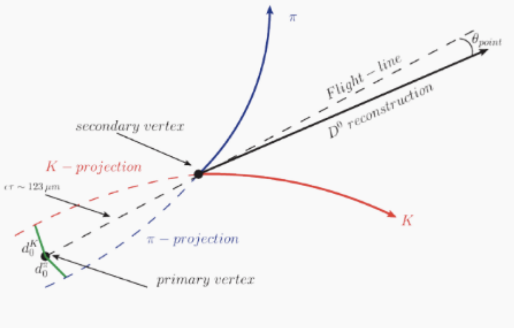
The inclusive jet reference in our measurement is a mixture of quark and gluon jets

Consequently, the baseline for no dead cone effect (m_C=0) is not at unity but rather depends on the difference of the angular distributions of light quarks and gluons

If $C_q = 1$, $R(\theta)_{mc=0} = 1$

If $C_q < 1$, $R(\theta)_{mc=0} > 1$ because light quark jets are more collimated than gluon jets

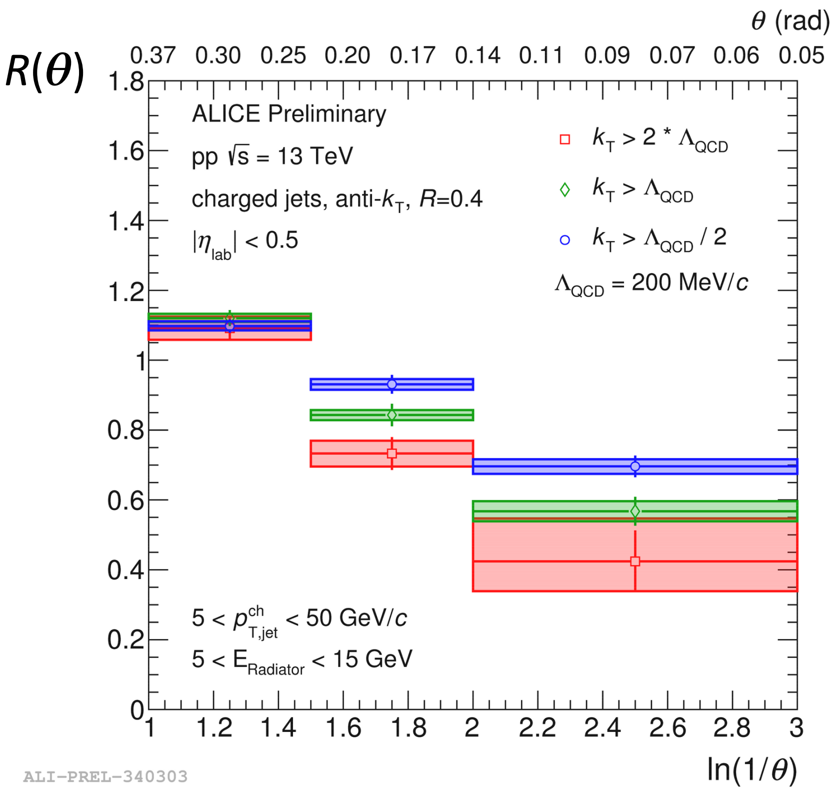
Direct observation of the dead cone, analysis strategy



D^0 reconstruction

- Decay channel: $D^0 \rightarrow K^{\pm}\pi^{\mp}$ (BR=3.8%)
- D^0 candidates are reconstructed using PID of K and π and topological cuts on the secondary vertex
- $K^{\pm}\pi^{\mp}$ pairs are replaced by the D^0 candidate prior to jet finding
- Jets are clustered with the anti-k_T algorithm with R=0.4
- Jets are reclustered using the Cambridge-Aachen algorithm
- A Lund plane is built using the info from the secondary prongs at each step of the declustering process, the leading prong always contains the D^0 candidate
- A 2D side-band procedure is applied in order to obtain the Lund Plane associated to the D^0 signal only
- A final observable is built as the ratio of the projections of the Lund planes onto θ axis for D and inclusive jets
- Detector effects cancel out in the ratio, which can be directly compared to particle-level calculations after appropriate weighting of the prompt and non-prompt fractions

Direct observation of the dead cone effect



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Dominant sources of the experimental uncertainty are:

- Fitting ranges and fitting functions of the invariant mass distribution
- Signal and bkg ranges in the SD subtraction procedure
- Variations of the topological and PID cuts for the D selection

Other sources are:

- Uncertainties of the POWHEG calculation used to derive the prompt/non-prompt fractions
- Tracking efficiency uncertainty of ~4%
- Leading track requirement in the inclusive case