Searching for the dead cone effect in beauty and charm jets at the LHCb experiment

CFNS Summer School

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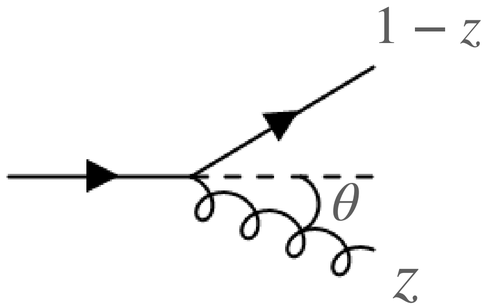
The Dead Cone Effect

Bremsstrahlung off moving charges

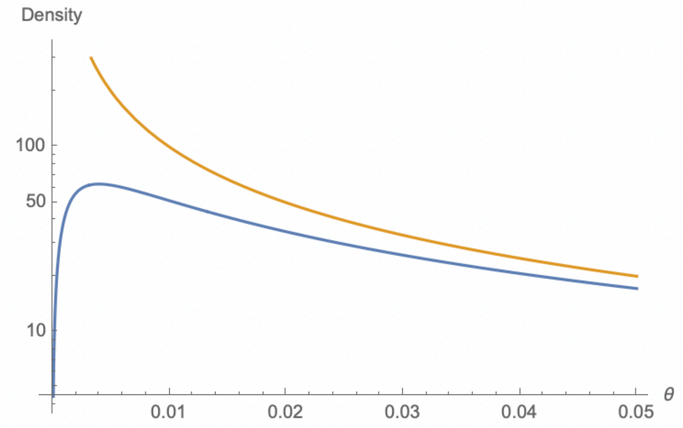


- The relativistic and massless splitting probability in pQCD is given by

$$dP_{i\to ig} = \frac{\alpha_s C_i}{\pi}\frac{d\theta^2}{\theta^2}\frac{dz}{z}$$

z : Energy Fraction
θ : Splitting angle
C_i : Color factor

- For heavy quarks (HQ), a characteristic angle appears in the equation



$$dP_{i\to ig} = \frac{\alpha_s C_i}{\pi}\frac{\theta^2 d\theta^2}{(\theta^2+\theta^2_{\mathrm{HQ}})^2}\frac{dz}{z}$$

$$\theta_{\mathrm{HQ}} = \frac{m_{\mathrm{HQ}}}{E}$$

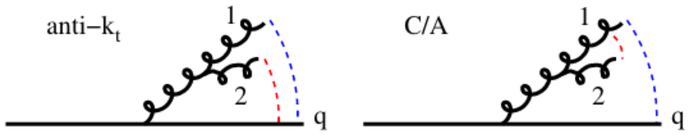
Dokshitzer, Y.L., Khoze, V.A. and Troyan, S.I., 1991.
Journal of Physics G: Nuclear and Particle Physics, *17*(10), p.1602.

$$\Delta R = \sqrt{(\eta_i - \eta_j)^2 + (\phi_i - \phi_j)^2}$$

R : Jet Radius

Jets and Clustering Algorithms

Anti-kT, Cambridge/Aachen



- Given a collection of particles, define a distance between two particles as:

$$d_{ij} = \min\left(p_{ti}^{2p}, p_{tj}^{2p}\right)\Delta R_{ij}^2/R^2$$

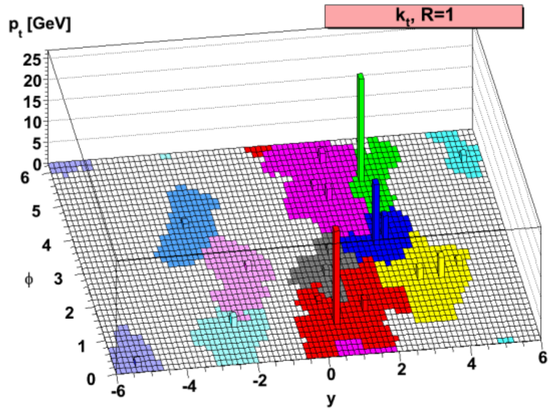
p = 1: kt

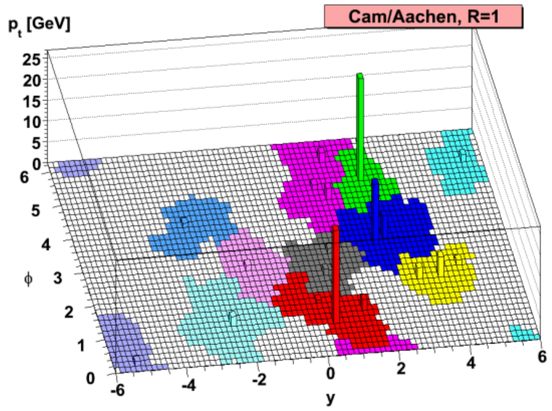
p = 0: Cambridge Aachen (C/A)

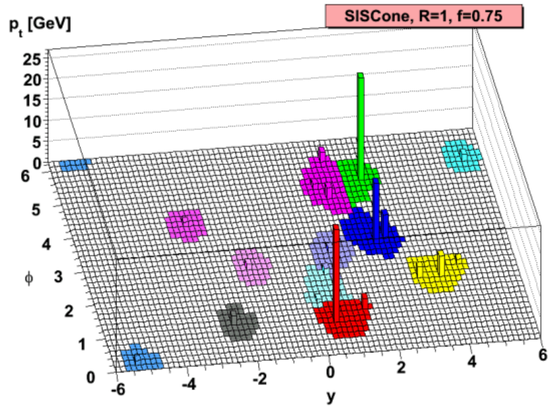
p = -1: Anti-kt

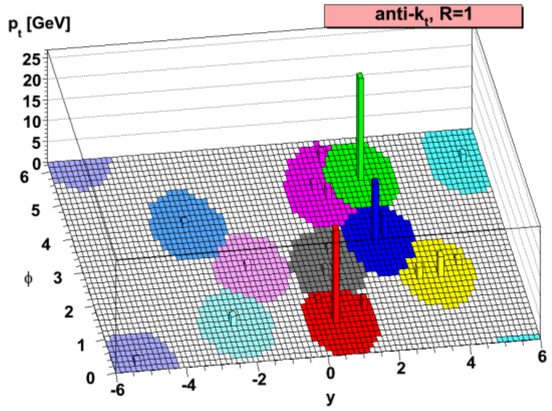
- Merge the two particles with the lowest distance first, repeat until all particles have been merged/clustered
- Anti-kt is infrared and collinear safe (IRC)
- C/A reflects the **angular ordering** of the parton shower in QCD

Angular ordering gives us access to the splitting history of the jet

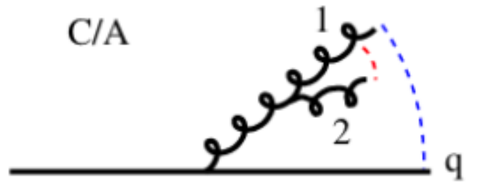






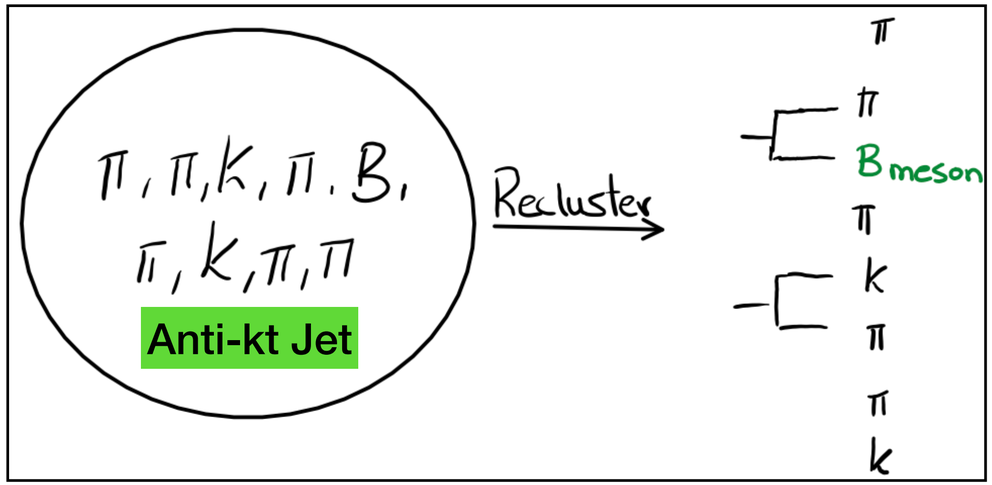


Iterative Declustering

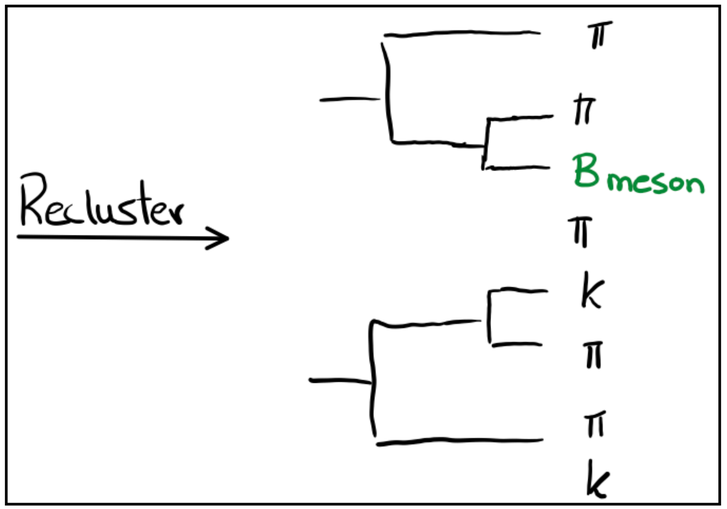


Recluster = combine most collinear particles

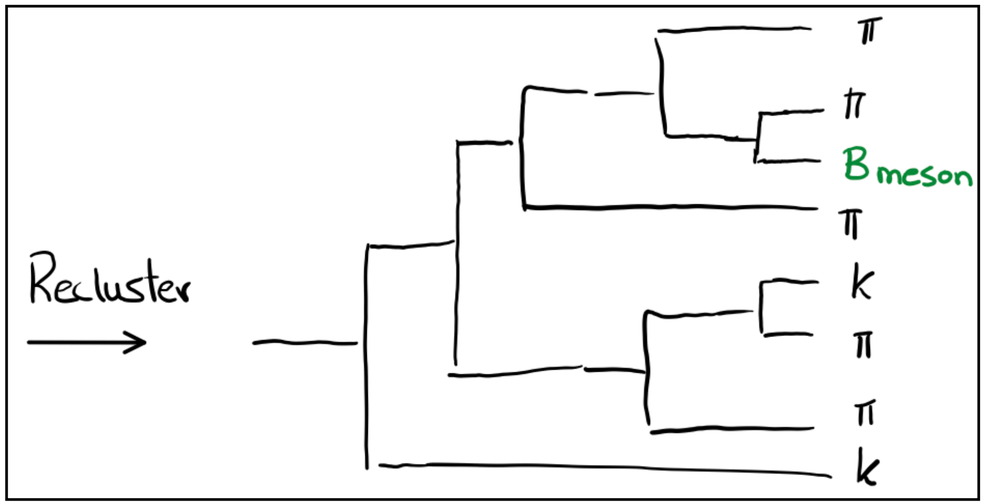
1a.



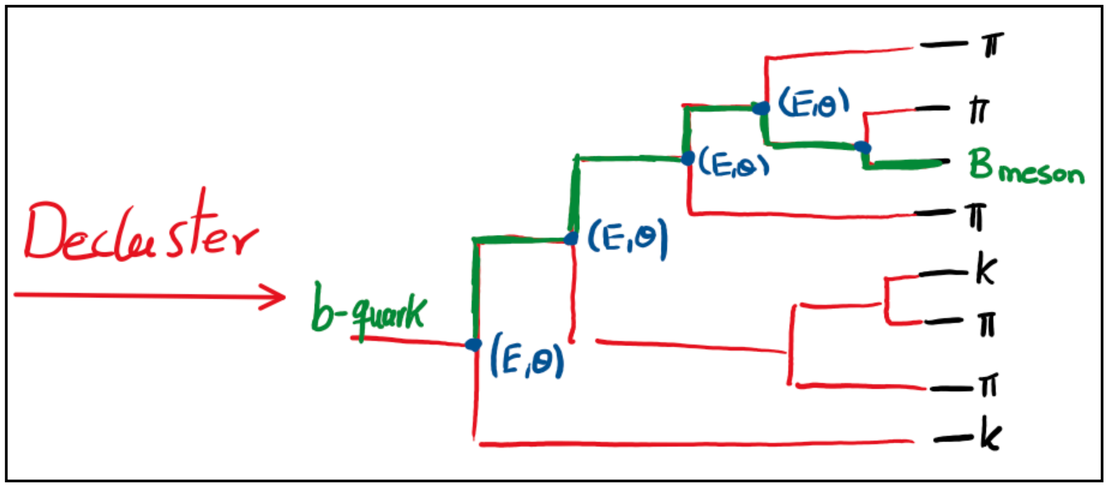
1b.



1c.



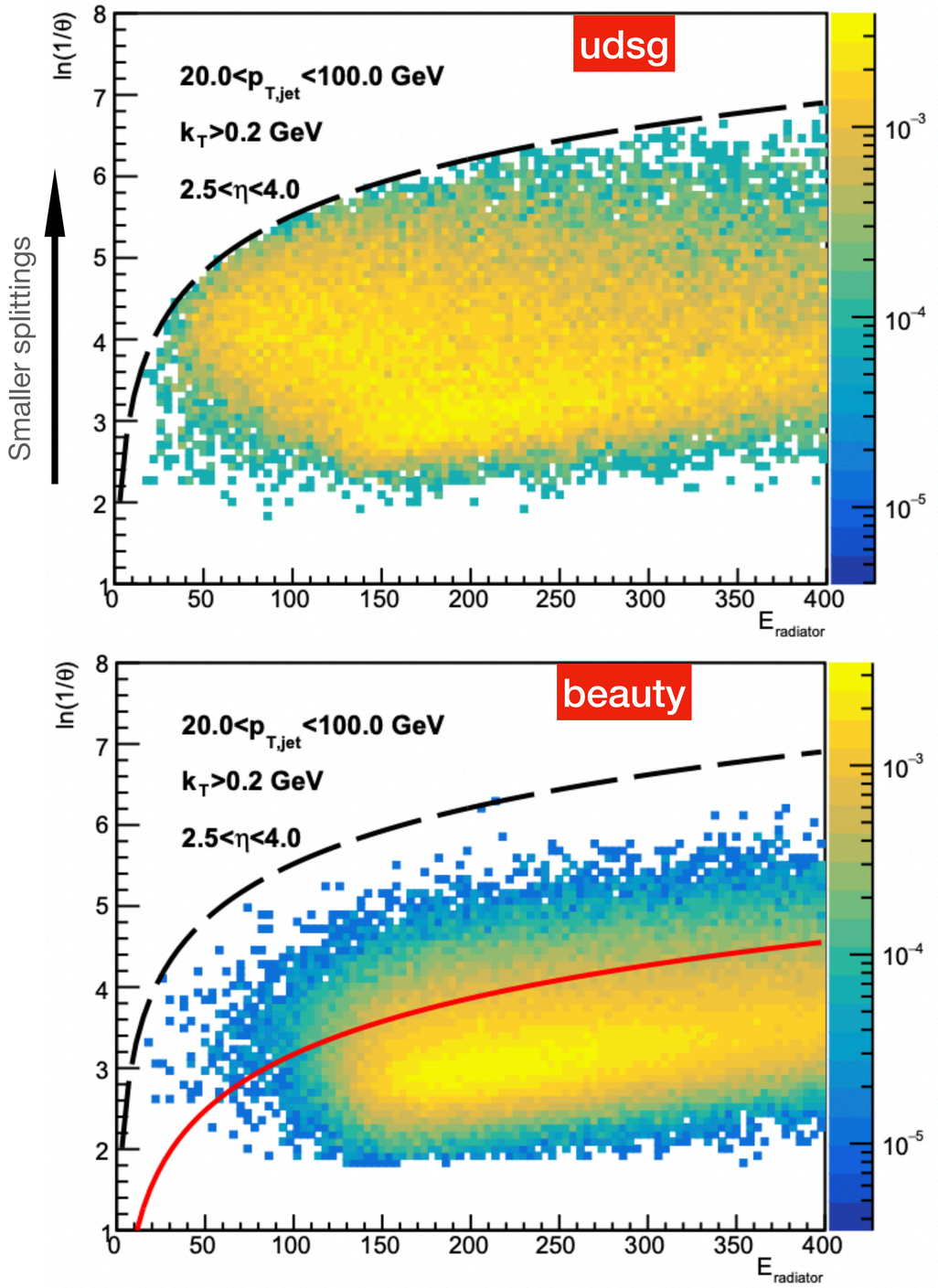
2.



Cunqueiro, L. and Płoskoń, M., 2019. *Physical Review D*, *99*(7), p.074027.

Lund Plane

- After declustering, populate the Lund plane with $\ln(1/\theta)$ and E_{rad}
- E_{rad} = Energy of radiating quark
- We plot $\ln(1/\theta)$ since the splitting probability goes like $\mathrm{d}\ln(\theta)$
- Lund planes are normalized by the number of jets N_{jets}
- Dead cone expected above the red line

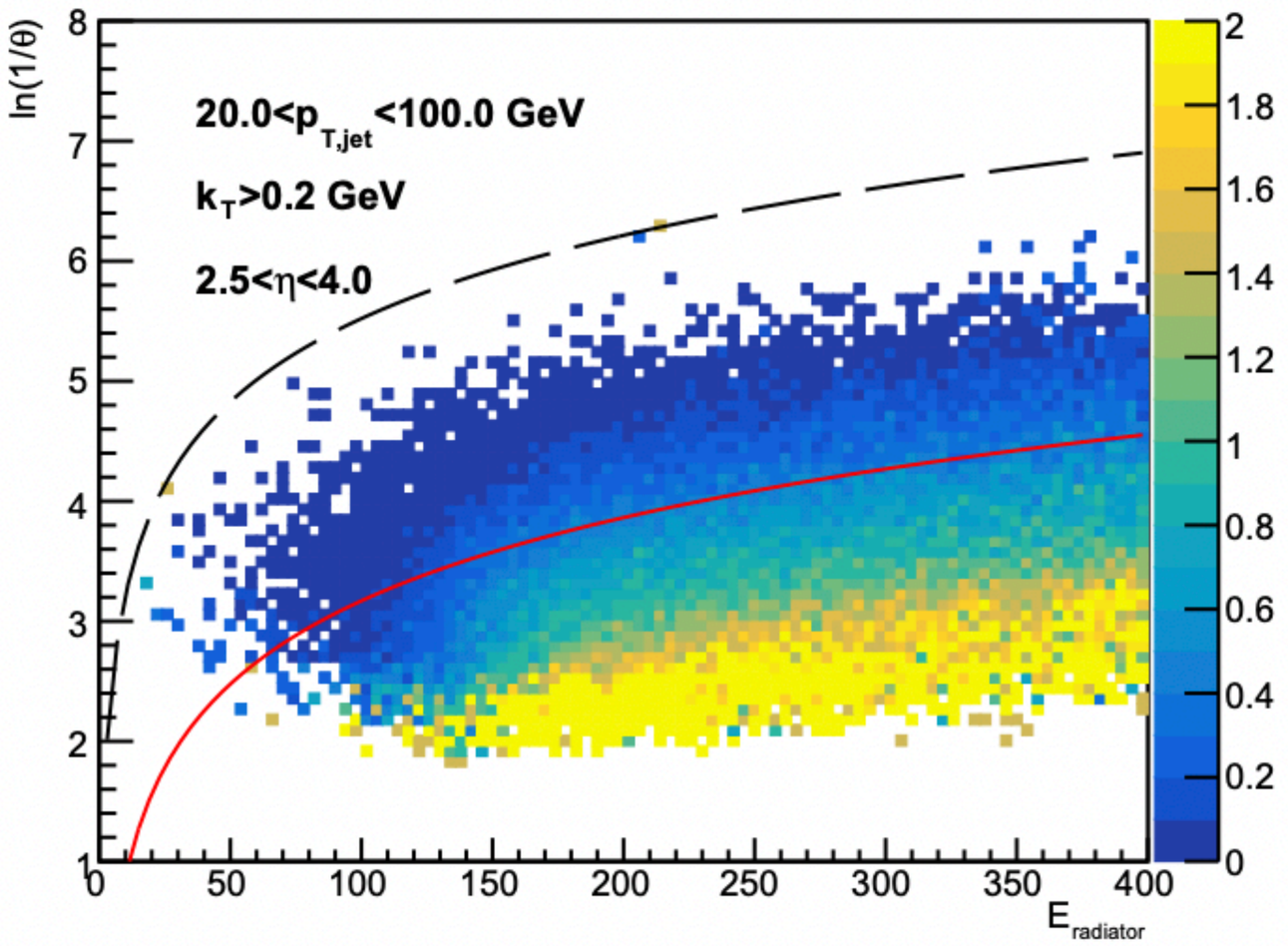


Results with Pythia

b-dijet/udsg jets

- Pseudorapidity cuts to mimic LHCb acceptance
- Fully reconstructed B meson
- Clear region of low ratio (dark blue) above the red line
- For large angles, we see a large ratio (in yellow) indicating more splittings in beauty jets compared to udsg jets. This is currently being investigated…

beauty/udsg ratio



Do we see this in experiments?

n = # of splittings

N = # of jets

$k_T = E_{\text{soft}} \sin(\theta)$

ALICE Measurement

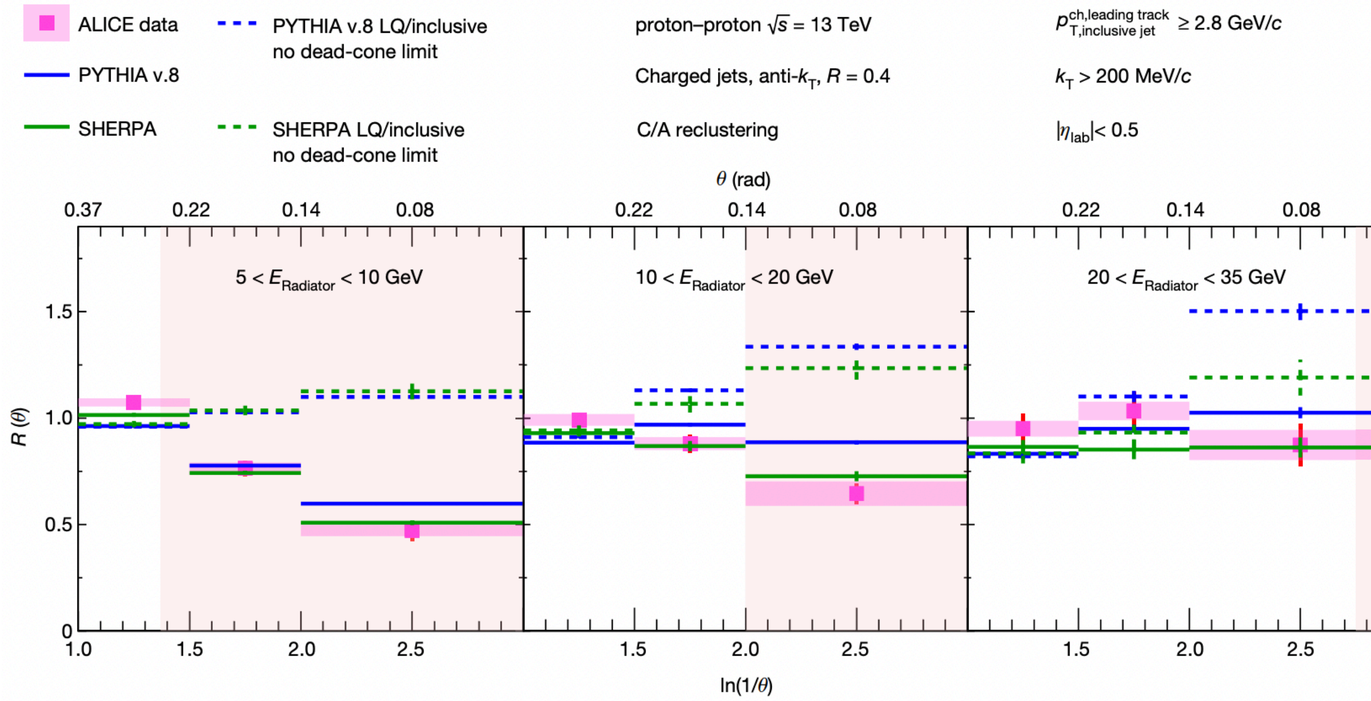
Ratio of heavy to udsg splitting density

- The main observable used to uncover the dead cone is

$$R(\theta) = \frac{1}{N^{\text{HQ jets}}} \frac{\mathrm{d}n^{\text{HQ jets}}}{\mathrm{d}\ln(1/\theta)} \Big/ \frac{1}{N^{\text{LQ jets}}} \frac{\mathrm{d}n^{\text{LQ jets}}}{\mathrm{d}\ln(1/\theta)} \Big|_{k_{\mathrm{T}}, E_{\text{Radiator}}}$$

- If HQ behave like LQ, then one expects $R(\theta) = 1$

- If HQ exhibit a dead cone, then one expects $R(\theta) < 1$ for $\theta < \theta_{\text{HQ}}$



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https://cds.cern.ch/record/2771612
Direct observation of the dead-cone effect in QCD (ALICE)

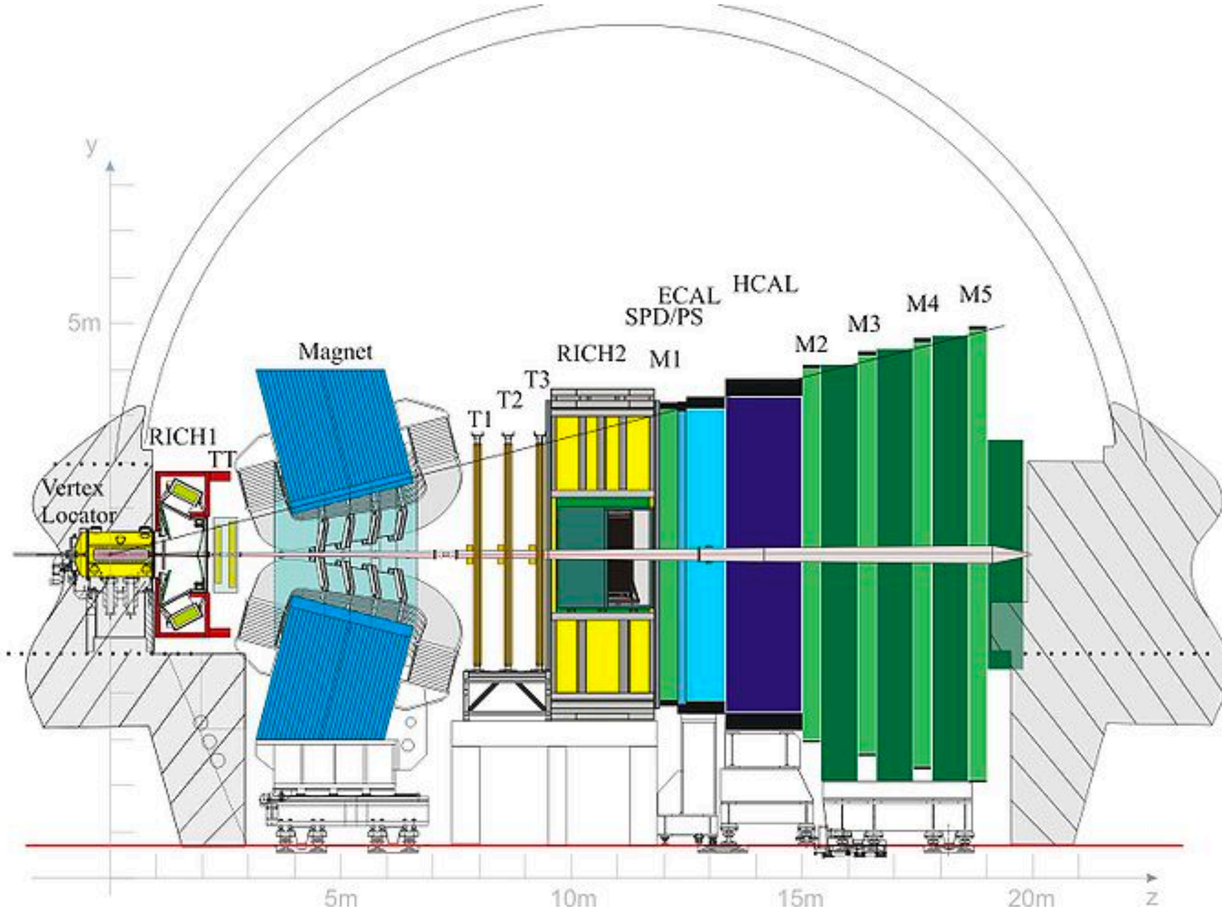
Going Beyond the ALICE Measurement

- Our measurement will go beyond the ALICE measurement in the following three ways:

1. Dead cone measurement of b and c jets, compared to just c jets.

2. Both all-particle and charged jets, compared to charged jets.

3. Direct ratio to LQ jets, compared to gluon-dominated midrapidity inclusive jets.



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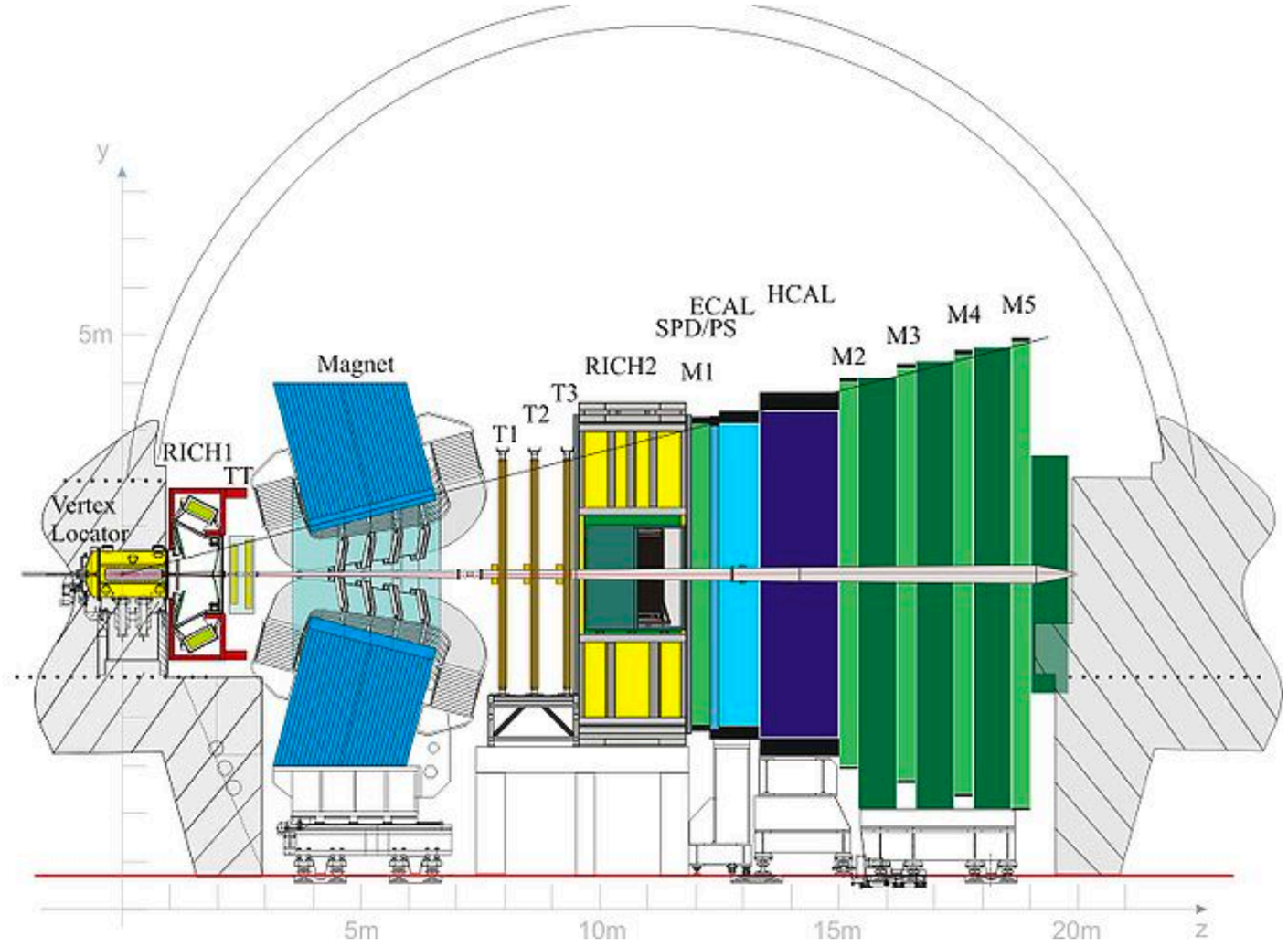
Direct observation of the dead-cone effect in QCD (ALICE)

The LHCb Experiment

- Single-arm forward detector ($2 < \eta < 5$), designed for b physics
- Tracking, PID, ECAL, HCAL, Muon, hardware and software triggers
- Secondary-Vertex (SV) tagging of heavy flavor mesons
- Boosted decision trees for b/c jet separation



Jet Samples

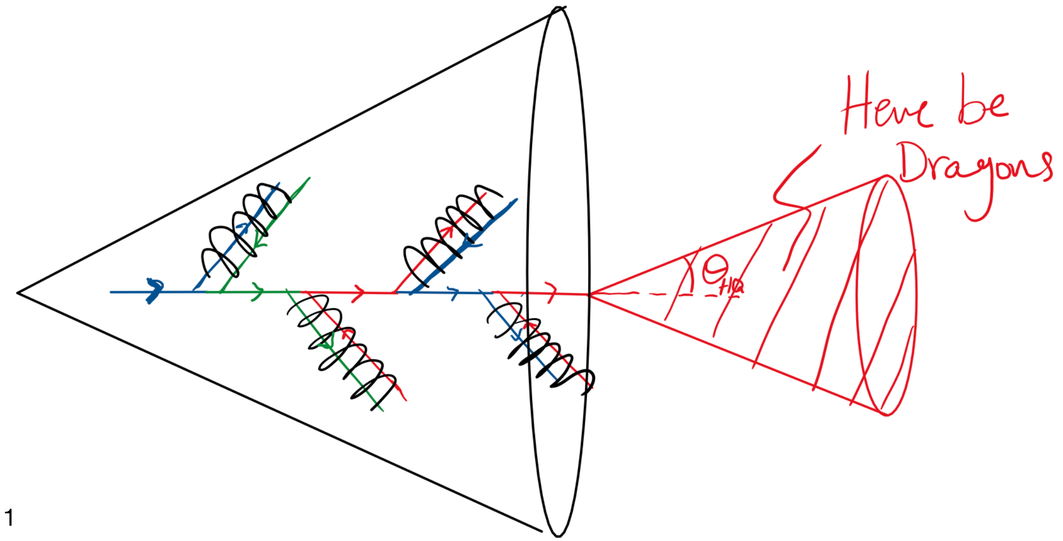
Heavy quark dijets, Z-tagged light quark jets

- For HQ jets, LHCb is particularly optimized to measure b- and c-dijets.
- HQ jets are tagged and identified through secondary vertex (SV) and boosted decision trees (BDT) respectively.
- For LQ jets, we use Z-tagged jets which enriches the jet content with light-quark jets. Follow the hardest prong through declustering.
- In both cases, we plan to use p+p Run II data at $\sqrt{s} = 13$ TeV for the years 2016-2018.

Summary and Next Steps

- pQCD predicts a suppression of radiation for heavy quarks ‘the dead cone’
- Using iterative declustering techniques, we can access the jet splitting history
- The LHCb has great reconstruction and resolution capabilities for this measurement
- ALICE has observed the dead cone in track-based charm jets, we will go three steps further

My analysis will study beauty & charm jets using all-particle jets compared to light-quark dominated Z-tagged jets



Back up Slides

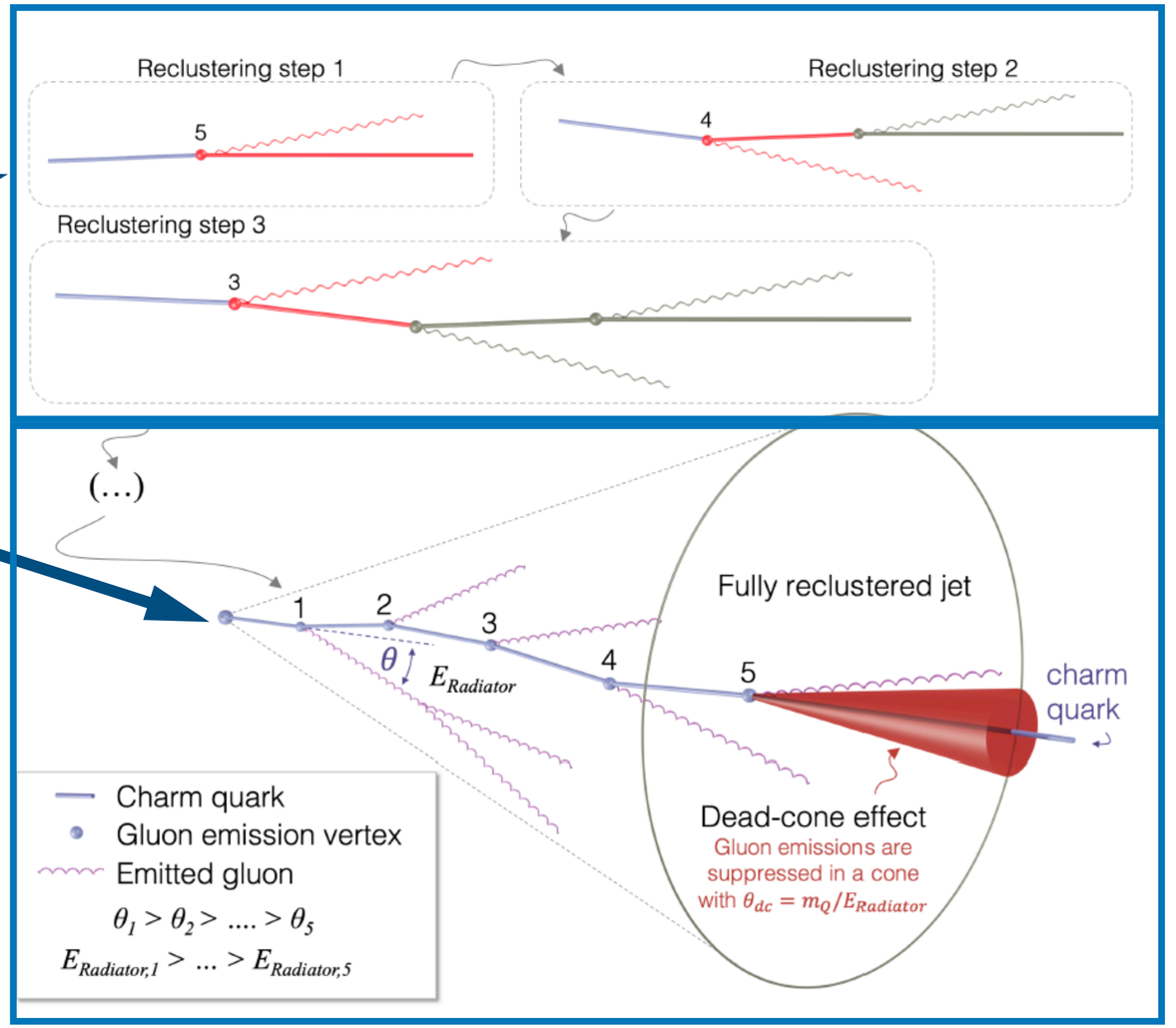
Uncovering the Dead Cone

Iterative declustering techniques

1. Recluster your standard anti-kt jet using Cambridge/Aachen (for angular ordering)

2. Decluster the jet by following the HQ evolution

3. At each splitting, record (E, θ) which are the HQ energy and the splitting angle



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F. A. Dreyer, G. P. Salam, and G. Soyez, The Lund jet plane, J. High Energy Phys. 12 (2018) 064

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