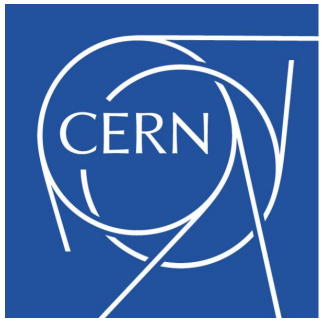
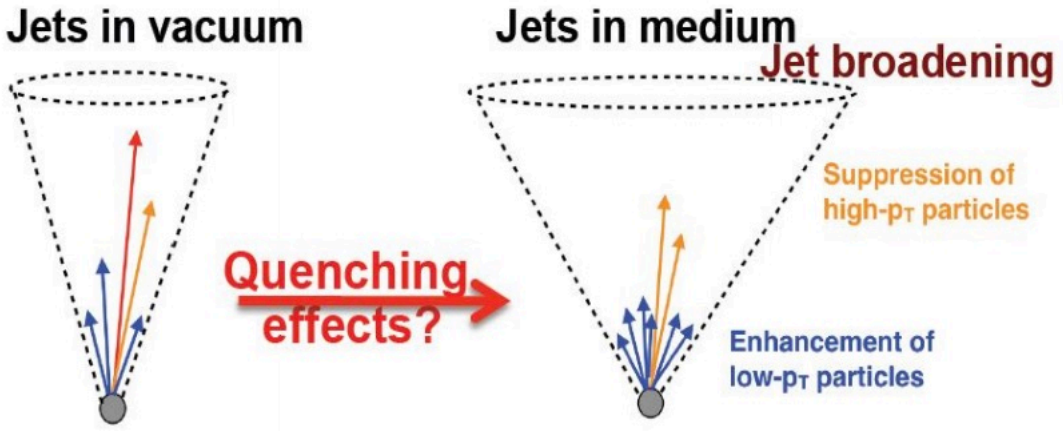


Probing the Properties of Fully Reconstructed Heavy Flavour Jets at ALICE

Nima Zardoshti

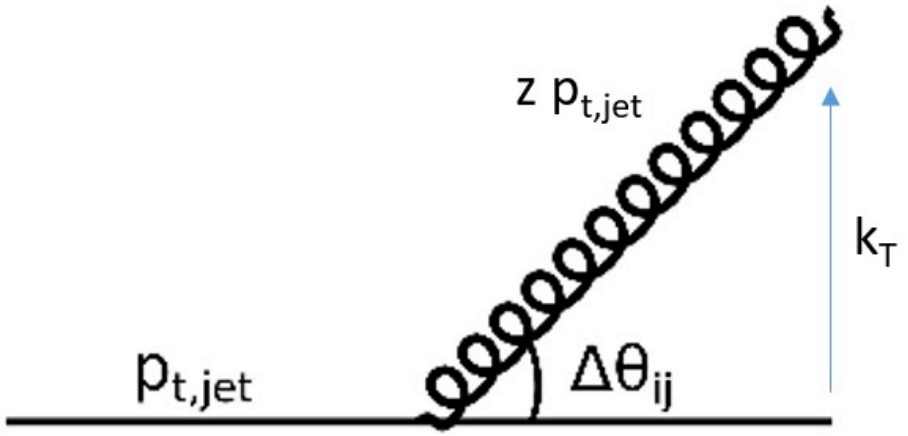
Jets and Jet Substructure

- Jets represent a multi-scale problem and probe both the hard and soft limits of QCD
- Sufficiently energetic jets have small formation times and are present through the full evolution of the collision dynamics
- Studies of jet substructure expose QCD at work:
  - In pp collisions this gives a handle on fundamental QCD effects
  - In heavy-ion collisions it is sensitive to medium induced modifications of the parton shower
- Jet substructure observables can be defined to expose theoretically predictable effects (colour coherence, medium induced semi-hard emissions, etc)



Why Heavy Flavour Jets in pp?

- Heavy flavour ($m_Q >> \Lambda_{QCD}$) partons are produced in the early stages of the collisions
  - Charm, Beauty and Top
- Their Production x-section is calculable in pQCD down to ~ 0 p_T
- Dead-cone effect leads to a change in the expected fragmentation of heavy and light quarks:
  - Gluons radiated with a small k_T are restricted
  - Fragmentation functions peak at larger values
- Study enriched quark-initiated jet samples
- Heavy flavour parton survives throughout the evolution of the shower

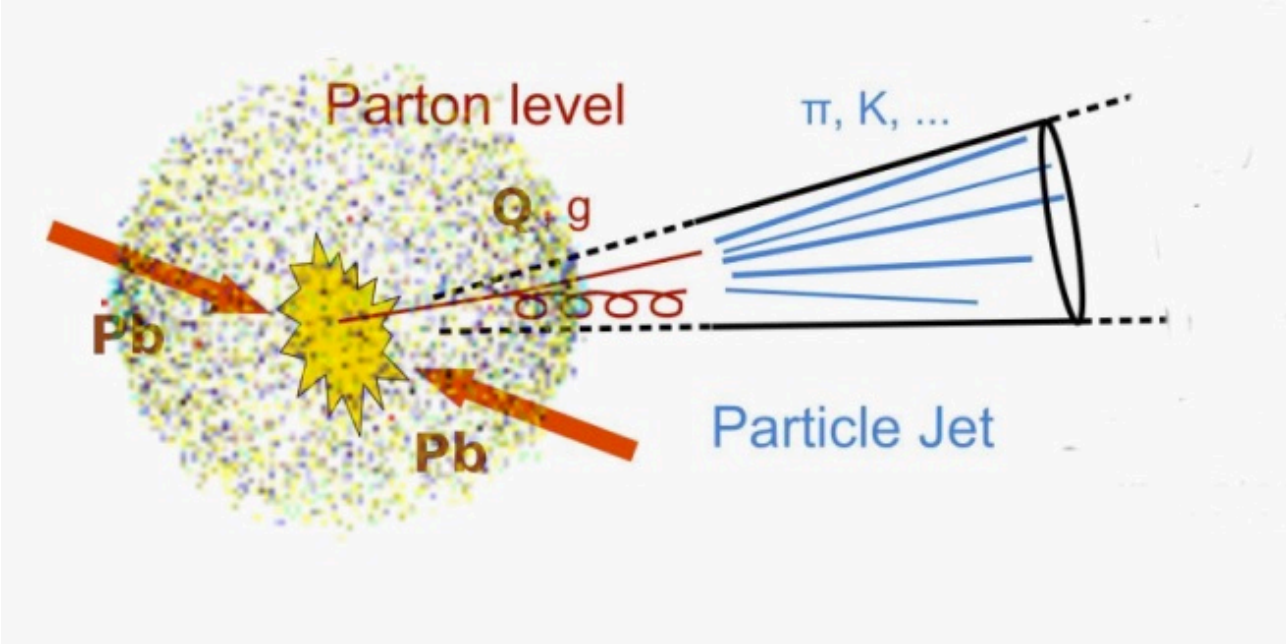


$\theta \sim k_T/zp_{t,jet}$

The dead-cone effects predicts a suppression of emissions from a quark within $\theta < \frac{Mq}{Eq}$

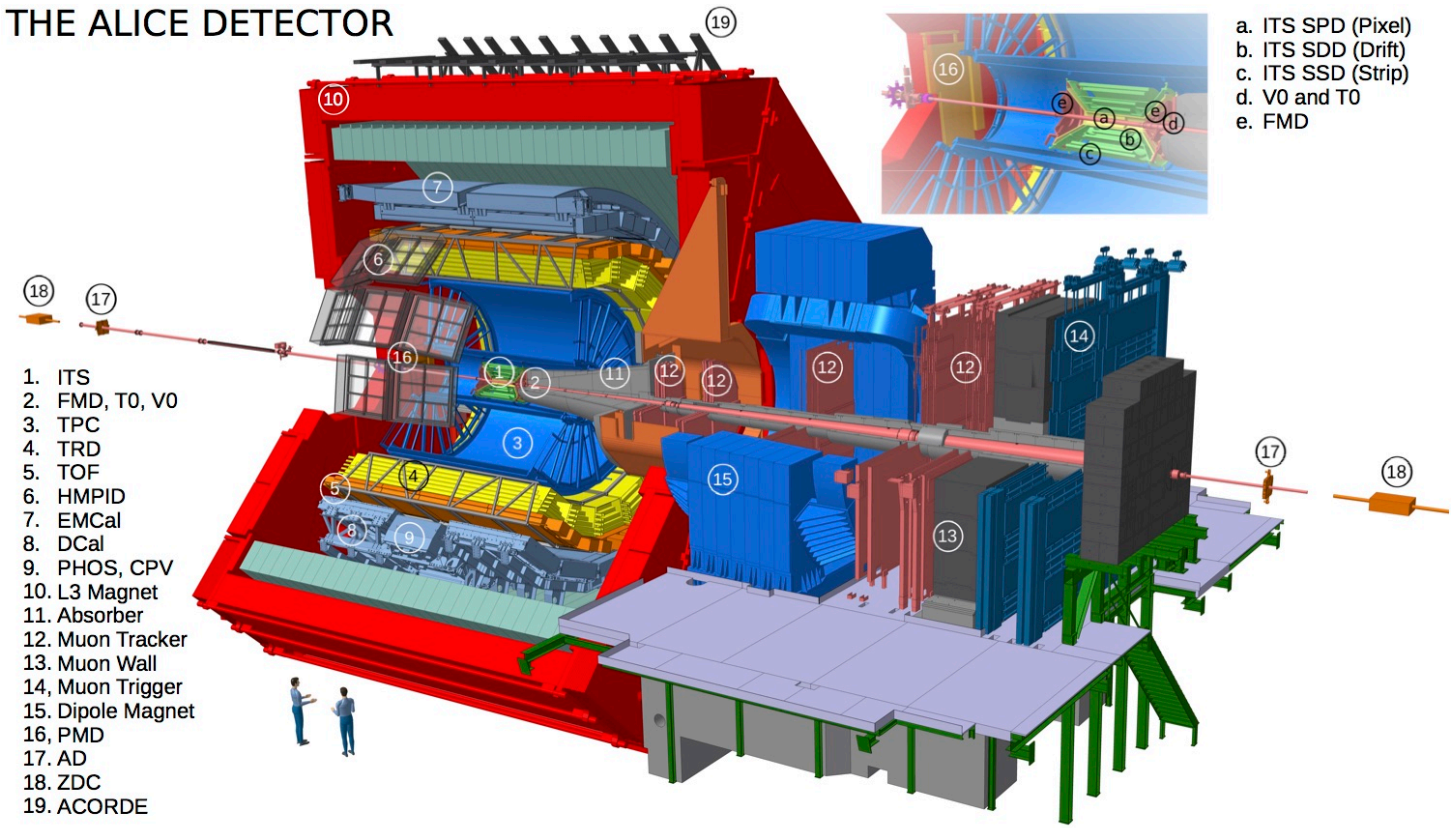
Why Heavy Flavour Jets in Heavy-Ion Collisions?

- Heavy flavour partons have negligible thermal production and annihilation rates
  - Reduces the need for combinatorial rejection even at low $p_{T,jet}$
- Early production assures sensitivity to the complete evolution of the medium
  - Strong quenching effects at low p_T
- Jet substructure measurements can probe the finer details of the pattern of energy loss
  - Opportunity to compare with light quark fragmentation



Heavy Flavour Jets at ALICE

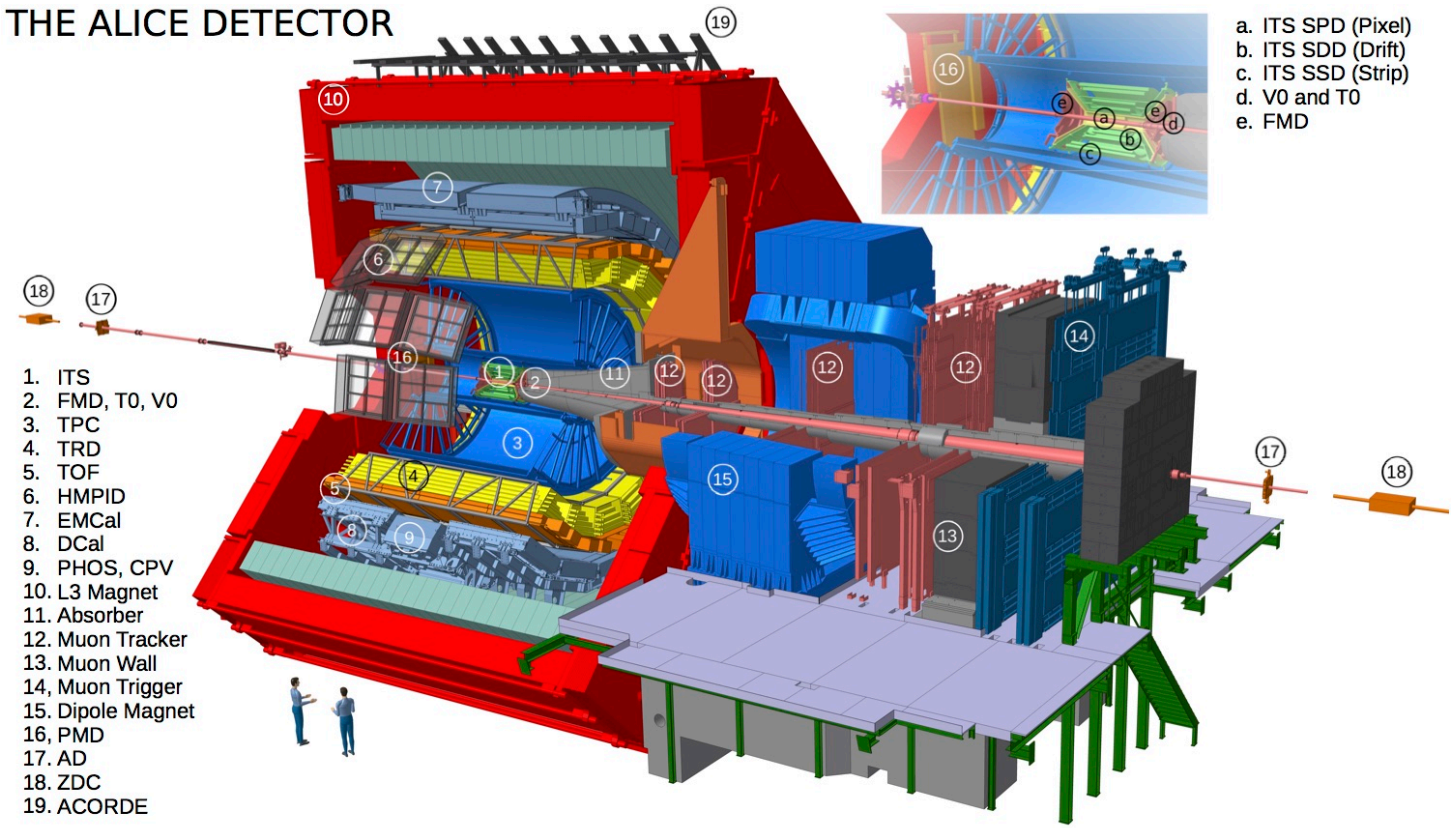
- Heavy flavor is well defined to low energies in pQCD
- This can be exploited with the low p_T reach of ALICE
- PID and tracking capabilities enable heavy flavour tagging
- Track-based jet finding beneficial to small angle substructure studies



The ALICE Detector

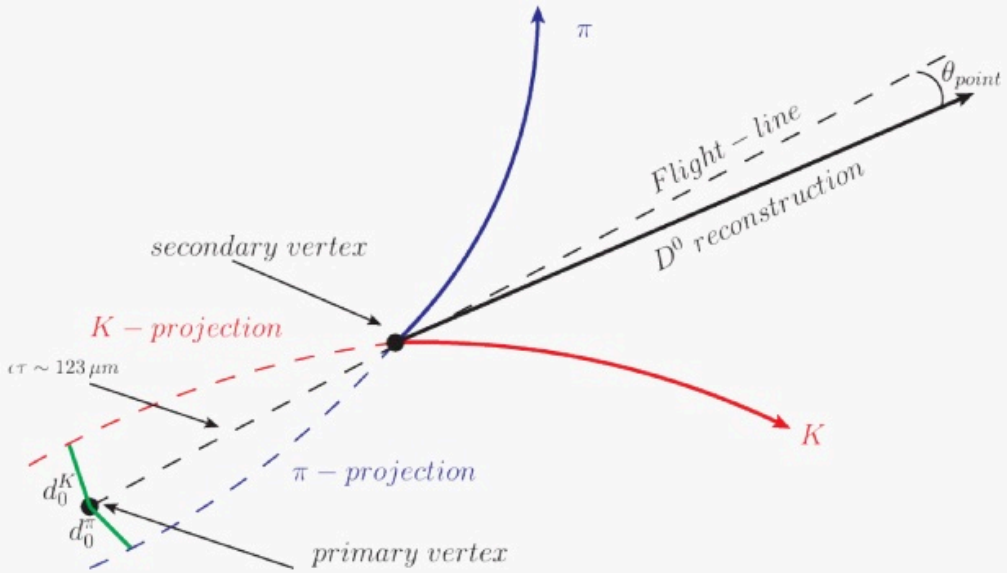
Detectors used for heavy flavor charged jets measurements:

- Inner Tracking System:
  - Low p_T tracking down to ~ 100 MeV/c
  - Reconstruction of secondary vertex
- Time Projection Chamber:
  - Charged particle tracking
  - PID from dE/dx
- Time of Flight detector:
  - PID
- EMCal:
  - PID
  - Triggering at high p_T



D^0 Hadronic Decay Channel

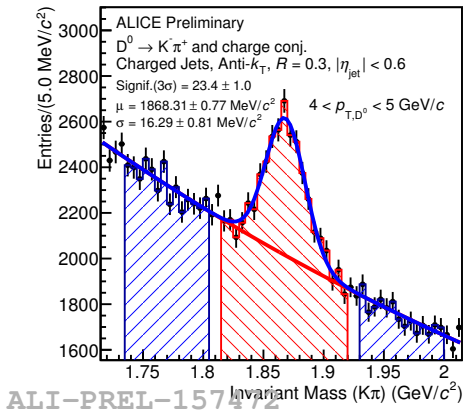
- $D^0 \rightarrow K^{\pm}\pi^{\mp}$ with a branching ratio of 3.89%
- D^0 candidates are reconstructed through:
  - PID of K and π
  - Cuts on secondary vertex
- K and π pairs replaced by D^0 candidate prior to jet finding
  - Mitigates against cases were the angle between the daughters is larger than the jet radius
- Jet finding is performed independently for each D^0 candidate in an event
- Invariant Mass fits + side-band method are used to extract the D^0 signal
- Corrections applied for D-jet efficiency, B feed-down and unfolding

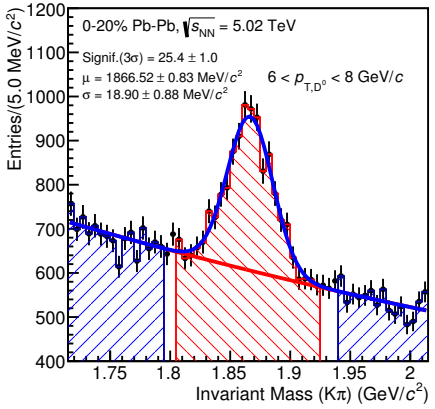


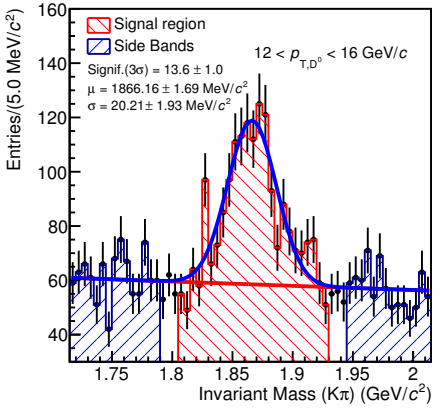
D^0 reconstruction

Side-Band Method

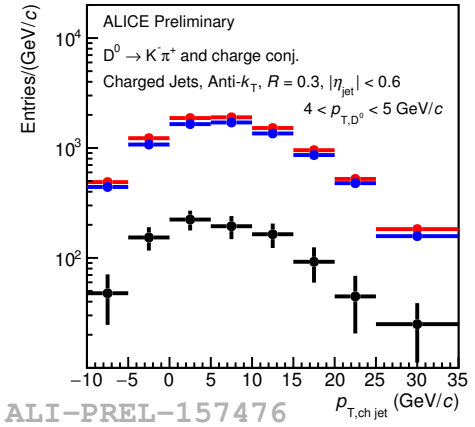
- Invariant mass distributions fitted in bins of $p_{T,D}$
- Signal region is ±2σ from the peak
- Side-band regions are 4-8σ away from the peak on either side
- Assumption is made that the side-band regions represent the background distribution in the signal region
- The area of the side-band region is scaled to the area of the background under the peak
- The scaled side-band contribution is subtracted from the signal region to obtain the signal distribution

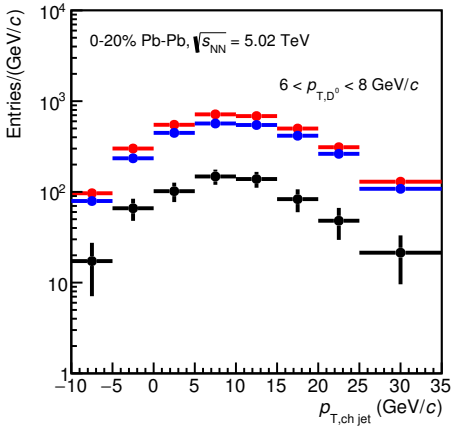


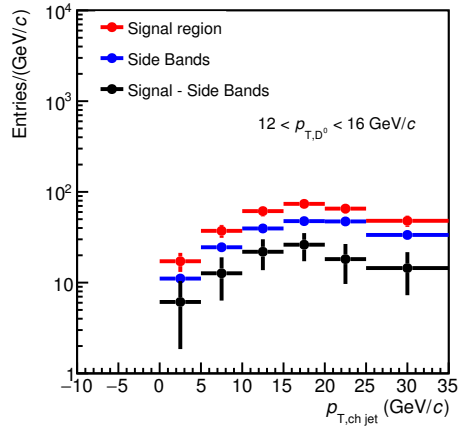




$4 < p_{T,D} < 5$ GeV/c $6 < p_{T,D} < 8$ GeV/c $12 < p_{T,D} < 16$ GeV/c

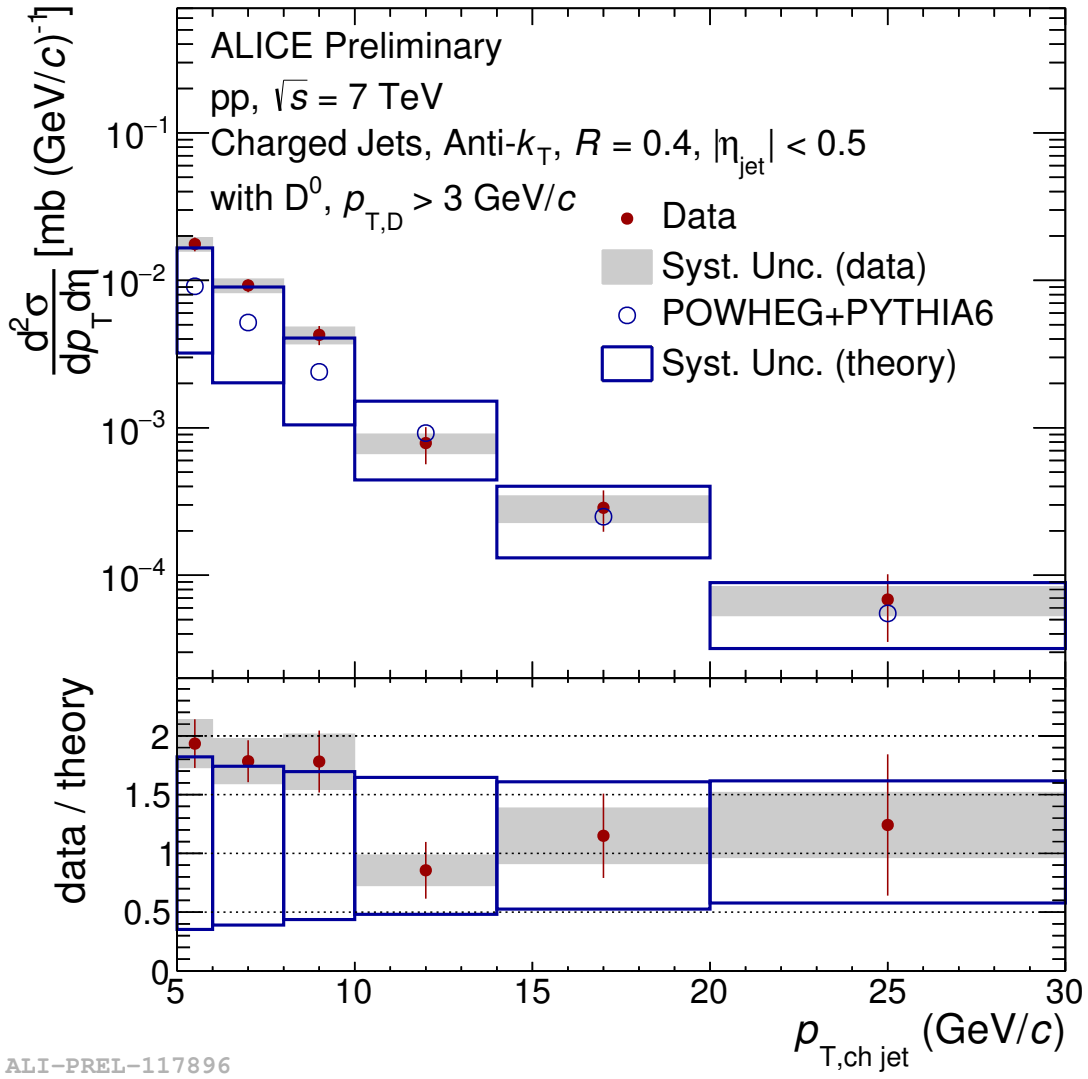






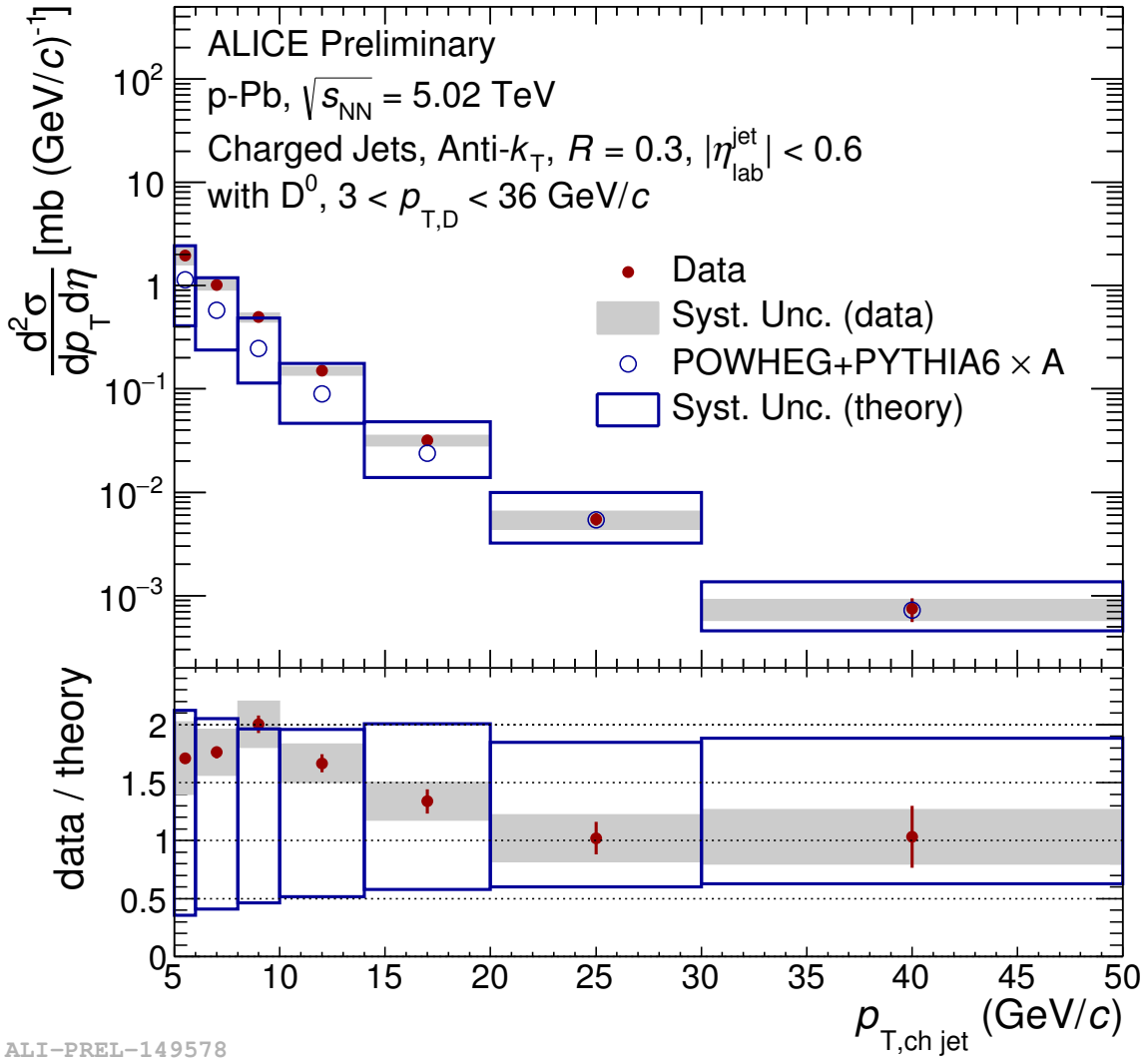
D^0 Jet x-section in pp Collisions

- Charged jet production x-section measured for jets containing a D^0
- Low $p_{T,jet}$ reach down to 5 GeV/c
  - $P_{T,D}$ > 3 GeV/c
- Good agreement with POWHEG + PYTHIA 6



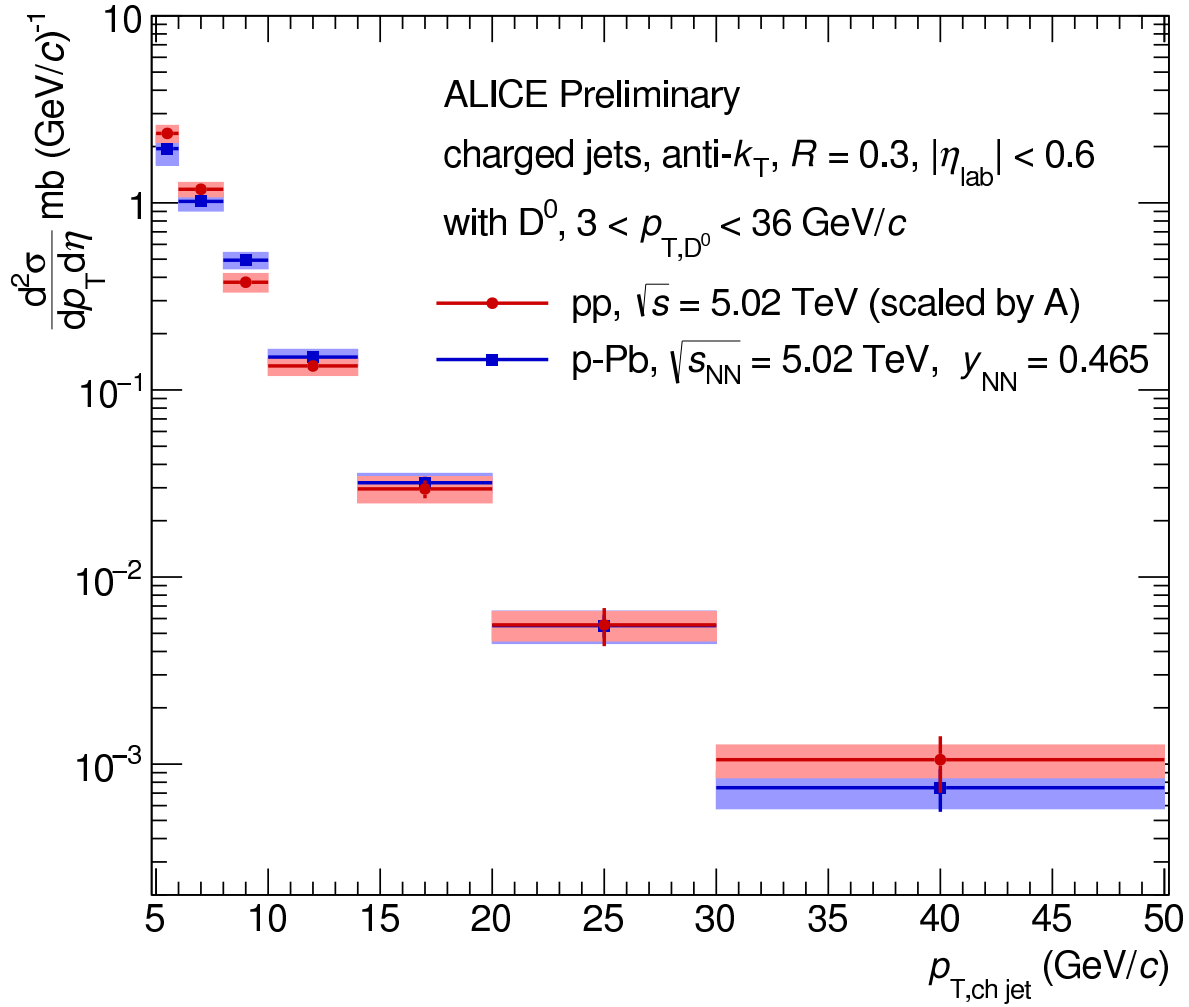
D^0 Jet x-section in p-Pb Collisions

- Charged jet production x-section measured for jets containing a D^0
- Low $p_{T,jet}$ reach down to 5 GeV/c
  - $3 < p_{T,D} < 36$ GeV/c
- Good agreement with scaled POWHEG + PYTHIA 6
- No hints of cold nuclear effects



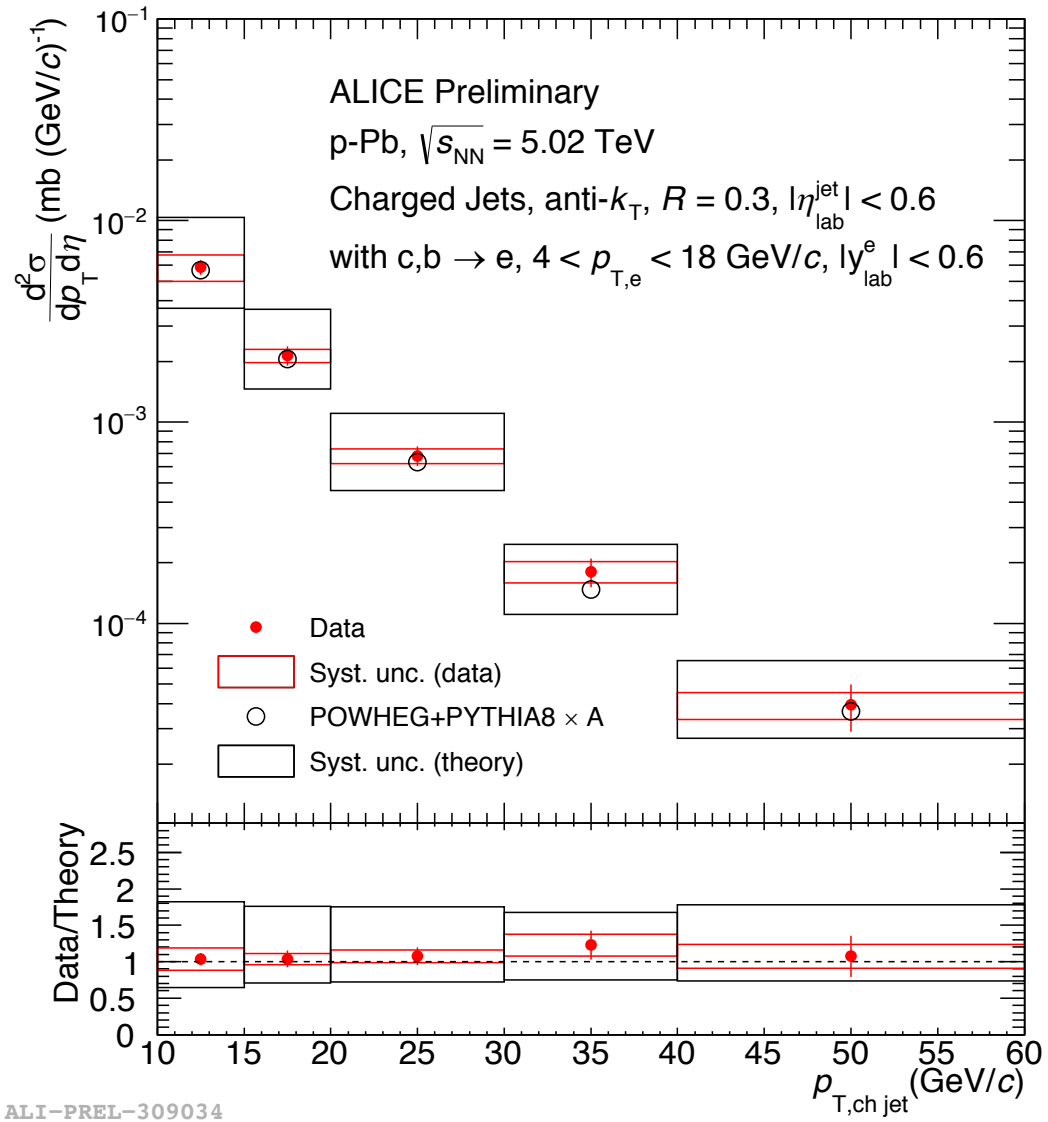
D^0 Jets x-section in p-Pb Collisions

- Charged jet production x-section measured for jets containing a D^0
- Low $p_{T,jet}$ reach down to 5 GeV/c
  - $3 < p_{T,D} < 36$ GeV/c
- Good agreement with scaled POWHEG + PYTHIA 6
- No quenching or cold nuclear effects
- Complementary pp measurement at same energy



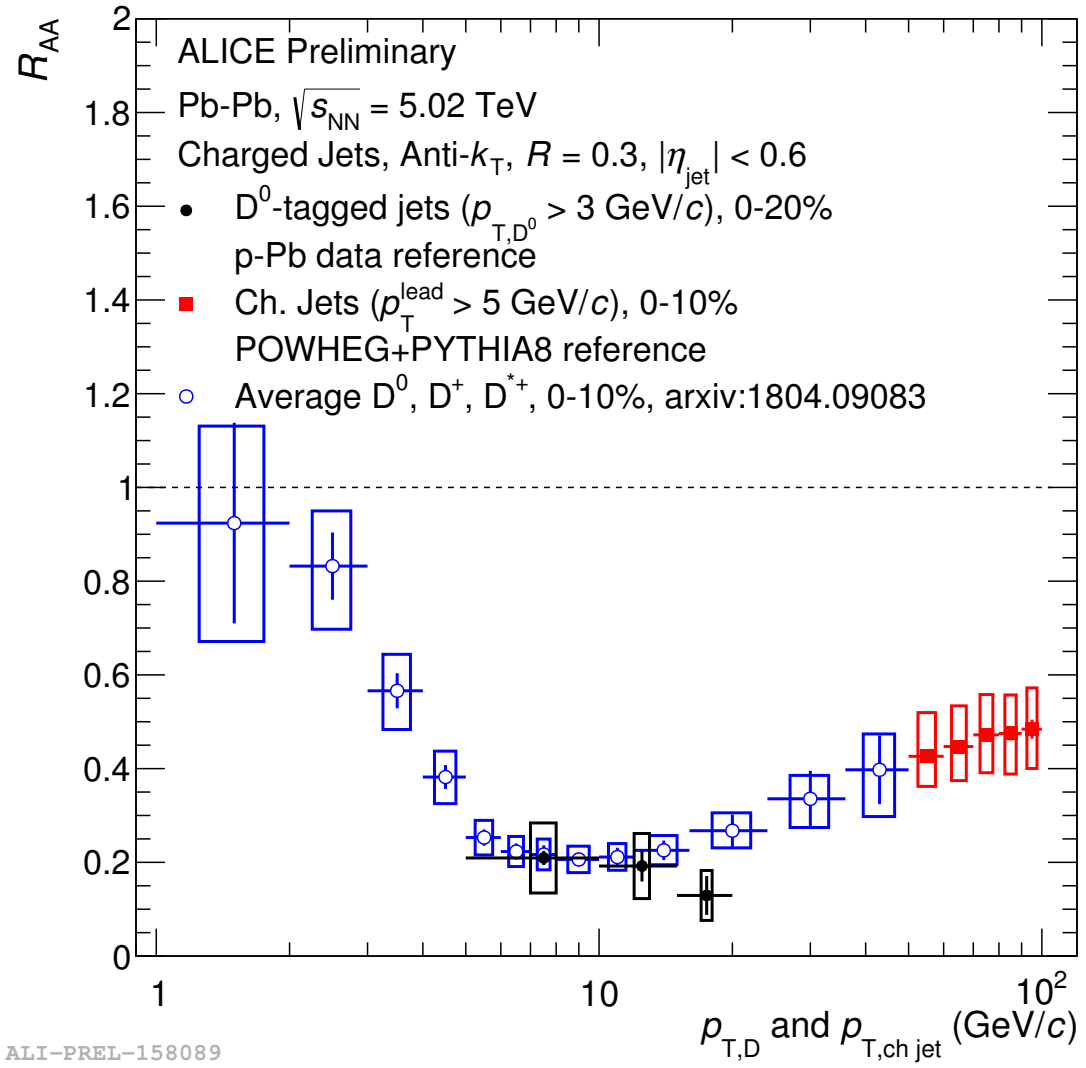
HF electron decay channel

- D,B → $e^{\pm}$
- Jets are required to contain identified electrons with $p_{T,e} > 4$ GeV/c
- Contribution of photonic electrons subtracted
- Measurement of x-section in p-Pb shows good agreement with POWHEG+PYTHIA 8



Nuclear Modification factor in Pb-Pb

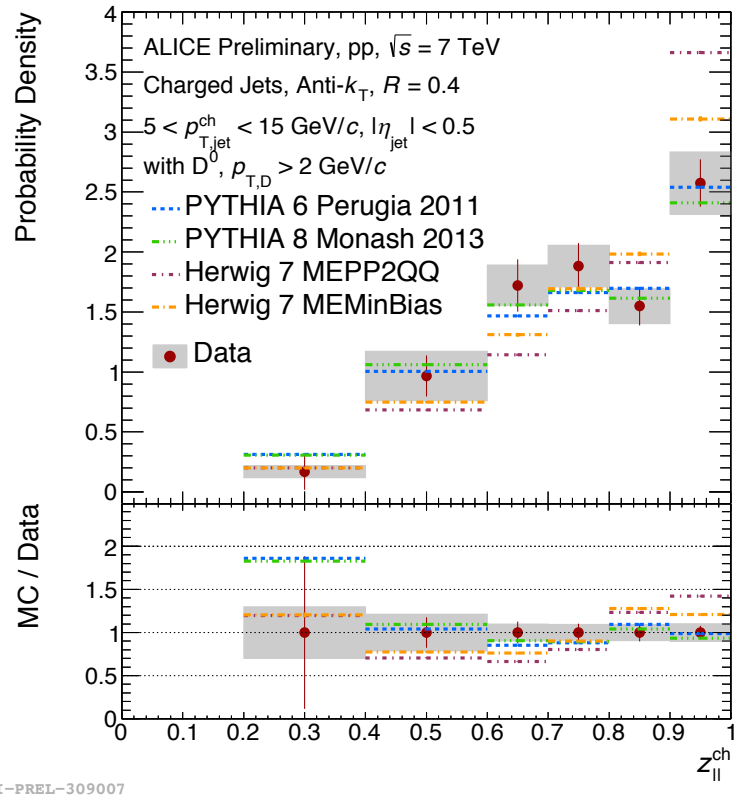
- R_{AA} shows strong quenching effects in central Pb-Pb collisions
- Distributions in Pb-Pb measured with $3 < p_{T,D} < 20$ GeV/c
- R_{AA} for D-meson jets is similar to that for D mesons

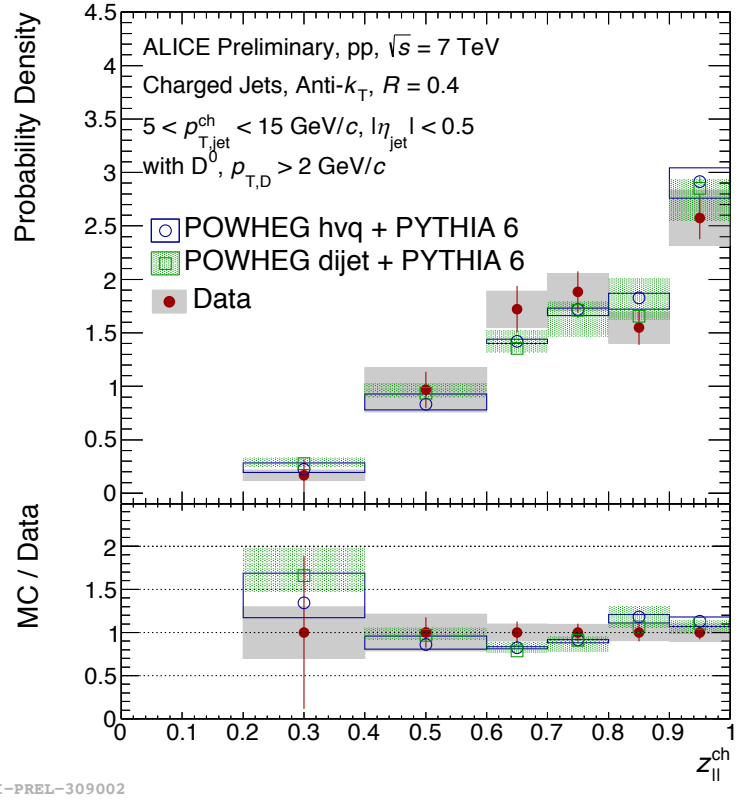


Jet Momentum Fraction Carried by D^0

$$z_{||}^{ch} = \frac{\vec{p}_{ch\ jet} \cdot \vec{p}_{D}}{\vec{p}_{ch\ jet} \cdot \vec{p}_{ch\ jet}}$$

- Measurement of fraction of jet momentum carried by the D^0
- $5 < p_{T,jet} < 15$ GeV/c
  - $p_{T,D} > 2$ GeV/c
- z distributions are in good agreement with MC generators
- Distributions peak at large values, indicating a hard fragmentation

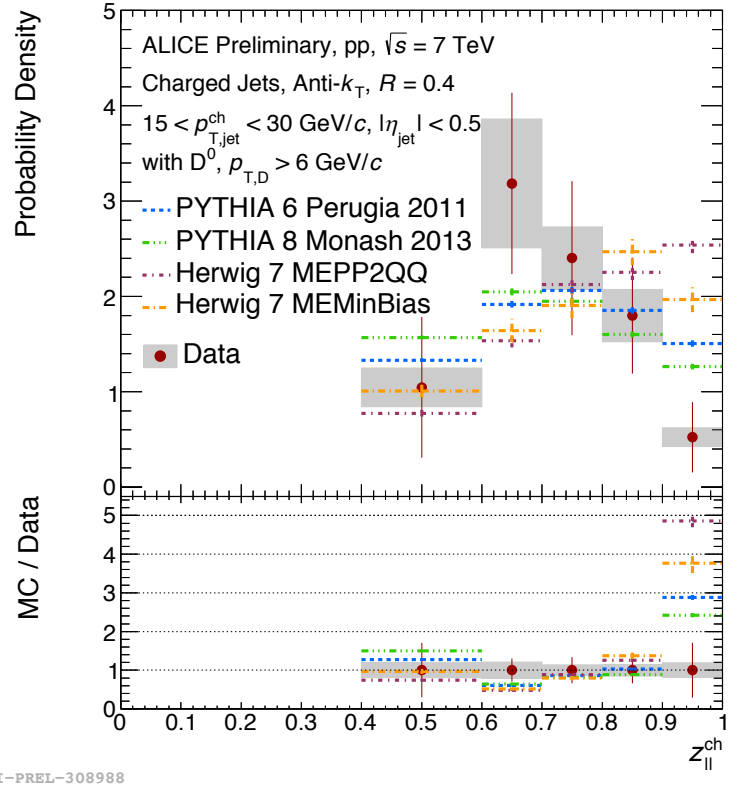


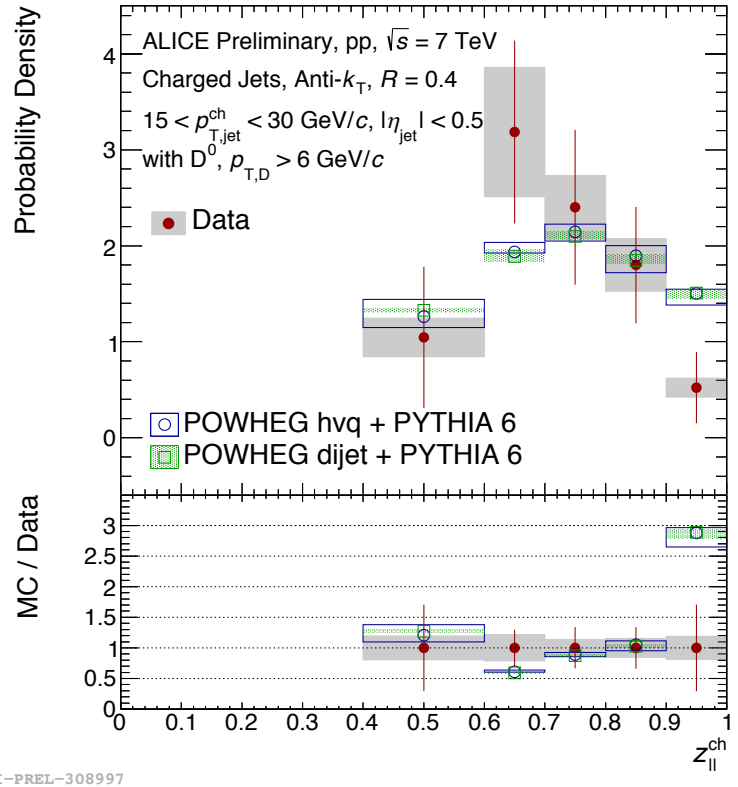


Jet Momentum Fraction Carried by D^0

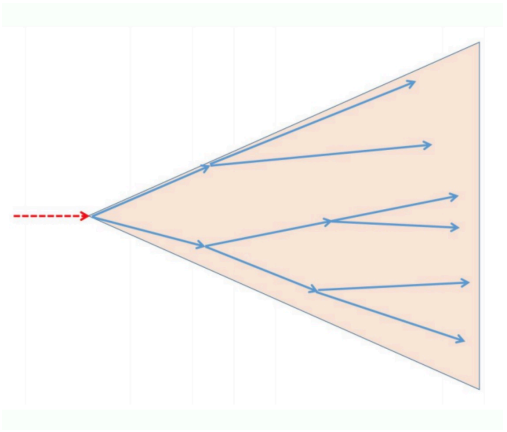
$$z_{||}^{ch} = \frac{\vec{p}_{ch\ jet} \cdot \vec{p}_D}{\vec{p}_{ch\ jet} \cdot \vec{p}_{ch\ jet}}$$

- Measurement of fraction of jet momentum carried by the D^0
- $15 < p_{T,jet} < 30$ GeV/c
  - $p_{T,D} > 6$ GeV/c
- z distributions are in good agreement with MC generators
- Softer fragmentation at large $p_{T,jet}$

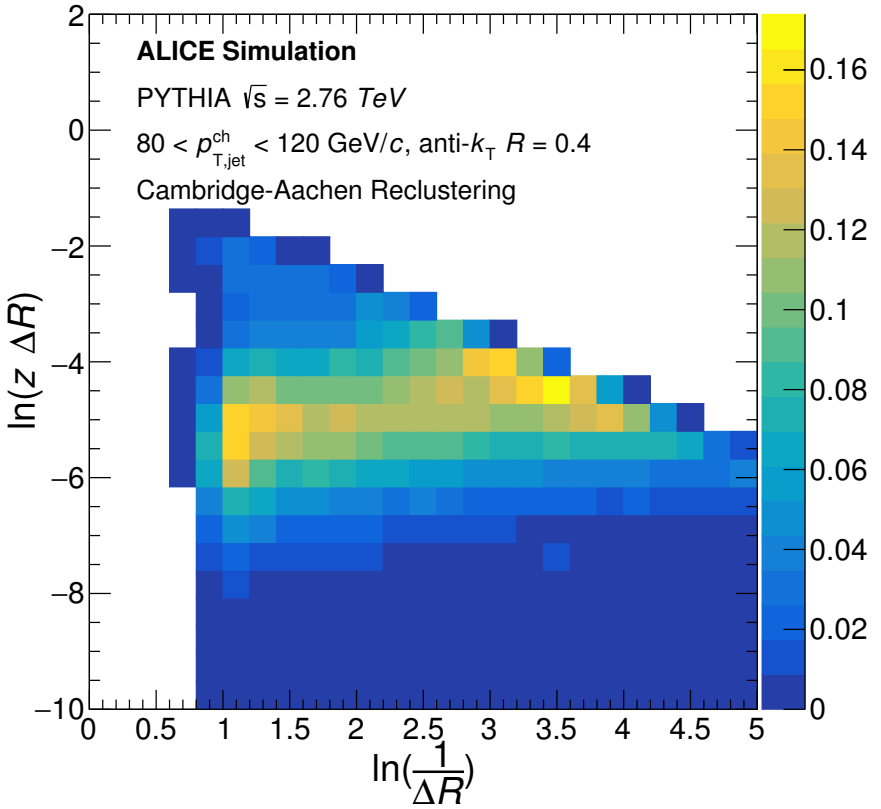




Recently Developed Substructure Tools

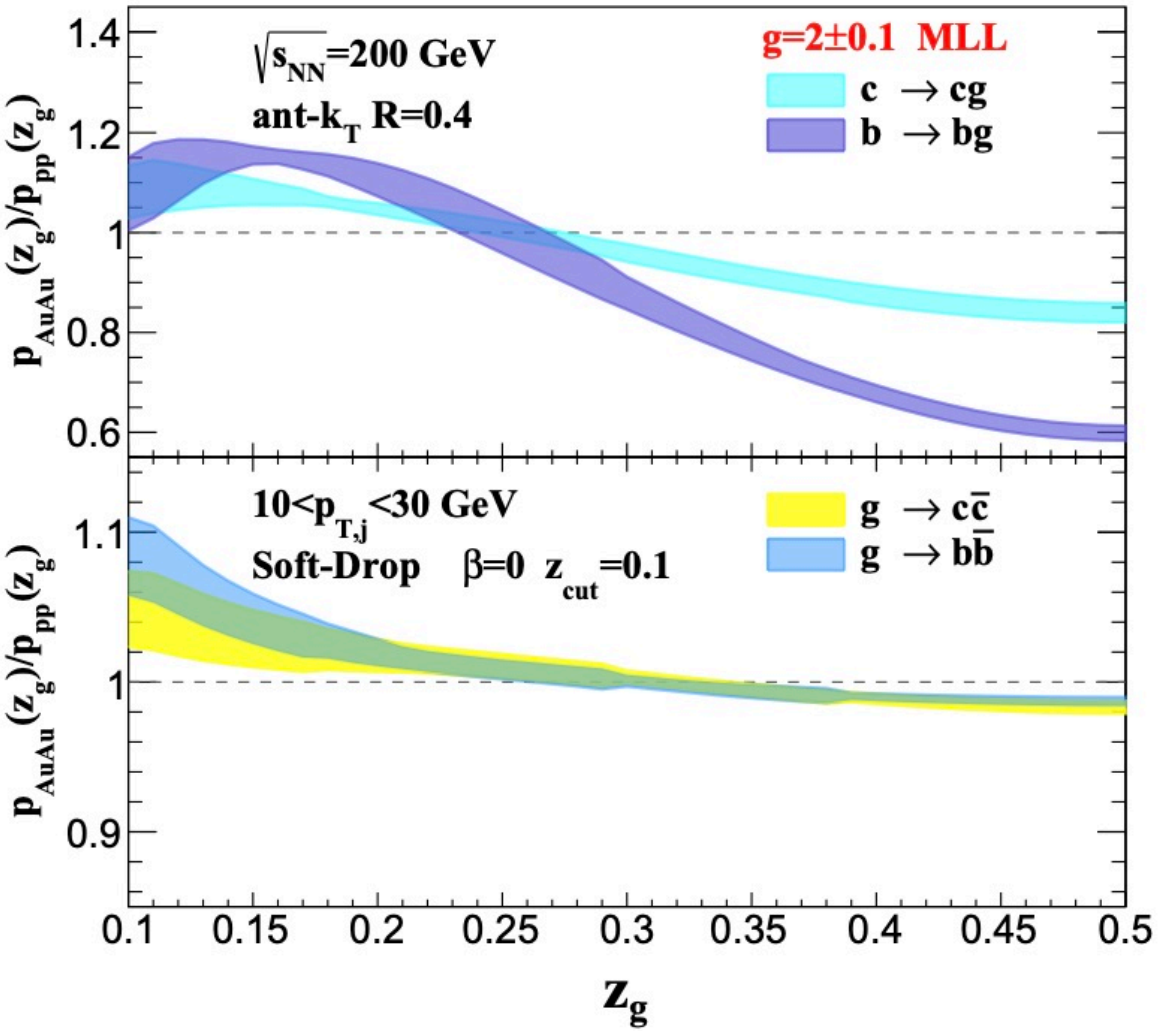


- Jet reclustering techniques can be used to access jet splittings
- The choice of reclustering algorithms and grooming techniques can expose different regions of the splittings phase spaces
- Lund Maps are powerful tools for scanning the splitting phase space
- Lund Maps have a flexible metric and can be filled with different aspects of the splittings



Applying Jet Substructure techniques to Heavy-Flavour Tagged Jets

- Possible next steps could be to apply the recently developed jet substructure techniques to heavy flavour tagged jets
- Possibility to probe jet shapes at very low $p_{T,jet}$
- Measure jet shapes for quark initiated jets
- Uncover the differences (in vacuum and medium) between light and heavy quark fragmentation
- Can we uncover the dead-cone?

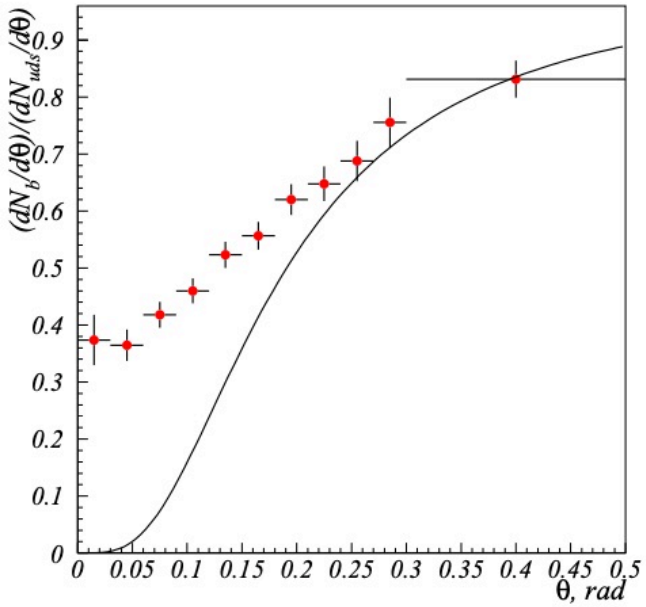


H.T. Li, I. Vitev arXiv:1801.00008

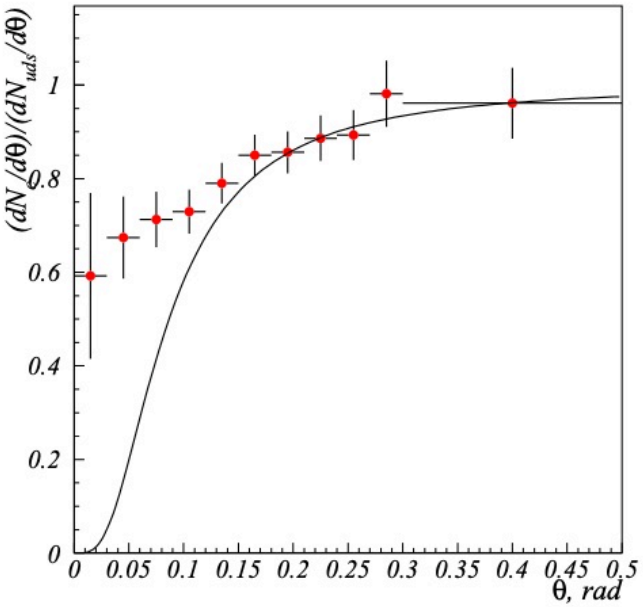
Previous Attempts to Uncover The Dead-Cone

- The dead-cone effect is expected to suppress radiation for $\theta < \frac{m}{E}$
- Decay products and uncorrelated background pollute the dead-cone region
- The small scale of the angles involved requires precise determination of the radiation axis
- **No direct measurment** made yet – indirect observation was made at DELPHI using the jet axis
- Can we use recent tools developed for jet substructure to make a direct observation?

Angular distribution of fragmentation particles in jets at DELPHI



b-jets / light quark jets



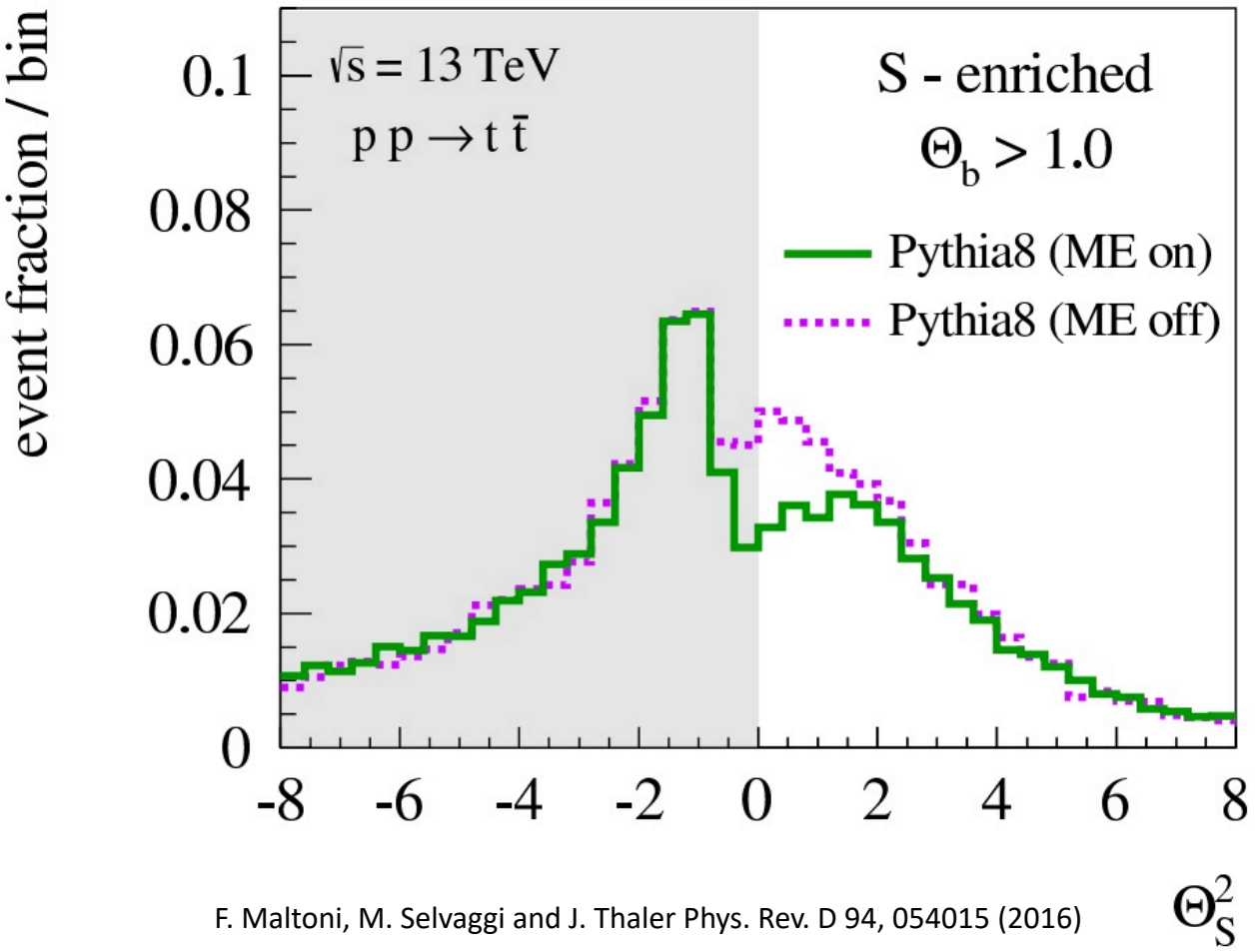
C-jets / light quark jets

M. Battaglia, R. Orava and L. Salmi DELPHI-2004-037 CONF 712

Uncovering The Dead-Cone – Top Quarks

- Proposed method using top quarks
  - large dead-cone angle
- Tag boosted top quark pairs where one decays hadronically and one decays leptonically
- Soft-Drop technique applied to leptonically decaying top quark to isolate b-quark and final state radiation (FSR) gluon subjets
- Take advantage of differing kinematics of top FSR and top decay to statistically separate the two types of radiation

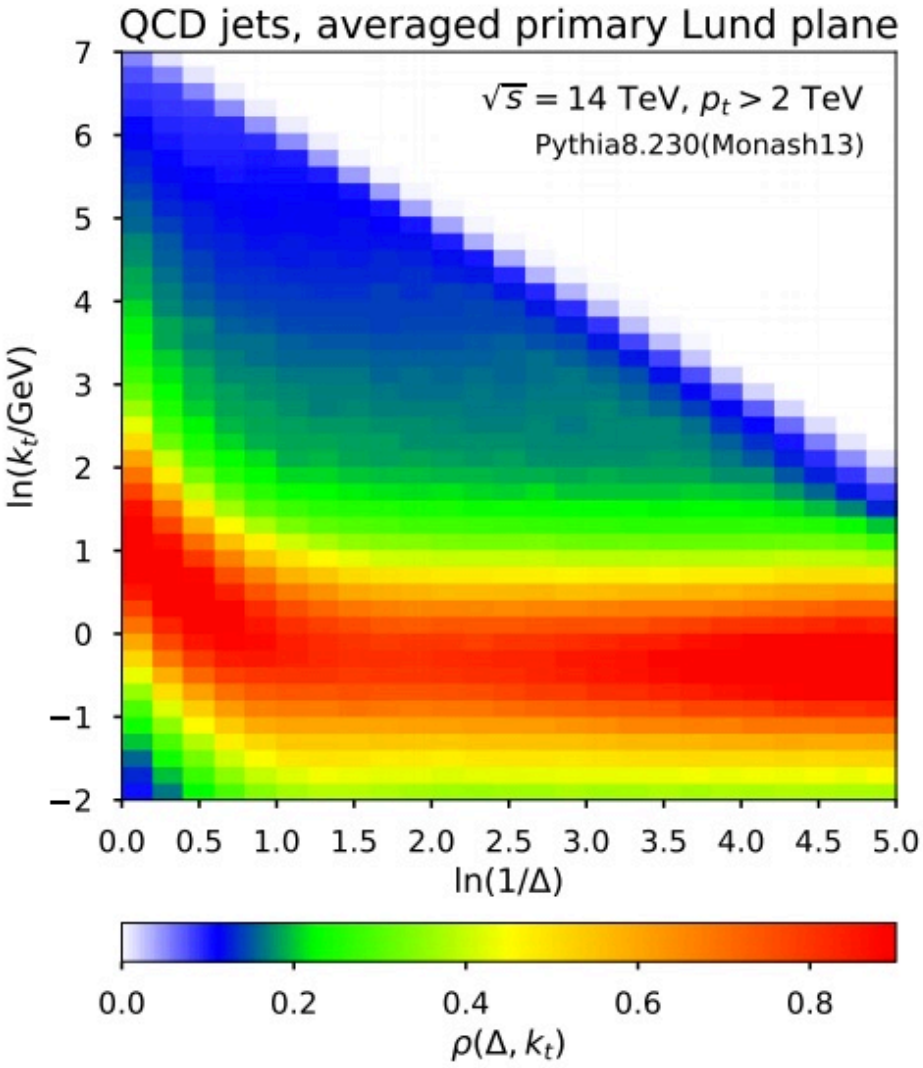
$$\Theta_S^2 = \mathrm{sign}(X)(X^2 + Y^2)$$



F. Maltoni, M. Selvaggi and J. Thaler Phys. Rev. D 94, 054015 (2016)

Uncovering The Dead-Cone for Charm and Beauty

- New method proposed for lighter quarks
  L. Cunqueiro, M. Ploskon arXiv:1812.00102
- Recluster c or b tagged jets
- **Iteratively decluster** the jet tree to fill a 2D Lund Map of jet splittings
  - Always following the hardest prong
- For each splitting, record the opening angle and scale k_T between the two prongs
- Advantage is that at each splitting the direction of the radiator axis is resolved
  - Possible through full reconstruction of heavy flavour

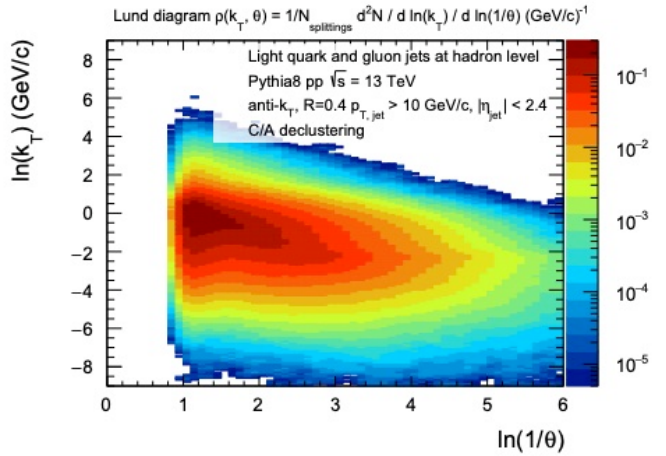


F.A. Dreyer, G.P. Salam, G. Soyez JHEP 1812 (2018) 064

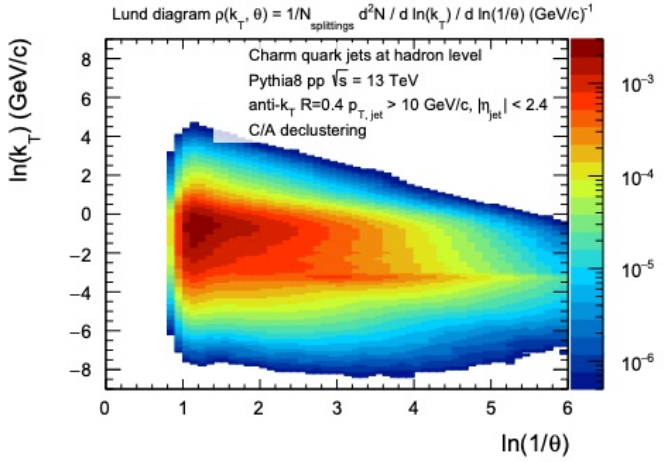
Visual Dead-Cone Signal at Hadron Level

L. Cunqueiro, M. Ploskon arXiv:1812.00102

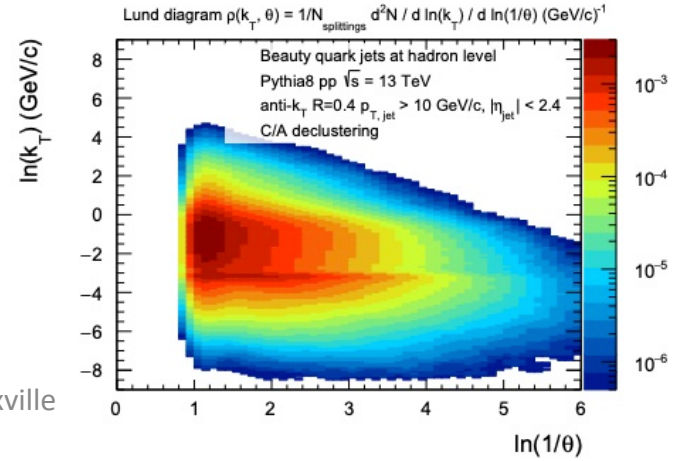
- B and D decays inhibited for the heavy flavour cases
- Dead-cone effect can be seen through Lund Maps of the splittings
- Radiation from the heavy flavor vertex appears suppressed at small angles compared to the inclusive distribution
- Larger suppression seen for beauty than charm quarks
- Structure bands seen for heavy flavor jets
- Minimum cuts on k_T can remove non-perturbative effects



Inclusive

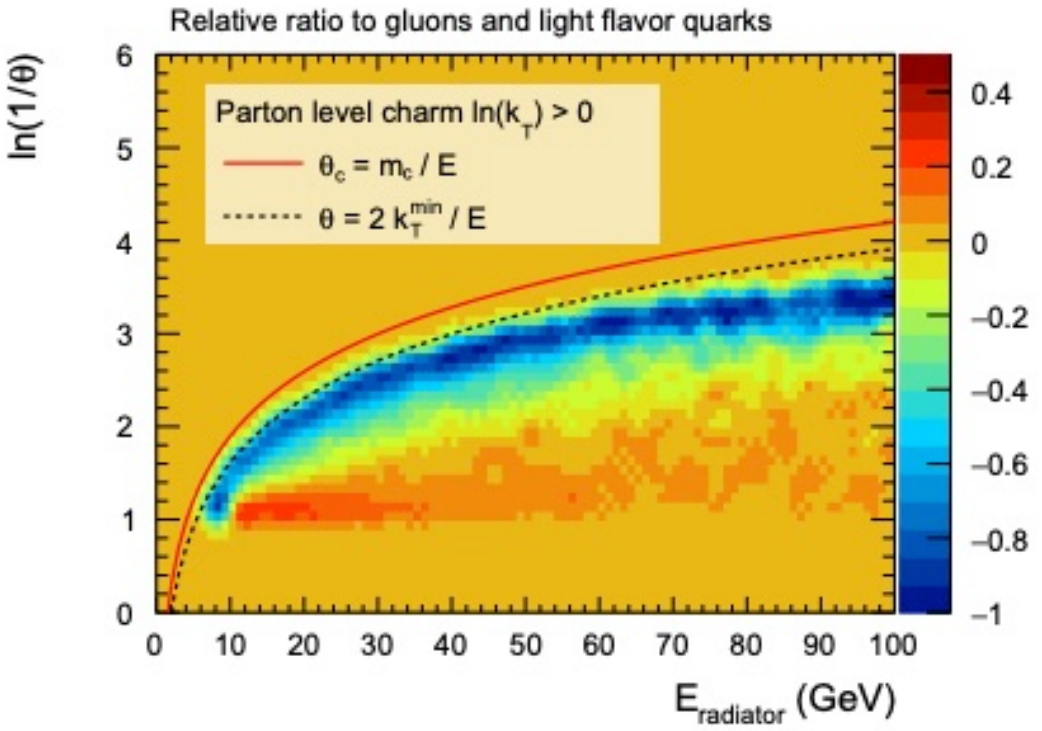


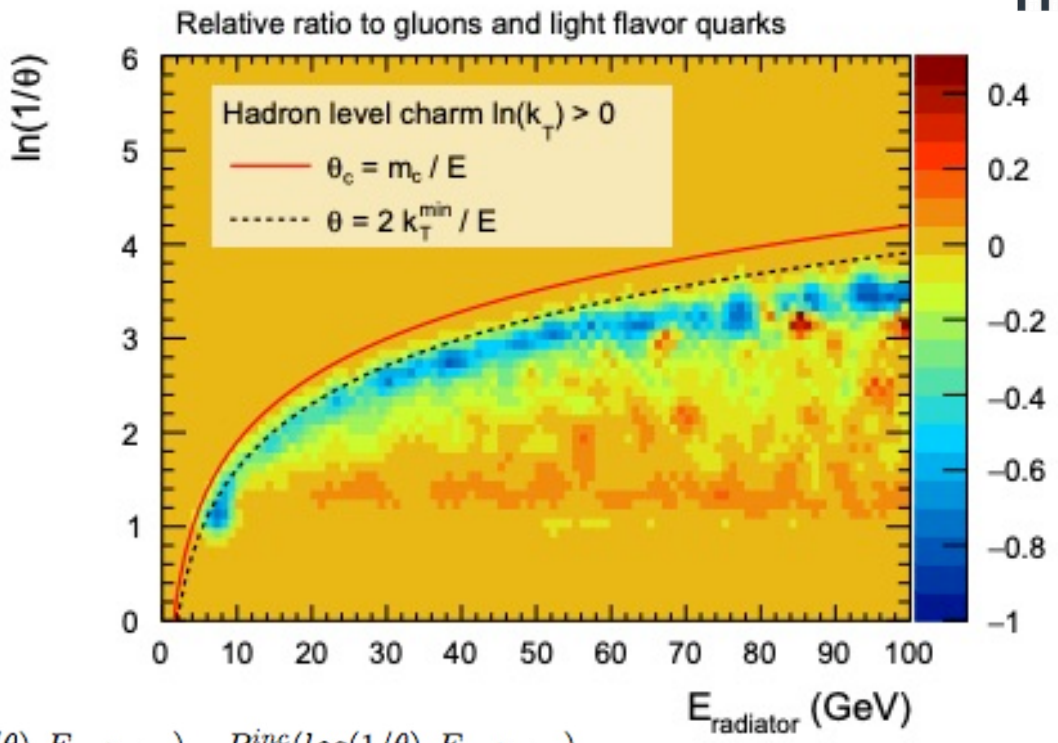
Charm



Beauty

Lund Map with Radiator Energy - Charm



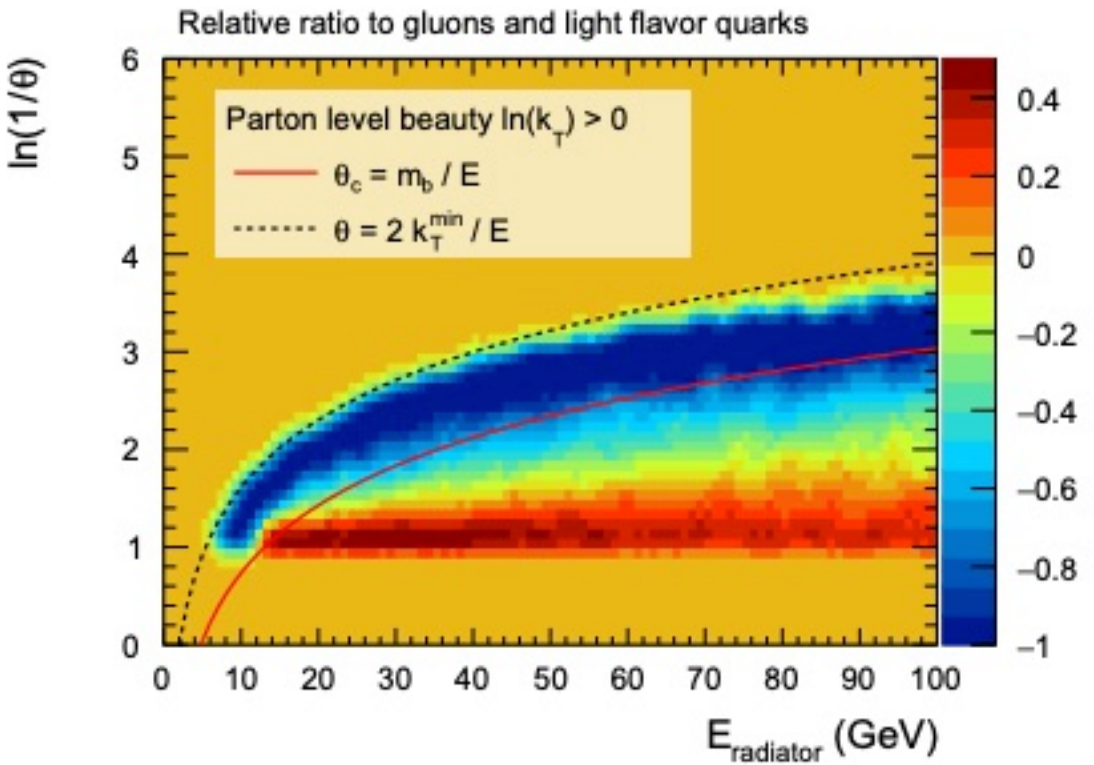


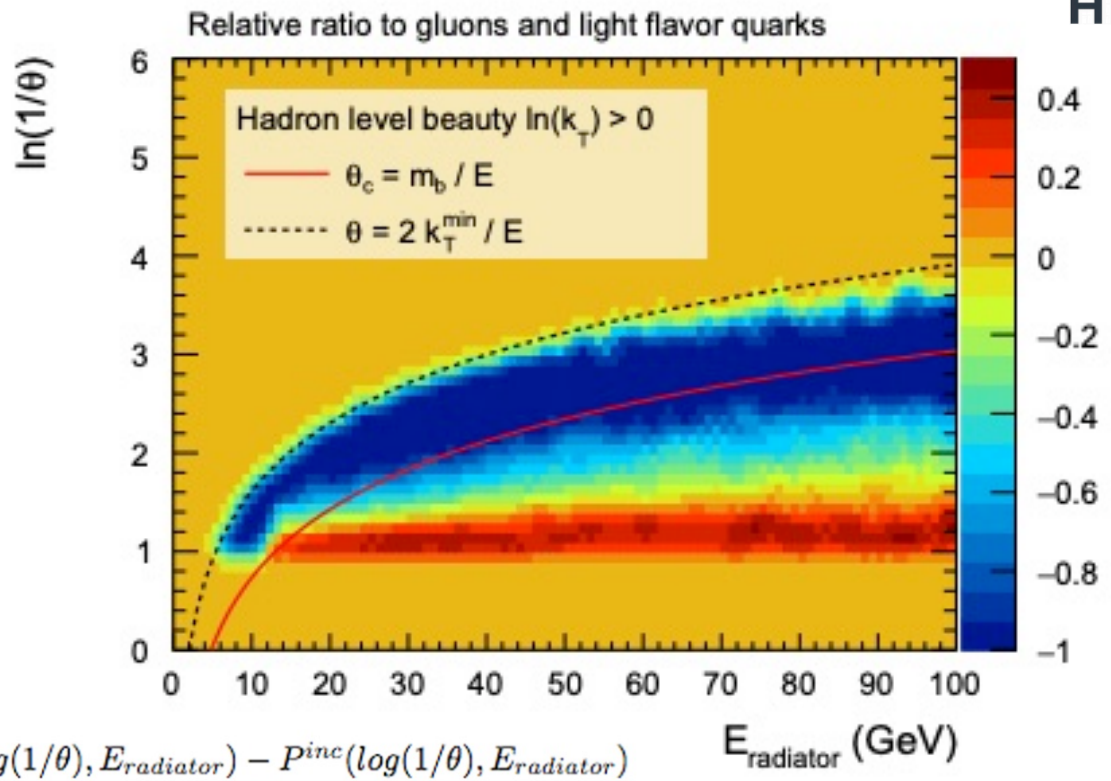
$$Q = \frac{P^{Q}(log(1/\theta), E_{radiator}) - P^{inc}(log(1/\theta), E_{radiator})}{P^{inc}(log(1/\theta), E_{radiator})}$$

- Lund Map constructed per splitting with radiator energy and angle between the two daughter prongs
- Cut on k_T translates to $E_{radiator} > \frac{k_{Tmin}}{z\theta}$
- Dashed line corresponds to z=0.5 - No entries allowed beyond this limit

- Larger angles suppressed at lower radiator energy
- For radiator energies of **10-30 GeV**, effects measurable at angles of **0.1 rad**

Lund Map with Radiator Energy - Beauty

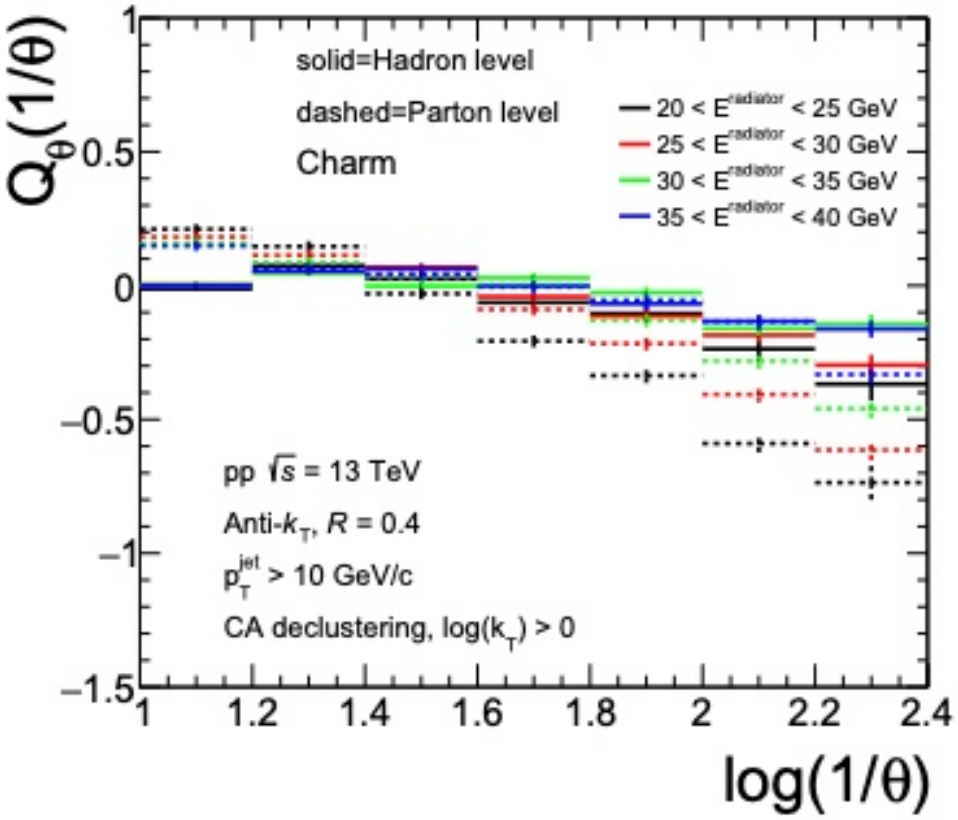




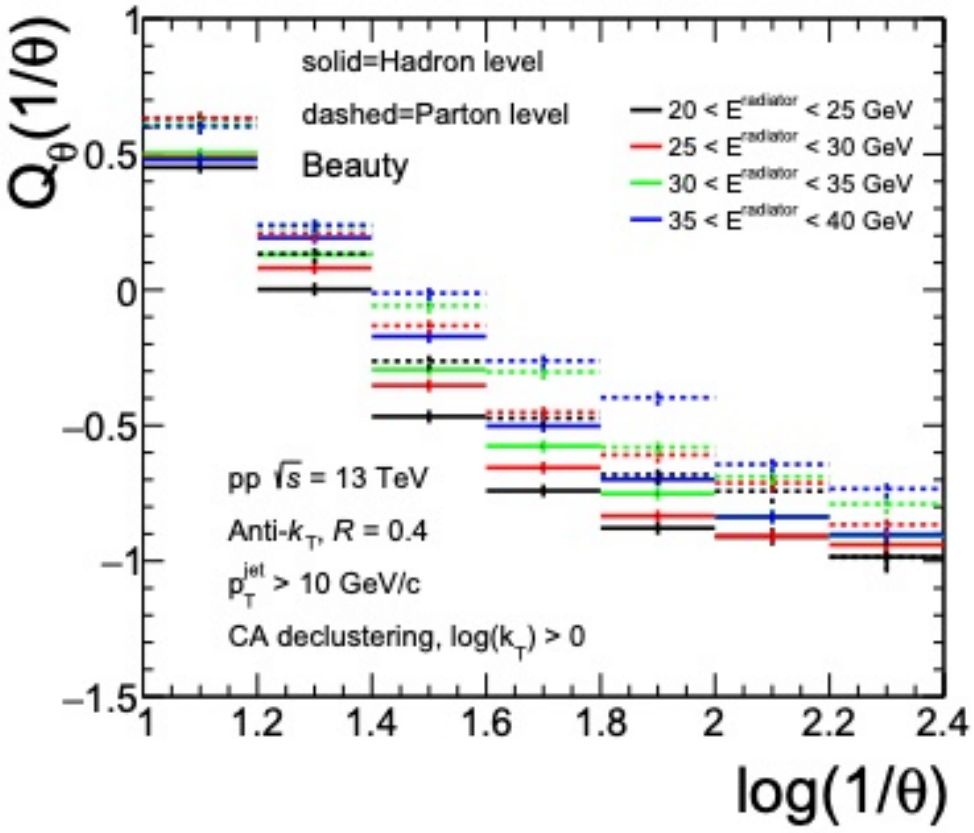
$$Q = \frac{P^{Q}(log(1/\theta), E_{radiator}) - P^{inc}(log(1/\theta), E_{radiator})}{P^{inc}(log(1/\theta), E_{radiator})}$$

- Dead-cone effects more apparent for b-jets
- Measurement accessible at hadron level (for both b and c)
- Larger angles suppressed at lower radiator energy
- For **larger radiator energies**, effects persist at angles of **0.1 rad**

Projections to log (1/θ)



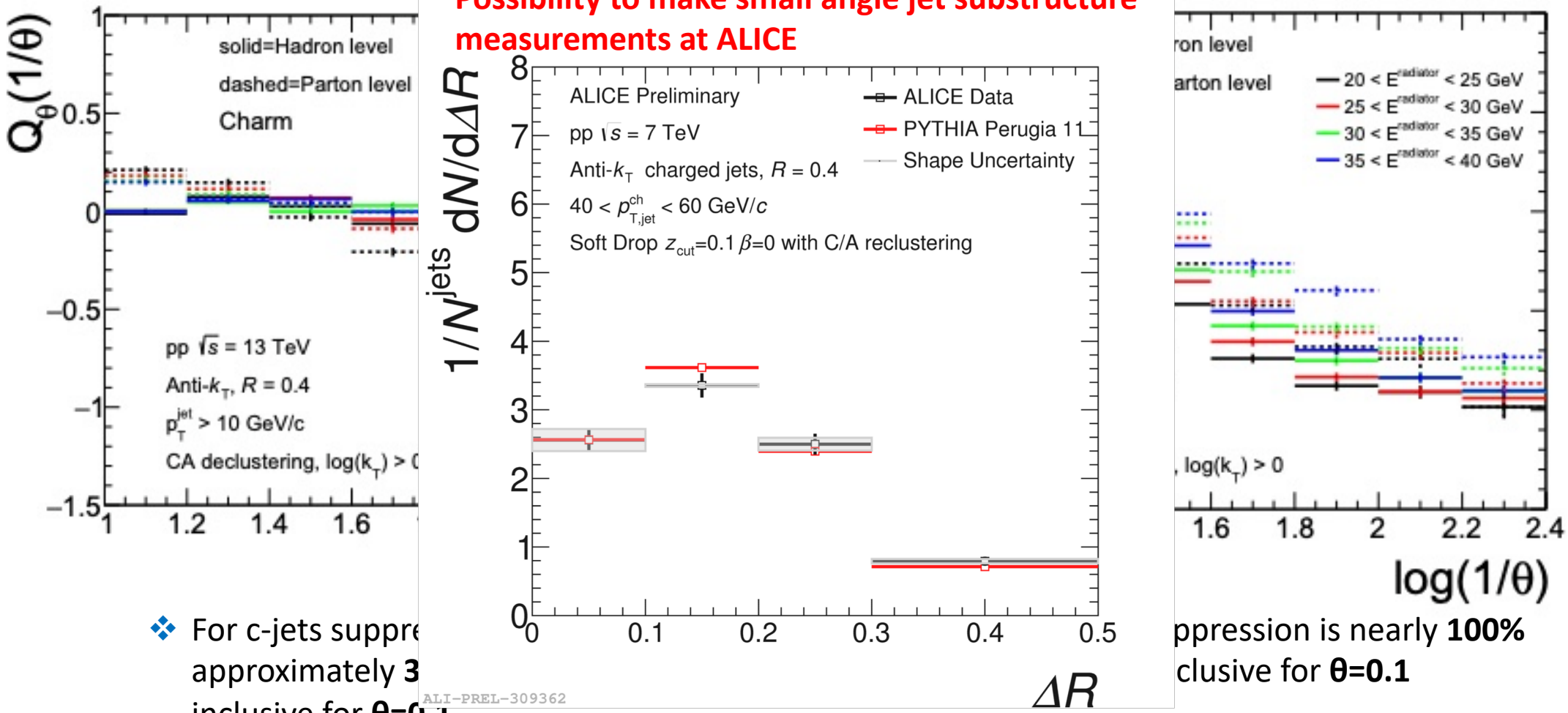
- For c-jets suppression is approximately **30%** relative to inclusive for **θ=0.1**



- For B-jets suppression is nearly **100%** relative to inclusive for **θ=0.1**

Projections to log (1/θ)

Possibility to make small angle jet substructure measurements at ALICE



- For c-jets suppre… approximately **3**… inclusive for **θ=0.1**
- …ppression is nearly **100%** …clusive for **θ=0.1**

Measurement of dead-cone in Data underway at ALICE

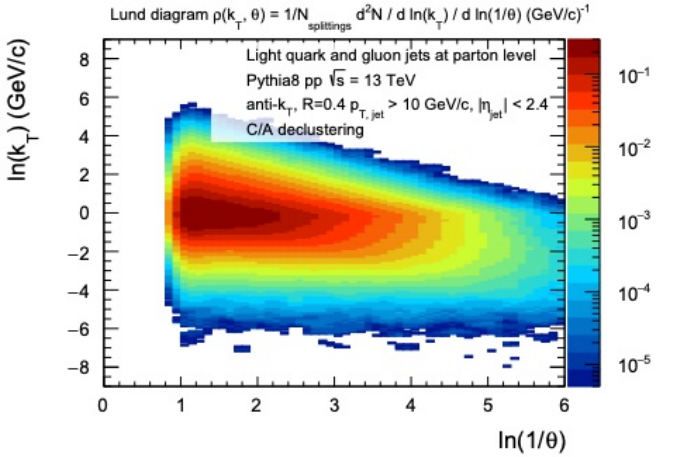
Conclusions

- Heavy flavour tagging of jets allows to extend jet measurements in pp and heavy-ion collisions to very **low $p_{T,jet}$**
- Heavy flavour jet tagging provides us with an enriched **quark-initiated** jet sample
- Measurements of Jets containing a Fully reconstructed D meson reported at ALICE
  - Jet x-sections in pp, p-Pb and Pb-Pb collisions
  - R_{AA} in central Pb-Pb collisions
  - Jet momentum fraction carried by D^0 in pp collisions
- A program to apply recently developed substructure techniques to heavy-flavour jets is underway

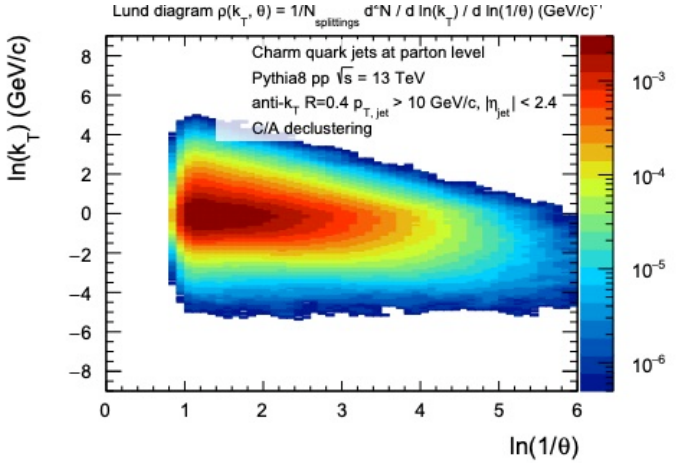
Backup

Visual Dead-Cone Signal at Parton Level

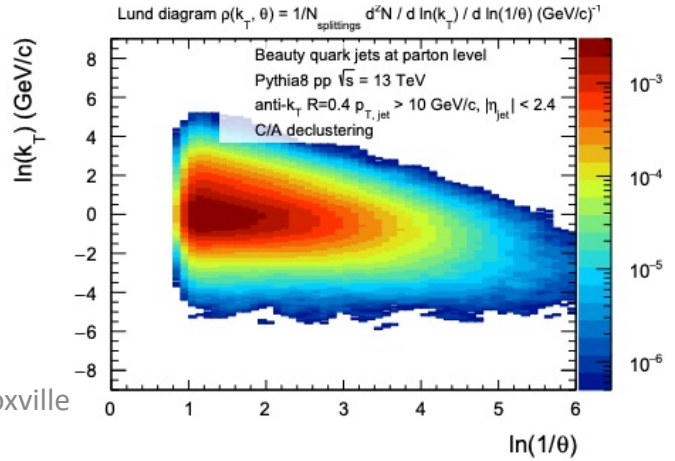
L. Cunqueiro, M. Ploskon arXiv:1812.00102



Inclusive



Charm



Beauty

- Dead-cone effect can be seen through Lund Maps of the splittings.
- Radiation from the heavy flavor vertex appears suppressed at small angles compared to the inclusive distribution.
- Larger suppression seen for Beauty than Charm quarks.