ALICE measurements of inclusive untagged and heavy flavor-tagged jets in pp, p-Pb and Pb-Pb collisions

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for the ALICE Collaboration

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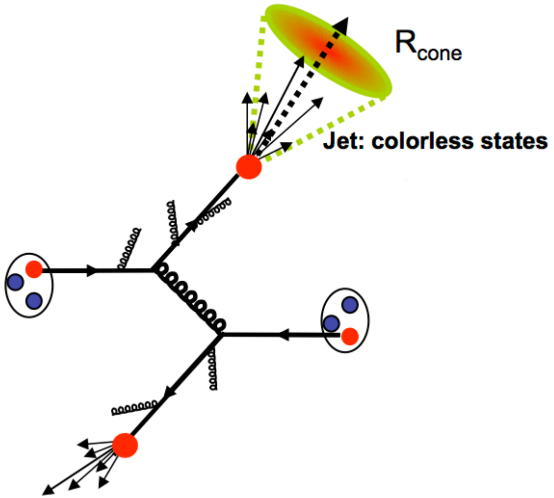
Jets

- **Jet** - collimated spray of particles, created during fragmentation of quark or gluon after hard scattering
- Defined via IRC safe algorithms (anti-k_T, Cambridge/Aachen, k_T)
- Well understood theoretically in pQCD for pp collisions
- **Heavy Flavour** jets are initiated by a heavy quark ($m_q > \Lambda_{QCD}$) → perturbative production down to low jet p_T



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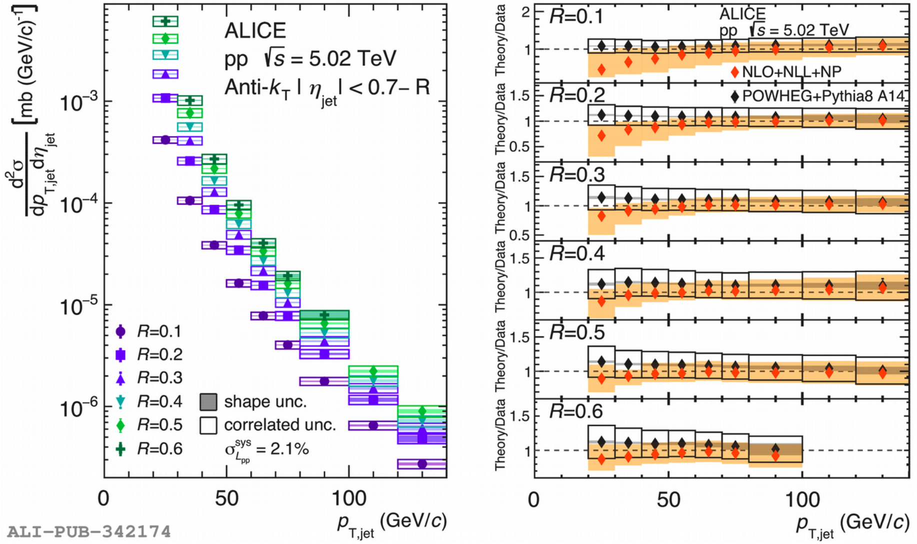

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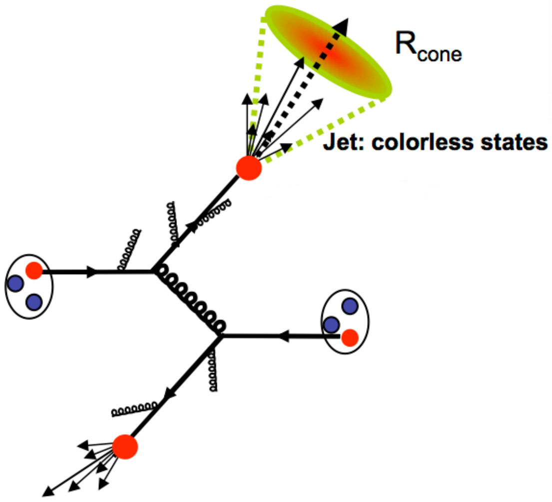


p-p

Test of the pQCD predictions

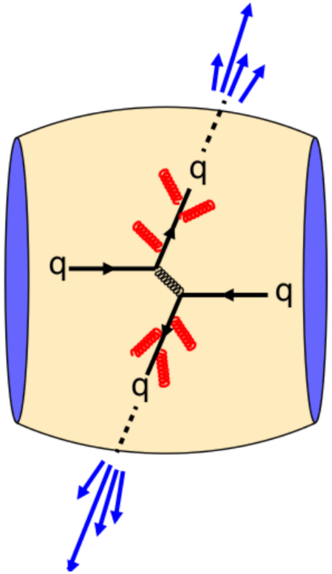
Reference for p-Pb and Pb-Pb

p-Pb

Study of the cold nuclear matter effects (CNM) nPDFs, Cronin effect, ...

Pb-Pb

In-medium energy loss: jet quenching for quark and gluon jets

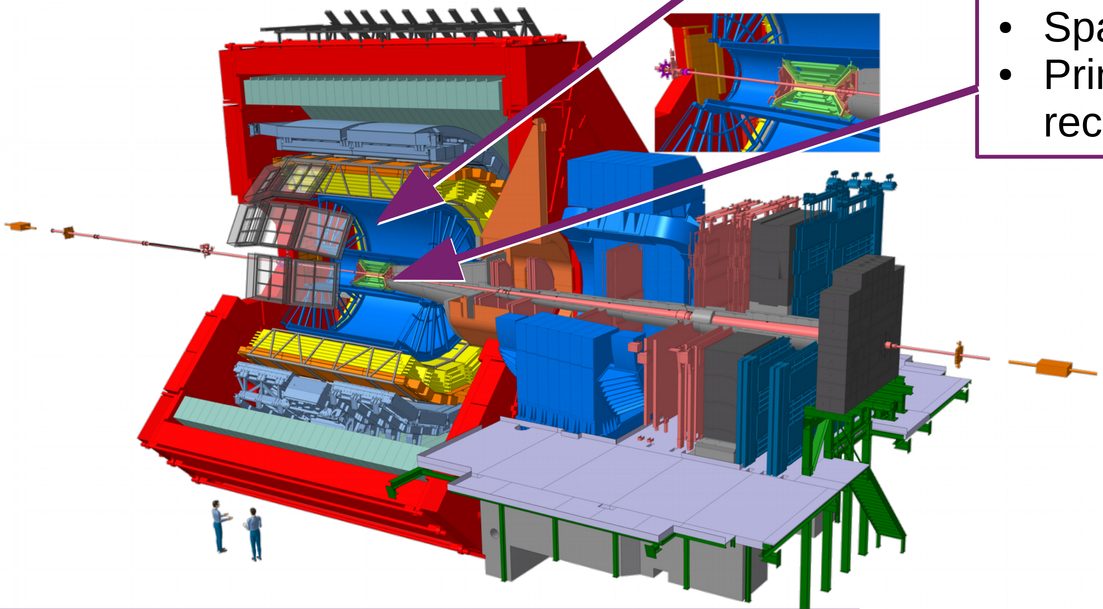


Jets in ALICE

EMCal:
- Triggering on high-p_T γ, e^{+-}, and jets

Time Projection Chamber:
- Space-time points for tracking
- Particle identification via dE/dx

Inner Tracking System:
- Space-time points for tracking
- Primary and secondary vertex reconstruction



Tracking and EMCal acceptance:
- $|\eta_{track}| < 0.9$
- Tracking in full azimuth
- $p_{T,\,track} > 0.15$ GeV/c
- $|\eta_{EMCal}| < 0.7$, $\varphi < 110°$

Jet reconstruction:
- anti-k_T charged particle jet
- $R = 0.2–0.6$
- $|\eta_{jet}| < 0.9 - R$

VZERO:
- scintillator arrays at forward and backward η
- triggering

Overview

1) Production of b-jets in pp and p-Pb @ $\sqrt{s_{NN}}$ = 5.02 TeV

2) Radial profile of D^0 and Λ_c^+ hadrons in jets in pp @ $\sqrt{s}$ = 13 TeV

3) Substructure of D^0-tagged jets and dead-cone measurement in pp @ $\sqrt{s}$ = 13 TeV

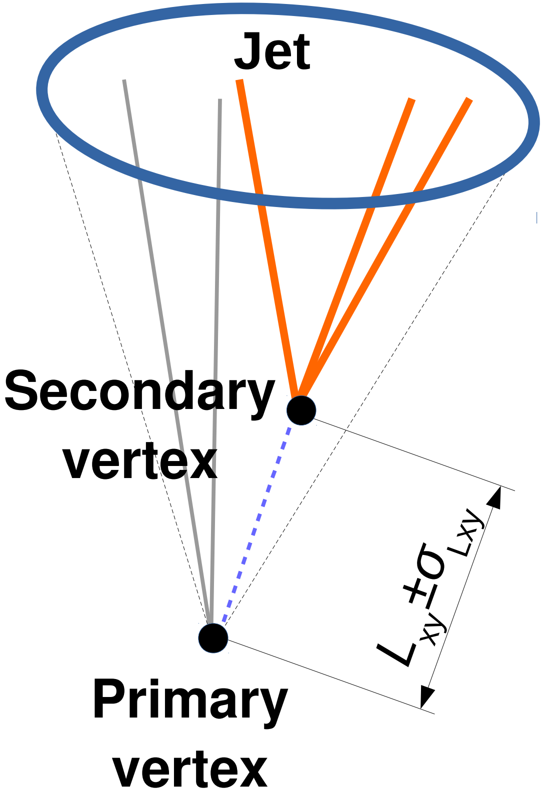
4) Subjet fragmentation in pp and Pb-Pb @ $\sqrt{s_{NN}}$ = 5 TeV

Methods to tag b-jets

Two independent methods were used for b-jet tagging

1) Impact parameter - distance of closest approach of jet constituents to primary vertex

2) Secondary vertex (SV) - properties of the most displaced 3-prong secondary vertex



- **Minimal significance of the SV displacement:** $SL_{xy} = L_{XY}/\sigma_{Lxy}$

  L_{XY} – distance between primary and secondary vertices

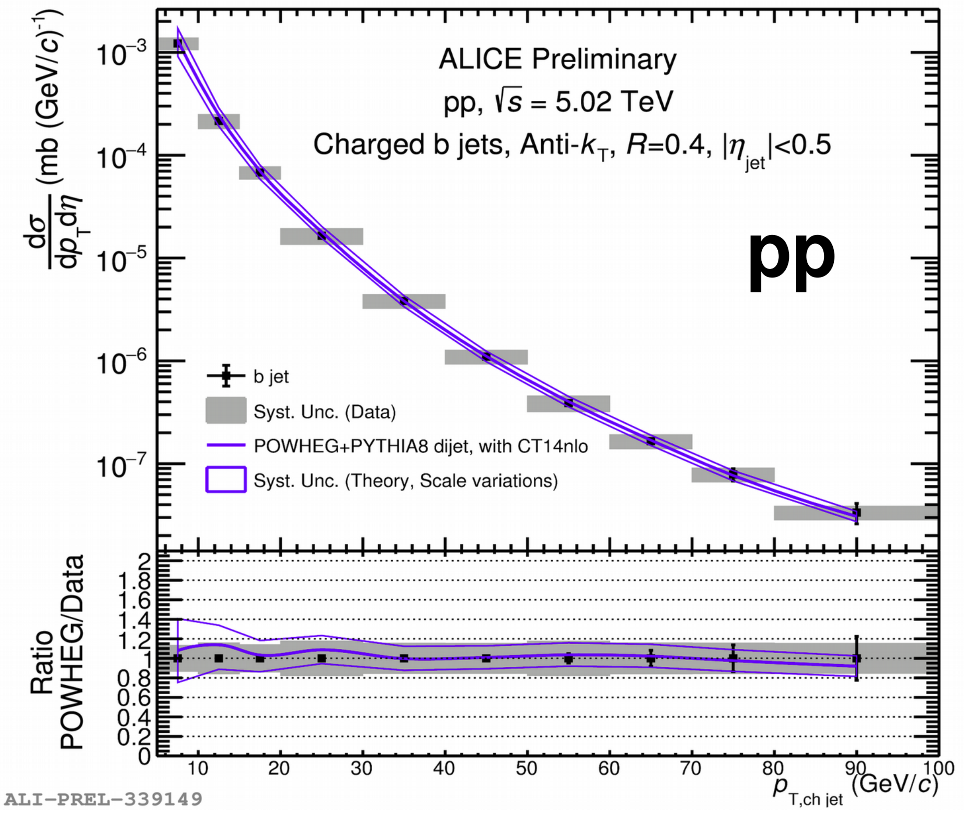
  σ_{Lxy} – uncertainty of L_{XY} measurement

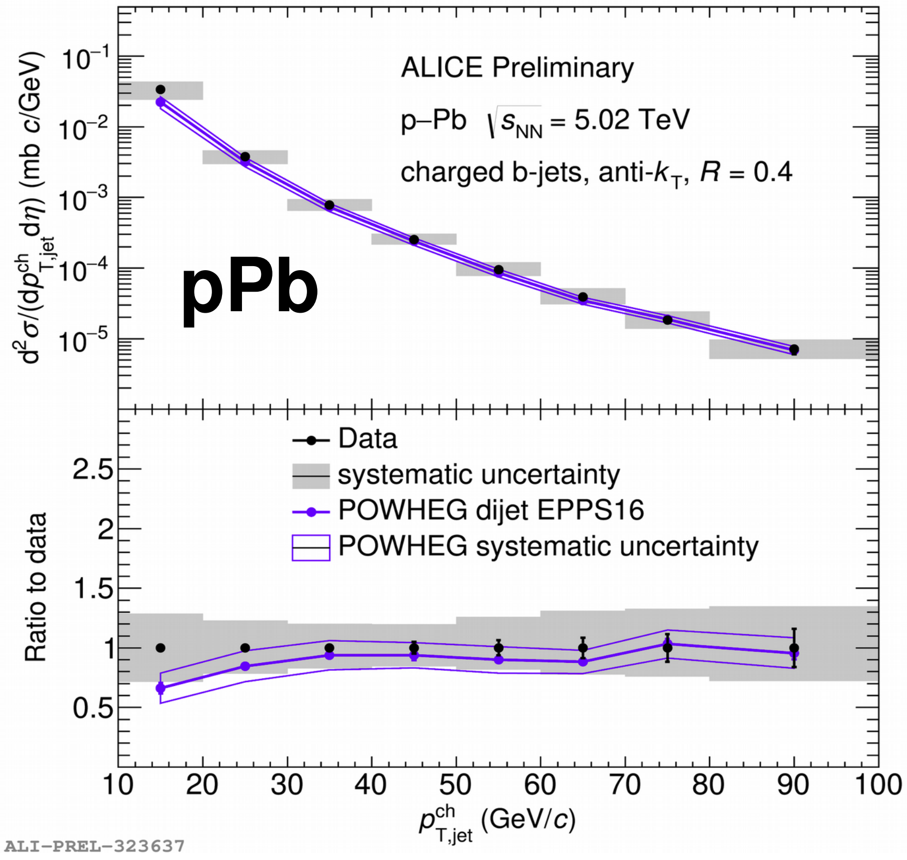
- **Upper limit on the SV resolution:** $\sigma_{SV} = \sqrt{\sum_{i=1}^{3} d_i^2}$

  d_i – distance of closest approach of *i*-th prong to the SV

Default SV cut: $\sigma_{SV} < 0.03$ cm, $L_{XY}/\sigma_{Lxy} > 7$

b-jets in minimum bias pp and p-Pb collisions

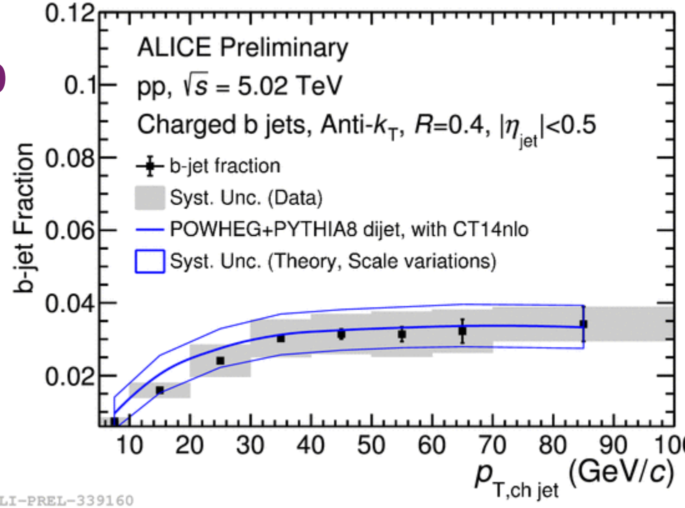




The measured b-jet production cross section reproduced with POWHEG+PYTHIA

b-jet fraction in pp and R_{pPb}

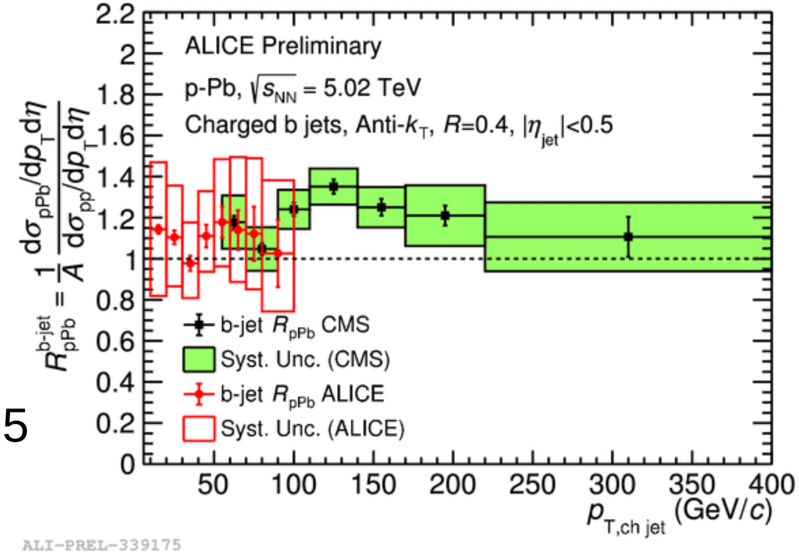
The measured b-jet fraction is compatible with the POWHEG prediction



Nuclear modification factor compares particle yield measured in p-Pb with the yield from the corresponding number of independent pp collisions:

$$R_{pPb}^{b\ jets} = \frac{1}{A} \frac{d\sigma_{pPb}^{b\ jet}/d\,p_{T,\,ch\ jet}}{d\sigma_{pp}^{b\ jet}/d\,p_{T,\,ch\ jet}}$$

where A is the number of nucleons in the Pb nucleus



CNM effects in p–Pb smaller than current resolution

CMS measured full anti-k_T R =0.3 b-jets with $-2.5 < \eta_{jet} < 1.5$

[CMS Phys. Lett. B754 (2016) , arXiv:1510.03373 [nucl-ex].

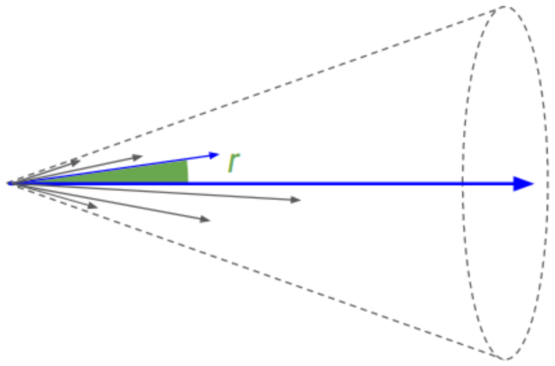
Comparison of radial profile of D^0 and Λ_c^+ in jets in pp

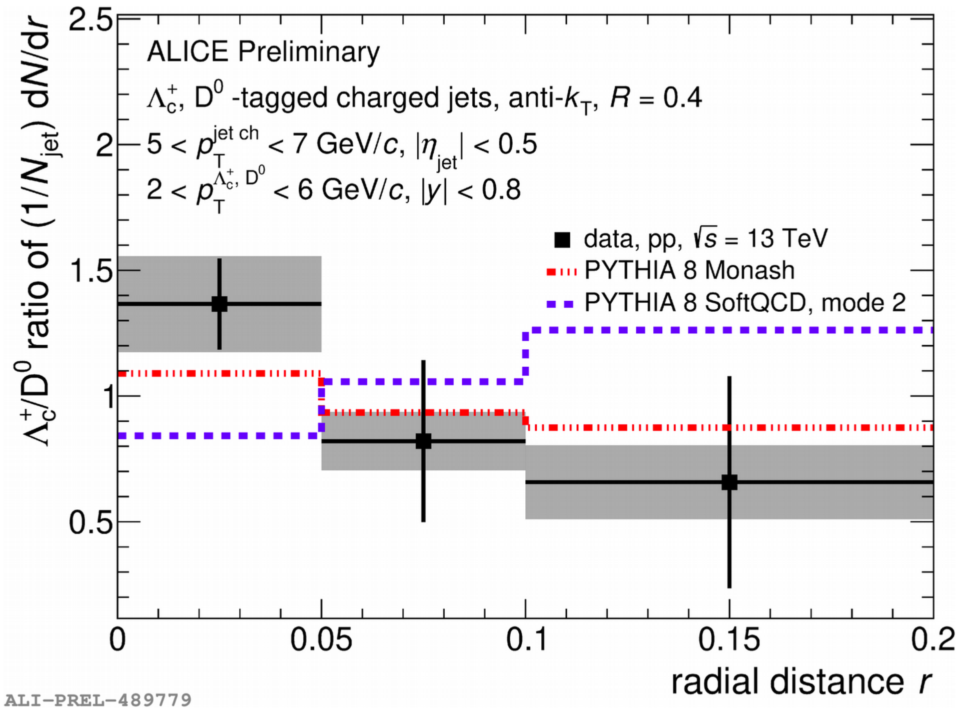
Distribution of **the radial distance** between the hadron and the jet axis

$$r = \sqrt{(\varphi_{jet} - \varphi_{HF})^2 + (\eta_{jet} - \eta_{HF})^2}$$

$\varphi_{jet}, \varphi_{HF}$ - azimuthal angles of jet and HF hadron

η_{jet}, η_{HF} - pseudorapidity of jet and HF hadron





- Λ_c^+ produced closer to the jet axis than D^0
- PYTHIA 8 Monash tune describes results better than PYTHIA 8 SoftQCD with color reconnection

Substructure of groomed D⁰-jets and untagged jets in pp

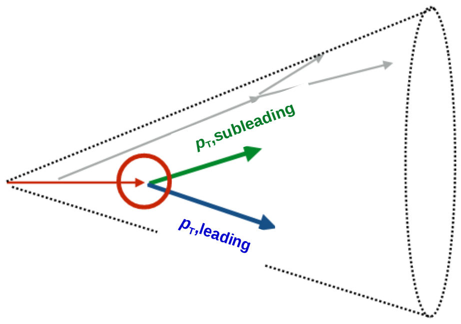
Study jet shower via unwinding history of the clusterization process

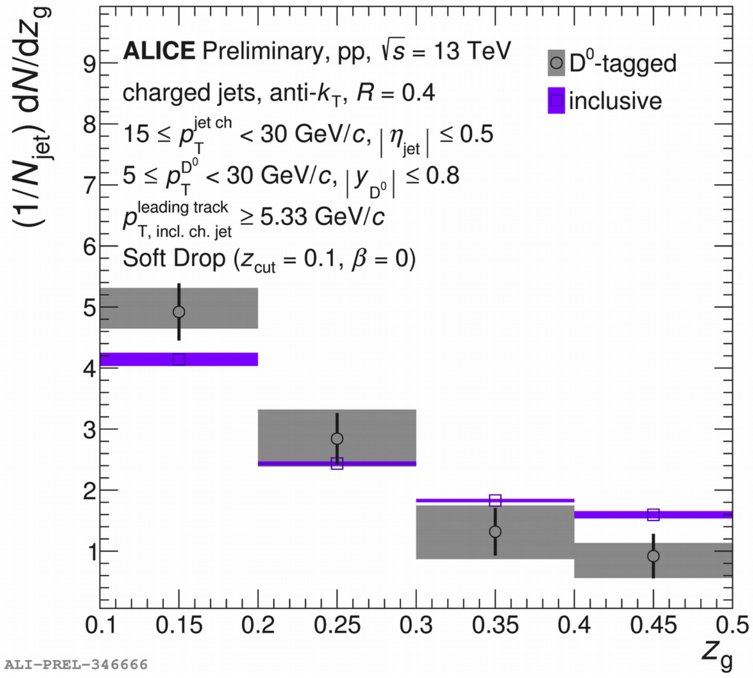
Soft radiation at large angles is groomed away from jet shower with **Soft Drop** (SD) condition:

$$z < z_{cut}\,\theta^{\beta}$$

Momentum fraction of subleading prong:

$$z_g \equiv \frac{p_{T,\text{ subleading}}}{p_{T,\text{ subleading}} + p_{T,\text{ leading}}}$$

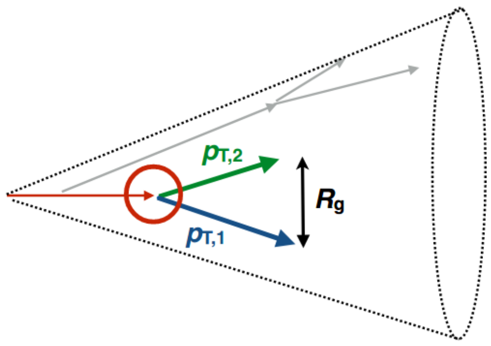




D⁰-jets exhibit larger p_T asymmetry in comparison to untagged jets.

Substructure of groomed D^0-jets and untagged jets in pp

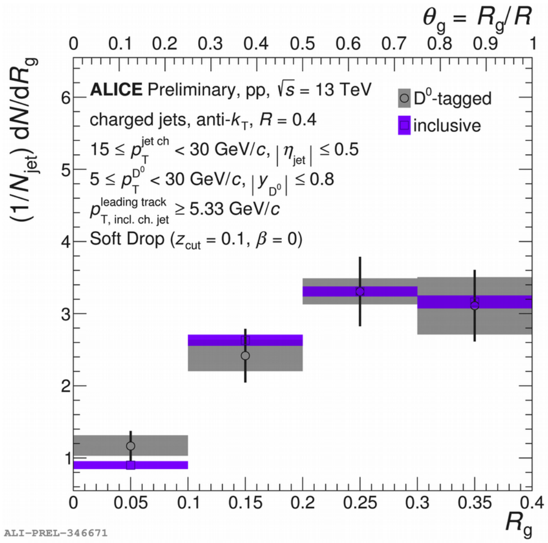
Angular distance R_g



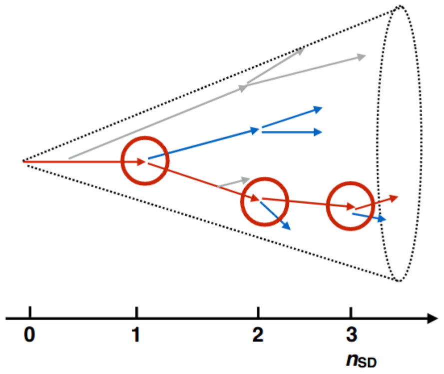
D^0-jets and untagged jets consistent within uncertainties

$$\theta_g \equiv \frac{\sqrt{\Delta y^2 + \Delta \varphi^2}}{R}$$

→ jet resolution parameter



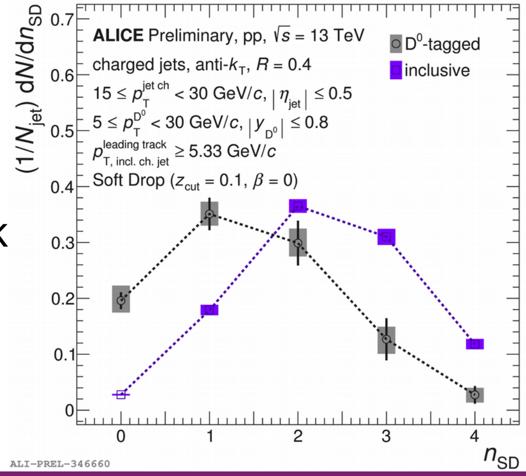
Number of splittings satisfying SD



Fewer splittings passed SD condition in D^0-jets than in untagged jets.

Result of harder fragmentation of the charm quark

- difference between quark and gluon jets
- dead-cone effect

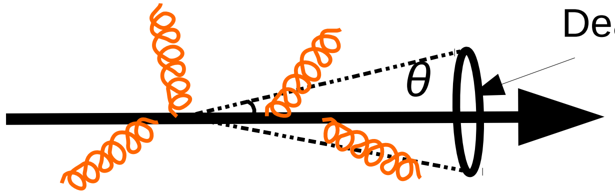


Manifestation of the dead-cone effect for D^0-tagged jets

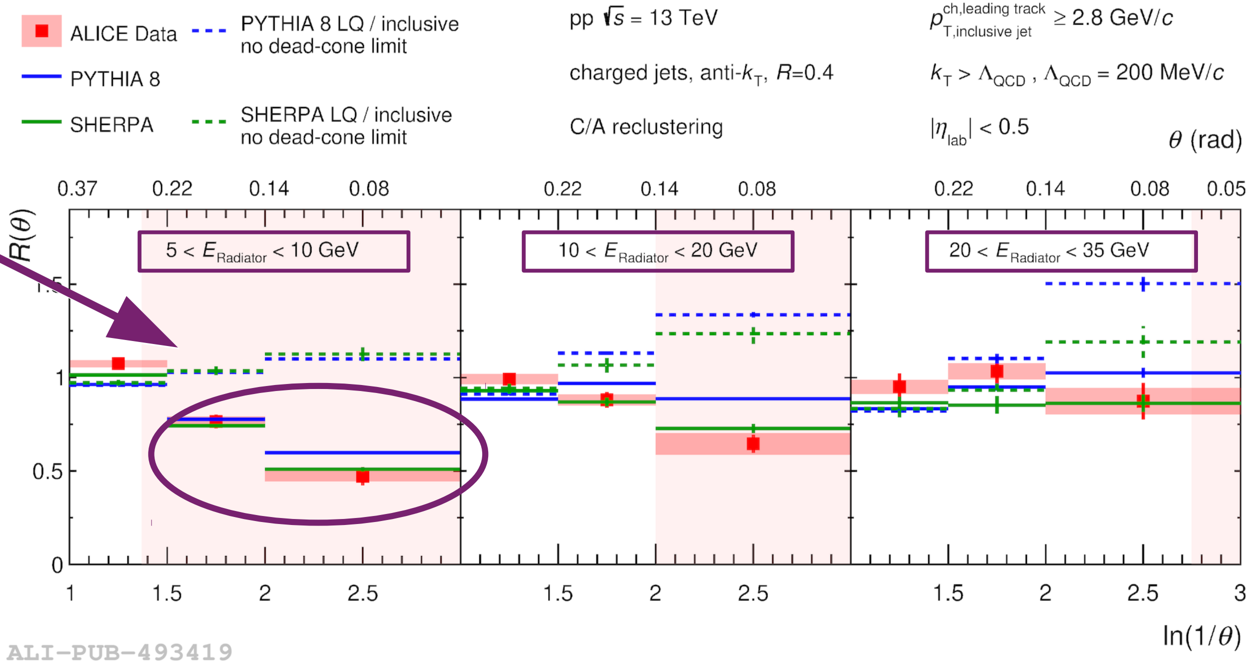
Dead-cone effect: suppression of gluon emission phase space for $\theta < \theta_{DC} = m_q/E_q$ → mass effects at low p_T

$$R(\theta) = \frac{1}{N^{D^0\,\text{jets}}} \frac{d n^{D^0\,\text{jets}}}{d \ln(1/\theta)} \Big/ \frac{1}{N^{\text{untagged jets}}} \frac{d n^{\text{untagged jets}}}{d \ln(1/\theta)} \Bigg|_{k_T, E_{\text{radiator}}}$$

Ratio of the splitting-angle population for D^0-tagged jets to untagged jets



- Significant suppression at small-θ
- Dead cone closing with increasing E_{radiator}
- **First direct observation in pp**



arXiv:2106.05713

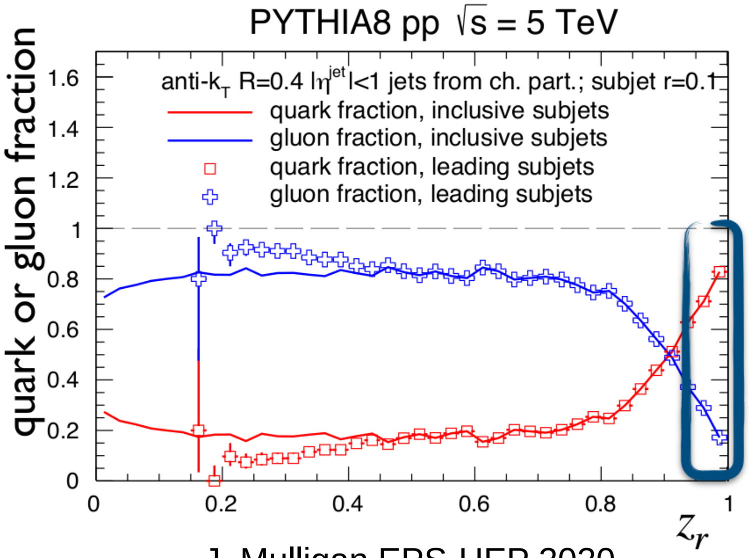
Subjet fragmentation in pp and central Pb-Pb collisions

Constituents of inclusive jet with radius ***R*** reclustered with anti-k_T algorithm to a subjet with radius ***r < R***.

$$z_r = \frac{p_T^{\text{ch subjet}}}{p_T^{\text{ch jet}}}$$

Subjet measurements:

- Jet quenching effect for q jets vs g jets
- Test of universality of jet fragmentation function
  parton → hadron vs parton → subjet

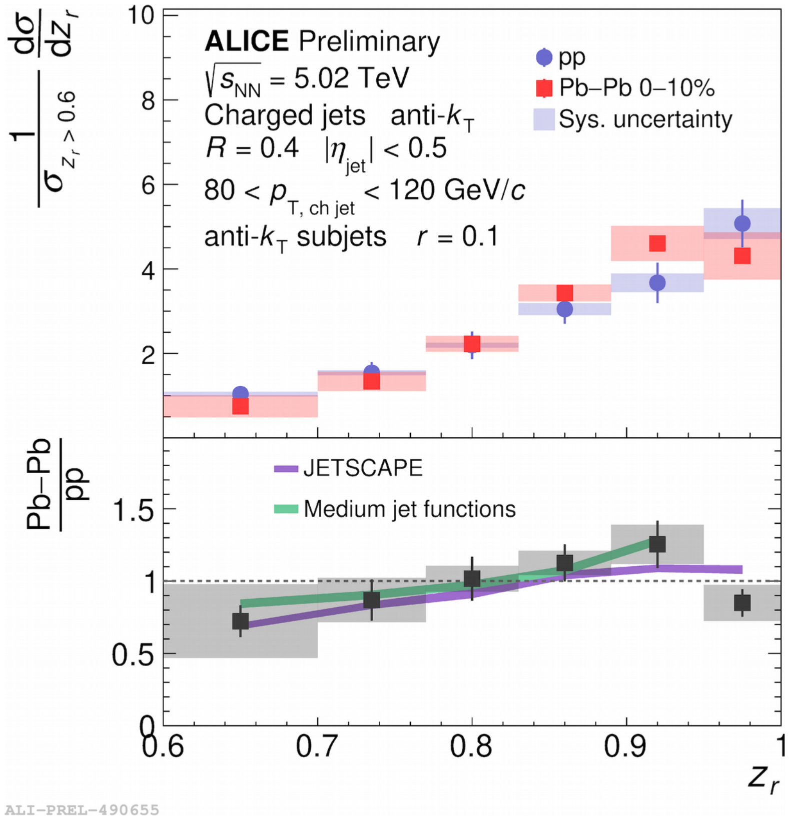


J. Mulligan EPS-HEP 2020

Subjet fragmentation in pp and central Pb-Pb collisions

$$z_r = \frac{p_T^{\text{ch subjet}}}{p_T^{\text{ch jet}}}$$

- **Intermediate z_r** :
  - Gluon suppression → larger z_r
  - Soft radiation → smaller z_r
- **Large z_r**: region depleted by soft medium induced with gluon emission → purely quark jets



First subjet fragmentation measurement in QGP medium

Summary

- Heavy-flavor jet tagging extends accessibility of perturbative QCD regime to low jet p_T
- The ALICE measurement of charged b-jet R_{pPb} at $\sqrt{s_{NN}}$= 5 TeV is compatible with unity
- Dead-cone effect is observed in pp collisions and it is seen to affect jet substructure
- Subjet fragmentation functions in Pb-Pb are affected by jet quenching

Outlook:

- ➢ Run3 will start next year
- ➢ New Inner Tracking System → improved capability for the HF tracking
- ➢ ALICE ready to take 100x larger luminosity w.r.t. Run 1 + Run 2