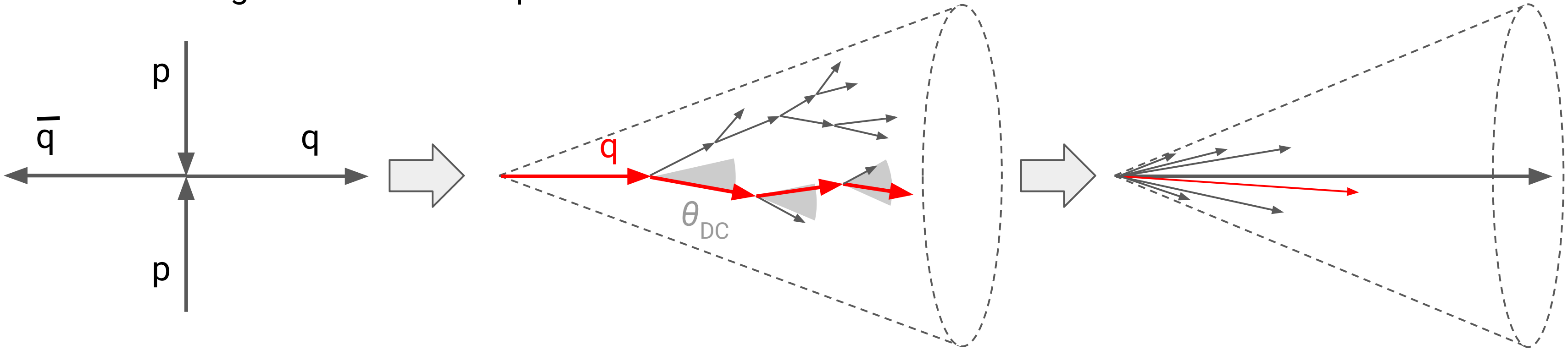
Heavy-flavour jet measurements in pp and Pb–Pb collisions by ALICE

Vít Kučera (Inha Univ.)
for the ALICE Collaboration

16 May 2023
34th Rencontres de Blois

Physics motivation for heavy-flavour jets

hard scattering | parton shower | hadronisation



Early perturbative production of heavy quarks
→ tests for pQCD down to low p_T

Heavy flavour conserved in the parton shower and experimentally traceable
→ access to properties of gluon emissions (e.g. splitting function)

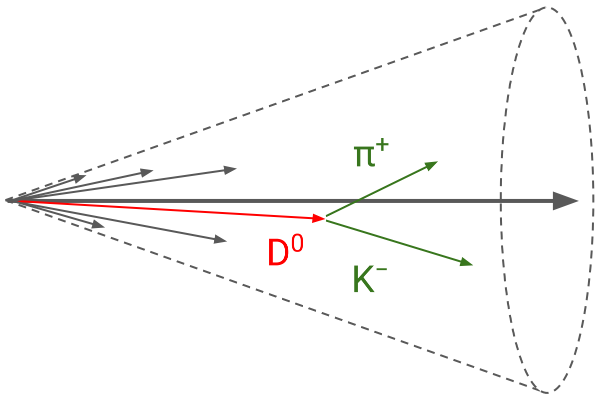
- Dead-cone effect, $\theta_{DC} = m_q/E_q$
- Casimir colour factors
- Modification in QGP

Hadronisation mechanisms

- Baryons vs mesons
- Fragmentation in QGP

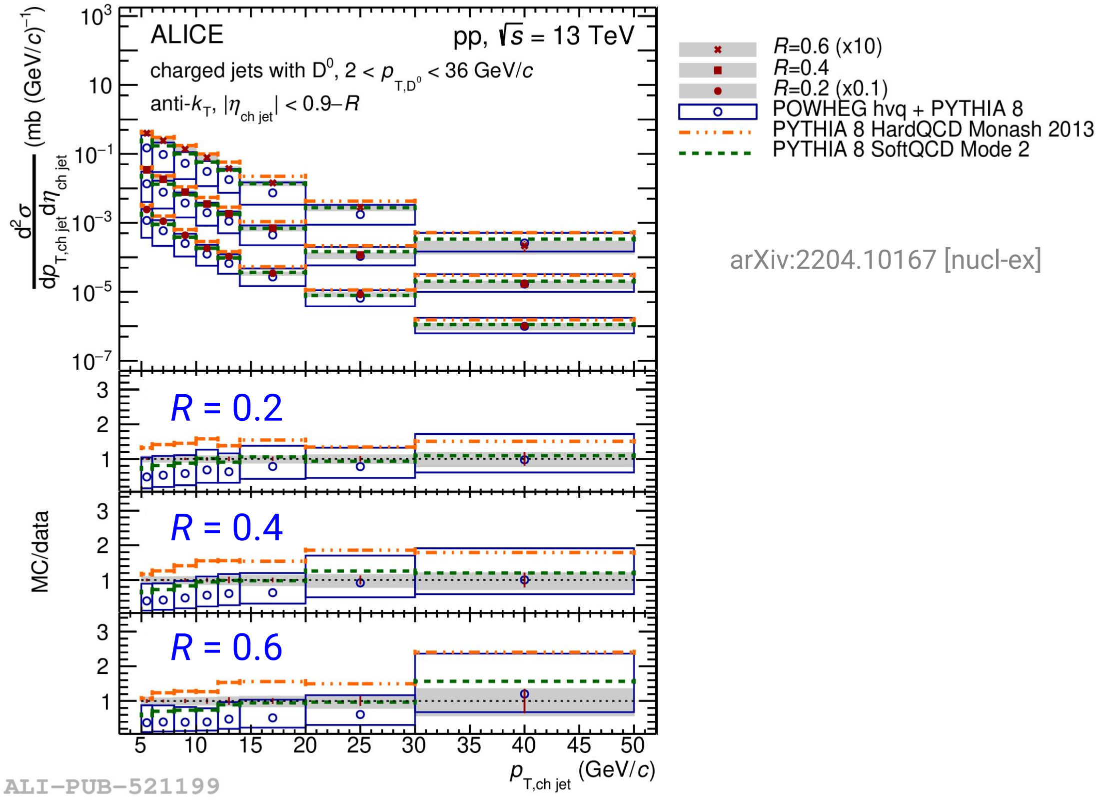
Charm-jet production in pp collisions

Tagged with reconstructed D^0



Jet resolution parameter (R) dependence probes the angular profile of the parton shower.

Agreement with pQCD in pp collisions
→ **calibrated baseline for Pb–Pb collisions**

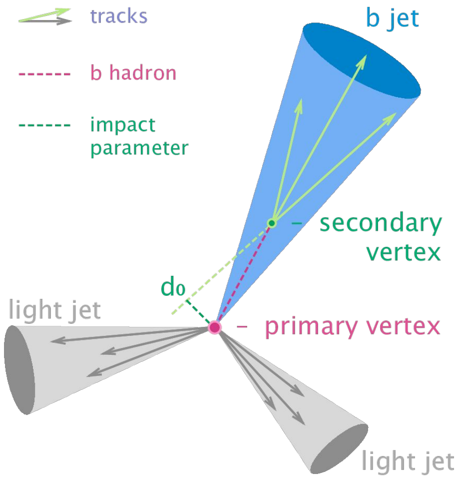


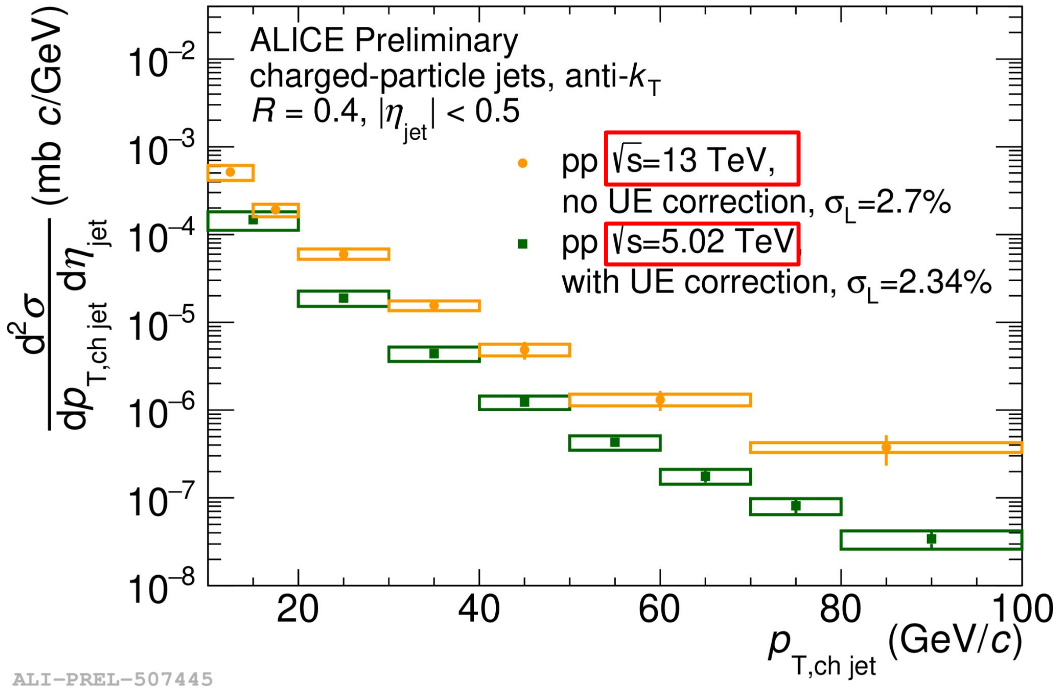
arXiv:2204.10167 [nucl-ex]

Beauty-jet production in pp collisions

Identification of b-jets using

- track impact-parameter distributions
- secondary-vertex displacement





Harder p_T dependence at larger collision energy

JHEP **01** (2022) 178

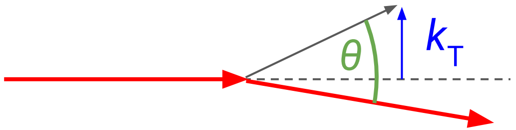
Dead-cone effect

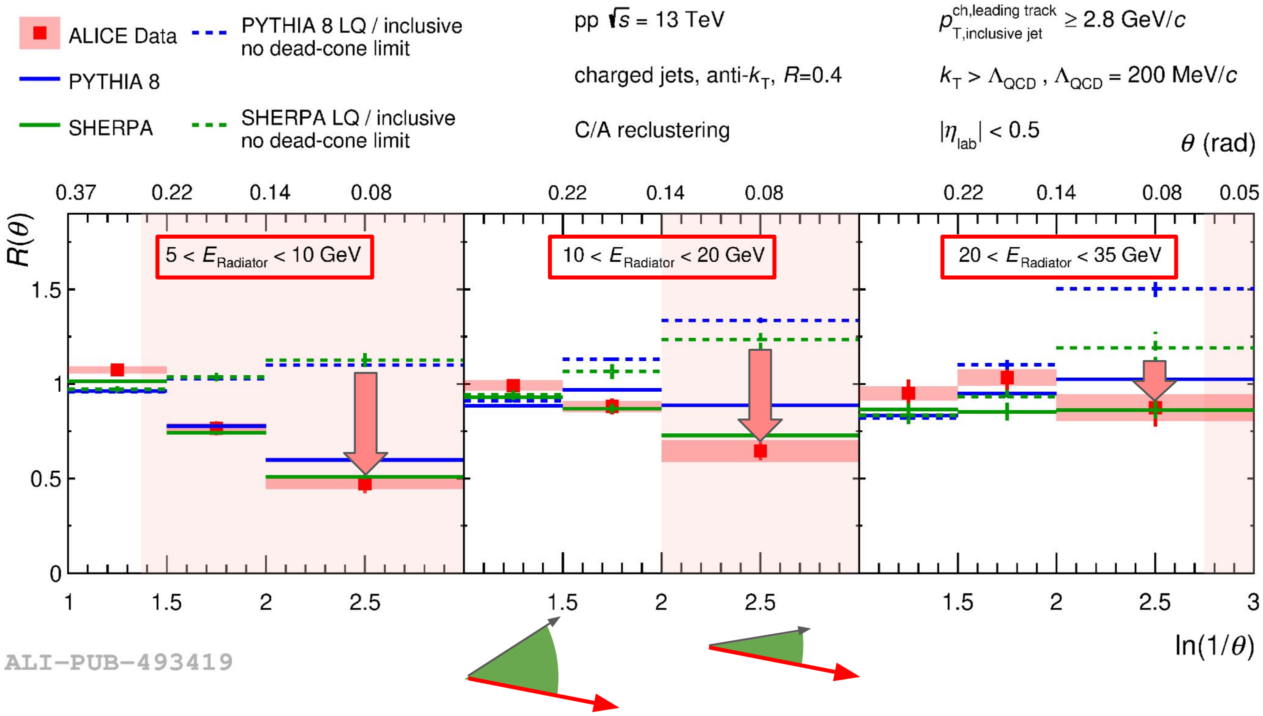
Ratio of distributions of splitting angles θ for heavy-flavour jets and inclusive jets

Significant suppression of small-θ emissions at low energy

Dead cone narrowing with increasing E_{Radiator}

First direct observation in QCD

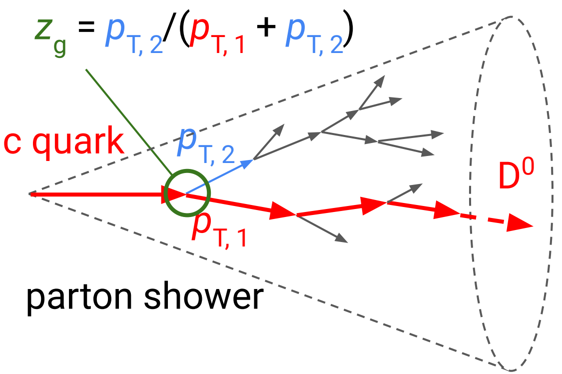




Nature **605** (2022) 440–446

Groomed-charm-jet substructure: z_g

p_T symmetry of the first perturbative splitting



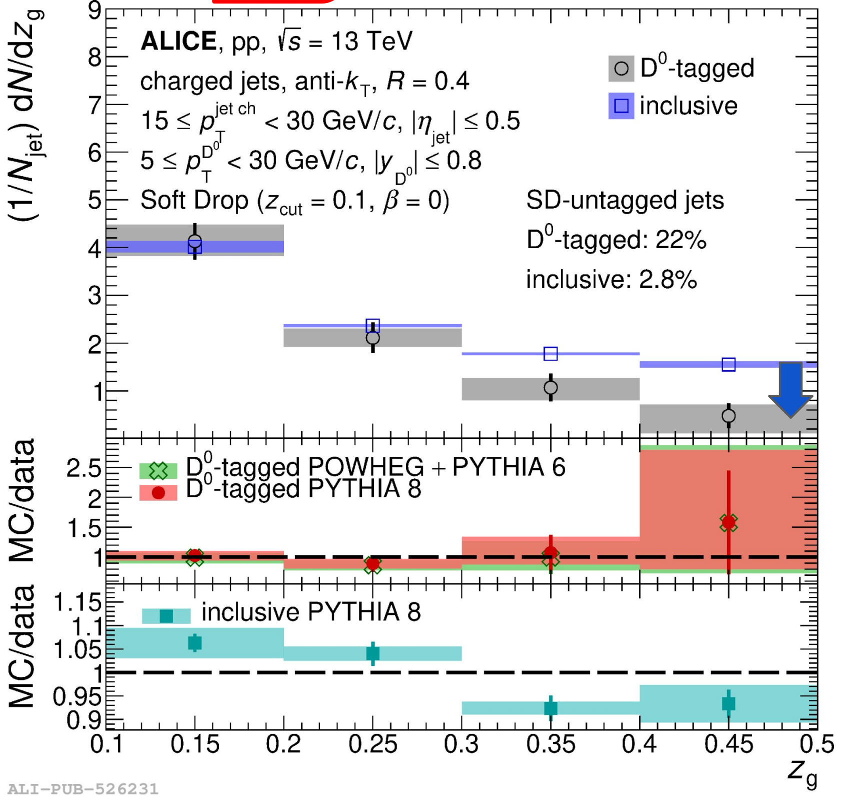
First direct experimental constraint on the splitting function of heavy quarks

Symmetric emissions from charm quarks suppressed

Good agreement with MC models for charm jets

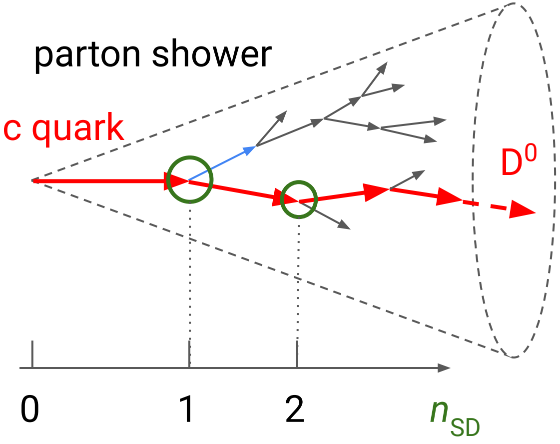
PYTHIA steeper than the measurement for inclusive jets

FINAL arXiv:2208.04857 [nucl-ex]



Groomed-charm-jet substructure: n_{SD}

Number of perturbative splittings of the leading branch



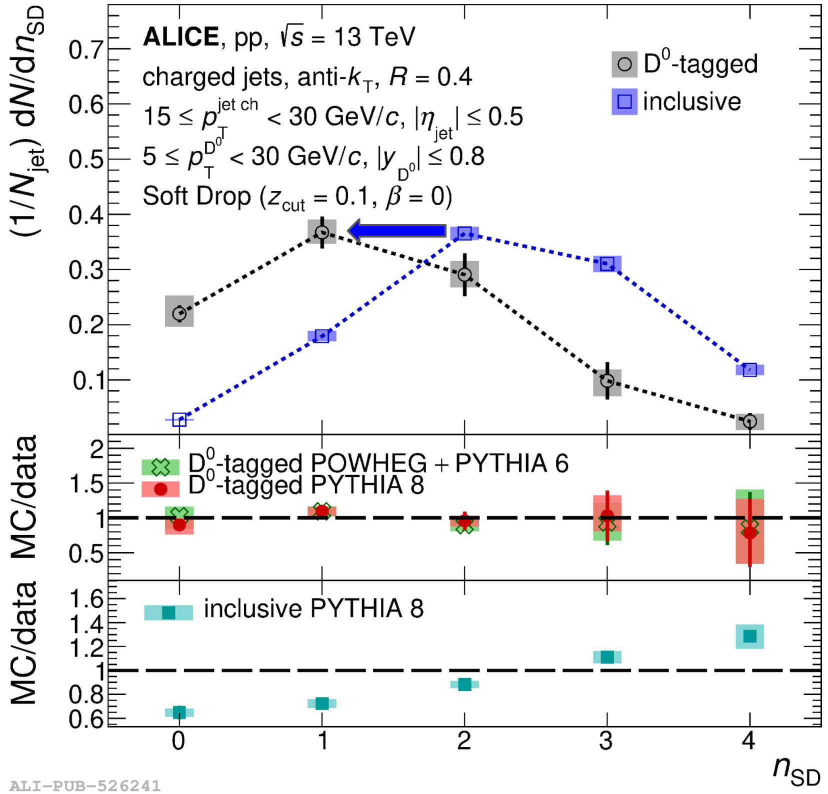
Fewer perturbative emissions from charm quarks

Fragmentation of charm quarks is harder.

Good agreement with MC models for charm jets

Shift to larger n_{SD} for PYTHIA for inclusive jets

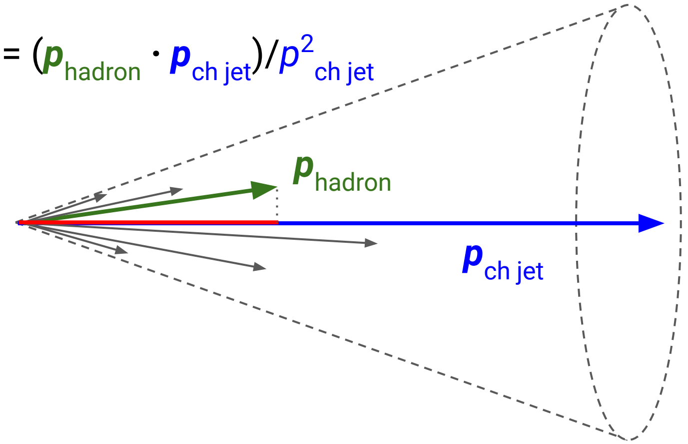
FINAL arXiv:2208.04857 [nucl-ex]



D^0 fragmentation function

Hadronisation stage of charm-quark fragmentation

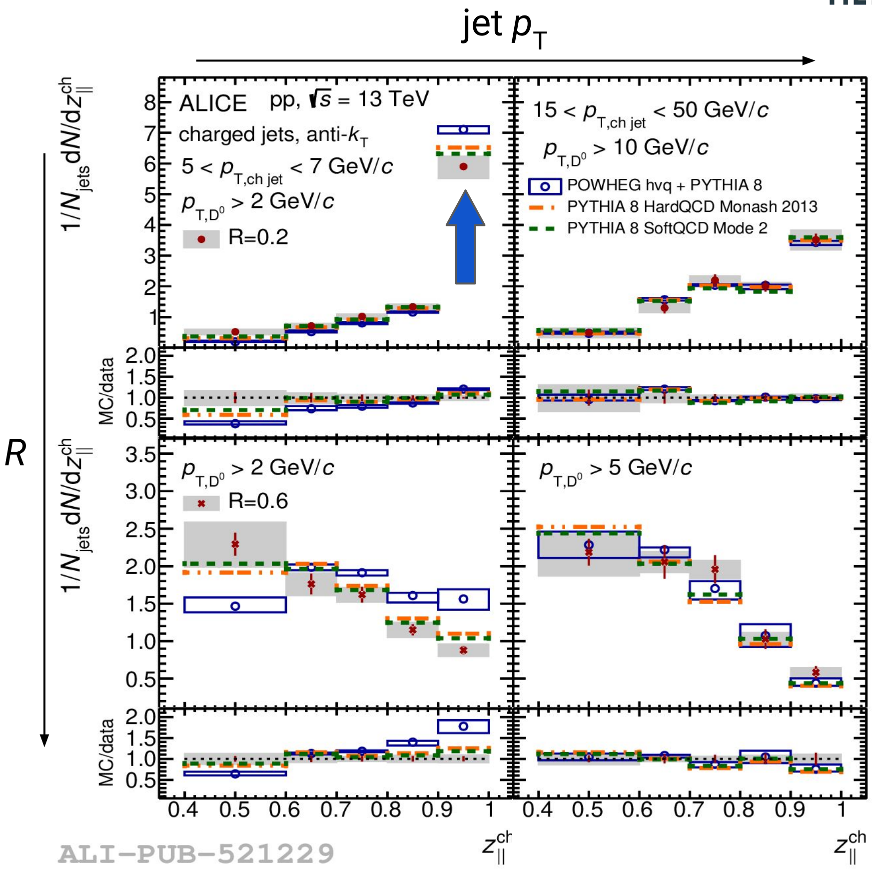
$$z^{ch}_{||} = (\boldsymbol{p}_{hadron} \cdot \boldsymbol{p}_{ch\ jet})/p^2_{ch\ jet}$$



Measured in a wide phase-space region:
$\sqrt{s}$ = 5.02 TeV, 13 TeV
Jet $p_T \in [5, 50]$ GeV/c
D^0 $p_T \in [2, 36]$ GeV/c
R = 0.2, 0.4, 0.6

Good description by models at high jet p_T and small R

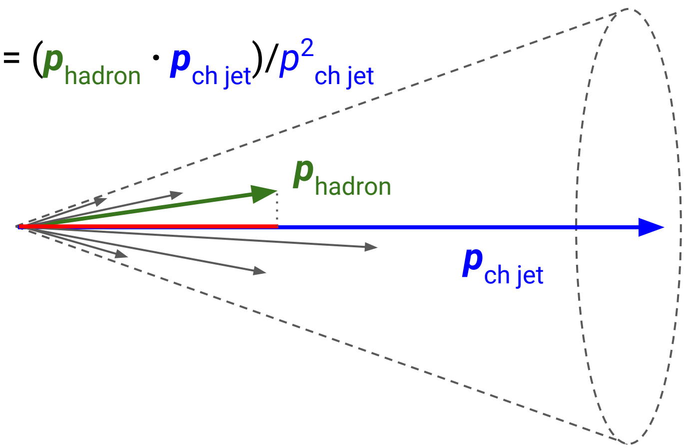
arXiv:2204.10167 [nucl-ex]



D_s^+ fragmentation function

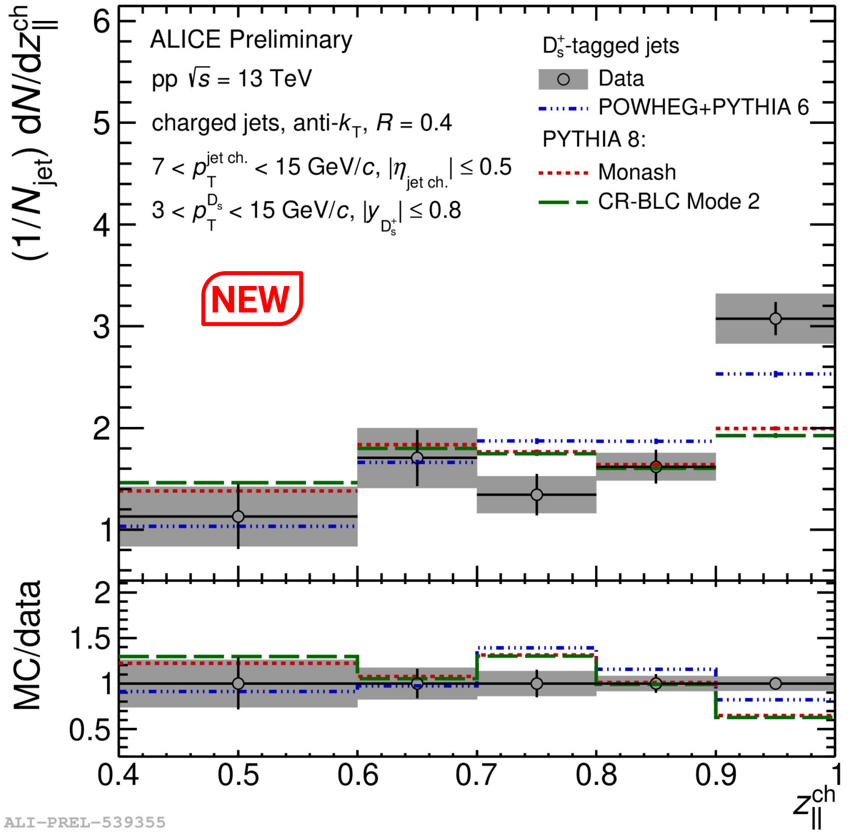
Hadronisation stage of charm-quark fragmentation

$z^{ch}_{||} = (\boldsymbol{p}_{hadron} \cdot \boldsymbol{p}_{ch\ jet})/p^2_{ch\ jet}$



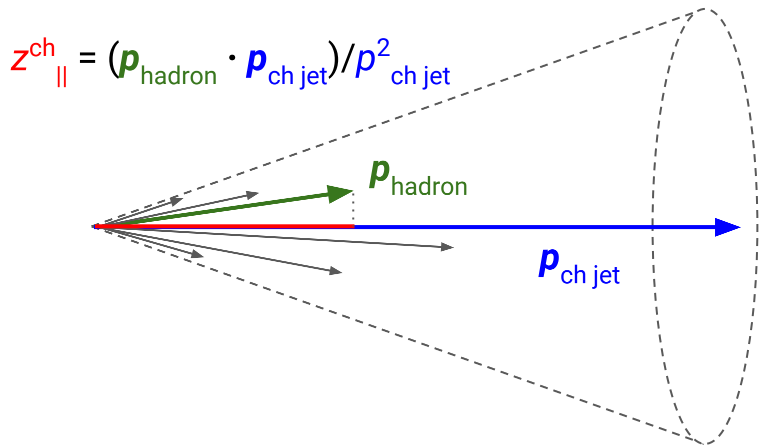
First $z^{ch}_{||}$ measurement for D_s^+

Exploring the effect of strangeness in the production of strange charm hadrons



D_s^+ fragmentation function

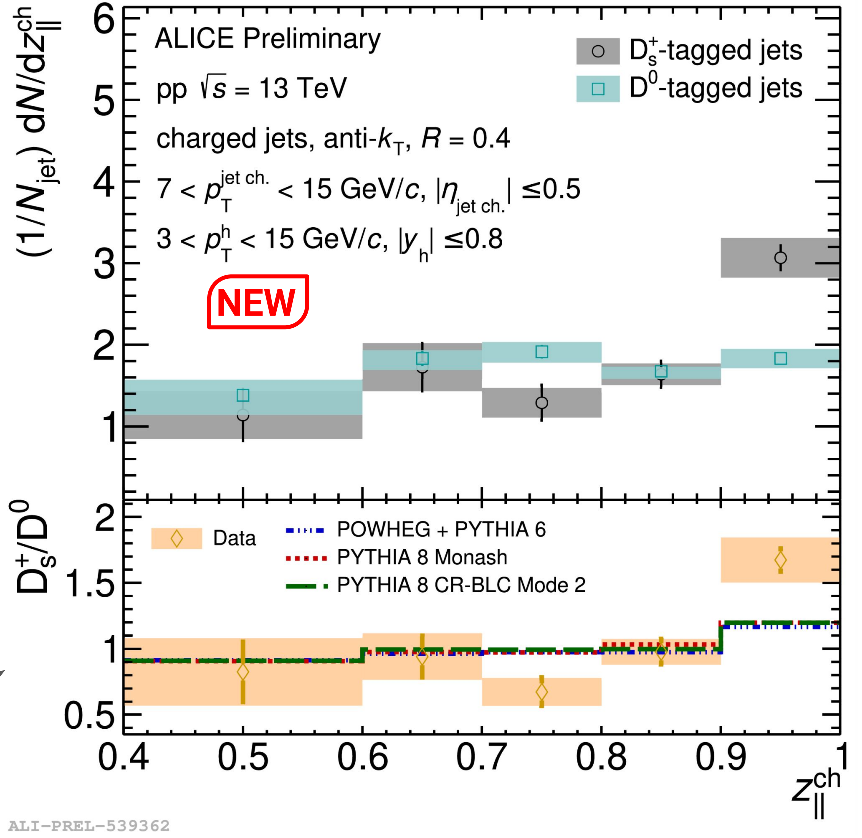
Hadronisation stage of charm-quark fragmentation



First $z^{ch}_{||}$ measurement for D_s^+

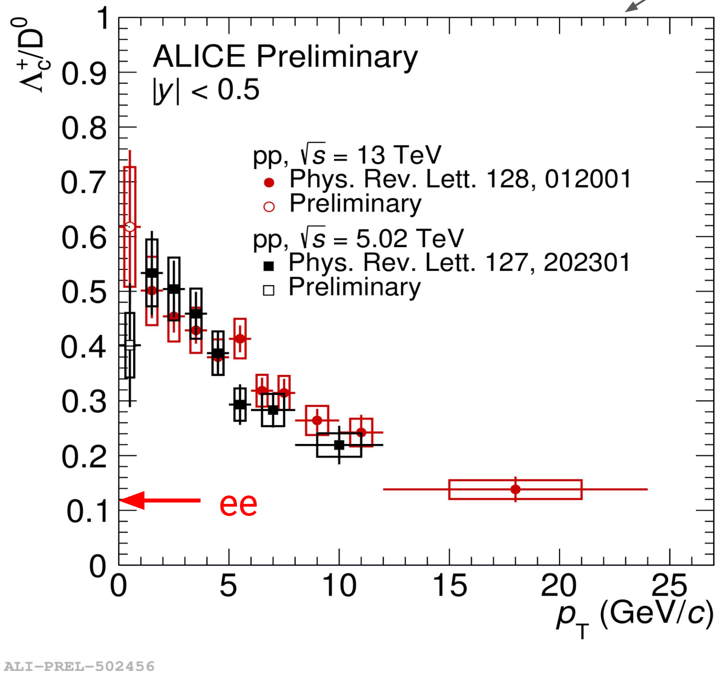
Exploring the effect of strangeness in the production of strange charm hadrons

Hint of harder fragmentation into D_s^+ than into D^0



Λ_c^+ fragmentation function

A more differential look at the baryon-to-meson ratio enhancement in pp w.r.t. ee/ep collisions



See Luigi Dello Stritto's talk, 16 May, 17:00
Studies on the hadronization of charm and beauty quarks with ALICE

Λ_c^+ fragmentation function

A more differential look at the baryon-to-meson ratio enhancement in pp w.r.t. ee/ep collisions

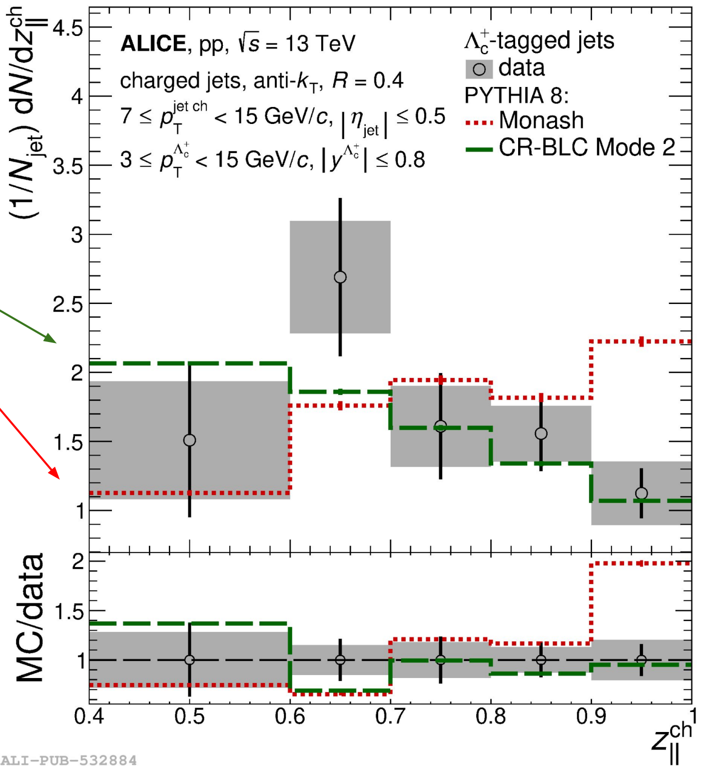
First $z^{ch}_{||}$ measurement for Λ_c^+ in hadronic collisions

Proof of feasibility of heavy-flavour baryon fragmentation measurements down to low p_T

Strong discrimination power for hadronisation models

FINAL

arXiv:2301.13798 [nucl-ex]



Λ_c^+ fragmentation function

ALICE

A more differential look at the baryon-to-meson ratio enhancement in pp w.r.t. ee/ep collisions

First $z^{ch}_{||}$ measurement for Λ_c^+ in hadronic collisions

Proof of feasibility of heavy-flavour baryon fragmentation measurements down to low p_T

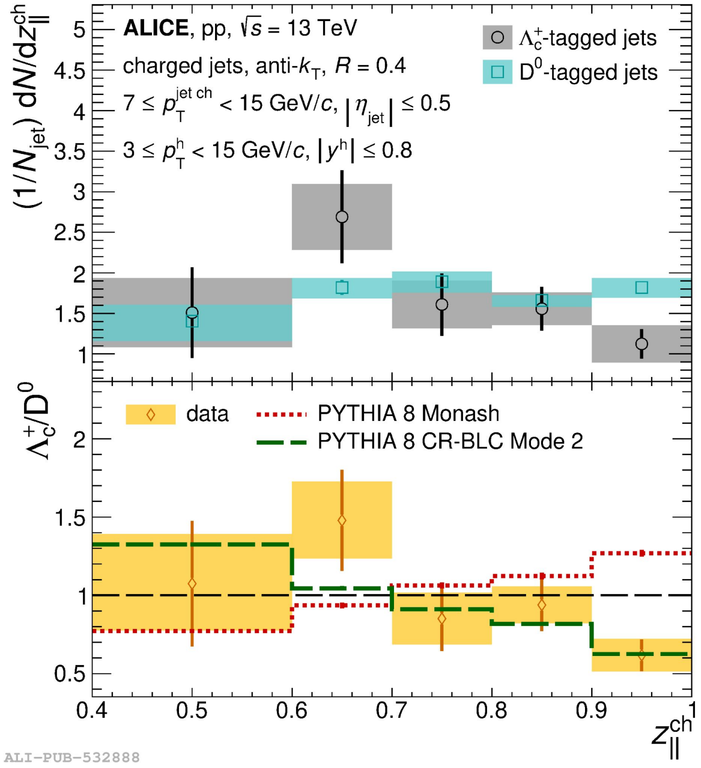
Strong discrimination power for hadronisation models

Hint of softer fragmentation into Λ_c^+ than into D^0

New way of constraining hadronisation mechanisms
(e.g. local parton density dependence of fragmentation)

FINAL

arXiv:2301.13798 [nucl-ex]



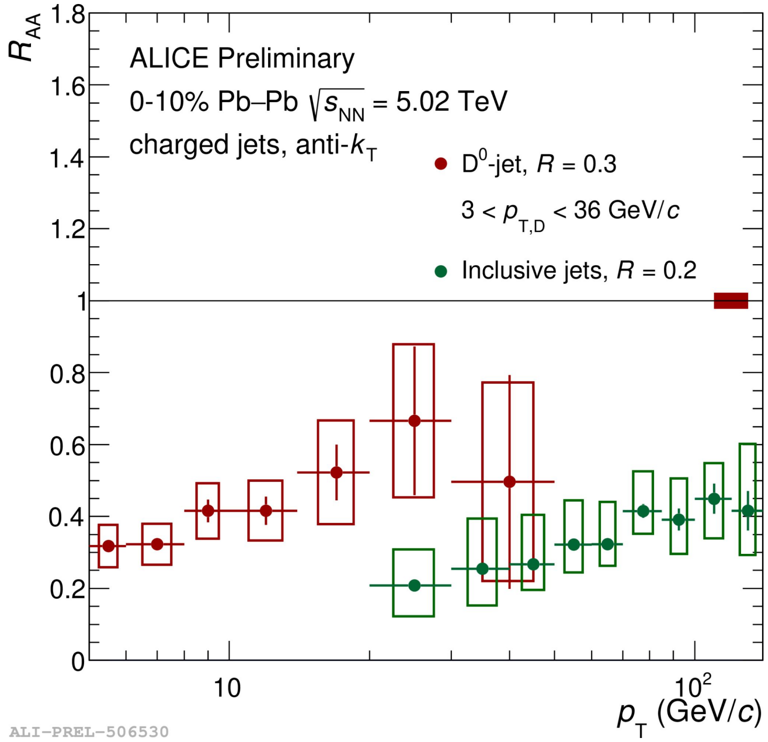
Modification of charm jets in Pb−Pb

Ratio of normalised differential yields of D^0-tagged jets in central Pb−Pb and pp collisions

Parton energy loss expected to depend on the mass

Hint of higher R_{AA} of charm jets compared to inclusive jets in the common p_T region

- Casimir colour factors
- Dead-cone effect



Summary and Run 3 prospects

Heavy-flavour jets are excellent probes for perturbative and non-perturbative QCD processes.

More data and better tracking resolution in Run 3 → better accuracy

Better characterisation of hadronisation mechanisms from fragmentation functions of Λ_c^+ and D^0

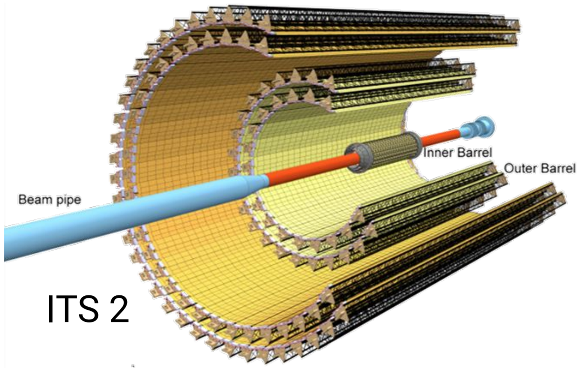
- Local parton multiplicity effects

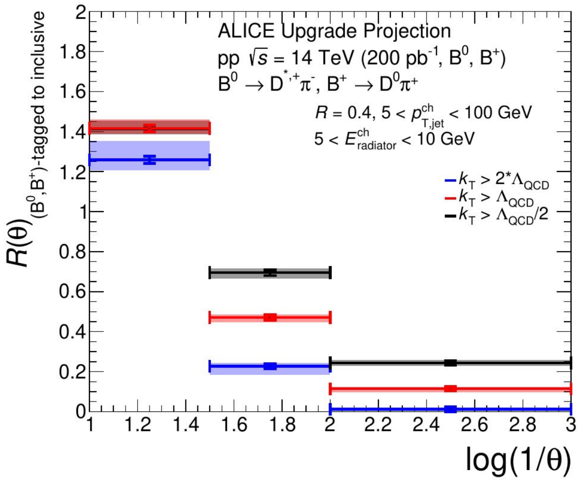
Substructure of charm and beauty jets

- Low p_T: dead-cone effect for charm vs beauty
- High p_T: Casimir colour factors for quarks vs gluons

Pb–Pb collisions: probe to study QGP

- Modification of heavy-quark fragmentation
- Mass dependence of parton energy loss





ALICE Collab. ALICE-PUBLIC-2020-005

Summary and Run 3 prospects

Heavy-flavour jets are excellent probes for perturbative and non-perturbative QCD processes.

More data and better tracking resolution in Run 3 → better accuracy

Better characterisation of hadronisation mechanisms from fragmentation functions of Λ_c^+ and D^0

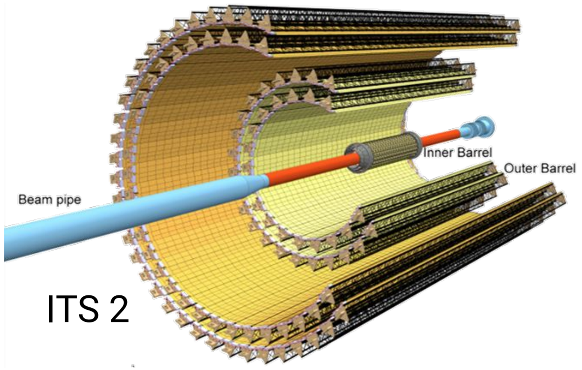
- Local parton multiplicity effects

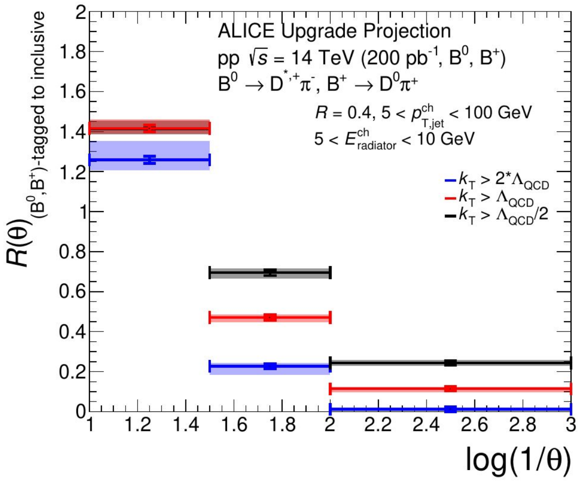
Substructure of charm and beauty jets

- Low p_T: dead-cone effect for charm vs beauty →
- High p_T: Casimir colour factors for quarks vs gluons

Pb–Pb collisions: probe to study QGP

- Modification of heavy-quark fragmentation
- Mass dependence of parton energy loss





ALICE Collab. ALICE-PUBLIC-2020-005

Thank you for your attention

Backup

Summary

Heavy-flavour jets are excellent probes of perturbative and non-perturbative QCD processes.

Heavy-quark production
→ Jet cross section

Parton shower evolution (dead-cone effect, Casimir colour factors)
→ Jet substructure from low to high jet p_T

Hadronisation mechanisms
→ Fragmentation functions of baryons vs mesons

Medium-induced modification of parton radiation
→ Heavy-ion collisions (R_{AA},...)

Thank you for your attention

D^0 fragmentation function

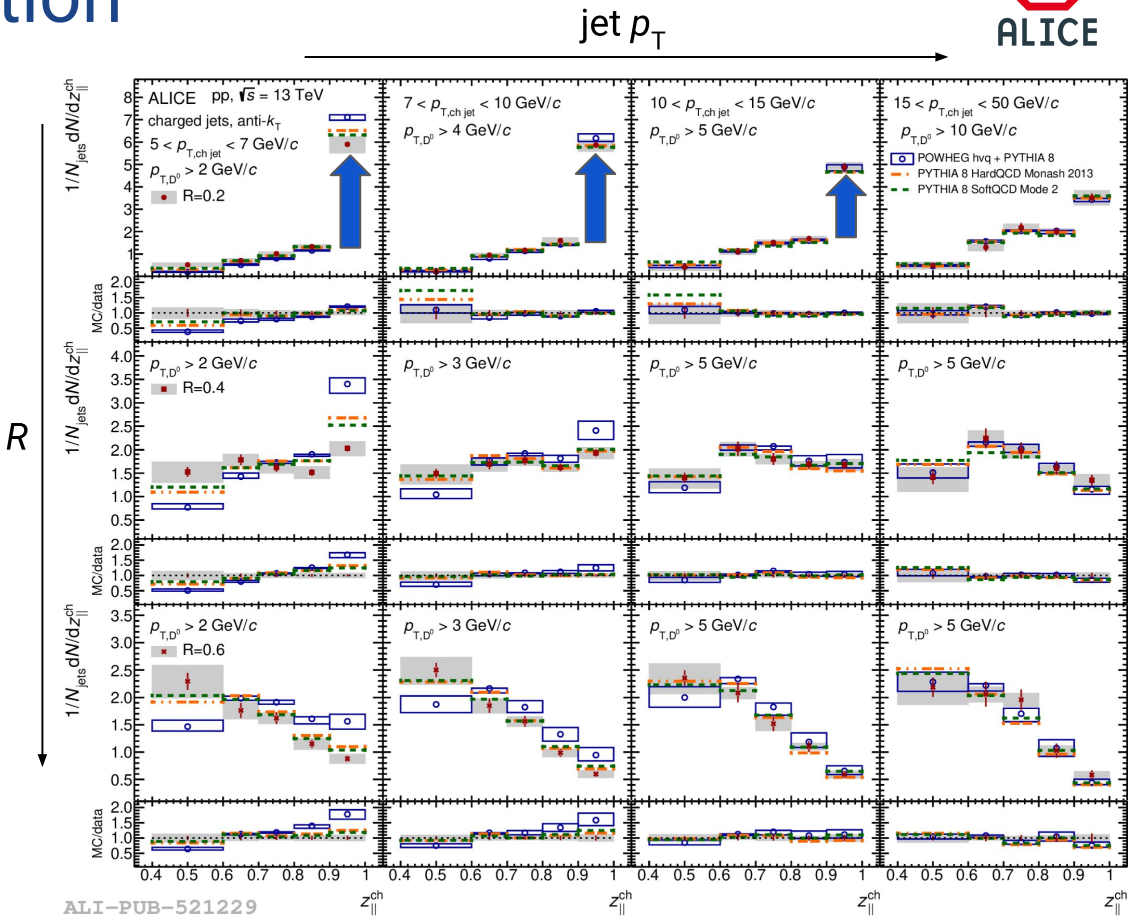
Narrow low-p_T jets are often single D^0.

Fragmentation softens with increasing R.

Significant shape transition for R = 0.4

Models harder at low jet p_T

Discrepancy larger at larger R



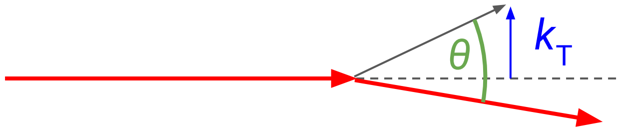
arXiv:2204.10167 [nucl-ex]

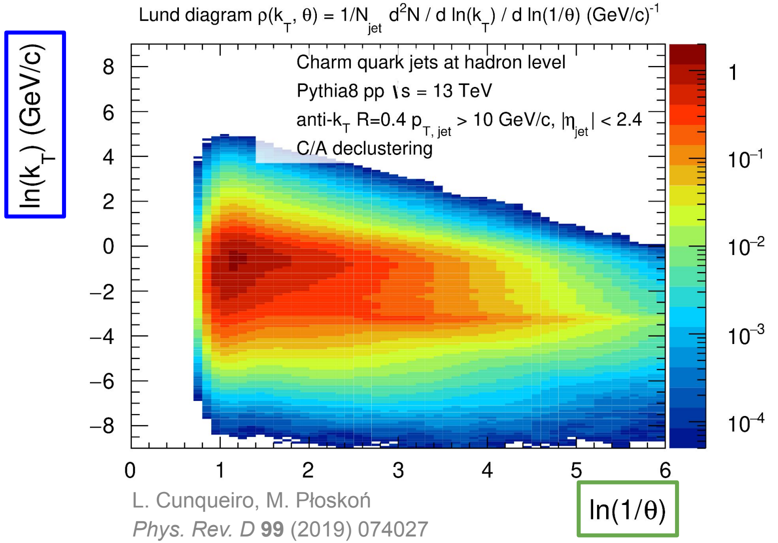
Jet substructure: Lund maps

Lund maps of splittings to access kinematics of parton shower evolution

- Splitting angle θ = ΔR of prongs
- Splitting scale k_T (transverse component of emission momentum)

  Requesting higher k_T suppresses non-perturbative effects.





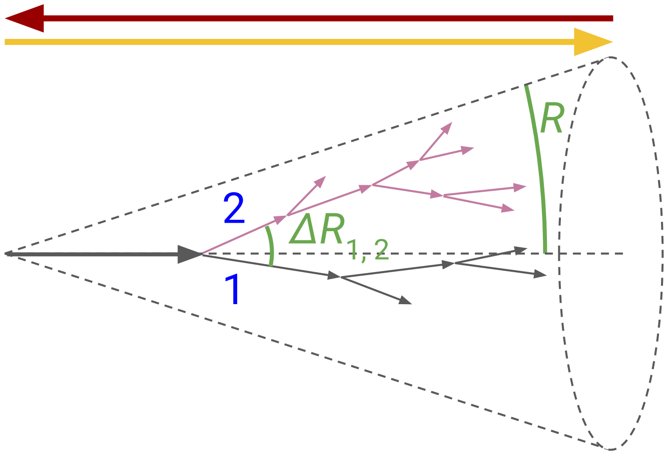
L. Cunqueiro, M. Płoskoń
Phys. Rev. D **99** (2019) 074027

Jet substructure: *declustering and grooming*

Access evolution of the parton shower: jet splittings (declustering)

Groom away soft radiation at large angles: isolate hard structures inside the jet (grooming)

- **Reclustering** with Cambridge/Aachen (angular ordering)
- **Declustering**: unwind reclustering history → chronologically ordered splittings
- **Grooming** with Soft Drop (SD): groom away soft prongs not satisfying the condition



$$\frac{p_{\mathrm{T},2}}{p_{\mathrm{T},1}+p_{\mathrm{T},2}} > z_{\mathrm{cut}}\left(\frac{\Delta R_{1,2}}{R}\right)^{\beta}$$

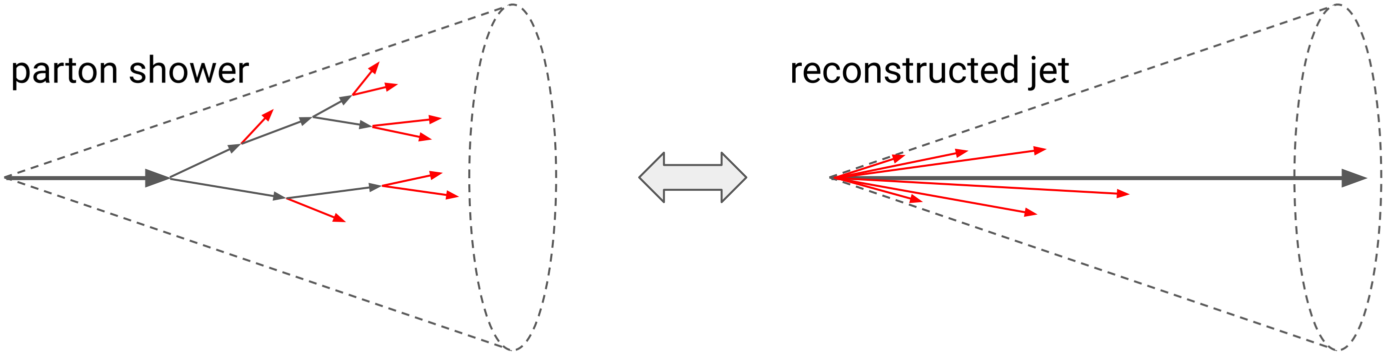
$$\Delta R_{\mathrm{a,b}} \equiv \sqrt{(y_{\mathrm{a}}-y_{\mathrm{b}})^2+(\varphi_{\mathrm{a}}-\varphi_{\mathrm{b}})^2}$$

A. J. Larkoski, S. Marzani, G. Soyez et al. *JHEP* **05** (2014) 146

Jet substructure

Jet substructure observables constructed from jet constituents after jet clustering

Characterise internal fragmentation pattern of parton shower



- Tests of QCD predictions
  - **Casimir colour factors**: different fragmentation of quarks and gluons
  - **Dead-cone effect**: suppression of emission phase space for $\theta < \theta_{DC} = m_q/E_q$
    → Mass effects sizeable in the low p_T kinematic range.
- Insight into nonperturbative phenomena (hadronisation, underlying-event effects)
- Baseline for medium effects of quark−gluon plasma in heavy-ion collisions

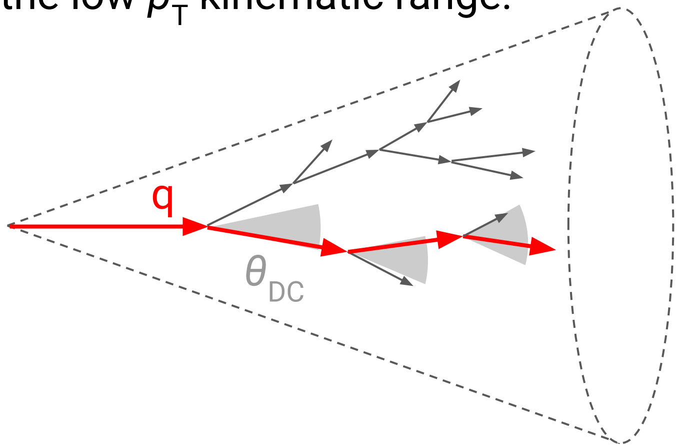
Substructure of heavy-flavour jets

$m_q > \Lambda_{QCD}$ → perturbative production down to low jet p_T

Heavy flavour conserved through the shower evolution

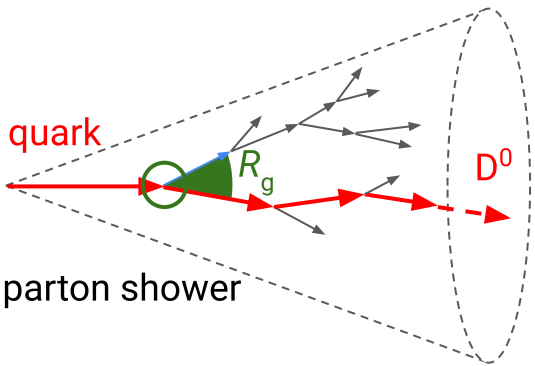
Inclusive vs heavy-flavour jets at low p_T:

- **Casimir colour factors**: different fragmentation of quarks and gluons
- **Dead-cone effect**: suppression of emission phase space for $\theta < \theta_{DC} = m_q/E_q$
  → Mass effects sizeable in the low p_T kinematic range.



Groomed-charm-jet substructure: R_g

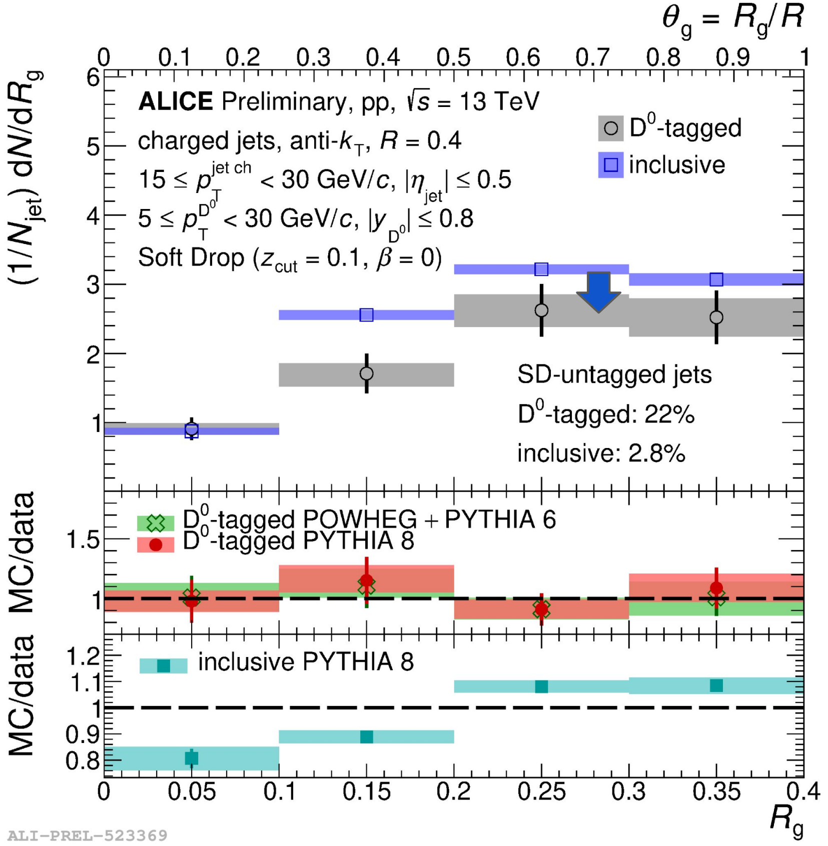
Angular size of the first perturbative splitting



Wide emissions from charm quarks suppressed.

Good agreement with MC models for charm jets

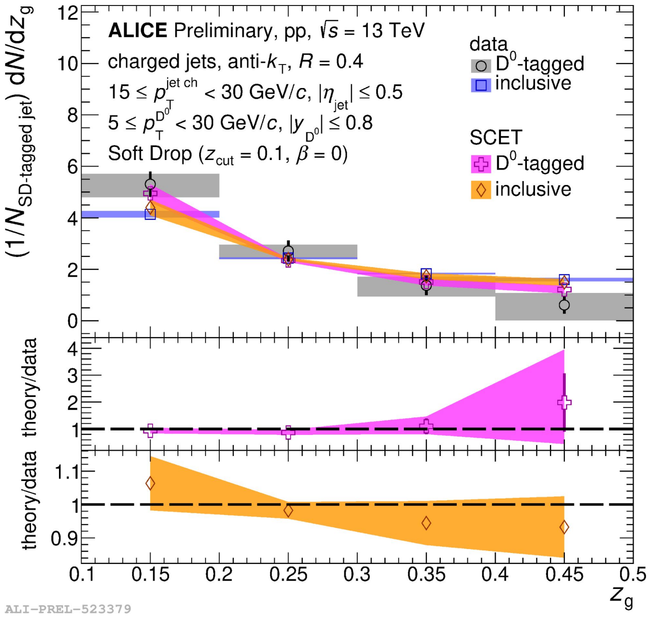
PYTHIA steeper than the measurement for inclusive jets



Groomed-jet substructure: z_g

Agreement within uncertainties with Soft-collinear effective theory (SCET)

Same trend as MC models.



H. T. Li and I. Vitev. *Phys. Lett. B* **793** (2019) 259–264
H. T. Li, Z. L. Liu, and I. Vitev. *Phys. Lett. B* **827** (2022) 137007