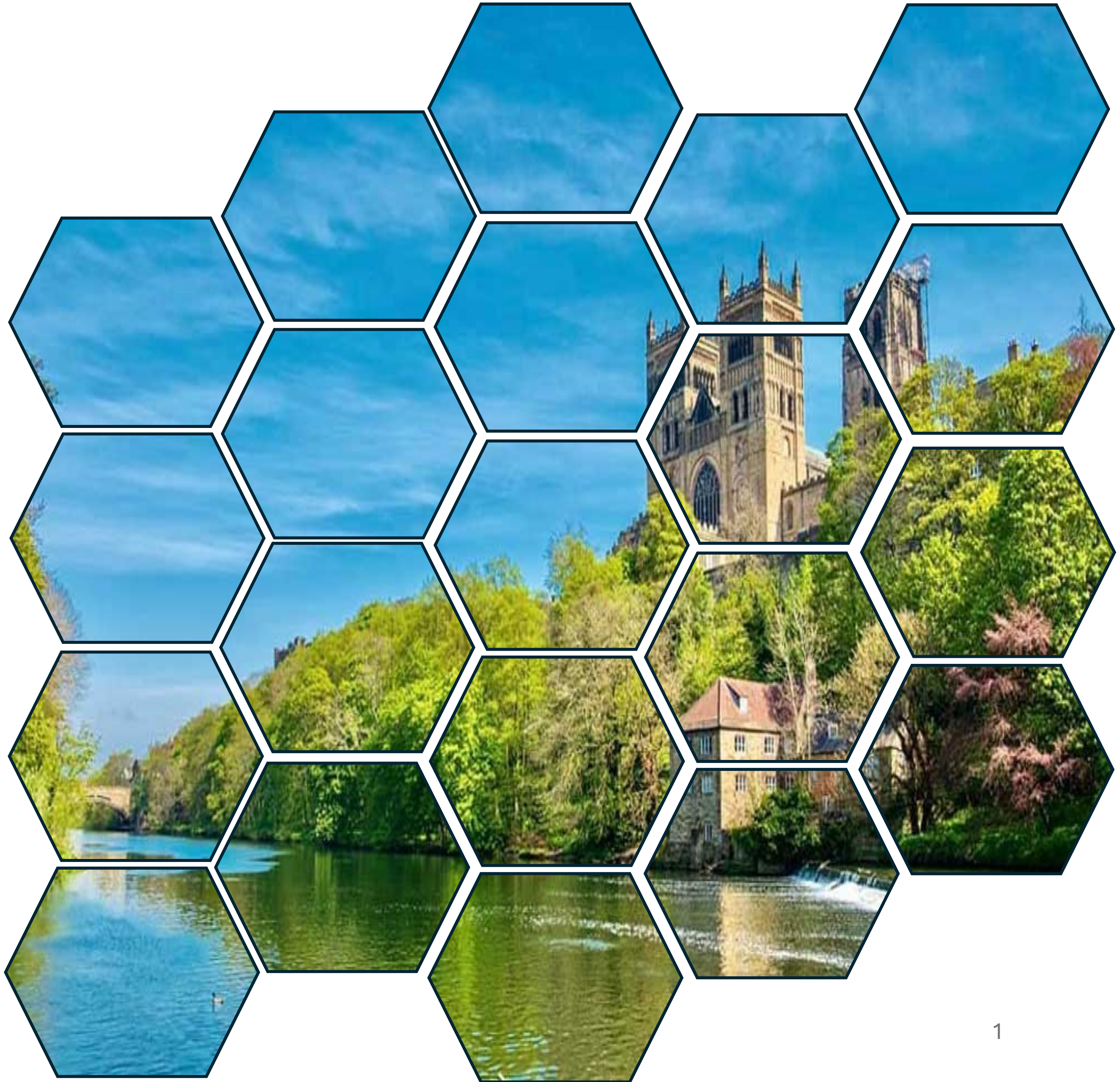
Heavy-flavour jets with ALICE

Nima Zardoshti

Flavoured jets at the LHC
Durham
11/06/2024

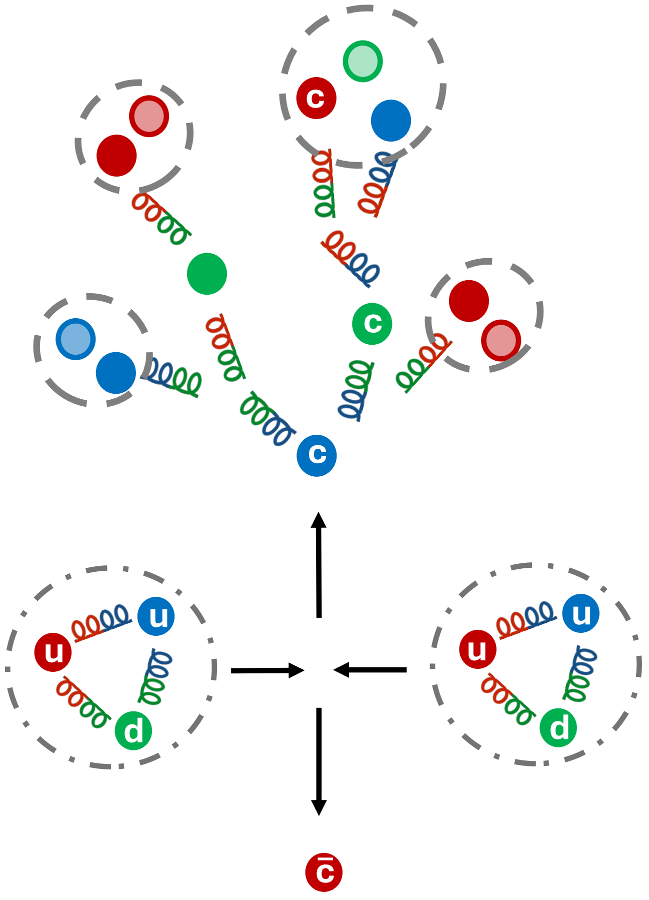


Heavy-flavour jets at low p_T

$m_Q >> \Lambda_{QCD}$ allows for a perturbative description of heavy-flavour production even for p_T -> 0 GeV/c

Reduced phase-space for non-perturbative effects compared to inclusive jets

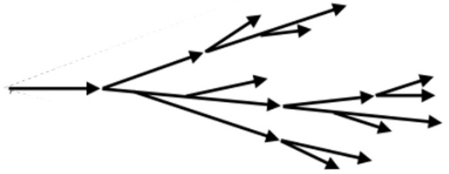
Significant mass effects dictate the shower evolution



Flavour dependence of QCD showers

Gluon-initiated shower

Broader shower profile
Higher number of emissions

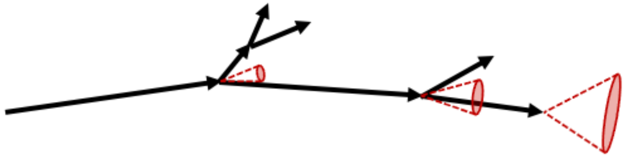


Quark-initiated shower

Narrower shower profile
Fewer emissions in the shower

Heavy-quark-initiated shower

Suppression of small angle emissions
Harder fragmentation



Casimir Colour factors

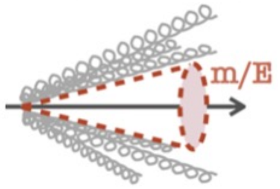
Different emission properties due to the different amount of colour charge carried by quarks and gluons

$$\frac{C_{\mathrm{A}}}{C_{\mathrm{F}}} = \frac{9}{4}$$

The dead-cone effect

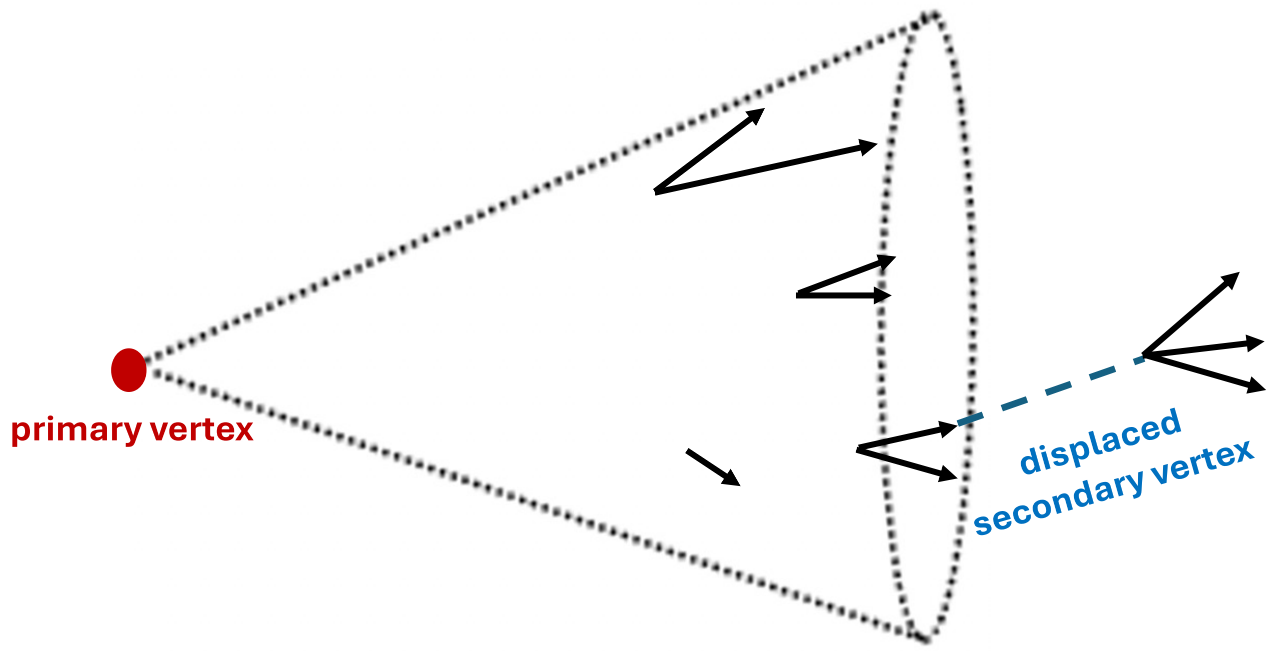
A suppression of emissions in a cone of size m/E around the direction of the emitter

Sizeable effect for low energy heavy quarks



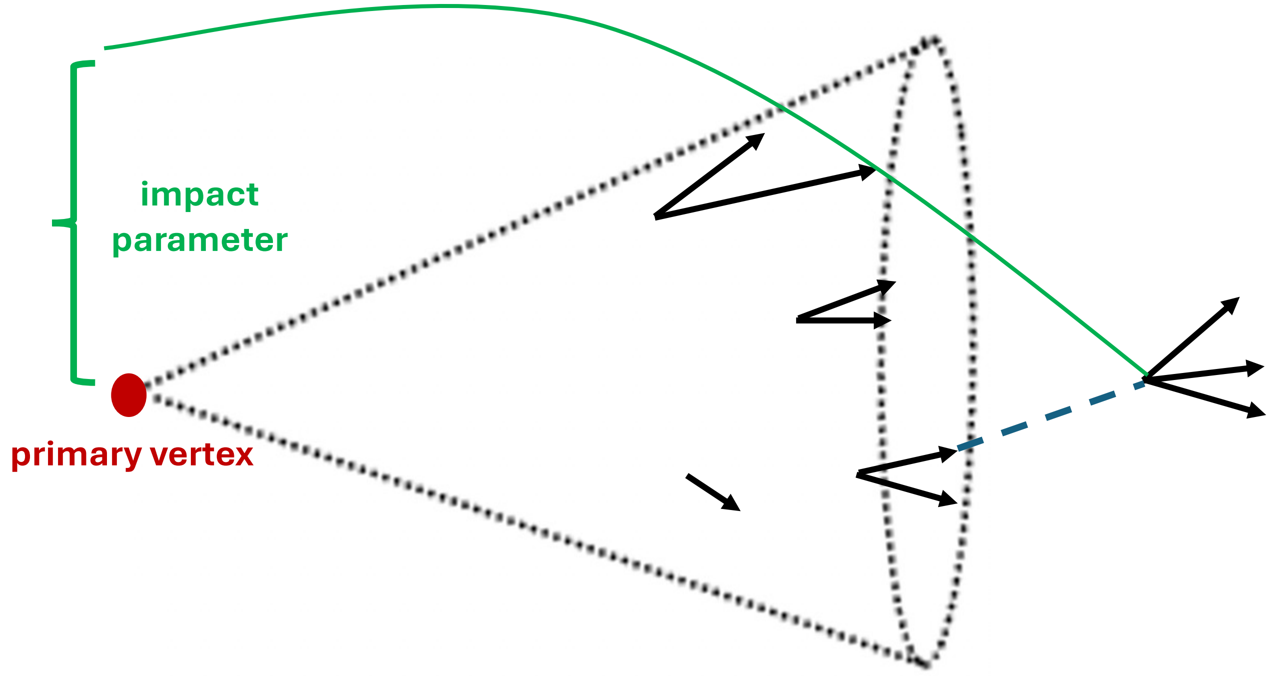
Y. L. Dokshitzer, J. Phys. G17 (1991) 1602

Tagging heavy-flavour jets with high efficiency



Take advantage of the long lifetime of heavy hadrons

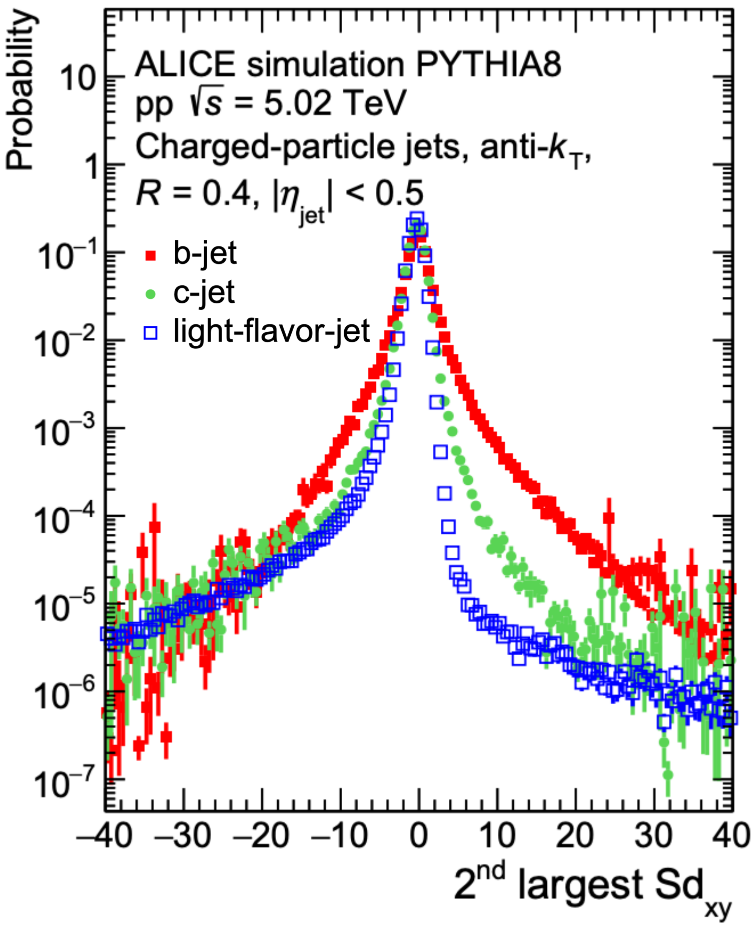
Tagging heavy-flavour jets with high efficiency



Take advantage of the long lifetime of heavy hadrons

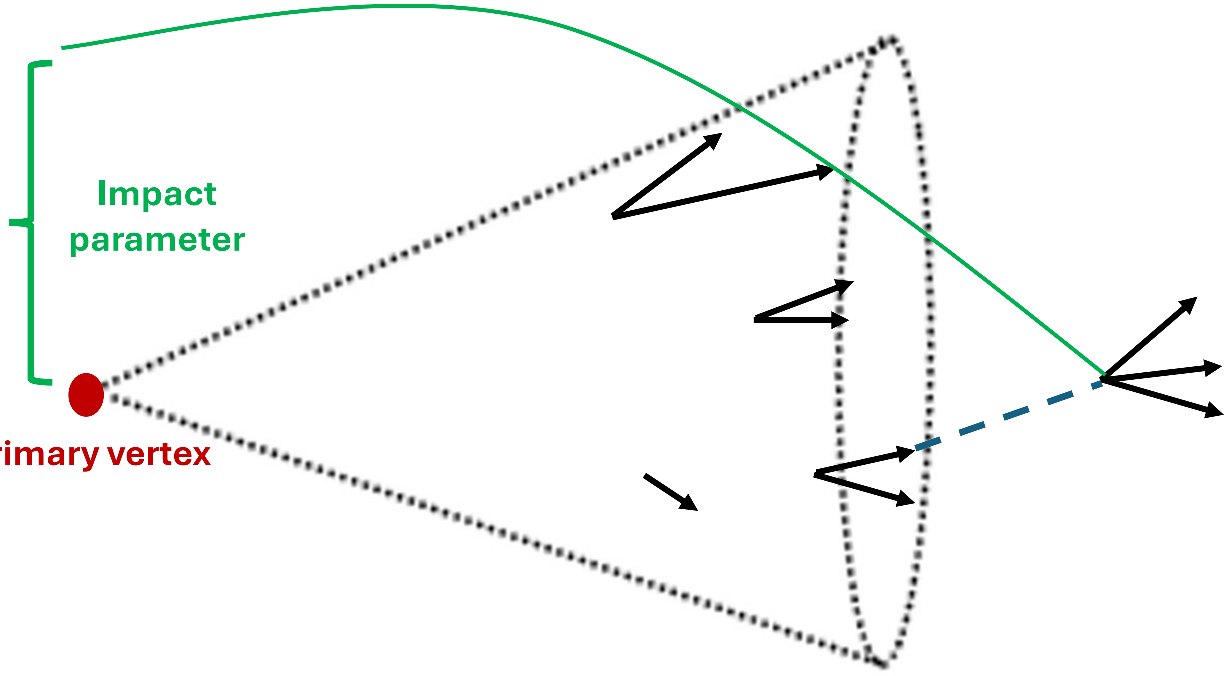
Discriminate based on impact parameter of jet constituents

JHEP 05(2024)041



$$\frac{\text{impact parameter}}{\text{impact parameter resolution}}$$

Tagging heavy-flavour jets with high efficiency



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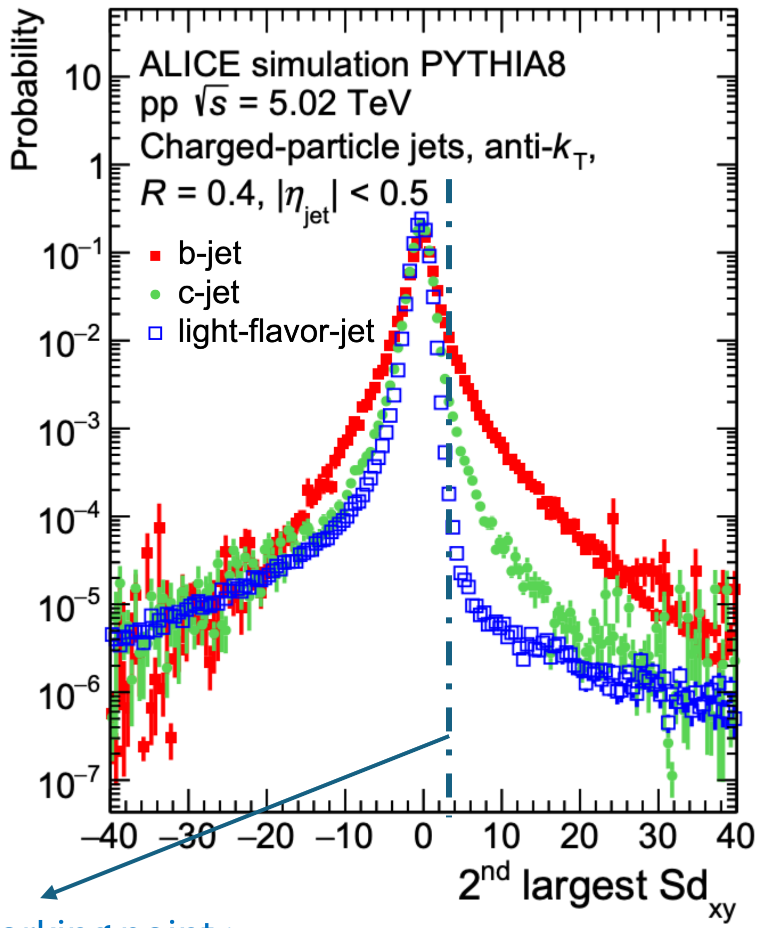
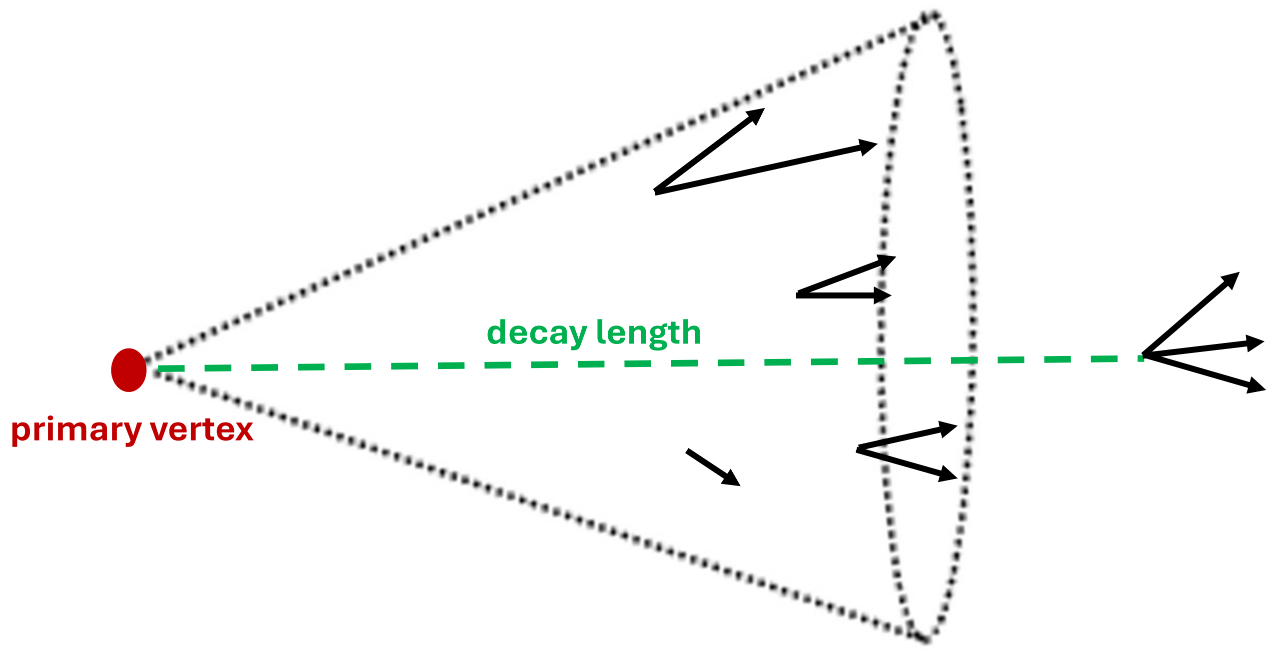


tagger working point :
55% b-jet efficiency
42% b-jet purity

$$\frac{\text{impact parameter}}{\text{impact parameter resolution}}$$

Tagging heavy-flavour jets with high efficiency

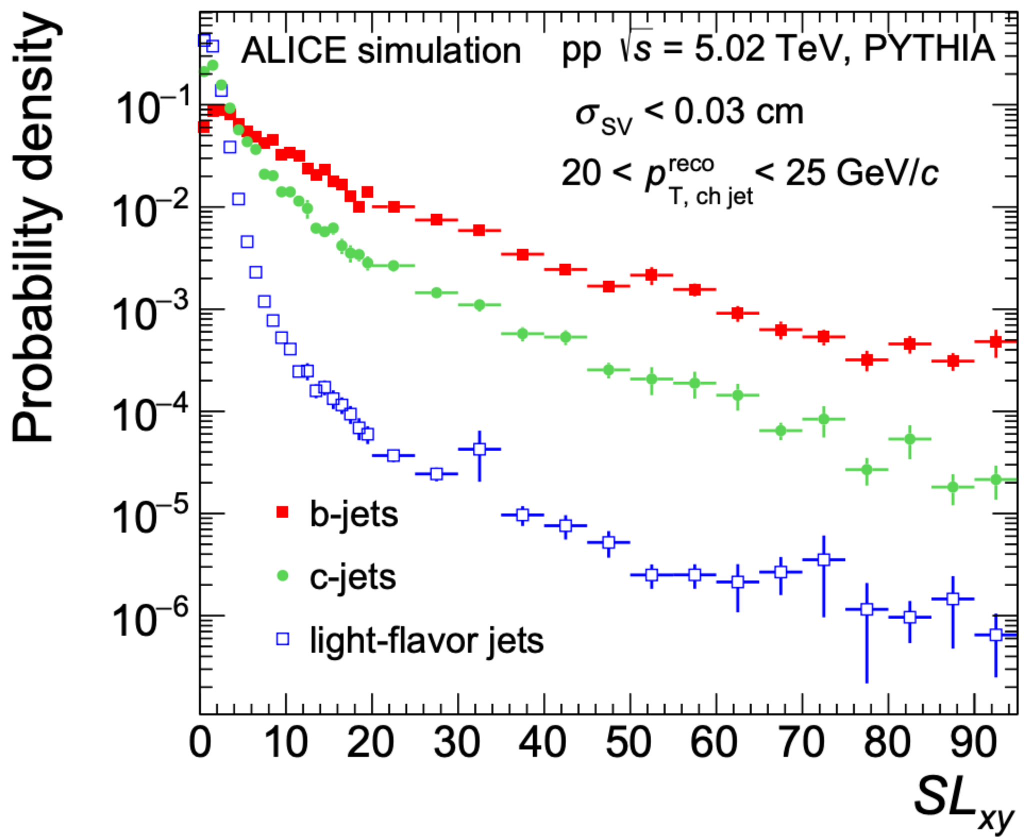


Take advantage of the long lifetime of heavy hadrons

Discriminate based on impact parameter of jet constituents

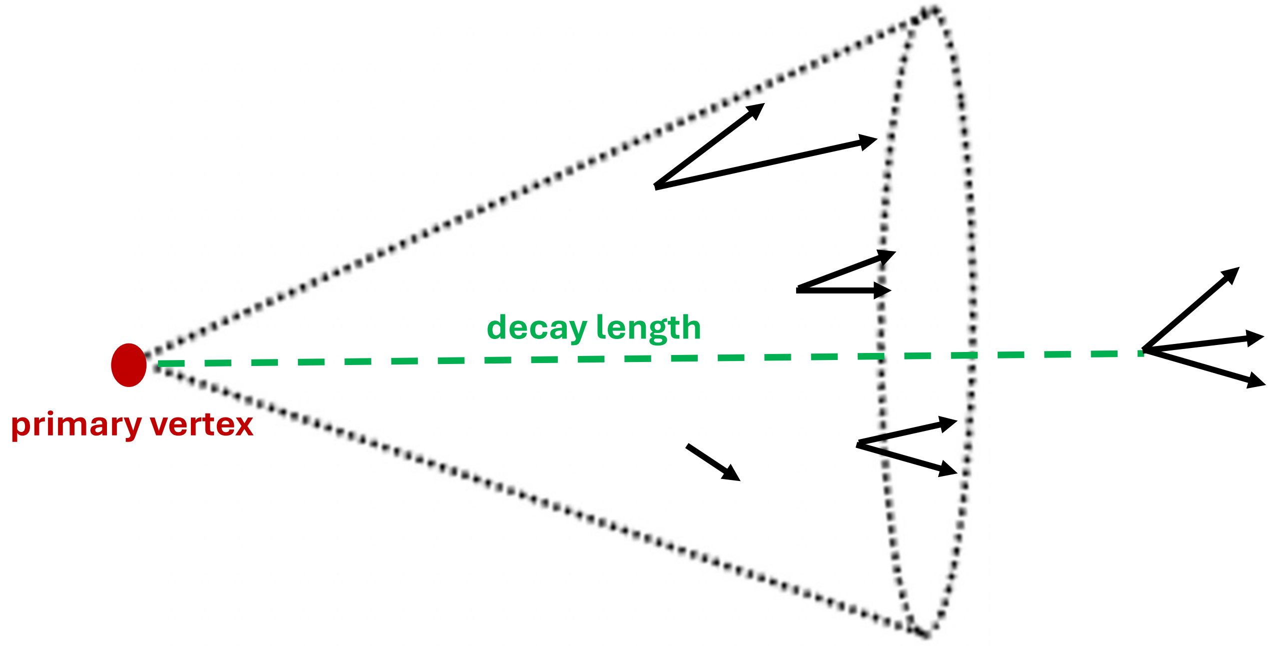
Discriminate based on displacement of reconstructed secondary vertex

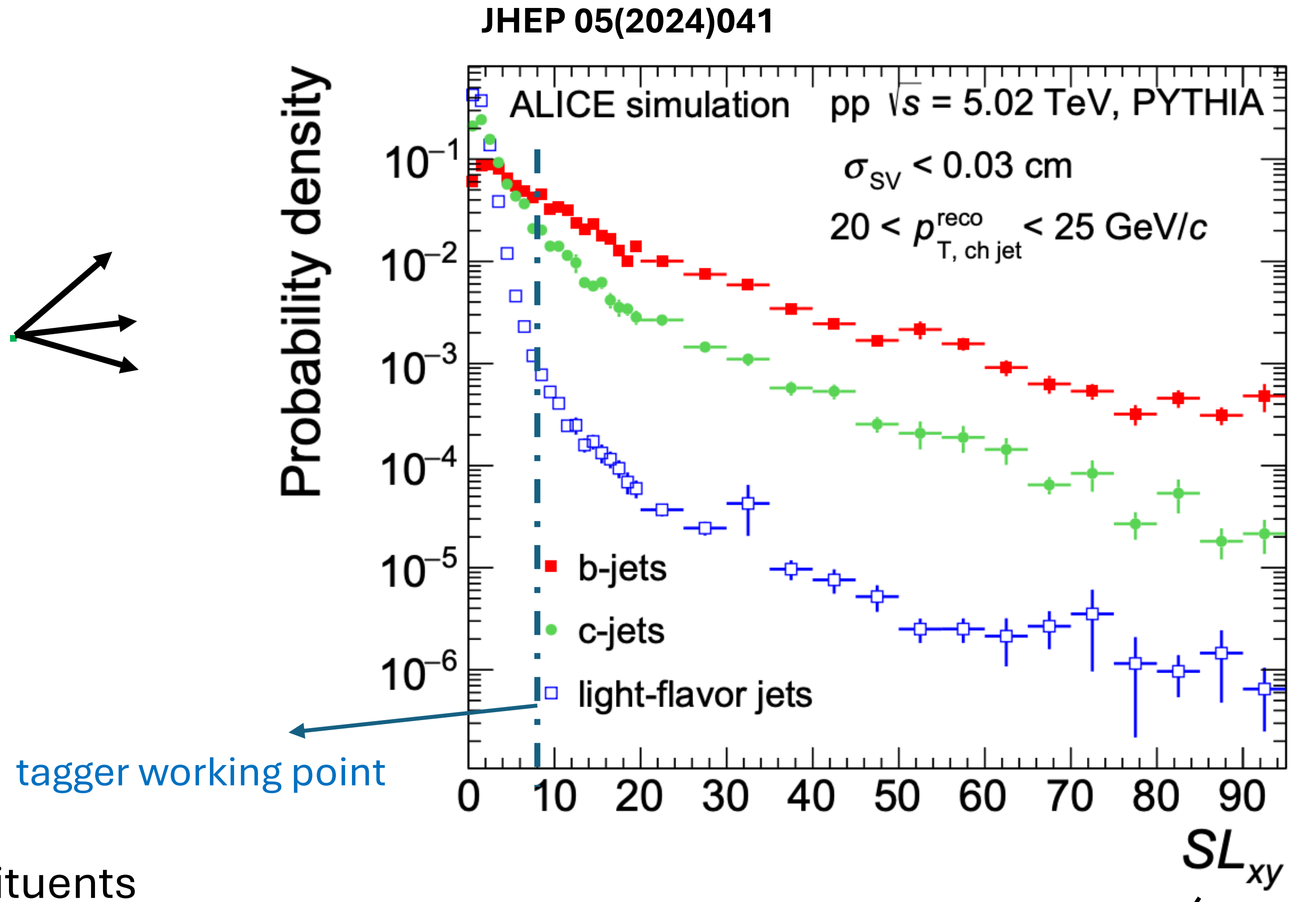
JHEP 05(2024)041



$$SL_{xy} = \frac{\text{decay length}}{\text{Decay length resolution}}$$

Tagging heavy-flavour jets with high efficiency





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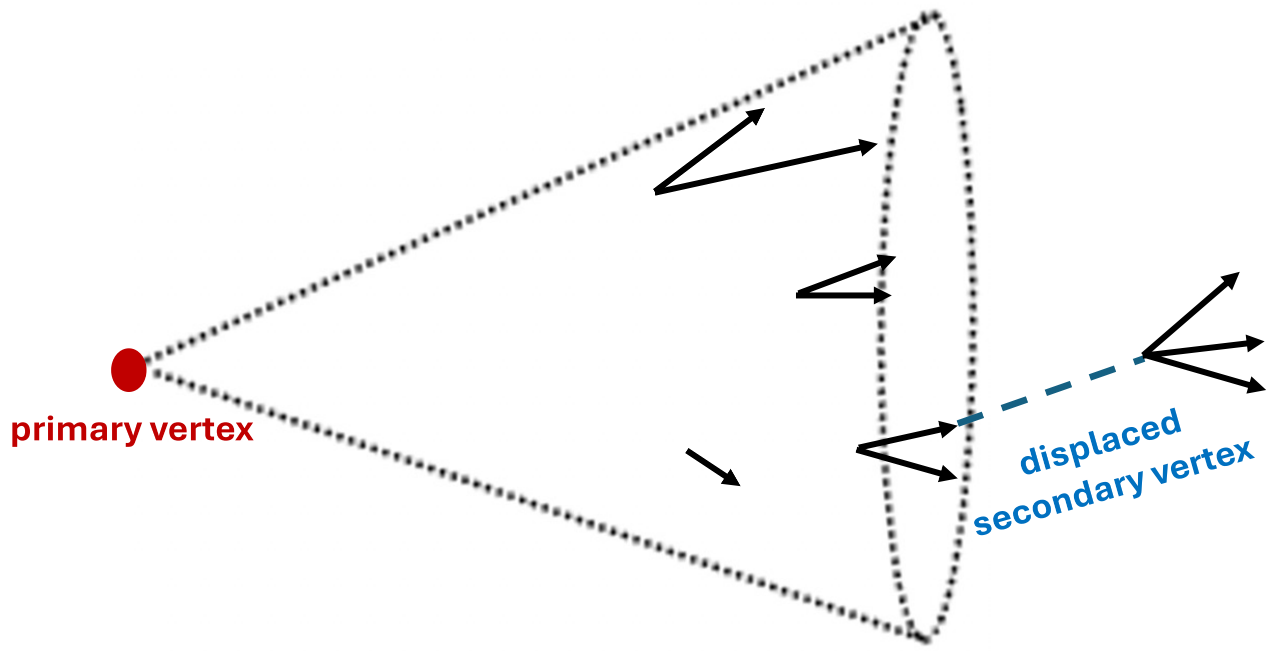
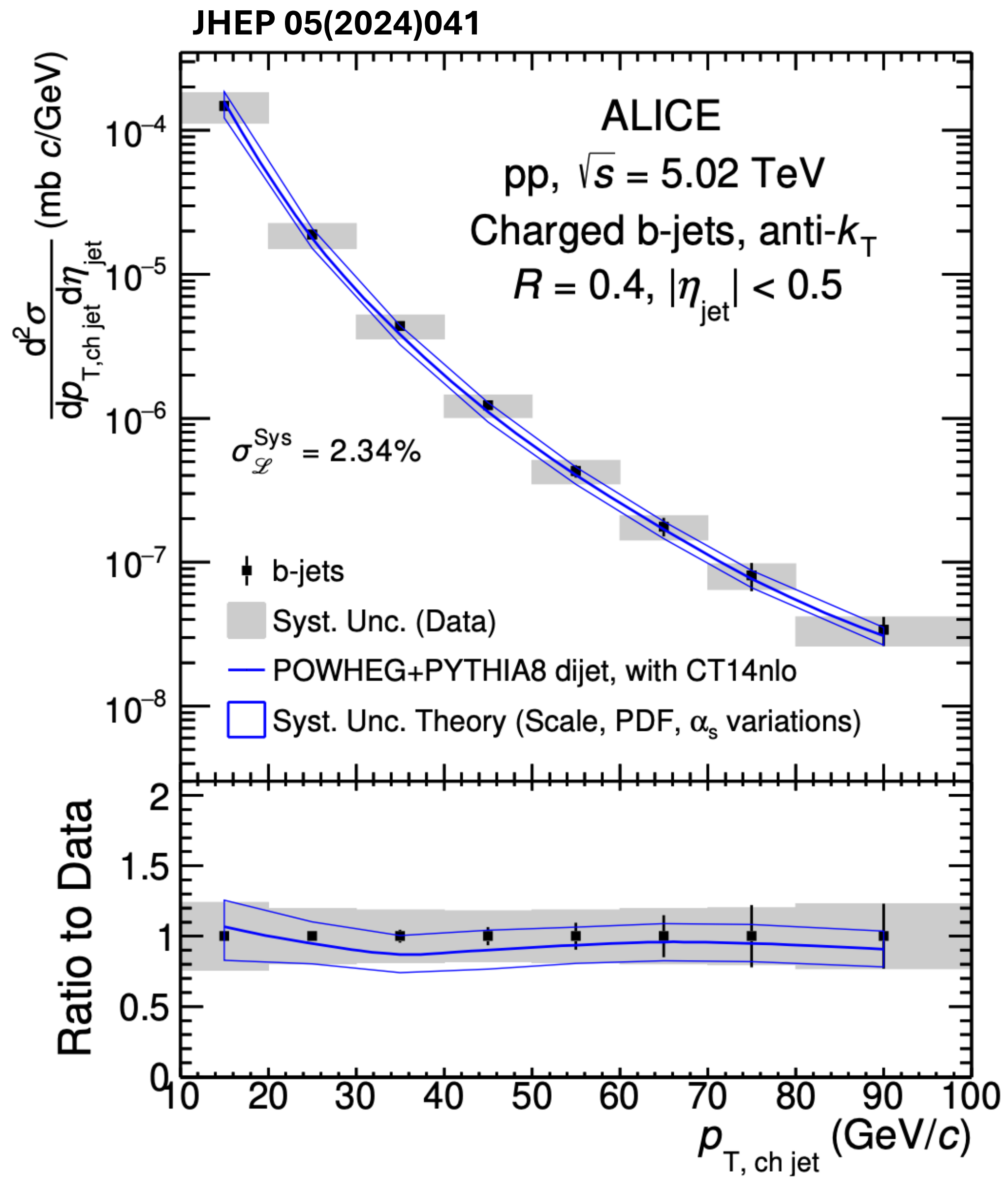




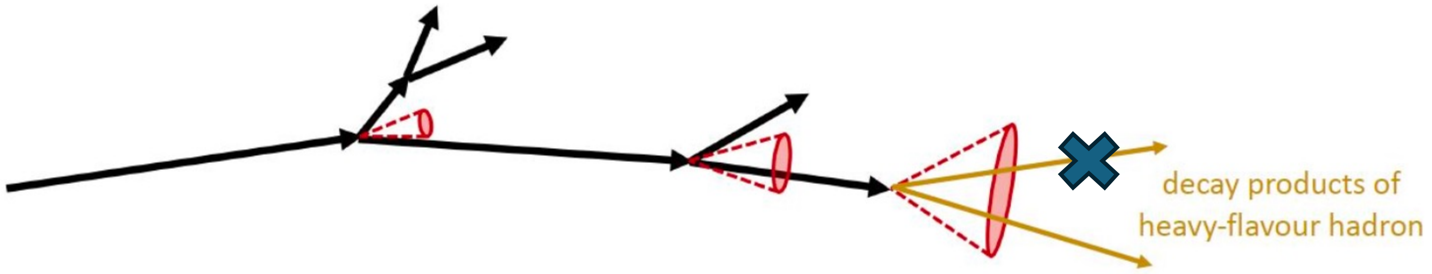
Can measure global jet properties such as the cross section

Pushing down measurements to low p_T

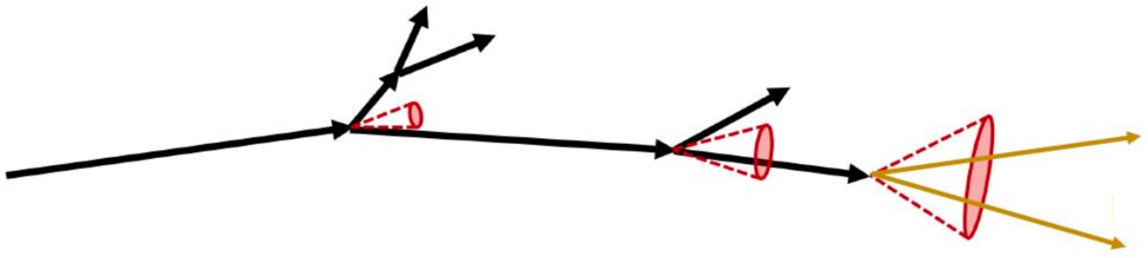
Good agreement of MC with data -> non-perturbative effects less important than in inclusive jets

Limitations of displaced jet tagging

These tagging methods have severe limitations for characterising jet substructure



Significant part of the jet p_T might be missed



Decay products smear the jet substructure

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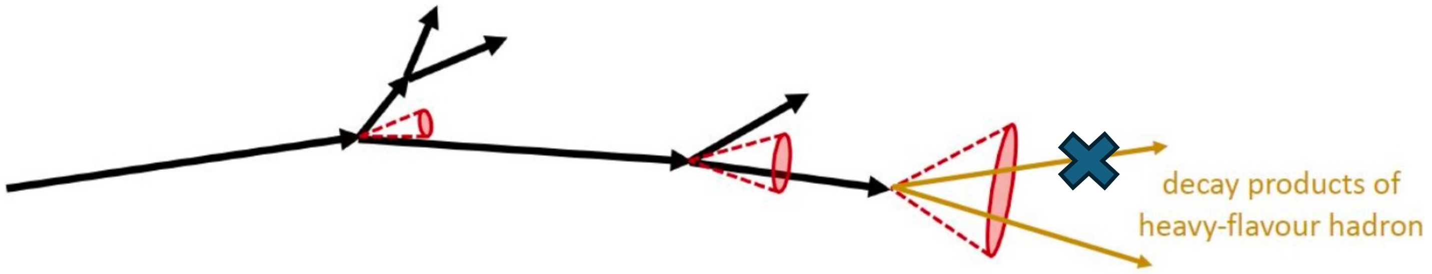
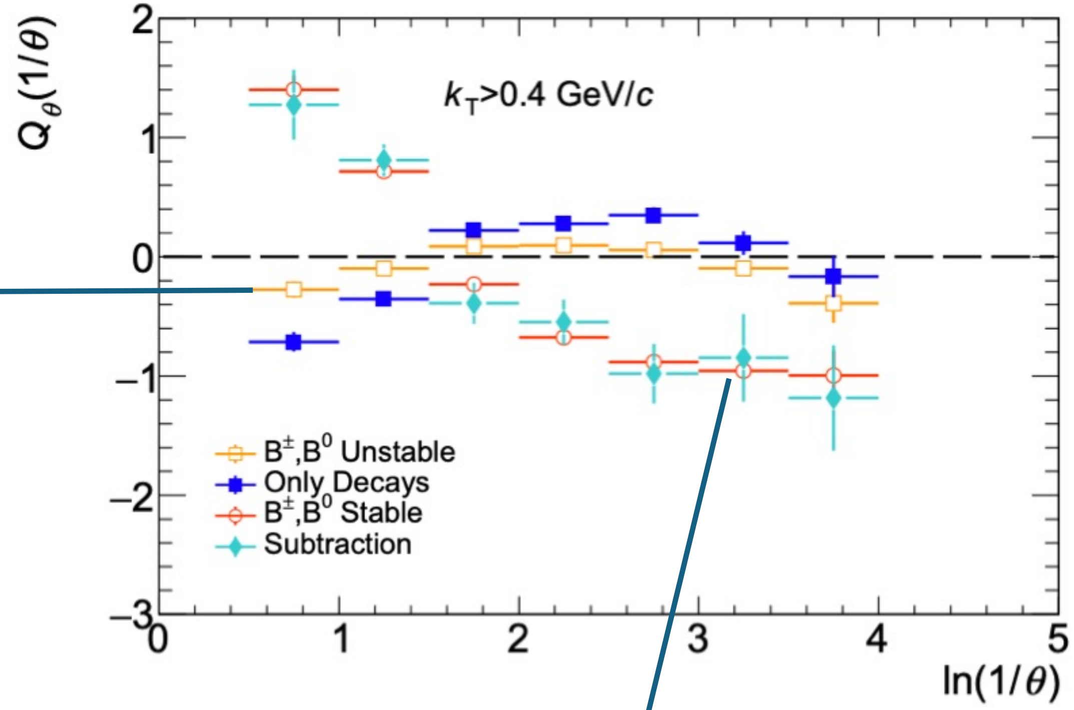


Significant part of the jet p_T might be missed

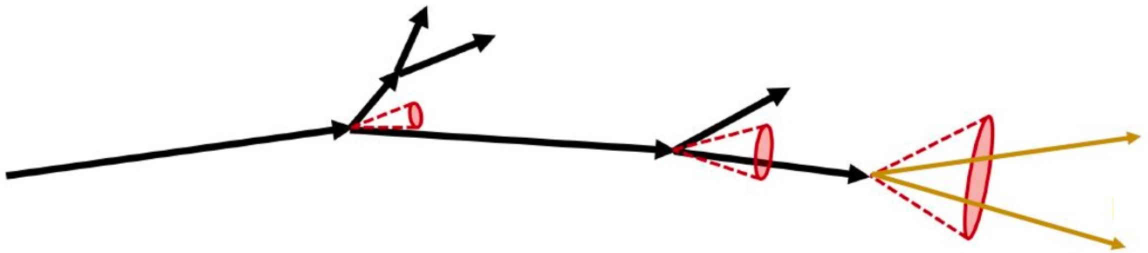
Significant differences in reconstructed jet substructure

angular distribution of splittings inside b-jets



decay products present

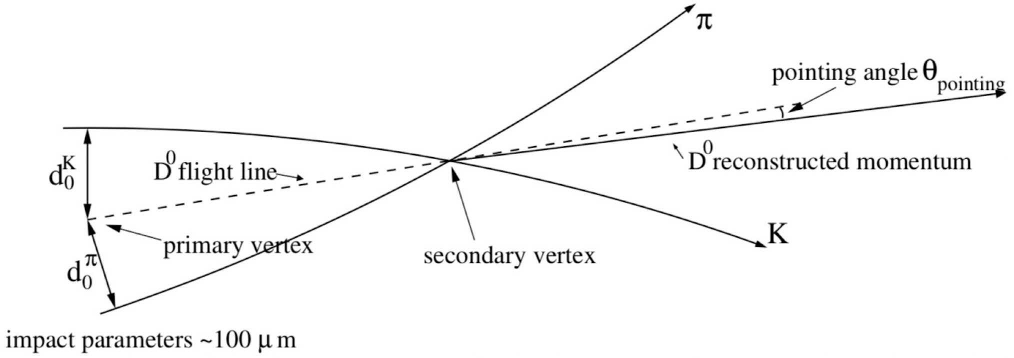
decay products not present



Decay products smear the jet substructure

Tagging via fully-reconstructed heavy-flavour hadrons

The solution for substructure is to fully reconstruct the heavy-flavour hadron



$$D^0 \to K^- \pi^+ (3.95\%) \qquad 2 < p_T^{D^0} < 36 \text{ GeV}/c$$

$$\Lambda_c^+ \to pK_s^0 \to p\pi^+\pi^- (1.10\%) \qquad 3 < p_T^{\Lambda_c^+} < 15 \text{ GeV}/c$$

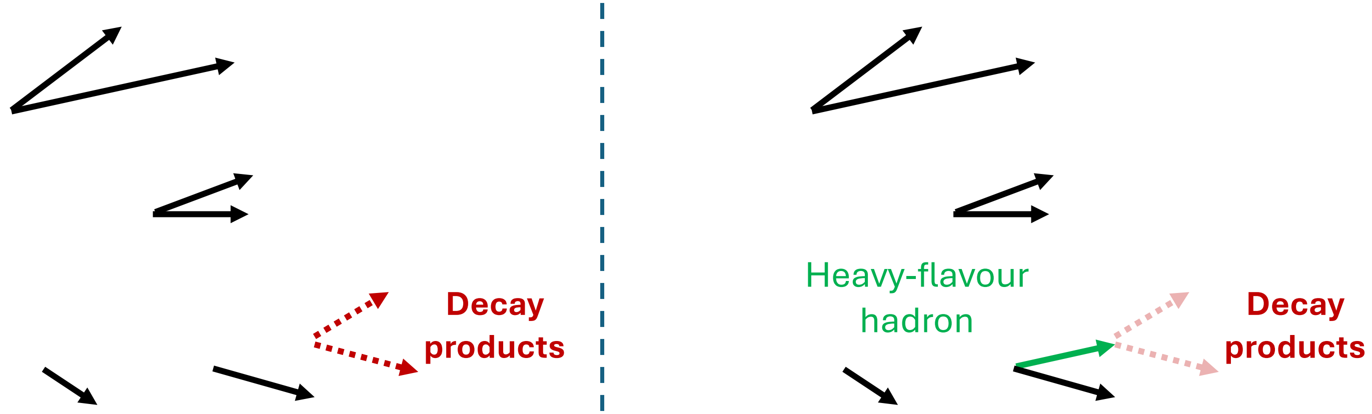
$$\text{anti-}k_T \; R = 0.4 \; p_T^{jet} > 5 \text{ GeV}/c$$

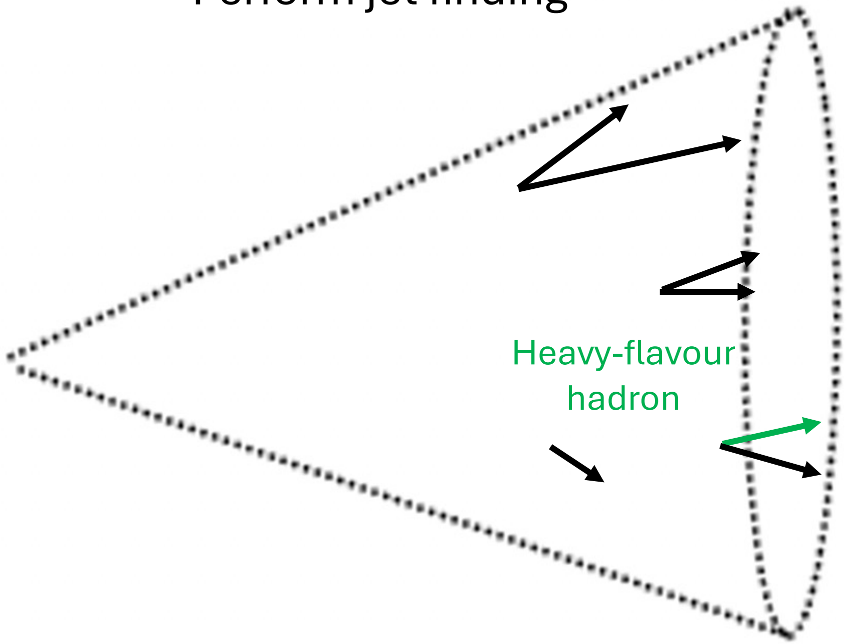
Identify decay products

Reconstruct the heavy hadron

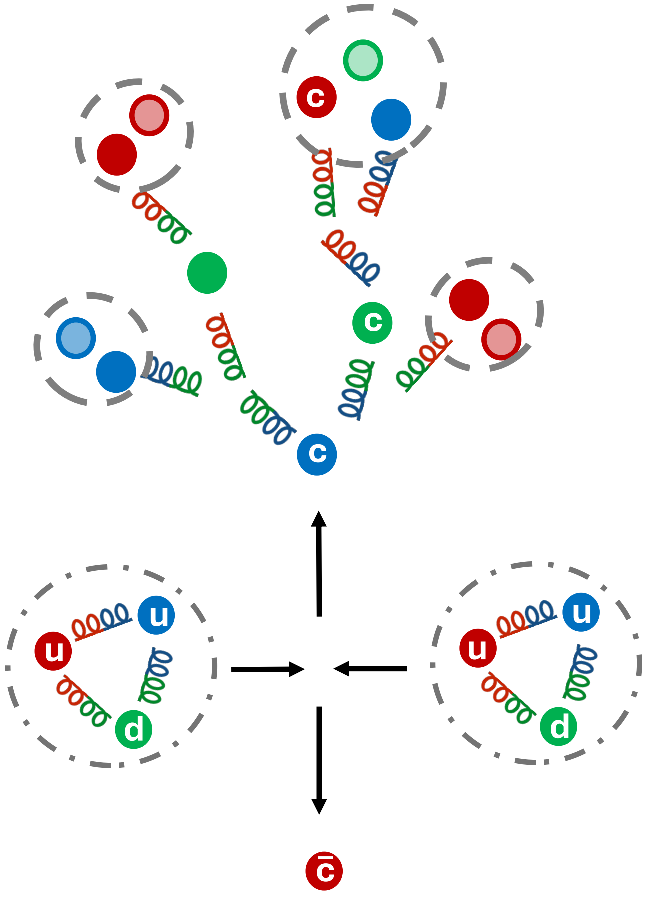
Hadronic state best connected to the shower

Perform jet finding





Probing the universality of charm fragmentation

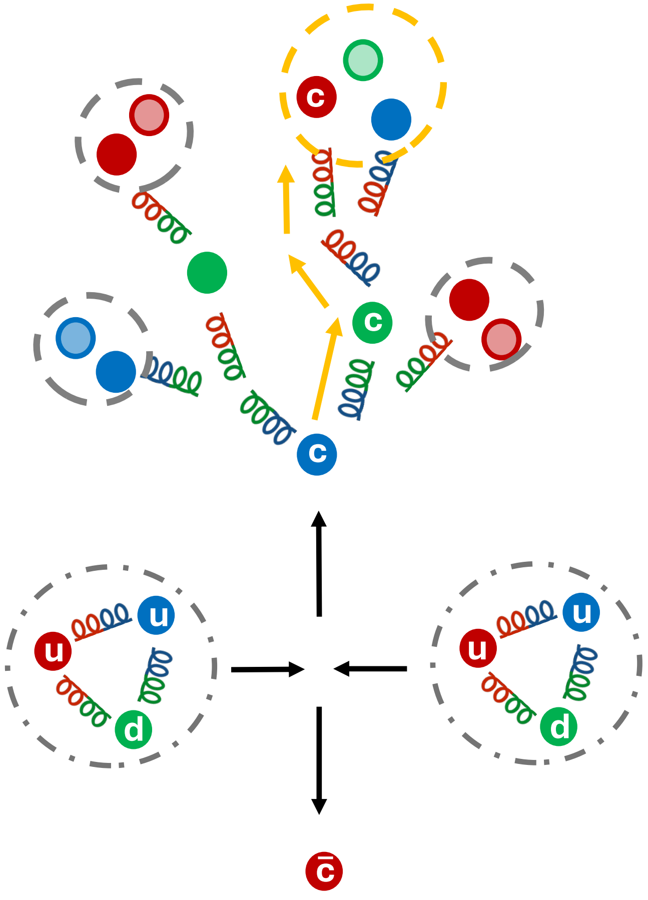


Probing the universality of charm fragmentation

Is hadronisation universal across collision systems?

Does the surrounding colour impact fragmentation?

$m_Q >> \Lambda_{QCD}$ suppressed hadronisation production ⟶ can connect hadron to parton



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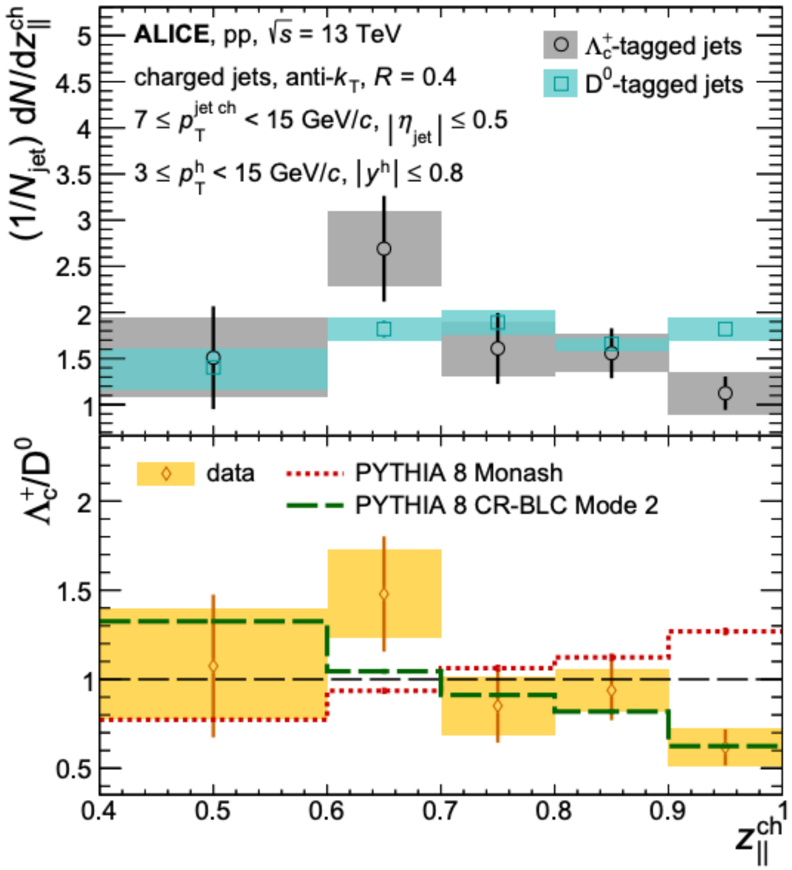


Fraction of longitudinal jet momentum

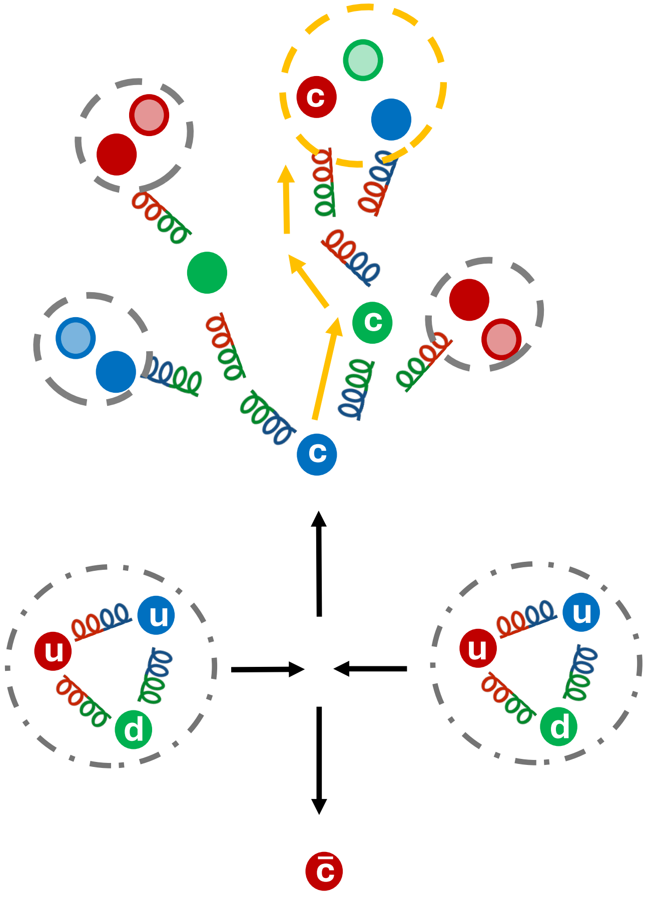
Phys. Rev. D 109 (2024) 072005

Compare fragmentation measurements of baryons and mesons

Softer fragmentation for baryons

Model tuned on e^+e^-

Additional hadronisation mechanisms sensitive to surrounding colour density



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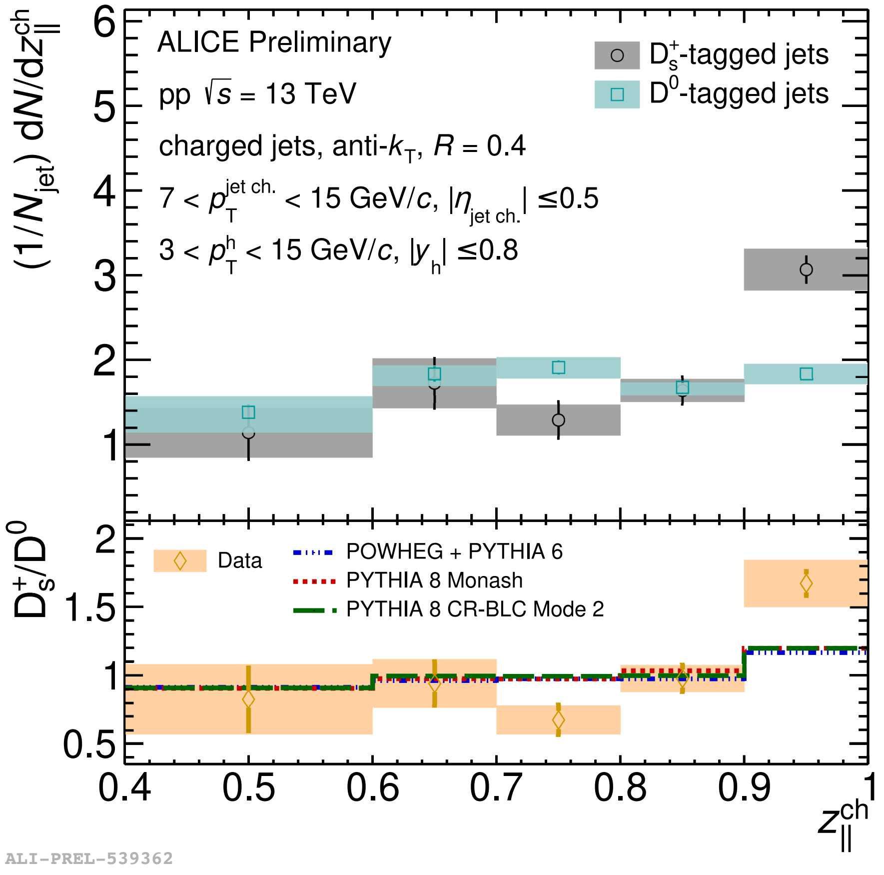
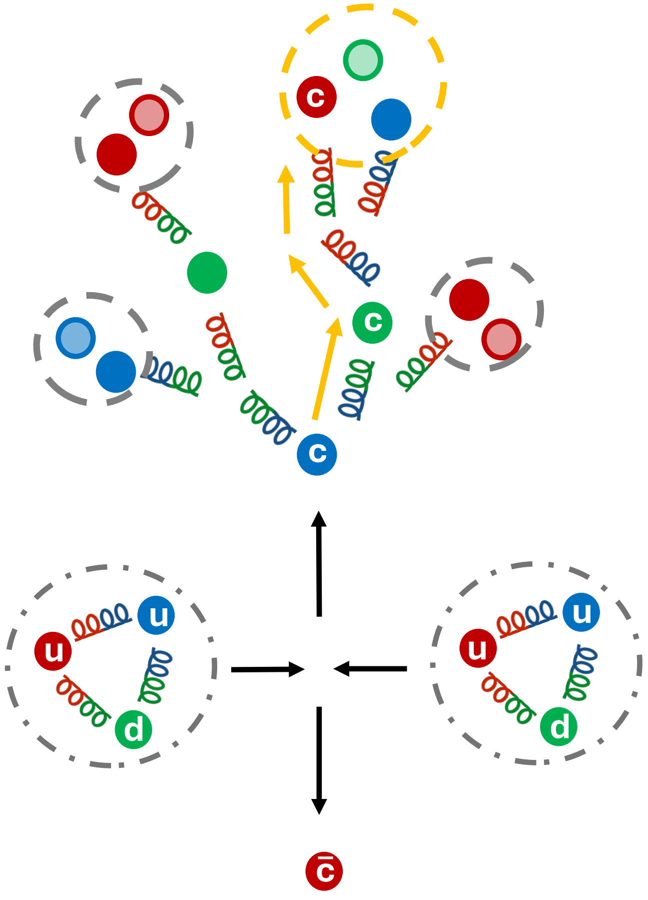
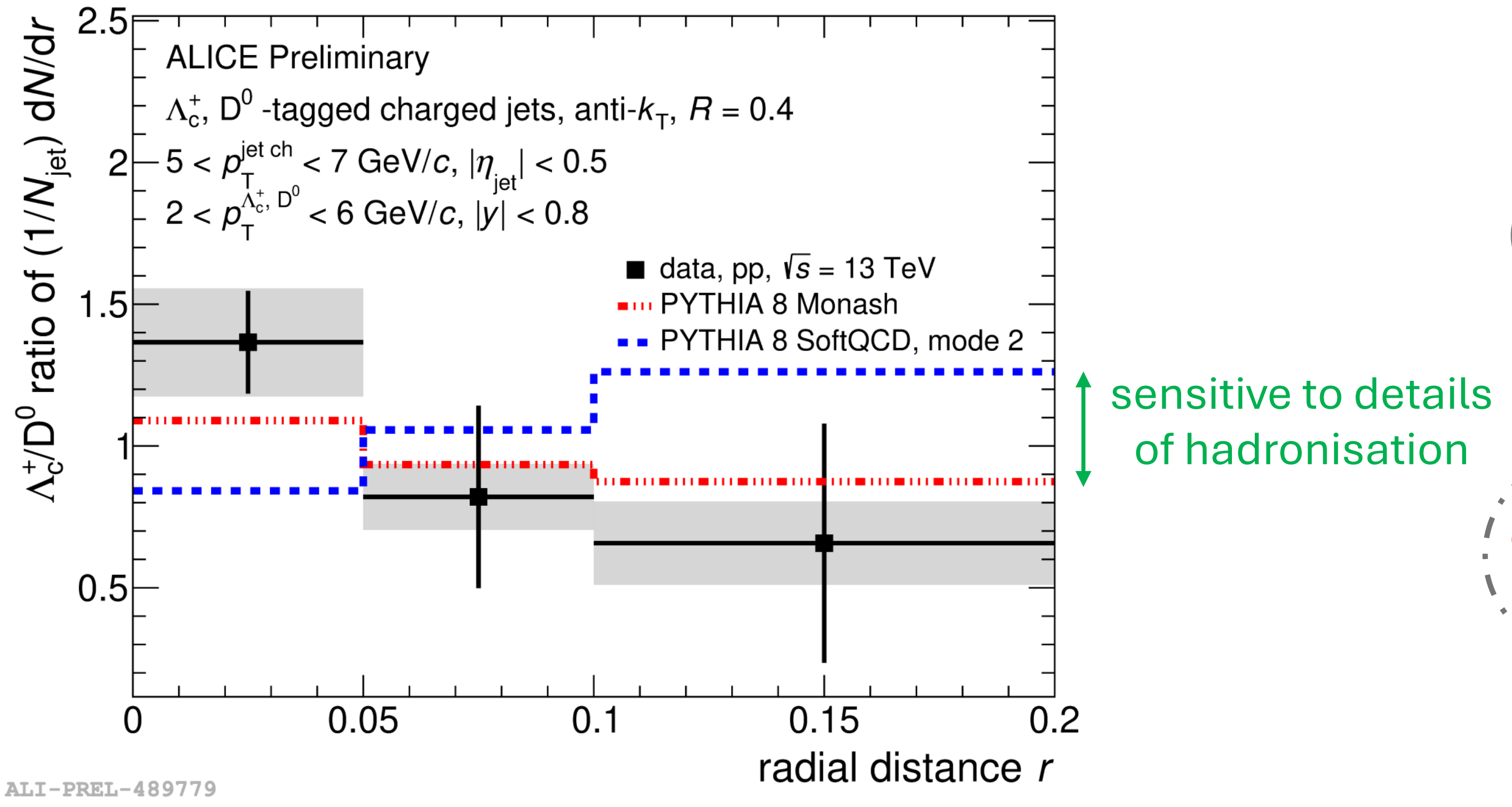


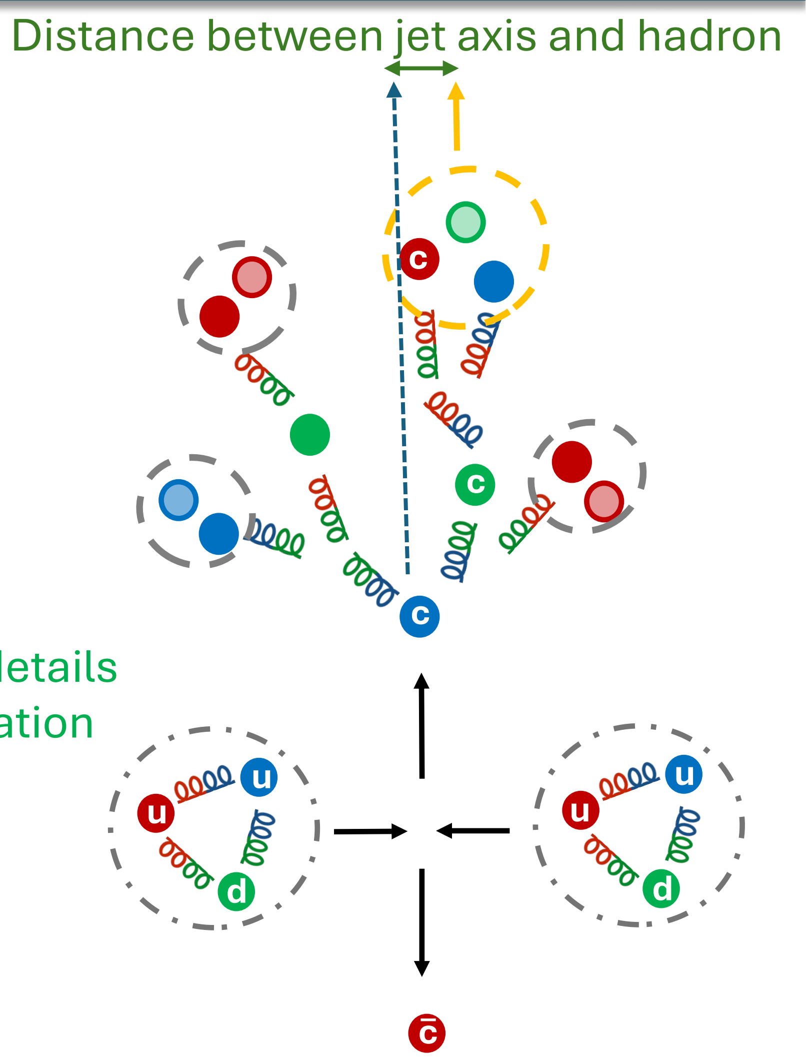
Compare fragmentation measurements of strange and non-strange charm mesons

Data shows hints of deviating from expectations



Distance between hadron and jet axis can give a handle on hadronisation properties





More precise measurements underway in Run 3

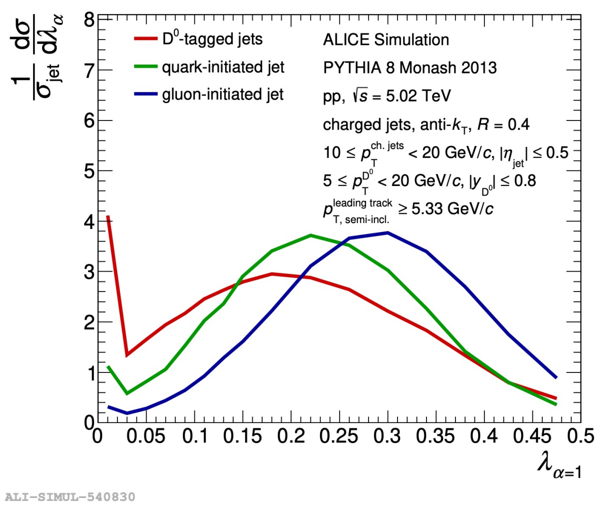
Unravelling the flavour-dependent properties of the shower

Angularities probe the momentum and spatial profile of the final state constituents $\lambda_{\alpha}^{\kappa} = \Sigma(\frac{p_{\mathrm{T,i}}}{p_{\mathrm{T,jet}}})^{\kappa}(\frac{\Delta R_{\mathrm{i,jet}}}{R})^{\alpha}$

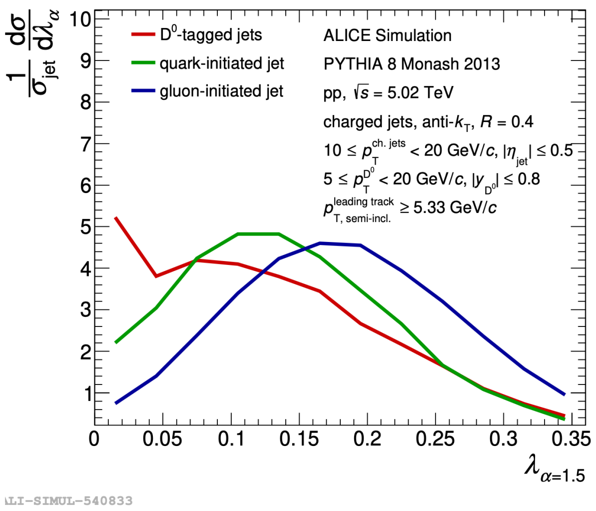
The free parameters can be tuned to increase or decrease the impact of different flavour effects

red – green comparison : mass effects
green – blue comparison : Casimir effects

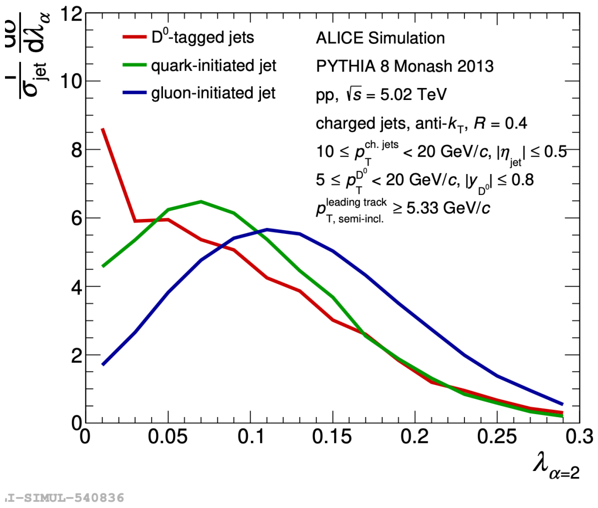
$\alpha = 1$



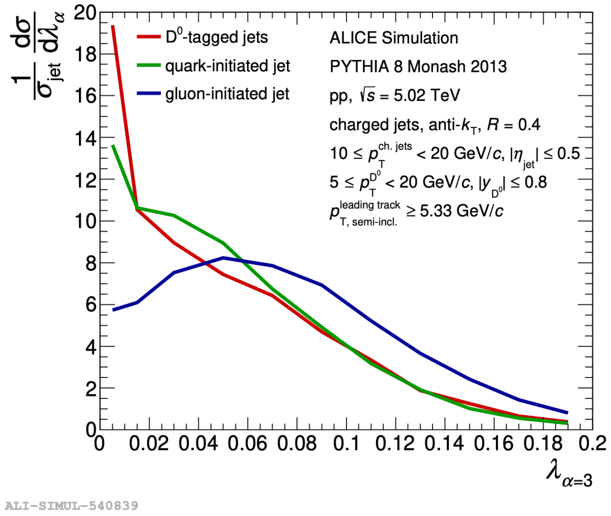
$\alpha = 1.5$



$\alpha = 2$



$\alpha = 3$



Sensitivity to mass effects | Sensitivity to Casimir effects

Increased importance of the core | Increased importance of large angle

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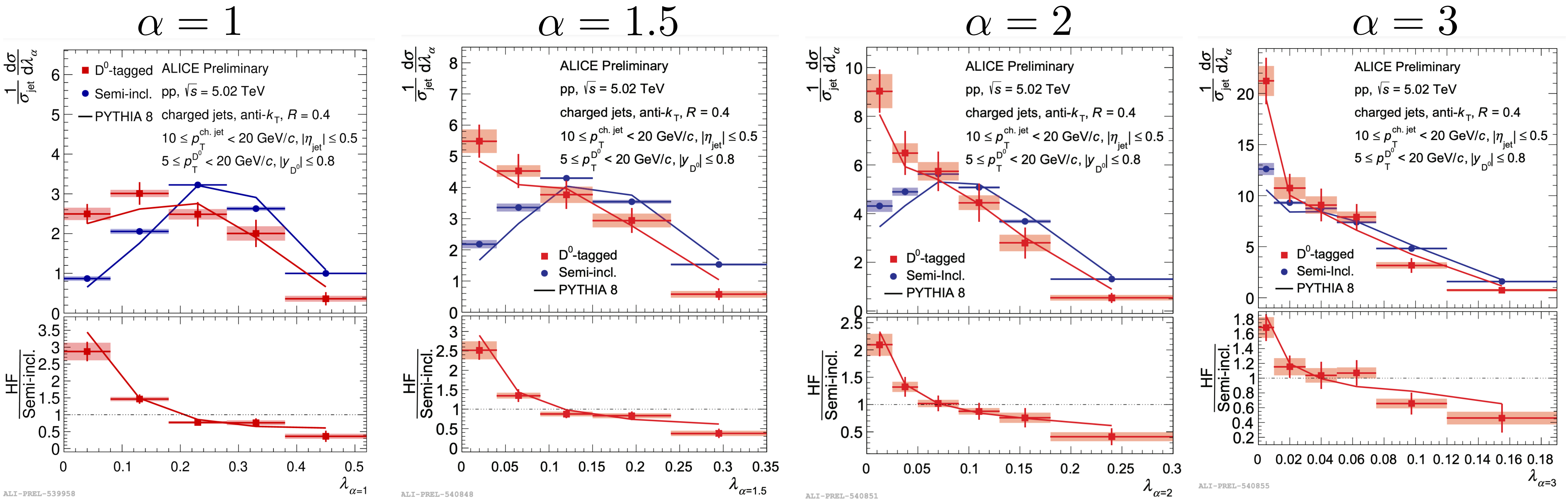


Sensitivity to mass effects

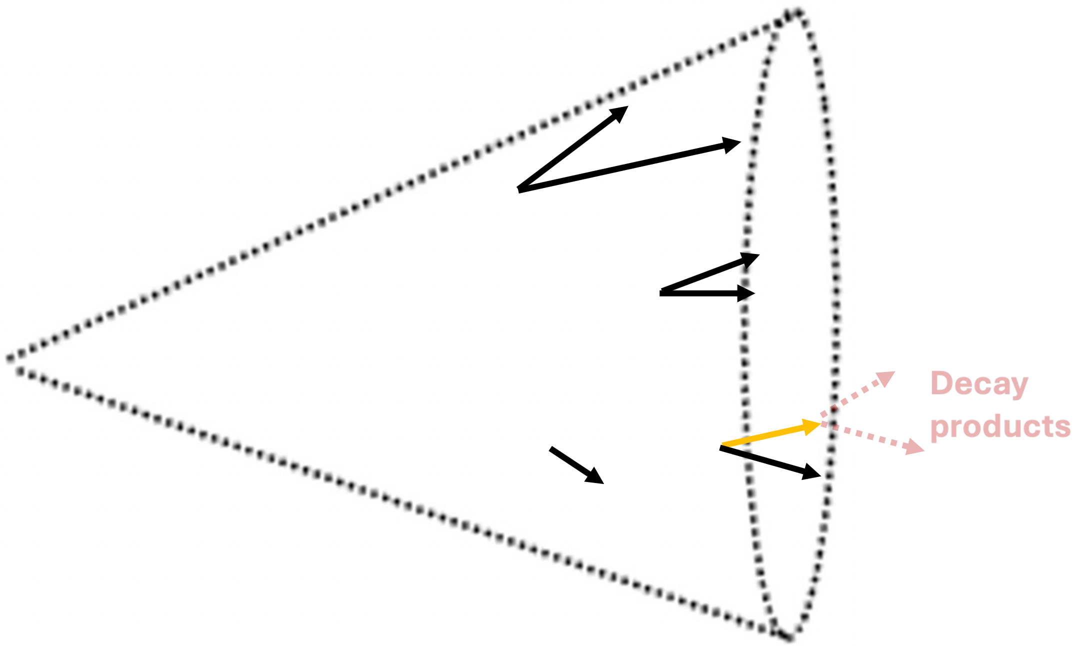
Mass effects dominant in this kinematic regime

Sensitivity to Casimir effects

Increased importance of the core

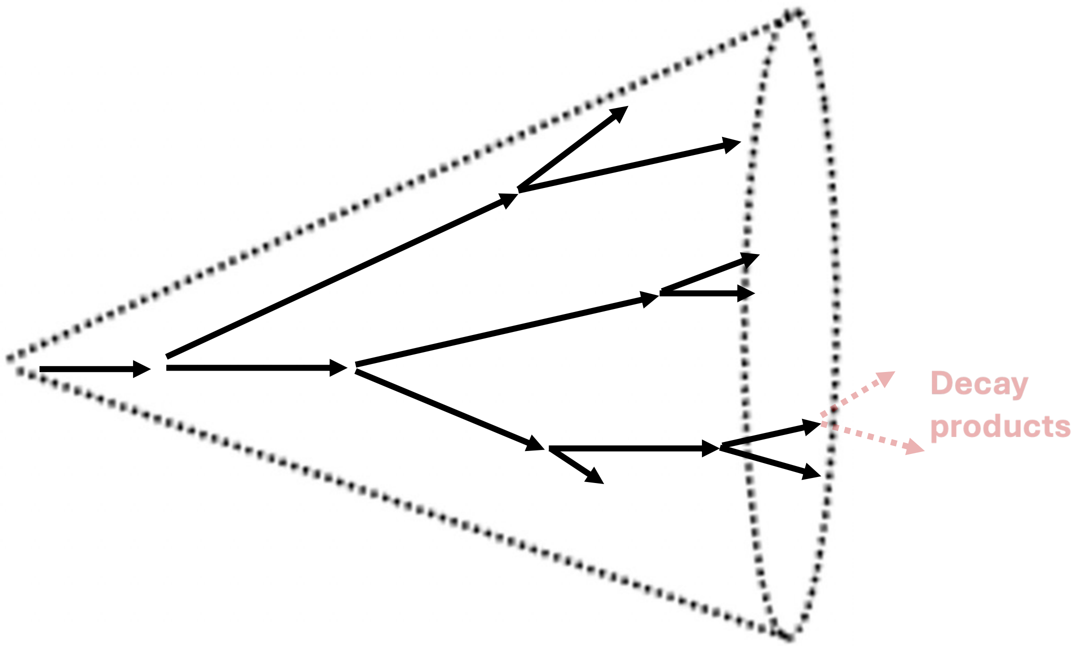
Increased importance of large angle

Phys. Rev. D 99, 074027 (2019)



Phys. Rev. D 99, 074027 (2019)

Recluster jet using C/A to reconstruct the shower



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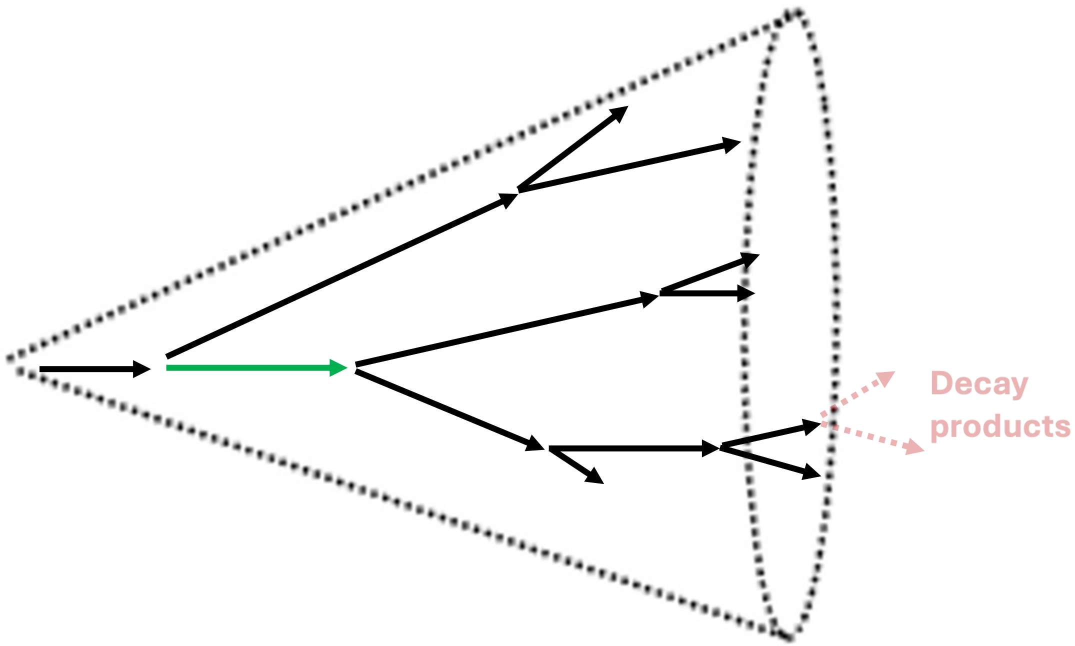
Recluster jet using C/A to reconstruct the shower

Heavy-flavour hadron maps directly to a heavy-quark in the shower

At each reclustering step the subjet containing the heavy-flavour hadron is the heavy quark in the shower



Reconstructing the evolution of a parton : heavy-flavour tracing

Phys. Rev. D 99, 074027 (2019)

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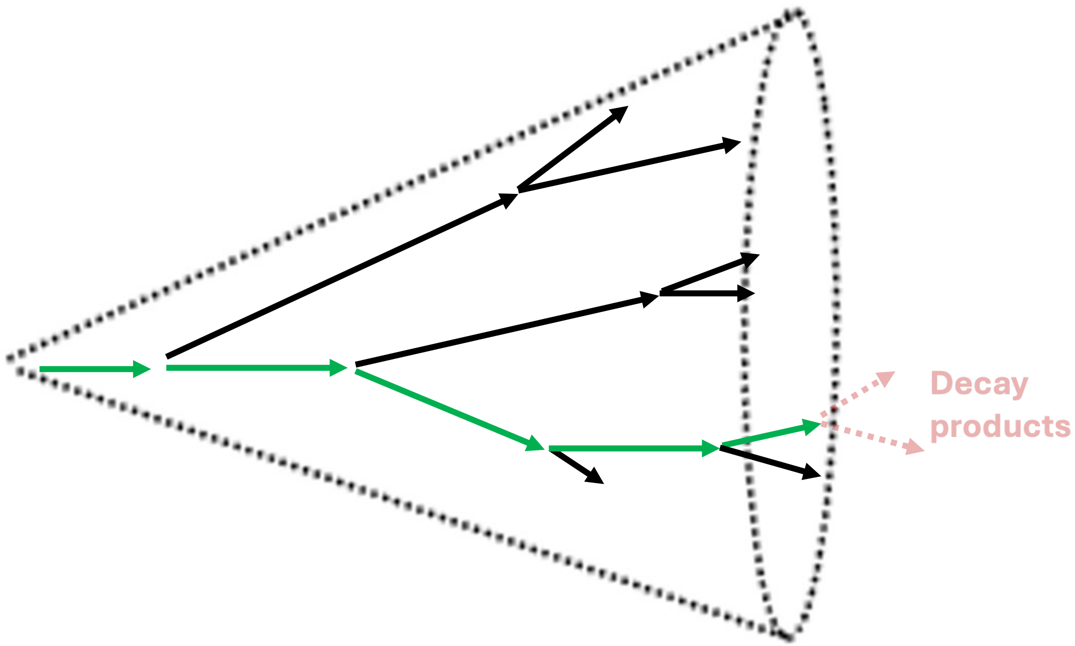

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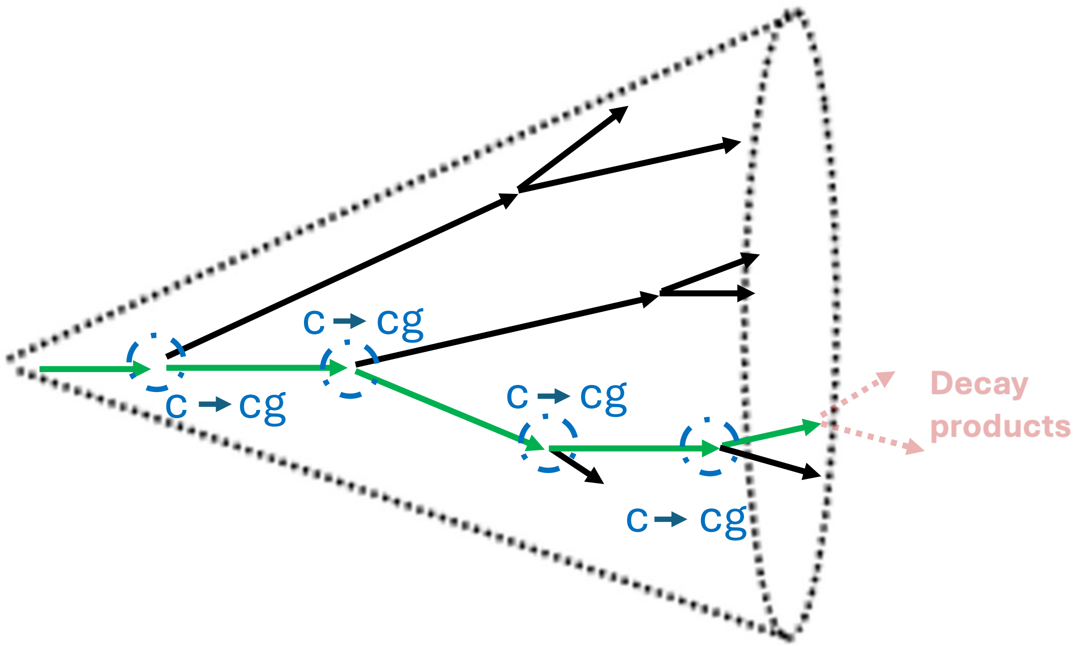

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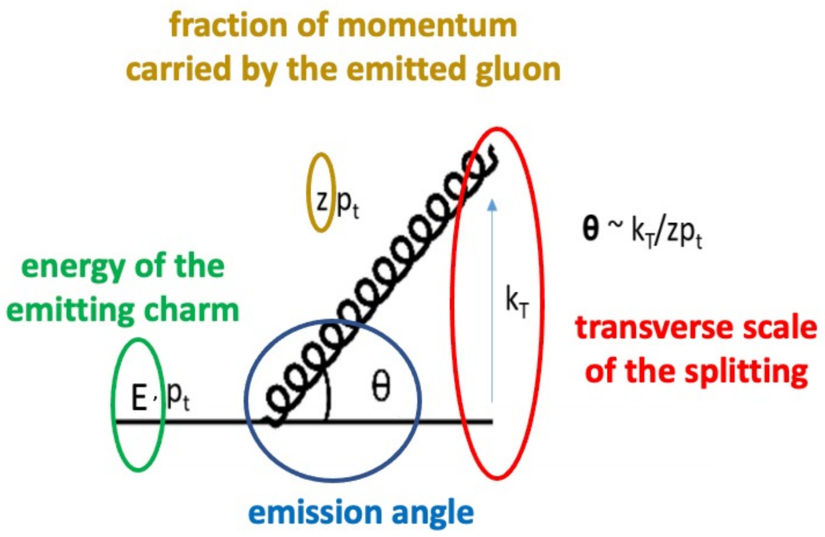
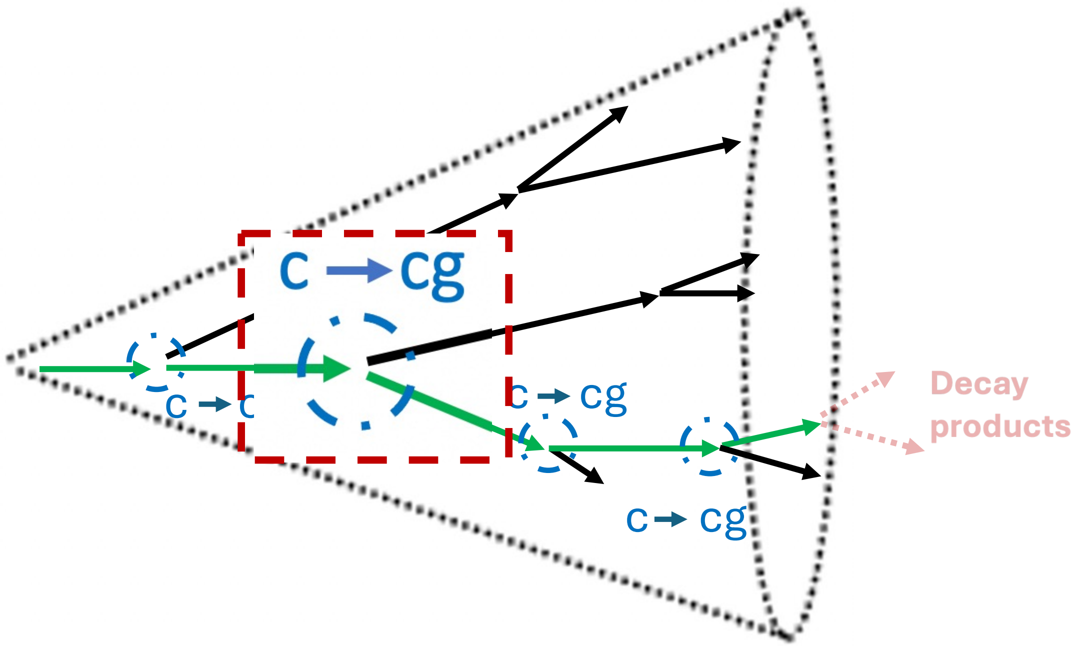
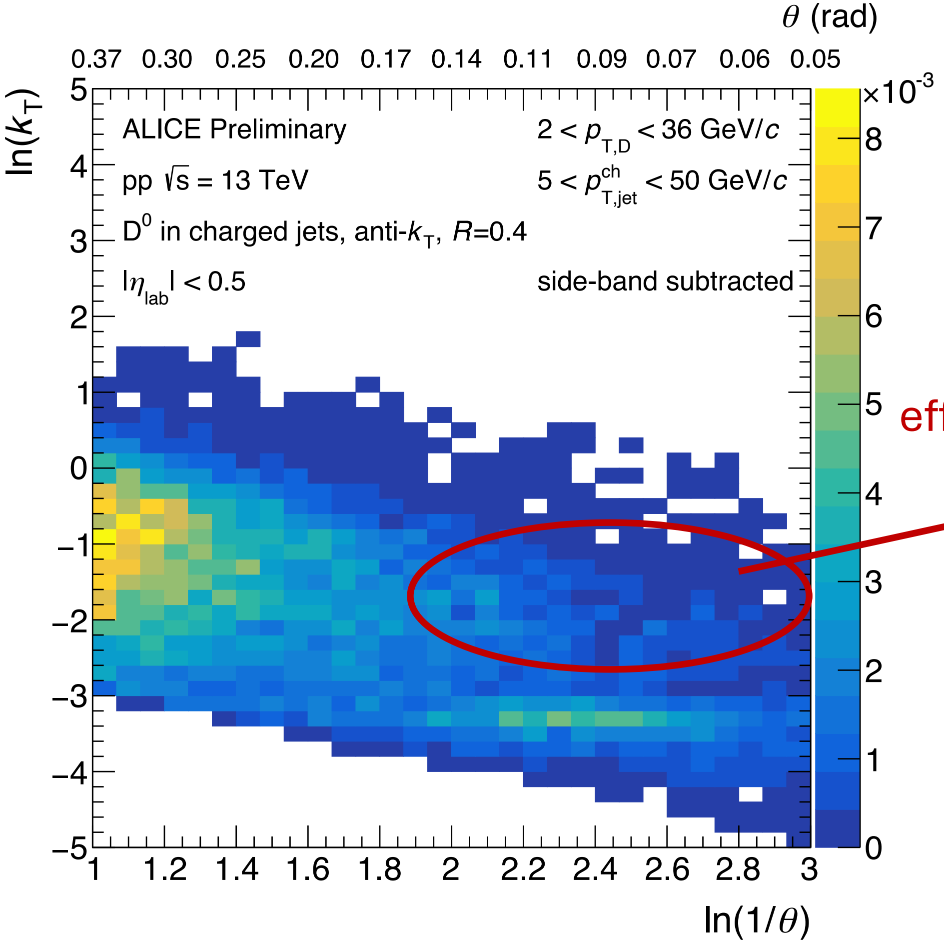




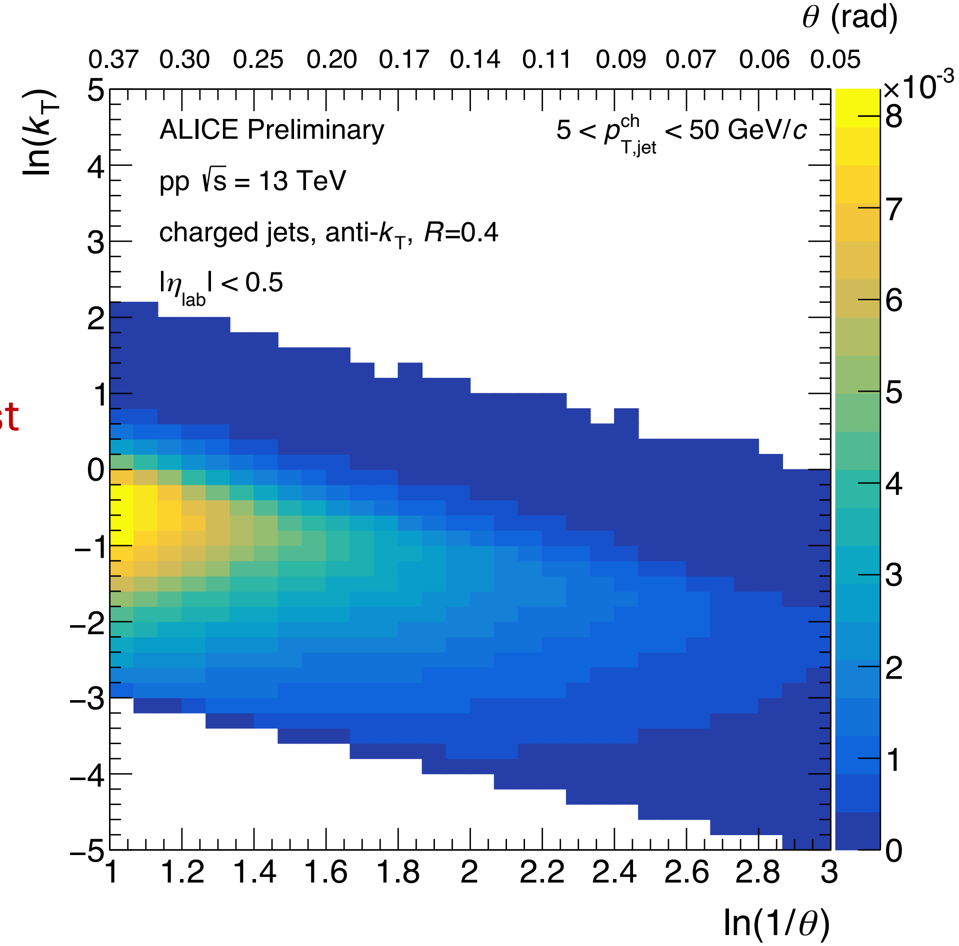
Reconstructing the evolution of a parton : heavy-flavour tracing

Lund plane of c -> cg emissions



Region where mass effects should manifest

Lund plane of light quark and gluon emissions



Uncovering the dead-cone effect

$$R(\theta) = \frac{1}{N^{\mathrm{D^0\,jets}}} \frac{\mathrm{d}n^{\mathrm{D^0\,jets}}}{\mathrm{d}\ln(1/\theta)} \Bigg/ \frac{1}{N^{\mathrm{inclusive\,jets}}} \frac{\mathrm{d}n^{\mathrm{inclusive\,jets}}}{\mathrm{d}\ln(1/\theta)} \Bigg|_{k_{\mathrm{T}}, E_{\mathrm{Radiator}}}$$

Compare the angular distribution of charm-quark emissions to those of light quarks and gluons

Uncovering the dead-cone effect

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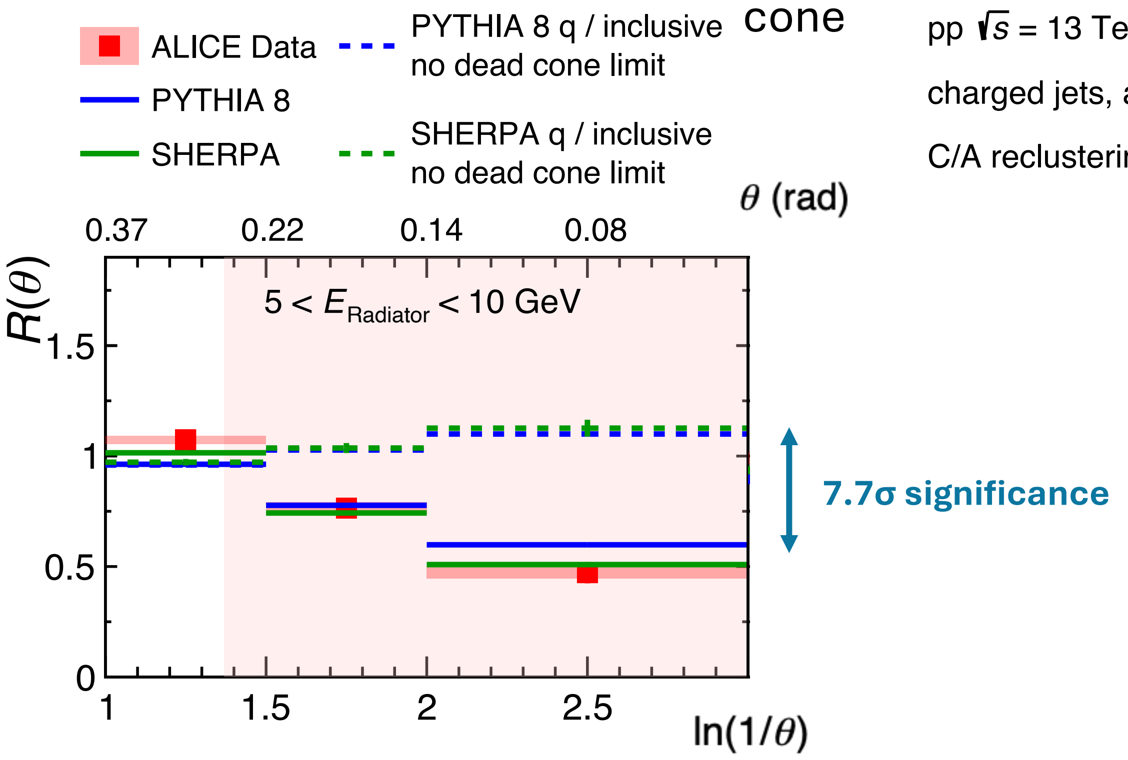
Nature 605 (2022) 440-446

Observation of the QCD dead cone



pp $\sqrt{s}$ = 13 TeV

charged jets, anti-k_T, R=0.4

C/A reclustering

$p_{T,\text{inclusive jet}}^{\text{ch,leading track}} \geq 2.8$ GeV/c

$k_T > \Lambda_{QCD}$, Λ_{QCD} = 200 MeV/c

$|\eta_{lab}| < 0.5$

θ (rad)

ln(1/θ)

Uncovering the dead-cone effect

$$R(\theta) = \frac{1}{N^{\mathrm{D^0\,jets}}} \frac{\mathrm{d}n^{\mathrm{D^0\,jets}}}{\mathrm{d}\ln(1/\theta)} \Bigg/ \frac{1}{N^{\mathrm{inclusive\,jets}}} \frac{\mathrm{d}n^{\mathrm{inclusive\,jets}}}{\mathrm{d}\ln(1/\theta)} \Bigg|_{k_\mathrm{T}, E_\mathrm{Radiator}}$$

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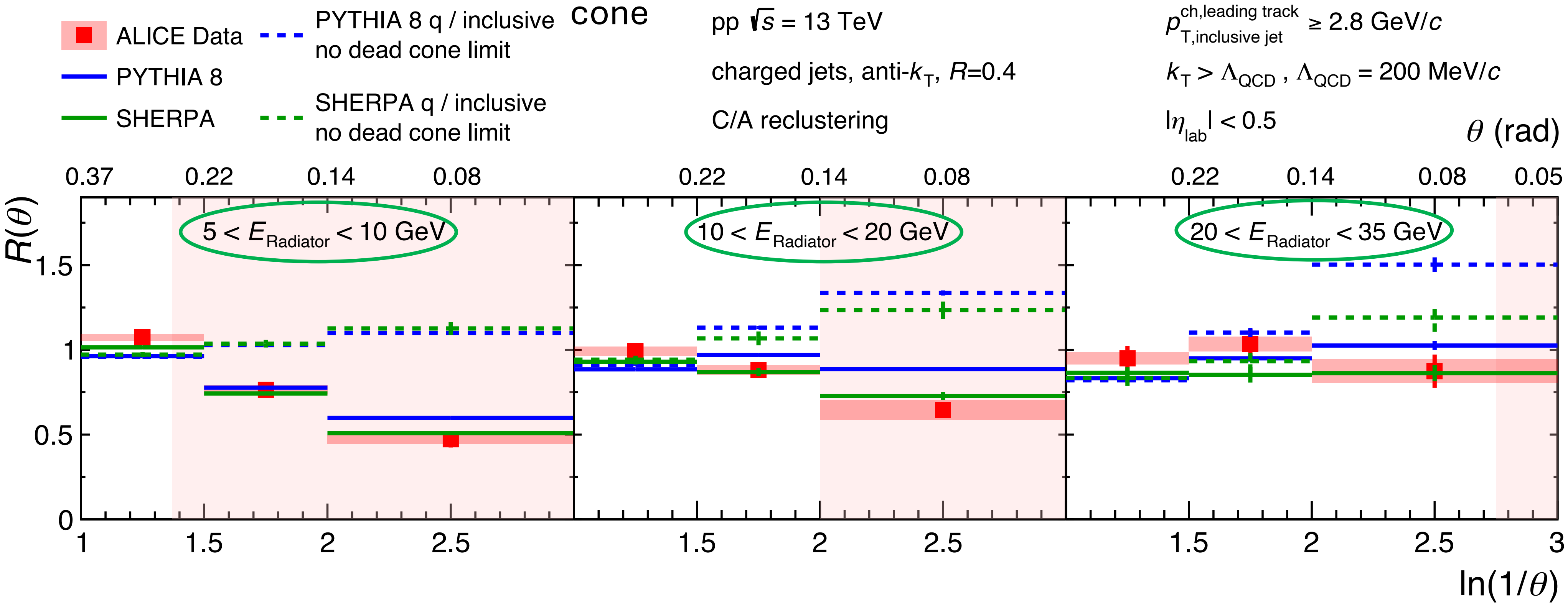

Increasing energy → Decreasing suppression

Uncovering the dead-cone effect

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

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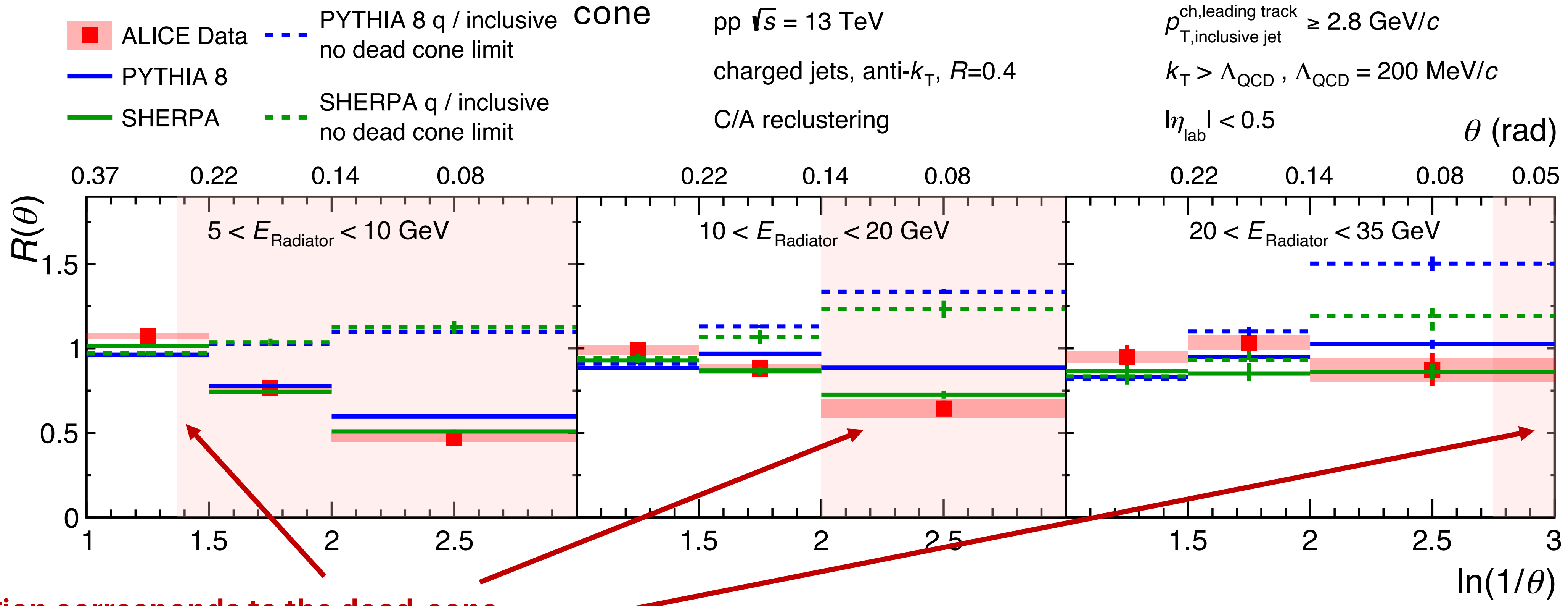

Shaded region corresponds to the dead-cone of a charm quark with a mass of 1.275 GeV/c

Uncovering the dead-cone effect

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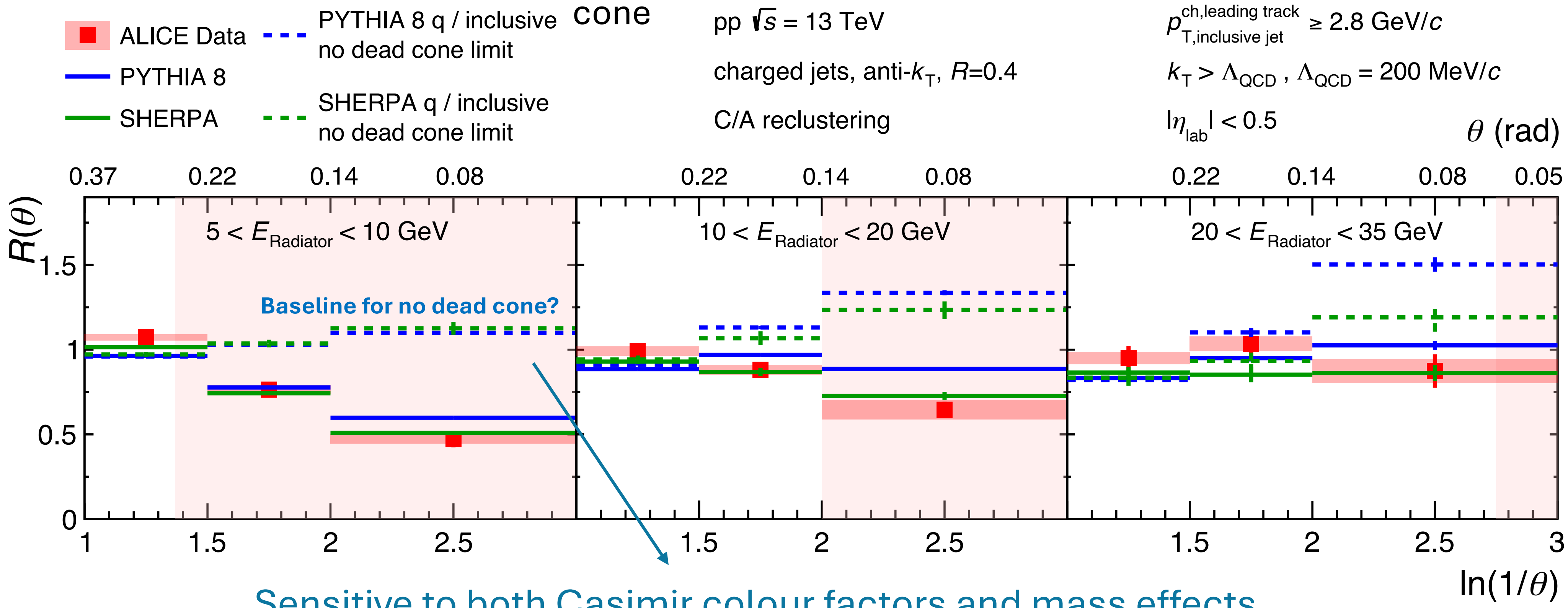
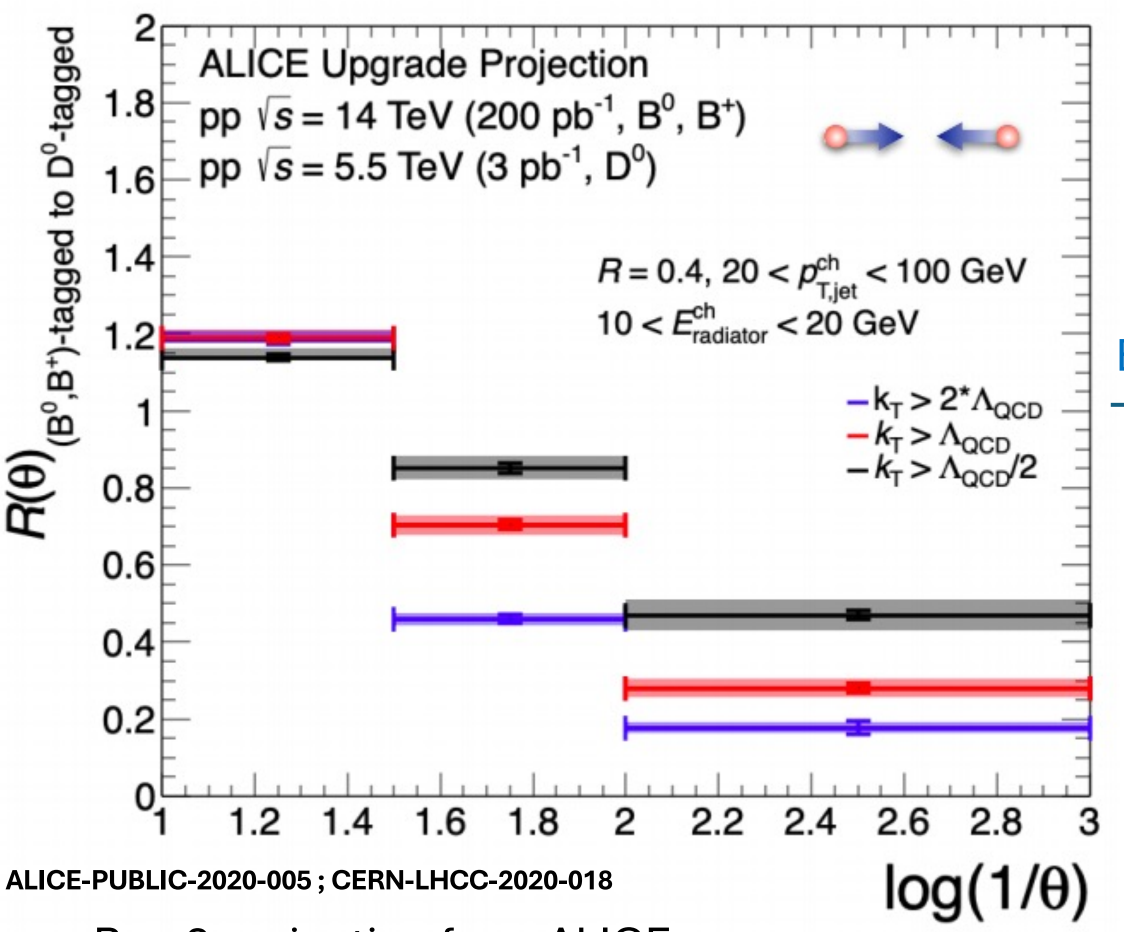


Sensitive to both Casimir colour factors and mass effects

Isolating mass effects

$$\frac{\text{Dead cone of } B^{+}\text{ - tagged jets}}{\text{Dead cone of } D^{0}\text{ - tagged jets}}$$



ALICE-PUBLIC-2020-005 ; CERN-LHCC-2020-018

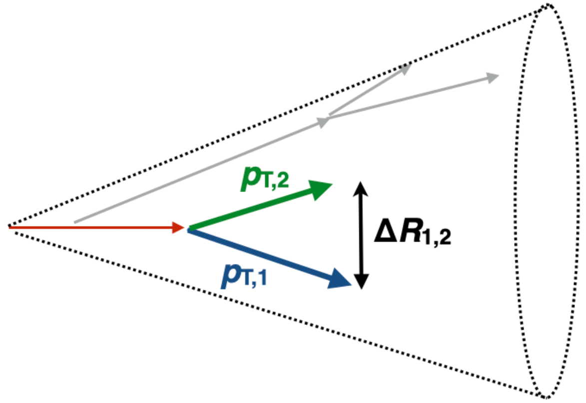
Run 3 projection from ALICE

Baseline of no mass effects

Comparing charm and beauty jets will allow for the isolation of mass effects

Comparing charm and inclusive at high p_T can isolate Casimir effects

$$\mathrm{d}P_{i\to jk} = \frac{\mathrm{d}\theta}{\theta}\mathrm{d}z\, P_{i\to jk}(z)$$



Soft Drop grooming condition

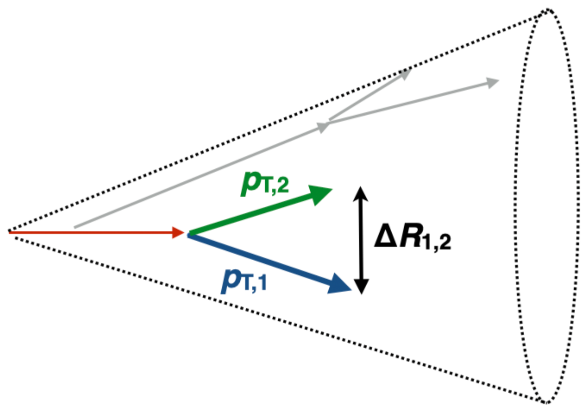
$$z = \frac{p_{T,2}}{p_{T,1} + p_{T,2}} > z_{cut}\left(\frac{\Delta R_{1,2}}{R}\right)^{\beta}$$

$$z = 0.1, \beta = 0$$

A. J. Larkoski et al. , JHEP 1405 (2014) 146

Converging on to the c -> cg splitting function

$$\mathrm{d}P_{i\to jk} = \frac{\mathrm{d}\theta}{\theta}\mathrm{d}z\, P_{i\to jk}(z)$$



Soft Drop grooming condition

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

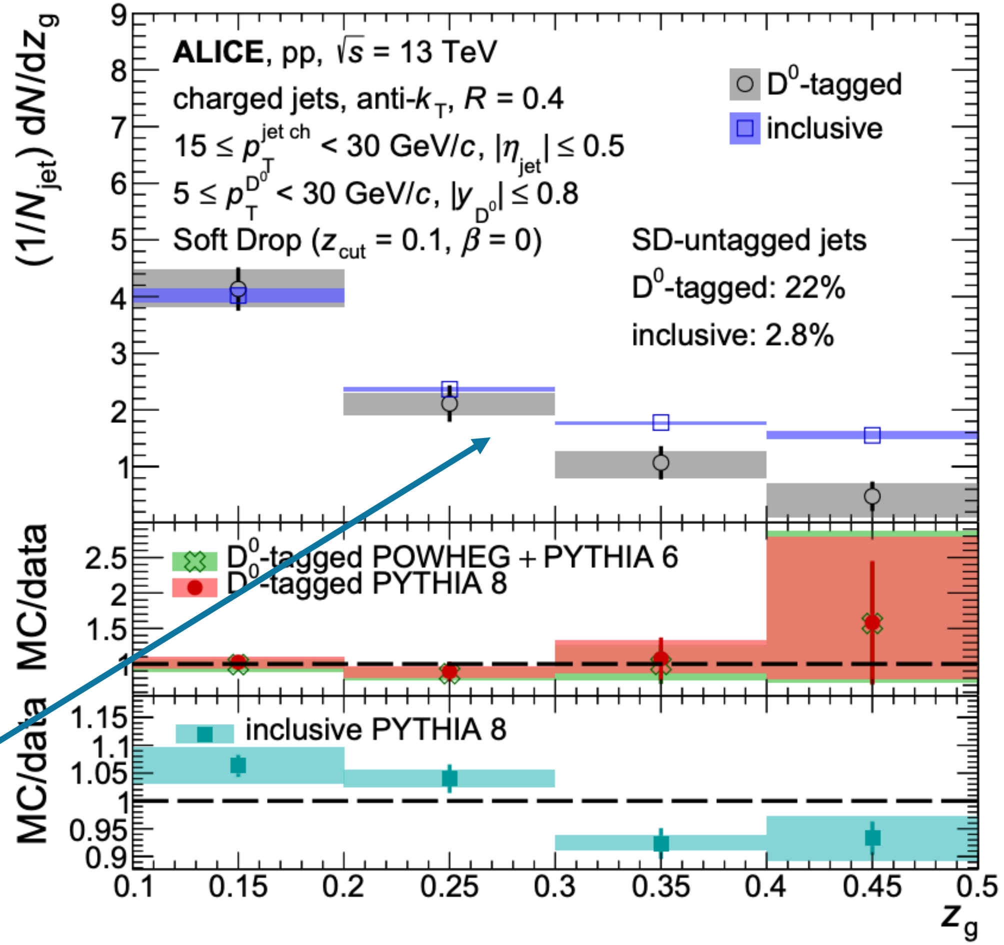
$$z = 0.1, \beta = 0$$

A. J. Larkoski et al. , JHEP 1405 (2014) 146

Converges onto the QCD splitting function for the first splitting that passes Soft Drop

Emissions from charm-quarks have a steeper splitting probability than light quarks and gluons

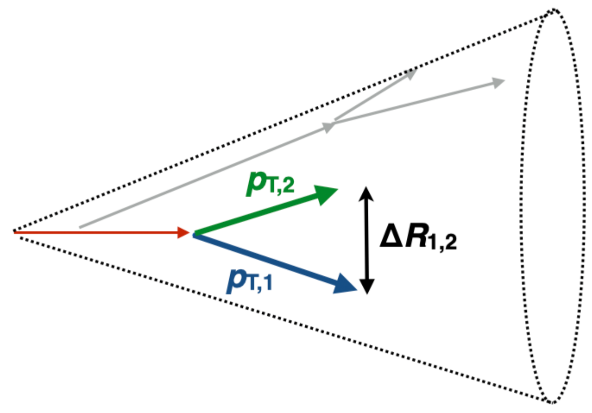
Fewer symmetric splittings



PRL 131.192301

Converging on to the c -> cg splitting function

$$dP_{i\to jk} = \frac{d\theta}{\theta} dz\, P_{i\to jk}(z)$$



Soft Drop grooming condition

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

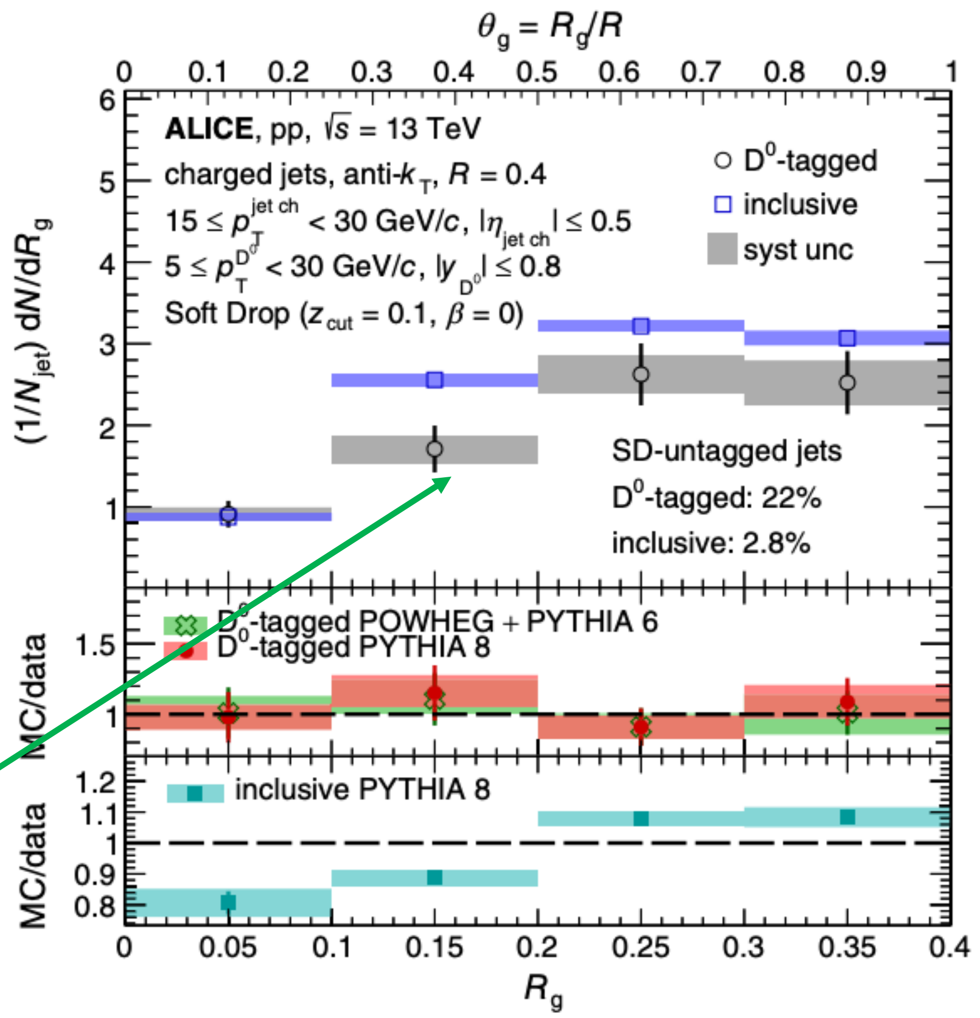
$$z = 0.1, \beta = 0$$

A. J. Larkoski et al. , JHEP 1405 (2014) 146

Opening angle of the first emission passing Soft Drop

Gluon jets have a broader shower profile than quark jets

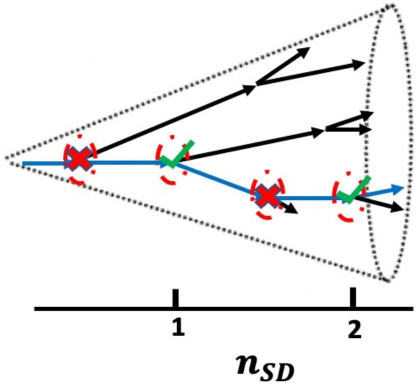
Competing effects between the dead cone and the increased quark emissions at small angles



PRL 131.192301

Converging on to the c -> cg splitting function

Towards isolating the perturbative physics of heavy-flavour fragmentation functions



Emission is groomed away

Emission satisfies Soft Drop

Soft Drop grooming condition

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

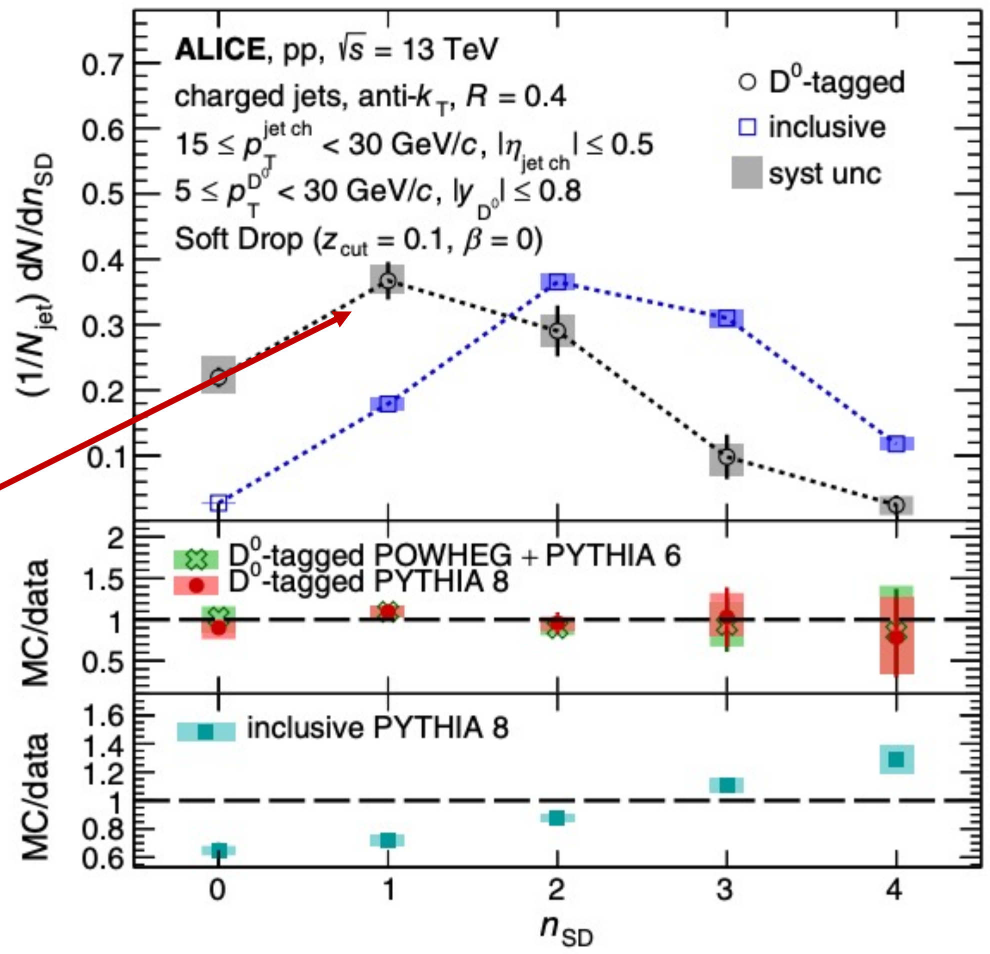
$$z = 0.1, \beta = 0$$

A. J. Larkoski et al. , JHEP 1405 (2014) 146

Strongly correlated to the number of perturbative emissions in the shower

Charm quarks on average have fewer hard emissions

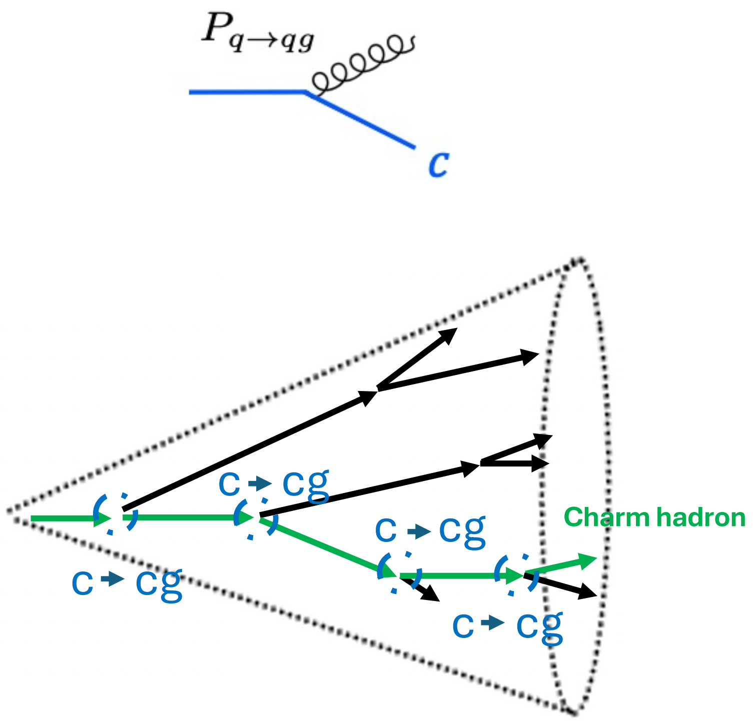
Hardening of the fragmentation function from the dead-cone



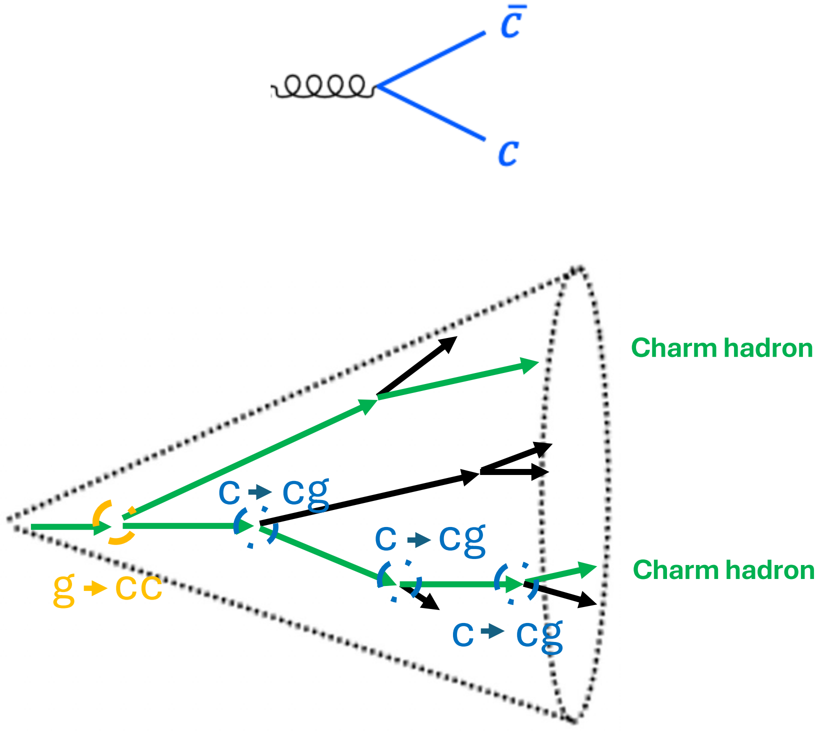
PRL 131.192301

Going beyond c -> cg splittings

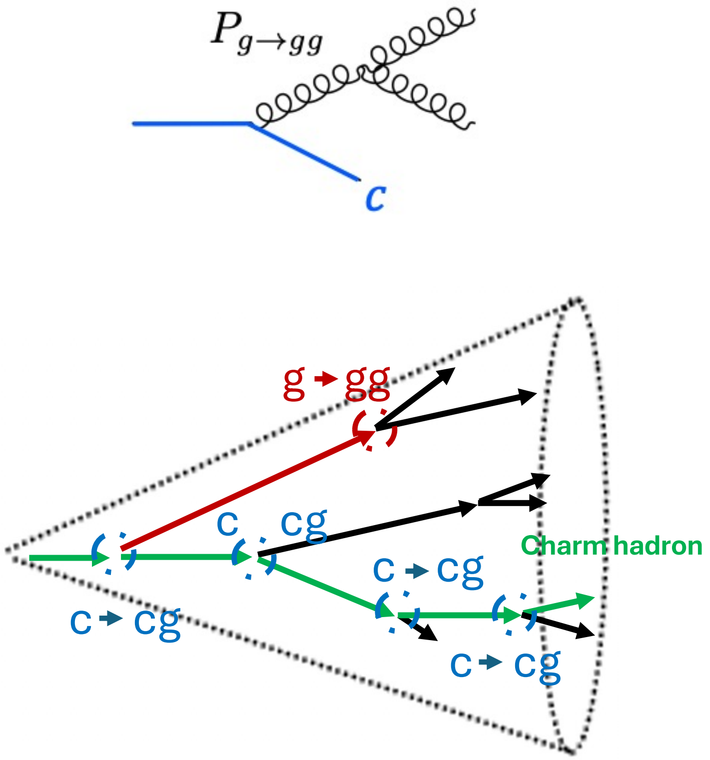
***PRL.* 132 (2024) 21**



q ⟶ qg



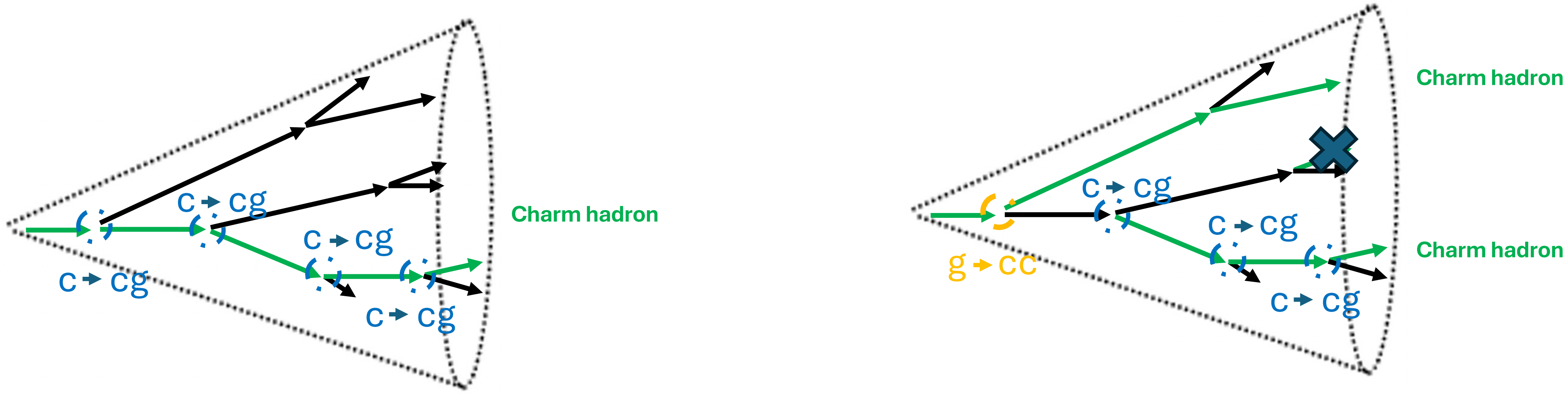
$g \longrightarrow q\bar{q}$



g ⟶ gg

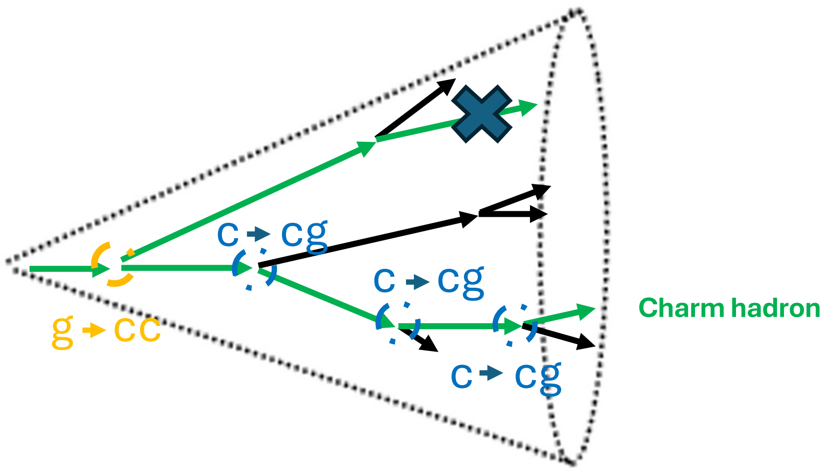
Gluon splitting contamination

The low efficiency of reconstructing heavy-flavour hadrons makes the final state of these two processes often indistinguishable



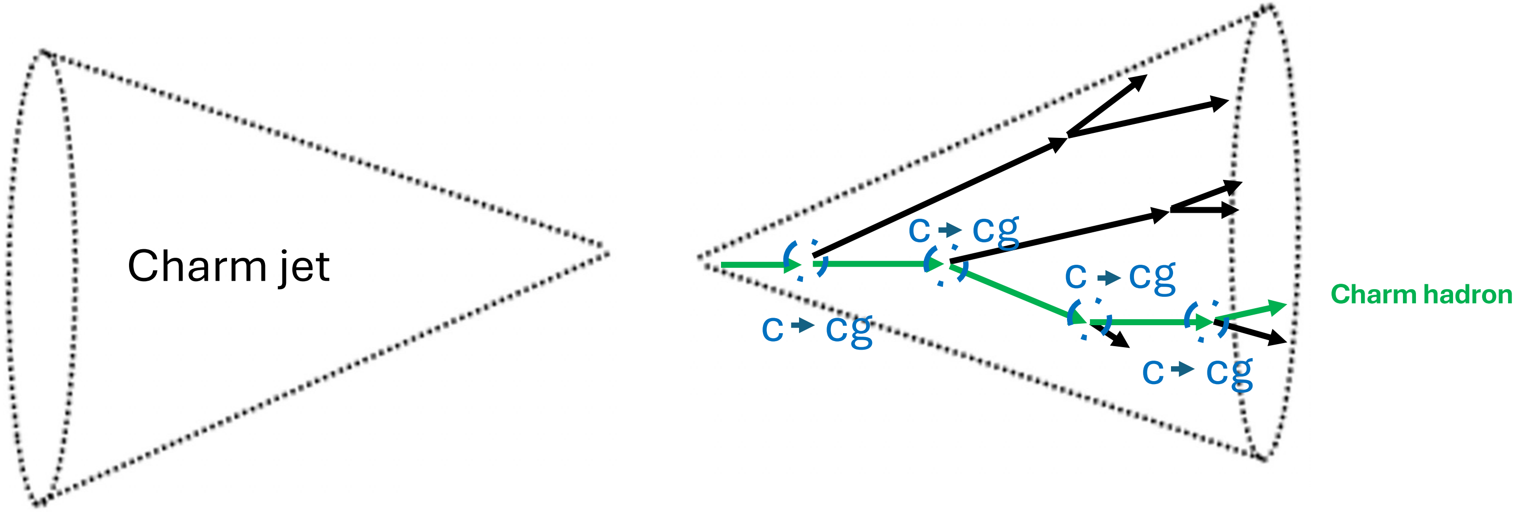
At low p_T early splittings are most problematic

Purity of c-> cg splittings should increase deeper into the shower

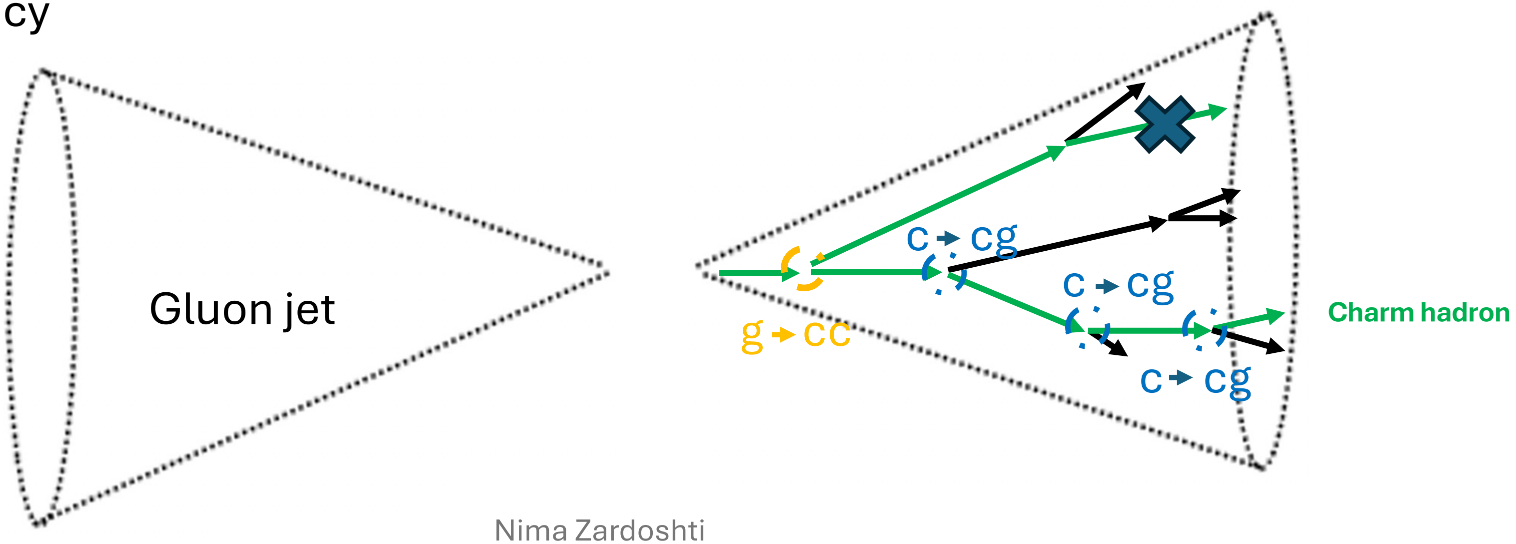


Possible solutions for substructure

One way of tackling the problem is to tag the back-to-back jet using high efficiency taggers



Need excellent tagging efficiency

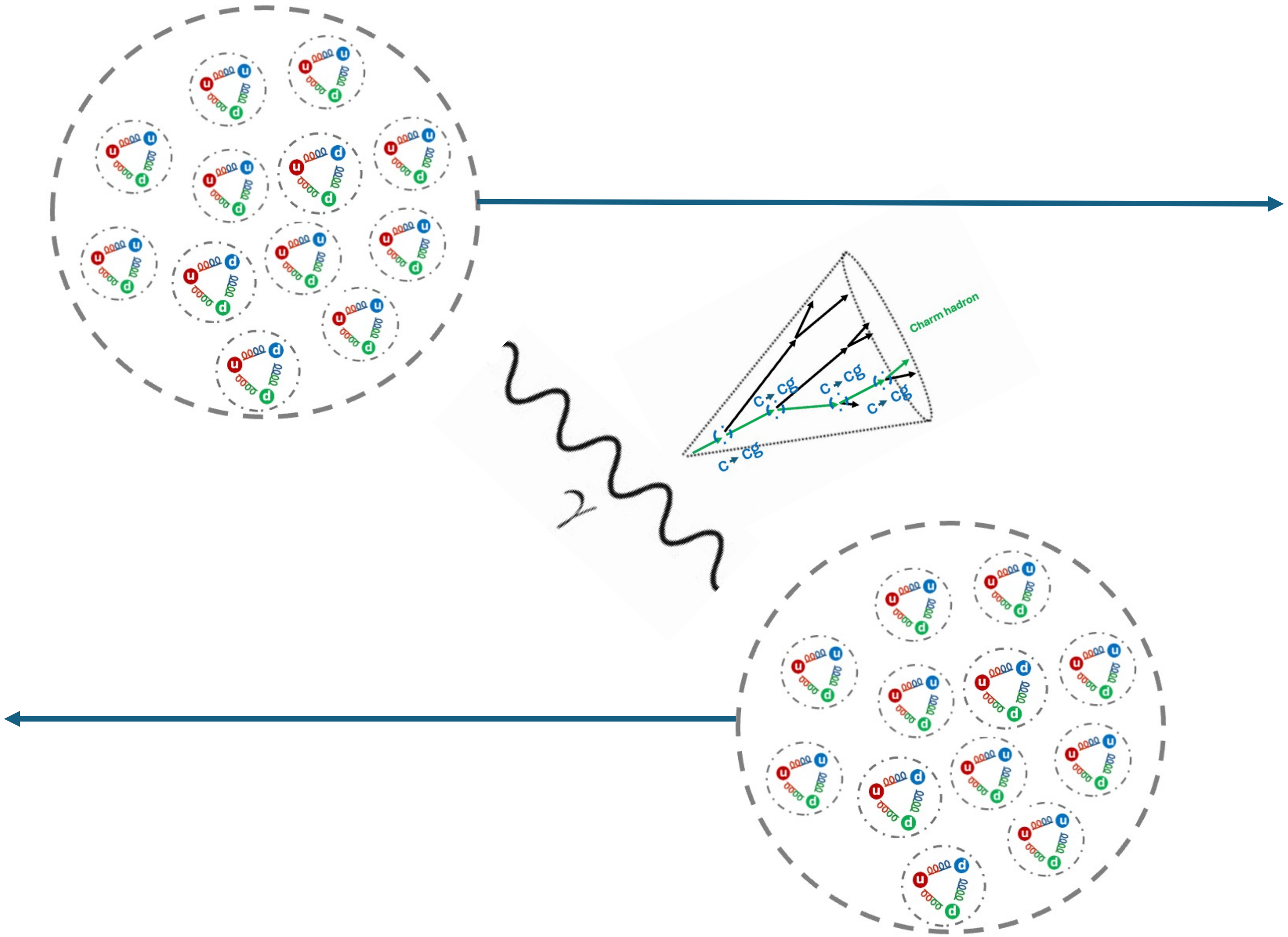


Possible solutions for substructure

Ultraperipheral collisions of heavy-ions are a photon-nucleus interaction

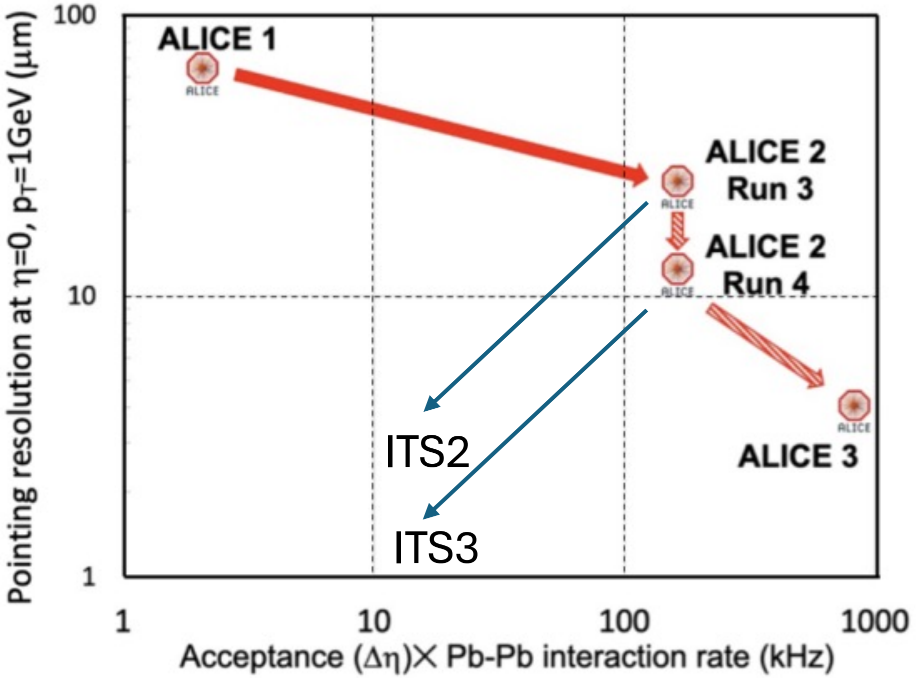
Scattered gluons are supressed – charm tagged jets are initiated by charm quarks

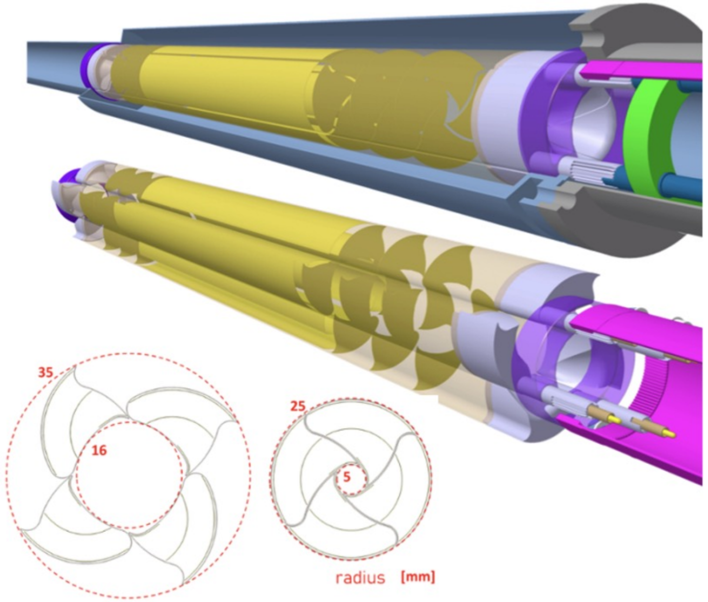
Interactions are on average soft, so need large statistics



Positional resolution is paramount for accurate tagging of displaced tracks and reconstruction of secondary vertices

ALICE 3 Iris Tracker



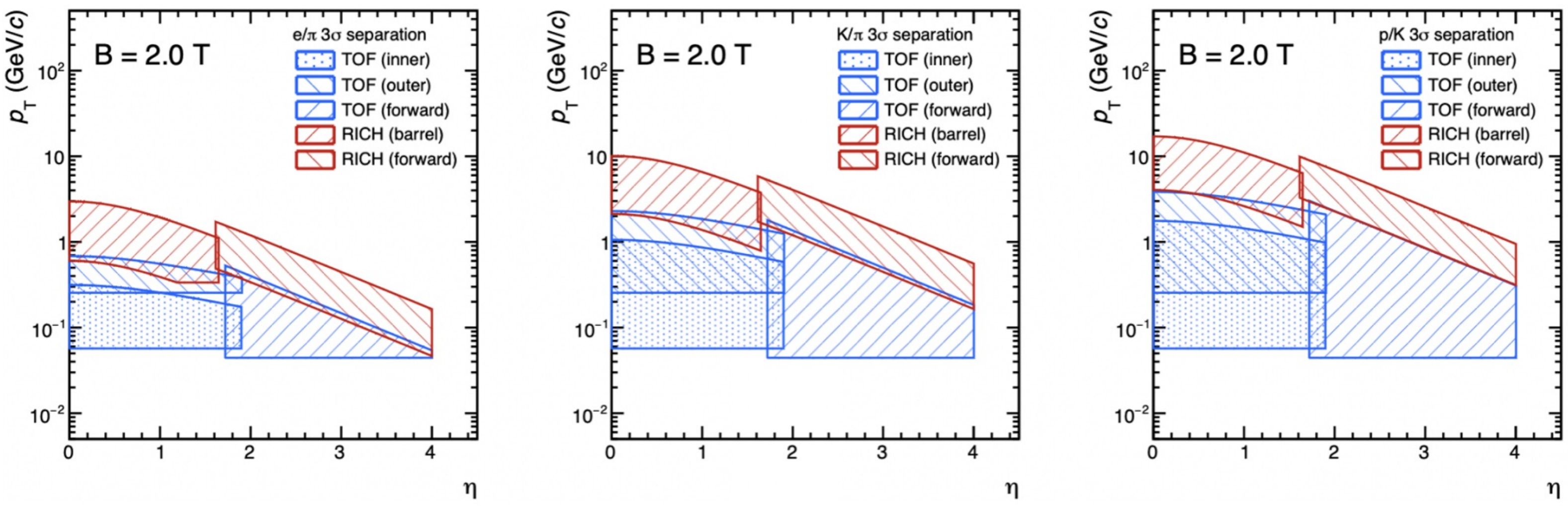


The tracker will be inside the beampipe

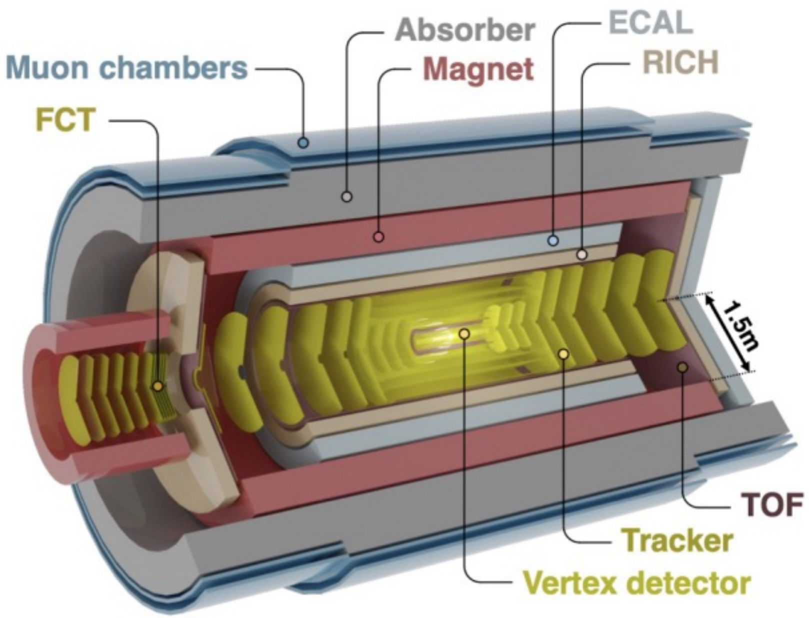
Excellent pointing angle resolution

Detector upgrades for heavy-flavour tagging

For supressing background when identifying reconstructed hadrons PID is vital

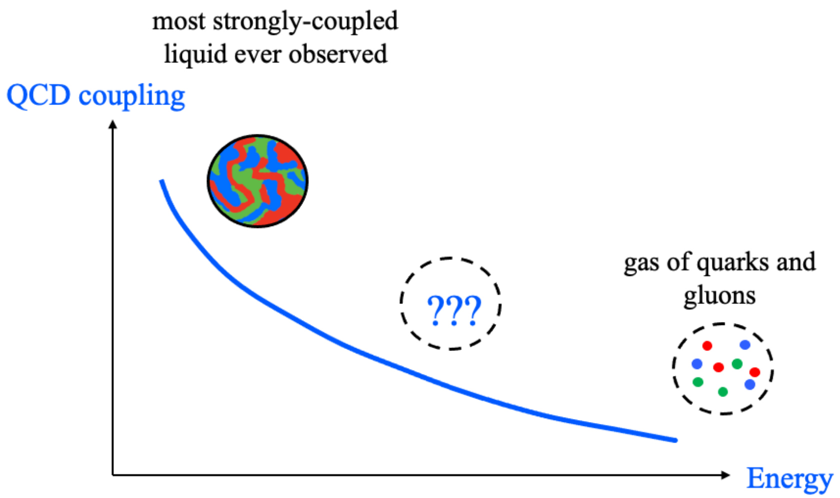


ALICE 3



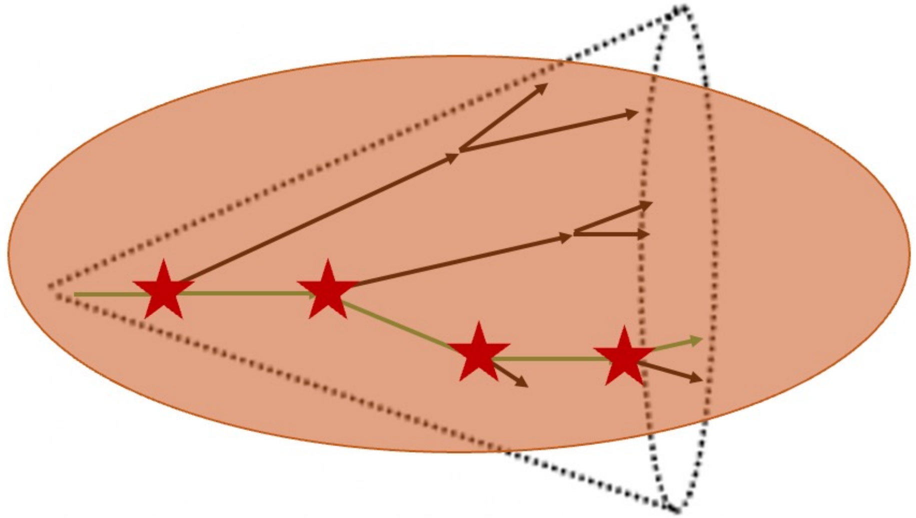
Excellent separation of particle species over a wide range of psuedo-rapidities

First foray of heavy-flavour jets in heavy-ions



$m_Q >> \Lambda_{QCD}$

$m_Q >> T_{QGP}$



Decreasing momentum scale

Traceable through the shower with heavy-flavours

Casimir Colour factors

The medium couples differently to quarks and gluons

The dead-cone effect

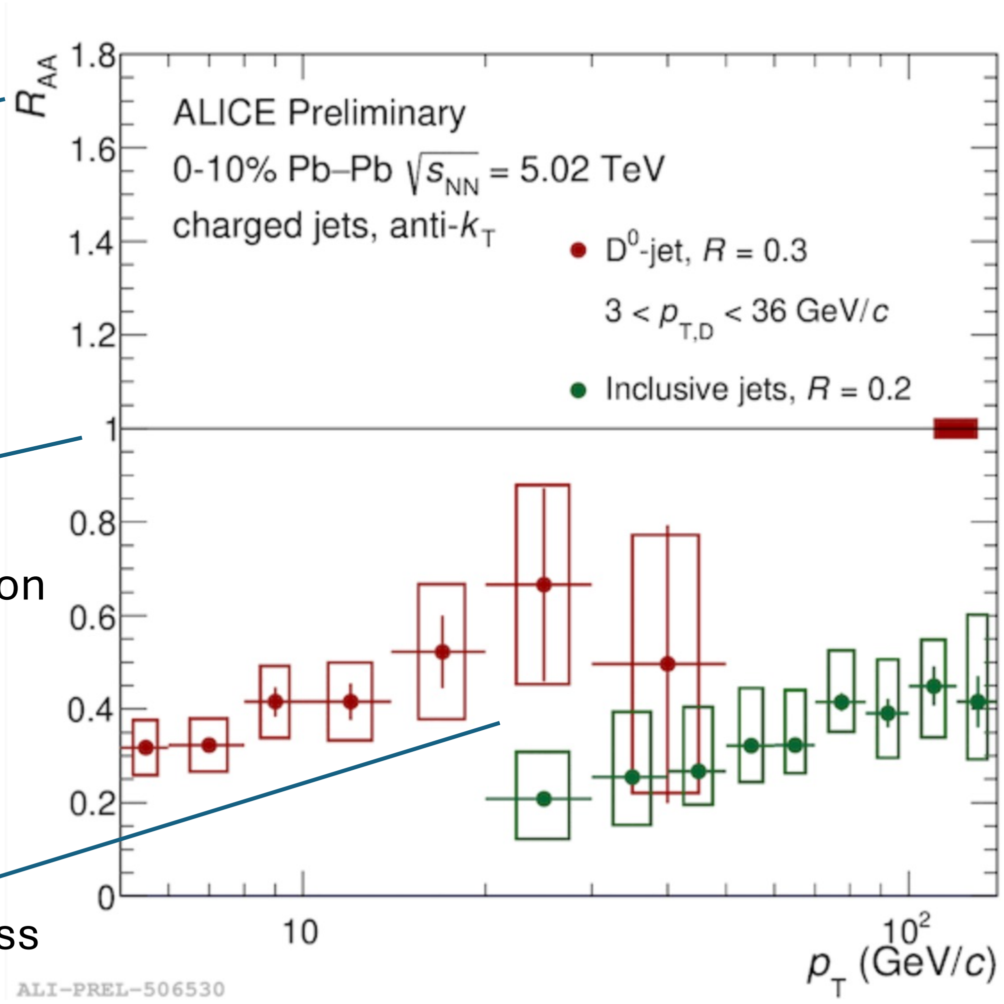
How does the dead-cone interplay with medium emissions?

First foray of heavy-flavour jets in heavy-ions

Ratio of yield in Pb-Pb collisions compares to (scaled) pp

Baseline for no medium modification

Hint of flavour-dependent energy-loss



substructure of heavy-flavour jets in PbPb accessible in Run 3

Summary

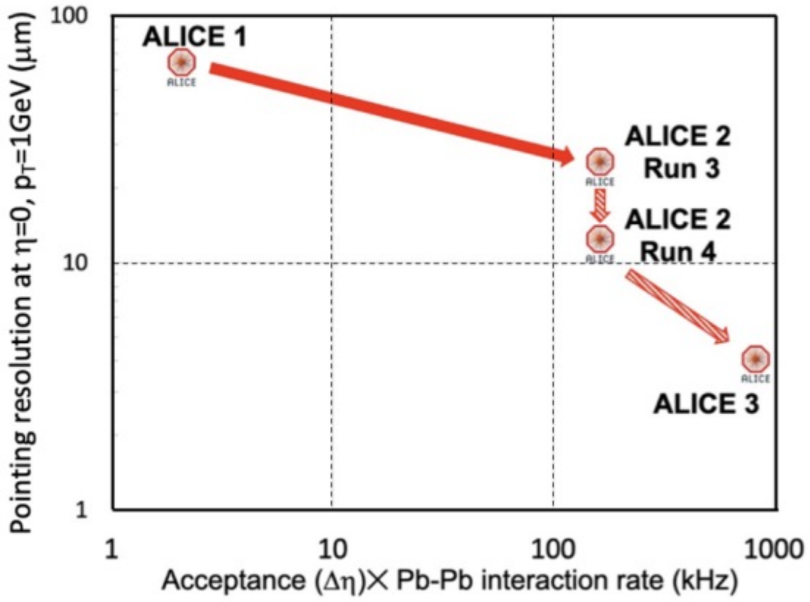
Measurements of heavy-flavour jets at low p_T where mass effects can significantly dictate the shower pattern

Focus on jet tagging via a reconstructed heavy-flavour hadron

Targeting hadronisation effects and shower-related flavour effects

Run 3 brings the promise of much better precision for pp collisions as well as the extension to heavy-ion collisions

ALICE will continue to grow in terms of heavy-flavour tagging capabilities with each new run



ALICE 3