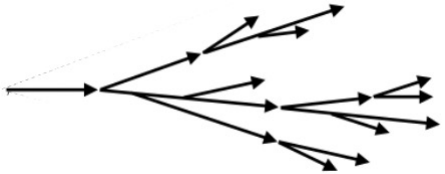
Direct observation of the QCD dead-cone effect

Nima Zardoshti (CERN)
On behalf of the ALICE Collaboration

Flavour dependence in QCD parton showers

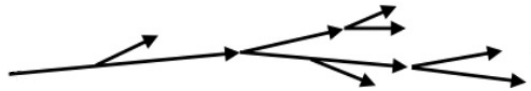
Gluon-initiated shower

Broader shower profile
Higher number of emissions



Quark-initiated shower

narrower shower profile
Fewer emissions in the shower



Casimir Colour factors

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

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

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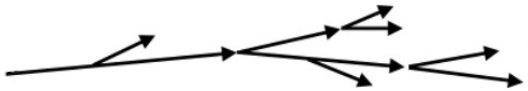
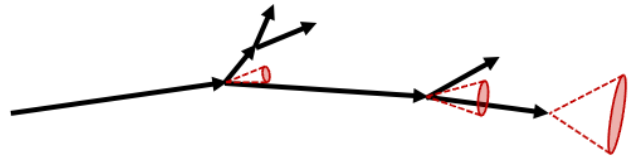


Heavy-quark-initiated shower

Suppression of small angle emissions
Harder fragmentation



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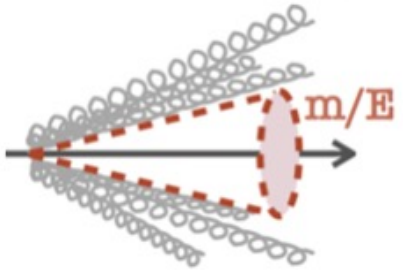
The dead-cone effect

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

Sizeable effect for low energy heavy quarks

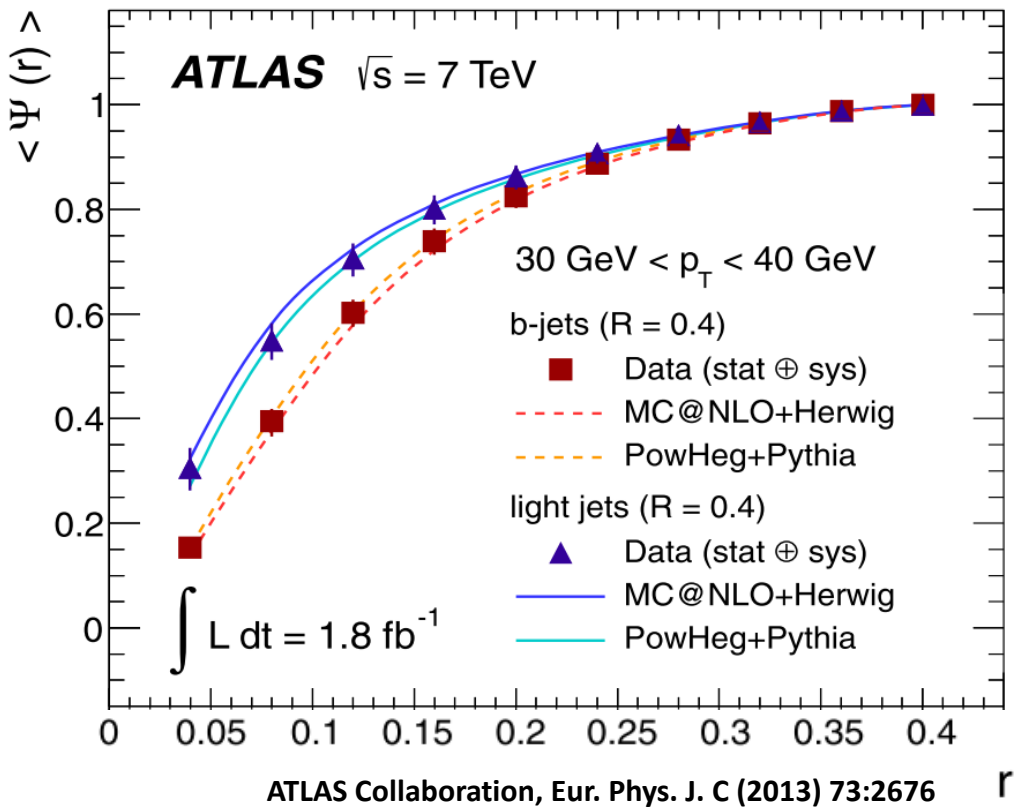


Previous indirect measurements

p_T density around the initial scattered b-quark direction is depleted compared to the density around light quarks and gluons

Consequence of the suppression of emissions in the dead cone of the b-quark

$$\Psi(r) = \frac{p_T(0,r)}{p_T(0,R)}; \quad r \le R$$



ATLAS Collaboration, Eur. Phys. J. C (2013) 73:2676

What is needed for a direct measurement?

Requirements for a direct observation of the dead cone

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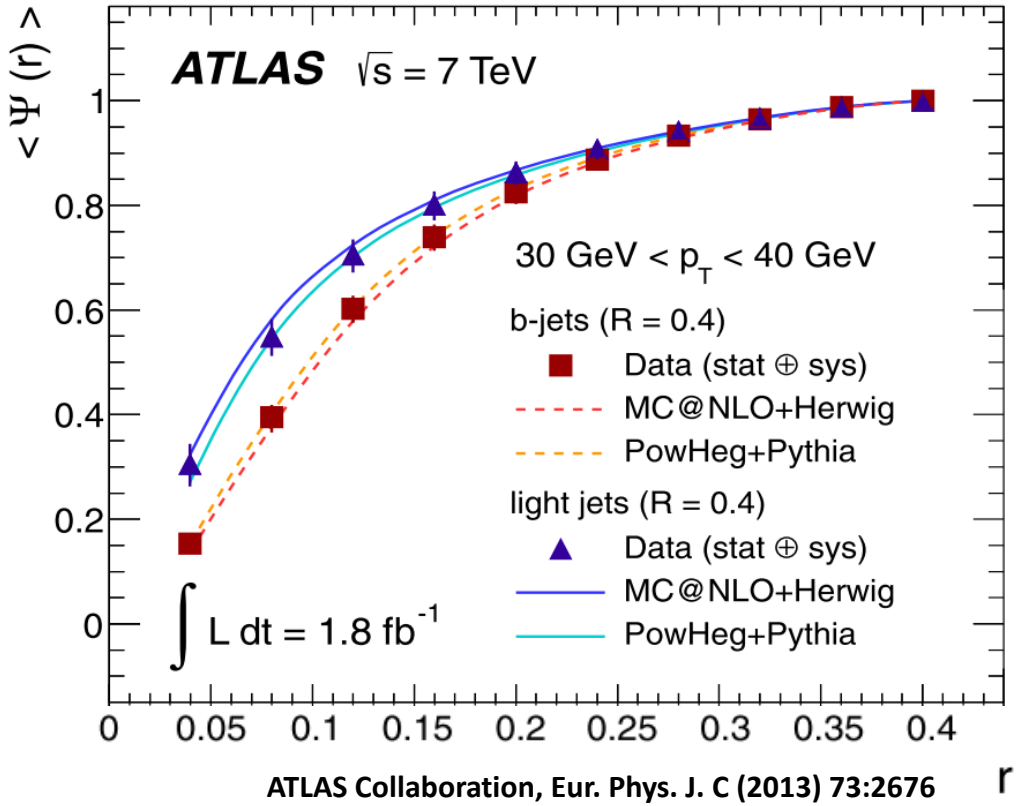

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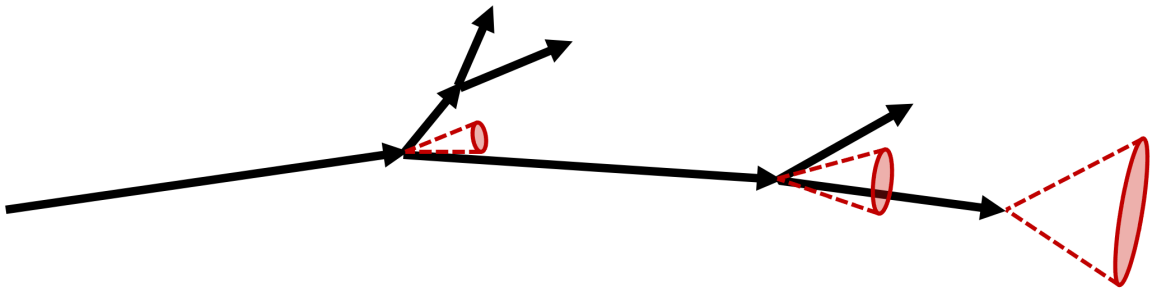

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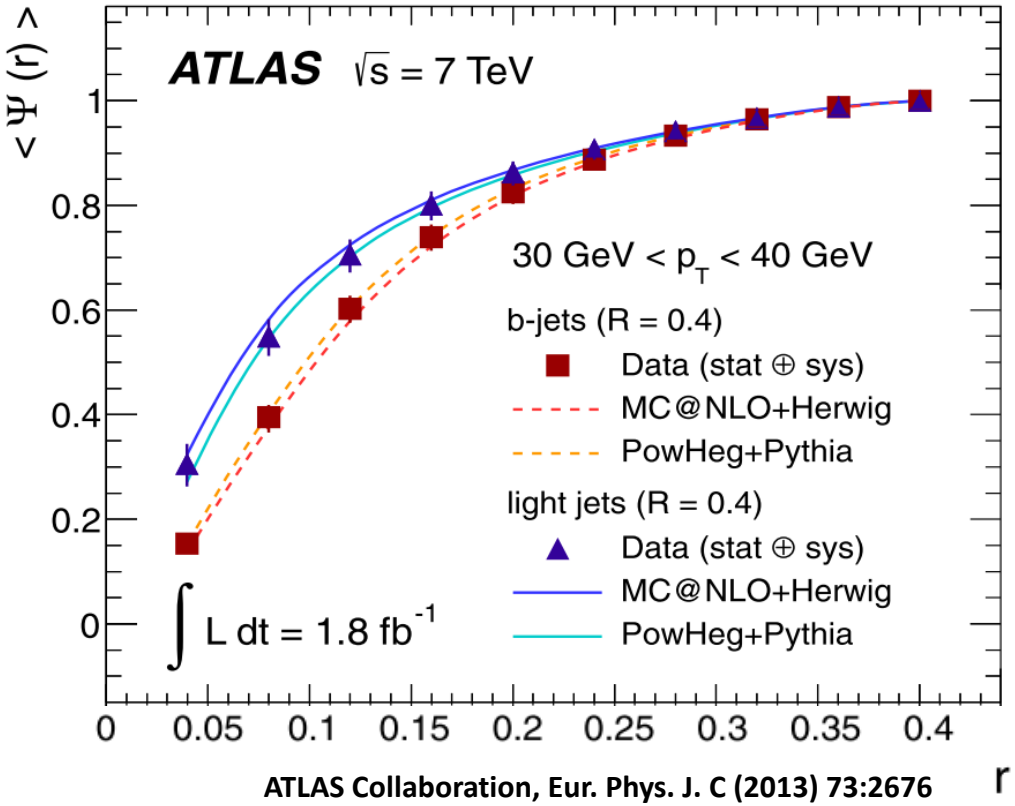
Requirements for a direct observation of the dead cone

The dead-cone angle appears in emissions at the partonic level - need to reconstruct the dynamically evolving direction of the heavy quark



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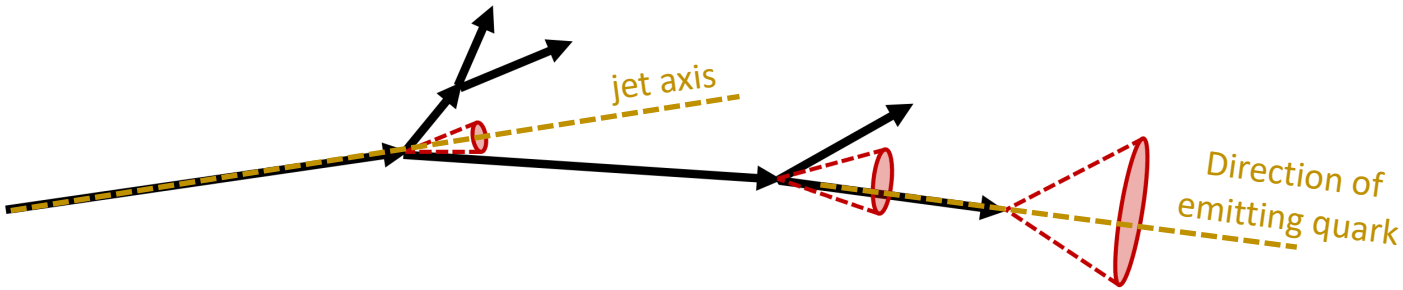

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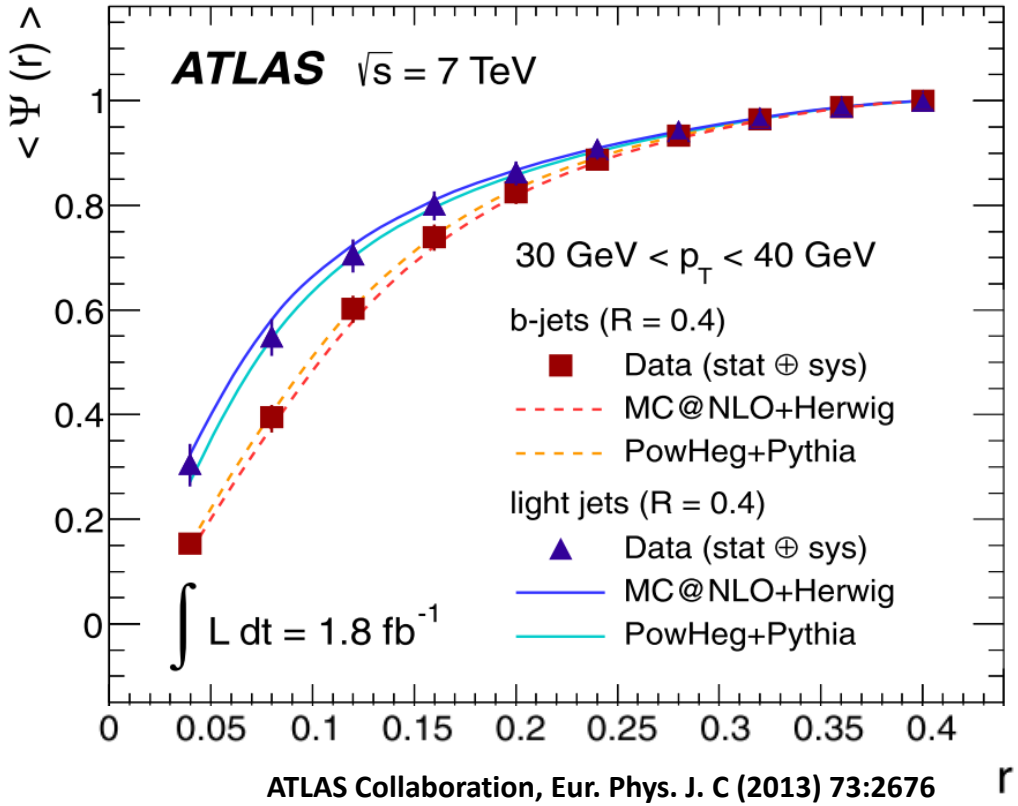
Sources such as the decay products of the heavy-flavour hadron can populate the dead-cone region



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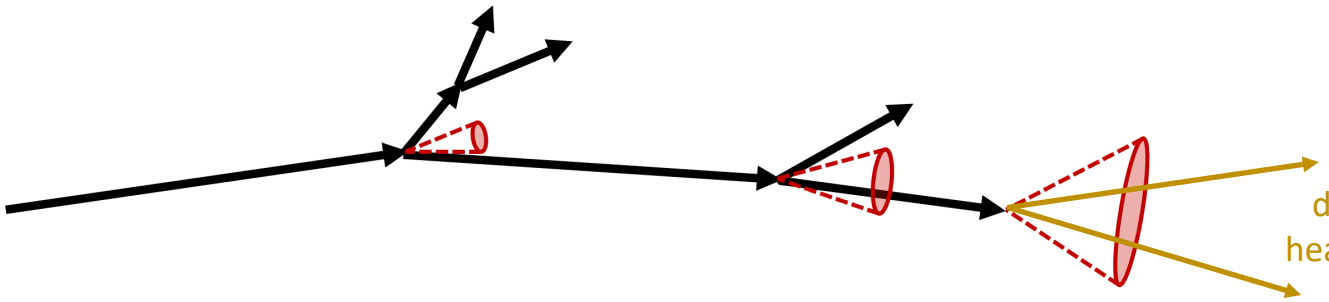
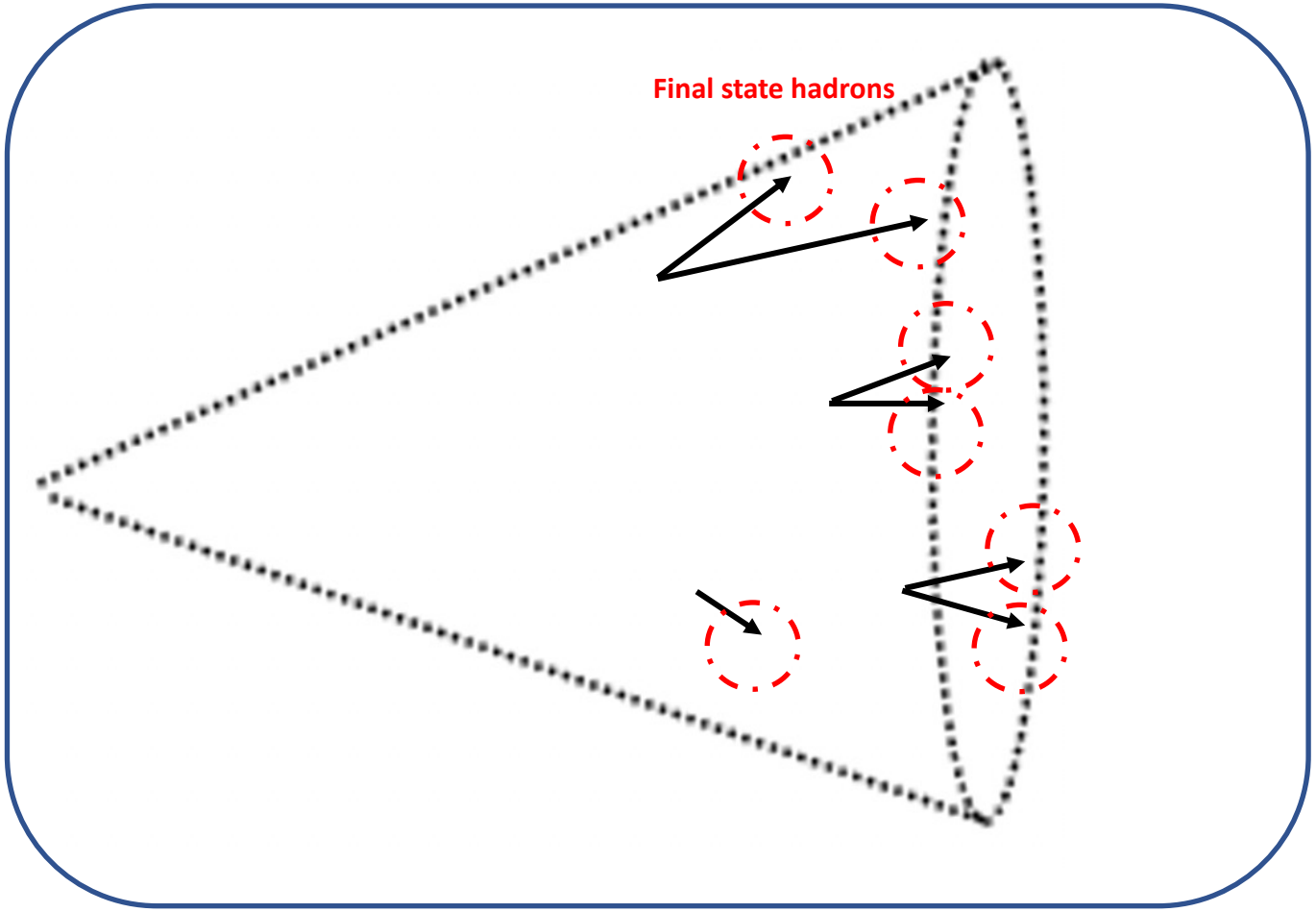
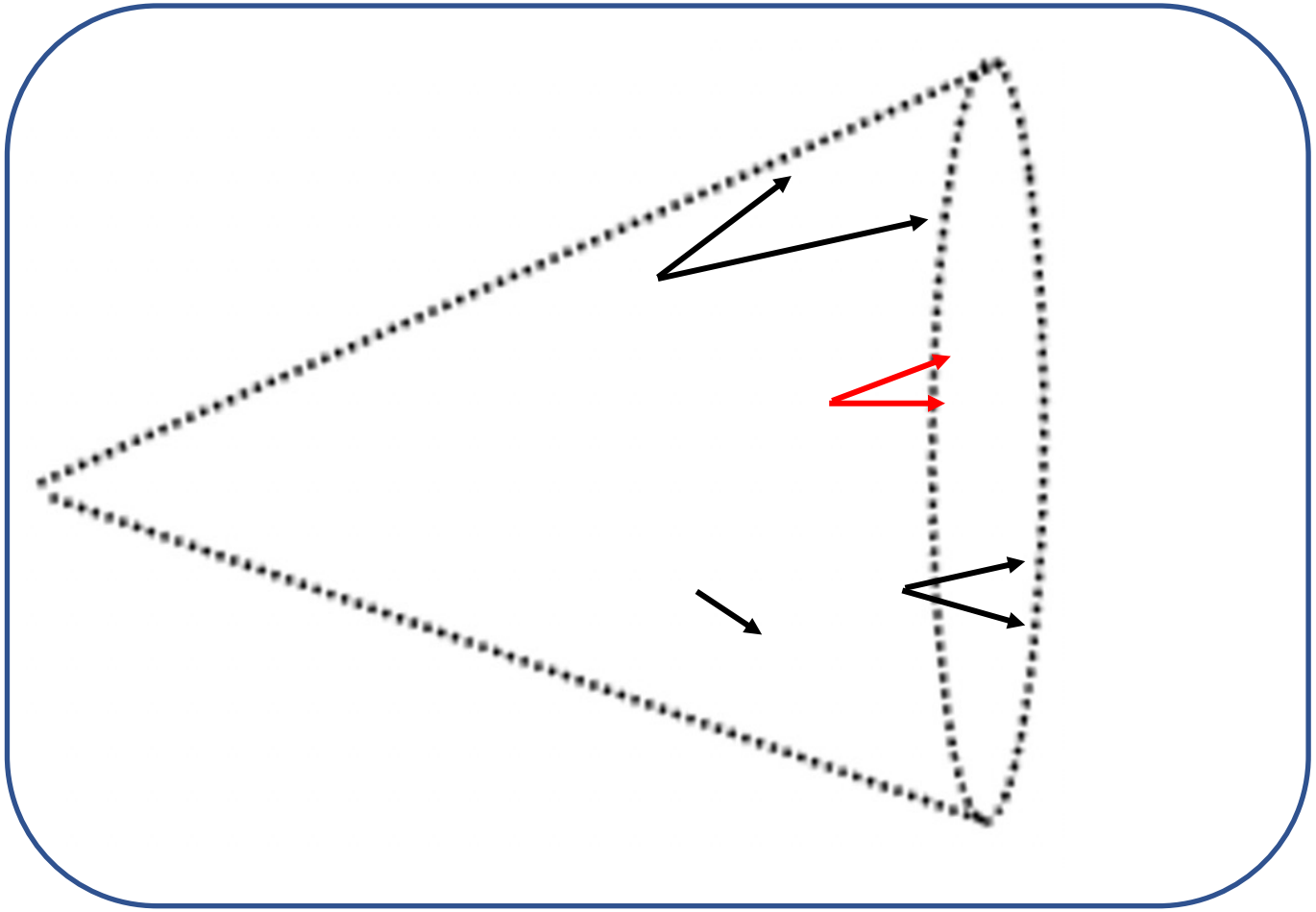


Dynamically reconstructing a parton shower



Jet clustering algorithms select the final state particles belonging to a given shower

Dynamically reconstructing a parton shower



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Take advantage of the angular ordering of QCD emissions to reconstruct the shower using the C/A algorithm

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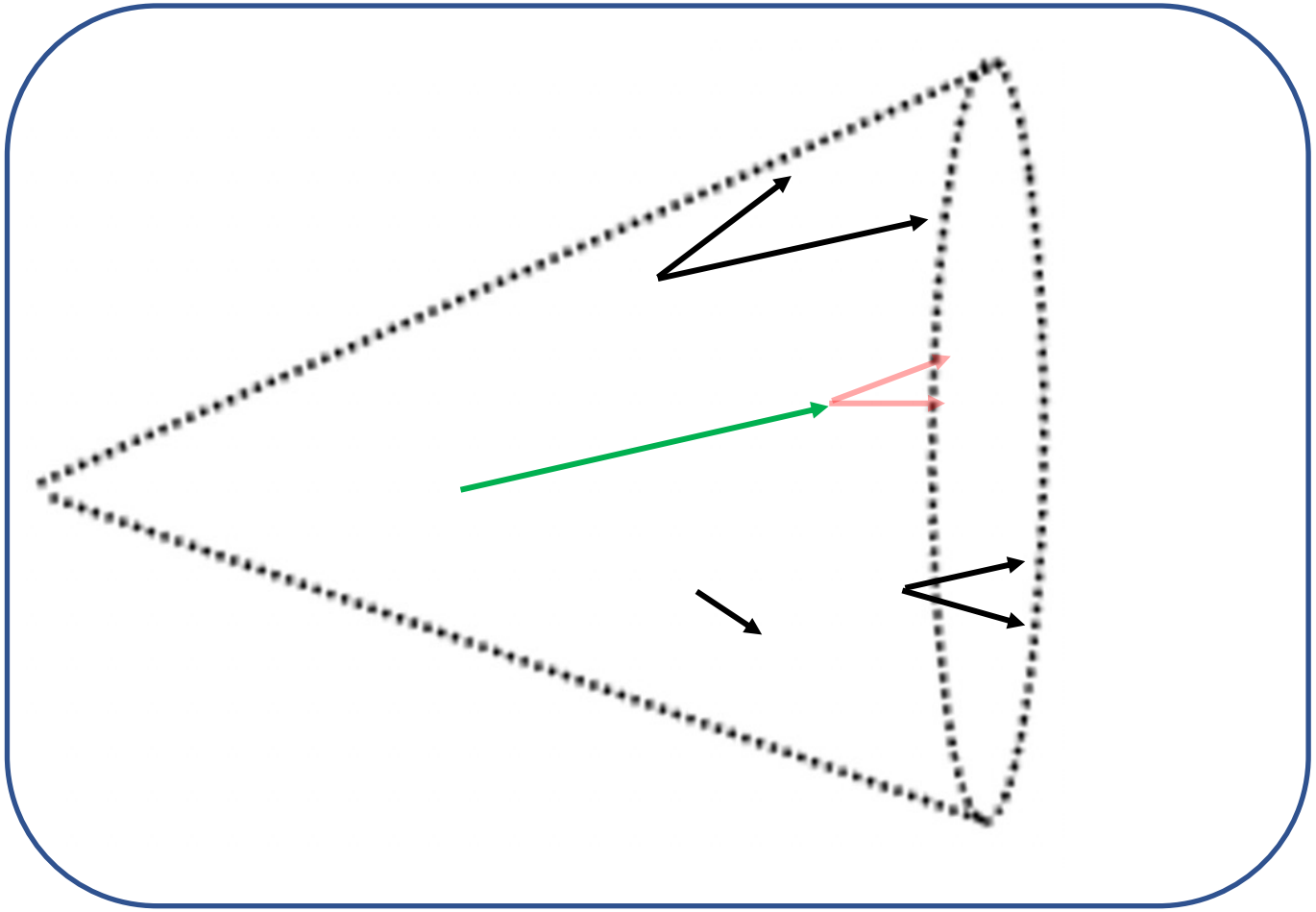

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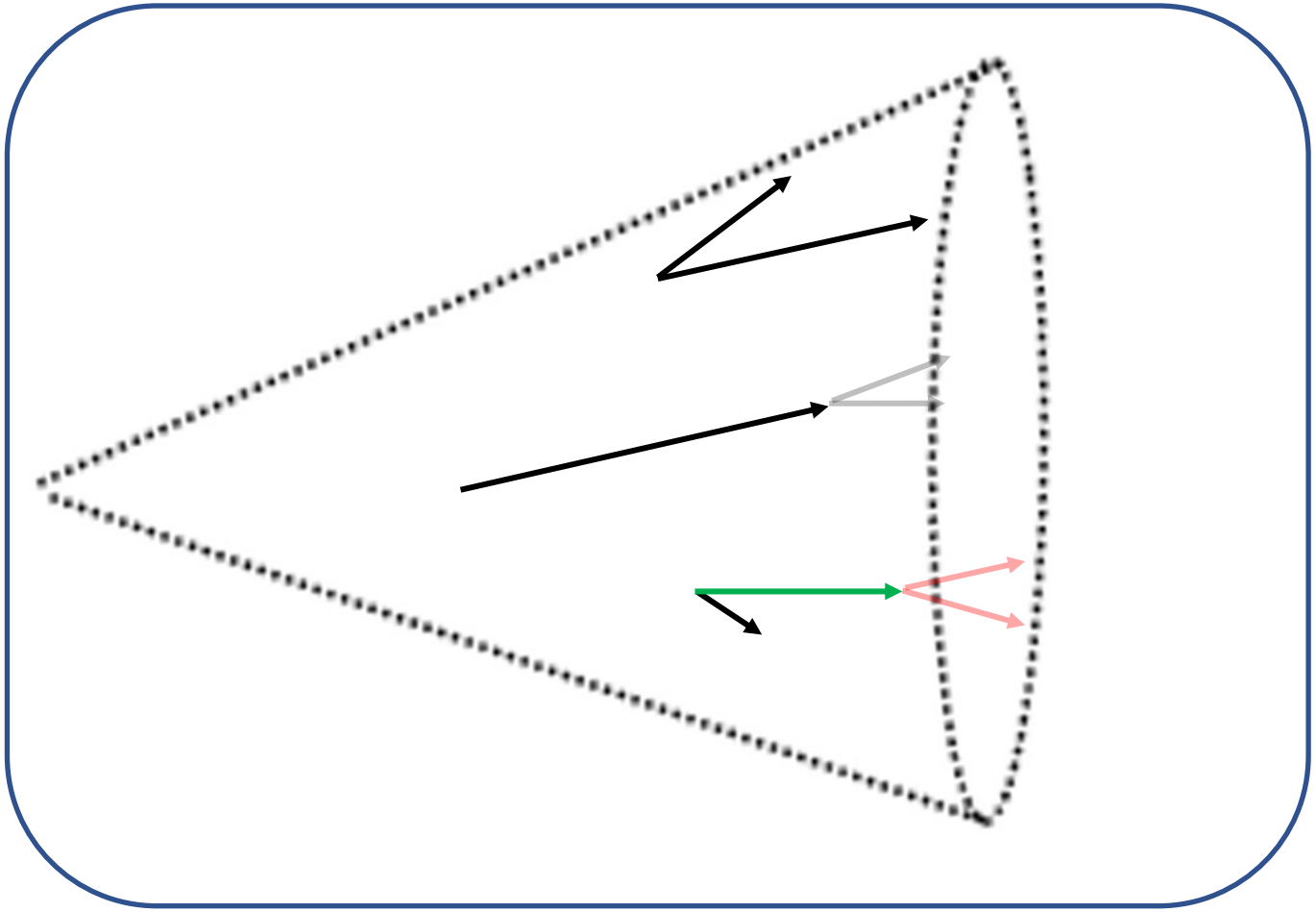

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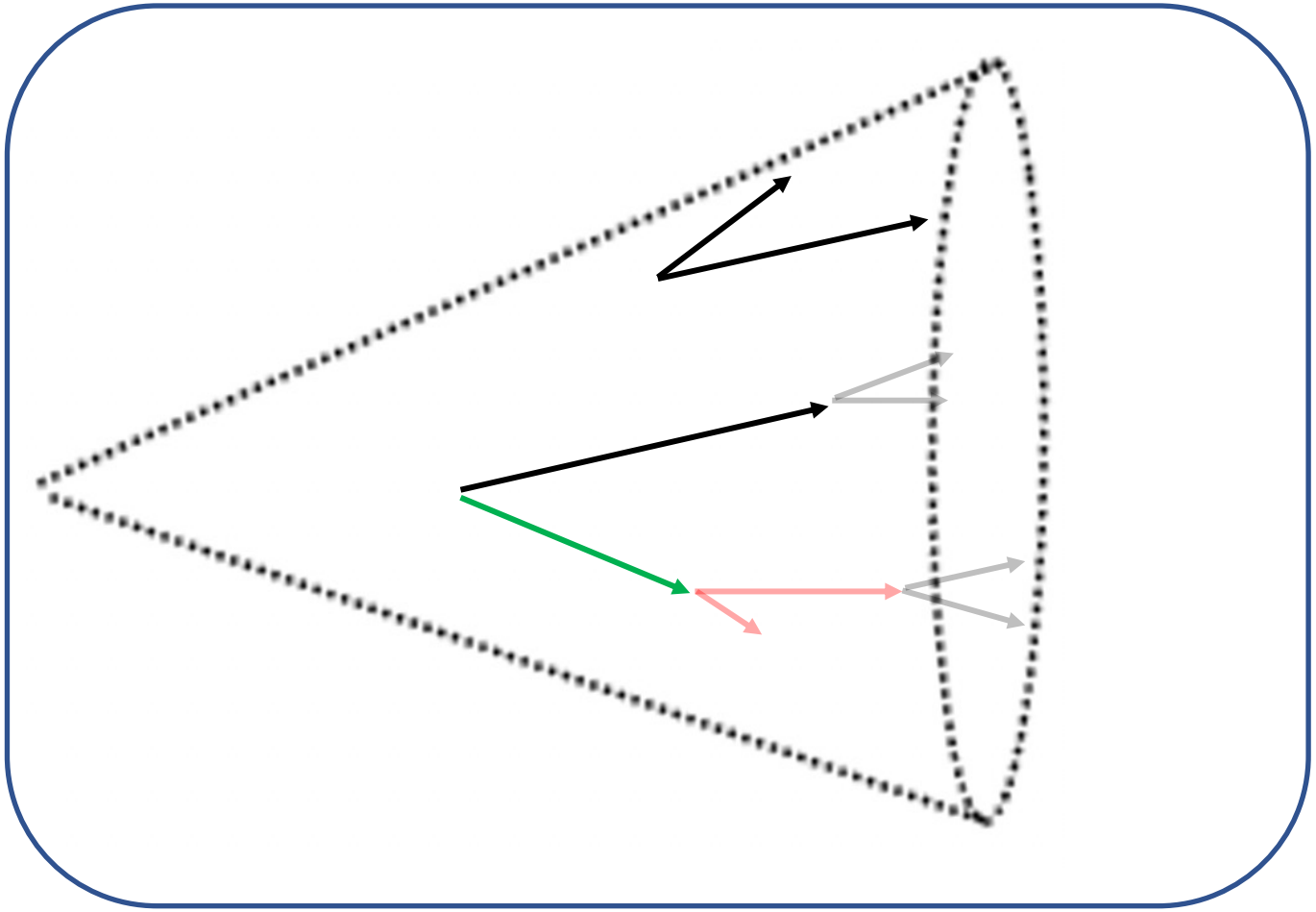

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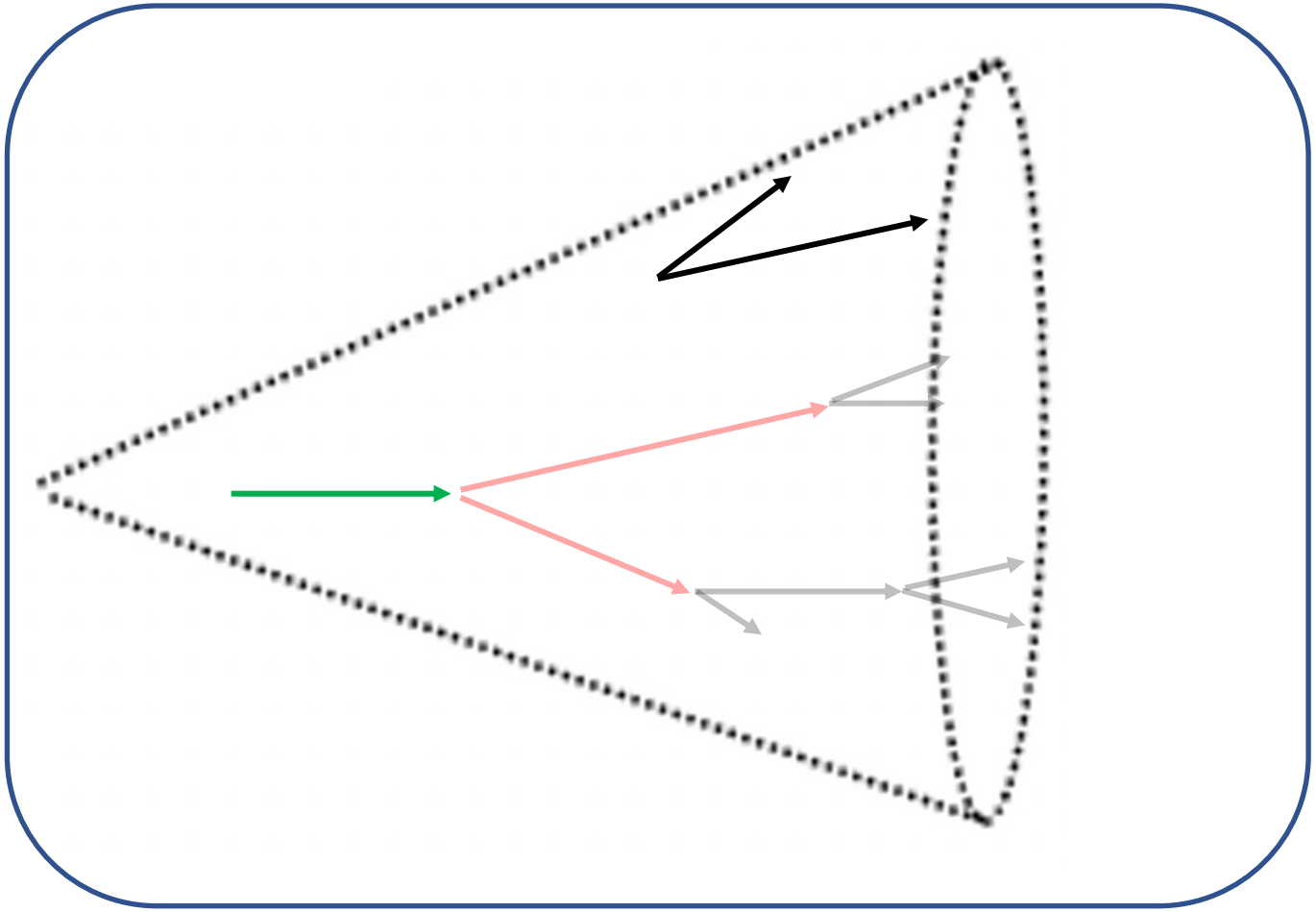

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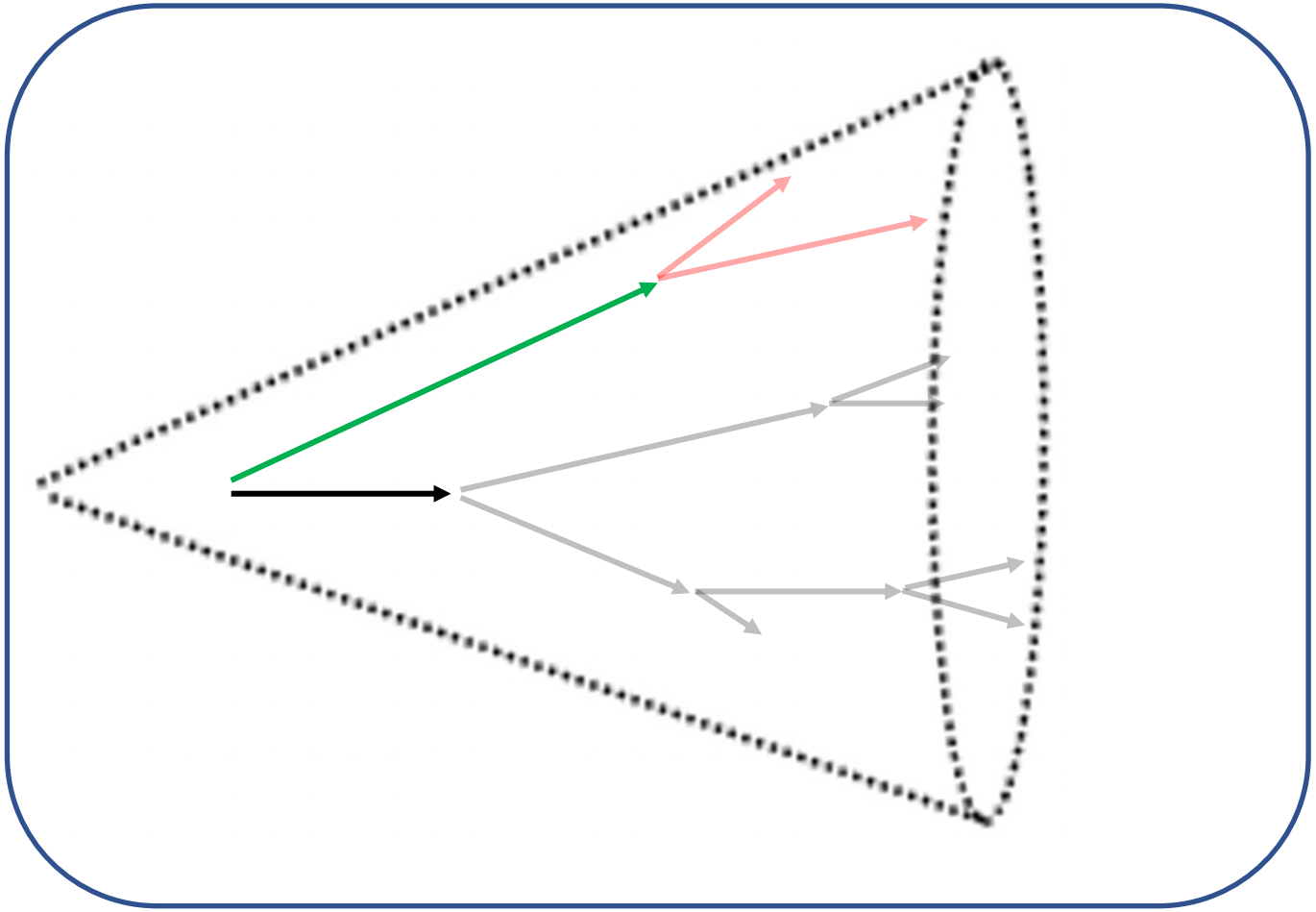

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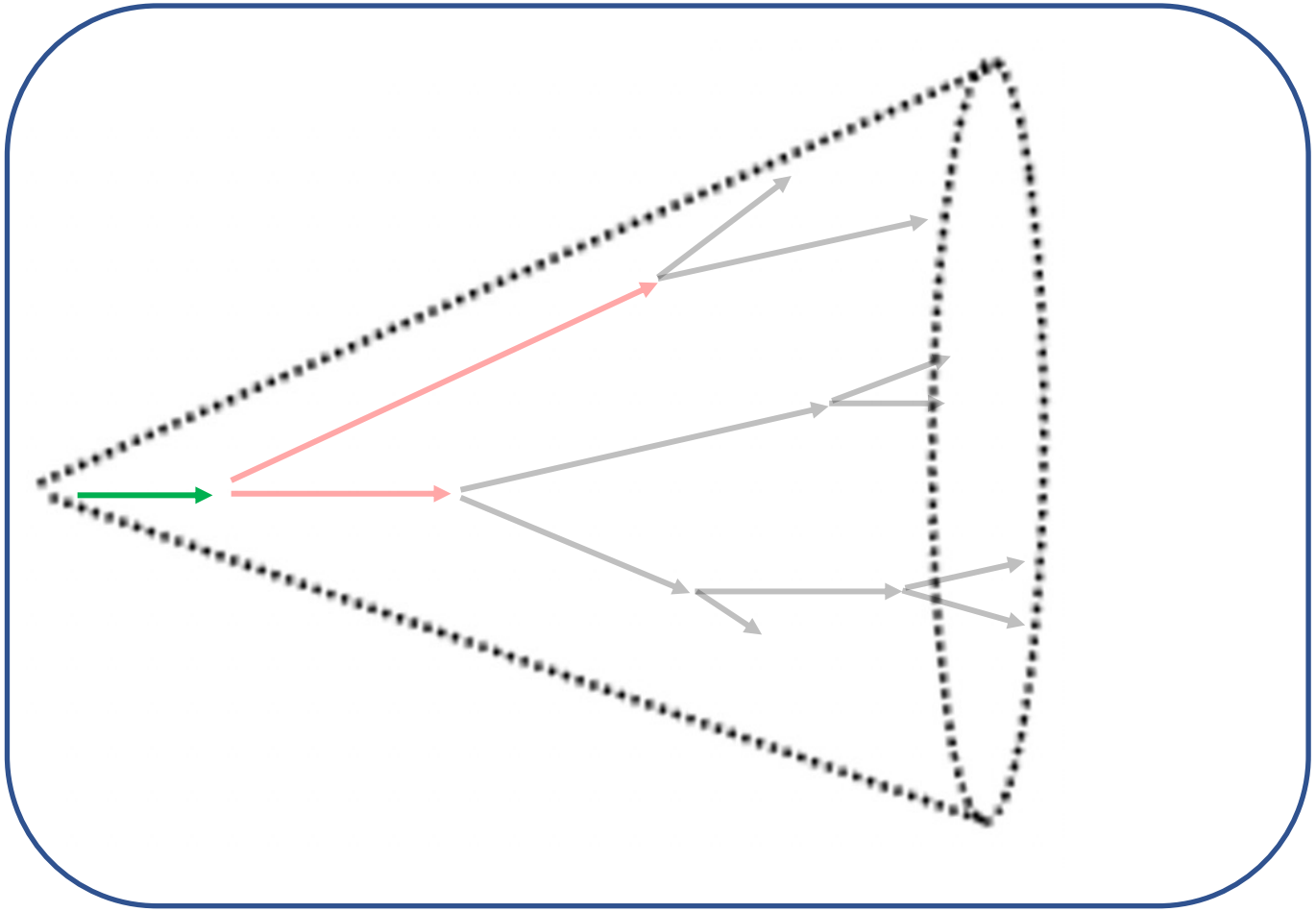

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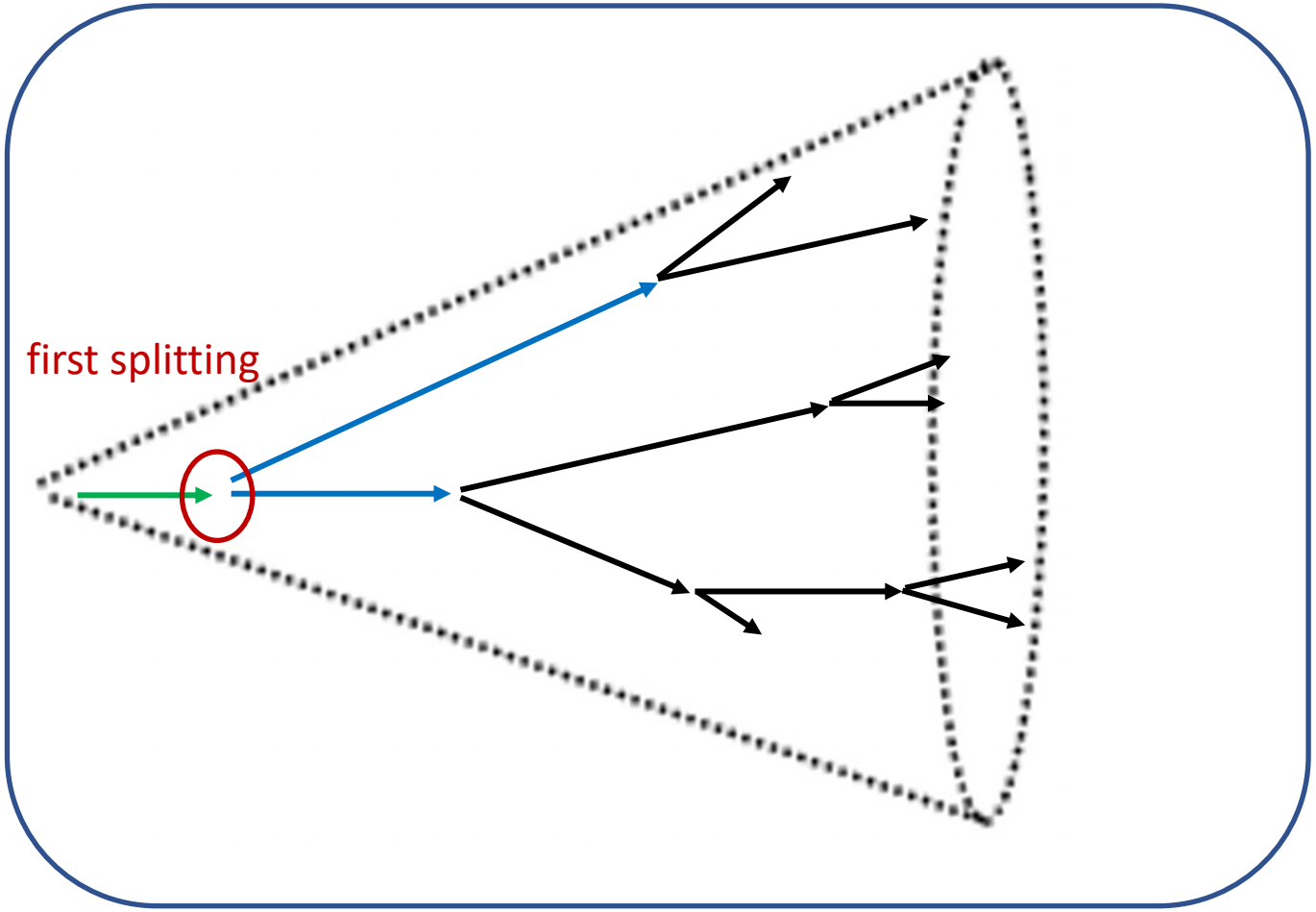

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Unwind the clustering history and follow a given branch of emissions through the shower

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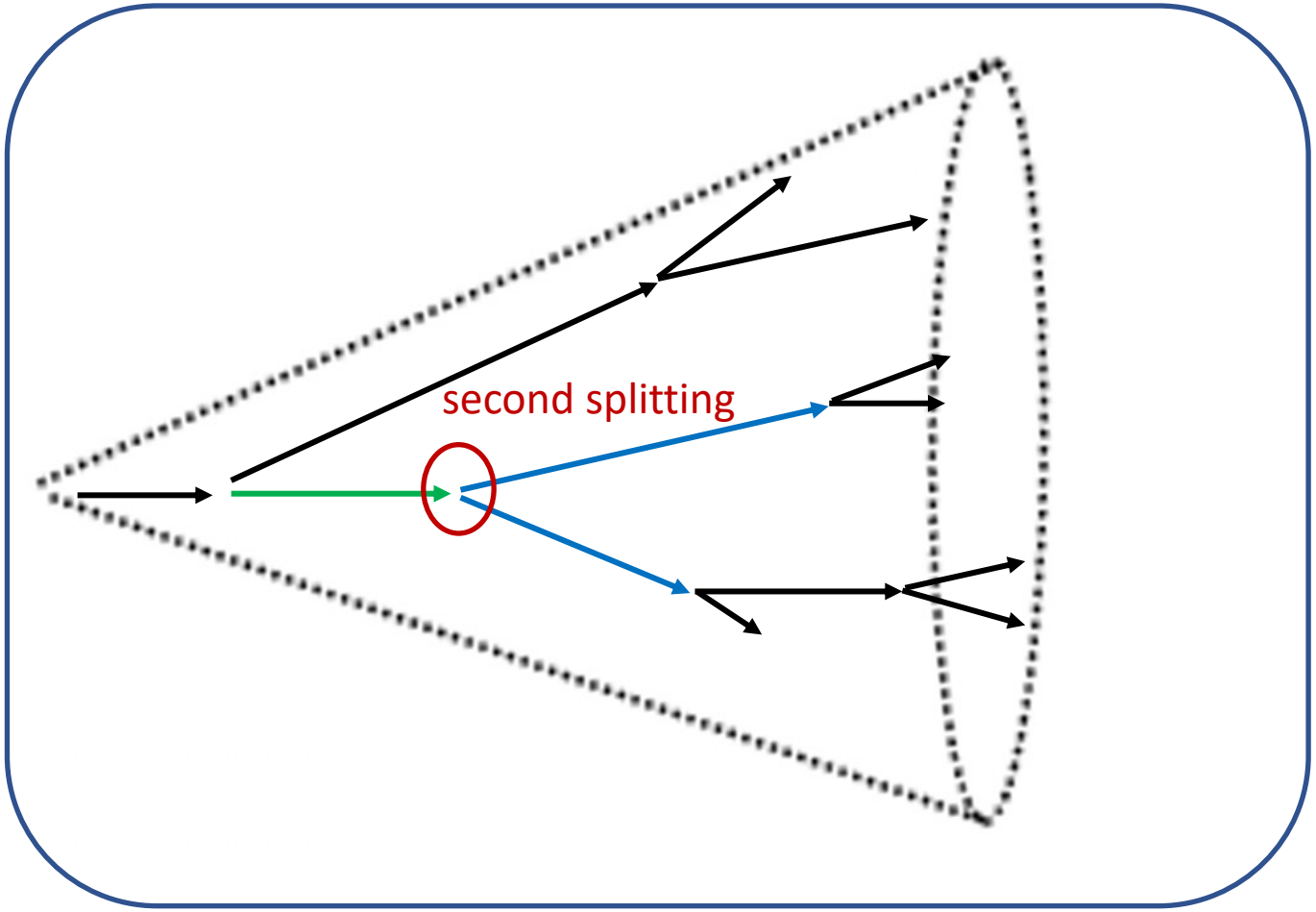

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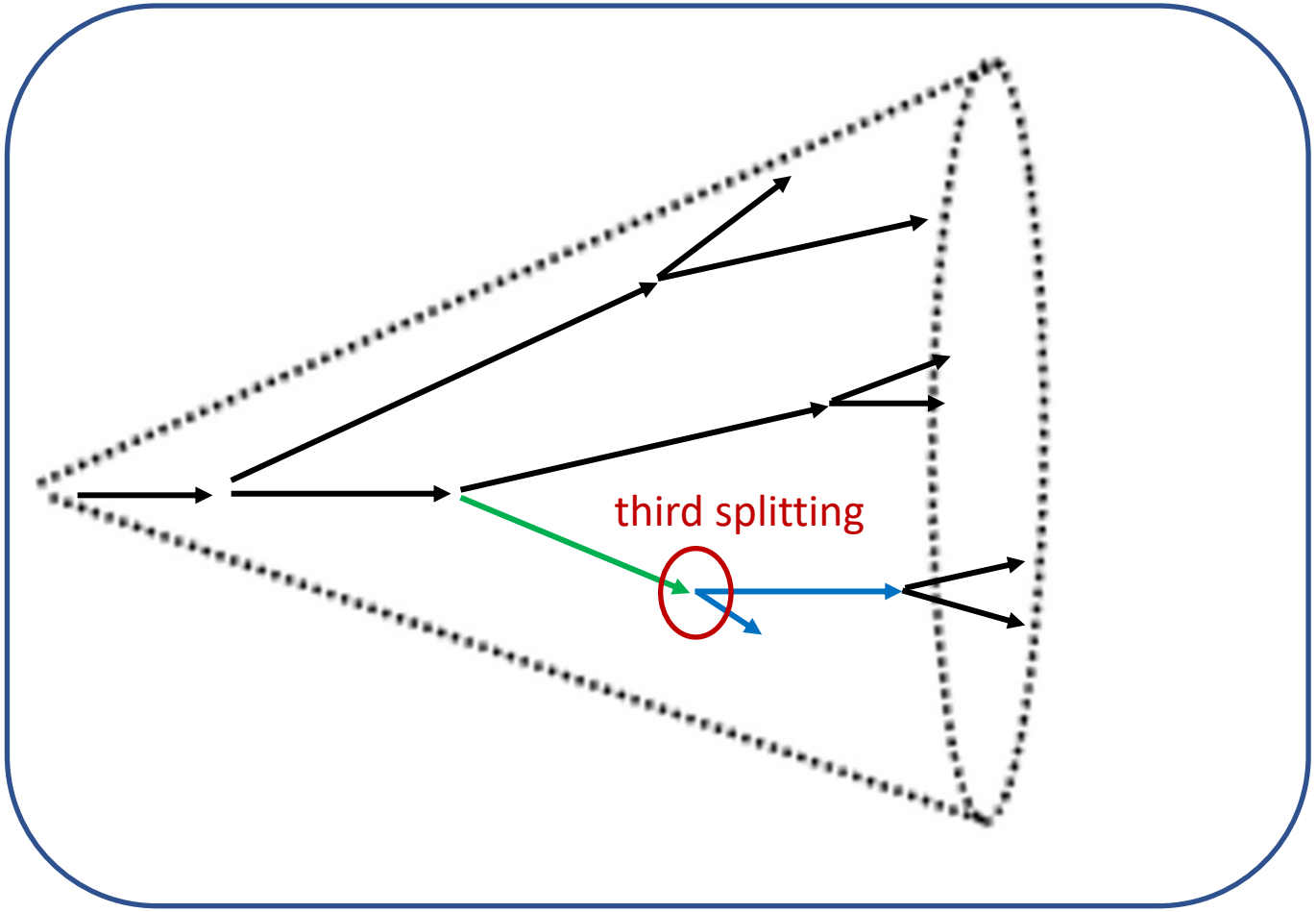

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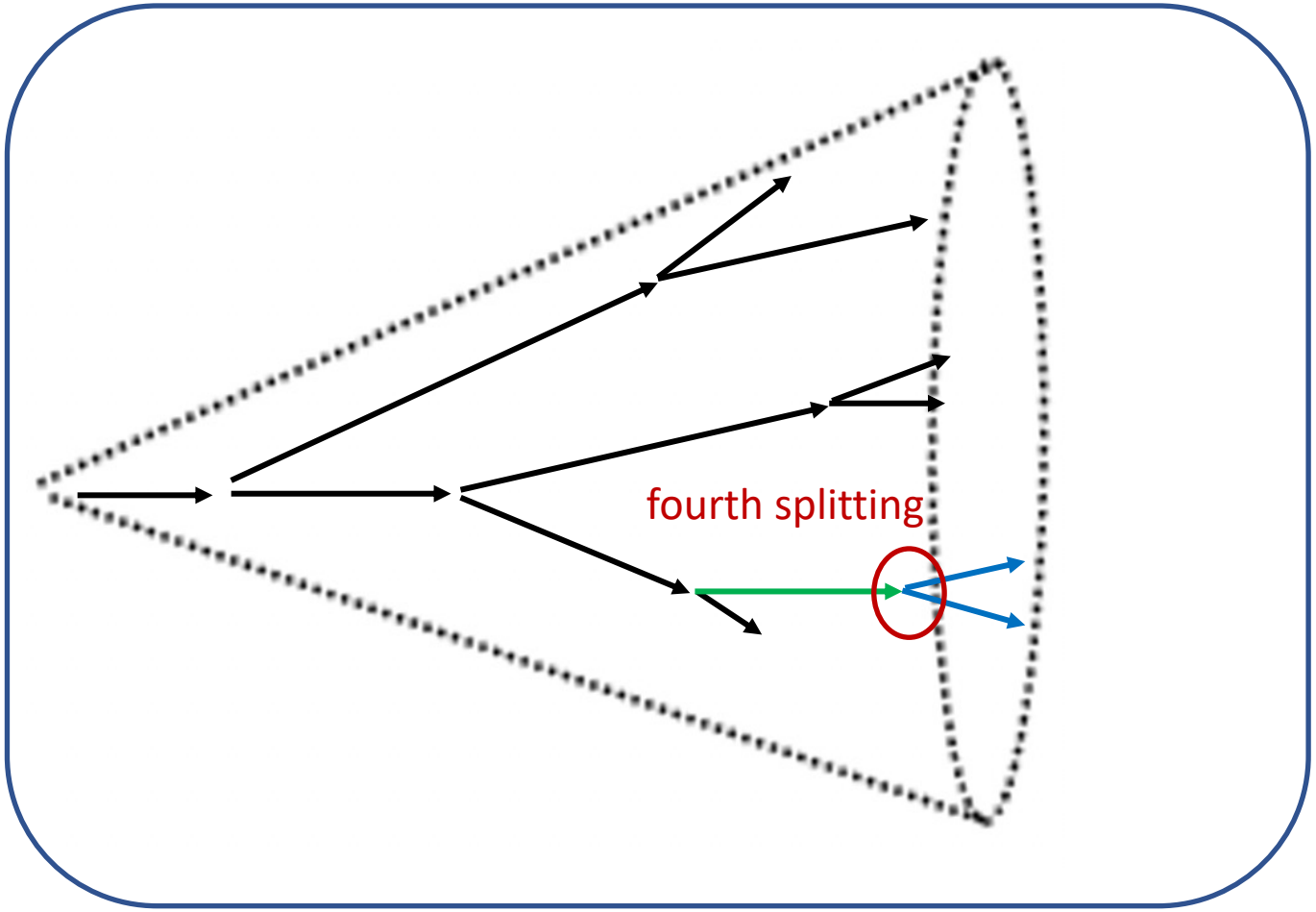

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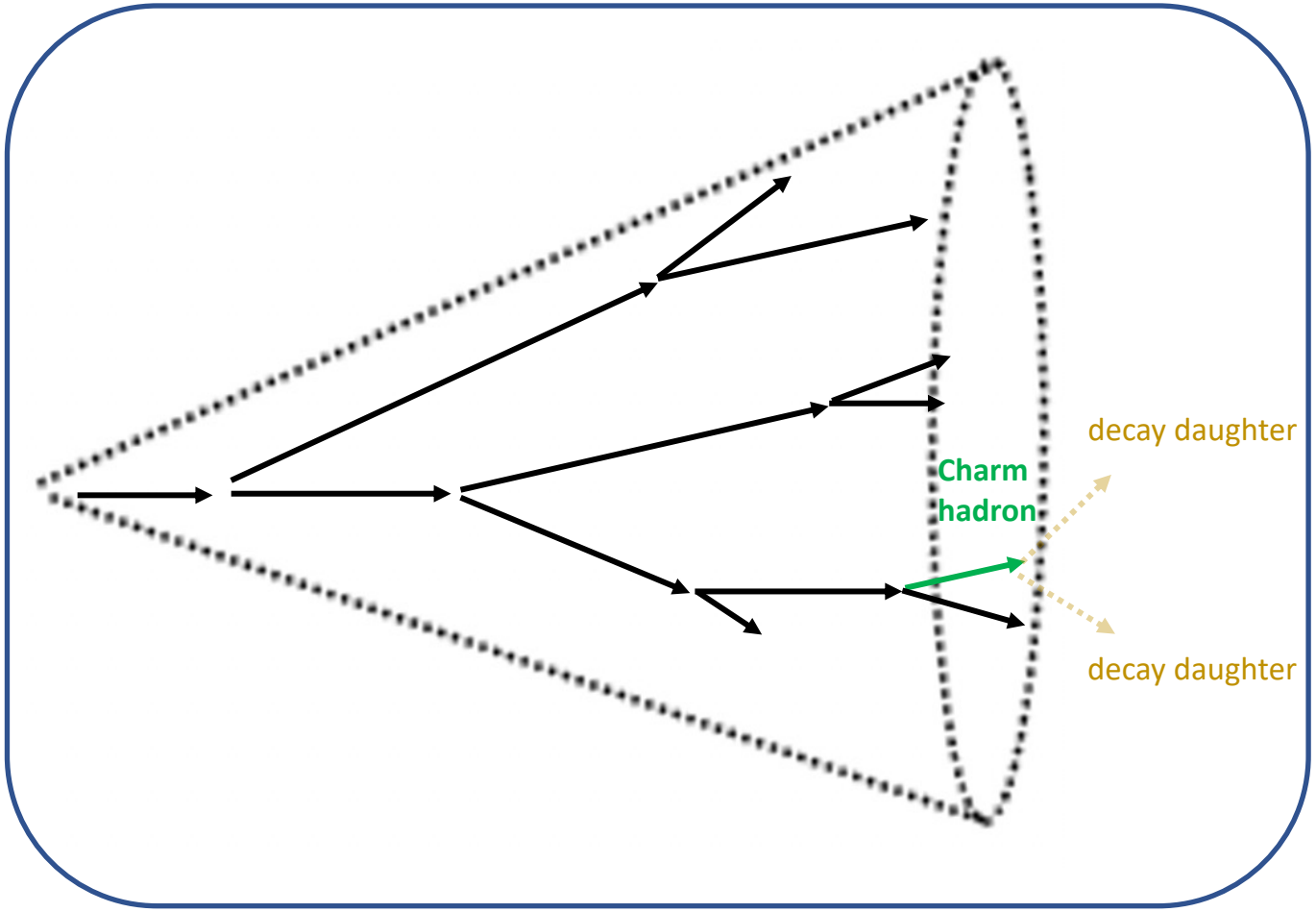
The parton flavour is not necessarily conserved along the followed branch

Using heavy-flavour jets to isolate c->cg splittings



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

Heavy-flavour quarks retain their flavour throughout the shower evolution

Only $Quark_{HF}$ -> $Quark_{HF}$ + Gluon emissions

Due to their large mass HF quarks production is supressed during hadronisation

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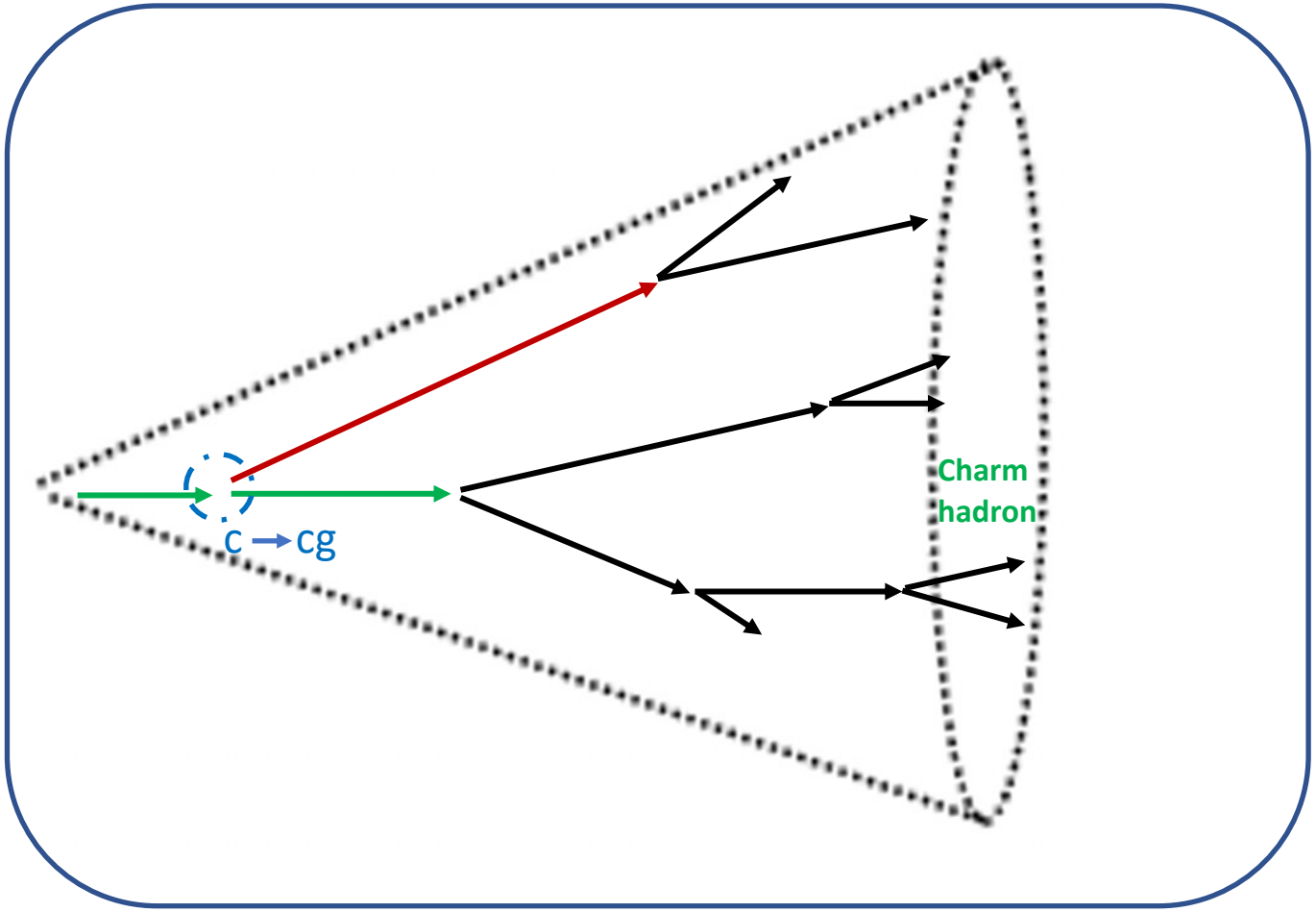

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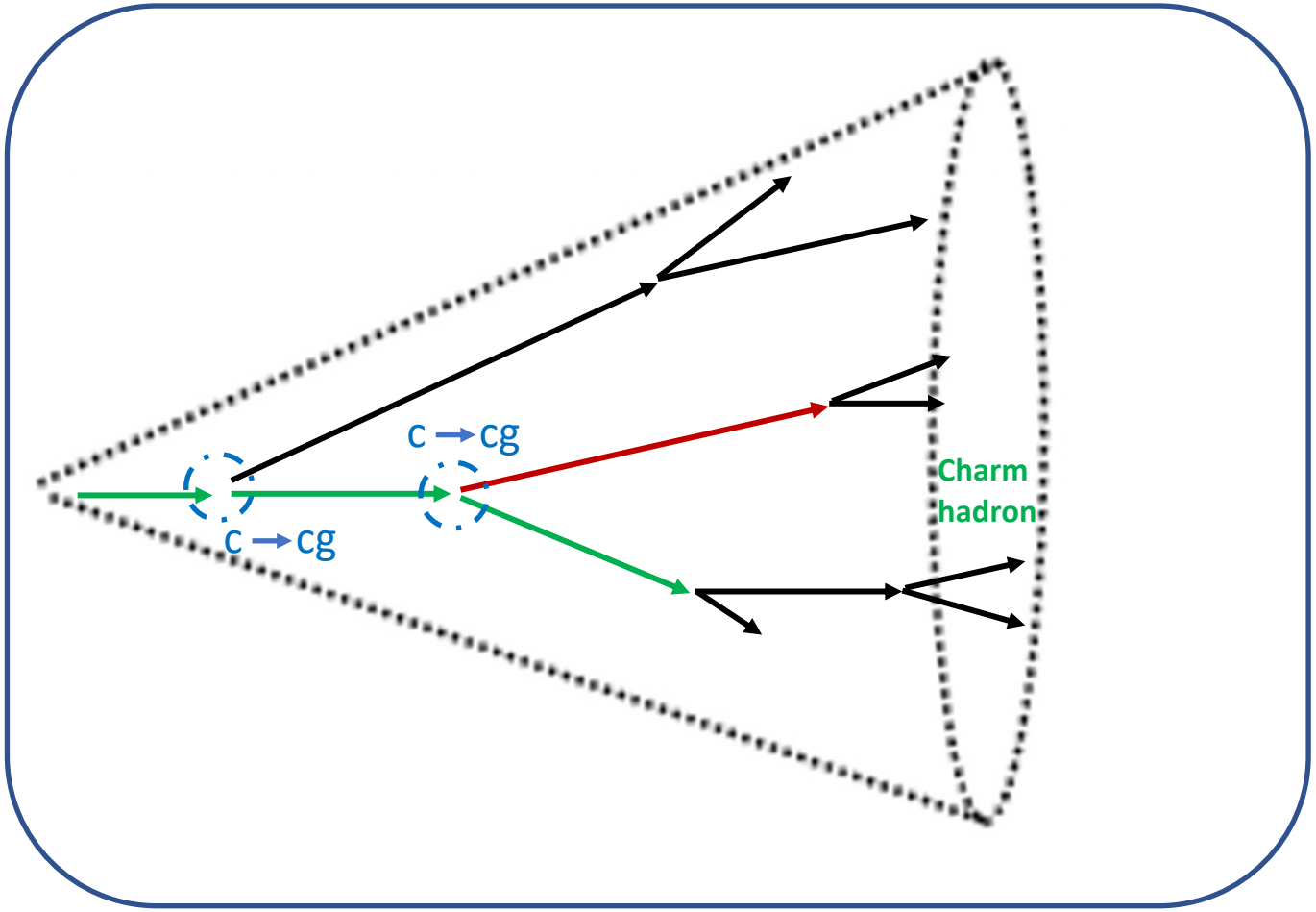

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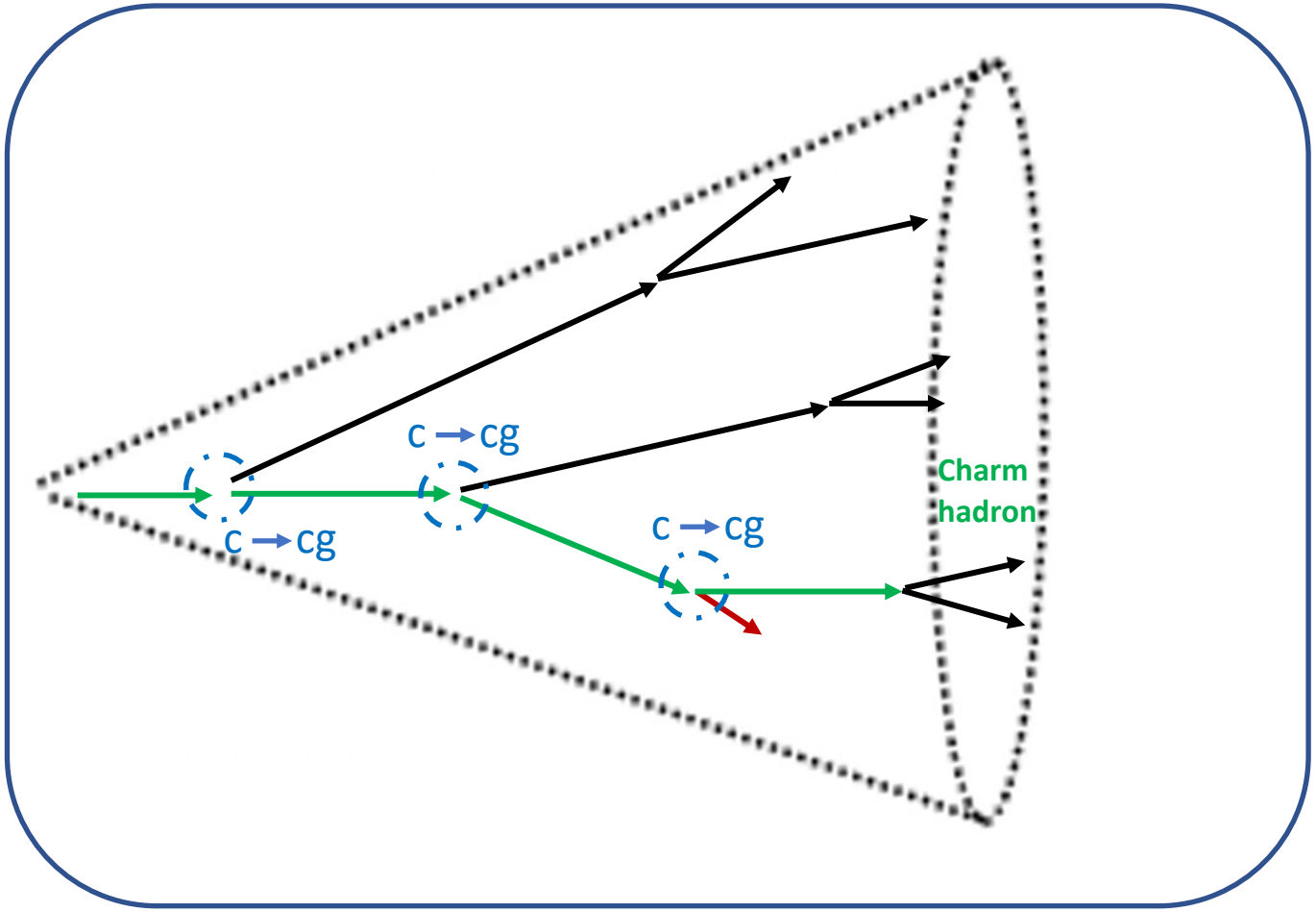

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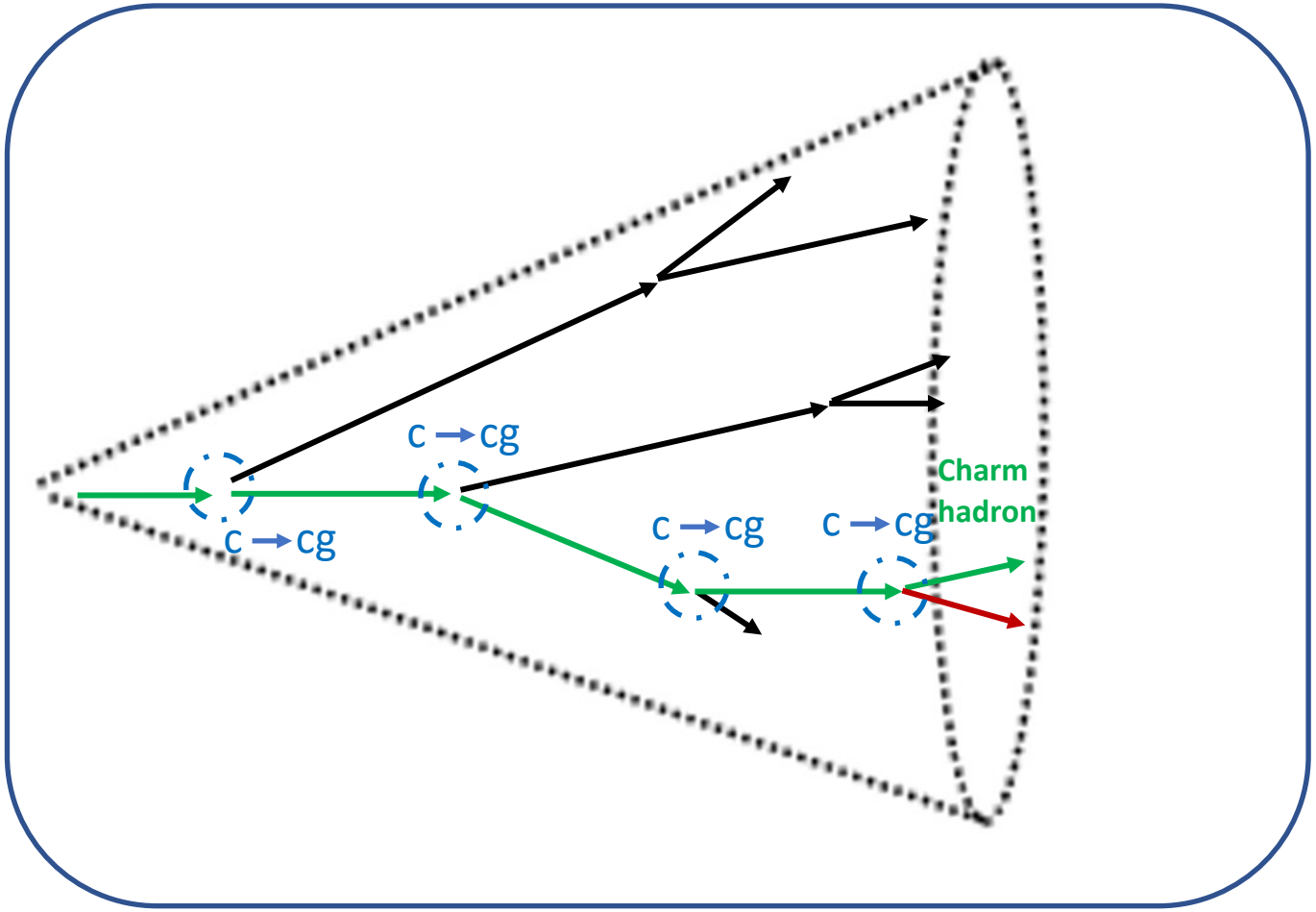

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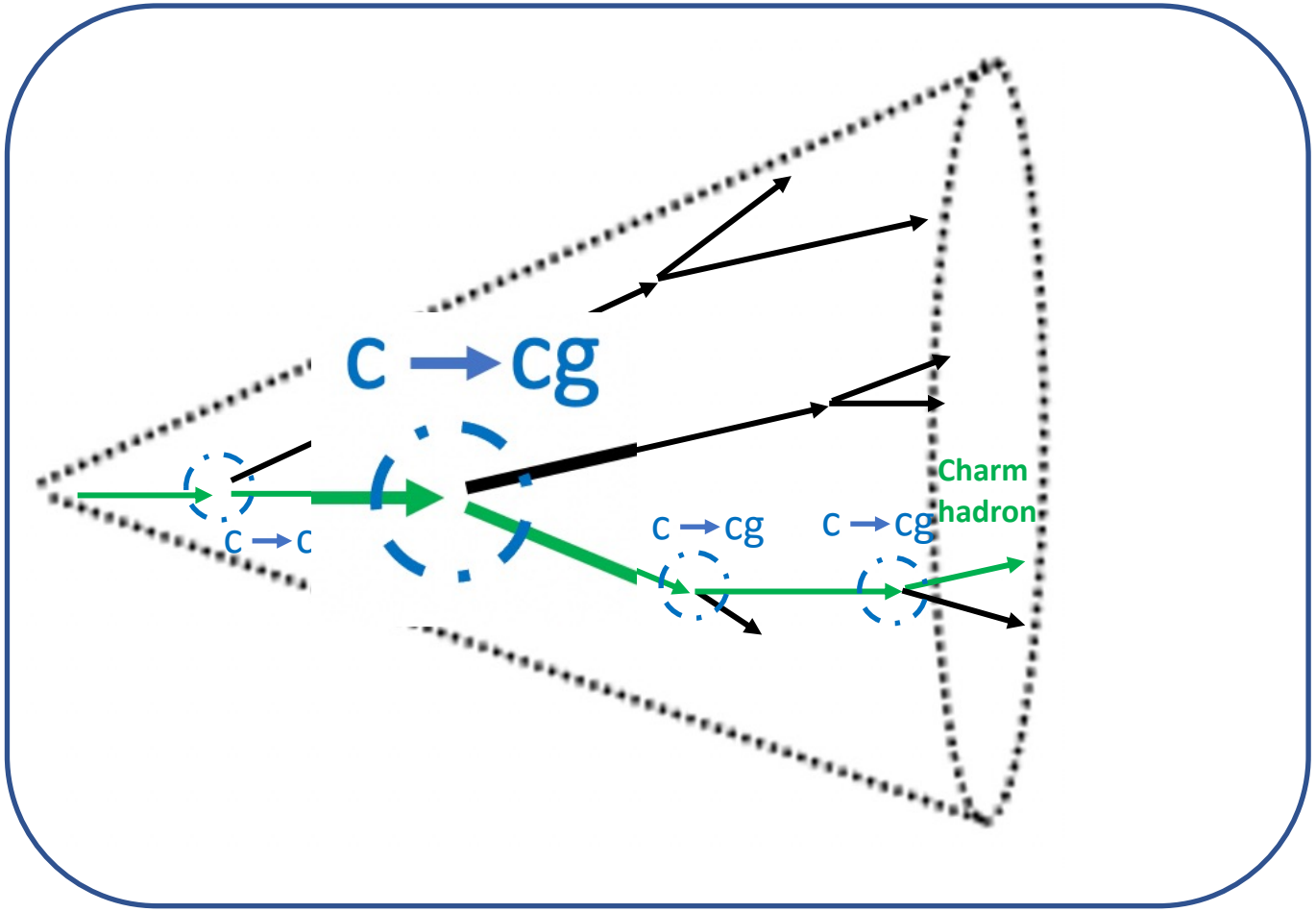
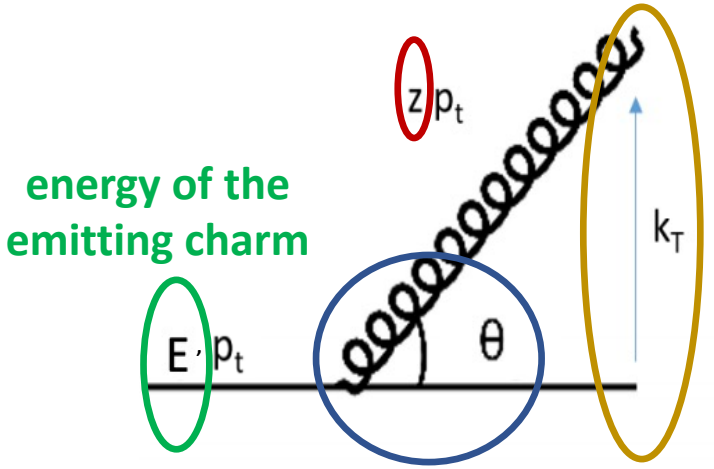
Can follow a quark sample of emissions

Taking a closer look at a reconstructed splitting



fraction of momentum carried by the emitted gluon



energy of the emitting charm

transverse scale of the splitting

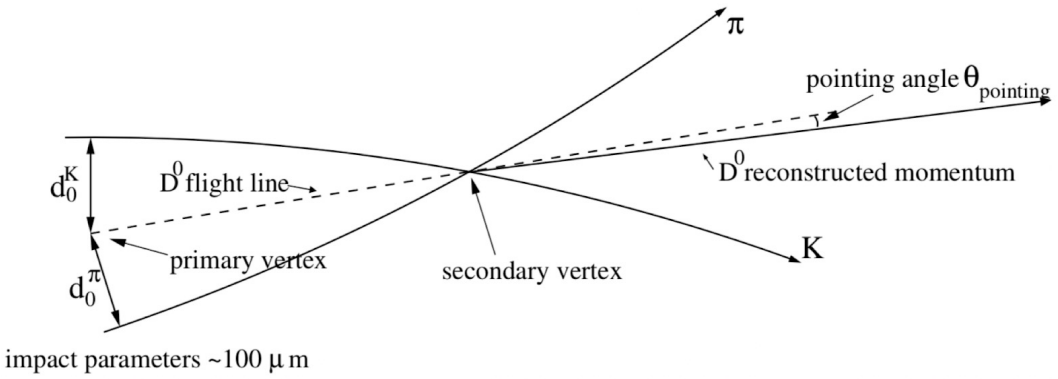
emission angle

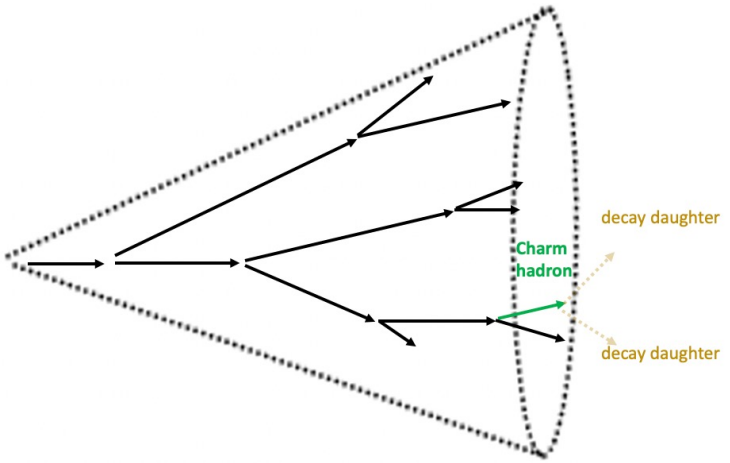
The angle of each gluon emission directly probes the dead-cone effect

The energy of the charm quark at each emission point directly sets the size of the dead-cone region

The transverse scale of each splitting will be used to suppress non-perturbative effects

Tagging a jet with a fully reconstructed HF hadron





Reconstruct the D^0 meson

D^0 mesons are reconstructed through the $D^0 \rightarrow K^- \pi^+$ (and charge conjugate) decay channel

Selections on decay topology and PID are used to identify D^0-meson candidates

$$2 < p_T^{D^0} < 36 \text{ GeV/c}$$

Jet Finding

The analysis is performed using Run 2 pp collisions at

$$\sqrt{s} = 13 \text{ TeV} \qquad \mathcal{L}_{int} = 25 \text{ nb}^{-1}$$

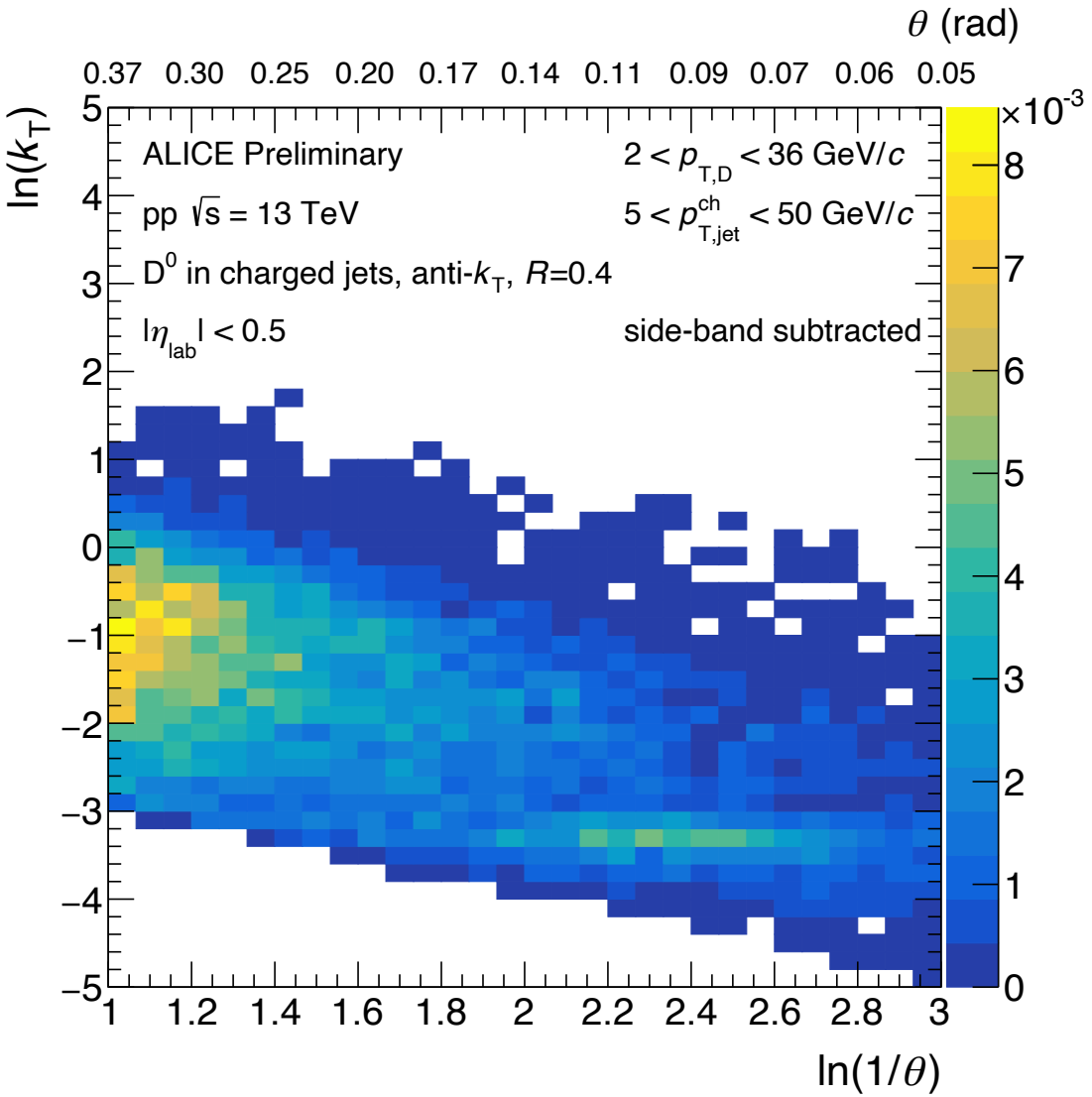
The D^0 decay daughters are replaced by the D^0 prior to jet finding

Jet finding is performed using the anti-k_T algorithm with R =0.4

$$5 < p_T^{jet} < 50 \text{ GeV/c}$$

Jets with a D^0-meson candidate amongst their constituents are selected

Obtaining a complementary inclusive measurement



Primary Lund plane of c->cg emissions

Measurement of a Lund plane of a particular splitting flavour in QCD

Uncovering the QCD dead cone

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

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

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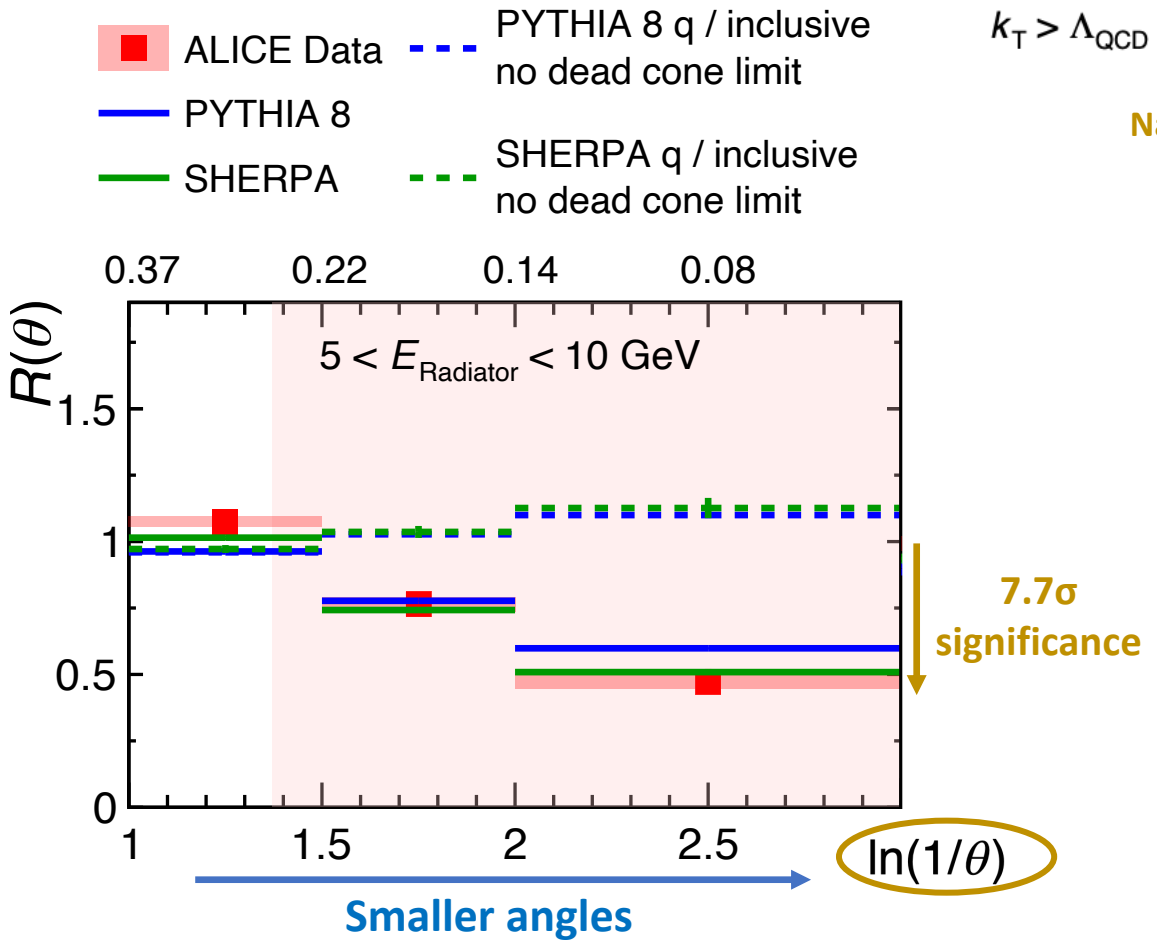

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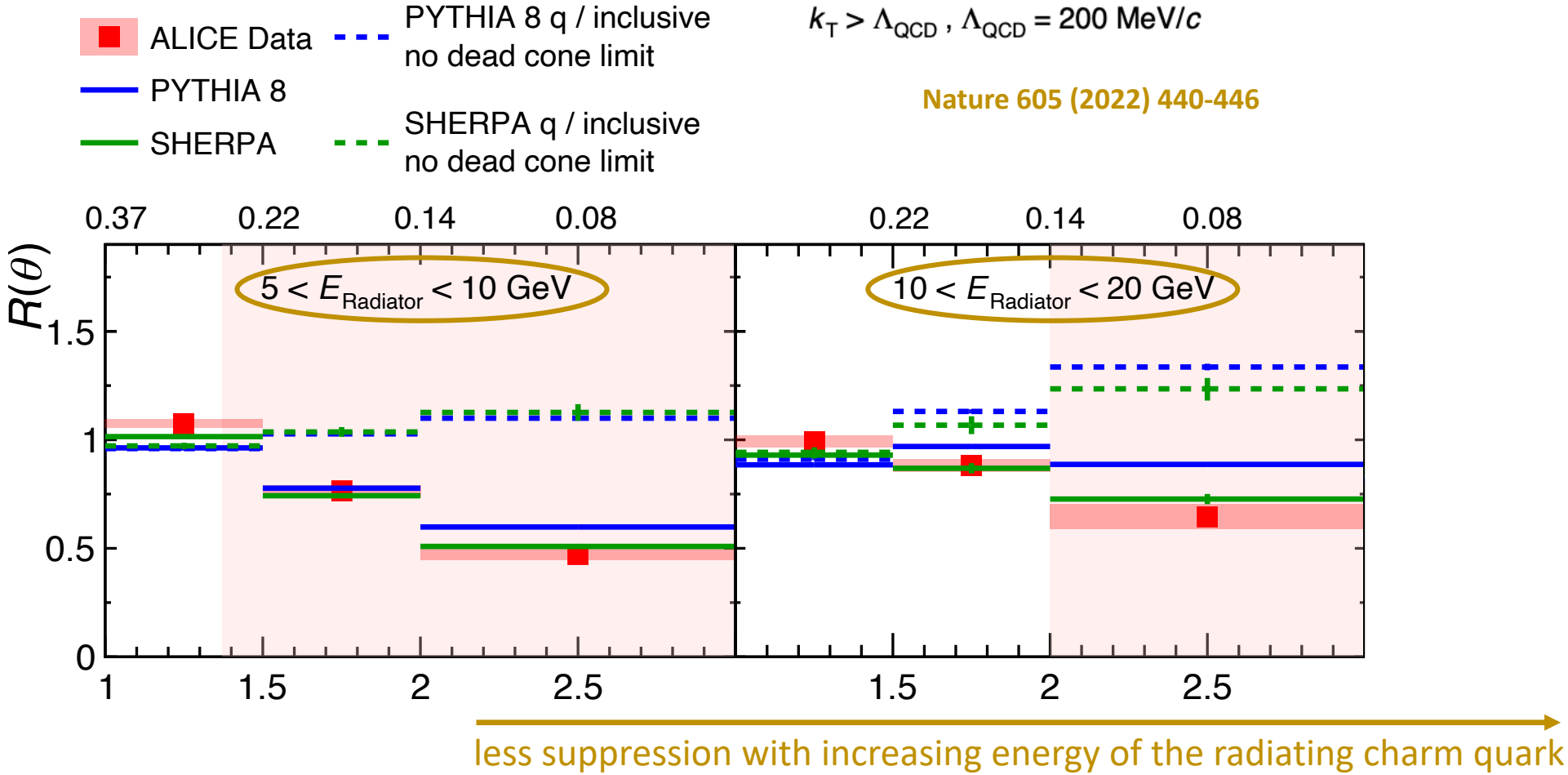

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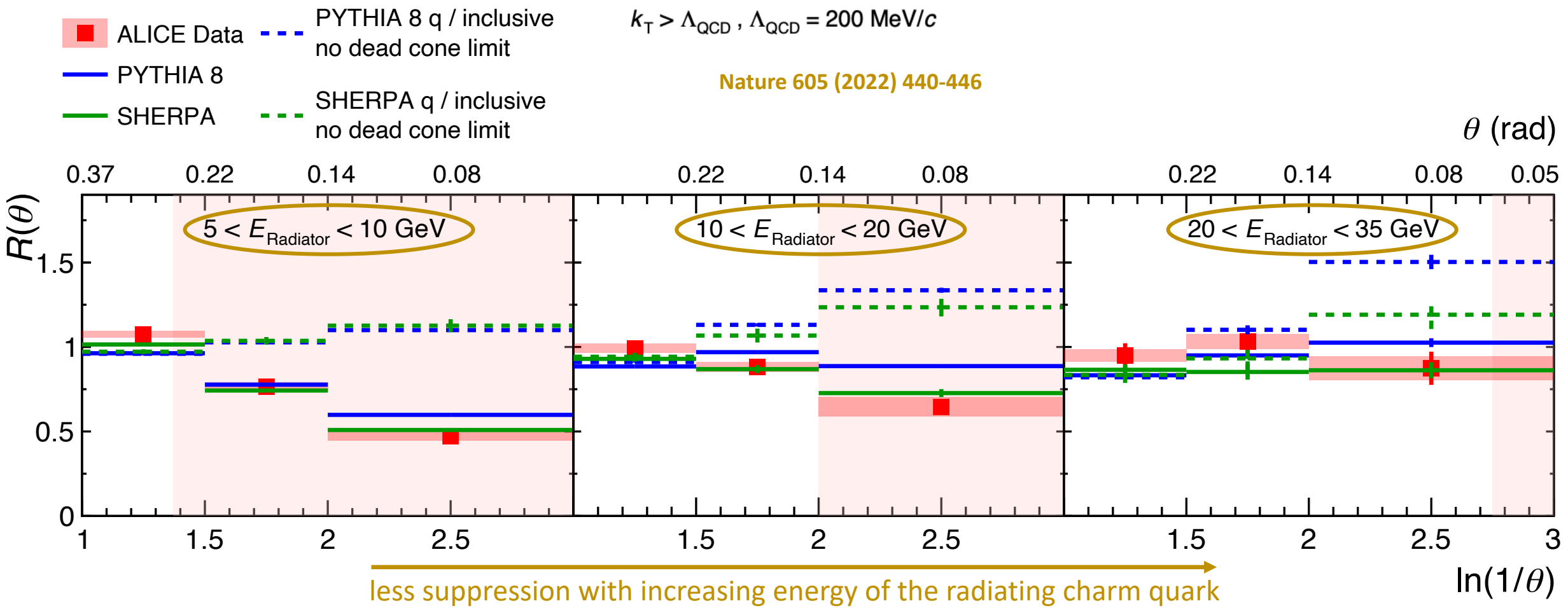

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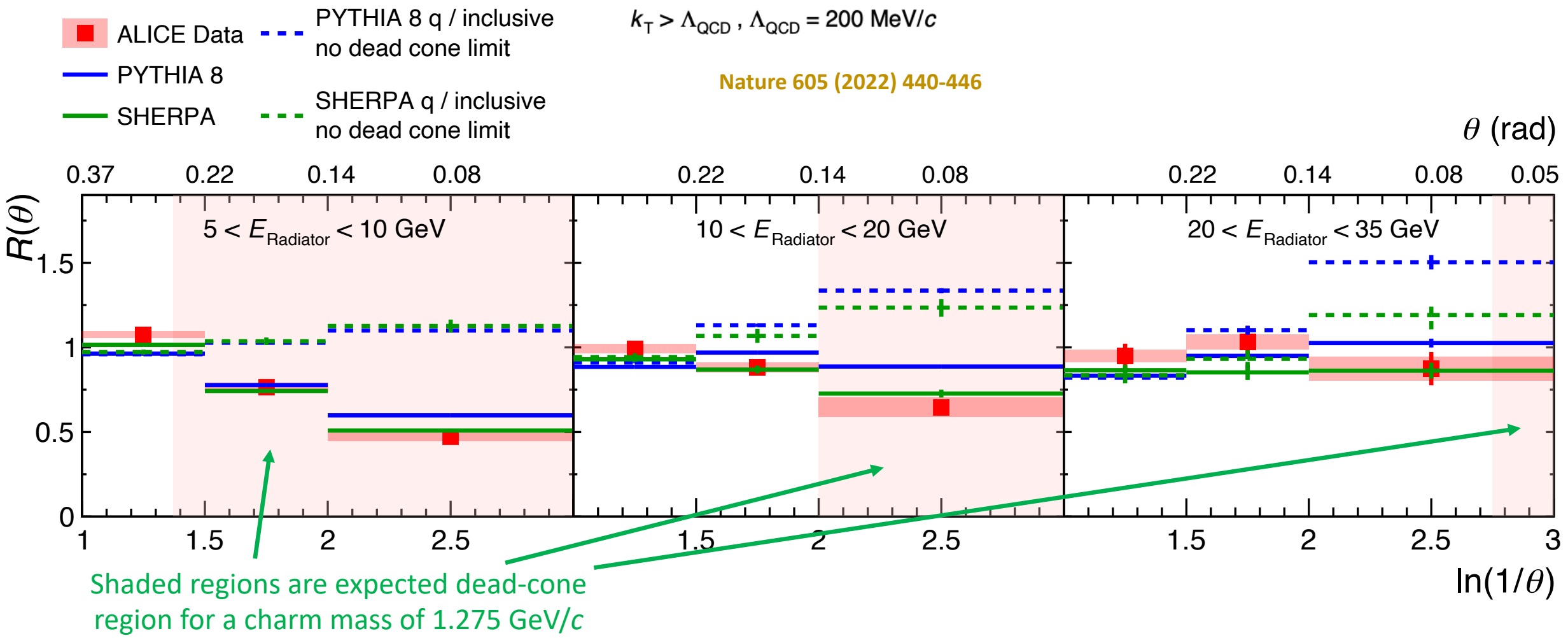

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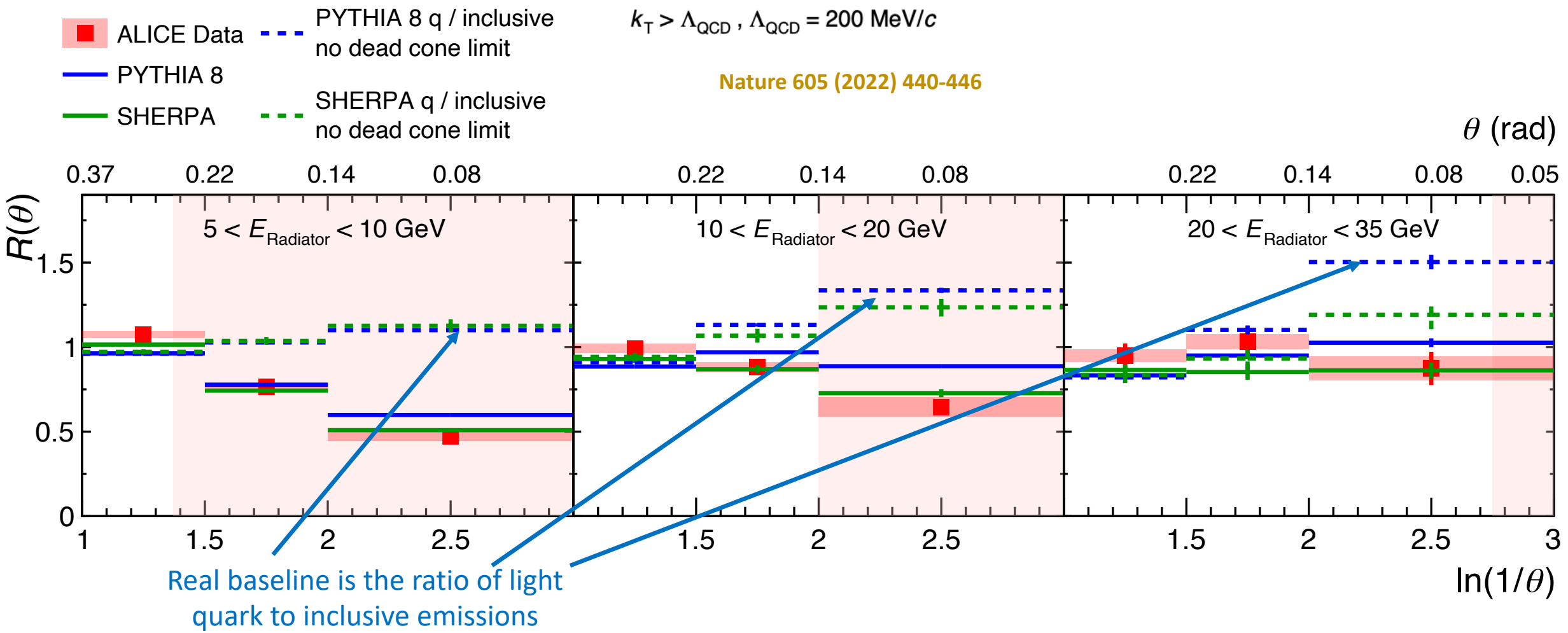

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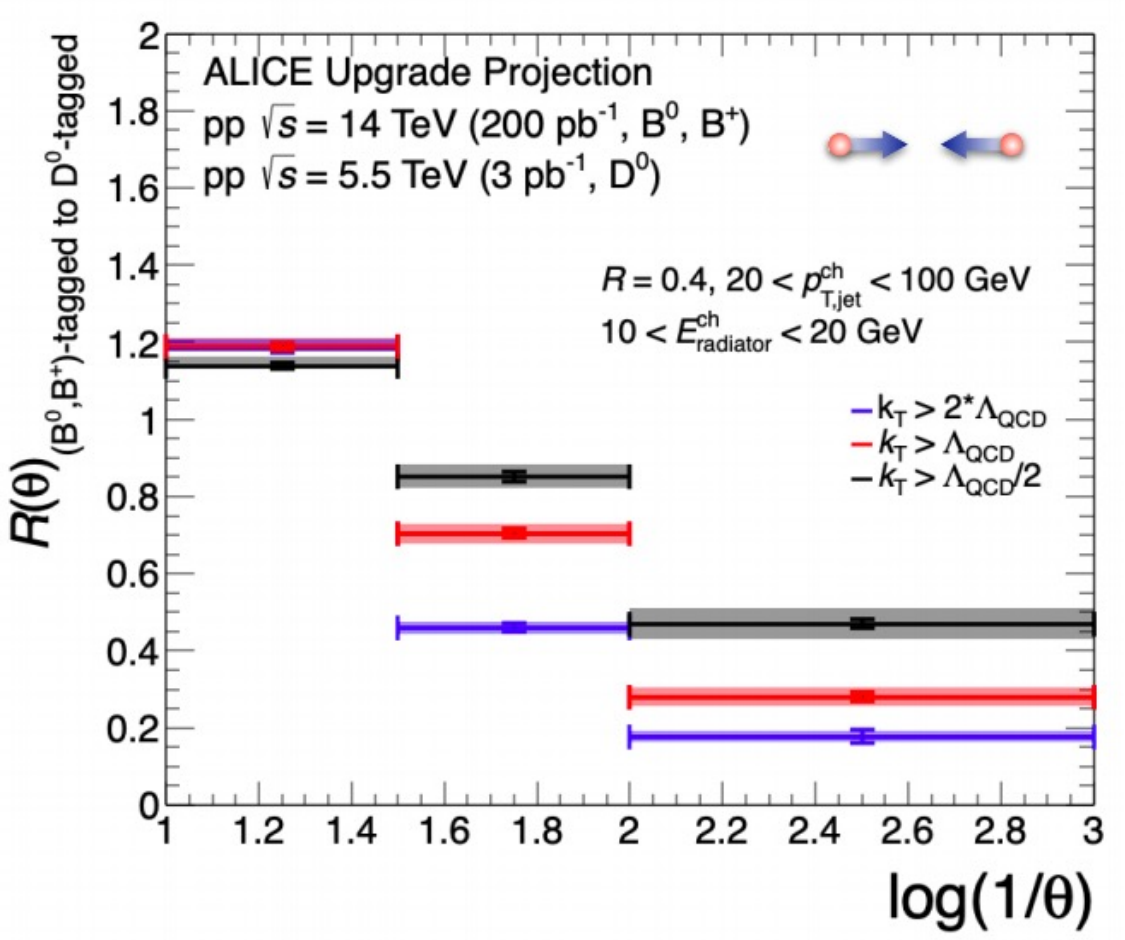
Compare the angular distribution of charm-quark emissions to those of light quarks and gluons

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

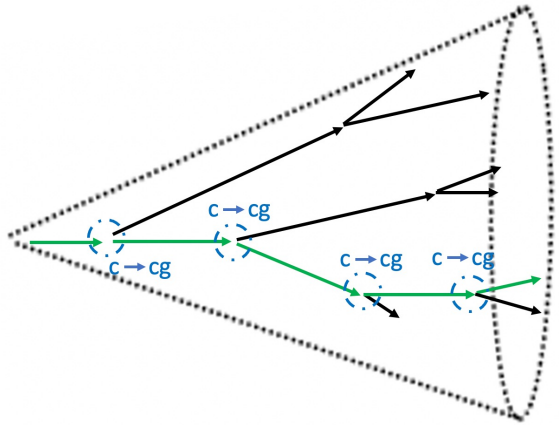


Low p_T charm and inclusive sensitive to both mass and Casmir colour effects (Run 2)

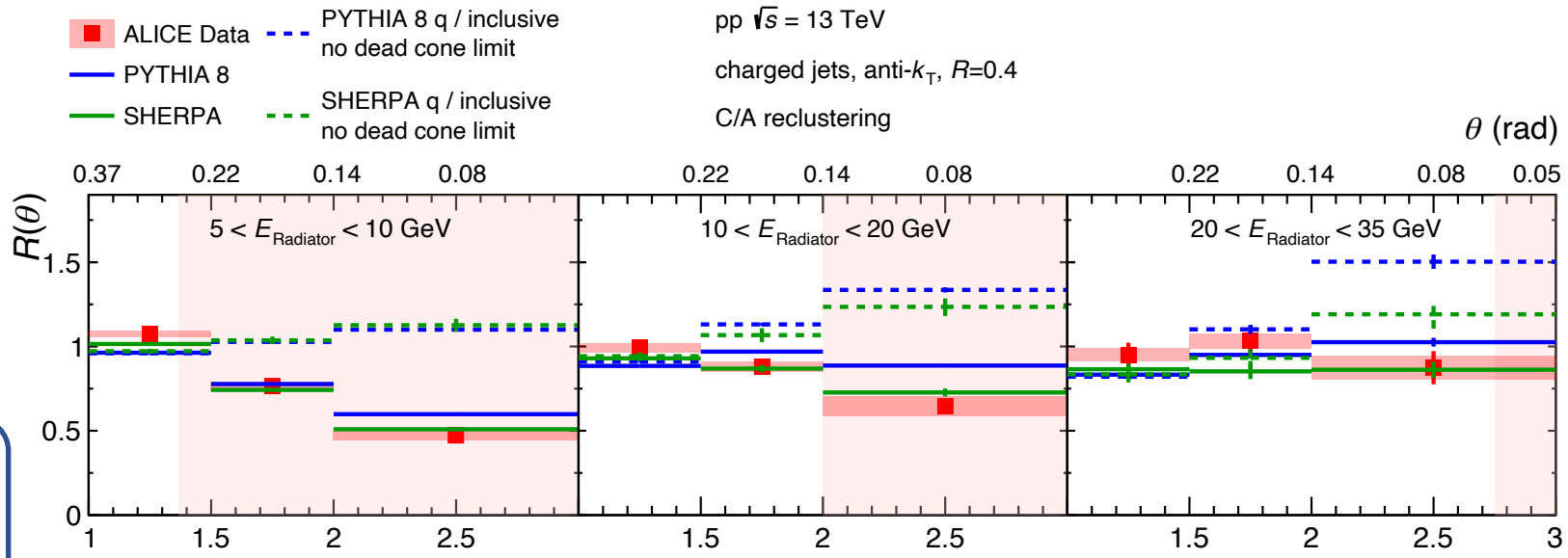
Beauty and charm-quark emissions isolate mass effects

High p_T charm and inclusive comparisons isolate Casmir colour factors

Summary

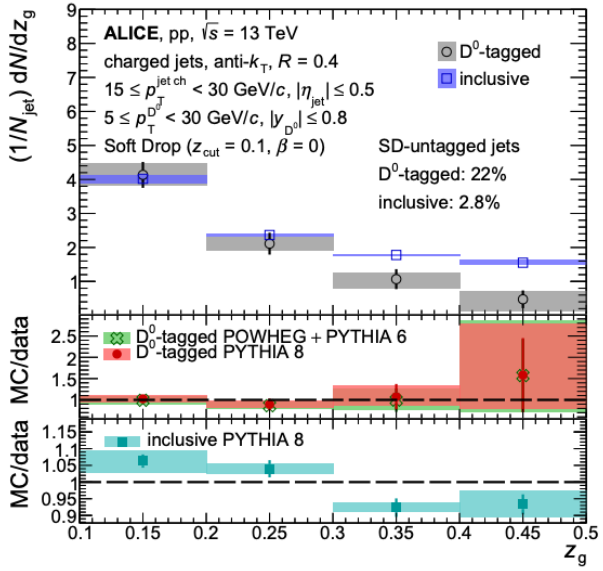


New experimental technique to reconstruct emissions of heavy-flavour quarks in the parton shower



Direct observation of the dead-cone effect

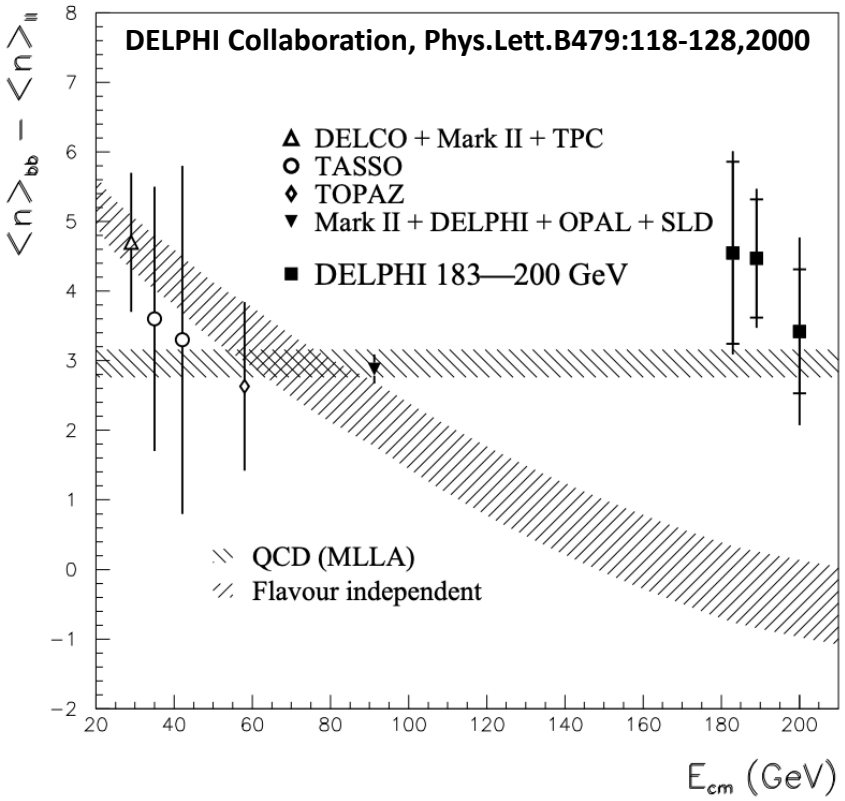
See G. M. Innocenti's talk on Tuesday for more details



Constraining the role of parton mass and Casimir colour factors in the parton shower

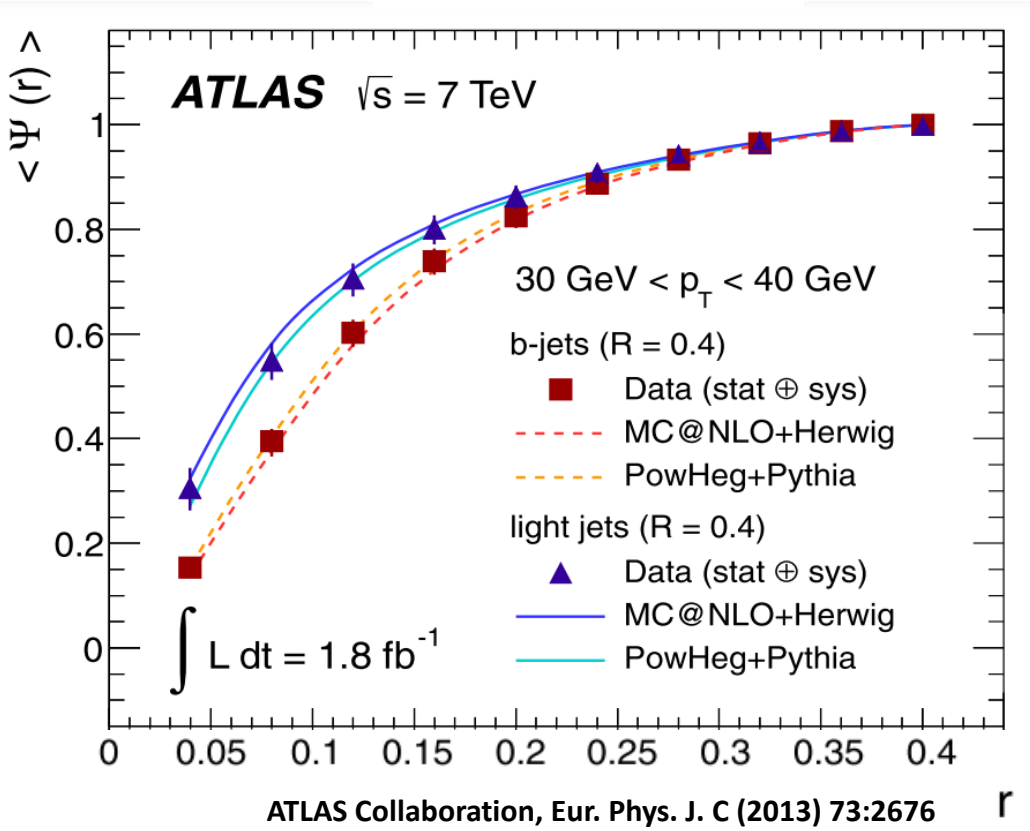
Backup

Previous indirect measurements



Difference in average multiplicity between events containing a b-quark jet and and those with a light-quark jet compatible with flavour dependent QCD calculations

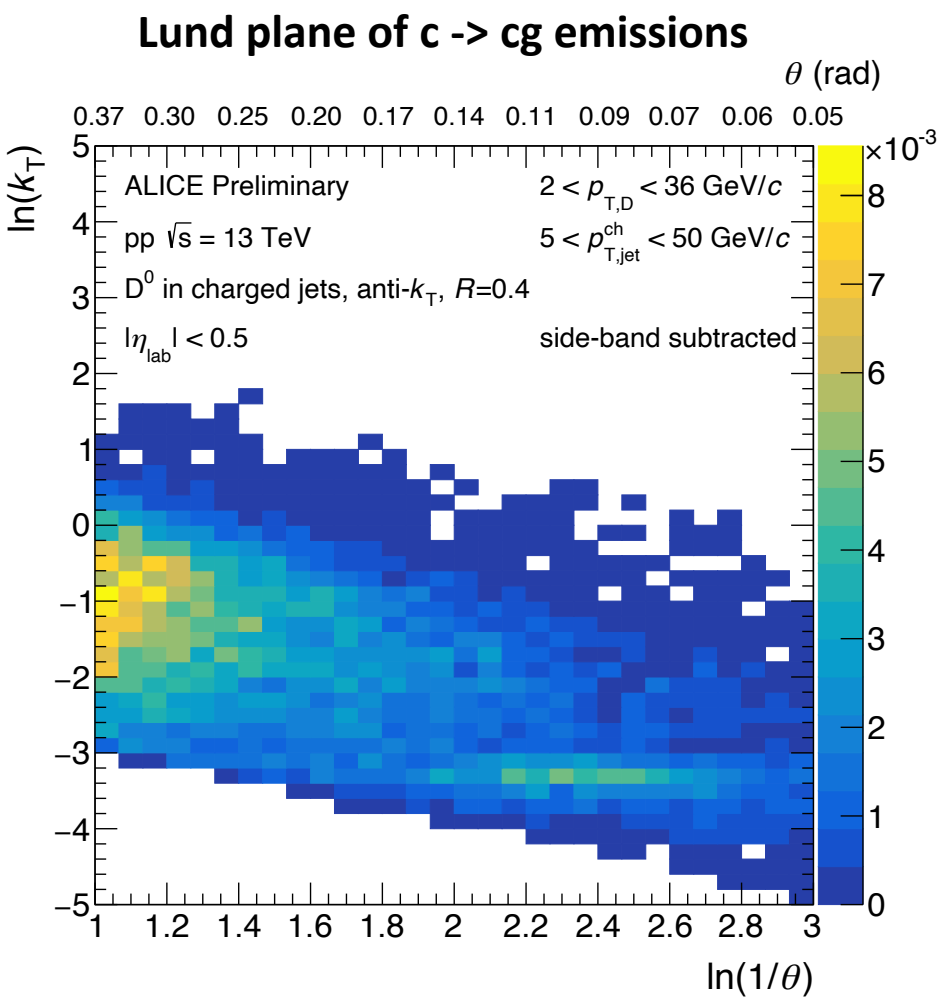
$$\Psi(r) = \frac{p_T(0,r)}{p_T(0,R)}; \quad r \le R$$



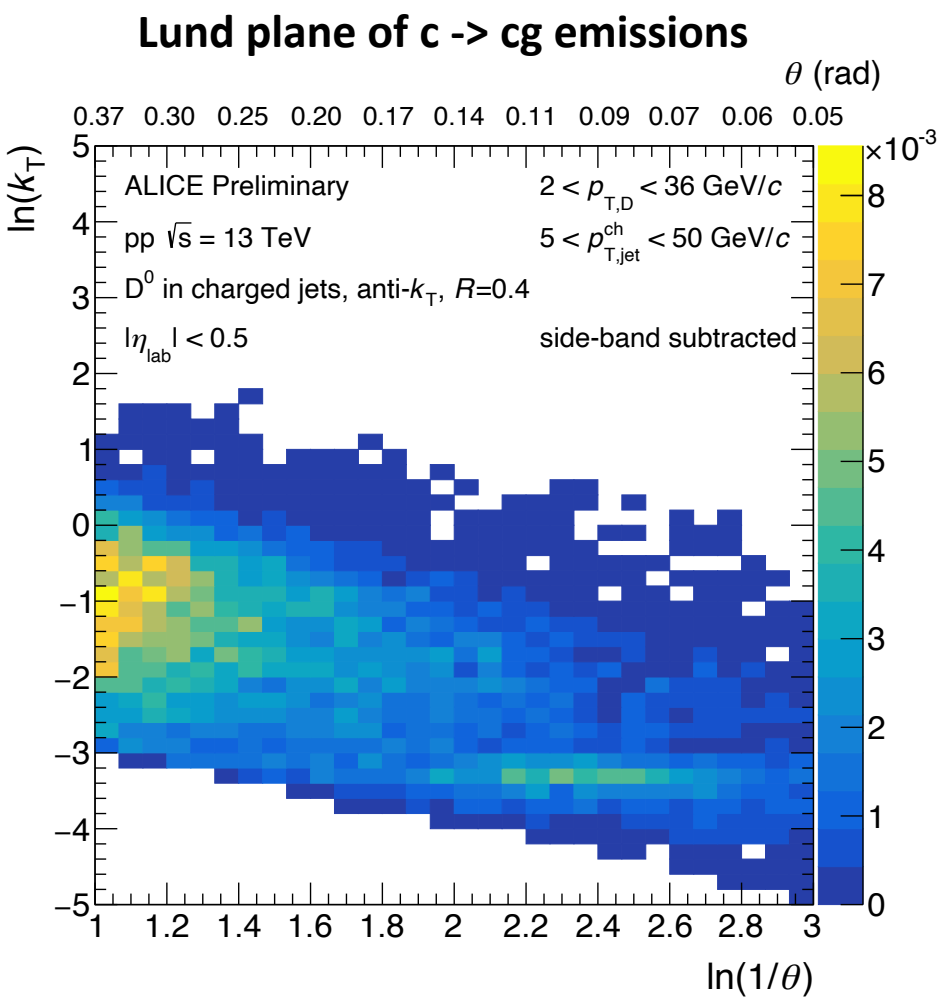
ATLAS Collaboration, Eur. Phys. J. C (2013) 73:2676

p_T density around the initial scattered b-quark direction is depleted compared to the density around light quarks and gluons

Obtaining a complementary inclusive measurement



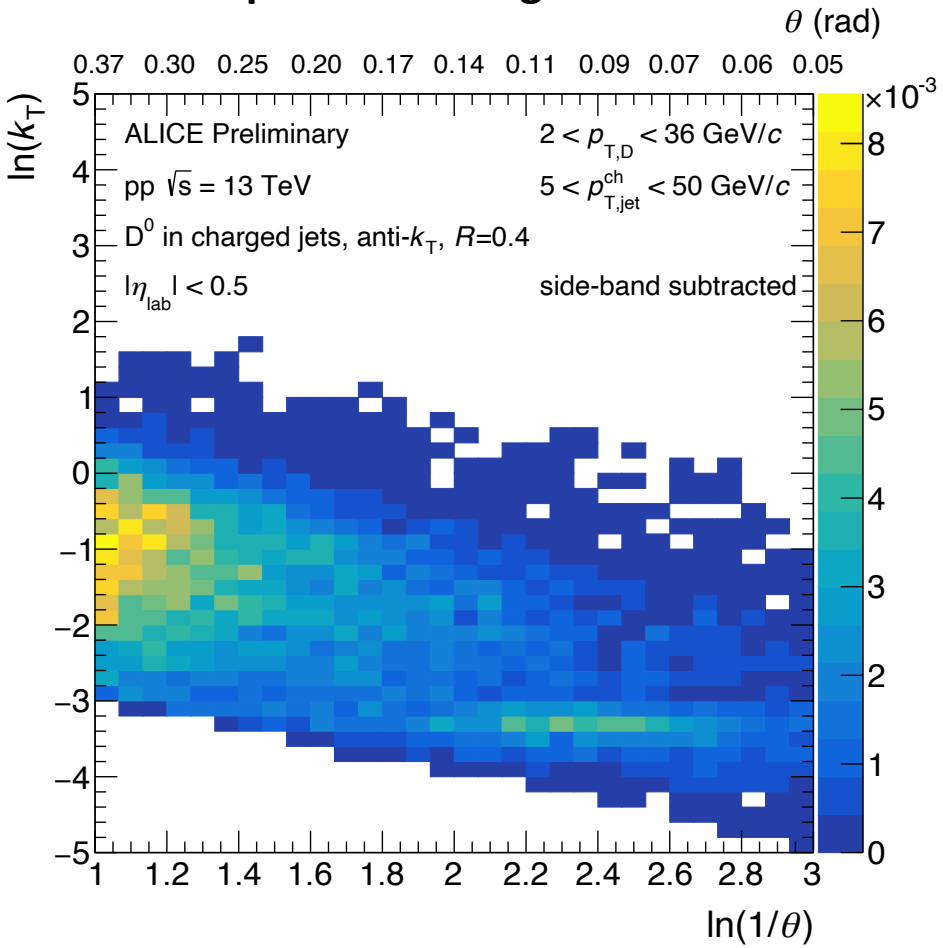
Obtaining a complementary inclusive measurement



Following the branch containing the D^0 coincides with following the hardest branch in 99% of cases

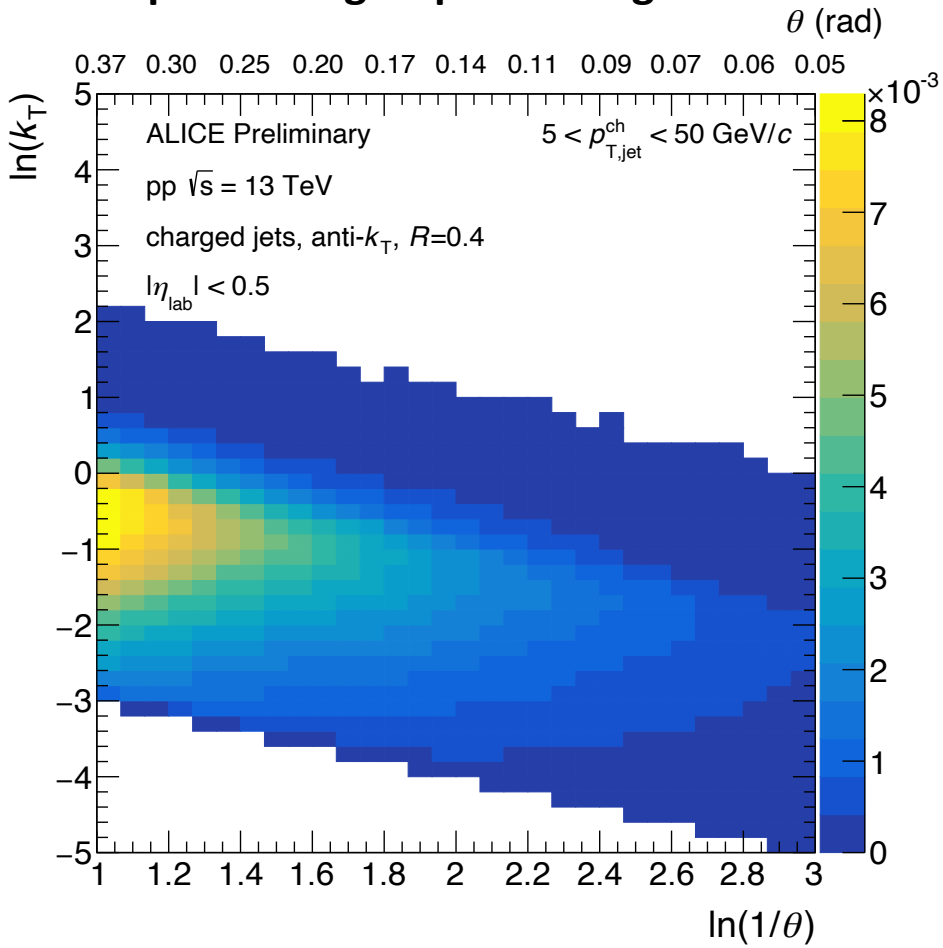
Obtaining a complementary inclusive measurement

Lund plane of c -> cg emissions



Following the branch containing the D^0 coincides with following the hardest branch in 99% of cases

Lund plane of light quark and gluon emissions

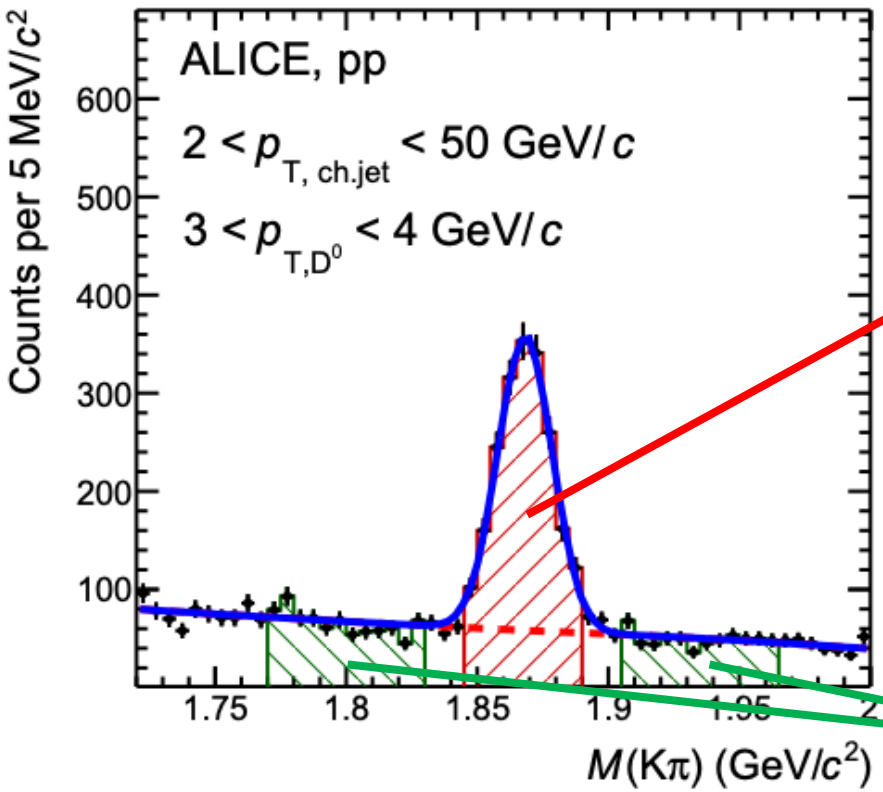


The hardest branch is followed at each declustering step

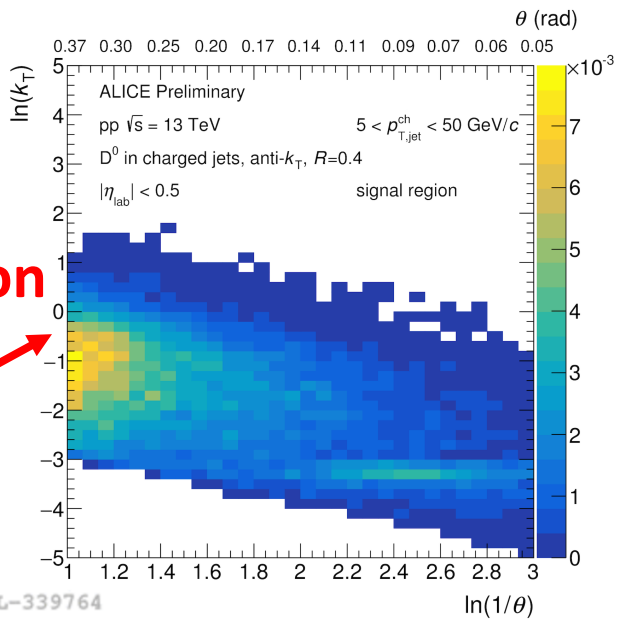
Extracting the D^0-meson signal

σ_{fit} Gaussian width

μ_{fit} Gaussian mean



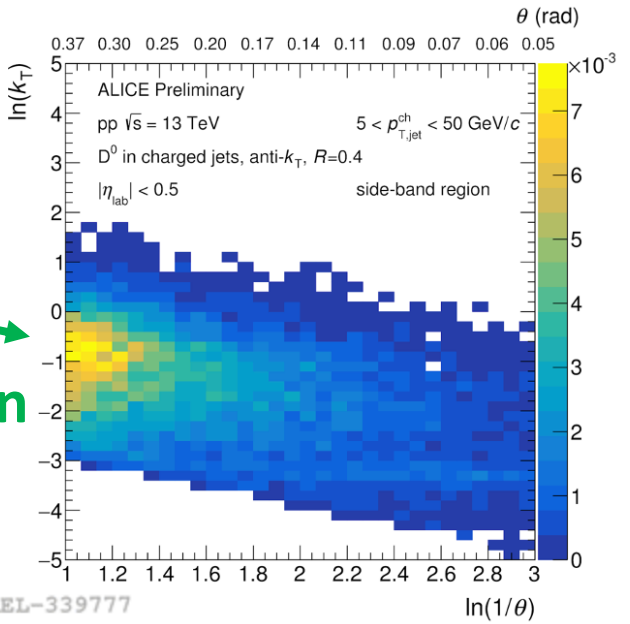
signal region



$|M - \mu_{\mathrm{fit}}| < 2\sigma_{\mathrm{fit}}$

Contains almost all of the signal and some background candidates

sideband region

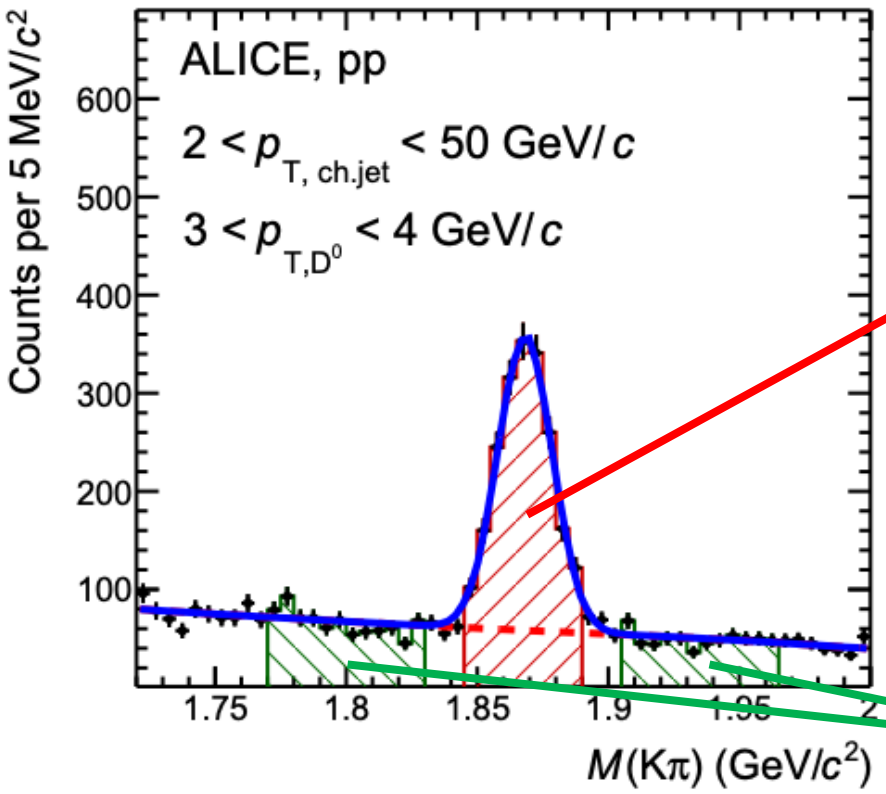


$4\sigma_{\mathrm{fit}} < |M - \mu_{\mathrm{fit}}| < 9\sigma_{\mathrm{fit}}$

Entirely composed of background candidates

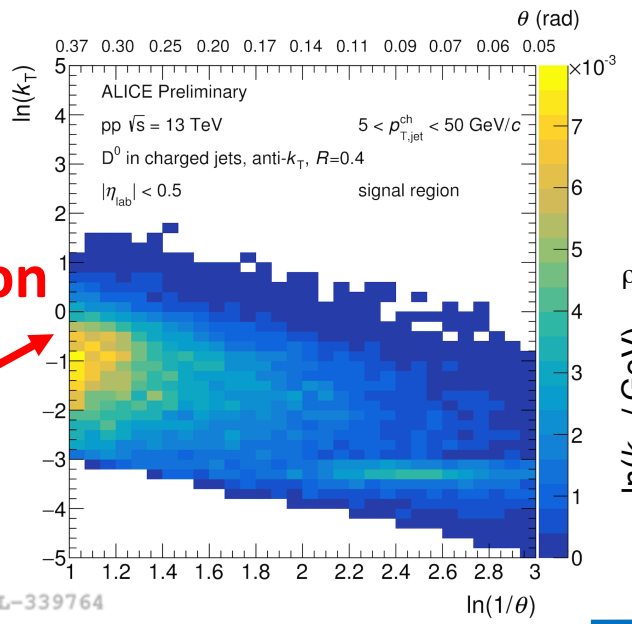
Performed in intervals of $p_{\mathrm{T,D^0}}$

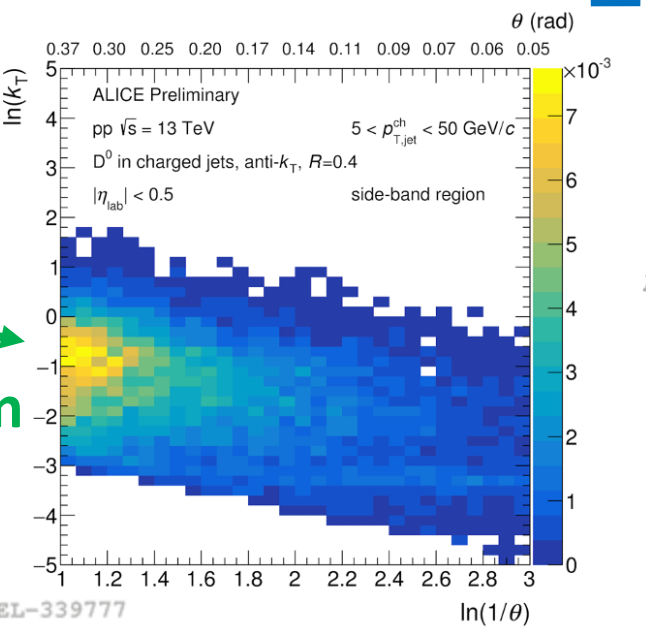
Extracting the D^0-meson signal



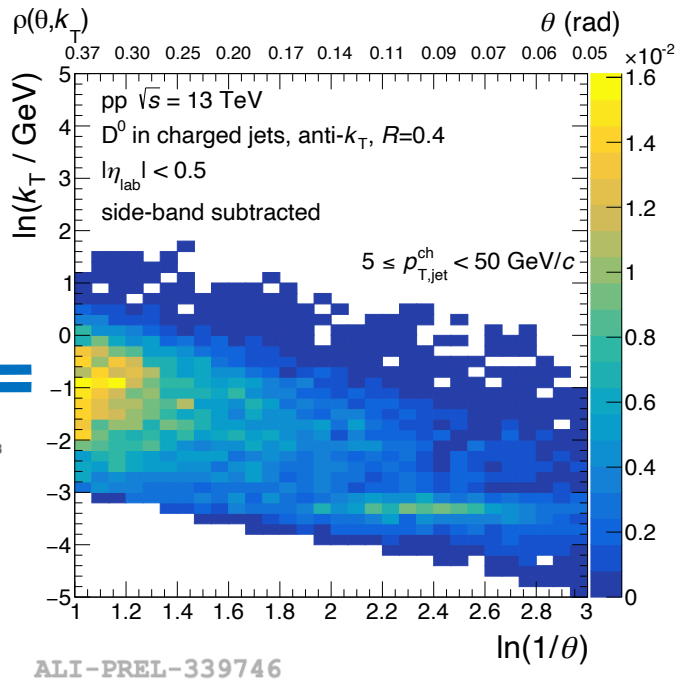
signal region

sideband region





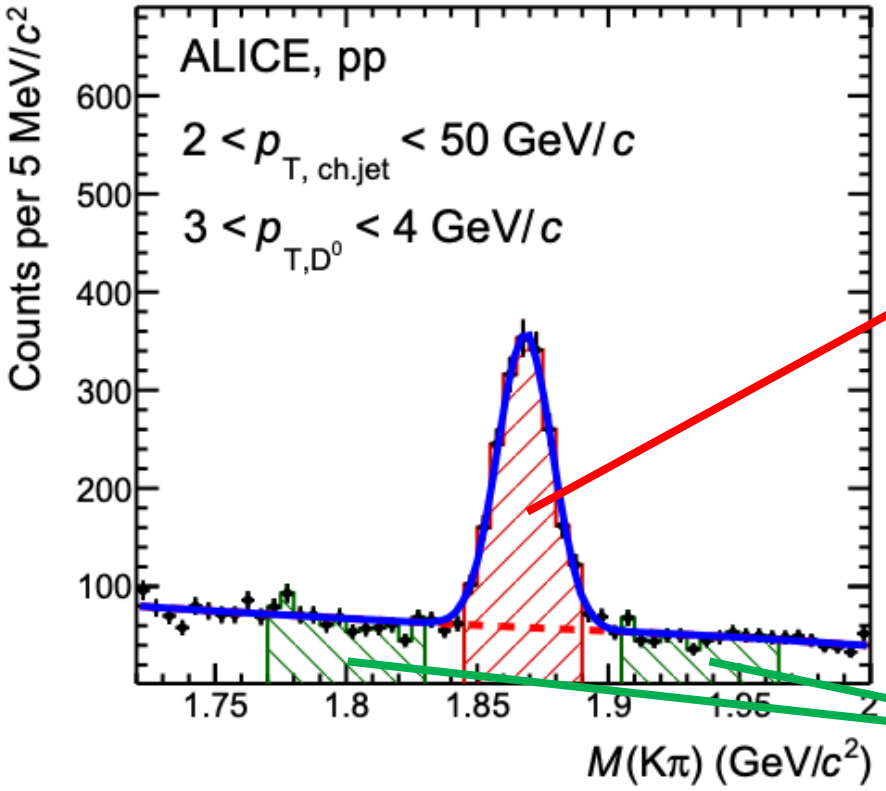
subtracted



Performed in intervals of $p_{\mathrm{T,D^0}}$

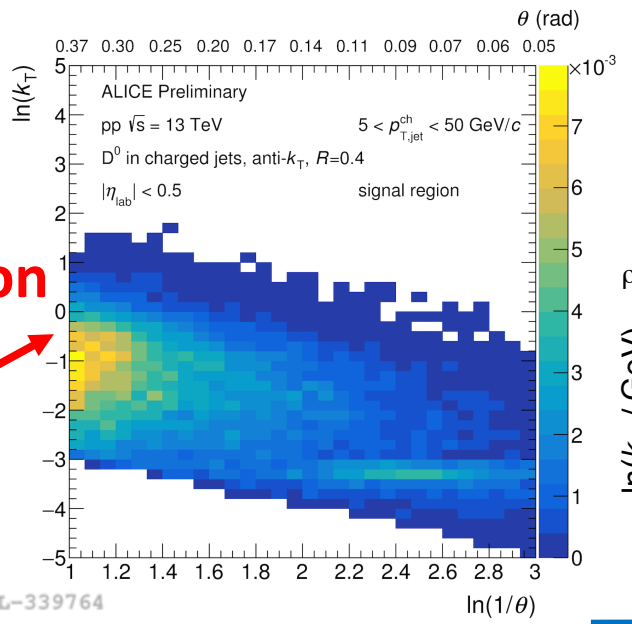
Purely signal D^0-tagged jet distribution extracted

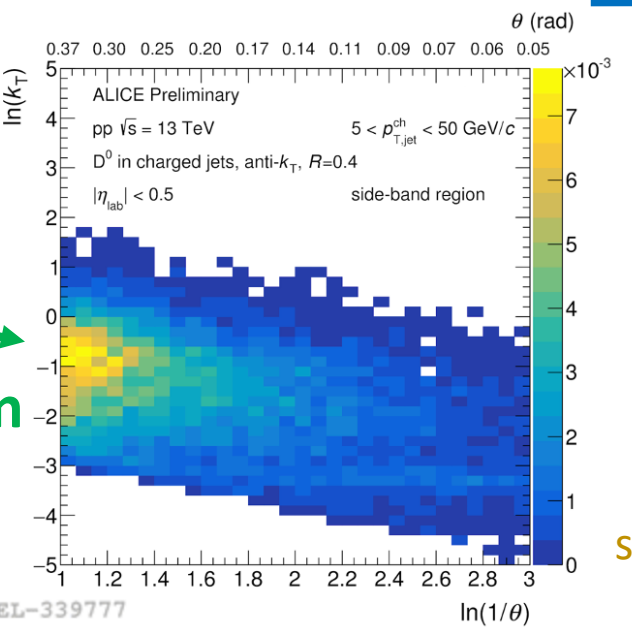
Extracting the D^0-meson signal



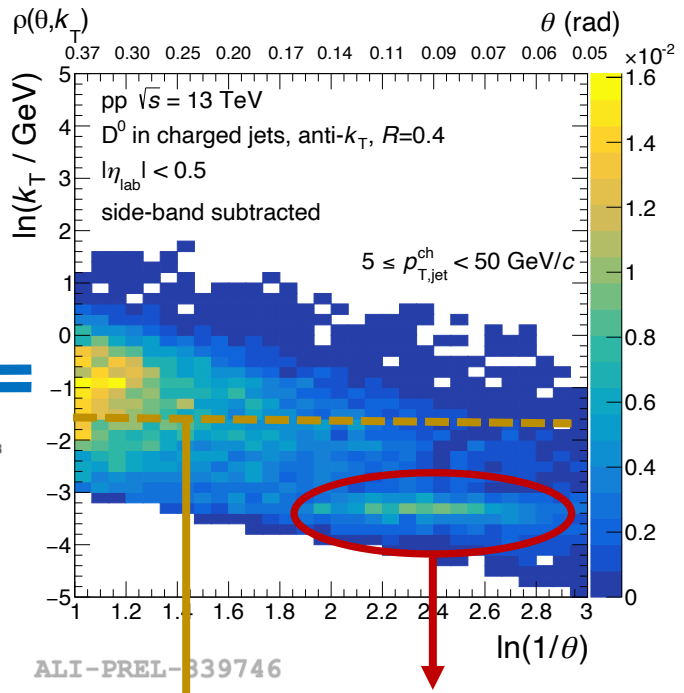
signal region

sideband region





subtracted



Soft π from D^* decays

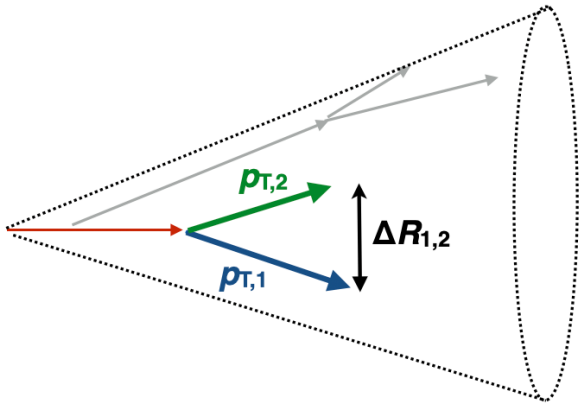
Selection in k_T of emissions suppresses non-perturbative effects

Performed in intervals of $p_{\mathrm{T,D^0}}$

Constraining the c->cg splitting function

See G. M. Innocenti's talk on Tuesday for more details

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



Soft Drop grooming condition

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

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

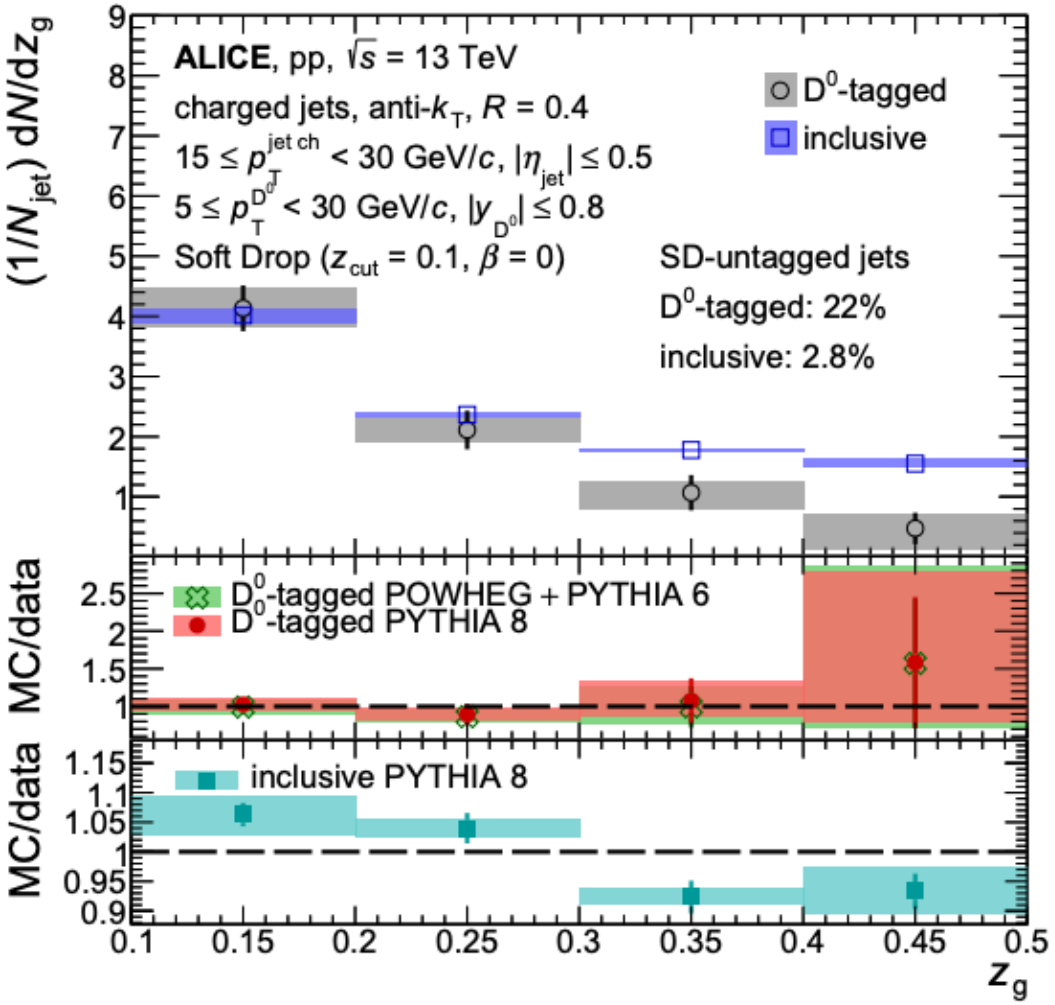
A. J. Larkoski et al. , JHEP 1405 (2014) 146

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

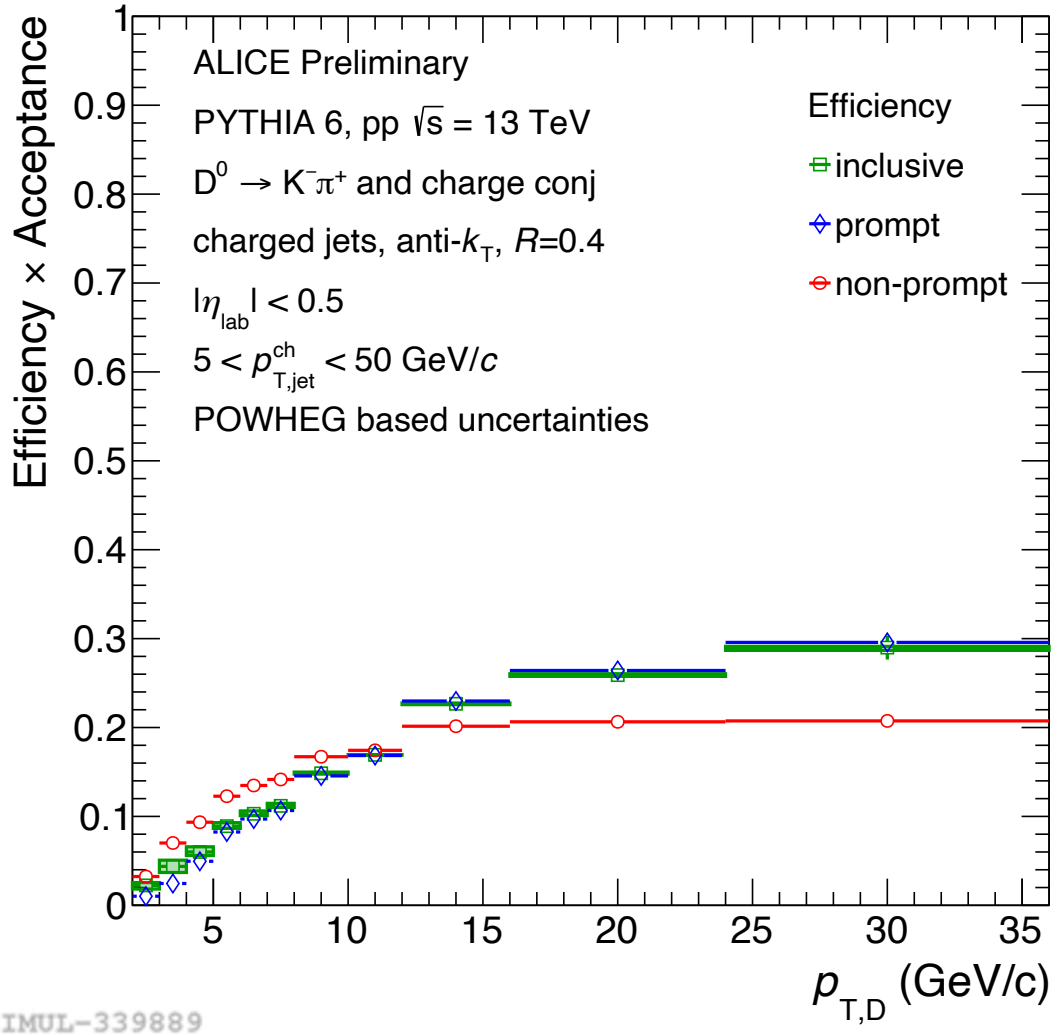
Emissions from charm-quarks have a steeper splitting probability than light quarks and gluons

Fewer symmetric splittings

arXiv:2208.04857



Extracting the D^0-meson signal



ALI-SIMUL-339889