Observation of the QCD dead-cone effect

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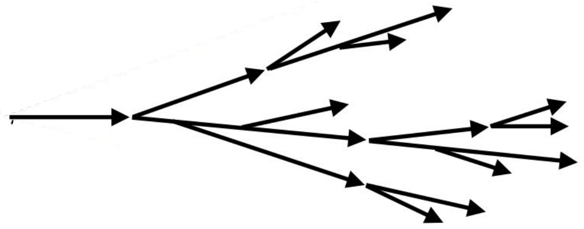
INSTITUTE for NUCLEAR THEORY

Heavy-flavour workshop 21/10/2022

Flavour dependence in QCD parton showers

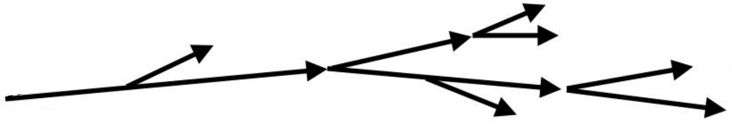
Gluon-initiated shower

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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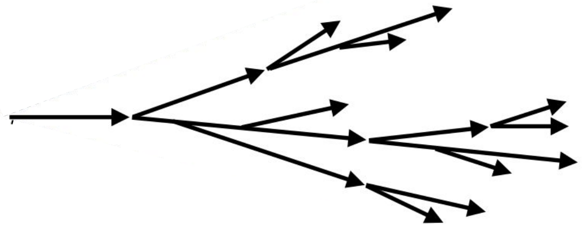

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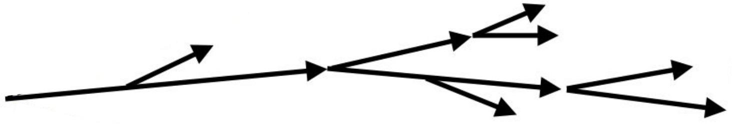
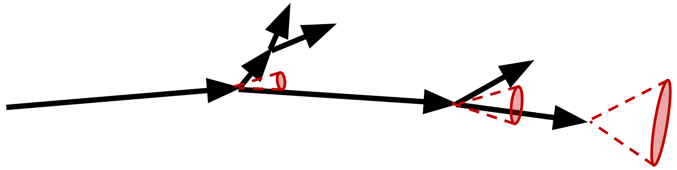


Heavy-quark-initiated shower

Suppression of small angle emissions
Harder fragmentation



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

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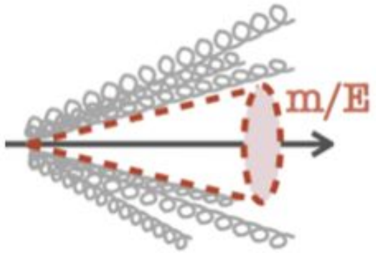
Dead-cone effect

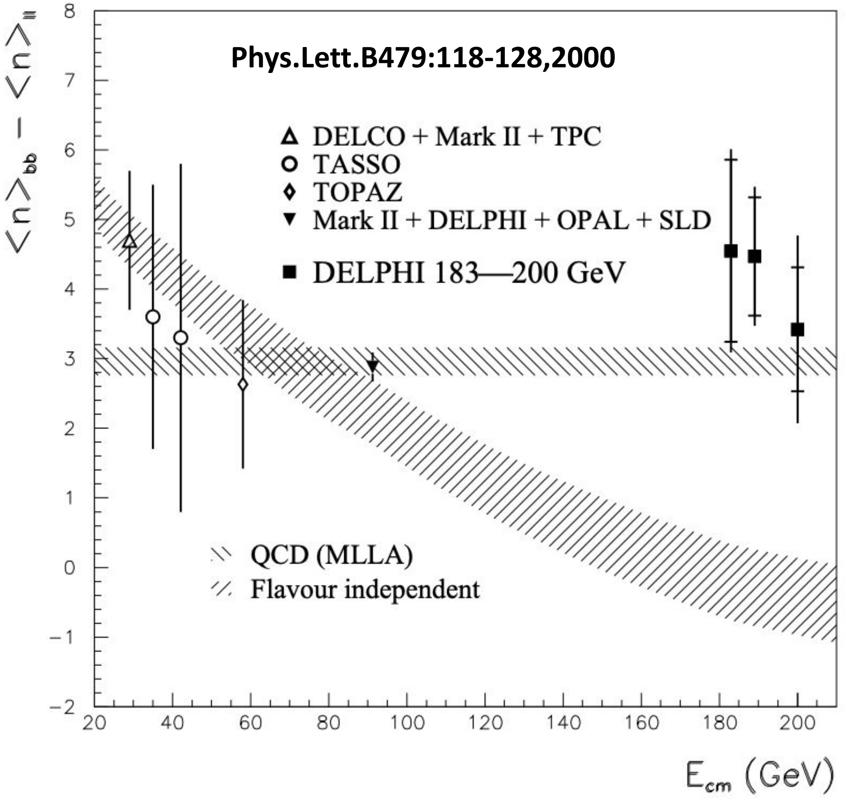
Suppression of emissions in a cone of size m/E around the direction of the emitter

Sizeable effect for low energy heavy quarks

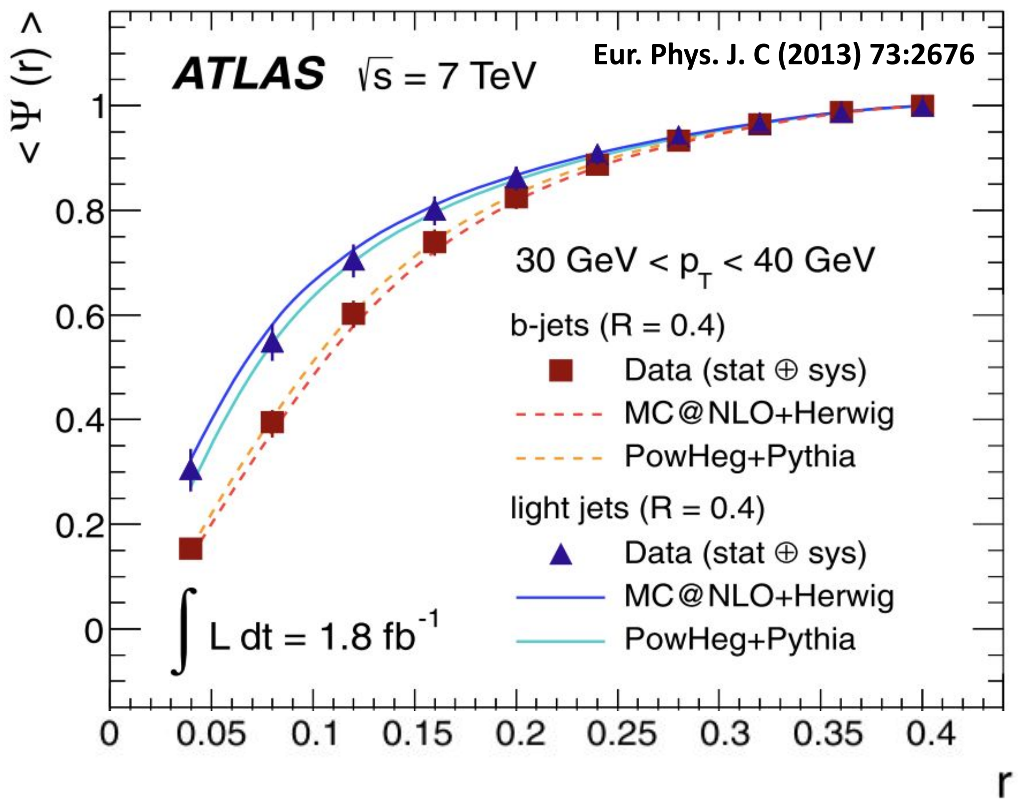


Indirect measurements of the dead cone

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



Difference in average multiplicity between events containing a b-quark jet and and those with a light-quark jet



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

Indirect measurements of the dead cone

What is missing for a direct observation of the dead cone?

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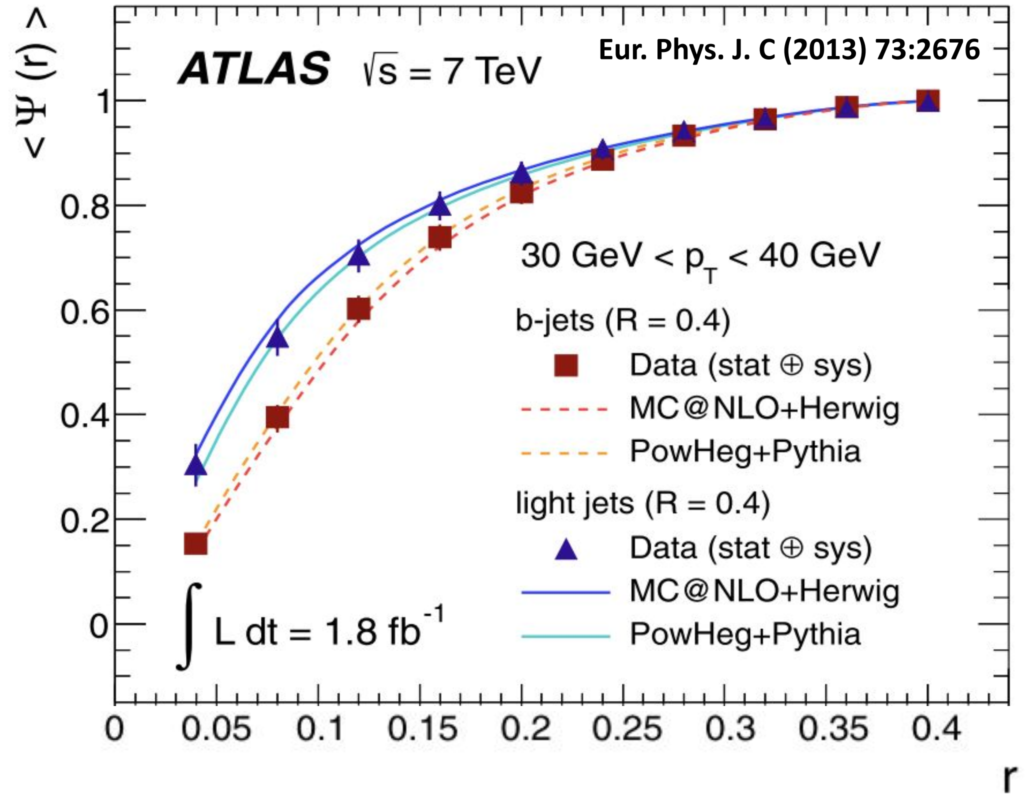

Indirect measurements of the dead cone

What is missing for a direct observation of the dead cone?

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

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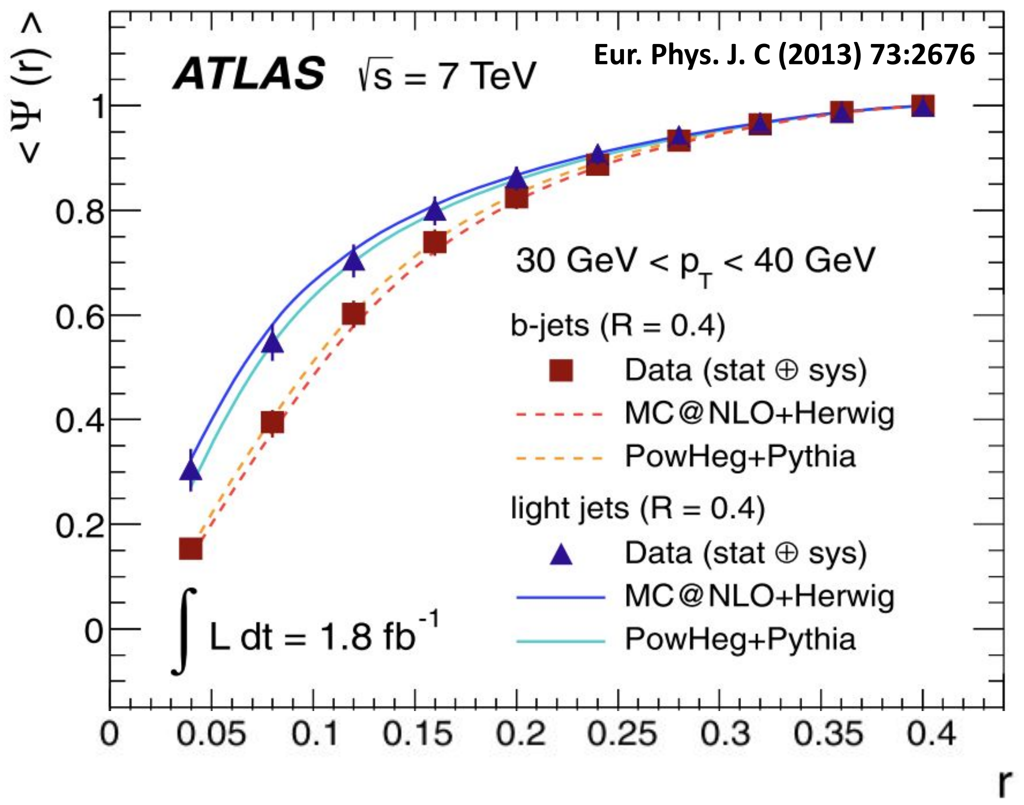

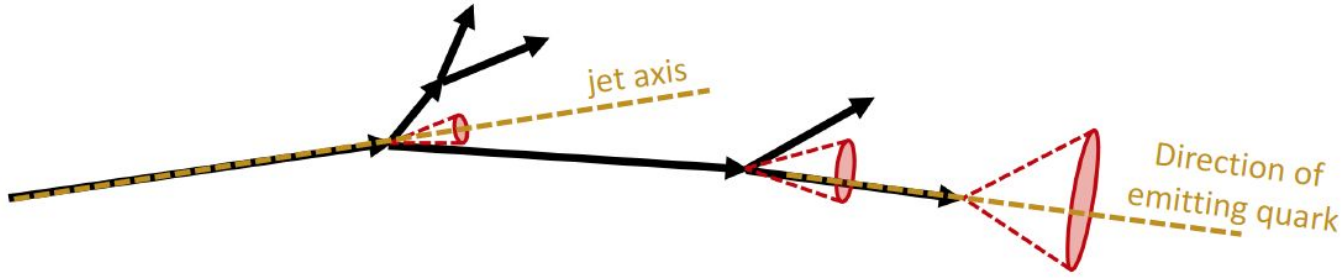

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Uncorrelated sources such as the decay products of the heavy-flavour hadron can populate the dead-cone region

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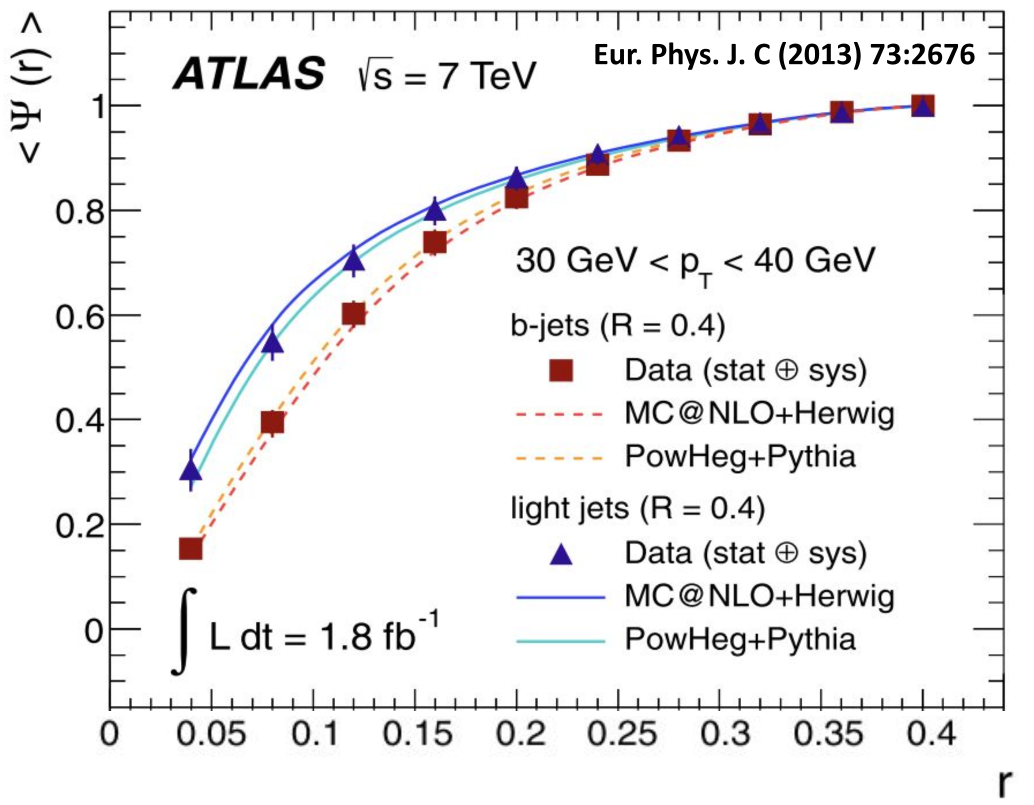
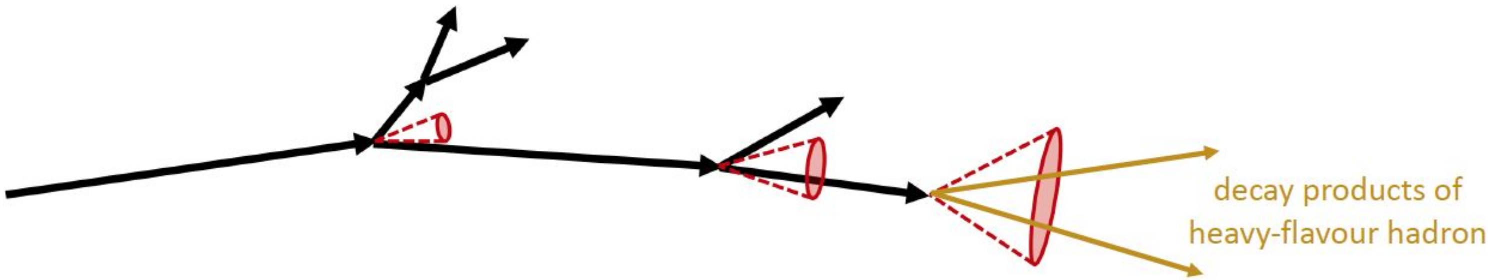
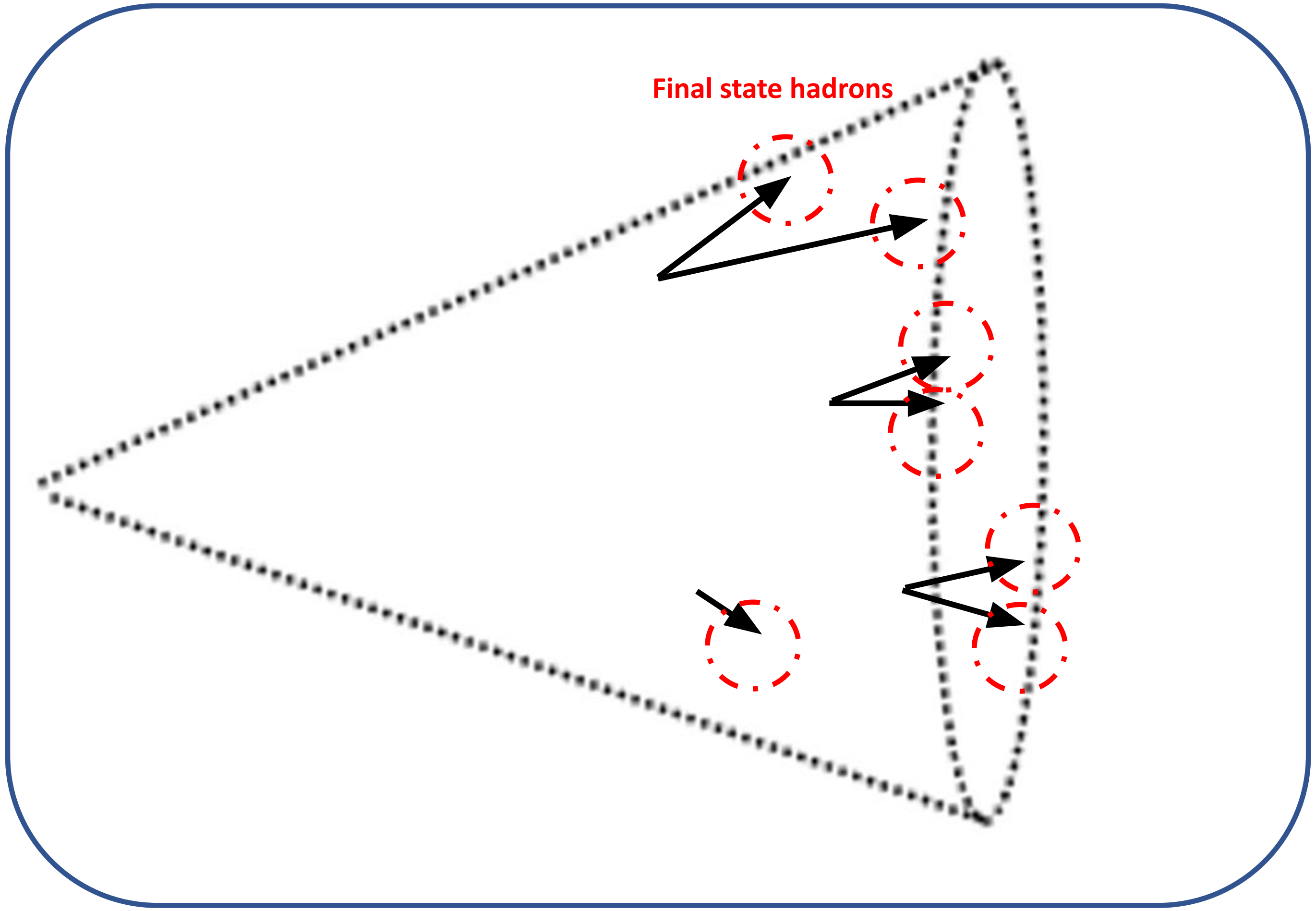
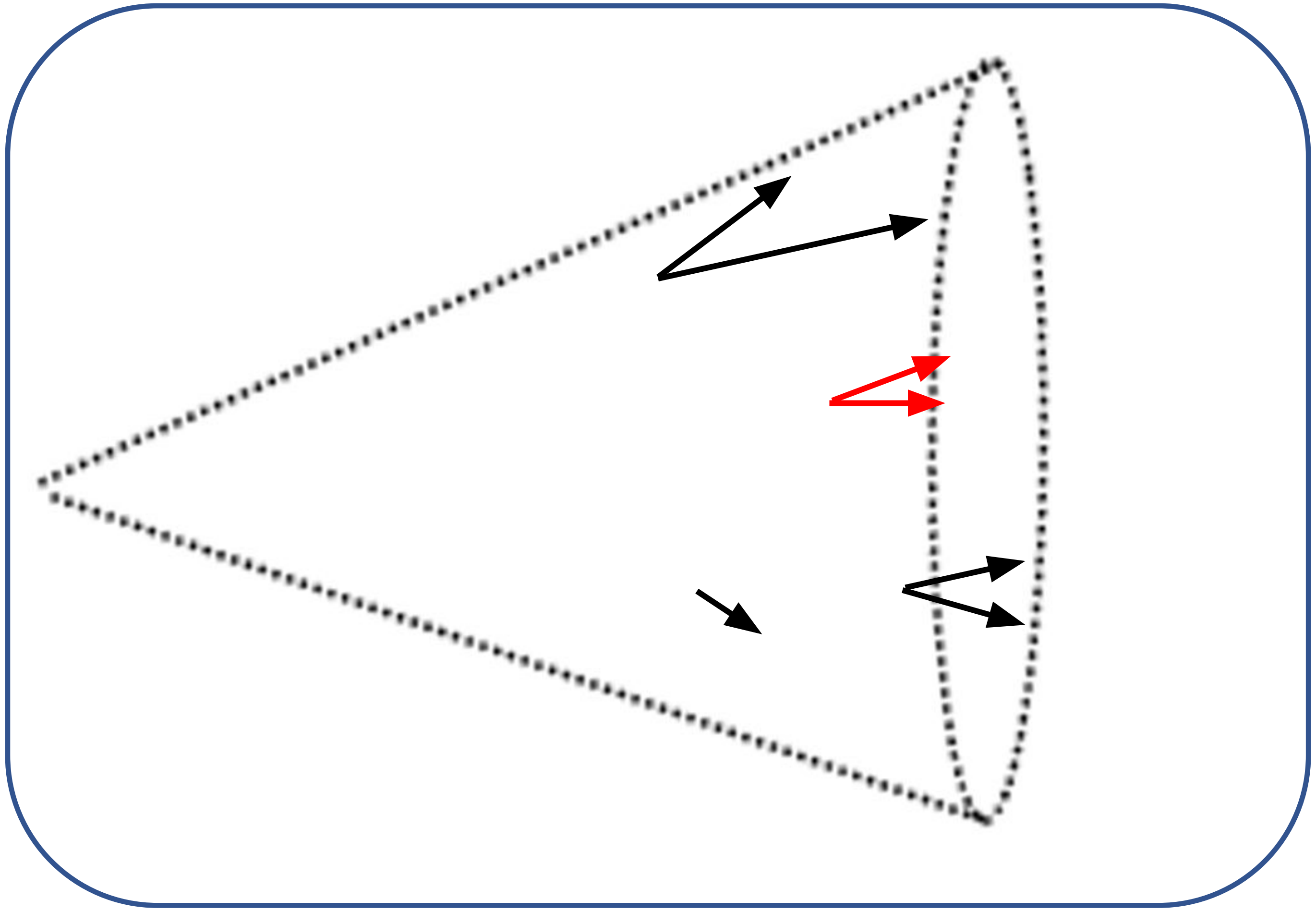




Dynamically reconstructing the parton shower



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



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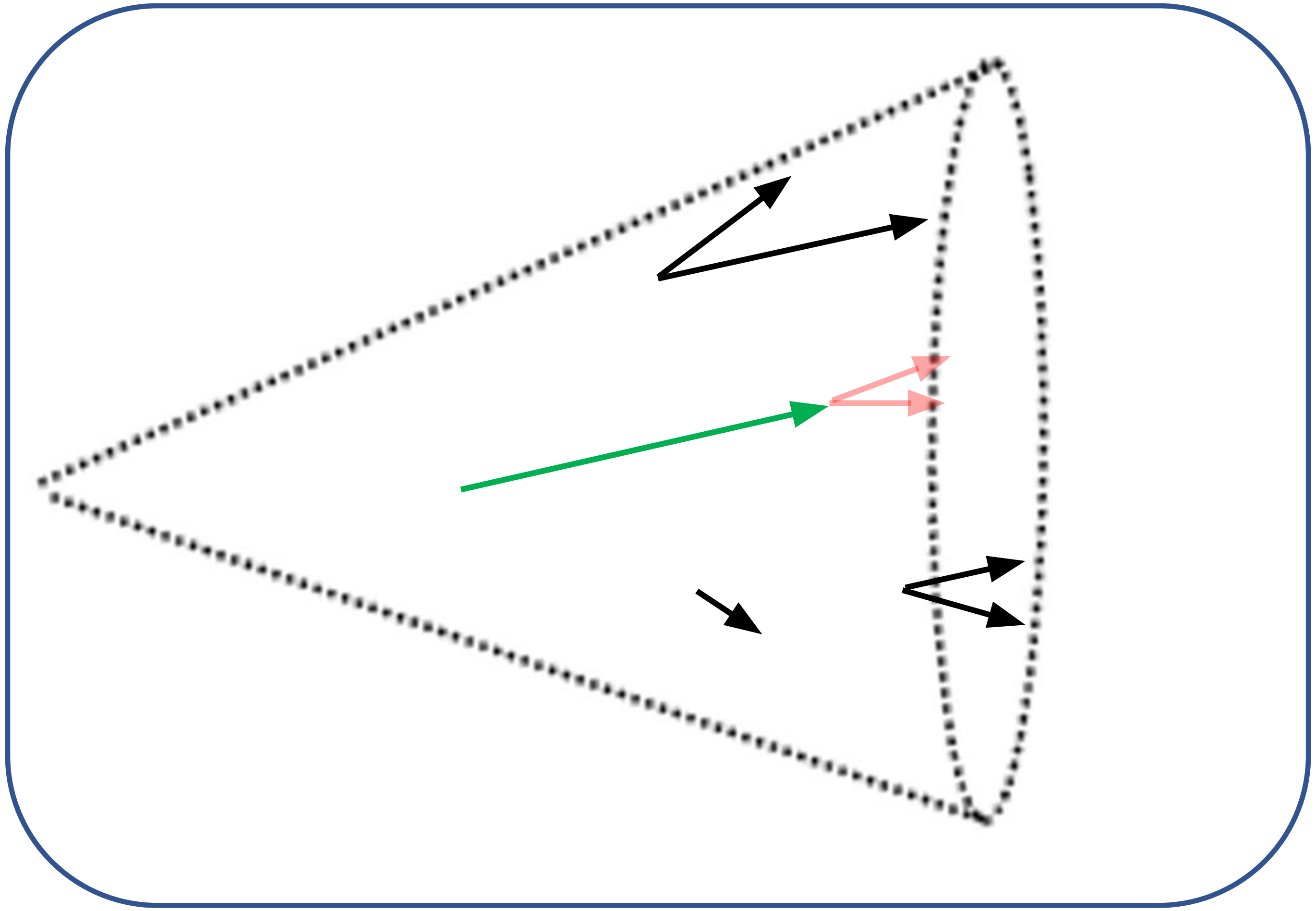
Take advantage of angular ordering of QCD emissions to reconstruct the shower with the C/A algorithm



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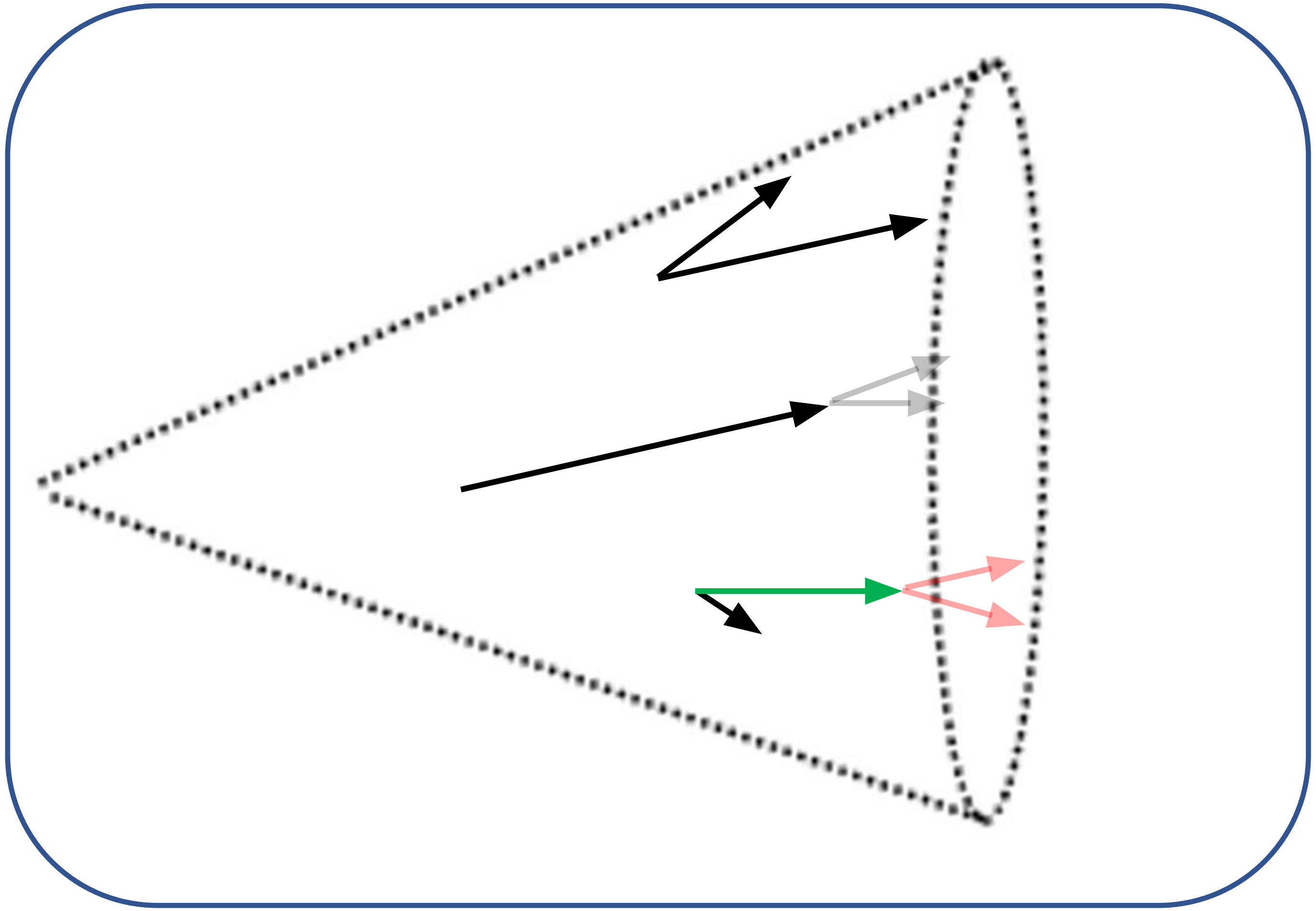

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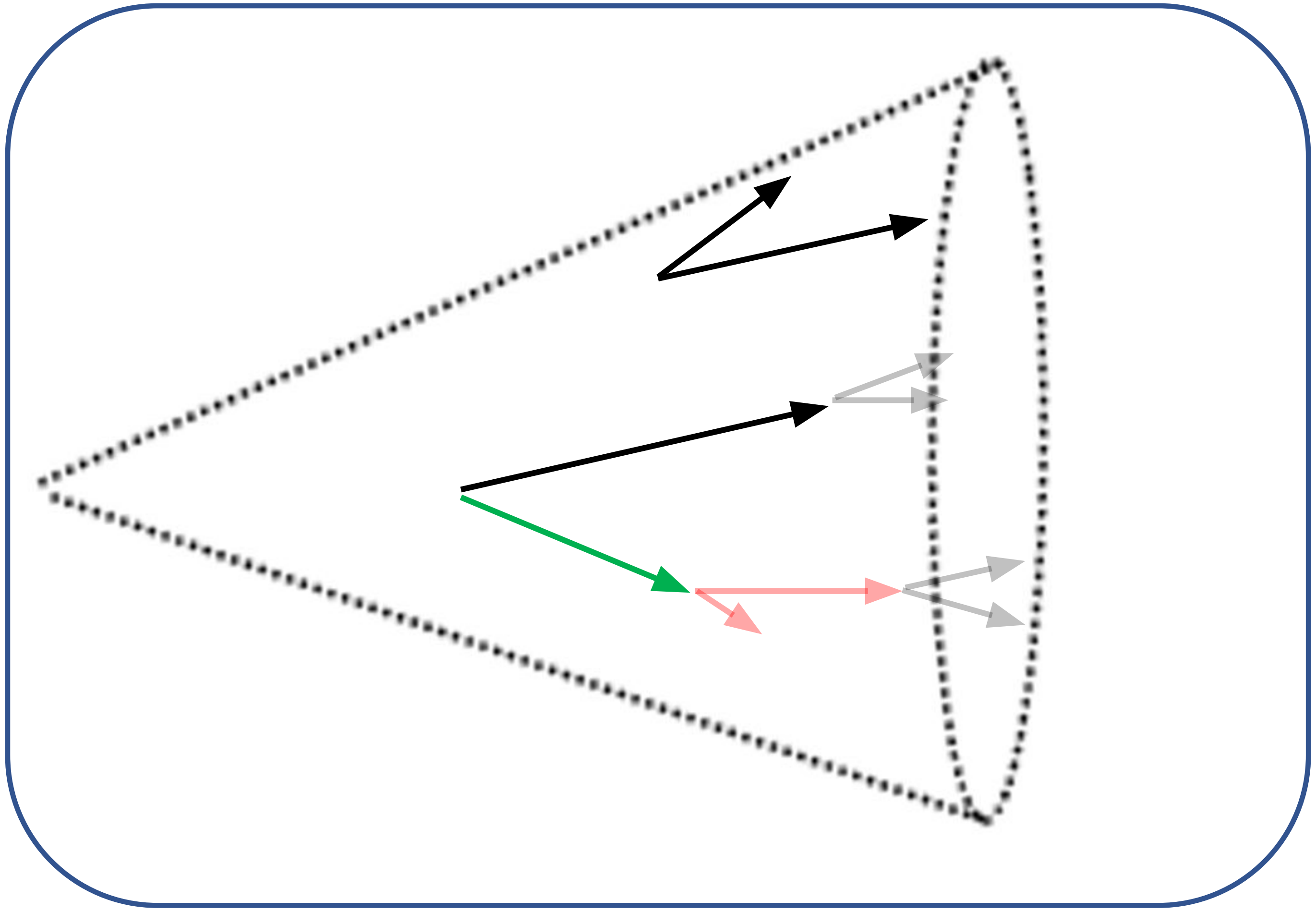

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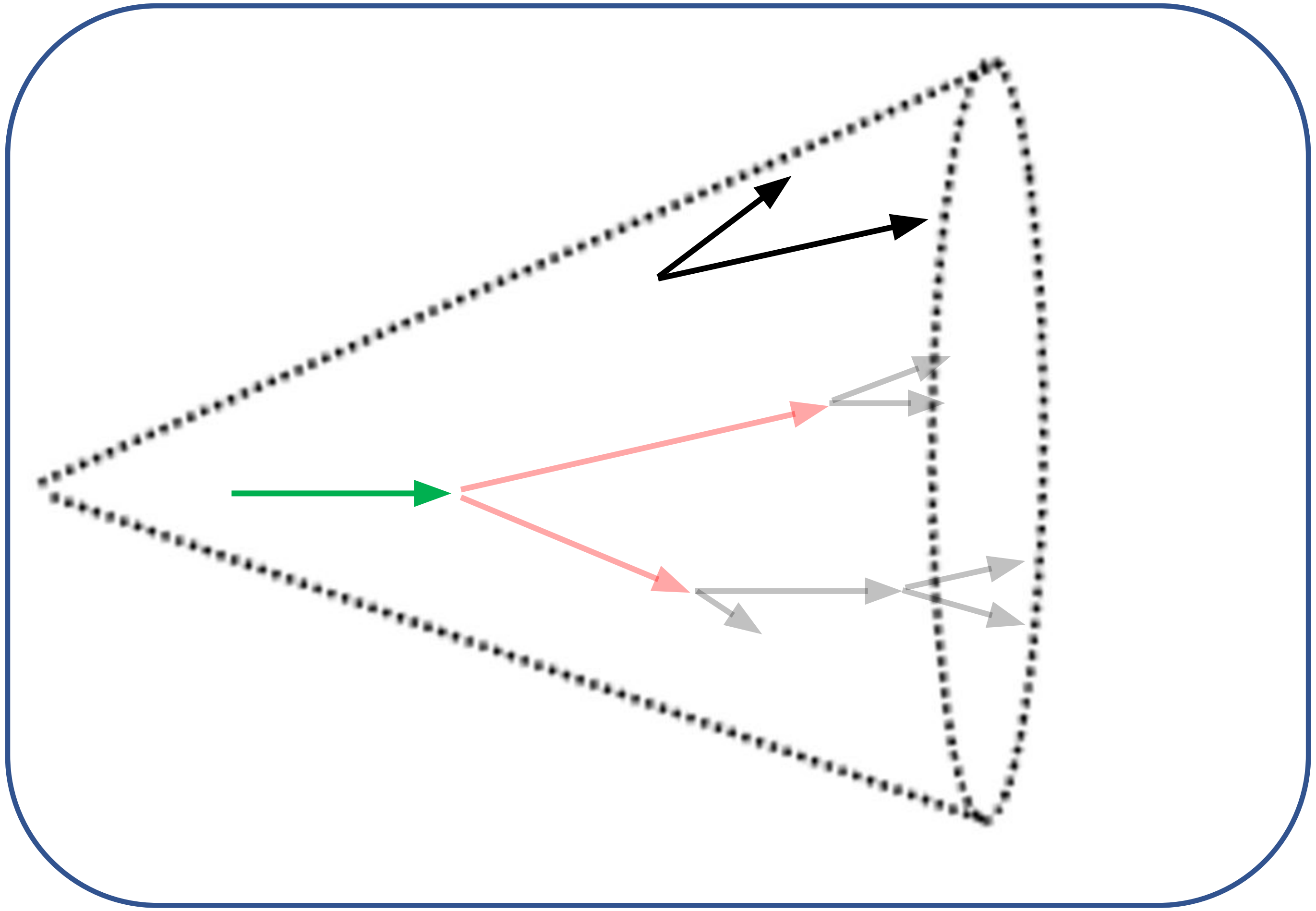

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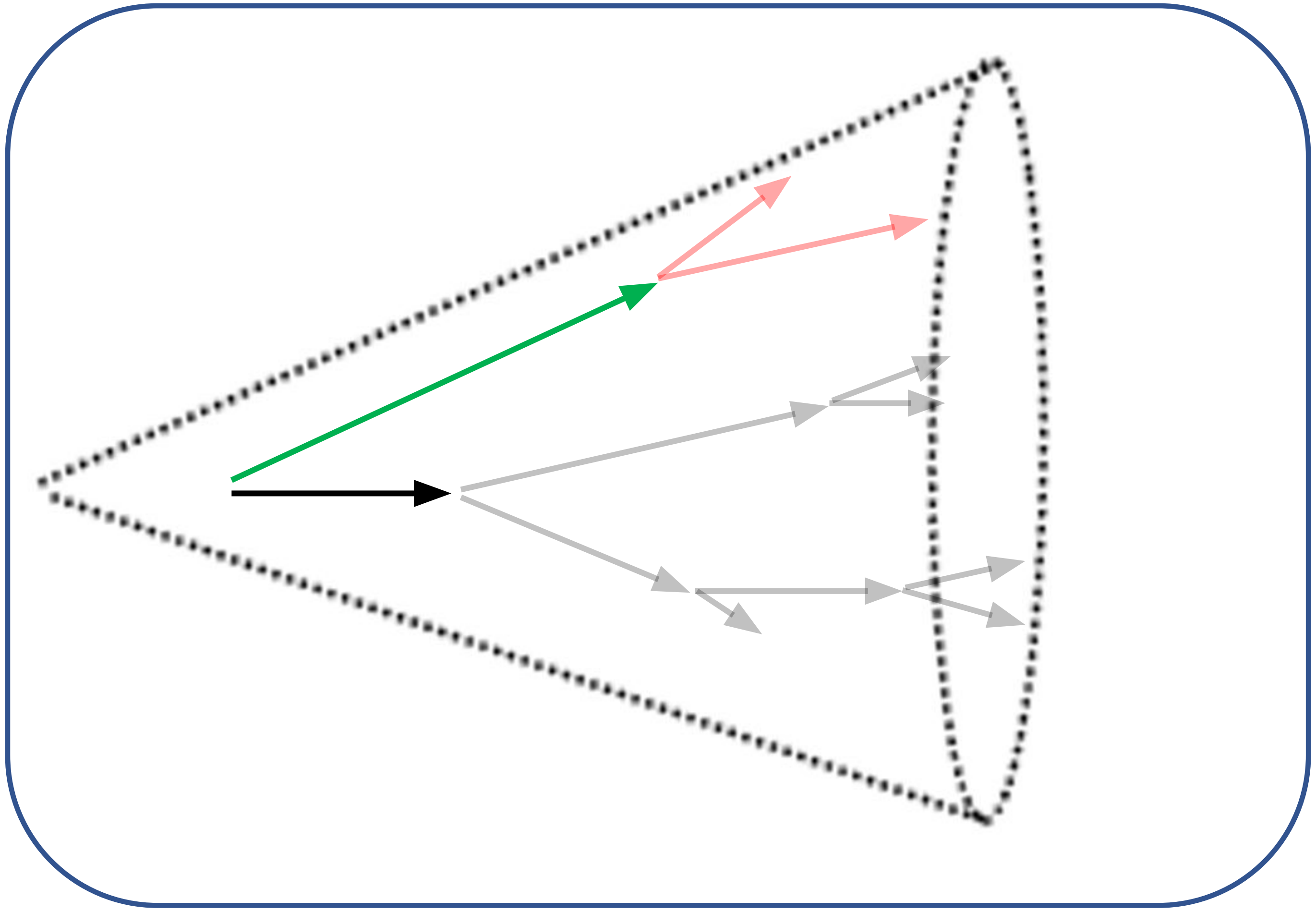

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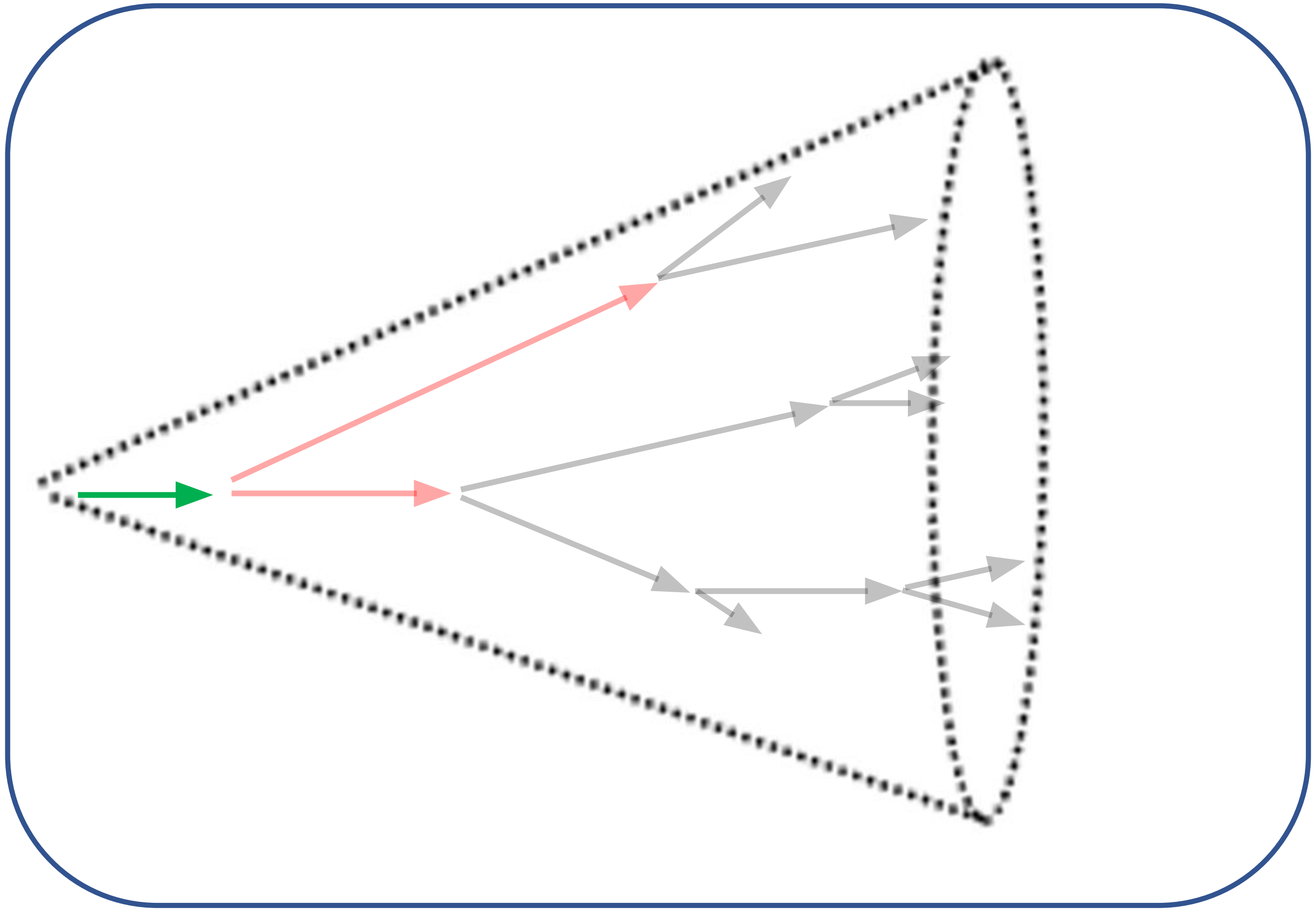

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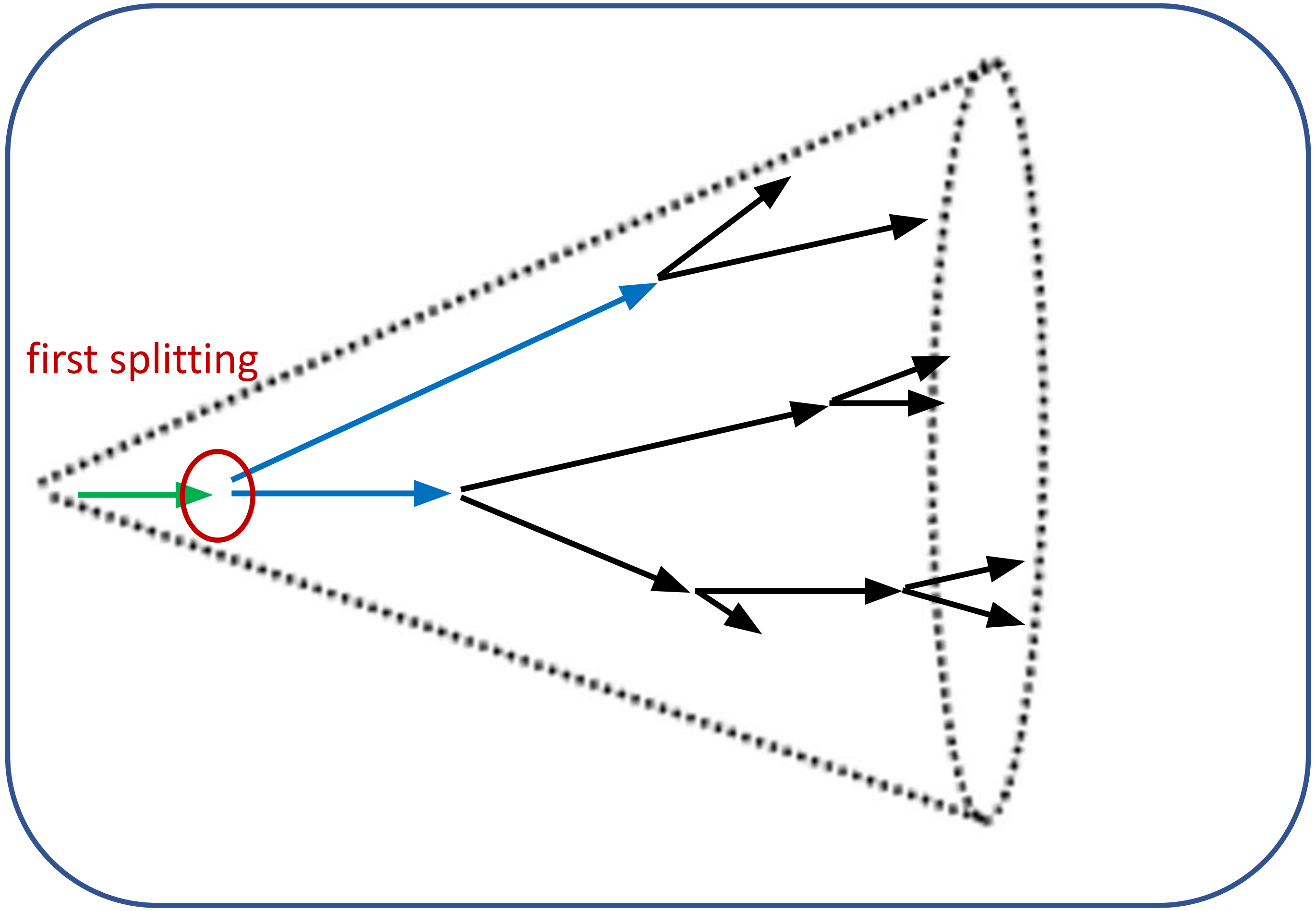

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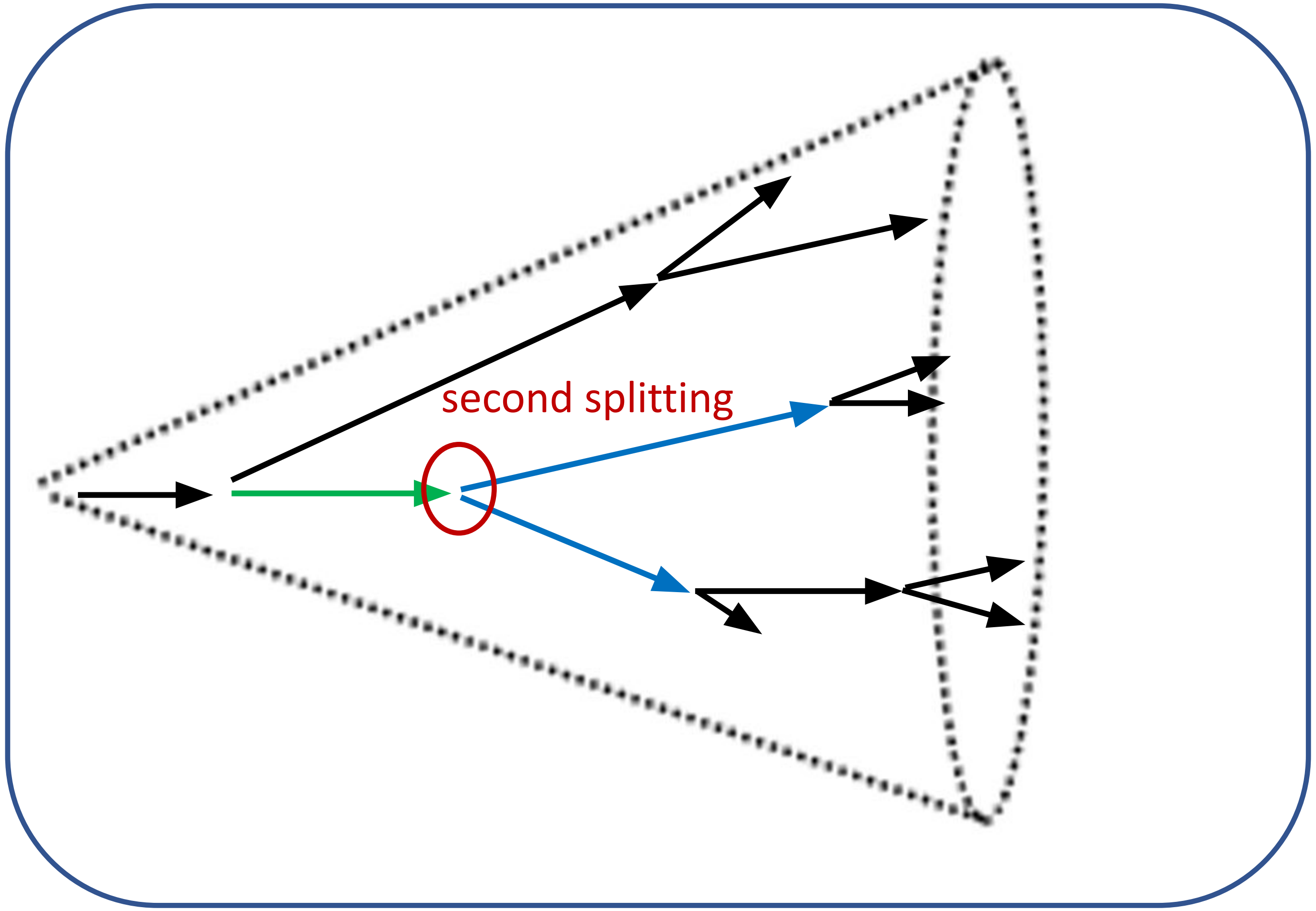
Take advantage of angular ordering of QCD emissions to reconstruct the shower with the C/A algorithm

Unwind the reclustering history and follow a particular branch of emissions through the shower

Dynamically reconstructing the parton shower



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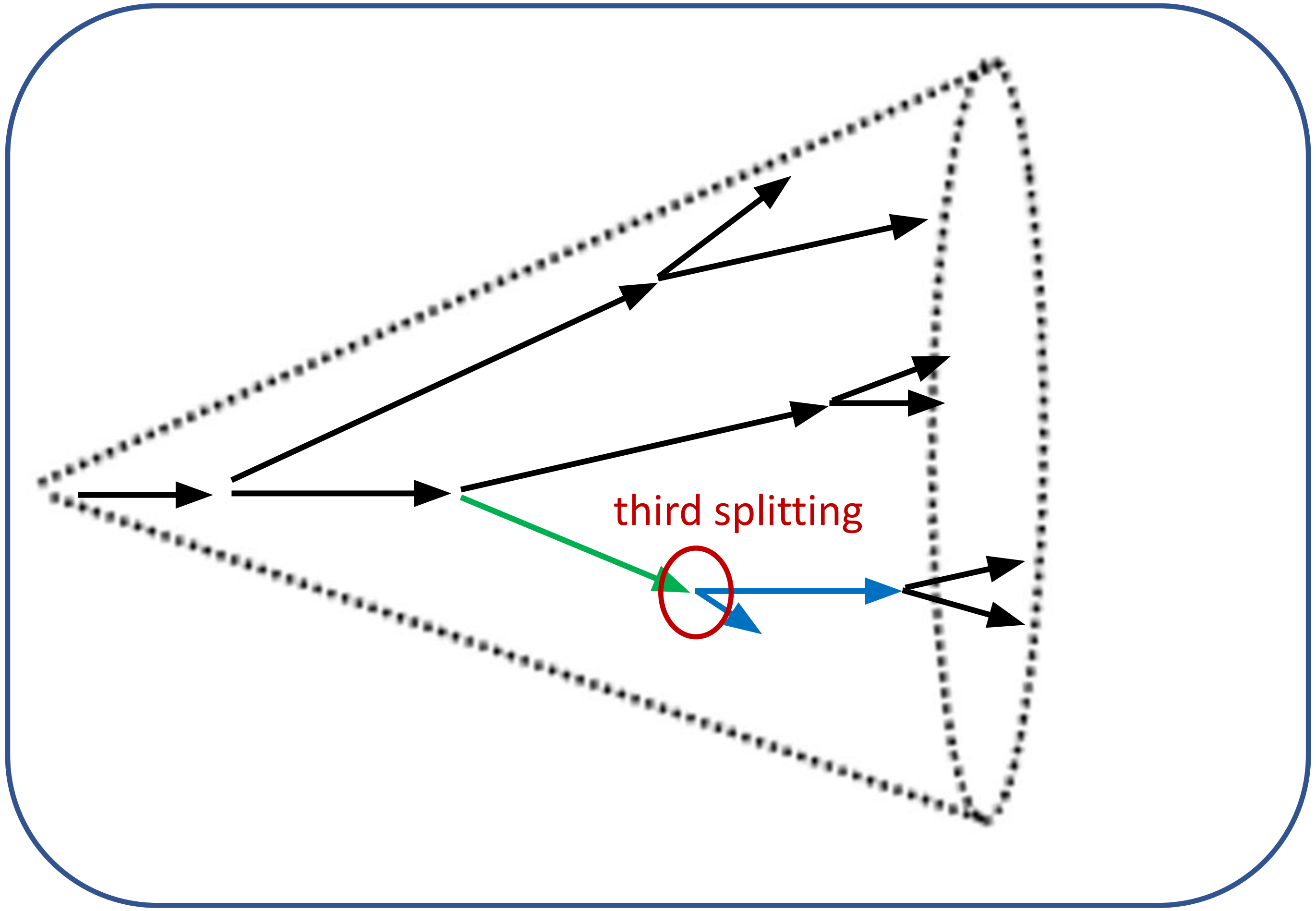

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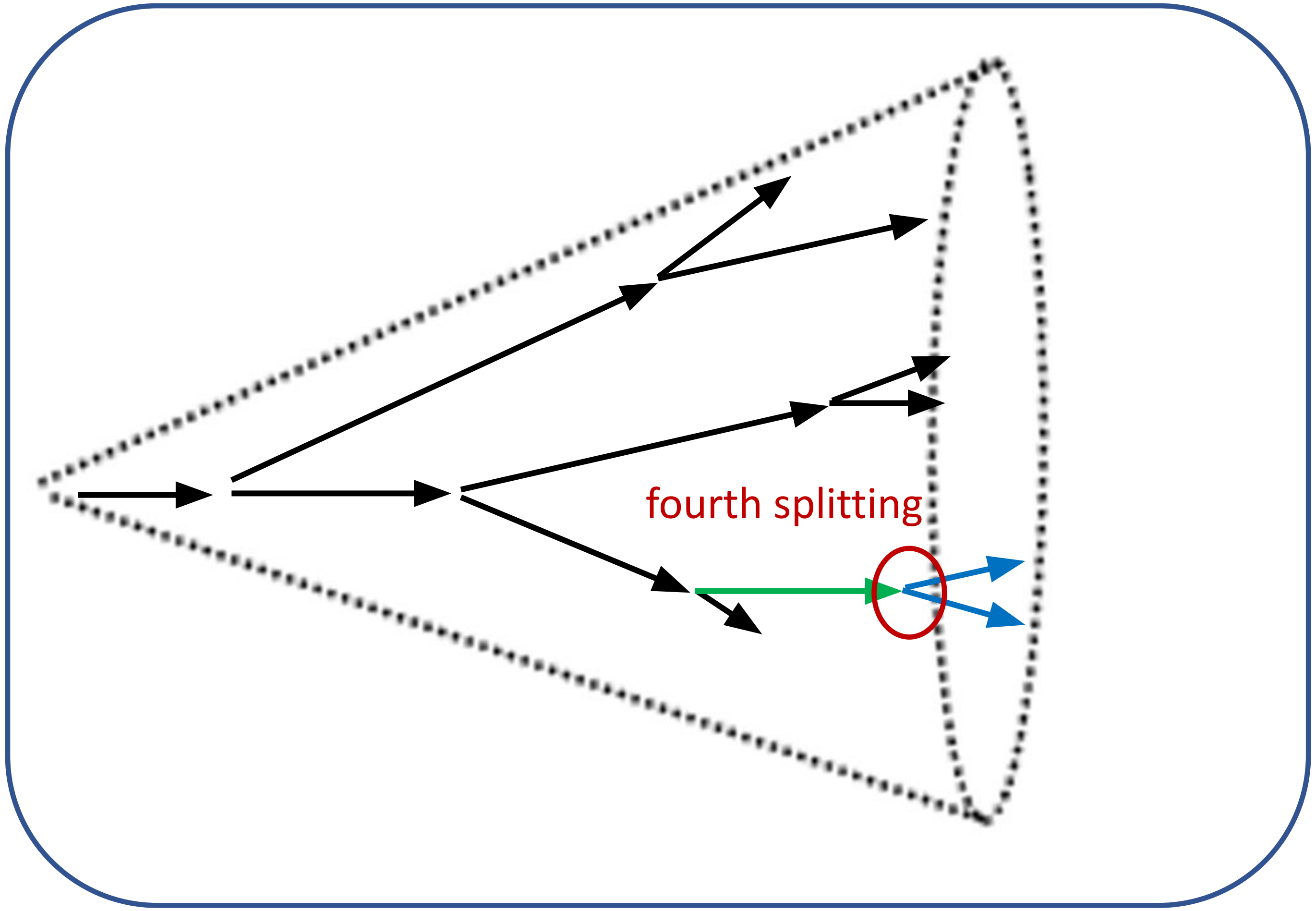

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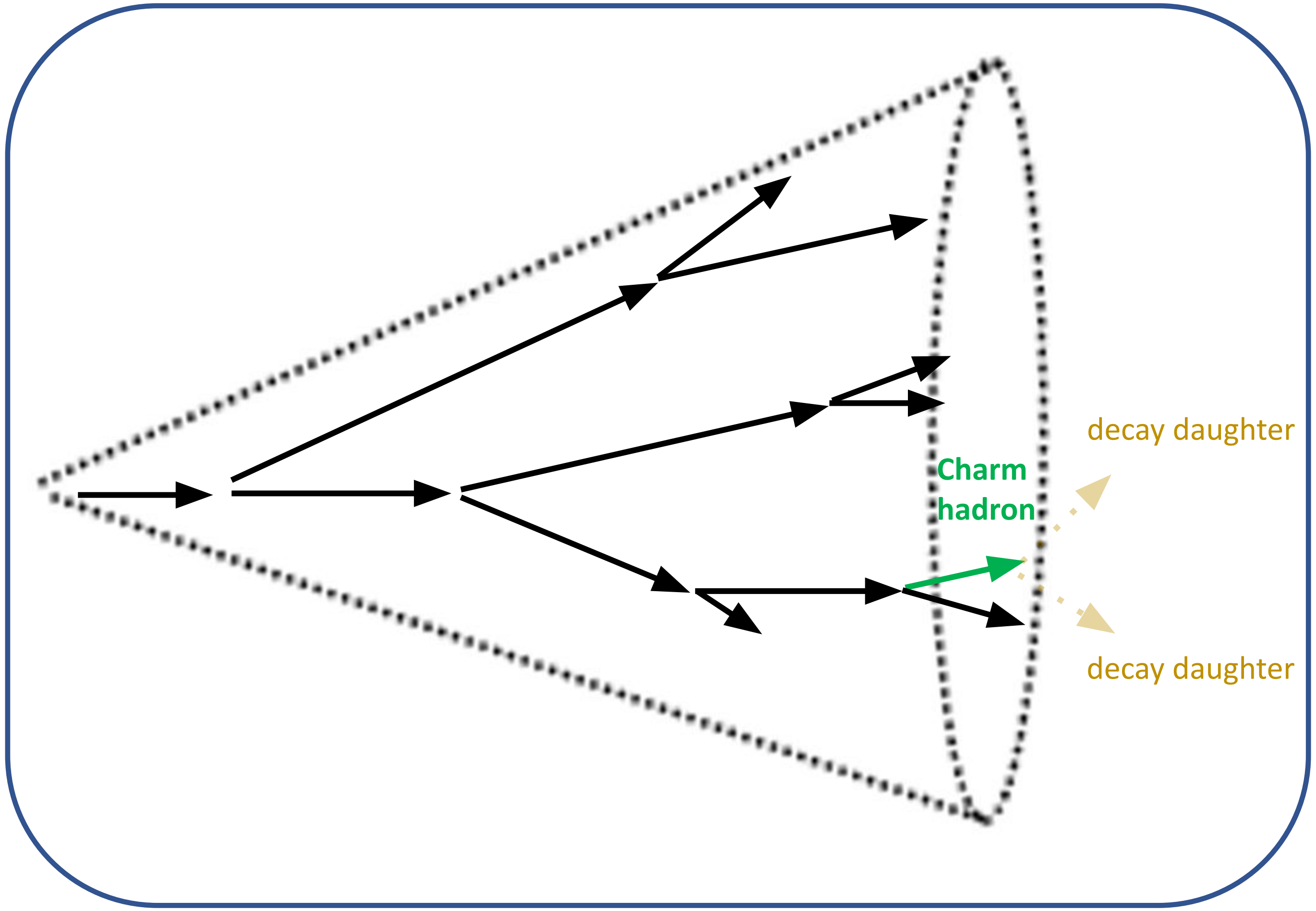
The parton flavour is not traced along the followed branch

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



Heavy-flavour quarks retain their flavour throughout the shower evolution
Q -> Qg emissions

Due to their large masses heavy-flavour quark production is suppressed during hadronisation

Heavy-flavour initiated showers can be identified through the presence of a heavy-flavour hadron

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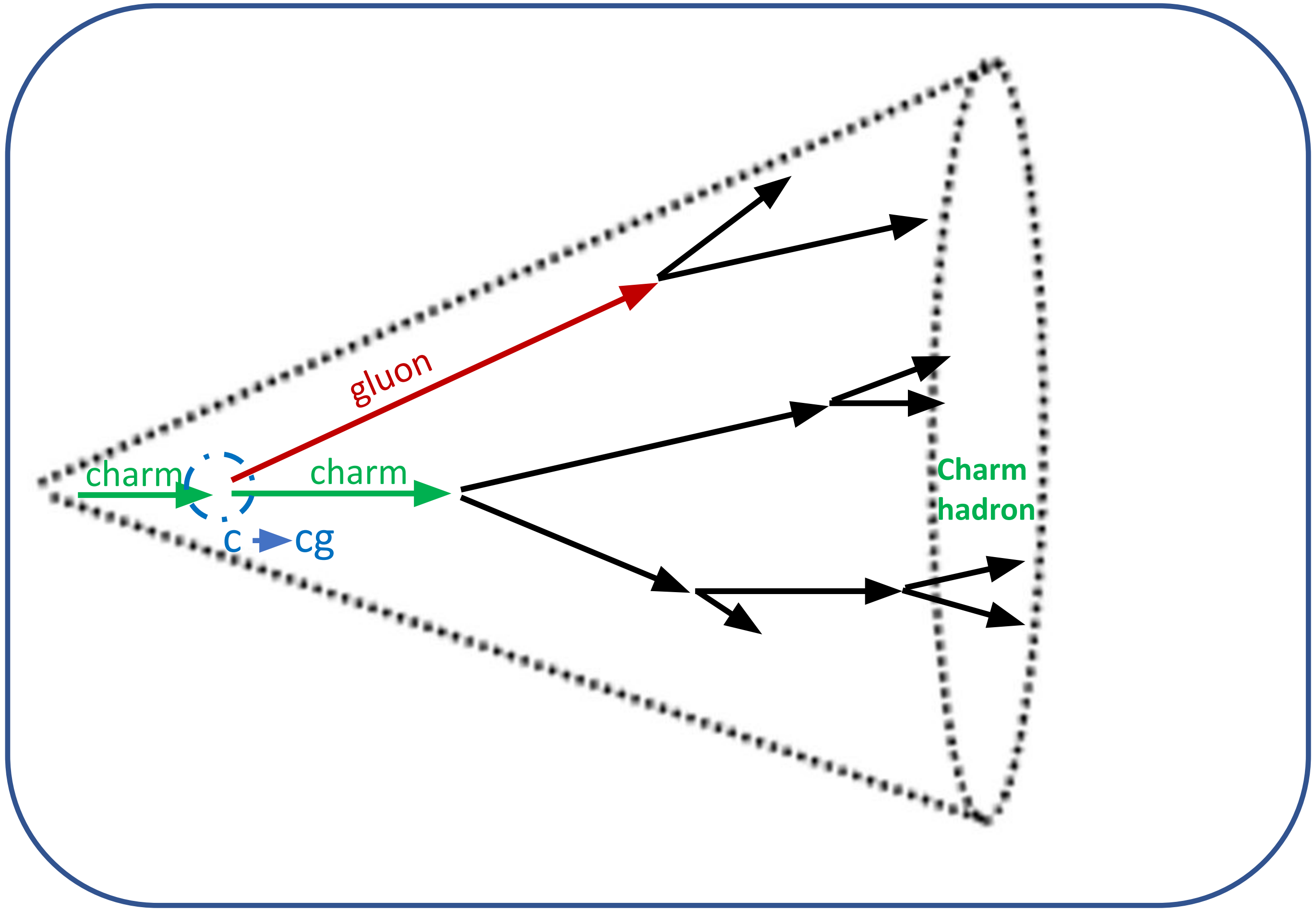

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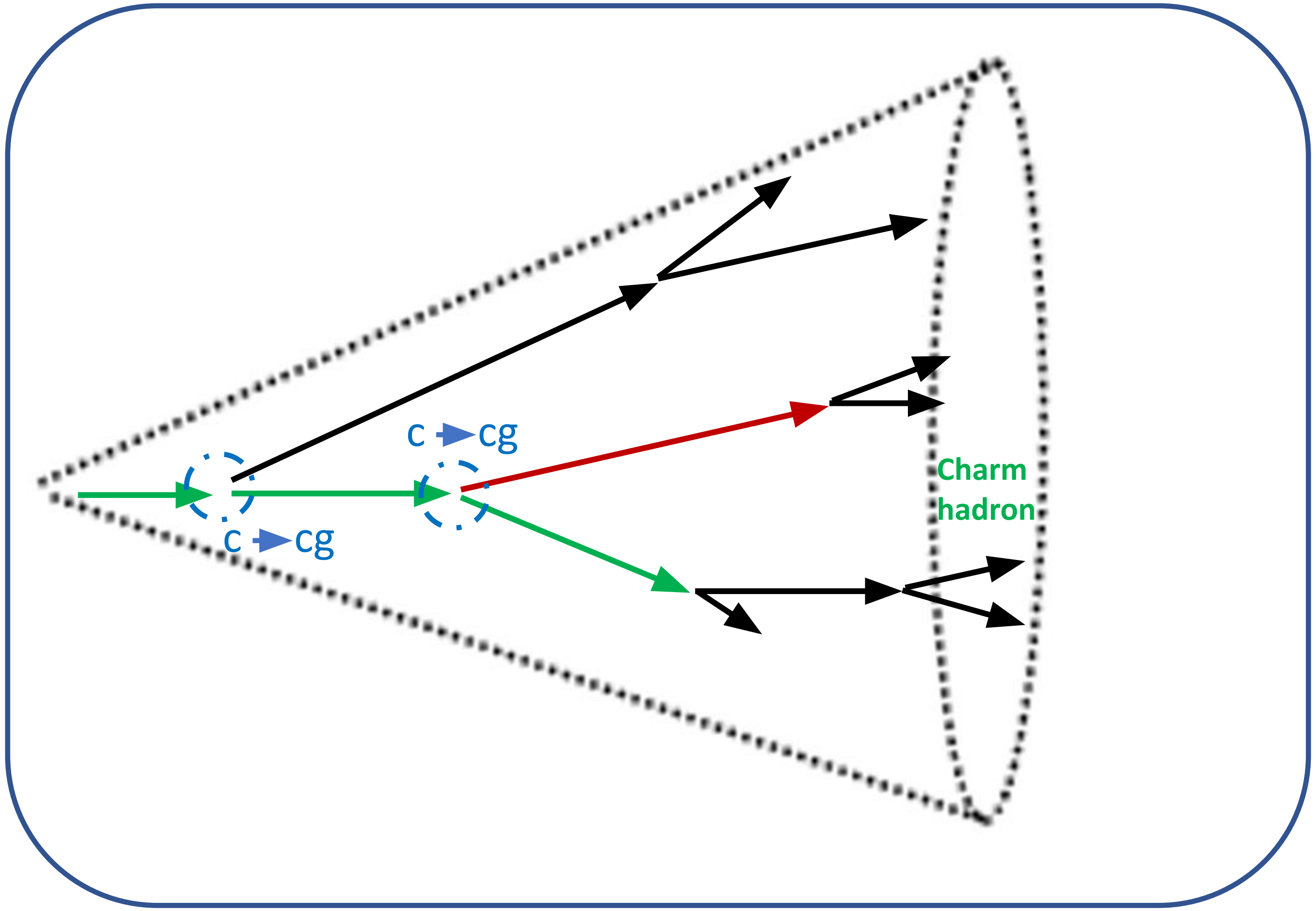

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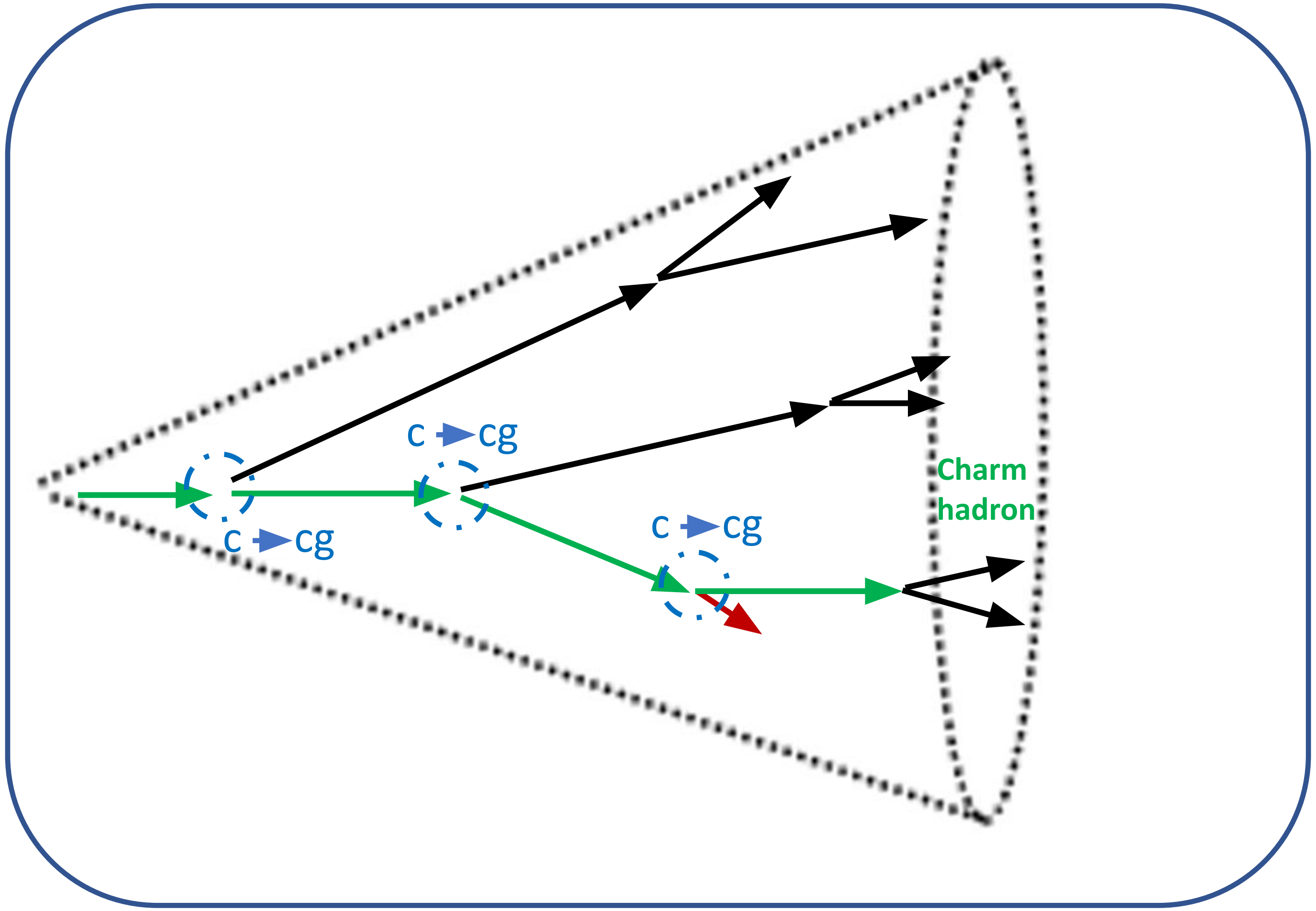

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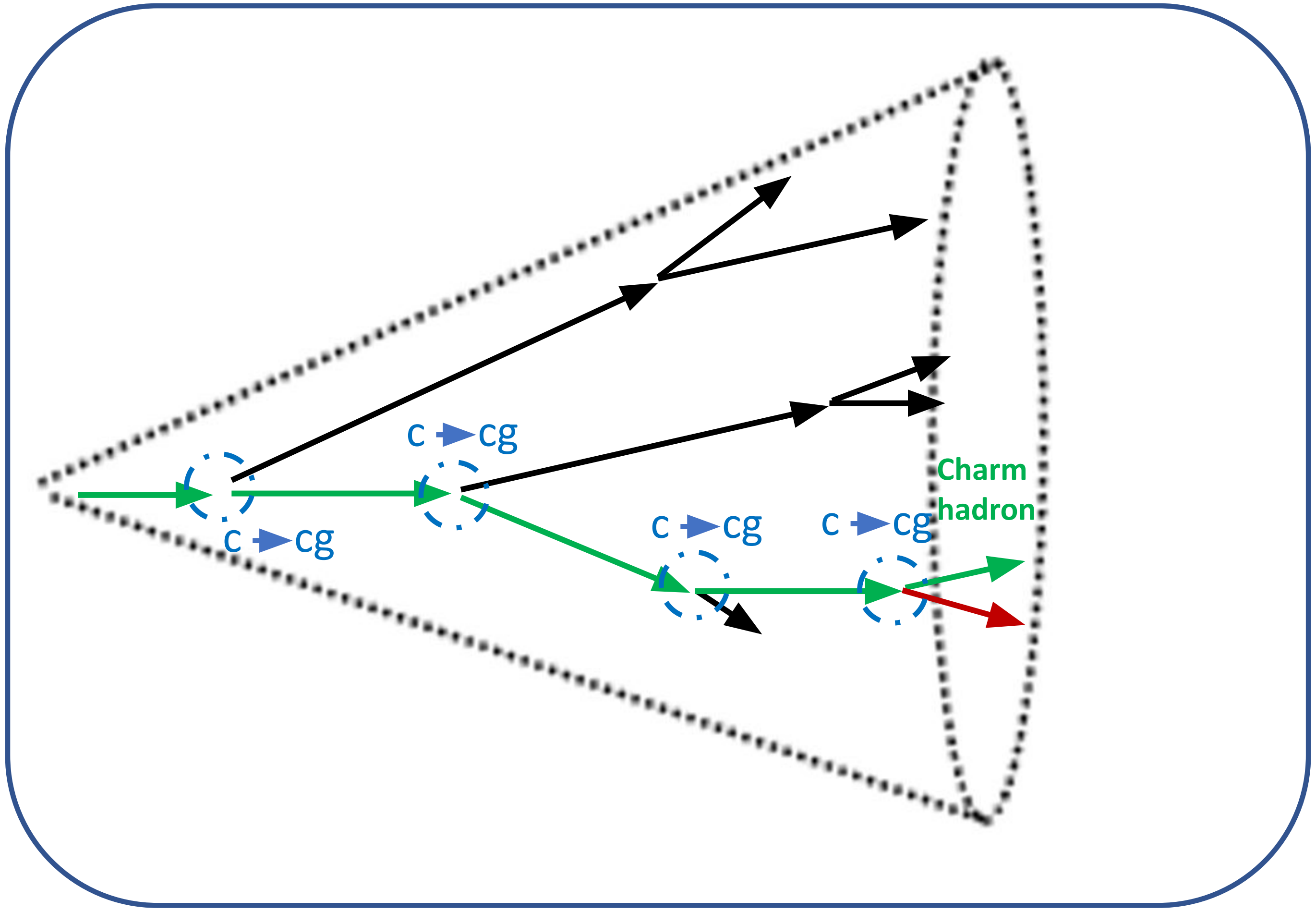

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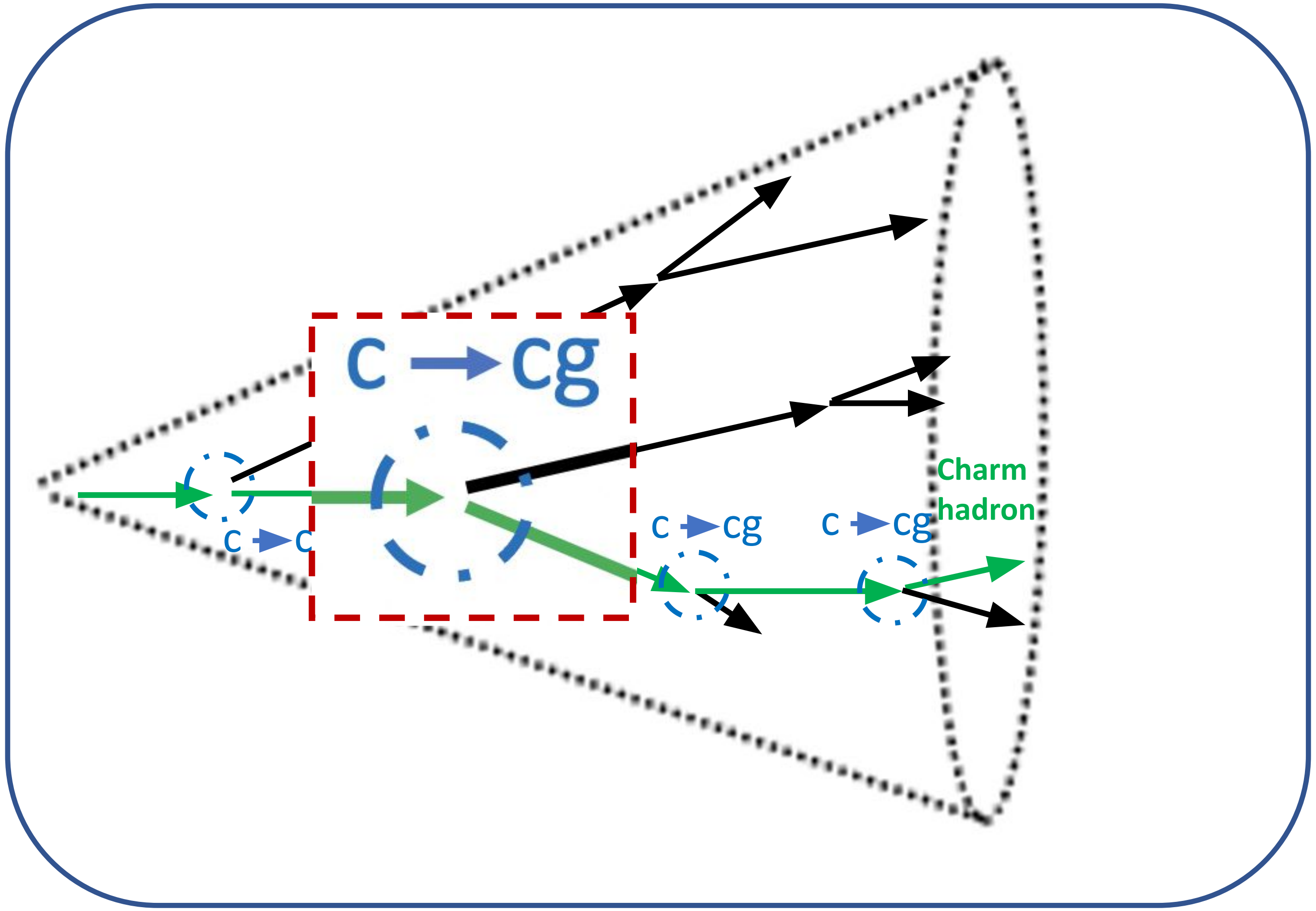
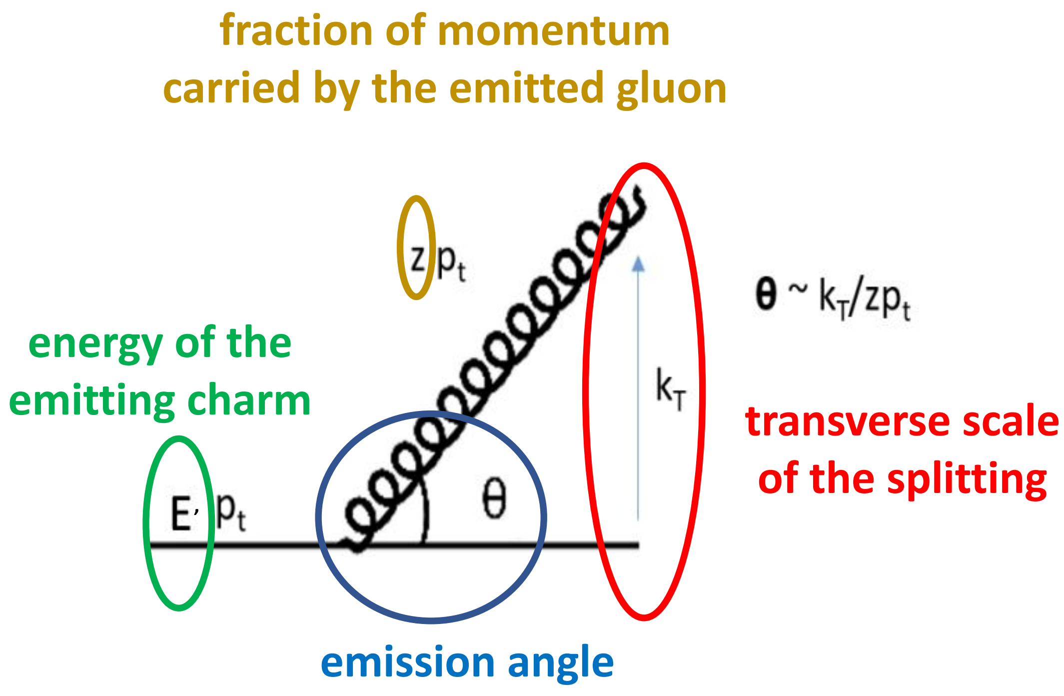
Reconstructed splitting kinematics



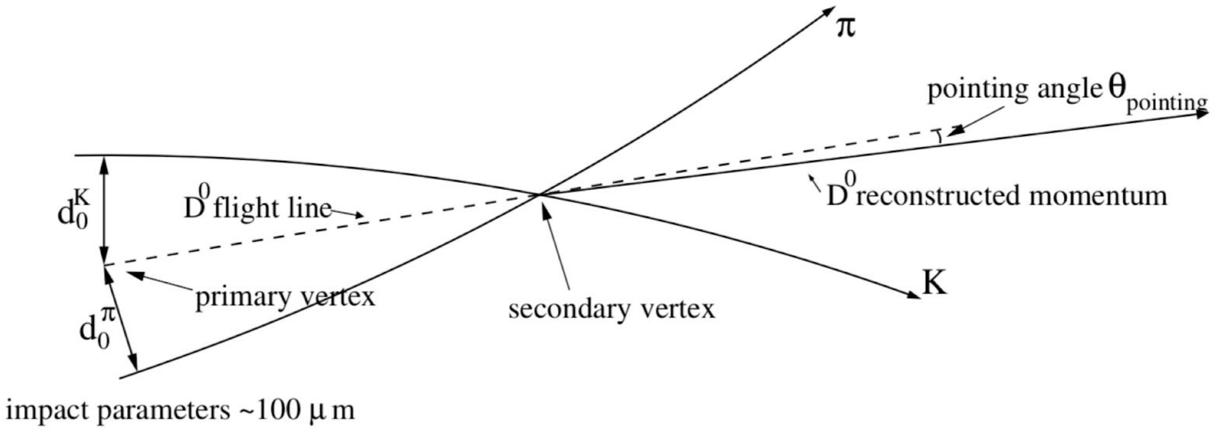


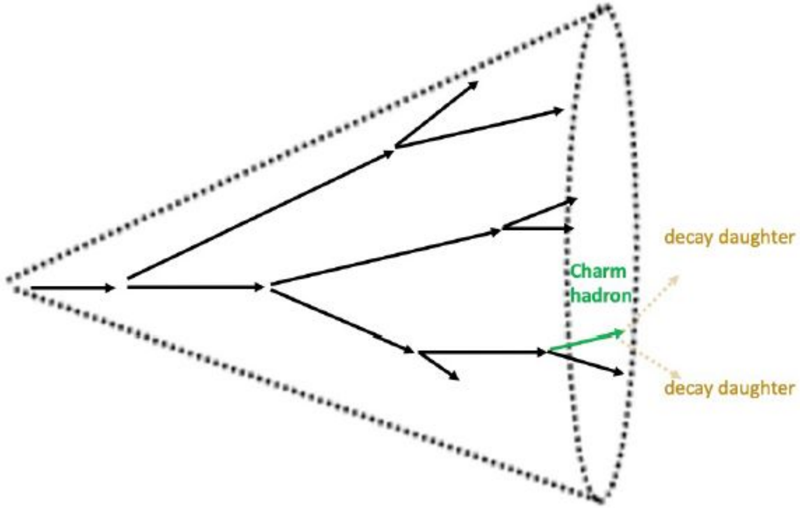
The angle of each gluon emission directly probes the dead-cone effect

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

Selections on the transverse scale of the splittings will be used to suppress non-perturbative effects

Fully reconstructing the charm hadron





Reconstructing the charm hadron (D^0)

D^0 mesons are reconstructed through the

$$D^0 \rightarrow K^- \pi^+$$

(and charge conjugate) channel

Selection 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 pp collisions

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

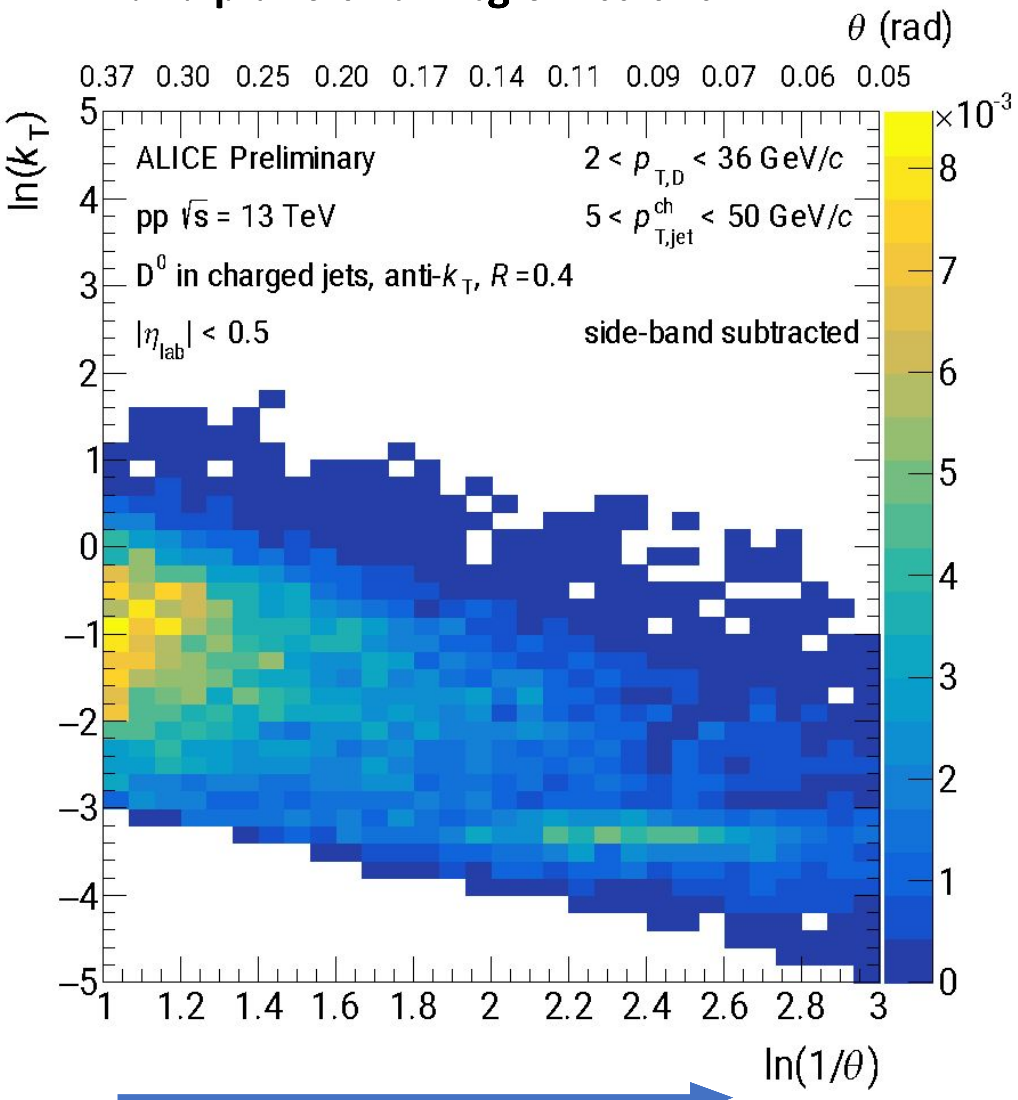
The D^0-decay daughters are replaced by the reconstructed D^0 candidate prior to jet finding

Jet finding is performed using the anti-k_T algorithm with R=0.4 and jets containing a D^0 meson are selected

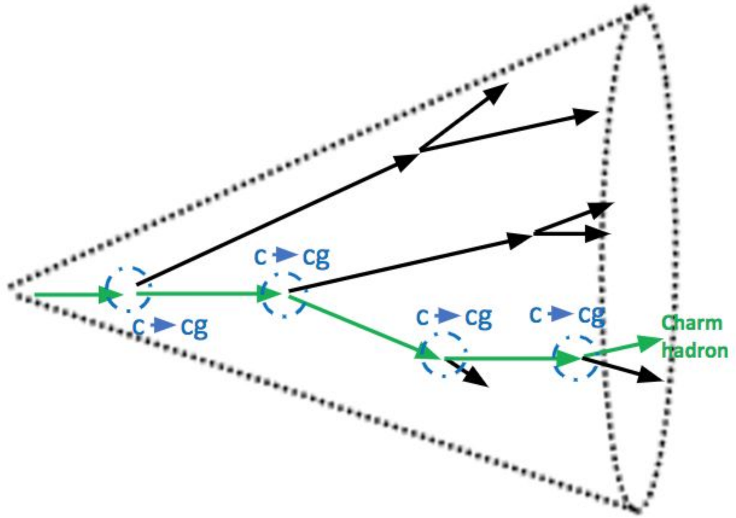
$$5 < p_T^{\text{jet}} < 50 \text{ GeV}/c$$

Populating the c->cg Lund plane

Lund plane of c -> cg emissions



Smaller angles



Measuring the Lund plane for a particular flavour of emissions in QCD

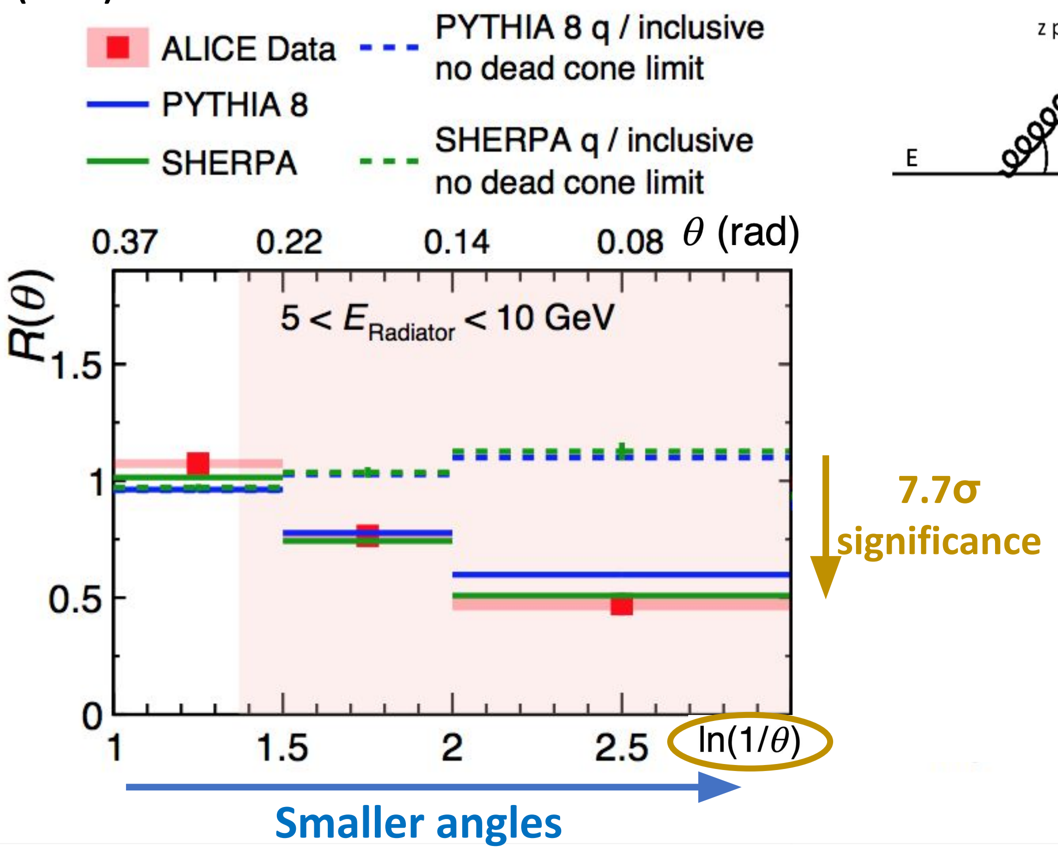
Uncovering the QCD dead cone

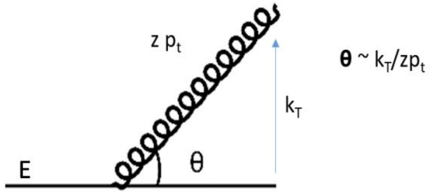
$$R(\theta) = \frac{1}{N^{\mathrm{D^0\,jets}}} \frac{\mathrm{d}n^{\mathrm{D^0\,jets}}}{\mathrm{d}\ln(1/\theta)} \Bigg/ \frac{1}{N^{\mathrm{inclusive\,jets}}} \frac{\mathrm{d}n^{\mathrm{inclusive\,jets}}}{\mathrm{d}\ln(1/\theta)} \Bigg|_{k_{\mathrm{T}},\,E_{\mathrm{Radiator}}}$$

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

Uncovering the QCD dead cone

Nature 605 (2022) 440-446





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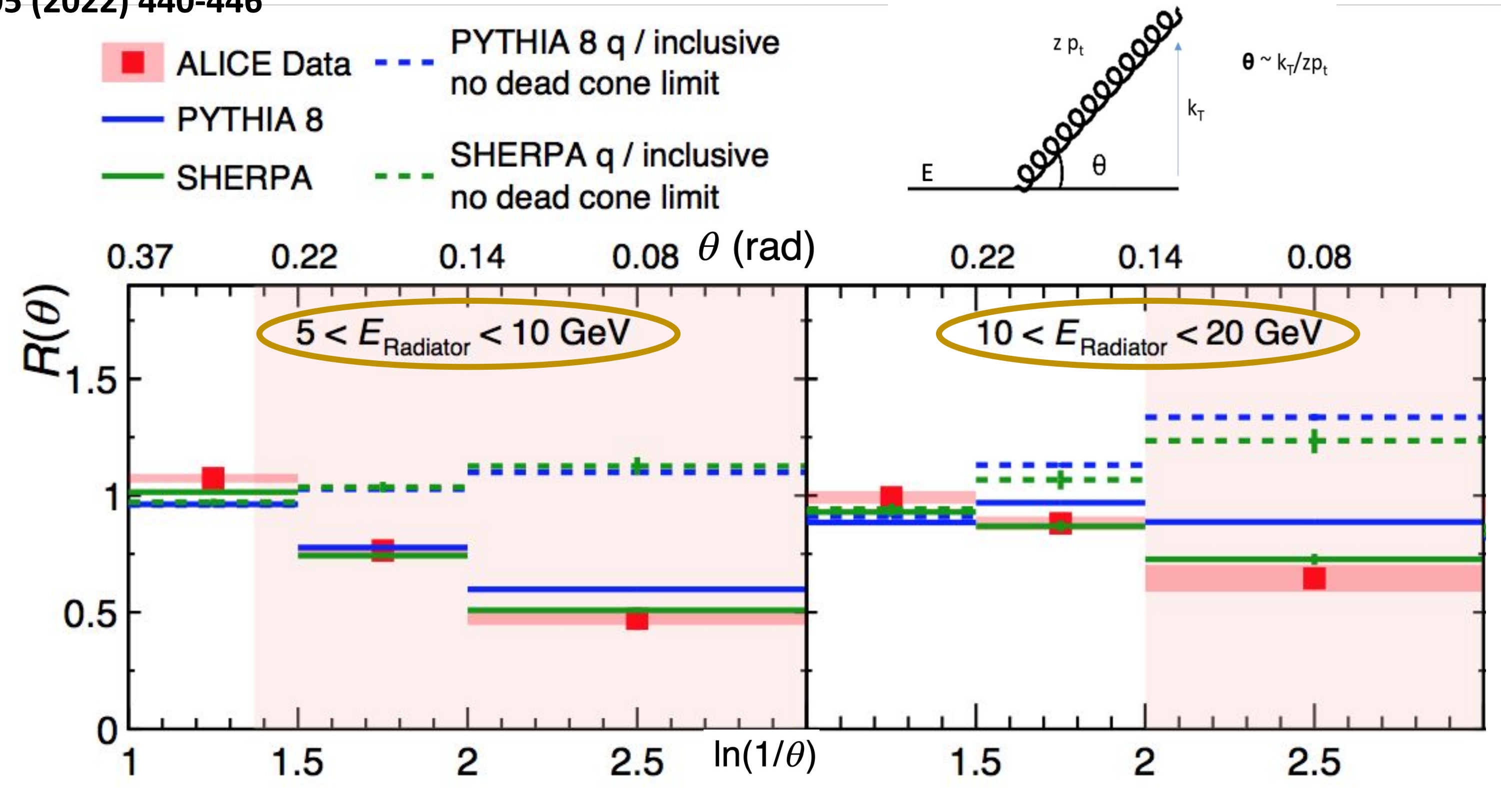

$\theta \sim k_T/zp_t$

less suppression with increasing energy of the radiating charm quark

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

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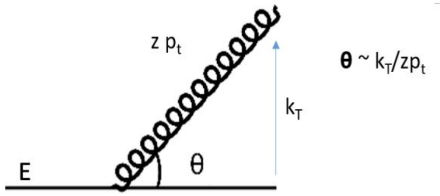

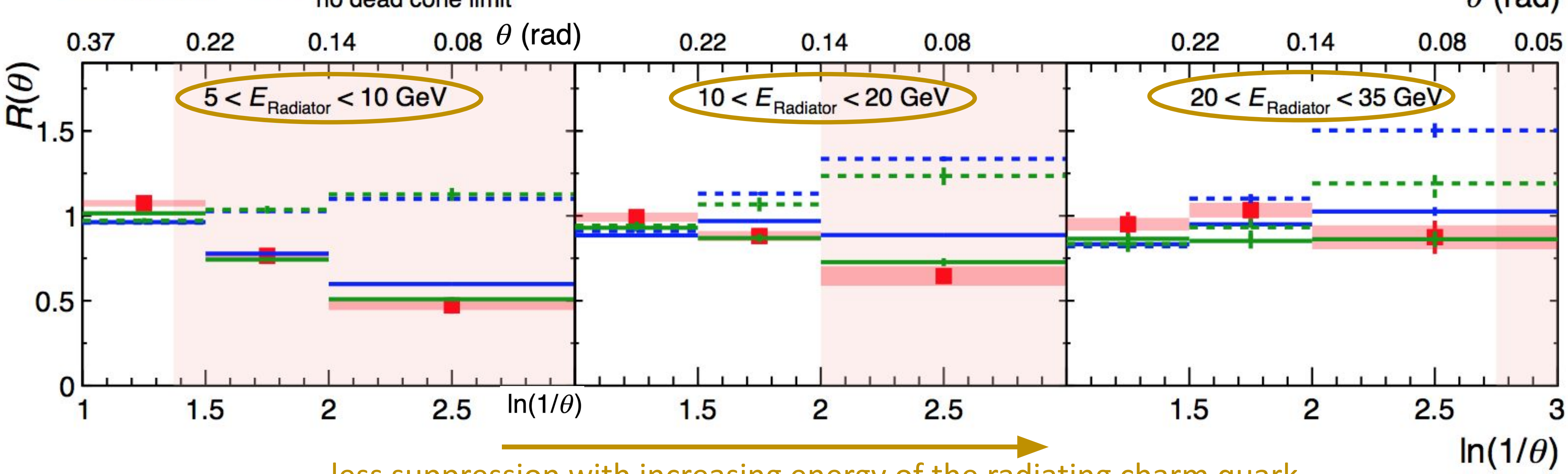

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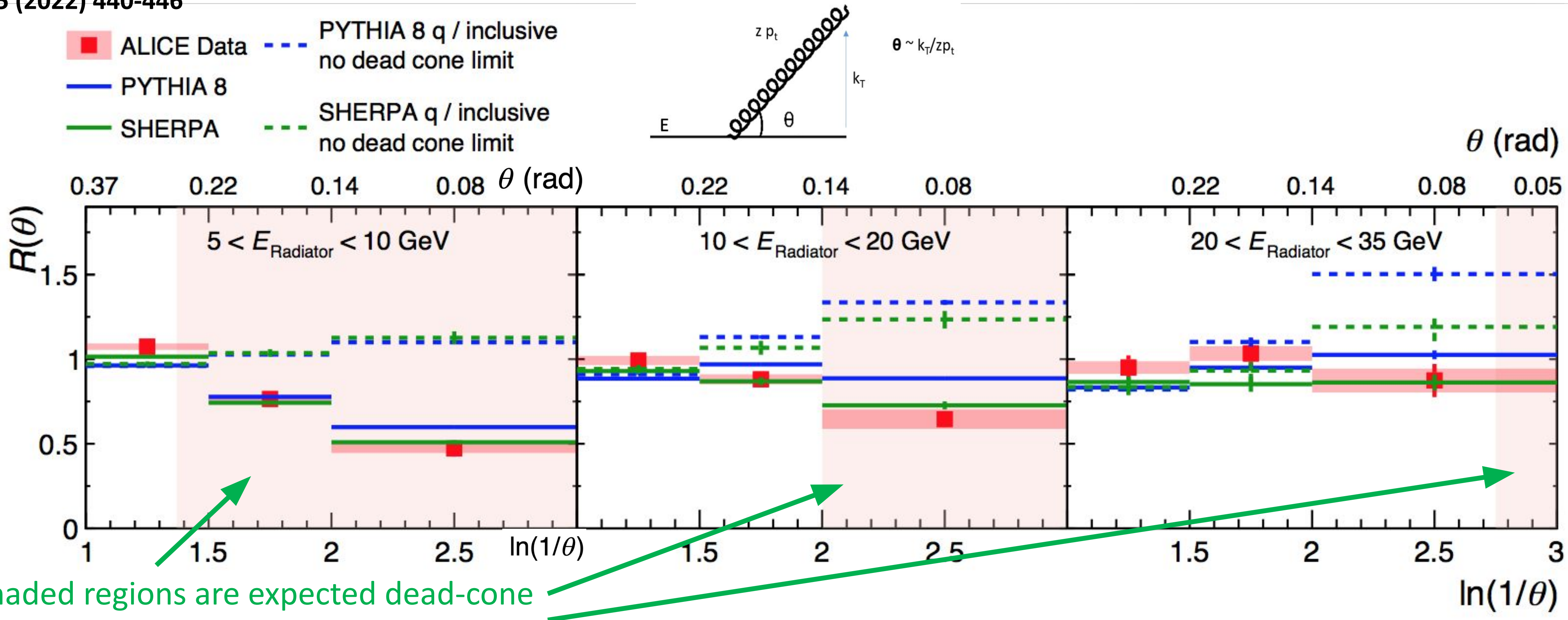

Shaded regions are expected dead-cone region for a charm mass of 1.275 GeV/*c*

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

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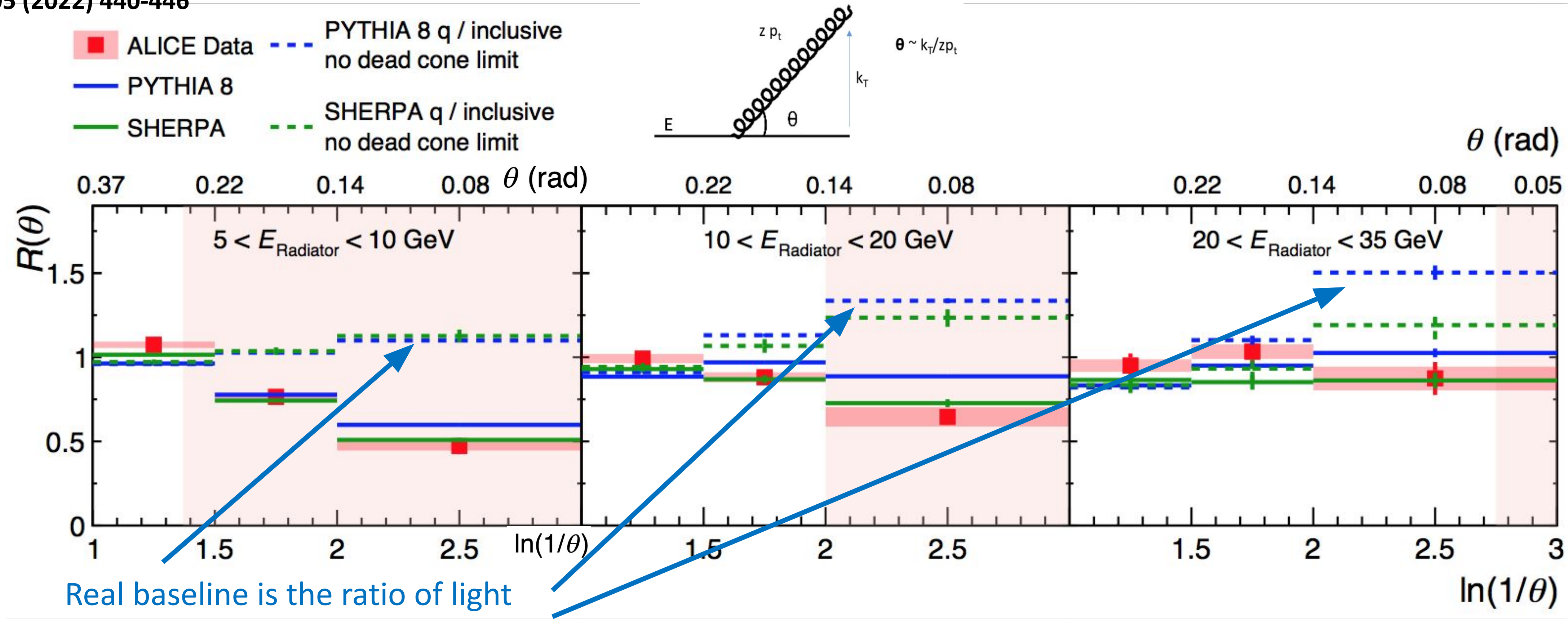


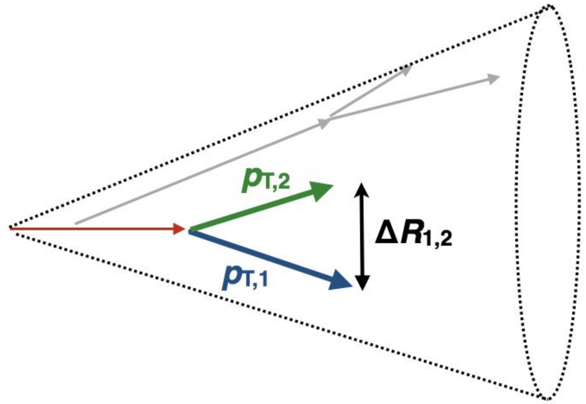
Real baseline is the ratio of light quark to inclusive emissions

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

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

Measuring the c->cg splitting function

Now that we have uncovered the mechanism responsible for mass effects in the QCD shower we extend the techniques to characterise the impact of these mass effects



Soft Drop grooming condition

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

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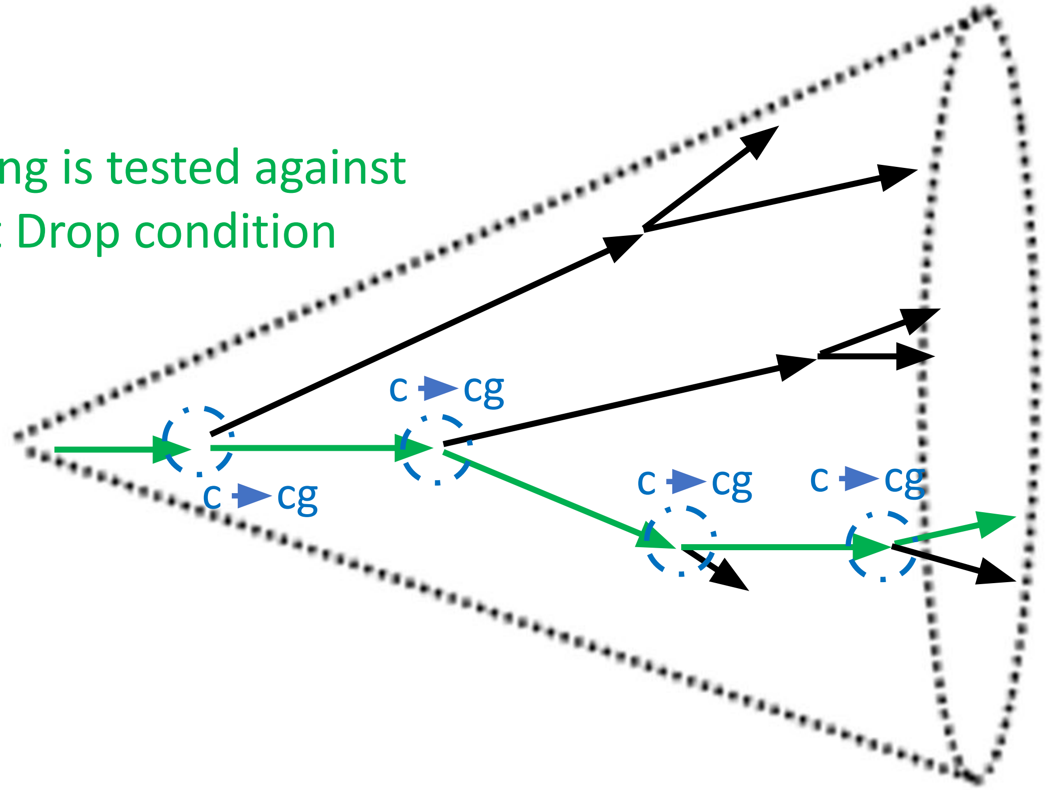
The grooming procedure reduces contribution of non-perturbative effects and enriches the selection with perturbative emissions

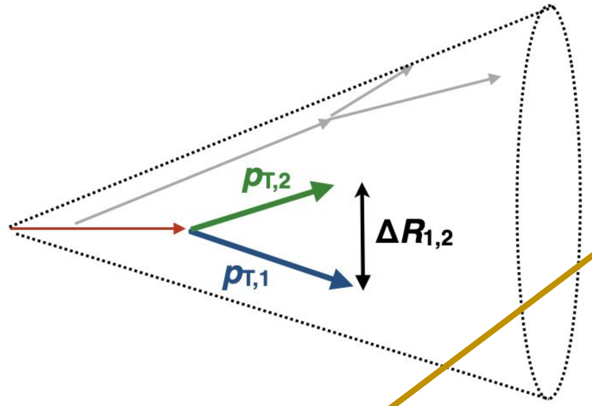
Each splitting is tested against the Soft Drop condition



Measuring the c->cg splitting function

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

arXiv:2208.04857



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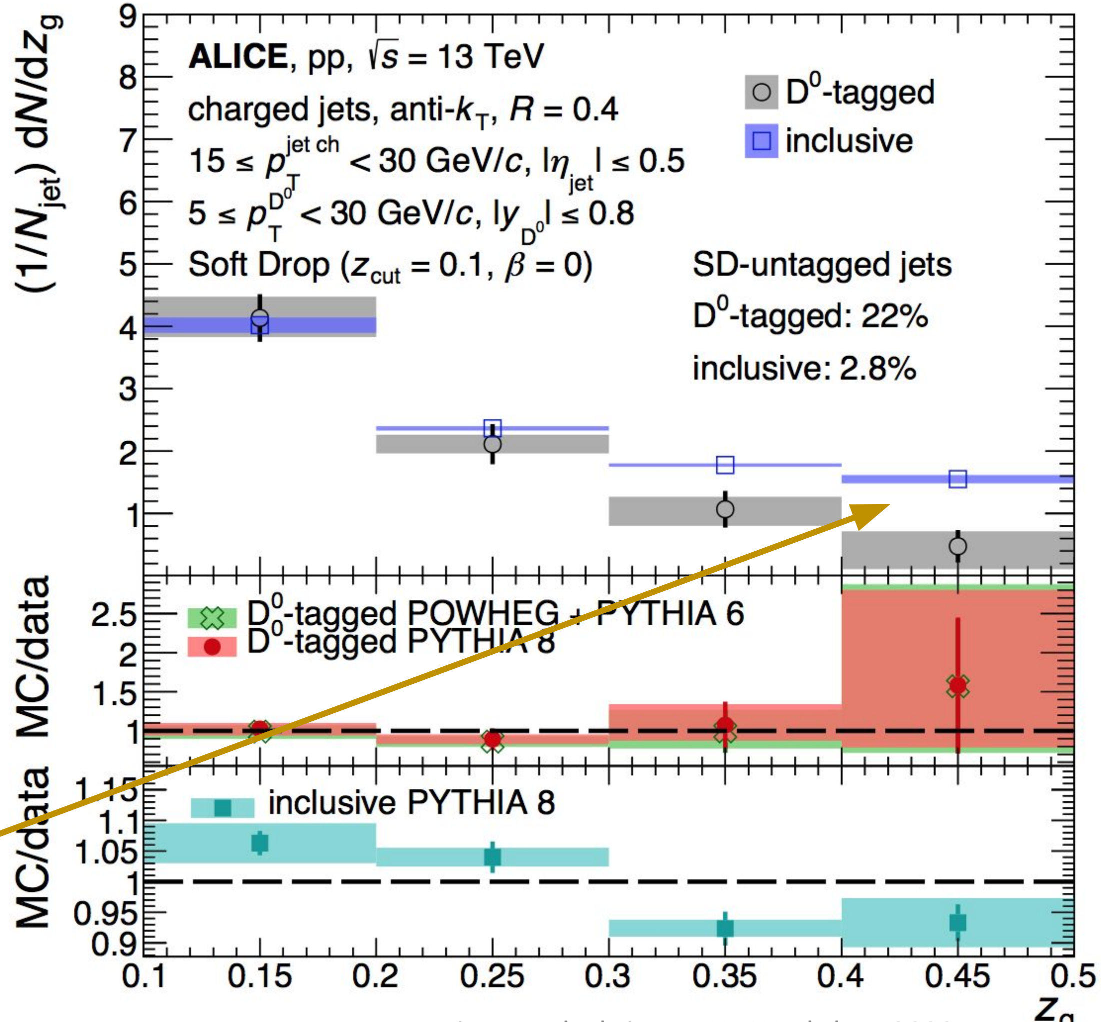
Converges onto the QCD splitting function for the first splitting that passes Soft Drop

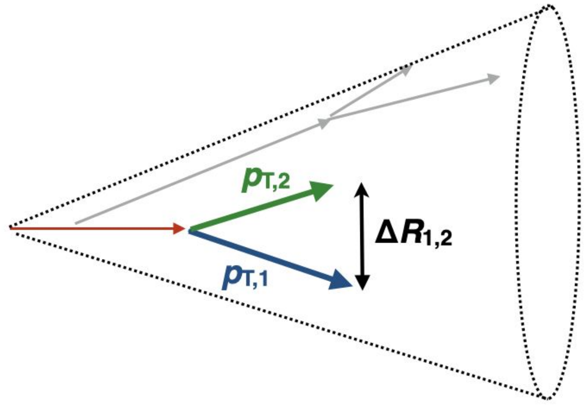
Emissions from charm-quarks have a steeper splitting probability than light quarks and gluons

Fewer symmetric splittings



Measuring the c->cg angular dependence

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



Soft Drop grooming condition

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

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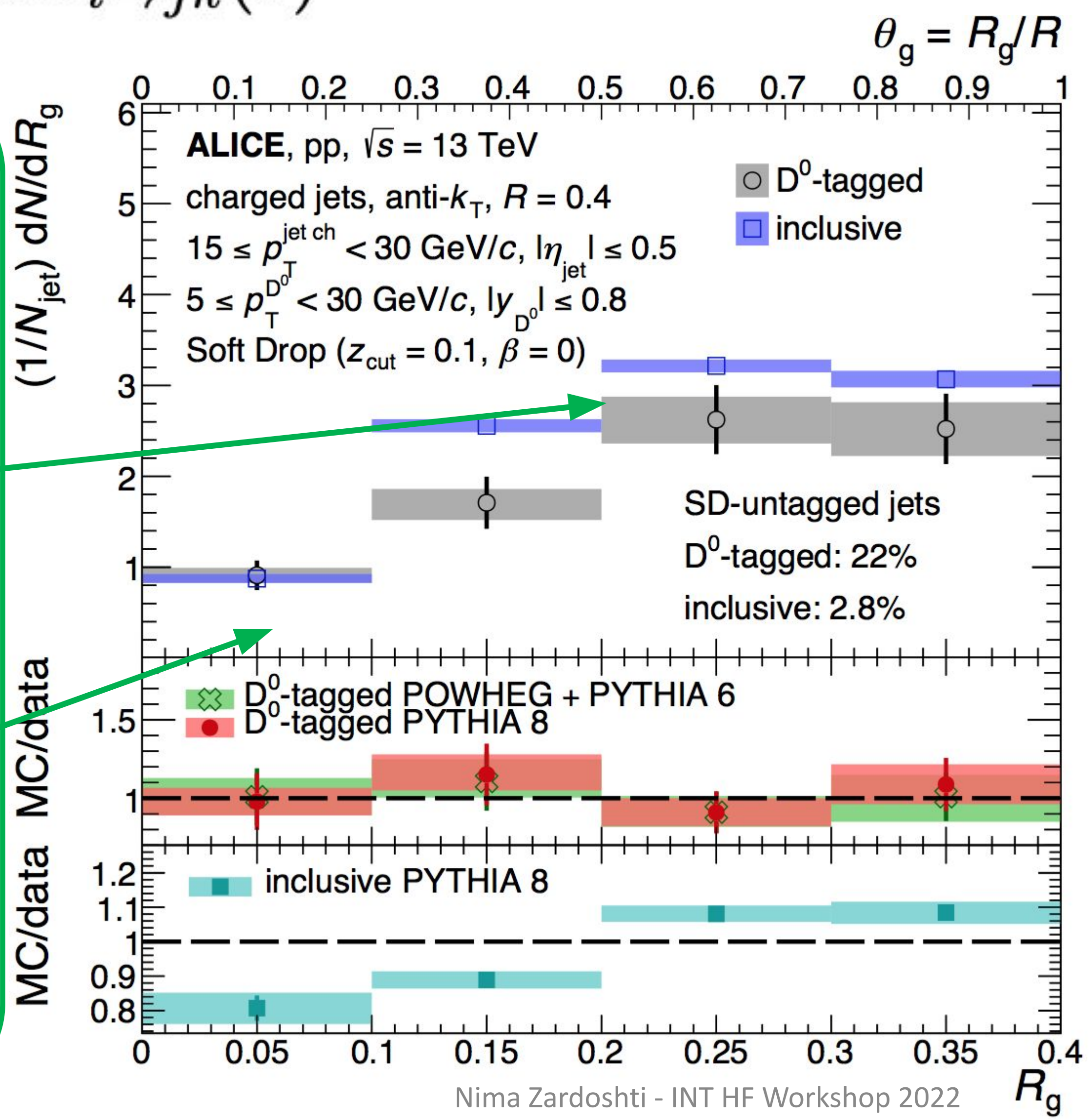
Opening angle of the first emission passing Soft Drop

Gluon jets have a broader shower profile than quark jets

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

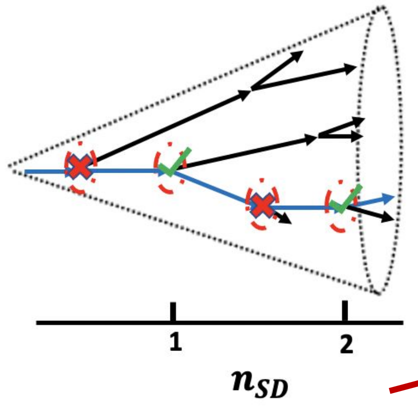
arXiv:2208.04857



Looking deeper into the perturbative shower

arXiv:2208.04857

Towards isolating the perturbative physics of heavy-flavour fragmentation functions



Emission is groomed away

Emission satisfies Soft Drop

Soft Drop grooming condition

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

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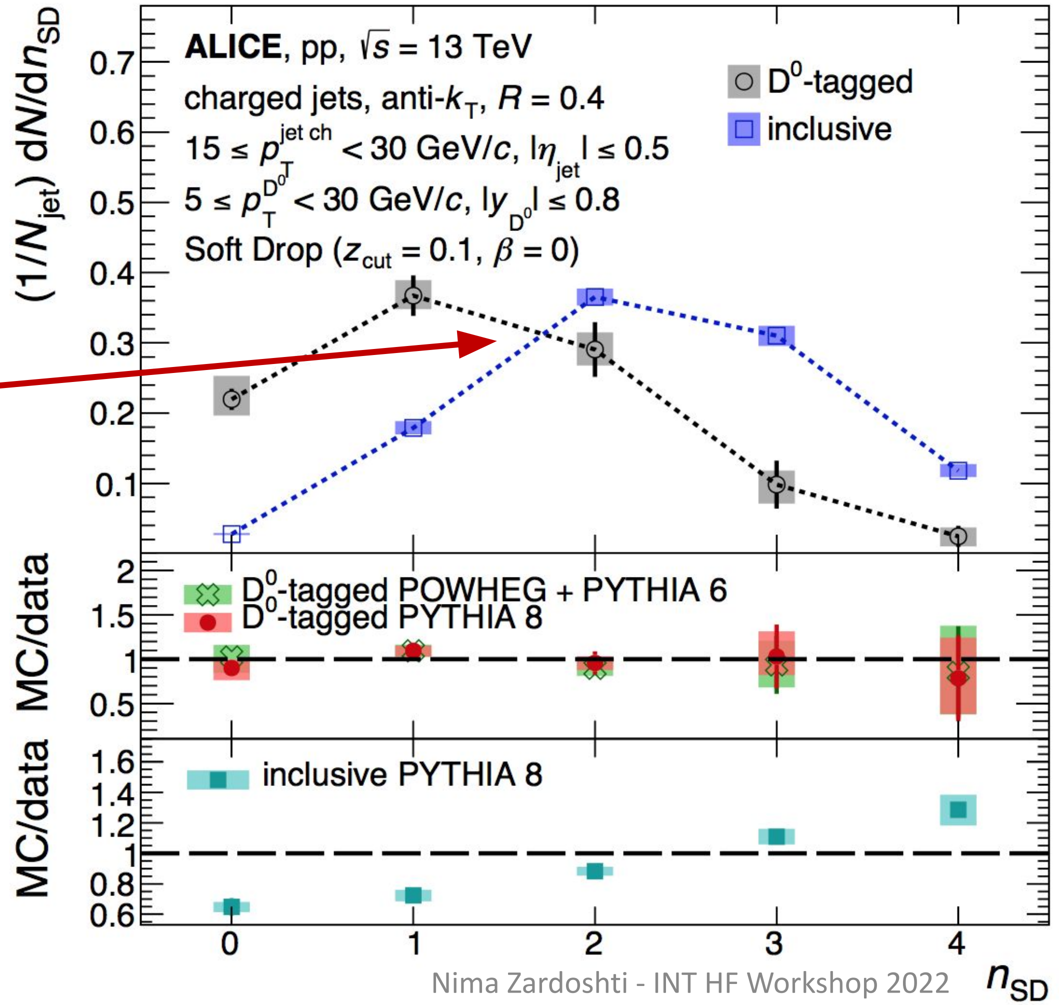
Strongly correlated to the number of perturbative emissions in the shower

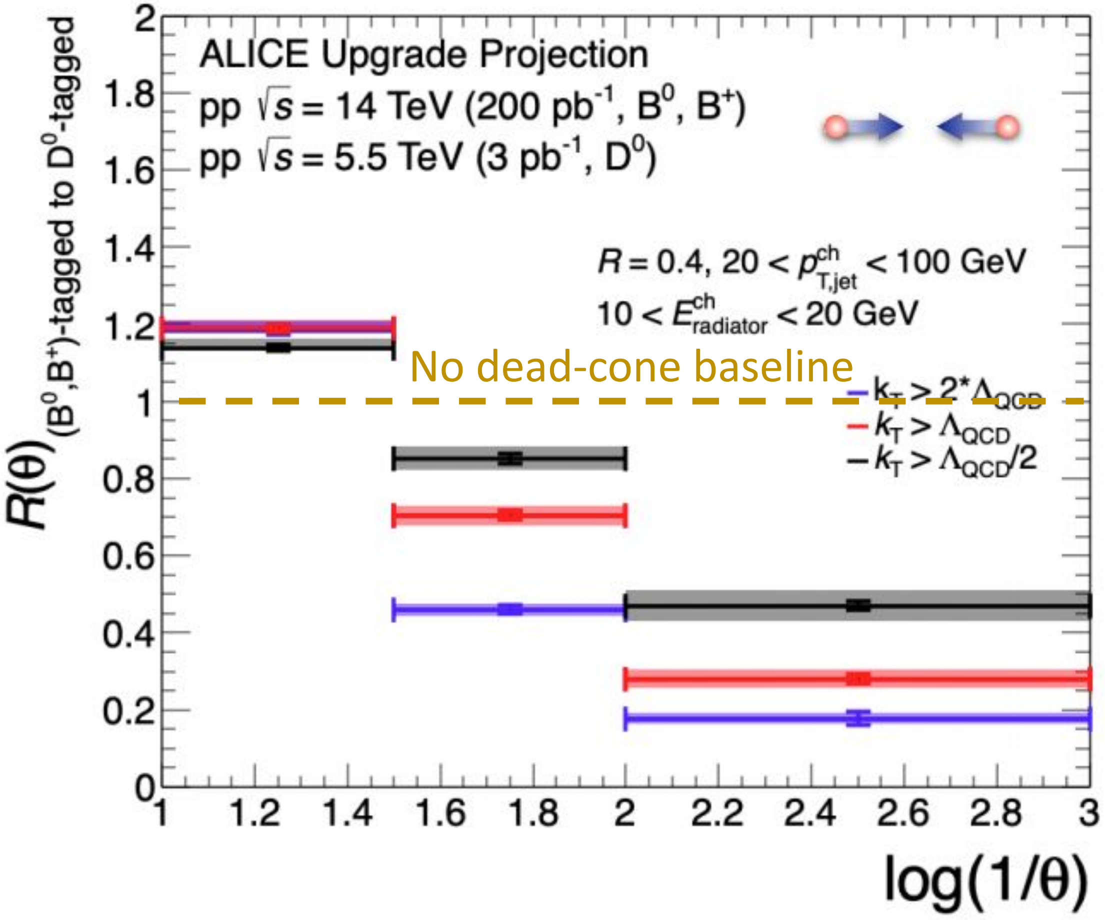
Charm quarks on average have fewer hard emissions

Hardening of the fragmentation function from the dead-cone



Disentangling mass and Casimir colour effects in Run 3

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



Comparisons in pp

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

Comparisons in Pb-Pb

Measurements of the heavy-flavour shower profile to be extended to heavy-ion collisions where these flavour dependent properties can unlock new insights into the nature of the deconfined medium