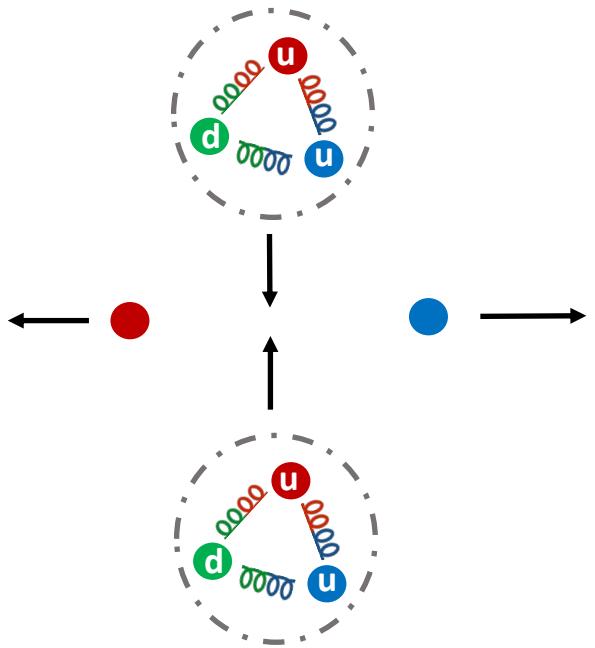
Tracing heavy-flavour quarks through the parton shower

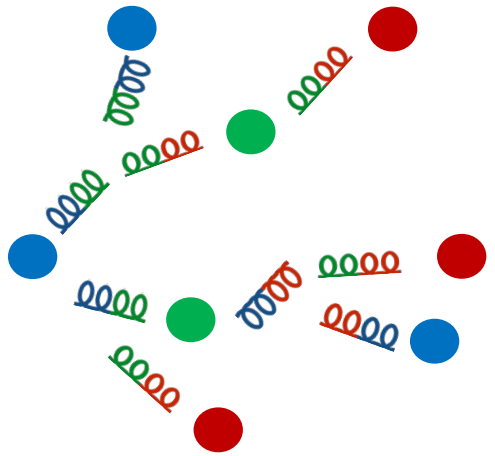
Nima Zardoshti

Heavy-flavours at high p_T workshop
Edinburgh
29/11/2023

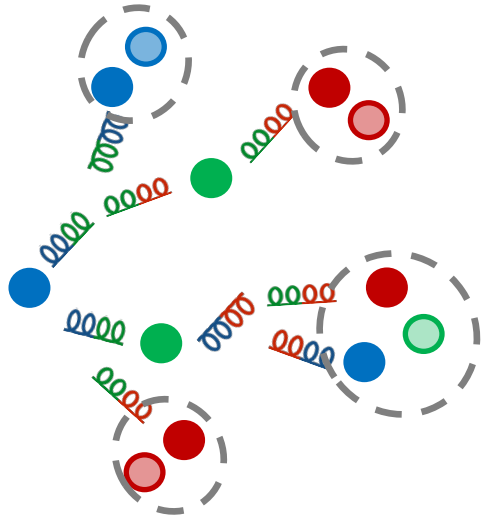
Stages of a collision



Initial hard scatter

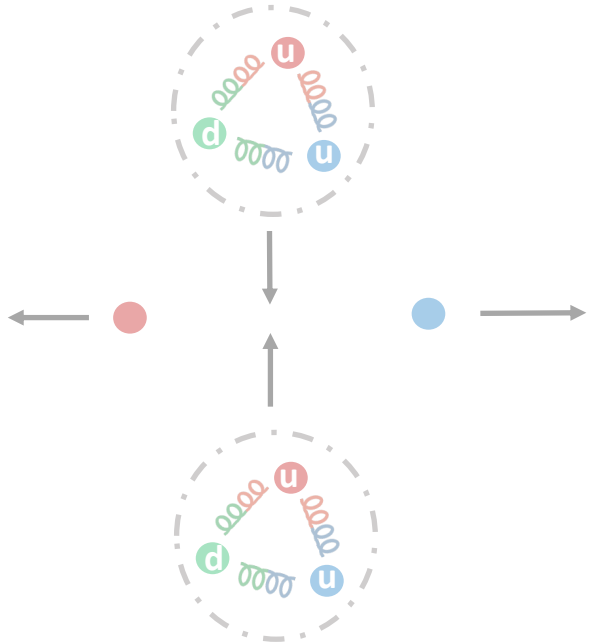


Shower evolution



Hadronisation

Stages of a collision



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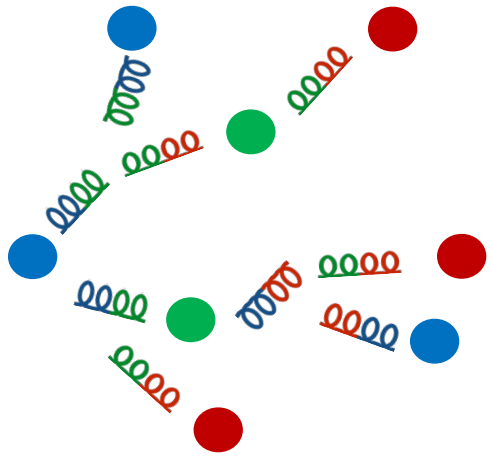

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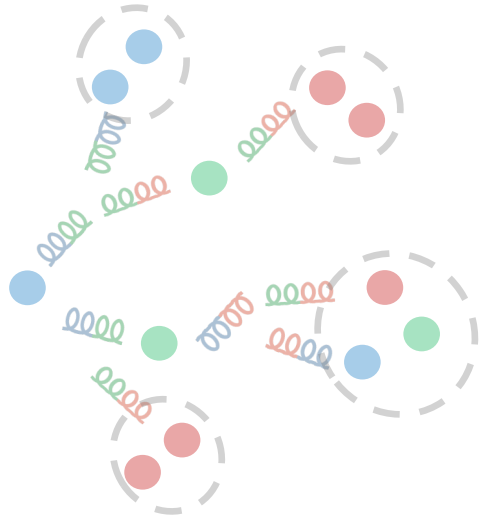


Hadronisation

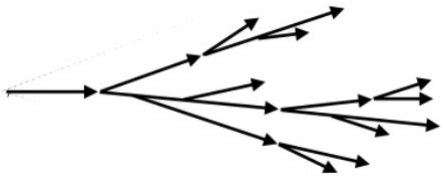
A wealth of partonic interactions to explore QCD

How can we access this region from final state hadrons?

Flavour dependence of QCD showers

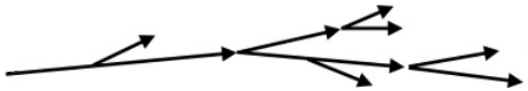
Gluon-initiated shower

Broader shower profile
Higher number of emissions



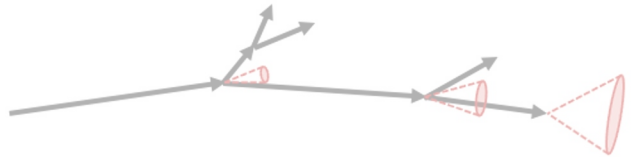
Quark-initiated shower

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

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

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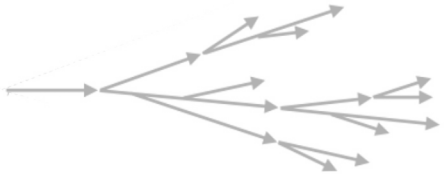

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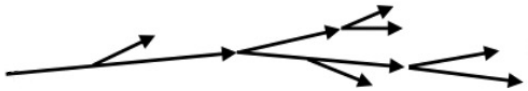

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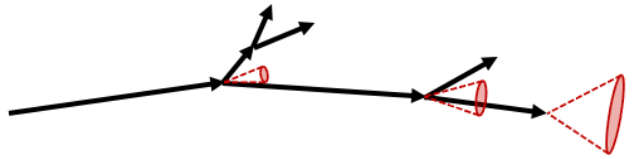

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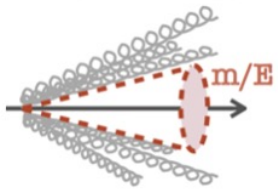
The dead-cone effect

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

Sizeable effect for low energy heavy quarks



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

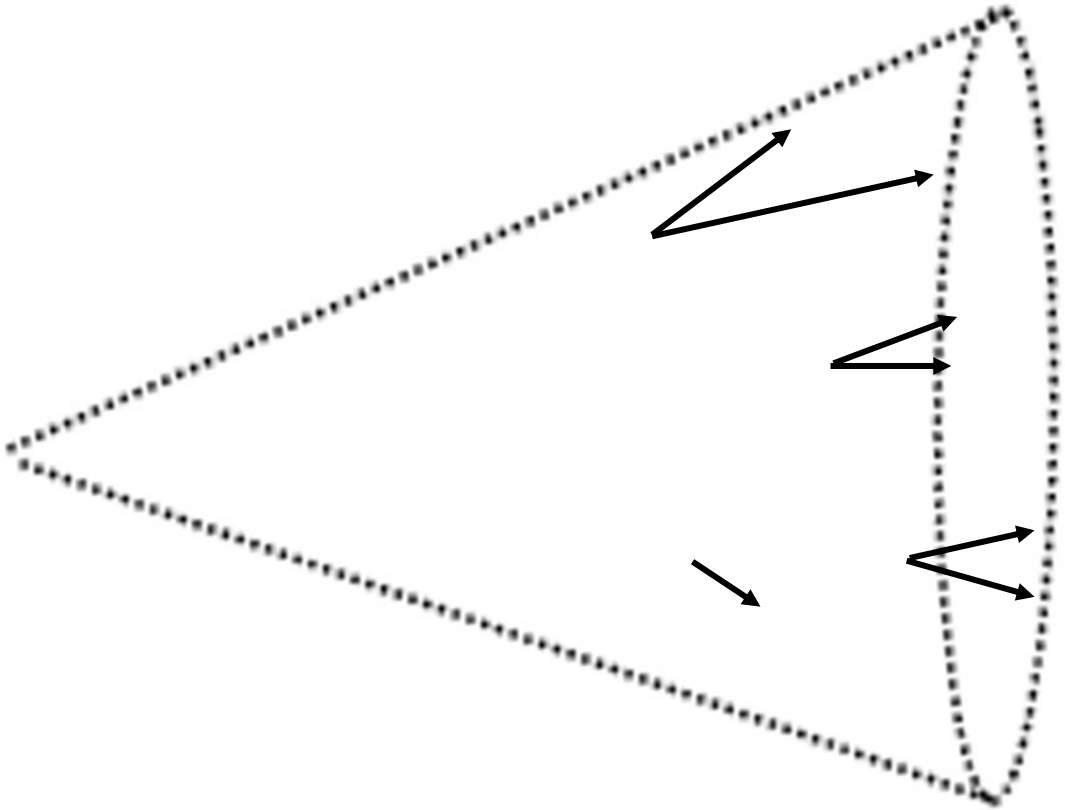
How do we access the shower?

Use the anti-k_T algorithm to cluster jets and identify the final state particles from the shower

Reconstructing the shower

Assume the evolution of the shower followed a given ordering

The jet is reclustered with an algorithm that respects that ordering
Angular ordering -> C/A



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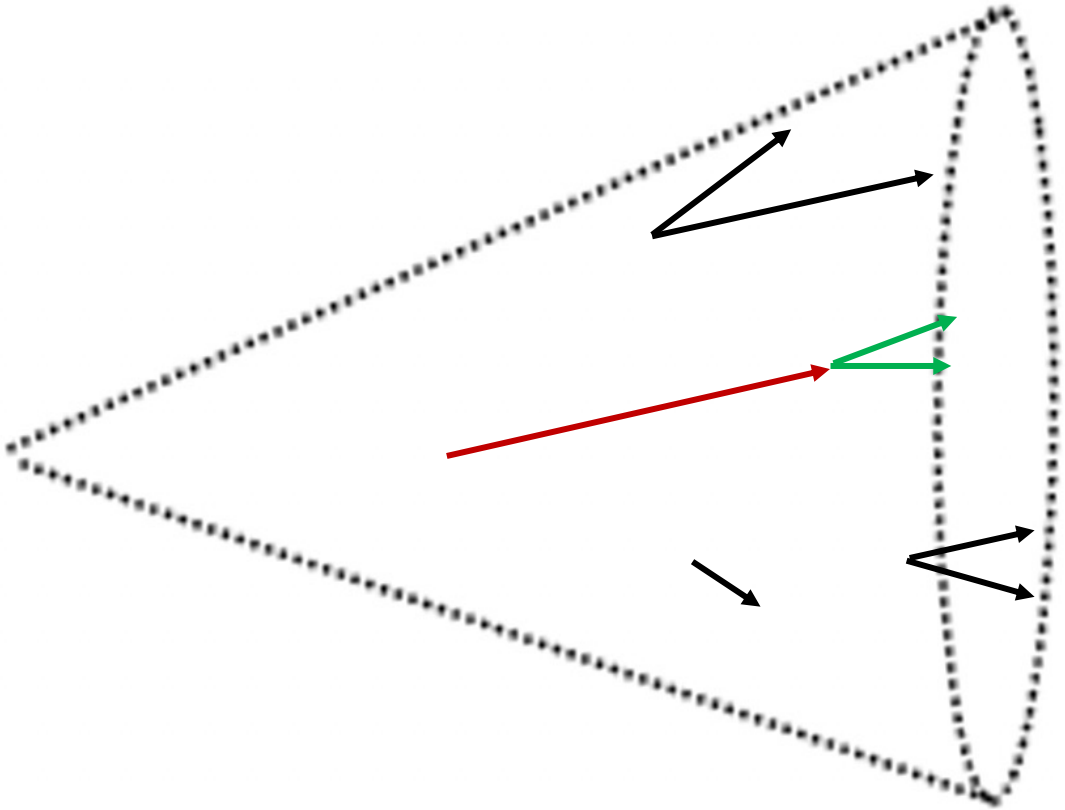

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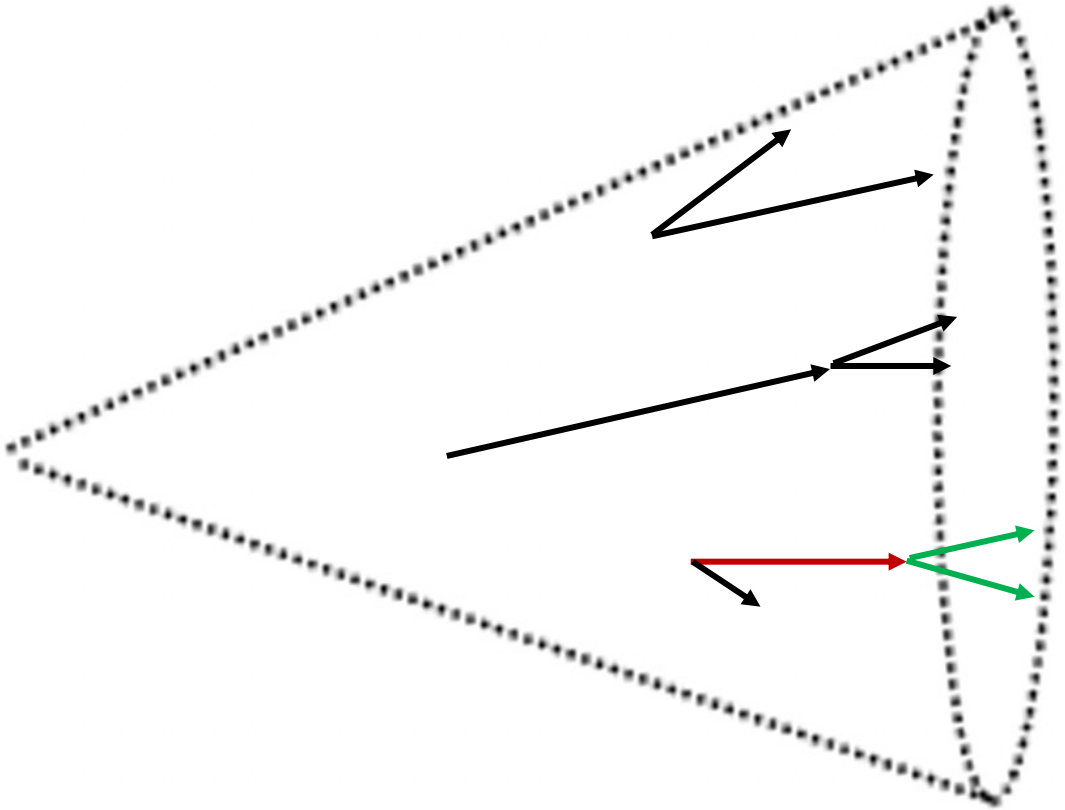

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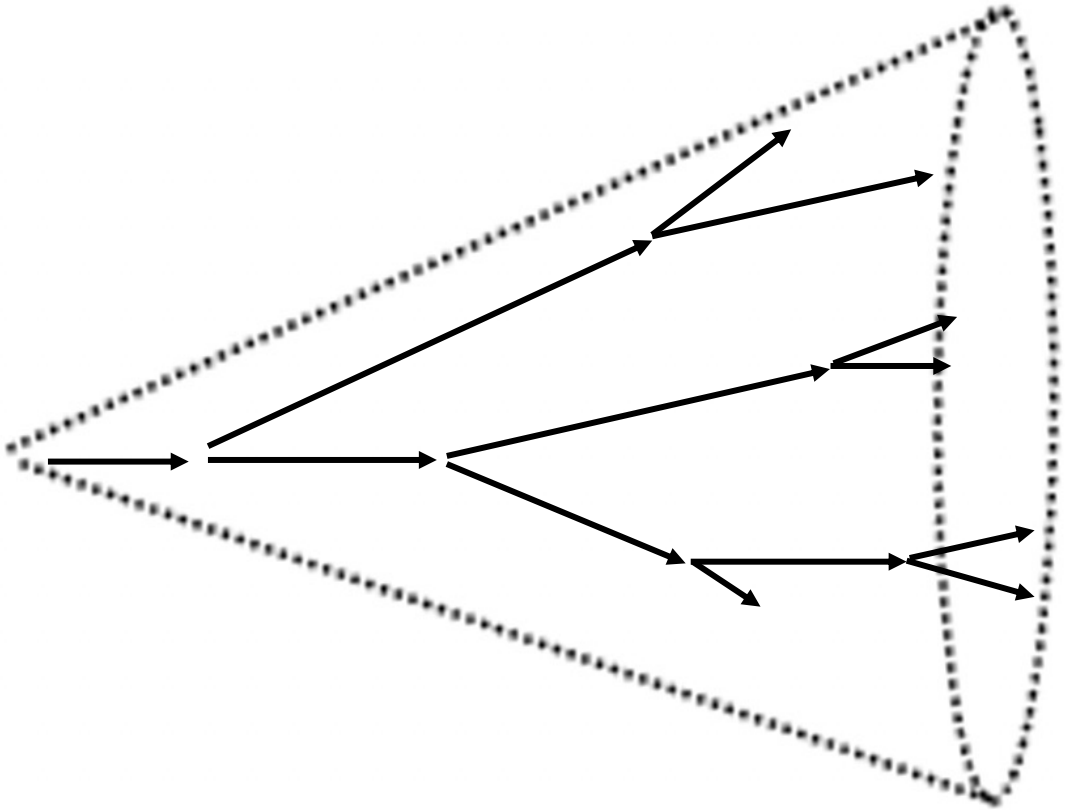


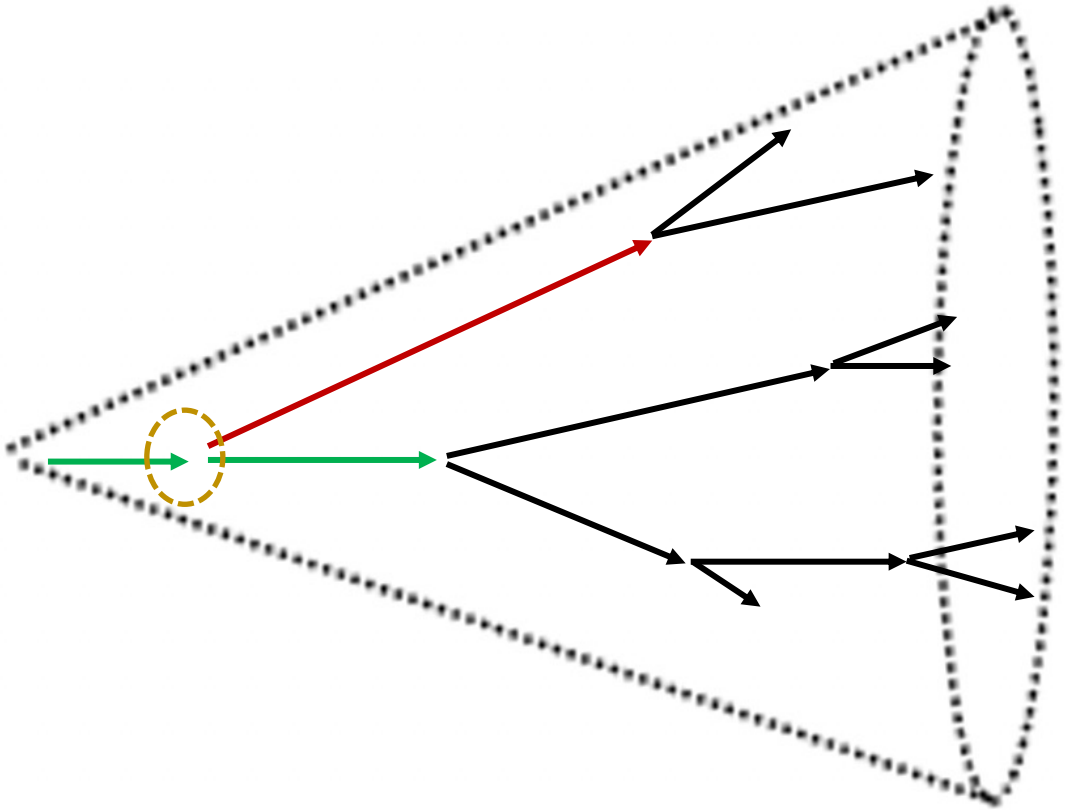
What is tracing?

The idea is to follow the evolution of a particular parton through the shower

Requirements for tracing

Access the structure of the shower

Make a choice at each splitting vertex of which branch to follow



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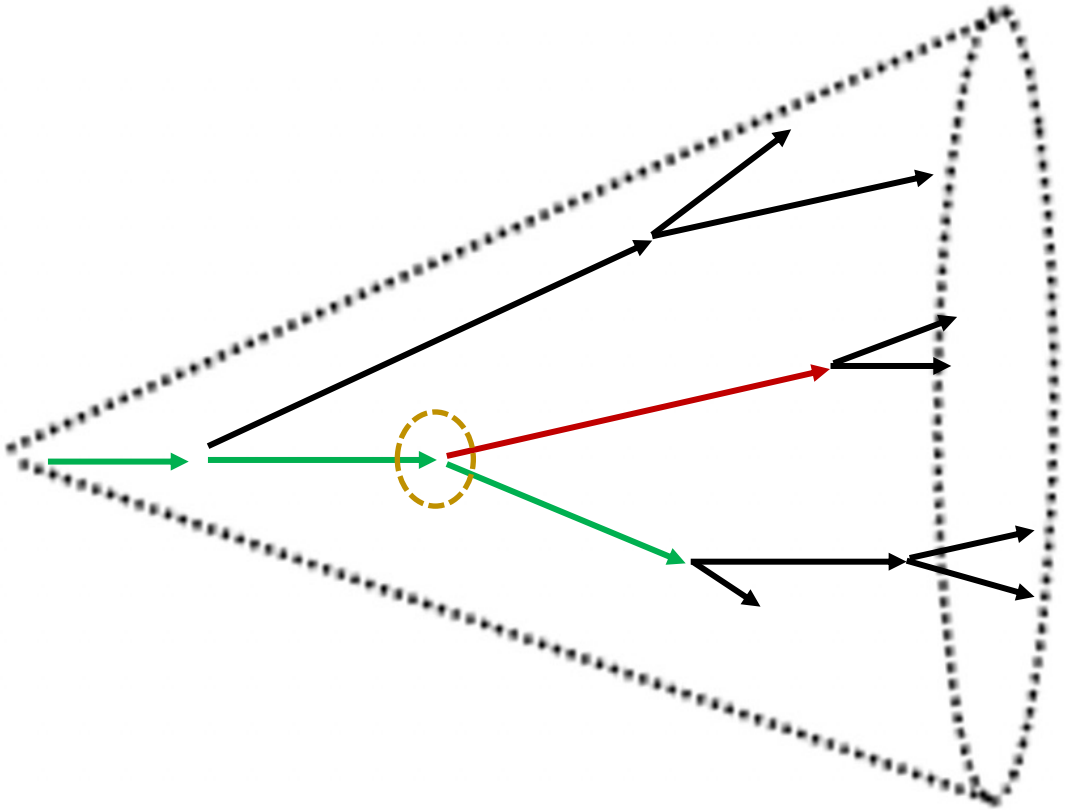

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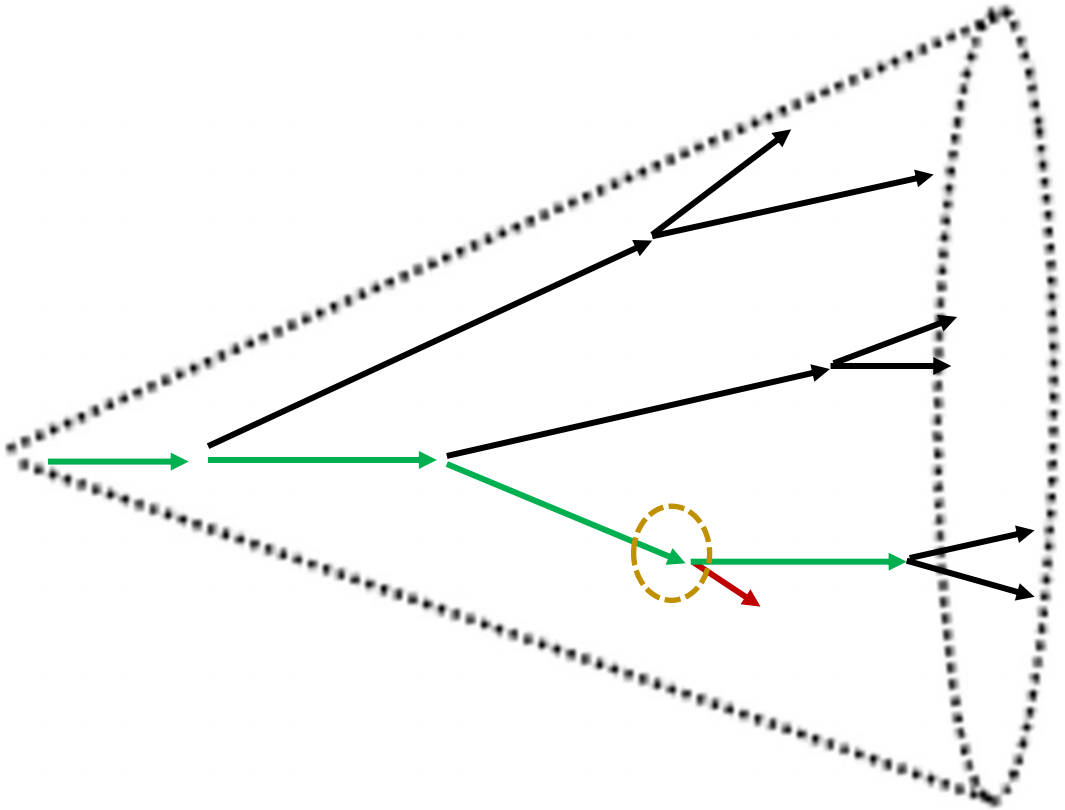

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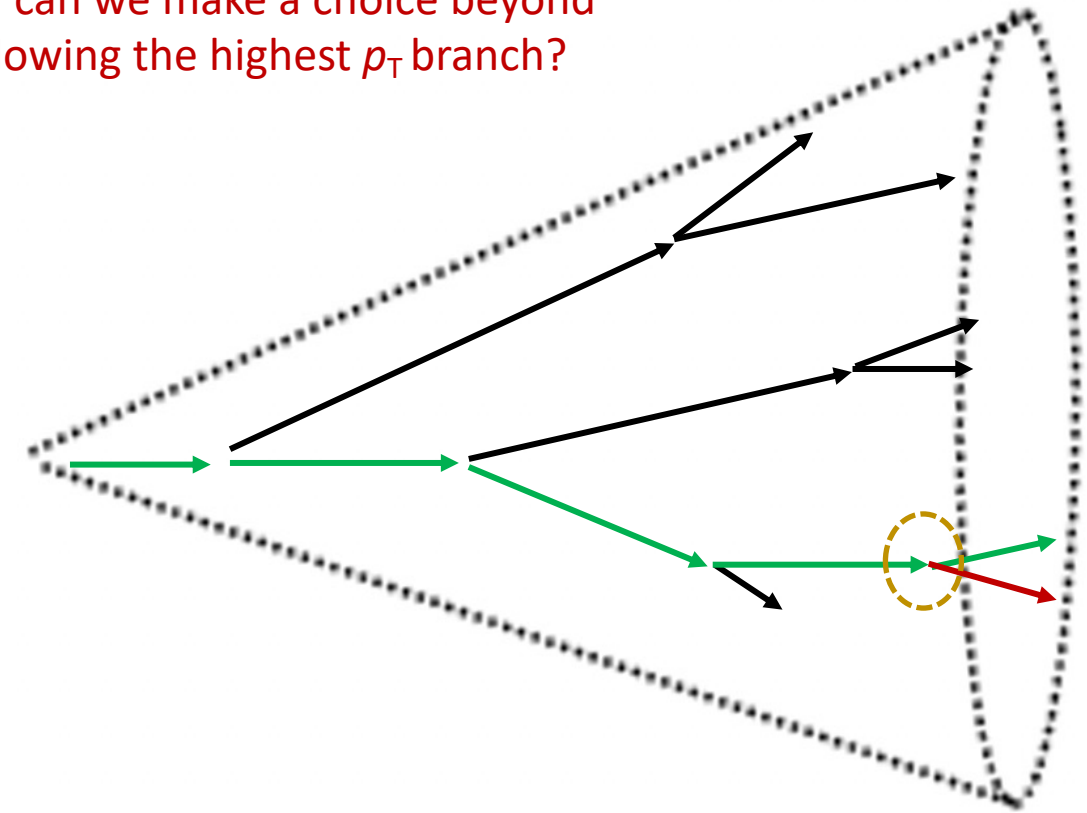
How can we make a choice beyond following the highest p_T branch?



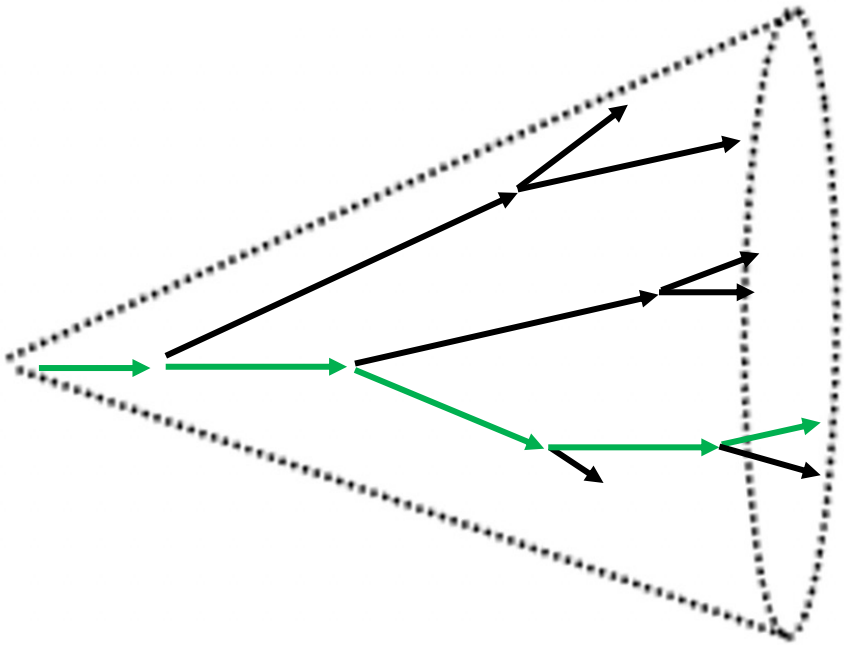
Requirements for tracing

Access the structure of the shower

Make a choice at each splitting vertex of which branch to follow

The key to tracing is to make the correct choice at each vertex

Following the heavy-flavour quark



At each splitting vertex follow the branch that contains a heavy-flavour quark

What makes heavy-flavour the ideal candidate for tracing?

Hadronisation

Heavy-quark production through string breaking is suppressed during hadronisation

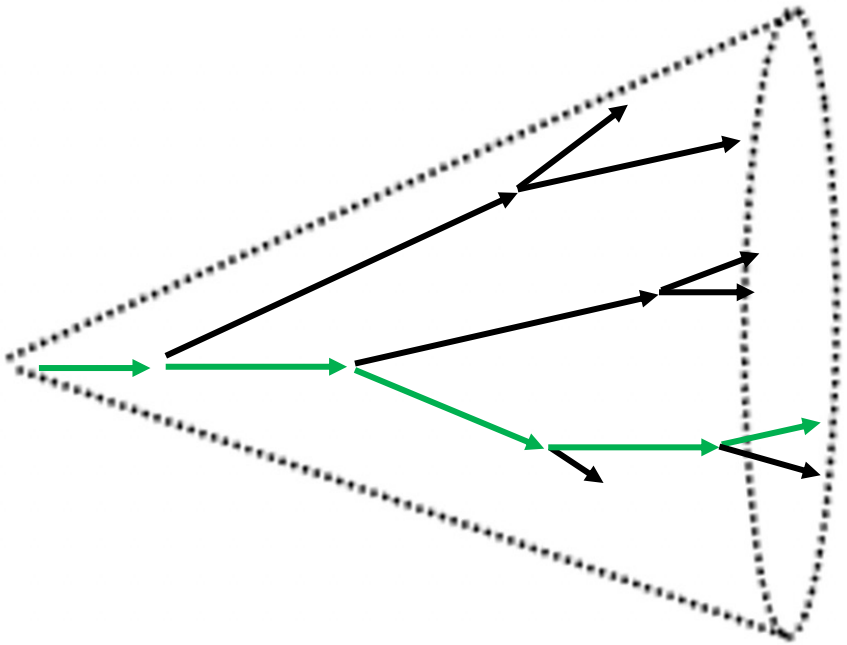
Factor of 10^{-11} suppression compared to light quarks

Single emission channel

Once a quark is produced in the shower it can only undergo q->qg emissions

c->cg or b->bg

Once a charm quark has been identified in the final state we can guarantee that it participated in the shower



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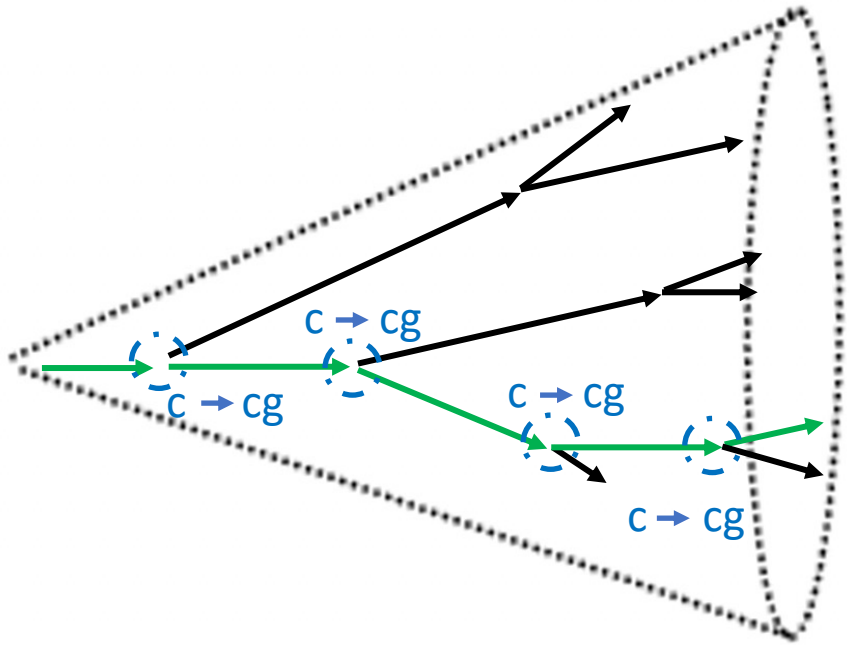
Following the charm quark through the shower gives access to a well controlled splitting flavour by only requiring its presence



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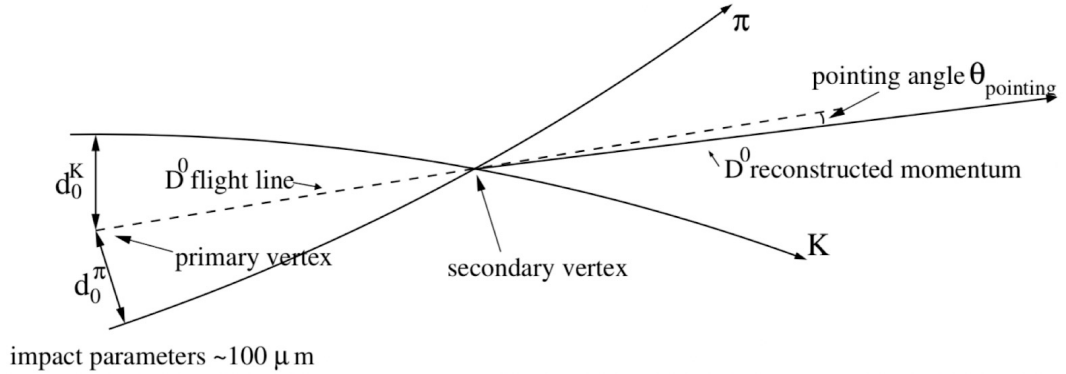
How do we tag the presence of the heavy-quark?

Methodology



The heavy-flavour hadron is a proxy for the final state of the heavy-quark in the shower

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

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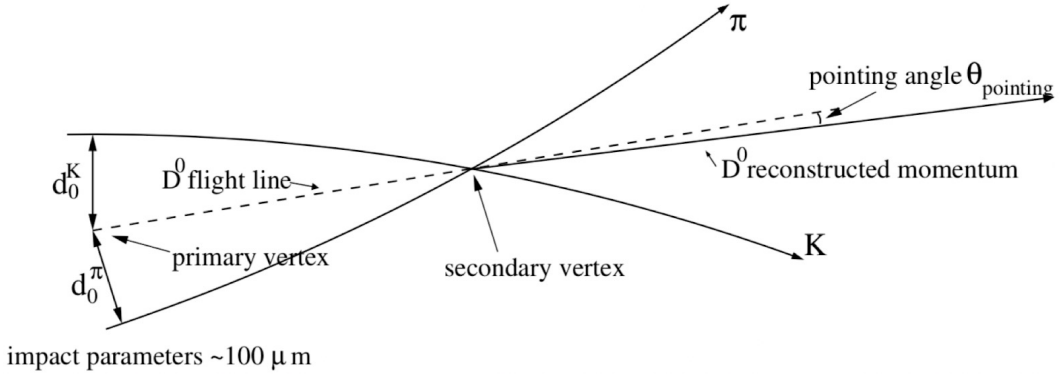
Heavy-flavour hadrons are identified from their decay products



Decay products

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

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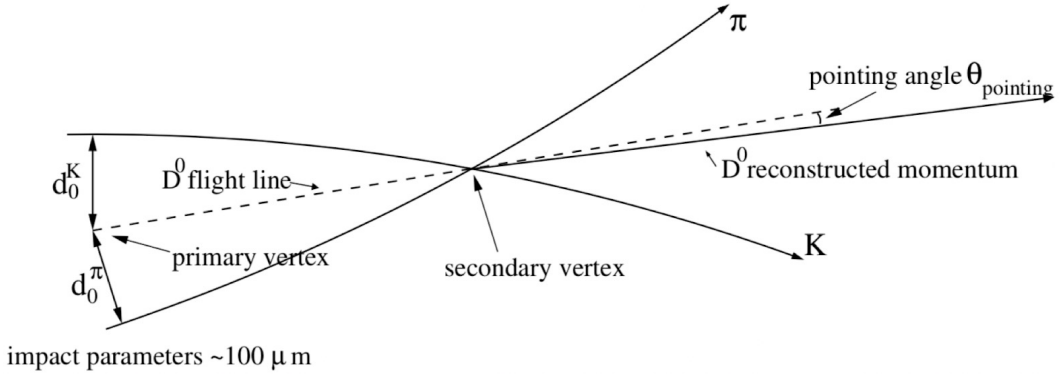
Replace the heavy-flavour hadron daughters with the parent's four-momentum



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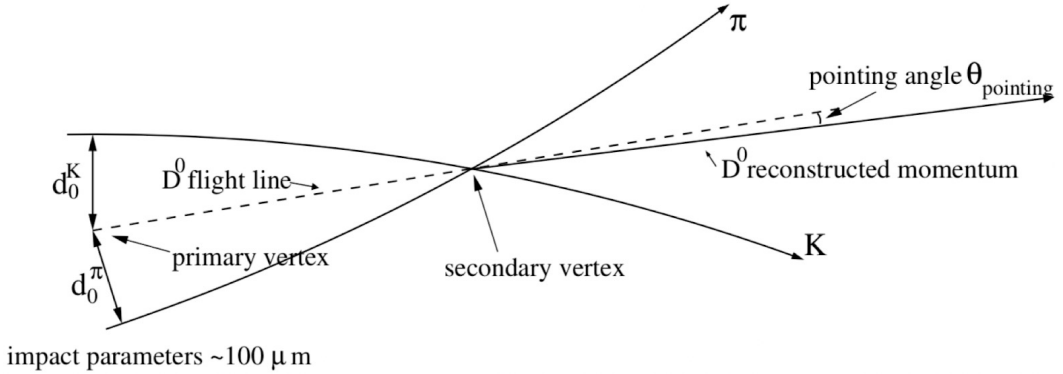

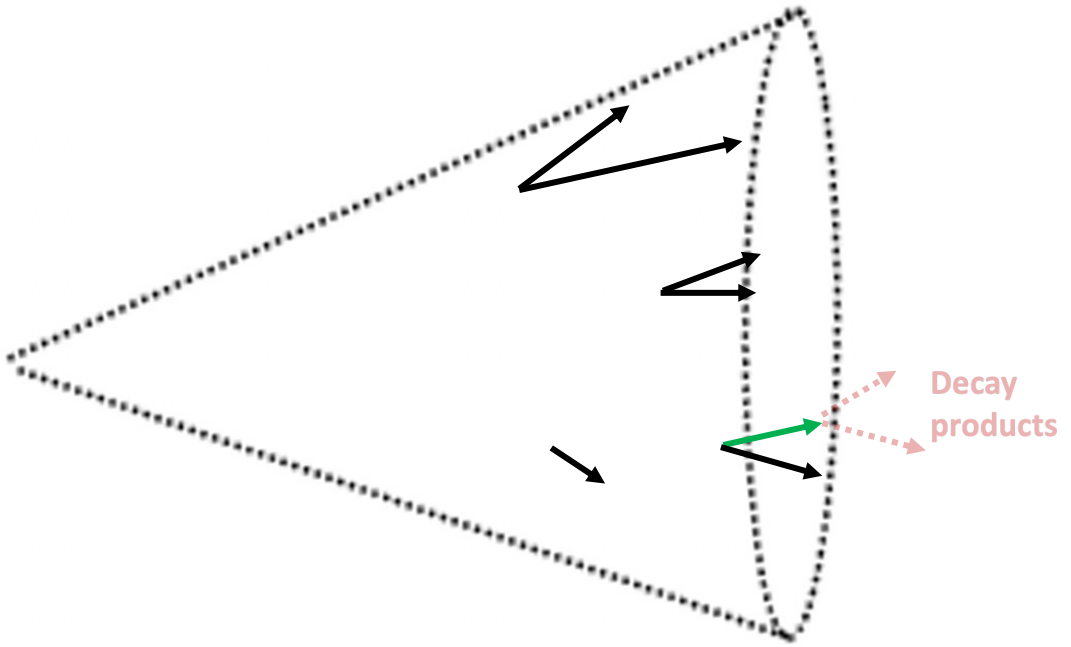

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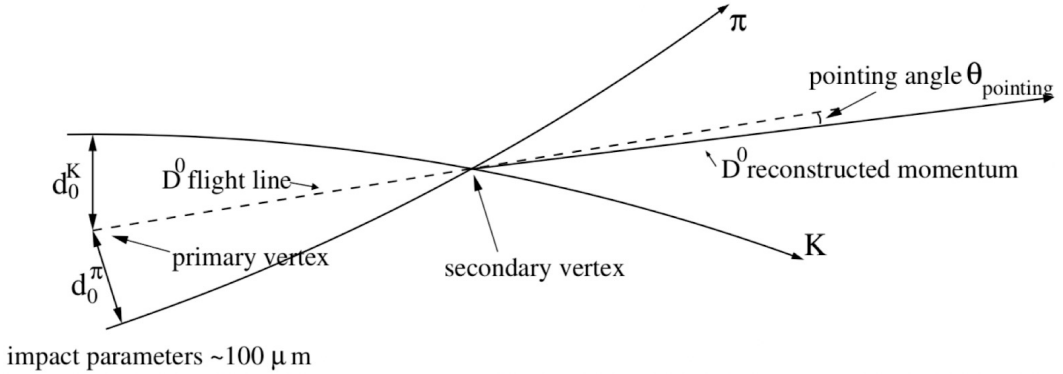

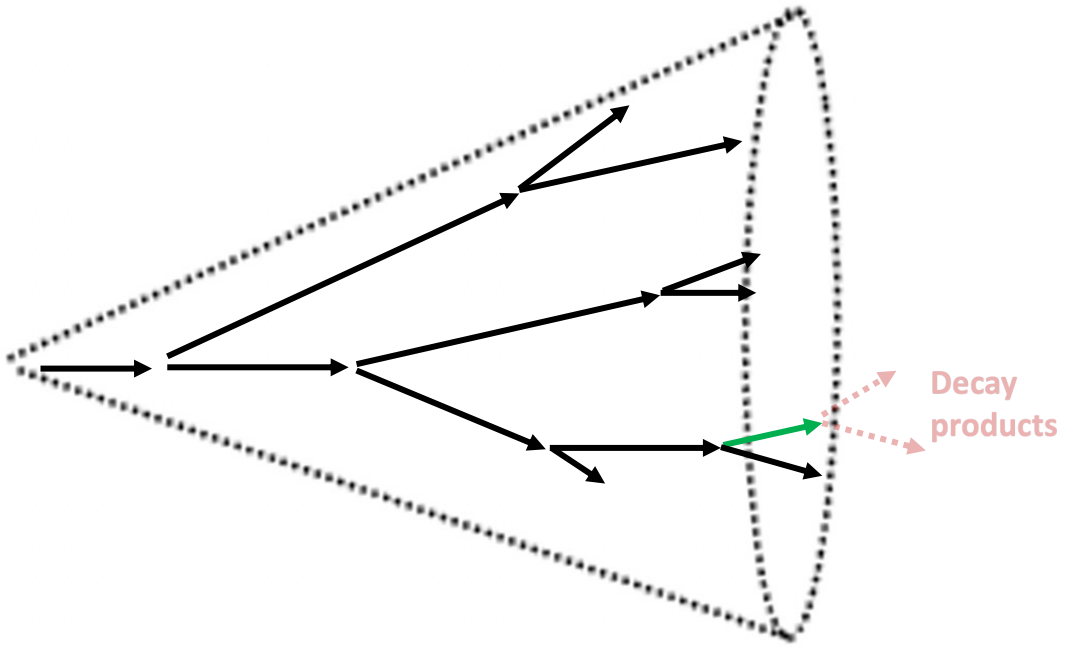

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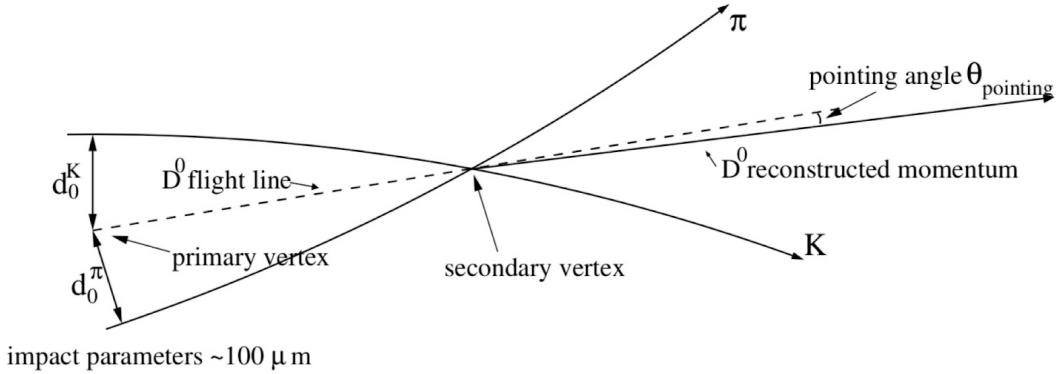

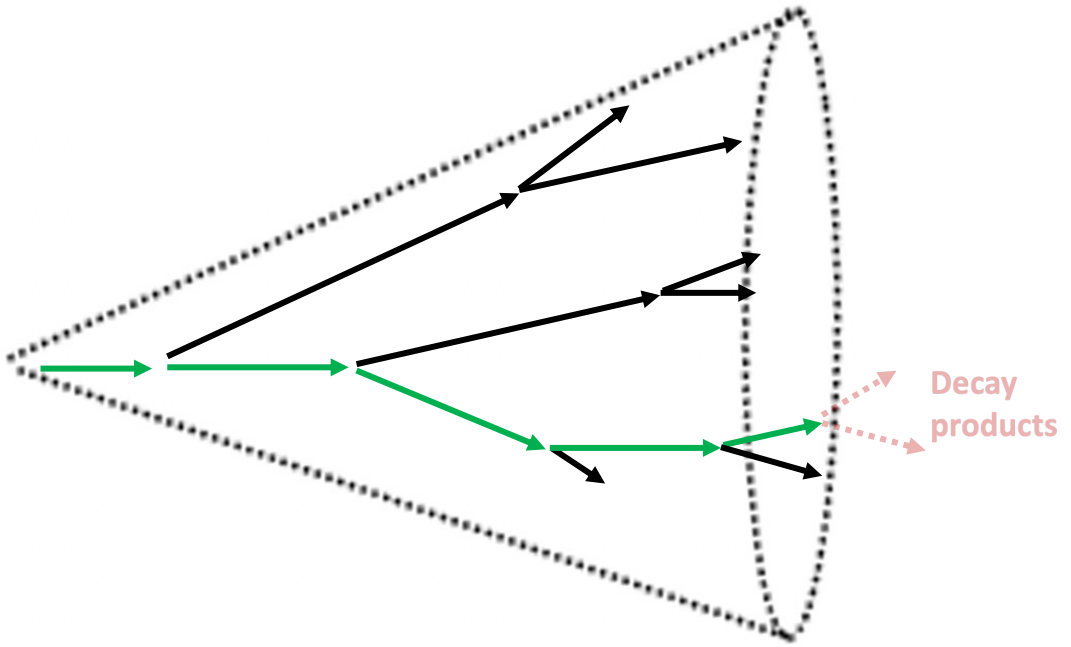

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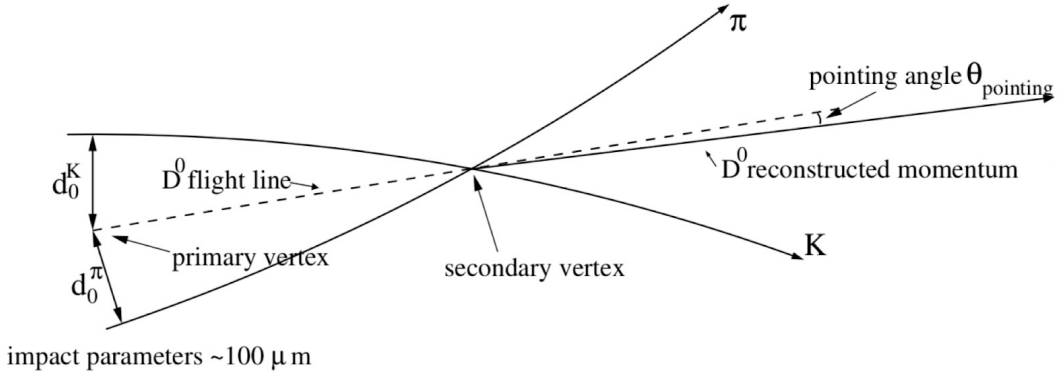
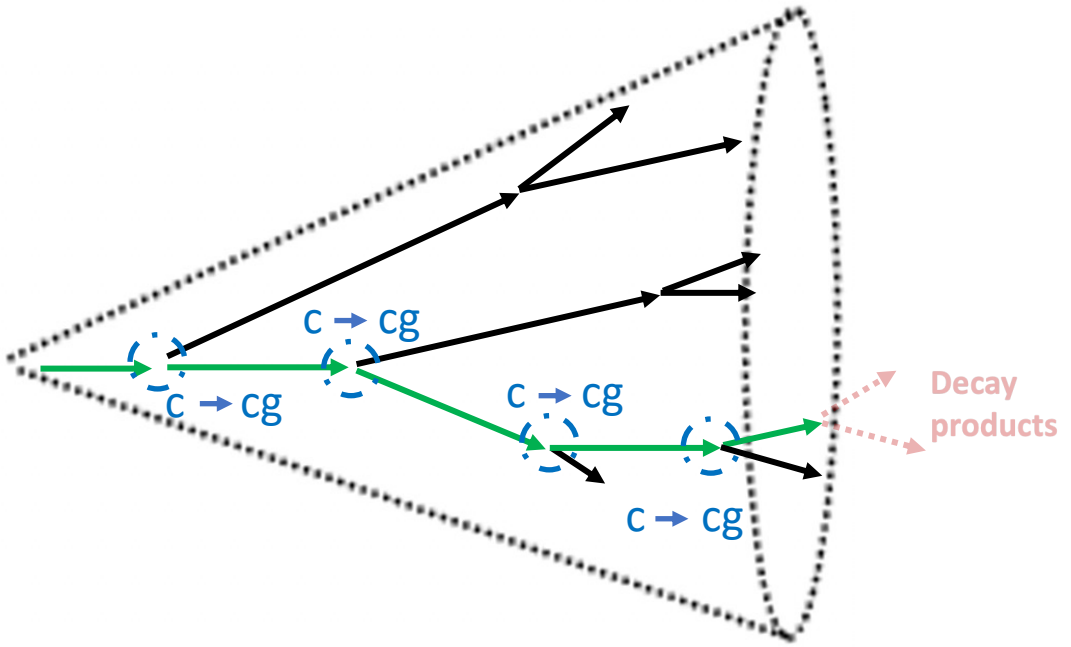
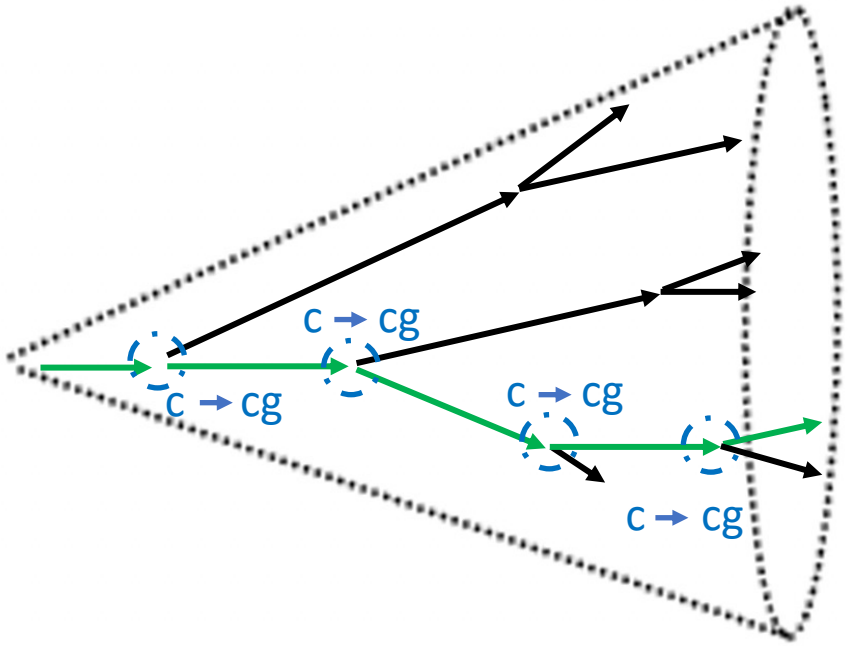




L. Cunqueiro, M. Ploskon, Phys. Rev. D 99, 074027 (2019)

Measuring the Lund plane of c->cg emissions



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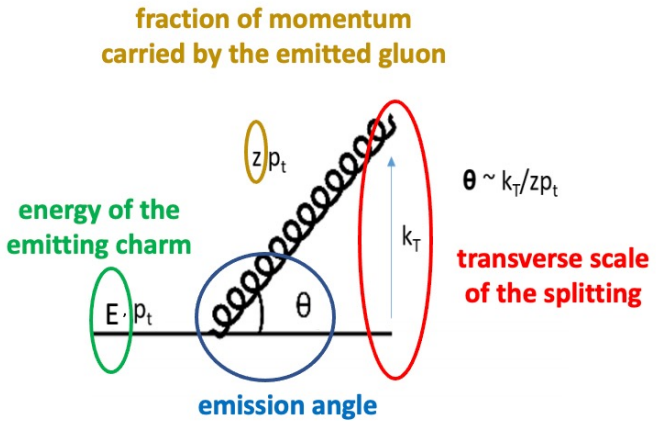

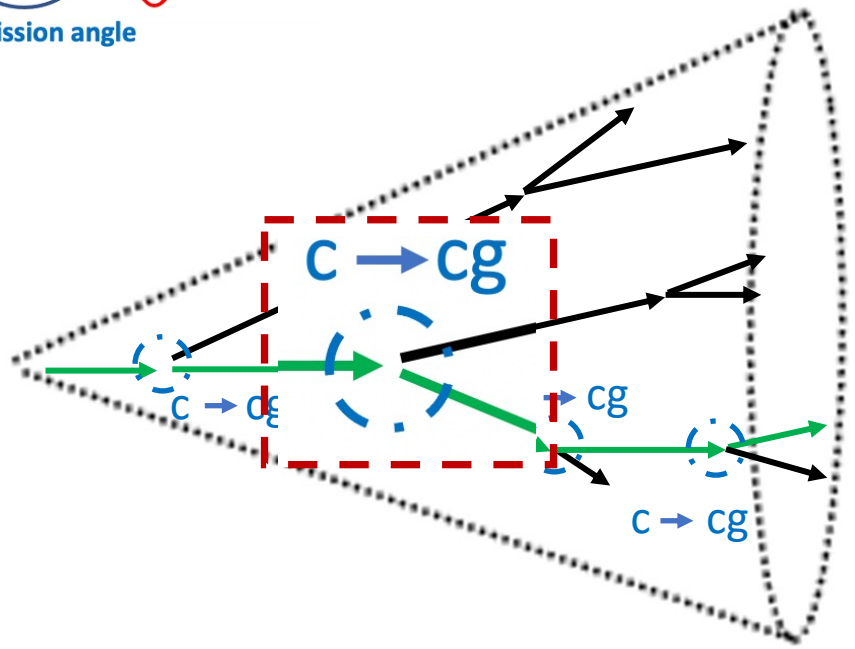

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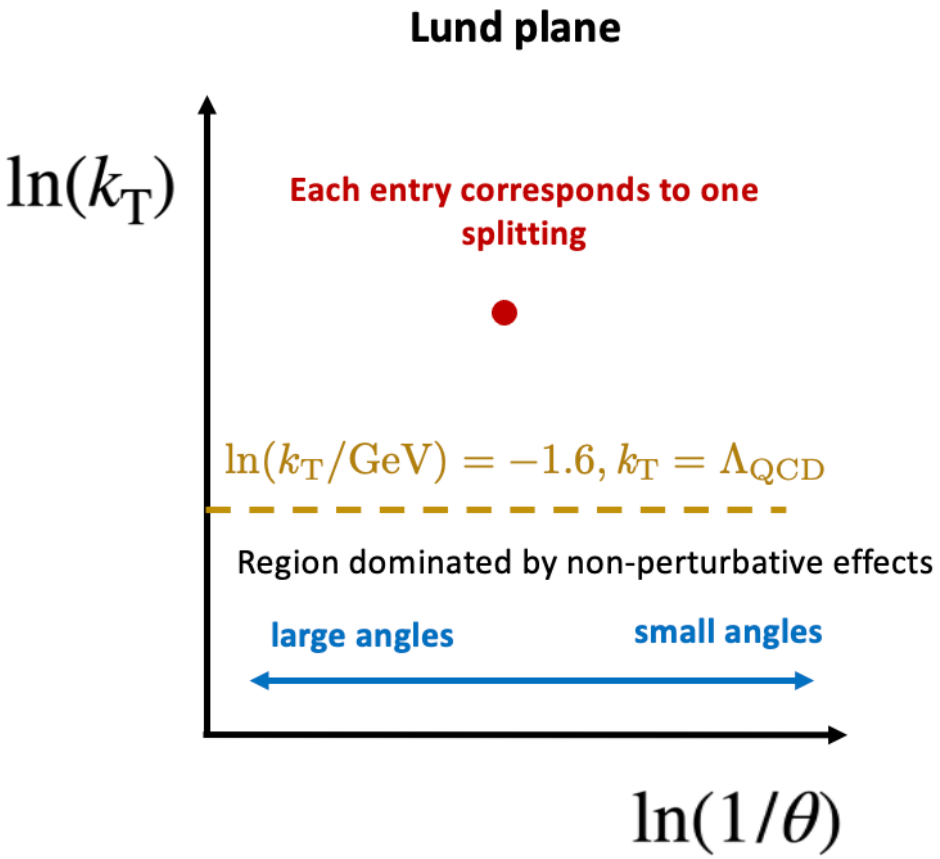

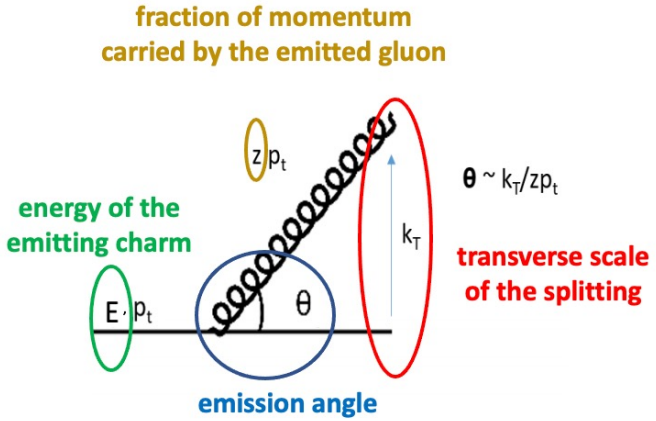

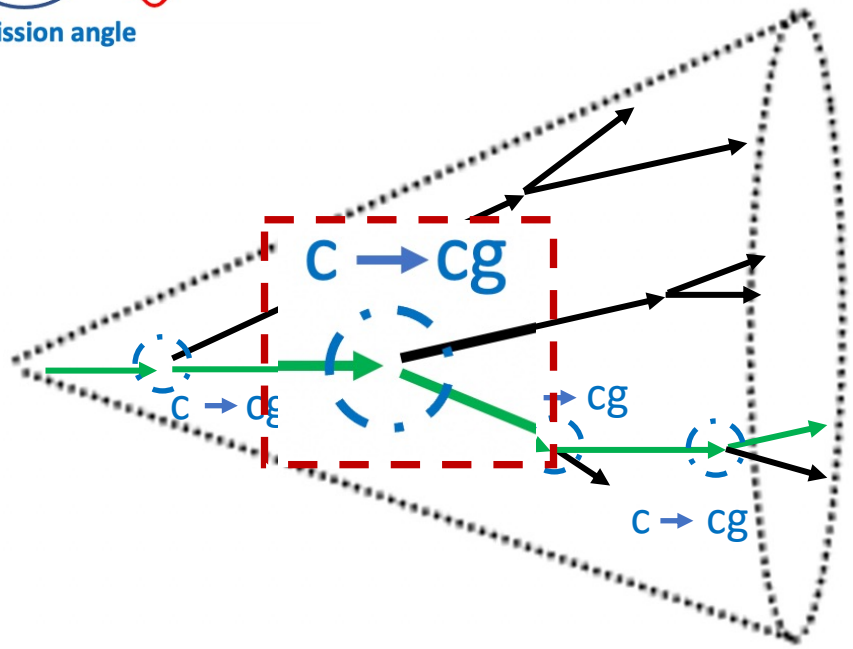

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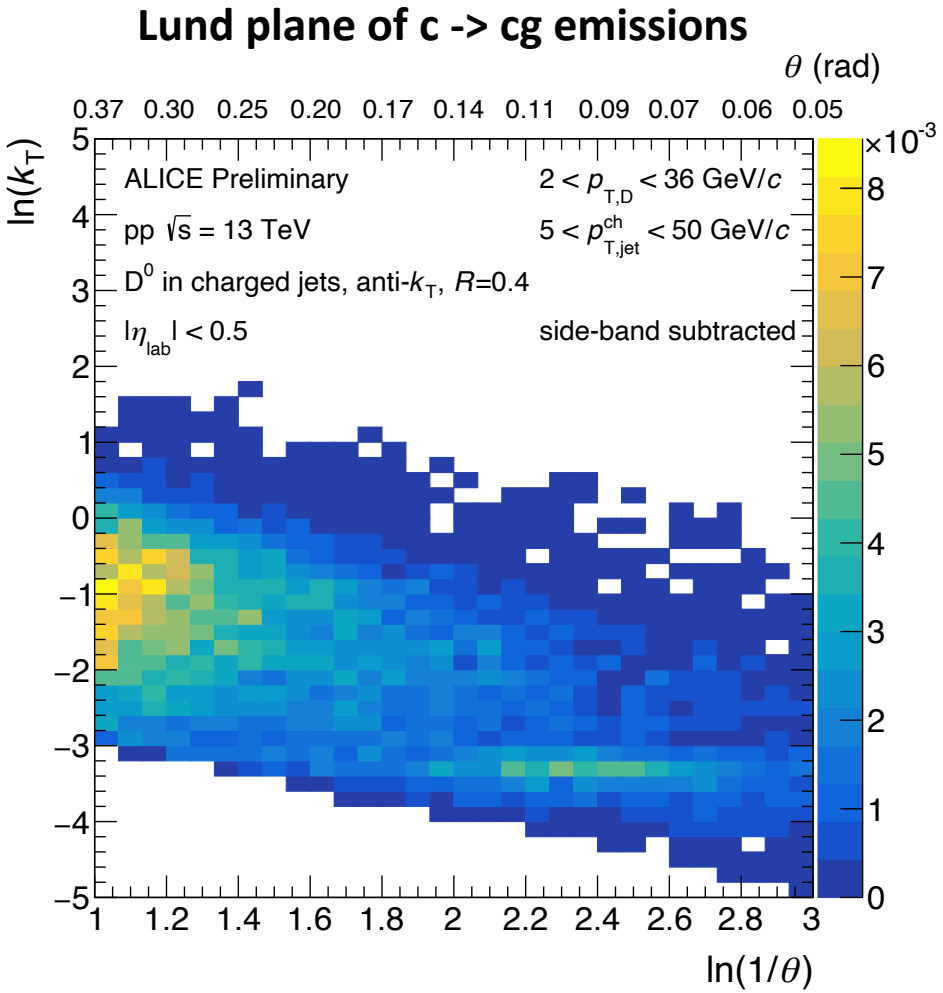

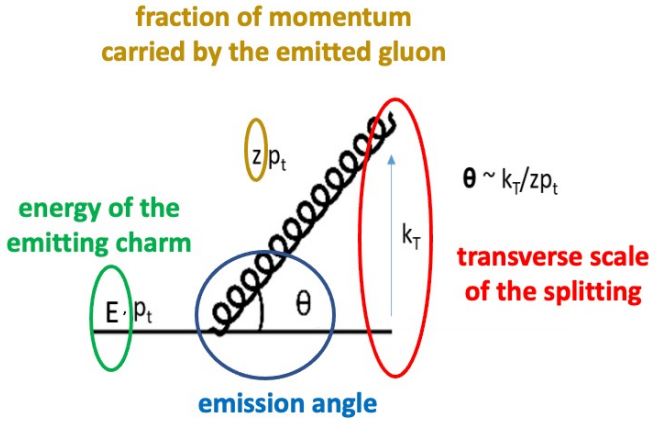

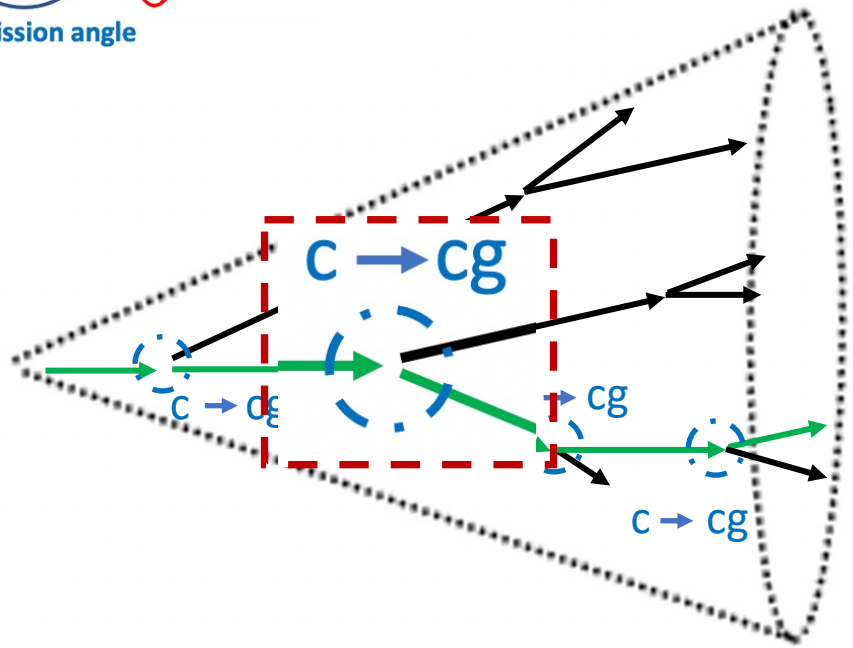

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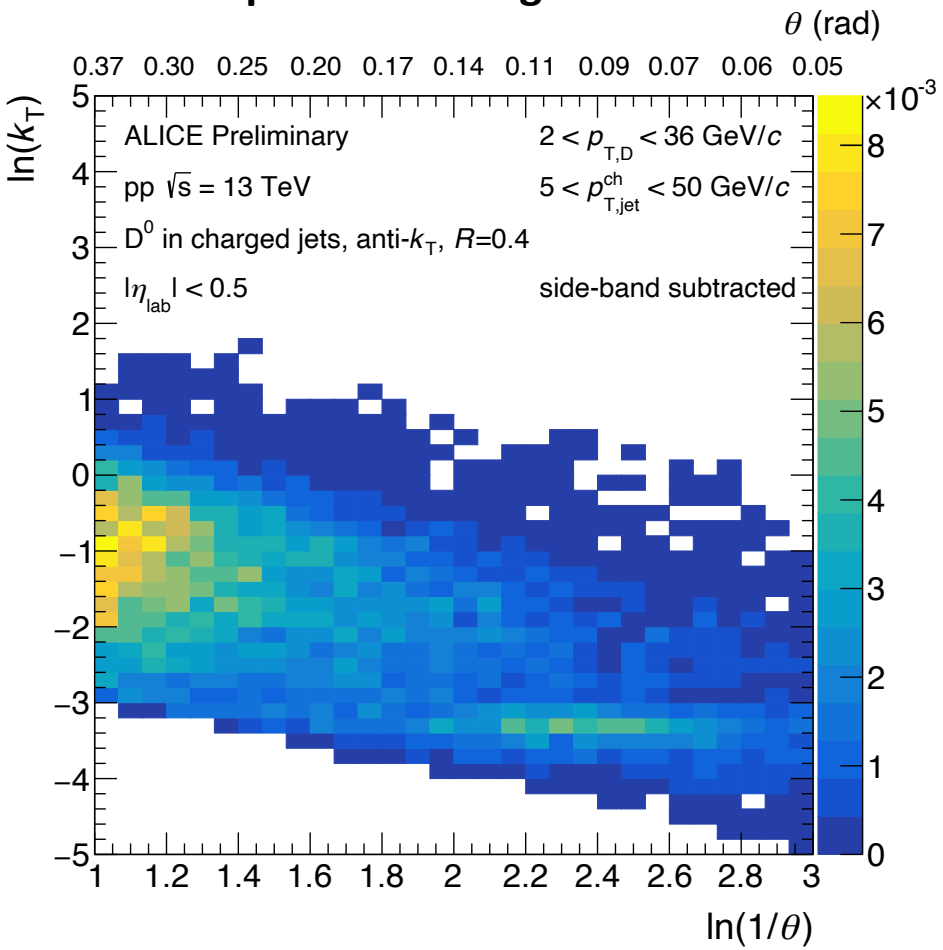
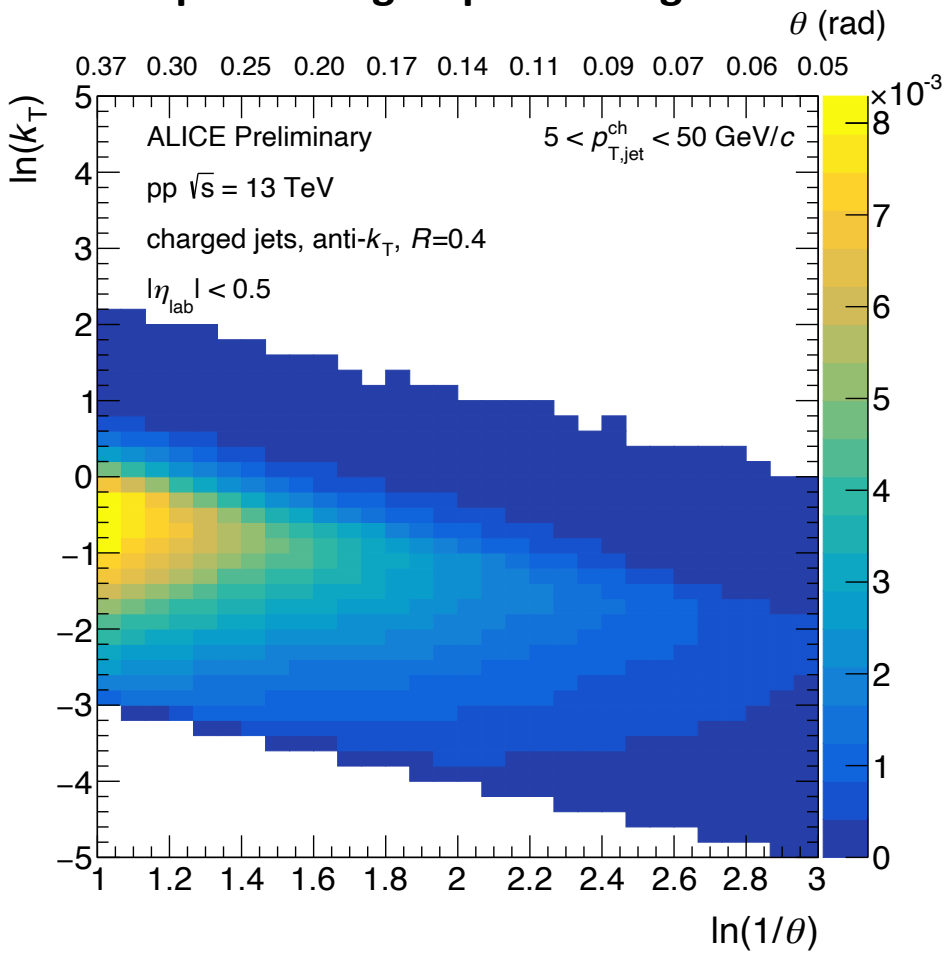


Lund plane of light quark and gluon emissions



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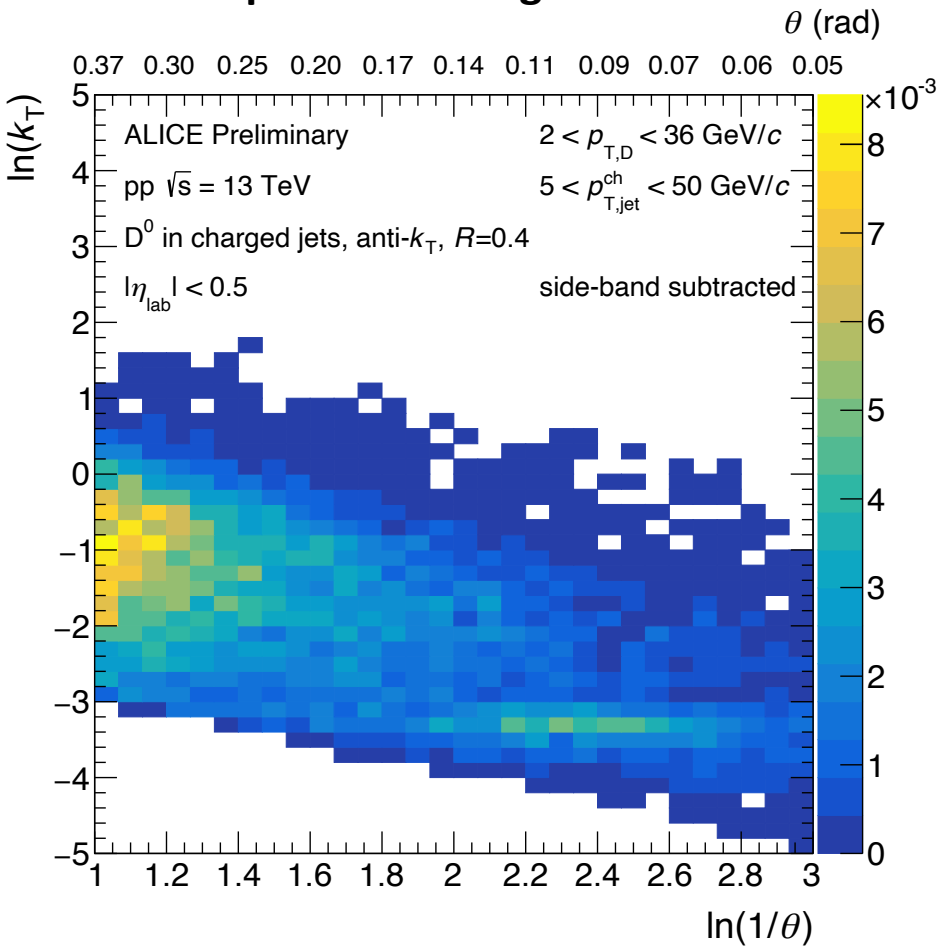
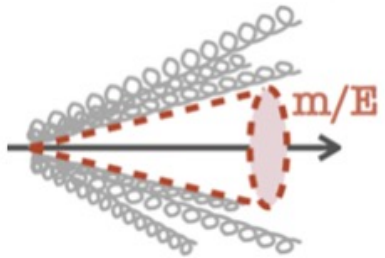
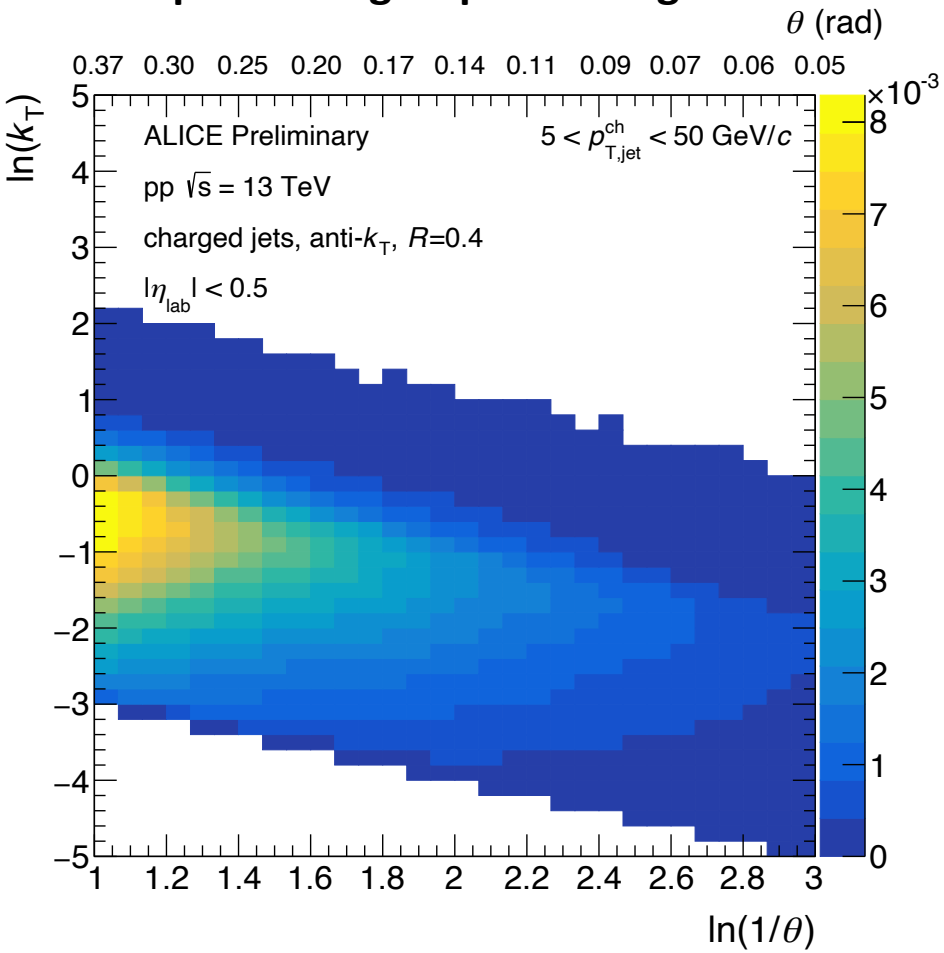


Are we sensitive to the dead-cone effect?

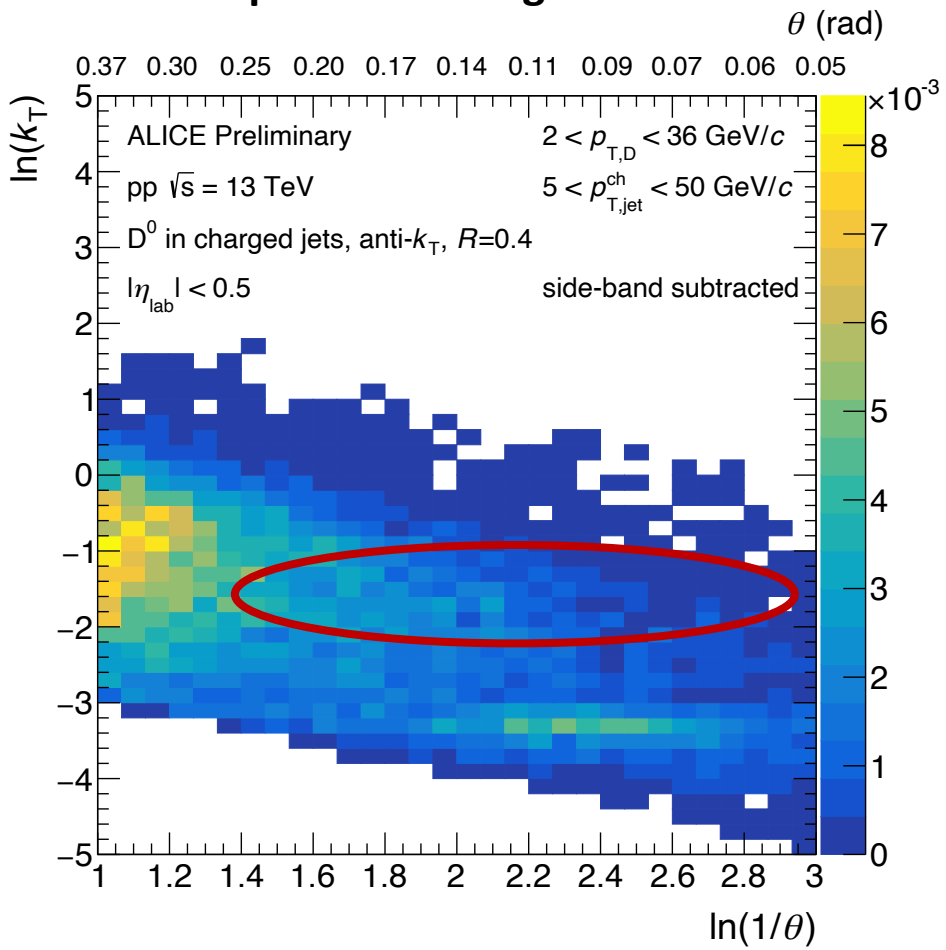


Lund plane of light quark and gluon emissions



Measuring the Lund plane of c->cg emissions

Lund plane of c -> cg emissions



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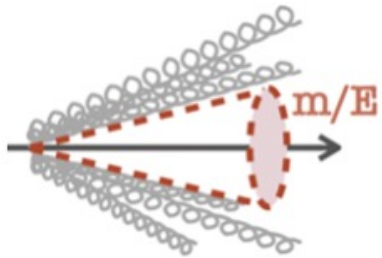
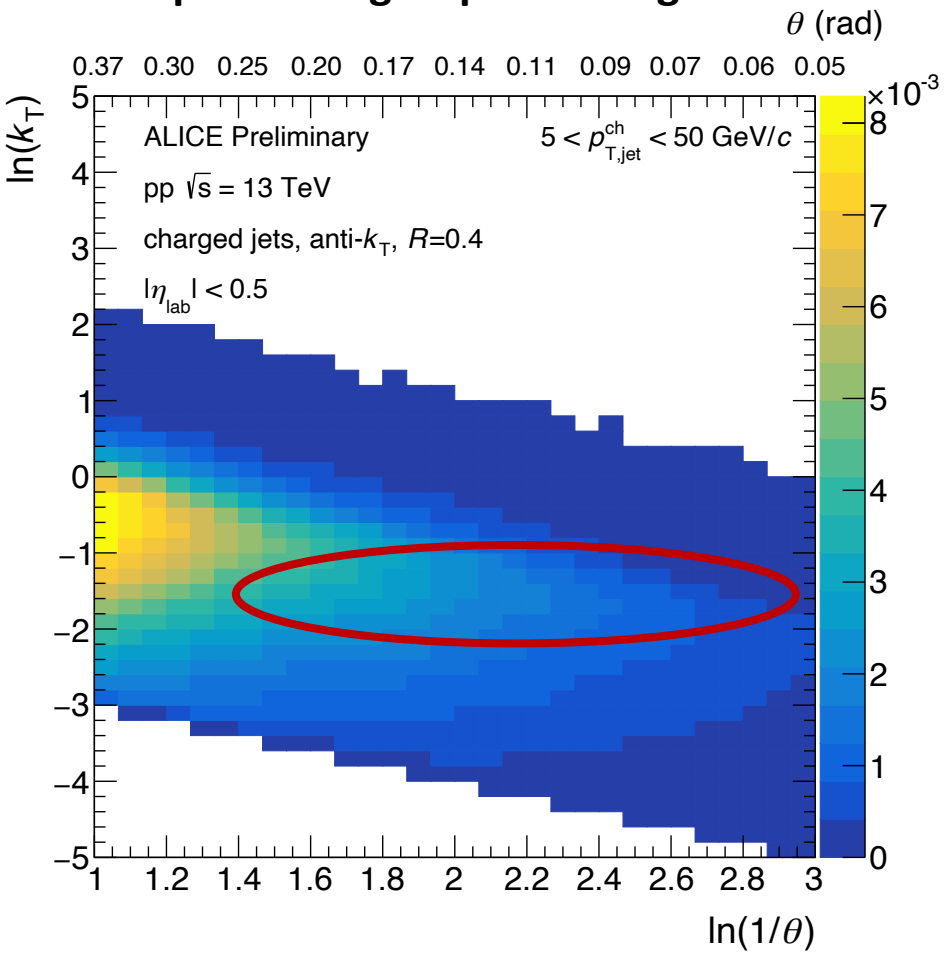


Lund plane of light quark and gluon emissions



Measuring the flavour properties of heavy-quark emissions

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

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

Measuring the flavour properties of heavy-quark emissions

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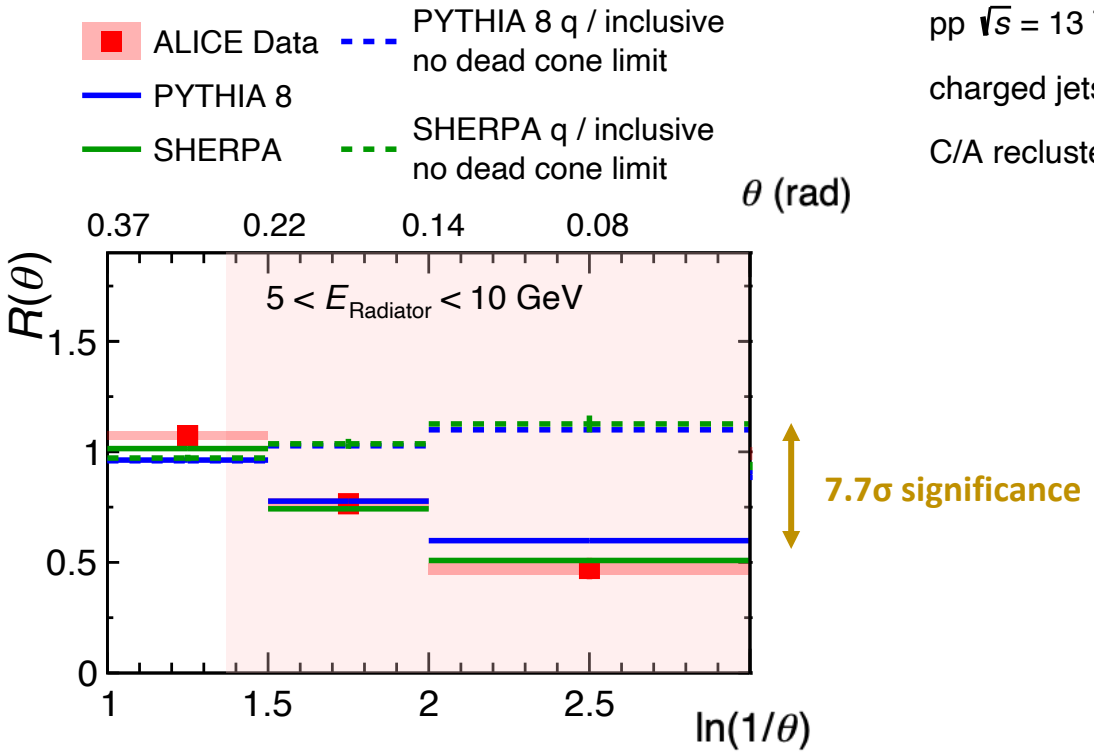
Nature 605 (2022) 440-446

Observation of the QCD dead cone



pp $\sqrt{s}$ = 13 TeV

charged jets, anti-k_{T}, R=0.4

C/A reclustering

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

$k_{\mathrm{T}} > \Lambda_{\mathrm{QCD}}$, $\Lambda_{\mathrm{QCD}} = 200$ MeV/c

$|\eta_{\mathrm{lab}}| < 0.5$

Measuring the flavour properties of heavy-quark emissions

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

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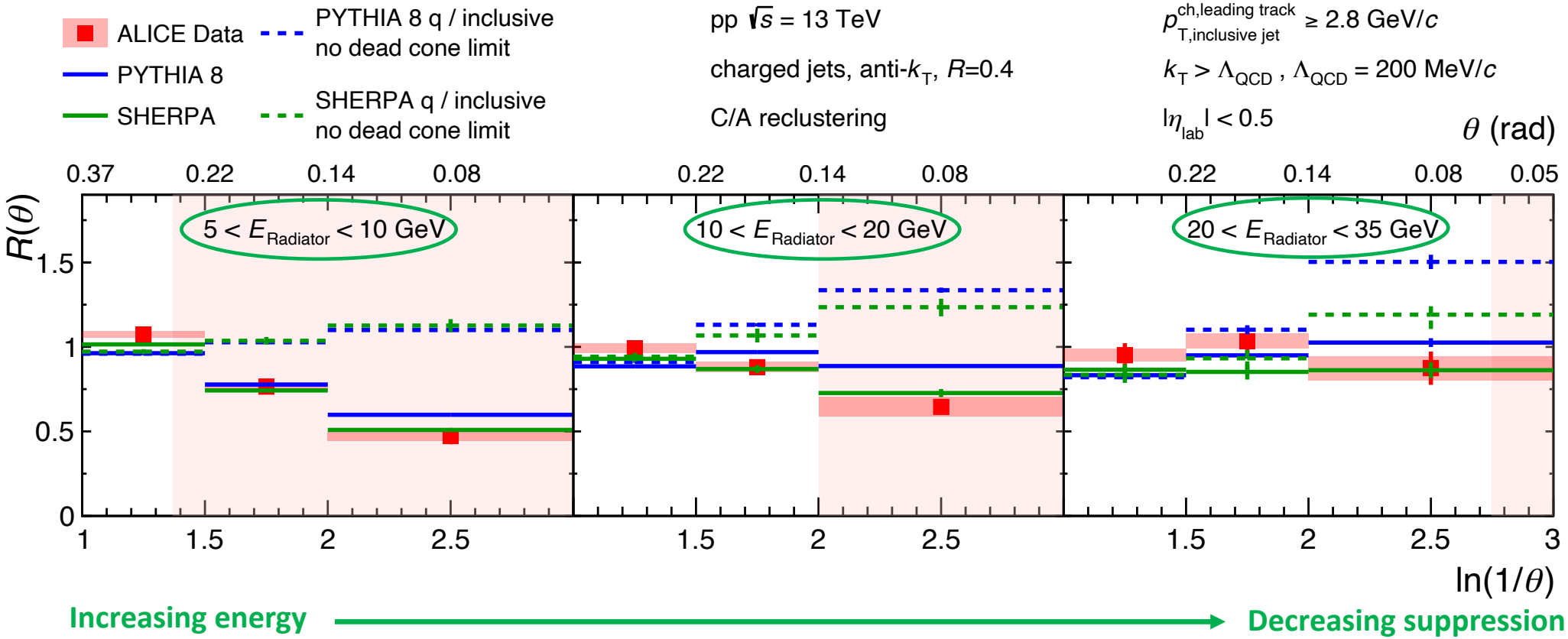

Increasing energy → Decreasing suppression

Measuring the flavour properties of heavy-quark emissions

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

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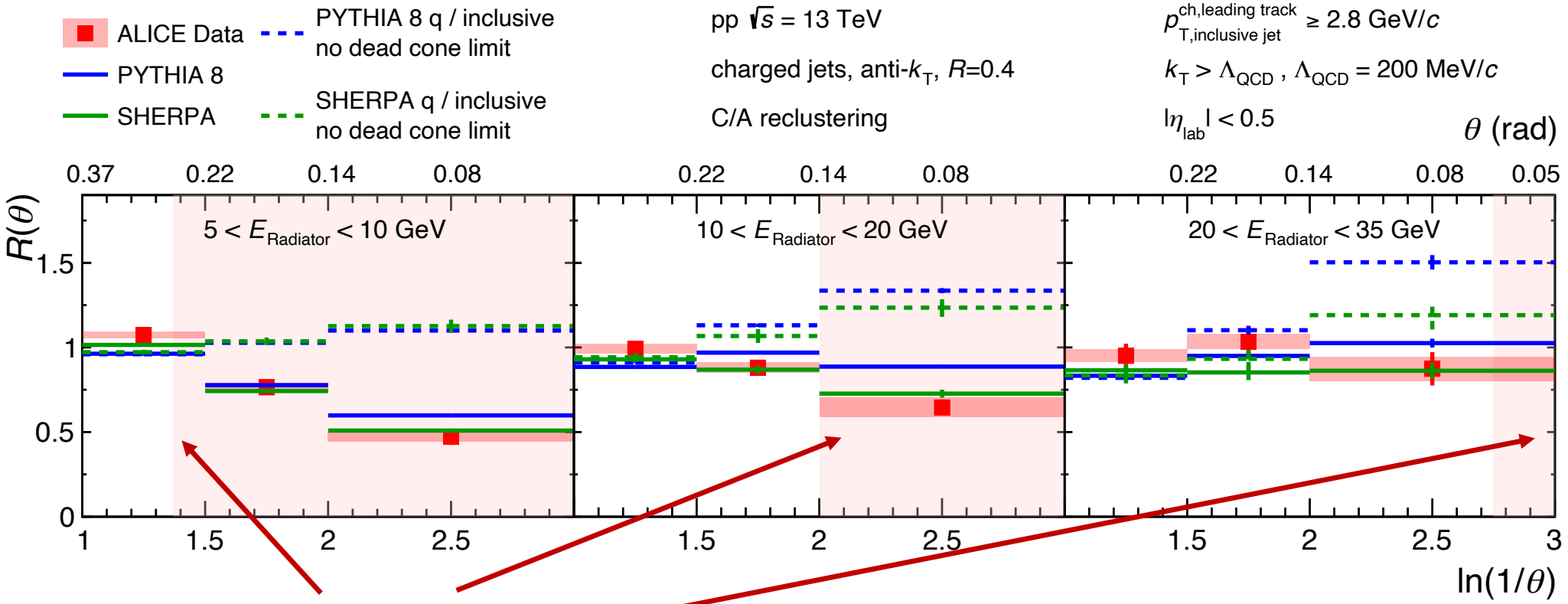
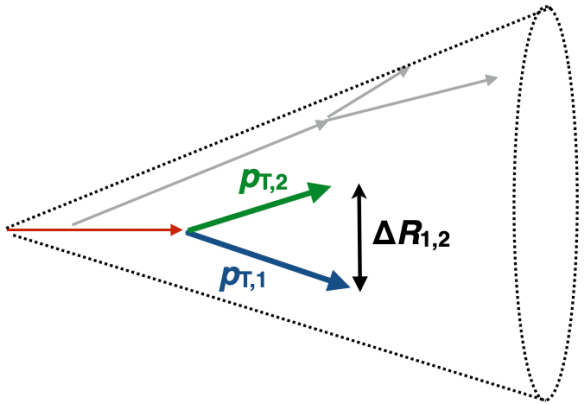


Shaded region corresponds to the dead-cone of a charm quark with a mass of 1.275 GeV/*c*

Measuring the flavour properties of heavy-quark emissions

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



Soft Drop grooming condition

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

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

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

Measuring the flavour properties of heavy-quark emissions

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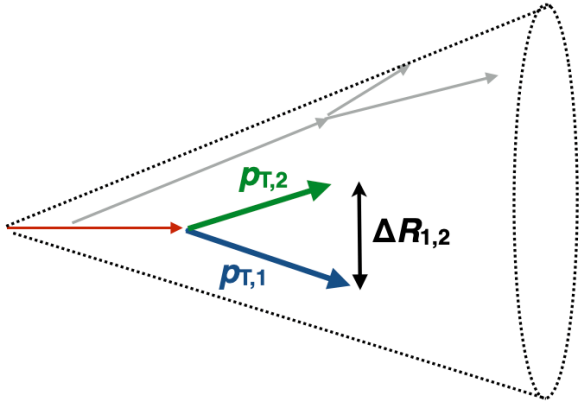

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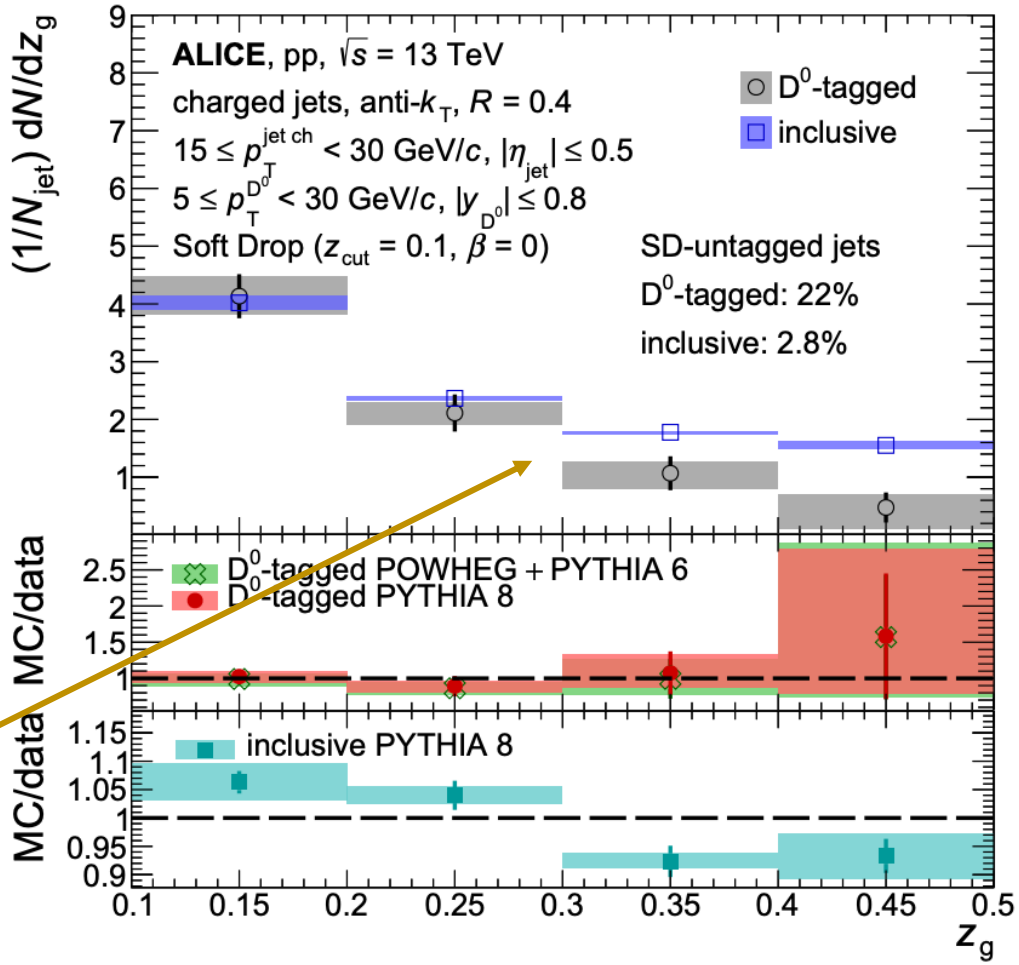
A. J. Larkoski et al. , JHEP 1405 (2014) 146

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

Measuring the flavour properties of heavy-quark emissions

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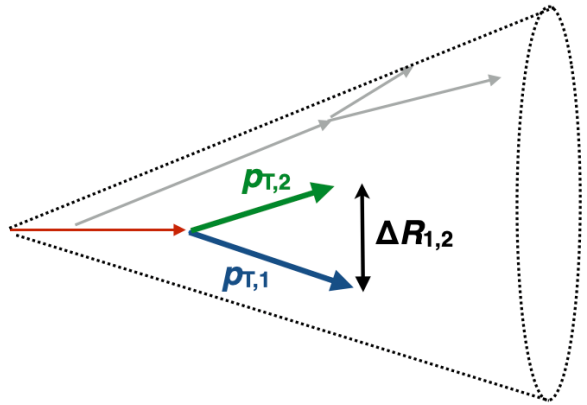

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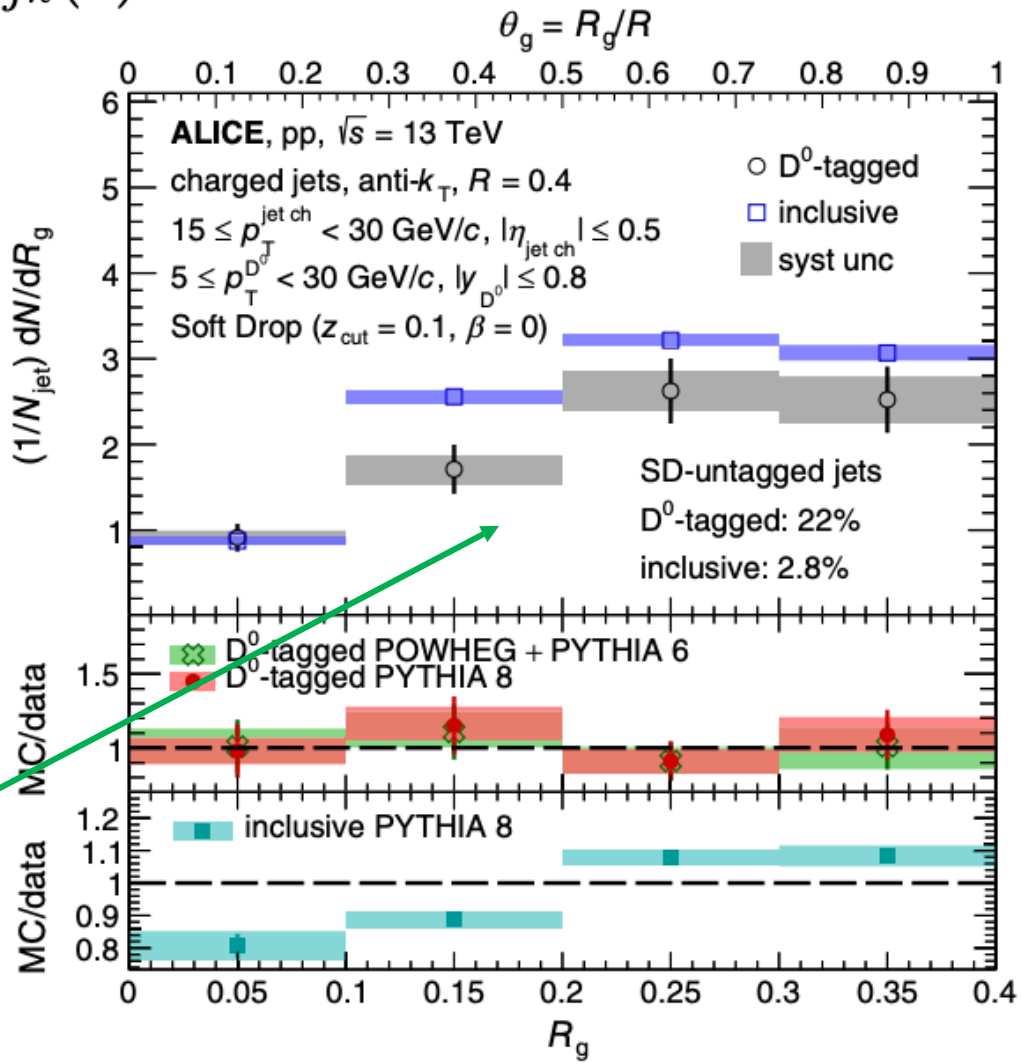
A. J. Larkoski et al. , JHEP 1405 (2014) 146

Opening angle of the first emission passing Soft Drop

Gluon jets have a broader shower profile than quark jets

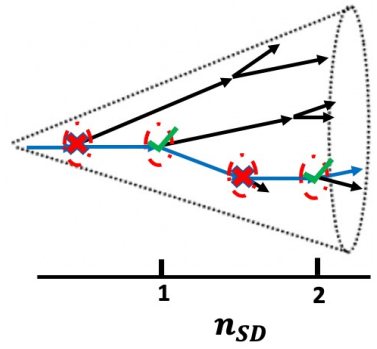
Competing effects between the dead cone and the increased quark emissions at small angles



PRL 131.192301

Measuring the flavour properties of heavy-quark emissions

Towards isolating the perturbative physics of heavy-flavour fragmentation functions



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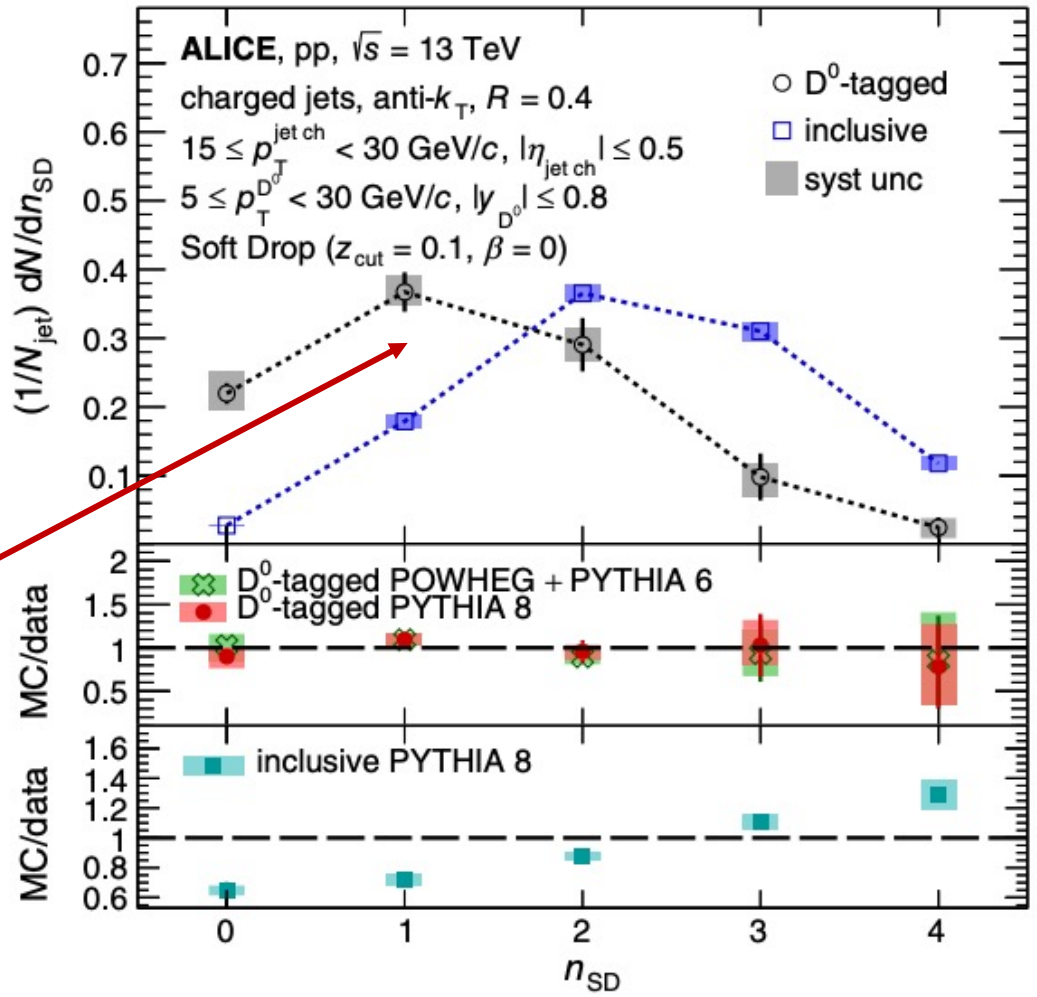
$$z = 0.1, \beta = 0$$

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

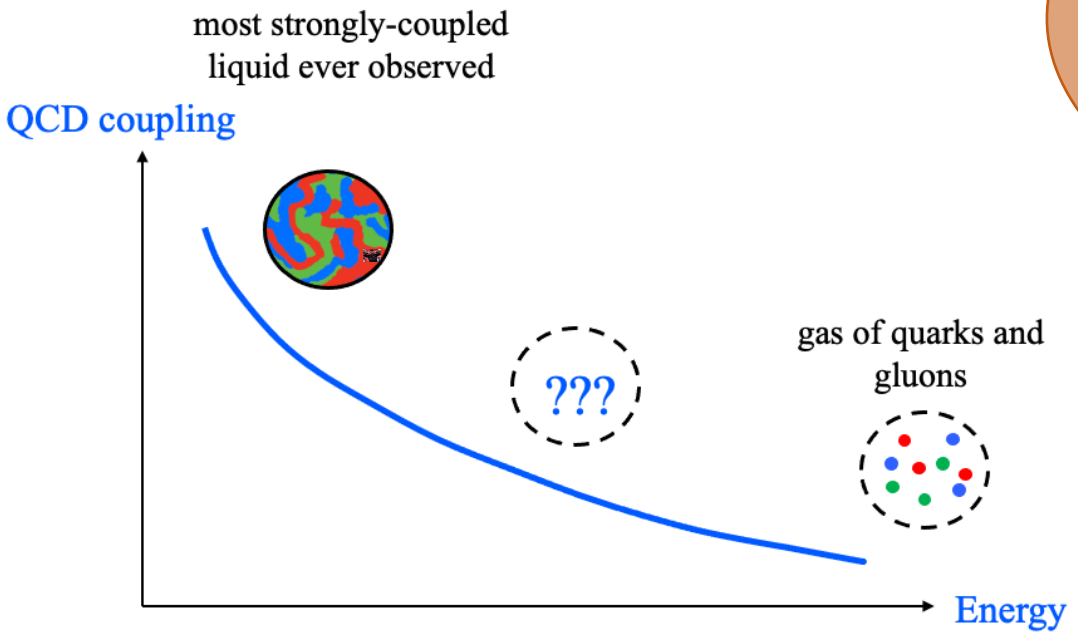


PRL 131.192301

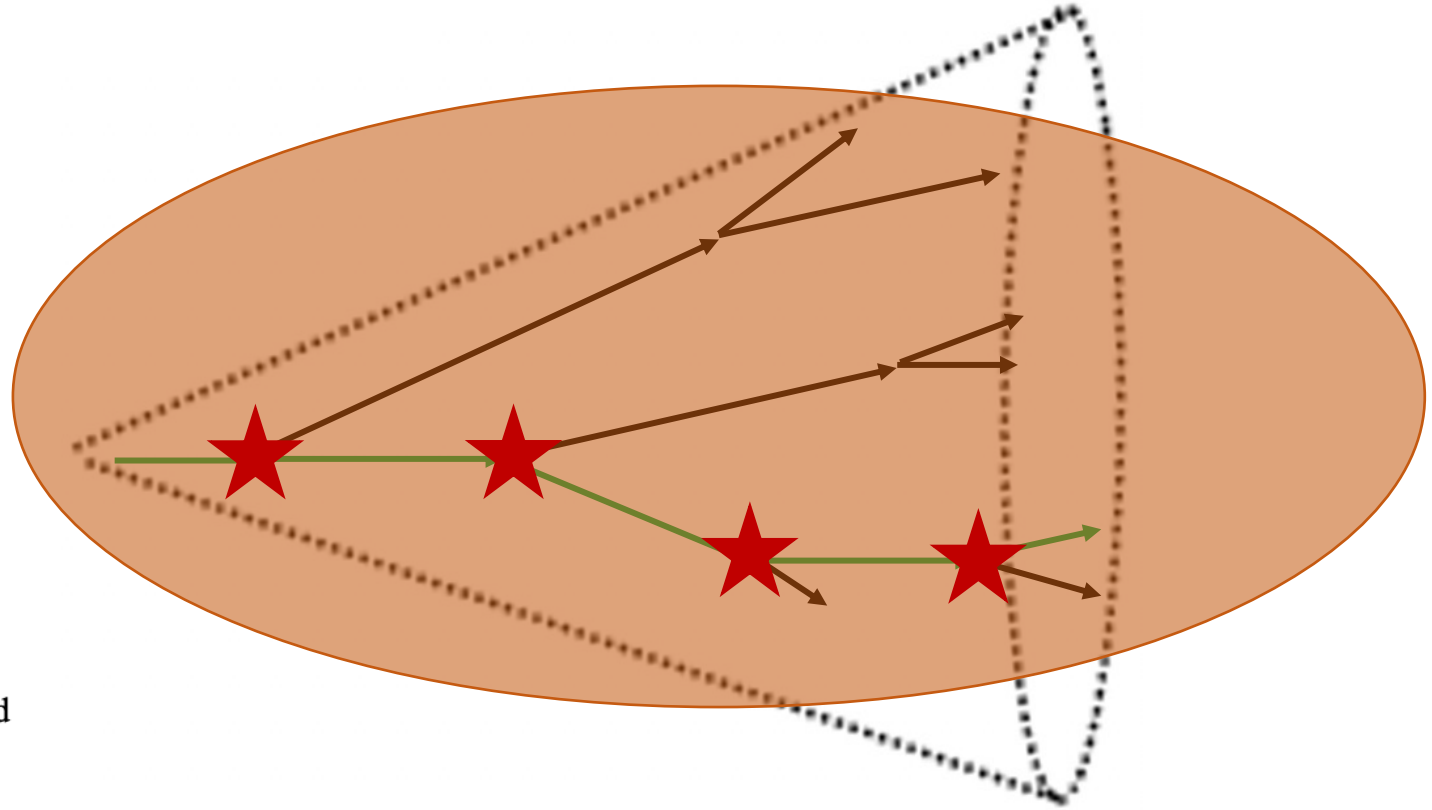
Tracing in heavy-ion collisions

Allows to access QCD at all momentum scales whilst starting with a perturbatively well controlled object

In the presence of the medium it allows us to probe the scale dependent features of the medium



State of the art

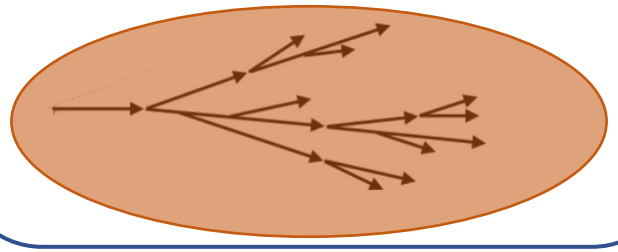


Decreasing momentum scale

Flavour dynamics in the QGP

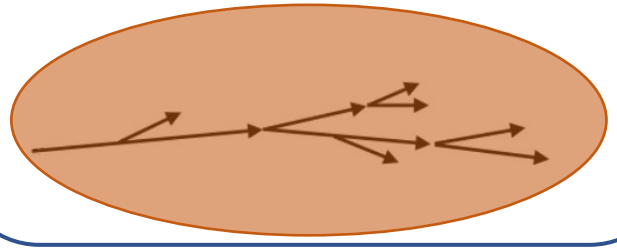
Gluon-initiated shower

Broader shower profile
Higher number of emissions



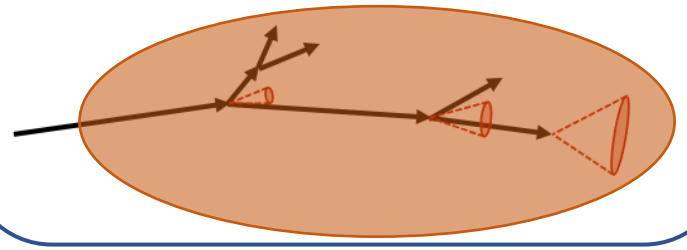
Quark-initiated shower

narrower shower profile
Fewer emissions in the shower



Heavy-quark-initiated shower

Suppression of small angle emissions
Harder fragmentation



Casimir Colour factors

The medium couples differently to quarks and gluons

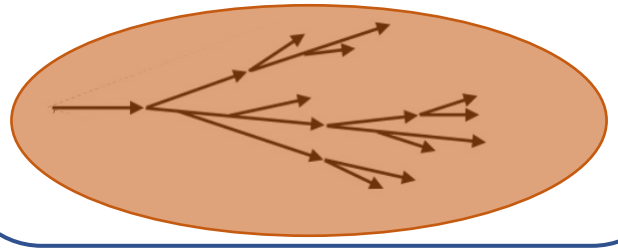
The dead-cone effect

How does the dead-cone interplay with medium emissions?

Flavour dynamics in the QGP

Gluon-initiated shower

Broader shower profile
Higher number of emissions



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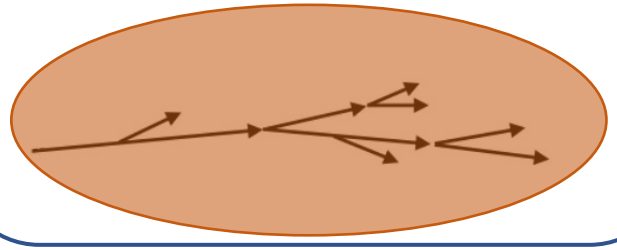

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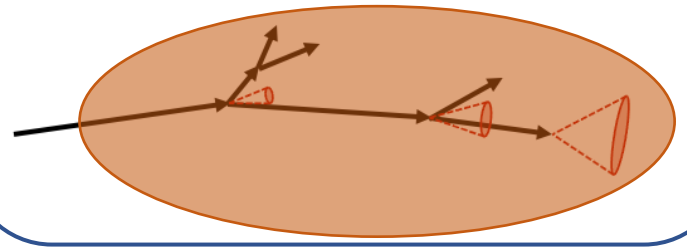


Casimir Colour factors

The medium couples differently to quarks and gluons

Theoretical frameworks describe medium interactions as a modification of individual splittings

$$P_{splitting}(z,\theta) = P_{vacuum}(z,\theta) + P_{medium}(z,\theta,E)$$

The dead-cone effect

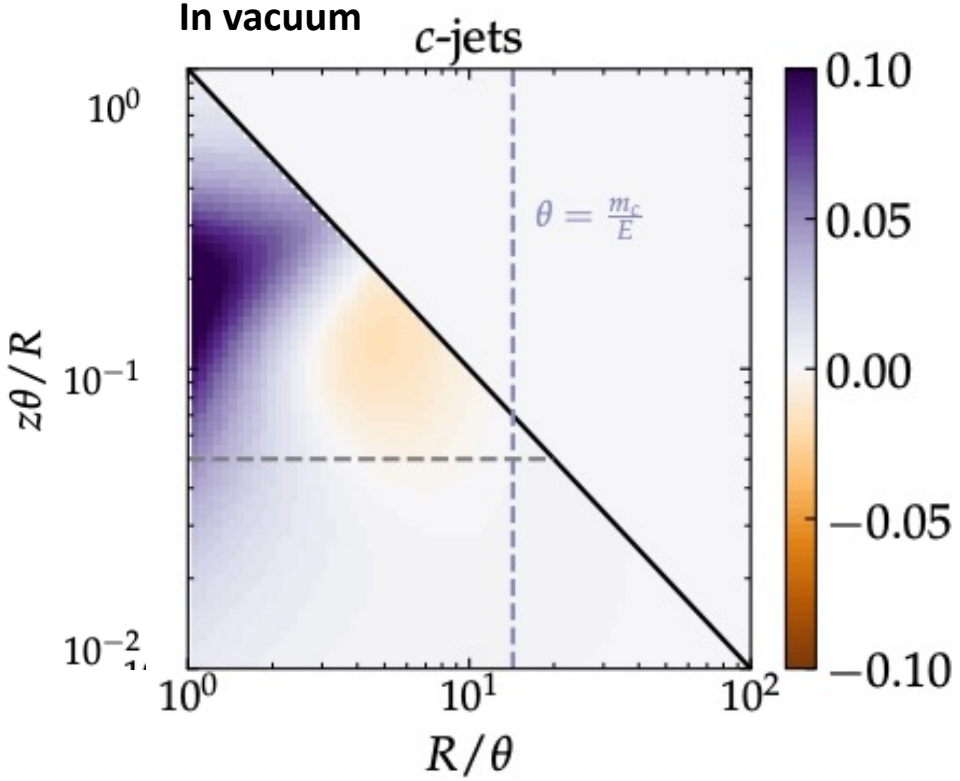
How does the dead-cone interplay with medium emissions?

Different splitting flavours at the same scale will be modified differently by the same medium

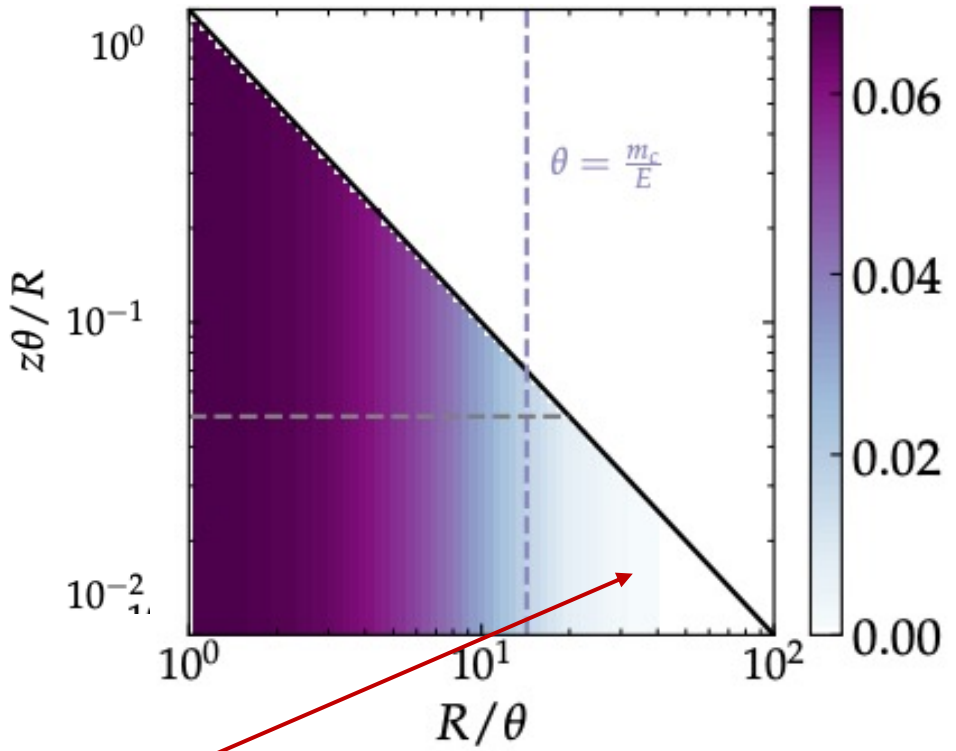
The fractions of splitting flavours are not known after quenching

Searching for medium effects in HI collisions

In vacuum



In medium



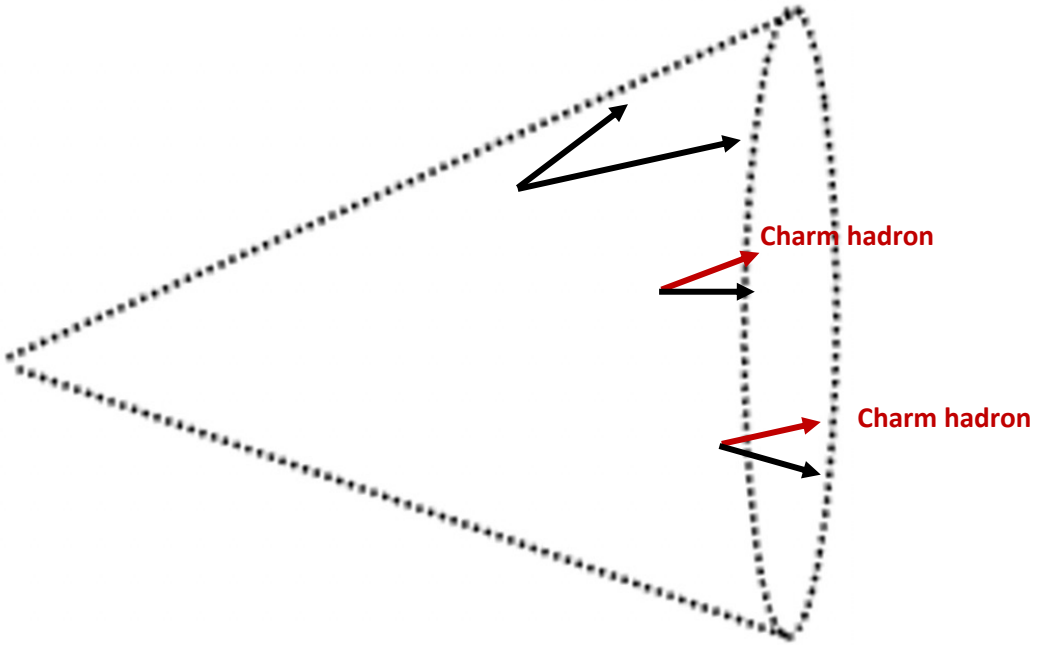
How do medium induced emissions interplay with the dead-cone region?

Opportunity to isolate medium emissions?

Splittings deep in the shower are less sensitive to background effects

L. Cunqueiro et al. arXiv: 2211.11789

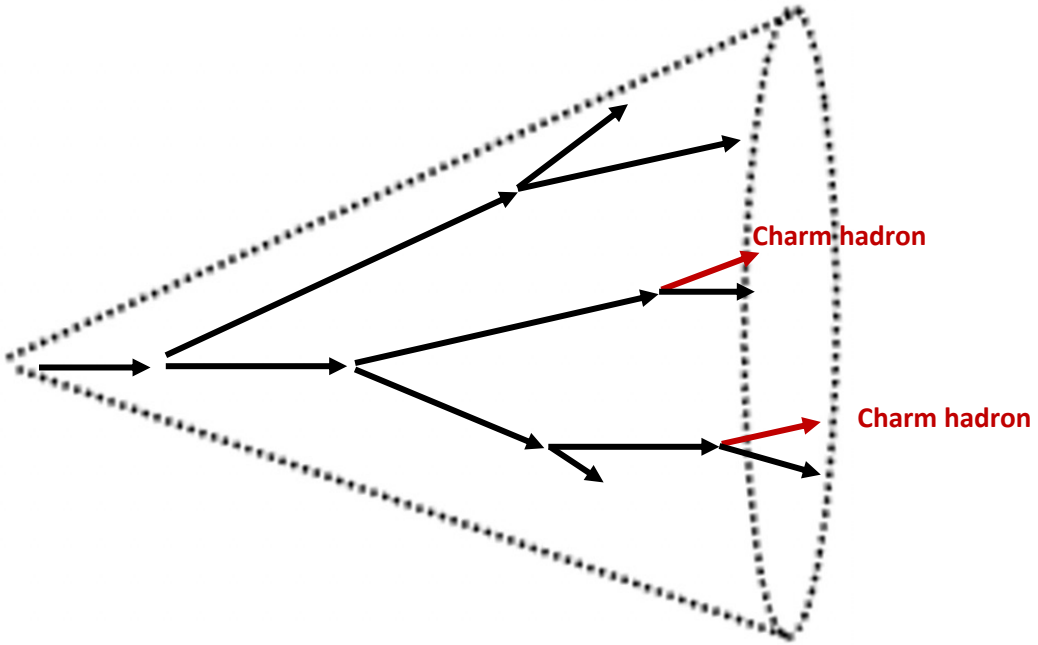
Accessing g->QQ splittings



Methodology

A jet containing two heavy-flavour hadrons is tagged

Accessing g->QQ splittings

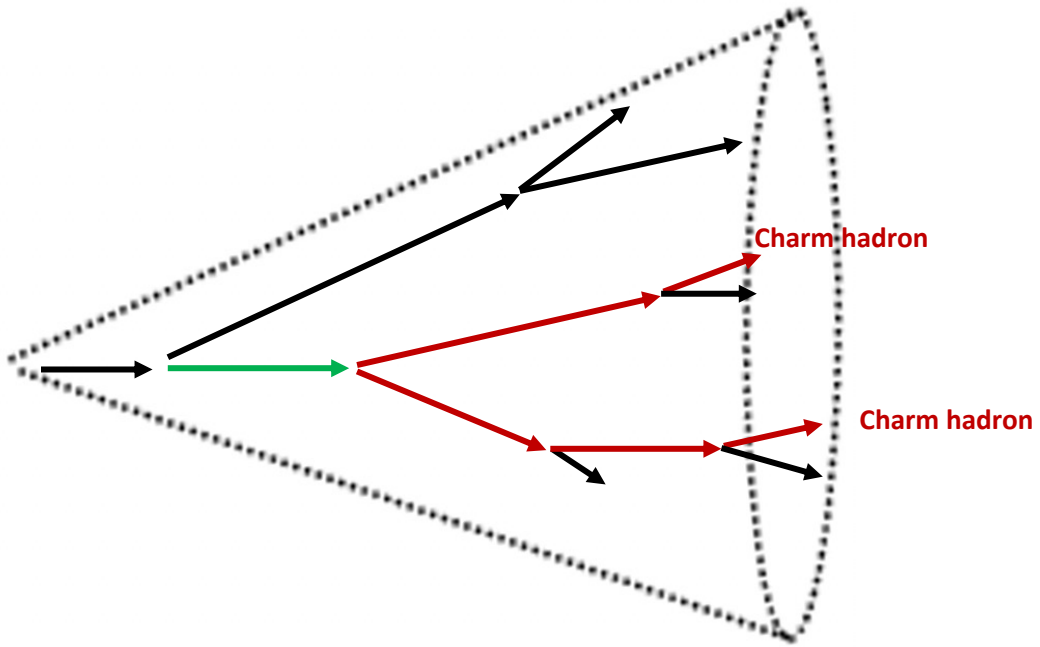


Methodology

A jet containing two heavy-flavour hadrons is tagged

Recluster the jet to access the splitting tree

Accessing g->QQ splittings



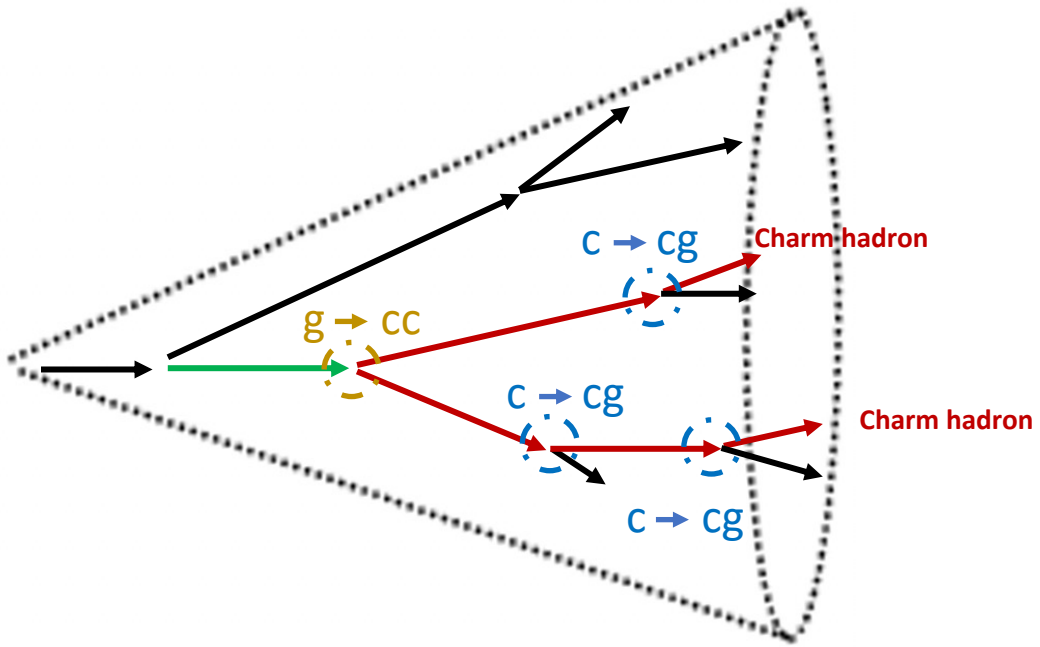
Methodology

A jet containing two heavy-flavour hadrons is tagged

Recluster the jet to access the splitting tree

Trace the heavy-flavour hadrons until the deepest splitting containing both is found

Accessing g->QQ splittings



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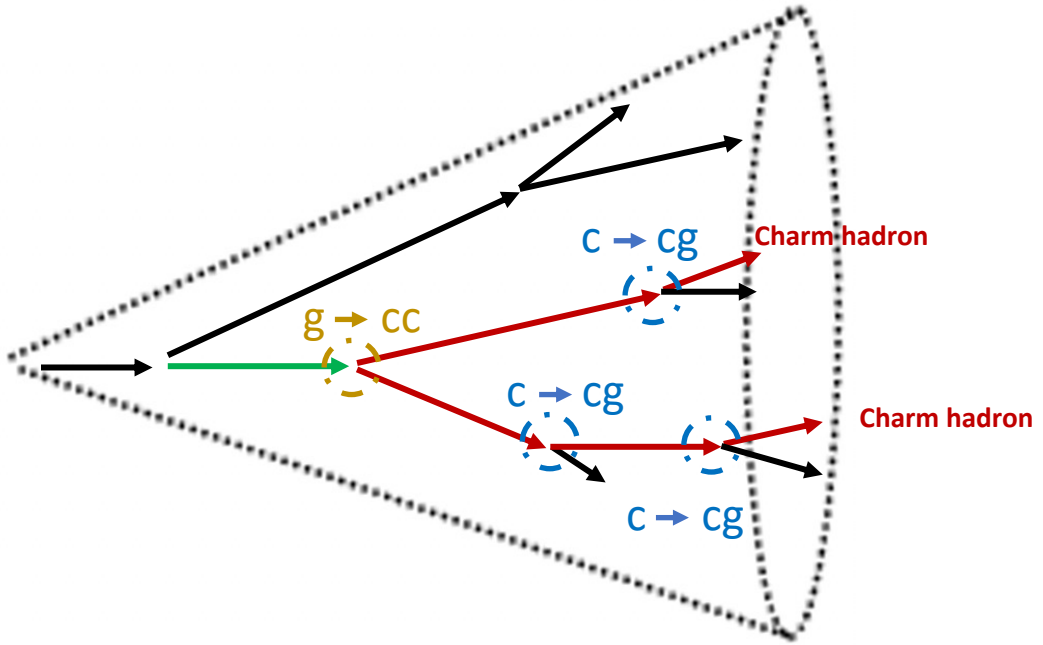


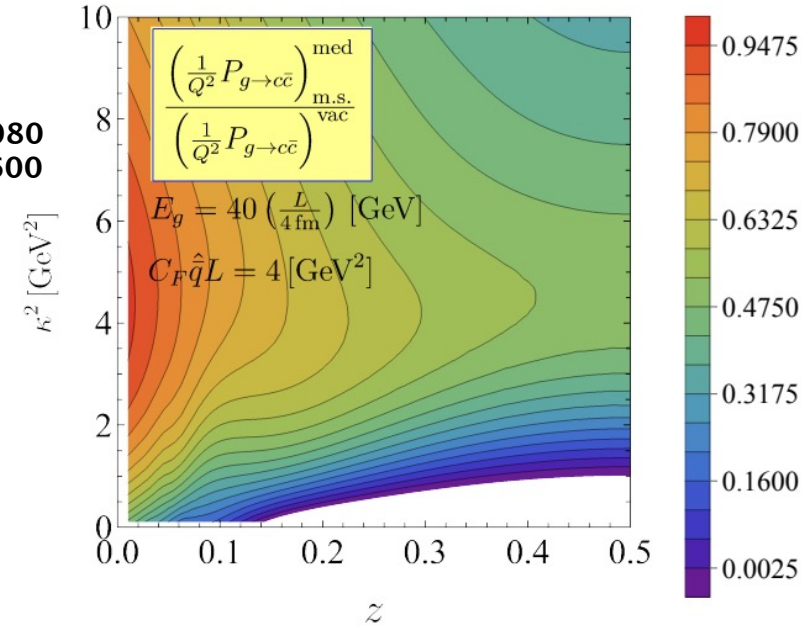
Methodology

A jet containing two heavy-flavour hadrons is tagged

Recluster the jet to access the splitting tree

Trace the heavy-flavour hadrons until the deepest splitting containing both is found

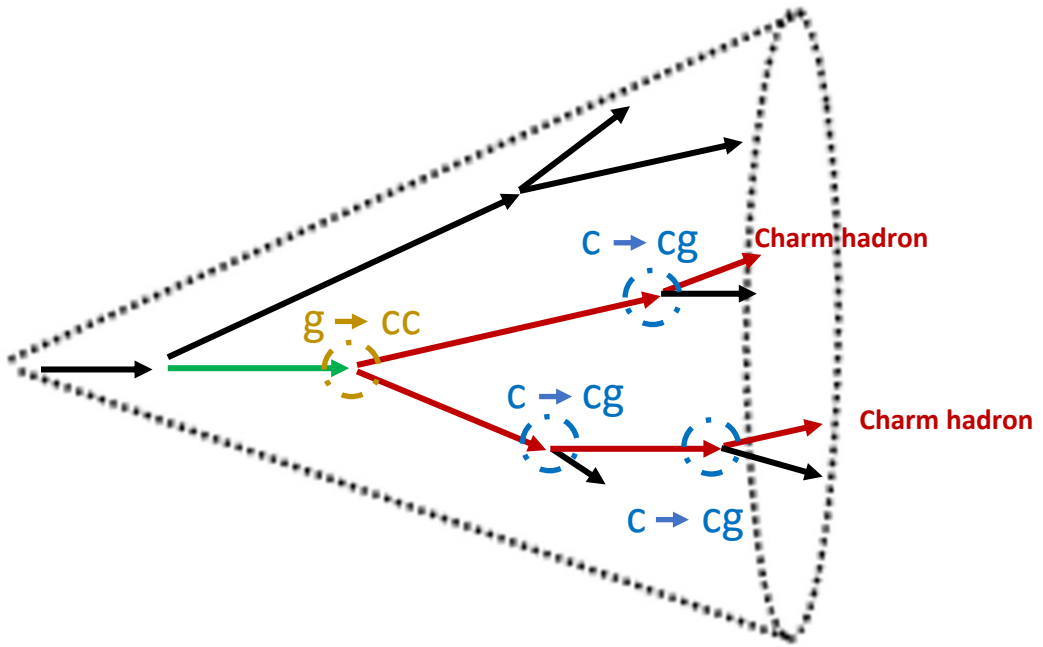
Attems et al. , JHEP 01(2023)080
Attems et al. , arXiv: 2209.13600



Controlled access to features of the g->QQ splitting

Next step of precision in accessing medium modification of splittings

Accessing g->QQ splittings



Methodology

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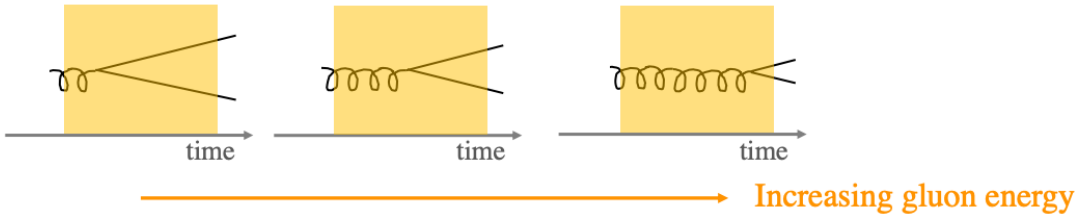
Recluster the jet to access the splitting tree

Trace the heavy-flavour hadrons until the deepest splitting containing both is found



Attems et al. , arXiv: 2209.13600

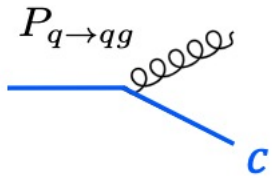
Controlled access to features of the g->QQ splitting

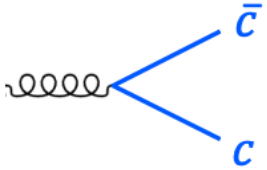
Next step of precision in accessing medium modification of splittings

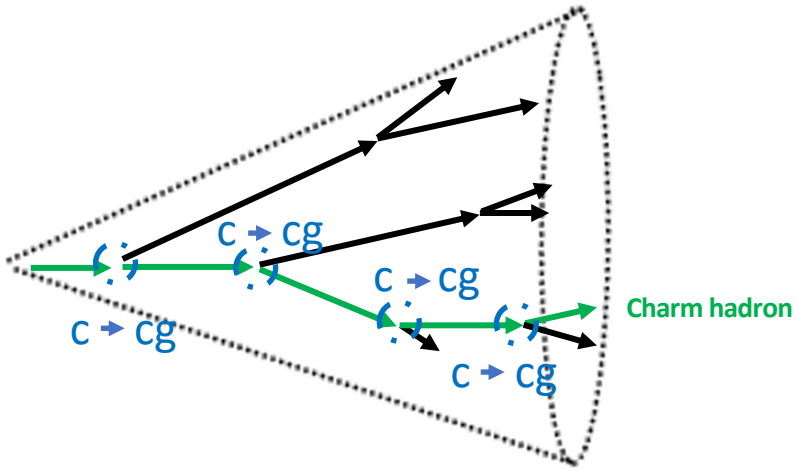
Can access features of the shower in a time and space dependent way

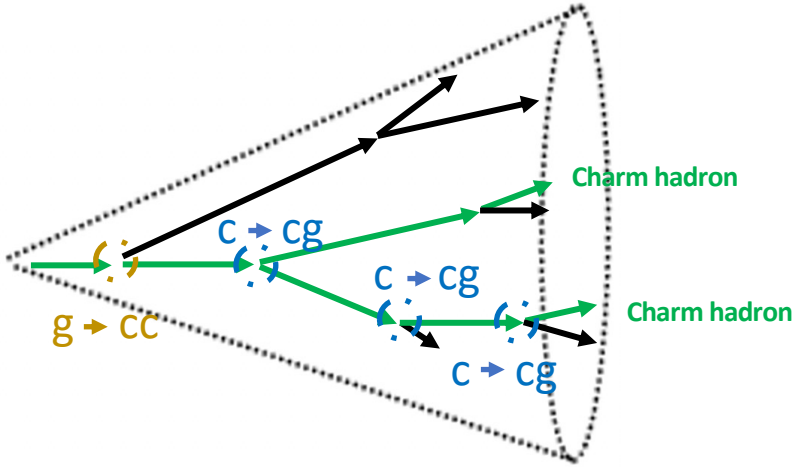
Outlook : going beyond heavy-flavour splittings

Using heavy-flavour tracing to access quark-initiated splittings









Outlook : going beyond heavy-flavour splittings

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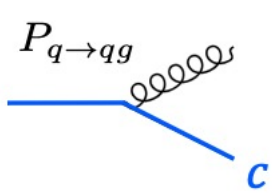
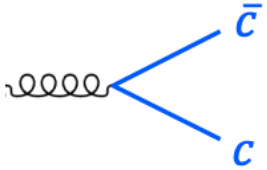
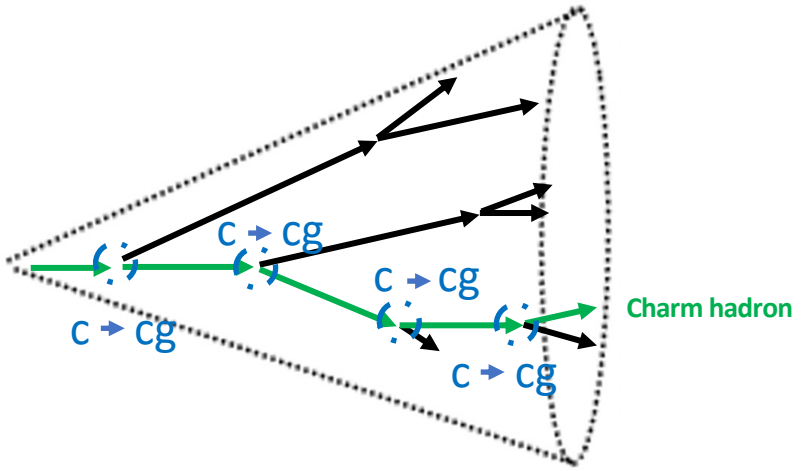
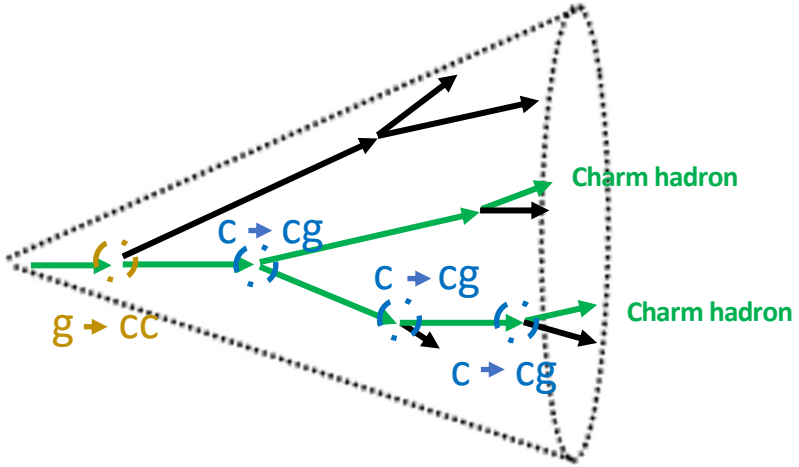




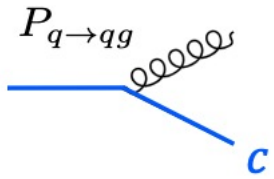
What about the remaining QCD splitting?

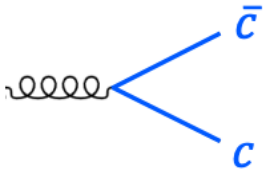




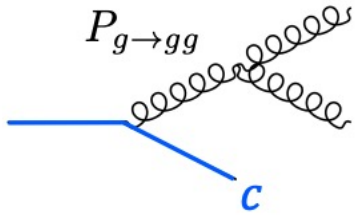
Outlook : going beyond heavy-flavour splittings

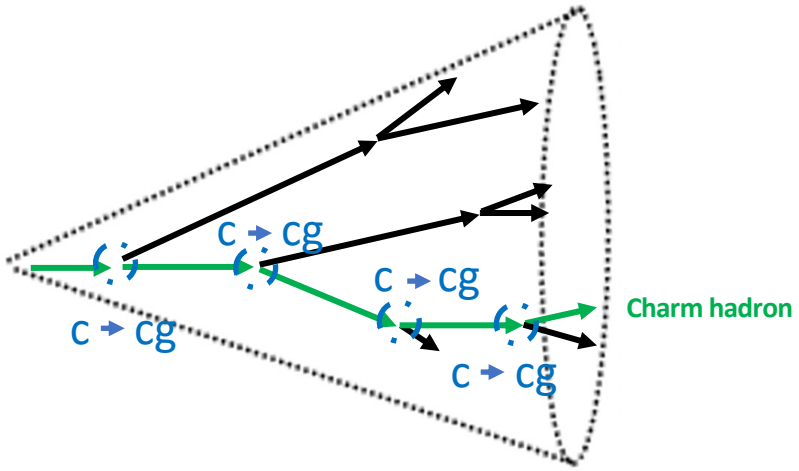
Using heavy-flavour tracing to access quark-initiated splittings

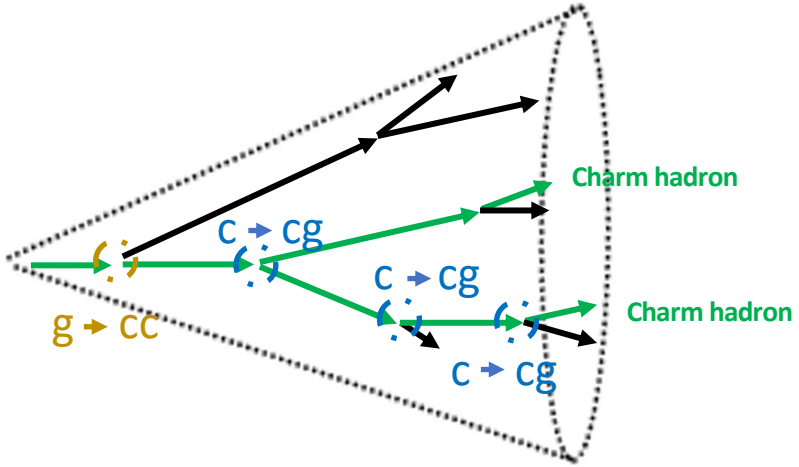




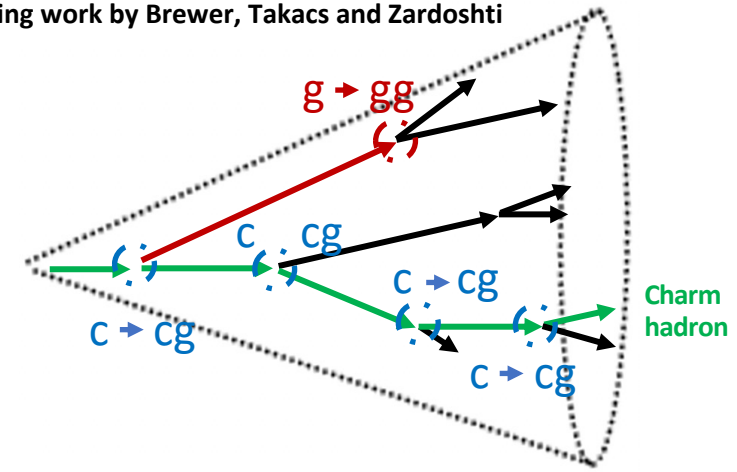
What about the remaining QCD splitting?





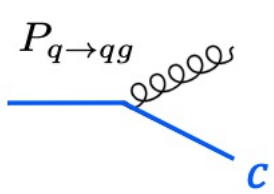


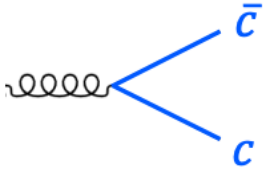
Ongoing work by Brewer, Takacs and Zardoshti



Outlook : going beyond heavy-flavour splittings

Using heavy-flavour tracing to access quark-initiated splittings





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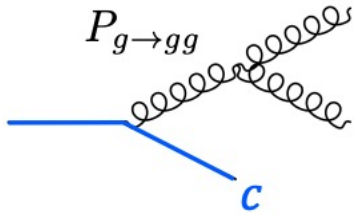

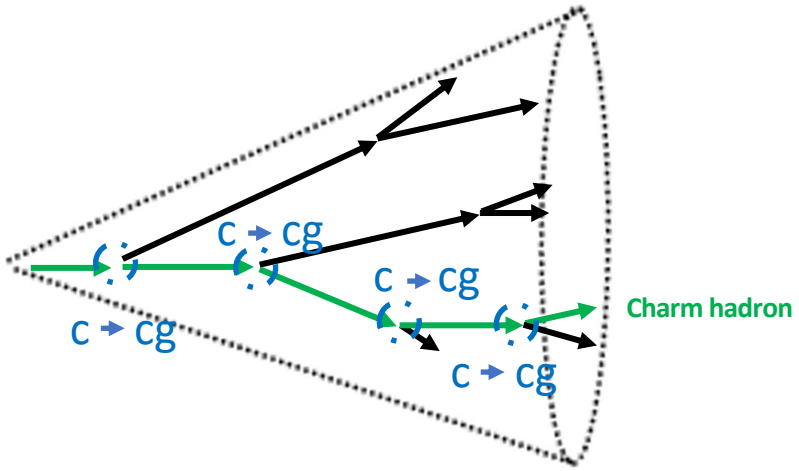

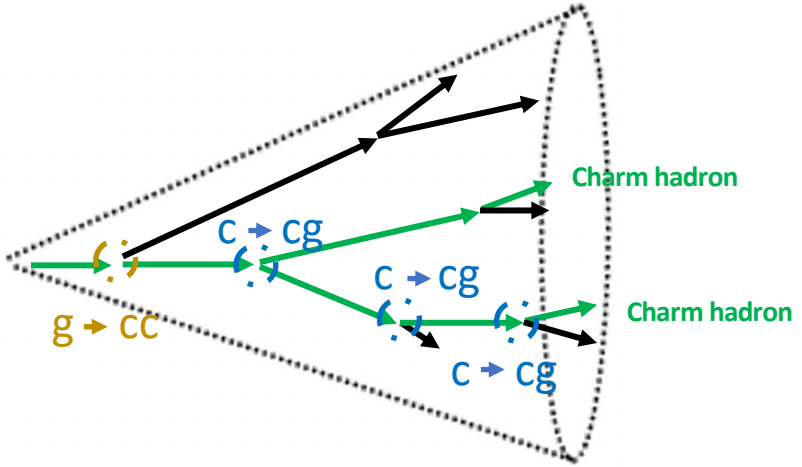

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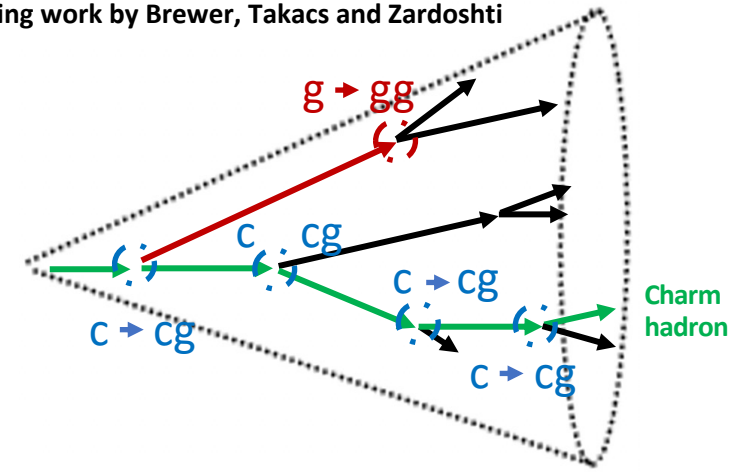
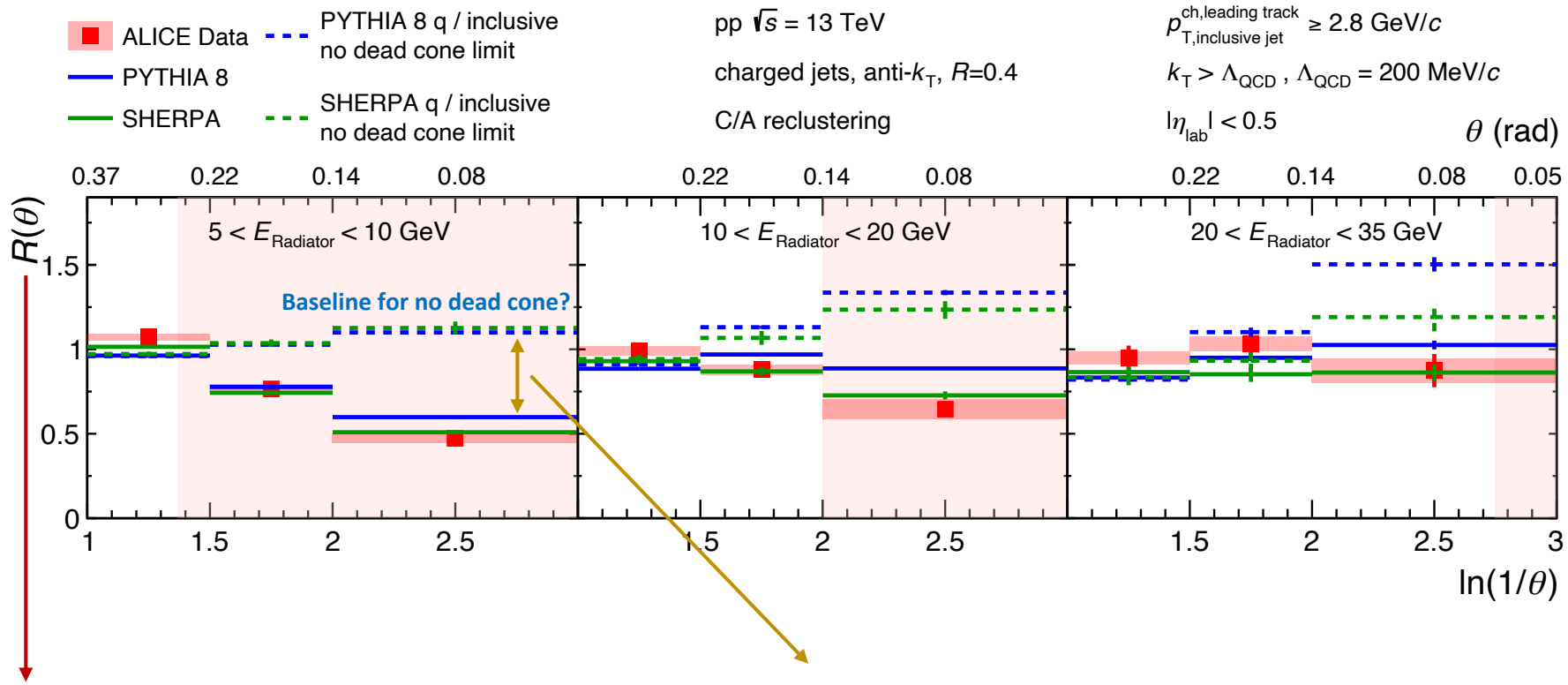


Heavy-flavour tracing tests our ability to calculate secondary splitting dynamics and beyond with control over all splitting flavours along the chain

Important in both pp and HI collisions

Outlook : using heavy-flavour to separate flavour effects

Observation of the QCD dead cone



angular distribution of charm emissions

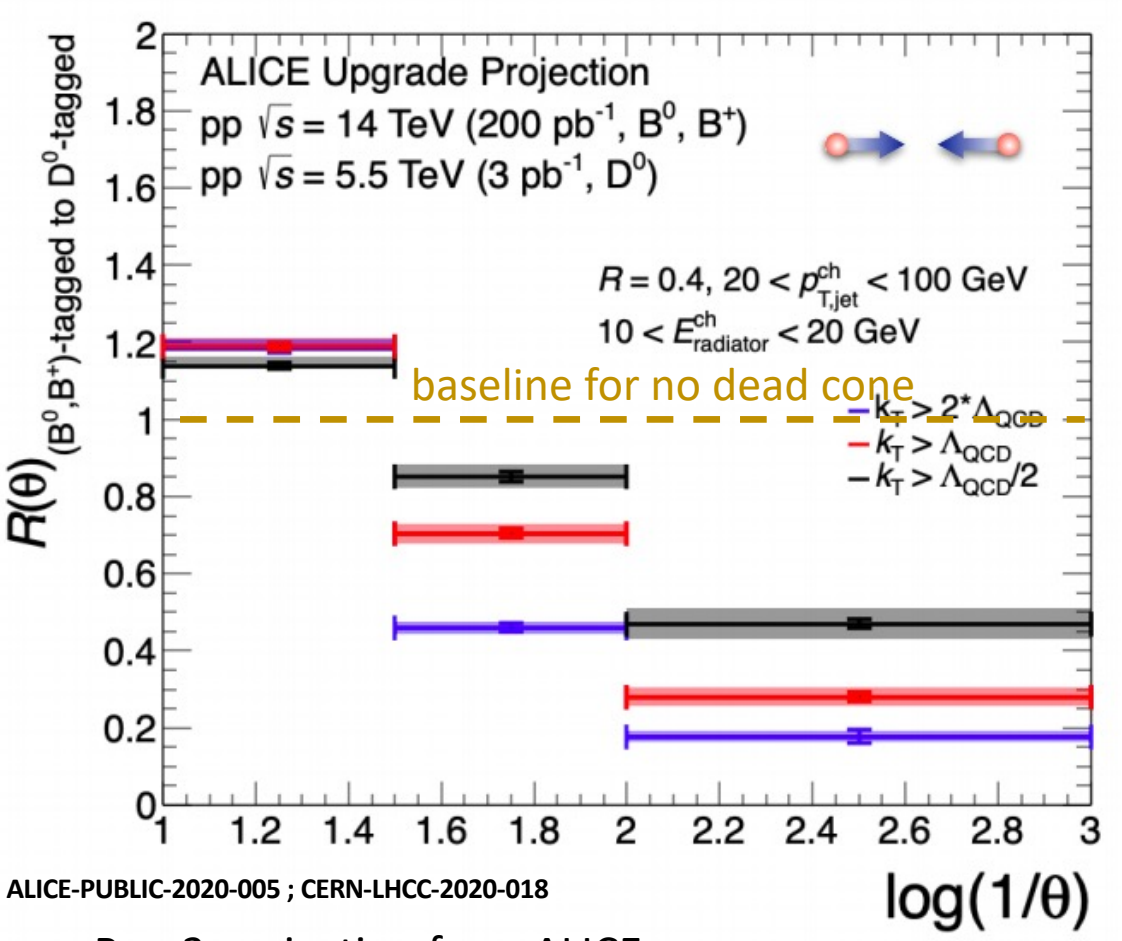
angular distribution of gluon + light quark emissions

Sensitive to both Casimir colour factors and mass effects

How can we separate flavour effects?

Outlook : using heavy-flavour to separate flavour 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

Accessing Mass Effects

Jets tagged with a charm or beauty hadron represent a sample of enhanced quark jets

Comparison of b->bg and c->cg emissions is only sensitive to mass effects

Accessing Casimir Effects

At high energies mass effects die out

Comparison of Q-> Qg and inclusive emissions are only sensitive to Casimir colour effects at high p_T

Summary

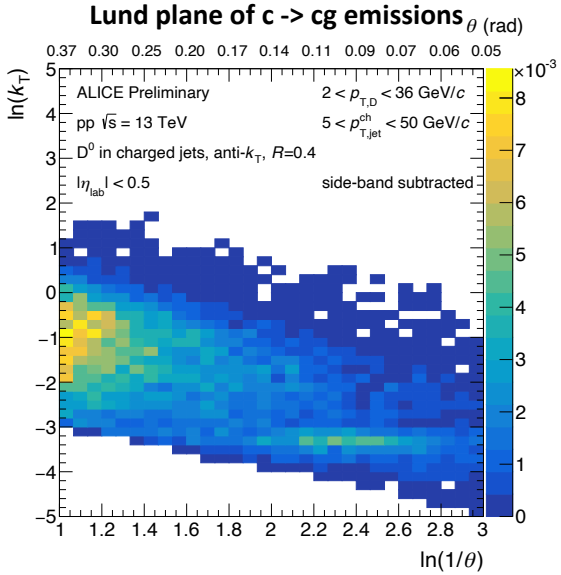
Heavy-flavour tracing is a powerful tool to take the next step in precision understanding of parton showers

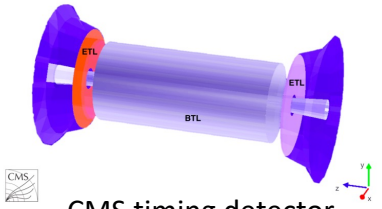
Heavy-flavour tracing can provide access to all three types of QCD splittings in pp and HI collisions

Full control over the flavour dynamics is necessary to connect experiment and theory in pp and HI collisions

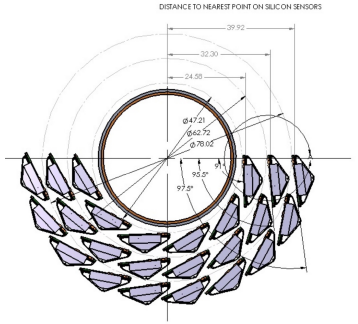
Many challenges accompanied by many opportunities

Run 3 and beyond promise to be fruitful and exciting times with experimental upgrades targeting improved heavy-flavour capabilities

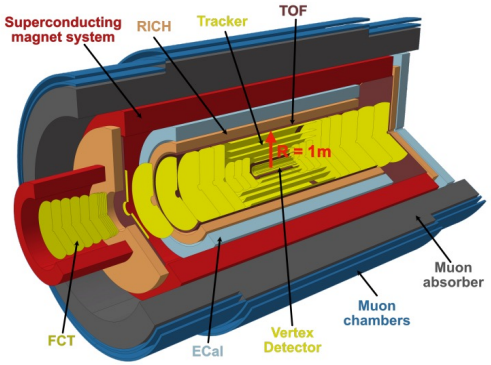




CMS timing detector



sPHENIX MVTX detector



ALICE 3

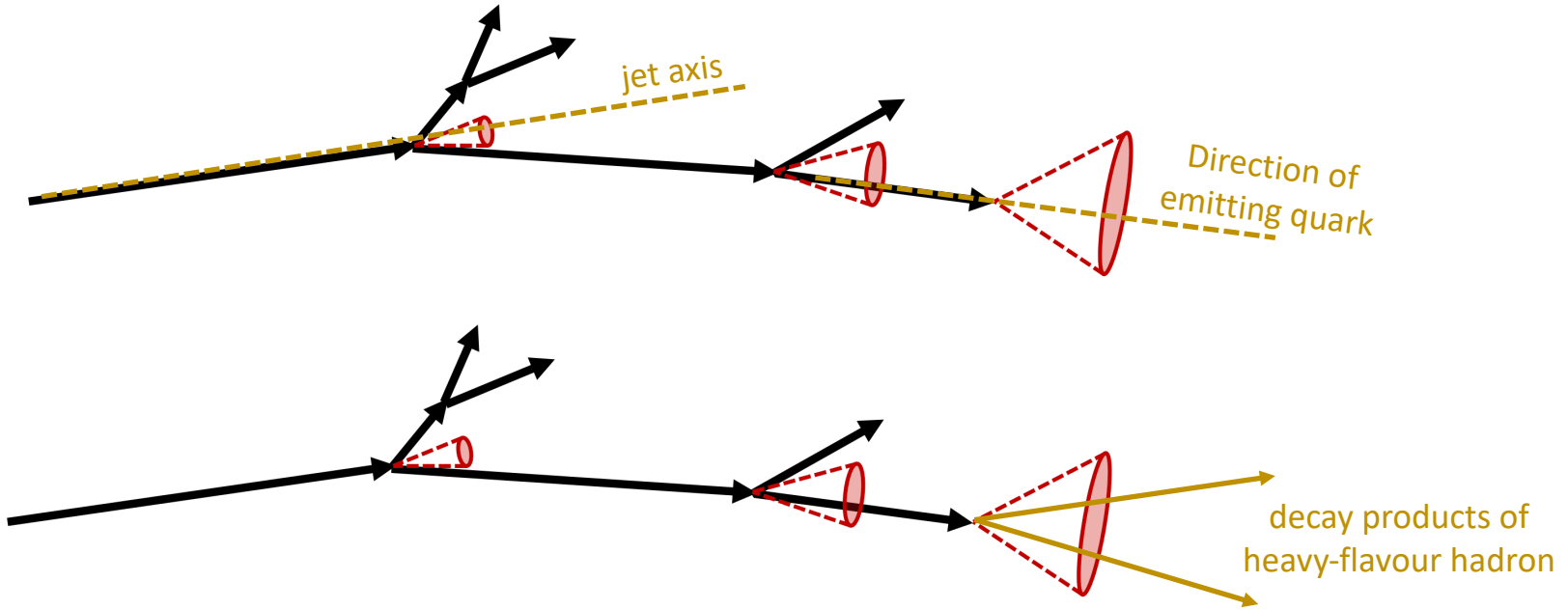
Backup

Can we avoid reconstructing the heavy-flavour hadron?

Full heavy-flavour hadron reconstruction

Jets contain information on the kinematics of the final state heavy-flavour quark

Significant statistical penalties due to small branching fractions and reconstruction efficiencies



Kinematics are updated at each vertex

Decay products do not smear the shower reconstruction

Can we avoid reconstructing the heavy-flavour hadron?

Full heavy-flavour hadron reconstruction

Jets contain information on the kinematics of the final state heavy-flavour quark

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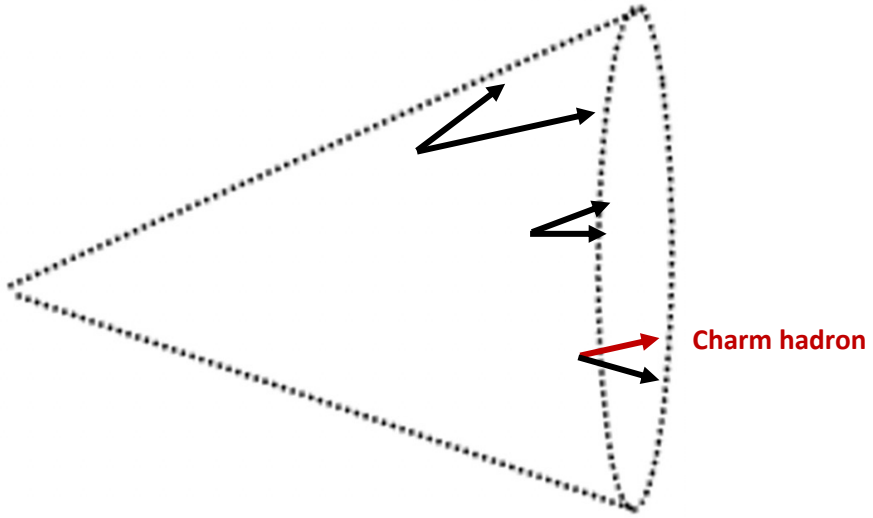
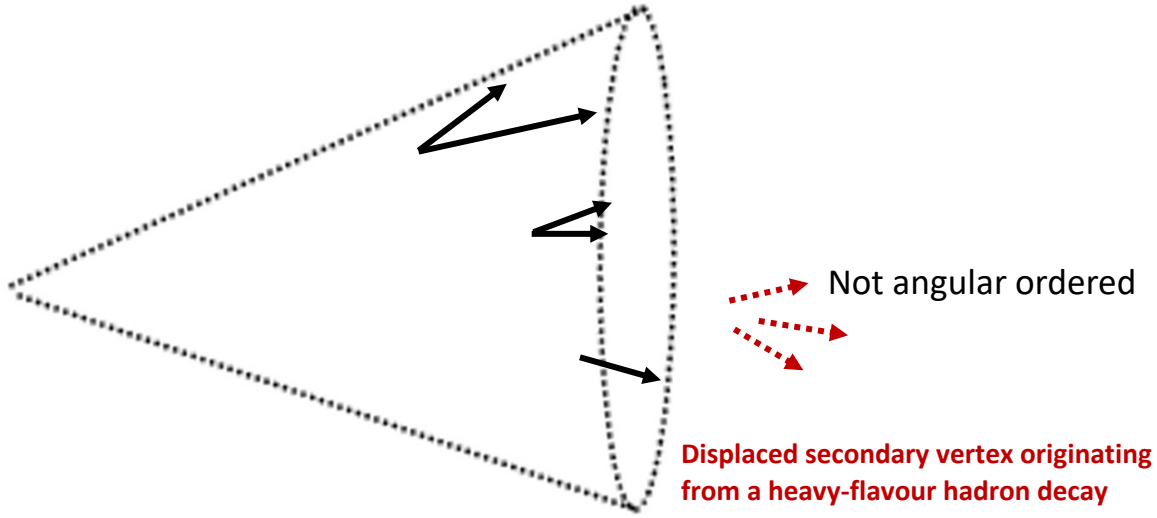
Jets with a displaced secondary vertex

Much better statistical precision

Jets lack full information on the kinematics of the final state heavy-flavour quark

How important is this?





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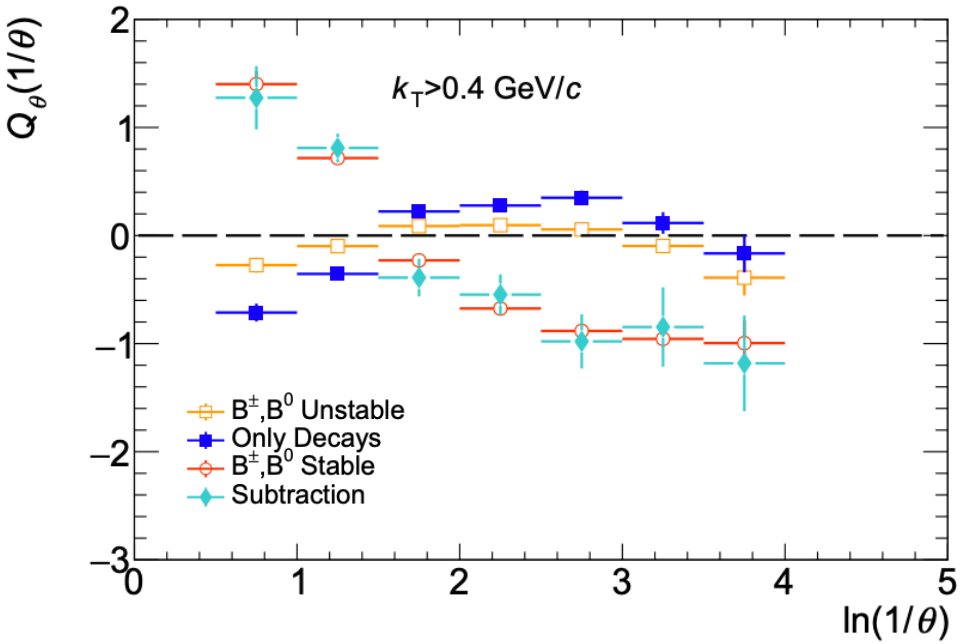


Substructure measurements with full heavy-flavour hadrons are much more sensitive to flavour effects

Decay particles of the heavy-flavour hadron and the partial jet information can wash out differences due to flavour

Fully reconstructing hadrons is key to tracing measurements as well as substructure

Is it possible to try to estimate the heavy-flavour hadron kinematics from topology of the secondary vertex?

Challenges of heavy-flavour tracing : gluon-initiated jets

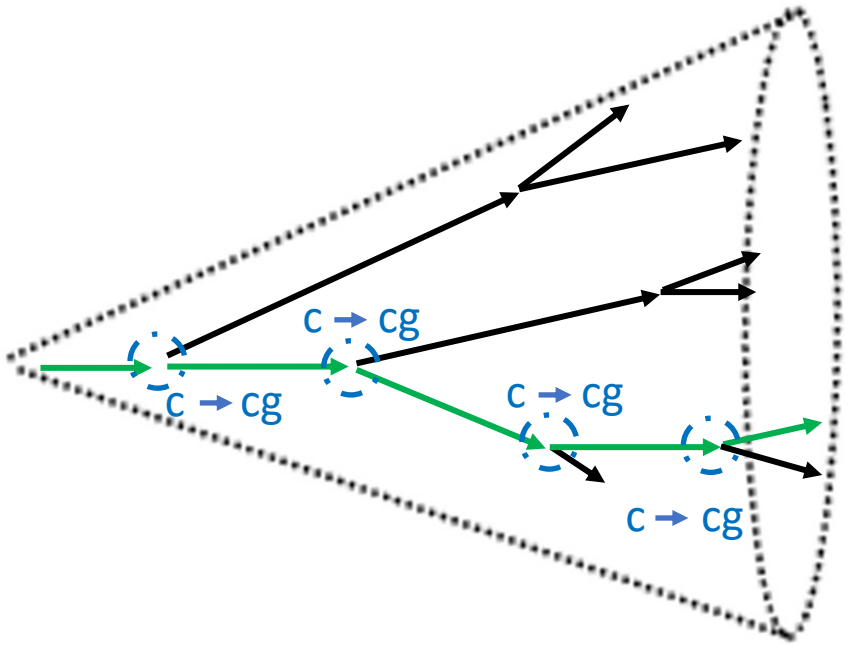
The picture presented so far assumes the heavy-flavour jet was initiated by a heavy-quark

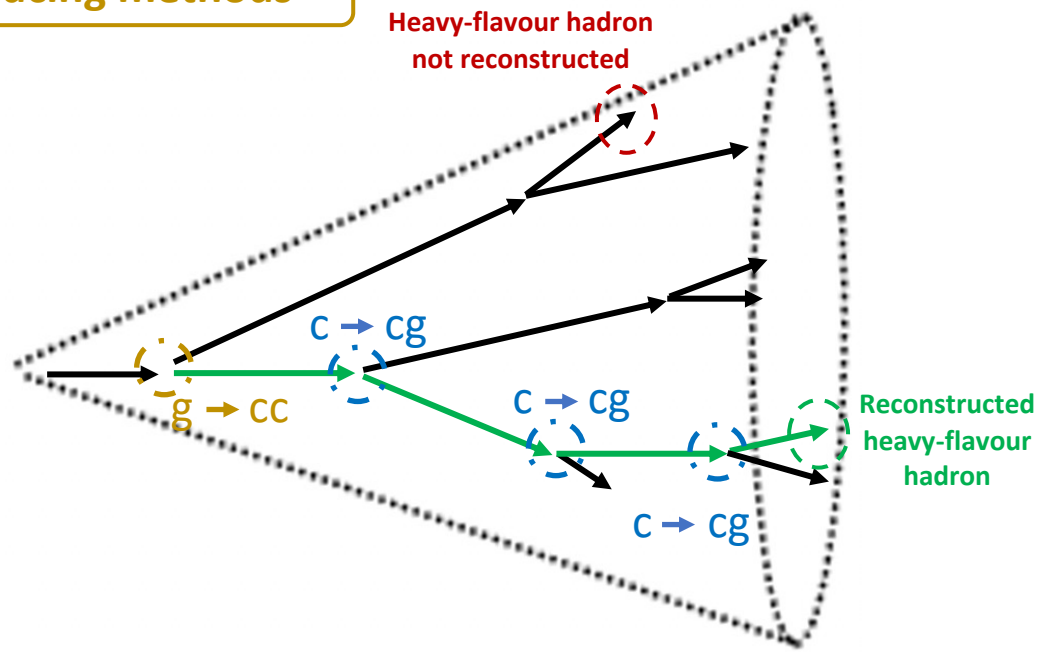
g->QQ processes or initial state radiation can reduce control over splitting flavours

Impact of gluon-splitting reduces deeper into the tree

Can we remove gluon-splitting processes with jet clustering algorithms, substructure cuts or cuts on the secondary vertex of the non-reconstructed heavy-flavour hadron?

Largest challenge for tracing methods



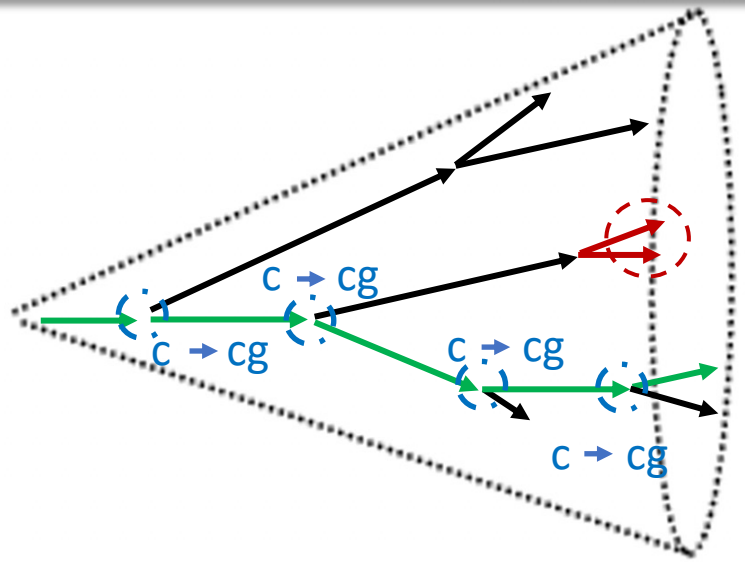


Challenges of heavy-flavour tracing : deep into the shower

Increased non-perturbative effects

Splittings deep in the shower are more sensitive to contamination from non-perturbative sources

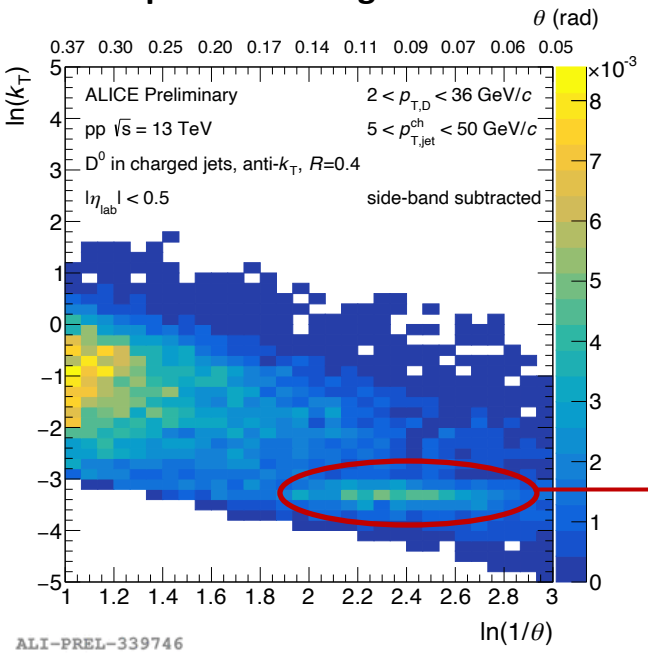
Strict cuts such as k_T required



Is this a splitting in the shower or a product of hadronisation?

Less problematic along the heavy-flavour branch

Lund plane of c -> cg emissions



Contamination of soft pions from $\mathrm{D}^* \to \mathrm{D}^0\pi$ Removed with a k_T cut

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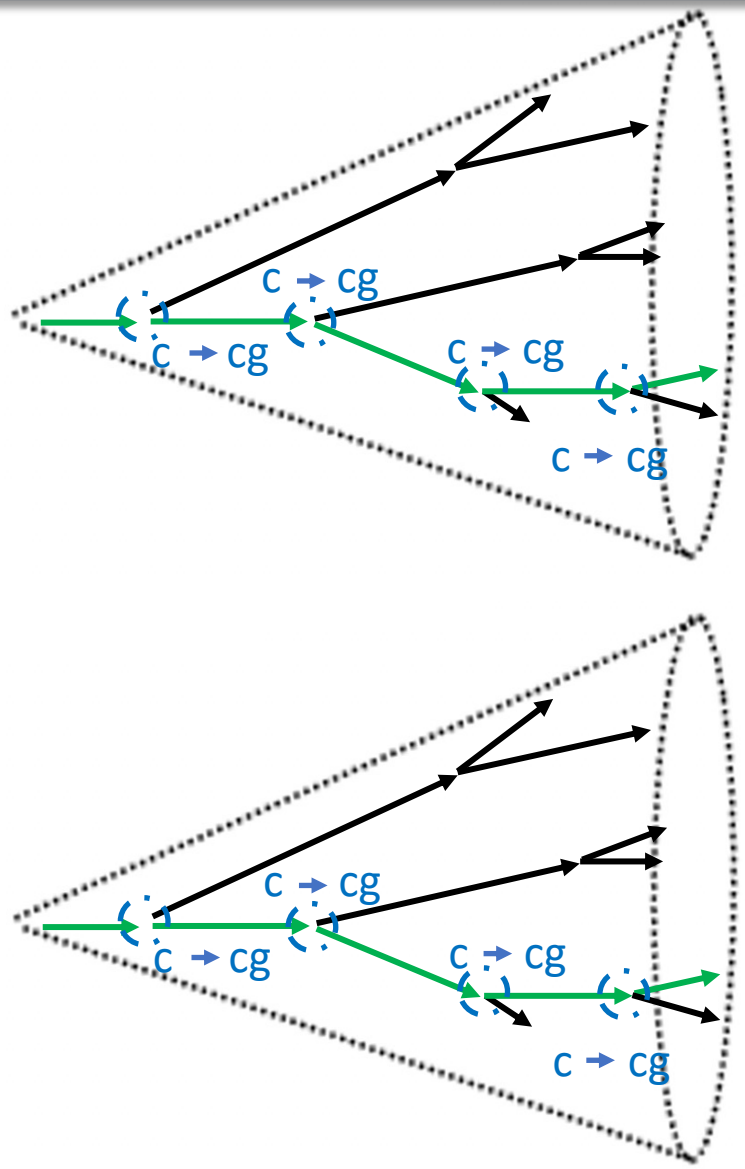
Is mistagging due to track losses or the underlying event more significant for deeper splittings?

Enhanced protection in heavy-flavour case as the heavy-flavour hadron cannot be lost



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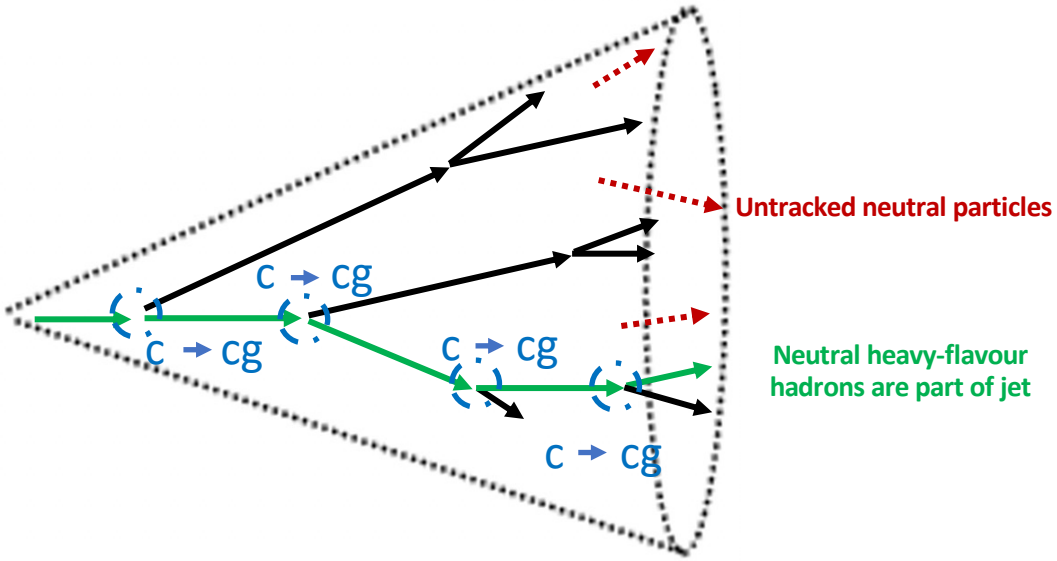
Impact of neutral component

Do the missing neutral particles impact deeper splittings more?

Can we treat this as tracking losses and correct with unfolding?

Tracing measurements often performed with track-based jets



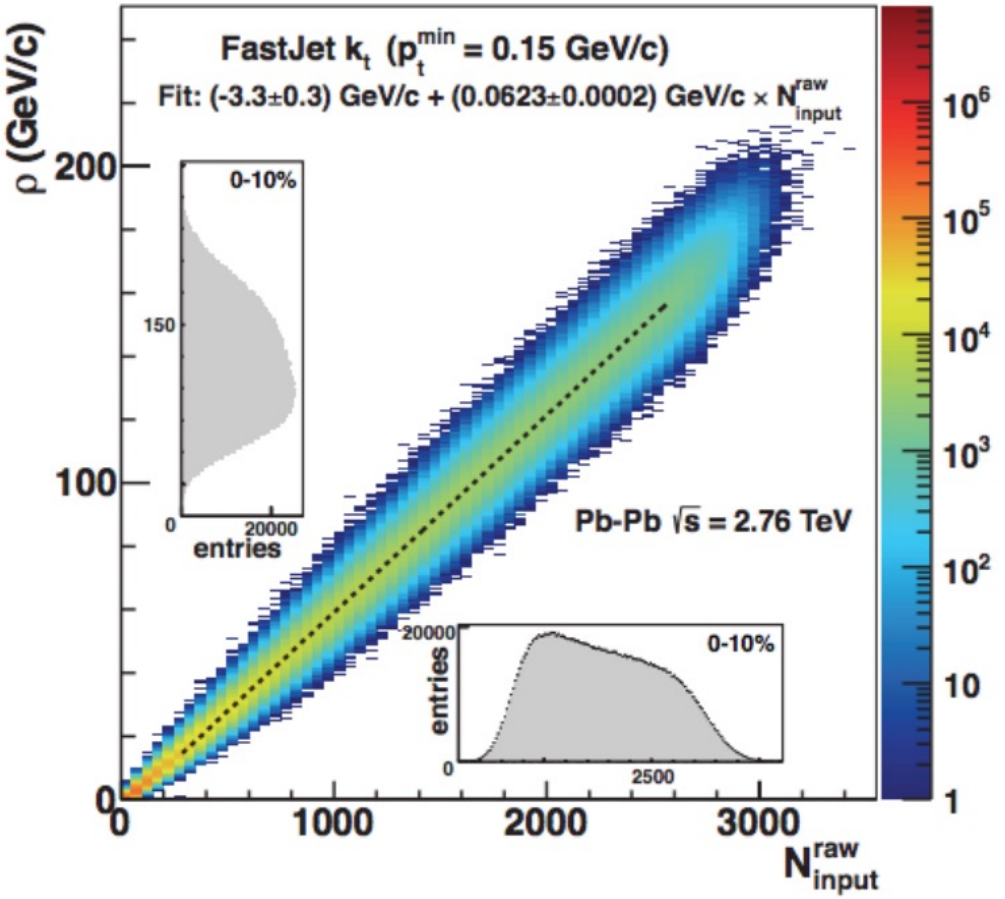
Challenges of heavy-flavour tracing : HI background

The heavy-ion background poses a large challenge to tracing measurements

Background effects are less significant deeper into the tree (at small angles)

However if present can they have a larger impact?

JHEP 1203 (2012) 053



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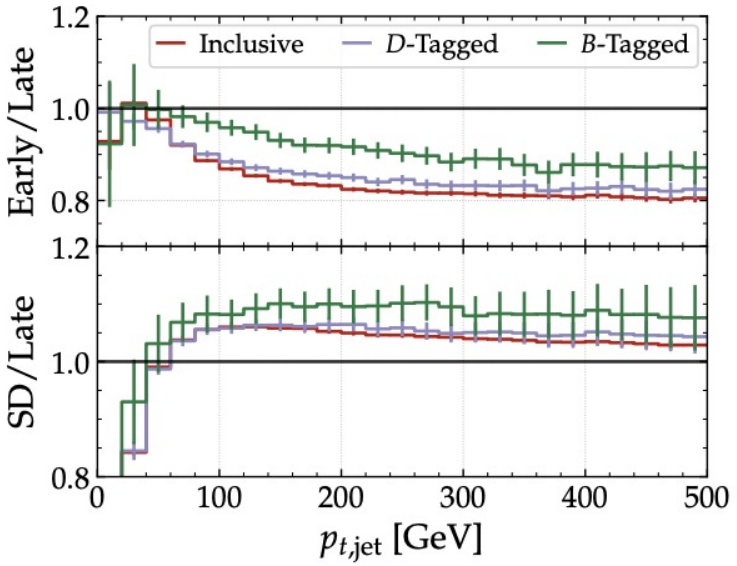
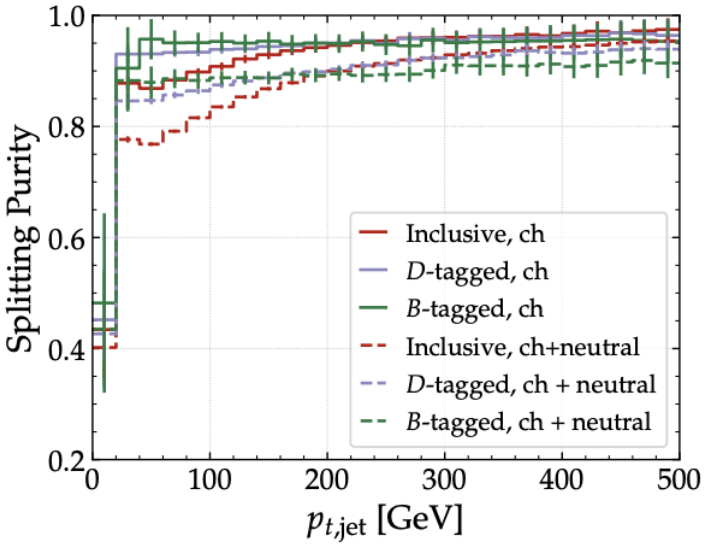
Studies show that the combination of late splittings with grooming selections have a higher resilience to the background

Jets tagged with a heavy-flavour hadron show less sensitivity to the background than inclusive jets

arXiv: 2211.11789

Ratio of splitting purities





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Heavy-flavour hadrons are guaranteed to be non-background

Need to modify background estimation and subtraction techniques accordingly
Opportunity to push to lower p_T jets?