Tracing heavy-flavour quarks through the shower in pp and HI

Nima Zardoshti

First Lund Jet Plane Institute

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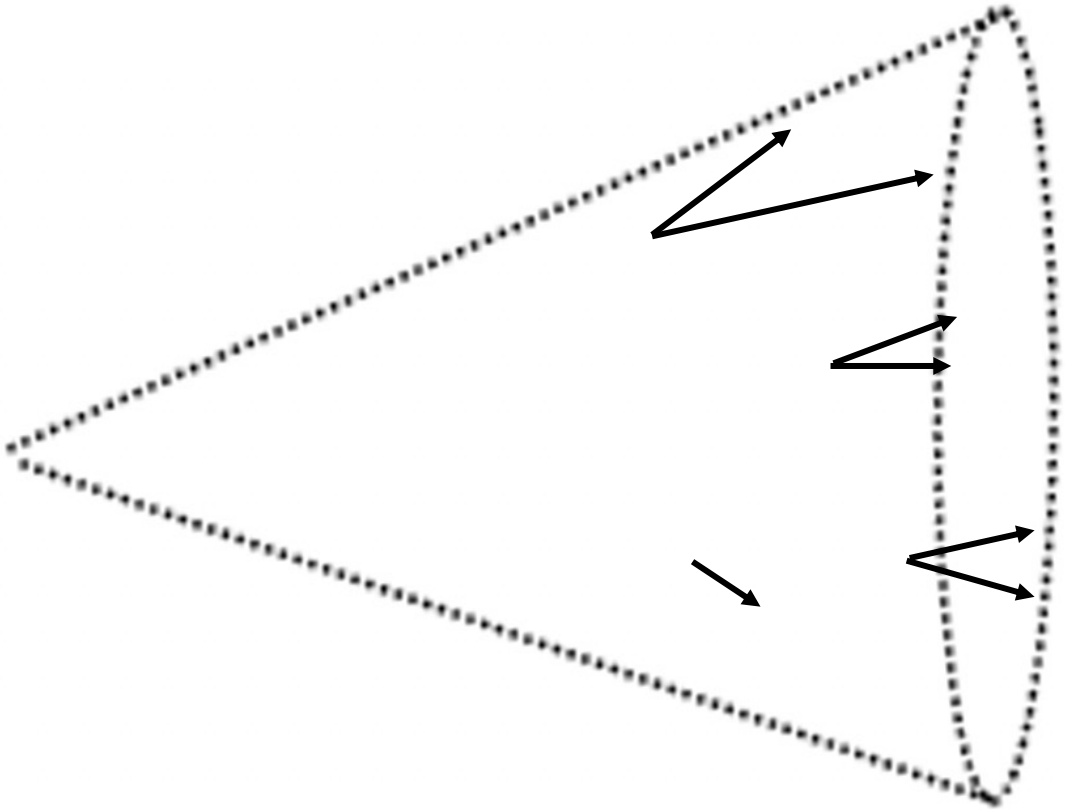
What is tracing?

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

Requirements for tracing



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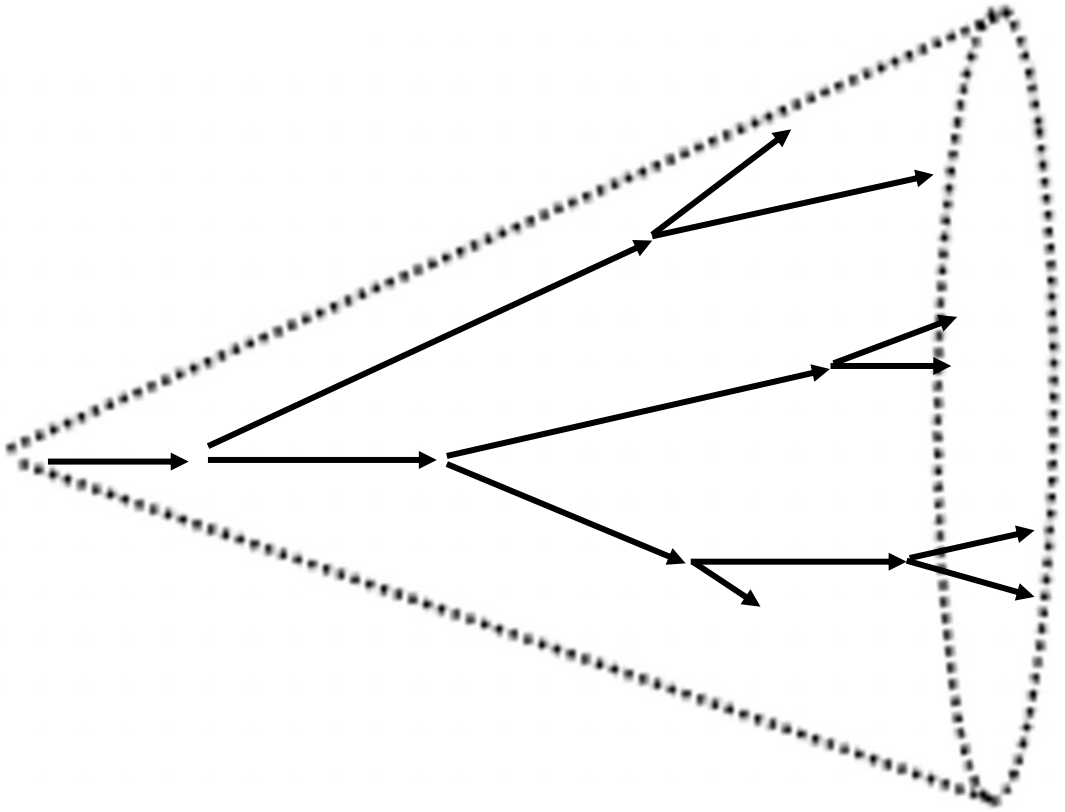

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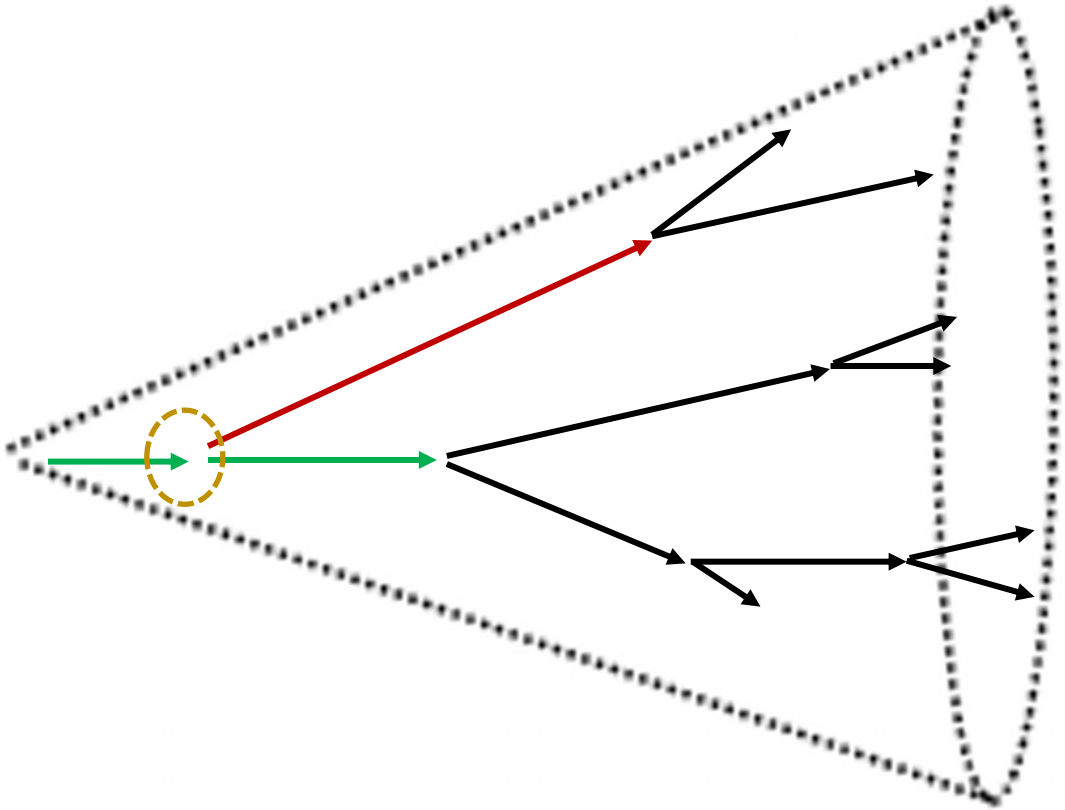

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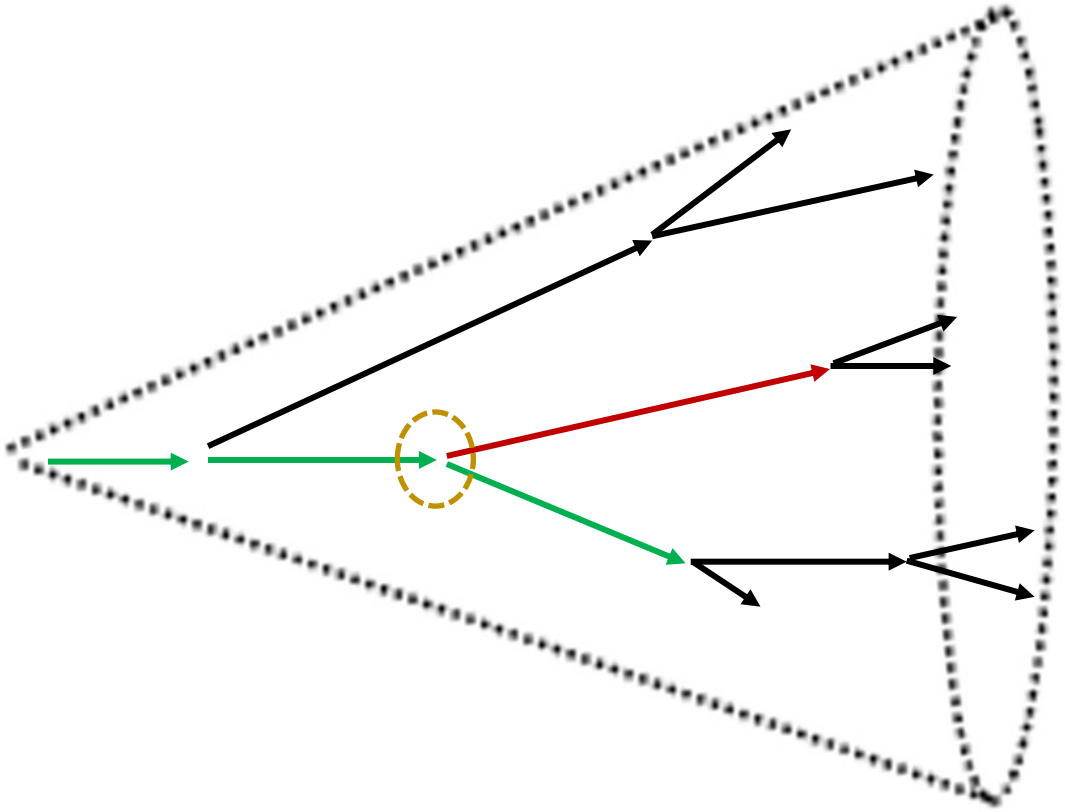

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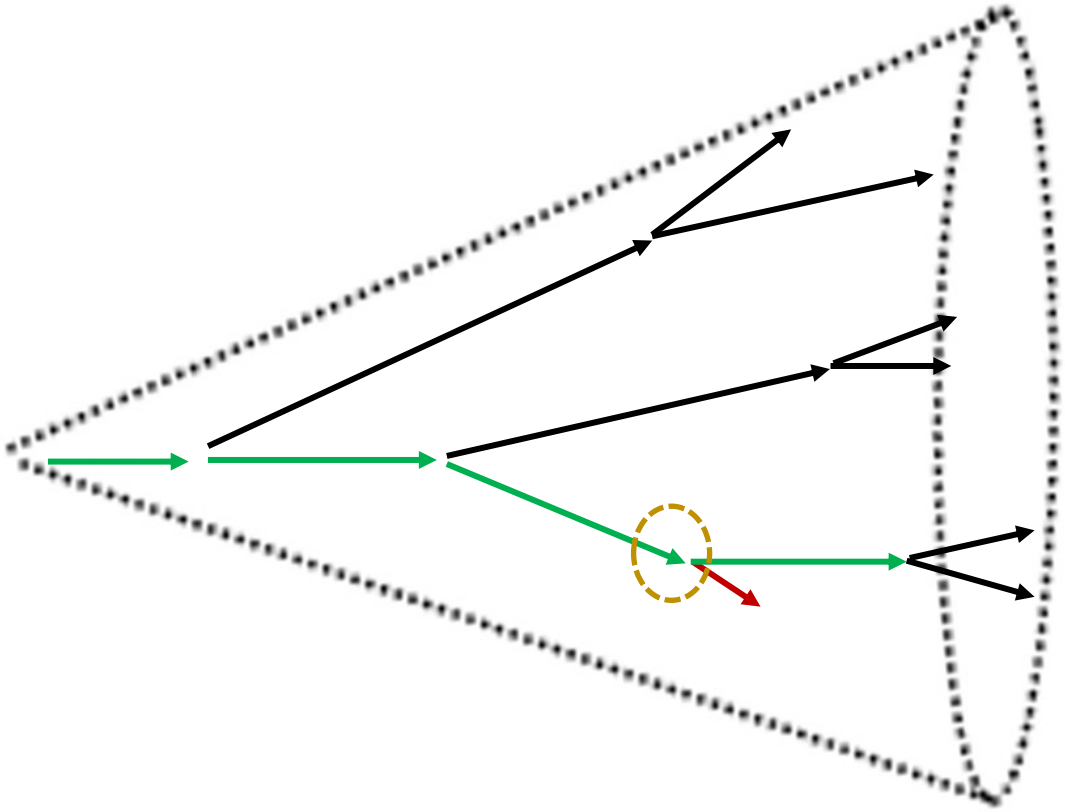

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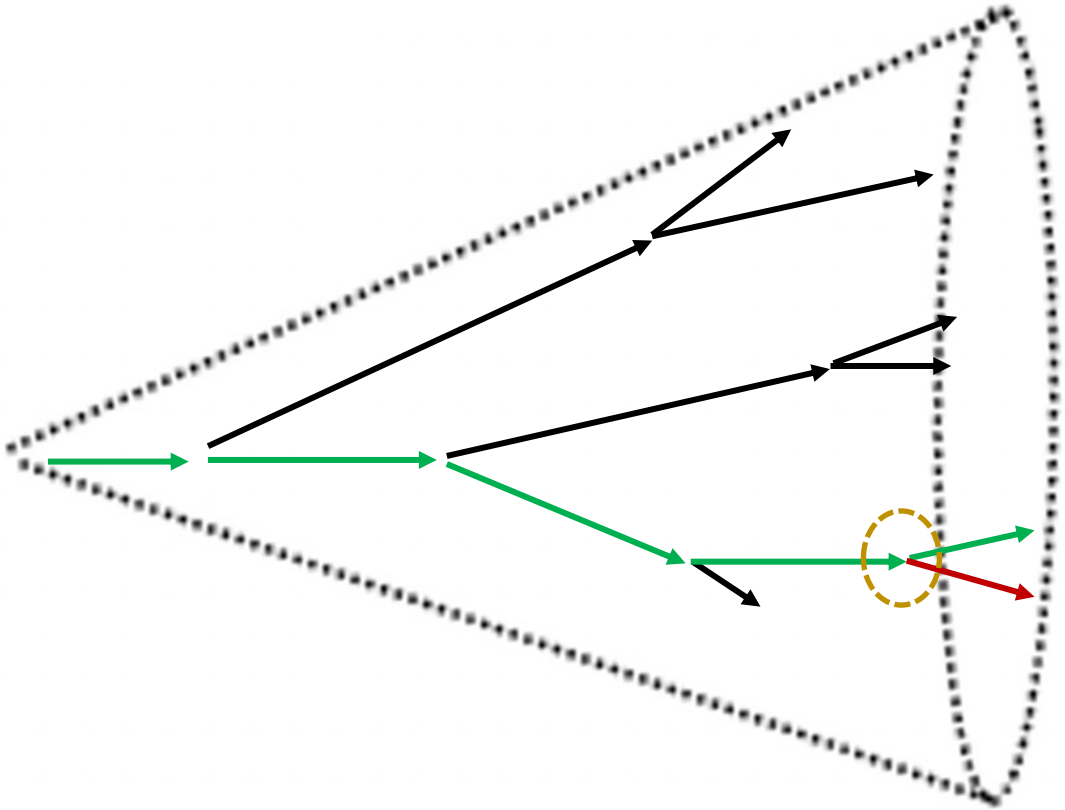

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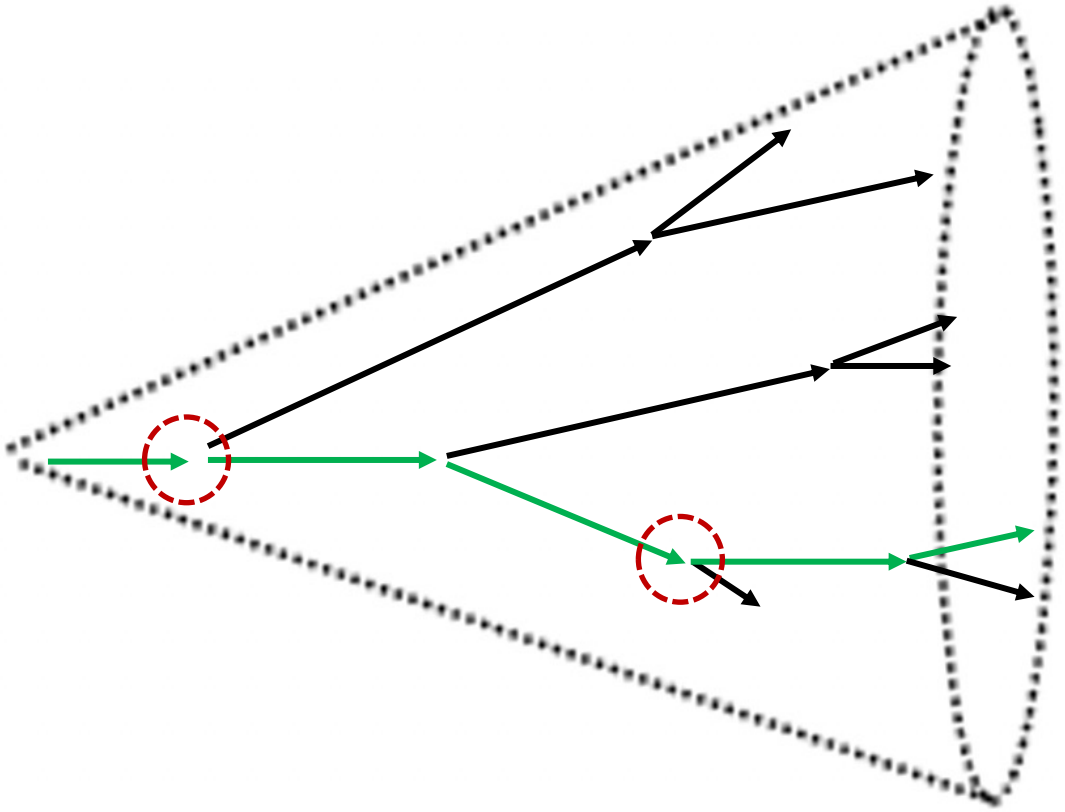


Requirements for tracing

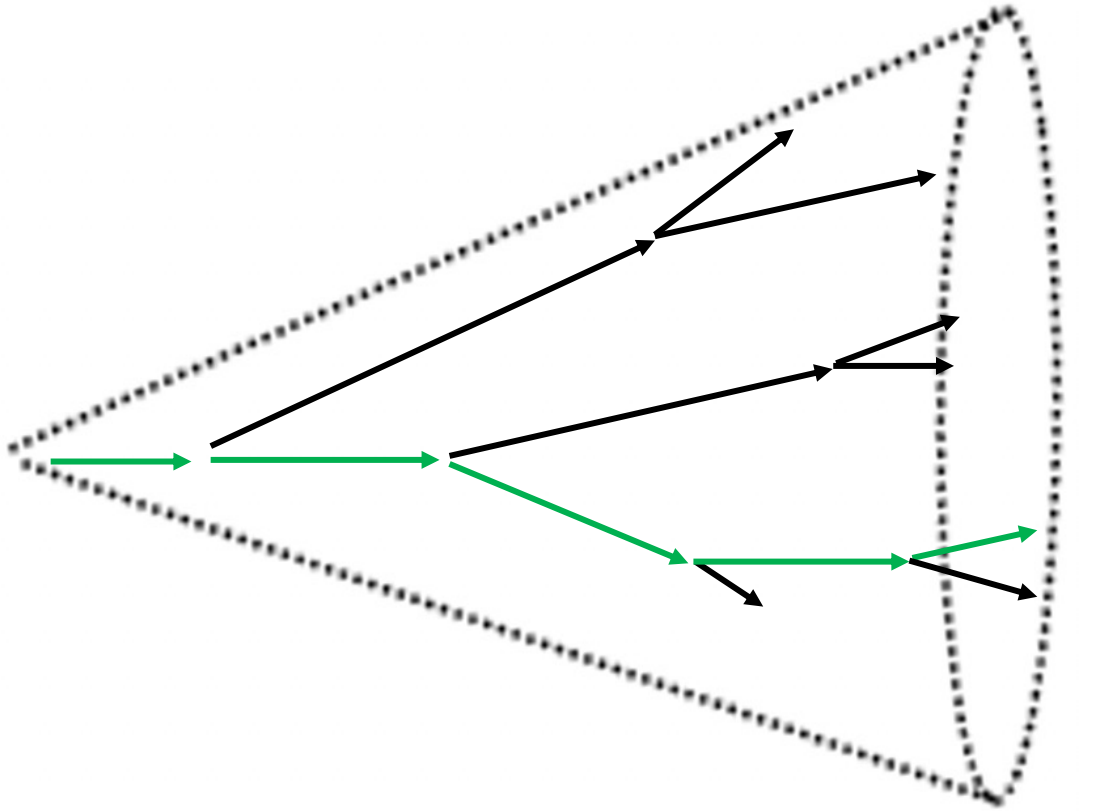
Access an ordered structure of the shower

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

Select particular splittings along the chosen branch (grooming, k_T cuts , etc)

Why is tracing important?

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



Decreasing momentum scale

Why is tracing important?

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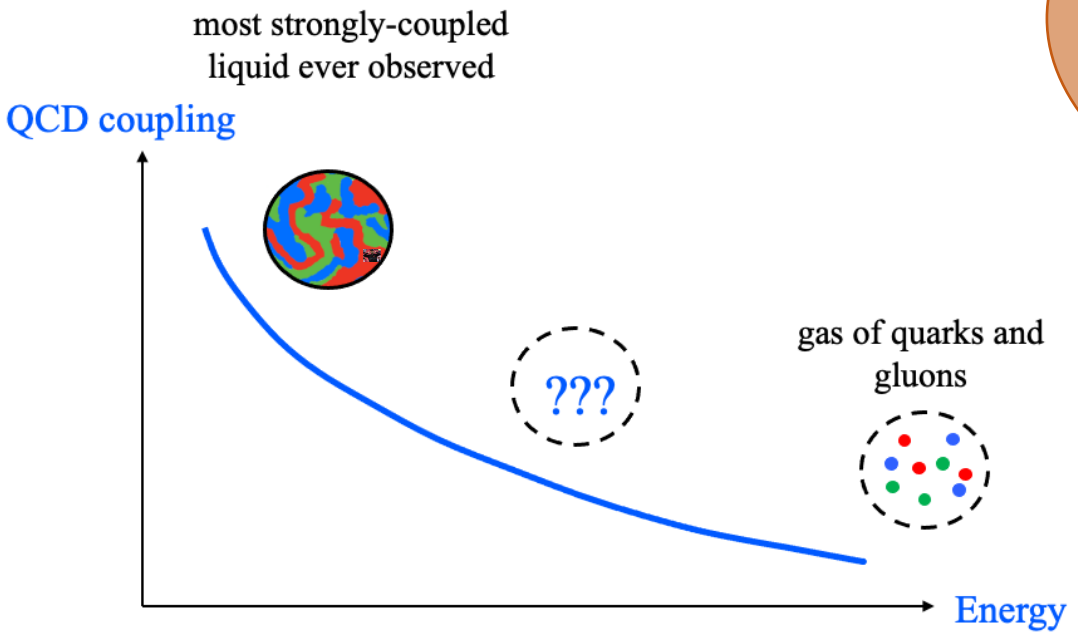
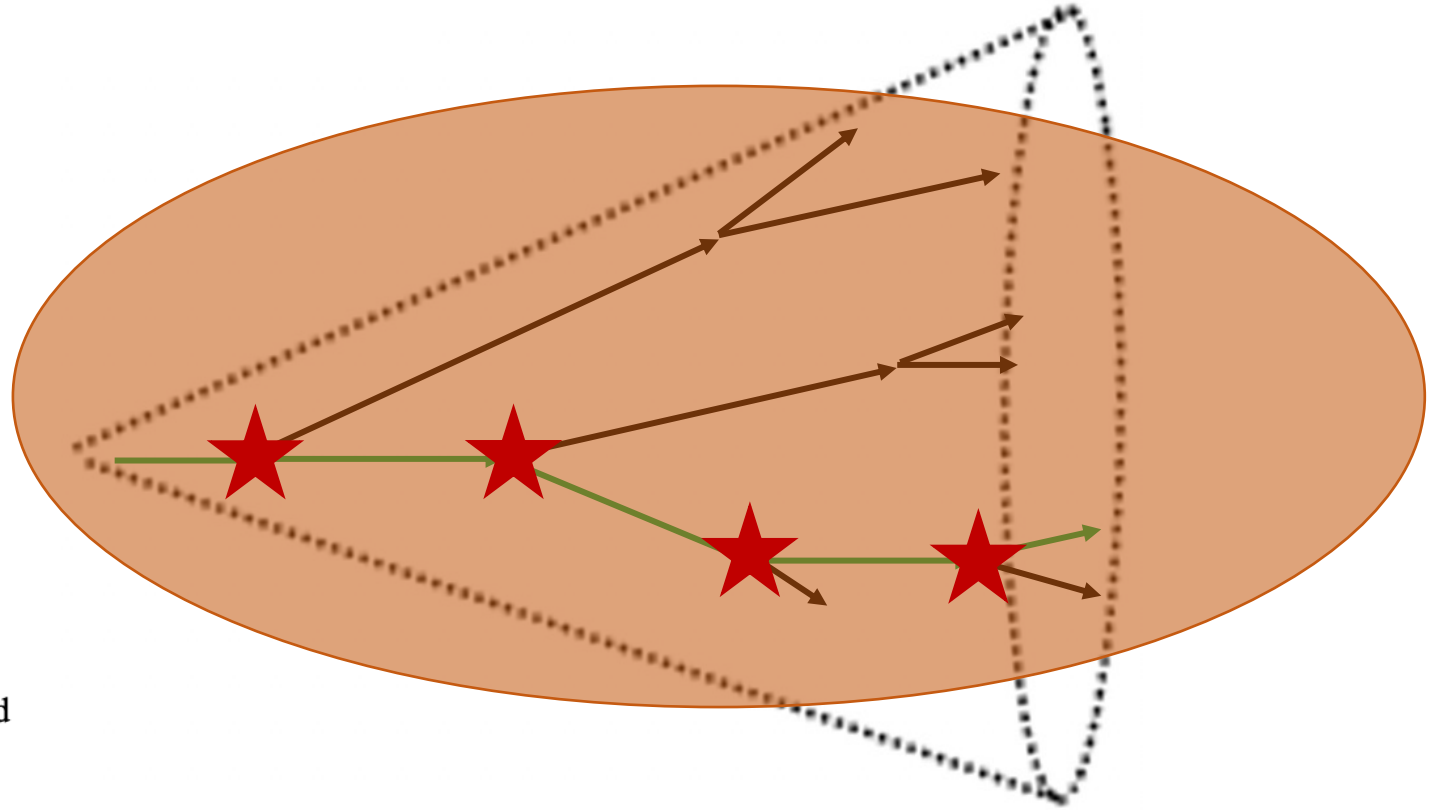
In the presence of the medium it allows us to probe the scale dependent features of the medium



State of the art

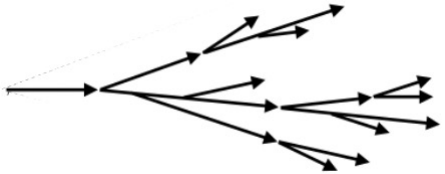


Decreasing momentum scale

The missing step : QCD flavour dependence

Gluon-initiated shower

Broader shower profile
Higher number of emissions

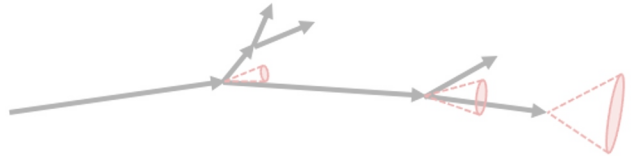


Quark-initiated shower

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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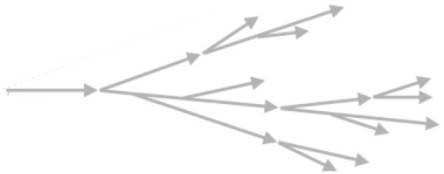

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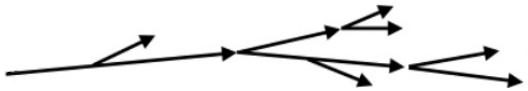

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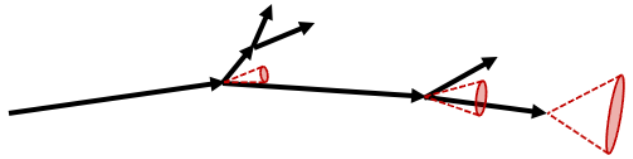

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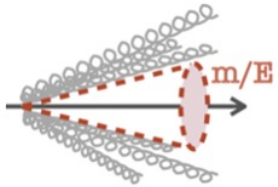
The dead-cone effect

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

Sizeable effect for low energy heavy quarks



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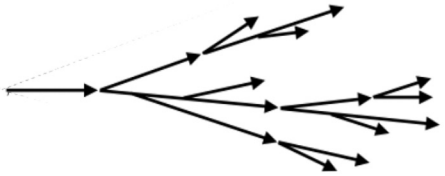

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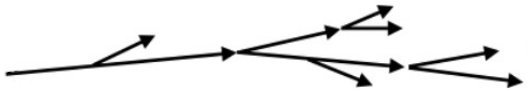

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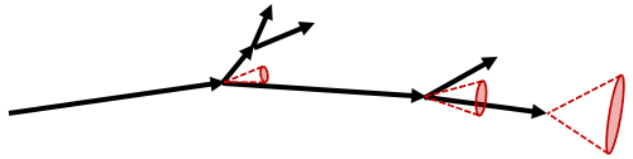

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Different emission properties due to the different amount of colour charge carried by quarks and gluons

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The dynamics of splitting flavours are at the heart of the structure of QCD showers

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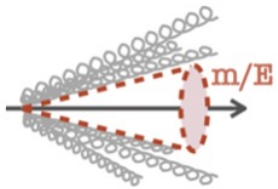

Flavour dynamics in the QGP

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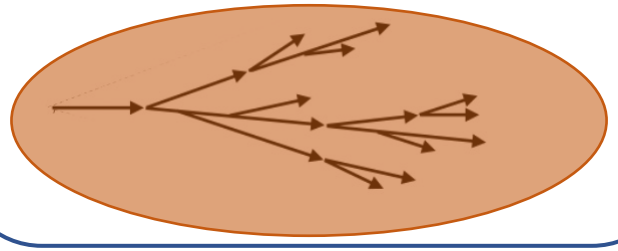

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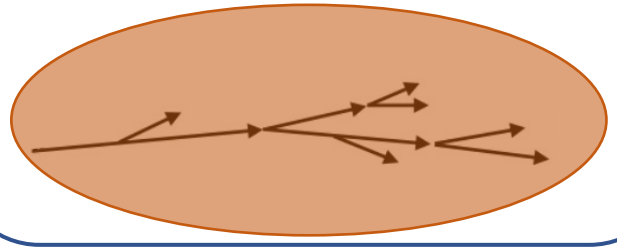

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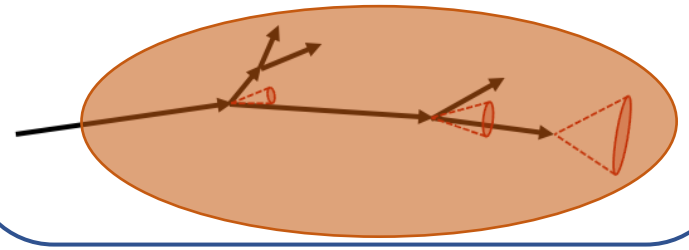

Casimir Colour factors

The medium couples differently to quarks and gluons

The dead-cone effect

How does the dead-cone interplay with medium emissions?

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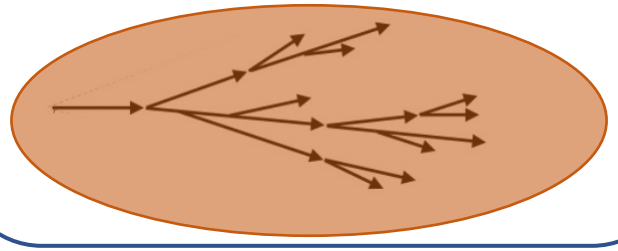

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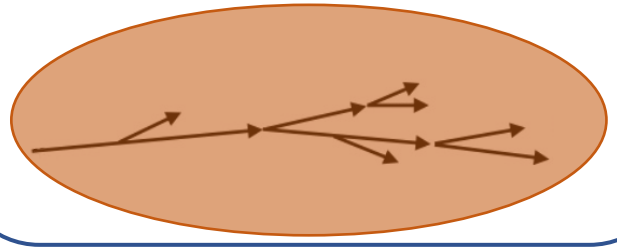

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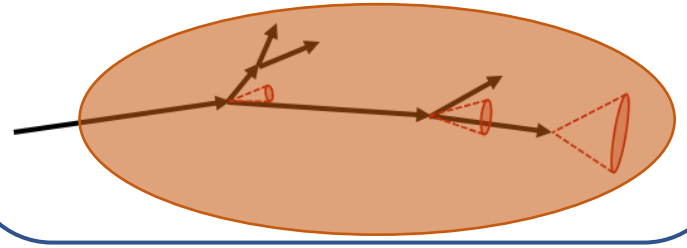

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The medium couples differently to quarks and gluons

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

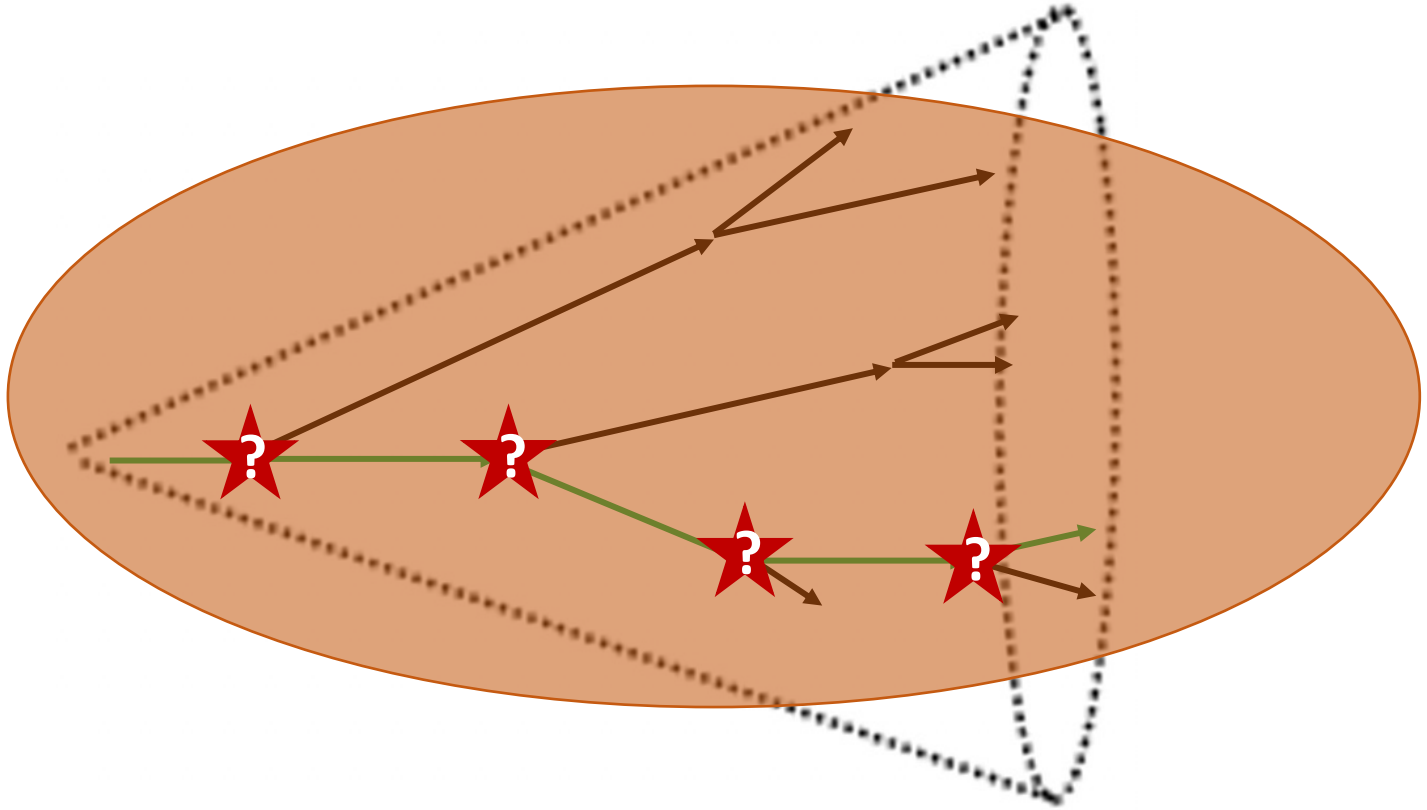
The fractions of splitting flavours are not known after quenching

Flavour dynamics in the QGP

To extract the properties of the medium from the modification of a splitting we need control over the splitting flavour

To describe splittings deeper in the tree the flavour of preceding splittings must also be known

Going beyond the state of the art will require full control over the splitting flavours along a traced branch



Decreasing momentum scale

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

Thermal production

Heavy-quarks are not produced thermally in the medium

Charm mass >> T_{QGP}

Single emission channel

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

c->cg or b->bg

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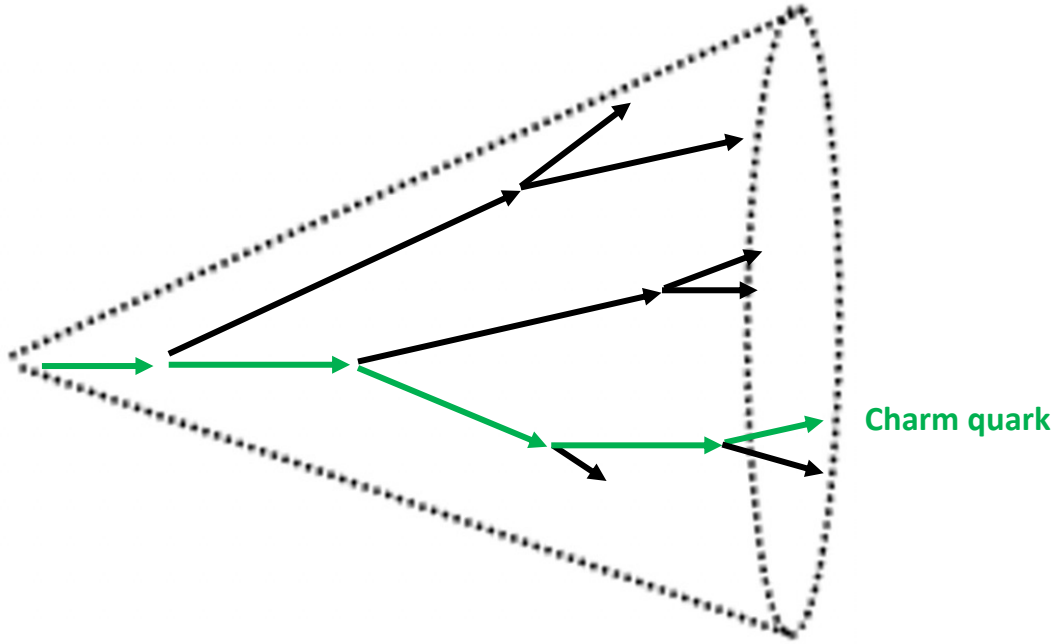

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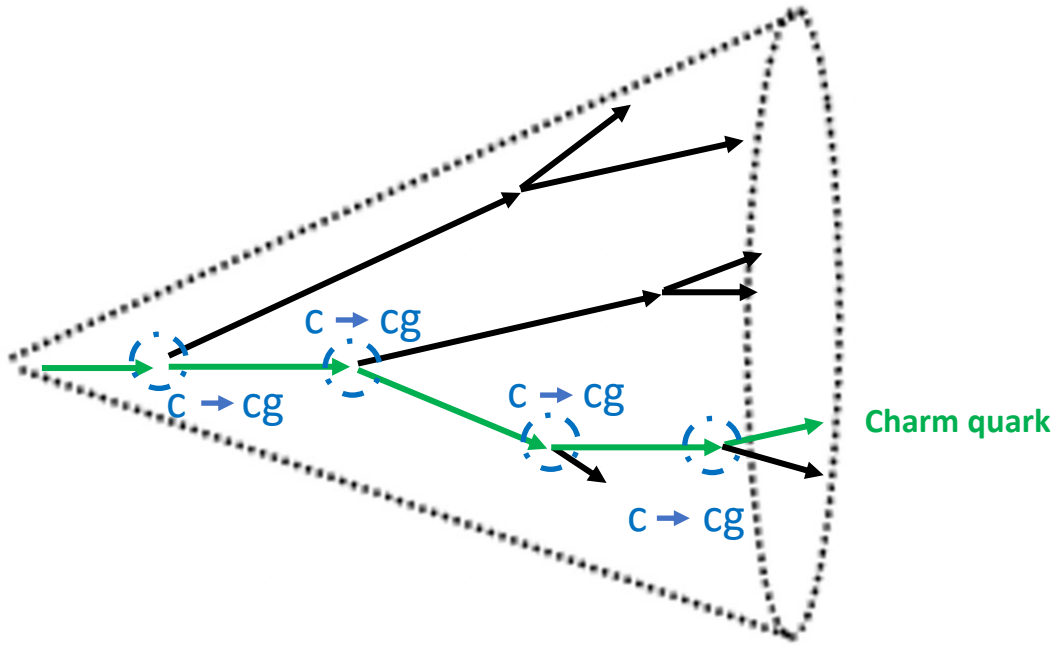
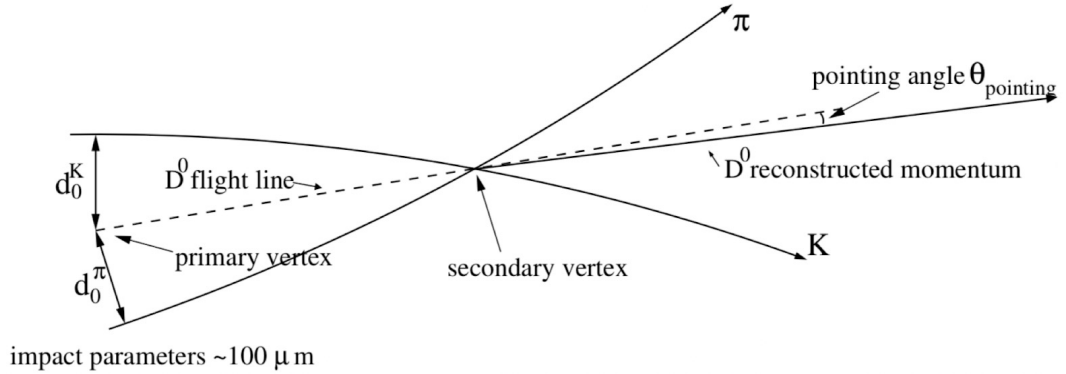
Following the charm quark through the shower gives access to a well controlled splitting flavour by only requiring its presence



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

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

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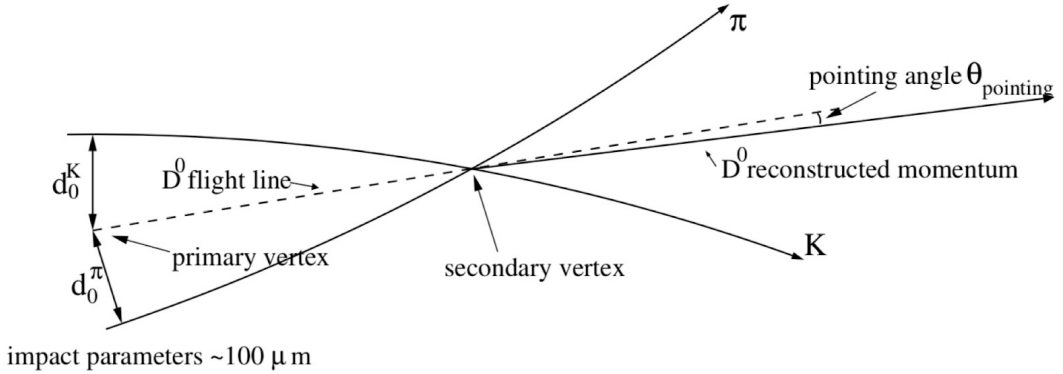
Heavy-flavour hadrons are identified from their decay products



Decay products

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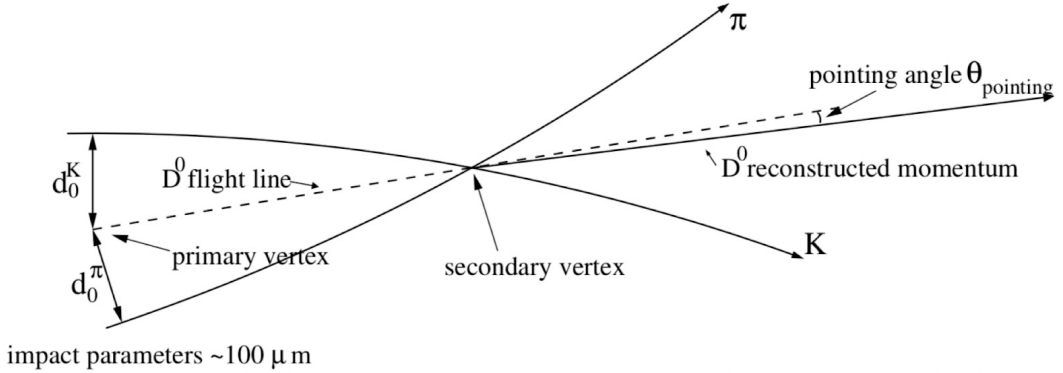
Replace the heavy-flavour hadron daughters with the parent's four-momentum



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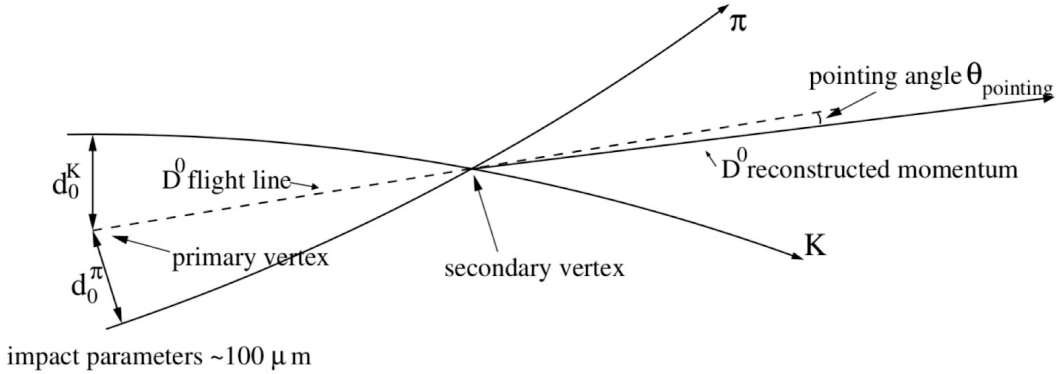

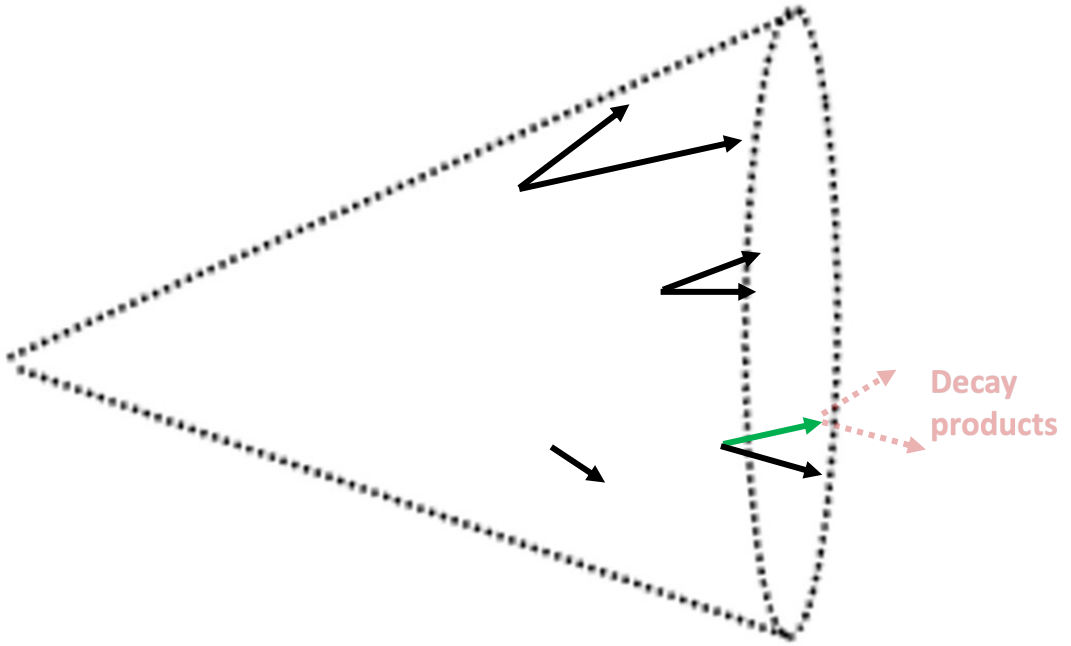

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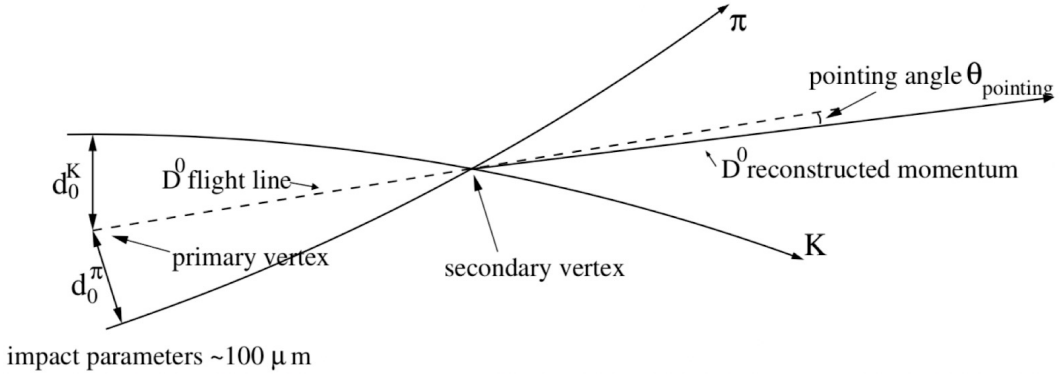
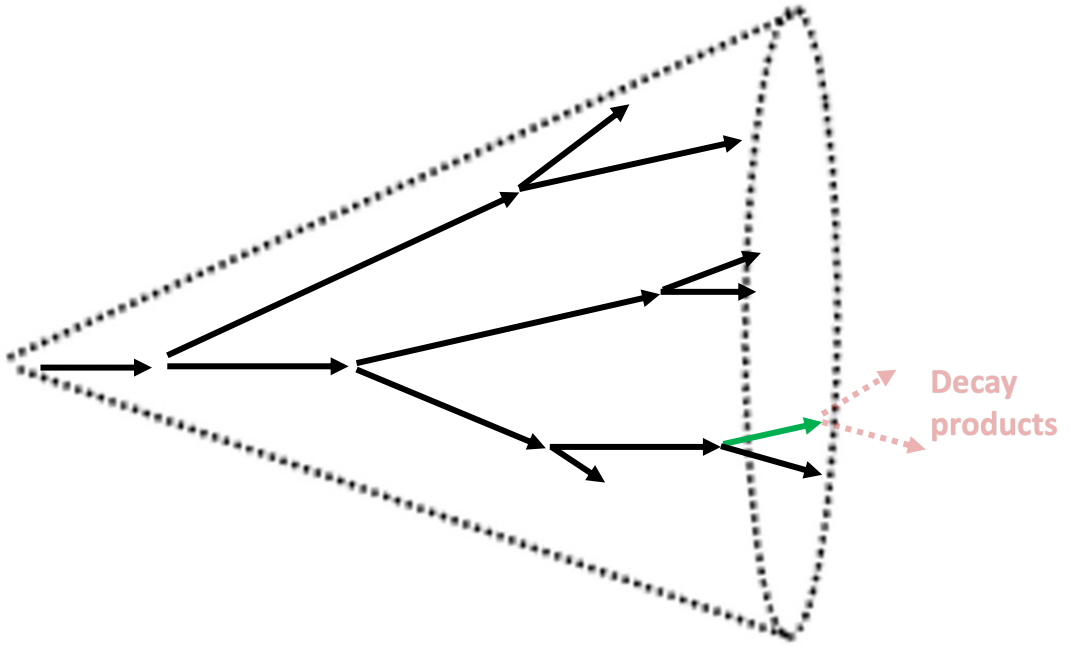
Recluster the jet to access the splitting tree





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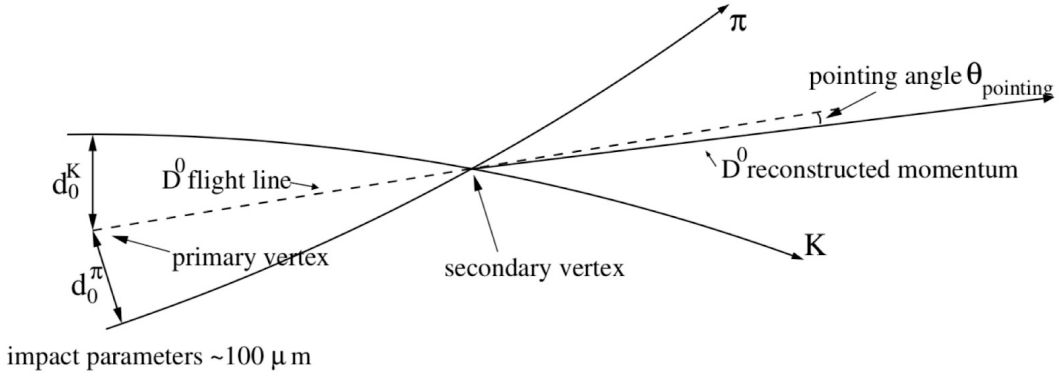

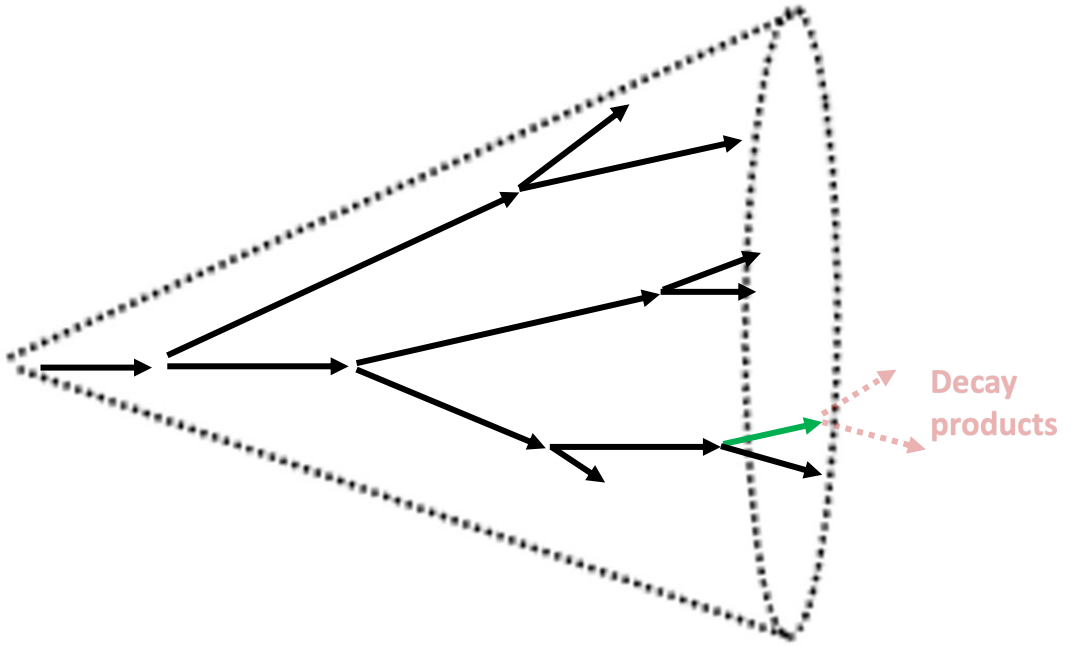

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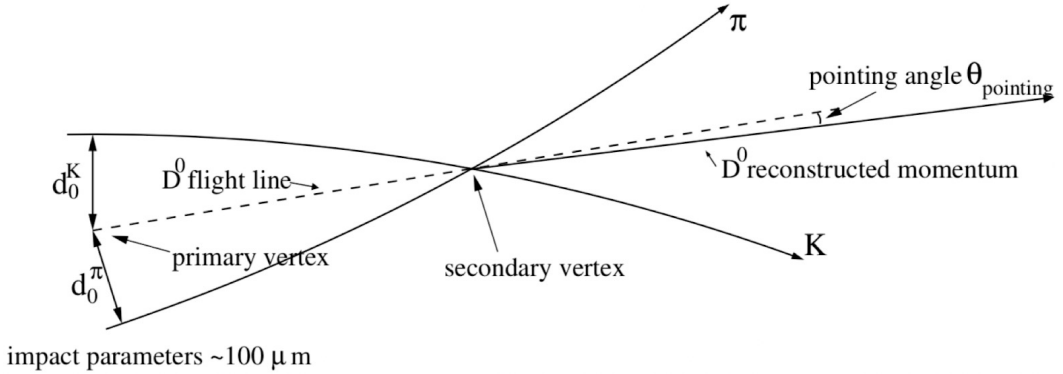
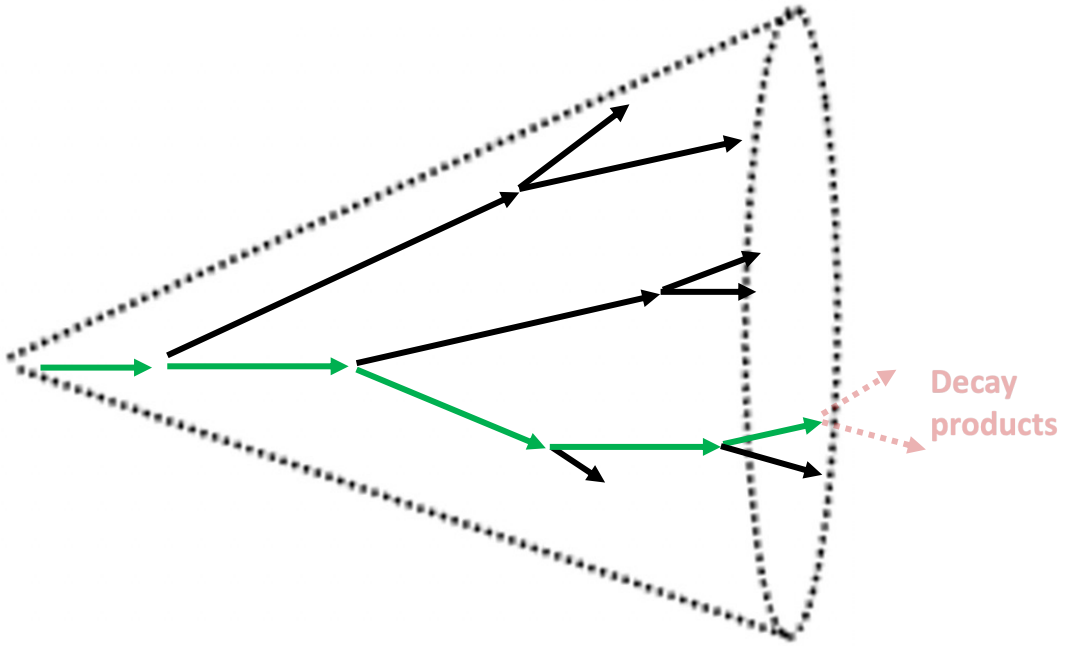
At each vertex follow the branch that contains the heavy-flavour hadron





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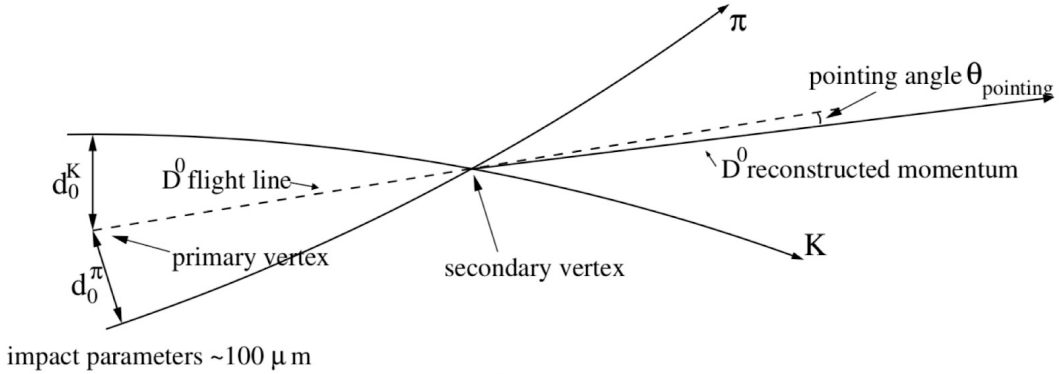
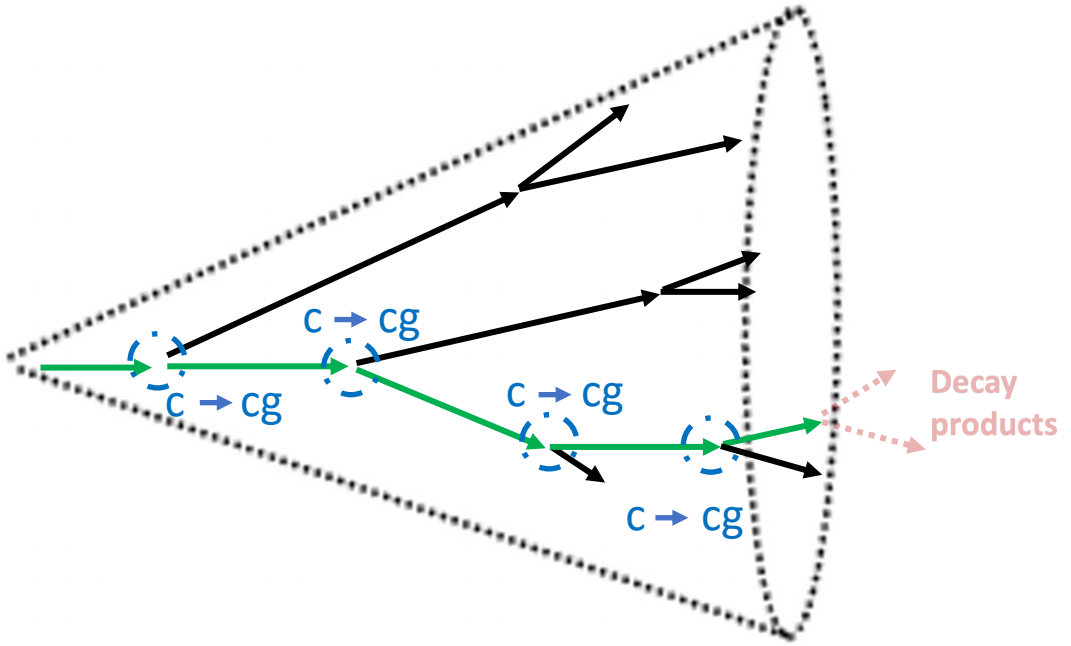
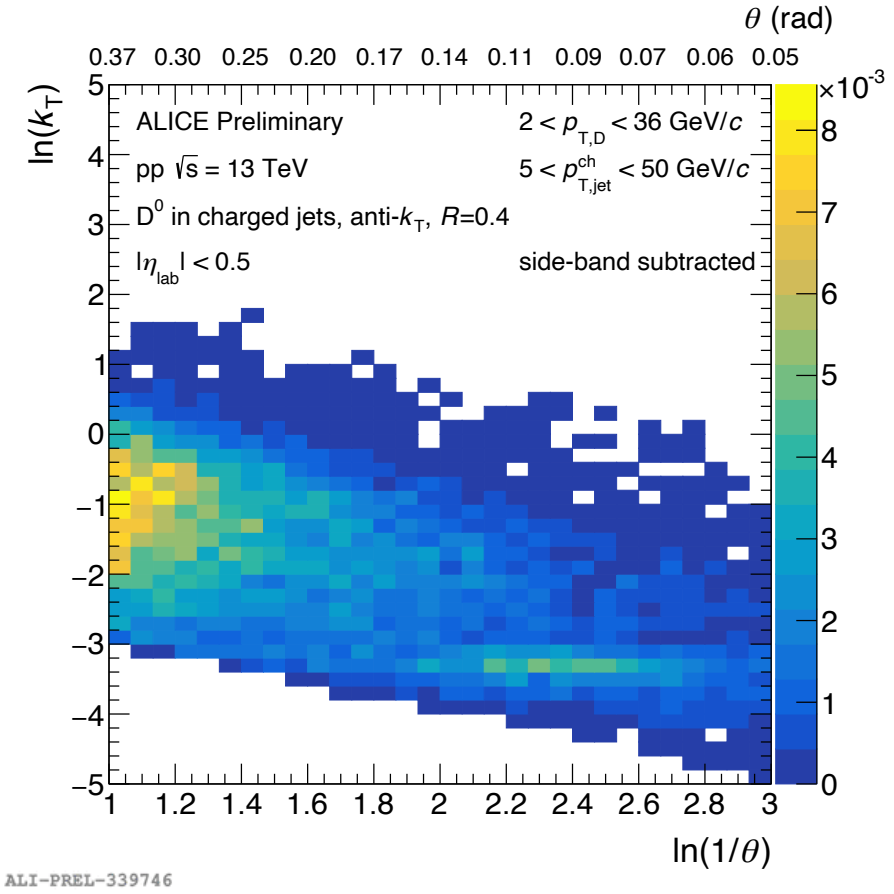




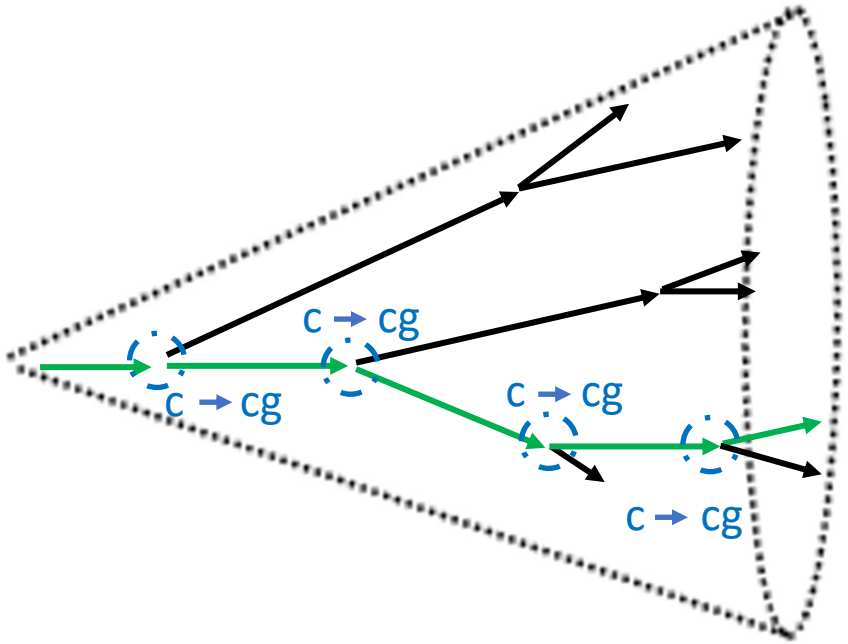
Measuring the Lund plane of c->cg emissions

Lund plane of c -> cg emissions



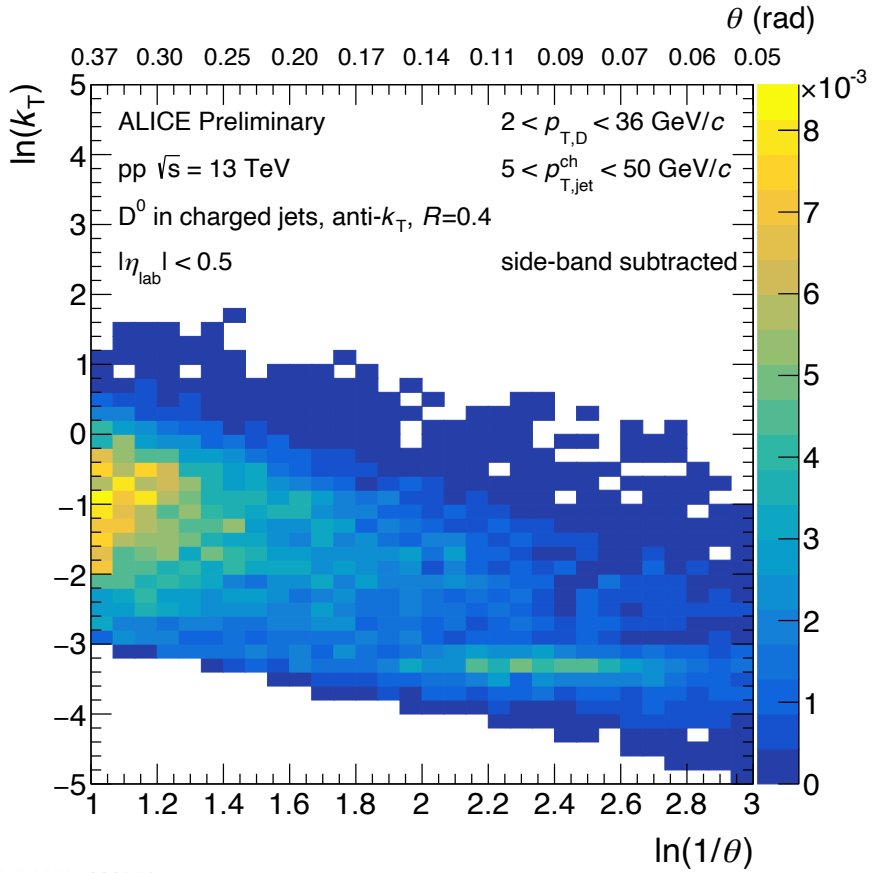
Measurement of the first flavour controlled Lund plane using jets tagged with a D^0-meson in pp collisions

Populated with all c->cg splittings in the jet



Accessing key features of QCD flavour

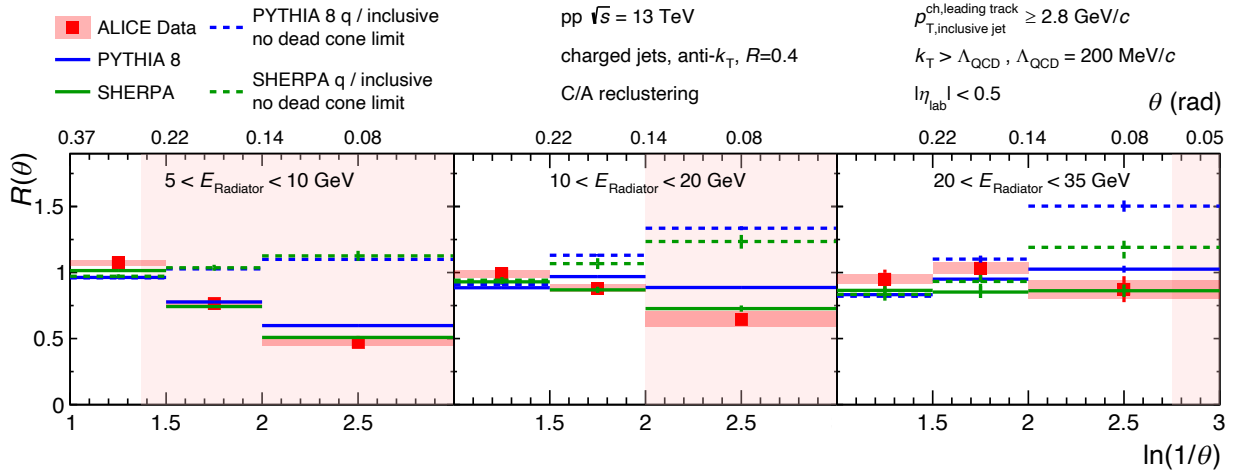
Lund plane of c -> cg emissions



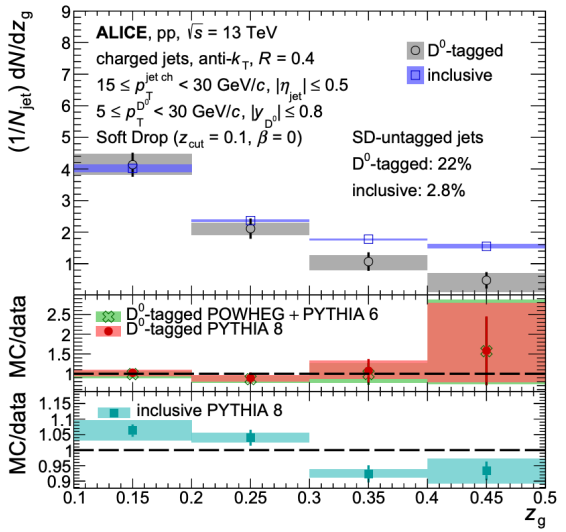
Accessing the dynamics of QCD flavour along the parton shower

Observation of the QCD dead cone

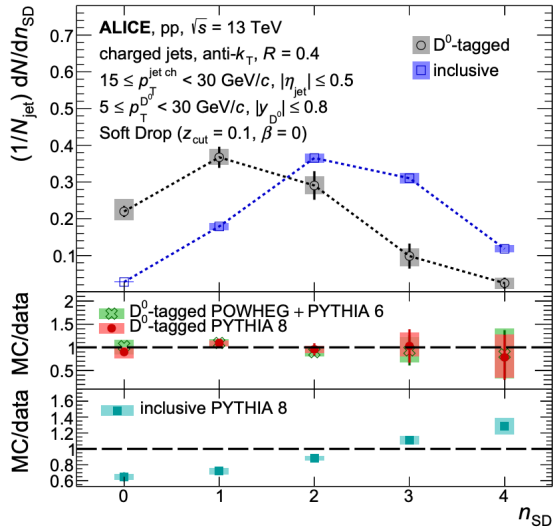
Nature 605 (2022) 440-446



Groomed momentum sharing fraction of the first splitting

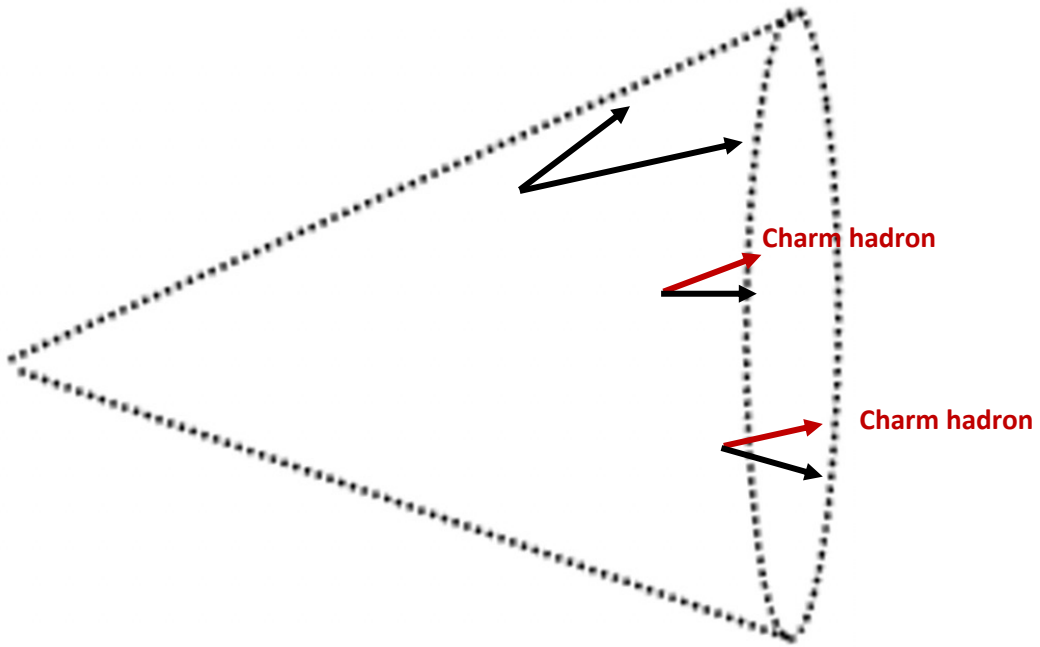


Number of Soft Dropped splittings along the charm-quark evolution



arXiv:2208.04857

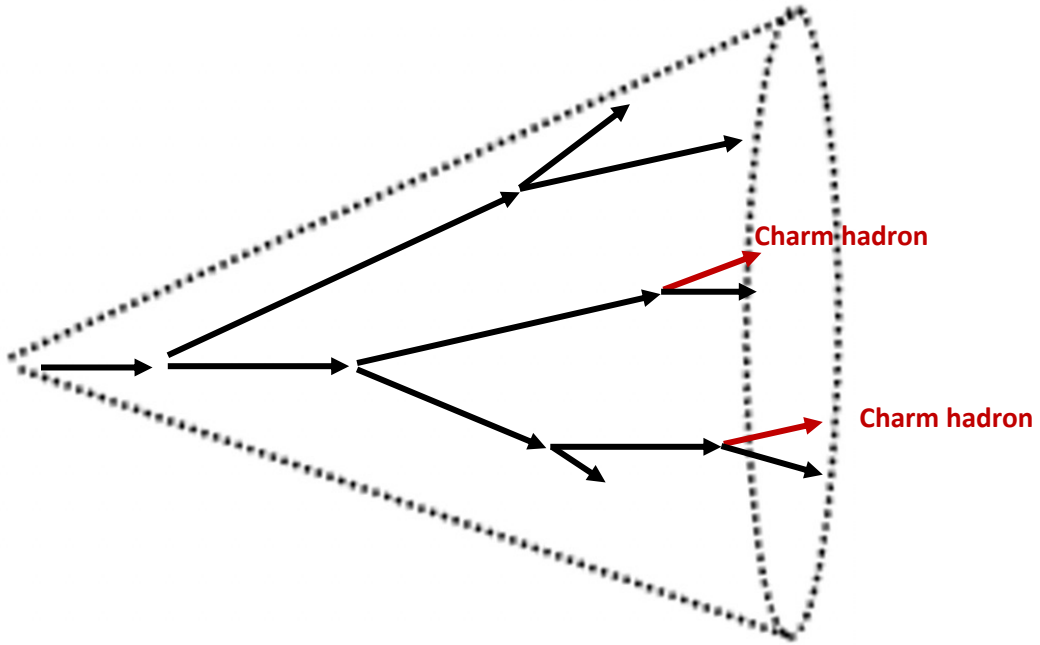
Accessing g->QQ splittings



Methodology

A jet containing two heavy-flavour hadrons is tagged

Accessing g->QQ splittings



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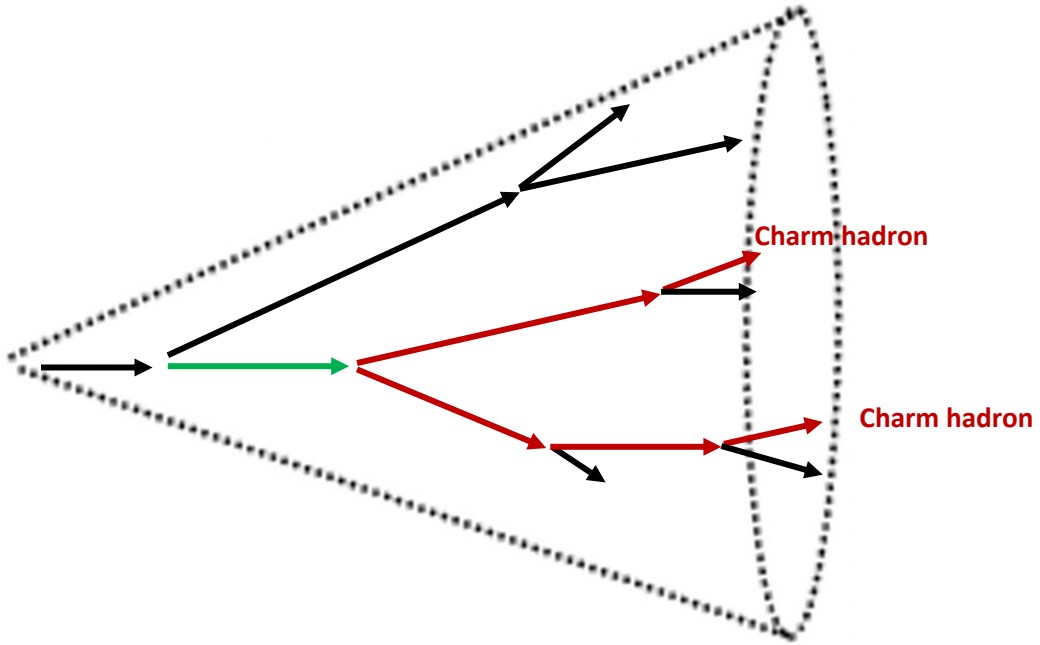

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Trace the heavy-flavour hadrons until the deepest splitting containing both is found

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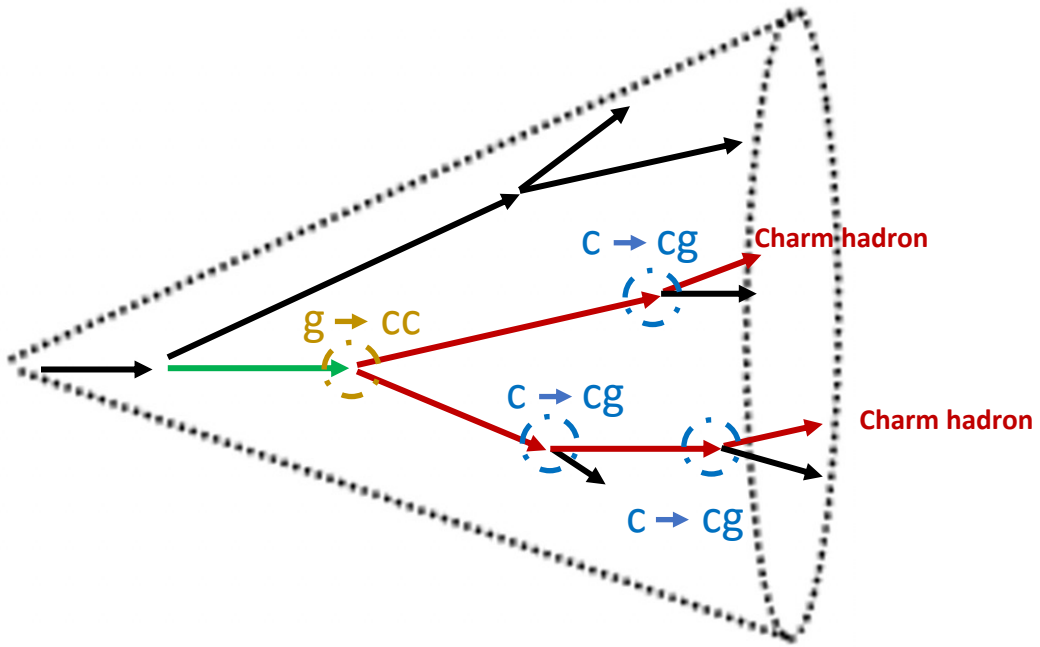

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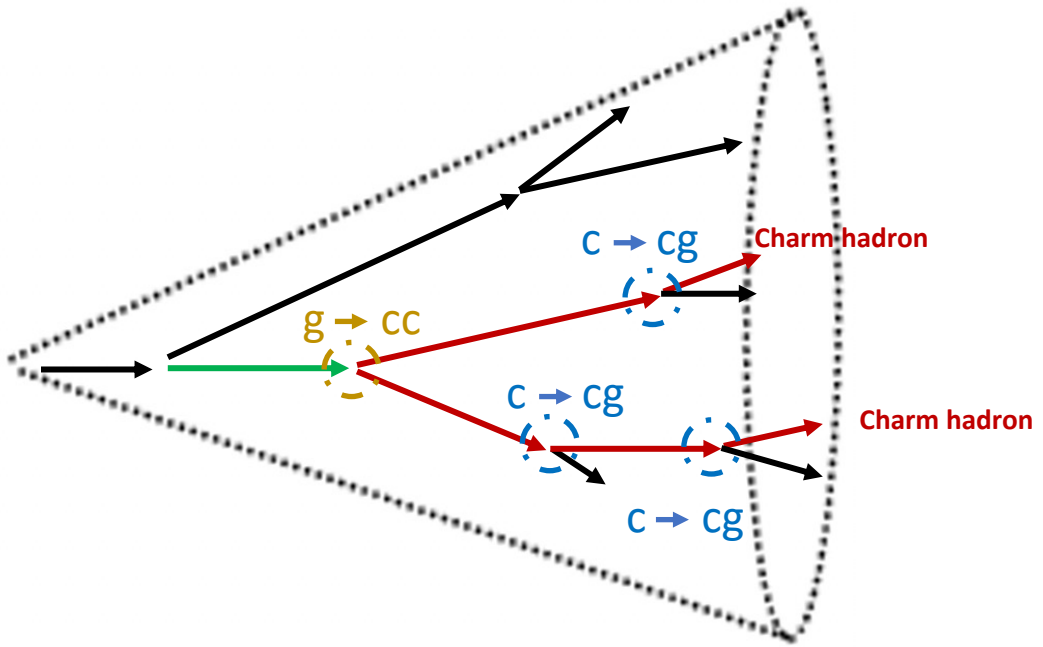

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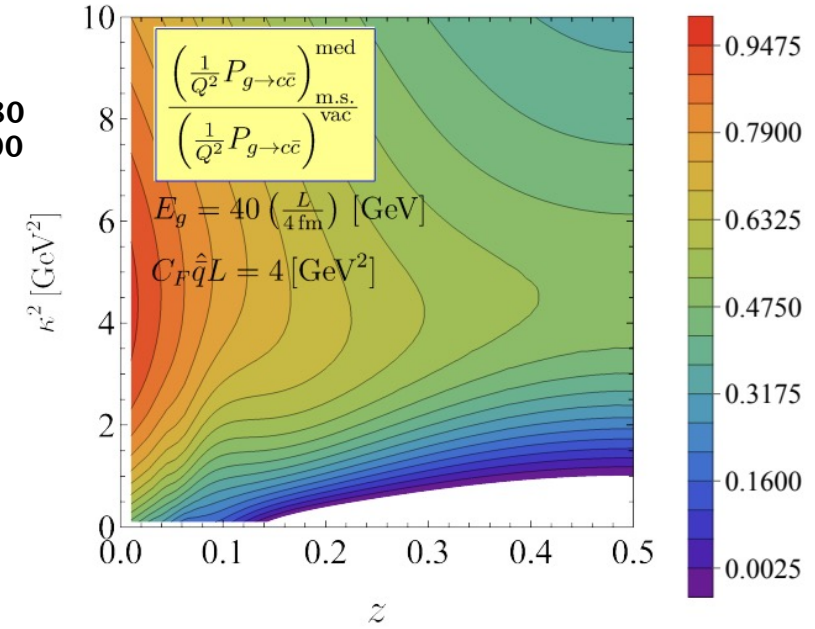
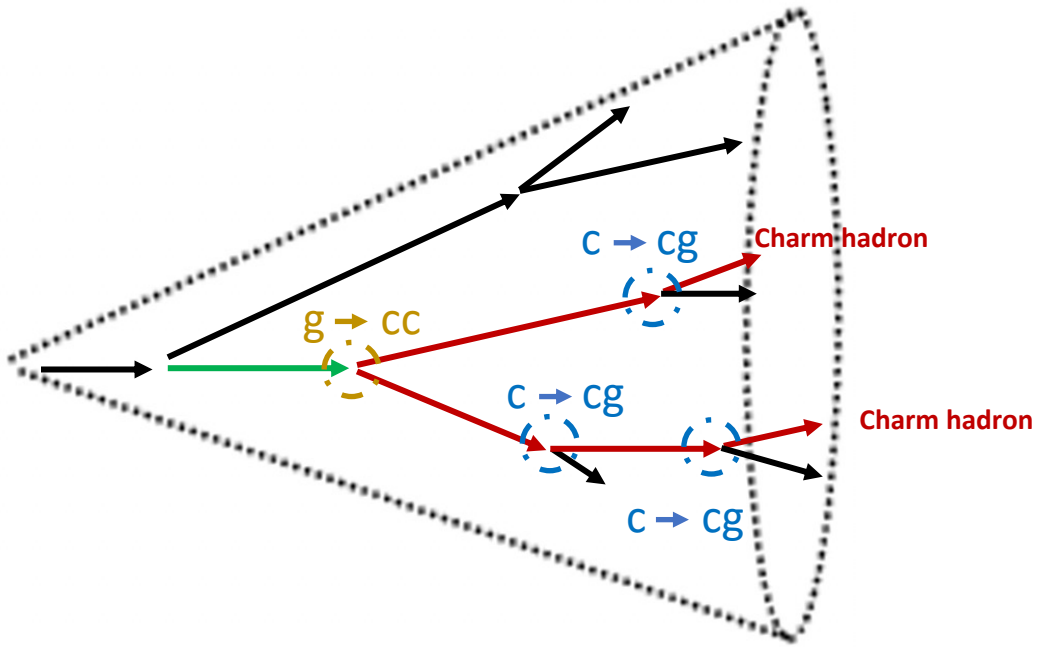
JHEP 01(2023)080
arXiv: 2209.13600



Controlled access to features of the g->QQ splitting

Next step of precision in accessing medium modification of splittings

Accessing g->QQ splittings



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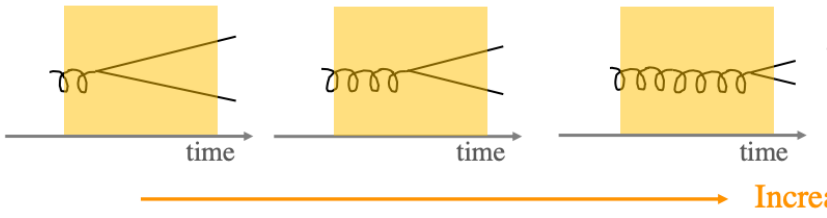

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Controlled access to features of the g->QQ splitting

Next step of precision in accessing medium modification of splittings

Clean signatures of broadening and time dependence can be obtained by knowing the flavour of the splitting

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

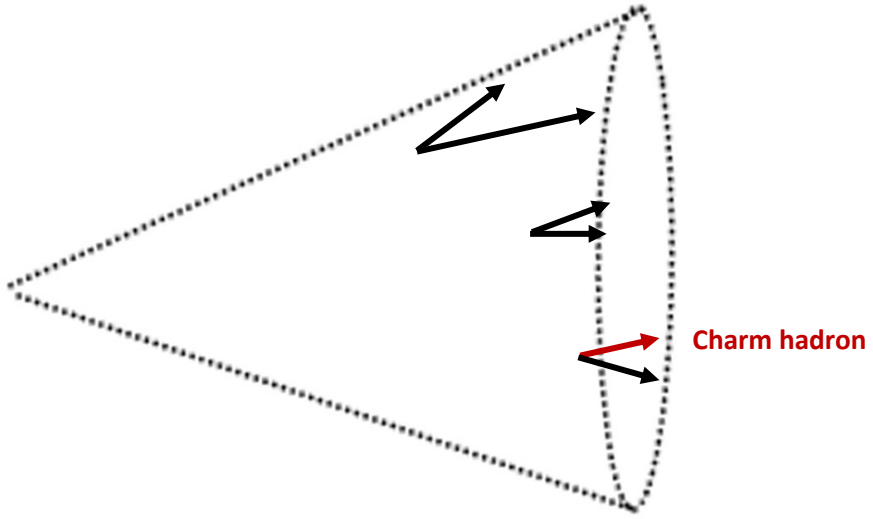
Significant statistical penalties due to small branching fractions and reconstruction efficiencies

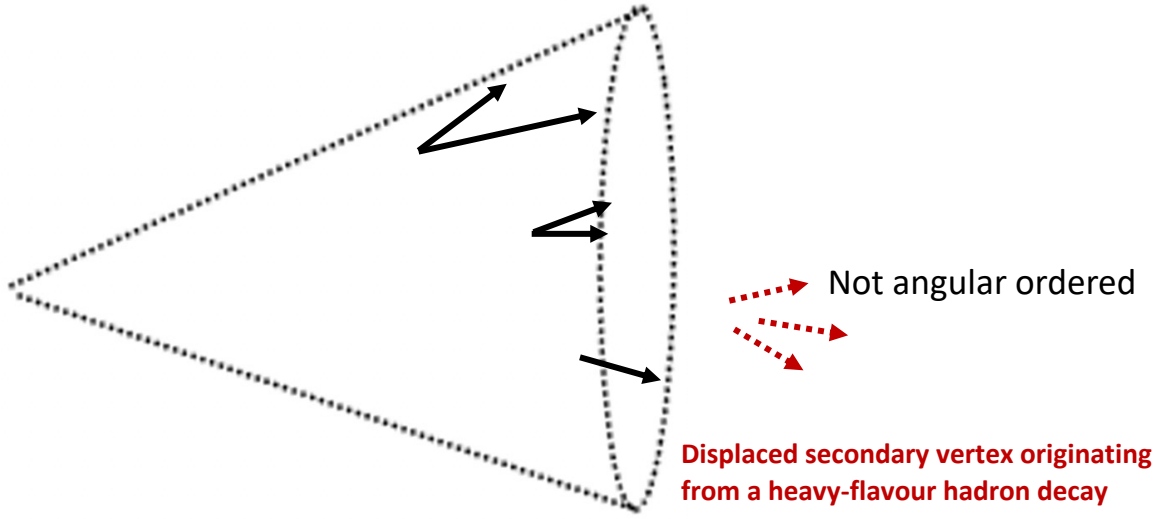
Jets with a displaced secondary vertex

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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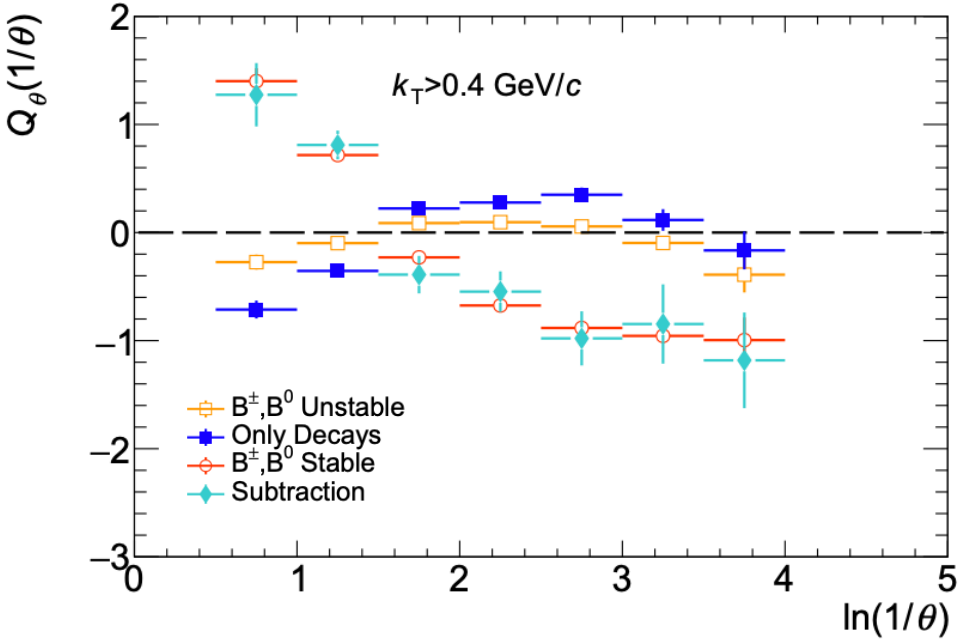


Substructure measurements with full heavy-flavour hadrons are much more sensitive to flavour effects

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

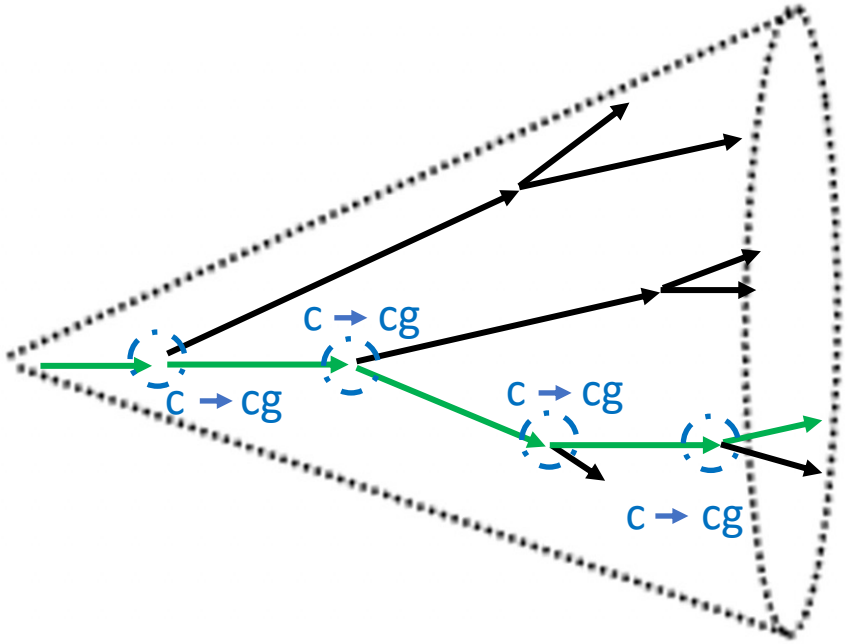
The picture presented so far assumes the heavy-flavour jet was initiated by a heavy-quark

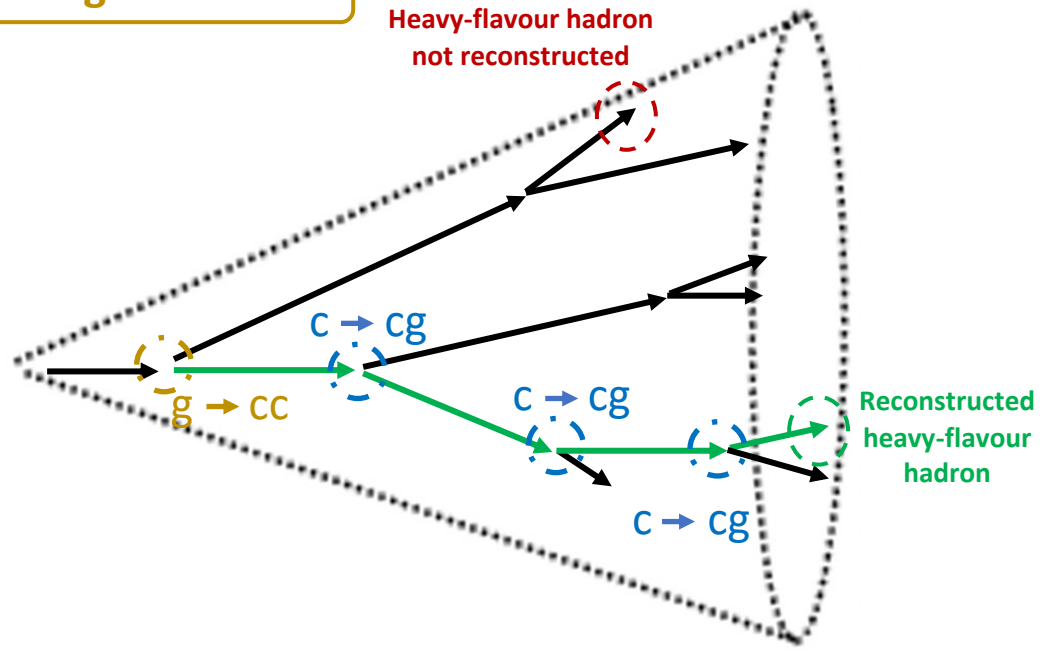
g->QQ processes or initial state radiation can reduce control over splitting flavours

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



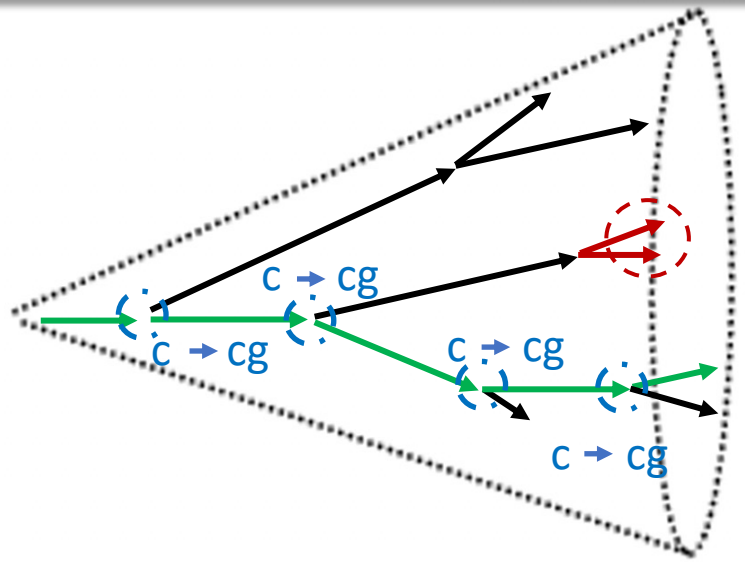


Challenges of heavy-flavour tracing : deep into the shower

Increased non-perturbative effects

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

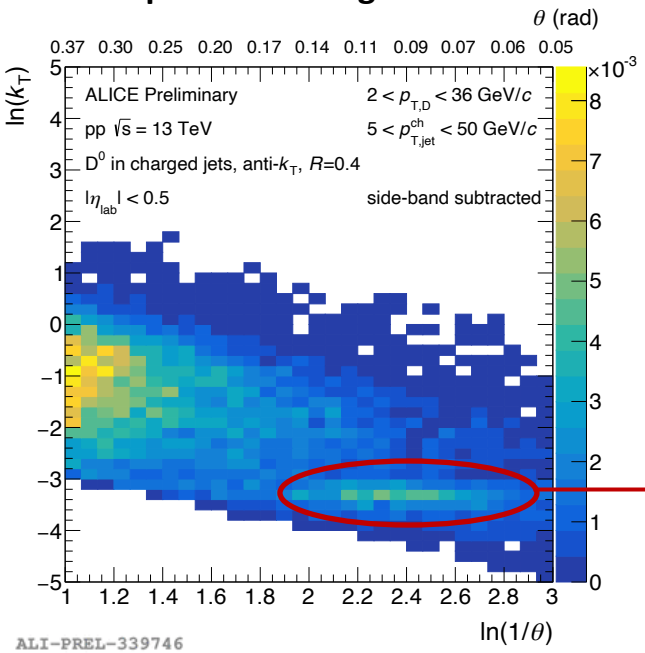
Strict cuts such as k_T required



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 $D^* \to D^0\pi$ Removed with a k_T cut

Challenges of heavy-flavour tracing : deep into the shower

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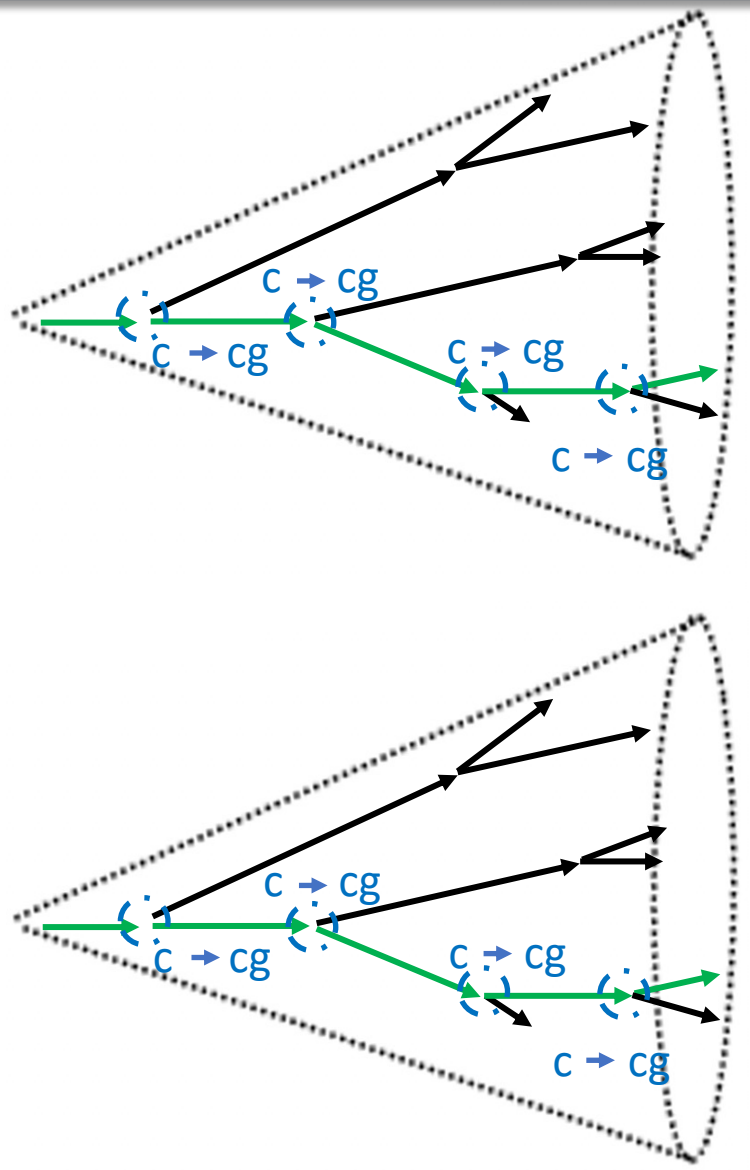
Greater impact of mistagging

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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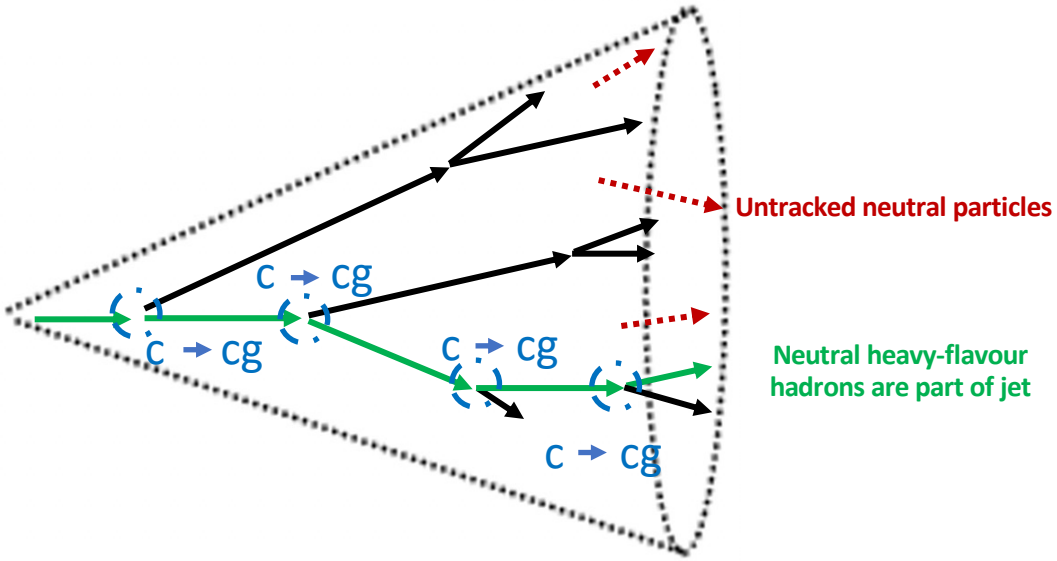
Impact of neutral component

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



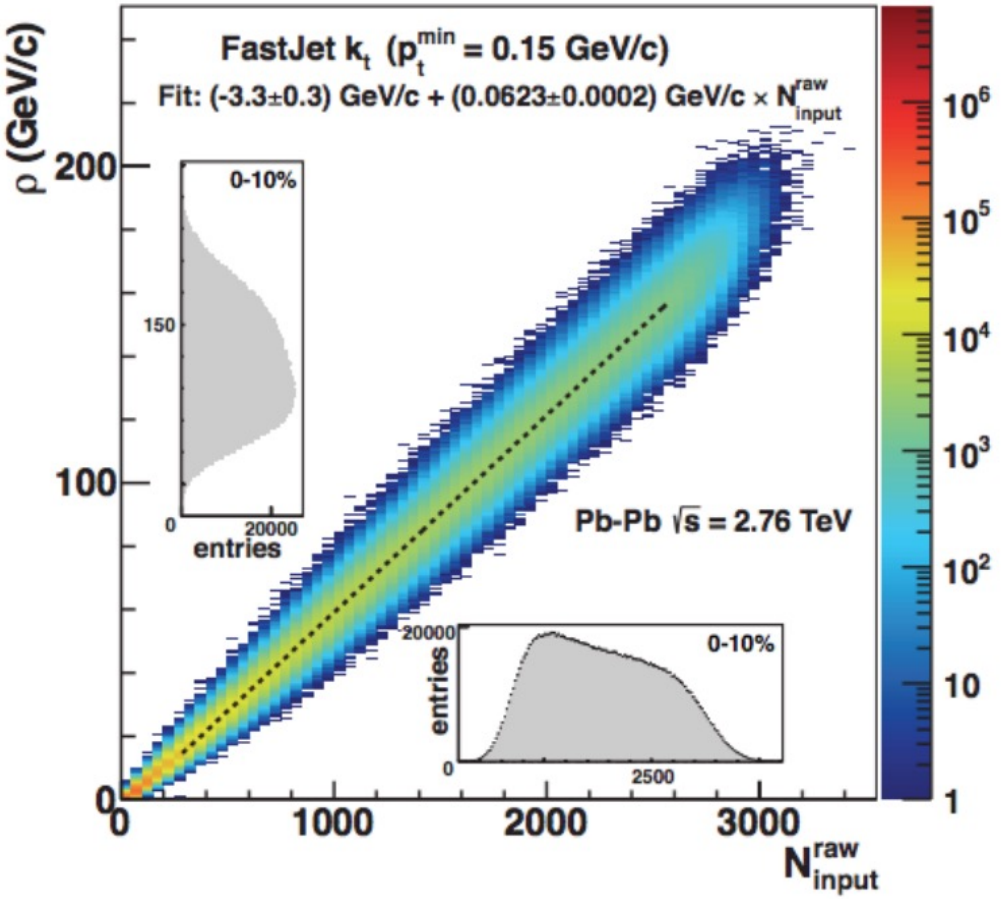
Challenges of heavy-flavour tracing : HI background

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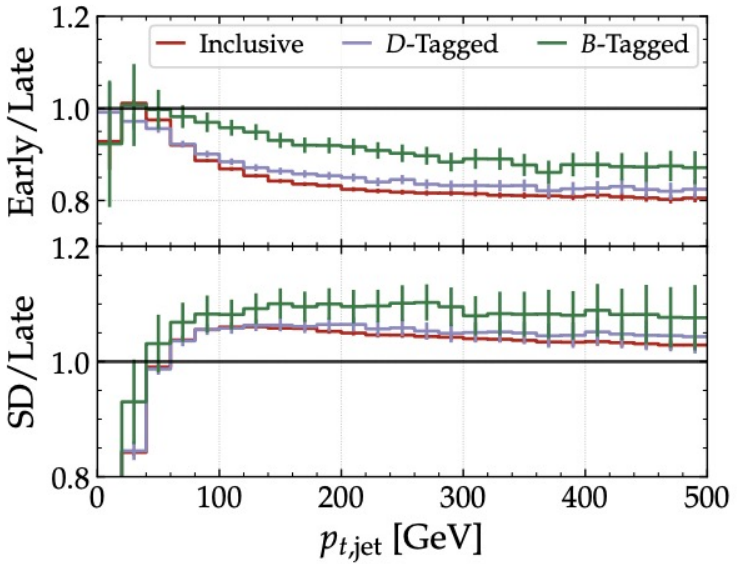
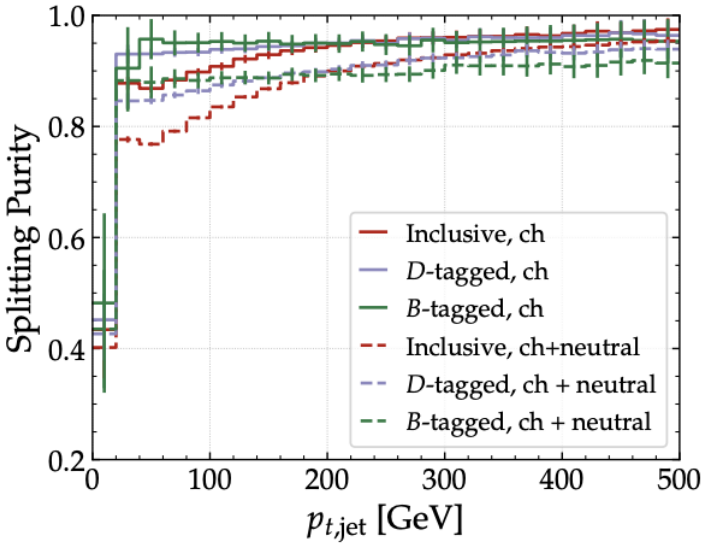
Studies show that the combination of late splittings with grooming selections have a higher resilience to the background

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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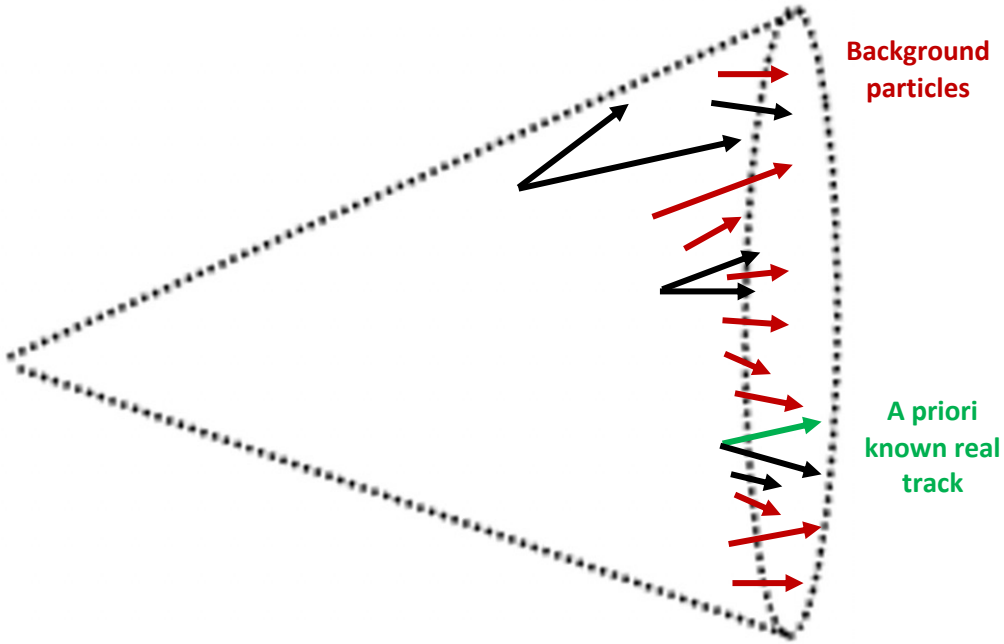
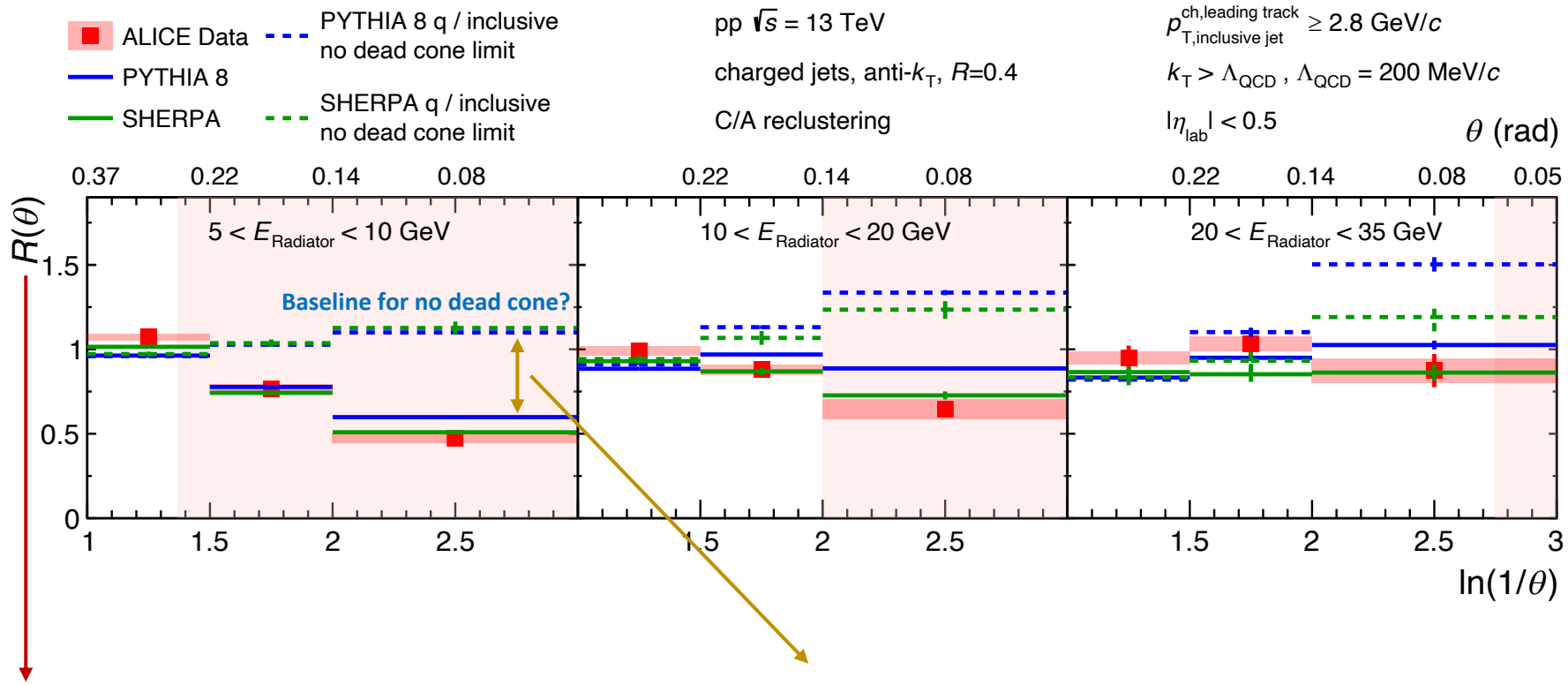
Heavy-flavour hadrons are guaranteed to be non-background

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



Outlook : using heavy-flavour to separate flavour effects

Observation of the QCD dead cone



angular distribution of charm emissions

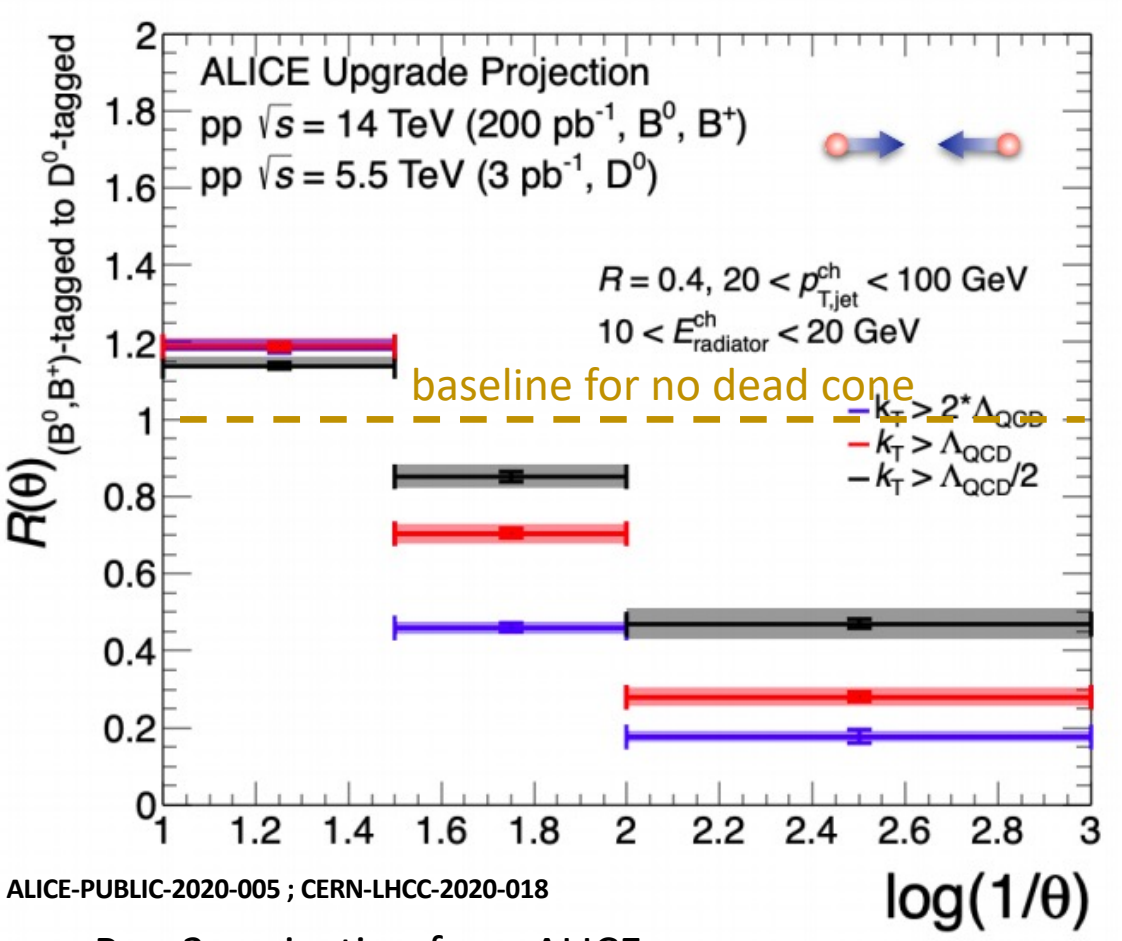
angular distribution of gluon + light quark emissions

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

Outlook : searching for medium effects in HI collisions

Heavy-flavour tracing measurements should become accessible in Run 3 at the LHC

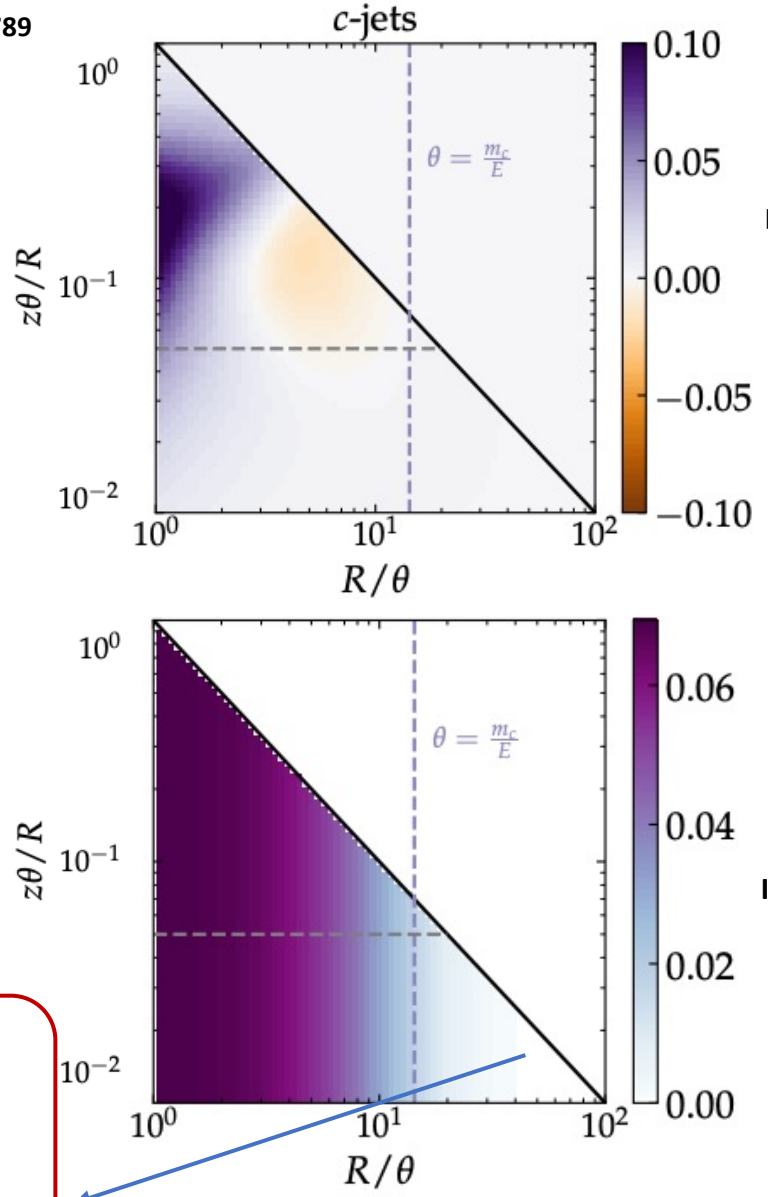
Exciting prospect to study flavour dependence of quenching effects

Flavour dependent splittings are the building blocks of theoretical calculations of medium-induced modifications

Bridge the gap between theoretical calculations and experimental results

arXiv: 2211.11789

See next talk by Leticia!

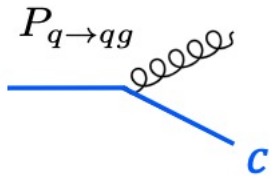


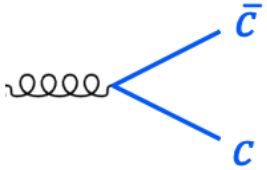
How do medium induced emissions interplay with the dead-cone region?

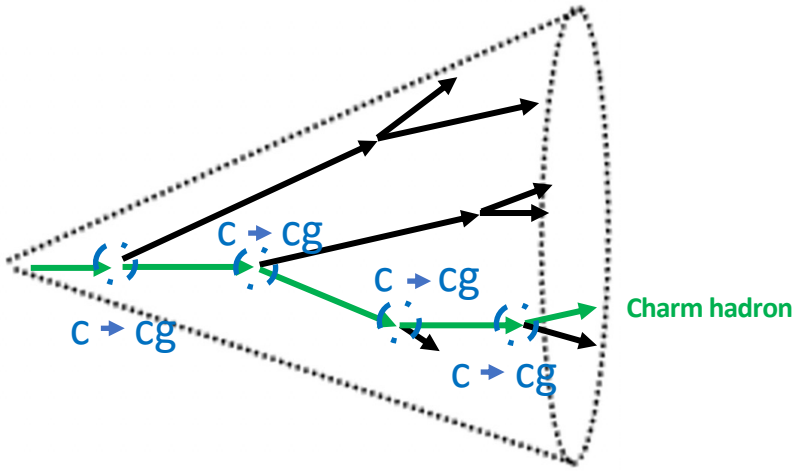
Opportunity to isolate medium emissions?

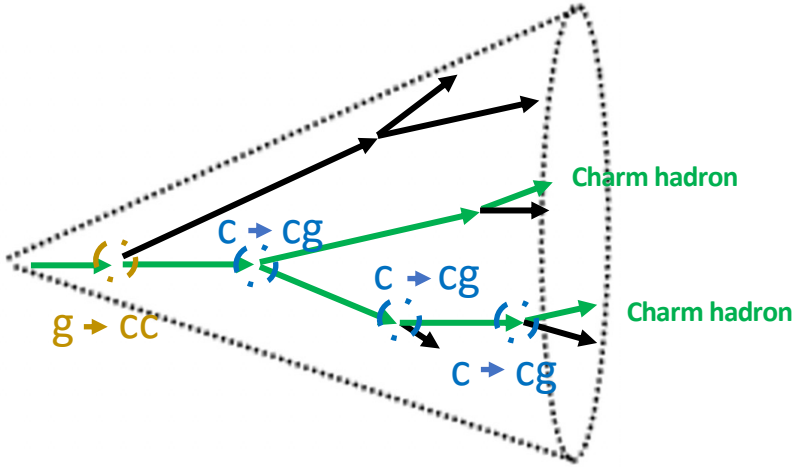
Outlook : going beyond heavy-flavour splittings

Using heavy-flavour tracing to access quark-initiated splittings









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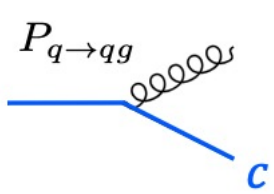
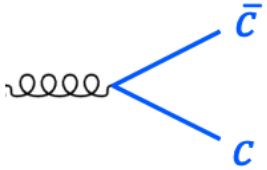
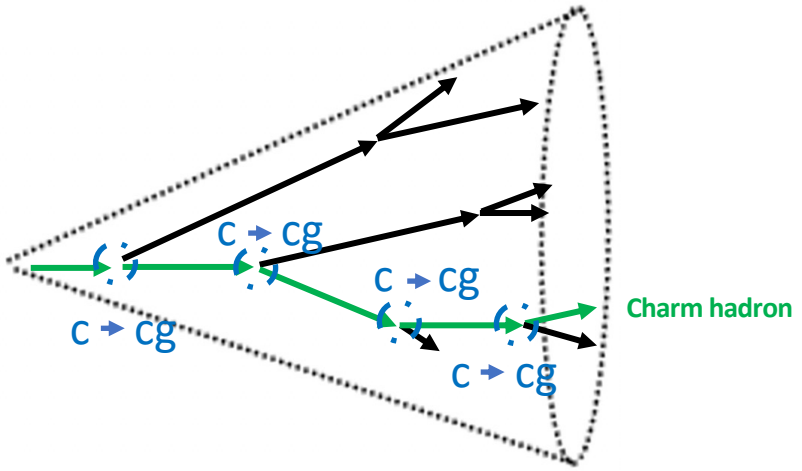
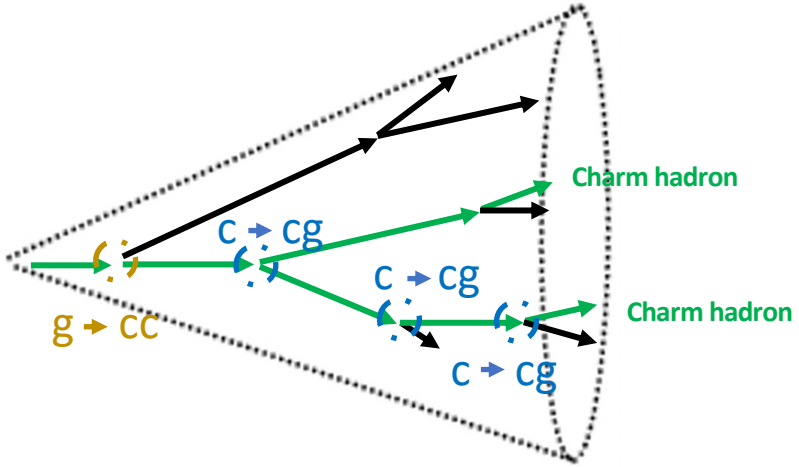




What about the remaining QCD splitting?





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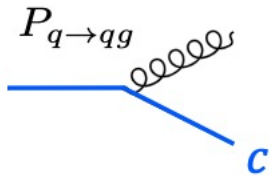

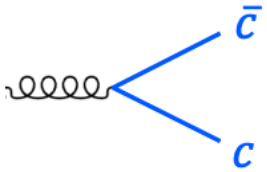

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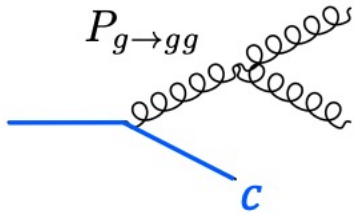
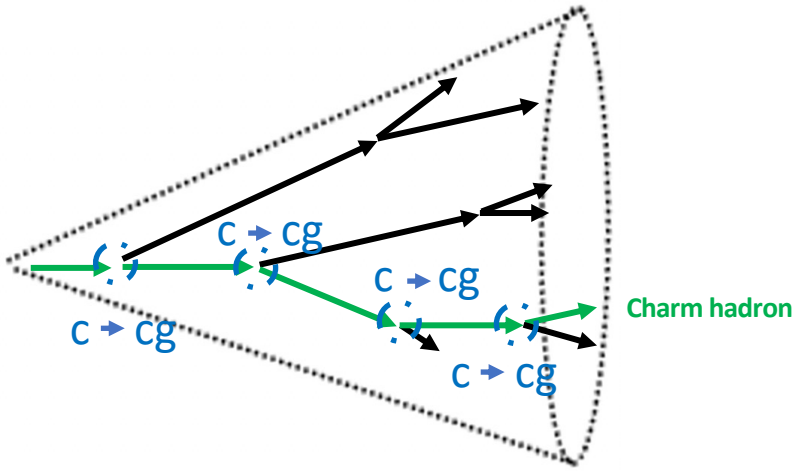
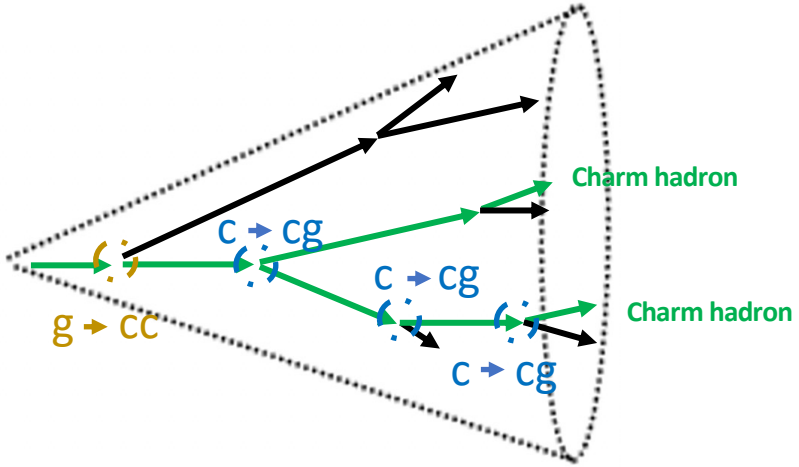
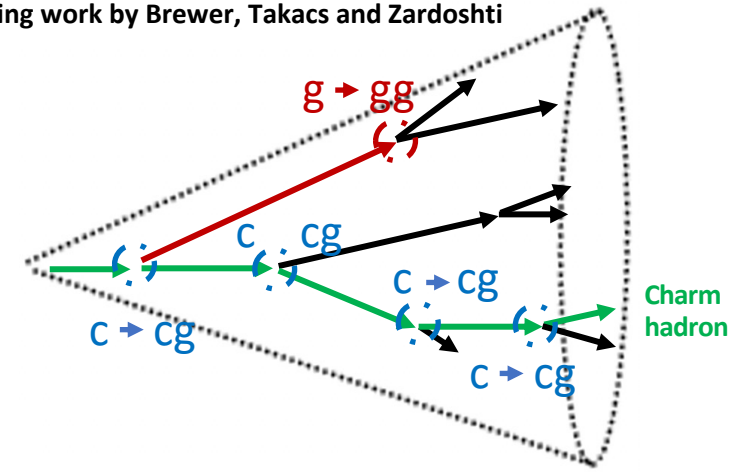






Ongoing work by Brewer, Takacs and Zardoshti



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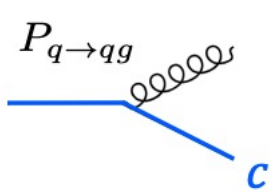

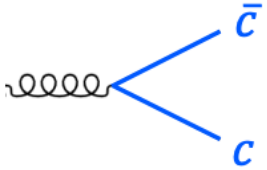

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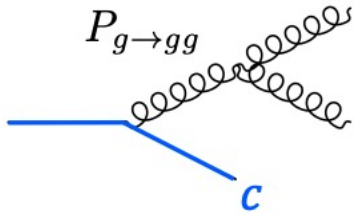
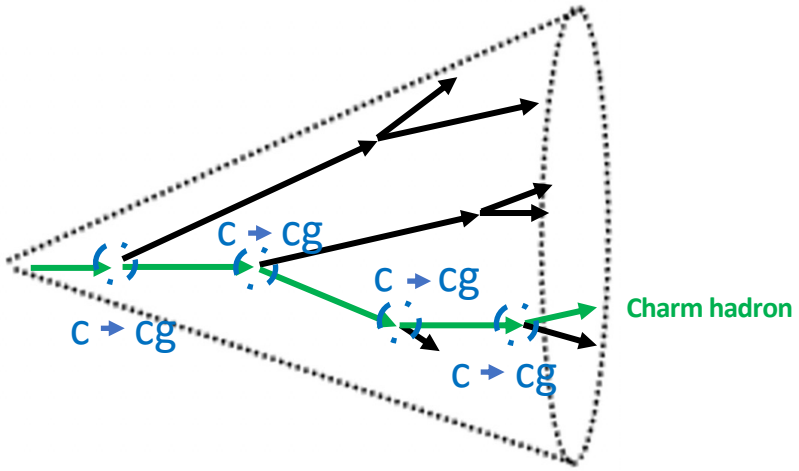
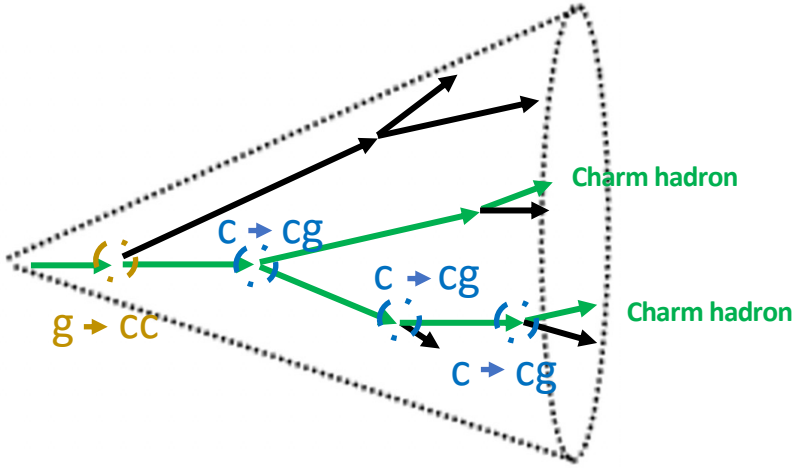
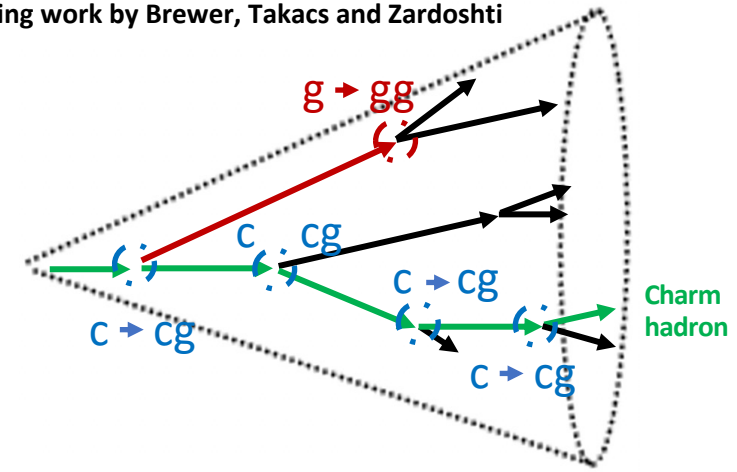






Ongoing work by Brewer, Takacs and Zardoshti



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

Summary

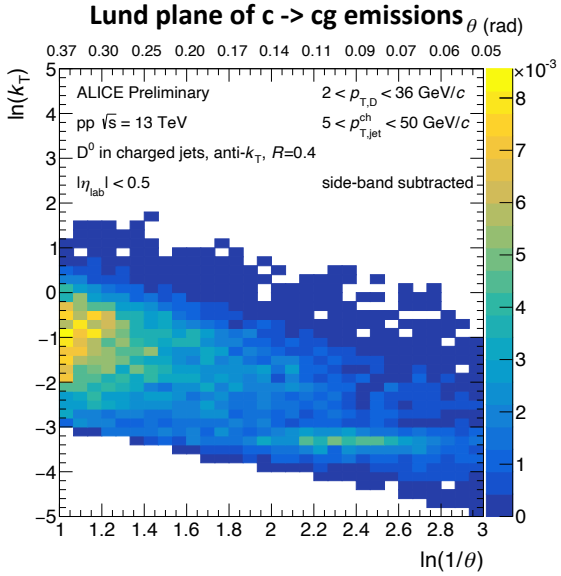
Heavy-flavour tracing is a powerful tool to take the next step in precision understanding of parton showers

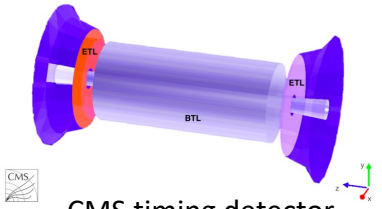
Heavy-flavour tracing can provide access to all three types of QCD splittings in pp and HI collisions

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

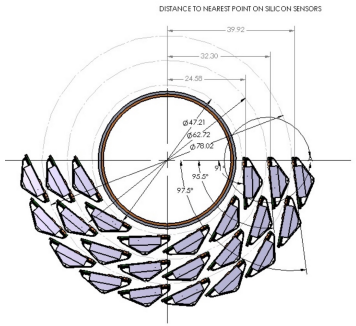
Many challenges accompanied by many opportunities

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

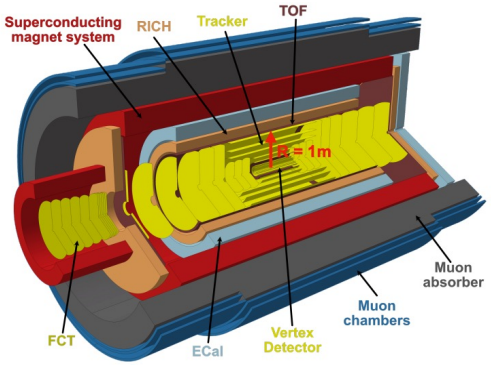




CMS timing detector



sPHENIX MVTX detector



ALICE 3