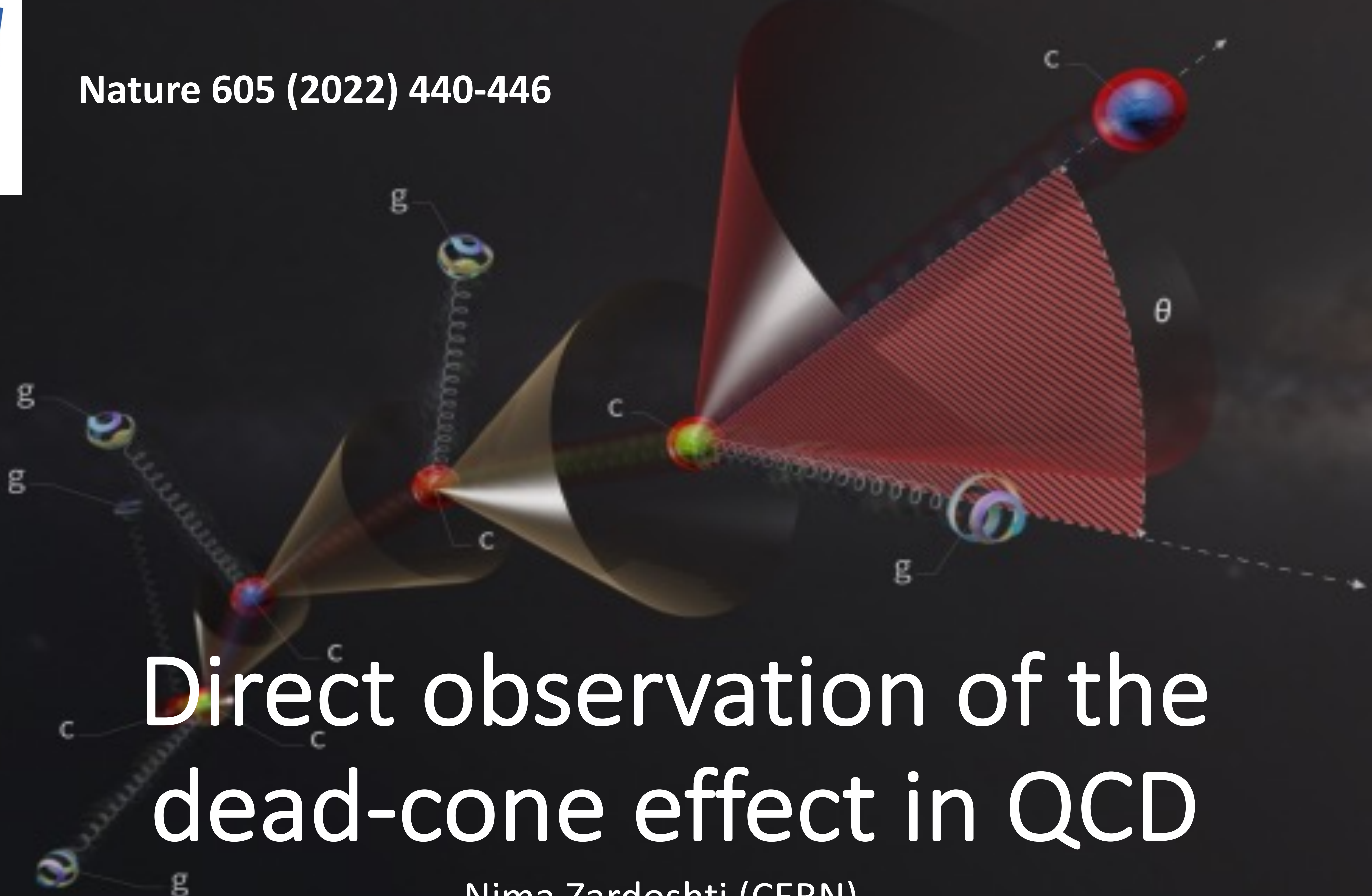
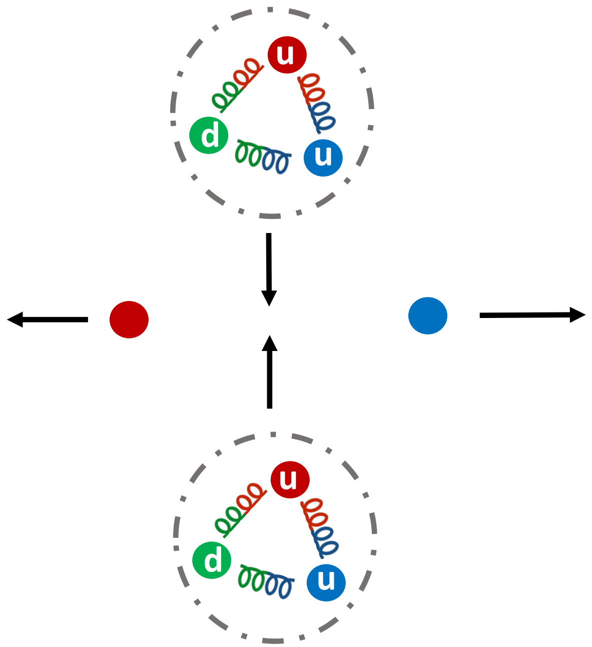
Nature 605 (2022) 440-446



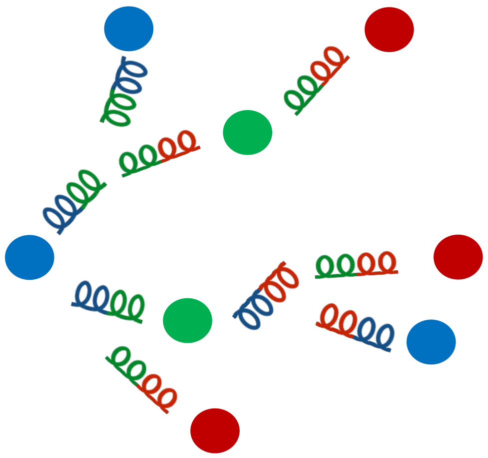
Direct observation of the dead-cone effect in QCD

Nima Zardoshti (CERN)

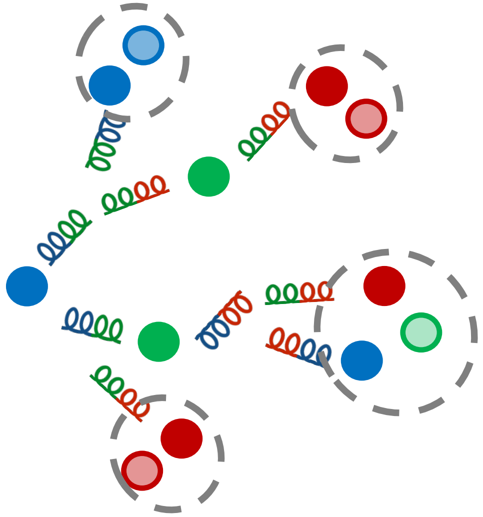
Factorising a pp collision



Initial hard scatter

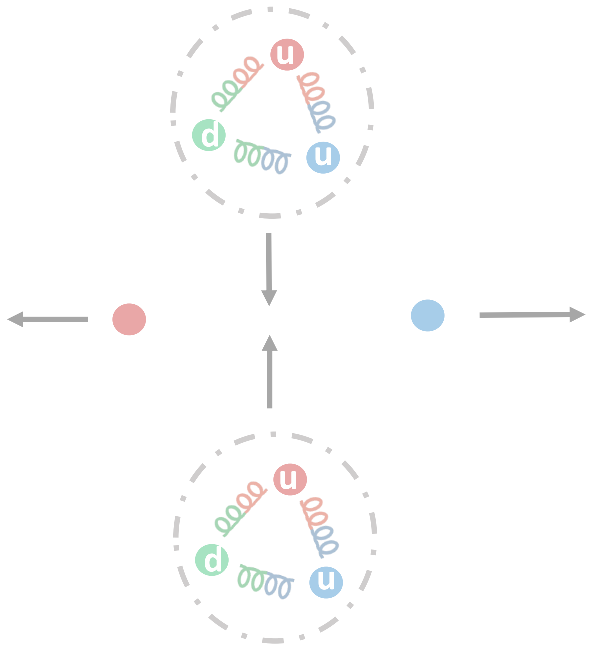


Shower evolution

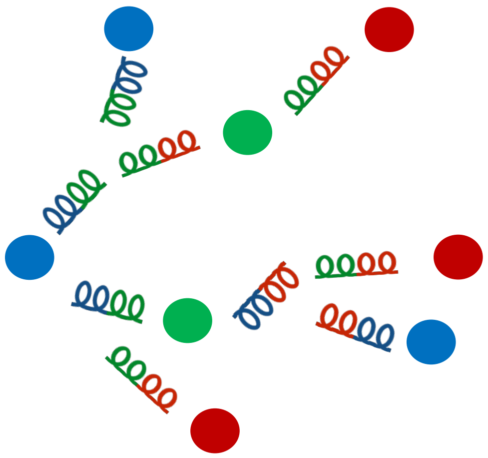


Hadronisation

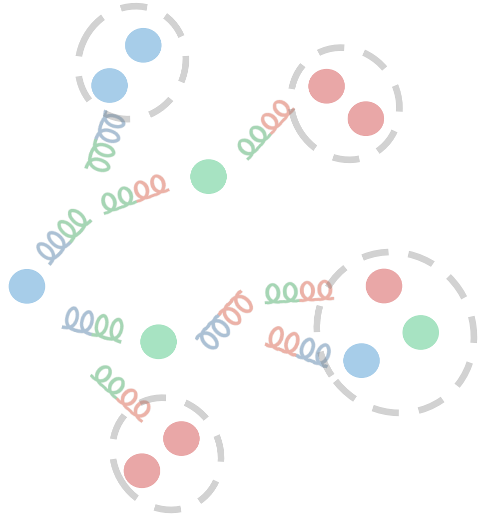
Factorising a pp collision



Initial hard scatter



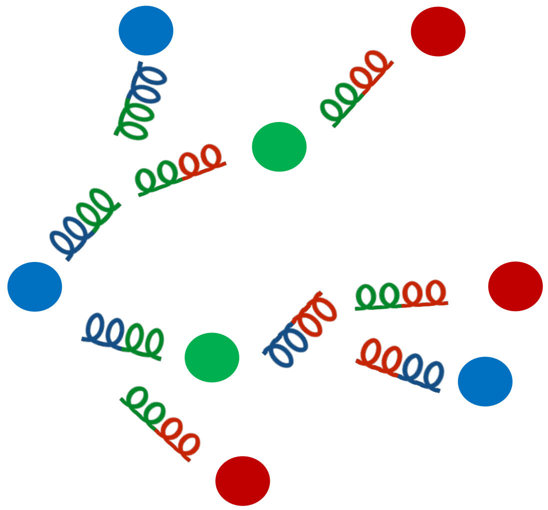
Shower evolution



Hadronisation

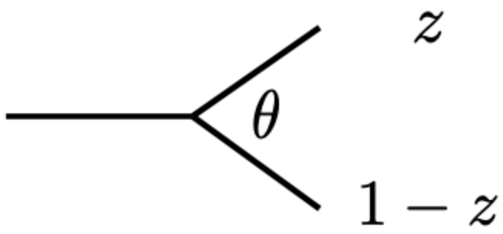
A wealth of partonic interactions to explore QCD
How can we access this region from final state hadrons?

The parton shower

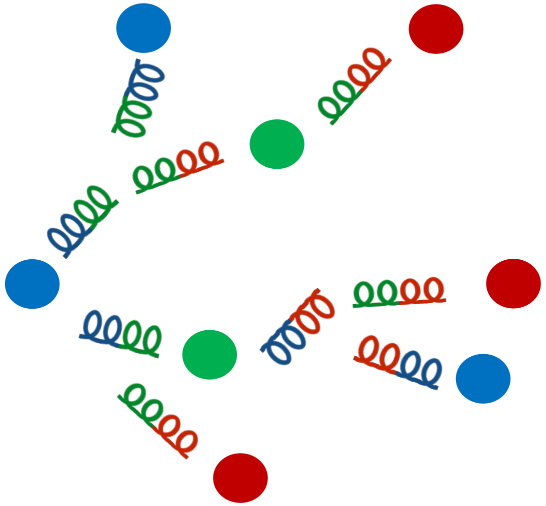


model the underlying QCD process

as a succession of 1 ⟶ 2 splittings

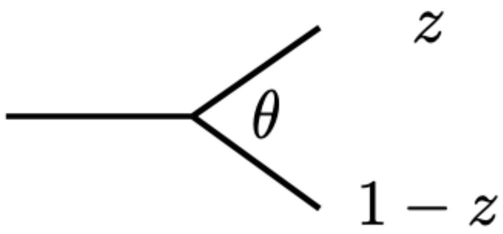


The parton shower



model the underlying QCD process

as a succession of $1 \longrightarrow 2$ splittings



Select an evolution scale to track the shower (e.g virtuality)

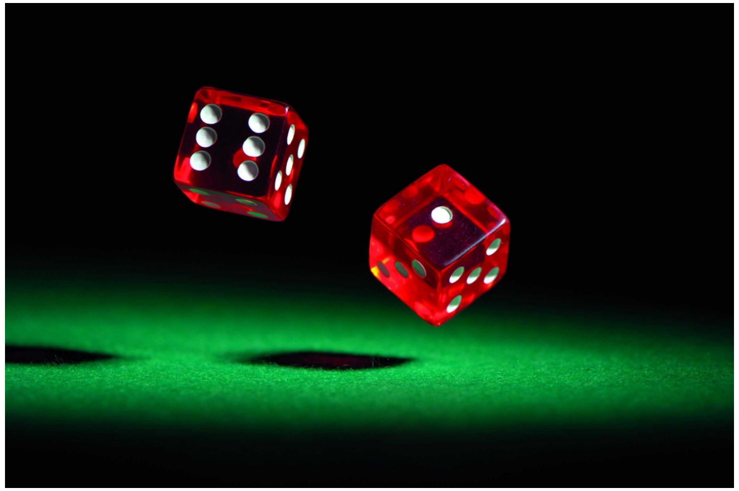
decrease the evolution scale with some probability by inducing a splitting

Check scale

split again

terminate shower

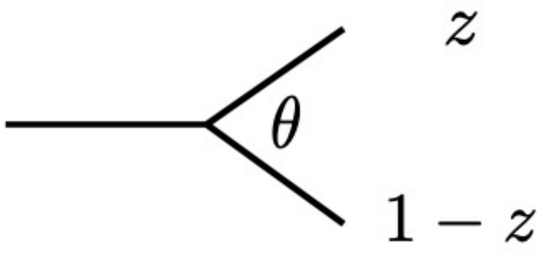
Splitting functions



Determining the splitting probabilities is a key ingredient of constructing the shower

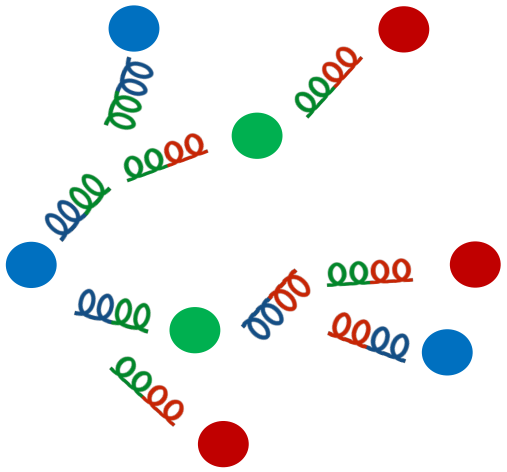
Altarelli-Parisi splitting functions G. Altarelli, G. Parisi, Nucl. Physics. B126 (1997) 298

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



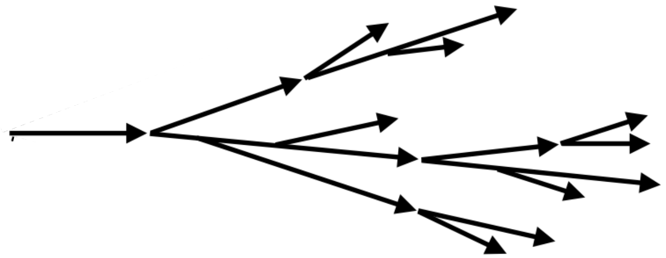
Flavour dependence in QCD

The pattern of the QCD parton shower exhibits a flavour dependence



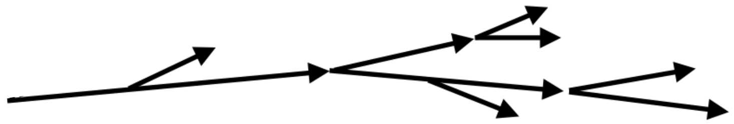
Casimir colour factors $\frac{C_{\mathrm{A}}}{C_{\mathrm{F}}} = \frac{9}{4}$

$$P_{g\rightarrow gg} = 2C_A \frac{(1-z(1-z))^2}{z(1-z)} \qquad P_{q\rightarrow qg} = C_F \frac{1+(1-z)^2}{z}$$



Gluon-initiated shower

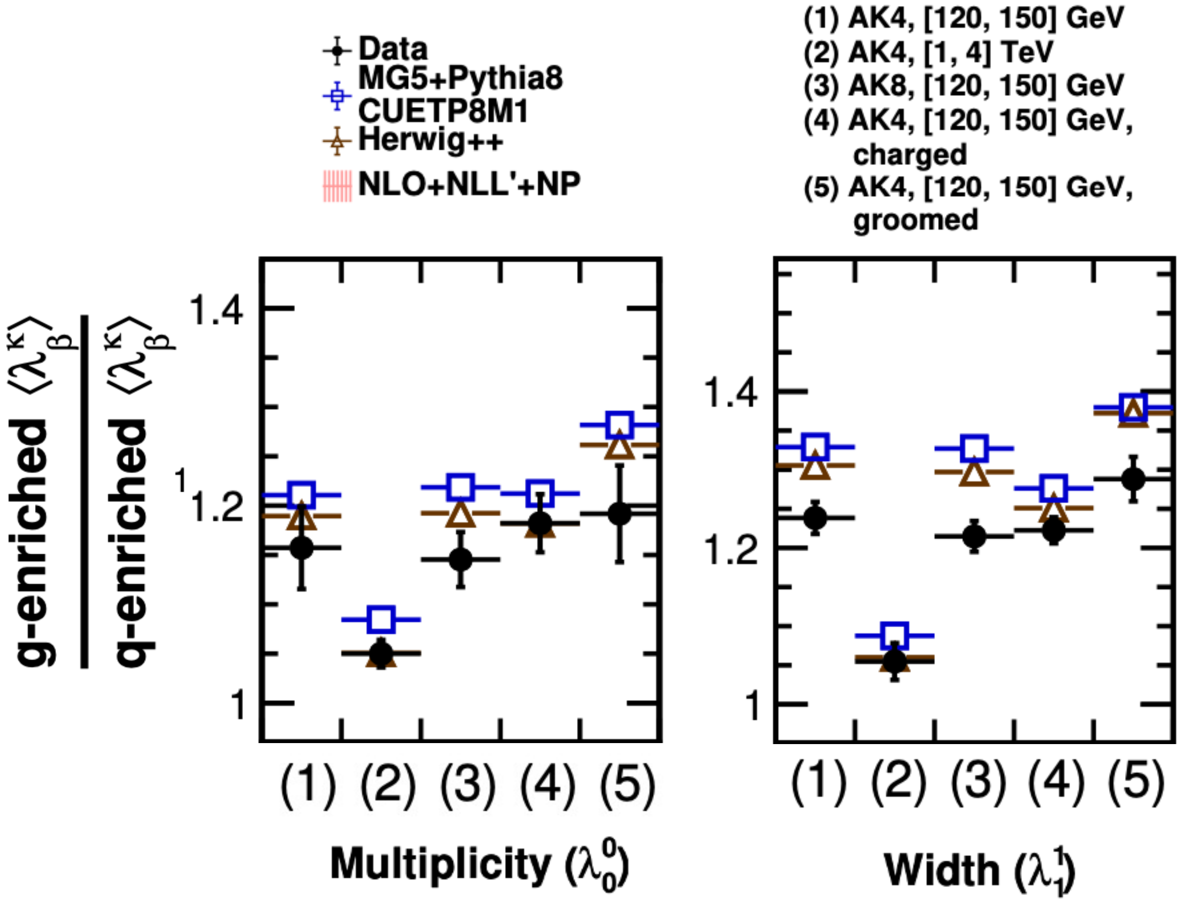
Broader shower profile
Higher number of emissions



Quark-initiated shower

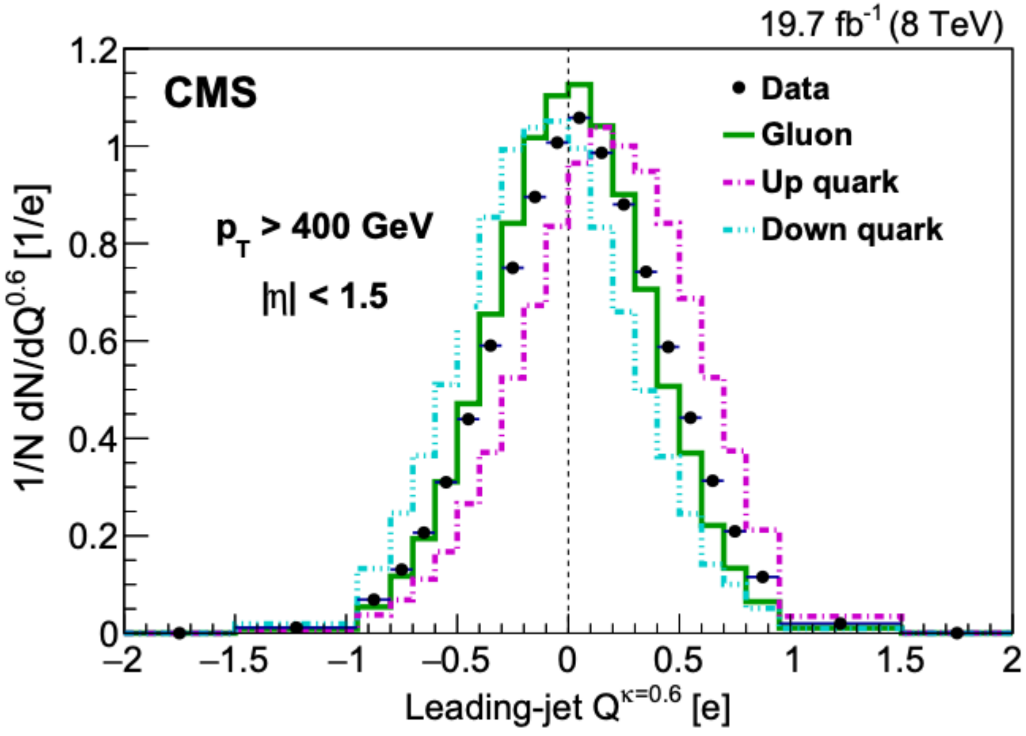
narrower shower profile
Fewer emissions in the shower

Flavour dependence in QCD



CMS Collaboration, JHEP 01 (2022) 188

Measurements of the shower profile of quark and gluon enriched showers

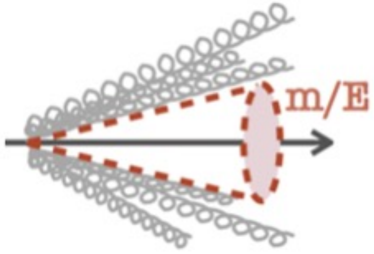


CMS Collaboration, JHEP 10 (2017) 131

Measurements constraining the different shower properties of quarks and gluons is an active area of interest
Separation of quark and gluon initiated showers is experimentally challenging

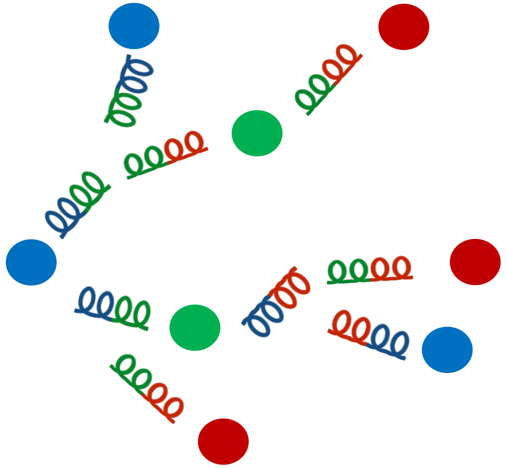
The dead-cone effect

The pattern of the QCD parton shower exhibits a flavour dependence

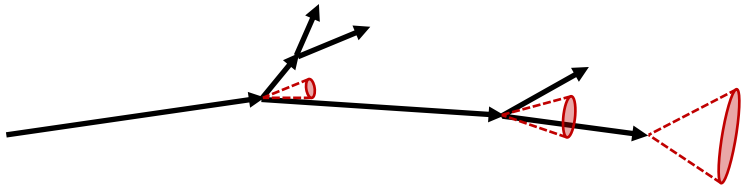


Angular region with size m_Q/E_Q within which emissions are suppressed

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



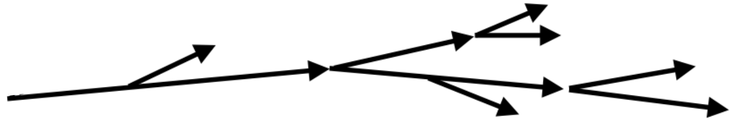
Heavy-quark-initiated shower



Suppression of small angle emissions
Harder fragmentation

$$P_{Q\rightarrow Qg} = C_F[\frac{1}{z} - 1 + \frac{z}{2} - \frac{z(1-z)m^2}{k_\perp^2 + z^2m^2}]$$

Light-quark-initiated shower

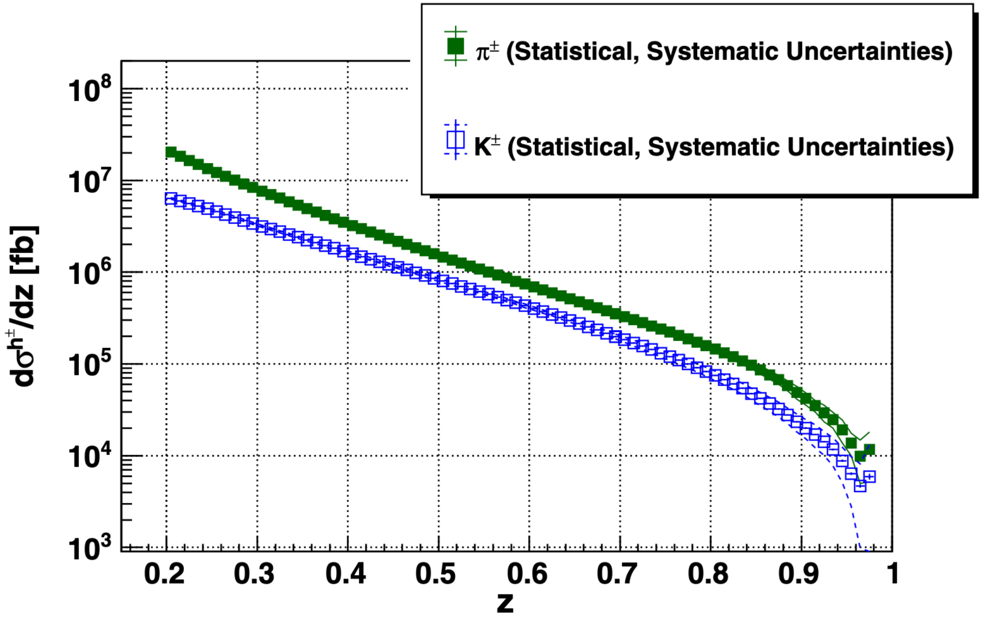


No small angle emission limit
Softer fragmentation

$$P_{q\rightarrow qg} = C_F\frac{1+(1-z)^2}{z}$$

Consequences of the dead-cone effect

Fragmentation into light hadrons

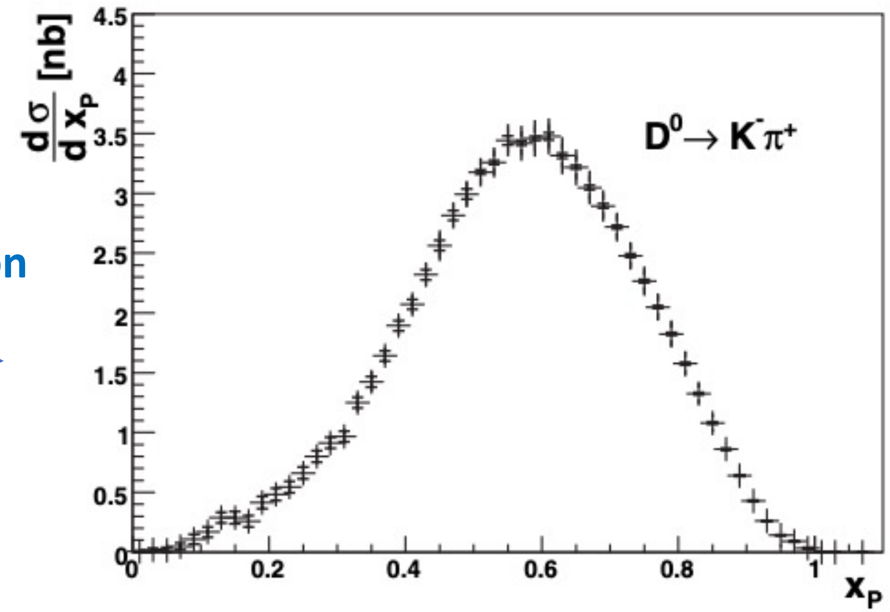


Belle Collaboration, Phys. Rev. Lett. 111, 062002

Hardening of the fragmentation for heavy-quarks

Leading-particle effect

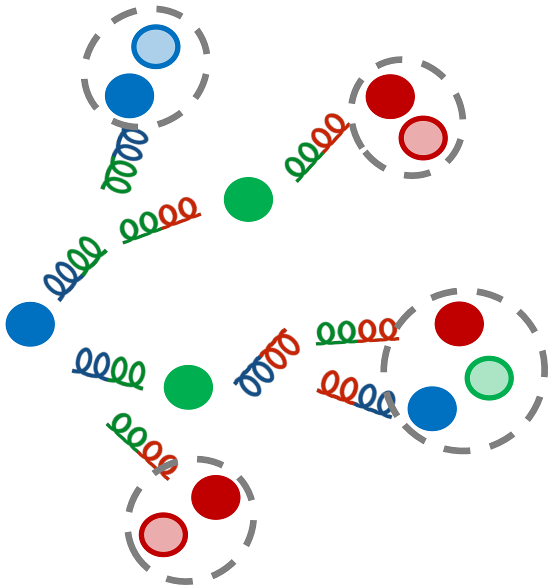
Fragmentation of heavy-flavour quarks



Belle Collaboration, Phys. Rev. D 73, 032002

Mass effects arising from the presence of a dead cone have significant consequences in QCD

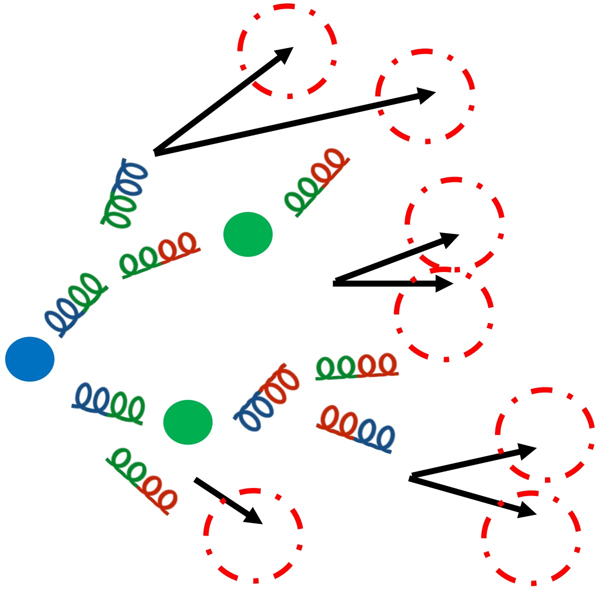
Capturing the parton shower



How can we experimentally reconstruct the final state of the initial hard scatter?

The scattered parton quickly fragments
Bound hadronic states reach the detector

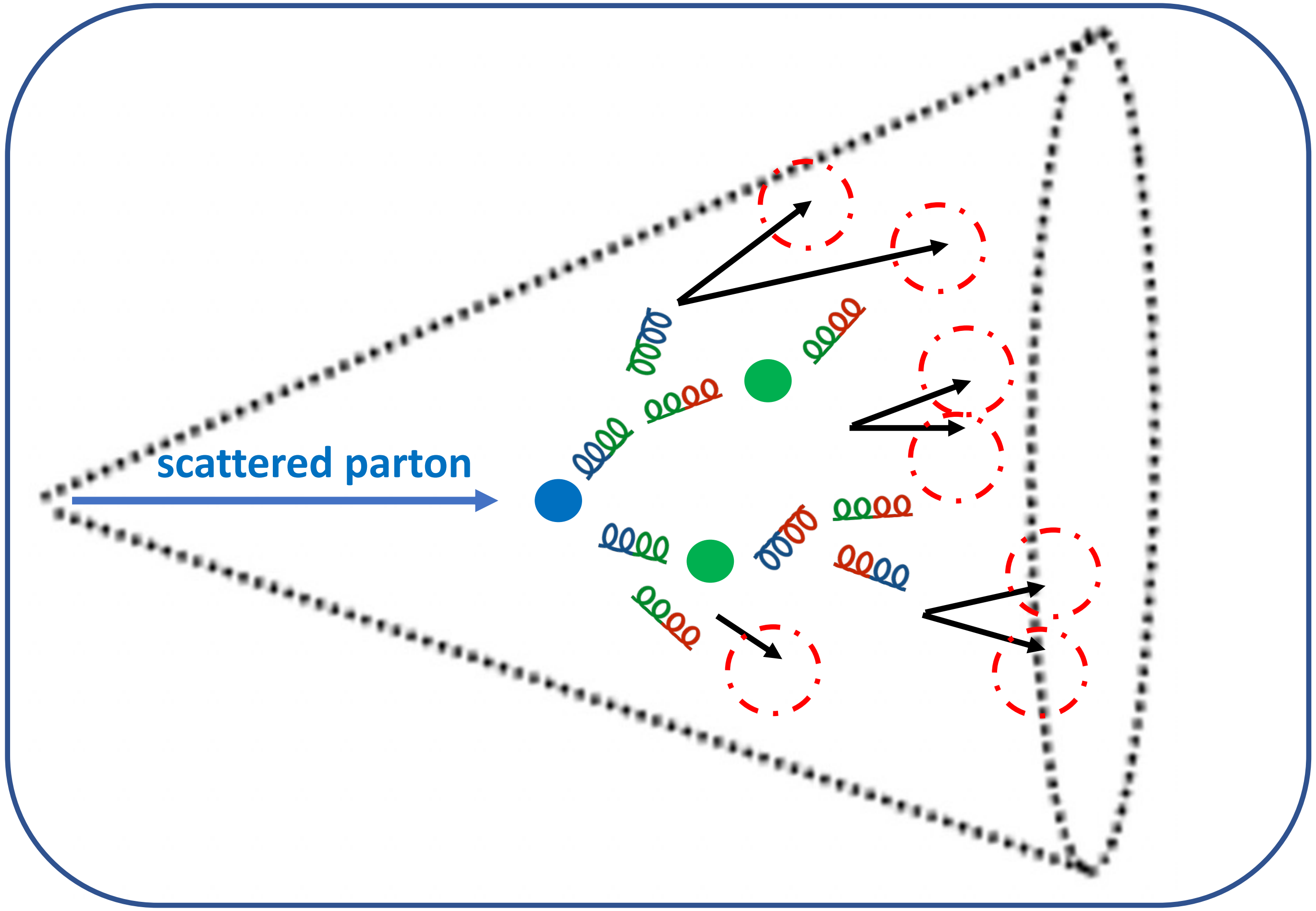
Capturing the parton shower



How can we experimentally reconstruct the final state of the initial hard scatter?

Bound hadronic states reconstructed as tracks

Capturing the parton shower

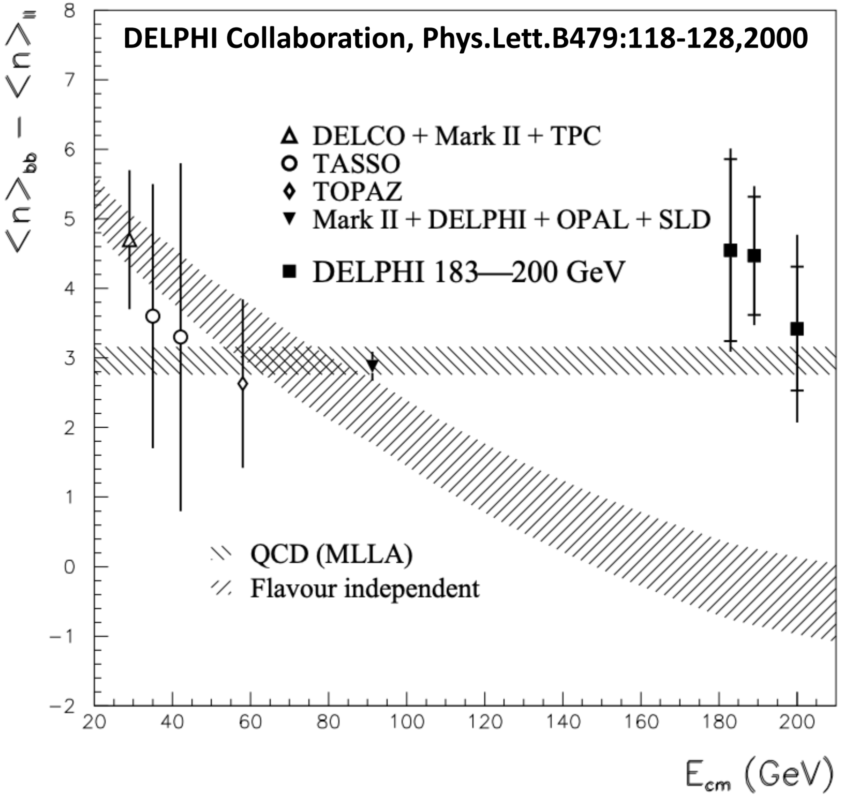


How can we experimentally reconstruct the final state of the initial hard scatter?

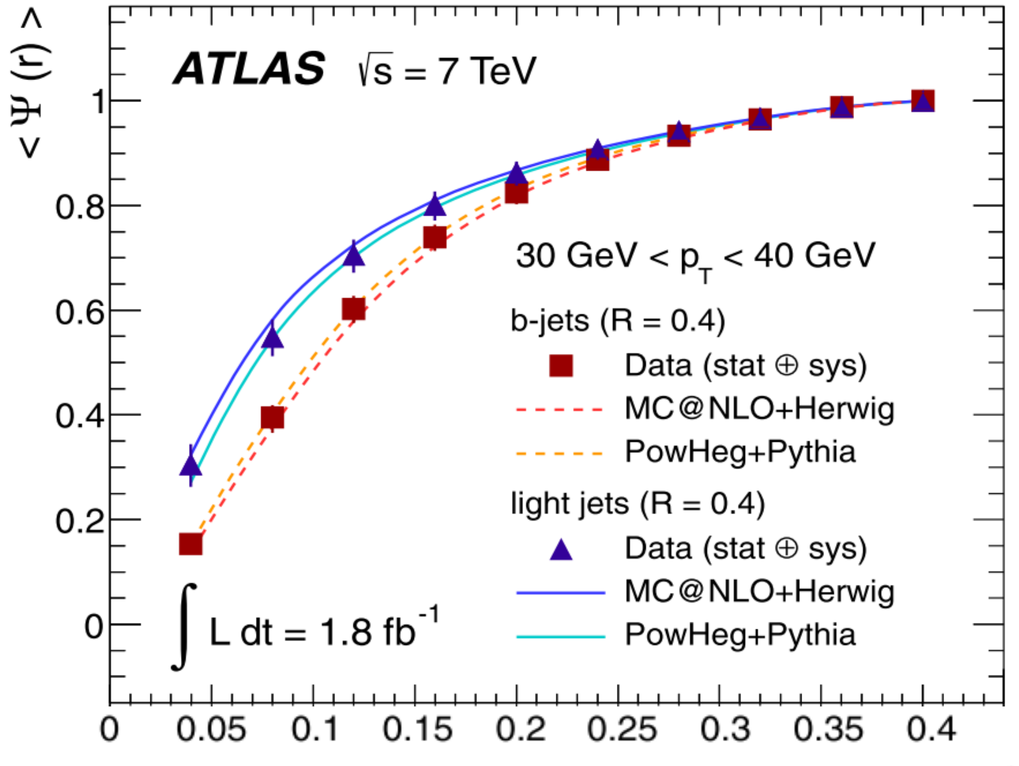
Jet algorithms identify and cluster hadrons originating from a single scattered parton

Indirect measurements of the dead cone

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



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



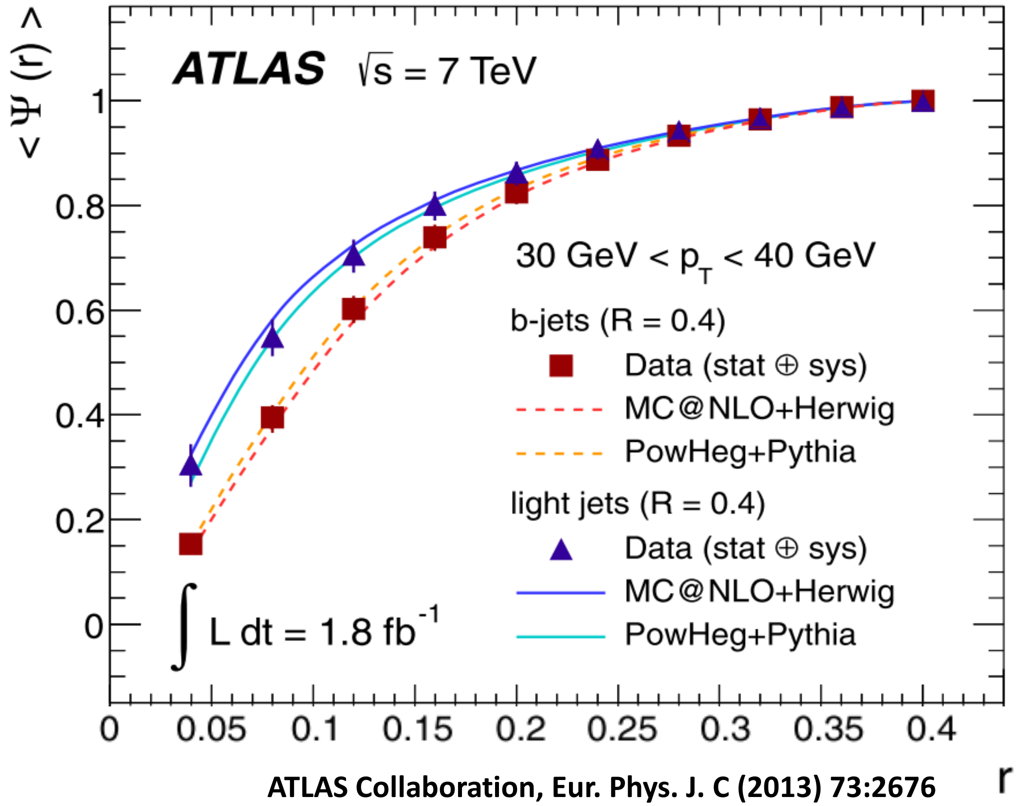
ATLAS Collaboration, Eur. Phys. J. C (2013) 73:2676

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?

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



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

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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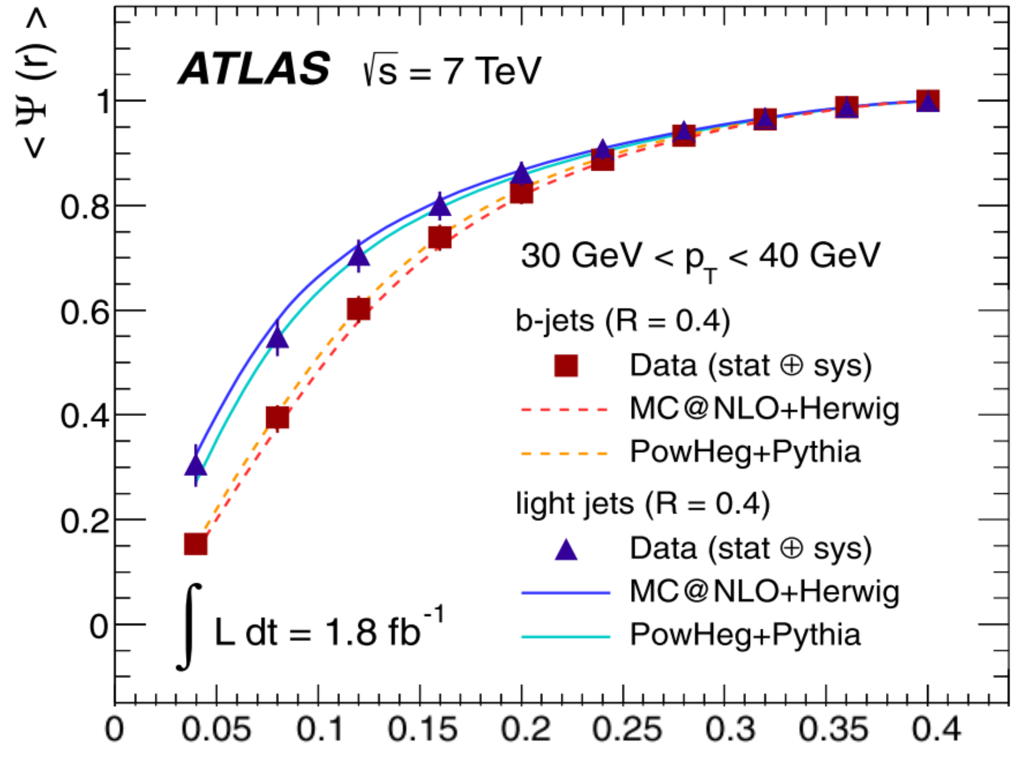
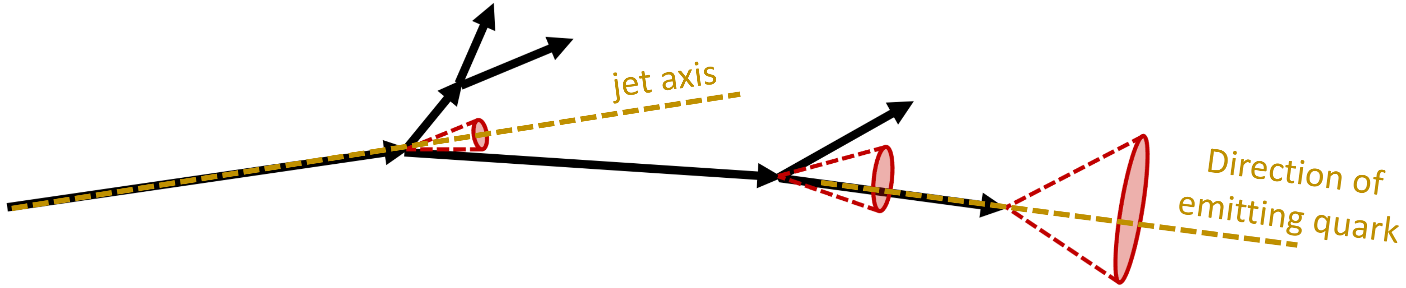


ATLAS Collaboration, Eur. Phys. J. C (2013) 73:2676



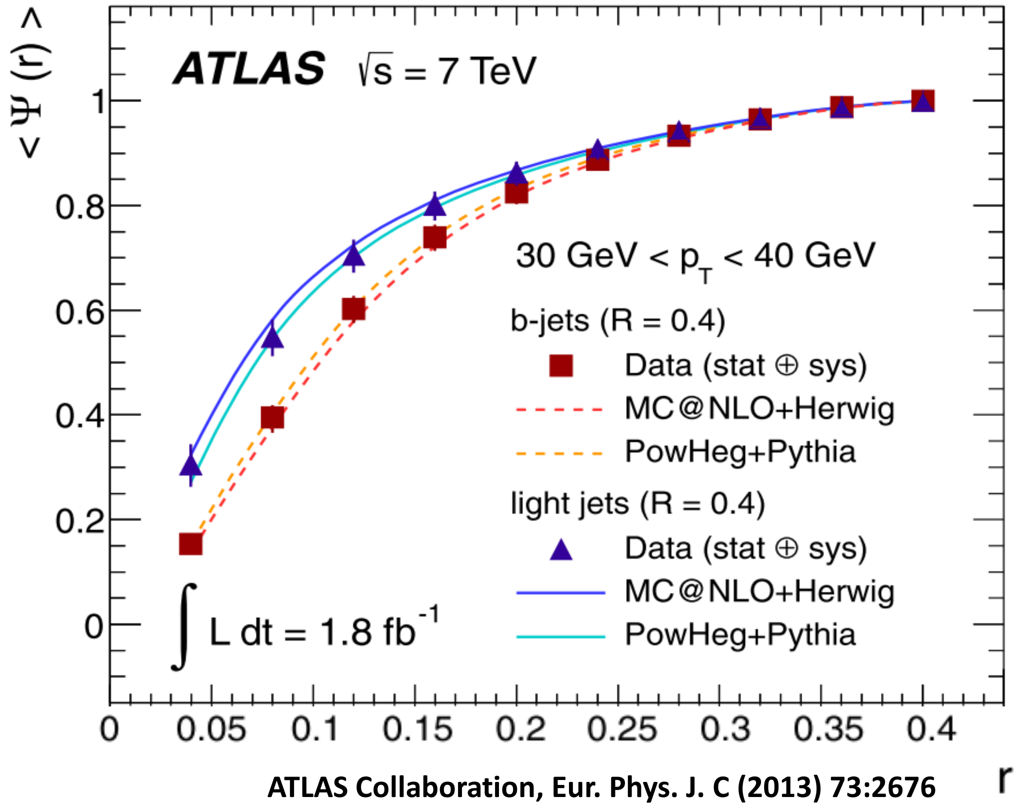
Indirect measurements of the dead cone

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

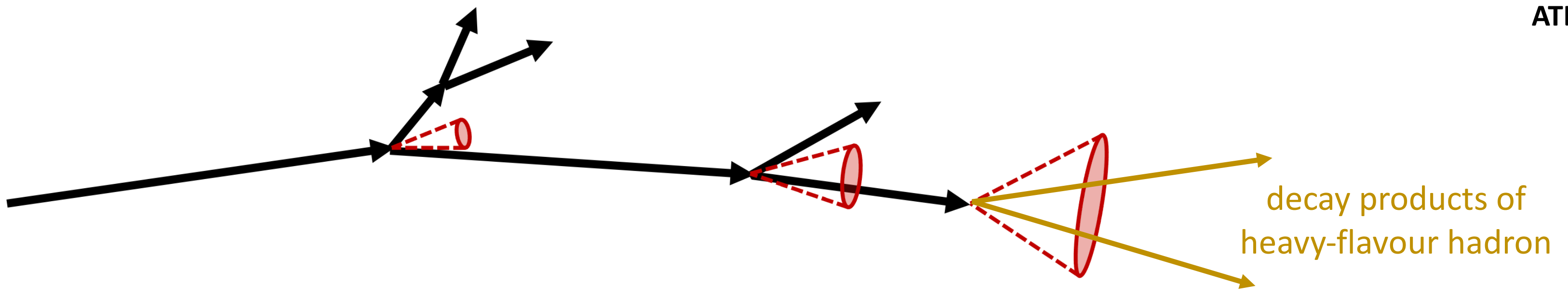
The dead-cone angle appears at the partonic emission level - need to reconstruct the dynamically evolving direction of the heavy quark

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

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

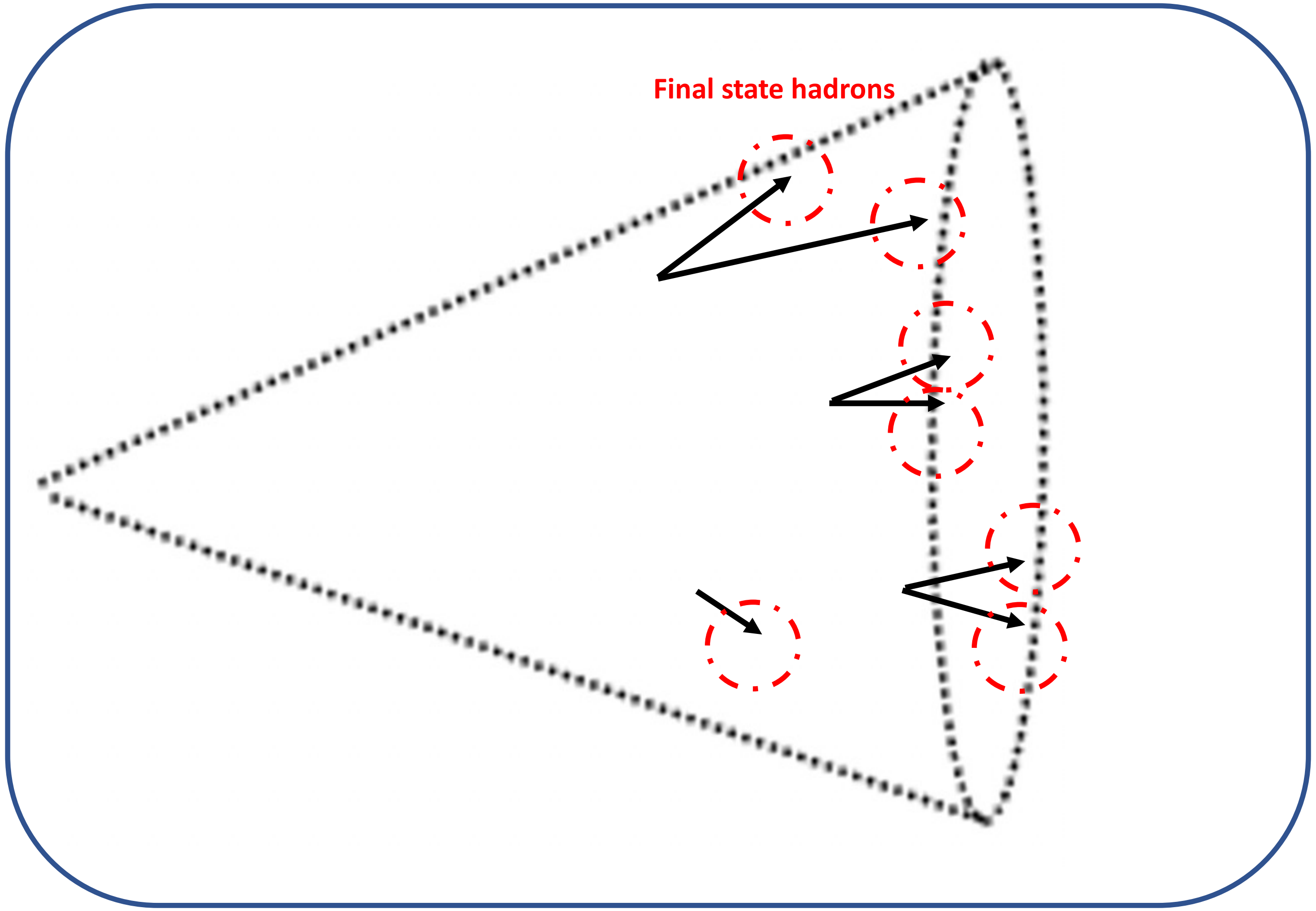


ATLAS Collaboration, Eur. Phys. J. C (2013) 73:2676



Dynamically reconstructing the parton shower

How can we access the intermediate partonic structure of the shower?



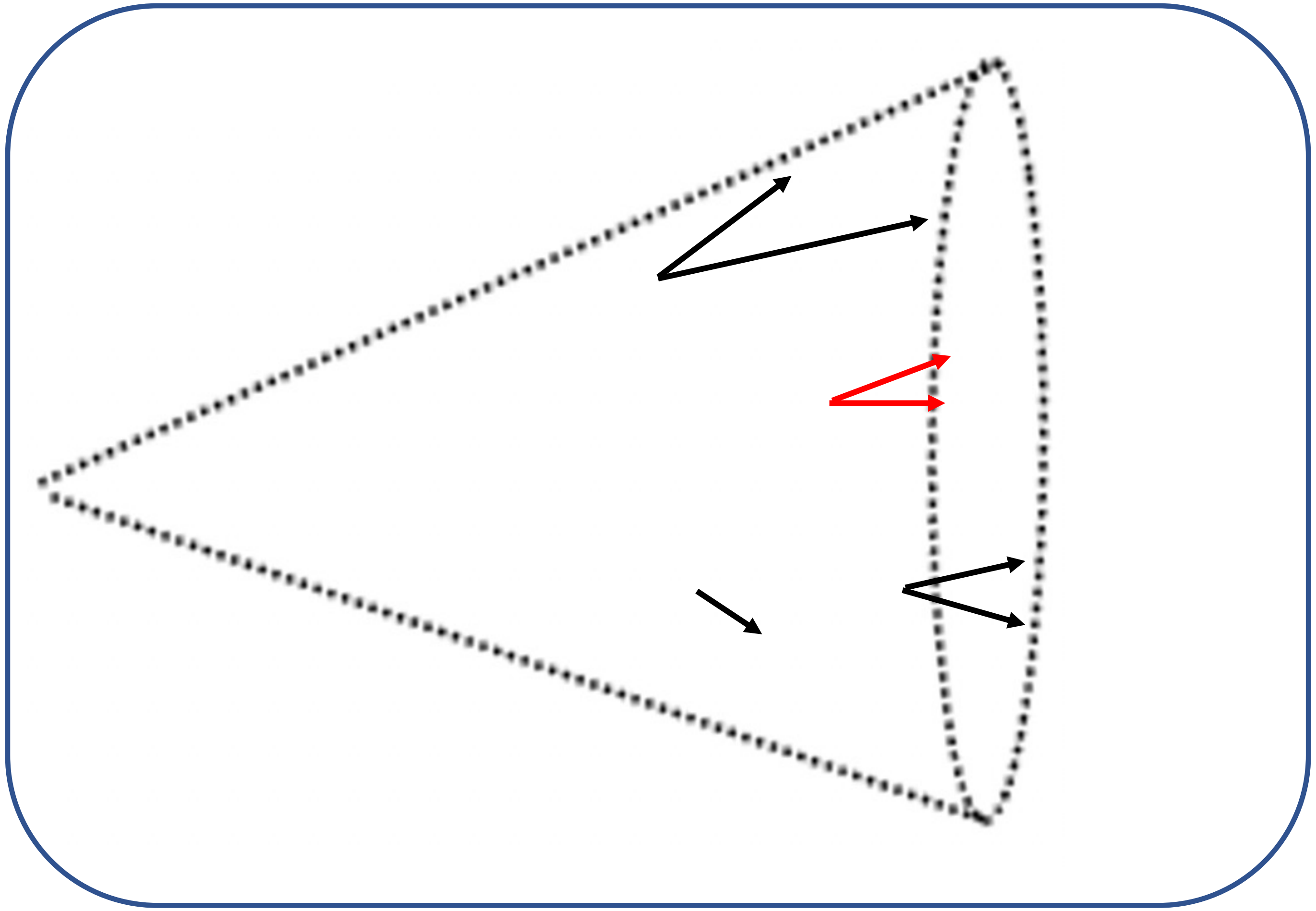
How can we access the partonic structure of the shower?

Take advantage of the implicit angular ordering of QCD to recluster the jet

Cambridge/Aachen algorithm is used

Y. L. Dokshitzer et al. JHEP 08(1997)001

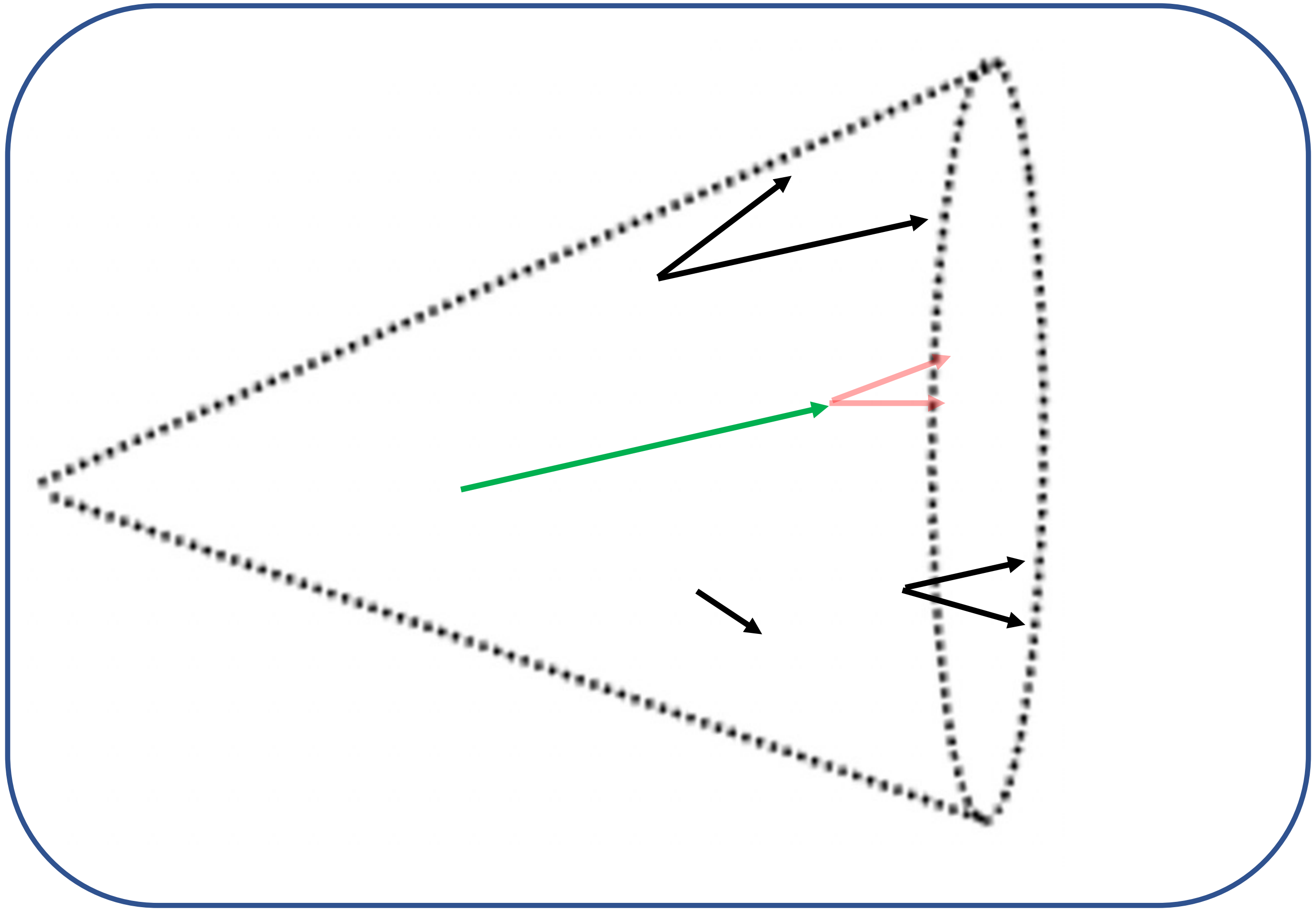
Dynamically reconstructing the parton shower



How can we access the partonic structure of the shower?

Start by clustering the closest constituents in angle : the last emissions in the jet

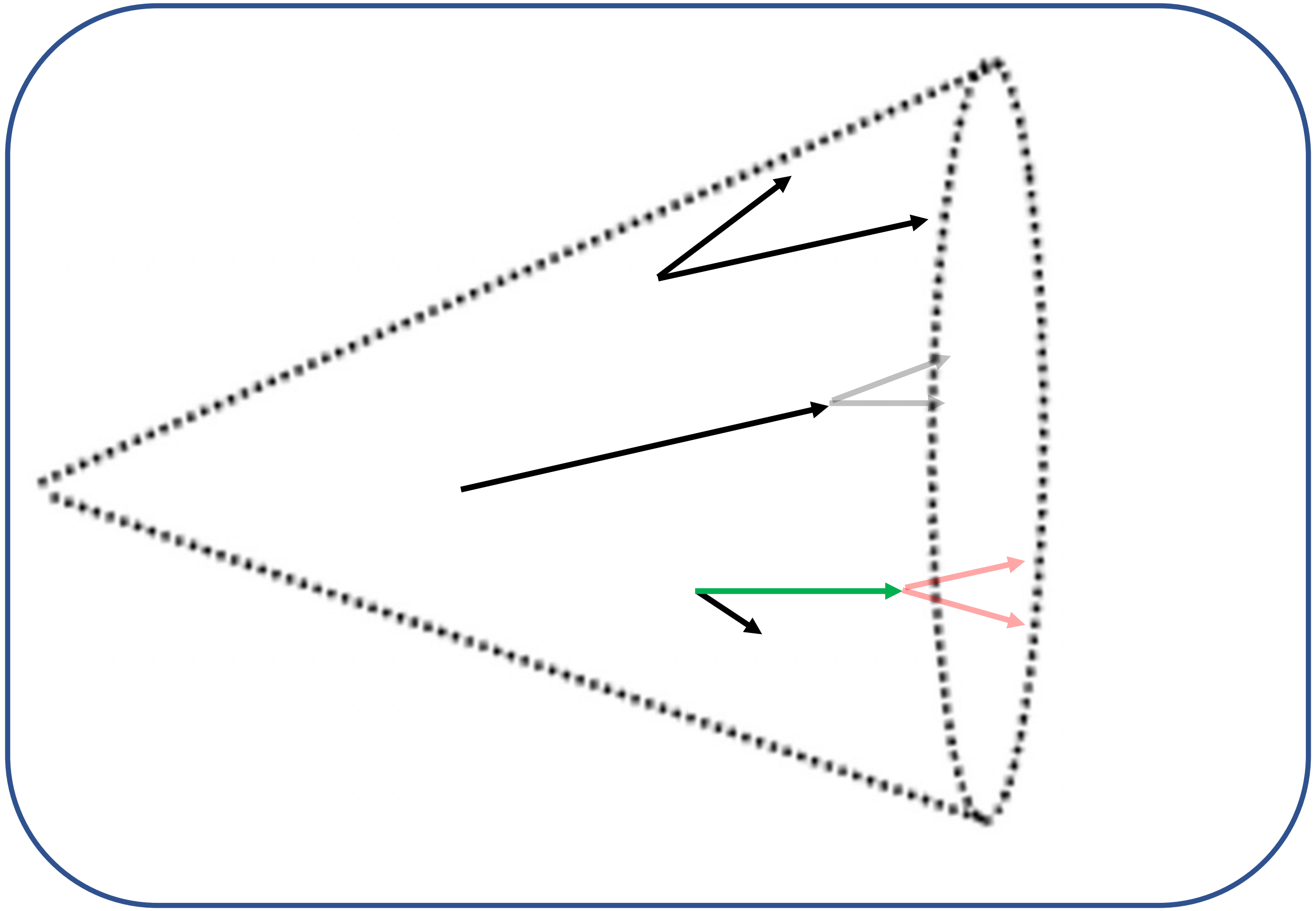
Dynamically reconstructing the parton shower



How can we access the partonic structure of the shower?

Start by clustering the closest constituents in angle : the last emissions in the jet

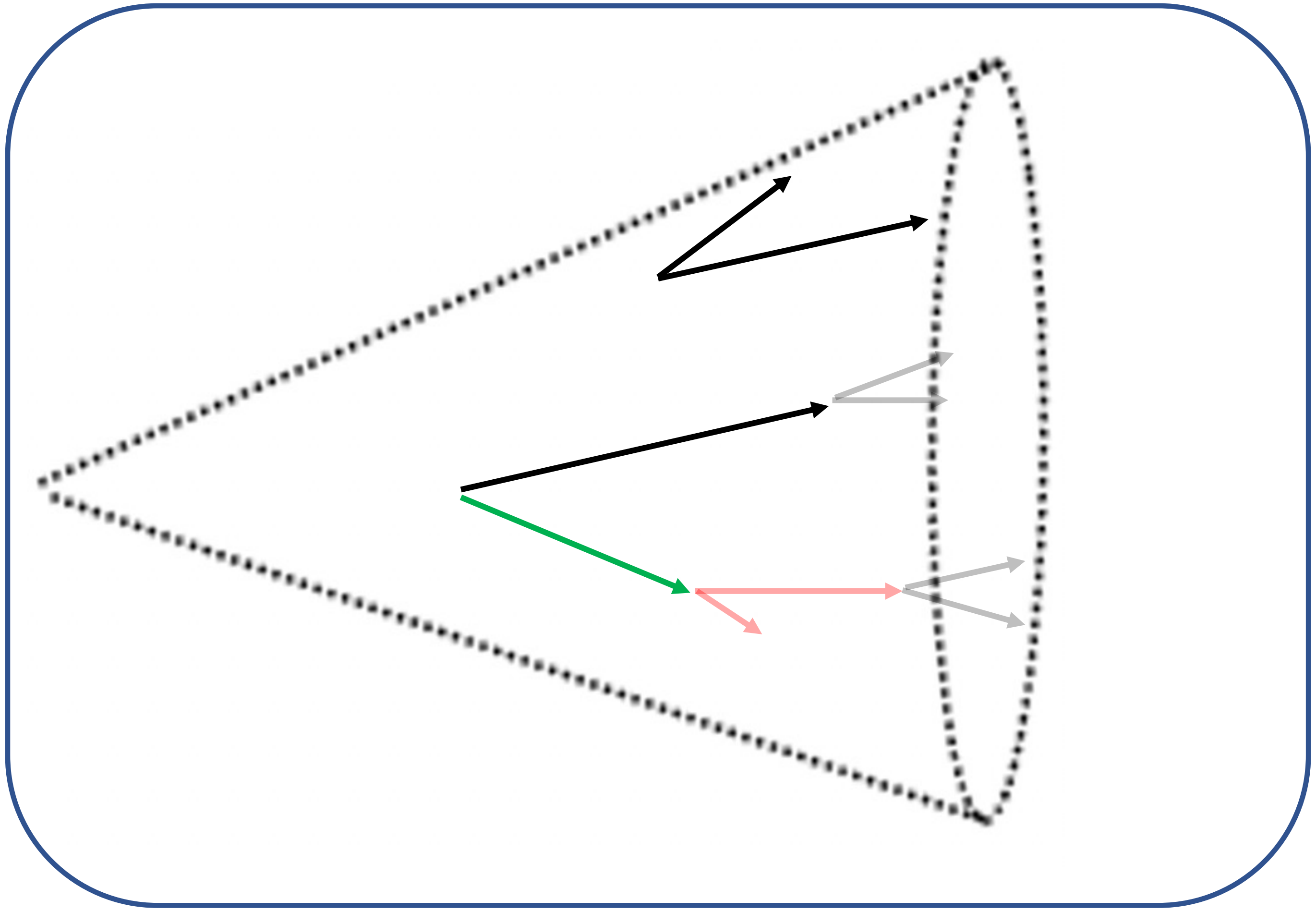
Replace emission prongs with the sum of their four-momenta : reconstruct emitter



How can we access the partonic structure of the shower?

The procedure is iteratively repeated with the next closest constituents

Dynamically reconstructing the parton shower



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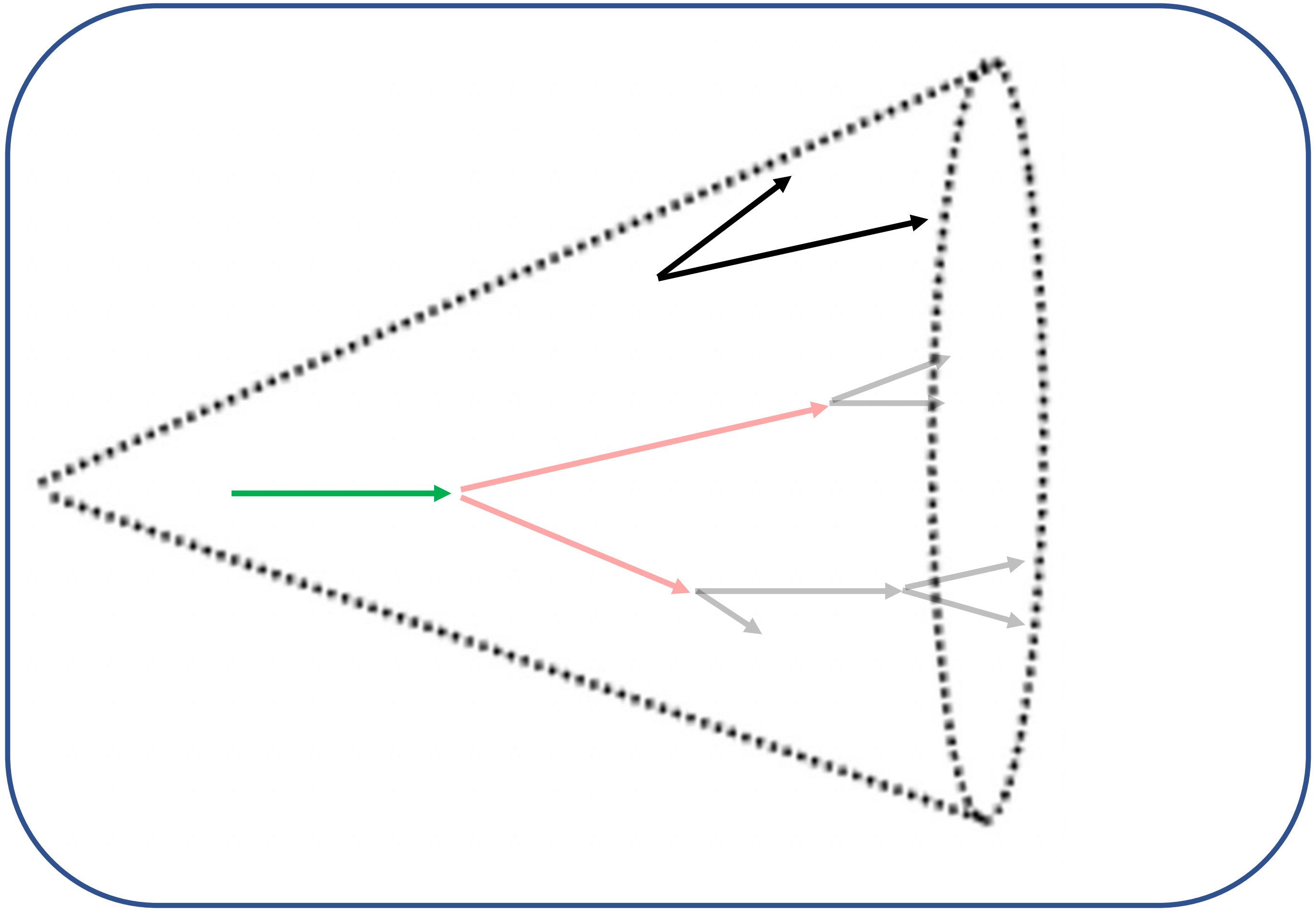

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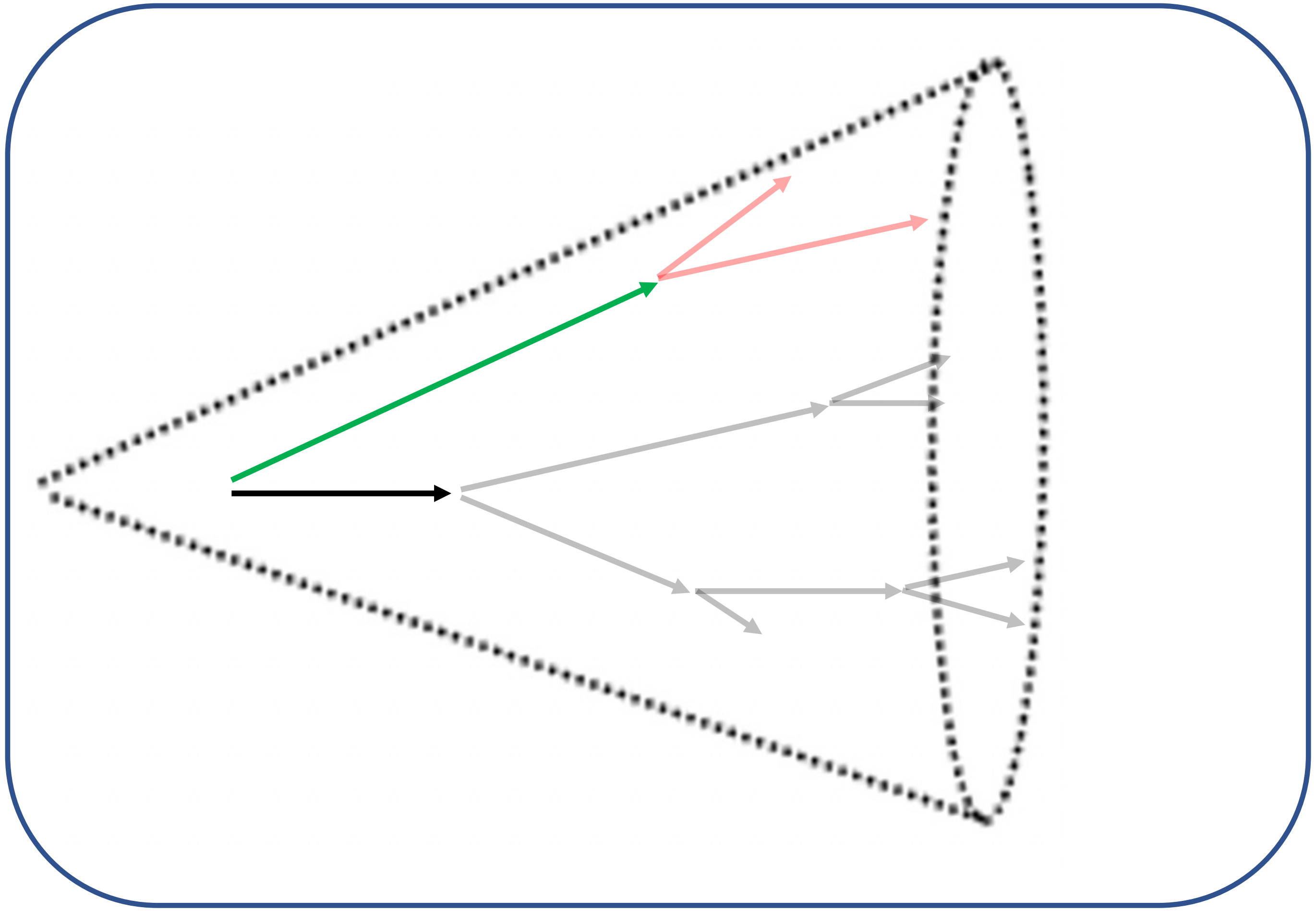

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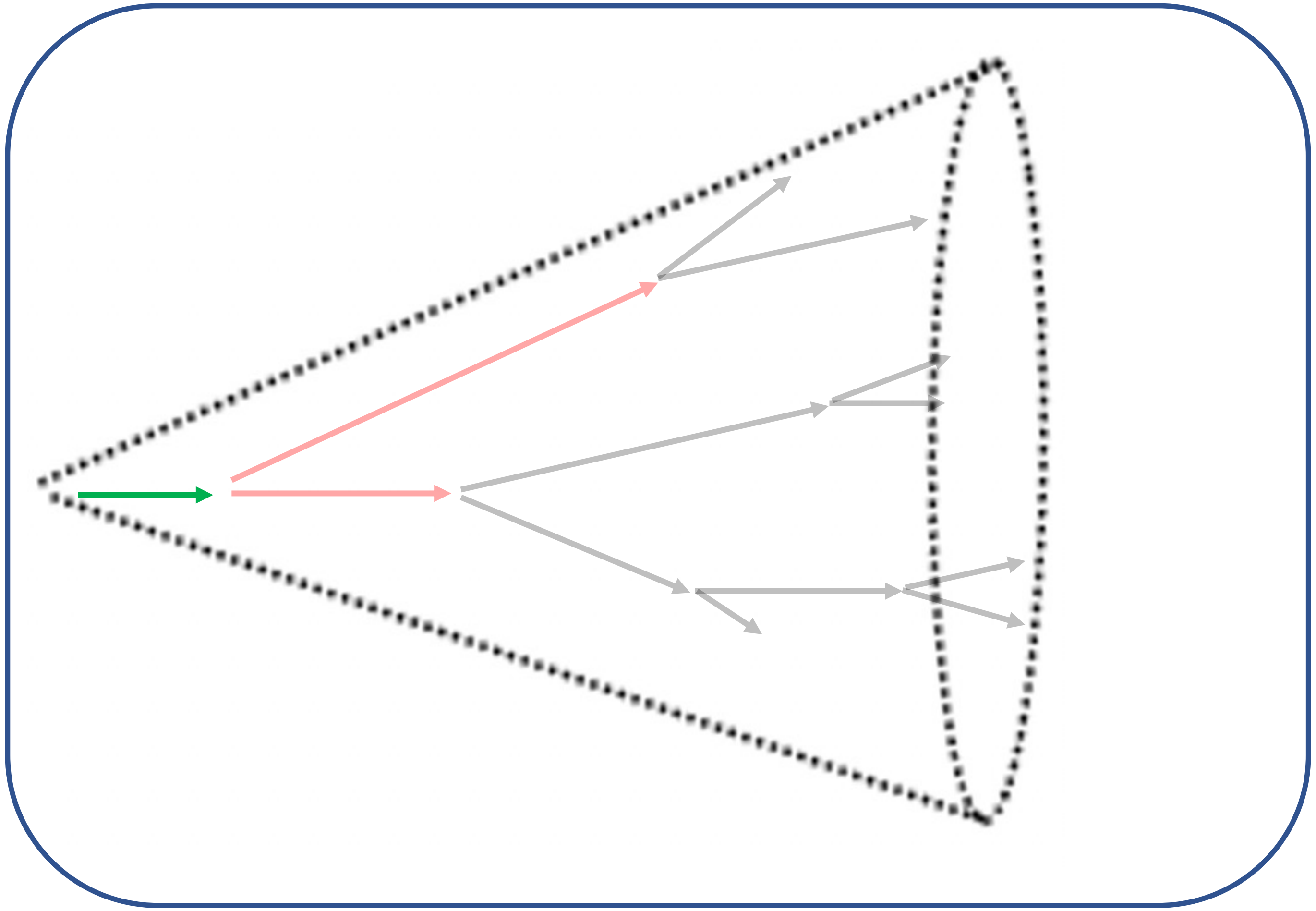

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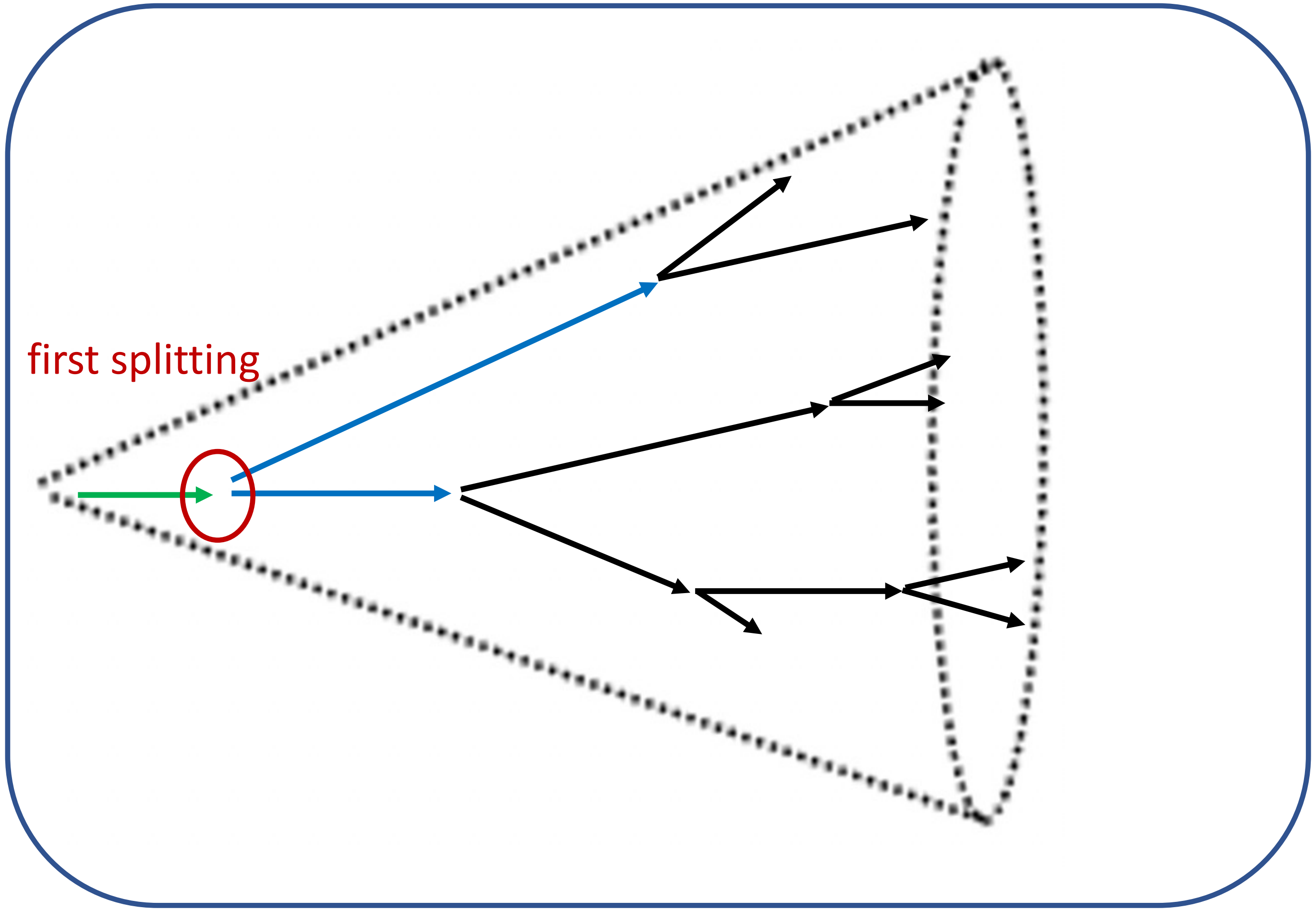
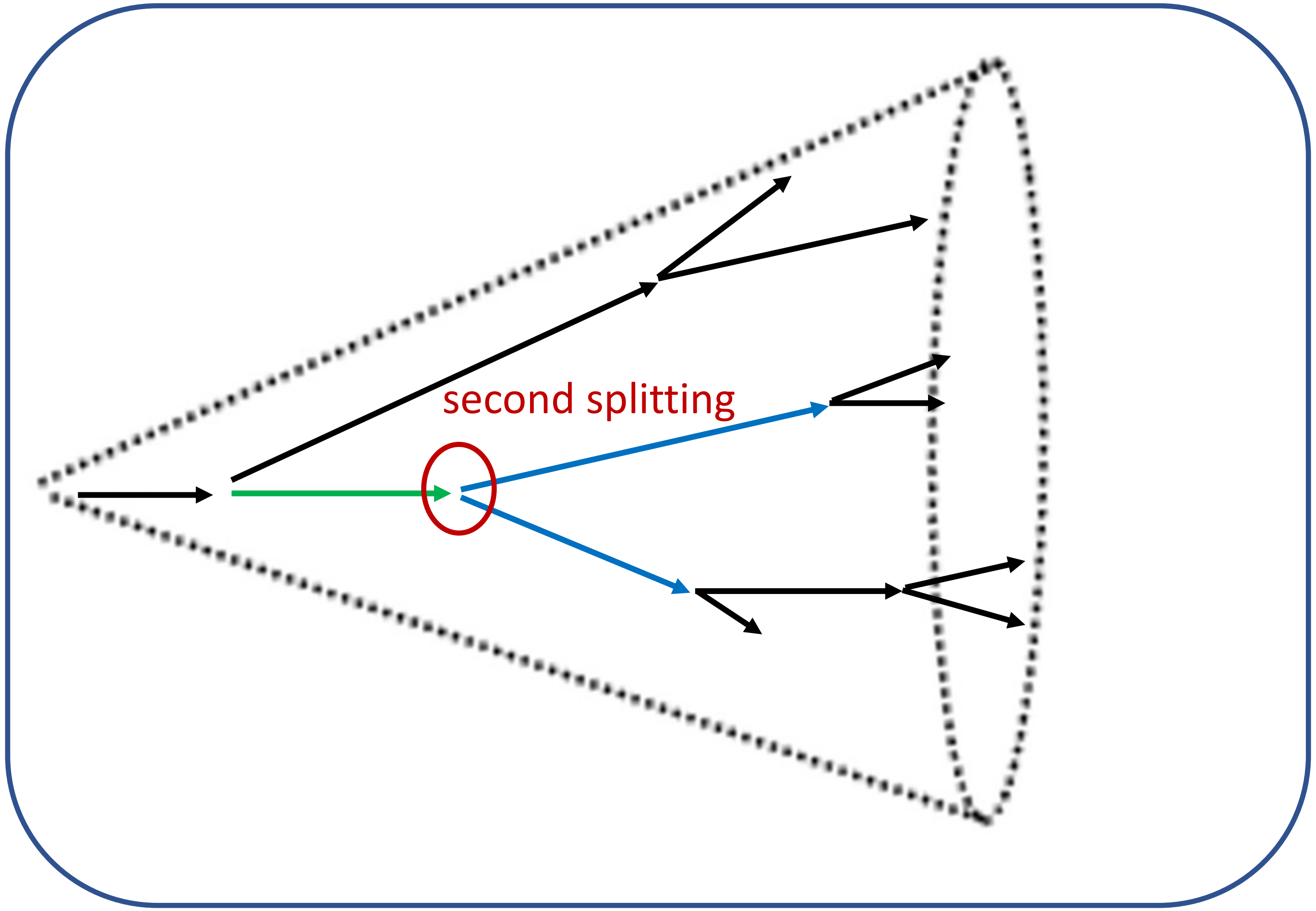
Dynamically reconstructing the parton shower



How can we access the partonic structure of the shower?

Once the jet has been reclustered the sequence of emissions are available by unwinding the reclustering history and following a branch

Dynamically reconstructing the parton shower



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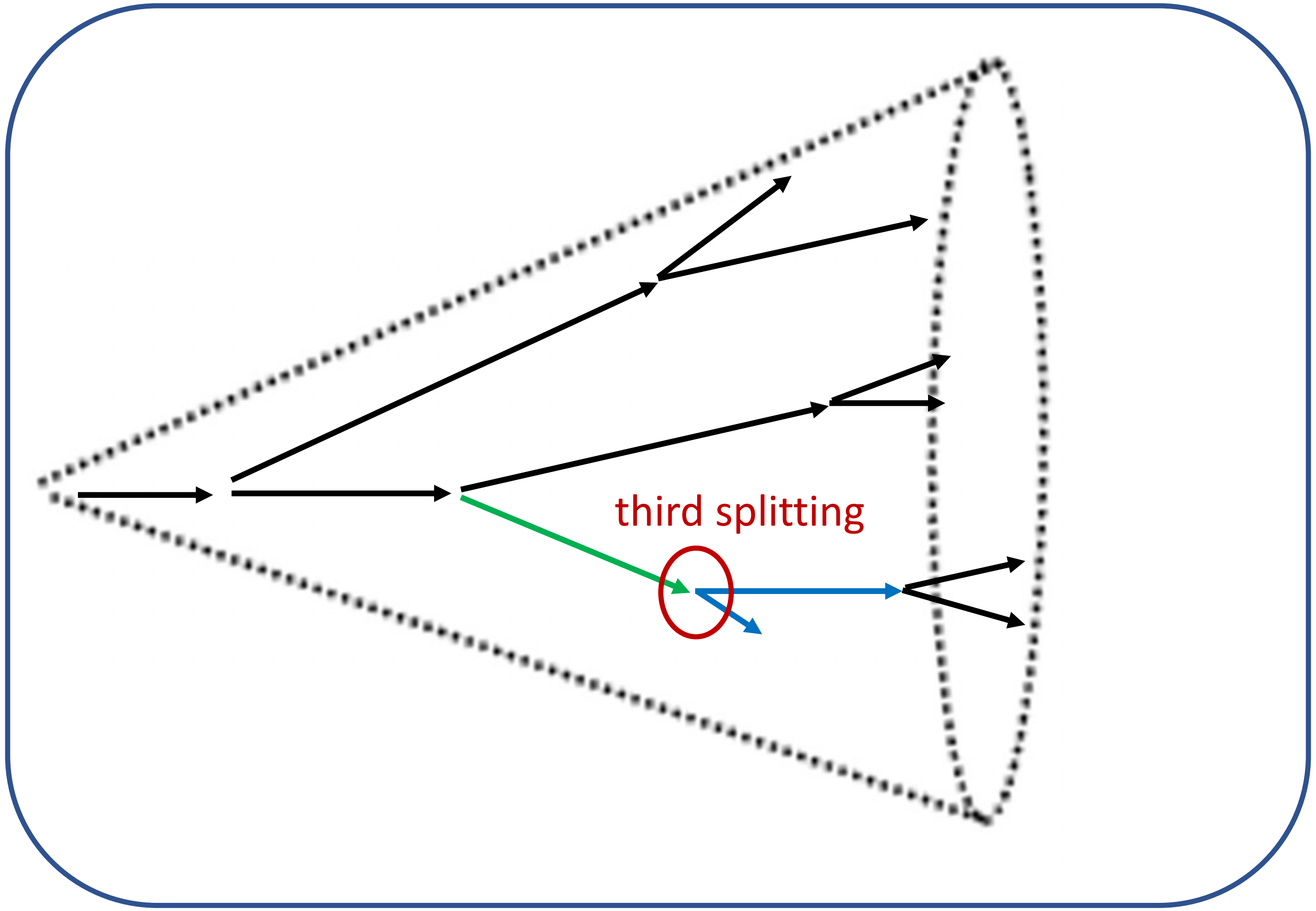
Dynamically reconstructing the parton shower



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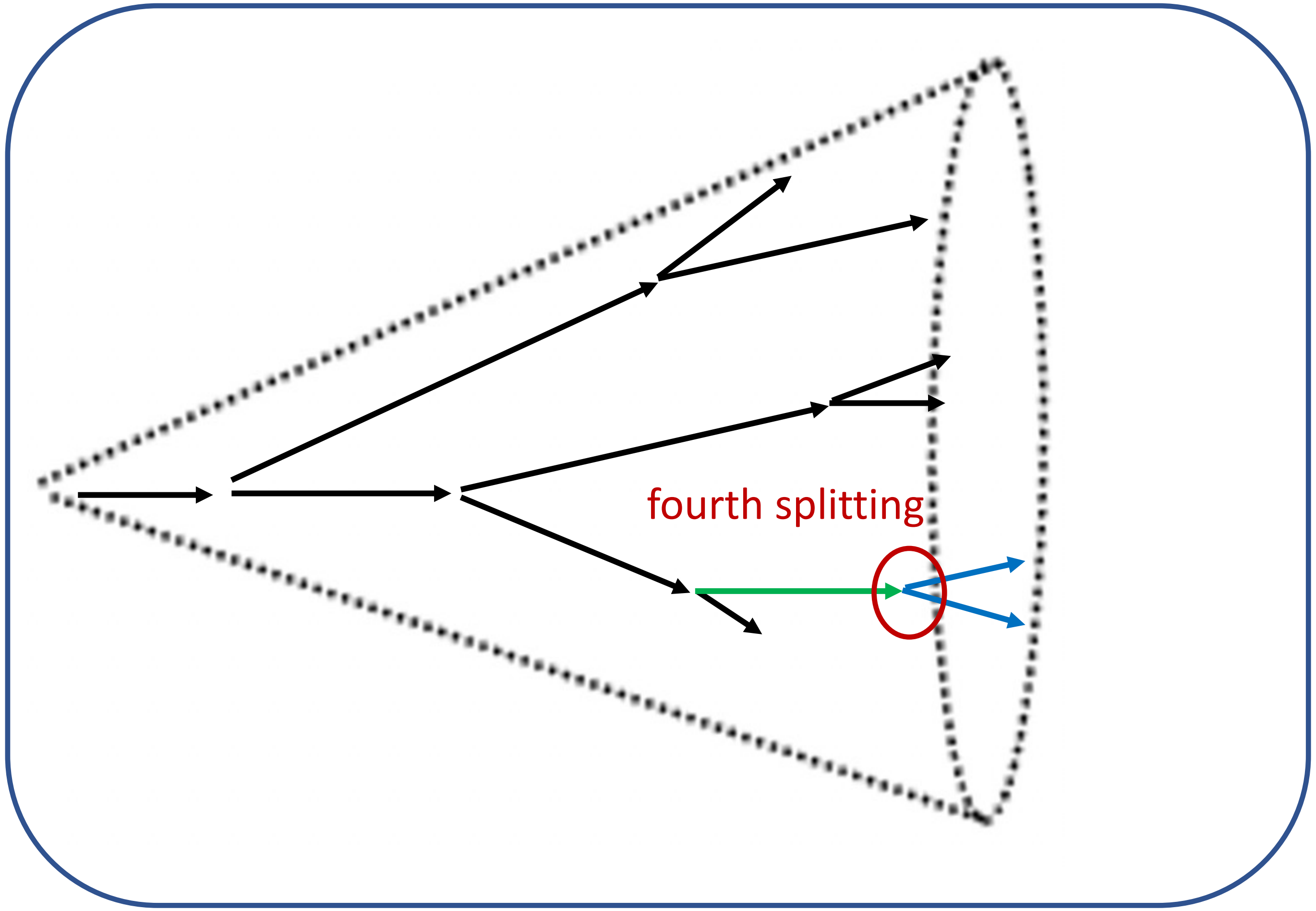
Dynamically reconstructing the parton shower

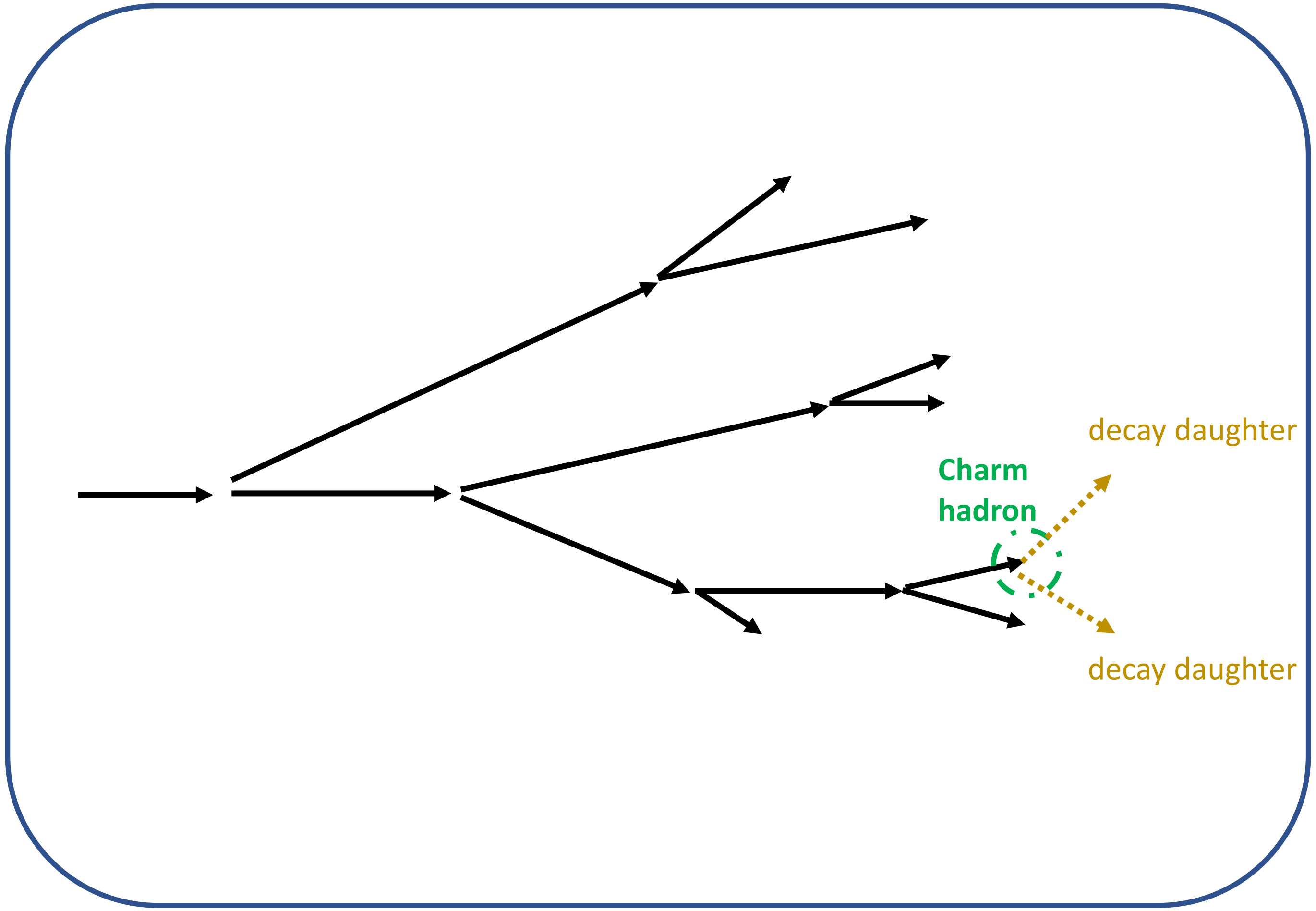


How can we access the partonic structure of the shower?

Once the jet has been reclustered the sequence of emissions are available by unwinding the reclustering history and following a branch

The splitting flavour is not conserved along the branch

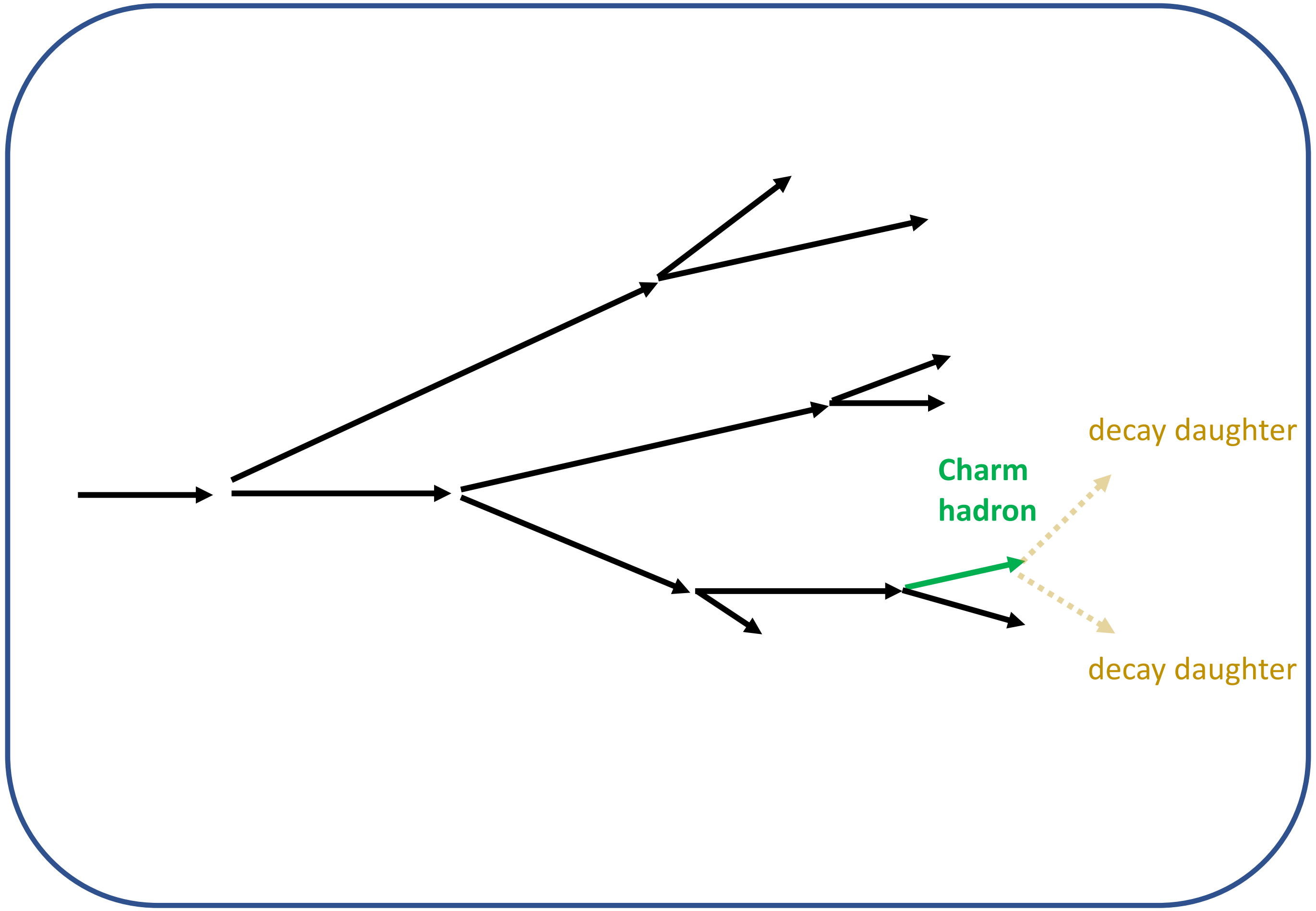
Using heavy-flavour jets to isolate c->cg splittings



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

The charm jet is identified by the presence of a charm hadron amongst its constituents

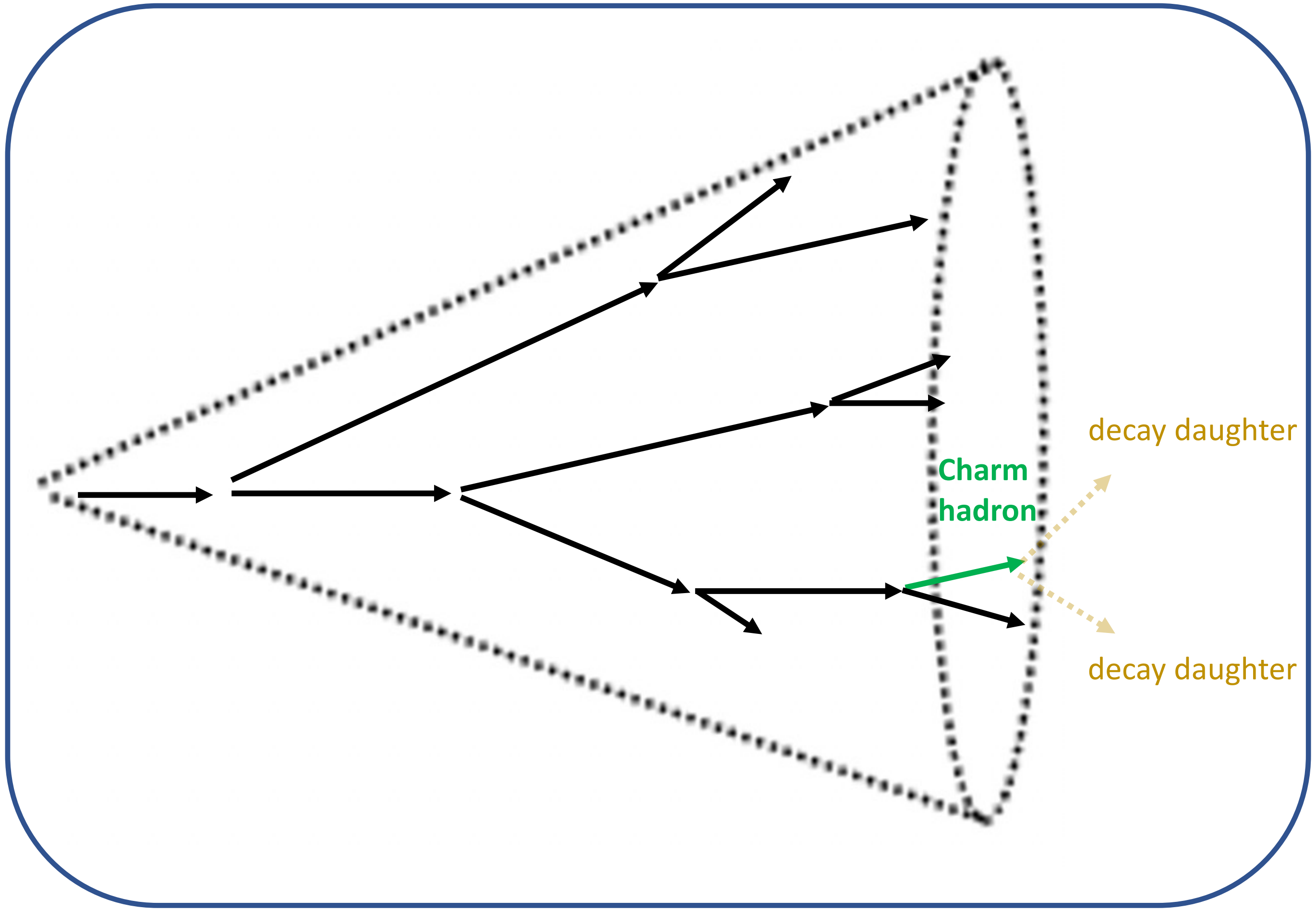
Using heavy-flavour jets to isolate c->cg splittings



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

The charm hadron is fully reconstructed through its decay tracks

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

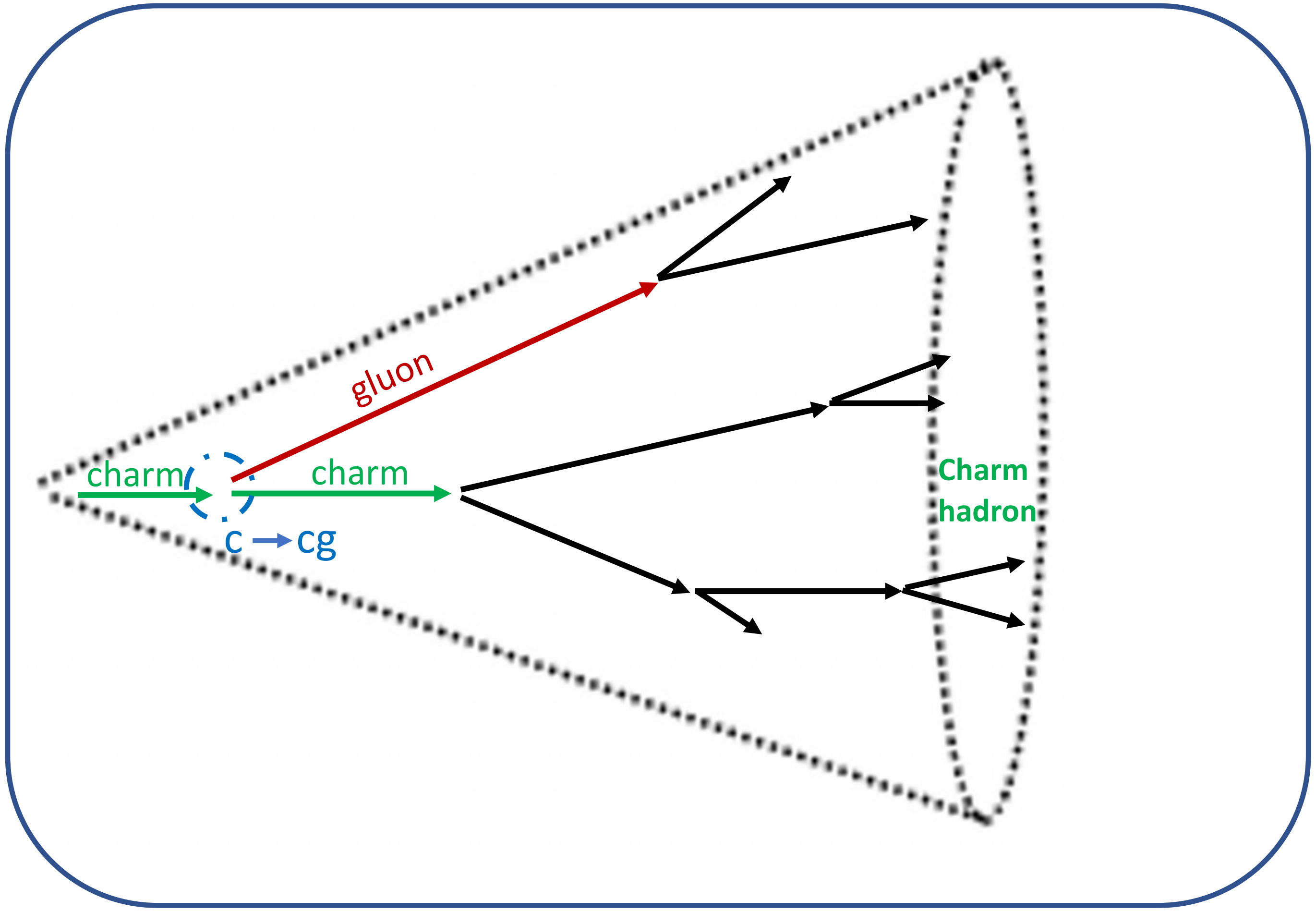


L. Cunqueiro, M. Ploskon, Phys. Rev. D 99, 074027 (2019)

The charm hadron is fully reconstructed through its decay tracks

The four-momentum of the charm hadron enters the reclustering procedure

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



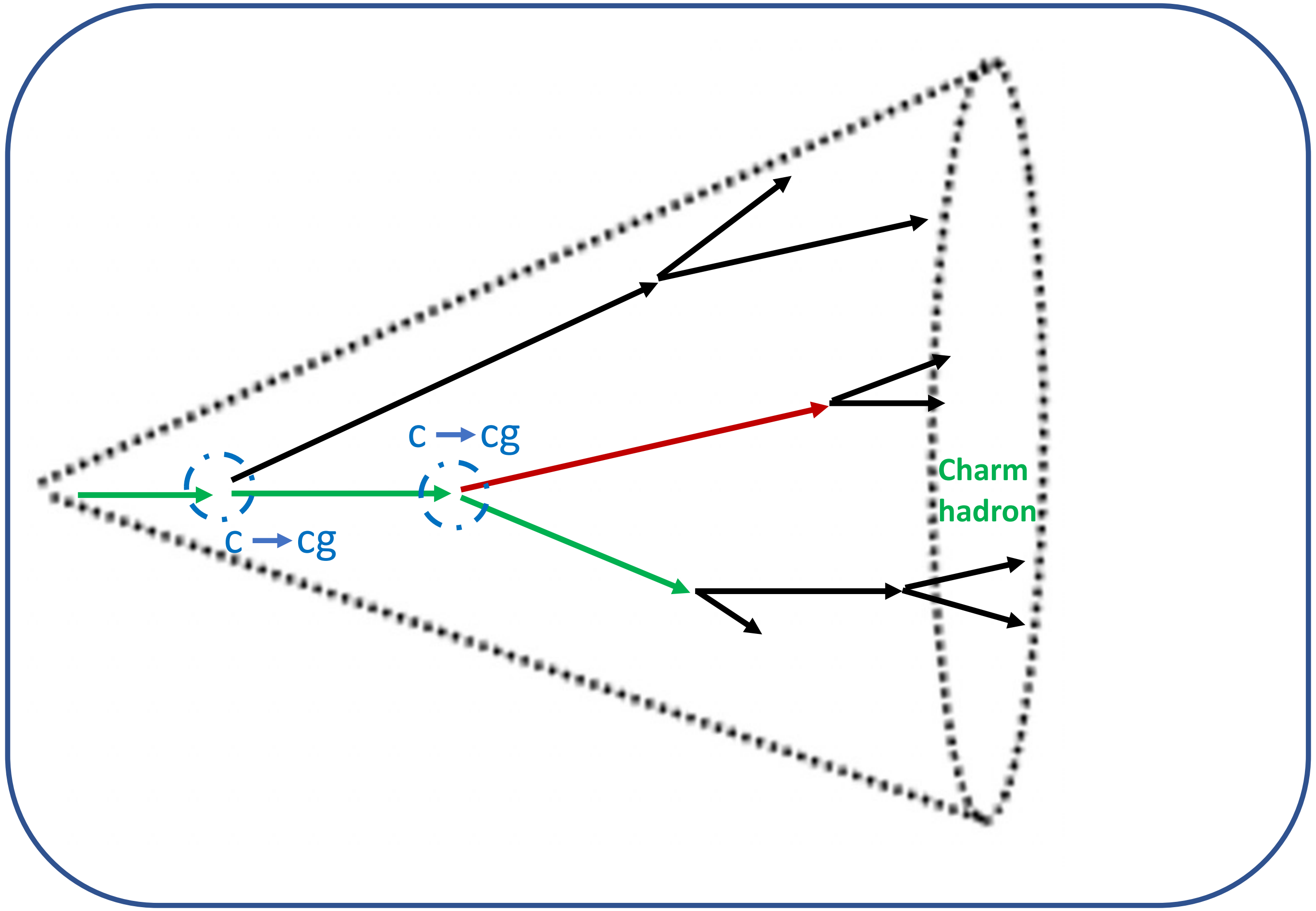
L. Cunqueiro, M. Ploskon, Phys. Rev. D 99, 074027 (2019)

The charm quark flavour is conserved throughout the shower

Following the branch with the charm hadron is equivalent to following the charm quark

The kinematics of each c->cg splitting are dynamically updated

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



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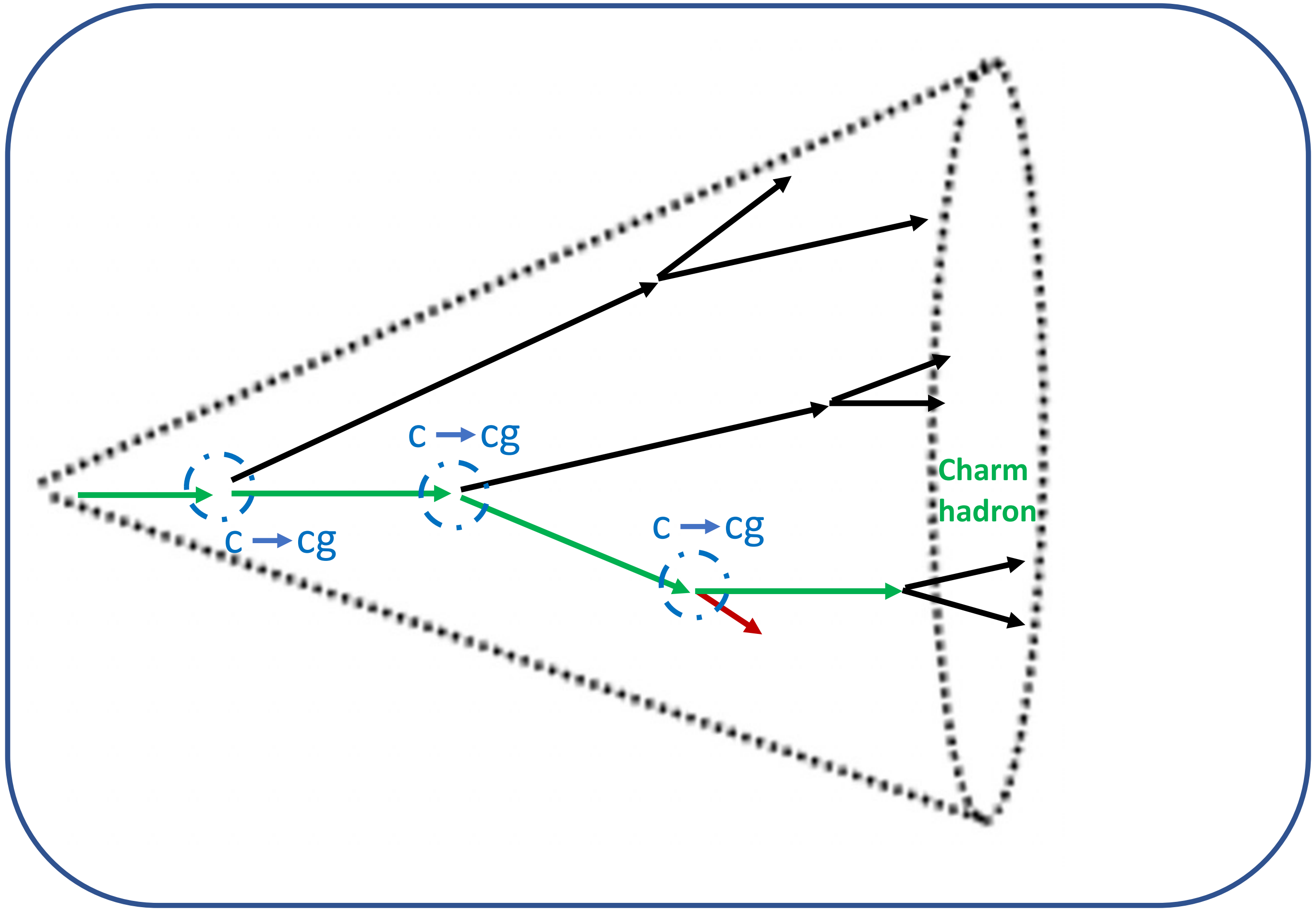

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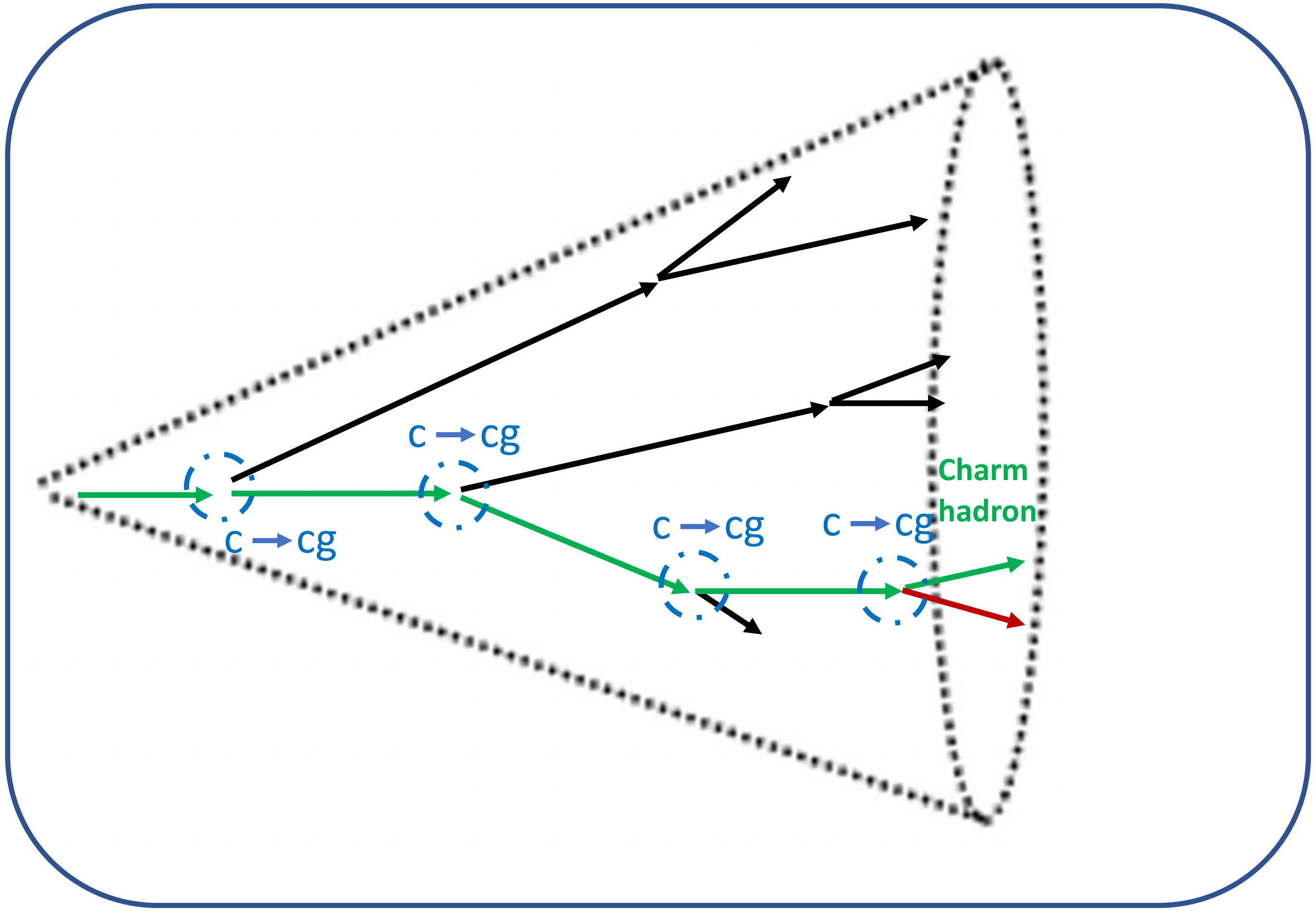

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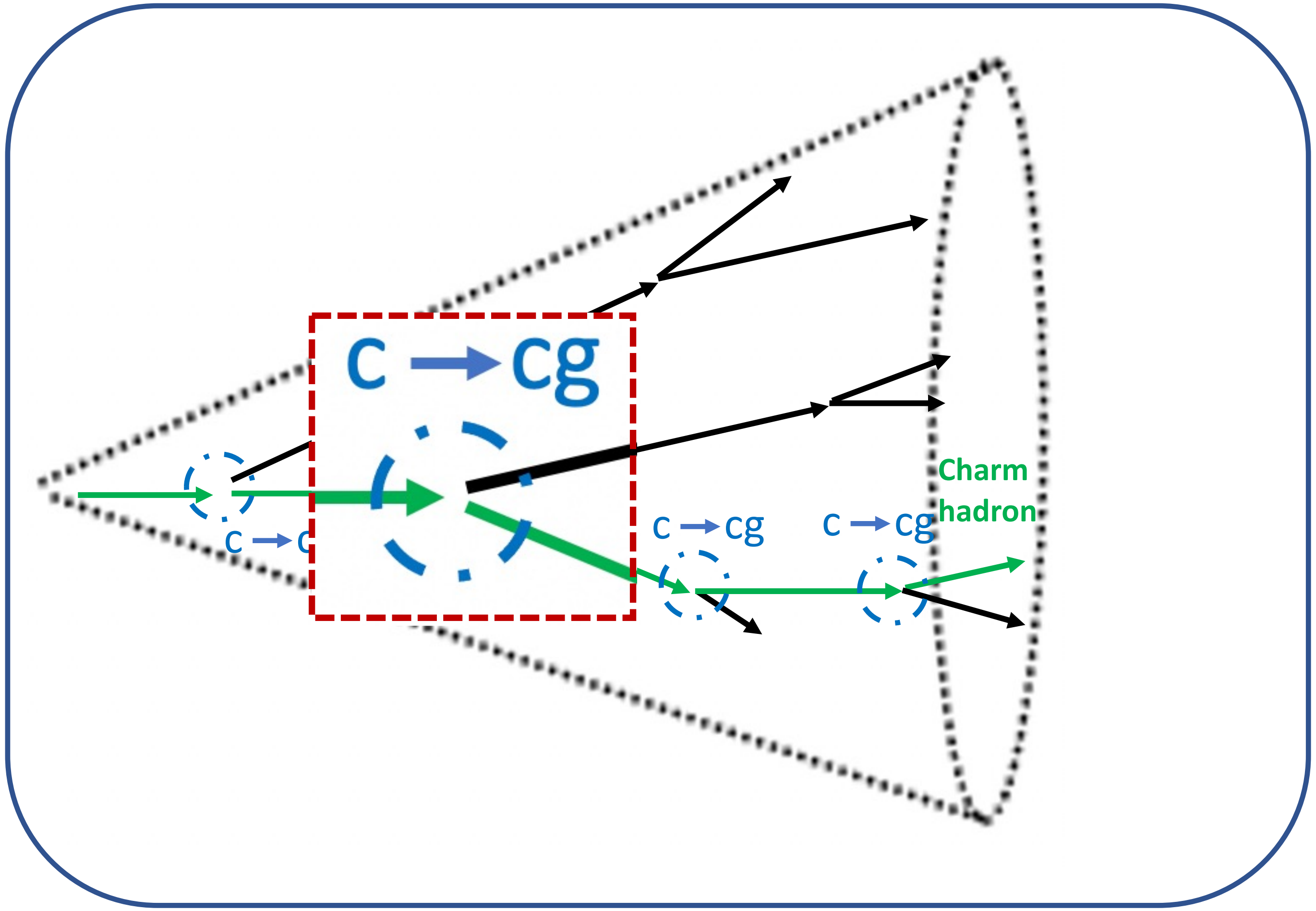
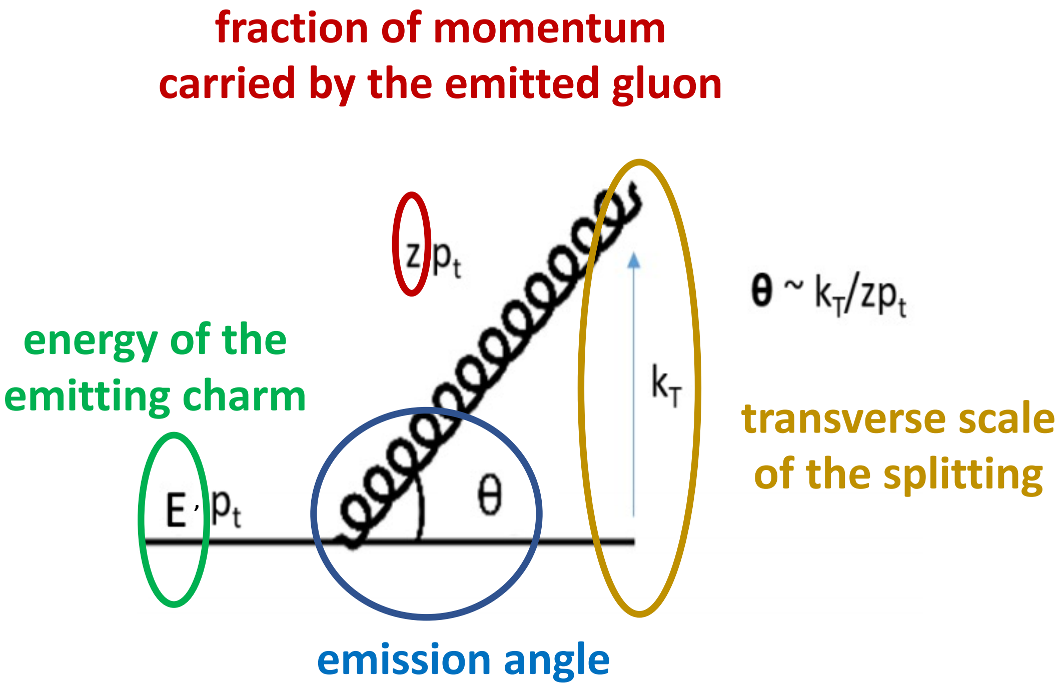
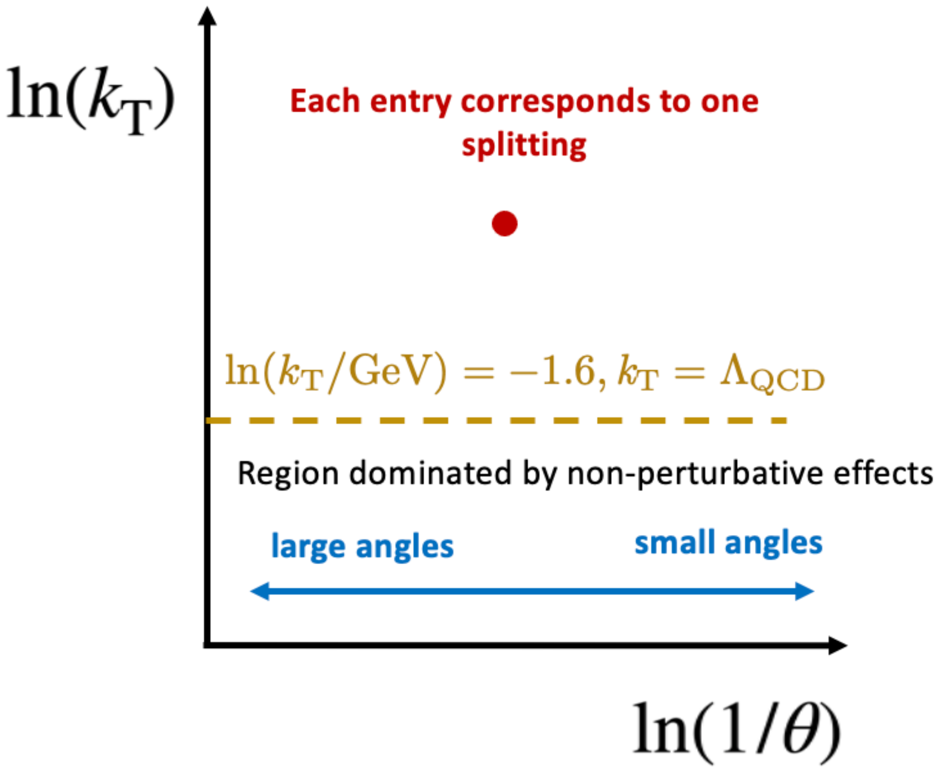
Reconstructed splitting kinematics

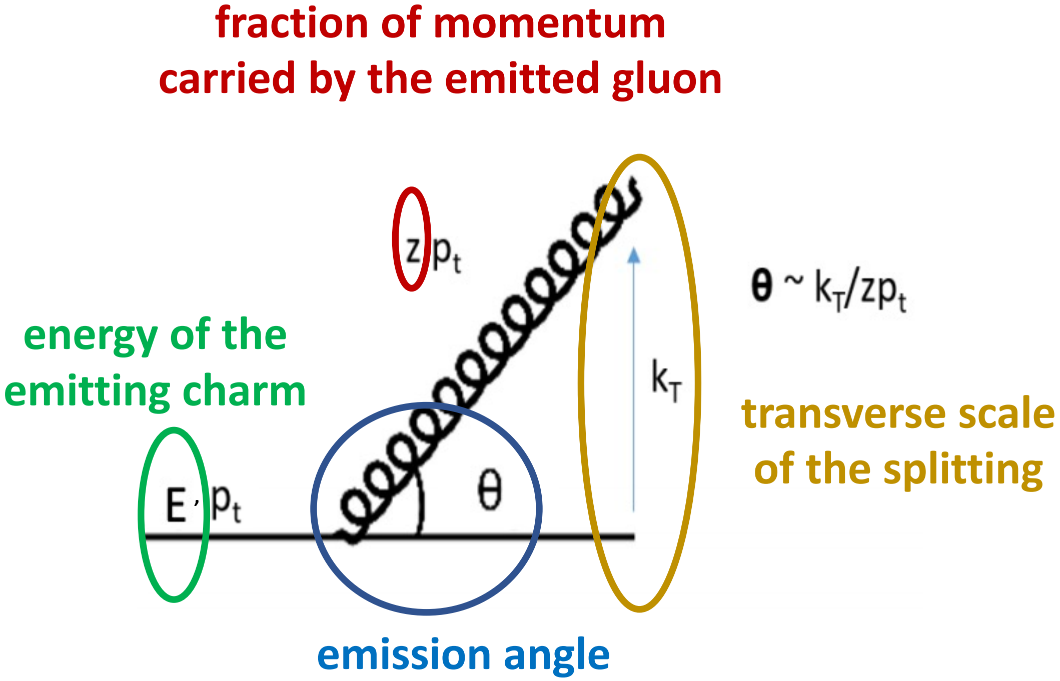




Reconstructed splitting kinematics

Lund plane F. A. Dreyer et al. JHEP 12 (2018) 064





The splitting phase spaced can be mapped through 2D distributions called Lund planes

QCD phenomena such as the dead-cone effect and the running of the strong coupling manifest in the Lund plane emission densities

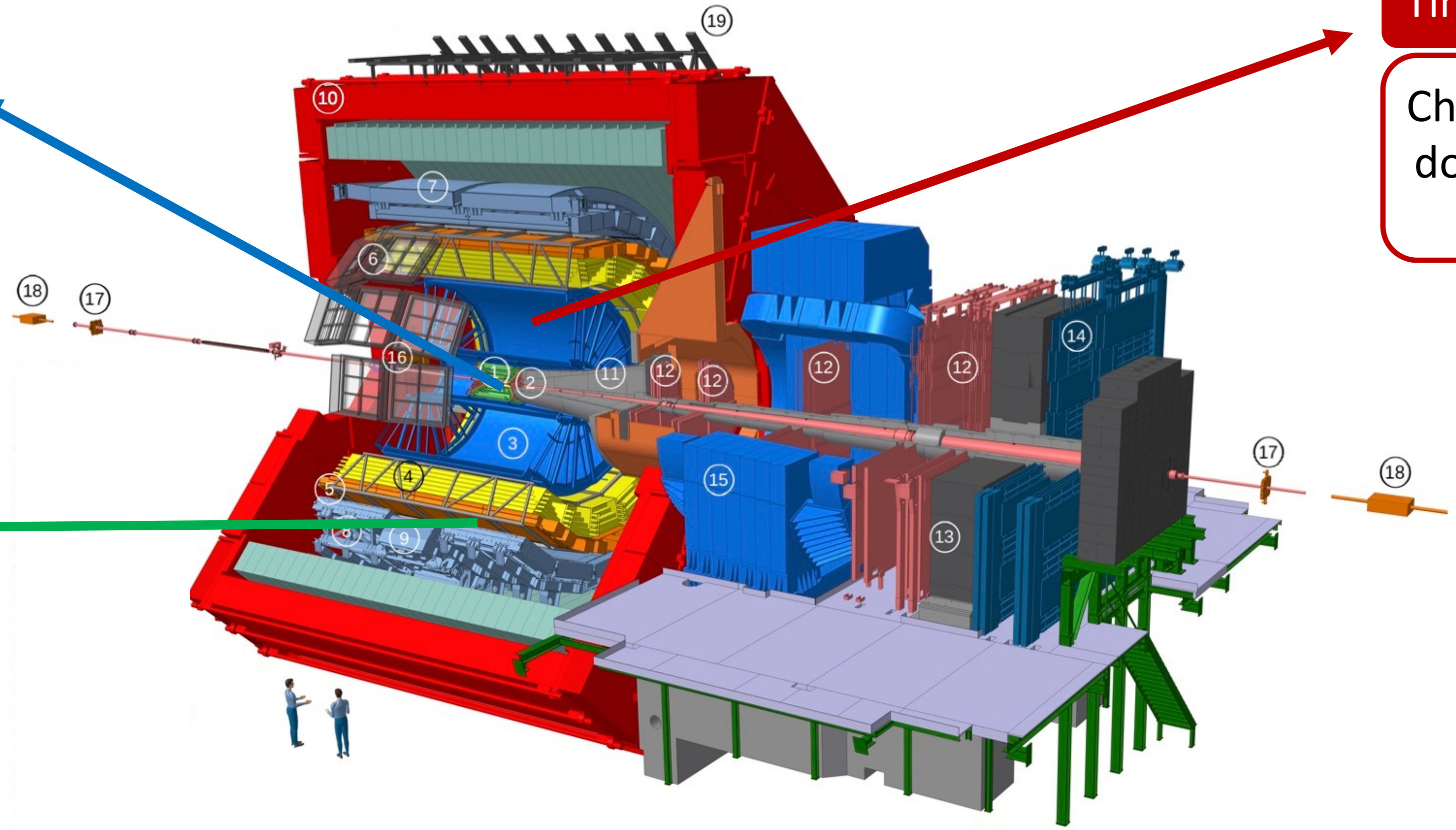
The ALICE detector

Inner Tracking System

Charged particle tracking with 60 µm impact parameter resolution at p_T = 1 GeV/c

Time of Flight Detector

PID separation with 60 ps resolution



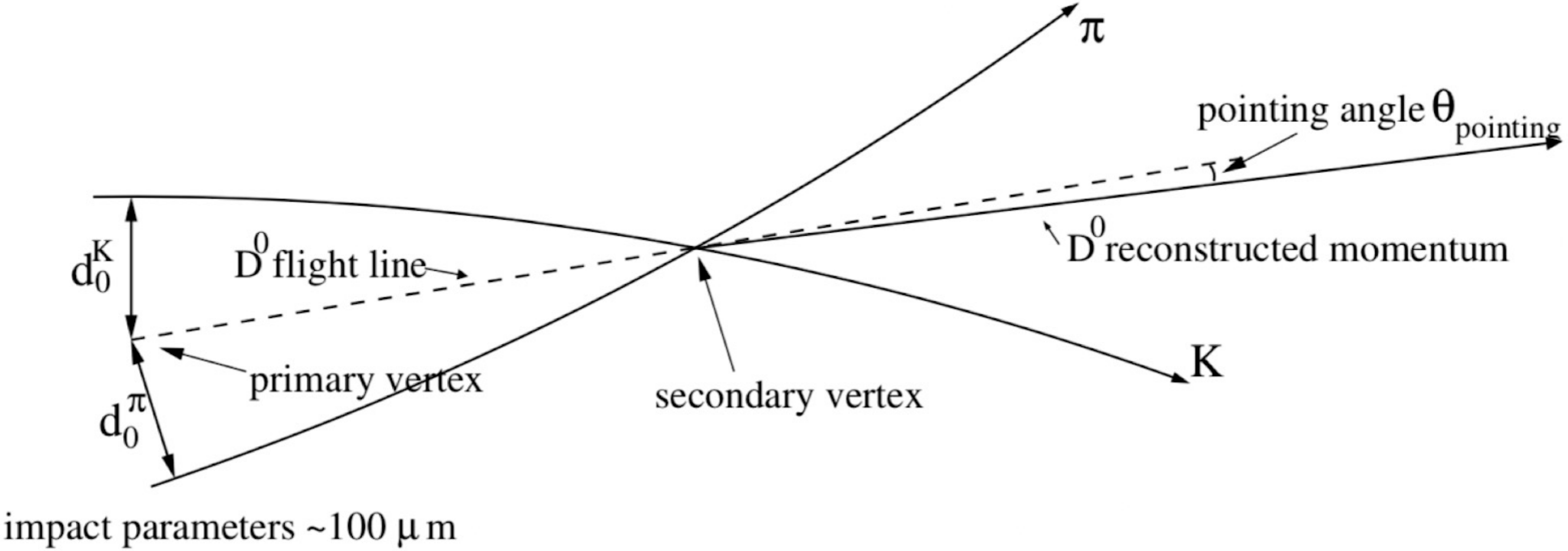
Time Projection Chamber

Charged particle tracking down to p_T = 150 MeV/c and PID separation

$$|\eta| < 0.9$$

Ideal for track–based heavy-flavour jets tagged with a fully reconstructed heavy-flavour hadron at low p_T where mass effects are most significant

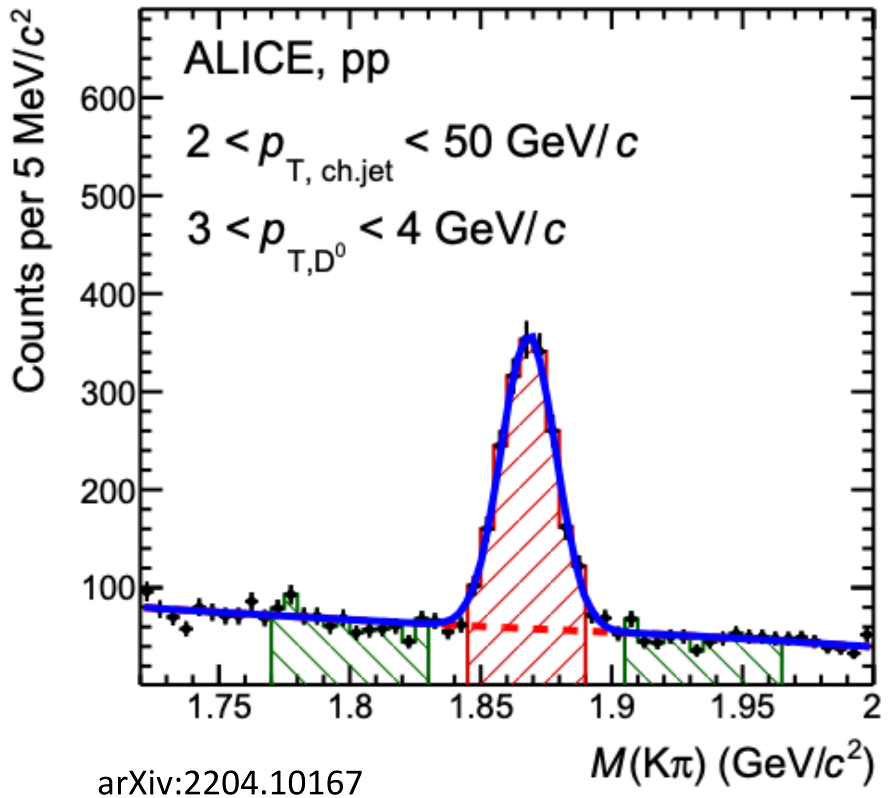
Fully reconstructing the charm hadron



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

Decay topology and PID selections are applied to identify D^0-meson candidates

Extracting the D^0-meson signal



arXiv:2204.10167

Measurement performed with Run 2 pp data from 2016, 2017 and 2018

$$\mathcal{L}_{\rm int} = 25\,{\rm nb}^{-1}$$

Track-based jets clustered with the anti-k_T algorithm with R=0.4 M. Cacciari et al. JHEP 04(2008)063

$$5 < p_{\rm T}^{\rm jet} < 50 \ {\rm GeV/c}$$

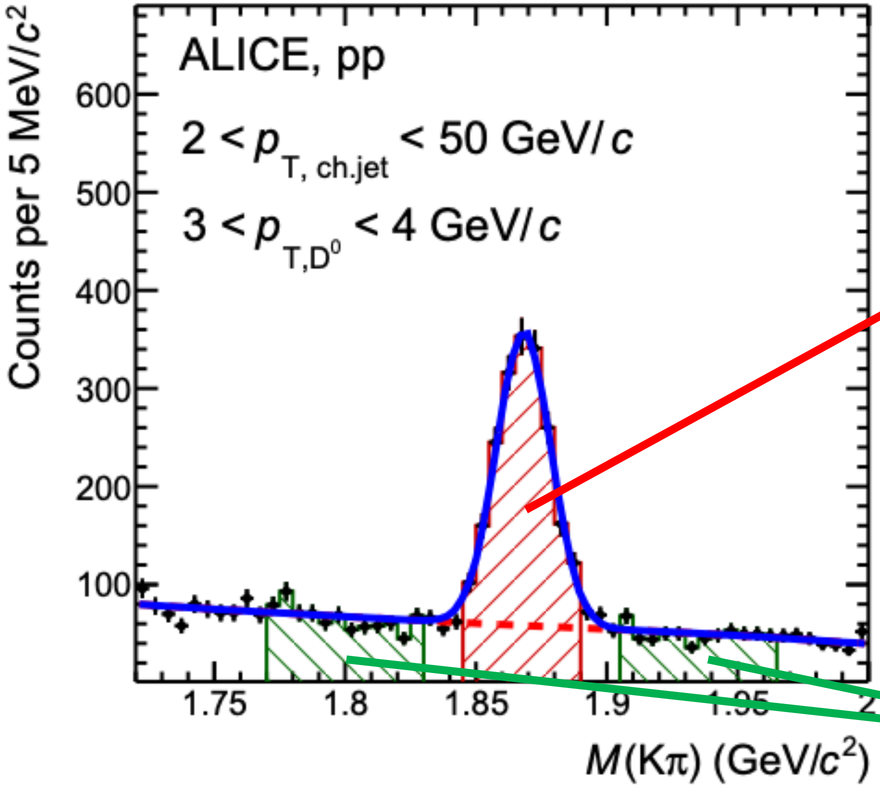
Measurements pushed to low p_T where the emitting charm has a large dead cone

$$2 < p_{\rm T}^{\rm D^0} < 36 \ {\rm GeV/c}$$

Extracting the D^0-meson signal

$\sigma_{\rm fit}$ Gaussian width

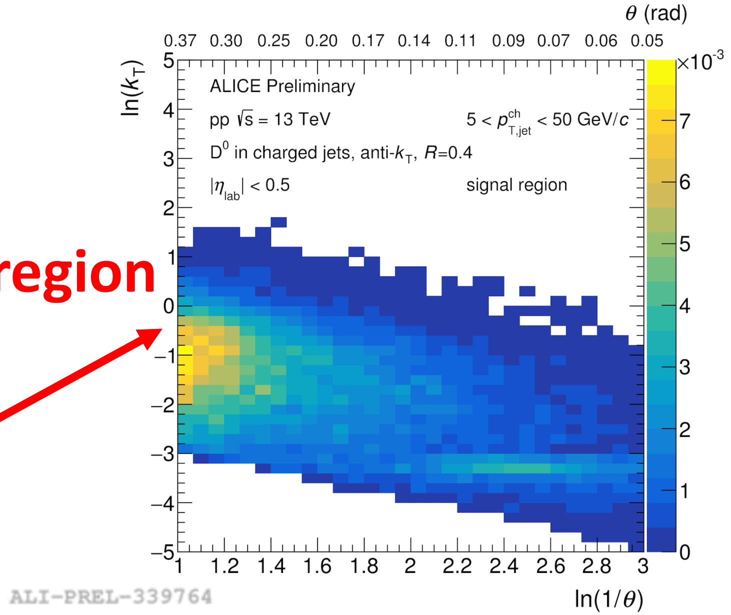
$\mu_{\rm fit}$ Gaussian mean

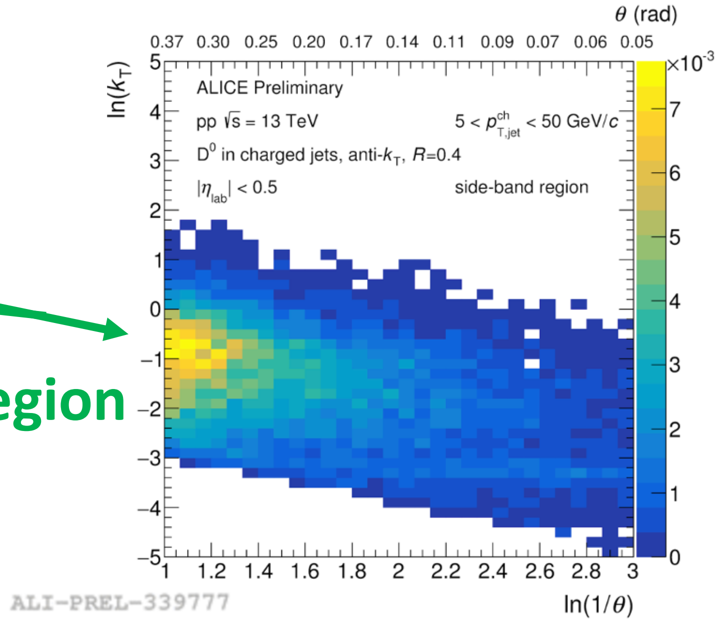


signal region

sideband region

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





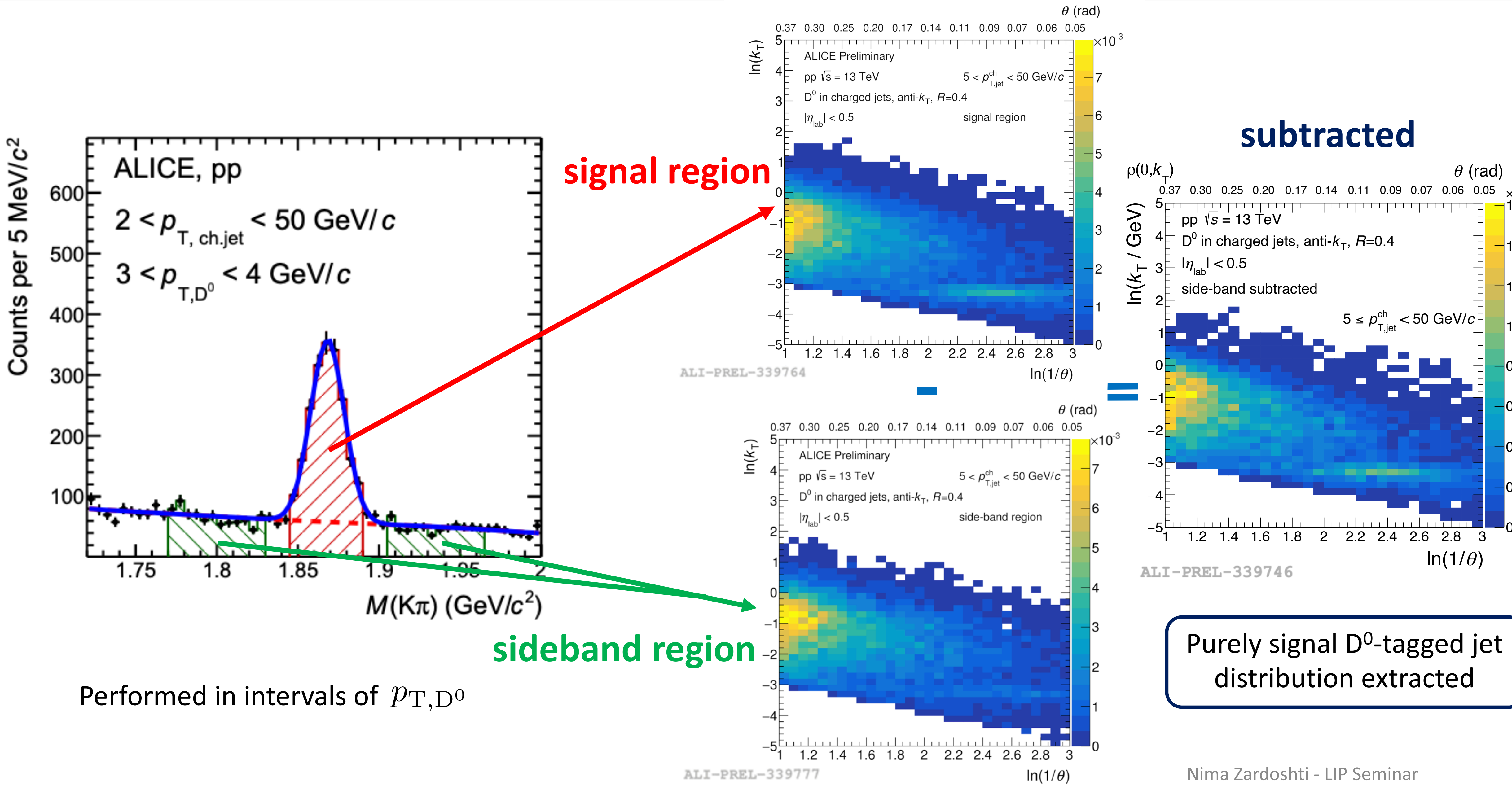
$|M - \mu_{\rm fit}| < 2\sigma_{\rm fit}$

Contains almost all of the signal and some background candidates

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

Entirely composed of background candidates

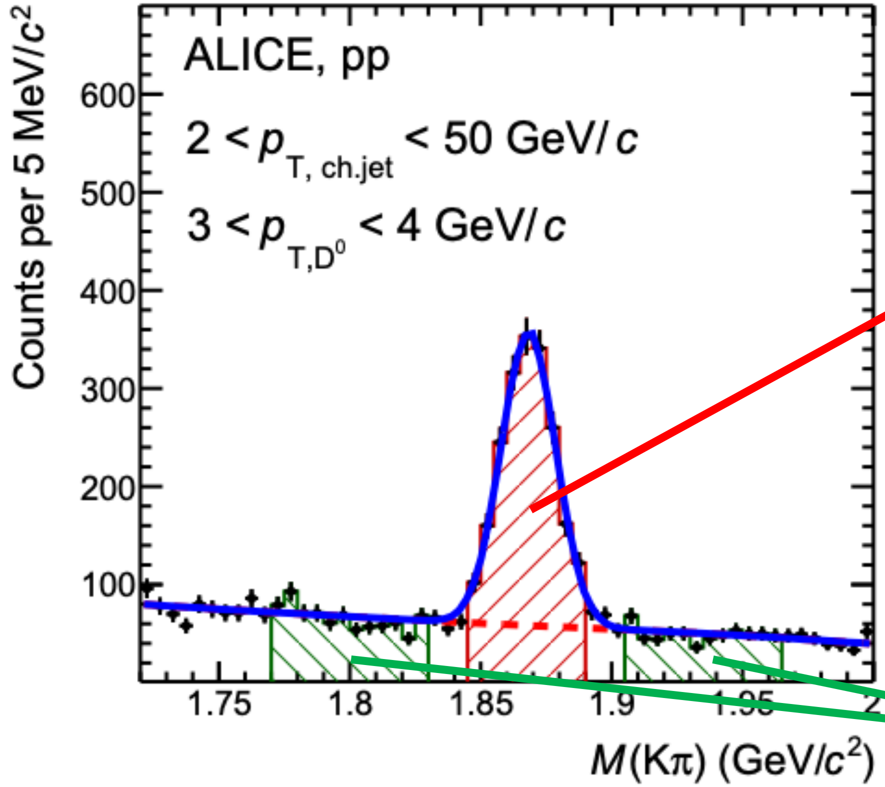
Extracting the D^0-meson signal



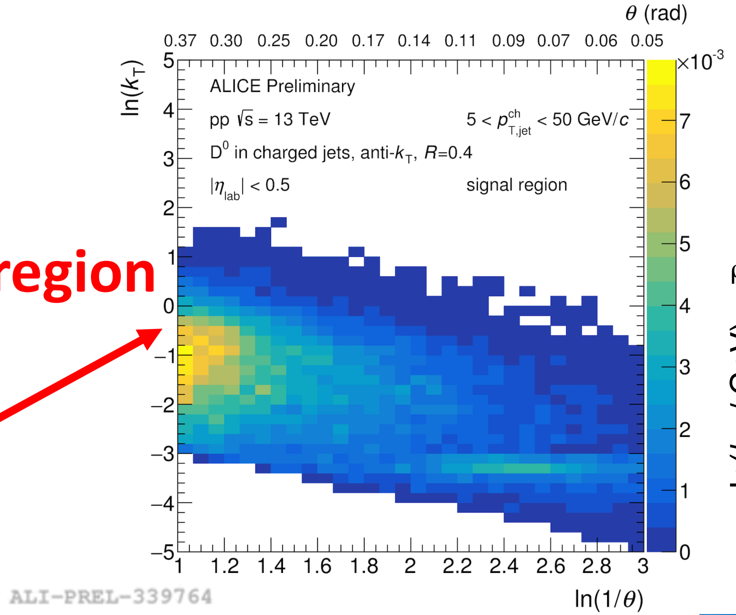
Performed in intervals of $p_{\mathrm{T,D^0}}$

Purely signal D^0-tagged jet distribution extracted

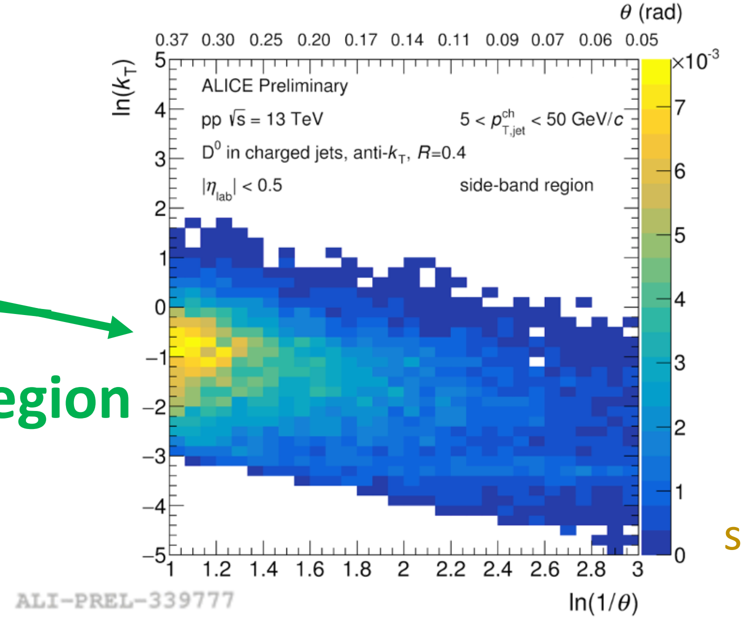
Extracting the D^0-meson signal



signal region



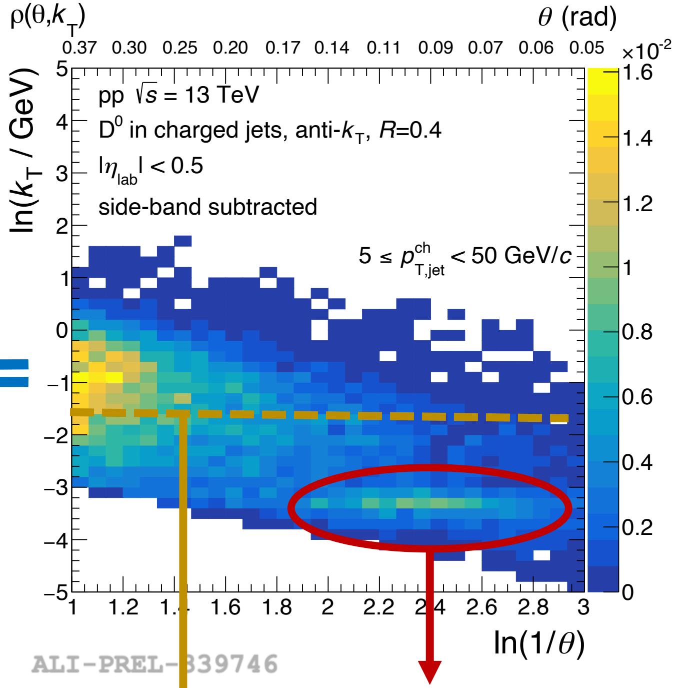
sideband region



-

=

subtracted

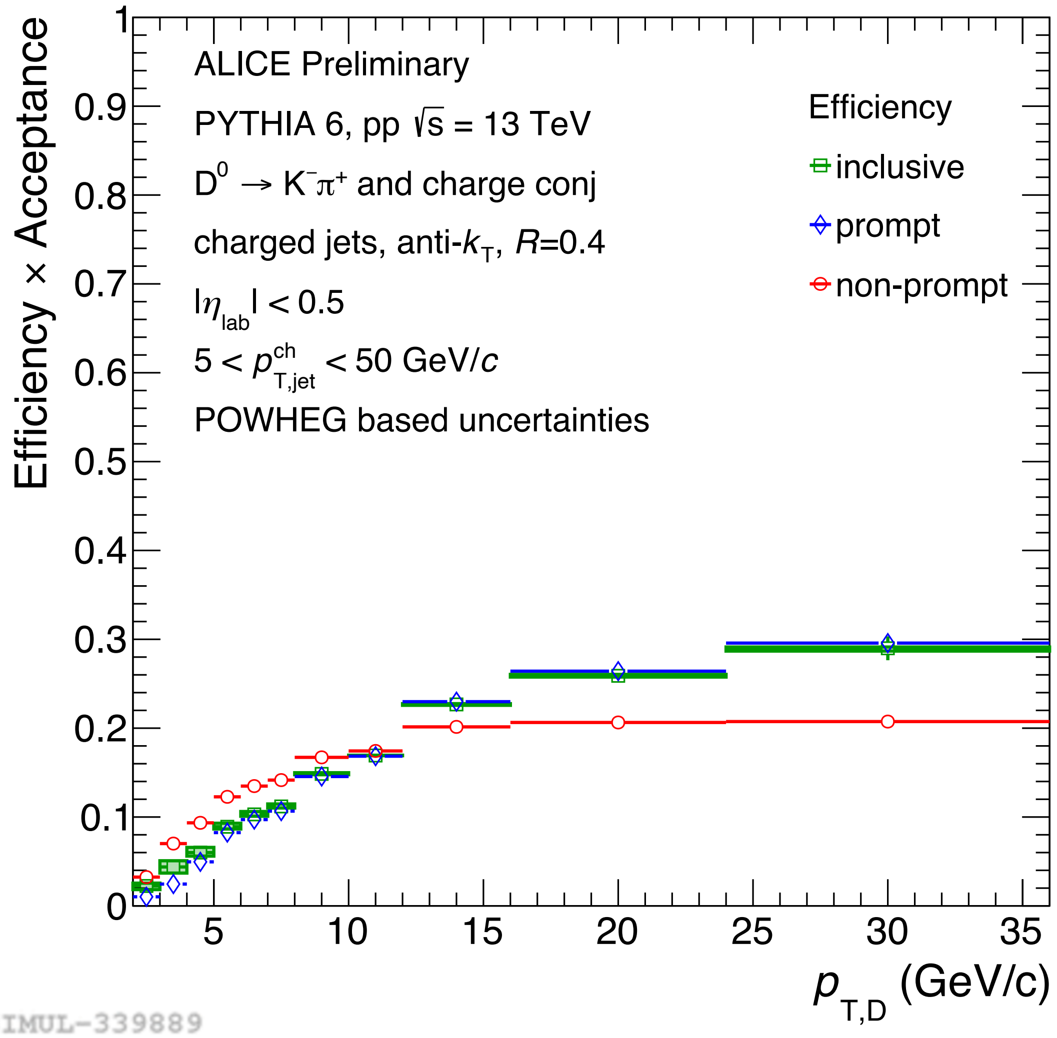


Soft π from D^* decays

Selection in k_T of emissions suppresses non-perturbative effects

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

Correction for D^0-jet reconstruction efficiency



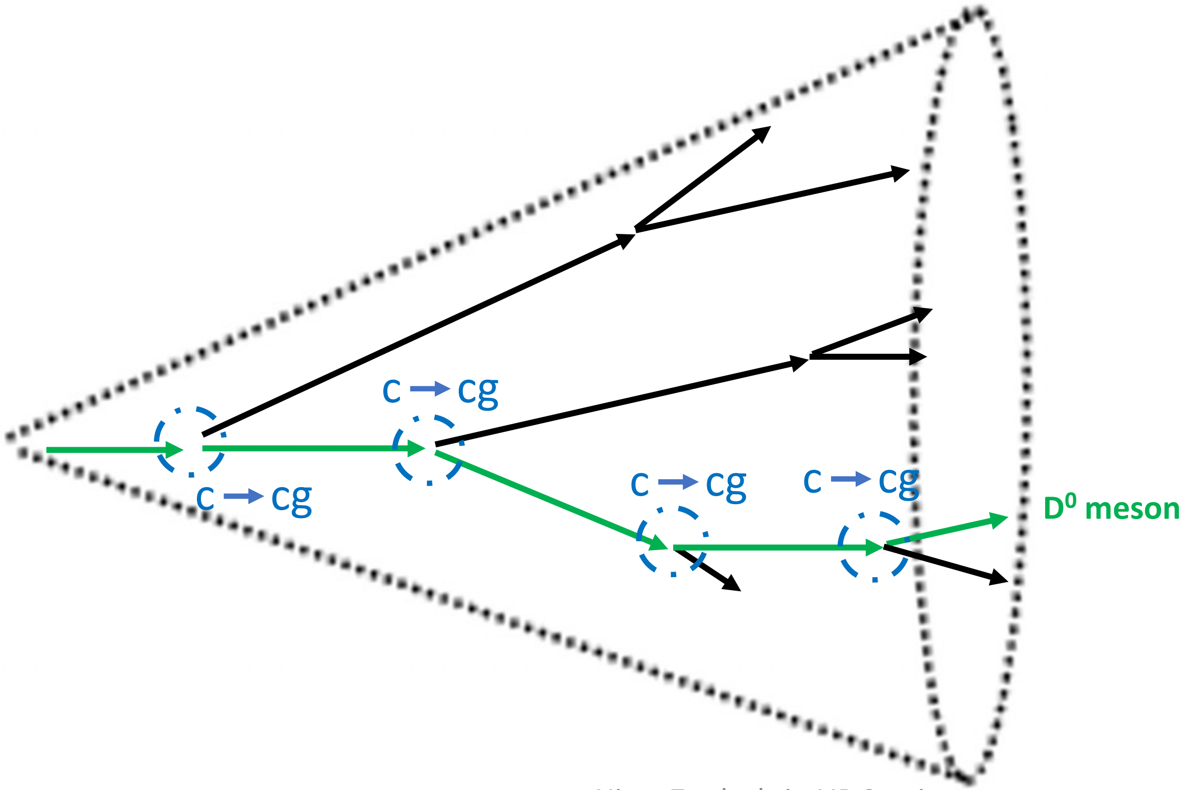
The efficiency of reconstructing D^0-tagged jet candidates is strongly $p_{\mathrm{T,D^0}}$ dependent

Each side-band subtracted distribution is corrected by the appropriate efficiency

Sum the corrected distributions over the $p_{\mathrm{T,D^0}}$ Intervals

Populating the c->cg Lund plane

By fully reconstructing the D^0-meson and following it in the shower we have isolated c -> cg splittings



Populating the c->cg Lund plane

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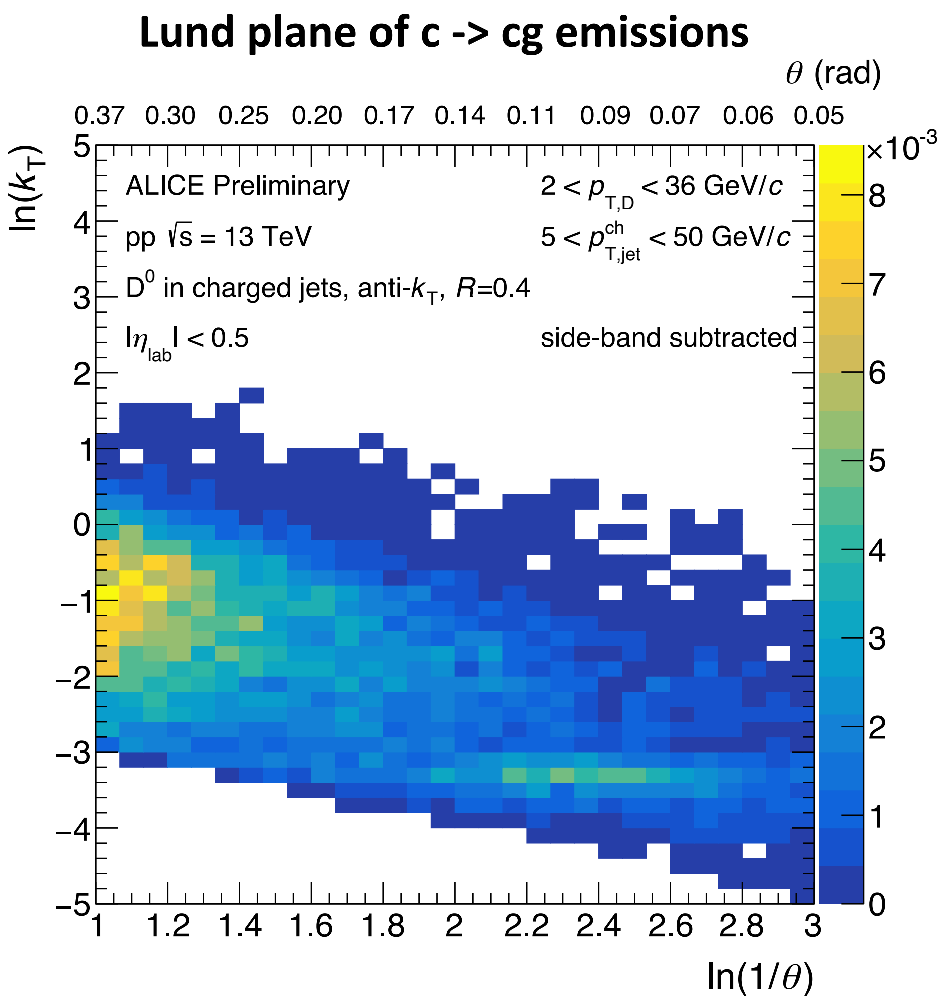
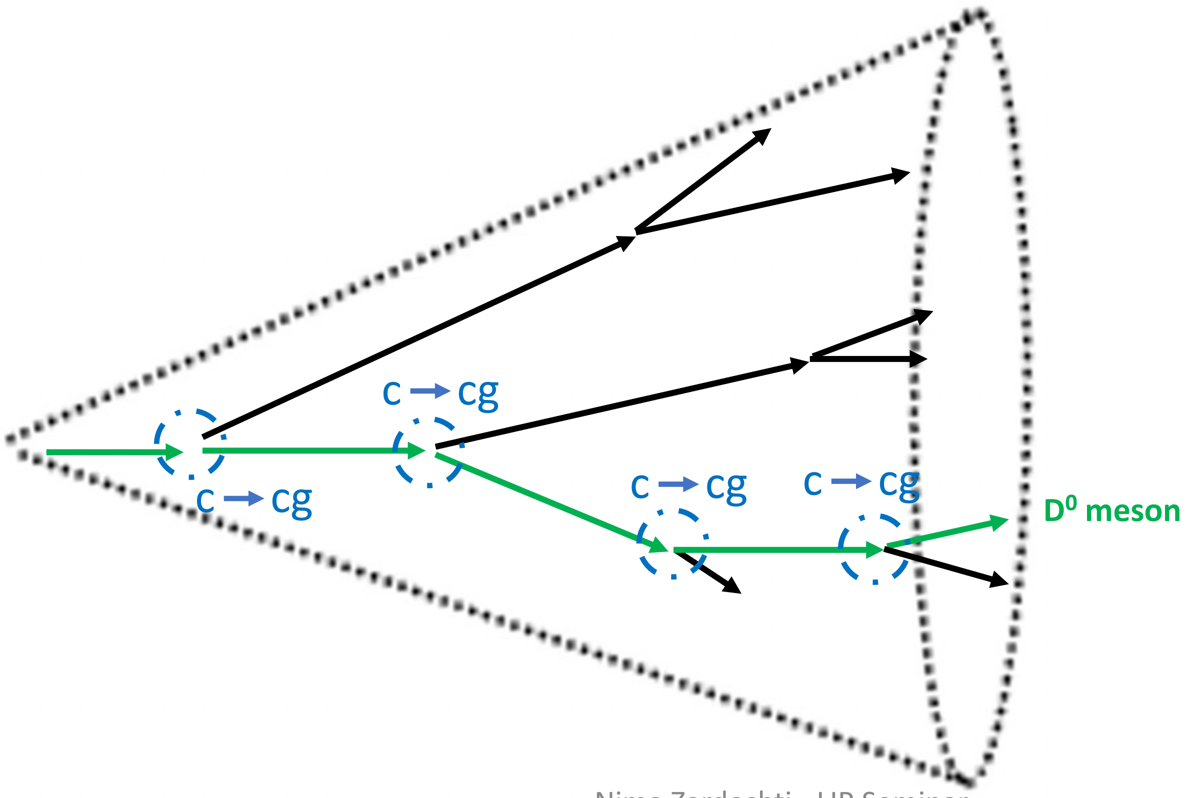
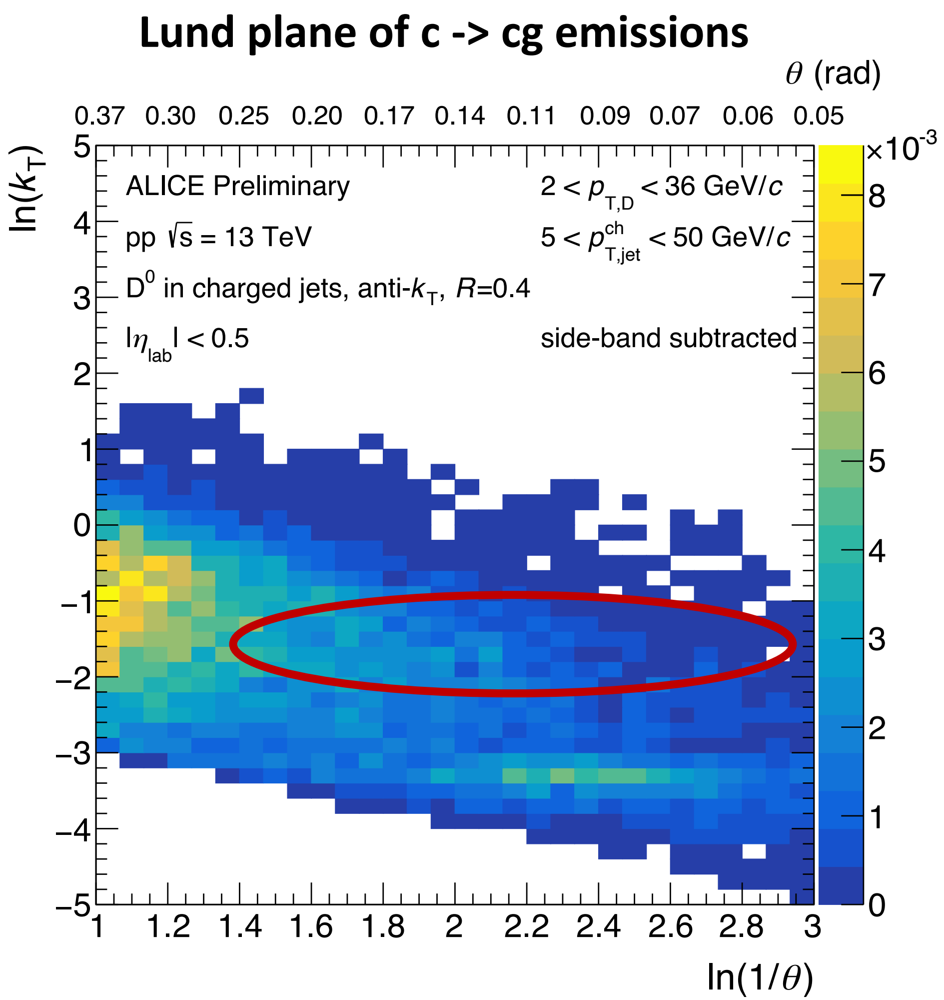


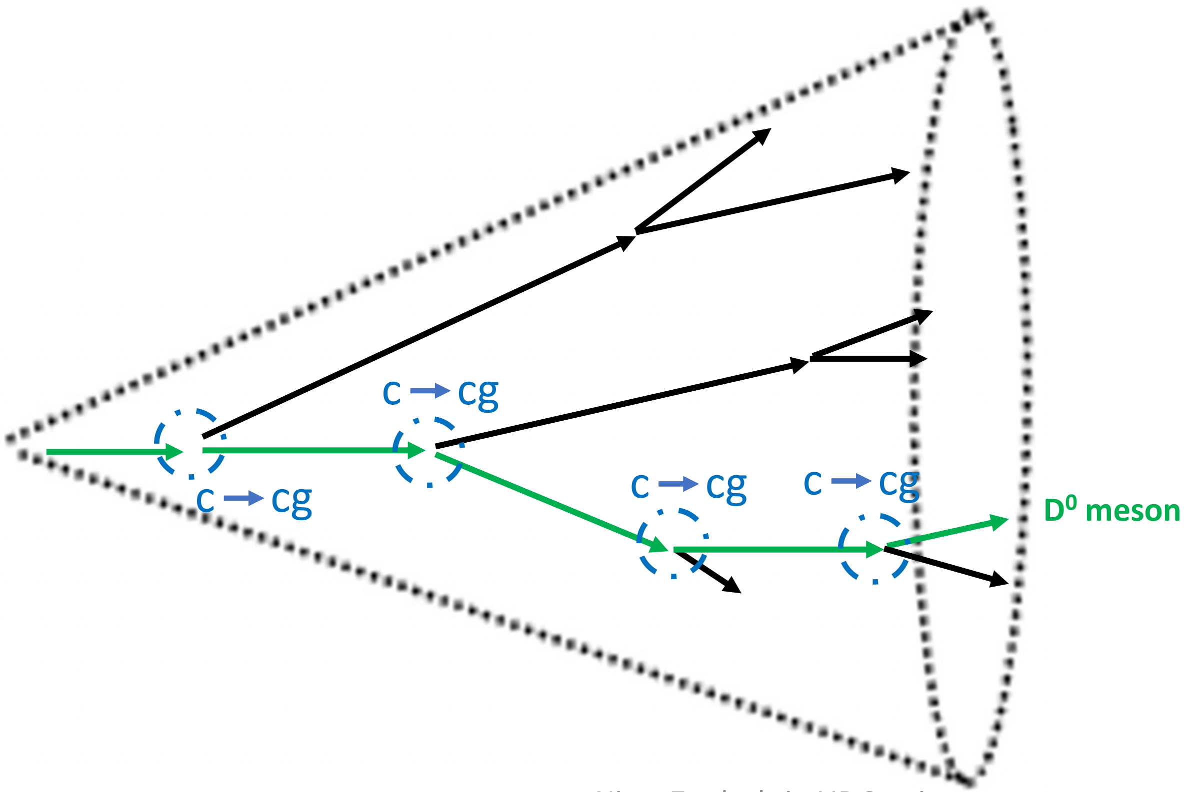
Smaller angles



Populating the c->cg Lund plane



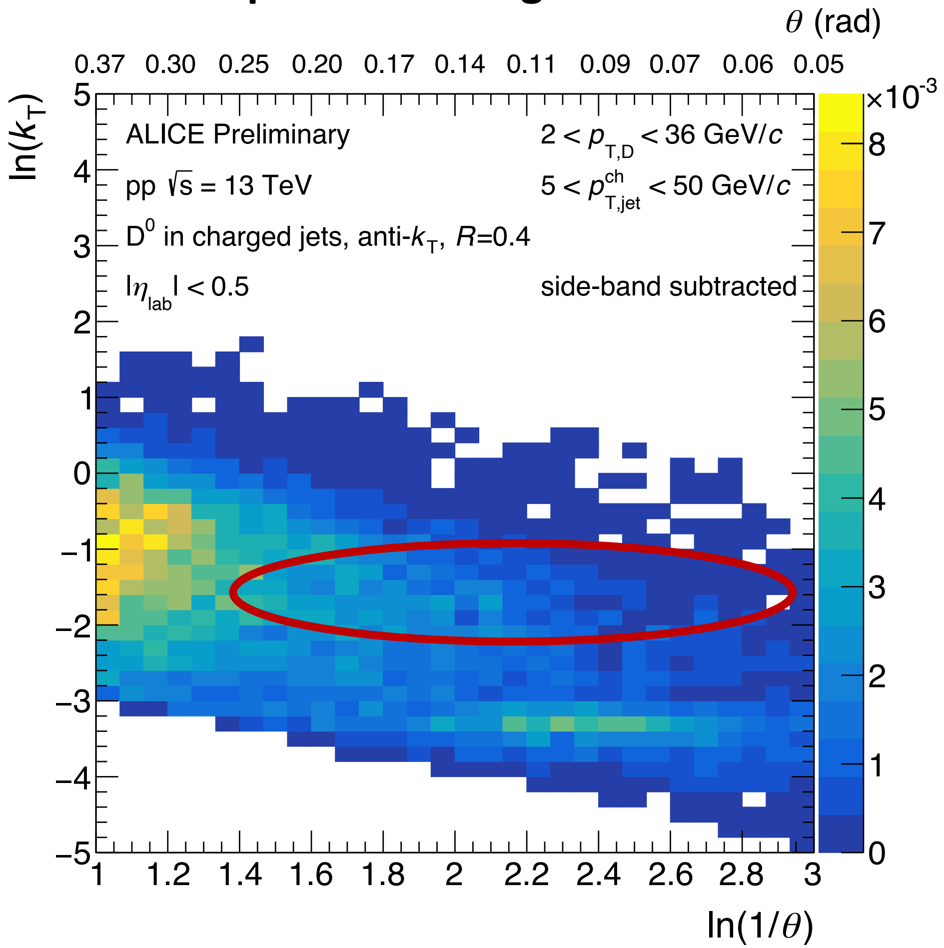
By fully reconstructing the D^0-meson and following it in the shower we have isolated c -> cg splittings



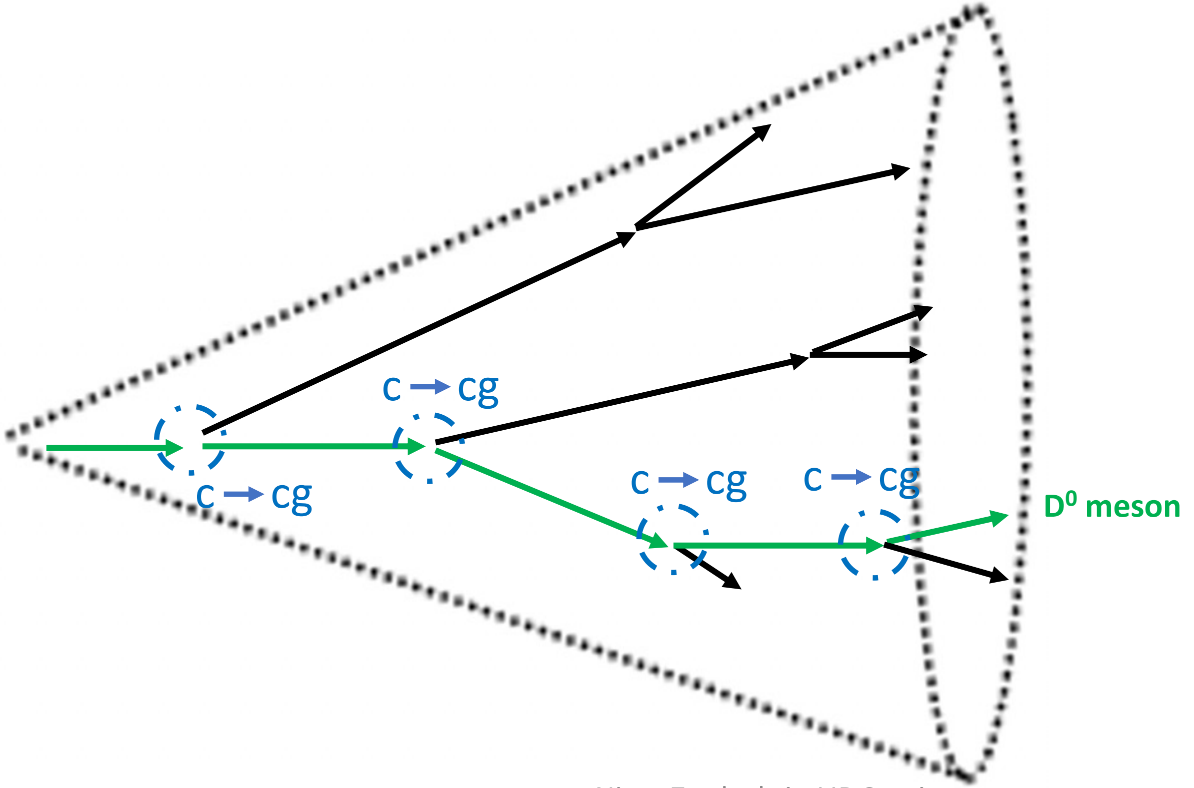
The signature of a significant dead cone in the charm-quark emissions would be a suppression of small angle emissions

Populating the c->cg Lund plane

Lund plane of c -> cg emissions

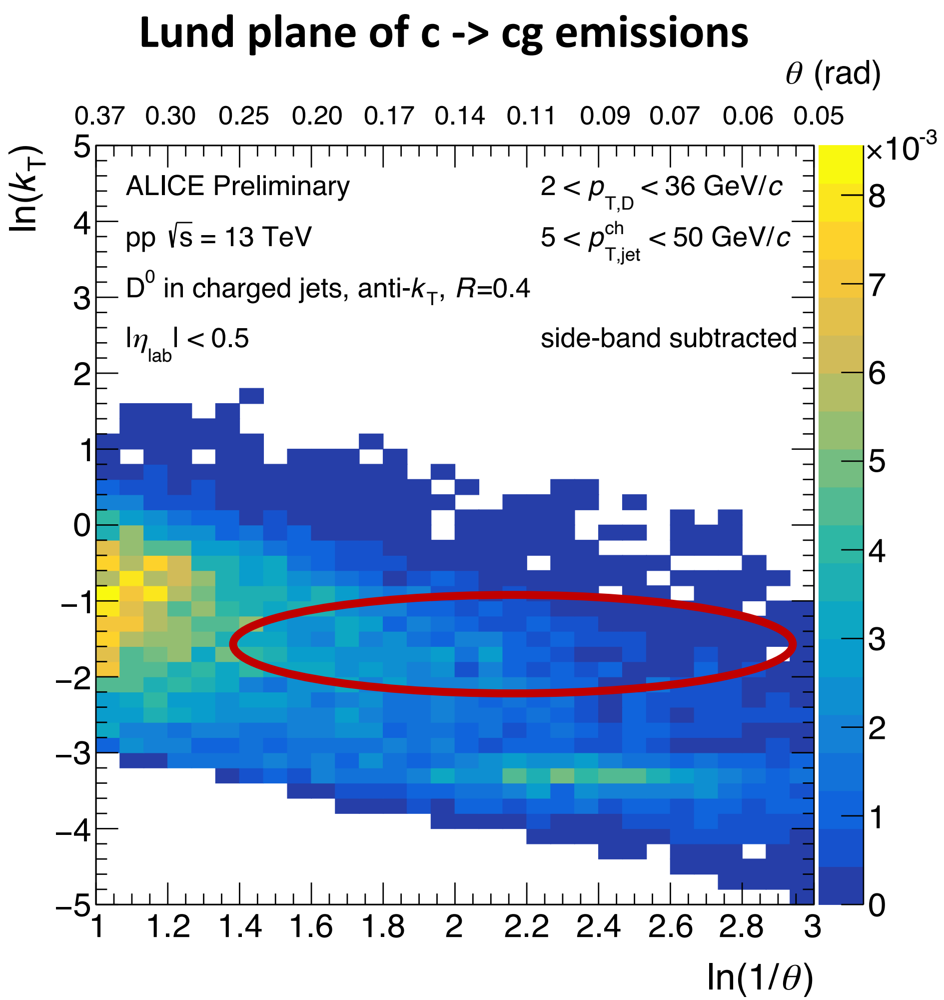


Can we construct a baseline where a dead cone is not expected?



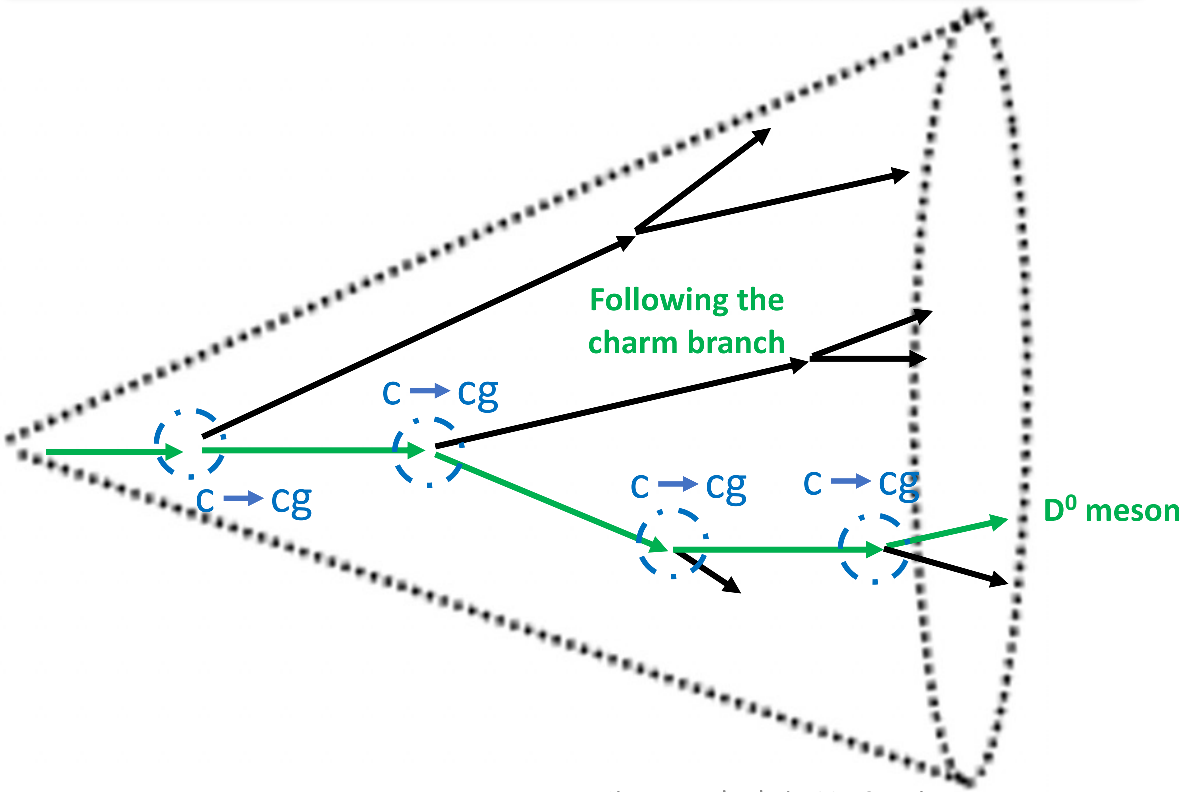
The signature of a significant dead cone in the charm-quark emissions would be a suppression of small angle emissions

Populating the c->cg Lund plane



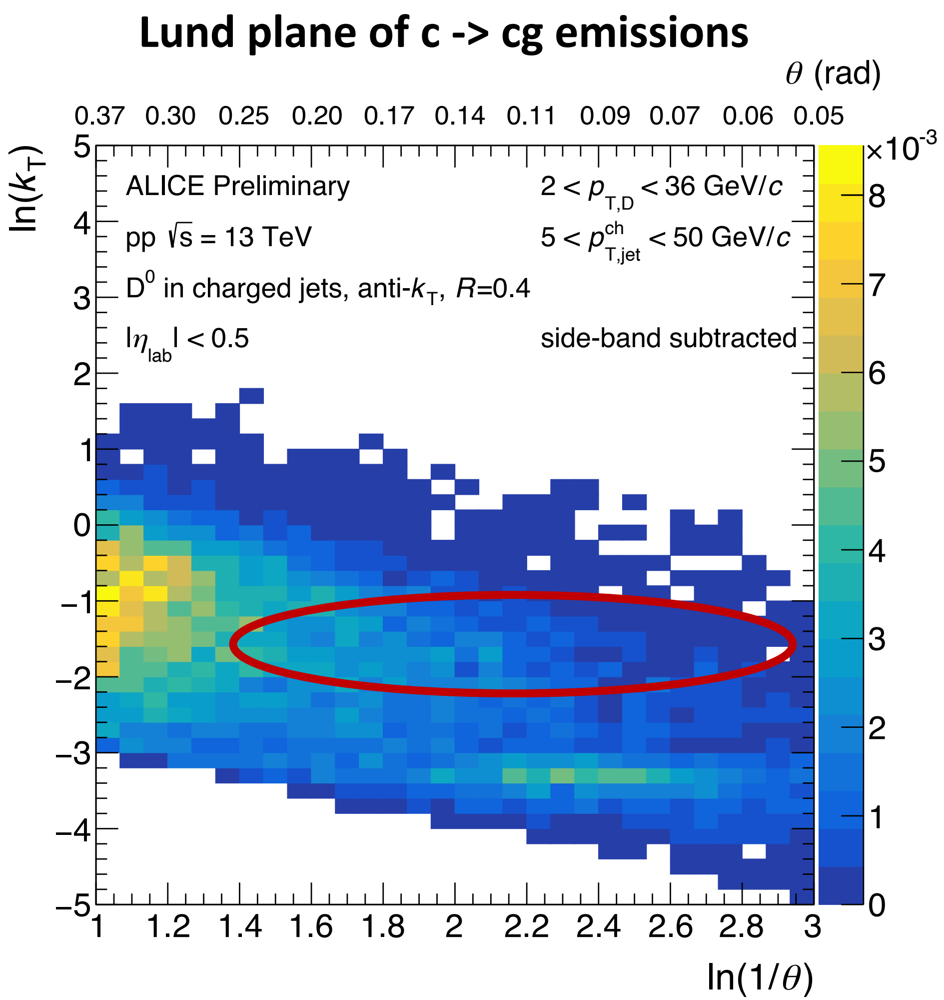
Can we construct a baseline where a dead cone is not expected?

Following the charm quark through the shower coincides with following the hardest prong in 99% of cases



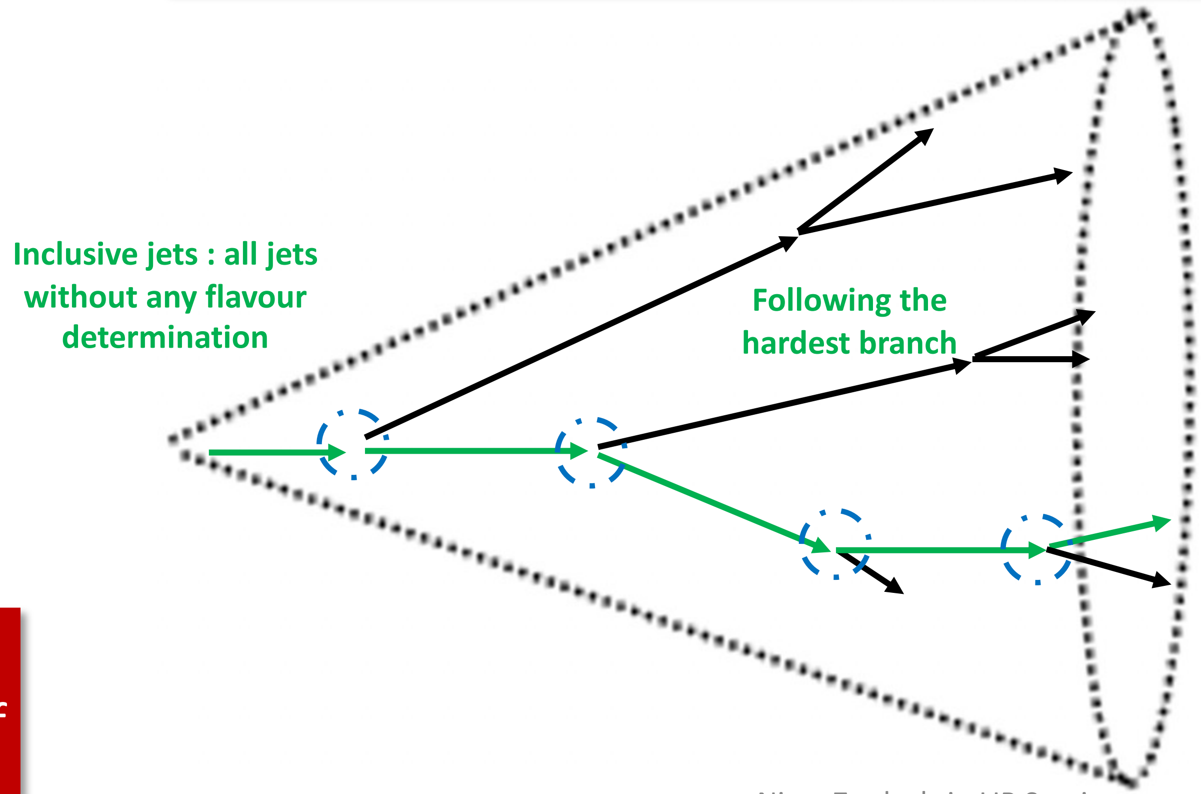
The signature of a significant dead cone in the charm-quark emissions would be a suppression of small angle emissions

Populating the c->cg Lund plane



Can we construct a baseline where a dead cone is not expected?

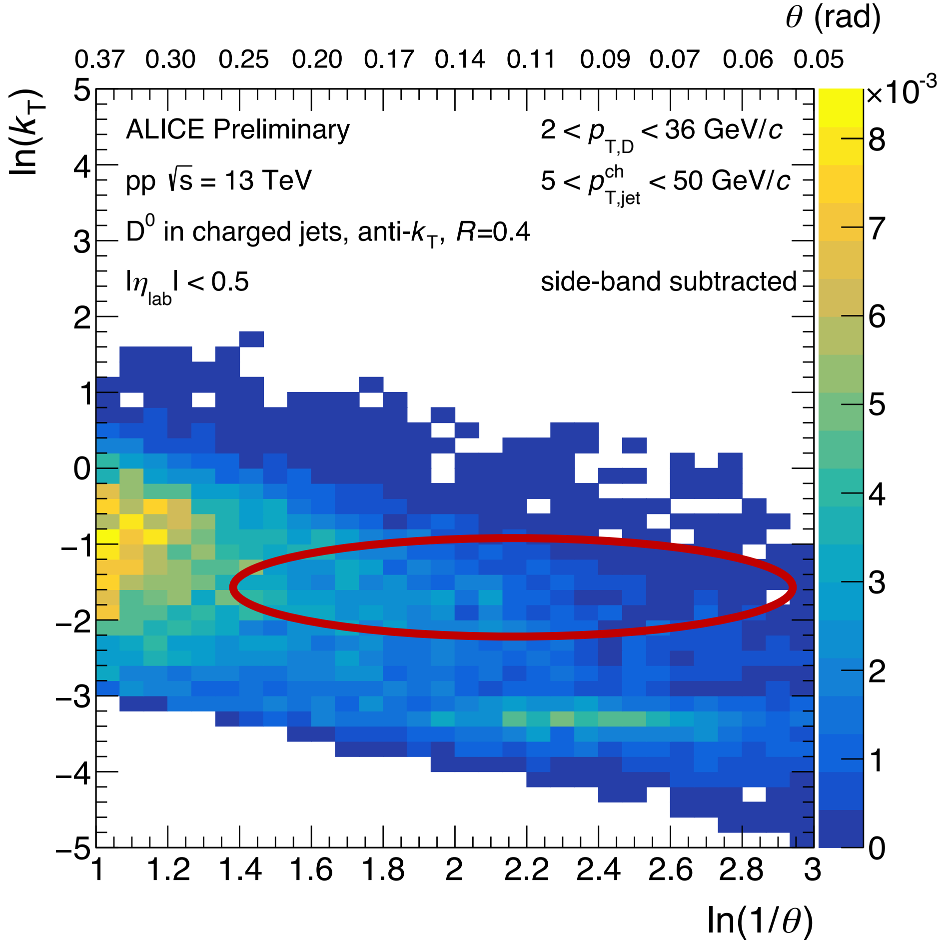
We can implement a complementary procedure in a non-flavour tagged jet sample to study emissions from light quarks and gluons



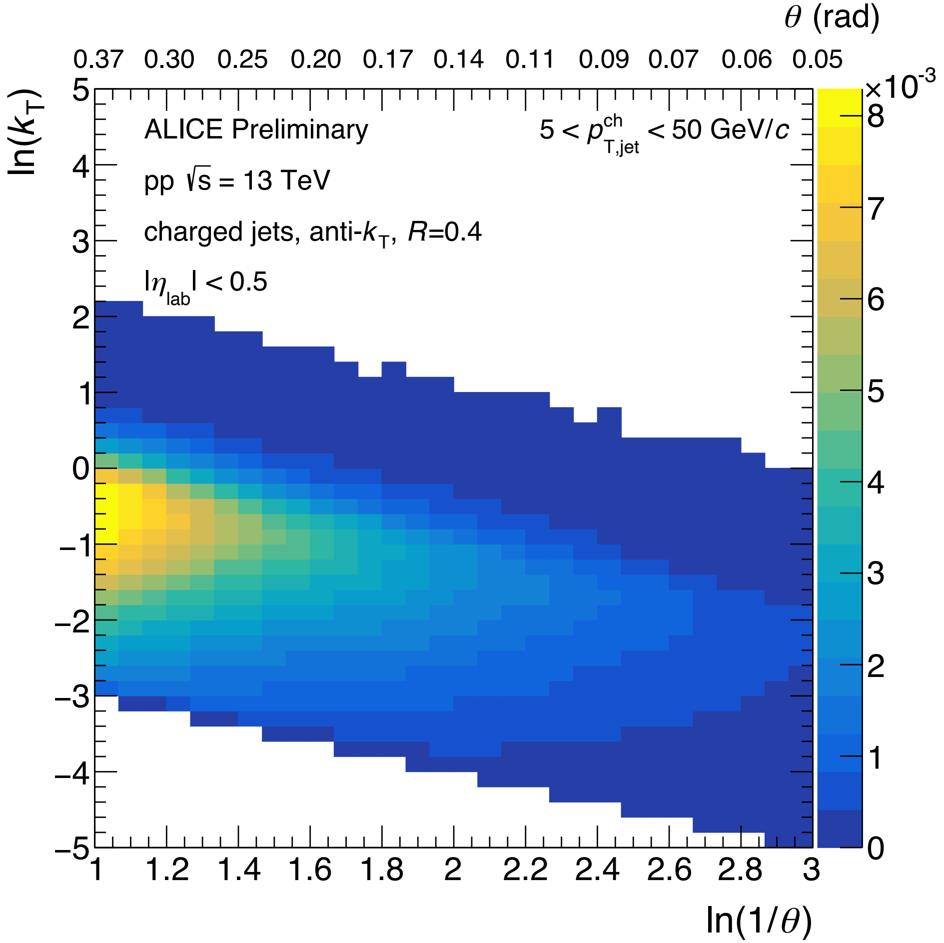
The signature of a significant dead cone in the charm-quark emissions would be a suppression of small angle emissions

Populating the c->cg Lund plane

Lund plane of c -> cg emissions



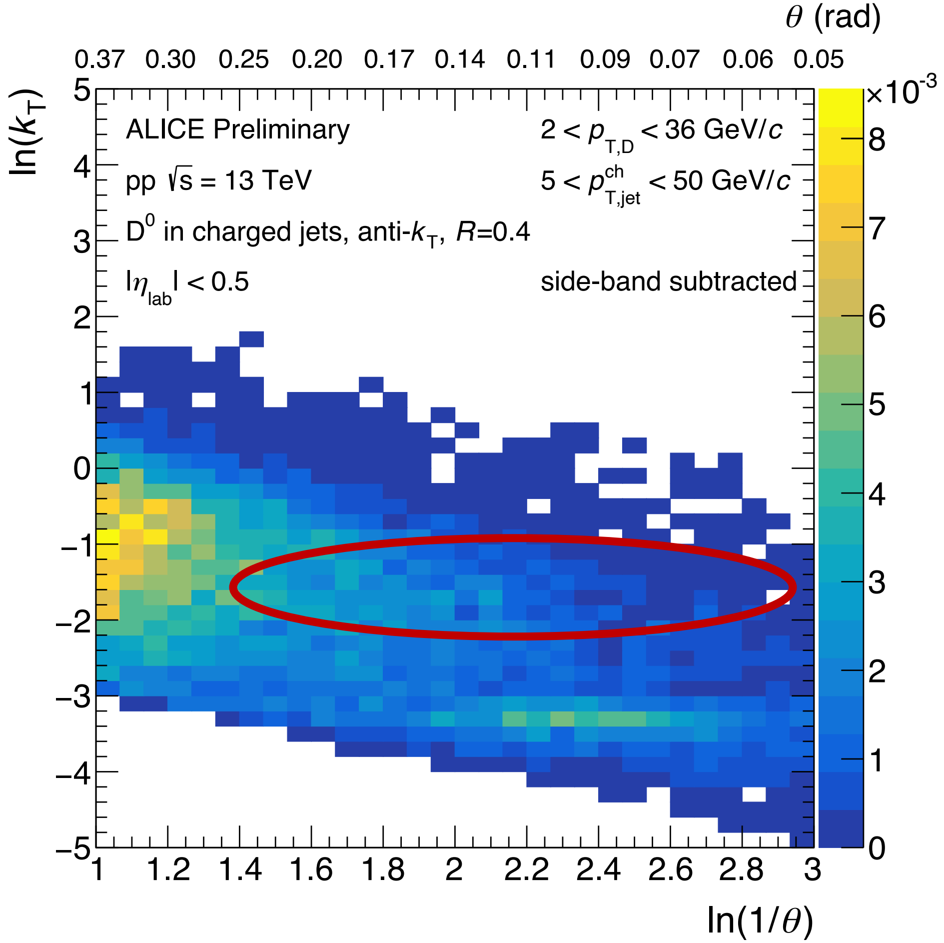
Lund plane of light quark and gluon emissions



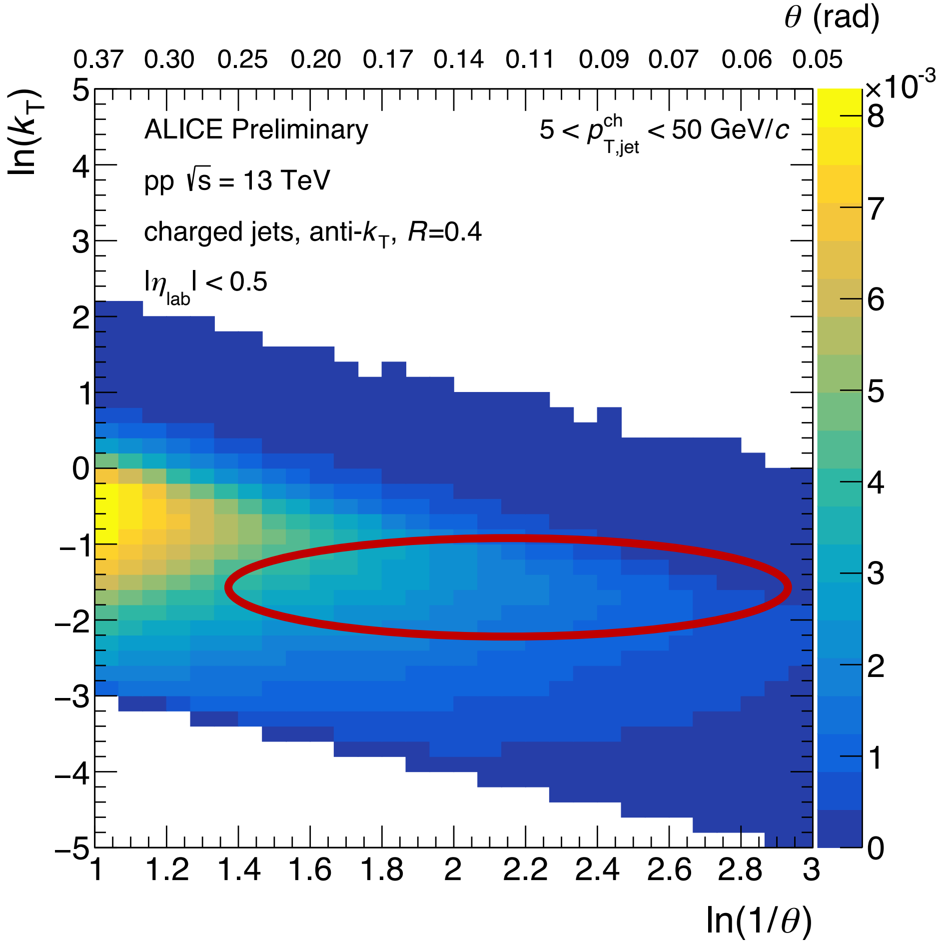
The signature of a significant dead cone in the charm-quark emissions would be a suppression of small angle emissions

Populating the c->cg Lund plane

Lund plane of c -> cg emissions



Lund plane of light quark and gluon emissions



The signature of a significant dead cone in the charm-quark emissions would be a suppression of small angle emissions

No dead-cone effect expected

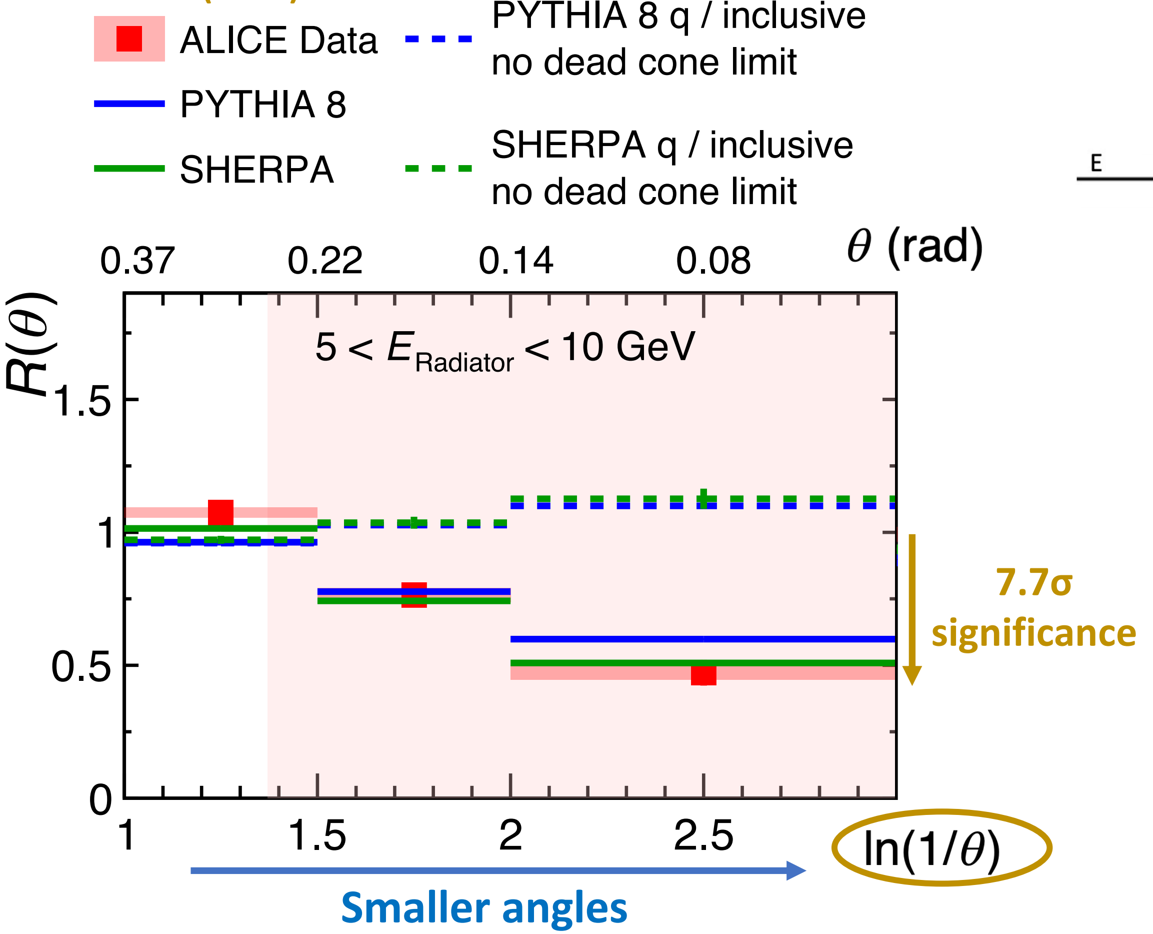
Uncovering the QCD dead cone

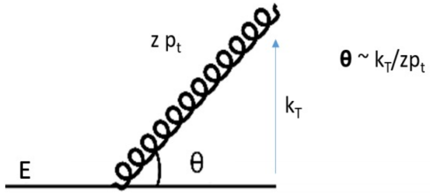
$$R(\theta) = \frac{1}{N^{\mathrm{D^0\,jets}}} \frac{\mathrm{d}n^{\mathrm{D^0\,jets}}}{\mathrm{d}\ln(1/\theta)} \Bigg/ \frac{1}{N^{\mathrm{inclusive\,jets}}} \frac{\mathrm{d}n^{\mathrm{inclusive\,jets}}}{\mathrm{d}\ln(1/\theta)} \Bigg|_{k_{\mathrm{T}},\, E_{\mathrm{Radiator}}}$$

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





The dead cone is uncovered through a direct measurement of the emission angle

Small angle emissions supressed for charm quarks compared to light quarks and gluons

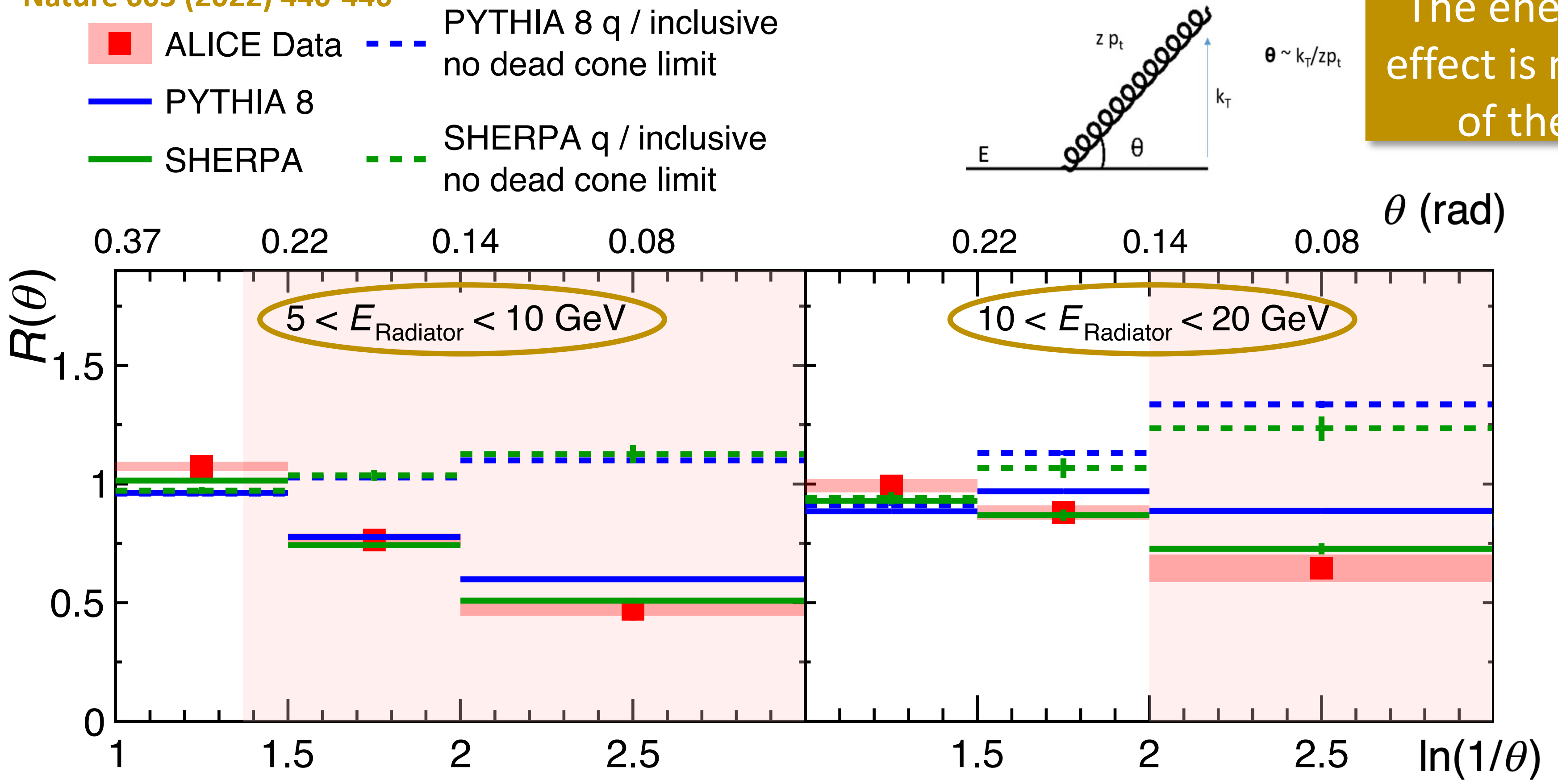
$$R(\theta) = \frac{1}{N^{\mathrm{D^0\,jets}}} \frac{\mathrm{d}n^{\mathrm{D^0\,jets}}}{\mathrm{d}\ln(1/\theta)} \Bigg/ \frac{1}{N^{\mathrm{inclusive\,jets}}} \frac{\mathrm{d}n^{\mathrm{inclusive\,jets}}}{\mathrm{d}\ln(1/\theta)} \Bigg|_{k_{\mathrm{T}}, E_{\mathrm{Radiator}}}$$

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

The energy dependence of the dead-cone effect is measured in intervals of the energy of the charm quark at each emission



less suppression with increasing energy of the radiating charm quark

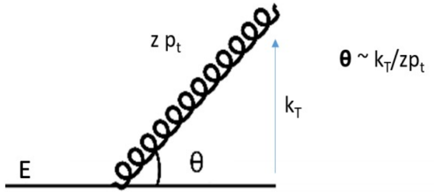
$$R(\theta) = \frac{1}{N^{\mathrm{D^0\,jets}}} \frac{\mathrm{d}n^{\mathrm{D^0\,jets}}}{\mathrm{d}\ln(1/\theta)} \Bigg/ \frac{1}{N^{\mathrm{inclusive\,jets}}} \frac{\mathrm{d}n^{\mathrm{inclusive\,jets}}}{\mathrm{d}\ln(1/\theta)} \Bigg|_{k_{\mathrm{T}}, E_{\mathrm{Radiator}}}$$

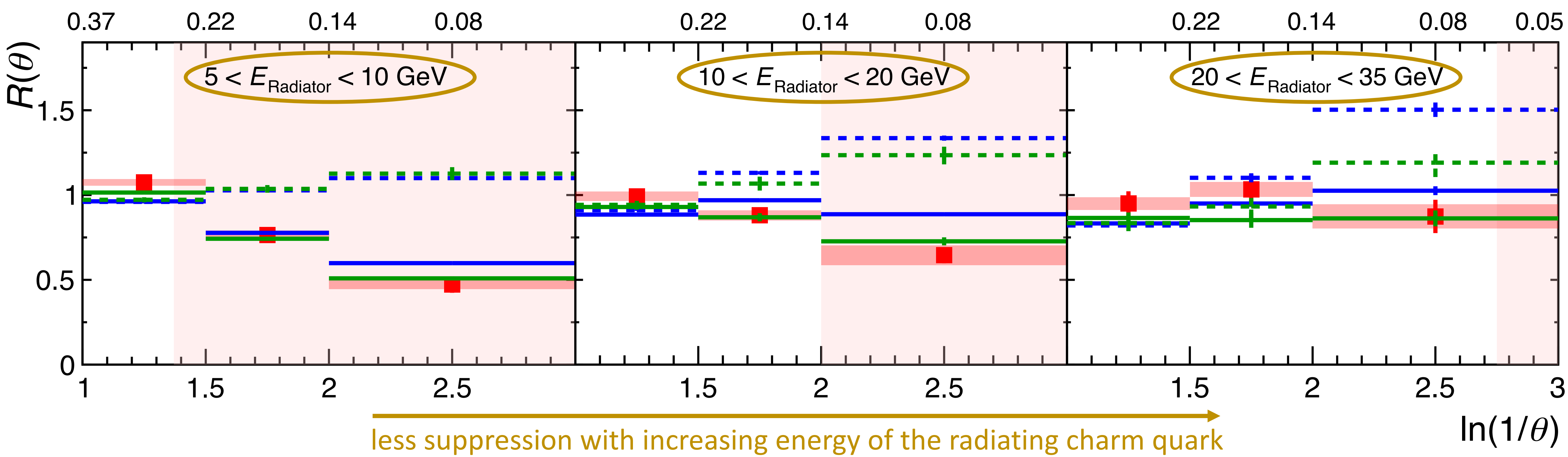
Compare the angular distribution of charm-quark emissions to those of light quarks and gluons

Uncovering the QCD dead cone

Nature 605 (2022) 440-446

The energy dependence of the dead-cone effect is measured in intervals of the energy of the charm quark at each emission





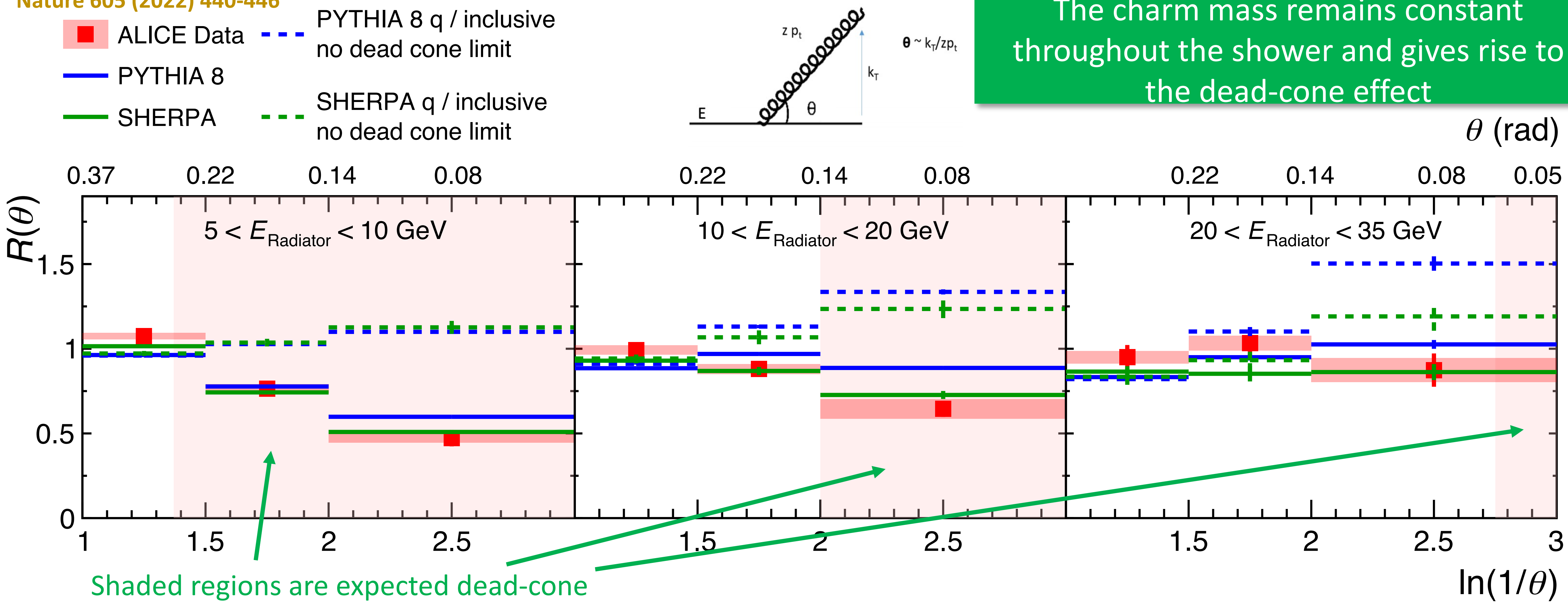
less suppression with increasing energy of the radiating charm quark

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

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



The charm mass remains constant throughout the shower and gives rise to the dead-cone effect

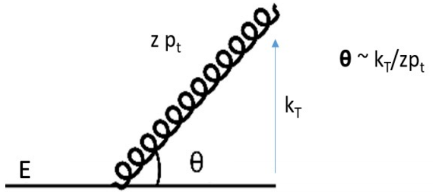
Shaded regions are expected dead-cone region for a charm mass of 1.275 GeV/c

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

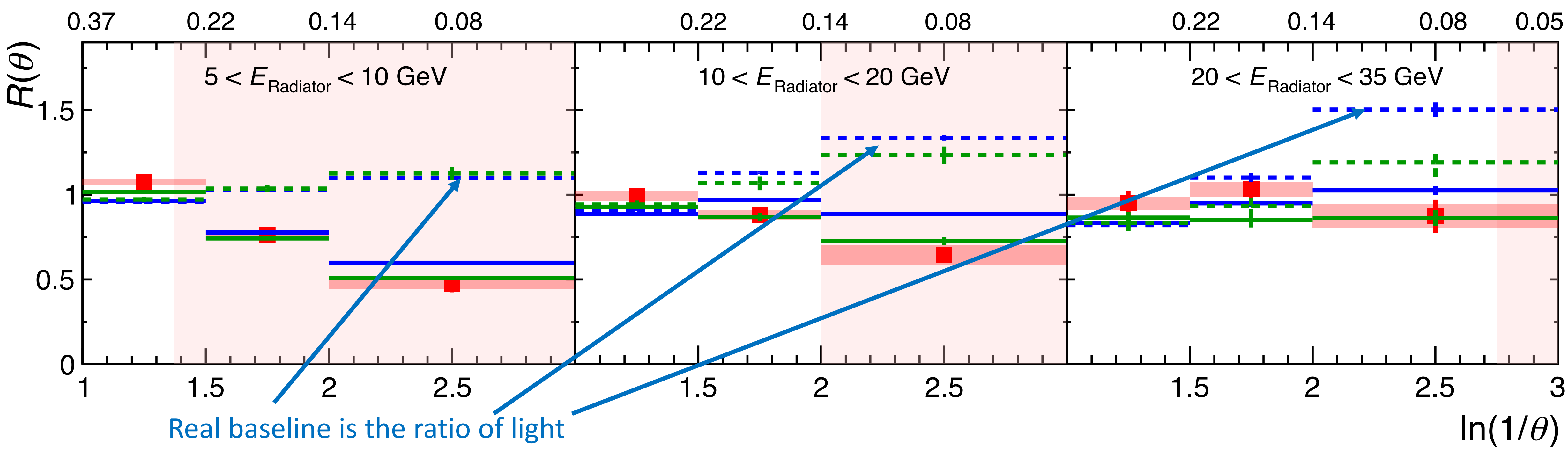
Compare the angular distribution of charm-quark emissions to those of light quarks and gluons

Uncovering the QCD dead cone

Nature 605 (2022) 440-446



The real baseline for the absence of a dead-cone is influenced by the differences between quark and gluon fragmentation



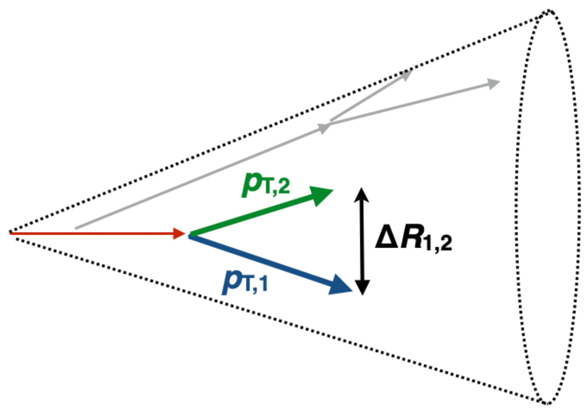
Real baseline is the ratio of light quark to inclusive emissions

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

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

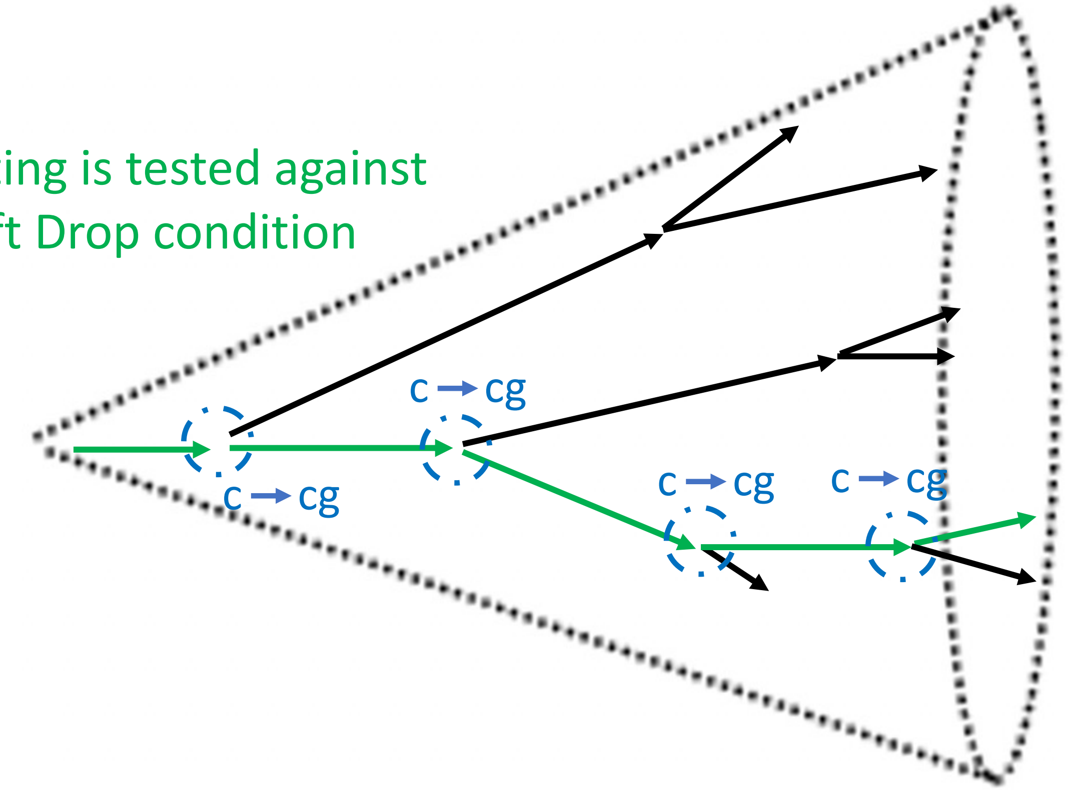
$$z = \frac{p_{T,2}}{p_{T,1} + p_{T,2}} > z_{cut} \left(\frac{\Delta R_{1,2}}{R} \right)^{\beta}$$

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

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

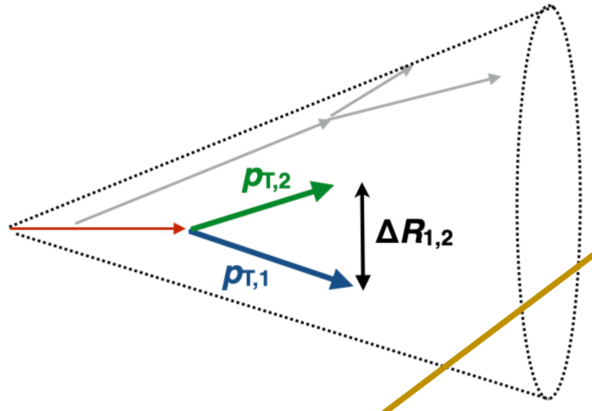
The grooming procedure reduces contribution of non-perturbative effects and enriches the selection with perturbative emissions

Each splitting is tested against the Soft Drop condition



Measuring the c->cg splitting function

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



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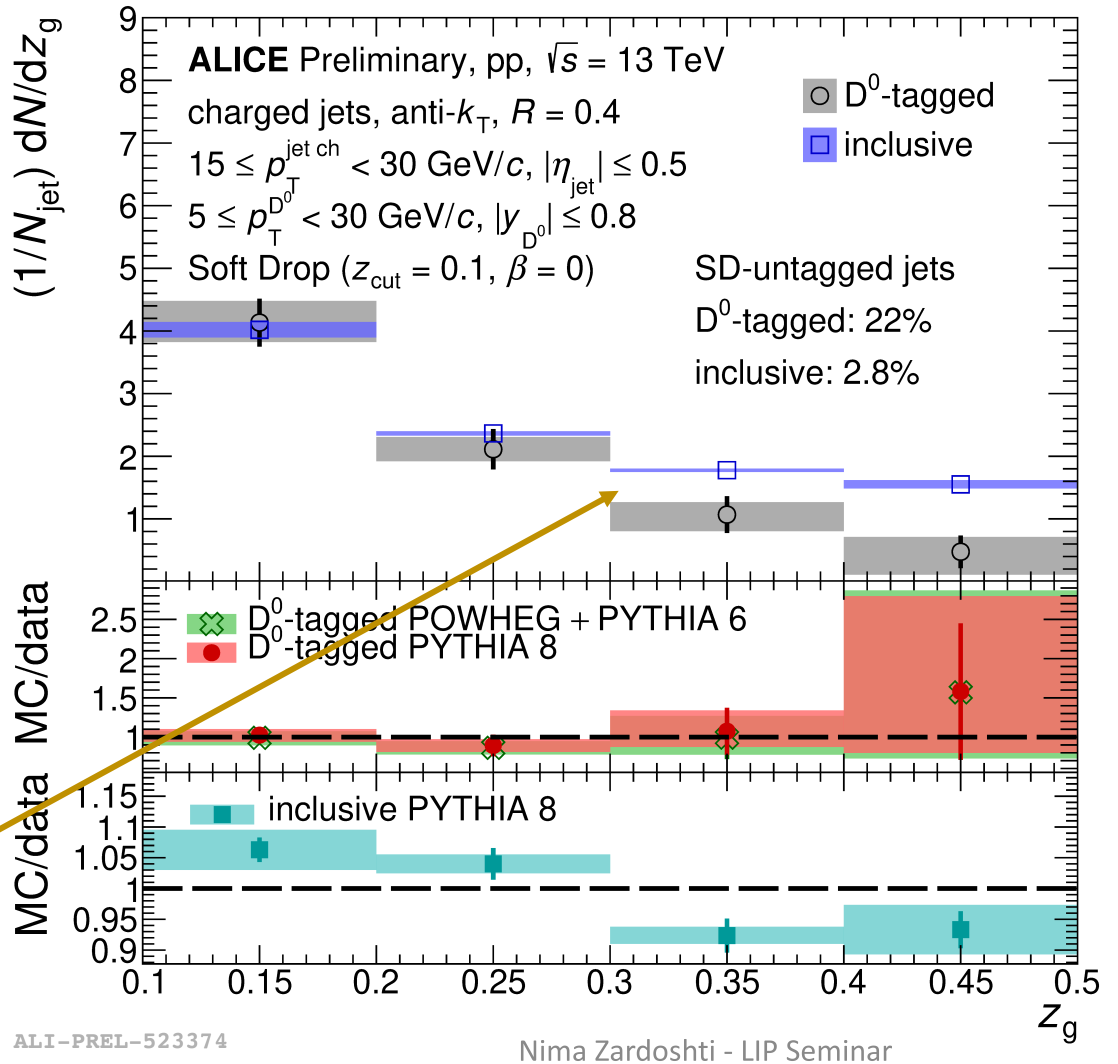
$$z = 0.1, \beta = 0$$

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

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

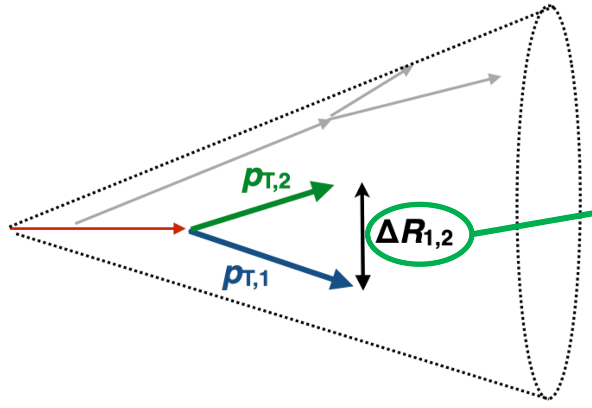
Emissions from charm-quarks have a steeper splitting probability than light quarks and gluons

Fewer symmetric splittings



Measuring the c->cg angular dependence

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



Soft Drop grooming condition

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

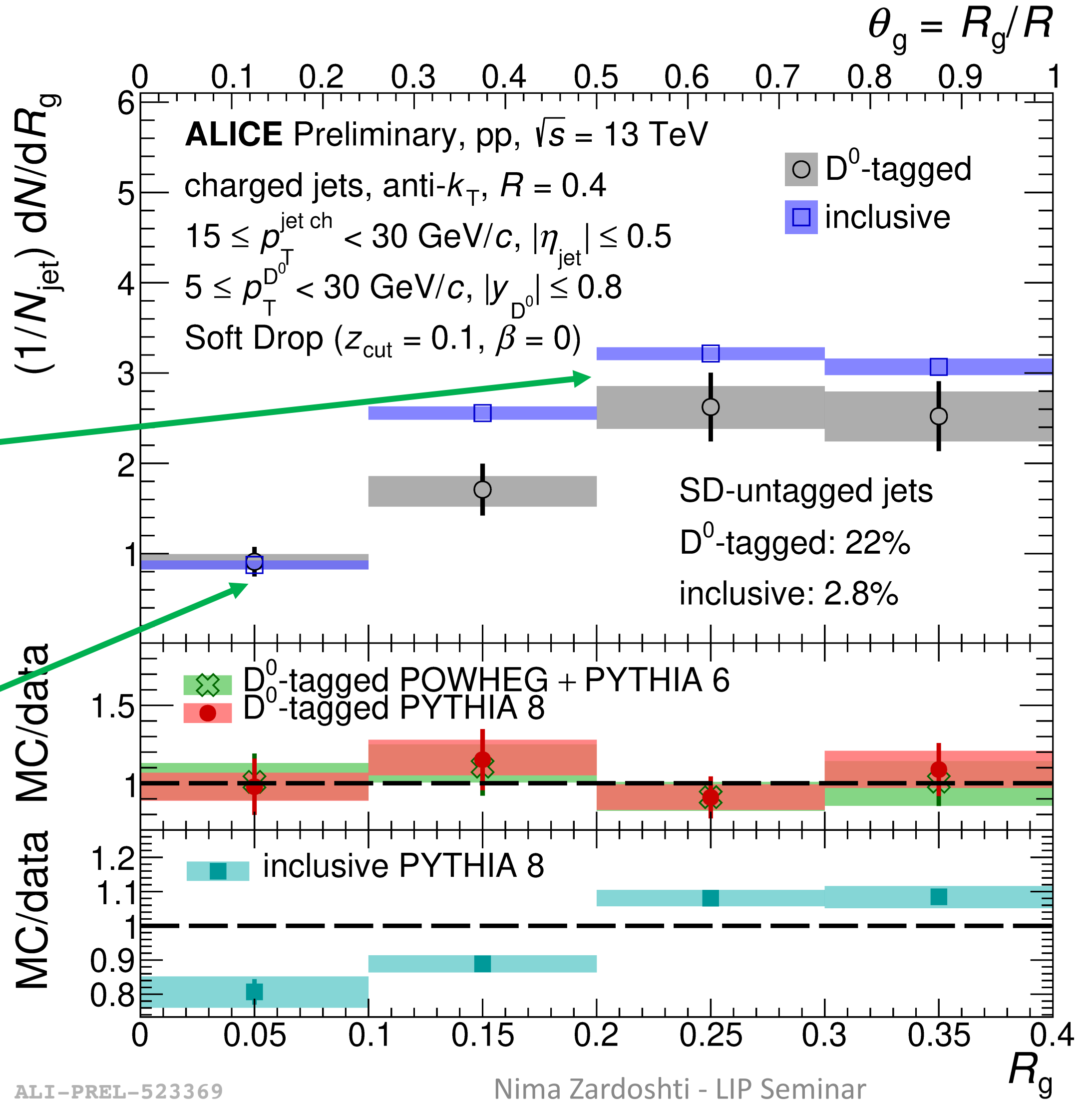
$$z = 0.1, \beta = 0$$

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

Opening angle of the first emission passing Soft Drop

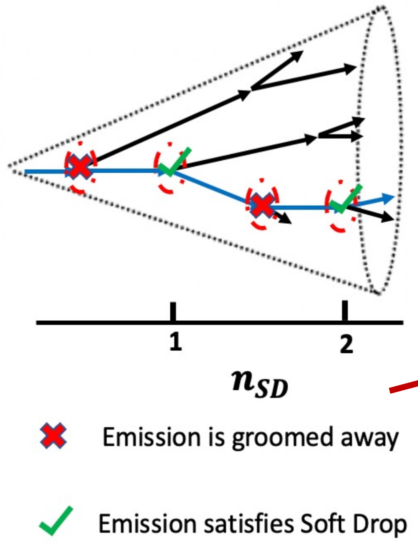
Gluon jets have a broader shower profile than quark jets

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



Looking deeper into the perturbative shower

Towards isolating the perturbative physics of heavy-flavour fragmentation functions



Soft Drop grooming condition

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

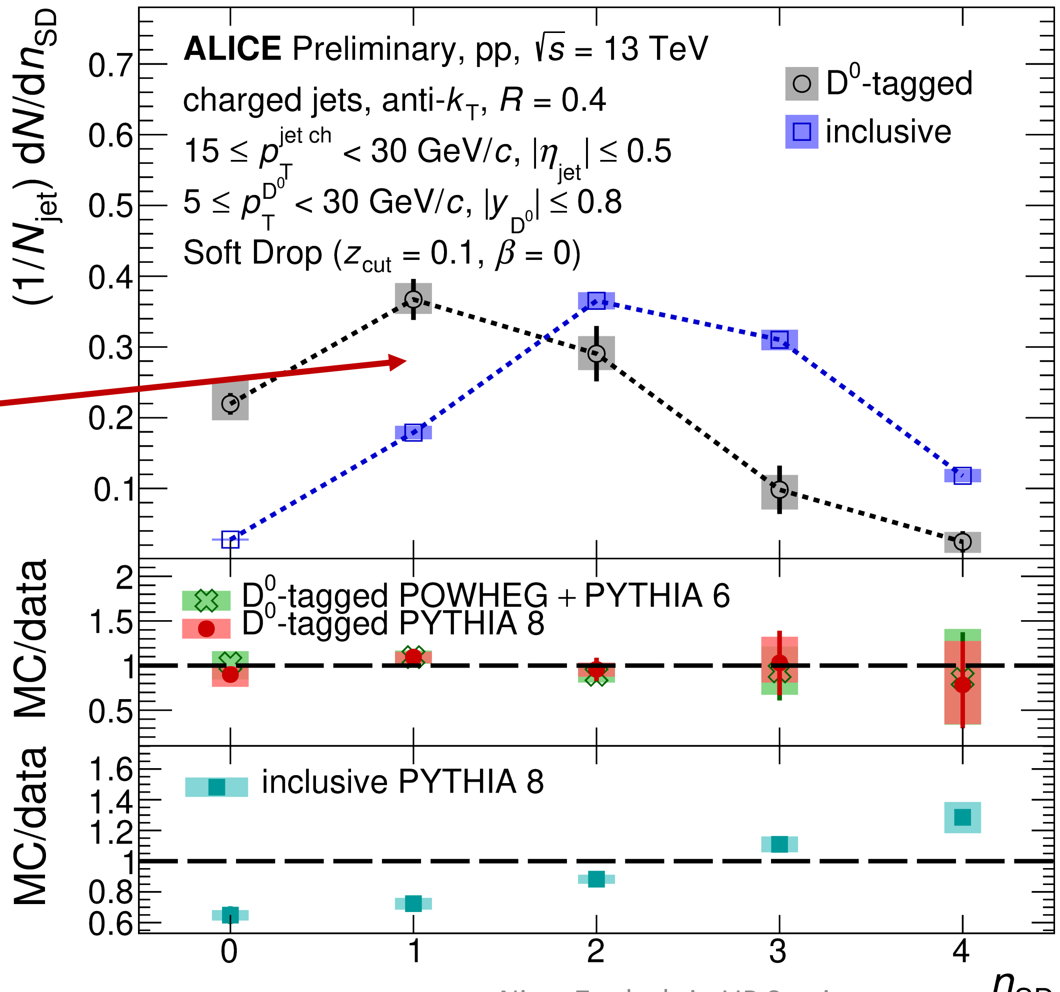
$$z = 0.1, \beta = 0$$

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

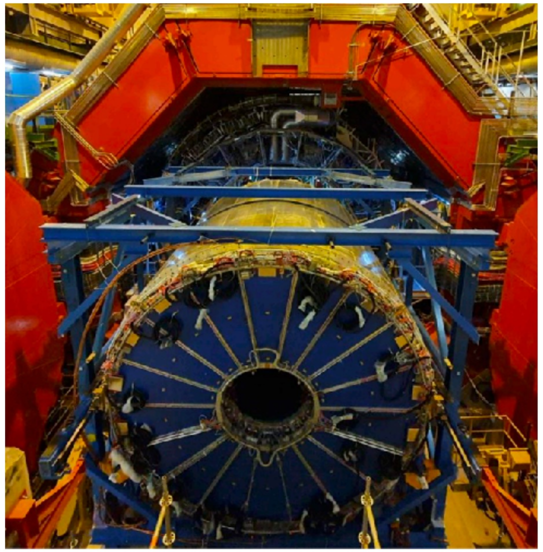
Strongly correlated to the number of perturbative emissions in the shower

Charm quarks on average have fewer hard emissions

Hardening of the fragmentation function from the dead-cone



A new era of heavy-flavour jet measurements with ALICE



Time Projection Chamber
GEM based readout

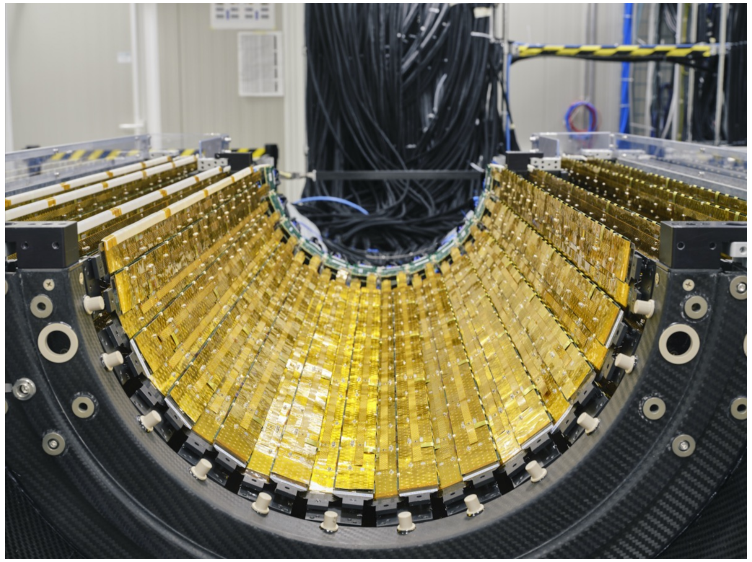
Run 3 and 4

faster readout to access rare probes

Impact parameter resolution of 25 µm at $p_T = 1$ GeV/c

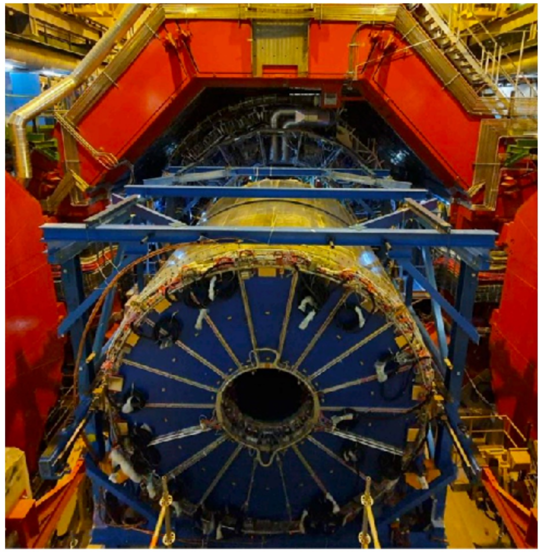
Access to fully reconstructed beauty and charm hadrons

Expected pp luminosity of 200 pb^{-1}



Inner Tracking System 2
7 layer pixel inner tracker

A new era of heavy-flavour jet measurements with ALICE



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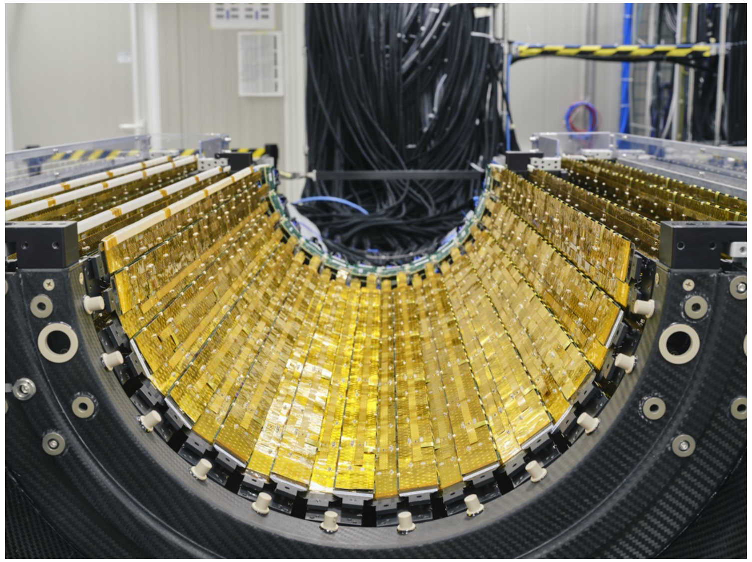
Impact parameter resolution of 25 μm at p_T = 1 GeV/c

Access to fully reconstructed beauty and charm hadrons

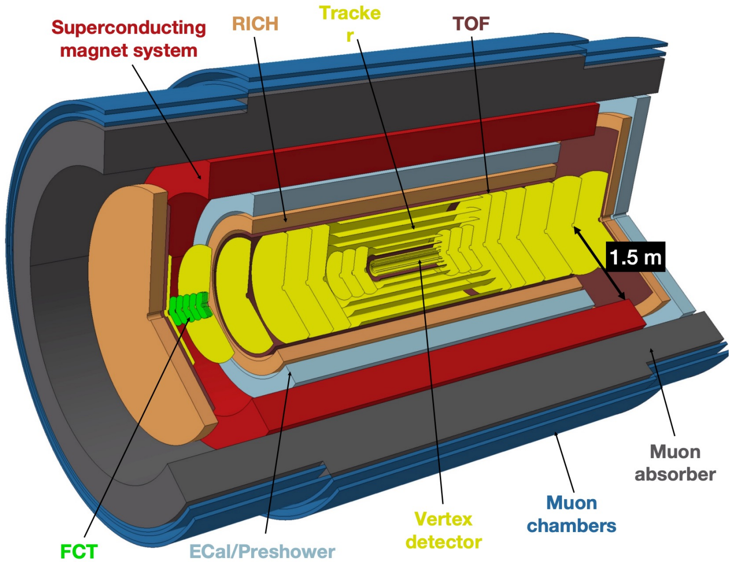
Expected pp luminosity of 200 pb^{-1}



Inner Tracking System 2
7 layer pixel inner tracker

ALICE 3

Letter of intent: CERN-LHCC-2022-009 ; LHCC-I-038



Run 5 and 6

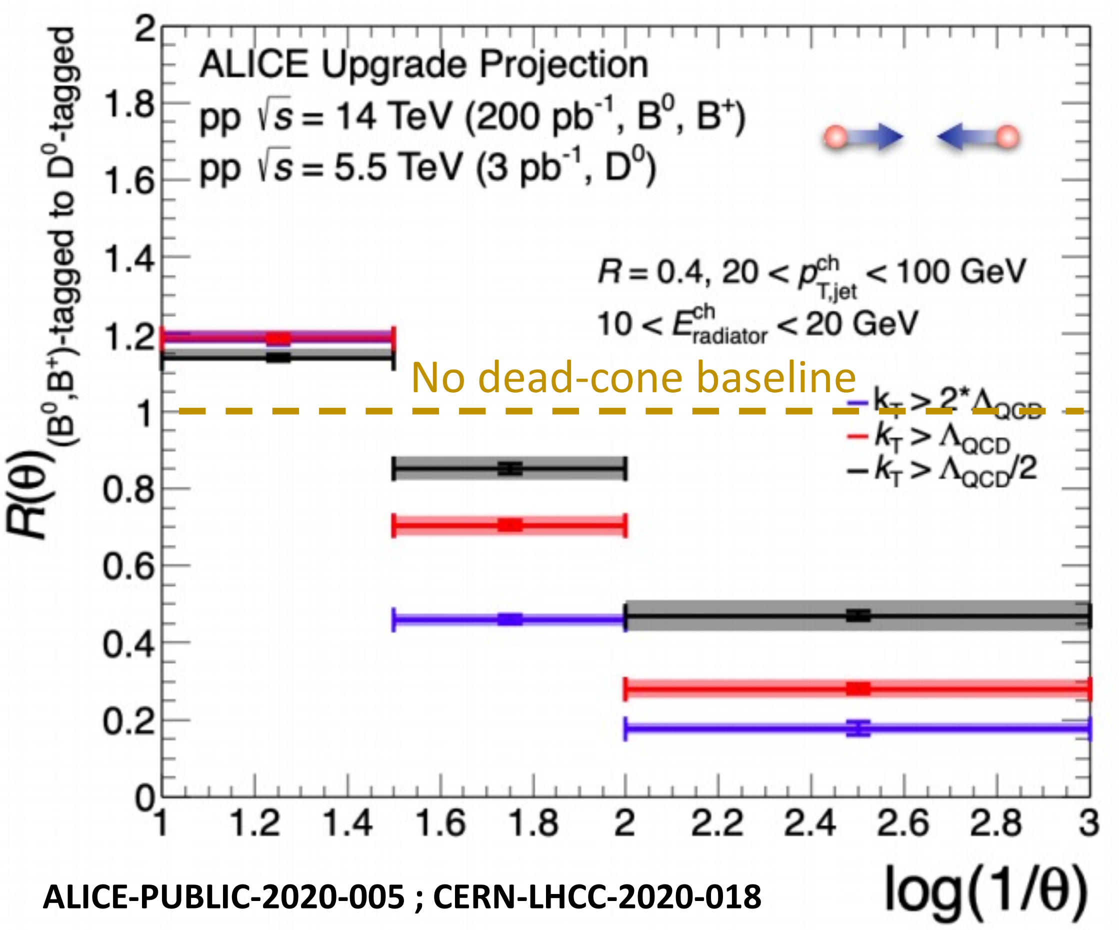
Impact parameter resolution of 3 μm at p_T = 1 GeV/c

Excellent PID capabilities to intermediate p_T

Unprecedented access to fully reconstructed beauty and charm hadrons

Disentangling mass and Casimir colour effects in Run 3

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



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

Comparisons in pp

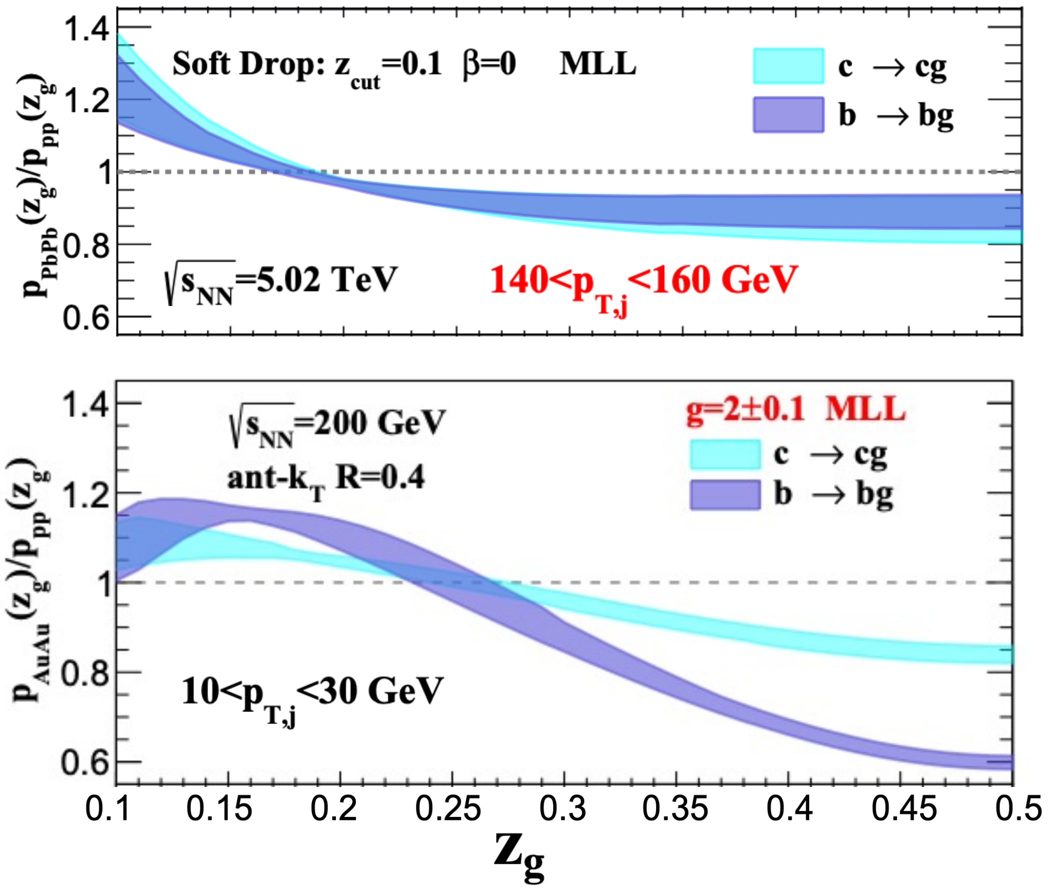
Low p_T charm and inclusive sensitive to both mass and Casmir colour effects (Run 2)

Beauty and charm-quark emissions isolate mass effects

High p_T charm and inclusive comparisons isolate Casmir colour factors

Disentangling mass and Casimir colour effects in Run 3

Modification of the heavy-flavour splitting functions in heavy-ion collisions



H. T. Li, I. Vitev, arXiv:1812.03348

Comparisons in pp

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

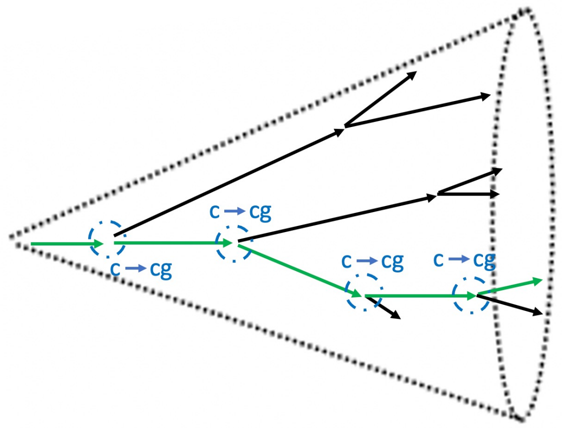
Beauty and charm-quark emissions isolate mass effects

High p_T charm and inclusive comparisons isolate Casmir colour factors

Comparisons in Pb-Pb

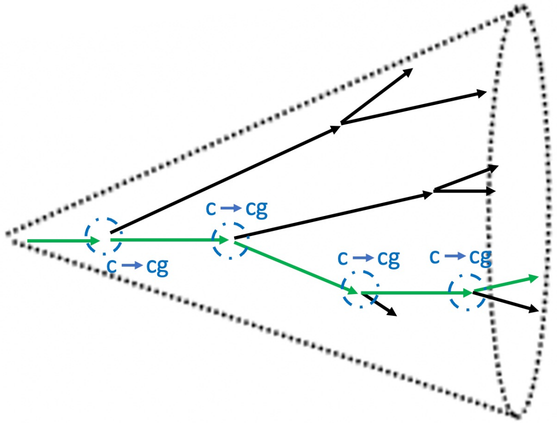
Measurements of the heavy-flavour shower profile to be extended to heavy-ion collisions where these flavour dependent properties can unlock new insights into the nature of the deconfined medium

Conclusions

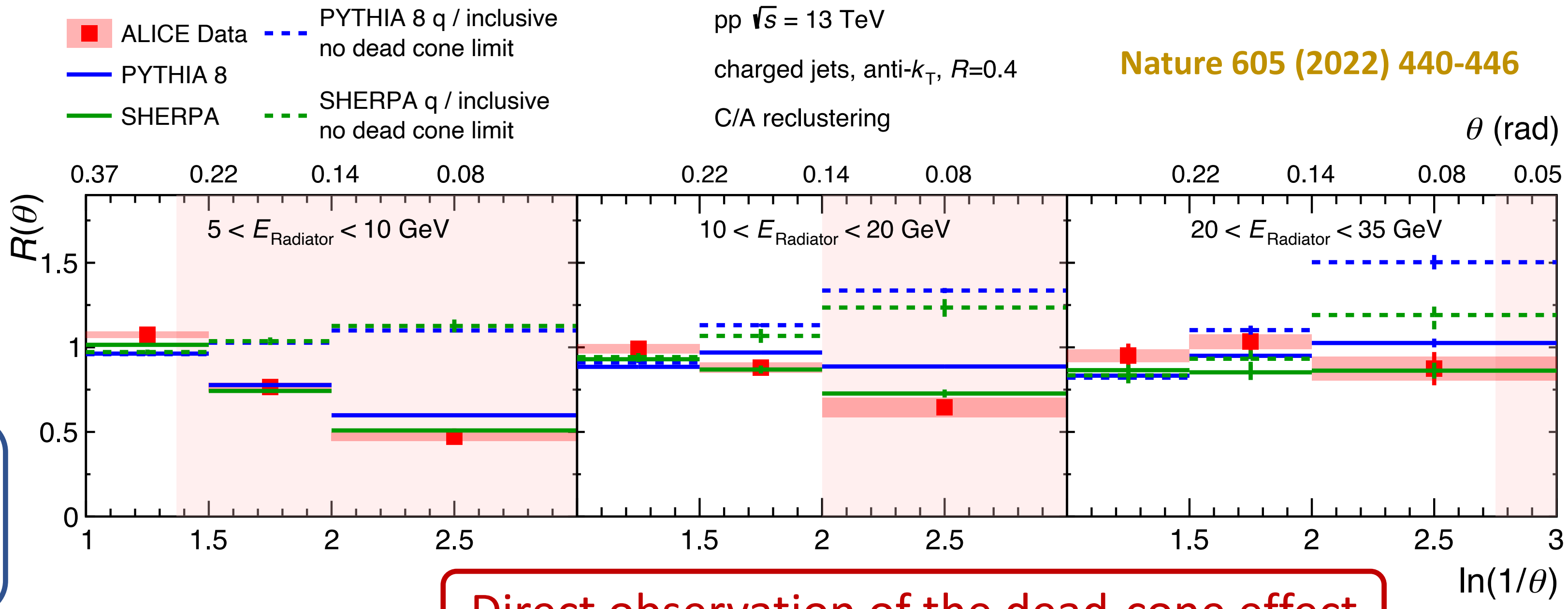


New experimental technique to reconstruct emissions of heavy-flavour quarks in the parton shower

Conclusions



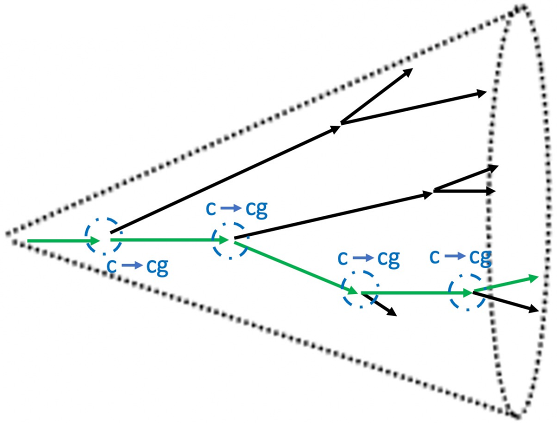
New experimental technique to reconstruct emissions of heavy-flavour quarks in the parton shower



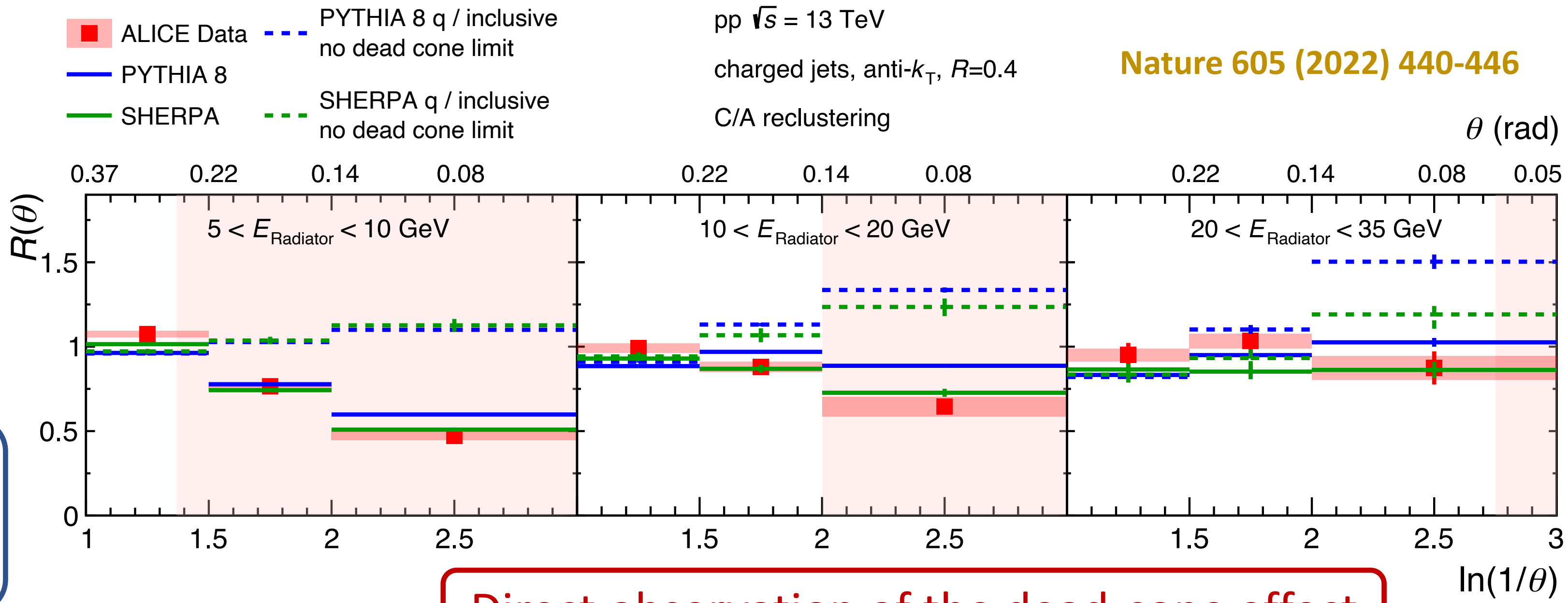
Nature 605 (2022) 440-446

Direct observation of the dead-cone effect

Conclusions

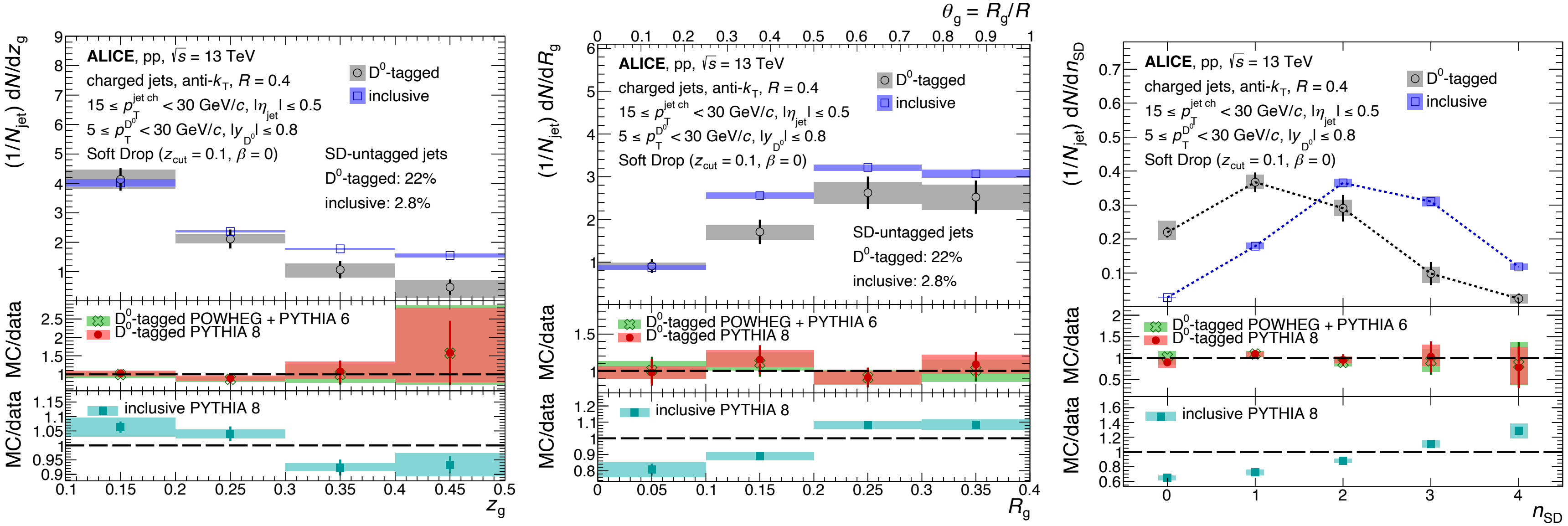


New experimental technique to reconstruct emissions of heavy-flavour quarks in the parton shower



Nature 605 (2022) 440-446

Direct observation of the dead-cone effect



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