The Jet Substructure Program at ALICE

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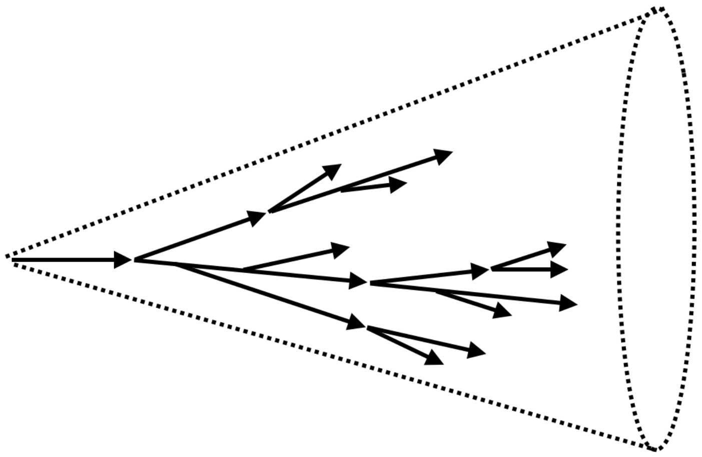
LHC Jets and EW Bosons mini workshop

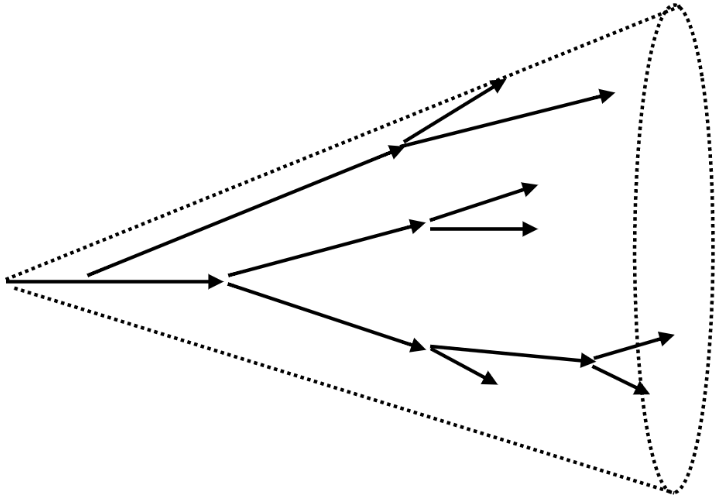
19/10/2020

Jets and Jet Substructure in QCD

- Jets probe a wide range of QCD scales :
  - Perturbative production – good theoretical control
  - Non-perturbative PDFs and hadronisation
  - Jet shower transitions the two regimes
- Jets reconstruct kinematics of the scattered parton:
  - access to free colour charges
- Jet substructure probes the details of the parton shower
- Sensitive to fundamental QCD properties such as:
  - splitting functions
  - casimir colour factors : quark vs gluon substructure
  - dead-cone effect : heavy vs light quarks
  - ….



Gluon-initiated jets

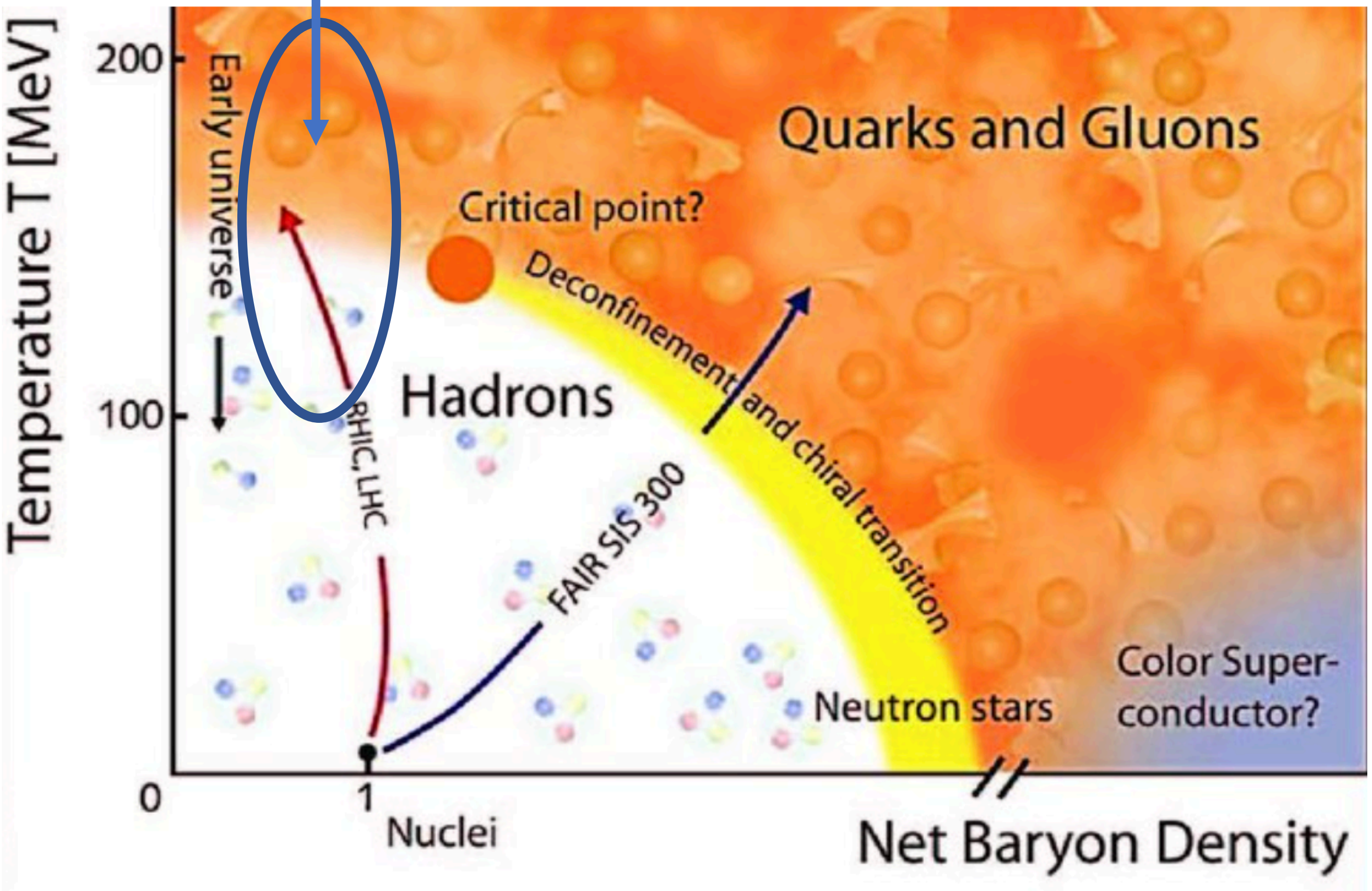


Quark-initiated jets

The Physics of Heavy-Ion Collisions : The Quark Gluon Plasma

- Under extreme temperatures and densities QCD matter undergoes a phase transition:
  - very early state of the universe

Phase-space accesible through heavy-ion collisions



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- A deconfined medium of quarks and gluons was expected:
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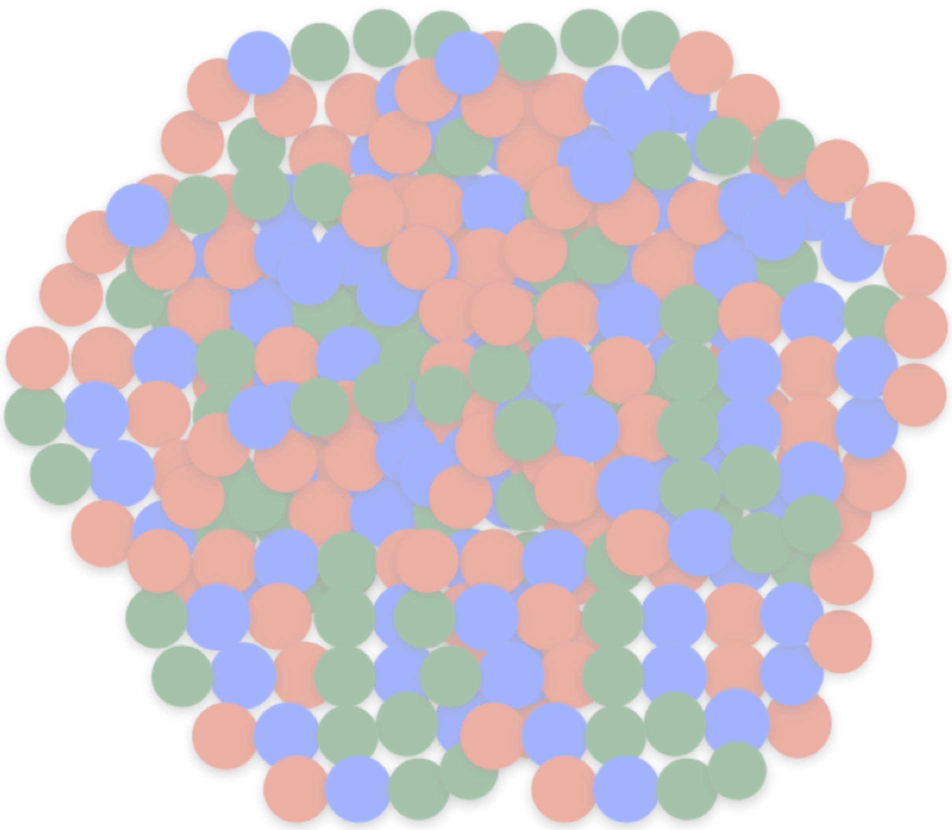
- The medium exhibits collective effects – strongly interacting quasi-particles

What are the constituent degrees of freedom?



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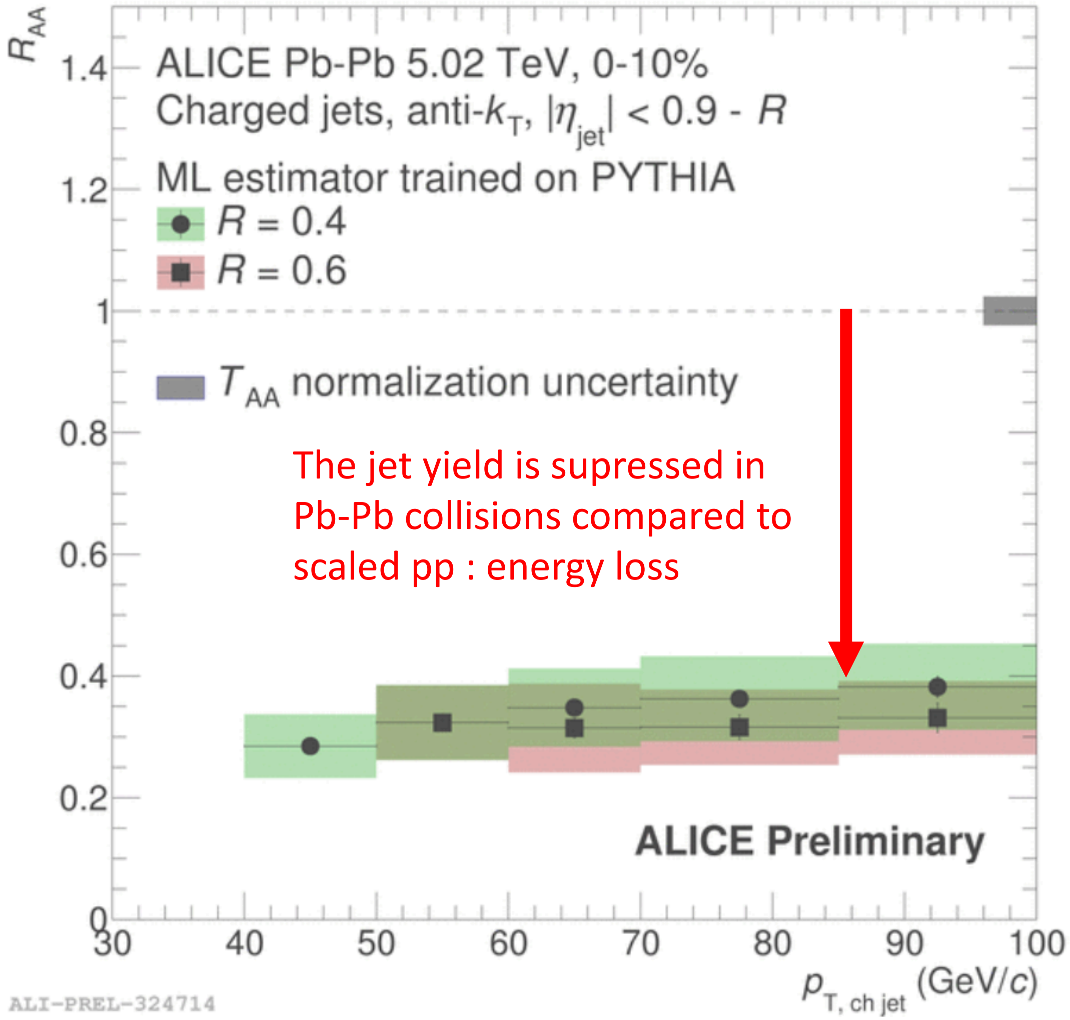
- The medium is opaque to high momentum colour charges:
  - Energy loss through interactions with the medium scattering centres – jet quenching



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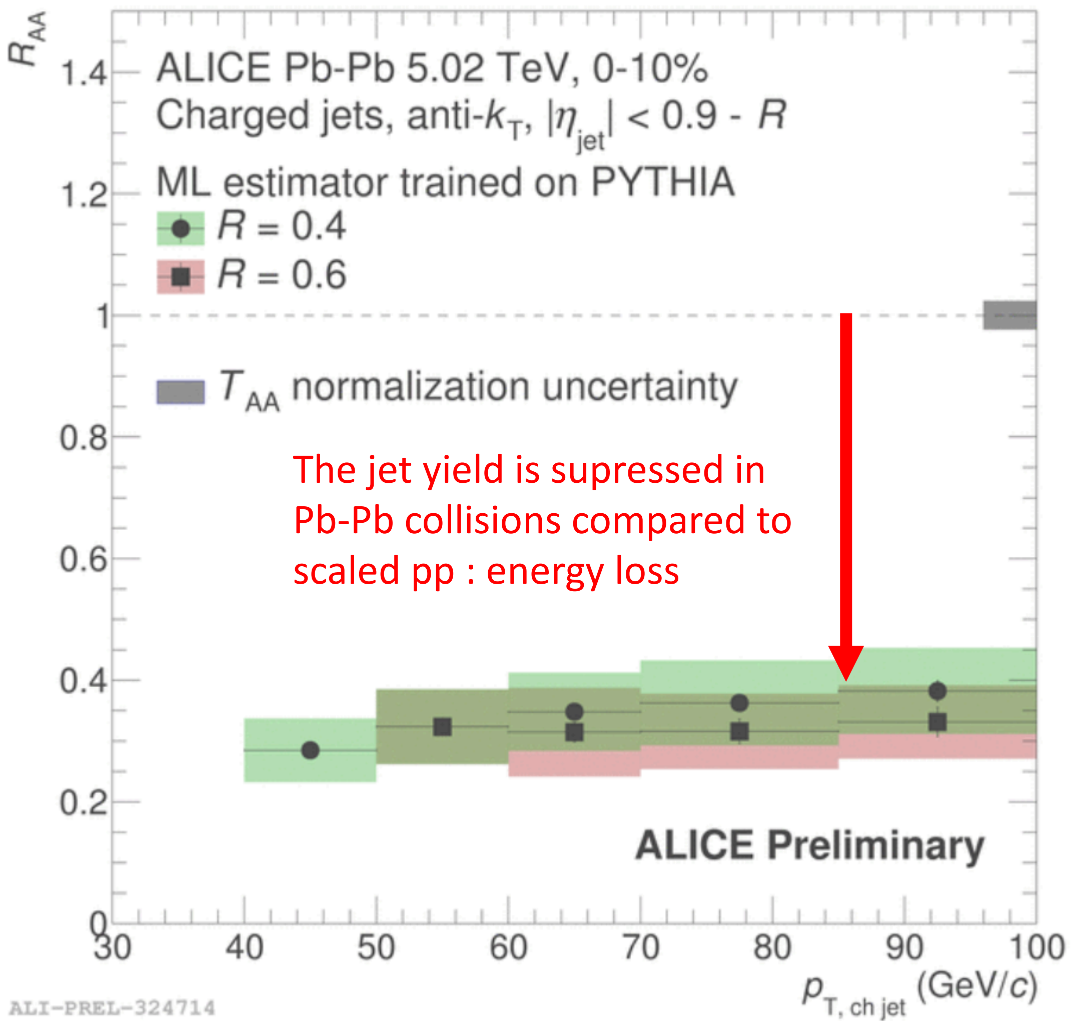
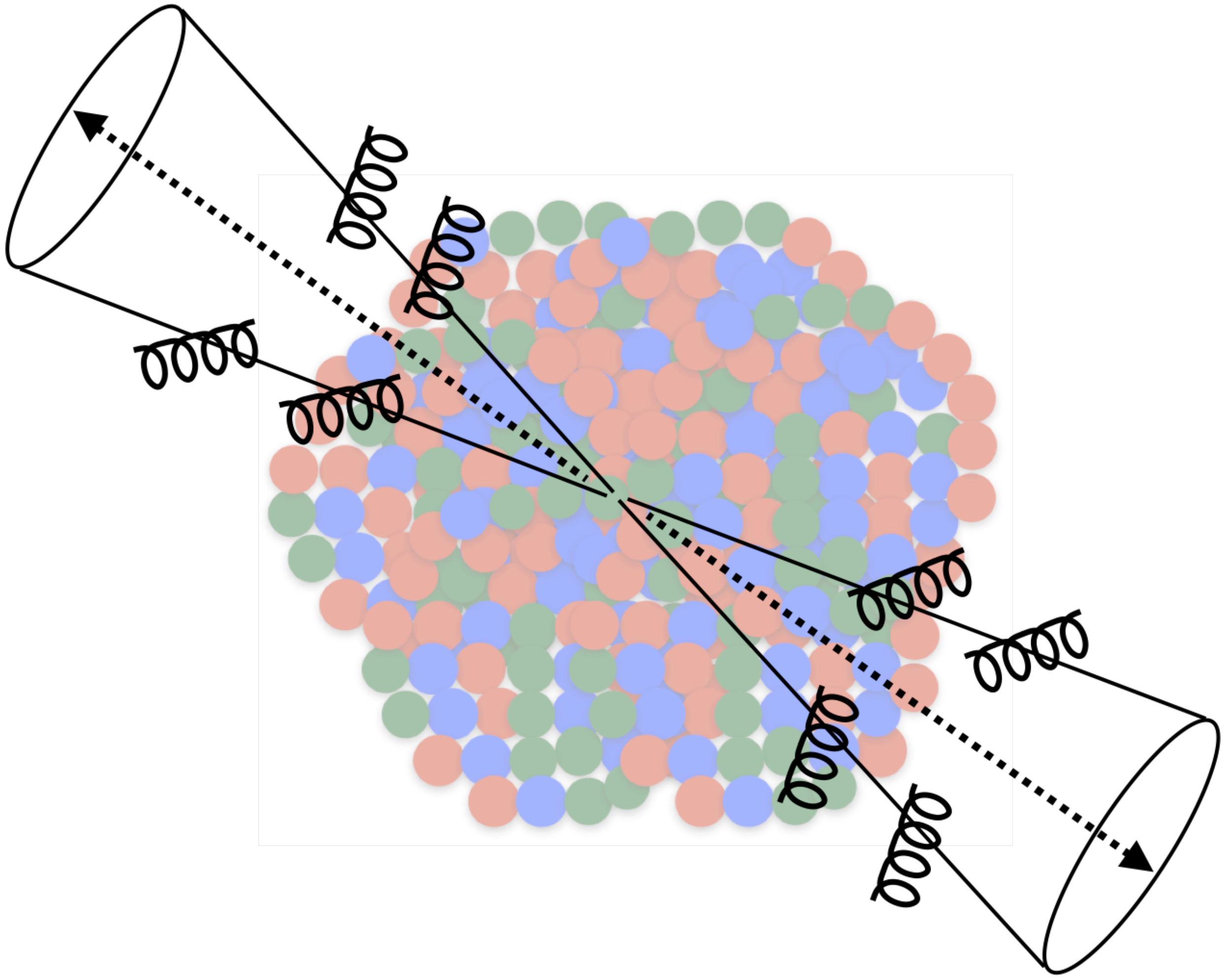


Can we describe the evolution of a strongly coupled medium from a weakly coupled theory? Need to probe the medium with different resolution scales

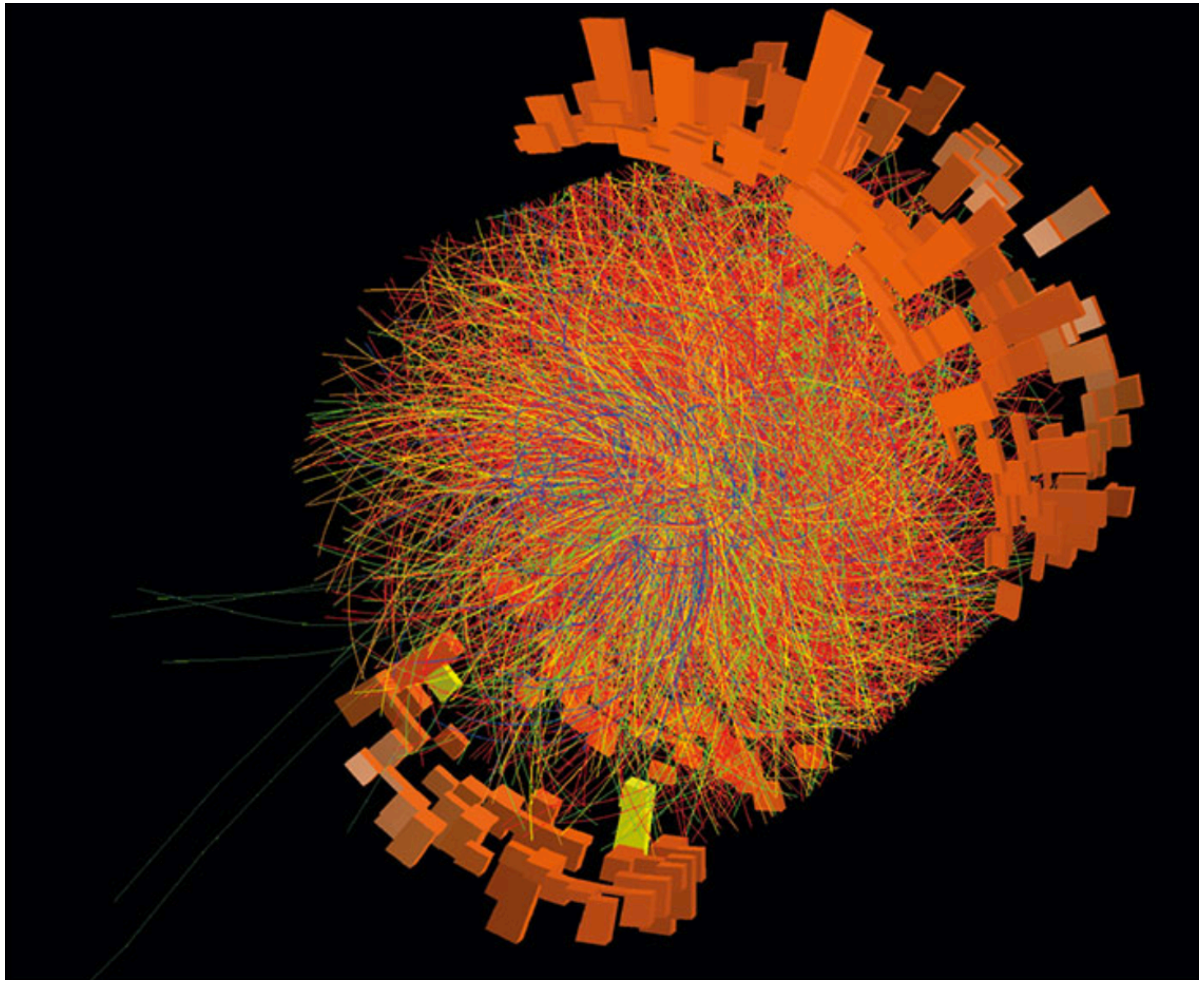
Why Do Jets Emerge As a Natural Probe of the QGP?

- Jet production occurs in the vacuum before the medium thermalises – well calibrated pQCD probes
- The scattered parton loses energy traversing the medium – the parton shower is modified
- Substructure variables are a powerful probe of the in-medium energy loss mechanisms
- Energy is found to be predominantly carried by soft constituents to large angles from the jet axis



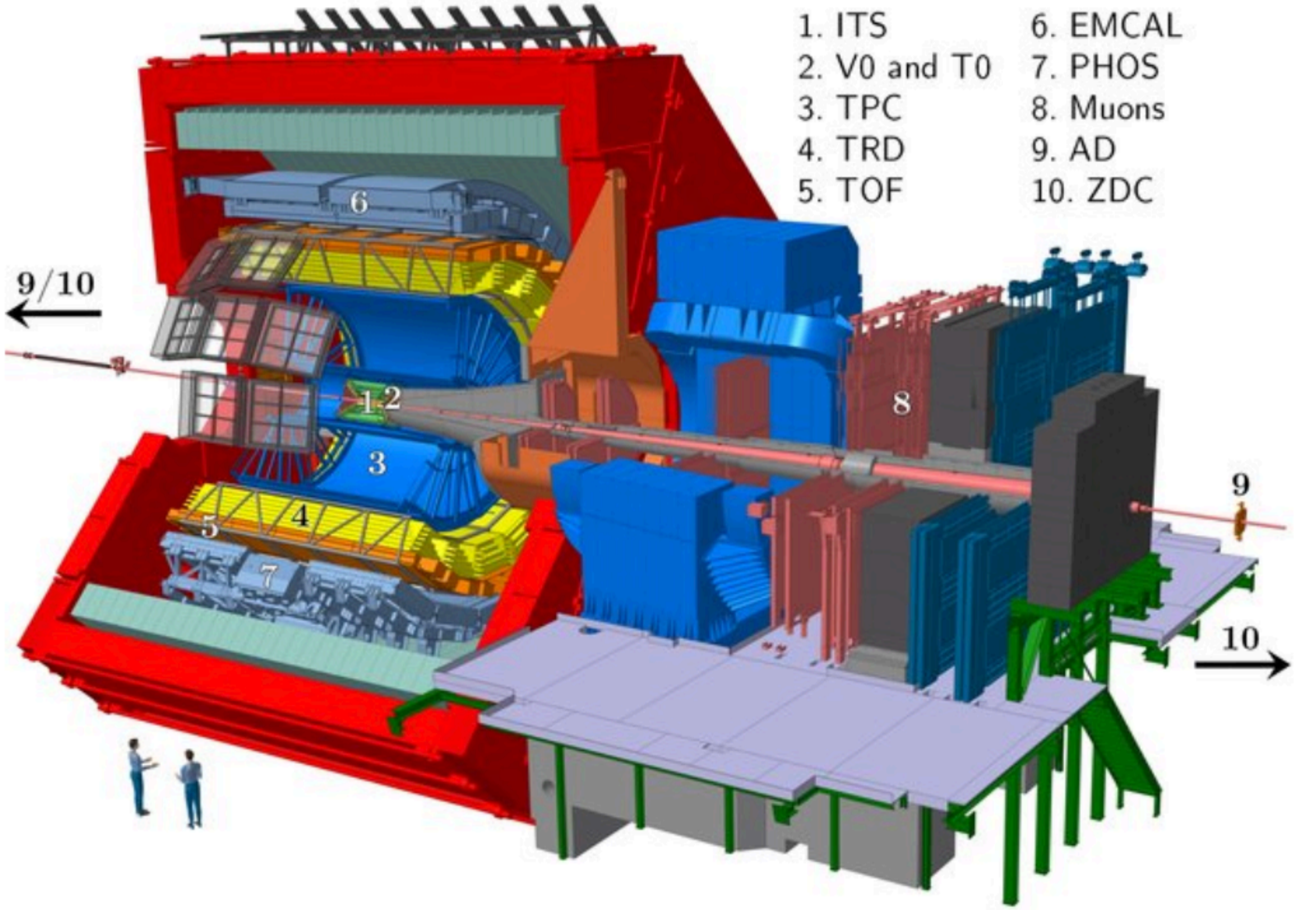
The Challenging Environment of Heavy-Ion Collisions

- Very large underlying event
  - Equivalent to ~1600 pp collisions
  - Up to 200 GeV/c per unit area
- Need for subtraction of the background from jet cone:
  - Often use algorithms developed for pile-up
  - Constituents subtraction
  - Derivatives subtraction
  - ….
- Need to remove combinatorial (wholly background) jets:
  - Restrict measurements to high* transverse momentum
  - h-jet coincidence technique
  - Mixed Events
  - Biases on fragmentation
  - …
- Correction of residual background fluctuations through unfolding – Typically 2D Bayesian:
  - Not possible for all variables
  - Grooming methods



The ALICE Detector

- High precision tracking capabilities down to 150 MeV/c
- Excellent PID information
- Coverage of central barrel: $|\eta| < 0.9$
- Track based jet finding down to low p_T:
  - Probing the limits of pQCD
  - Very good angular resolution
  - Heavy-flavour jets

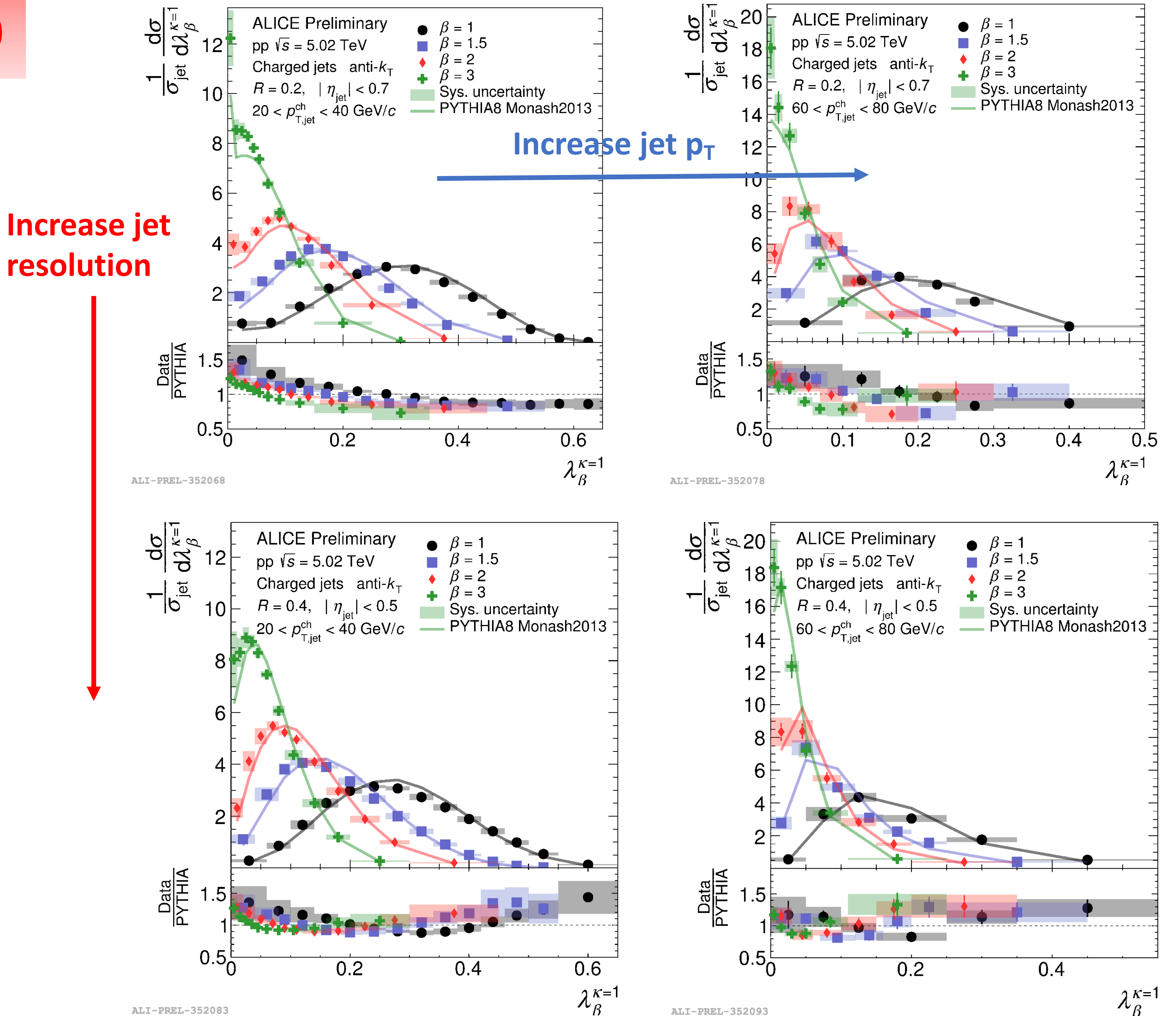


Jet Angularity in pp

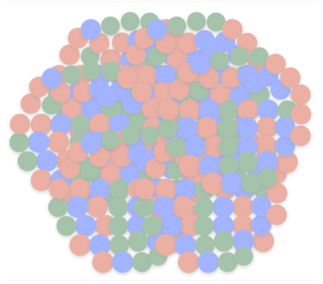
$$\lambda_{\beta}^{\kappa} \equiv \sum_{i \in \text{jet}} \left(\frac{p_{T,i}}{p_{T,\text{jet}}}\right)^{\kappa} \left(\frac{\Delta R_{jet,i}}{R}\right)^{\beta}$$

$$\kappa = 1, \beta > 0$$

- An IRC-safe measure of the p_T weighted angular distribution of jet fragments within the cone
- Systematic test of QCD by changing the jet resolution and angular dependence weight of fragments
- Reasonably well described by PYTHIA



Jet Angularity in PbPb – What Can We Learn?

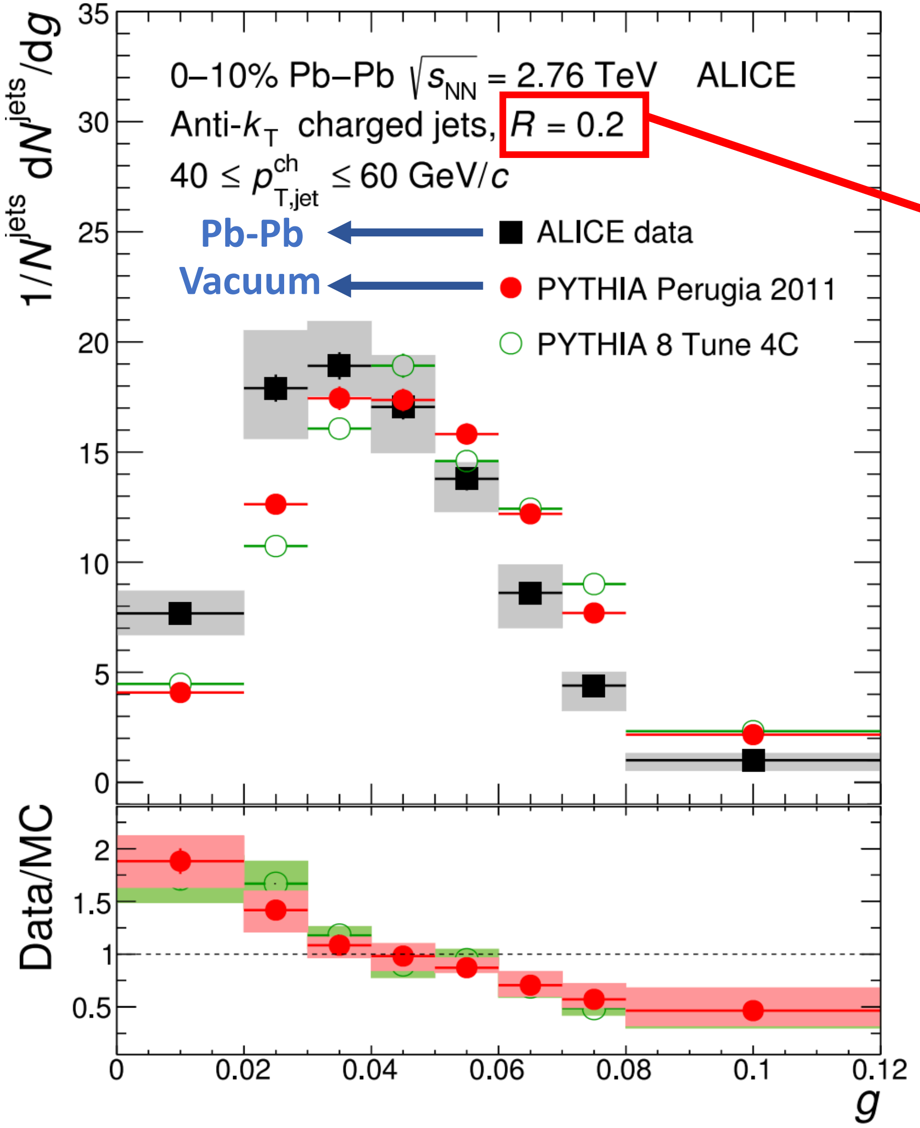


$$\lambda_\beta^\kappa \equiv \sum_{i \in \mathrm{jet}} \left(\frac{p_{T,i}}{p_{T,\mathrm{jet}}}\right)^\kappa \left(\frac{\Delta R_{jet,i}}{R}\right)^\beta$$

- Internal structure of jet significantly modified in the presence of the medium

- Jet core has a narrower and harder fragmentation
  - Do more quark jets survive the medium compared to gluon jets?
  - Are observed modification due to p_T evolution of the vacuum shower?

- Many other shapes measured at ALICE supporting these observations:
  - Jet Mass
  - Momentum dispersion
  - LeSub
  - …



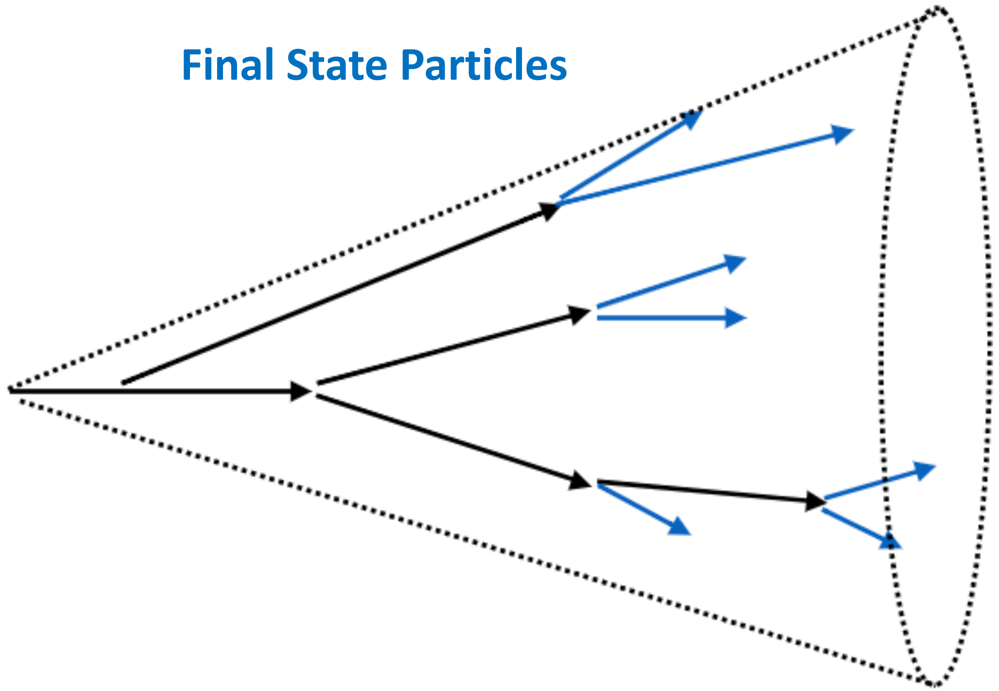
Looking at the jet core

$\kappa = 1, \beta = 1$

$g = R\,\lambda_1^1$

Reclustering Techniques – Accessing the Jet Splittings

- Individual splittings in the jet shower can be accessed through reclustering techniques



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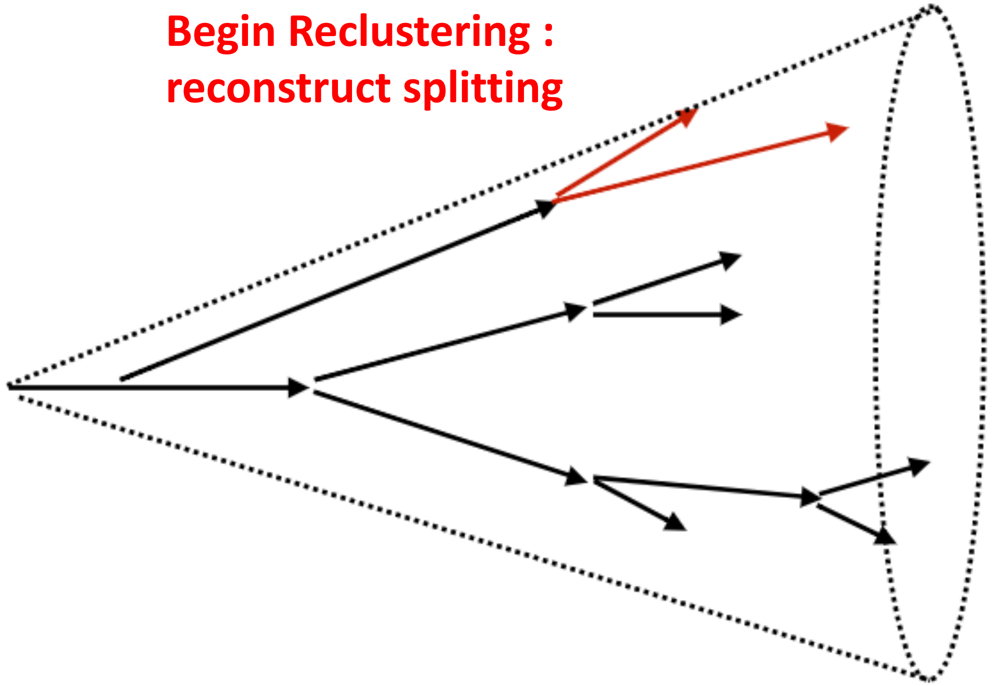

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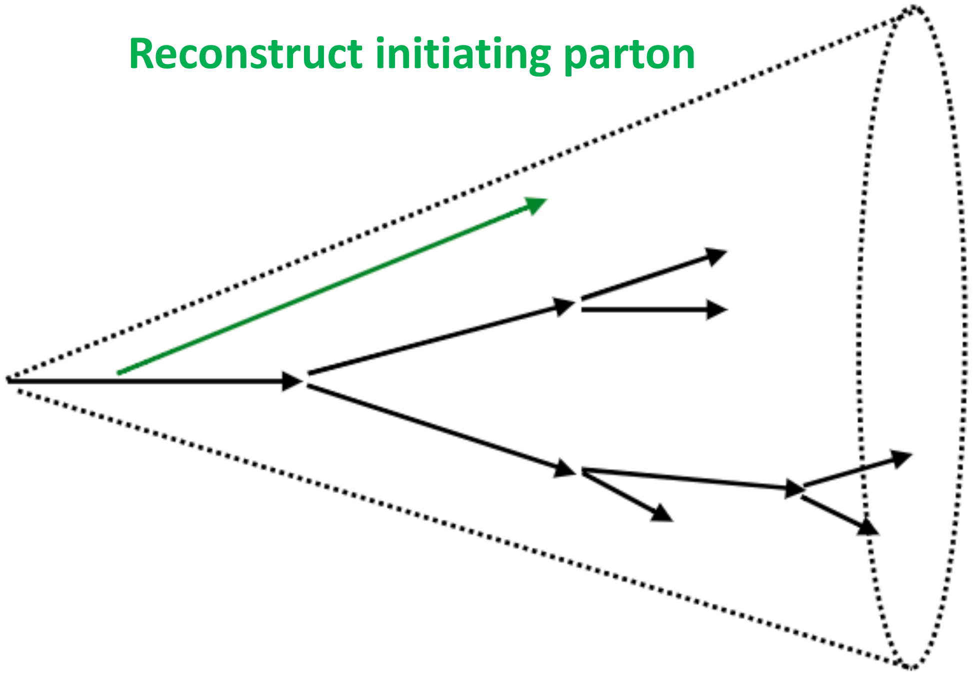

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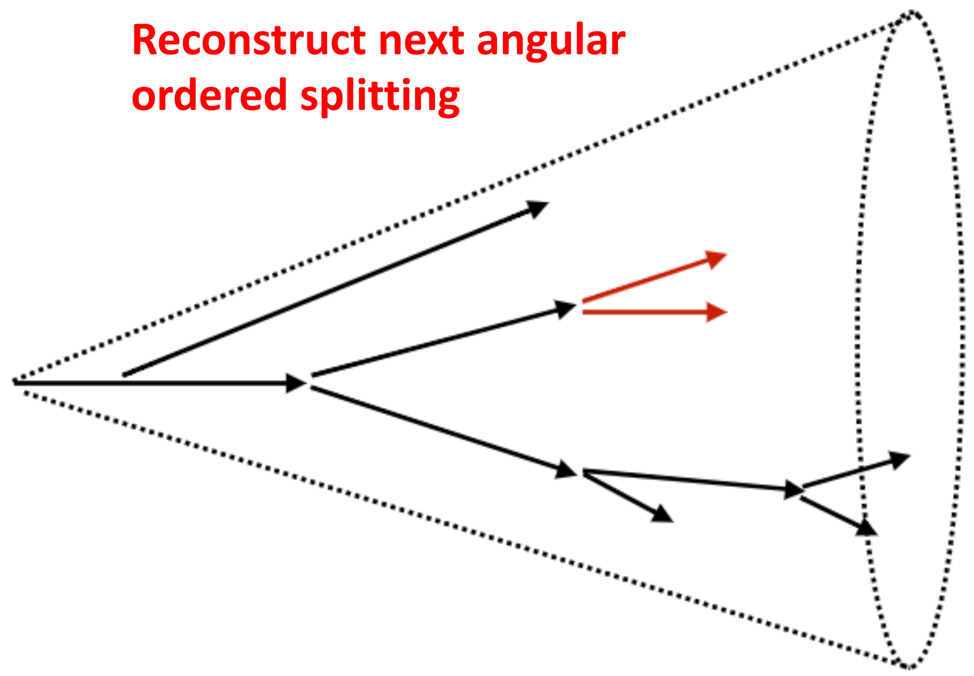

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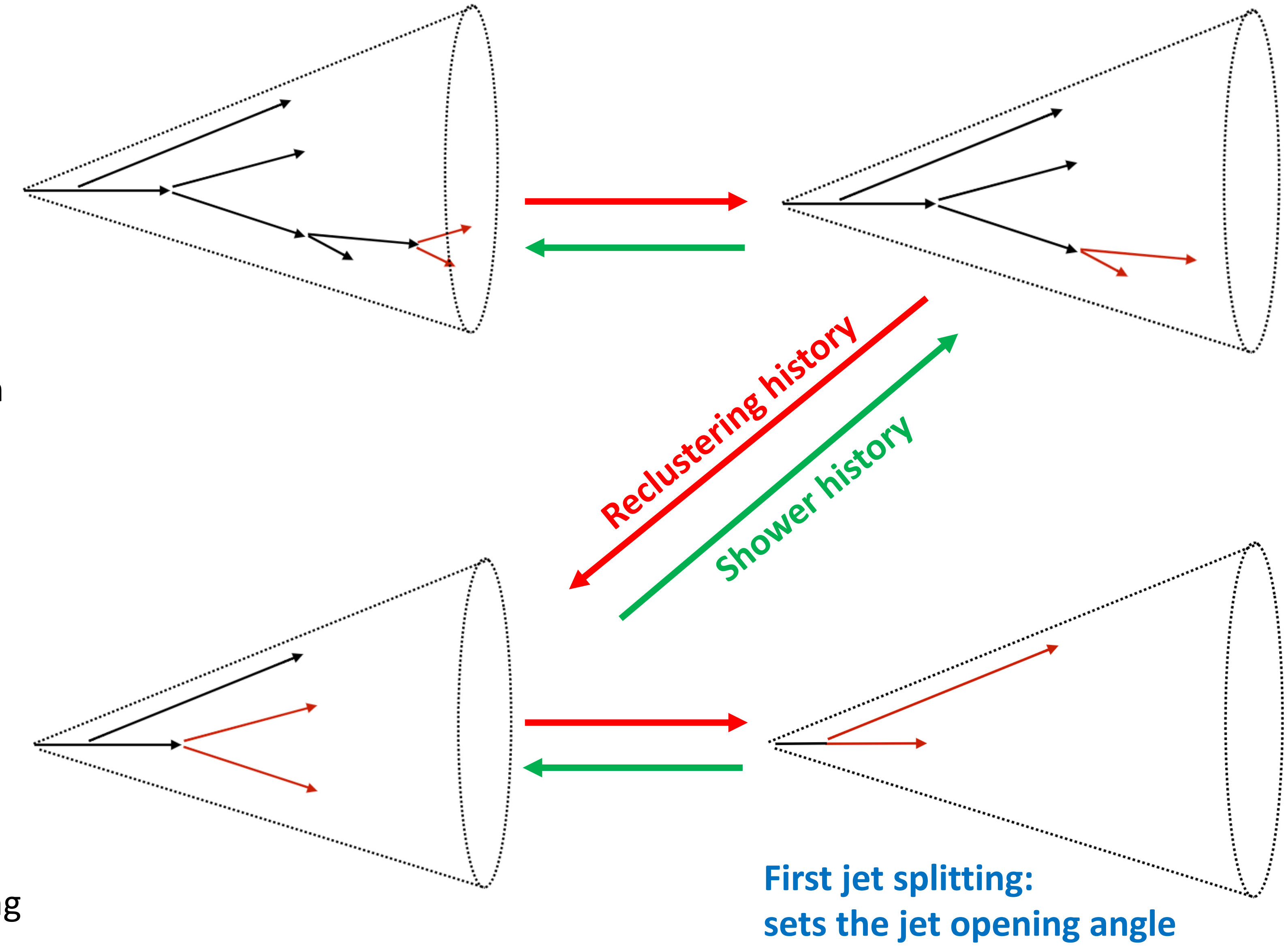
- Individual splittings in the jet shower can be accessed through reclustering techniques
- Jet constituents are reclustered using Cambridge/Aachen (angular ordered)
- Initiating parton is reconstructed at each splitting
- Next closest splitting in angle is reconstructed
- Recluster through the jet shower
- Unwind Reclustering history to access chronological shower history
- What can we learn about QCD by studying these splittings?

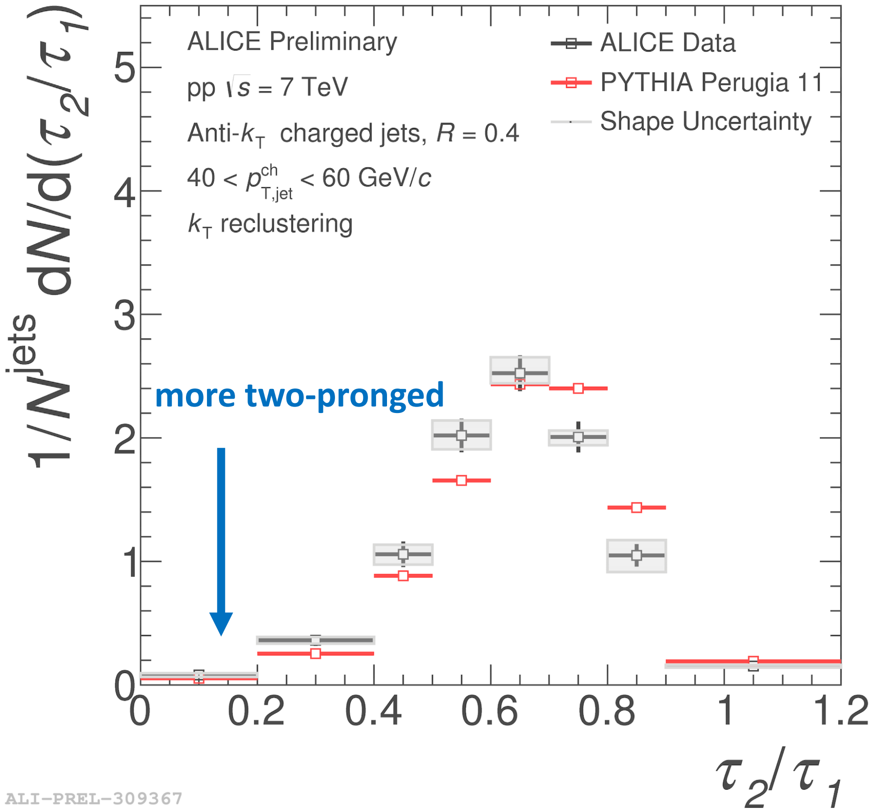


Nsubjettiness – a Test of Colour Coherence

- A measure of the degree to which a jet is composed of N-distinct substructures
- $\frac{\tau_2}{\tau_1}$ sensitive to two prongness in jets – constructed against the first returned (chronological) splitting

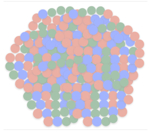
$$\tau_N = \frac{1}{p_{\mathrm{T,jet}} \times R} \sum_k p_{\mathrm{T,k}} \min(\Delta R_{1,\mathrm{k}}, \Delta R_{2,\mathrm{k}}, ..., \Delta R_{\mathrm{N,k}})$$

PYTHIA underestimates two-prongeness of jets in pp

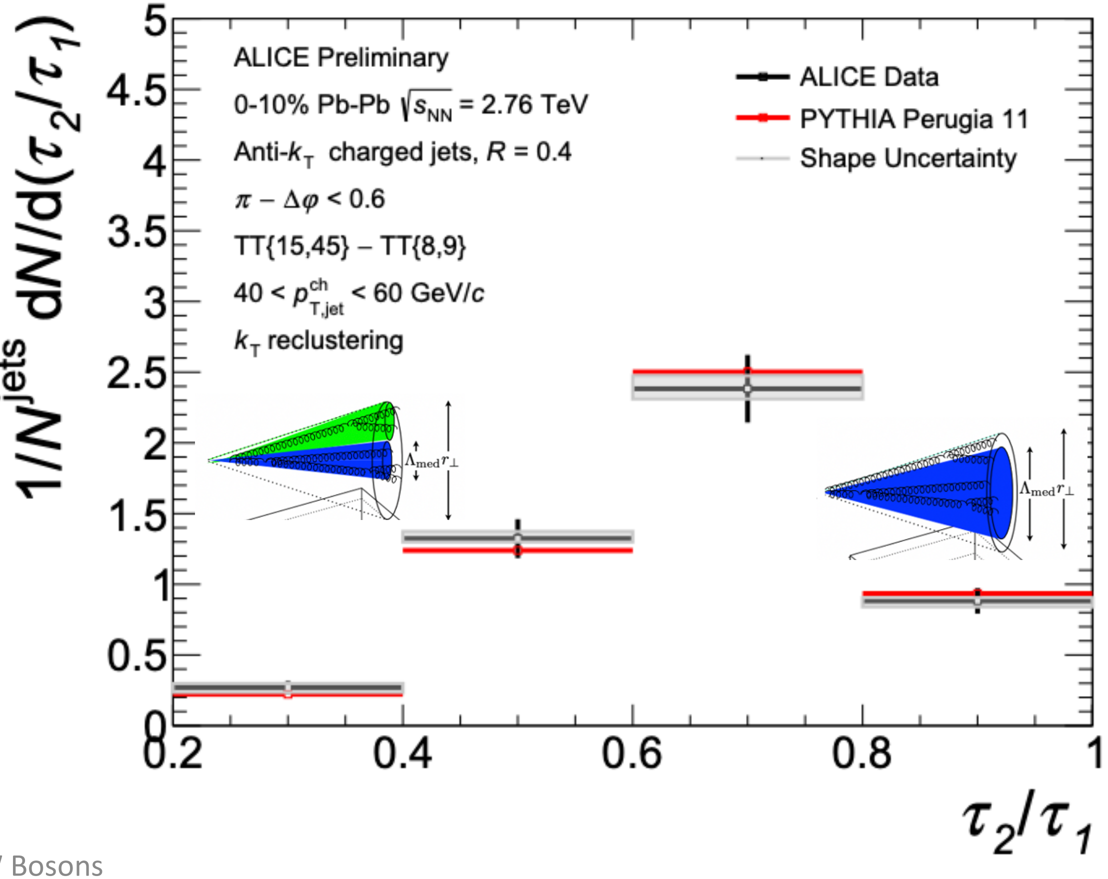


A variety of reclustering algorithms tested: Sensitive to different regimes of the QCD shower

- Can the medium resolve the jet colour substructure?
  - Two prong jets expected to lose more energy than single cored jets – colour coherence

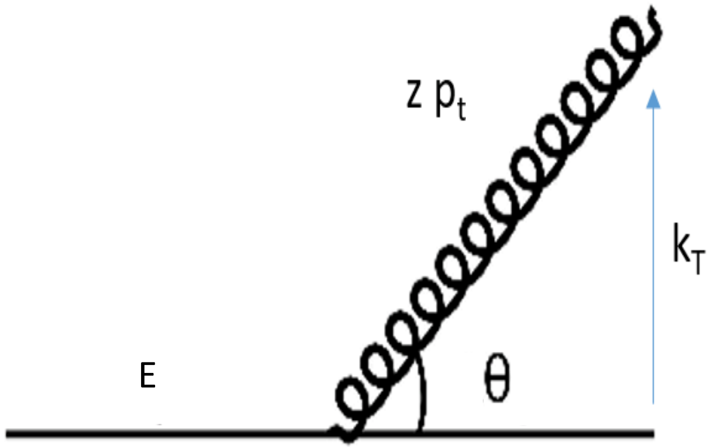


Hint of suppression of two-pronged jets in the medium

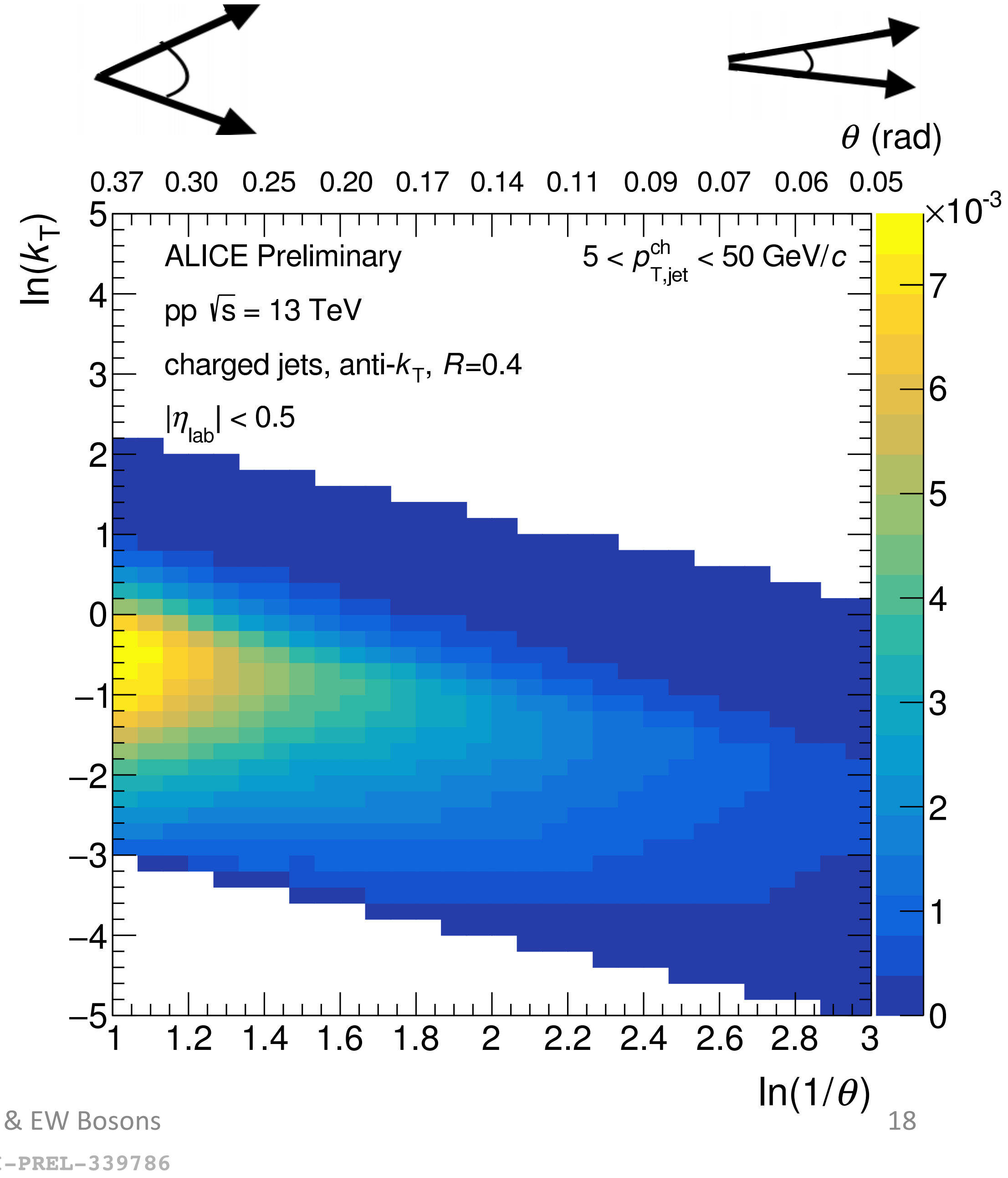


Lund Plane – Mapping the Phase-Space

- Lund planes are two-dimensional representations of the splitting phase-space
- Can be filled with splittings uncovered by following the **hardest branch** during reclustering
- Powerful tools to study/isolate specific regions of interest:
  - Which QCD effects populate different regions of the splitting phase-space?



$\theta \sim k_T/zp_t$



Isolating Hard Splittings

- Lund planes are two-dimensional representations of the splitting phase-space
- Can be filled with splittings uncovered by following the **hardest branch** during reclustering
- Powerful tools to study/isolate specific regions of interest:
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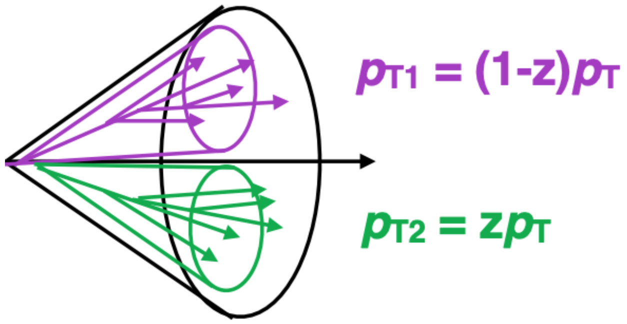
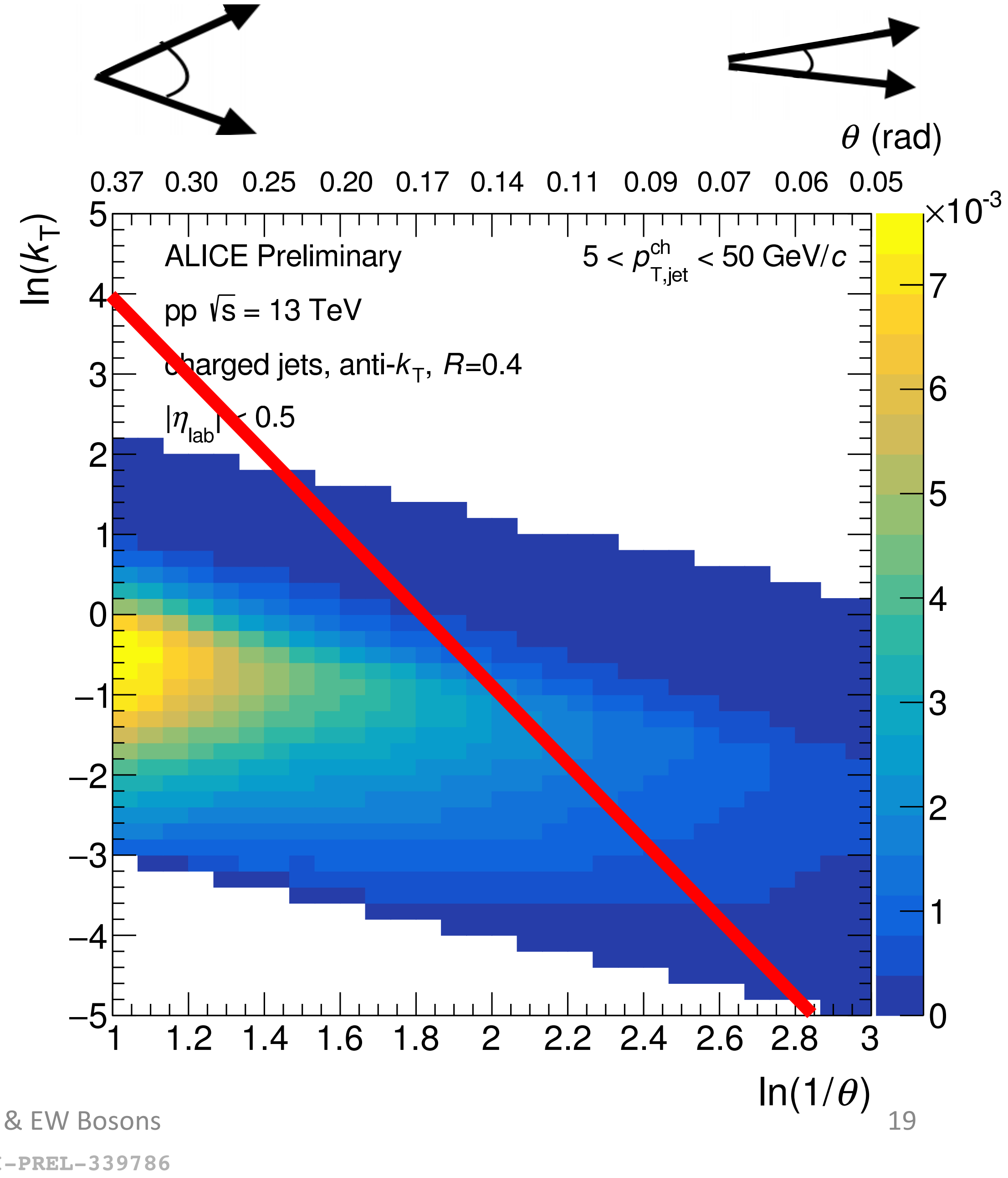
- Make a cut of constant *z* – hardness of the splitting





Reducing Non-Perturbative Effects

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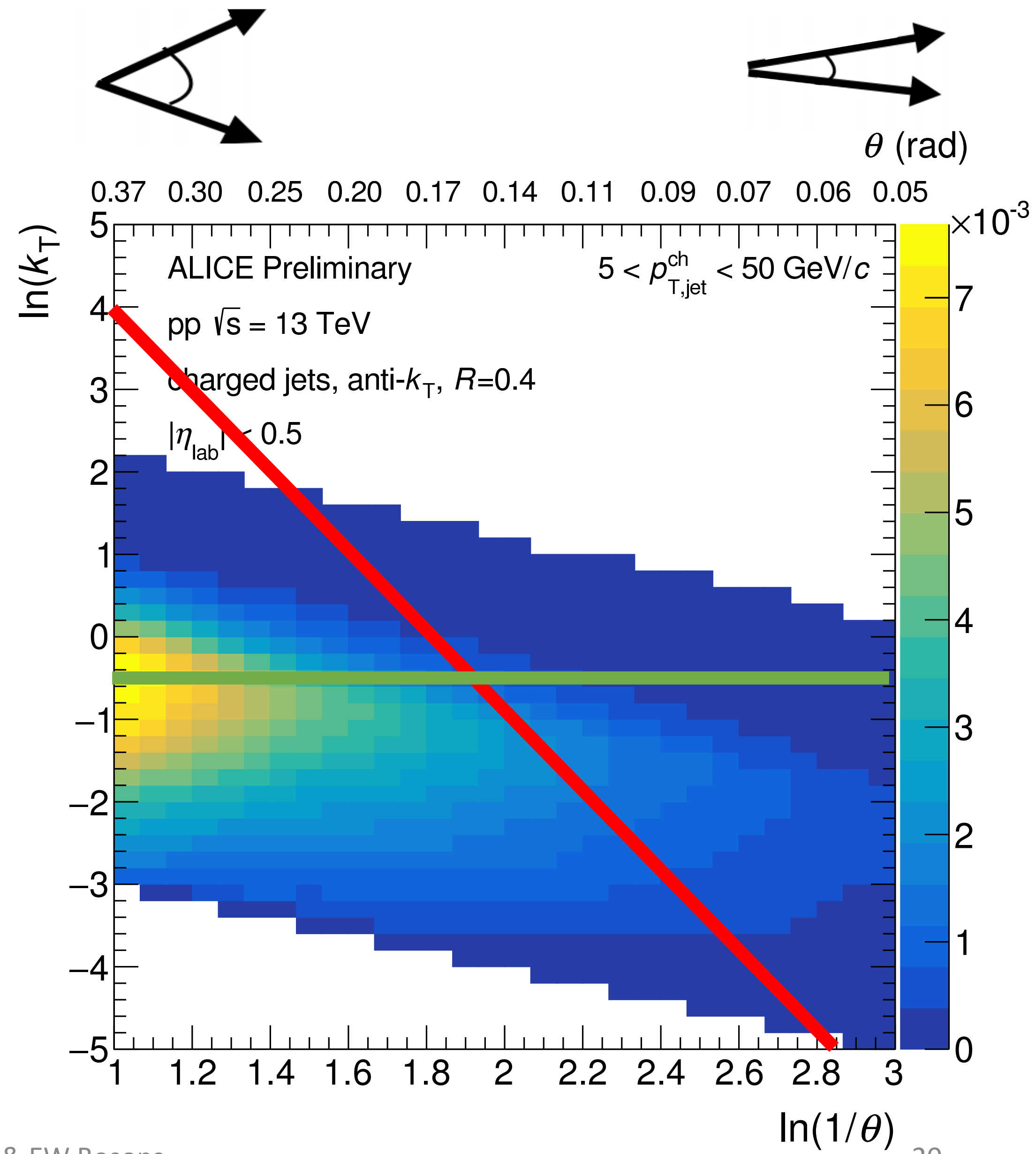
- Make a cut of constant *z* – hardness of the splitting
- Make a cut on log(k_T) - suppress non-perturbative effects



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Selecting Splittings Chronologically

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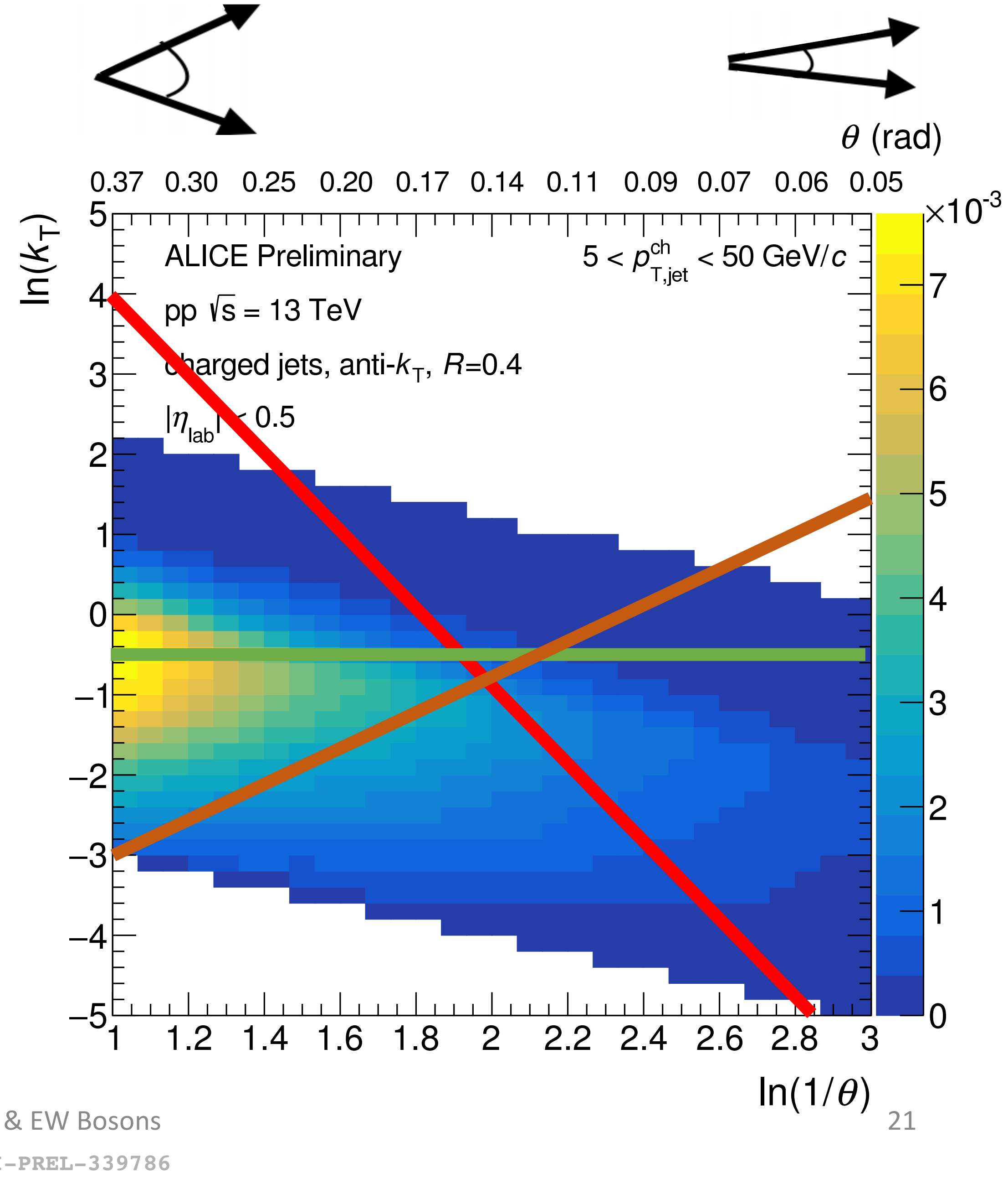
- Powerful tools to study/isolate specific regions of interest:
  - Which QCD effects populate different regions of the splitting phase-space?
- Make a cut of constant z – hardness of the splitting
- Make a cut on $\log(k_T)$ - suppress non-perturbative effects
- Make a cut on the formation time $t_f = \dfrac{1}{(1-z)k_T\Delta R}$
- Many measurements at ALICE isolating these regions



Soft Drop Grooming : Perturbative Splittings

- Jet grooming can be used to isolate pertubative splittings in the shower

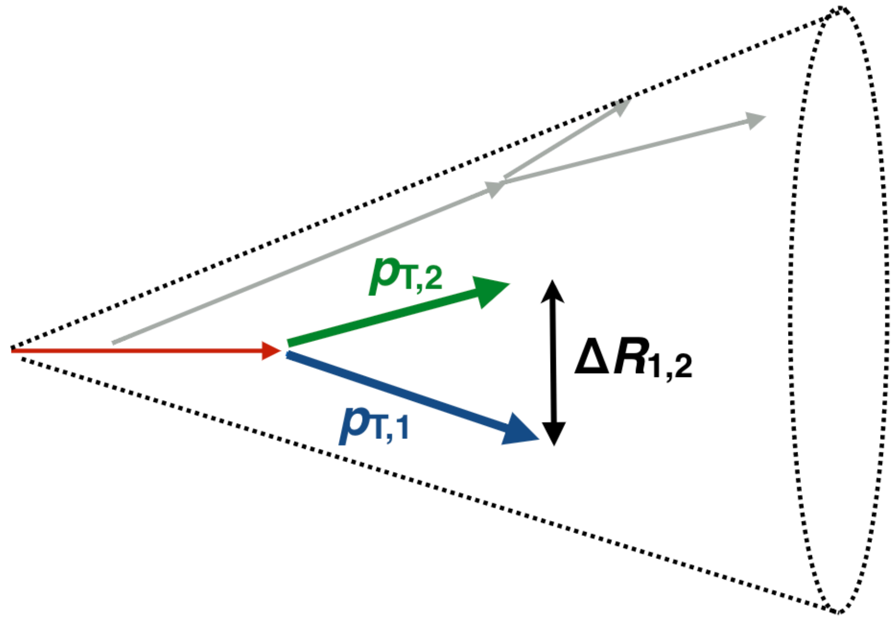
- As the reclustering history is unwound each splitting is tested against the Soft Drop condition

Soft Drop (SD) grooming condition:

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

$$\Delta R_{1,2} = \sqrt{(y_1 - y_2)^2 + (\varphi_1 - \varphi_2)^2}$$

$R =$ jet resolution parameter



- If successful : the splitting is accepted
- If unsuccessful : the hardest prong is unwound and the condition is tested again – the subleading prong is groomed away

- Allows access to the first hard splitting in the medium – despite possible breakdown of angular ordering

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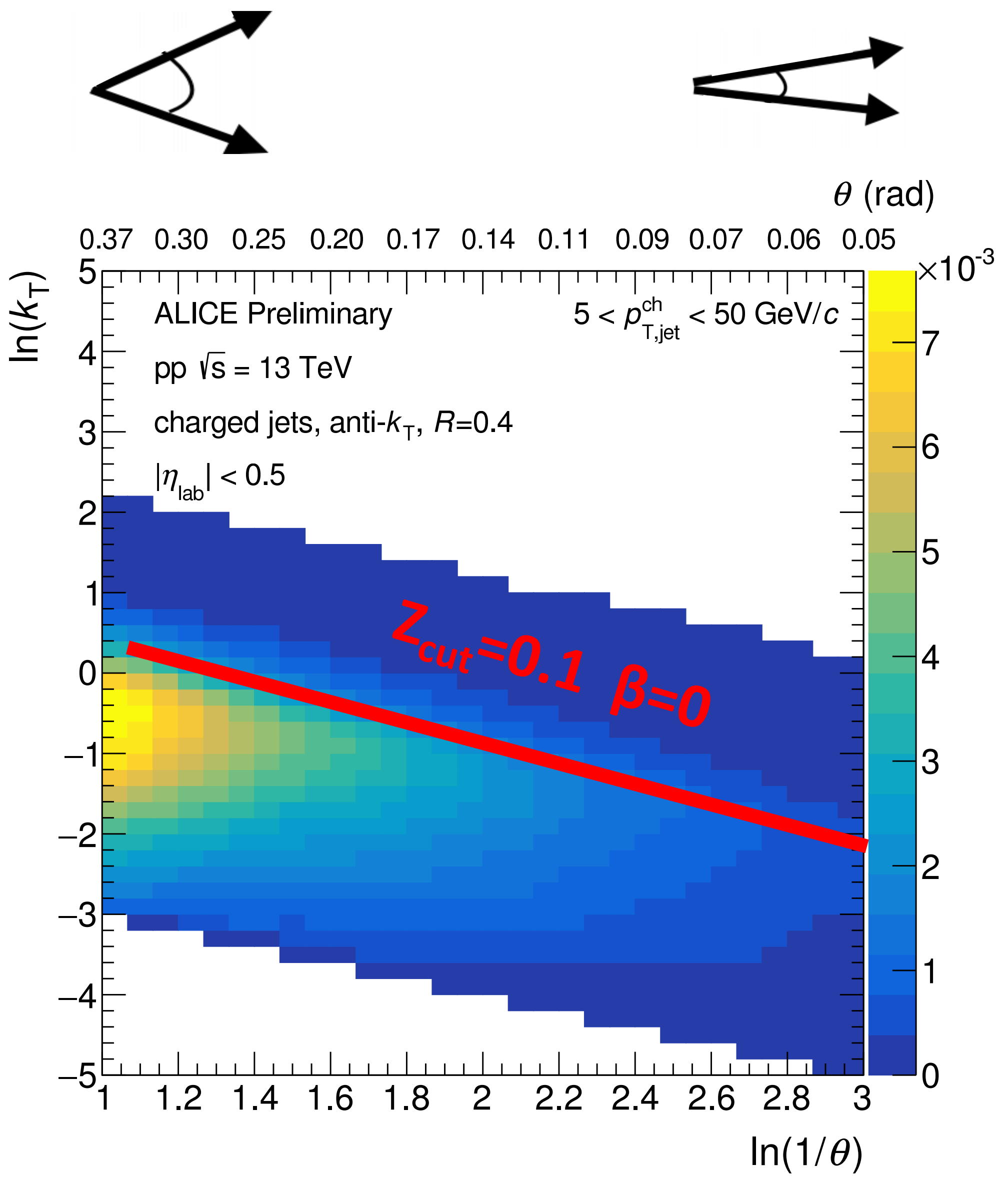
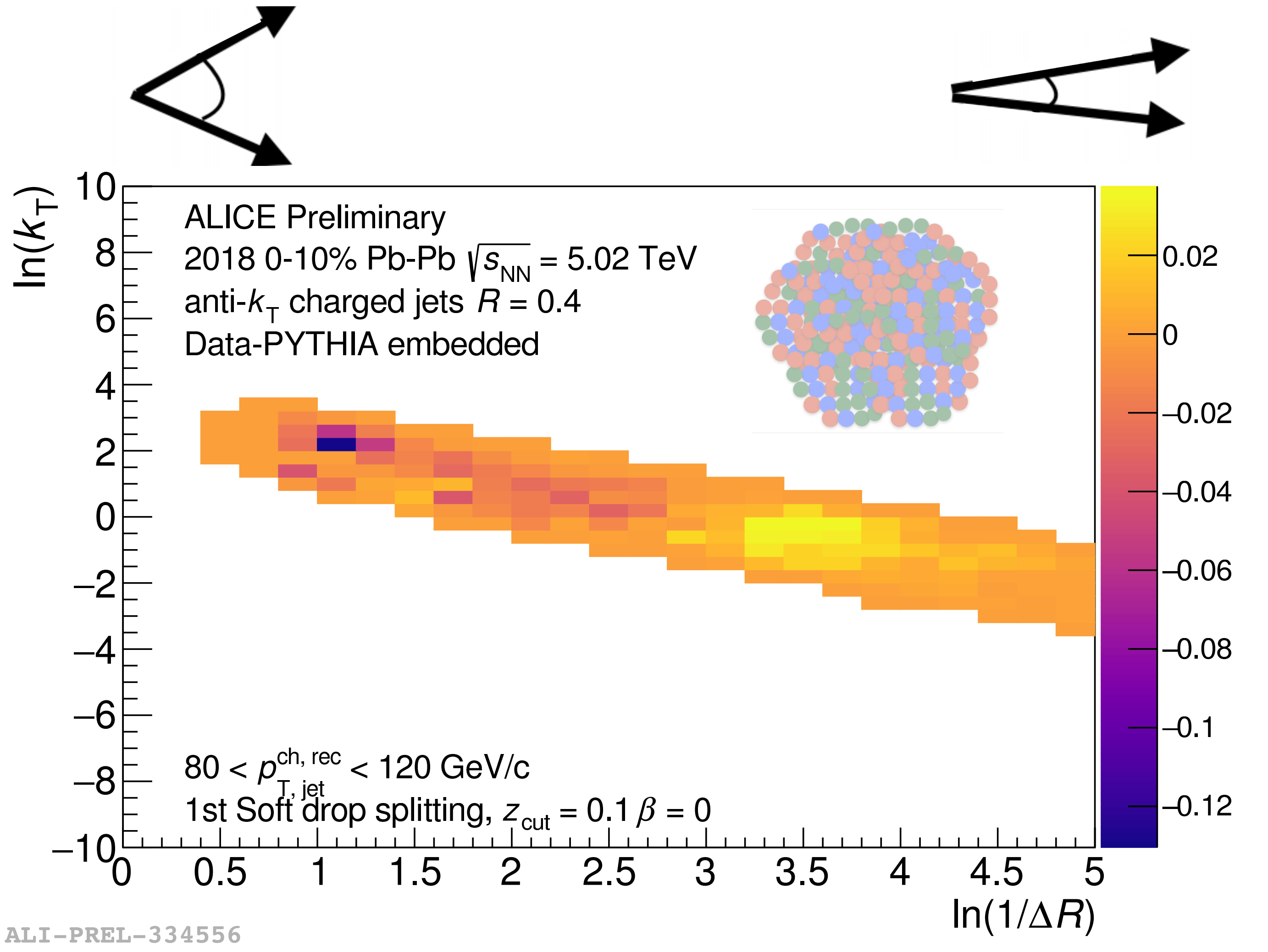


Lund Planes : Data – Embedded PYTHIA

Not unfolded!
Large contamination of fake splittings due to residual background

- Lund plane filled with first splitting that passes Soft Drop
- Lund planes in Pb-Pb data compared to PYTHIA embedded into the Pb-Pb background
- Remaining differences due to quenching effects :
    - Underlying Event accounted for



Normalised to toal number of jets in given $p_{T,jet}$ bin

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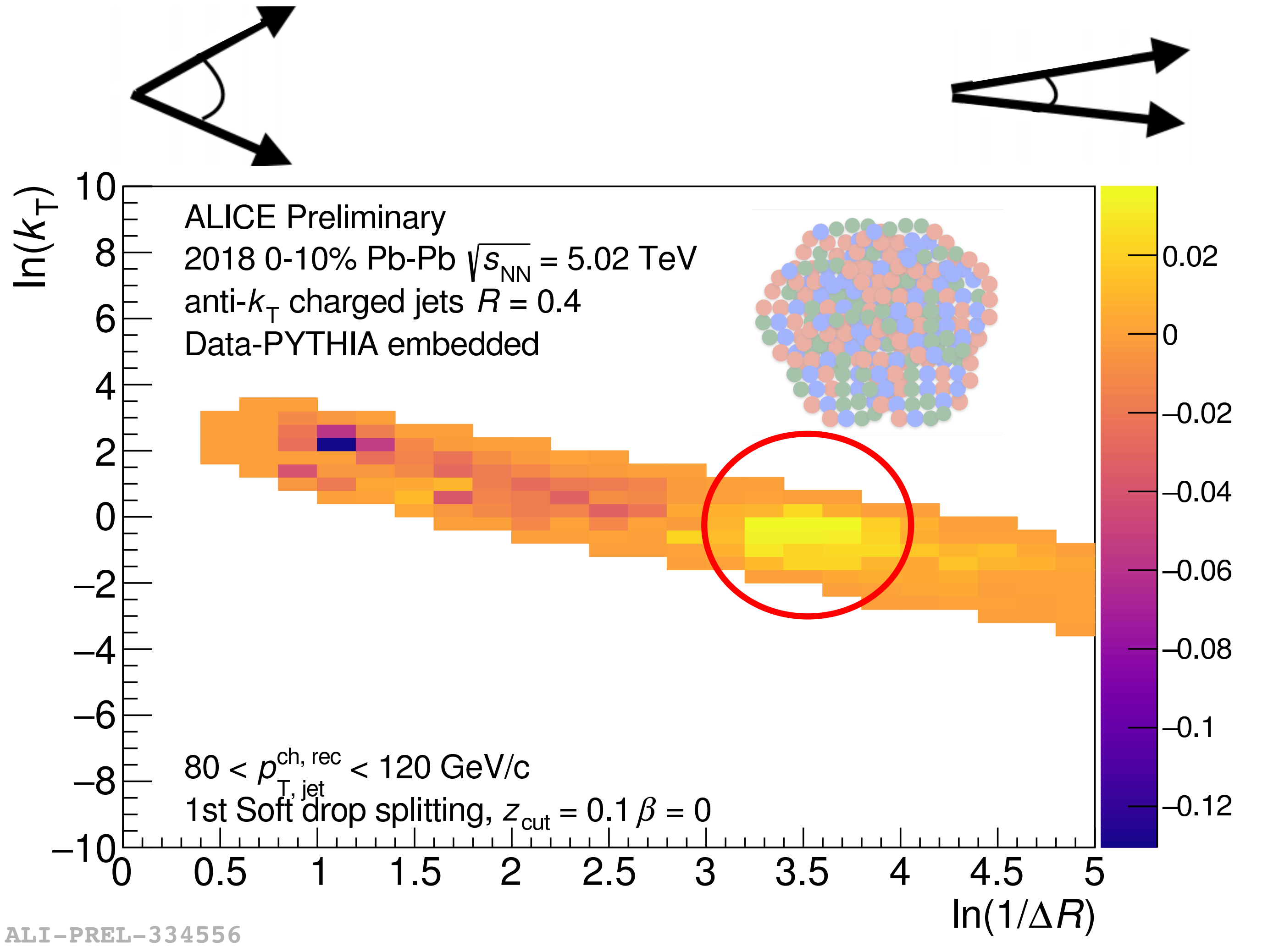

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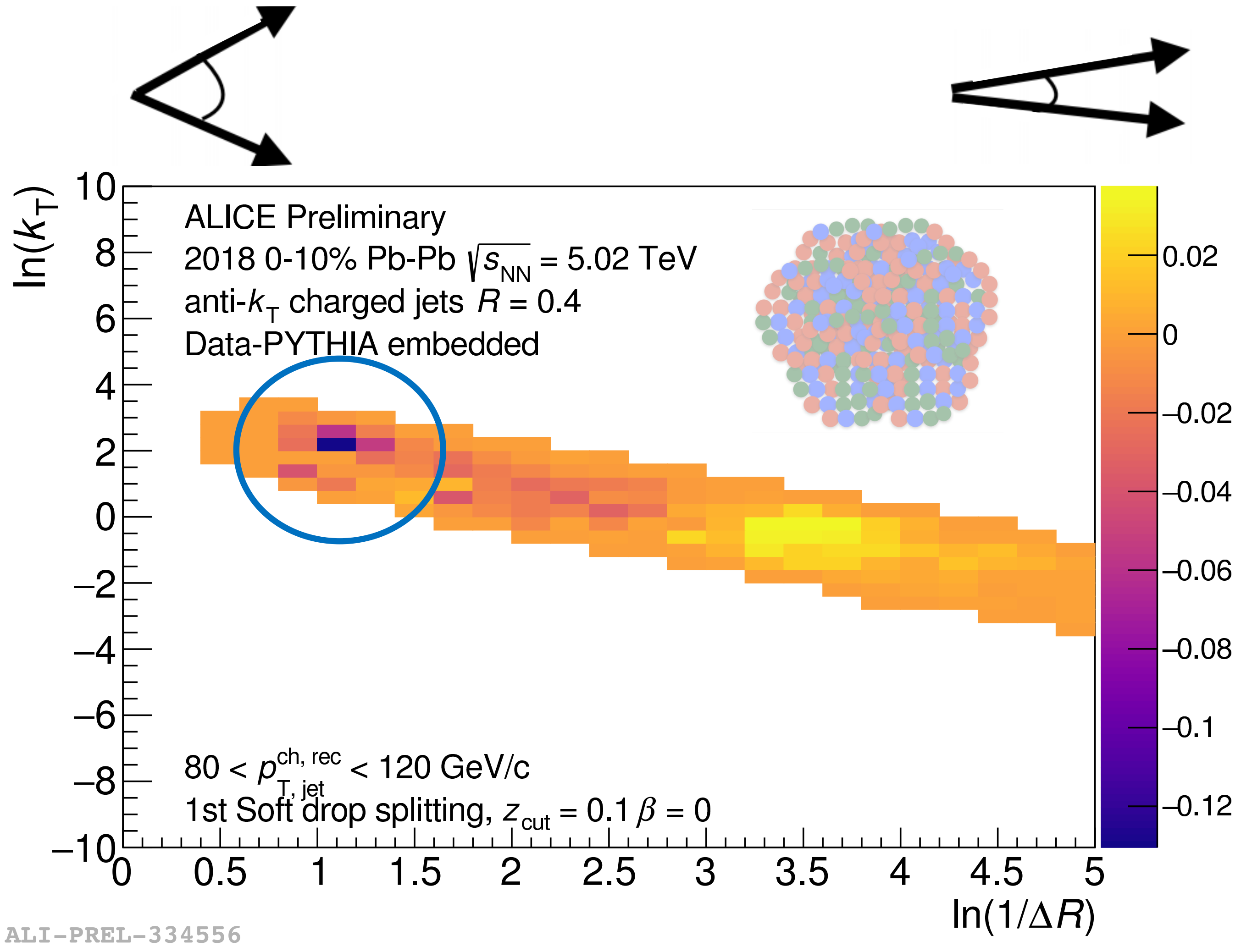
  - Underlying Event accounted for
- Enhancement of narrow splittings
- Suppression of wide splittings
  - Early formatin times?
  - Colour coherence?

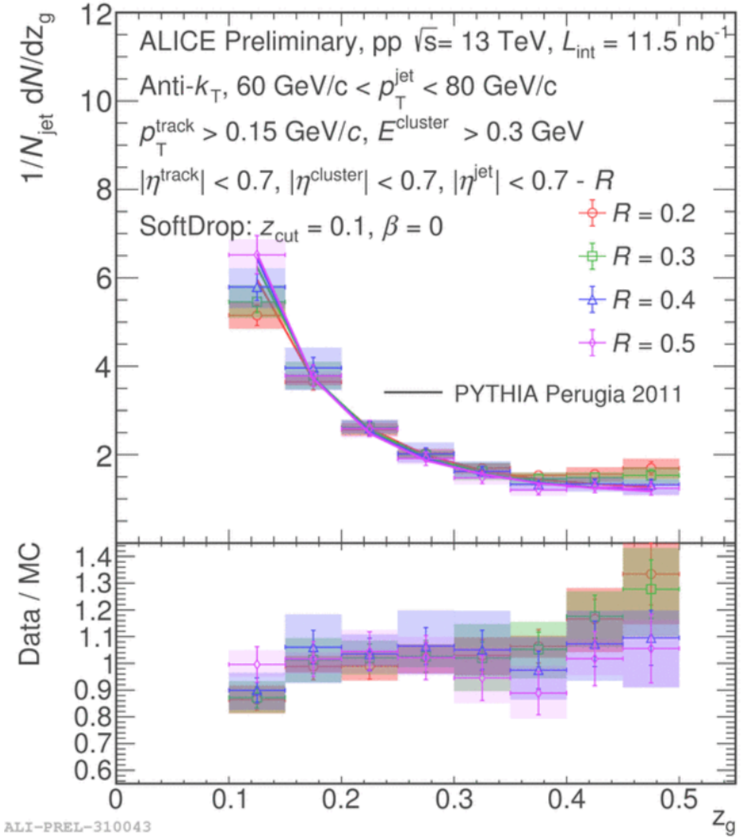


Normalised to toal number of jets in given $p_{T,jet}$ bin

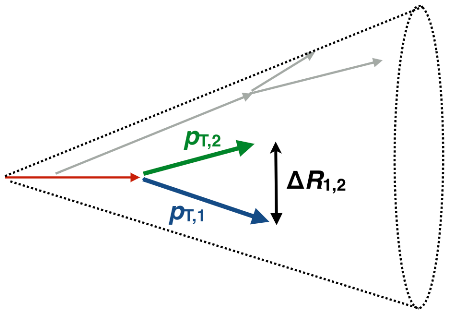
Testing the QCD Splitting Function

- The Soft Drop groomed shared momentum fraction
  - Access first perturbative splitting
- Changing the jet resolution varies the contribution of perturbative and non-perturbative effects

Jet resolution ordering of the QCD splitting kernel observed



charged + neutral (EMCal) jet measurement



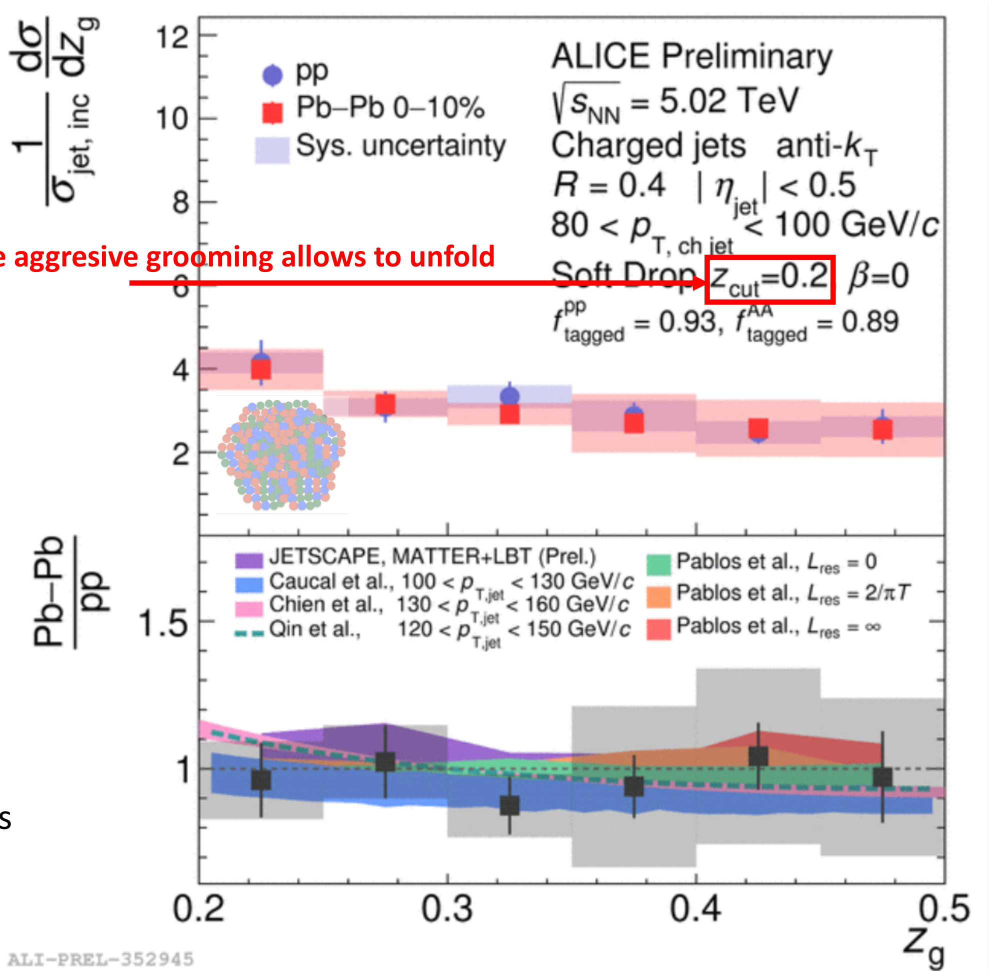
$$z_g = \frac{p_{T,2}}{p_{T,2} + p_{T,1}}$$

Differential measurements across jet p_T and grooming conditions

- Are symmetric or asymmetric splittings modified differently in the presence of the medium?

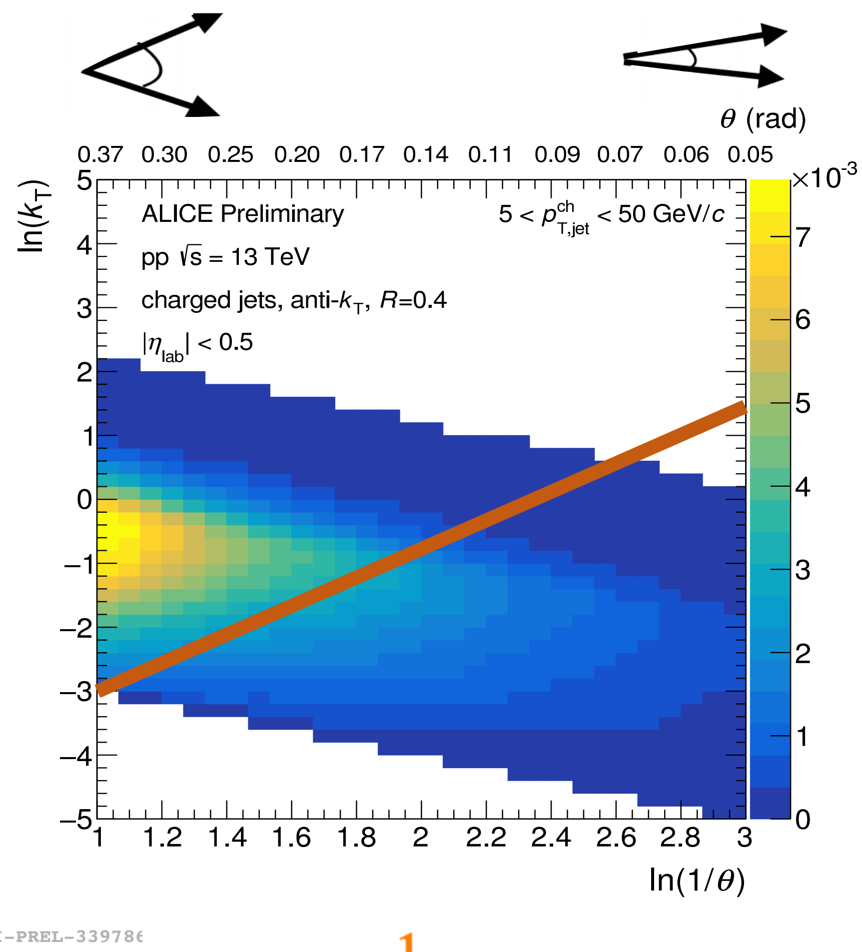
No medium-induced modifications observed

More aggresive grooming allows to unfold

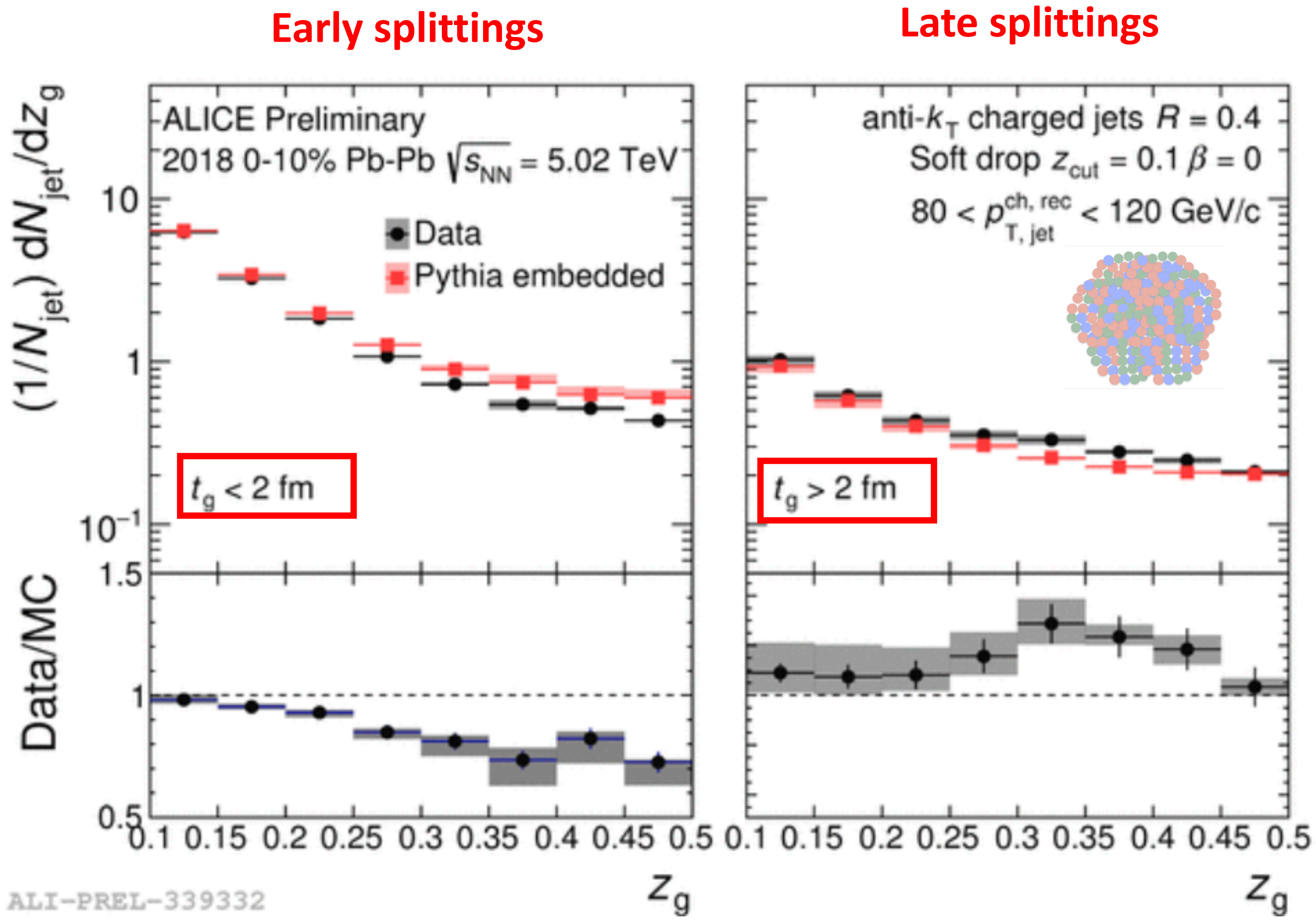


Can We Isolate Regions on the Lund plane?

Not unfolded!



$$t_f = \frac{1}{(1-z)k_T \Delta R}$$



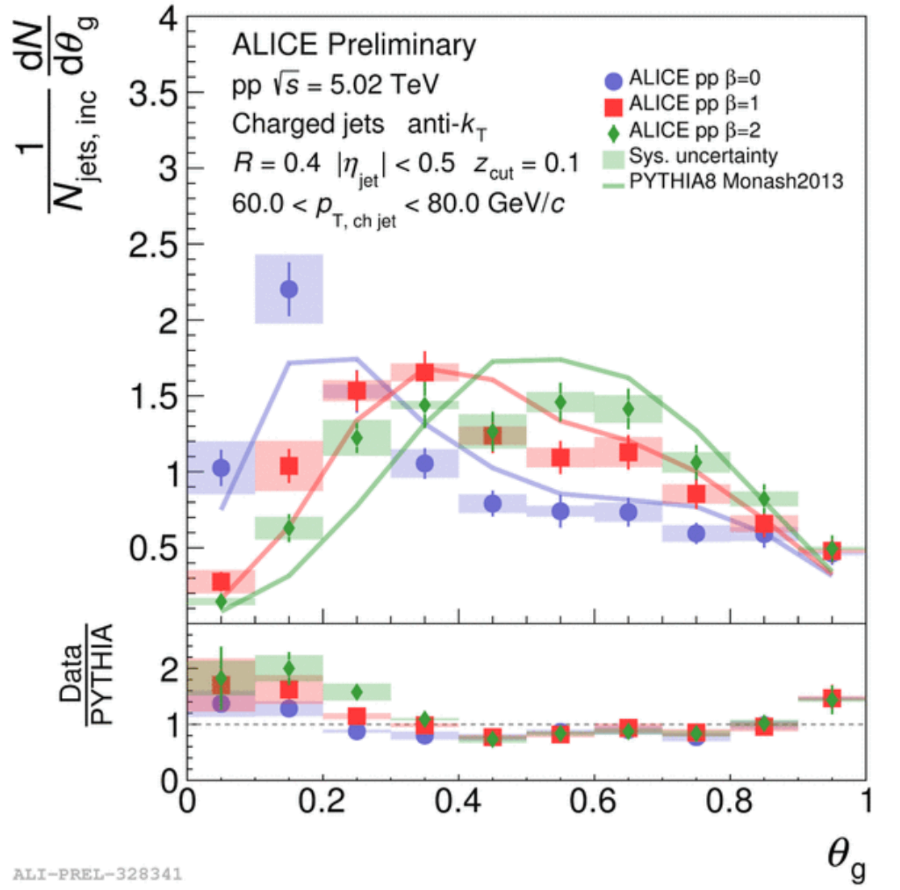
- Cuts on groomed formation time can separate early and late perturbativ splittings
- Early splittings supressed in the medium

The Jet Opening Angle

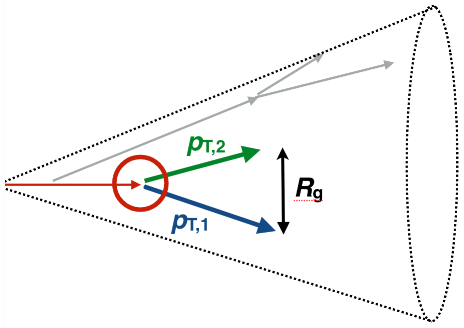
- ➢ The angular scale of the first splitting passing soft drop
- ➢ Systematically testing the angular dependence of the QCD shower

- ➢ Wide-angle splittings formed early – more energy loss
- ➢ Does the medium resolve wide-angle splittings?
  - ❖ Colour coherence?

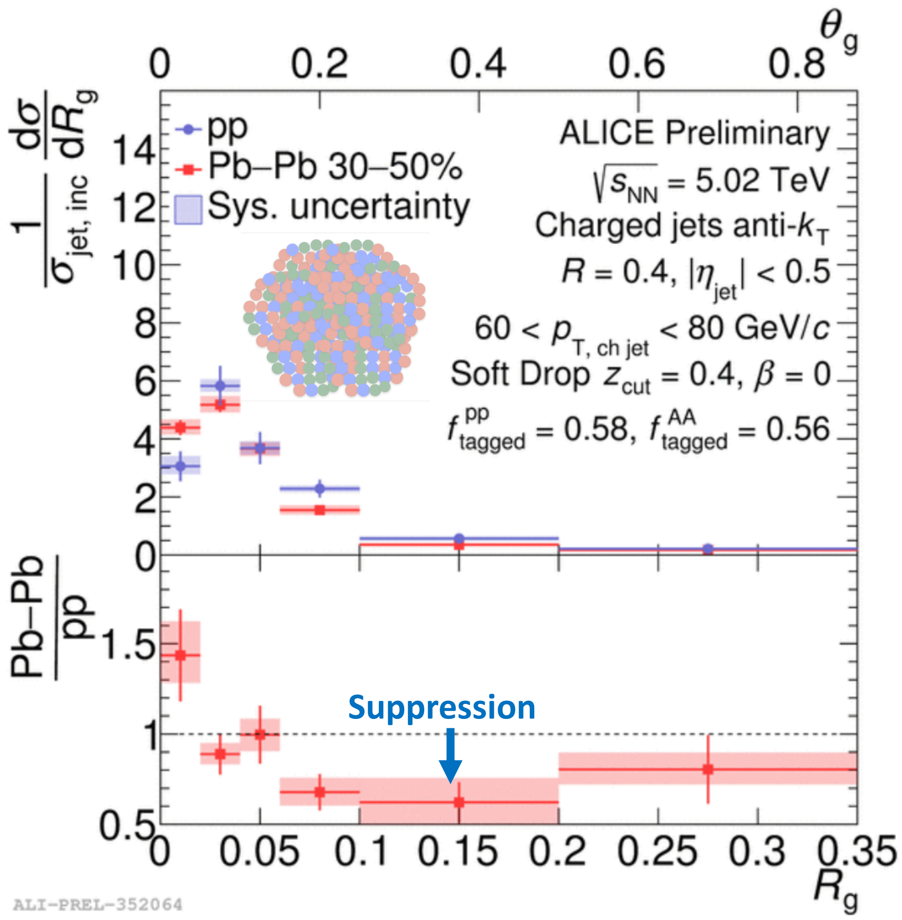
Room for improvement for PYTHIA



$$\theta_g = \frac{R_g}{R}$$

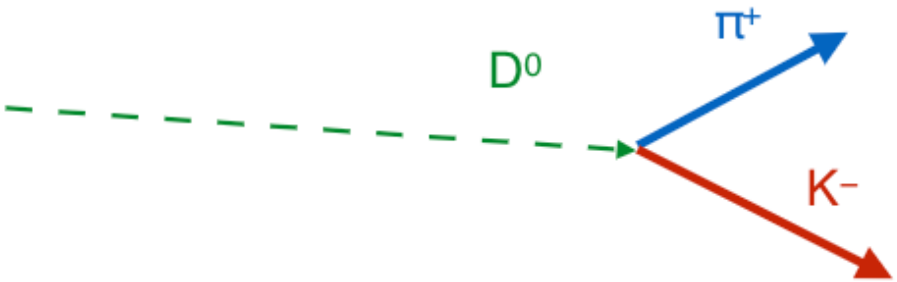


Suppression of wide-angle splittings in the medium



Heavy-Flavour at ALICE

- Excellent tracking and PID capabilities at ALICE allow for the full reconstruction of HF candidates
- Topological and PID selections on daughter tracks



Full Reconstruction of HF Candidates

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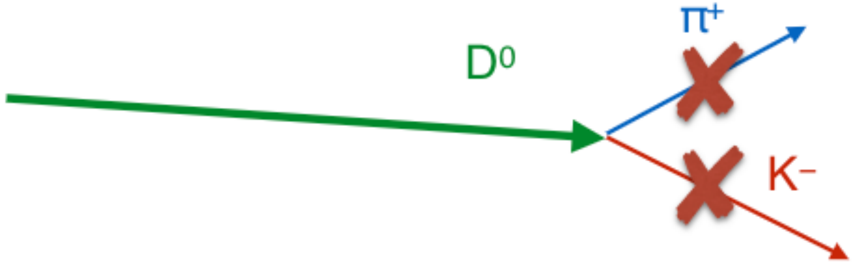
- Topological and PID selections on daughter tracks

- Full reconstruction of the D^0 : Replace 4-momenta of daughters with that of D^0



Heavy Flavour Jets – D0

- Excellent tracking and PID capabilities at ALICE allow for the full reconstruction of HF candidates
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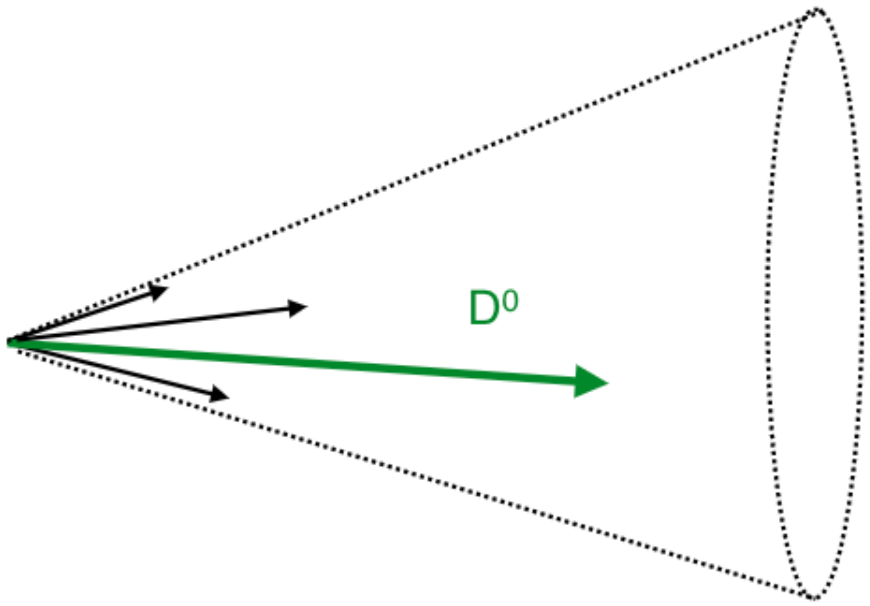
- Full reconstruction of the D^0 : Replace 4-momenta of daughters with that of D^0
- Tag charm jets via the presence of a D^0 candidate



Accessing the Charm Quark

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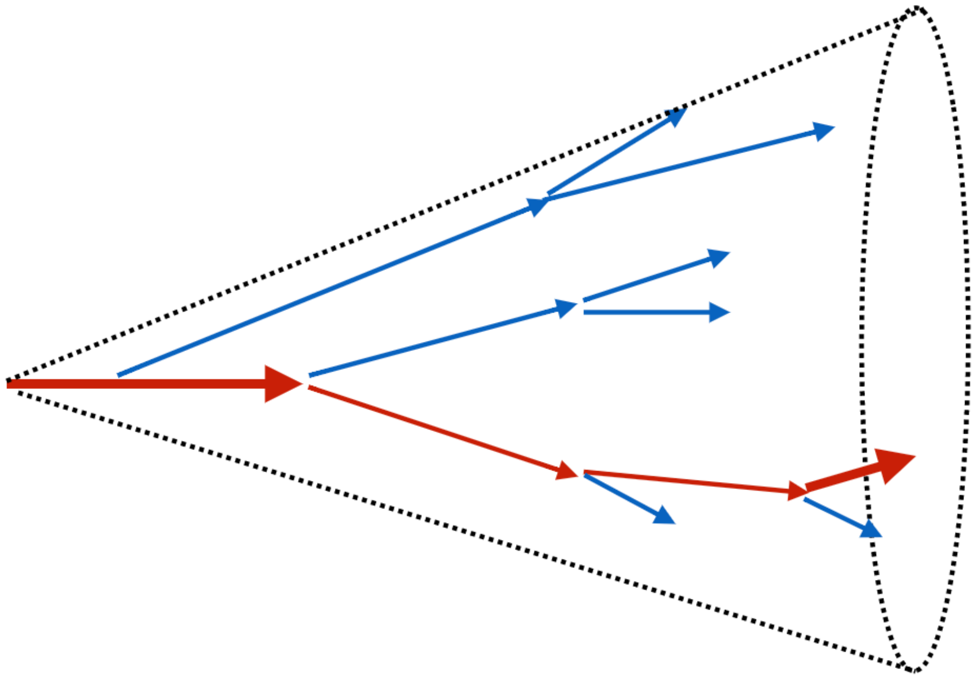
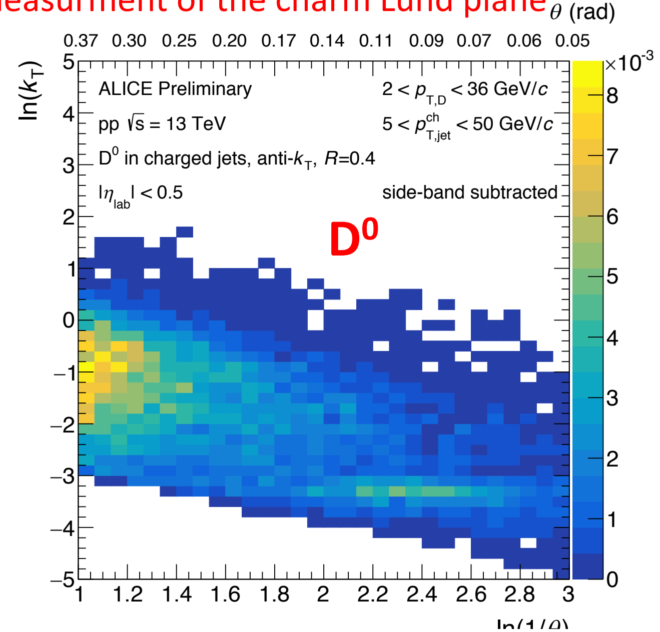
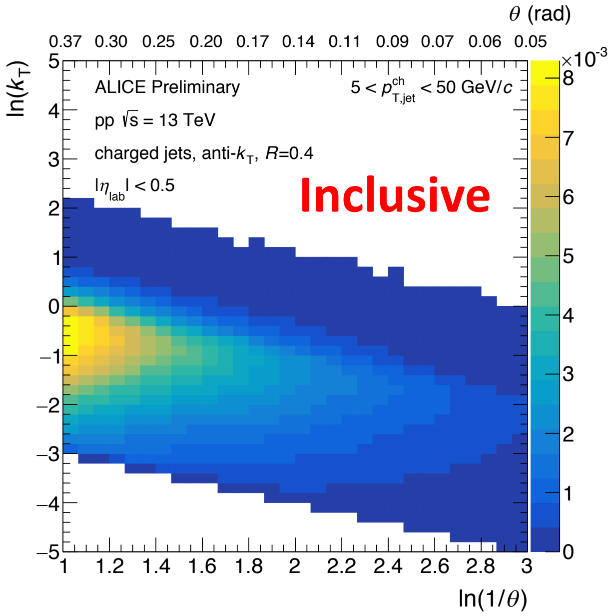
- Topological and PID selections on daughter tracks
- Full reconstruction of the D^0 : Replace 4-momenta of daughters with that of D^0
- Tag charm jets via the presence of a D^0 candidate
- Charm flavour conserved throughout fragmentation :
  - Full reconstruction of D^0 allows for tracing of charm quark throughout shower
  - Access to partonic splittings of the charm quark



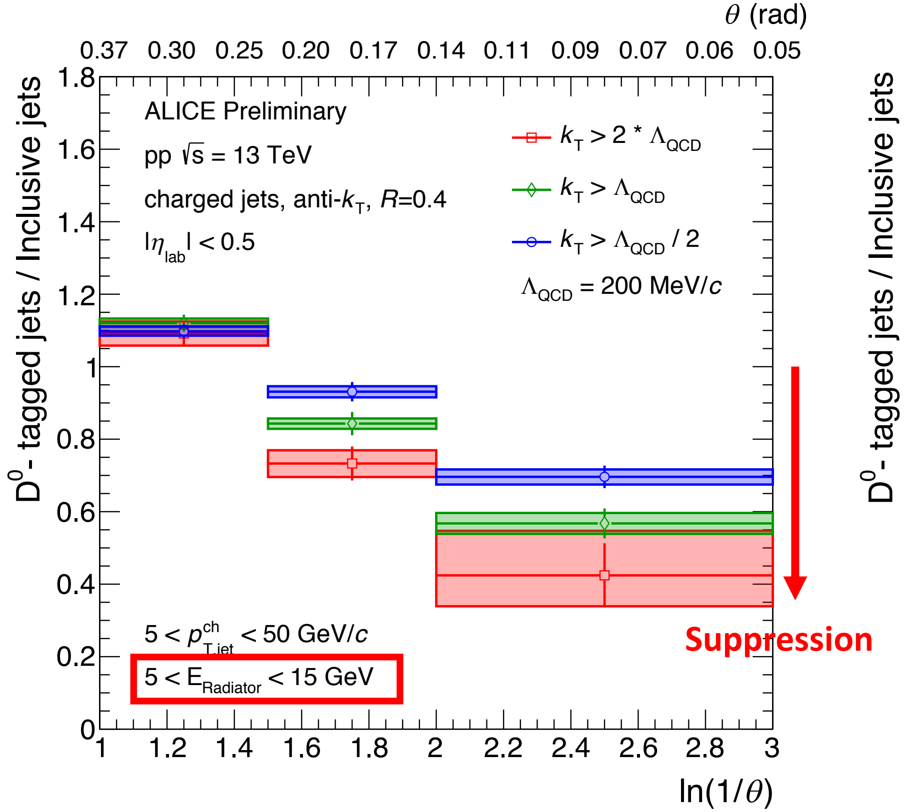
Uncovering the QCD Dead-Cone

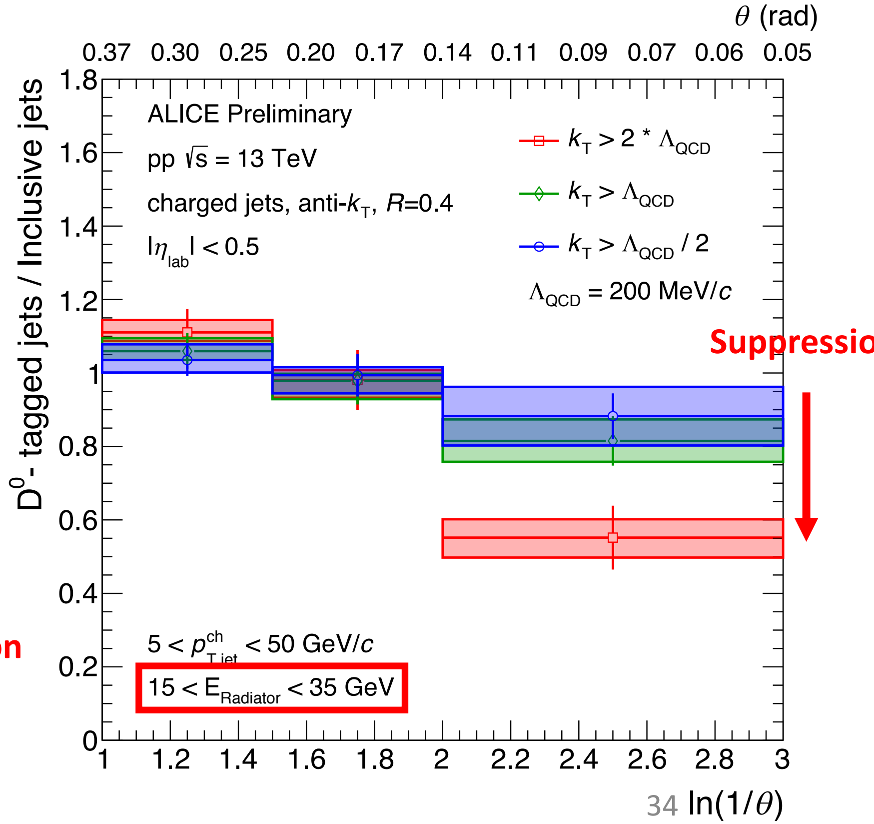
First measurment of the charm Lund plane





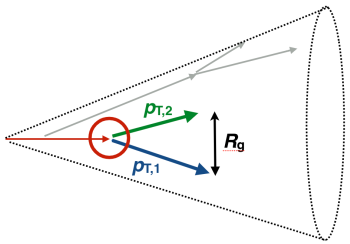
- Dead-cone effect : suppression of radiation from an emitter within an angle m/E
- The angular distribution of emissions of the charm quark and inclusive partons compared – all the way through the splitting tree
- Suppression of small-angle emissions for charm quarks – first direct measurement of the QCD dead-cone
- Suppression Larger for less energetic charm quarks
- First measurement to access the bare quark mass in the partonic state



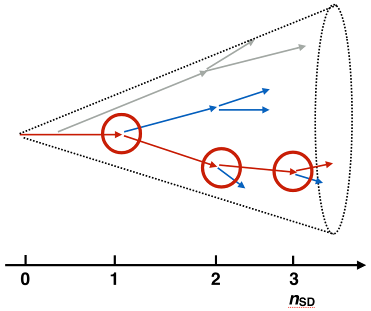


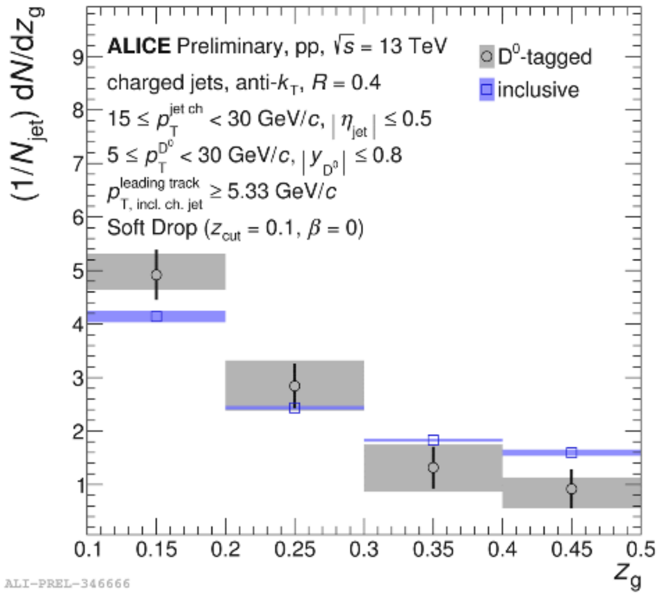
D^0-tagged Jet Substructure in pp

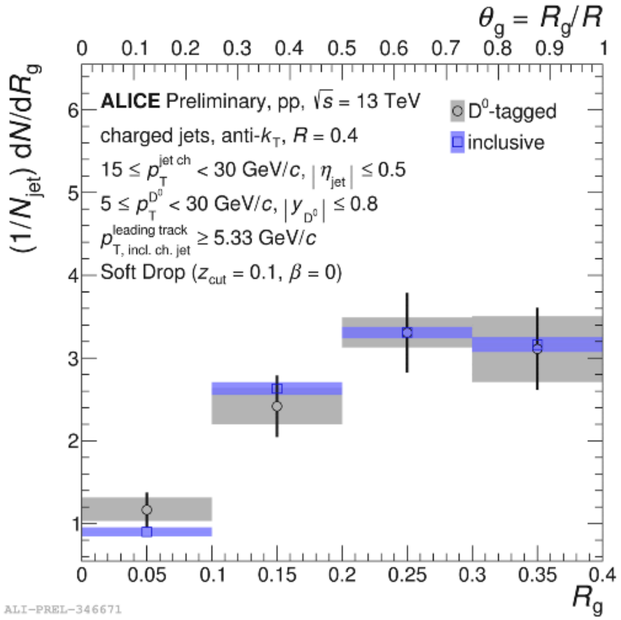
- HF jets provide a quark enriched sample:
    - Differences to gluon jets due to casimir colour factors
- Heavy vs light quark jet substructure : the dead-cone effect
- Measurement of Soft Drop Variables

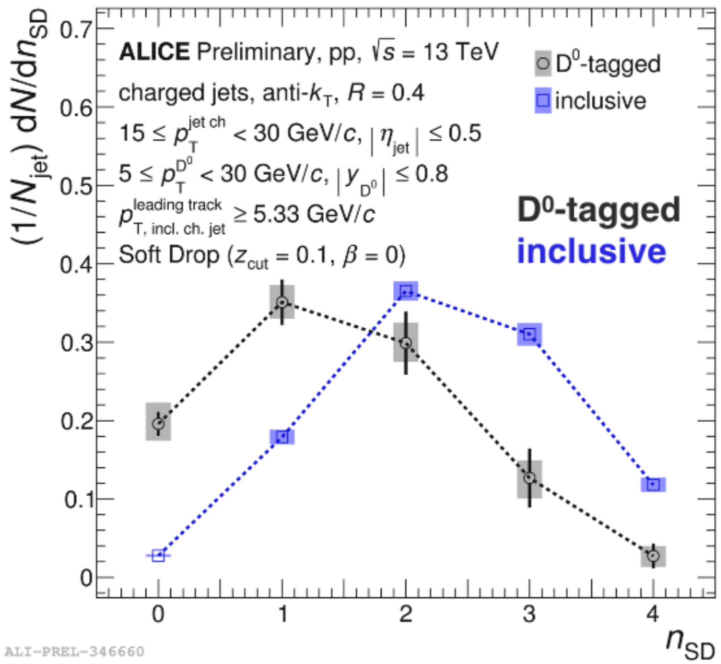


- Go deeper into the splitting tree
- Measure number of perturbative splittings satisfying Soft Drop









No statistically significant difference between charm-tagged and inclusive jets – need more stats

Fewer hard splittings for charm quarks: due to the charm dead-cone

Prospects for Run 3 and Beyond

- Exciting and extensive jet substructure program underway at ALICE:
  - Systematically testing QCD in the little explored low and intermediate p_T regimes – pp collisions
  - Characterising the mechanisms of jet quenching - Pb-Pb collisions
- Improved tracking resolution and faster readout upgrades for Run 3:
  - 100 times more statistics – allows for more differential inclusive measurements
  - HF factory :
    - Precision measurements of charm jet substructure
    - Jets tagged with fully reconstructed beauty hadrons accessible
- Exciting potential for a new detector for Run5 :
  - Excellent tracking up to $|\eta| < 4$
  - Very low material budget
  - Strong PID capabilities
  - Potential for a very rich jet substructure program

Run5