



First Direct Measurement of the Dead-Cone Effect at Colliders in pp Collisions

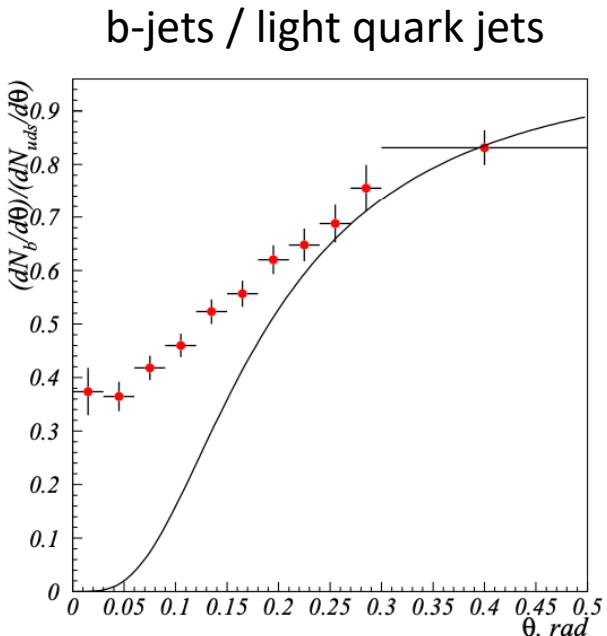
Nima Zardoshti (CERN)
for the ALICE Collaboration

Quark-Matter 2019 - Wuhan - 05/11/2019

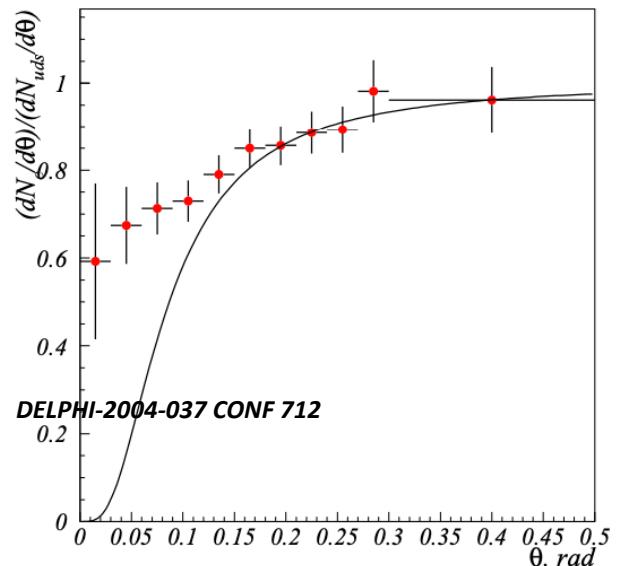
The Dead-Cone Effect

- The dead-cone is a universal property of all radiative theories
- It predicts a suppression of emissions from a radiator (quark) within $\theta < \frac{Mq}{Eq}$
- In QCD this leads to a change in the expected fragmentation of heavy and light quarks:
 - ❖ Gluons radiated with a **small k_T** are restricted
 - ❖ Fragmentation functions of heavy quarks peak at **larger values**
- Never been directly measured at colliders
 - ❖ Dead-cone region populated by **decay products** and **uncorrelated background**
 - ❖ Difficult to precisely determine the **splitting axis**

Depletion of jet fragments



c-jets / light quark jets

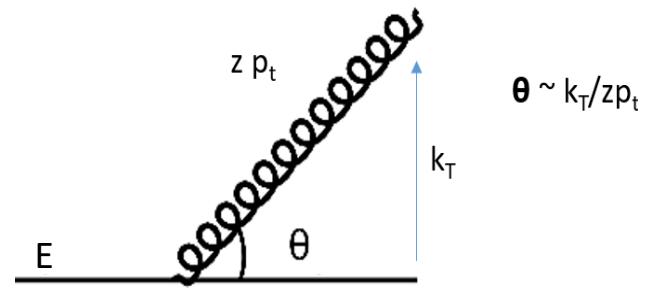
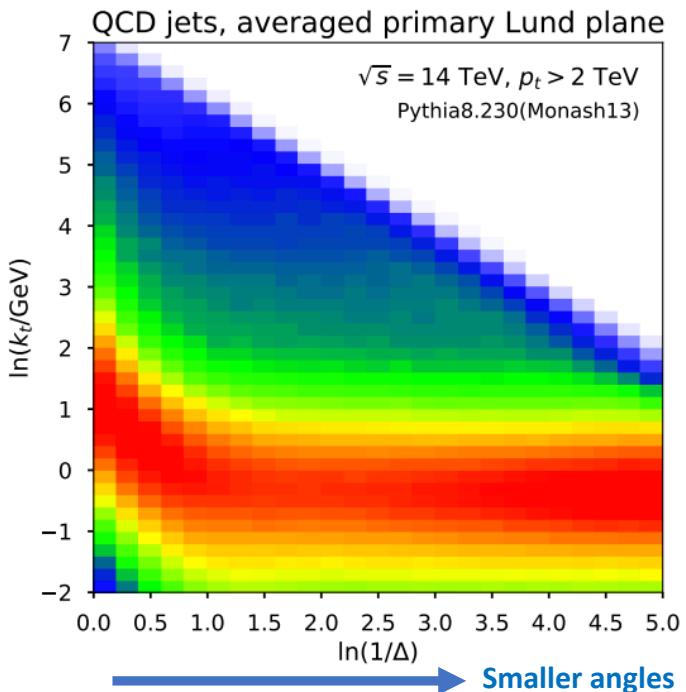


DELPHI-2004-037 CONF 712

The Dead-Cone Effect

- The dead-cone is a universal property of all radiative theories
- It predicts a suppression of emissions from a radiator (quark) within $\theta < \frac{Mq}{Eq}$
- In QCD this leads to a change in the expected fragmentation of heavy and light quarks:
 - ❖ Gluons radiated with a **small k_T** are restricted
 - ❖ Fragmentation functions of heavy quarks peak at **larger values**
- Never been directly measured at colliders
 - ❖ Dead-cone region populated by **decay products** and **uncorrelated background**
 - ❖ Difficult to precisely determine the **splitting axis**

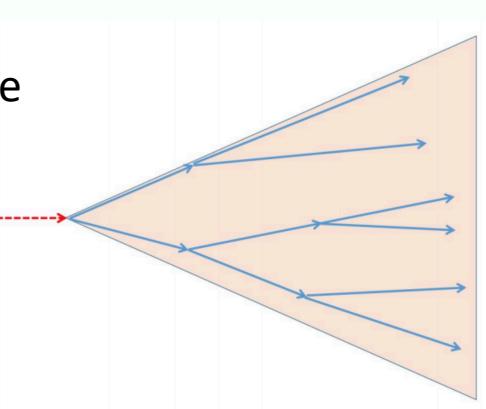
F. A. Dreyer , G. P .Salam and G. Soyez, JHEP 1812, 064



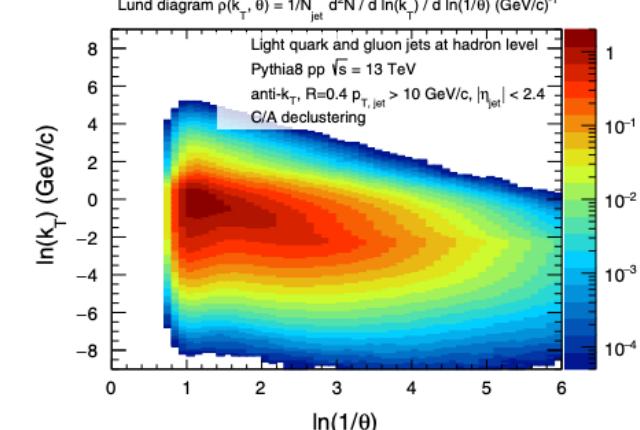
- E : Total energy of the radiator
- θ : Angle between daughter prongs
- k_T : Splitting scale

Strategy to Uncover the Dead-Cone

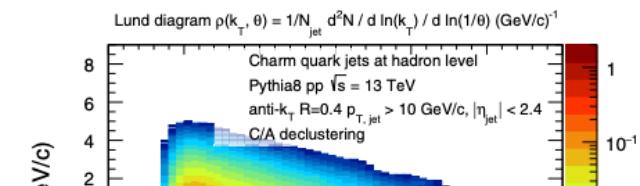
- Individual splittings in a jet can be reconstructed using jet reclustering techniques – reclustering history is unwound
- At each stage of the splitting tree, the kinematics of the splitting can be accurately obtained
- Splittings are used to populate 2D Lund-Maps



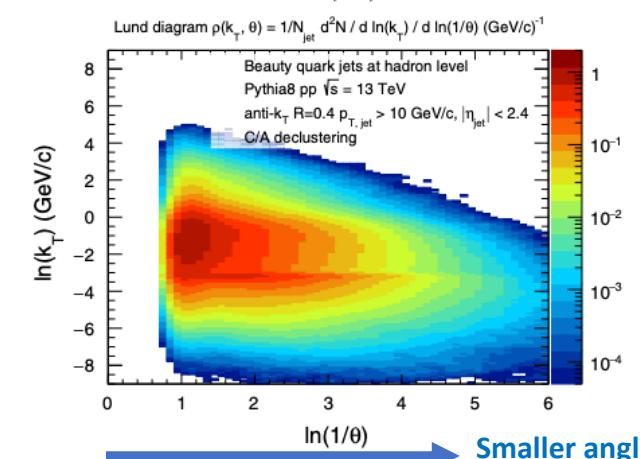
Lund diagram $\rho(k_T, \theta) = 1/N_{\text{jet}} d^2N / d \ln(k_T) / d \ln(1/\theta)$ (GeV/c)⁻¹



Inclusive



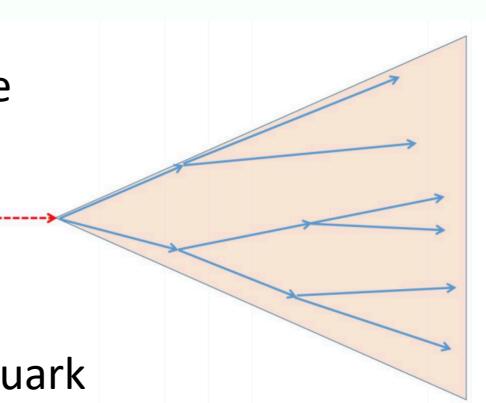
Charm



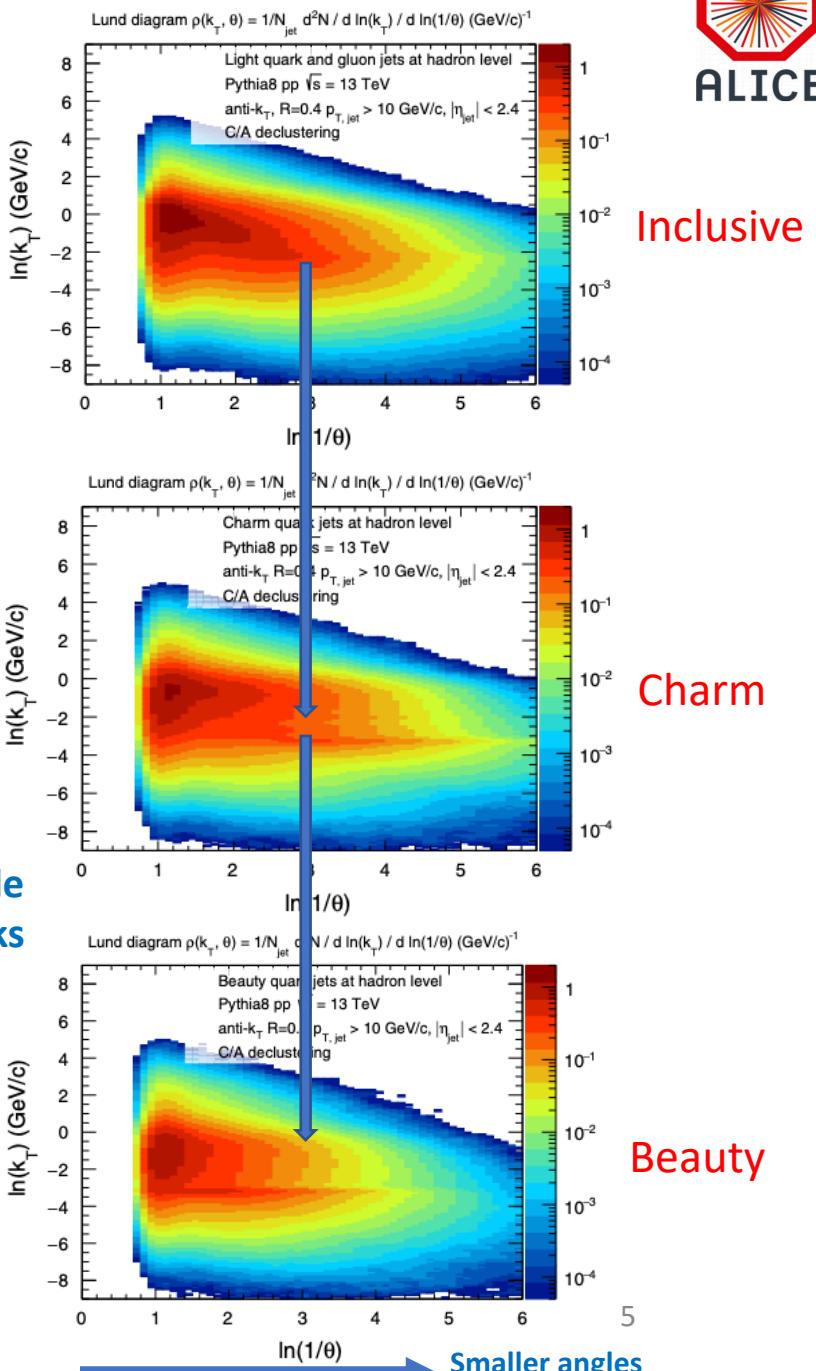
Beauty

Strategy to Uncover the Dead-Cone

- Individual splittings in a jet can be reconstructed using jet reclustering techniques – reclustering history is unwound
- At each stage of the splitting tree, the kinematics of the splitting can be accurately obtained
- Splittings are used to populate 2D Lund-Maps
- Differences between the Lund-Map for heavy flavour quark jets and inclusive jets are used to uncover the dead-cone effect

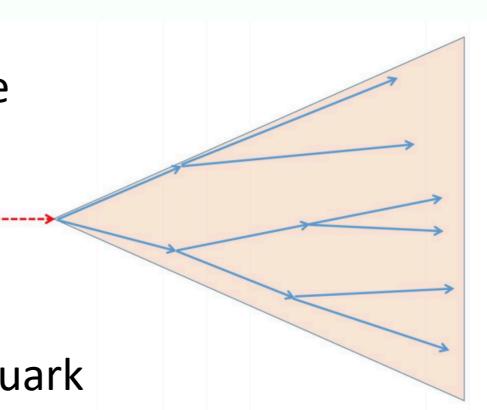


Expect to see a suppression of small angle radiation for heavy-quarks

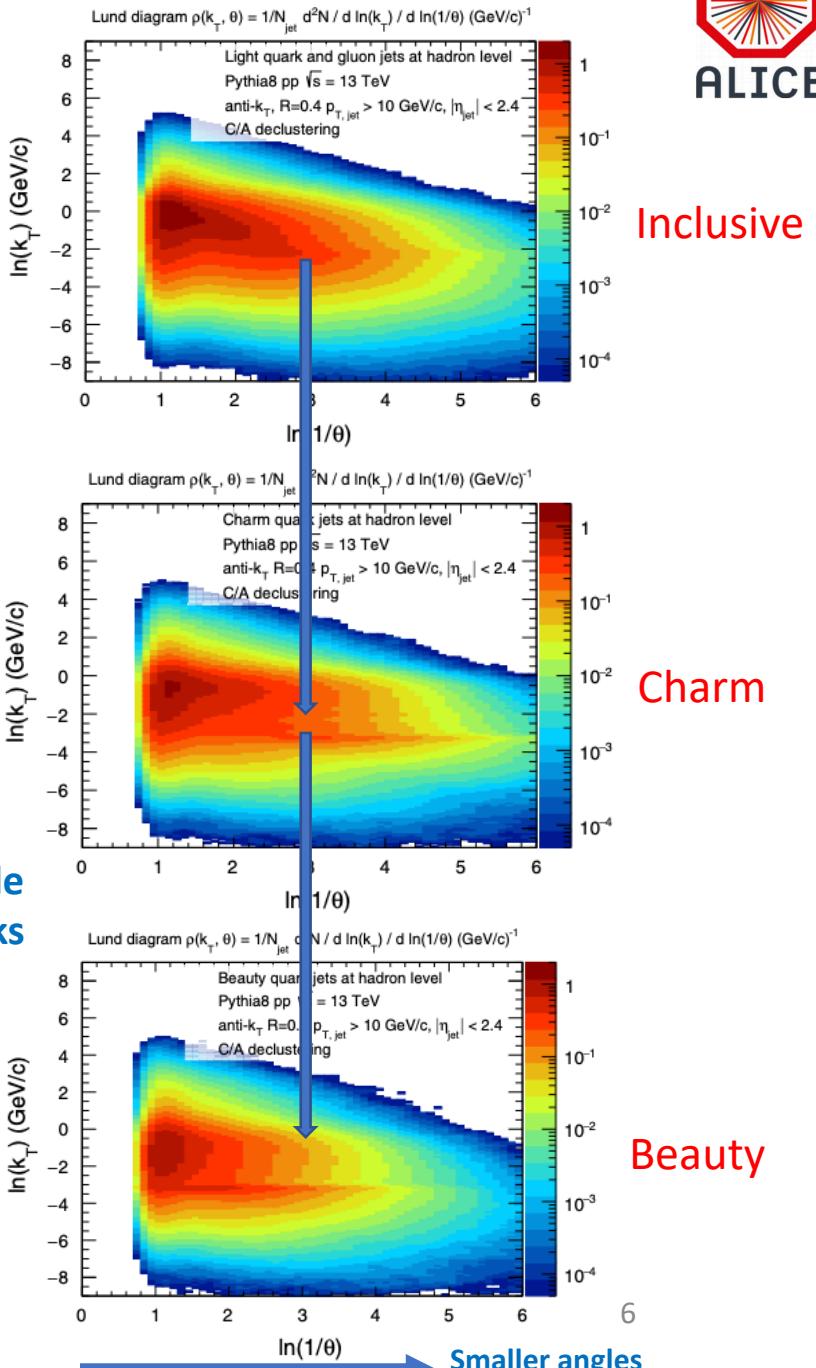


Strategy to Uncover the Dead-Cone

- Individual splittings in a jet can be reconstructed using jet reclustering techniques – reclustering history is unwound
- At each stage of the splitting tree, the kinematics of the splitting can be accurately obtained
- Splittings are used to populate 2D Lund-Maps
- Differences between the Lund-Map for heavy flavour quark jets and inclusive jets are used to uncover the dead-cone effect
- Projecting the angular plane of the Lund-Map can provide the first direct measurement of the dead-cone effect
- At ALICE the heavy flavour candidate (D^0) is fully reconstructed in the jet and its emissions are isolated
- The low $p_{T,jet}$ reach and excellent angular separation of ALICE's track-based detectors probe the phase-space where the effect is strongest

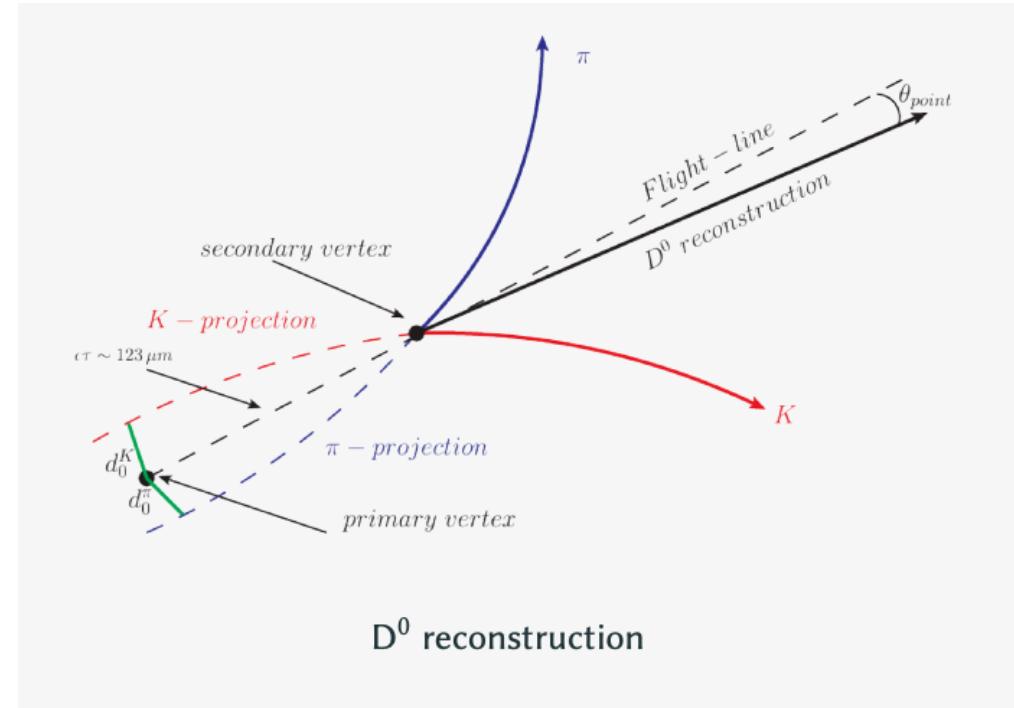


Expect to see a suppression of small angle radiation for heavy-quarks



D^0 Hadronic Decay Channel

- $D^0 \rightarrow K^\pm \pi^\mp$ with a branching ratio of 3.89%
- D^0 candidates are reconstructed through:
 - ❖ PID of K and π
 - ❖ Topological cuts on the secondary vertex
- K and π pairs are replaced by the D^0 candidate prior to jet finding
 - ❖ Mitigates against cases where the angle between the daughters is larger than the jet radius – better jet energy resolution
 - ❖ D^0 candidate can be tracked through the splitting tree
- Jet finding is performed independently for each D^0 candidate in an event
- Jets are clustered using the anti- k_T algorithm with $R=0.4$
- The jets are reclustered with the Cambridge-Aachen algorithm in exclusive mode
- $5 < p_{T,\text{jet}} < 50 \text{ GeV}/c$ $2 < p_{T,D} < 36 \text{ GeV}/c$ $|\eta_{jet}| < 0.5$



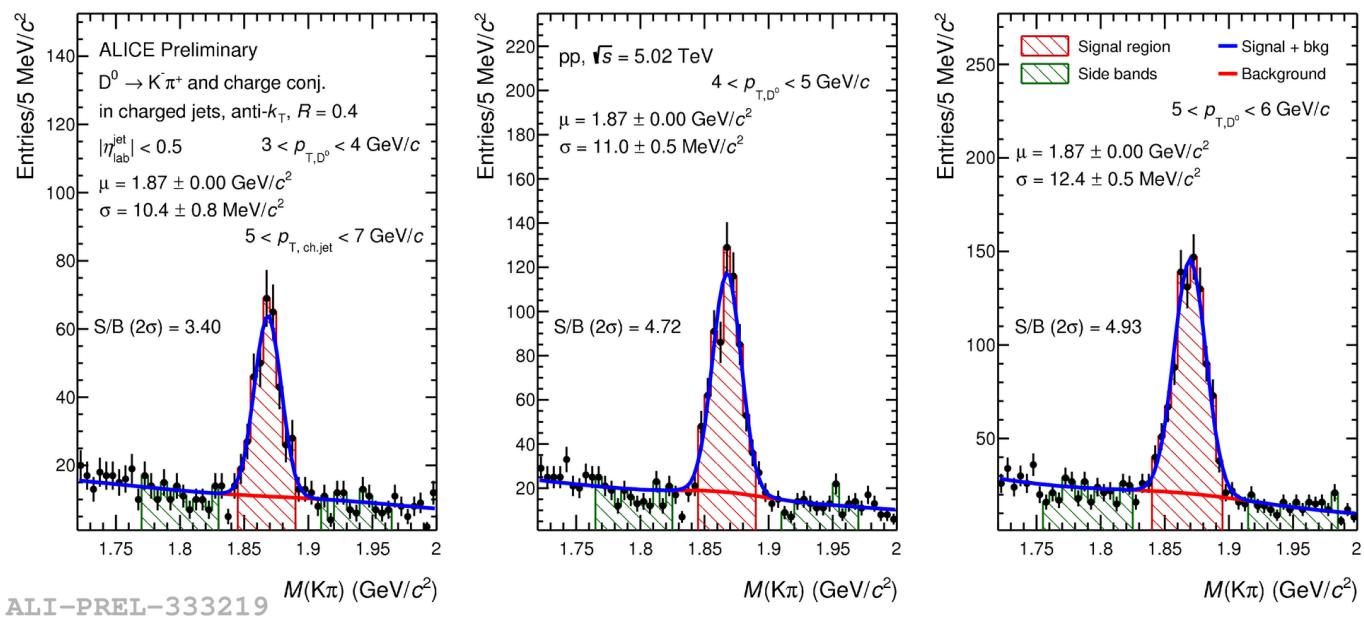
D⁰ Signal Extraction

- Invariant mass distributions of $k^\pm \pi^\mp$ fitted in bins of $p_{T,D}$

- Fitting performed with a Gaussian (signal) and an Exponential (background) function

$$Ax^B + Ce^{-\left(\frac{x-m}{2\sigma}\right)^2}$$

- A side-band subtraction technique is used to extract the signal
- Signal region is $\pm 2\sigma$ from the peak
- Side-band regions are $4-9\sigma$ away from the peak in either direction
- The area of the side-band region is scaled to the area of the background under the peak
- The scaled side-band contribution is subtracted from the signal region to obtain the signal only distribution



D⁰ Signal Extraction

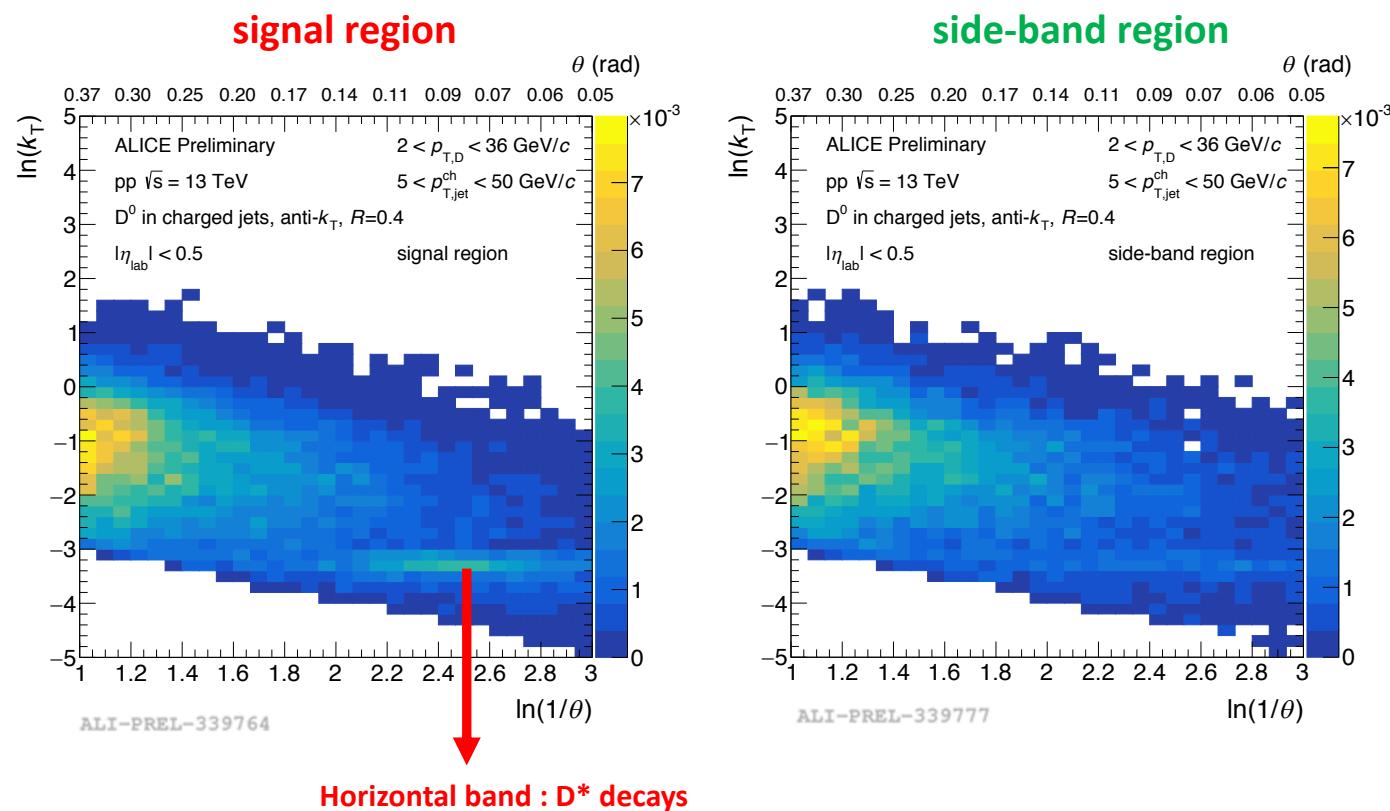
- Invariant mass distributions of $k^\pm \pi^\mp$ fitted in bins of $p_{T,D}$

- **Fitting** performed with a Gaussian (signal) and an Exponential (background) function

$$Ax^B + Ce^{-\left(\frac{x-m}{2\sigma}\right)^2}$$

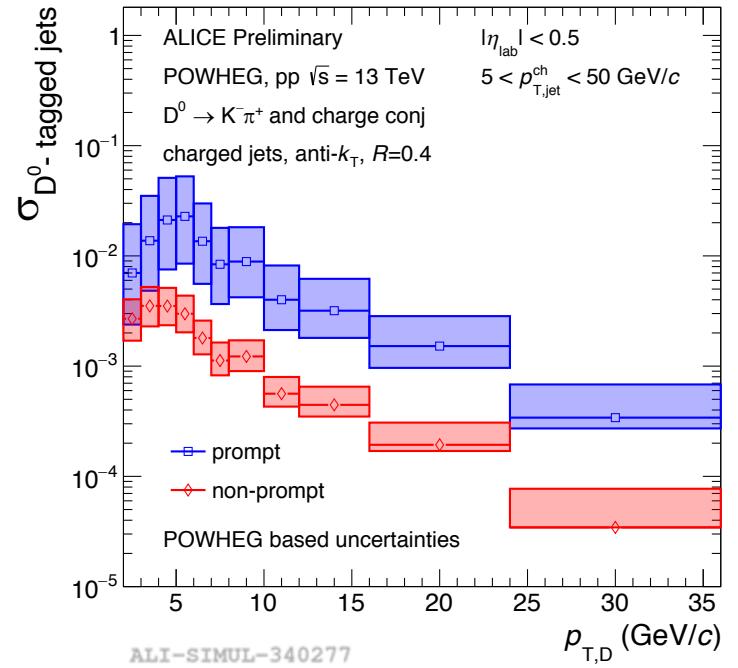
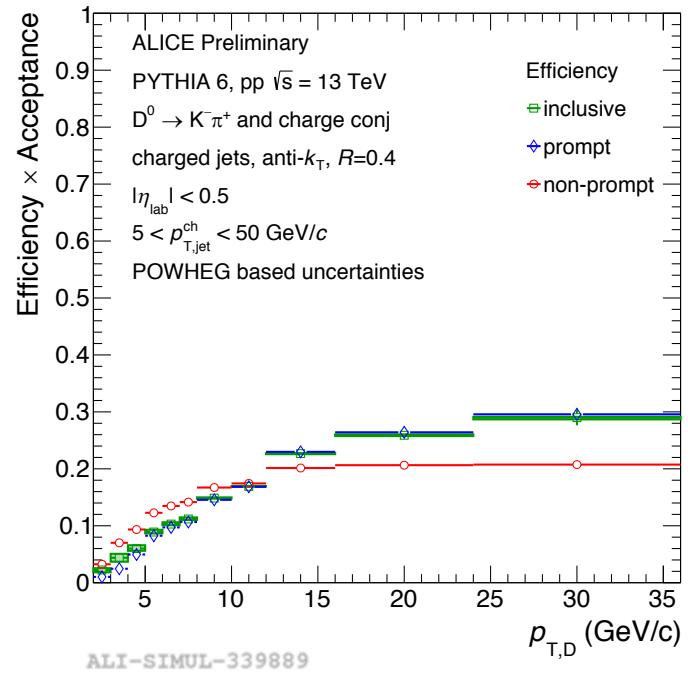
- A side-band subtraction technique is used to extract the signal
- **Signal region** is $\pm 2\sigma$ from the peak
- **Side-band regions** are $4-9\sigma$ away from the peak in either direction
- The area of the side-band region is scaled to the area of the background under the peak
- The scaled side-band contribution is subtracted from the signal region to obtain the signal only distribution
- The procedure is done in 2D on Lund-Maps

Note : Side-band subtraction is performed in bins of $p_{T,D}$
distributions shown here are integrated over $p_{T,D}$ for visual purposes

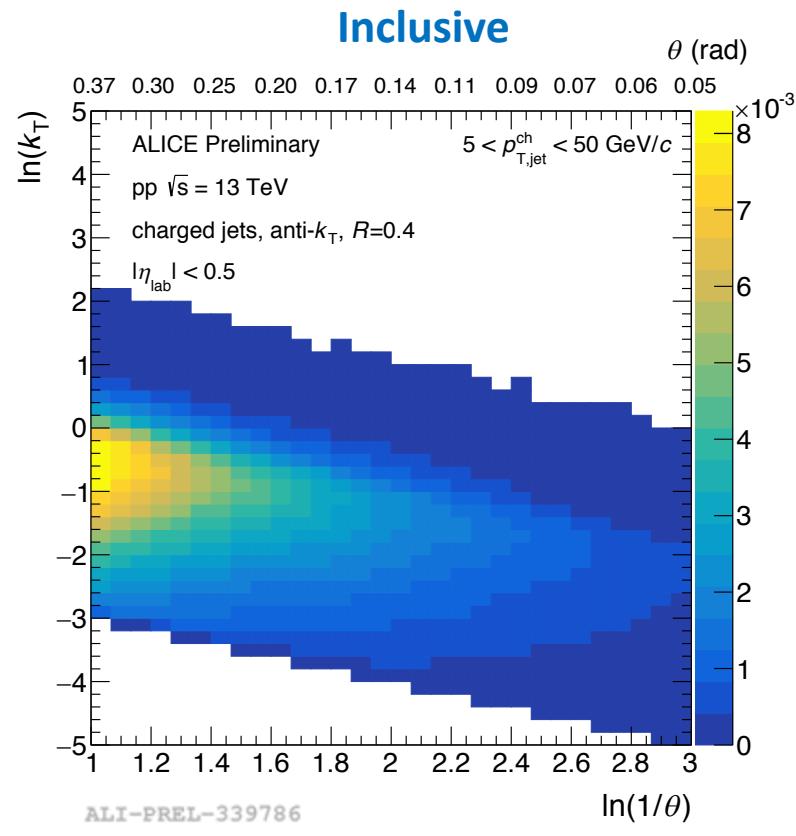
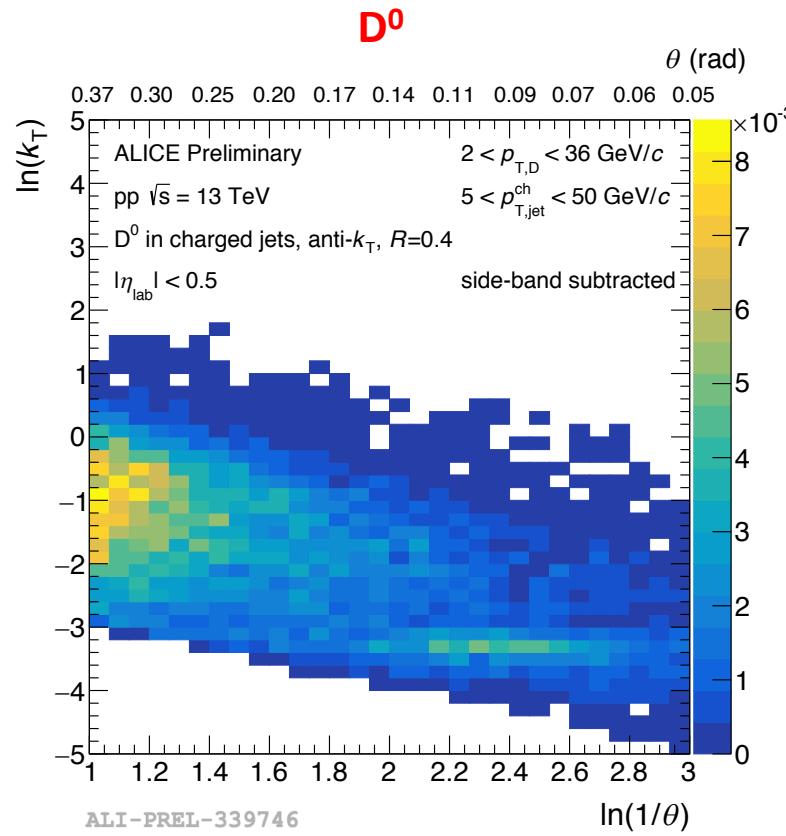


D⁰ Jet Finding Efficiency

- The topological and PID cuts used for the D⁰ candidate selection have a finite efficiency
- These efficiencies are calculated from MC in bins of $p_{T,D}$ for charm (prompt) and beauty (non-prompt) initiated D⁰ jets separately
- The **prompt** and **non-prompt** efficiencies are weighted according to their σ from POWHEG
- A **final efficiency value** per $p_{T,D}$ bin representing the correct admixture of **prompt** and **non-prompt** D⁰ jets is extracted
- The side-band subtracted distributions (in $p_{T,D}$ bins) are scaled by the D⁰ jet finding efficiency
- Scaled side-band subtracted Lund-Maps are added across $p_{T,D}$ bins to obtain the final D⁰ splittings Lund-Map



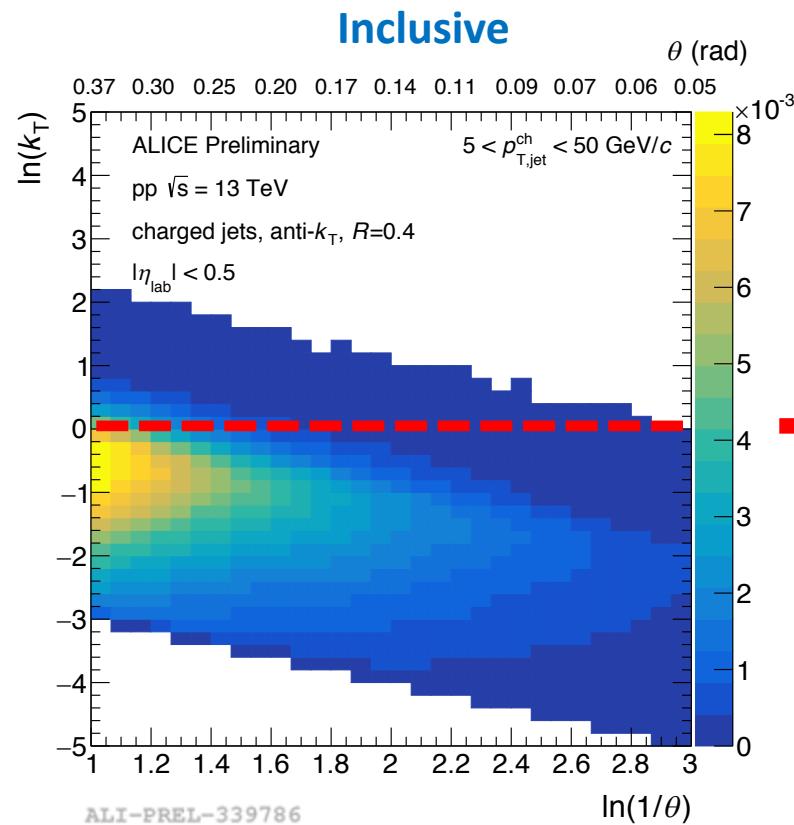
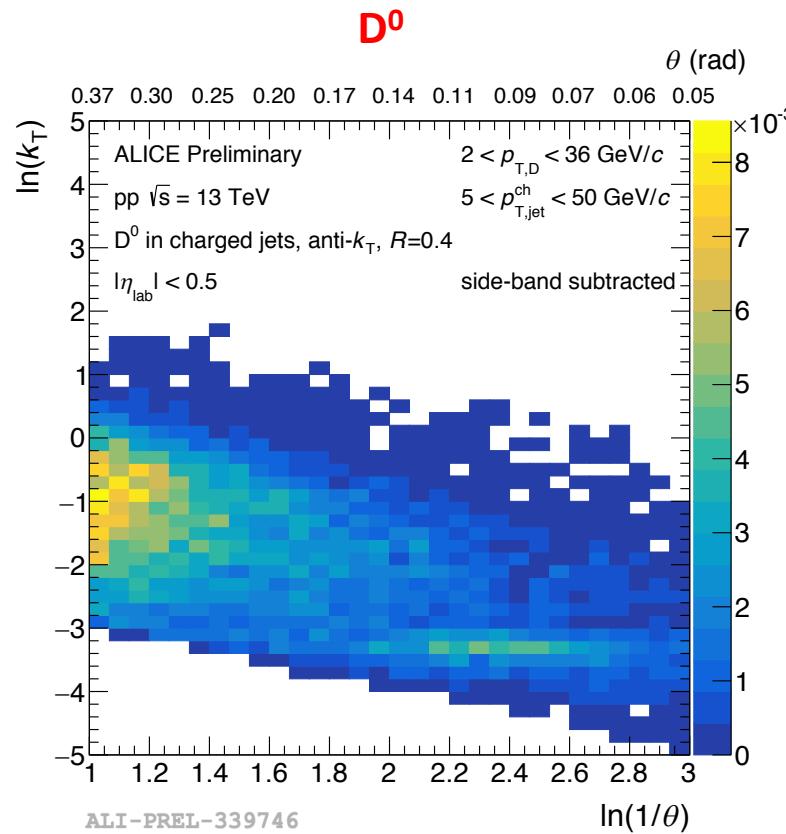
Splitting Lund Maps



- The Lund-Maps for the D^0 and inclusive jets show a hint of suppression of splittings at small angles in the former compared to the latter
- Alternative Lund-Maps with a y-axis consisting of the splitting radiator energy are derived
- Projections of the angular dimension in bins of radiator energy will be used to expose the dead-cone effect

- ❖ Each splitting in the inclusive jet sample has a leading track requirement of $p_T > 2.8 \text{ GeV}/c$ corresponding to the minimum $m_{T,D}$

Splitting Lund Maps

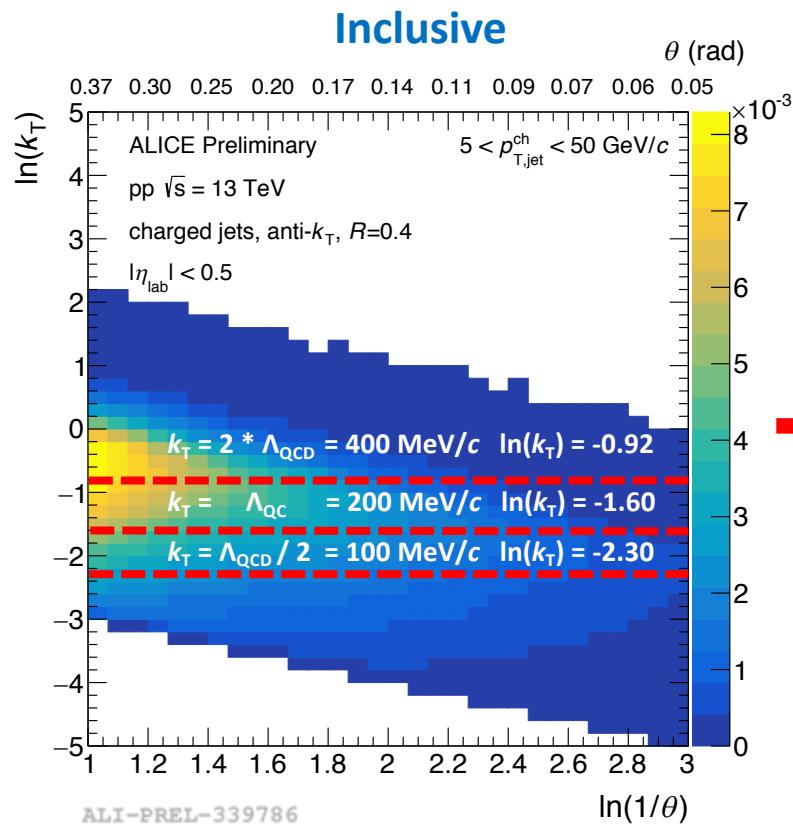
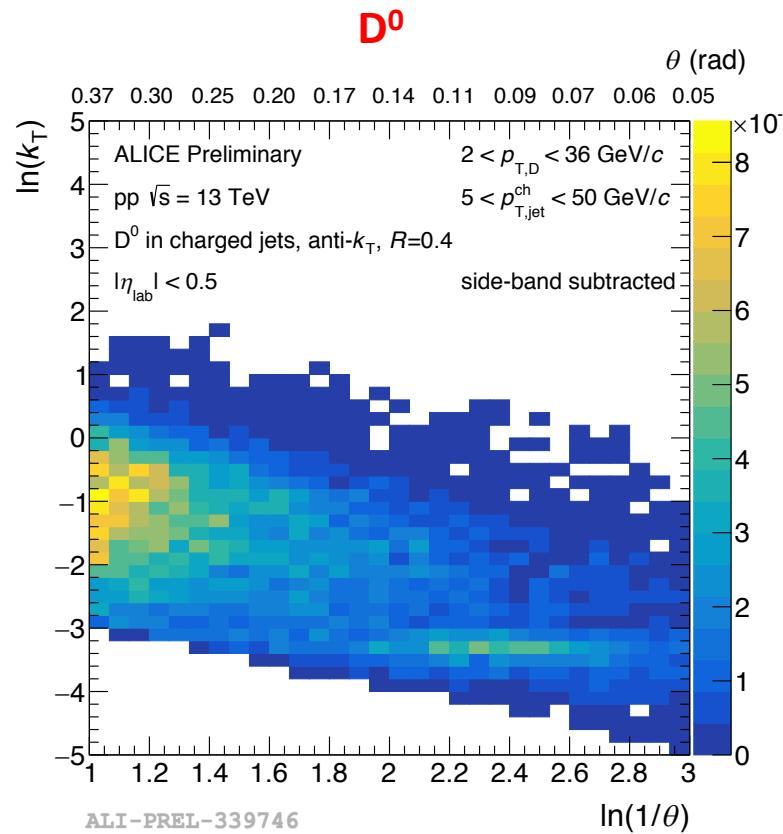


- ❖ Minimum k_T cuts for splittings are imposed to reduce hadronisation effects
- ❖ Expect to see a stronger suppression for stricter cuts of k_T
- ❖ Stricter k_T cuts come at a cost to statistics

- The Lund-Maps for the D^0 and inclusive jets show a hint of suppression of splittings at small angles in the former compared to the latter
- Alternative Lund-Maps with a y-axis consisting of the splitting radiator energy are derived
- Projections of the angular dimension in bins of radiator energy will be used to expose the dead-cone effect

- ❖ Each splitting in the inclusive jet sample has a leading track requirement of $p_T > 2.8$ GeV/ c corresponding to the minimum $m_{T,D}$

Splitting Lund Maps



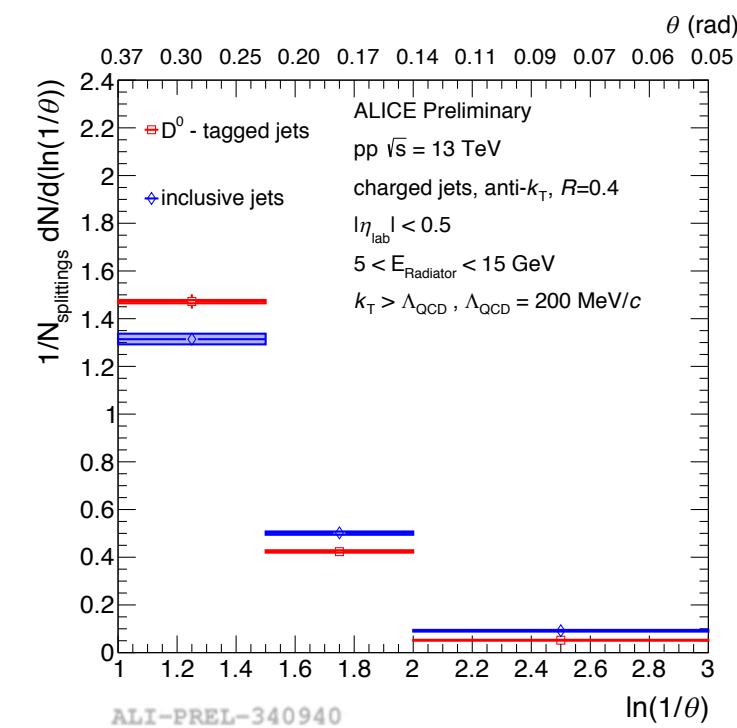
- ❖ Minimum k_T cuts for splittings are imposed to reduce hadronisation effects
- ❖ Expect to see a stronger suppression for stricter cuts of k_T
- ❖ Stricter k_T cuts come at a cost to statistics

- The Lund-Maps for the D^0 and inclusive jets show a hint of suppression of splittings at small angles in the former compared to the latter
- Alternative Lund-Maps with a y-axis consisting of the splitting radiator energy are derived
- Projections of the angular dimension in bins of radiator energy will be used to expose the dead-cone effect

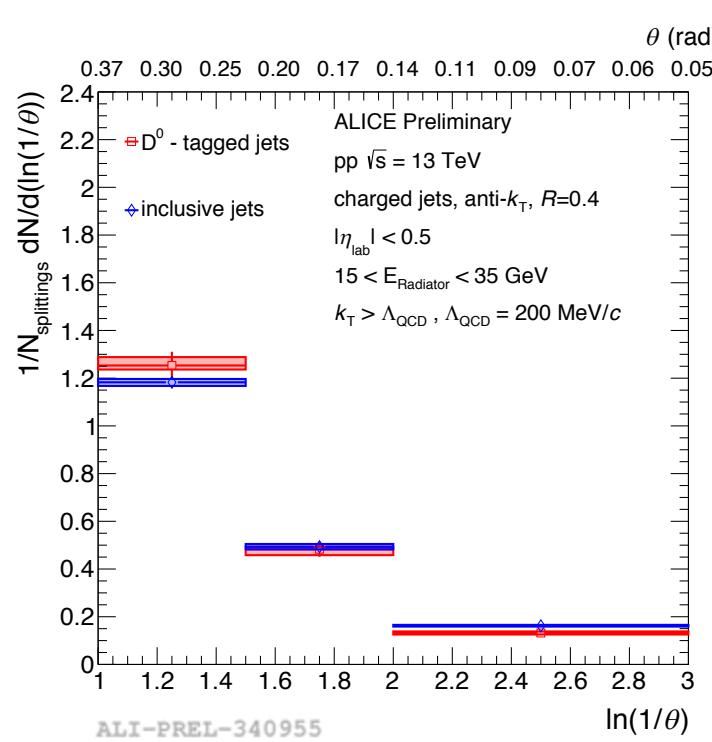
- ❖ Each splitting in the inclusive jet sample has a leading track requirement of $p_T > 2.8$ GeV/ c corresponding to the minimum $m_{T,D}$

Jet Splittings Angular Projections

$5 < E_{\text{Radiator}} < 15 \text{ GeV}$



$15 < E_{\text{Radiator}} < 35 \text{ GeV}$



➤ Lund-Maps are projected in bins of E_{Radiator}

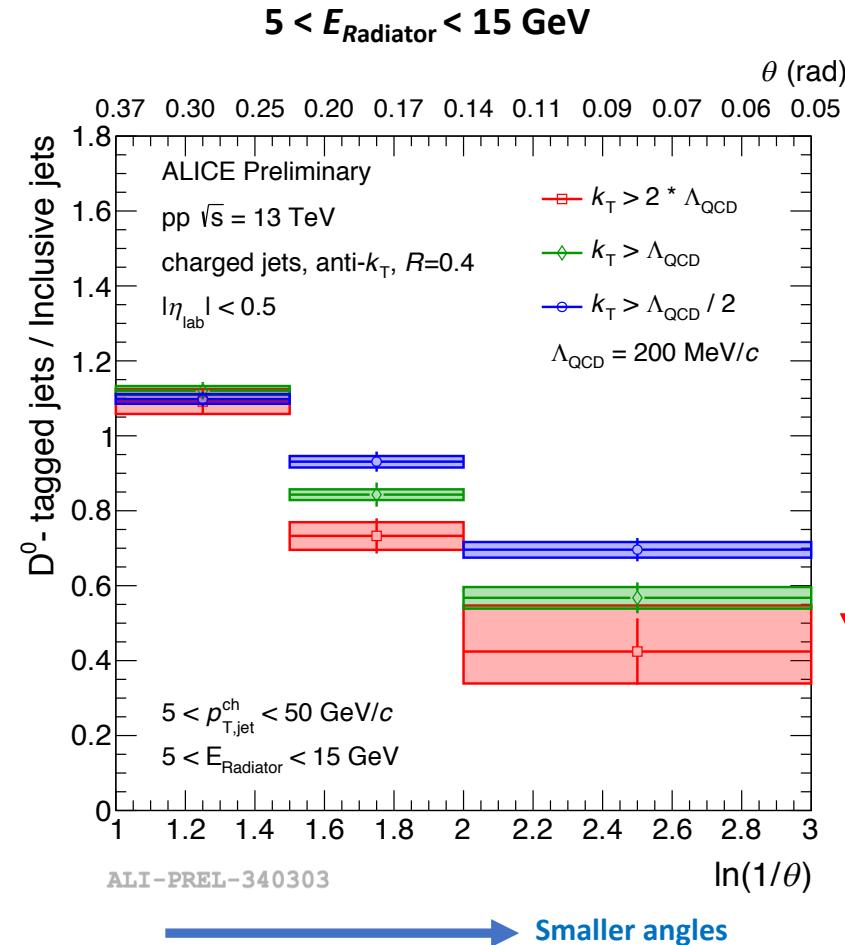
➤ Sources of systematic uncertainty for D^0 jets :

- ❖ Fitting variations
- ❖ Cut variations
- ❖ Side-band variations
- ❖ POWHEG variations
- ❖ Tracking Efficiency

➤ Sources of systematic uncertainty for inclusive jets :

- ❖ Min p_T cut on hardest track in leading splitting prong varied
- ❖ Tracking Efficiency

The Dead-Cone Uncovered

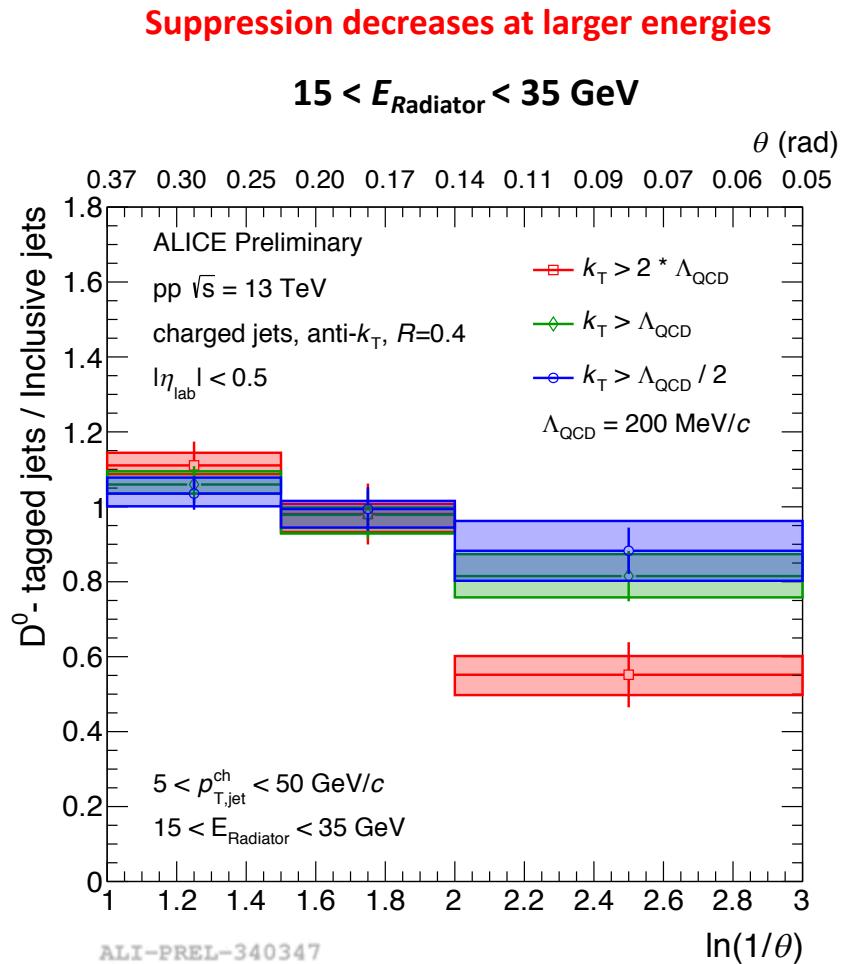
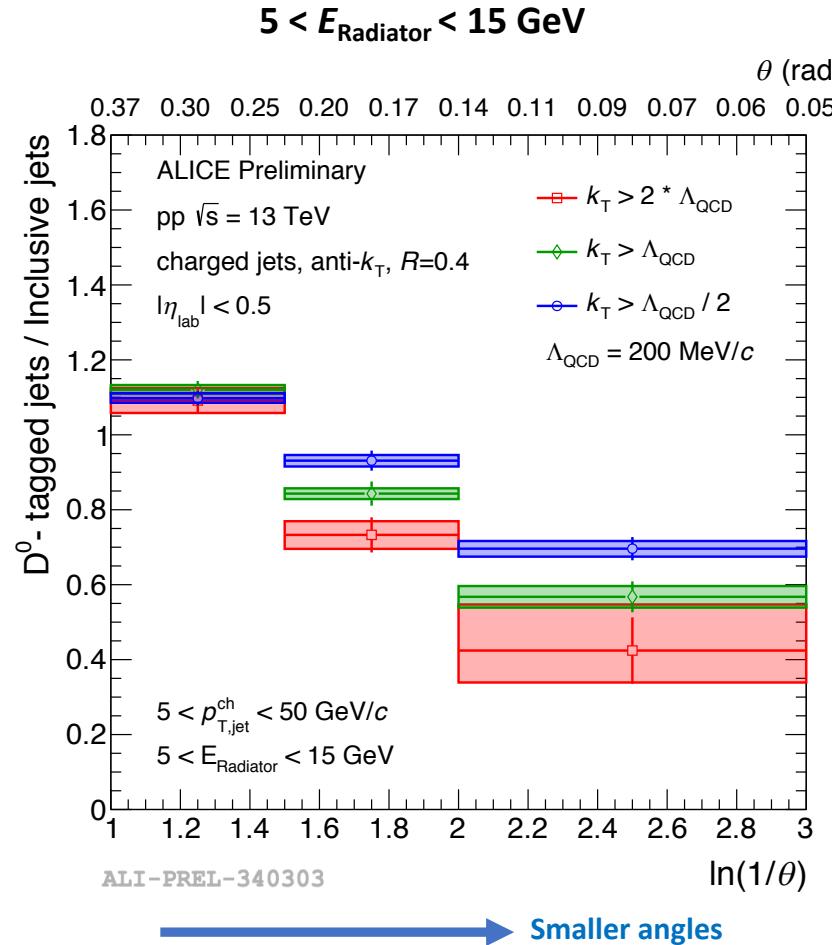


Suppression of splittings in D^0 -tagged jets compared to inclusive jets

First direct observation of the dead-cone effect!

- ❖ Ratio of angular projections of D^0 and inclusive jet splittings are made
- ❖ **Suppression** of splittings at **small angles** in heavy flavour jets due to the dead-cone effect
- ❖ The magnitude of suppression increases at smaller angles
- ❖ The suppression also increases with stricter cuts on k_T
 - Contamination of hadronisation effects reduced

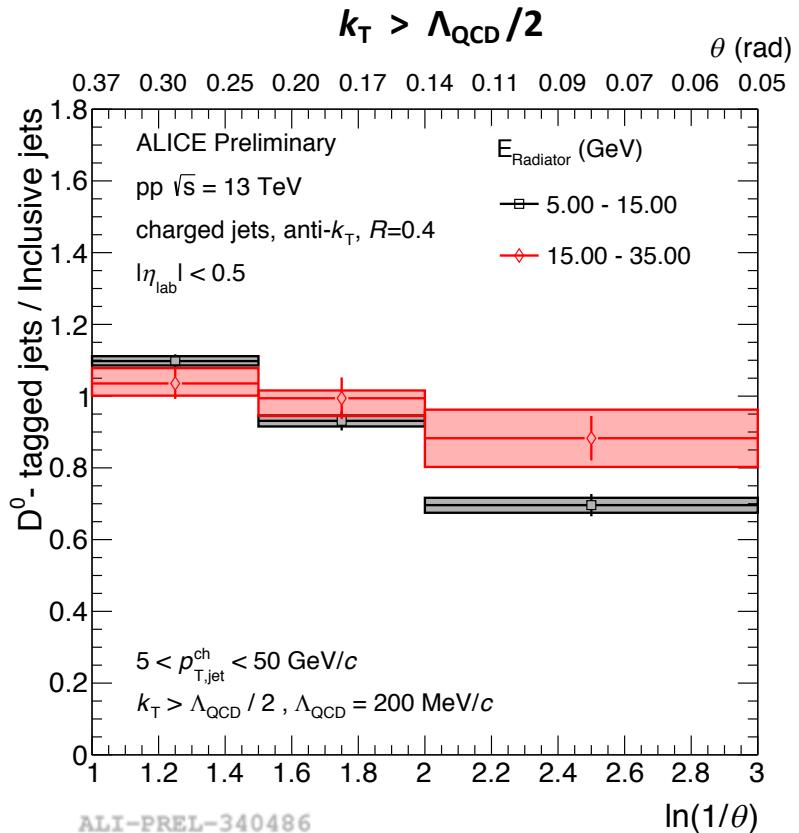
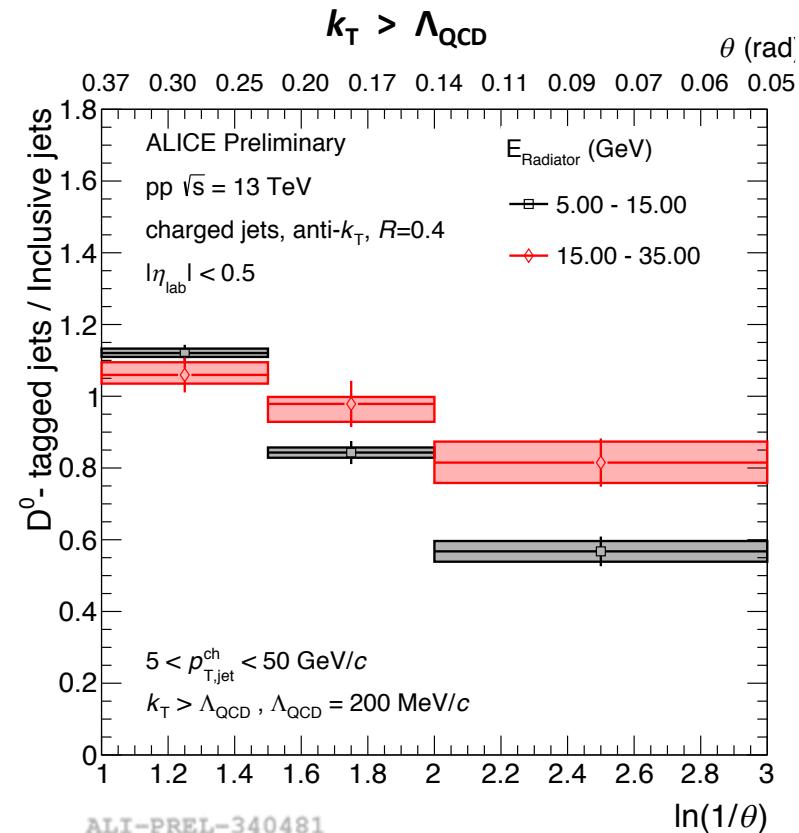
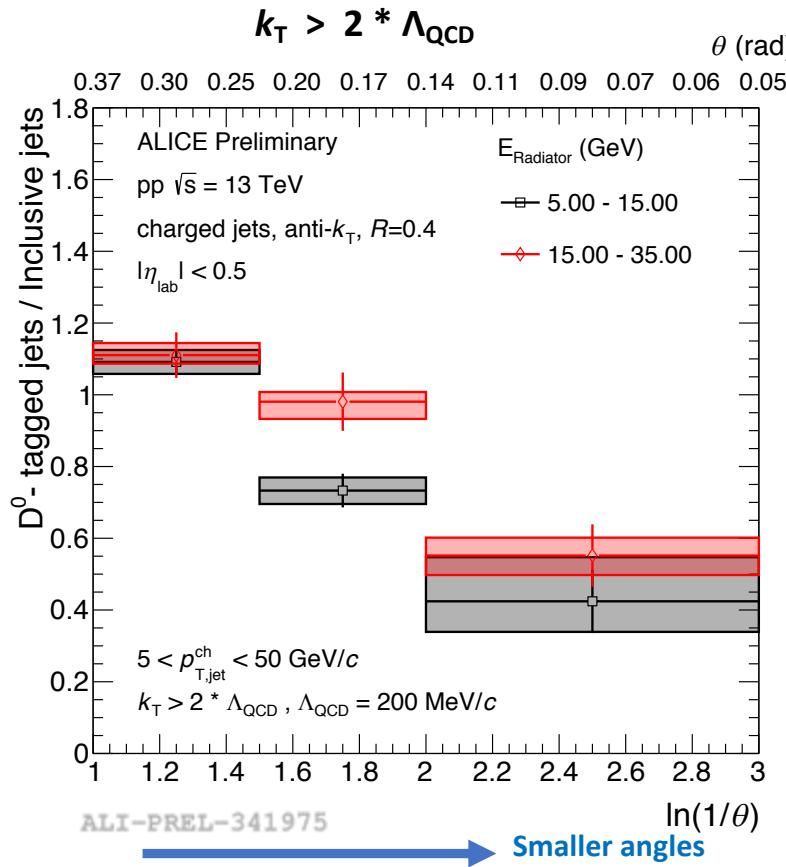
The Dead-Cone Uncovered



Suppression decreases at larger energies

- ❖ Ratio of angular projections of D⁰ and inclusive jet splittings are made
- ❖ **Suppression** of splittings at **small angles** in heavy flavour jets due to the dead-cone effect
- ❖ The magnitude of suppression increases at smaller angles
- ❖ The suppression also increases with stricter cuts on k_T
 - Contamination of hadronisation effects reduced

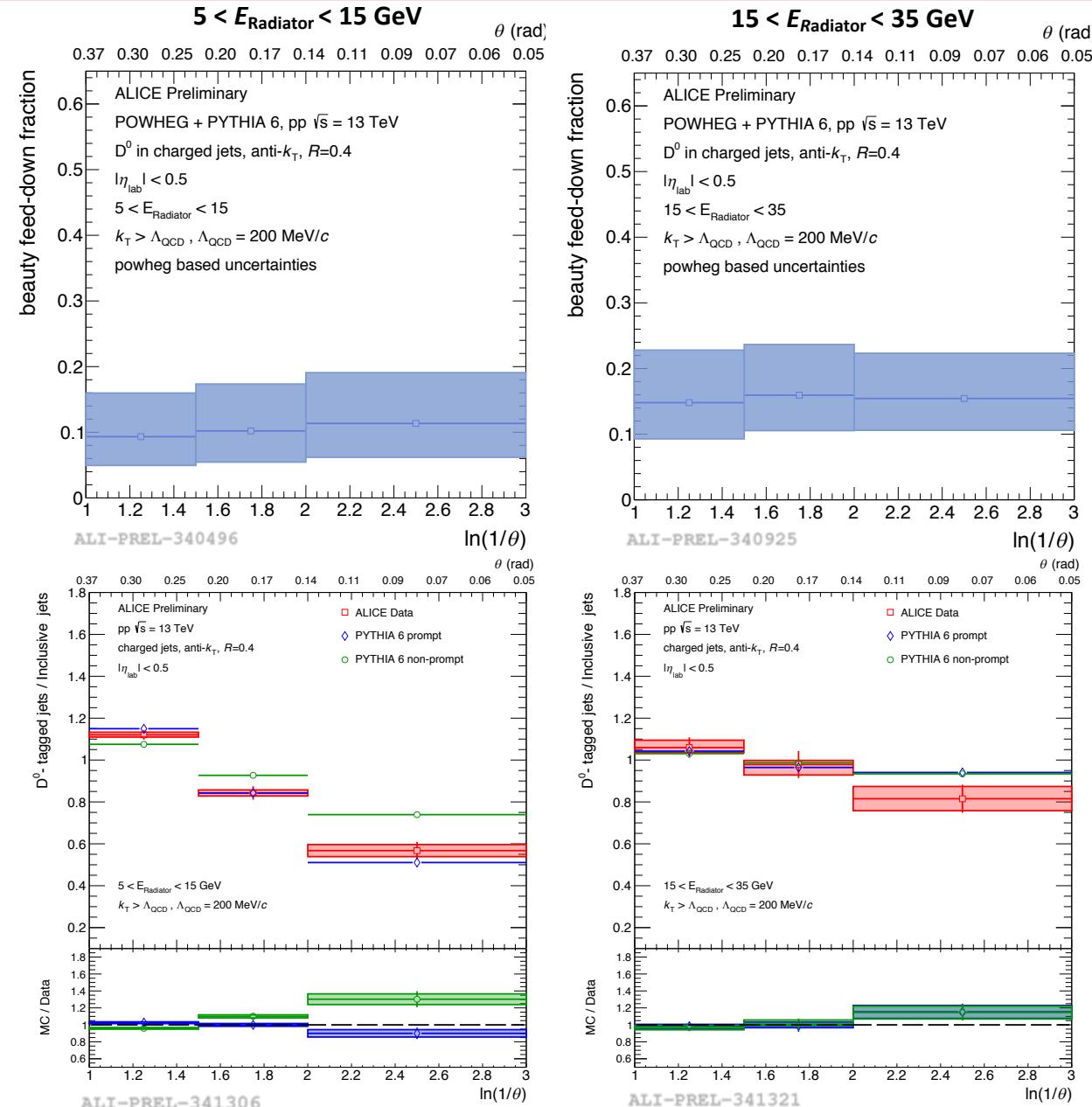
The Dead-Cone Energy Dependence



- ❖ The E_{Radiator} dependence of the dead-cone effect can be explored
- ❖ **Suppression is stronger** for **lower energy splittings**
- ❖ This is in line with the inverse dependence of the dead-cone angle on the radiator energy

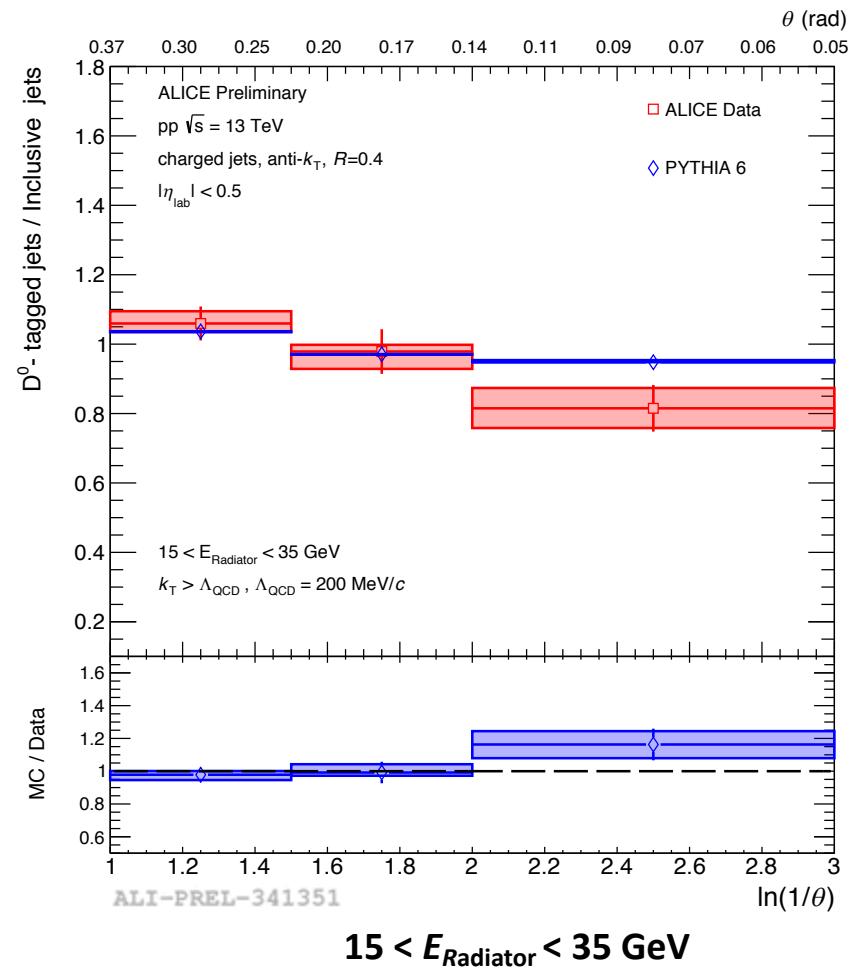
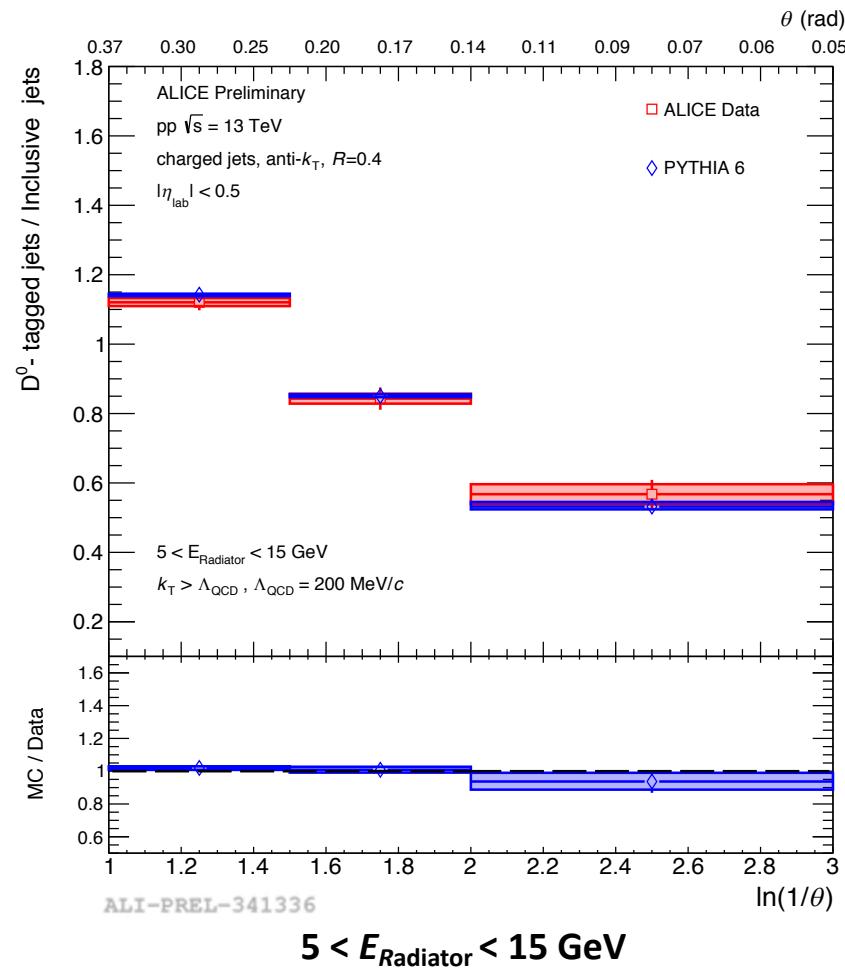
Dead-cone : $\theta < \frac{Mq}{Eq}$

Feed-Down



- ❖ The feed-down fraction of the D^0 splittings angular distributions are estimated using POWHEG + PYTHIA 6
- ❖ Uncertainties on the fractions are theoretical
- ❖ At $5 < E_{\text{Radiator}} < 15 \text{ GeV}$ feed-down fraction is about 10%
- ❖ At $15 < E_{\text{Radiator}} < 35 \text{ GeV}$ feed-down fraction is about 15%
- ❖ Final results are not corrected for feed-down
- ❖ Comparisons to reconstructed level PYTHIA are made
- ❖ Fully non-prompt PYTHIA shows much less suppression compared to prompt PYTHIA at low energies
- ❖ Additional decay products of the beauty-hadron cloud the dead-cone region

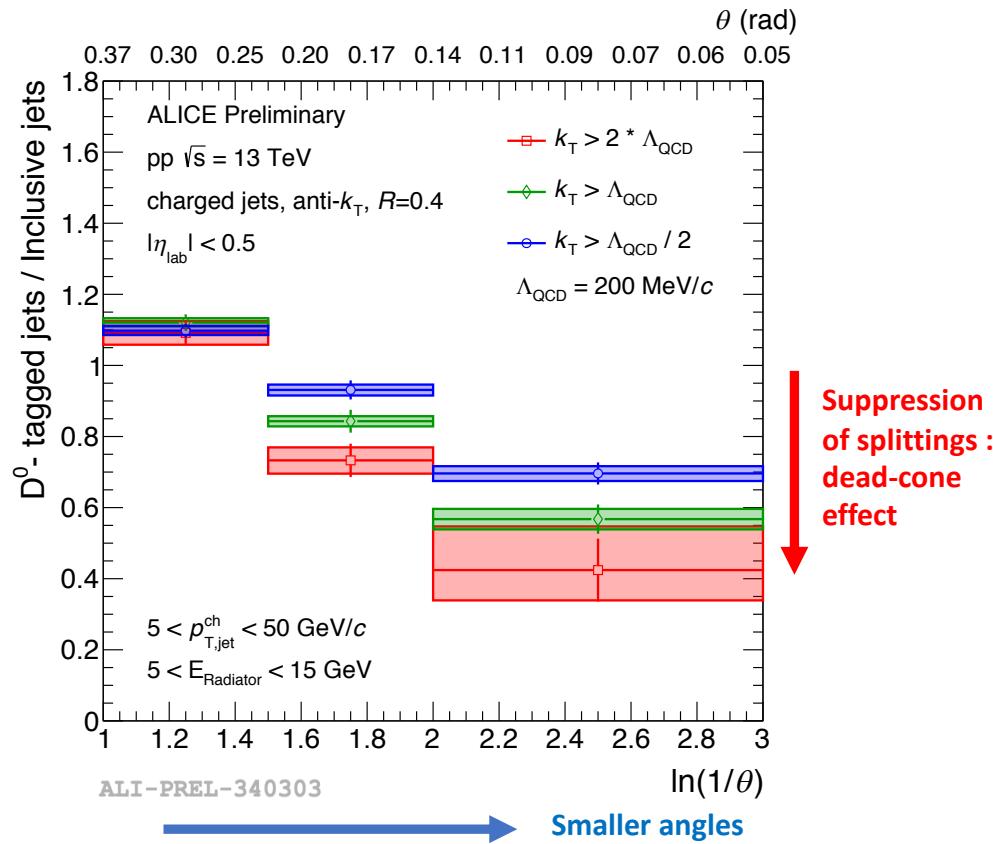
Model Comparisons



- Reconstructed level PYTHIA simulations with the same admixture of prompt and non-prompt jets as in data are obtained
- Ratios to inclusive distributions are compared
- Good agreement with data

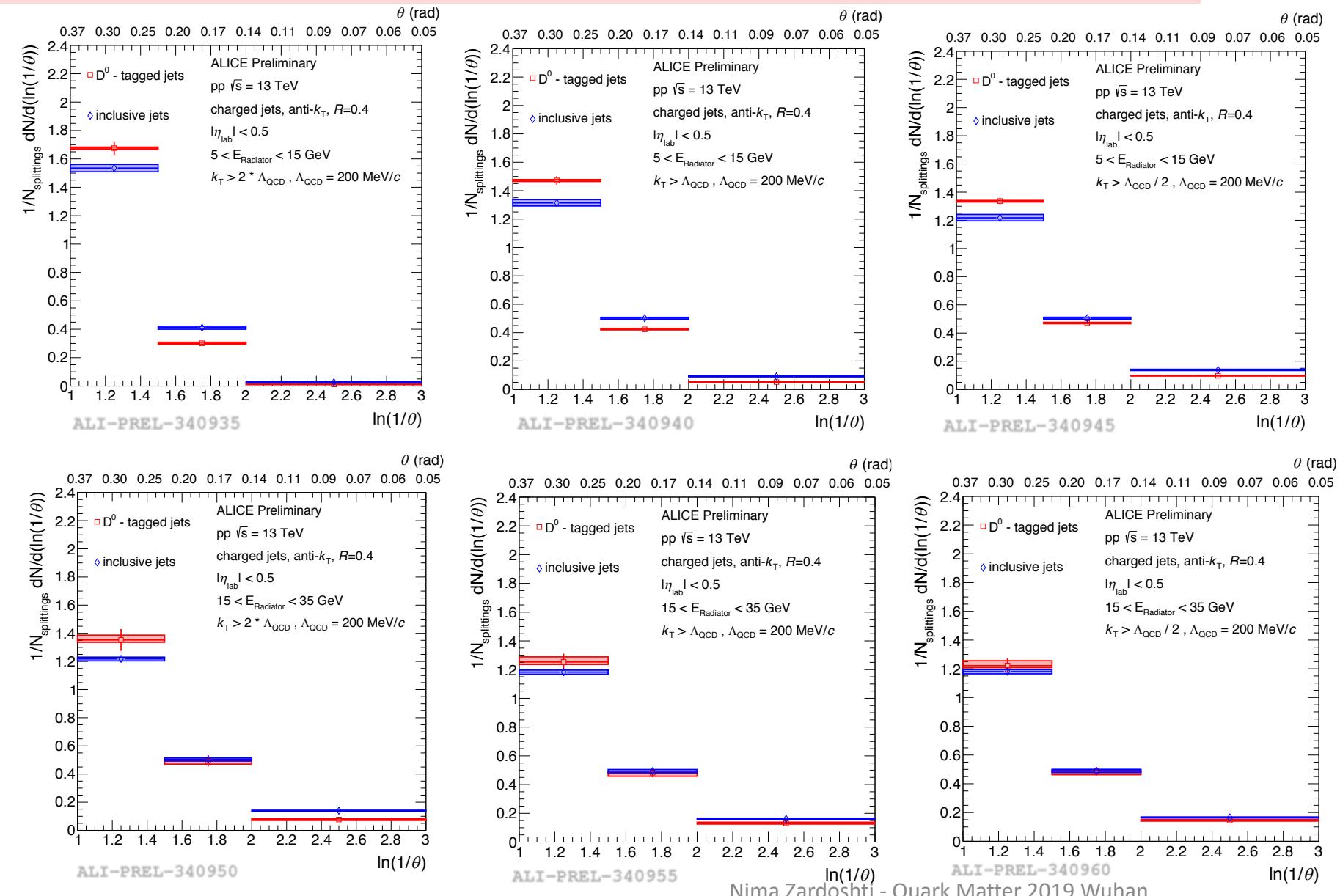
Conclusions

- The **first direct measurement** of the dead-cone effect at colliders is presented
- Jet reclustering techniques allow for an accurate reconstruction of splitting kinematics
- k_T cuts are used to reject hadronisation effects
- Splittings initiated by charm quarks (via the D^0) are **suppressed at small angles** compared to inclusive jets
- Stricter k_T cuts are accompanied by more suppression
- The **suppression is larger** at **lower energy** splittings
- Dead-cone signal not enhanced by non-prompt jets
- Results in agreement with models



Backup

Jet Splittings Angular Projections



➤ Lund-Maps are projected in bins of $E_{Radiator}$

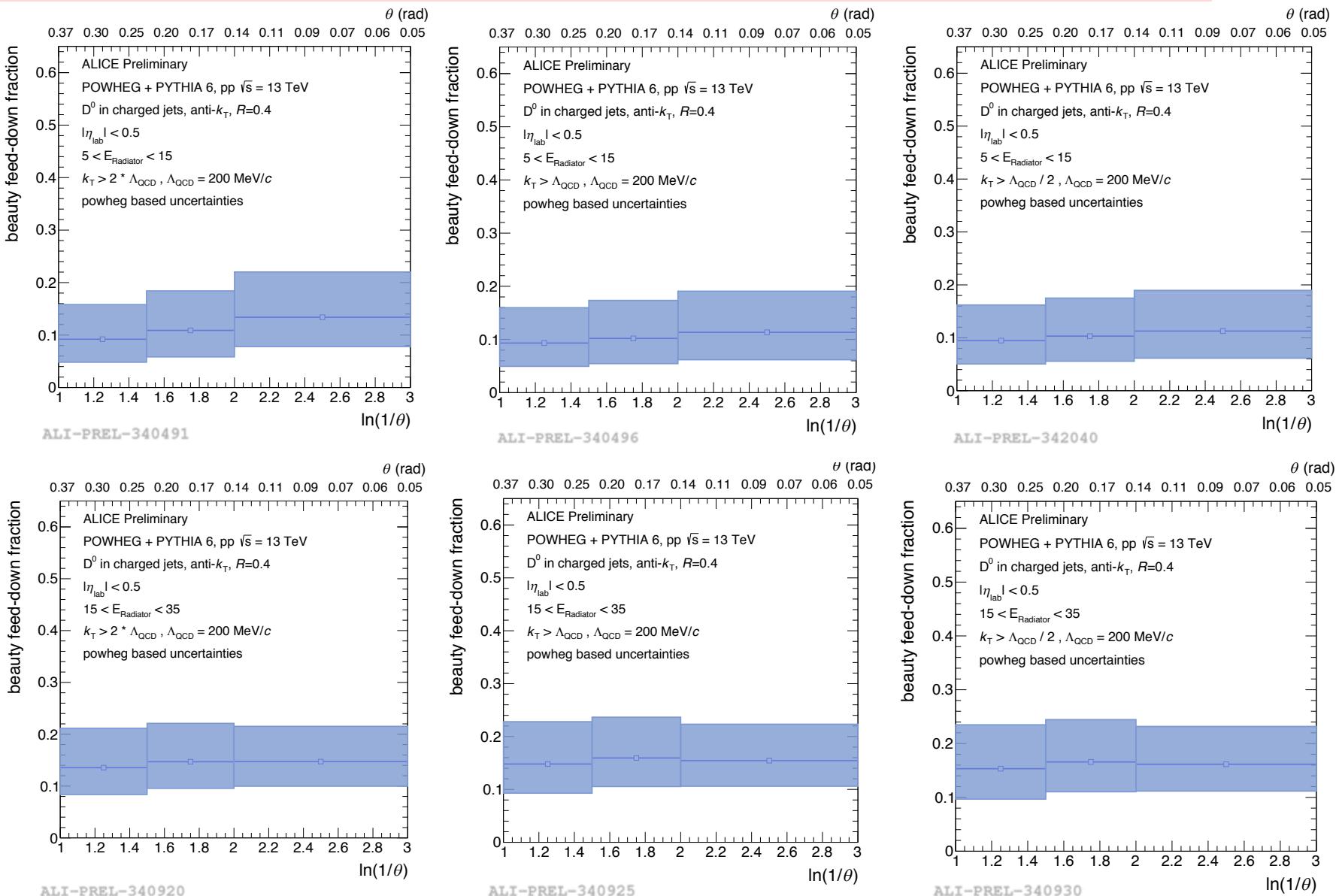
➤ Sources of systematic uncertainty for D^0 jets :

- ❖ Fitting variations
- ❖ Cut variations
- ❖ Side-band variations
- ❖ POWHEG variations
- ❖ Tracking Efficiency

➤ Sources of systematic uncertainty for inclusive jets :

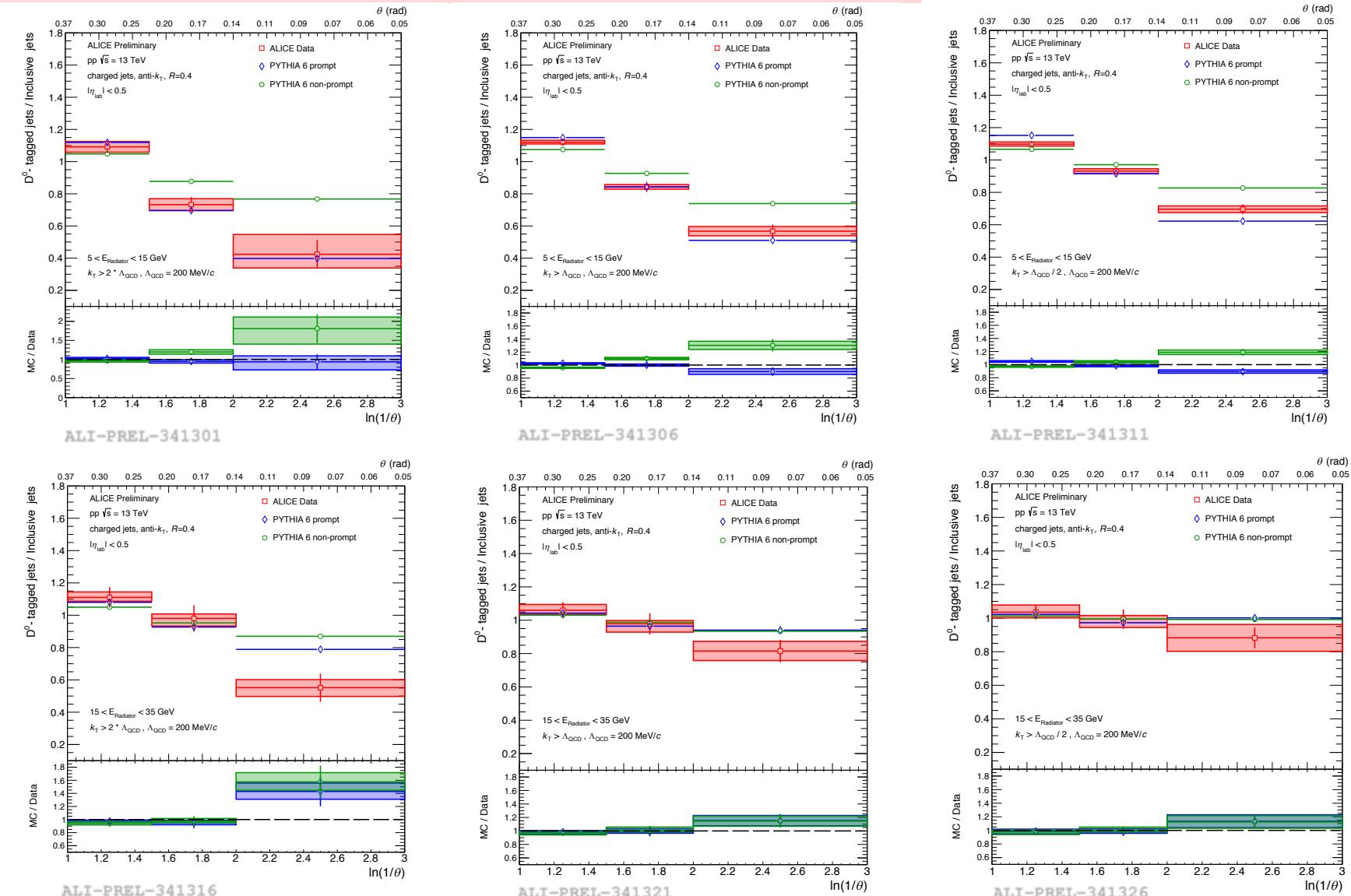
- ❖ Min p_T cut on hardest track in leading splitting prong varied
- ❖ Tracking Efficiency

Feed-Down Fraction



- ❖ The feed-down fraction of the D^0 splittings angular distributions are estimated using POWHEG + PYTHIA 6
- ❖ Uncertainties on the fractions are theoretical
- ❖ At $5 < E_{\text{Radiator}} < 15 \text{ GeV}$ feed-down fraction is about 10%
- ❖ At $15 < E_{\text{Radiator}} < 35 \text{ GeV}$ feed-down fraction is about 15%
- ❖ Final results are not corrected for feed-down

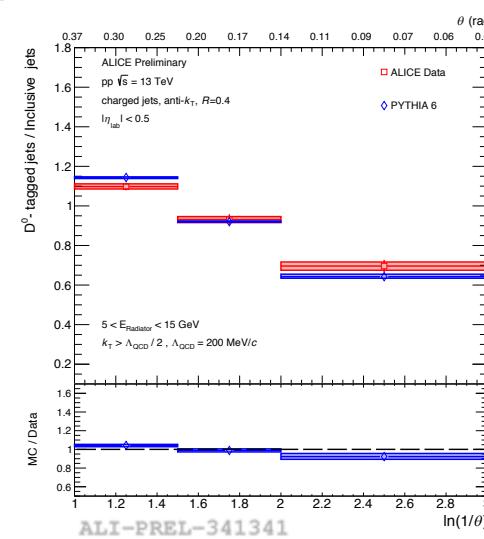
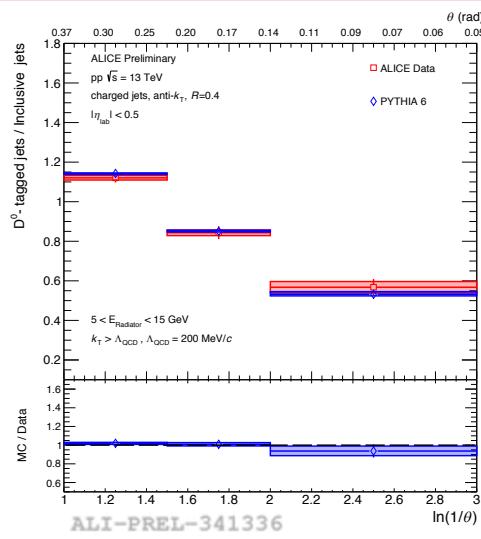
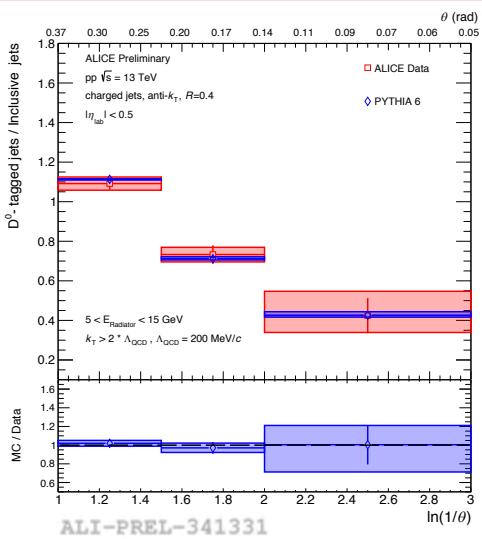
Feed-Down Effects



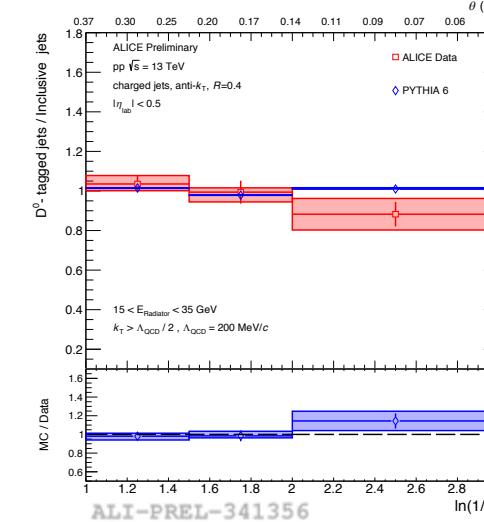
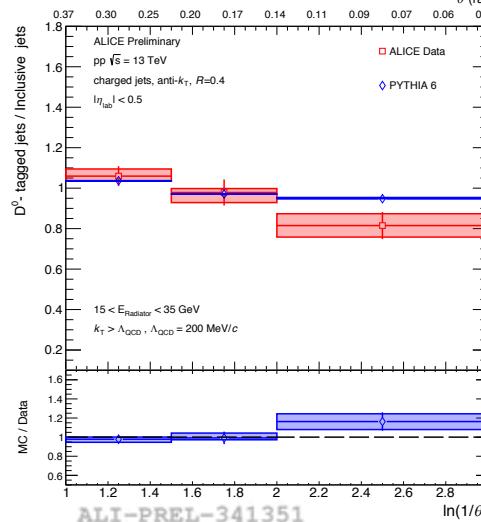
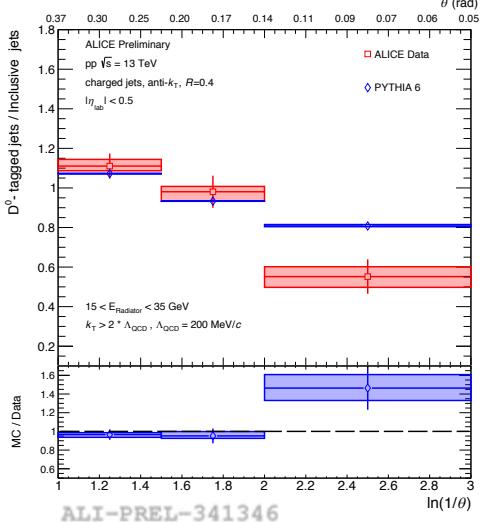
- ❖ Fully non-prompt PYTHIA shows much less suppression compared to prompt PYTHIA at low energies
- ❖ Additional decay products of the beauty-hadron cloud the dead-cone region

Model Comparisons

$5 < E_{\text{Radiator}} < 15 \text{ GeV}$



$15 < E_{\text{Radiator}} < 35 \text{ GeV}$



- Reconstructed level PYTHIA simulations with the same admixture of prompt and non-prompt jets as in data are obtained
- Ratios to inclusive distributions are compared
- Good agreement with data