Measurements of groomed heavy-flavour jet substructure with ALICE

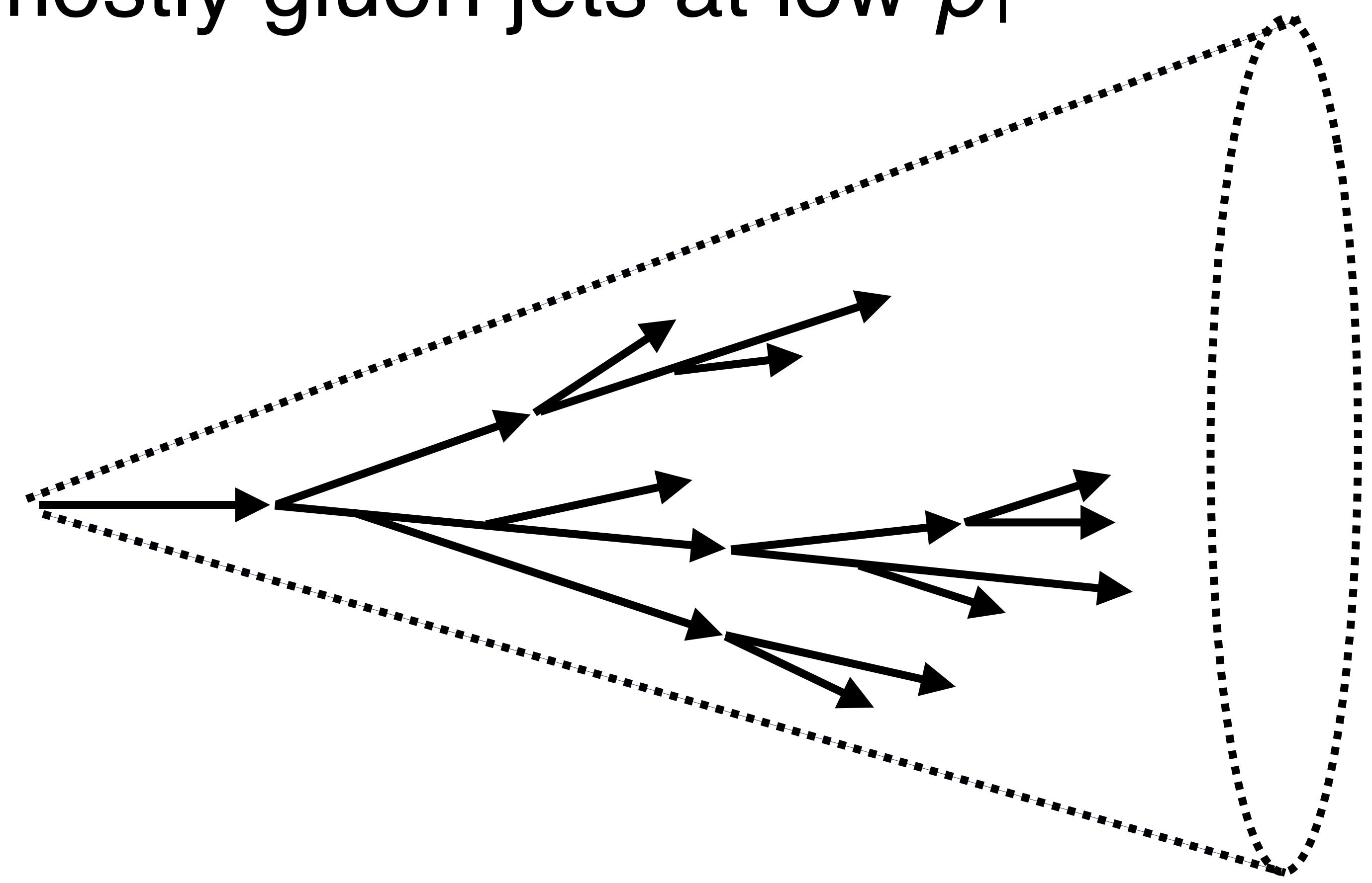
Hard Probes 2020
3rd of June

Vít Kučera (CERN)
for the ALICE Collaboration

ALICE-PUBLIC-2020-002

“Soft”-jet studies in pp collisions

inclusive sample:
mostly gluon jets at low p_T



Inclusive jets:

- powerful probes of QCD across a range of scales
- well constrained pQCD production requires measurements at high p_T
  → low p_T region experimentally challenging!

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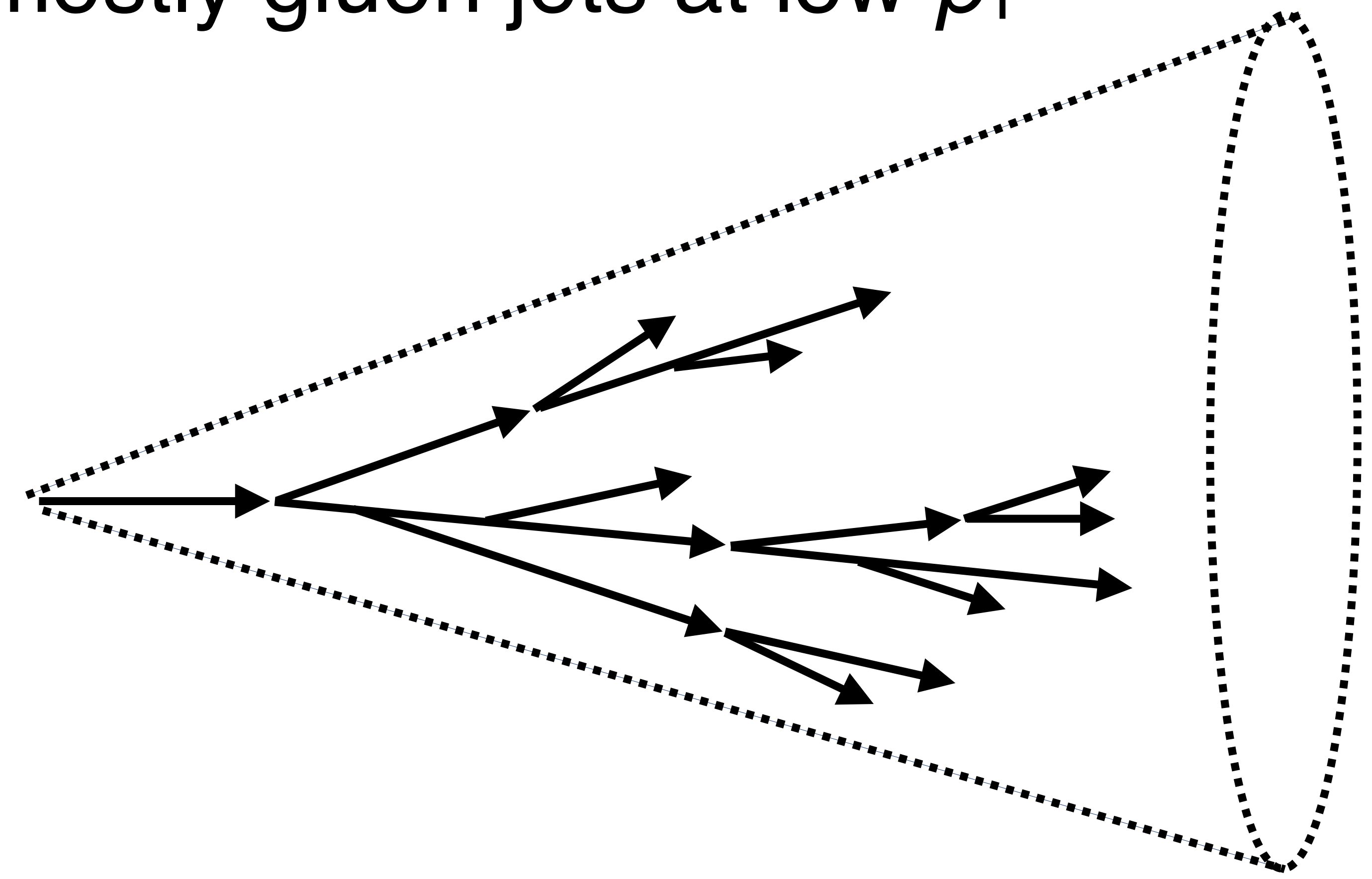

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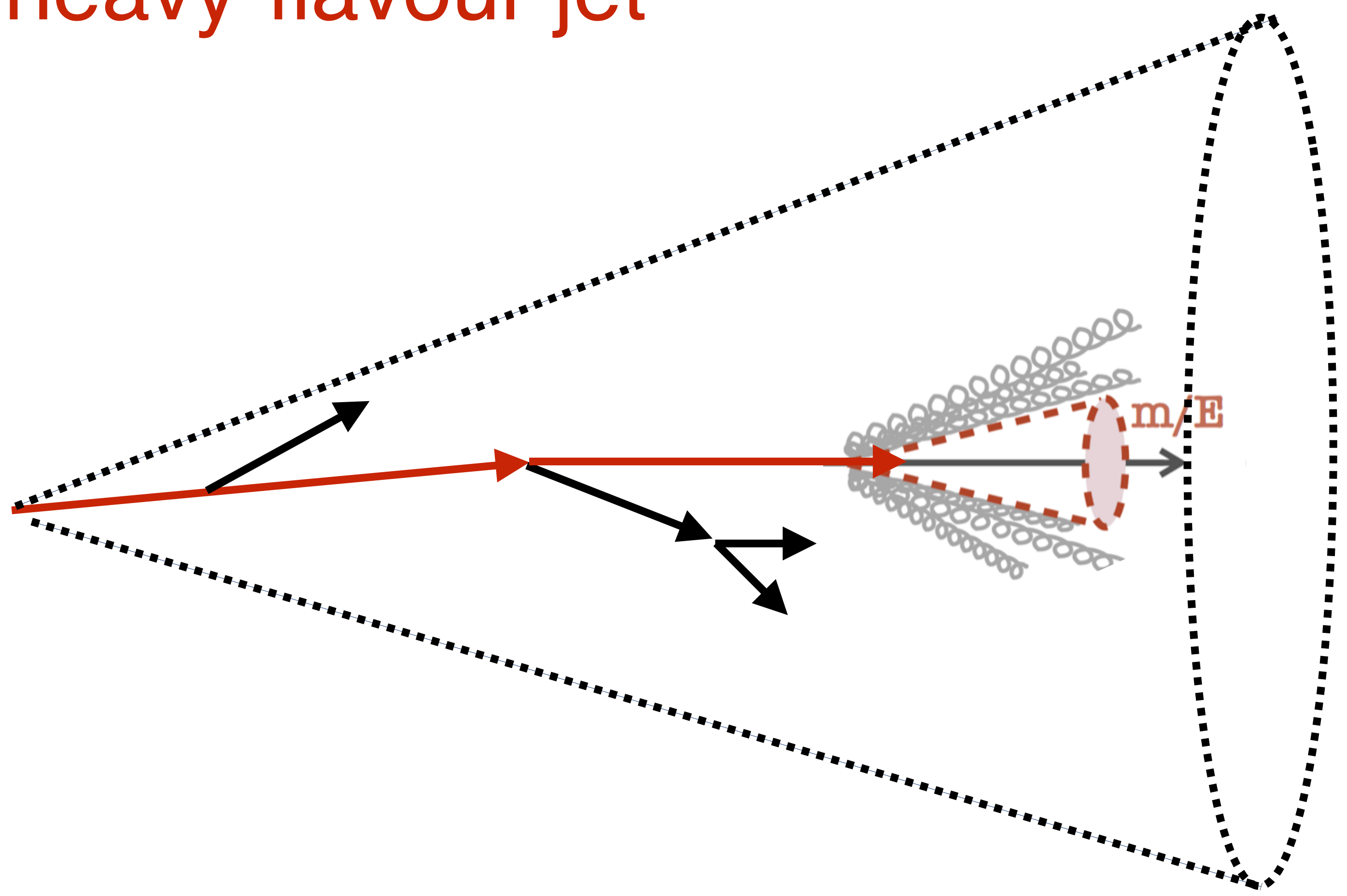
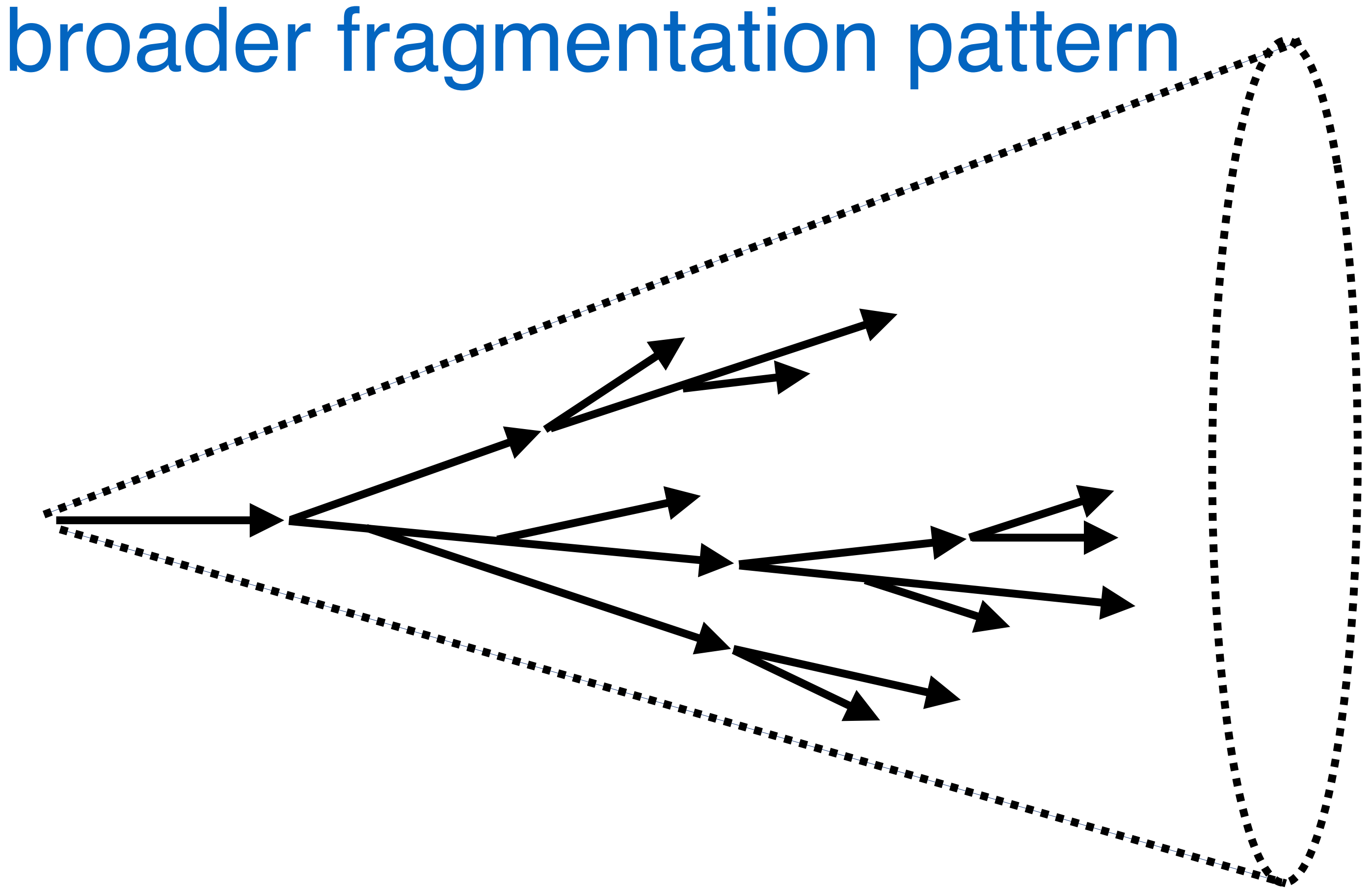
heavy-flavour jet



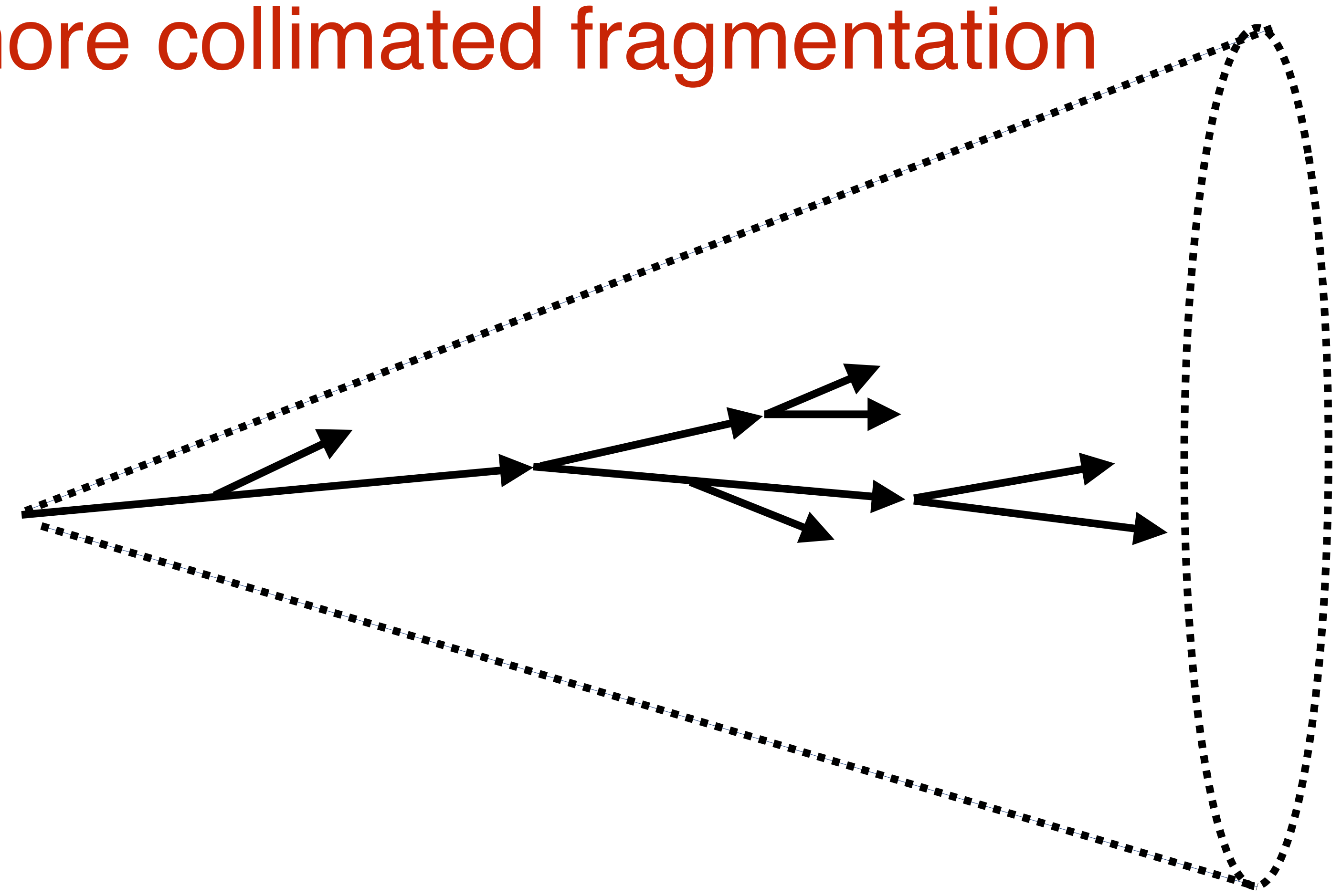
Heavy-flavour (HF) jets:
- $m_q > \Lambda_{QCD} \rightarrow$ perturbative production down to low jet p_T
- heavy flavour conserved through the shower evolution

“Soft”-jet studies in pp collisions

gluon-initiated jet: softer and broader fragmentation pattern



quark-initiated jet: harder and more collimated fragmentation



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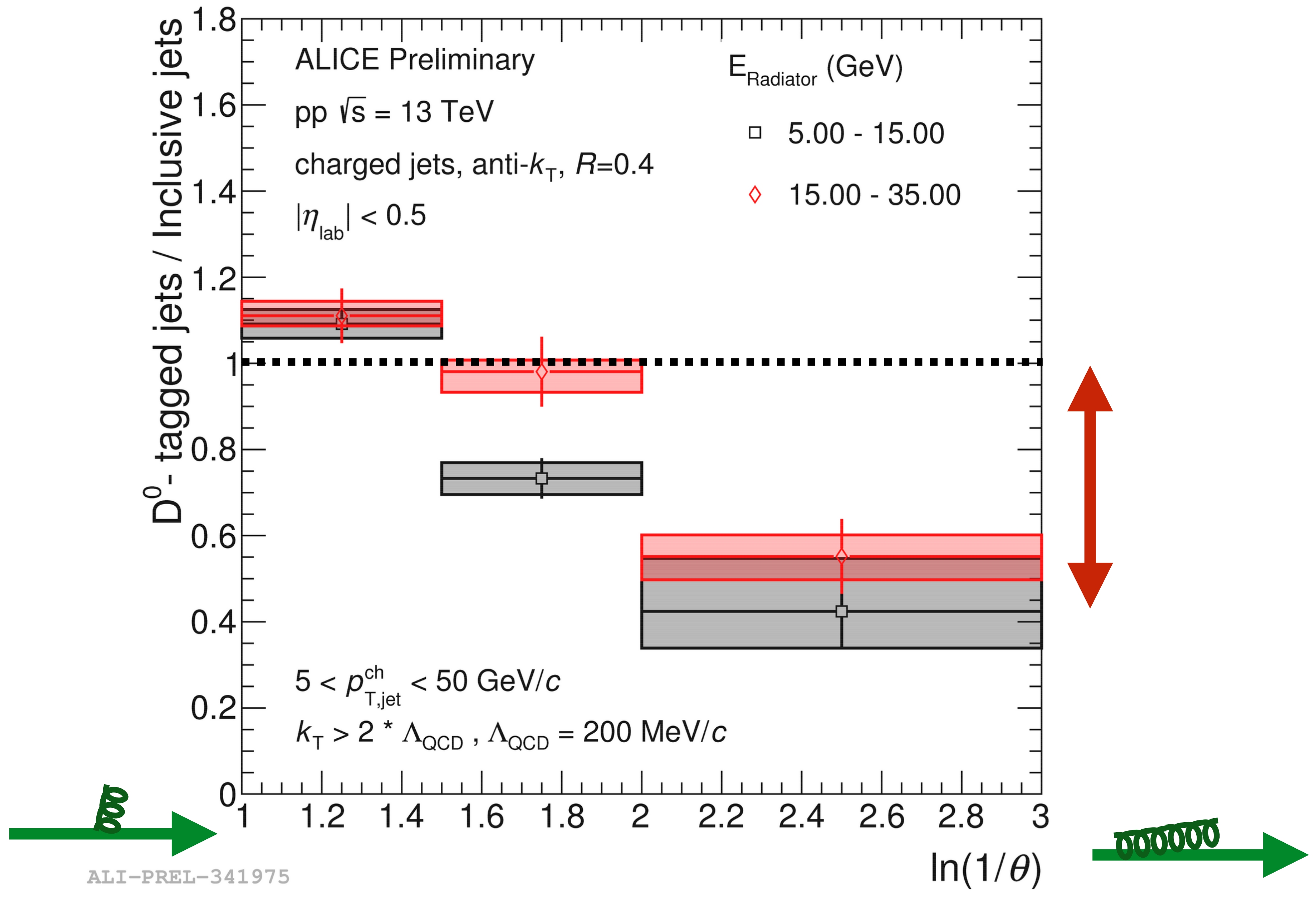
Inclusive vs heavy-flavour jets at low p_T:

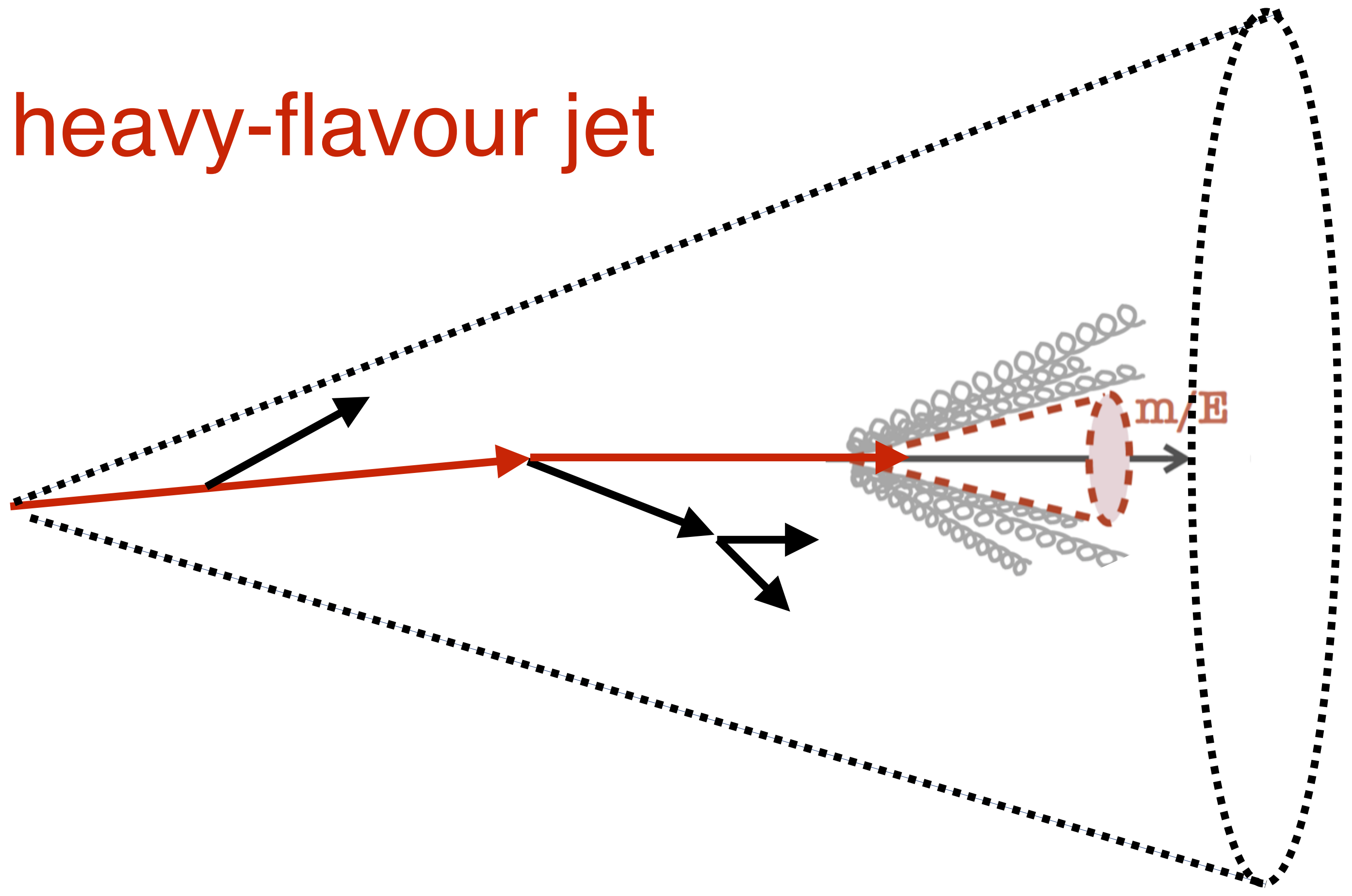
- **Casimir colour factors**: different fragmentation of quarks and gluons

"Soft"-jet studies in pp collisions

D⁰-tagged/inclusive jets



heavy-flavour jet



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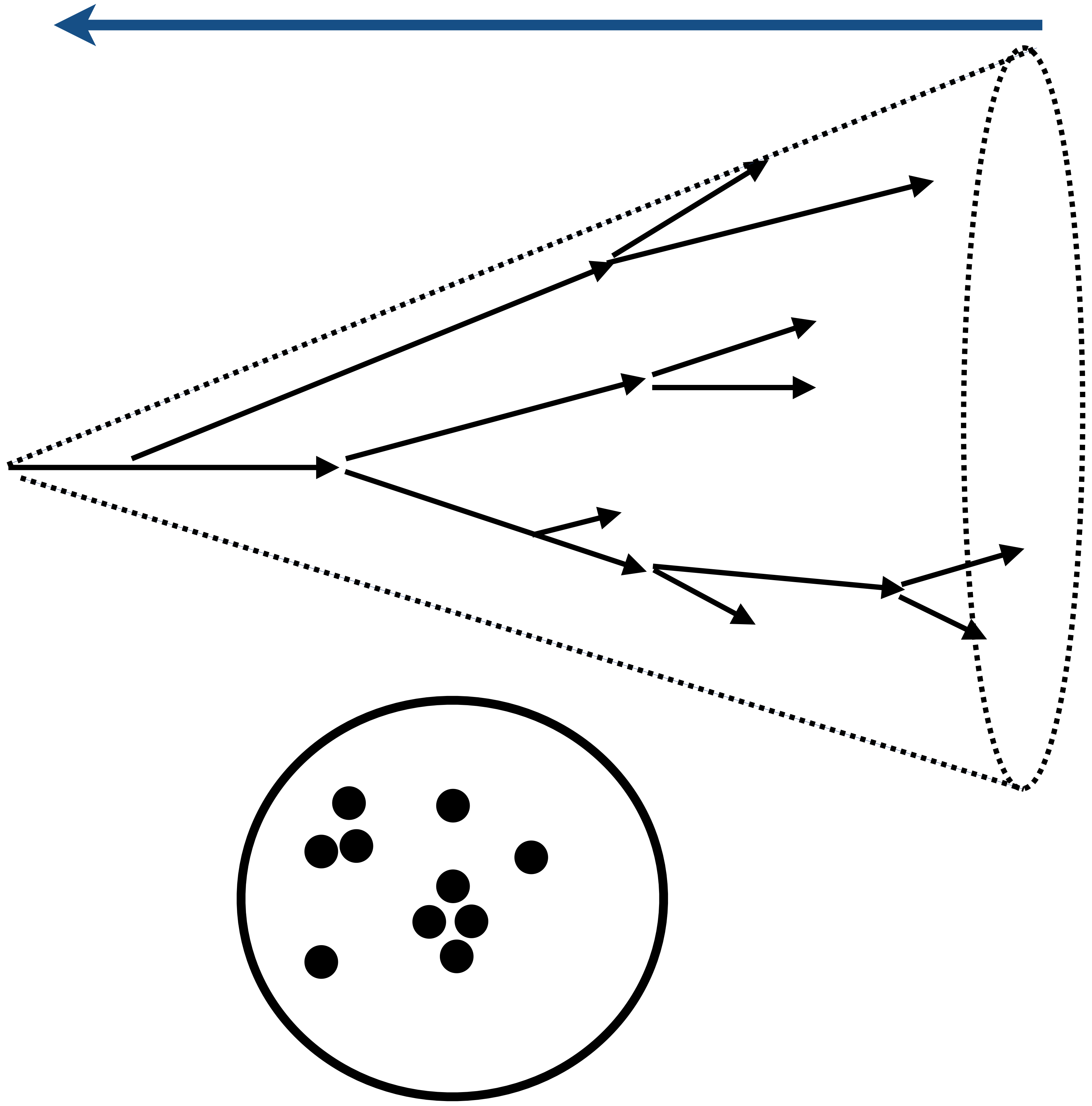
Inclusive vs heavy-flavour jets at low p_T:

- **Casimir colour factors**: different fragmentation of quarks and gluons
- **dead-cone effect**: suppression of emission phase space $\theta < m_q/E_q$

→ Mass effects are sizeable in the low p_T kinematic range

Substructure techniques: declustering

→ access evolution of the parton shower: jet splittings (**declustering**)



- **reclustering** with Cambridge/Aachen (angular ordering)

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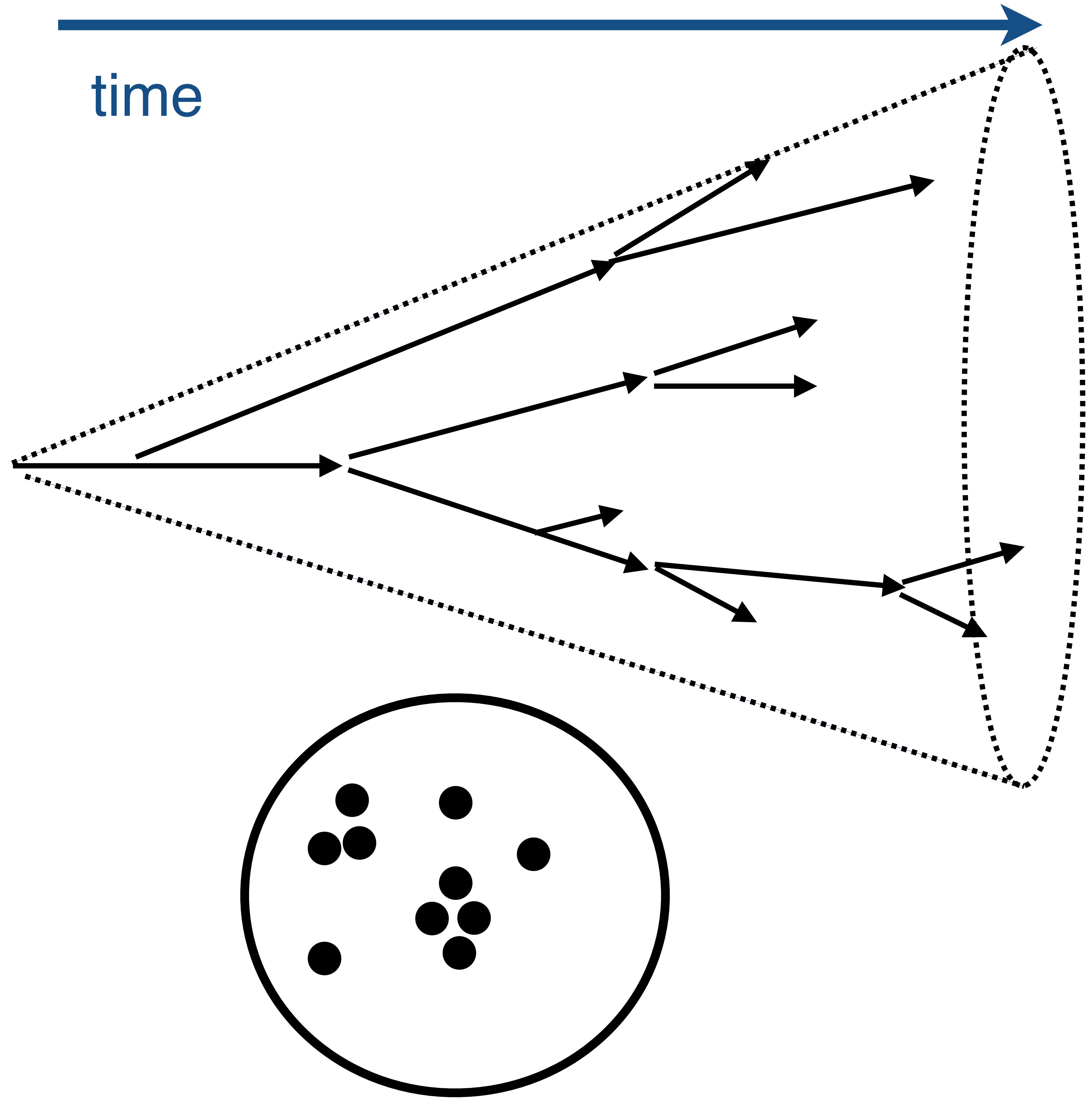
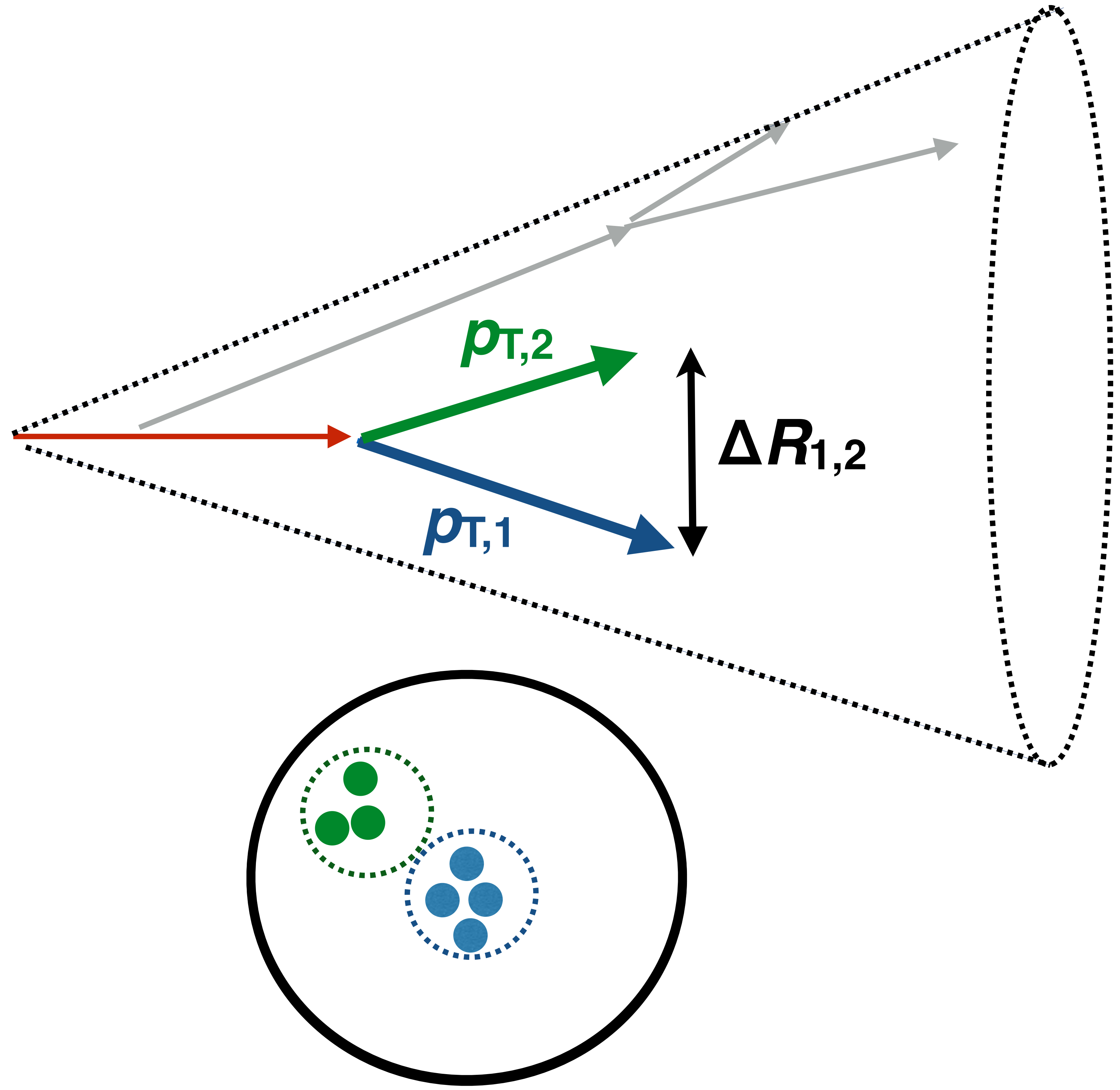


- **reclustering** with Cambridge/Aachen (angular ordering)
- **declustering**: unwind reclustering history
  → chronologically ordered splittings

Substructure techniques: grooming

→ access evolution of the parton shower: jet splittings (**declustering**)

→ groom away soft radiation at large angles: isolate hard structures inside the jet (**grooming**)



- **reclustering** with Cambridge/Aachen (angular ordering)
- **declustering**: unwind reclustering history
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- **grooming** with Soft Drop (SD): groom away soft prongs not satisfying SD condition

Soft Drop (SD) grooming condition:

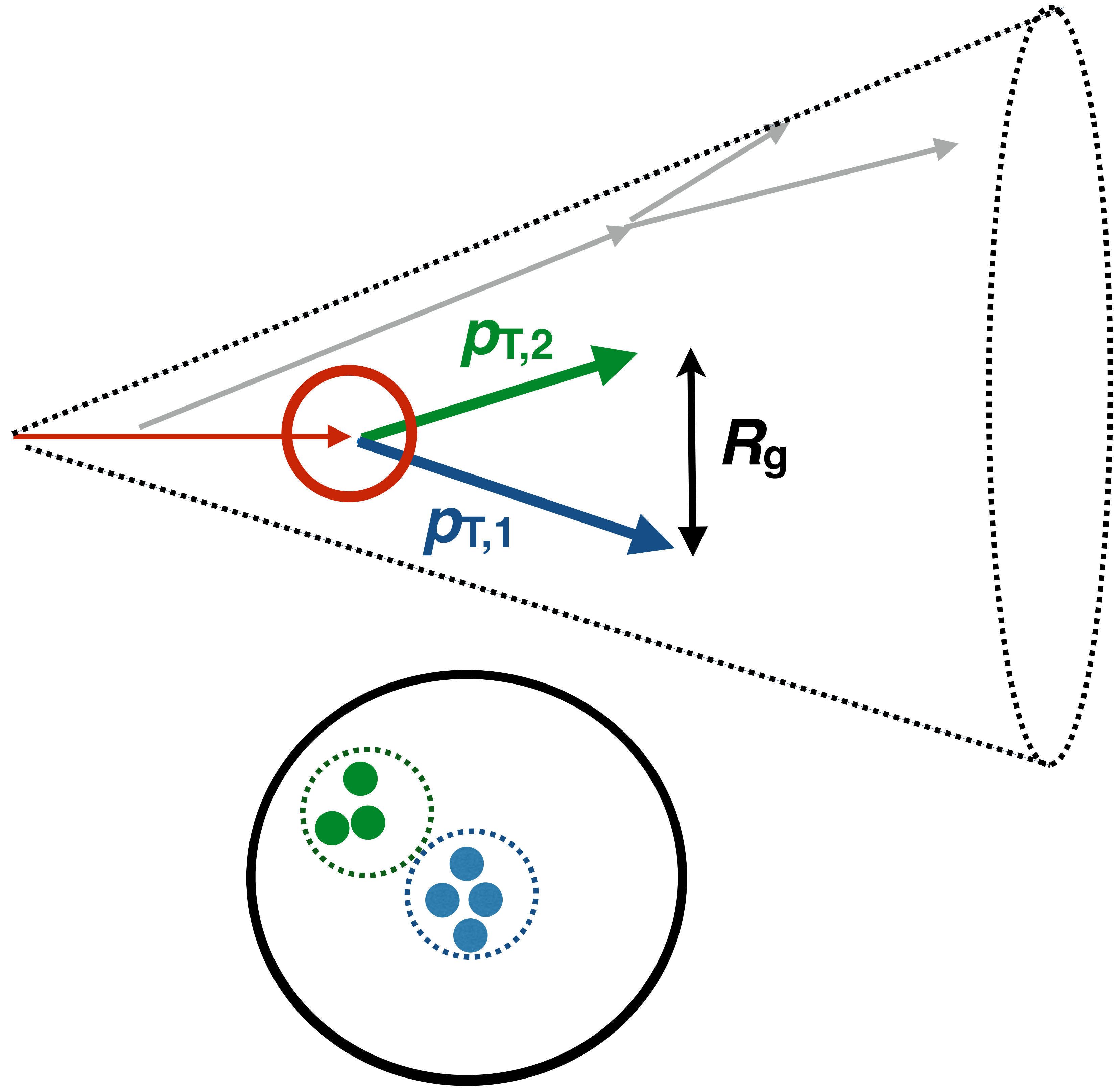
$$z = \frac{p_{T,2}}{p_{T,1} + p_{T,2}} > z_{cut} \left(\frac{\Delta R_{1,2}}{R} \right)^{\beta}$$

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

$R =$ jet resolution parameter

Substructure techniques: first-splitting observables

→ access evolution of the parton shower: jet splittings (**declustering**)
→ groom away soft radiation at large angles: isolate hard structures inside the jet (**grooming**)



- **reclustering** with Cambridge/Aachen (angular ordering)
- **declustering**: unwind reclustering history
  → chronologically ordered splittings
- **grooming** with Soft Drop (SD): groom away soft prongs not satisfying SD condition
- **observables constructed against the first splitting satisfying SD:**
  → $z_g = z$ momentum fraction of subleading prong
  → $R_g = \Delta R_{1,2}$ angular distance between prongs

Soft Drop (SD) grooming condition:

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Substructure techniques: n_{SD}

→ access evolution of the parton shower: jet splittings (**declustering**)
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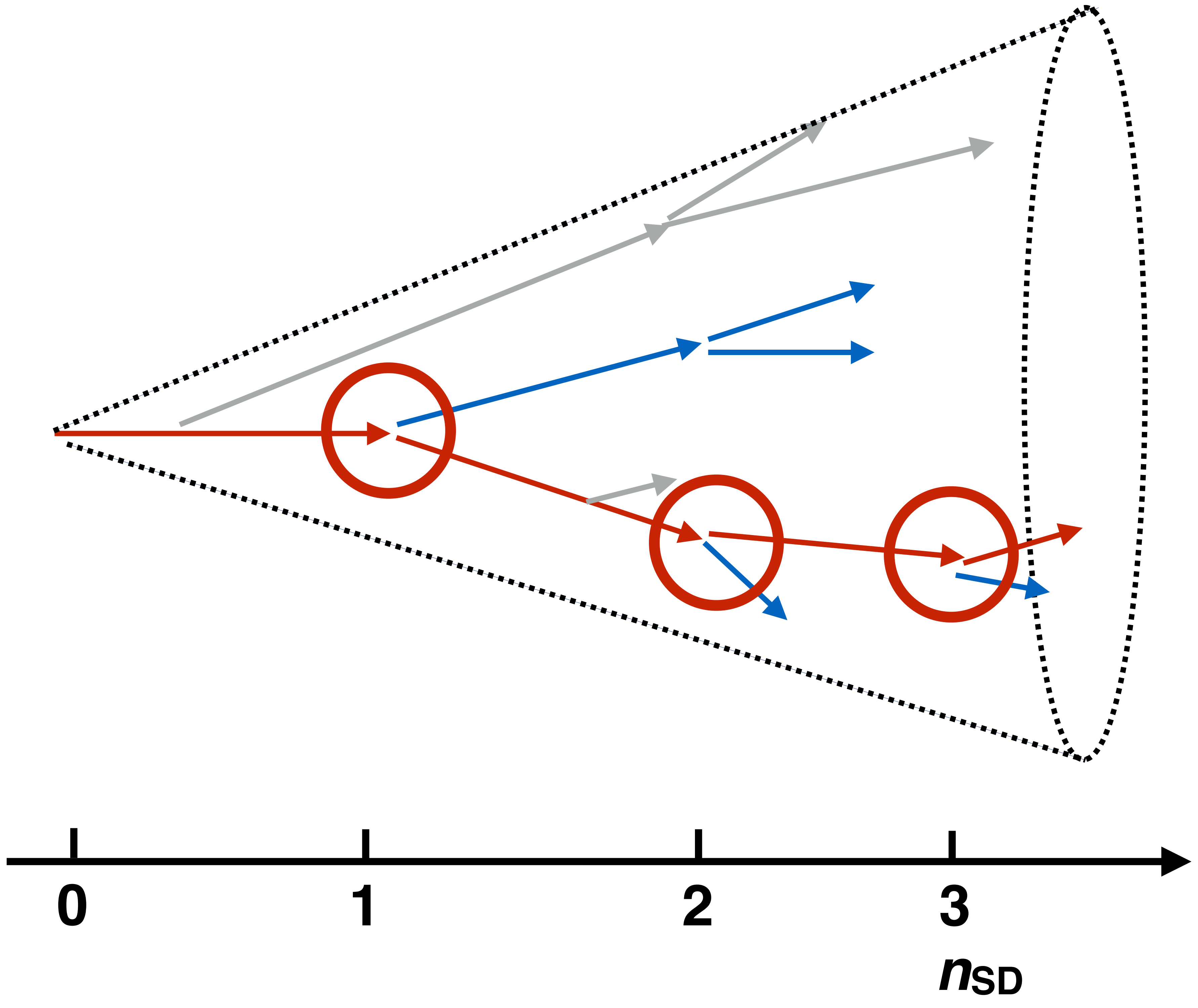

- **reclustering** with Cambridge/Aachen (angular ordering)
- **declustering**: unwind reclustering history
  → chronologically ordered splittings
- **grooming** with Soft Drop (SD): groom away soft prongs not satisfying SD condition
- ***n_{SD}***: total number of splittings satisfying SD
  → following hardest branch

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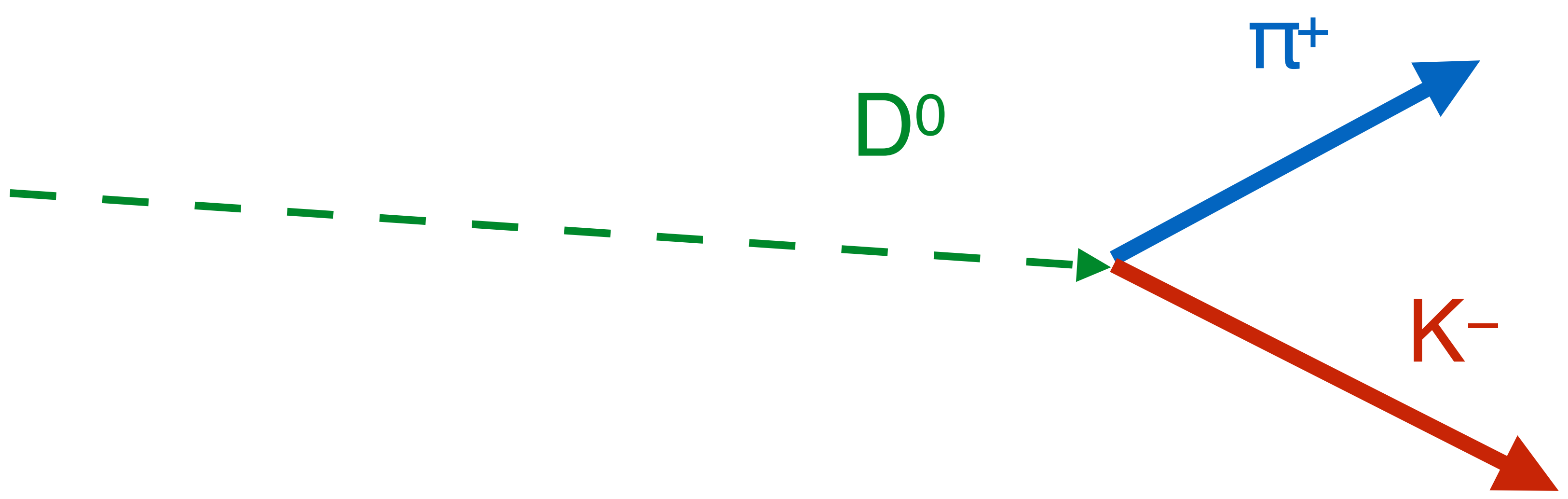
Analysis strategy

D^0 meson reconstruction

D^0

$D^0 \rightarrow K^- \pi^+$



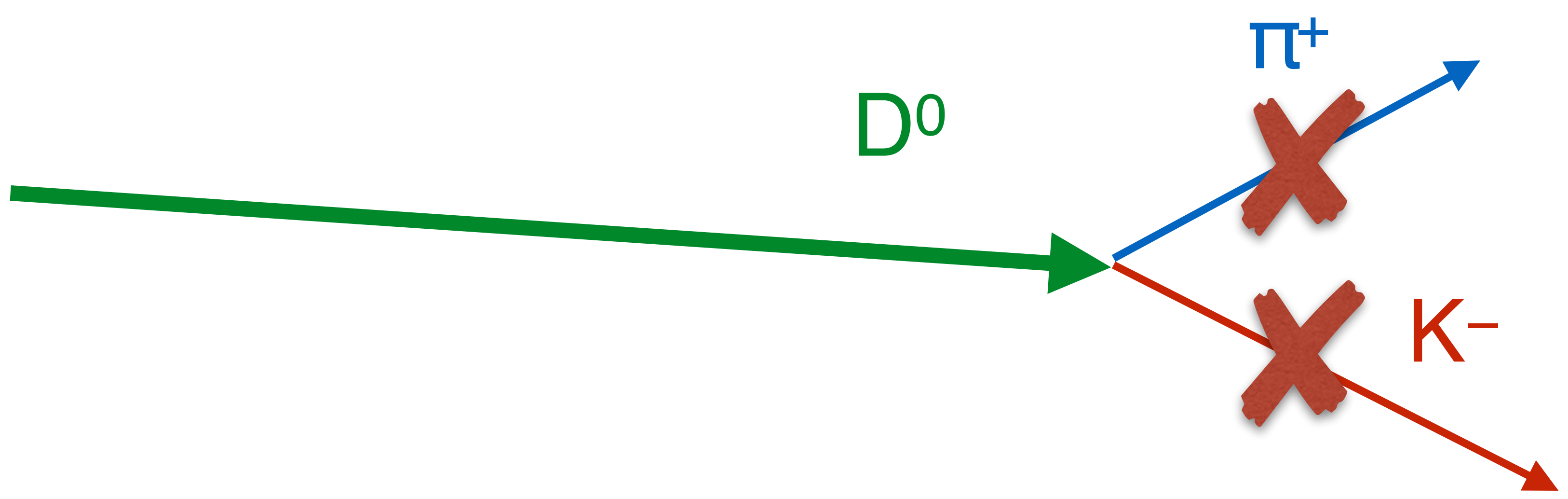
D^0 selection:

- topological cuts
- particle ID (TPC dE/dx, time of flight)

D^0 meson reconstruction

D^0

$D^0 \to K^- \pi^+$



$5 < p_T^D < 30$ GeV/c

D^0 selection:

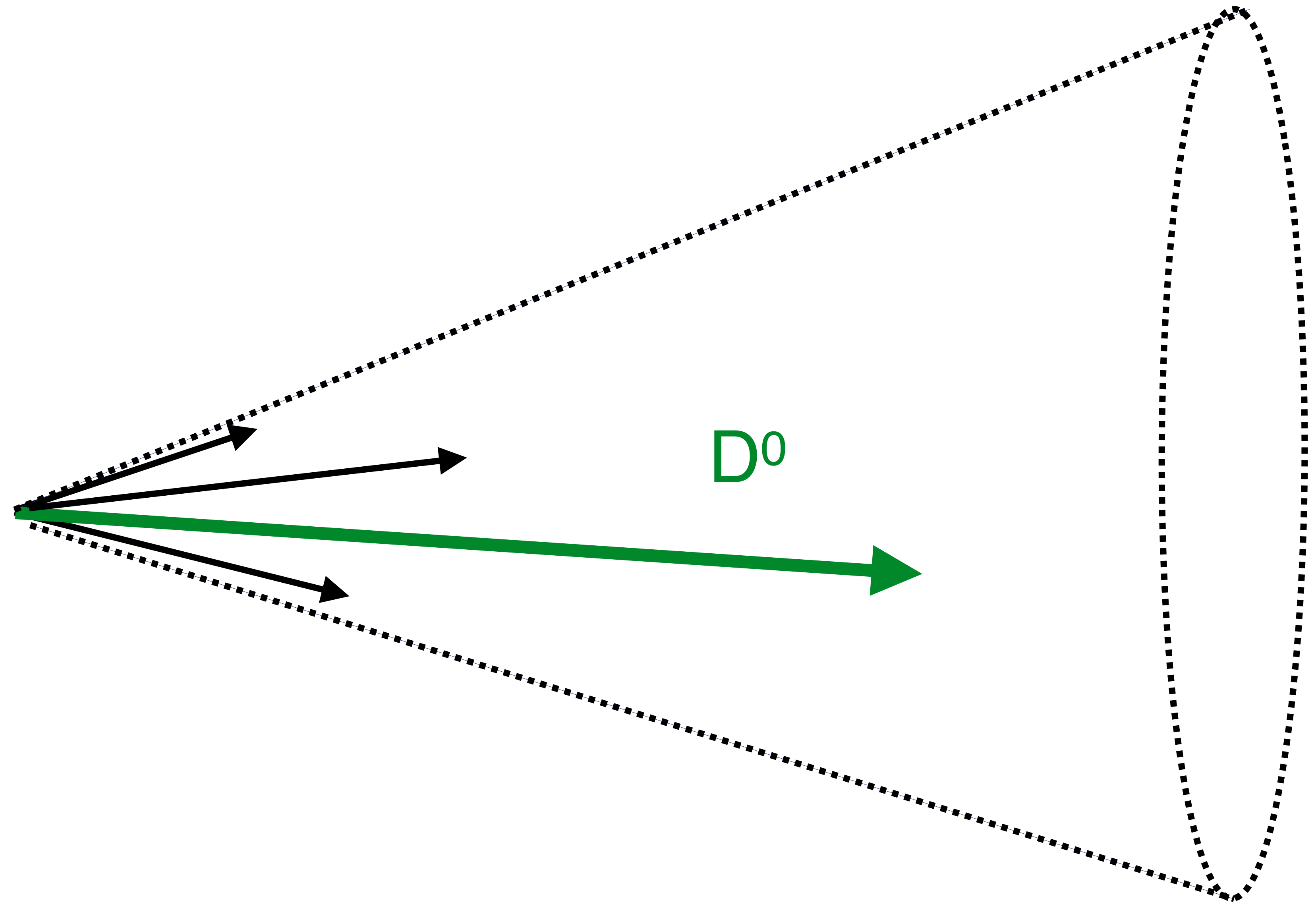
- topological cuts
- particle ID (TPC dE/dx, time of flight)

$K^- \pi^+$ pairs replaced by D^0:

- D^0 always inside the jet cone
- D^0 traceable through the splitting tree

D^0-tagged-jet reconstruction

D^0 | D^0 jet



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Jet finding:
- performed independently for each D^0 candidate
- anti-k_T algorithm, $R = 0.4$

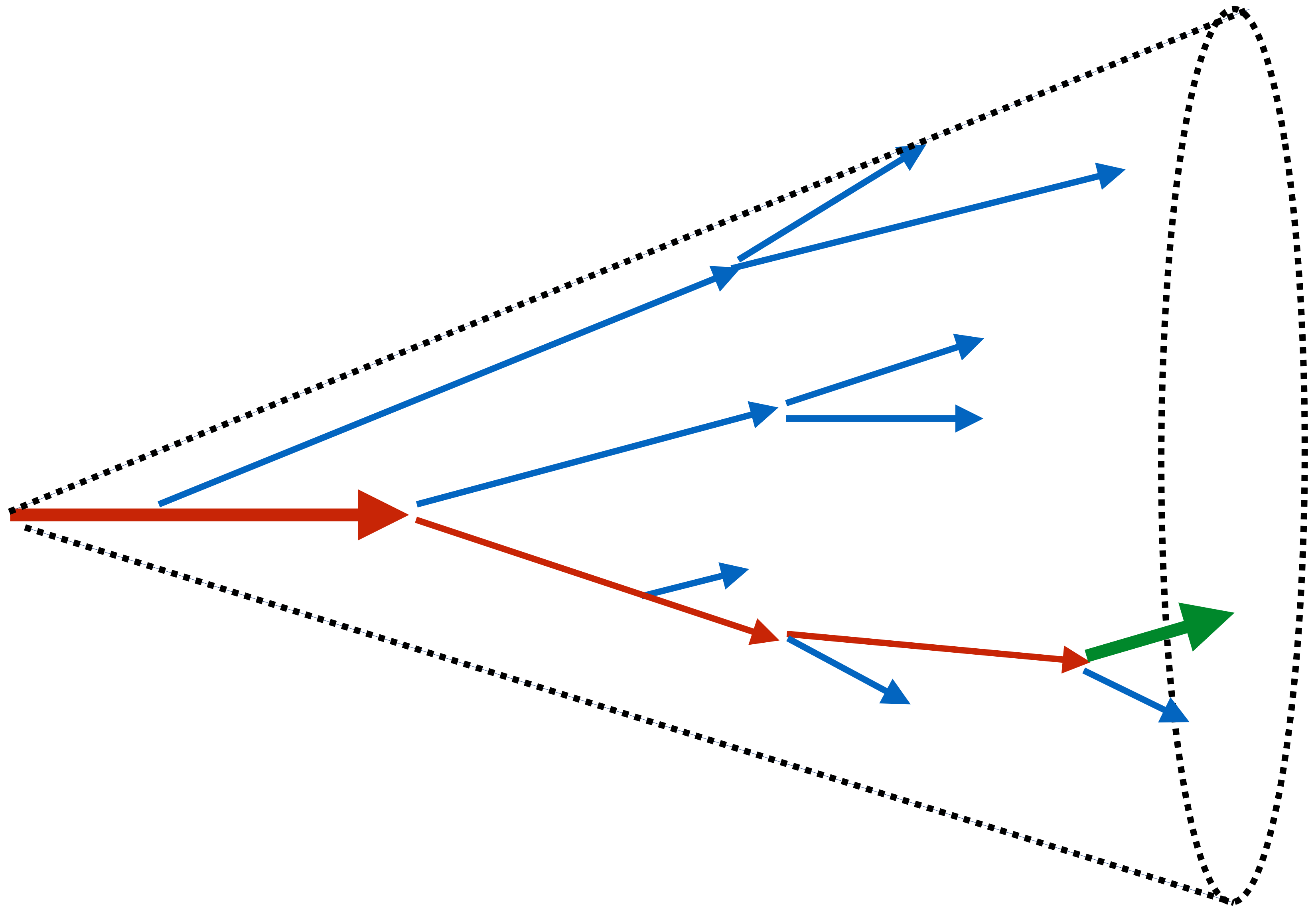
→ **D^0-tagged charged jets**

$5 < p_T^D < 30$ GeV/c

$15 < p_T^{\text{jet ch}} < 30$ GeV/c

Jet reclustering and declustering

D^0 | D^0 jet | declustering



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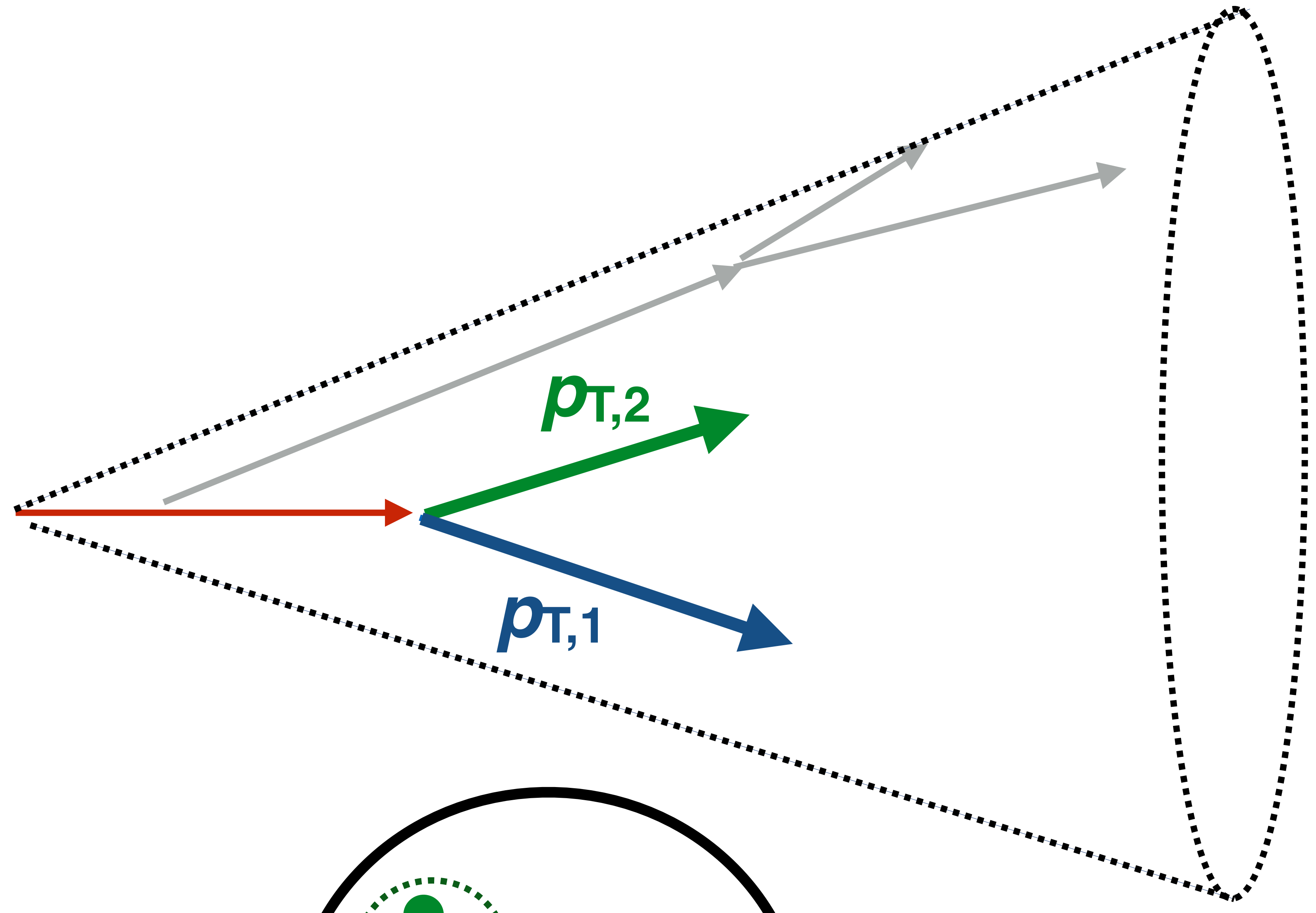
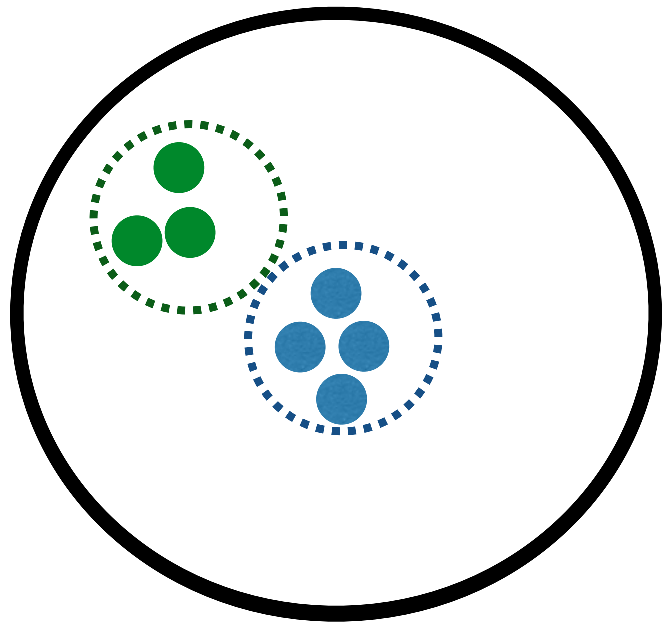
Reclustering: C/A algorithm (**angular ordered**)

Jet grooming: Soft Drop

D0 | D0 jet | declustering | **grooming**





D0 selection:
- topological cuts
- particle ID (TPC dE/dx, time of flight)

K⁻π⁺ pairs replaced by D0:
- D^0 always inside the jet cone
- D^0 traceable through the splitting tree

Jet finding:
- performed independently for each D^0 candidate
- anti-k_T algorithm, $R = 0.4$

→ **D^0-tagged charged jets**

Reclustering: C/A algorithm (**angular ordered**)

Grooming: $z_{cut} = 0.1, \ \beta = 0$

Soft Drop (SD) grooming condition:

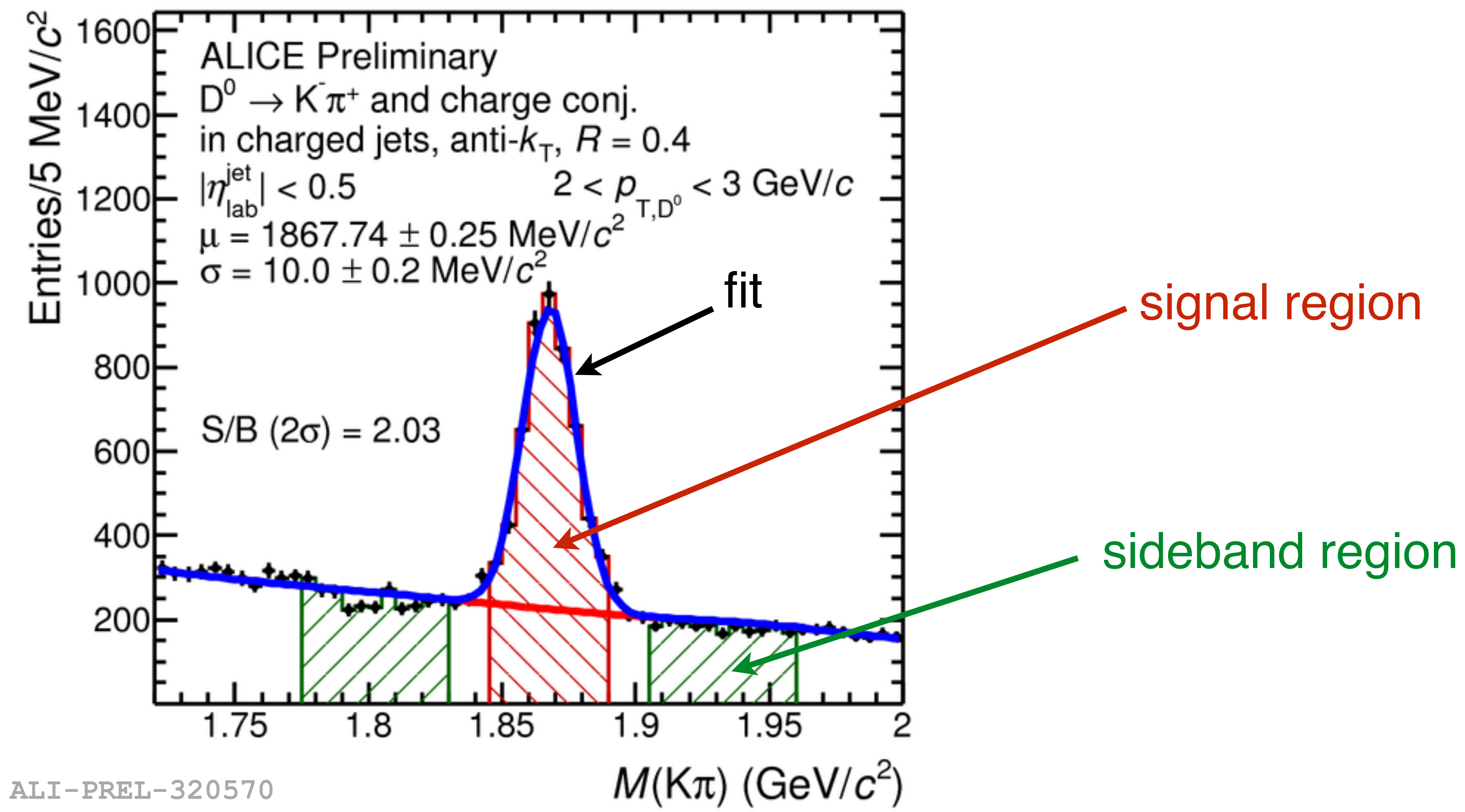
$$z = \frac{p_{T,2}}{p_{T,1} + p_{T,2}} > z_{cut} \left(\frac{\Delta R_{1,2}}{R} \right)^{\beta}$$

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

$R =$ jet resolution parameter

Signal extraction

D0 | D0 jet | declustering | grooming | **signal extraction**

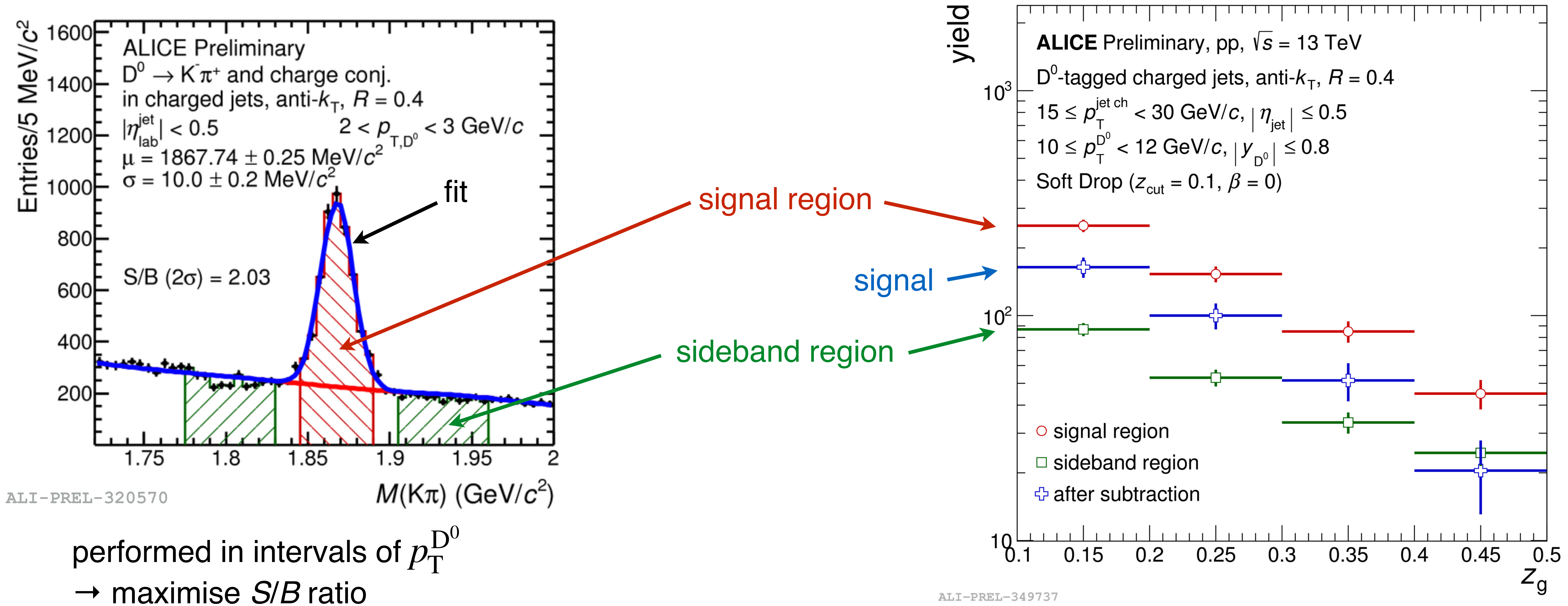


performed in intervals of $p_{\mathrm{T}}^{\mathrm{D}^0}$

→ maximise *S*/*B* ratio

Signal extraction

D⁰ | D⁰ jet | declustering | grooming | **signal extraction**



performed in intervals of $p_T^{D^0}$
→ maximise *S*/*B* ratio

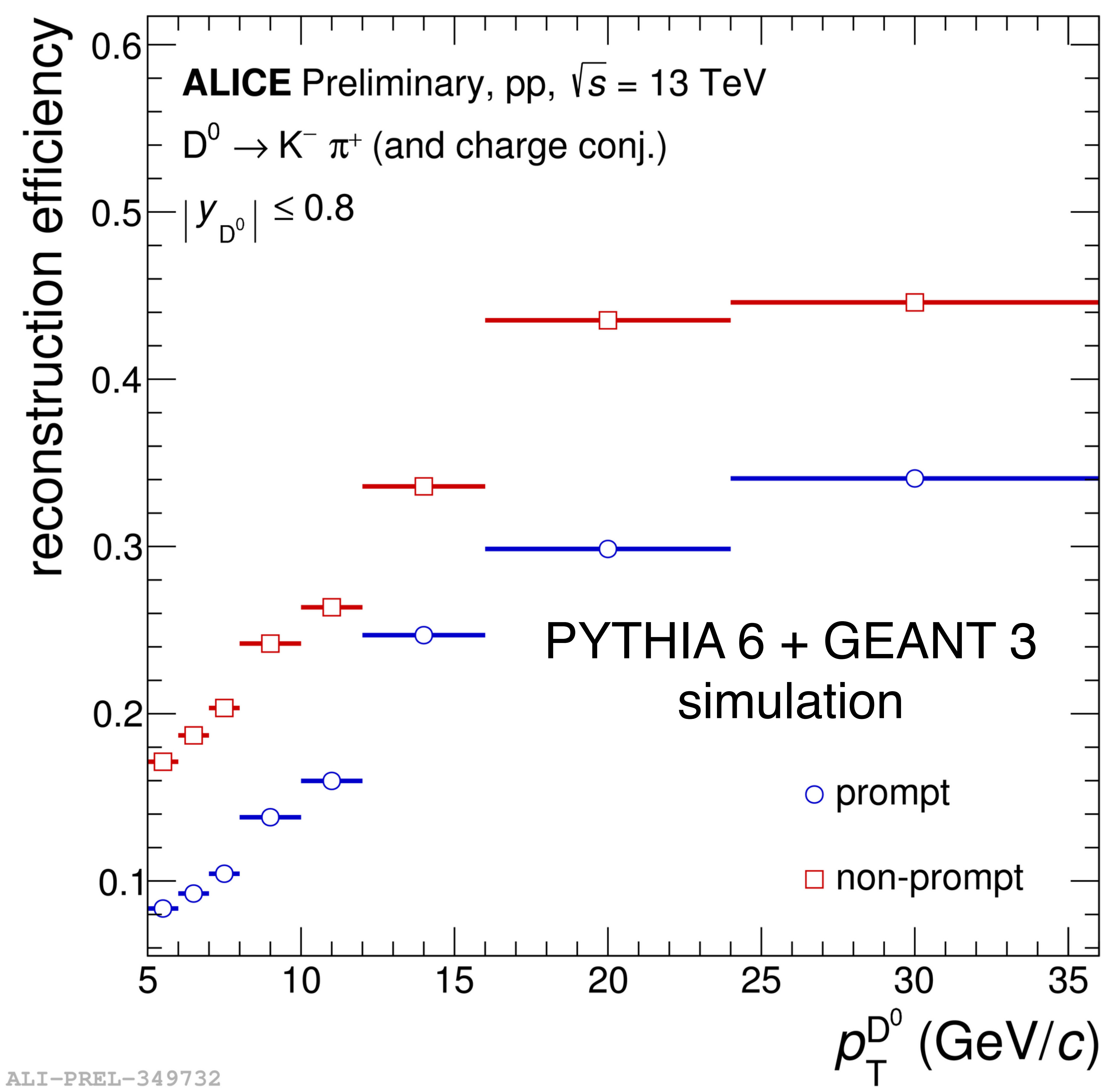
D^0 reconstruction efficiency

D⁰ | D⁰ jet | declustering | grooming | signal extraction | **efficiency**

ALICE

- **prompt ($c \to D^0$)** efficiency:
  → correct in bins of D^0 p_T

- **b feed-down ($b \to D^0$)** efficiency:
  → contribution of b feed-down decay



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b→D⁰ feed-down subtraction

D⁰ | D⁰ jet | declustering | grooming | signal extraction | efficiency | **b feed-down**

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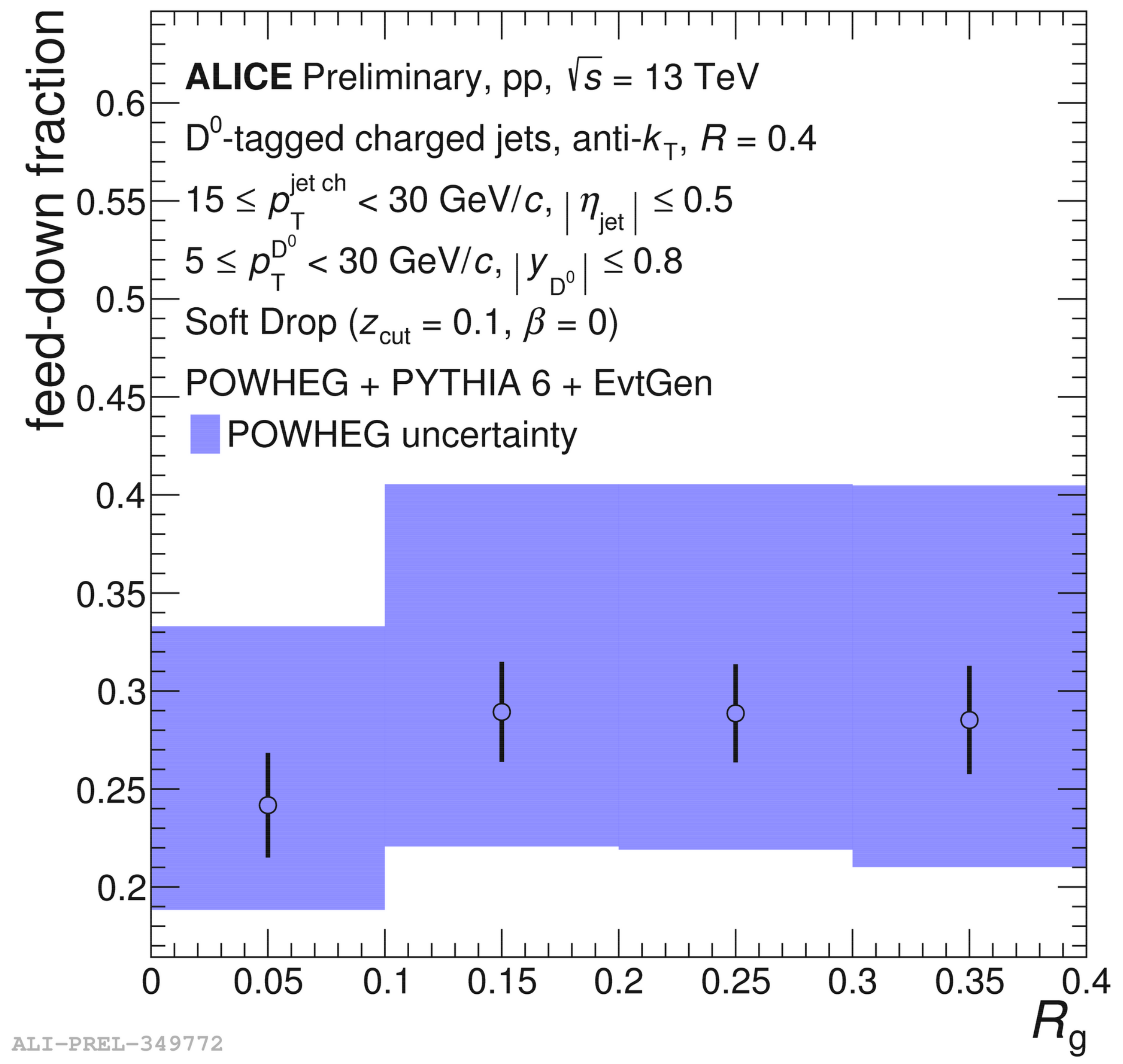
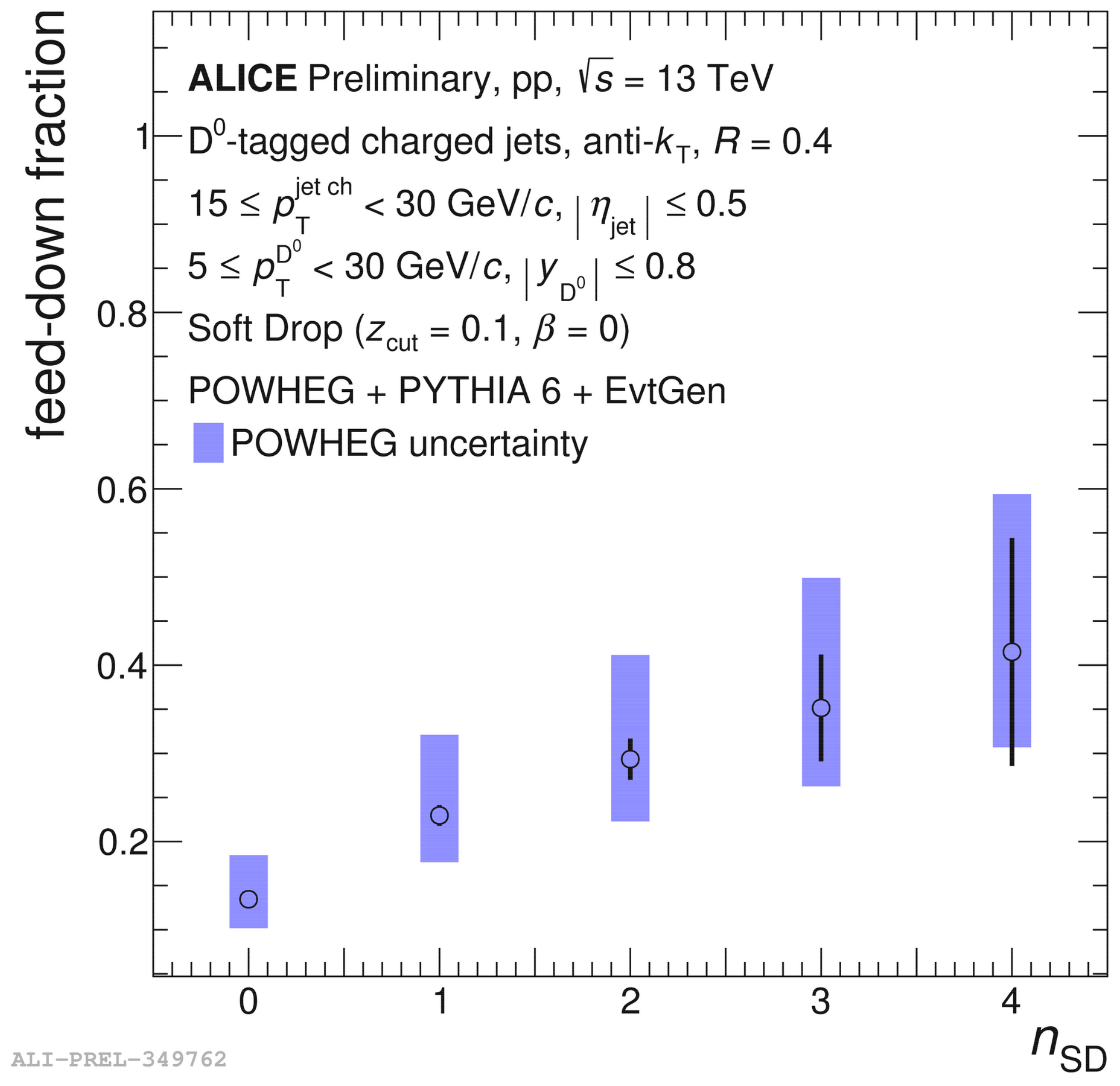
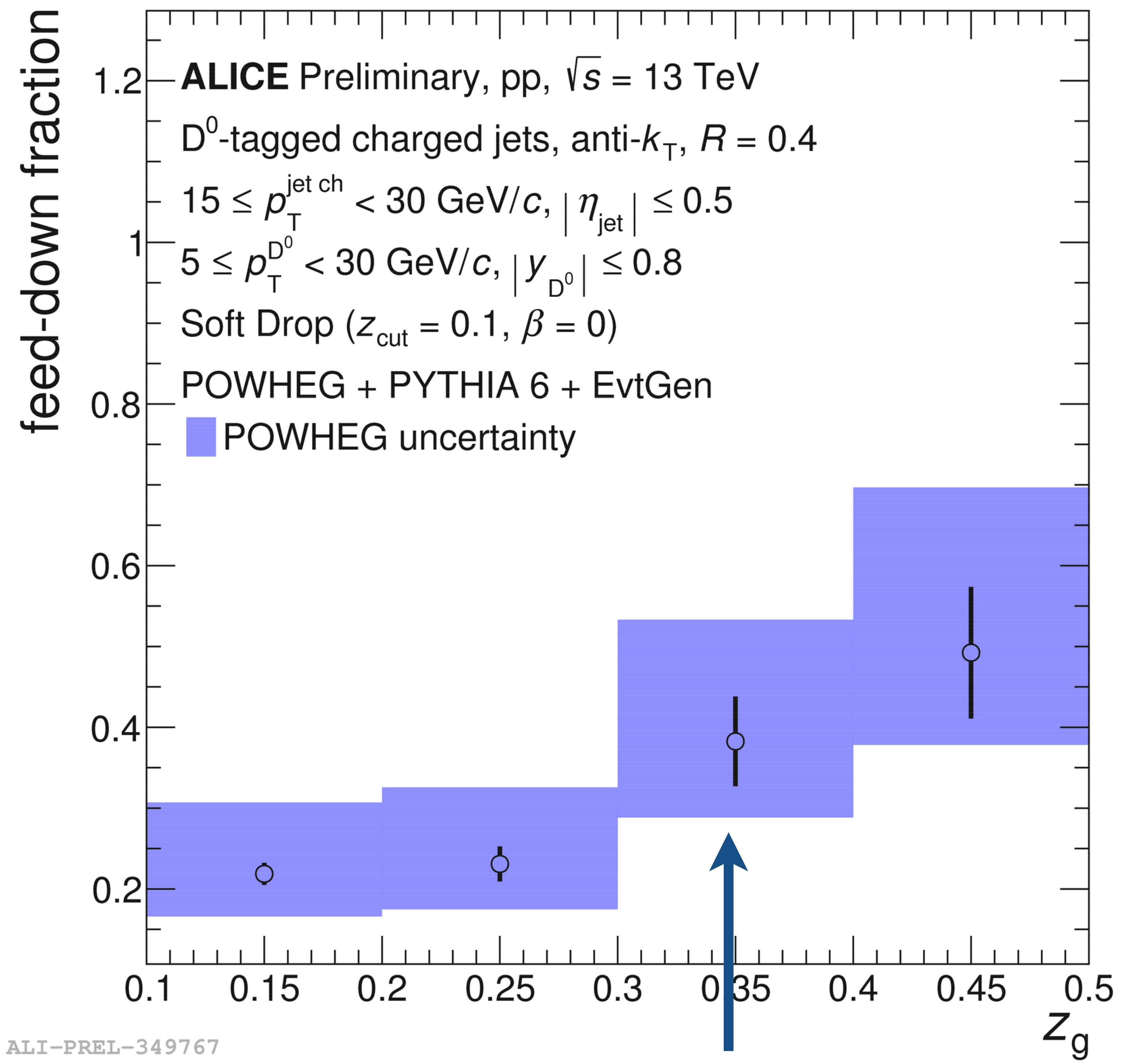
- $\sigma^{b\to D^0}$ simulated with POWEG + PYTHIA 6 + EvtGen
- folded to detector level with the response matrix of **b→D⁰-tagged jets**







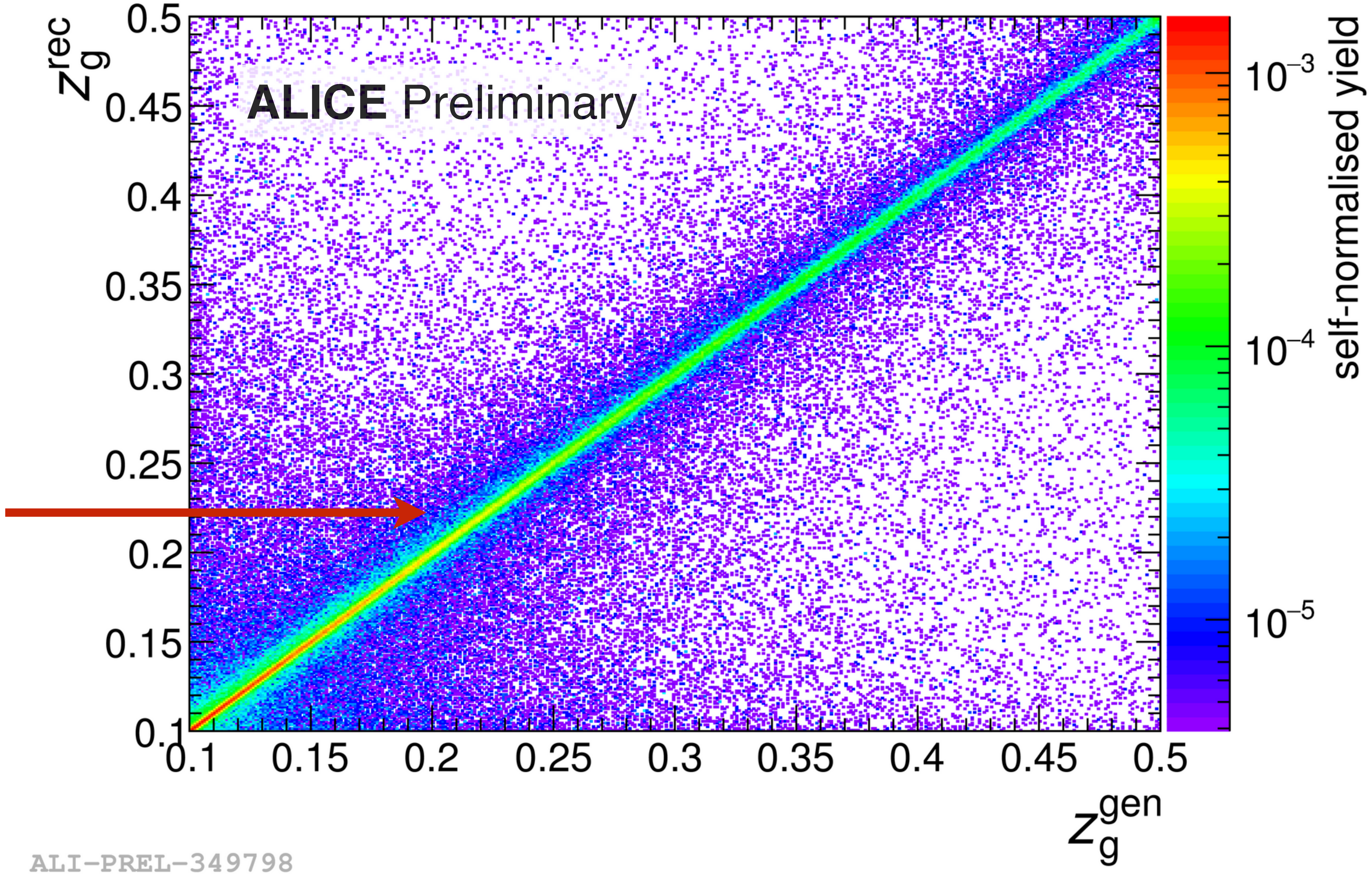
feed-down fraction typically shape-dependent

Unfolding

D0 | D0 jet | declustering | grooming | signal extraction | efficiency | b feed-down | **unfolding**

Correction for detector effects
using 2D Bayesian unfolding: $p_{T}^{\text{jet ch}}$ and z_{g}

- **4D response matrix:**
  - ($p_{T}^{\text{gen, jet}}$, z_{g}^{gen}, $p_{T}^{\text{rec, jet}}$, z_{g}^{rec})
  - estimated using MC simulations



Inclusive jet analysis

yields unfolding

- **4D response matrix:**
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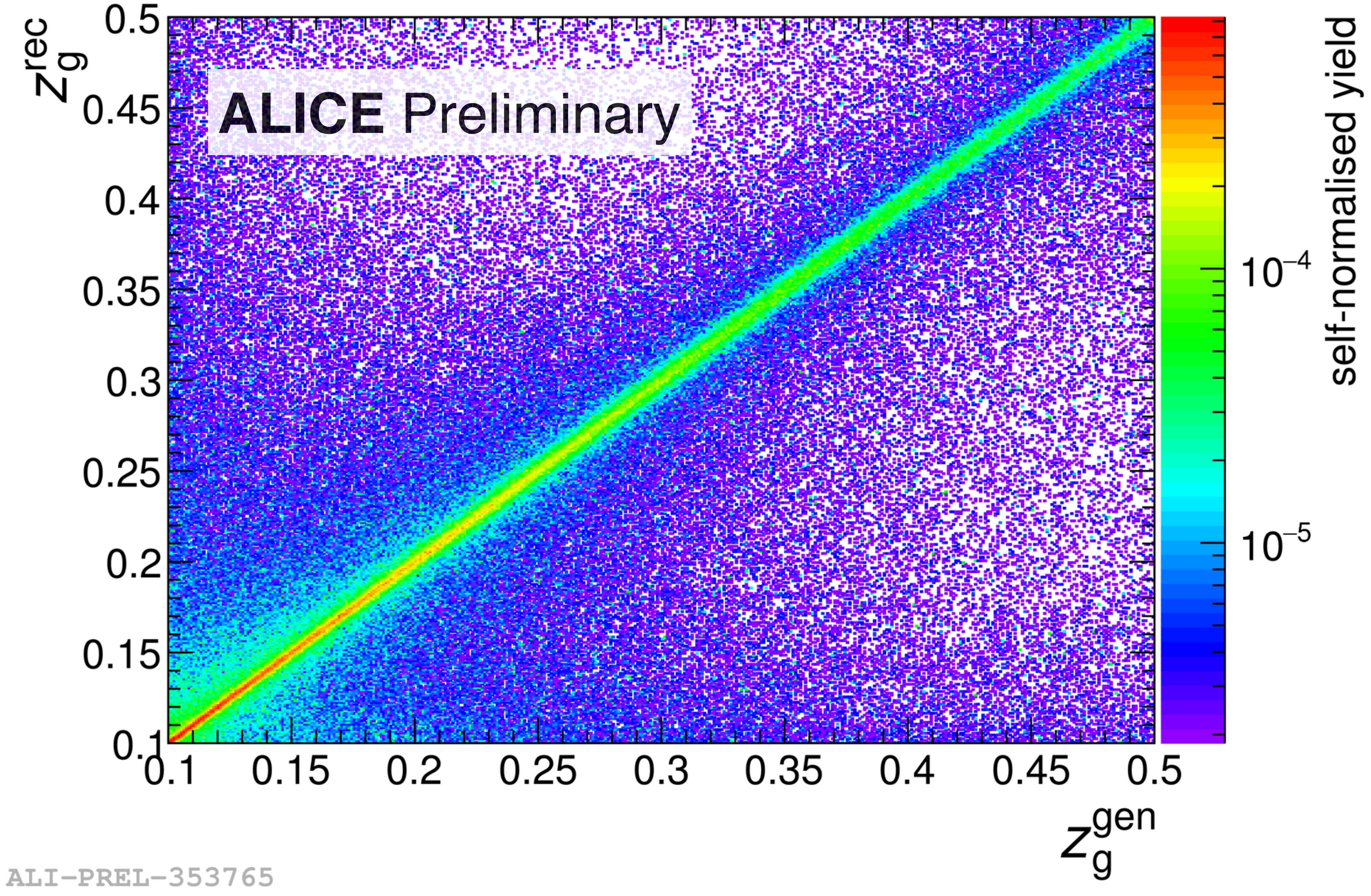
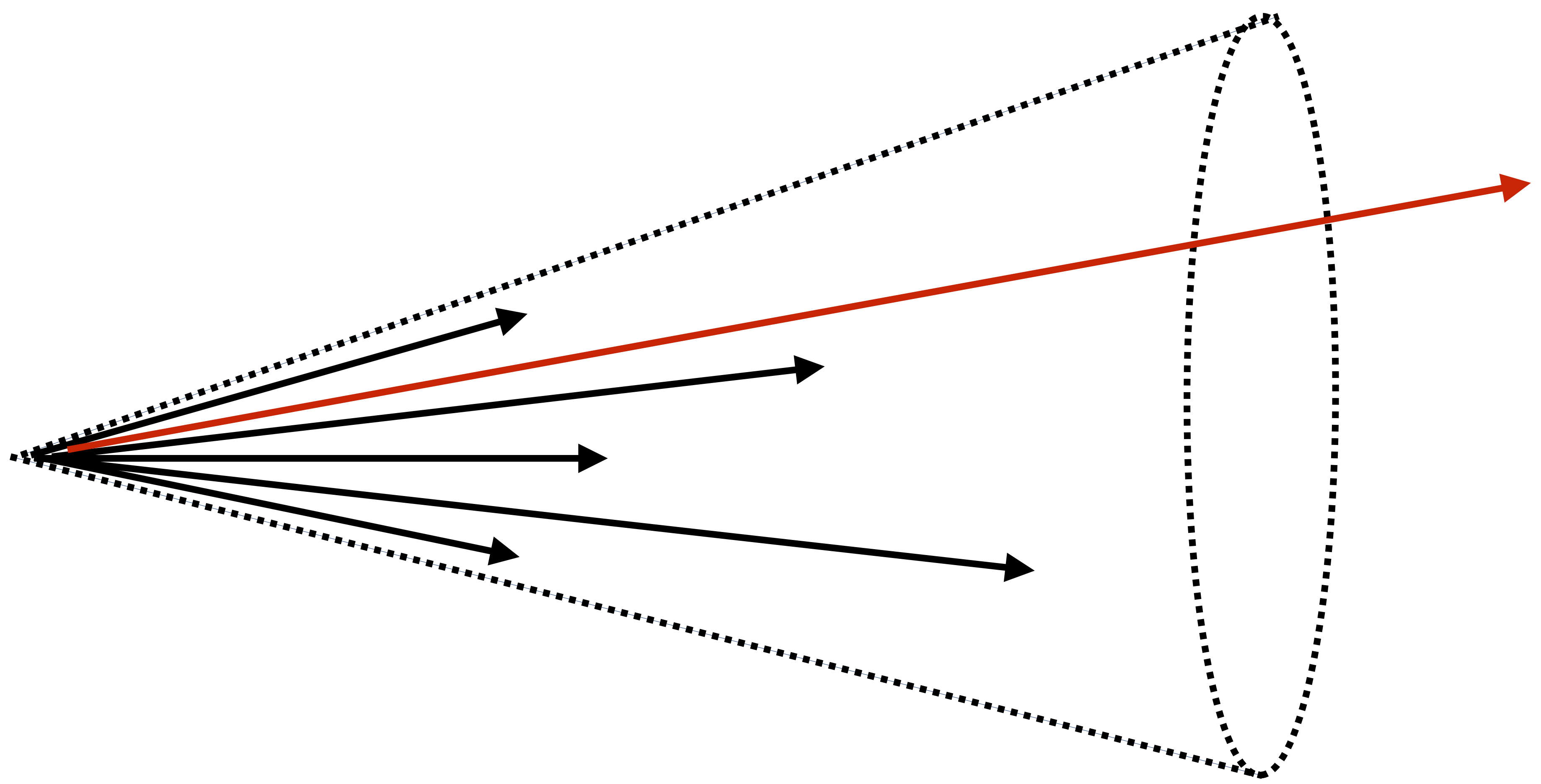
  - estimated using MC simulations



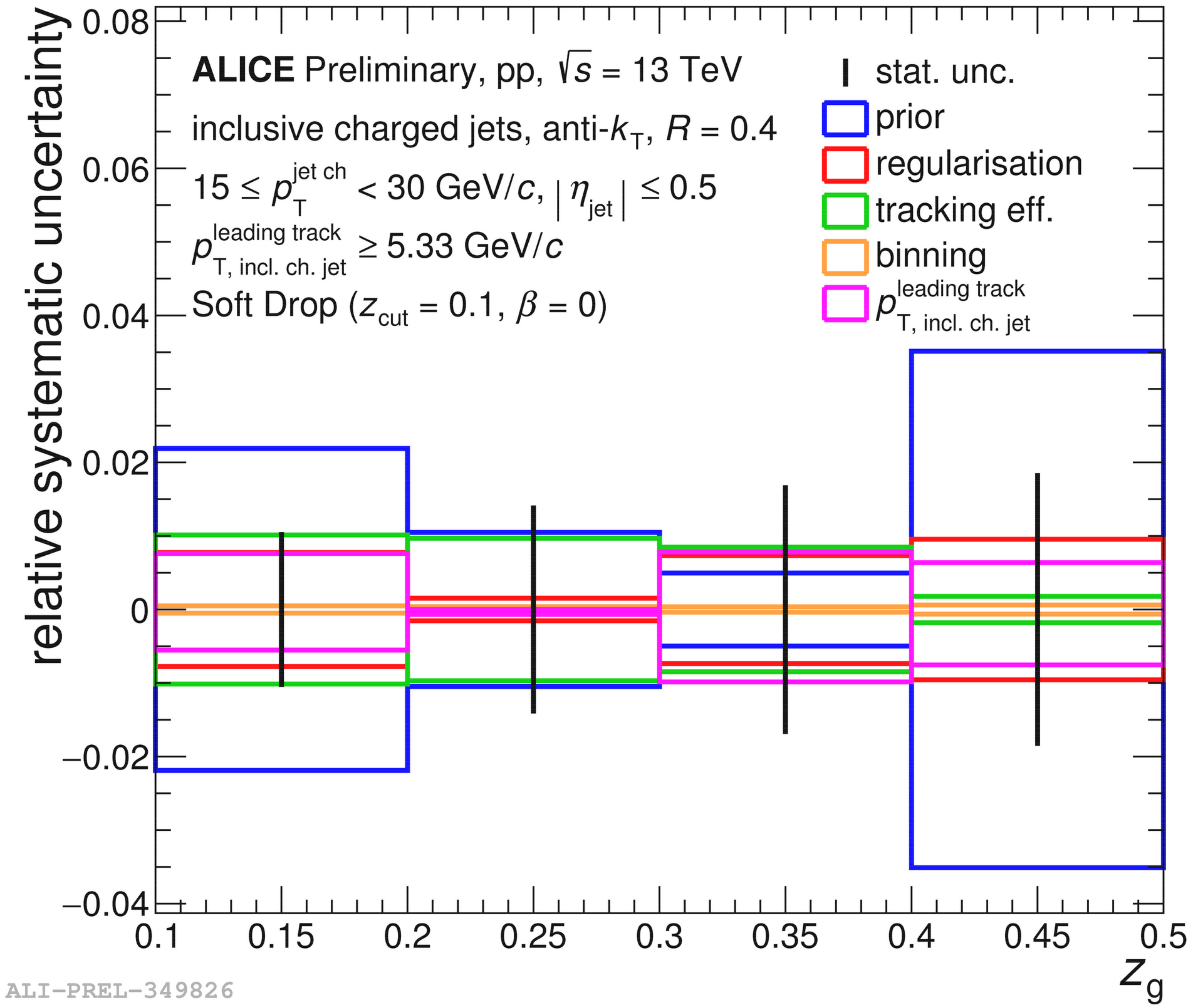


leading-track p_T selection:
- mimic the selection on the D^0 p_T
- account for D^0 m_T

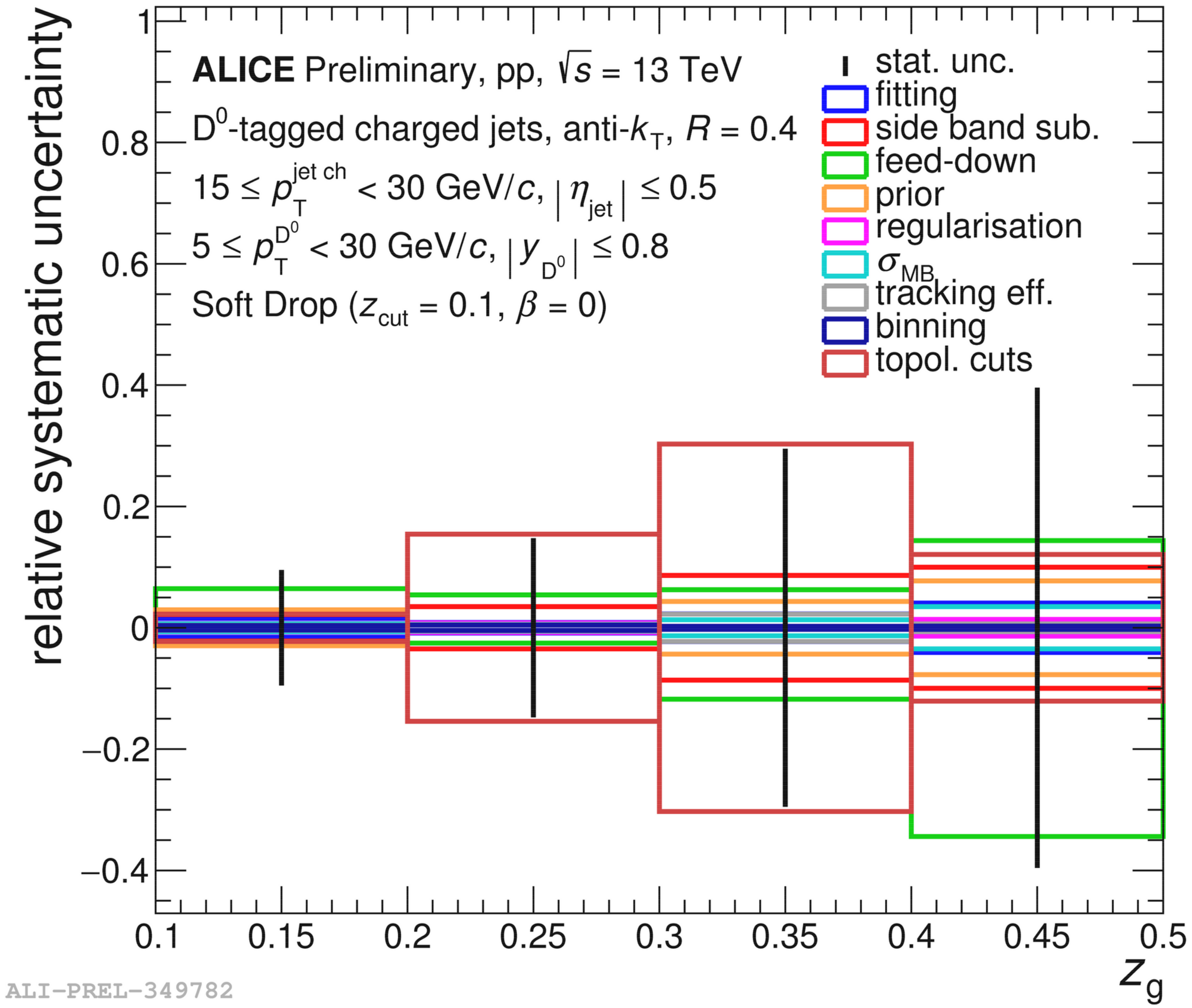
→ **similar interaction Q^2**

Systematic uncertainties

Inclusive jets



D⁰-tagged jets

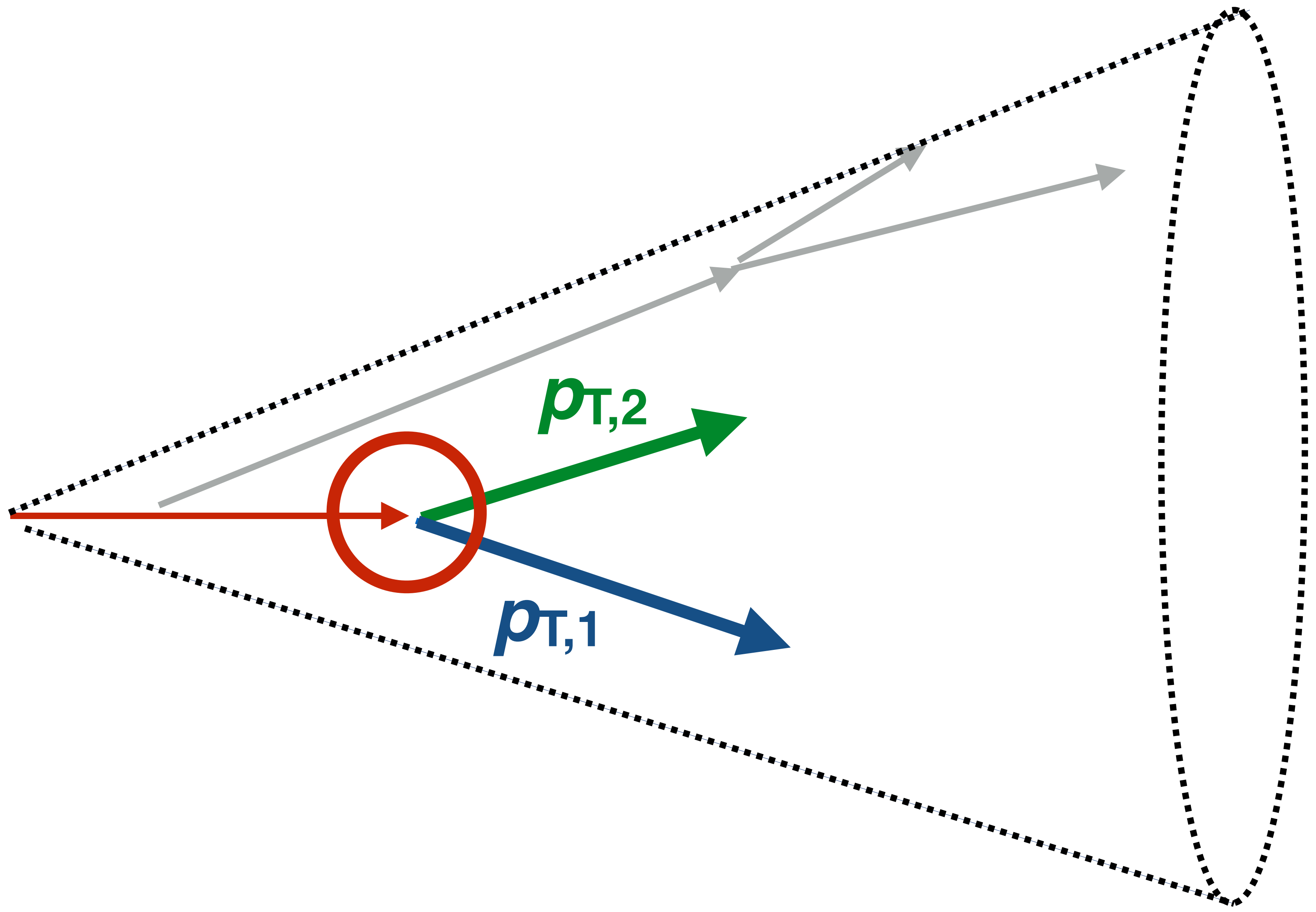


Uncertainty per category estimated as RMS of deviations from the central values.

Uncertainties from all categories combined in quadrature.

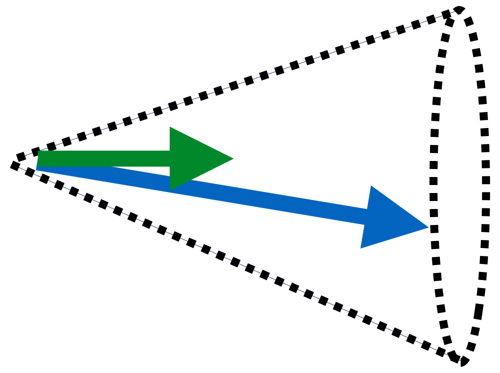
Results

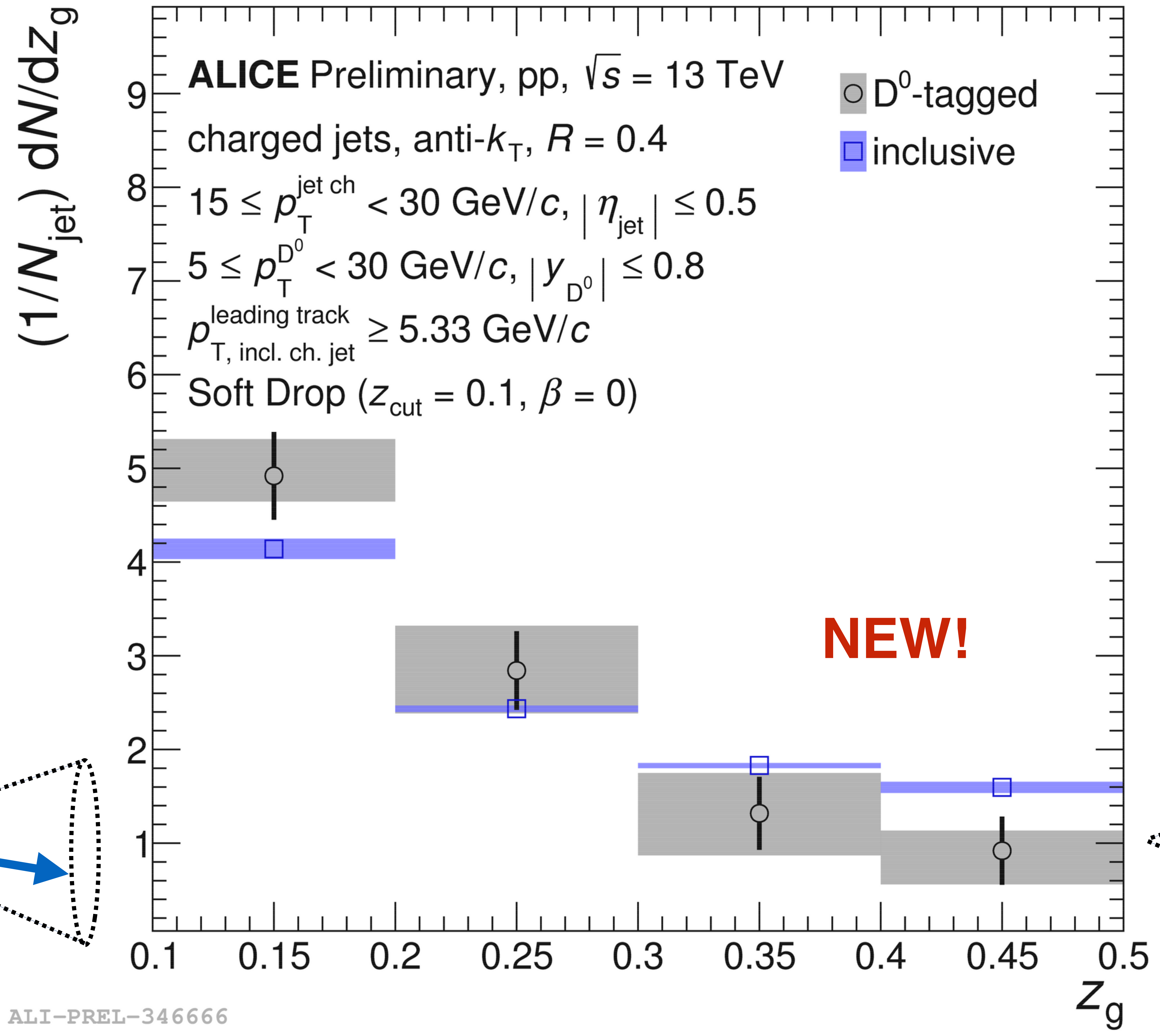
z_g for D^0-tagged and inclusive jets

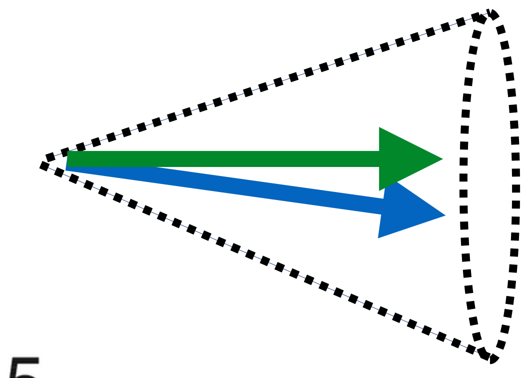


p_T balance between prongs

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

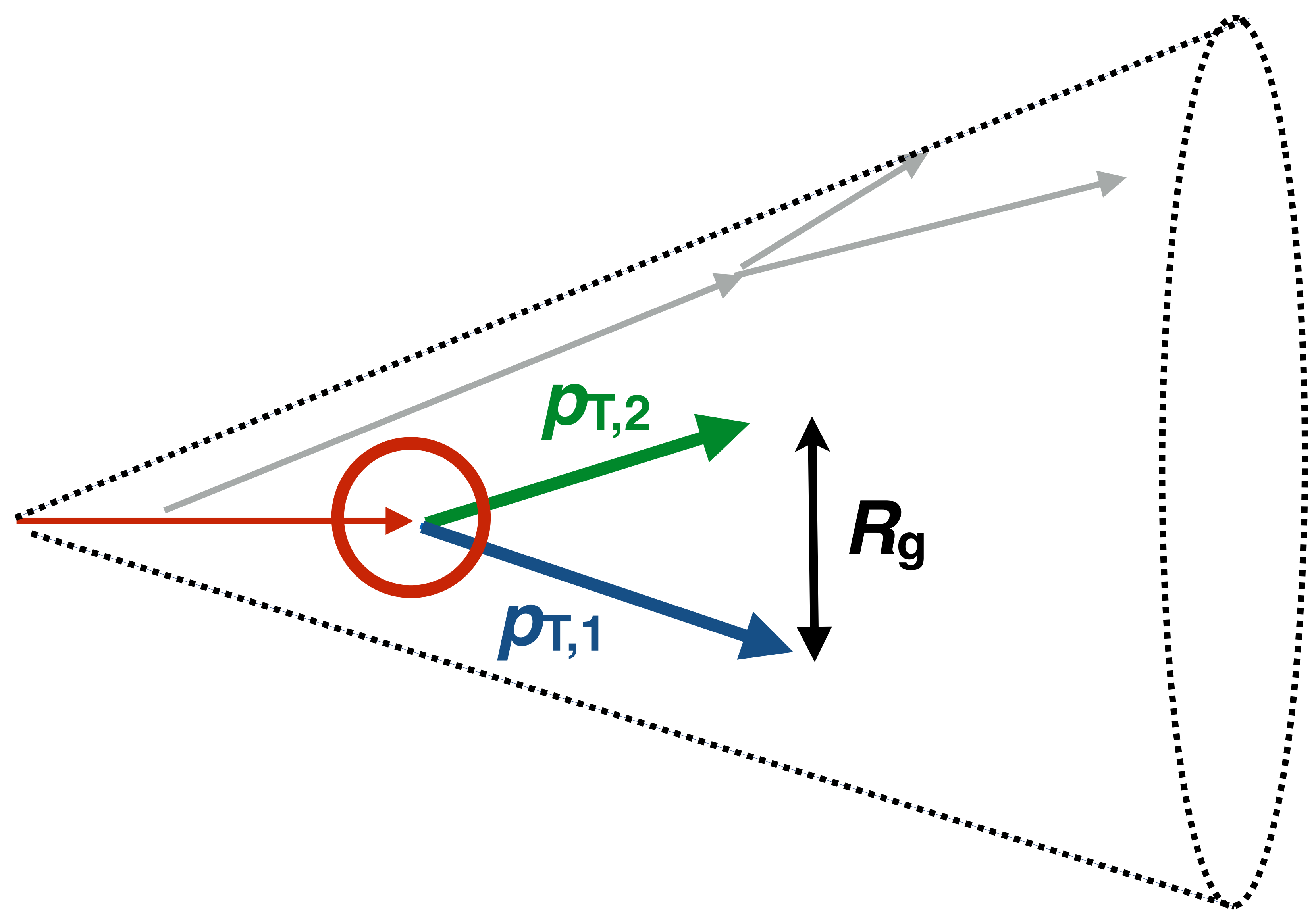




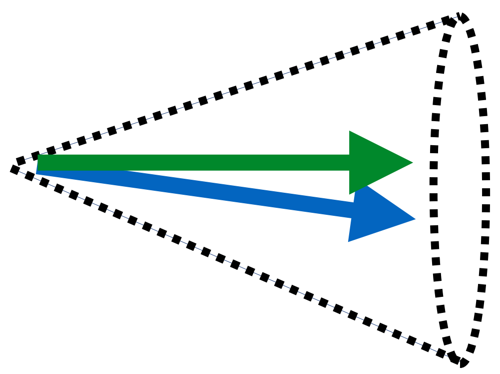


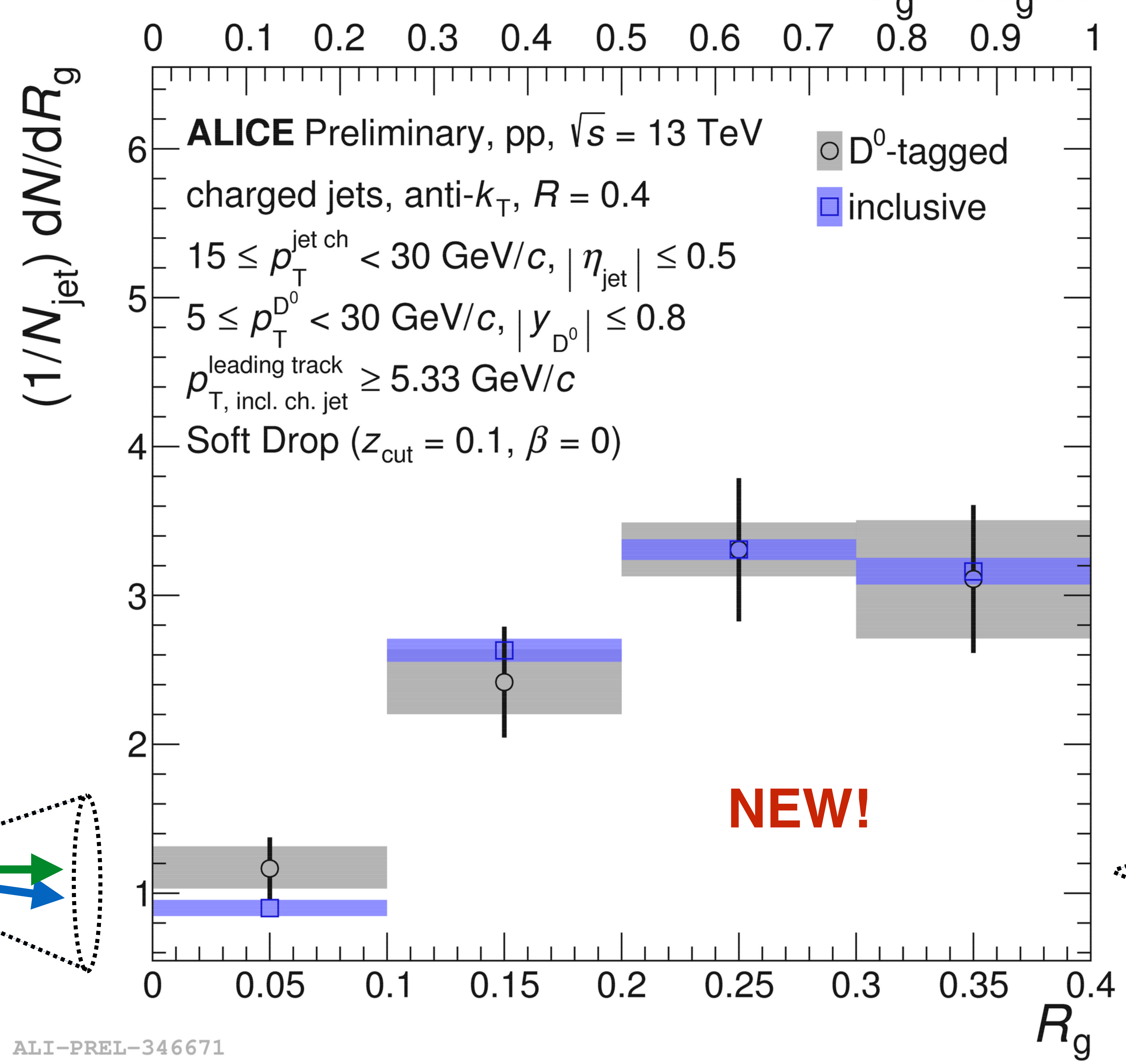
larger p_T asymmetry for **charm** jets?

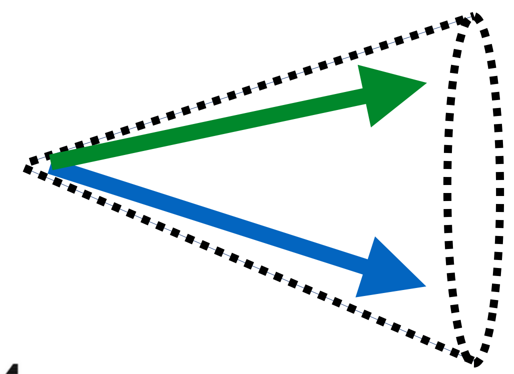
R_g for D^0-tagged and inclusive jets



angular distance $\boldsymbol{R_g}$

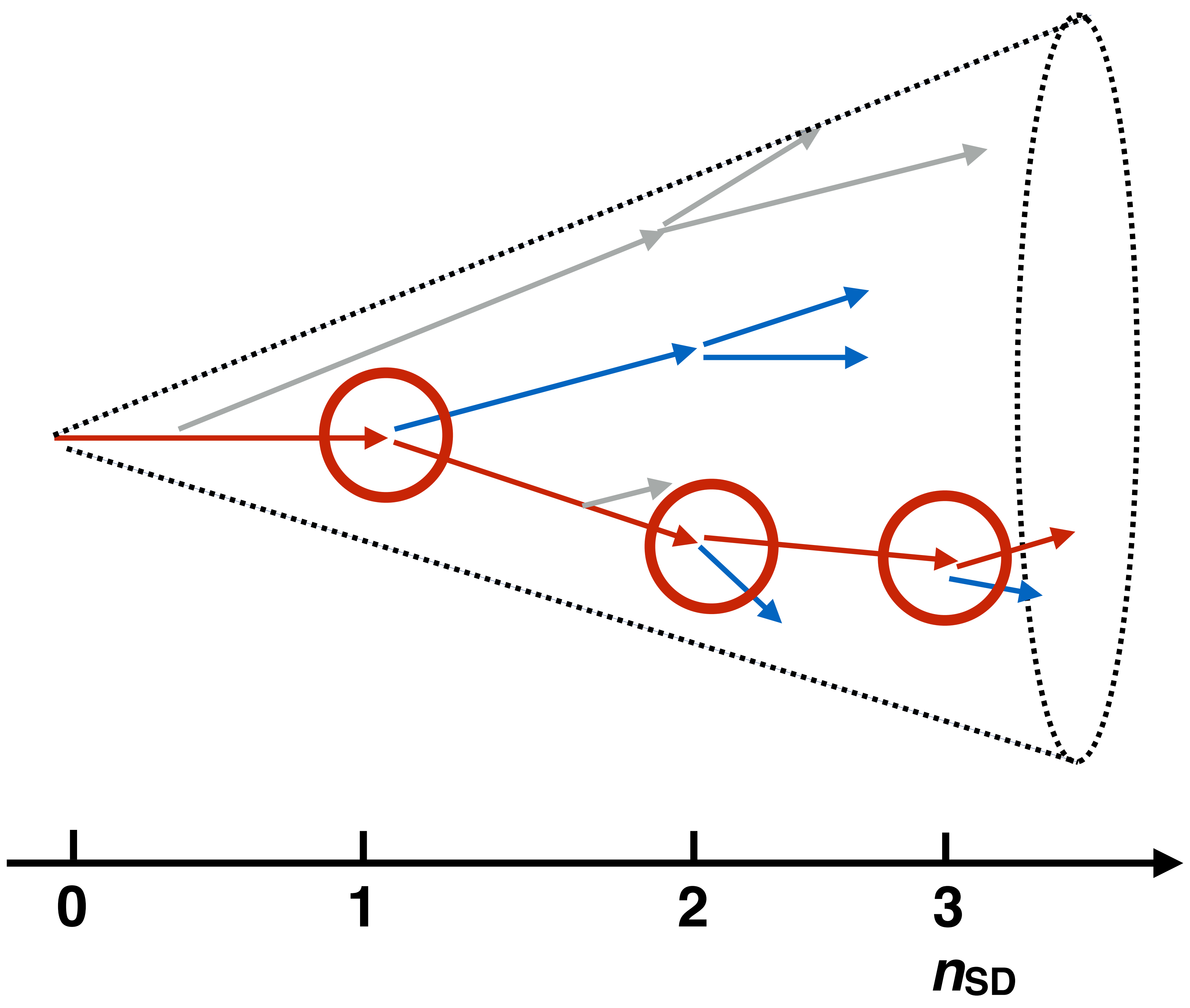






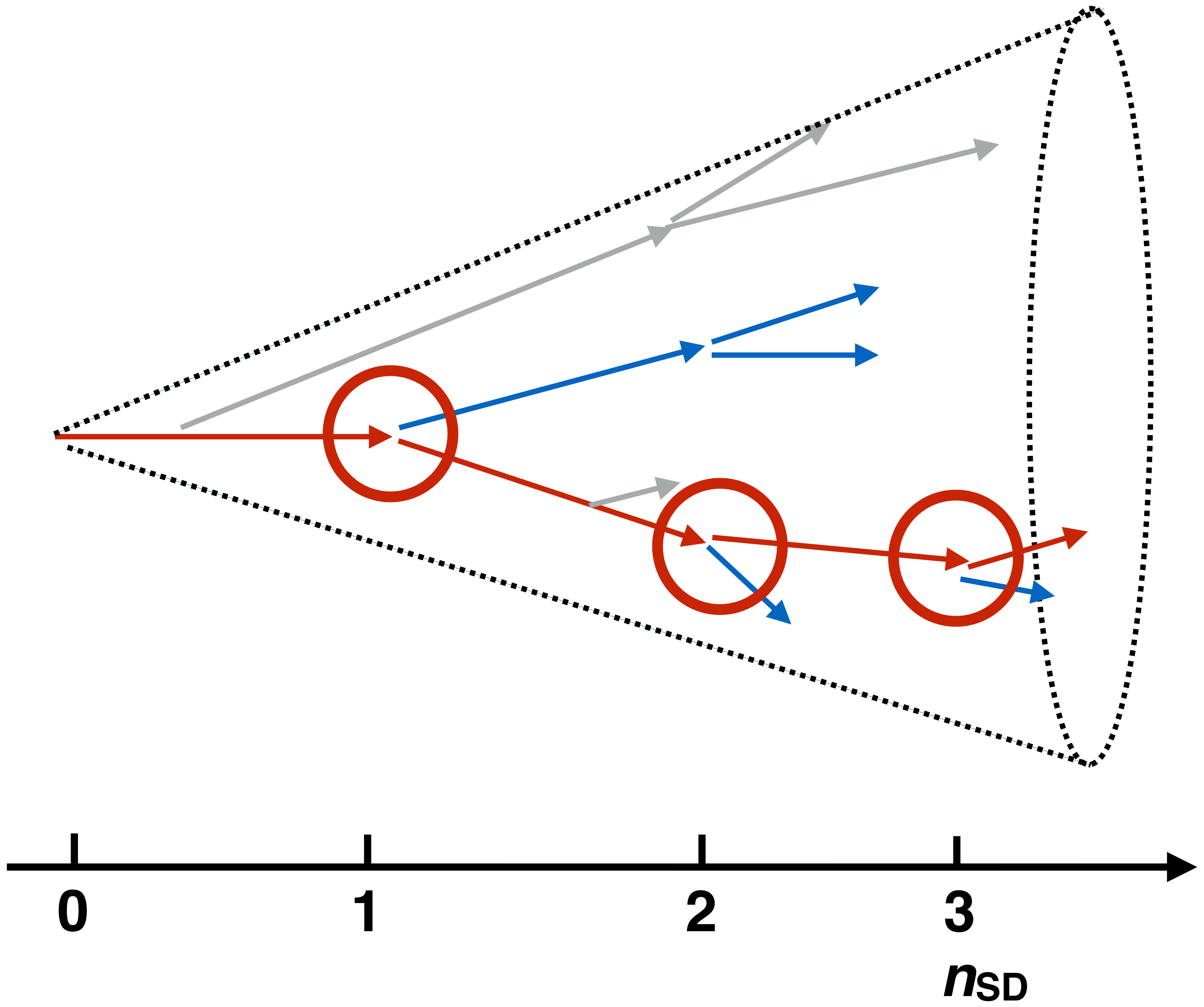
charm jets and **inclusive jets** consistent within uncertainties

n_{SD} for D^0-tagged and inclusive jets



total number of splitting satisfying SD n_{SD}

n_{SD} for D⁰-tagged and inclusive jets



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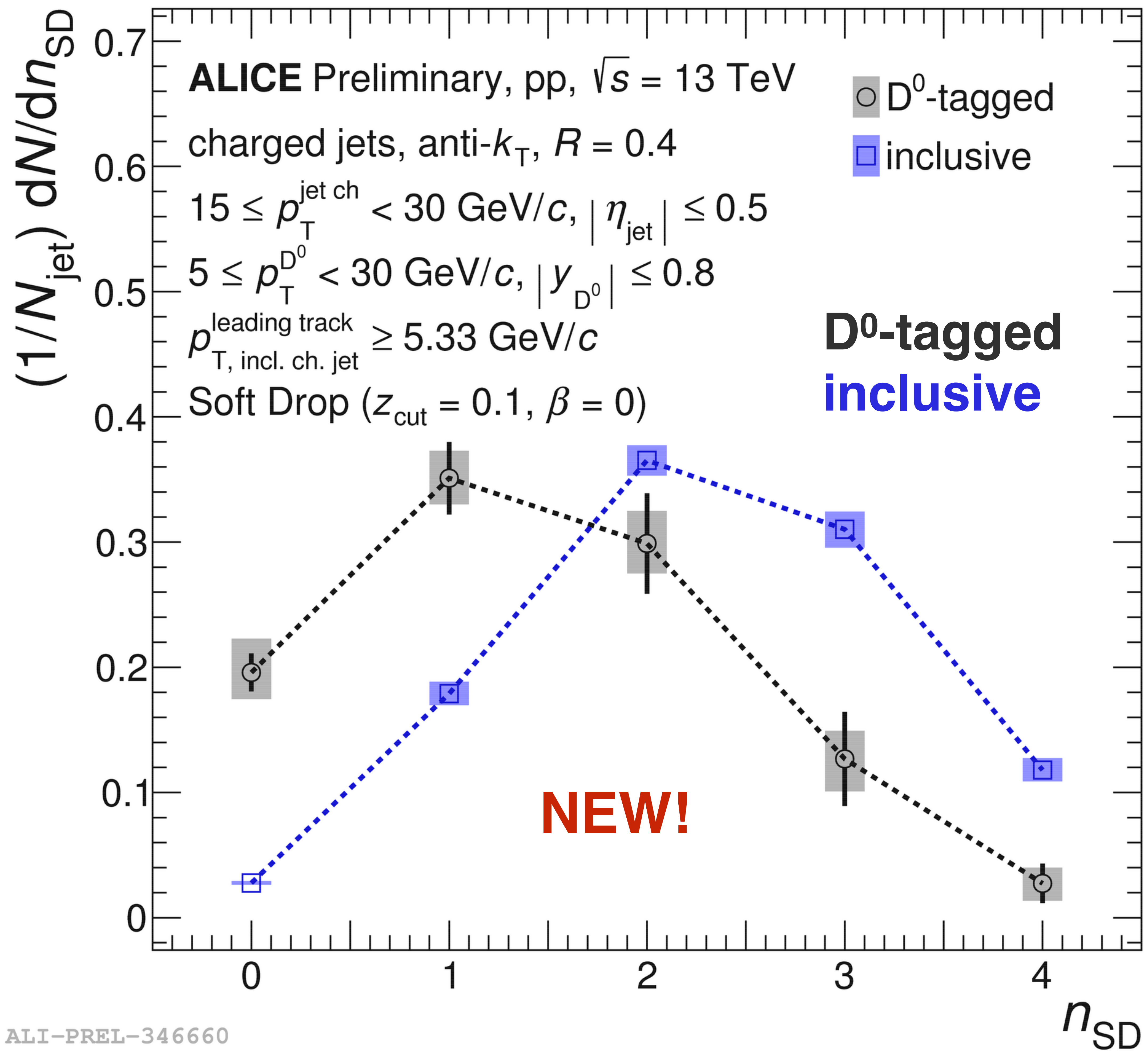

Charm jets have fewer splittings passing the SD than **inclusive jets**.

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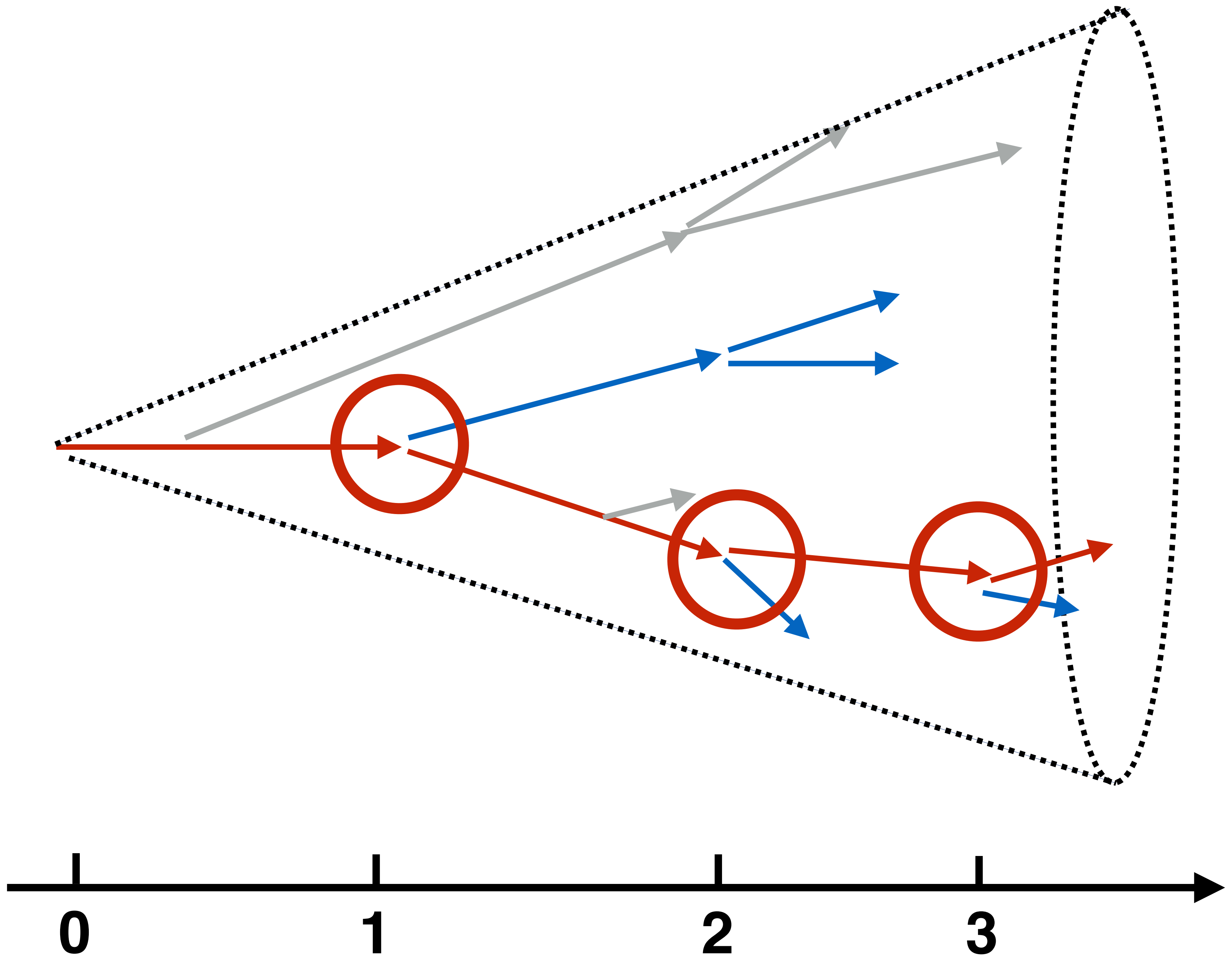
n_{SD} for D⁰-tagged and inclusive jets



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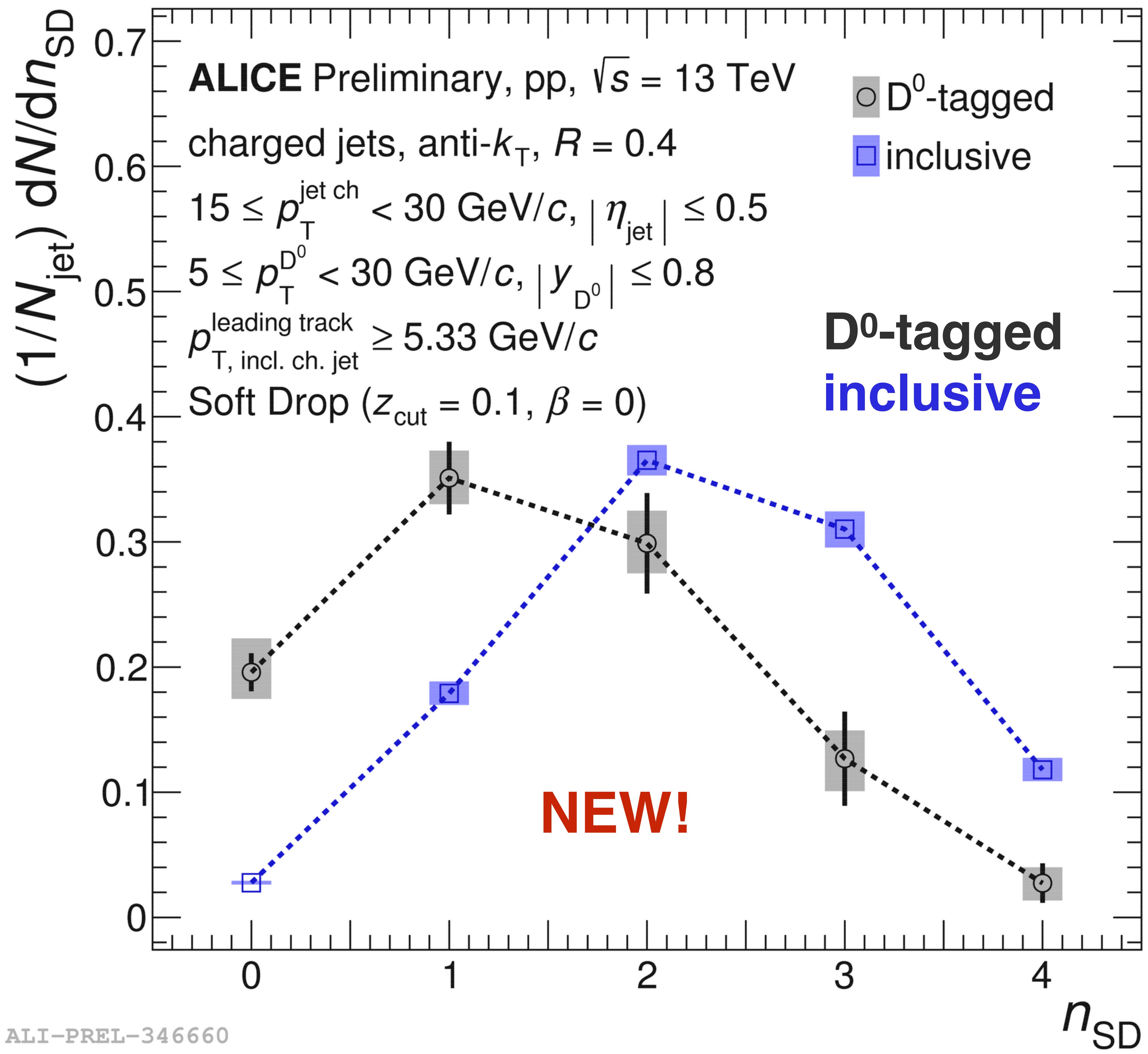

Consistent with harder fragmentation of the charm quark (compared to inclusive jet fragmentation)

→ dead-cone effect

→ quark vs gluon jets

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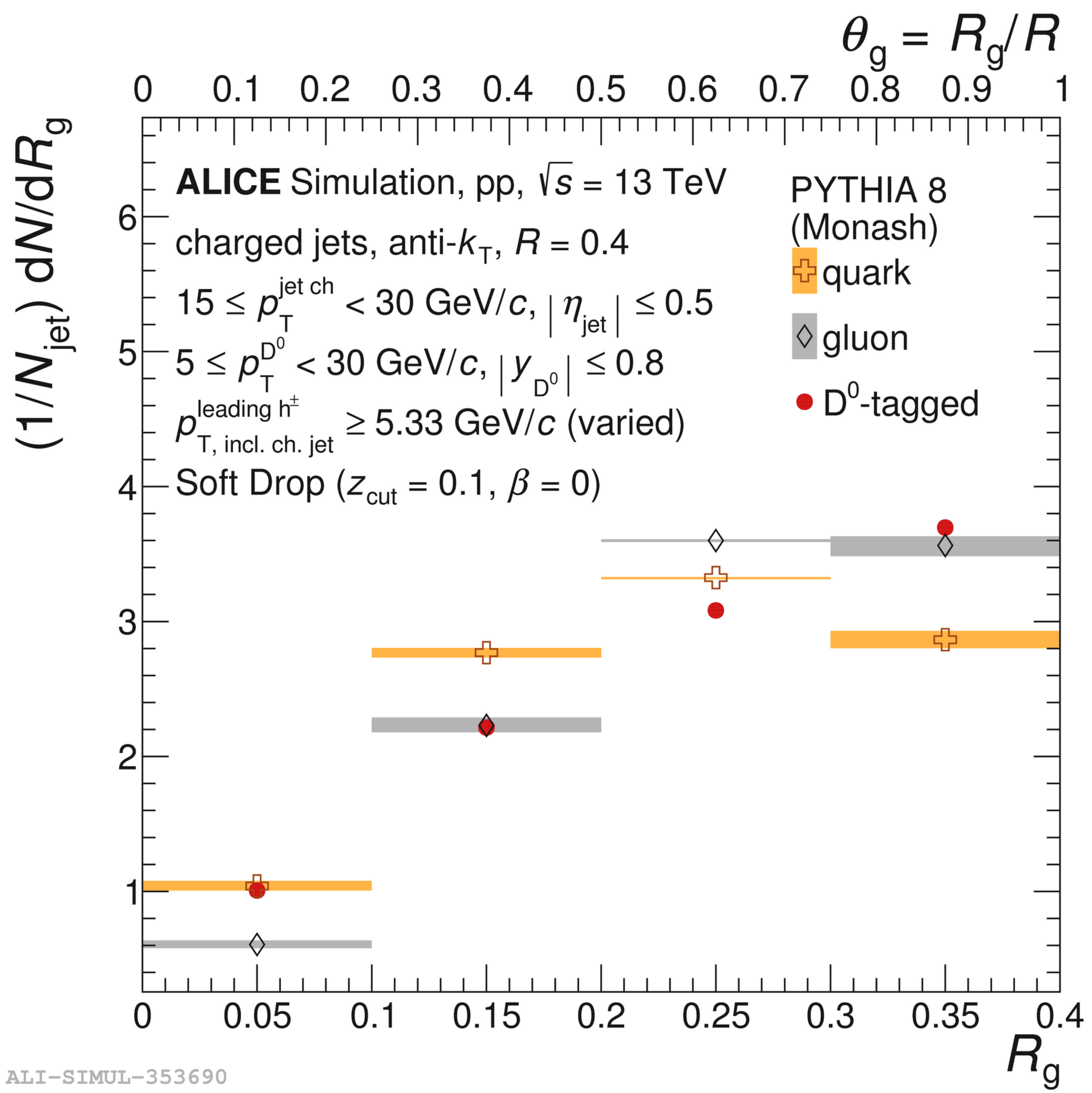
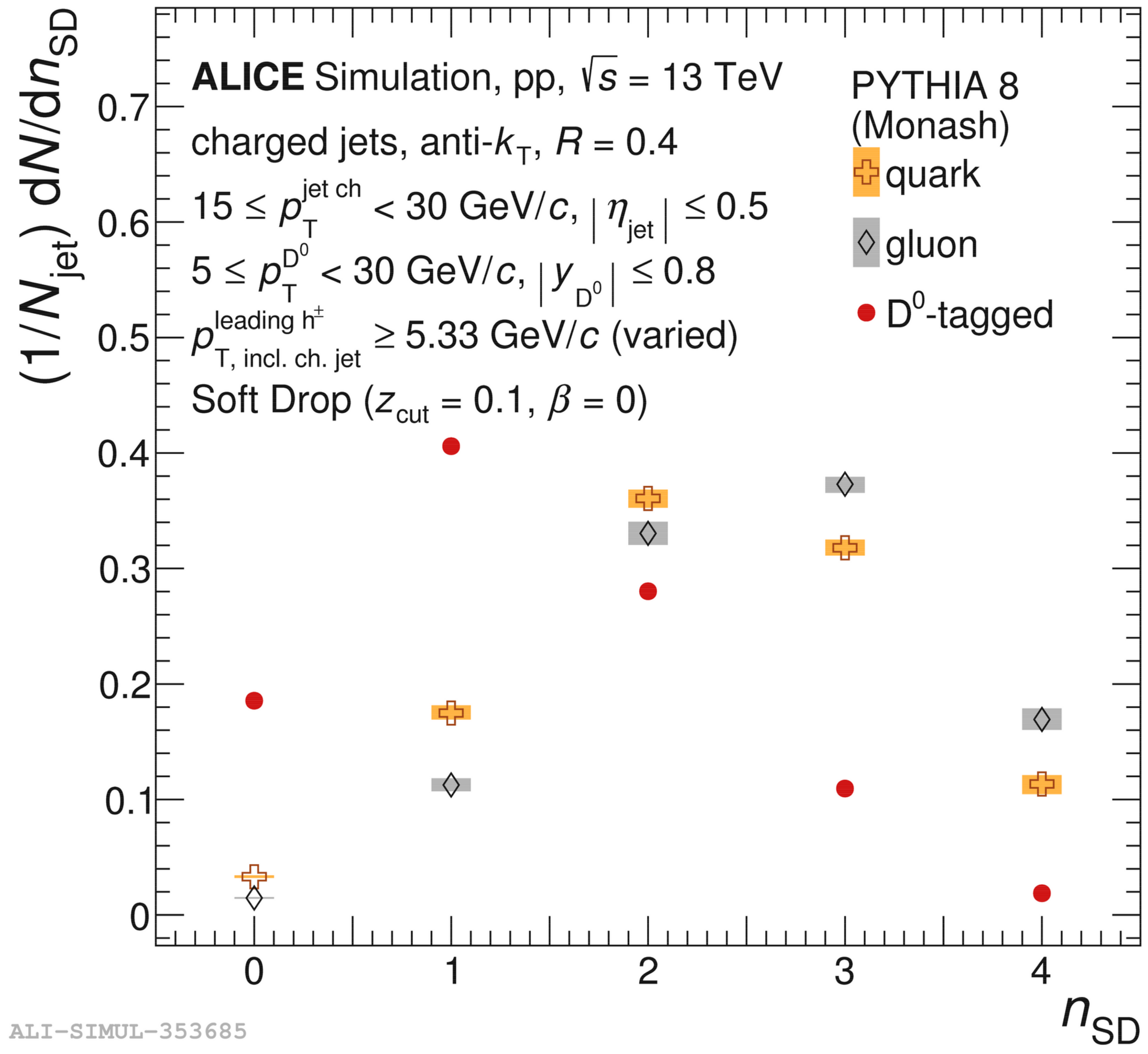
Comparison to PYTHIA

PYTHIA predictions for quark/gluon-jets





- **quark** vs **gluon** fragmentation: Casimir colour factors
- **charm** vs **(light)-quark** fragmentation: dead cone
- **charm** quarks exhibit harder fragmentation compared to inclusive jets

D^0-tagged-jet results: comparison with PYTHIA

PYTHIA 8 Monash tune describes the data well.

Inclusive-jet results: comparison with PYTHIA

Some discrepancies observed between PYTHIA 8 and inclusive jet measurement:
→better constraints on q vs g fractions in PYTHIA needed?

Conclusions

FIRST measurement of groomed charm-jet substructure in pp collisions

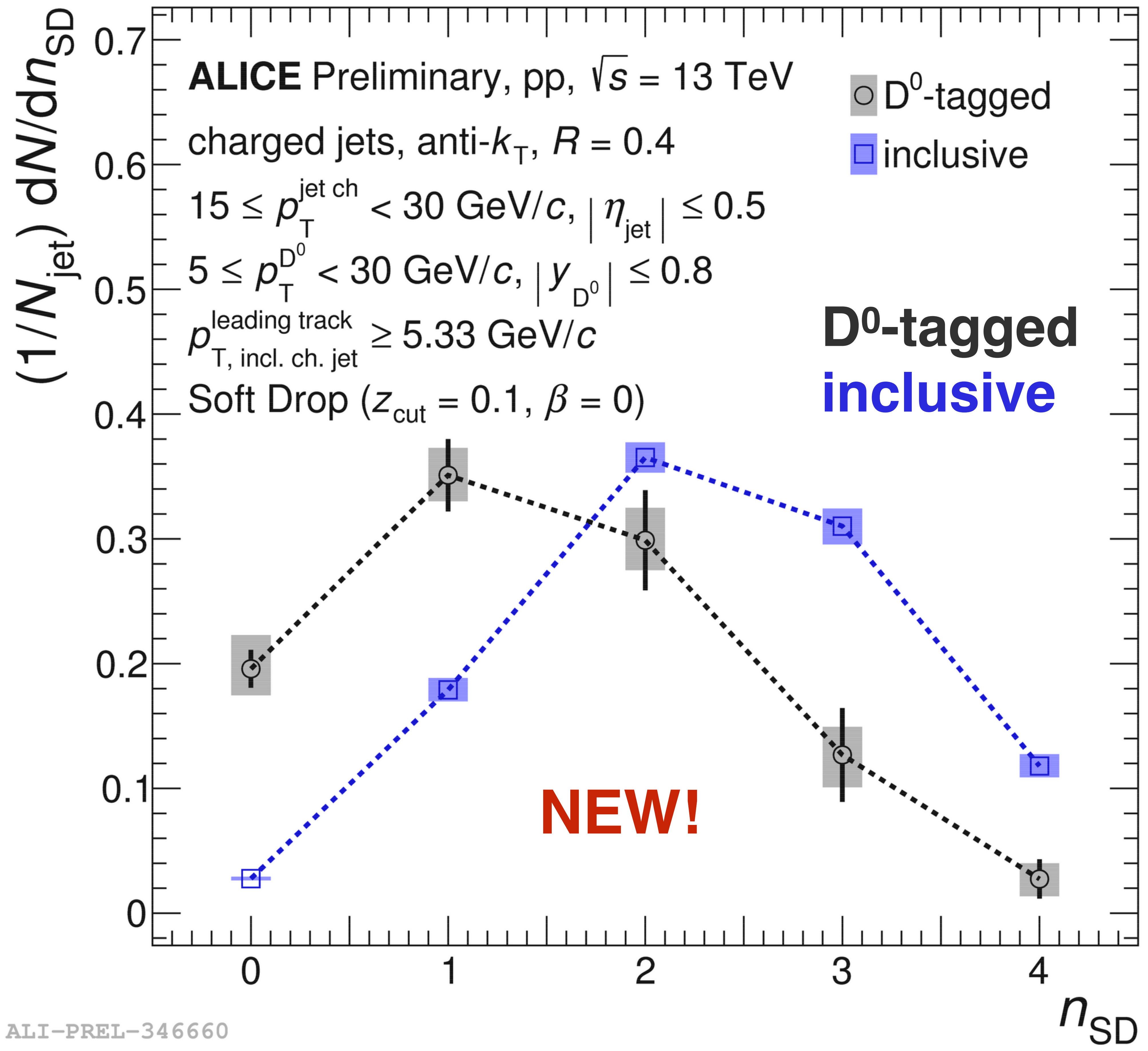
$15 < p_T^{\text{jet ch}} < 30$ GeV/c
$5 < p_T^{D} < 30$ GeV/c

D^0-tagged and inclusive jet measurement

- z_g , R_g, n_{SD}

Flavour dependence observed!

- **harder fragmentation of the charm quark** (compared to inclusive jets)
- well described by PYTHIA



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Flavour dependence observed!

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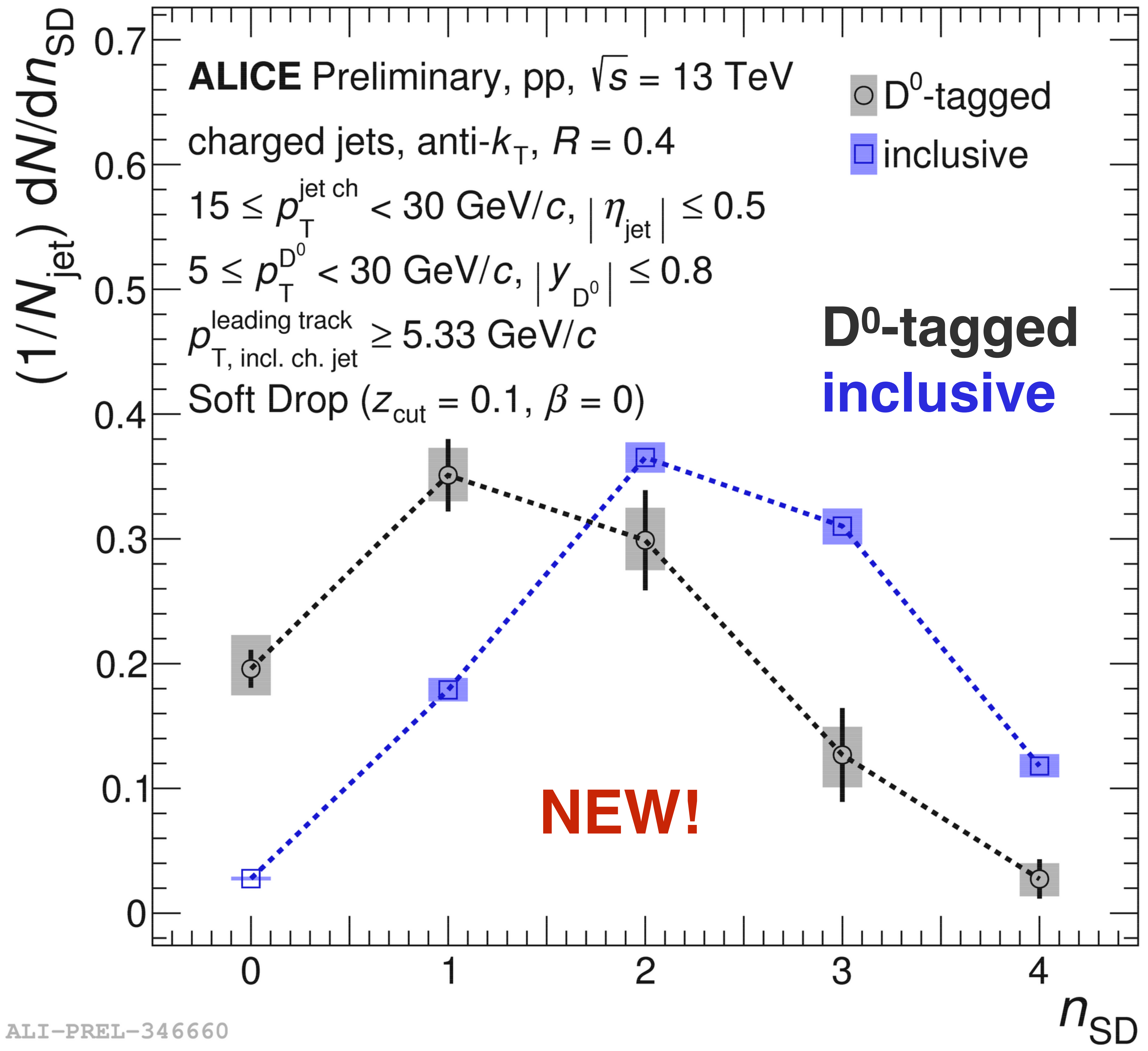
Future prospectives:

- **jet p_T scan**: evolving magnitudes of QCD effects (Casimir colour factors vs dead cone)
- **quark vs gluon fractions** via data-driven method
- baseline for **flavour-dependent E_{loss} in HI collisions**



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Conclusions

15 < $p_T^{jet\ ch}$ < 30 GeV/*c*
5 < p_T^D < 30 GeV/*c*

FIRST measurement of groomed charm-jet substructure in pp collisions

D^0-tagged and inclusive jet measurement

- z_g , R_g, n_{SD}

Flavour dependence observed!

- **harder fragmentation of the charm quark** (compared to inclusive jets)
- well described by PYTHIA

Future prospectives:

- **jet p_T scan**: evolving magnitudes of QCD effects (Casimir colour factors vs dead cone)
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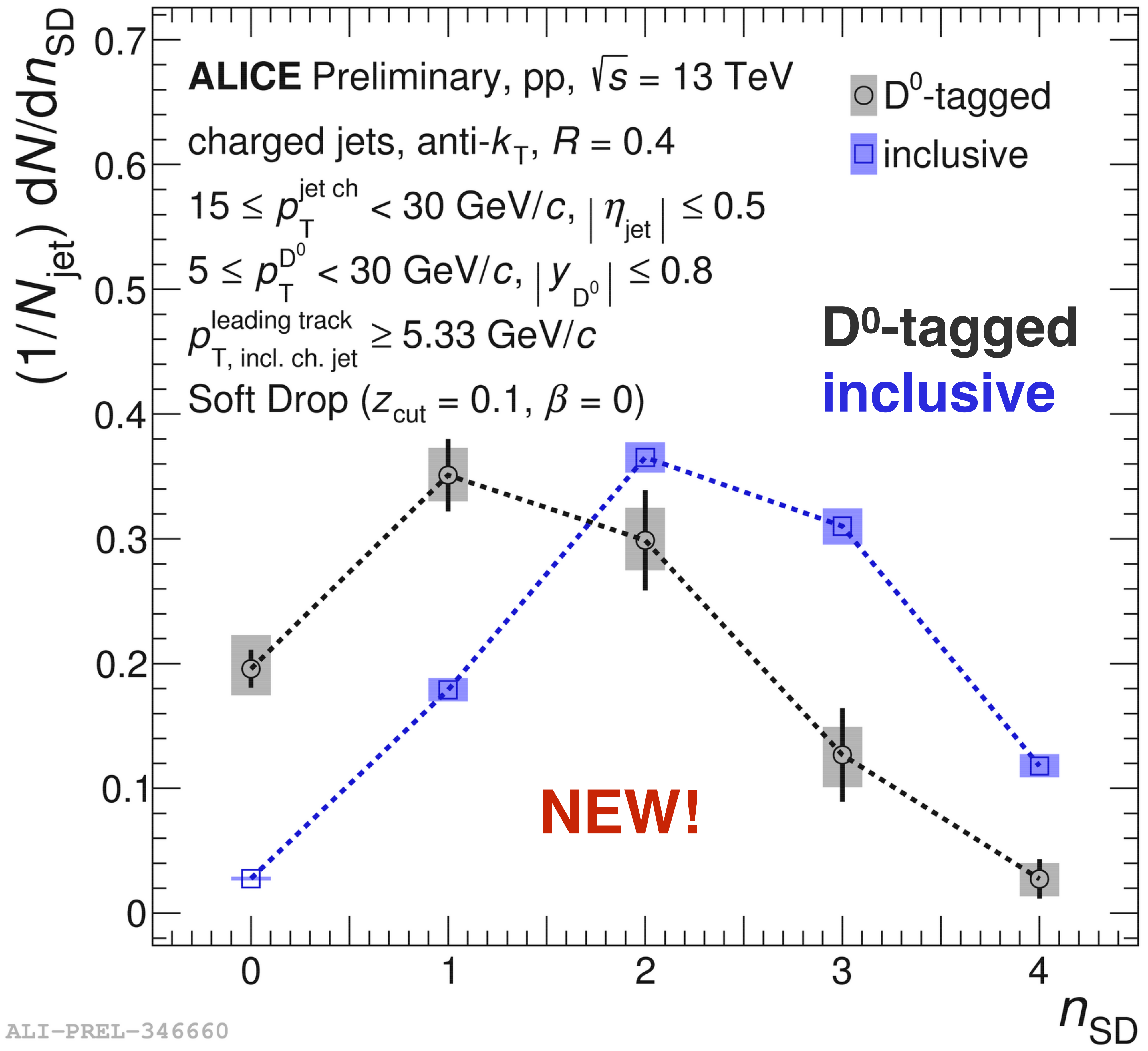

Thank you for your attention!

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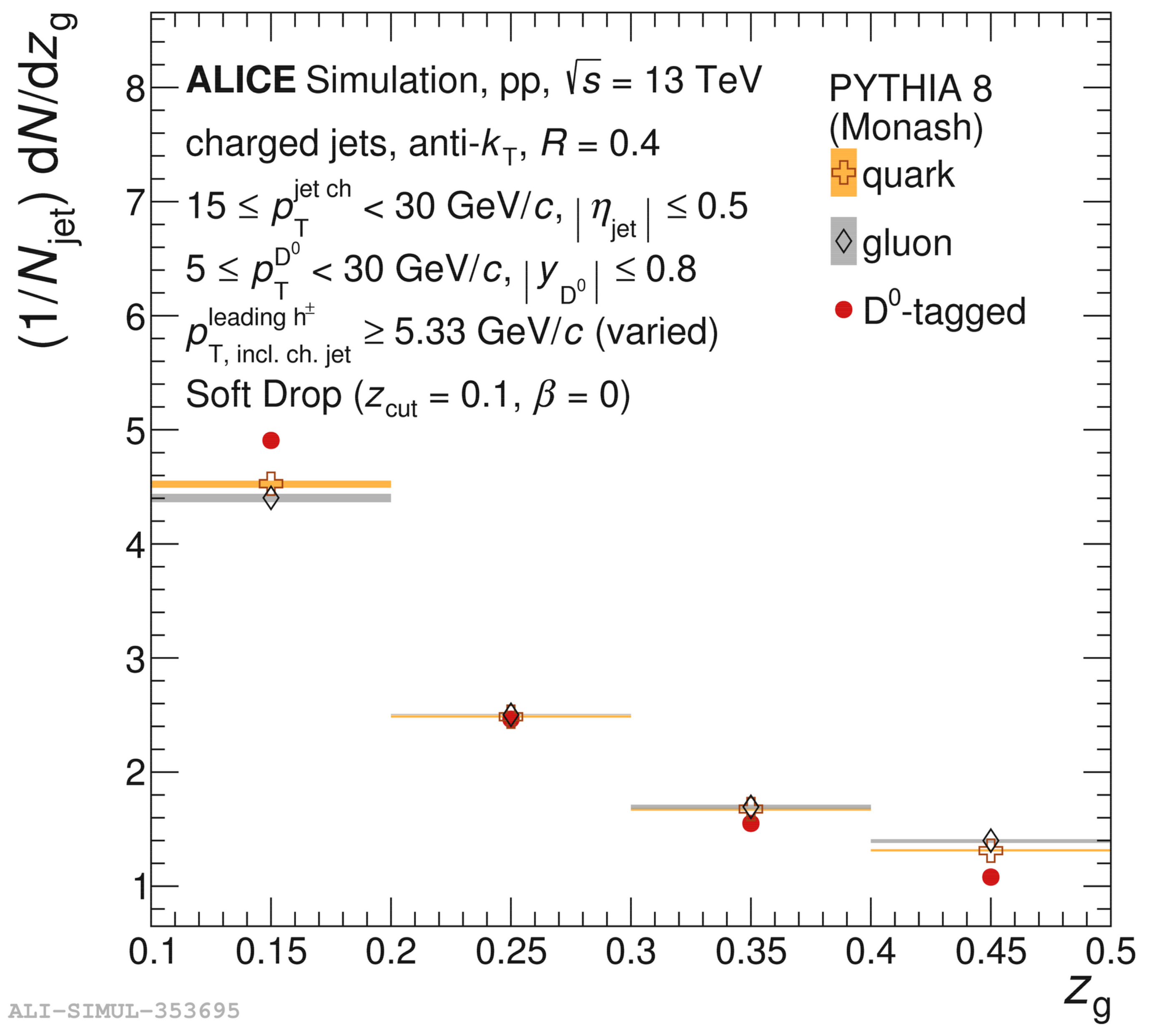
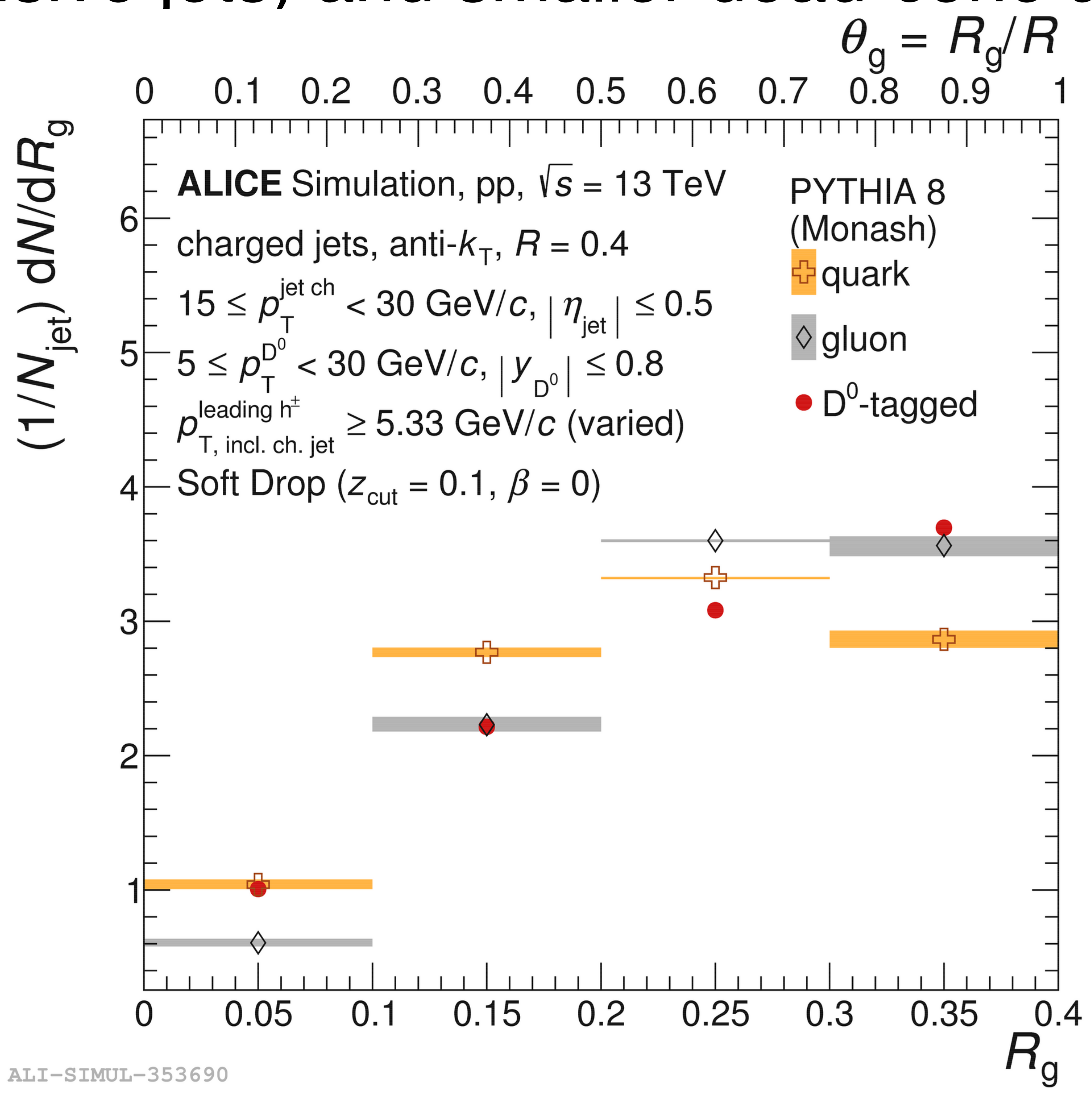
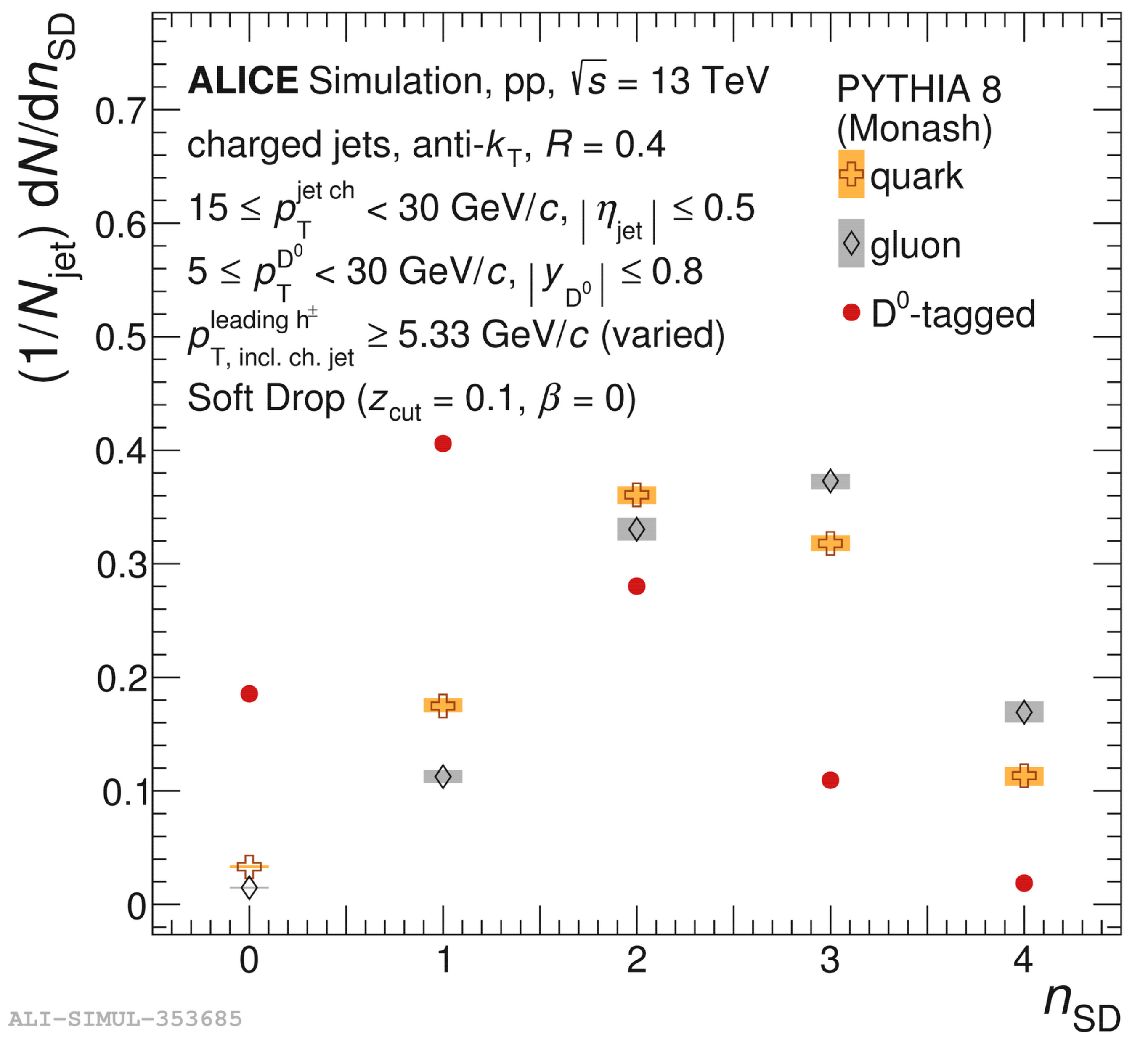
Backup

Model predictions for quark/gluon-jets

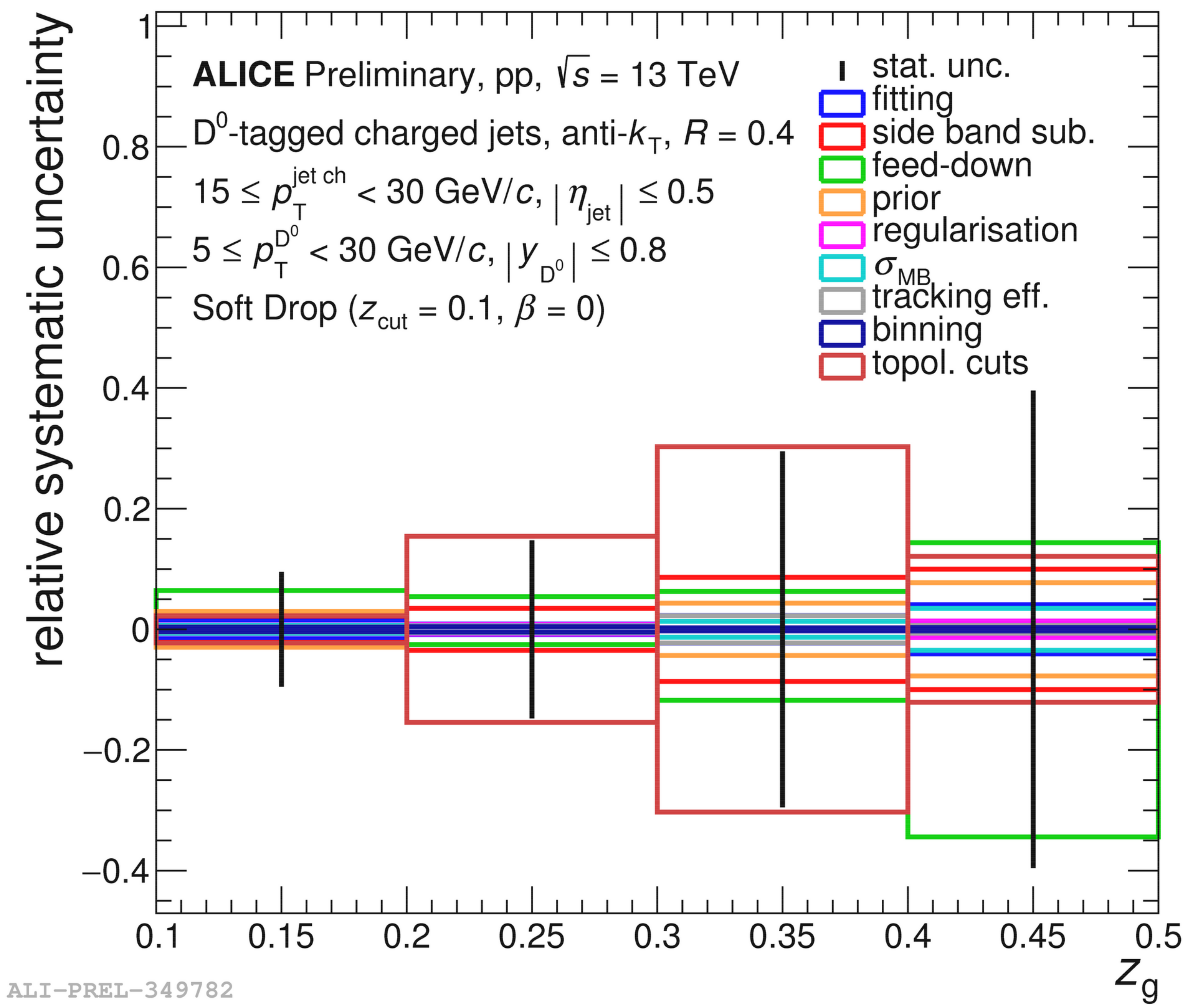
- PYTHIA calculations for gluon, quark and charm initiated jet substructure explored
- Gluon jets exhibit a softer and broader fragmentation compared to quark jets (**Casimir colour factors**)
- Charm jets appear broader than (light) quark jets, with a harder fragmentation (**dead cone effect**)
- The n_{SD} observable in particular shows a strong sensitivity to the QCD effects governing fragmentation
- In this kinematic regime, the inclusive jet yield is dominated by gluon jets
  - Increasing jet p_T can test different QCD effects:
    - Increasing quark jet fraction (inclusive jets) and smaller dead-cone angle (HF jets)







Systematic uncertainties



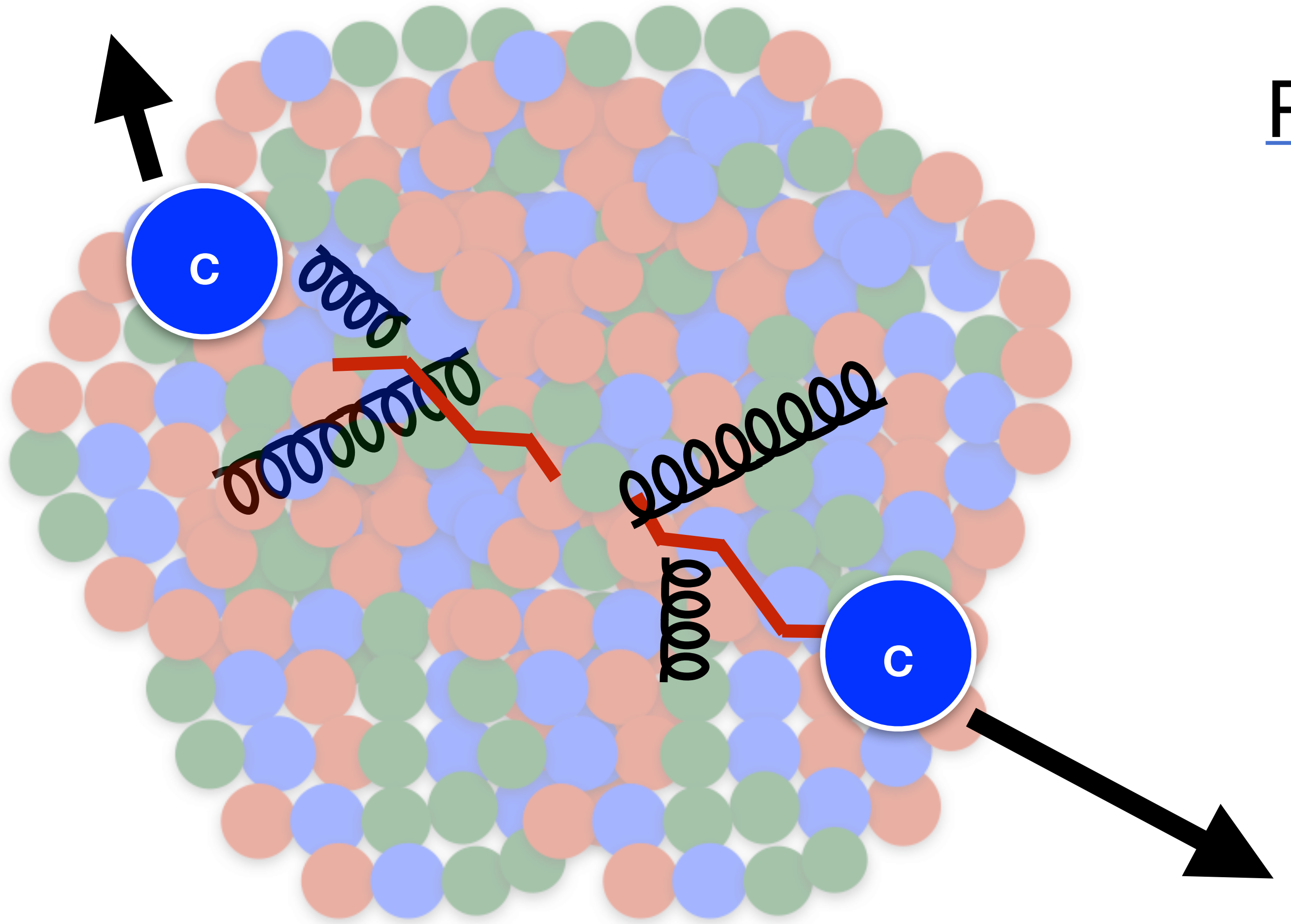
- D^0 signal extraction:
  - fitting -> inv. mass fitting params varied
  - sideband sub -> sideband and signal regions redefined
  - **selection cuts -> dominant effect**
- D^0 non-prompt subtraction:
  - **feed-down -> theoretically motivated uncertainties**
  - luminosity scaling
- Unfolding:
  - **tracking efficiency -> jet energy scale resolution**
  - binning
  - prior
  - regularisation -> choice of unfolding iteration

→Uncertainty per category estimated as RMS of deviations from the central values.
→Uncertainties from all categories combined in quadrature.

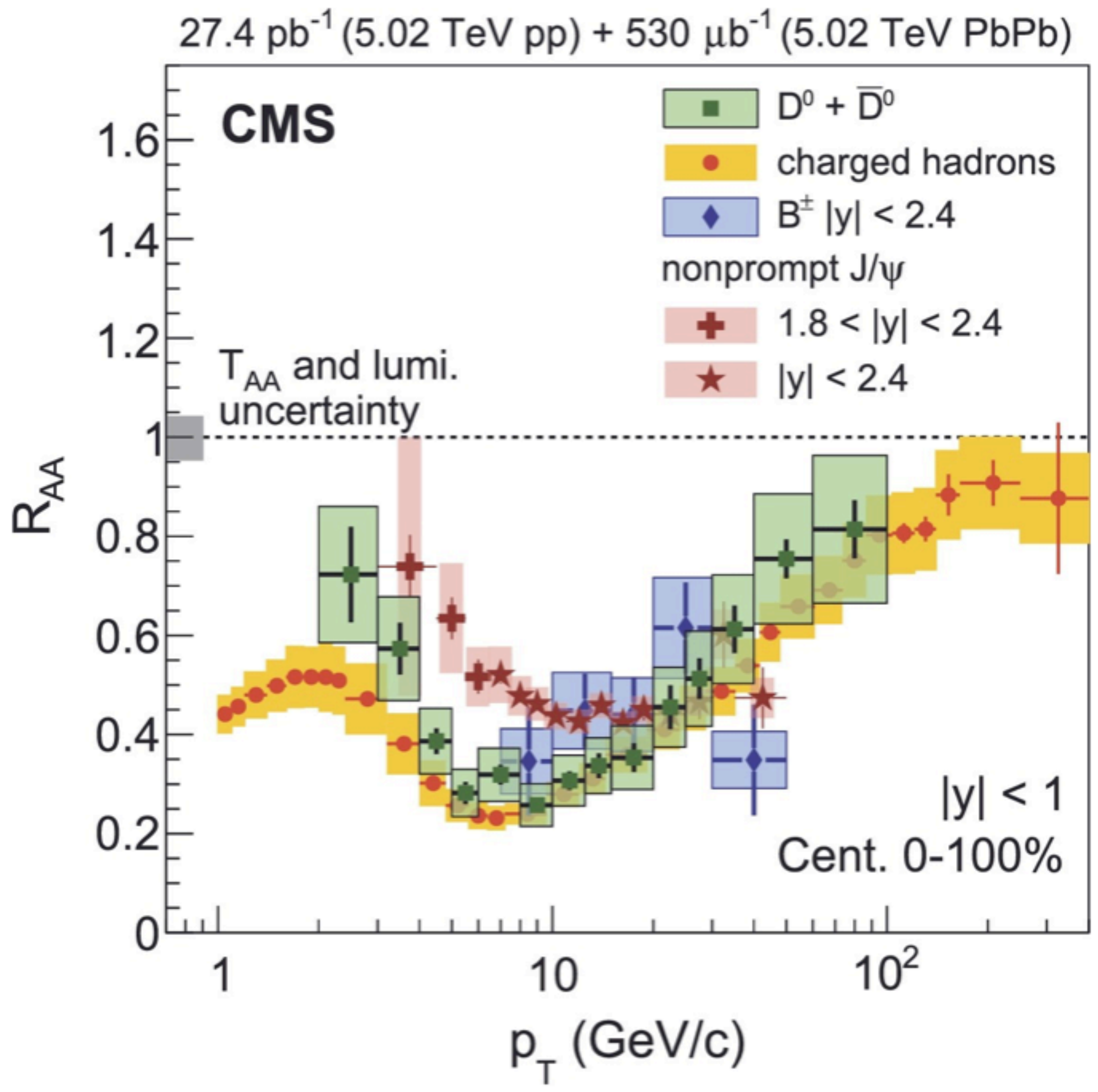
Results: comparison with predictions

Flavour dependence of E_{loss}

In-medium energy loss as a consequence of **radiative** and **collisional** processes.

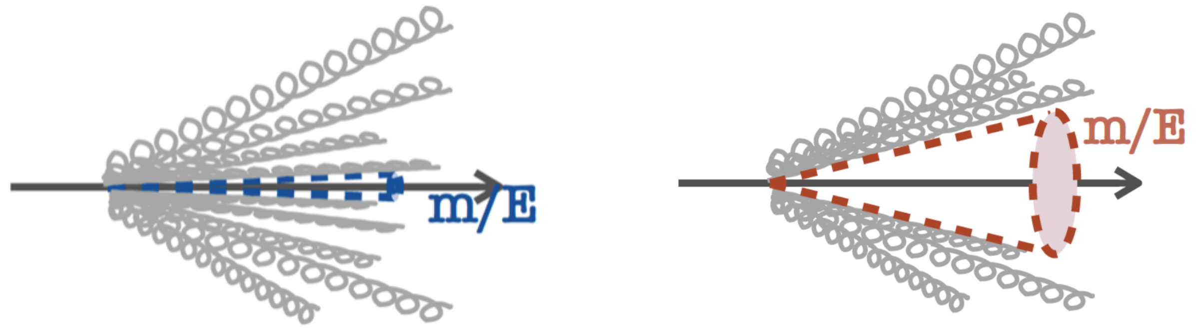


Phys. Lett. B 782 (2018) 474 et al.



Flavour dependence of radiative E_{loss}:

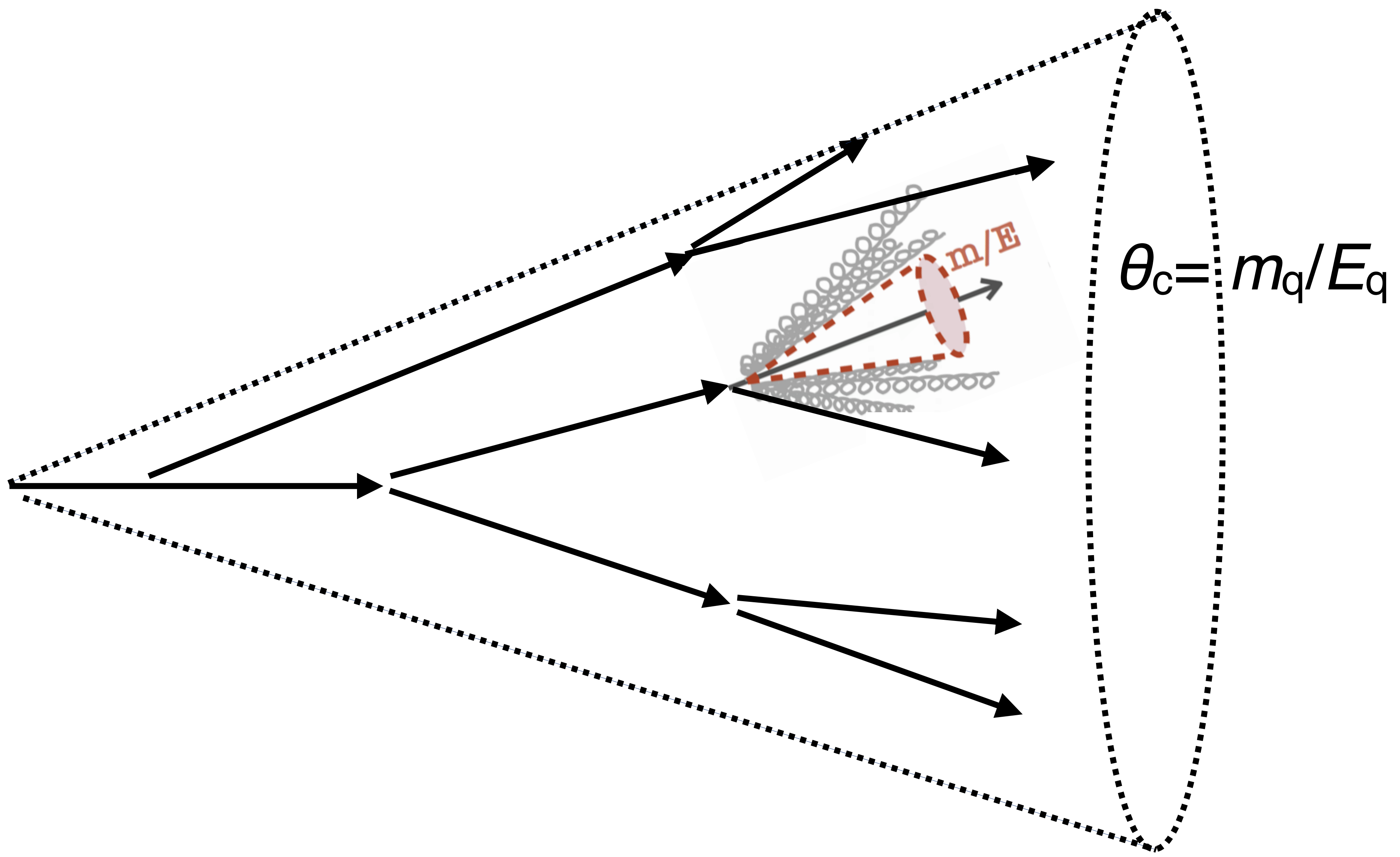
- **different Casimir factors** for quark and gluons $C_R = 3$ for gluons, $C_R = 4/3$ for quarks
- **dead cone effect:**



→ **E_{loss} (gluon) > E_{loss} (charm) > E_{loss} (beauty)**

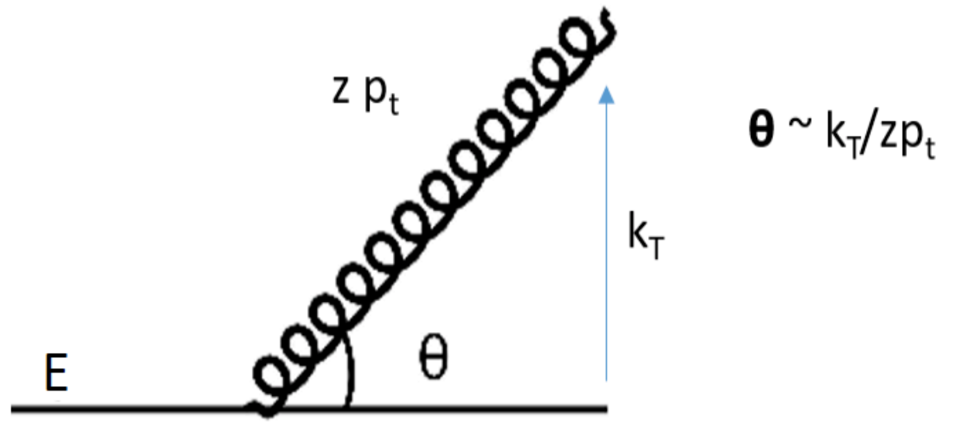
Indication of a milder suppression for **b→J/ψ** (b-quark energy loss) compared to prompt **D meson** at mid p_T

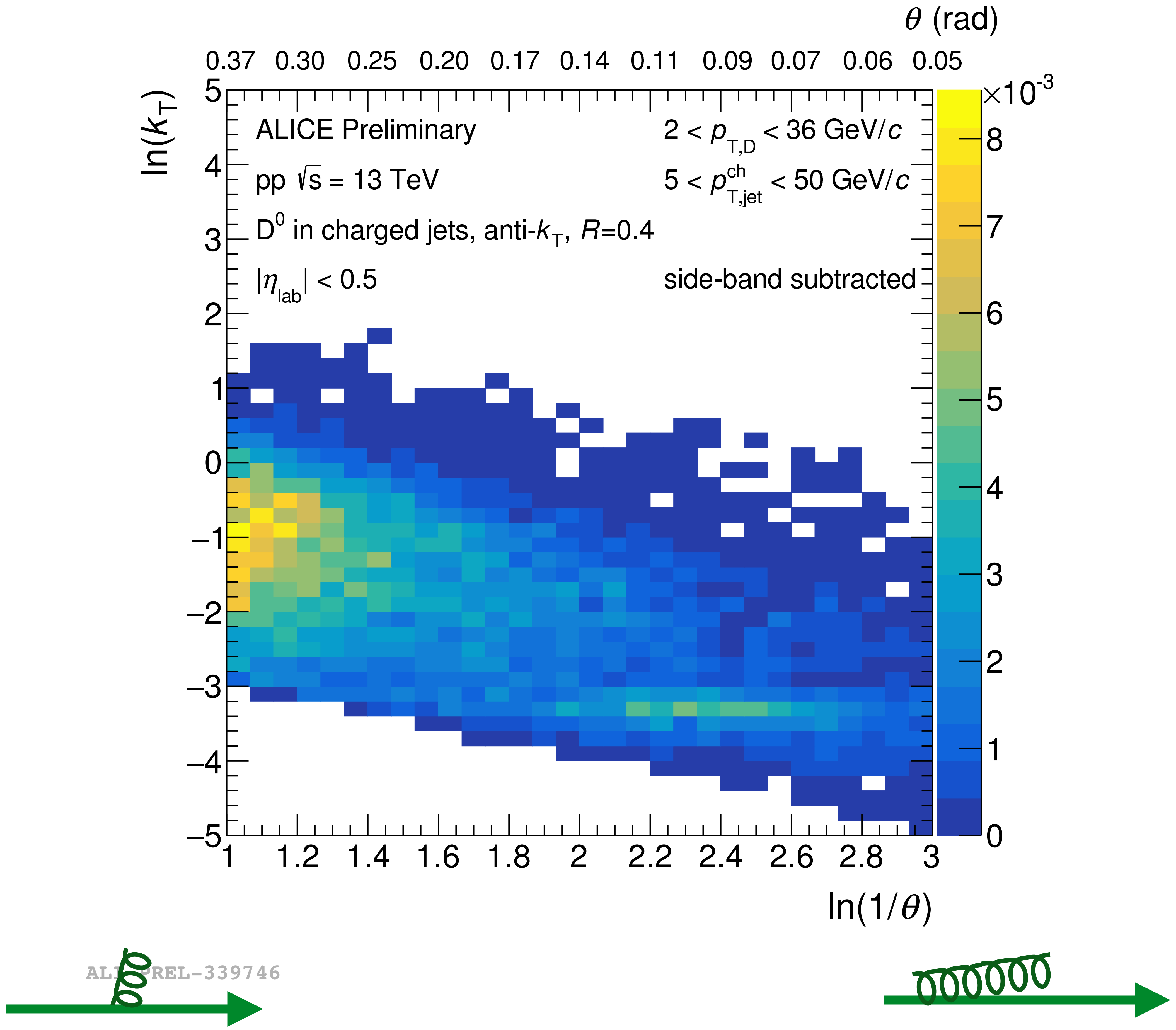
HF jets to test QCD predictions: dead cone effect



Dead cone: suppression of small angle radiation for heavy quarks.
→**Fundamental QCD effect never observed at colliders directly**

For both inclusive and charm jets:
- Iterative declustering with C/A - access to each splitting
- Fill a Lund plane with θ, k_T of each splitting
- project in θ





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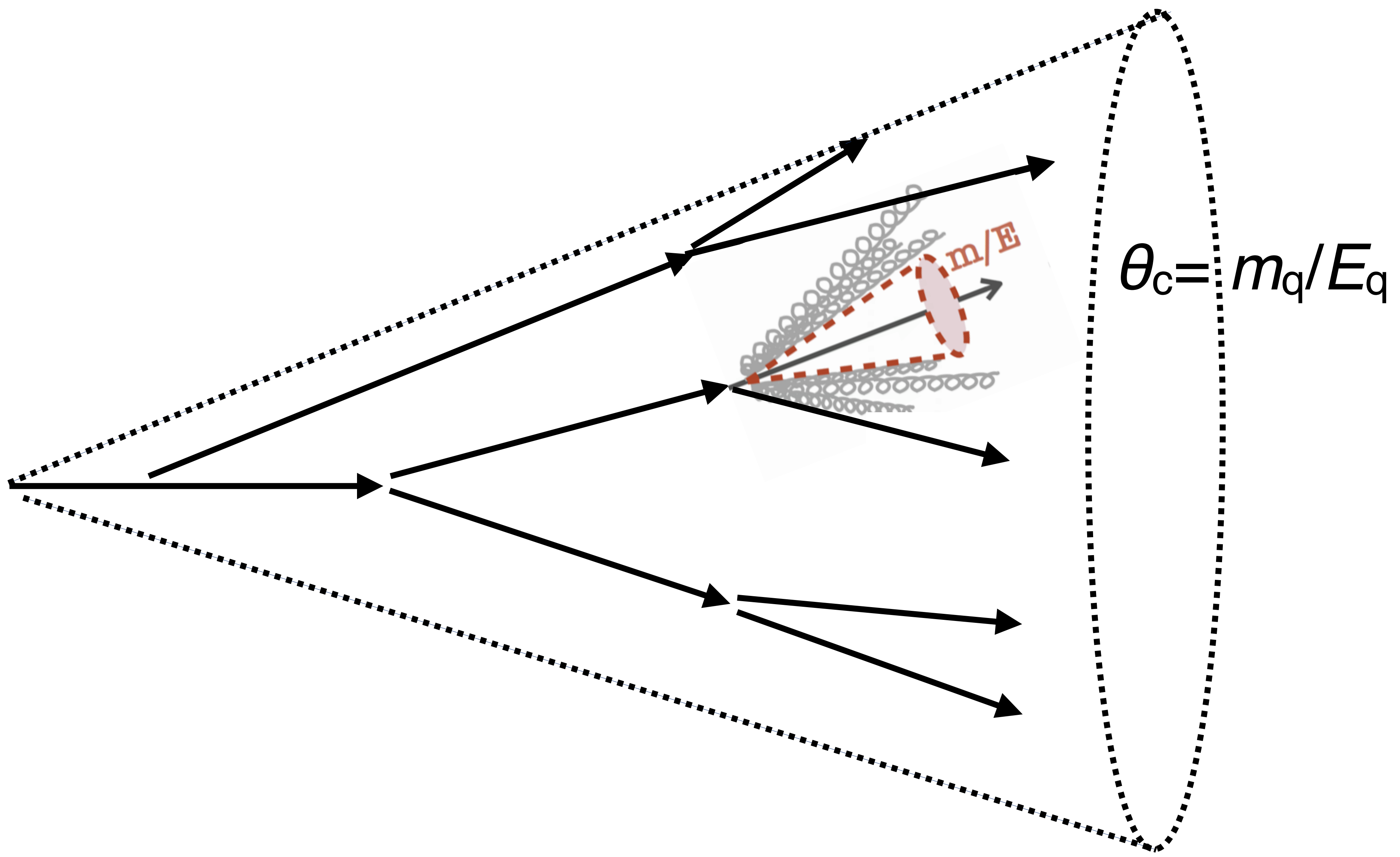

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J. Phys. G17, 1602–1604 (1991).

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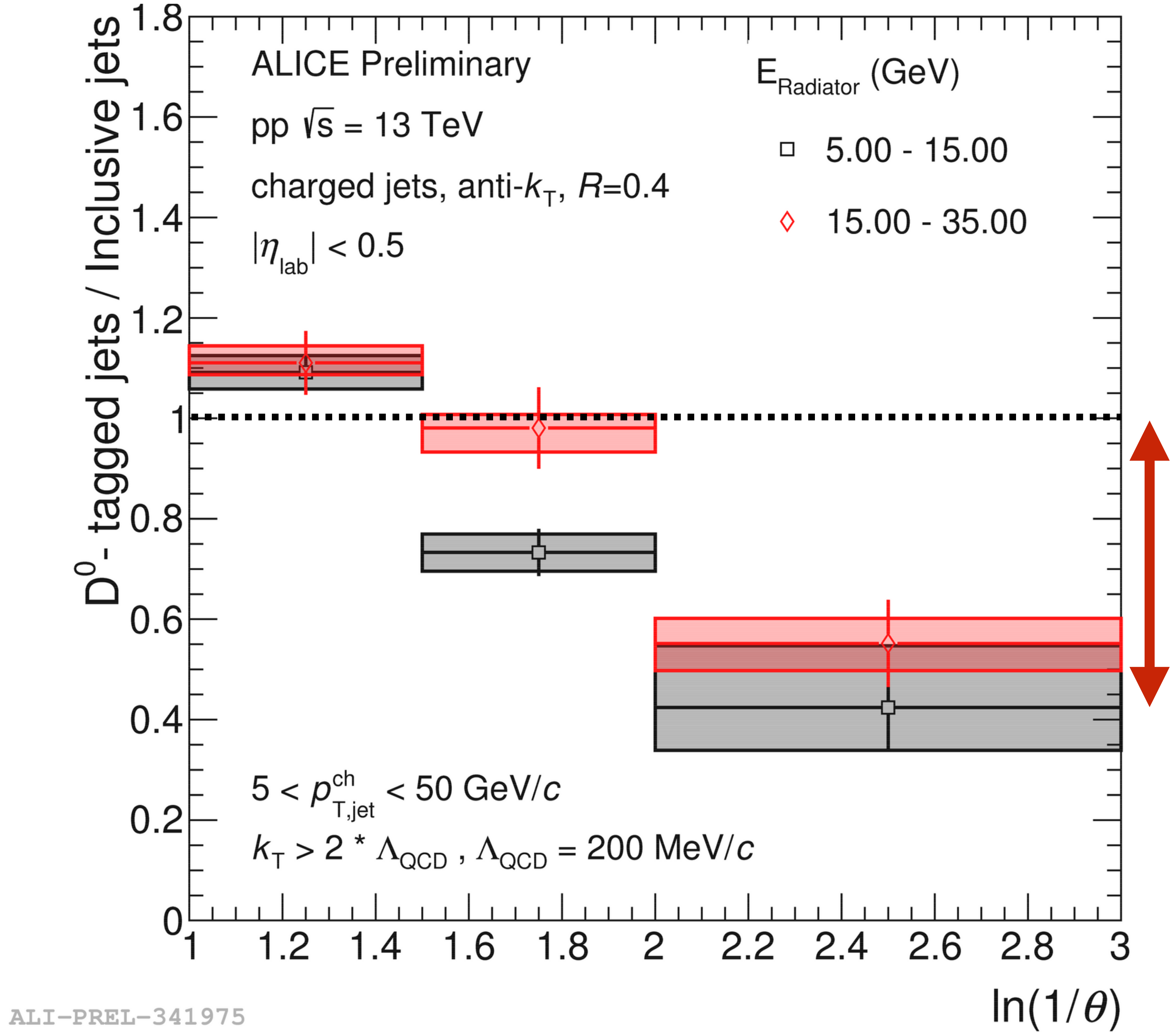
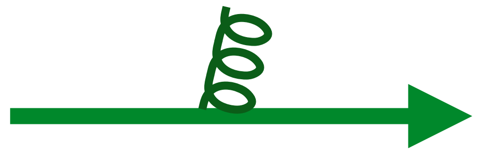
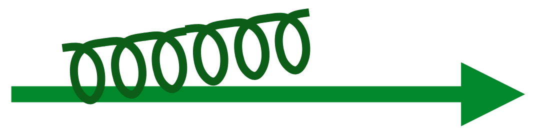
ratio of D⁰-tagged / inclusive jet distributions







→Evidence of suppression of small angle radiation for D^0-tagged jets
"dead-cone effect"