Testing perturbative QCD calculations with charm-tagged jets and correlations of charm hadrons with charged particles

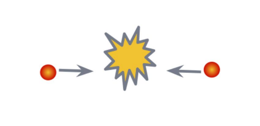
Samuele Cattaruzzi*
on behalf of the ALICE Collaboration

*University of Trieste and INFN, Trieste (Italy)

Heavy-flavour hadron production

Charm quark mass ~1.3 GeV/c^2, **beauty quark** mass ~4.2 GeV/c^2
→ produced in **hard parton-parton scattering** processes in hadronic collisions

- Perturbative QCD test
- Hadronisation
- Reference for Pb-Pb



Heavy-flavour hadron production cross section calculated using a **factorisation approach**:

$$\frac{d\sigma^{\mathrm{H_c}}}{dp_{\mathrm{T}}}(p_{\mathrm{T}};\mu_{\mathrm{F}},\mu_{\mathrm{R}}) = \mathrm{PDF}(x_1,\mu_{\mathrm{F}}) \otimes \mathrm{PDF}(x_2,\mu_{\mathrm{F}}) \otimes \frac{d\sigma^{\mathrm{c}}}{dp_{\mathrm{T}}^{\mathrm{c}}}(p_{\mathrm{T}};\mu_{\mathrm{F}},\mu_{\mathrm{R}}) \otimes D_{\mathrm{c}\to\mathrm{H_c}}(z = p_{\mathrm{H_c}}/p_{\mathrm{c}},\mu_{\mathrm{F}})$$

Parton Distribution Functions

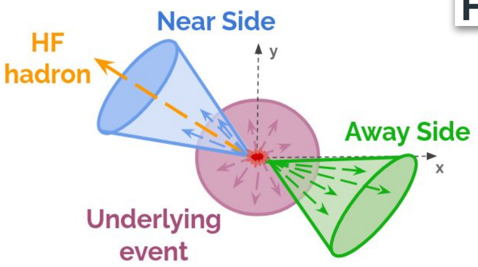
Hard scattering cross section (pQCD)

Fragmentation functions (hadronisation)

Assumed **universal** across collision systems (ee,..., AA)

Towards a better understanding of charm-quark hadronisation

- **Azimuthal correlations** of **charmed hadrons** with **charged particles**
  - Multidifferential investigation of fragmentation processes
  - Characterisation of jet shape and particle composition



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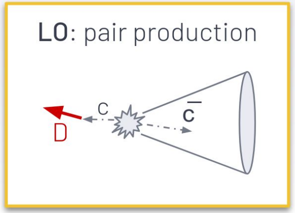
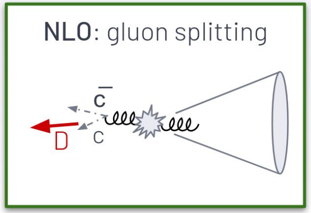
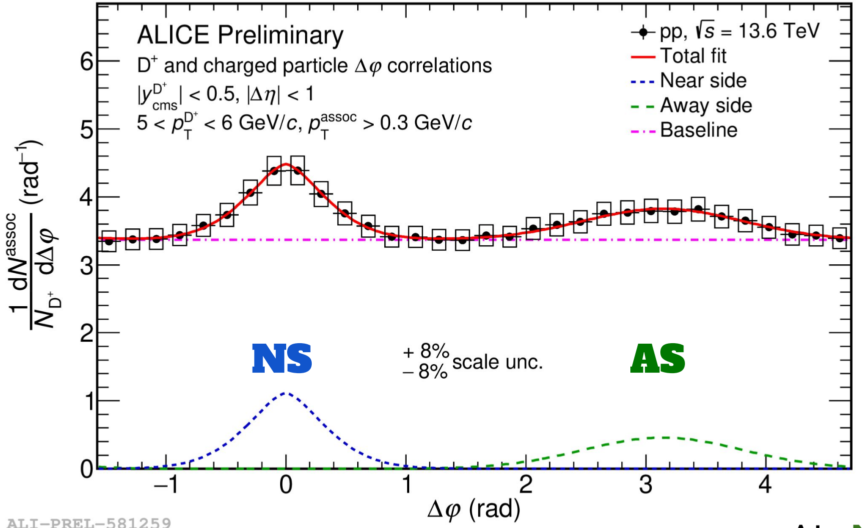






ALI-PREL-581259

Maolin Zhang's poster, Wed, T05, 19:23

- At **LO** approximation
  - **Near Side (NS)**: fragmentation of the tagged charm quark
  - **Away Side (AS)**: fragmentation of the recoil charm quark
  - **Baseline**: parametrizes the underlying event activity, assumed to be isotropic
- At **NLO**: production mechanisms, relevant at the LHC energies, can alter this topology

Towards a better understanding of charm-quark hadronisation

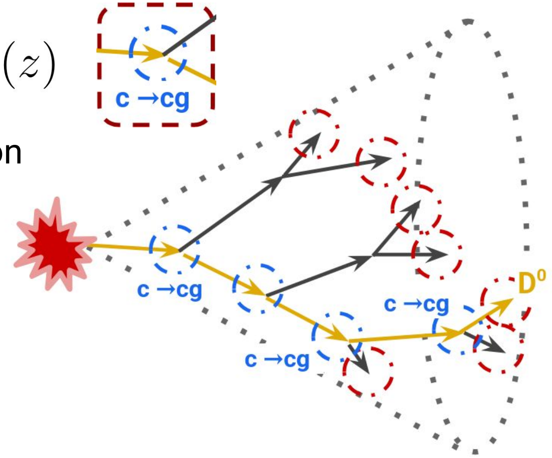
- **Charm tagged jets**
  - ➢ Provide access to the original parton kinematics
  - ➢ Constrain the charm fragmentation function
  - ➢ Probe the charm splitting function

Soft Drop algorithm:

- Remove soft, wide-angle radiation from jets

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

1 → 2 QCD splitting function



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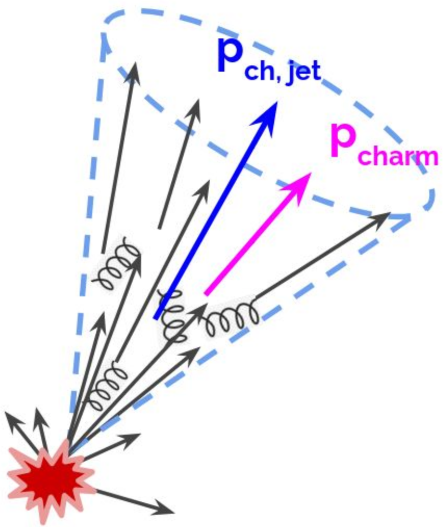

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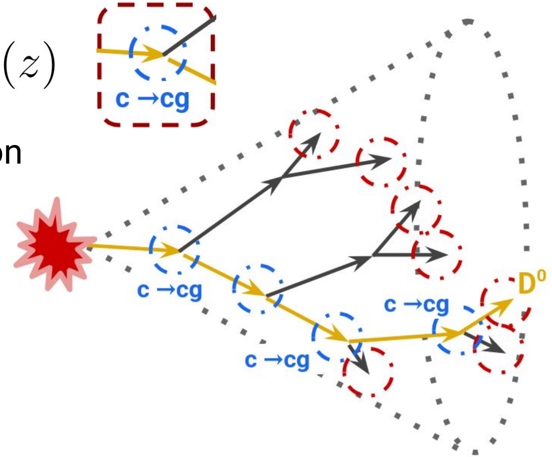
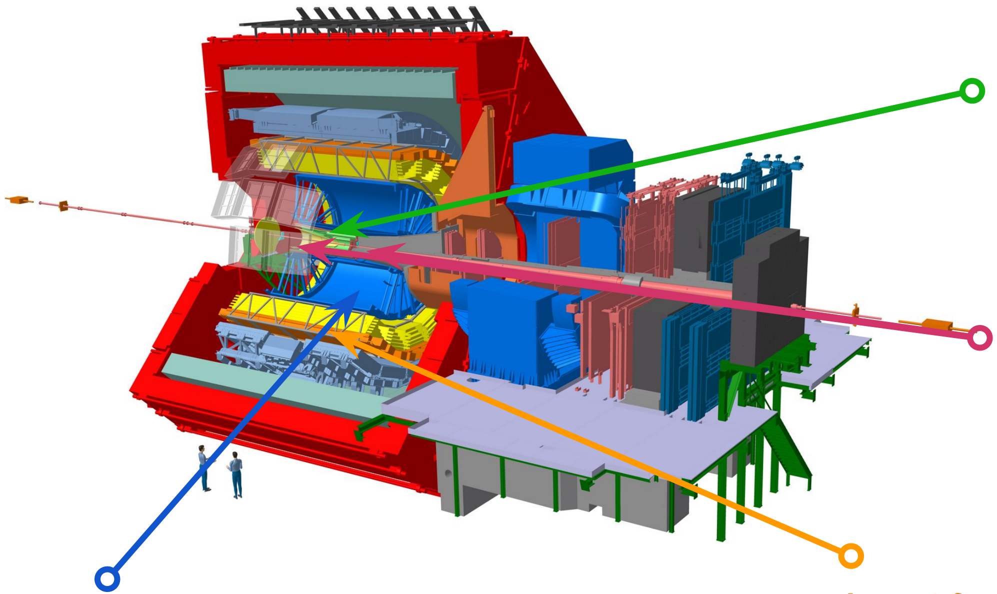


Longitudinal momentum fraction

$$z_{||} = \frac{\vec{p}_{\mathrm{ch,\ jet}} \cdot \vec{p}_{\mathrm{HF}}}{\vec{p}_{\mathrm{ch,\ jet}} \cdot \vec{p}_{\mathrm{ch,\ jet}}}$$

The ALICE detector in Run 3



Inner Tracking System (ITS) upgrade

- 🔧 7-layer pixel detector, based on MAPS
- 🔧 First layer closer to IP w.r.t. Run 2 (22.4 mm)
- ❏ Improved vertexing performance (×2-5 better impact-parameter resolution)

New Fast Interaction Trigger (FIT)

- ❏ Initial indicator of the vertex position, and forward multiplicity counter

Time Projection Chamber (TPC) upgrade

- 🔧 GEM-based readout pads (continuous readout and higher interaction rate up to a factor ×500-1000 in pp)
- ❏ Main detector for tracking, Particle Identification (PID) (dE/dx)

Time-Of-Flight detector (TOF)

- ❏ PID through time of flight

Higher interaction rate → larger luminosity collected.

MB pp collisions:

Run 2: $\mathcal{L}_{\text{int}}$ = 32 nb^{-1}

Run 3: $\mathcal{L}_{\text{int}} \approx$ 7 pb^{-1}

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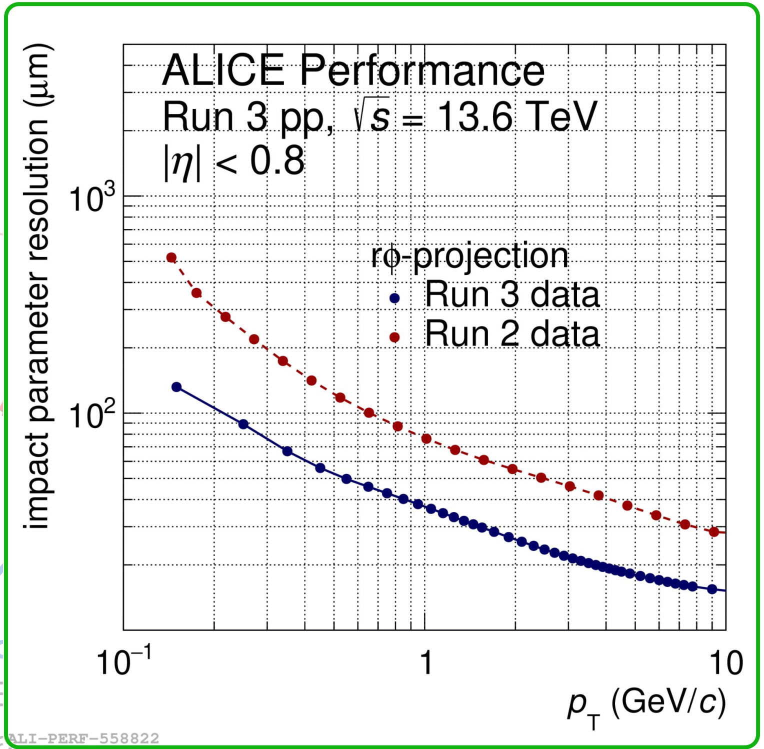

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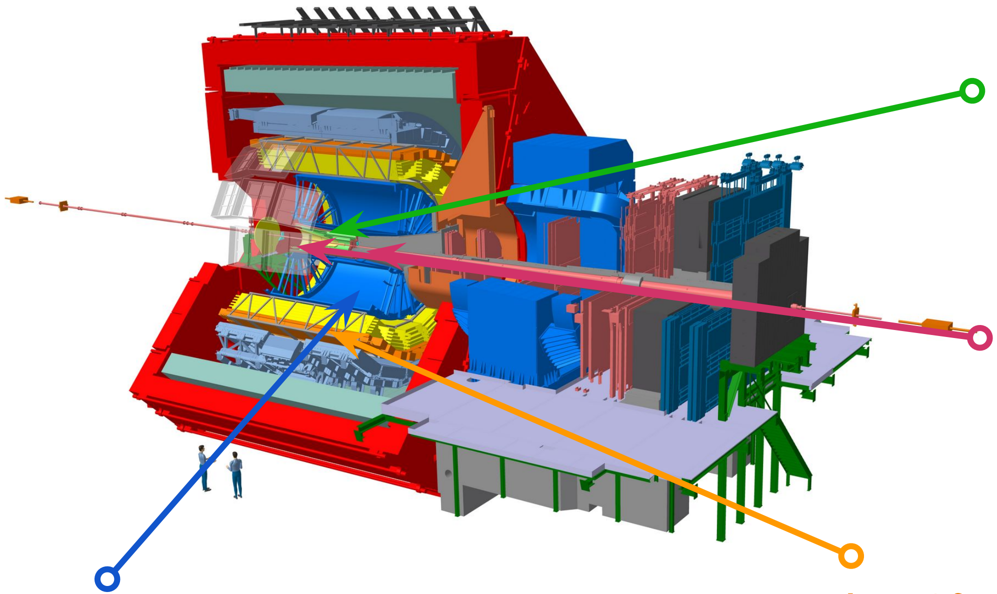

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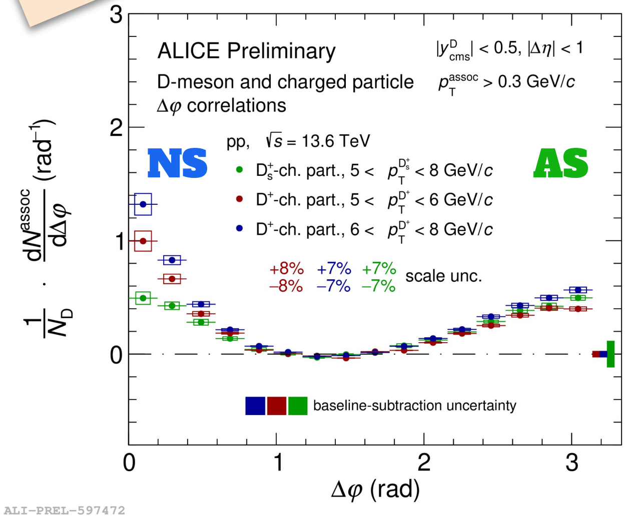
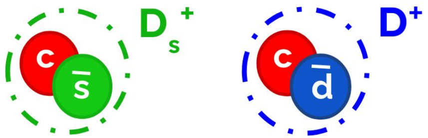
D-charged particles azimuthal correlations

NEW!





Comparison of the **Δφ shape** between the **D_s^+-ch. part.** and **non-strange D-ch. part. (pp @ 13.6 TeV)** correlation measurements:

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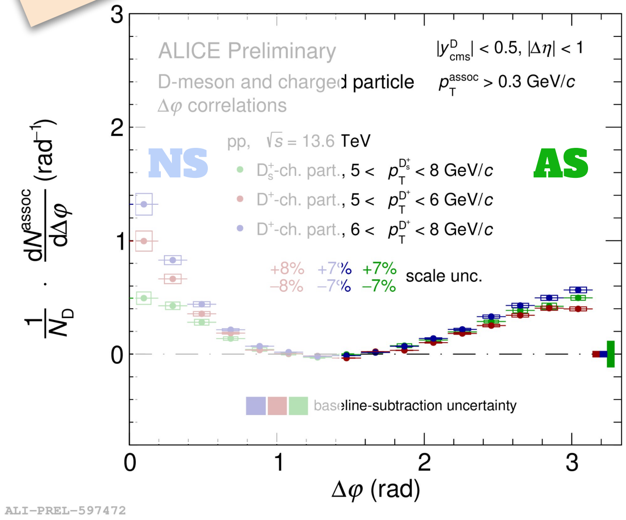

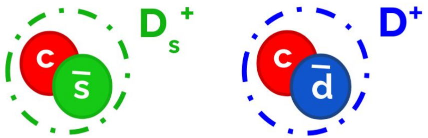

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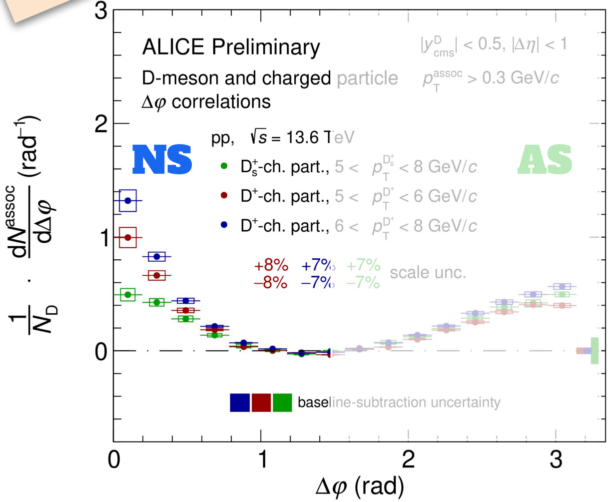
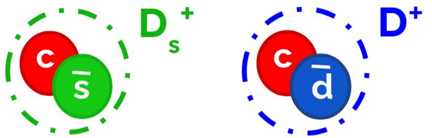
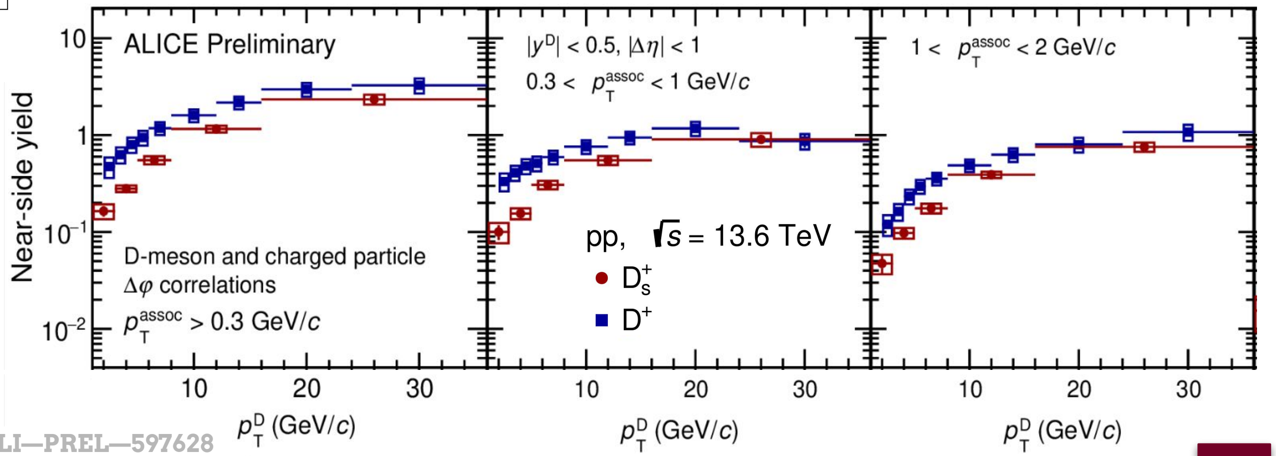


ALI-PREL-597472

Comparison of the **Δφ shape** between the **D_s^+-ch. part.** and **non-strange D-ch. part.** **(pp @ 13.6 TeV)** correlation measurements:

- **Away Side (AS)**: **good agreement** over the whole p_T range
- **Near Side (NS) yield**: D_s^+-meson associated particle yield **systematically lower** than that of non-strange D mesons





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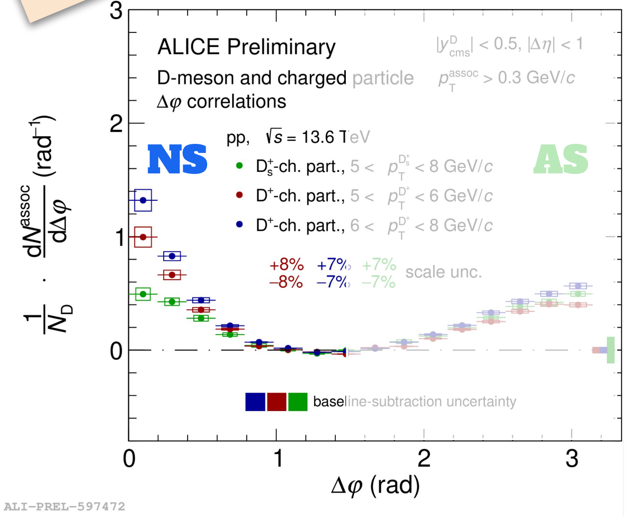
NEW!

D-charged particles azimuthal correlations



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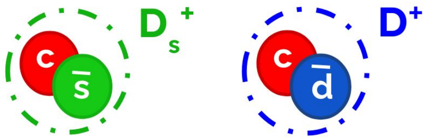

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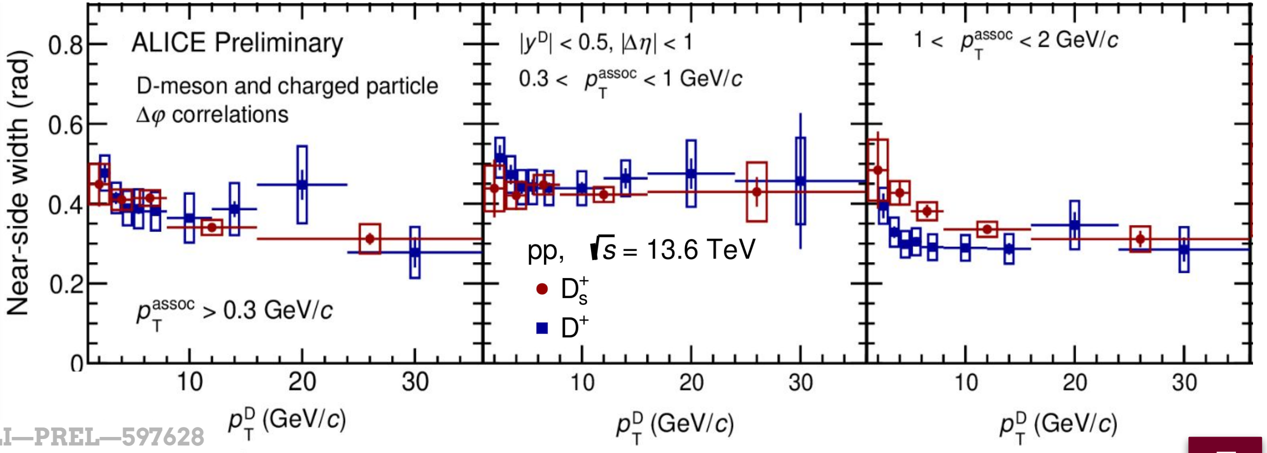
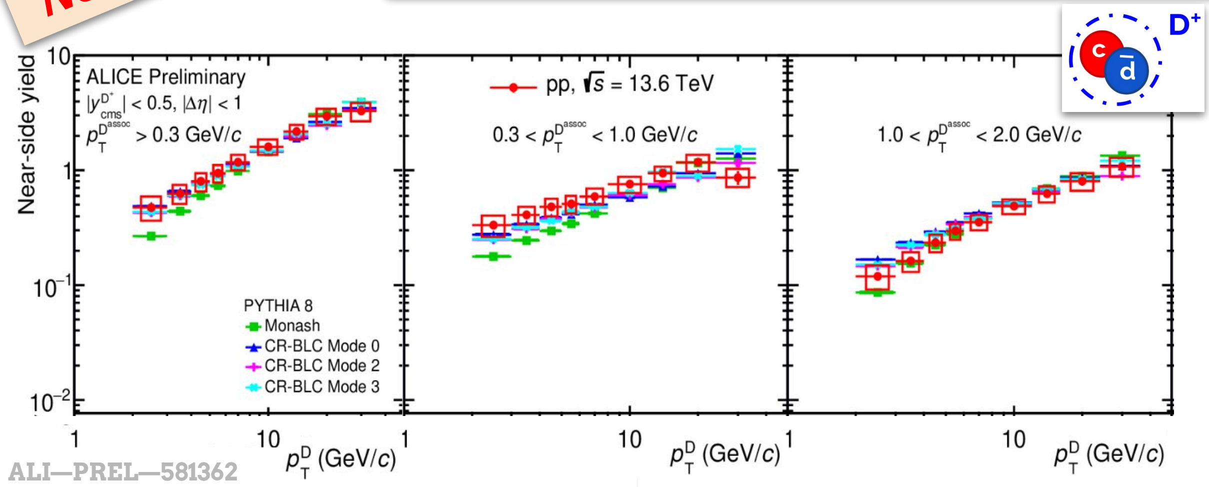


NEW!

Comparison with models



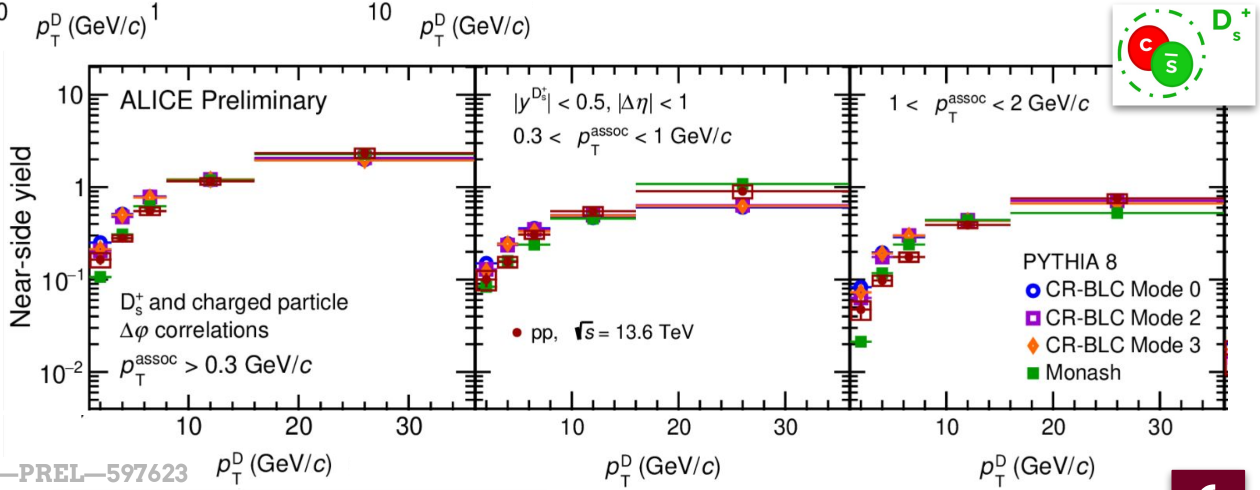
- Validation of parton-shower models and Monte Carlo generators

📒 **PYTHIA 8 CR-BLC** (JHEP 1508 (2015) 003)

📘 **PYTHIA 8 Monash** (EPJC 74 (2014) 3024)

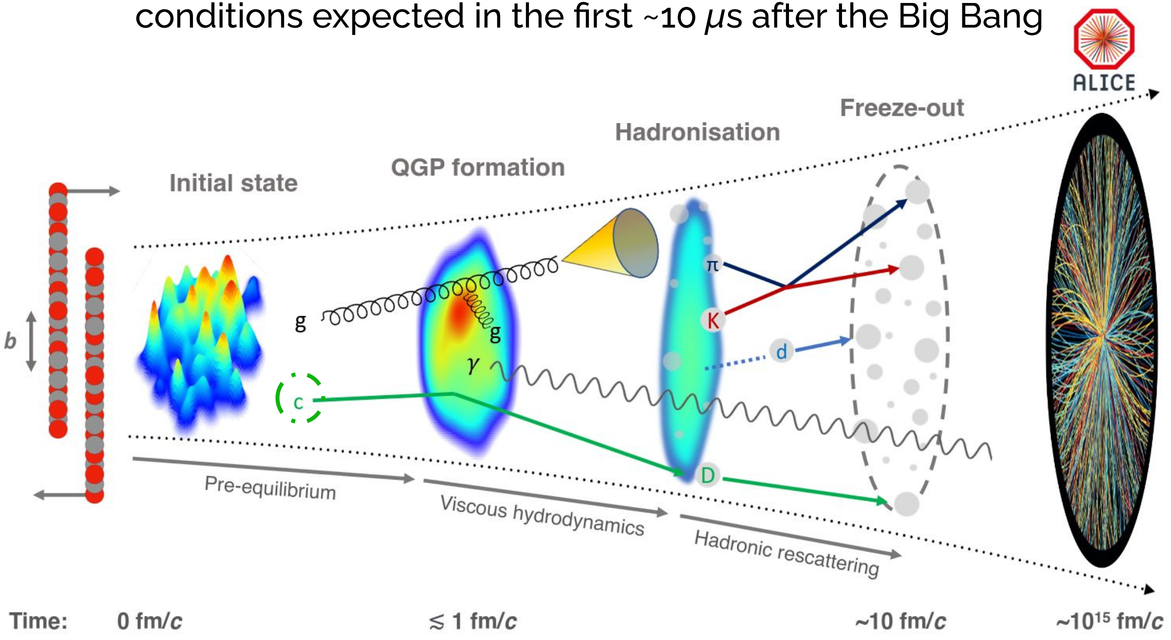
- **PYTHIA 8 CR-BLC** tunes provides a good description of the **NS yield** dependence on p_T

- **PYTHIA 8 Monash** underestimates the **NS yield** at low p_T^D and low p_T^{assoc}



Outlook: D-charged particles correlation in Pb–Pb

- In **heavy-ion** collisions:
  - **Quark-gluon plasma (QGP)**:
    - ➢ Colour-deconfined state of matter predicted by lattice QCD in ultrarelativistic heavy-ion collisions
    - ➢ Formed at extremely high temperatures and/or energy densities, similar to the conditions expected in the first ~10 μs after the Big Bang



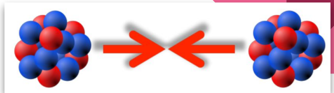
- **Heavy quarks** are produced via hard scatterings before the QGP formation:
  - ➢ Experience the full evolution of the system

Outlook: D-charged particles correlation in Pb–Pb

- **Characterisation of QGP properties** via D-charged particle azimuthal correlations:
  - 🔎 **Charm-quark energy loss** through the interaction with the medium and impact on peak features
  - 🔎 Observation of **jet quenching** through parton energy loss on the away-side

- Modification of charm-quark hadronisation

📌 **Additional challenge (w.r.t. pp)** : proper removal of the flow contribution



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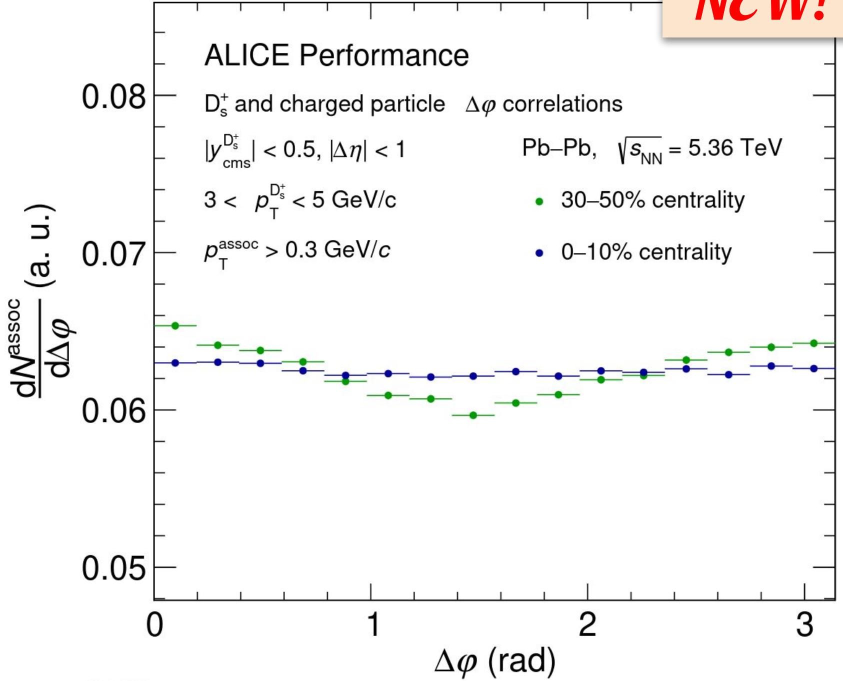

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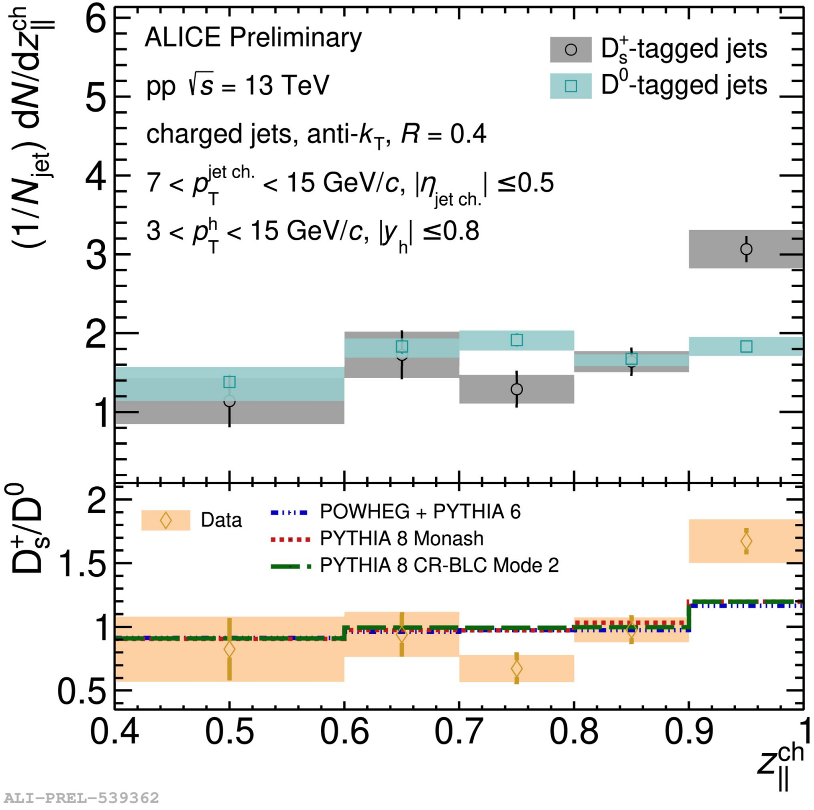
D_s^+ vs. D^0 tagged jets



- Alternative way of probing charm fragmentation into D_s^+

D_s^+- tagged jets vs. **D^0-tagged jets** $z_{||}^{ch}$ measurement

Longitudinal momentum fraction

$$z_{||} = \frac{\vec{p}_{\text{ch, jet}} \cdot \vec{p}_{\text{HF}}}{\vec{p}_{\text{ch, jet}} \cdot \vec{p}_{\text{ch, jet}}}$$

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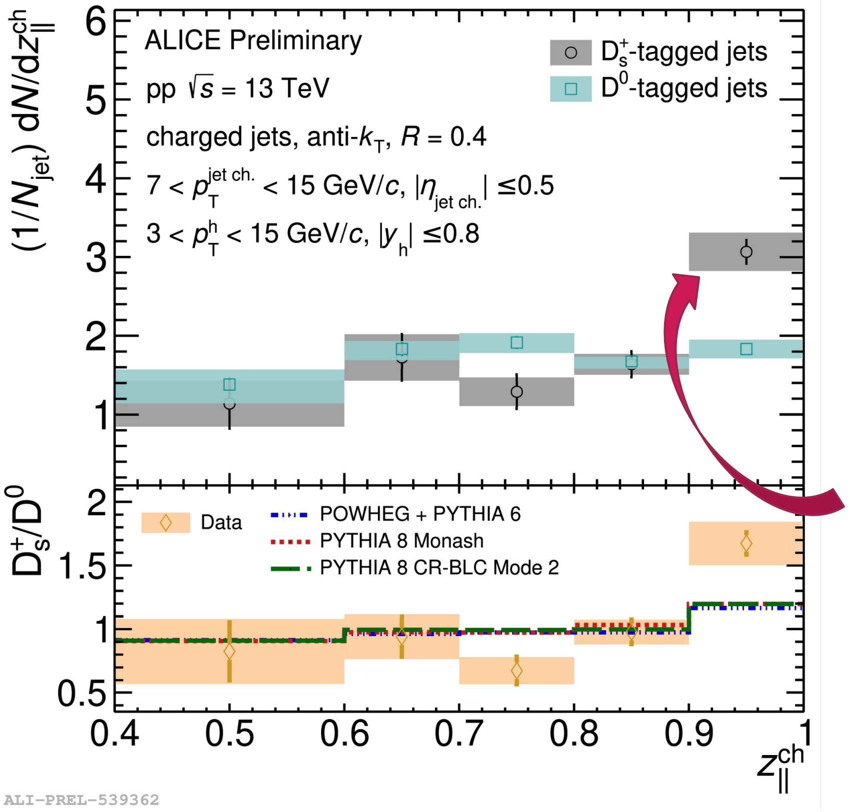

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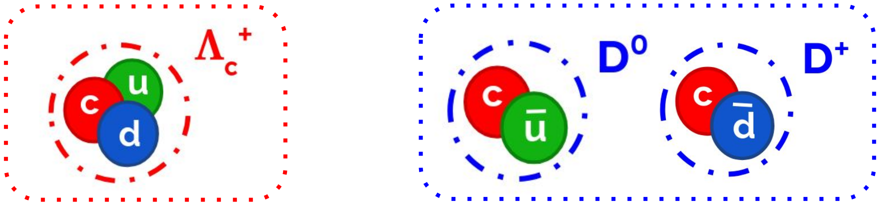
Hint of **harder fragmentation** of charm into **D_s^+** than **D^0** in the studied p_T (ch-jet, D_s^+) range

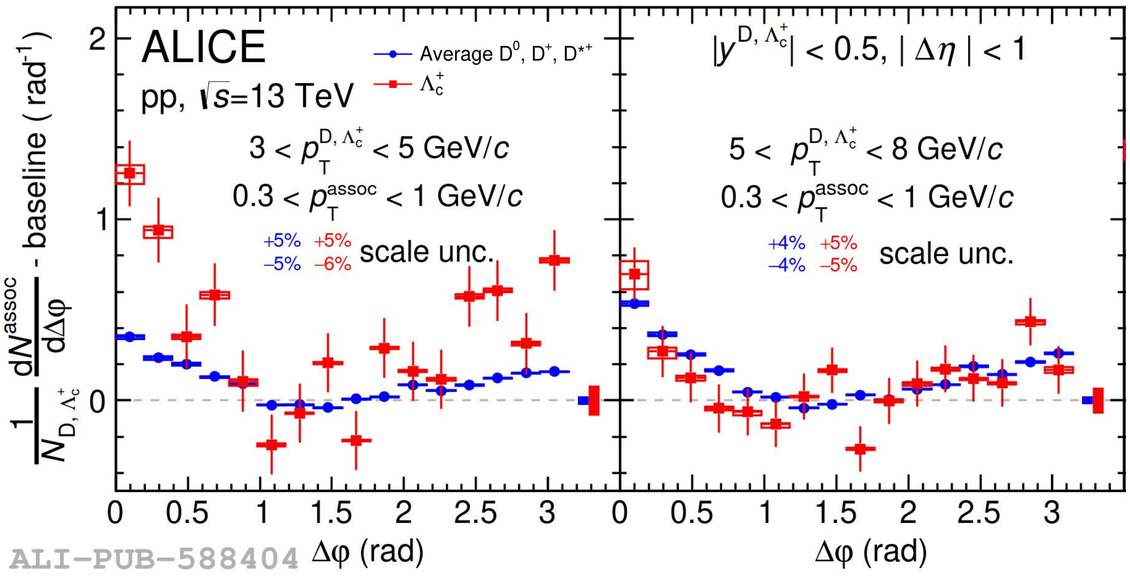
Would be consistent with the observation of a lower NS associated yield for D_s^+ than non strange-D azimuthal correlations with ch. part.

Λ_c^+-charged particles correlation distribution



- Address charm fragmentation into baryons

arXiv:2411.10104



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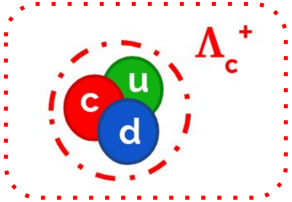
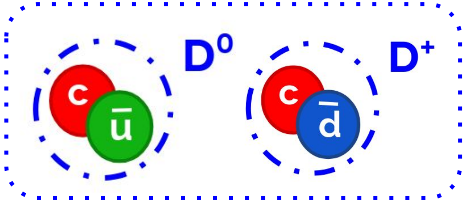
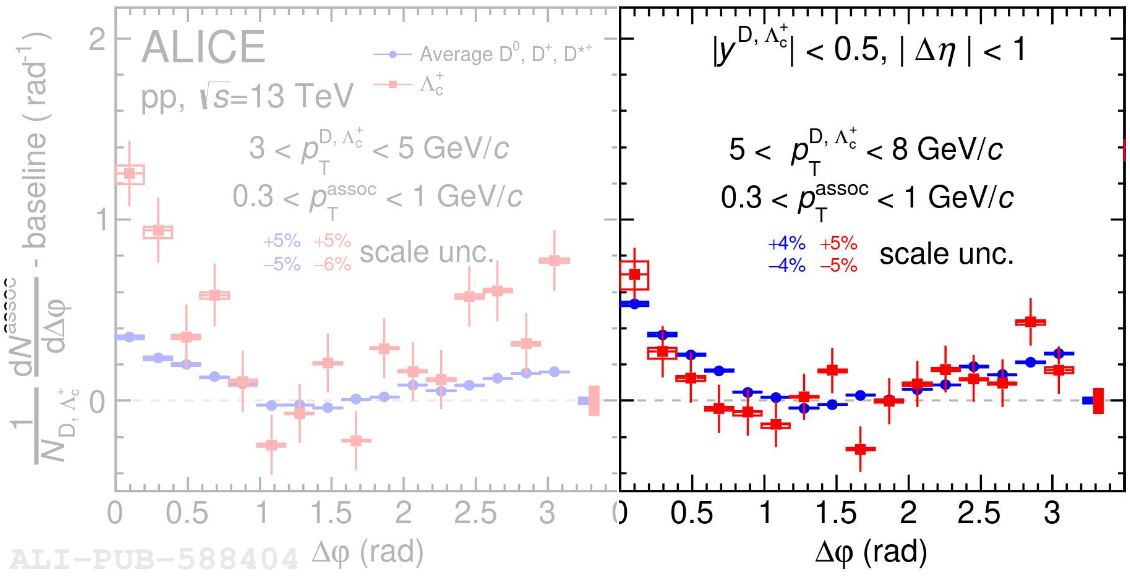




Phys. Lett. B 868 (2025) 139681



- Address charm fragmentation into baryons
- From the comparison of the Δφ shape:
  - **Good agreement** between the Δφ distributions for $p_T(D, \Lambda_c^+) > 5$ **GeV/c**

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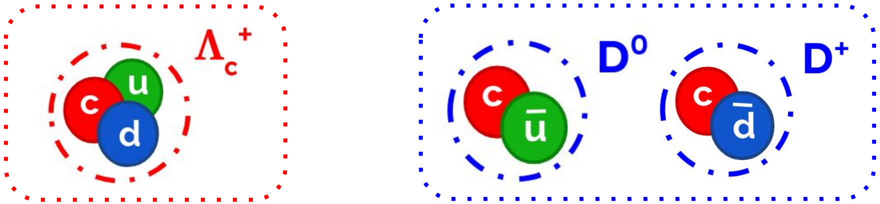

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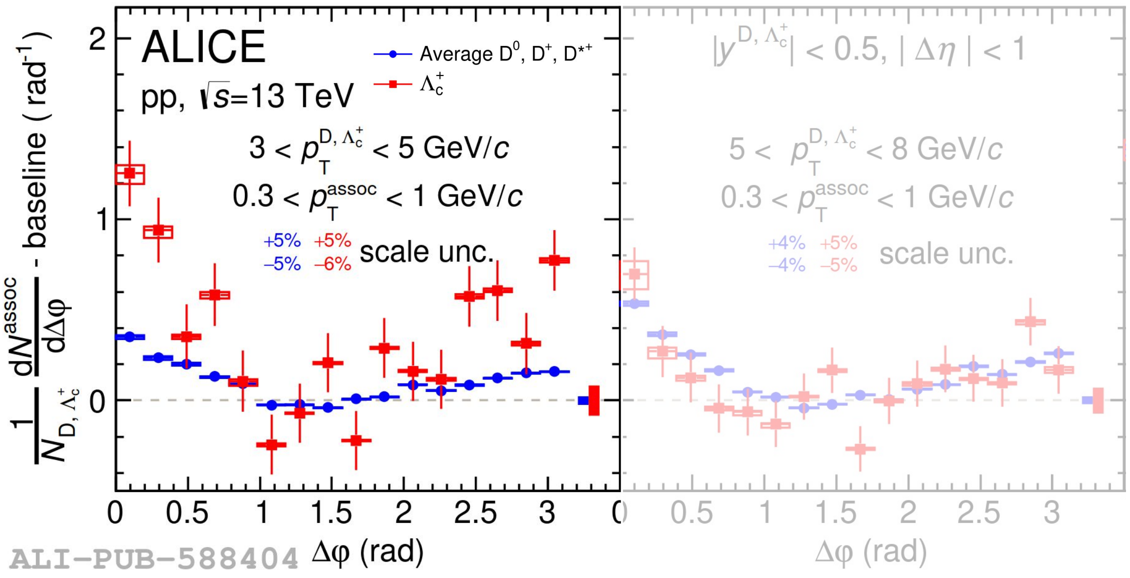


- Address charm fragmentation into baryons
- From the comparison of the $\Delta\varphi$ shape:
  - **Good agreement** between the $\Delta\varphi$ distributions for $\boldsymbol{p_T}$**(D, Λ_c^+) > 5 GeV/*c***
  - Tendency towards an **enhancement of both Λ_c^+-ch. part. correlation peaks** at **low-p_T(D, Λ_c^+)** from **D-ch. part. measurement**

Characterisation of Λ_c^+-charged particles correlation

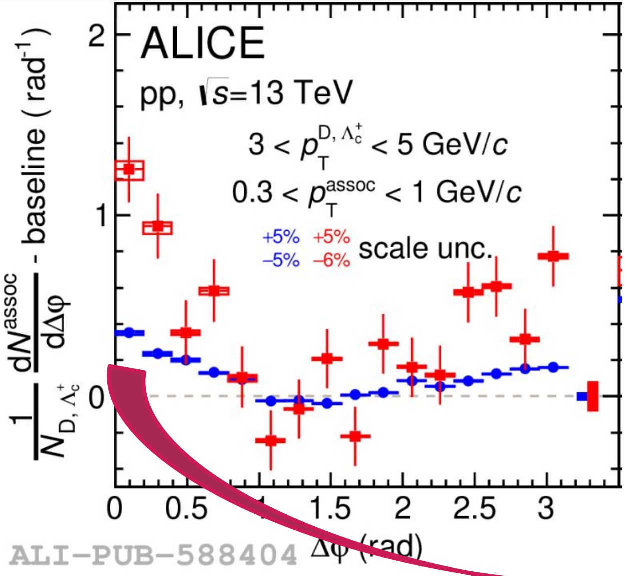
Possible motivations of the observed difference:

a) Different energy of the charm quark as a consequence of a **softer Λ_c^+ fragmentation**

b) Decay of higher-mass charm states (**RQM**)

📙 Phys. Rev. D 84 (2011) 014025

c) Hadronisation by **quark recombination** (to be tested with predictions from dedicated models)



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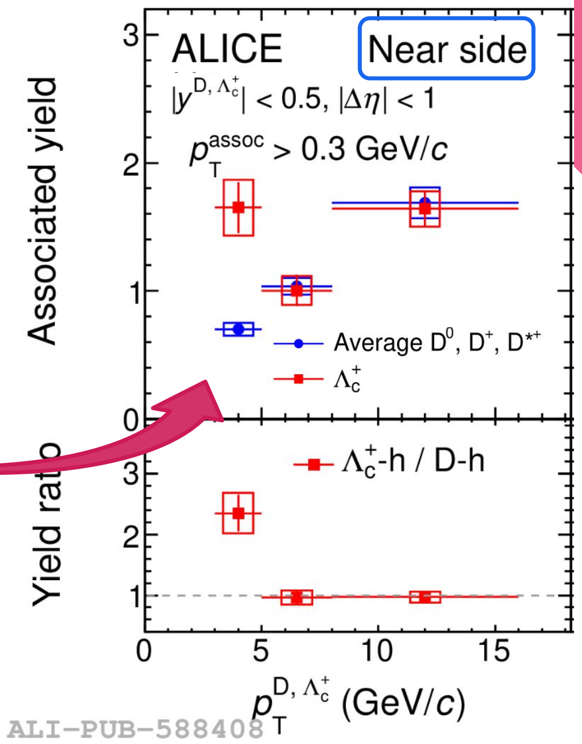

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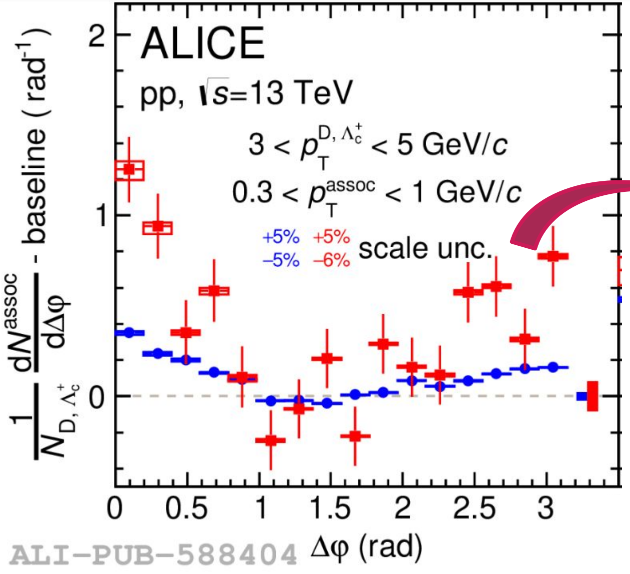

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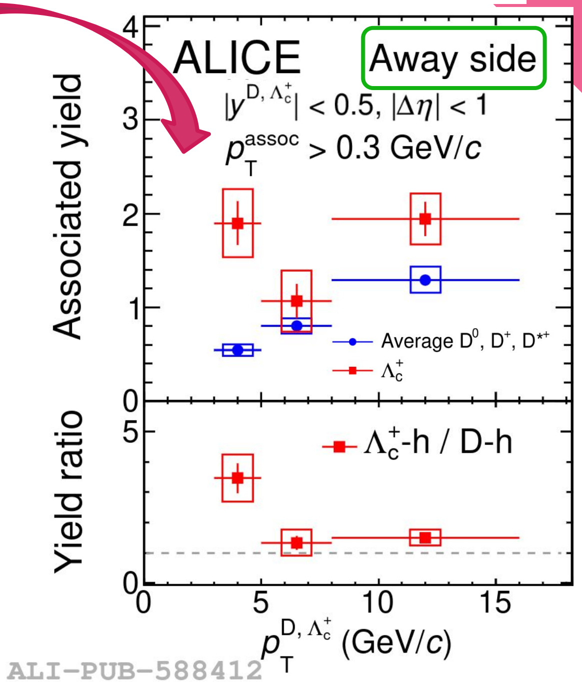

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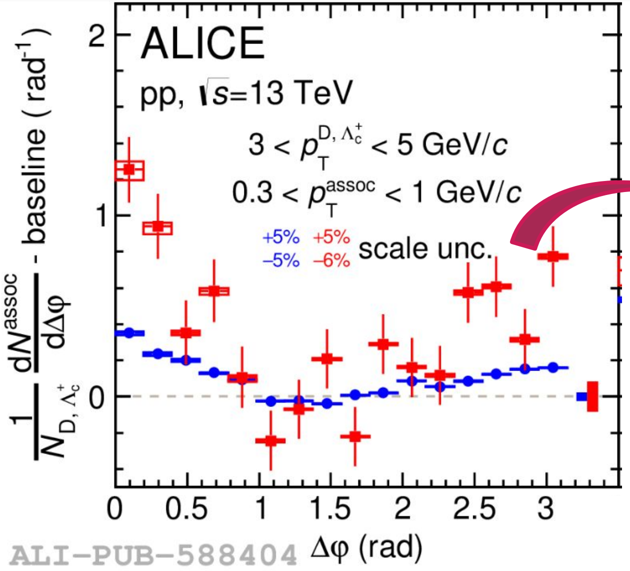

📈 To be revised with Run 3 datasets which should allow for a better assessment of the effect

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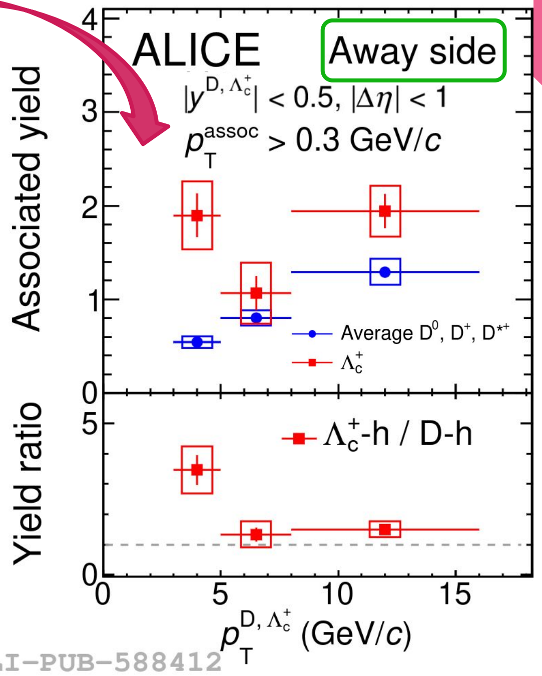
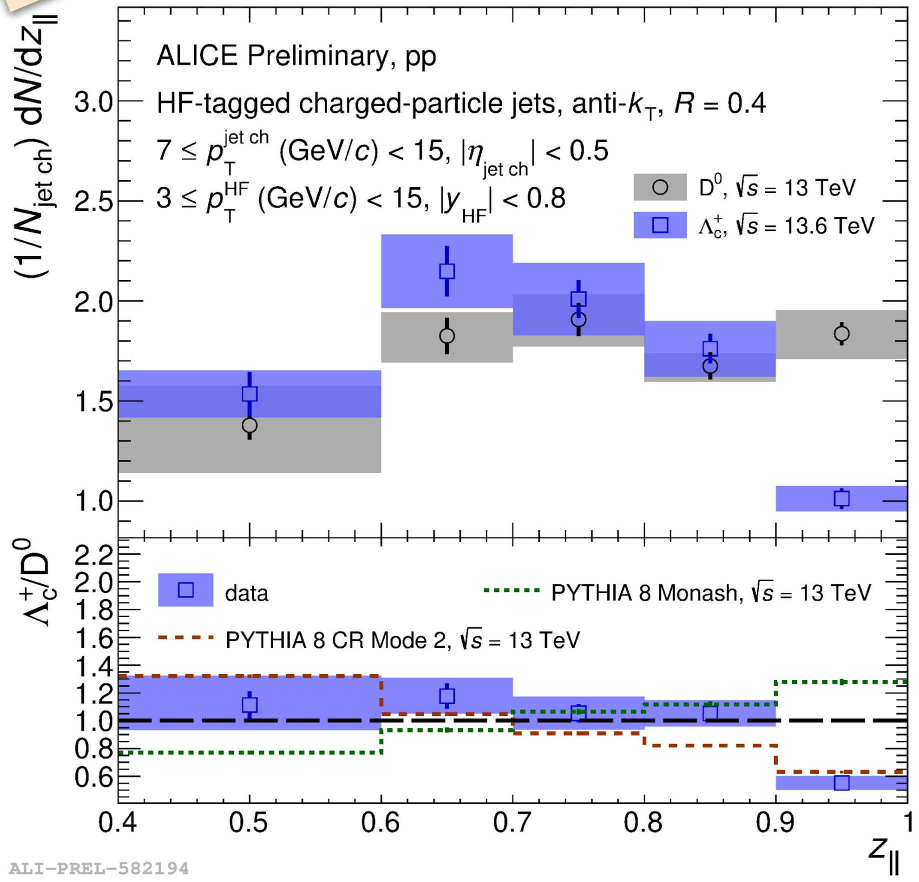


Λ_c^+ tagged jets

NEW!



- Access the charm jet properties

Longitudinal momentum fraction

$$z_{||} = \frac{\vec{p}_{\rm ch,\ jet} \cdot \vec{p}_{\rm HF}}{\vec{p}_{\rm ch,\ jet} \cdot \vec{p}_{\rm ch,\ jet}}$$

Hint of softer fragmentation of charm into Λ_c^+ than D° in the measured p_T (ch-jet, Λ_c^+) range

In agreement with Λ_c^+-ch. part. results for $3 < p_T(\Lambda_c^+) < 5$ GeV/c

NEW!

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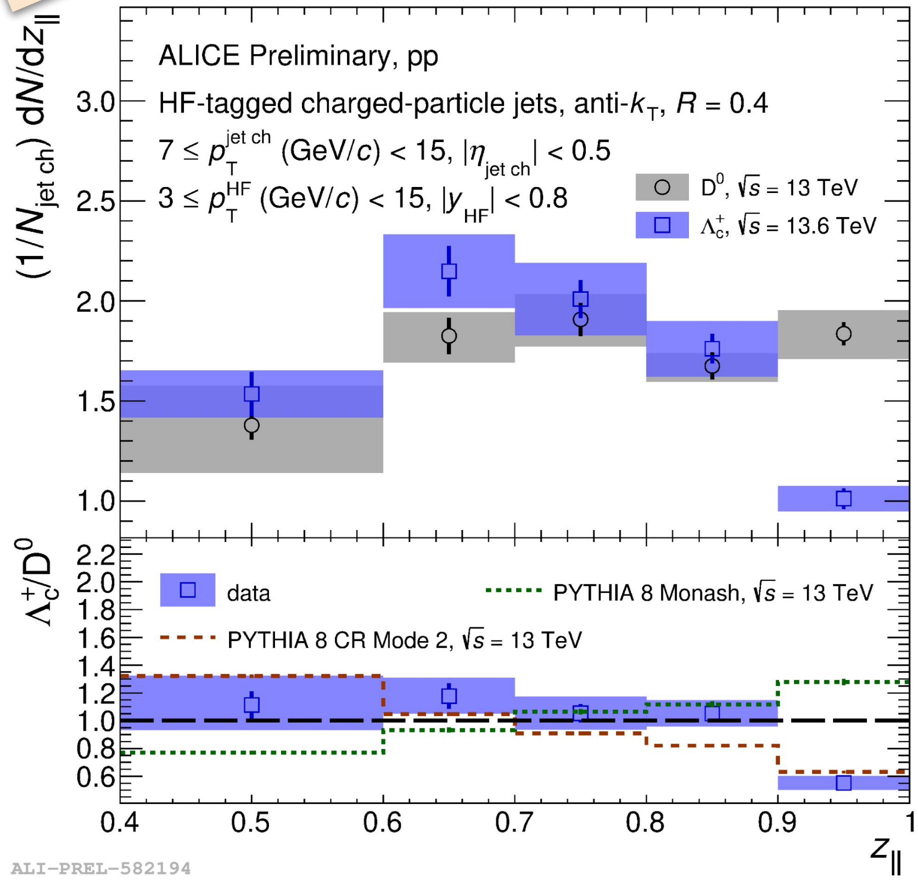

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$$z_{||} = \frac{\vec{p}_{\text{ch, jet}} \cdot \vec{p}_{\text{HF}}}{\vec{p}_{\text{ch, jet}} \cdot \vec{p}_{\text{ch, jet}}}$$

Hint of softer fragmentation of charm into Λ_c^+ than D^0 in the measured p_T (ch-jet, Λ_c^+) range

In agreement with Λ_c^+-ch. part. results for $3 < p_T(\Lambda_c^+) < 5$ GeV/c

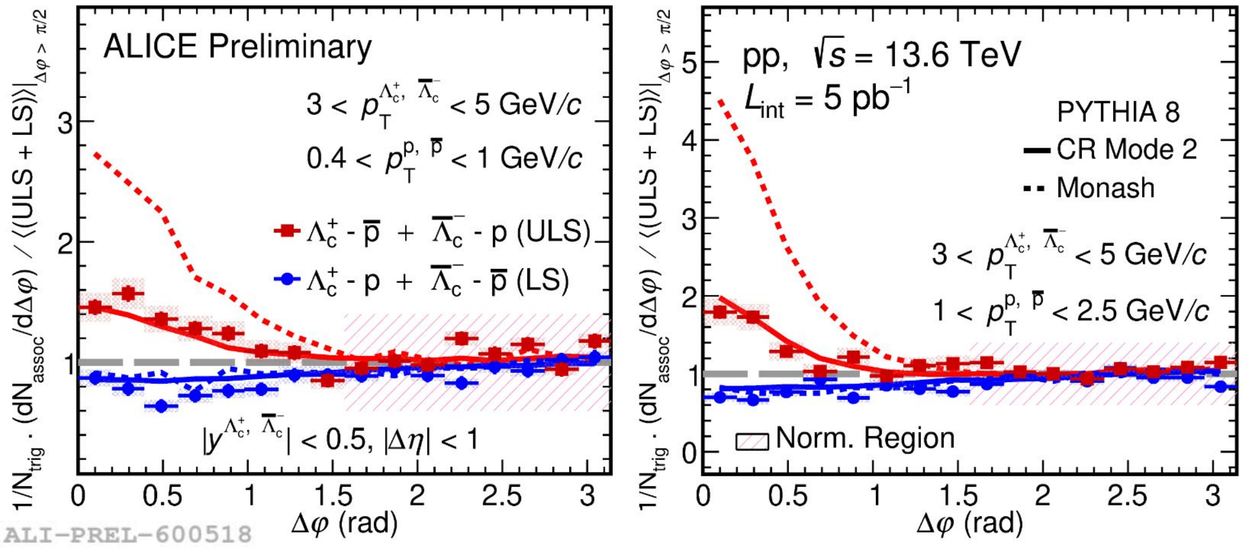
- **PYTHIA 8 CR-BLC Mode 2** shows better agreement with data than the **PYTHIA 8 Monash** tune

PYTHIA 8 CR-BLC (JHEP 1508 (2015) 003)

PYTHIA 8 Monash (EPJC 74 (2014) 3024)

NEW!

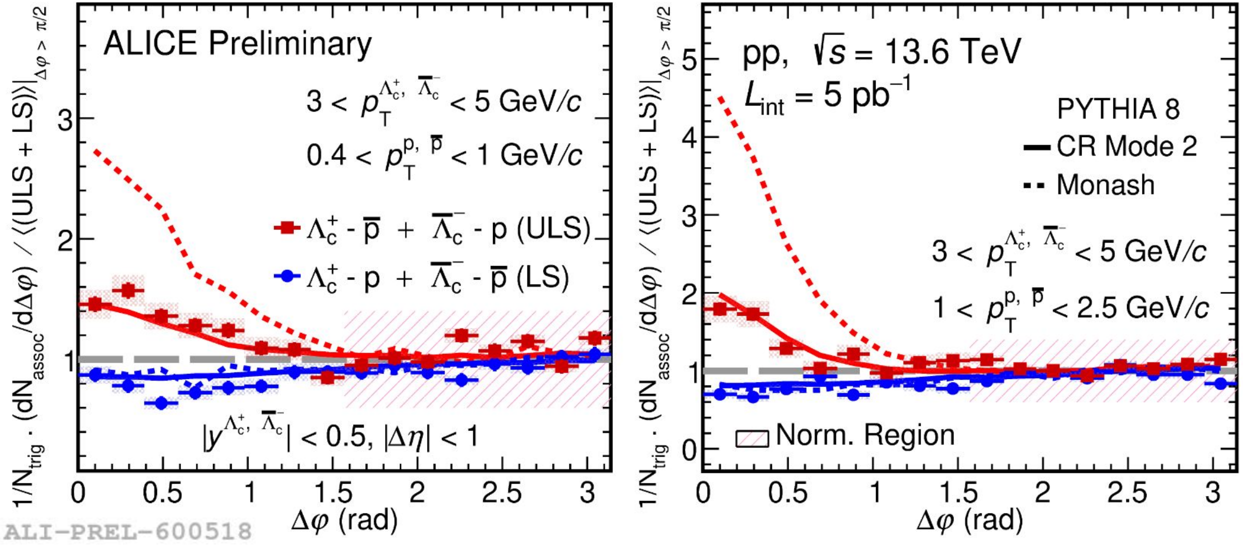
Λ_c^+-p correlation



- **Further** study to better investigate **charm-quark hadronisation**
- Open the possibility to explore **local baryon number conservation**
- Azimuthal correlation distributions normalised to the integral in the $\Delta\varphi > \pi/2$ region

NEW!

Λ_c^+-p correlation



- **Further** study to better investigate **charm-quark hadronisation**
- Open the possibility to explore **local baryon number conservation**
- Azimuthal correlation distributions normalised to the integral in the $\Delta\varphi > \pi/2$ region

- **Clear correlation** in the NS present in **unlike-sign (ULS)** Λ_c^+-antiproton pairs, absent for **LS pair**

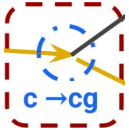
→ **Possibly due to local baryon number conservation?**

- **Effect** significantly more **pronounced in the PYTHIA 8 Monash** tune compared to **CR Mode2**
- **PYTHIA 8** with **CR Mode 2** beyond leading colour approximation well describes the data

NEW!

Accessing the charm splitting function

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

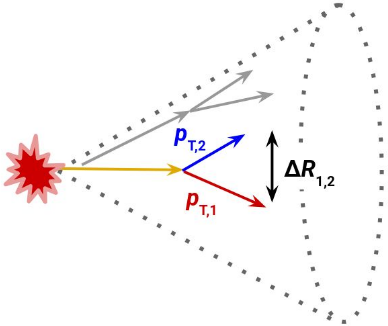


Soft Drop grooming condition

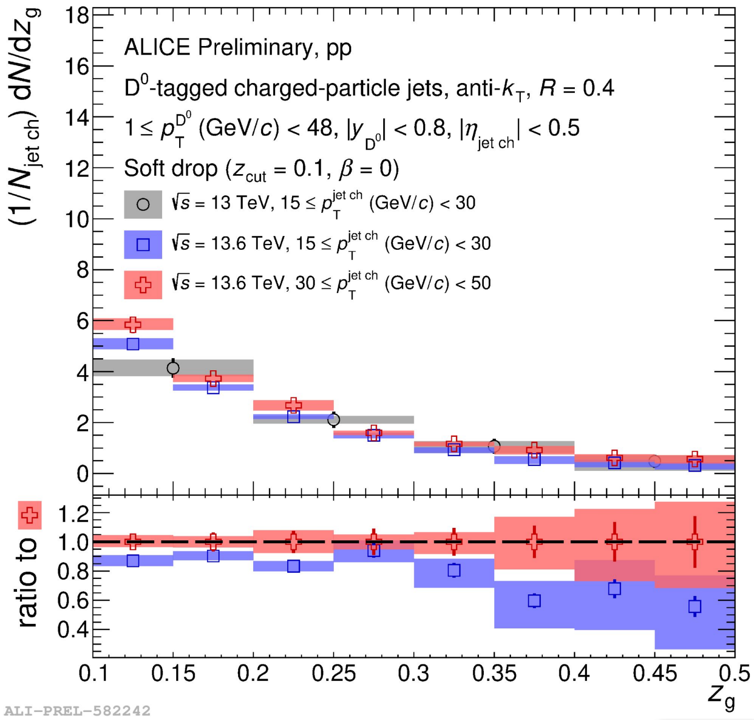
$$z = \frac{min(p_{\mathrm{T},1},\, p_{\mathrm{T},2})}{p_{\mathrm{T},1} + p_{\mathrm{T},2}} > z_{cut}\left(\frac{\Delta R_{1,2}}{R}\right)^{\beta}$$

$$z_{cut} = 0.1,\quad \beta = 0$$

JHEP 1405 (2014) 146



- z_g: **shared momentum fraction** of the first splitting that satisfies the Soft Drop condition
- **Run 3**:
  - Possibility for **increased precision** and **greater granularity** in z_g
  - Extended the measurement in the 30 < $p_T^{\text{jet ch}}$ < 50 GeV/c interval
- More jets pass Soft Drop at higher $p_T^{\text{jet ch}}$ → reduction of the dead cone effect



NEW!

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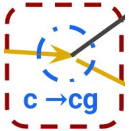

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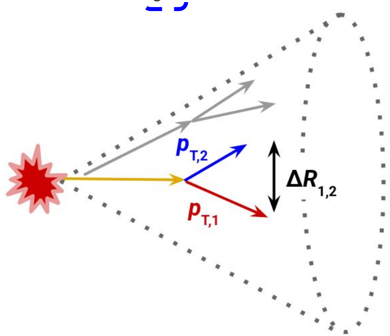
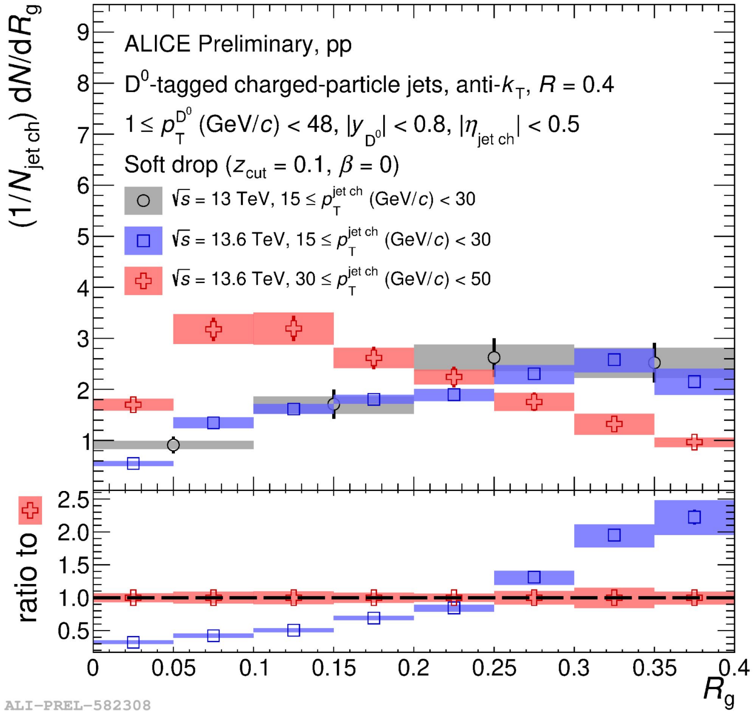
📘 JHEP 1405 (2014) 146





- ***R*$_g$: groomed emission angle (Δ*R*$_{1,2}$)** of the first splitting that satisfies the Soft Drop condition

📌 **Evolution of parton mass effect** can be tested by going to high $p_T^{\text{jet ch}}$

🔎 **Narrower angular distribution** of charm splitting function in the 30 < $p_T^{\text{jet ch}}$ < 50 GeV/*c* kinematic interval

Summary and outlook

D-charged particles azimuthal correlations and tagged jets:

- Indication of a harder hadronization for charm quarks into D_s^+ mesons
- Good agreement with model predictions (PYTHIA 8 CR-BLC)

Λ_c^+-charged particles azimuthal correlations and tagged jets:

- Indication of softer charm quark fragmentation into Λ_c^+ compared to D mesons
- Correlation studies with identified protons open the possibility to explore local baryon number conservation

Accessing charm splitting function:

- Investigation of the role of parton mass effects in parton shower dynamics
- Enhanced granularity and extended measurement reach to higher $p_T^{\text{jet ch}}$

Further results expected shortly on new Run 3 data samples

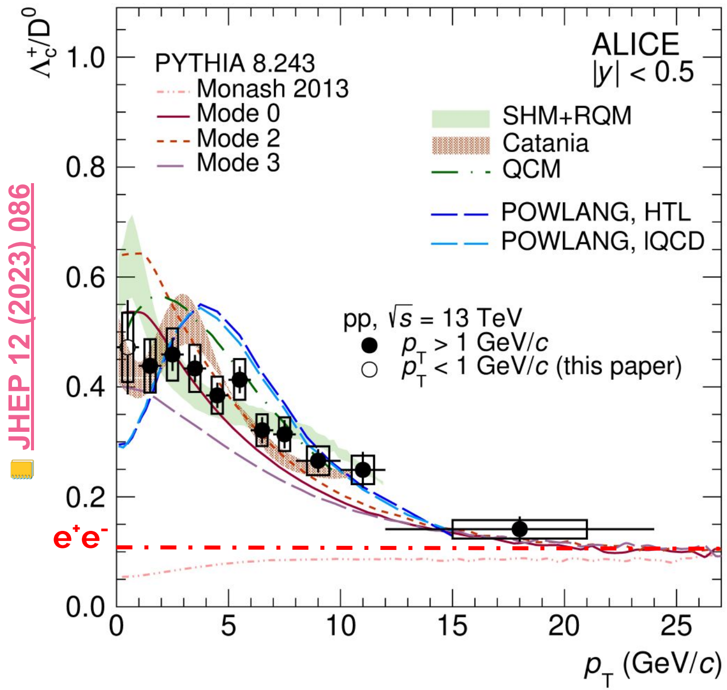
Thanks for your attention!

BACKUP SLIDES

Charm baryon-to-meson enhancement in pp collisions

ALICE

p_T**-dependent** enhancement of Λ_c^+/D^0 ratio in **pp** w.r.t. e^+e^-



LEP average: (0.113 ± 0.013 ± 0.006) EPJC 75 (2015) 19

- **PYTHIA 8 Monash** (EPJC (2014) 3024), with FF tuned on e^+e^-, significantly **underestimates** the data

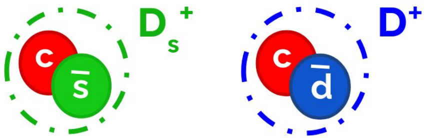
- Different **hadronisation mechanisms proposed**
  - **PYTHIA 8 CR-BLC** (JHEP 1508 (2015) 003)
  - **CATANIA** (arXiv:2012.12001) and **QCM** (EPJC (2018) 78:344)
  - **SHM + RQM** (PLB 795 (2019) 117-121))
  - **POWLANG** (arXiv:2306.02152)

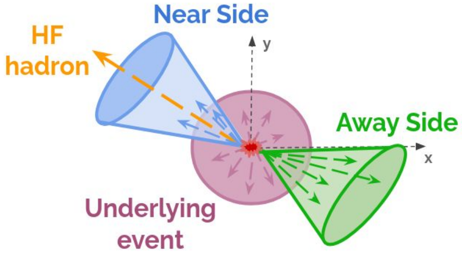
- Baryon-to-meson measurement focuses solely on the **charm hadron production**

- **Further studies** can shed light on **charm-quark hadronisation** by considering also the other particles produced in association to the charm hadron

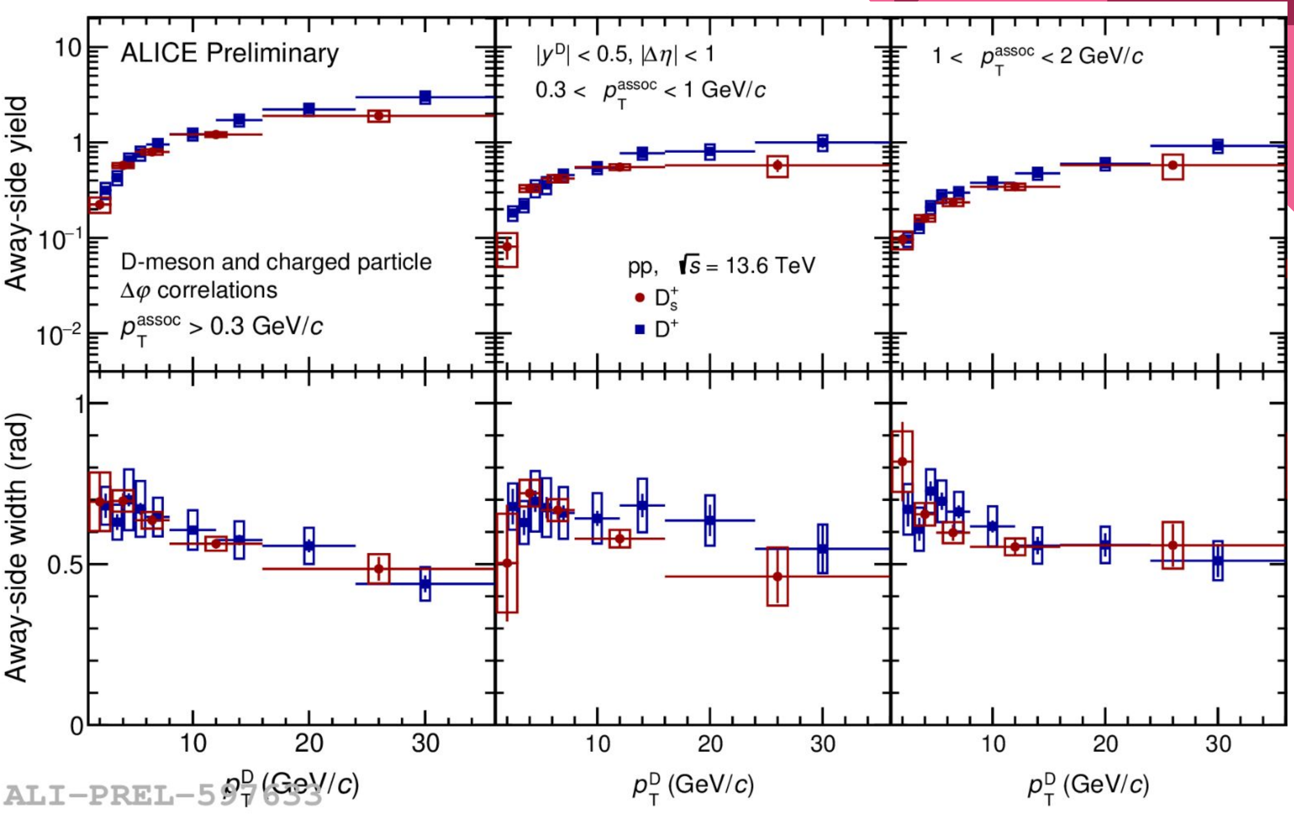
D-charged particles azimuthal correlations

NEW!

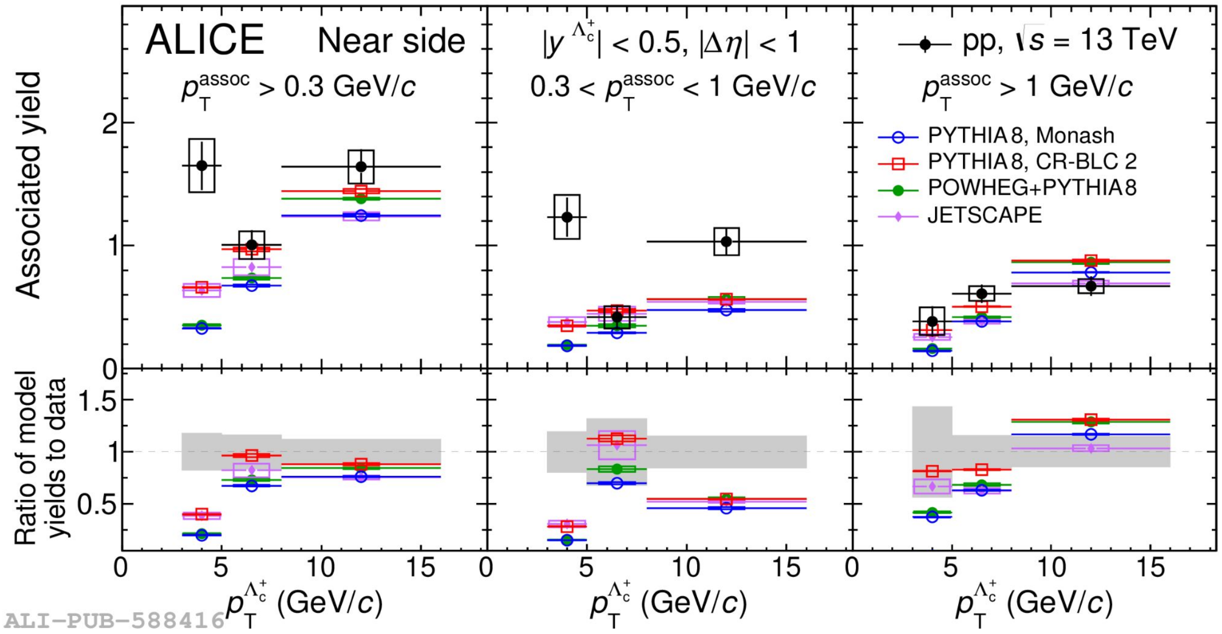




- **Away Side (AS) yield and width**: **good agreement** over the whole p_T range



Λ_c^+-charged particles correlation comparison with models



- **Yields**:
  - Tensions with PYTHIA8 predictions
  - Low-$p_T(\Lambda_c^+)$ not correctly reproduced

arXiv:2411.10104

PYTHIA 8 CR-BLC modes, despite predicting the Λ_c^+/D^0 p_T-dependence, do not describe the differences in the charm-jet