Study of charm fragmentation with charm meson and baryon angular correlation measurements with ALICE

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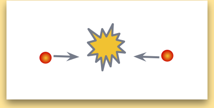
SQM Strasbourg 2024
Strangeness in Quark Matter

ALICE

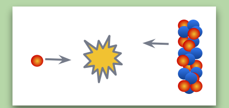
Heavy-flavour physics

Heavy-flavour (HF) quark mass of the order of ~ GeV/c^2

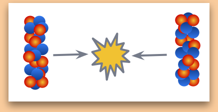
→ mainly produced in **hard-scattering** processes



Test for pQCD
Hadronisation
Reference for Pb–Pb



Cold Nuclear Matter (**CNM**) effects
Modification of PDFs in nuclei
Hot nuclear matter effects ?
Collective motion



Hot nuclear matter effects
Energy loss in the QGP
Modification to hadronisation

Open heavy-flavour hadron production cross section calculated by factorisation approach:

$$\frac{d\sigma^{H_c}}{dp_T}(p_T;\mu_F,\mu_R) = \mathrm{PDF}(x_1,\mu_F)\otimes\mathrm{PDF}(x_2,\mu_F) \otimes \frac{d\sigma^{c}}{dp_T^{c}}(p_T;\mu_F,\mu_R) \otimes D_{c\to H_c}(z = p_{H_c}/p_c,\mu_F)$$

Parton distribution functions

Hard scattering cross section (pQCD)

Fragmentation functions (hadronisation)

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

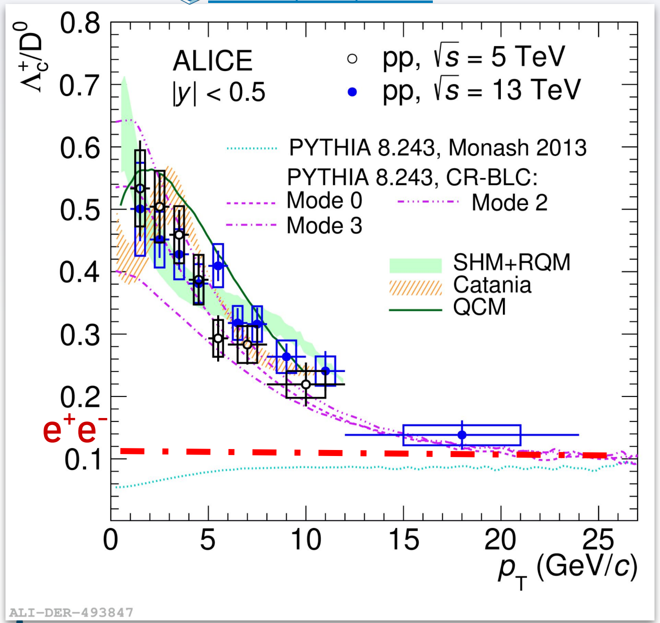
Enhanced charm baryon-to-meson production in pp

Baryon-to-meson yield ratio measurements in **hadronic collisions** questioned fragmentation universality

ALICE

Jaeyoon Cho
Tuesday 04/06

PRL 128 (2022) 012001



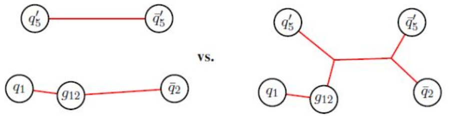
LEP: (0.113 ± 0.013 ± 0.006) EPJC 75 (2015) 19

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

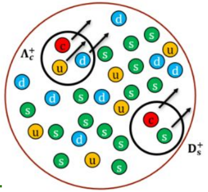
✗ PYTHIA 8 Monash, with FF tuned on e^+e^-, significantly underestimates the data

Different hadronisation mechanisms proposed:

✓ CR modes in PYTHIA 8
JHEP 1508 (2015) 003



✓ Coalescence in:
→ Catania
arXiv:2012.12001
→ QCM
EPJC (2018) 78:344



✓ Augmented feed-down to charm baryons in **SHM+RQM**
→ PDG: 5 Λ_c, 3 Σ_c, 8 Ξ_c, 2 Ω_c
→ RQM: + 18 Λ^*_c, 42 Σ^*_c, 62 Ξ^*_c, 34 Ω^*_c

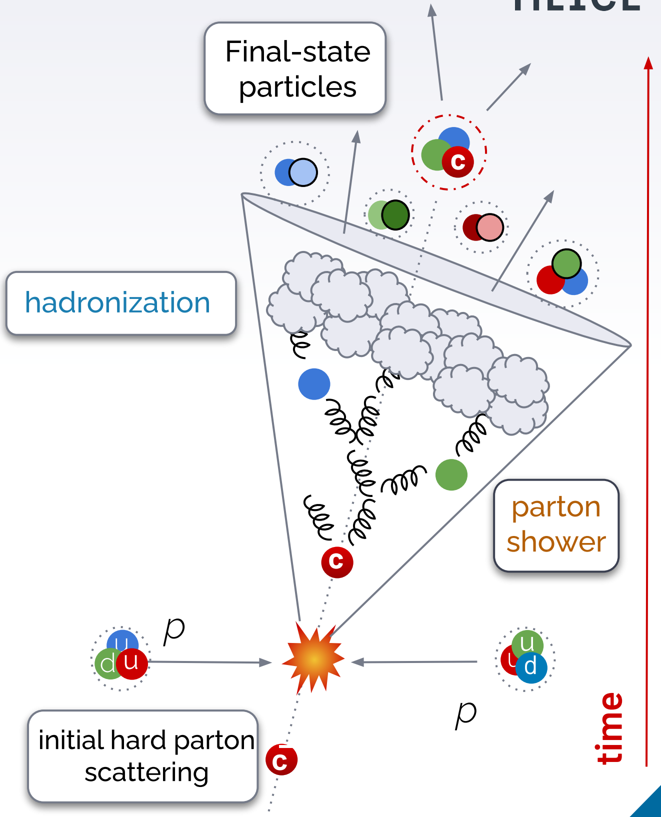
PLB 795 (2019) 117-121

Fragmentation measurements

HF fragmentation can be further characterised by studying:

- azimuthal correlations of HF hadrons with charged particles
  - → jet shape and its particle composition
  - → multidifferential investigation of fragmentation processes

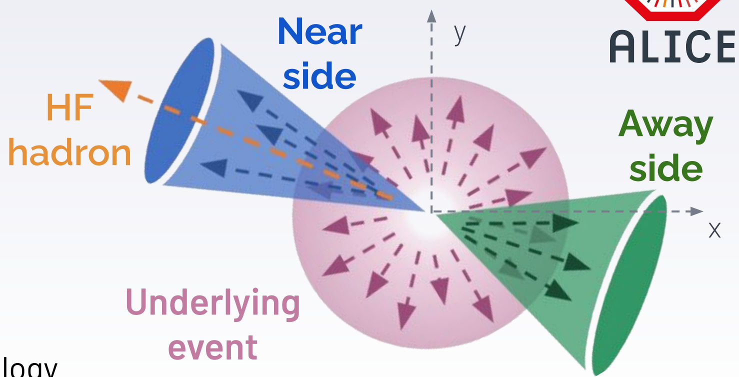
- HF-tagged jets
  - → access to the original parton kinematics
    - → constrain the fragmentation functions



Azimuthal correlations of HF and charged particles

At LO approximation:

- ➢ Near Side (NS): fragmentation of the tagged charm quark;
- ➢ Away Side (AS): fragmentation of the recoil quark;
- ➢ Transverse Region: information on the underlying event



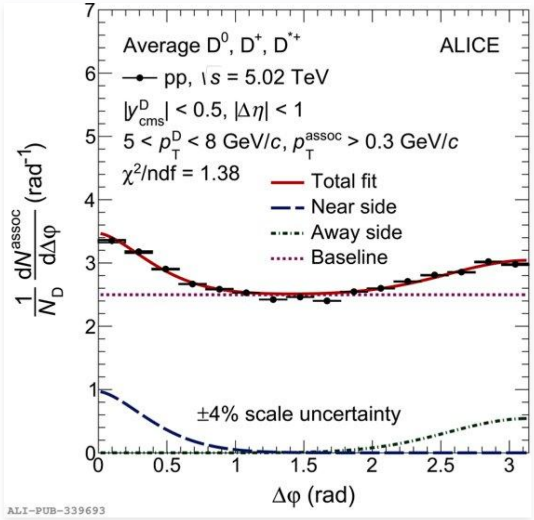
NLO production mechanisms, relevant at the LHC energies, can alter this topology

The heavy-flavour jet is characterised by:

→ Angular profile

→ Multiplicity of particles

→ Momentum distribution of its constituents



EPJC 80 (2020) 979

ALICE measurements:

D meson-charged particles (D-h) Λ_c^+-charged particles (Λ_c^+-h)

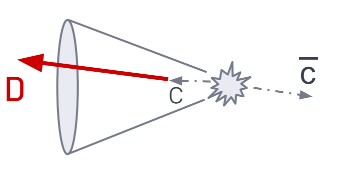
HF decay electrons - charged particles (HFe-h)

Charm-to-meson fragmentation

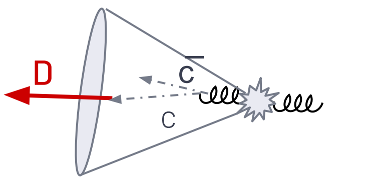
D-h near-side properties comparison with √s

Near-Side: description of **charm-jet** constituents, their **momentum** and **angular displacement** w.r.t. the D trigger

LO: pair production



NLO: gluon splitting

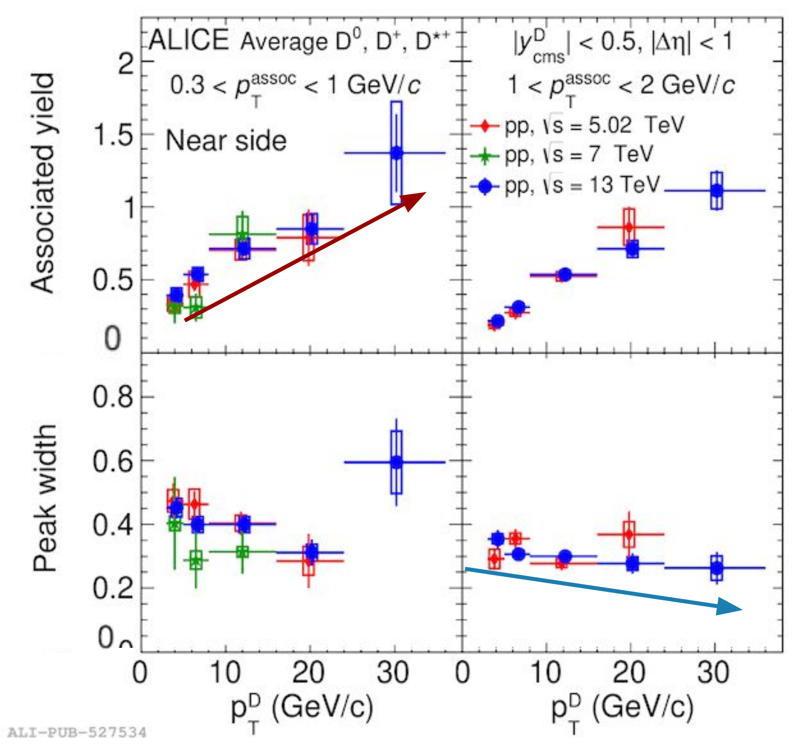


With increasing p_T^D:

→ More energetic charm quark
→ more phase space to produce other fragments
→ increasing yields

→ Larger heavy-quark boost
→ more collimated shower
→ sharpening of the peak

No centre-of-mass energy dependence

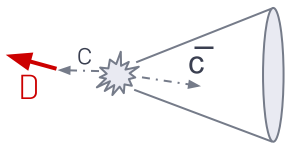


Eur. Phys. J. C 82 (2022) 335

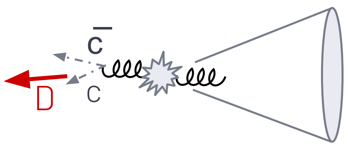
D-h away-side properties comparison with √s

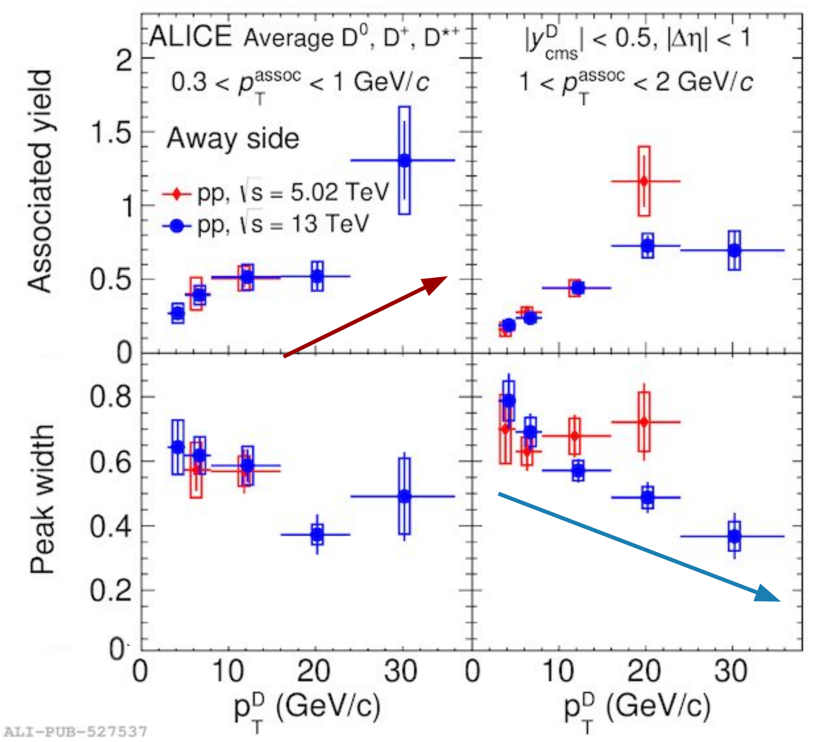
Away-Side provide description of the recoil jet, not necessarily developed by a charm quark

LO: pair production



NLO: gluon splitting





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Similarly as for the NS, with increasing p_{T}^{D}:

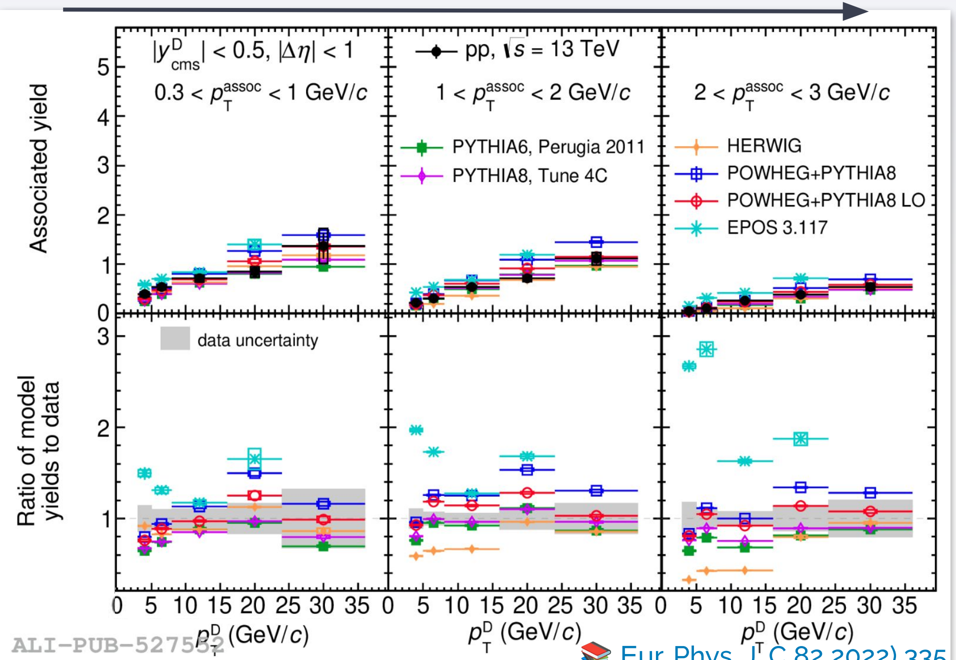
- ➢ More energetic parton
  - → increasing yields
  - → sharpening of the peak

No centre-of-mass energy dependence

Near-side comparison to predictions

Validation of parton-shower models and Monte Carlo generators

p_T(assoc)



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NS yields:

- ➔ Larger values at high-p_T(D) by POWHEG+PYTHIA 8 than PYTHIA 8
- ➔ About 10% larger yields for POWHEG+PYTHIA 8 w.r.t. POWHEG+PYTHIA8 LO
- ➔ HERWIG tends to underestimate the data at low p_T(D) and at high p_T(assoc)
- ➔ EPOS overestimates the results over the whole p_T range

PYTHIA 8 and POWHEG+PYTHIA 8 provide the best description

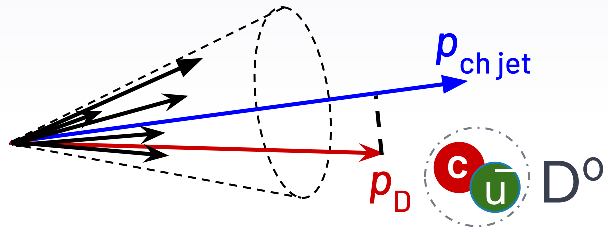
PYTHIA: Eur. Phys. J. C 74, 3024 (2014)
POWHEG: JHEP 06 (2010) 043
EPOS 3: Phys.Rev.C 82(2010)044904
HERWIG: Eur.Phys.J C76 (2016) 196

D⁰-tagged jets

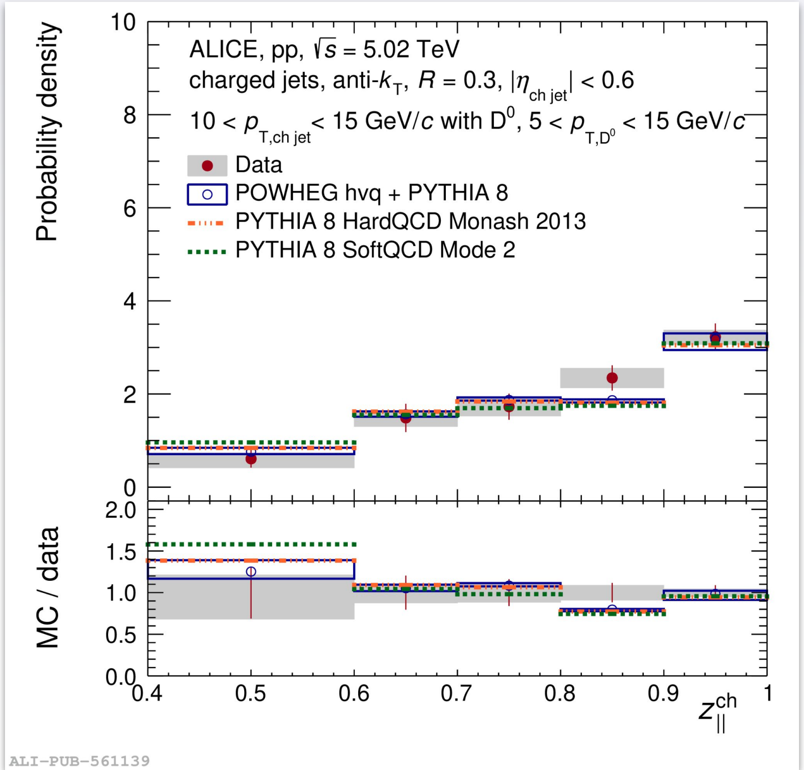
Constrain **charm fragmentation functions**

Longitudinal momentum fraction

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



- Good description of the $z_{||}^{\text{ch jet}}$ distribution by MC predictions
- **charm-to-mesons** fragmentation not significantly modified varying PYTHIA 8 tunes

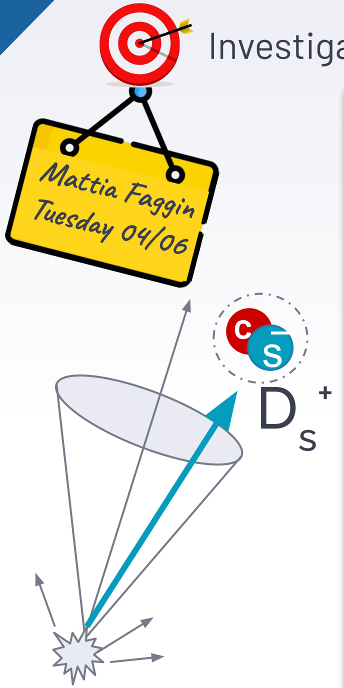


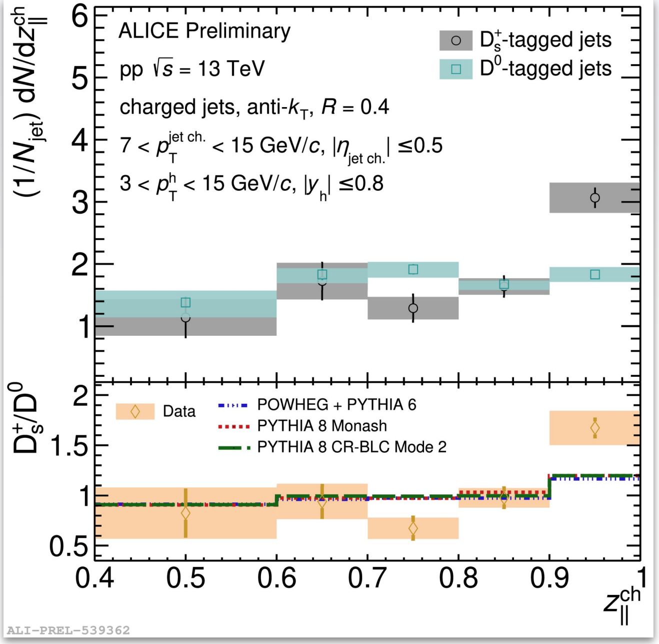
JHEP 06 (2023) 133

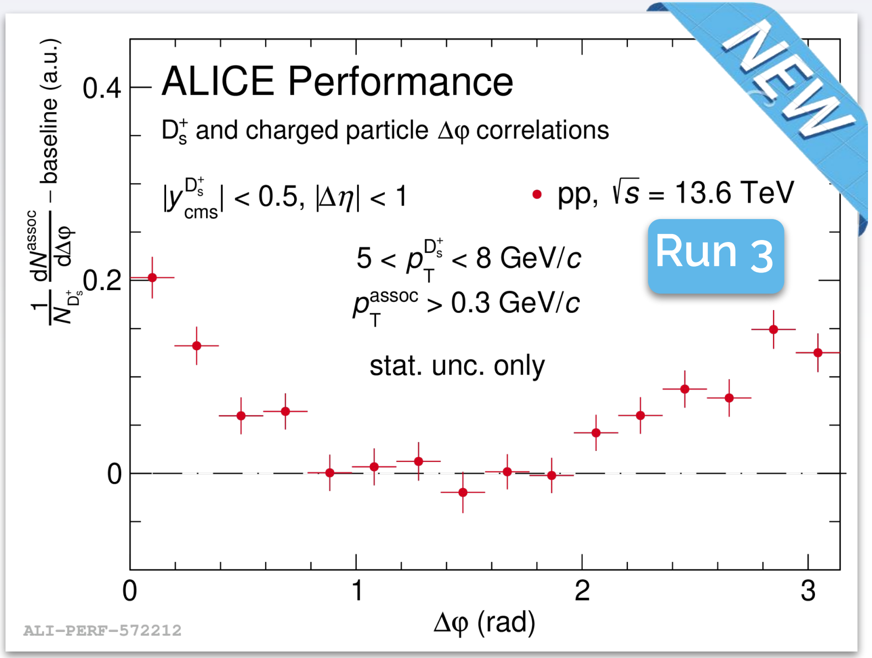
PYTHIA: EPJC 74 3024 (2014), JHEP 1508 (2015) 003
POWHEG: JHEP 06 (2010) 043

Charm fragmentation with D_s^+ mesons

Investigating the charm fragmentation in mesons with strange quark content







- ➢ Similar $z_{\parallel}^{\text{ch jet}}$ distribution to **non-strange D mesons** → correctly described by **PYTHIA 8** simulations
- ➢ First studies of D_s-h correlation with Run 3 data → D_s - jet characterisation soon accessible

PYTHIA: EPJC 74 3024 (2014), JHEP 1508 (2015) 003 POWHEG: JHEP 06 (2010) 043

Charm-to-baryon fragmentation

Comparison between Λ_c^+-h and D-h $\Delta\varphi$ distributions

Address charm fragmentation into baryons

D meson - h

Λ_c^+ baryon - h

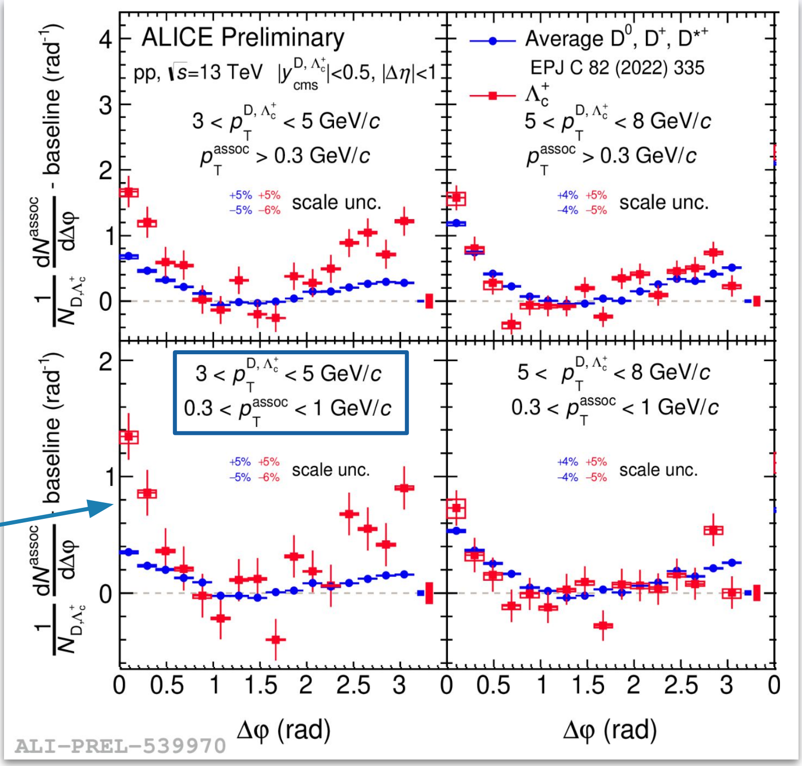
Eur. Phys. J. C 82, 335 (2022)

From the comparison of the $\Delta\varphi$ shape:

→ good agreement between the $\Delta\varphi$ distribution for $p_T(\Lambda^+_c) > 5$ GeV/c

→ Significant peak enhancement at low-$p_T(\Lambda_c^+)$ wrt D-h measurements

p_T(D, Λ_c^+)



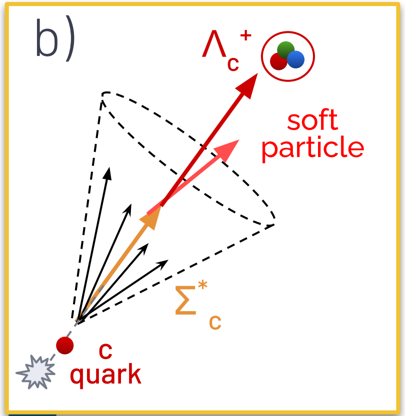
Characterisation of the Λ_c^+-h near-side peak

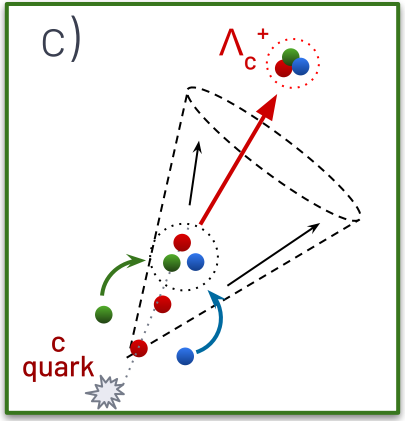
➢ Higher **NS yields** in Λ_c^+-h than D-h at low-p_T

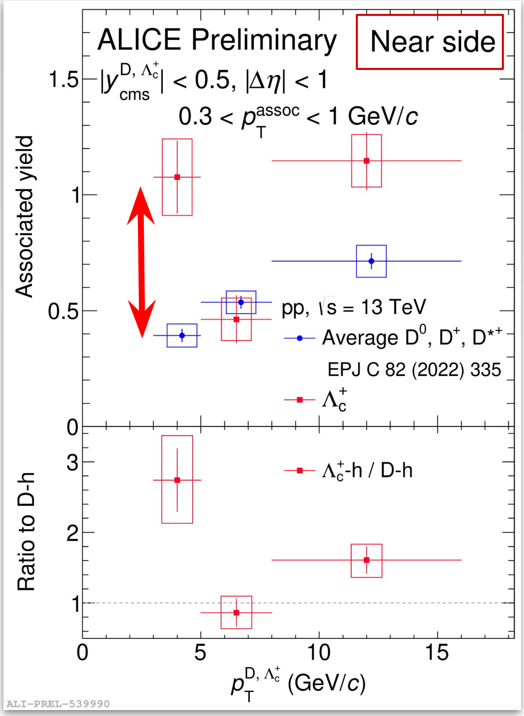
a) different energy of the charm quark as a consequence of a softer Λ_c^+ fragmentation ?

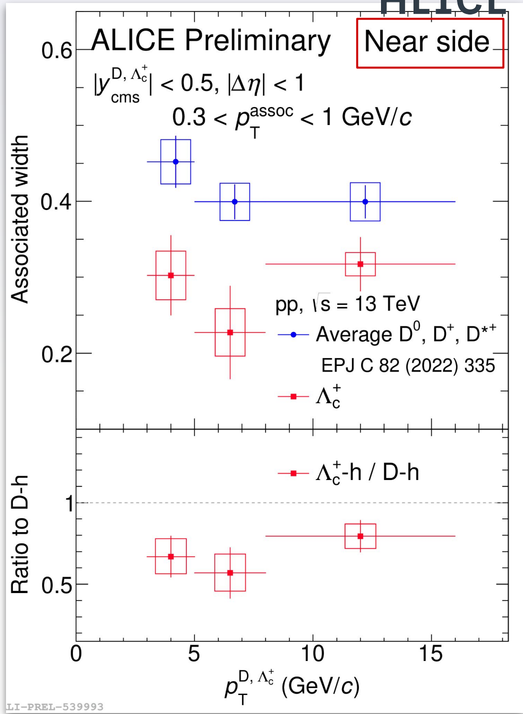
b) decay of yet unobserved heavier charm-baryon states (SHM+RQM) ?

c) hadronisation by coalescence ?









Difference between charm-to-meson and charm-to-baryon fragmentation

Characterisation of the recoil-jet in Λ_c^+-h

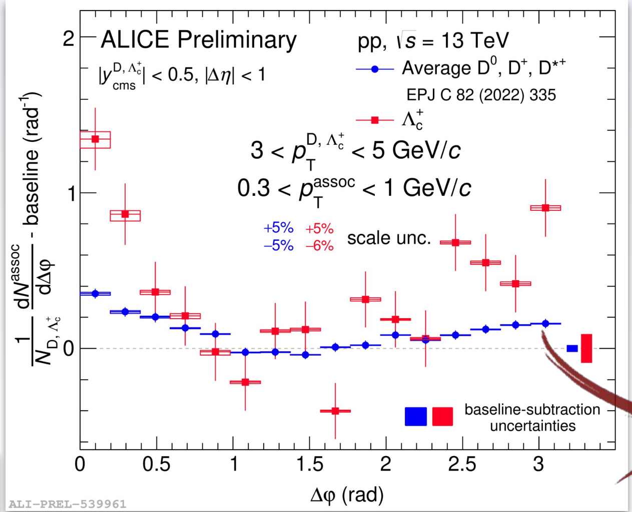
- ➢ Enhancement of the **AS yields at low-p_T**

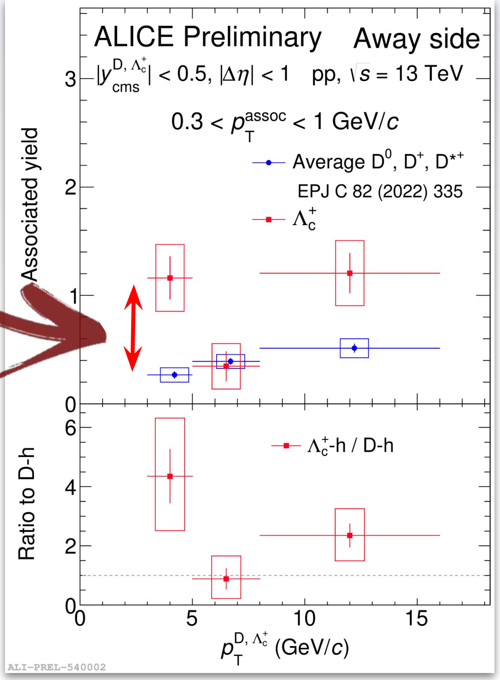
a) softer Λ_c^+ fragmentation ?

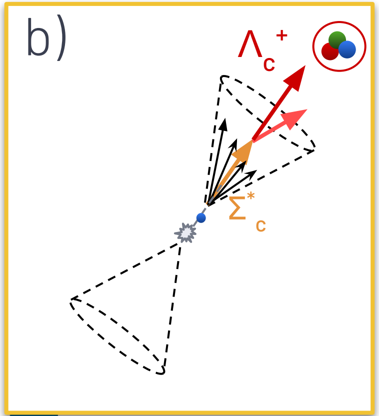
Less probable hypotheses:

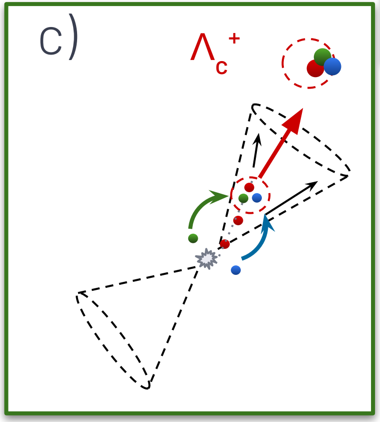
b) **decay of** yet unobserved higher mass charm states (SHM+RQM)

c) hadronisation by coalescence







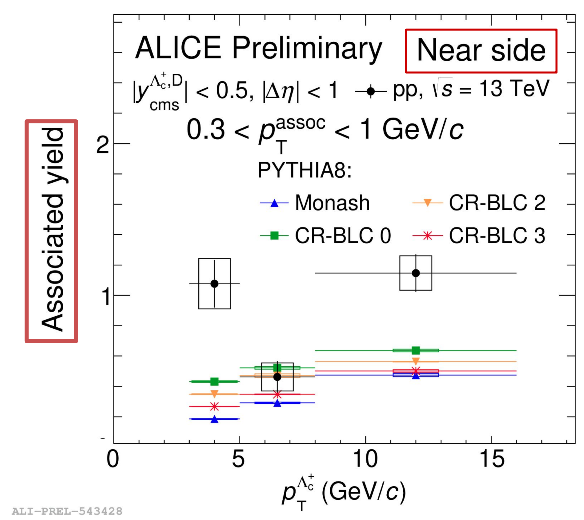


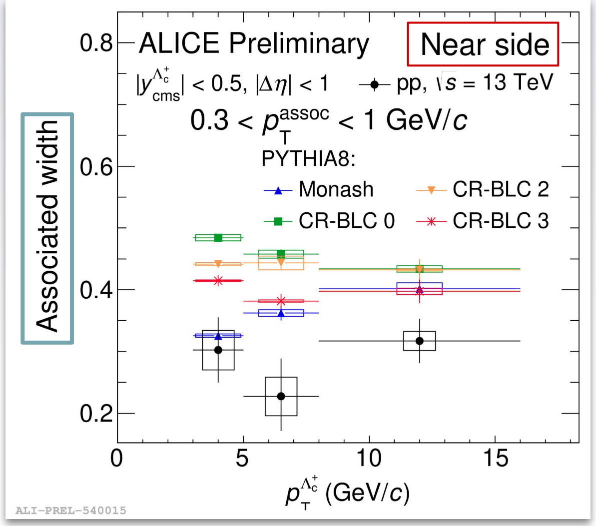
Λ_c^+-h: near-side peak description in simulations

Correlation distributions studied in **PYTHIA 8** including modes with **CR beyond leading colour approximation (CR-BLC)**

➢ yields:
→ tensions with PYTHIA 8 predictions
→ low-p_T (Λ_c^+) not correctly reproduced

➢ widths:
→ generally overestimated, though with large uncertainties





PYTHIA: EPJC 74 3024 (2014), JHEP 1508 (2015) 003

charm-to-baryon fragmentation
not properly described by MC generators

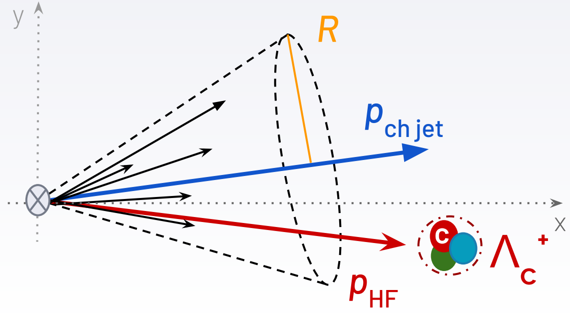
PYTHIA 8 CR-BLC modes, despite reproducing the Λ_c^+/D^0 p_T**-dependence**, do not describe the Λ_c^+-h correlation peak observables

Charm-baryon tagged jets

Access the charm-quark properties if it hadronises into a baryon

Jet longitudinal momentum fraction

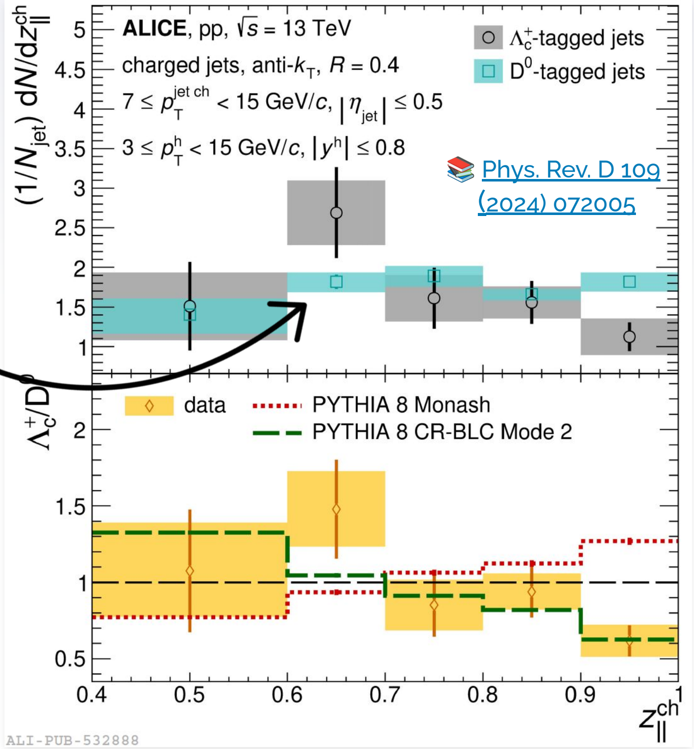
$$z_{||} = \frac{\vec{p}_{\mathrm{ch\ jet}} \cdot \vec{p}_{\mathrm{HF}}}{\vec{p}_{\mathrm{ch\ jet}} \cdot \vec{p}_{\mathrm{ch\ jet}}}$$



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

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

- ➢ PYTHIA 8 CR mode in better agreement with data than the PYTHIA 8 Monash tune



Phys. Rev. D 109 (2024) 072005

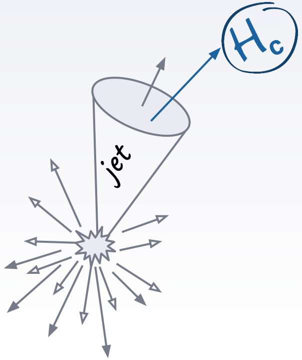
PYTHIA: EPJC 74 3024 (2014), JHEP 1508 (2015) 003

Summary

ALICE has detailed the charm-quark fragmentation in D mesons via jets and correlations:

→ p_T-differential description of the charm-jet properties,

→ fragmentation in PYTHIA 8 reproduces within uncertainties the measurements.



The **charm-to-baryon** fragmentation accessible with pp data at $\sqrt{s}$ = 13 TeV:

→ indications of ***softer fragmentation*** from both **Λ^+_c - h** and **Λ^+_c - jets**;

→ observed discrepancies between **Λ^+_c - h** measurements and PYTHIA 8 predictions.

More will come with **Run 3** data:

- ➢ extended trigger p_T reach, higher granularity, ...
- ➢ more charm hadron states can be studied (D_s^+, Σ_c^+, ...)
- ➢ larger collision systems (Pb–Pb)

Thanks for your attention!

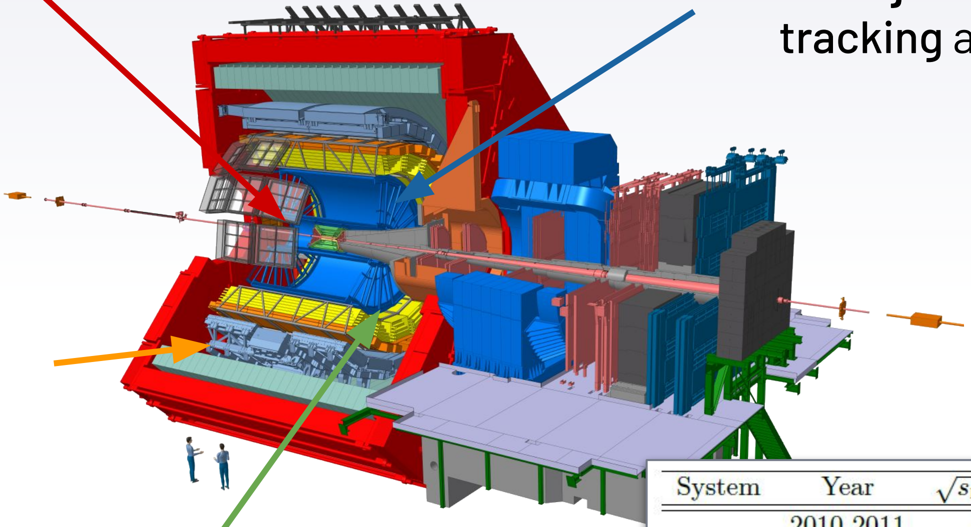
Additional Material

A Large Ion Collider Experiment

ALICE

V0:
trigger and event selection

Time Projection Chamber (TPC):
tracking and PID via dE/dx



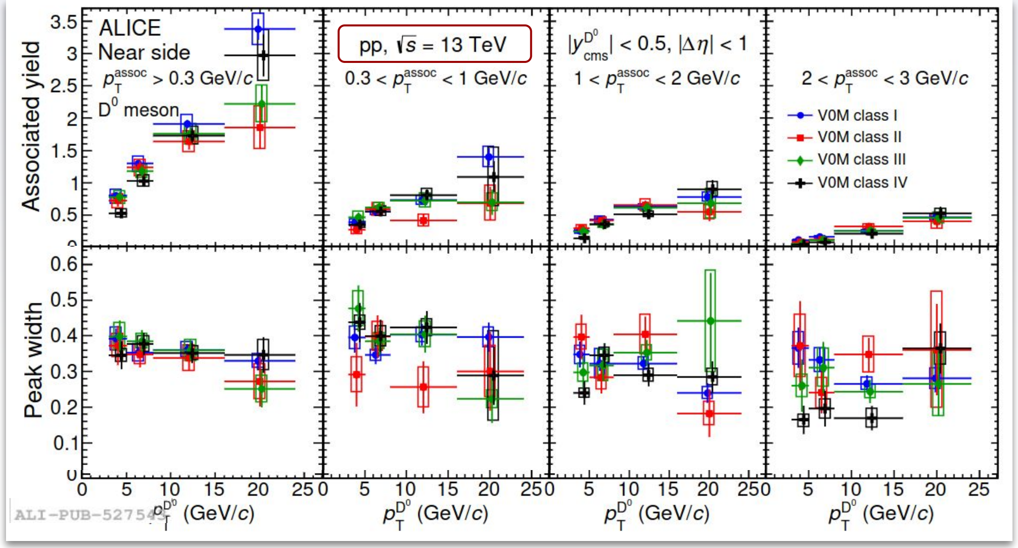
Time-Of-Flight Detector (**TOF**):
PID via time of flight

Inner Tracking System (ITS):
tracking, vertexing

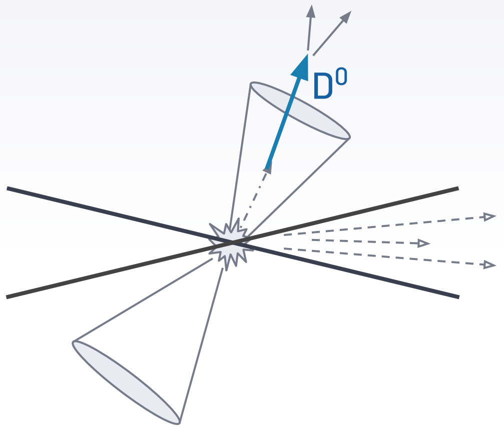
System	Year	$\sqrt{s_{NN}}$ (TeV)	L_{int}
Pb–Pb	2010-2011	2.76	$\approx 75\,\mu b^{-1}$
	2015	5.02	$\approx 250\,\mu b^{-1}$
	2018	5.02	$\approx 1\,nb^{-1}$
pp	2009-2013	0.9, 2.76	$\approx 200\,nb^{-1}$, $\approx 100\,nb^{-1}$
		7, 8	$\approx 1.5\,pb^{-1}$, $\approx 2.5\,pb^{-1}$
	2015-2017	5.02	$\approx 1.8\,pb^{-1}$
	2015-2018	13	$\approx 25\,pb^{-1}$

Charm fragmentation with event multiplicity

Near side



V0M class I < ... < V0M class IV



Charm-jet characterisation as a function of different **underlying-event activity**:

→ correlation peaks consistent across both pp **high-** and **low-**multiplicity events

No evidence of modification in **charm-to-meson fragmentation** with event multiplicity

Is it coalescence?

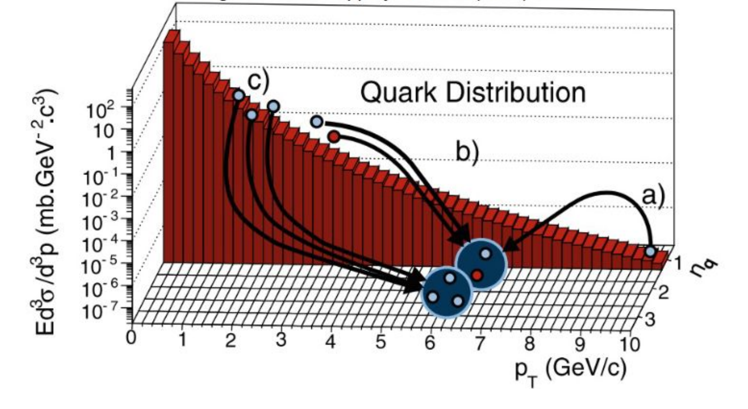
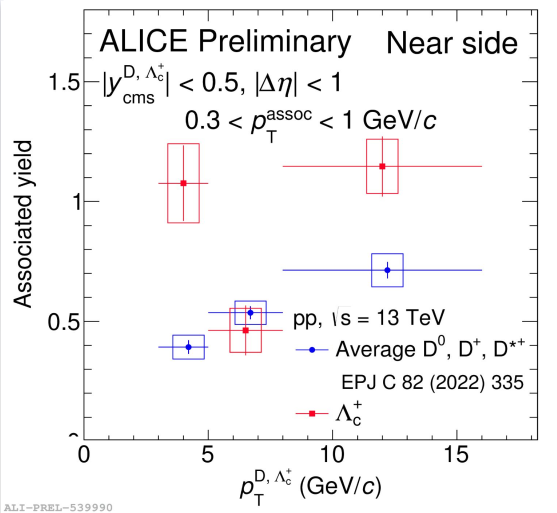


Figure from B. Hippolyte, EPJC (2009) 62: 237–242

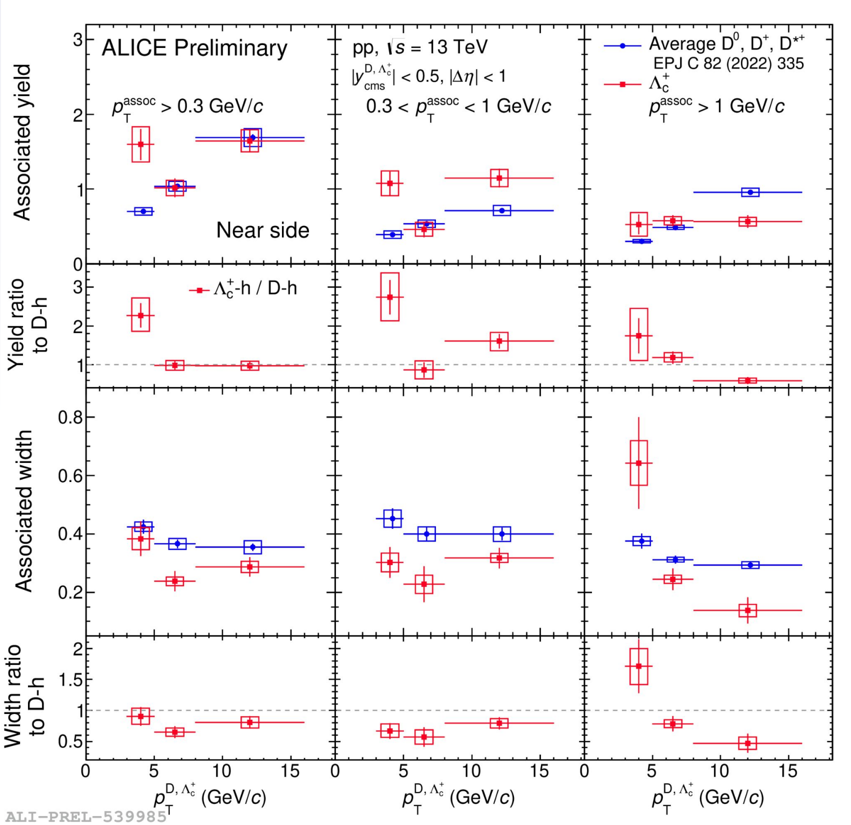


- For the same p_T^c $\rightarrow$ $\overline{p_T^{\Lambda c,\,coal}} > \overline{p_T^{\Lambda c,\,fragm}}$
- The yields depends mainly on p_T^c

→ To a $p_T^{\Lambda c,\,coal}$ would correspond a yield depending on p_T^c
Should we observe a suppression wrt the fragmentation?

Rich parton environments required (?) :
→ high-mult ?
→ augmented not-correlated particles
→ larger baseline → NOT OBSERVED

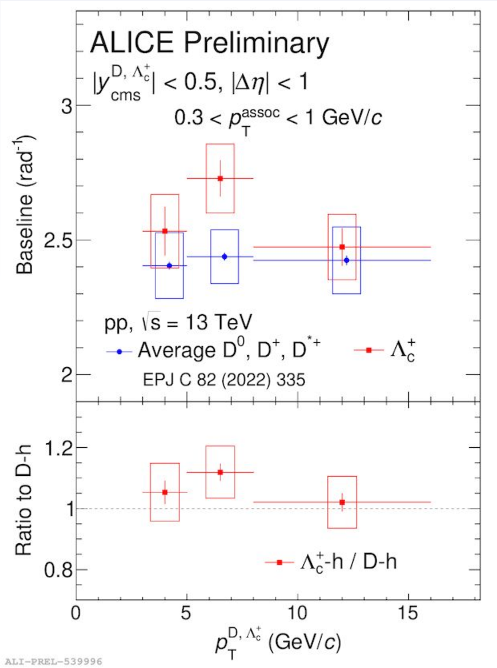
Λ_c^+-h correlations: Near-side and Baseline



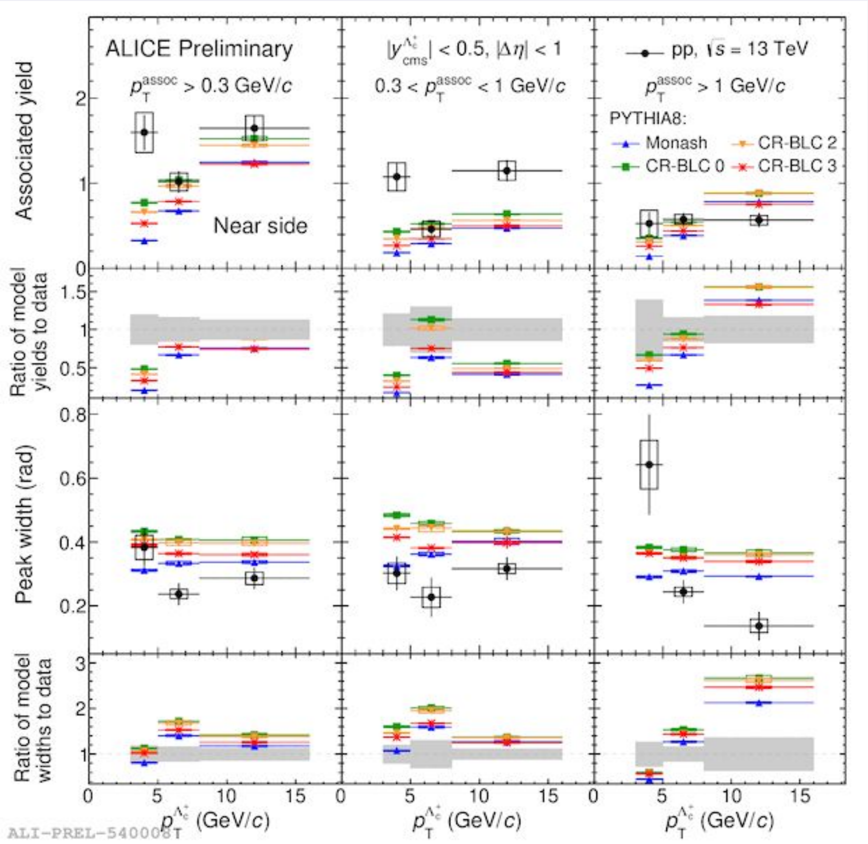
PYTHIA: JHEP 1508 (2015) 003

POWHEG: JHEP 06 (2010) 043

Baseline



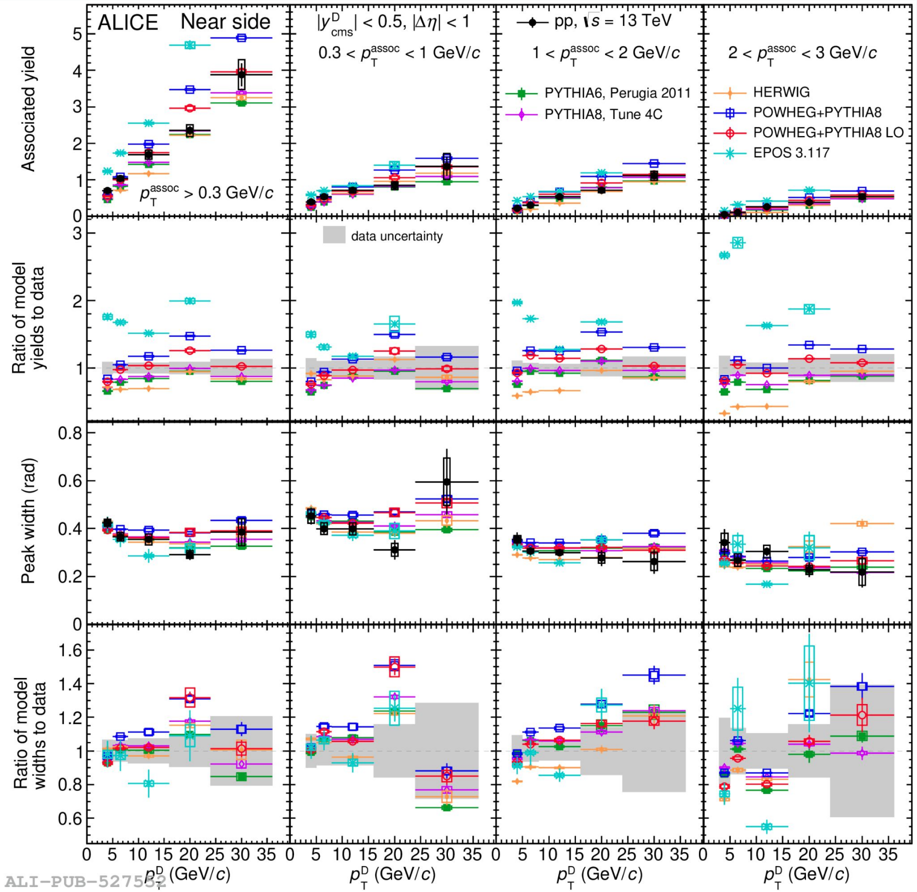
Λ_c^+-h correlations: Near-side



PYTHIA: JHEP 1508 (2015) 003

D-h: Near-side comparisons with MC models predictions

Eur. Phys. J. C 82, 335 (2022)



PYTHIA: JHEP 1508 (2015) 003

POWHEG: JHEP 06 (2010) 043

EPOS 3: Phys.Rev.C 82(2010)044904

HERWIG: Eur.Phys.J C76 (2016) 196