QNP 2024

Exploring charm-quark fragmentation with correlation and jet measurements by ALICE

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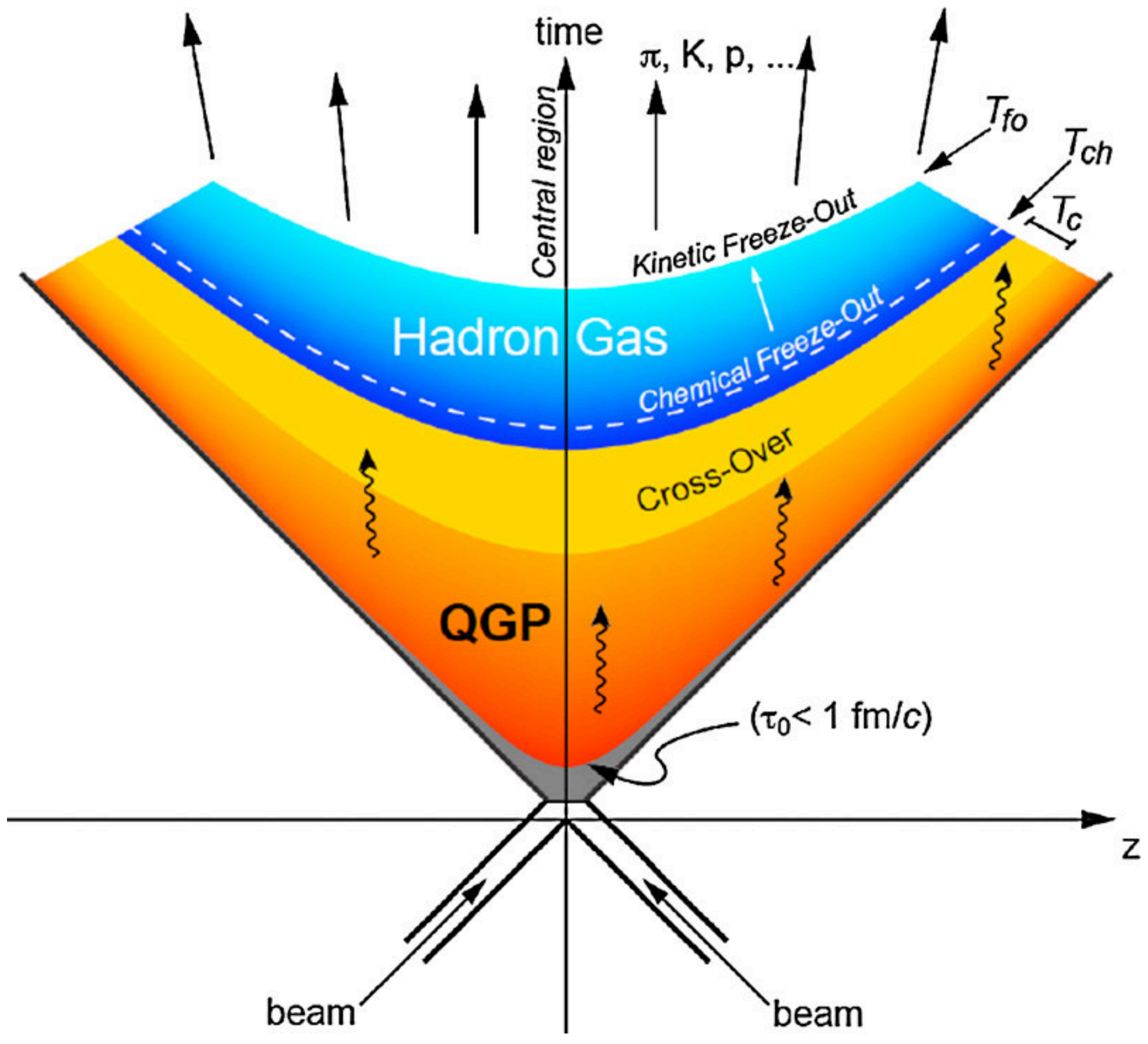
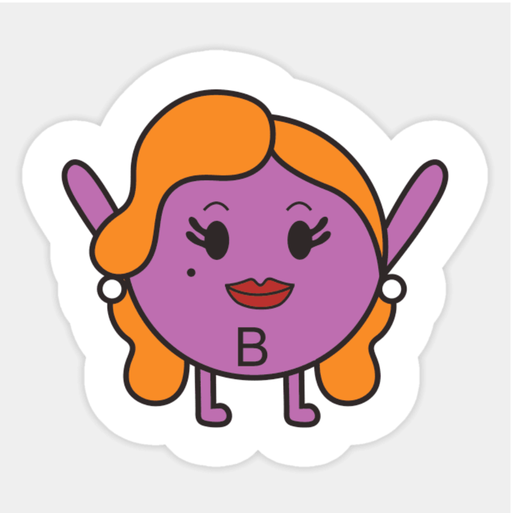
Heavy quarks: a unique probe of QGP

- Heavy quarks: charm and beauty, predominantly produced by the parton-parton hard scattering in hadronic collisions -> perturbative QCD can be applied.
- In heavy-ion collisions: a quark-gluon plasma (QGP) state is produced
  - -> Heavy quarks are produced before QGP formation (t_{QGP} ~ 1 fm/c and $t_Q = 1/2m_Q \leq 0.1$ fm/c)
  - -> Identity is preserved while traversing the medium
  - -> Experience the complete evolution of QGP medium





Charm
m_c ~ 1.3 GeV/c^2
t_c ~ 0.08 fm/c

Beauty
m_b ~ 4.2 GeV/c^2
t_b ~ 0.03 fm/c

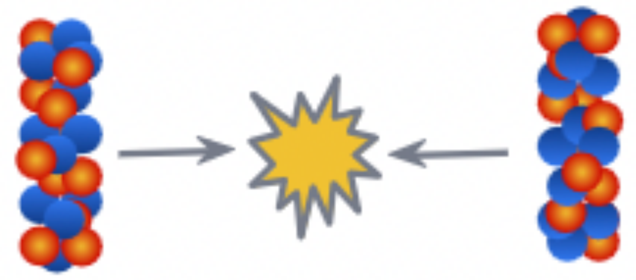
- Energy loss of partons traversing the QGP is expected to occur via both inelastic (radiative energy loss via medium-induced gluon radiation) and elastic (collisions with the QGP constituents) processes.

★ **Therefore, heavy quarks act as important tools for characterizing the medium formed in heavy-ion collisions.**

Heavy Flavours: The Physics Behind the Exploration

pp collisions:
- Test pQCD calculations down to $p_T \approx 0$
- Study heavy-flavour quark production, fragmentation and hadronization
- Reference for p—Pb and Pb—Pb systems

p—Pb collisions:
- Study cold nuclear matter (CNM) effects
- Possible collective effects

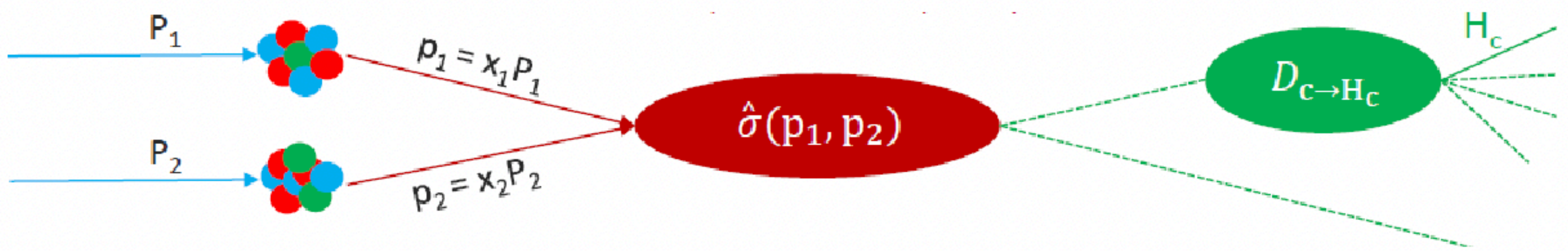


Pb—Pb collisions:
- Sensitivity to the energy-loss mechanism of heavy quarks (collisional and radiative processes)
- Colour/mass dependence of in-medium energy loss
- Possible modification of the quark hadronization

Production of heavy-quark hadrons can be calculated using the factorization approach:

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

Parton distribution functions (PDFs) — **Hard scattering cross section (pQCD)** — **Fragmentation function (hadronisation)**

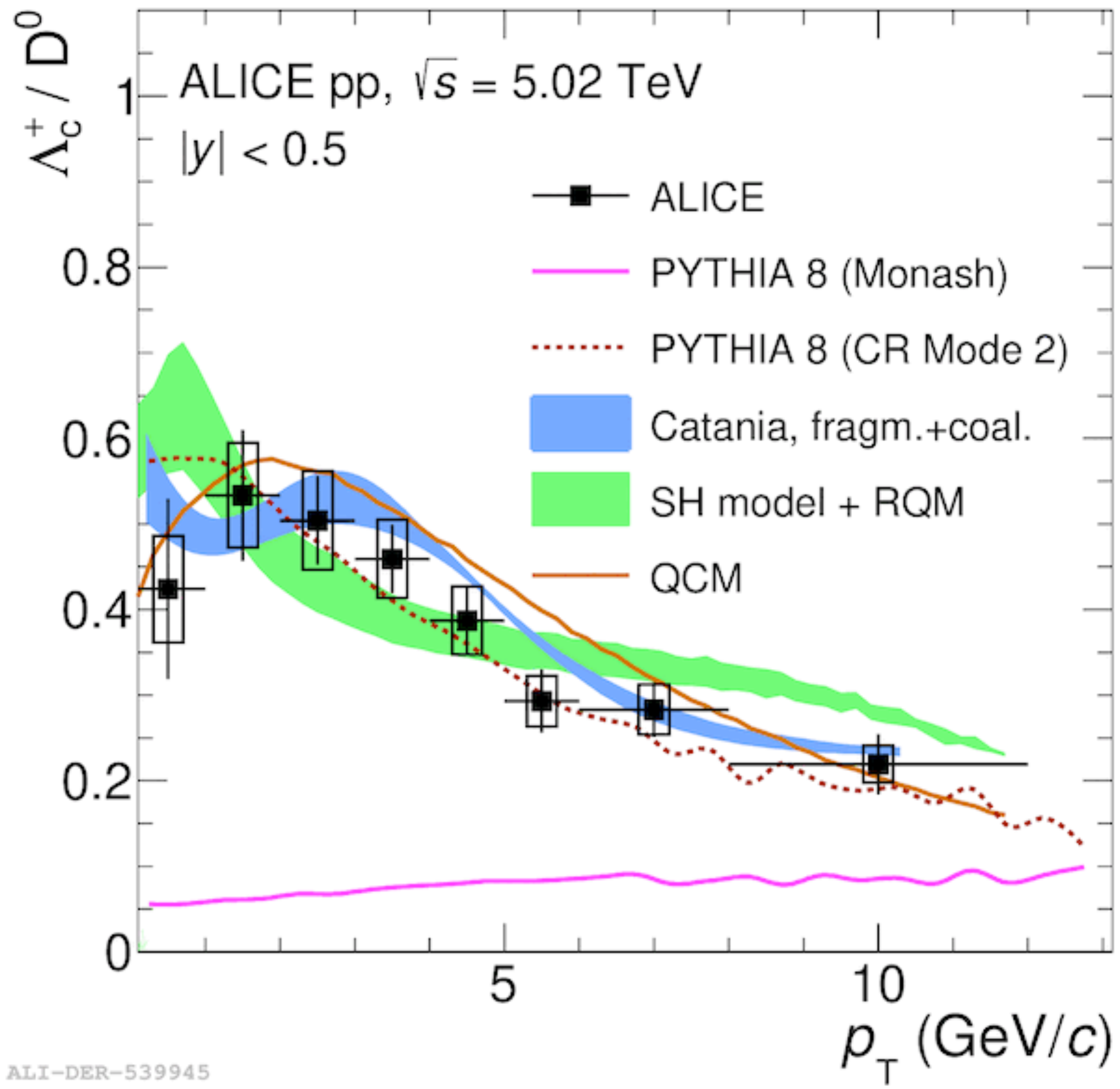


Assumed to be universal across collision systems

Questioning the Universality: Insights from ALICE Measurements

Measurements of the baryon-to-meson yield ratio -> p_T-dependent enhancement of Λ_c^+/D^0 ratio in pp w.r.t. e^+e^-

Phys. Rev. C 107 (2023) 064901



Models based on fragmentation functions evaluated from e^+e^- collisions underestimate the data (PYTHIA 8 Monash)

Different hadronization mechanisms proposed:

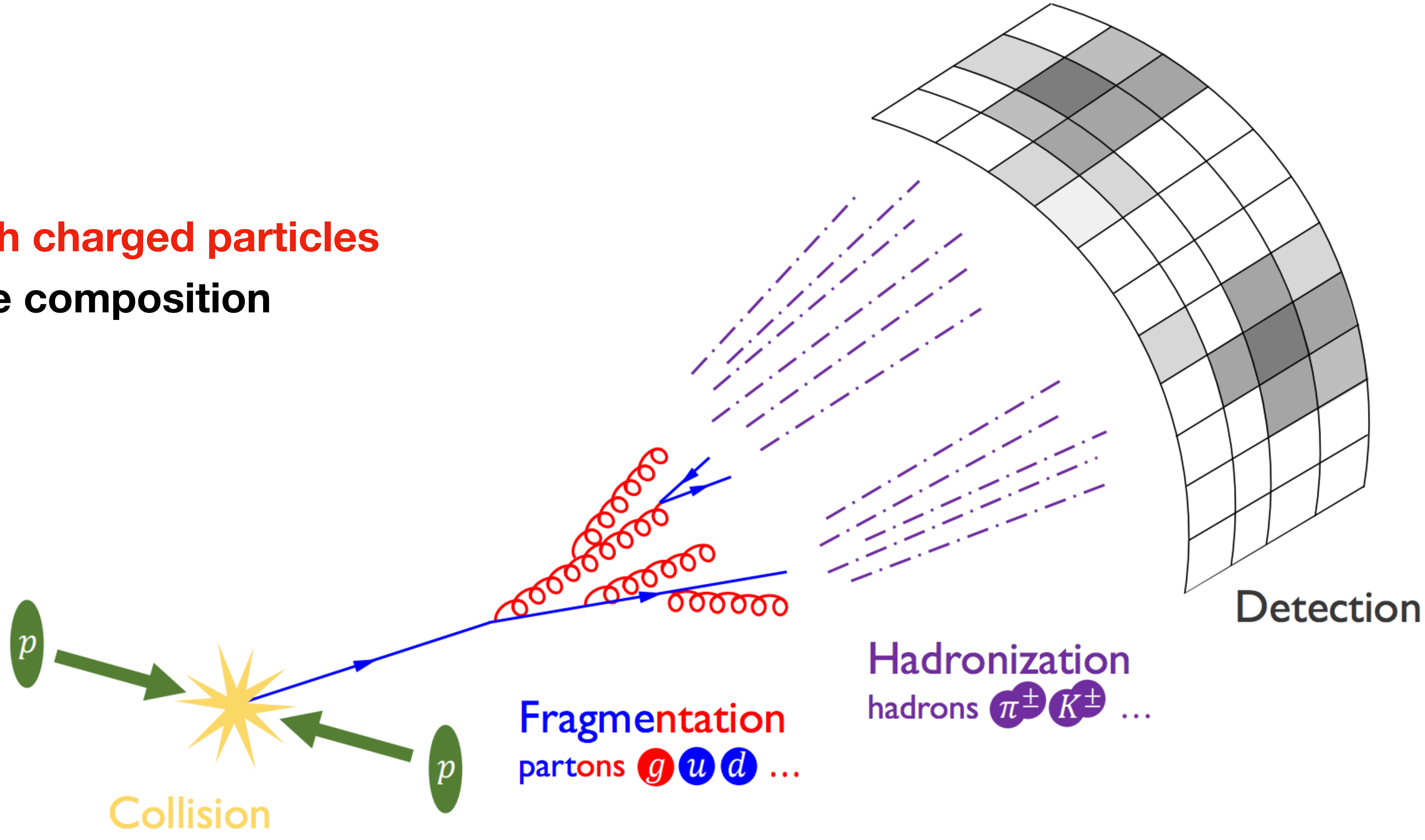
- **Color reconnection beyond leading color (PYTHIA 8 CR Mode 2).**
- **Hadronization via coalescence and fragmentation in a thermalised system of gluons, light quarks and antiquarks (Catania, Quark (re)Combination Model).**
- **Increased feed-down from an augmented set of excited charm baryons (Statistical Hadronisation model + Relativistic Quark model).**

Diving Deeper: Further Investigation of Charm Fragmentation

Regarding fragmentation, additional insights compared to single-particle studies are offered by:

→ **Charm-hadron tagged jets:**
- → **access to the original parton kinematics**
- → **constrain the fragmentation functions**

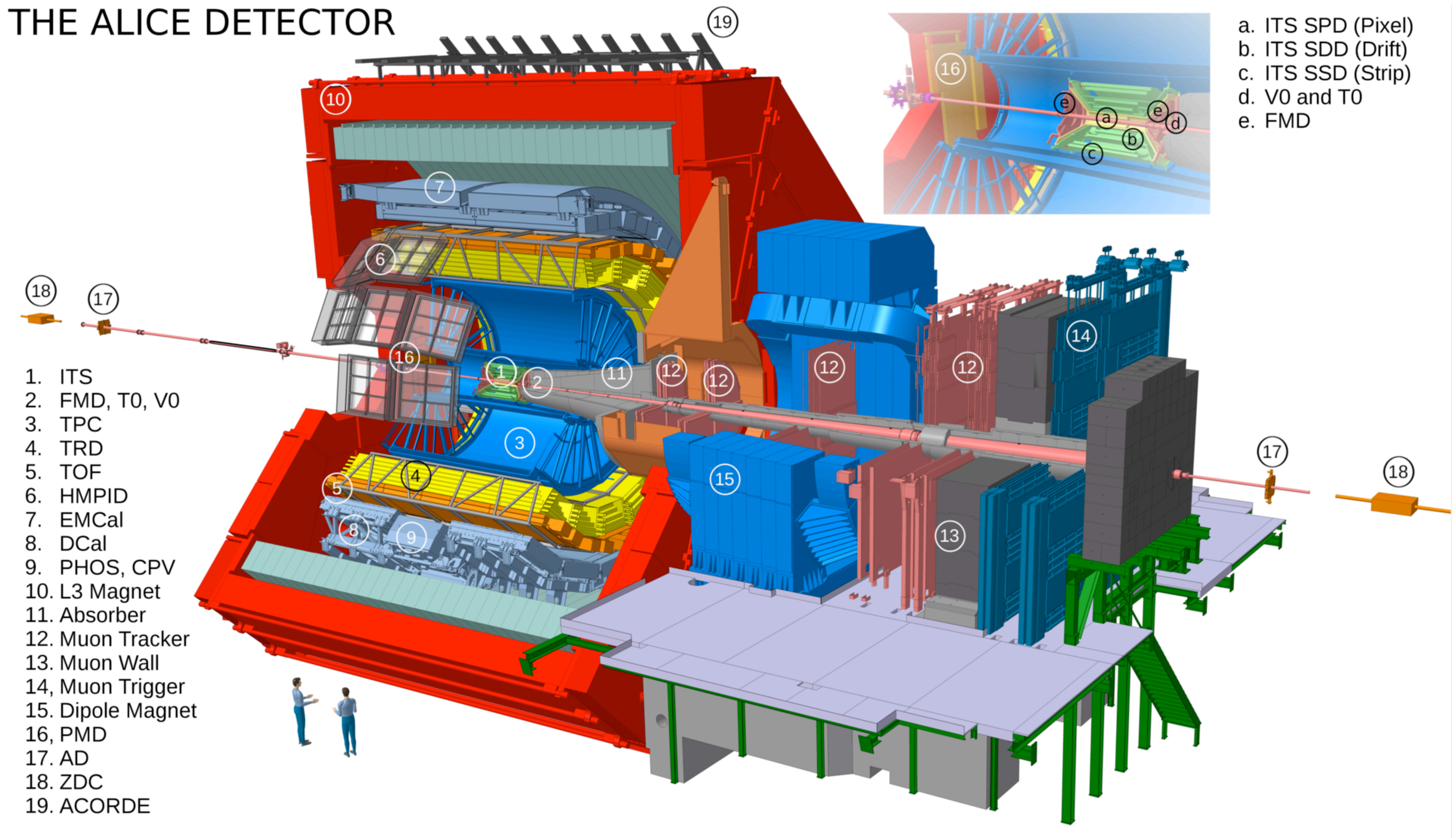
→ **Azimuthal correlations of charm hadrons with charged particles**
- → **description of the jet shape and its particle composition**
- → **sensitivity to production mechanisms**



The ALICE detector (Run 2)

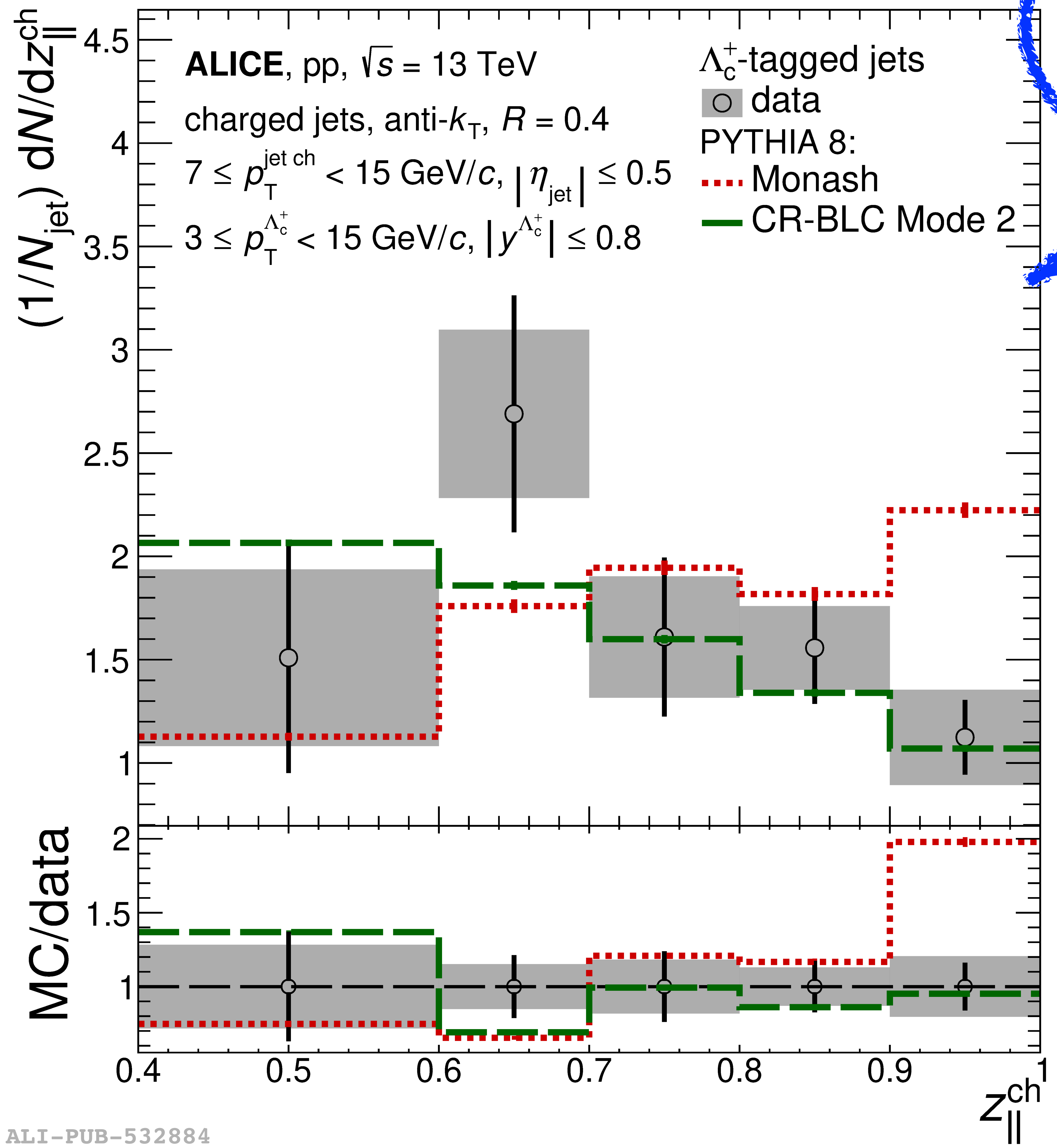
The ALICE detector is excellent in reconstructing identified particles over a broad momentum range and in reconstructing primary and displaced secondary vertices.

- **Inner Tracking System (vertexing, tracking, PID, $|\eta|< 0.9$)**
- **Time Projection Chamber (tracking, PID, $|\eta|< 0.9$)**
- **Time-Of-Flight detector (PID, $|\eta|< 0.9$)**
- **V0 detectors (multiplicity and event activity determination, triggering, $2.8 < \eta < 5.1$, $-3.7 < \eta < -1.7$)**



Λ_c^+-jets momentum fraction

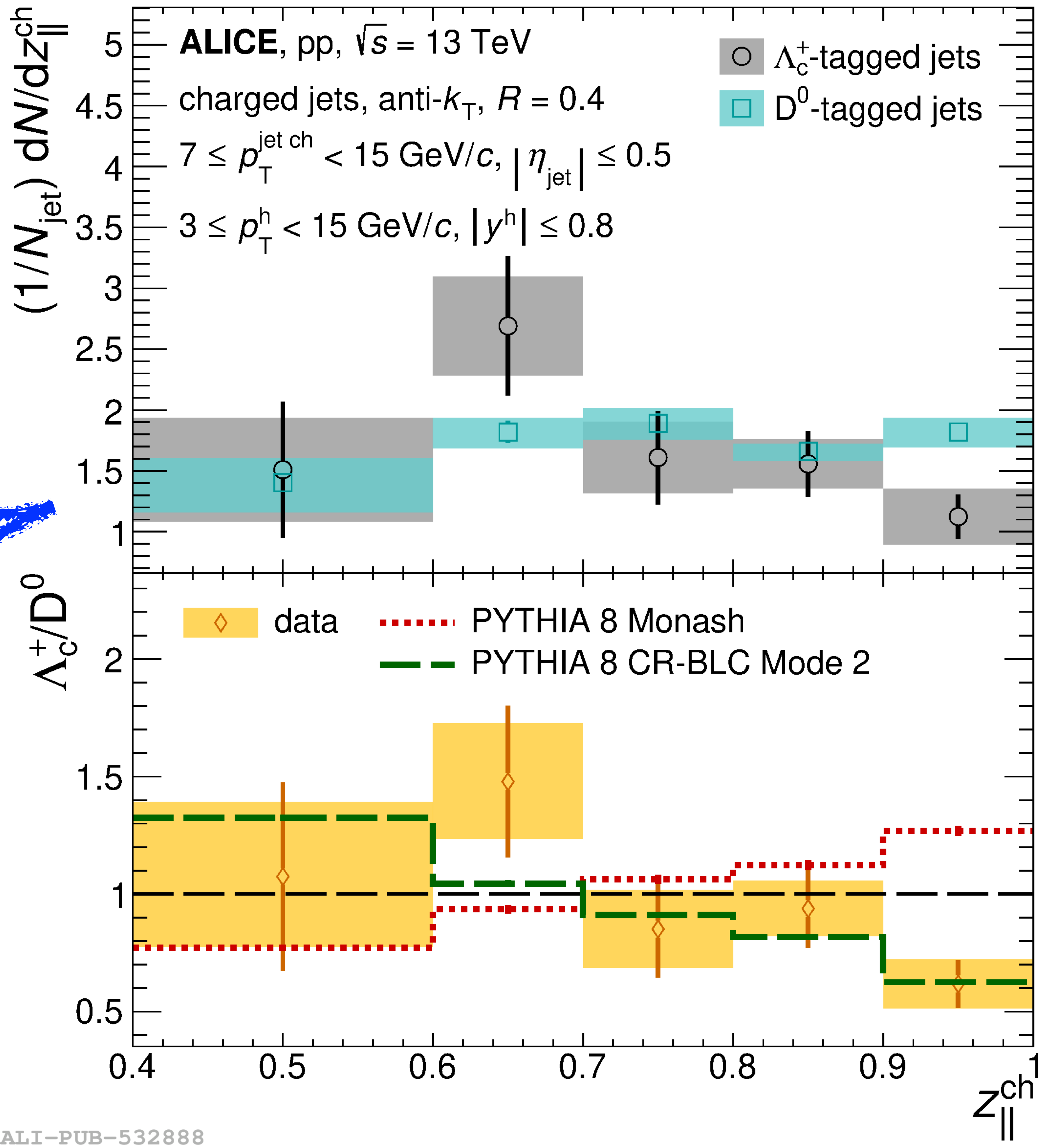
Phys. Rev. D 109 (2024) 072005



ALI-PUB-532884

- **Slightly harder fragmentation in PYTHIA 8 Monash.**
- **PYTHIA 8 CR-BLC Mode 2 shows better agreement with data.**

Phys. Rev. D 109 (2024) 072005



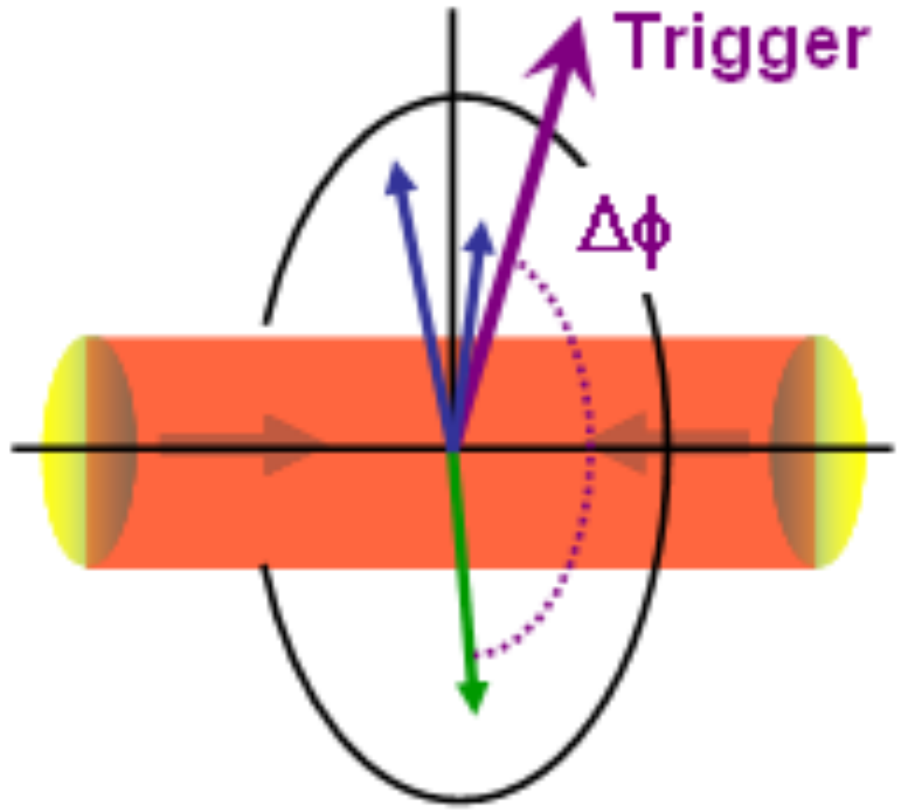
ALI-PUB-532888

Data hint that fragmentation of charm quarks into charm baryons is softer with respect to charm mesons, in the studies kinematic region.

Study of two-particle azimuthal correlations

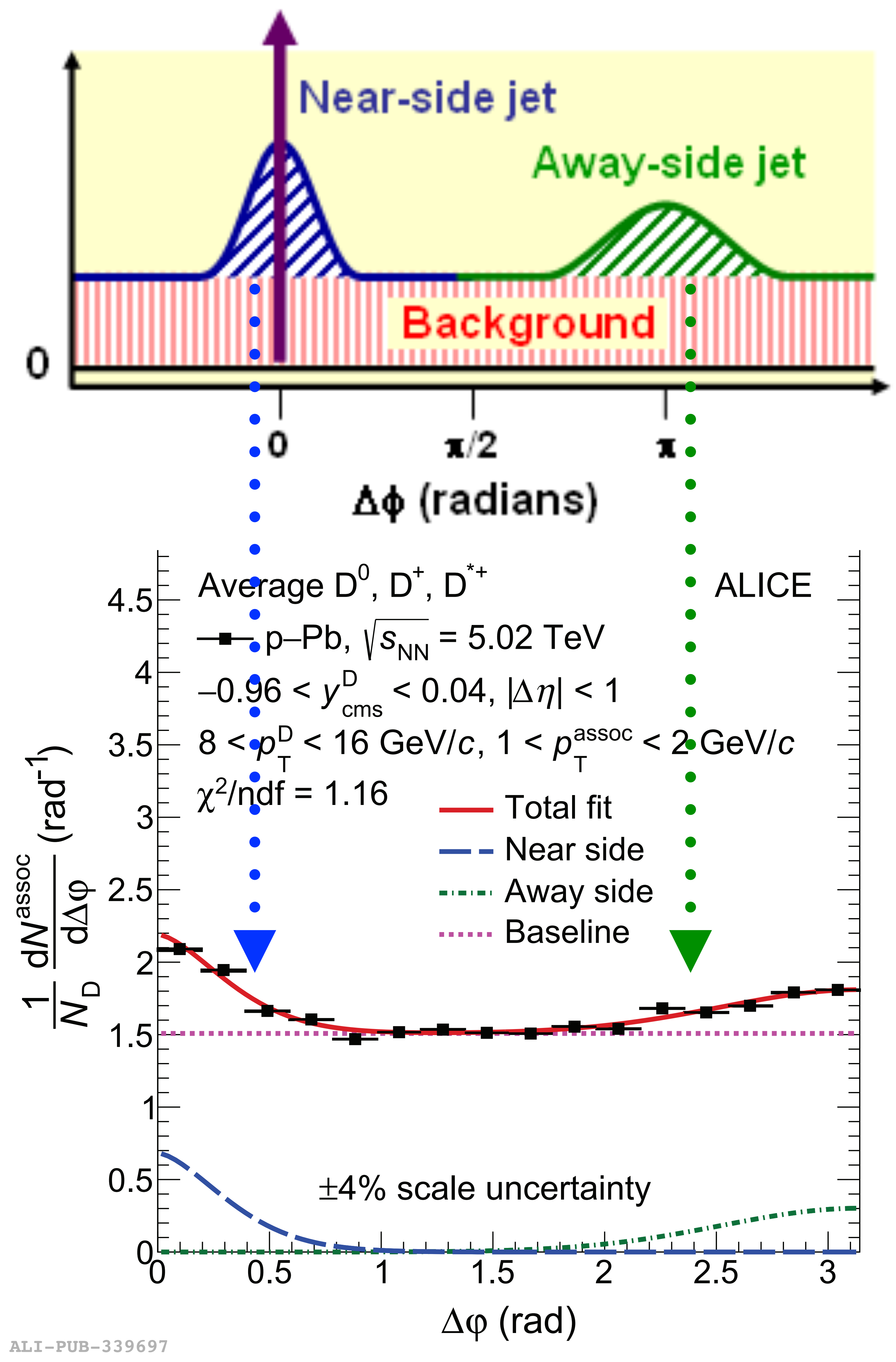
ALICE

The angular distribution of the final-state particles with respect to the direction of the tagged charmed hadron is studied, providing an insight into the fragmentation of the charm quark.



Fit function:

$$f(\Delta\varphi) = C + \frac{Y_{\mathrm{NS}}\,\beta}{2\alpha\Gamma(1/\beta)} \exp\left(-\frac{(\Delta\varphi)^{\beta}}{\alpha^{\beta}}\right) + \frac{Y_{\mathrm{AS}}}{\sqrt{2\pi\sigma_{\mathrm{AS}}^{2}}} \exp\left(-\frac{(\Delta\varphi-\pi)^{2}}{2\sigma_{\mathrm{AS}}^{2}}\right)$$



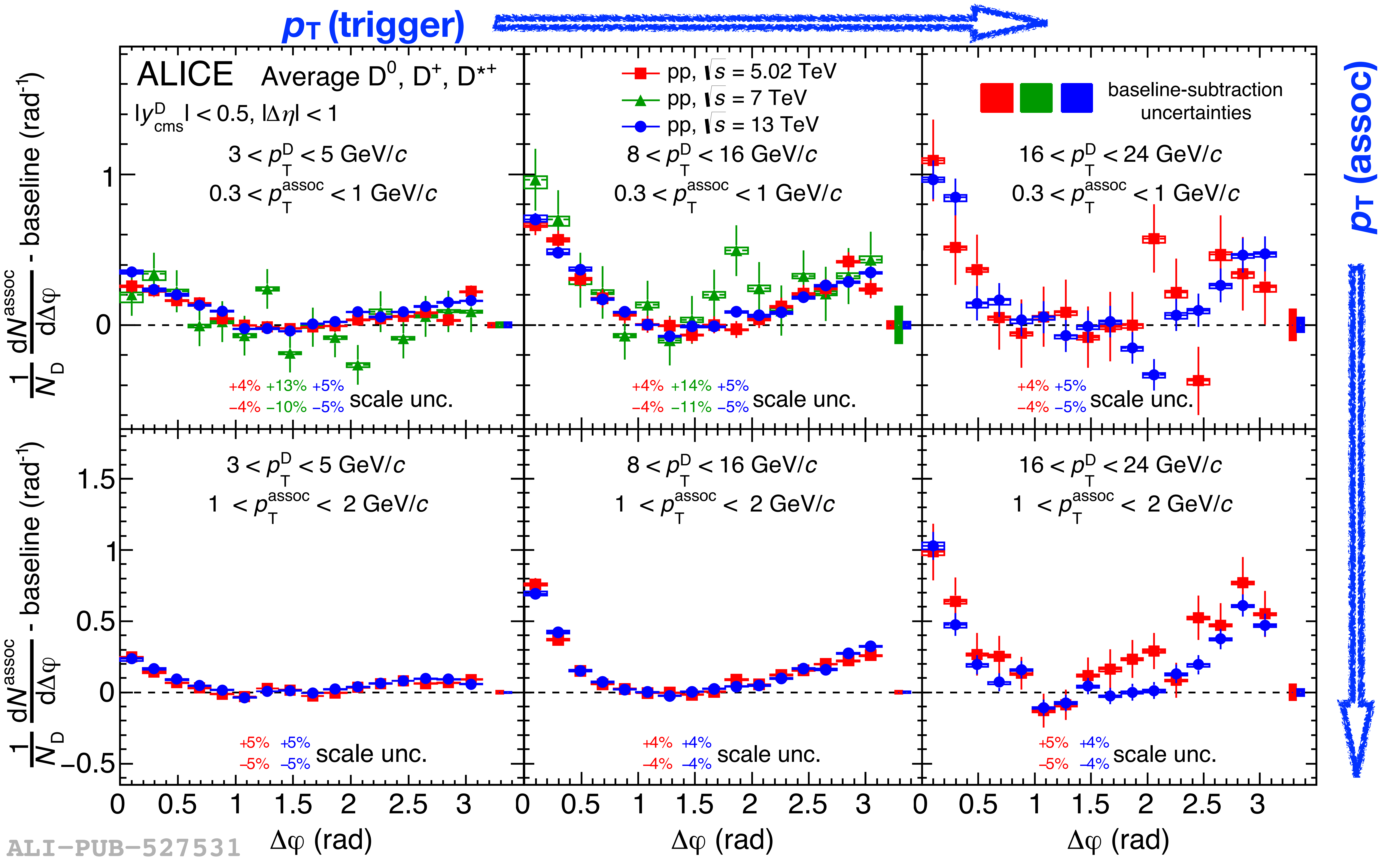
Characterization of the jet shape and its composition (for Leading Order $c\bar{c}$ production) :

- Near Side (NS): fragmentation of the tagged charm quark;
- Away Side (AS): fragmentation of the other charm quark;
- Transverse Region: sensitivity to underlying event

EPCJ 80 (2020) 979

Two-particle azimuthal correlations between D mesons and charged particles

Comparison of correlation distributions among different collision energies in pp collisions :



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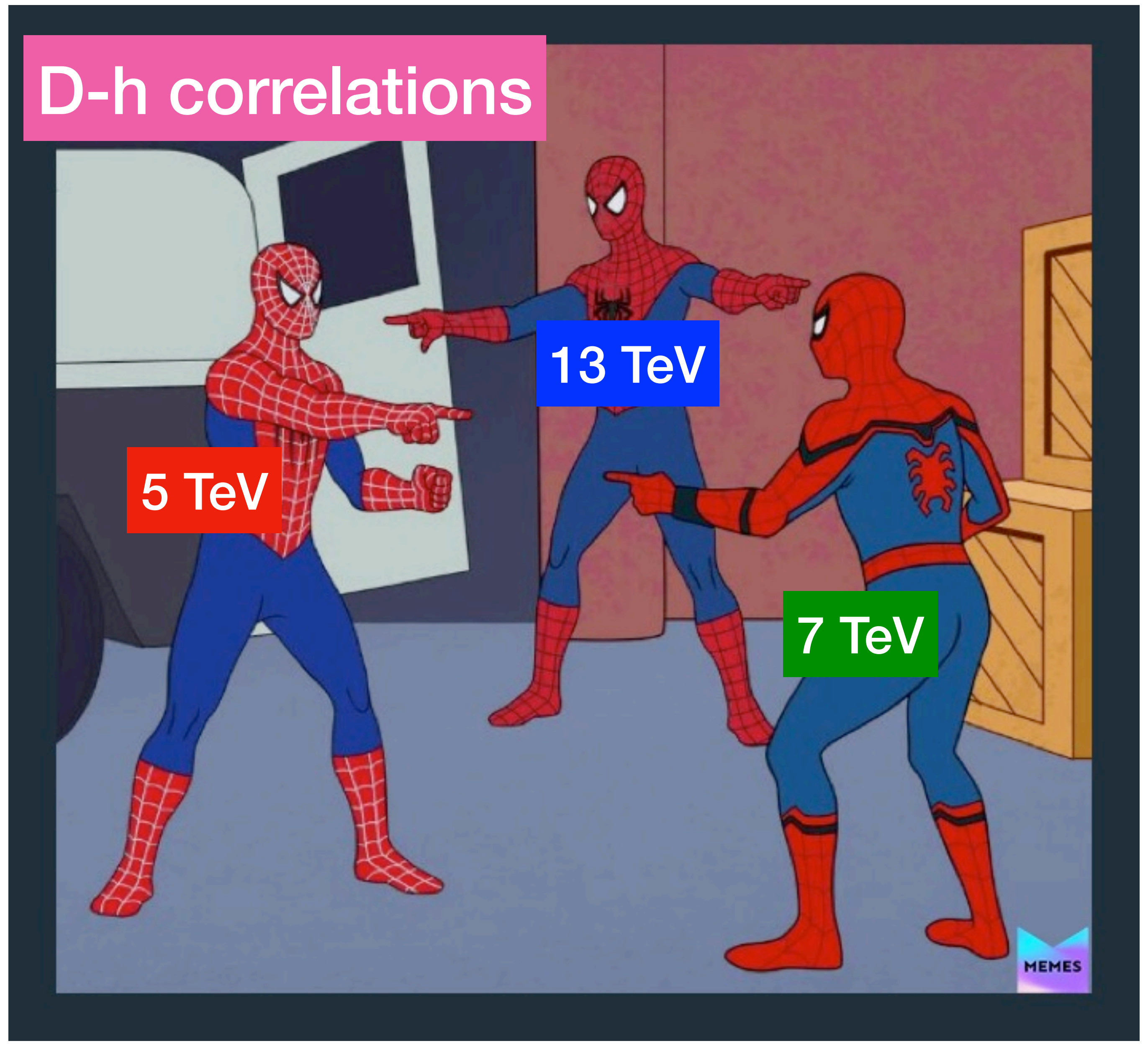
Compatibility found within uncertainties in all kinematic ranges.



D-h correlations : Near- and away-side peak observables

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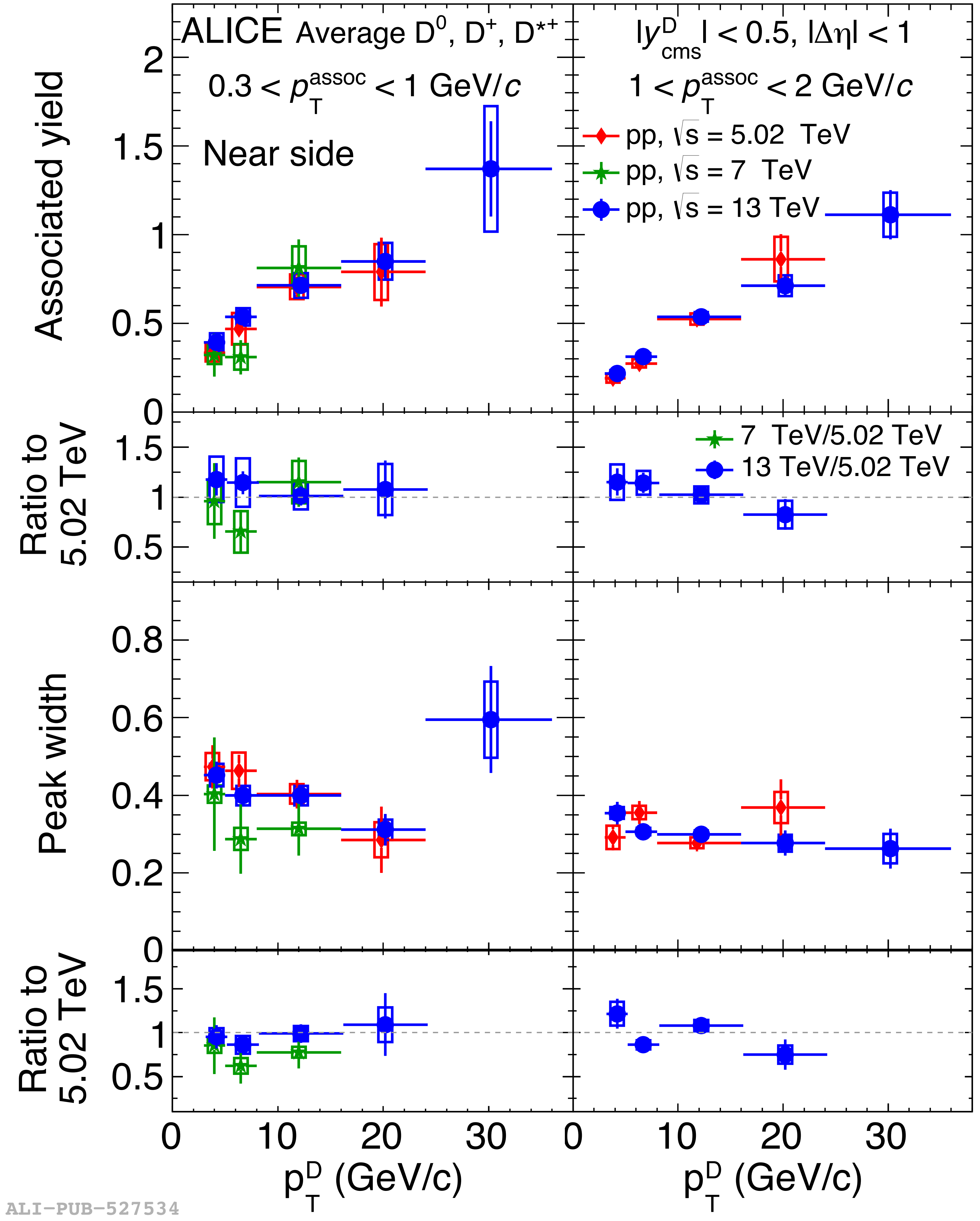
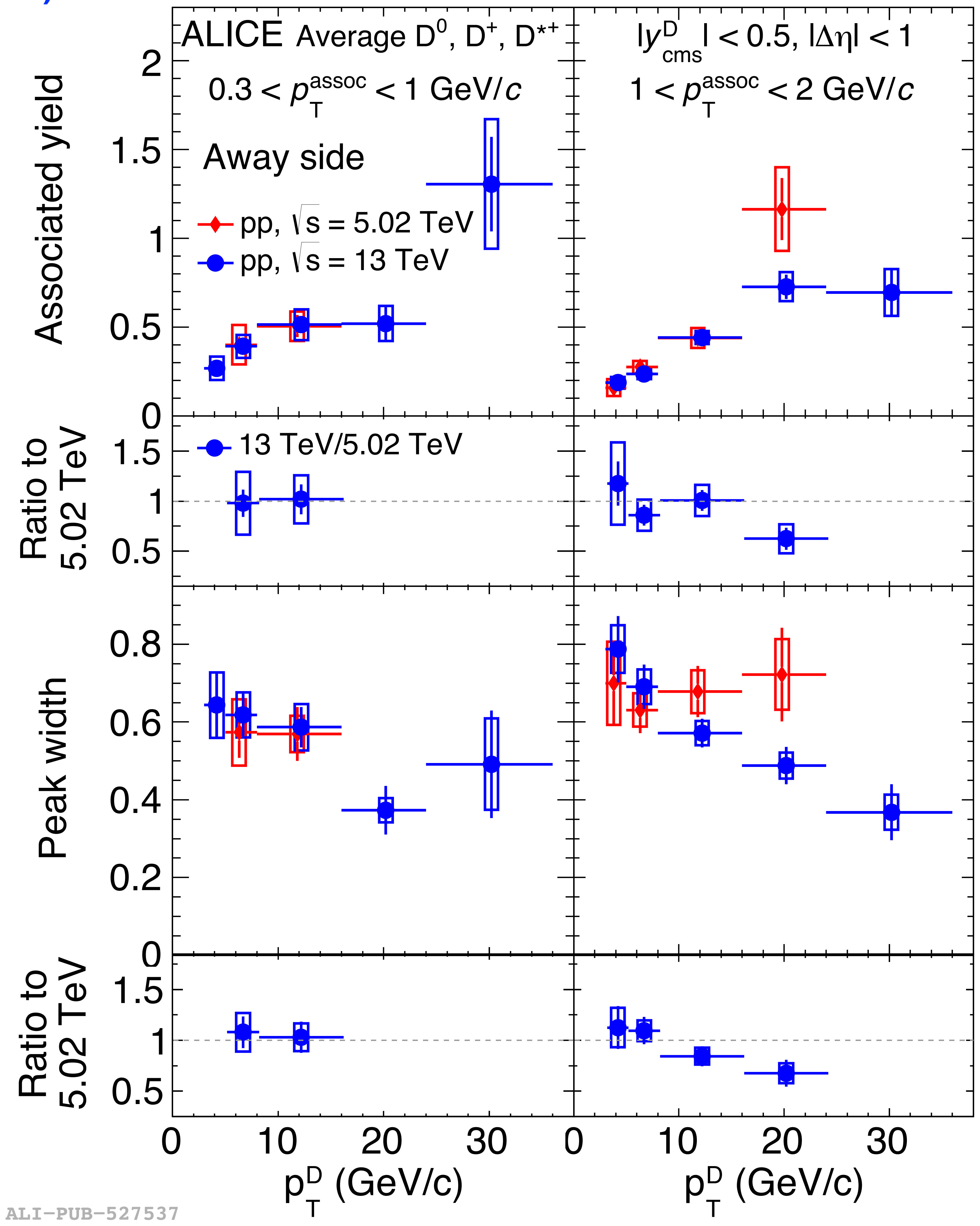
Near side



Away side



Increase of associated particles in NS and AS peaks with increasing D-meson p_T

→ Due to the larger energy available to the parton

→ Characterization of particle multiplicity in jets

Decrease of the peak width with increasing D-meson p_T

→ Jet hard core more collimated due to larger parton Lorentz boost

No centre-of-mass energy dependence observed

D-h correlations : Comparison with theoretical models

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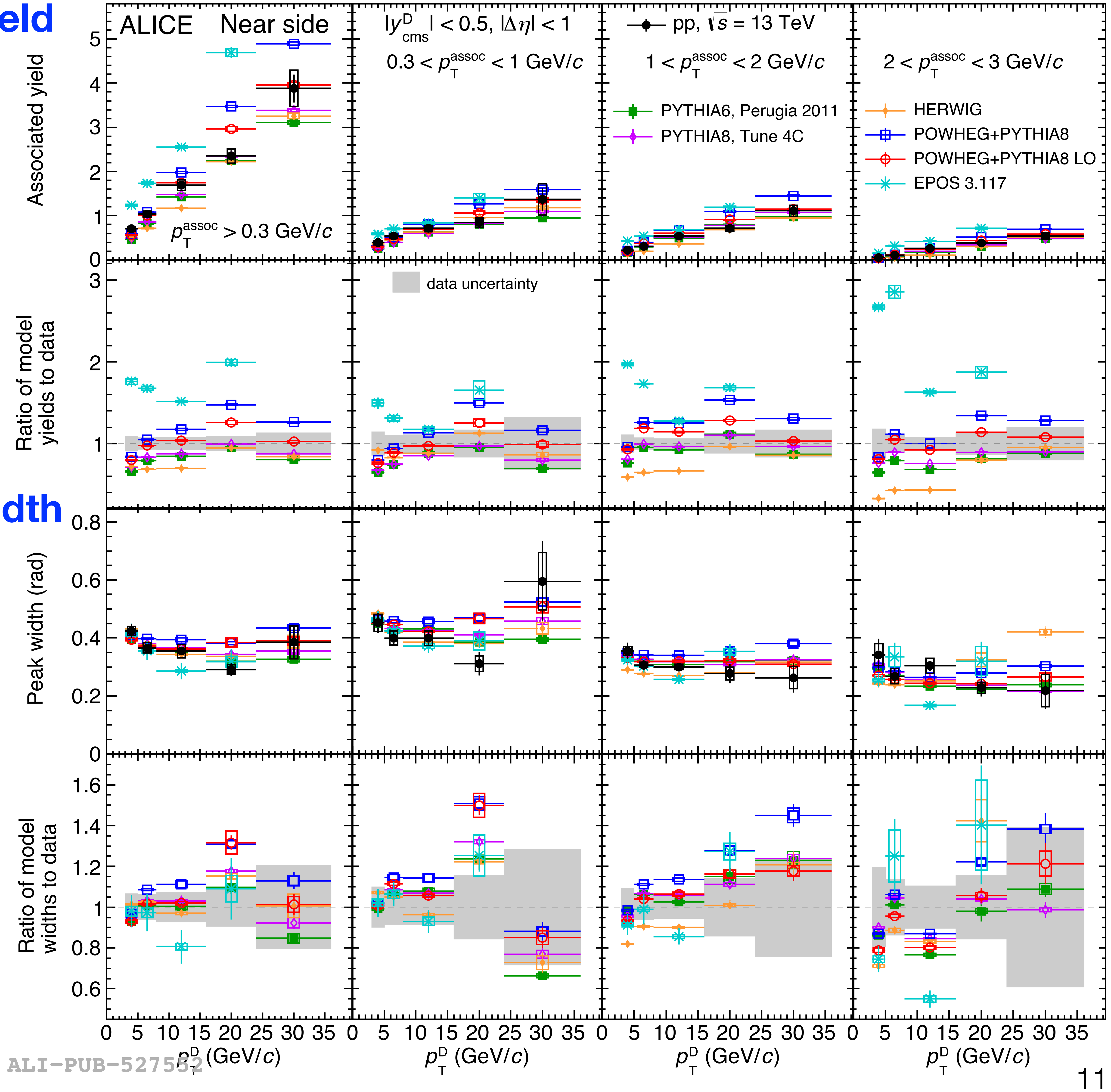
Yield

Width



Validation of parton-shower models and Monte-Carlo generators :

For yields:

- PYTHIA 8 and POWHEG+PYTHIA provide the best description
- HERWIG tends to underestimate the NS peak yield at low p_T (D) and at high p_T (assoc)
- EPOS overestimates the NS yields over the whole p_T range

For widths:

- All models provide the reasonably good description of the measurement

Two-particle azimuthal correlations between Λ_c^+ baryon and charged particles

D meson - h vs. **Λ_c^+ baryon - h**

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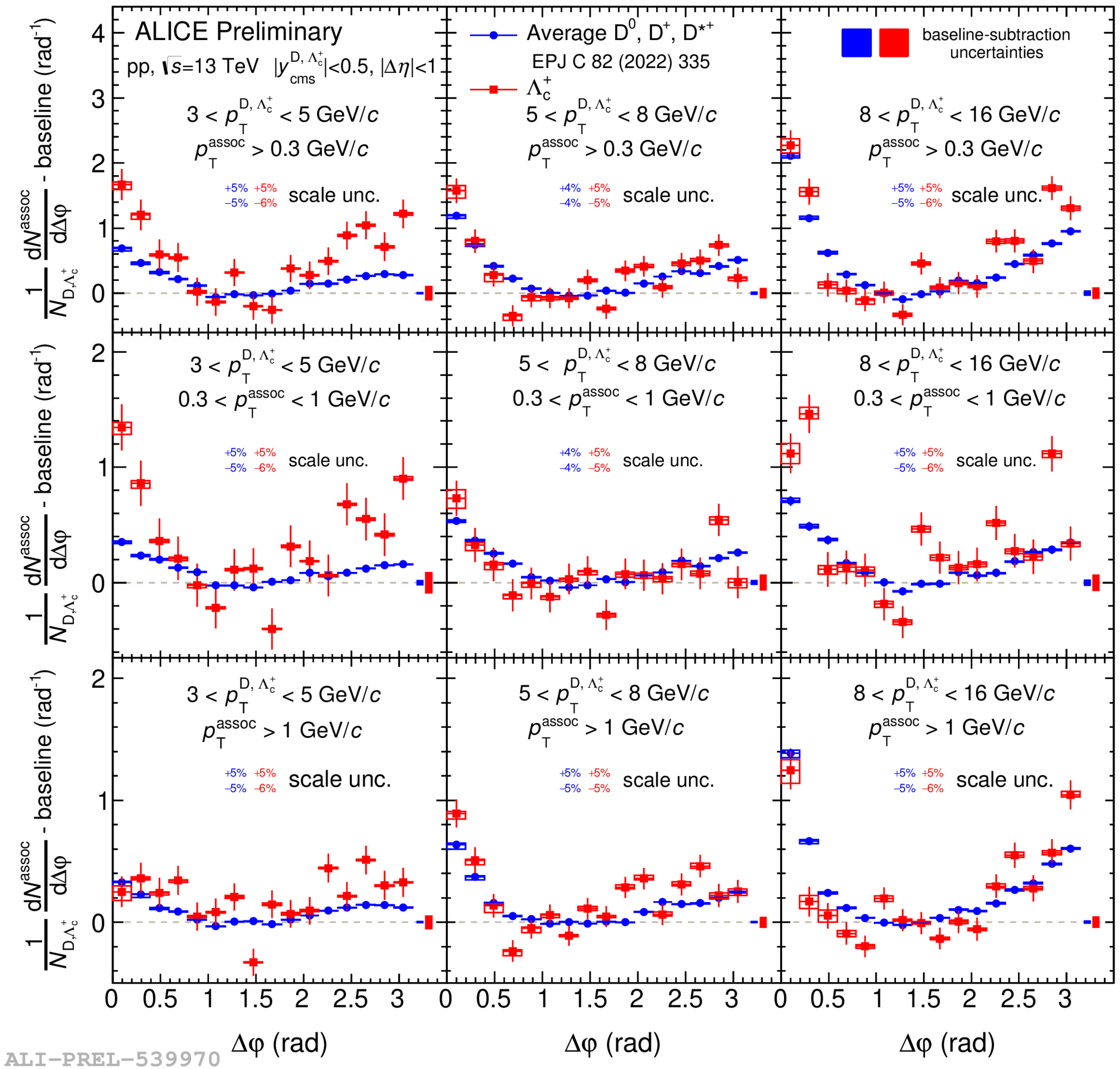
From the comparison of the Δφ shape :

- Higher yield observed for Λ_c^+-trigger particle for the low-p_T trigger and low-p_T associated particles region.
- More populated peaks characterise the charm fragmentation in this p_T region when it hadronizes into a baryon rather than into a meson.



Possible explanations :

a) different energy of the charm quark as a consequence of a softer Λ_c fragmentation w.r.t D meson (hints in Λ_c^+-jet FF measurement, Phys. Rev. D 109 (2024) 072005)

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

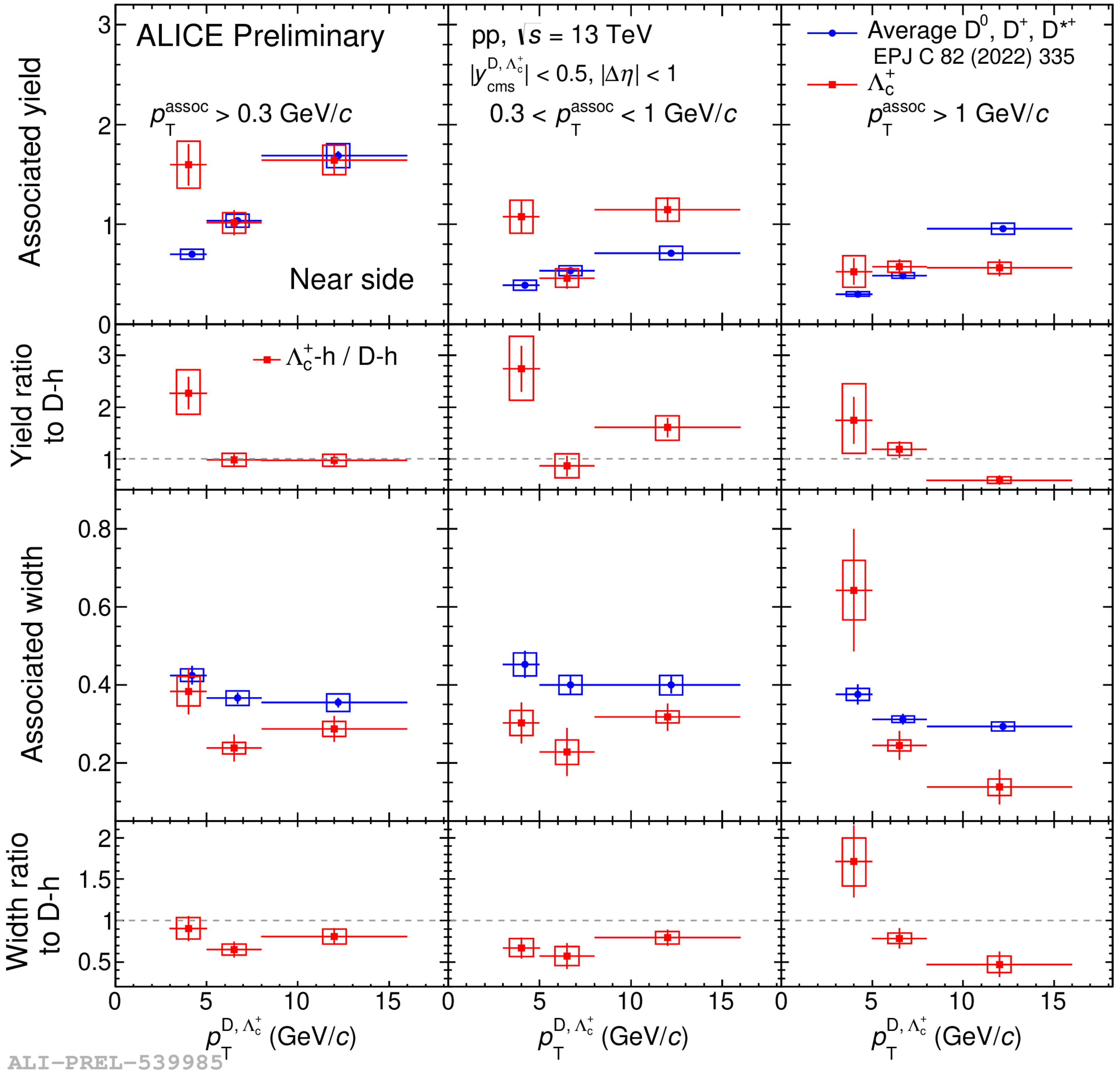
c) hadronization by coalescence

Λ_c^+-h correlations: Near- and away-side peak observables

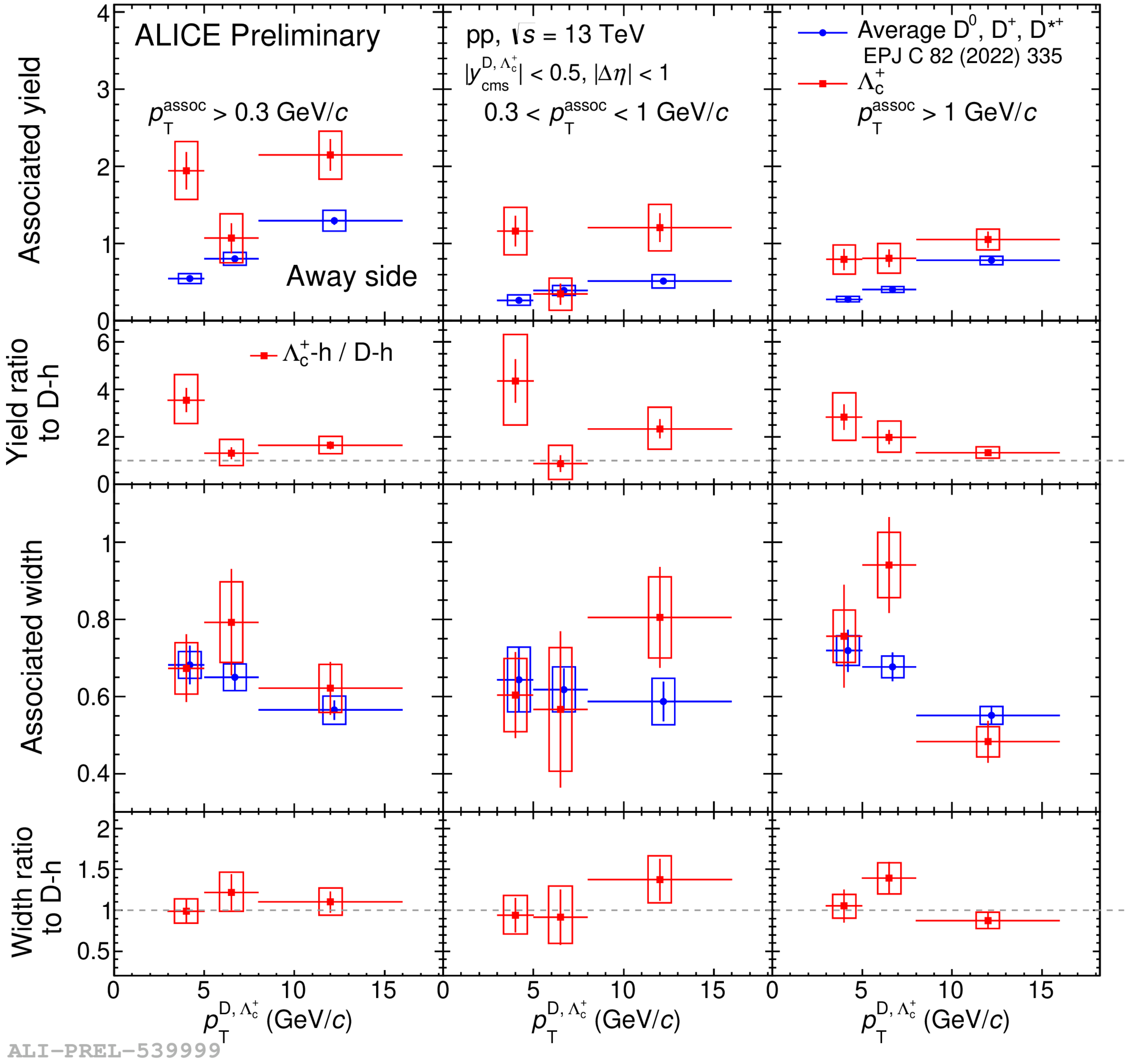
Near Side

Yield

Width



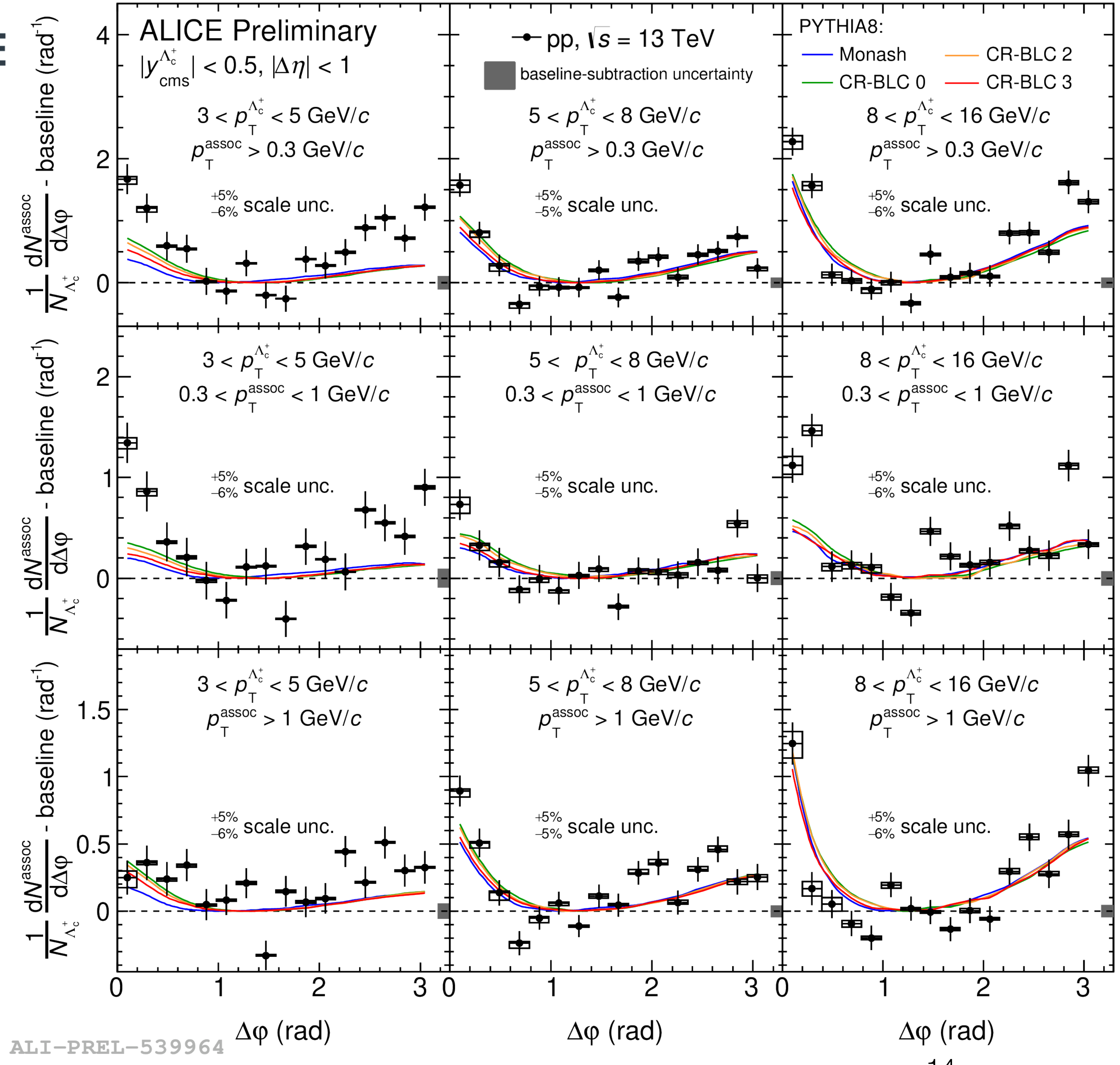
Away Side



→ **larger particle multiplicity in near-side jet with respect to D-h correlations for small p_T trig**

→ **larger yields are also observed for the away-side, which tends to favour softer Λ_c^+ fragmentation w.r.t D meson**

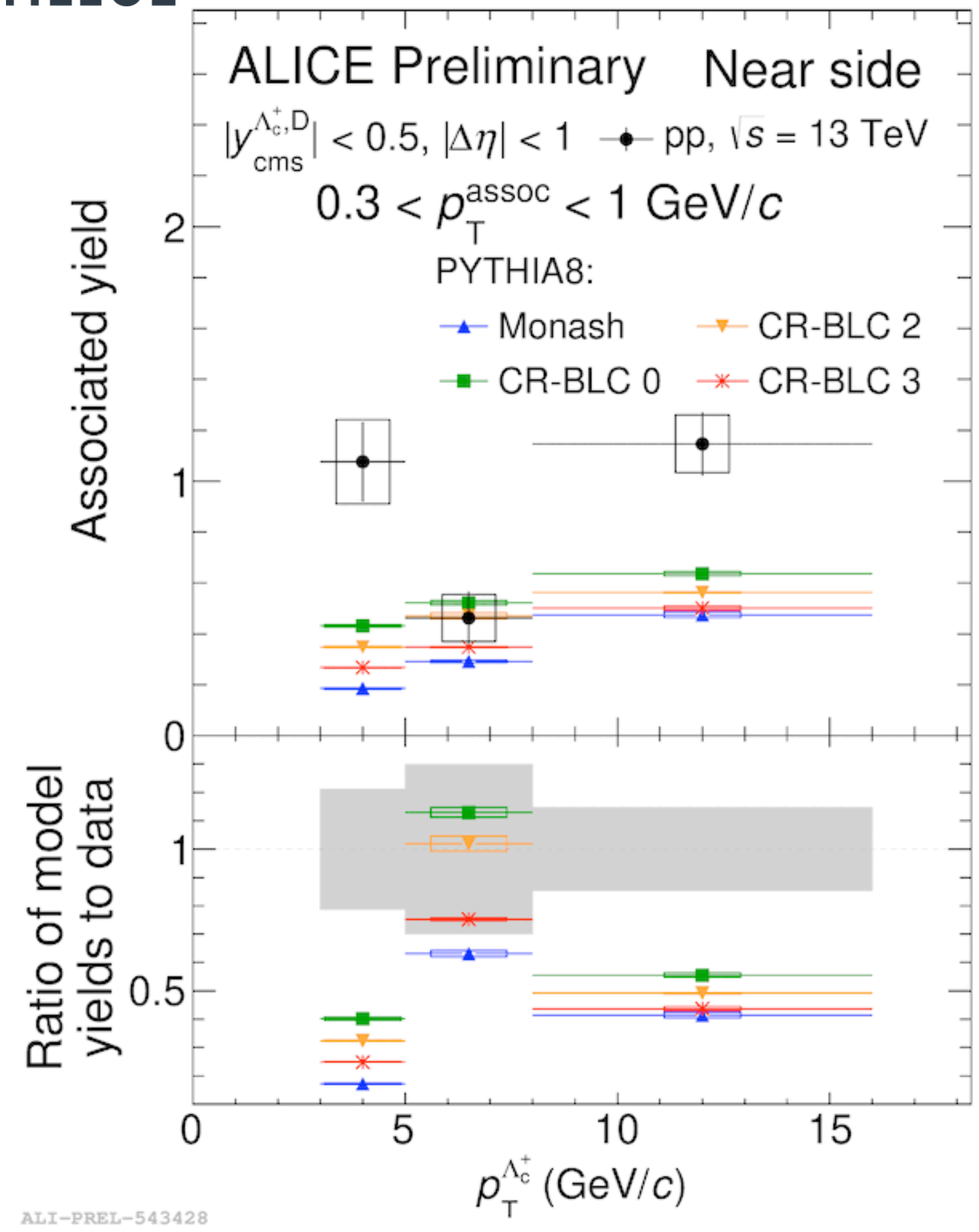
Λ_c^+ - h correlations: Comparison with theoretical models



- **Underestimation of associated particle production in the NS and AS regions in PYTHIA 8.**
- **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-to-baryon fragmentation not properly described by MC generators

Λ_c^+ - h correlations: Comparison with theoretical models

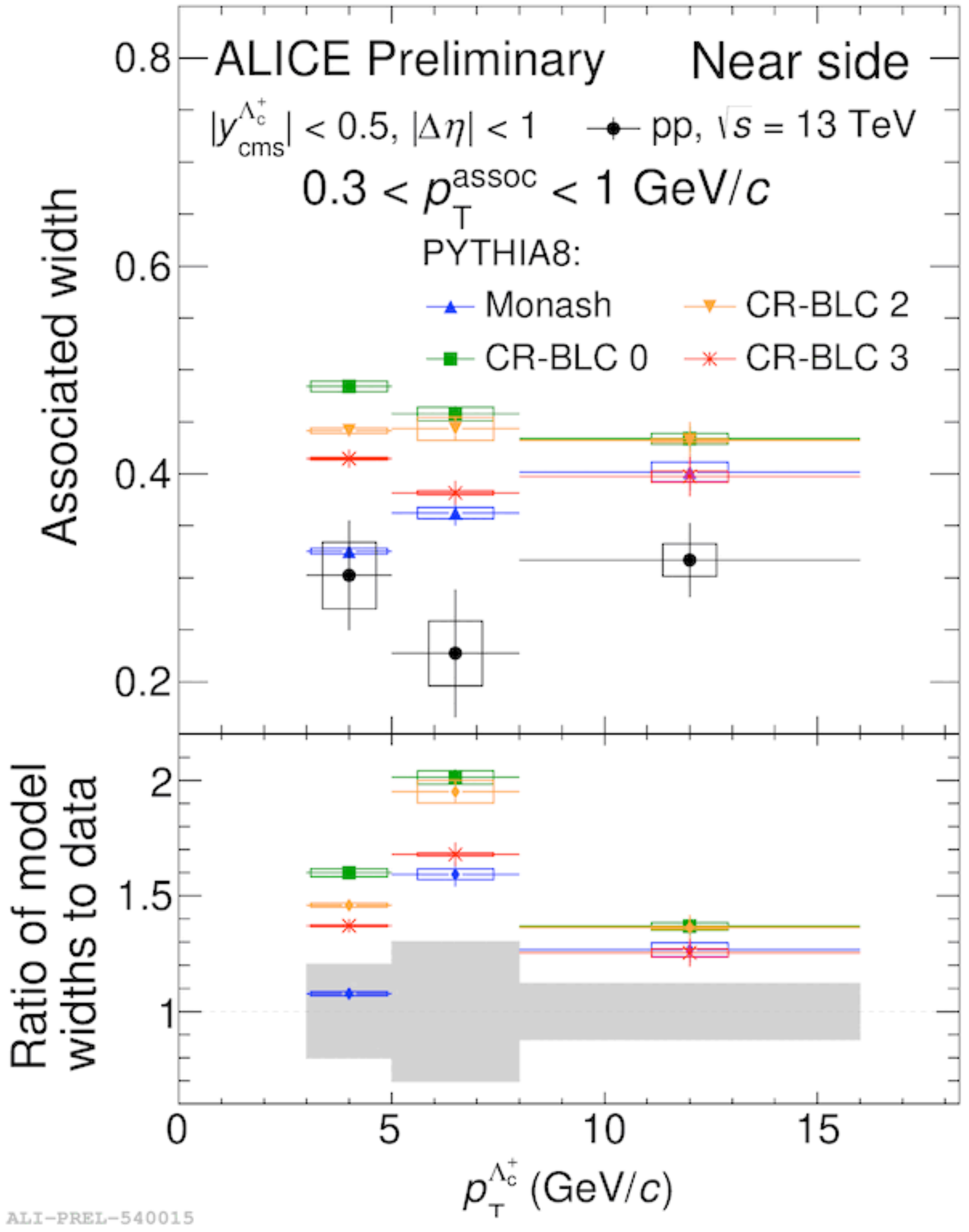


Yields:

- **Increasing trend with increasing $p_T(\Lambda_c^+)$**
- **All models underestimate the measured near-side yields (including PYTHIA 8 with CR-BLC modes)**

Widths:

- **Overall, all model predictions tend to overestimate the near-side wdths (though experimental uncertainties are large)**



Summary

- **HF - tagged jets:**
  - D^0 and Λ_c^+ -jet momentum fraction generally consistent with theory
  - Hint for softer Λ_c^+ fragmentation in data for low $p_{T,jet}$ compared to D^0

- **HF correlations:**
  - PYTHIA 8 and POWHEG+PYTHIA provide the best description of data for D-h correlation measurements
  - Hint of softer fragmentation of charm baryon w.r.t charm mesons
  - Observed discrepancies between Λ_c^+- h measurements and PYTHIA 8 predictions

What to expect from Runs 3 and 4?

- Larger data sample and improved DCA resolution
- Expand the successful pp program to explore pQCD and hadronization mechanisms and modifications in central heavy-ion collisions
- Study B-tagged jet production and HF-jet substructure

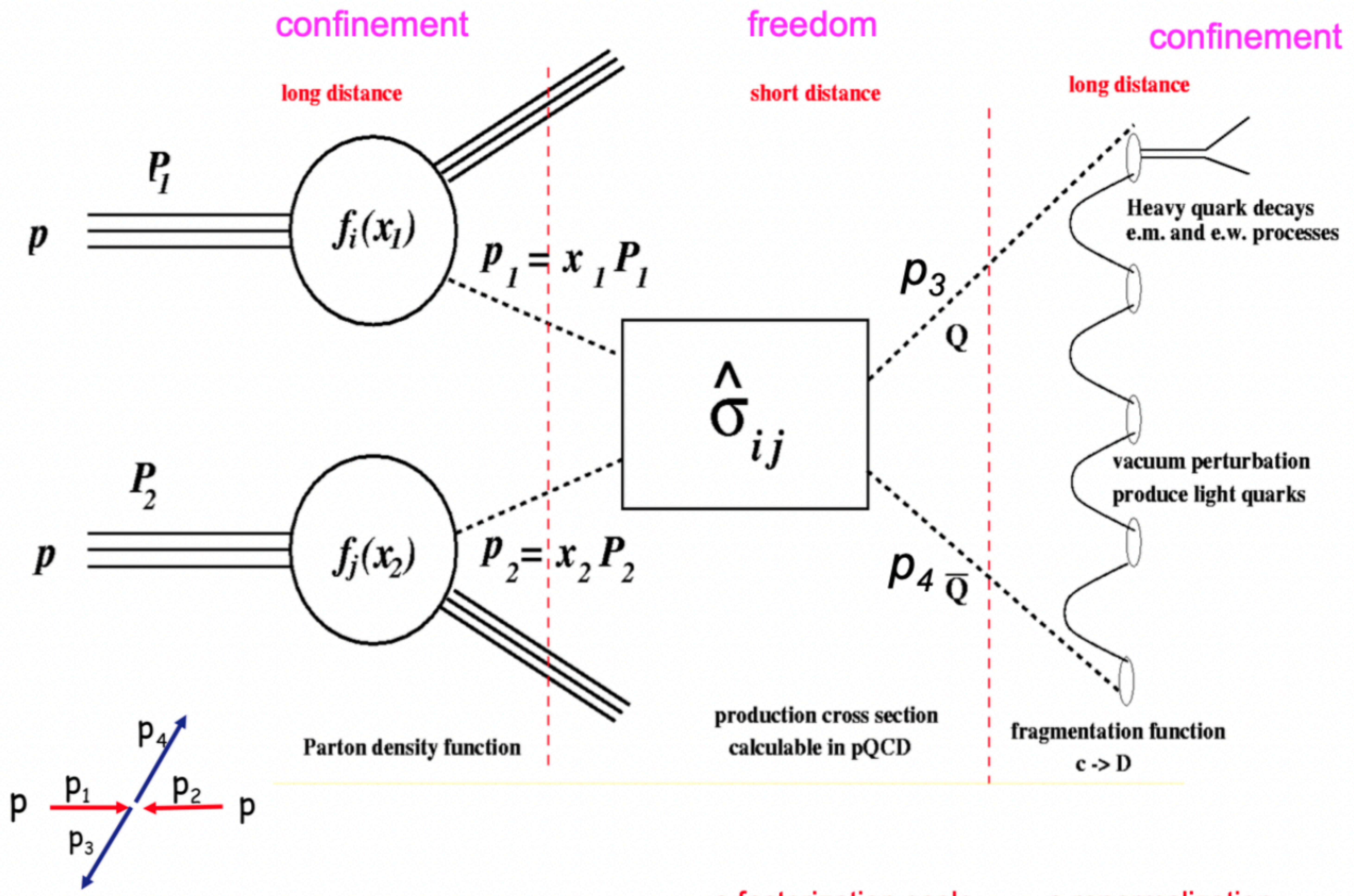
ALICE3 Detector

- Wide η range
- Excellent precision for secondary vertexing and PID.
- Correlation measurements in Pb-Pb collisions will be accurate enough to assess the effects of in-medium broadening and thermalisation.

Thank you

Backup

QCD Factorisation theorem



a factorization scale μ_F

a renormalization scale μ_R

$$\sigma_{2\to n} = \sum_{a,b} \int_0^1 \mathrm{d}x_a \mathrm{d}x_b\, f_{a/h_1}(x_a, \mu_F)\, f_{b/h_2}(x_b, \mu_F)\, \hat{\sigma}_{ab\to n}(\mu_F, \mu_R)$$

D⁰-jet production in pp collisions

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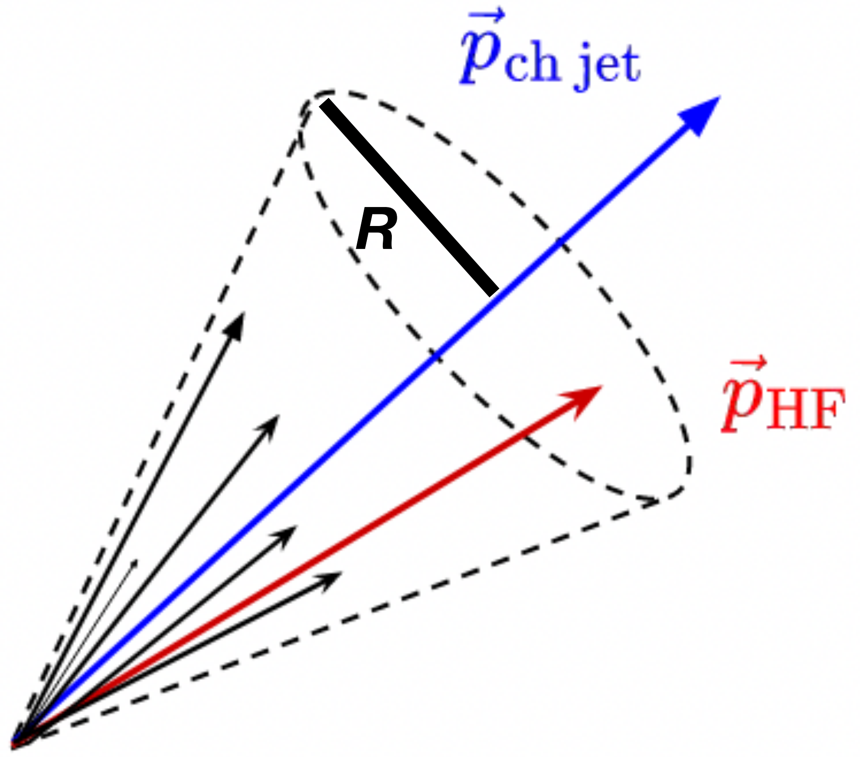
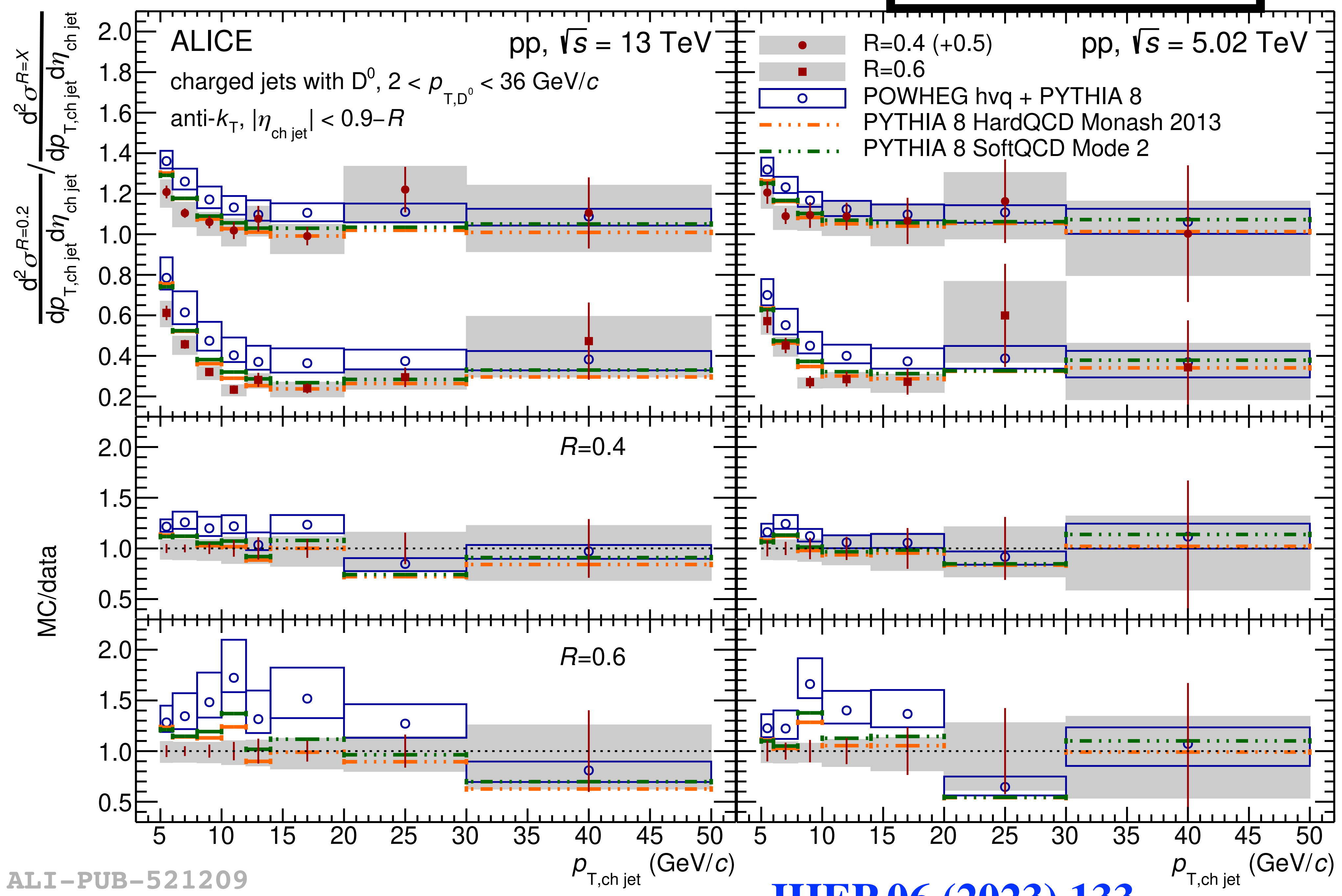


$$R = \sqrt{(y_i - y_{jet})^2 + (\varphi_i - \varphi_{jet})^2}$$

Jet resolution parameter (*R*) allows us to explore the parton shower shape and access the interplay between perturbative and non-perturbative processes.

R=0.2 / *R*=X



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13 TeV / 5 TeV

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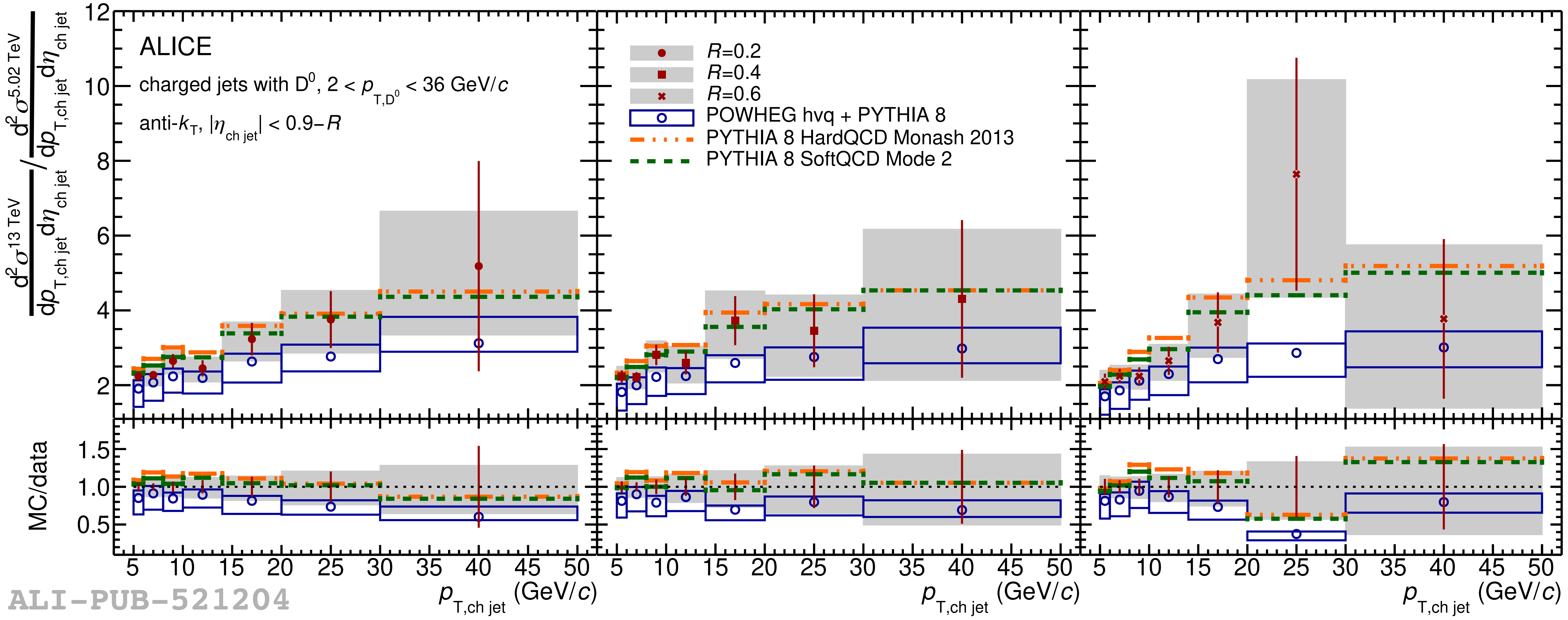


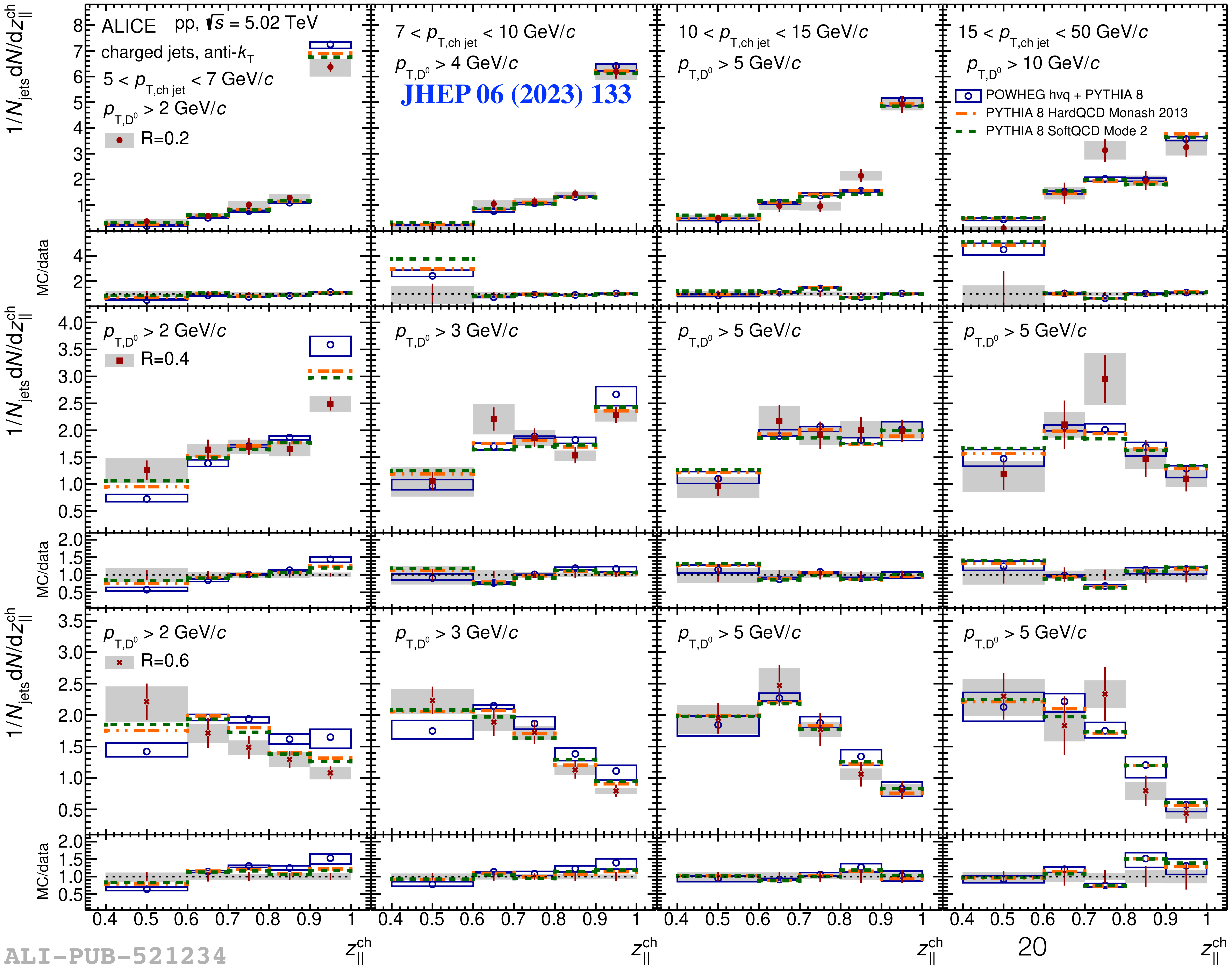
The observed departure from unity of the cross-section ratios can be interpreted by the emission of QCD radiation.

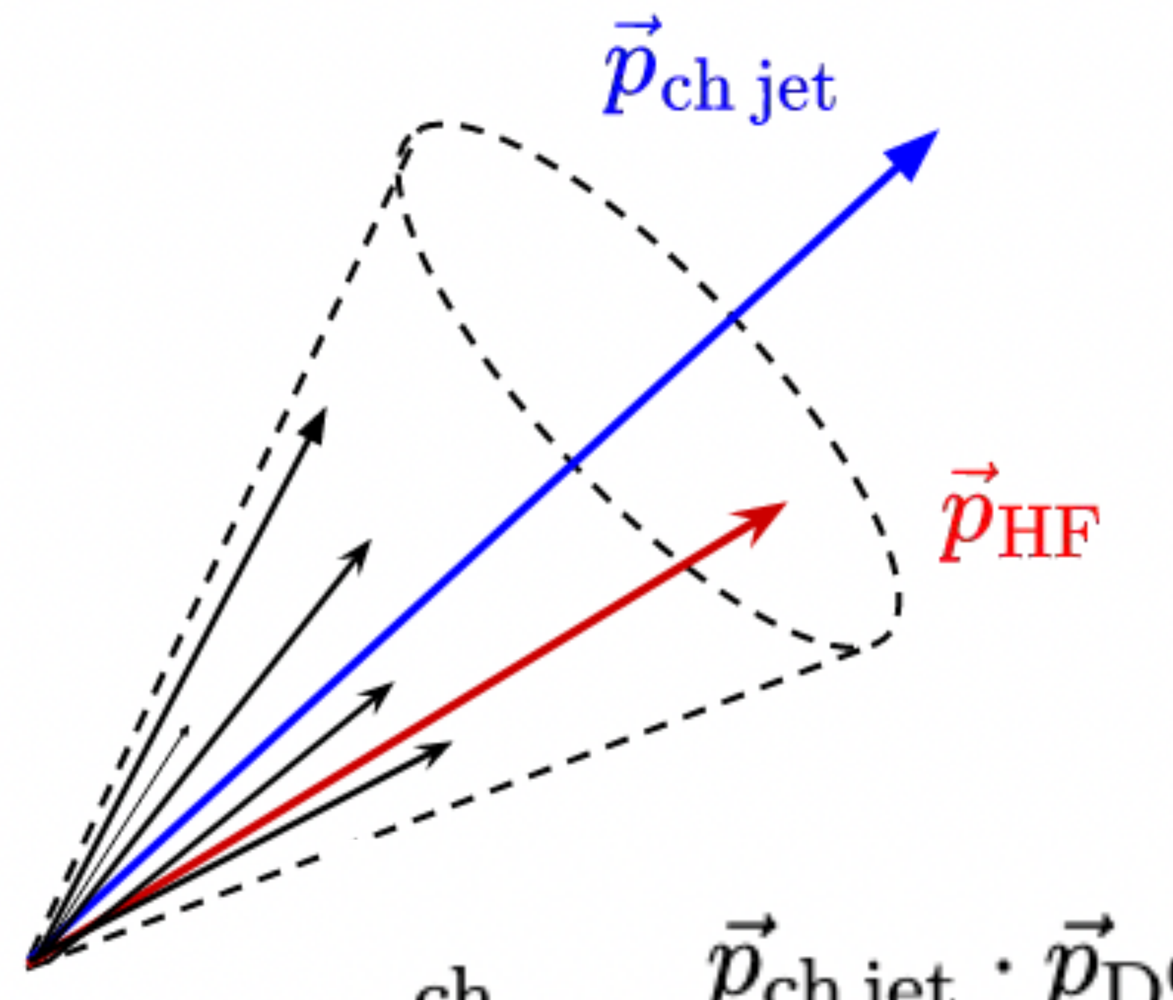
Hardening of D⁰-jet transverse momentum distribution with increasing centre-of-mass energy

D^0-jets momentum fraction

$p_{\mathrm{T,\,ch\,D^0}}$, $p_{\mathrm{T,\,ch\,jet}}$ →

R ↓





$$z_{||}^{\mathrm{ch}} = \frac{\vec{p}_{\mathrm{ch\,jet}} \cdot \vec{p}_{\mathrm{D^0}}}{\vec{p}_{\mathrm{ch\,jet}} \cdot \vec{p}_{\mathrm{ch\,jet}}}$$

- **Dependence of momentum fraction on resolution parameter:**
  - **Smaller R → Dominated by heavy-flavour hadron. Compatible with suppression of gluon emission at low angles**
  - **Larger R → Emissions at large angles are recovered**
- **Hint of softer fragmentation in data compared to models for low $p_{\mathrm{T,\,ch\,jet}}$ and large R.**