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ALICE

Study of heavy–flavor fragmentation using angular correlations with the ALICE experiment at the LHC

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Physics Motivation

Heavy-flavor (HF) hadron production cross sections are calculated in pQCD via a convolution of 3 components:

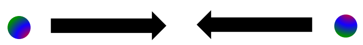
Parton distribution function (PDF)

Partonic cross-section

Fragmentation function (FF)

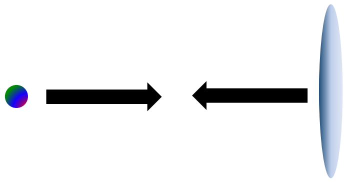
$$\frac{d\sigma^{\mathrm{HFh}}}{dp_{\mathrm{T}}^{\mathrm{HFh}}}(p_{\mathrm{T}};\mu_{\mathrm{F}},\mu_{\mathrm{R}}) = PDF(x_1,\mu_{\mathrm{F}}) \otimes PDF(x_2,\mu_{\mathrm{F}}) \otimes \frac{d\sigma^{\mathrm{Q\bar{Q}}}}{dp_{\mathrm{T}}^{\mathrm{Q\bar{Q}}}}(p_{\mathrm{T}};\mu_{\mathrm{F}},\mu_{\mathrm{R}}) \otimes \mathrm{FF}_{\mathrm{Q}\rightarrow\mathrm{HFh}}(z = p_{\mathrm{HFh}}/p_{\mathrm{c}},\mu_{\mathrm{F}})$$

- ❖ Recent discoveries in charm-baryon production measurements indicate non-universality of heavy-quark fragmentation functions [JHEP 12 (2023) 086]
  - Necessitates further differential measurements to investigate the causes of this non-universality
- ❖ Two primary measurement approaches to further investigate HF hadronization:
  - HF hadron-tagged jets
  - Angular correlations of HF particles and charged particles
- ❖ Measurements in different hadronic collision systems can elucidate how hadronization can be modified



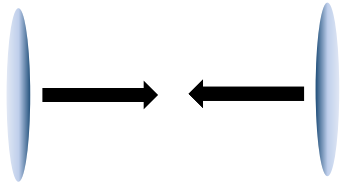
pp collisions

Study of HF fragmentation



p—A collisions

Cold-nuclear matter effects on HF fragmentation



A—A collisions

Quark Gluon Plasma (QGP) effects on HF hadronization

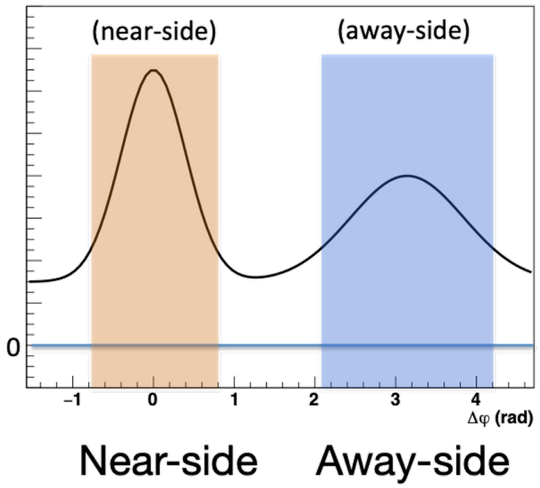
Angular Correlation Analysis Method

- Angular correlations are a differential measurement that can be used to study HF jet fragmentation
  - Correlates the production of an associated particle with a specific trigger particle in the azimuthal plane
  - Sensitive to NLO quark production mechanisms
  - Can investigate jet fragmentation and characterize the features of HF jets without jet reconstruction
  - Utilized at both RHIC and LHC

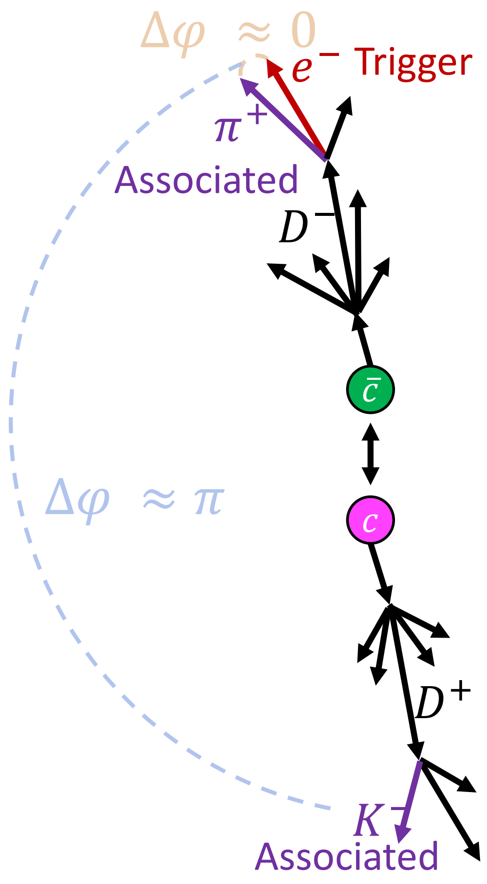
- $\Delta\varphi\ (\mathrm{HF-h}) \equiv \varphi^{\mathrm{HF}}_{\mathrm{Trig}} - \varphi^{\mathrm{h}}_{\mathrm{Asso}}$
  - $\varphi^{\mathrm{HF}}_{\mathrm{Trig}}$: Azimuthal angle of HF trigger particle
  - $\varphi^{\mathrm{h}}_{\mathrm{Asso}}$: Azimuthal angle of associated particle

- Can extract quantitative observables to compare to model predictions
  - $\Delta\varphi$ correlation distribution
  - Near and away-side peak width
  - Per-trigger associated peak yield

- Note: “HF-h” will be used to abbreviate for HF trigger particle correlations with associated charged particles (which are predominantly charged hadrons)

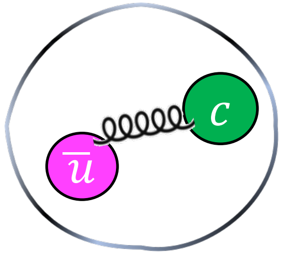


- Near-side: $\Delta\varphi \approx 0$
  - Correlates associated to trigger within the same jet
- Away-side: $\Delta\varphi \approx \pi$
  - Correlates associated from recoil jet

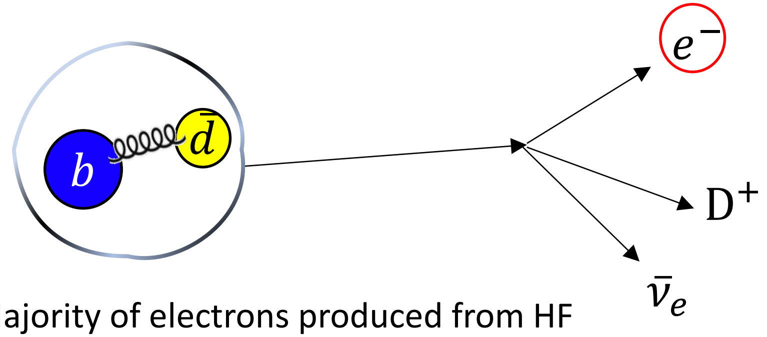


Analyses of Heavy-Flavor Fragmentation

- **D-meson triggered correlations and D-meson tagged jets**
  - Three D-meson species (D^0, D^+, D^{*+}) can be reconstructed and correlated with charged particles
  - Used to study fragmentation of charm quark into jets



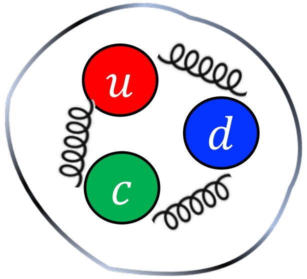
D^0-meson



Majority of electrons produced from HF decay of D and B-mesons

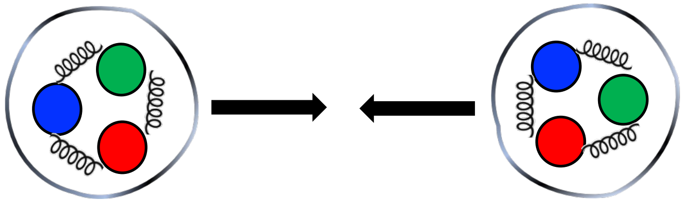
- **HF decay electron (HFe) correlations**
  - Correlates electrons from HF hadron decays with charged particles
  - Can probe higher associated p_{T} than D-h
    - Relatively high branching ratio of D, B → e (~10%)
  - Can correlate electrons predominantly coming from beauty by selecting a high trigger p_{T}

- **Λ_c^+-baryon correlations and Λ_c^+-tagged jets**
  - Λ_c^+/ D^0 production ratio differs in pp compared to $\mathrm{e}^+\mathrm{e}^-$ measurements [Phys. Rev. C 107, 064901 (2023)]
    - Fragmentation functions not universal among collision systems
  - More than 1/3 of charm quarks hadronize to baryons [PRD 105, L011103 (2022)]
  - Probe possible differences of charm jets in case of charm hadronization into a baryon rather than a meson



Λ_c^+-baryon

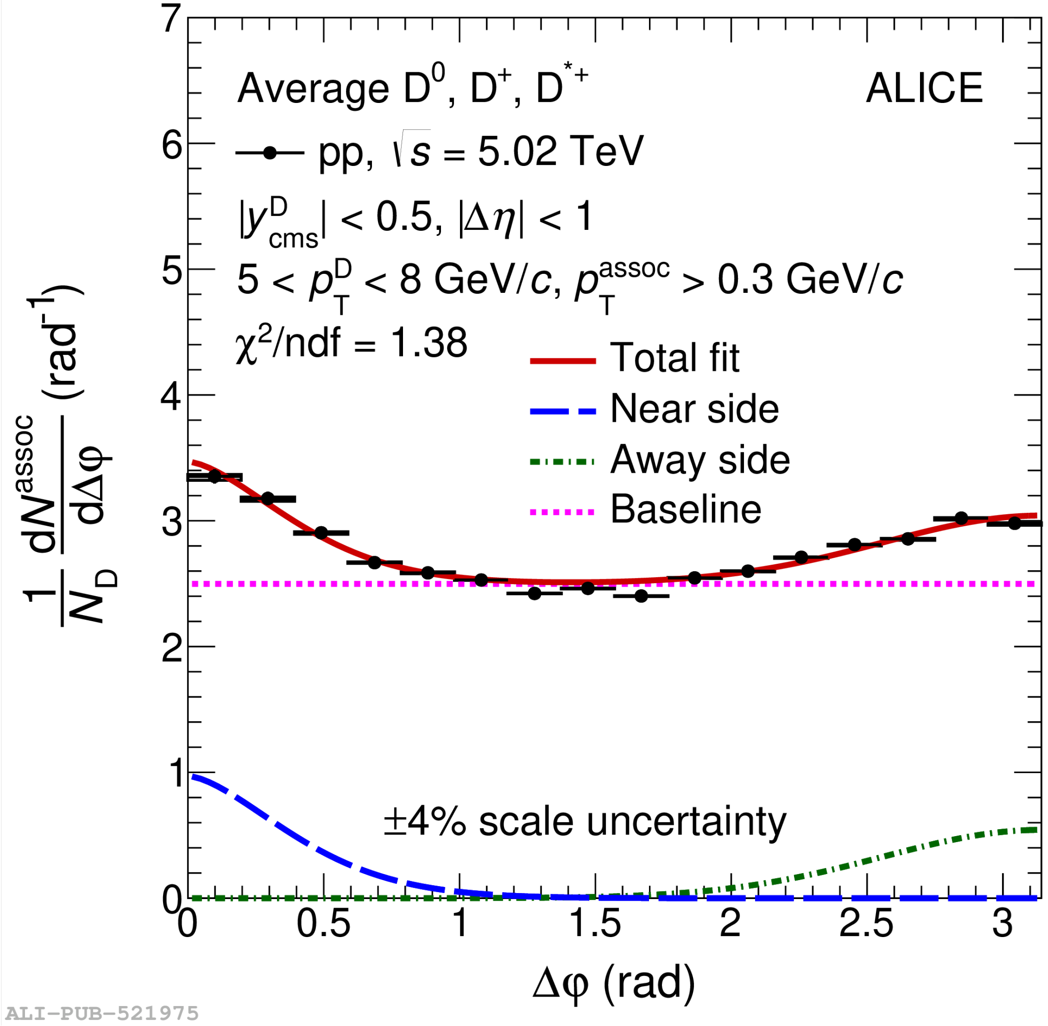
Proton-Proton Collisions



- D-meson correlations with charged associated particles
  - Measurements at different $\sqrt{s}$
  - Correlation observables in different multiplicity classes
  - Comparison to models
- HFe-h correlations
  - Comparison to models
  - Investigating flavor vs parton energy dependence of associated yield
- Λ_c^+-h correlations
  - Comparison to D-h
  - Comparison to models

D-Meson Azimuthal $\Delta\varphi$ Correlations

EPJC 80 (2020) 979
Eur. Phys. J. C 82, 335(2022)



- The $\Delta\varphi$ correlation distribution of D mesons with charged particles is plotted
  - Normalized by the number of D-meson triggers
- Distribution is fit with the function:
  - $f(\Delta\varphi) = b + \frac{Y_{\mathrm{NS}} \times \beta}{2\alpha\Gamma(1/\beta)} \times e^{-\left(\frac{\Delta\varphi}{\alpha}\right)^{\beta}} + \frac{Y_{\mathrm{AS}}}{\sqrt{2\pi}\sigma_{\mathrm{AS}}} \times e^{-\frac{(\Delta\varphi-\pi)^2}{2\sigma_{\mathrm{AS}}^2}}$
- Fit function consists of:
  - Generalized Gaussian on near-side
  - Gaussian on away-side
  - Flat baseline, b, to remove uncorrelated background pairs
- By fitting the correlation distribution, the per-trigger **associated peak yield** and peak **width** observables can be extracted

D-Meson Correlations at different $\sqrt{s}$

pp, 5.02 TeV
pp, 7 TeV
pp, 13 TeV

Eur. Phys. J. C 82, 335(2022)
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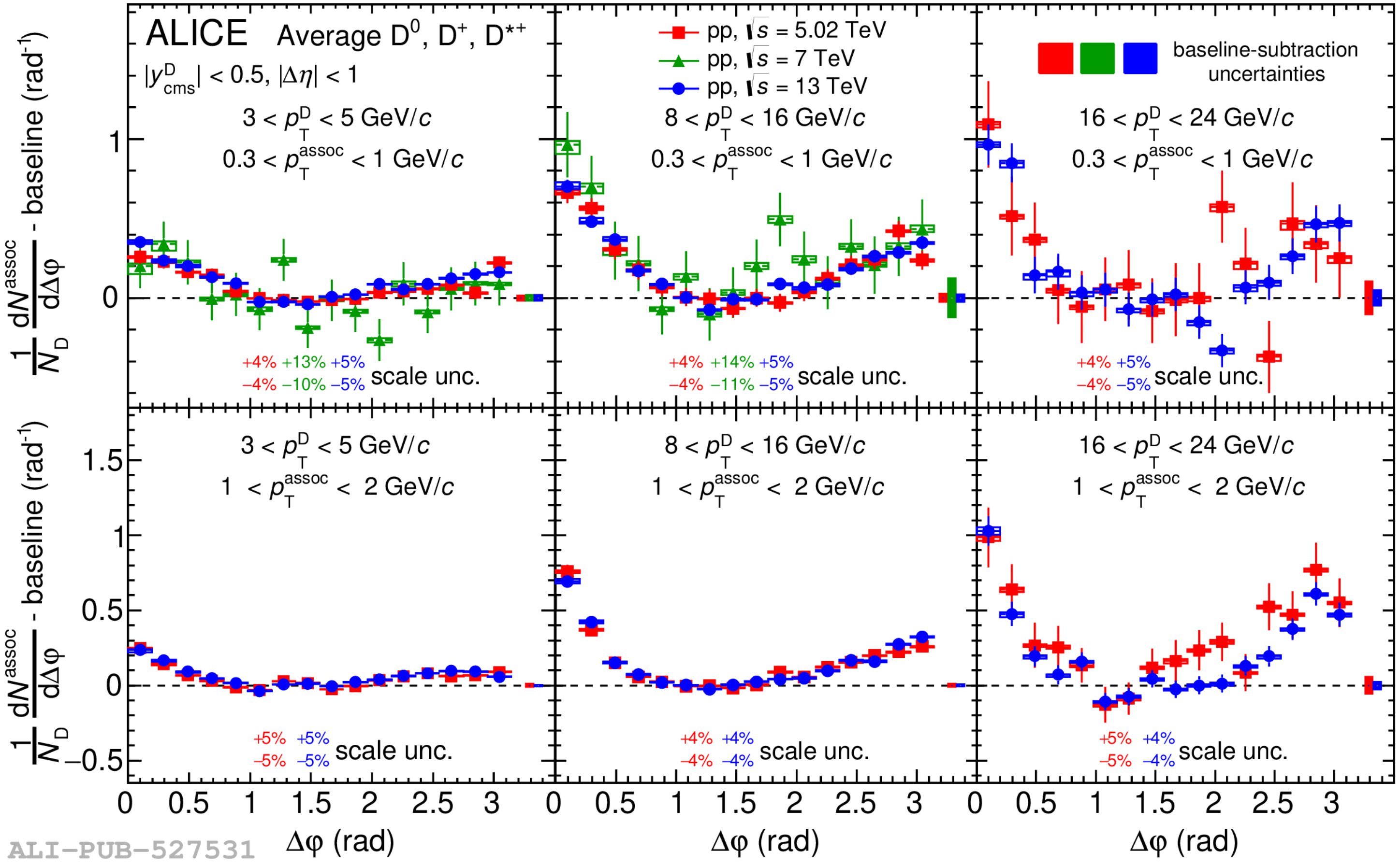
EPJC 80 (2020) 979

Increasing trigger p_T

Increasing associated p_T



- D-meson and charged-particle correlation distribution measured for different trigger and associated p_T ranges and compared at different $\sqrt{s}$ in pp collisions

- Distribution shape after baseline subtraction of the $\sqrt{s} = 5.02$, 7, and 13 TeV measurements
  - No $\sqrt{s}$ -dependence for near- and away-side peak shape and transverse-momentum evolution

D-Meson Correlation Observables Compared to Models

List of models and event generators used:

- **PYTHIA6 Perugia 2011**
- **PYTHIA8, Tune 4C**
- **HERWIG**
- **POWHEG+PYTHIA8**
- **EPOS 3.117**

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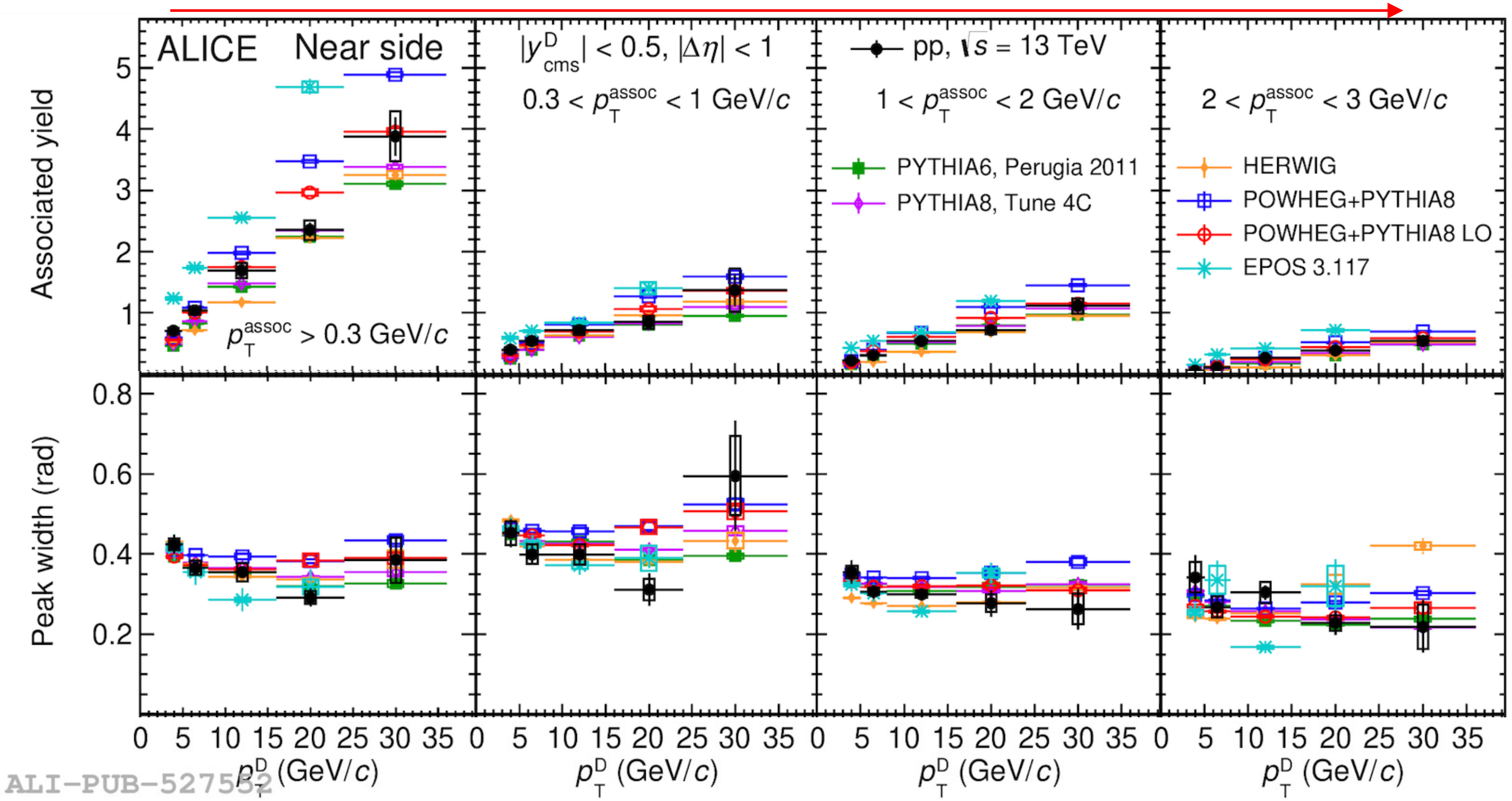
Increasing associate p_{T}



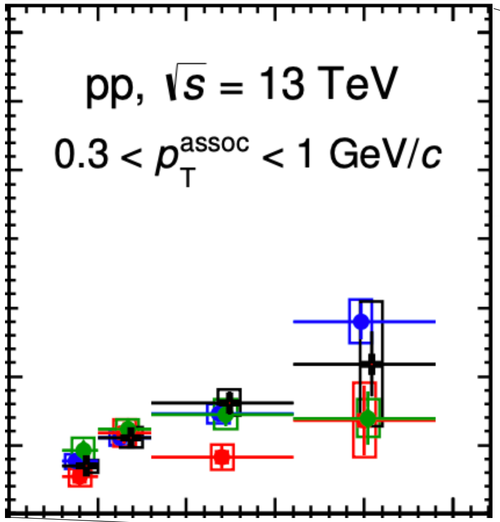
- Trend of increasing near-side peak associated yield as $p_{\mathrm{T}}^{\mathrm{D}}$ increases
- General hierarchy among models:
  - **EPOS** provides highest associated yields, followed by **POWHEG+PYTHIA8 NLO**, **POWHEG+PYTHIA8 LO**, then **PYTHIA6**, and the lowest is **PYTHIA8**
  - **HERWIG** predicts lowest associated yields for $p_{\mathrm{T}}^{\mathrm{D}} < 8$ GeV/c, and $p_{\mathrm{T}}^{\mathrm{asso.}} > 1$ GeV/c
- When comparing to models, near-side associated yield and near-side width are best described by **POWHEG+PYTHIA8** and **PYTHIA8** models

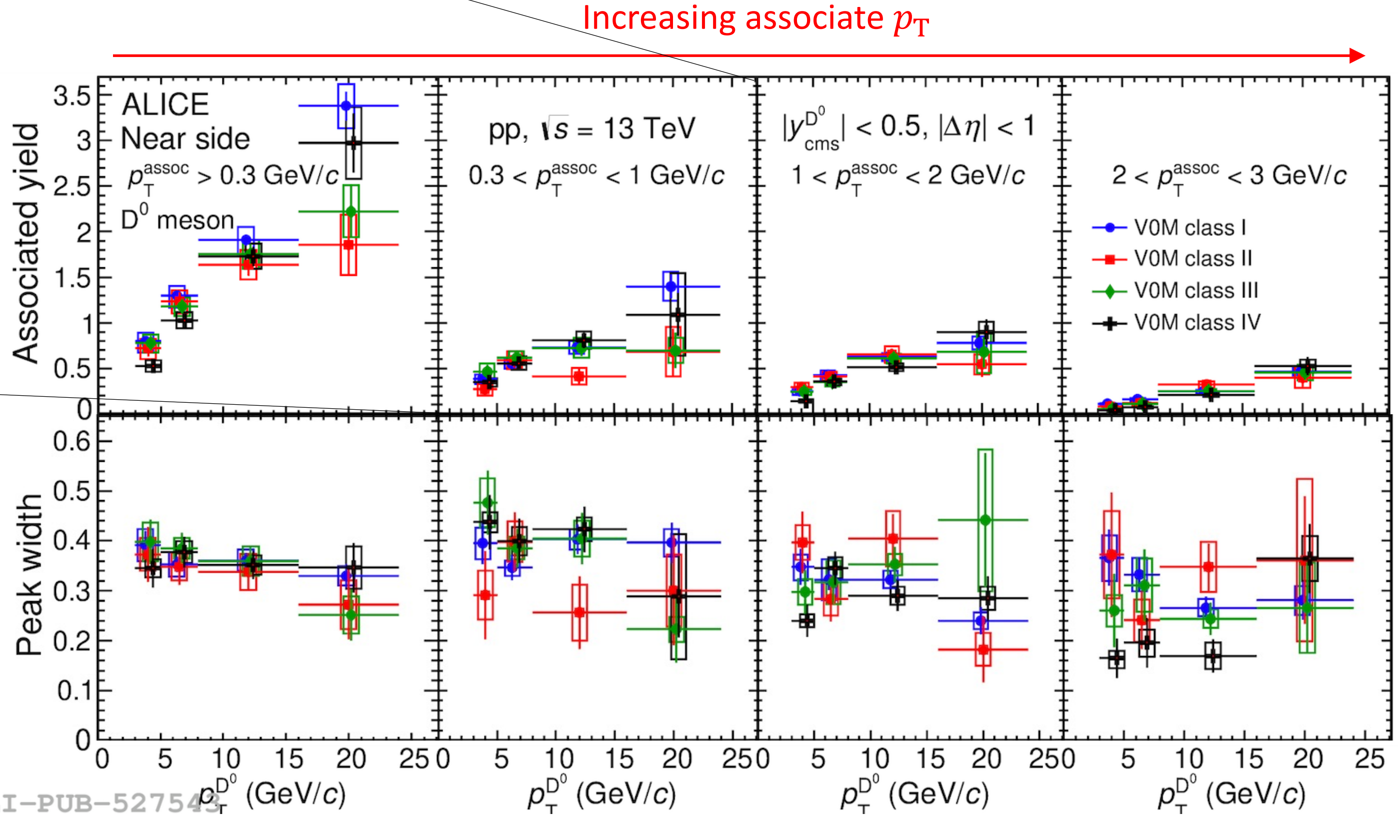
D-Meson Correlations in Different Multiplicity classes

Multiplicity classification:

V0M Class I: Largest multiplicity

V0M Class IV: Smallest multiplicity





- Near-side observables in different V0M classes were compared
  - Trend of increasing associated yield as a function of p_{T}^{D} in all four multiplicity classes
  - Near-side yield and width consistent within uncertainties amongst all V0M classes
  - No significant modification of charm fragmentation and hadronization at different charged-particle event multiplicities

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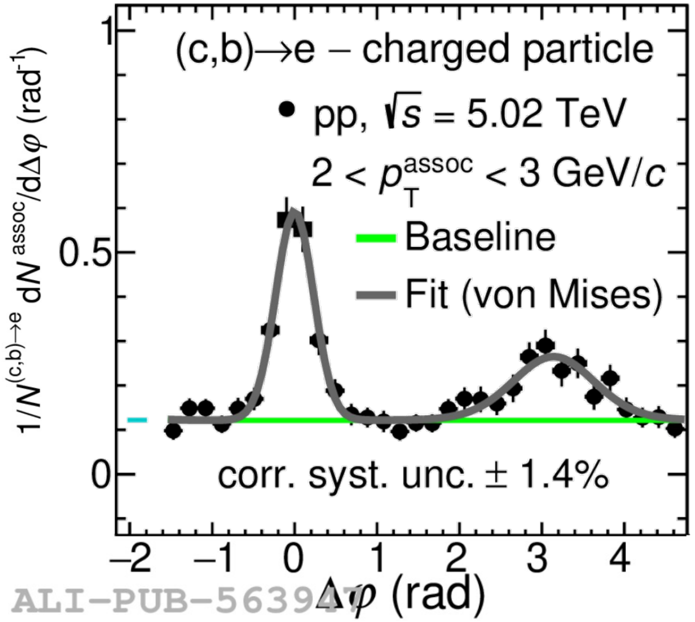
HFe-h Correlations



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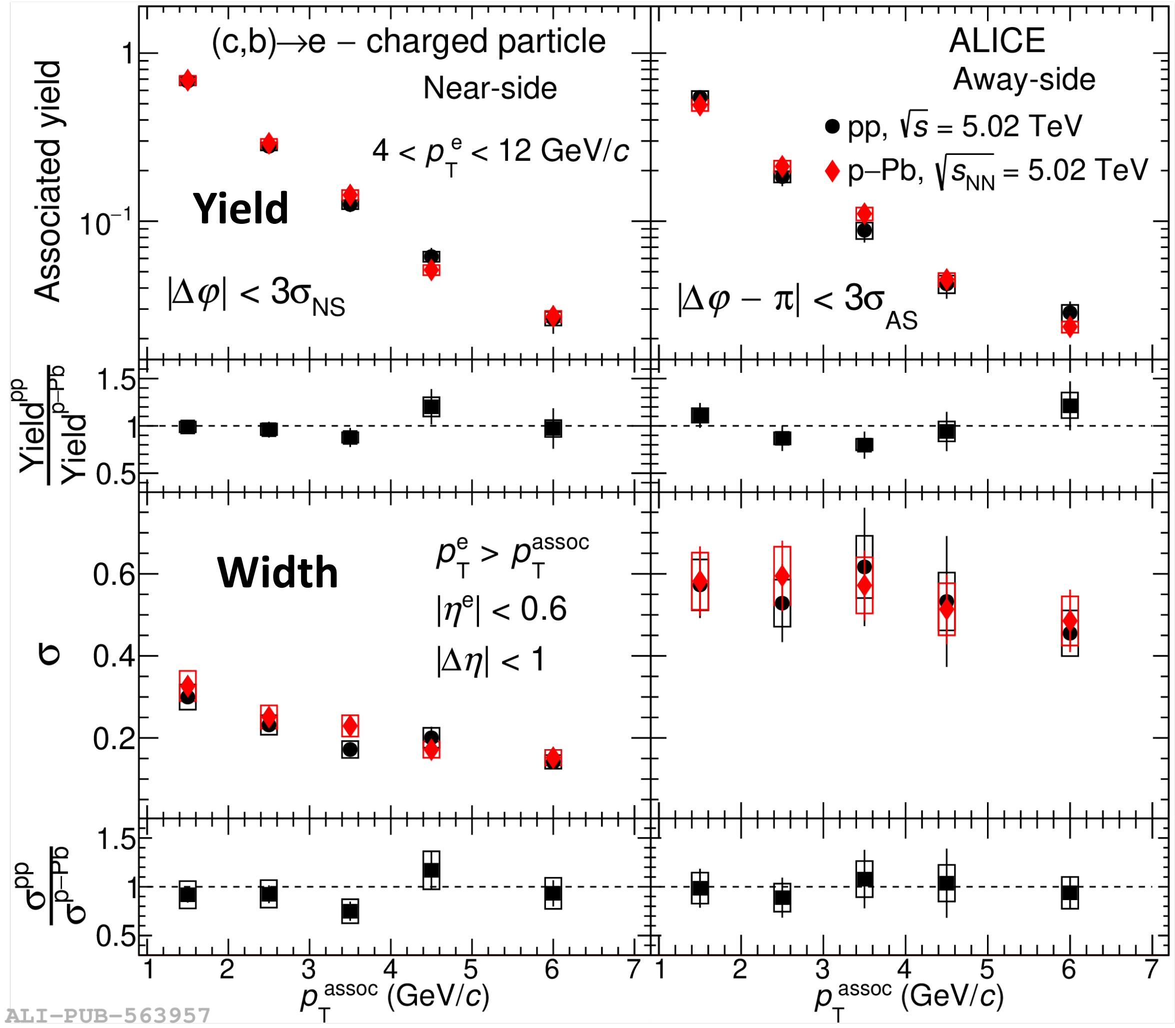

- HFe-h correlations were measured in pp and p-Pb collisions
  - Measured with trigger p_T^{HFe} in ranges: 4 – 7, 4 – 12, and 7 – 16 GeV/*c*
- Correlation distributions fitted with von Mises function on both peaks
  - $f(\Delta\varphi) = b + \frac{Y_{NS}e^{\kappa_{NS}\cos(\Delta\varphi)}}{2\pi I_0(\kappa_{NS})} + \frac{Y_{AS}e^{\kappa_{AS}\cos(\Delta\varphi-\pi)}}{2\pi I_0(\kappa_{AS})}$
  - $\sigma = \sqrt{-2\log(\frac{I_1(\kappa)}{I_0(\kappa)})}$
- Near-side peak width decreases (becomes more collimated) as associated p_T increases in both collision systems

HFe-h Correlations compared to models

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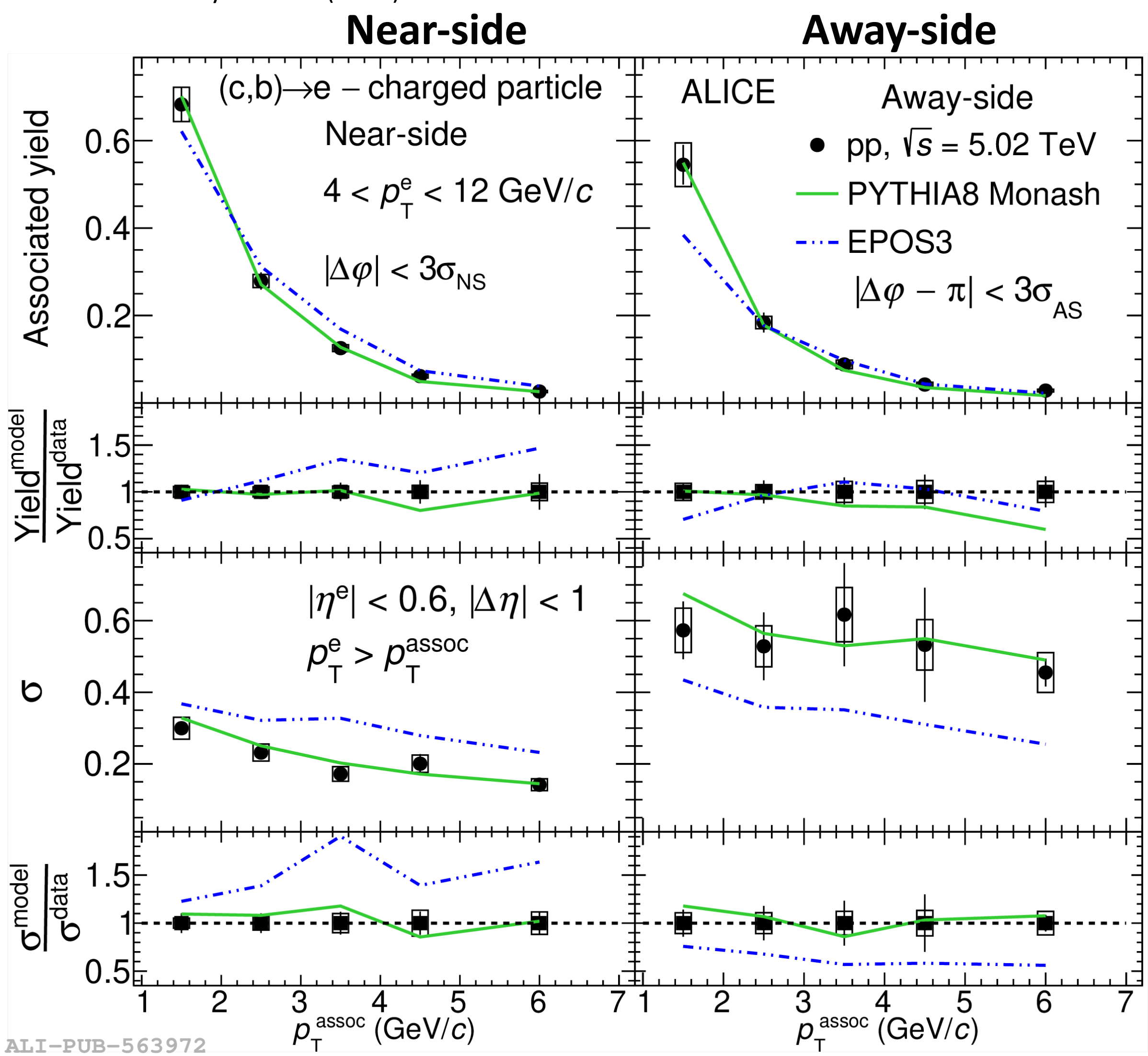
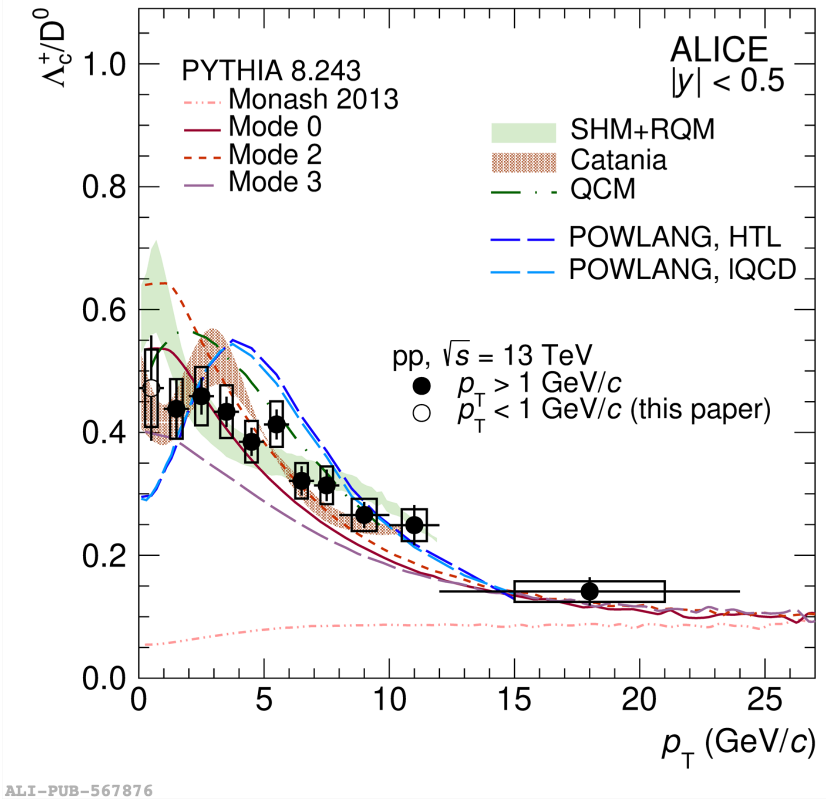


- PYTHIA8 Monash
  - Tune of PYTHIA with constraints on HF fragmentation set to e^+e^- measurements
- Associated yield and peak width results consistent with PYTHIA8 Monash predictions
- EPOS3 tends to overpredict near-side widths while under-predicting away-side widths

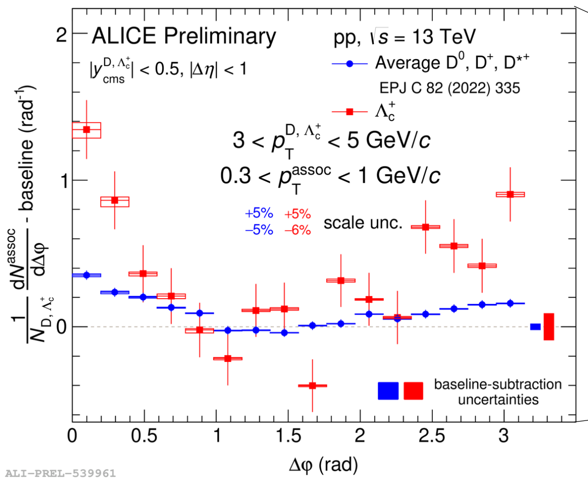
Comparison of Λ_c^+-h with D-h azimuthal correlations in pp

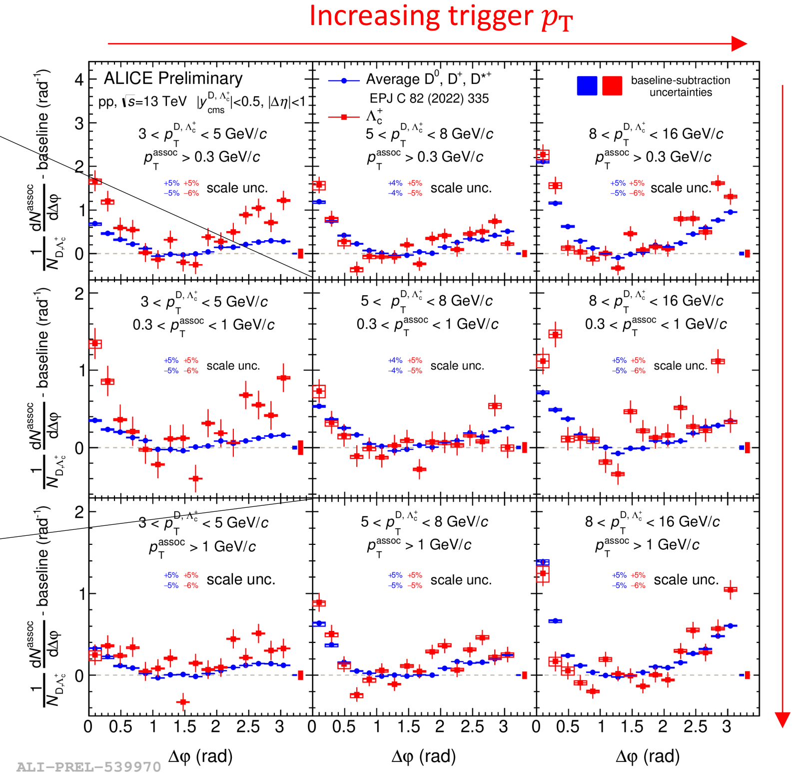
JHEP 12 (2023) 086



D-h $0.3 < p_T^{asso} < 1$

Λ_c^+-h $3 < p_T^{trig.HF} < 5$ GeV/c



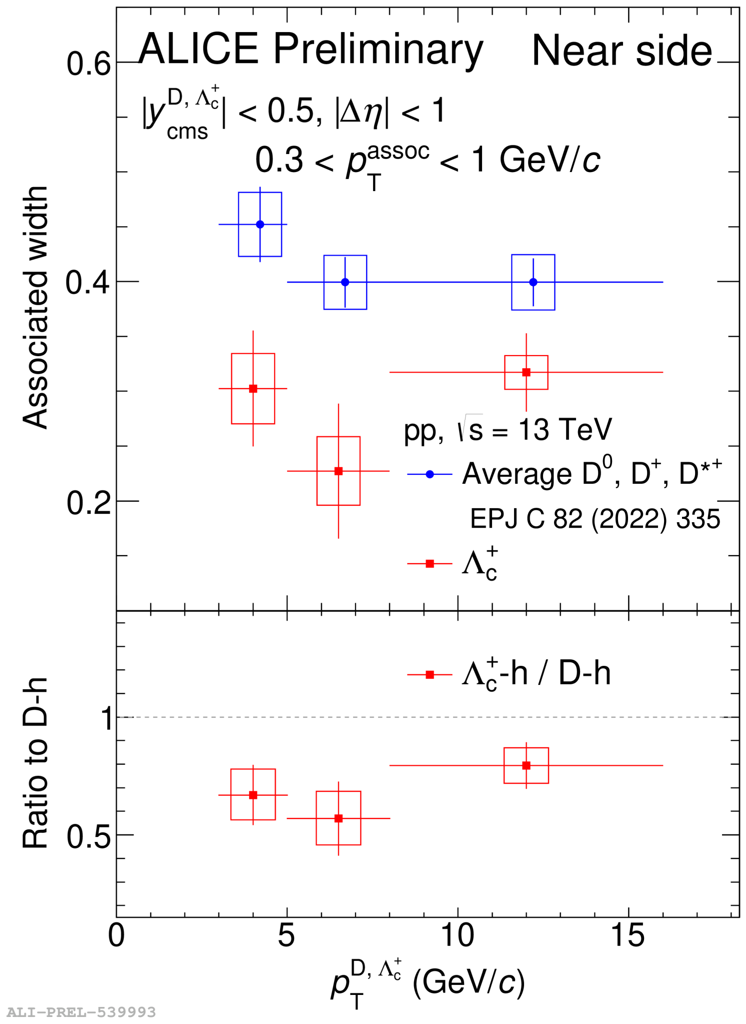


- (Above) $\Lambda_c^+/\,D^0$ ratios are plotted as a function of p_T at $\sqrt{s} = 13$ TeV
- Monash and CR-BLC tunes apply different constraints on allowed reconnections among color sources
- CR-BLC modes describe data within uncertainty, differently from Monash tune

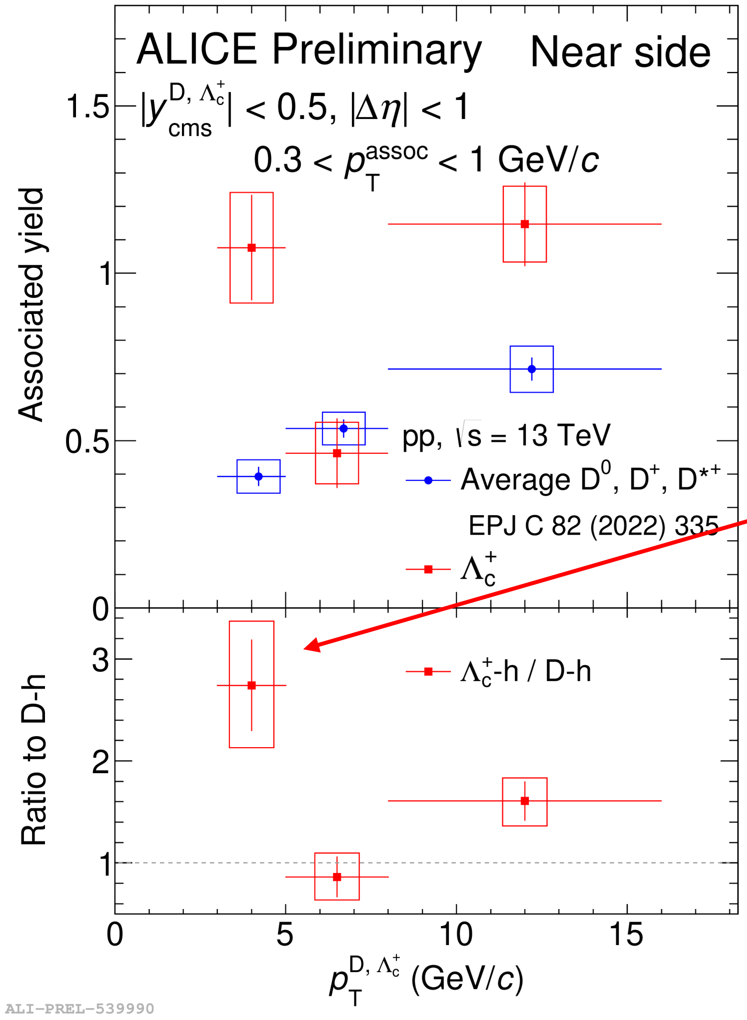
- (Above) First preliminary Λ_c^+-h correlation results in pp collisions at $\sqrt{s} = 13$ TeV
- Probes charm → baryon fragmentation
  - Compared to D-meson correlation distribution for the common trigger and associated p_T ranges studied
- In lowest associated and trigger p_T interval ($0.3 < p_T^{asso} < 1$, $3 < p_T^{trig.HF} < 5$ GeV/c), both near-side and away-side peaks are larger for Λ_c^+ correlations than for D-mesons
  - At higher p_T, no significant difference between correlation distributions

Near-Side Comparison, Λ_c^+ and D-meson correlations

Width

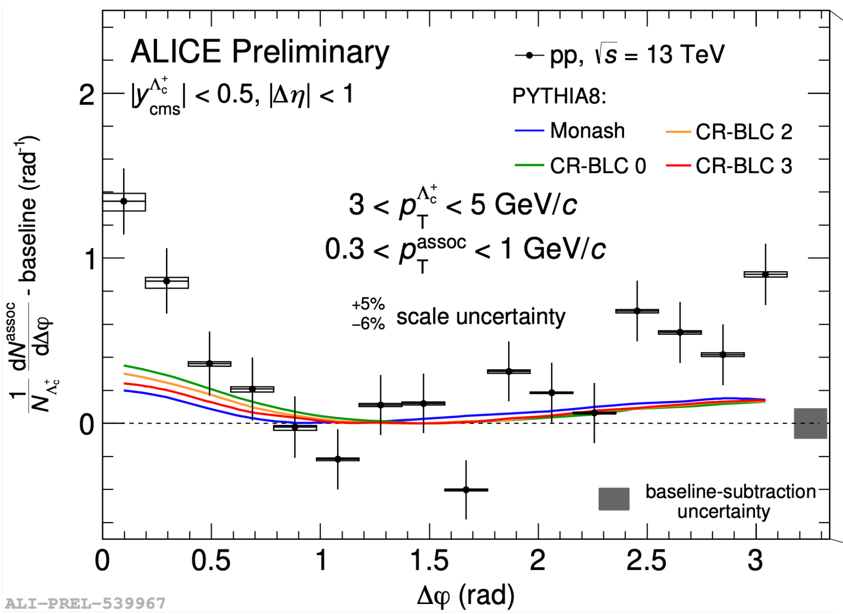


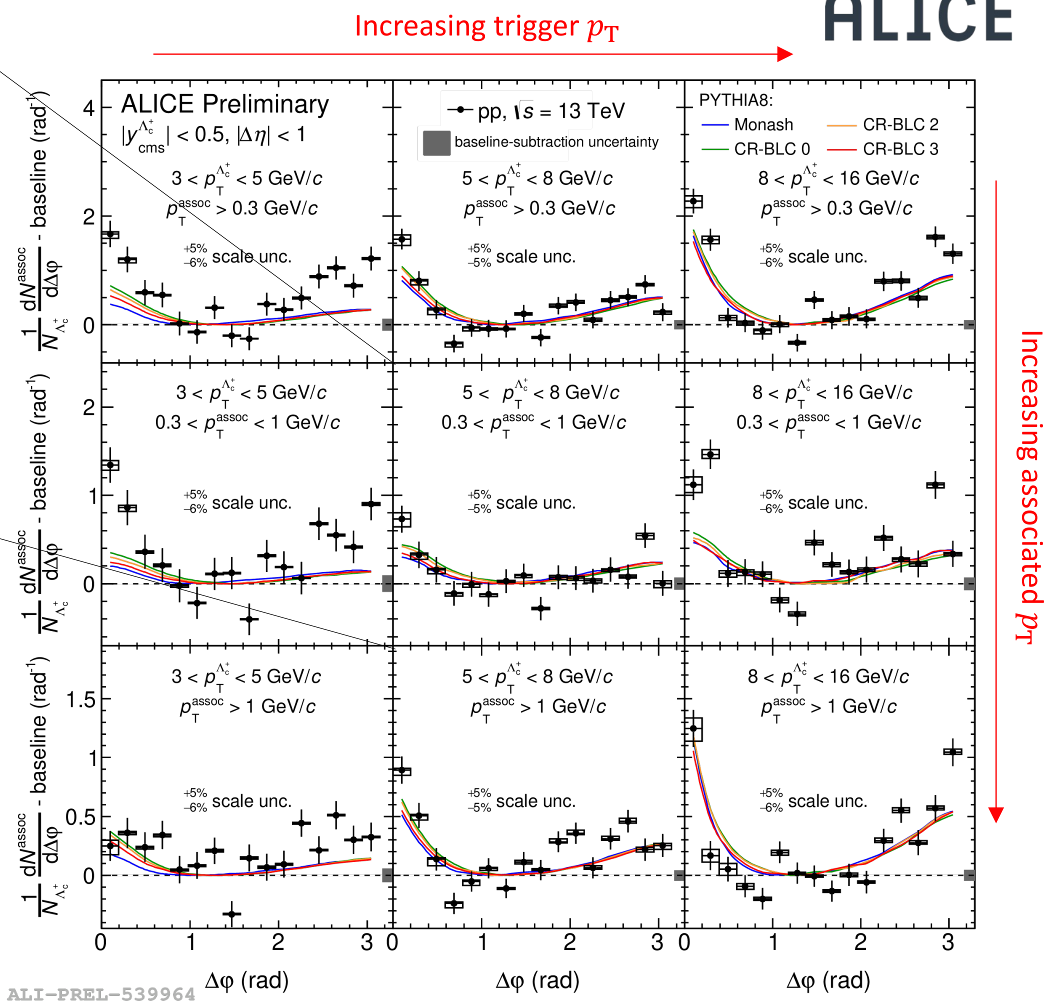
Yield



- For low p_T associated particles, wider near-side peaks in D-Meson correlations than Λ_c^+-h
- Λ_c^+-h associated yield ~3× larger than D-h yield in lowest trigger and associated p_T (~2.6σ difference)
  - More associated particles in a low p_T jet containing a Λ_c^+ compared to D-meson

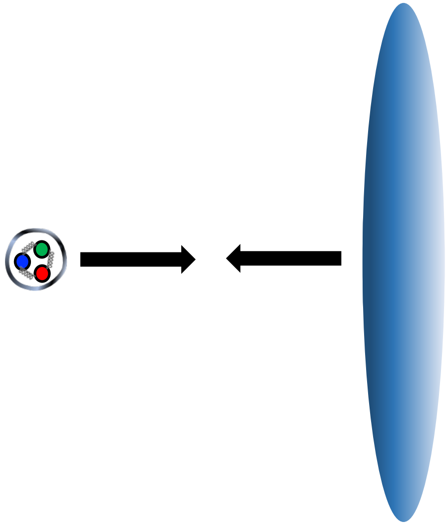
Comparison of Λ_c^+—h with Monte Carlo predictions





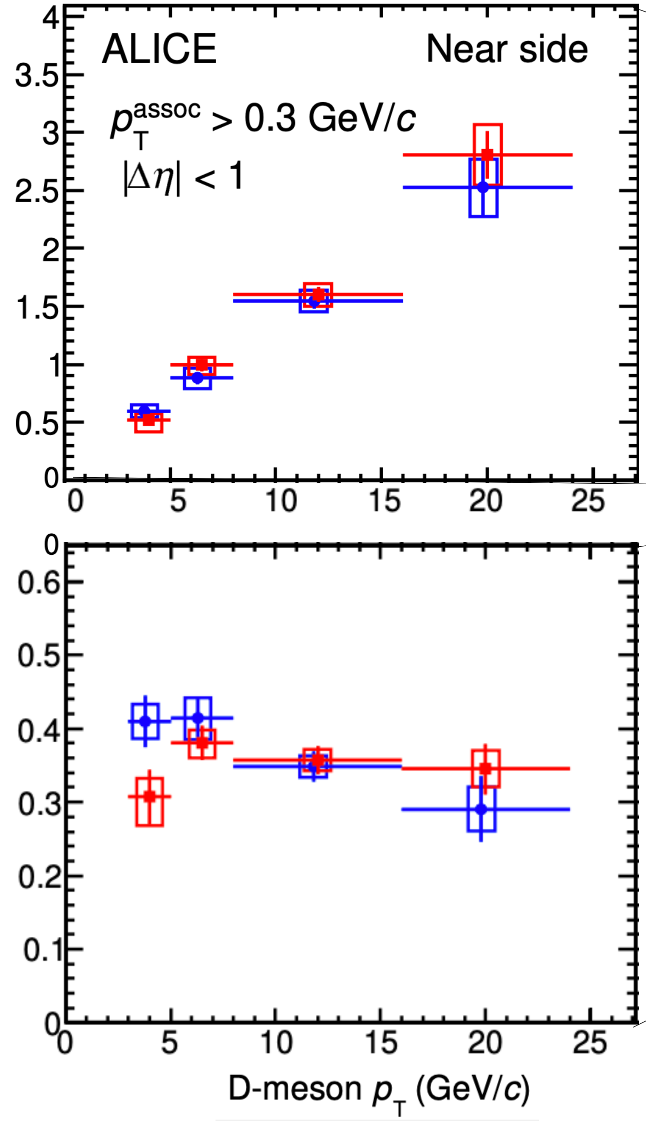
- Λ_c^+—h correlation distribution was compared to PYTHIA8 with different parameter tunings
  - CR-BLC (color reconnection beyond leading color) reproduces the Λ_c^+/D^0 yield ratio measured by ALICE in pp collisions (see slide 13)
- All models underpredict correlation distribution peaks for $3 < p_T^{\Lambda_c^+} < 5$ GeV/c and associate $p_T < 1$ GeV/c
- For larger p_T, the agreement is better

Proton—Lead Collisions



- D-h correlations
  - Comparison of observables to pp
  - Comparison across different centrality classes
- HFe-h correlations
  - Comparison of correlation distributions to pp
  - Comparison to models

D-Meson Correlation Observables in p-Pb



pp

p-Pb

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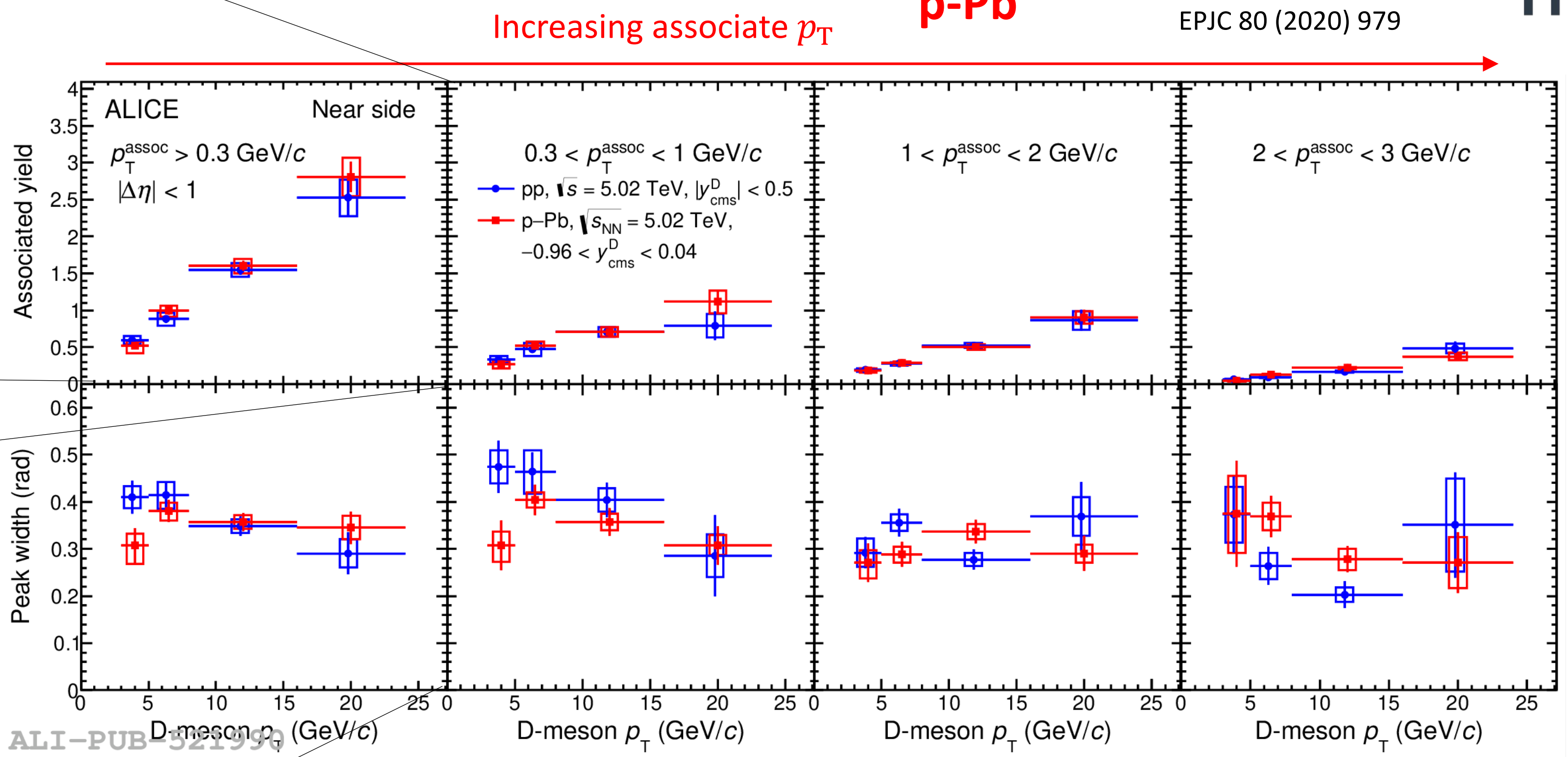
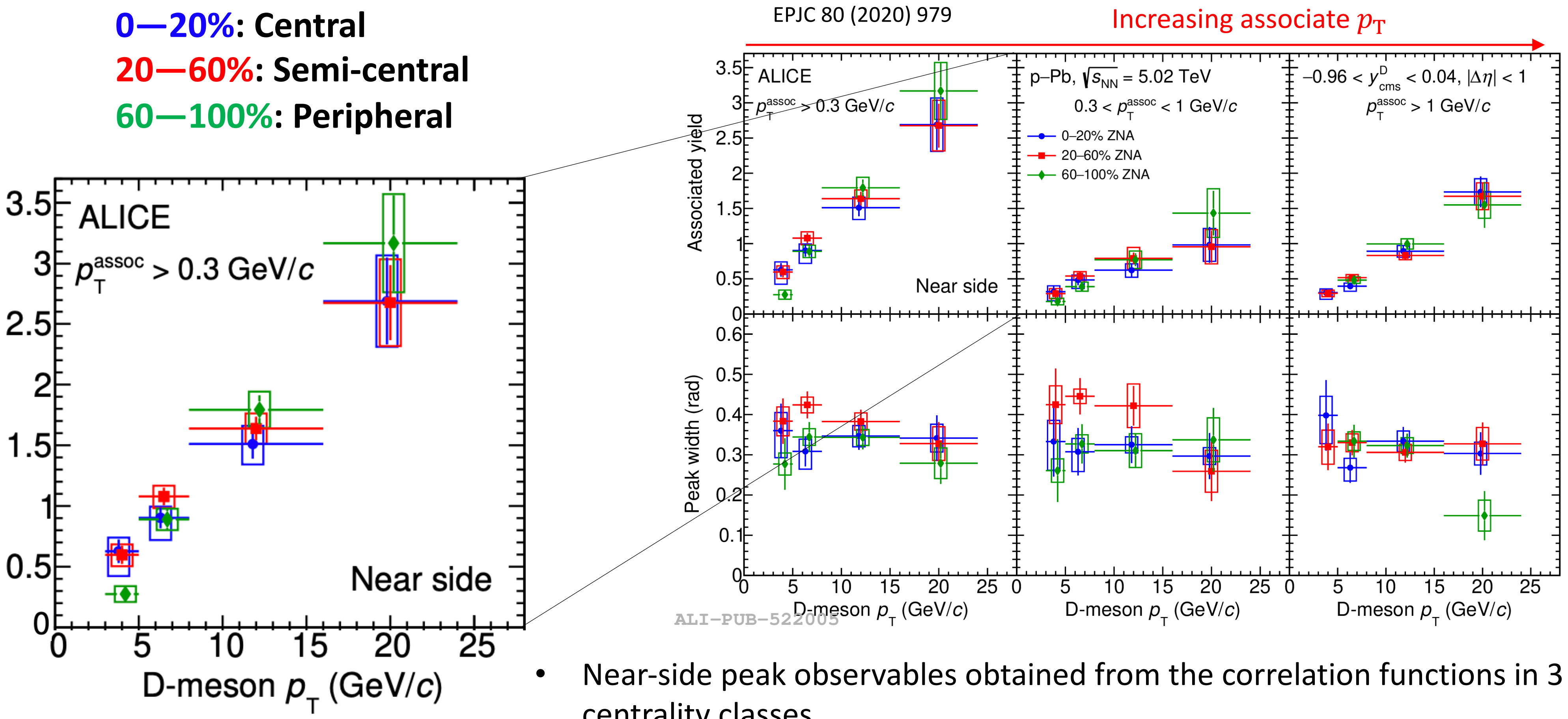


- Near-side associated yields and widths in pp and p-Pb collisions compared at $\sqrt{s} = 5.02$ TeV
- No significant impact from cold-nuclear-matter effects on charm fragmentation and hadronization in the D-meson range measured

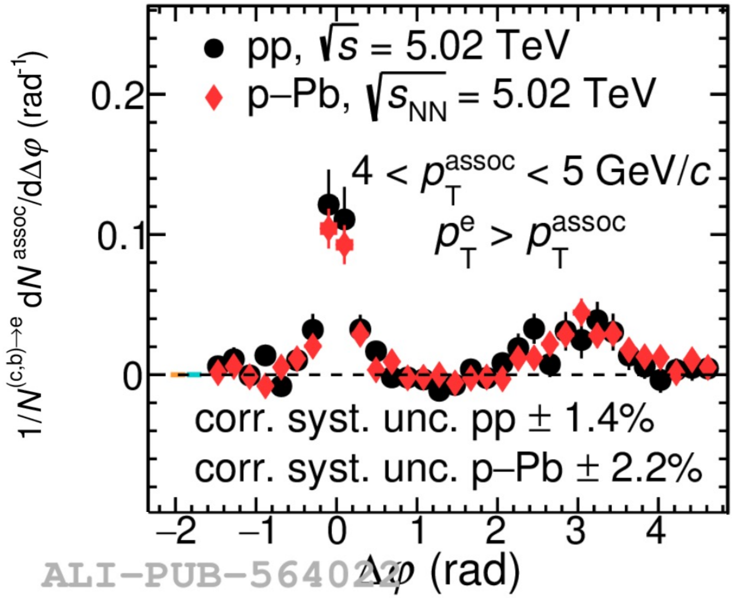
D-Meson Correlation Observables in p-Pb

0—20%: Central
20—60%: Semi-central
60—100%: Peripheral



- Near-side peak observables obtained from the correlation functions in 3 centrality classes
- Near-side peak yields and widths are in agreement within uncertainties
- No centrality dependence on correlation peaks within experimental uncertainties
  - Similar to pp observations

HFe-h Observables in p-Pb



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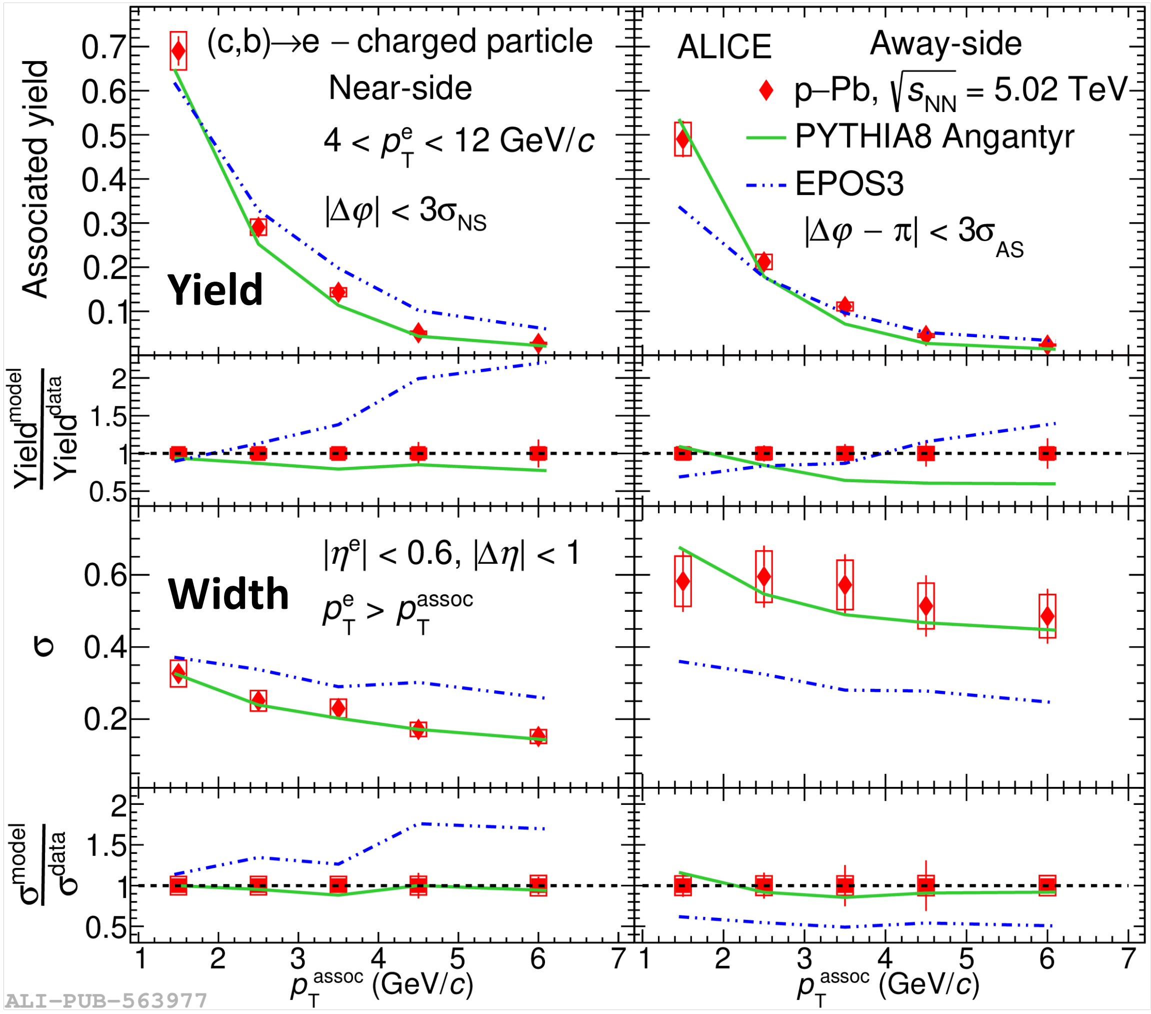
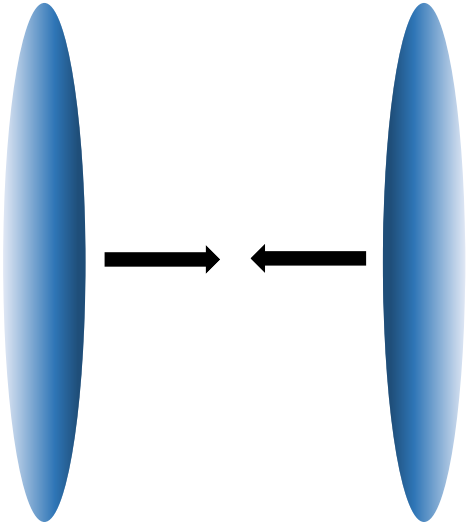


- pp and p-Pb correlation distribution and observables consistent within uncertainties
  - No significant cold-nuclear matter effects on HF quark fragmentation in the p_{T} range measured
- Compared to **EPOS3**, **PYTHIA8 Angantyr** describes better the measured observables
  - **Angantyr** combines several nucleon-nucleon collisions to build p-A or A-A collision
  - **EPOS3** slightly overpredicts near-side width and underpredicts away-side width in both $p_{\mathrm{T}}^{\mathrm{HFe}}$ ranges

Lead-Lead Collisions

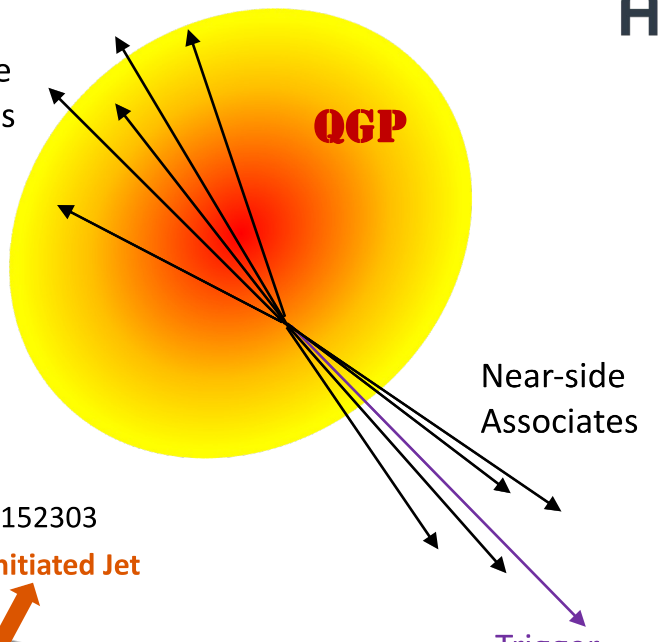


- Preliminary measurements of HFe-h correlations
    - Correlation distributions compared to pp in two centralities
    - I_{AA} measurement compared to light flavor results

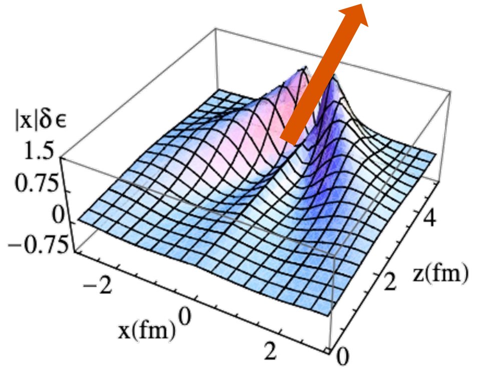
Angular Correlations in Pb-Pb Collisions

- In Pb-Pb collisions, HF quarks interact with the QGP via elastic collisions and are subject to energy loss via gluonsstrahlung
- Angular correlations in this collision system allows for a variety of physics measurements
  - HF hadronization in the presence of the QGP medium
  - Jet-medium interactions, such as jet quenching
- The per-trigger nuclear modification factor (I_{AA}) can be used to study the effect of the QGP medium on HF fragmentation, as well as potentially the effect of the parton shower on the medium (so called “wake” effect)
- The I_{AA} is defined as the ratio of per-trigger associated yield in Pb-Pb collisions to pp collisions:

$$I_{AA} = \frac{Y_{\Delta\varphi}^{\text{Pb-Pb}}}{Y_{\Delta\varphi}^{\text{pp}}}$$



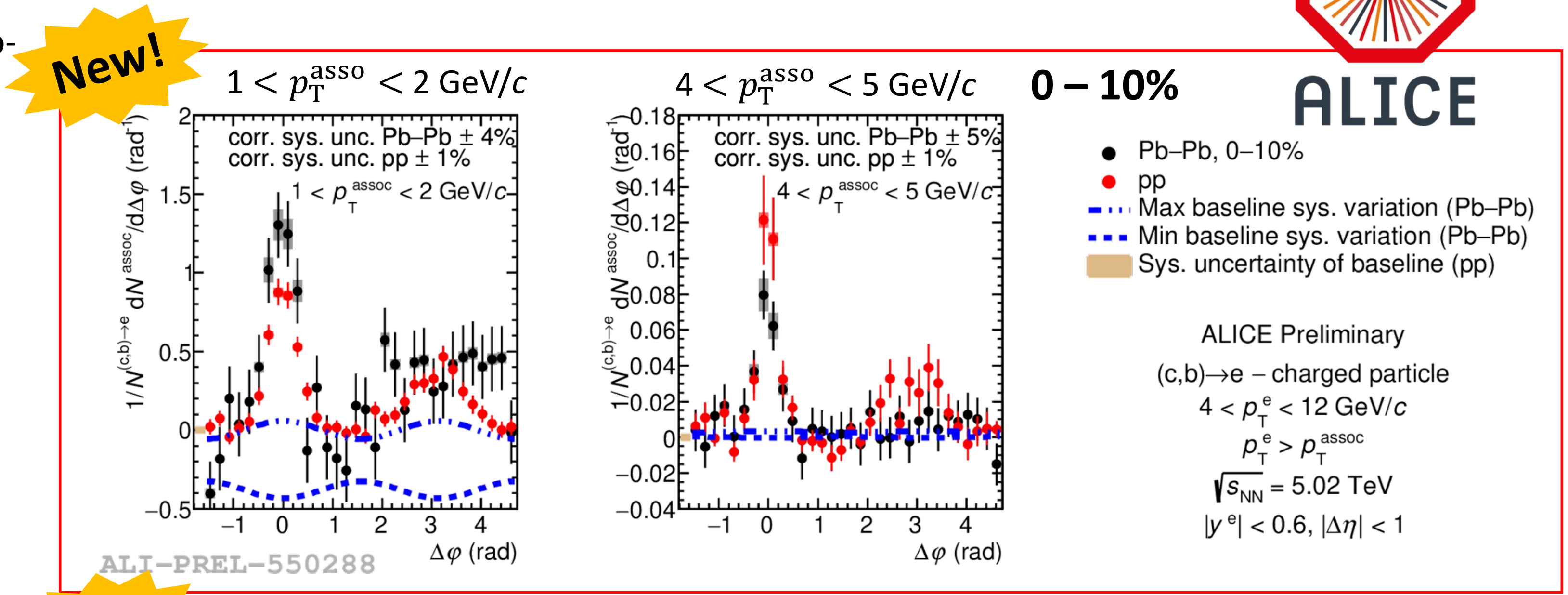
G.-Y. Qin et al, PRL 103, 152303 (2009)

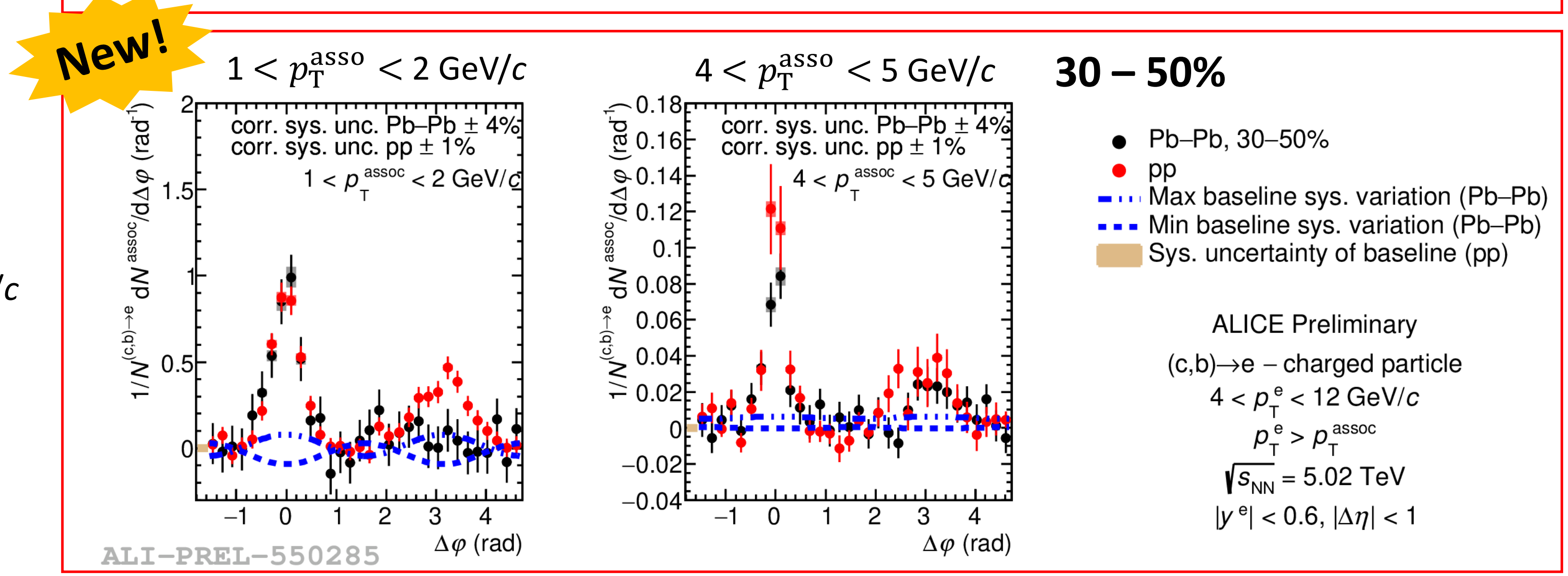


Change in energy density within the medium from quark-initiated jet

HFe-h Correlations in Pb-Pb Collisions

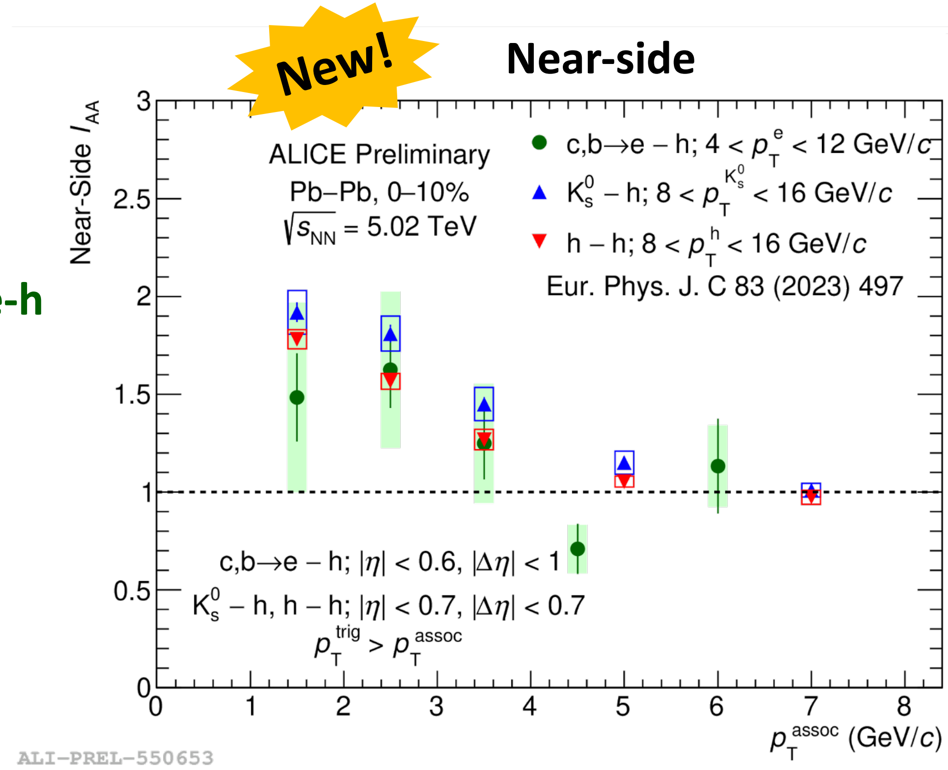
- Preliminary measurements of HFe-h correlations in Pb-Pb in 0—10% and 30—50% centrality
- Uncorrelated background was subtracted by fitting a baseline function to the transverse region, including elliptic flow modulation:
  - $B(\Delta\varphi) = b\left[1 + 2v_2^{\mathrm{HFe}} v_2^{\mathrm{Ch\ asso}} \cos(2\Delta\varphi)\right]$
- Both centralities:
  - More collimated near-side peak at high associated p_{T}
    - Similar to pp and p-Pb analysis
- 0 – 10% centrality:
  - Near-side peak is slightly higher in Pb-Pb compared to pp at low p_{T}
  - Away-side peak shape differs significantly as associated p_{T} increases
  - Larger away-side peak for $1 < p_{\mathrm{T}}^{\mathrm{asso}} < 2$ GeV/c
  - Away-side jet quenched for $4 < p_{\mathrm{T}}^{\mathrm{asso}} < 5$ GeV/c
- 30 – 50% centrality:
  - No clear away-side peak at low $p_{\mathrm{T}}^{\mathrm{asso}}$
  - Away-side peak smaller in Pb-Pb than in pp at higher $p_{\mathrm{T}}^{\mathrm{asso}}$

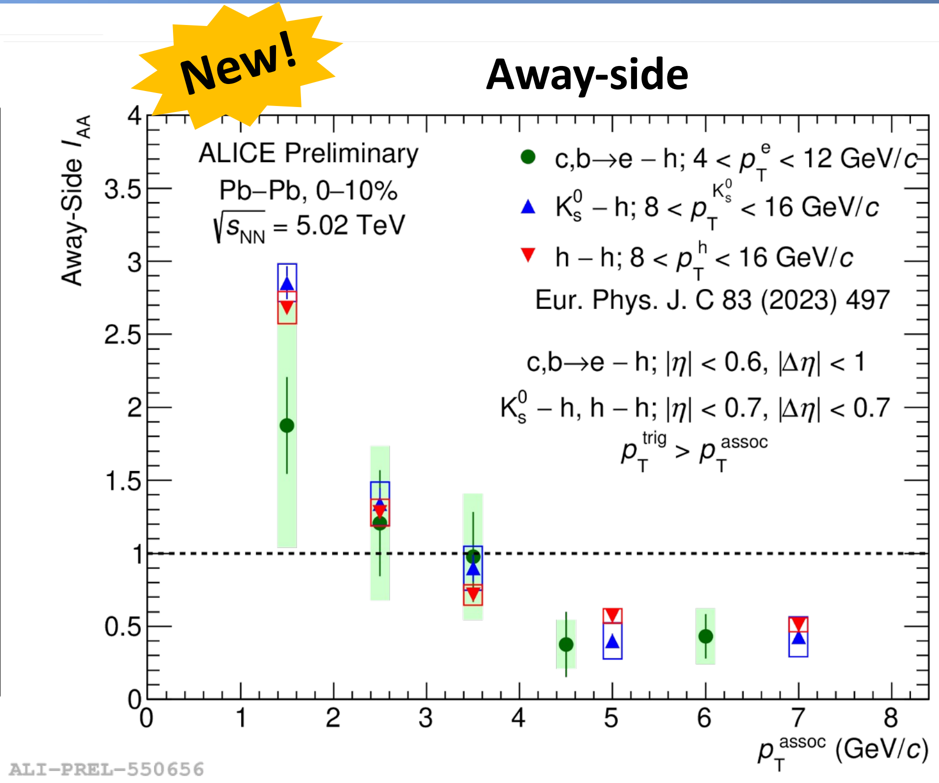




Preliminary HFe I_{AA} compared to light flavor

c, b→e-h
K_S^0-h
h-h





- Preliminary measurement of per-trigger nuclear modification factor (I_{AA}) compared to published di-hadron and K_S^0-h I_{AA}
- Near-side: I_{AA} points above unity at low p_T, but no significant enhancement due to large uncertainties
  - Combined significance of 1.31σ above 1 for $1 < p_T < 3$ GeV/c
  - Fluctuates about unity at higher p_T
- Away-side: Hint of suppression at high p_T
  - Significance of ~2.5σ for $I_{AA} < 1$ for $p_T > 4$ GeV/c
- Despite large systematic uncertainty in first p_T bin, both near and away-side HFe I_{AA} displays similar trends as LF

Summary

- Angular correlations and HF jet reconstruction are complementary techniques to baryon-to-meson yield measurements for studying heavy-flavor fragmentation

- pp
  - Extensive study of D-meson correlations with charged particles comparing different $\sqrt{s}$ and multiplicity classes
    - Fragmentation does not appear to significantly differ among the studied energies/multiplicites
  - Preliminary Λ_c^+-baryon correlations measured and compared to D-meson observables
    - Hint of enhancement in near- and away-side correlation peaks for lowest trigger and associated p_T

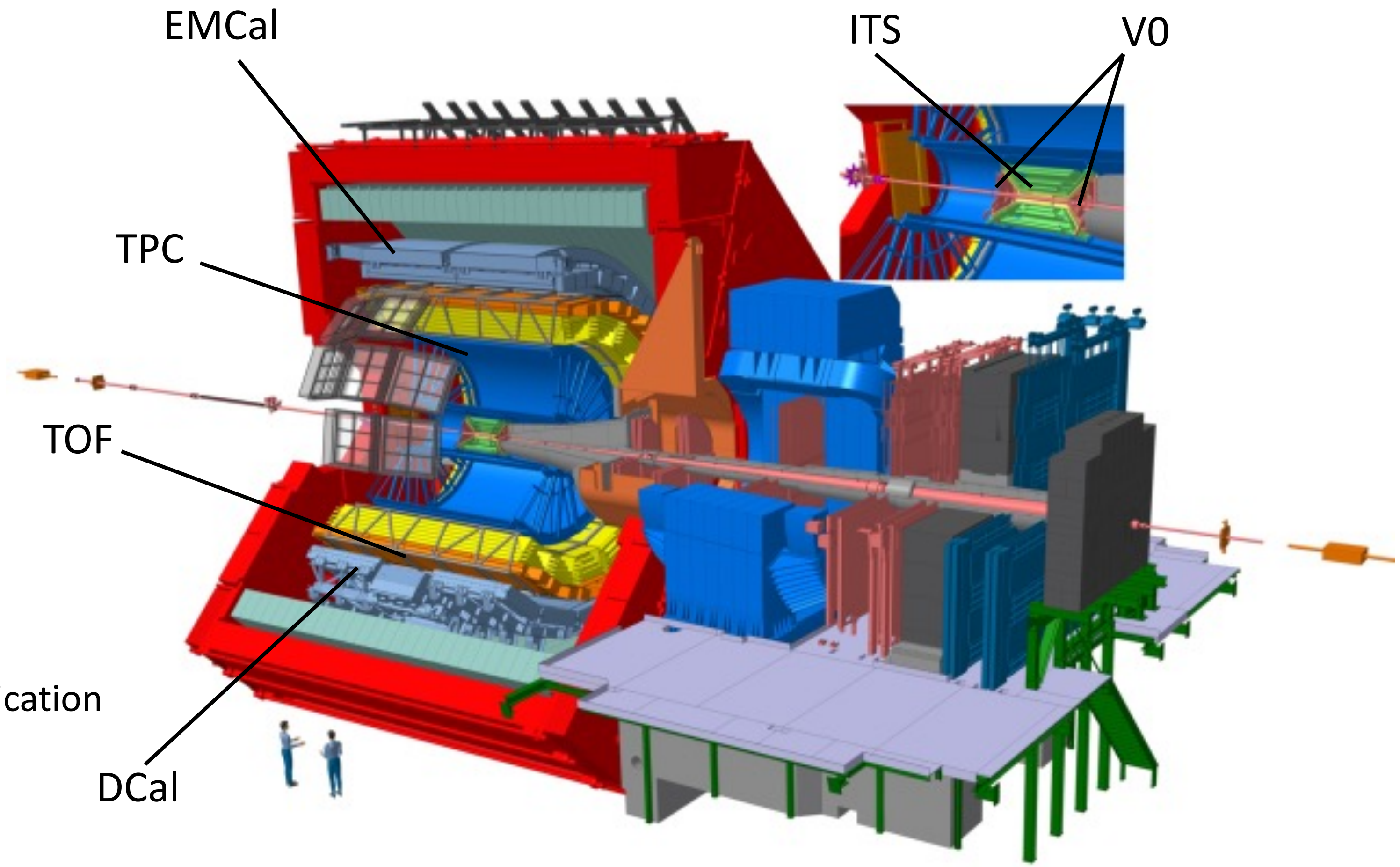
- p-Pb
  - D-meson and HFe correlations with charged particles measured and compared to pp
    - No significant cold nuclear-matter effect observed in D-h and HFe-h correlation measurements
  - D-meson correlations studied for different centrality classes
    - No significant difference in observables at different centralities

- Pb-Pb
  - Preliminary HFe-h I_{AA} compared to published light flavor I_{AA} results
    - Near and away-side I_{AA} between HFe and LF appear to follow similar trends, although HFe results have large uncertainty at low associated particle p_T

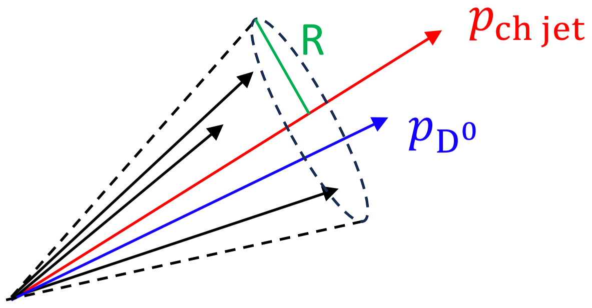
Additional Slides

The ALICE Detector

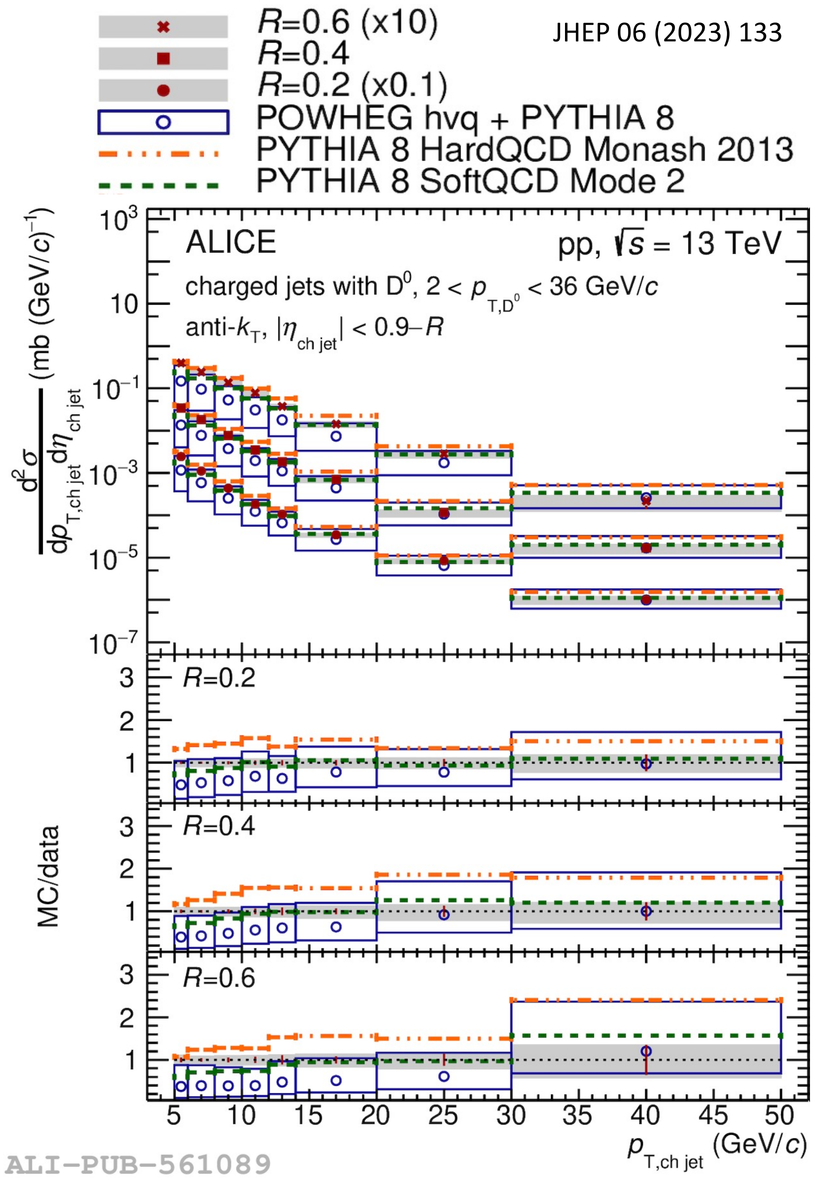
- Internal Tracking System (ITS)
  - Vertexing, tracking
- Time Projection Chamber (TPC)
  - Tracking, Particle identification
- Time-of-Flight (TOF)
  - Particle identification
- Electromagnetic calorimeter (EMCal, DCal)
  - Particle Identification
- V0 detector
  - Triggering, centrality and multiplicity classification



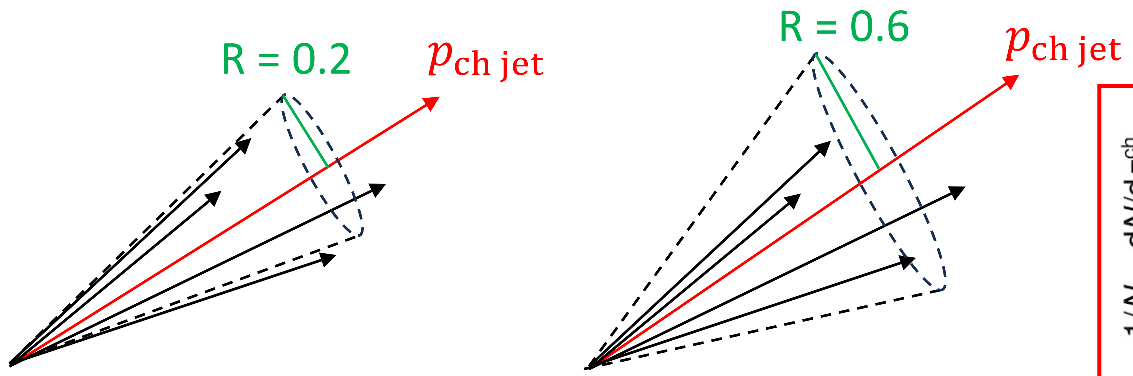
D^0-tagged Jet Differential Cross Section



- Jets are reconstructed with FastJet anti-k_T algorithm, considering charged-particle constituents, and tagged by searching for a fully reconstructed D^0 meson within the jet cone
- Production cross section of jets containing D^0 mesons have been measured at $\sqrt{s}$ = 5.02 and 13 TeV
- PYTHIA8 predictions with SoftQCD and Mode 2 settings provides the closest description of the $p_{\mathrm{T,ch\ jet}}$-differential cross sections for both energies and all resolution parameters R



D^0-tagged Jet Differential Yield

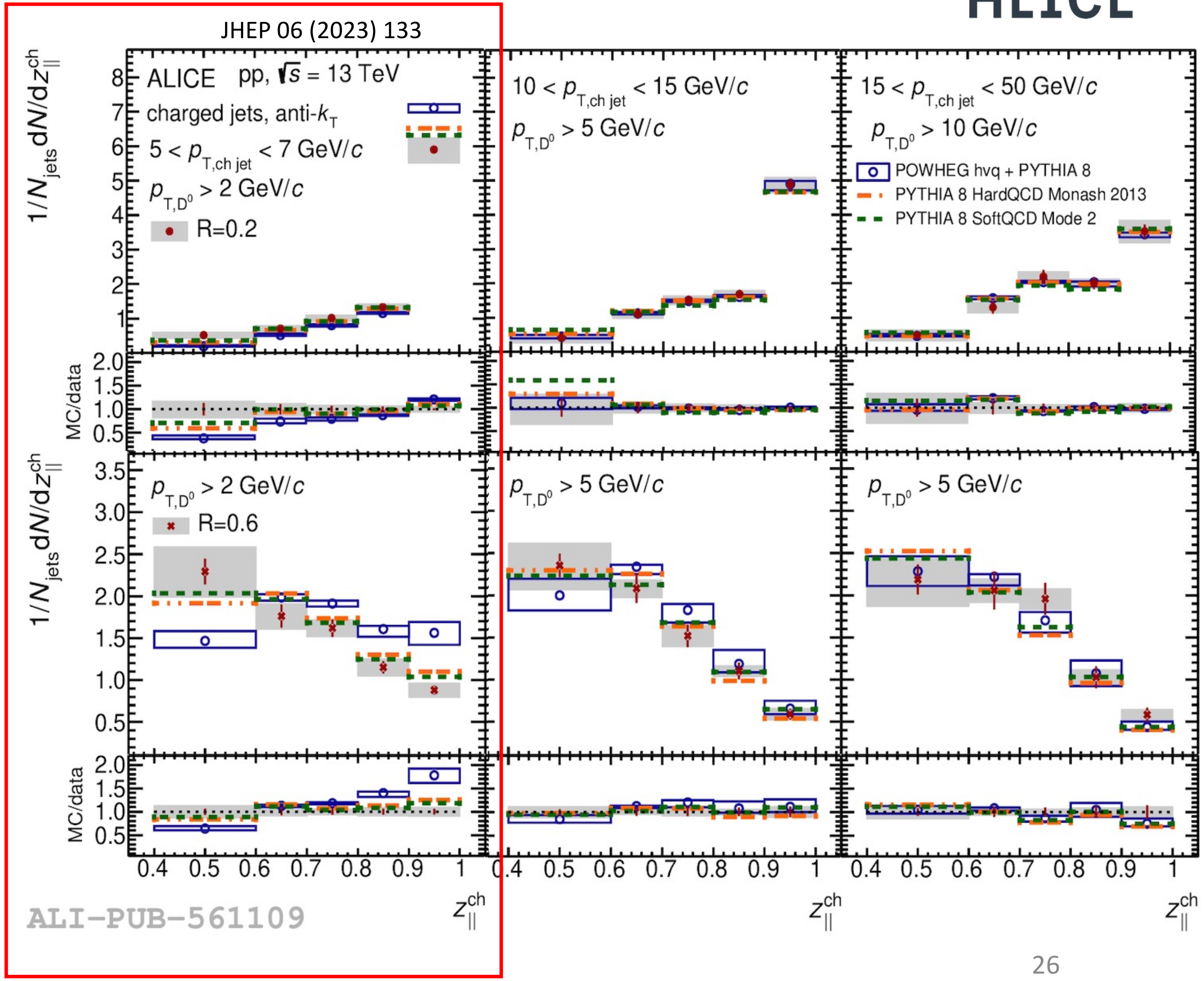


- Longitudinal jet-momentum fraction of D^0 in $5 < p_{\text{T,ch jet}} < 7$ GeV/c and for largest R shows hints of softer charm fragmentation with respect to PYTHIA8 and POWHEG+PYTHIA8 predictions

- All models in closer agreement with data at $15 < p_{\text{T,ch jet}} < 50$ GeV/c

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

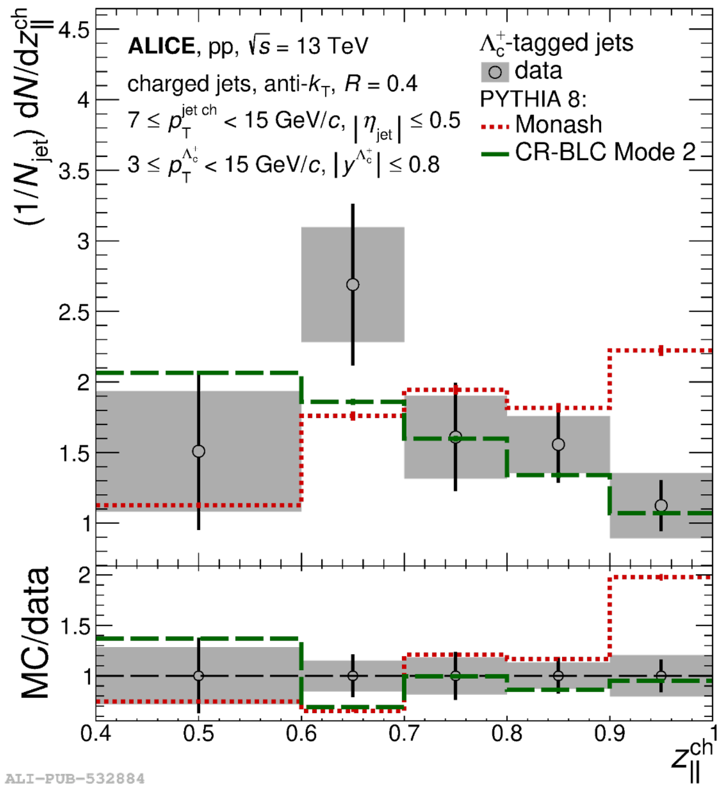
Fraction of longitudinal momentum carried by HF particle

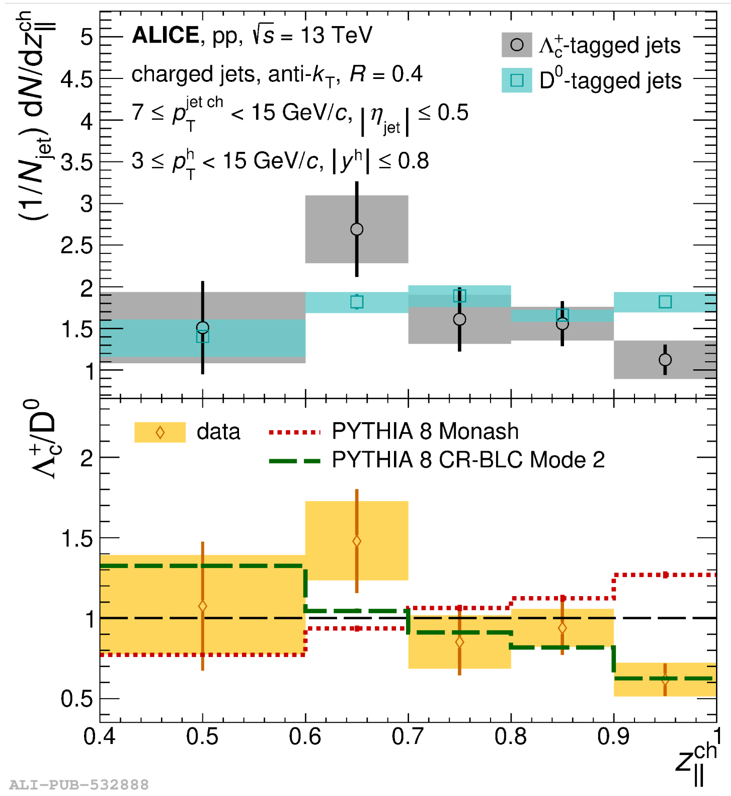


Λ_c^+-tagged Jet Production

- (Left) $z_{\parallel}^{ch}$ distribution of Λ_c^+-tagged jets compared to two different PYTHIA8 tunes
  - Monash
    - Charm fragmentation is tuned on e^+e^- measurements and predicts harder fragmentation
  - CR-BLC Mode 2
    - Includes color reconnection mechanisms beyond leading-color approximation
  - Both models generally within 1σ of uncertainty of data, but CR-BLC Mode 2 describes better at higher $z_{\parallel}^{ch}$
- (Right) Λ_c^+-tagged jet distribution compared to D-tagged jets
  - CR-BLC Mode 2 better describes the data compared to Monash

arXiv: 2301.13798





List of models compared to D-h observables

Models and event generators used:

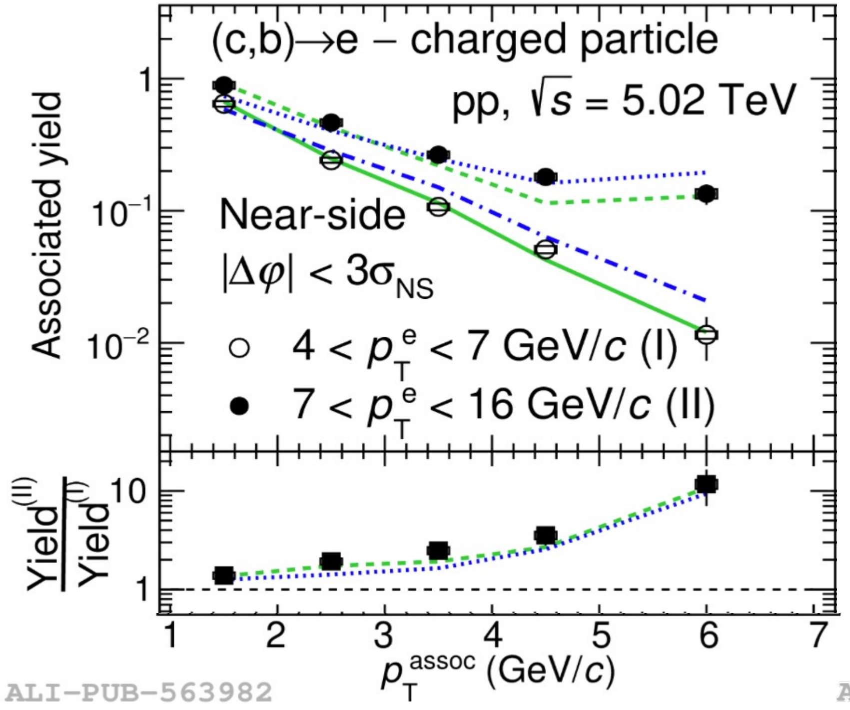
- PYTHIA6, Perugia 2011
  - PYTHIA6: pQCD generator implementing hard-scattering matrix elements at LO accuracy
  - Perugia 2011: Used to generate templates for $\Delta\varphi$ beauty-feed down uncertainty estimation
- PYTHIA8, Tune 4C
  - PYTHIA8: Implements better handling of multiple-parton interactions and color reconnection than PYTHIA6
  - Tune 4C: Used to generate templates for $\Delta\varphi$ beauty-feed down uncertainty estimation
- HERWIG
  - pQCD generator with NLO accuracy
  - Parton showering performed with angular ordering of fragments
  - Hadronization with cluster hadronization model
- POWHEG + PYTHIA8
  - POWHEG: pQCD generator implementing hard-scattering matrix elements with NLO accuracy
  - Hard-scattering matrix elements evaluated at NLO or LO
- POWHEG+PYTHIA8 LO
  - pQCD generator with hard-scattering matrix elements at only LO
- EPOS 3.117
  - Considers flux tube initial conditions
  - Employs core-corona description of fireball in heavy-ion collision
  - Generated in Gribov-Regge multiple-scattering framework and applies 3+1D viscous hydrodynamical evolution

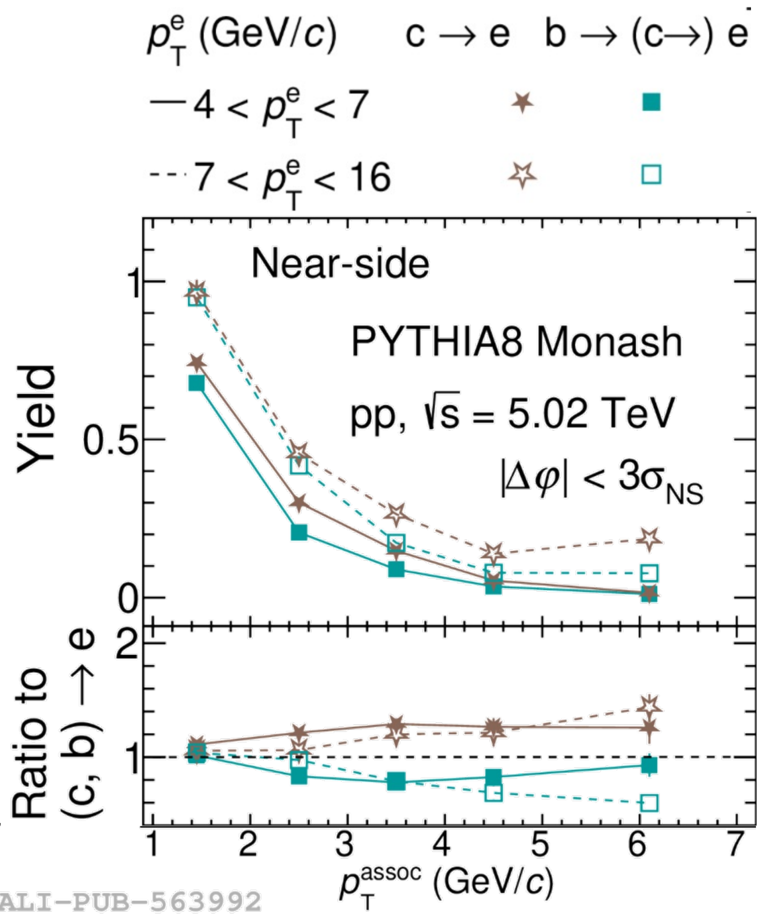
Hfe-h Yield in pp with predominantly Beauty electrons

PYTHIA8 Monash

EPOS3

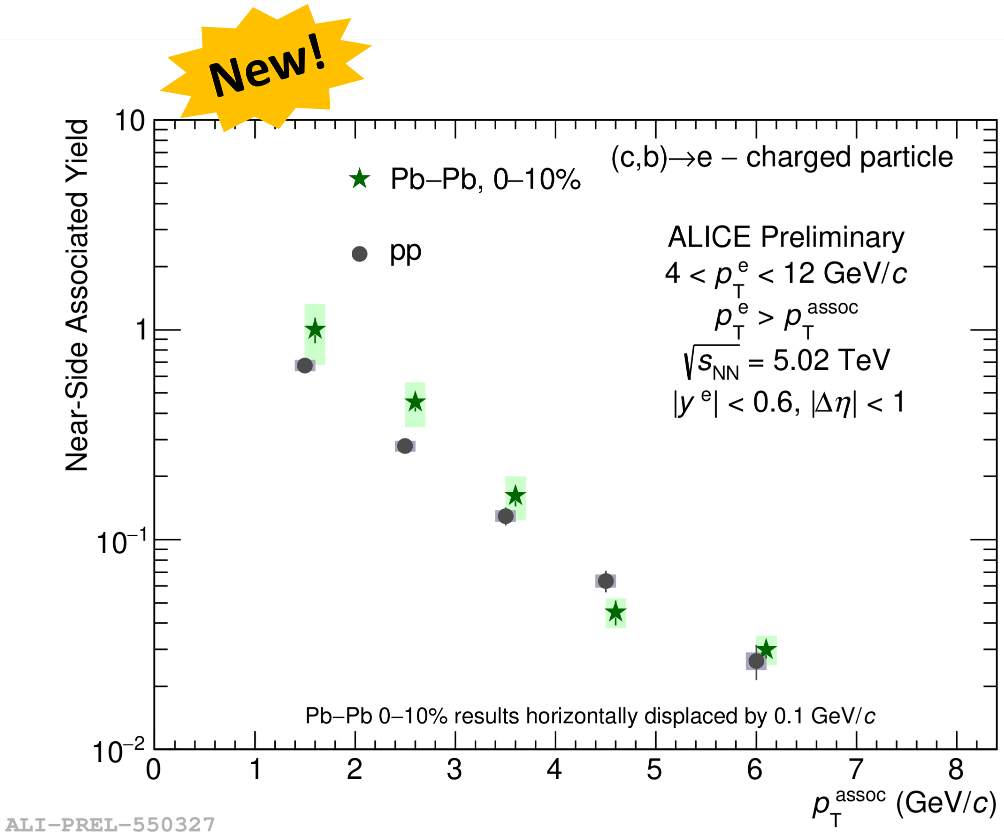
Eur. Phys. J. C 83 (2023) 741

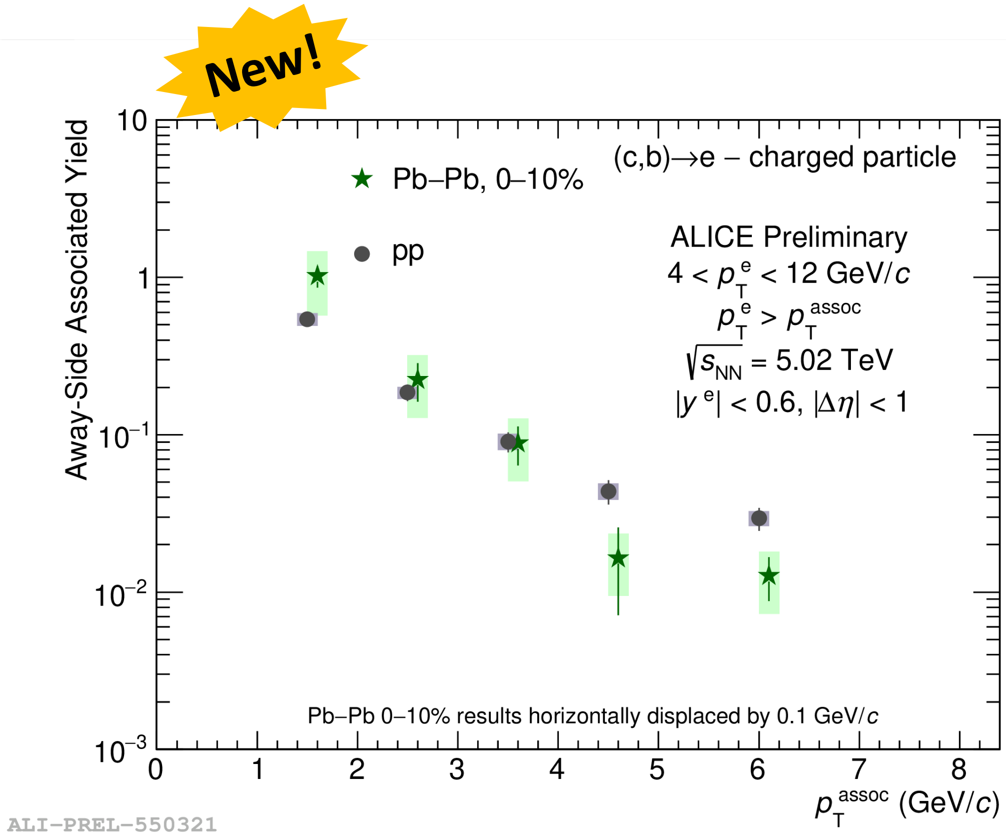




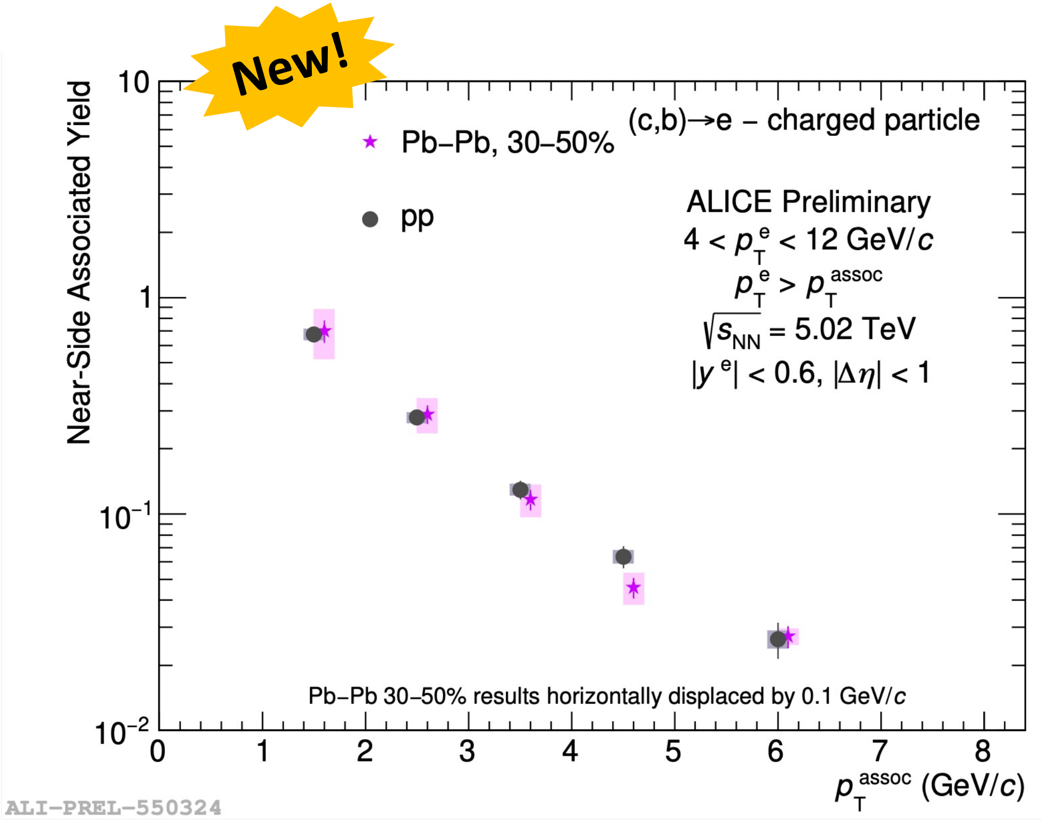
- Fraction of $b \to e/(b+c) \to e$ exhibits strong p_T dependence
  - $\sim$60% of HF electrons with $p_T > 7$ GeV/c produced from beauty [Phys. Lett. B 738 (2014) 97]
- For electrons within $7 < p_T^{HFe} < 16$ GeV/c, the near-side associated yields are larger, and does not fall as steeply with associate p_T than the $4 < p_T^{HFe} < 7$ GeV/c yields
- PYTHIA8 calculations show electrons from charm are produced with larger number of collimated associate particles compared to beauty
  - This indicates that the increase in associate yields observed on data for $7 < p_T^{HFe} < 16$ GeV/c is not flavor-dependent but is parton energy dependent

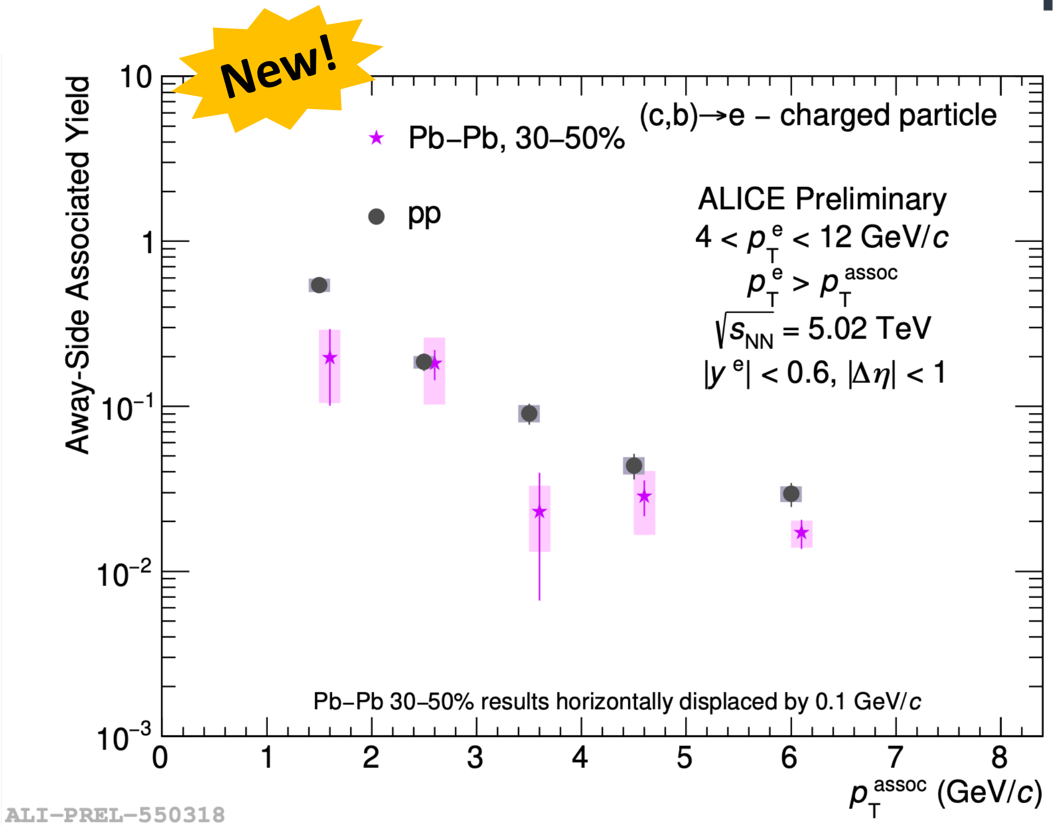
Near and Away-Side per-trigger yields, Hfe-h in Pb-Pb, 0—10%





Near and Away-Side per-trigger yields, Hfe-h in Pb-Pb, 30—50%





Near and Away-Side I_{AA}, HFe-h in Pb-Pb, 30—50%