Charm fragmentation studies with ALICE at the LHC

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on behalf of the ALICE collaboration

QUARK-GLUON PLASMA CHARACTERISATION WITH HEAVY FLAVOUR PROBES

Trento, 16/11/2021

Physics outline

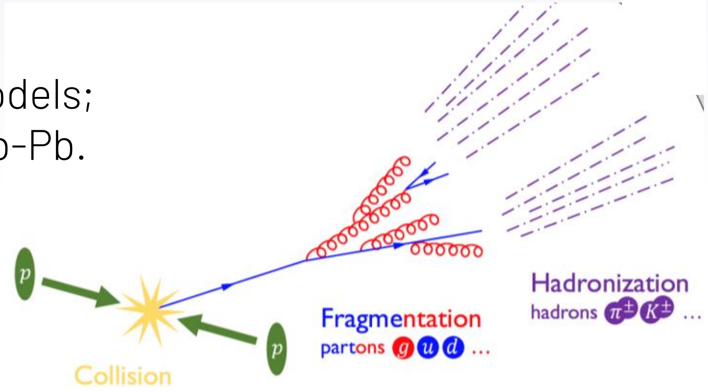
The study of Heavy-Flavour (HF) quarks in small systems provides the reference for the understanding of their interaction with quark-gluon plasma (QGP).

In pp collisions:

- test pQCD calculation;
- constrain and validate fragmentation and hadronization models;
- provide a reference for larger systems, such as p-Pb and Pb-Pb.

In p—Pb collisions:

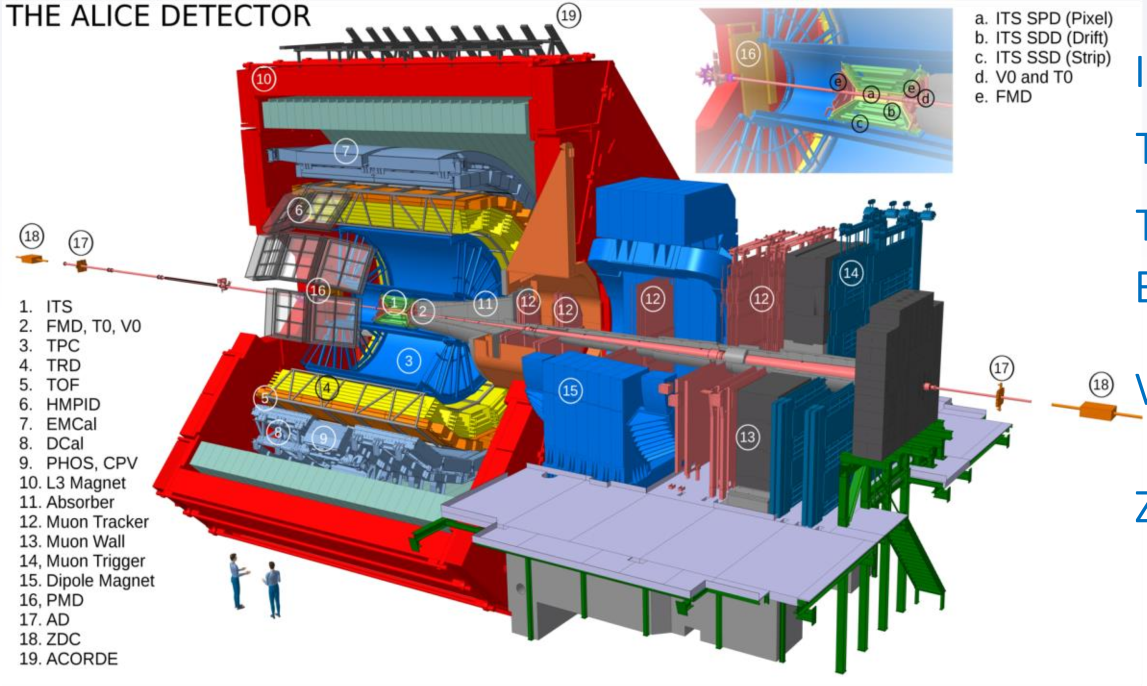
- their production and kinematic properties can be modified by cold nuclear matter (CNM) effects



HF-jets and HF-correlations can provide additional information than single parton studies:

→ fragmentation and hadronization mechanisms are detailed

ALICE: A Large Ion Collider Experiment



ITS: tracking + vertexing ($|\eta| < 0.9$)

TPC: tracking + PID ($|\eta| < 0.9$)

TOF: PID ($|\eta| < 0.9$)

EMCAL: high-pT trigger + electron ID ($|\eta| < 0.7$)

V0: trigger + centrality/multiplicity estimation ($-3.7 < \eta < -1.7$, $2.8 < \eta < 5.1$)

ZDC: centrality estimation ($4.8 < \eta < 5.7$)

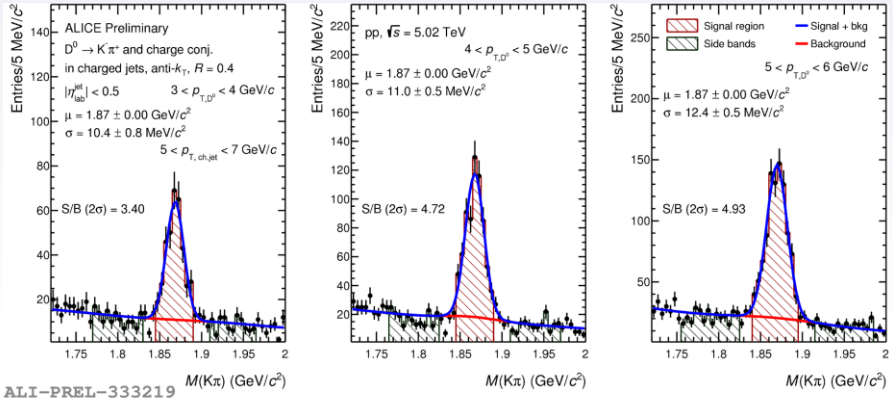
Charm-tagged jet measurements

D^0- and Λ_c^+- tagged jets

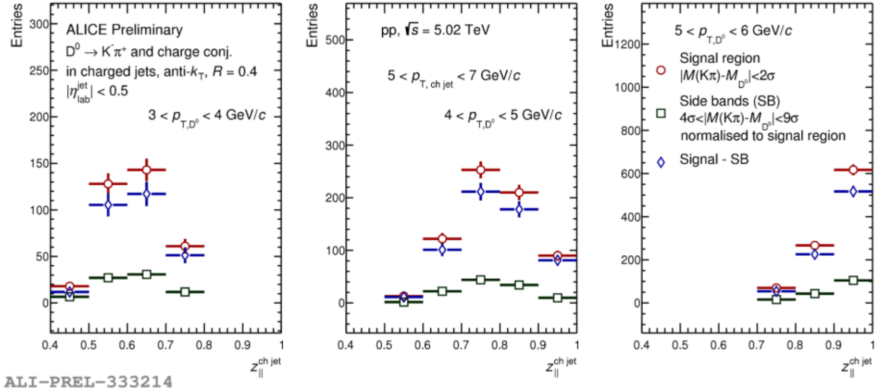
- D^0- and Λ_c^+-tagged jet reconstruction:
  - ✓ Identification of charm candidates

    $D^0 \rightarrow K^-\pi^+ + \text{conj. (B.R. 3.95\%)}$

    $\Lambda_c^+ \rightarrow pK_S^0 + \text{conj. (B.R. 1.59\%)}$
  - ✓ Charged particles are clusterized into jets:
    → to each D^0 and Λ_c^+ corresponds a jet (Fastjet, anti-k_T algorithm)

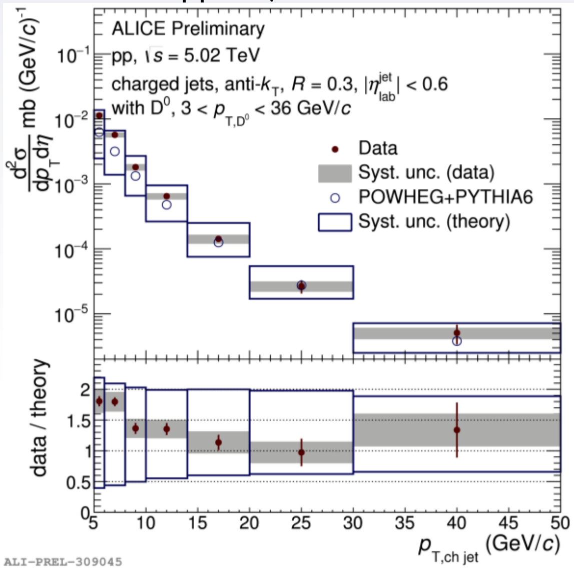


- Invariant mass analysis to extract the D^0- and Λ_c^+-jet raw yield
  - ✓ Sideband subtraction method
  - ✓ correction on jet efficiency and beauty feed-down
  - ✓ 2D unfolding $(z_{||}^{ch}, p_{T,ch\,jet})$ for detector effects

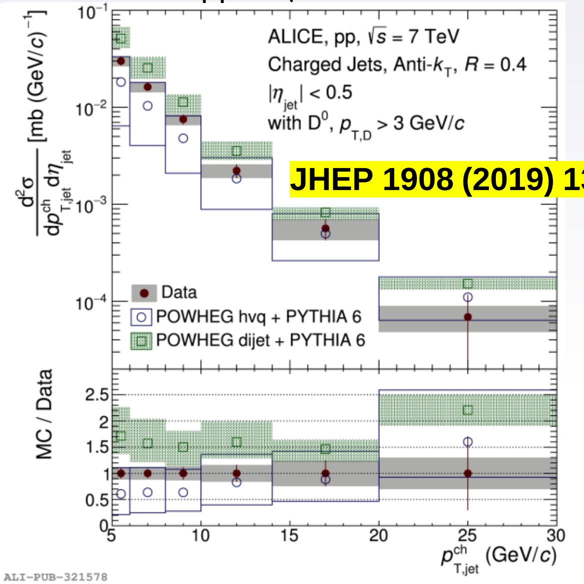


D^0-tagged jets production cross-section

pp at $\sqrt{s}$= 5.02 TeV



pp at $\sqrt{s}$= 7 TeV



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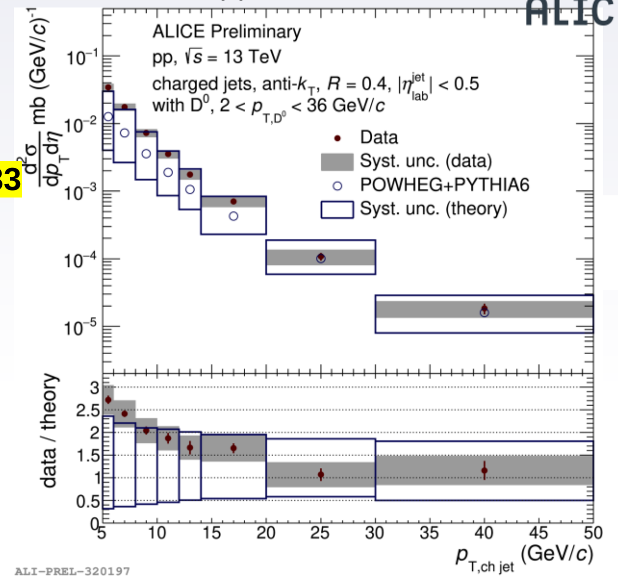
pp at $\sqrt{s}$= 13 TeV



Similar trends of the D^0 jets cross section with increasing $p_{\mathrm{T,\,ch\,jet}}$ between collision energies

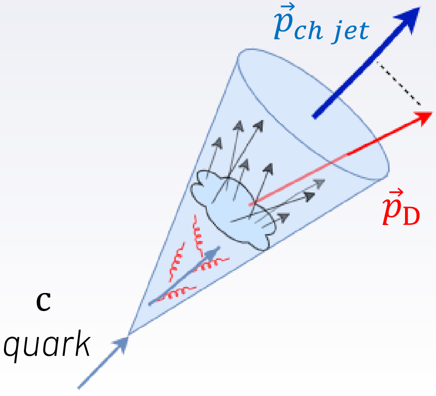
POWHEG hvq CT10NLO + PYTHIA6

- ✓ good agreement with data
- ✓ increasing compatibility with $p_{\mathrm{T,\,ch\,jet}}$

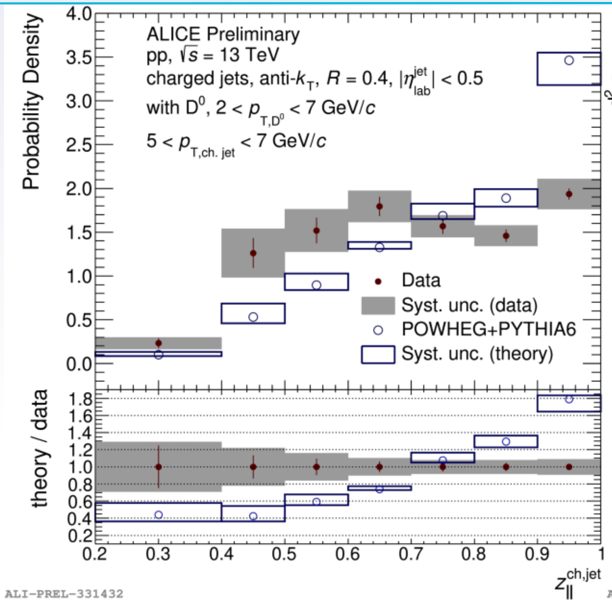
POWHEG dijet + PYTHIA6

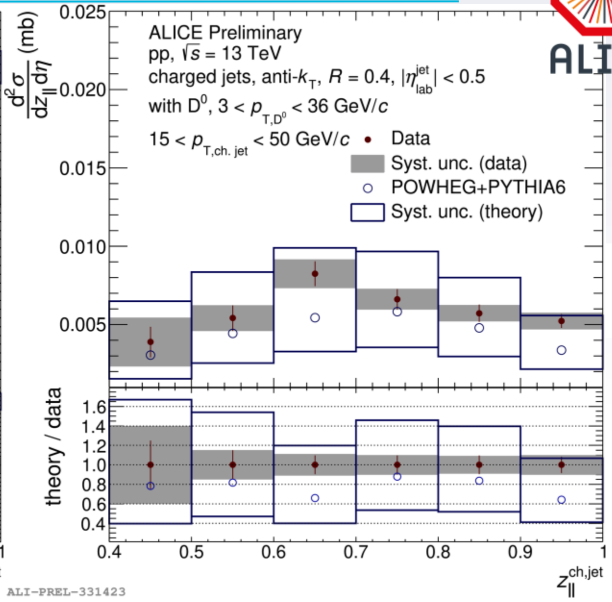
- ✓ constantly above data points
- ✓ different trend wrt **POWHEG hvq**

D^0-tagged jets: parallel momentum fraction



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





From the comparison with **POWHEG**:

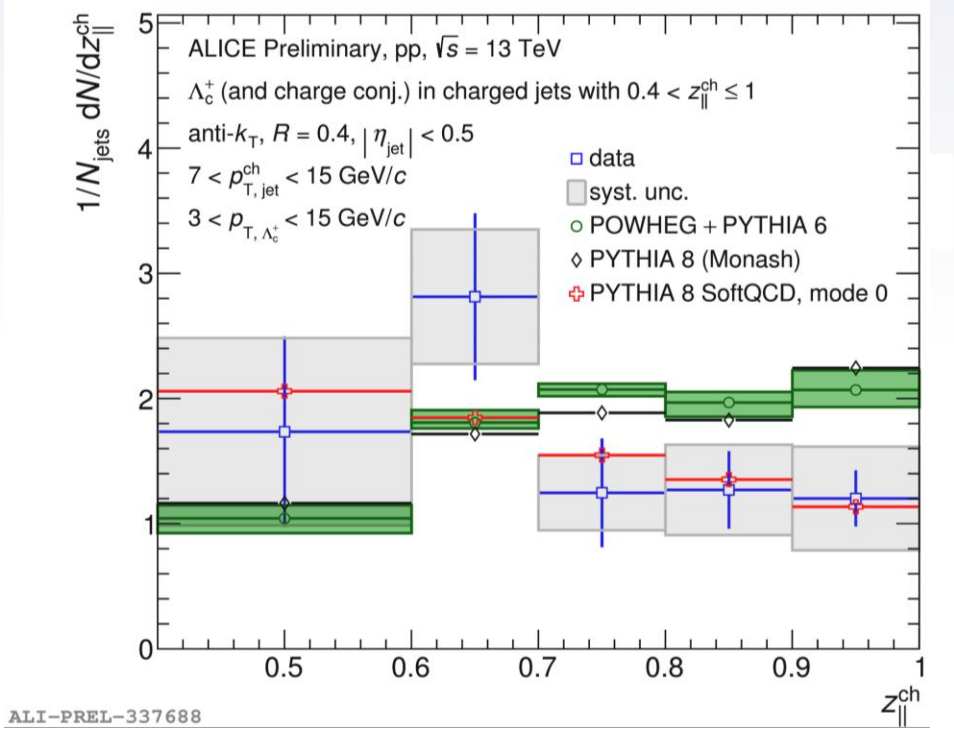
- A *softer fragmentation* is observed at small $z_{||}$ and small p_T^D and in the low-$p_{T,\text{ch jet}}$ range.
- At large $p_{T,\text{ch jet}}$ predictions are compatible within the syst. uncertainties.

Λ_c^+-tagged jets: parallel momentum fraction

$$z_{||}^{\text{ch}} = \frac{\vec{p}_{\text{ch jet}} \cdot \vec{p}_{\Lambda_c^+}}{\vec{p}_{\text{ch jet}} \cdot \vec{p}_{\text{ch jet}}}$$

The $z_{||}^{\text{ch}}$ probability density in Λ_c^+ -tagged jets has been measured with limited precision.

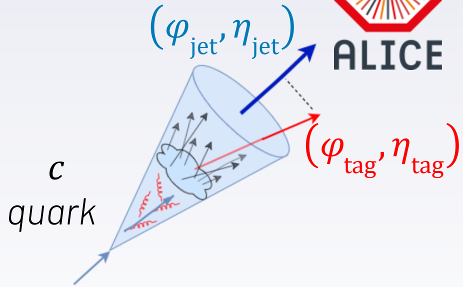
- **POWHEG** and **PYTHIA8 (Monash)** :
  - → harder fragmentation than data
- **PYTHIA8 SoftQCD**
  - → good agreement with data

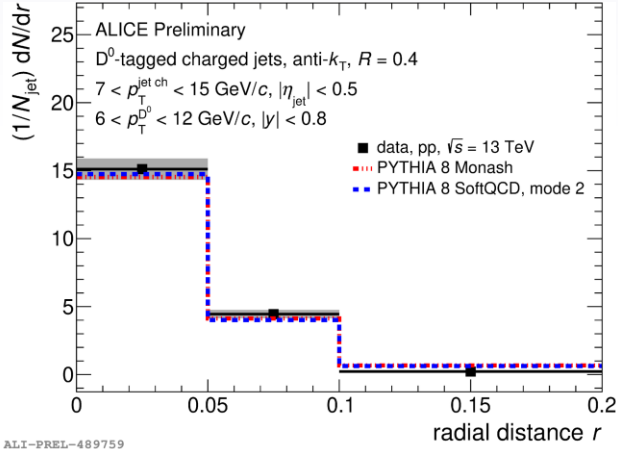


▶ D^0- and Λ_c^+-tagged jets: Radial Displacement

Addressing possible modifications of the hadronization through the radial shape of the jet

Radial Distance $$r = \sqrt{(\varphi_{jet} - \varphi_{tag})^2 + (\eta_{jet} - \eta_{tag})^2}$$





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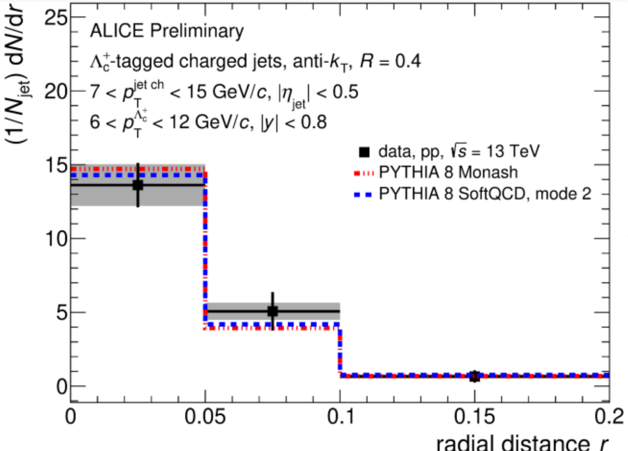

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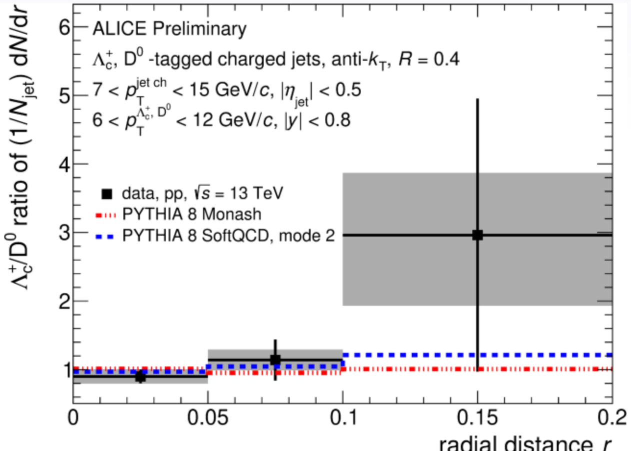

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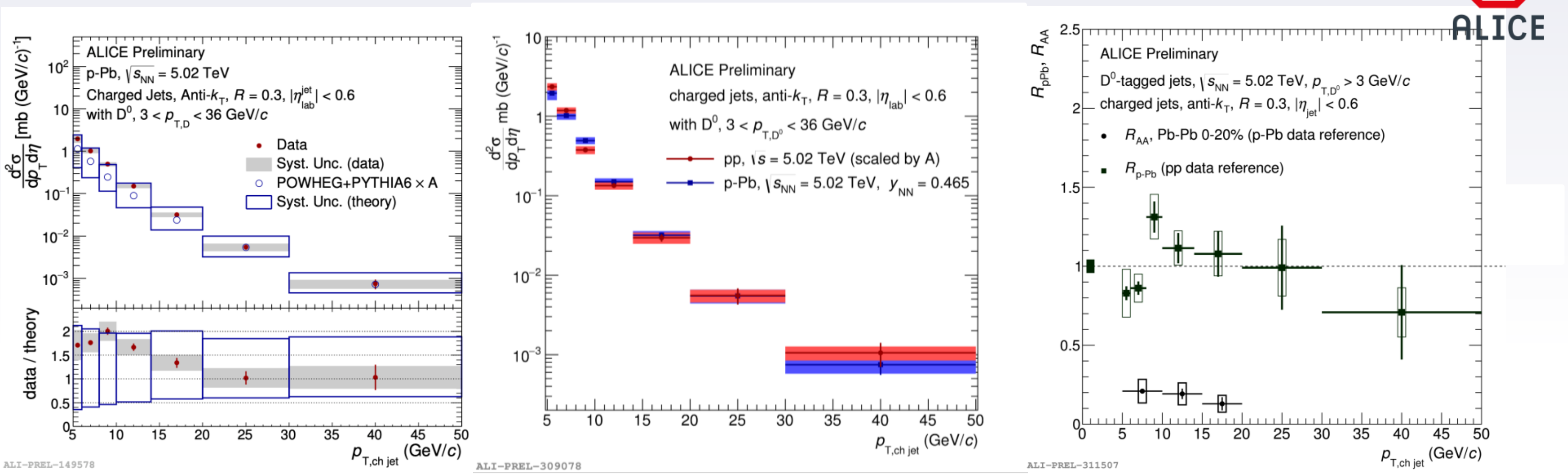
Is there a dependence of the Λ_c^+ / D^0 as function of the radial distance?

→ Are baryons produced less collimated than mesons w.r.t. the direction of the jet?

D^0-tagged jets in p—Pb at $\sqrt{s_{NN}}$ = 5.02 TeV

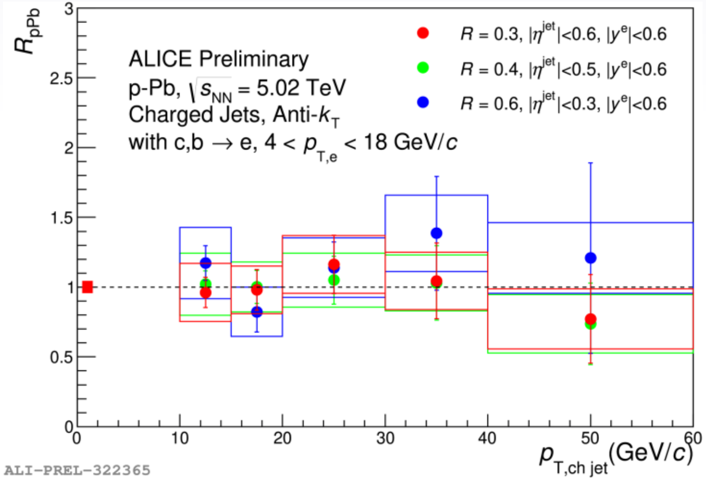


- **POWHEG** well reproduce p-Pb measurements.
- The differential p—Pb cross section is in agreement with the pp (scaled by A) within statistical uncertainties.
- The nuclear modification factor $R_{pPb} \approx 1$ over the $p_{T,\,ch\,jet}$ interval.
- The D^0-jet R_{AA} is also shown.

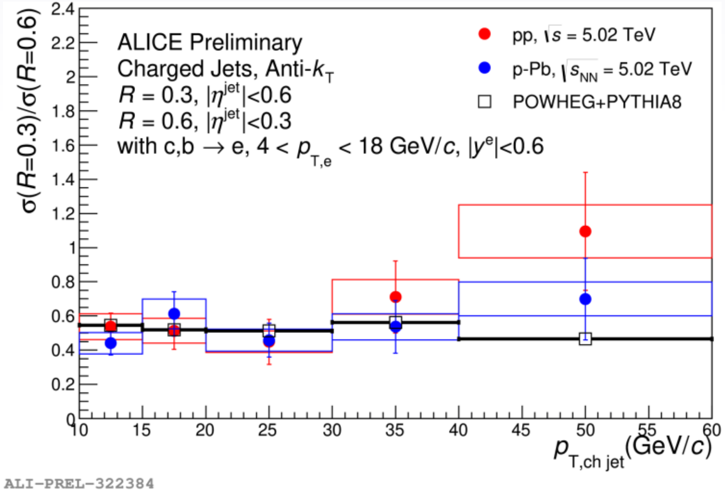
HF-electron jets in p—Pb at $\sqrt{s_{NN}}$ = 5.02 TeV

In p—Pb, possible modification to the jet shape or spectrum could evidence cold nuclear matter effects.

- *jet broadening*: dependence on R (jet cone size)
- *jet suppression*: modification to the $p_{\mathrm{T,\,jet}}$ spectrum



R_{pPb} not dependent on jet R



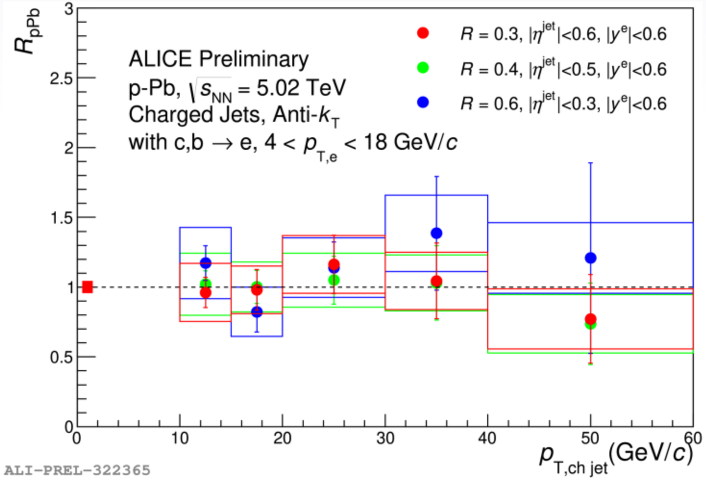
No evident modification to the jet shape depending on the collision system

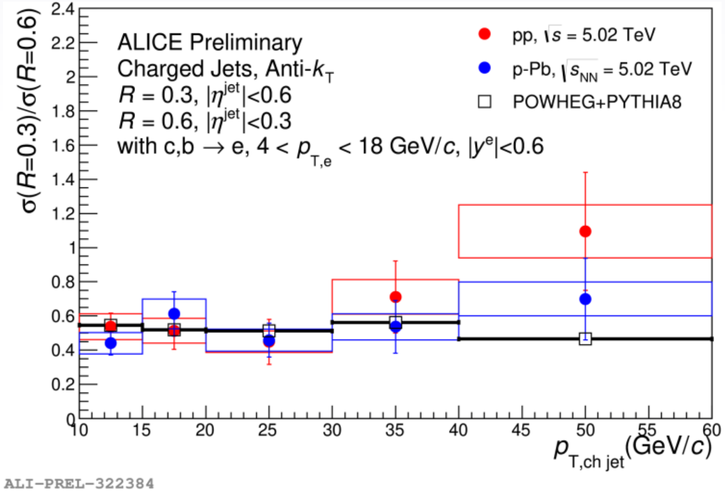
HF-electron jets in p—Pb at $\sqrt{s_{NN}}$ = 5.02 TeV

In p—Pb, possible modification to the jet shape or spectrum could evidence cold nuclear matter effects.

- *jet broadening*: dependence on R (jet cone size)
- *jet suppression*: modification to the $p_{T,\,jet}$ spectrum

No evidences of modification of the jet in small system





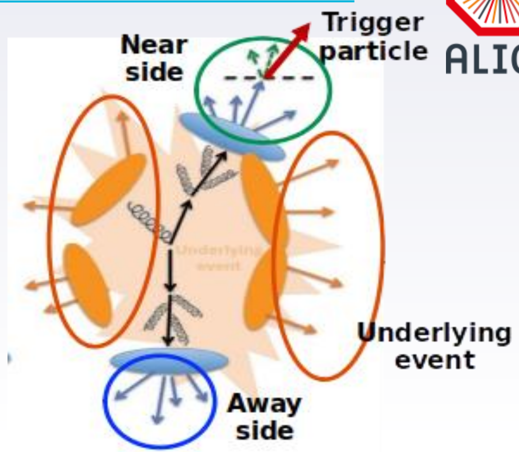
R_{pPb} not dependent on jet R

No evident modification to the jet shape depending on the collision system

Azimuthal correlations

D - charged particles azimuthal correlations

Final state particles are studied by means of their angular distribution with respect to the direction of the tagged D meson



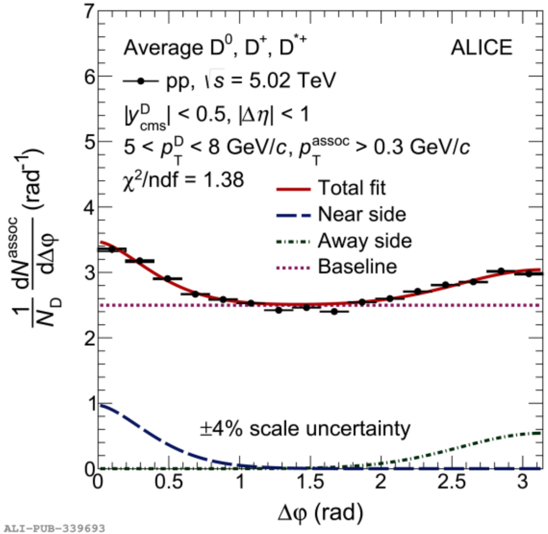
By relating an HF hadron to other particles produced in the same event, information can be retrieved about:

- ➢ the fragmentation of the tagged HF quark;
- ➢ the fragmentation of the other HF quark;
- ➢ the underlying event.

Differential description of the peaks shape with p_T^{assoc}

- Characterization of the jet shape and its composition

In p—Pb, find modifications to the correlation shape induced by CNM effects.



D - charged particles azimuthal correlations

How are they extracted?

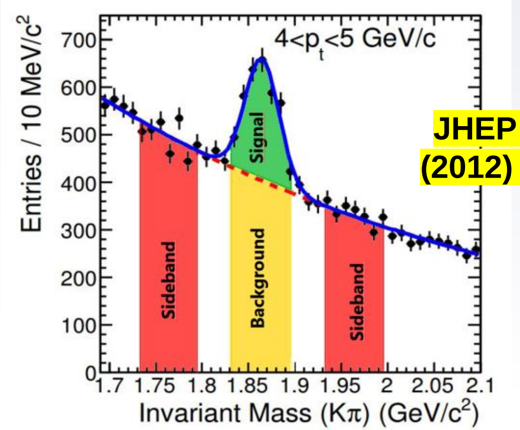
- Reconstruction of D-meson candidates

$$D^0 \rightarrow K^-\pi^+ + \text{conj.} \quad (\text{B.R. } 3.95\%)$$
$$D^+ \rightarrow K^-\pi^+\pi^+ + \text{conj.} \quad (\text{B.R. } 9.38\%)$$
$$D^{*+} \rightarrow D^0\pi^+ \rightarrow K^-\pi^+\pi^+ + \text{conj.} \quad (\text{B.R. } 2.67\%)$$

- Identification of associated (charged) particles

⟶ 2D correlations are computed ($\Delta\varphi$, $\Delta\eta$)

- Sideband subtraction;



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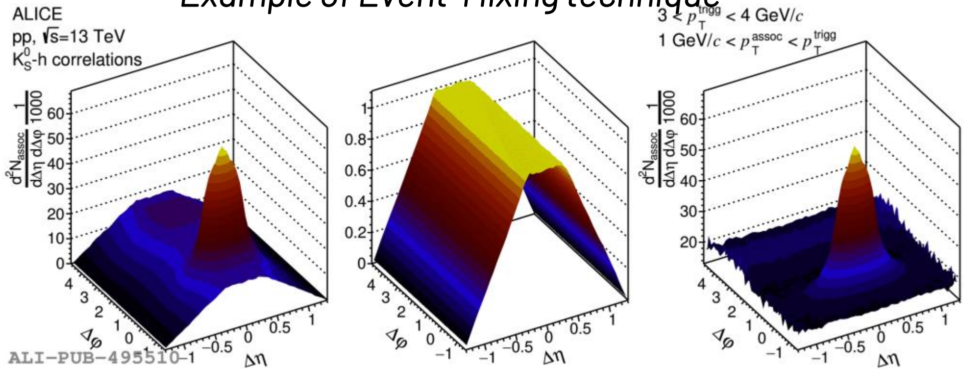
Corrections for:

- Event Mixing: limited detector acceptance and detector spatial inhomogeneities
- Reconstruction and tracking efficiency
- Contamination from secondary particles
- Beauty feed-down contribution

Example of Event-Mixing technique



arXiv:2107.11209

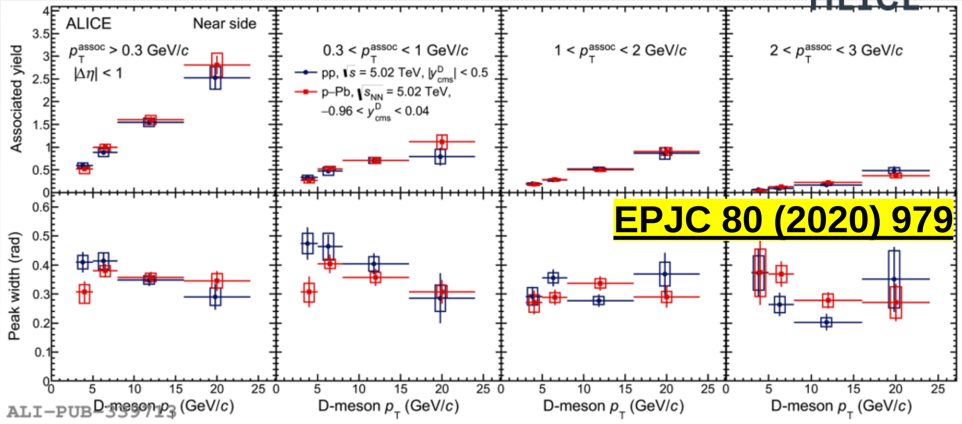
D - charged particles azimuthal correlations

pp and p–Pb at $\sqrt{s}$= 5.02 TeV

The azimuthal correlations are then fitted considering:

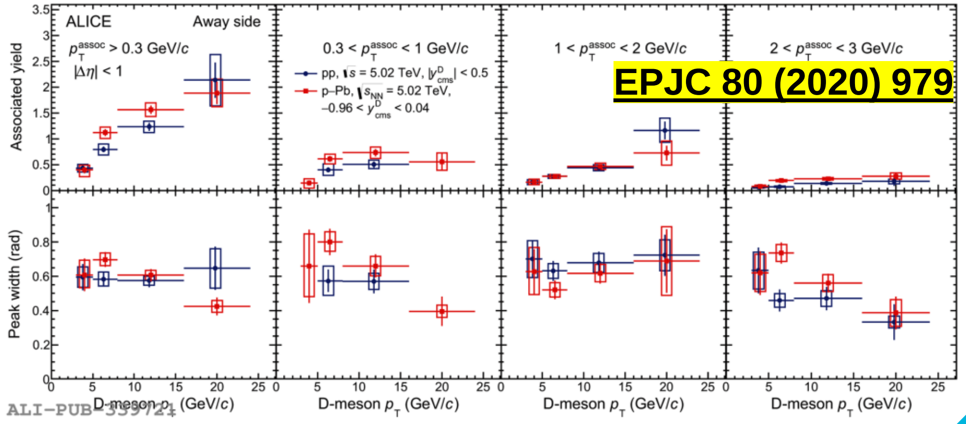
- a generalized gaussian ($\Delta\varphi = 0$);
- a standard gaussian ($\Delta\varphi = \pi$),
- constant baseline

providing an estimation of the yields and the widths of the two peaks.



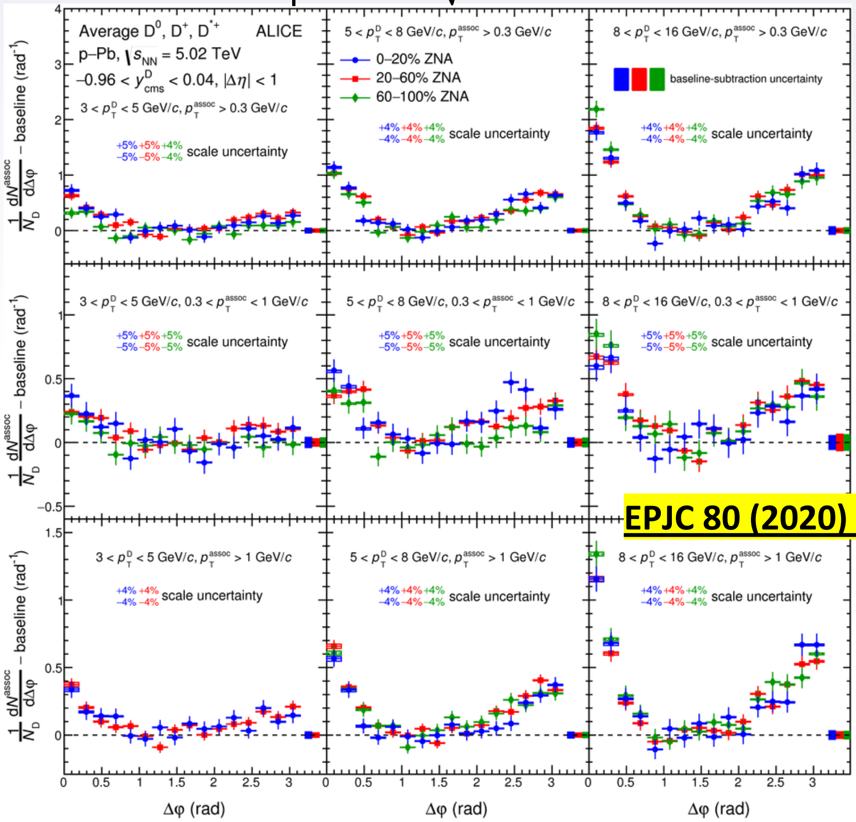
Consistent values of the yield and peak width in pp and p–Pb collisions are observed in all kinematic ranges.

→ no significant impact from cold-nuclear-matter effects on the charm fragmentation arises with current statistics.

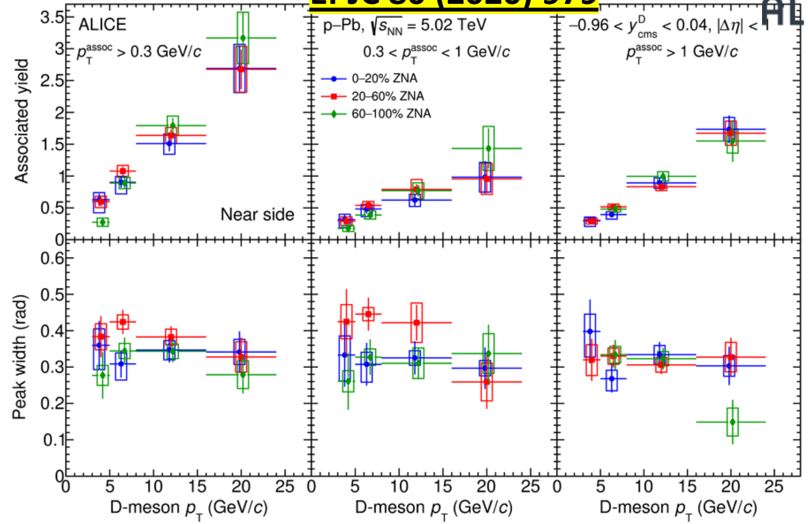


D - charged particles azimuthal correlations

p—Pb at $\sqrt{s}$= 5.02 TeV



EPJC 80 (2020) 979



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D-h as function of the collision centrality

- p—Pb distribution shapes are compatible within statistical uncertainties. The yield and peak width do not show a dependence on the collision centrality

→ No apparent modification to the charm fragmentation

HFe-charged particles azimuthal correlation distributions

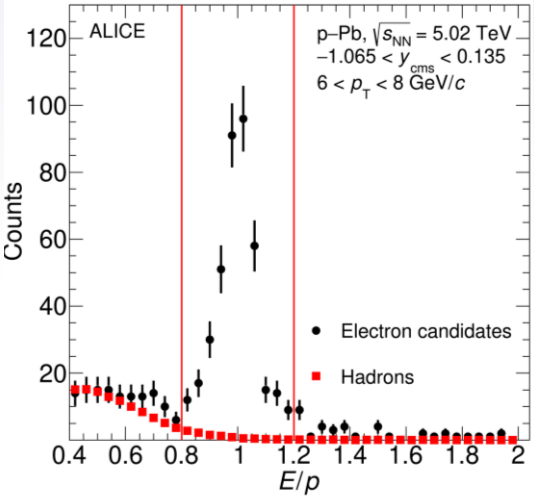
Electron sources are:

- semi-leptonic decays of heavy-flavour hadrons
- background contributions mainly come from:
  - Dalitz decays of light neutral mesons
  - photon conversion in the detector material

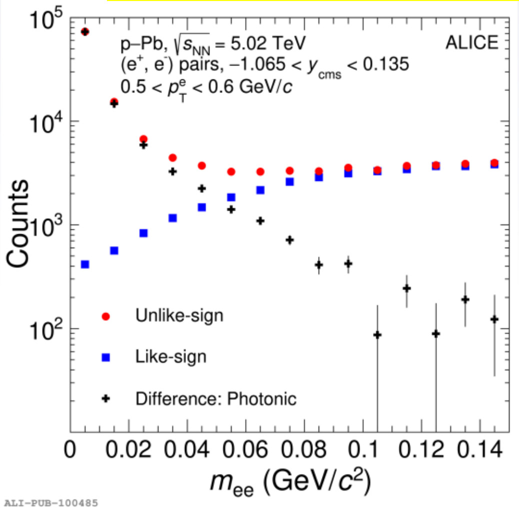
Starting from the inclusive e spectrum, **e-h** correlation distributions are built.
Several corrections are performed:

- Event-Mixing,
- Efficiency ,
- Contamination from:
  - secondary particles;
  - hadrons;
  - non-HFe.

Phys. Lett. B 754 (2016)



E/p distribution for estimating the hadron contamination



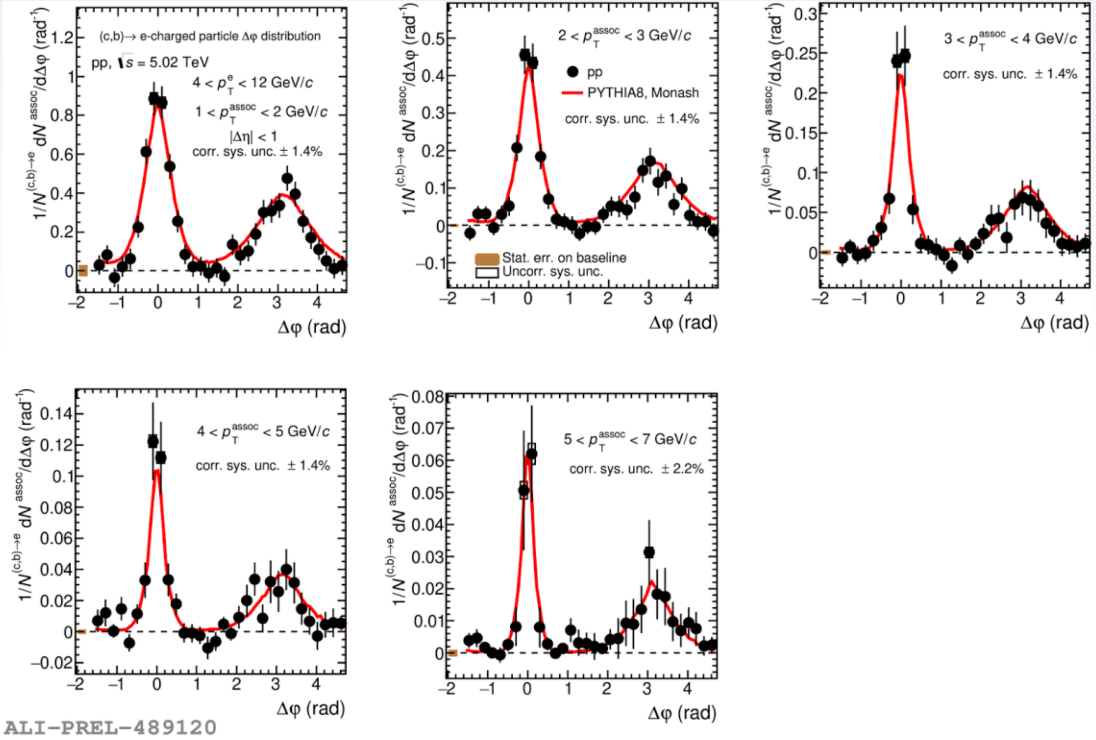
non-HFe identified thrugh M_{ee}

Their contribution to the measured e-h correlation distribution is evaluated and subtracted after a proper normalization to get the HFe-h correlation distributions.

HFe-charged particles azimuthal correlation distributions

HFe-h azimuthal correlation distributions are fitted with two generalized gaussian after the baseline has been subtracted.

PYTHIA8 predictions well reproduce the shape of the correlation distributions

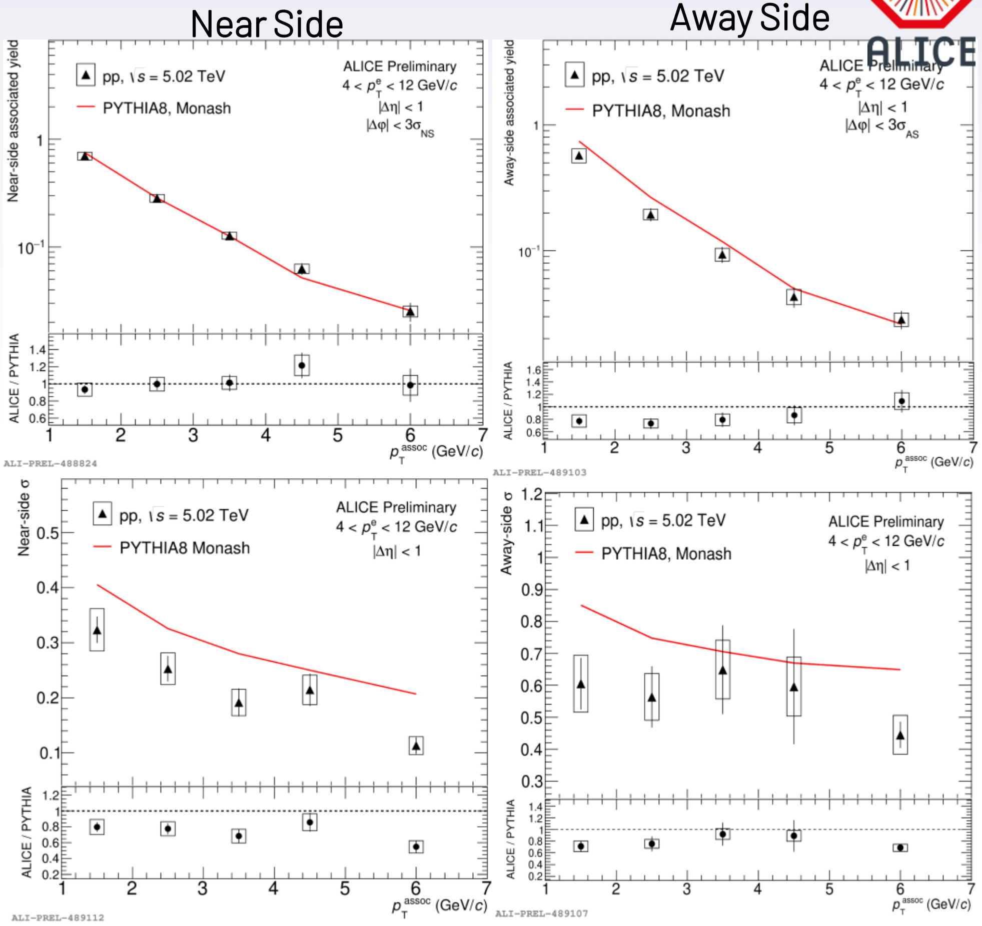


HFe-charged particles azimuthal correlation distributions

HFe-h azimuthal correlation distributions are fitted with two generalized gaussian after the baseline has been subtracted.

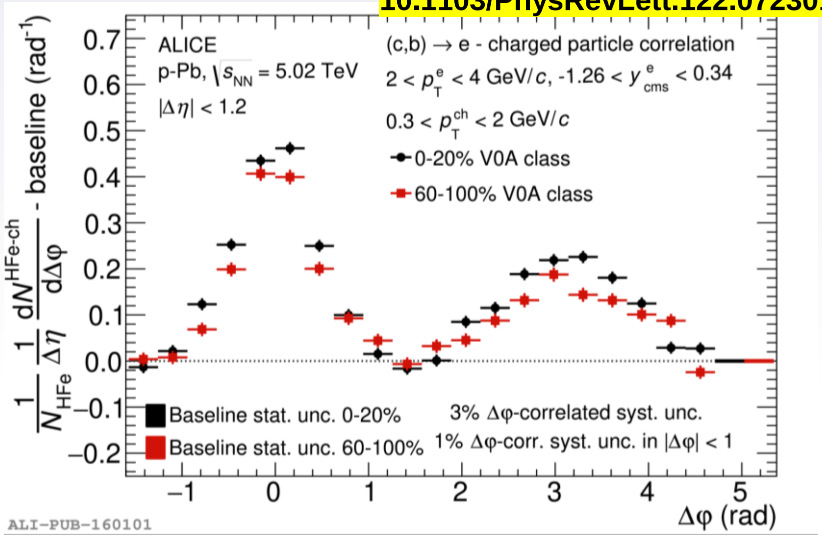
PYTHIA8 predictions well reproduce the shape of the correlation distributions

- NS yield predictions are in agreement with data
- AS yield is slightly underestimated at low-p_{T}^{assoc}
- both NS and AS widths are underestimated by predictions.



HFe-charged particles azimuthal correlation distributions

10.1103/PhysRevLett.122.072301



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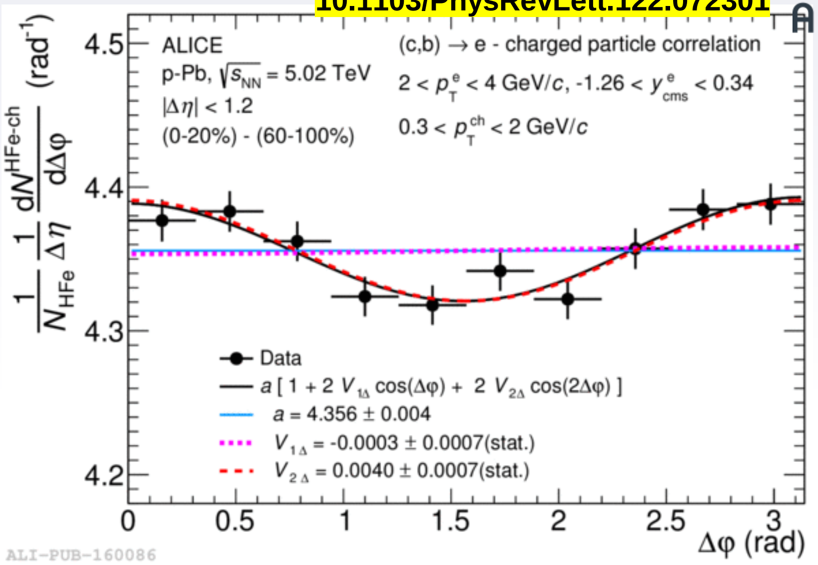

Azimuthal correlations between heavy-flavour decay electrons with charged particles are computed in two multiplicity classes considering p-Pb collisions:

- HM (high multiplicity, 0-20%)
- LM (low multiplicity, 60-100%)

The jet-induced correlation peaks are removed by subtracting the LM from the HM distribution and fitting the resulting distribution with a Fourier decomposition.

Azimuthal Anysotropy is found:

$$\nu_{2\Delta} = 0.0040 \pm 0.0007\,(\text{stat})$$

HFe-charged particles azimuthal correlation distributions

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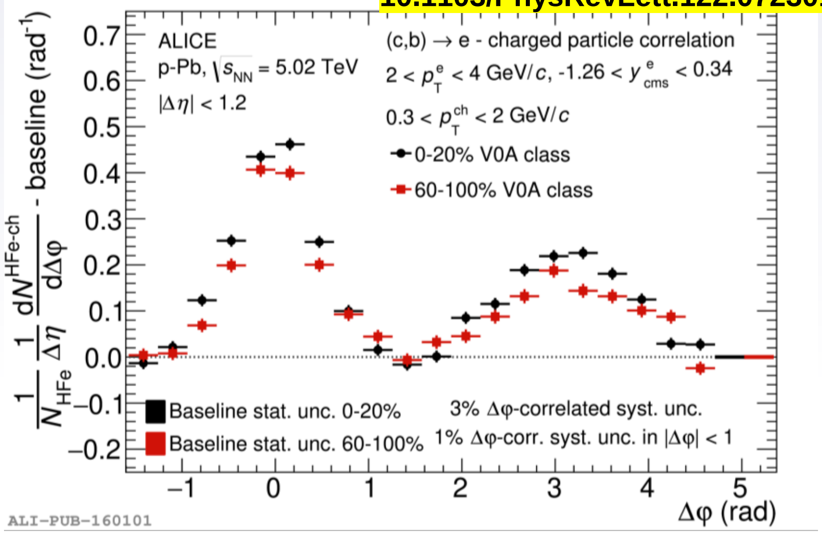

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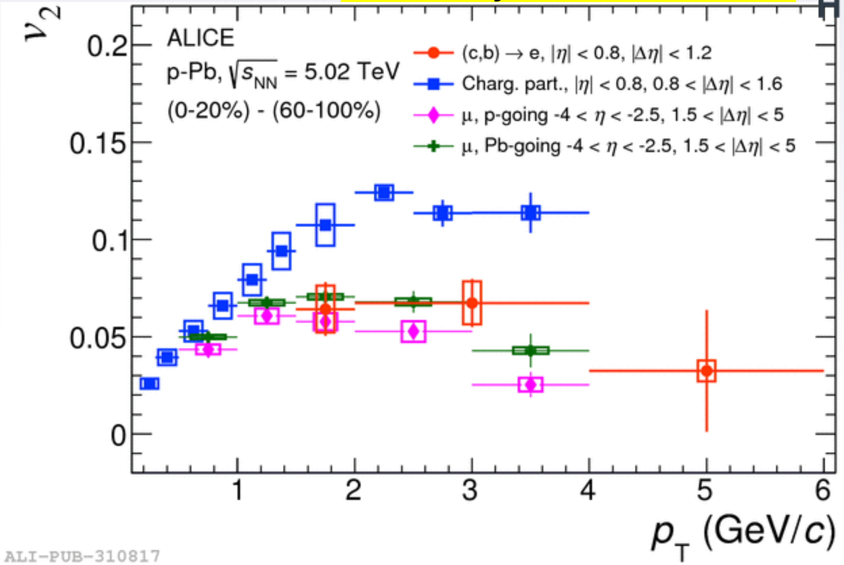


Azimuthal correlations between heavy-flavour decay electrons with charged particles are computed in two multiplicity classes considering p-Pb collisions:

- HM (high multiplicity, 0-20%)
- LM (low multiplicity, 60-100%)

HFe v_2 is larger than zero (about 5σ significance in $1.5 < p_T^e < 4$ GeV/c)

→ Comparable with charged particles and muons

Can this be interpreted as a final state effects ?

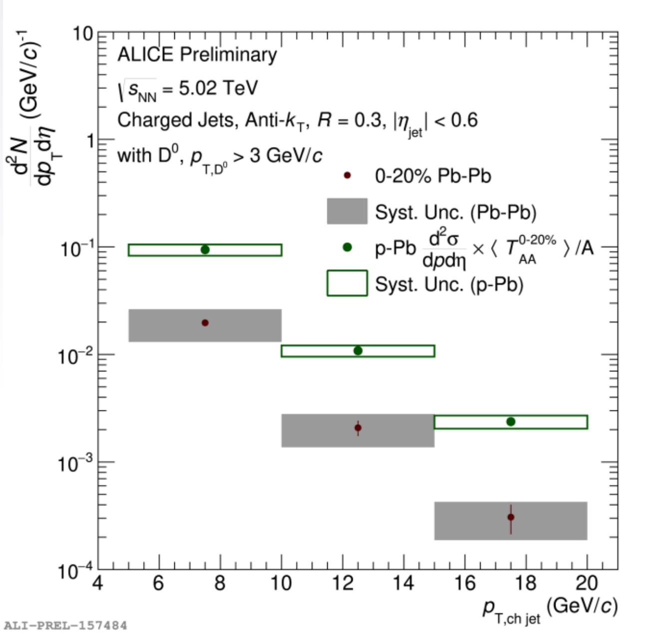
Summary

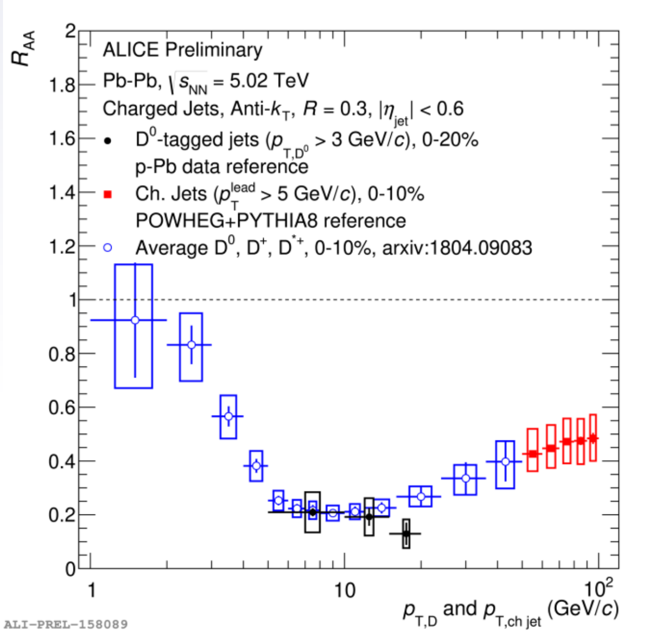
- HF-tagged jets:
  - ✓ Most of theoretical predictions successfully describe the experimental cross section;
  - ✓ softer fragmentation at low $p_{\mathrm{T,\,ch\,jet}}$ is observed with respect to model predictions;
  - ✓ Hints of possible modifications of hadronization through radial displacement measurements;
  - ✓ no modification in HF-tagged jets induced by CNM in p—Pb;

- HF-h azimuthal correlation distribution:
  - ✓ Fragmentation differential study vs $p_{\mathrm{T}}^{\mathrm{D}}$ and $p_{\mathrm{T}}^{\mathrm{assoc}}$;
  - ✓ D-h: negligible impact observed with current statistics of CNM;
  - ✓ HFe–h first measurements in pp at $\sqrt{s}$=5.02 TeV;
  - ✓ Anisotropic flow for HFe in p—Pb, possible final state effect.

Thanks for your attention

D⁰-tagged jets in Pb-Pb at $\sqrt{s_{NN}}$ = 5.02 TeV



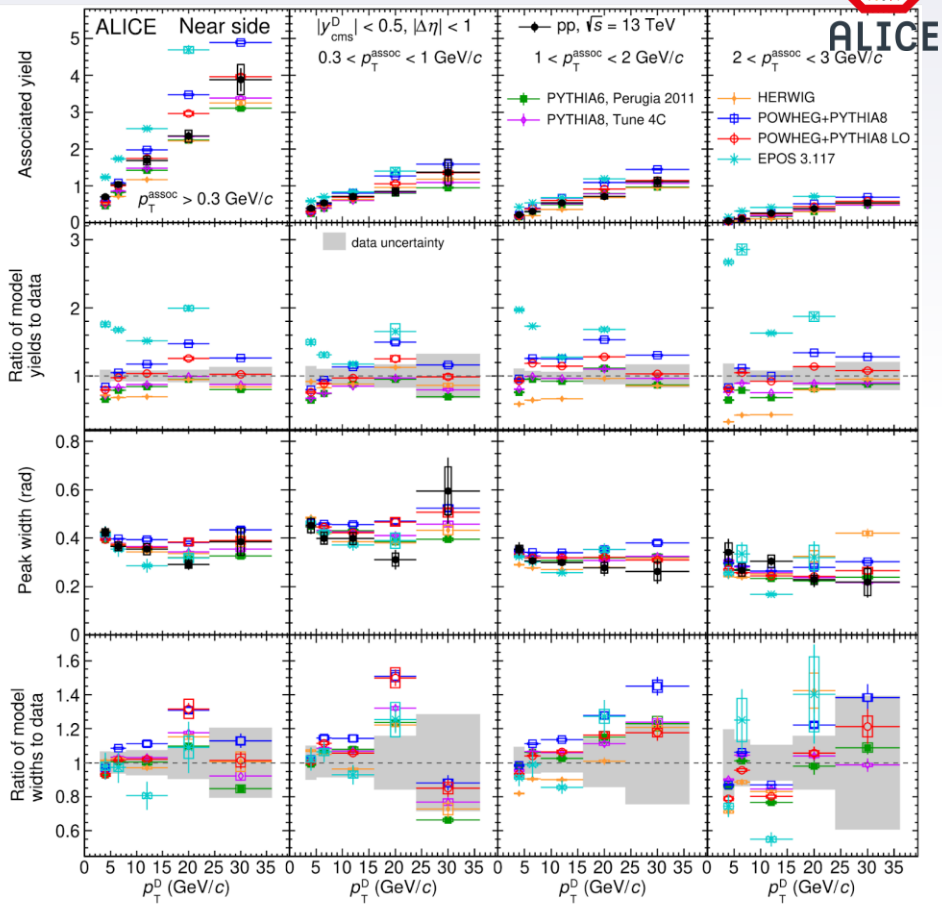


- ✓ Strong suppression of D^0-tagged jets in central Pb—Pb collisions.
- ✓ D^0-jets R_{AA} compatible within statistical uncertainties with R_{AA} from D mesons

D - charged particles azimuthal correlations

Comparison of NS yields and widths with several model predictions

→ Different shower ordering, hadronisation approach, MPI treatment, UE description



NS yields:

- PYTHIA8 and POWHEG+PYTHIA8 both provide an overall good description
- About 10% larger yields for POWHEG NLO w.r.t. LO → more collinear production via GS
- HERWIG tends to underestimate the NS yields at low p_T(D) and at high p_T(assoc)
- EPOS overestimates the yields over the whole p_T range

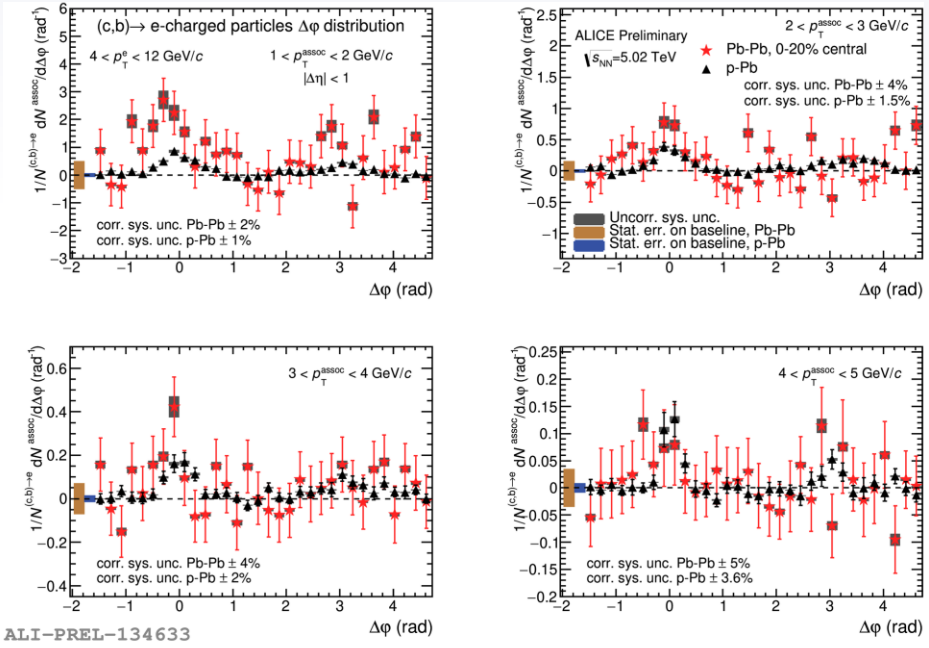
NS widths:

- Overall, all models describe the peak width within uncertainties

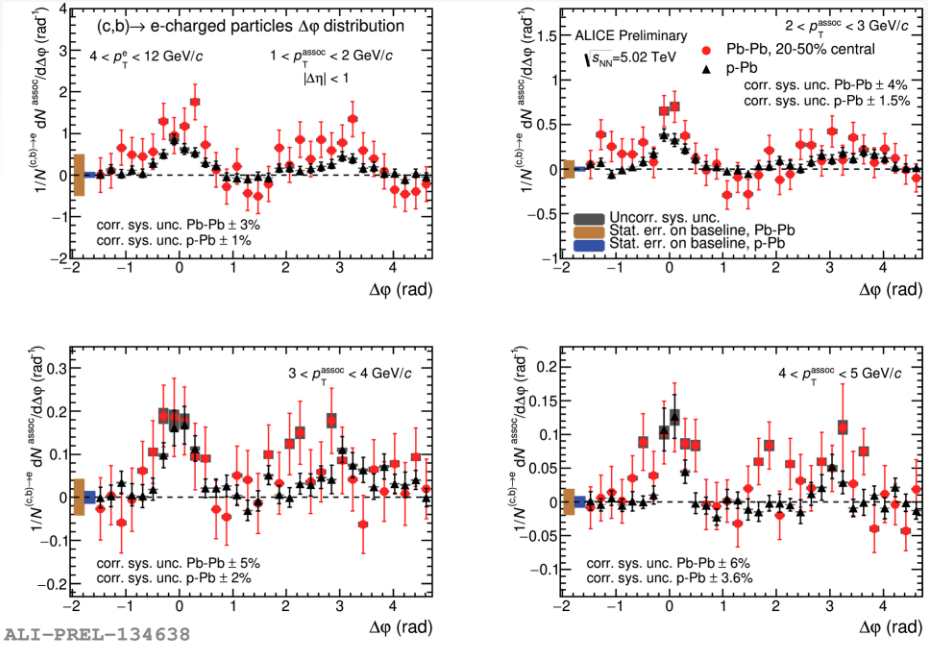
HFe-charged particles azimuthal correlation distributions

Azimuthal correlations of heavyflavour decay electrons and charged particles in central (0-20%) and semi-central(20-50%) Pb—Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV.

0-20% central



20-50% central



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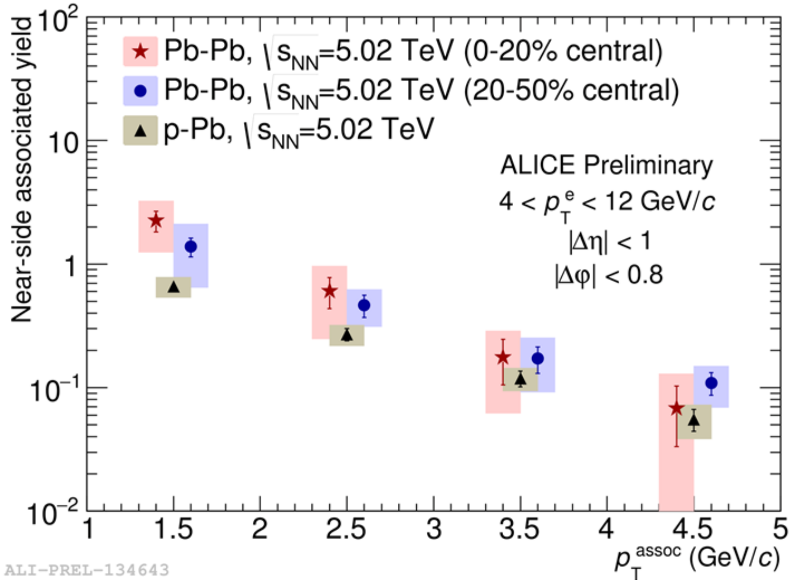
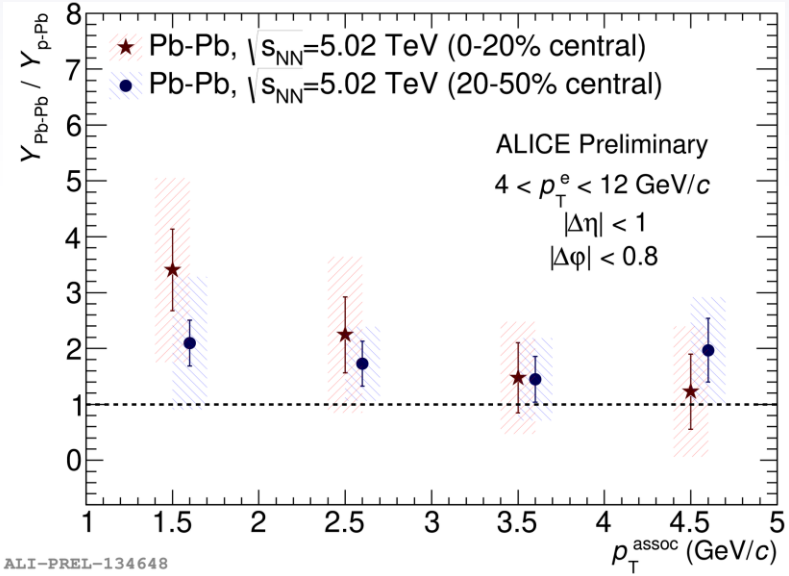


Near-side yields in 0-20% and 20-50% Pb—Pb collisions compared to p—Pb collisions at $\sqrt{s_{NN}}$= 5.02 TeV

- ✓ Hint of enhancement of yield in central Pb – Pb collisions at low-$p_{\mathrm{T}}^{\mathrm{assoc}}$
- ✓ Hints of NS yield hierarchy among collision systems, at low $p_{\mathrm{T}}^{\mathrm{assoc}}$, with large uncertainties

HFe-charged particles azimuthal correlation distributions

Azimuthal correlations of heavyflavour decay electrons and charged particles in central (0-20%) and semi-central(20-50%) Pb – Pb collisions at $\sqrt{s_{NN}}$ = 5.02 TeV.



Near-side yields in 0-20% and 20-50% Pb–Pb collisions compared to p–Pb collisions at $\sqrt{s_{NN}}$= 5.02 TeV

- ✓ Hint of enhancement of yield in central Pb – Pb collisions at low-p_T^{assoc}
- ✓ Hints of NS yield hierarchy among collision systems, at low p_T^{assoc}, with large uncertainties
- ✓ Ratio ~1 at high-p_T