Study of charm fragmentation using charm-hadron angular correlation measurements with ALICE

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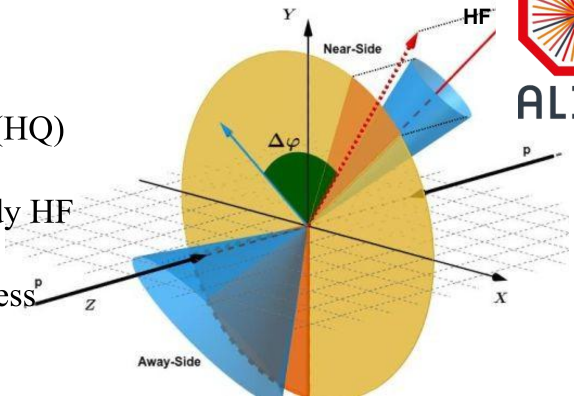
Heavy-flavour (HF) correlations

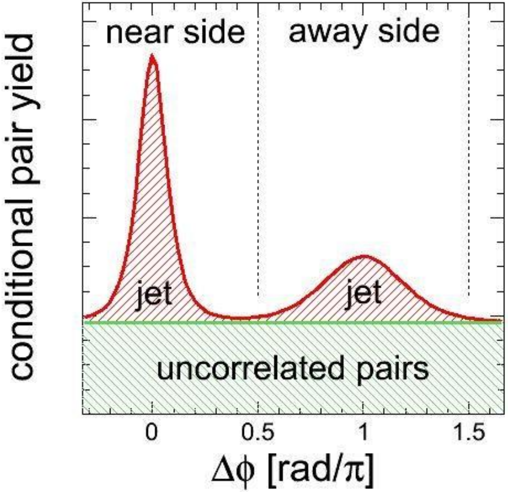
- Heavy quarks are produced in hard scattering process with high Q^2
  - Radiate gluons, generating a parton shower and hadronize → heavy-quark (HQ) jet
- Angular correlations of heavy-flavour hadrons with charged particles allow to study HF parton shower.
  - Description of peak shapes and width, connected to HQ hadronisation process
- Give access to the production mechanisms:
  - LO and NLO processes



ALICE

What do we learn by investigating different systems?

- **pp collisions**
  - Test for pQCD calculations, study of heavy-flavour hadronisation, baseline for heavy-ion collisions.
- **p-Pb Collisions**
  - Modification due to Cold Nuclear Matter (CNM) effects, gluon saturation effect[1]
- **Pb-Pb collisions**
  - Modification due to the interaction with the Quark Gluon Plasma (QGP), such as energy loss mechanisms[1]



[1] Universe 10 (2024) 3, 109

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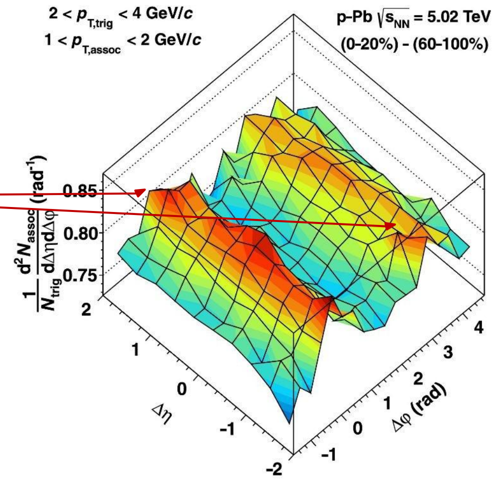
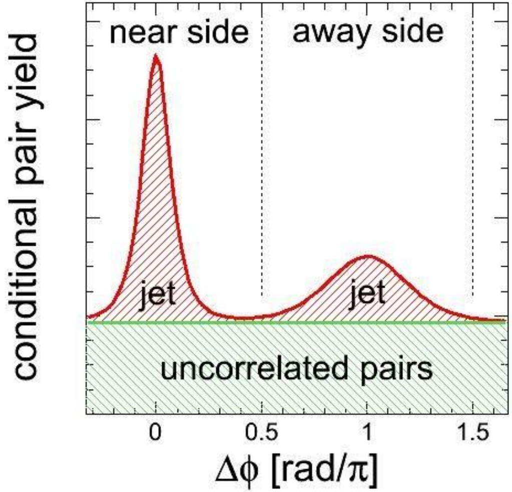
Phys.Lett.B 719 (2013) 29-41

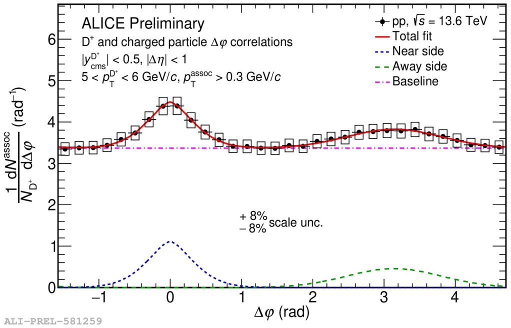
Additionally:
Hint of collective flow in small system
Long-range ridge-like structures in near- ($\Delta\varphi = 0$) and away-side ($\Delta\varphi = \pi$) regions ("double ridges").





Δη→ large →Collective flow
Δη→ small →Collective flow + Jet contribution

Azimuthal correlation of D meson with charge particles

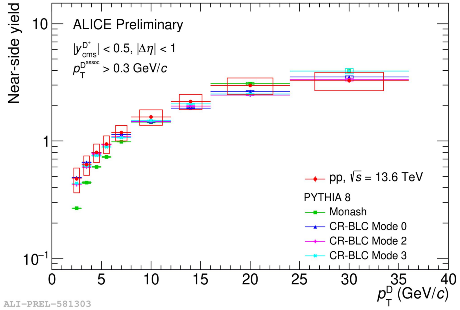


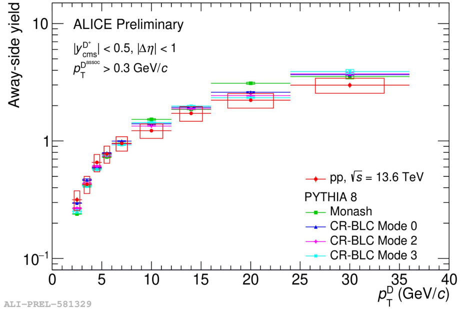
pp, √s = 13.6 TeV

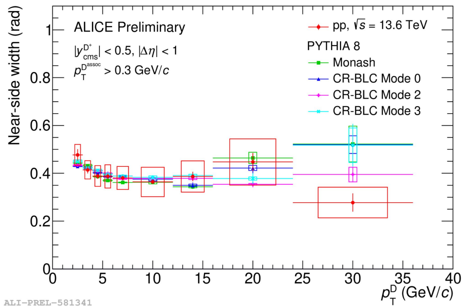
$\Delta\varphi = \varphi_D - \varphi_h$

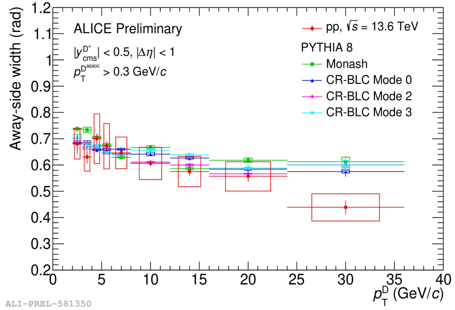
- Detector inhomogeneities and limited pair acceptance corrected by mixed-event technique
- Correlation distributions fitted with generalized Gaussian to describe the near-side and away-side peaks + pedestal

  - High $p_T^{trigger}$ →Higher associated peak yield→ More energy available for fragmentation
  - High $p_T^{trigger}$ →Larger heavy quark boost →More collimated peaks





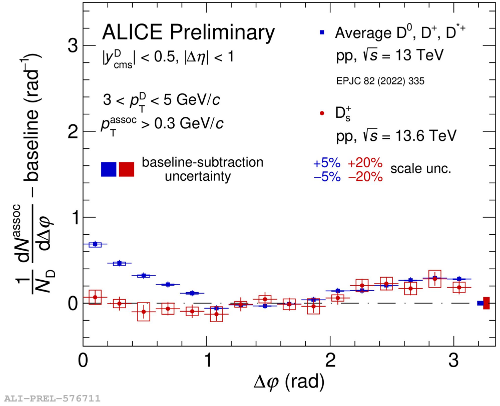


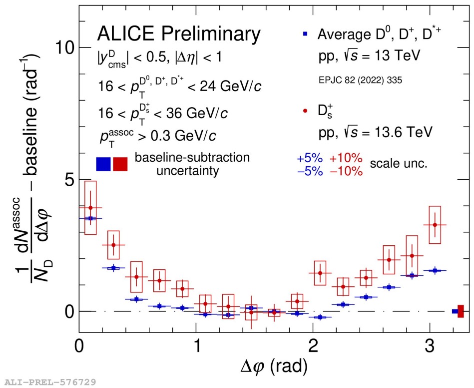


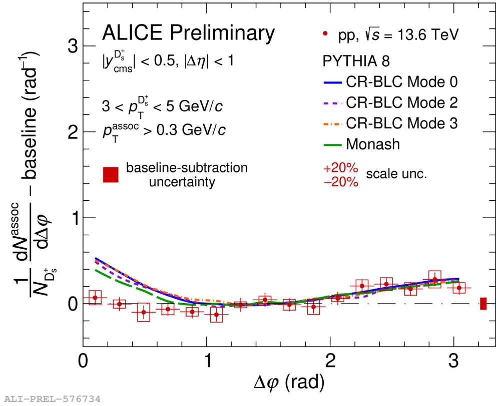
- All the exploited PYTHIA8 tunes are consistent with data

D_s^+ meson (strange HF) correlation with charge particles

pp, $\sqrt{s}$ = 13 TeV **pp, $\sqrt{s}$ = 13.6 TeV**







- Larger sample in Run 3 →allows the study of D_s^+ angular correlations (not accessible in Run 2).
- Near-side:
  - Lower associated peak yield for D_s^+ compared to D^+ at low $p_T^{trigger}$
  - Consistent with D^+ correlations at higher $p_T^{trigger}$
- Away-side:
  - Consistent with D^+ triggered correlations at all p_T

- Different PYTHIA tunes overestimate the near-side peak at low p_T, but are consistent with data at high p_T
- The away-side peak is consistent with PYTHIA prediction for the entire p_T range

D_s^+ meson (strange HF) correlation with charge particles

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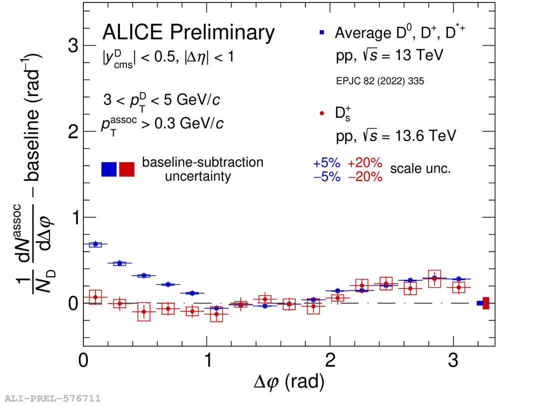
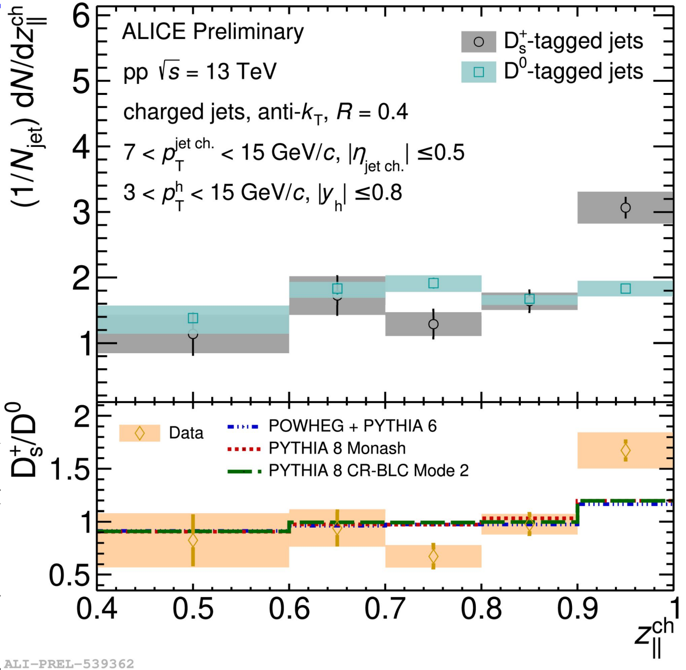
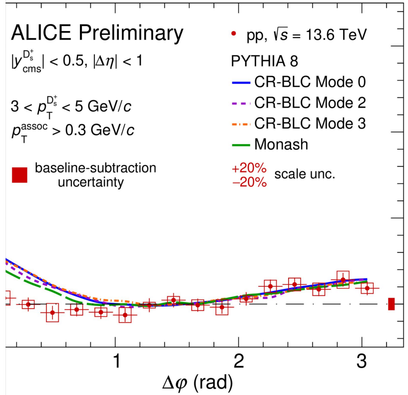






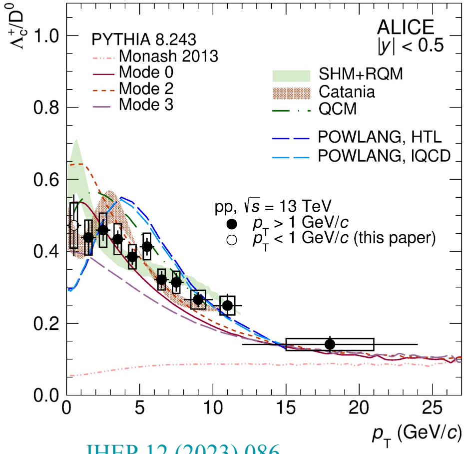
- Larger sample in Run 3 →allows correlations (not accessible in Ru
- Near-side:
  - Lower associated peak yiel D$^+$ at low $p_T^{trigger}$
  - Consistent with D$^+$ correlations at higher $p_T^{trigger}$
- Away-side:
  - Consistent with D$^+$ triggered correlations at all p_T

YTHIA tunes overestimate the near-side p_T, but are consistent with data at high p_T ide peak is consistent with PYTHIA or the entire p_T range

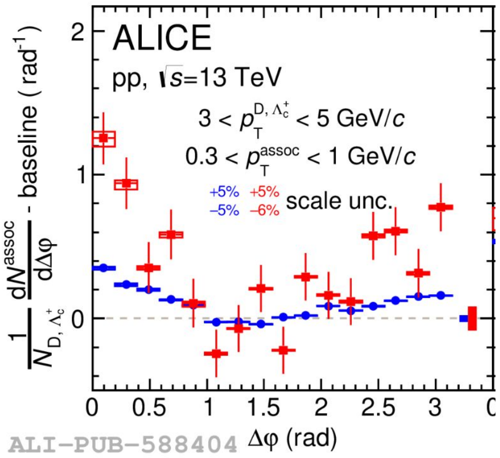
Possible explanation for the difference: harder fragmentation of charm quark into D_s^+ than non-strange D mesons (consistent with $z_{||}$ measurement)

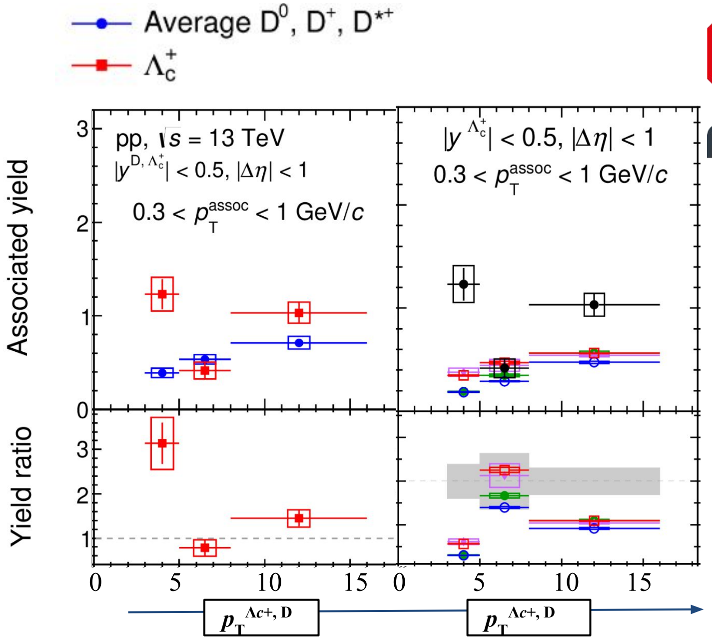
HF baryon correlations in pp

$\Delta\varphi(\Lambda_c^+\text{-h})$ correlations in pp collisions: study charm-baryon hadronization mechanism and possible differences from meson hadronization



[JHEP 12 (2023) 086](#)



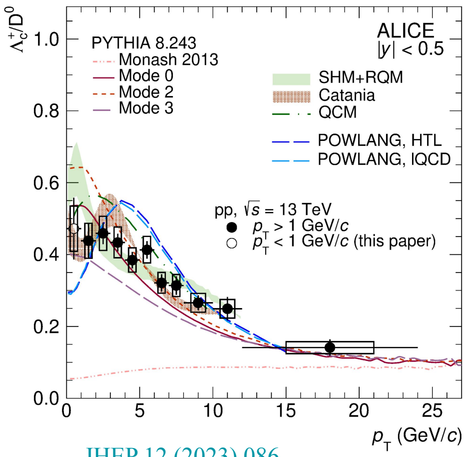


[arXiv:2411.10104](#)

- Larger Λ_c^+/D^0 ratio measured in pp compared to e^+e^- at low and intermediate p_T.
- PYTHIA with CR-BLC modes, and models with coalescence describes the data within uncertainty.
- Λ_c^+ triggered correlations shows higher yield compared to D-meson at low p_T, no model is able to explain the observation

HF baryon correlations in pp

$\Delta\varphi(\Lambda_c^+\text{-h})$ correlations in pp collisions: study charm-baryon hac
mechanism and possible differences from meson hadronization



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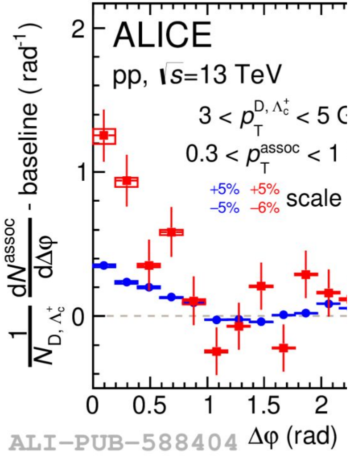

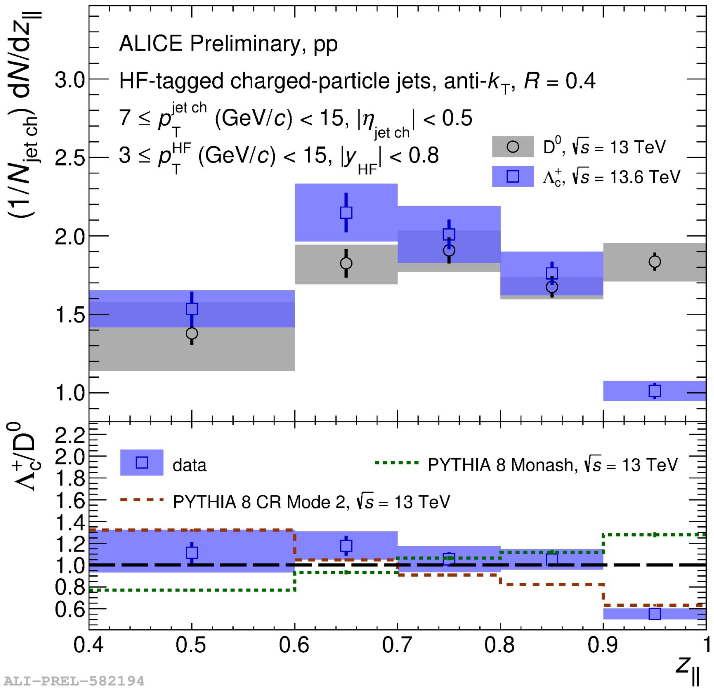

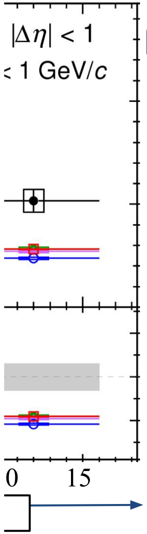

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- Larger Λ_c^+/D^0 ratio measured in pp compared to e^+e^- at low and intermediate p_T.
- PYTHIA with CR-BLC modes, and models with coalescence describes the data within uncertainty.

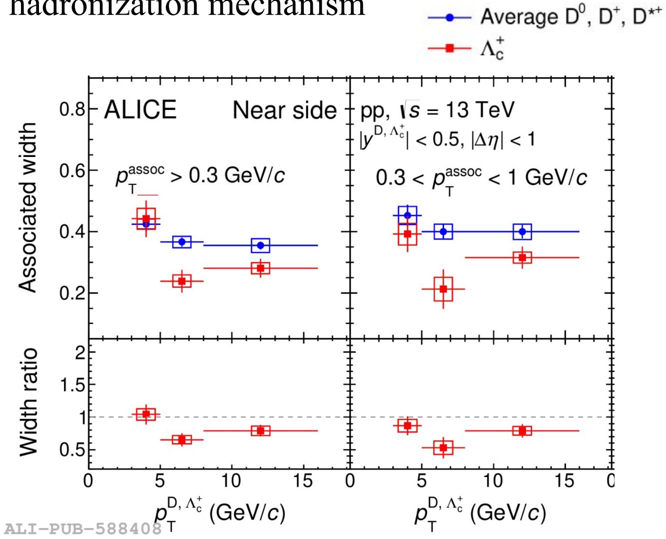
- Possible explanations:
  - Softer fragmentation of charm quark into Λ_c, consistent with $z_{||}$ measurement
  - Contribution from decay of higher mass charm states (SHM+RQM)
  - Hadronization by coalescence impacting the mean p_T and associated-particle multiplicity

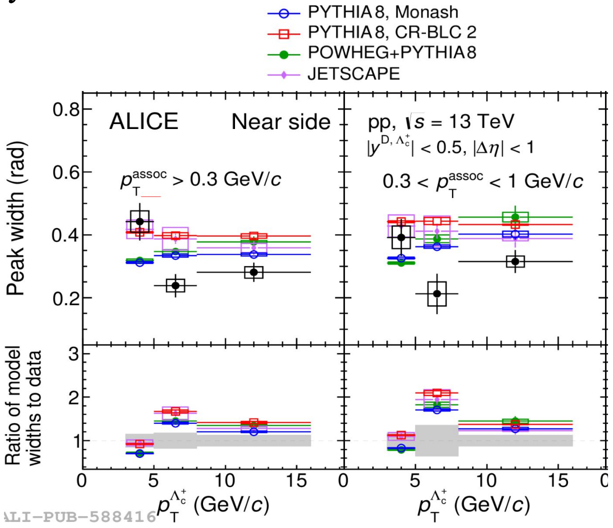
HF baryon correlations in pp

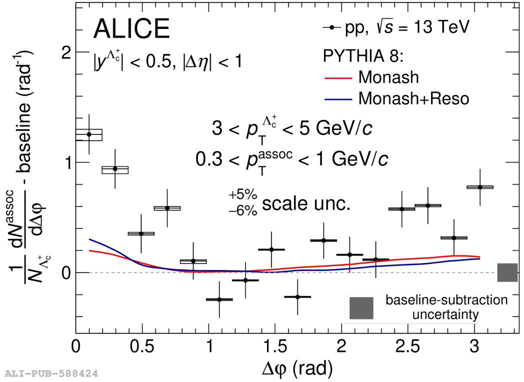
pp, $\sqrt{s}$ = 13 TeV

$\Delta\varphi(\Lambda_c - h)$ correlations in pp collisions: study baryon hadronization mechanism

arXiv:2411.10104







- Λ_c^+ triggered correlations shows slightly lower width compared to D-meson at higher p_T, consistent within 2σ

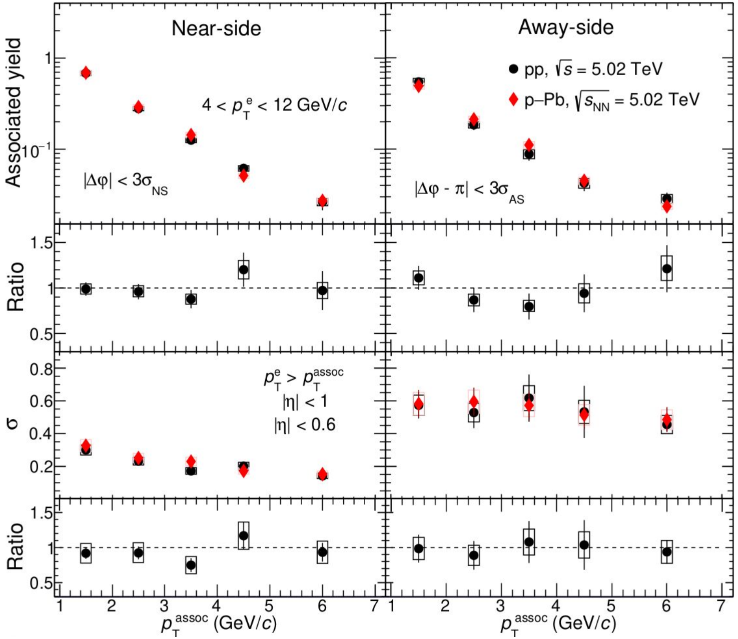
- All models tend to overestimate the Λ_c^+ correlations peak width, though being consistent within 2σ
- PYTHIA8 Monash with additional resonant states (SHM+RQM) shows higher near-side yield compared to the default, and fails to reproduce data
- Resonance-decay with larger opening angles →a small increase of the baseline level→decrease away-side yields

HF-h correlation in p-Pb

Advantages of HFe-h correlations compared to D-h correlations:

- Higher p_T^{assoc} reach due to larger amount of correlation pairs
- Access to beauty fragmentation at high p_T^{HFe}

HF electron-h correlation in pp and p-Pb



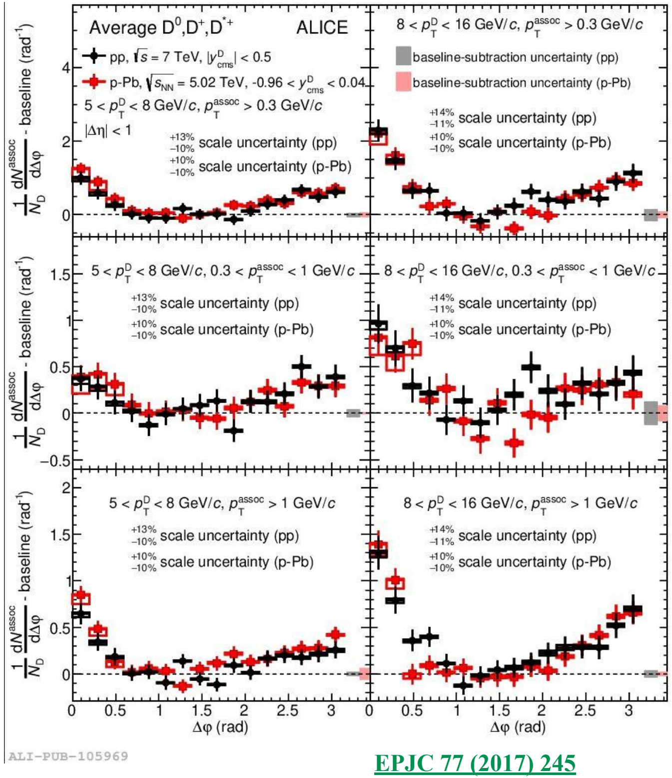
EPJC 83, 741 (2023)

pp

p-Pb

D-h correlation in pp and p-Pb

pp, $\sqrt{s}$ = 7 TeV **p–Pb, $\sqrt{s}$ = 7 TeV**



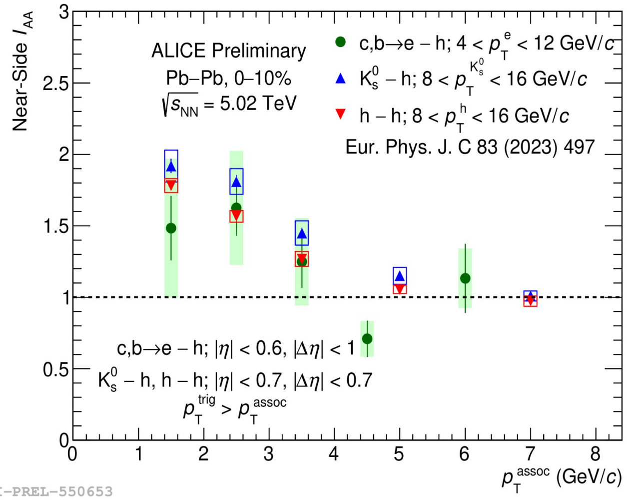
EPJC 77 (2017) 245

- ❑ Near and away-side yields and width consistent in pp and p–Pb.
- ❑ No modification in p-Pb→No evidence of cold nuclear matter effects with current precision.

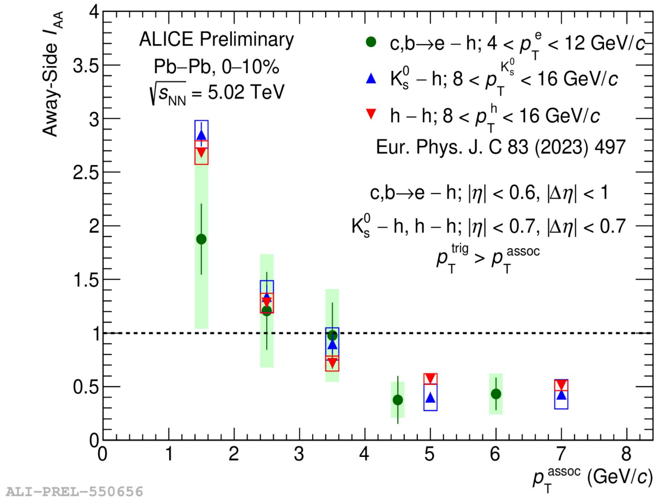
HF-h correlation in Pb-Pb

The per-trigger nuclear modification factor (I_{AA}) in 0-10% Pb-Pb

Near-side I_{AA}



Away-side I_{AA}



I_{AA} for **c,b → e** compared to **K_s^0-hadron** and di-hadron correlations

- Similar trends for LF and HF triggers
- Caveats for comparing LF and HF: different hadron-to-parton p_T scale; additional decay kinematics for c,b -> e

- Near-side:
  - I_{AA} trends slightly above unity (1.3σ) at low p_T^{assoc}; I_{AA} ~ 1 at high p_T^{assoc}
- Away-side:
  - Hint of suppression (2.5σ) for p_T^{assoc} > 4 GeV/c

Summary:

- Azimuthal angular correlations of heavy-flavor trigger and charged hadrons → study and characterize heavy-flavor jet fragmentation and its modification in the presence of a QGP medium.

- pp collisions:
  - ✓ Non-strange charm-meson correlations well described by PYTHIA8 MC simulations.
  - ✓ Different correlation peak distributions observed for D_s^+ and Λ_c^+ compared to $D^{0,+}$ → not described by MC
    - possible effects from different fragmentation/additional hadronisation mechanisms.

- p-Pb collisions:
  - ✓ No sizeable impact of cold nuclear matter effect is observed with current precision.

- Pb-Pb collisions:
  - ✓ Presence of QGP affects the angular correlation distributions.
  - ✓ Hint of suppression of associated particle yield at high p_T^{assoc} on the away-side.
  - ✓ I_{AA} for heavy-flavor triggered correlations similar to light-flavor triggers.

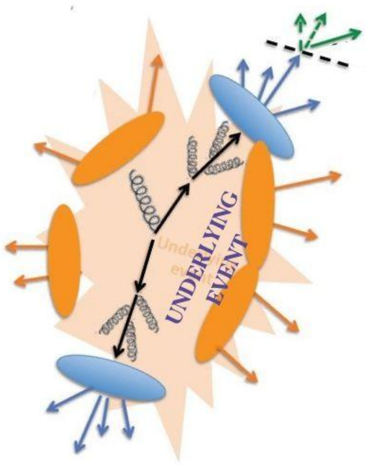
Outlook:

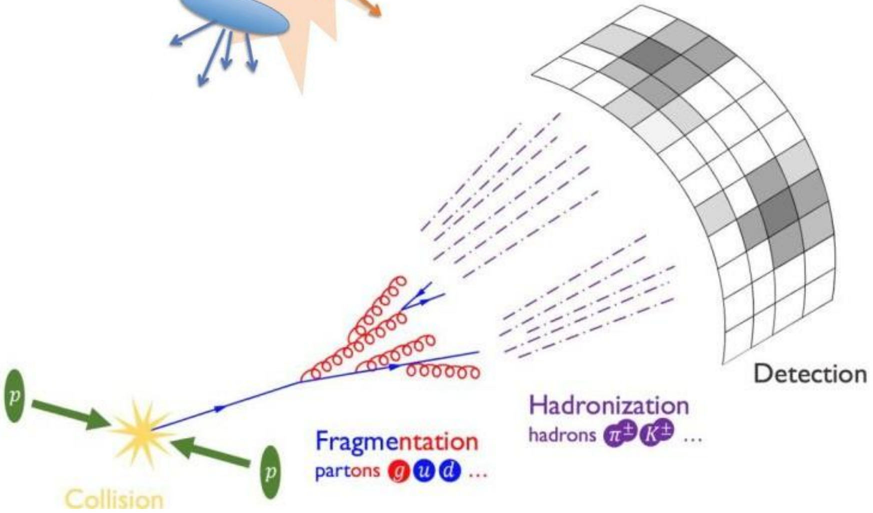
- Run 3 measurements with higher statistics and precision, and access to new/more differential observables will provide deeper insights into heavy-flavor fragmentation, in particular in the baryon sector

Back-up slides

Why heavy-flavour jets?

- Smaller dependence on the hadronization models allows for a better comparison to QCD.
- Access to the heavy-parton kinematics.
- Investigate fragmentation and hadronization models.
- Mass dependence of parton radiation .





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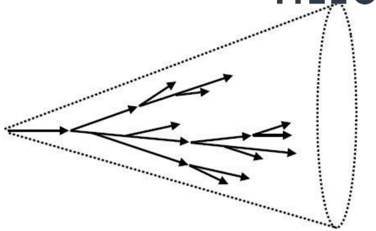
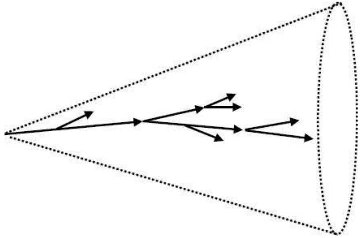
Jets can be gluon initiated or quark initiated

Gluon initiated jets



Quark jets



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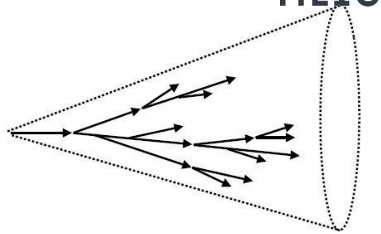
Gluon initiated jets

Casimir colour factors

$C_A/C_F = 9/4$



Jets can be gluon initiated or quark initiated

- Inclusive jets
  - Well constrained at high p_T, low p_T experimentally challenging.
  - Mostly gluon initiated jets – broader fragmentation

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Jets can be gluon initiated or quark initiated

- Inclusive jets
  - Well constrained at high p_T, low p_T experimentally challenging.
  - Mostly gluon initiated jets – broader fragmentation
- Heavy-flavour jets:
  - Heavy quarks are conserved through the parton shower
  - Quark initiated jets – more collimated
- Inclusive vs heavy-flavour jets
  - Effect of Casimir factors and dead cone

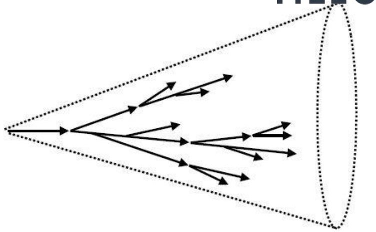
Casimir colour factors

$C_A/C_F = 9/4$

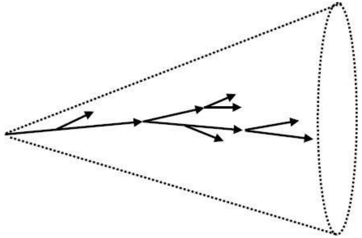
Radiation is suppressed for:

$\theta < \theta_{dc} = m_q/E_q$

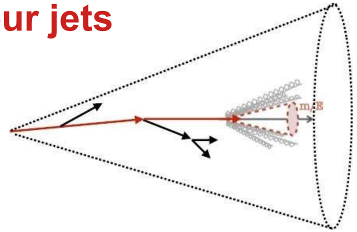
Gluon initiated jets



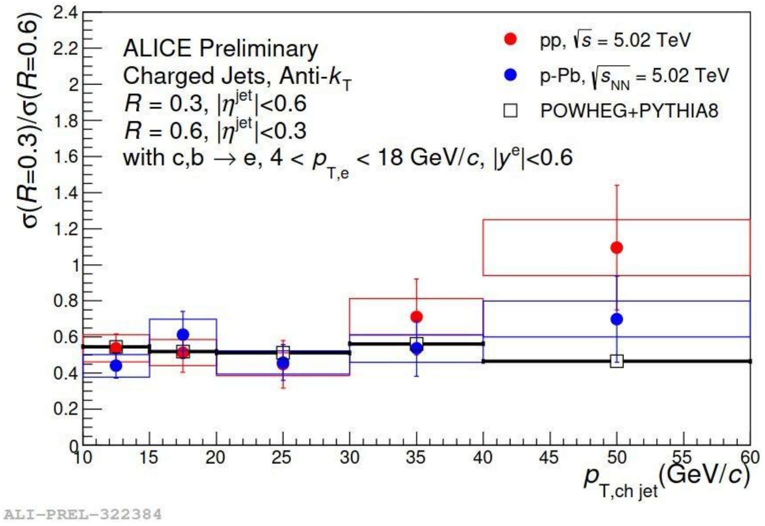
Quark jets

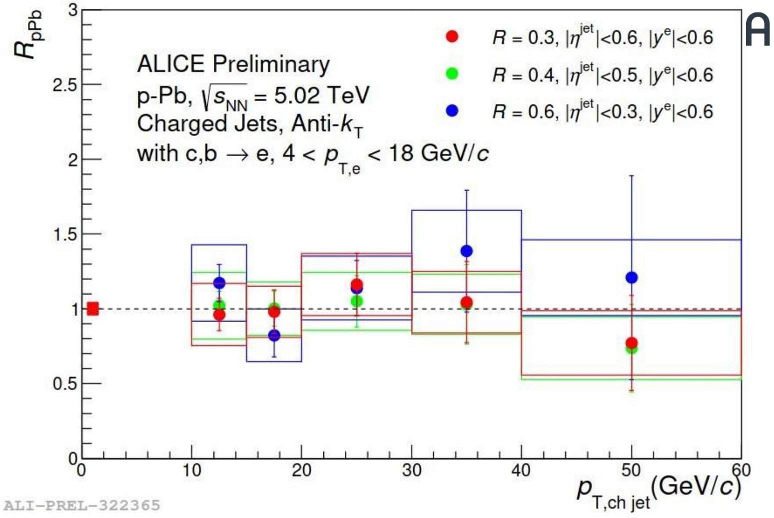


Heavy-flavour jets



Measurements of HFe-tagged Jets





- *R* dependence on jet production is sensitive to internal structure of the jet
- pp and p–Pb results are similar within uncertainties
- Consistent with POWHEG prediction

- R_{pPb} of HFE-jet measured with R=0.3, 0.4, and 0.6 are consistent with unity
- No evidence of cold nuclear matter effect
- No *R* dependency found in R_{pPb}.

Why heavy-flavour?

- Heavy-flavours (charm and beauty) are produced mainly by hard scattering processes at the early stages of the ultra-relativistic heavy-ion (or hadronic) collision due to large mass ($m_{c,b} >> \Lambda_{QCD}$) .
- QGP τ ~ 0.1-1 fm/c
  charm τ ~ 0.07 fm/c, beauty τ ~ 0.02 fm/c ⇨ Created before QGP ⇨ Experience full evolution of QGP

What do we learn by investigating different systems?

- **pp collisions**
  - Test for pQCD calculations, baseline for heavy-ion collisions.
- **p-Pb Collisions**
  - Modification due to Cold Nuclear Matter (CNM) effects, gluon saturation effect.
- **Pb-Pb collisions**
  - Modification due to the interaction with the Quark Gluon Plasma (QGP), such as energy loss mechanisms.

To quantify the nuclear matter effects, nuclear modification factor (R_{AA} or R_{pA}) is used:

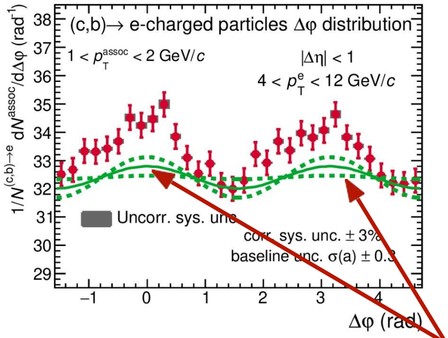
$$R_{\mathrm{XA}} = \frac{1}{<N_{coll}>}\frac{Y_{\mathrm{XA}}}{Y_{\mathrm{pp}}}$$

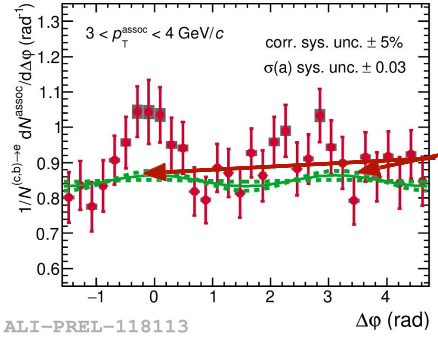
R_{XA} = 1 → No modification

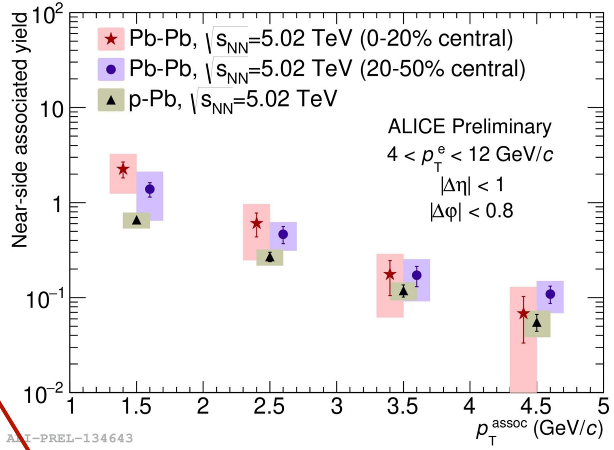
$$\Delta E(g) > \Delta E(u,d,s) > \Delta E(c) > \Delta E(b)$$

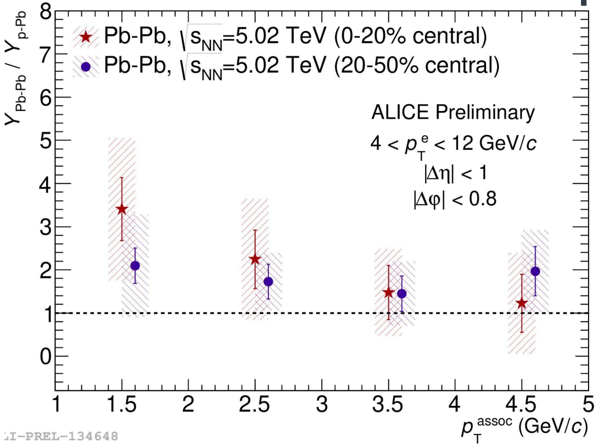
HFe-charged particle correlations in Pb–Pb collisions

Centrality: 20-50 %





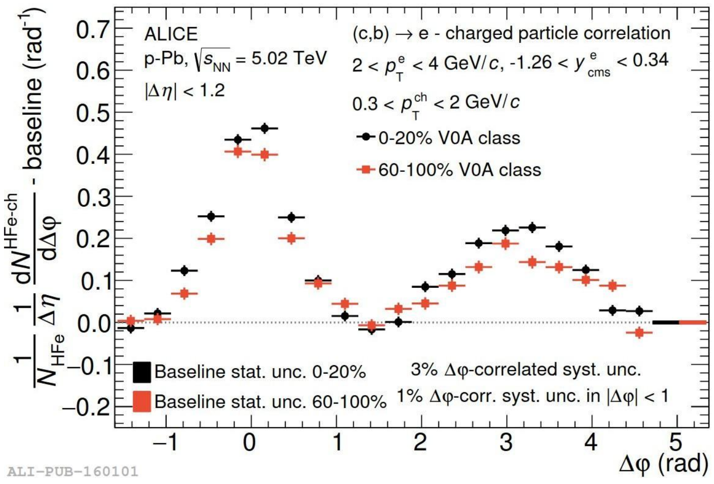


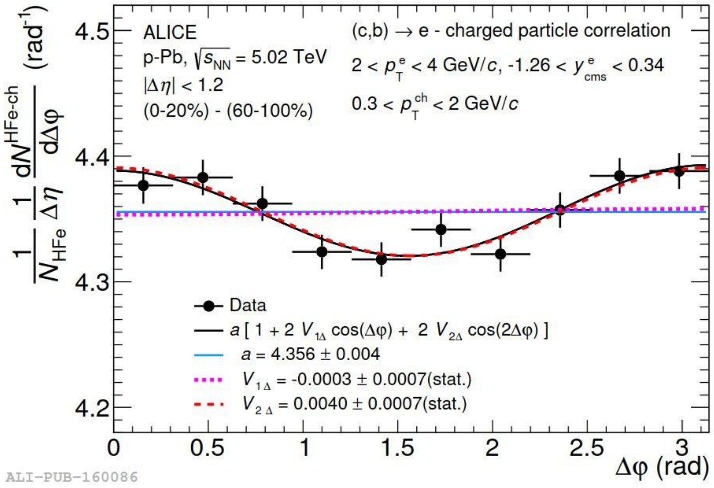


Background flow contribution in the peak regions need to be subtracted

- Near-side yield is higher in Pb–Pb collisions at low associated p_T.
- Ratio to p–Pb yields show a hint of centrality dependence.
  - A hint of higher yield is observed for 0-20% centrality.
- Indication of possible modification of heavy quarks fragmentation.

Elliptic flow coefficient (v_2) in p–Pb collisions?





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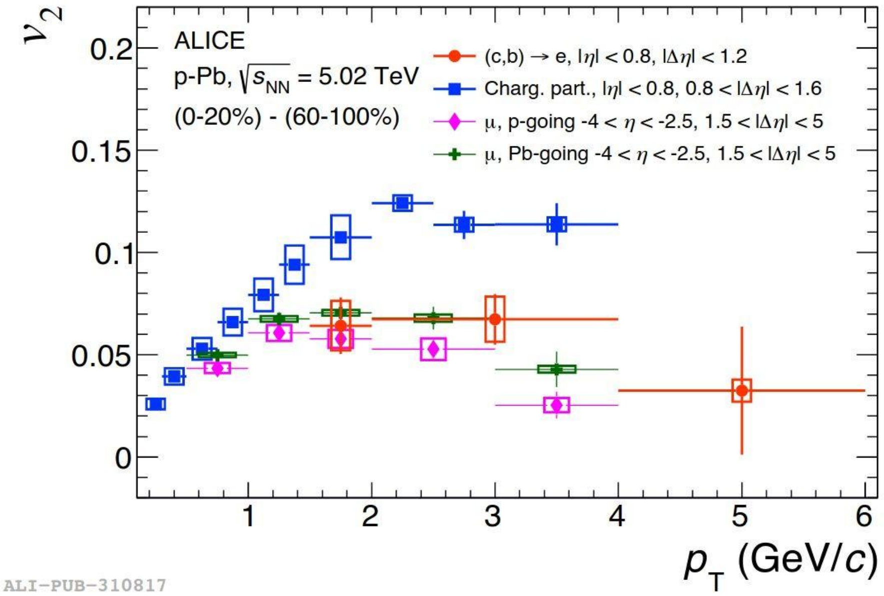
- High-multiplicity collisions→Enhancement of the near- and away-side peak regions.
- Low multiplicity event correlations are subtracted from the high multiplicity event to remove the jet-induced peaks.

Assumption: jet correlation function is not modified in low and high multiplicity events

V_2 of HFE-h correlation in p–Pb collisions

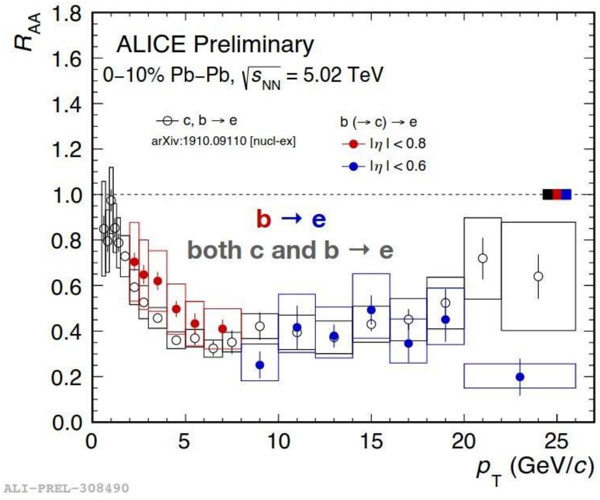


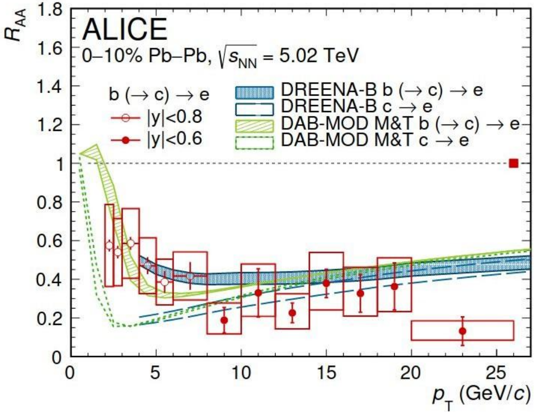
[Phys.Rev.Lett 122 (2019) 07-22]

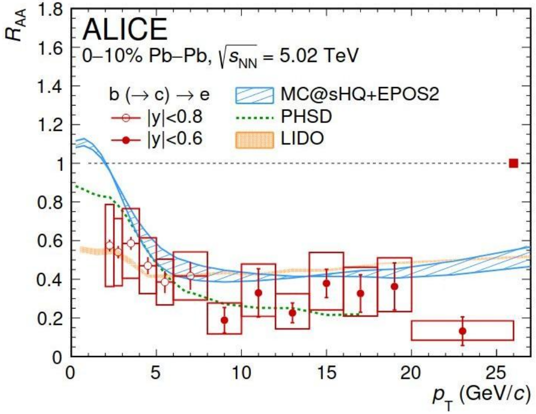
Positive v_2(HFe) with significance: 5.1σ

- Presence of long-range anisotropy with a significance of 5.1σ for heavy-flavour decay electrons.
- The effect is smaller to the one observed in the light-flavour sector.

Electrons from beauty quarks







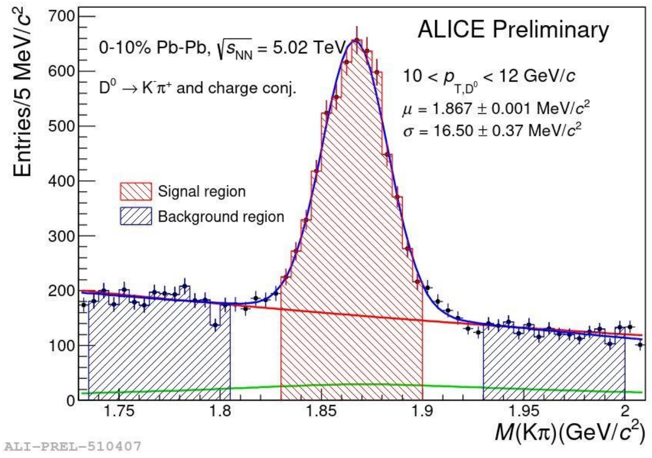
https://arxiv.org/abs/2211.13985

- Compare b→e with combined c,b→e
- See hint that R_{AA}(b→e) > R_{AA}(c,b→e) at low p_T → hint of less energy loss of beauty versus charm in the QGP
- High p_T, results fully overlap; b→e/c→e increases with p_T

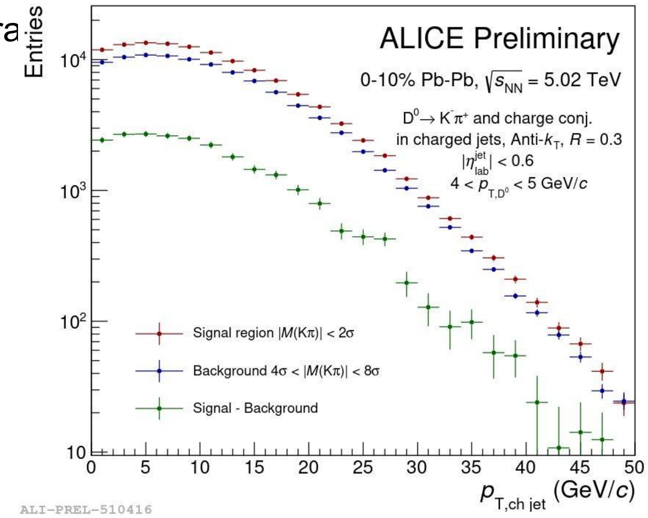
- Energy loss is observed in the medium (R_{AA} < 1).
- A hint of smaller suppression of b (→ c)→ e with respect to (b, c) → e (in the models).
- R_{AA} is consistent with models that consider mass-dependent radiative and collisional energy loss.

Medium effects: D^0-jets in 0-10% Pb-Pb

- Invariant mass was used to extract D^0-jet raw signal spectrum with side-band subtraction.
- Correction for the D^0-jet efficiency and D^0-reflections.
- Subtraction of feed-down D^0-jet component.
- POWHEG predictions convoluted with measured non-prompt D^0 R_{AA}
- Jet-p_T spectra corrected for detector effects and background fluctuations
- Unfolding using an itera

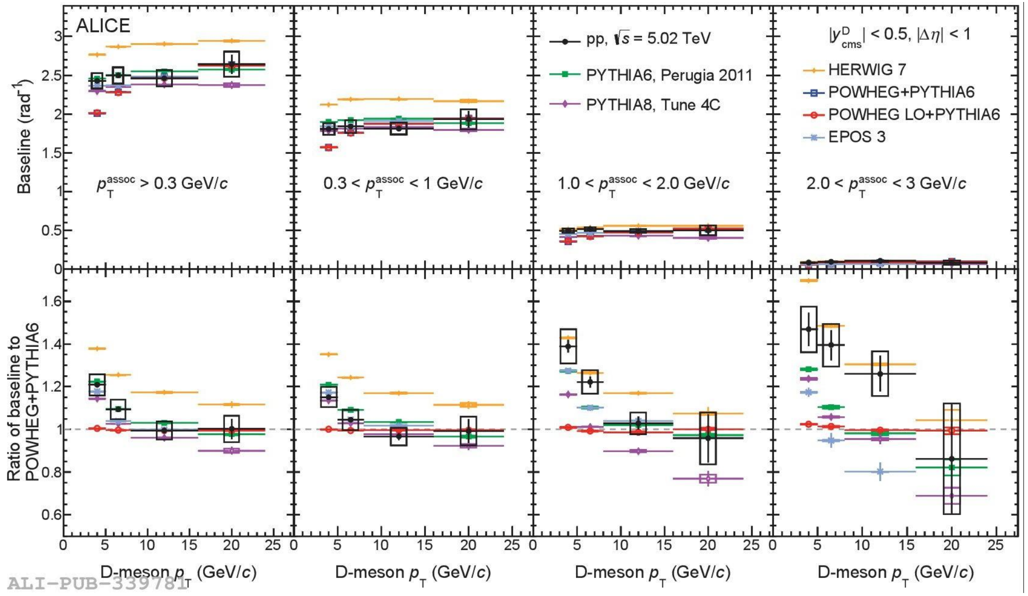


Raw jet spectrum corrected for D^0-jet efficiency



- D^0-meson $3 < p_T < 36$ GeV/c
- Charged jets, anti-k_T algorithm with R = 0.3
- Jet $5 < p_T < 50$ GeV/c

D-meson Baseline comparison with models in pp at 5.02 TeV



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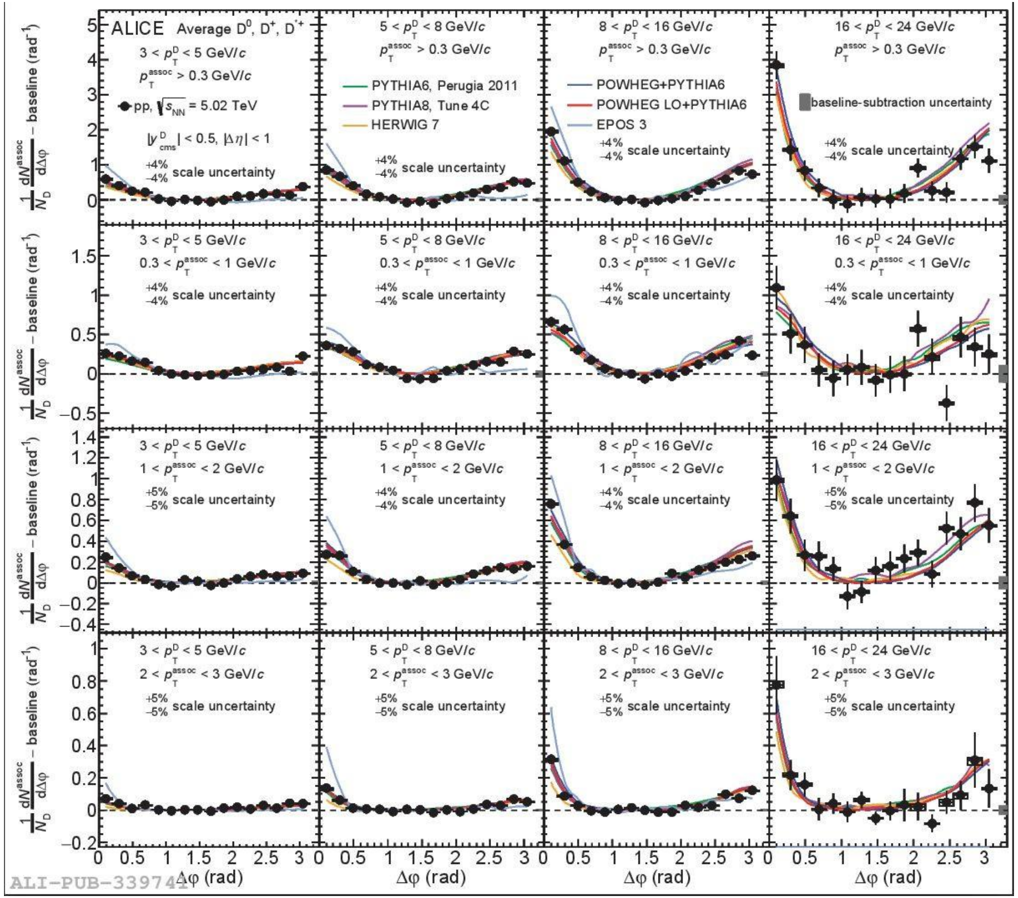
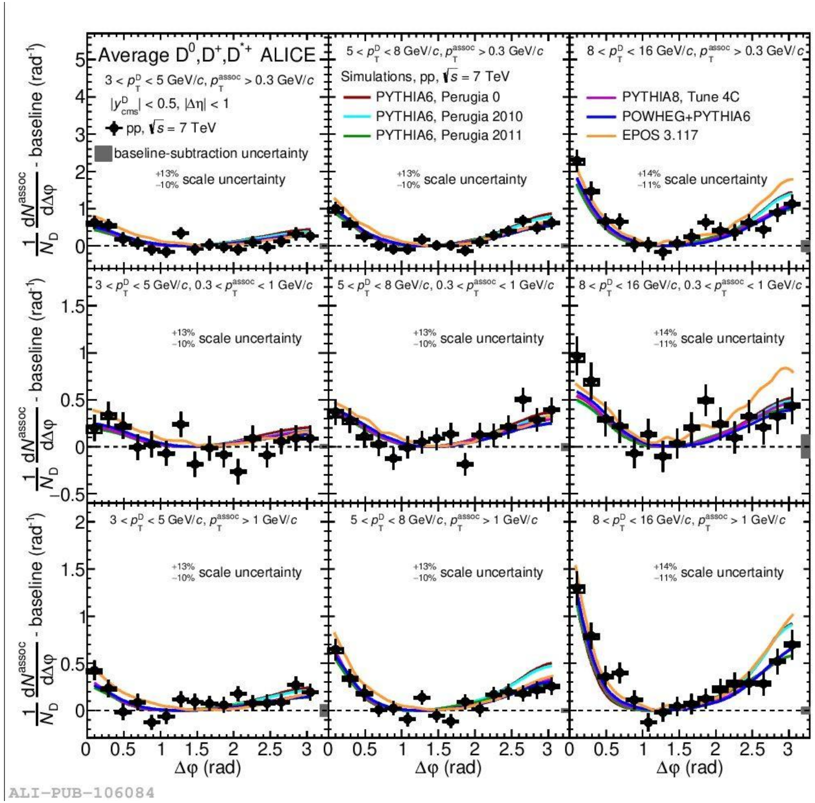
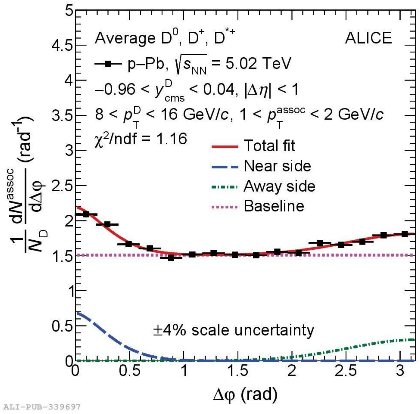
Model comparisons of D-charged particle correlation distribution in at 5.02 and 7 TeV

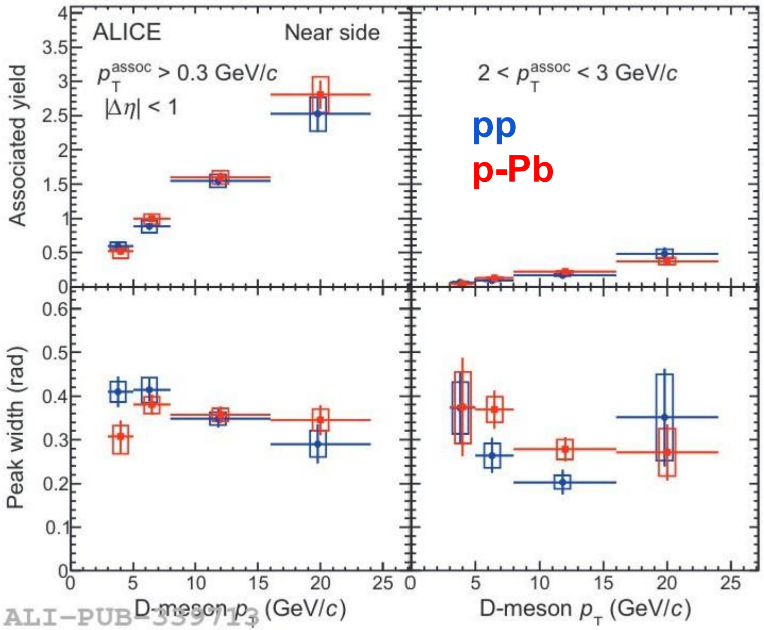




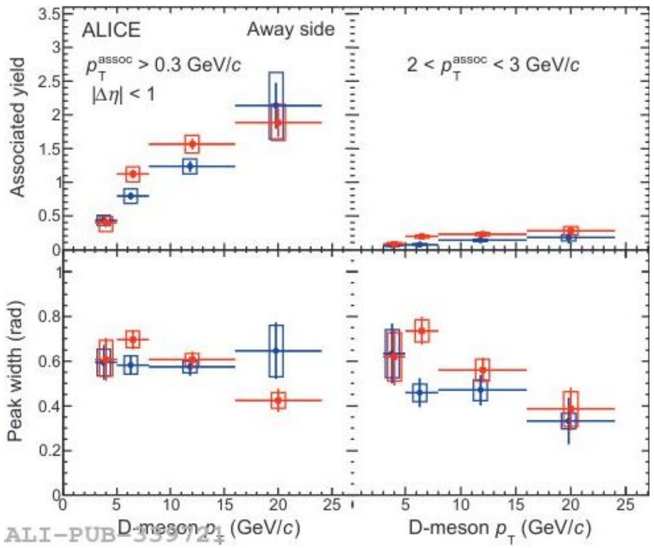
[EPJC 77 (2017) 245]

D-meson and charged particle azimuthal correlation





- Consistent values of the fit observables in pp and p-Pb collisions are observed in all kinematic ranges.
- no significant impact from cold-nuclear-matter effects on the charm fragmentation is observed with current statistics.



Fitting procedure:
•constant term (Baseline) + Generalized Gaussian (Near-side) + Gaussian (Away-side)

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

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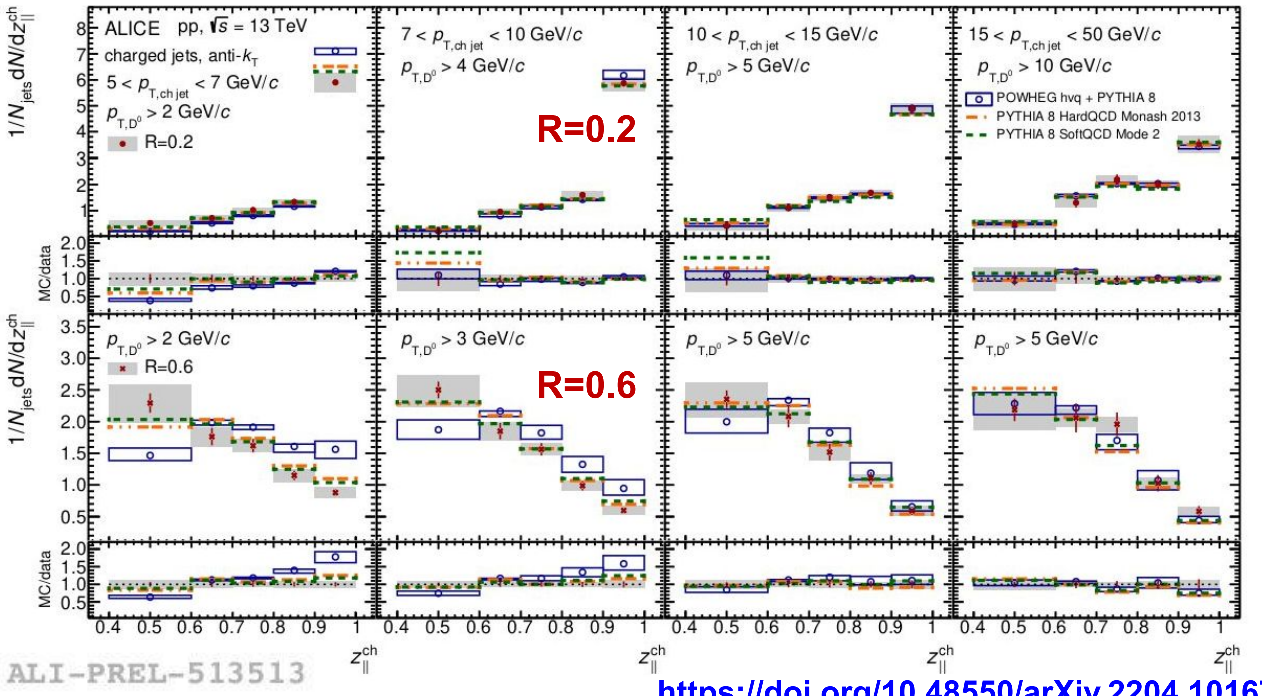
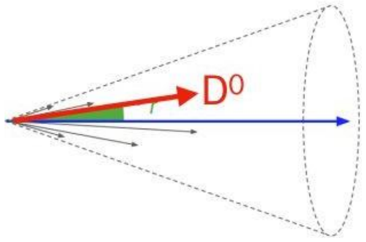
HF jets to look into fragmentation



https://doi.org/10.48550/arXiv.2204.10167

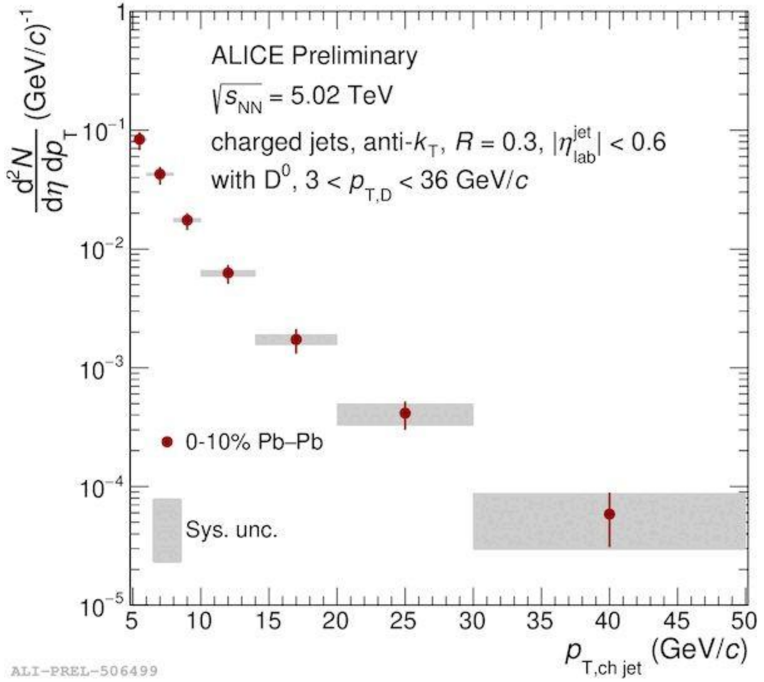
Provide access to the properties of heavy-quarks fragmentation and hadronization

$$Z_{\parallel}^{ch} = \frac{\vec{p}_{ch\ jet} \cdot \vec{p}_{HF}}{\vec{p}_{ch\ jet} \cdot \vec{p}_{ch\ jet}}$$

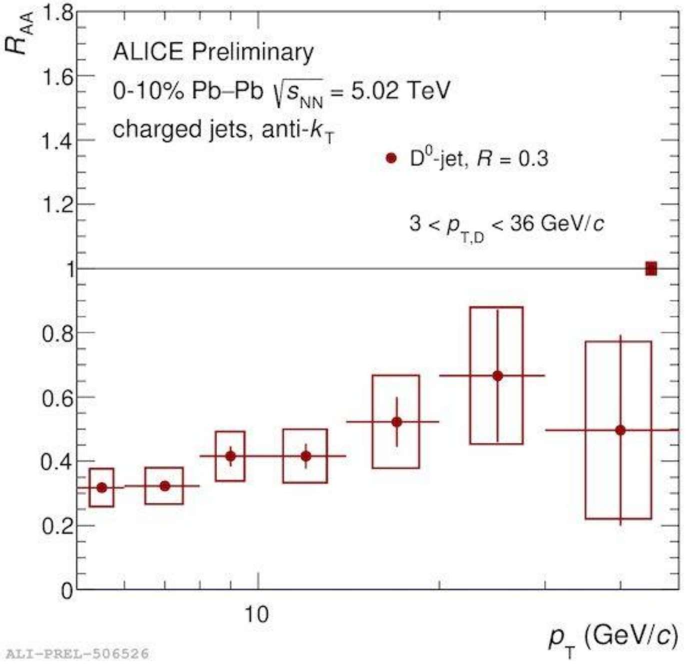


- Hint of a softer fragmentation in data with respect to model predictions (especially NLO) for low $p_{T,ch\ jet}$ and large R.
- The core of the jet (R=0.2) is dominated by the HF hadron, as expected from the suppression of small angle emissions.
- At large angle (R>0.2) the charm quark emissions are recovered.

Medium effects: D^0-jets in 0-10% Pb-Pb



p_T-differential cross section in Pb-Pb central collisions



- Baseline: D^0-jet $p_T$differential cross section in pp at 5.02 TeV with same jet reconstruction as in Pb-Pb.
- An area based background subtraction performed in Pb-Pb.

Sizeable suppression of D^0-jets in central Pb-Pb collisions

Medium effects: D^0-jets in 0-10% Pb-Pb

- Higher R_{AA} of D^0-jet compared to inclusive jets in Pb-Pb?
  - Comparison is sensitive to difference between quarks and gluon energy loss (Casimir colour effect)
  - Comparison could also be sensitive to mass effects (dead-cone).