Investigating the fragmentation of charm quarks with correlation and jet measurements by ALICE

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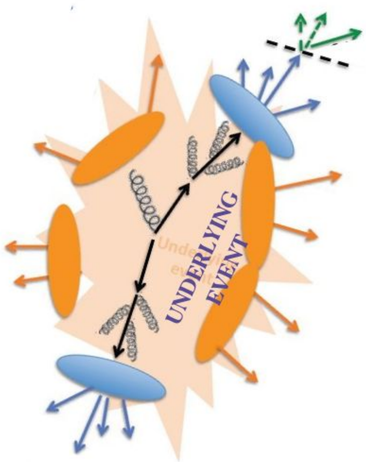
Indian Institute of Technology Indore (IN)

DAE-HEP2022, 12-16 Dec 2022

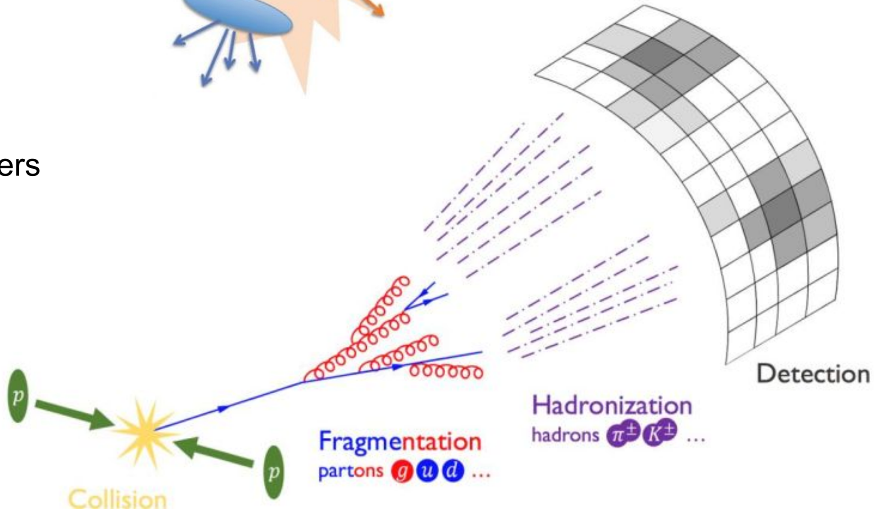
Why heavy-flavour jets?

- Heavy-Flavours
  - Heavy-flavour jets minimize dependence on hadronization process due to including all particles from parton shower.



What do we learn by investigating different systems?

- **pp collisions**
  - Test for pQCD calculations
  - Investigate fragmentation and hadronization models
  - Mass dependence of parton radiation
  - Differences between quark-initiated and gluon initiated showers
- **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.



How the jets can help?

- Smaller dependence on the hadronization models allows for a better comparison to QCD.
  - Gluon initiated jets – broader fragmentation
  - Quark initiated jets – more collimated

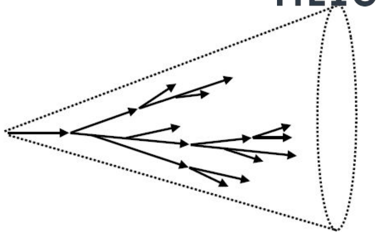
- Inclusive jets
  - Well constrained at high p_T, low p_T experimentally challenging.
  - Mostly gluon initiated.

- Heavy-flavour jets:
  - Heavy quarks are conserved through the parton shower
  - Quark initiated

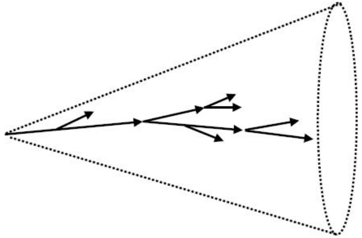
- Inclusive vs heavy-flavour jets
  - Effect of Casimir factors and dead cone

Gluon initiated jets

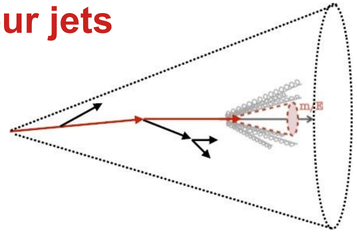
Casimir colour factors
$C_A/C_F = 9/4$



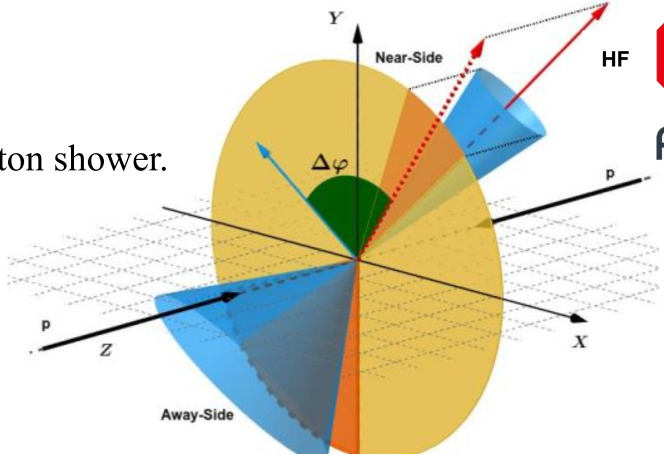
Quark jets



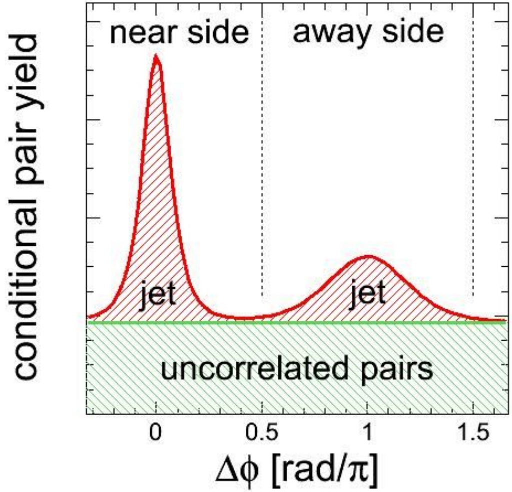
Heavy-flavour jets



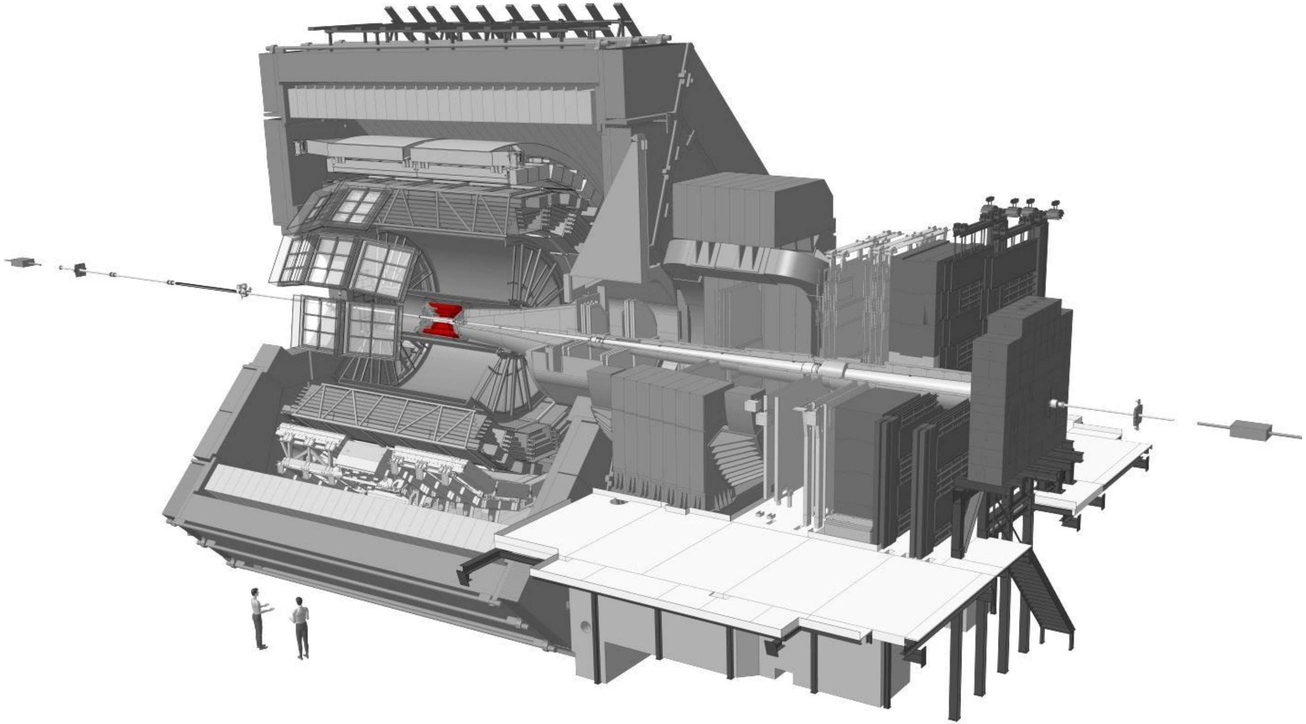
Heavy-flavour (HF) correlation



- HF correlations represents an alternative method to study the HF parton shower.
  Advantage over jet:
- Better access to low p_T parton showers
- Description of peak shapes and width
- **Give access to the production mechanisms:**
  - Pair Creation (LO):
    - quarks are produced back-to-back
    - "Near Side" peak at $\Delta\varphi = 0$: Produced by the particle associated with high p_T trigger particle.
    - "Away side" peak at $\Delta\varphi = \pi$: Produced by the particles associated with the recoiled jet.
  - Hard gluon radiation (NLO):
    - Broadening of both peaks
  - Gluon splitting (NLO):
    - Heavy-flavours are produced close in phase space
  - Flavour excitation (NLO):
    - Flat $\Delta\varphi$ contribution.

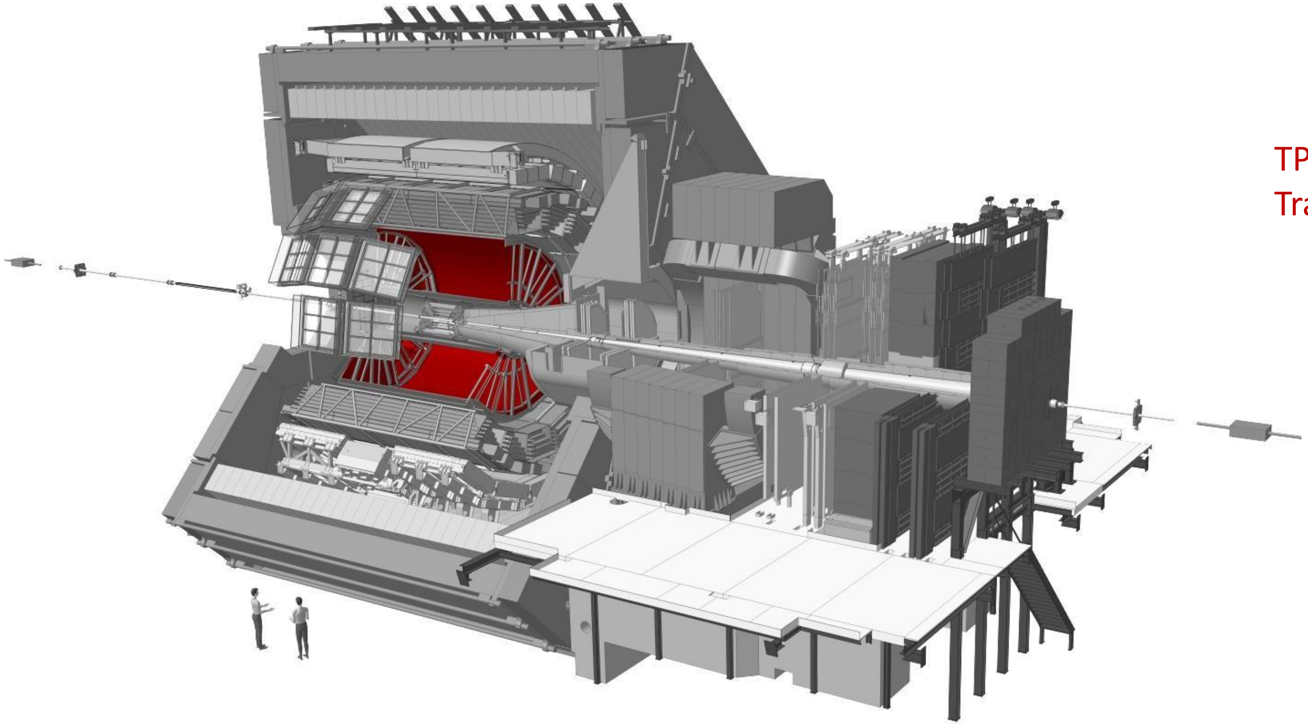


The ALICE Detector – Inner Tracking System



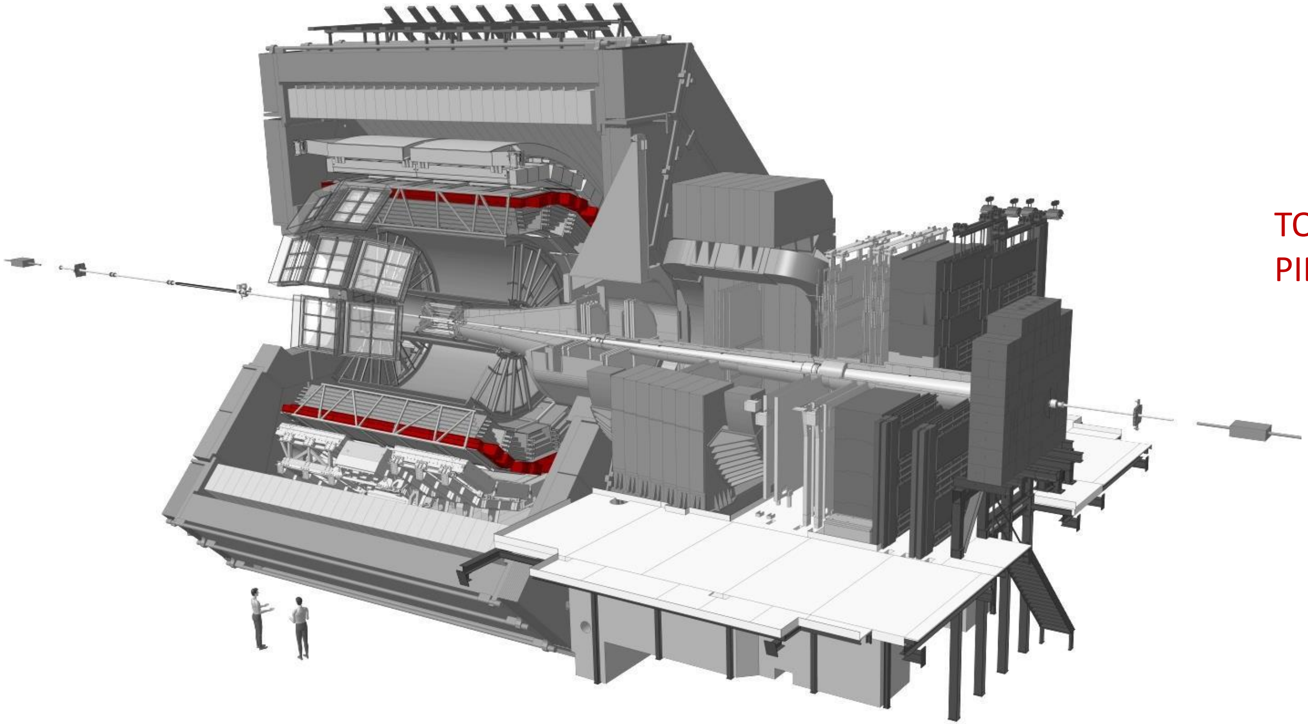
Detectors
ITS $|\eta| < 0.9$
Vertexing and tracking

The ALICE Detector (Time Projection Chamber)



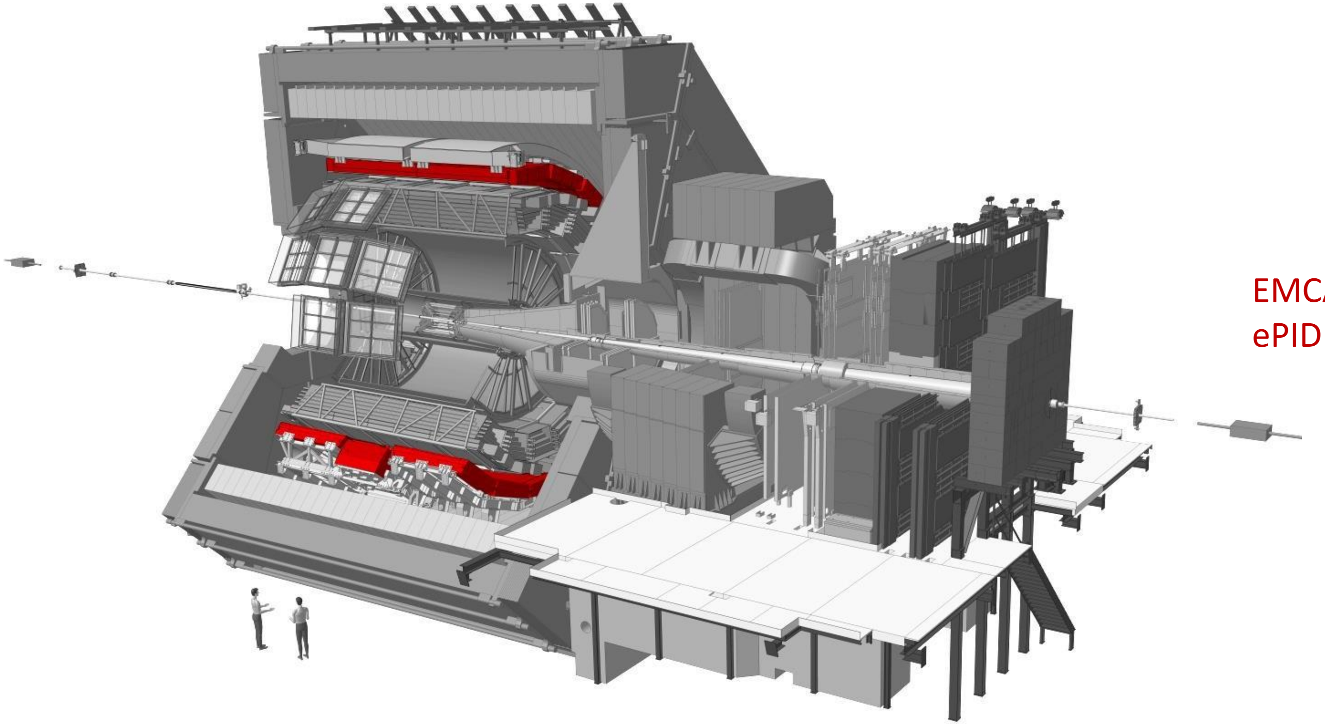
TPC $|\eta| < 0.9$
Tracking and PID

The ALICE Detector – Time of Flight



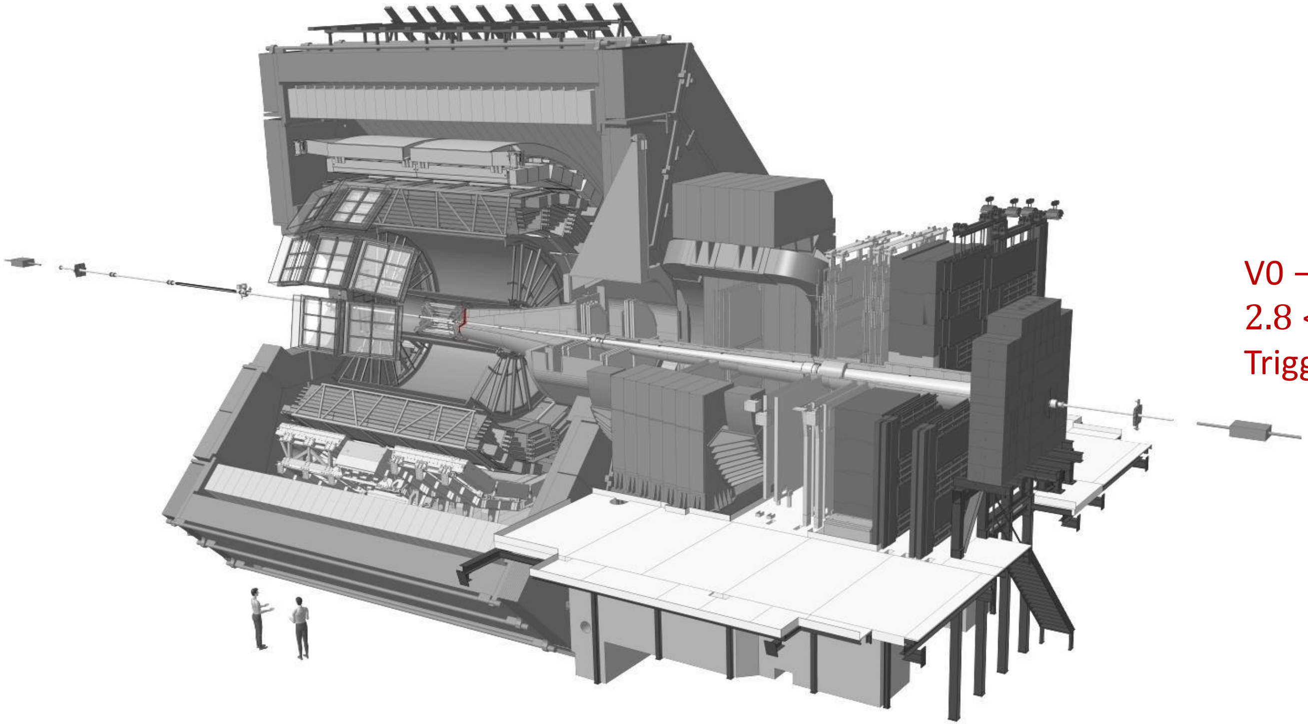
TOF $|\eta| < 0.9$
PID

The ALICE Detector – Calorimeters



EMCAL/PHOS $|\eta| < 0.7$
ePID and trigger

The ALICE Detector – V0

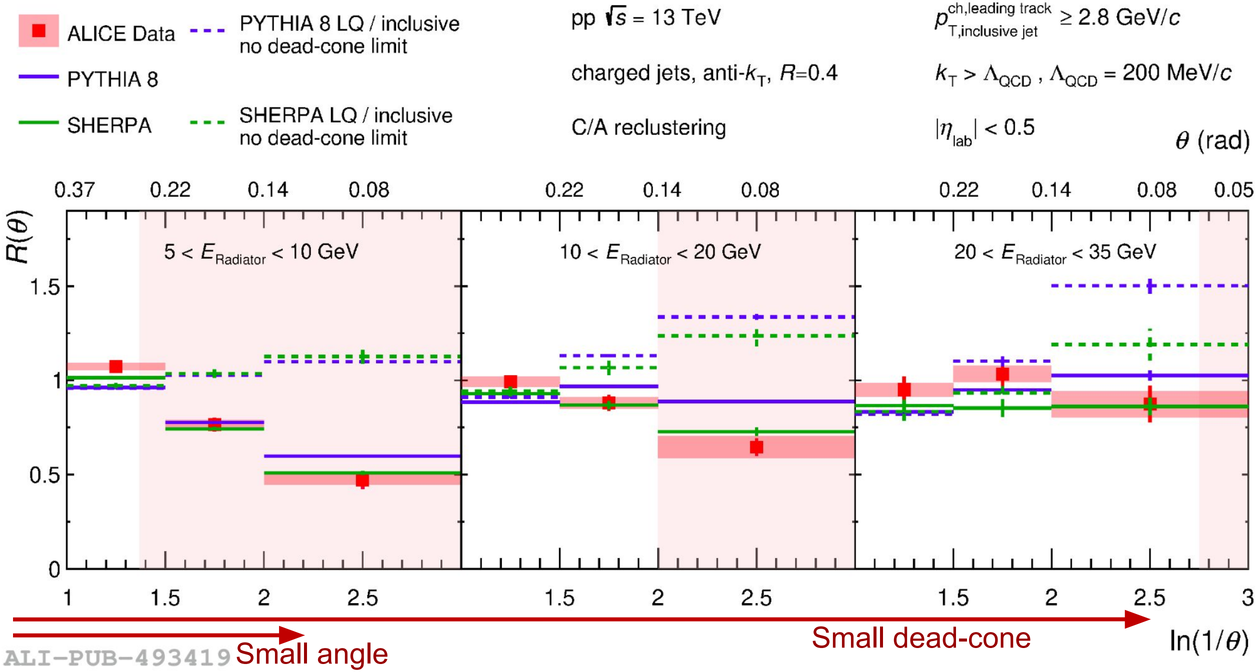


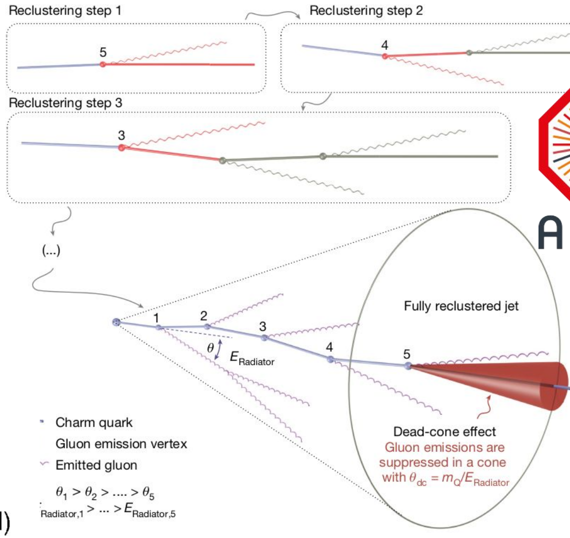
V0 $-3.7 < \eta < -1.7$
$2.8 < \eta < -5.1$
Trigger and background rejection

Dead-cone effect

- The dead-cone (DC) effect is a fundamental feature of all gauge field theories
- The radiation of the emitter is suppressed for $$\theta < \theta_{\rm DC} = \frac{m_q}{E_q}$$

Mass↑ →$\theta_{\rm DC}$↑ → collinear radiation↓





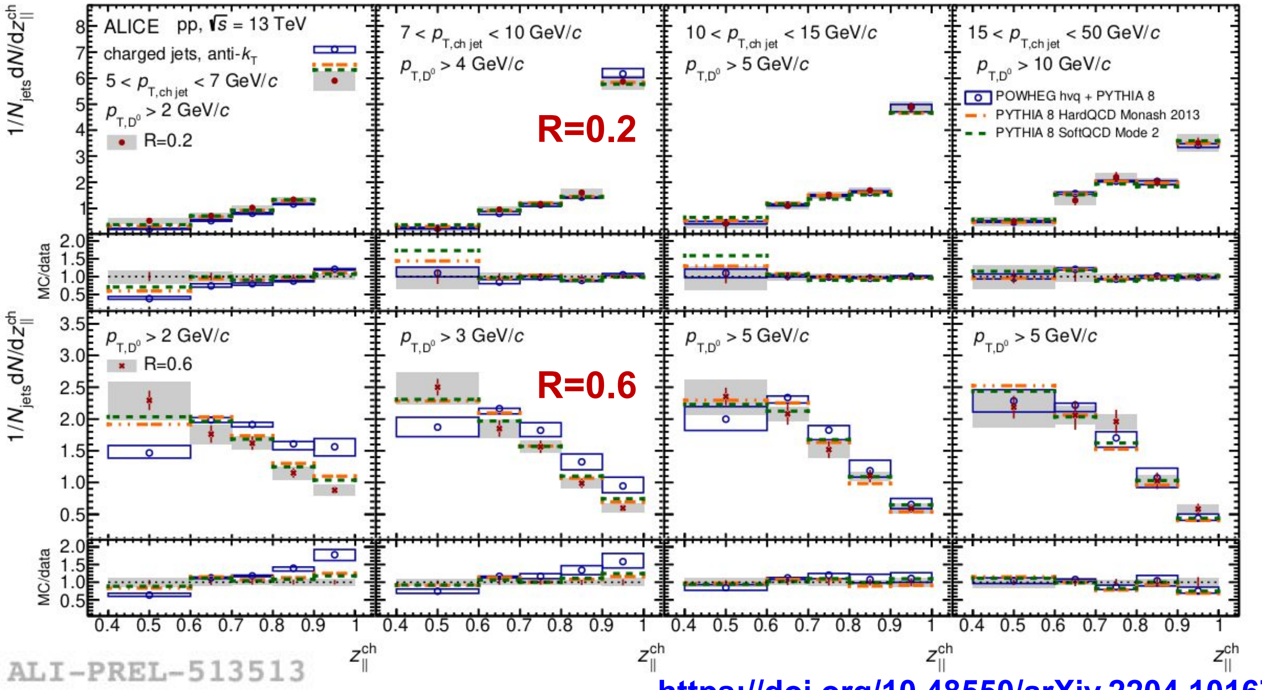
D^0 reconstruction→ C/A algorithm
→angular-ordered splitting tree
Unwind the charm shower process→ ($E_{\rm rad}$, θ)

$$R(\theta) = \frac{1}{N^{\rm D^0\,jets}} \frac{dn^{\rm D^0\,jets}}{d\ln(1/\theta)} \Big/ \frac{1}{N^{\rm inclusive\,jets}} \frac{dn^{\rm inclusive\,jets}}{d\ln(1/\theta)} \Bigg|_{k_T, E_{\rm Radiator}}$$

➔ Suppression for D^0-meson tagged jets
➔ Dependency on $E_{\rm rad}$ of the suppression

ALICE, Nature 605 (2022)

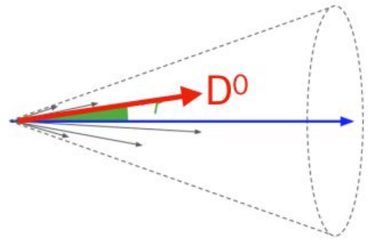
HF jets to look into fragmentation



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

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

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



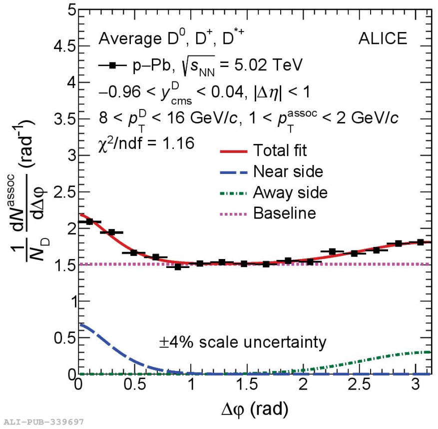
- Hint of a softer fragmentation in data with respect to model predictions (especially NLO) for low $p_{T,ch\,jet}$ and large R.
- The core of the jet (R=0.2) is dominated by the HF hadron, as expected from the suppression of small angle emissions.
- At large angle (R>0.2) the charm quark emissions are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

D-meson and charged particle azimuthal correlation

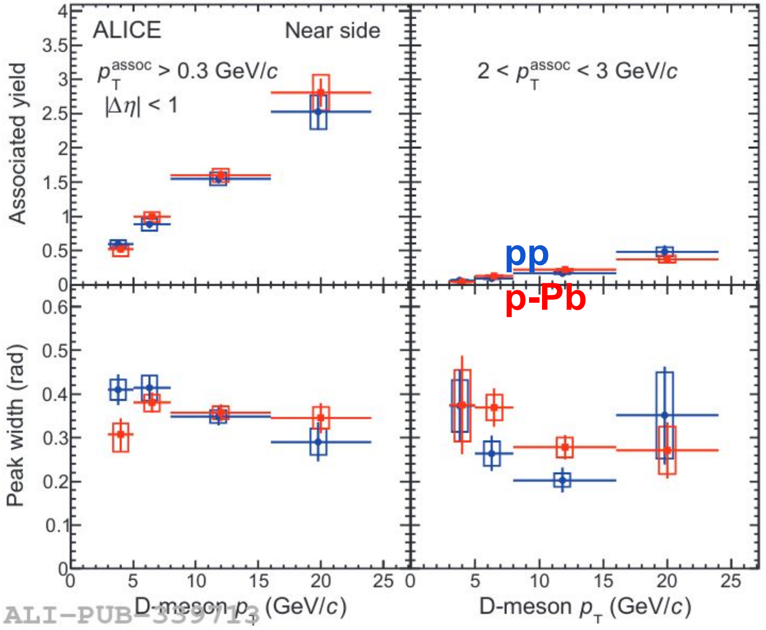
→ Yield: indication of charm-shower multiplicity
→ Width: angular distribution of charm-shower

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

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



$p_T^D \uparrow$ Yield $\uparrow$ Width $\downarrow$

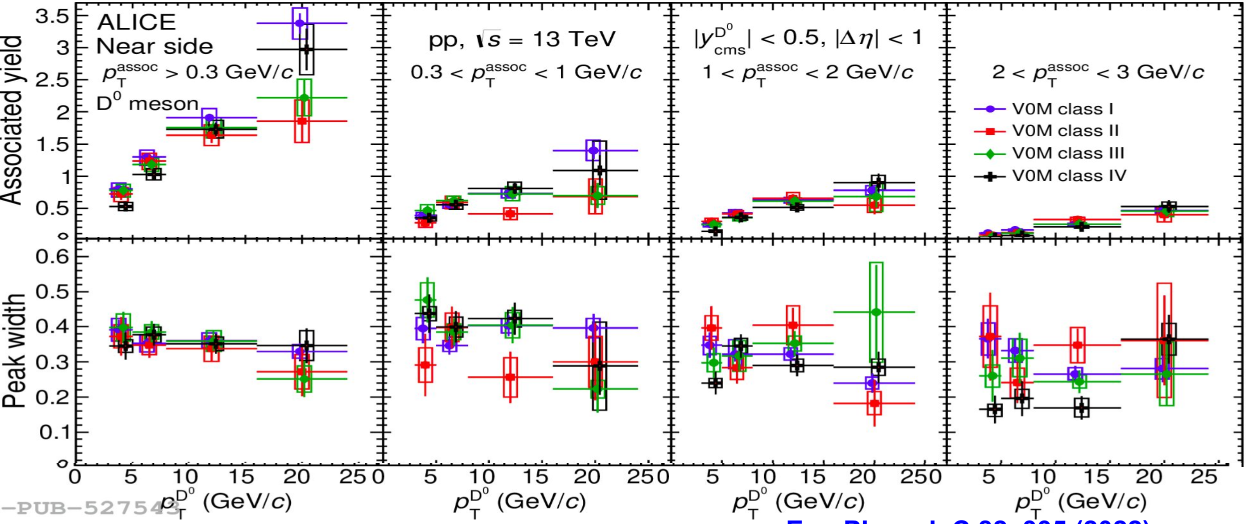


EPJC 80 (2020) 979

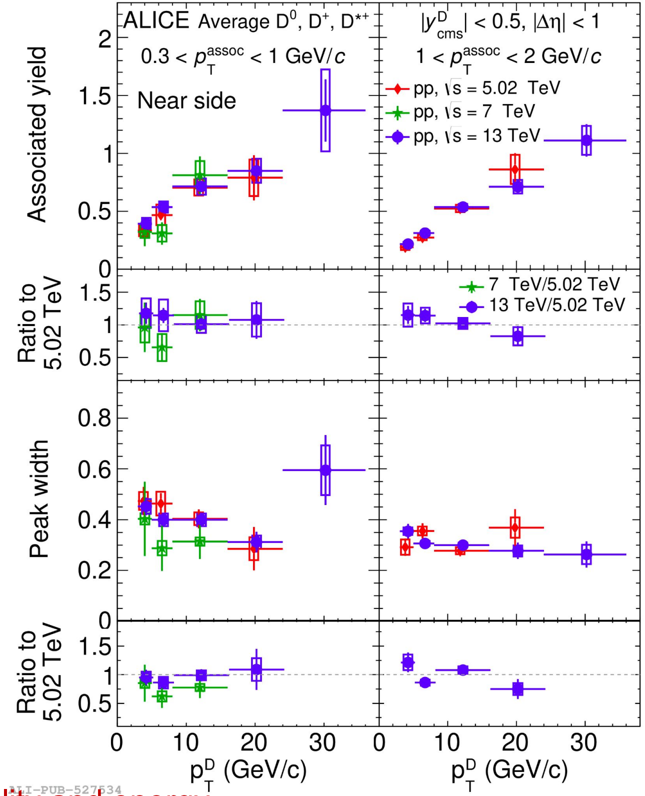
- Consistent values of the near-side observables in pp and p-Pb collisions are observed for all kinematic ranges.
- no significant impact from cold-nuclear-matter effects on the charm fragmentation is observed with current statistics.

D-meson and charged particle azimuthal correlation

Comparison with different centrality classes and collision energies



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

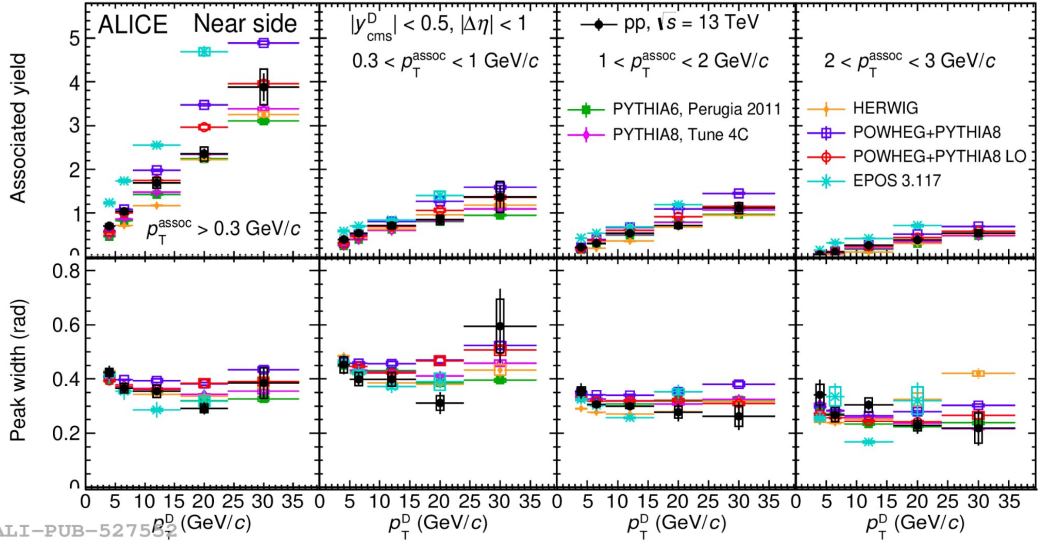


V0M multiplicity class	I	II	III	IV
$\sigma/\sigma_{INEL>0}$ (%)	0–0.0915	0.0915–9.149	9.149–27.50	27.50–100
$\langle dN_{ch}/d\eta \rangle$	31.15 ± 0.40	18.39 ± 0.23	11.46 ± 0.15	4.41 ± 0.06

- An increasing trend is observed with p_T^D.
- Charm fragmentation and hadronization show no dependence on collision centrality and energy.

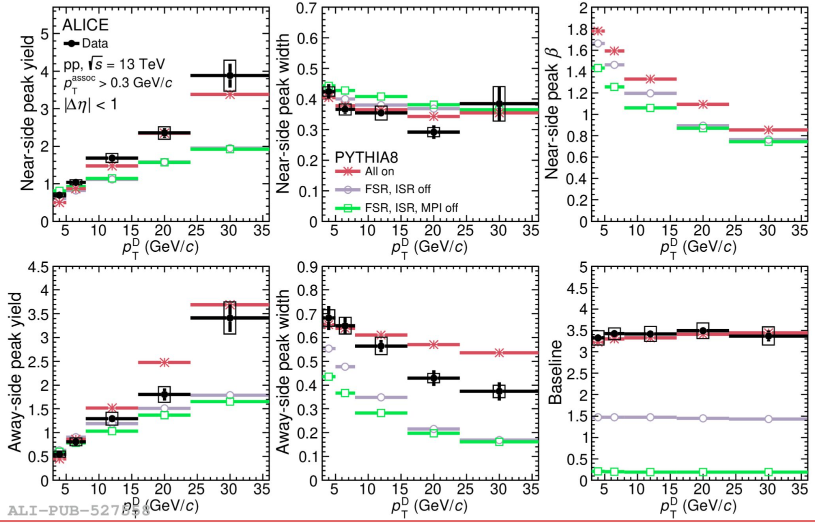
D-meson and charged particle azimuthal correlation

Comparison with different models and investigation of partonic processes



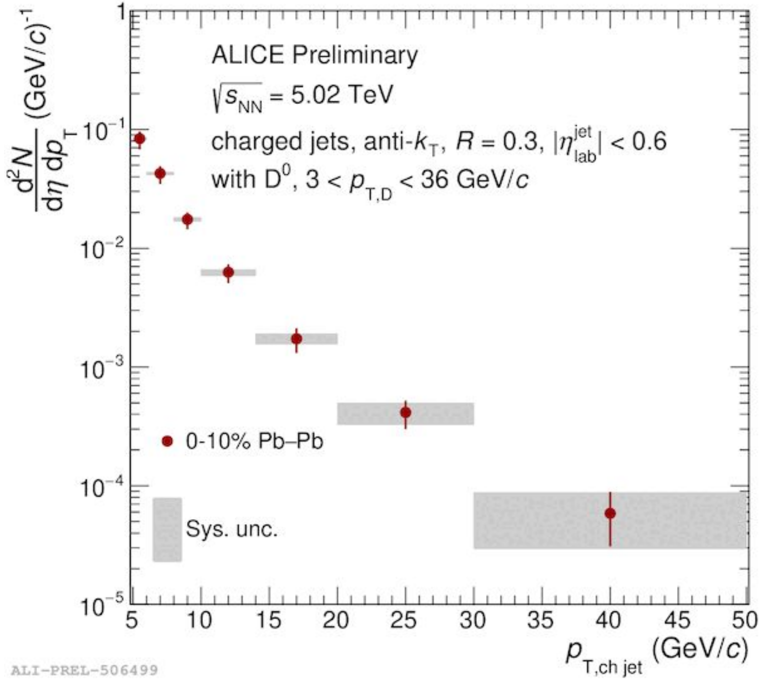
From the comparison with MonteCarlo predictions, PYTHIA and POWHEG+PYTHIA provide the best description

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

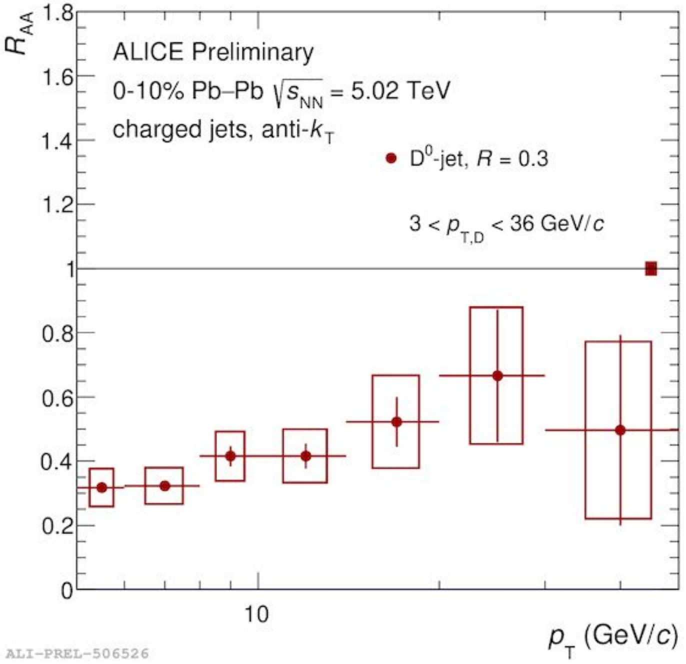


Multi-partonic interaction (MPI) →No change in yields
(Contribute to underlying events)
Initial- and final-state radiation processes→increase peak yields
(additional production of collinear particles)
All partonic processes →increase widths
(Presence of hard gluons)

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



p_T-differential cross section in Pb-Pb central collisions

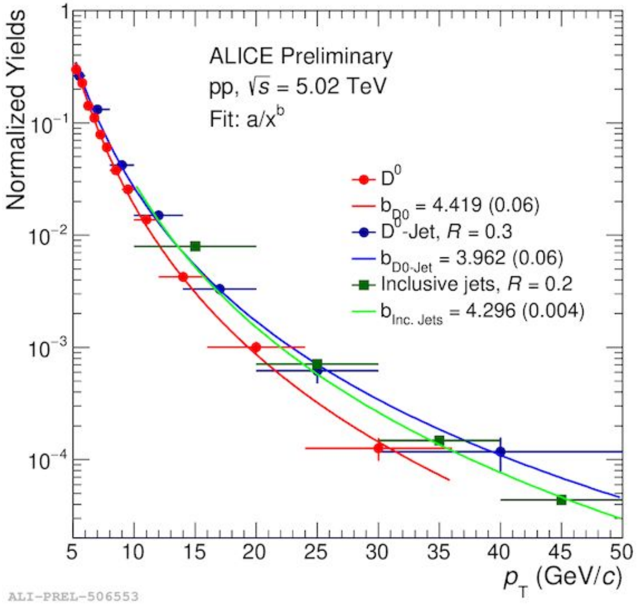


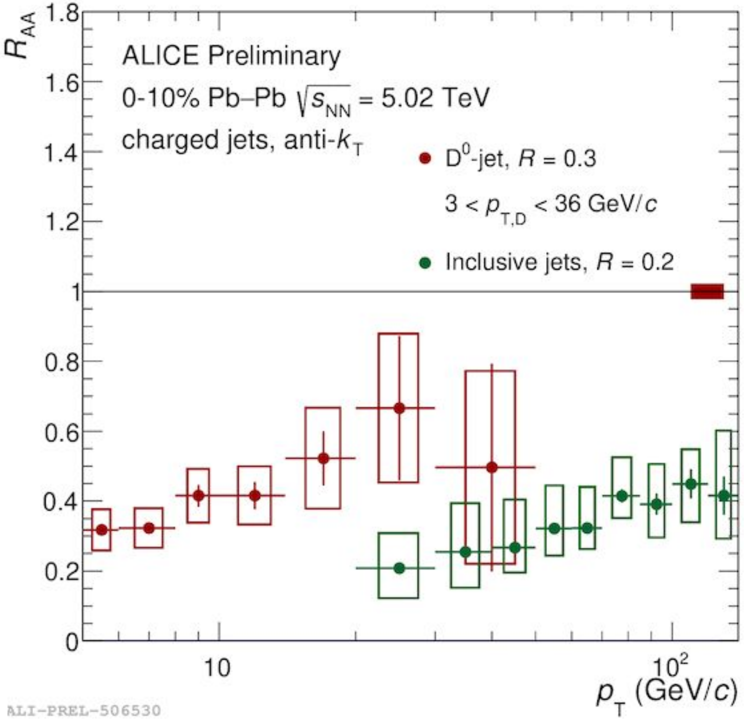
- Baseline: D^0-jet p_T differential cross section in pp at 5.02 TeV with same jet reconstruction as in Pb-Pb.
- An area based background subtraction performed in Pb-Pb.

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).

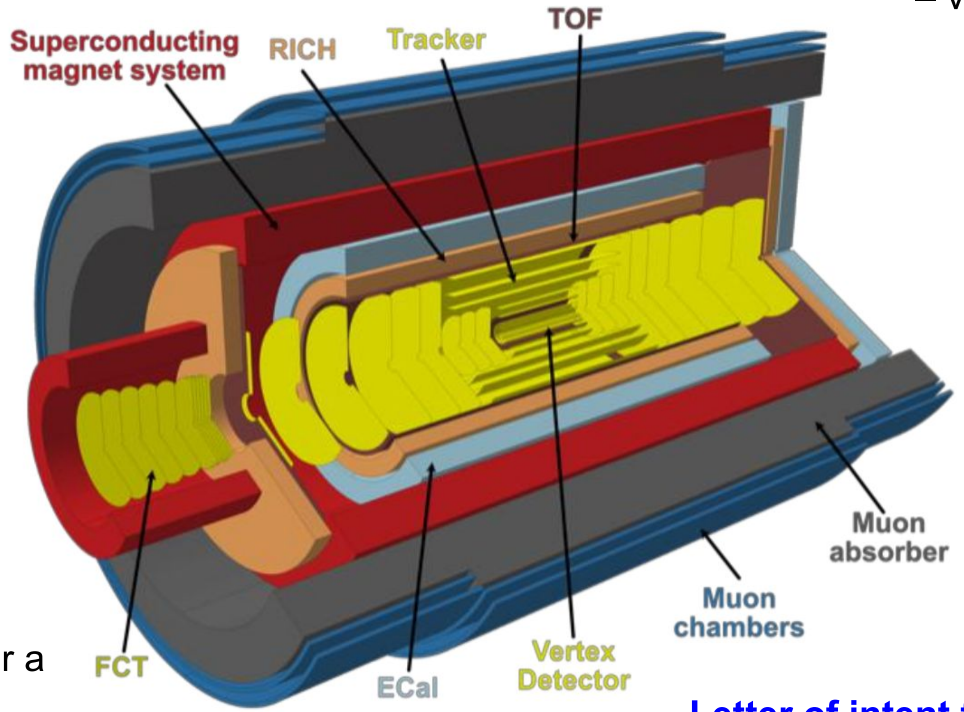




ALICE 3 Detector

- ALICE 3: a next-generation heavy-ion experiment for LHC Run 5 and 6.
- Compact all-silicon tracker with high-resolution vertex detector.

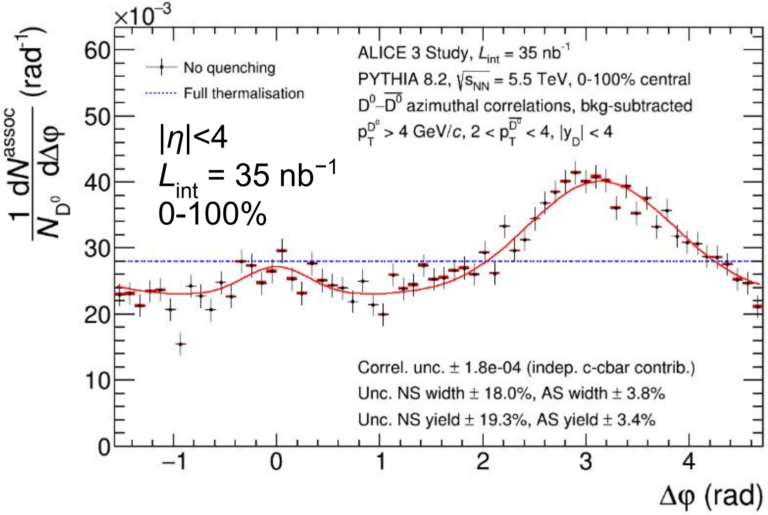
Heavy-flavour hadrons ($p_T \rightarrow 0$, wide η range) – vertexing, tracking, hadron ID

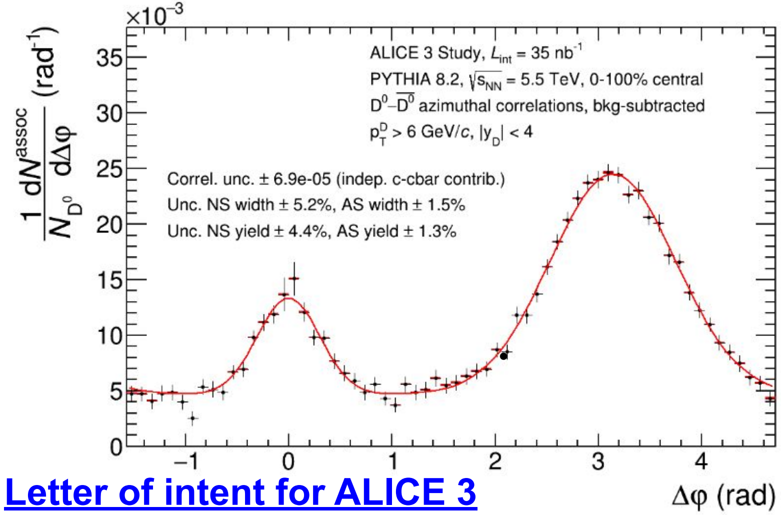


Particle identification over a large acceptance.

[Letter of intent for ALICE 3]

Expected performance of D^0-$\bar{D}^0$azimuthal correlation in Pb-Pb collisions





[Letter of intent for ALICE 3]

- Includes background subtraction and weights to account for D^0-$\bar{D}^0$ reconstruction and selection efficiencies. Normalization to the number of trigger D^0 mesons.
- Correlation patterns in Pb-Pb collisions will be accurate enough to assess the effects of in-medium broadening and thermalisation, using pp collisions as a reference.

Summary:

- HF - tagged jets:

✓ Softer fragmentation at low $p_{\mathrm{T,ch\ jet}}$ is observed by looking at the fragmentation function.
✓ Nuclear modification factor in D-meson tagged jets shows suppression up to 70%.

- D-h azimuthal correlation distribution:

✓ Comparison between pp and p-Pb measurements showing consistency with each other.
✓ No significant modifications were observed due to the CNM effect.
✓ Jet-fragmentation dependency on multiplicity and collision energy not observed.
✓ PYTHIA and POWHEG+PYTHIA provide the best description of data.

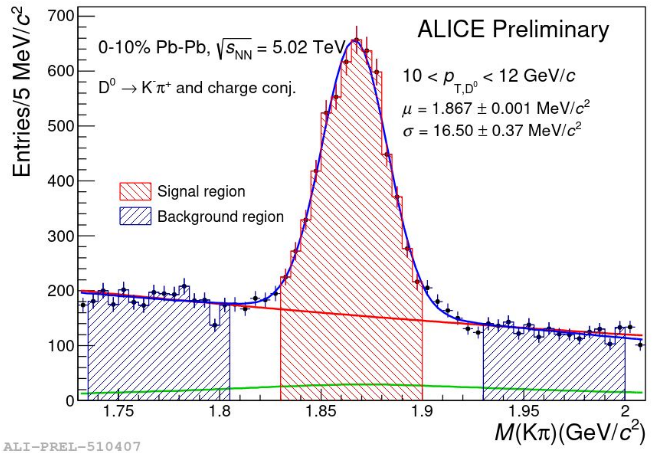
- ALICE3 Detector

✓ Wide η range
✓ Correlation patterns in Pb-Pb collisions will be accurate enough to assess the effects of in-medium broadening and thermalisation.

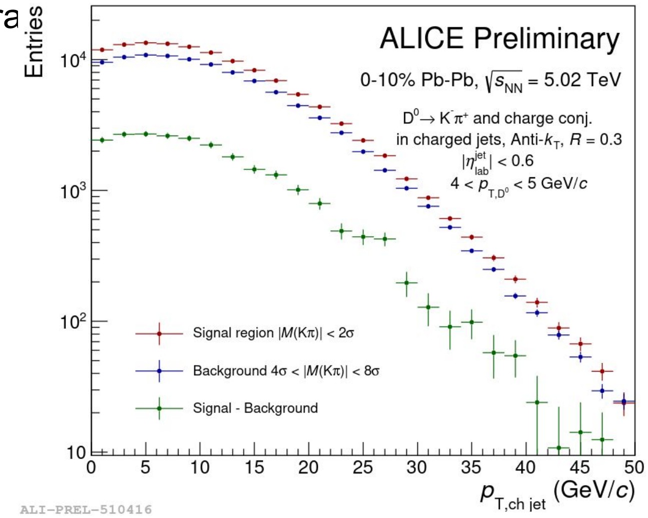
Back-up slides

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

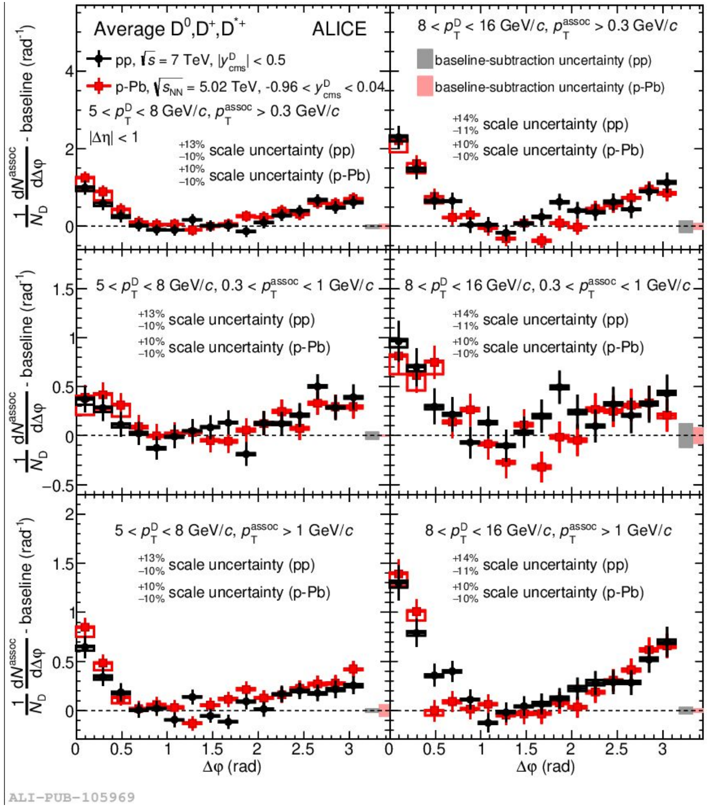


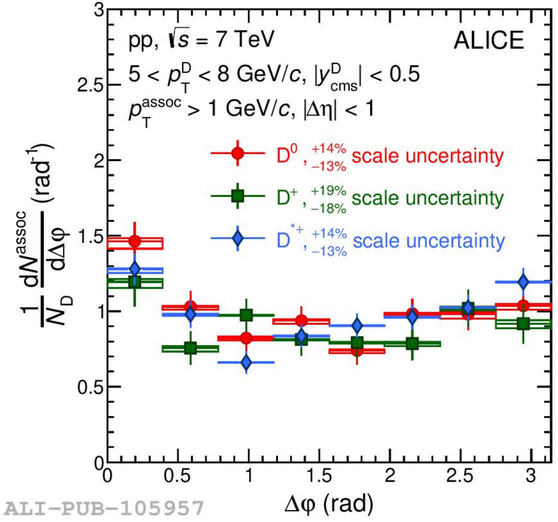
Raw jet spectrum corrected for D^0-jet efficiency

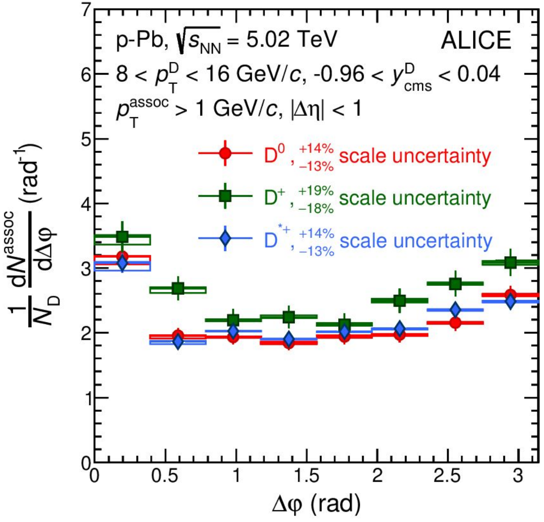


- D^0 -meson $3 < p_T < 36$ GeV/c
- Charged jets, anti-k_T algorithm with R = 0.3
- Jet $5 < p_T < 50$ GeV/c

Comparison of correlation distributions in pp and p–Pb collisions

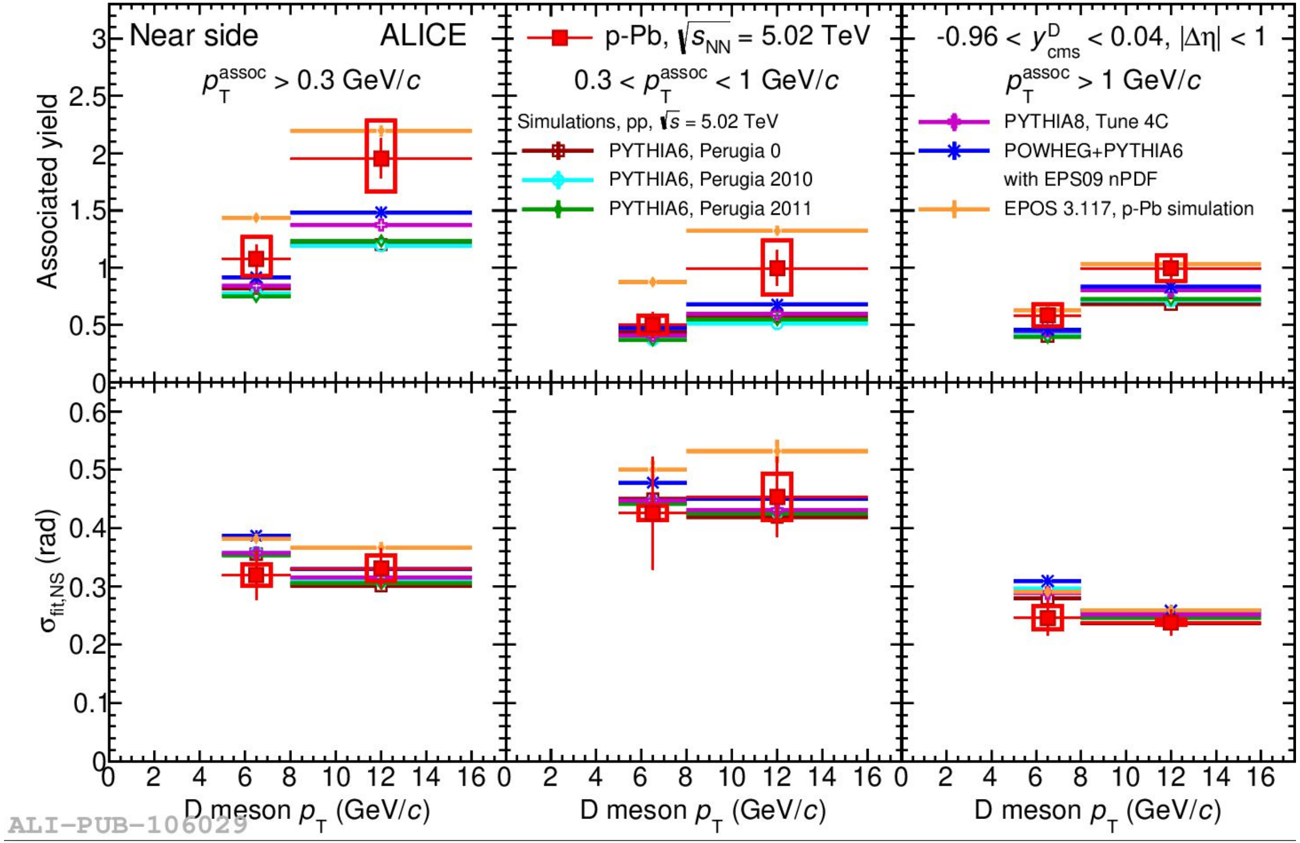






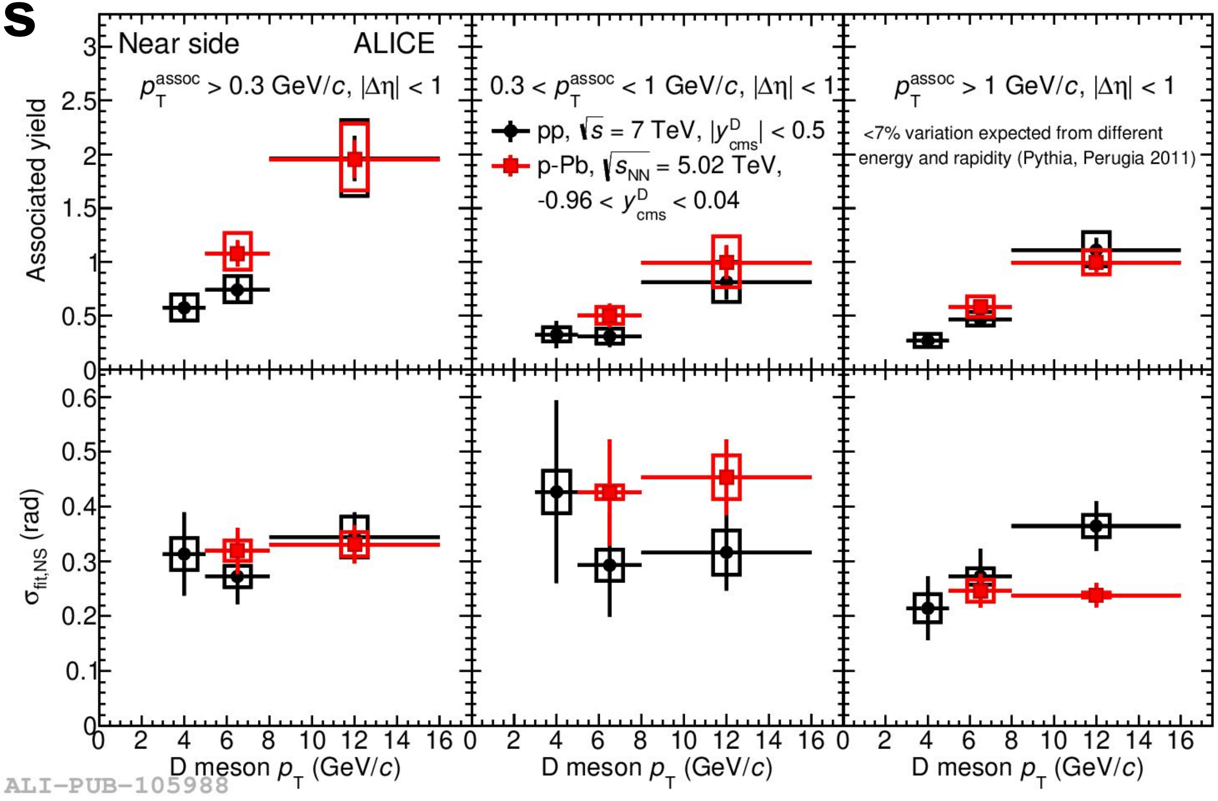
EPJC 77 (2017) 245

Near-side yield and widths in p–Pb collisions at 5.02 TeV



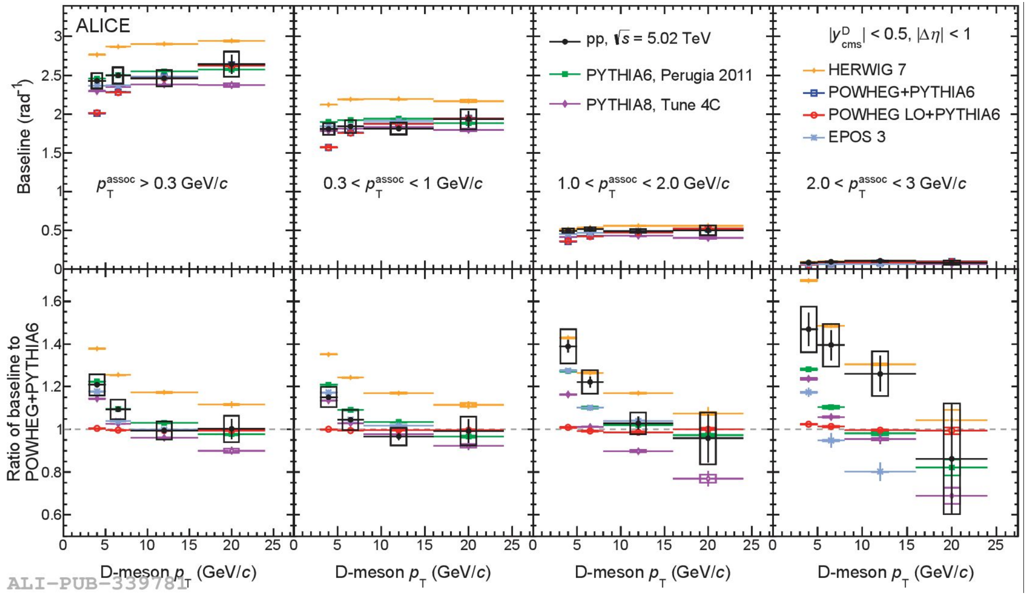
EPJC 80 (2020) 979

Comparison of near-side observables in pp and p–Pb collisions



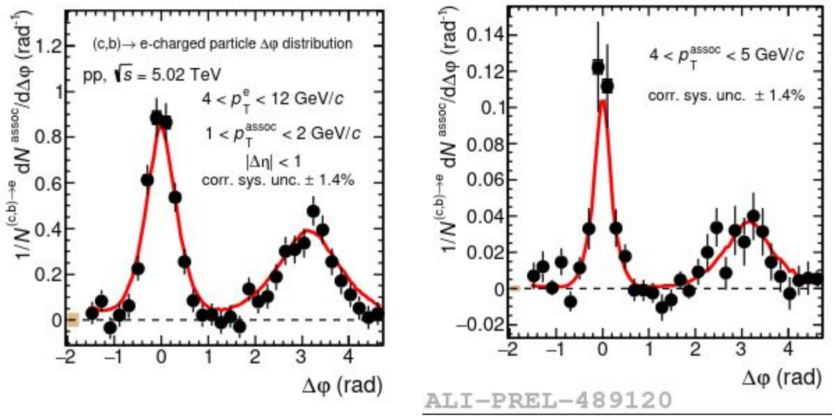
EPJC 77 (2017) 245

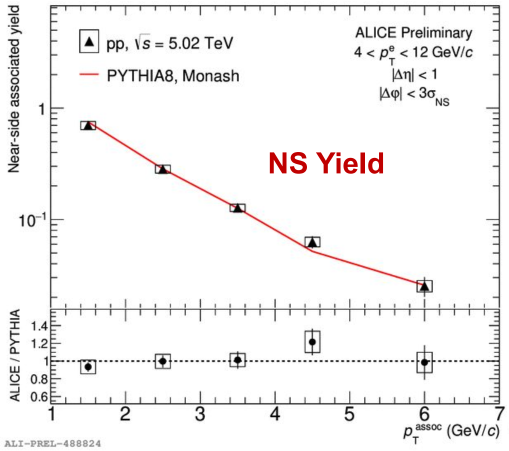
D-meson Baseline comparison with models in pp at 5.02 TeV

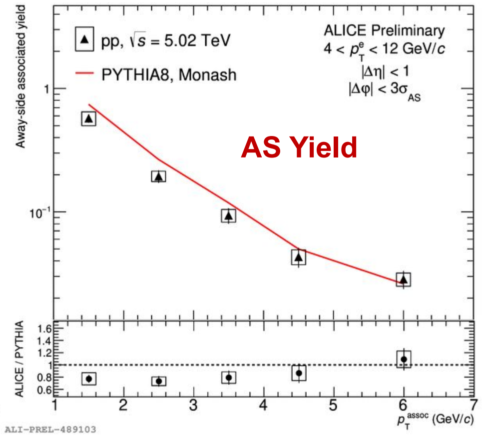


EPJC 80 (2020) 979

HFe-charged particles azimuthal correlation distributions







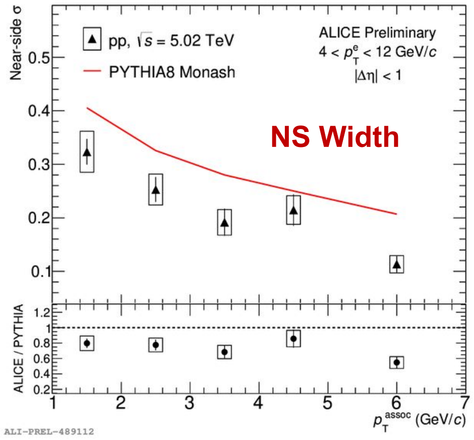
HF-electron sources are:

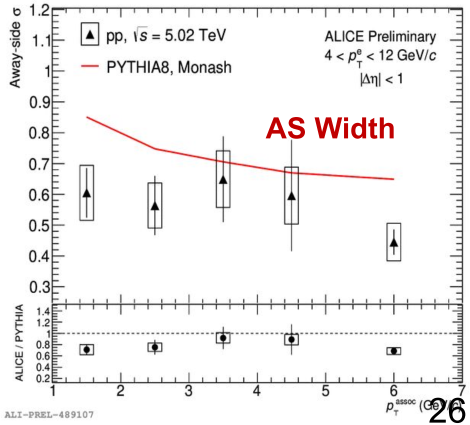
- semi-electronic decays of heavy-flavour hadrons.

Main background contributions come from:

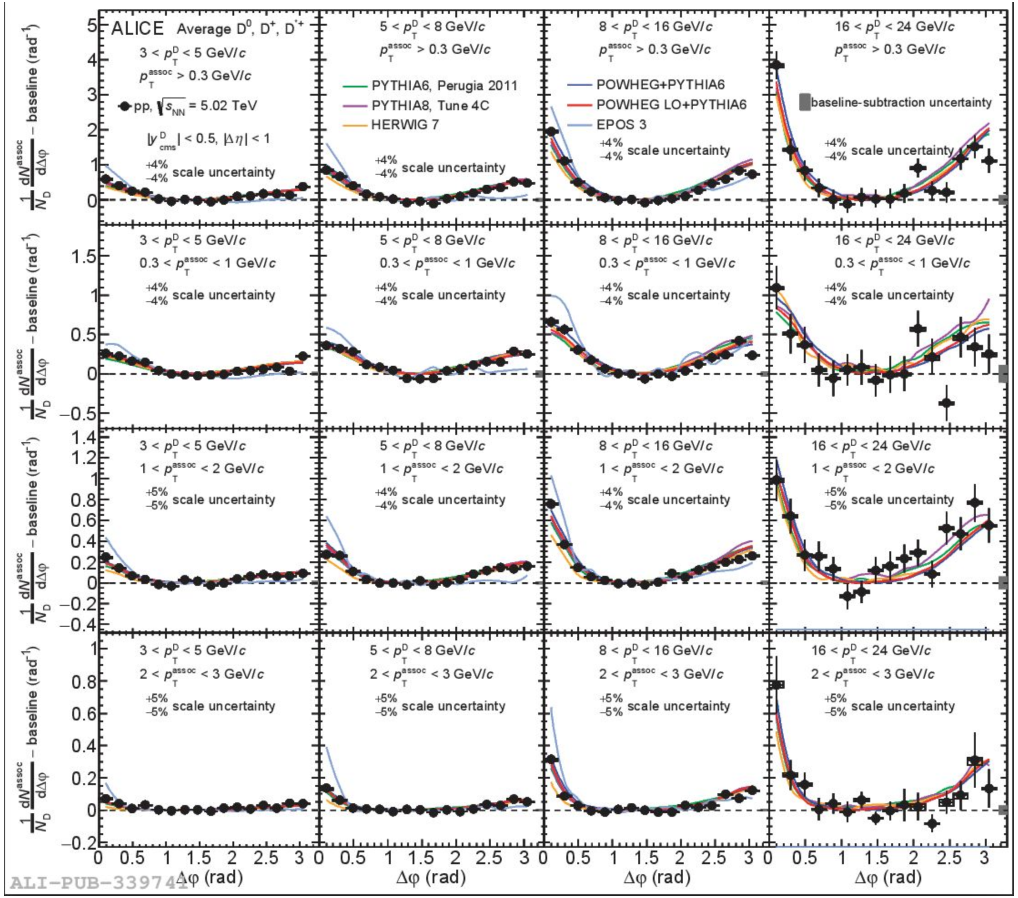
- Dalitz decays of light neutral mesons.
- Photon conversion in the detector material.
- The azimuthal correlation distribution undergoes a correction procedure similar to that of the D-meson distribution.
- Fitting procedure is same as in D-meson.

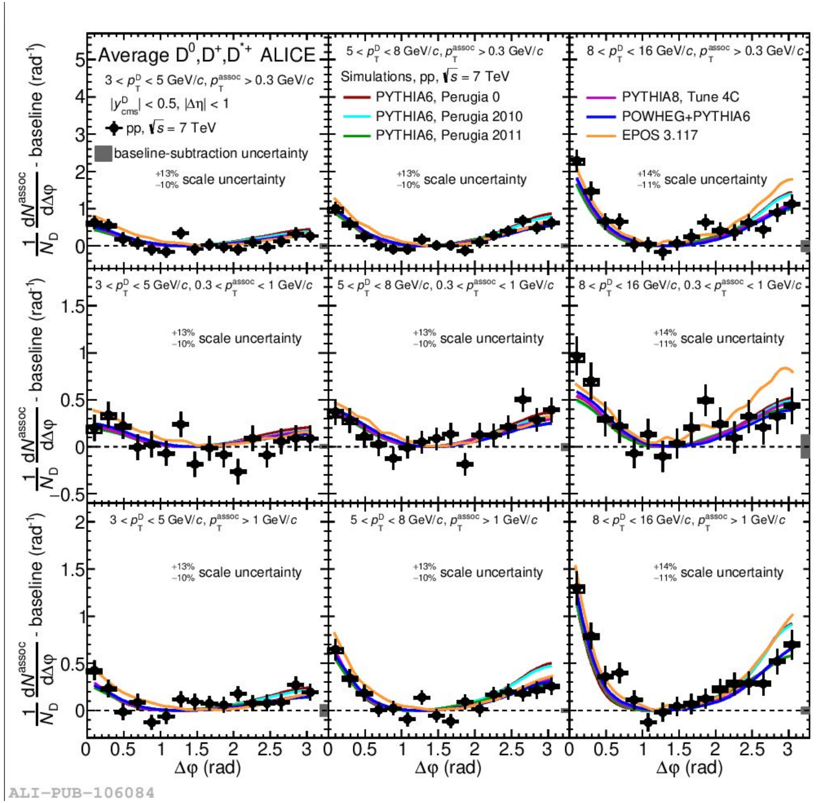
- NS yield is very well reproduced by the PYTHIA8.
- Both the widths are underestimated by the PYTHIA8 predictions.





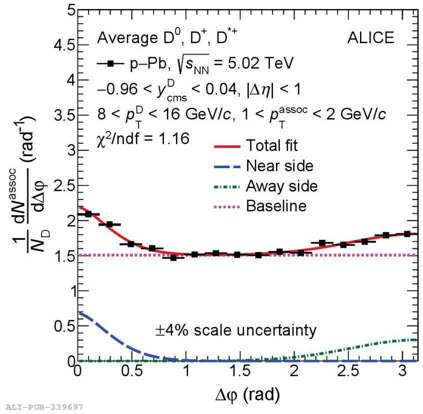
Model comparisons of D-charged particle correlation distribution in at 5.02 and 7 TeV

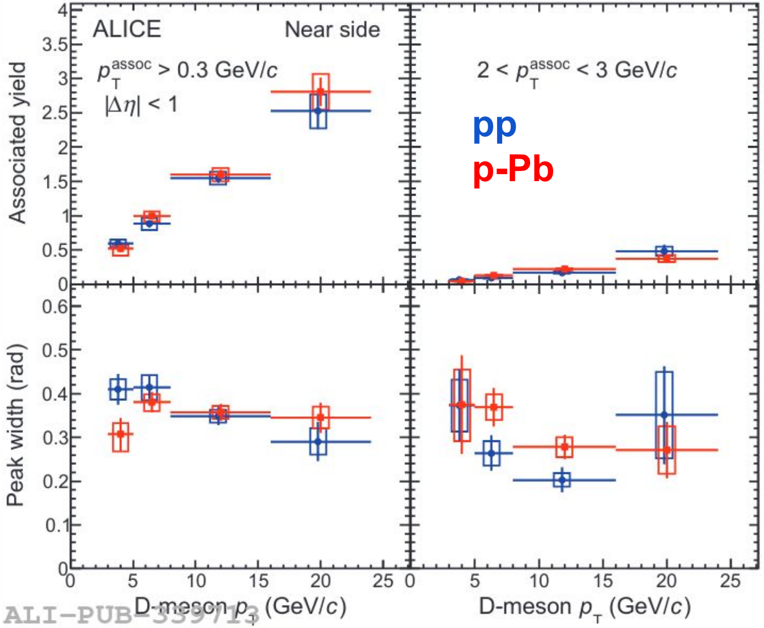




EPJC 77 (2017) 245

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.
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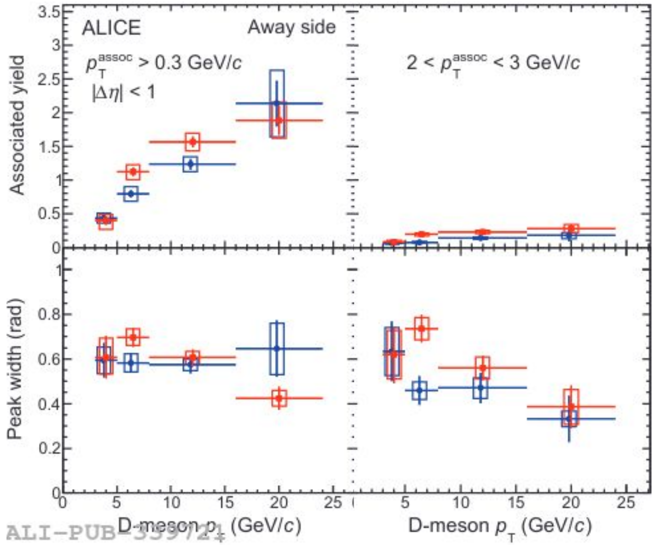

EPJC 80 (2020) 979

Fitting procedure:

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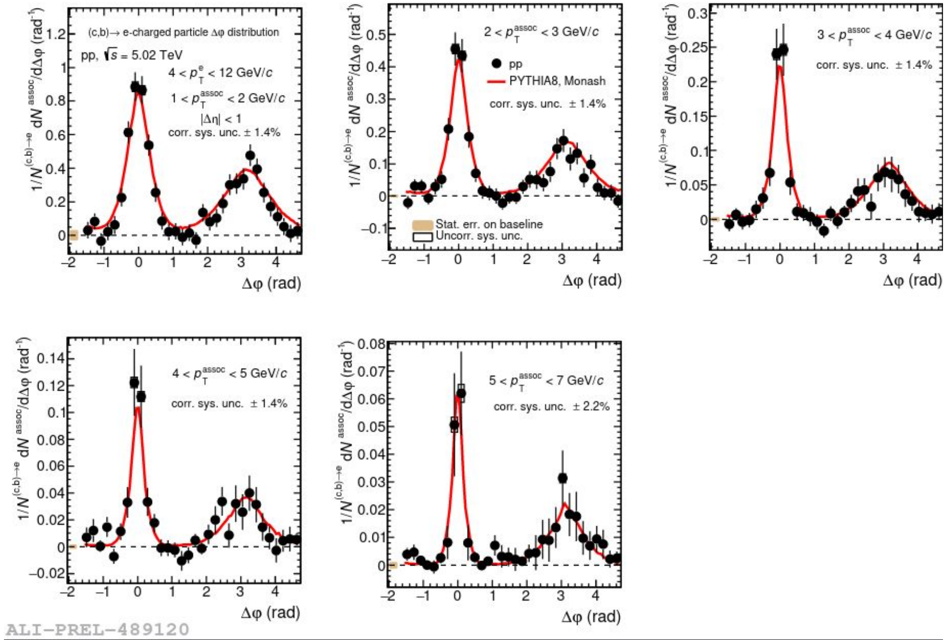
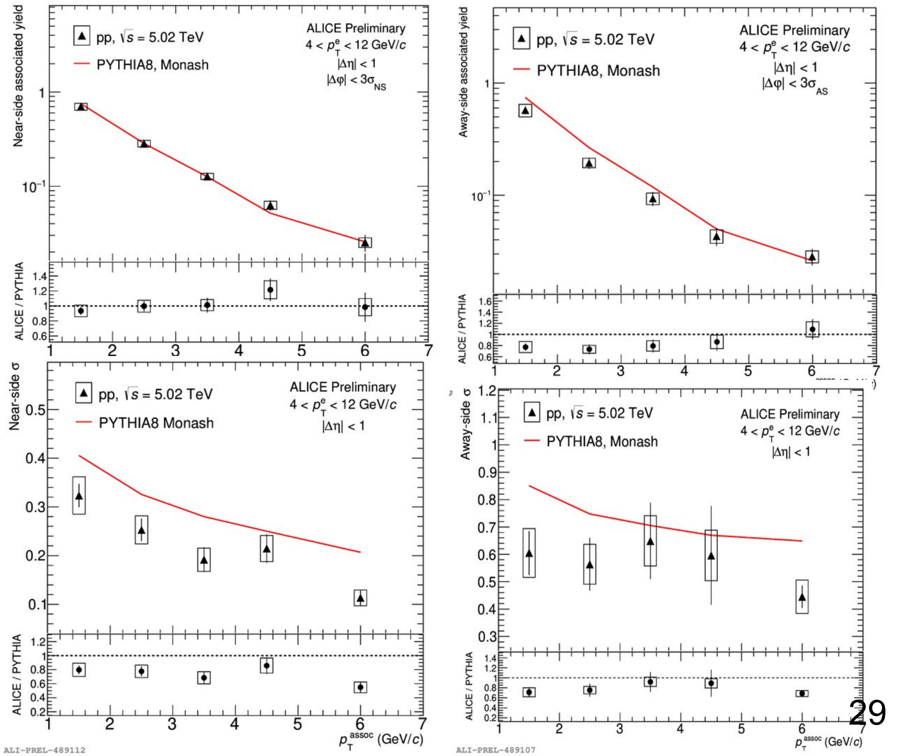
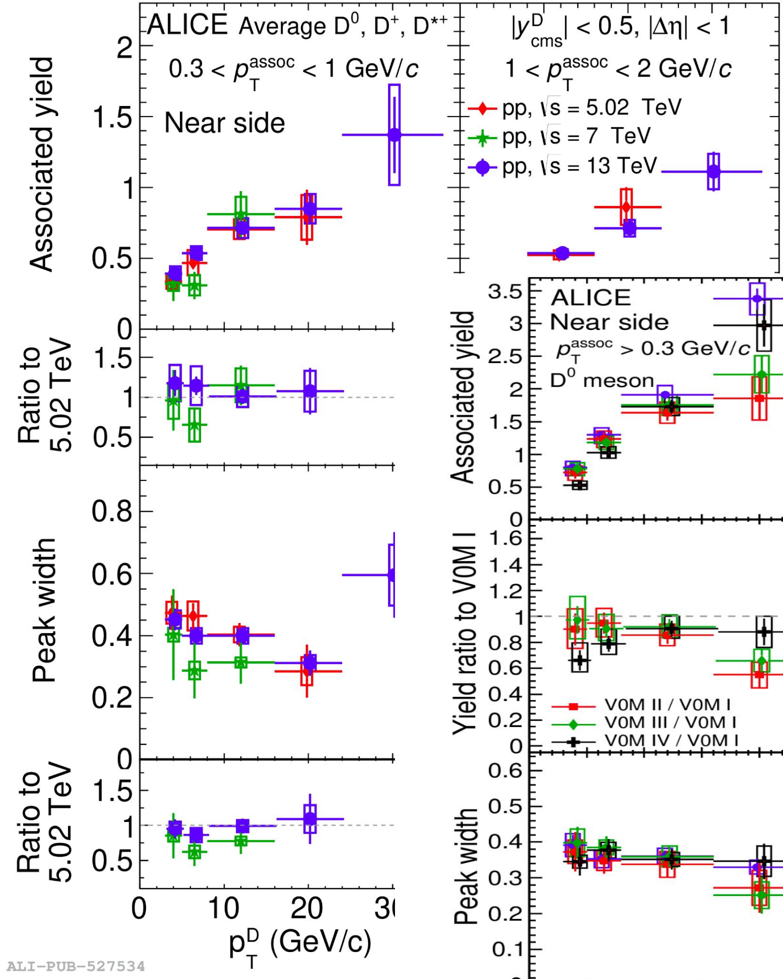
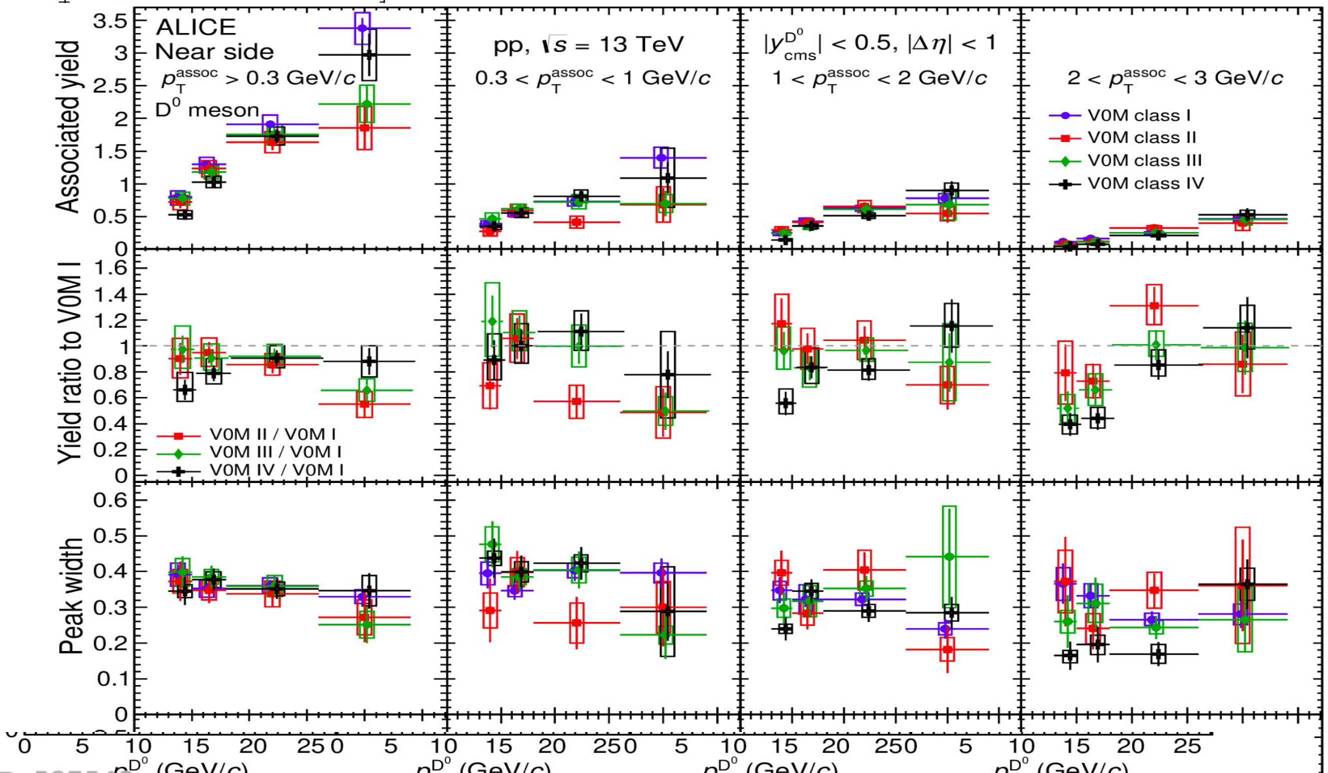
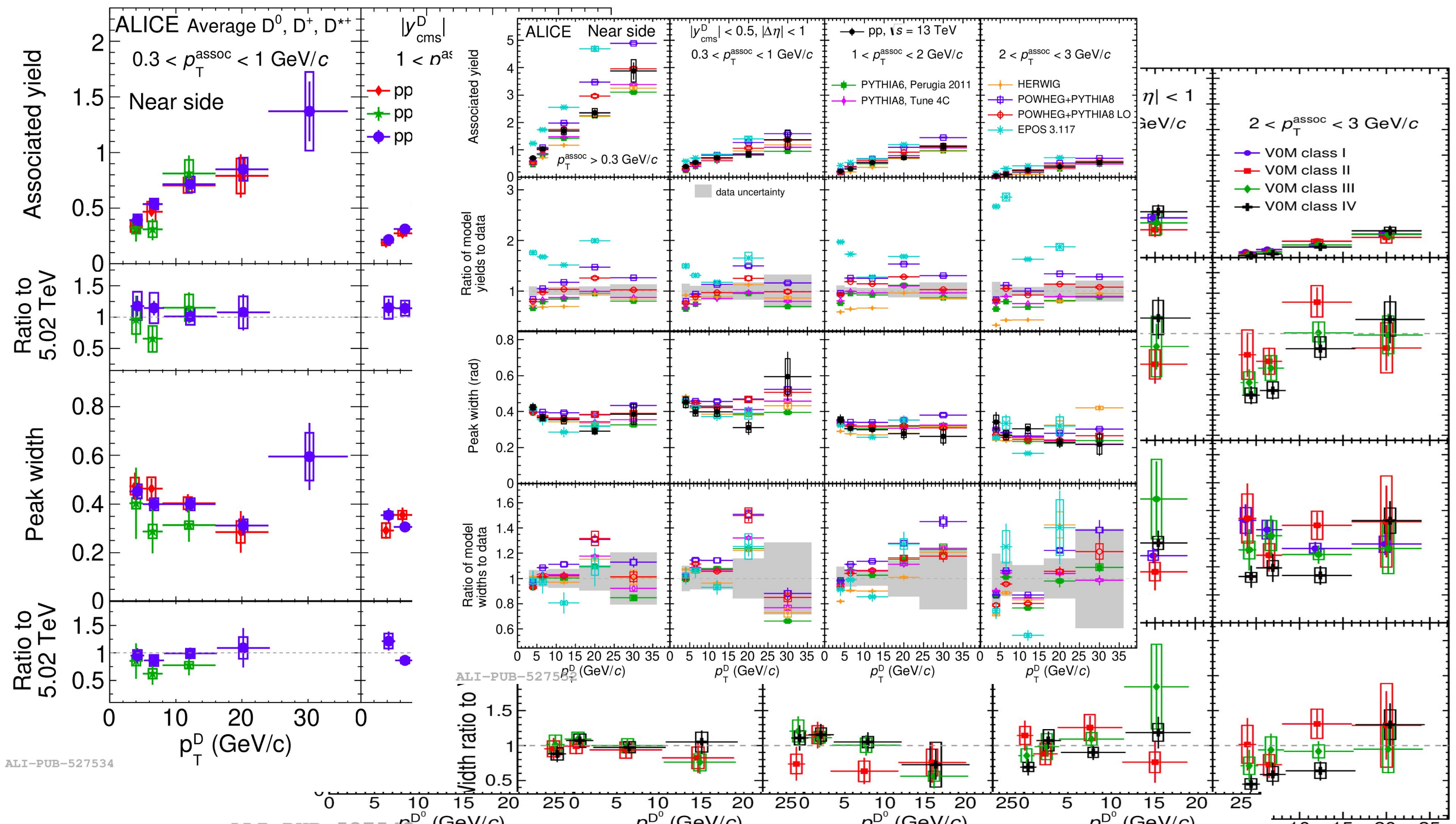
- Both the widths are underestimated by the PYTHIA8 predictions.



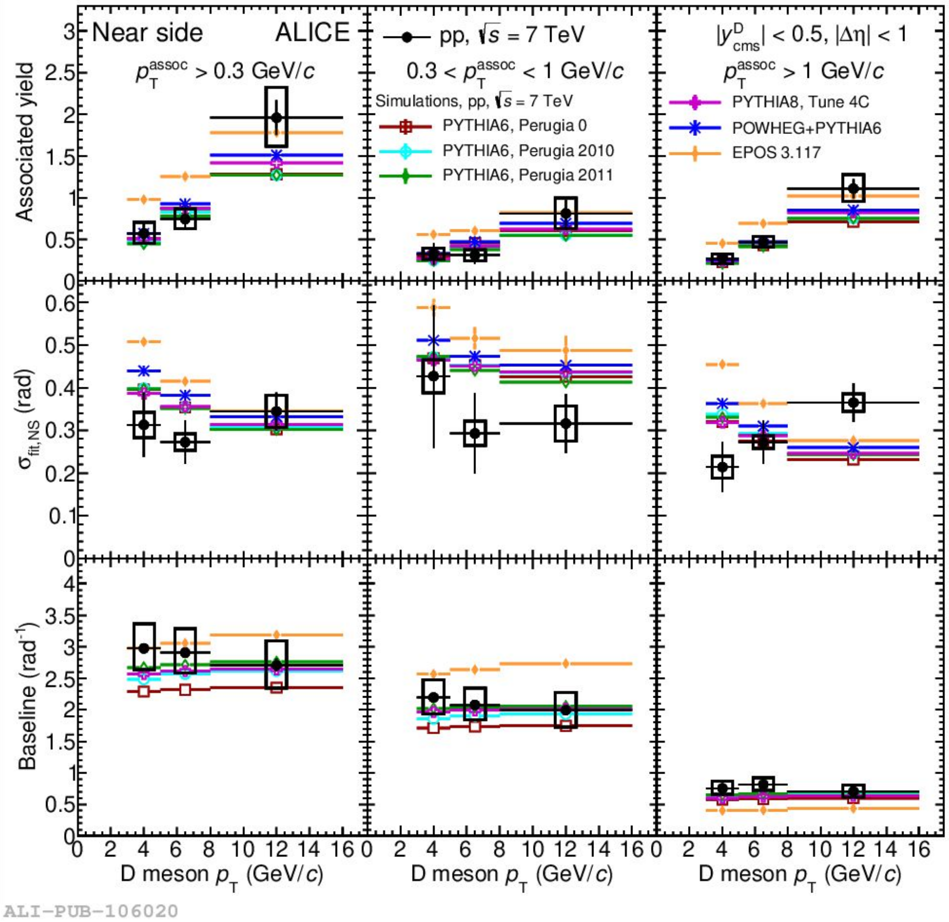



ALICE Average D^0, D$^+$, D^{*+}
$|y^{D}_{cms}| < 0.5$, $|\Delta\eta| < 1$
$0.3 < p_T^{assoc} < 1$ GeV/c
$1 < p_T^{assoc} < 2$ GeV/c
Near side
pp, $\sqrt{s}$ = 5.02 TeV
pp, $\sqrt{s}$ = 7 TeV
pp, $\sqrt{s}$ = 13 TeV
Associated yield
Ratio to 5.02 TeV
Peak width
Ratio to 5.02 TeV
p_T^D (GeV/c)
ALI-PUB-527534


ALICE
Near side
$p_T^{assoc} > 0.3$ GeV/c
D^0 meson
pp, $\sqrt{s}$ = 13 TeV
$0.3 < p_T^{assoc} < 1$ GeV/c
$|y^{D^0}_{cms}| < 0.5$, $|\Delta\eta| < 1$
$1 < p_T^{assoc} < 2$ GeV/c
$2 < p_T^{assoc} < 3$ GeV/c
V0M class I
V0M class II
V0M class III
V0M class IV
V0M II / V0M I
V0M III / V0M I
V0M IV / V0M I
Associated yield
Yield ratio to V0M I
Peak width
$p_T^{D^0}$ (GeV/c)

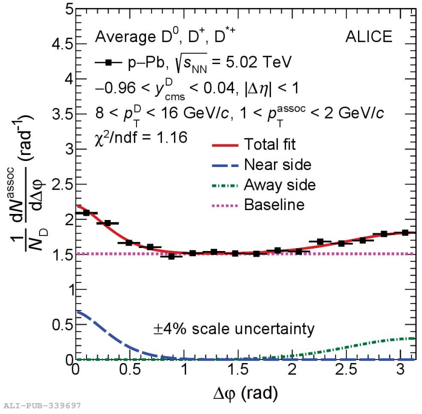

ALICE Average D^0, D$^+$, D^{*+}
0.3 < p_T^{assoc} < 1 GeV/c
Near side
Associated yield
Ratio to 5.02 TeV
Peak width
p_T^D (GeV/c)
ALI-PUB-527534
ALICE Near side
$|y^D_{cms}|$ < 0.5, $|\Delta\eta|$ < 1
pp, $\sqrt{s}$ = 13 TeV
p_T^{assoc} > 0.3 GeV/c
0.3 < p_T^{assoc} < 1 GeV/c
1 < p_T^{assoc} < 2 GeV/c
2 < p_T^{assoc} < 3 GeV/c
PYTHIA6, Perugia 2011
PYTHIA8, Tune 4C
HERWIG
POWHEG+PYTHIA8
POWHEG+PYTHIA8 LO
EPOS 3.117
data uncertainty
Ratio of model yields to data
Peak width (rad)
Ratio of model widths to data
p_T^D (GeV/c)
ALI-PUB-527552
2 < p_T^{assoc} < 3 GeV/c
V0M class I
V0M class II
V0M class III
V0M class IV
Width ratio to
$p_T^{D^0}$ (GeV/c)

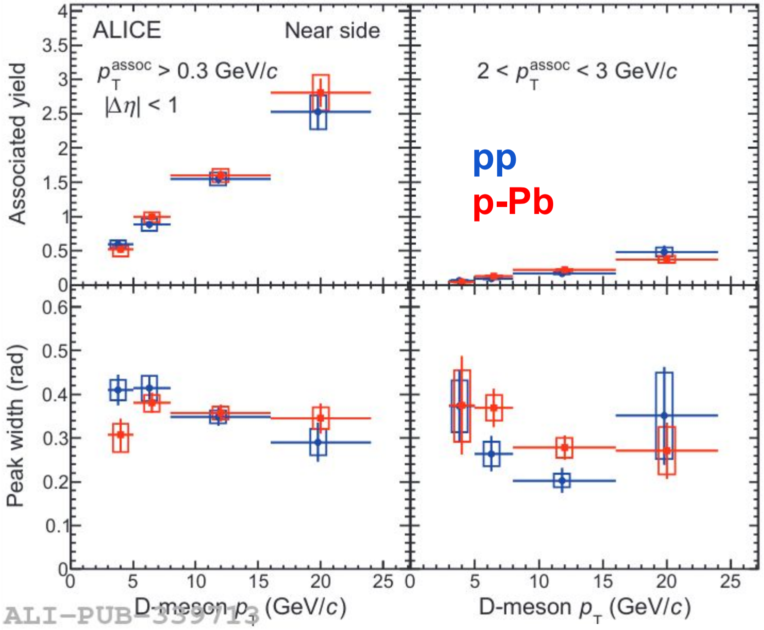
Near-side observables and baseline in pp collisions at 7 TeV



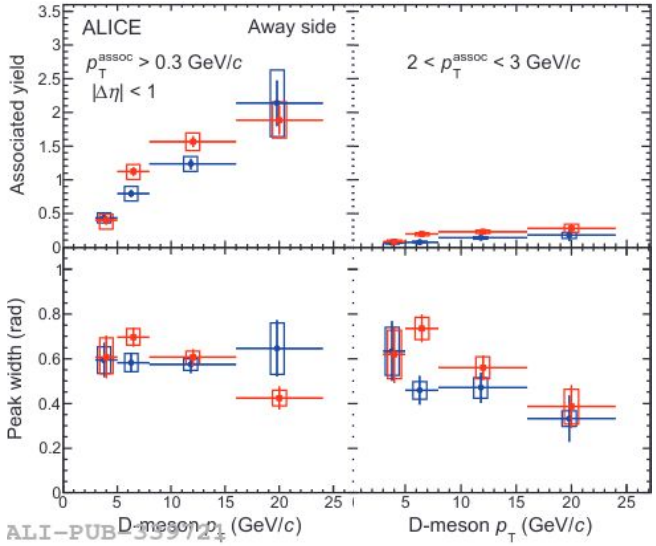
[EPJC 77 (2017) 245]

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)

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

EPJC 80 (2020) 979

D-meson and charged particle azimuthal correlation

Comparison among partonic processes with PYTHIA8 and POWHEG+PYTHIA8