Heavy-flavour correlations with charged particles and collective effects in small systems with ALICE at the LHC

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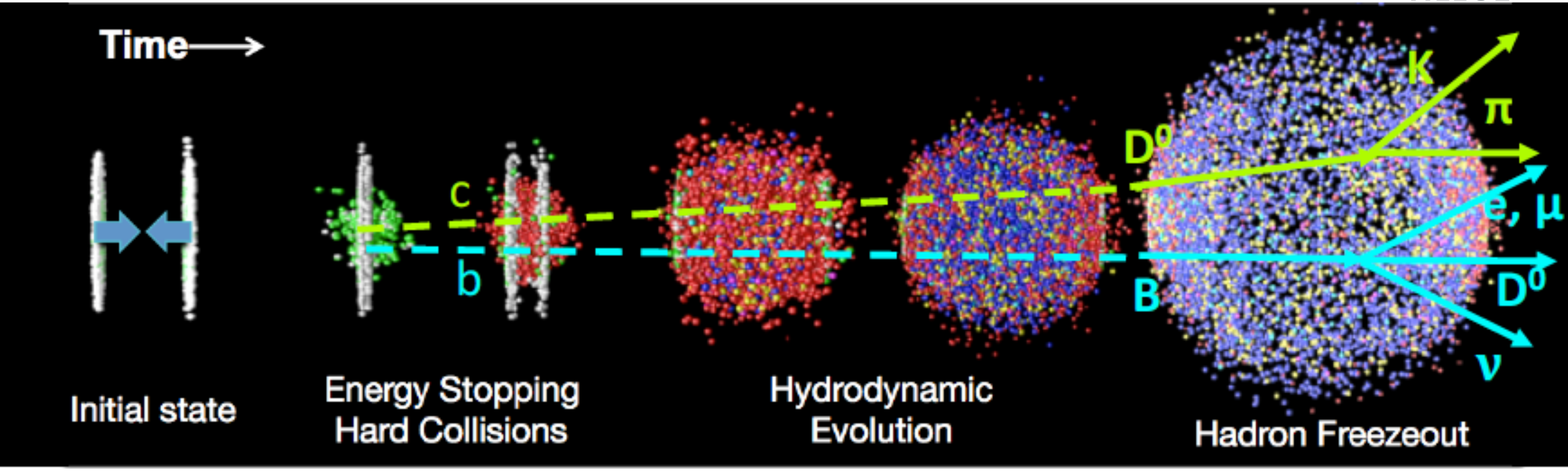
Hard-soft correlations in hadronic collisions GDR-QCD

23-25 July 2018

Motivations



- Heavy quarks (charm and beauty) are produced in hard scattering processes taking place in the initial stages of the heavy-ion collision
  - They experience the full evolution of the Quark-Gluon Plasma, a state of matter of deconfined quarks and gluons, formed in ultra-relativistic heavy-ion collisions

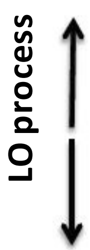
- In the heavy-flavour sector, ALICE has observed:
  - Positive **elliptic flow** (v_2) for D mesons in semi-central collisions
  - Significant **suppression** of D-meson production in central Pb-Pb collisions

Angular correlations with HF signals: introduction

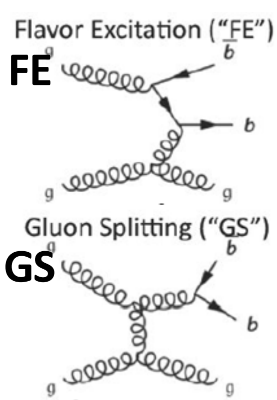
From heavy-quark production to final state

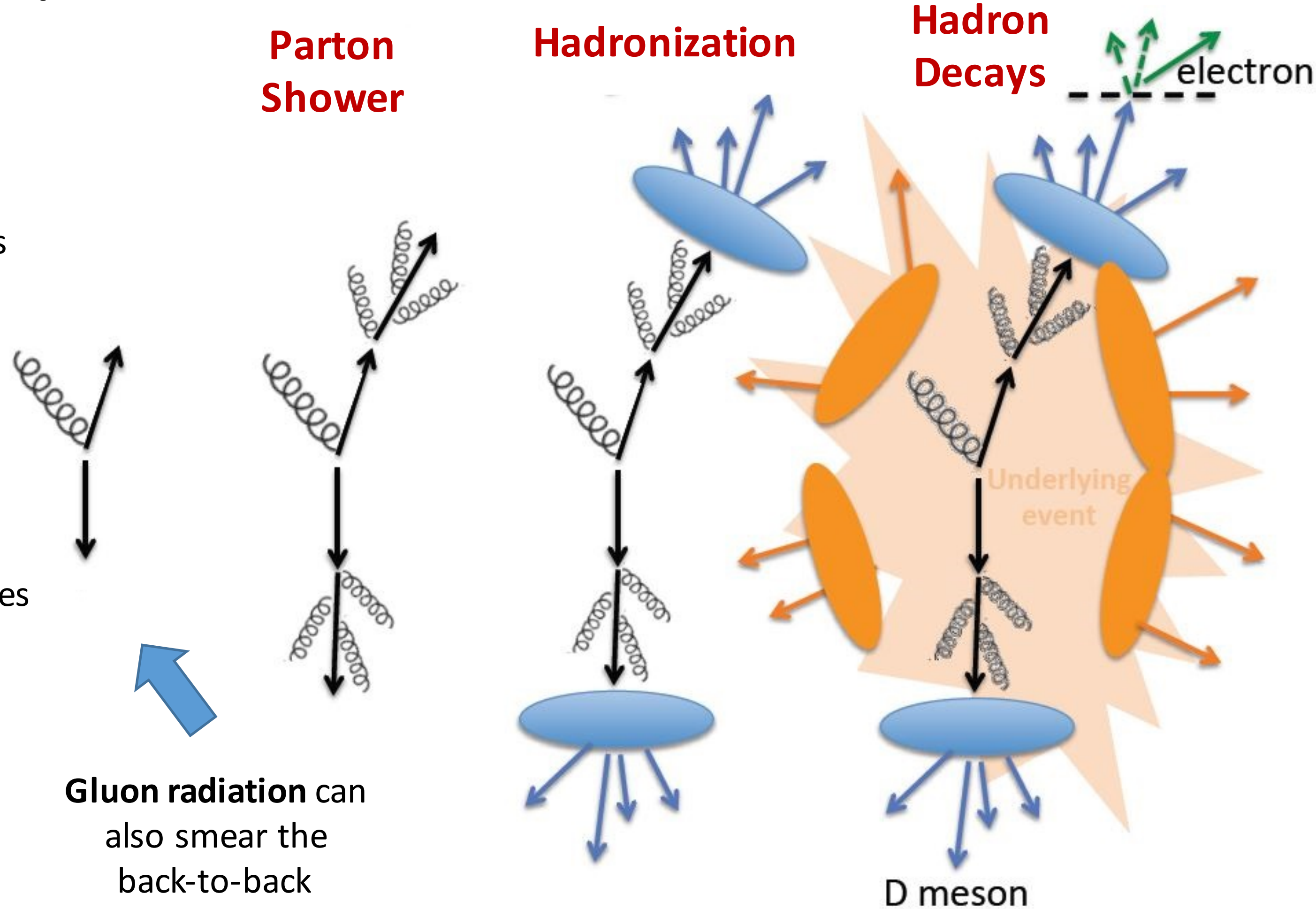
Hard Scattering | **Parton Shower** | **Hadronization** | **Hadron Decays**

N.B. heavy-quark production not always back-to-back…



…due to NLO processes



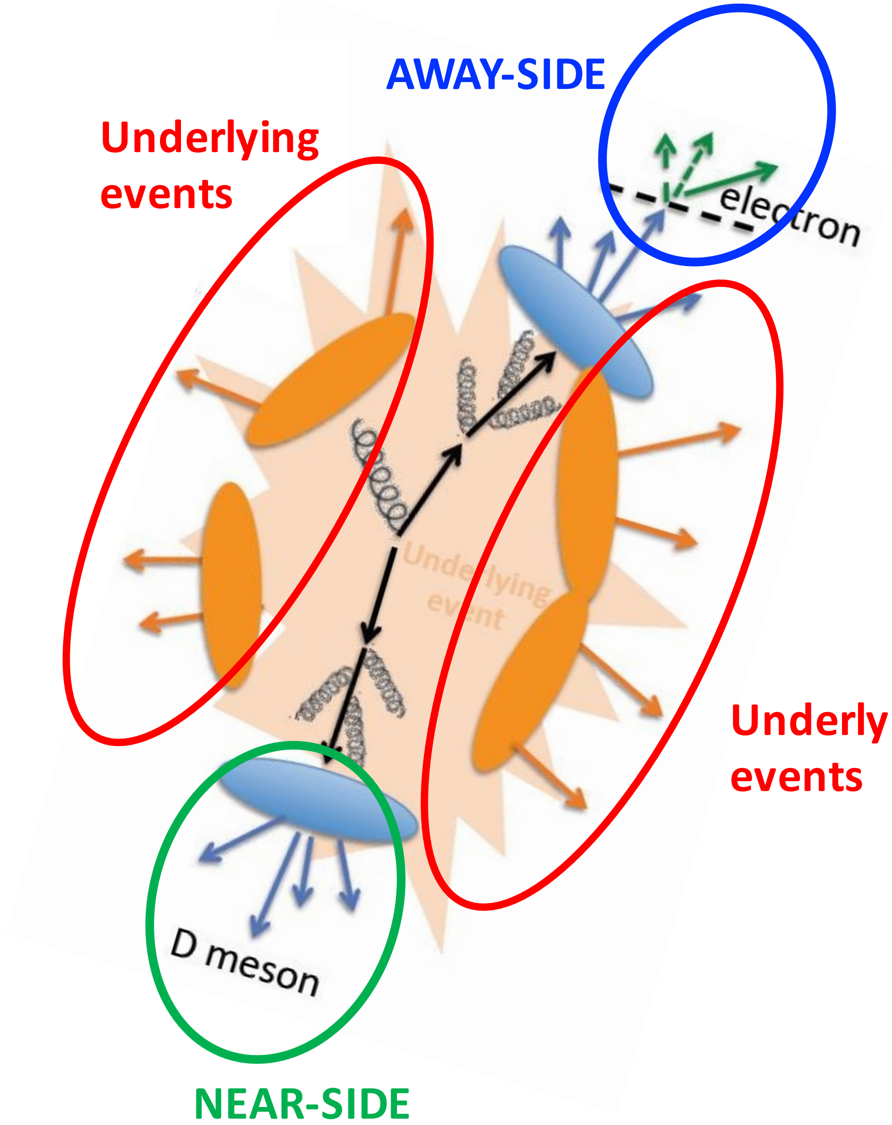


Gluon radiation can also smear the back-to-back structure of HF jets in final state

This is in vacuum. In Pb-Pb, additional effects by the QGP medium!

Angular correlations with HF signals: introduction

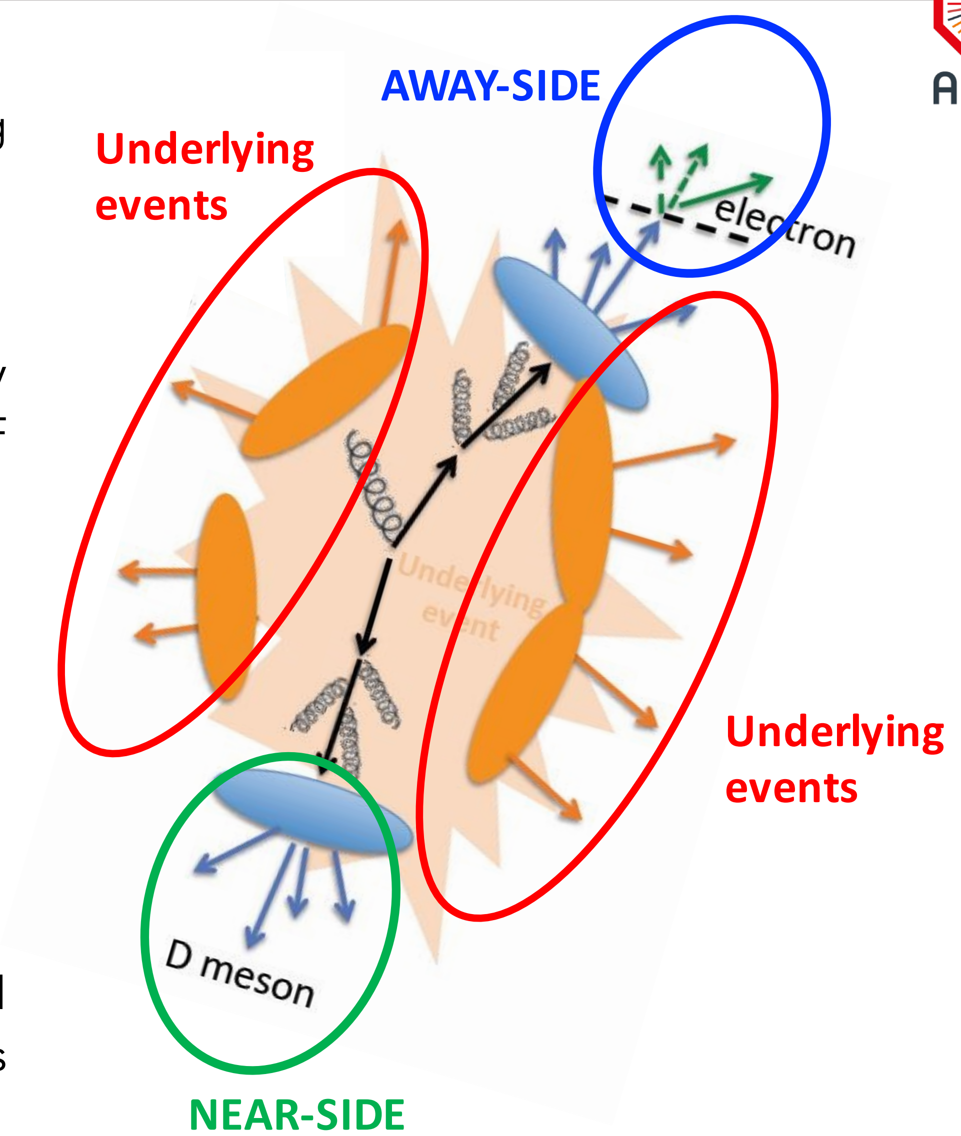
- Interesting regions for HF correlation studies:
  - Near side ($\Delta\varphi=0$) → particles from jet containing the trigger
  - Away side ($\Delta\varphi=\pi$) → particles from fragmentation of the other HF jet
  - Transverse region → Underlying event tracks (flat in $\Delta\phi$)



Angular correlations with HF signals: introduction

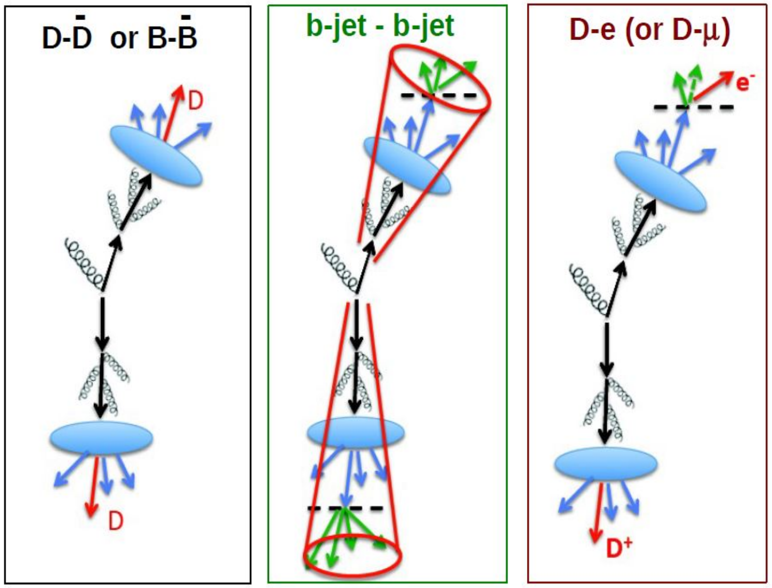
- Further insight on HF studying **HF Correlations** (vs $\Delta\varphi, \Delta\eta$)

- Access to complementary information w.r.t. "standard" HF observables:
  - HQ production mechanisms
  - HQ fragmentation and jets
  - Fragmentation/production modification in p-Pb, Pb-Pb
  - HQ elliptic flow in small systems via correlations with hadrons

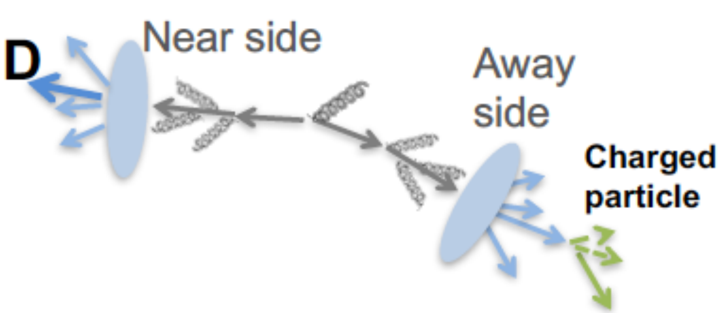


Possible observables

- Observables directly tracking $Q\bar{Q}$ azimuthal correlations (**$D\bar{D}$, $B\bar{B}$, b jet-b jet, HFe-HFe , B/D – HFe/μ**)
  - Huge statistics is needed
  - Challenging, will be studied after detector upgrade (LS2)



- Observables including the underlying event, also sensitive to fragmentation, intra-jet properties (**D-hadron, HF (e/μ)-hadron**)
  - Access to $Q\bar{Q}$ angular correlations is more indirect and "washed out"
  - Less demanding in terms of statistics

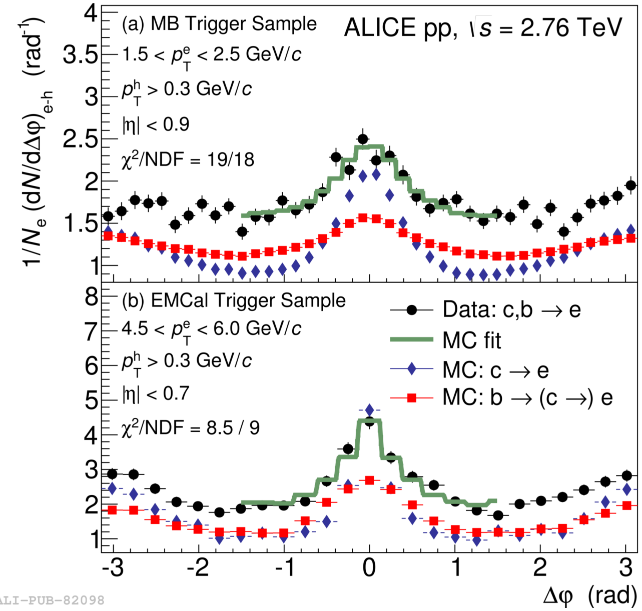


HF correlation with charged particles: motivation

pp Collisions

- Investigate heavy-flavour quark fragmentation properties and characterize heavy-flavour jets:
  - Angular opening of the jet
  - Multiplicity of particles
  - Momentum distribution inside the jet

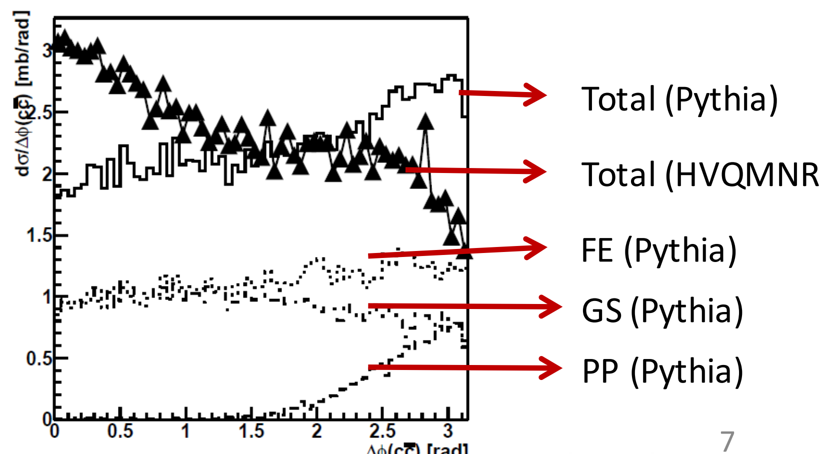
  all differentially in p_T of trigger and associated particles



- Sensitivity to **LO** and **NLO** heavy-quark production processes?

- Extract relative fraction of electrons from charm and beauty decays triggering on heavy-flavour hadron decay electrons (HFe)

- Reference for p-Pb and Pb-Pb results



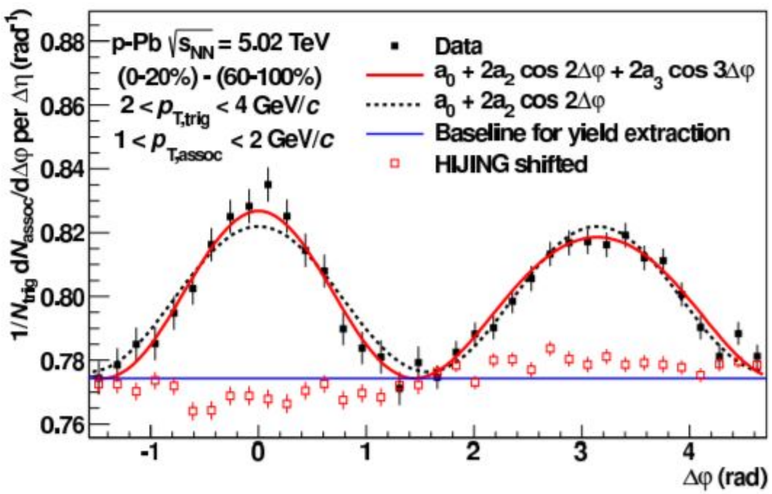
Sjostrand et al., Comput.Phys.Commun. 135 (2001) 238

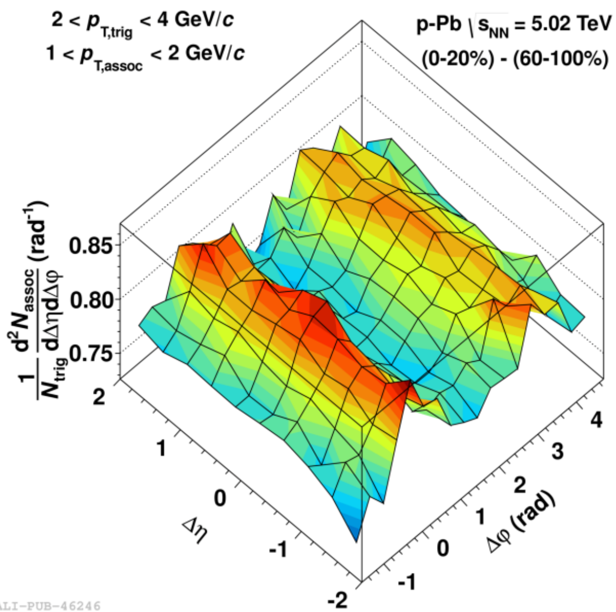
HF correlation with charged particles: motivation

p-Pb Collisions

- Investigate possible modifications of angular correlations which could derive from initial-state effects (e.g. CGC) or possible final-state effects (e.g. hydrodynamics)

- Search for long-range ridge-like structures (double ridge), observed in di-hadron correlations, also in the heavy-flavour sector
  - charm/beauty elliptic flow in p-Pb collisions?





ALICE
PLB 719 (2013) 29

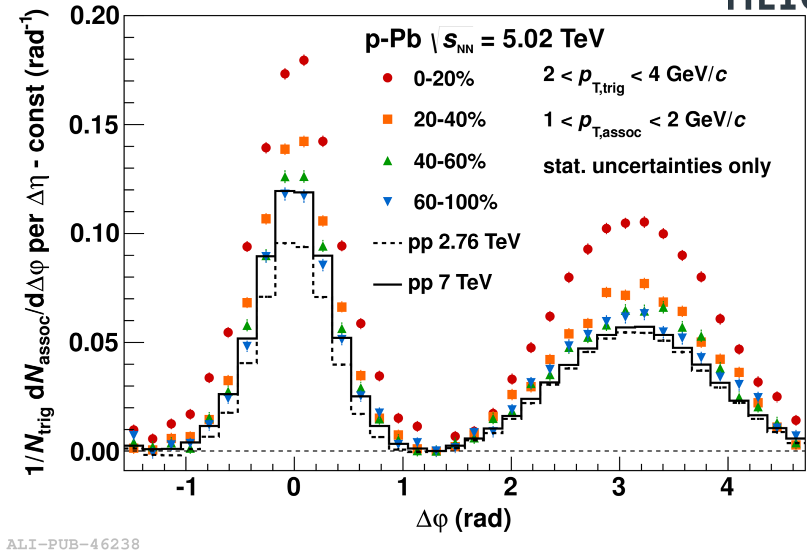
h-h correlations in p-Pb collisions (High-mult events – Low-mult events)

HF correlation with charged particles: motivation

p-Pb Collisions

- In di-hadron correlations the per-trigger yield in $\Delta\varphi$ on the near-side and on the away side are similar for low-multiplicity p-Pb collisions and pp collisions and increase with increasing multiplicity in p-Pb collisions.

- v_2 and v_3 in qualitative agreement with the hydrodynamical model calculation (*arXiv:1211.0845*)



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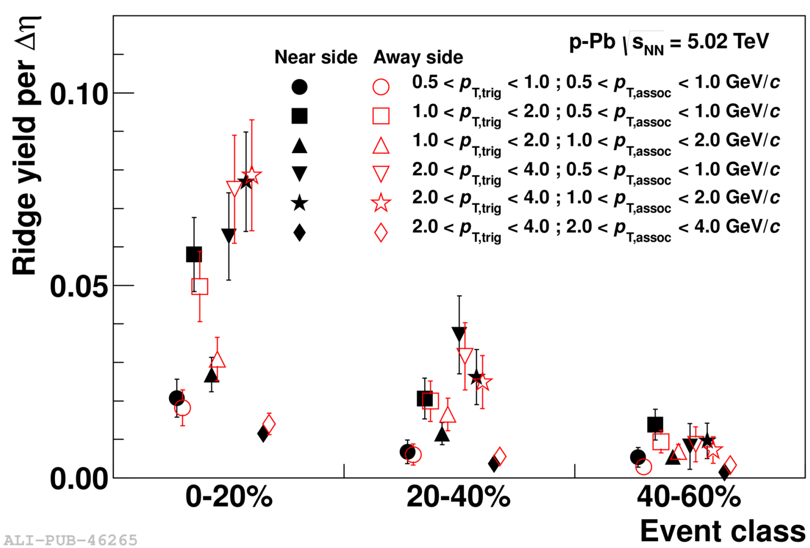
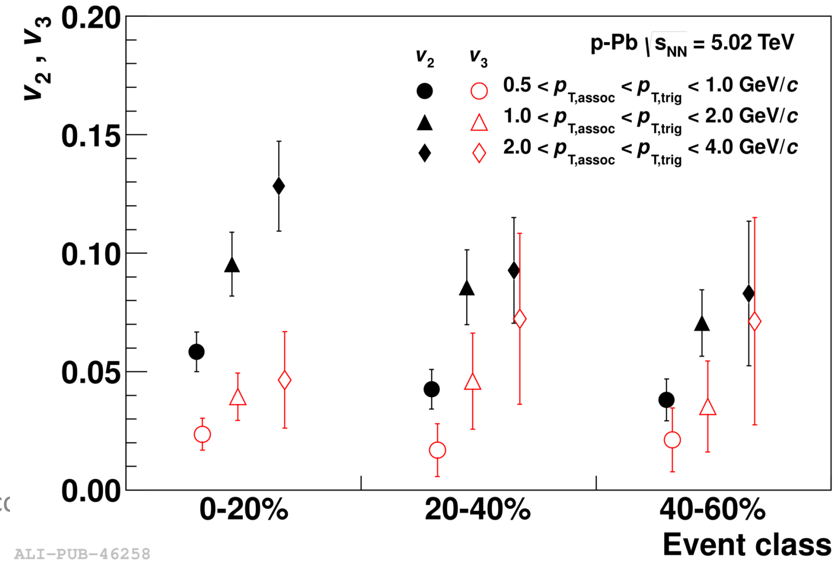




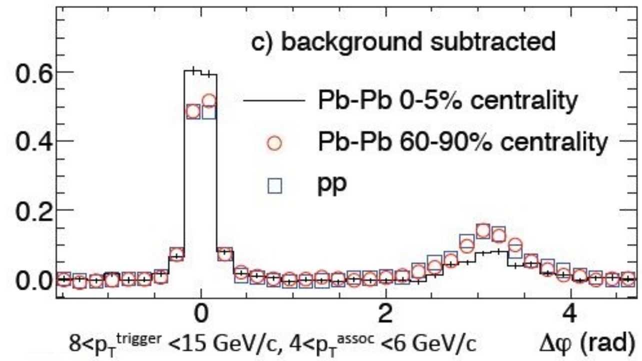
HF correlation with charged particles: motivation

Pb-Pb Collisions

- Probe the QGP effects on heavy quarks by studying how correlation distributions of heavy-flavour particles are modified w.r.t. vacuum
  - **Near side** → modification of parton fragmentation function in QCD medium
  - **Away-side** → path-length dependence of in-medium energy loss
- Disentangle **radiative** and **collisional** parton energy loss in QGP medium

h-h correlations

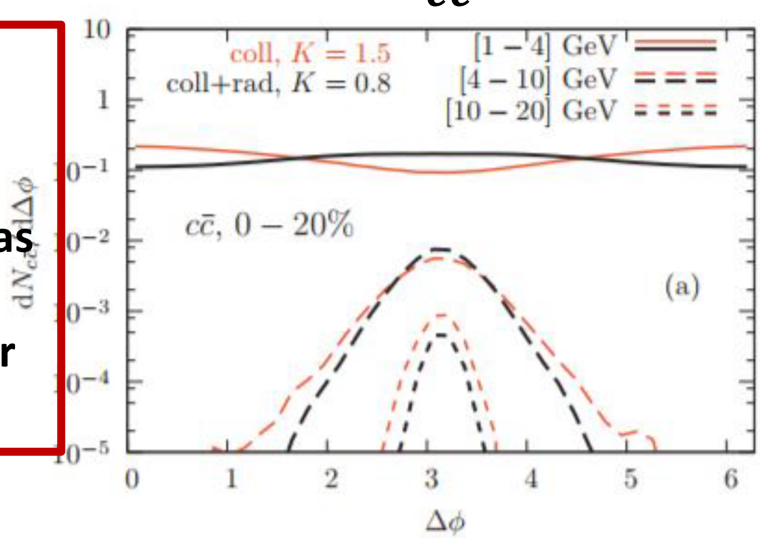
ALICE PRL 108 (2012) 092301



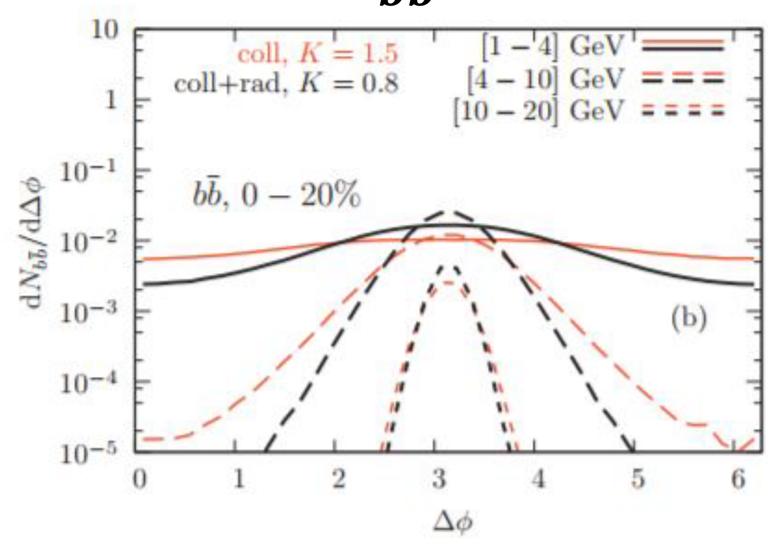
Phys. Rev. C 90 (2014) 024907

Back-to-back ($\Delta\varphi = \pi$) $Q\bar{Q}$ initial distribution, as expected at Leading Order in QCD

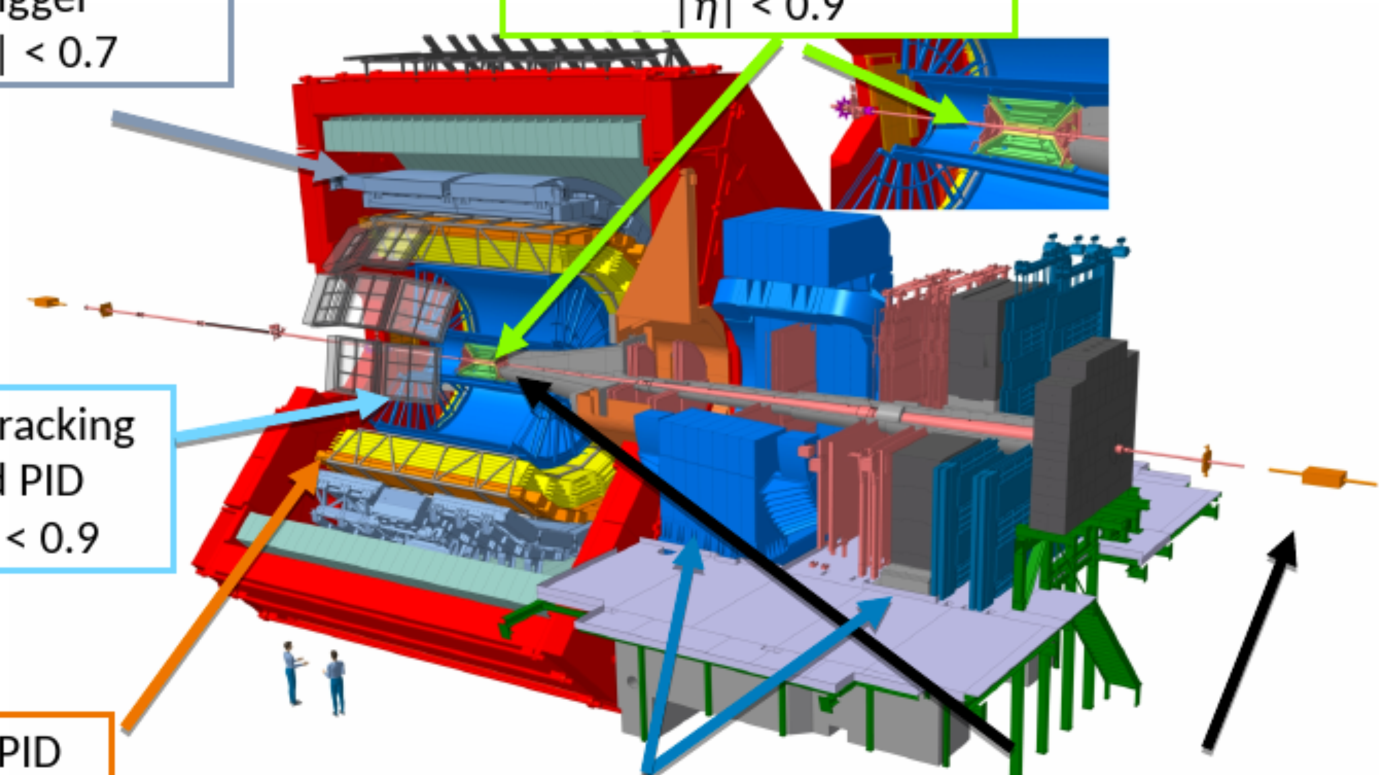
$c\bar{c}$



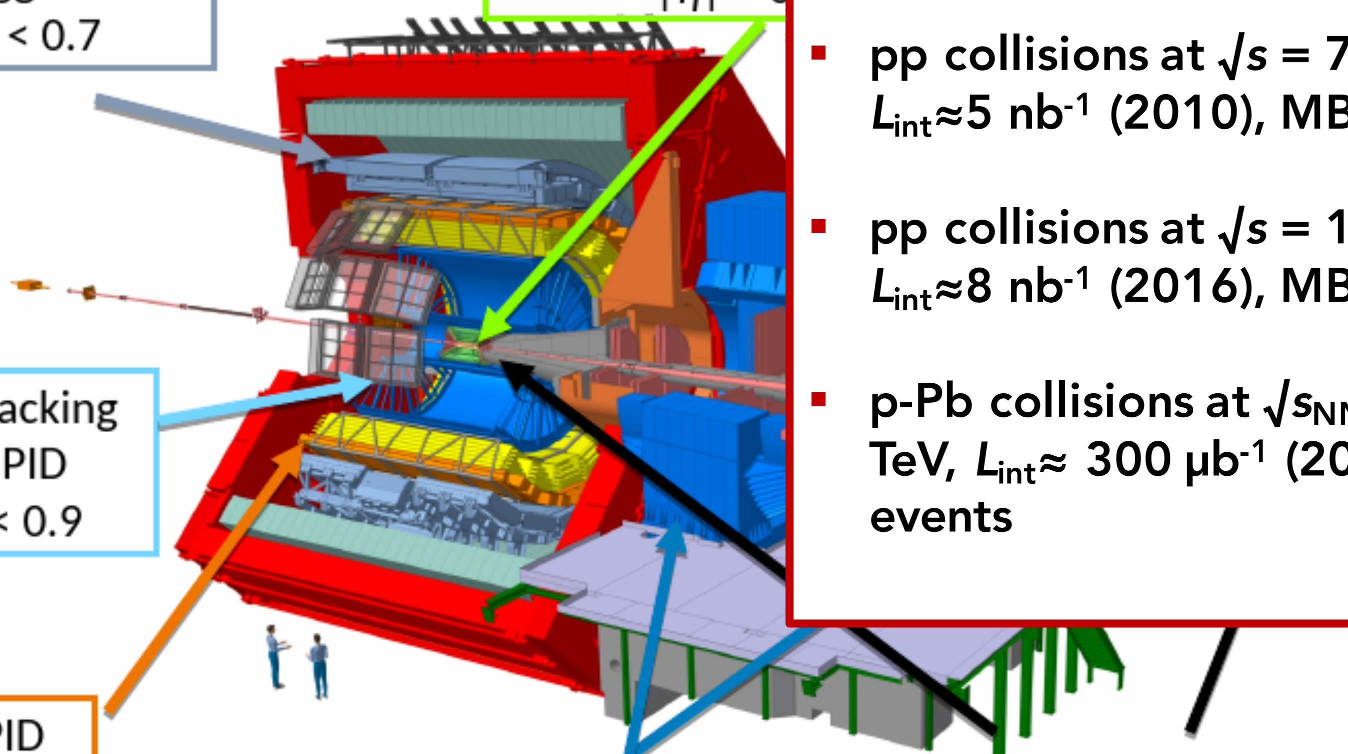
$b\bar{b}$



ALICE central barrel detector



ALICE central barrel detector



DATA SAMPLES:

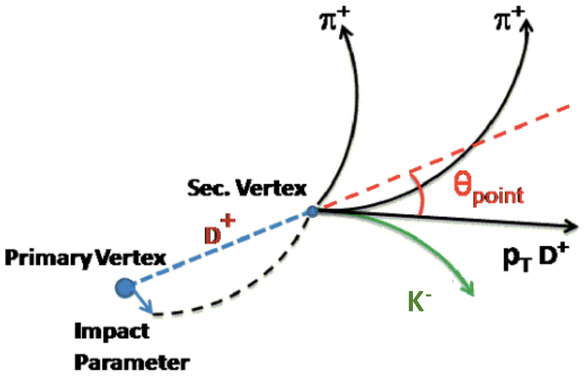
- **pp collisions at $\sqrt{s}$ = 7 TeV, L_{int}≈5 nb^{-1} (2010), MB events**
- **pp collisions at $\sqrt{s}$ = 13 TeV, L_{int}≈8 nb^{-1} (2016), MB events**
- **p-Pb collisions at $\sqrt{s_{NN}}$ = 5.02 TeV, L_{int}≈ 300 μb^{-1} (2016), MB events**

D-h angular correlations

D-h analysis strategy

- ALICE can identify D mesons using fully reconstructed hadronic decays
- D-meson signal extracted from invariant mass distributions

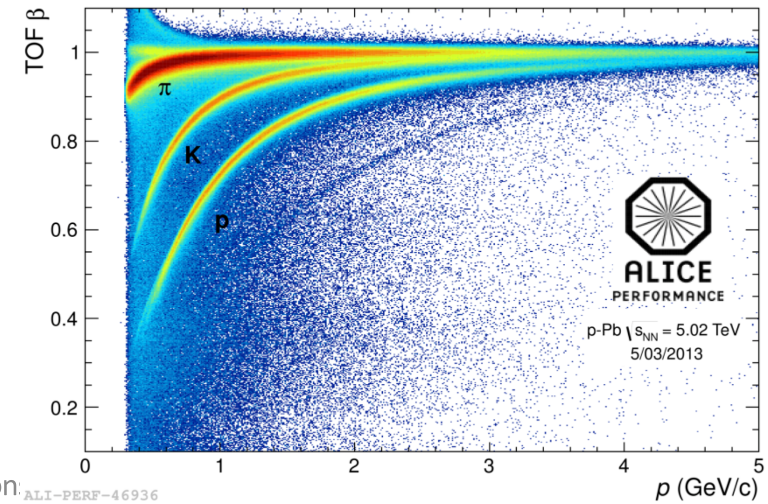
$D^0 \rightarrow K^- \pi^+$ (B.R. 3,93%)
$D^{*+} \rightarrow D^0 \pi^+$ ($D^0 \rightarrow K^- \pi^+$) (B.R. 67,7%*3,93%)
$D^+ \rightarrow K^- \pi^+ \pi^+$ (B.R. 9,46%)



- D-meson candidates selected by exploiting:
  - Topology of the decay, displacement of secondary vertex
  - Particle identification (π, K) using TPC and TOF response

- Selected D mesons (including background) → «trigger» particles for building the angular correlation distribution in 2d ($\Delta\varphi$,$\Delta\eta$)

- «Associated» particles correlated with D mesons selected via track-quality cuts for $p_T >$ 0.3 GeV/c, $|\eta| < 0.8$

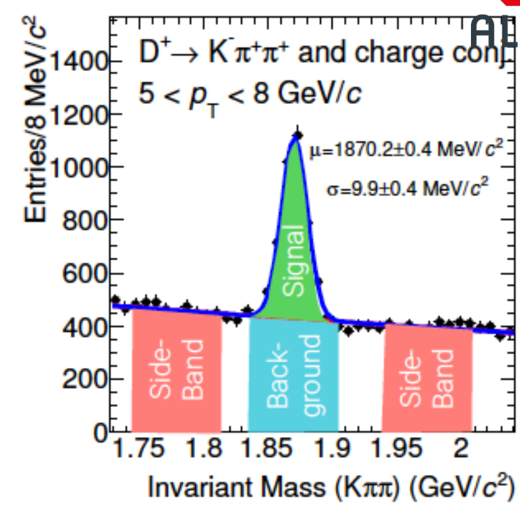


D-h analysis strategy

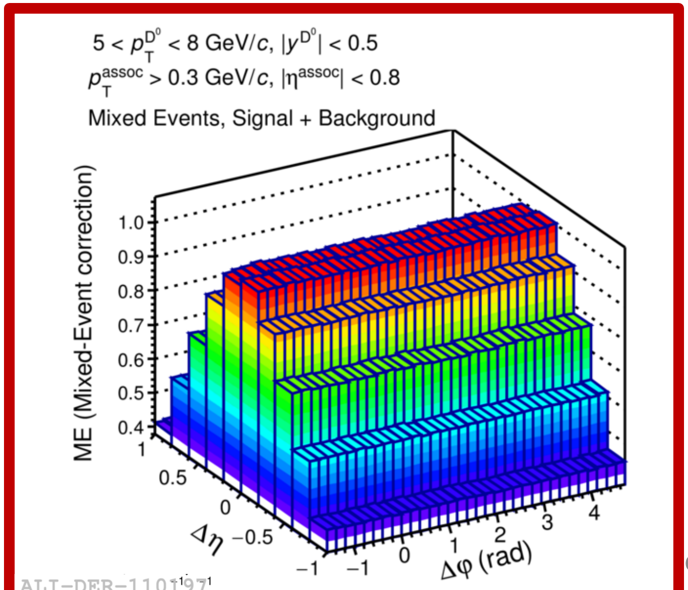
- Sideband subtraction → Removal of correlation contribution from background D-meson candidates

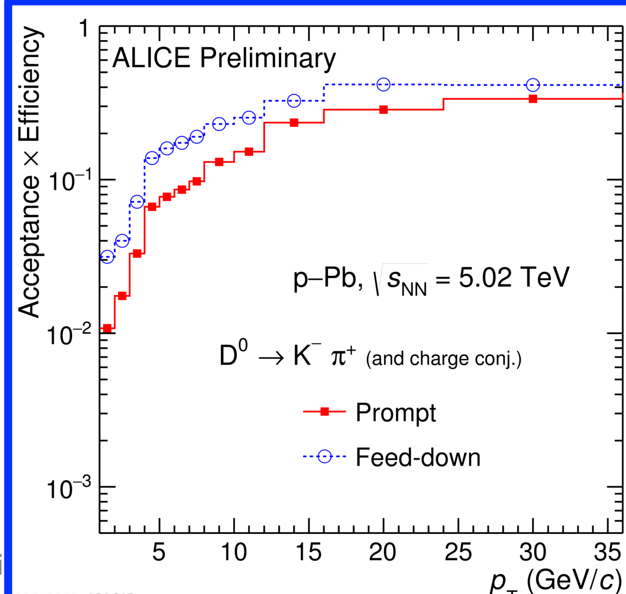
- Event Mixing → Correction for limited detector acceptance and detector spatial inhomogeneities

- Efficiency correction for D-meson and associated track reconstruction



Run 1 Results: Eur. Phys. J. C 77 (2017) 245





D-h analysis strategy

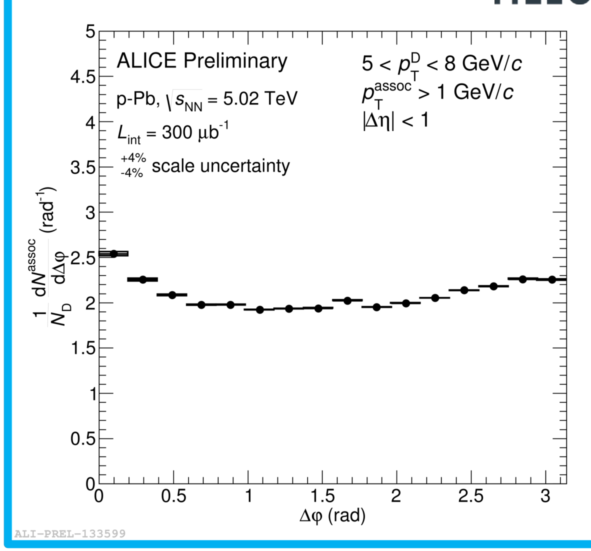
- **B→D feed-down** contribution → subtracted exploiting templates of angular correlation distribution of B→D mesons (**FONLL**)

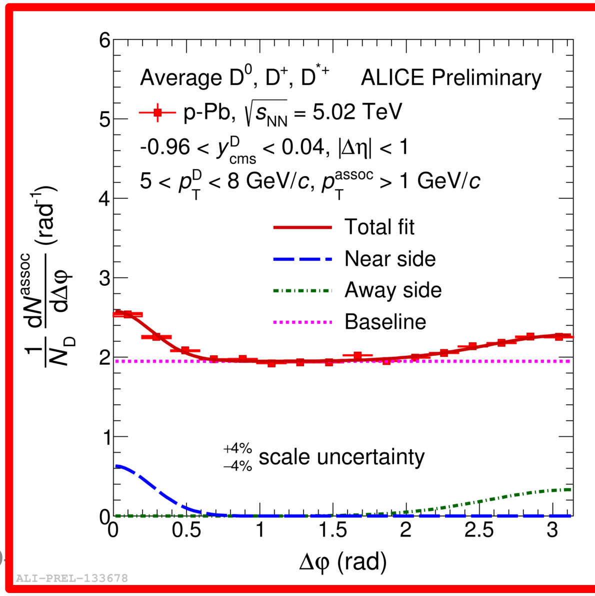
- **Purity estimation** → Removal of secondary tracks residual contamination

- Weighted average of D-meson species correlation distributions

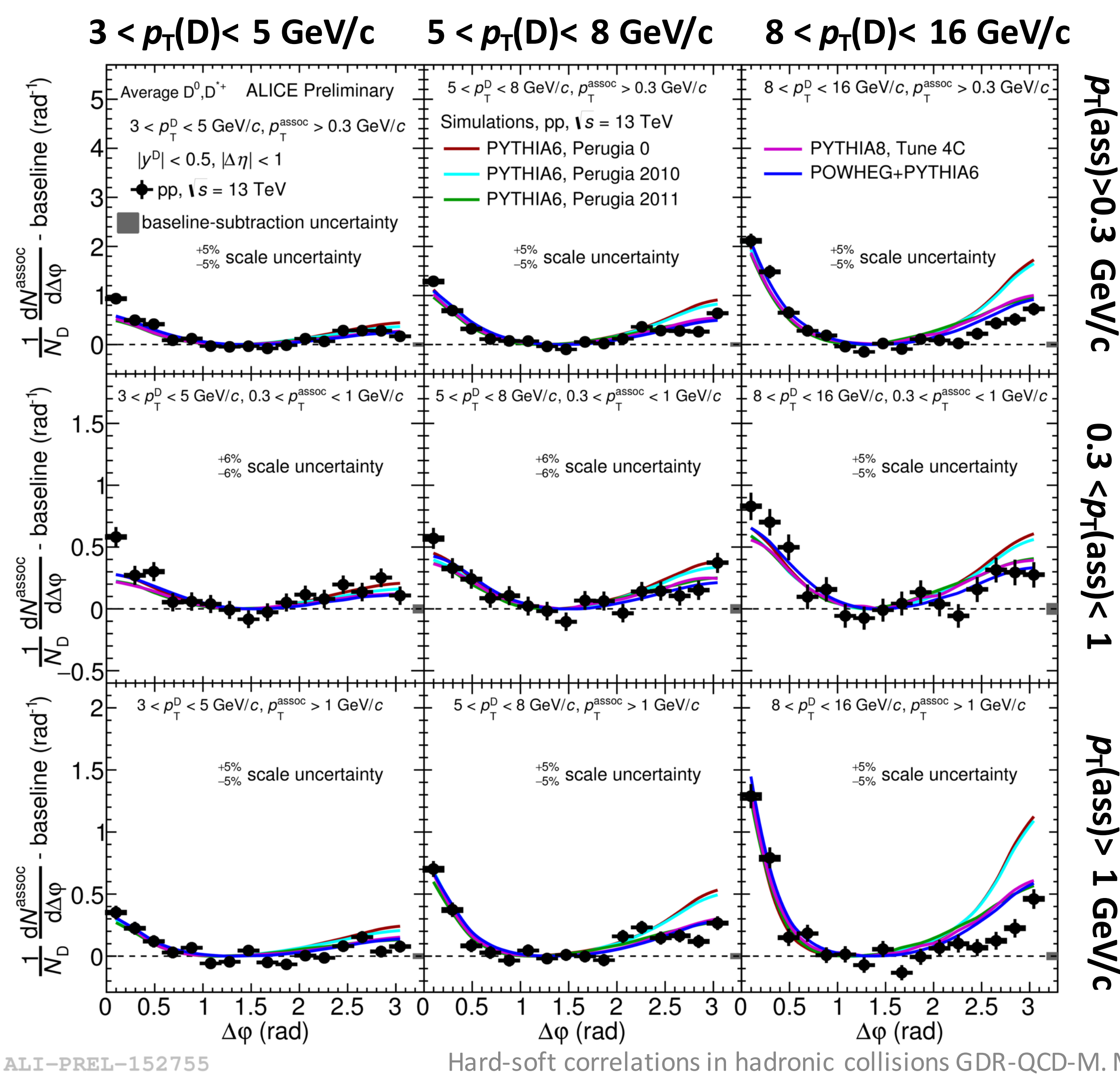
- Fit to correlation distributions to extract quantitative observables (near- and away-side peak yields and widths, baseline height)

$$f(\Delta\phi) = c + \frac{Y_{NS}}{\sqrt{2\pi}\sigma_{NS}} e^{\frac{(\Delta\phi - \mu_{NS})^2}{2\sigma_{NS}^2}} + \frac{Y_{AS}}{\sqrt{2\pi}\sigma_{AS}} e^{\frac{(\Delta\phi - \mu_{AS})^2}{2\sigma_{AS}^2}}$$



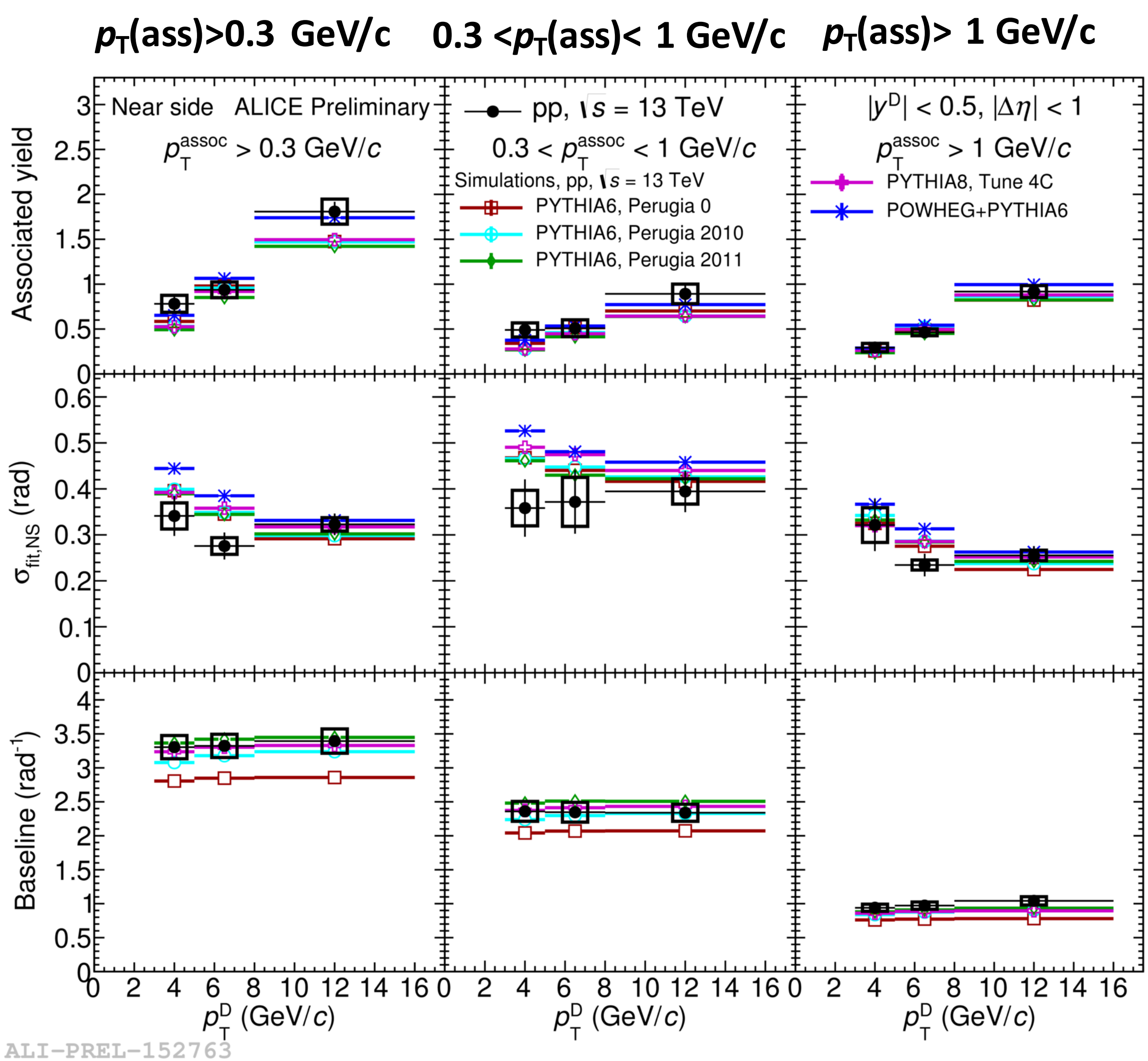


D-h correlations: pp@13 TeV vs. models



- **Comparison with models after baseline subtraction on the average distributions of D⁰ and D* mesons**
- **Models describe qualitatively data:** charm fragmentation in jets fairly described
- Away-side data could set contraints on models and contribution of different HF production processes
- Good observable for investigating possible medium modification to charm jets

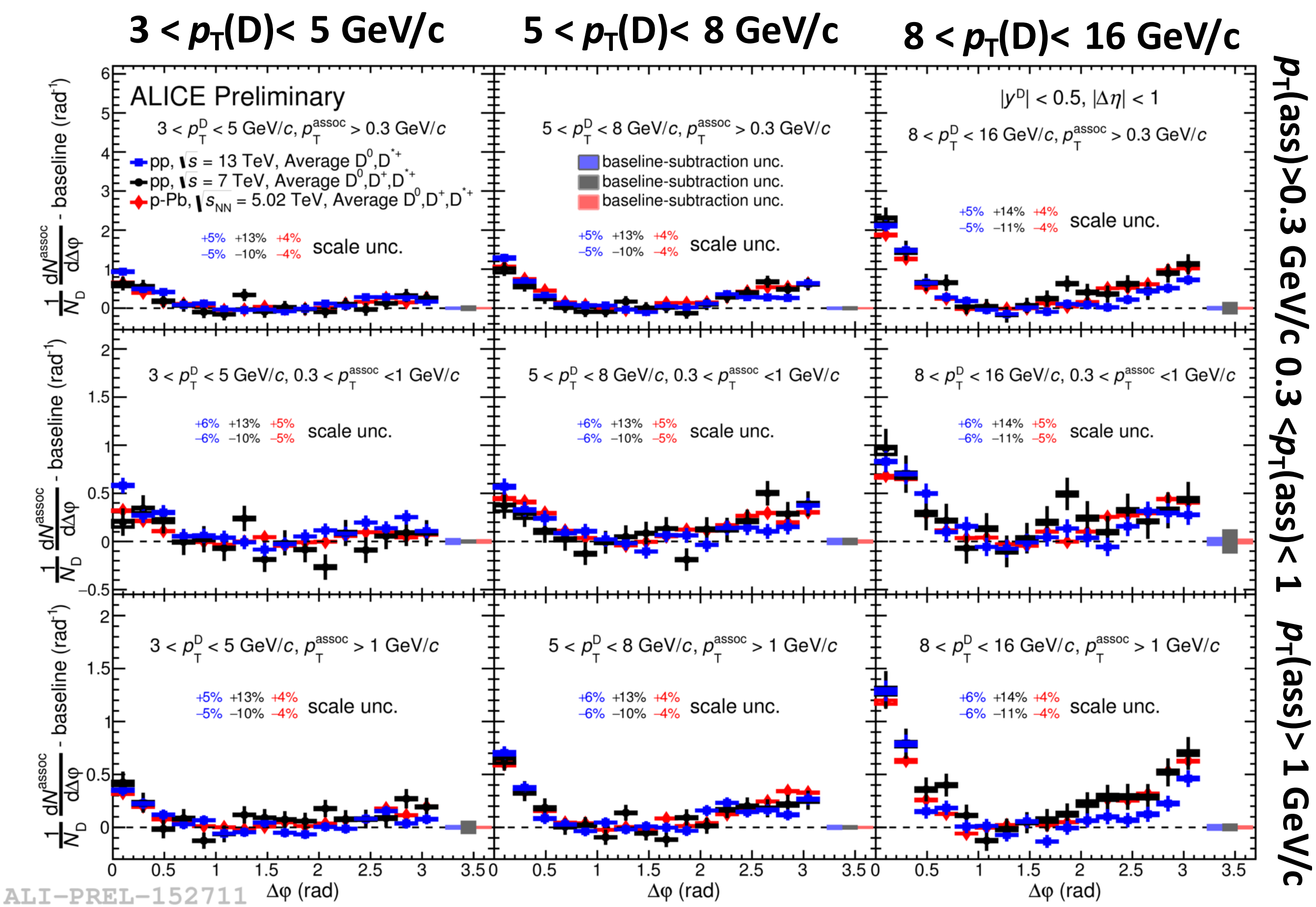
D-h correlations: pp@13 TeV vs. models



- POWHEG+PYTHIA tends to generally predict larger associated yields and broader peaks than PYTHIA
- **Data yields** seem to be described better with POWHEG predictions
- Precision still not enough to have firm conclusions about the **peak widths**
- Apart for Perugia-0 tune all the models catch well the **baseline** values and trend with current uncertainties

D-h correlations: pp and p-Pb

Superimposed correlation distributions in **pp at $\sqrt{s}$=7, 13TeV** and centrality integrated **p-Pb collisions at $\sqrt{s_{NN}}$= 5.02 TeV**

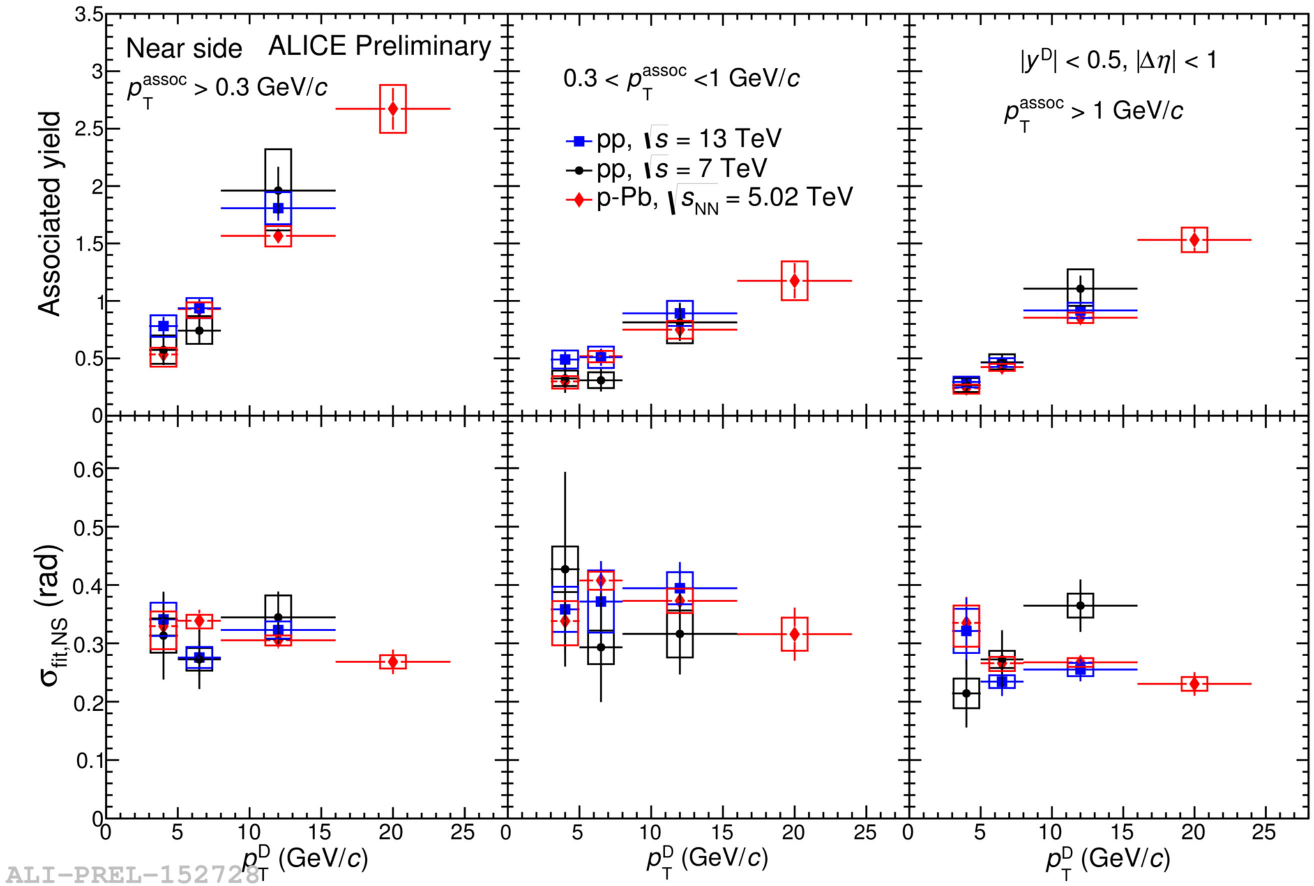


- **Similar behaviour of the correlation distributions** between the three energies and collision systems
- No evidence of CNM effects in p-Pb collisions

D-h correlations: pp and p-Pb

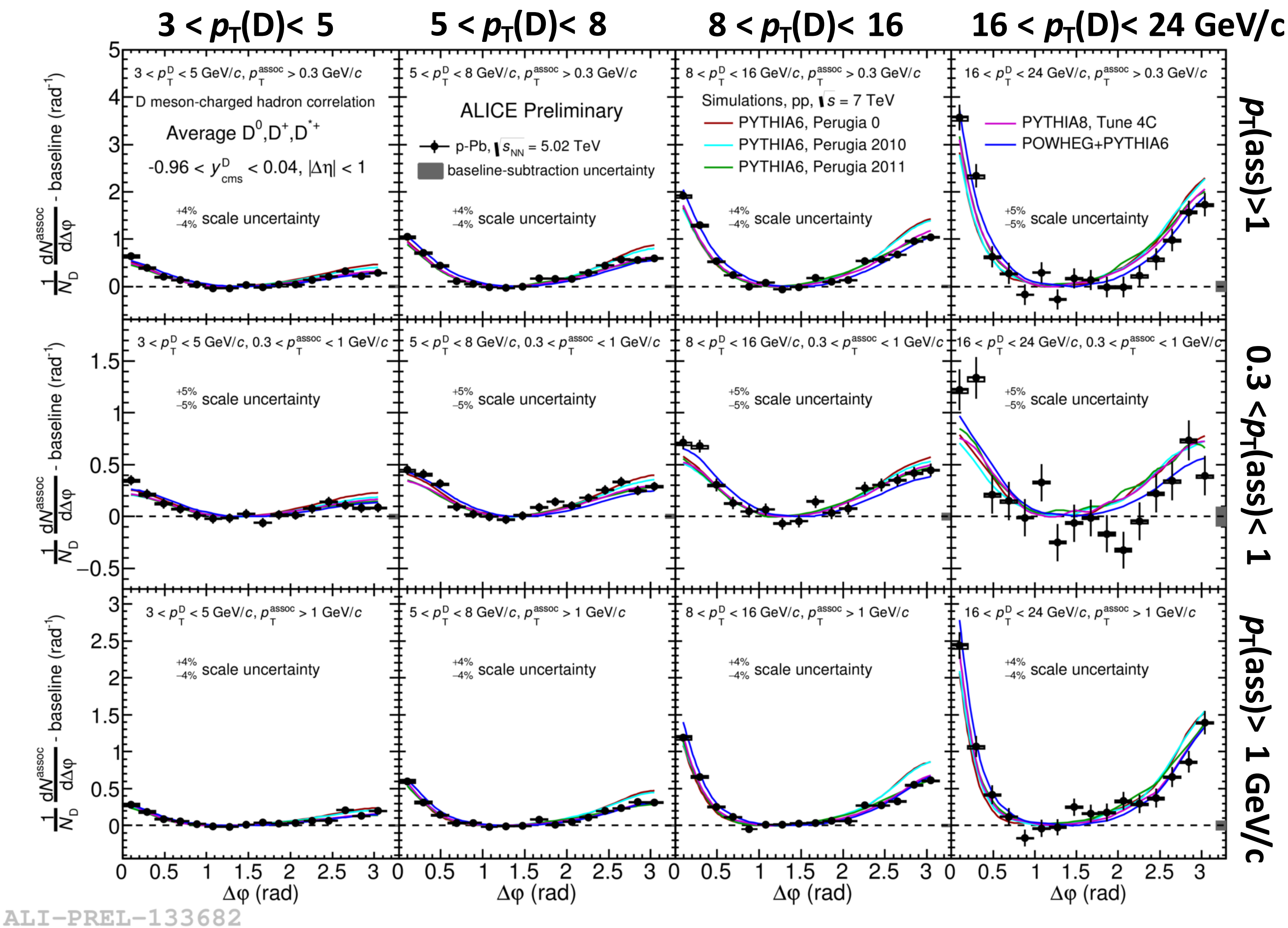
Comparison of the near-side yields and widths in **pp at $\sqrt{s}$=7, 13TeV** and centrality integrated **p-Pb collisions at $\sqrt{s_{NN}}$= 5.02 TeV**

p_T(ass)>0.3 GeV/c **0.3 <p_T(ass)< 1 GeV/c** **p_T(ass)> 1 GeV/c**



- **Compatible near-side peak properties** between the three energies and collision systems
- No evidence of modification due to initial-state or final-state effects in p-Pb collisions, within uncertainties

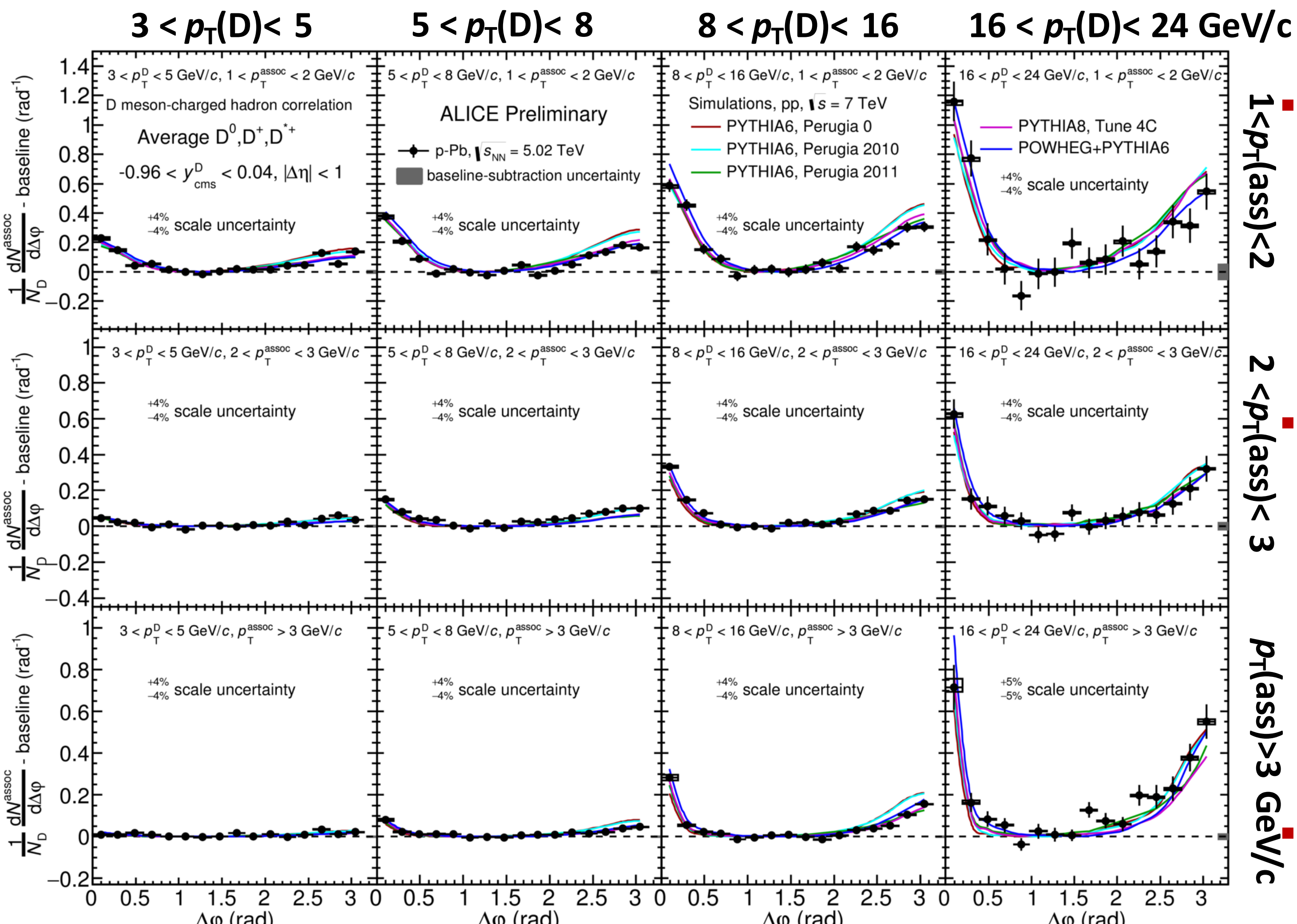
D-h correlations: p-Pb@5 TeV vs. models



- Results in different D meson (trigger) and hadron (associate) p_T ranges
- New p-Pb data sample offers better precision when compared to Run 1 sample
- **Higher p_T(D)** and p_T (assoc) ranges accessible
- **First quantitative access to away side**

- Correlation distributions and their p_T trend qualitatively described by PYTHIA6,8 & POWHEG

D-h correlations: p-Pb@5 TeV vs. models

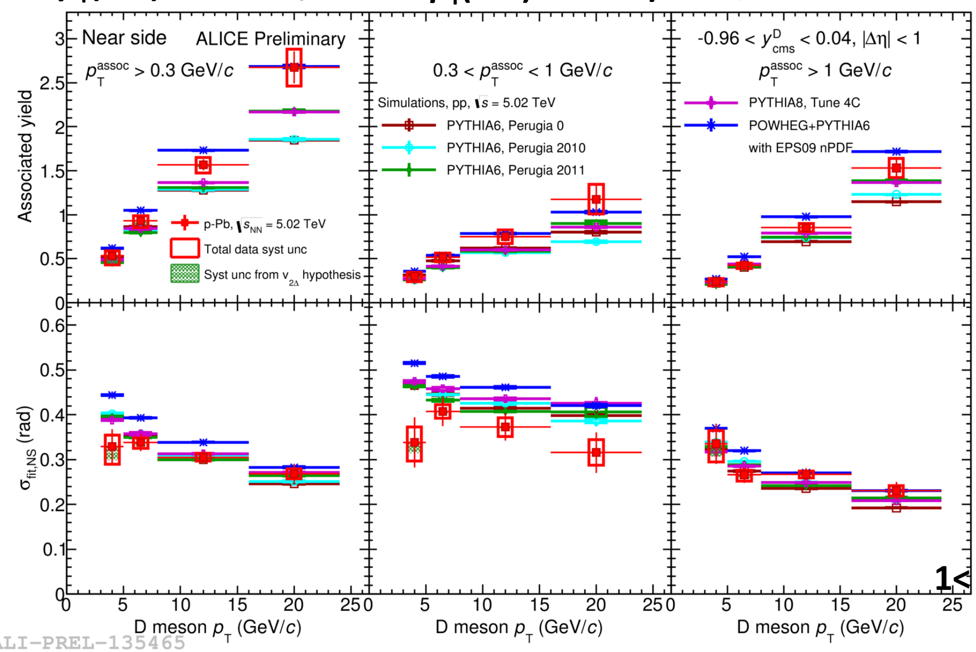


- **New p_T(ass) ranges** are accessible thanks to higher p-Pb statistics
- Closer to (angular) kinematics of hard-scattering -> enhance sensitivity to charm production processes?
- Important tool to investigate charm-jet internal structure and kinematics!

Bottom-left panel: $\boldsymbol{p_T^{assoc} \approx p_T^D}$
Sensitivity to production processes: no NS peak expected at LO due to high *z* of D meson (could arise from NLO)

D-h correlations: p-Pb@5 TeV vs. models

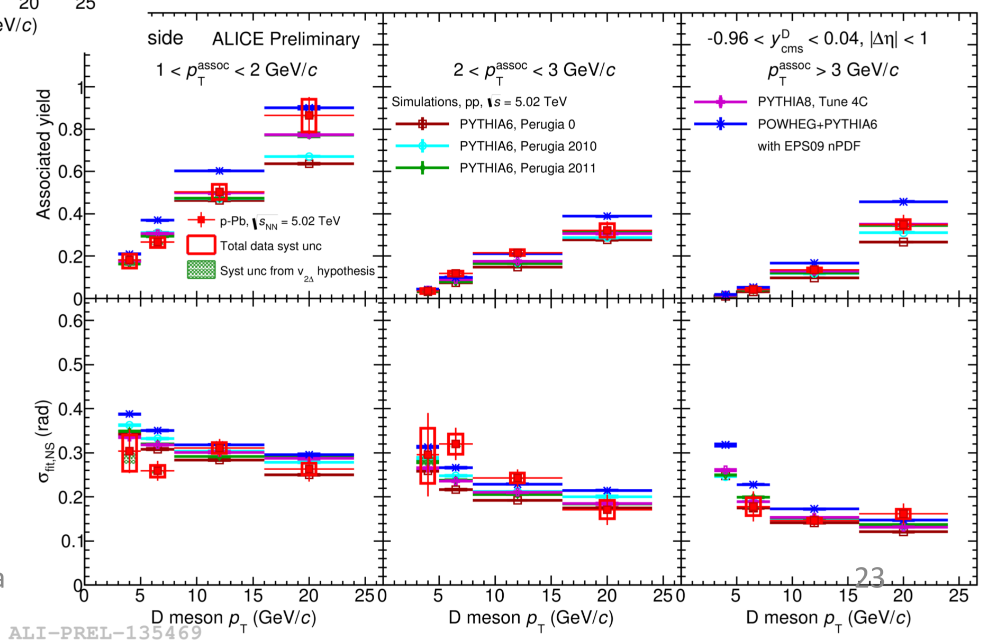
p_T(ass)>0.3 GeV/c 0.3 <p_T(ass)< 1 GeV/c p_T(ass)> 1 GeV/c



NEAR SIDE

- Measured trends qualitatively described by models (PYTHIA6, 8 and POWHEG+PYTHIA)
- Some tension observed at high p_T^D, low p_T^{assoc} vs PYTHIA6,8

1< p_T(ass)<2 GeV/c 2<p_T(ass)< 3 GeV/c p_T(ass)> 3 GeV/c

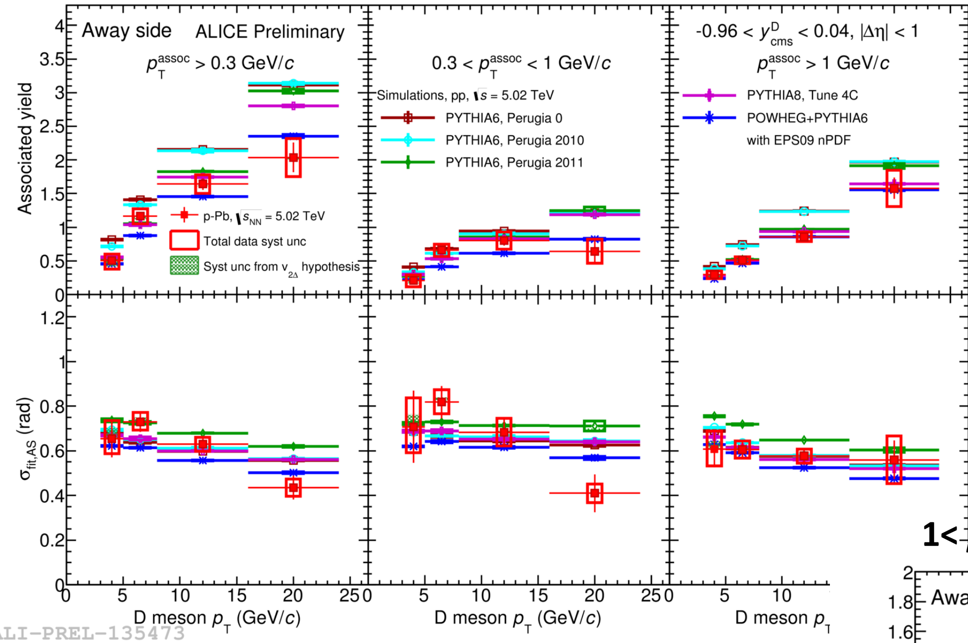


NEAR SIDE

- Rather good description of **NS sigma**; except at low p_T^{assoc} for the NS, especially w.r.t. POWHEG

D-h correlations: p-Pb@5 TeV vs. models

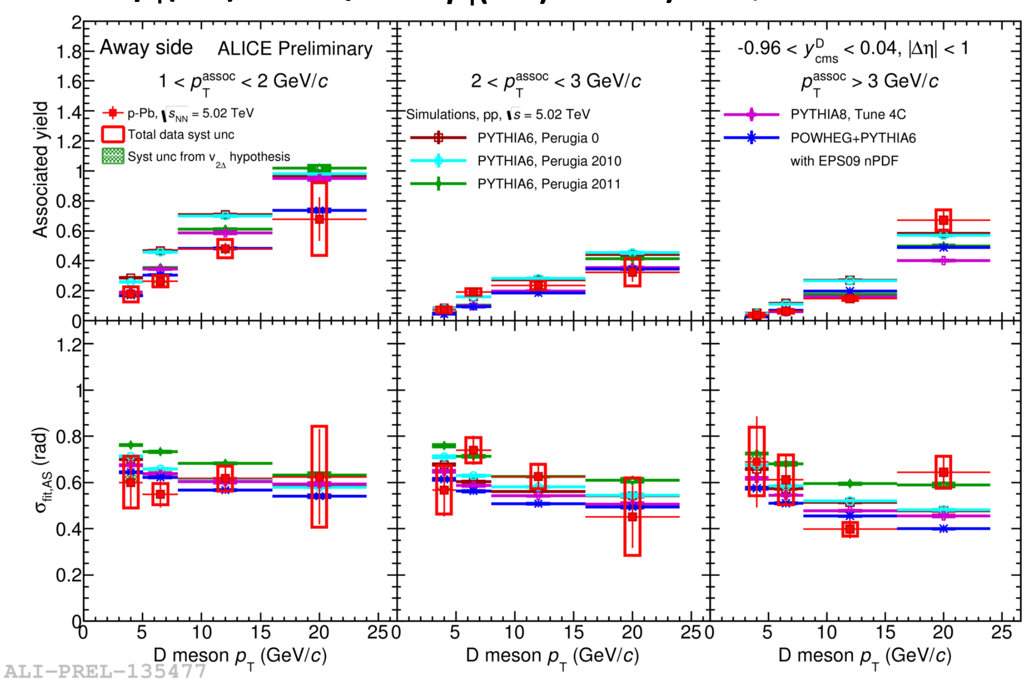
p_T(ass)>0.3 GeV/c   0.3<p_T(ass)< 1 GeV/c p_T(ass)> 1 GeV/c



AWAY SIDE

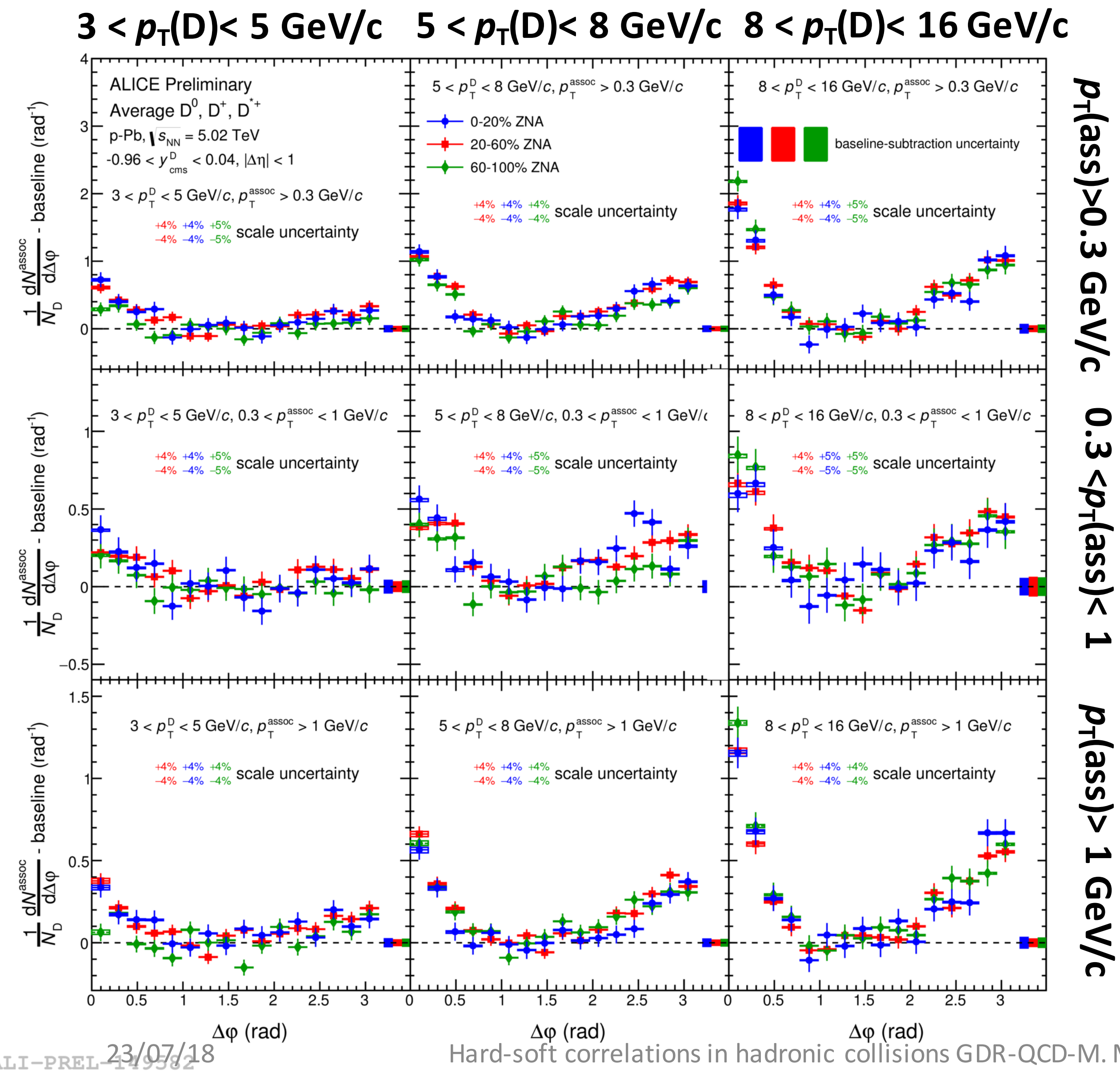
- Compatible AS yields (though on the lower side of PYTHIA simulations) and width
- POWHEG gives lower AS yields than PYTHIA6,8 (the opposite to NS yields) → Hint that POWHEG is closer to data

1<p_T(ass)<2 GeV/c   2<p_T(ass)< 3 GeV/c p_T(ass)> 3 GeV/c



- Main uncertainty from assumptions used for baseline subtraction —> can be reduced with larger stat. samples

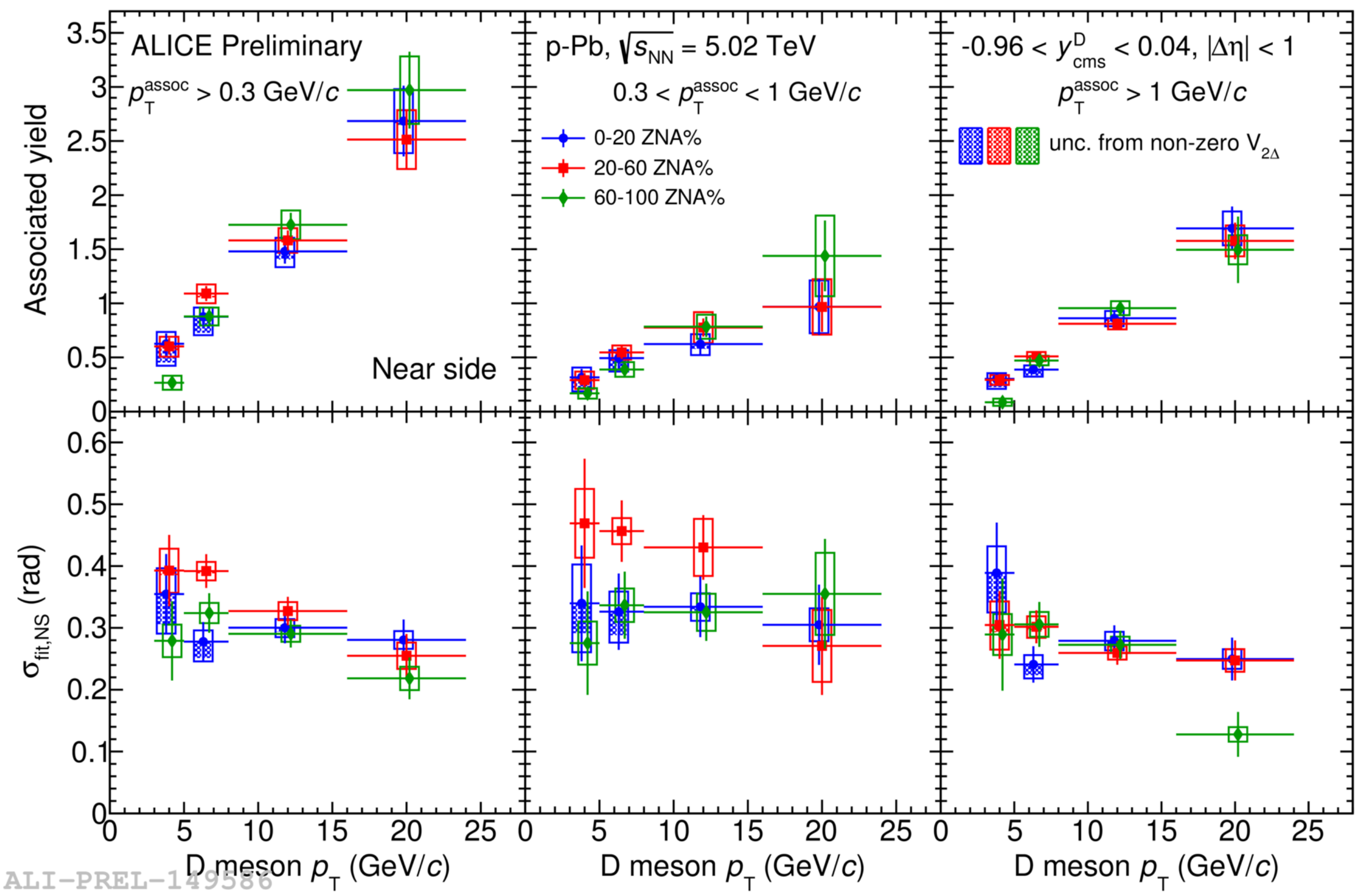
D-h correlations: p-Pb 2016 vs. centrality



- Do jet properties depend on multiplicity? Are they modified at high multiplicity in p-Pb? Collectivity behaviour (HF v_2)?
- Measurement performed in 3 centrality classes (**0-20%, 20-60%, 60-100%**)

D-h correlations: p-Pb 2016 vs. centrality

p_T(ass)>0.3 GeV/c **0.3 <p_T(ass)< 1 GeV/c** **p_T(ass)> 1 GeV/c**



- **No modification of near-side peak properties** among different centralities, within the uncertainties
- Not enough sensitivity to extract the D-meson v_2 (observed in HF-electrons and charged-particle correlations)

HFe-h angular correlations

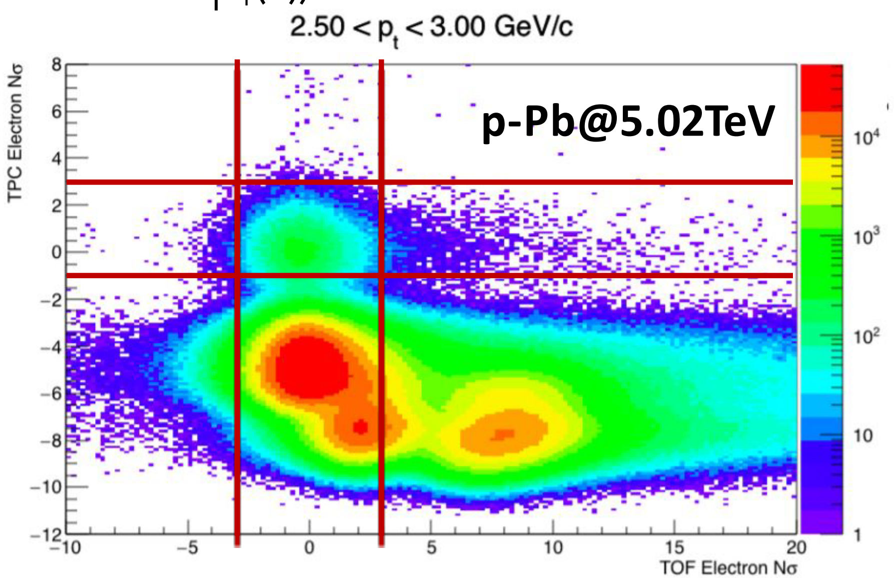
HFe-h analysis strategy

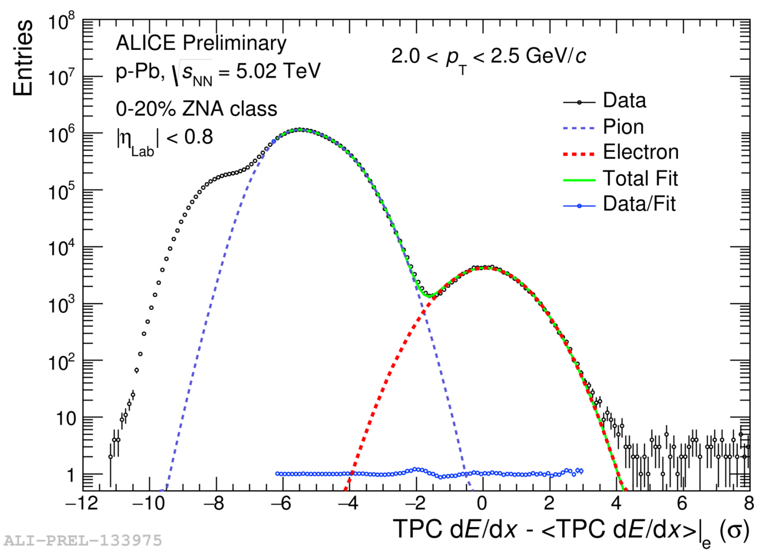
- Heavy-flavour hadron (B and D) semileptonic decay channels (B.R. ~10%)

B → e + X
D → e + X

Main differences w.r.t. D-hadron case:

1. Electron identification
   - Quality cuts on the track reconstruction
   - Particle identification based on TPC and TOF response + EMCAL (at high $p_T(e)$)



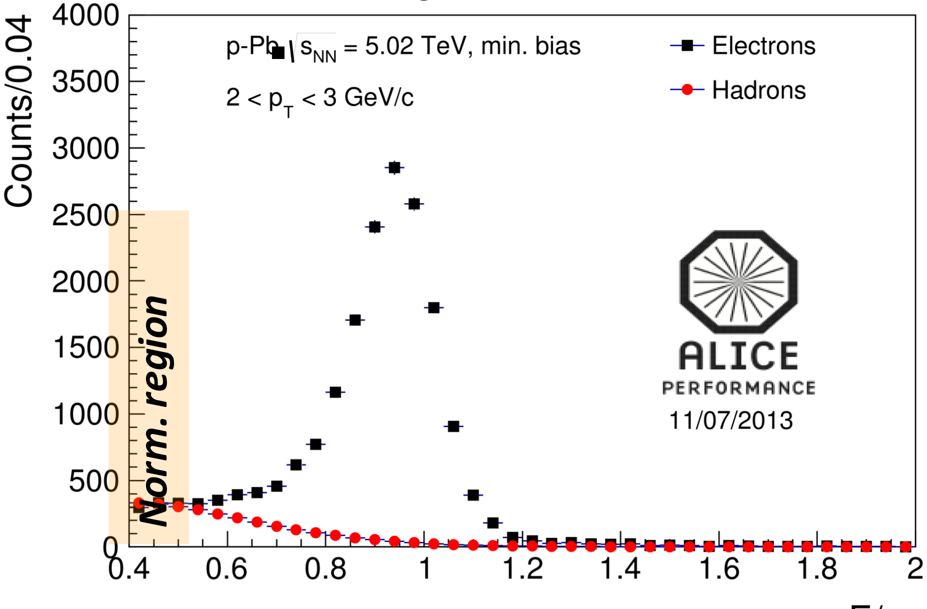


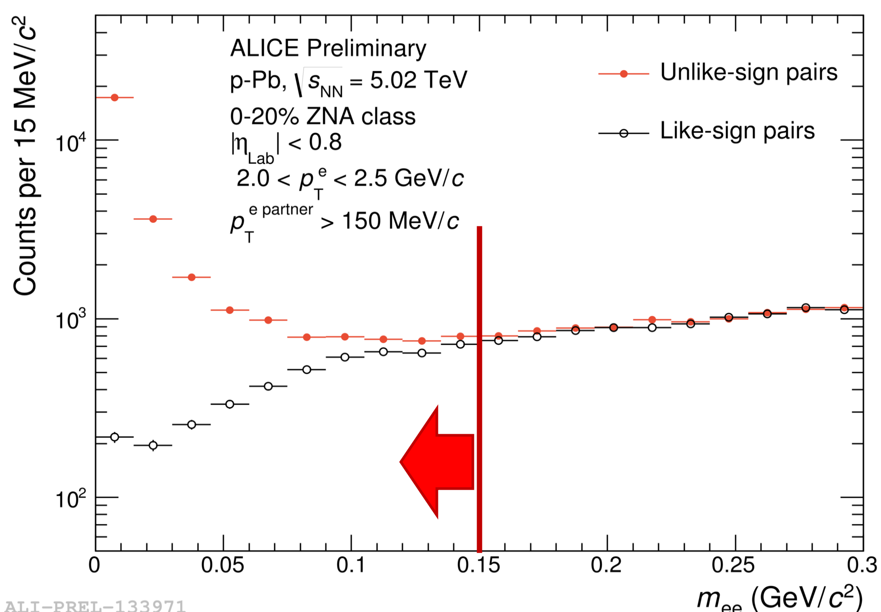
HFe-h analysis strategy

Main differences w.r.t. D-hadron case:

2. Removal of:

- ❑ residual h-h correlation (statistical subtraction)
- ❑ non-HFe contribution:
  - Sources of non-HFe: conversions ($\gamma \rightarrow e^+e^-$), Dalitz decays ($\pi^0$, $\eta \rightarrow \gamma e^+e^-$)
  - Non-HFe correlations built using ULS pairs of M_{ee} distributions (with upper M_{ee} cut), and considering correlations from LS pairs to remove combinatorial background



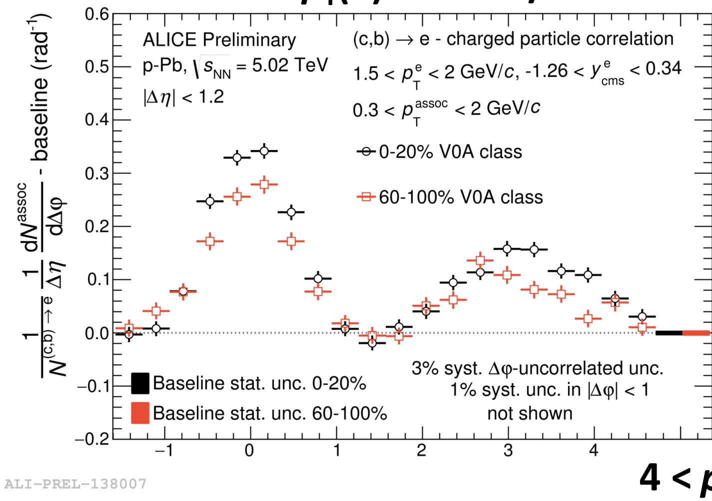


p-Pb results as a function of multiplicity

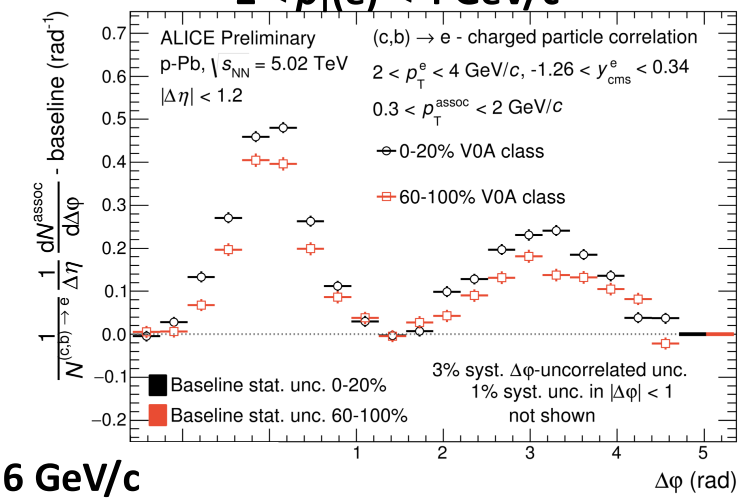
Looking for possible modulations (v_2 like) in the heavy-flavour sector in p-Pb collisions (not enough statistics to observe 2d long-range ridges).

$0.3 < p_T(\text{ass}) < 2$ GeV/c

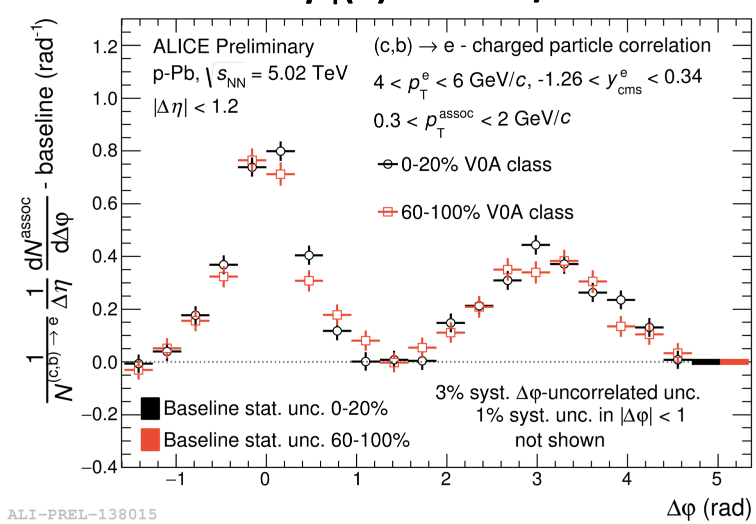
$1.5 < p_T(e) < 2$ GeV/c



$2 < p_T(e) < 4$ GeV/c



$4 < p_T(e) < 6$ GeV/c



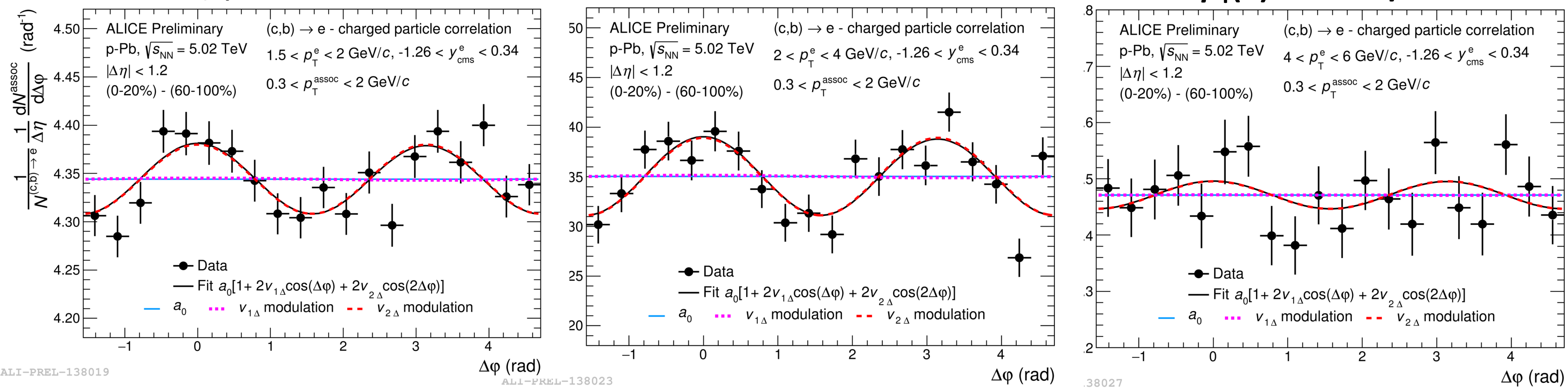
Near ($\Delta\phi=0$) and Away side ($\Delta\phi=\pi$) excess from Low Multiplicity (60-100%) to High Multiplicity (0-20%) → **elliptic flow** also for heavy quarks?

$v_{2\Delta}^{Hfe\text{-}ch}$ estimation

ALICE

- Low multiplicity correlation functions are subtracted from the high multiplicity ones to remove the **jet component**.

$1.5 < p_T(e) < 2$ GeV/c | **$2 < p_T(e) < 4$ GeV/c** | **$4 < p_T(e) < 6$ GeV/c**



- $v_{2\Delta}$ quantified fitting the distribution via Fourier series:

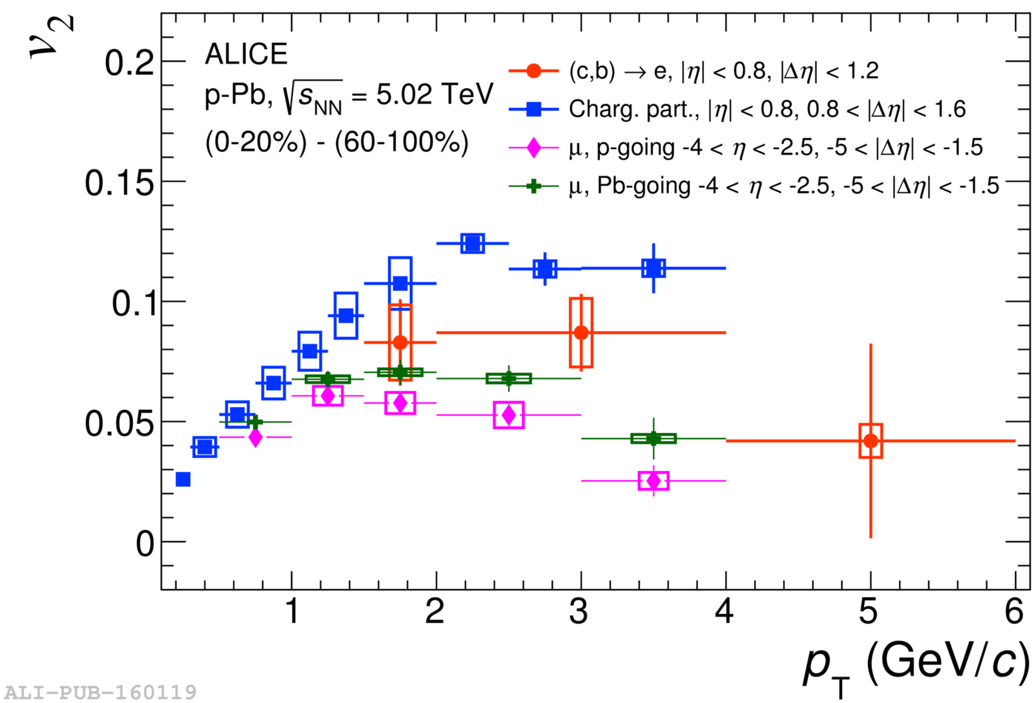
$$C_{HM}(\Delta\varphi) - C_{LM}^{sub} = a_0(1 + 2V_{1\Delta}\cos(\Delta\varphi) + 2V_{2\Delta}\cos(2\Delta\varphi)).$$

The resulting distribution requires a non-zero coefficient of the second-order modulation in the Fourier decomposition

v_2^{HFe} estimation

- $v_2^{HFe} = v_{2\Delta}^{Hfe\text{-}ch} / v_2^{ch}$
- **First measurement** of heavy-flavour electron v_2^{HFe}{2PC, sub} in p-Pb collisions
- Results show a **positive v_2^{HFe}(2PC,sub)** for electrons with $1.5 < p_T < 4$ GeV/c
- v_2 qualitatively similar for heavy- and light- flavour hadron in the common p_T interval
- Comparison with muon-v_2 not straightforward due to different CNM effects on HF production at different rapidities. Moreover, it includes also non-HF muons and it is subject to a larger η-gap.

arXiv:1805.04367 [nucl-ex]



Conclusions

- Azimuthal correlation studies are complementary to jet studies
  - Allow to characterize the "rest" of the jet produced by the charm fragmentation
  - Can provide relevant information on the properties of charm production, fragmentation and hadronization

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- Compatible near-side yields and widths in **pp at $\sqrt{s}$=7, 13 TeV** and in **p-Pb at $\sqrt{s_{NN}}$ = 5.02 TeV**
  - No evidence of CNM effects with current uncertainty level
- Good agreement of near-side observables with MC predictions in pp collisions
- Near-side and away-side yields are qualitatively described by PYTHIA and POWHEG+PYTHIA expectation in p-Pb collisions
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HFe-hadron correlations:

- Evidence of v_2^{HFe} in high-multiplicity p-Pb collisions
- Compatible v_2 strength for heavy- and light- flavour hadron in the common p_T interval

Outlook

- Analysis ongoing on **pp@5TeV** (2017) sample (**L_{int}≈ 19 nb^{-1} for MB events)**
  - Precise reference for the upcoming Pb-Pb studies
  - Extended p_T range and more p_T-differential analyses to probe energy dependence of charm-jets in-vacuum fragmentation ($\sqrt{s}$=5, 7, 13 TeV)

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UPGRADE

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- D-h analysis on Pb-Pb also feasible, in addition to e-h
- Large-stat sample should also allow to look at the more 'direct' observables (D-e, e-e, HFjet-HFjet)

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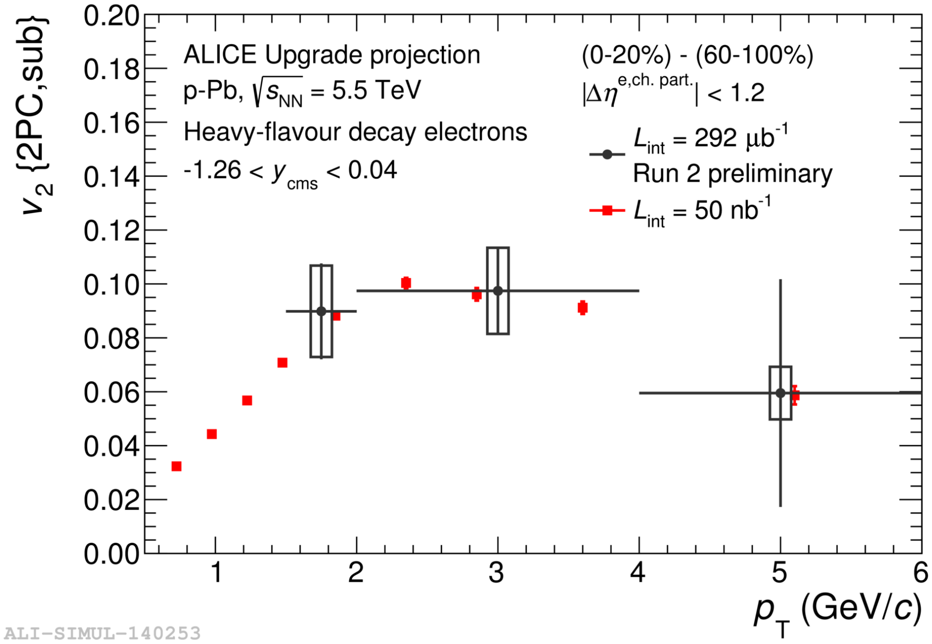

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Looking forward for theoretical predictions on these observables!!