Study of in-medium energy loss with heavy-flavour correlations in pp and Pb-Pb collisions with ALICE at the LHC

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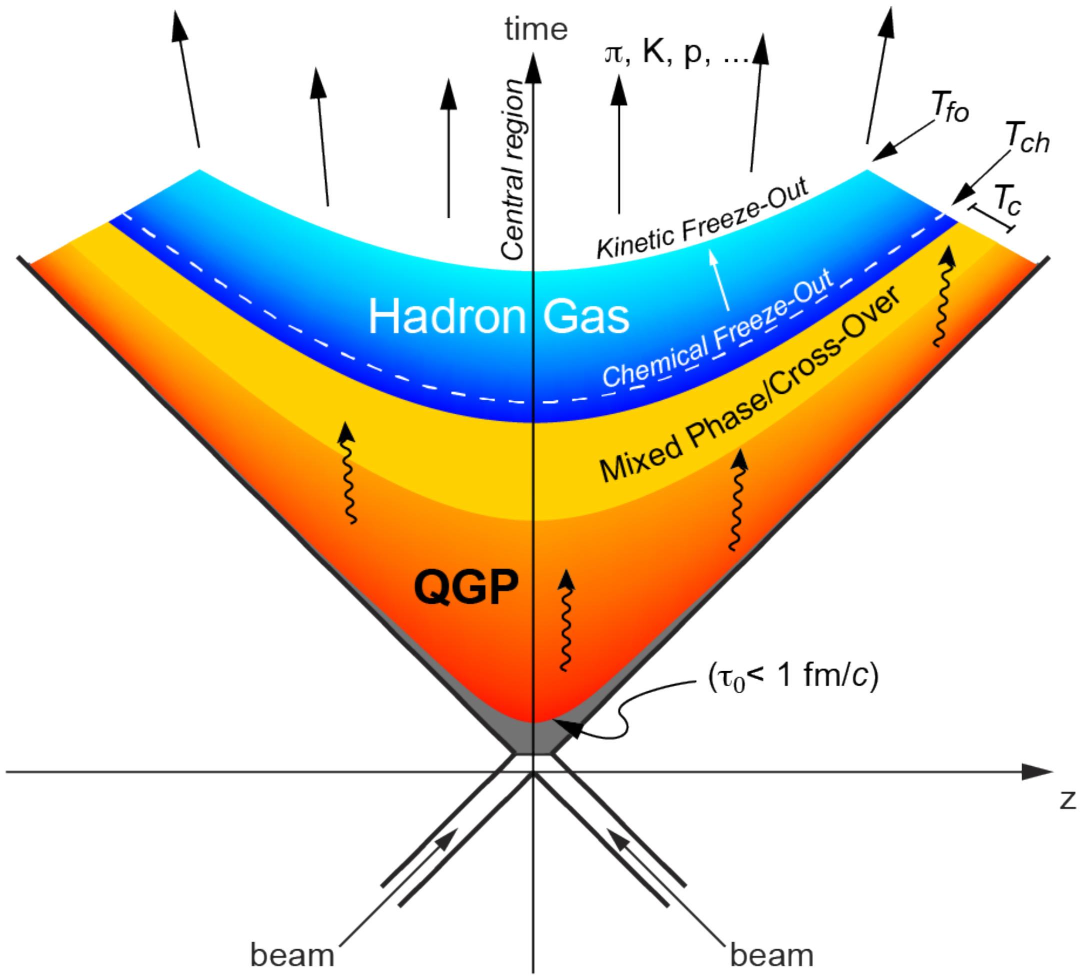
Hot Quarks 2018, 7th to 14th Sept.,2018

Physics motivation : Why do we study heavy flavour?



- Heavy quarks with their heavy masses: charm, m_c ~ 1.3 GeV/c^2 and bottom, m_b ~ 4.2 GeV/c^2 .
- Predominantly produced by parton-parton hard scattering in the early stages of the collision -> Experience the complete evolution of QGP medium: Production time: $t_Q = 1/2m_Q \leq 0.1$ fm/c.
- Produced due to hard scattering -> perturbative QCD can be applied.
- QCD energy loss is expected to occur via both
  - Inelastic (radiative energy loss via medium-induced gluon radiation) and
  - Elastic (collisional energy loss) processes.

Therefore, heavy quarks act as important tools for characterizing the medium formed in heavy-ion collisions.

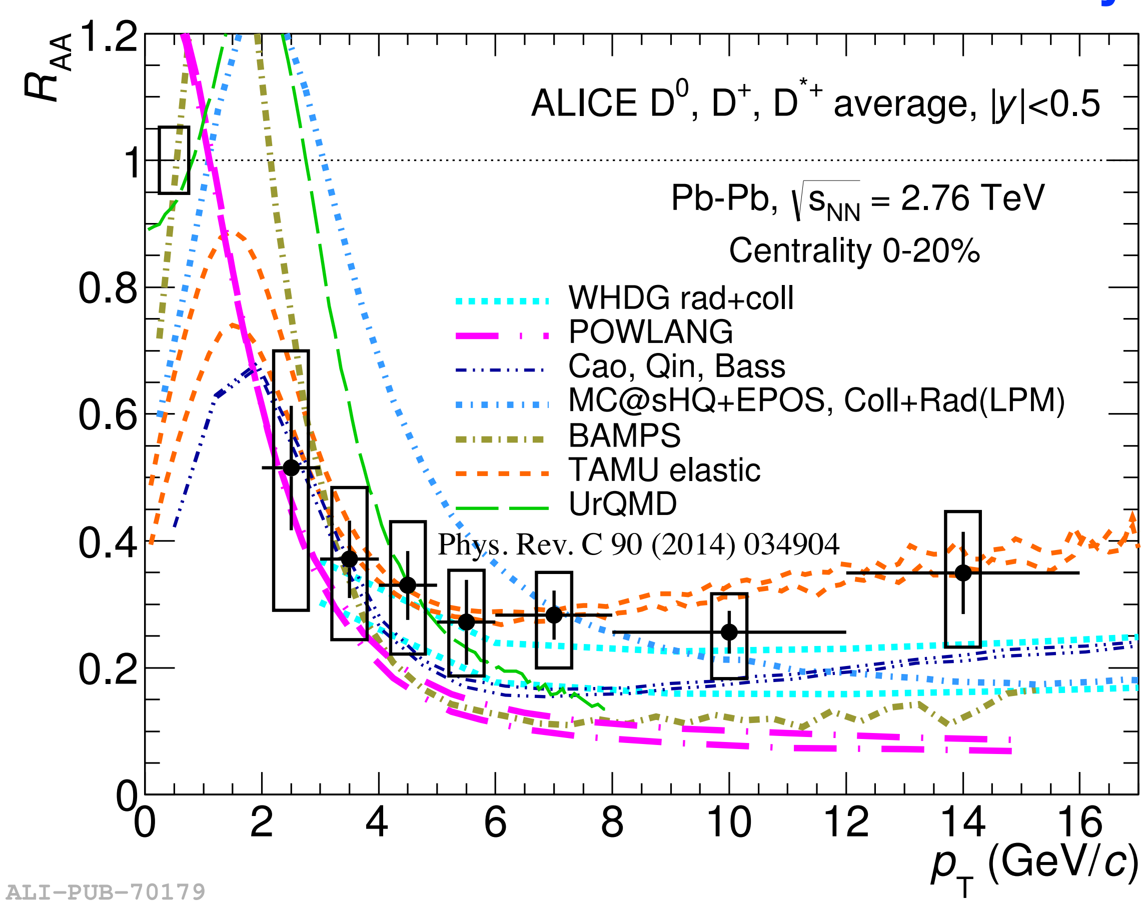
Physics motivation : Open heavy flavour in Pb-Pb collisions

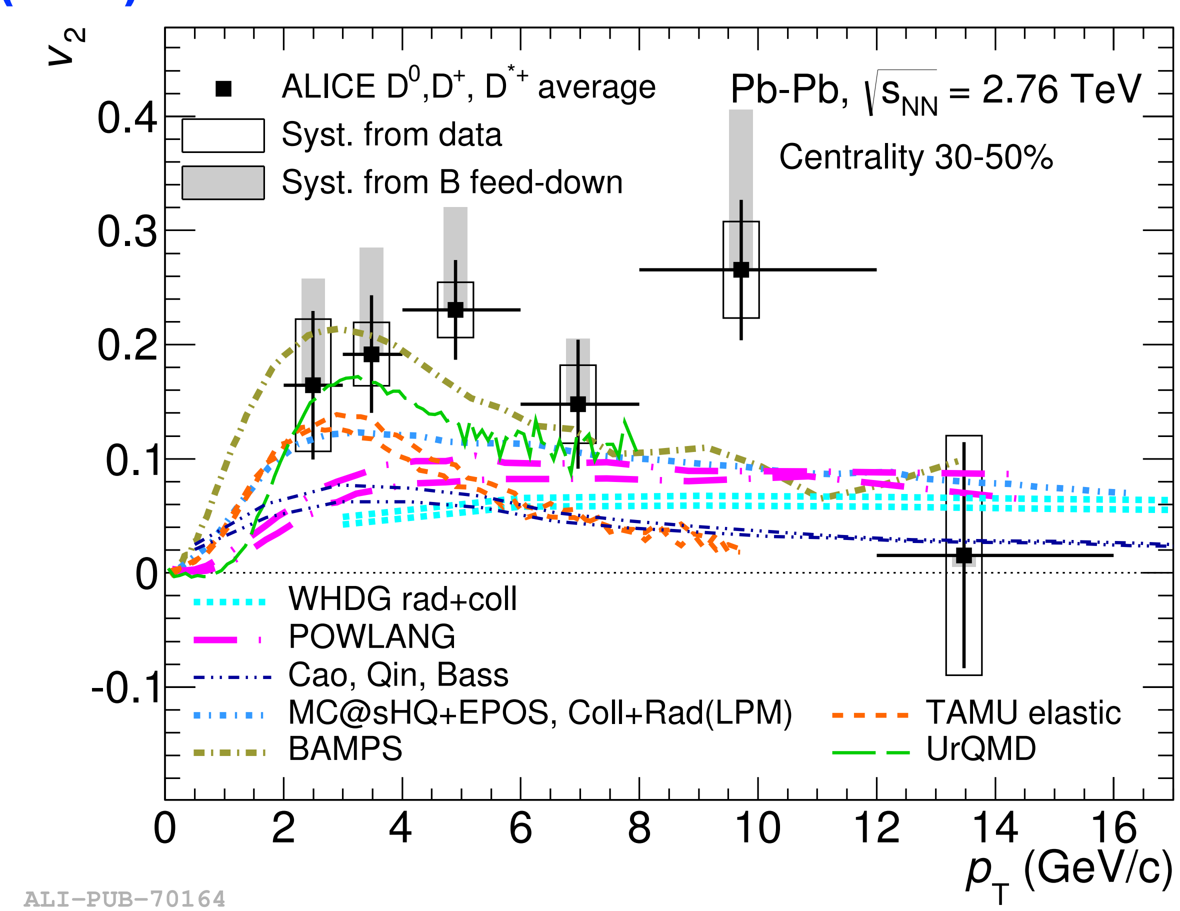
- **Contribute to the collective motion inside the system -> provide information on medium transport properties.**
- **In charm sector, ALICE has observed:**

-> A significant suppression (factor 4-5) of D-meson production for $p_T > 5$ GeV/c in central Pb-Pb collisions with respect to pp and p-Pb collisions, indicating charm quark energy loss due to interactions with the medium constituents.

-> Positive elliptic flow (v_2) for D mesons in semi-central collisions (30-50%), for $2 < p_T < 6$ GeV/c, suggesting that charm quarks participate to the collective motion of the medium.

Phys. Rev. C 90 (2014) 034904





Physics motivation : Open heavy flavour in small systems

p-Pb collisions:

Heavy-flavour production and kinematic properties can be modified by:

- **Cold nuclear matter effects, like shadowing, gluon saturation/color glass condensate, Cronin effect, possible energy loss mechanisms.**
- **“Collective-like" effects (e.g. elliptic flow), which resembles the observations from heavy-ion collisions.**

pp collisions:

- **Test and set constraints on production mechanisms -> Production cross section can be treated perturbatively due to the large Q^2 involved -> pQCD-based calculations describe reasonably well open charm and beauty production at the LHC**
- **Probe parton distribution function (especially for gluons) at low values of Bjorken *x***
- **Reference for studies in p-Pb and Pb-Pb collisions**

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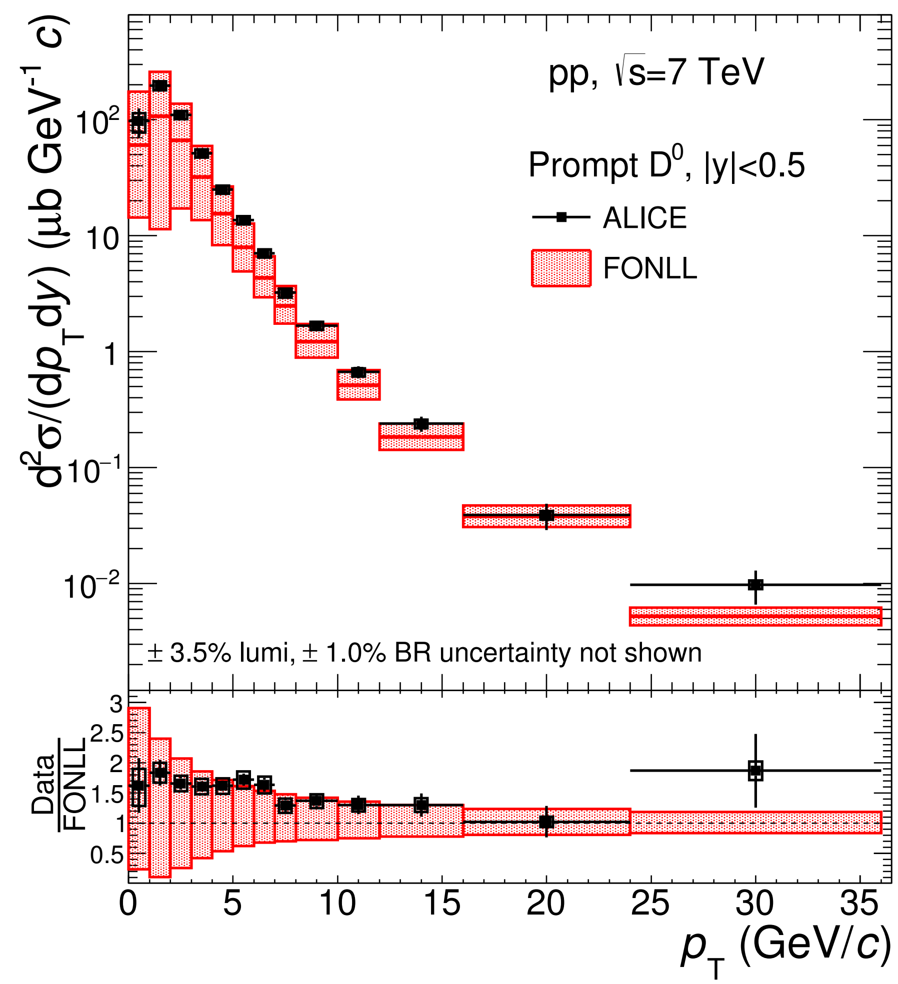


Physics motivation: Heavy-flavour correlations

Azimuthal correlations of heavy-flavour particles or heavy-flavour decay electrons with charged hadrons are important to study :

In Pb-Pb collisions:

- **Energy loss of heavy-flavour partons.**
- **Possible modification of jet fragmentation in QCD medium.**

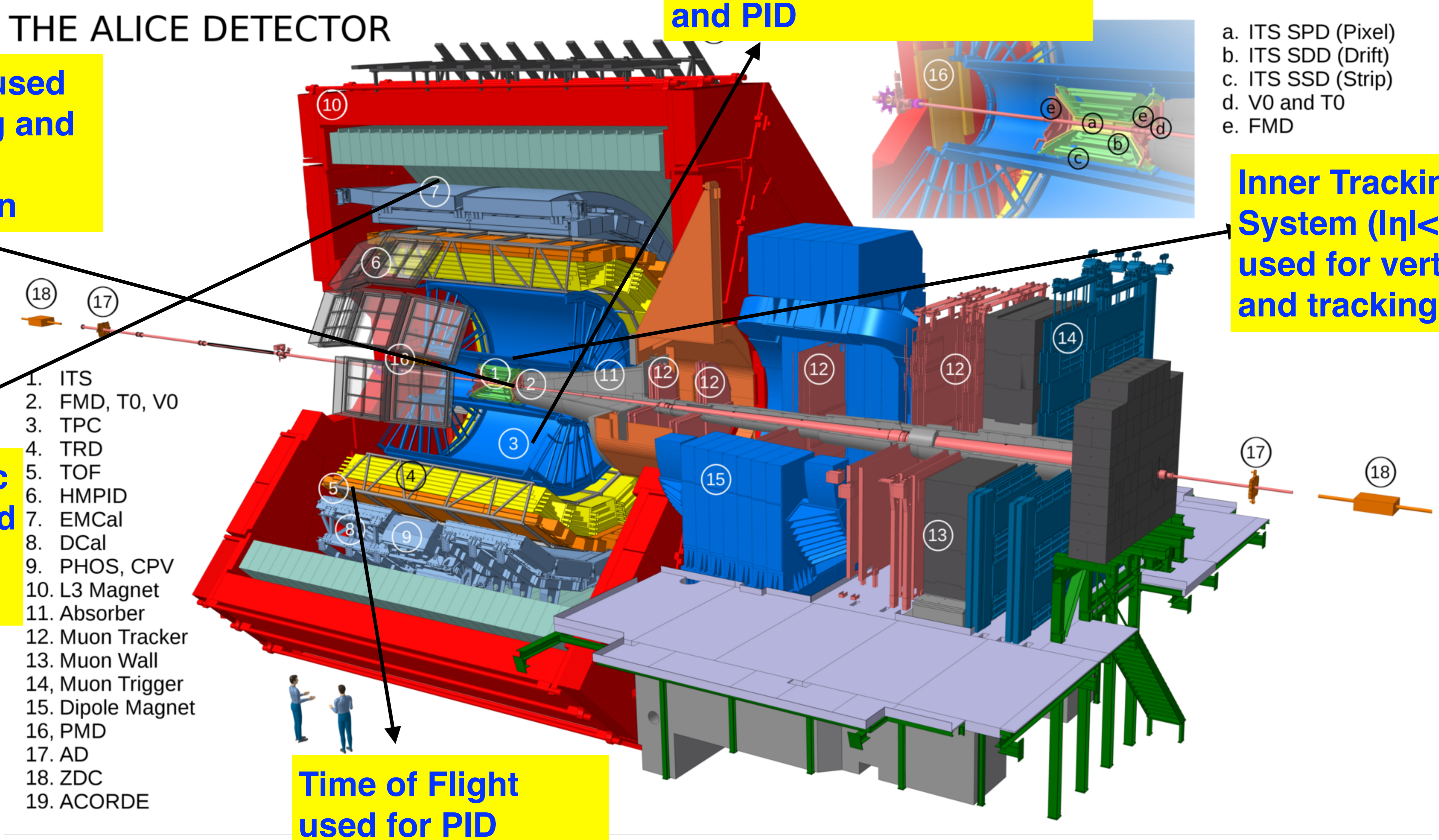
In p-Pb collisions:

- **Investigate possible modifications of angular correlation pattern due to cold nuclear matter effects.**
- **Search for long-range ridge-like structure observed in di-hadron correlations, also in the heavy-flavour sector, possibly due to initial (e.g. CGC) or final (e.g. hydrodynamics) state effect.**

In pp collisions:

- **Investigate heavy-flavour quark fragmentation properties and characterize heavy-flavour jets.**
- **Sensitivity in modelling of HQ processes.**
- **Reference of p-Pb and Pb-Pb collisions.**

ALICE apparatus



Time Projection Chamber (|η|<0.9) used for tracking and PID

V0 detector used for triggering and multiplicity determination

Inner Tracking System (|η|<0.9) used for vertexing and tracking

ElectroMagnetic Calorimeter used for high p_T trigger, PID

Time of Flight used for PID

Azimuthal correlation of D mesons and charged particles

Data sample:

pp, $\sqrt{s}$ = 13 TeV (2016 data), 437M minimum-bias events

pp, $\sqrt{s}$ = 7 TeV (2010 data), 314M minimum-bias events

p-Pb, $\sqrt{s_{NN}}$ = 5.02 TeV (2016 data), 602M minimum-bias events

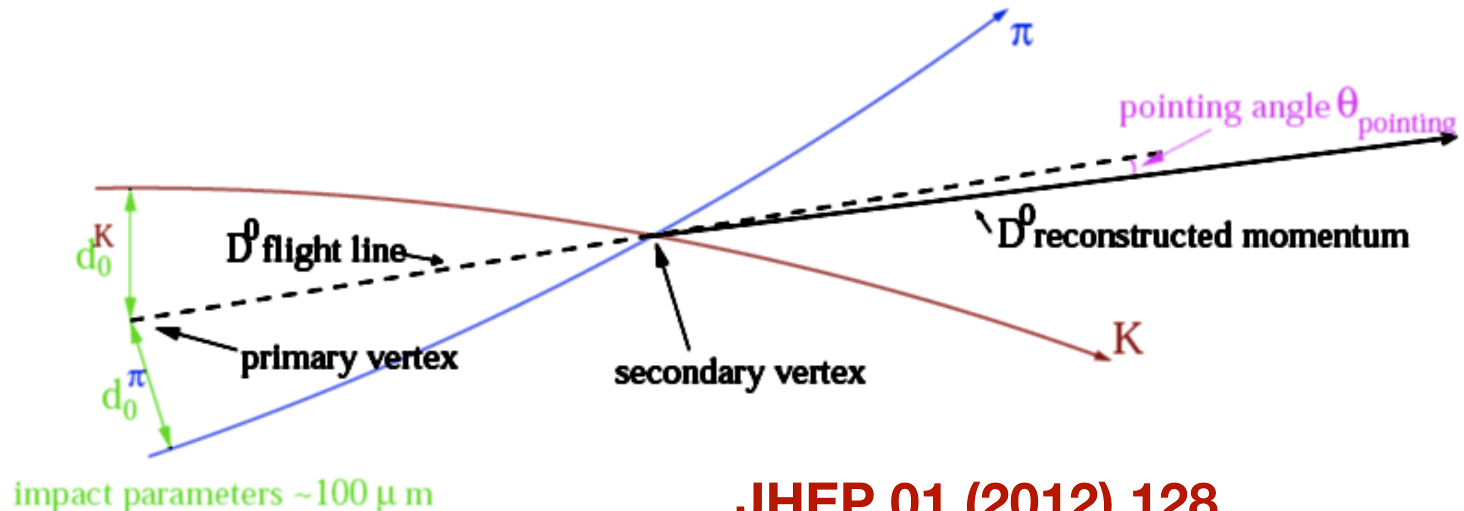
Talk by Marianna Mazzilli : Multiplicity and centrality dependent azimuthal correlation studies on 12.09.2018

Analysis Strategy

• Reconstruction of D mesons

Reconstruction is based on the secondary vertex which is displaced from the primary vertex of the collision

Decay Channel	Branching Ratio
$D^0 \rightarrow K^- \pi^+$	3.88±0.05%
$D^+ \rightarrow K^- \pi^+ \pi^+$	9.13±0.19%
$D^{*+} \rightarrow D^0 \pi^+ \rightarrow K^- \pi^+ \pi^+$	2.62±0.10%



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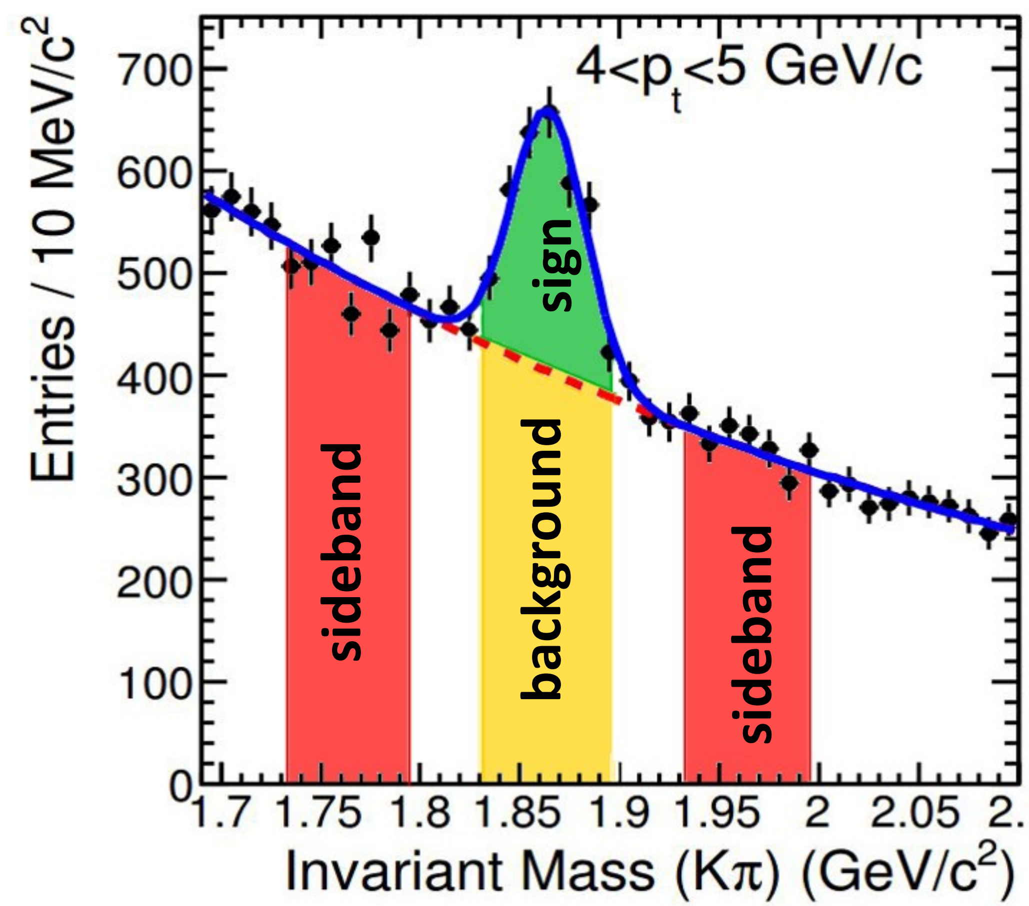

- **Selected D mesons (including background) are used as "trigger" particles for building the angular correlation distribution. "Associated" particles are selected via kinematic ($p_T > 0.3$ GeV/c, $|\eta| < 0.8$) and track-quality cuts.**
- **To remove the contribution from background D-meson candidates, sideband region correlations are normalized to the background contribution under the signal and then subtracted from signal region correlations**

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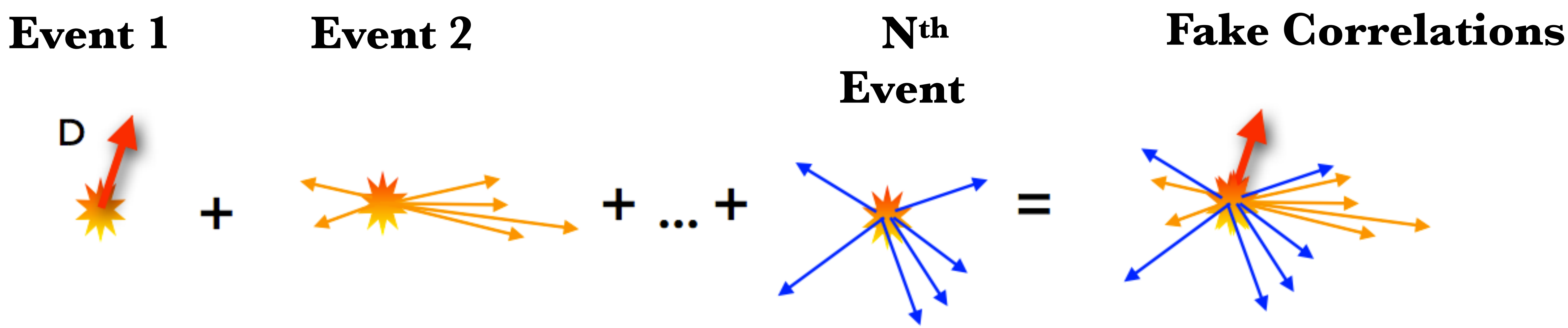
- **Event Mixing correction**



- **The correlation distributions are corrected for the limited detector acceptance and detector spatial inhomogeneities using the event-mixing technique.**
- **Mixed events are obtained by taking the D-meson candidate from the event N and the associated tracks from other preceding selected events.**

$$\frac{d^2N^{corr}(\Delta\varphi\Delta\eta)}{d\Delta\varphi d\Delta\eta} = \frac{\frac{d^2N^{SE}(\Delta\varphi\Delta\eta)}{d\Delta\varphi d\Delta\eta}}{\frac{d^2N^{ME}(\Delta\varphi\Delta\eta)}{d\Delta\varphi d\Delta\eta}} \frac{d^2N^{ME}(0,0)}{d\Delta\varphi d\Delta\eta}$$

• Efficiency correction

- **Each (D, hadron) pair is weighted by the inverse of the D-meson reconstruction efficiency and of the associated track reconstruction efficiency .**
- **D-meson p_T and event multiplicity dependencies considered for D-meson efficiency; track p_T, η and *z* position of primary vertex dependencies considered for track efficiency**

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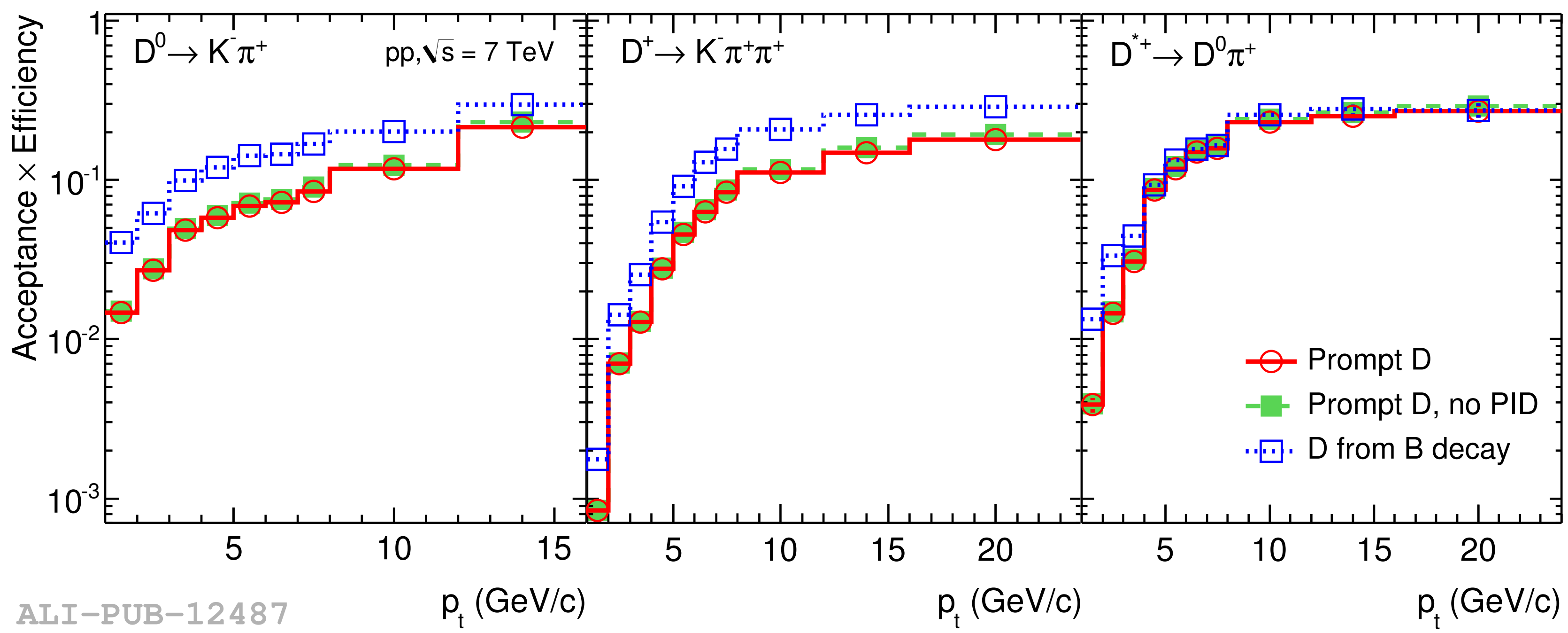


• Correction for b->D topological bias

This correction is implemented by using Monte-Carlo closure test.

- **Removal of contamination of secondary track**

- There are tracks from strange-hadron decays or produced in interactions of particles with the detector material.
- The contribution of secondary track particles, evaluated via Monte Carlo studies, is removed by a fit of the ratio $\Delta\varphi$(primary)/$\Delta\varphi$(all) with a 9th order polynomial.

- **Feed-down D-meson subtraction**

- A template of angular correlation distribution of D mesons from beauty-hadrons decays (from PYTHIA) is subtracted from the data distributions

Ref: M. Cacciari, M. Greco, P. Nason, The p_T spectrum in heavy flavor hadroproduction. JHEP 05, 007 (1998).

$$C_{\text{prompt D}}(\Delta\phi) = \frac{1}{f_{\text{prompt}}}\left(C_{\text{inclusive}}(\Delta\phi) - (1 - f_{\text{prompt}})\, C^{\text{MC templ}}_{\text{feed-down}}(\Delta\phi)\right)$$

- **Weighted average of D-meson species**

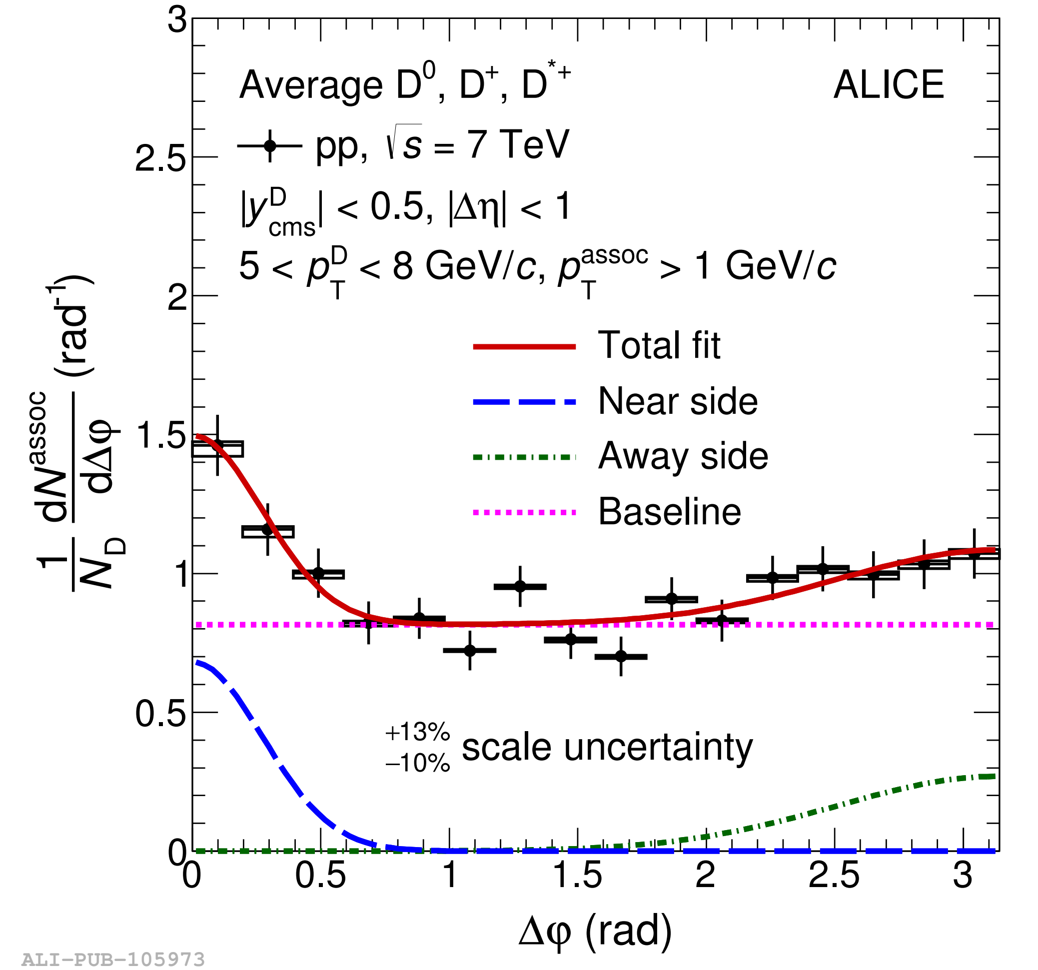
$$\langle \frac{1}{N_D}\frac{dN_{assoc}}{dp_T}\rangle_{\text{Dmesons}} = \frac{\sum_{i=meson} w_i \frac{1}{N_D}\frac{dN_{assoc}}{d\varphi}}{\sum_{i=meson} w_i}; w_i = \frac{1}{\sigma^2_{i,stat} + \sigma^2_{i,uncorr.syst.}}$$

- **Fit of Averaged correlations**

Fit function:

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

- Physical observables: Baseline height **(c)**, near side and away side peak associated yield **(Y_{NS}, Y_{AS})** and width **(σ_{NS}, σ_{AS})** .



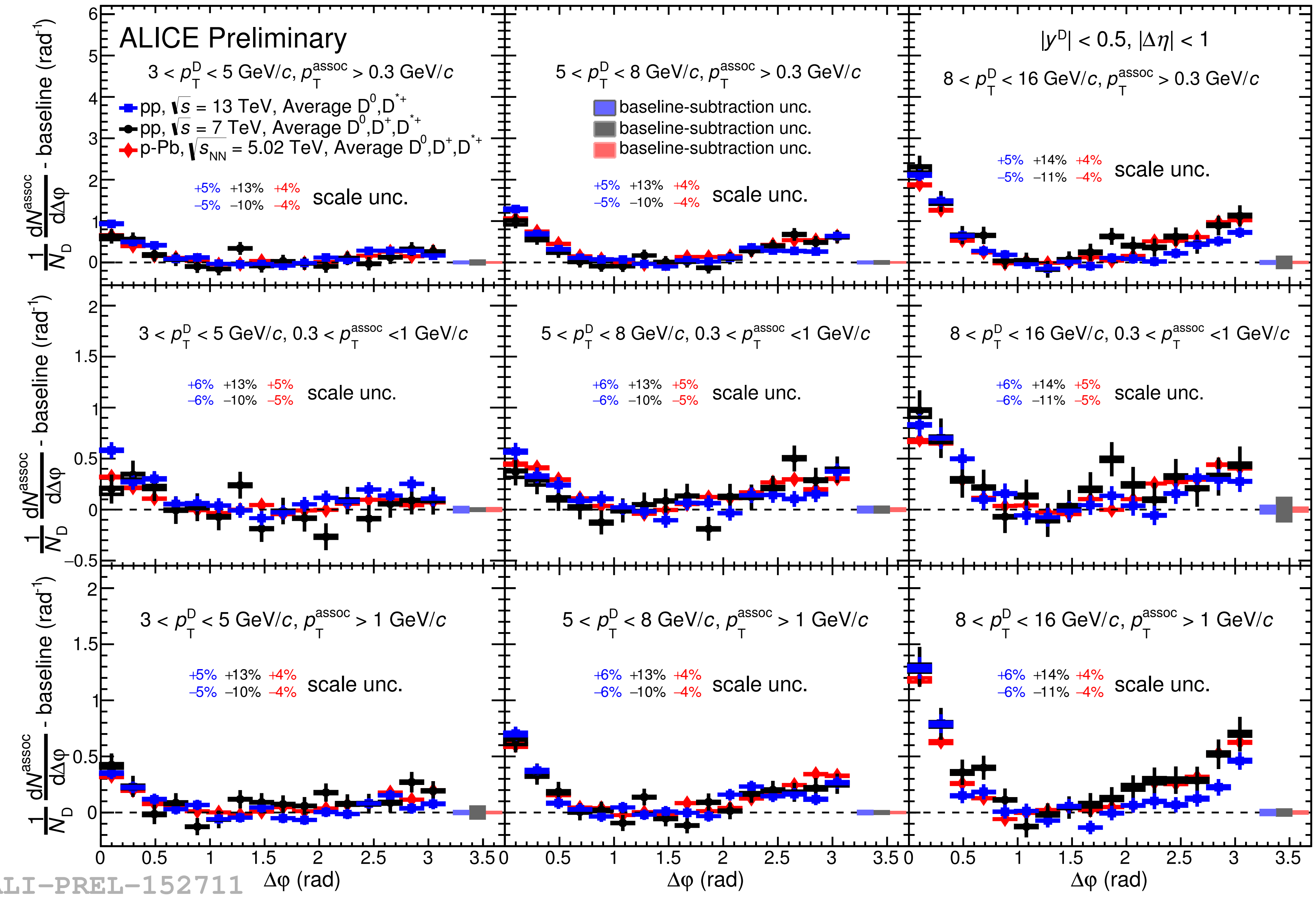
- **Estimation of systematic uncertainties**

- Repeat fit shifting the points upward/downward in the $\Delta\varphi$-uncorrelated syst. uncert. range.
- Maximum variation of the parameters taken as systematic uncertainty, adding in quadrature the $\Delta\varphi$-correlated systematics.

Results : D-hadron correlations

pp, $\sqrt{s}$ = 13 TeV
pp, $\sqrt{s}$ = 7 TeV
p-Pb, $\sqrt{s_{NN}}$ = 5.02 TeV

$3<p_T(D)<5$ GeV/c | $5<p_T(D)<8$ GeV/c | $8<p_T(D)<16$ GeV/c



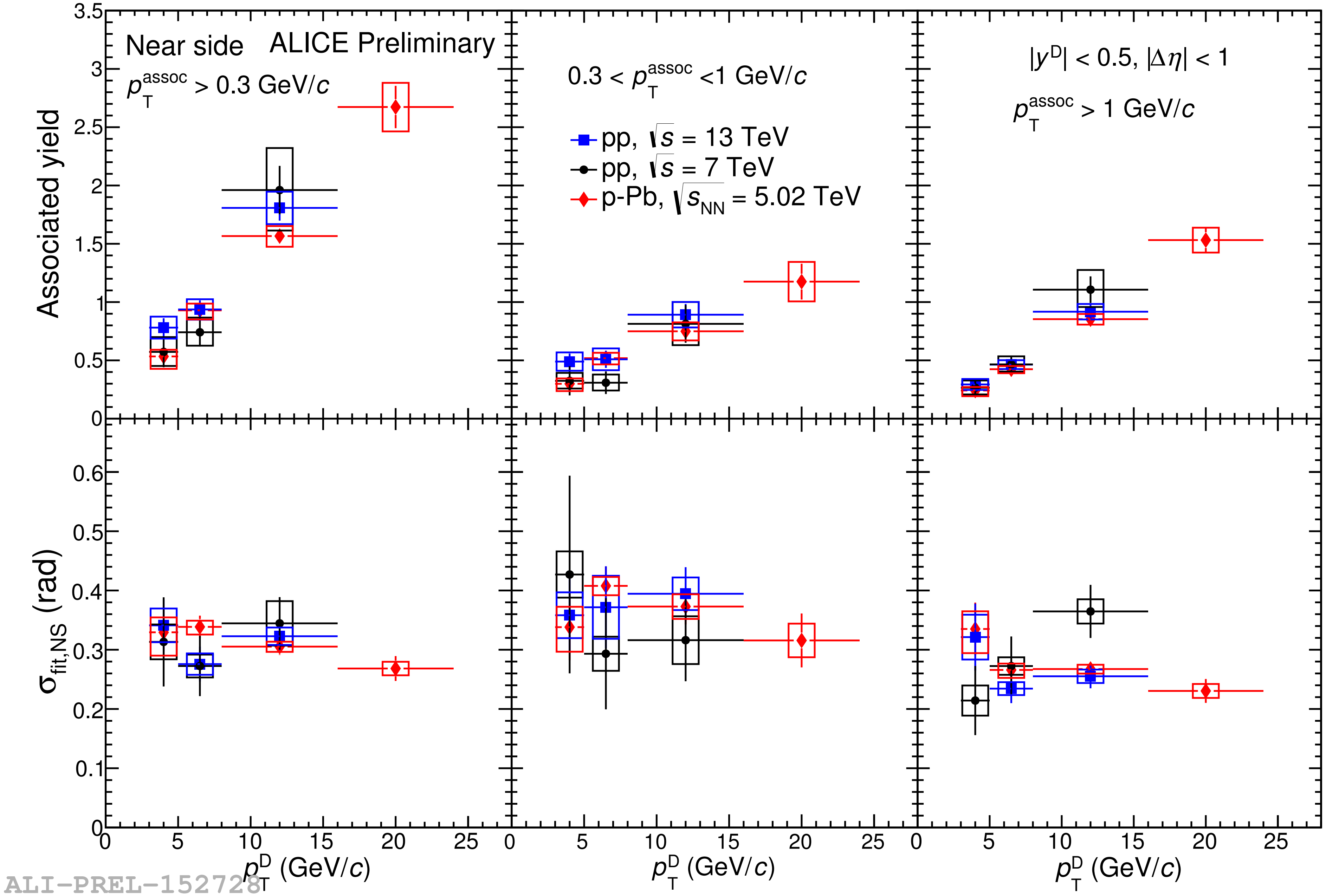
p_T(assoc)>0.3 GeV/c

0.3<p_T(assoc)<1 GeV/c

p_T(assoc)>1 GeV/c

- Average of the results from three D-mesons species (D^0 and D^{*+} only for pp $\sqrt{s}$ = 13 TeV), weighted with statistical and uncorrelated systematic uncertainties.
- The comparison of the results is performed after subtraction of the baseline.
- Compatibility within uncertainty is found for all the kinematic ranges.

Results : Near-side physical observables



pp, √s = 13 TeV

pp, √s = 7 TeV

p-Pb, $\sqrt{s_{NN}}$ = 5.02 TeV

- **Near-side yields and widths are extracted from the fit to the average correlation distributions.**
- **Compatible values and p_T evolution of the near-side peak yield and width are found within uncertainties for all the kinematic ranges.**

Results : D-hadron correlations (comparison with Monte-Carlo)

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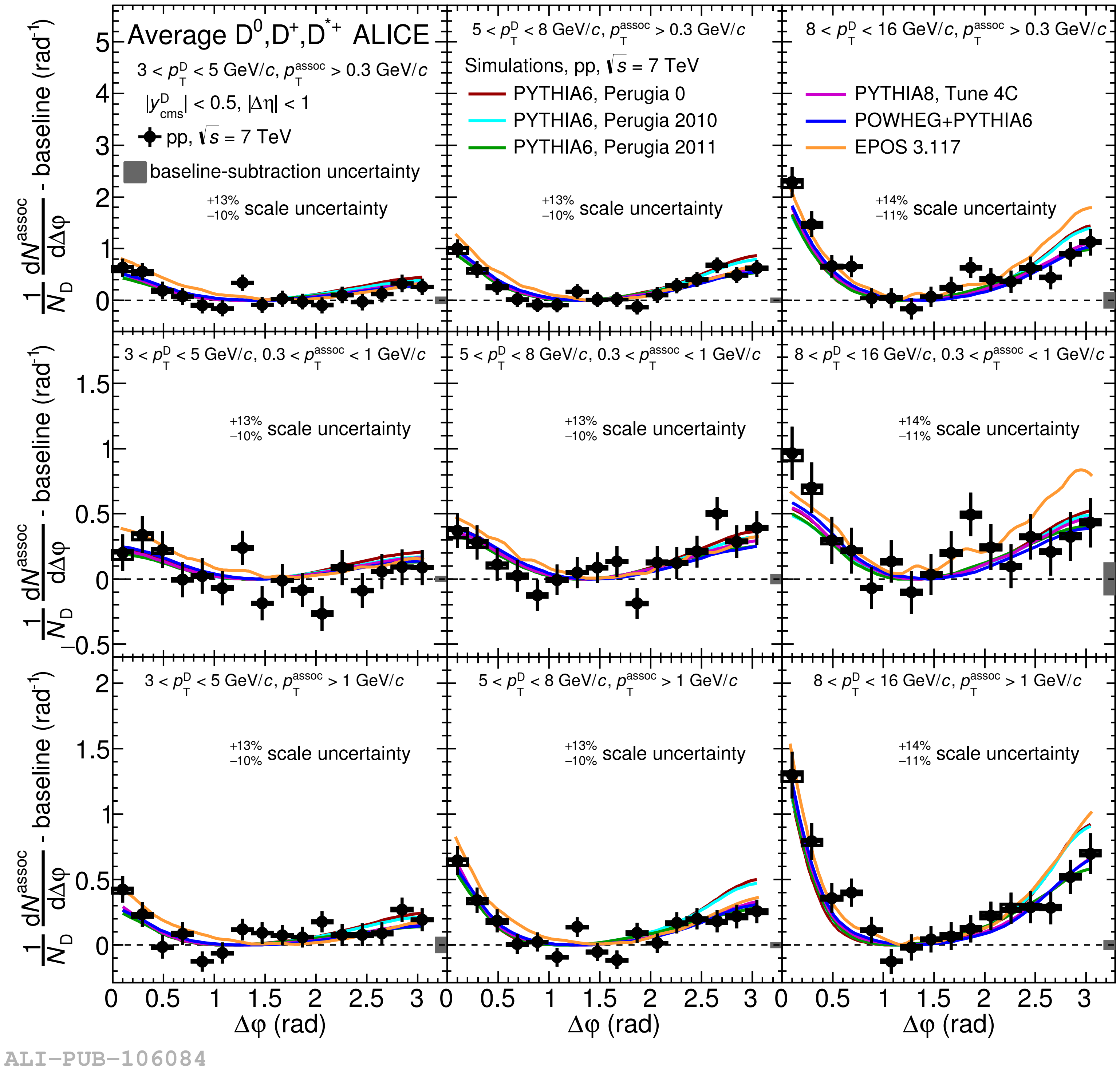
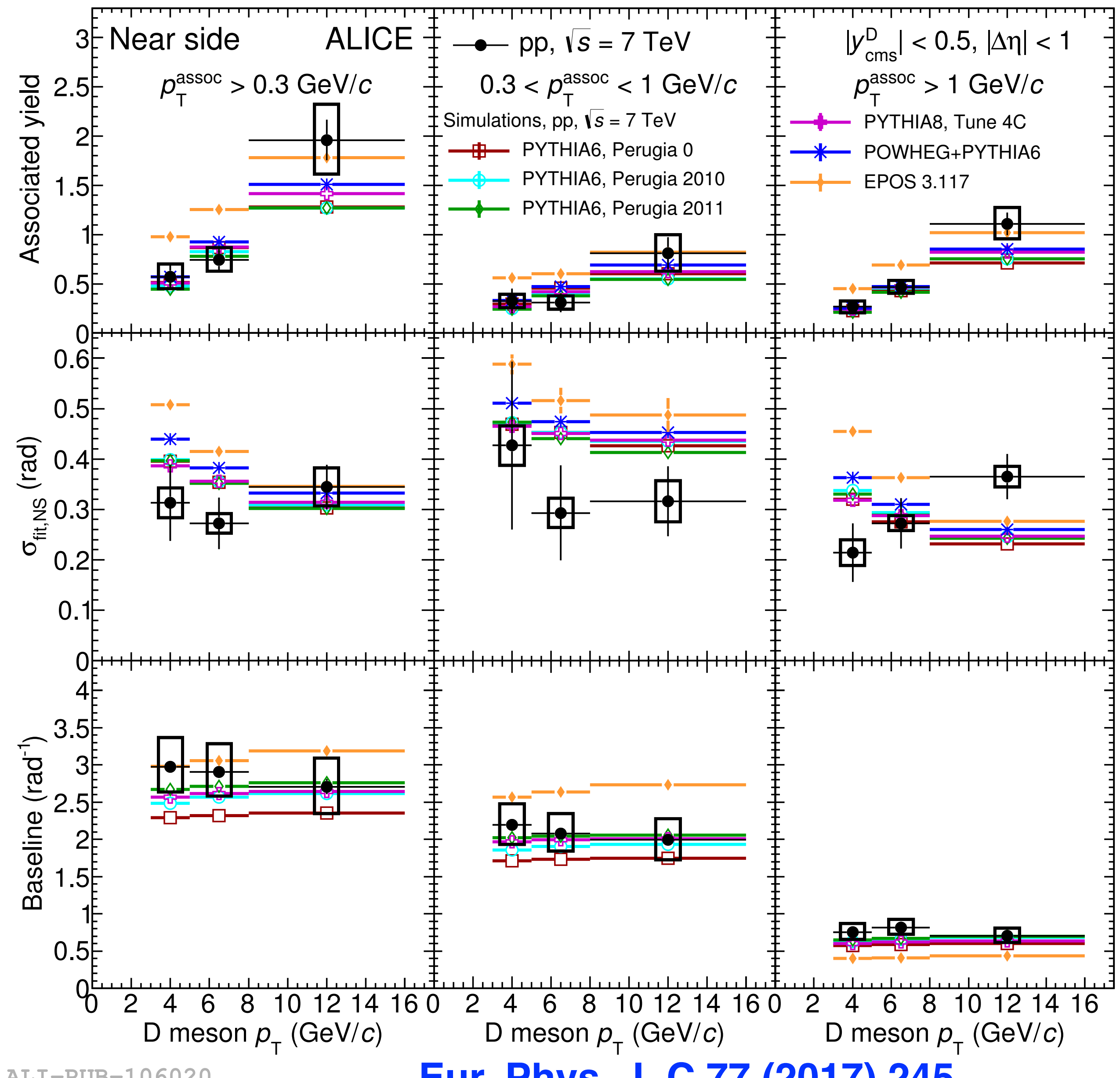


pp, $\sqrt{s}$ = 7 TeV

- **The comparison is performed after baseline subtraction.**
- **The shape of the correlation distributions and the evolution of correlation peaks with D-meson and associated charged-particle p_T are reproduced within uncertainties by the generators in the near side.**
- **In the away side POWHEG+PYTHIA6 and PYTHIA8 are closer to the data.**

Results : Near-side physical observables (comparison with Monte-Carlo)

pp, √s = 7 TeV



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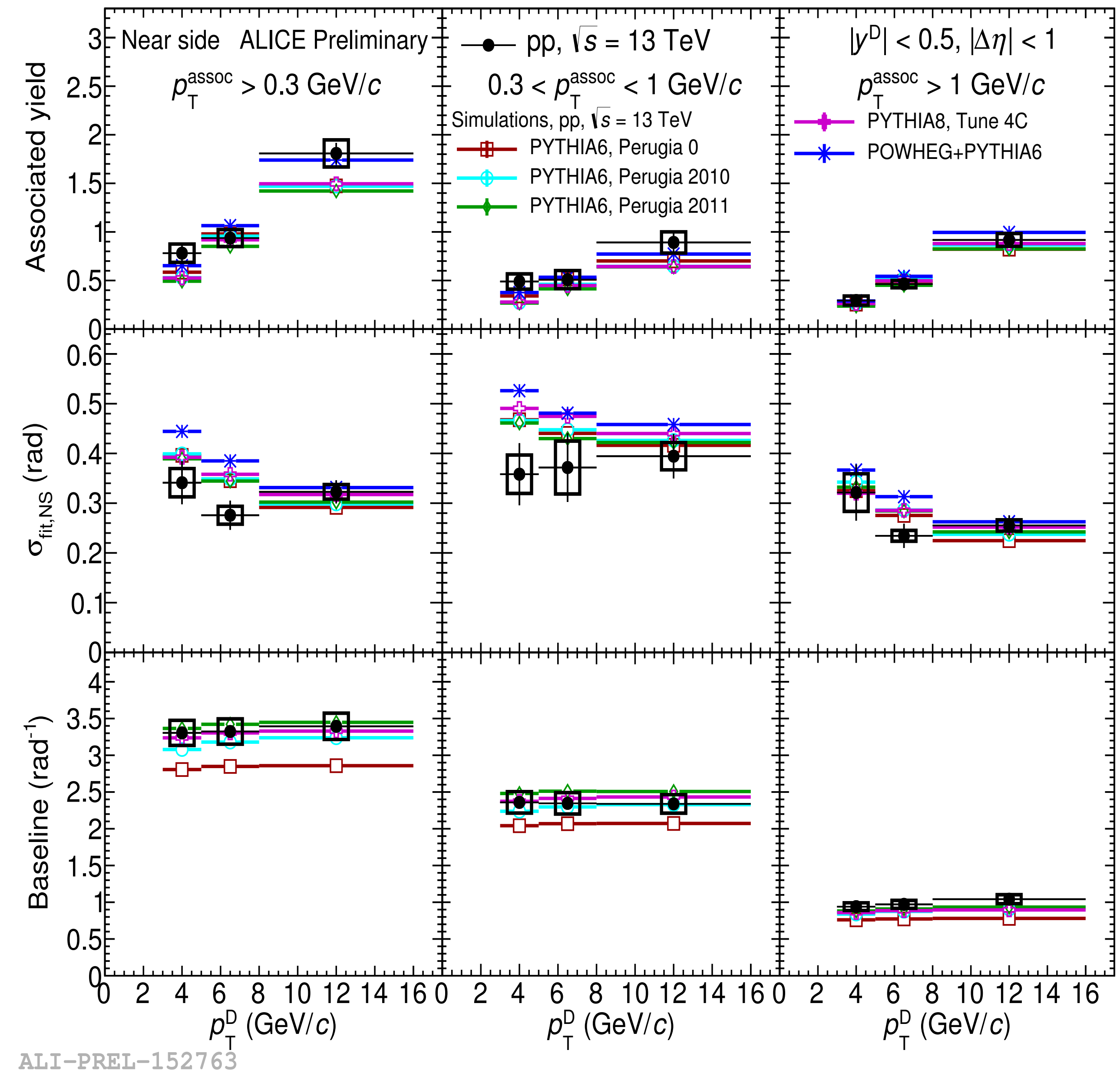
pp, √s = 13 TeV



- **Overall compatibility of near-side yields with MC predictions.**
- **Good description of near-side width within the uncertainties.**

Azimuthal correlation between heavy-flavour decay electrons and charged particles

Data Sample
Pb-Pb 5.02 TeV (2015 data), 24.6M Minimum-bias events
p-Pb 5.02 TeV (2016 data), 257M Minimum-bias events

Analysis Strategy

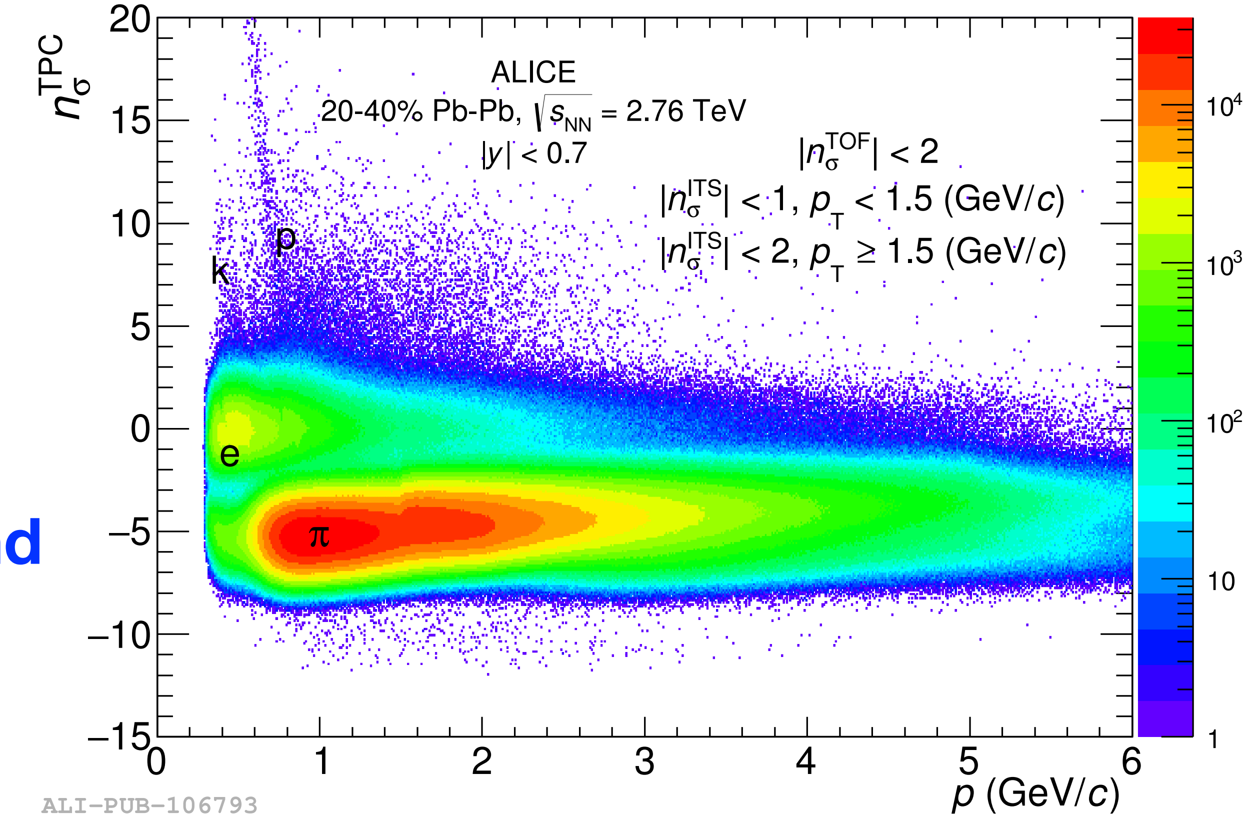
- **Electron identification**
- **Semi-leptonic decays of heavy-favour hadrons:**

$b,c \rightarrow e^{\pm}X$ (*BR*≈10%)

- **Electron identification (TPC,TOF, ITS, EMCal):**

d*E*/d*x* and *E/p*

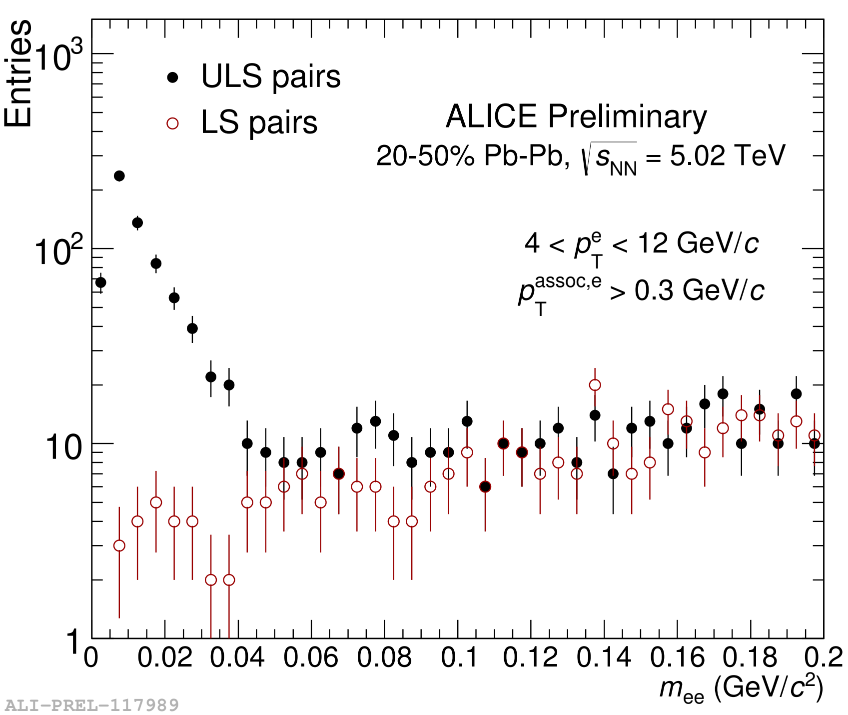
JHEP 09 (2016) 028

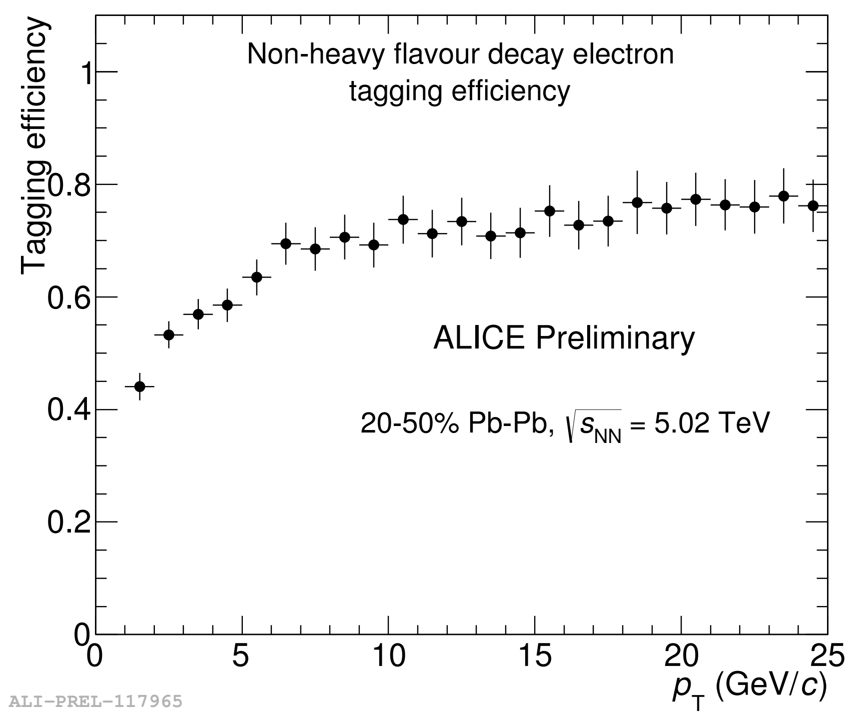


- **Non heavy-flavour electron identification and efficiency calculation**

- **Sources: Conversion ($\gamma \rightarrow e^{+}e^{-}$)**

Dalitz decay ($\pi/\eta \rightarrow \gamma e^{+}e^{-}$)



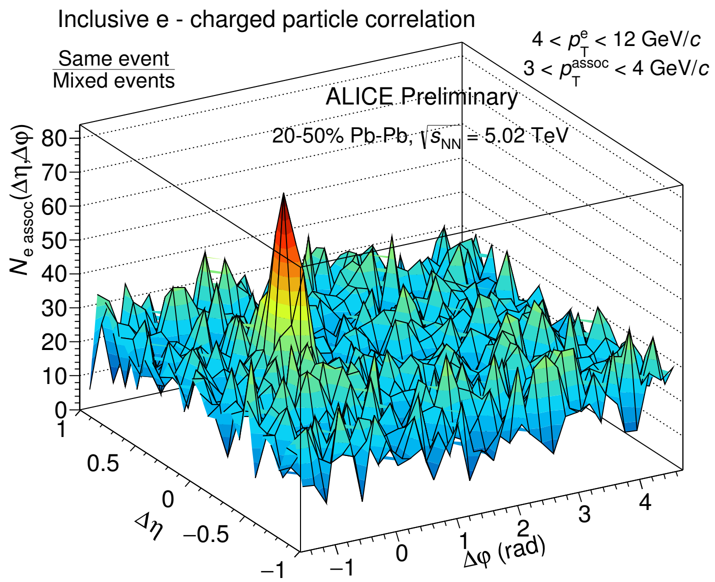


Invariant mass method is used to identify non HF electrons combining e⁻ candidates with all other e⁺ candidates with a constraint opening angle.

$$N_{NonHFE} = N_{ULS} - N_{LS}$$

- **Obtain ($\Delta\varphi$, $\Delta\eta$) distribution between inclusive electrons and charged particles.**
- **Detector effects corrected using mixed event technique and project onto $\Delta\varphi$.**
- **Efficiency corrected non-HF decay electrons obtained using invariant mass calculation.**

$$\Delta\varphi_{NonHFE} = (1/\varepsilon_{NHFE})\ \Delta\varphi_{reco\text{-}NonHFE}$$



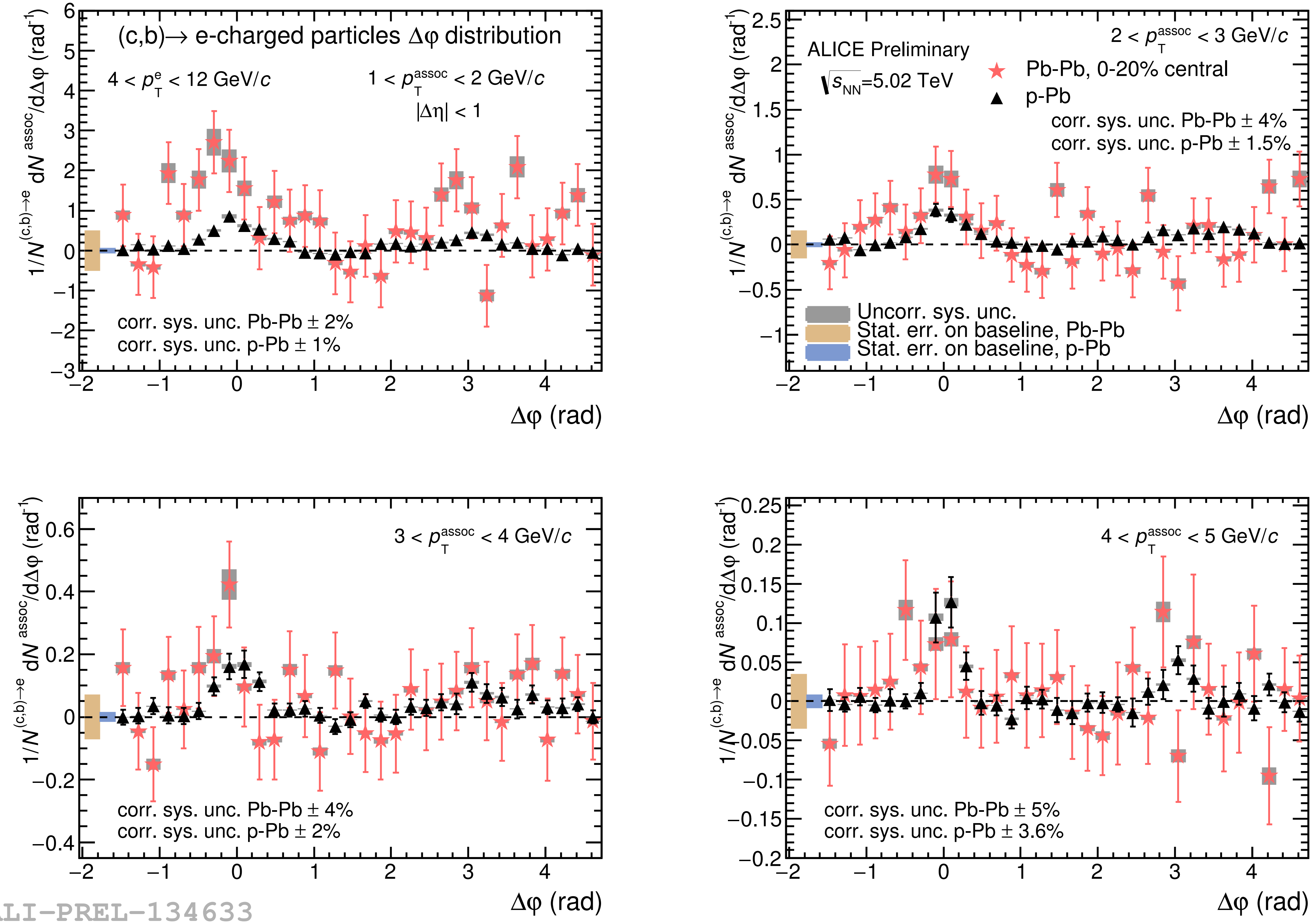
Correlations between HFE and charged particles obtained as:

$$\Delta\varphi_{HFE} = \Delta\varphi_{IncE} - \Delta\varphi_{NonHFE}$$

- **Apply charged-particle tracking efficiency and normalize with number of trigger HF-decay electrons.**

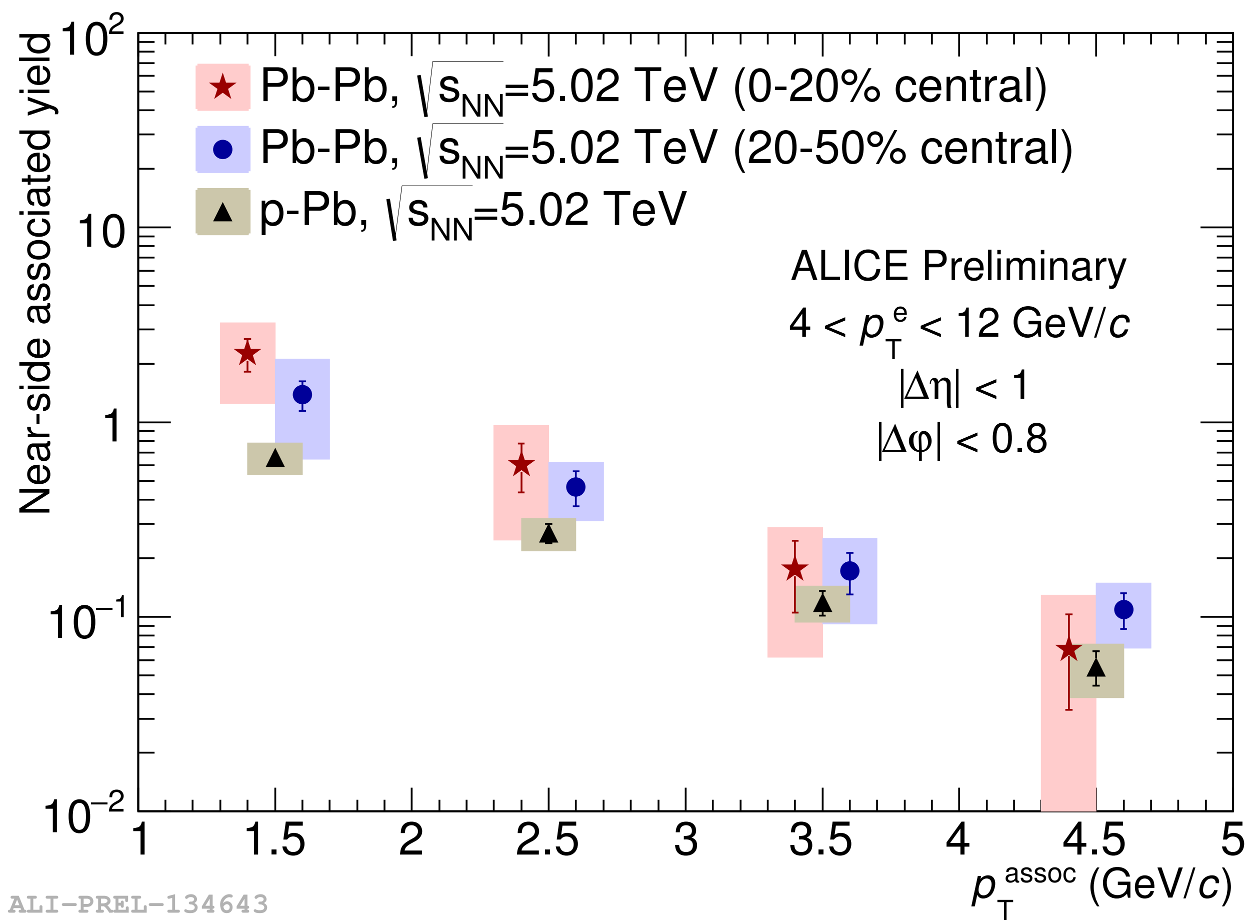
$$1/(N_{TrigE} * \varepsilon_{Had})\ [\Delta\varphi_{IncE} - 1/\varepsilon_{NHFE} * \Delta\varphi_{\ reco\ non\text{-}HFE}]$$

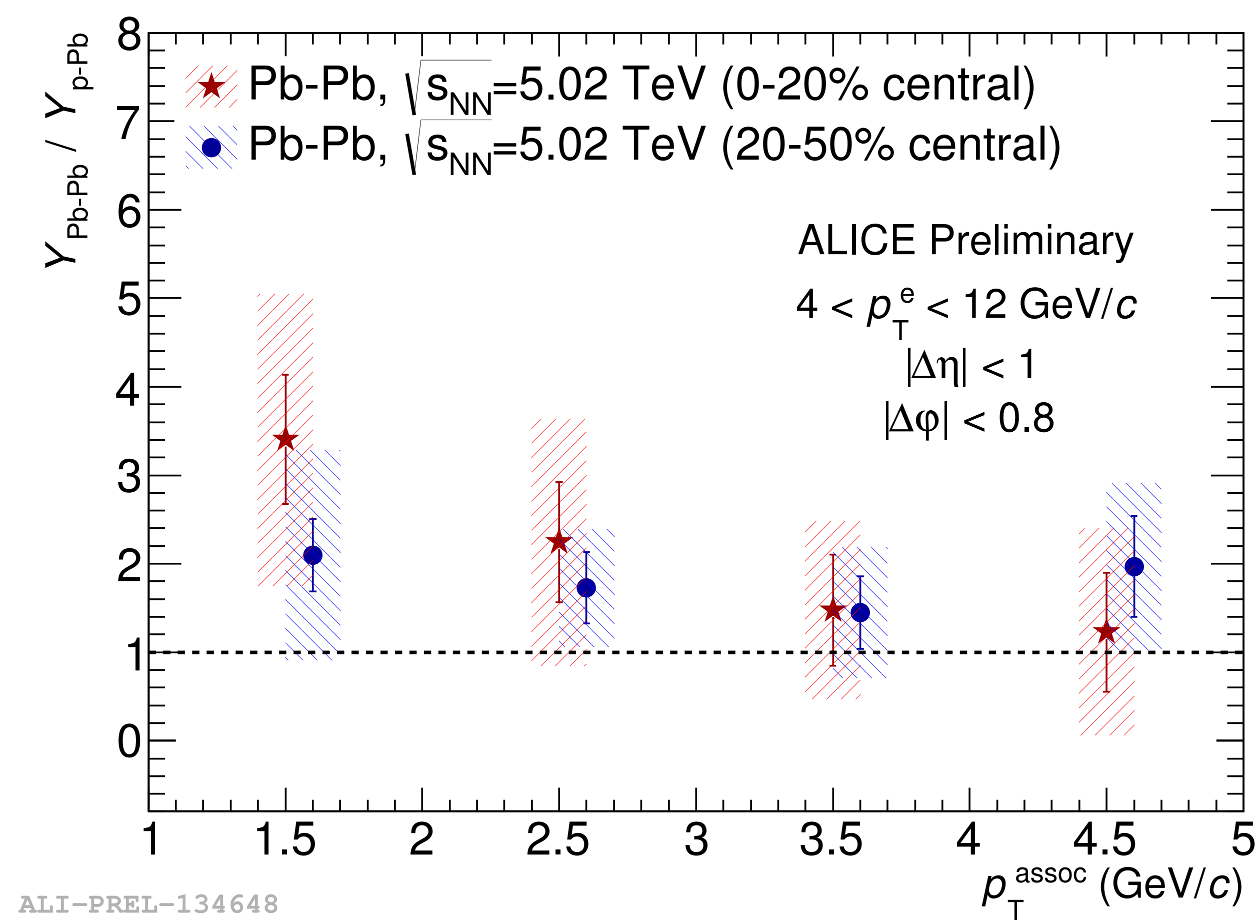
Results: Correlation between heavy-flavour decay electron-charged particle



- **The central flow contribution subtracted $\Delta\varphi$ distribution in Pb-Pb collisions is compared to the pedestal subtracted distribution in p-Pb collisions.**
- **The comparison shows a hint of increase in the near-side yield in Pb-Pb collisions w.r.t p-Pb collisions.**

Results: Near-side yield extraction from Heavy-flavour decay electron-charged particle correlation





- **Near-side yield in Pb–Pb collisions is consistent with that in p–Pb collisions at high associated p_T within uncertainties**
- **Hint of near-side yield enhancement in the 20% most central Pb–Pb collisions w. r. t. p–Pb collisions at low associated p_T — more precise measurement is expected in the next Pb–Pb run (end of 2018)**

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Summary:

D-hadron correlations:

- compatible near-side yields and widths in pp at $\sqrt{s}$ = 7, 13 TeV and p-Pb at $\sqrt{s_{NN}}$ = 5.02 TeV.
- Good agreement of near-side observables with MC predictions.

HFe-h correlations:

- Hint of near-side yield enhancement in central Pb-Pb collisions.

Suppression of the away-side correlation peak gives a hint to in-medium energy loss.

Outlook:

- More precise and differential measurements expected with pp data of 2017 and 2018 and 2018 Pb-Pb run.
- Looking forward to theoretical predictions for these observables !

Thank you