Study of azimuthal correlations between D mesons and charged particles with the ALICE experiment

Fabio Colamaria, for the ALICE Collaboration

Università degli Studi di Bari Aldo Moro

INFN Istituto Nazionale di Fisica Nucleare

ALICE

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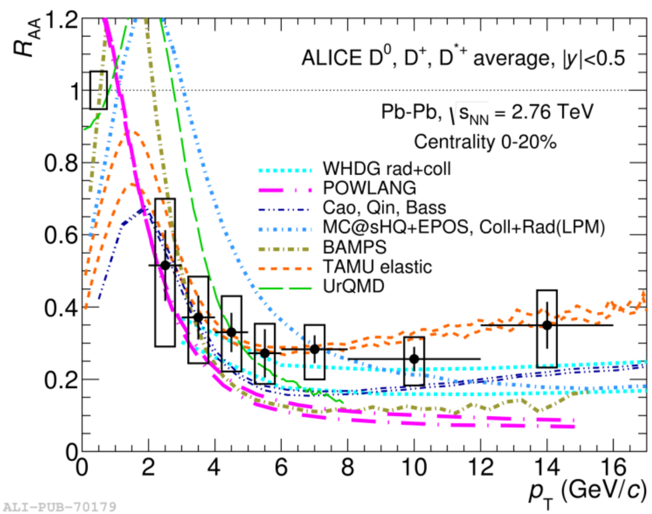
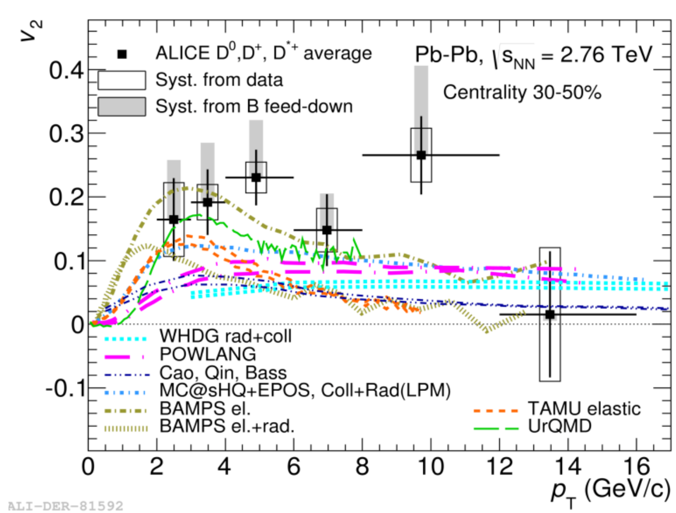
Outline

- Physics motivations
- ALICE detector
- D-hadron correlation analysis
  - Analysis strategy and steps
  - Results in pp and p-Pb collisions
  - Perspectives for Pb-Pb collisions
- Conclusions

PHYSICS MOTIVATIONS: CHARM IN HEAVY-ION COLLISIONS

- 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, expected to be formed in such collisions
- In the 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 collective motion of the medium

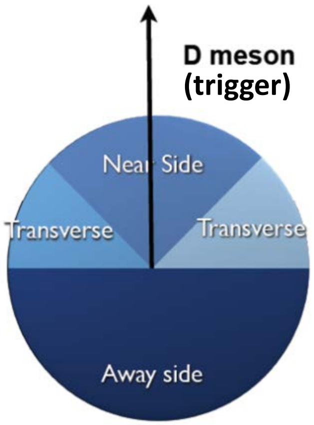




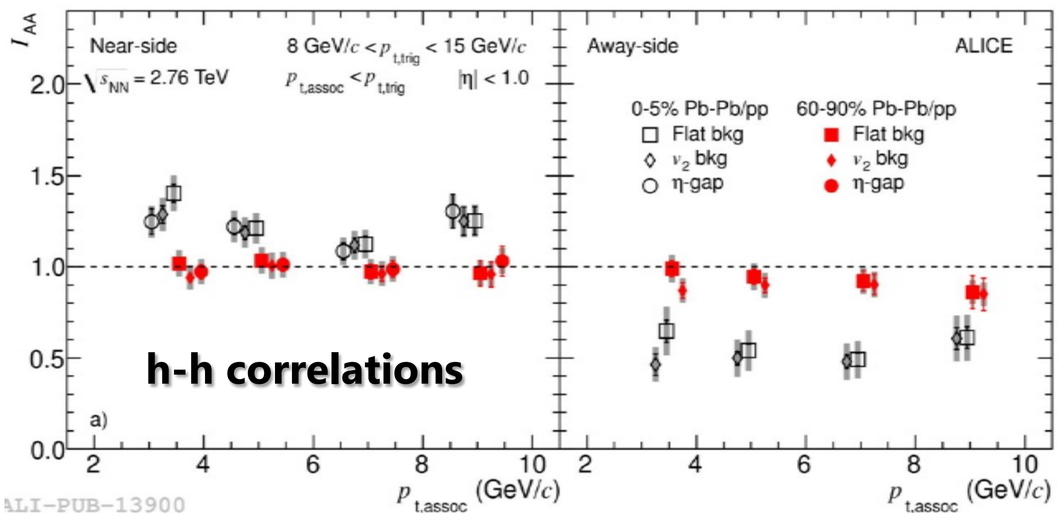
arXiv: 1405.2001

Physics motivations for charm correlation studies

- Further information about interaction of charm quarks with the QGP medium can be obtained by studying the angular correlations of D mesons with the other charged particles of the event
- Interesting regions for azimuthal correlation studies:
  - Near side: modifications of jets properties
  - Away side: address path-length dependence of energy loss by studying away-side peak suppression



- Main observable: $$I_{AA}(p_{T,\mathrm{trig}}; p_{T,\mathrm{assoc}}) = \frac{Y^{AA}(p_{T,\mathrm{trig}}; p_{T,\mathrm{assoc}})}{Y^{pp}(p_{T,\mathrm{trig}}; p_{T,\mathrm{assoc}})}$$ → *$Y_{AA/pp}$ = yields of near-side or away-side peaks in AA/pp collisions*



- ALICE results for h-h correlations (0-5% Pb-Pb vs pp):
  - Near side (Δφ ~ 0): 20% enhancement
  - Away side (Δφ ~ π): 50% suppression

PRL 108, 092301 (2012)

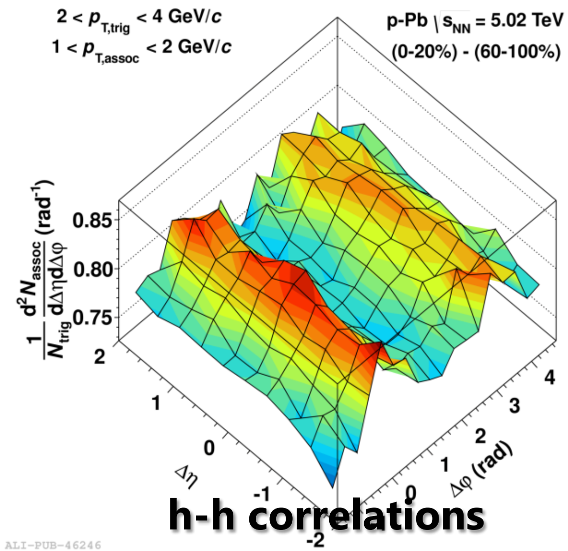
Physics motivations for charm correlation studies

Main goals of D-hadron correlation studies

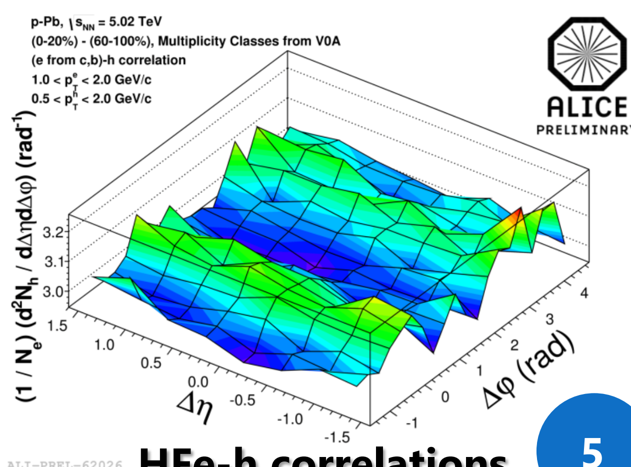
- In pp collisions:
  - Characterize charm quark fragmentation and study charm jet properties
  - Study the contribution of charm production from different hard scattering processes (pair production, flavour excitation, gluon splitting)
    → **Norrbin and Sjostrand, Eur. Phys. J. C17 (2000) 137**
  - Reference for p-Pb and Pb-Pb results

- In p-Pb collisions:
  - Investigate on possible modifications of angular correlations which could derive from initial state effects (e.g. CGC) or possible final state effects
  - Search for long-range ridge-like structures (double ridge) as those found in h-h and electrons from HF-h correlations

Phys. Lett. B709, 29 (2013)



h-h correlations



HFe-h correlations

Analysis target & steps

- Target: fully corrected azimuthal correlation distribution of D mesons and charged primary hadrons
  - Study performed in p_T intervals: **3 <** $\boldsymbol{p_T}$**(D) < 5** GeV/c, **5<** $\boldsymbol{p_T}$**(D) < 8** GeV/c and **8 <** $\boldsymbol{p_T}$**(D) < 16** GeV/c, with $\boldsymbol{p_T}$**(assoc) >0.3, 0.5, 1** GeV/c, with $|y_D| < 0.5$

- Analysis steps:
  - D-meson reconstruction and correlation to selected associated tracks
  - Subtraction of correlation of background D-meson candidates
  - Corrections for:
    - ✓ Detector effects and pair acceptance via event mixing
    - ✓ D-meson and associated track efficiency
    - ✓ Feed-down from B-meson decays
    - ✓ Residual contamination from secondary tracks
  - Fit to azimuthal correlation distributions and extraction of physical observables
    - ✓ Near-side yield, near-side peak width, height of baseline

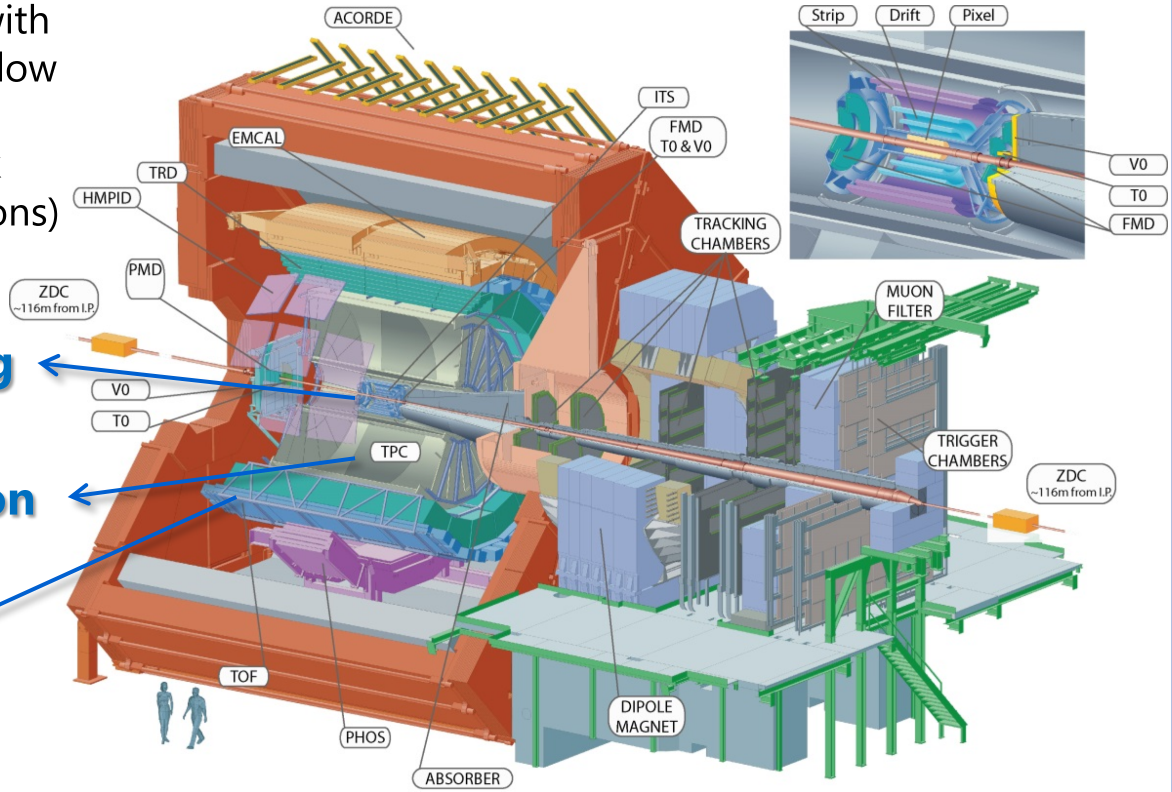
THE ALICE EXPERIMENT

ALICE: General purpose detector with excellent PID capabilities and very low p_T reach (~100 MeV/c)
Optimized to work in high track density environment (Pb-Pb collisions)

ITS: tracking & vertexing

TPC: tracking, K/π separation

TOF: K/π separation



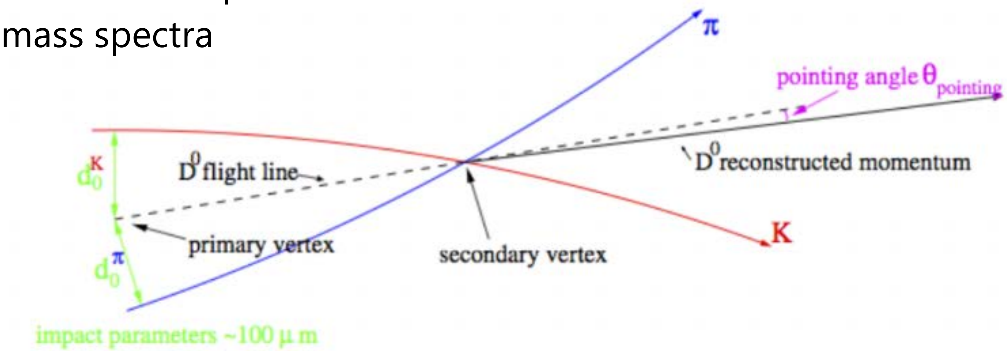
Data samples

- pp collisions at $\sqrt{s}$ = 7 TeV (L_{int} = 5 nb^{-1}, from 2010 run)
- p-Pb collisions at $\sqrt{s_{NN}}$ = 5.02 TeV (L_{int} = 50 μb^{-1}, from 2013 run)

D-MESON AND ASSOCIATED TRACK SELECTION

- D-meson signal extracted from an invariant mass analysis of fully reconstructed decays
- D-meson candidates selected by exploiting:
  - **Topology** of the decay, displacement of secondary vertex
  - **Particle identification** using TPC and TOF response

Raw yield extraction via fit to invariant mass spectra

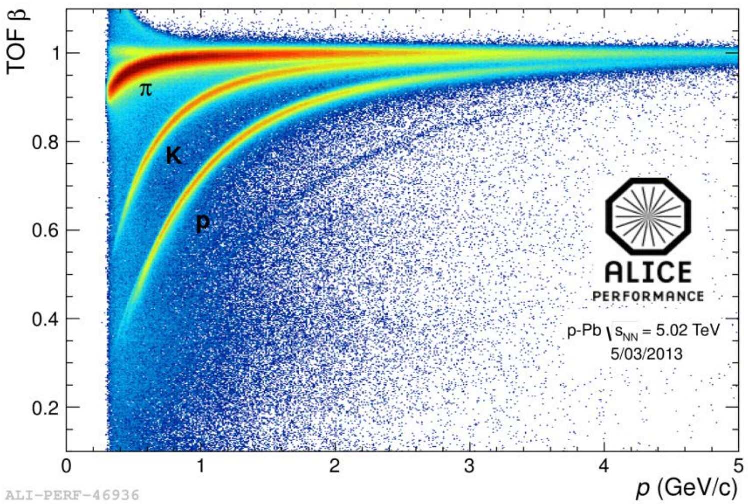


Reconstructed decay channels:

$D^0 \rightarrow K^- \pi^+$

$D^{*+} \rightarrow D^0 \pi^+ \; (D^0 \rightarrow K^- \pi^+)$

$D^+ \rightarrow K^- \pi^+ \pi^+$



- 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, |η| < 0.8) and track-quality cuts

Correlation evaluation and background subtraction

- Each selected D meson is correlated with the selected associated particles found in the same event
- 2D angular correlation distributions are produced, with variables:
  - $\Delta\varphi = \varphi_{Trig} - \varphi_{Track}$
  - $\Delta\eta = \eta_{Trig} - \eta_{Track}$
- 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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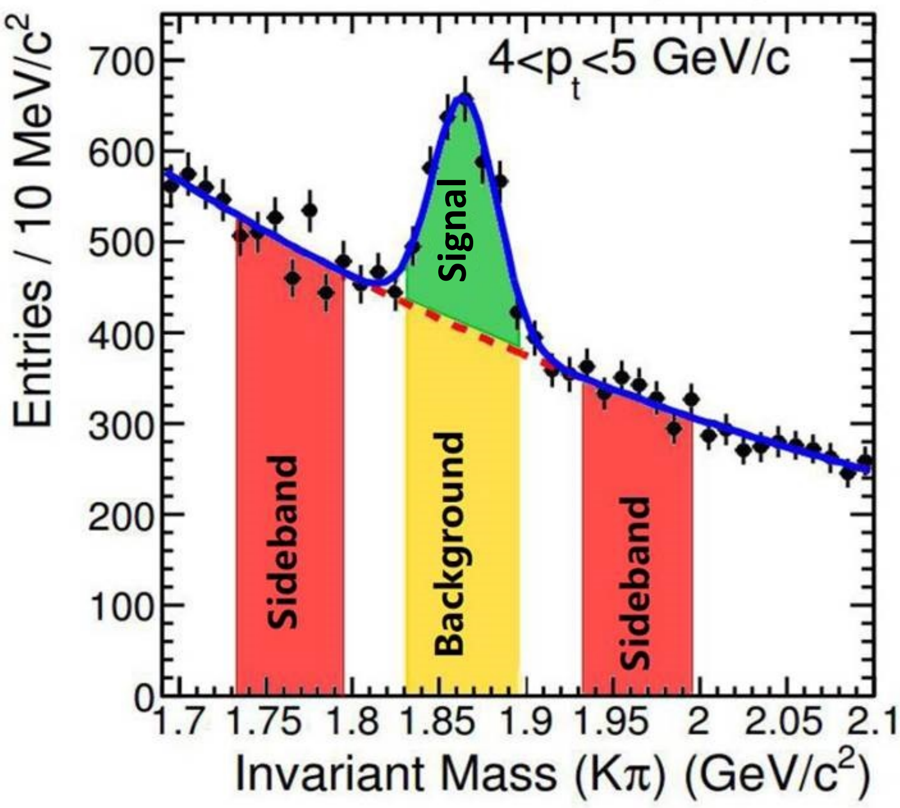
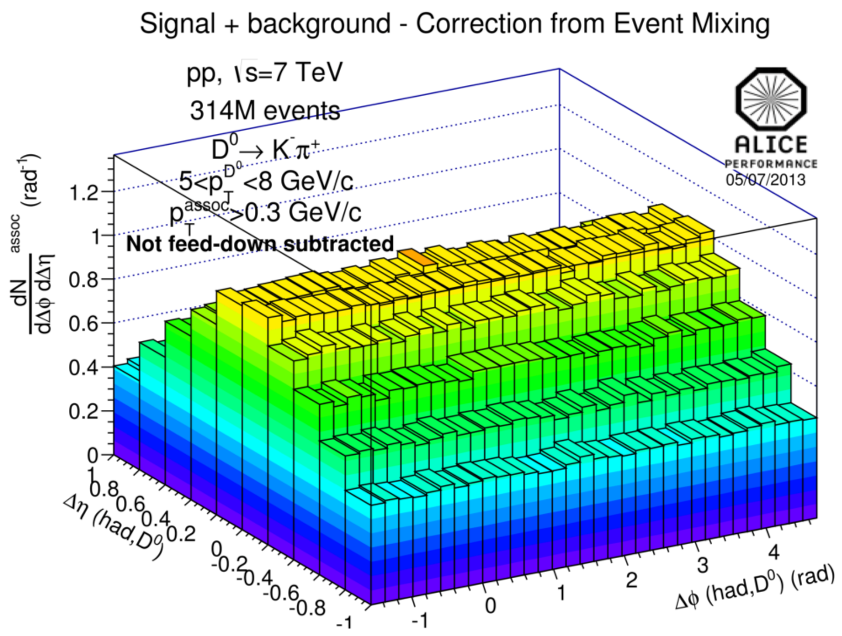


EVENT MIXING CORRECTION

- Results are corrected for the limited detector acceptance and for detector spatial inhomogeneities using the **event mixing** (EM) technique:

  - D mesons from an event are correlated with tracks from other events with similar features (z position of primary vertex, event multiplicity)

  - Event mixing distribution is normalized to 1 at (Δφ,Δη) = (0,0) and used to correct 'same event' correlations as:

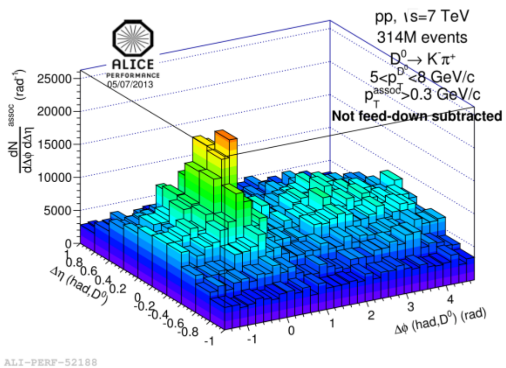


$$\frac{d^2N^{\mathrm{EMcorr}}(\Delta\varphi,\Delta\eta)}{d\Delta\varphi d\Delta\eta} = \frac{\frac{d^2N^{\mathrm{SE}}(\Delta\varphi,\Delta\eta)}{d\Delta\varphi d\Delta\eta}}{\frac{d^2N^{\mathrm{Mixed}}(\Delta\varphi,\Delta\eta)}{d\Delta\varphi d\Delta\eta}} \frac{d^2N^{\mathrm{Mixed}}(0,0)}{d\Delta\varphi d\Delta\eta}$$

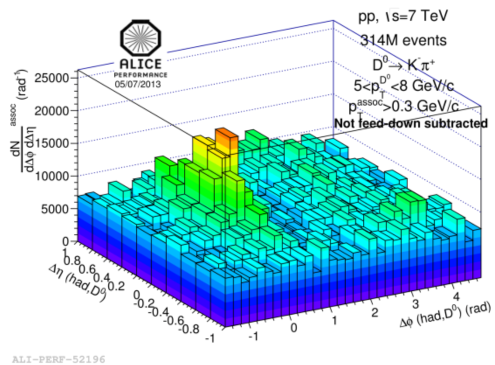
Event Mixing correction

Example for pp collisions, for $5 < p_T(D^0) < 8$ GeV/c and associated track $p_T > 0.3$ GeV/c

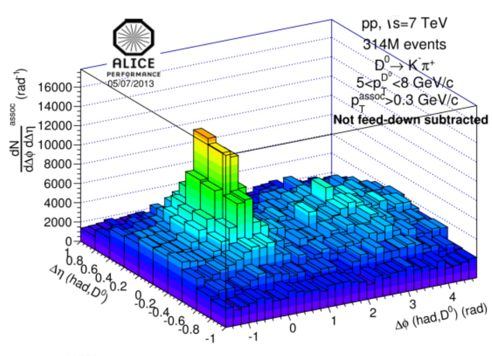
Signal region



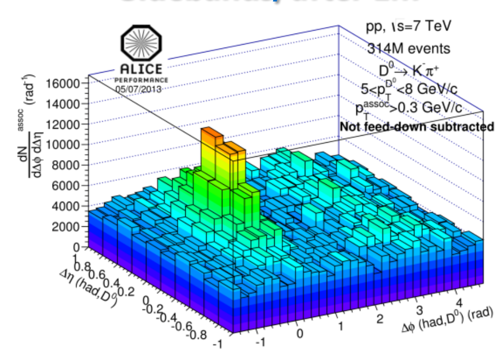
Signal region, after EM



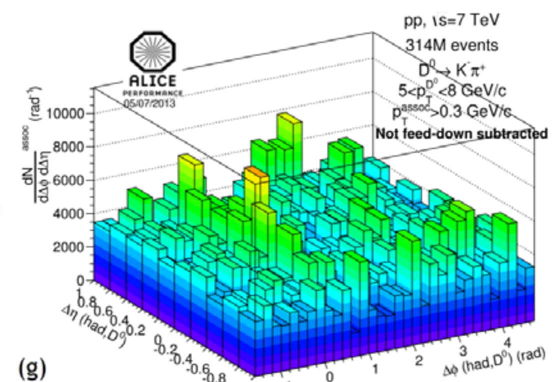
Sidebands



Sidebands, after EM



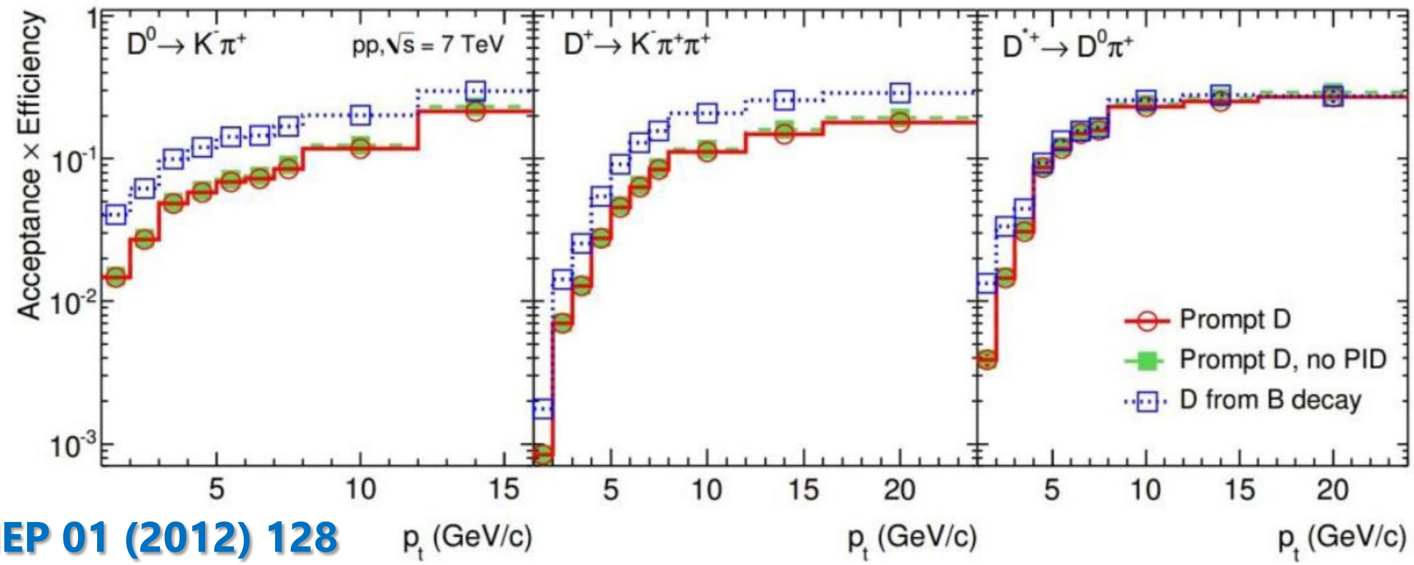
Signal (bkg subtracted) after EM



Projection onto Δφ axis

EFFICIENCY CORRECTION

- D-meson and associated track efficiency correction:
  - Accounts for associated track reconstruction efficiency and for p_T dependence of D-meson reconstruction and selection efficiency
  - 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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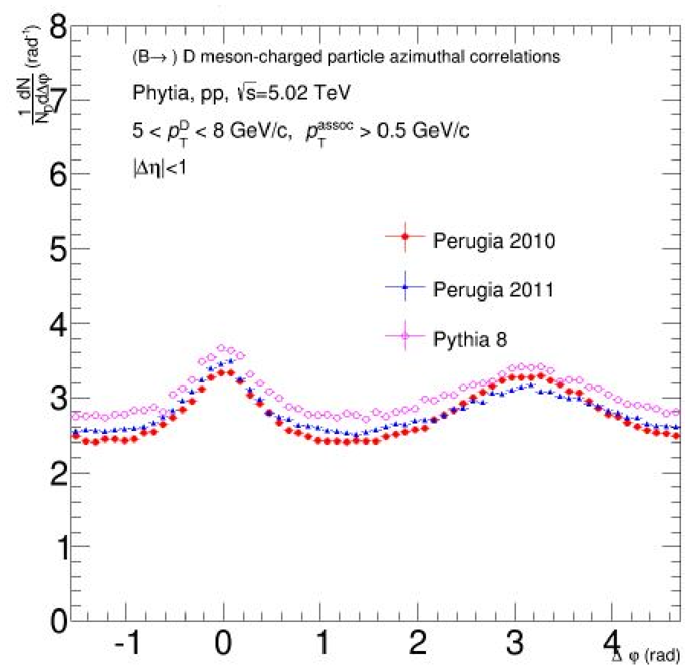
FURTHER CORRECTIONS

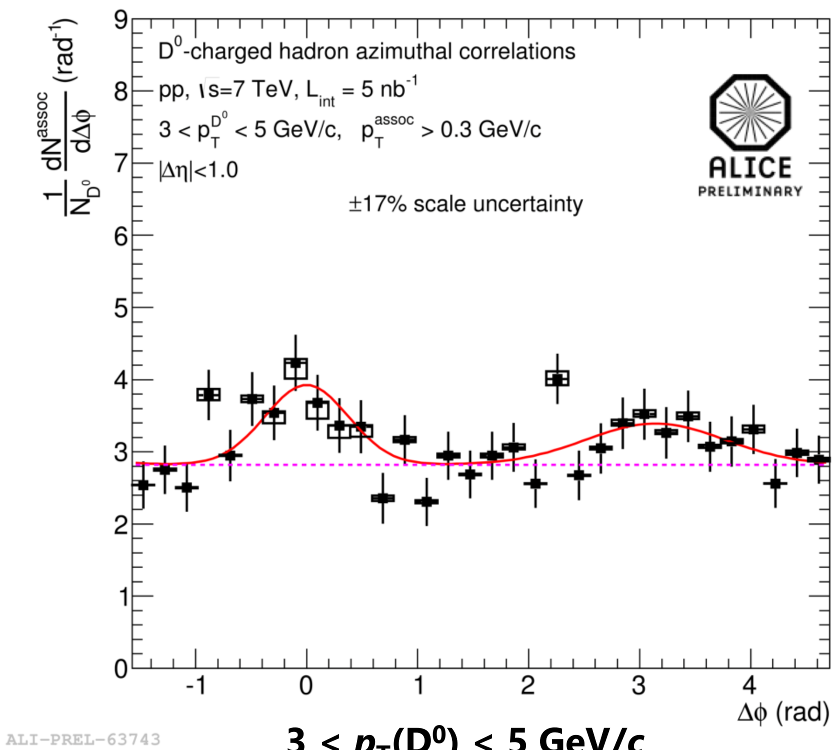
- Feed-down D contribution subtraction:
  - A template of angular correlation distribution of D mesons from beauty hadrons decays (from PYTHIA) is subtracted from the data distributions
  - Different PYTHIA parameter «tunes» exploited for the templates, after matching their baselines to the data level, to obtain a systematic uncertainty on the correction



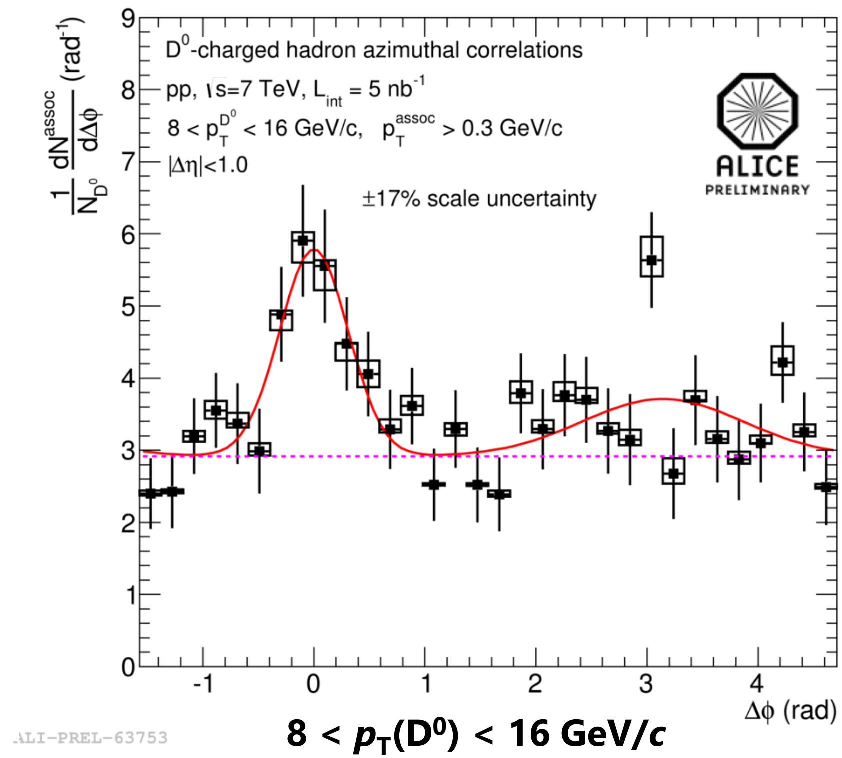
- Removal of contamination from secondary tracks:
  - Tracks from strange-hadron decays or produced in interactions of particles with the detector material
  - The contribution of secondary track particles, evaluated via Monte Carlo studies, is flat in Δφ and is removed by multipliying the data correlation distributions by the the fraction of primary particles in the track sample

D^0 MESON-CHARGED PARTICLE CORRELATION DISTRIBUTIONS

Example of azimuthal correlation distributions with D^0 mesons as trigger particles, in pp collisions



3 < $p_T(D^0)$ < 5 GeV/c
p_T(assoc) > 0.3 GeV/c



8 < $p_T(D^0)$ < 16 GeV/c
p_T(assoc) > 0.3 GeV/c

Azimuthal correlation distributions of D^0, D^{*+} and D^+ are compatible within uncertainties in all the kinematical ranges studied

Fit to the correlation distributions

- Weighted average of the azimuthal correlations of the three D-meson species:

$$\left\langle \frac{1}{N_{\rm D}} \frac{dN^{\rm assoc}}{d\Delta\varphi} \right\rangle_{\rm D} = \frac{\sum_{i=D^0,D^{*+},D^+} w_i \frac{1}{N_D} \frac{dN^{assoc}}{d\Delta\varphi}}{\sum_{i=D^0,D^{*+},D^+} w_i} \quad \text{with weights:} \quad w_i = \frac{1}{\sigma^2_{i,\rm stat} + \sigma^2_{i,\rm uncorr.syst.}}$$

- Fit to the distributions to extract physical observables:
  - Focus on baseline height (**C**), near side peak associated yield (**Y_{NS}**) and width (**σ_{NS}**)
  - Fit function: two Gaussians with fixed mean + constant term for baseline, with periodicity condition

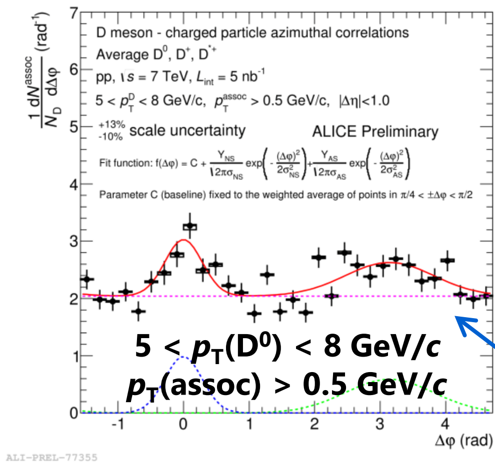
$$f(\Delta\varphi) = C + \frac{Y_{\rm NS}}{\sqrt{2\sigma^2_{\rm NS}}} \exp\left(\frac{(\Delta\varphi - \mu_{\rm NS}|_0)^2}{2\sigma^2_{\rm NS}}\right) + \frac{Y_{\rm AS}}{\sqrt{2\sigma^2_{\rm AS}}} \exp\left(\frac{(\Delta\varphi - \mu_{\rm AS}|_\pi)^2}{2\sigma^2_{\rm AS}}\right)$$

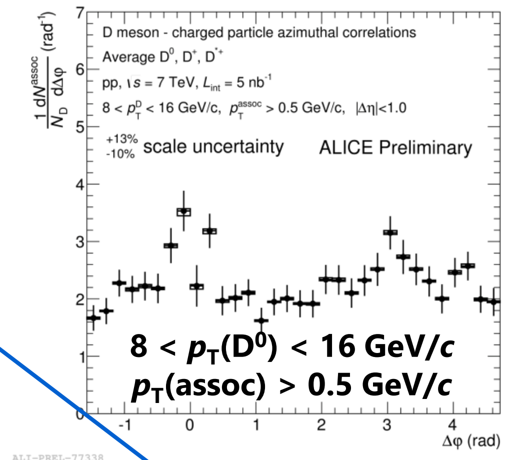
- To estimate the systematic uncertainty on the parameters:
  - Repeat fit shifting the points upward/downward in the Δφ-uncorrelated syst. uncert. range
  - Maximum variation of the parameters taken as systematic uncertainty, adding in quadrature the Δφ-correlated systematics (except for the near side width)

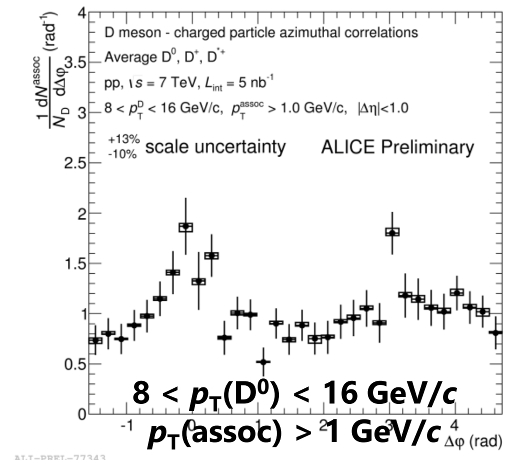
D MESON-CHARGED PARTICLE CORRELATION DISTRIBUTIONS

D meson-charged particle azimuthal correlation distributions in pp and p-Pb (D^0, D^{*+}, D^+ average)

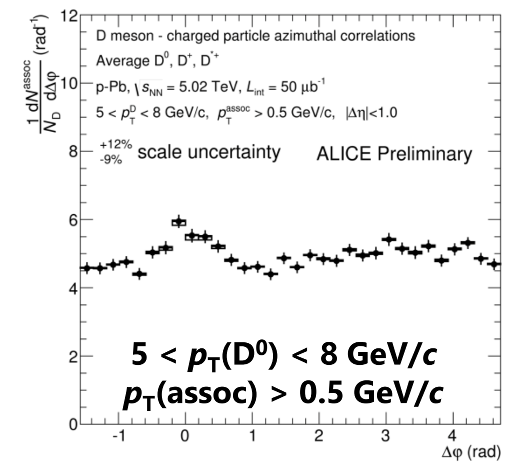
pp

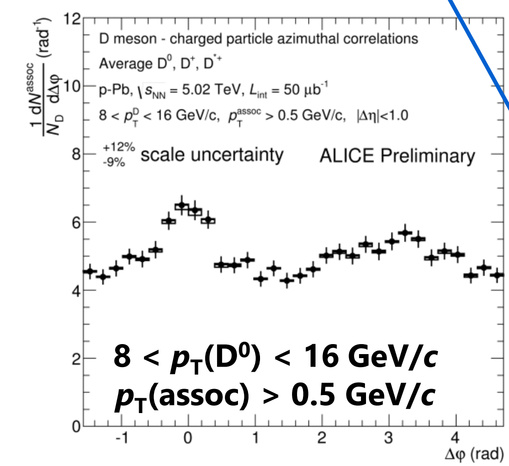


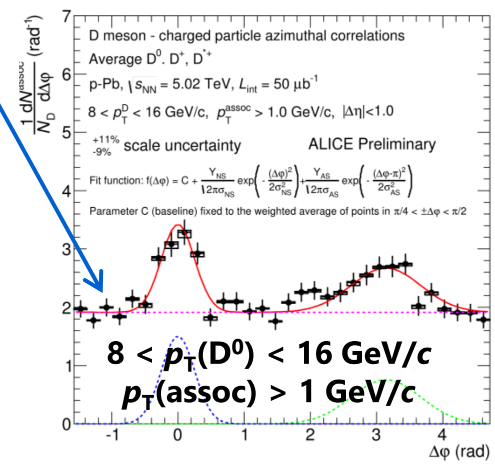




Example of fit results



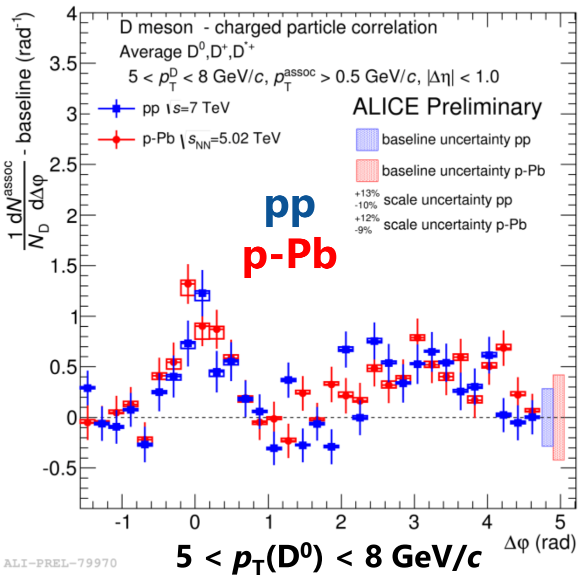




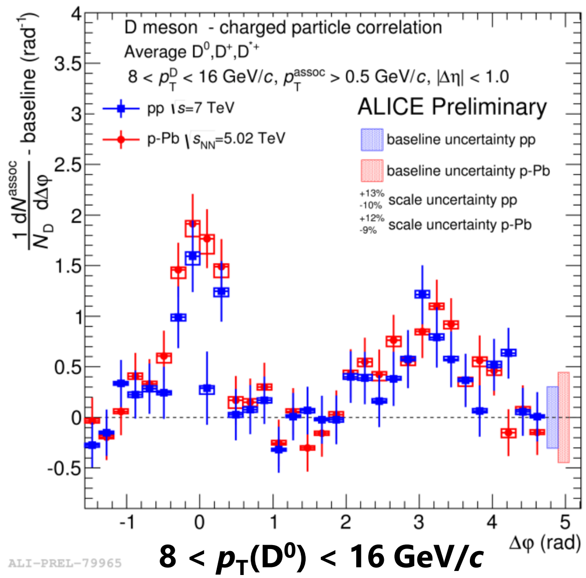
p-Pb

Comparison of Δφ distributions in pp and p-Pb

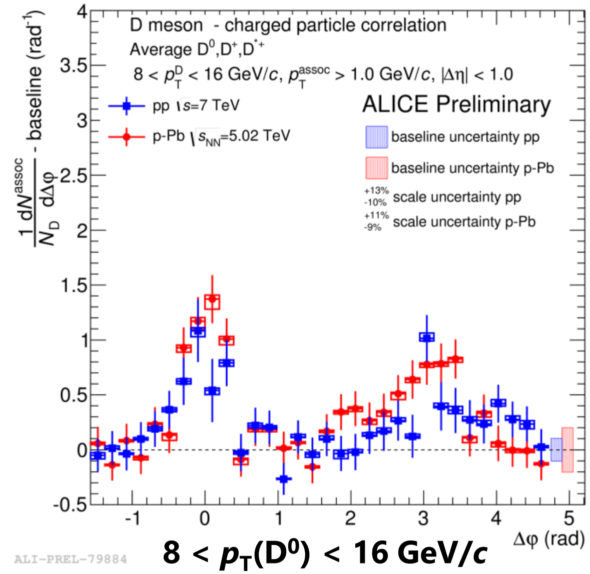
The comparison of pp and p-Pb results is performed after subtracting the baseline, evaluated from the fit to the distributions



5 < $p_T(D^0)$ < 8 GeV/*c*
p_T(assoc) > 0.5 GeV/*c*



8 < $p_T(D^0)$ < 16 GeV/*c*
p_T(assoc) > 0.5 GeV/*c*

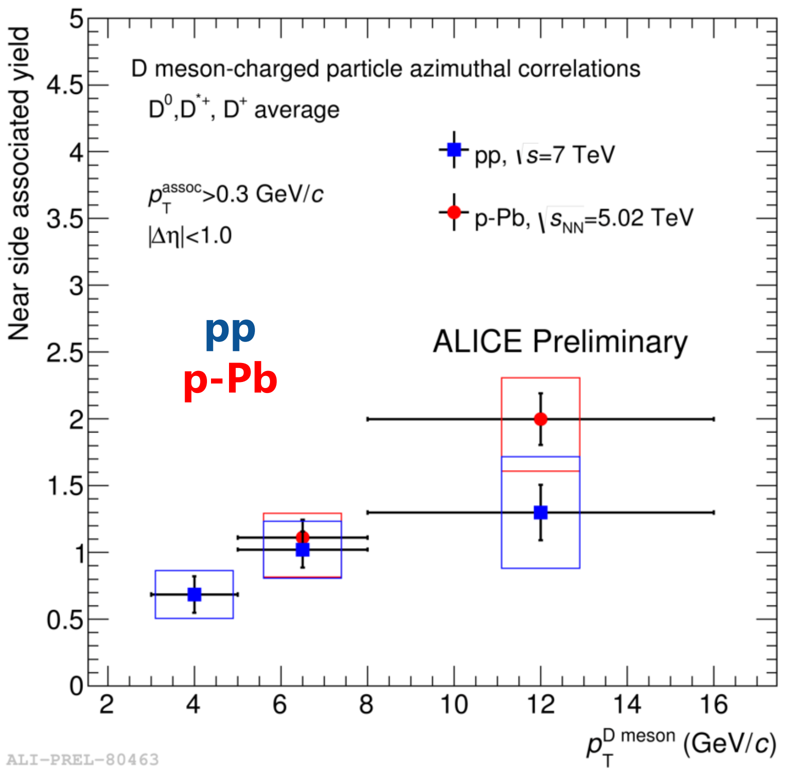


8 < $p_T(D^0)$ < 16 GeV/*c*
p_T(assoc) > 1 GeV/*c*

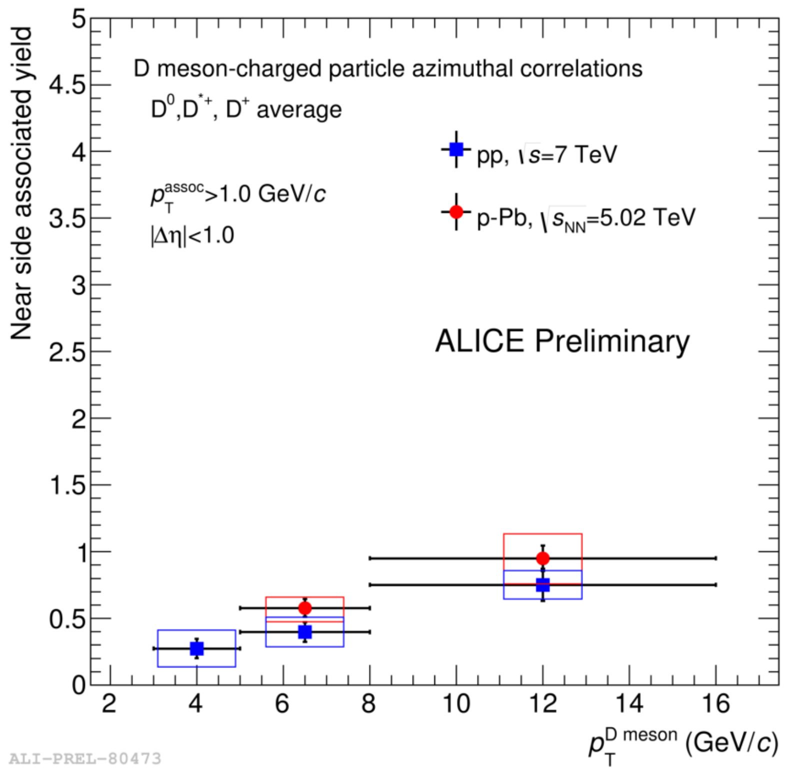
Compatibility within uncertainties found for the azimuthal correlation distributions in pp collisions at $\sqrt{s}$ = 7 TeV and in p-Pb collisions at $\sqrt{s_{NN}}$ = 5.02 TeV, for all the kinematic ranges considered in the analysis.

Comparison of near side yields in pp and p-Pb

p_T(assoc) > 0.3 GeV/c



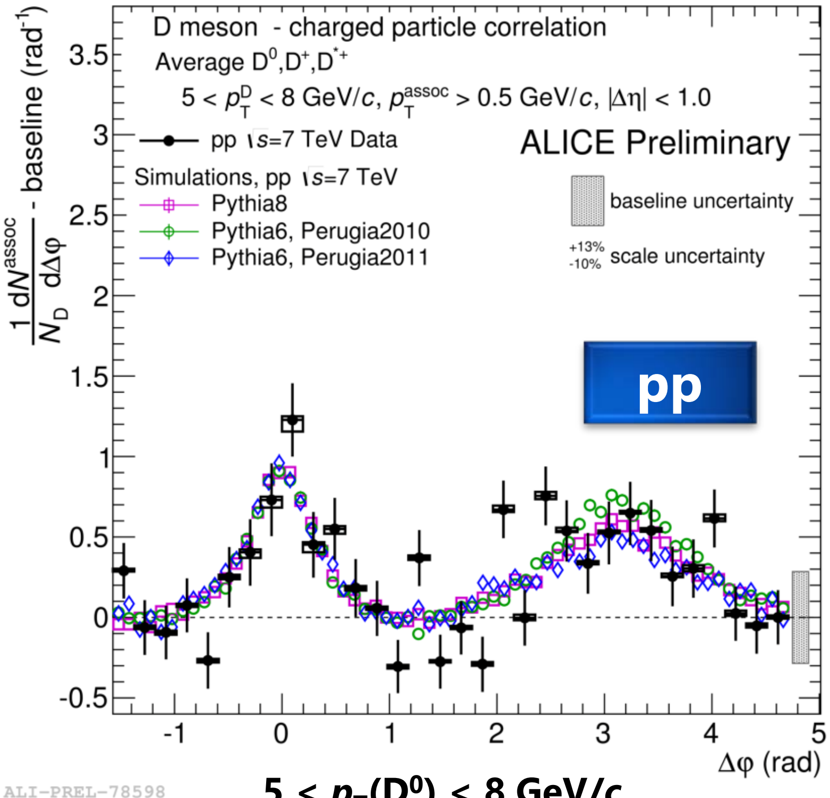
p_T(assoc) > 1 GeV/c



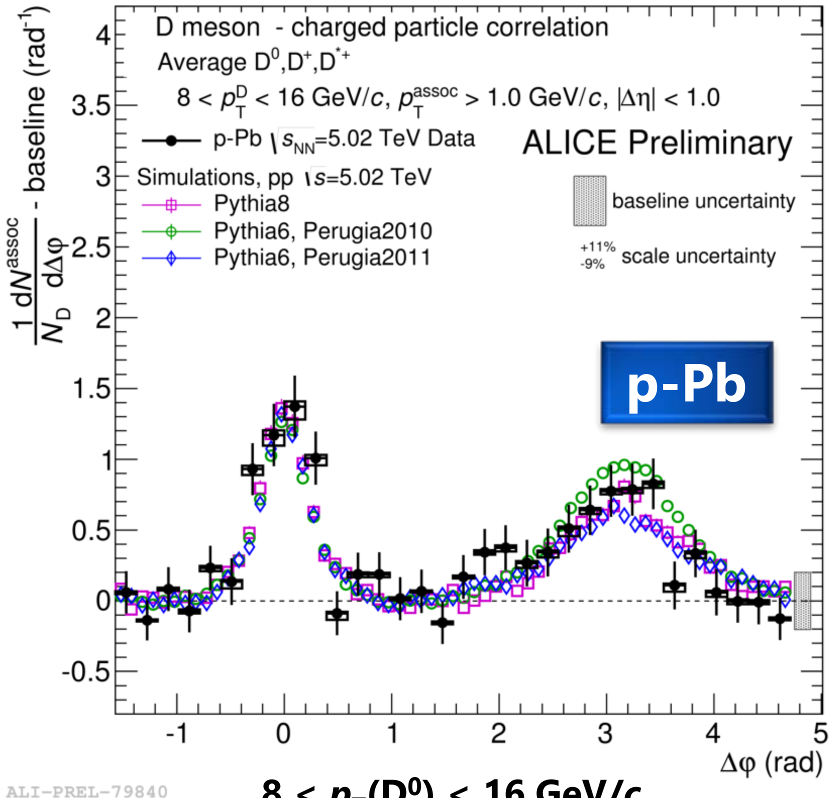
The near side associated yields in pp collisions at $\sqrt{s}$ = 7 TeV and p-Pb collisions at $\sqrt{s_{NN}}$ = 5.02 TeV are compatible within uncertainties

MONTE CARLO SIMULATIONS

Compatibility within uncertainties with expectations from different tunes of PYTHIA parameters was found



5 < $p_T(D^0)$ < 8 GeV/*c*
p_T(assoc) > 0.5 GeV/*c*

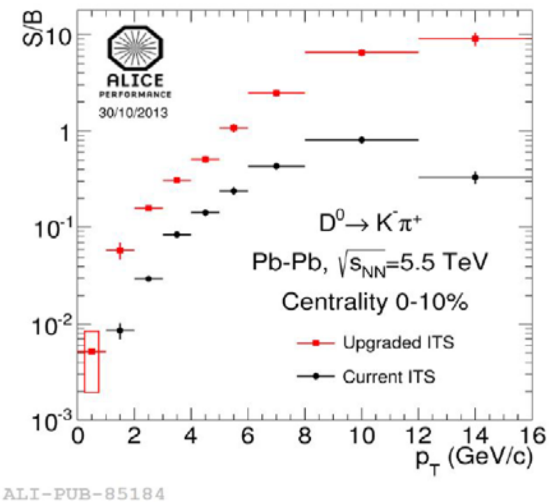


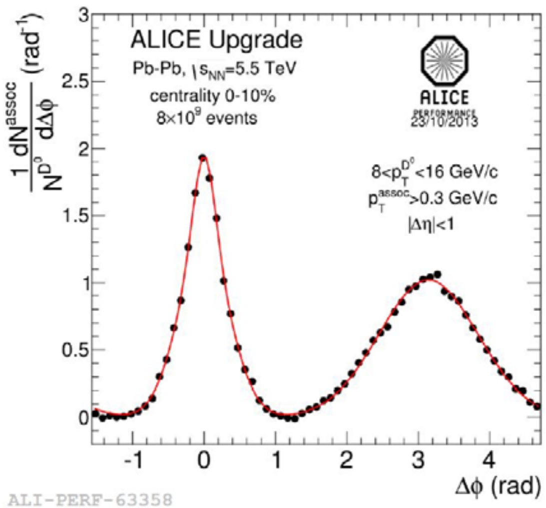
8 < $p_T(D^0)$ < 16 GeV/*c*
p_T(assoc) > 1 GeV/*c*

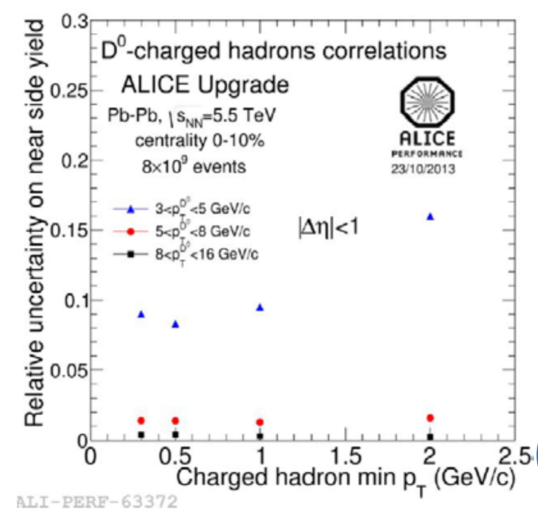
PERSPECTIVES FOR THE ANALYSIS IN Pb-Pb COLLISIONS

- Analysis feasibility verified for central Pb-Pb collisions at $\sqrt{s_{NN}}$ = 2.76 TeV (2011 data)
  - Analysis limited by statistics: distributions are dominated by fluctuations induced by background subtraction
- Dramatic improvements expected for S/B after the ALICE upgrade (during LS2, 2018-19)
- Estimate of Pb-Pb analysis performance (ITS upgrade, high rate, L_{int}= 10 nb^{-1})
  - Statistical fluctuations greatly reduced in the azimuthal correlation distributions
  - Statistical uncertainty on near side yield below 2% for $p_T(D^0)$ >5 GeV/c (about 10% for 3 < $p_T(D^0)$ < 5 GeV/c)

ALICE-TDR-017







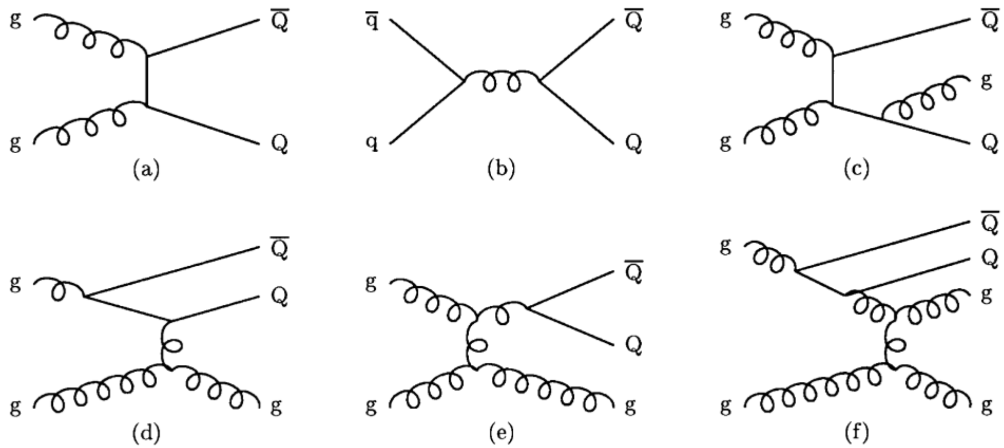
Conclusions

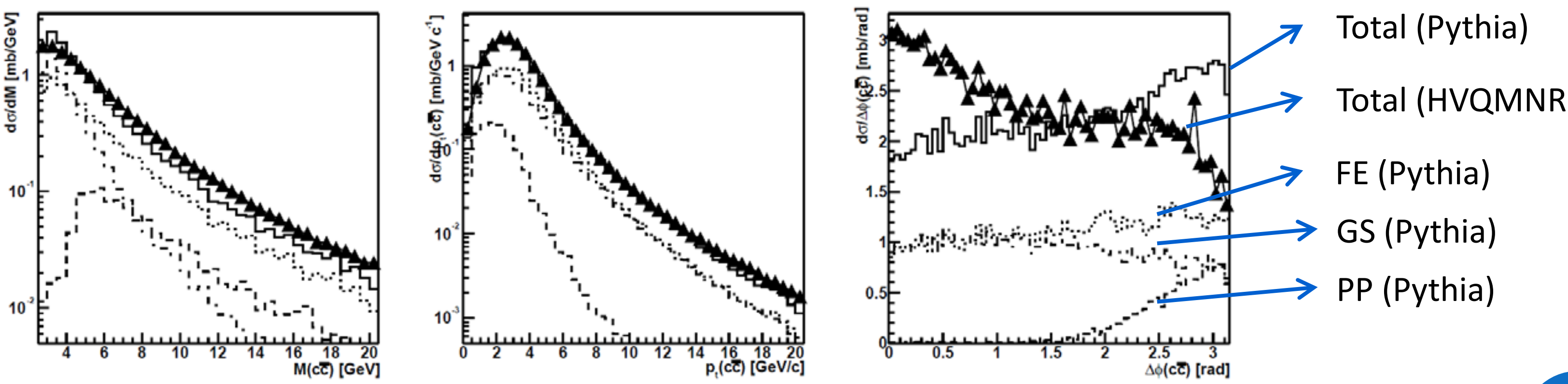
- D-hadron correlations can provide relevant information on the properties of charm production, fragmentation and hadronization and, in Pb-Pb collisions, on in-medium charm quark energy loss
- The analysis was performed and completed for pp and p-Pb collisions:
  - Results evaluated for different kinematical ranges of D^0, D^+, D^{*+} mesons and associated tracks
  - Both the Δφ correlation distributions and the near side yields are compatible in pp and p-Pb collisions, for all the kinematic ranges studied.
  - PYTHIA expectations are in agreement with data
- Perspectives for the Pb-Pb analyses were evaluated:
  - Analysis is not feasible with current statistics
  - The upgrade of the ALICE detector and the larger statistics collected with the upgraded detector will allow for precise measurements of D-hadron azimuthal correlations also in Pb-Pb, enabling a comparison of the results in the three collision systems over a wide 4_T range

BACKUP SLIDES

Charm azimuthal correlations

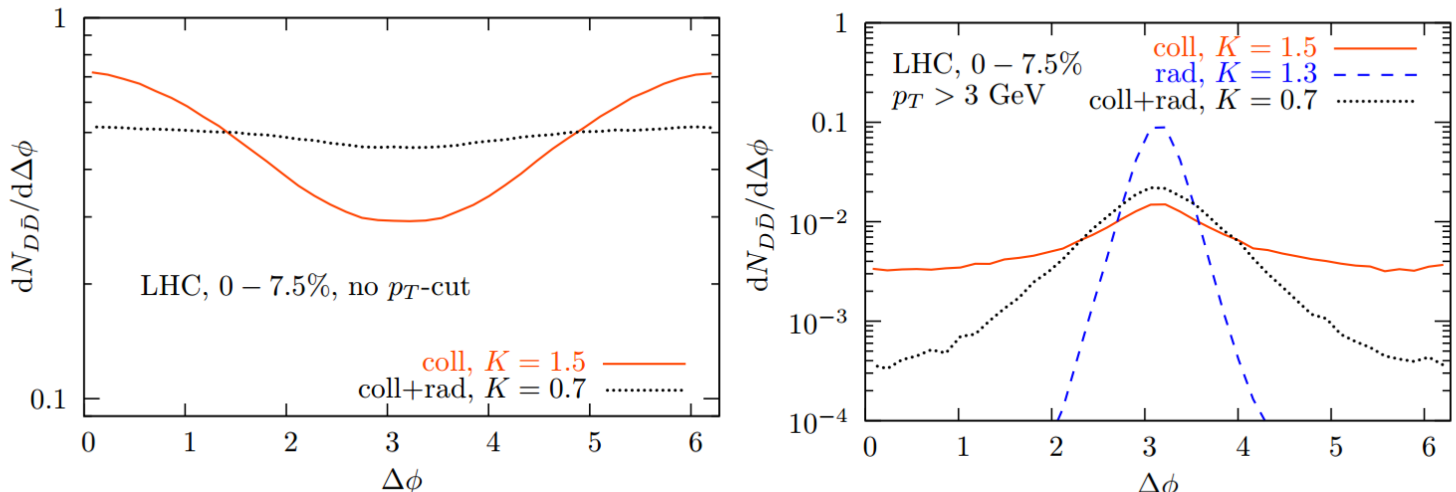
- Can we disentangle the charm production mechanisms?
  - Pair production (a, b)
  - Flavour excitation (d)
  - Gluon splitting (e)





Charm azimuthal correlations

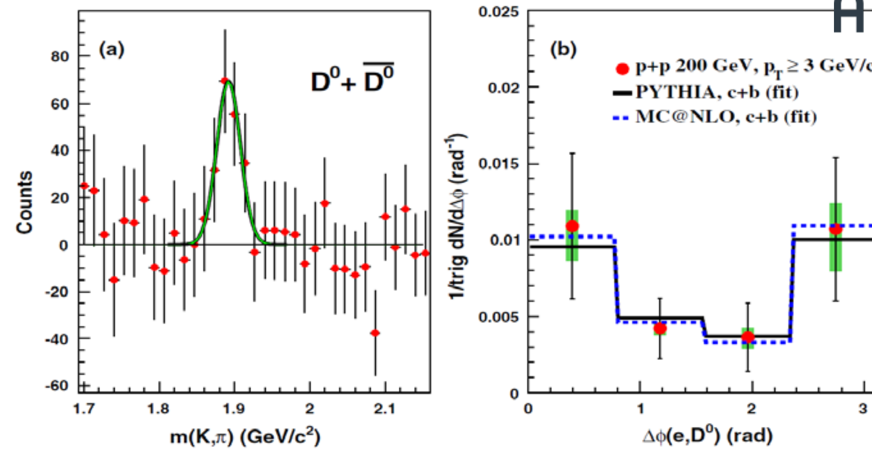
- Model by Nahrgang, Aichelin, Gossieau and Werner:
  - Radiative and collisional energy loss modify the azimuthal correlations of final charmed hadrons w.r.t. an initial back-to-back quark production
  - Collisional energy loss washes out most of the away side peak, radiative energy loss preserves it
  - Effects more visible at low pT, where 'partonic wind' effect causes even a near side peak in collisional only case!
  - NLO processes not considered in the model (only LO quark pair production)



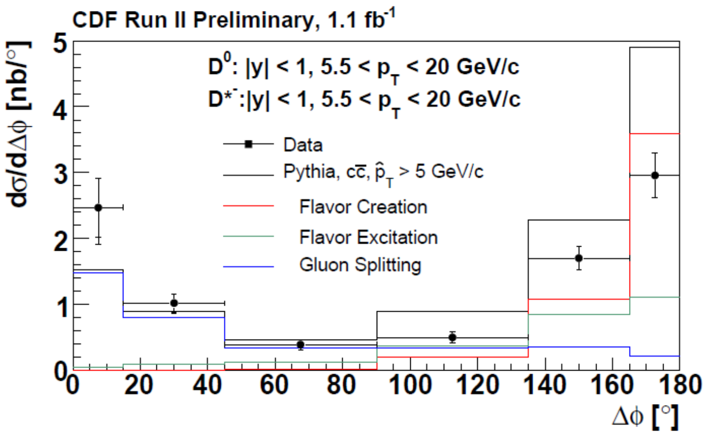
***M. Nahrgang et al.*, arXiv:1310.2218**

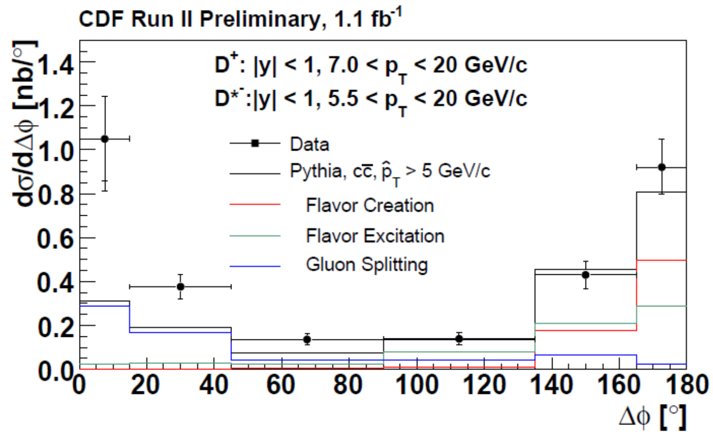
PREVIOUS RESULTS ON HF CORRELATIONS

- STAR measurements for D^0-HFe correlations in pp collisions at 200 GeV, compared with PYTHIA simulation and MC@NLO theoretical predictions



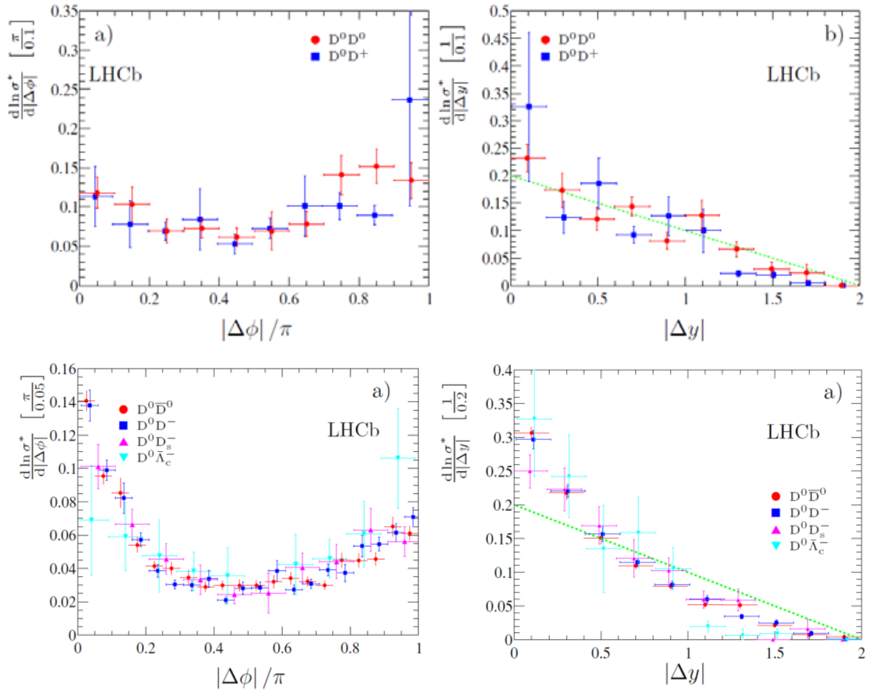
- CDF measurements for D^0-D^{*+} and D^+-D^{*+} correlations
  - Comparison to PYTHIA, with different production mechanism breakdown
  - PYTHIA overestimates LO (b2b) and underestimates NLO contribution (collinear production)

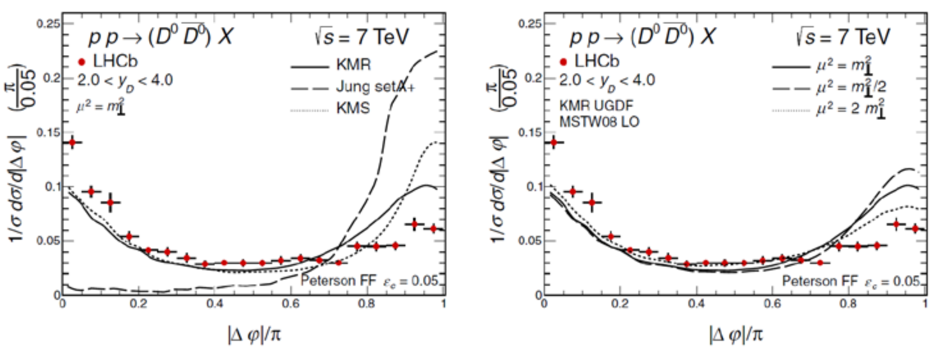




PREVIOUS RESULTS ON HF CORRELATIONS

- LHCb measurements for DD (top row) and DDbar (bottom row) angular correlations in pp collisions at 7 TeV:
  - DD are uncorrelated (independently produced)
  - DDbar are mostly produced in the same hard scattering
    - NS and AS peaks are clearly visible



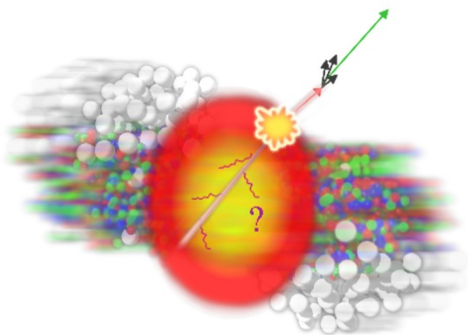


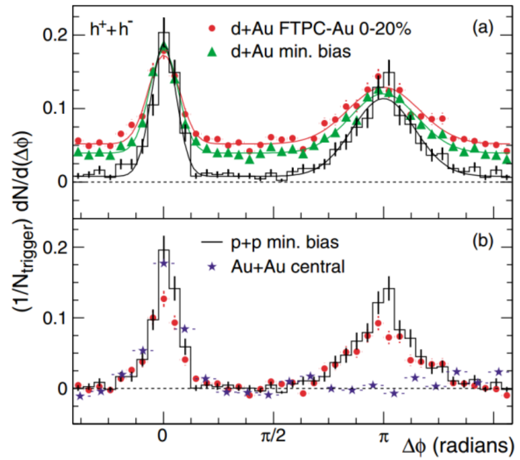
- LHCb measurements for D^0-D^0bar correlations compared with calculations from k_T-factorization approach, in pp collisions at 7 TeV

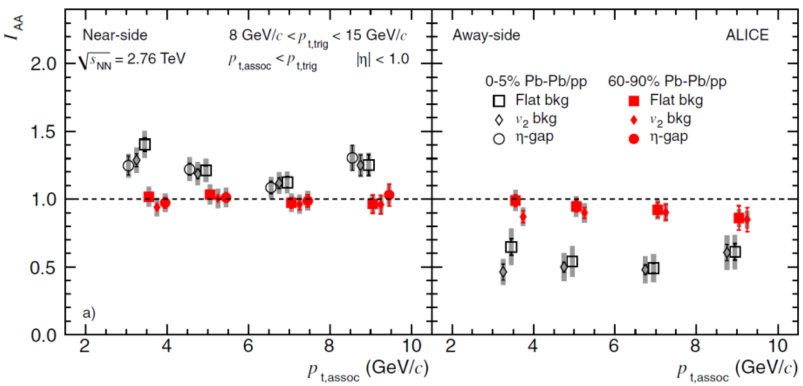
Comparison: Jet suppression at RHIC and LHC

- I_{AA} definition: $$I_{AA}(p_{T,\mathrm{trig}}; p_{T,\mathrm{assoc}}) = \frac{Y^{AA}(p_{T,\mathrm{trig}}; p_{T,\mathrm{assoc}})}{Y^{pp}(p_{T,\mathrm{trig}}; p_{T,\mathrm{assoc}})}$$

- From STAR measurements, heavy suppression of away side for h-h correlations in Au-Au central collisions (not in d-Au)

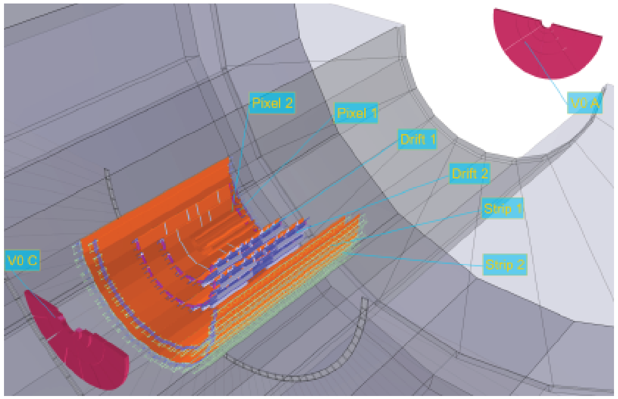






- ALICE I_{AA} for h-h correlations:
  - 20% enhancement of near side peak in p-Pb collisions, no away side effects
  - Strong away side suppression in central Pb-Pb, but by a lower factor w.r.t. RHIC

MINIMUM-BIAS TRIGGER AND INTEGRATED LUMINOSITY



- **"Minimum bias"**, based on interaction trigger:
  - **SPD or V0-A or V0-C**
    - at least one charged particle in 8 η units
    - ~95% of σ_{inel}
  - read out all ALICE
- **single-muon** trigger:
  - forward muon in coincidence with Min Bias
  - read out MUON, SPD, V0, FMD, ZDC

- pp analysis performed on 314M minimum-bias events, corresponding to L_{Int} = 5 nb^{-1}
- Integrated luminosity evaluated using as a reference the minimum-bias trigger cross section:

$$L_{int} = N_{MB} / \sigma_{MB}$$

- σ_{MB} (**62.3** ± 0.4(stat) ± 4.3(syst) mb) evaluated through a Van der Meer scan.

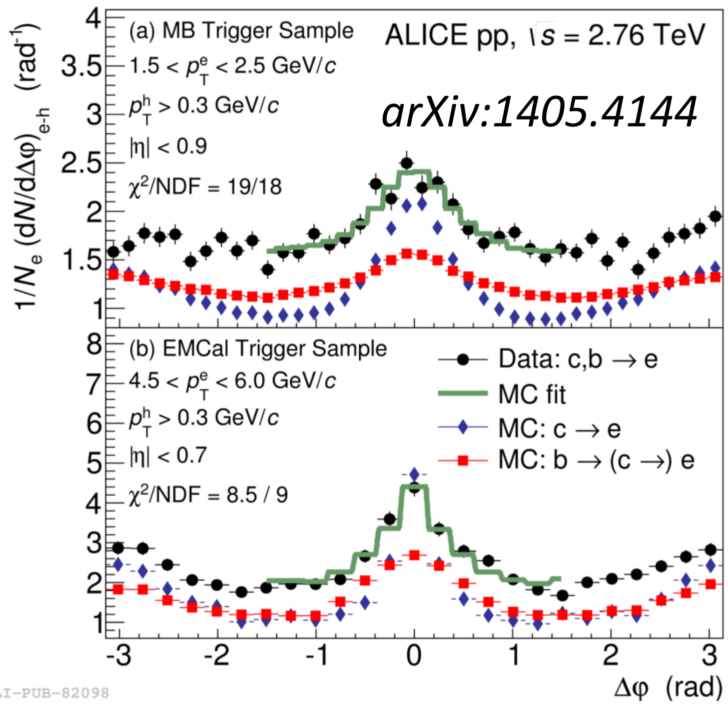
HFE-h correlations

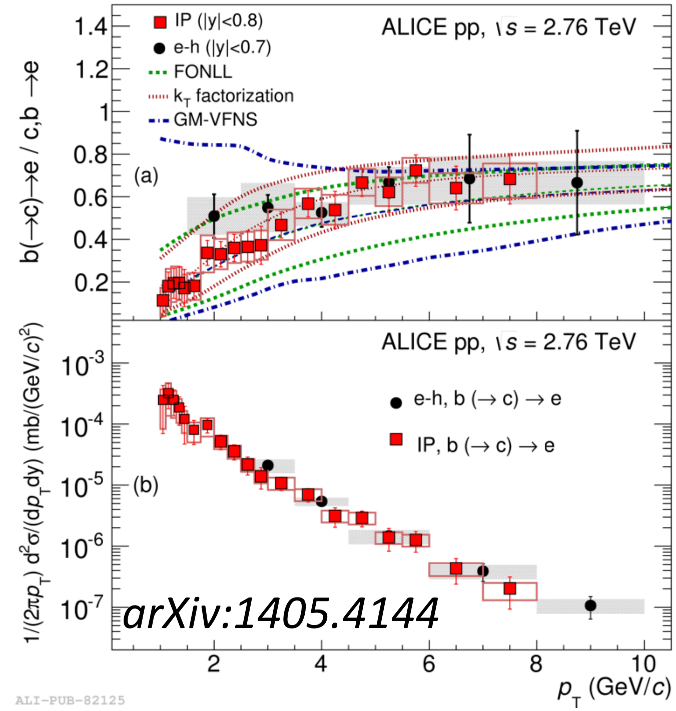
Possibility to separate the beauty and charm contributions to heavy-flavour decay electrons (HFE) due to the differences of the azimuthal correlation shapes

$$\Delta\phi = const + r_B \Delta\phi^{B}_{templ} + (1 - r_B)\Delta\phi^{C}_{templ}$$

↓

beauty fraction ⟶ $r_B = \dfrac{N_B}{N_B + N_C}$

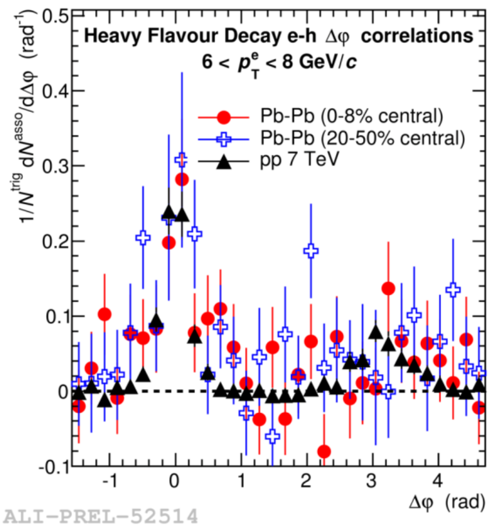


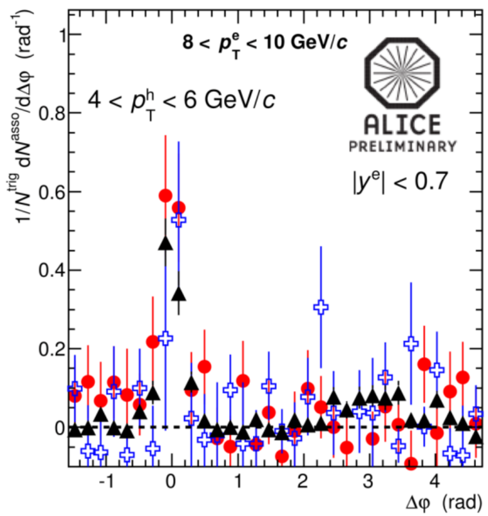


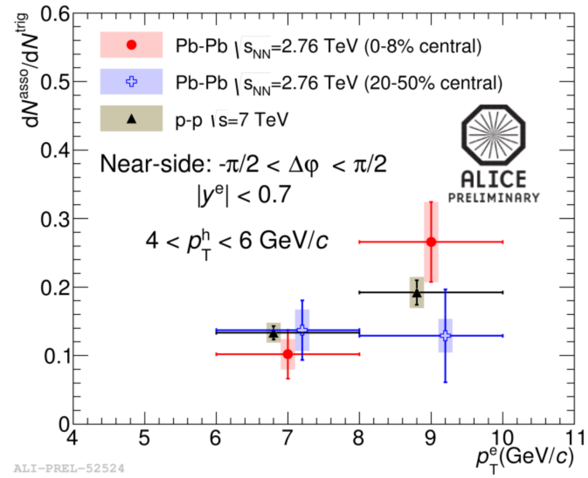
Beauty fraction compatible with results obtained with the selection on the e⁻ impact parameter and with FONLL predictions

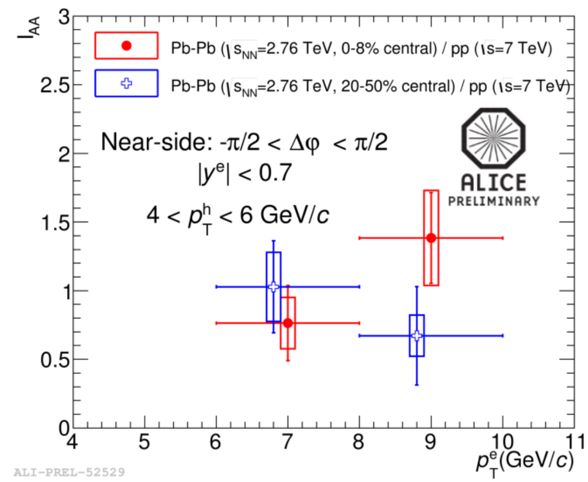
HFE-h correlations

Search for possible modification of the near side correlation peak in Pb-Pb collisions w.r.t pp collisions





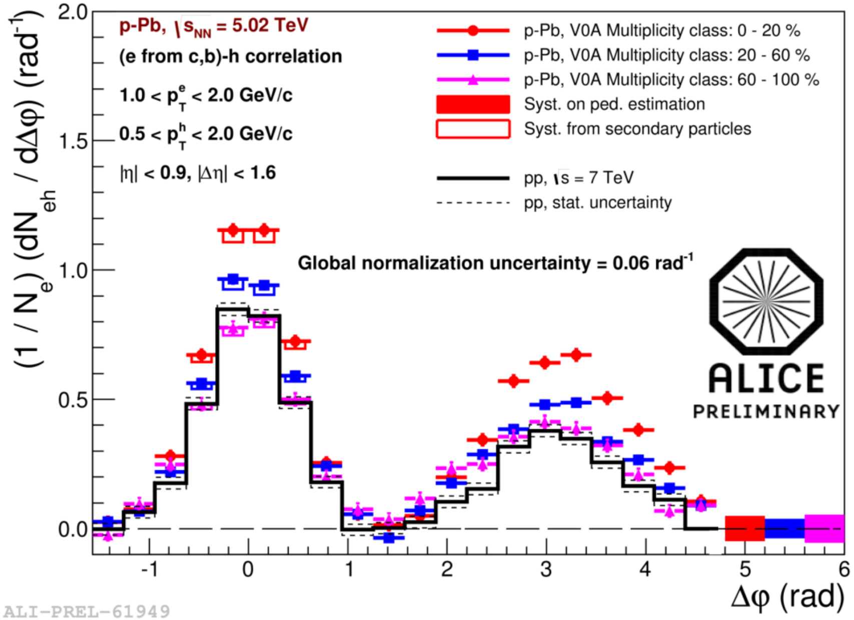


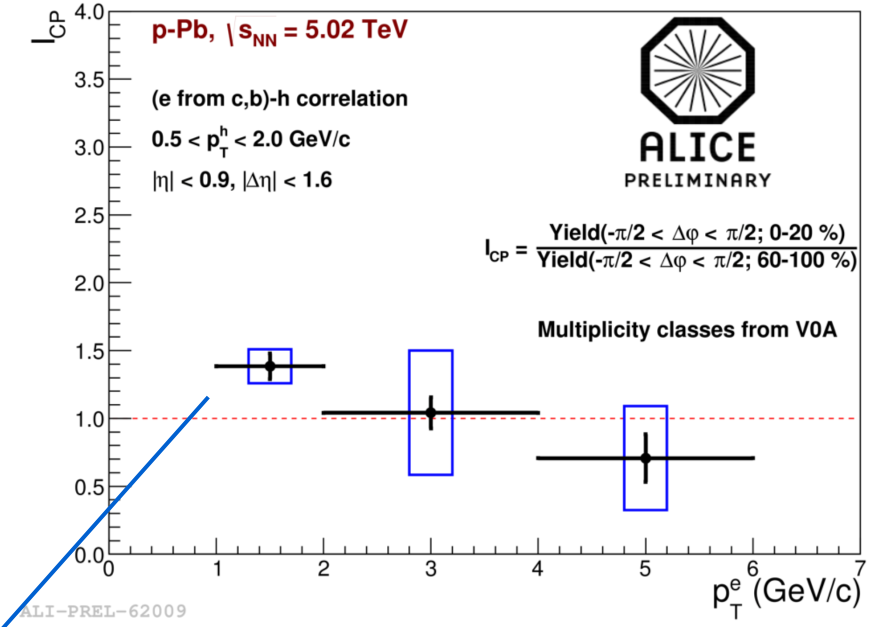


Measured I_{AA} for NS is compatible with 1
→ the limited statistics do not allow to draw firm conclusions on possible modifications of the fragmentation induced by the medium

HFE-h correlations

I_{CP} (ratio of NS yield in 0-20% class w.r.t. 60-100% class) is used to study the multiplicity dependence of the NS yield in Hfe-hadron correlations

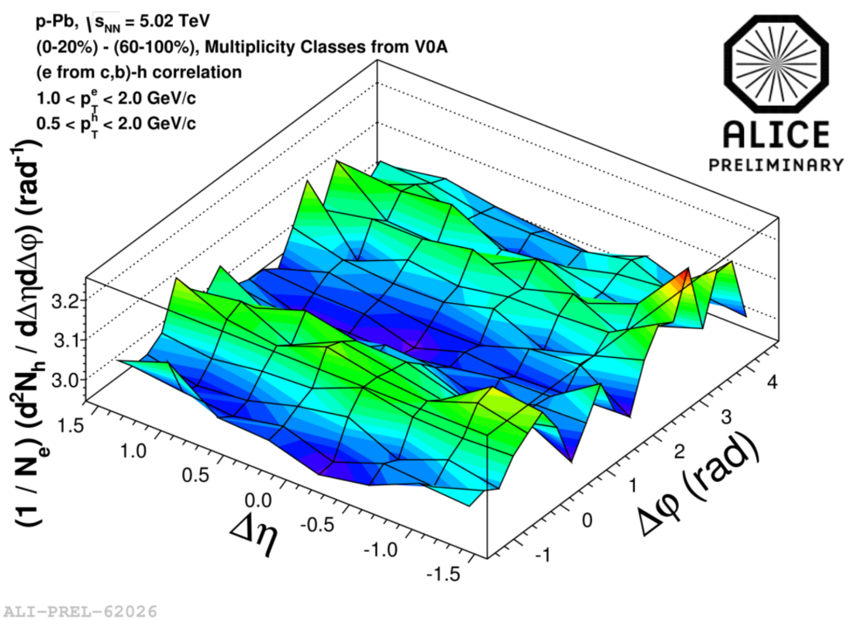


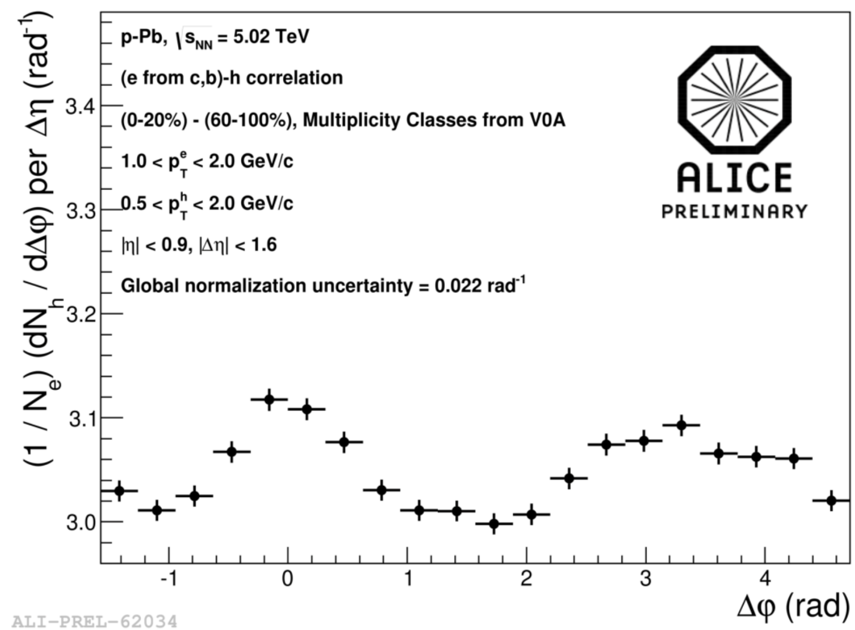


$I_{CP} > 1$ for electrons in the p_T range $1 < p_T^e < 2$ GeV/c

HFE-h correlations

Removal of jet peak in NS via subtraction of low mult events from high mult events: (0-20%) - (60-100%)





Long range correlation with double ridge structure observed for:
$1 < p_T^e < 2$ GeV/c, $0.5 < p_T^h < 2$ GeV/c

Tracking and Trigger efficiency correction

- To recover the correlations with tracks not reconstructed and to account for the p_T dependence of the D-meson efficiency, each pair is weighted by the inverse of the **D meson reconstruction efficiency** and of the **associated track reconstruction efficiency**.
  - For D meson efficiency, dependencies from D meson p_T and event multiplicity are considered
  - For associated track efficiency, dependencies from track p_T, η and z position of primary vertex are considered

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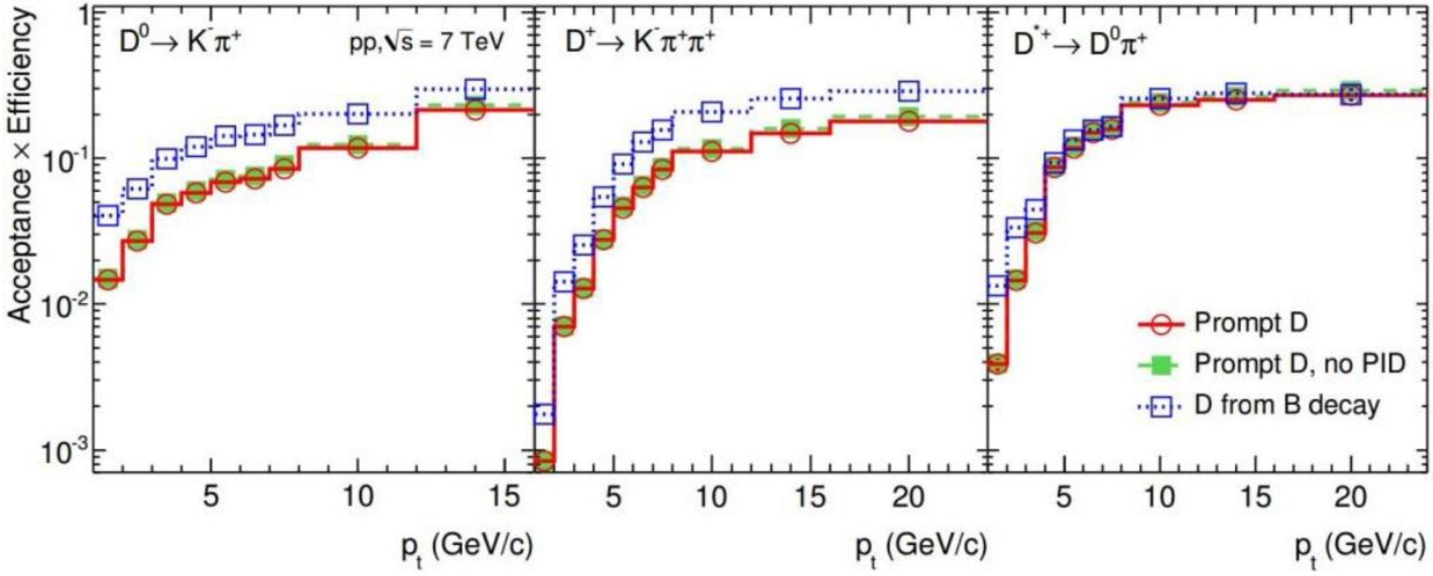
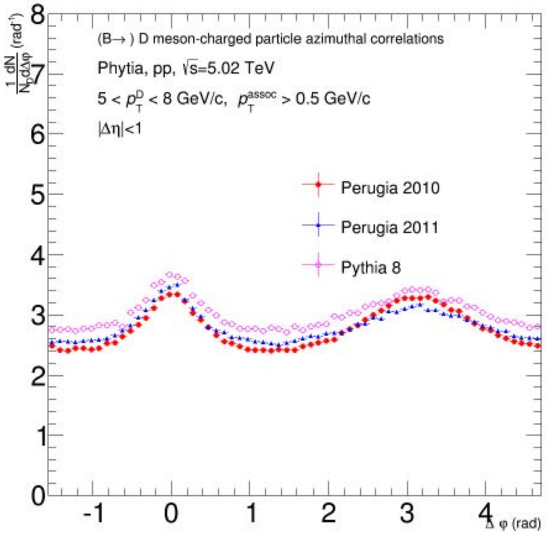


Further corrections

- Feed-down D contribution subtraction:
  - A template of angular correlation distribution of D meson from B-meson decay (from PYTHIA) is subtracted from the data distributions according to:

$$C_{\mathrm{prompt}}(\Delta\varphi)\frac{1}{f_{\mathrm{prompt}}}\left[C_{\mathrm{inclusive}}(\Delta\varphi)-(1-f_{\mathrm{prompt}})C_{\mathrm{feed-down}}^{\mathrm{MCtempl}}(\Delta\varphi)\right]$$

→ $\boldsymbol{f}_{\mathbf{prompt}}$ = *fraction of prompt D mesons, calculated on the basis of prompt and secondary D-meson reconstruction efficiencies and pQCD predictions of secondary D-meson cross-section*



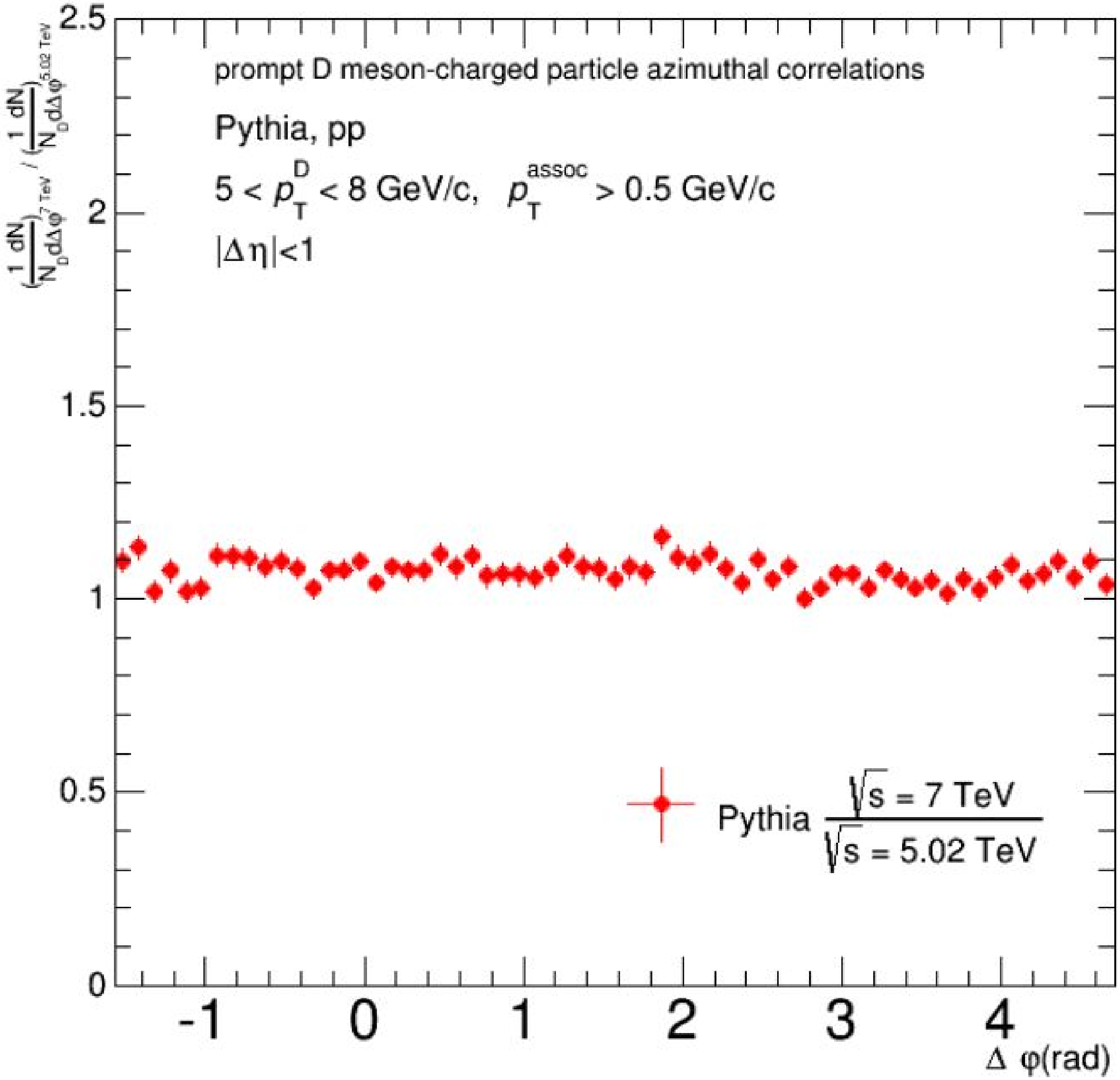
  - Different Pythia parameter «tunes» exploited for the templates, after matching their baselines to the data level, to obtain a systematic uncertainty of the procedure

- Removal of contamination from secondary tracks
  - Tracks from strange-hadron decays or produced in interaction of particles with the detector material
  - The contribution of secondary track particles, evaluated via Monte Carlo studies, is flat in Δφ and is removed by multipliying the data correlation distributions by the primary particle purity of the track sample

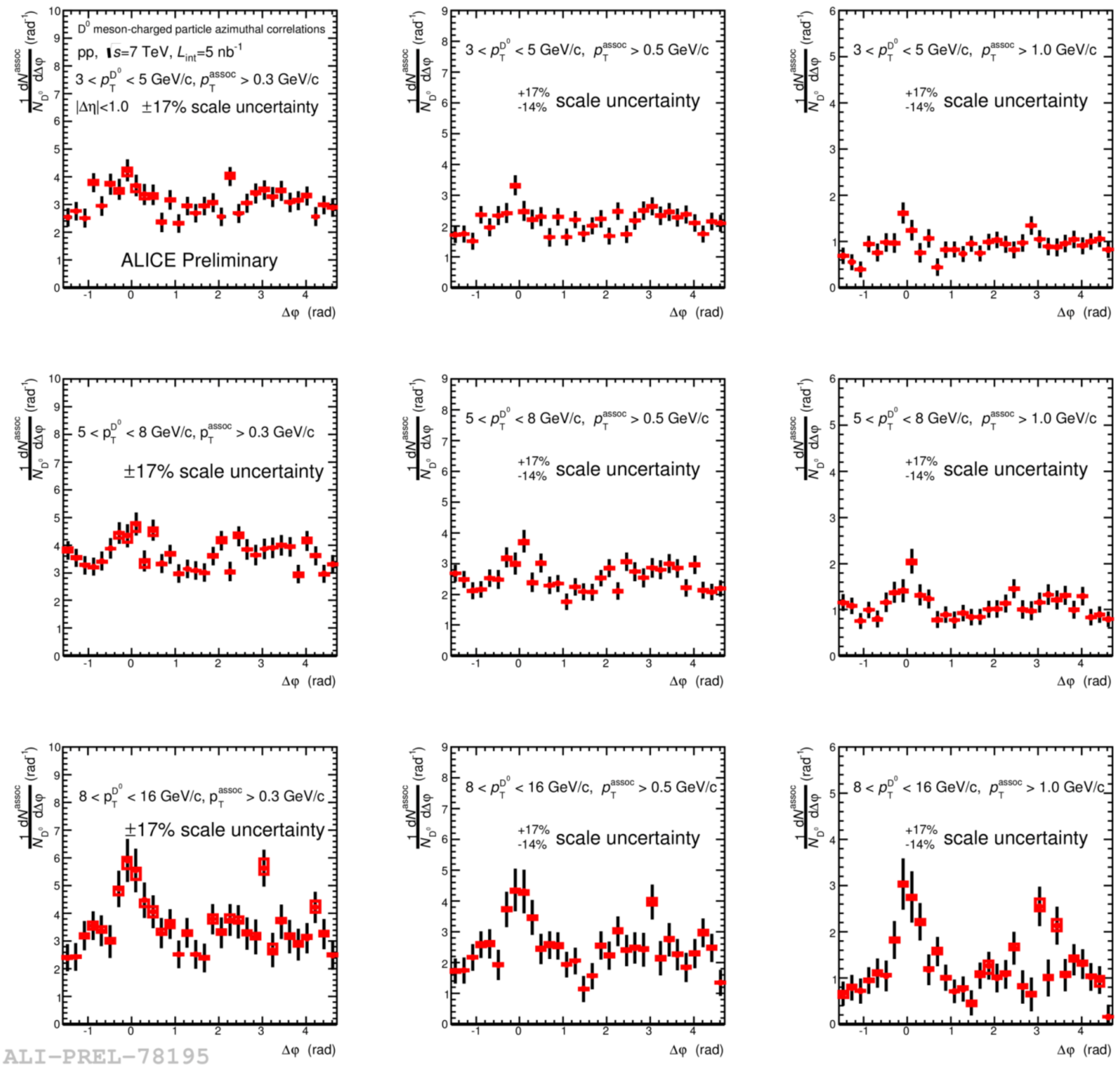
SYSTEMATIC UNCERTAINTIES LIST

- **D yield extraction**: change fit parameters (rebin spectra, modify fit range/fit functions, bin counting) - Affects both normalization to N of triggers and background subtraction.
- **Background subtraction:** vary the invariant mass regions from which we take the background correlation shape.
- **Fit of correlation plot**: use different fit functions: (e.g. 2 gauss+pedestal+periodicity condition, pedestal as minimum of the correlation histo, …)
- **Beauty feed-down**: use a range of f_{PROMPT} values, and use templates from different generators like POWHEG.
- **Correction for contamination from secondary**: estimate the contribution from MC and its $\Delta\varphi$ shape. Some studies on DCA cut already started (in backup slides).
- **Soft pion removal for D^0 correlations**: estimate efficiency and purity of the invariant mass cut from MC and evaluate the effect of the cut on the near side yields on data → Negligible!
- **Associate tracking efficiency**: use different track selections.
- **D meson reconstruction and selection efficiency**: extracted from varying the cuts for D meson selection.

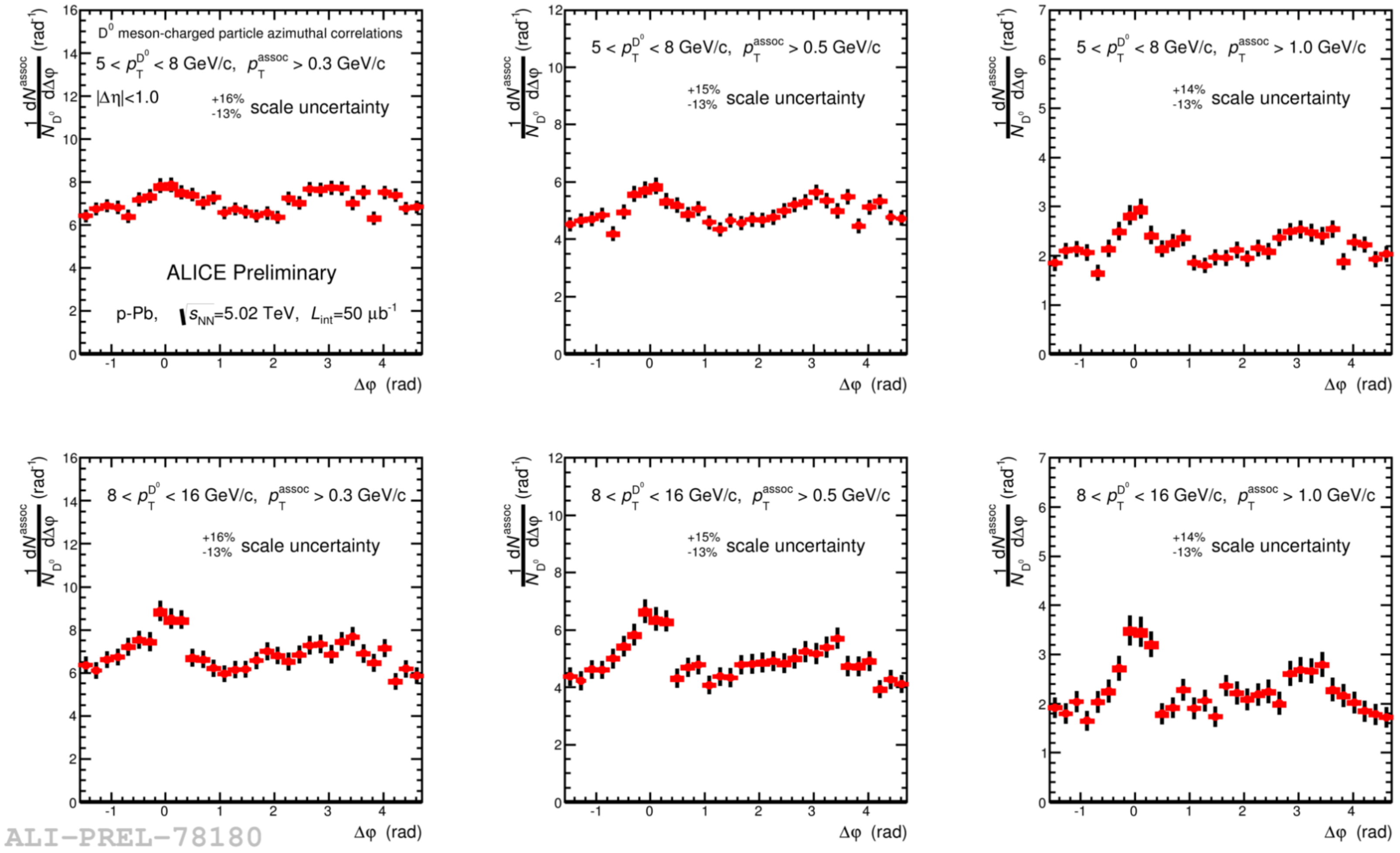
PYTHIA ENERGY RESCALING



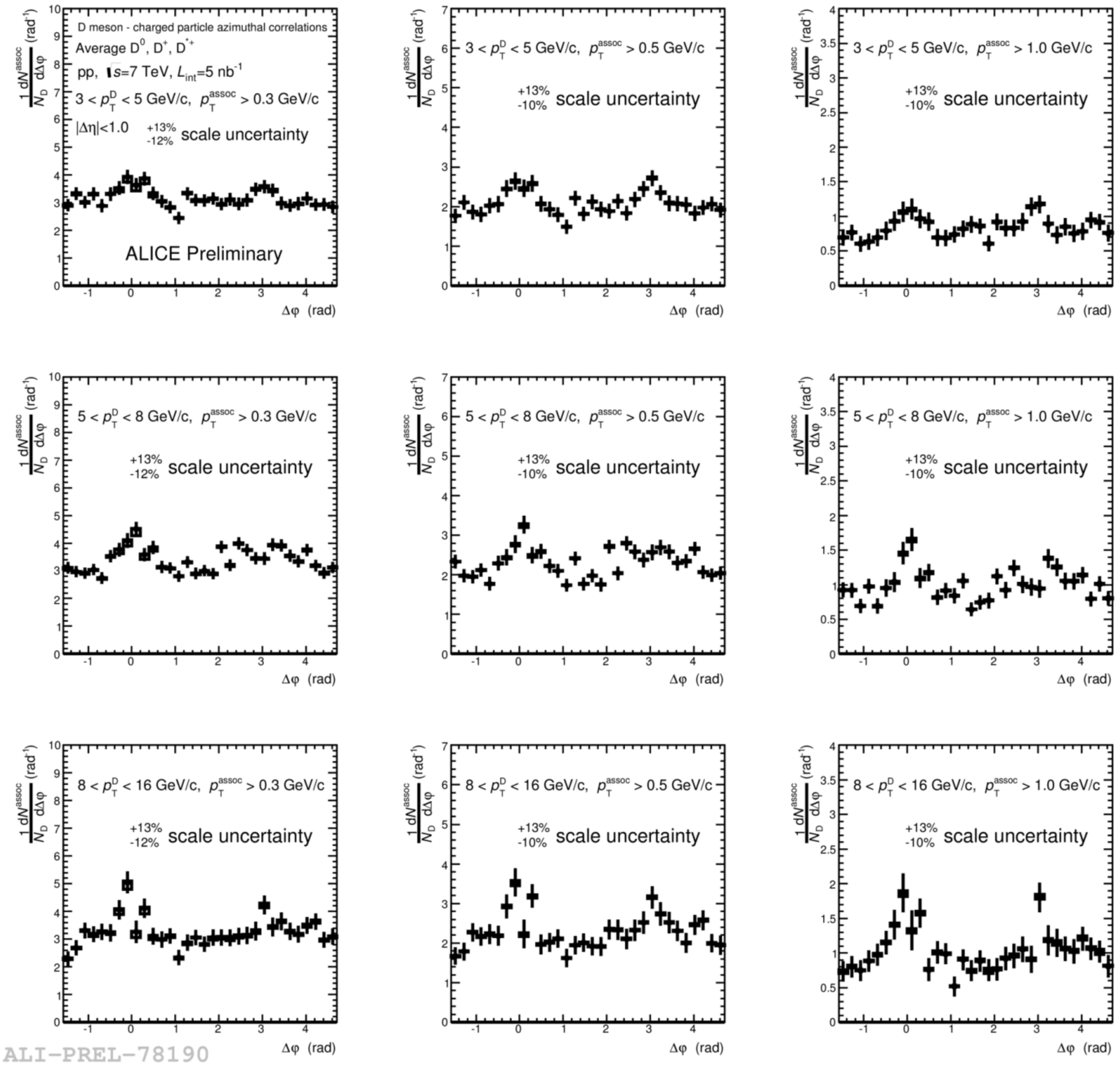
D^0 CORRELATIONS - PP



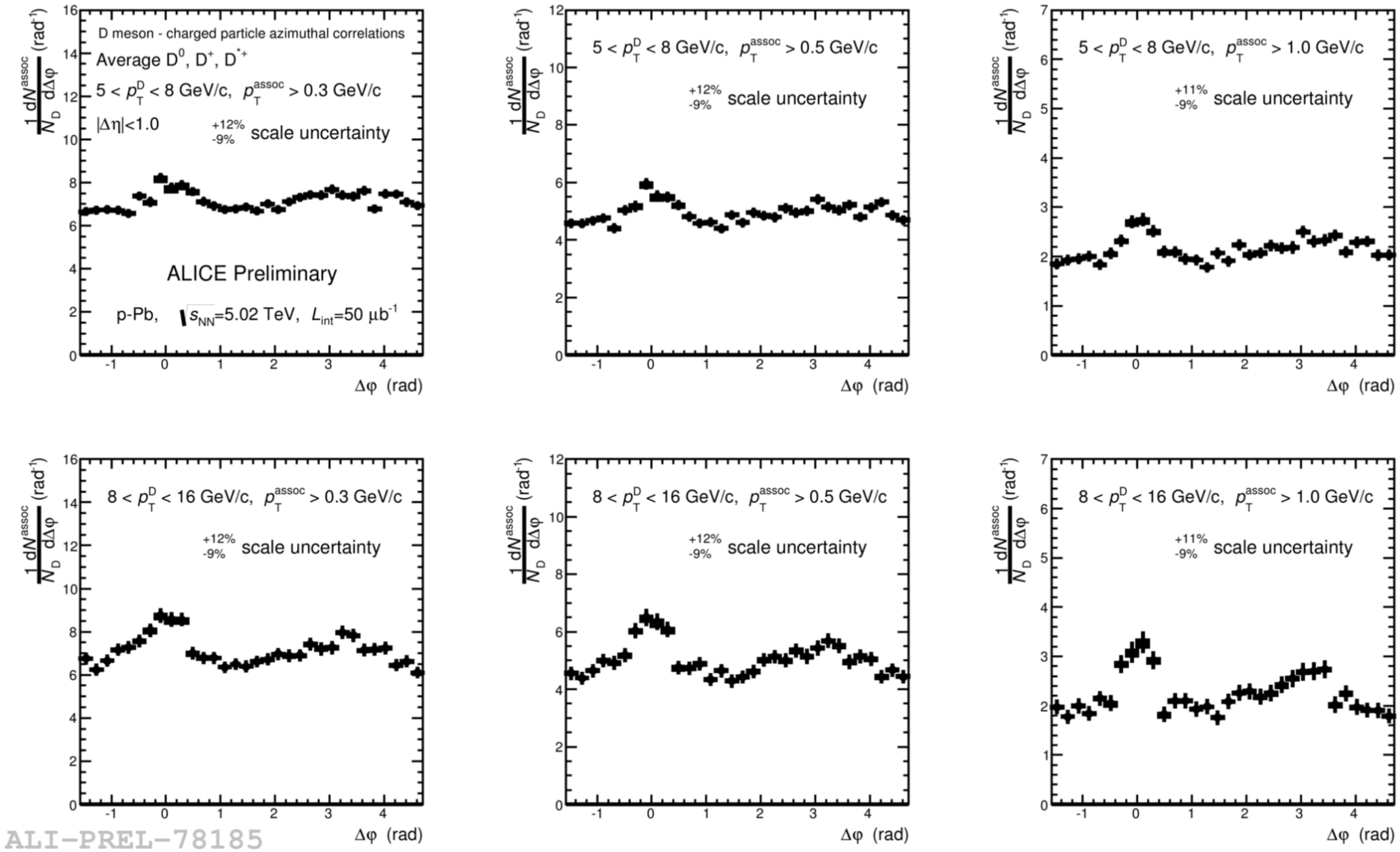
D^0 correlations – p-Pb



AVERAGE D CORRELATIONS - PP



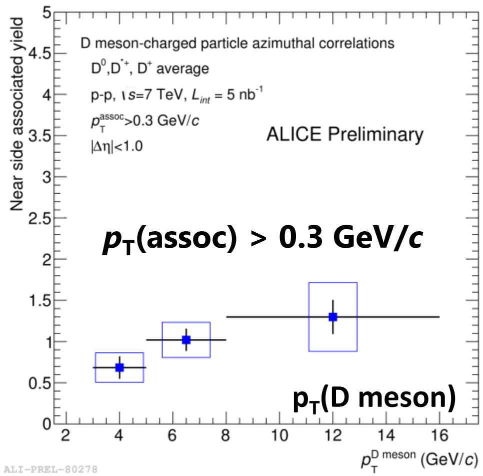
Average D correlations – p-Pb

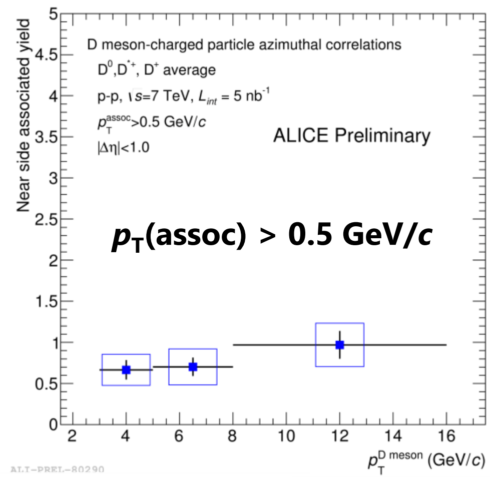


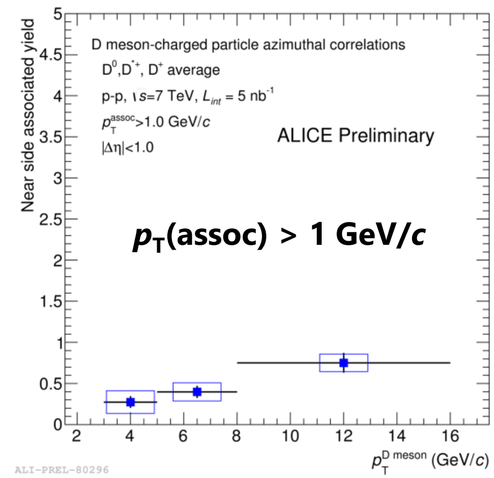
p_T TREND OF NEAR SIDE ASSOCIATED YIELD

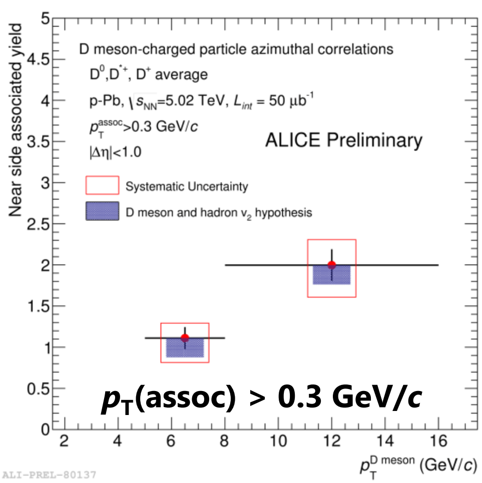
Evolution of near side yield with D meson p_T, for different thresholds of associated track p_T

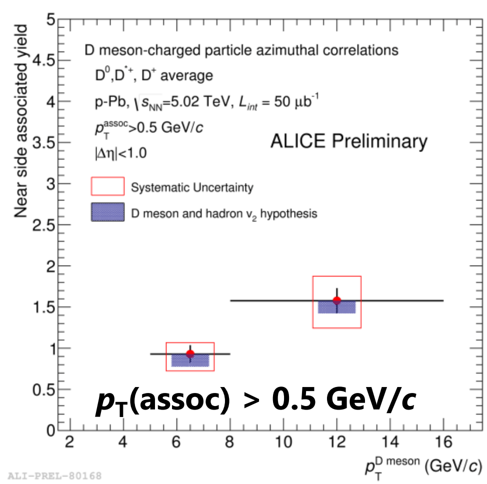
pp

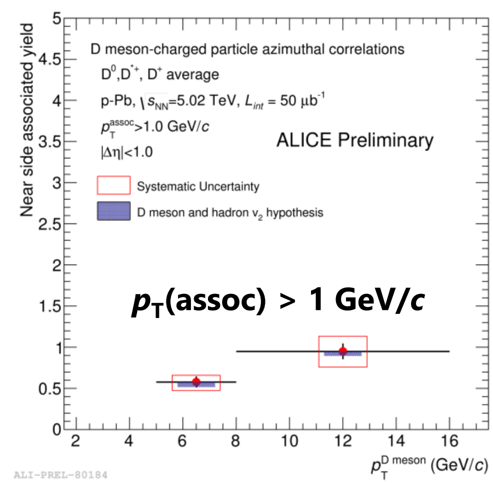






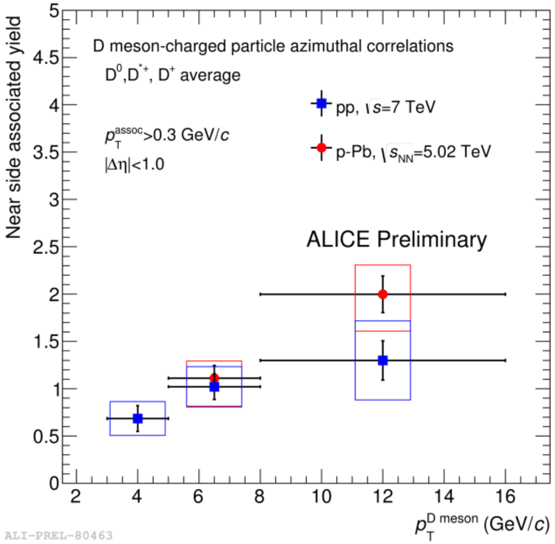


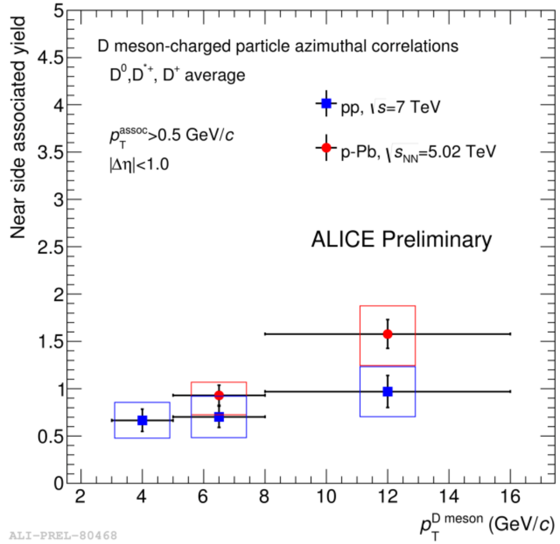


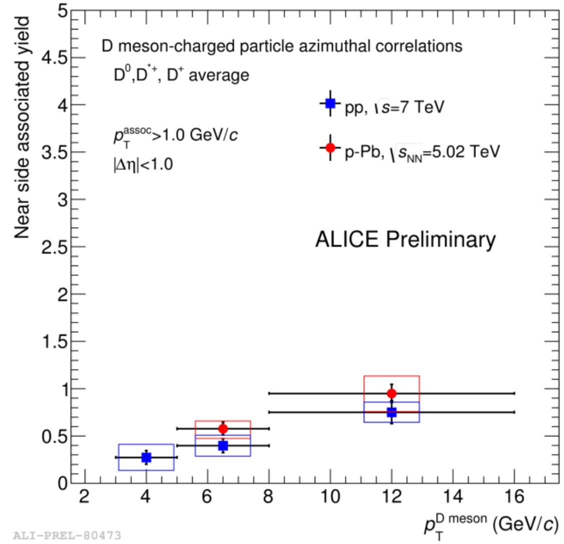


p-Pb

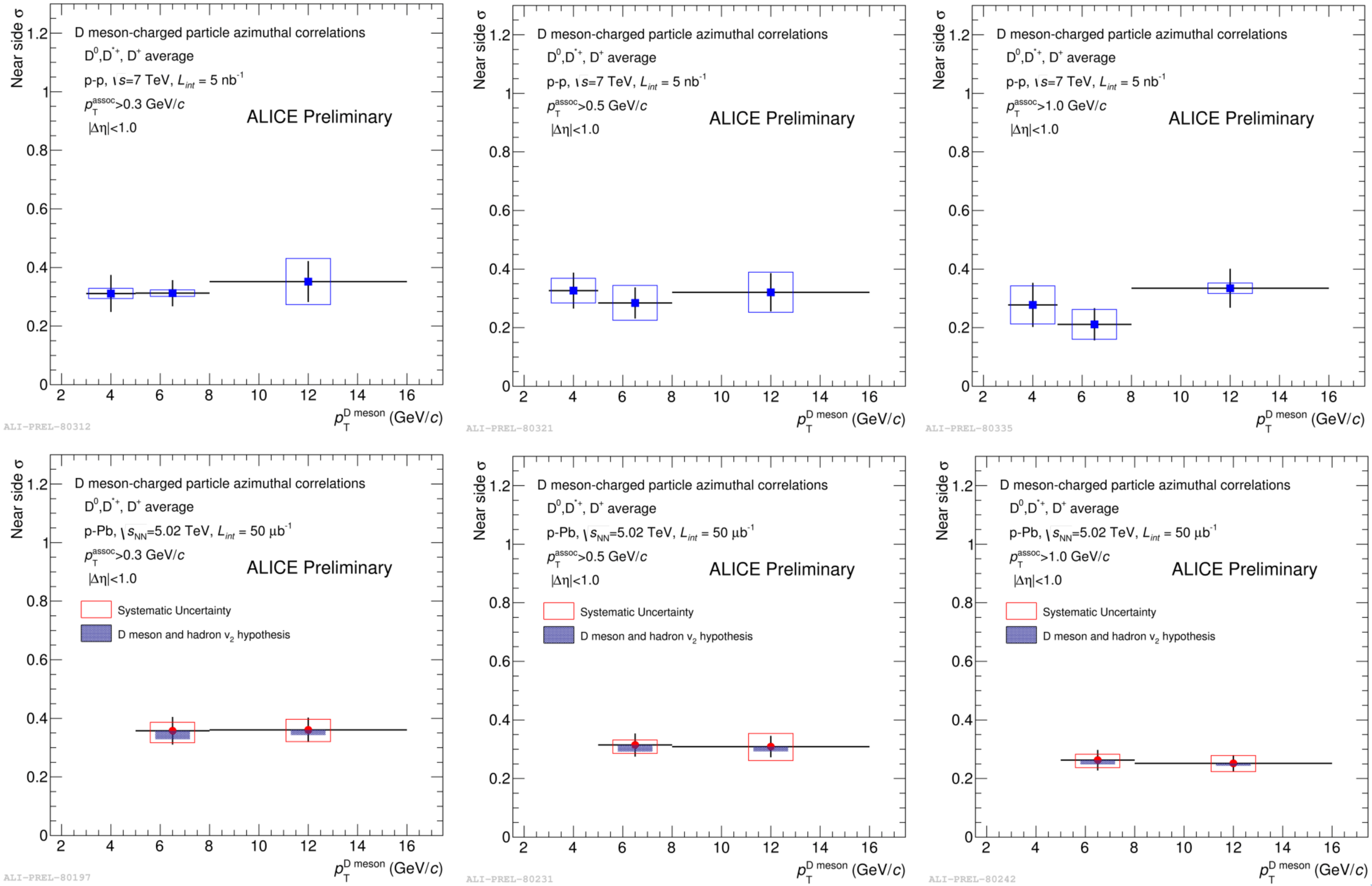
Near Side Yields – Comparison All Ranges







Near Side Sigma – pp And p-Pb all ranges



All-in-one, further correction (slides ver2)

- D-meson and associated track efficiency correction:
  - Accounts for associated track reconstruction efficiency and for p_T dependence of D-meson reconstruction and selection efficiency
  - 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
- Feed-down D contribution subtraction:
  - A template of angular correlation distribution of D mesons from beauty hadrons decays (from PYTHIA) is subtracted from the data distributions
  - Different PYTHIA parameter «tunes» exploited for the templates, after matching their baselines to the data level, to obtain a systematic uncertainty on the correction
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  - The contribution of secondary track particles, evaluated via Monte Carlo studies, is flat in $\Delta\varphi$ and is removed by multipliying the data correlation distributions by the the fraction of primary particles in the track sample