Results on open heavy-flavour production in pp and p-Pb collisions with ALICE at the LHC

QCD@Work, International Workshop on QCD, theory and experiment
27-30 June, Martina Franca, Italy

Elisa Meninno
INFN and University of Salerno, Italy
on behalf of the ALICE Collaboration

ALICE

INFN Istituto Nazionale di Fisica Nucleare

OUTLINE

- Physics motivations
- The ALICE experiment
- Open heavy-flavour measurements in ALICE
- Results in pp and p-Pb collisions:
  - Open heavy-flavour cross section → **down to p_T = 0 at 7 TeV**
  - Multiplicity dependence of open heavy-flavour production
  - Azimuthal correlations of D mesons with charged particles
- Conclusions

Why Open Heavy Flavours (HF)

- ***In Pb-Pb collisions***

Powerful probes to study the Quark-Gluon Plasma in heavy-ion collisions:

- Large masses (m_c ≈1.5 GeV/c^2, m_b ≈ 5 GeV/c^2) in high virtuality processes ($Q > 2m_{c|b}$)

  → **produced in the early stages of the collision**

- Flavour is conserved in strong interactions

  → **Heavy quarks experience the whole evolution of the medium, interacting with its constituents**

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  - Test of perturbative QCD (pQCD) calculation predictions at the highest collision energies

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- ***In p-Pb collisions***

  - Reference for Pb-Pb collisions
  - Study cold nuclear matter (CNM) effects:
    - Modification of Parton Distribution Functions, gluon saturation at low *x*
    - Energy loss in the initial and final state of the collisions
    - k_T broadening

K.J.Eskola et al., JHEP 0904(2009)65
I.Vitev at al., PRC 75(2007)064906
Z.Phys.C21(1983)155

HF multiplicity studies

What can we learn?

- Study the interplay between hard and soft mechanisms in particle production
- Investigate the contribution of Multiple-Parton Interactions (MPI)
- Insights into CNM effects in p-Pb collisions
- Explore the dependence of HF production on the collision geometry and/or multiplicity density of final-state particles

Phys.Rev.D36(1987)2019
Nucl.Phys.Proc.Suppl.214(2011)181–184

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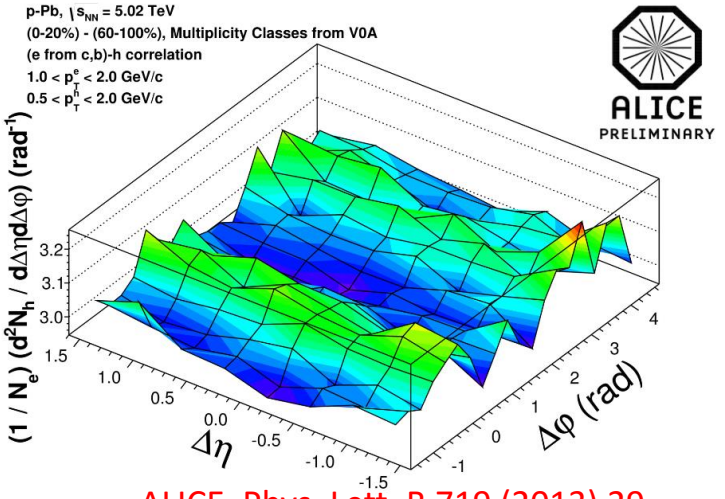
Phys.Rev.D36(1987)2019
Nucl.Phys.Proc.Suppl.214(2011)181–184

HF azimuthal correlations studies

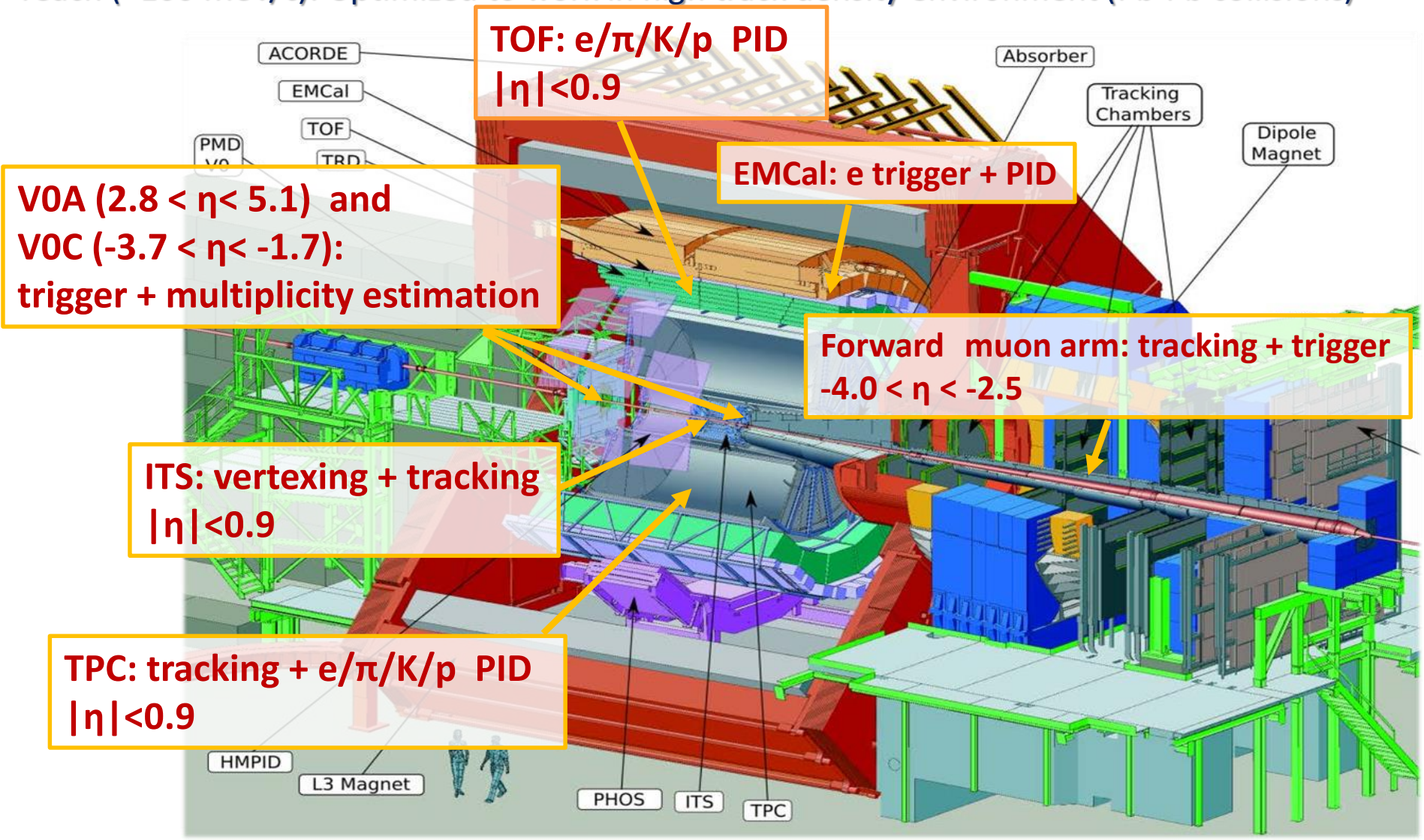
- ***In pp collisions***
- Allow to investigate heavy-flavour quark fragmentation.
- Provide a reference for the measurements in p-Pb and Pb-Pb collisions.
- ***In p-Pb collisions***
- Study possible modifications of heavy-quark fragmentation, due to initial-state effects (e.g. CGC) or finale-state effects (e.g. hydrodynamics).
- Search for long-range ridge-like structures (double ridge) in the heavy-flavour sector, already observed in hadron-hadron correlations.



ALICE, Phys. Lett. B 719 (2013) 29

ALICE detector

ALICE: dedicated heavy-ion detector at the LHC, with excellent PID capabilities and very low p_T reach (~100 MeV/c). Optimized to work in high track density environment (Pb-Pb collisions)



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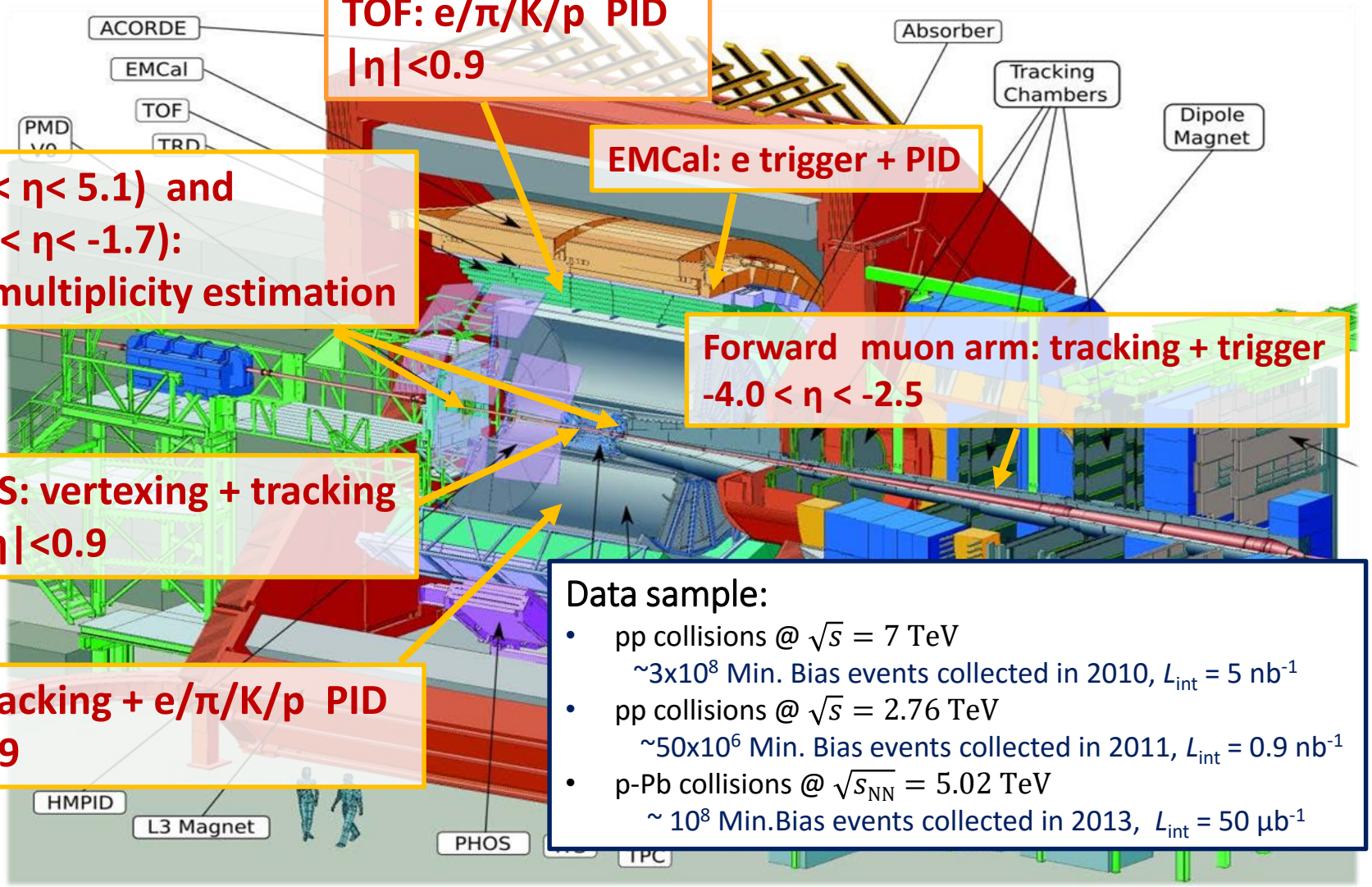


TOF: e/π/K/p PID
|η|<0.9

EMCal: e trigger + PID

V0A (2.8 < η< 5.1) and
V0C (-3.7 < η< -1.7):
trigger + multiplicity estimation

Forward muon arm: tracking + trigger
-4.0 < η < -2.5

ITS: vertexing + tracking
|η|<0.9

TPC: tracking + e/π/K/p PID
|η|<0.9

Data sample:

- pp collisions @ $\sqrt{s} = 7$ TeV
  ~3x10^8 Min. Bias events collected in 2010, L_{int} = 5 nb^{-1}
- pp collisions @ $\sqrt{s} = 2.76$ TeV
  ~50x10^6 Min. Bias events collected in 2011, L_{int} = 0.9 nb^{-1}
- p-Pb collisions @ $\sqrt{s_{NN}} = 5.02$ TeV
  ~ 10^8 Min.Bias events collected in 2013, L_{int} = 50 μb^{-1}

Open HF measurements

With ALICE Central Barrel

- Open charm from hadronic decays at central rapidity

  $D^0 \rightarrow K^-\pi^+$ ($c\tau$ = 123 μm, BR = 3.88 ± 0.05 %)

  $D^+ \rightarrow K^-\pi^+\pi^+$ ($c\tau$ = 312 μm, BR = 9.13 ± 0.19%)

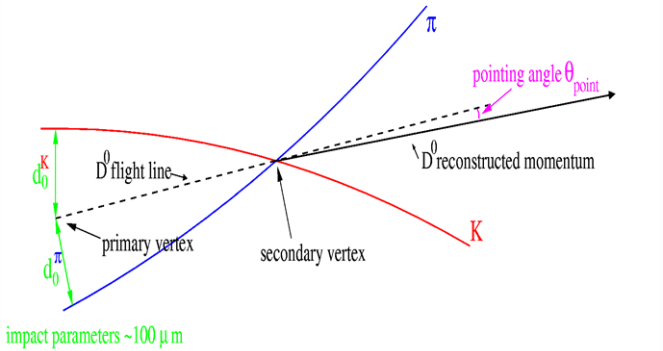
  $D^{*+} \rightarrow D^0\pi^+$ (strong decay , BR = 67.7 ±0.5 %)

  $D_s \rightarrow \phi(\rightarrow K^-K^+)\pi^+$ ($c\tau$ = 150 μm, BR = 2.28 ± 0.12)

  $\Lambda_c^+ \rightarrow pK^-\pi^+$ ($c\tau$ = 60 μm, BR = $6.84^{+0.32}_{-0.40}$)

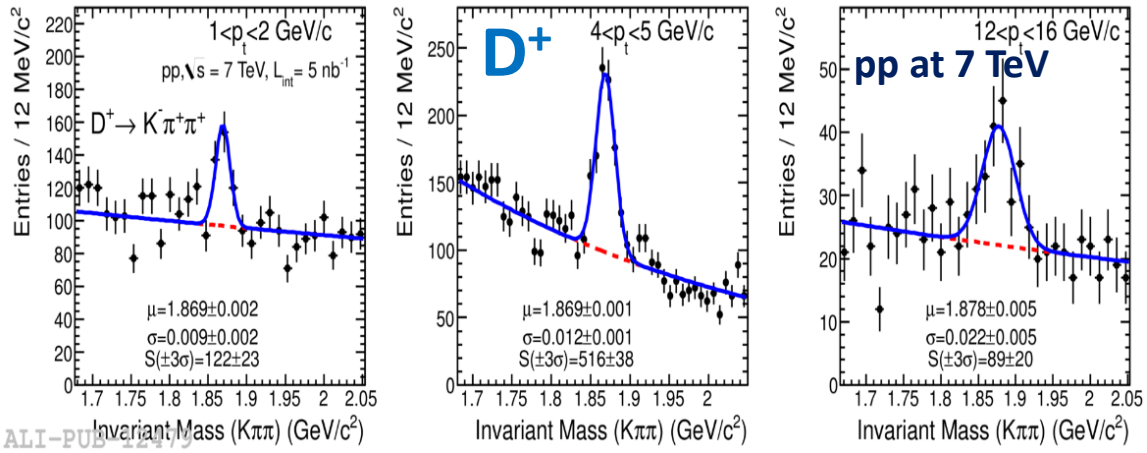
  $\Lambda_c^+ \rightarrow pK^0_S$ ($c\tau$ = 60 μm, BR = 1.1 ± 0.1)

  ongoing



- Reconstruction of secondary vertex, displaced from the primary vertex by few hundred μm.
- Candidates selected applying topological selections and PID
- Correction for beauty feed-down (based on FONLL) to extract results for prompt D mesons and Λ_c

ALICE, JHEP 1201 (2012) 128



ALI-PUB-12479

Open HF measurements

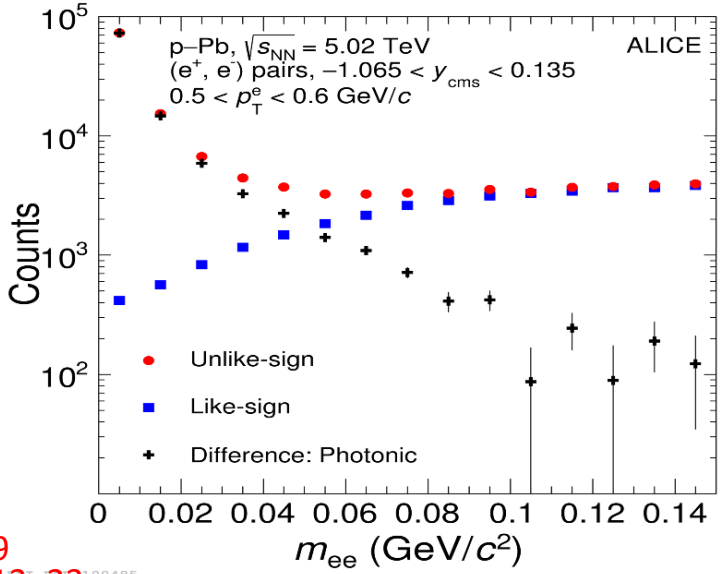
Still with ALICE Central Barrel

- Open heavy-flavour (charm and beauty) from semi-leptonic decays

  C, B, $\Lambda_c \rightarrow$ e + anything

- Electron identification using TPC, TOF and EMCal PID
- Background (mainly π^0 and η Dalitz decays, photon conversions) subtracted with invariant mass (e^+e^-) and/or cocktail methods
  - Also measurements of beauty decay electrons, separating contribution from c and from b

ALICE, Phys. Lett. B 754 (2016) 81-93



ALICE, Physics Letters B 738 (2014) 9
ALICE, Physics Letters B 721 (2013) 13–23

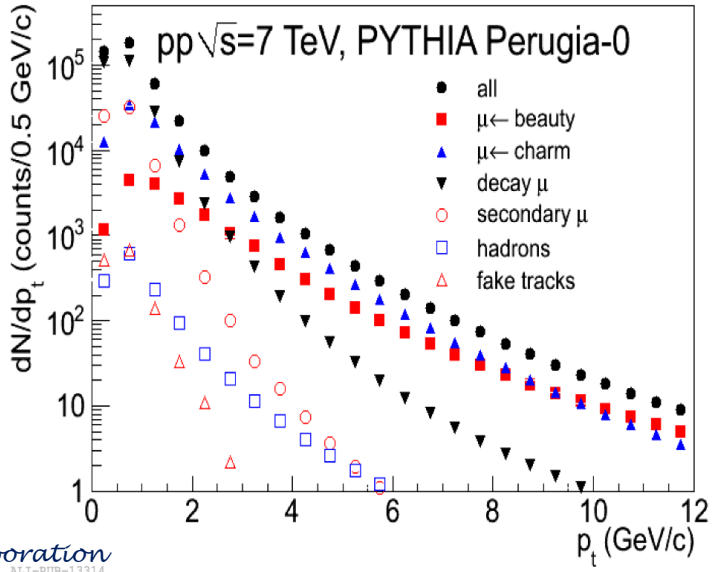
With ALICE Muon Arm

- Open heavy-flavour (charm and beauty) from semi-leptonic decays

  C, B, $\Lambda_c \rightarrow$ μ + anything

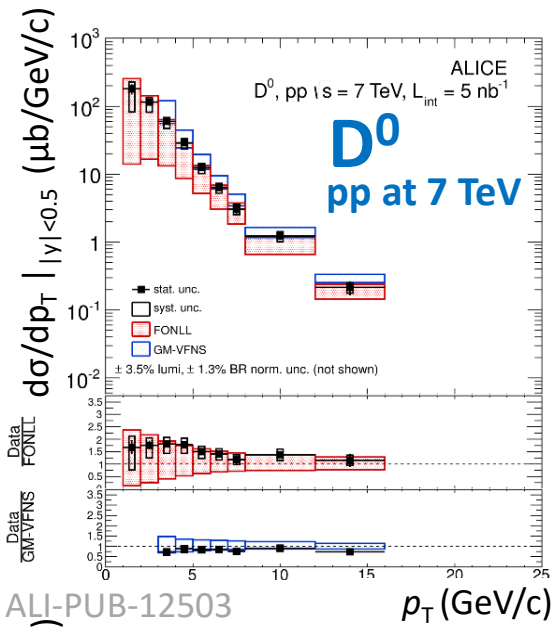
- Muon identification using muon spectrometer
- Background (mainly π,K) subtracted with MC simulations (in pp collisions) and data-tuned MC cocktail (in p-Pb, Pb-Pb collisions)

ALICE, PLB 708 (2012) 265

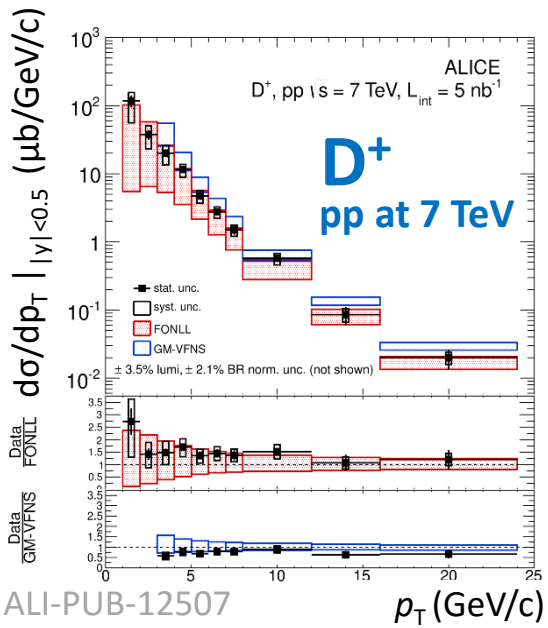


Cross sections in pp and p-Pb collisions

Cross sections in pp collisions

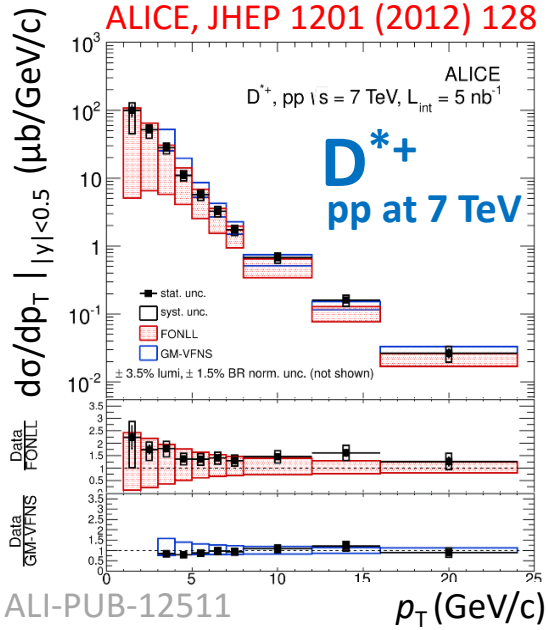


ALI-PUB-12503



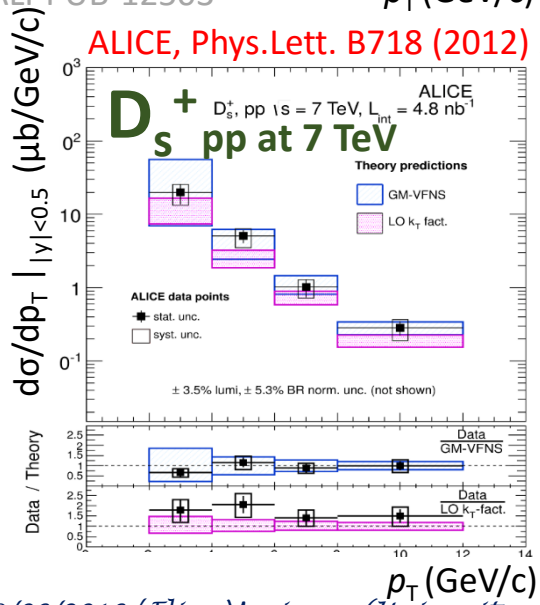
ALI-PUB-12507

ALICE, JHEP 1201 (2012) 128



ALI-PUB-12511

ALICE, Phys.Lett. B718 (2012) 279-294



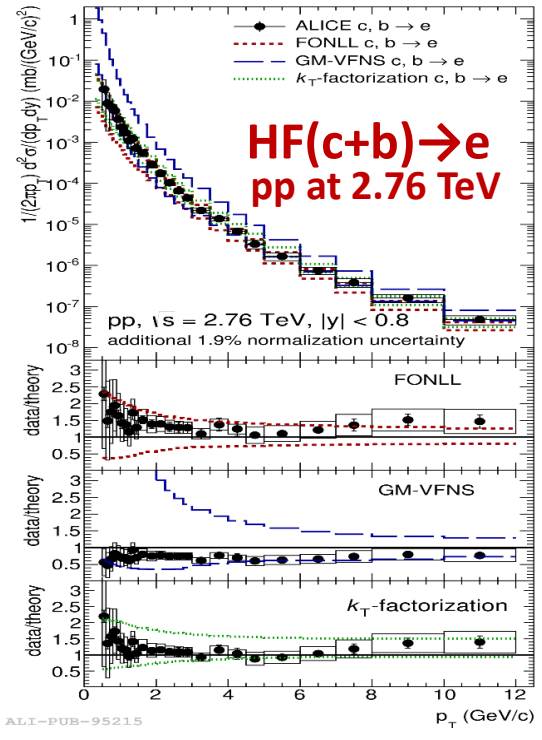
- p_T-differential cross sections reproduced within uncertainties by theoretical predictions based on pQCD*:*
  FONLL, GM-VFNS, k_T-factorization approach

  CERN-PH-TH/2011-227
  Eur.Phys.JC72(2012) 2082
  EPJ Web Conf. 37 (2012) 06008

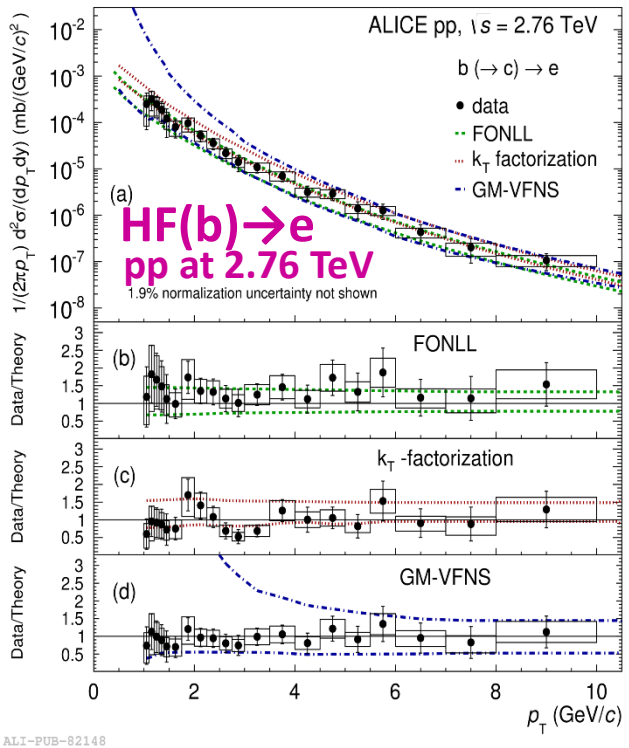
Similar trend at $\sqrt{s}$ = 2.76 TeV ALICE, JHEP 1207 (2012) 191

Cross sections in pp collisions

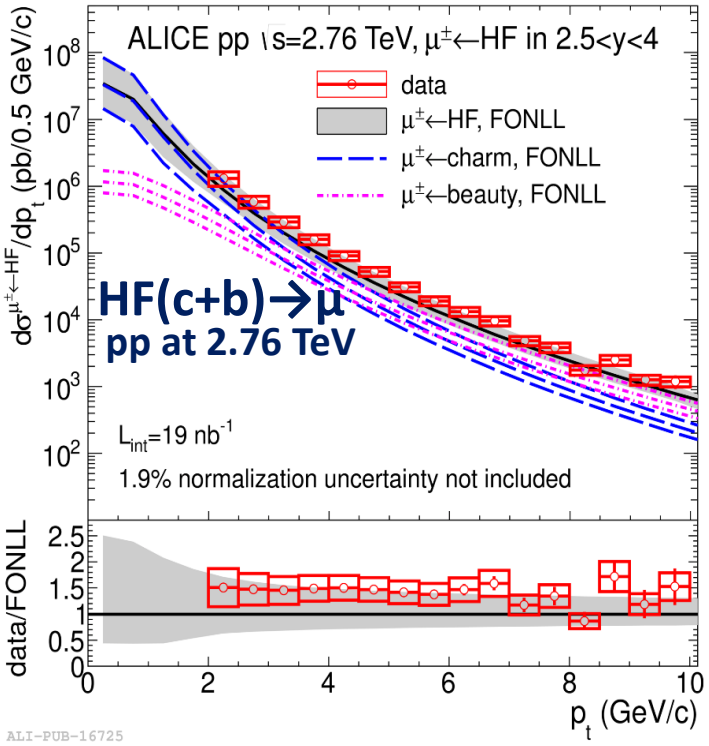
ALICE, Phys. Rev. D 91 (2015) 012001



ALICE, Phys. Lett. B 738 (2014) 9



ALICE, Phys. Rev. Lett.109.112301



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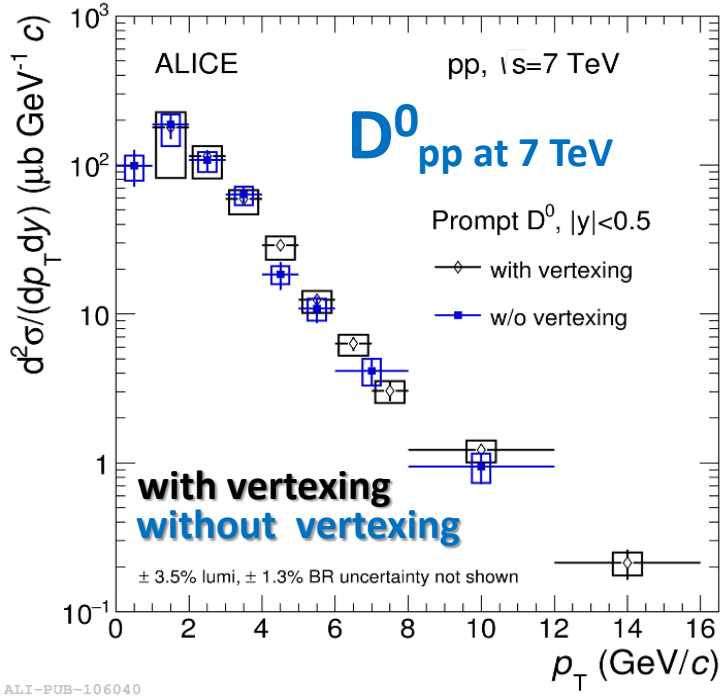
Eur.Phys. JC72(2012) 2082
EPJ Web Conf. 37 (2012) 06008

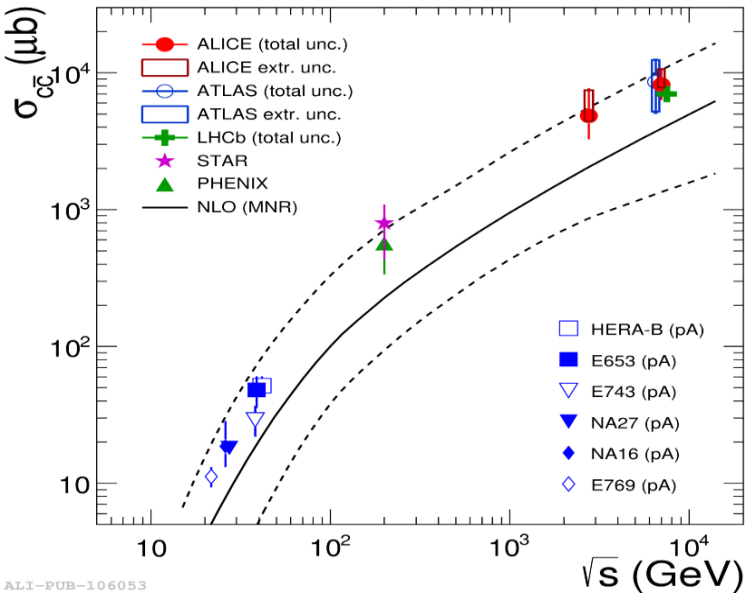
D^0 cross section down to p_T =0 in pp collisions

new arXiv:1605.07569



- Analysis method without selection on secondary vertex displacement, based on PID and subtraction of combinatorial background.
- Results in good agreement with the analysis with decay-vertex reconstruction.

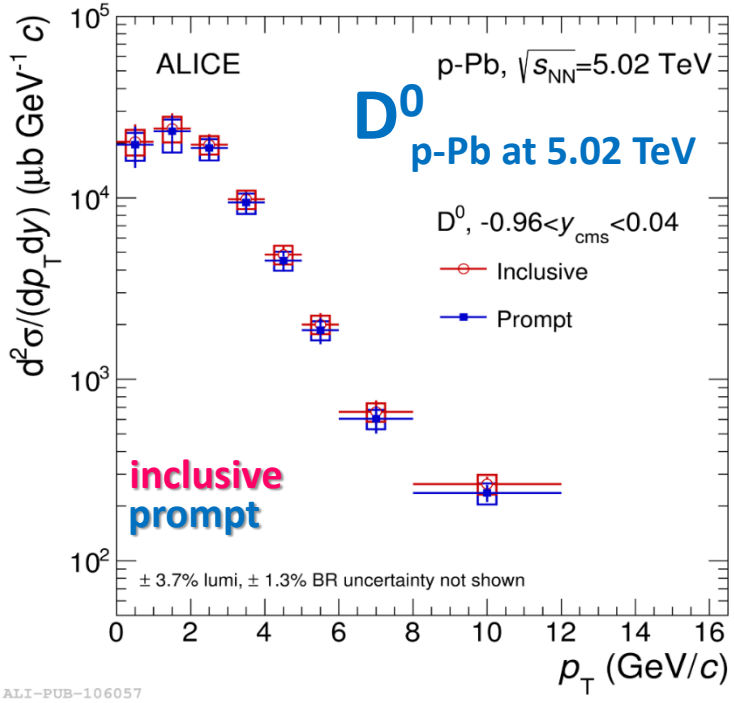
$$\sigma^{\text{prompt } D^0}_{pp,7TeV}/dy = 518 \pm 43(\text{stat.})^{+57}_{-102}(\text{syst.}) \pm 18(\text{lumi.}) \pm 7(\text{BR})\ \mu b.$$

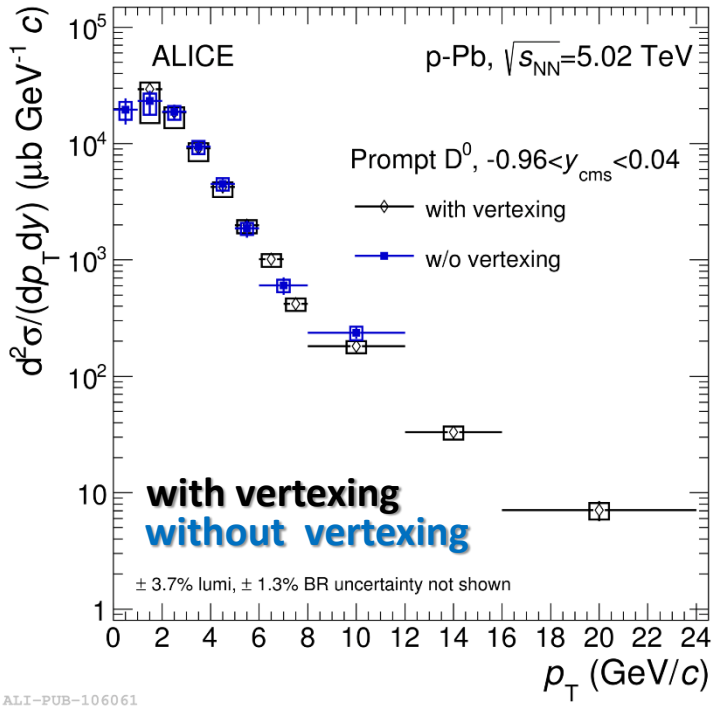


total charm production cross section updated with smaller uncertainties

D^0 cross section down to p_T =0 in p-Pb collisions

new arXiv:1605.07569





- Measurement of **inclusive** (no B feed-down subtraction) and **prompt** D^0 meson
- Results in good agreement with the analysis with decay-vertex reconstruction.

$$\sigma^{\text{prompt } D^0}_{\text{p–Pb,5.02TeV}}/\text{dy} = 79.0\pm7.3(\text{stat.})^{+7.1}_{-13.4}(\text{syst.})\pm2.9(\text{lumi.})\pm1.0(\text{BR})\ \text{mb.}$$

$$\sigma^{\text{inclusive } D^0}_{\text{p–Pb,5.02TeV}}/\text{dy} = 83.0\pm7.9(\text{stat.})\ \pm7.2(\text{syst.})\ \pm\ 3.1(\text{lumi.})\pm1.1(\text{BR})\ \text{mb.}$$

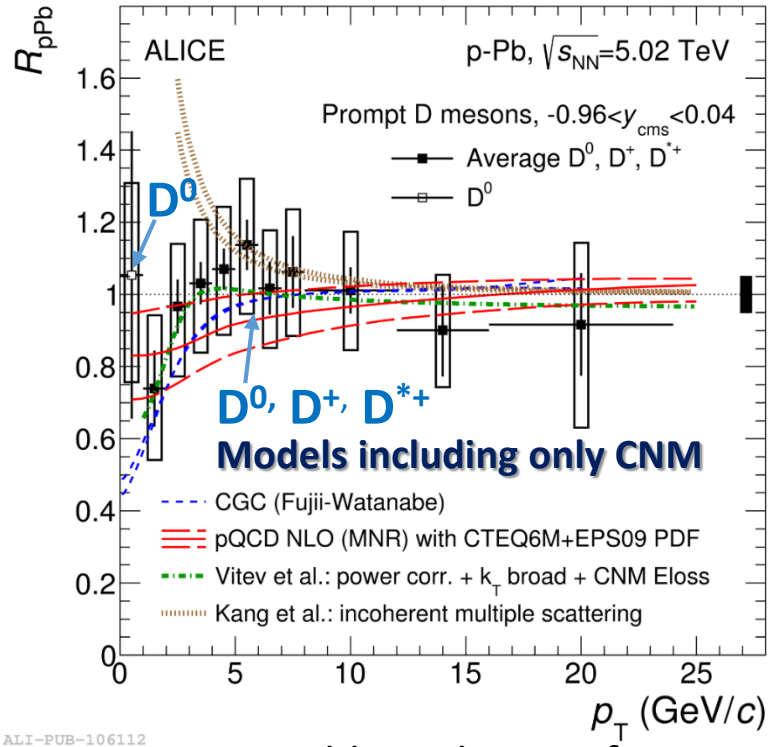
Nuclear modification factor in p-Pb collisions

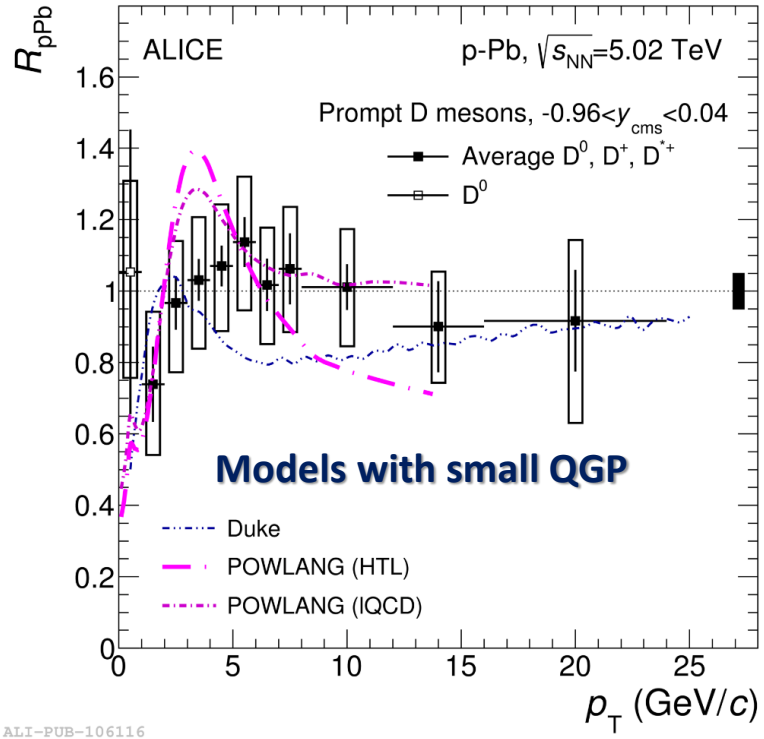
$$R_{\mathrm{pA}} = \frac{d\sigma_{\mathrm{pA}}/dp_{\mathrm{T}}}{A \times d\sigma_{\mathrm{pp}}/dp_{\mathrm{T}}}$$

R_{pPb} down to p_T = 0 in p-Pb collisions

new arXiv:1605.07569

$$R_{pPb} = \frac{d\sigma_{pPb}^{\text{prompt D}}/dp_T}{A \times d\sigma_{pp}^{\text{prompt D}}/dp_T}$$





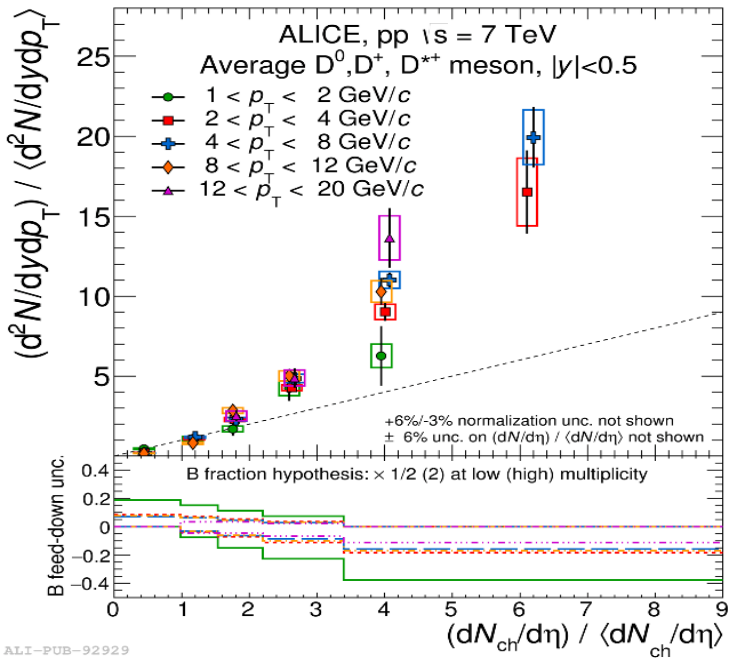
- R_{pPb} compatible with unity for p_T > 2 GeV/c within uncertainties
- Results described within uncertainties by models including initial-state effects
- Results described also by models including final-state effects due to the presence of deconfined medium
  - Data disfavour suppression larger than 20% at high p_T

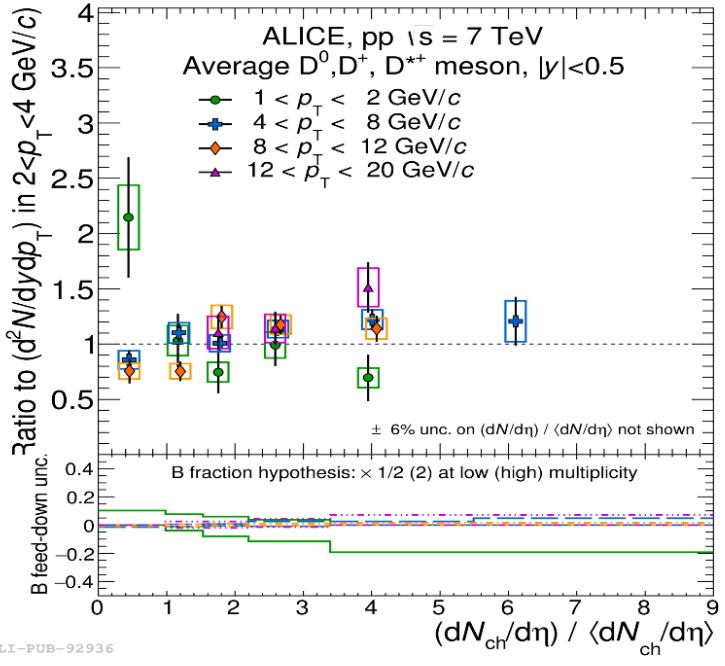
H. Fuji et al., Nucl Phys A920 (2013) 78
M. Mangano et al., Nucl. Phys. B373 (1992) 295
K. J. Eskola et al., JHEP 0904 (2009) 065
Vitev et al., Phys. Rev. C 80 (2009) 05490
Z.-B. Kang et al., Phys. Lett.B740 (2015)23
Y. Xu et al., arXiv:1510.07520
A. Beraudo et al., JHEP 03 (2016) 123

Multiplicity dependence of the open HF

Multiplicity dependence in pp collisions

ALICE, JHEP 09 (2015) 148



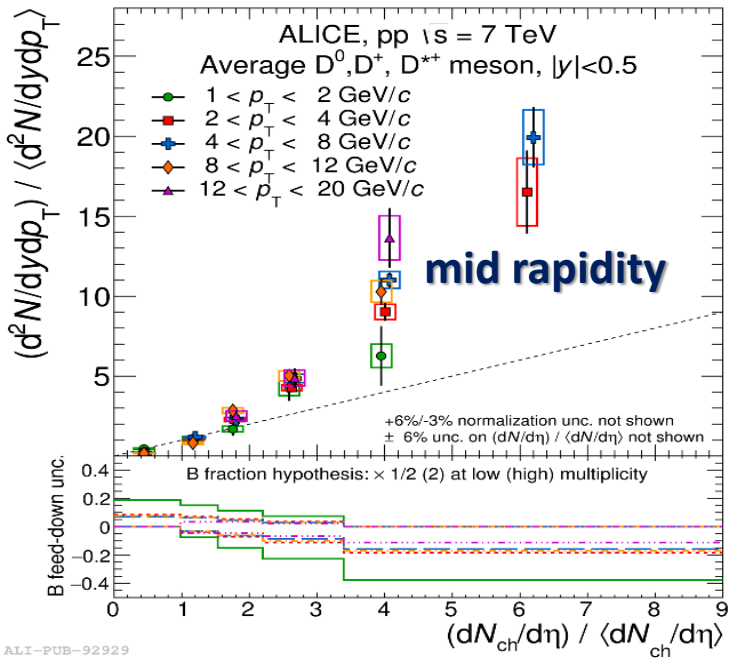


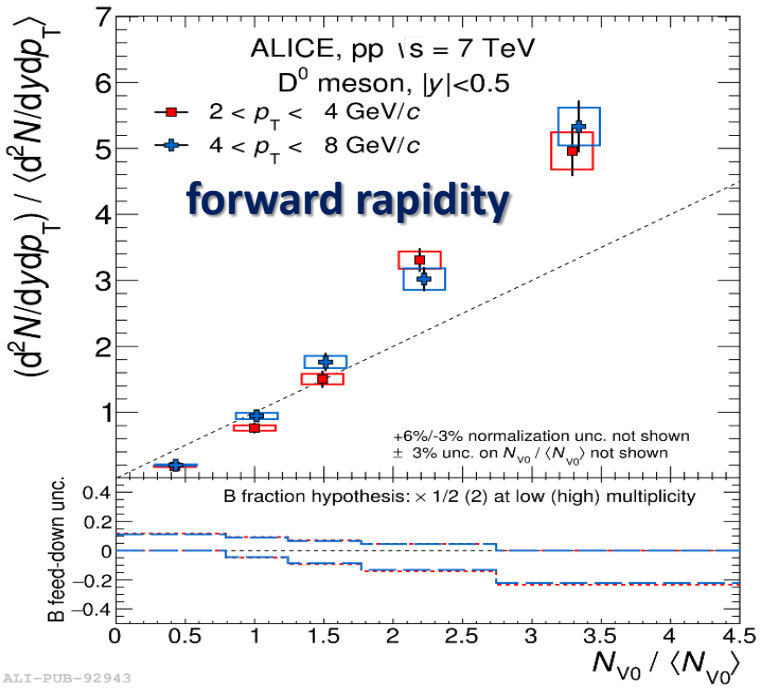
$$\frac{\mathrm{d}^2\mathrm{N}/\mathrm{dyd}p_\mathrm{T}}{<\mathrm{d}^2\mathrm{N}/\mathrm{dyd}p_\mathrm{T}>} = \frac{\mathrm{Y}^{\mathrm{mult}}/(\epsilon^{\mathrm{mult}} \times \mathrm{N}_{\mathrm{event}}^{\mathrm{mult}})}{\mathrm{Y}^{\mathrm{tot}}/(\epsilon^{\mathrm{tot}} \times \mathrm{N}_{\mathrm{event}}^{\mathrm{tot}}/\epsilon^{\mathrm{trigger}})}$$

- The relative D-meson yields increase with the charged-particle multiplicity.
  Faster-than-linear increase at large multiplicities
- Yield increase independent of transverse momentum within the uncertainties.

Multiplicity dependence in pp collisions

ALICE, JHEP 09 (2015) 148



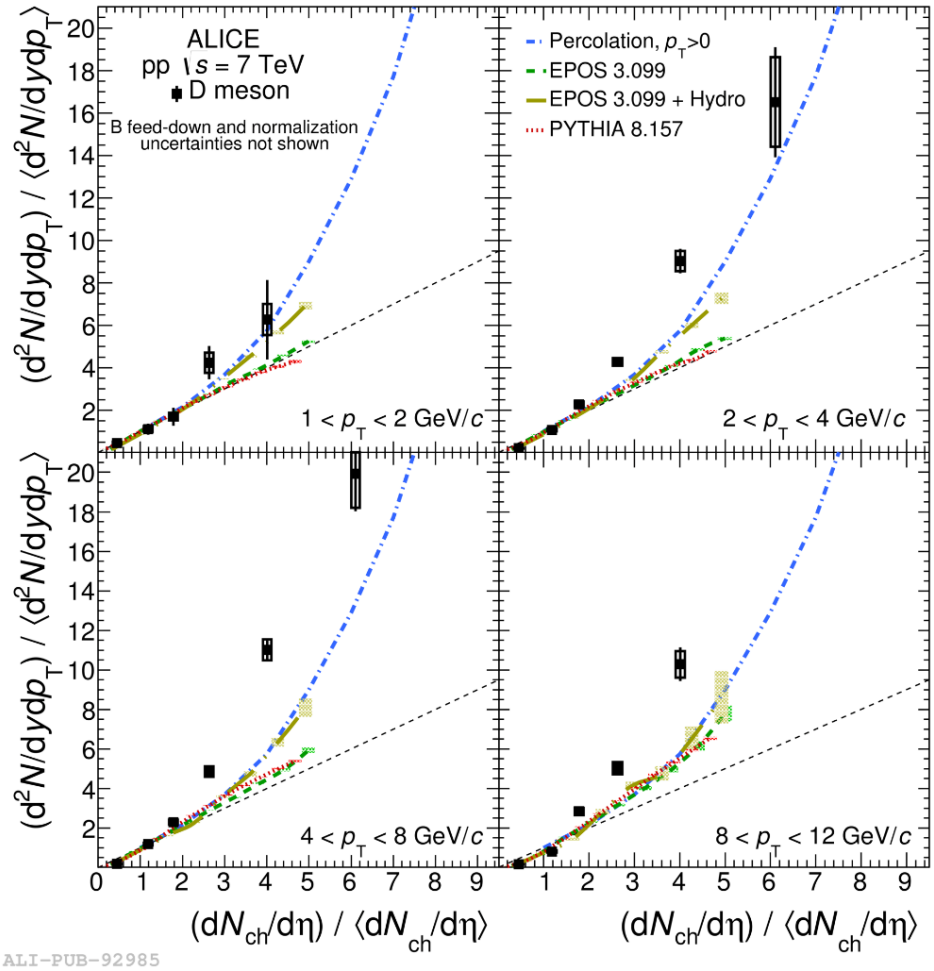


- Similar increasing trend of D-meson yield with multiplicity when an η gap is introduced between the regions where the D mesons and the multiplicity are measured

  → increase not related to the fact that charmed mesons, originating from the fragmentation of charm quarks, and charged-particle multiplicity are measured in the same pseudo-rapidity range.

Comparison with models in pp collisions

new arXiv:1602.07240



Different models used:

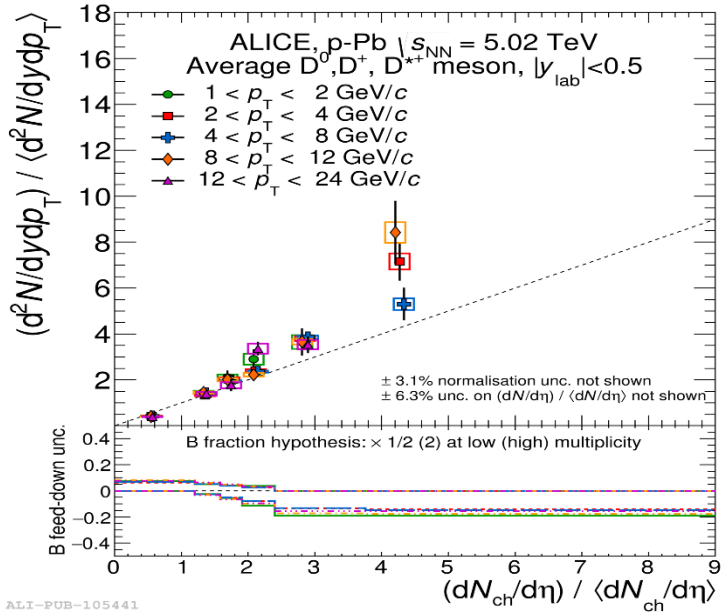
- **PYTHIA calculations**, including contribution from MPI
- **Percolation models**, estimates of the influence of the colour-charge exchanges during the interactions
- **EPOS3 event generator**, providing description of initial conditions followed by hydrodynamical evolution.

- Results qualitatively described by models including MPIs
- PYTHIA event generator seems to under-estimate the increase of heavy-flavour yields with the charged-particle multiplicity at high multiplicities.

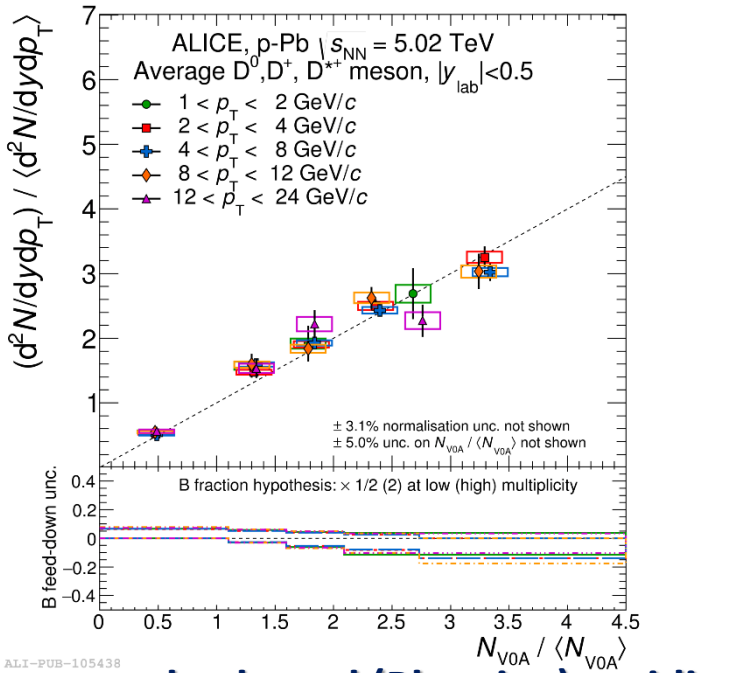
E. G. Ferreiro and C. Pajares, Phys.Rev. C86 (2012) 034903
E. G. Ferreiro and C. Pajares, arXiv:1501.03381 (2015)
ALICE, JHEP 09 (2015) 148
H. Drescher, M. Hladik, S. Ostapchenko, T. Pierog, and K. Werner, Phys.Rept. 350 (2001) 93
K. Werner, B. Guiot, I. Karpenko, and T. Pierog, Phys.Rev. C89 (2014) 064903
T. Sjostrand, S. Mrenna, and P. Z. Skands, Comput.Phys.Commun. 178 (2008) 852

Multiplicity dependence in p-Pb collisions

new arXiv:1602.07240



mid rapidity



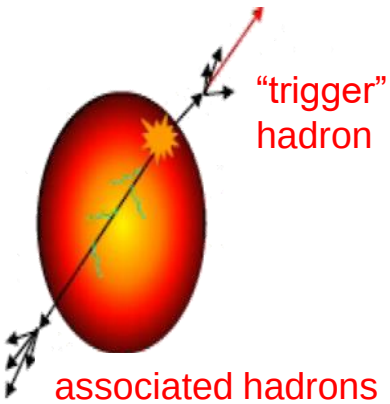
backward (Pb going) rapidity

- Increase of D-meson yields with charged-particle multiplicity at mid rapidity
  - slightly faster-than-linear increase at large multiplicities
- Linear increase of yields with the multiplicity at backward rapidity
- In p-Pb collisions multiple binary nucleon-nucleon collisions also contribute

Correlations between D mesons and charged particles in pp and p-Pb collisions

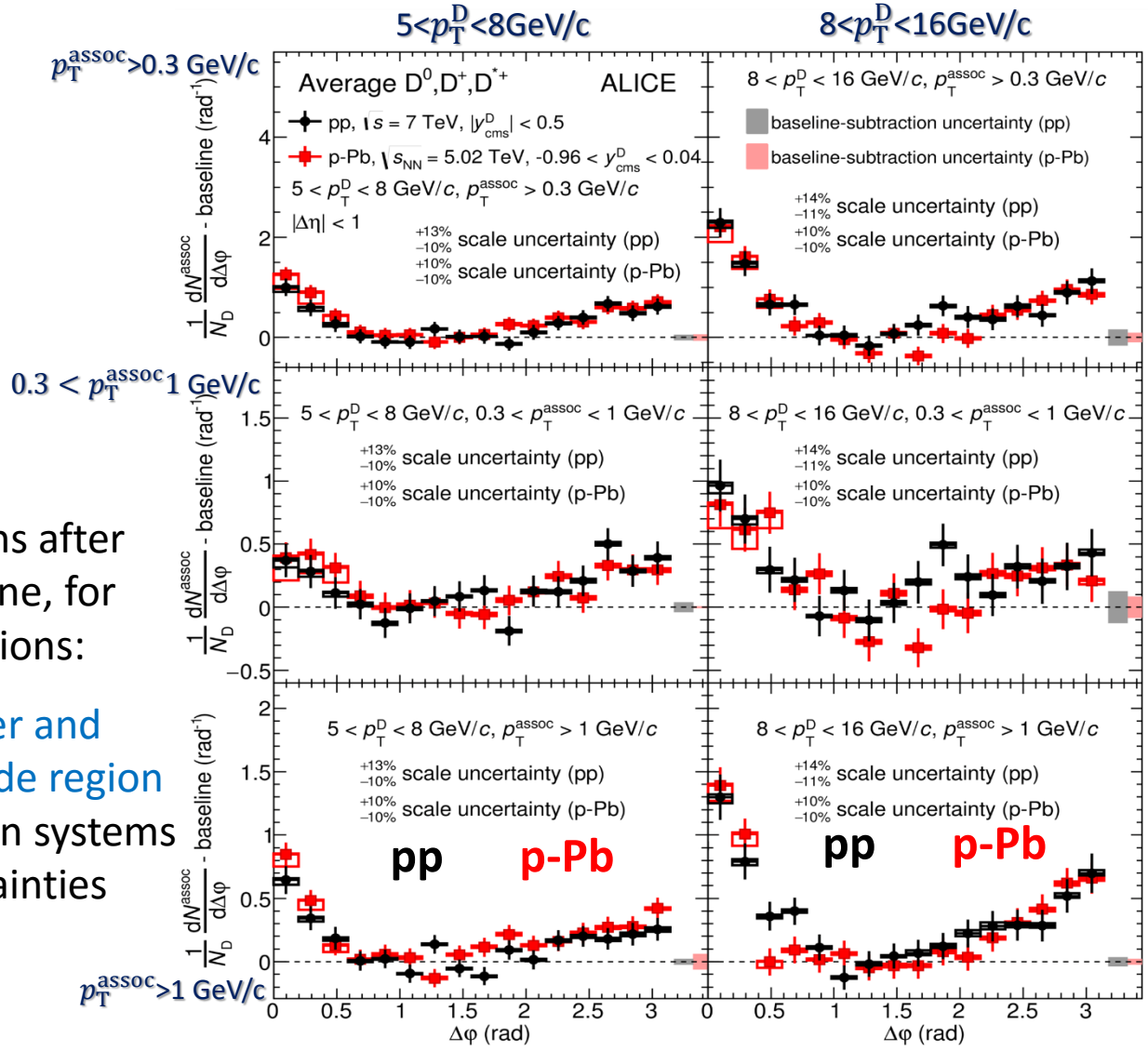
Angular correlations in pp and p-Pb collisions

new arXiv:1605.06963



Distributions for D mesons after subtraction of the baseline, for different kinematic regions:

- near-side peak and a wider and lower peak in the away-side region
- results for the two collision systems compatible within uncertainties



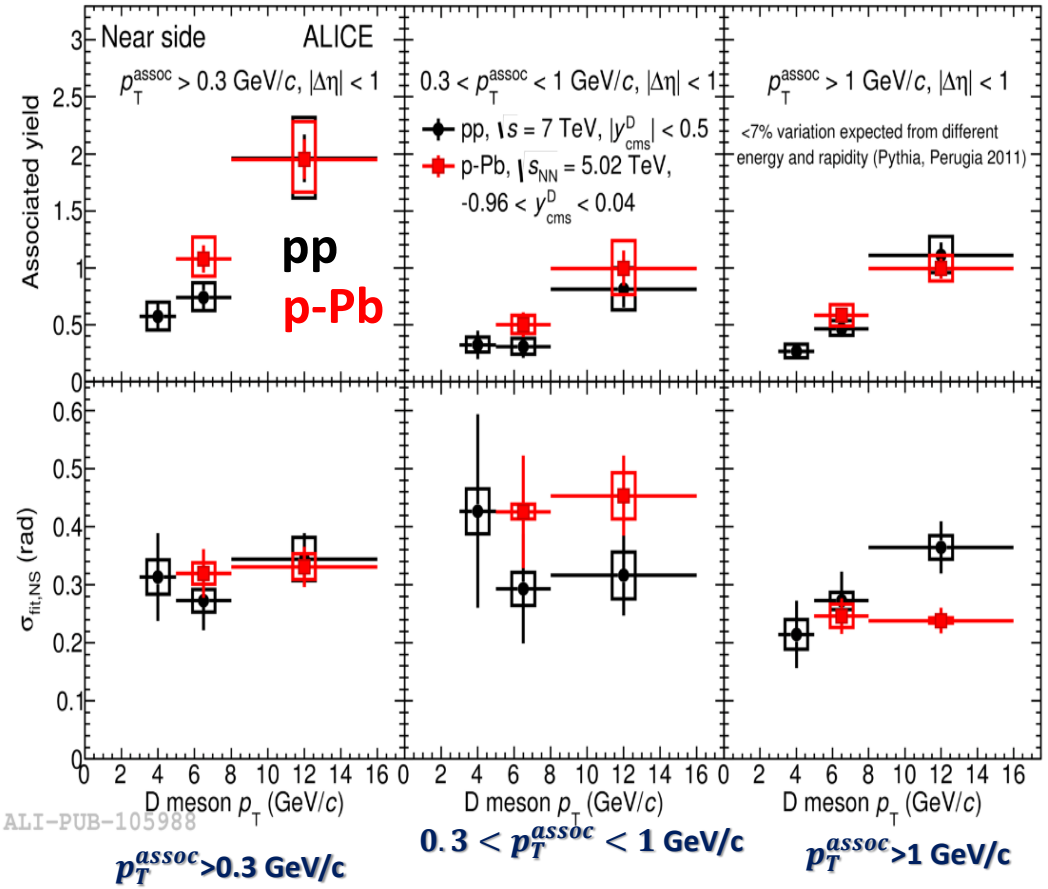
ALI-PUB-105969

Near-side yields and widths in pp and p-Pb collisions

new arXiv:1605.06963

Evolution of the near-side peak associated yield and peak width as a function of $p_{\mathrm{T}}^{\mathrm{D}}$, for different $p_{\mathrm{T}}^{\mathrm{assoc}}$:

- The near-side peak associated yield exhibits an increasing trend with D-meson p_{T}
- The values obtained for pp and p–Pb collisions data are compatible within uncertainties.

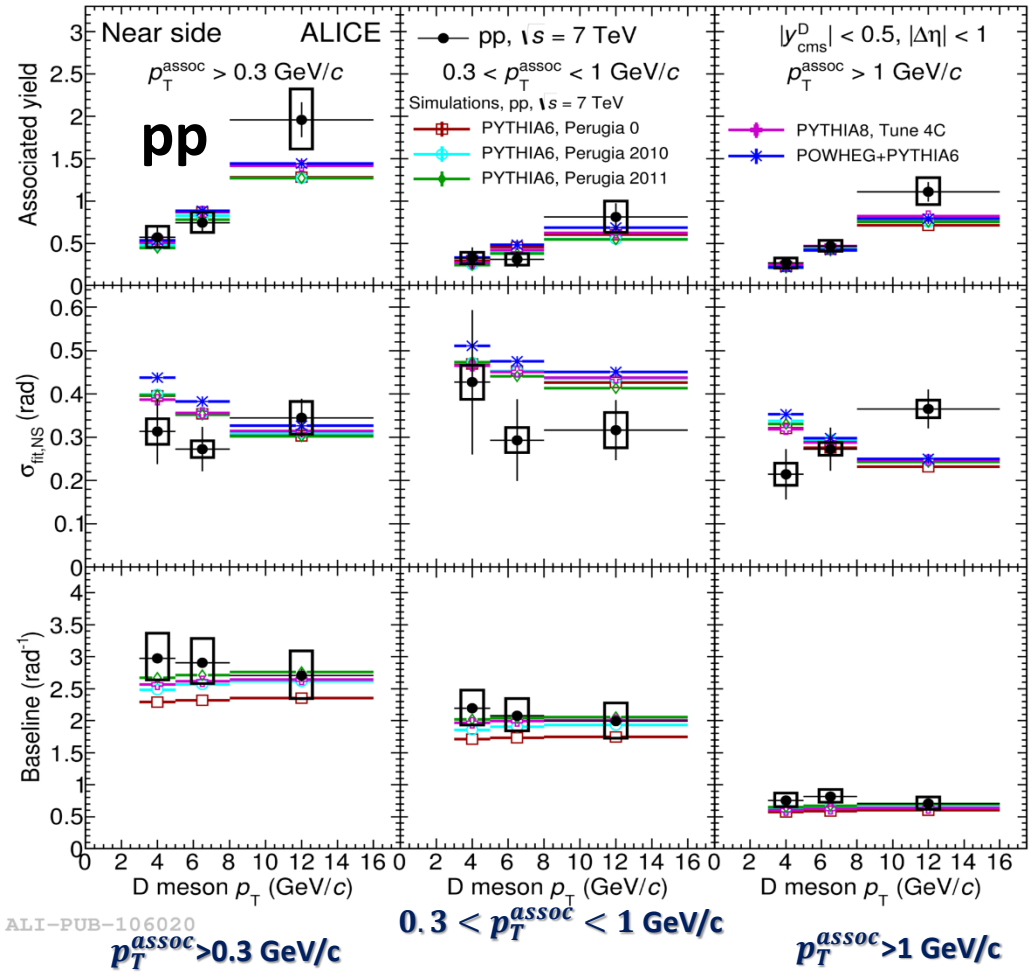


Near-side yields and widths in pp collisions: Comparison with MC

new arXiv:1605.06963

- Different tunes and models used
  - **PYTHIA 6, Perugia 0**
  - **PYTHIA 6, Perugia 2010**
  - **PYTHIA 6, Perugia 2011**
  - **PYTHIA 8 Tune 4C**
  - **POWHEG+PYTHIA6**

- Near-side yields, widths and baseline vs $p_{\mathrm{T}}^{\mathrm{D}}$ compatible in data and simulations within uncertainties



Conclusions

- Cross sections in pp collisions for D mesons and leptons from heavy-flavour decays well described by pQCD calculations within uncertainties **down to p_T = 0 (D^0)**
- R_{pPb} measurement in p-Pb collisions **down to p_T = 0 (D^0)**
  - compatible with unity within uncertainties
  - better described by models including cold nuclear matter effects
- Relative D-meson yields increase with charged-particle multiplicity in pp and p-Pb collisions
    - Models including multiple-parton interactions reproduce pp results.
    - In p-Pb collisions, also contributions from multiple nucleon-nucleon collisions
- Azimuthal correlation between D mesons and charged particles in pp and p-Pb collisions, in different kinematic ranges:
  - Compatibility within the uncertainties both for correlation shapes and for near-side associated yields
  - Near-side structures in good agreement with Monte Carlo generators

Outlook:

- Larger data samples in Run 2, higher $\sqrt{s}$, higher multiplicities
- ALICE upgrade (2019-2020): improved tracking and vertexing performance of the experiment

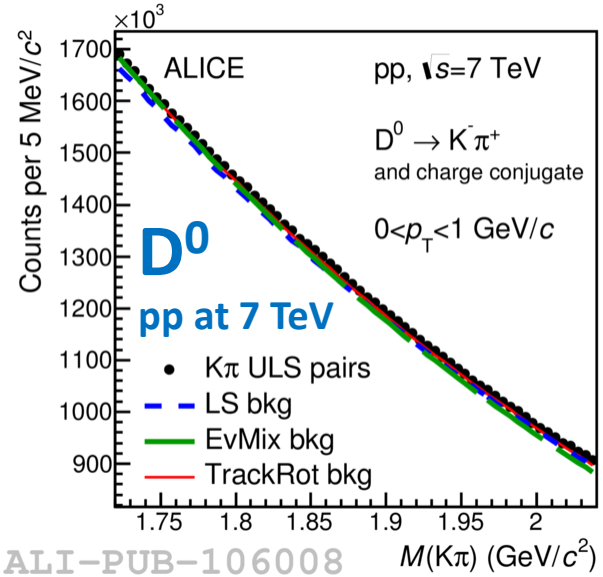
➡ Access to a physics-rich program

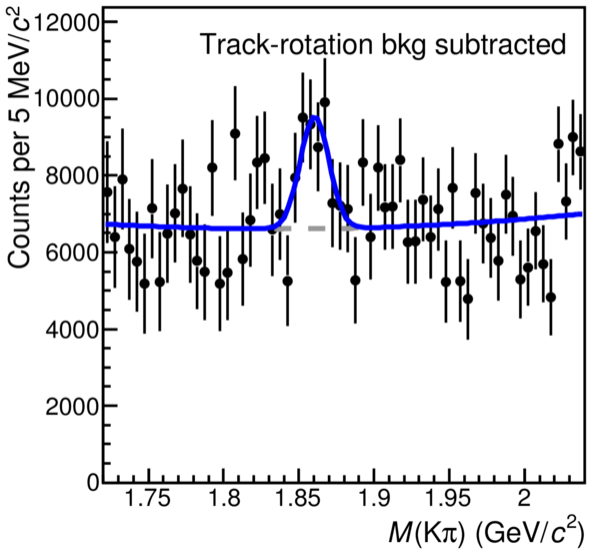
Thanks for your attention

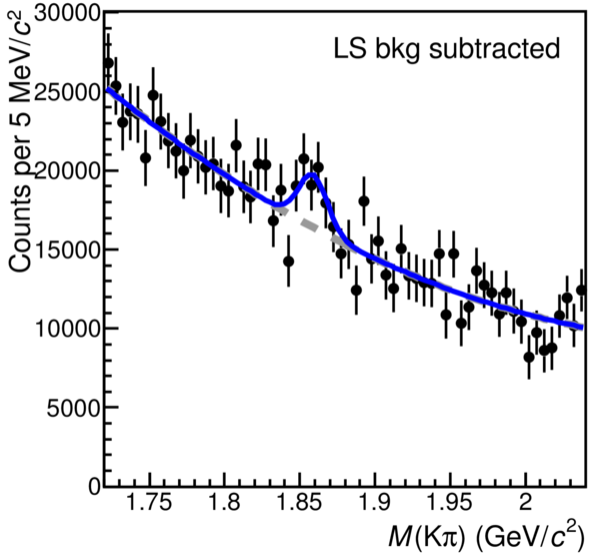
Backup Slides

Cross sections down to p_T =0 in pp collisions

new arXiv:1605.07569





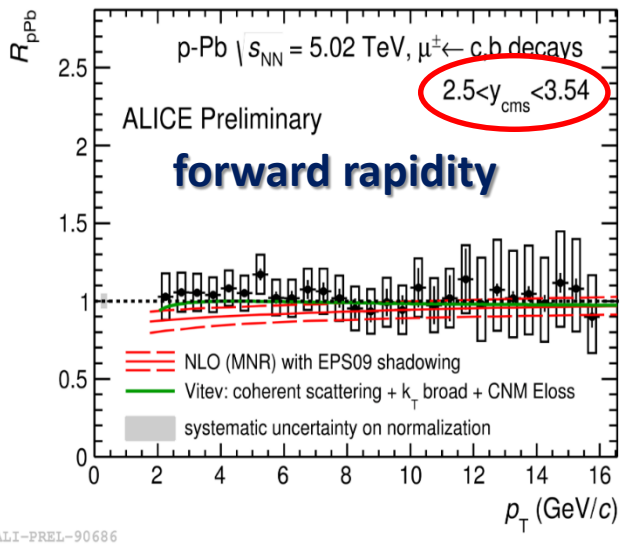


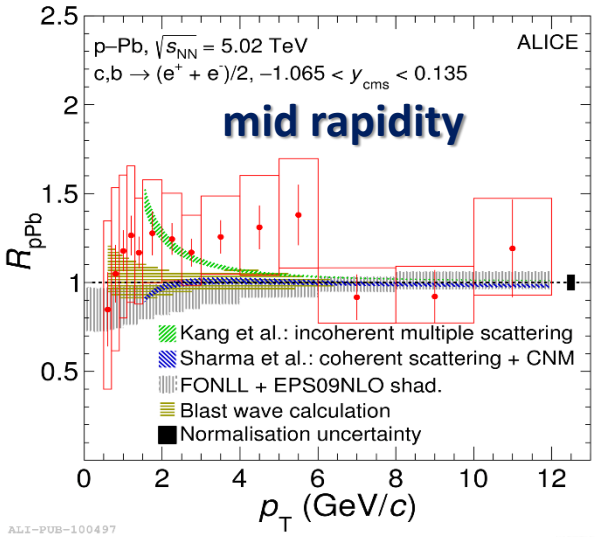
- Analysis method, without selection on secondary vertex displacement.
- Analysis technique based on PID and subtraction of the combinatorial background via:
  - like-sign pairs
  - event mixing
  - track rotation
  - side-band fit

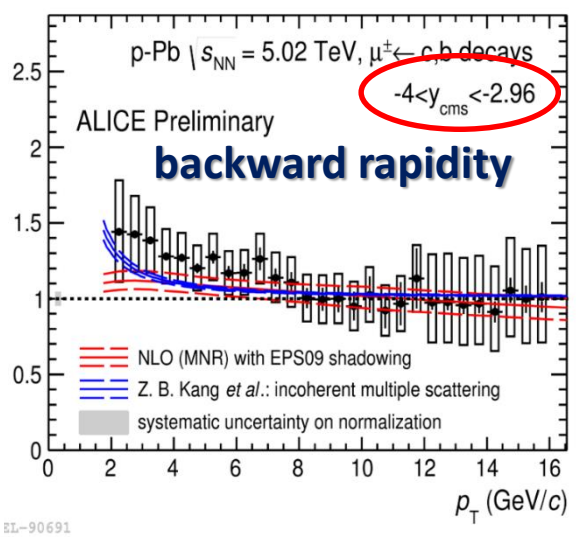
Heavy flavour decay lepton R_{pPb}

$$R_{pA} = \frac{d\sigma_{pA}/dp_T}{A \times d\sigma_{pp}/dp_T}$$

Phys. Lett. B 754 (2016) 81







- Different *x* regimes explored in different rapidity ranges with HF probes
  → shadowing/saturation relevant at low p_T at the LHC
- HF decay e^+/e^- R_{pPb} consistent with unity within uncertainties
- R_{pPb} of HF decay μ
  - consistent with unity at forward rapidity (p-going direction)
  - slightly larger than unity in the range 2 < p < 4 GeV/c at backward rapidity (Pb-going direction)
- Data described within uncertainties by the models with CNM effects

M. Mangano, P. Nason and G. Ridolfi, Nucl. Phys. B373 (1992) 295
K. J. Eskola, H. Paukkunen and C. A. Salgado, JHEP 0904 (2009) 065
R. Sharma, I. Vitev et al., PRC 80 (2009) 054902
Z.B. Kang et al., PLB 740 (2015) 23

HF multiplicity studies

What can we learn?

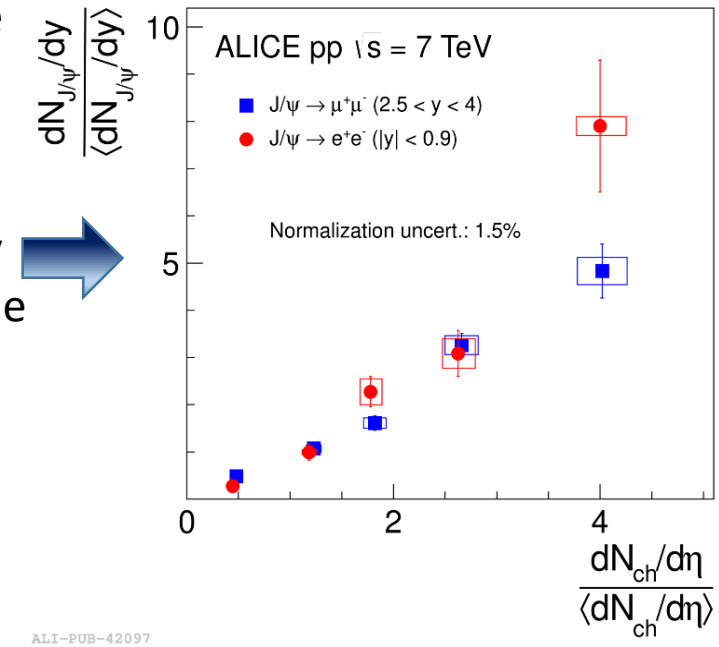
- Study the interplay between hard and soft mechanisms in particle production
- Investigate the contribution of Multiple-Parton Interactions (MPI)

Phys.Rev.D36(1987)2019
Nucl.Phys.Proc.Suppl.214(2011)181–184

- Insights into CNM effects in p-Pb collisions
- Explore the dependence of HF production on the collision geometry and/or multiplicity density of final-state particles

Previous results:

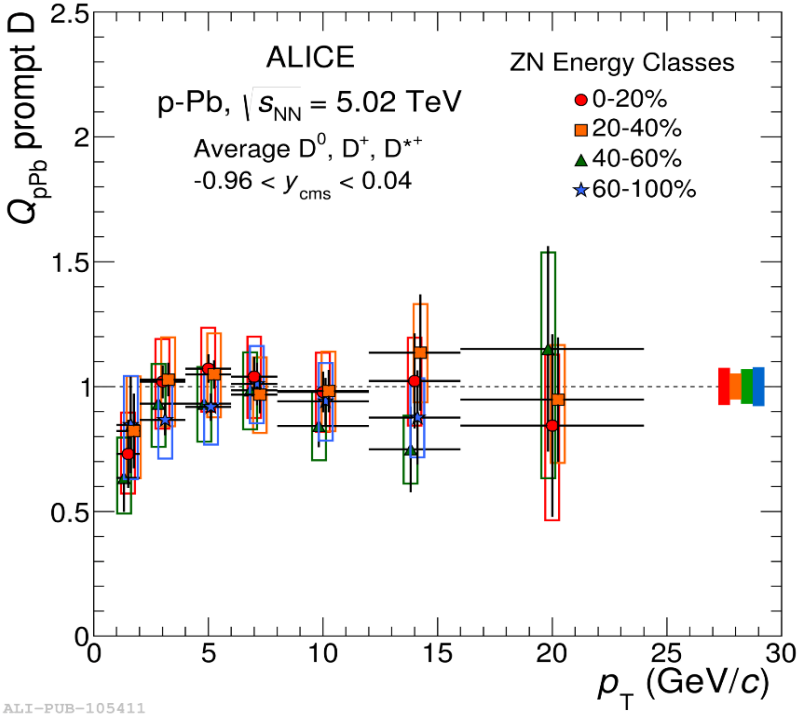
- **NA27 (1988, pp $\sqrt{s}$ = 28 GeV):** observed higher average charged-particle multiplicity in events with open charm production Z. Phys. C 41 (1988) 191
- **ALICE (2012, pp $\sqrt{s}$ = 7 TeV):** first measurements of inclusive J/ψ production vs charged-particle multiplicity show an approximately linear increase of the yield of the J/ψ with the multiplicity. ALICE, Phys. Lett. B 712 (2012) 165
- **CMS (2013, p-Pb $\sqrt{s_{NN}}$ = 5.02 TeV**): increase of Y(nS) production yields as a function of the charged-particle multiplicity JHEP1404(2014)103



D meson production in different centrality classes in p-Pb collisions

new arXiv:1602.07240

$$Q_{\mathrm{pPb}} = \frac{(\mathrm{d}N^{\mathrm{D}}/\mathrm{d}p_{\mathrm{T}})^{\mathrm{cent}}_{\mathrm{pPb}}}{\langle T_{\mathrm{pPp}}\rangle \times (\mathrm{d}\sigma^{\mathrm{D}}/\mathrm{d}p_{\mathrm{T}})\mathrm{pp}}$$

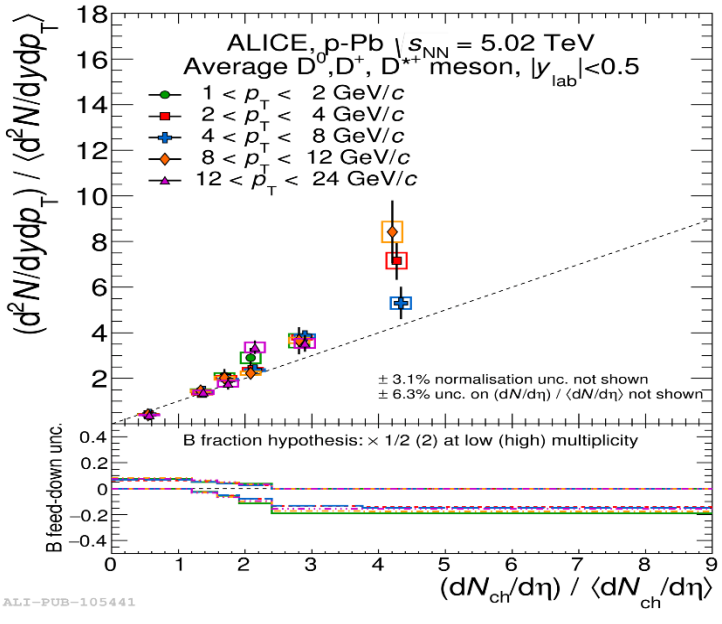


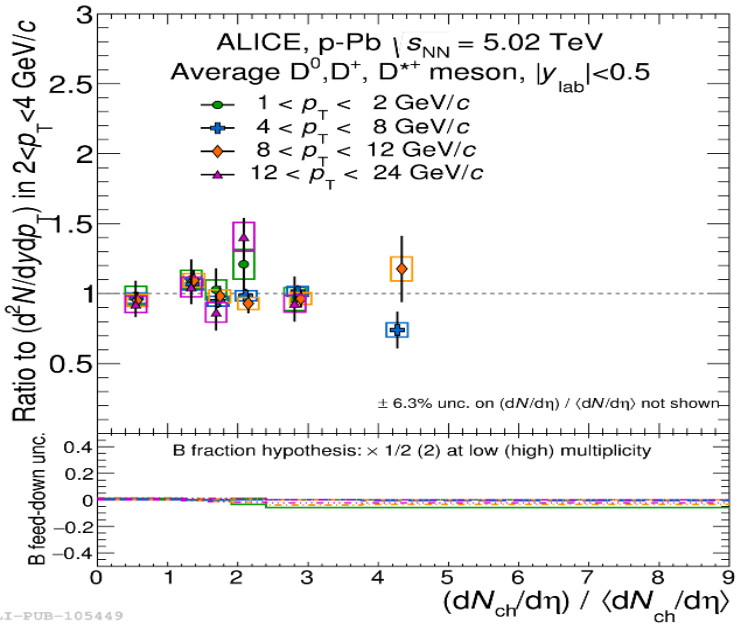
Nuclear modification factors estimated, with ZNA estimator (energy deposited in the zero-degree neutron calorimeter in Pb-going side, no bias expected due to the event selection), in different centrality classes:

- Results consistent within unity within the uncertainties
- Results consistent with binary collision scaling of the yield in pp collisions, independent of the geometry of the collisions.

Multiplicity dependence in p-Pb collisions

new arXiv:1602.07240



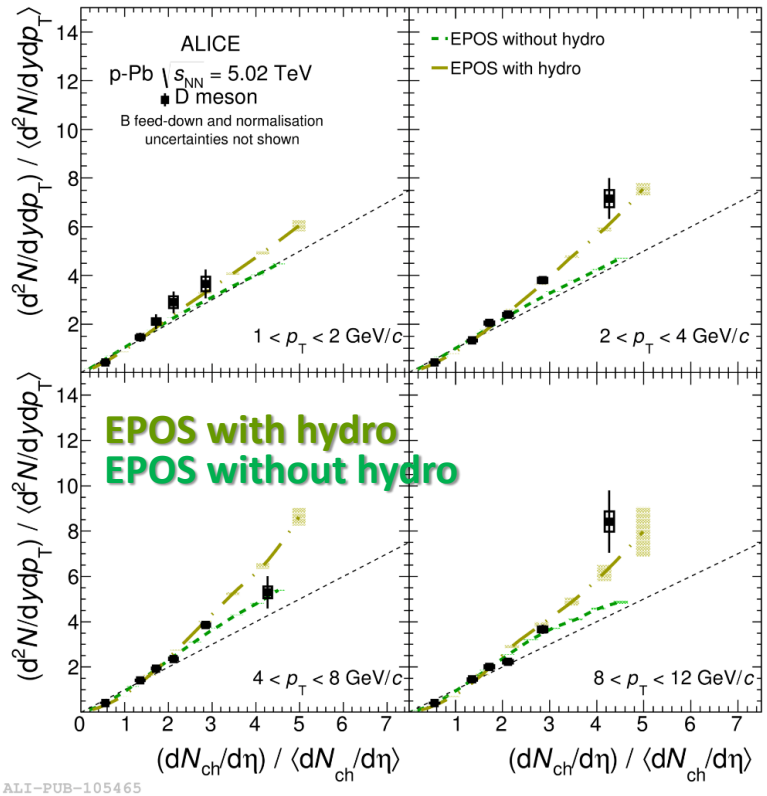


- The D meson yields show a slightly faster-than-linear increase with the charged-particle multiplicity at central rapidity.
- The yield increase is independent of transverse momentum within the uncertainties of the measurement.

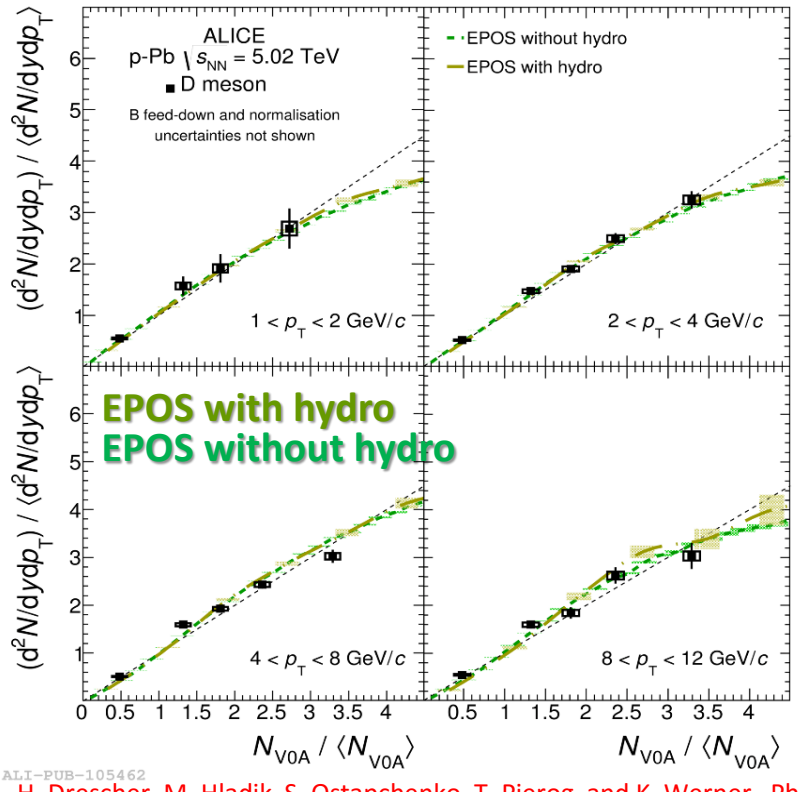
Comparison with models in p-Pb collisions

new arXiv:1602.07240

mid rapidity



backward rapidity

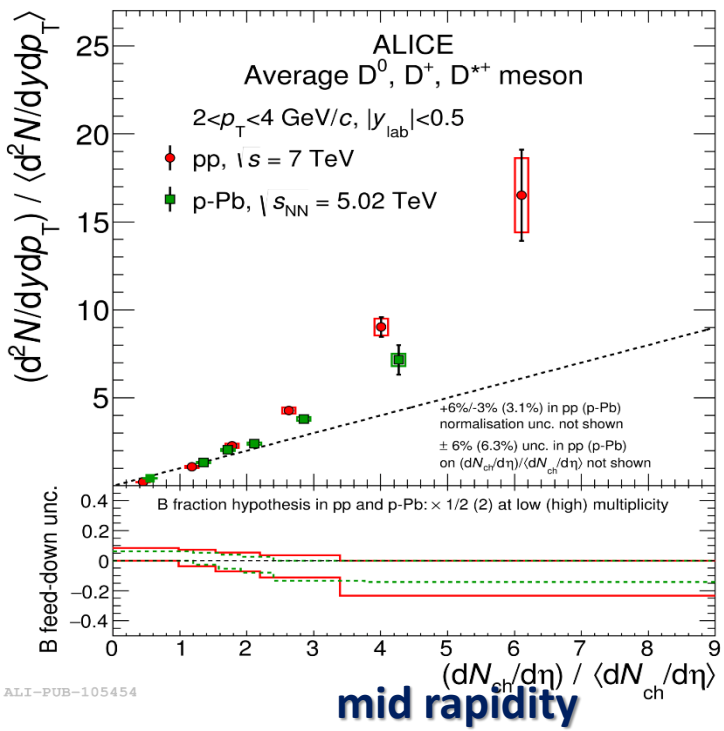


H. Drescher, M. Hladik, S. Ostapchenko, T. Pierog, and K. Werner, Phys.Rept. 350 (2001) 93
K. Werner, B. Guiot, I. Karpenko, and T. Pierog, Phys.Rev. C89 (2014) 064903

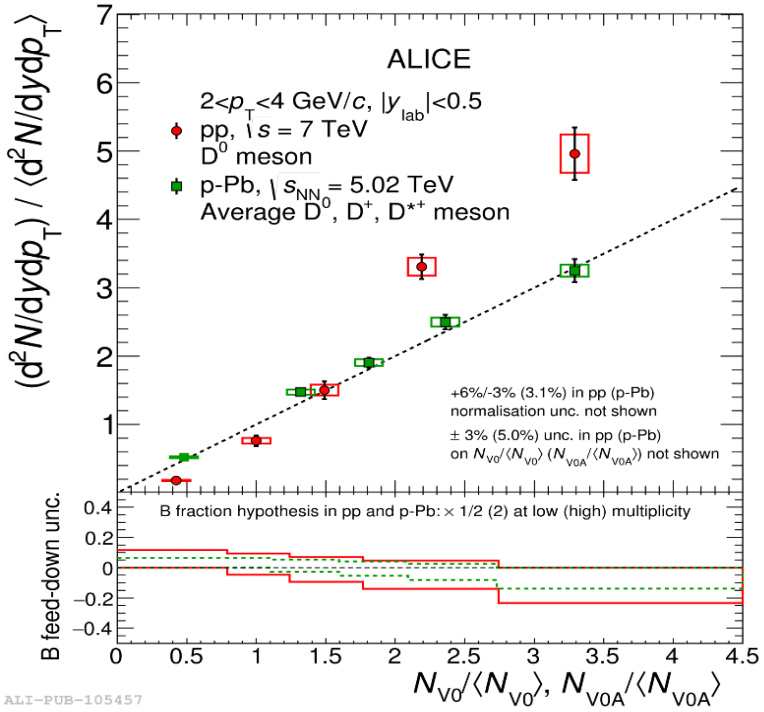
- The measurements agree with the EPOS3 model calculations (with initial conditions and hydrodynamic evolution) within uncertainties
  - faster-than-linear increase of D-meson yields with multiplicity at mid rapidity
  - approximately linear trend with multiplicity at backward rapidity

Comparison of pp and p-Pb collisions

new arXiv:1602.07240



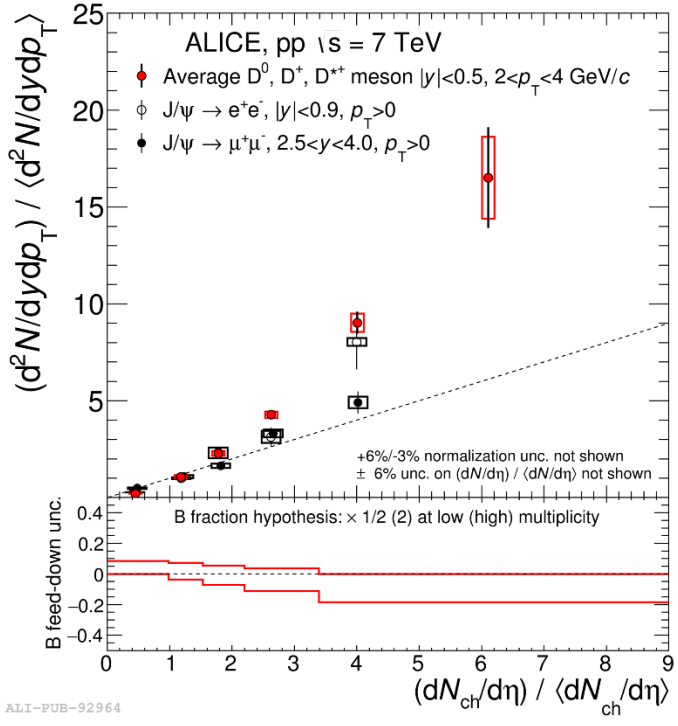
mid rapidity

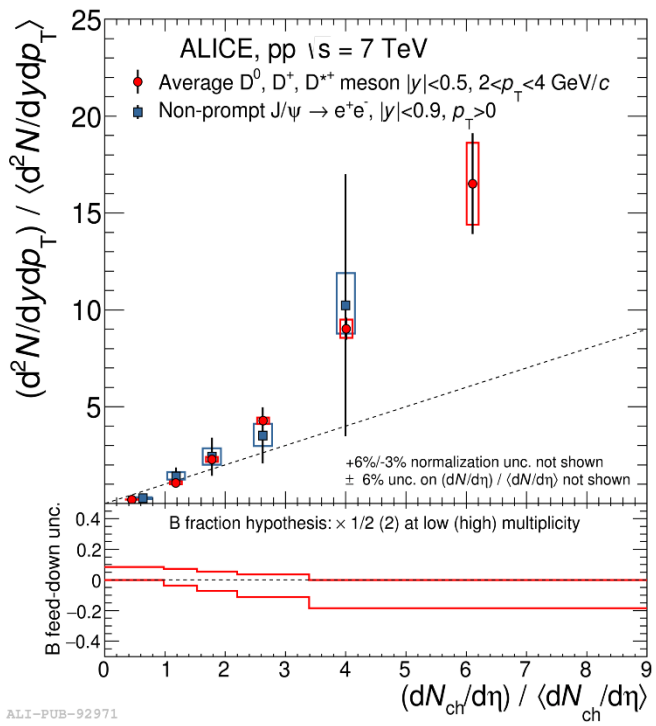


forward rapidity

- At mid rapidity similar relative increase of charmed-meson yield with charged-particle multiplicity is observed in pp and p–Pbcollisions
- At backward rapidity the D-meson yields increase faster in pp than p–Pb collisions:
  - Increase can be described by calculations taking into account the contribution of MIP in high-multiplicity pp collisions
  - different pseudorapidity intervals of the multiplicity measurement
  - in p-Pb multiple binary nucleon-nucleon collisions also contribute

Multiplicity dependence in pp collisions
Comparison with hidden heavy flavours



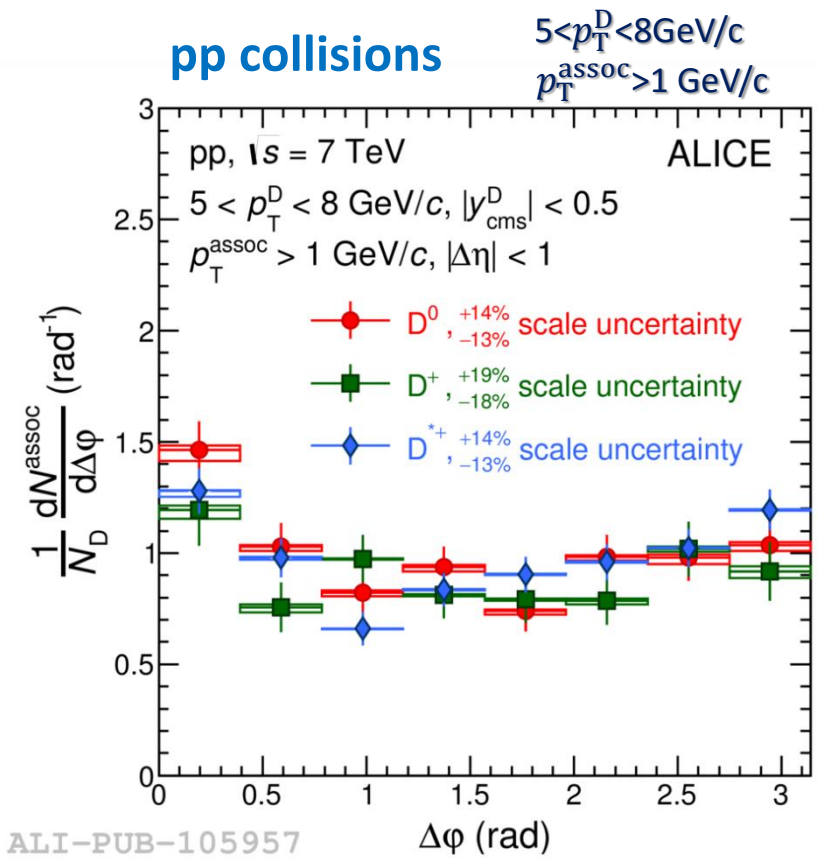


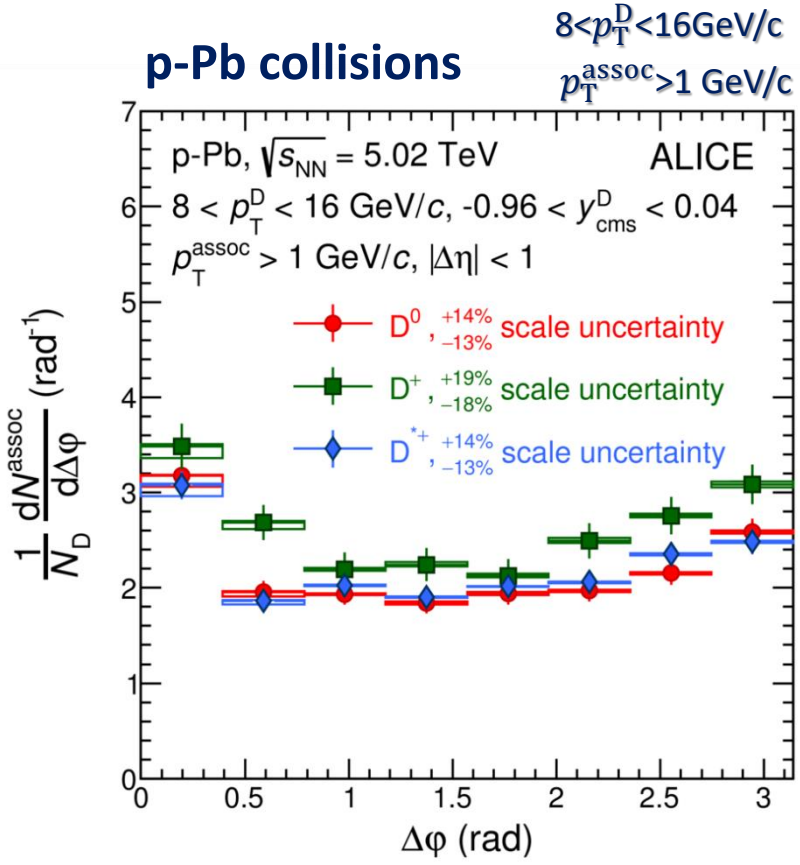
- Similar increase of the relative yield with the charged-particle multiplicity is observed for open and hidden heavy flavour production both at central and forward rapidities:
  - Suggestion that this behaviour is most likely related to the $c\bar{c}$ and $b\bar{b}$ production processes, not significantly influenced by hadronisation

Angular correlations in pp and p-Pb collisions

new arXiv:1605.06963

- Azimutahal-correlation distributions for D^0, D^+ and D^{*+} mesons in different kinematic ranges



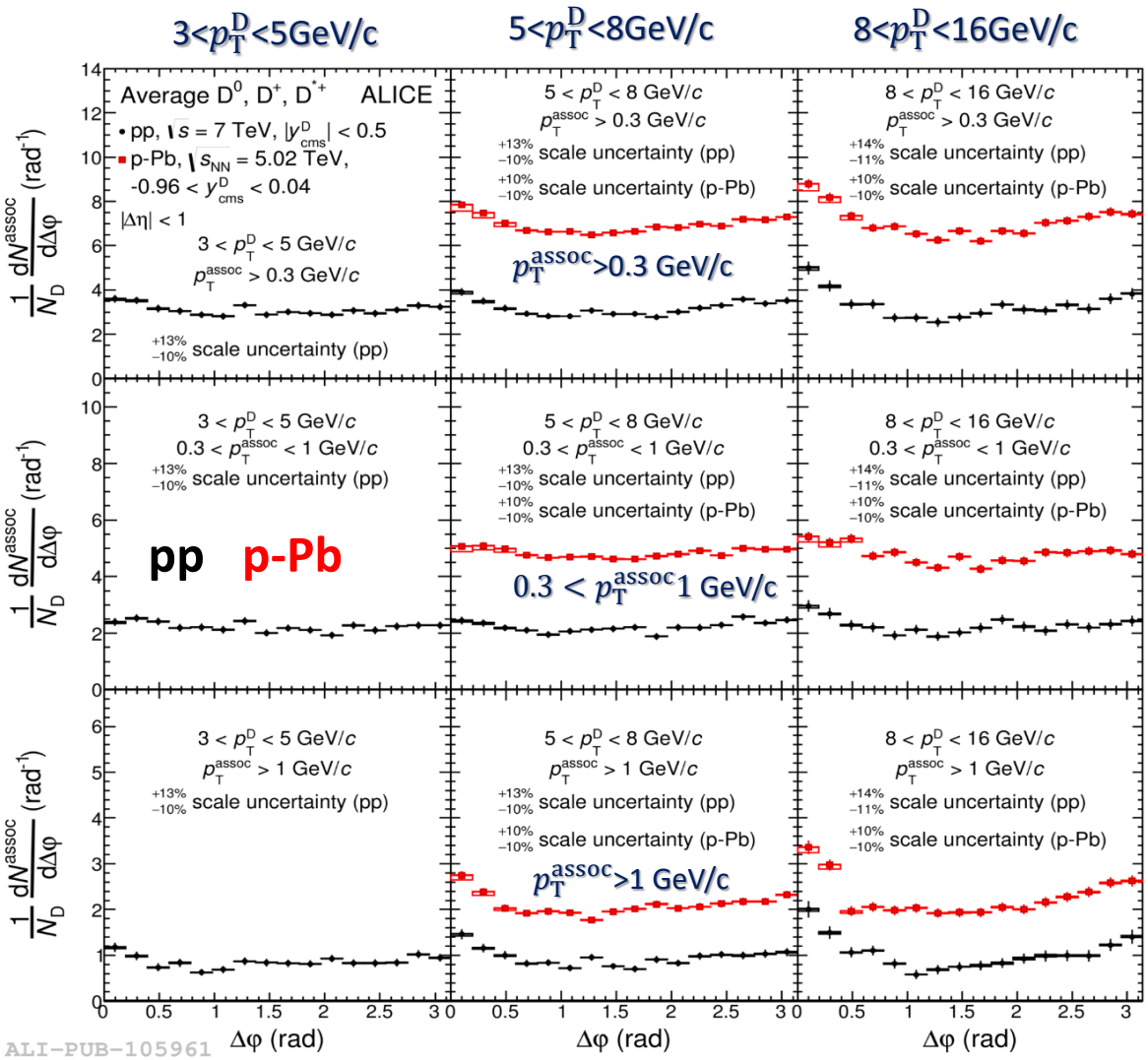


Angular correlations in pp and p-Pb collisions

new arXiv:1605.06963

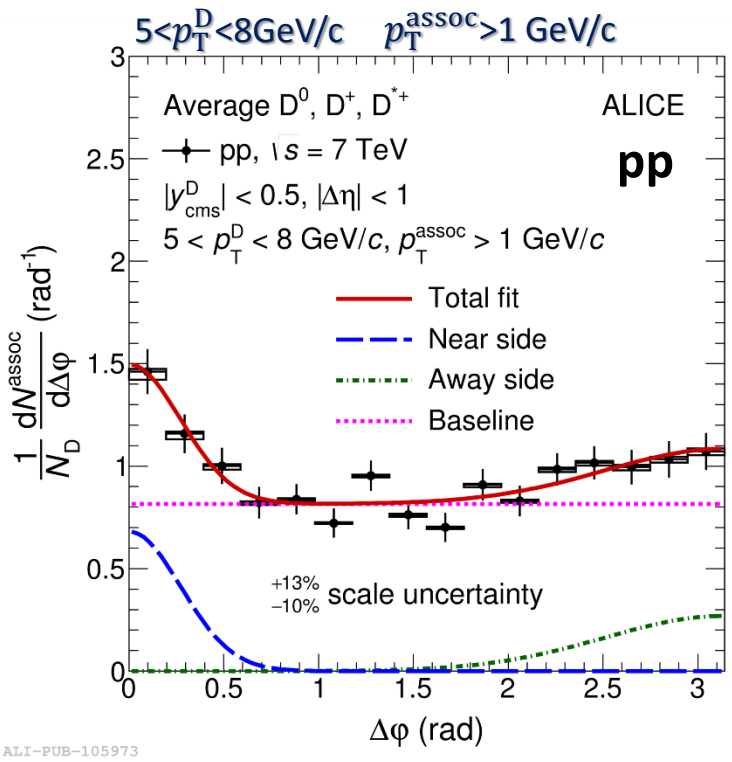
Azimutahal-correlation distributions for D mesons for both collision systems:

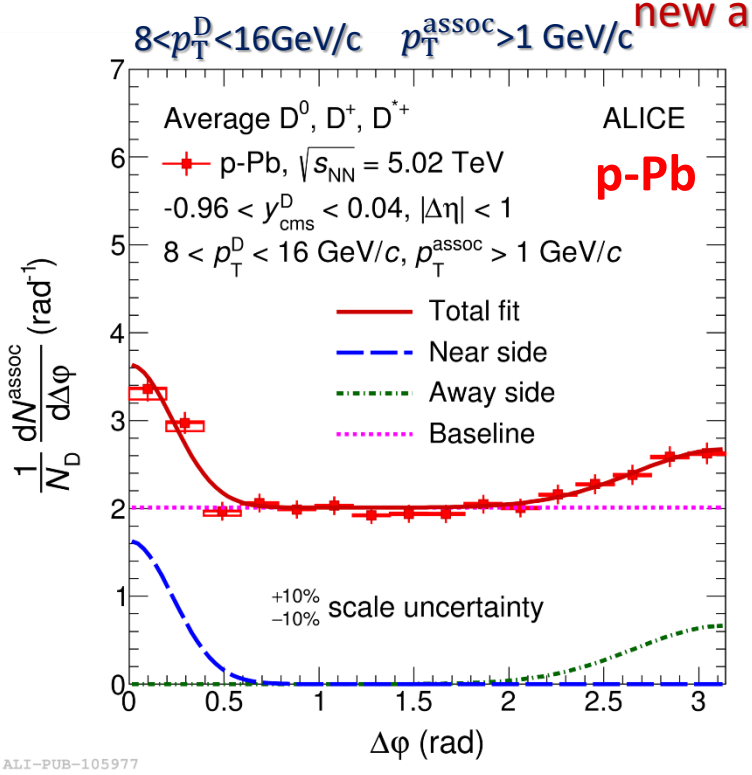
- Rising trend of the height of the near-side peak with increasing D-meson p_T
- Decrease of the baseline level with increasing p_T of the associated particles.



Angular correlations in pp and p-Pb collisions

new arXiv:1605.06963





Fit to the azimuthal-correlation distribution, in different kinematic ranges.

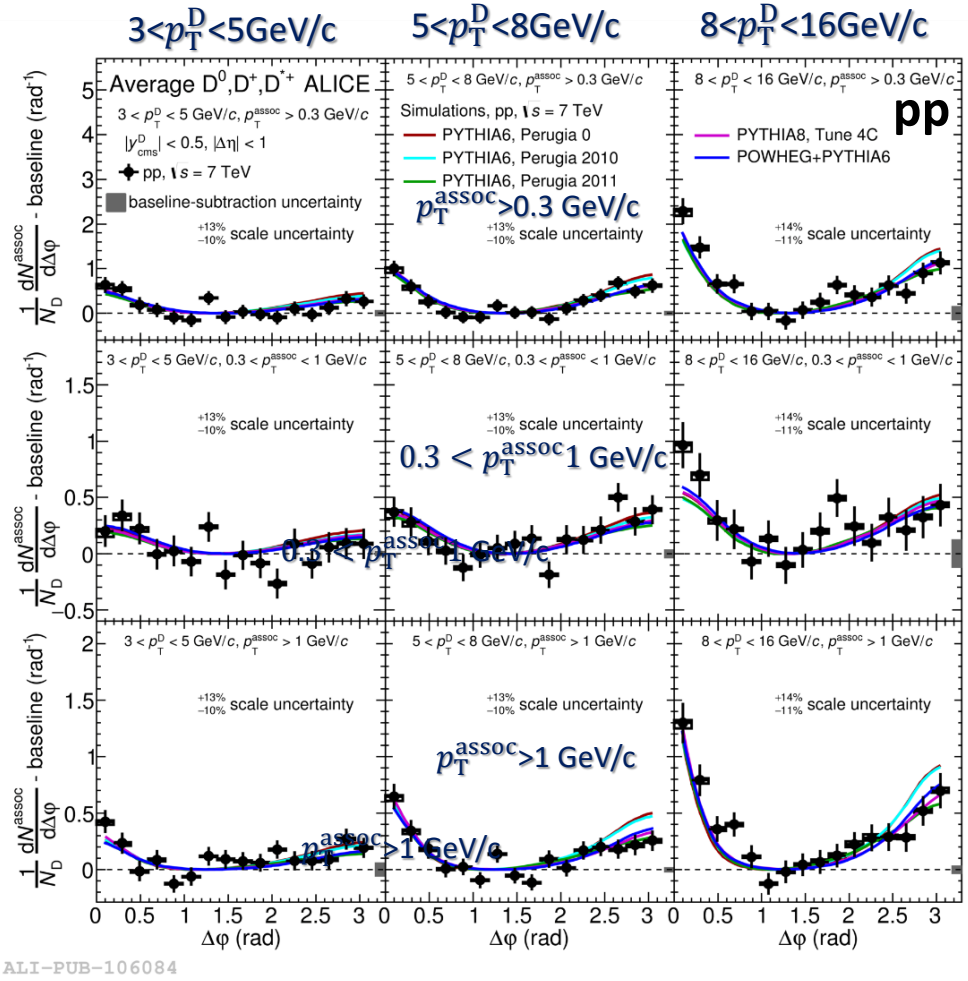
- Fit function made by 3 terms: near-side Gaussian function (blue dashed line), away-side Gaussian function (green dashed-dotted line) and baseline constant term (magenta dotted line).
- The fit function describes, within uncertainties, the measured distributions in all kinematic cases, providing values of χ^2/NDF close to unity

Angular correlations in in pp collisions: comparison with models

new arXiv:1605.06963

Comparison with expectations from simulations performed with PYTHIA and POWHEG+PYTHIA:

- All the considered Monte-Carlo simulations describe, within the uncertainties, the data in the whole Δ φ range
- hint for a more pronounced peak in the near side in data than in models is present for D mesons with $8 < p_T < 16$ GeV/c for $p^{assoc}_T > 0.3$ GeV/c.



Near-side yields and widths in p-Pb collisions: Comparison with MC

new arXiv:1605.06963

- Different tunes and models used
  - **PYTHIA 6, Perugia 0**
  - **PYTHIA 6, Perugia 2010**
  - **PYTHIA 6, Perugia 2011**
  - **PYTHIA 8 Tune 4C**
  - **POWHEG+PYTHIA6**

- Near-side yields and widths compatible in data and simulations within uncertainties