ALICE measurements of heavy-flavour production as a function of multiplicity and angular correlations in pp and p-Pb collisions at the LHC

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University of Trieste & INFN-Trieste

Outline

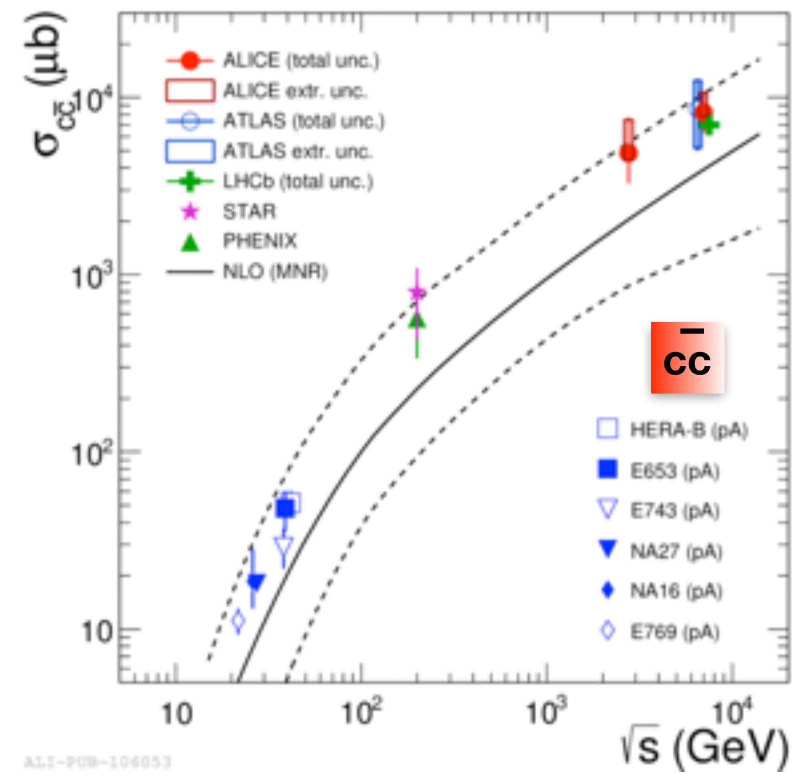
- ✓ **Physics motivations** for open heavy-flavour measurements in pp and p-Pb collisions
- ✓ The **ALICE detector** and **open heavy-flavour reconstruction**
- ✓ **Main results**
  - **Extension of D-meson cross-sections down to p_T=0**
  - **Nuclear modification factor of electrons from beauty-hadron decays**
  - **Open heavy-flavour production as a function of the charged-particle multiplicity**
  - **Centrality-dependent nuclear modification factor**
  - **Angular correlations of D mesons and charged particles**
- ✓ **Conclusions**

Open-heavy flavours in pp and p-Pb collisions

Charm and beauty quarks are produced in partonic scattering processes with large Q^2 transfer -> production cross sections can be calculated with perturbative QCD factorisation approach

- **Multiplicity-integrated measurements**
  - Test of pQCD predictions in **pp collisions**
  - Assess Cold Nuclear Matter (CNM) effects in **p-Pb collisions**
    - Modification of parton densities in nuclei, k_T-broadening, parton energy loss in CNM
  - Possible final-state effects in p-Pb collisions?

arXiv:1605.07569



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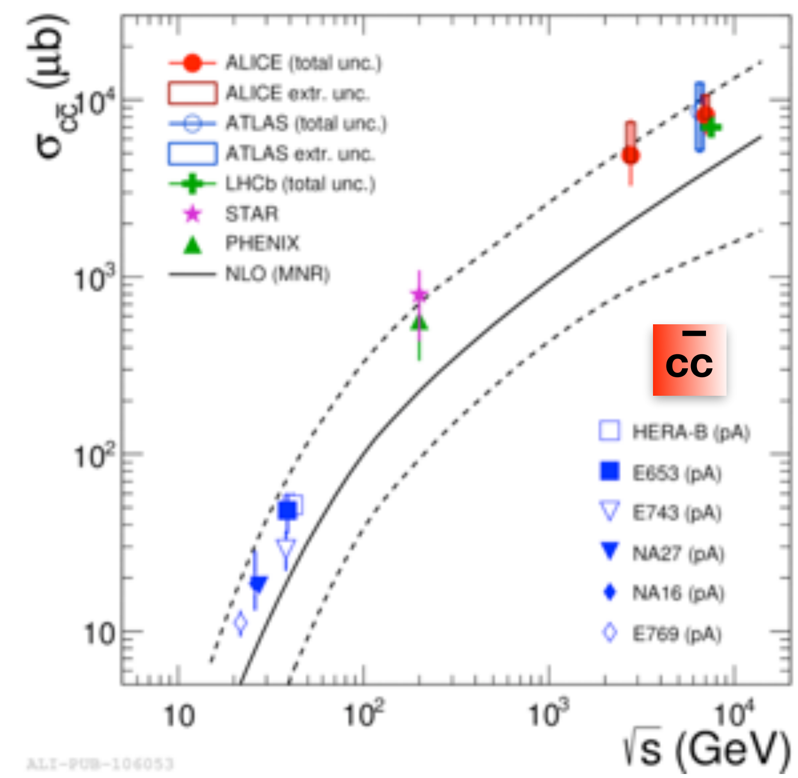

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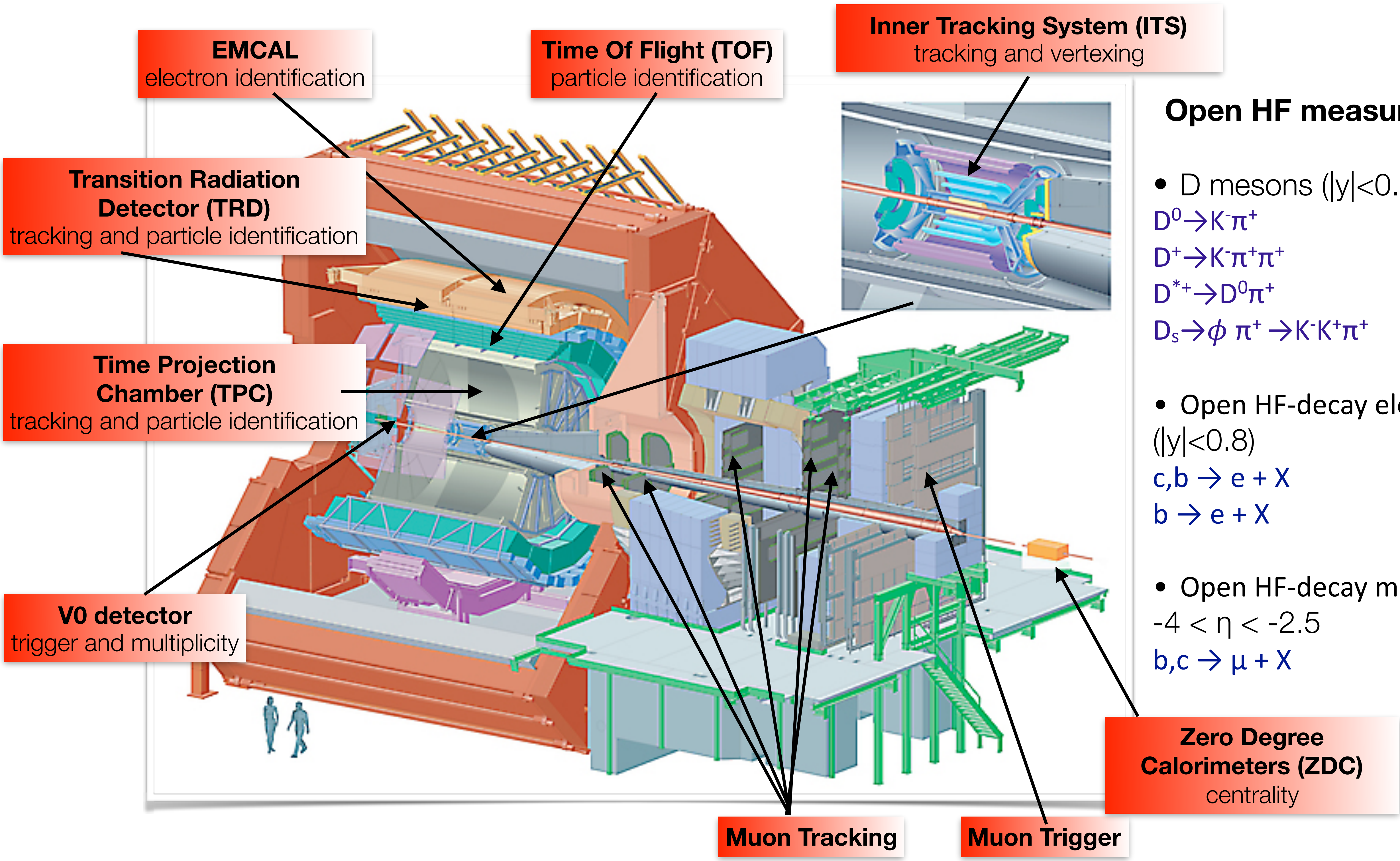
- **More differential measurements**
  - **HF production vs multiplicity/centrality in pp and p-Pb**
    - **Interplay between hard and soft processes** in particle production
    - Study the role of **multi-parton interactions (MPI)** in the heavy-flavour sector
    - Investigate a possible **centrality dependent modification** of the p_T spectra in p-Pb wrt pp collisions
  - **HF - charged hadrons azimuthal correlations**
    - Heavy-flavour quark **fragmentation** properties
    - Understand the contribution of LO and NLO mechanisms to heavy-quark production
    - **Modifications of angular correlations** in p-Pb wrt pp collisions

ALICE detector



Open HF measurements

- D mesons (|y|<0.8)
  $D^0 \rightarrow K^- \pi^+$
  $D^+ \rightarrow K^- \pi^+ \pi^+$
  $D^{*+} \rightarrow D^0 \pi^+$
  $D_s \rightarrow \phi\ \pi^+ \rightarrow K^- K^+ \pi^+$
- Open HF-decay electrons (|y|<0.8)
  c,b → e + X
  b → e + X
- Open HF-decay muons
  $-4 < \eta < -2.5$
  b,c → μ + X

D-meson measurements down to p_T= 0 GeV/c

- Standard D-meson analysis with secondary vertex reconstruction inefficient at p_T < 2 GeV/c (small Lorentz boost)
- Alternative method based on PID only
- Background subtraction with different methods
- The most precise measurement obtained with the "w/o vertexing method" at p_T < 2 GeV/c and "with vertexing" at p_T > 2 GeV/c

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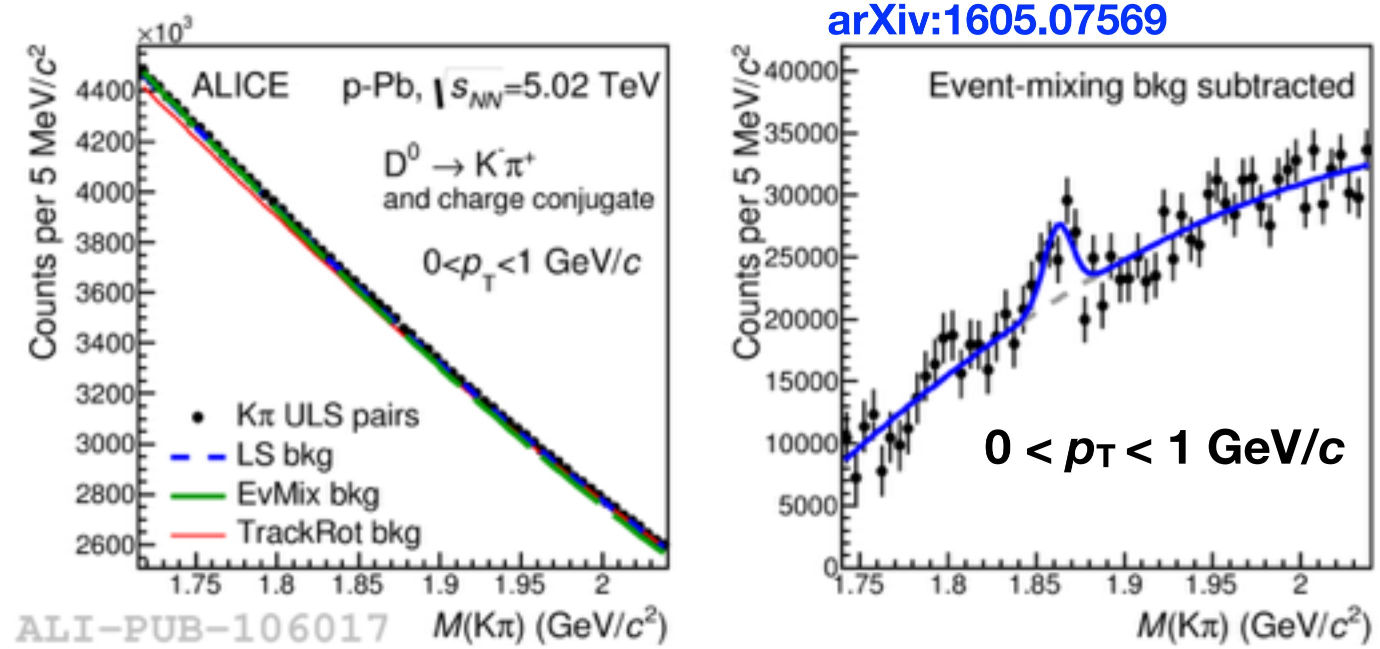

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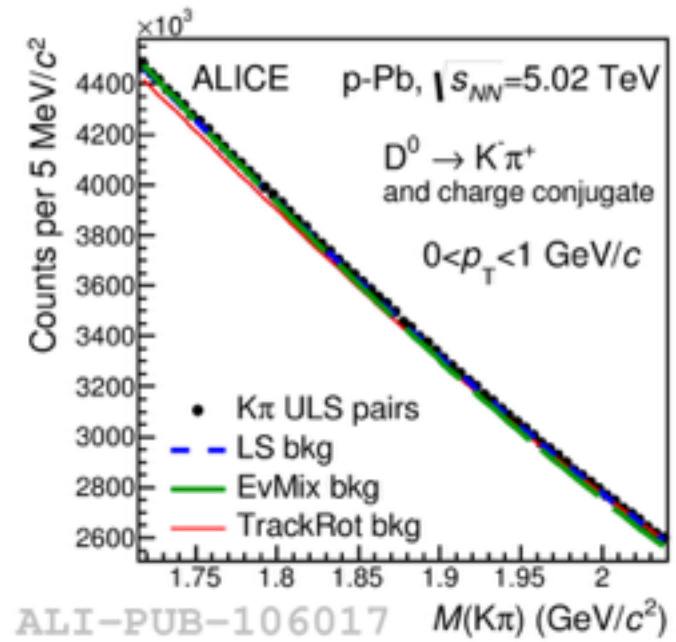

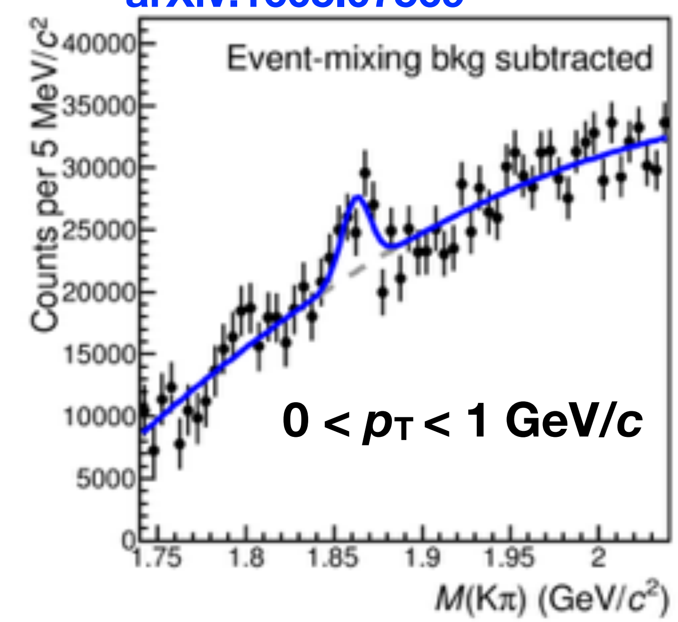

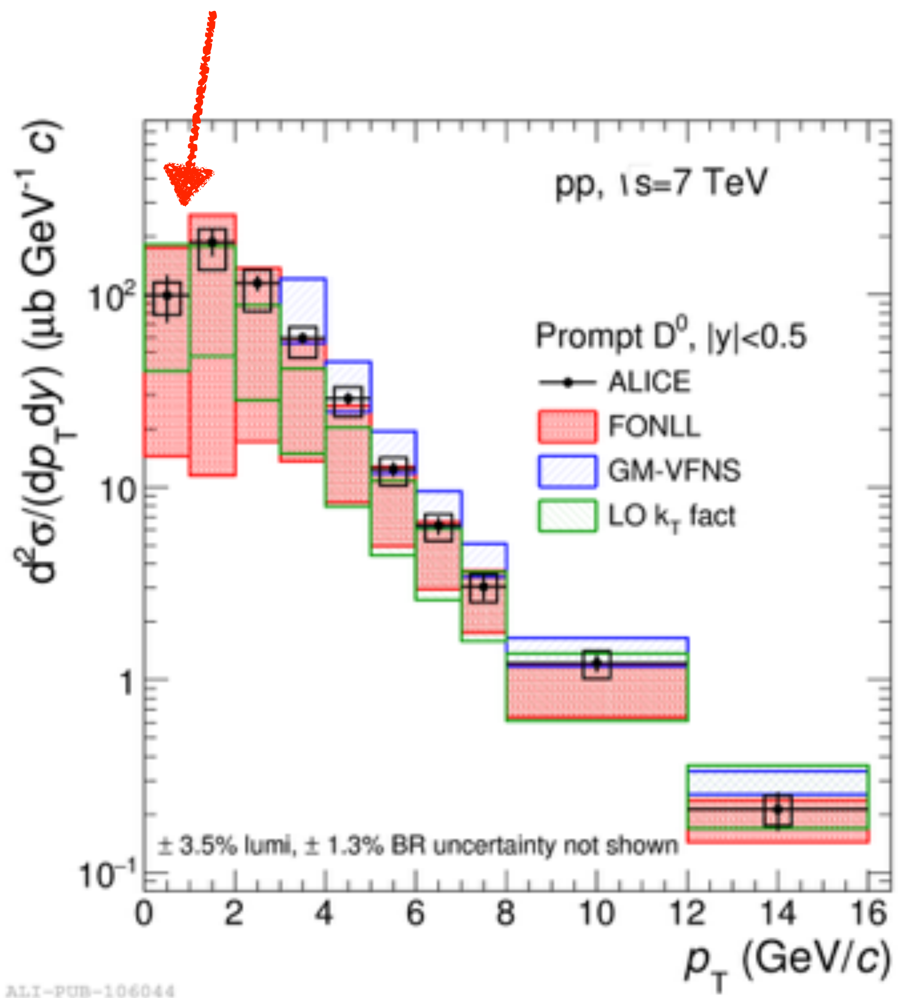

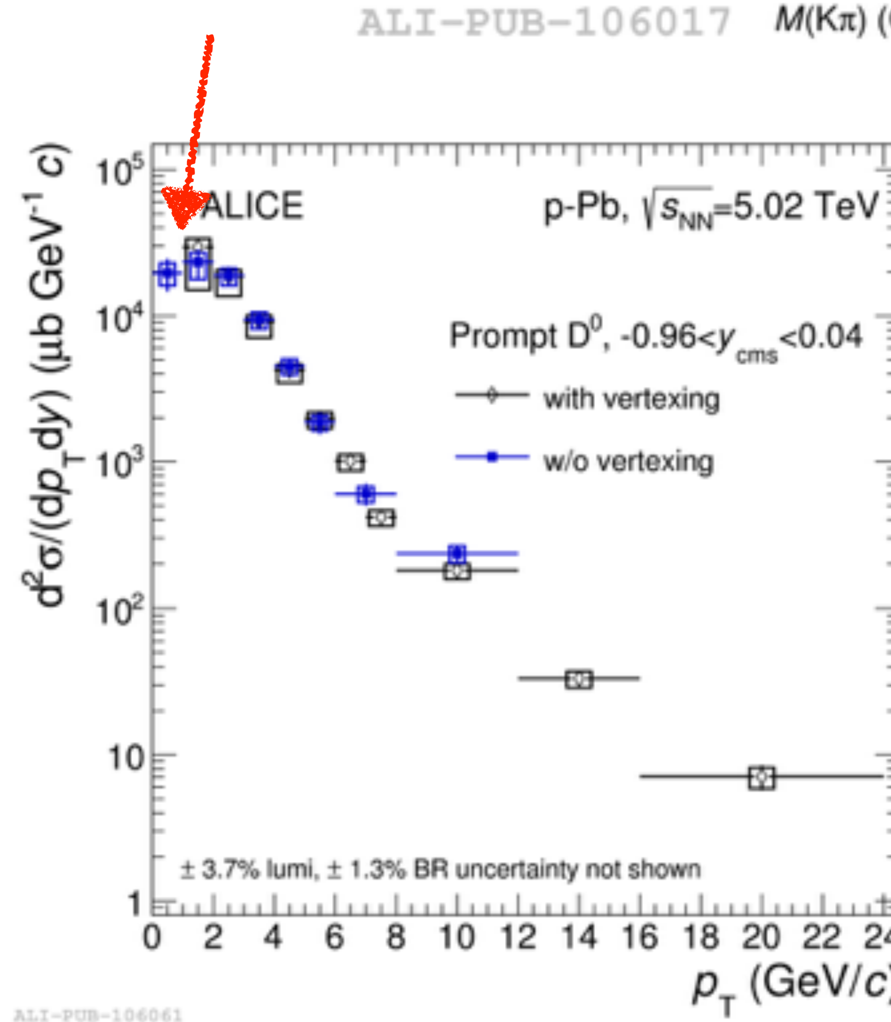

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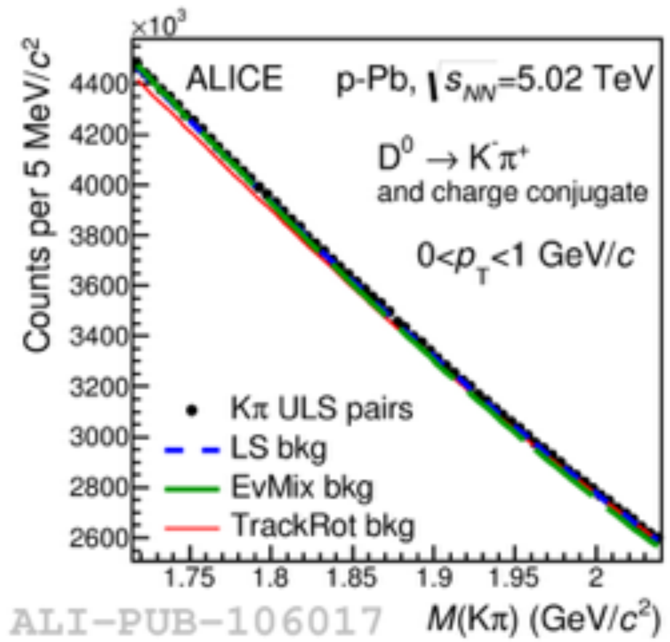
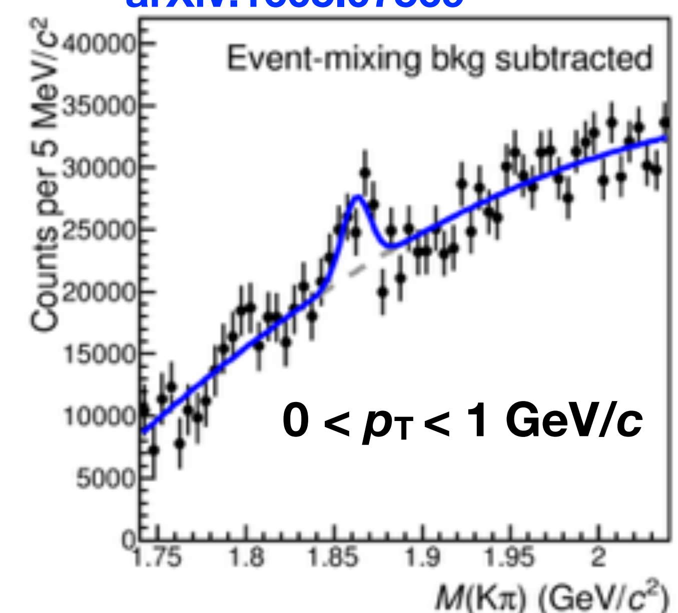
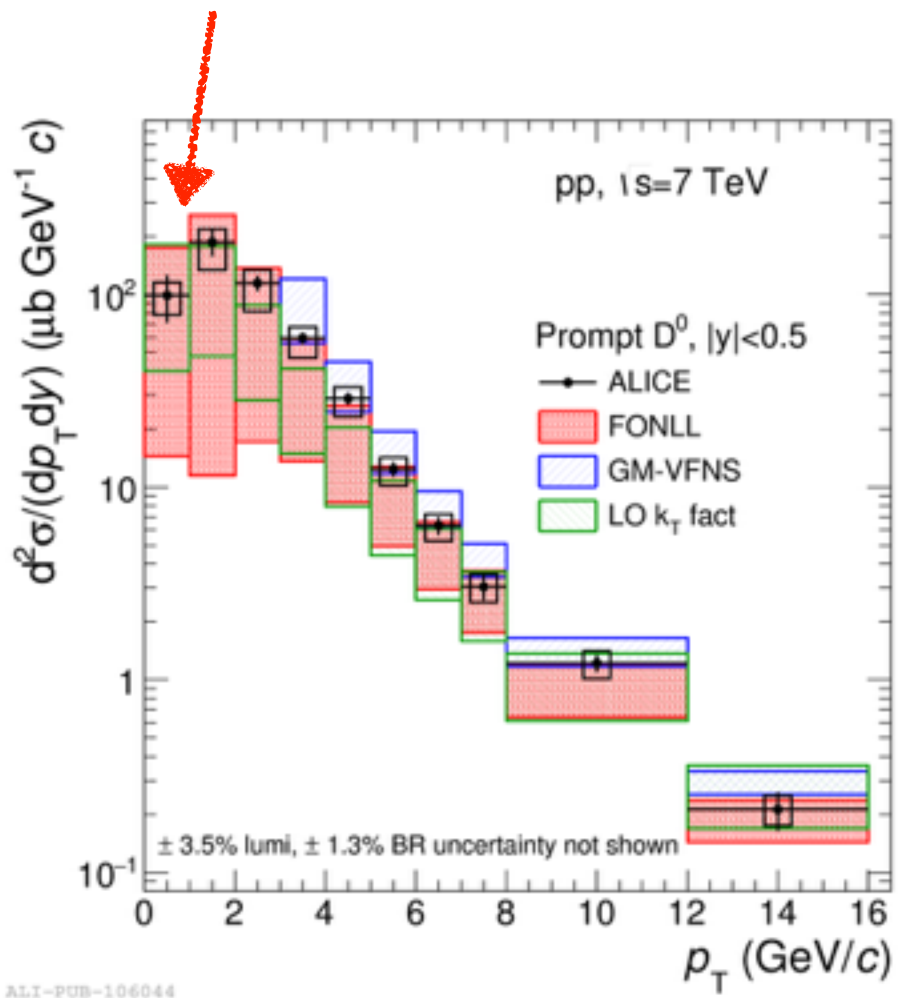
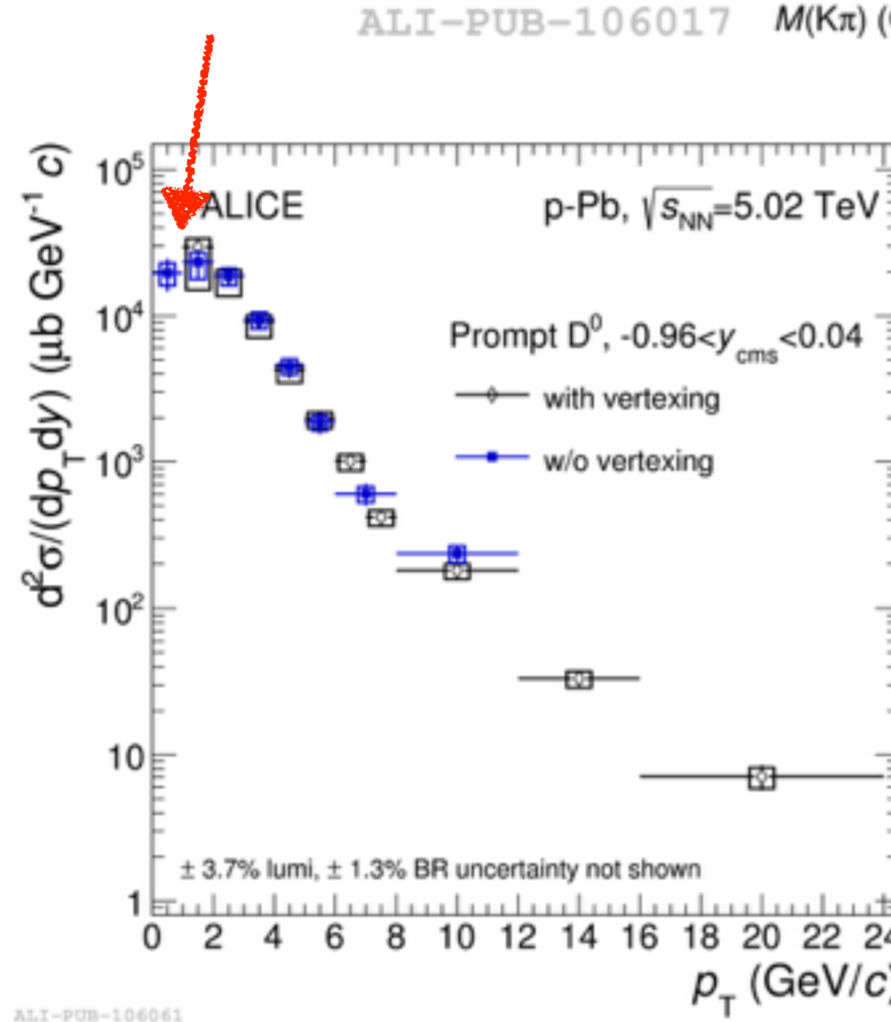
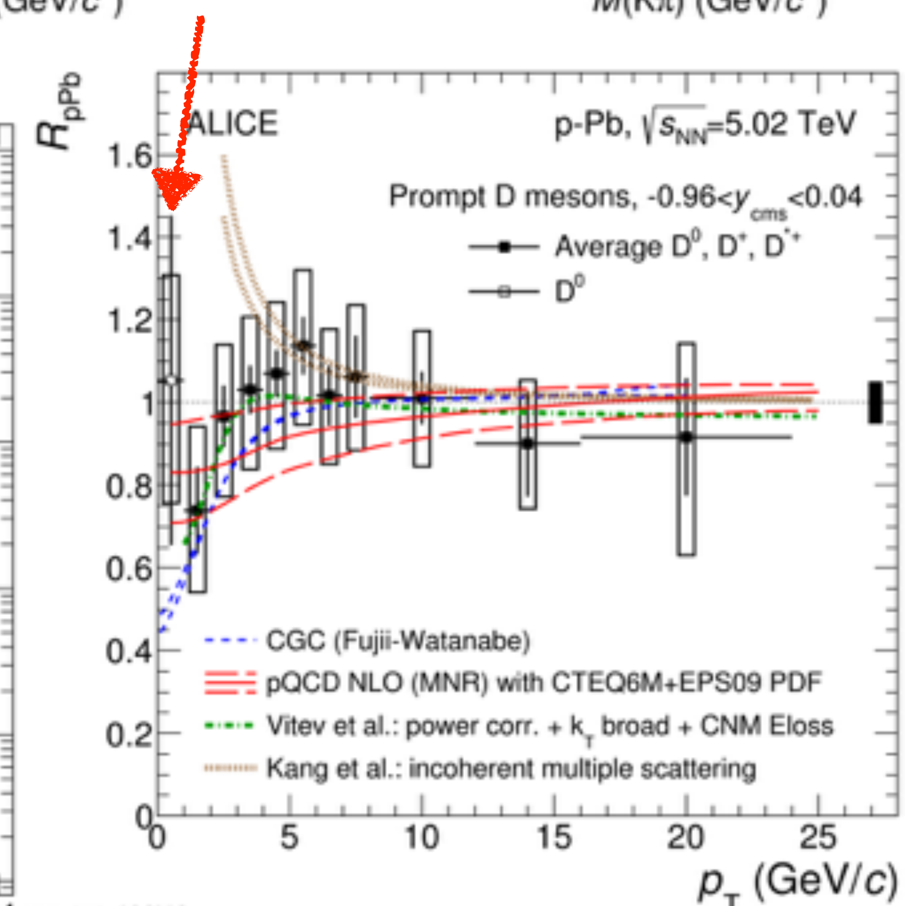






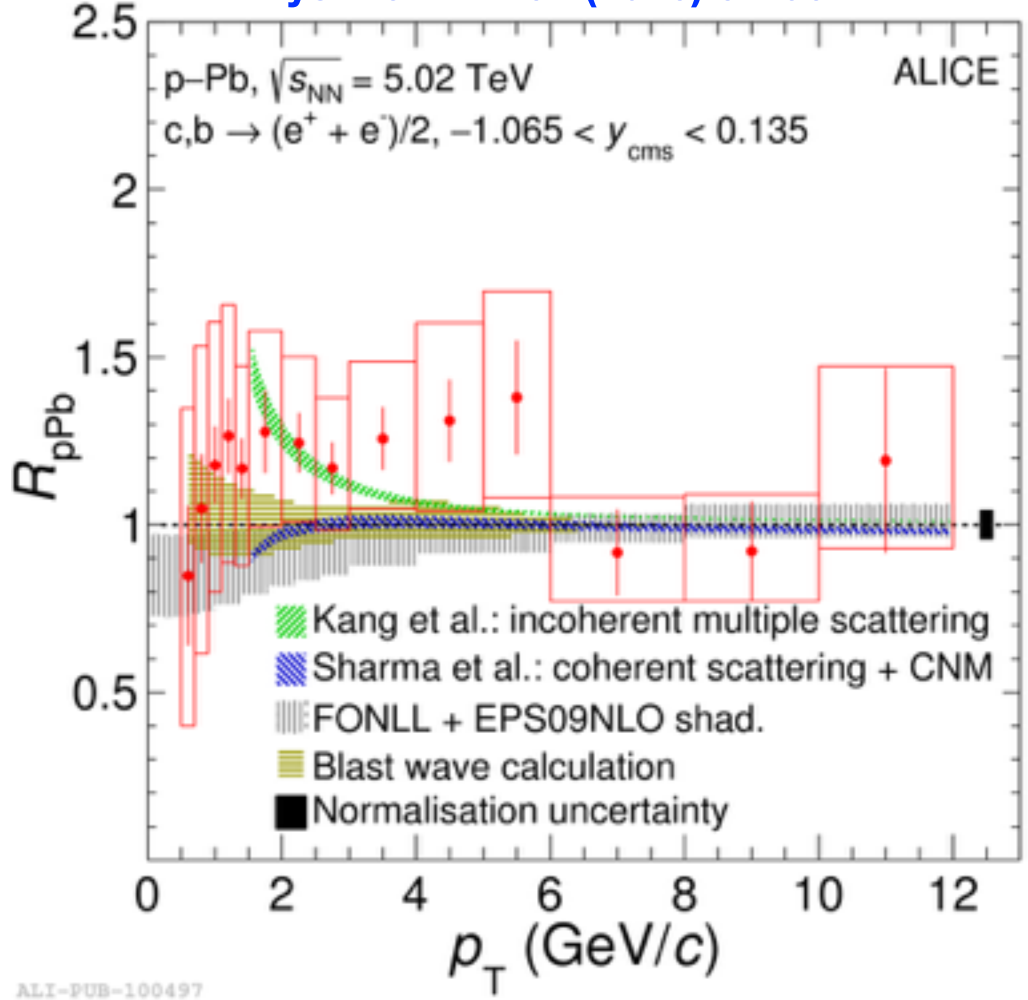




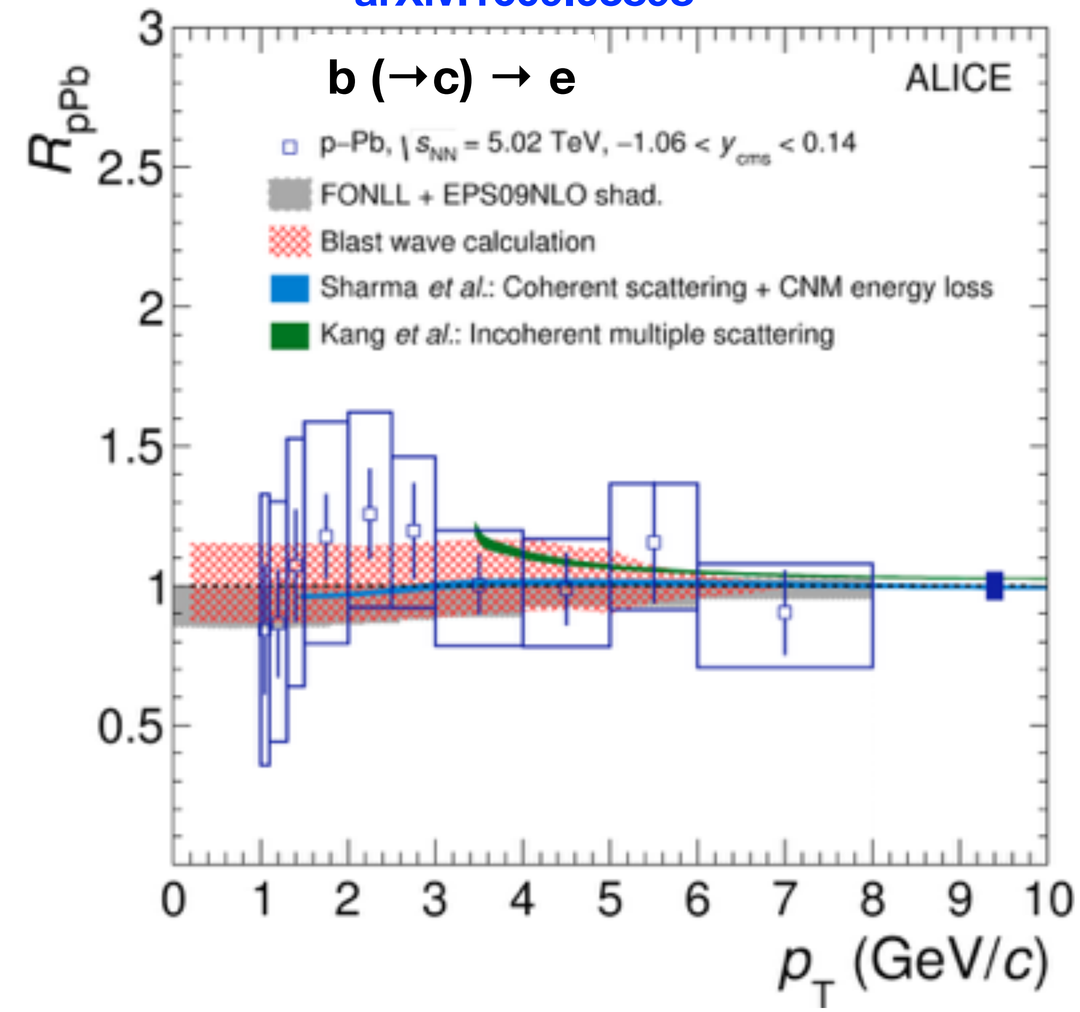
- **R_{pPb} compatible with unity and with models within uncertainties**

R_{pPb} of electrons from open heavy-flavour hadron decays

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



arXiv:1609.03898

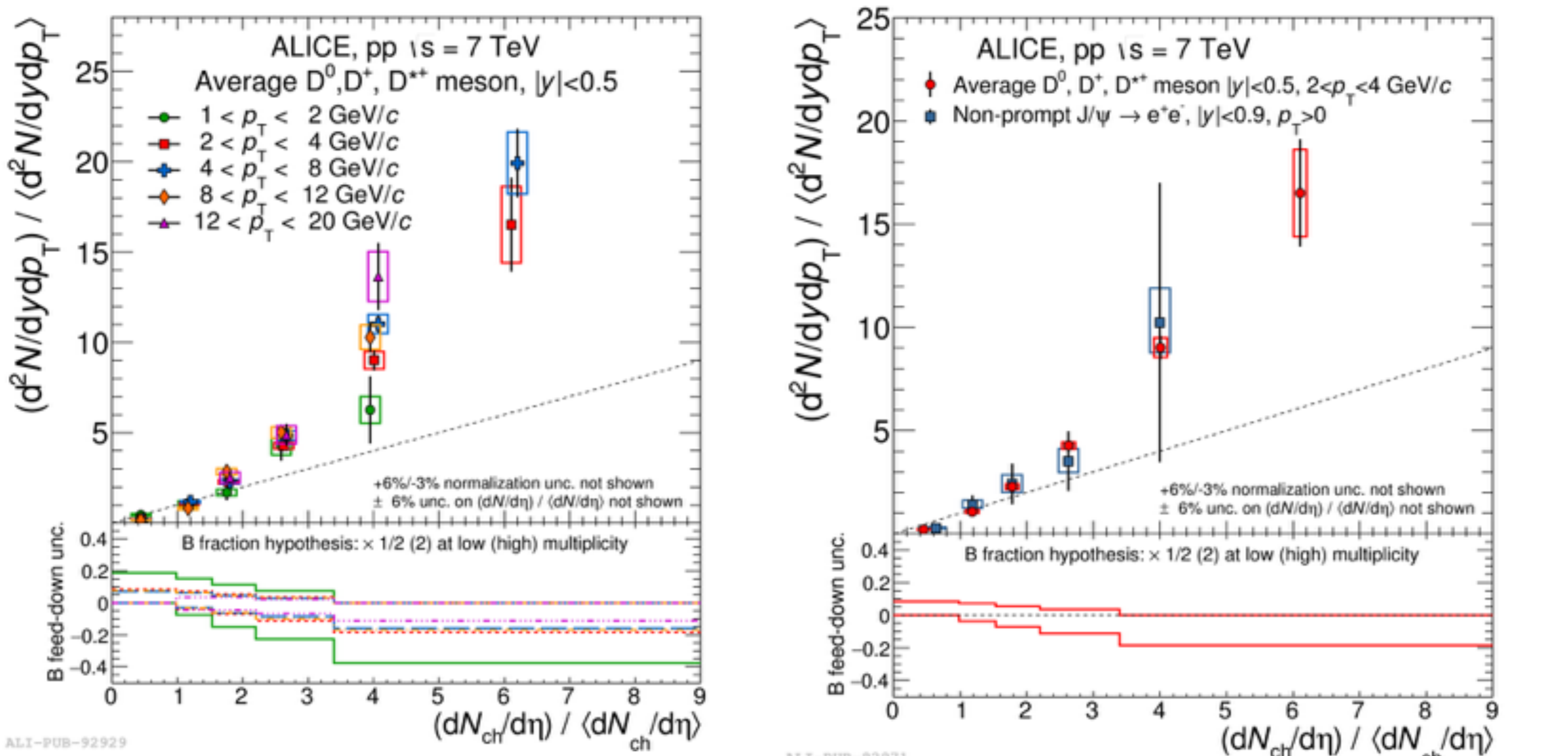


- R_{pPb} of electrons from decays of charm and beauty hadrons and from beauty hadrons only compatible with unity within uncertainties
- Compatible with different models simulating cold nuclear matter effects and models considering final state effects in p-Pb collisions

D-meson yields vs multiplicity in pp collisions

JHEP 09 (2015) 148

$$\frac{d^2N/dydp_T}{\langle d^2N/dydp_T \rangle} = \frac{Y^{mult}/(\epsilon^{mult} \times N^{mult}_{event})}{Y^{tot}/(\epsilon^{tot} \times N^{tot}_{event}/\epsilon^{trigger})}$$

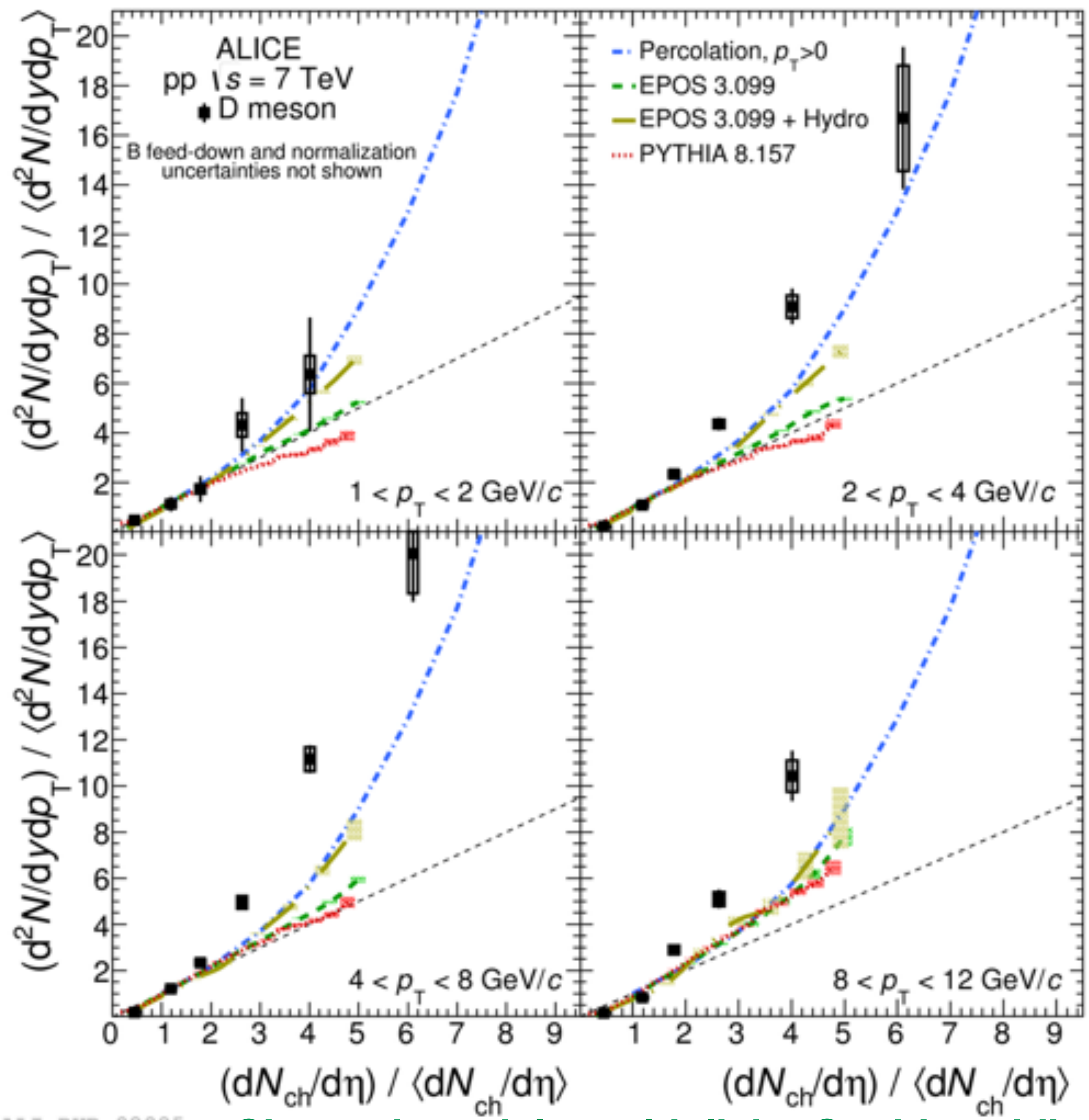


Charged-particle multiplicity @ mid-rapidity

- Faster-than-linear increase of self-normalized D-meson yields as a function of the charged-particle multiplicity at mid-rapidity
- Similar increase with multiplicity for D mesons and non-prompt J/Ψ (i.e. for charm and beauty)

Comparison with models (pp collisions)

JHEP 09 (2015) 148



Charged-particle multiplicity @ mid-rapidity

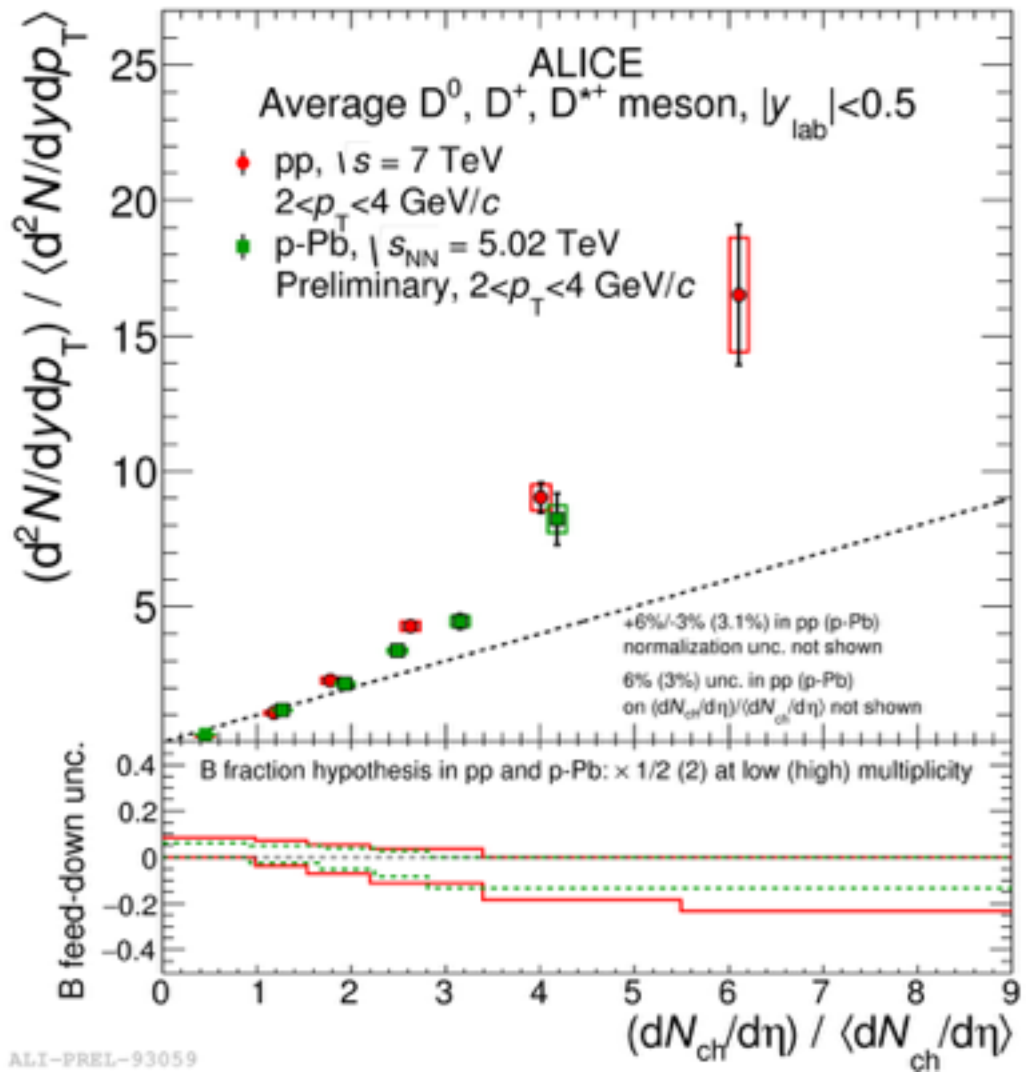
- **Models qualitatively describe the increase**

- **Percolation** Ferreiro, Pajares, PRC 86 (2012) 034903
  - Particle production via exchange of colour sources between projectile and target (close to MPI scenario)
    - faster-than-linear increase
- **EPOS 3.099** Werner et al., PRC 89 (2014) 064903
  - Gribov-Regge multiple-scattering formalism
  - Saturation scale to model non-linear effects
  - Number of MPI directly related to multiplicity
    - linear increase
  - With hydrodynamical evolution applied to the core of the collision
    - faster-than-linear increase
- **PYTHIA 8** Sjostrand et al, Comput.Phys.Commun. 178 (2008) 852
  - Soft-QCD tune
  - Colour reconnections
  - MPI
  - Initial and final state gluon radiation
    - linear increase

D-meson yields vs multiplicity in p-Pb collisions

JHEP 08 (2016) 1
JHEP 09 (2015) 148

$$\frac{d^2N/dydp_T}{\langle d^2N/dydp_T\rangle} = \frac{Y^{mult}/(\epsilon^{mult}\times N^{mult}_{event})}{Y^{tot}/(\epsilon^{tot}\times N^{tot}_{event}/\epsilon^{trigger})}$$



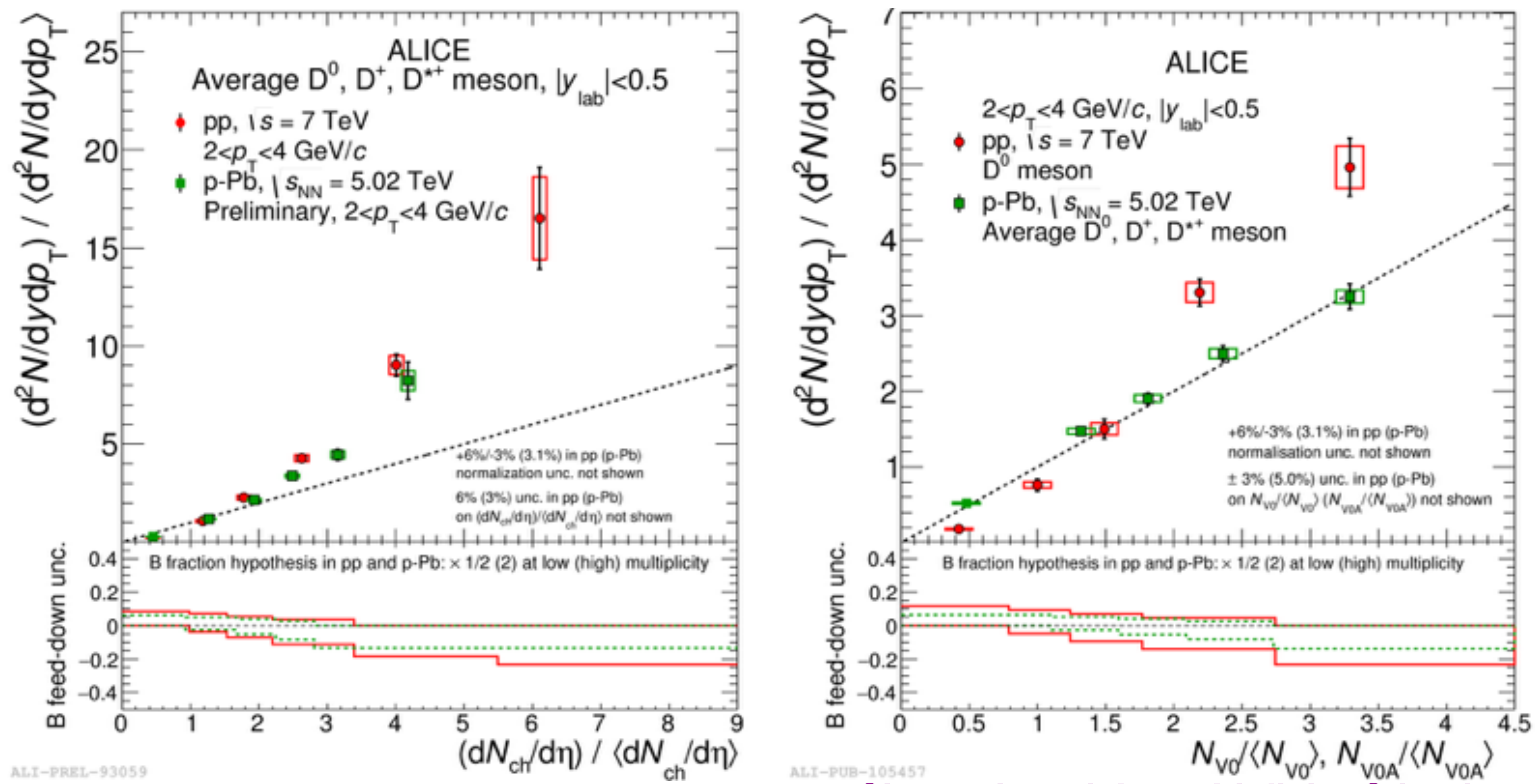
Charged-particle multiplicity @ mid-rapidity

- Multiplicity at mid-rapidity: similar faster-than-linear increase observed in pp and p-Pb collisions

D-meson yields vs multiplicity in p-Pb collisions

JHEP 08 (2016) 1
JHEP 09 (2015) 148

$$\frac{d^2N/dydp_T}{\langle d^2N/dydp_T\rangle} = \frac{Y^{mult}/(\epsilon^{mult} \times N^{mult}_{event})}{Y^{tot}/(\epsilon^{tot} \times N^{tot}_{event}/\epsilon^{trigger})}$$

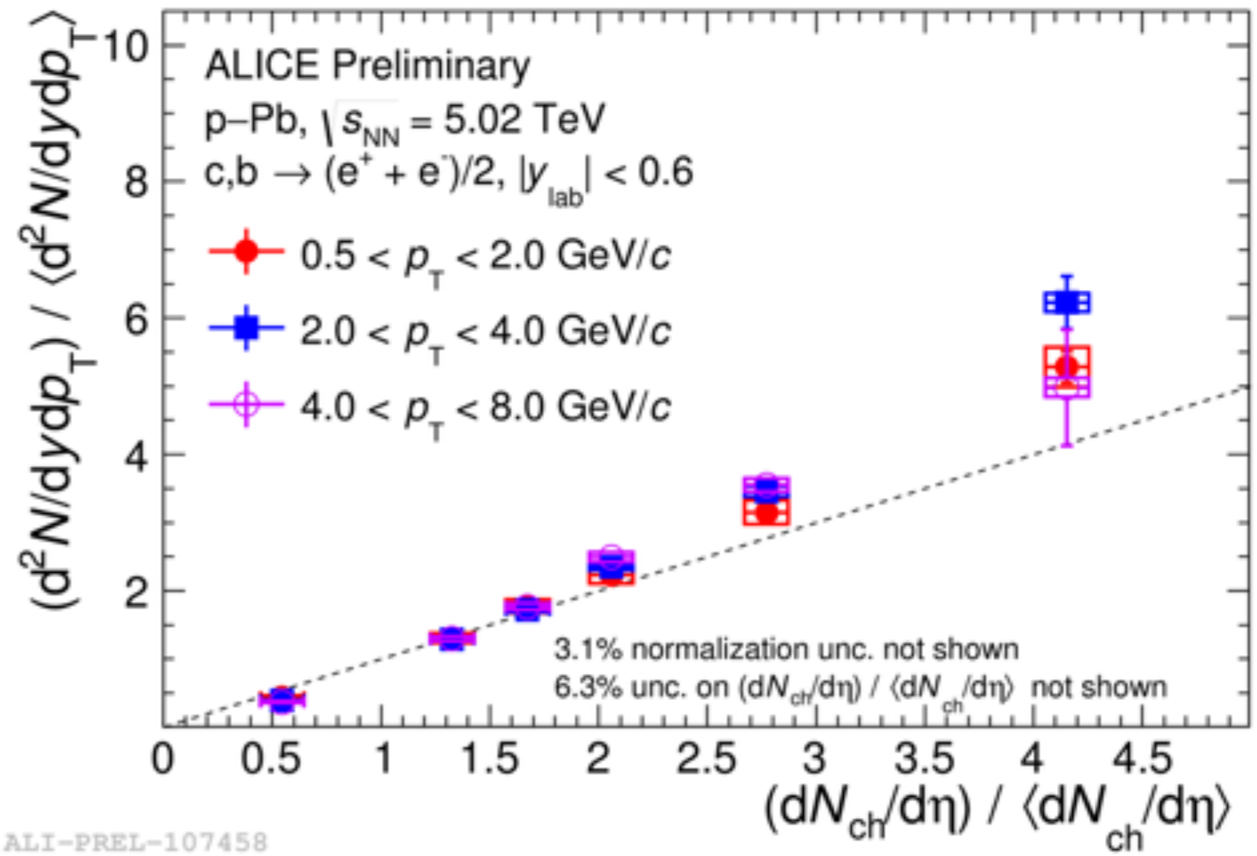


Charged-particle multiplicity @ mid-rapidity **Charged particle multiplicity @ backward-rapidity**

- Multiplicity at mid-rapidity: similar faster-than-linear increase observed in pp and p-Pb collisions
- Multiplicity at backward-rapidity: faster increase in pp than in p-Pb collisions
- Some caveats:
  - Different η range in pp and p-Pb collisions
  - MPI & N_{coll}>1 contributions in p-Pb collisions difficult to disentangle

HF-decay electrons vs multiplicity in p-Pb collisions

JHEP 08 (2016) 1



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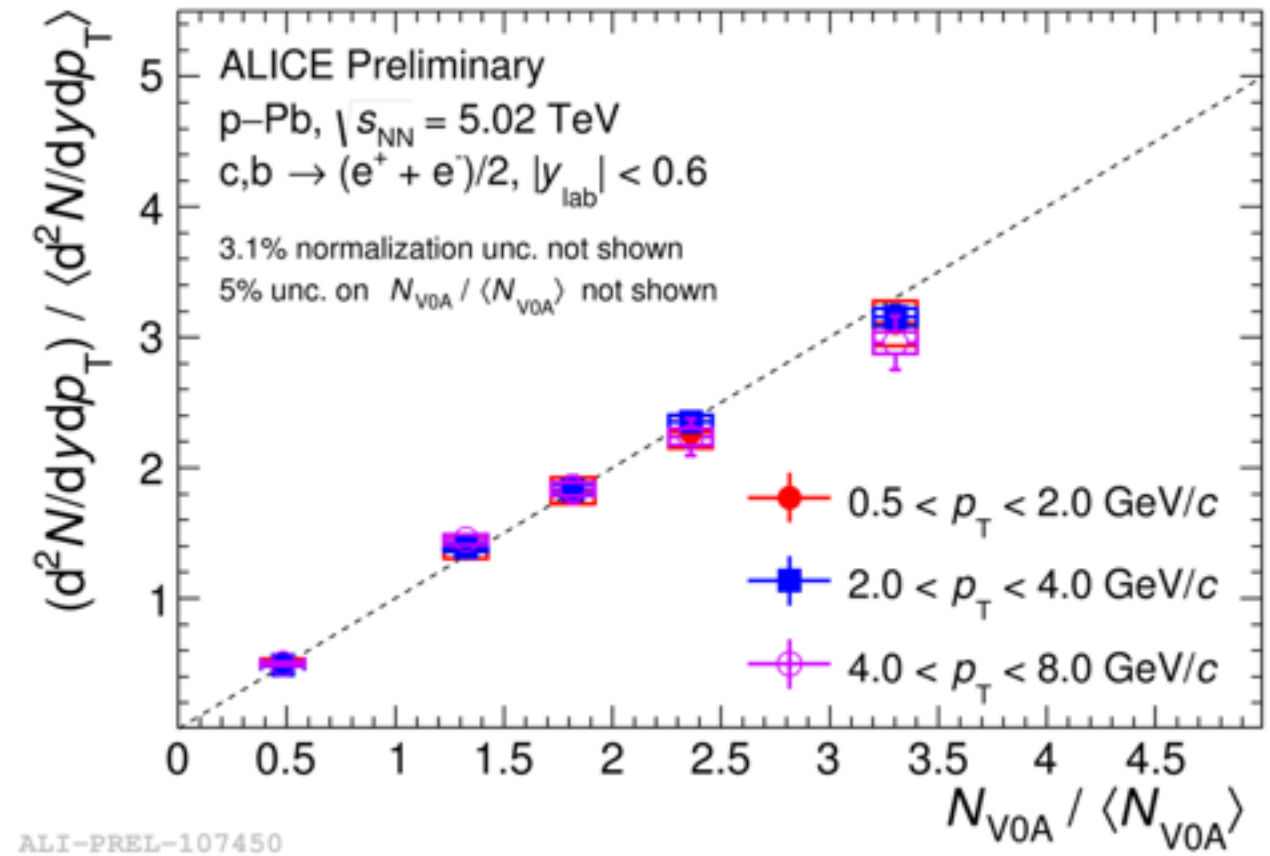
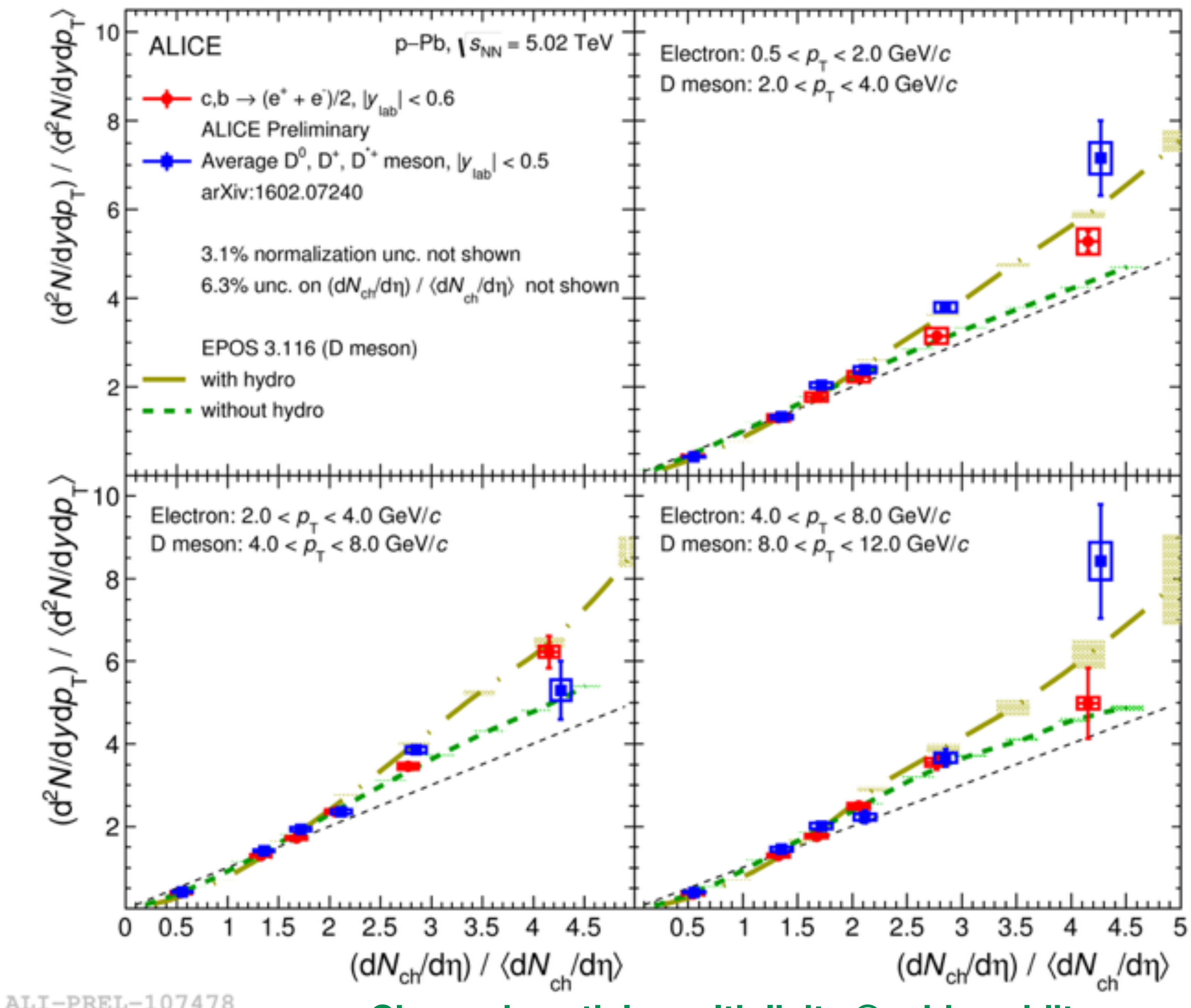


Charged particle multiplicity @ backward-rapidity

- Self-normalized HF-decay electrons yields increase as a function of the charged-particle multiplicity
  - No evidence of p_T-dependence within uncertainties
  - Multiplicity at mid-rapidity: faster-than-linear increase
  - Multiplicity at backward-rapidity: linear increase
- No significant change for p_T > 4 GeV/c (beauty contribution b-> e⁻ >50%)

Comparison with models (p-Pb collisions)

JHEP 08 (2016) 1



Charged-particle multiplicity @ mid-rapidity

- D meson and HF-decay electrons self-normalized yields compatible within their uncertainties
- Different p_T ranges for better kinematic comparisons

Werner et al., PRC 89 (2014) 064903

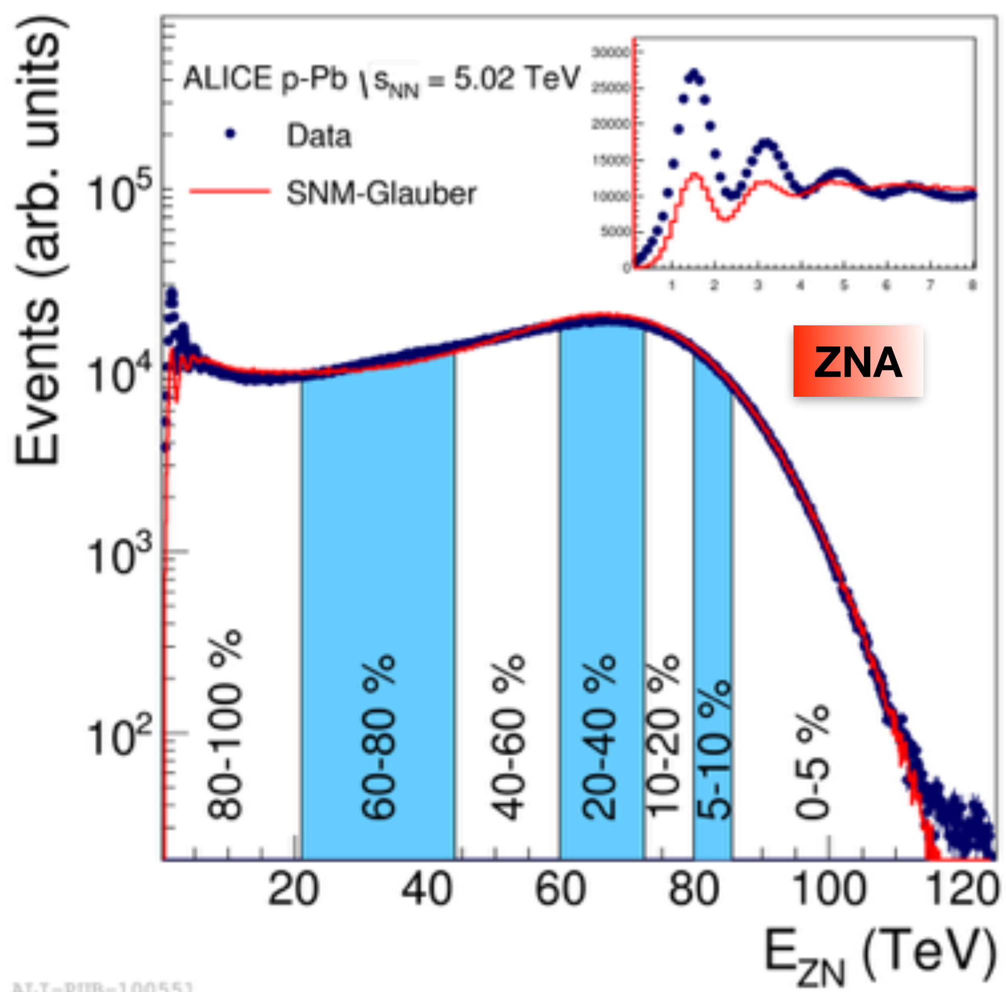
- **EPOS 3.116**
  - Calculations for D mesons
  - Initial conditions and hydrodynamical evolution
  - D mesons more compatible with calculations with hydro

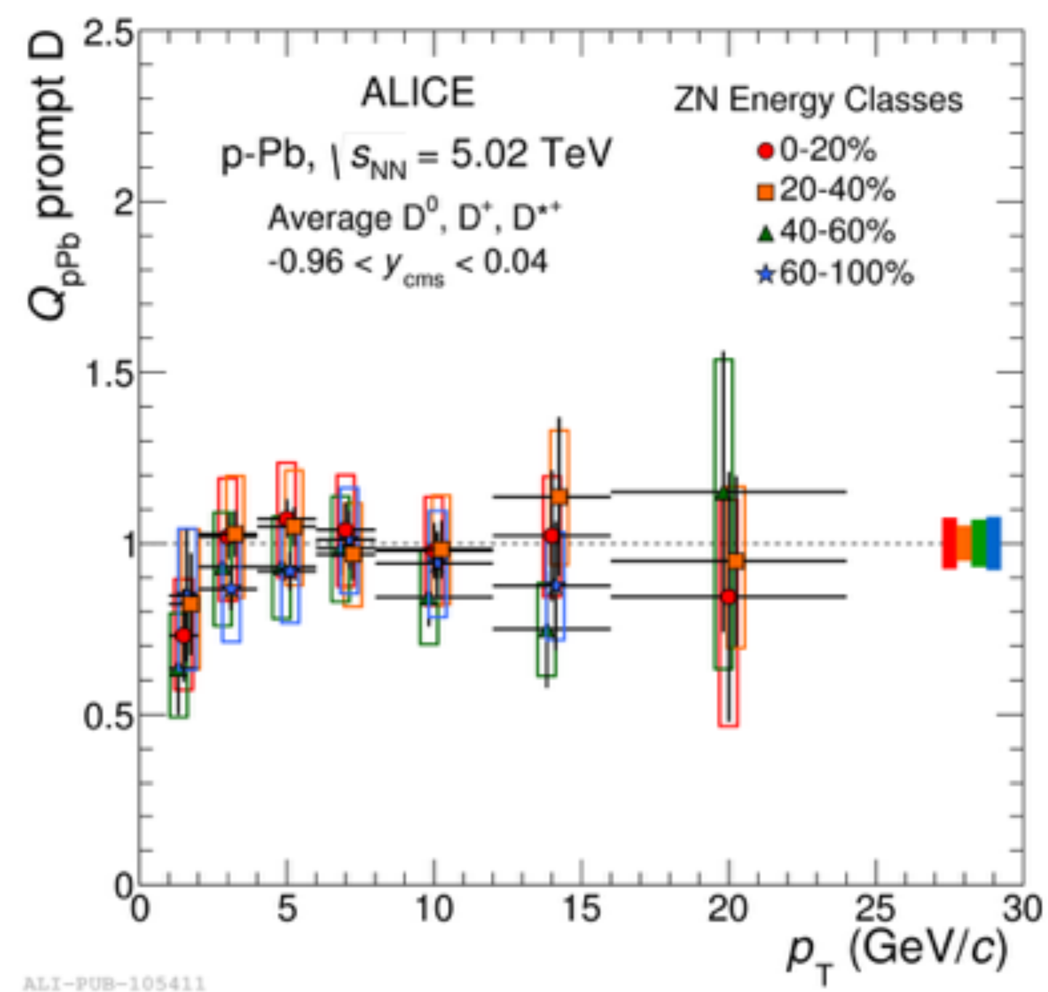
Centrality dependent nuclear modification factor

JHEP 08 (2016) 1

- Centrality estimated with **ZNA on the basis of the energy deposited in the neutron ZDC** in the Pb-going direction
- $<N_{coll}>$ from hybrid approach $\langle N_{coll}\rangle_i = \langle N_{coll}\rangle_{MB}\left(\frac{\langle dN/d\eta\rangle_i}{\langle dN/d\eta\rangle_{MB}}\right) - 1$

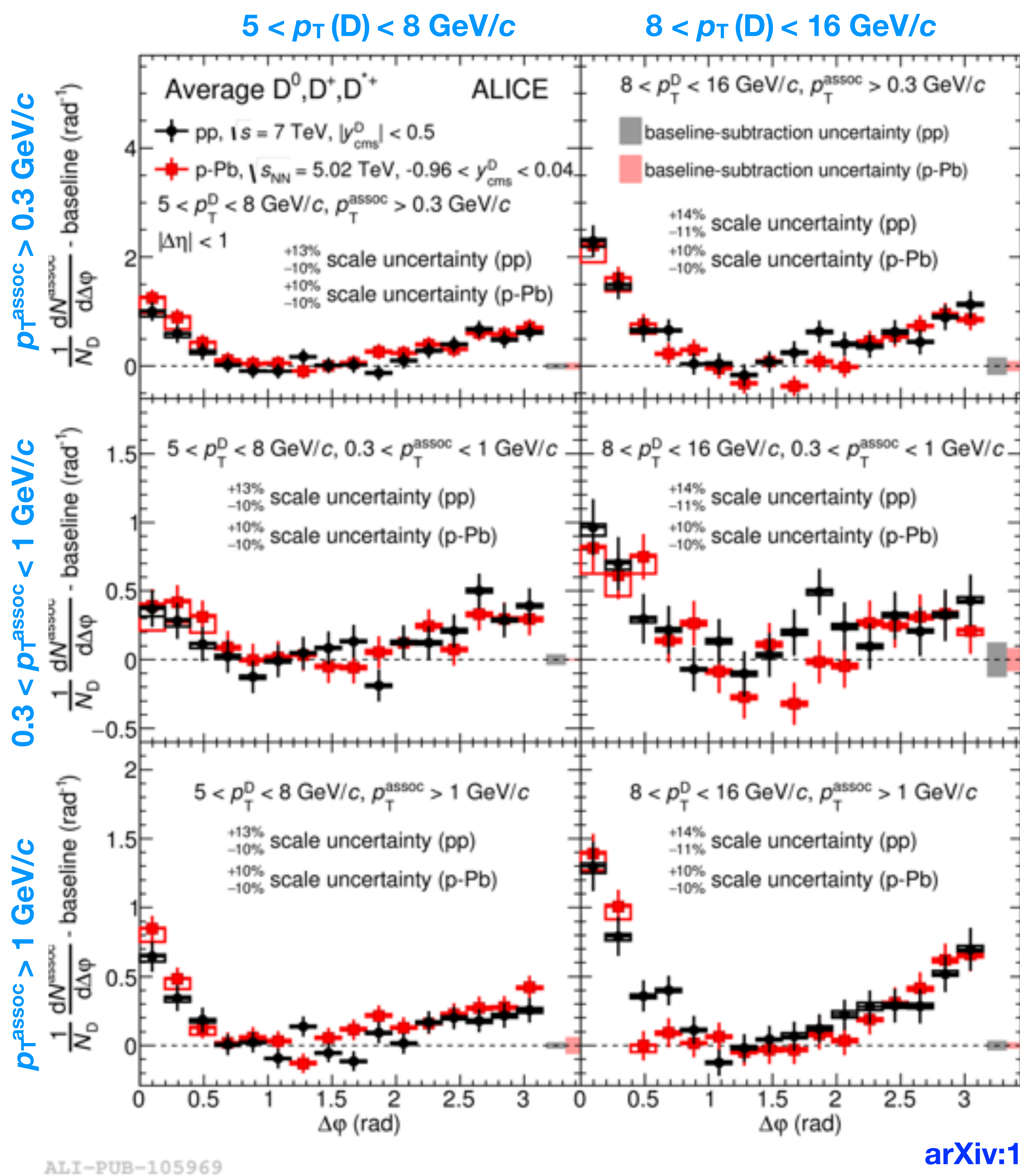
$$Q_{pPb}^{multi}(p_T) = \frac{(dN_{pPb}^{multi}/dp_T)_i}{\langle N_{coll}\rangle_i \, dN_{pp}/dp_T}$$

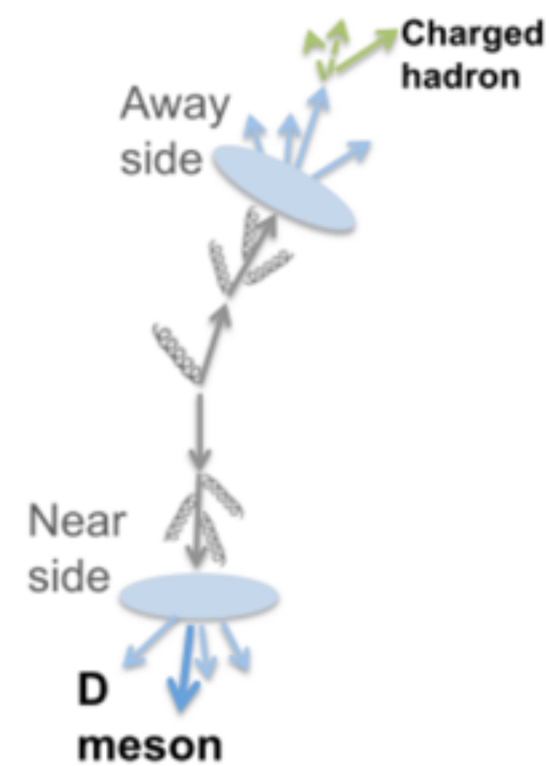




- No centrality dependence observed within uncertainties
- Similar observation with charged hadrons at high p_T

D meson - charged particle angular correlations

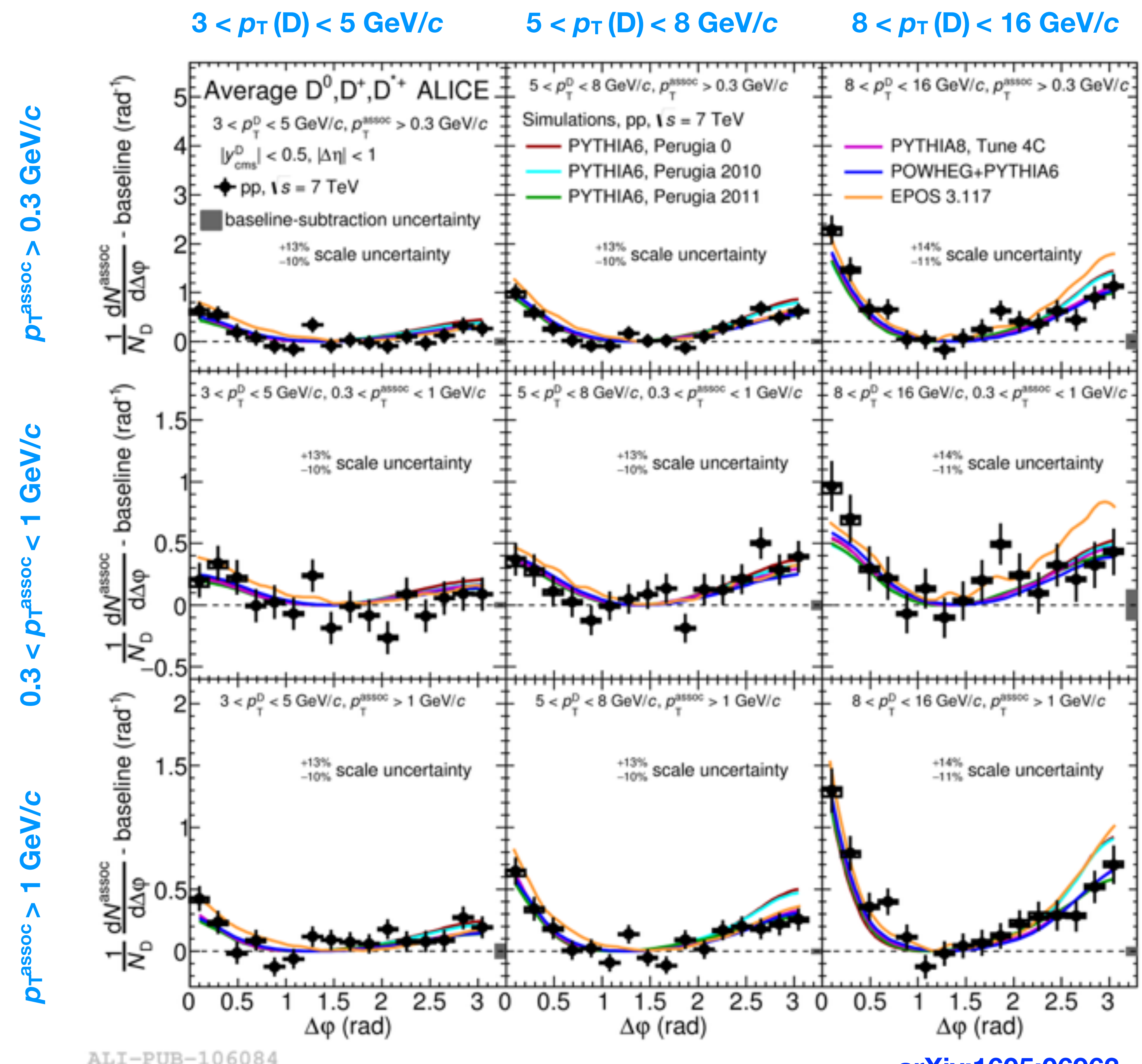




- **pp** and **p-Pb** baseline-subtracted correlations are consistent within uncertainties

arXiv:1605:06963

D meson - charged particle angular correlations

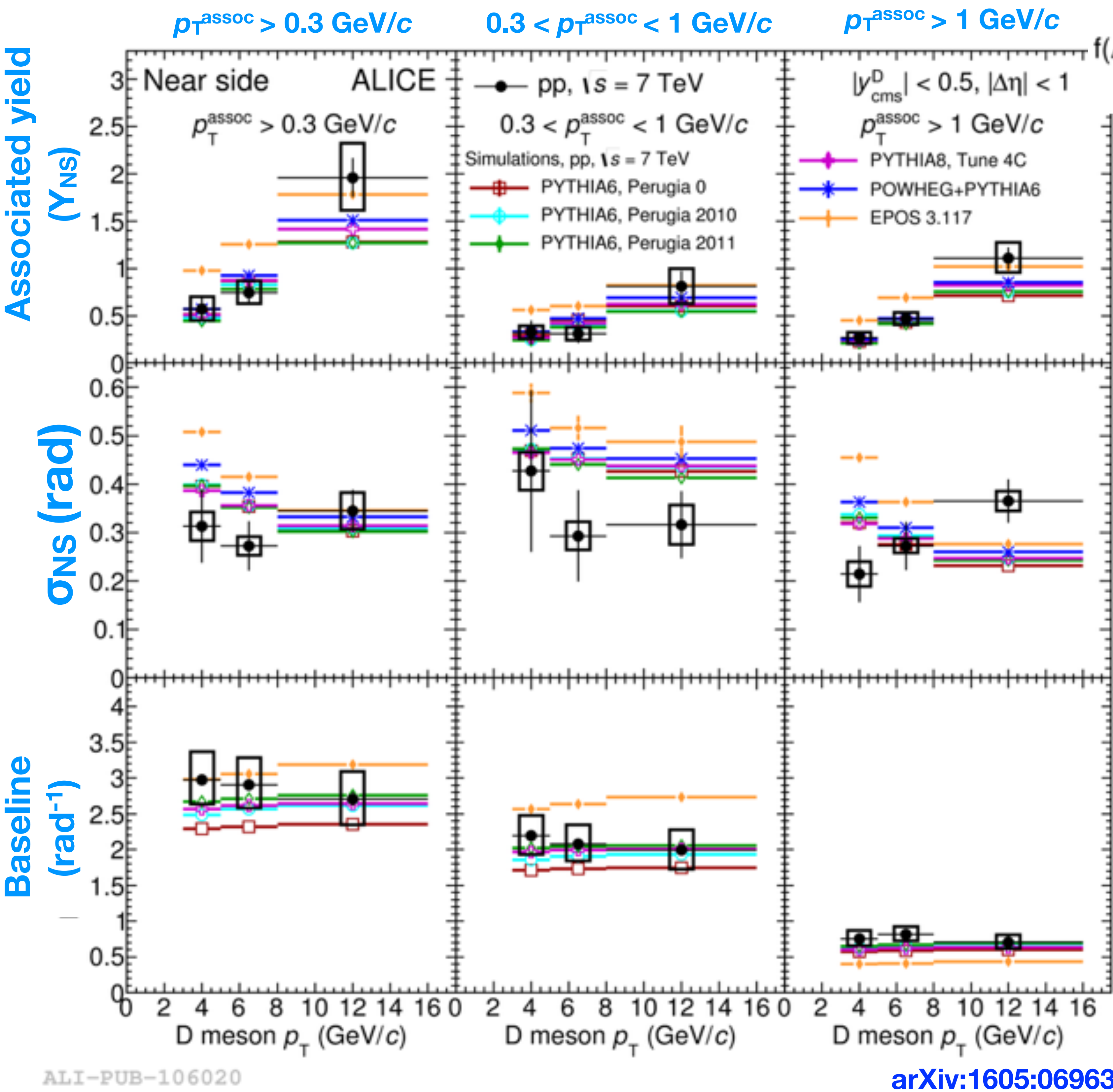


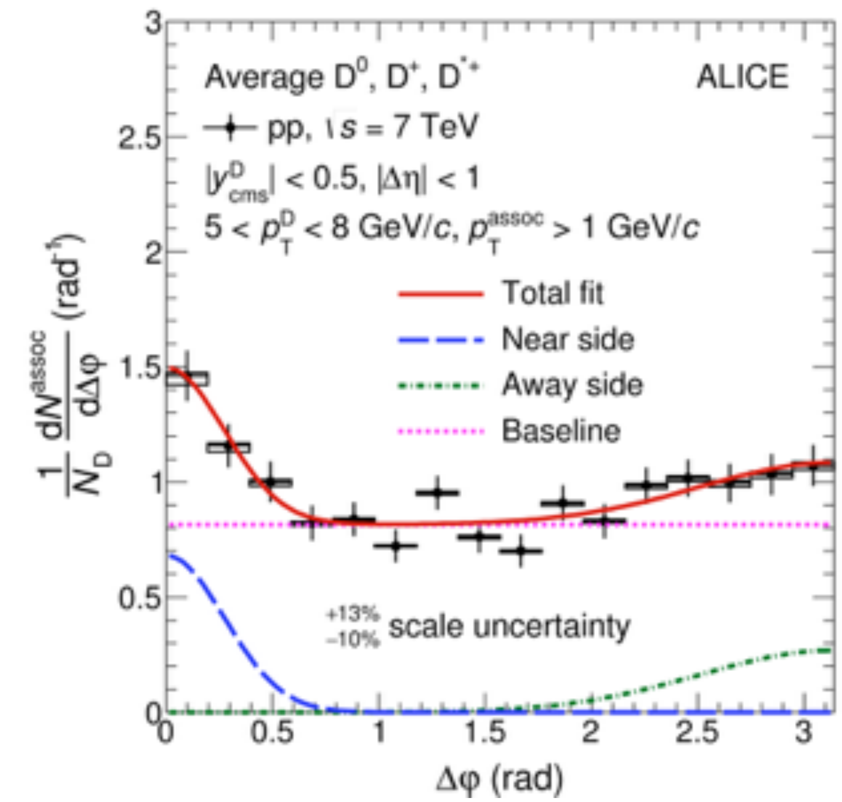
arXiv:1605:06963

- Correlation distributions in pp collisions after background subtraction are well described by
  - **PYTHIA6 (with different Perugia tunes)**
  - **PYTHIA8**
  - **POWHEG+PYTHIA6**
  - **EPOS**

D meson - charged particle angular correlations

$$f(\Delta\varphi) = C + \frac{Y_{NS}}{\sqrt{2\pi}\sigma_{NS}} \exp\left(-\frac{(\Delta\varphi)^2}{2\sigma_{NS}^2}\right) + \frac{Y_{AS}}{\sqrt{2\pi}\sigma_{AS}} \exp\left(-\frac{(\Delta\varphi)^2}{2\sigma_{AS}^2}\right)$$



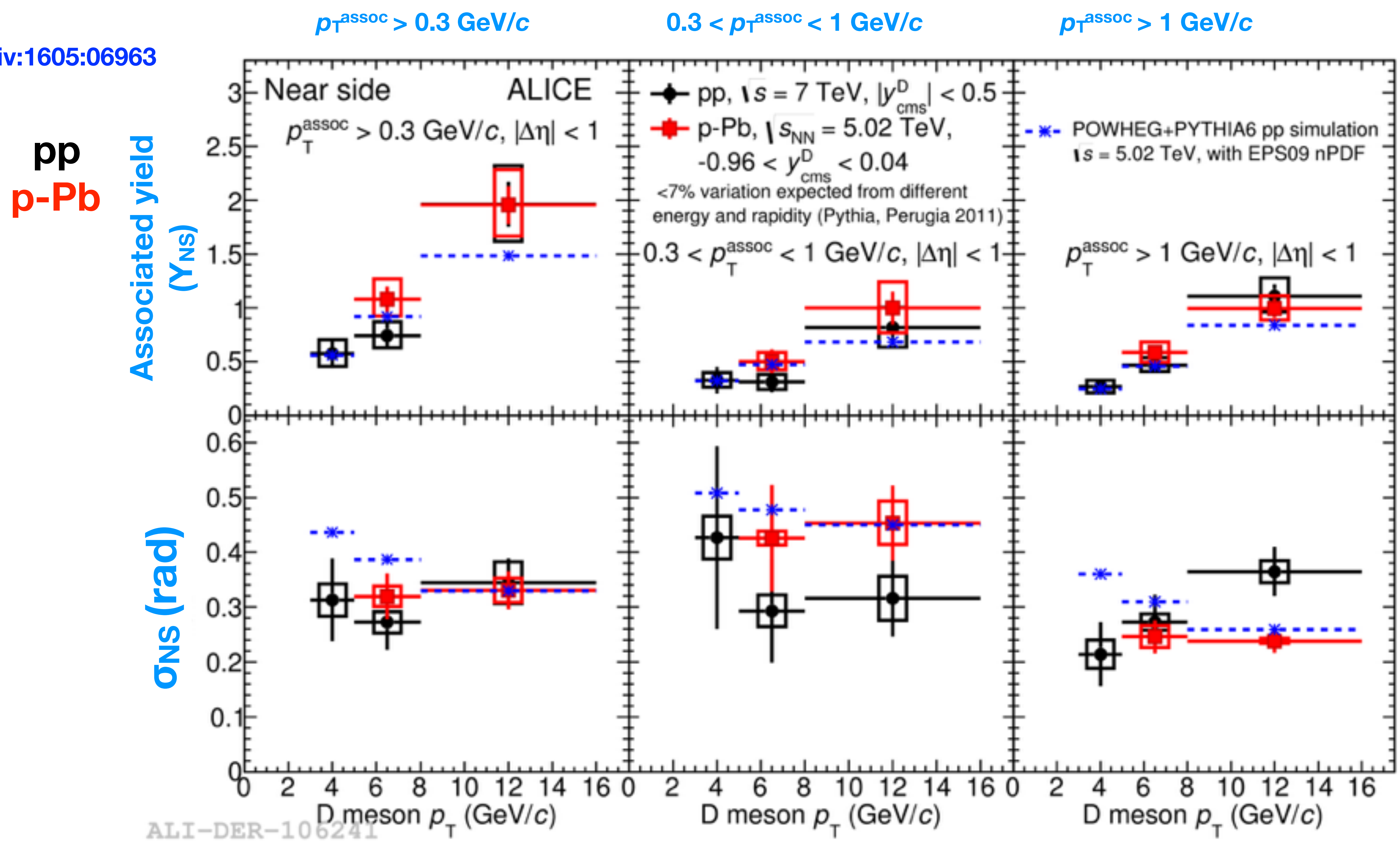


- Agreement between data and Monte Carlo expectations

arXiv:1605:06963

D meson - charged particle angular correlations

arXiv:1605:06963



- Near-side peak properties compatible between pp and p-Pb collisions
- No evidence of modifications due to initial-state or final-state effects within uncertainties

Conclusions

- **R_{pPb} is compatible with unity within uncertainties for D-mesons, electrons from beauty or both charm and beauty decays**

- **Open heavy-flavour (charm and beauty) hadron yields increase with the multiplicity of charged particles produced in the collision in both pp and p-Pb collisions**
  - Results are qualitatively well described by models including MPIs in pp collisions
  - D meson results are better described by expectations from EPOS including hydrodynamic evolution of the medium in p-Pb collisions

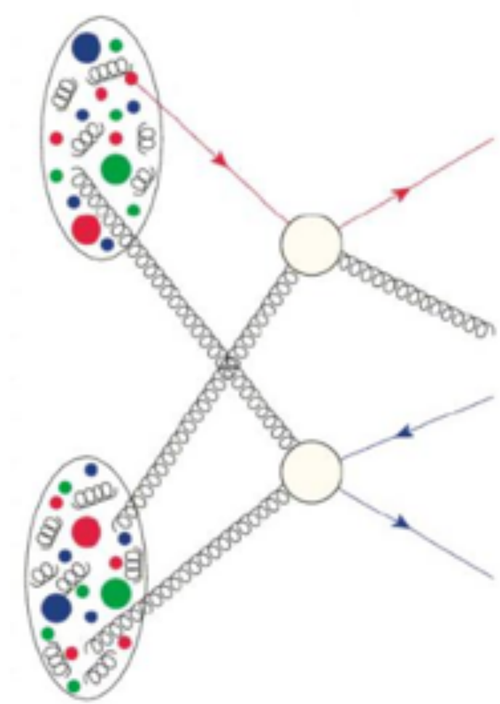
- **Centrality dependent nuclear modification factor**
  - No multiplicity dependent modification of the p_T distributions of D mesons in p-Pb collisions with respect to the binary-scaled pp collisions

- **D meson - charged particle angular correlations measured**
  - Correlation distributions and near-side yields in pp and p-Pb collisions compatible within uncertainties
  - Results are reproduced by PYTHIA, POWHEG+PYTHIA and EPOS expectations

Back-up slides

Open heavy-flavour production vs multiplicity

- **Interplay between hard and soft processes in particle production**
- **Study the role of multi-parton interactions (MPI)**

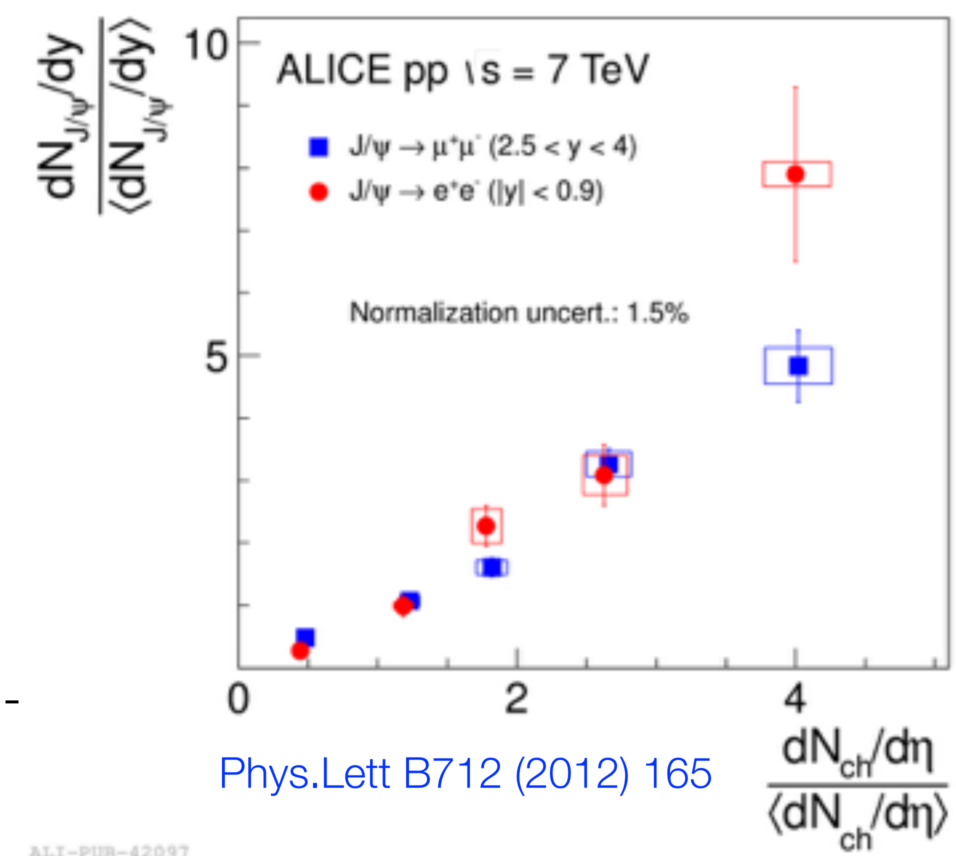


MPI at the LHC

- Particle production in high-energy pp collisions at the LHC expected to have a substantial contribution from MPI
- CMS measurement of jets and underlying events Eur. Phys. J. C73(2013) 2674
  - better agreement with models including MPI
- ALICE minijet analysis in pp collisions JHEP 09 (2013) 049
  - increase of MPI with charged-particle-multiplicity

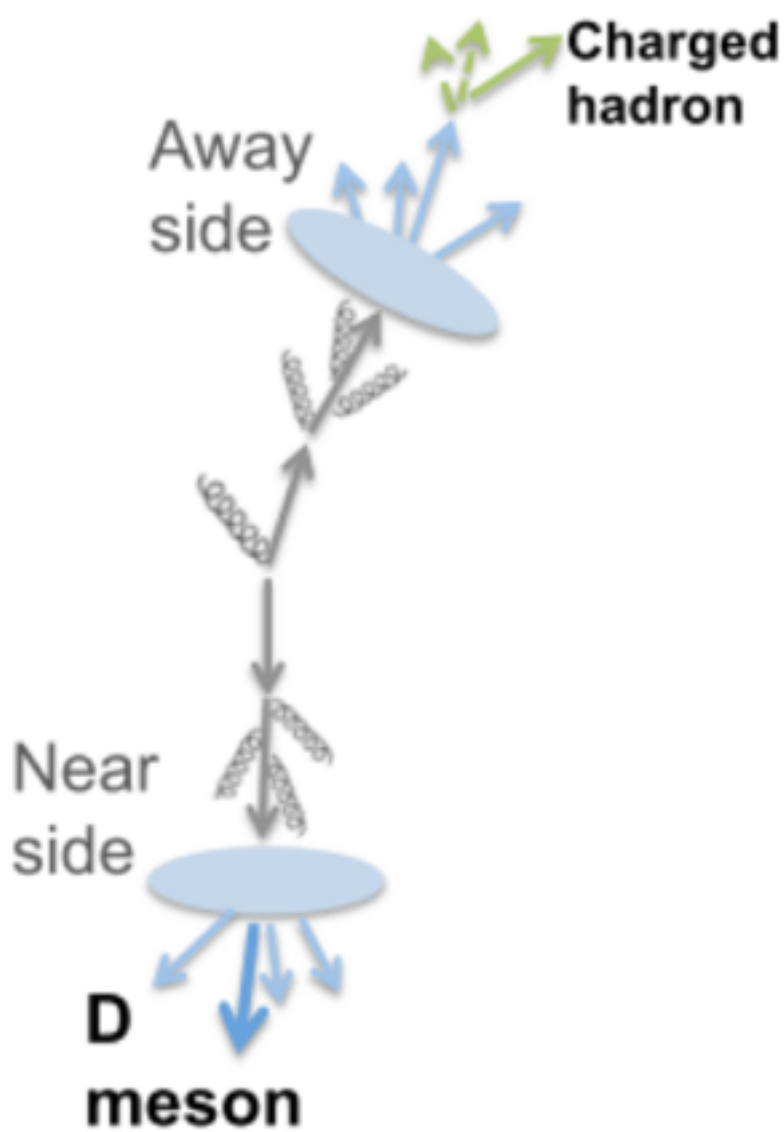
What has been observed in the charm sector?

- NA27 (pp collisions at $\sqrt{s}$=28 GeV) NA27 Coll. Z.Phys.C41 (1988)191
  - Events with charm have larger charged-particle multiplicity
- LHCb measurement of double-charm production JHEP 06 (2012) 141
  - better agreement with models including double-parton scattering
- ALICE measurement of increase of J/ψ yields with increasing charged-particle multiplicity. Phys.Lett B712 (2012) 165



Phys.Lett B712 (2012) 165

Open HF - charged-particle angular correlations



Angular correlation between **open heavy-flavour particles (i.e. D mesons or heavy-flavour decay electrons) and charged hadrons**

In pp:

- Investigate heavy-flavour quark fragmentation properties
- Sensitive to the relative contribution of different LO and NLO heavy-quark production processes Norrbin and Sjostrand, EPJ C17 (2000) 137
- Sensitive to jet-parton showers and fragmentation
- Extract relative contribution of electrons from charm and beauty decays using correlations between heavy-flavour decay electrons and charged particles PLB 738 (2014) 97-108
- Reference for p-Pb and Pb-Pb measurements

In p-Pb

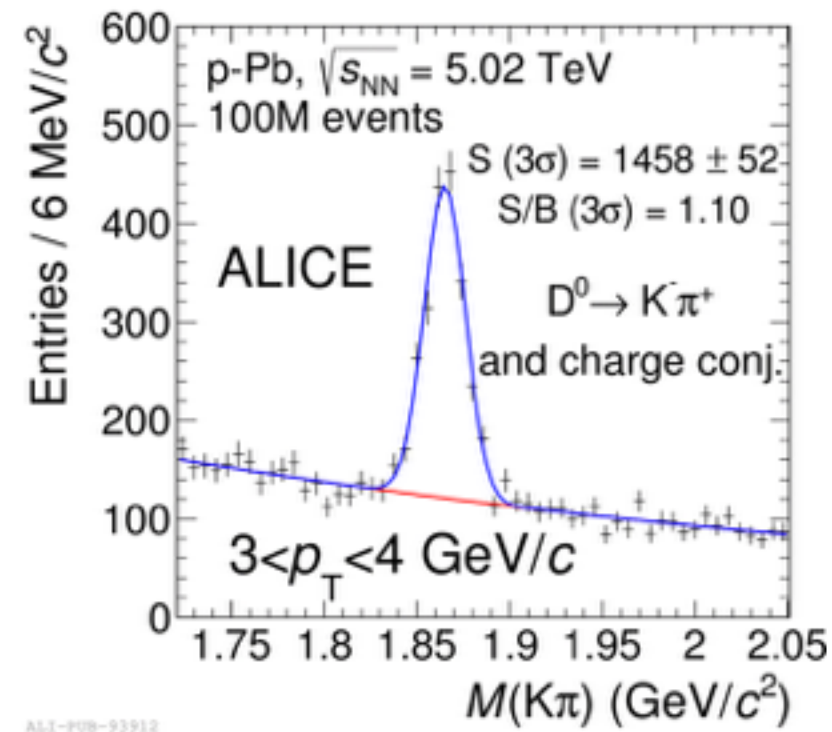
- Investigate possible modifications of angular correlations which could derive from initial-state effects (e.g. CGC) or possible final-state effects (e.g. hydrodynamics)
- Are there long-range ridge-like structures (double ridge) also in the heavy-flavour sector? PLB 709 (2013) 29

Open HF measurements in ALICE

D mesons in the hadronic decay channels

$D^0 \rightarrow K^-\pi^+$ BR=(3.88±0.05)%, cτ ≈ 120μm
$D^+ \rightarrow K^-\pi^+\pi^+$ BR=(9.13±0.19)%, cτ ≈ 310μm
$D^{*+} \rightarrow D^0\pi^+$ BR=(67.7±0.5)% [strong decay]
$D_s \rightarrow \phi\ \pi^+ \rightarrow K^-K^+\pi^+$ BR=(2.28± 0.12)%, cτ ≈ 150μm

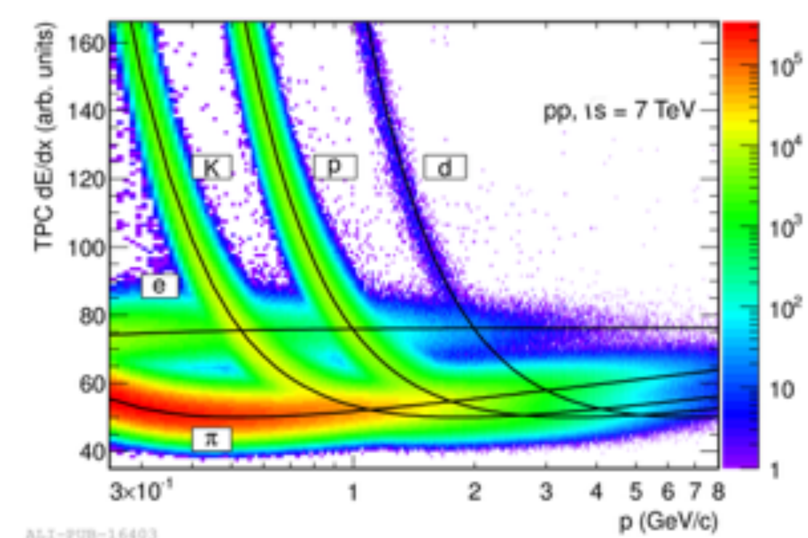
- Reconstruction of secondary vertices displaced from the primary vertex and invariant mass analysis



Open heavy-flavour decay electrons

B-> e + X (BR ~ 11%)
C-> e + X (BR ~ 10%)

- Identified at mid-rapidity with TPC, TOF, TRD, EMCAL
- Background subtraction based on a MC cocktail of the relevant background sources (photon conversions, Dalitz decay of π^0, η and light mesons)



Open heavy-flavour decay muons

B-> μ + X (BR ~ 11%)
C-> μ + X (BR ~ 10%)

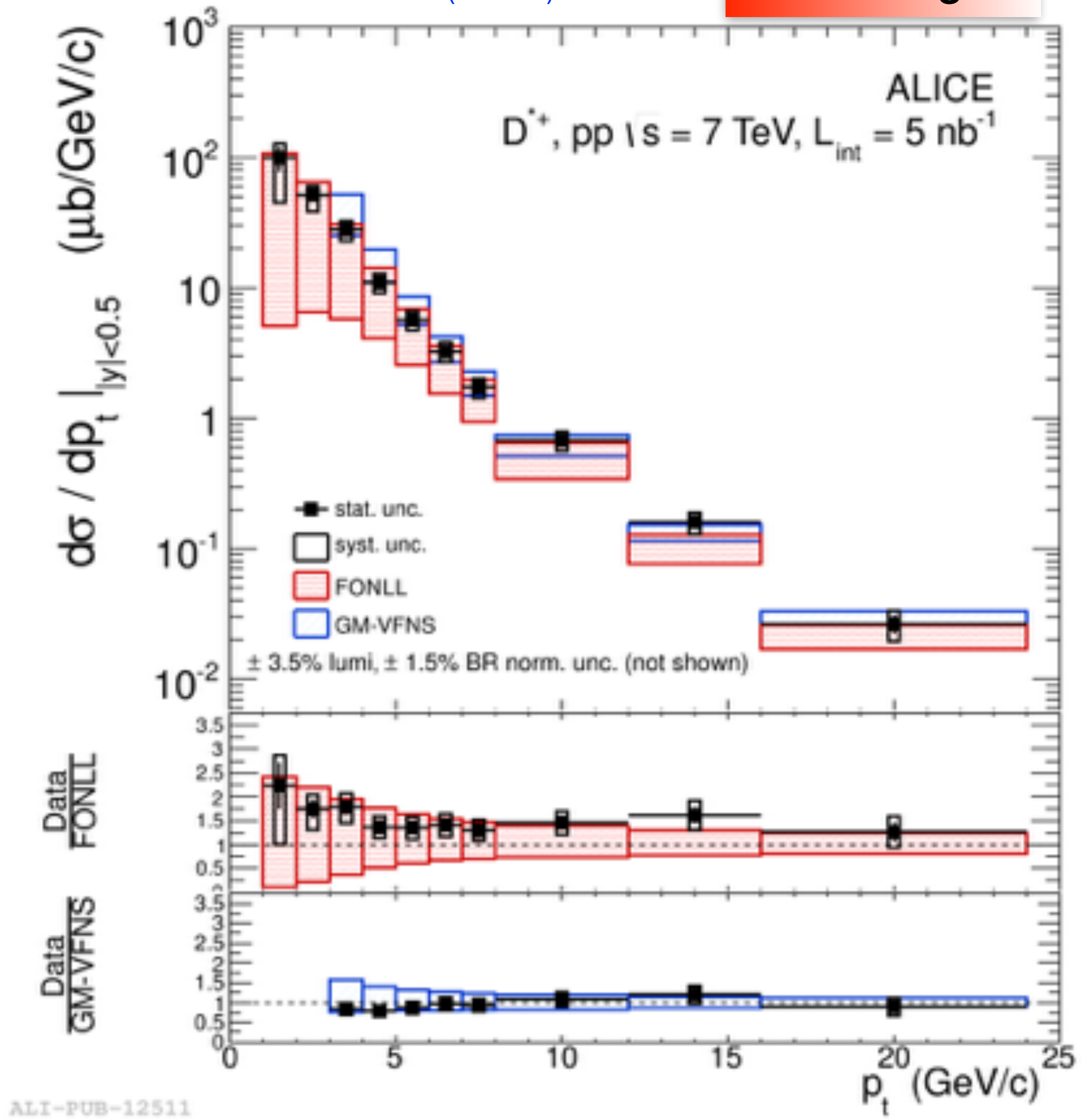
- Identified with the Muon Spectrometer at -4 < η <-2.5
- Background from $\pi^{\pm}$ and $K^{\pm}$ estimated with event generators and subtracted

Prompt D meson p_T-differential cross sections

pp

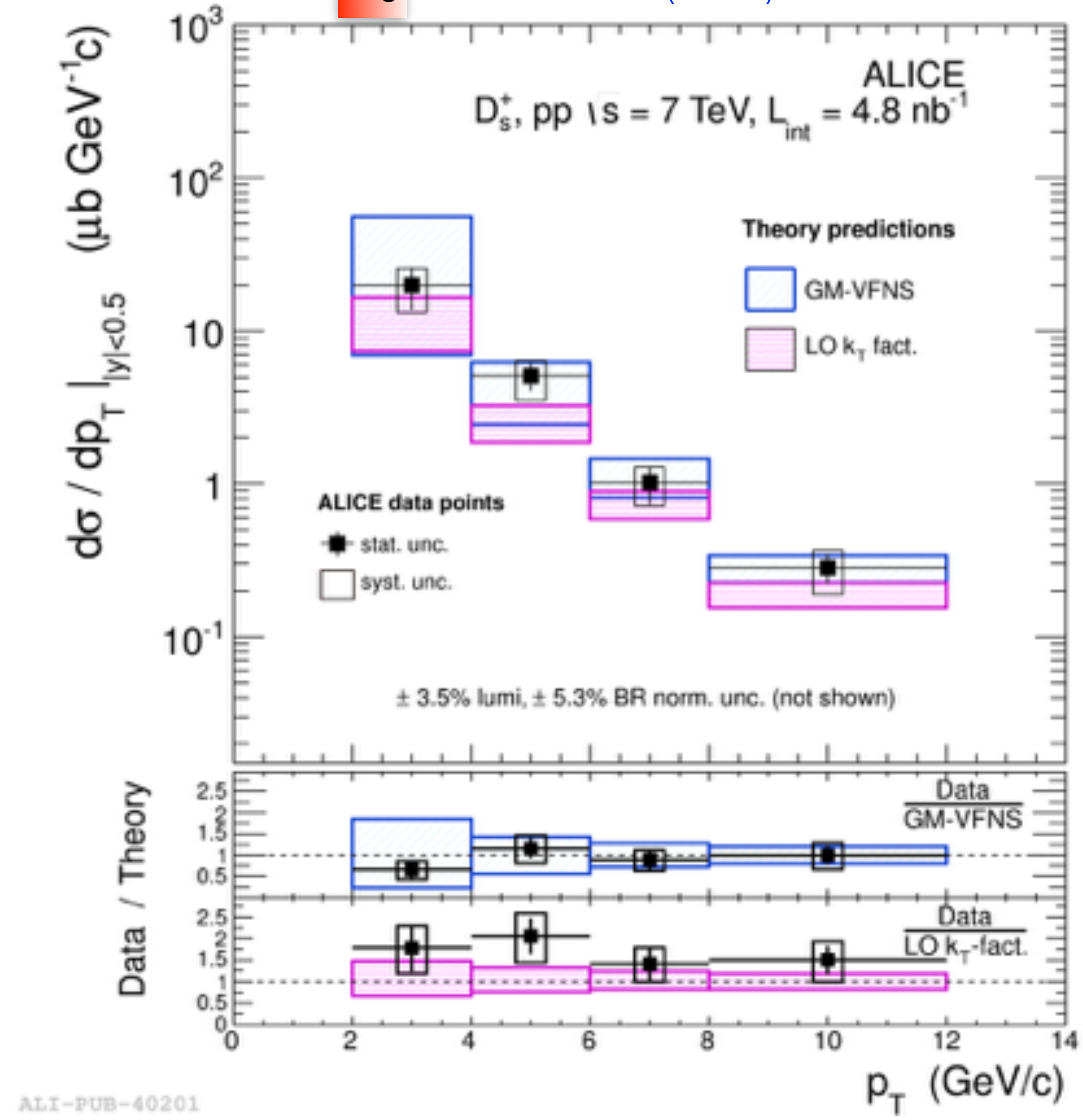
JHEP 1201 (2012) 128

Non-strange D



Ds

PLB 718 (2012) 279



FONLL: JHEP1210(2012)137;
GM-VFNS: Eur.Phys.JC72(2012) 2082;
LO k_T-factorization: Phys. Rev. D(2013)094022

D mesons at $\sqrt{s}$= 2.76 TeV
JHEP 1207 (2012) 191

- **pQCD calculations are compatible with data at both $\sqrt{s}$ = 2.76 TeV and 7 TeV**

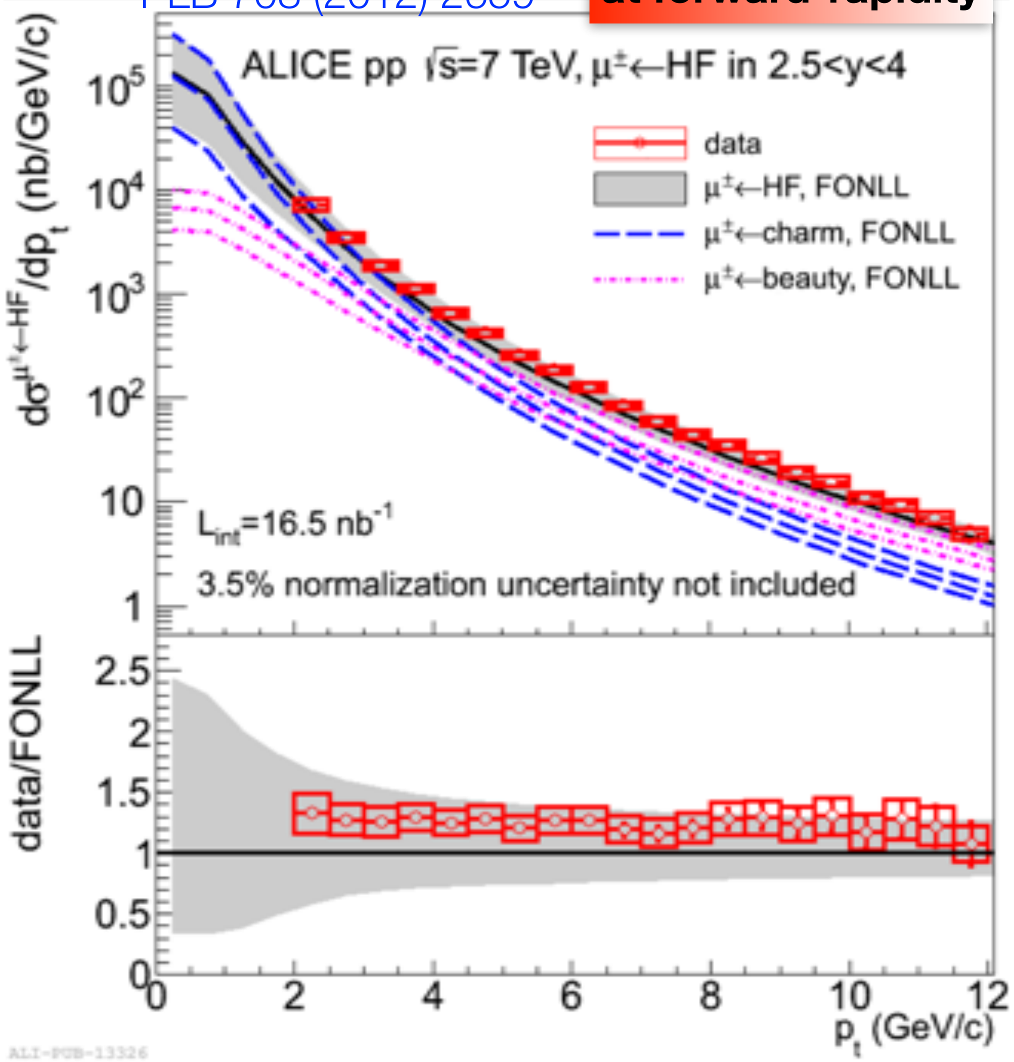
HF-decay lepton p_T-differential cross sections

pp

PLB 708 (2012) 2659

HF-decay muons at forward-rapidity

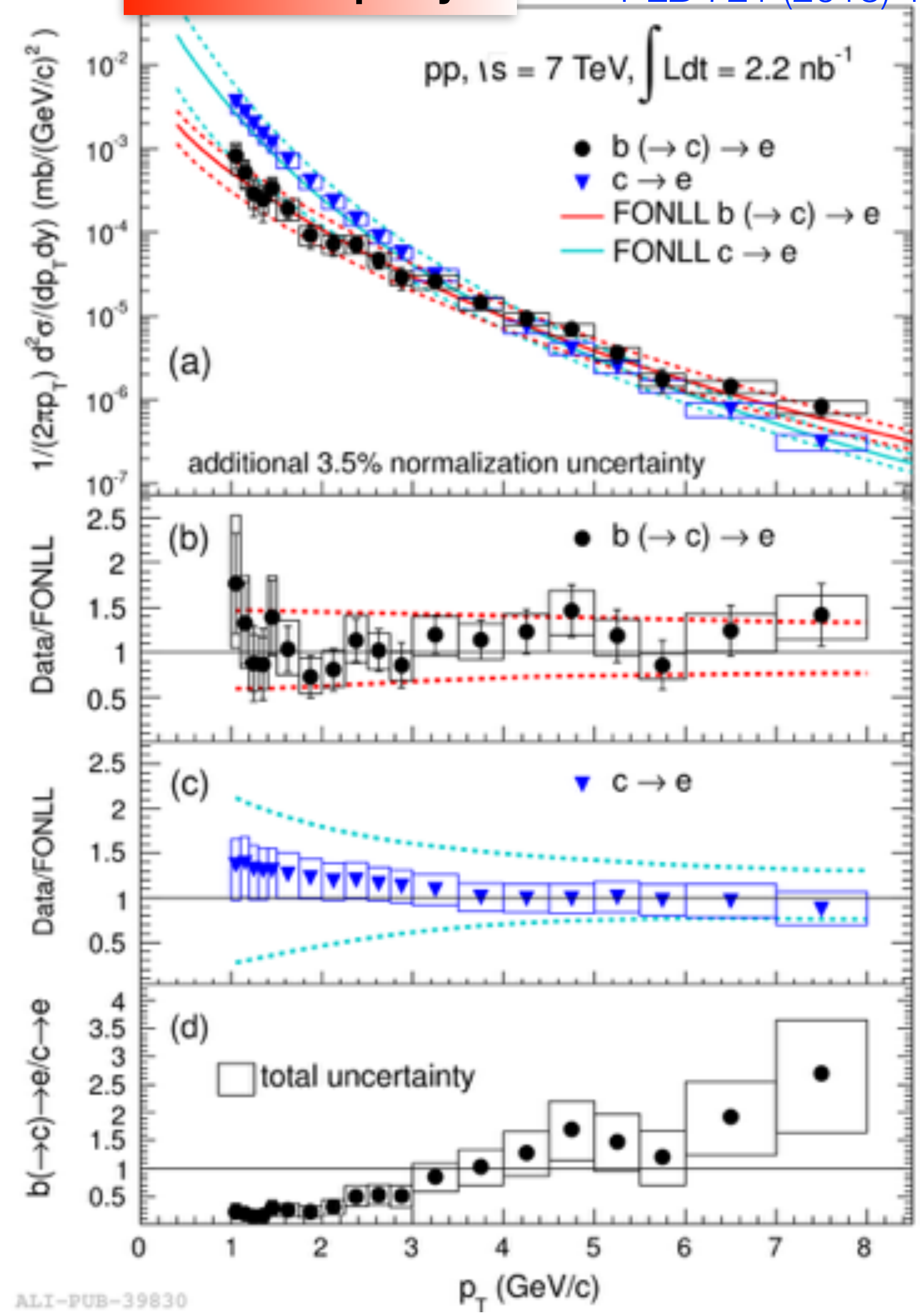
Includes contributions from charm and beauty



HF-decay electrons at mid-rapidity

PLB 721 (2013) 13

Charm and beauty contributions are separated



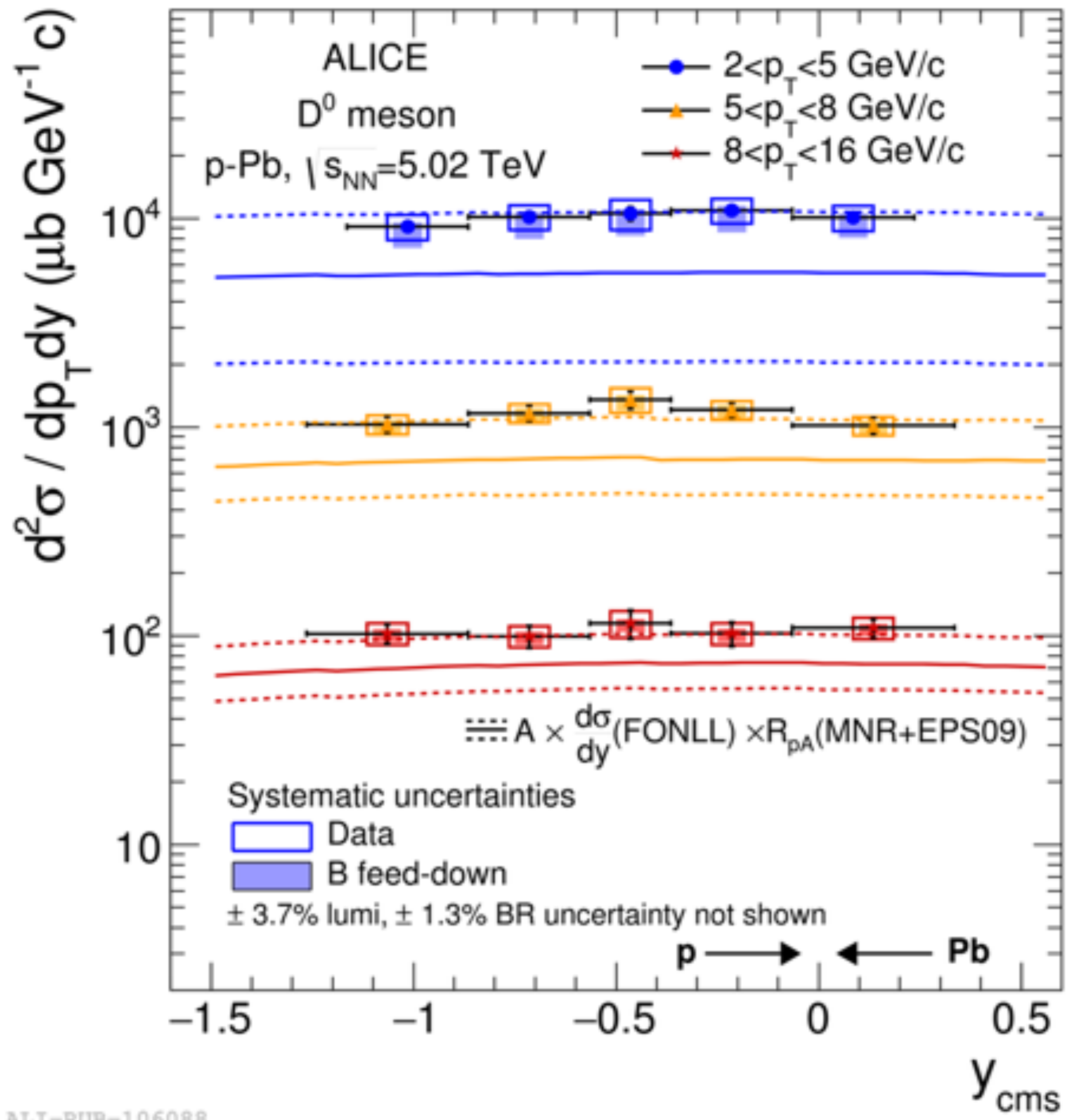
FONLL: JHEP1210(2012)137;
GM-VFNS: Eur.Phys.JC72(2012) 2082;
LO k_T-factorization: Phys. Rev. D(2013)094022

HF-decay e at $\sqrt{s}$= 2.76 TeV: PLB 738 (2014) 97-108
HF-decay μ at $\sqrt{s}$= 2.76 TeV: PRL 109(2012)112301

- **pQCD calculations are compatible with data at both $\sqrt{s}$ = 2.76 TeV and 7 TeV**

Prompt D meson y-differential cross sections

p-Pb



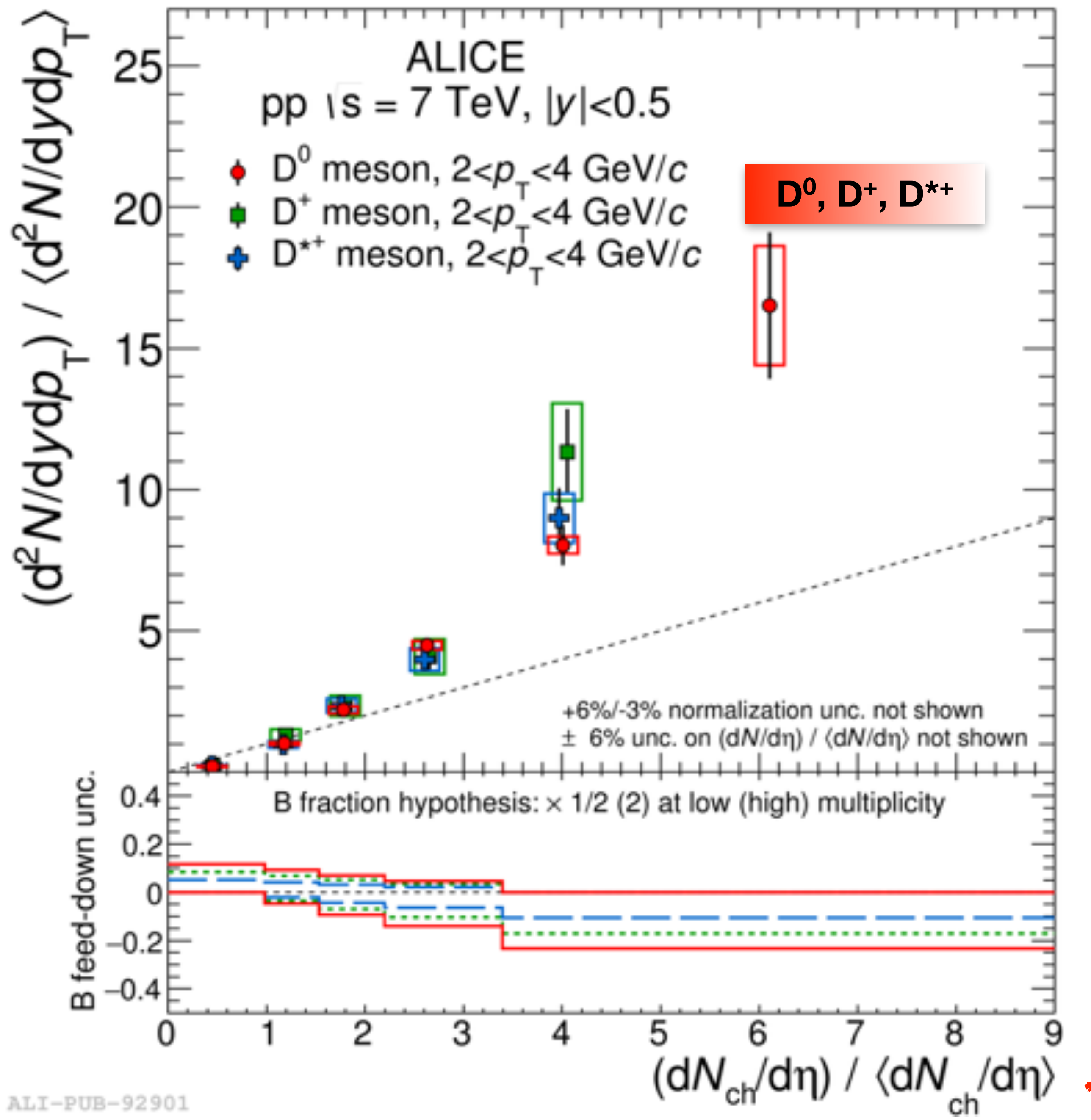
- Measurement done in p-Pb collisions at $\sqrt{s_{NN}}$= 5.02 TeV
- *y*-differential cross section does not vary in the considered *y* interval
- Good agreement with the cross section calculated from FONLL multiplied by an R_{pA} based on MNR+EPS09 predictions and by the atomic mass number *A*

FONLL: JHEP1210(2012)137;
MNR: Nucl. Phys. B373 (1992) 295
EPS09: JHEP 04 (2009) 065

Multiplicity dependence of open HF production (pp)

pp

arXiv:1505:00664



Charged-particle multiplicity at mid-rapidity

Self-normalised yields

$$\frac{d^2N/dydp_T}{\langle d^2N/dydp_T\rangle} = \frac{Y^{mult}/(\epsilon^{mult} \times N^{mult}_{event})}{Y^{tot}/(\epsilon^{tot} \times N^{tot}_{event}/\epsilon^{trigger})}$$

- **Self-normalised D-meson yields increase as a function of the charged-particle multiplicity**
  - Compatible for the different D-meson species
  - Faster-than-linear increase
- **Suggest that MPI affect hard momentum scale relevant for open heavy-flavour production**

D meson yields vs multiplicity in pp collisions

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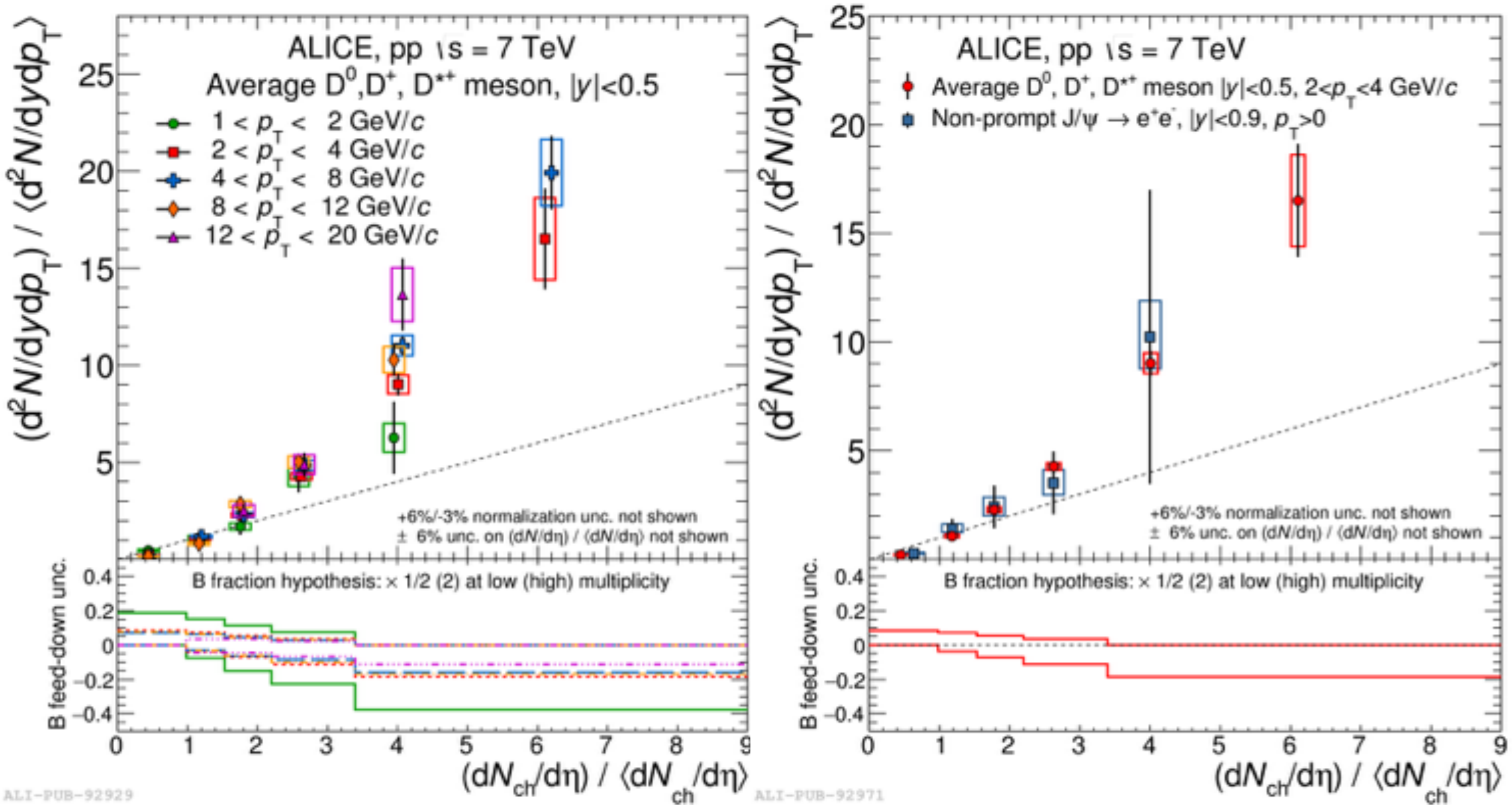
$$\frac{d^2N/dydp_T}{\langle d^2N/dydp_T\rangle}=\frac{Y^{mult}/(\epsilon^{mult}\times N^{mult}_{event})}{Y^{tot}/(\epsilon^{tot}\times N^{tot}_{event}/\epsilon^{trigger})}$$



Charged-particle mult @ mid-rapidity

Charged particle mult @ forward-rapidity

- Faster-than-linear increase of self-normalized D-meson yields as a function of the charged-particle multiplicity at mid-rapidity
- Similar increase with multiplicity for D mesons and non-prompt J/Ψ (i.e. for charm and beauty)
- Similar trend introducing an η-gap between the region of D-meson reconstruction (mid-rapidity) and multiplicity estimation (forward-rapidity) -> increase is not due to possible bias

D meson yields vs multiplicity in pp collisions

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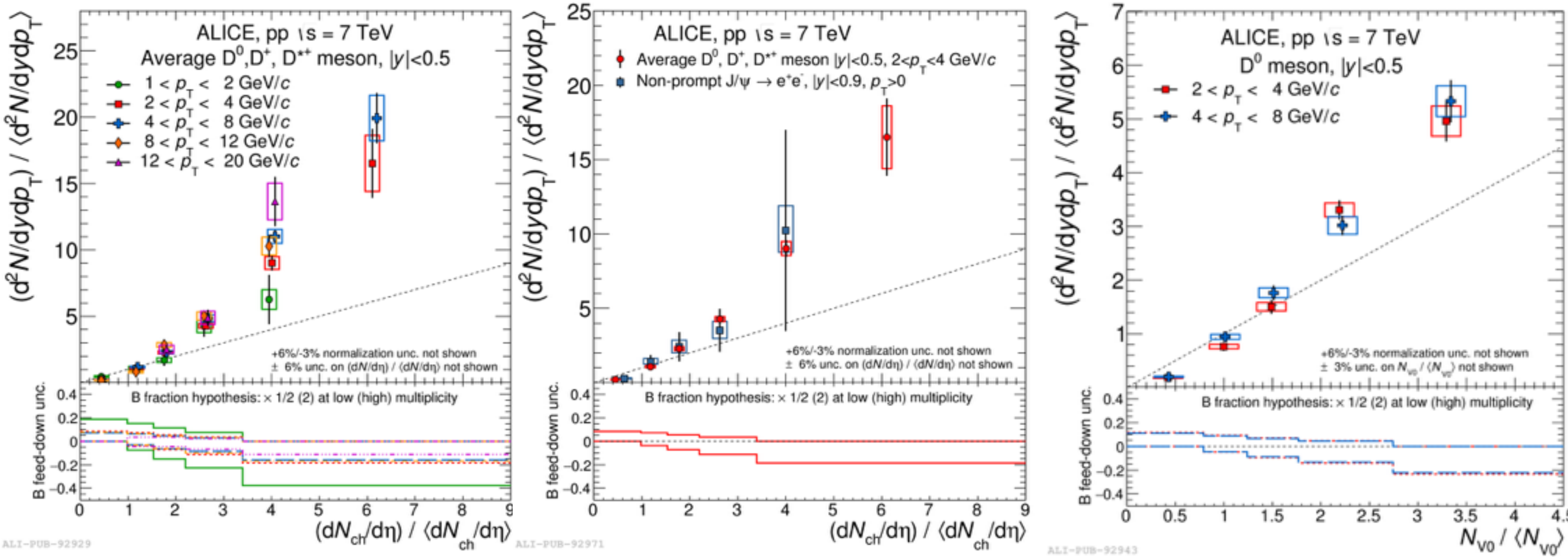
$$\frac{d^2N/dydp_T}{\langle d^2N/dydp_T\rangle} = \frac{Y^{mult}/(\epsilon^{mult}\times N^{mult}_{event})}{Y^{tot}/(\epsilon^{tot}\times N^{tot}_{event}/\epsilon^{trigger})}$$



Charged-particle mult @ mid-rapidity **Charged particle mult @ forward-rapidity**

- Faster-than-linear increase of self-normalized D-meson yields as a function of the charged-particle multiplicity at mid-rapidity
- Similar increase with multiplicity for D mesons and non-prompt J/Ψ (i.e. for charm and beauty)
- Similar trend introducing an η-gap between the region of D-meson reconstruction (mid-rapidity) and multiplicity estimation (forward-rapidity) -> increase is not due to possible bias

Open charm vs hidden charm (prompt and feed-down)

pp

$$\frac{d^2N/dydp_T}{\langle d^2N/dydp_T \rangle} = \frac{Y^{mult}/(\epsilon^{mult} \times N^{mult}_{event})}{Y^{tot}/(\epsilon^{tot} \times N^{tot}_{event}/\epsilon^{trigger})}$$

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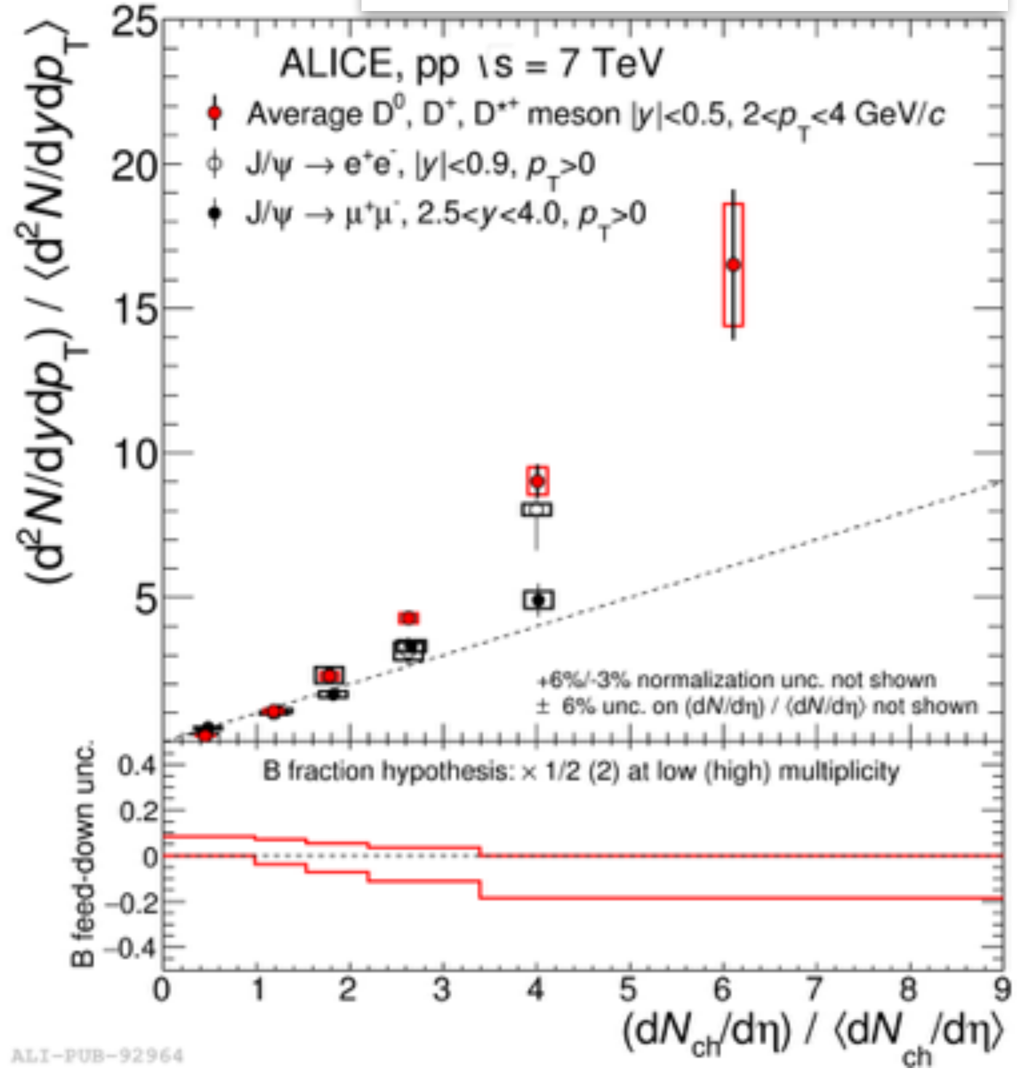
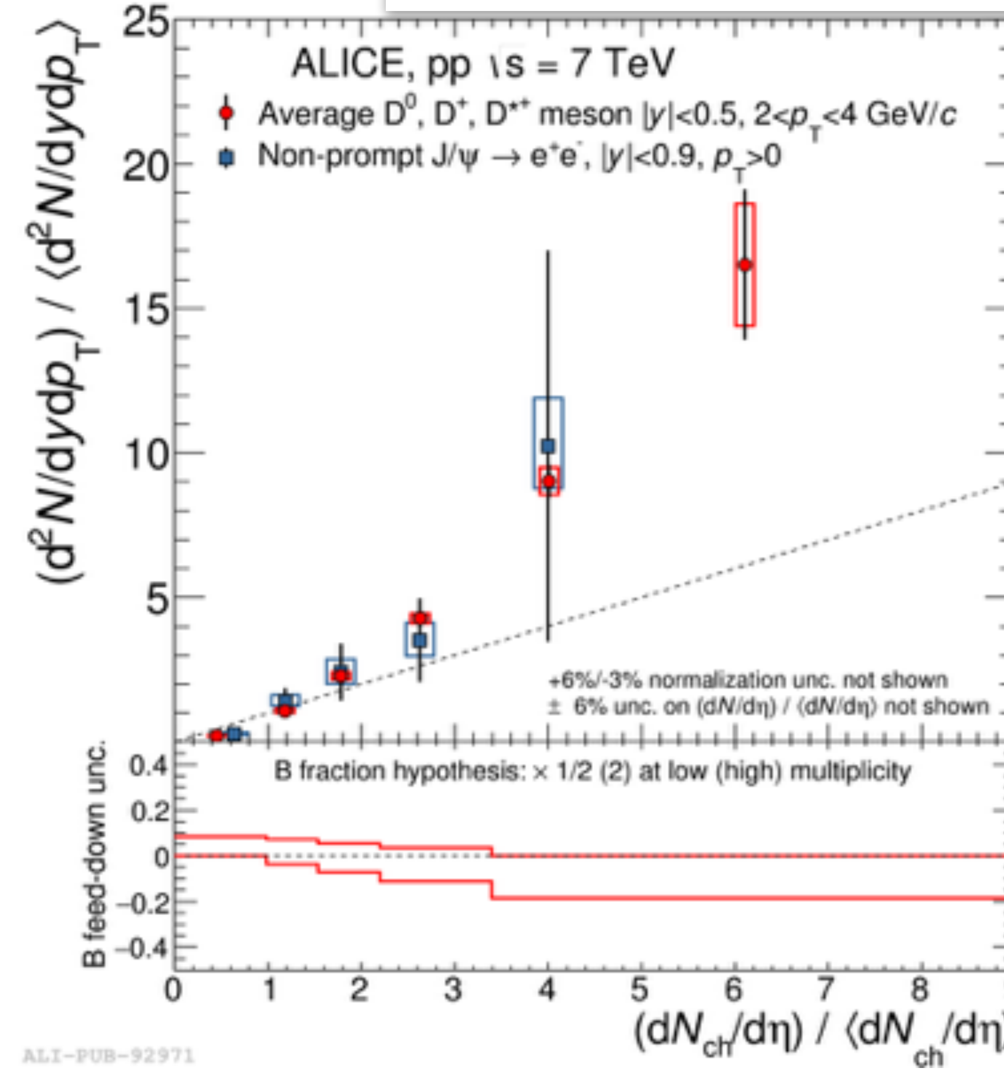
D mesons: 2< p_T < 4 GeV/c
Inclusive J/Ψ: p_T>0

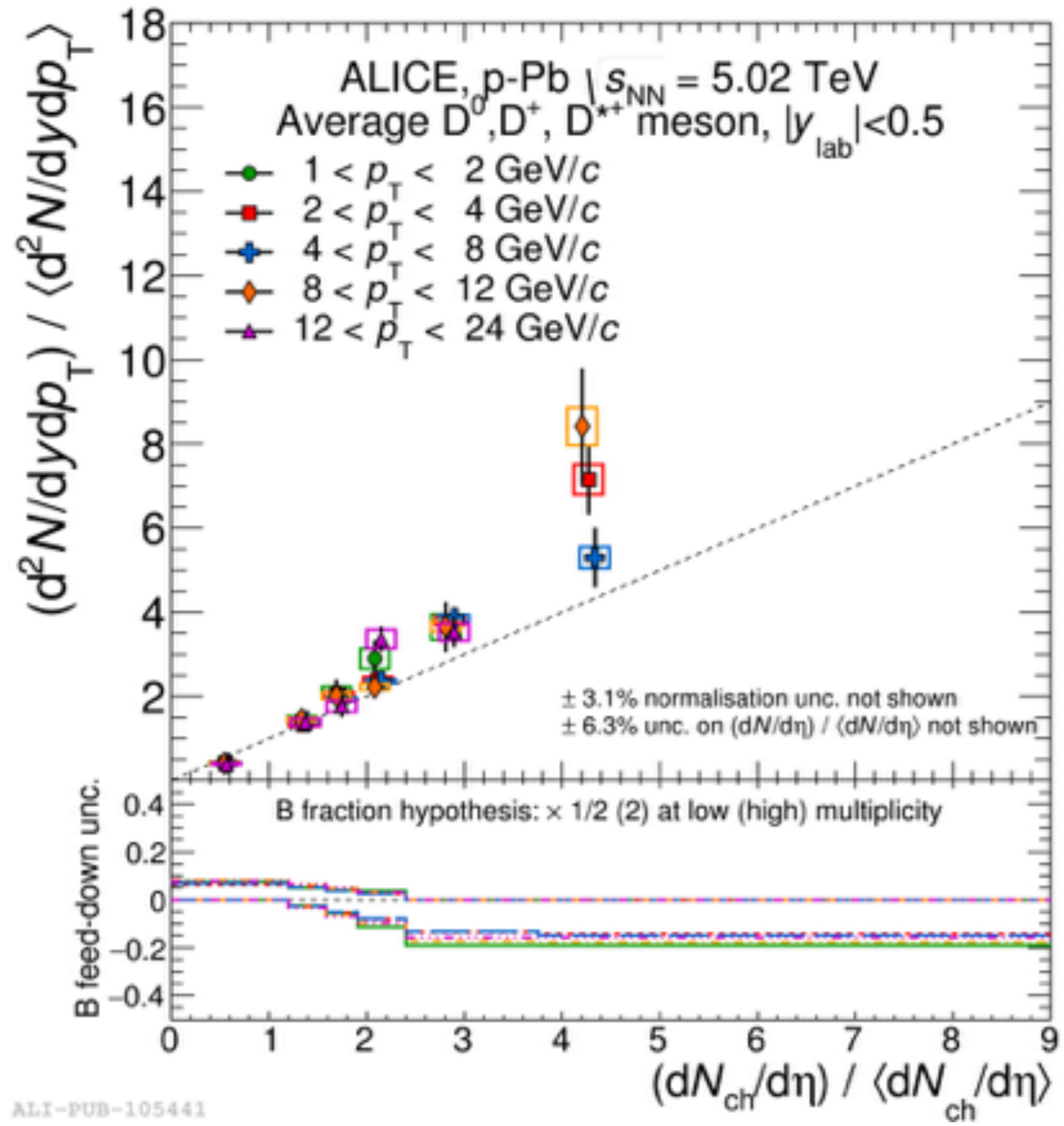


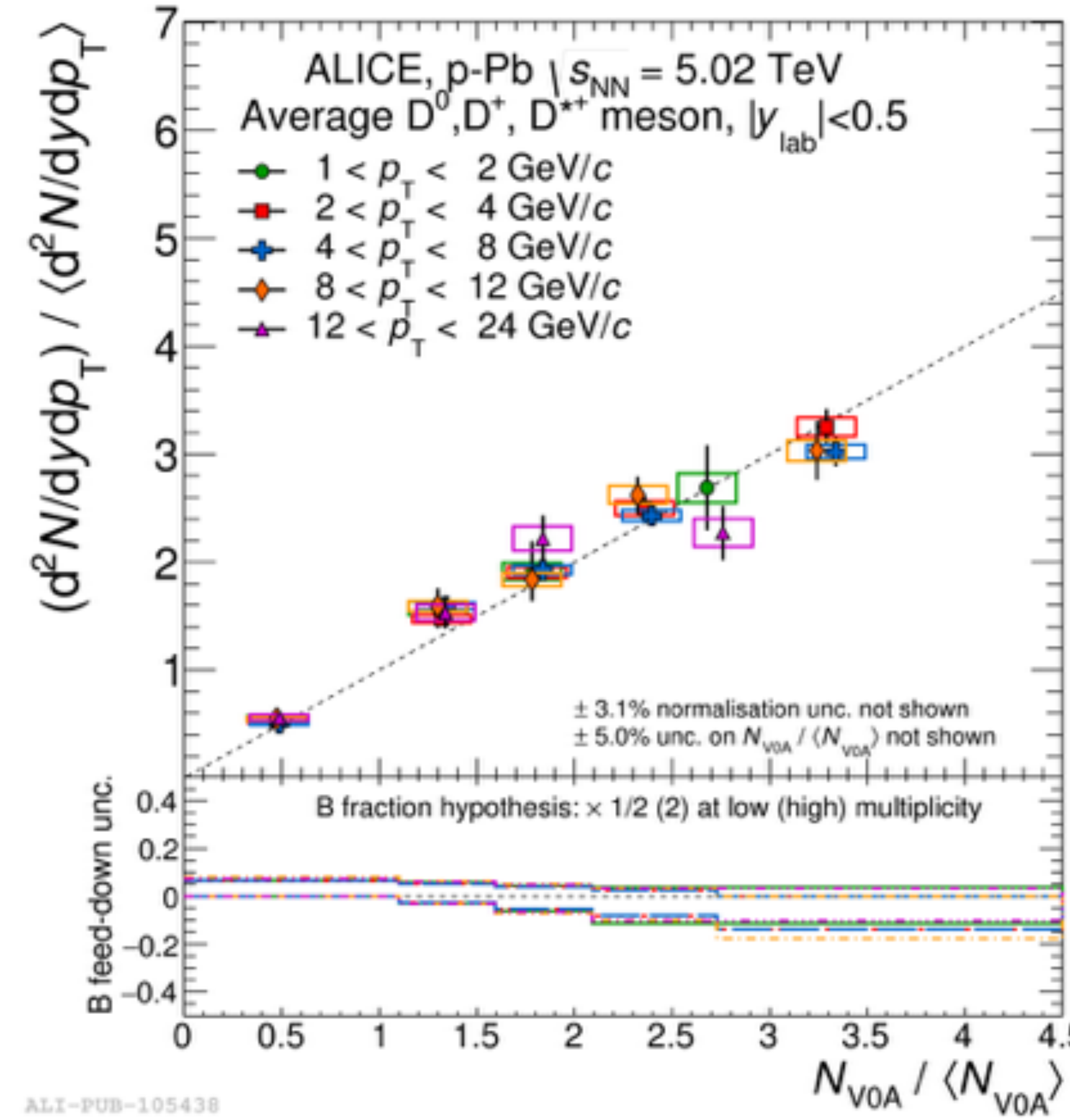
D mesons: 2< p_T < 4 GeV/c
Non-prompt J/Ψ: p_T>0



- Similar increase with multiplicity for open and hidden charm (different p_T and η range)
- Similar increase with multiplicity for D mesons and non-prompt J/Ψ (i.e. for charm and beauty)
- Suggest that the effect is not due to the hadronisation mechanism

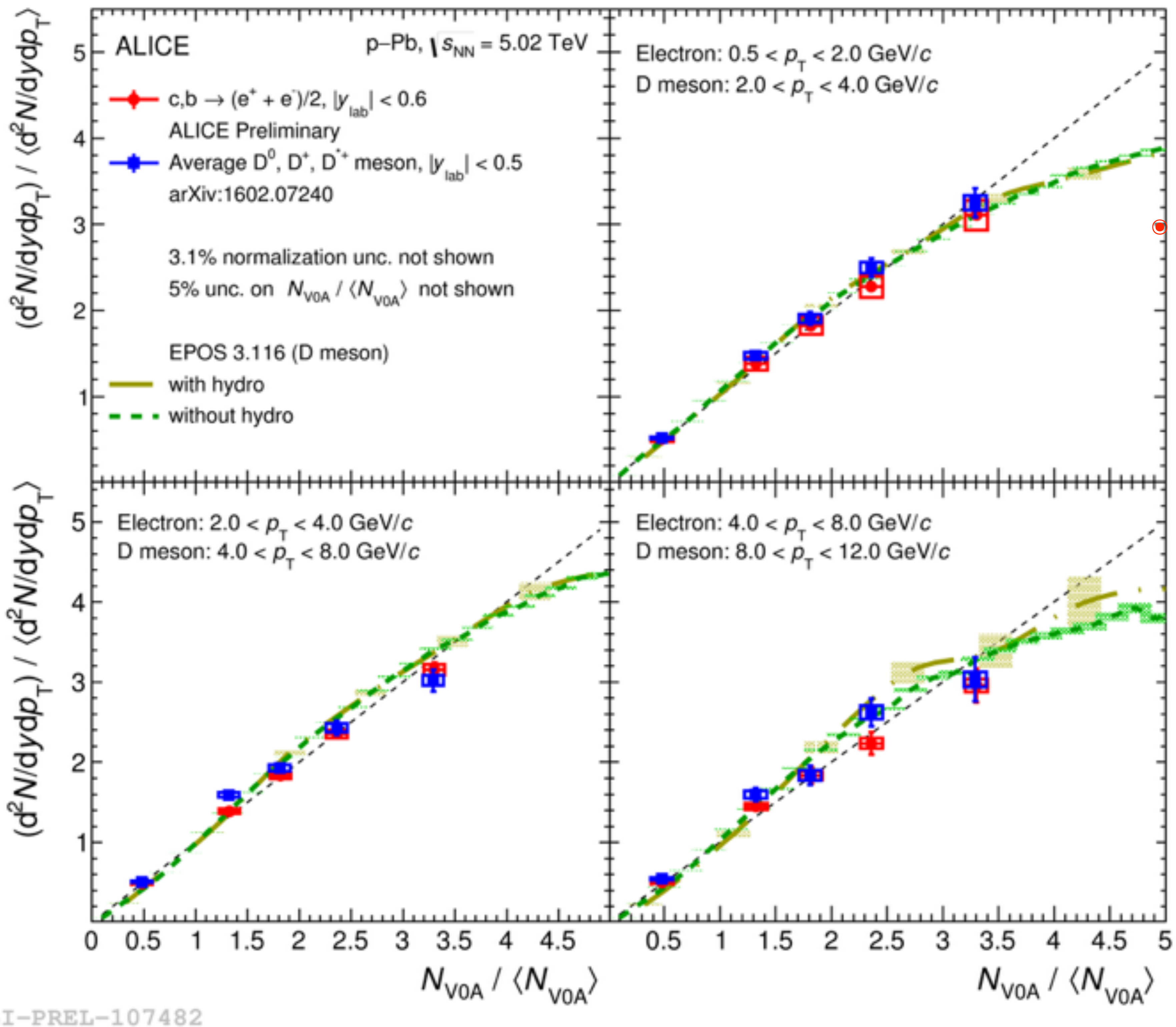
Multiplicity dependence of open HF production (p-Pb)





Comparison with models (p-Pb)

p-Pb



Werner et al., PRC 89 (2014) 064903

- **EPOS 3.116**
  - Initial conditions and hydrodynamical evolution
  - D mesons more compatible with hydro

Centrality in p-Pb collisions

- <N_{coll}> needed to investigate the centrality dependent modification of the p_T-dependent yields in p-Pb collisions wrt pp collisions

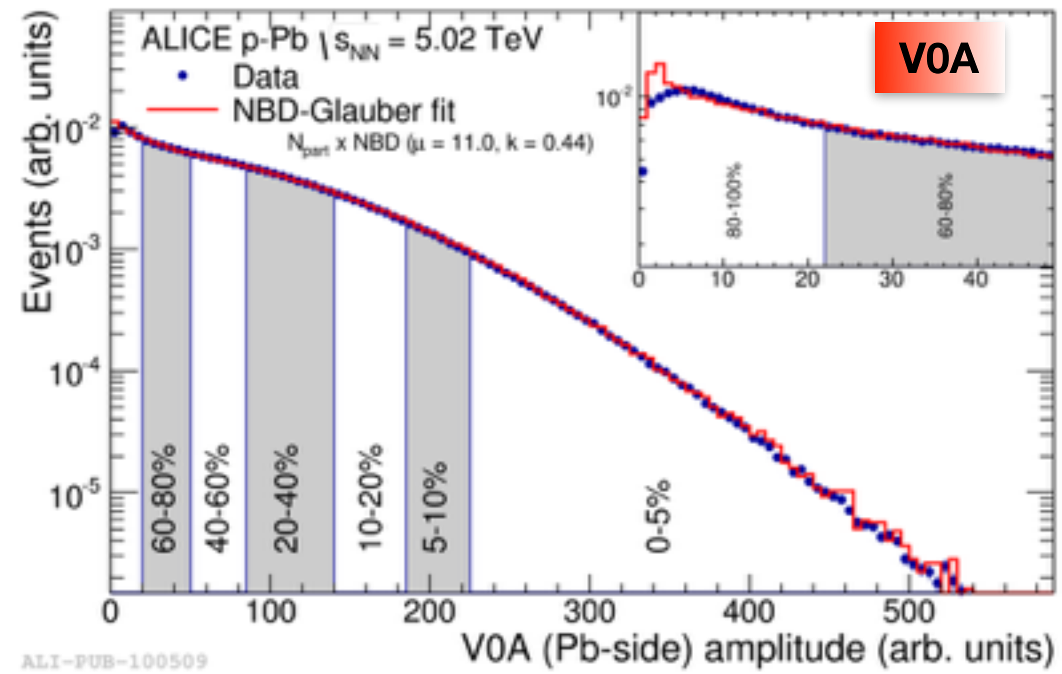
$$Q_{pPb}^{multi}(p_T) = \frac{(dN_{pPb}^{multi}/dp_T)_i}{\langle N_{coll}\rangle_i dN_{pp}/dp_T}$$

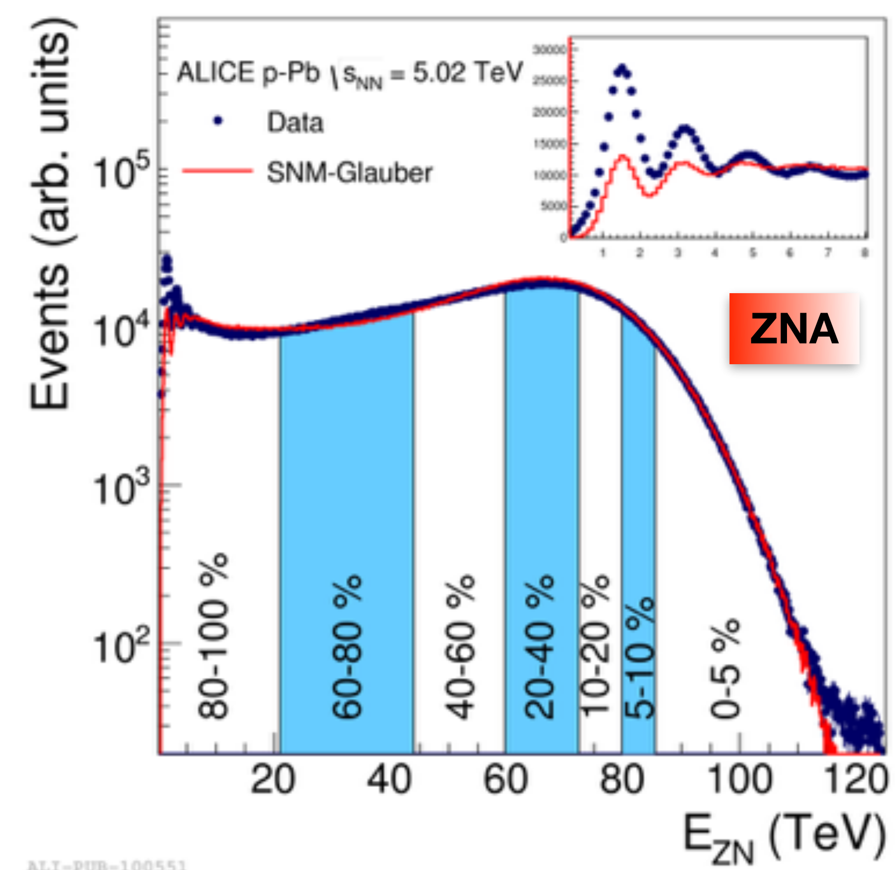
- In p-Pb collisions biases are present in the determination of <N_{coll}>
  - Multiplicity bias, jet-veto bias, geometrical bias
- Lose correlations between N_{part}, multiplicity and impact parameter
- Bias depends on the estimator used

Centrality estimators in p-Pb collisions

- **V0A**: <N_{coll}> determined by Glauber fit to V0 amplitude
- **ZNA**: Event classes defined by energy deposited in the neutron ZDC and <N_{coll}> from hybrid approach

$$\langle N_{coll}\rangle_i = \langle N_{coll}\rangle_{MB}\left(\frac{\langle dN/d\eta\rangle_i}{\langle dN/d\eta\rangle_{MB}}\right) - 1$$





Centrality dependent nuclear modification factor

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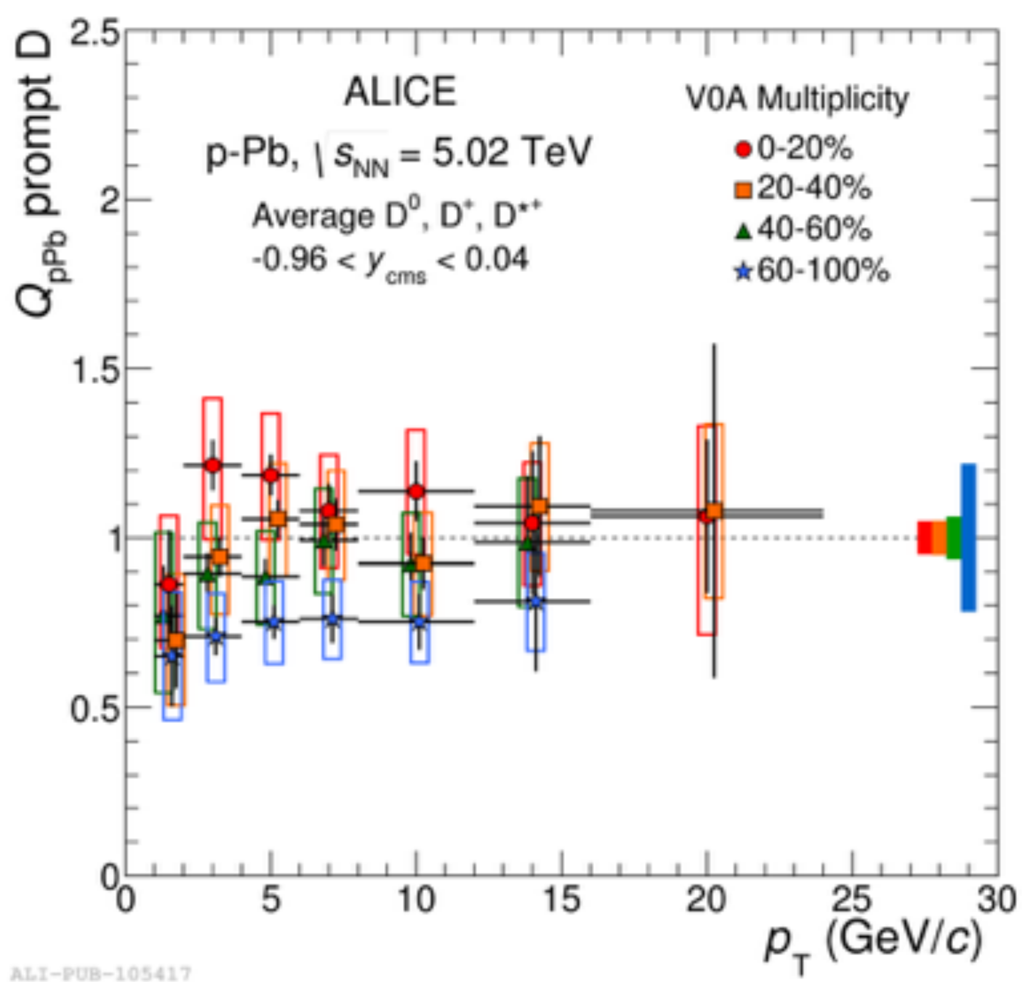
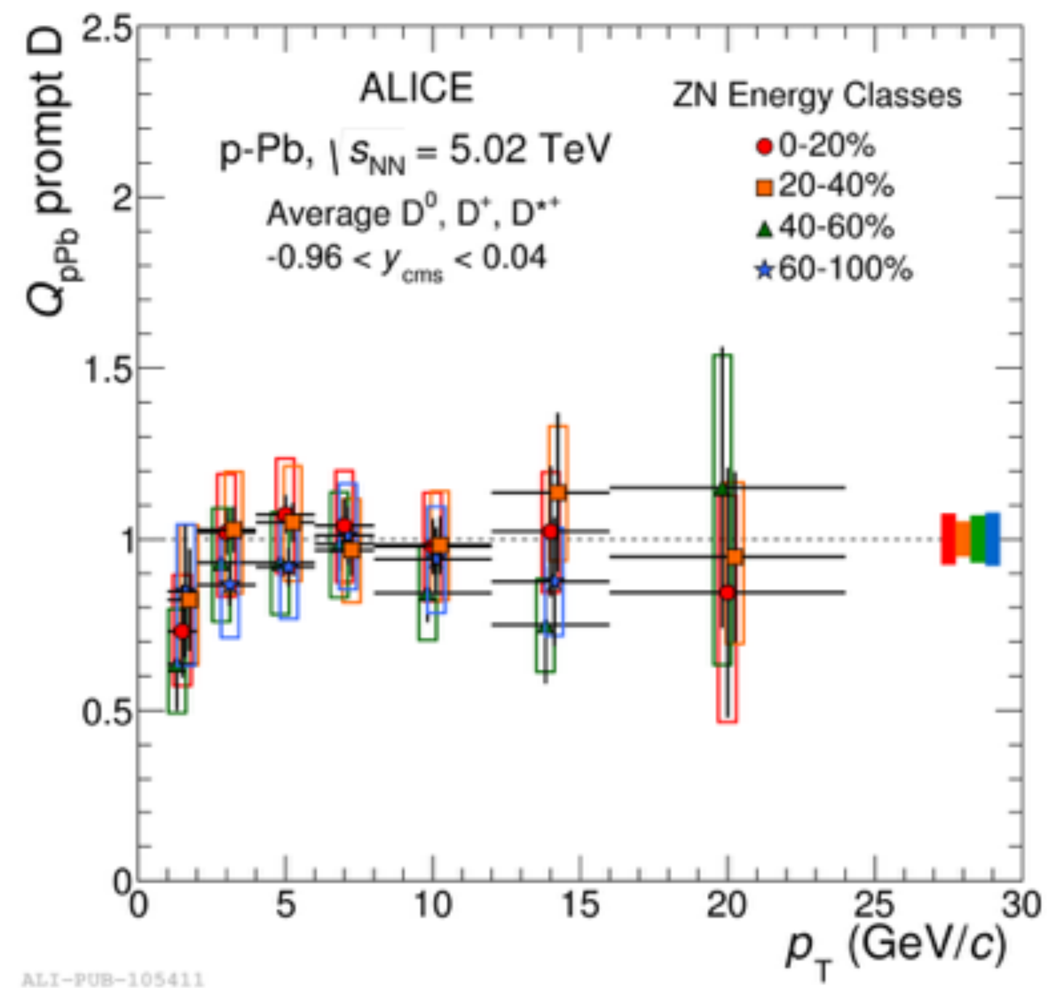
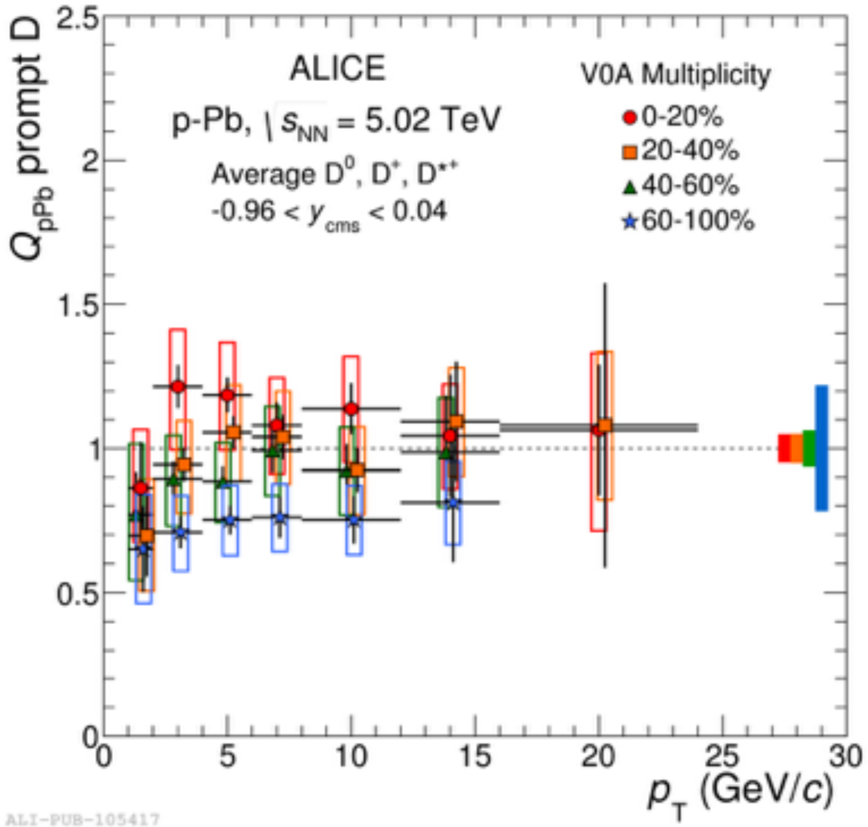
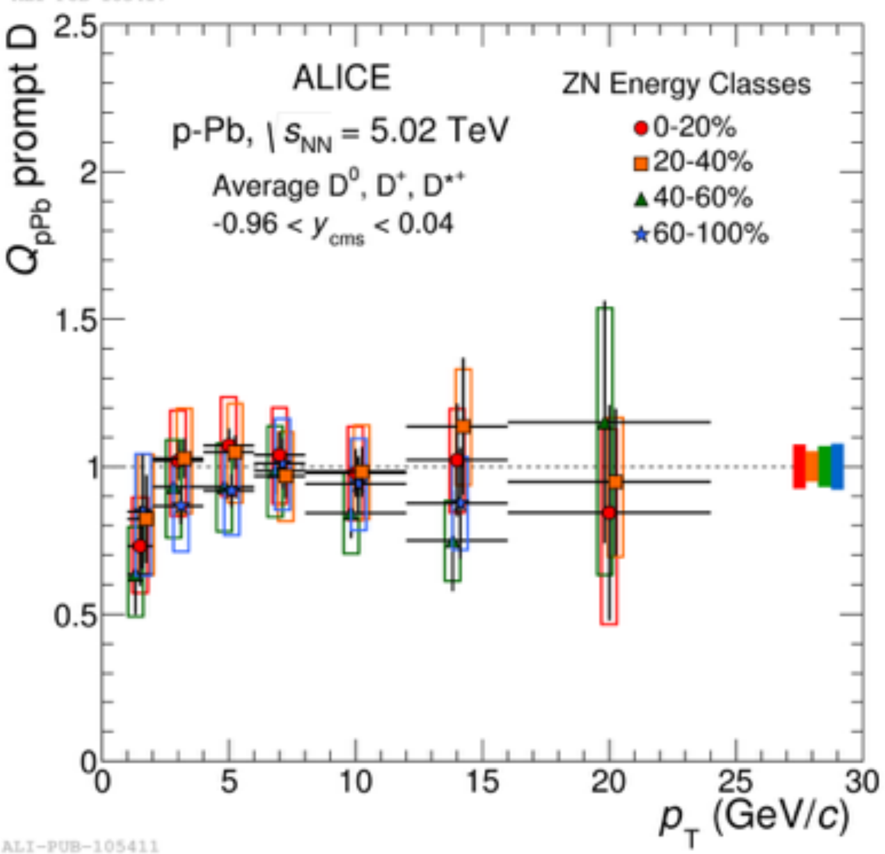




- Q_{pPb} with V0A estimator: hierarchy going from higher to lower multiplicity
- Q_{pPb} with ZNA estimator: no hierarchy is present
- Consistent with charged hadrons at high p_T

Centrality dependent nuclear modification factor





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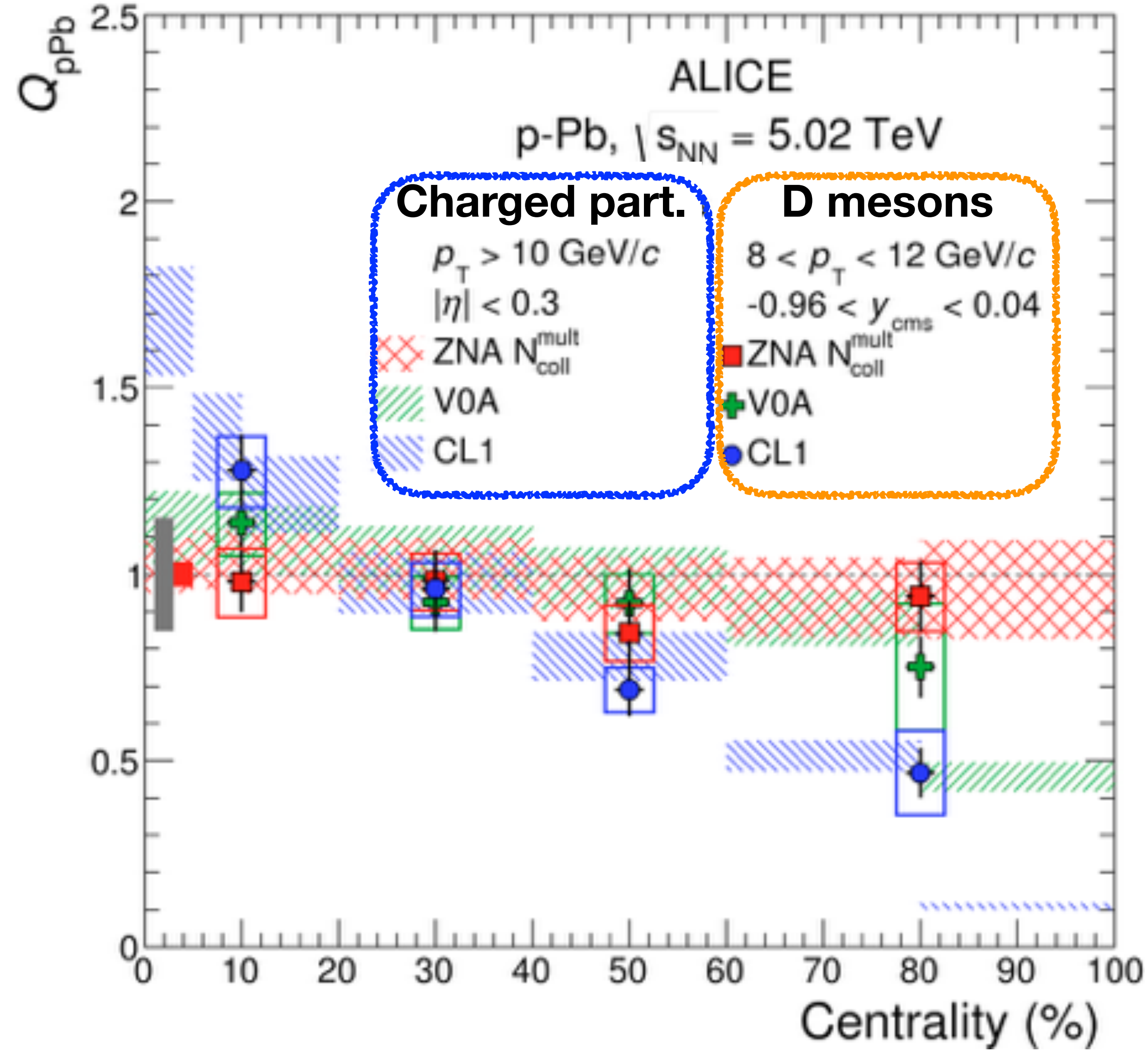
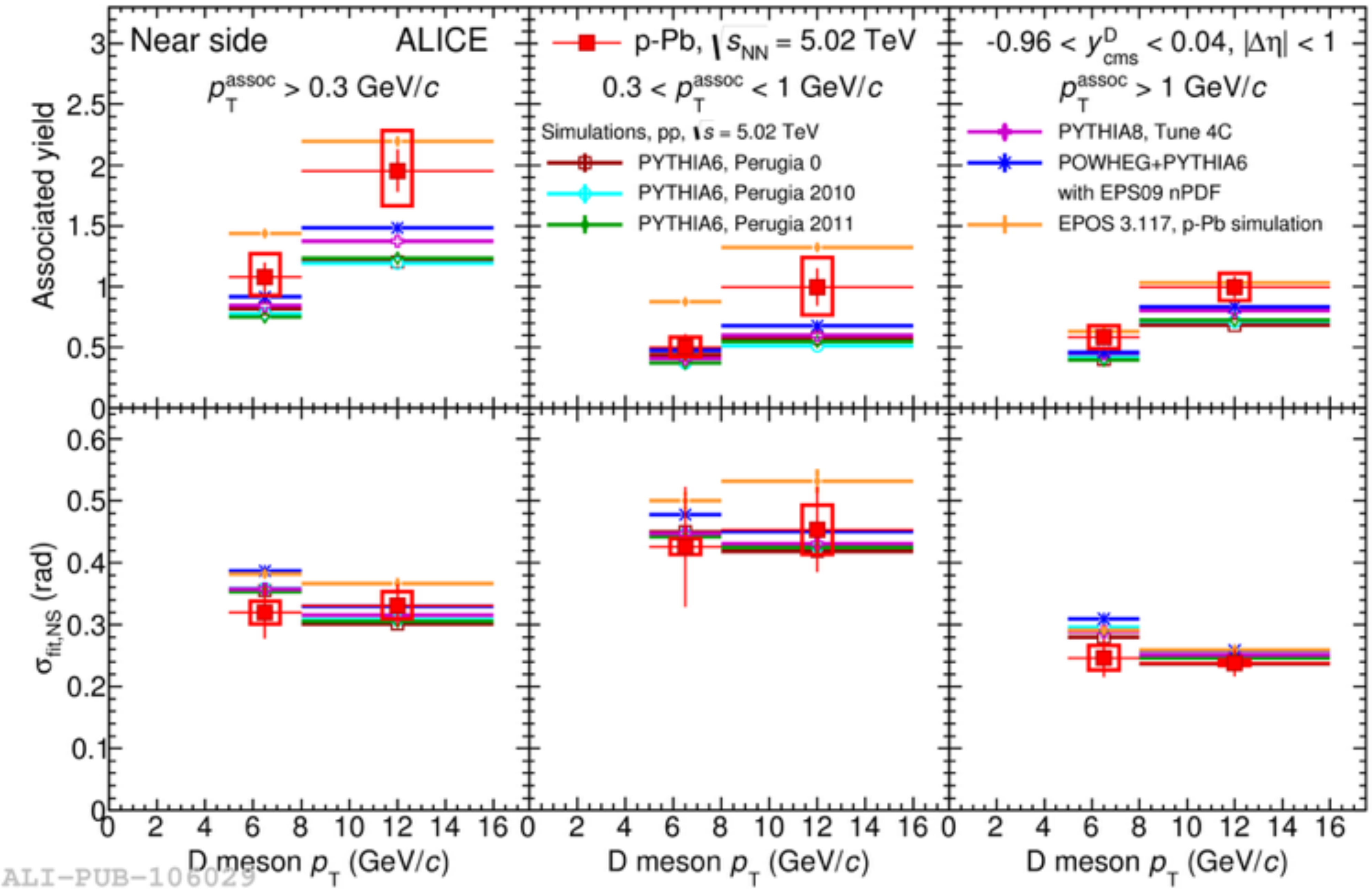


- Q_{pPb} with V0A estimator: hierarchy going from higher to lower multiplicity
- Q_{pPb} with ZNA estimator: no hierarchy is present
- Consistent with charged hadrons at high p_T

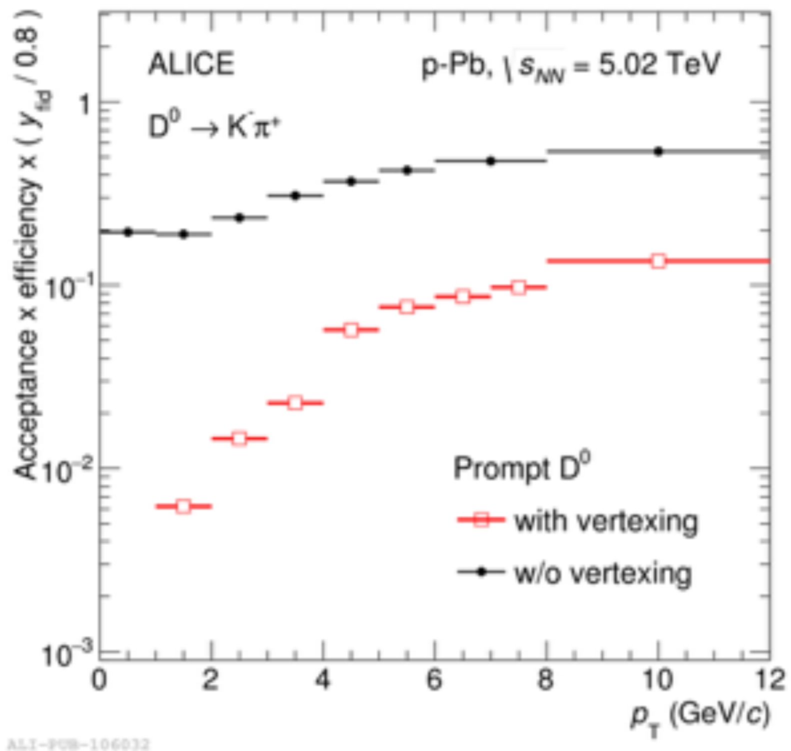
D meson - charged particle angular correlations

arXiv:1605:06963

$p_T^{assoc} > 0.3$ GeV/c | $0.3 < p_T^{assoc} < 1$ GeV/c | $p_T^{assoc} > 1$ GeV/c



- Near-side peak properties compatible between pp and p-Pb collisions
- No evidence of modifications due to initial-state or final-state effects within uncertainties


ALICE
p-Pb, $\sqrt{s_{NN}}$ = 5.02 TeV
$D^0 \rightarrow K^-\pi^+$
Prompt D^0
with vertexing
w/o vertexing
Acceptance x efficiency x (y_{fid} / 0.8)
p_T (GeV/c)
ALI-PUB-106032