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

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Edith Zinhle Buthelezi
for the ALICE Collaboration,
iThemba LABS, Cape Town, South Africa

ALICE

science & technology
Department:
Science and Technology
REPUBLIC OF SOUTH AFRICA

NRF
National Research Foundation

iThemba LABS
Laboratory for Accelerator Based Sciences

Outline

- Motivation
  - ✓ Heavy-flavour production
  - ✓ Heavy-flavour production vs charged-particle multiplicity
- Measurements in ALICE
  - ✓ Heavy-flavour measurements in ALICE
  - ✓ Multiplicity measurements in ALICE
- Results:
  - ✓ pp collisions at $\sqrt{s}$ = 7 TeV
  - ✓ p-Pb collisions at $\sqrt{s_{NN}}$ = 5.02 TeV
  - ✓ pp vs p-Pb collsions
- Conclusion

Heavy-flavour (HF) production

- Heavy quarks (charm and beauty) are produced in initial partonic scattering processes with large Q^2 → short formation time: $\tau_{c,b}$~$1/2m_{c,b}$~0.1 *fm* ≤ τ_{QGP}~5-10 *fm*
- Total production cross sections are calculable with pQCD

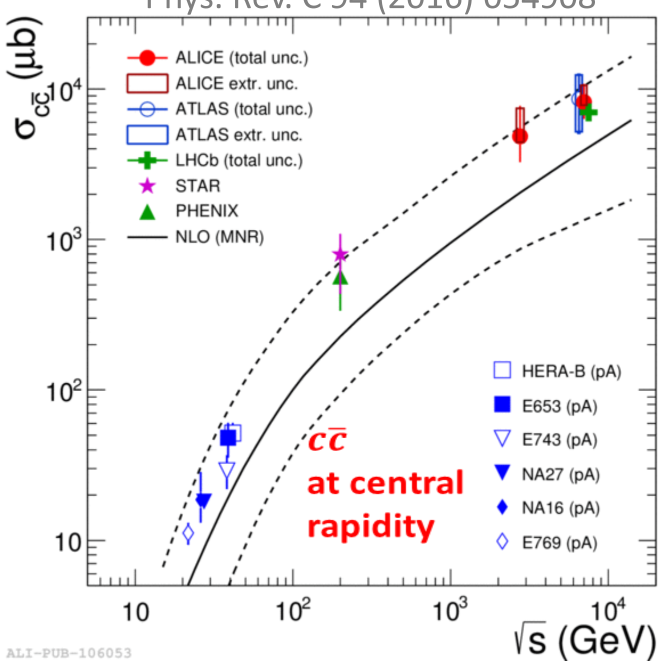
In pp collisions: test pQCD calculations

reference for p-Pb and Pb-Pb collisions

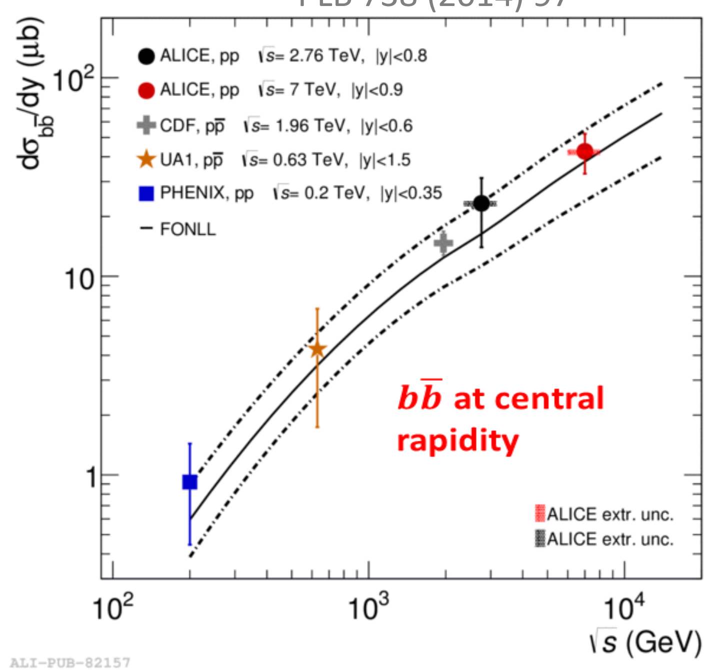
In p-Pb collisions: provide the control experiment to study cold nuclear matter (CNM) effects

- Copious amount of charm and beauty production at the LHC

Phys. Rev. C 94 (2016) 054908



PLB 738 (2014) 97



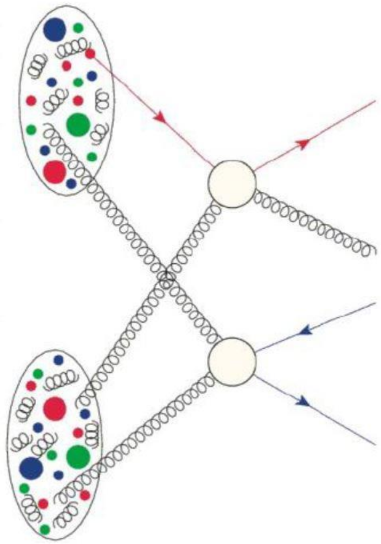
HF production vs charged-particle multiplicity

- Charged-particle multiplicity dependence provides **insight into processes occurring in the collision at the partonic level** and the interplay between **soft** and **hard** processes in particle production

- Multiplicities in pp collisions at the LHC can reach values similar to those measured in semi-peripheral heavy ion collisions at low $\sqrt{s}$

  → **Collectivity in pp collisions for high multiplicity**

  Werner *et al.*, PRC 83 (2011) 044915



Possible explanations:

✓ Several hard partonic interactions can occur in parallel

→ **multi-parton interactions (MPIs)**

✓ Role of collisional geometry

Frankfurt, Strikman, Weiss, PRD 83 (2011) 054012
Azarkin, Drenim, Strikman, PLB 735 (2014) 244

✓ Final-state effects (colour reconnections, saturation, string percolations)

Ferreiro, Pajares, PRC 86 (2012) 034903

- In **p-Pb collisions** the charged-particle multiplicity dependence is also affected by the presence of **multiple binary nucleon-nucleon interactions** and the initial conditions modified by **cold nuclear matter (CNM) effects**

Differential HF observable: HF production yields vs charged-particle multiplicity will provide insight into particle production

HF measurements in ALICE

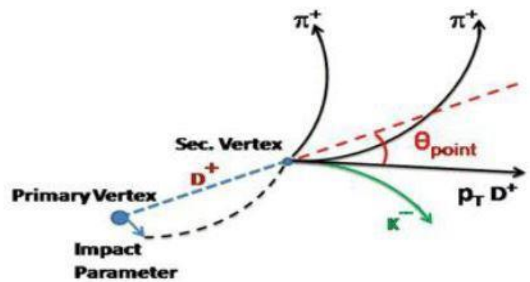
HF hadrons decay via weak interactions. Decay lengths c_τ ~ few 100 μm → measure decay products

Full reconstruction of D-meson hadronic decays (prompt D mesons)

$D^0 \xrightarrow{3.88\pm0.05\%} K^-\pi^+$ c_τ~123μm

$D^+ \xrightarrow{9.13\pm0.19\%} K^-\pi^+\pi^-$ c_τ~312μm

$D^{*+} \xrightarrow{67.7\pm0.05\%} D^0\pi^+$, where D^0→ $K^-\pi^+$



Invariant mass analysis based on displaced **secondary vertices**, selected with **topological cuts and PID**

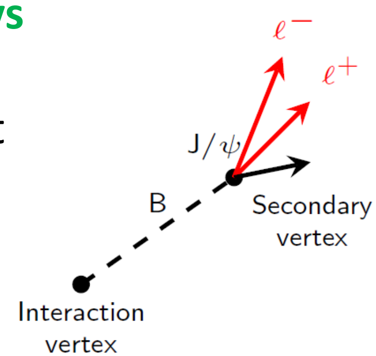
Correction for beauty feed-down, based on FONLL, to extract results for **prompt D mesons**

JHEP 9805 (1998) 007 [arXiv:hep-ph/9803400], JHEP 0103 (2001) 006 [arXiv:hep-ph/0102134]

Displaced electrons, J/ψ from B decays (b→J/ψ→e+e-)

Separation of prompt and non-prompt J/ψ using pseudo-proper decay length

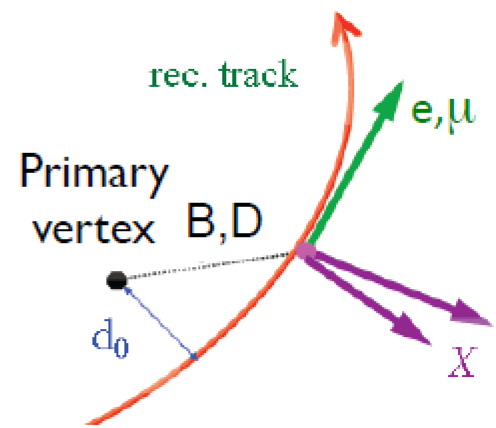
Beauty-decay electrons: exploits displaced track impact parameter



Semi-leptonic decays (c, b → e, μ)

Electron (e): mid-rapidity

Muons (μ): forward rapidity

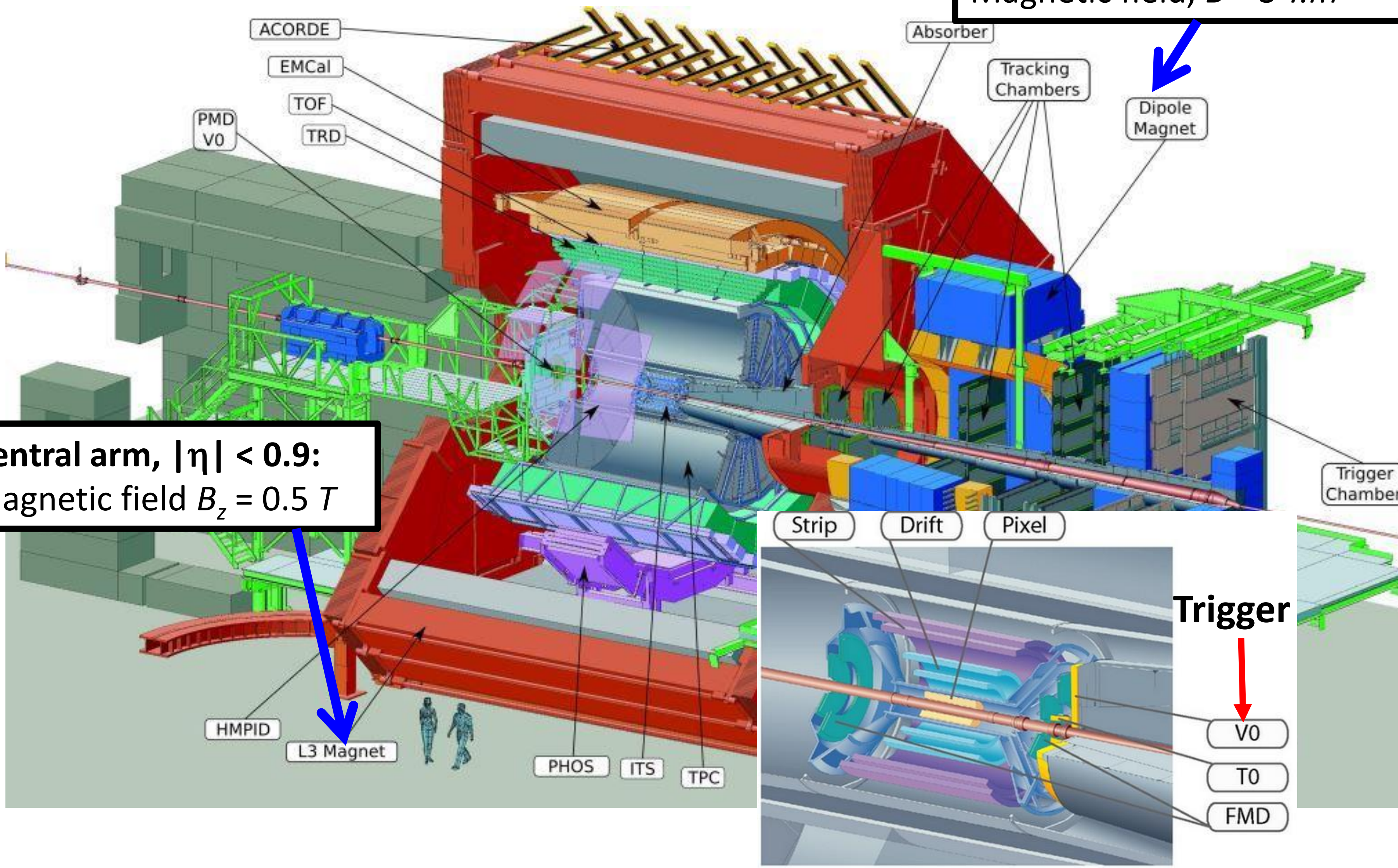


Electrons: background (π^0 and η Dalitz decays, photon conversions) subtraction with **invariant mass method (e^+e^-)** & **cocktail**

Muons: background (π, K → μ) subtraction with MC (**pp**) & data-tuned MC cocktail (**p-Pb**)

ALICE detector layout

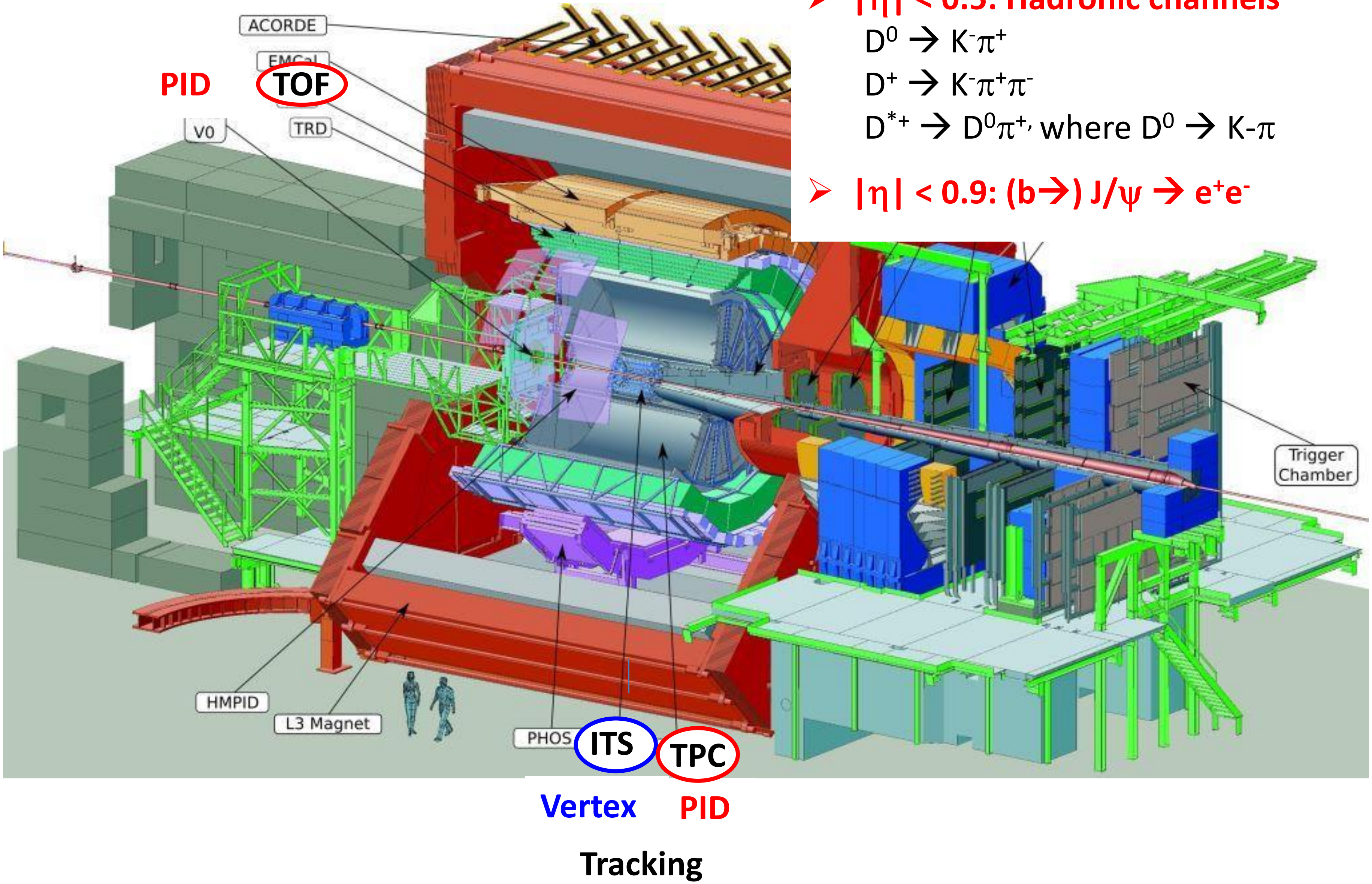
Muon arm: $-4.0 < \eta < -2.5$
Magnetic field, $B = 3$ *T.m*



Central arm, $|\eta| < 0.9$:
Magnetic field $B_z = 0.5$ *T*

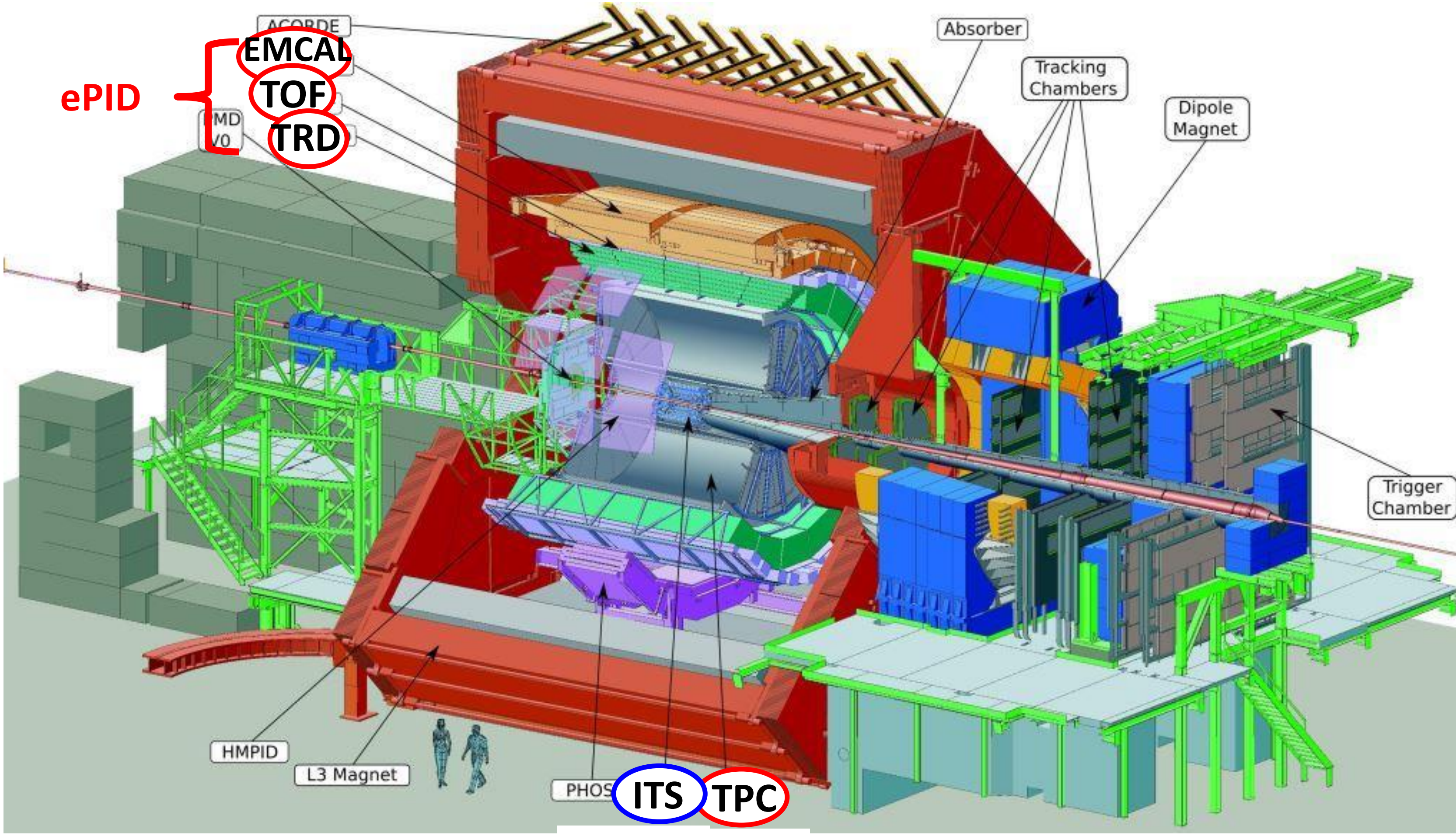
HF measurements in the central barrel

- **$|\eta| < 0.5$: Hadronic channels**
  - $D^0 \rightarrow K^-\pi^+$
  - $D^+ \rightarrow K^-\pi^+\pi^-$
  - $D^{*+} \rightarrow D^0\pi^+$, where $D^0 \rightarrow K\text{-}\pi$
- **$|\eta| < 0.9$: $(b\rightarrow)\ J/\psi \rightarrow e^+e^-$**



HF measurement in the central barrel

|η| < 0.6: c, b → e + X



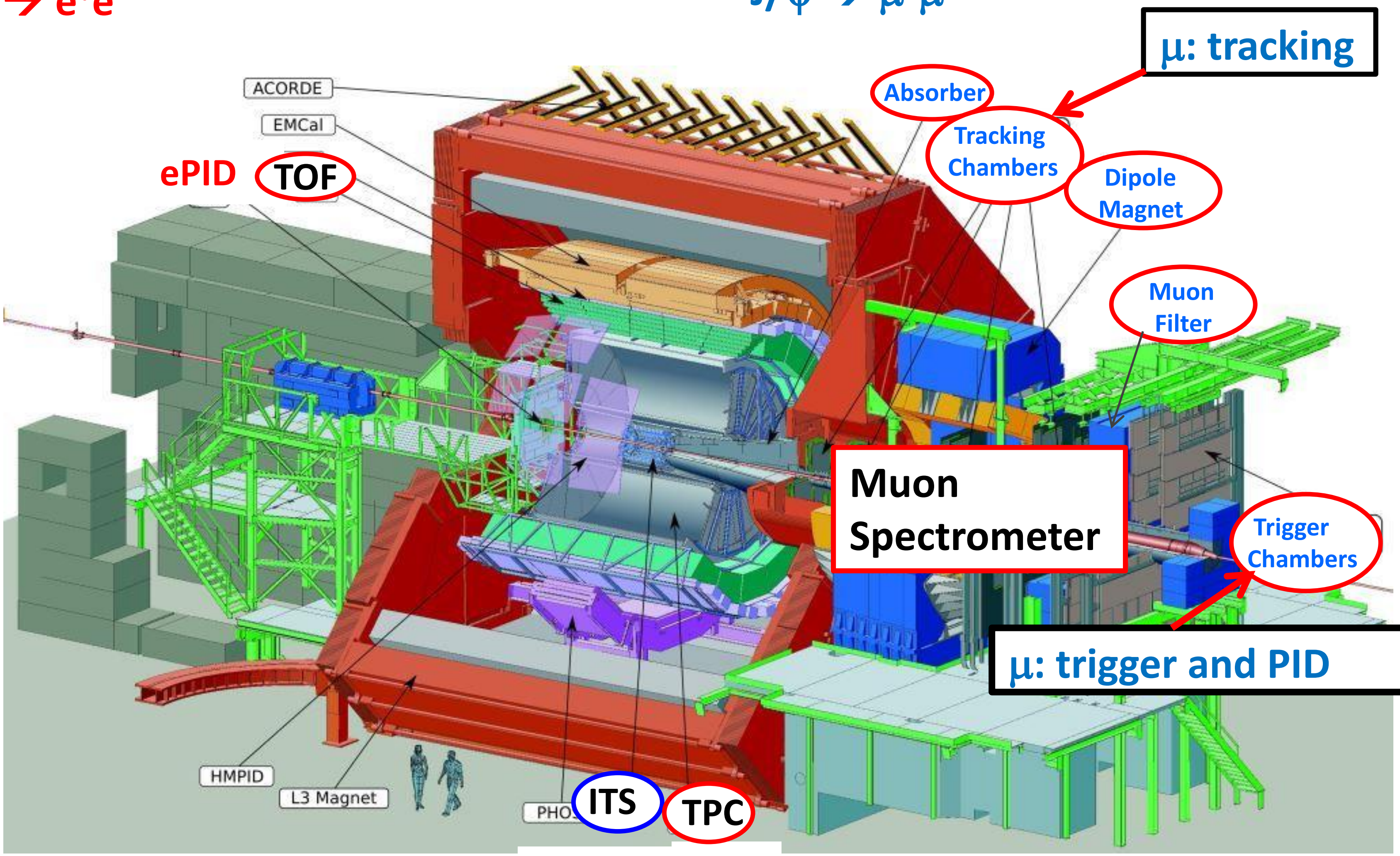
Vertex **ePID**

Tracking

Inclusive J/ψ measurements

Central rapidity, $|\eta| < 0.9$:
$J/\psi \rightarrow e^+e^-$

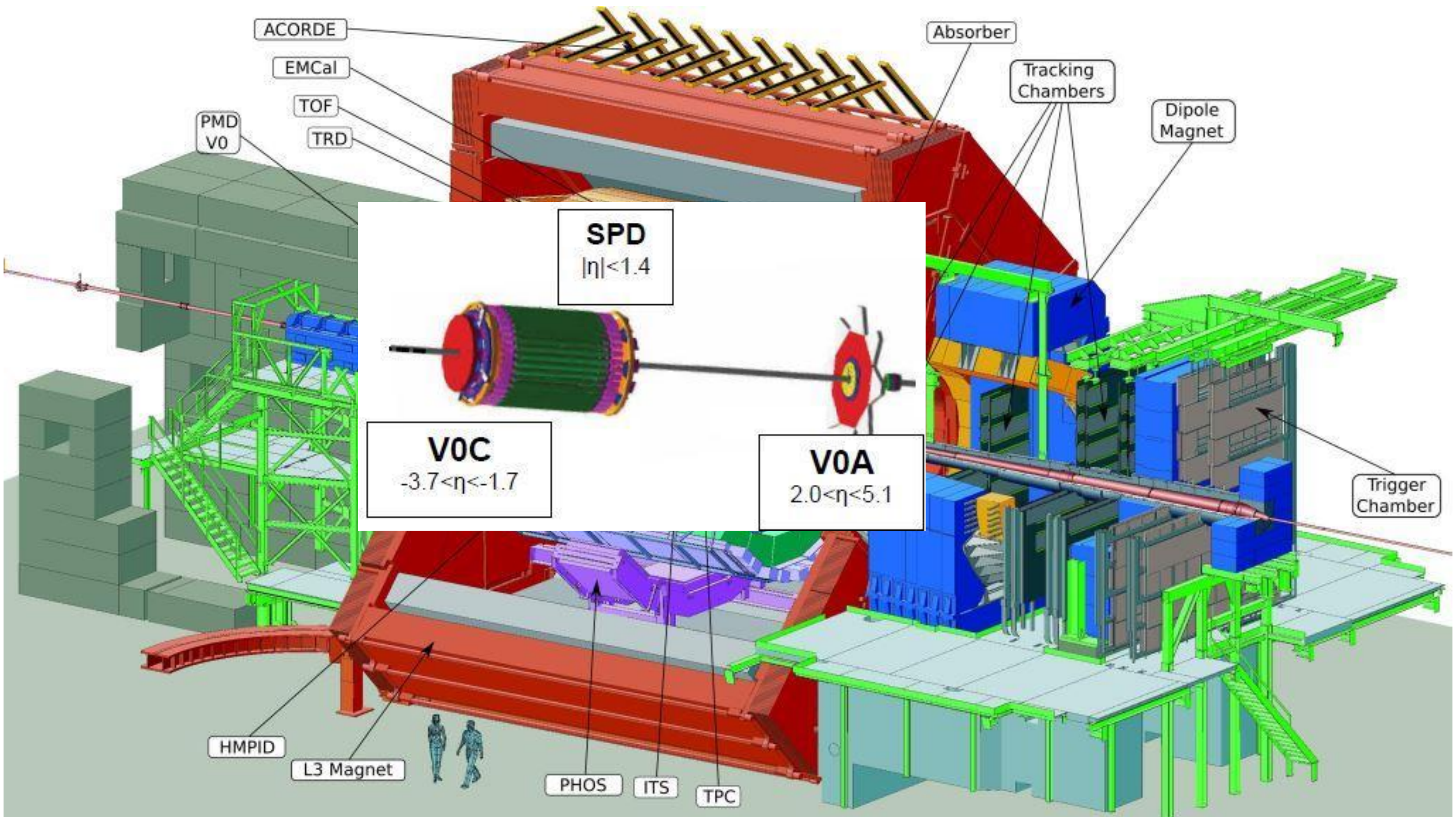
Forward rapidity, $-4.0 < \eta < -2.5$:
$J/\psi \rightarrow \mu^+\mu^-$



Tracking

Multiplicity measurement

- **Mid-rapidity**: number of track segments (or tracklets) of the **SPD**
- **Forward rapidity**: sum of the amplitudes in the **V0A** and **V0C**. In p-Pb **only V0A** is used at backward rapidity or Pb-going direction
- **Rapidity gap between SPD and V0**: mid and forward rapidity



Results from pp collisions at $\sqrt{s}$ = 7 TeV

Data sample: ~ 3×10^{8} minimum-bias (MB) events collected in 2010

→ **MB trigger**: signal in V0A|V0C|SPD, L_{int} ~ 5 nb^{-1}

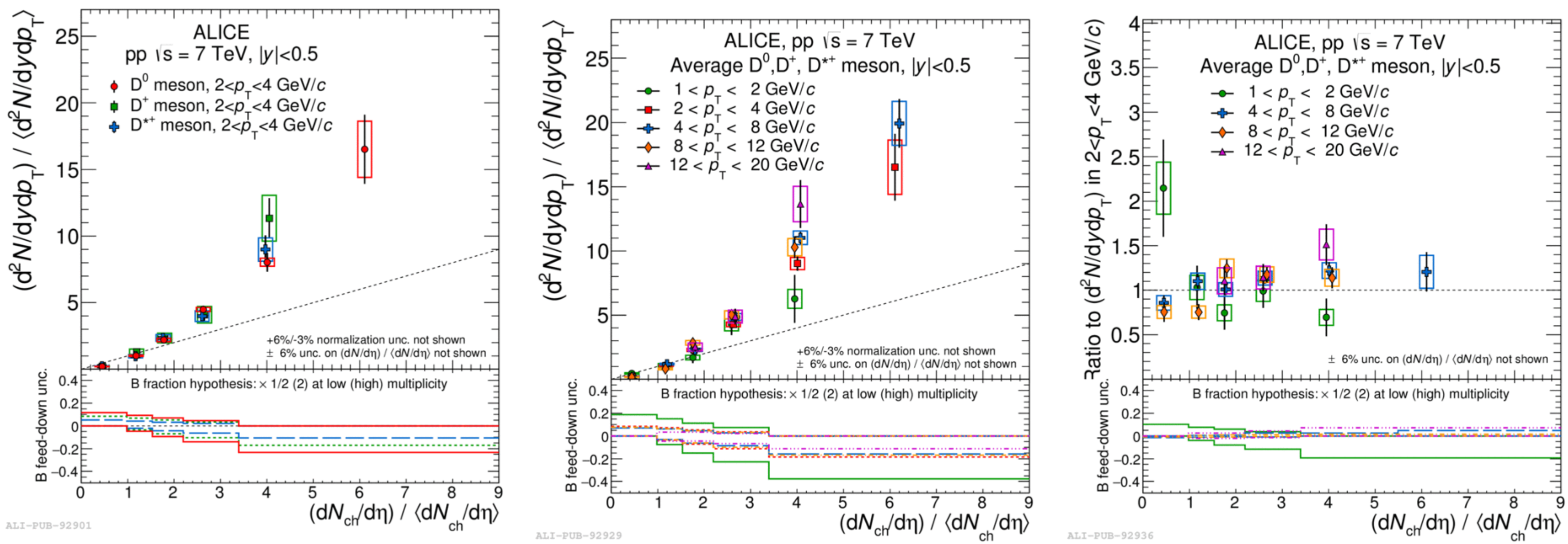
→ **High multiplicity trigger**: Threshold on number of fired chips in SPD, L_{int} ~14 nb^{-1}

→ **Dimuon unlike-sign trigger**: Opposite sign muons, p_{T} > 0.5 GeV/c, L_{int} ~ 7.7 nb^{-1}

D-meson yields vs charged-particle multiplicity

Self normalised yields $\left(\frac{d^2N/dydp_T}{\langle d^2N/dydp_T \rangle}\right)$ as a function of charged-particle multiplicity $\left(\frac{dN_{ch}/d\eta}{\langle dN_{ch}/d\eta \rangle}\right)$ at mid-rapidity

ALICE, JHEP 09 (2015) 148

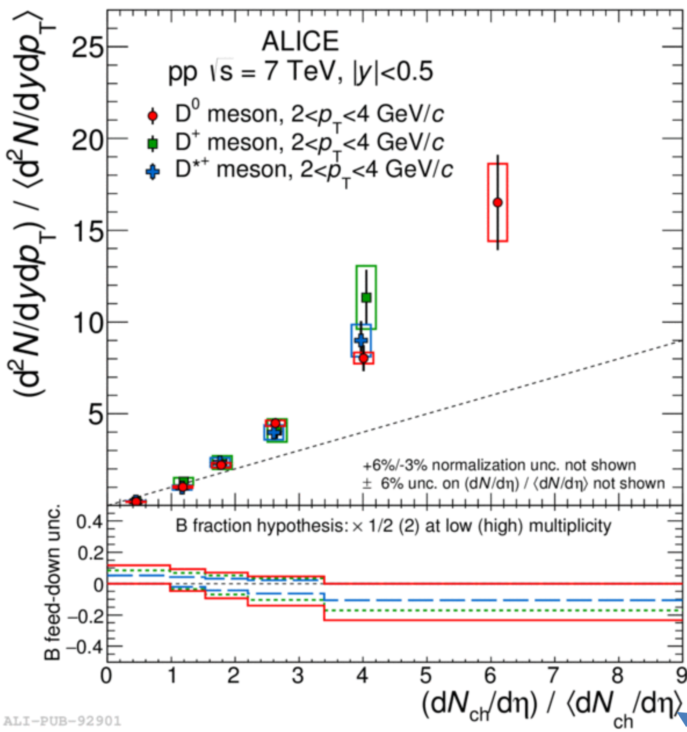


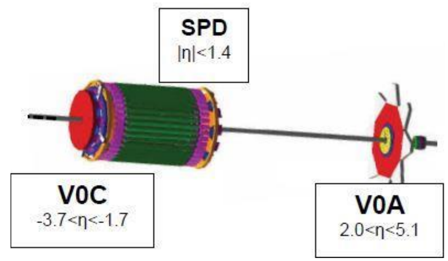
- Results for D^0, D^+ and D^{*+} mesons are consistent within uncertainties
- The yields of D mesons increase with charged-particle multiplicity at mid rapidity
  - ✓ A faster-than-linear increase of the yield is observed for large multiplicities
  - ✓ Increase is independent of p_T within uncertainties

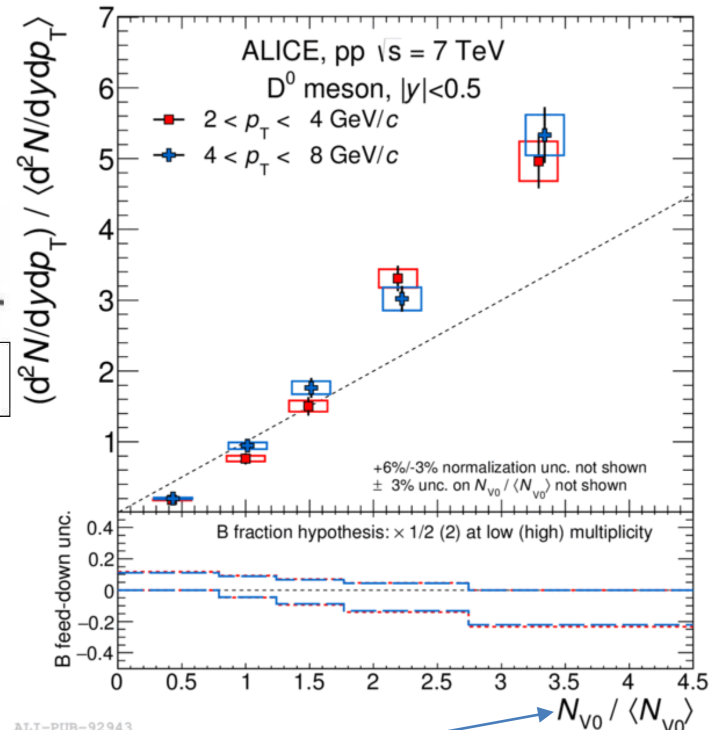
D-meson yields vs charged-particle multiplicity: η gap

Left: charged-particle multiplicity and D mesons are measured in the same η range
Right: test effects of possible auto-correlations: multiplicity measured using V0 detector

ALICE, JHEP 09 (2015) 148







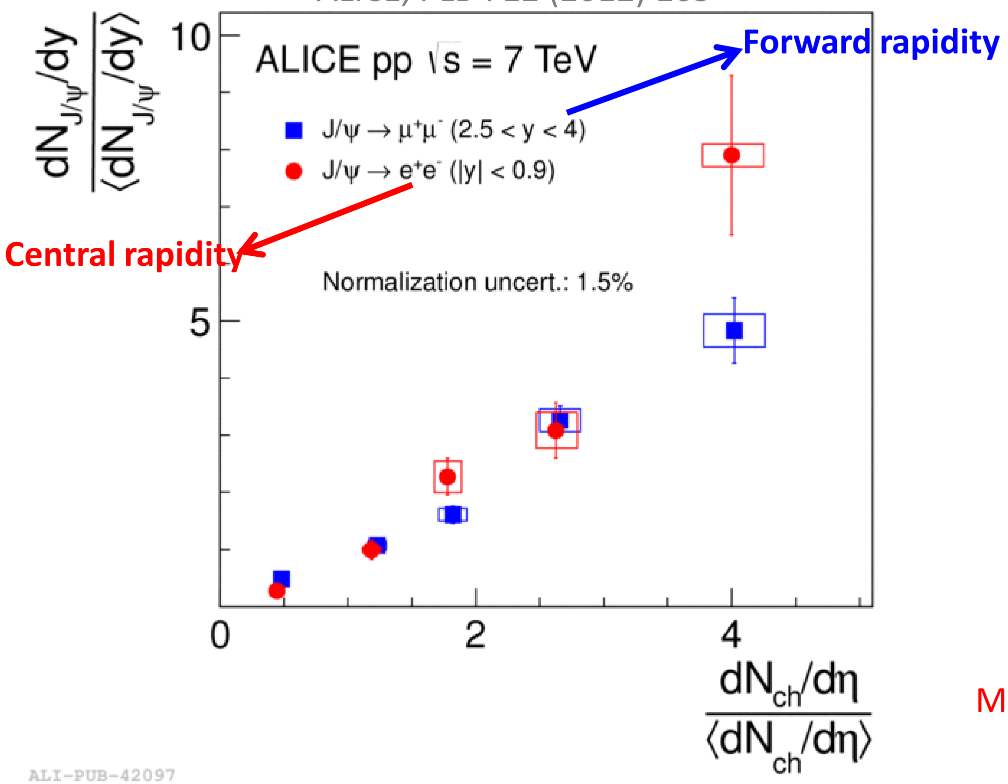
measured at mid-rapidity

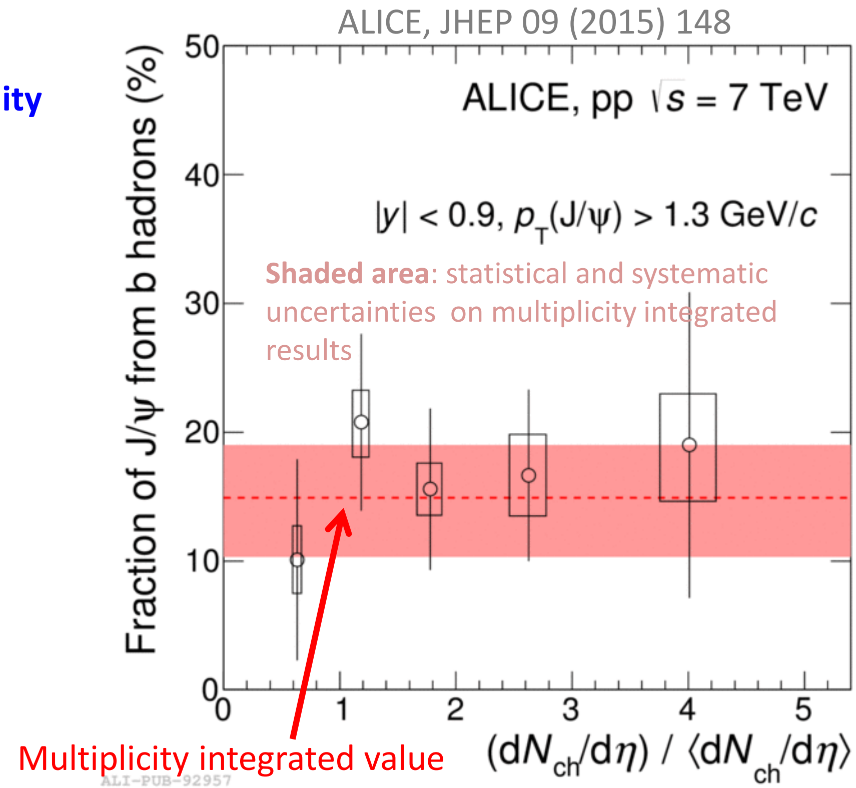
measured at forward rapidity

Same increase of D-meson yields when η gap is introduced between the regions where charmed mesons and charged-particle multiplicity are measured

The case of J/ψ

- Production of B-hadron via non-prompt J/ψ will help gain more insight in mechanisms influencing particle production



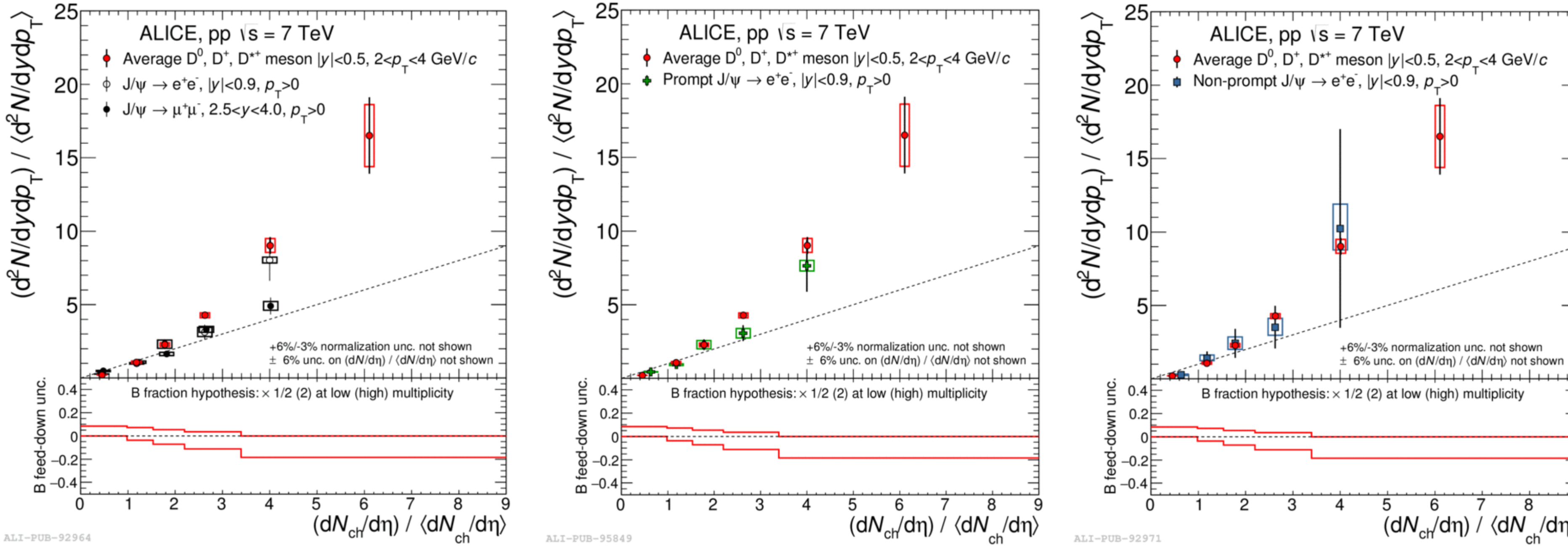


- Per-event J/ψ yields increase approximately linearly with the charged-particle multiplicity
- Similar increase of J/ψ yield with charged-particle multiplicity at mid- and forward rapidity
- Fraction of non-prompt J/ψ in the inclusive yields is almost flat as a function of charged-particle multiplicity → no dependence with multiplicity within uncertainties

Comparison of D mesons with beauty hadrons (via J/ψ)

ALICE, JHEP (2015) 148

ALICE, PLB 712 (2012) 165

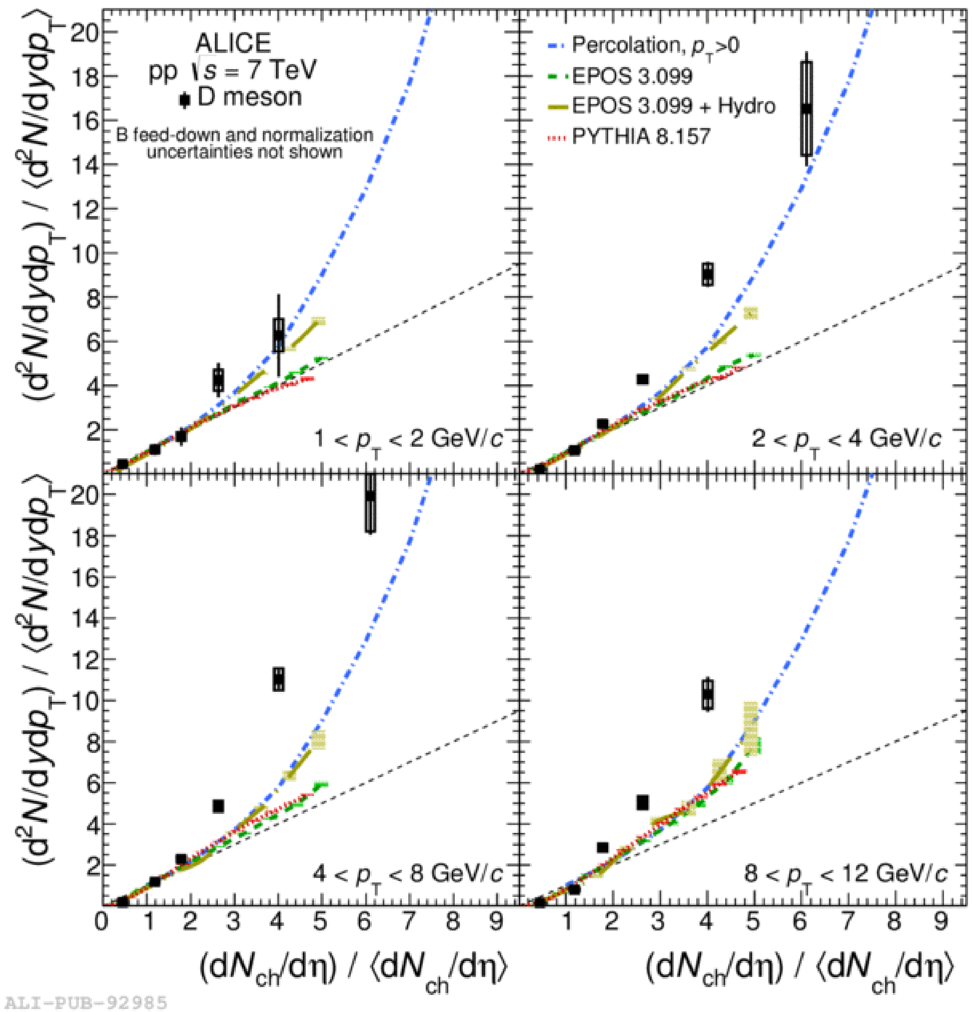


- Similar increase of open charm, open beauty and inclusive J/ψ yields with charged-particle multiplicity at mid rapidity
  - → Likely related to heavy-flavour production processes and not significantly influenced by hadronisation mechanisms

<u>**Caveats:**</u> different rapidity and p_T intervals for the measurements

Comparison of D-meson results with theoretical models

ALICE, JHEP 09 (2015) 148



Percolation Ferreiro and Pajares, Phys. Rec. C 86 (2012) 034903

- Interaction driven by color sources (string ~ MPI scenario) formed in parton-parton collisions

EPOS 3 (event generator) Dreshner *et al*. Phys Rept. 350, 93 (2001)

- Initial conditions
- Hydrodynamic evolution Werner *et al.*, Phy. Rev. C 89, no. 6, 064903 (2014)

Pythia 8.157 T Sjöstrand, S Mrenna and P.Z Skands, Comp. Phys. Comm. 178, 852 (2008)

- Soft QCD process selection
- Include colour reconnection
- and MPI
- Initial- and final-state radiation

Models including MPI qualitatively describe the increase of the HF yield as a function of charged-particle multiplicity

Results from p-Pb collisions at $\sqrt{s_{NN}}$ = 5.02 TeV

Data sample: ~ 10^8 minimum-bias (MB) events collected in 2013

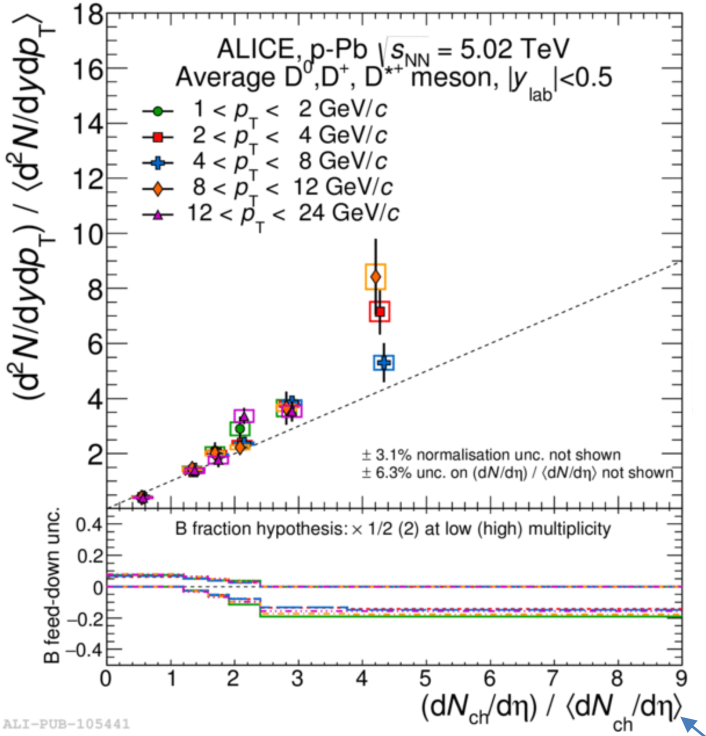
→ **MB trigger:** signal in V0A and V0C, L_{int} ~ 48.6±1.6 nb^{-1}

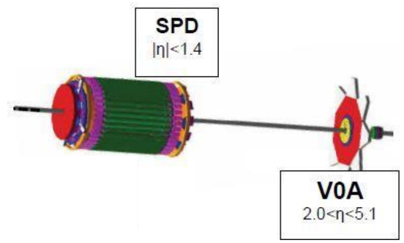
→ **Dimuon unlike-sign trigger**: Opposite sign muons, p_T > 0.5 GeV/c, L_{int} = 5.0 (5.8) nb^{-1} in p-Pb (Pb-p)

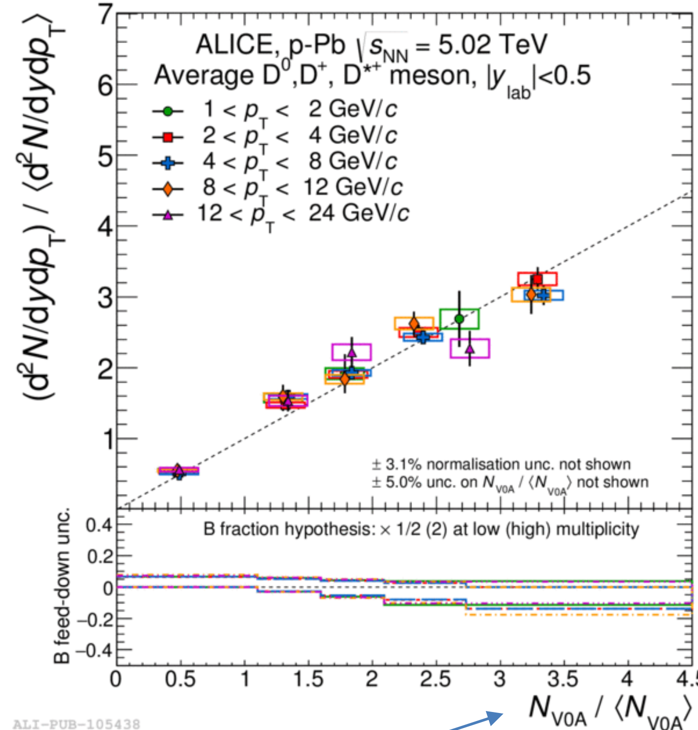
Caveat: In p-Pb collisions the charged-particle multiplicity dependence is also affected by the presence of multiple binary nucleon-nucleon interactions and the initial conditions modified by CNM effects

D mesons vs charged-particle multiplicity

ALICE, JHEP 08 (2016) 078





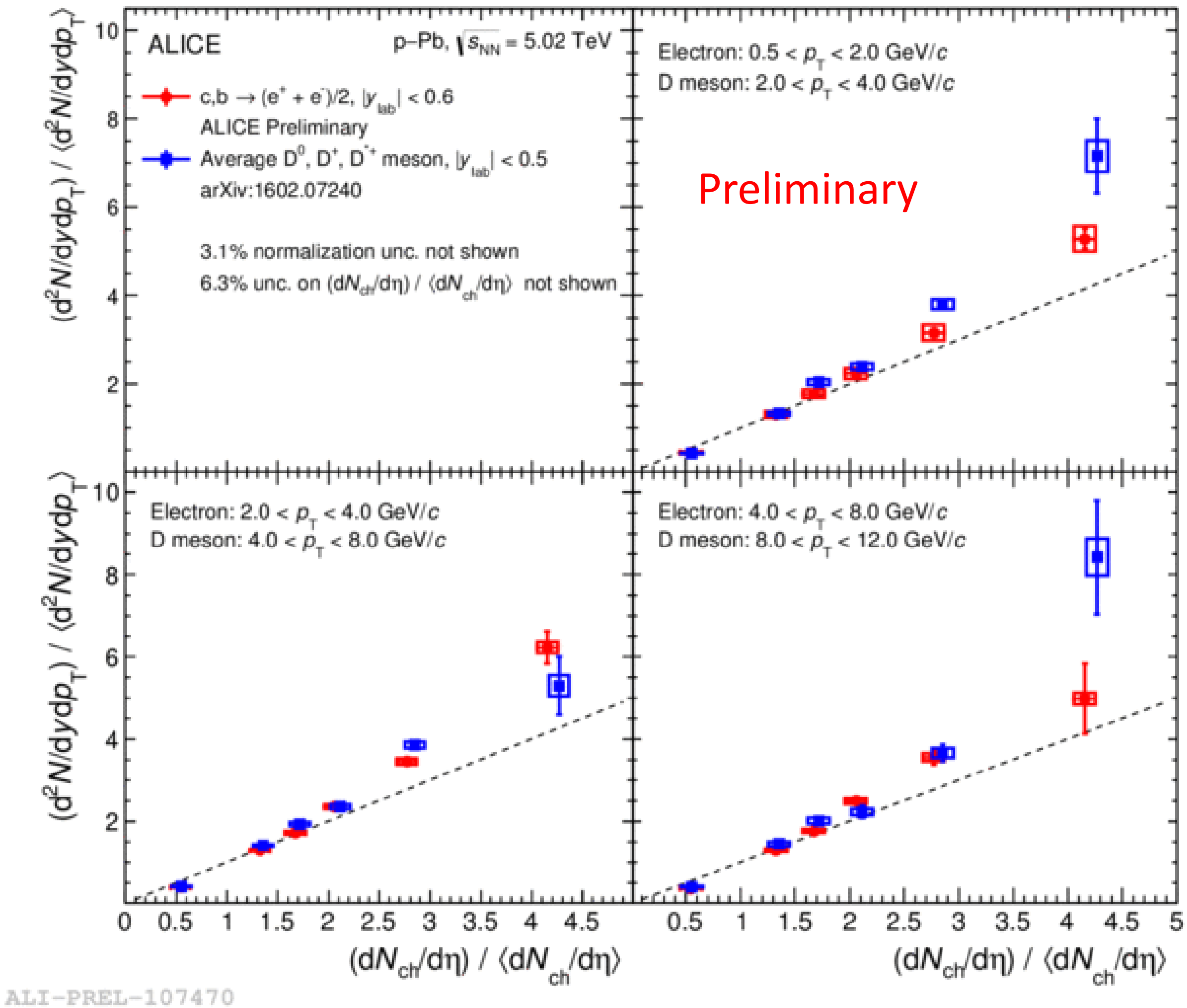


measured at mid-rapidity

measured at backward rapidity (Pb-going)

- D-meson yields increase with charged-particle multiplicity
- For the charged-particle multiplicity measured at mid rapidity the increase is more than linear at higher multiplicity while a nearly linear increase with multiplicity at backward rapidity (Pb-going direction) is observed
- The yields are consistent in the measured p_T interval within uncertainties

D mesons and HF decay electrons vs charged-particle multiplicity

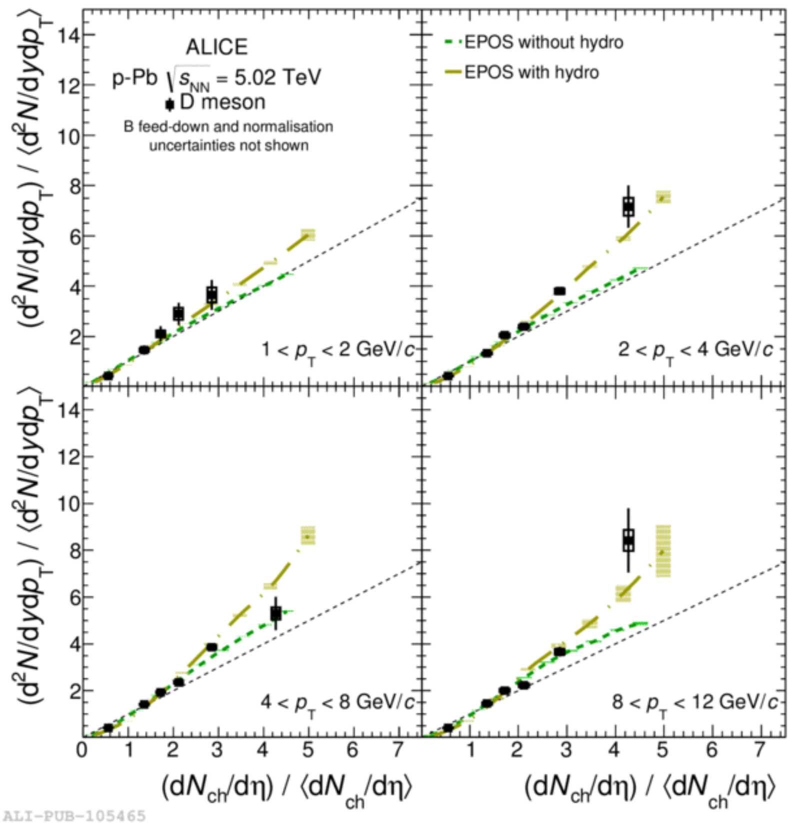


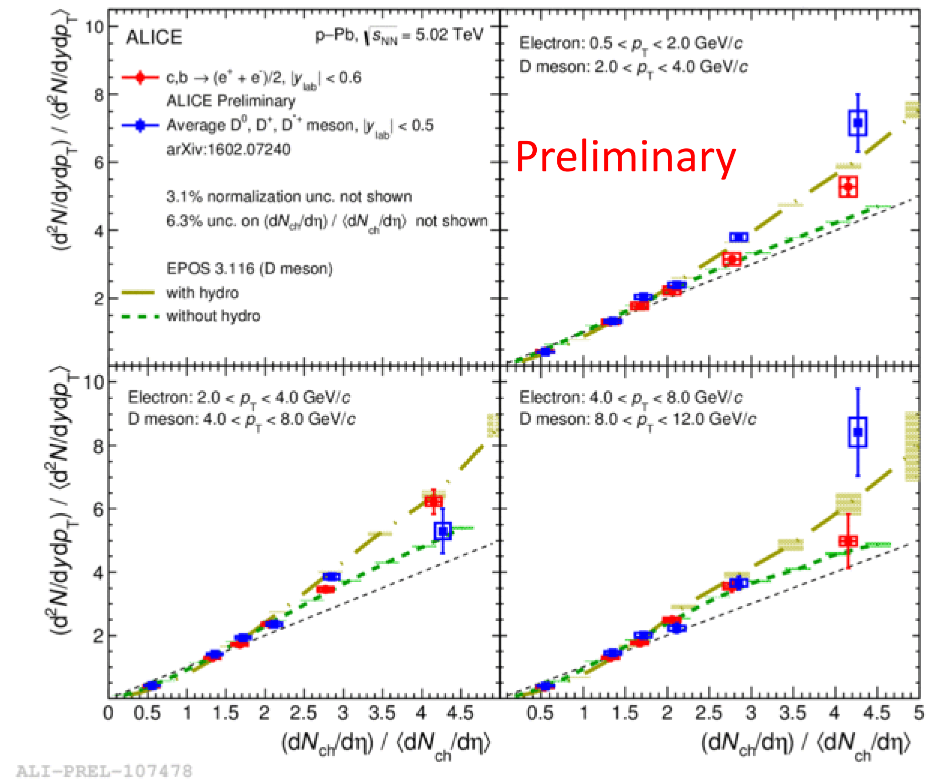
D-meson and HF decay electrons yields show a similar increase with the charged-particle multiplicity

Comparison of D-meson results with theoretical models

EPOS 3 calculations are with and without initial conditions and hydrodynamic evolution estimates. EPOS calculations for HF decay electrons not yet available!!

ALICE, JHEP 8 (2016) 1-44, arXiv:1602.07240



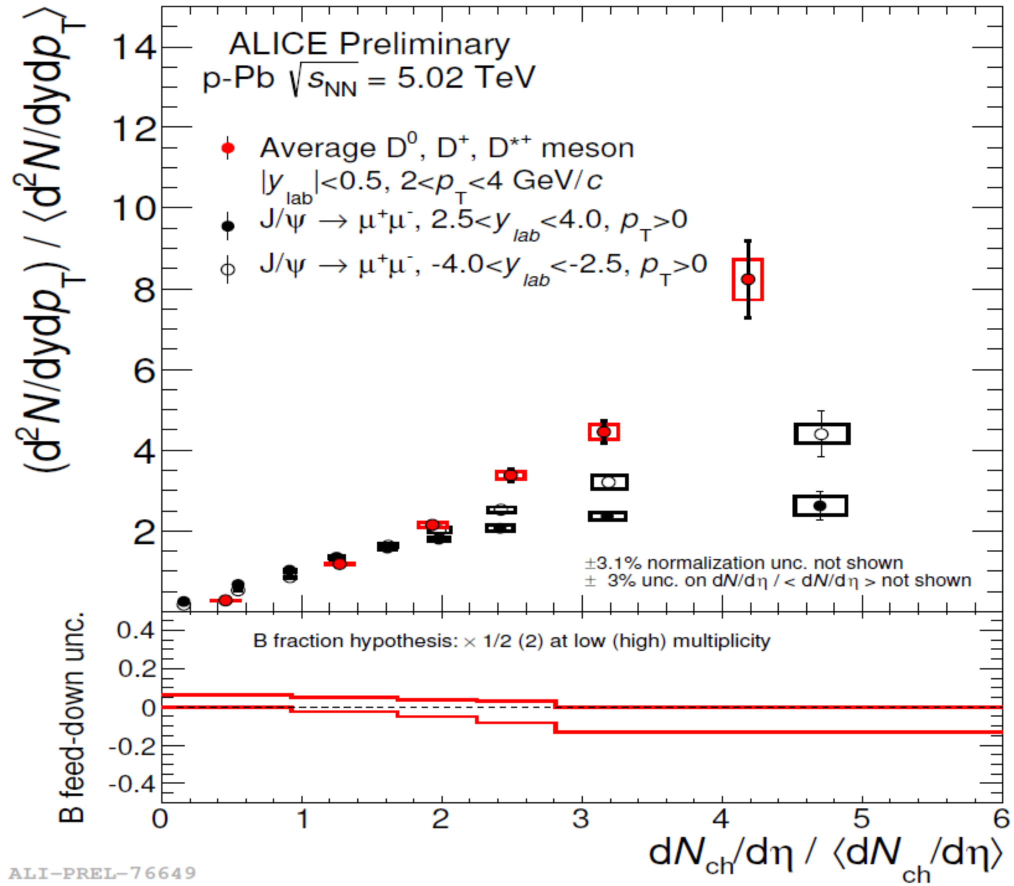


- A faster than linear increase for both the D-meson and heavy-flavour decay electron yields with charged-particle multiplicity at mid rapidity.
- Comparison with EPOS 3 with initial conditions: better agreement when hydrodynamic evolution is included Werner *et al.*, PRC 89, no. 6, 064903 (2014)

D mesons and inclusive J/ψ vs charged-particle multiplicity

- D-meson yields and charged-particle multiplicity measured at mid-rapidity
- J/ψ yields measured at forward (p-going) and backward (Pb-going) rapidity

ALICE, JHEP 09 (2015) 148

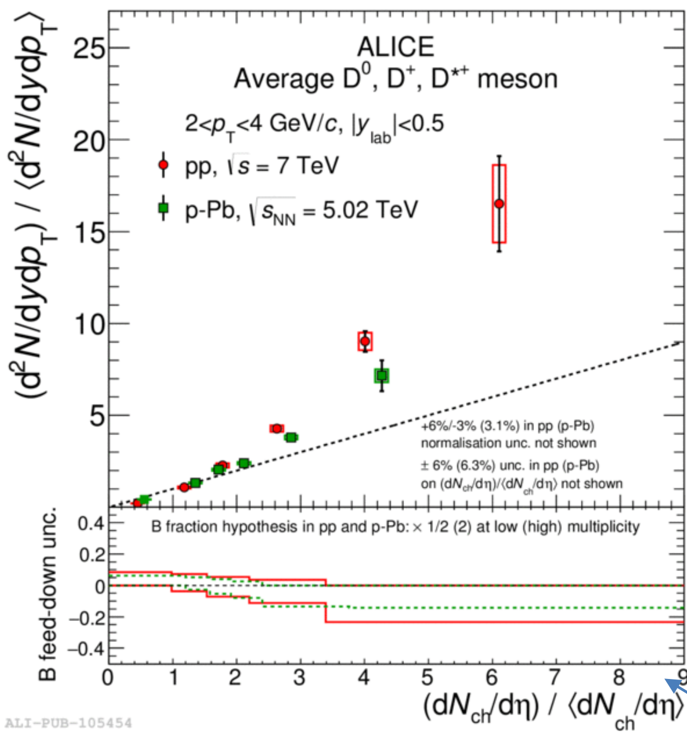


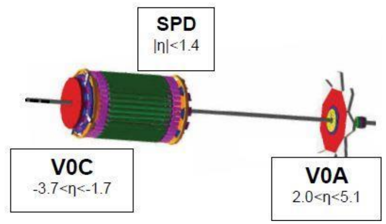
- D-meson yields increase faster than J/ψ yields, in particular to that measured at forward rapidity (p-going direction) → **More effects at play for J/ψ than for D mesons**

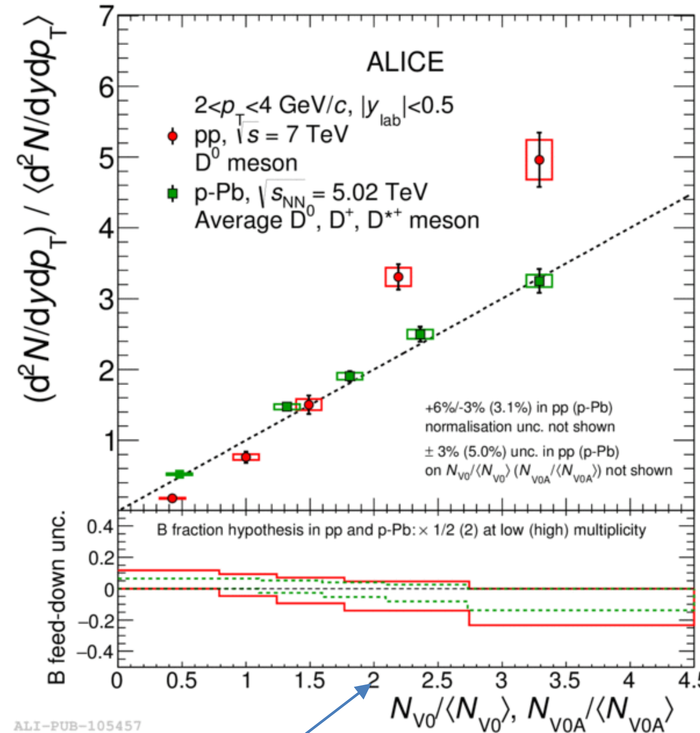
ALICE, PRL 113 (2014) 232301 ALICE, JHEP 02 (2014) 073

D mesons vs charged-particle multiplicity in pp and p-Pb collisions

ALICE, JHEP 09 (2015) 148







measured at mid-rapidity

measured at backward rapidity (Pb-going)

- Similar increase for D-meson yields with charged-particle multiplicity in pp and p-Pb collisions at mid rapidity
- For multiplicity at backward rapidity:
  - ✓ measurements in pp and p-Pb collisions are done at different η range.
  - ✓ D-meson yields in pp collisions increase faster than in p-Pb collisions
  - → **Possible effects due to MPI in high-multiplicity pp collisions while in p-Pb collisions multiple (and softer) nucleon-nucleon collisions also contribute**

Conclusions

The ALICE collaboration measured HF hadron yields as a function of charged-particle multiplicity in pp collisions at $\sqrt{s}$ = 7 TeV and in p-Pb collisions at $\sqrt{s_{NN}}$ = 5.02 TeV

➢ **In pp collisions:**
- ✓ The yields show an increase with charged-particle multiplicity
- ✓ The increase is faster-than-linear at high multiplicity
- ✓ Results for D mesons are consistent in the measured p_T within uncertainties
- ✓ A similar trend is observed for open and hidden HF → related to charm and beauty production mechanisms (small influence of hadronisation)
- ✓ Models including MPI qualitatively describe the increase of the HF yield as a function of charged-particle multiplicity

➢ **In p-Pb collisions:**
- ✓ HF yields increase with charged-particle multiplicity at mid rapidity
- ✓ D-meson yields increase faster with multiplicity as opposed to that of J/ψ
- ✓ D-mesons and HF decay electrons yields show a similar increase with multiplicity
- ✓ EPOS 3 calculations describe the D-meson trend. Looking forward to results from model calculations for beauty-hadrons and charmonium production

➢ **D-meson yields in pp collisions increase faster than in p-Pb collisions**

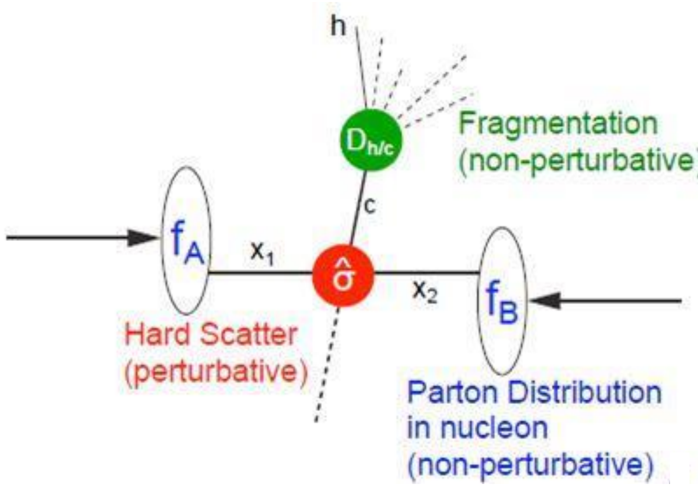
→ Stay tuned for results at high $\sqrt{s}$, higher multiplicity ....

Thanks for your attention!

Back-up slides

Heavy-flavour production cross section in pp collisions

- Heavy-flavour cross sections can be calculated with pQCD based on the factorization approach

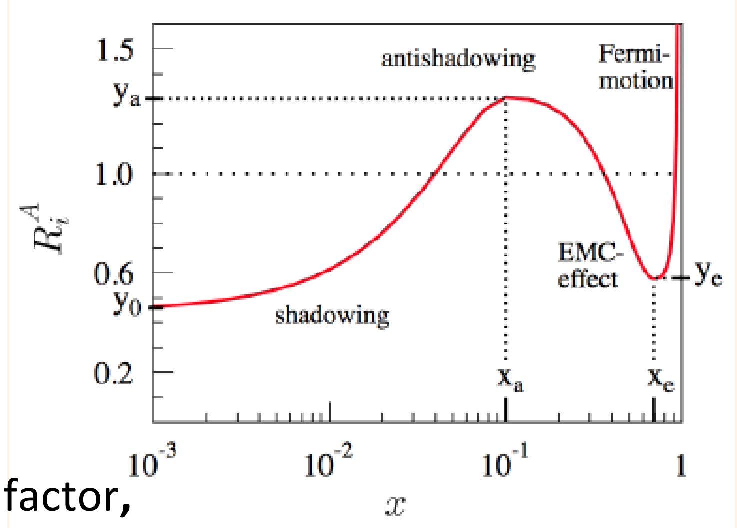


$$\sigma_{hh \to Hx} = PDF(x_a, Q^2) PDF(x_b, Q^2) \otimes \hat{\sigma}_{ab \to q\bar{q}} \otimes D_{q \to H}(z_q, Q^2)$$

Mangano *et al.*, NPB 373 (1992) 295 Cacciari *et al.*, JHEP 05 (1998) 007 Kniehl *et al.*, PRD 71 (2005) 014018
Jung *et al.*, JHEP 1101 (2011) 085

HF production vs charged-particle multiplicity in p-Pb collisions

- Heavy-flavour yields are expected to scale with the number of binary nucleon-nucleon collisions
- CNM effects in p-Pb collisions:
  - ✓ modification of parton distributions in nuclei (shadowing - nuclear PDFs), gluon saturation
  - ✓ Initial-state k_T broadening (due to multiple parton collisions before hard scattering)
  - ✓ Initial / final state or coherent energy loss
- CNM effects are quantified by the nuclear modification factor,



Eskola *et al.*, JHEP 0904, 065 (2009)

$$R_{pPb} = \frac{1}{\langle N_{coll}\rangle_{pPb}} \frac{dN_{pPb}/dp_T}{dN_{pp}/dp_T}$$

In addition

→ Collective-like effects observed for light quarks. Same mechanism (hydro, CGC) for light and heavy flavours?

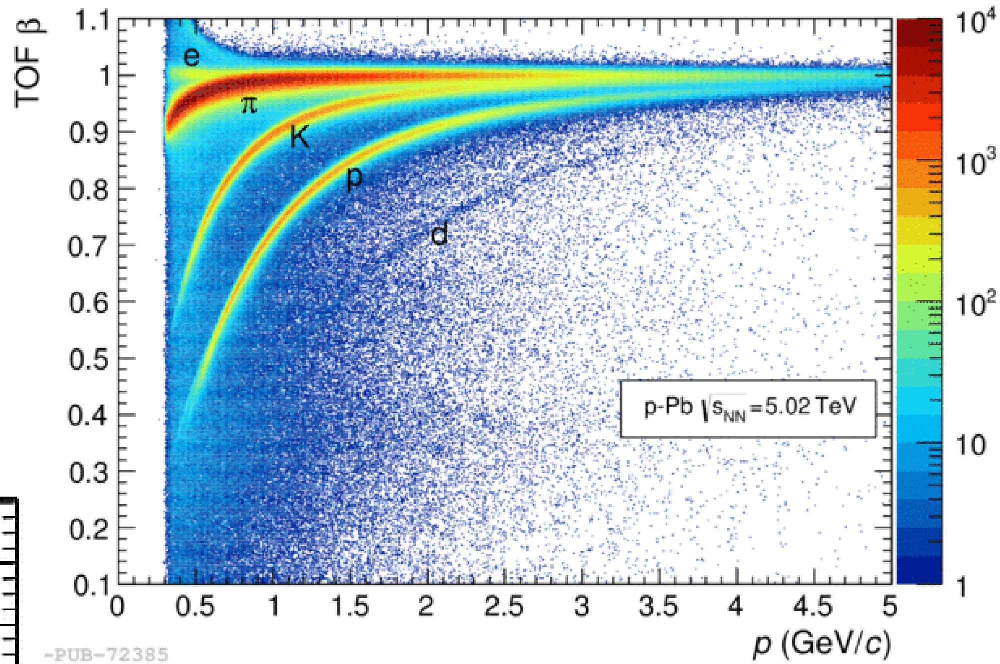
→ In p-Pb, do CNM effect dependence on collisional geometry and/or multiplicity density influence heavy-flavour production?

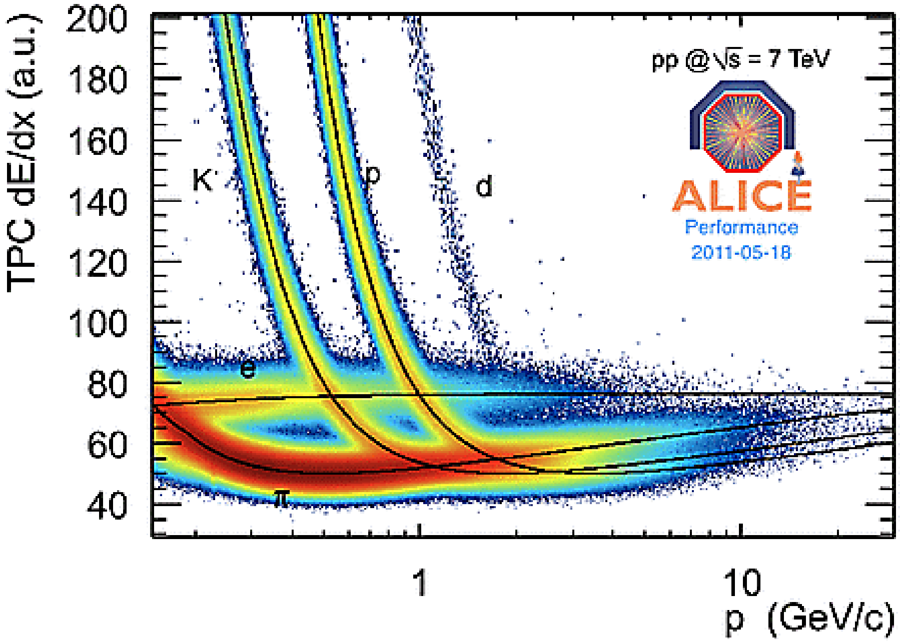
More differential HF observable: HF production yields vs charged-particle multiplicity in p-Pb collisions

PID in the central barrel

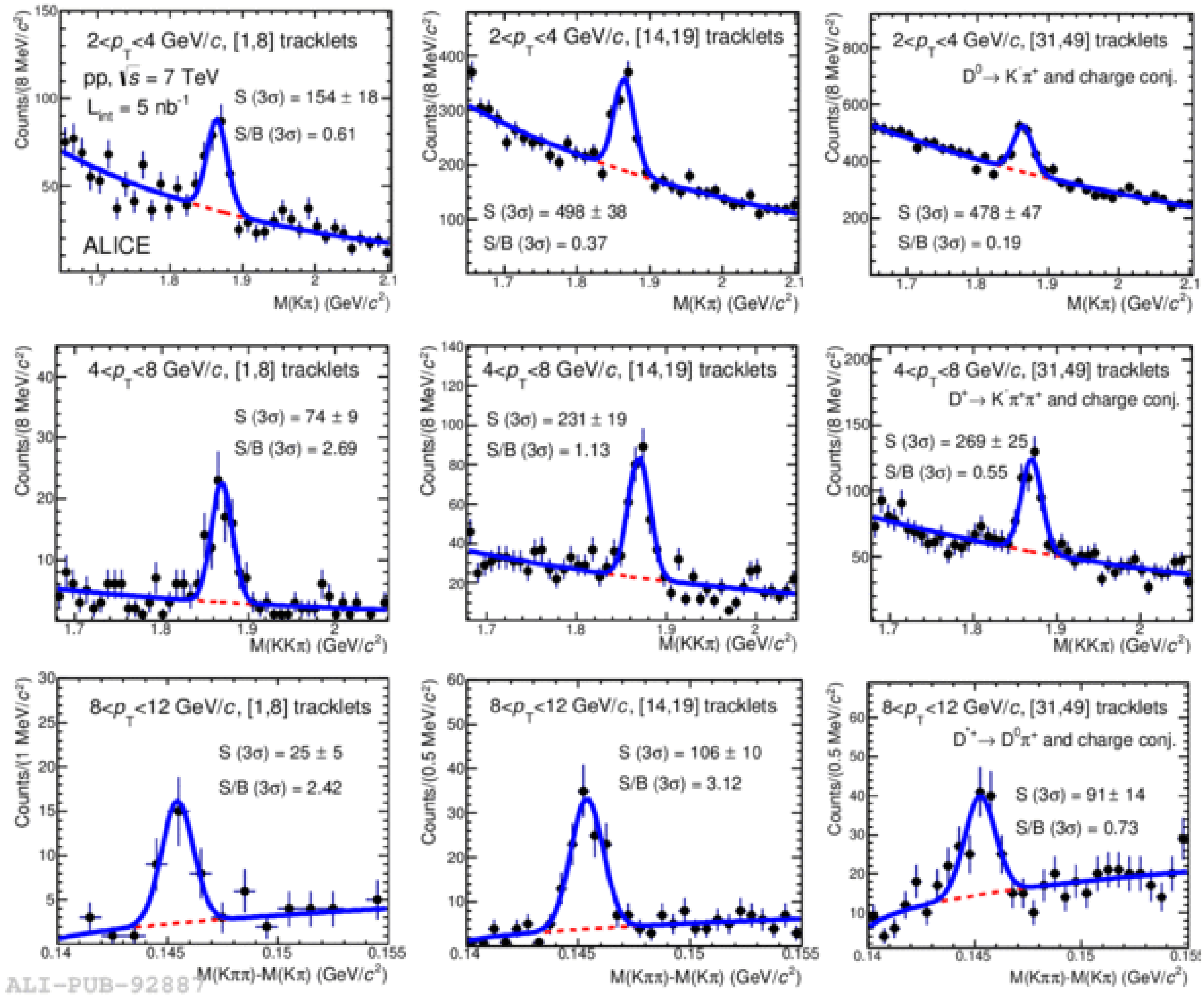
- **$|\eta| < 0.5$: Hadronic channels**
  $D^0 \rightarrow K^-\pi^+$
  $D^+ \rightarrow K^-\pi^+\pi^-$
  $D^{*+} \rightarrow D^0\pi^{+,}$ where $D^0 \rightarrow$ K-π

- **$|\eta| < 0.9$:_(b→) $J/\psi \rightarrow e^+e^-$**



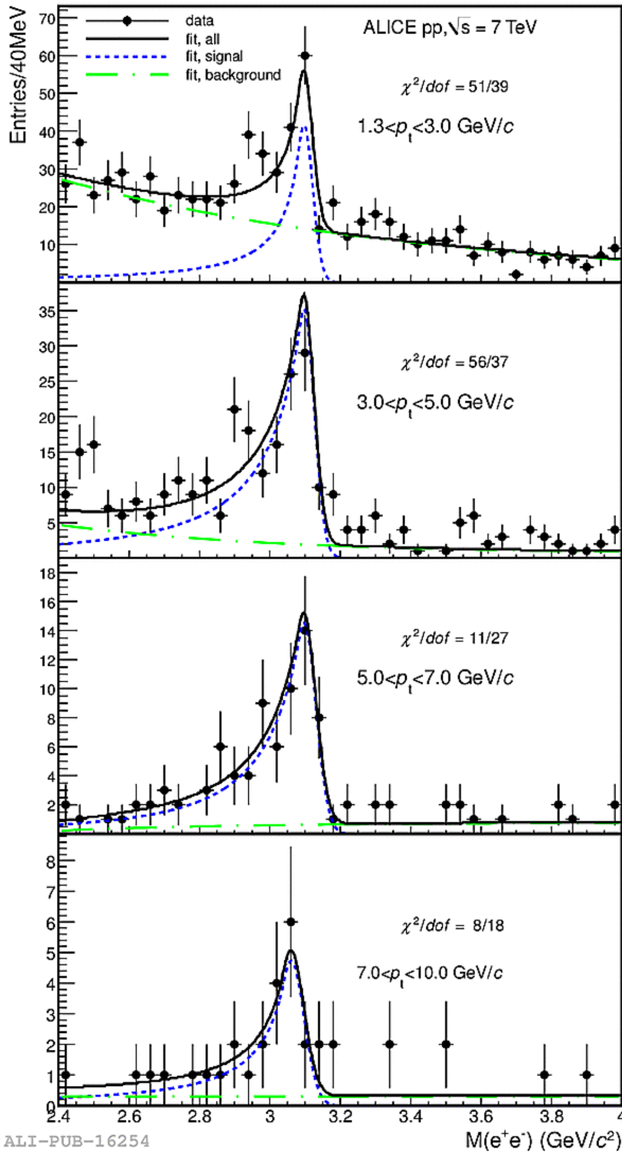


D meson invariant-mass spectra

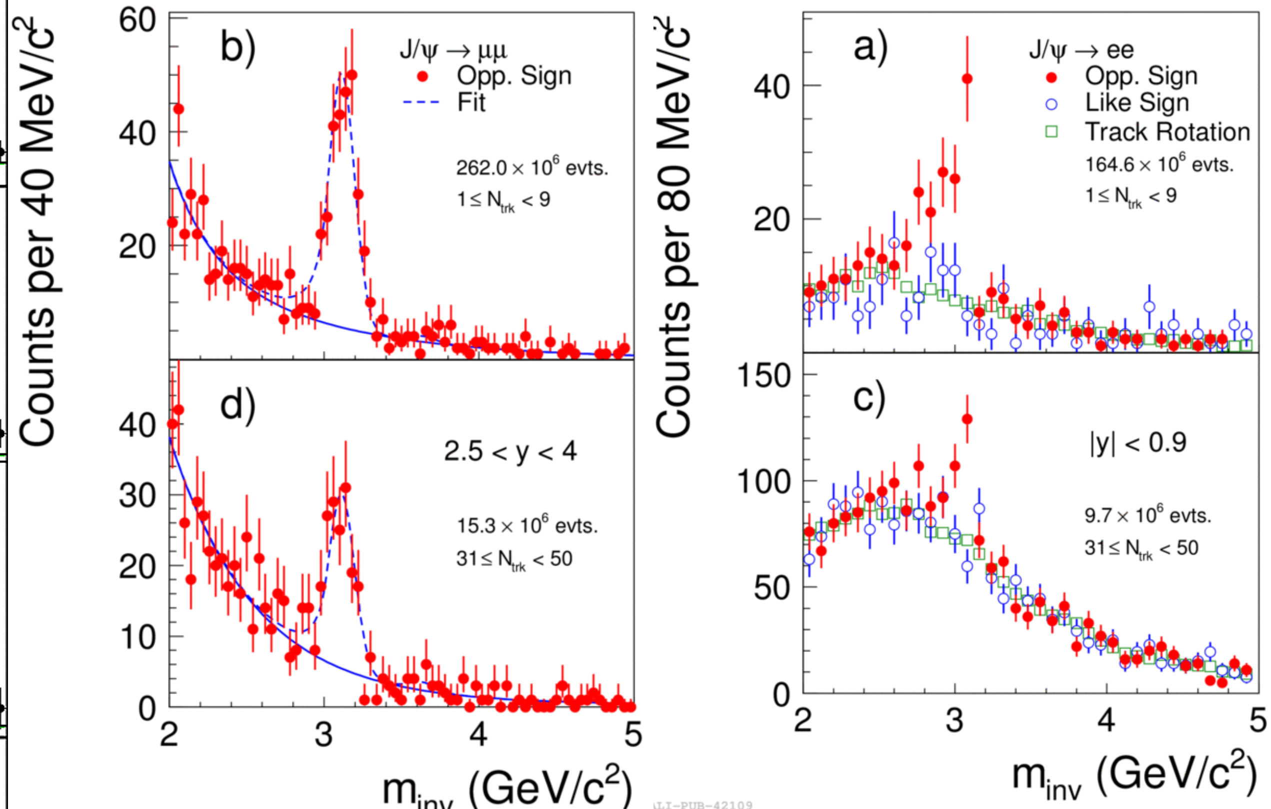


HFE and quarkonia invariant masses

|η| < 0.9, c, b → e + X



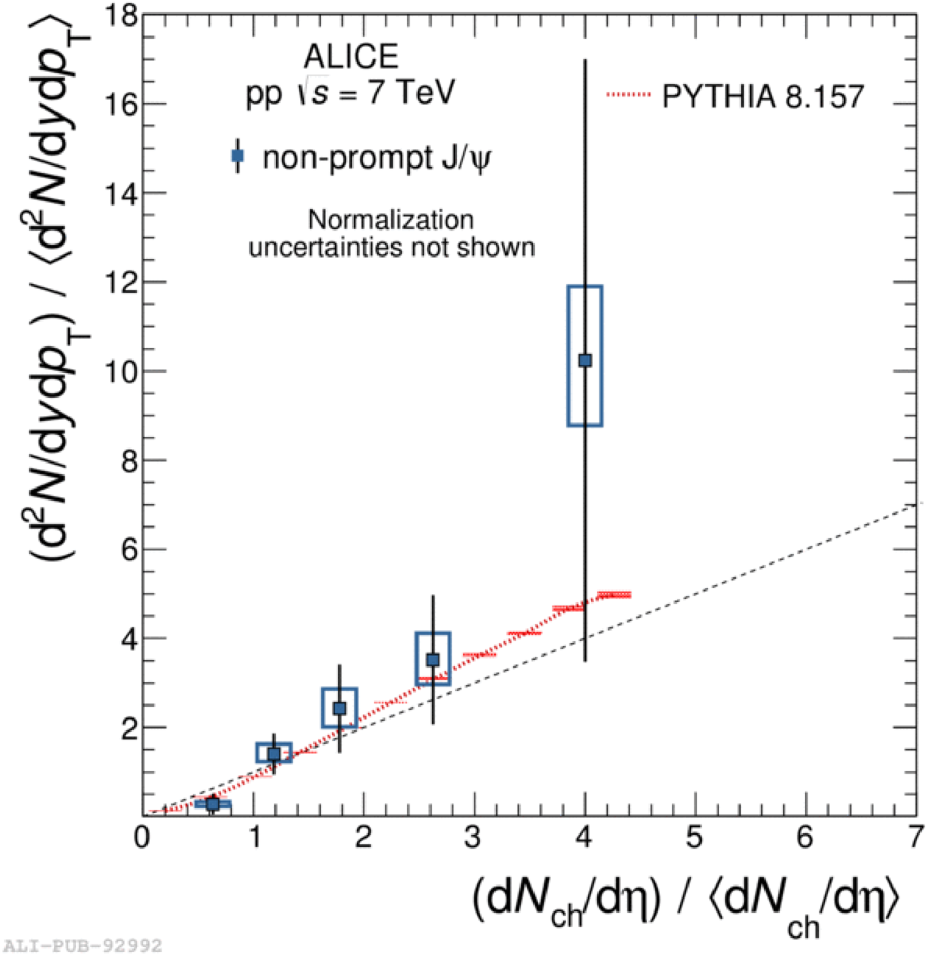
-4.0 <η< -2.5: J/ψ → μ⁺μ⁻



|η |< 0.9: J/ψ → μ⁺μ⁻

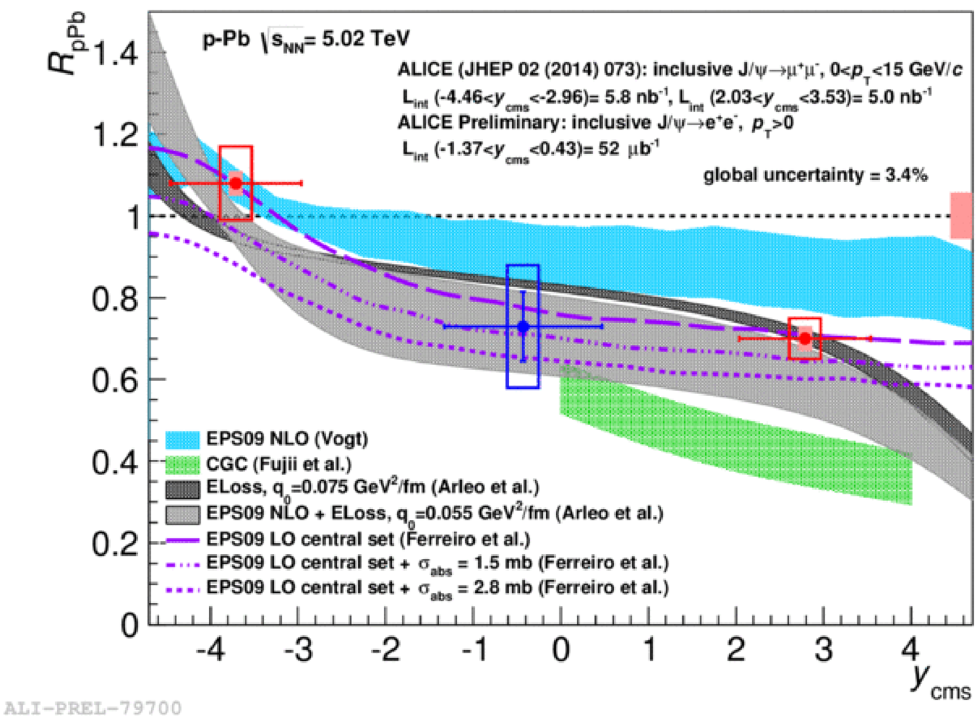
B-hadrons from non-prompt J/ψ decays vs PYTHIA 8 in pp collisions

Results from PYTHIA show a trend which is almost linear for B-hadron yields as a function of the charged-particle multiplicity

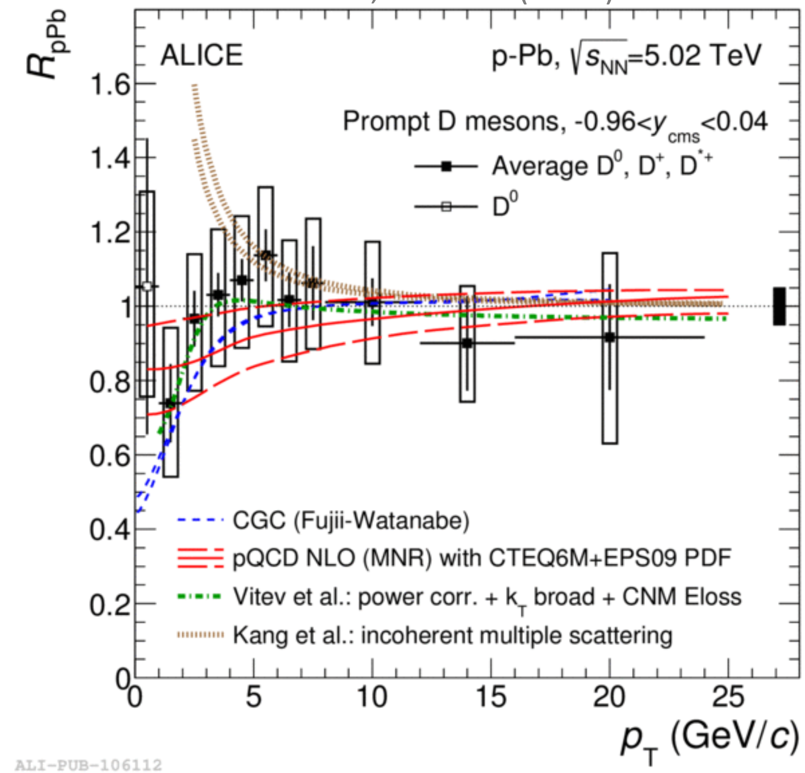


J/ψ and D meson nuclear modification factors in p-Pb collisions

ALICE, JHEP 02 (2014) 073



ALICE, PRL 113 (2014) 232301



- The R_{pPb} of prompt D-meson is close to unity at high p_T
- A suppression (R_{pPb} < 1) is observed for J/ψ at forward rapidity (p-going direction, low-x in Pb nucleus) and low p_T.
- Data is relatively well described by models including cold nuclear matter effects.