Measurements of heavy-flavour production as a function of charged-particle multiplicity in pp and p–Pb collisions with ALICE at the LHC

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Heavy Flavour Meet 2019, IIT Indore

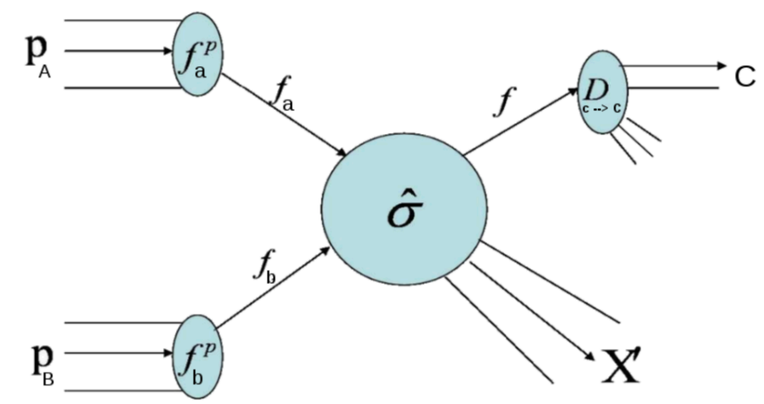
Heavy quarks (**charm and beauty** quarks), due to their large masses ($m_c \sim 1.3$ GeV/c^2, $m_b \sim 4.2$ GeV/c^2)

➔ Produced via initial hard scatterings at the early stages of the collision.

➔ Production cross-section calculable perturbatively down to low p_T.

$$d\sigma^{hard}_{AB\to C} = \sum_{a,b} f_{a/A}(x_a, Q^2) \otimes f_{b/B}(x_b, Q^2) \otimes d\sigma^{hard}_{ab\to c}(x_a, x_b, q^2) \otimes D_{c\to C}(z, Q^2)$$

Parton Distribution Function (PDF) — **Partonic hard scattering cross-section** — **Fragmentation function**



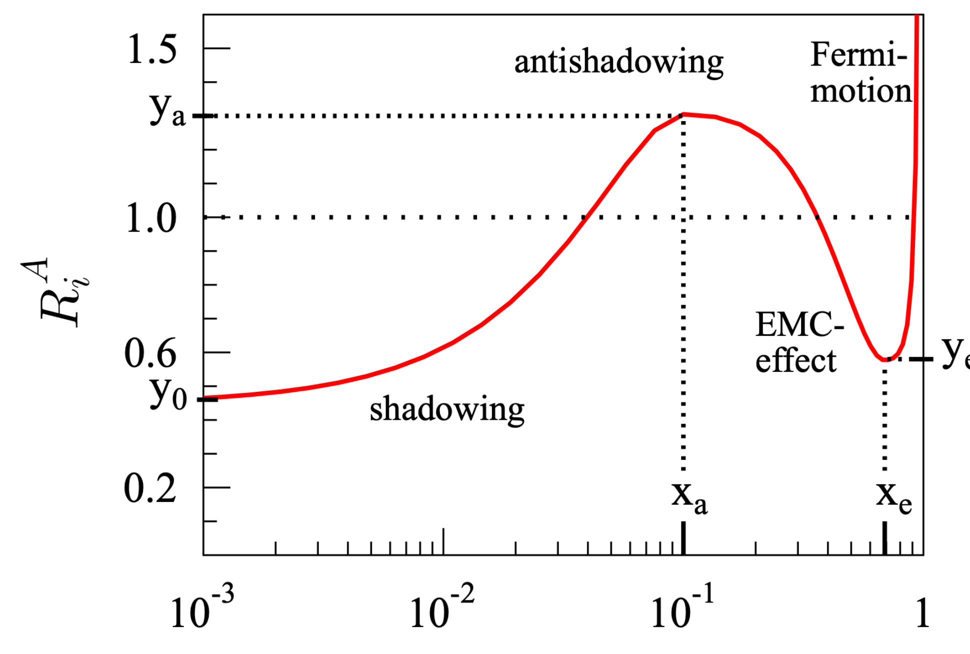
In pp collisions:

- Important test of perturbative QCD calculations
- Reference for nuclear modification in pA, AA collisions.

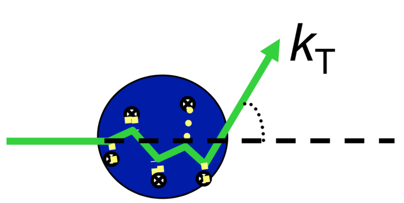
In p-Pb collisions:

Studies provide access to **cold nuclear matter(CNM)** effects.
Heavy-flavour yield can be modified by

- **Nuclear modification of the PDFs**
- ***k*$_T$ broadening**: Multiple elastic scattering of the parton before the hard scattering. Modifies the p_T distribution.
- **Energy loss in cold nuclear matter** (in the initial or final state)



JHEP 0904:065,2009

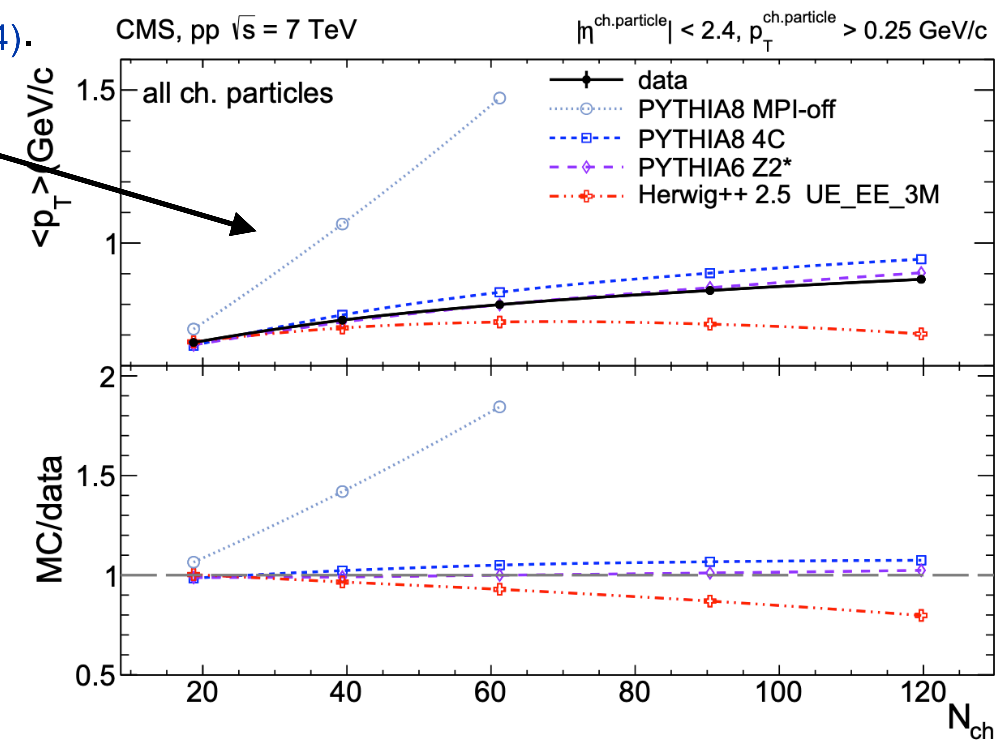


Heavy-flavour production as a function of multiplicity:

- Insights about the **interplay between hard and soft mechanisms** for particle production.
- Study the role of **multiple parton interactions(MPI)** in the heavy-flavour sector.

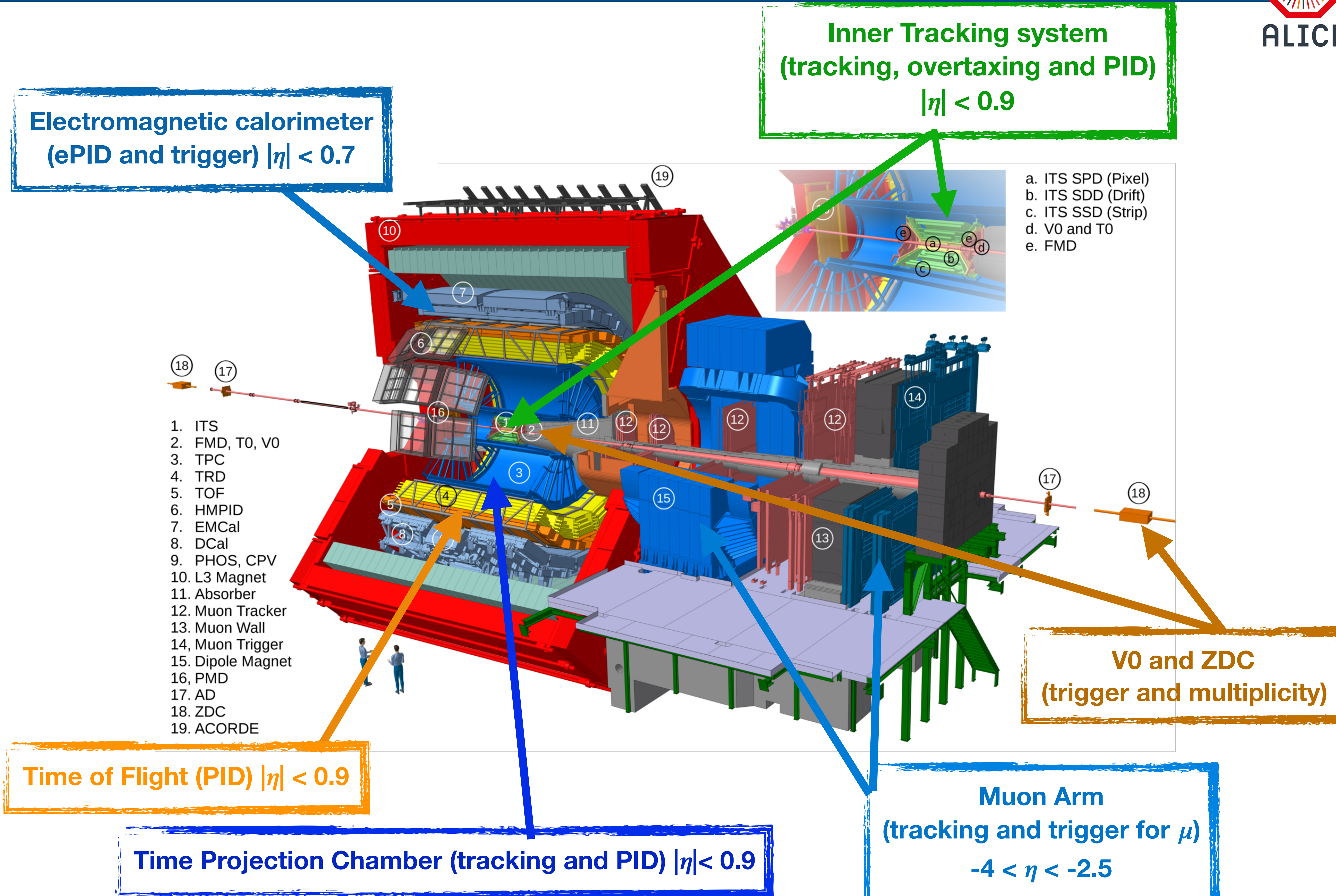
MPI related measurement at the LHC :

- **CMS** : Studies on jets and underlying event (Eur. Phys. J. C73(2013) 2674).
  PYTHIA cannot reproduce the trend in data without MPI.
  MPIs have a substantial contribution at large multiplicity.
- **LHCb** : Double charm production(J. High Energy Phys., 06 (2012) 141).
  agrees better with models including double parton scattering.
- **ALICE** : Analysis of minijet production (JHEP 09 (2013) 049)
  MPI increases at higher multiplicities



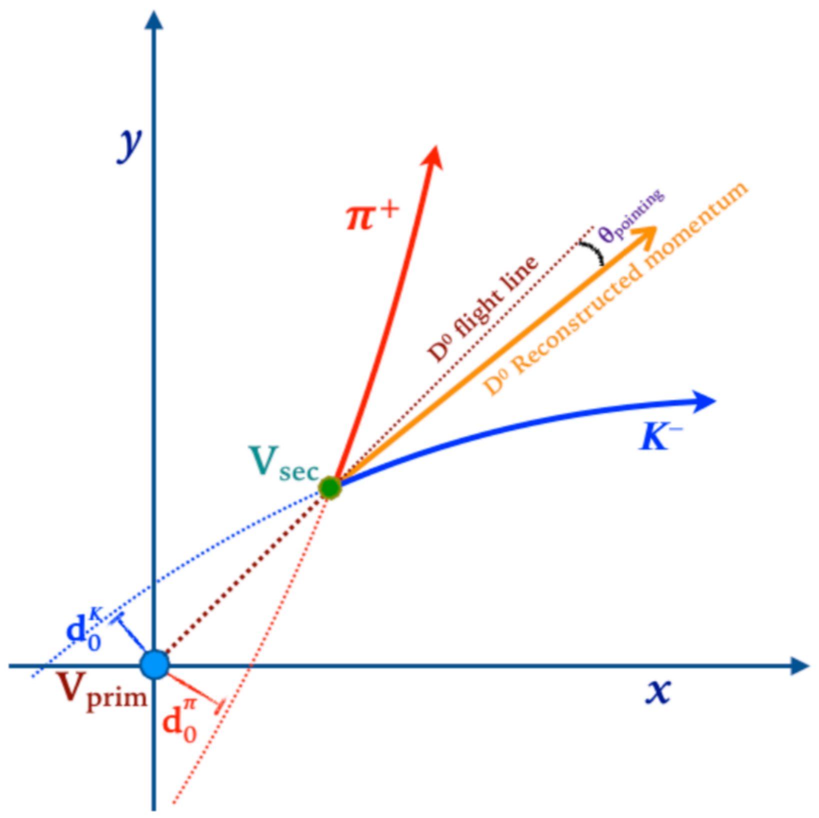
Average charged-particle p_T as a function of Multiplicity

- Also allows us to study of possible centrality-dependent modification of p_T spectra in p-Pb collisions.


Inner Tracking system
(tracking, overtaxing and PID)
$|\eta| < 0.9$
Electromagnetic calorimeter
(ePID and trigger) $|\eta| < 0.7$
a. ITS SPD (Pixel)
b. ITS SDD (Drift)
c. ITS SSD (Strip)
d. V0 and T0
e. FMD
1. ITS
2. FMD, T0, V0
3. TPC
4. TRD
5. TOF
6. HMPID
7. EMCal
8. DCal
9. PHOS, CPV
10. L3 Magnet
11. Absorber
12. Muon Tracker
13. Muon Wall
14, Muon Trigger
15. Dipole Magnet
16, PMD
17. AD
18. ZDC
19. ACORDE
V0 and ZDC
(trigger and multiplicity)
Time of Flight (PID) $|\eta| < 0.9$
Muon Arm
(tracking and trigger for μ)
$-4 < \eta < -2.5$
Time Projection Chamber (tracking and PID) $|\eta|< 0.9$

1) HF hadron via **hadronic decays**

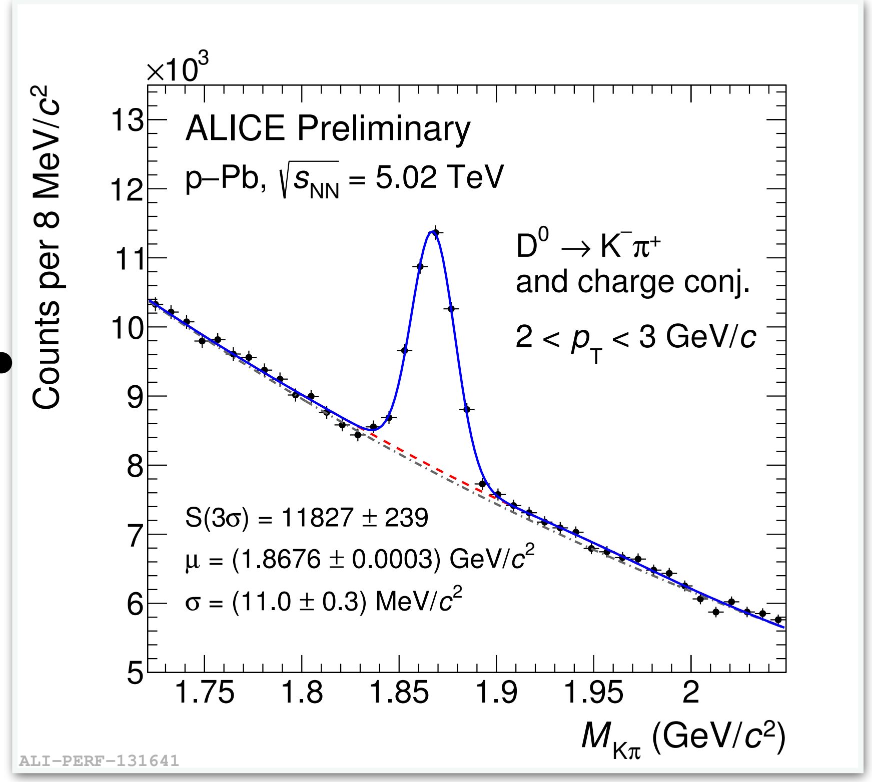
$D^0 \rightarrow \pi^- K^+$	$BR \approx 3.93$ %
$D^+ \rightarrow K^- \pi^+ \pi^+$	$BR \approx 9.46$ %
$D^{*+} \rightarrow D^0(\rightarrow K^- \pi^+)\pi^+$	$BR \approx 2.66$ %
$D_s^+ \rightarrow \Phi(\rightarrow K^- K^+)\pi^+$	$BR \approx 2.27\%$
$\Lambda_c^+ \rightarrow pK^-\pi^+$	$BR \approx 6.35\%$
$\Lambda_c^+ \rightarrow pK_s^0(\rightarrow \pi^+\pi^-)$	$BR \approx 1.58\%$



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

HF hadron reconstruction

- Full reconstruction of the HF hadron via hadronic decay channel.
- Displaced secondary vertex topology due to large decay length of HF hadrons (D $c\tau$ ~ 123 - 312 μm, Λ_c $c\tau$ ~ 60 μm, B and Λ_b $c\tau$ ~ 450 μm).
- PID of the decay products (kaon and pion ID for charm hadrons).
- Invariant mass analysis to obtain the raw yield.



2) lepton channel

c,b → (e + μ) + X, BR ≈ 10%

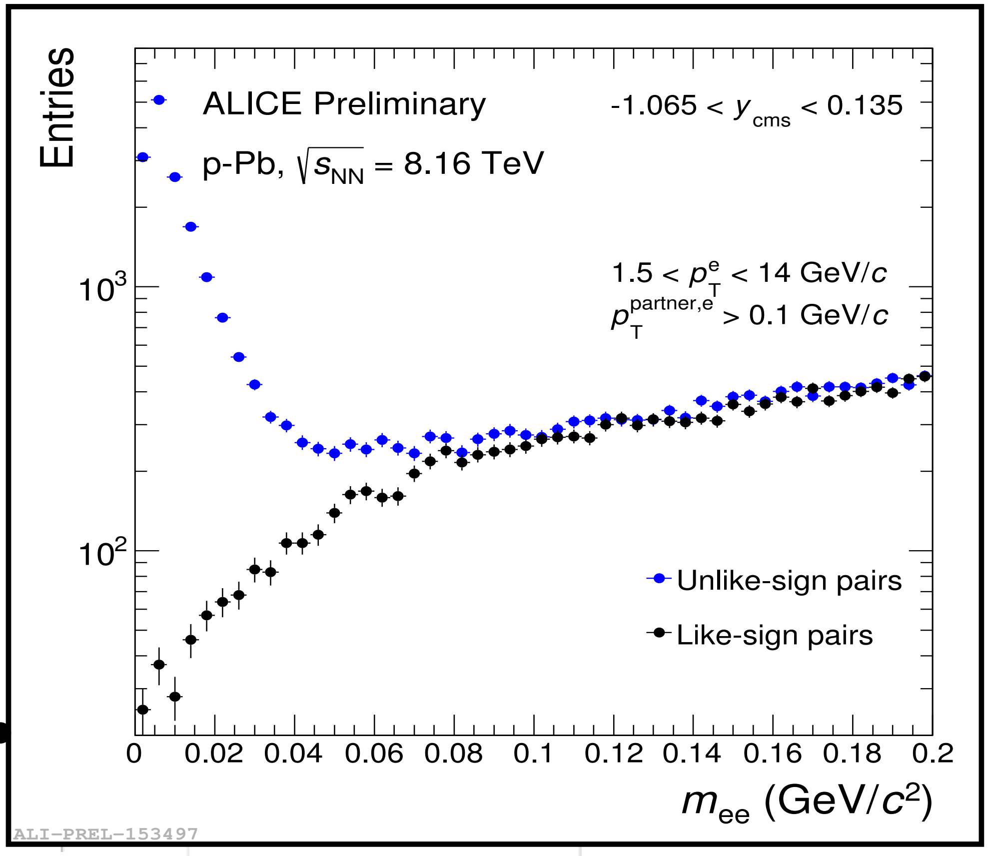
Electron Channel: Heavy-flavour decay electron (HFE)

- Electron identification:

  Low and intermediate p_T : TPC and TOF

  Intermediate and high p_T : TPC and EMCAL

- Background (π^0 and η Dalitz decays, γ conversions) subtracted with e^+e^- invariant mass analysis



Muon Channel: Heavy-flavour decay muon (HFM)

- Muon identification: Muon arm (tracking, trigger and absorbers for muon -4.0 < η <-2.5).
- Background from primary π, K decay subtracted → via simulation tuned on central barrel data: data-driven MC cocktail

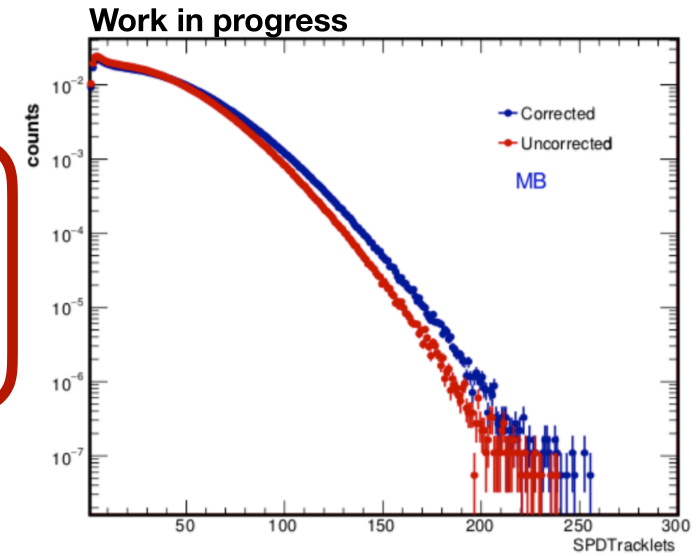
Background from W/Z subtracted → with templates obtained from simulation
Background from J/ψ subtracted

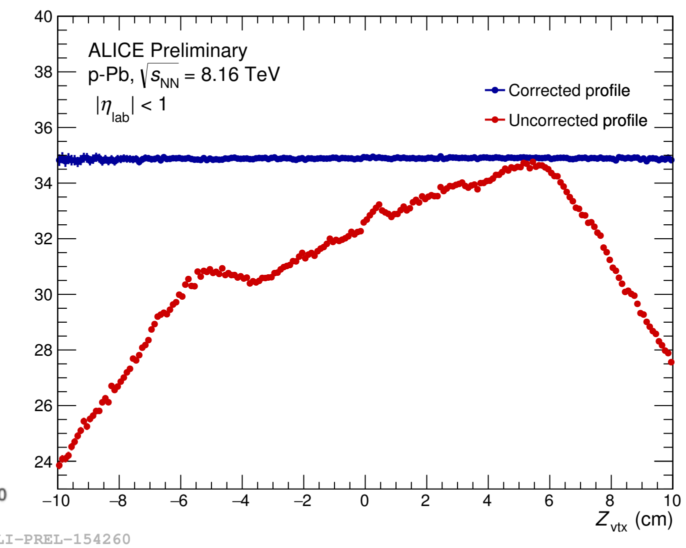
Charged- particle multiplicity estimation:

- At mid-rapidity $|\eta| < 1$, charged particle multiplicity is estimated using SPD tracklets.
  - **SPD tracklets** - reconstructed by connected hit in either of SPD layer with origin at the vertex.
- The variation of the SPD efficiency with the z position of the primary vertex (z_{vertex}) is corrected using a data-driven method.

$$N^{corr}_{trklts} = N_{trklts} - Poisson\left(N_{trklts}\left(\frac{< N_{ref} >}{< N_{trklts} >} - 1\right)\right)$$

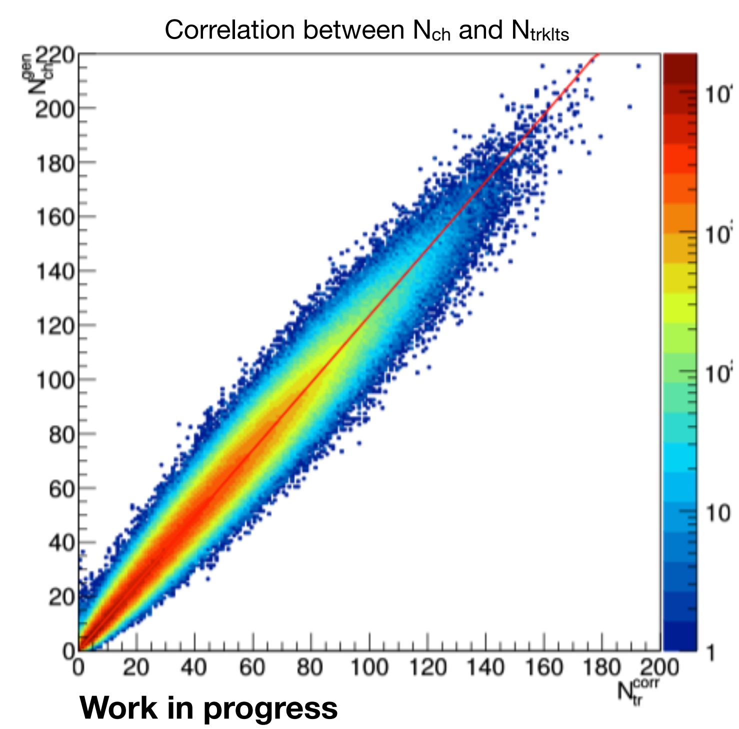
$< N_{ref} >$ corresponds to $z_{vertex} = z_0$ position where $< N_{trklts} >$ is maximum.

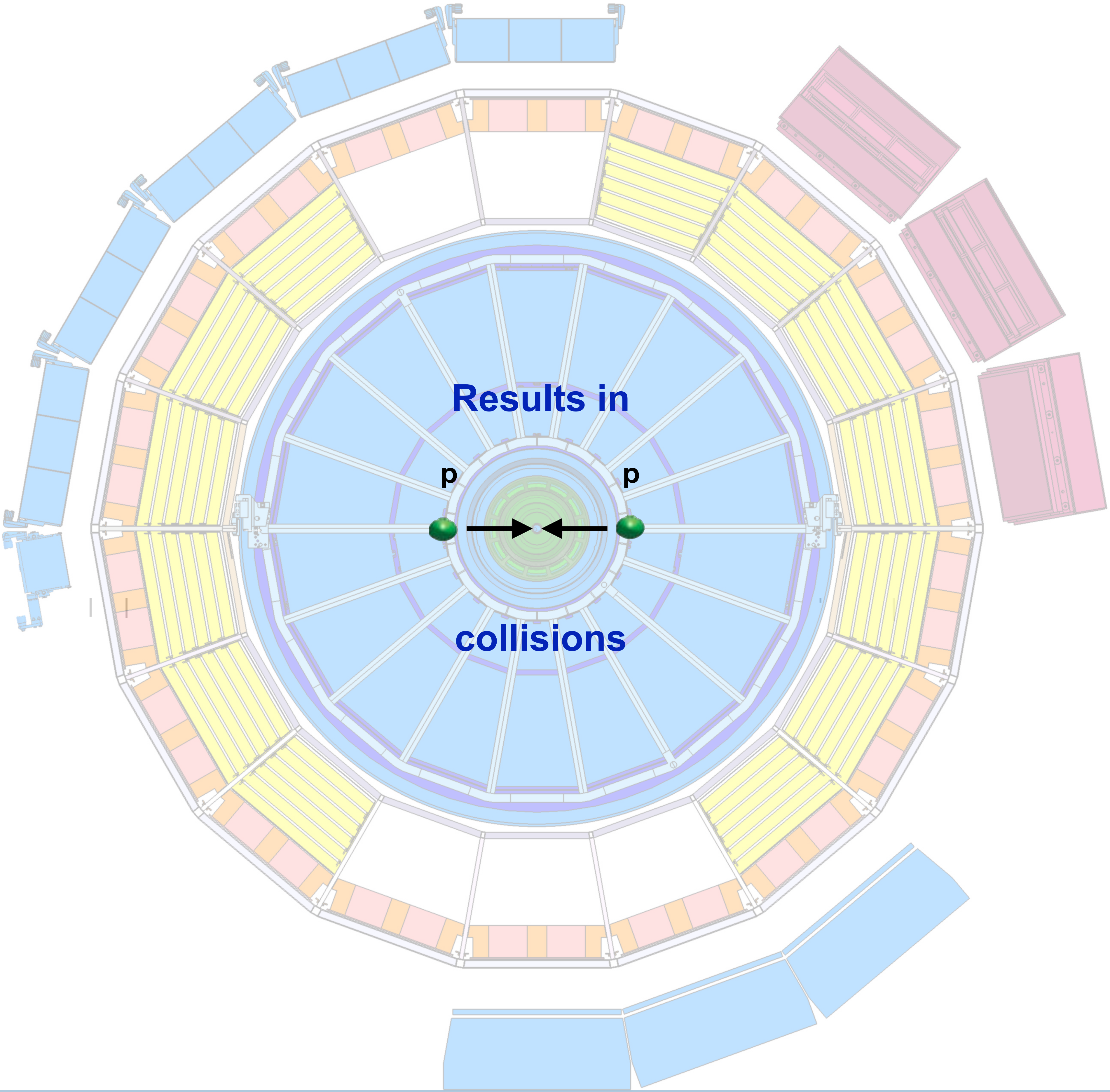




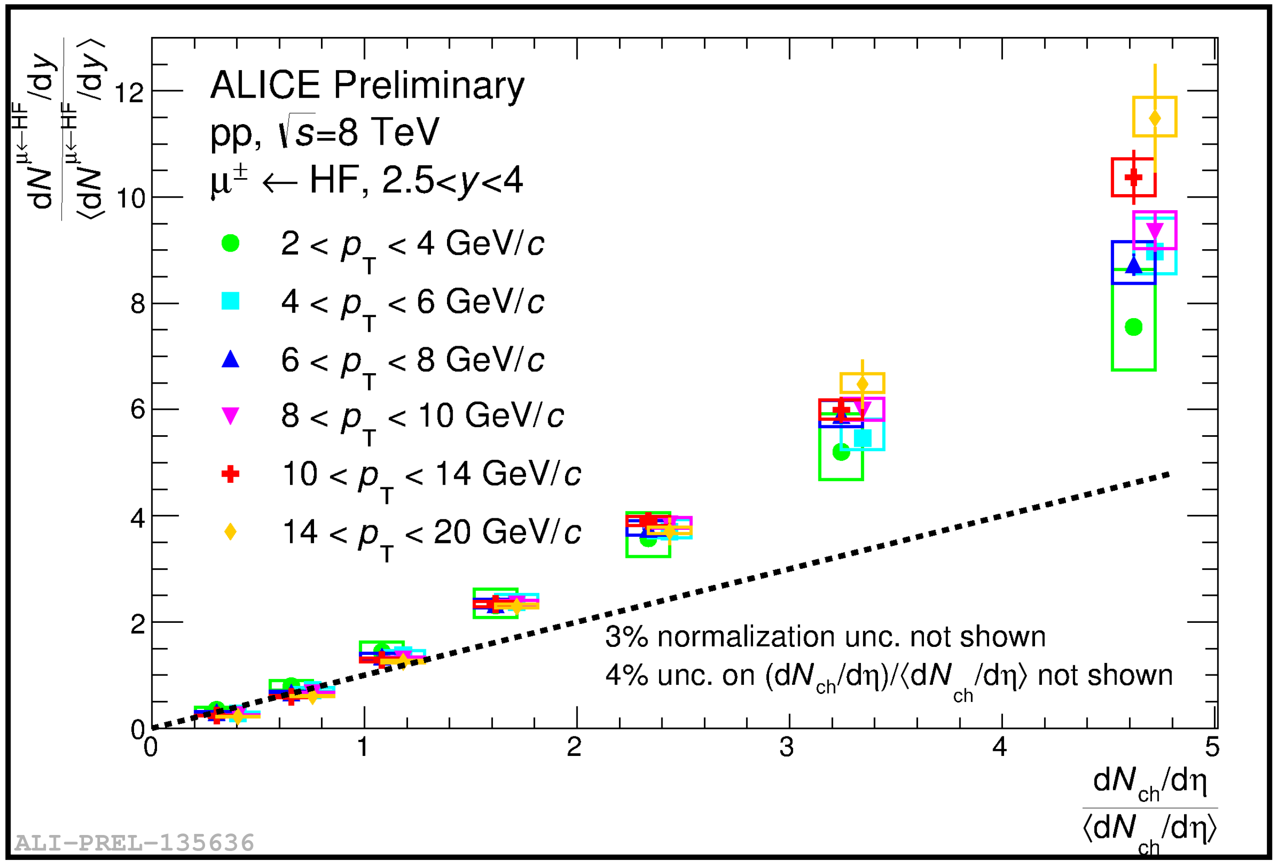
- The efficiency loss at z_0(reference point) and other track-to-particle-corrections need to be taken into account to evaluate the actual charged-particle value N_{ch}. Corrected using MC information.

$$N_{ch} = \alpha N^{corr}_{trklts}$$

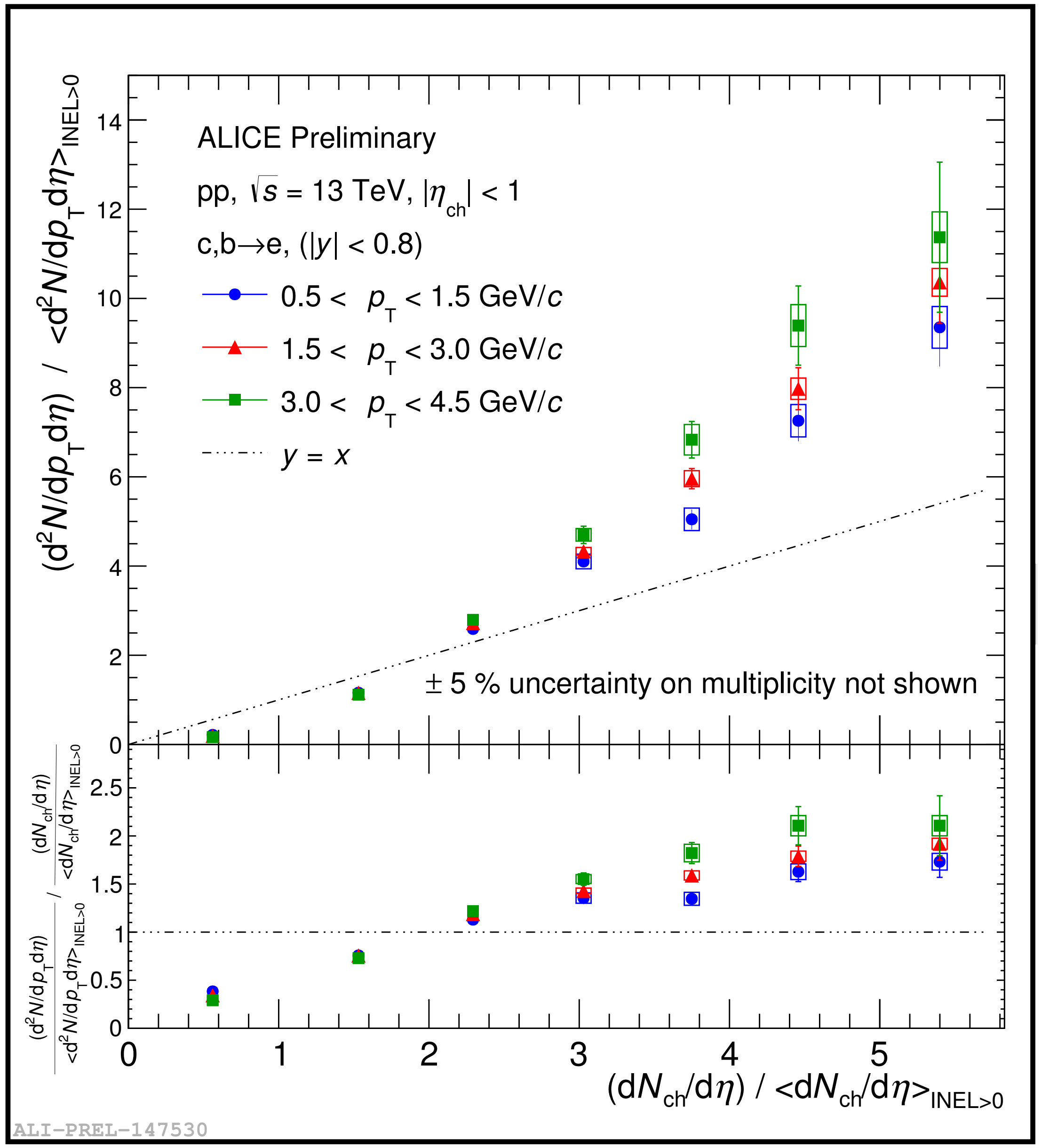



Results in
p
p
collisions

- Self-normalised yield of heavy-flavour decay muons ($\sqrt{s}$ = 8 TeV, forward rapidity) and electrons ($\sqrt{s}$ = 13 TeV, mid rapidity) versus self-normalised multiplicity.
- Multiplicity measured using SPD tracklets at mid rapidity ($|\eta| < 1$).



pp , $\sqrt{s}$ = 8 TeV
c,b → μ , 2.5 < y < 4

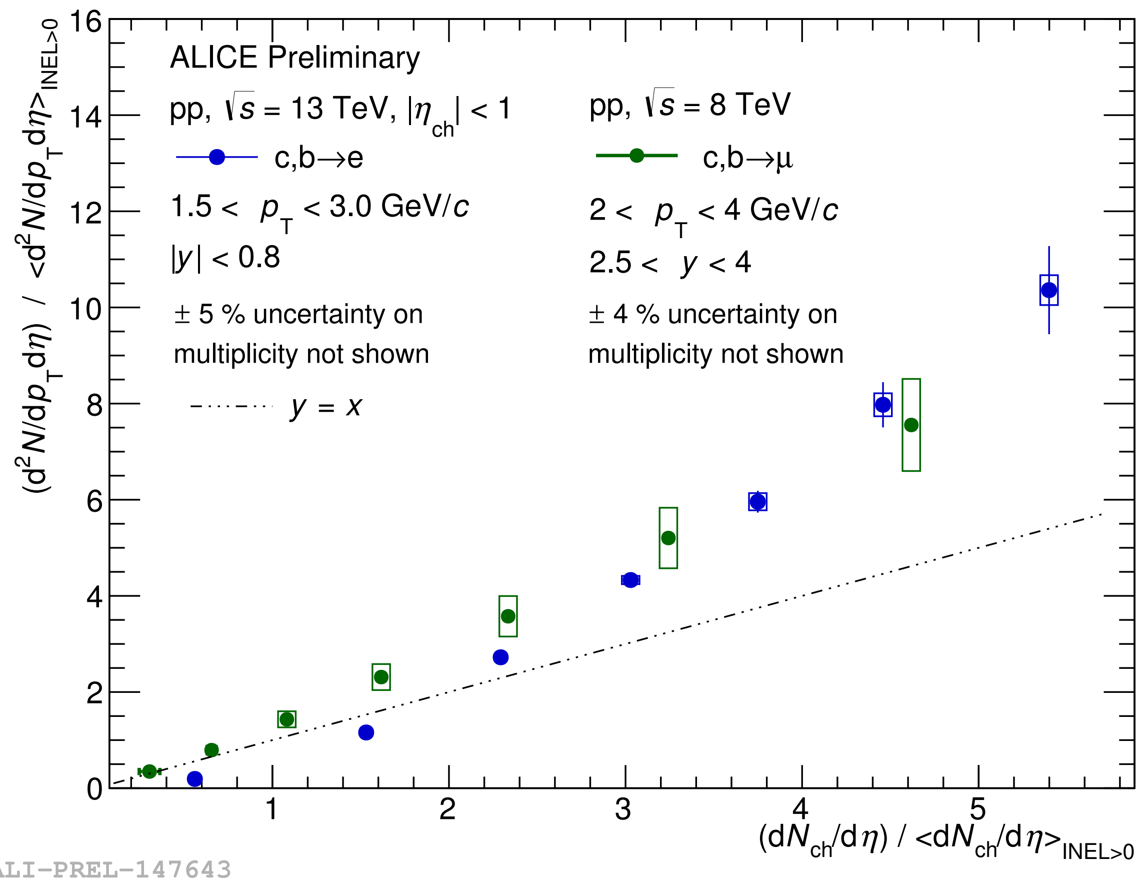


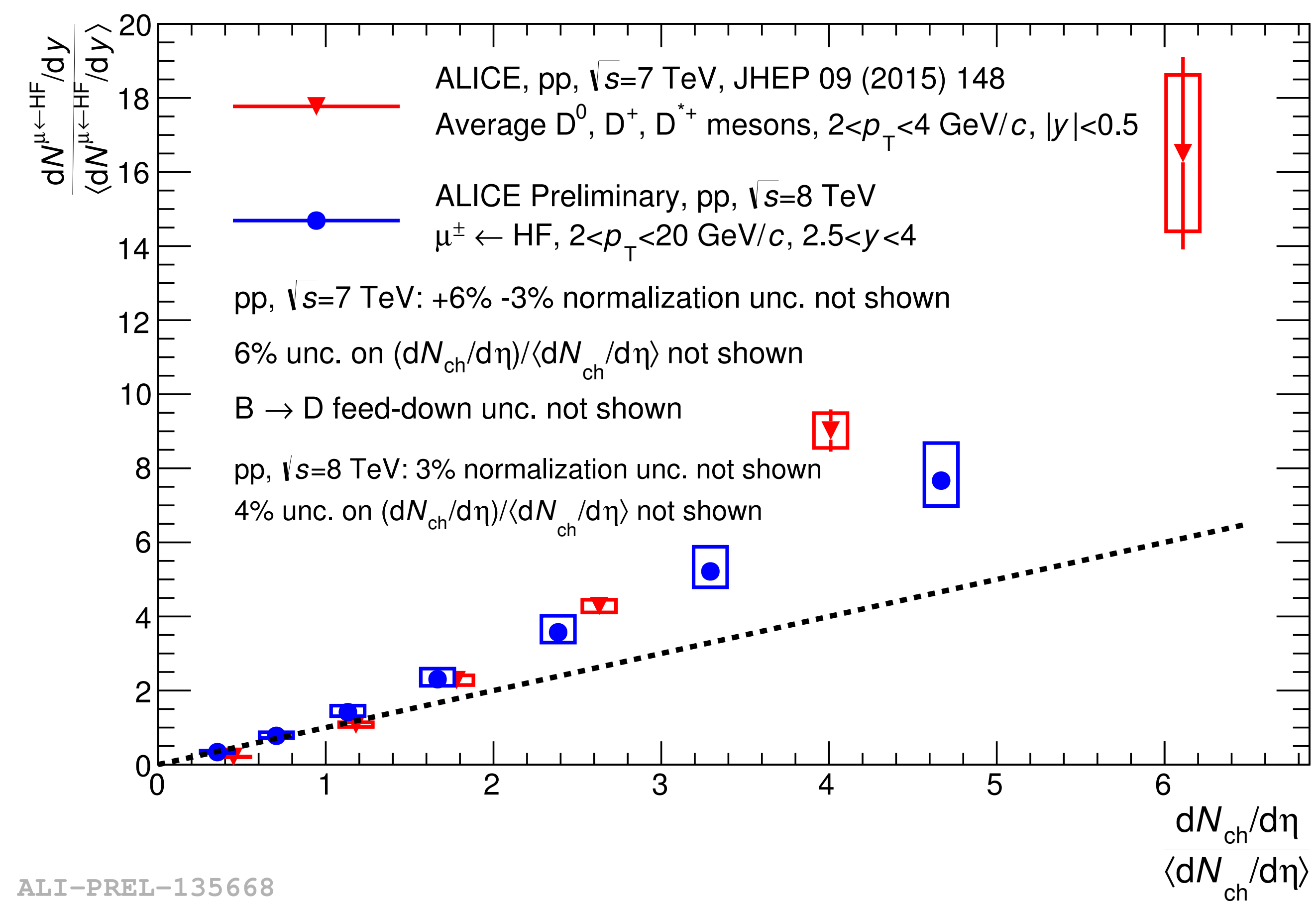
pp , $\sqrt{s}$ = 13 TeV
c,b → e , $|y|$ < 0.8

- The self-normalised yields show a faster than linearly increasing trend.
- Higher p_T ranges show tendency for steeper increase.

Heavy-flavour dependence on event multiplicity: self-normalised yield

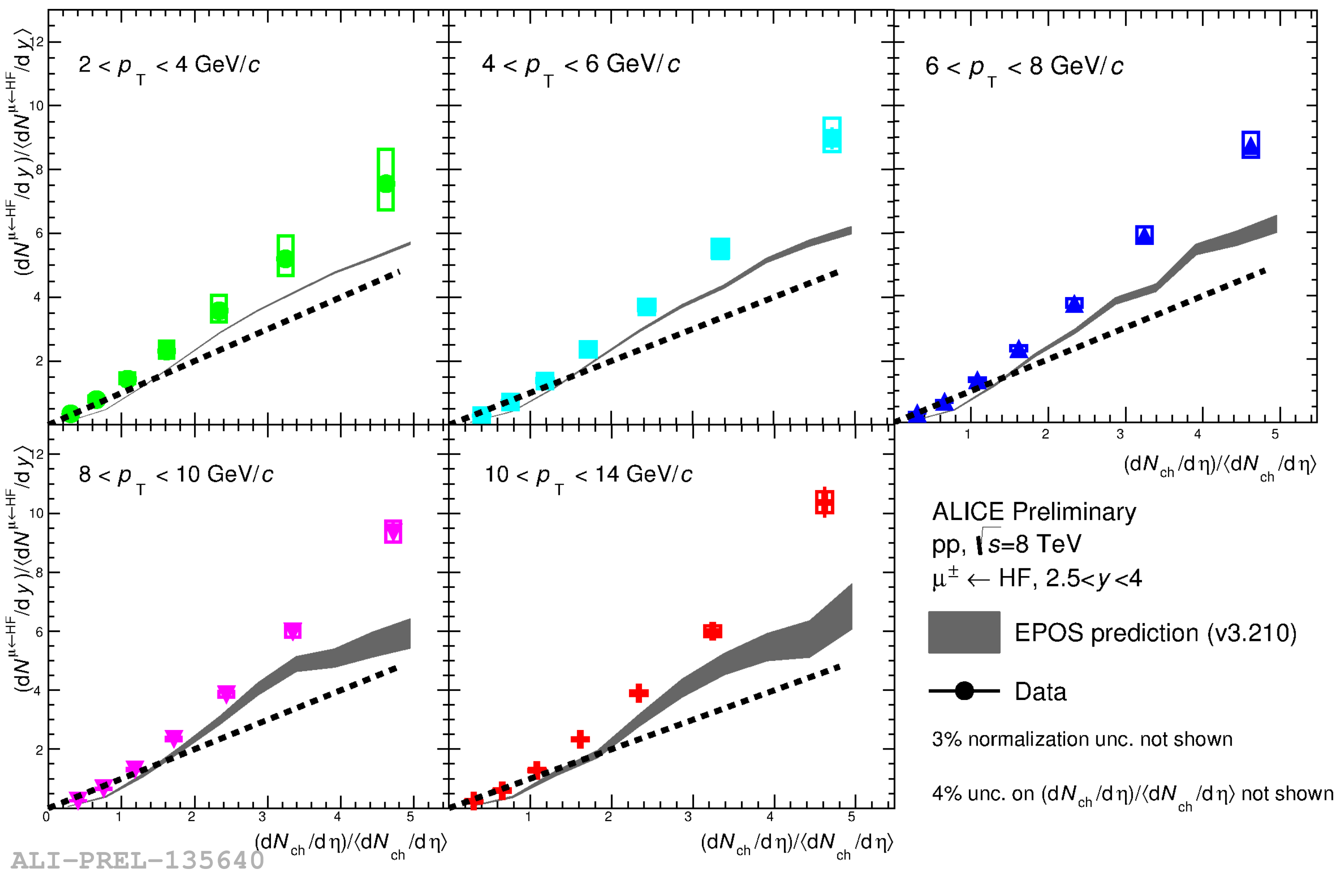
Comparison of self-normalised yield at forward (c,b → μ) and at mid rapidity (c,b → e, D-mesons)

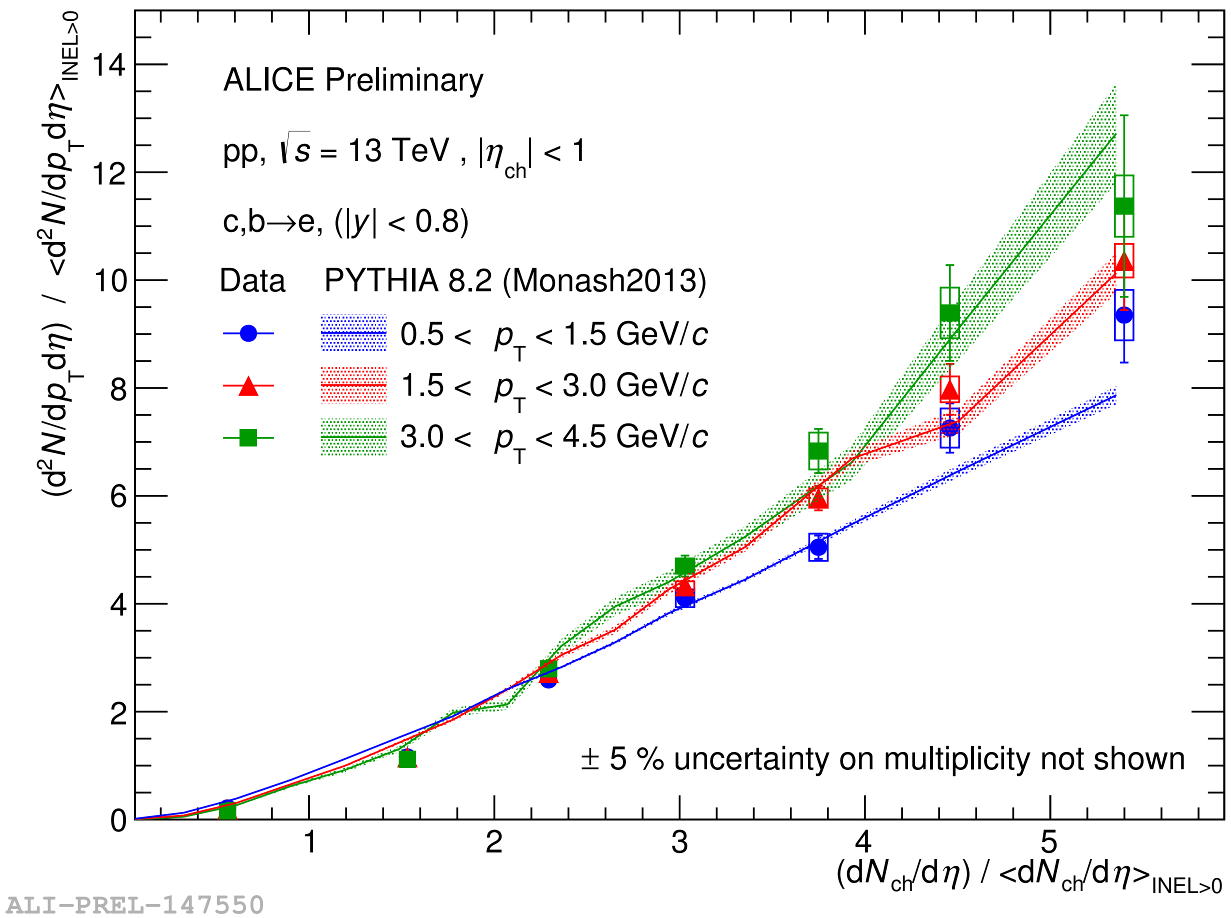




- Different trend of self-normalised yield for mid rapidity (c,b → e) and forward rapidity (c,b → μ). However for D-meson the trend is compatible with heavy-flavour decay muons within uncertainties.
- difference in the trend of HF decay at mid-rapidly and at forward can be due to autocorrelation effect and jet bias.
  - Due to overlap in the rapidity regions of multiplicity estimator (mid rapidity) and HF yield (c,b → e , D-mesons at mid rapidity).

Heavy-flavour dependence on event multiplicity: model comparison



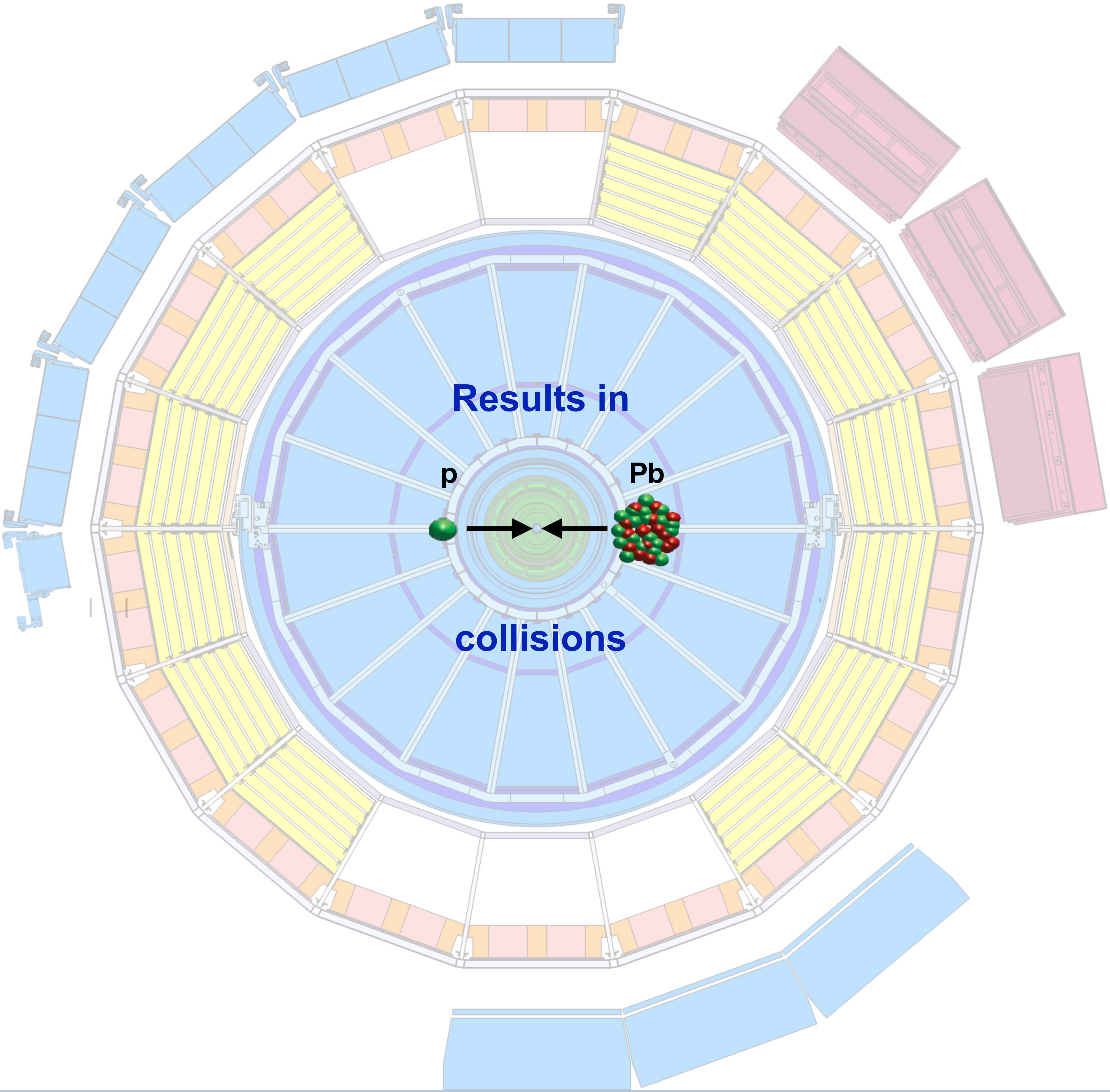


– c, b → μ data compared to EPOS3.210 prediction without hydrodynamics (Phys. Rev. C 89 (2014) 064903).

- EPOS3.210 underestimates data at higher multiplicities for all p_T ranges.

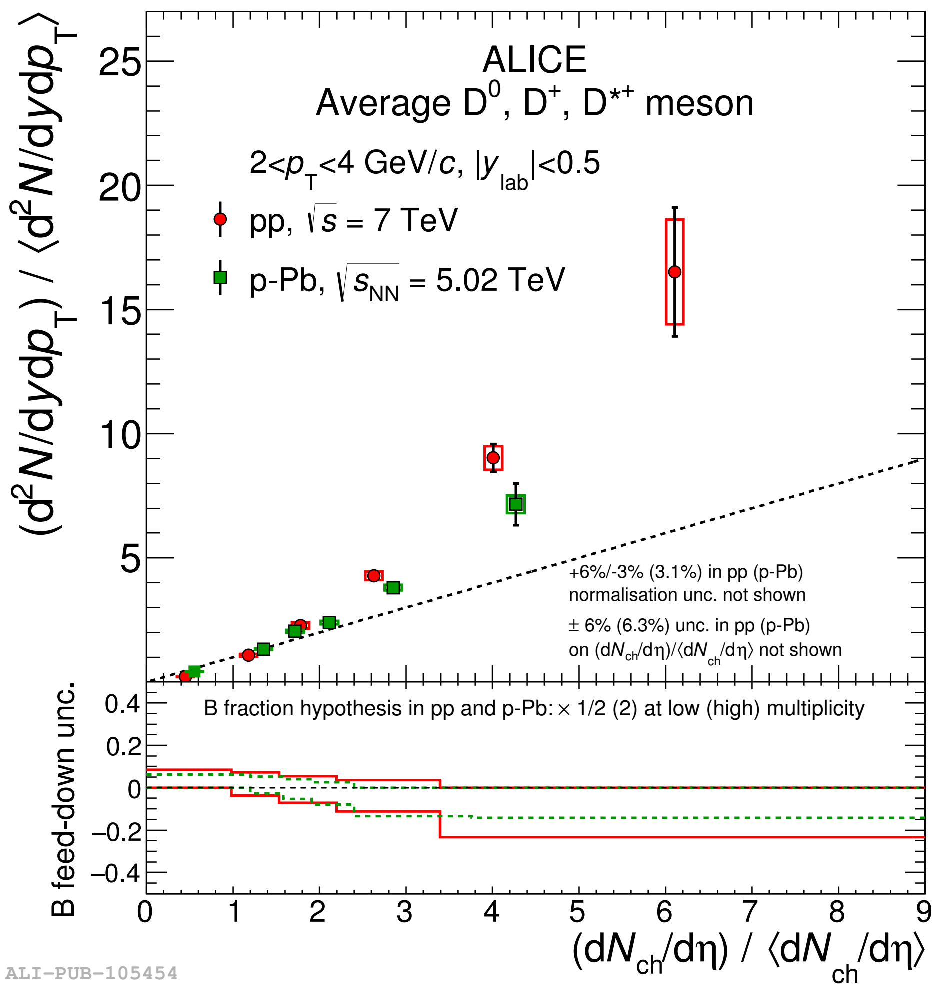
– c, b → e data compared to PYTHIA8.2 prediction (Comput. Phys.Commun. 191 (2015) 159).

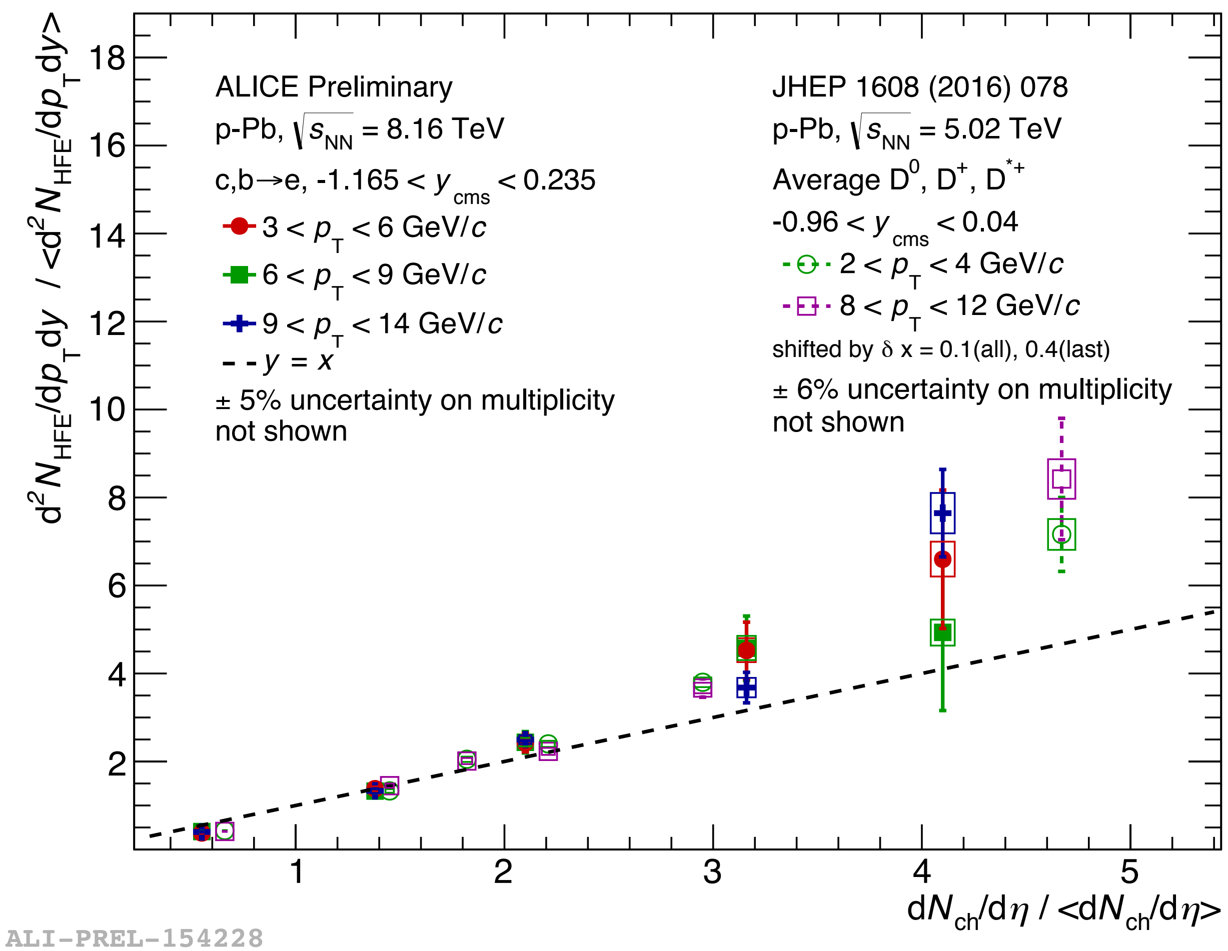
- PYTHIA8.2 predictions fairly match with the data.


Results in
p
Pb
collisions

Heavy-flavour dependence on event multiplicity: self-normalised yield

Comparison of self-normalised yield of D-meson with HF-decay electron at mid rapidity.

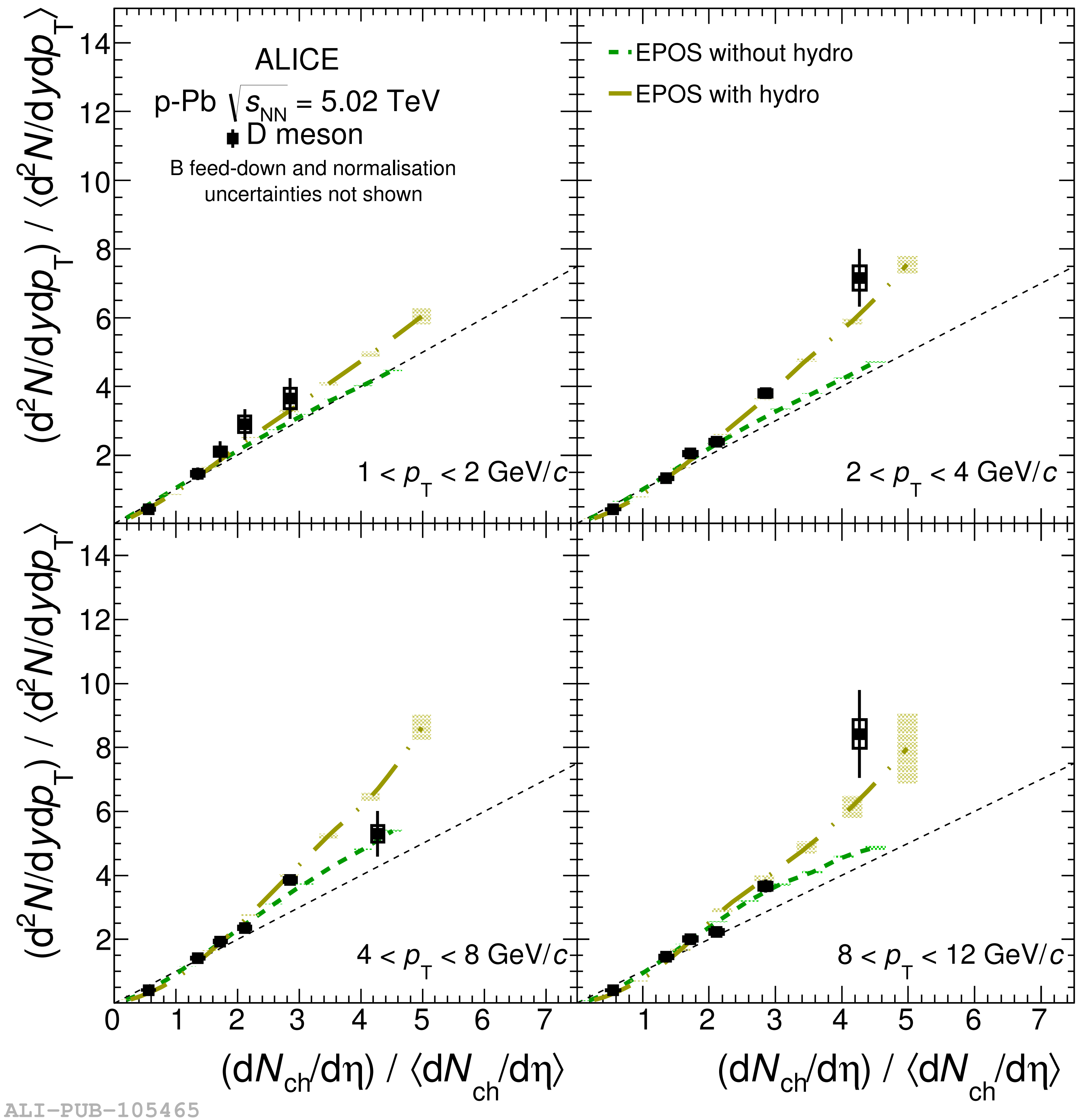




- Compatible trend in both pp and p-Pb collisions.
- High-multiplicity p-Pb collisions: MPI (like pp) but also have higher number of binary nucleon-nucleon collisions.
- The trend of HF-decay electron is compatible with the average D meson.

ALICE

arXiv:1602.07240v2



Comparison of self-normalised yield of D-meson in p-Pb collisions at 5.02 TeV with models.

EPOS 3.116 without hydrodynamics

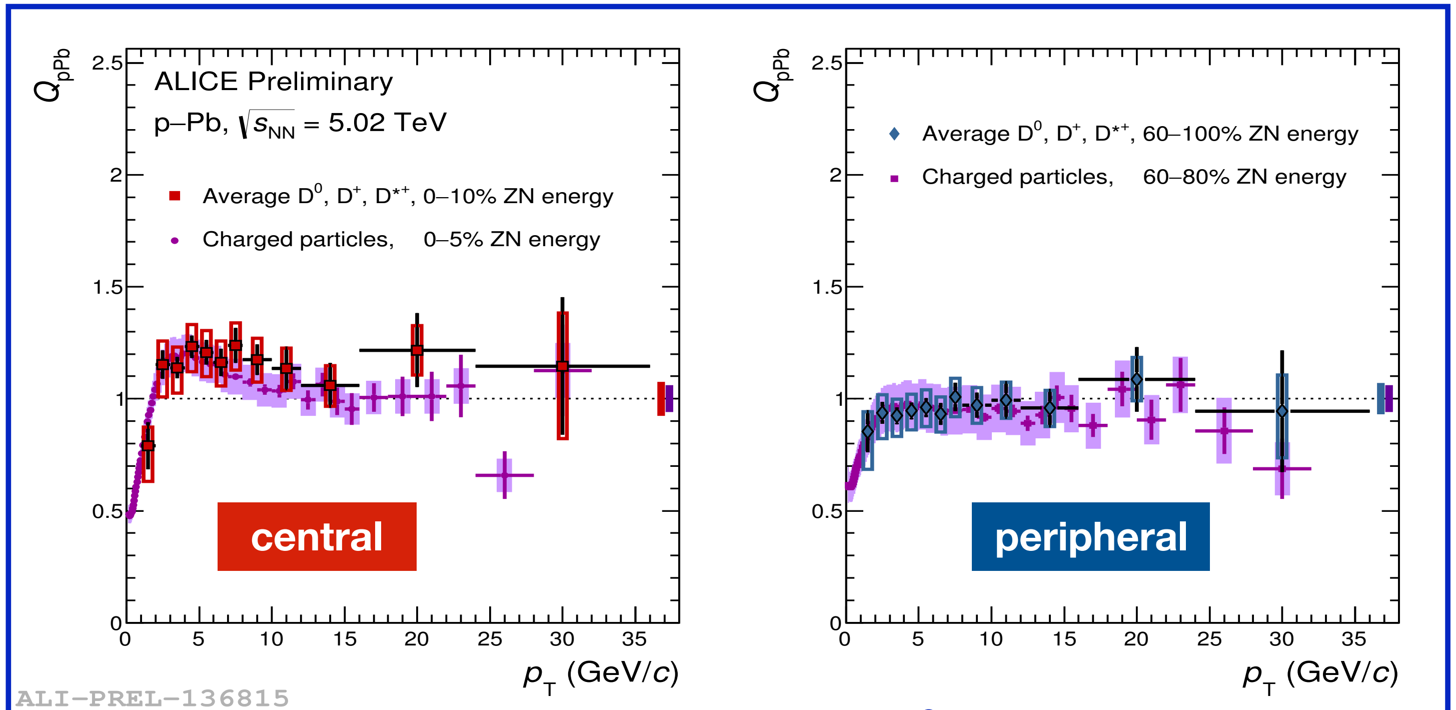
initial condition: "Parton-based Gribov-Regge" formalism of multiple scatterings.

EPOS 3.116 with hydrodynamics

along with the initial condition, a 3D+1 viscous hydrodynamical evolution is applied to the core of the collision

- measurements agree with the EPOS 3 model calculations within uncertainties.
- The results at high multiplicity are better reproduced by the EPOS 3 with hydrodynamic evolution.
  → Faster than linear increase

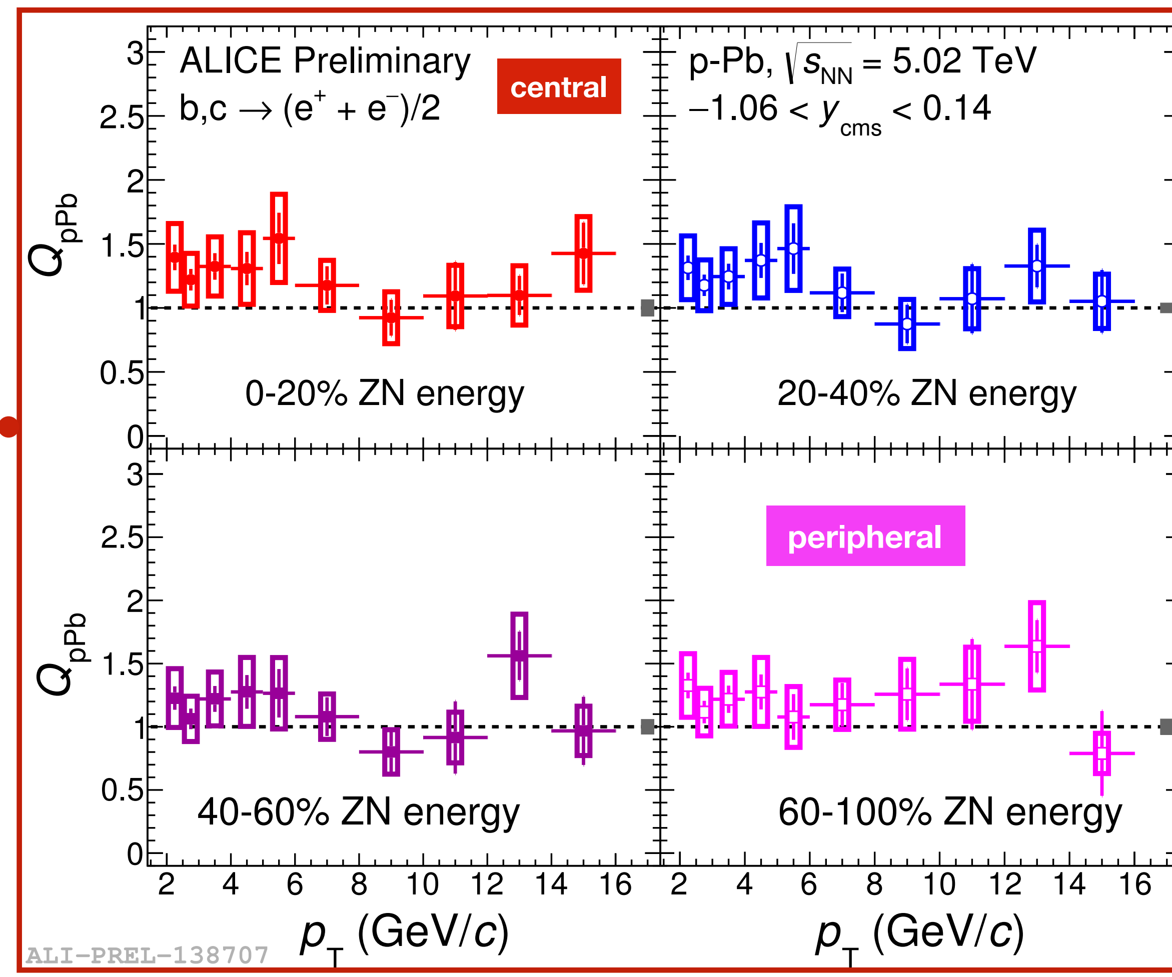
Heavy-flavour dependence on centrality: Q_{pPb}



- Nuclear modification factor provides access to **cold nuclear matter(CNM)** effects.
- Q_{pPb}: centrality-dependent nuclear modification factor. → centrality-dependent **CNM effects**.

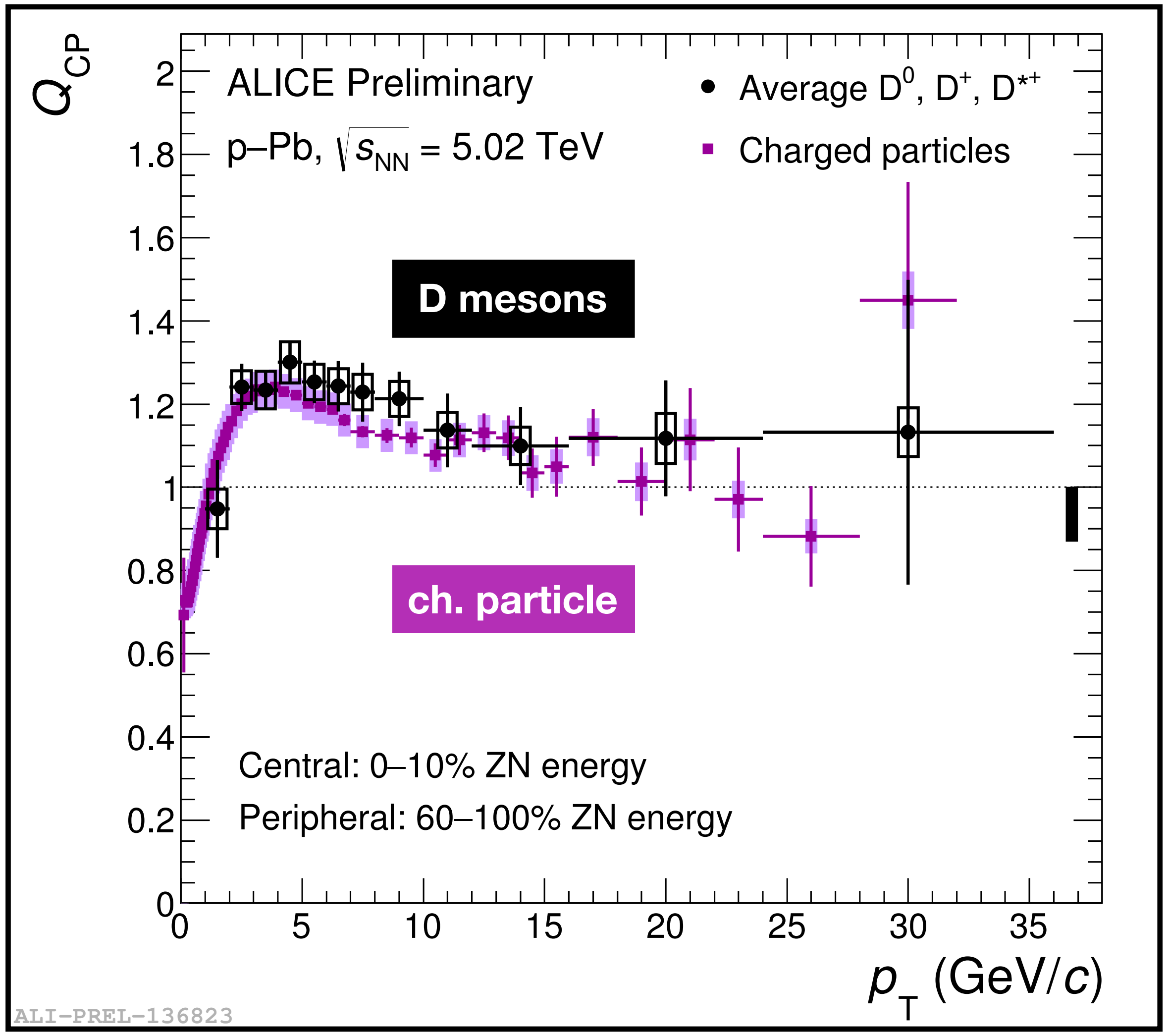
$$Q_{pPb}^{cent} = \frac{1}{< T_{pPb}^{cent} >} \frac{dN_{pPb}^{cent}/dp_T}{d\sigma_{pp}/dp_T}$$

- Central and peripheral results are compatible with each other and with unity for **D meson** and **HF-decay electrons**.
- D-meson Q_{pPb} similar to charged particles within uncertainties.



Heavy-flavour dependence on centrality: Q_{cp}

ALICE



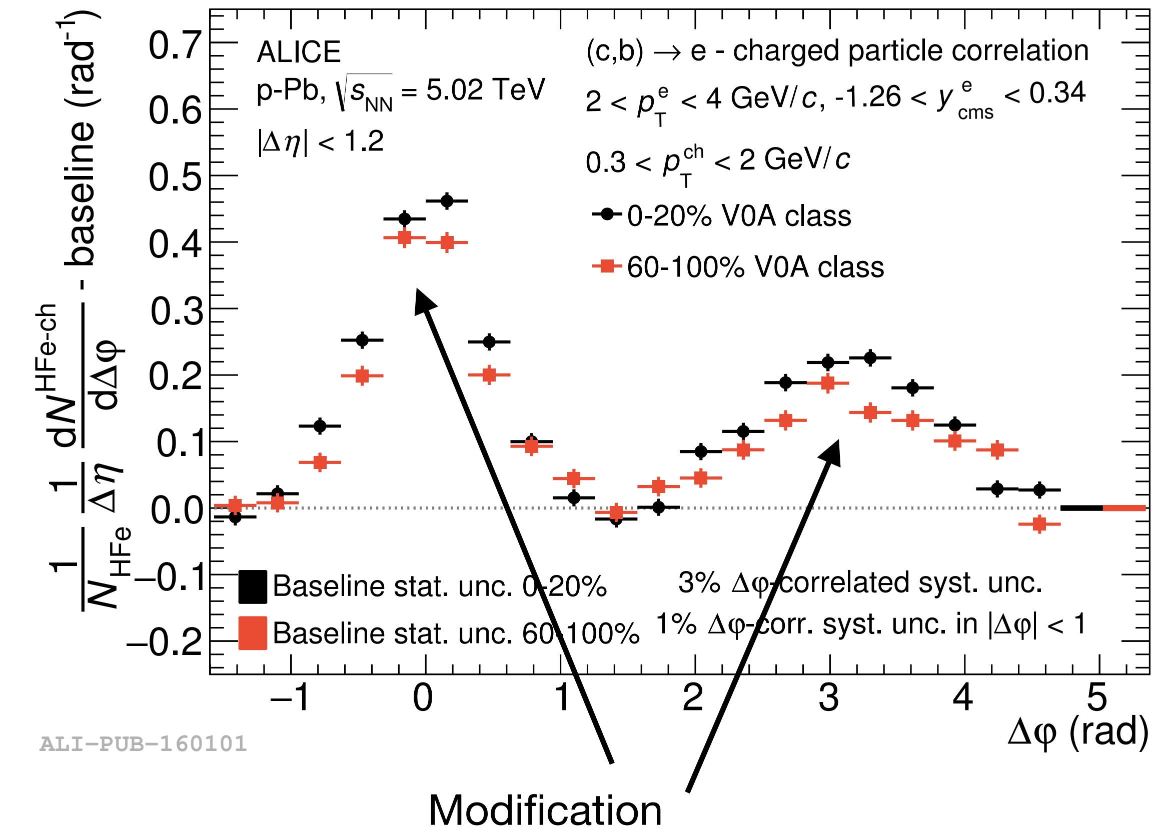
- Q_{cp}: Ratio of most central collisions to the most peripheral collisions spectra.
  Central : 0-10% Peripheral : 60 - 100%

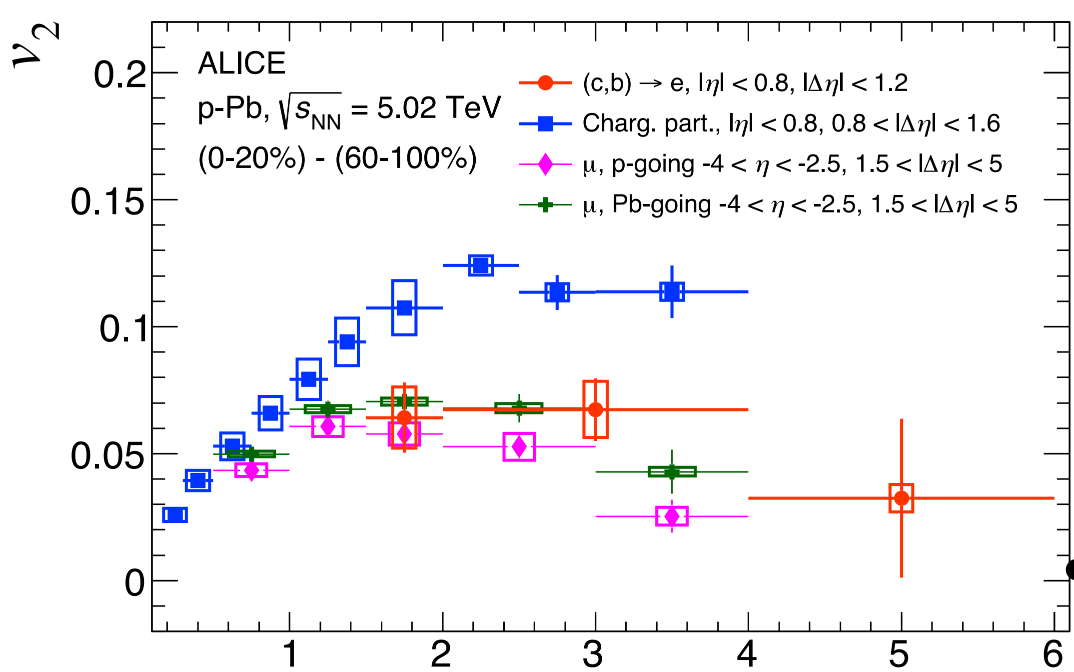
$$Qcp = \frac{N^{cent}_{pPb}/dp_T}{< T^{cent}_{pPb} >} / \frac{dN^{peri}_{pPb}/dp_T}{< T^{peri}_{pPb} >}$$

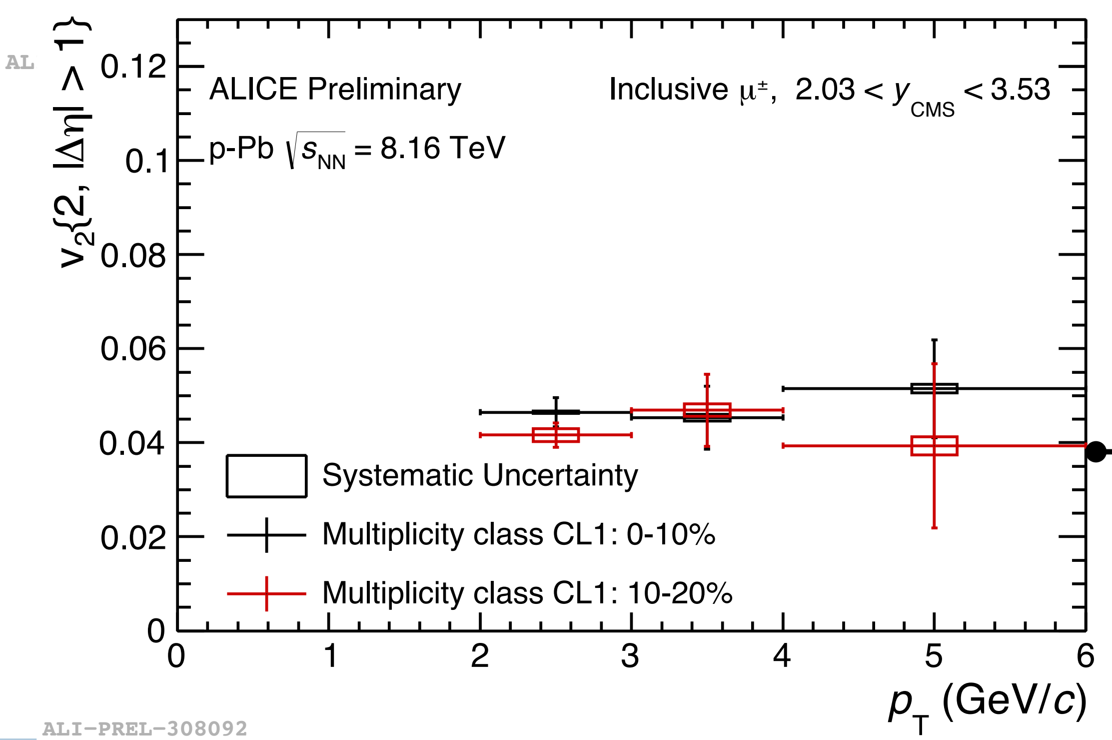
- Hint of D-meson Q_{cp} > 1 in 2 < p_T < 8 GeV/c with 1.5 σ significance.→ similar trend as charged particles. Initial or final-state effect? Need model for interpretation.

Heavy-flavour decay electron and inclusive muons v_2

- Two-particle correlations between HF-decay electron (central rapidity) with charged particles at central rapidity in high-multiplicity (0-20%) and low-multiplicity (60-100%) events.
- Jet bias subtraction: high mult. - low mult.







- **Positive v_2** observed for HF-decay electrons ($1.5 < p_T < 4$ GeV/c) with significance of ~ 5σ.
- Effect is qualitatively similar to the one observed for light flavours and inclusive muons.
- Collective effects can be present. Or Initial or final state effect? → need model predictions
- **Positive v_2** observed for inclusive muons.
- Method: Q-cumulants with 2- and 4- particle correlations

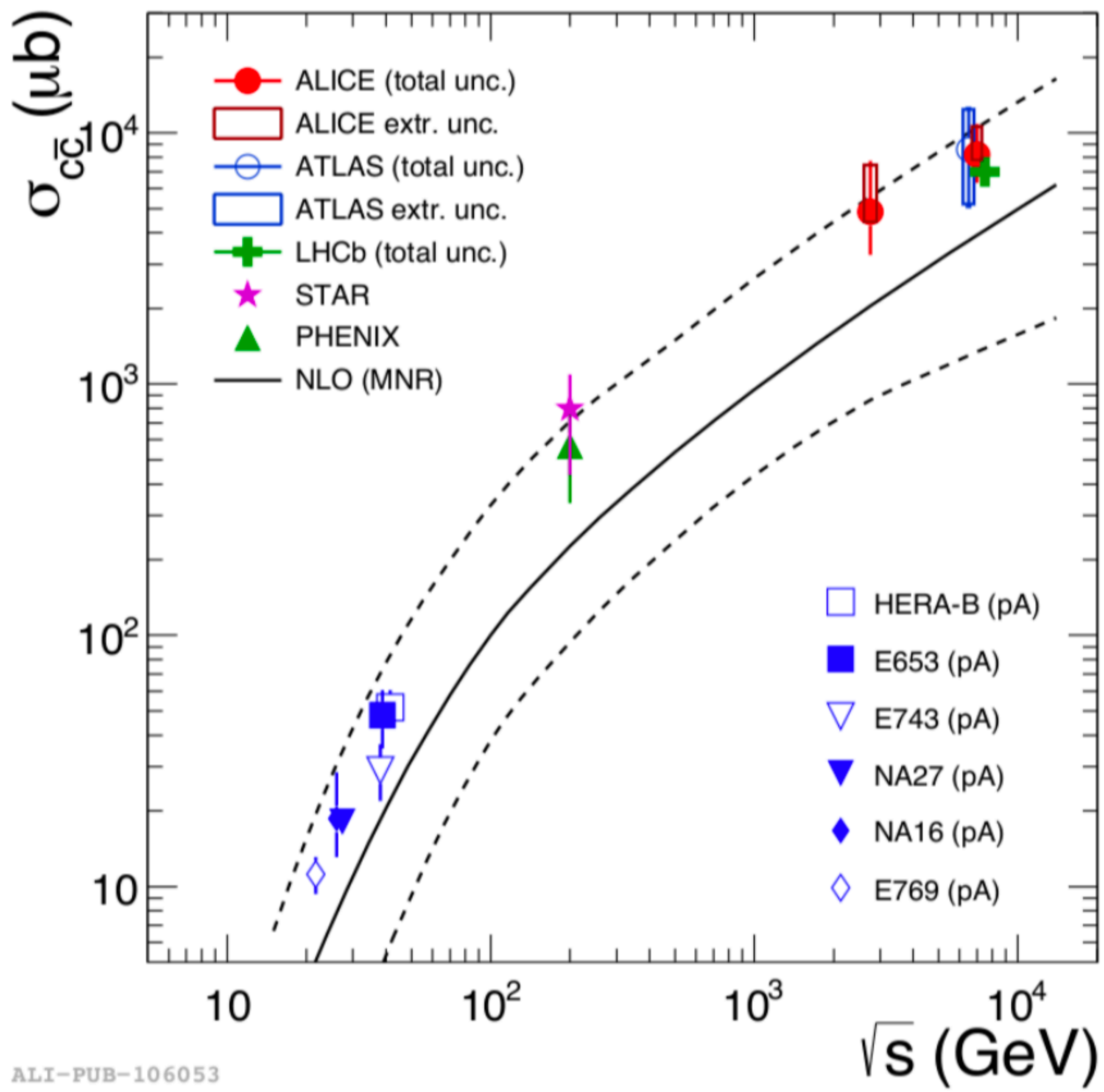
Summary

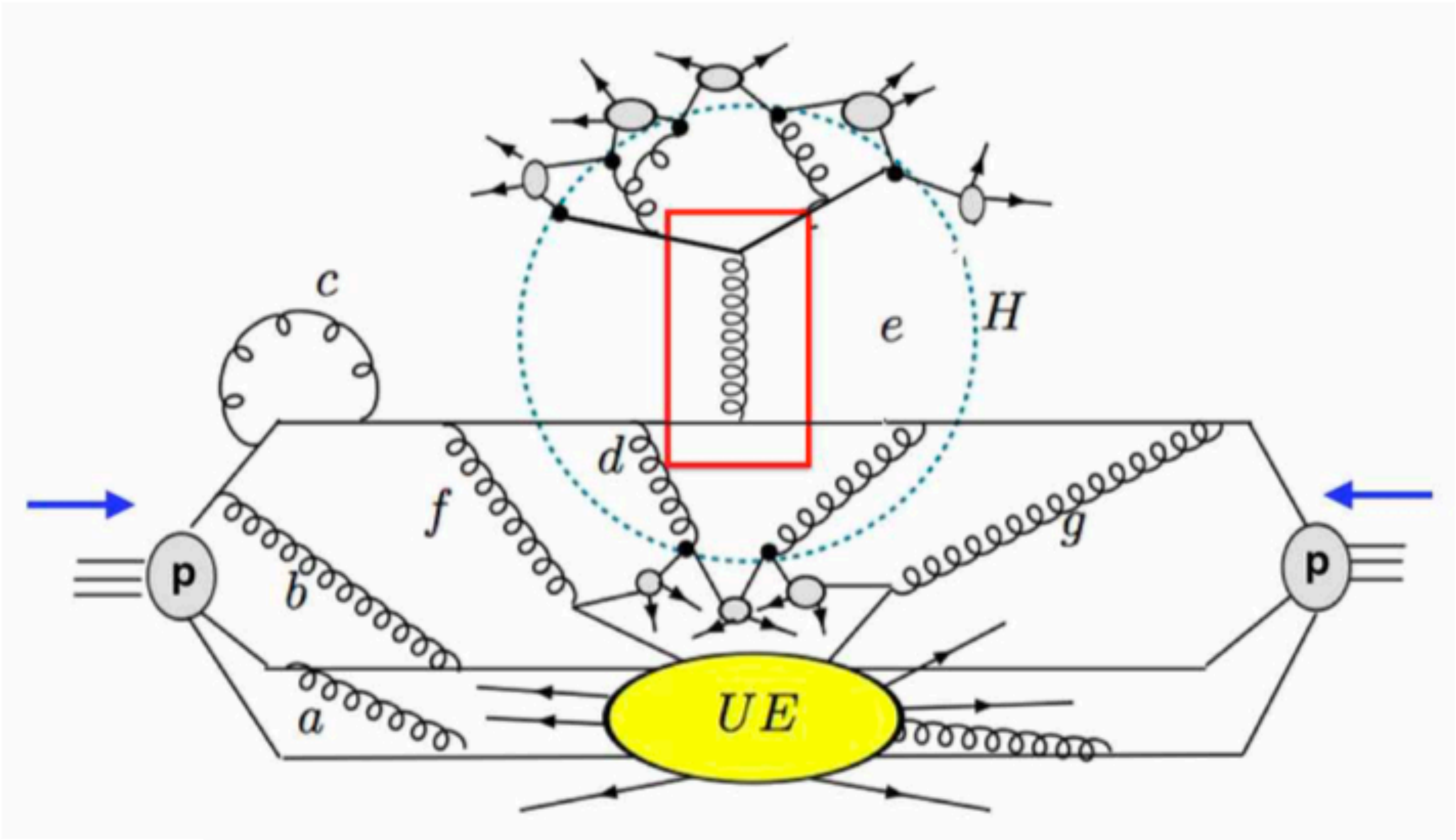
- Multiplicity dependent production of heavy-flavour hadrons and leptons results are presented in pp and pPb systems.
  - Results show **stronger than linear enhancement** as a function charged-particle multiplicity estimated at mid-rapidity.
  - The factors that can be attributed to this trend are contribution from **Multiple- Parton Interactions (MPI)** and further influenced by multiple binary nucleon–nucleon interactions, and the initial conditions of the collision modified by **CNM** effects in p-Pb system. or auto-correlation effects.
  - Further investigation is needed and also model comparison to better understand the trend.
- **Q_{pPb} compatible with unity** for HF-decay electrons and D mesons.
- **Hints of Q_{cp} >1 for D mesons** in $3 < p_T < 8$ GeV/c (~**1.5σ**), possible modification of the production. From initial- or final-state effects?
- **Positive v_2** measured for HF-decay electrons with more than **5σ significance** for $1.5 < p_T < 4$ GeV/c. Collective effects? Initial- or final-state effect?
- **Positive v_2** measured for inclusive muons.

Thank you!

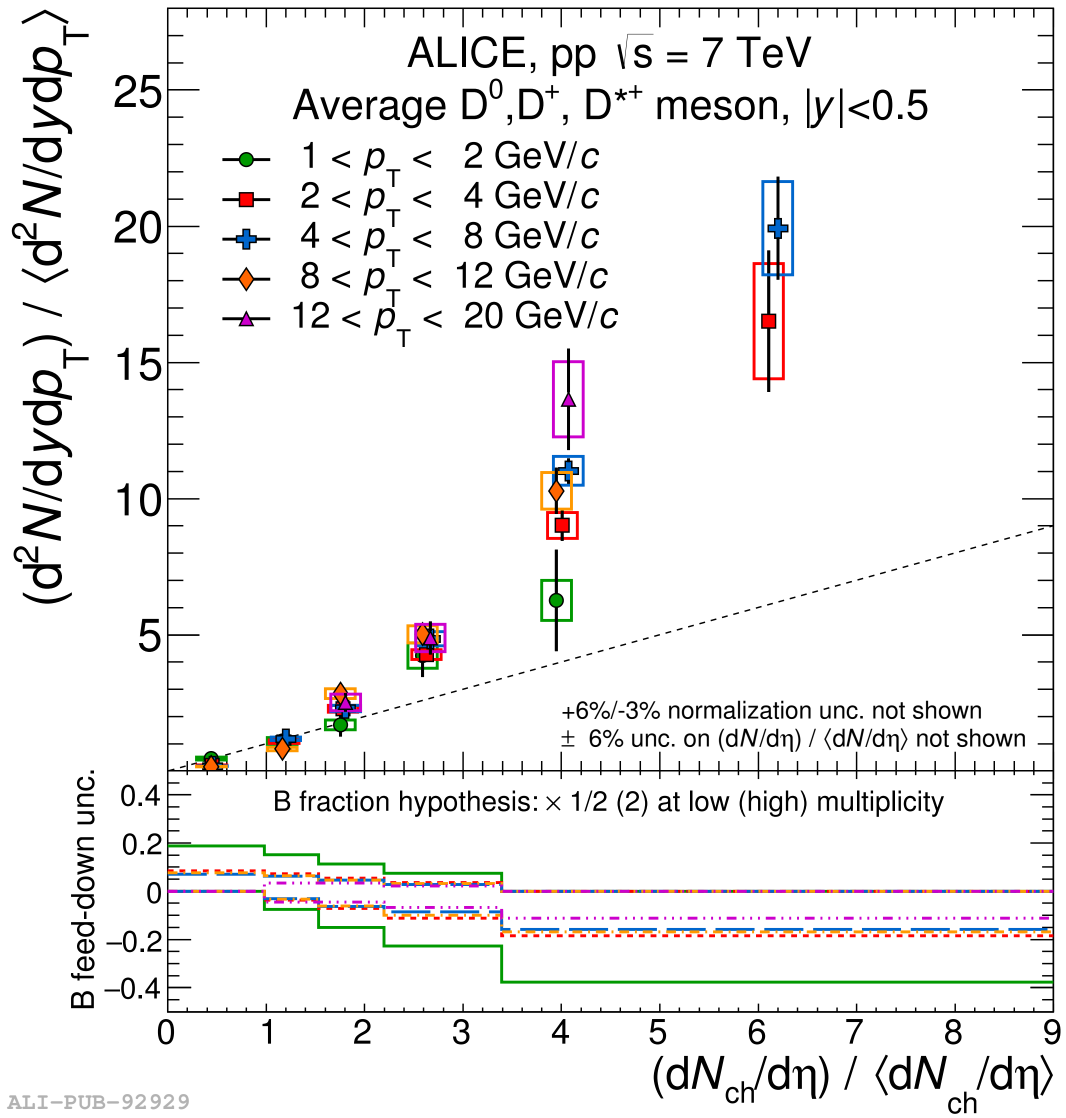
Back-up slides

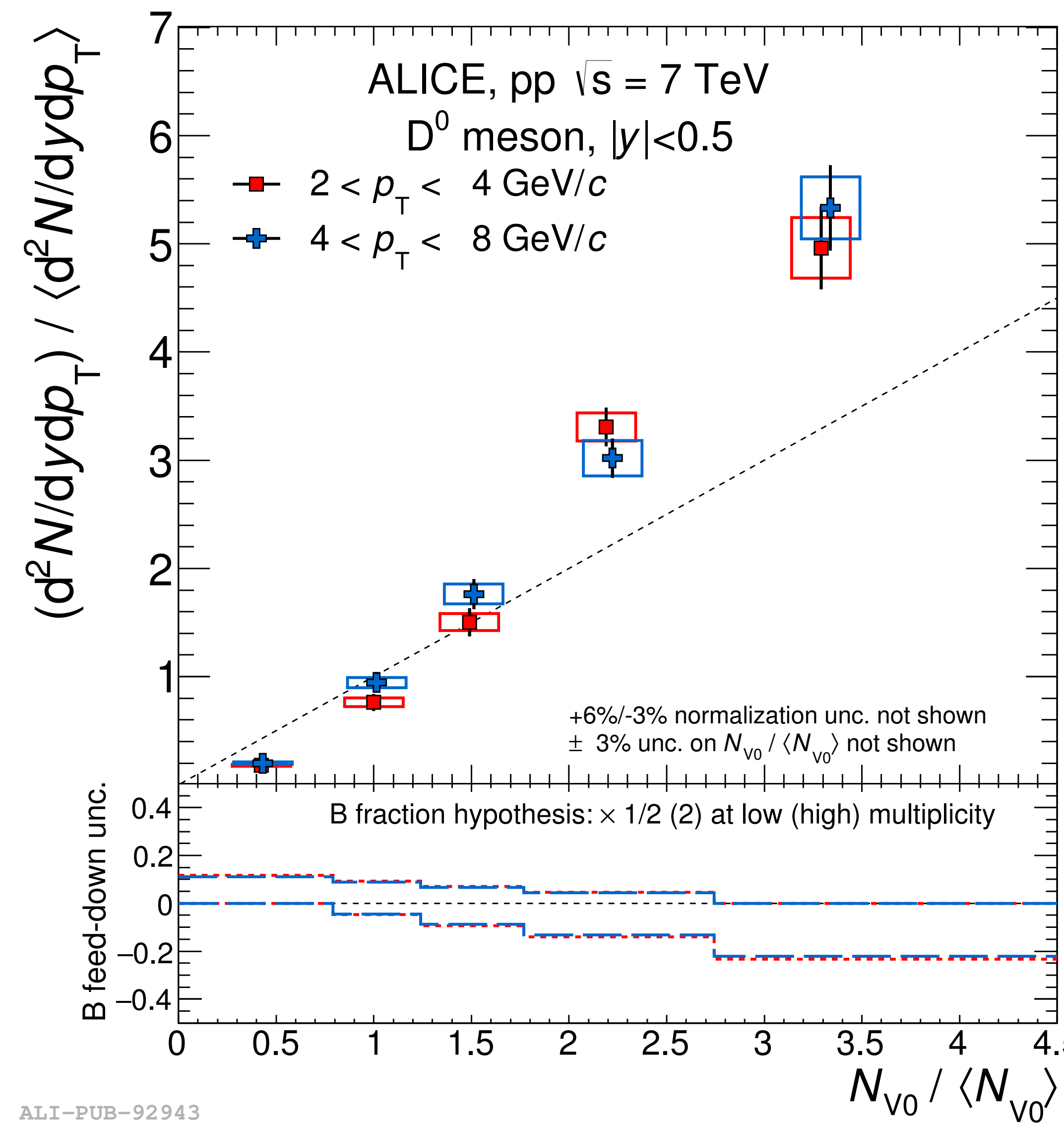
Total Charm cross-section

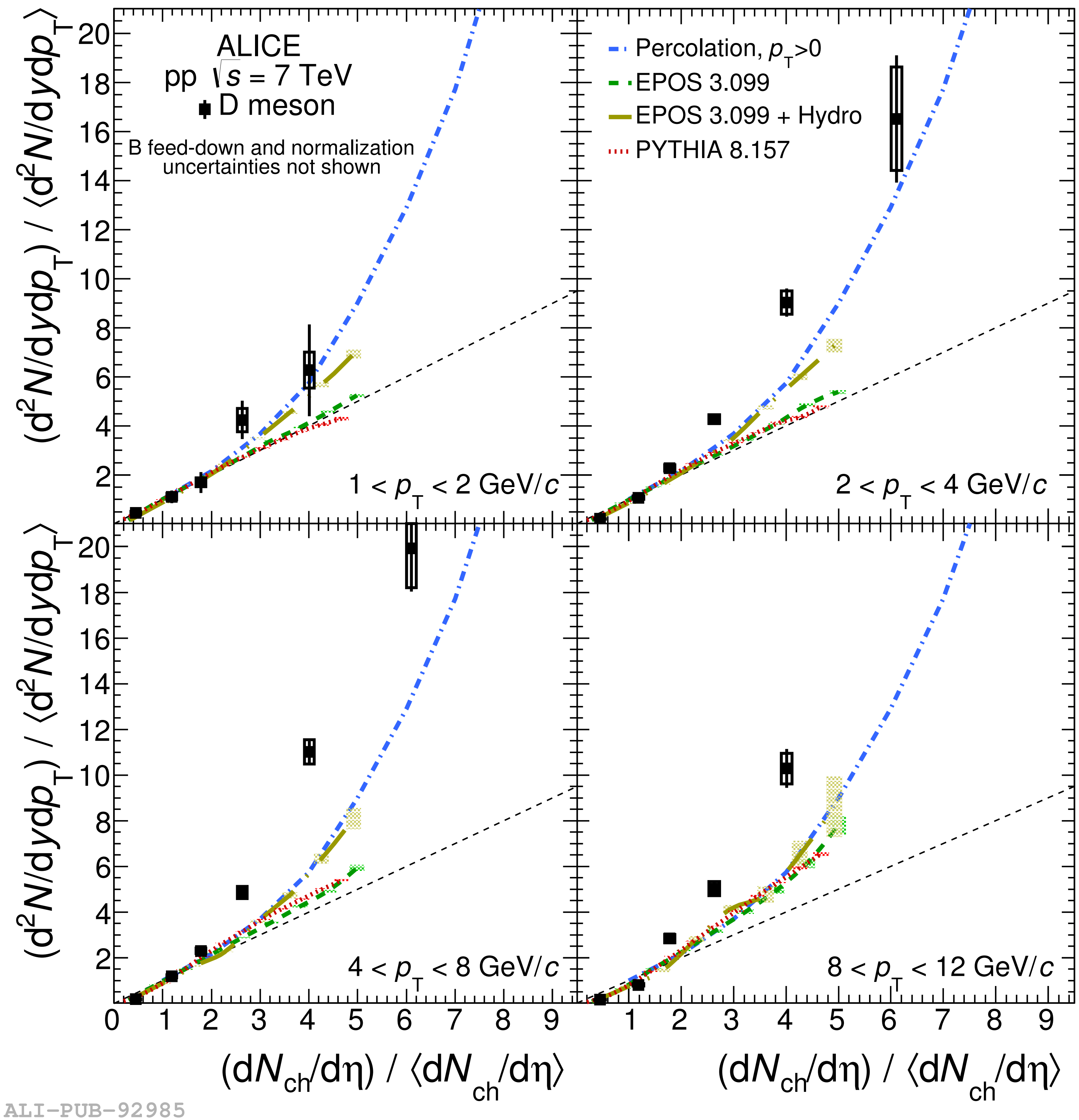




chematic view of a pp interaction in which a hard scattering between two valence quarks (red box) takes place


ALICE, pp √s = 7 TeV
Average D0,D+, D*+ meson, |y|<0.5
1 < pT < 2 GeV/c
2 < pT < 4 GeV/c
4 < pT < 8 GeV/c
8 < pT < 12 GeV/c
12 < pT < 20 GeV/c
+6%/-3% normalization unc. not shown
± 6% unc. on (dN/dη) / ⟨dN/dη⟩ not shown
B fraction hypothesis: × 1/2 (2) at low (high) multiplicity
(d2N/dydpT) / ⟨d2N/dydpT⟩
B feed-down unc.
(dNch/dη) / ⟨dNch/dη⟩
ALI-PUB-92929


ALICE, pp √s = 7 TeV
D0 meson, |y|<0.5
2 < pT < 4 GeV/c
4 < pT < 8 GeV/c
+6%/-3% normalization unc. not shown
± 3% unc. on NV0 / ⟨NV0⟩ not shown
B fraction hypothesis: × 1/2 (2) at low (high) multiplicity
(d2N/dydpT) / ⟨d2N/dydpT⟩
B feed-down unc.
NV0 / ⟨NV0⟩
ALI-PUB-92943



Percolation(Ferreiro, Pajares, PRC86(2012)034903)

Particle production via exchange of colour sources between projectile and target(close to MPI)

→ Faster than linear increase

EPOS3.099(Werneretal., PRC 89(2014)064903)

Gribov-Regge multiple-scattering formalism

Saturation scale to model non- linear effects

Number of MPI directly related to multiplicity.

→ Faster than linear increase

PYTHIA8(Sjostrand etal., Comput.Phys.Commun.178 (2008) 852)

- Soft-QCD tuned
- Color reconnection
- MPI

→ Linear increase