# An overview of recent open heavy flavour results with ALICE at the LHC

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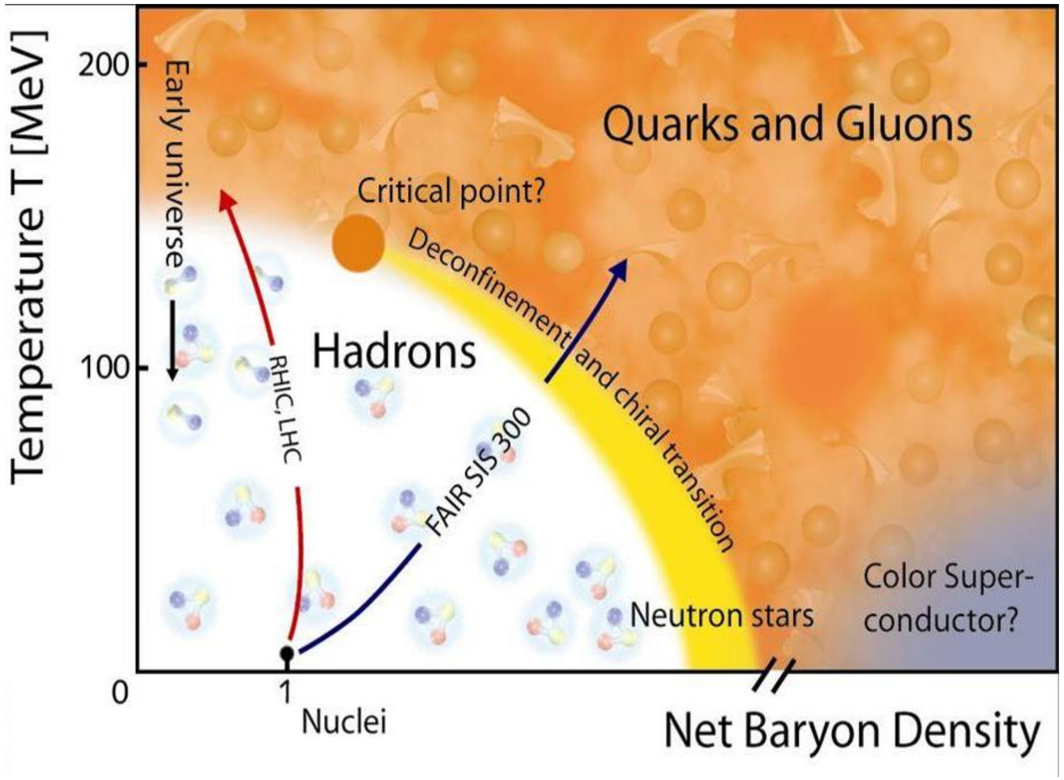
**Heavy Flavour Meet-2019, IIT Indore**

# Heavy-Ion Collisions

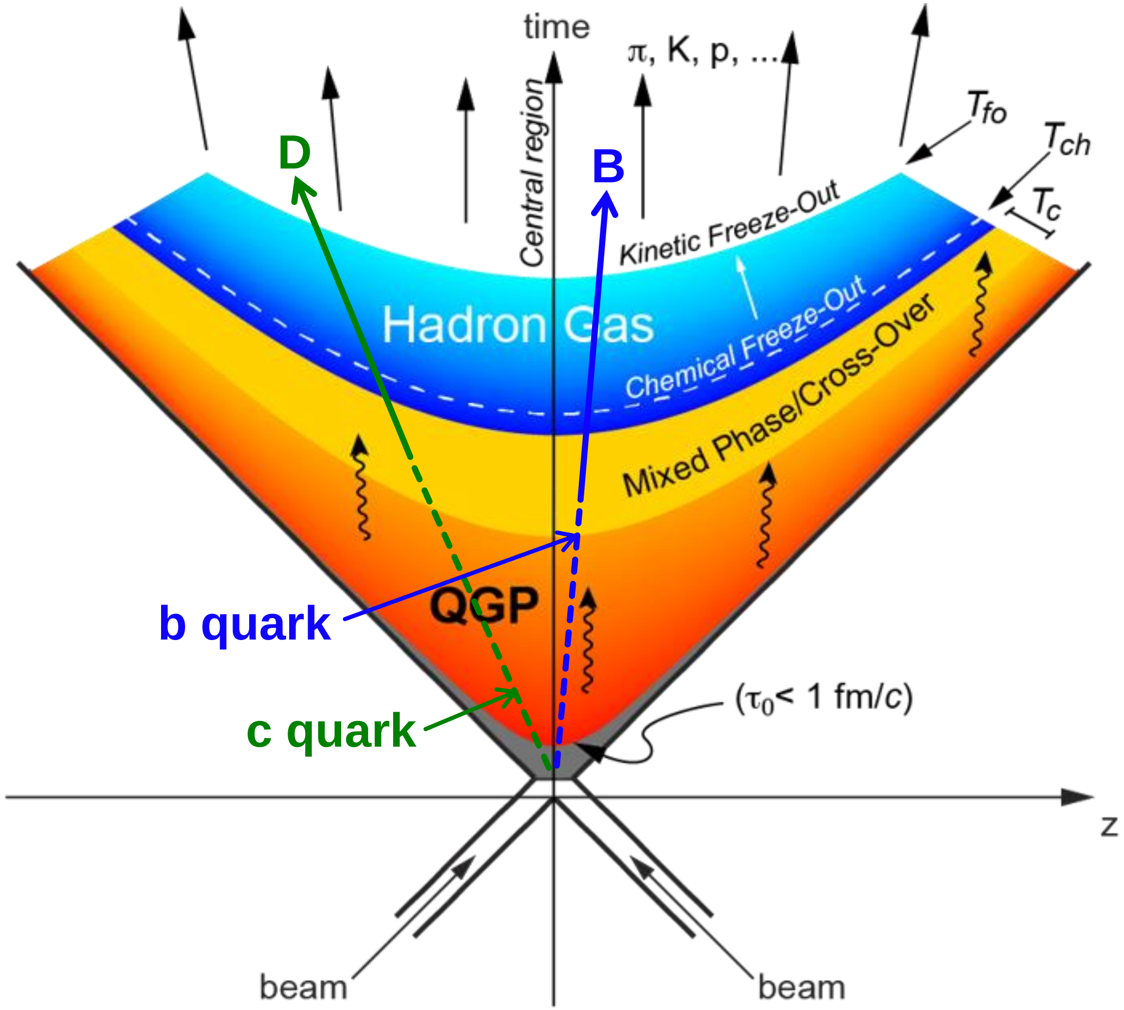
Motivation : To study the properties of nuclear matter at extreme conditions of temperature and energy density

- Transition to a state where quarks and gluons are deconfined (Quark- Gluon Plasma, QGP)
  - From lattice QCD: $T_C \approx$ 145-160 MeV $\rightarrow \varepsilon_C \approx 0.5$ GeV/fm$^3$




📖 **Bazavov et al, PRD90 (2014) 094503**
📖 **Borsanyi et al, JHEP 1009 (2010) 073**

# Heavy Quarks as QGP Probes

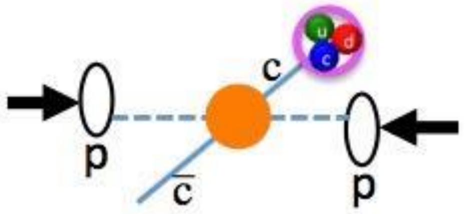


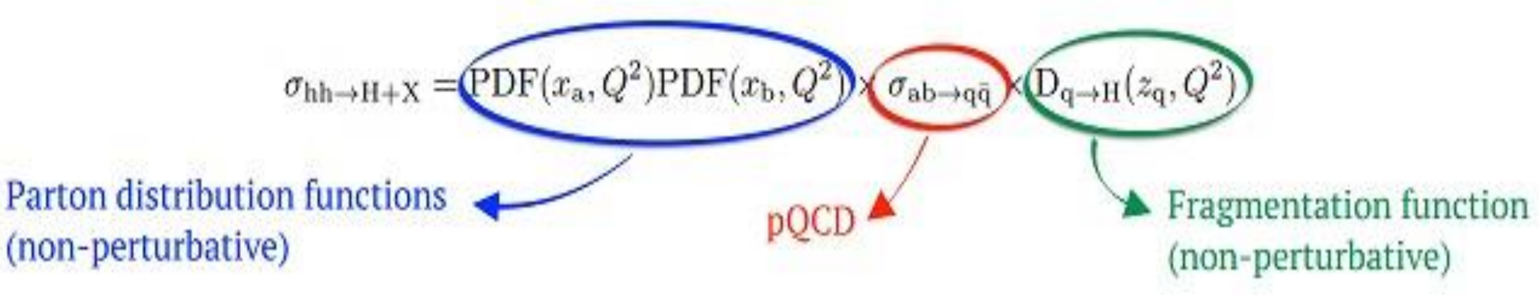

- **Charm and beauty quarks: unique probes of the medium**
  - Produced at the very early stage of the collision in partonic scattering processes with large $Q^2$
    - pQCD can be used to calculate initial cross sections
  - Small rate of thermal production in the QGP
  - Large mass, short formation time
    - Experience the entire evolution of the medium
  - Interactions with medium constituents don‘t change the flavor, but can modify the phase-space distribution of heavy quarks
- Heavy quarks interact with the medium
  - Energy loss via radiative and collisional mechanism
  - ***Heavy quarks provide a benchmark for energy loss models***
- Do charm (and beauty) quarks thermalize with the medium and participate in the collective motion?

# Heavy Flavours in small collision systems

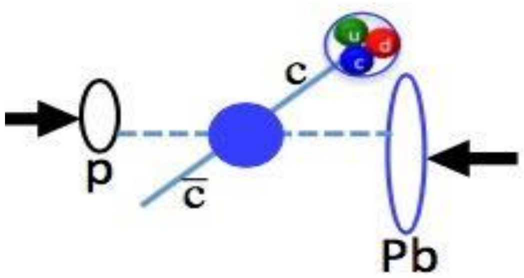
**pp collisions**:

- Important to test of perturbative QCD calculations
- Production cross section calculated down to $p_T$~0 using the factorization theorem




- Reference to study the effects in pA and AA collisions




**p-Pb collisions**

- Address  cold nuclear matter (CNM) effects in the initial and final stage of the collisions
- Collective effects in high multiplicity events as observed in AA collisions?
- Small size QGP?

# Heavy flavours in Pb-Pb collisions

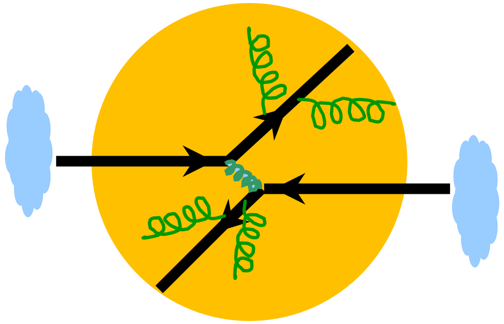
Production of HF in AA collisions is expected to scale with the number of nucleon-nucleon collisions **(binary scaling)**

**Observable: Nuclear Modification Factor $R_{AA}$**

$$R_{AA}(p_T) = \frac{1}{\langle N_{coll} \rangle} \frac{dN_{AA}/dp_T}{dN_{pp}/dp_T} \sim \frac{QCD\ \text{medium}}{QCD\ \text{vacuum}}$$

If no nuclear effects are present → $R_{AA}$=1

Pb-Pb measurement



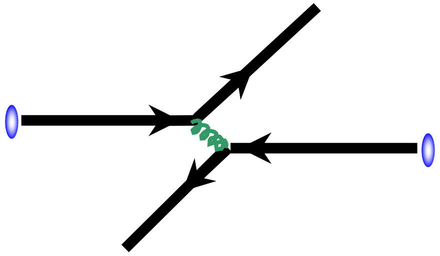
Interactions with the constituents of the hot, dense and deconfined medium created in the collision can modify (→$R_{AA}$≠1) the phase space distribution of heavy quarks

In-medium **parton energy loss** via elastic collisions and gluon radiation depends on

- Medium density, path-length
- Colour-charge(Casimir effect)
- parton mass (e.g Dead cone effect)

📖 Dokshitzer and Kharzeev, PLB 519 (2001) 199

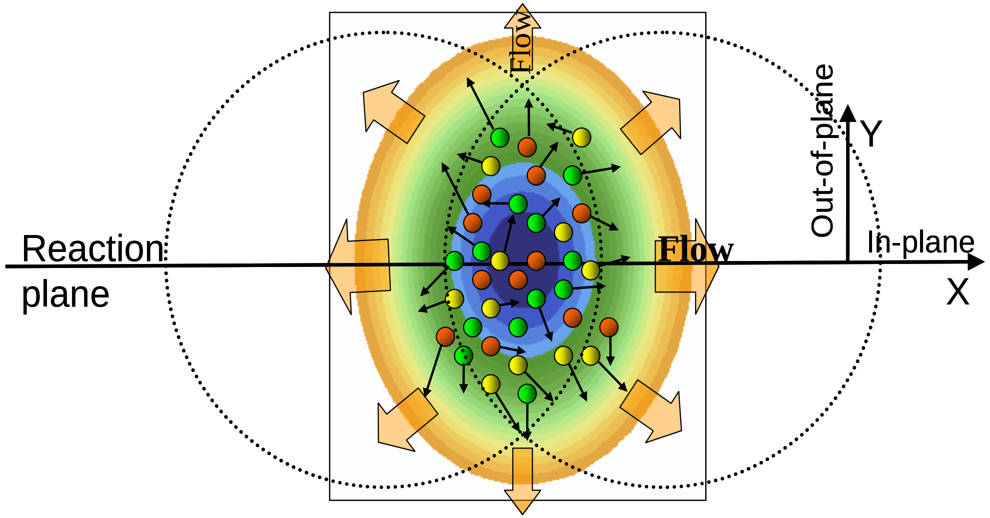
pp reference



# Heavy flavours in Pb-Pb collisions

## Observable: Elliptic Flow ($v_2$)

- Interaction among medium constituents convert the initial geometrical anisotropy into momentum anisotropy of final-state particles
- Quantified by the 2nd order fourier coefficient




$$\frac{dN}{d\phi} = \frac{N_0}{2\pi}\{1 + 2v_2 \cos[2(\phi - \Psi_{RP})] + \ldots.\}$$

$$v_2 = \langle \cos[2(\phi - \Psi_{RP})] \rangle$$

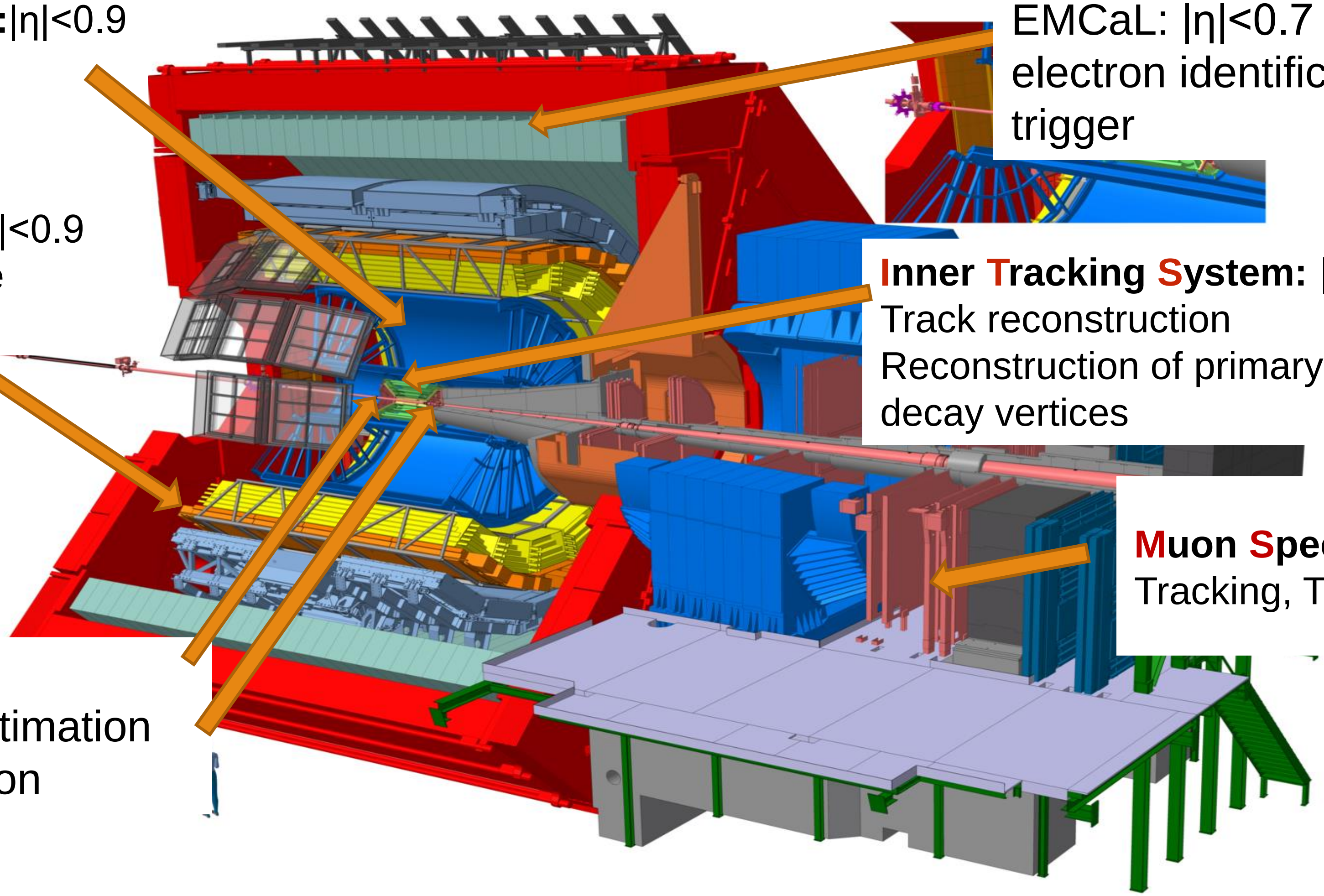
Carries information on the medium transport properties :

- At low $p_T$: participation in the collective motion and possible thermalisation of heavy quarks in the medium
- At high $p_T$: path-length dependence of energy loss

# A Large Ion Collider Experiment (ALICE)

**Time Projection Chamber:**|η|<0.9
Track reconstruction
Particle identification via specific energy loss

**Time of Flight detector:** |η|<0.9
Particle identification via the time-of-flight measurement



**EMCaL:** |η|<0.7
electron identification
trigger

**Inner Tracking System:** |η|<0.9
Track reconstruction
Reconstruction of primary and decay vertices

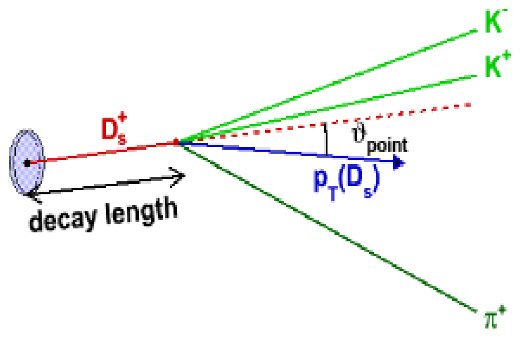
**Muon Spectrometer**: $-4<\eta<-2.5$
Tracking, Trigger, μID

**V0 detectors**
Trigger, Centrality estimation
Event-plane estimation

# Open heavy flavours with ALICE

- Fully reconstructed charmed and baryon mesons via hadronic and semi-leptonic decays

  $D^0 \rightarrow K^-\pi^+$, $D^+ \rightarrow K^-\pi^+\pi^+$, $D^{*+} \rightarrow D^0\pi^+$, $D_s^+ \rightarrow \Phi\,\pi^+ \rightarrow K^-K^+\pi^+$,
  $\Lambda_c^+ \rightarrow \pi^+K^-p$, $\Lambda_c^+ \rightarrow K^0_s\,p$, $\Lambda_c^+ \rightarrow e^+\nu_e\Lambda$, $\Xi_c^0 \rightarrow e^+\,\Xi^-\nu_e$

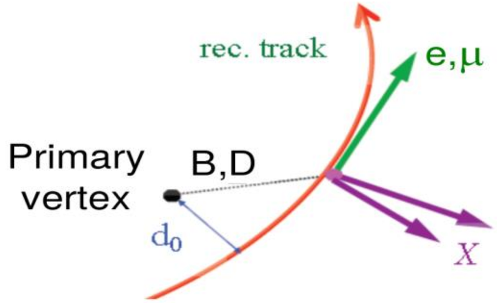



- Invariant mass analysis of fully reconstructed decay topologies displaced from the primary vertex
- Particle identification using TPC and TOF to reduce the background

Partially reconstructed **semi-leptonic decays**

**Electron channel:** D, B $\rightarrow e^{\pm} + X$

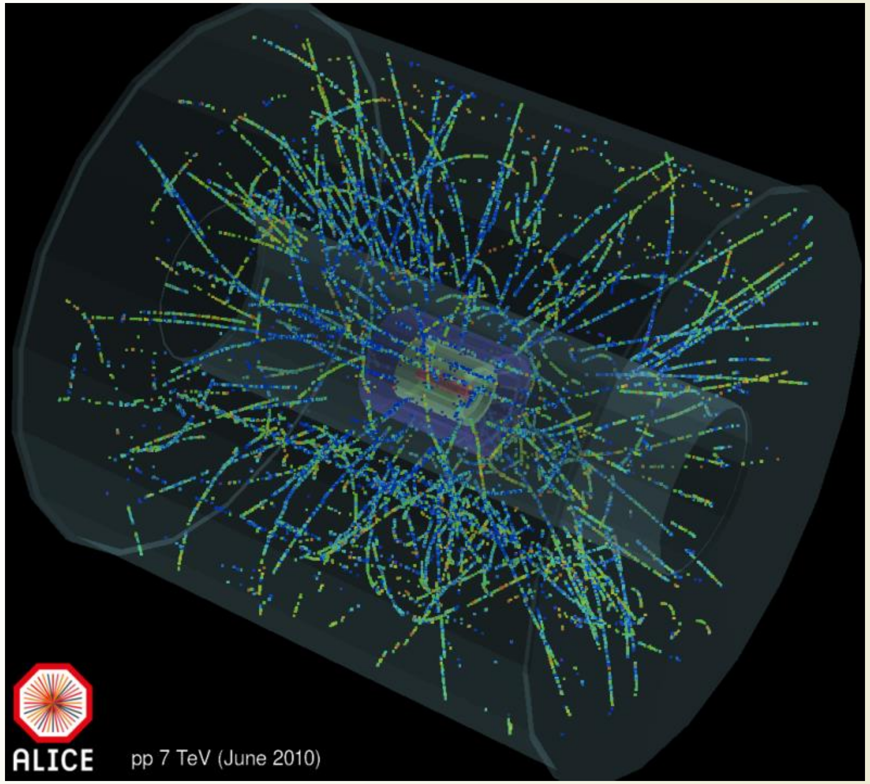
- Electron identification using TPC and TOF at low and intermediate $p_T$ and EMCAL at high $p_T$
- Background (Dalitz decay of neutral mesons and ϒ conversions) subtraction via invariant mass analysis of electron pair
- Background (J/Ψ decays and W/Z/ϒ decays) subtraction via Monte carlo simulation



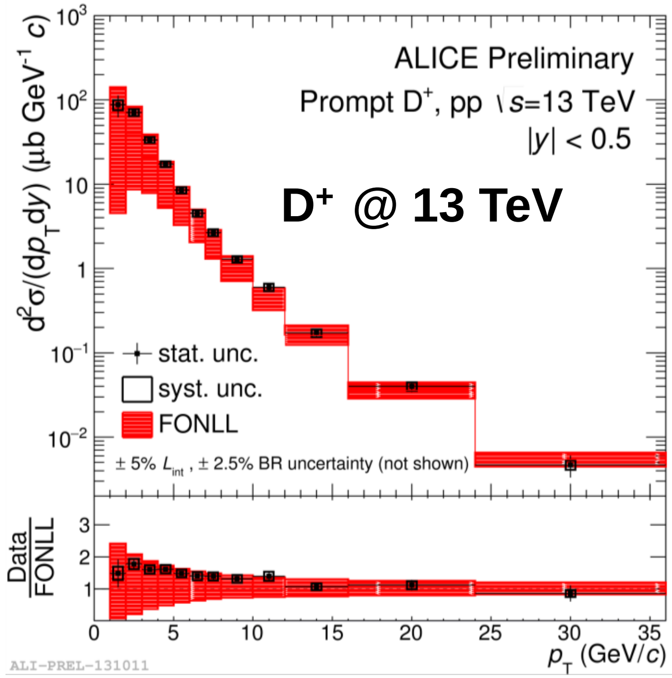

**Muon channel:** D, B $\rightarrow \mu^{\pm} + X$

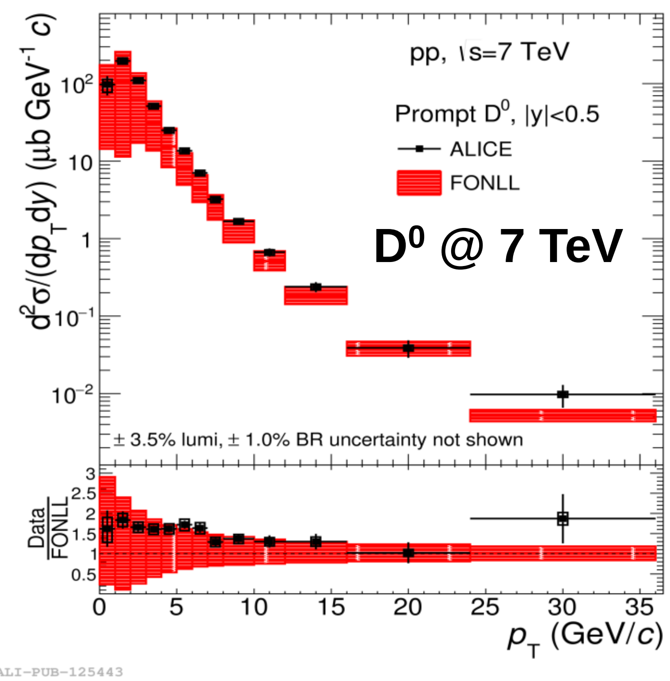
- Background (non-HF muons from light-hadron decays, J/Ψ decays and W/Z/ϒ decays) subtraction via Monte carlo simulation

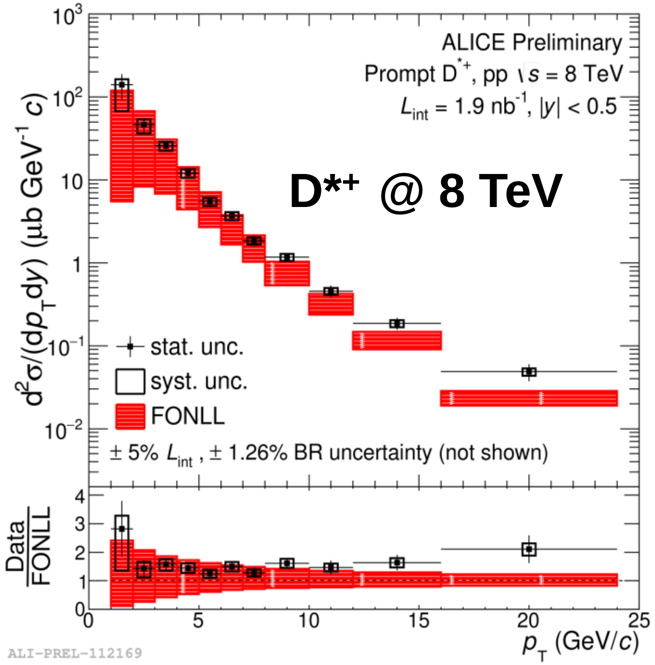
# pp collisions: a benchmark !!



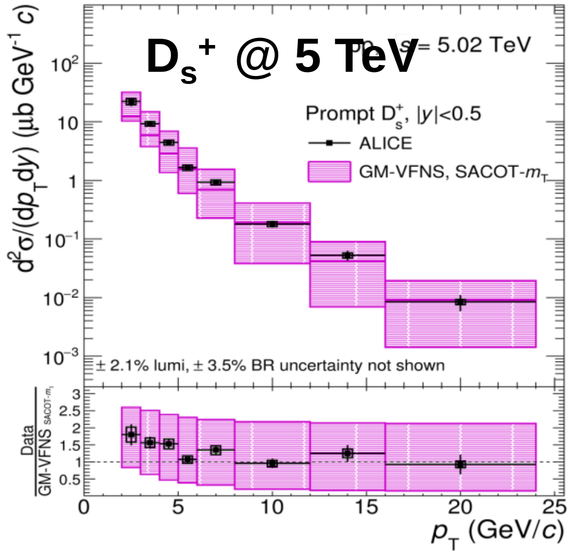
# D-meson production cross section




- D-meson cross section at 4 different collision energies: 13 TeV, 8TeV, 7 TeV and 5 TeV
- Cross sections at LHC energies well **described by NLO pQCD predictions**
- Data tends to sit on the upper side of the FONLL uncertainty band

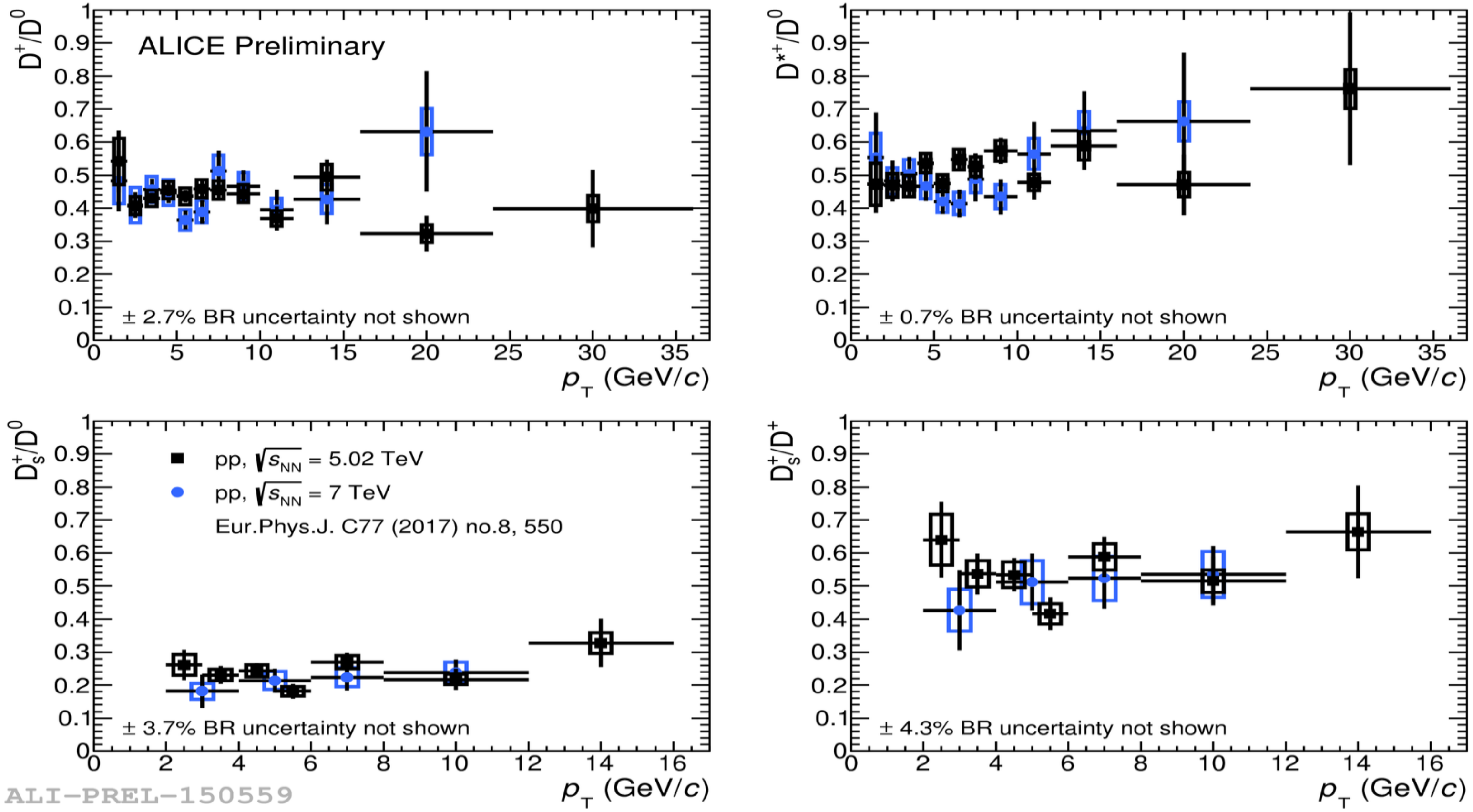




ALICE, arXiv:1901.07979
ALICE, EPJC77 (2017) 550

FONLL: JHEP, 1210 (2012) 137
GM-VFNS: Eur.Phys.J., C72(2012)2082, Nucl. Phys. B, 872(2013) 253
LO $k_T$ fact: Phys.Rev., D87 (2013) 094022

# D-meson production cross section ratio

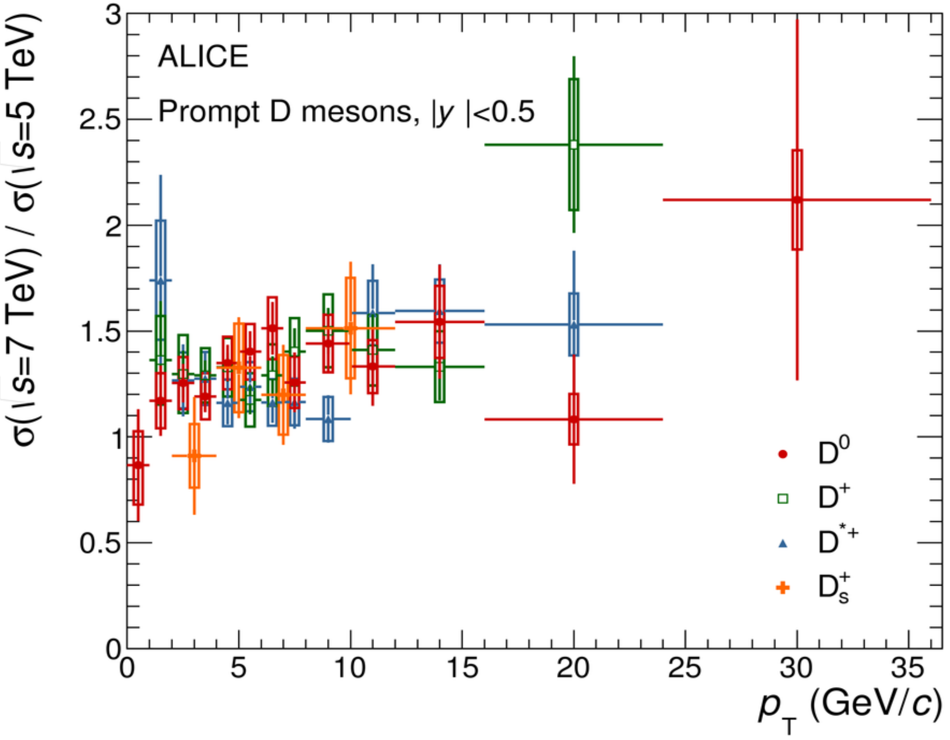


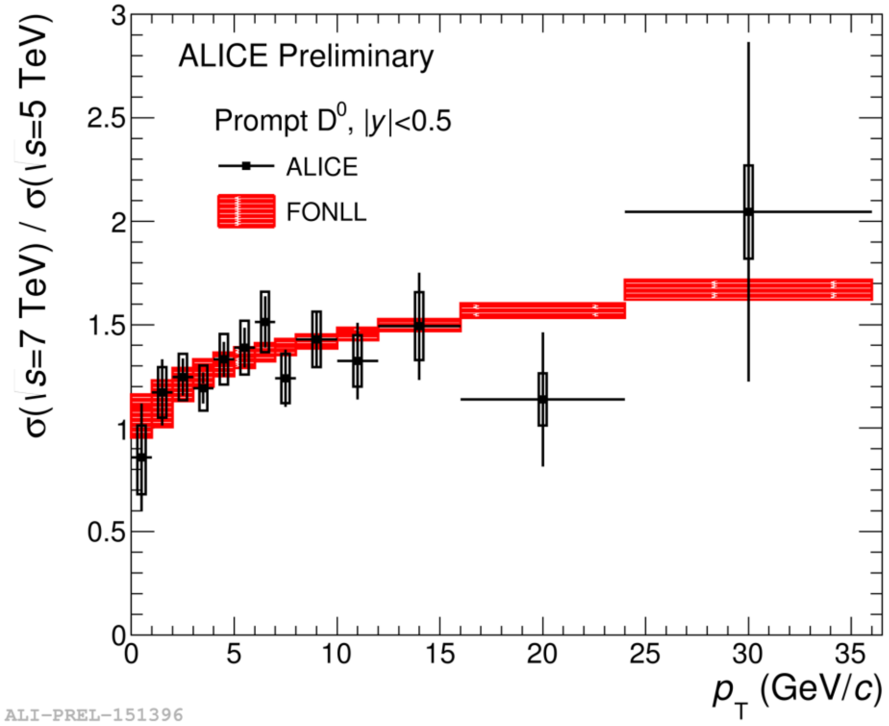

D-meson cross section ratios do not show a significant $p_T$ dependence within the experimental uncertainties

- ➢ No noticeable difference between fragmentation functions of charm quarks to strange and non-strange D mesons

# D-meson production cross section: energy dependence

D-meson measurement down to $p_T$=0 at different centre of mass energies and rapidities provide the sensitivity to the gluon PDF at small values of Bjorken $x$ ($10^{-4}$-$10^{-5}$)



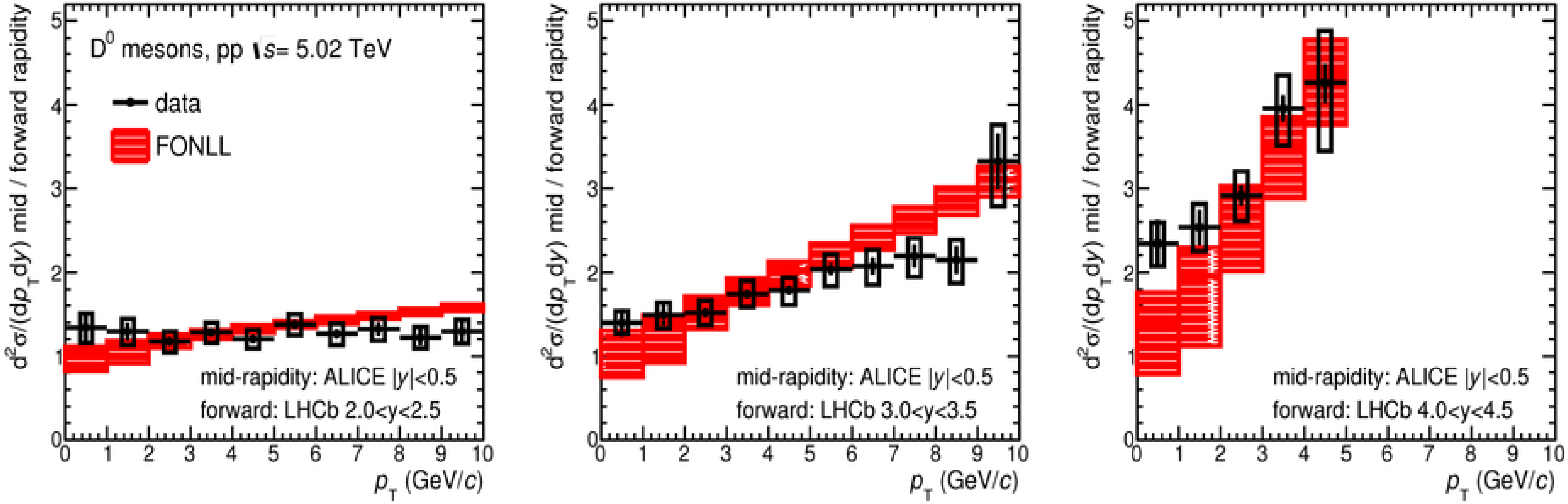




- Ratio of production cross sections of different D-meson species in pp collisions at $\sqrt{s}$ **=7 TeV and** $\sqrt{s}$ **= 5 TeV are compatible within uncertainties**
  - Comparison with FONLL calculation shows consistently an increasing trend as a function of $p_T$

# D-meson production cross section: rapidity dependence

D-meson measurement down to $p_T$=0 at different centre of mass energies and rapidities provide the sensitivity to the gluon PDF at small values of Bjorken $x$ ($10^{-4}$-$10^{-5}$)

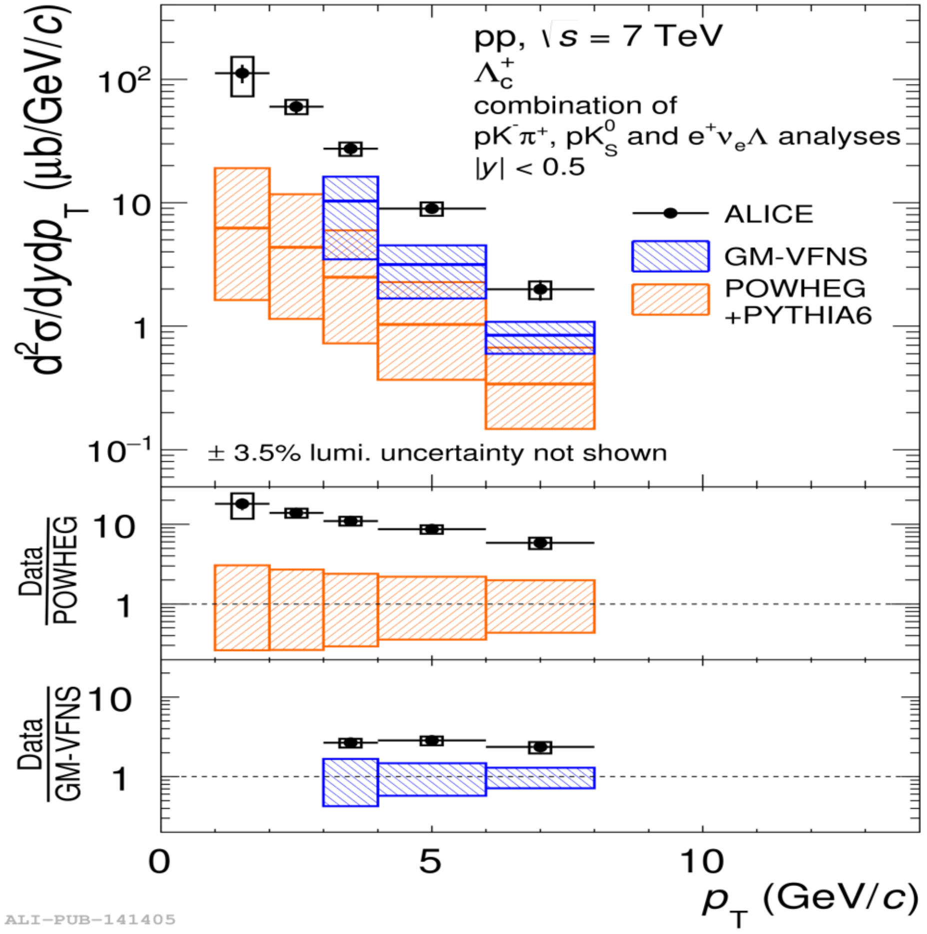
ALICE, arXiv:1901.07979



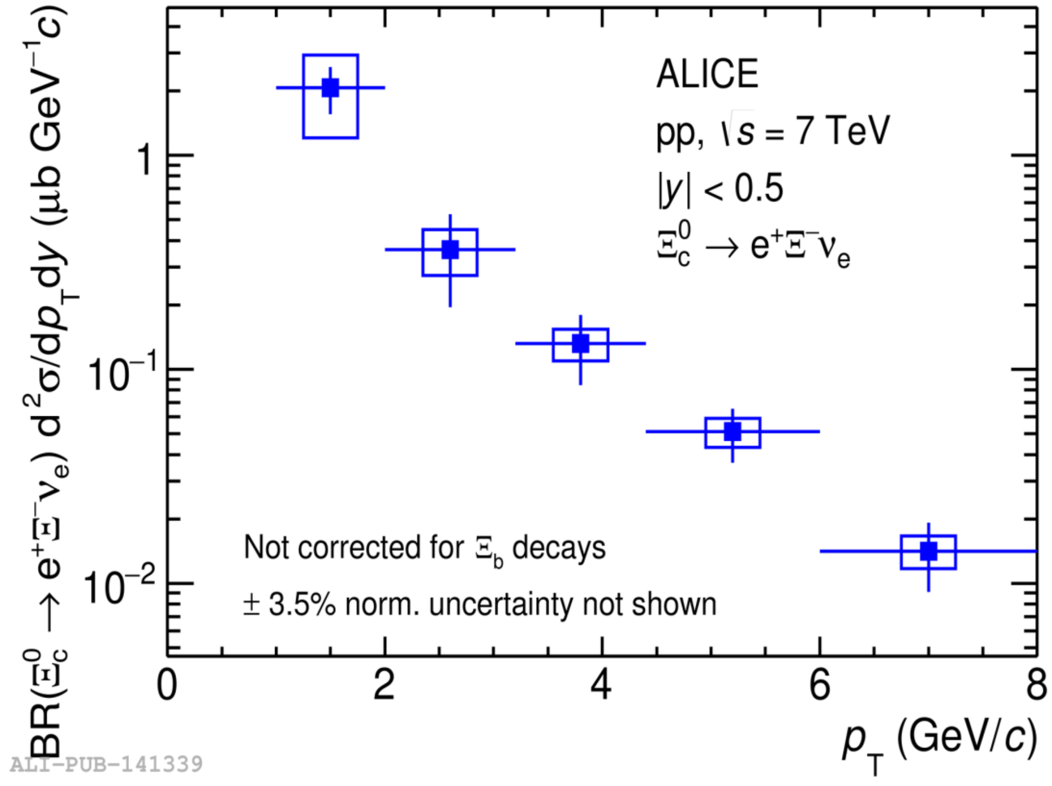

- Ratio of $D^0$ meson production cross section measured with ALICE (midrapidity) and LHCb (forward rapidity) compatible with FONLL calculations
  - hint of different slopes in data with respect to theoretical predictions

# Charmed-baryon production

JHEP 1804 (2018) 108




PLB781 (2018)

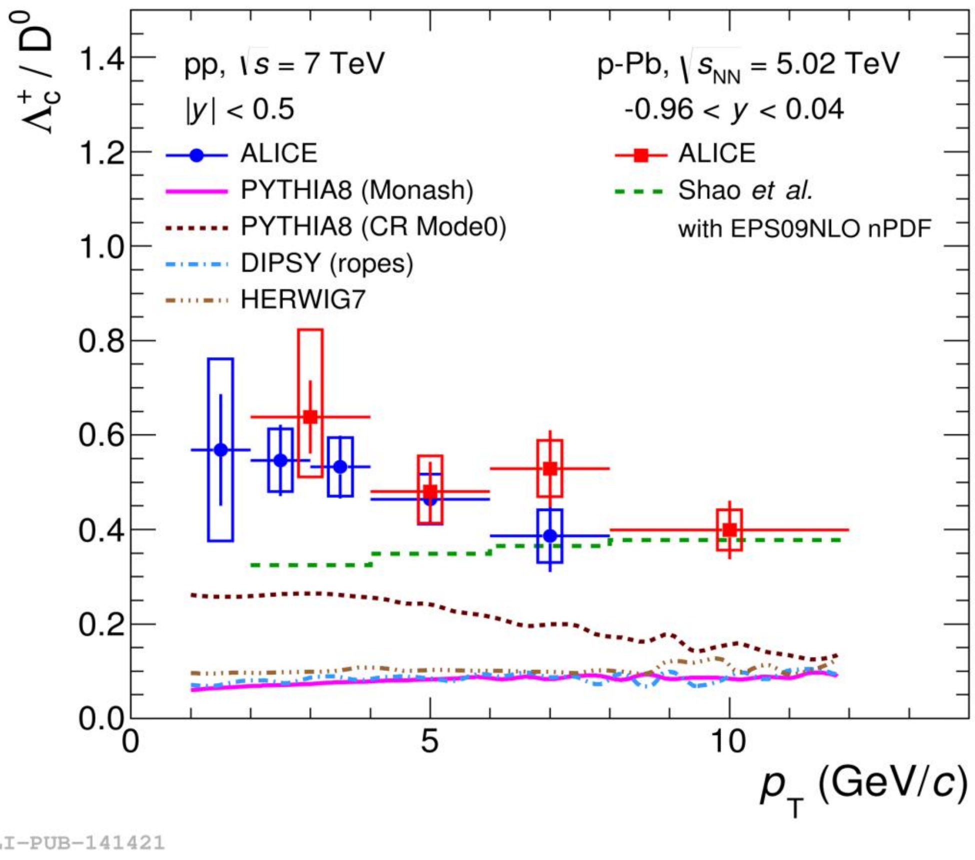



**First measurement of $\Xi_c^0$ $p_T$-differential cross section in pp collisions at the LHC (BR unknown)**

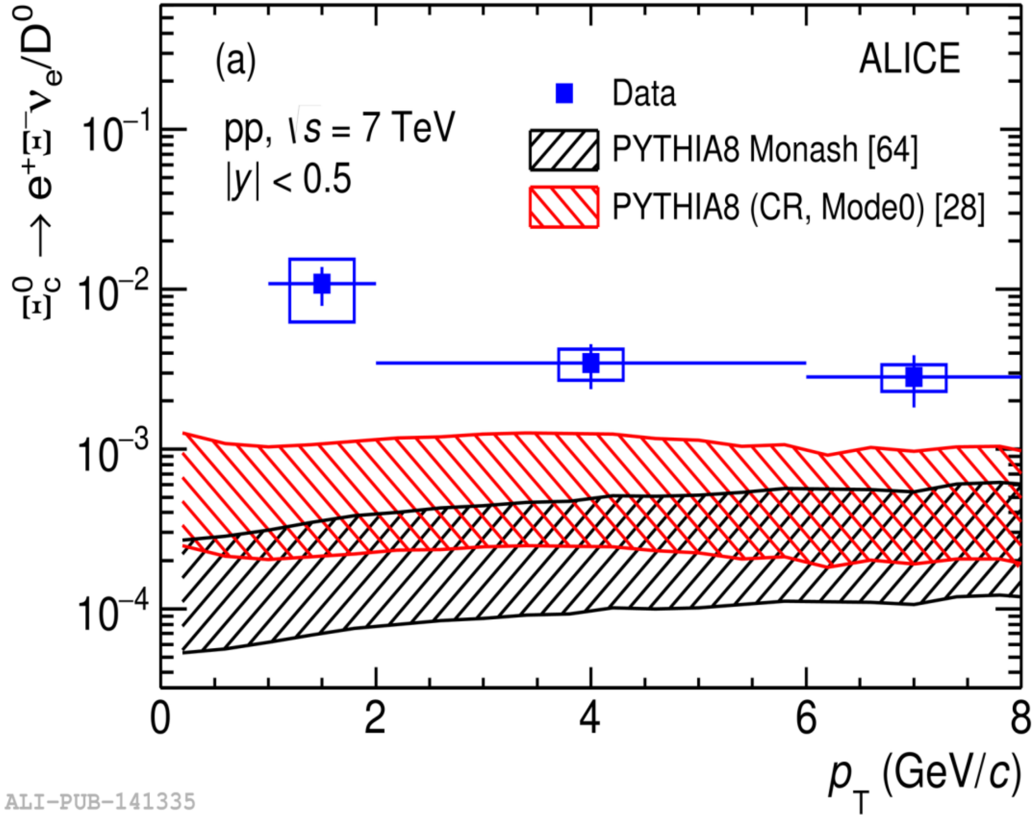
- Combination of $\Lambda_c^+ \to pK^-\pi^+$, $\Lambda_c^+ \to pK^0_s$, $\Lambda_c^+ \to e^+\nu_e\Lambda$
- $\Lambda_c^+$ $p_T$-differential cross section **underestimated** by NLO theory: GM-VFNS, POWHEG+PYTHIA
  - describe well D mesons
  - Fragmentation tuned to results from lower energy, $e^+e^-$ (GM-VFNS)

# Charmed-baryon production

JHEP 1804 (2018) 108




PLB781 (2018)




- **$\Lambda_c^+/D^0$ and $\Xi_c^0/D^0$** ratios larger than model predictions (PYTHIA8 with enhanced color reconnection closer to data)
- $\Lambda_c^+/D^0$ ratios compatible in pp and p-Pb collisions
- Crucial to constrain models of charm hadronization

# Open heavy-flavour decay electron

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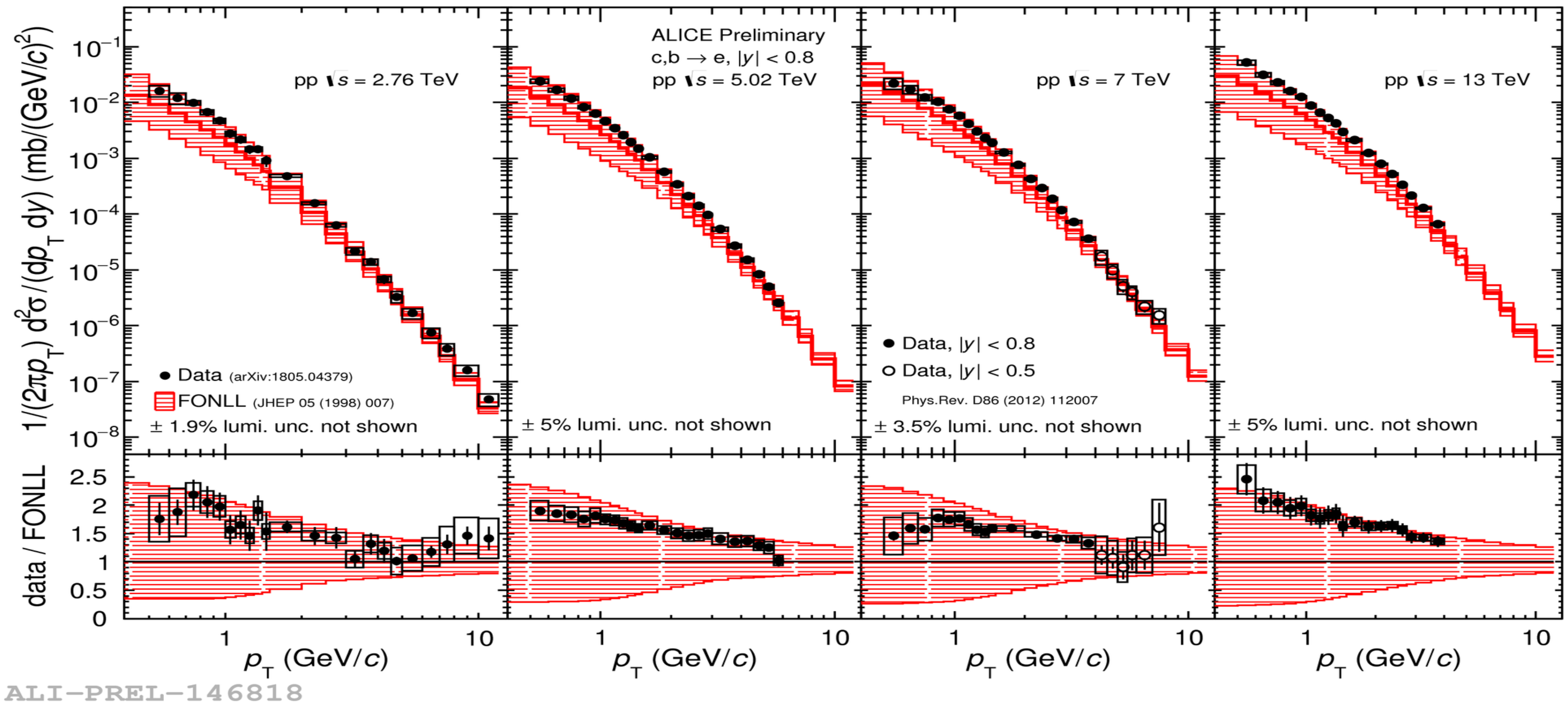
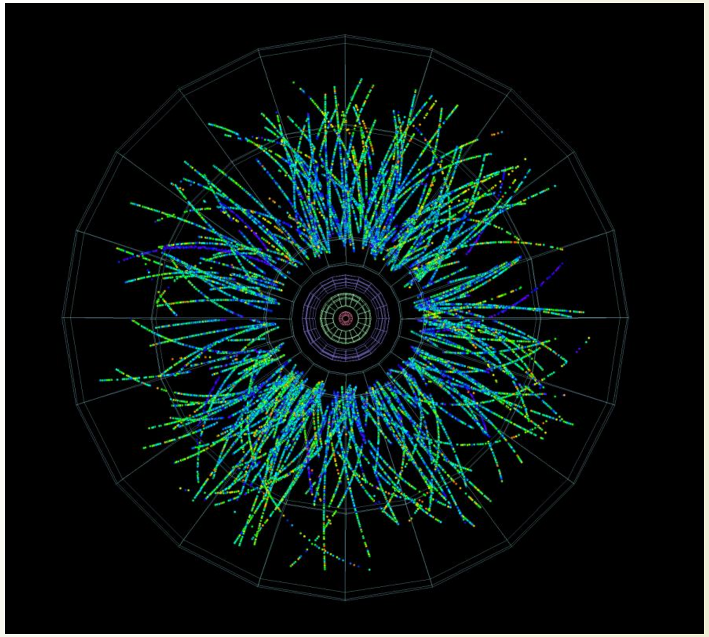
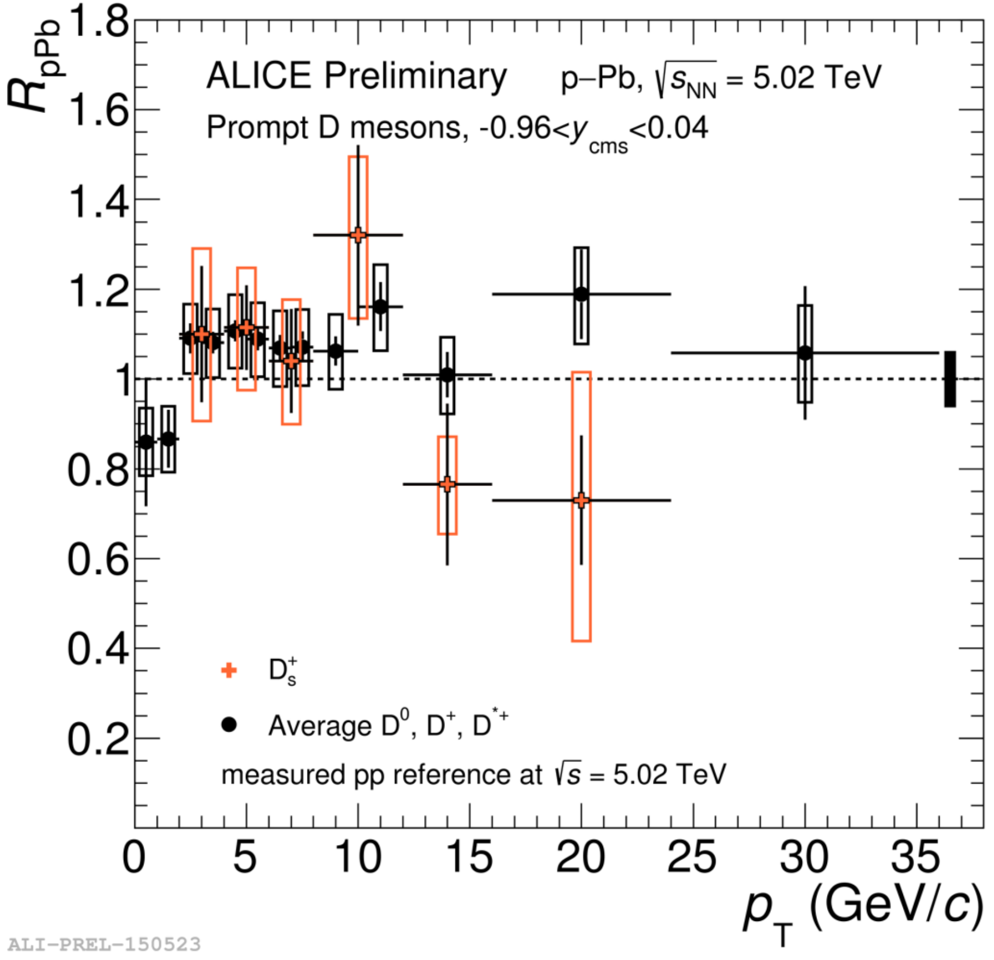



- Electrons from c and b(→ c) decays at mid-rapidity
- Data consistently at the upper edge of FONLL calculation at all energies (2.76, 5.02, 7 and 13 TeV)
- Large reduction of systematic uncertainty in the measurements w.r.t. previous publications (data-driven method to subtract non-HF decay electron background)

# p-Pb collisions: the control experiment



# D-meson Nuclear Modification factor ($R_{\mathrm{pPb}}$)

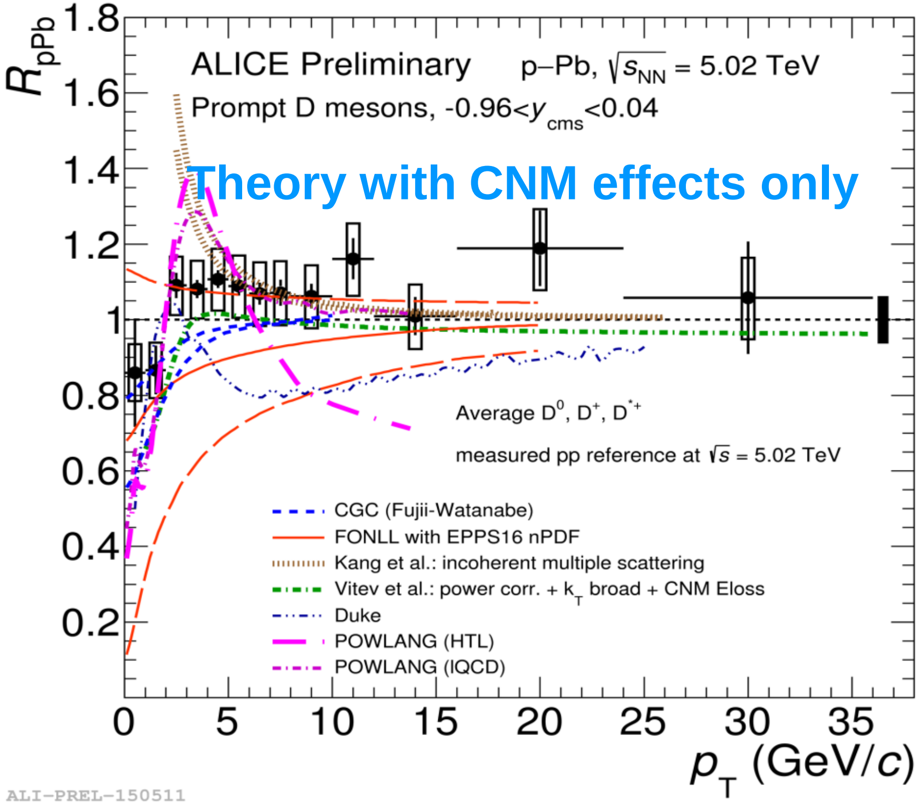


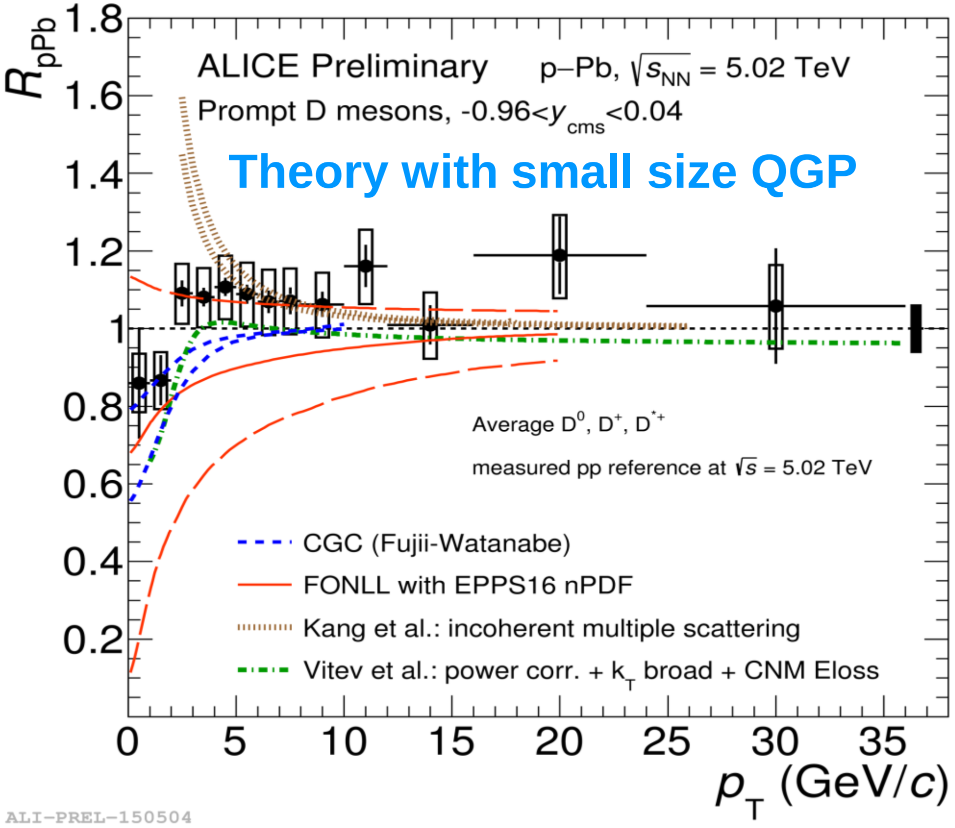

$$R_{\mathrm{pPb}} = \frac{1}{A} \frac{\mathrm{d}^2\sigma_{\mathrm{pPb}}^{\mathrm{prompt\,D}}/\mathrm{d}p_{\mathrm{T}}\mathrm{d}y}{\mathrm{d}^2\sigma_{\mathrm{pp}}^{\mathrm{prompt\,D}}/\mathrm{d}p_{\mathrm{T}}\mathrm{d}y}$$

- $D^0$ measured down to $p_T$ = 0:
  - improved precision due to new reference
- $R_{\mathrm{pPb}}$ compatible with unity for both non-strange and strange D mesons

**No significant modification of D-meson production in p-Pb collisions wrt pp collisions is observed within uncertainties**

# D-meson Nuclear Modification factor ($R_{pPb}$) vs Models



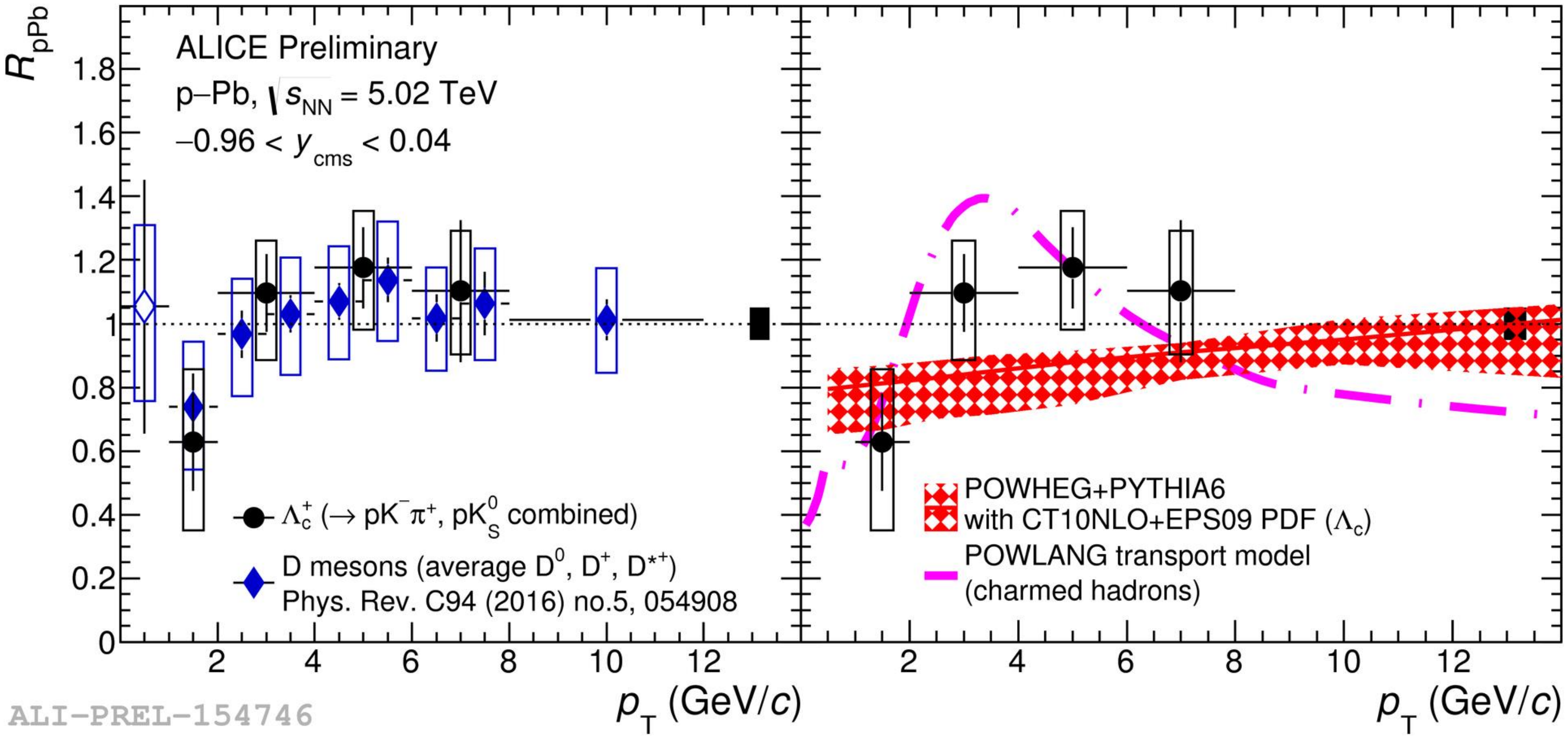




**Models** including:

- Cold Nuclear Matter (CNM) effects are compatible with data within uncertainties
- Incoherent scattering describes the data $p_T$>5 GeV/c within uncertainties
- Small size QGP can describe data at low and intermediate $p_T$

Data do not favour a suppression larger than 10-15% for 5 < $p_T$ < 12 GeV/$c$

# Charmed baryons $R_{\mathrm{pPb}}$

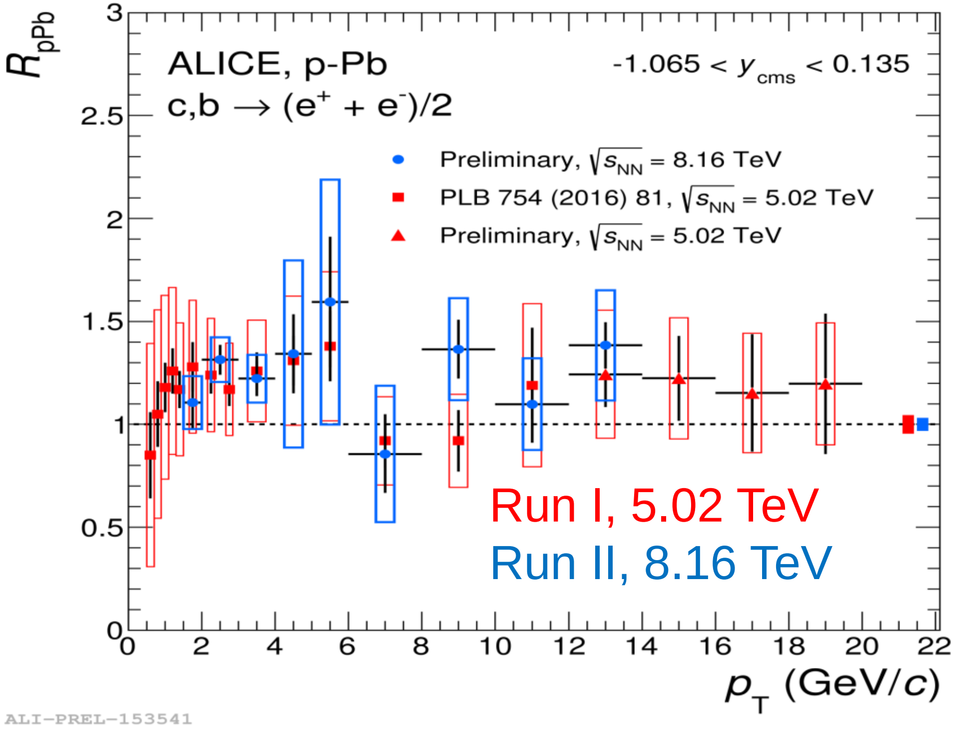



- Charmed baryon **$\Lambda_c$ $R_{pPb}$** compatible with **D-meson $R_{pPb}$** and consistent with unity within uncertainties
- Data well described by the models including CNM effects and small size QGP formation in p-Pb collisions

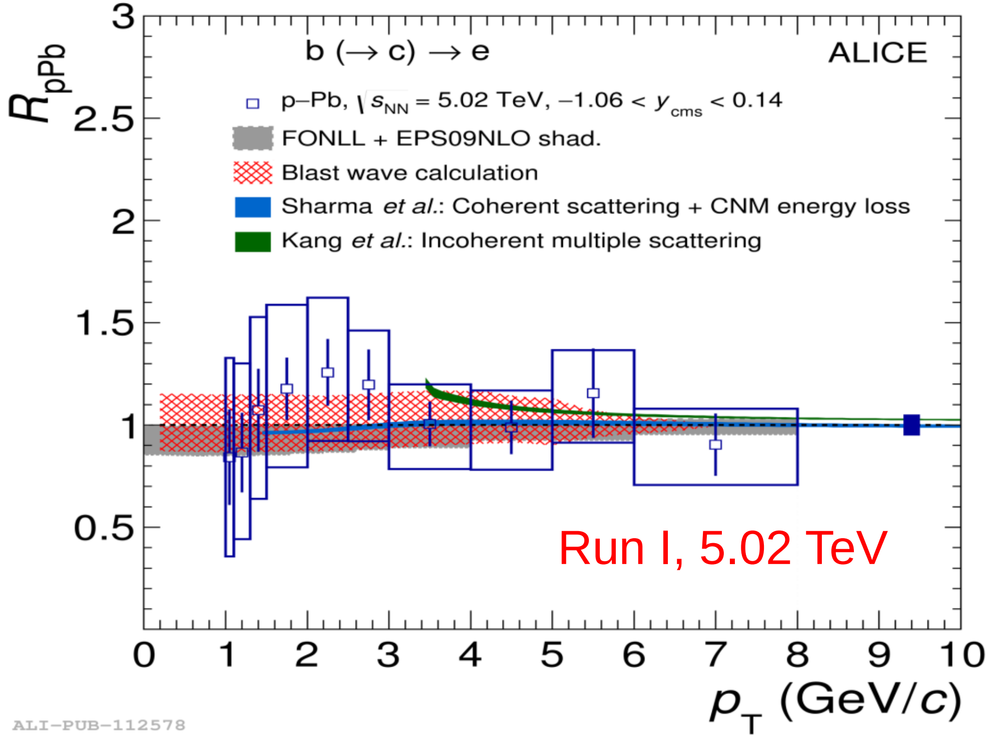
# Heavy-flavour decay electron $R_{pPb}$

JHEP 1707 (2017) 052

**electrons from charm+beauty decays**




**electrons from beauty decays**

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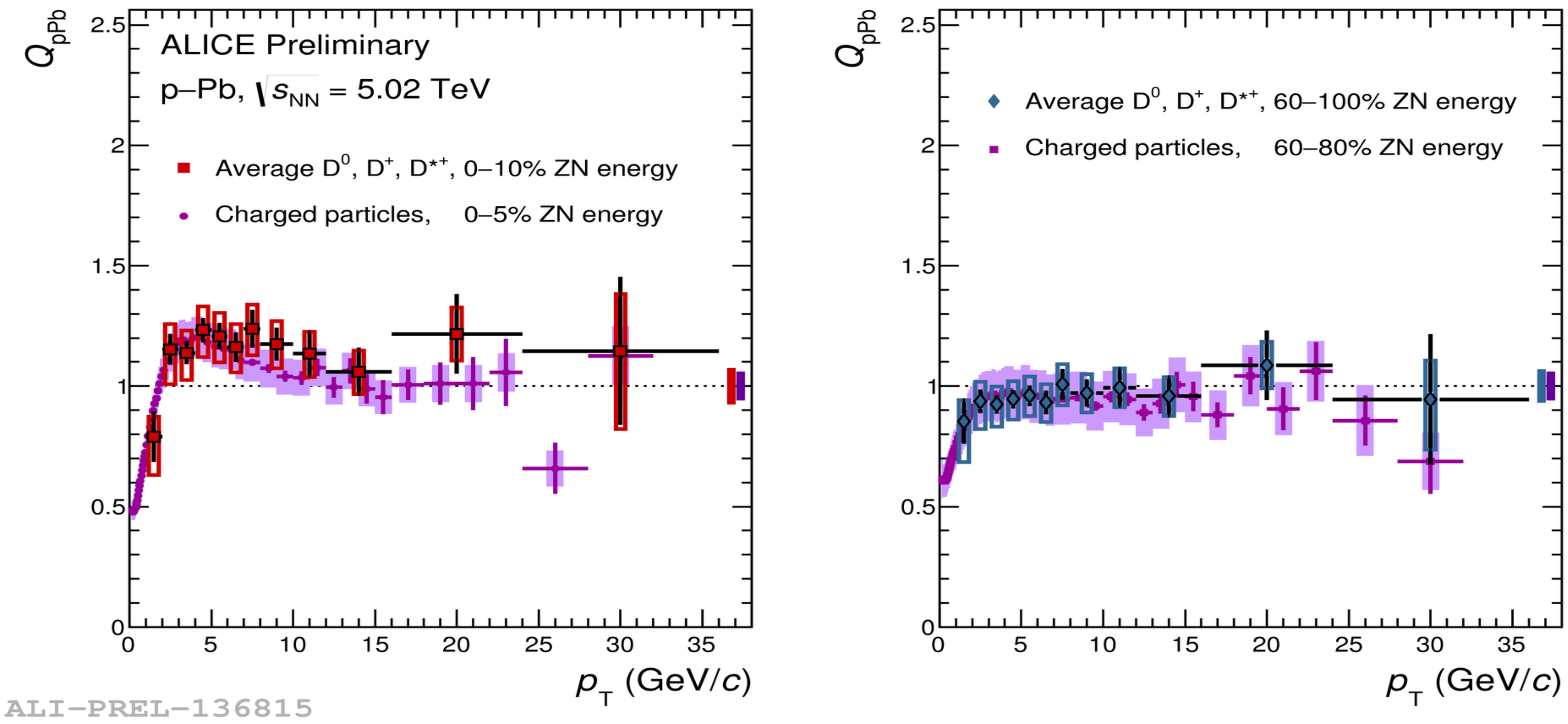
- Heavy-flavour hadron decay electron $R_{pPb}$ compatible with unity
- $R_{pPb}$ from Run-1 at $\sqrt{s_{NN}}$ = 5.02 TeV and Run-II at $\sqrt{s_{NN}}$ = 8.16 TeV are compatible within uncertainties → no energy dependence within uncertainties
- Data described by models that include CNM effects

# D-meson production in different centrality classes: $Q_{\mathrm{pPb}}$

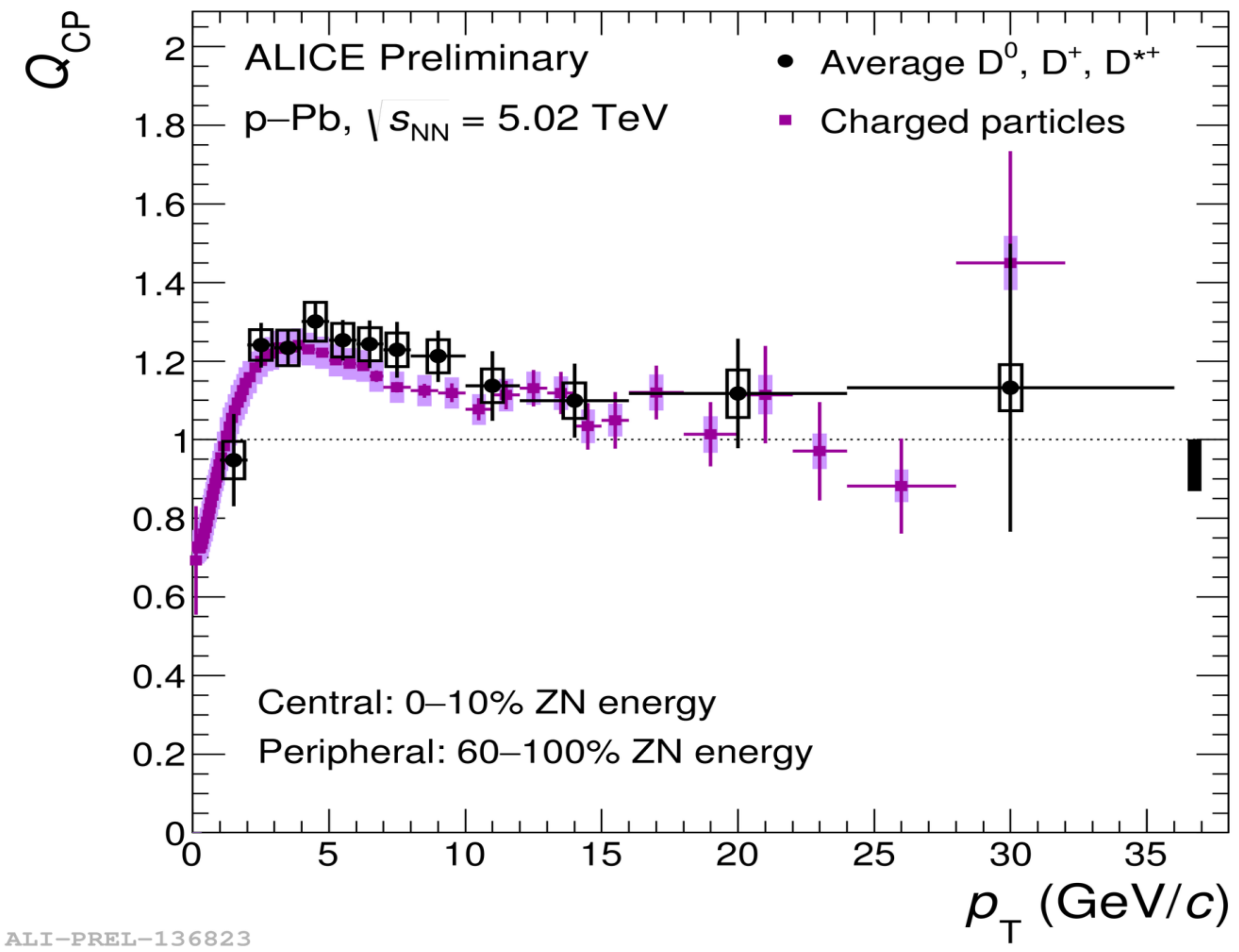
To investigate the high multiplicity p-Pb collisions




$$Q_{\mathrm{pPb}}^{\mathrm{cent}} = \frac{\left(\mathrm{d}^2 N^{\mathrm{prompt\,D}}/\mathrm{d}p_{\mathrm{T}}\mathrm{d}y\right)_{\mathrm{pPb}}^{\mathrm{cent}}}{\langle T_{\mathrm{pPb}}\rangle^{\mathrm{cent}} \times \left(\mathrm{d}^2\sigma_{\mathrm{pp}}^{\mathrm{prompt\,D}}/\mathrm{d}p_{\mathrm{T}}\mathrm{d}y\right)}$$

- $Q_{\mathrm{pPb}}$ in most **central (0-10%)** and **peripheral (60-100%)** centrality classes compatible within uncertainties and consistent with unity
- $Q_{\mathrm{pPb}}$ for D mesons and charged particles agree within uncertainties (slightly different centrality ranges)
- Hint of $Q_{\mathrm{pPb}}>1$ in central 0-10% in $3 < p_{\mathrm{T}} < 8$ GeV/$c$

# D-meson production in different centrality classes: $Q_{CP}$



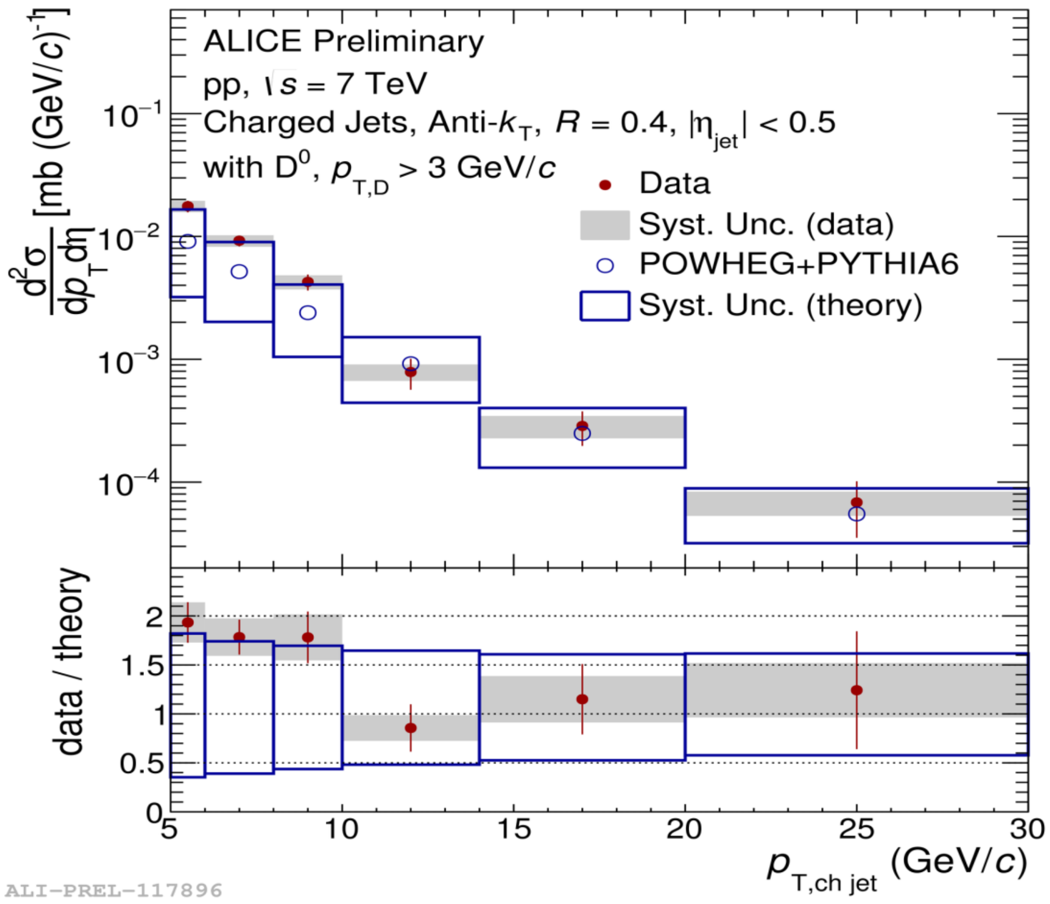

$$Q_{CP} = \frac{\left(d^2N^{\text{prompt}D}/dp_T dy\right)^{0-10}_{pPb} / \langle T_{pPb}\rangle^{0-10}}{\left(d^2N^{\text{prompt}D}/dp_T dy\right)^{60-100}_{pPb} / \langle T_{pPb}\rangle^{60-100}}$$

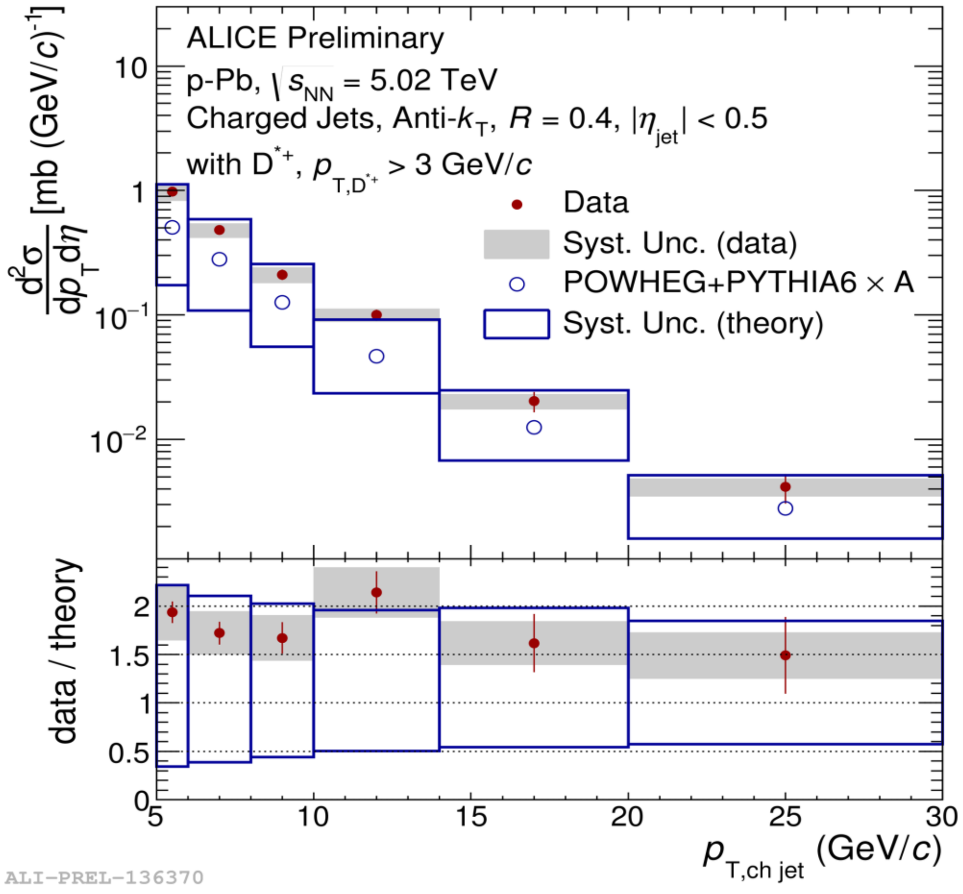
**$Q_{CP}$ more precise measurement than $Q_{pPb}$**

- ➢ independent from pp reference
- ➢ some sources of systematic uncertainties cancel in the ratio

- ➢ D meson central to peripheral ratio ($Q_{CP}$) similar to charged particle $Q_{CP}$
- ➢ Hint of $Q_{CP} > 1$ in $3 < p_T < 8$ GeV/c with **1.5 σ**
  - ➢ Initial or final-state effect?
  - ➢ Radial flow?

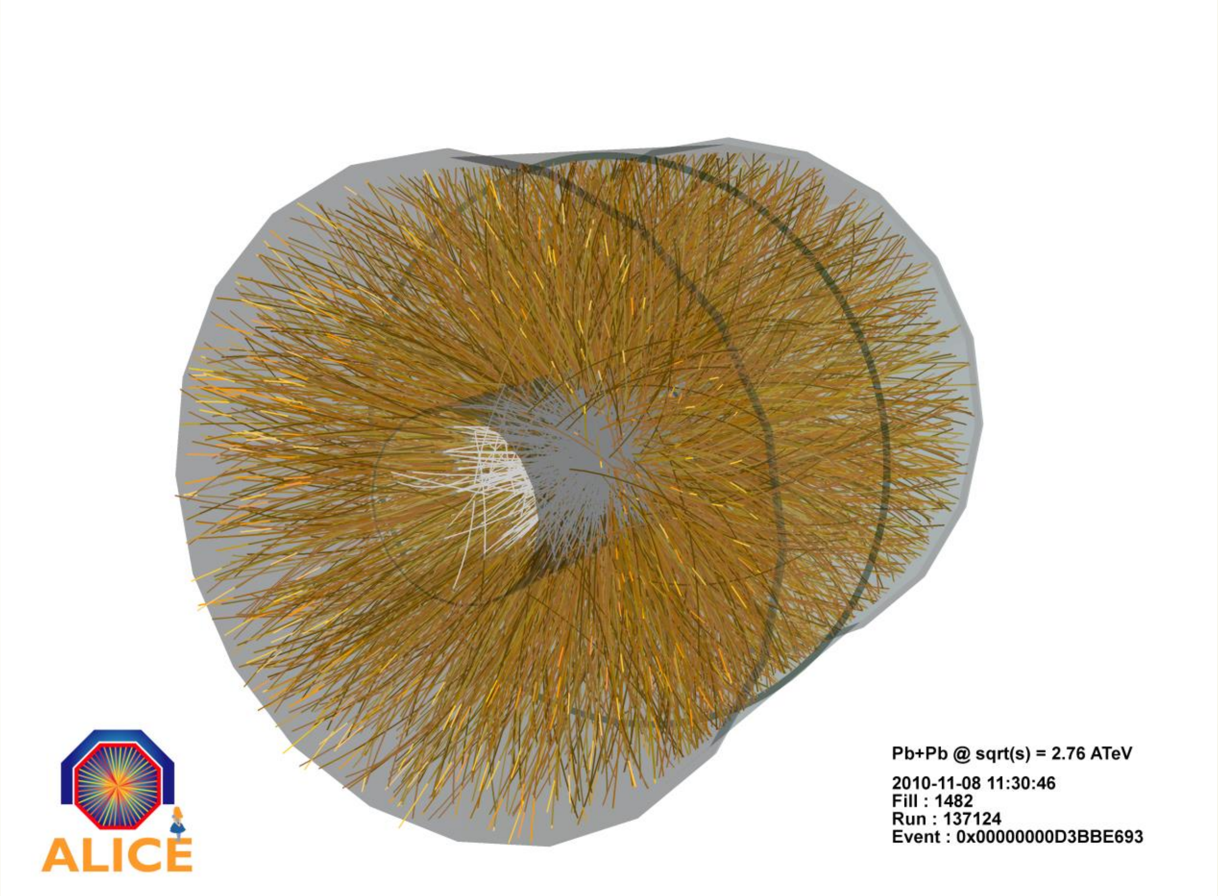
# D-tagged jets in pp and p-Pb collisions




- $p_T$-differential cross section of charged jets with a reconstructed $D^0$ meson inside the jet cone in pp and p-Pb collisions
  - Allow a closer access to charm-parton kinematics
- POWHEG+PYTHIA6 (Perugia11) describes data within uncertainties

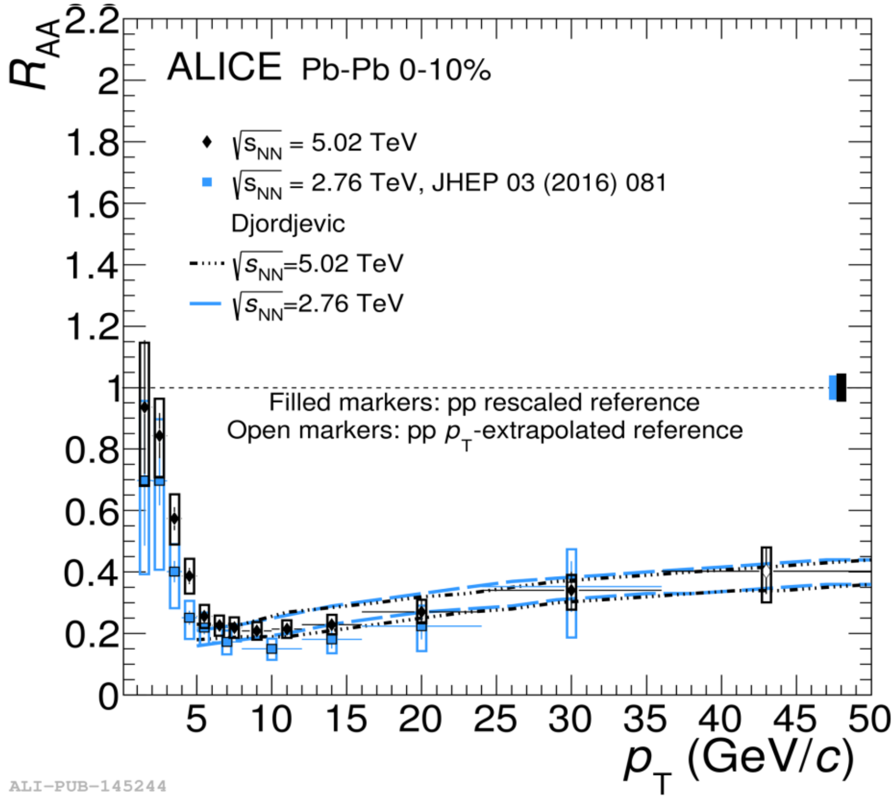
# Pb-Pb collisions: To study the medium effects

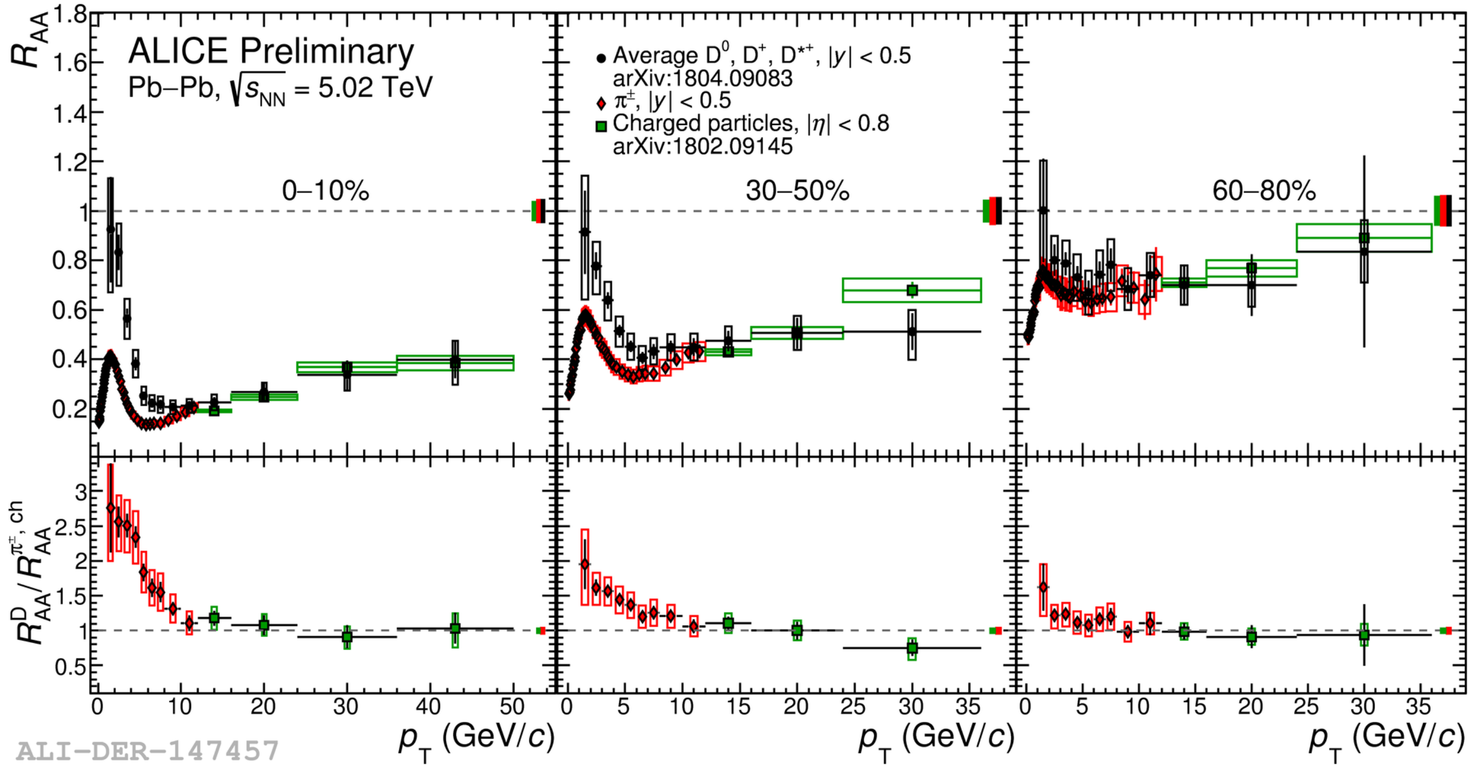


# D-meson nuclear modification factor

$$R_{AA}(p_T) = \frac{(dN/dp_T)_{AA}}{\langle T_{AA}\rangle \times (dN/dp_T)_{pp}}$$

arXiv:1804.09083




- Strong suppression of D-mesons in Pb-Pb collisions
- increasing with centrality
- Similar suppression between 2.76 and 5.02 TeV measurements (and improved precision in Run-2)
- Suppression described by model at the two energies → harder spectra and denser medium counterbalance

Comparison of D mesons and light hadrons $R_{AA}$

To investigate the quark mass and color charge dependence

$R_{AA}$(D) > $R_{AA}(\pi^\pm)$ for $p_T$ < 8 GeV/$c$ in 0-10% and 30-50%

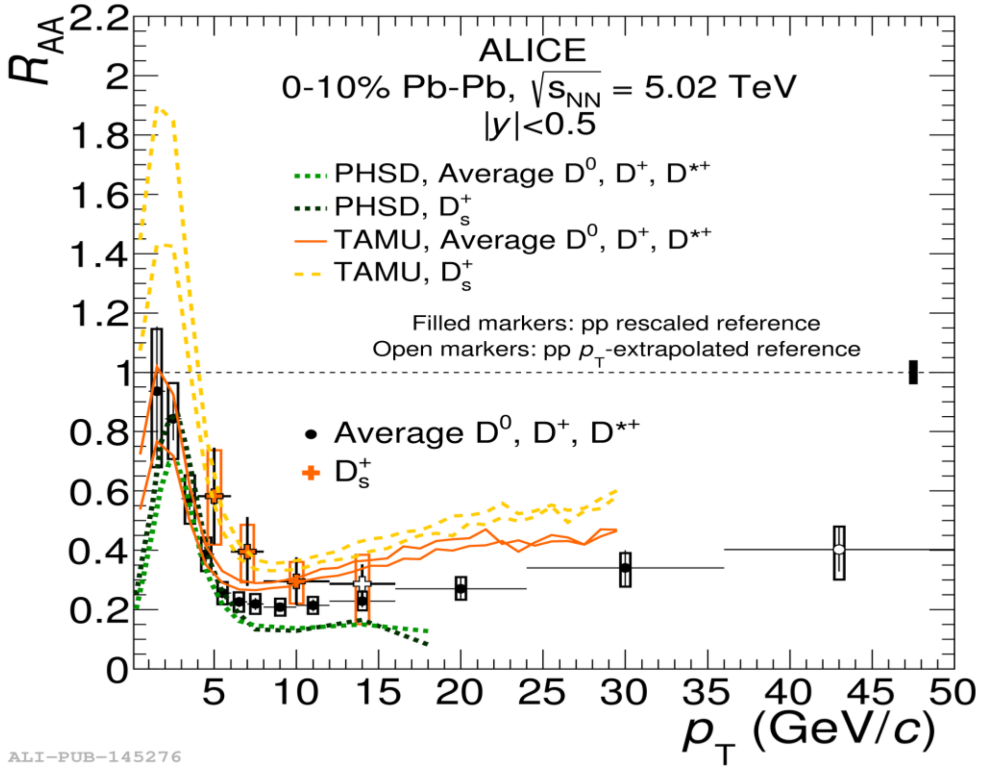
$R_{AA}$(D) ≃ $R_{AA}(\pi^\pm)$ ≃ $R_{AA}$(charged particles) in 60-80% and for $p_T$ > 8 GeV/$c$ in 0-10% and 30-50%

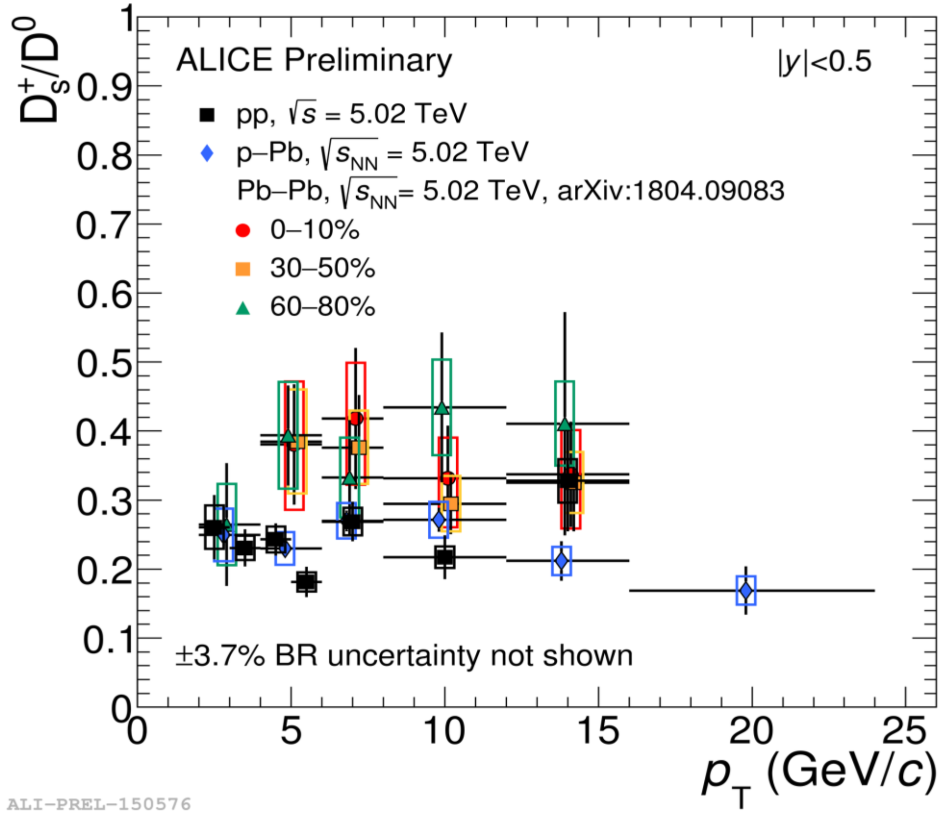
# $D_s^+$ nuclear modification factor

$$R_{AA}(p_T) = \frac{(dN/dp_T)_{AA}}{\langle T_{AA}\rangle \times (dN/dp_T)_{pp}}$$

ALICE

arXiv:1804.09083



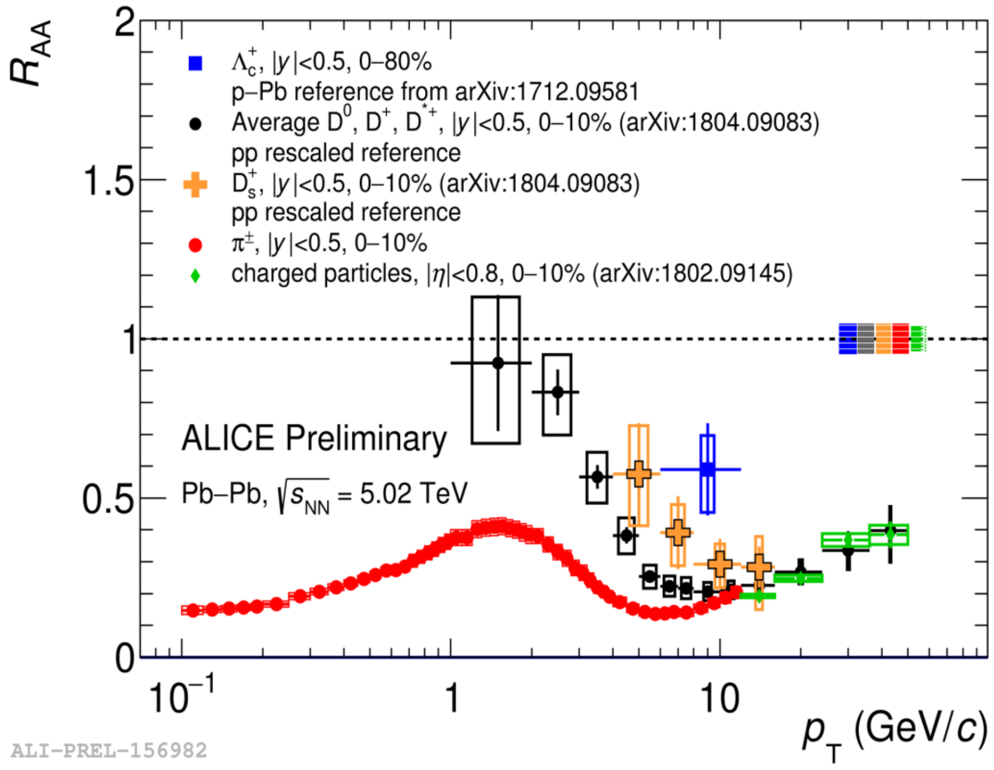




- Hint of **less suppression of $D_s^+$** than non-strange D-mesons in Pb-Pb collisions
- Models including charm quark coalescence describe the data

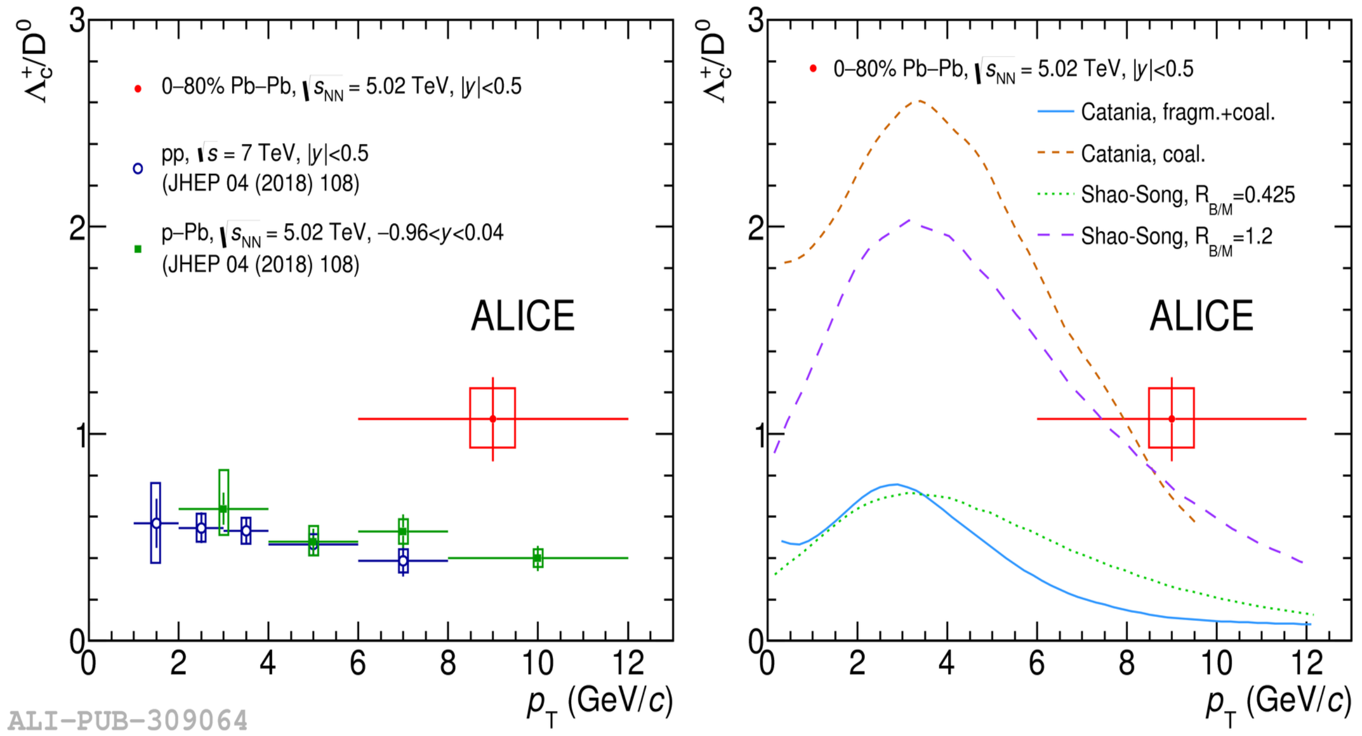
- Hint of **enhanced production of $D_s^+$** compared to non-strange D mesons in Pb-Pb wrt pp and p-Pb collisions (~1σ)

# $\Lambda_c^+$ nuclear modification factor

$$R_{AA}(p_T) = \frac{(dN/dp_T)_{AA}}{\langle T_{AA}\rangle \times (dN/dp_T)_{pp}}$$




arXiv:1809.10922



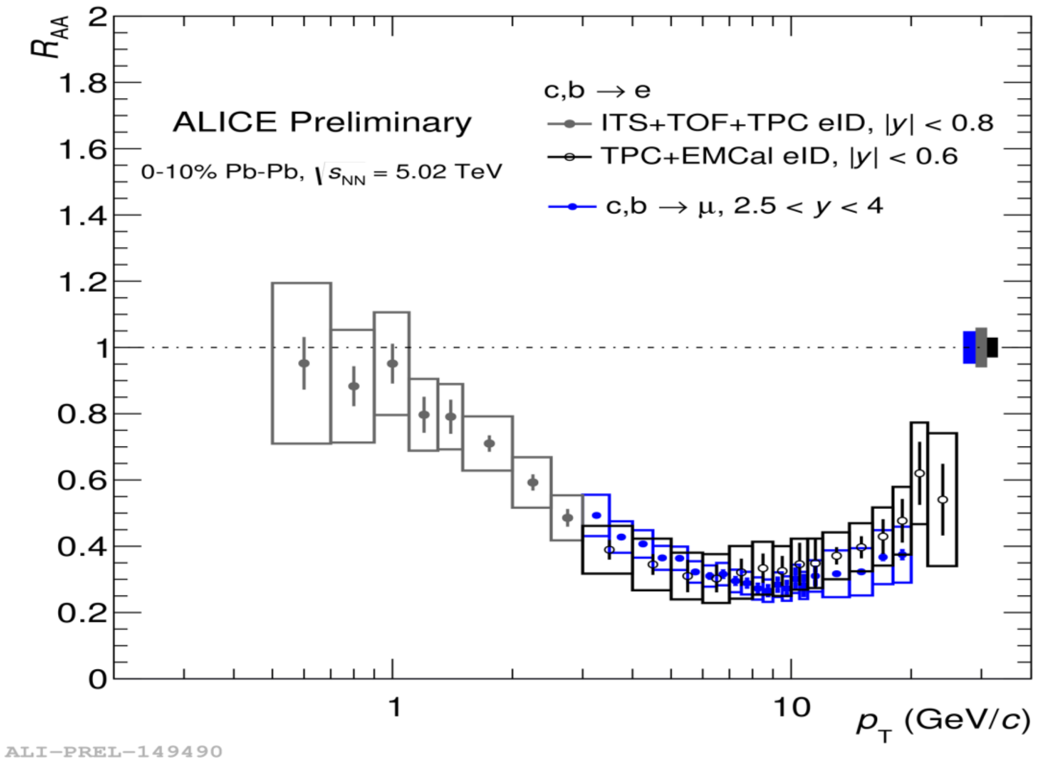

- $\Lambda_c^+$ $R_{AA}$ in 0-80% for 6 < $p_T$ < 12 GeV/$c$ higher (1.7σ) than that of D mesons
- Hint of an hierarchy: $\Lambda_c^+$ $R_{AA}$ > $D_s^+$ $R_{AA}$ > non-strange D mesons $R_{AA}$ > charged-particle $R_{AA}$

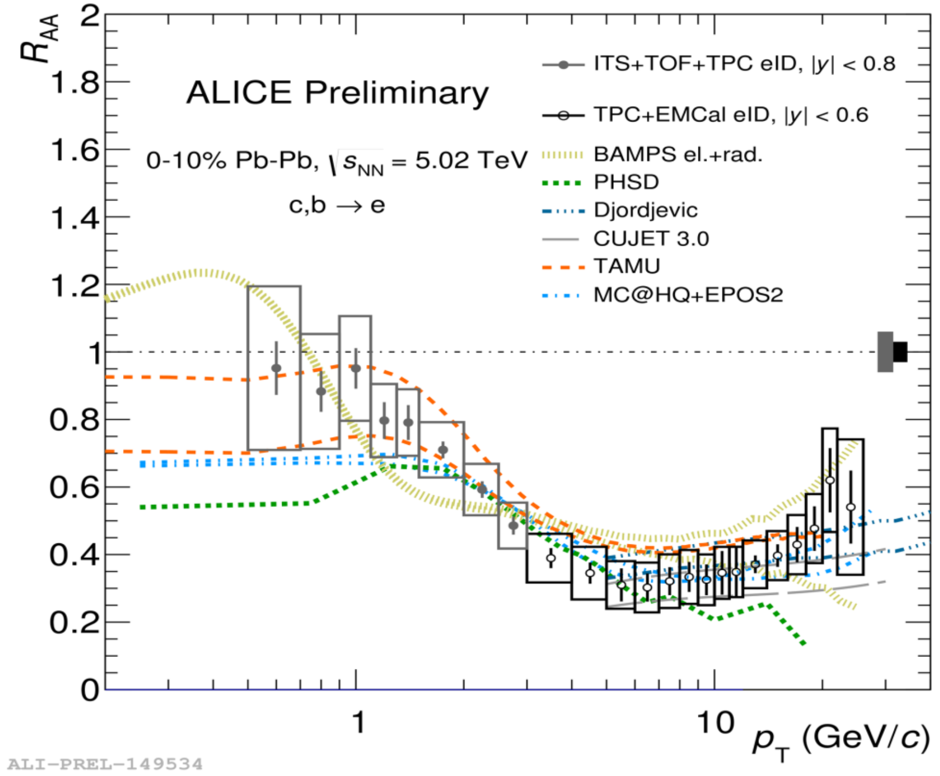
Charmed-baryon production increased by hadronisation via coalescence?

- $\Lambda_c^+$ /$D^0$ in Pb-Pb higher (2σ) than that in pp and p-Pb collisions
- Results described by model calculations including only coalescence

# Open heavy-flavour decay lepton $R_{AA}$

$$R_{AA}(p_T) = \frac{(dN/dp_T)_{AA}}{\langle T_{AA} \rangle \times (dN/dp_T)_{pp}}$$

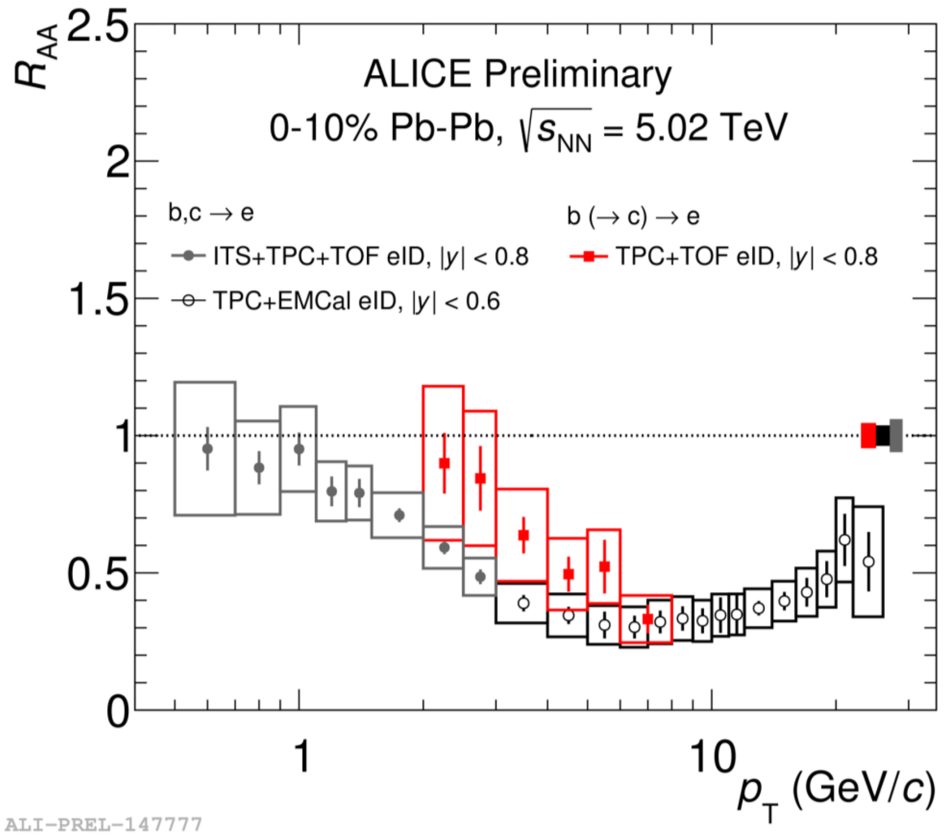


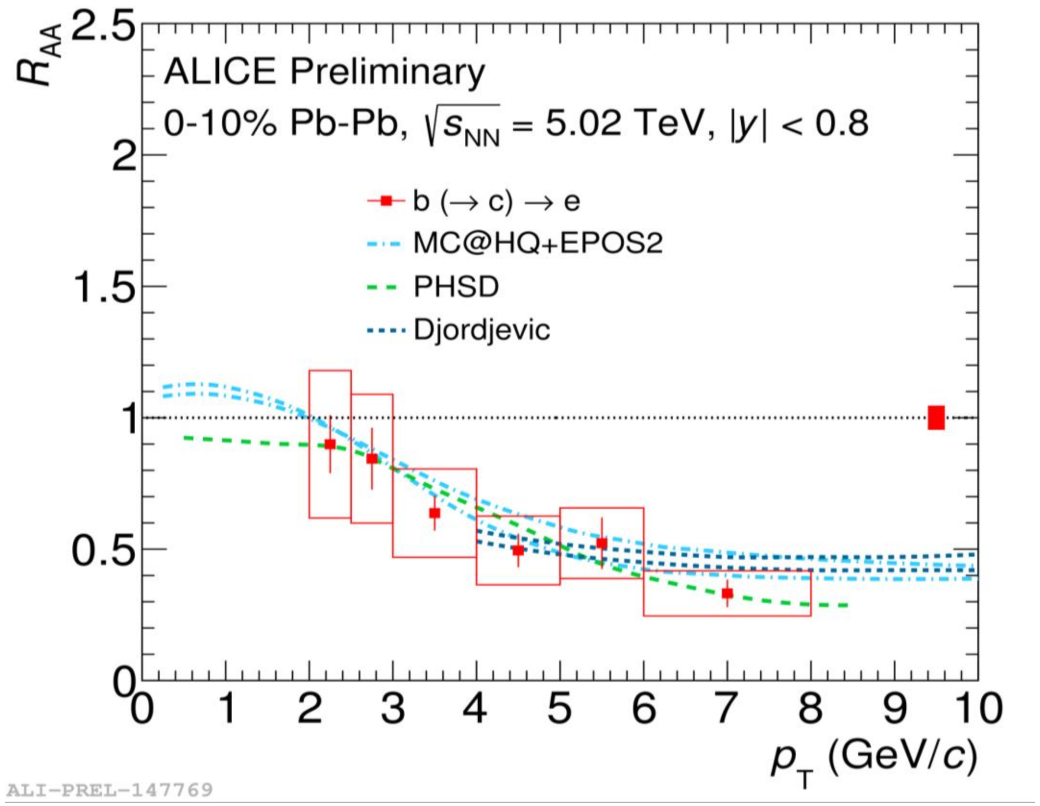




- Open heavy-flavour decay electron $R_{AA}$ in Pb-Pb 0-10% collisions at 5.02 TeV down to $p_T$ = 0.5 GeV/c
- Similar suppression of electrons at mid rapidity and muons at forward rapidity from heavy flavour hadron decay (dominated by beauty at high $p_T$)
- Large suppression at high $p_T$ in Pb-Pb collisions (factor ≈ 4 around 10 GeV/c)
  - consistent with model predictions (radiative + collisional energy loss)

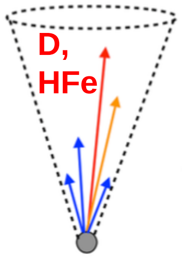
# Beauty $R_{AA}$

$$R_{AA}(p_T) = \frac{(dN/dp_T)_{AA}}{\langle T_{AA}\rangle \times (dN/dp_T)_{pp}}$$



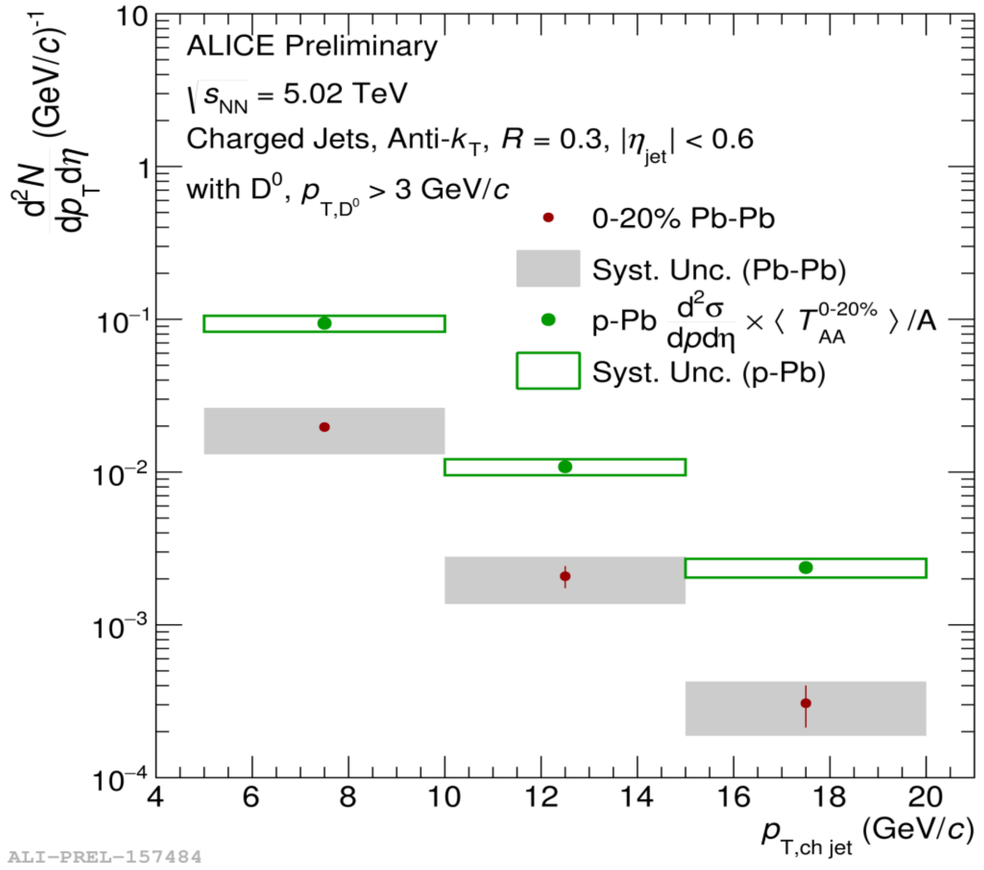



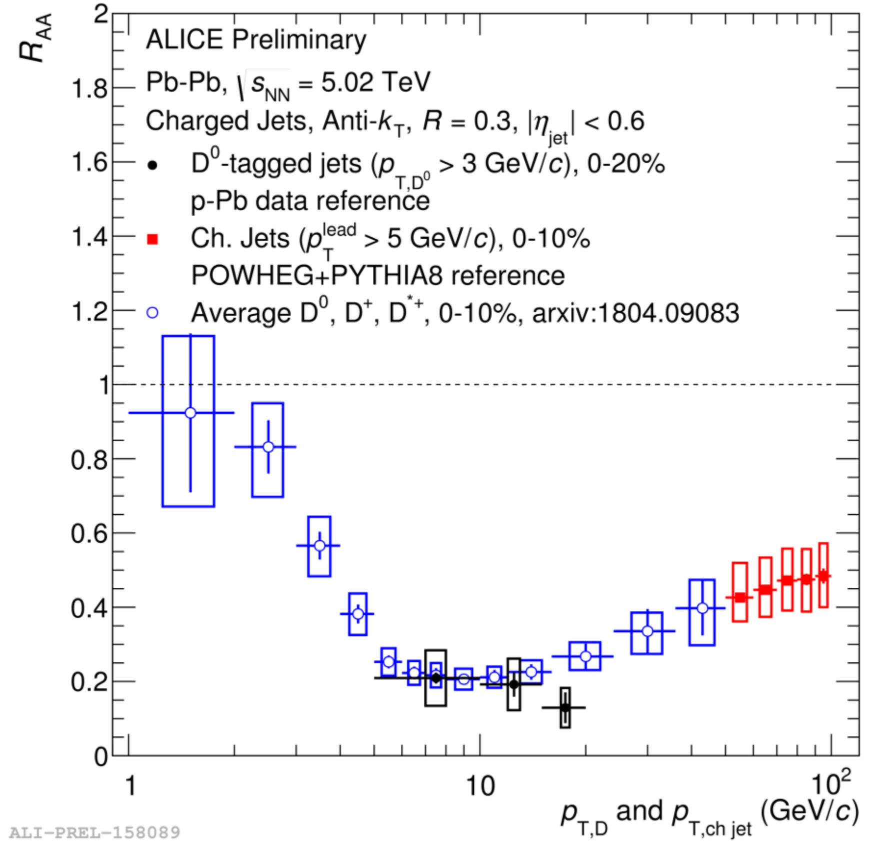

- Electrons from beauty- hadron decay in 0-10% Pb-Pb collisions at 5.02 TeV
- Hint of smaller suppression for beauty than charm+beauty decay electrons at the same electron $p_T$
- Observed suppression for $p_T$>3 GeV/c
- Suppression is consistent with the models including mass dependent energy loss




# D-tagged jets $R_{AA}$

$$R_{AA}(p_T) = \frac{(dN/dp_T)_{AA}}{\langle T_{AA}\rangle \times (dN/dp_T)_{pp}}$$

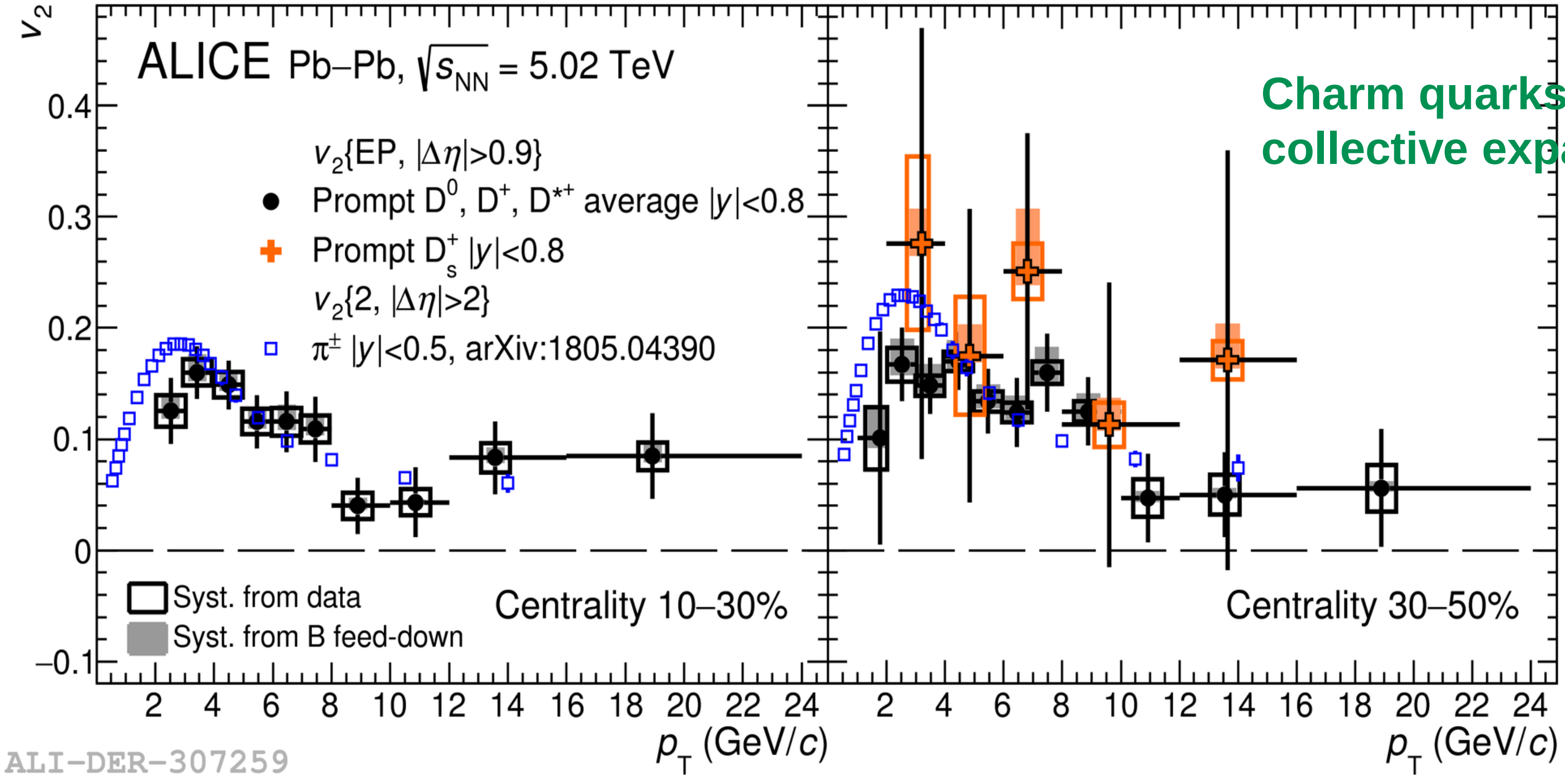



- Strong suppression of $D^0$ jets for $p_T$ > 5 GeV/$c$
- Hint of smaller $R_{AA}$ than track-based jets with $p_T$ > 50 GeV/$c$
- Similar suppression for $D^0$ jets and $D^0$ mesons

# D meson $v_2$

$v_2 = \langle \cos[2(\phi - \Psi_{RP})] \rangle$




**Charm quarks participate in the collective expansion of the medium**

- Positive non-strange D-meson $v_2$ for $2 < p_T < 8\text{-}10$ GeV/$c$ in mid-central (10-30% , 30-50%) Pb-Pb collisions
- $D_s^+$ $v_2$ in 30-50% compatible within uncertainties with non-strange D-meson

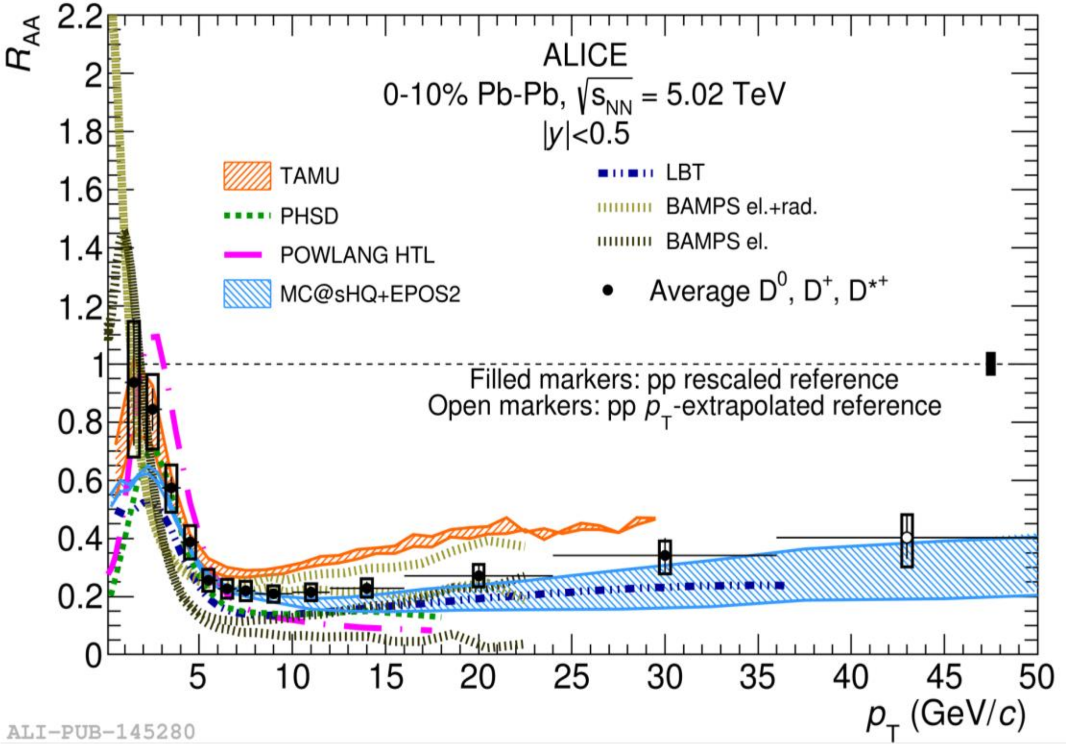
Comparison with charged particles:

$v_2(D) \simeq v_2(\pi^{\pm})$ for $p_T > 4$ GeV/$c$ in the 10-30% and 30-50% centrality classes

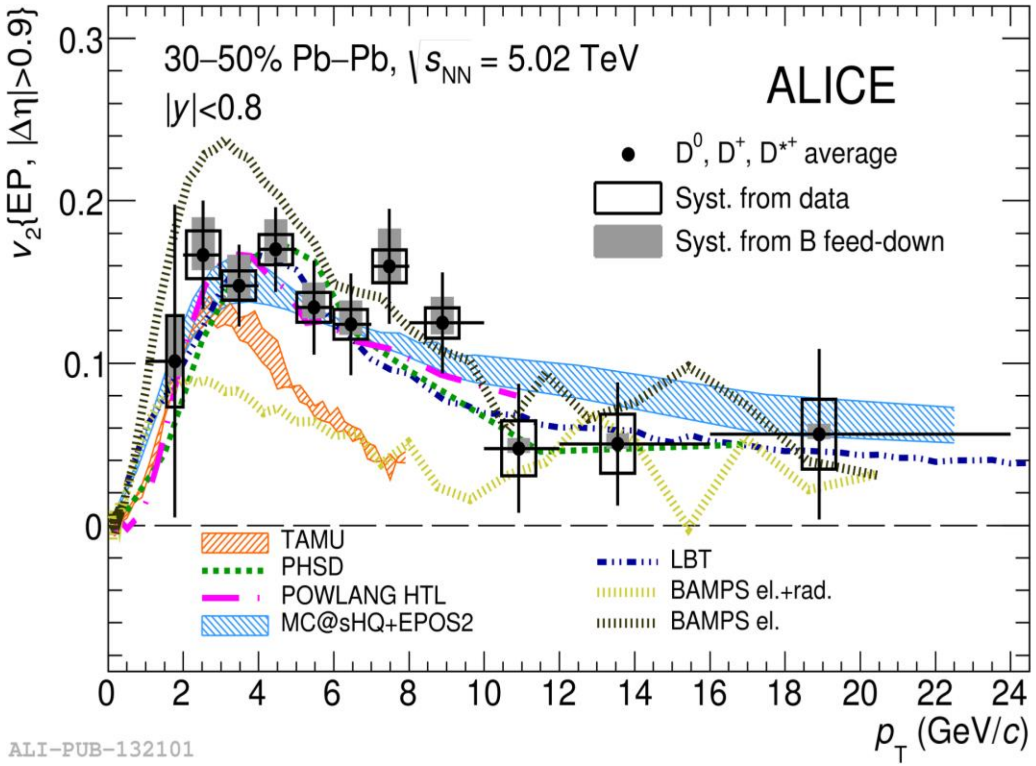
Hint of $v_2(D) < v_2(\pi^{\pm})$ for $p_T < 4$ GeV/$c$ in the 10-30% and 30-50% centrality classes

# D meson $R_{AA}$ and $v_2$ vs models

arXiv:1804.09083




PRL 120, 102301 (2018)




- A simultaneous description of complementary observables ($R_{AA}$ and $v_2$) over a wide $p_T$ range is a challenging task: measurement together provides a strong constraint on models
- Models in which charm quarks pick up collective flow via recombination and/or subsequent elastic collisions in expanding hydrodynamic medium do better at describing both $R_{AA}$ and $v_2$ at low $p_T$ (BAMPS elastic, LBT, MC@sHQ+EPOS2, TAMU, POWLANG, PHSD)
- Models able to reproduce $v_2$ with a diffusion coefficient $2\pi T D_s(T)$ in the range 1.5-7 at $T_c$ with a corresponding thermalisation time of charm quarks of 3-14 fm/$c$

# Summary and outlook

- A wealth of data for the study of heavy-flavour production in pp ($\sqrt{s}$ = 2.76, 5, 7, 8 and 13 TeV), p-Pb ($\sqrt{s_{NN}}$= 5.02 and 8.16 TeV ) and Pb-Pb ($\sqrt{s_{NN}}$= 2.76 and 5.02 TeV) collisions

## pp collisions

- D-mesons and open heavy-flavour decay leptons: $p_T$ differential cross section adequately described by pQCD models
- Charmed baryons: models unable to describe data → Need better understanding of fragmentation functi…

## p-Pb collisions

- $R_{pPb}$ of non-strange D-mesons, $D_s^+$ meson and $\Lambda_c^+$ all compatib… …models including CNM effects
- Charmed baryon to meson ratio in pp and p-… …ted → coalescence in small systems?

**Higher precision** on current observables and **more differential measurement** expected with 2018 Pb-Pb run and in the next runs after the ALICE upgrade

## Pb-Pb collisions

- L… …particle in central collision due to heavy quark energy loss in the QGP.
- E… …production of $D_s^+$ and $\Lambda_c^+$ production in Pb-Pb: described by the models including coalescence.
- Positive $v_2$ observed for open heavy-flavour hadrons and decay leptons: → Charm quarks participate in the collective expansion of the medium
- Hints of smaller suppression for beauty-decay electrons from $p_T$> 3 GeV/$c$: models including mass dependent energy loss mechanism provide a good description of data
- First measurement of $D^0$-tagged jets in Pb-Pb: large suppression observed in 0-20% collisions.

Thank you for your kind attention!!!