Heavy flavor production at the LHC

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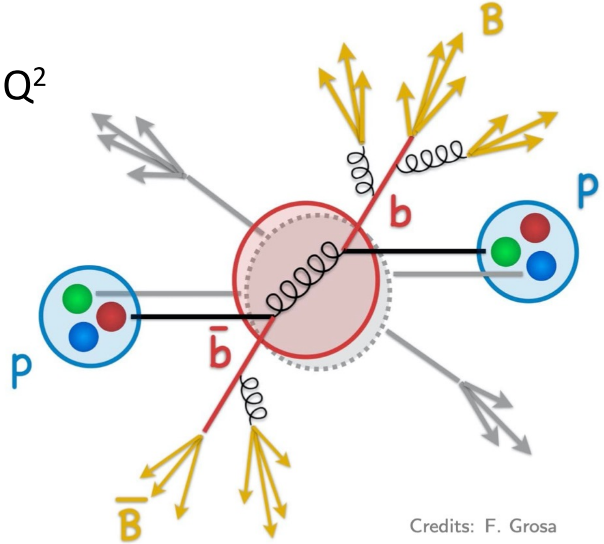
On behalf of the ALICE, ATLAS, CMS and LHCb collaborations

Introduction – Heavy flavors

- Heavy flavor hadrons contain one heavy *c* or *b* quark
- Because of their large masses ($m_b > m_c \gg \Lambda_{QCD}$), they have a short formation time and experience the whole medium evolution
- Heavy quarks are produced in initial hard scattering with moderate to large Q^2 -> their production can be described with perturbative QCD calculations



- The production can be described with the factorization approach :

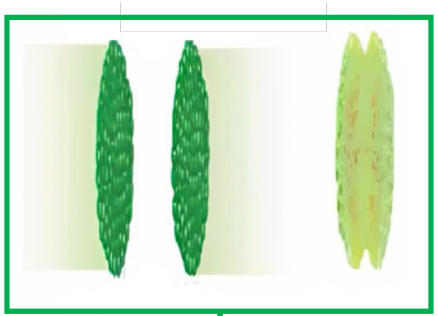
$$\int \sigma_{(AB\to CX)} \propto PDF(x_a, Q^2) PDF(x_b, Q^2) \otimes \sigma_{(ab\to cd)} \otimes D_c^C(z_c, Q^2)$$

- Parton distribution functions (non perturbative)
- Partonic cross section (perturbative)
- Fragmentation functions (non perturbative)

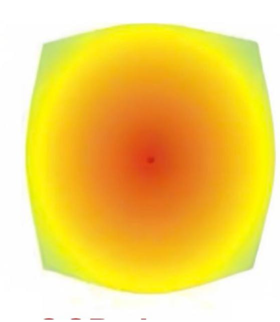
- Fragmentation functions are assumed to be universal across collision systems

Introduction – What can we measure and learn?

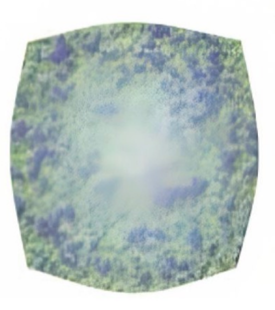
Initial phase



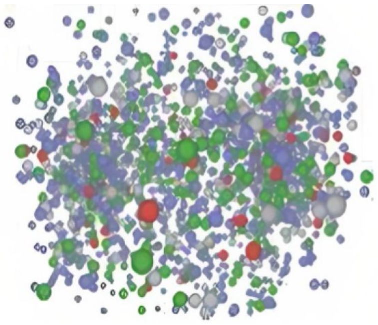
QGP phase



Hadronisation



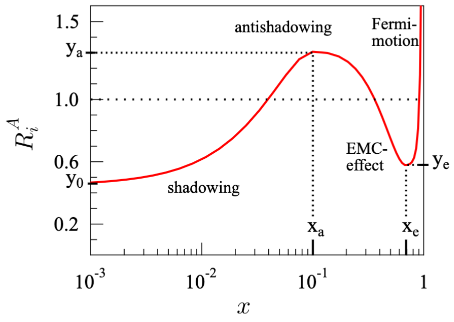
Hadronic phase



Initial State effects :

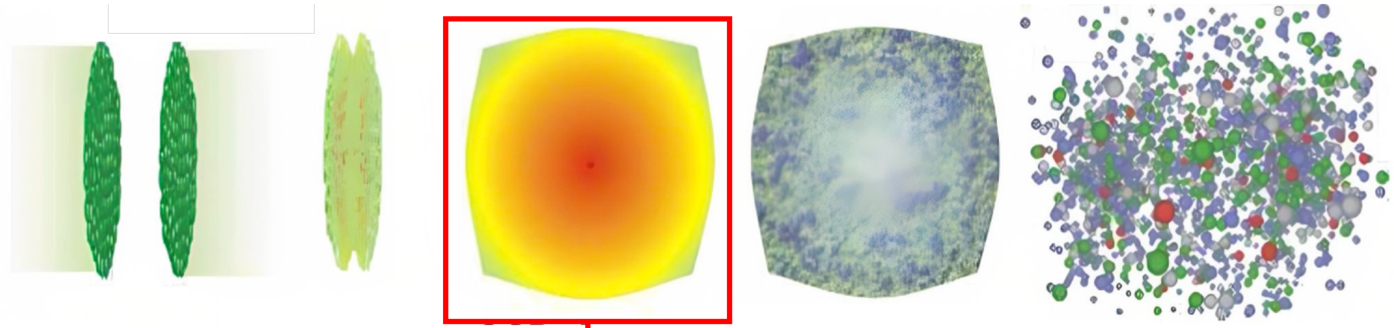
- Saturation
- Modification of PDFs
- …

JHEP 04 (2009) 065



Introduction – What can we measure and learn?

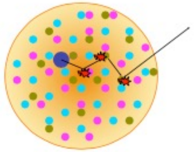
Initial phase QGP phase Hadronisation Hadronic phase



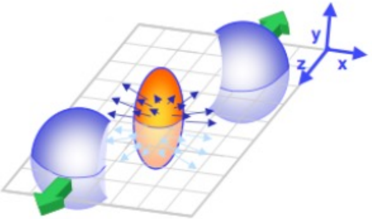
In medium effects :

- Energy loss : Interaction of heavy quarks with the medium

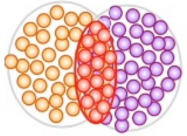
$$R_{\mathrm{AA}} = \frac{Y_{\mathrm{AA}}}{N_{\mathrm{coll}} \cdot Y_{\mathrm{pp}}}$$



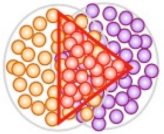
- Collectivity: $\frac{\mathrm{d}^3 N}{\mathrm{d}^3 p}_{\mathrm{AA}} = \frac{1}{2\pi} \frac{\mathrm{d}^2 N}{p_{\mathrm{T}} \mathrm{d}p_{\mathrm{T}} \mathrm{d}y} \left[1 + \sum_{n=1}^{\infty} 2 v_n \cos\left(n(\phi - \Psi_R)\right)\right]$



Elliptic flow v_2 : initial anisotropy and reintteractions

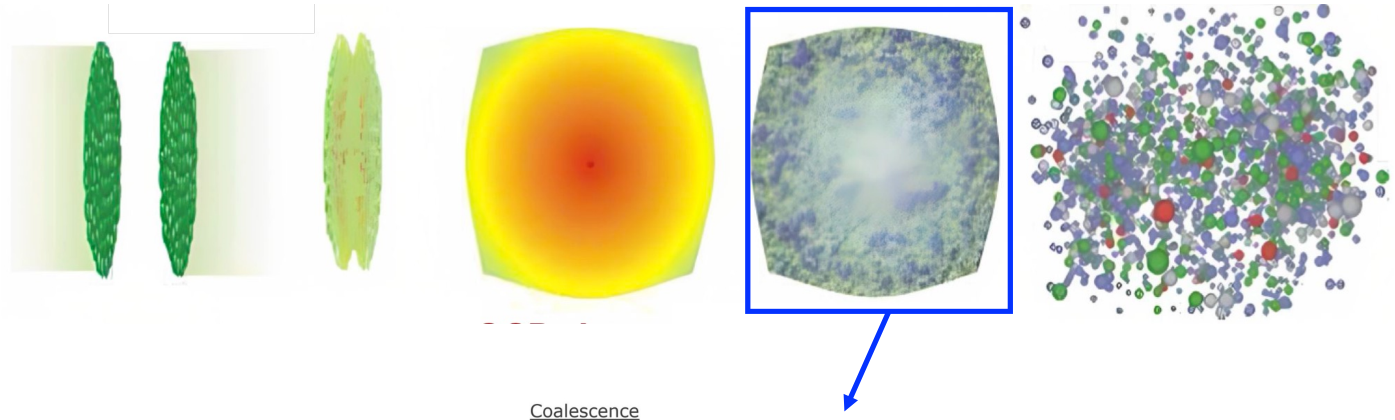


Triangular flow v_3:fulctuations of the initial state

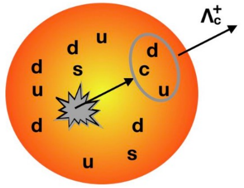


Introduction – What can we measure and learn?

Initial phase   QGP phase   Hadronisation   Hadronic phase



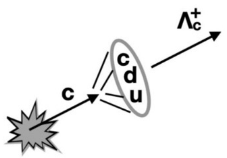
Coalescence



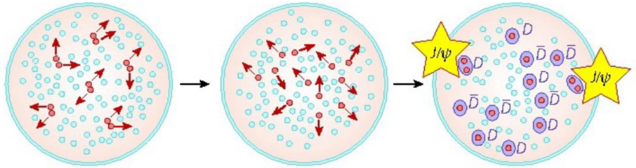
- Coalescence: combination of quarks close in phase space

- Fragmentation: 'break up' of charm quark

Fragmentation



- Statistical hadronization : charm quarks distributed to hadrons according to thermal weights

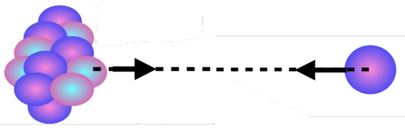


Introduction – Different collision systems

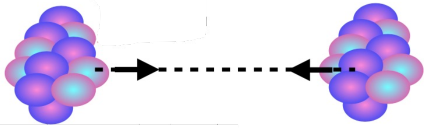
- Measurements in different collision size allow to investigate several properties

- Proton-proton collisions :
  - Measurement of fragmentation fractions
  - Test of pQCD models regarding hadron formation

- Proton-Nucleus collisions :
  - Initial state effects
  - Interplay between soft and hard process



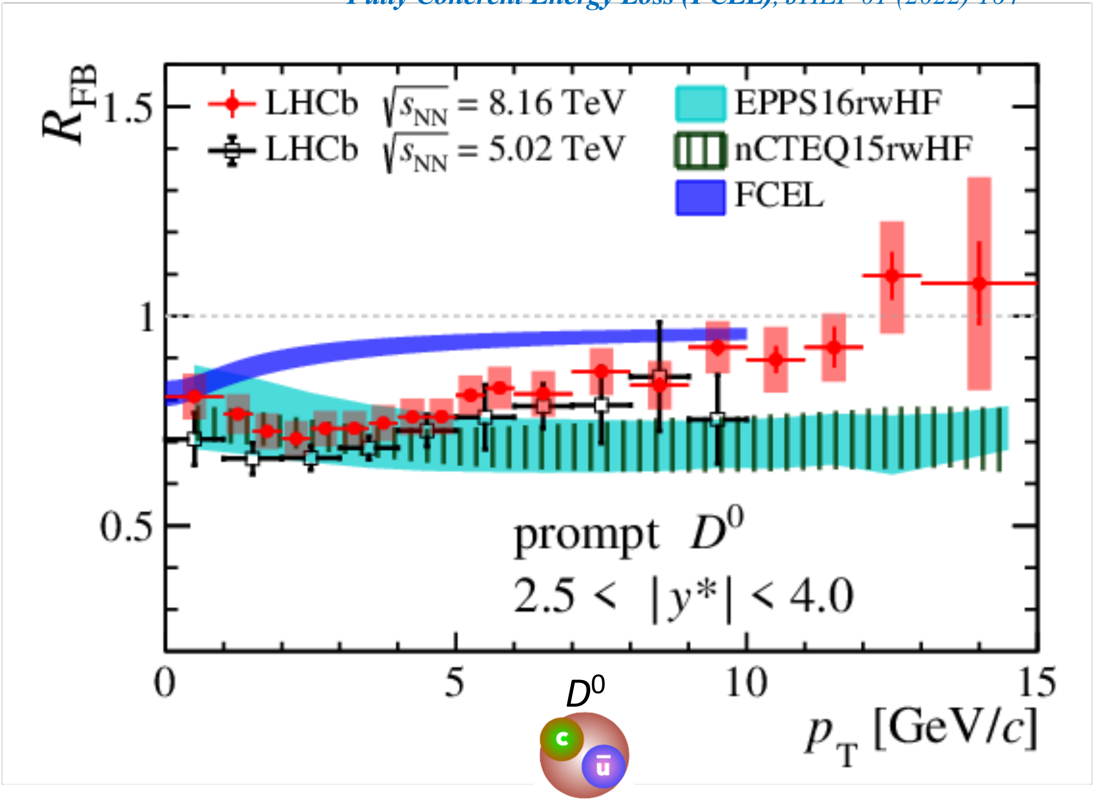
- Nucleus-Nucleus collisions
  - Properties of the Quark-Gluon Plasma
  - Final state effects



D^0 production in p–Pb at 8.16 TeV

- The measurement of D^0 production in p–Pb allows to investigate partonic structures
- R_{FB} is the forward/backward production ratio
- Significant production asymmetry at low p_T
- R_{FB} shows a rising trend with p_T, beyond 5 GeV/c somewhat higher than nPDF calculations

LHCb, *arXiv:2205.03936*
EPPS16*, Eur. Phys. J. C 77 (2017) 163*
nCTEQ15*, Phys. Rev. D 93 (2016) 085037*
Fully Coherent Energy Loss (FCEL)*, JHEP 01 (2022) 164*



Λ_c^+ measurements

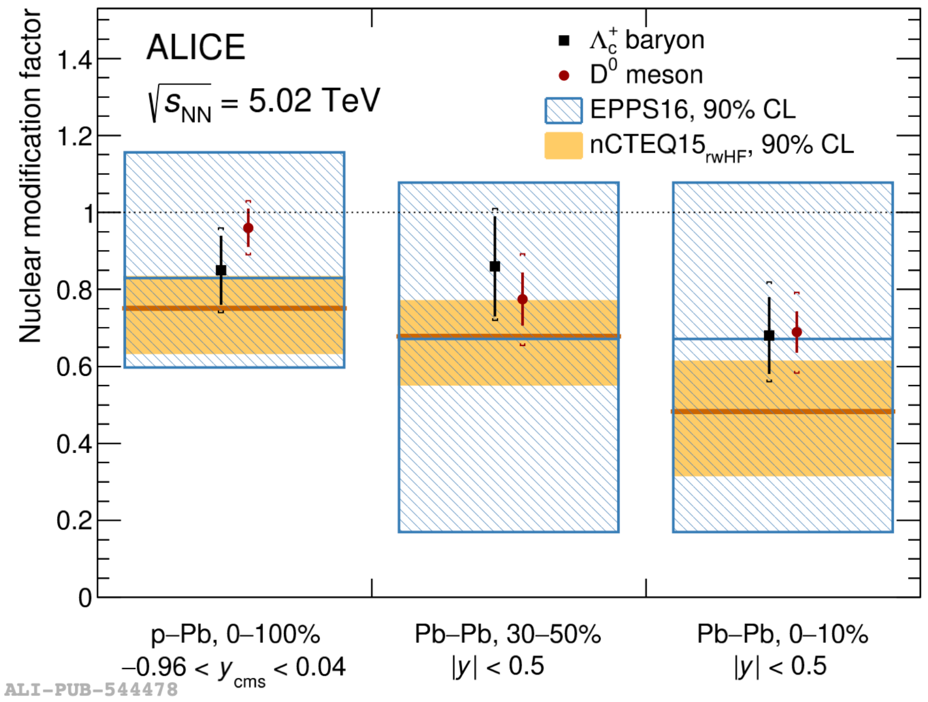
- The Λ_c^+ R_{AA} is < 1 in central Pb–Pb collisions, lower than in p–Pb
  ⇨ suppression due to shadowing and modifications in the hadronisation mechanism.

- In the 30–50% centrality interval, the Λ_c^+ R_{AA} is compatible with 1 within the uncertainties.

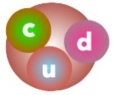
- The Λ_c^+ R_{pPb} is closer to 1 than the R_{AA} in central collisions
  ⇨ expected because of smaller shadowing effects in p–Pb compared to Pb–Pb collisions

- The Λ_c^+ and D^0 R_{AA} are very similar
  ⇨ no significant enhancement of charm baryons compared to charm mesons in Pb–Pb vs pp

***ALICE**, Phys. Rev. C 107 (2023) 6, 064901*

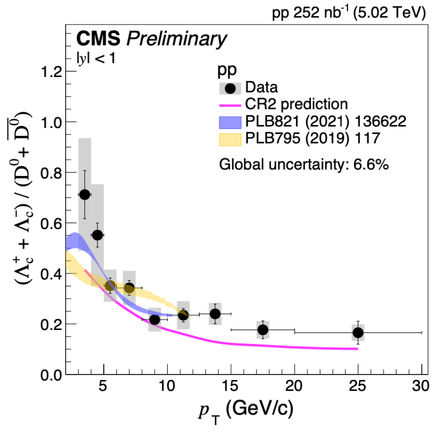


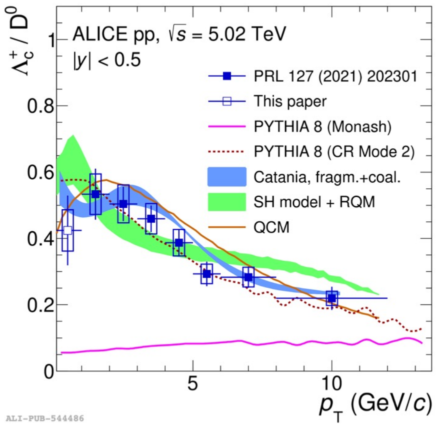
Λ_c^+

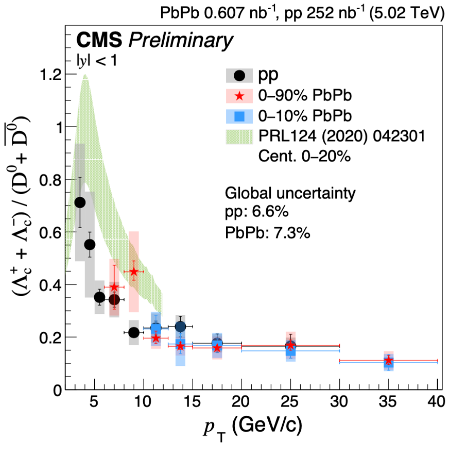


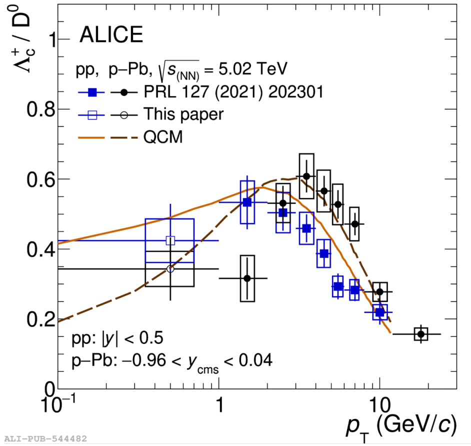
***EPPS16**, Eur. Phys. J. C 77 (2017) 163*
***nCTEQ15**, Phys. Rev. D 93 (2016) 085037*

Λ_c^+/D^0 measurement vs p_T







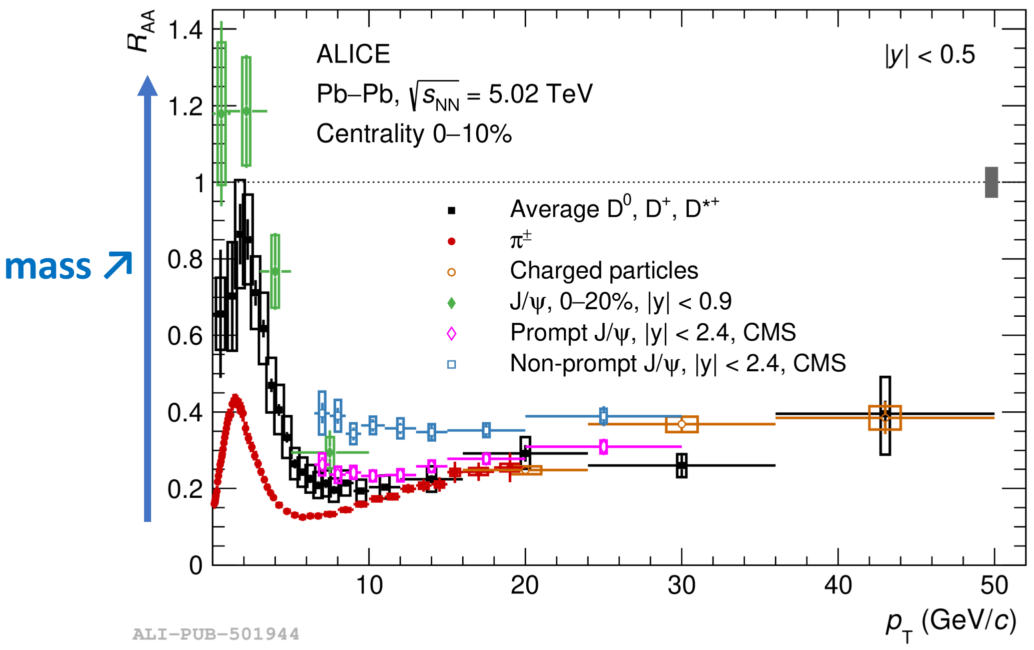


- Models successfully describe Λ_c^+/D^0 ratio in pp with a combination of completely different theoretical frameworks
- The ratio in p–Pb is compatible with pp at low p_T
- The shift of the maximum towards higher p_T can be explained by radial flow
- The ratio in Pb–Pb at high p_T is compatible with pp ⇨ no significant contribution from the coalescence process at high p_T

__ALICE,__ Phys. Rev. C 107 (2023) 6, 064901
__CMS,__ CMS-PAS-HIN-21-004
__PYTHIA8+CR2,__ JHEP 08 (2015) 003
__Catania__, PLB 821 (2021) 136622
__SHM+RQM__, PLB 795 (2019) 117
__He and Rapp__, PRL124 (2020) 042301
__QCM__, Li, Shao & Song, Chin. Phys. C 45 113105

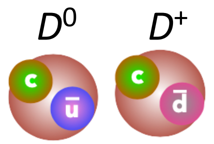
D meson in QGP

- D meson R_{AA} compared to other particles shows strong indication of mass ordering at low p_T.



- For $p_T < 8$ GeV/c, $R_{AA}(\pi) < R_{AA}(D) \leq R_{AA}(J/\psi)$

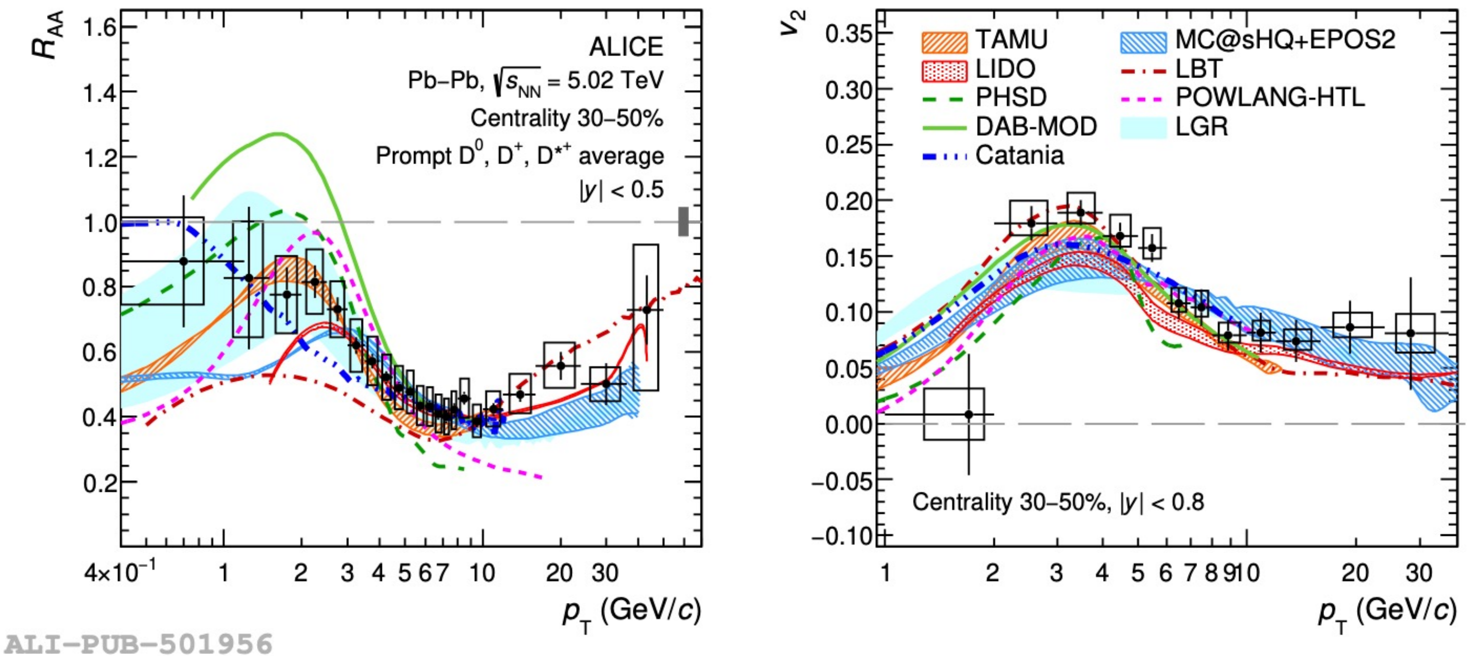
- For $10 < p_T < 20$ GeV/c, $R_{AA}(D) \leq R_{AA}(J/\psi^{non\text{-}prompt})$ but $R_{AA}(D) \sim R_{AA}(J/\psi^{prompt})$
  ⇨ charm quarks lose more energy than beauty quarks in the QGP



ALICE, JHEP 01 (2022) 174

D meson in QGP

- Models struggle to provide a good description of both R_{AA} and v_2 in semi-central collisions.



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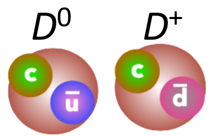
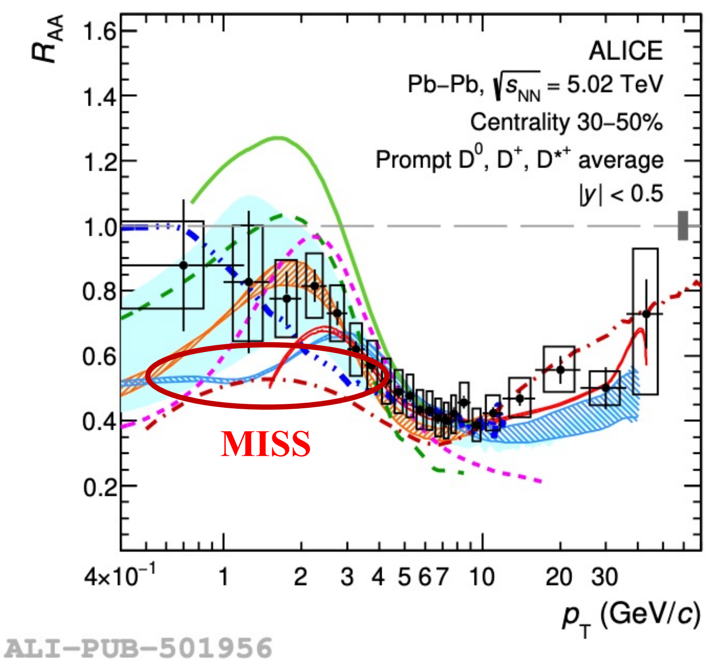
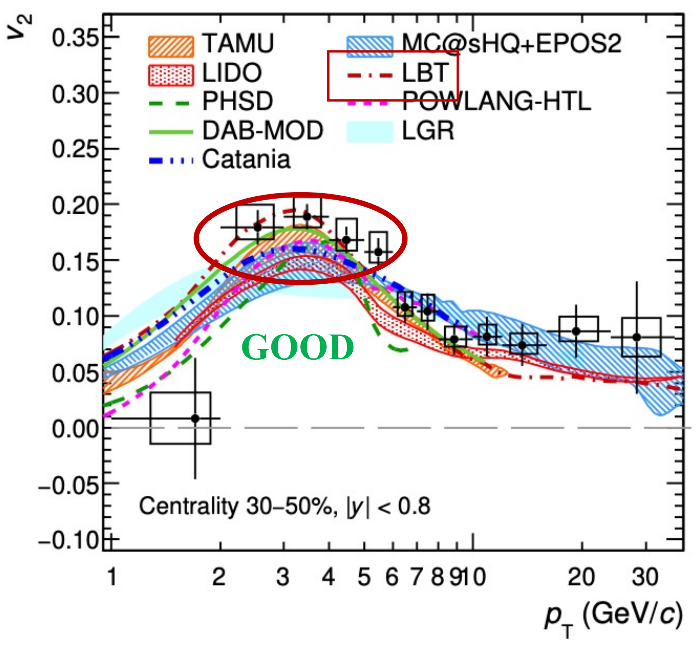


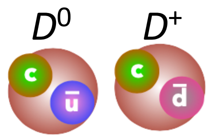
ALICE, JHEP 01 (2022) 174
TAMU: PRL124 (2020) 042301
LIDO: PRC 100 n.6 (2019) 064911
PHSD: Phys. Rev. C 96 (2017) 014905
DAB-MOD: Phys. Rev. C 102 n.2 (2020) 024906
LBT: Phys. Rev. C 94 n.1 (2016) 014909
POWLANG+HLT: EPJC 75 n.3 (2015) 121
LGR: EPJC 80 (2020) 671, EPJC 80 (2020) 1113
MC@sHQ+EPOS2: Phys. Rev. C 89 (2014) 014905
Catania: Phys. Rev. C 96 (2017) 044905

D meson in QGP

- Models struggle to provide a good description of both R_{AA} and v_2 in semi-central collisions.
- For example : Linear Boltzmann Transport (LBT) model reproduces v_2 but misses the R_{AA} at low p_T







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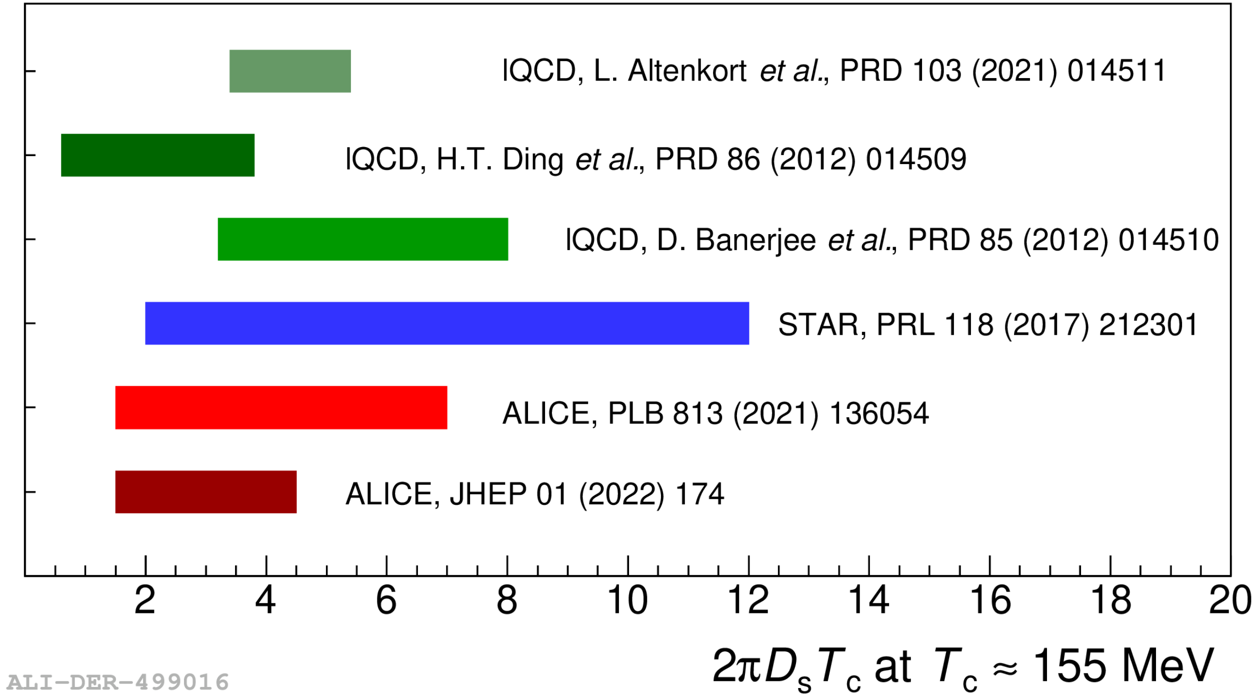
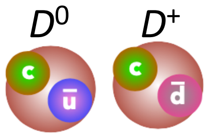
D meson in QGP

- The data-model comparison allows to constrain the heavy quark spatial diffusion coefficient : $1.5 < 2\pi D_s T_c < 4.5$ T_c~155 MeV
  ⇨ the thermalisation time of charm quark $3 \lesssim \tau_{charm} \lesssim 9$ fm/*c*, compatible with the QGP lifetime



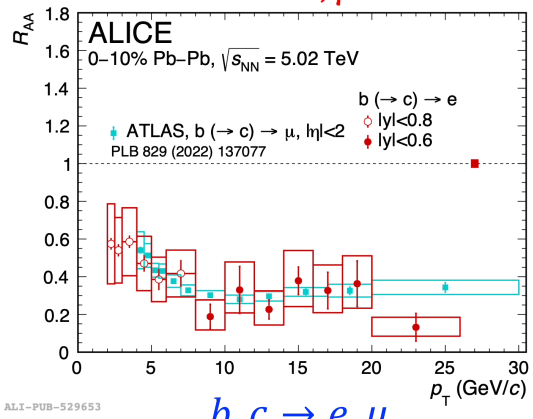


ALICE, *JHEP 01 (2022) 174*

Charm and beauty hadrons in QGP

- There is substantial suppression of muons from both charm- and bottom-hadron decays for the p_T range covered

$b \rightarrow e, \mu$



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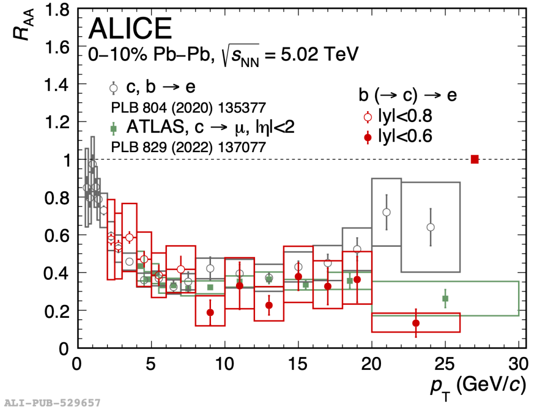

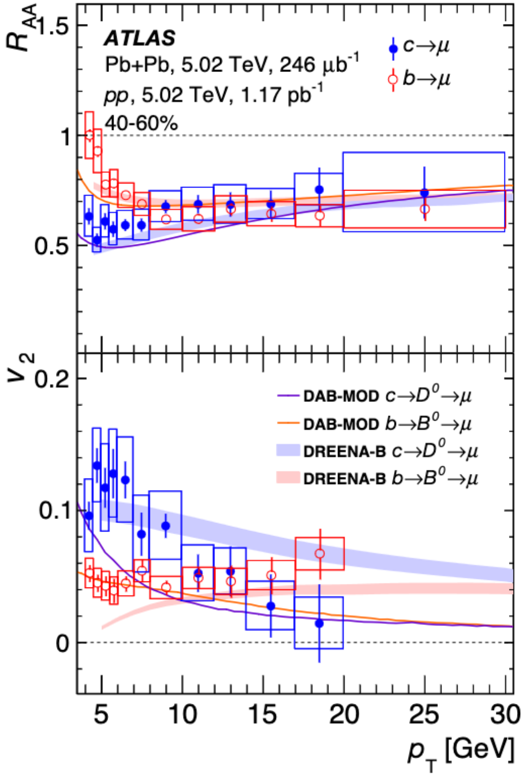

***ALICE**, arxiv:2211.13985*
***ATLAS**, Phys.Lett.B 829 (2022) 137077*
***DAB-MOD**, Phys. Rev. C 96 (2017) 064903*
***DREENA-B**, Phys. Lett. B 791 (2019) 236–241*

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- ALICE and ATLAS measurments shows good agreement
- Model calculations agree qualitatively with both v_2 and R_{AA} for both charm and bottom muons

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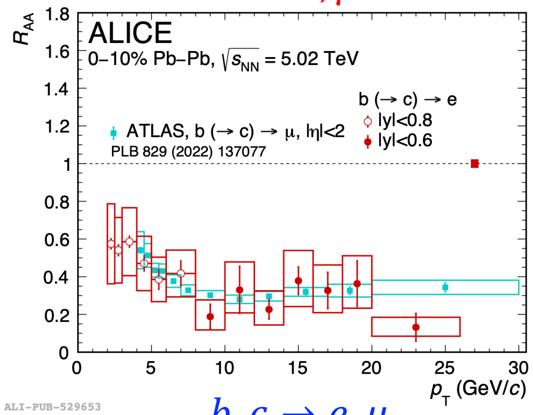

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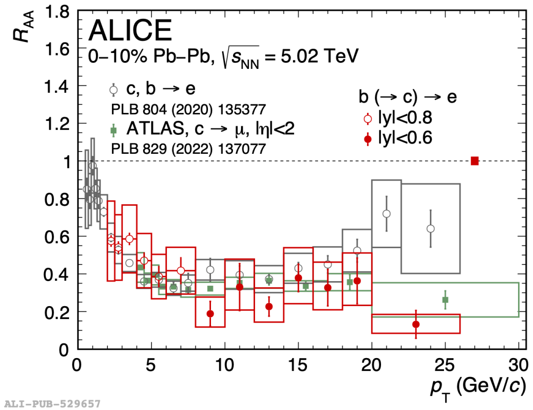

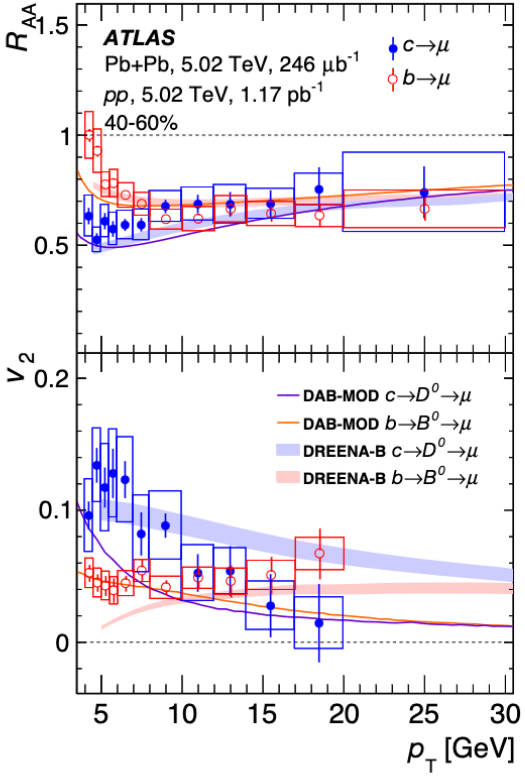

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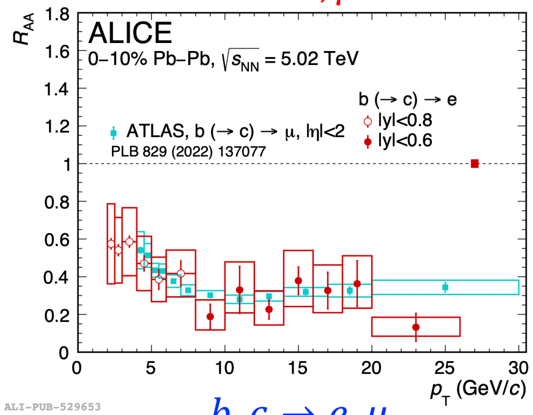
- ALICE and ATLAS measurments shows good agreement
- Model calculations agree qualitatively with both v_2 and R_{AA} for both charm and bottom muons
- The mass ordering at low p_{T} follows expectations?
  ⇨ charm quarks lose more energy than beauty quarks in the QGP since $m_b > m_c$ (dead cone effect)

$b \rightarrow e, \mu$



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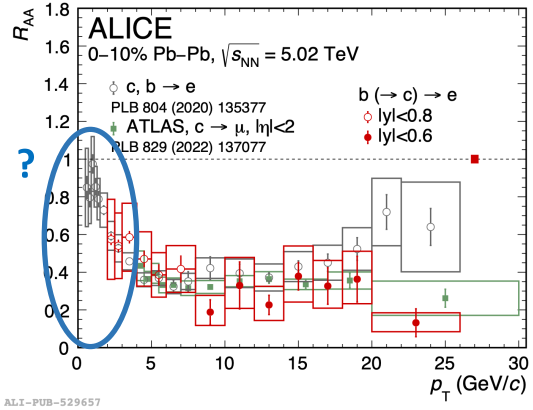

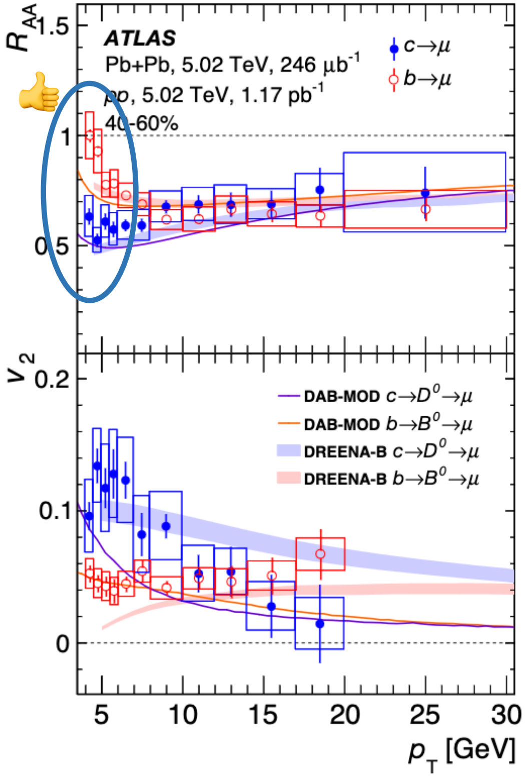

ALICE, *arxiv:2211.13985*
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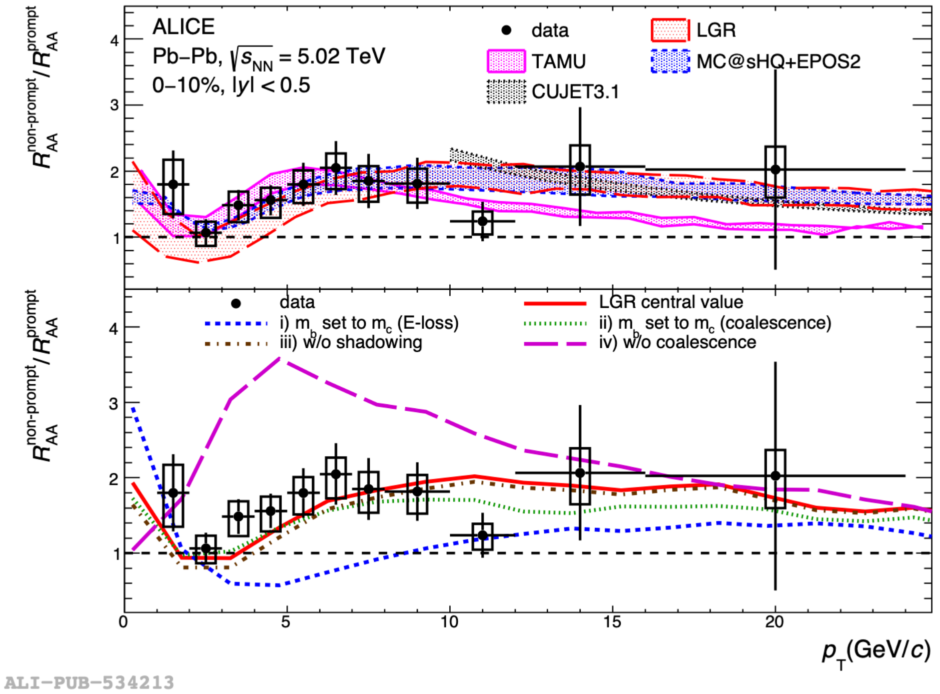
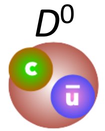
Non-prompt and prompt D^0 in QGP

ALICE, JHEP 12 (2022) 126

- Models reproduce the $R_{AA}^{non-prompt}/R_{AA}^{prompt}$ and show a similar trend at low p_T
  - including elastic collisions only (TAMU)
  - including both radiative and collisional processes (Langevin-transport with Gluon Radiation (LGR), MC@sHQ+EPOS2)
- For $p_T > 5$ GeV/c, the ratio is larger than unity ⇨ larger suppression of prompt D^0





TAMU: Phys. Lett. B 735 (2014) 445–450
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CUJET3: Chin. Phys. C 43 (2019) 04410

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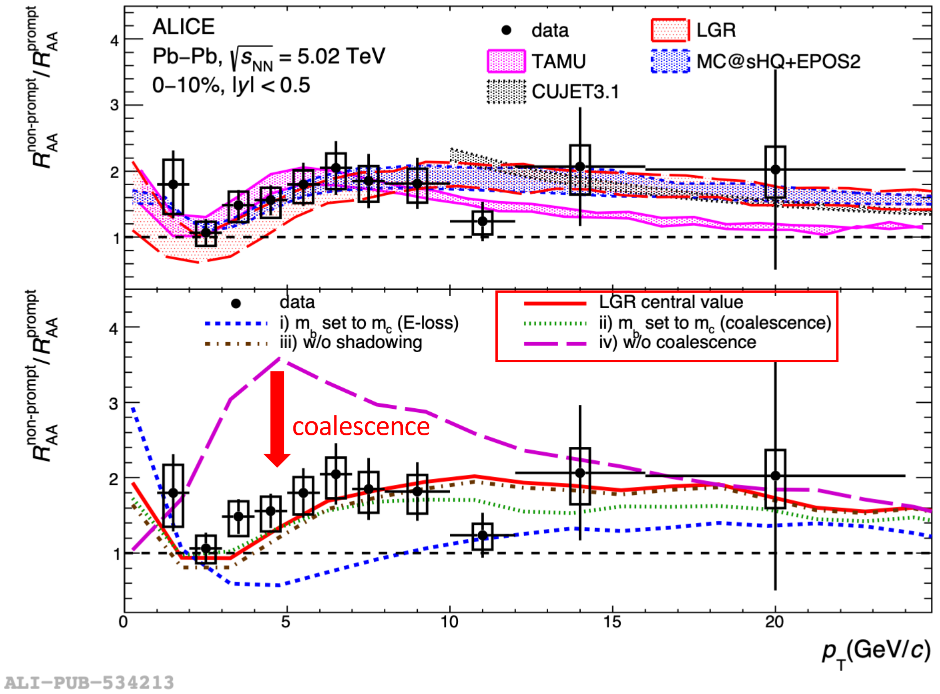
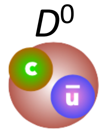
- For $p_{\mathrm{T}} > 5$ GeV/c, the ratio is larger than unity
  ⇨ larger suppression of prompt D^0
- Coalescence can also explain the minimum : prompt D^0 acquire a higher momentum than the parent charm quark
  ⇨ hardening of the p_{T} spectra





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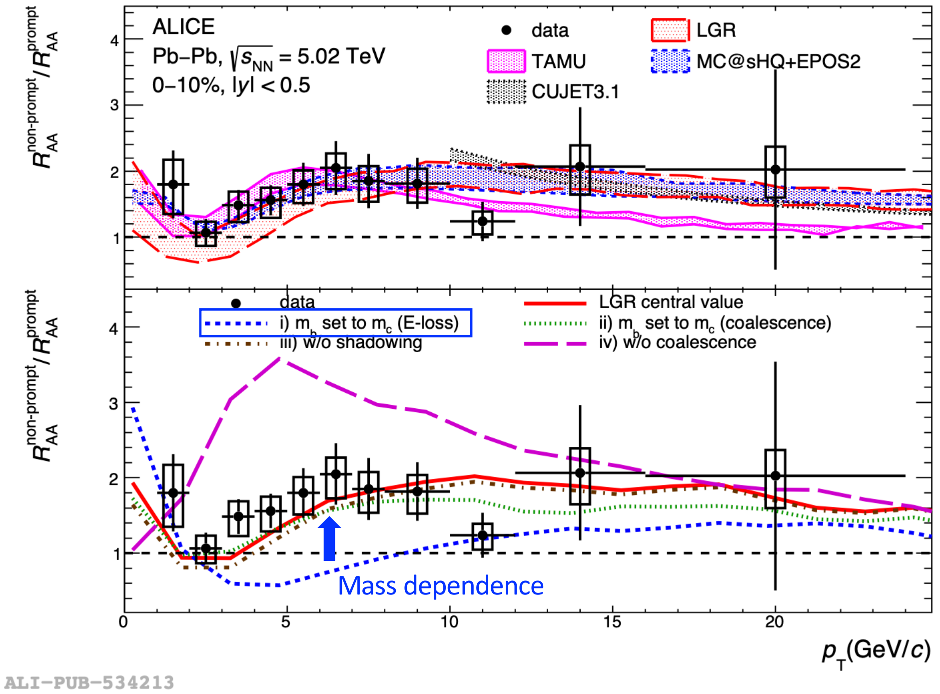
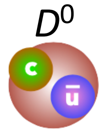
  ⇨ larger suppression of prompt D^0
- Coalescence can also explain the minimum : prompt D^0 acquire a higher momentum than the parent charm quark
  ⇨ hardening of the p_T spectra
- The energy loss in medium is dependent on the mass
  ⇨ Non-prompt to prompt D^0 Ratio > 1



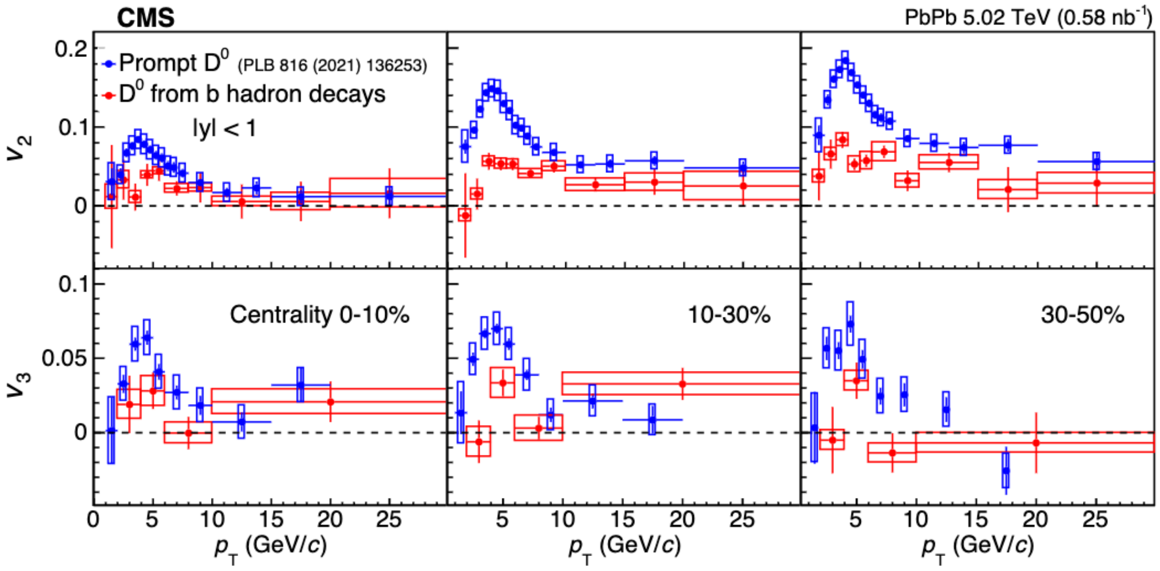


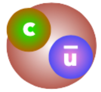
TAMU: Phys. Lett. B 735 (2014) 445–450
LGR: EPJC 80 (2020) 671, EPJC 80 (2020) 1113
MC@sHQ+EPOS2: Phys. Rev. C 89 (2014) 014905
CUJET3: Chin. Phys. C 43 (2019) 04410

Non-prompt and prompt D^0 in QGP

CMS, *arXiv:2212.01636*

- The v_2 of non-prompt D^0 is significantly lower prompt D^0 v_2 at low p_T
- This difference becomes more pronounced in peripheral collisions where v_2 is large
- Flow is shifted to higher p_T with increasing mass
  ⇨ incomplete thermalization of *b* quark?





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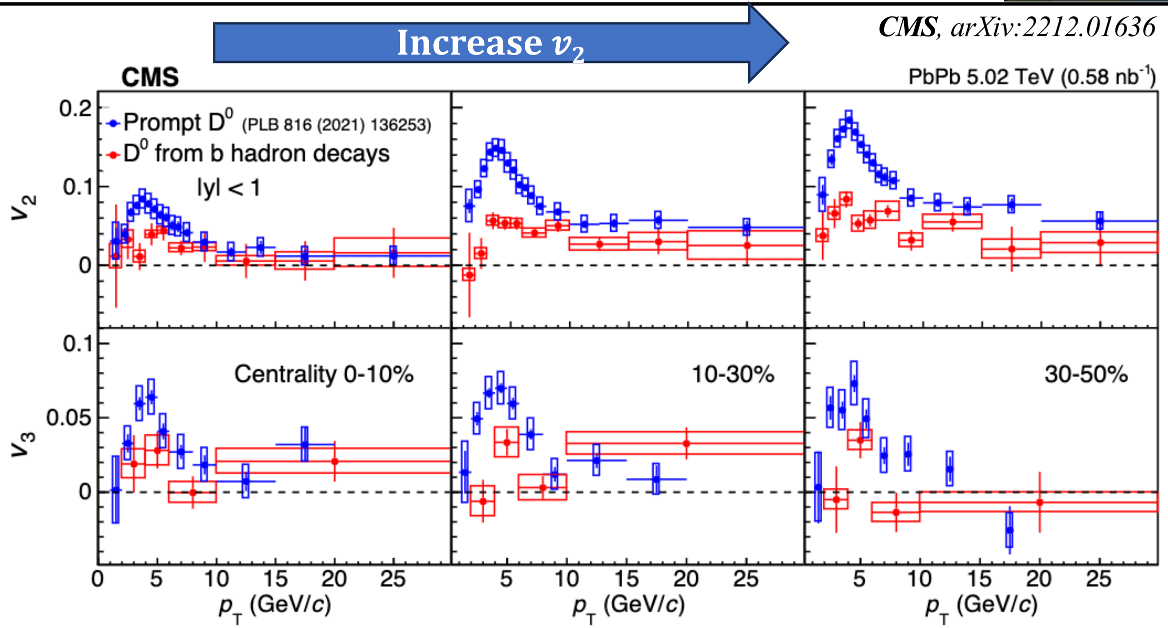
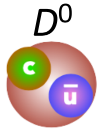


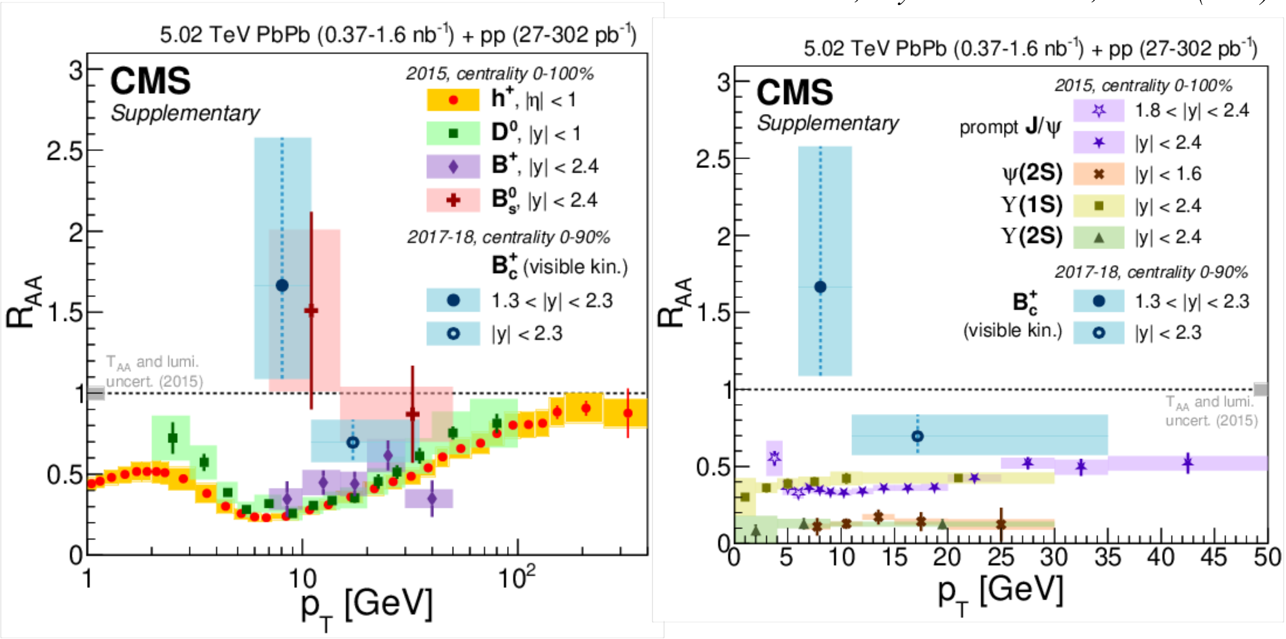


- Measurements also suggest an increase of v_2 towards peripheral collisions, similar to light hadrons
  ⇨ further indication that flow is a consequence of initial space anisotropy

B_c^+ in the QGP

- B_c^+ is a unique charm-bottom state, sensitive to both energy loss (suppression) and recombination
- Moderate suppression at high p_T, hint of an enhancement at low p_T
- Less suppression than other heavy mesons (except for B_s^+) ⇨ Recombination is an important component of B_c^+ production

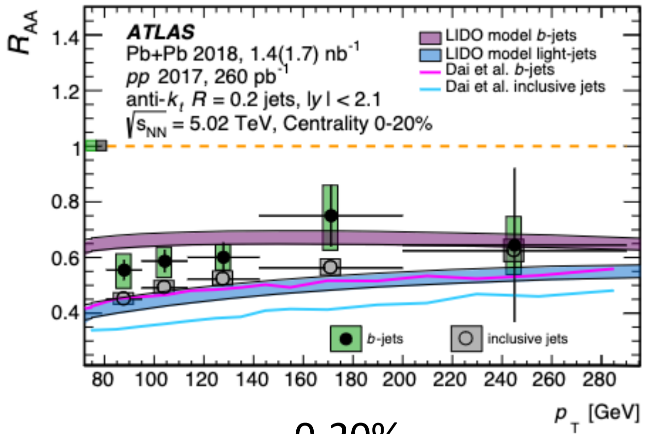
CMS, *Phys. Rev. Lett. 128, 252301 (2022)*



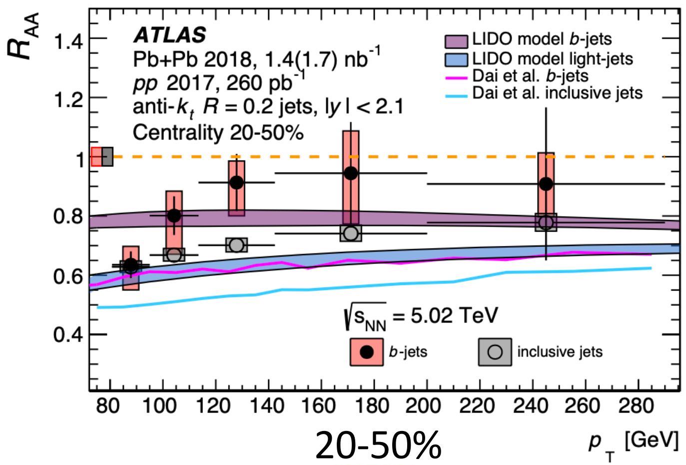
b-jets in QGP

- Jets from b are interesting because of the large mass of the b quark and the color charge is controlled as opposed to inclusive jets
- In central collisions the R_{AA} values for b-jets are higher than for inclusive jets
- Possible influence of b-jet fragmentation and/or mass effect on parton energy loss (expected to be small at large p_T)

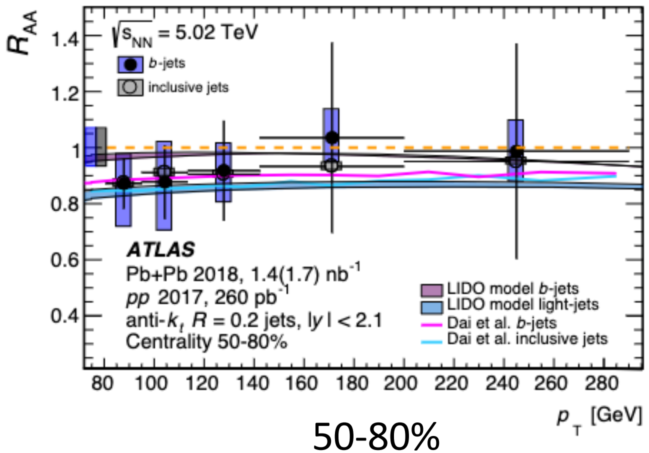
***ATLAS**, arXiv:2204.13530*
***LIDO**: Phys. Rev. C 100, 064911 (2019)*
***Dai et al**: Chinese. Phys. C 2020, 44:104105*



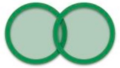
0-20%



20-50%



50-80%

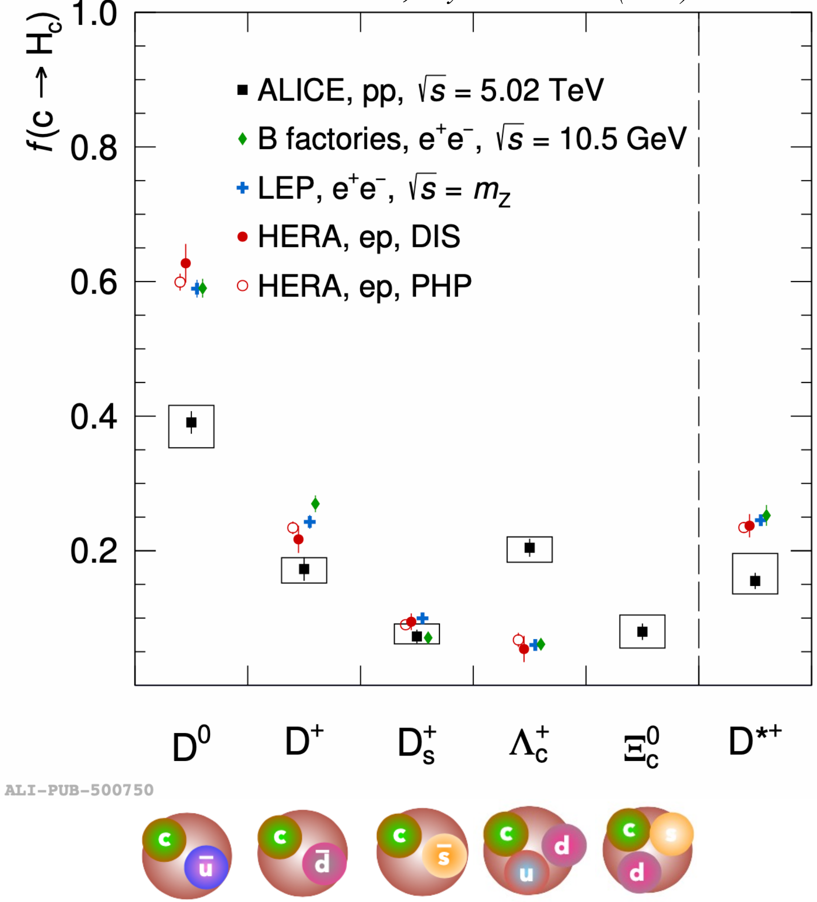


Charm fragmentation fractions in pp

- Heavy-flavor charm mesons and baryons are used to evaluate the charm fragmentation functions

- A difference is observed in pp collisions with respect to e^+e^- and ep collisions

ALICE, Phys. Rev. D 105 (2022) L011103



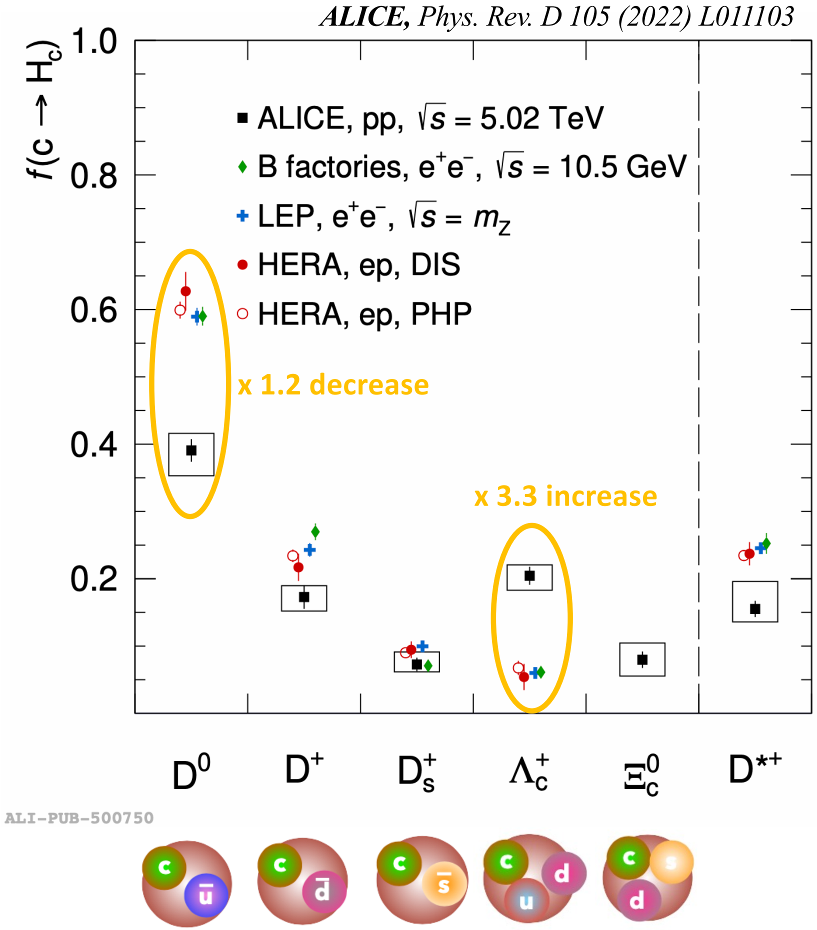
Charm fragmentation fractions in pp

- Heavy-flavor charm mesons and baryons are used to evaluate the charm fragmentation functions

- A difference is observed in pp collisions with respect to e^+e^- and ep collisions

- Increase in Λ_c^+ production accompanied by a concomitant decrease in D^0

  ⇨ evidence that universality (i.e. collision-system independence) of parton-to-hadron fragmentation is not valid



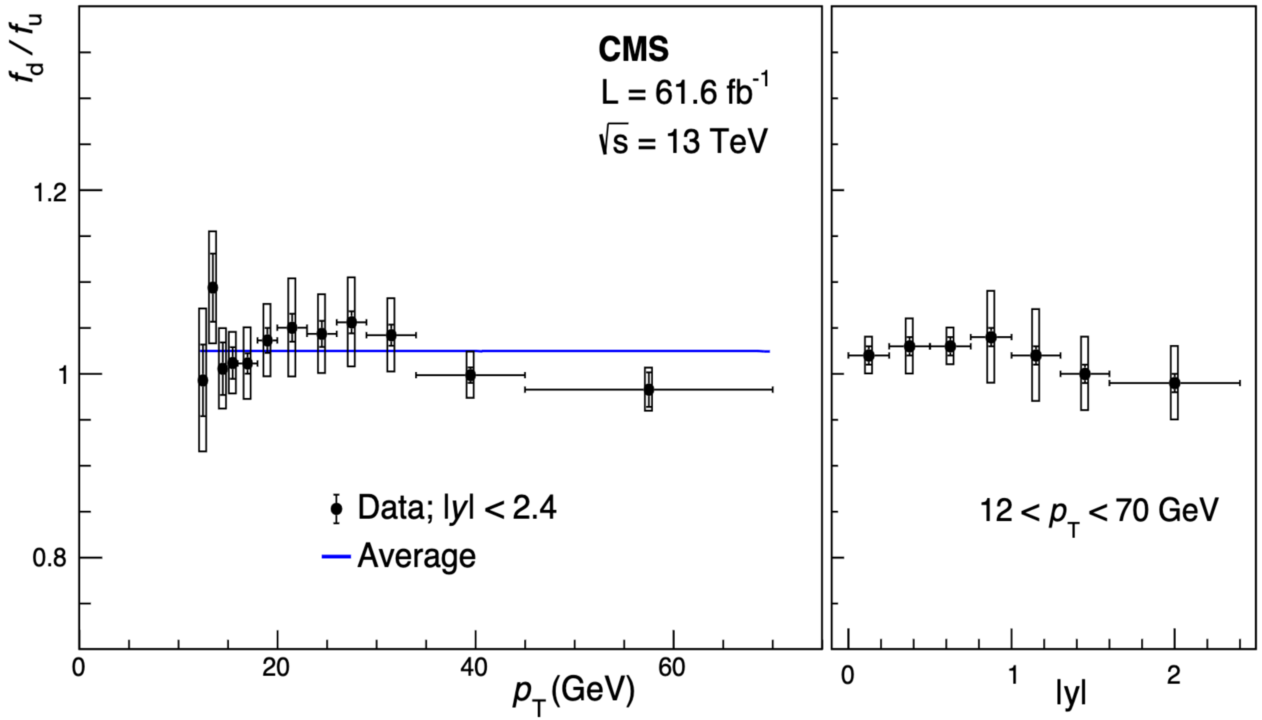
Beauty fragmentation functions

- Heavy-flavor beauty mesons and are used to evaluate the beauty fragmentation fractions ratio

CMS, arXiv:2212.02309

- The ratio f_d/f_u does not depend on p_T or rapidity

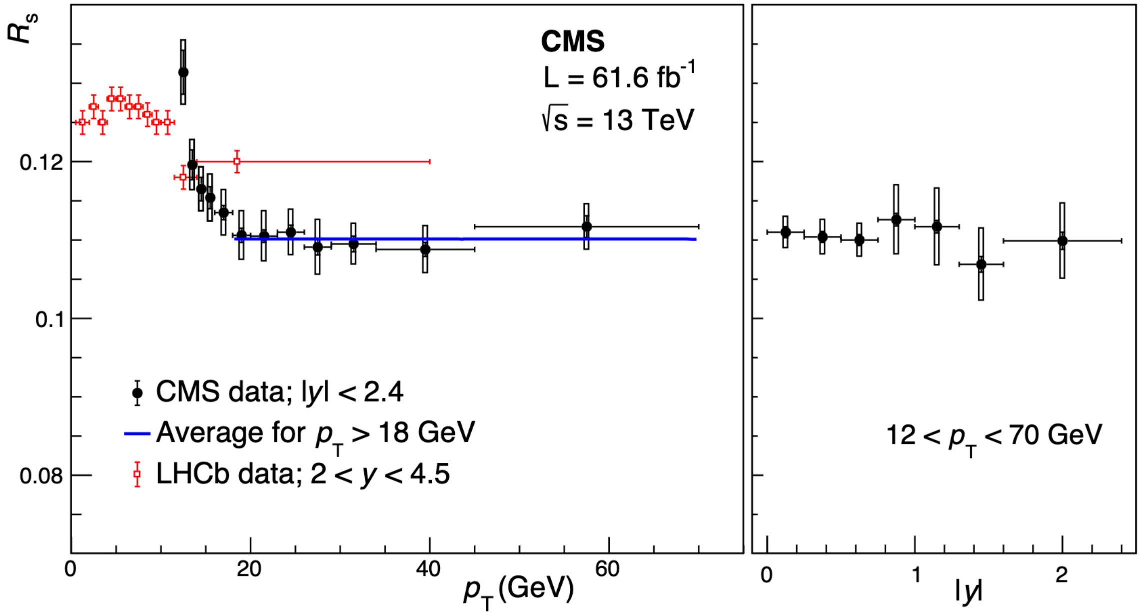
- The average is consistent with 1 ⇨ expected from strong isospin symmetry.



Beauty fragmentation functions

- The ratio of B_s^0 to B^+ decreases as a function of p_T and the is flat for p_T > 18 GeV/c and shows no rapidity dependence

CMS, *arXiv:2212.02309*
LHCb, *PRL 124 (2020) 122002*



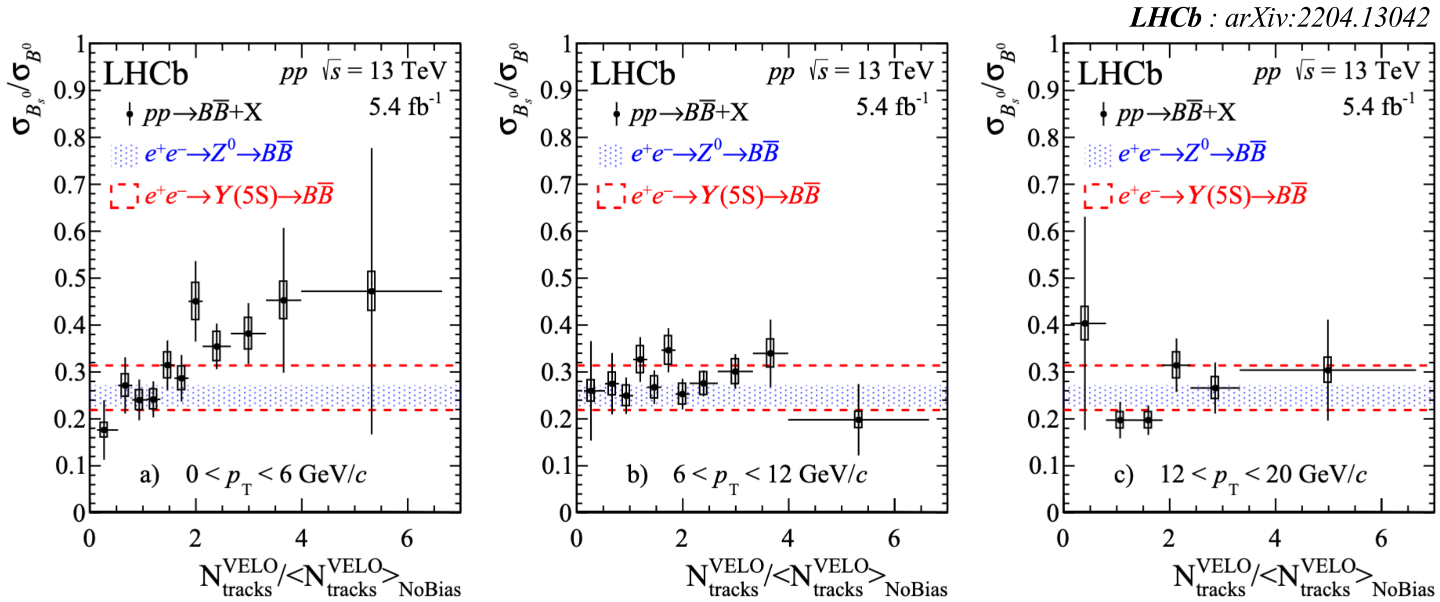
$$R_S = f_s/f_u \frac{BR(B_s^0 \to J/\psi\phi) BR(\phi \to K^+K^-)}{BR(B^+ \to J/\psi K^+)}$$

is the efficiency corrected ratio used since available f_s and $BR(B_s^0 \to J/\psi\phi)$ measurements are correlated

- LHCb data at forward rapidity is compatible in the overlapping p_T range

Beauty fragmentation functions

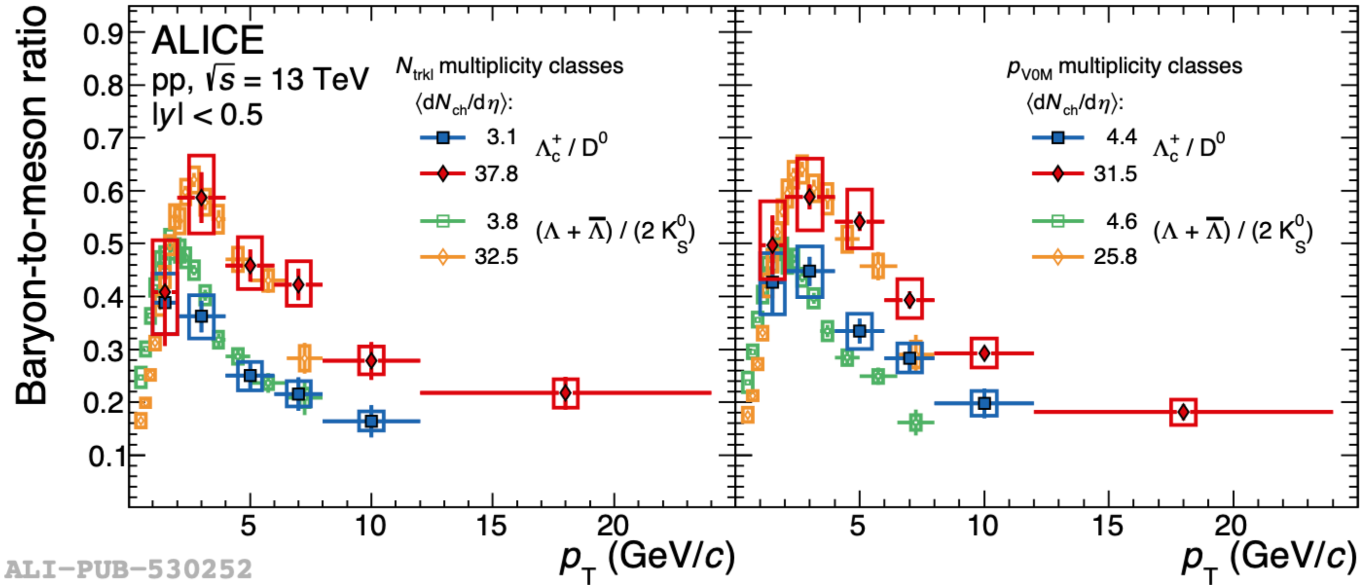
- The B_s^0/B^+ cross section ratio increases with multiplicity of $p_T < 6$ GeV/c
- No significant dependence on multiplicity for $p_T > 6$ GeV/c, consistent with data from e^+e^- collisions
  ⇨ Expected with hadronisation via quark coalescence in high-multiplicity pp collisions at low p_T and via fragmentation in vacuum for high-p_T b quarks



Baryon to meson ratio

- The light- and heavy-flavour baryon-to-meson ratios, $\Lambda/\mathrm{K^0_S}$ and $\Lambda_c^+/\mathrm{D^0}$, show a similar trend as a function of multiplicity.
- The peaks shifts towards higher p_T, with increasing multiplicity
  ⇨ potential common mechanism for light valence quark- and charm-baryon formation in hadronic collisions at LHC energies.

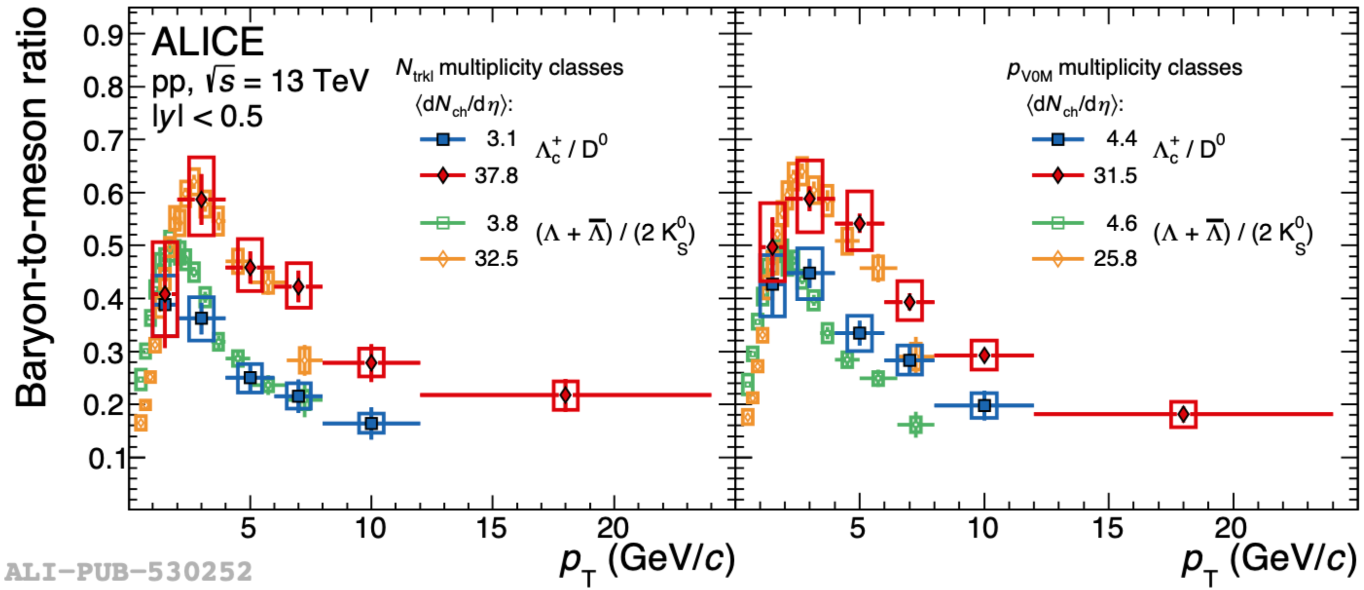
ALICE, Phys. Lett. B 829 (2022) 137065



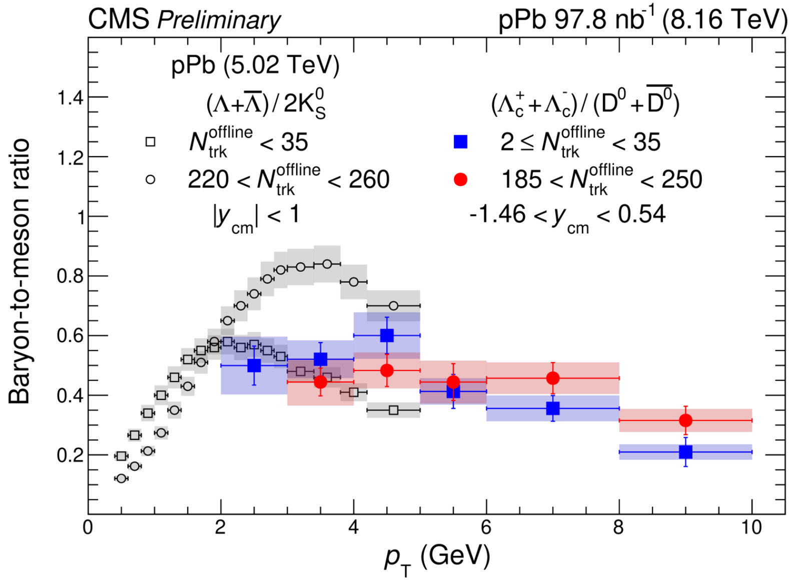
Baryon to meson ratio

- The light- and heavy-flavour baryon-to-meson ratios, $\Lambda/\mathrm{K}^0_\mathrm{S}$ and $\Lambda^+_\mathrm{c}/\mathrm{D}^0$, show a similar (different?) trend as a function of multiplicity.
- The peaks shifts towards higher p_T, with increasing multiplicity
  ⇨ potential common mechanism for light valence quark- and charm-baryon formation in hadronic collisions at LHC energies?

***ALICE**, Phys. Lett. B 829 (2022) 137065*



***CMS**, CMS-PAS-HIN-21-016*



Conclusion

- The ability to measure several observables (R_{AA}, v_2 , production ratios…) provides a solid base for model comparison and improves our understanding of heavy quark interaction with the medium

- However more precise measurements and models are needed to differentiate between different scenarios :
  - The apparent collective motion in small systems can be explained by intial and final state effects
  - The role of fragmentation and hadronisation is still being studied, both in medium and in vacuum.

- Run 3 data will allow more precise measurments with smaller uncertainties. Stay tuned!

THANK YOU FOR YOUR ATTENTION!