Recent results on multiplicity dependent open and hidden HF

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HF2022: Heavy Flavor from Small to Large Systems
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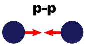
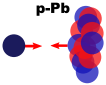
Why measure heavy flavor in hadronic collisions?

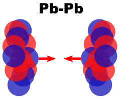
- The quark pair is created in the initial hard scattering hence experience the full evolution of the system.
- Their heavy mass $m_b > m_c \gg \Lambda_{QCD}$ hence can be described by pQCD.
- The subsequent hadronization dominated by soft processes.



- Study production mechanism, compare with models to test QCD.
- Baseline for pPb and PbPb.



- Study effects of presence of nucleus in the collision on particle production.
- 'Cold nuclear matter' reference for PbPb data.



- Map transition from hadronic to partonic matter.
- Study properties of hot nuclear matter.

Motivation to measure multiplicity dependence of HF

Open HF production cross section is usually factorized as

$$\frac{\mathrm{d}\sigma}{\mathrm{d}p_{\mathrm{T}}} = \text{pdfs describing partons inside the two colliding hadrons} \times \text{partonic HF cross section} \times \text{fragmentation function}$$

FF are assumed to be universal - their parametrization is often based on data from $e^{+}e^{-}$ and *ep* collisions.

Existing measurements show that **fragmentation is not universal in case of charm and beauty.**

The emergence of a hadronic medium may lead to a modification of the hadronization mechanism.

This would lead to **modification of baryon-to-meson ratio** and to **strangeness enhancement** in charm and beauty sector.

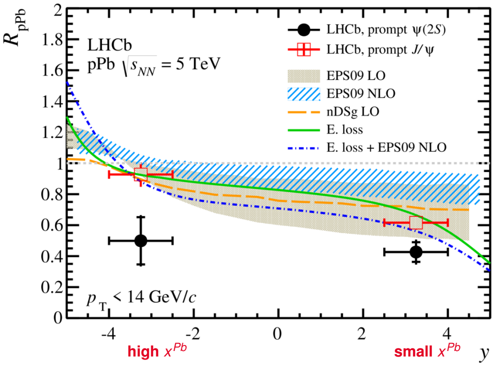
Motivation to measure quarkonia

Production of quarkonia is modified in nuclear collisions compared to that in pp.

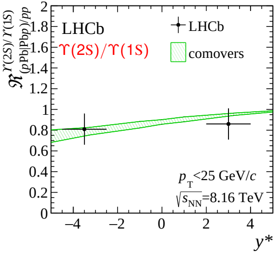
$$R_{p-Pb} = \frac{1}{A}\frac{\sigma_{p-Pb}(\Delta p_{\mathrm{T}}, \Delta y^*)}{\sigma_{pp}(\Delta p_{\mathrm{T}}, \Delta y^*)}$$

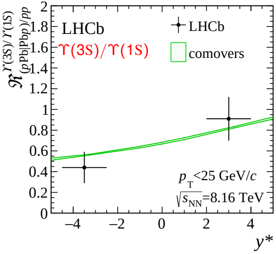
Higher excited states are more suppressed, as they are increasingly weakly bound.

LHCb, JHEP 1603 (2016) 133



LHCb, JHEP 11 (2018) 194





Such difference in suppression of states with the same quark content can be explained with final-state effects.

Charged particle multiplicity across collision systems

The charged particle multiplicity N_{ch} describes the final state and carries information on the production mechanisms.

In a pp event, N_{ch} is correlated with the number of parton-parton scatterings - **Multi-Parton Interactions (MPI)**.

In a pA collision, N_{ch} is correlated with the number of binary scatterings and allows for scrutiny of **MPI, NN interactions, and nuclear matter effects**.

Characterizing collisions by multiplicity opens a door to study events ranging from e^+e^--like (very low multiplicity) to AA-like (high multiplicity) and possibly onset/transition between their related effects.

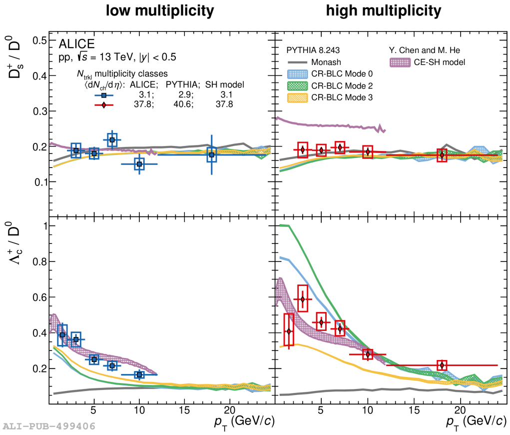
Correlating HF with multiplicity allows us to:

- **Study the interplay between the hard scattering and the underlying event dominated by soft processes.**
- **Study the onset of medium effects.**
- **Scrutinize the hadronization processes in different environments.**

Open HF results

Baryon-to-meson ratio in charm sector

ALICE, PLB 829 (2022) 137065



The D_s^+/D^0 and Λ_c^+/D^0 measured in various multiplicity classes show distinct behavior as a function of p_{T}.

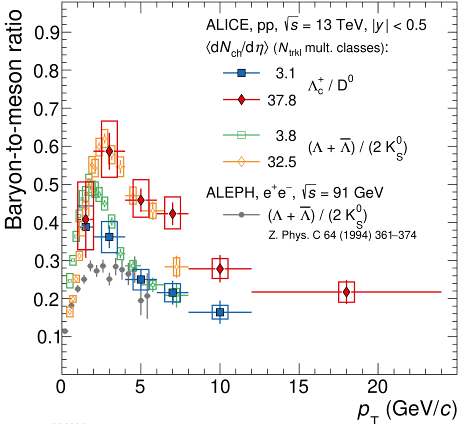
The D_s^+/D^0 is constant in p_{T} and in multiplicity, which is described by fragmentation models (solid gray line, Pythia Monash).

The Λ_c^+/D^0 manifests a p_{T} dependent behavior. The ratio is underestimated in fragmentation models which show a constant trend in p_{T}. Morevoer, the ratio increases with N_{ch}.

The p_{T}- and N_{ch}-dependent behavior can be reproduced in Pythia tune with novel color-reconnection topologies or through statistical hadronization models with augmented number of baryon species. The latter however overshoots the meson-to-meson ratio at high N_{ch}.

Baryon-to-meson ratio in charm sector (cont'd)

ALICE, PLB 829 (2022) 137065



The p_{T}-differential Λ_c^+/D^0 ratio displays identical behavior as $\Lambda/\mathrm{K}^0_{\mathrm{S}}$.

This suggests a common mechanism for strange and charmed baryon formation at LHC energies.

At $p_{\mathrm{T}} \gtrsim 4$ GeV$/c$, all low multiplicity distributions are consistent $\Rightarrow$ the formed baryons do not interact much with the environment and form as in vacuum.

At low p_{T}, the low multiplicity LHC data are above the values measured in e^+e^- $\Rightarrow$ modification of production mechanism.

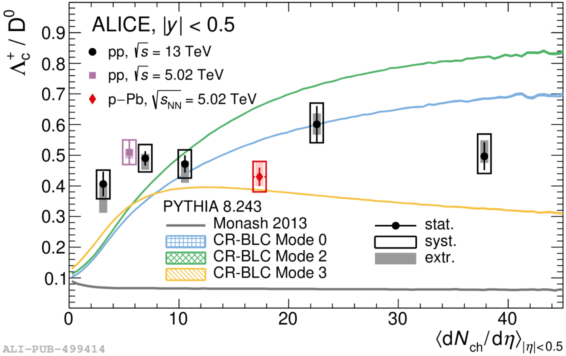
Baryon-to-meson ratio in charm sector (cont'd)

ALICE, PLB 829 (2022) 137065

The p_T integrated ratio show no significant multiplicity dependence.

This suggests the the multiplicity dependence seen in p_T differential ratio stems from redistribution of p_T being different for baryons and for mesons rather than due to overall enhancement of the baryon yield.

Moreover, LHCb measurement at forward rapidity show a different behavior.



Strangeness enhancement in b sector

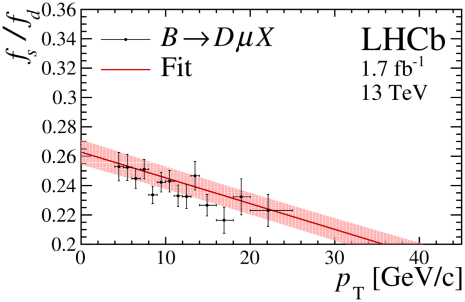
LHCb, PRD 104 3 (2021) 032005

LHCb recently measured the multiplicity dependence of $\mathrm{B_s^0}/\mathrm{B^0}$ ratio, comparing the fraction of b quarks that hadronize with an s quark to that hadronizing with a d quark, f_s/f_d

Both mesons reconstructed from the same channel - allows for reduction of systematical uncertainties.

In e^+e^- collisions, the constant f_s/f_d points to a universality of b-quark fragmentation.

In pp collisions, f_s/f_d shows a dependence on p_T.



Strangeness enhancement in b sector (cont'd)

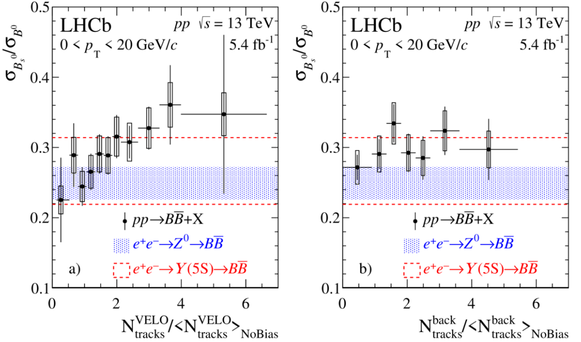
LHCb, arXiv:2204.13042

Ratio correlated with all charged tracks ($N_{\text{tracks}}^{\text{VELO}}$) and with a subset of charged tracks pointing away from the detector ($N_{\text{tracks}}^{\text{back}}$).

All tracks $\rightarrow f_s/f_d$ increases with multiplicity.

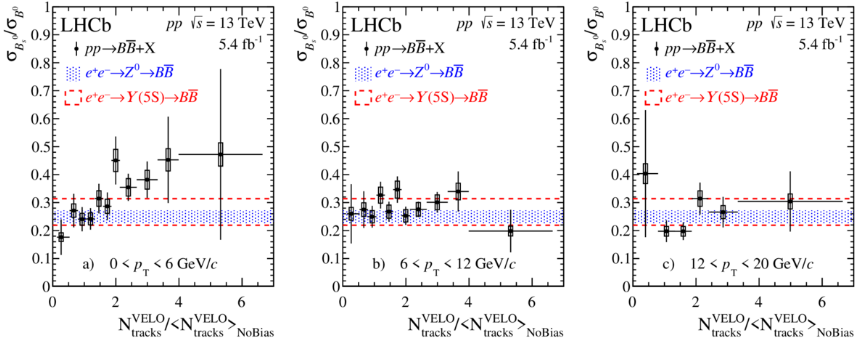
Backward tracks $\rightarrow f_s/f_d$ is constant in multiplicity.

The difference could stem from the local increase in partonic density in a similar rapidity region to that of the meson.



Strangeness enhancement in b sector (cont'd)

LHCb, arXiv:2204.13042



The ratio at low p_{T} shows a dependence on multiplicity $\Rightarrow$ hadronization via coalescence?

At $p_{\mathrm{T}} > 6$ GeV$/c$, the ratio is constant $\Rightarrow$ production in vacuum.

Open charm mesons in ALICE

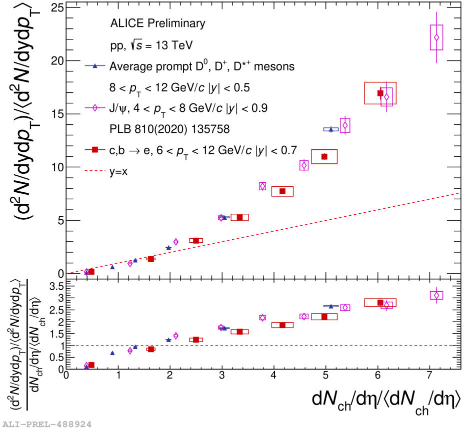
J/ψ: ALICE, PLB 810 (2020) 135758

Normalized D-meson yields show a **stronger-than-linear increase** with relative multiplicity.

- Steeper increase with increasing p_{T}.
- No significant energy dependence

- The observed increase with multiplicity is qualitatively described by models including medium effects.

- Observed behavior shared among other HF mesons.



Quarkonia

J/ψ versus multiplicity in pp

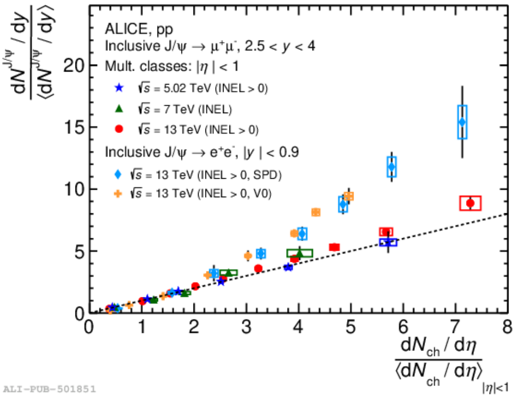
mid: ALICE, PLB 810 (2020) 135758
fwd: ALICE, JHEP 06 (2022) 015

J/ψ has been studied as a function of multiplicity at midrapidity rather extensively (not only) at the LHC, particularly by ALICE.

Midrapidity J/ψ show a similar trend to open charm. The relative ratio is independent of energy spanning from RHIC to the LHC.

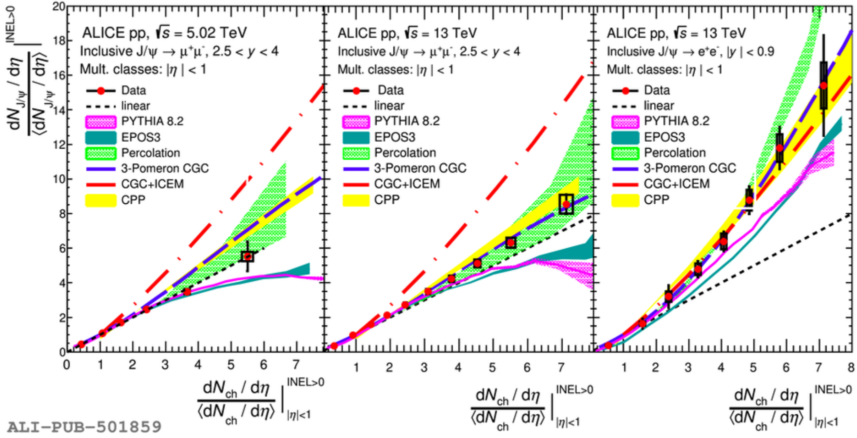
To same behavior is observed for multiplicity at mid- and forward rapidity.

Forward J/ψ show an increase consistent with linear trend with unity slope.



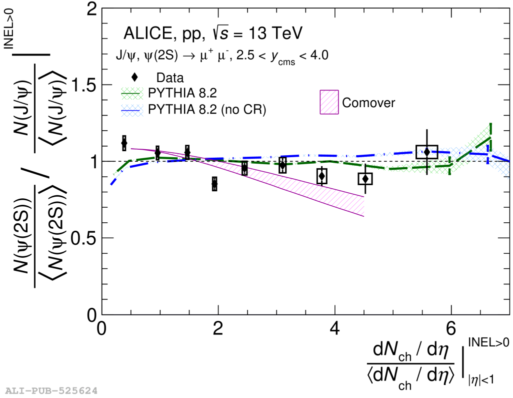
J/ψ versus multiplicity in pp (cont'd)

mid: ALICE, PLB 810 (2020) 135758
fwd: ALICE, JHEP 06 (2022) 015



$\psi(2S)$ vs multiplicity in pp

ALICE, arXiv:2204.10253



Forward $\psi(2S)$ as a function of midrapidity N_{ch} show consistent behavior with that of J/ψ. The ratio is consistent with a flat trend and with a linear trend with negative slope.

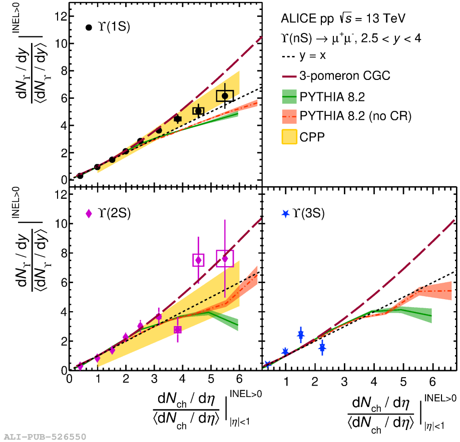
Such behavior is reproduced in models.

In the comover scenario, the lower binding energy of the $\psi(2S)$ makes it more prone to dissociation due to interactions with the environment.

The MPI scenario assumes a proportional increase of relative yields with the number of hard scatterings in the collision.

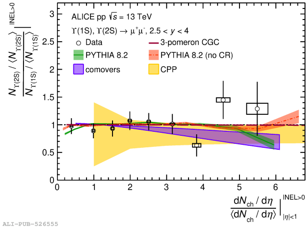
$\Upsilon(\mathrm{nS})$ versus multiplicity in pp

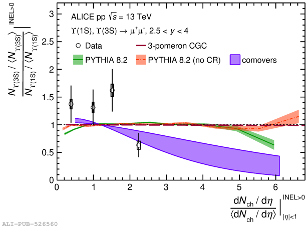
ALICE, arXiv:2209.04241



$\Upsilon(\mathrm{nS})$ show the same behavior as charmonia and can be described by models.

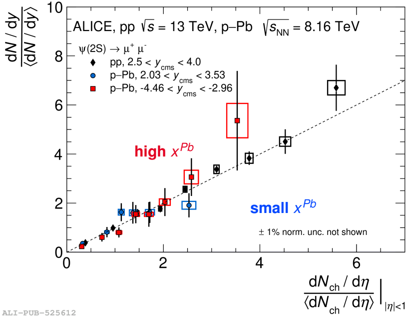
The $\Upsilon(2S)/\Upsilon(1S)$ and $\Upsilon(3S)/\Upsilon(1S)$ ratio agree with calculations assuming MPIs but also nuclear effect. Conclusion is limited by uncertainties and in case of $\Upsilon(3S)$ by the very narrow multiplicity range.





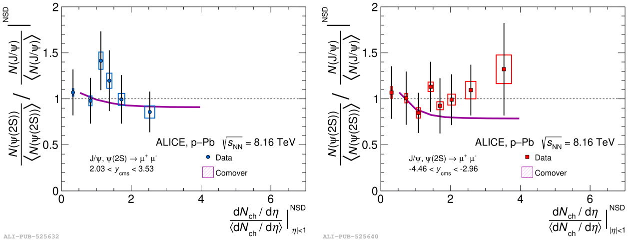
$\psi(2S)$ vs multiplicity in pPb

ALICE, arXiv:2204.10253



Forward and backward $\psi(2S)$ show a consistent increase, the observed trend is similar to the one measured in pp.

The $\psi(2S)$-to-J/ψ ratio is reproduced in comover model.

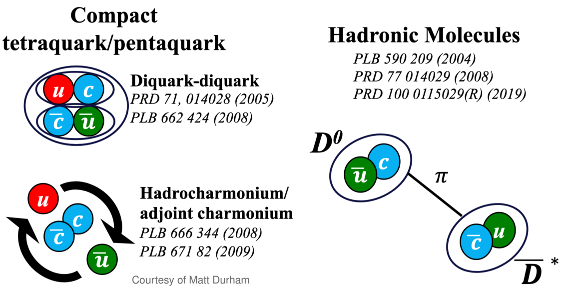


HF as a tool to study exotics

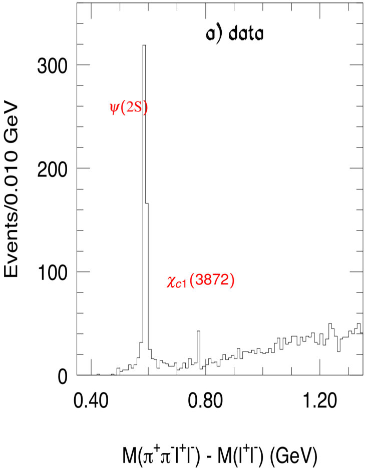
Multiplicity-dependent study of $\chi_{c1}(3872)/\psi(2S)$

The $\chi_{c1}(3872)$ exotic hadron was first observed in 2003 by Belle in decays of $B \to \mathrm{J}/\psi\pi^+\pi^-$.

Belle, PRL 91 (2003) 262001

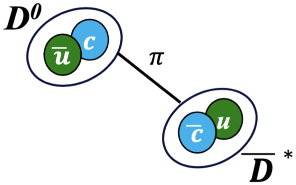


Courtesy of Matt Durham



Multiplicity-dependent study of $\chi_{c1}(3872)/\psi(2S)$ (cont'd)

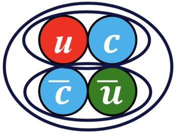
The nature of $\chi_{c1}(3872)$ can be scrutinized by studying its multiplicity dependent relative suppression compared to a conventional charmonium state such as $\psi(2S)$.



Hadronic molecule $\Rightarrow$ very weakly bound with a large radius $\sim$ 10 fm.

$$M_{\chi_{c1}(3872)} - M_{\bar{D}} - M_{D^*} = 0.1 \pm 0.27 \text{ MeV}$$

Compact tetraquark $\Rightarrow$ tightly bound with small radius $\sim$ 1 fm.

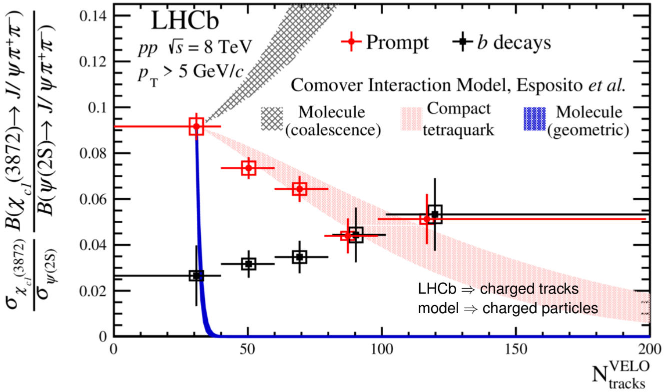


Multiplicity-dependent study of $\chi_{c1}(3872)/\psi(2S)$ (cont'd)

LHCb, PRL 126 (2021) 9, 092001

- The prompt ratio decreases with multiplicity - stronger suppression of $\chi_{c1}(3872)$ compared to $\psi(2S)$.
- The non-prompt ratio is constant in multiplicity.

Such behaviour is consistent with the idea of a weakly-bound $\chi_{c1}(3872)$ being more dissociated than a more tightly bound $\psi(2S)$.



Comover interaction model by Espacito *et al.*, EPJC 81 (2021) 669, favors the **compact tetraquark scenario**.
A tweaked model by Braaten *et al.*, PRD 103 (2021) 071901, suggests the $\chi_{c1}(3872)$ is a **D-meson molecule**.

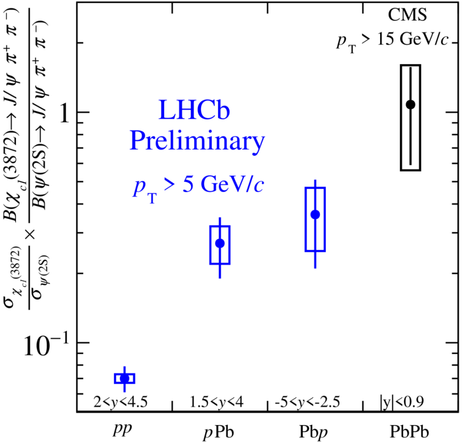
$\chi_{c1}(3872)$ across systems

pp: LHCb, PRL 126 (2021) 9, 092001
pPb: LHCb-CONF-2022-001
PbPb: CMS,PRL 128 (2022) 032001

- The ratio increases with average multiplicity.
- Initial state effects in nuclear events mostly cancel out in the ratio

The $\psi(2S)$ are suppressed in pPb and PbPb collisions, which drives the ratio up. This is in contradiction with the ratio in pp decreasing with multiplicity.

The larger multiplicities in nuclear events may allow for formation of $\chi_{c1}(3872)$ via coalescence.



low multiplicity $\longrightarrow$ high multiplicity

Summary

Measuring correlation of HF with multiplicity allows for thorough scrutiny of the production processes and allows to test the modification of production across systems of various size.

Recent open HF results point to different production mechanisms a function of characteristics of both the collisions and the probe. The same behavior is also observed in strange sector.

Relative HF yields as a function of relative multiplicity show a common trend shared among multiple species, suggesting that the observed behavior is independent of hadronization. Recent results probing correlation with multiplicity measured in different rapidity windows show that, at least for J/ψ, the measured increase is not a product of measurement bias.

The increase in relative yields in pp and pPb are reproduced in models.

Multiplicity dependent HF may also serve as a probe of production mechanism to more exotic states such as $\chi_{c1}(3872)$.

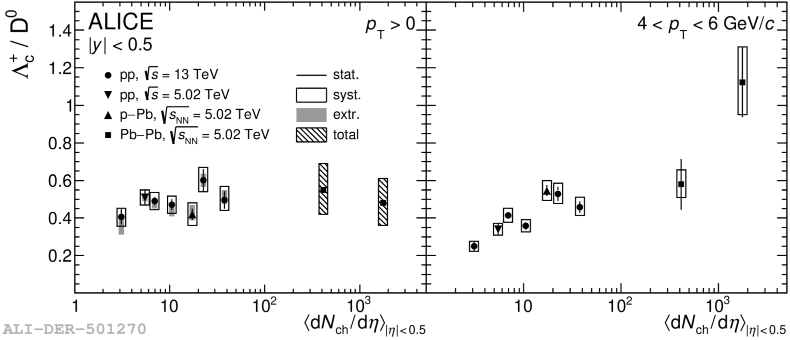
Outlook

There are still many open question - hopefully Runs 3 & 4 will bring enough data to answer some of these.

- ? The Λ_c/D multiplicity conundrum? Seeming discrepancy between Λ_c/D in ALICE and in LHCb?
- ? Are multiplicity dependent quarkonia ratios in pp better modeled with MPI or with comover models? This could be (partially) answered with extending the reach in data and increasing precision.
- ? Future separation of prompt and non-prompt quarkonia could help differentiating between models.
- ? On the experimental side, there is aim to better understand different multiplicity estimators and their biases.

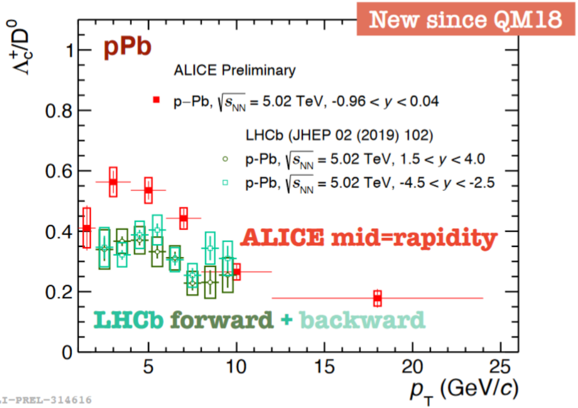
Back up

Λ_c/D vs multiplicity vs p_{T}



ALICE, JHEP 2020 (2020) 162

More info of hadronization: Λ_c/D^0 ratio in pPb



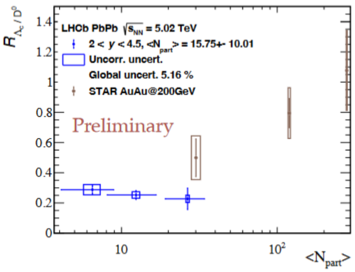
- Λ_c/D^0 ratio: nPDF effect almost cancelled
- Λ_c/D^0 (mid-rapidity) > Λ_c/D^0 (FB) ➡ Tension or feature?

Jing Wang (MIT), Open HF: Experiments, QM 2019 (Wuhan) 32

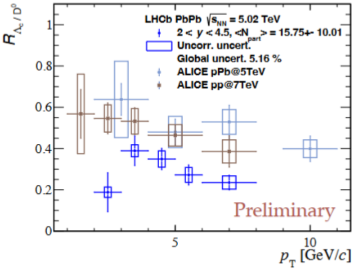
New Λ_c^+-to-D^0 ratio in peripheral PbPb collisions

LHCB-PAPER-2021-046

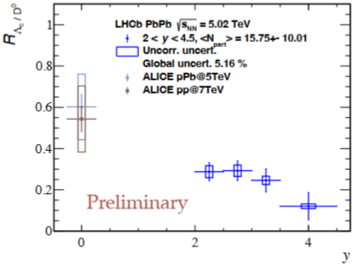
First Λ_c^+-to-D^0 production ratio measured in peripheral PbPb collisions at forward rapidity.



- Most central point compatible with STAR measurements.
- Rising trend ?



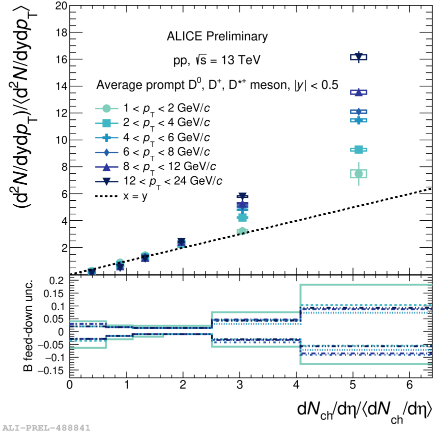
- Similar p_T trend between ALICE and LHCb for $p_T > 4$ GeV/c.



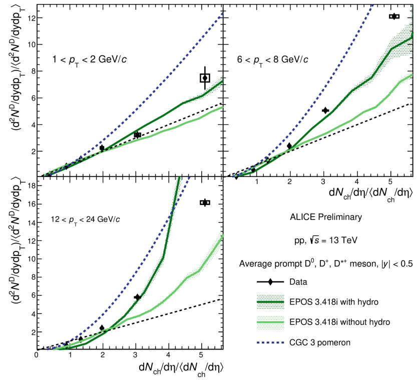
- Difference between LHCb and ALICE data versus rapidity.

Systematically lower Λ_c^+-to-D^0 ratio in LHCb compared to ALICE due to different rapidity range confirmed?

D mesons as a function of multiplicity in pp



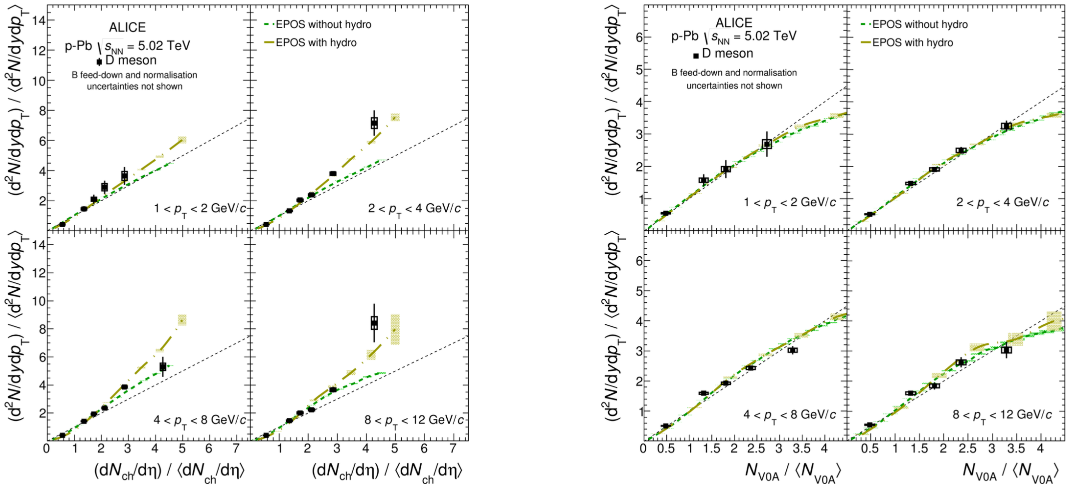
ALI-PREL-488841



ALI-PREL-488879

D mesons as a function of multiplicity in pPb

ALICE, JHEP 08 (2016) 078



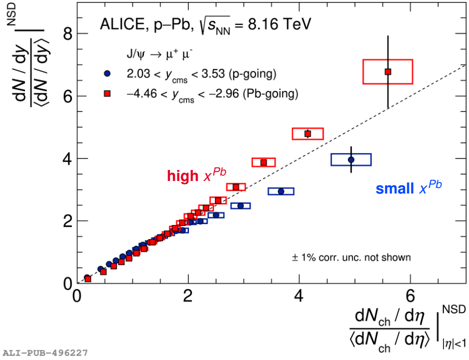
J/ψ vs multiplicity in pPb

ALICE, JHEP 2020 (2020) 162

In pPb, the relative J/ψ shows a faster increase with multiplicity when the meson is measured at backward region compared to forward.

This behavior is independent of energy. In the measured multiplicity range, the trend is consistent with a proportional increase.

At midrapidity, the J/ψ show a similar increase as D mesons.



J/ψ vs multiplicity in pPb (cont'd)

ALICE, JHEP 2020 (2020) 162