Recent LHCb results on open charm and charmonium production

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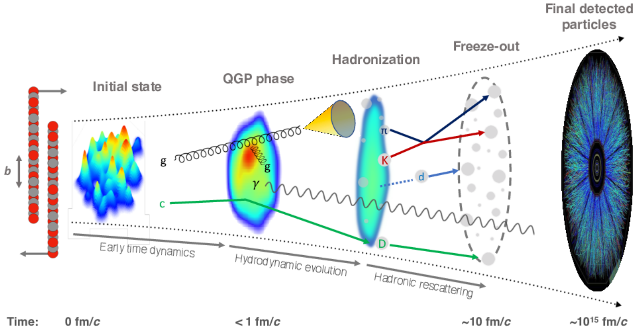
On behalf of LHCb Collaboration

October 30, 2025

Contents

Charm quark in heavy-ion collisions

- Charm quarks are excellent probes, produced at early-stage hard process $\tau \sim 1/m_c$, experience the medium evolution with long lifetime



source: arXiv:2303.17254

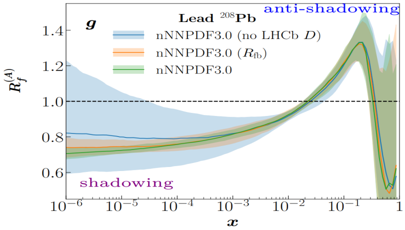
- Nuclear shadowing
- Gluon saturation
- Initial state scatterings

- Color screening
- Comoving effect
- Collectivity
- In-medium energy loss

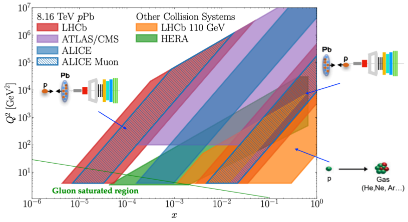
- Modification of hadronization
- Quarkonia regeneration

Nuclear shadowing

- Modification of **n**uclear **p**arton **d**istribution **f**unctions (nPDFs) relative to *pp* collisions



source: EPJC82(2022)6,507

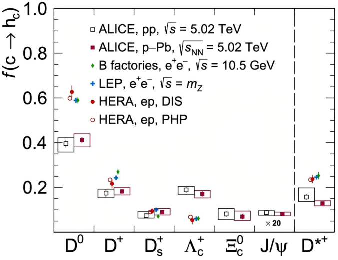


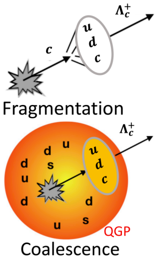
source: J.Phys.Conf.Ser.1271(2019)1, 012008

- Large theoretical uncertainty in high-x region
- Charm production helps to constrain gluon density in large (x, Q^2) region
- LHCb covers unique kinematics regions of low-x (pPb), medium-x (Pbp), and large-x (fixed-target) regions

Modification of hadronization

- Fragmentation universality expected across different collision systems
  - Different fragmentation fraction observed



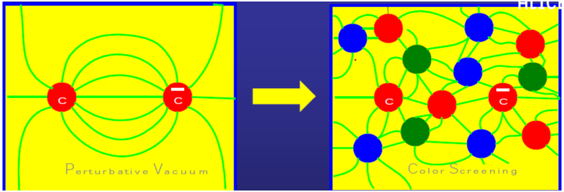


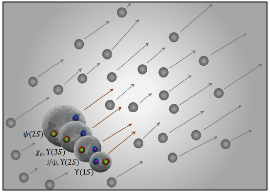
source: EPJC84(2024)12,1286

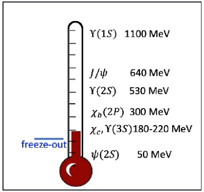
- In high-density medium, quarks can hadronize via colascence mechanism
  - Strangeness enhancement (abundant $s\bar{s}$ pair in medium)
  - Higher baryon-to-meson ratio

Quarkonia dissociation

- Interaction between $c\bar{c}$ can be screened by medium (Debye screening)
- Charmonia dissociate by interaction with co-moving particles
- Charmonia serve as thermometer for studying local temperature



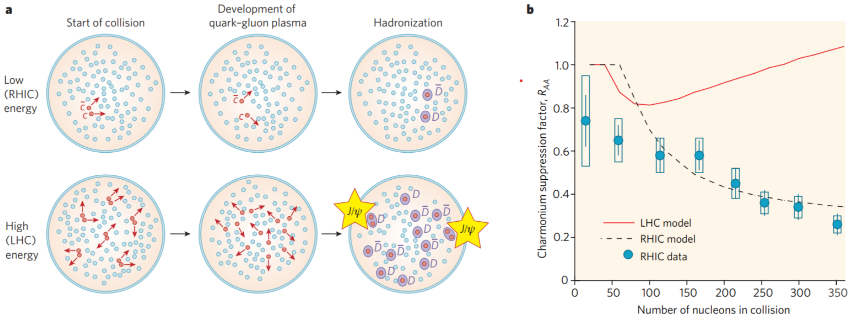




thermometer adapted from: Eur.Phys.J.C 61 (2009) 705-710

Charmonia regeneration

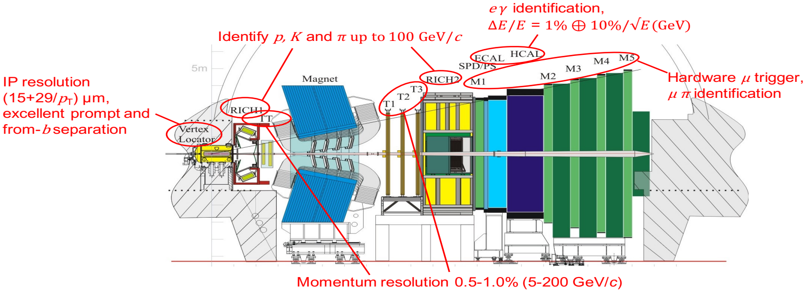
- At high LHC energies:
  - Much more $c\bar{c}$ are produced
  - All charm quarks are produced in hard collisions, $N_{c\bar{c}} = const$
  - All charmonia dissolved in QGP
  - J/ψ produced through statistical regeneration, $N_{J/\psi} \sim N^2_{c\bar{c}}$



source: Nature 448 (2007) 302-309

LHCb detector

- Single-arm forward spectrometer covering pseudo-rapidity $2 < \eta < 5$
- Designed for studying particles containing b or c quarks

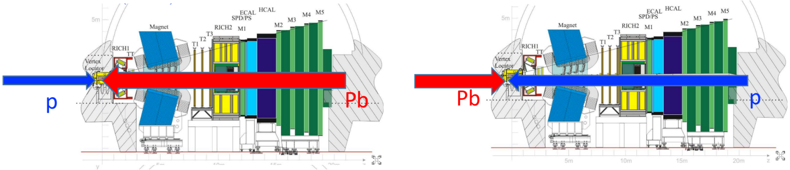


source: JINST 3 (2008) S08005 and IJMPA 30 (2015) 1530022

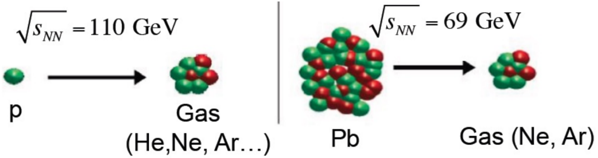
- Provide excellent vertex reconstruction and separation, precise tracking, full PID, efficient and fast trigger and unique acceptance
- Playing more and more important roles in heavy-ion physics

Data set

- Forward ($p\mathrm{Pb}$) and backward ($\mathrm{Pb}p$) rapidities for $p\mathrm{Pb}$ collisions



- Fixed-target mode acquired by injecting gases in vertex locator (VELO)



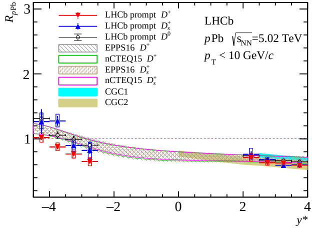
- Huge pp collision data set for small-system studies
  - System size: $pp < p\mathrm{A} < \mathrm{A}p < \mathrm{AA}$ collisions (**small** $\rightarrow$ **large** system)
  - Charm production in pp collisions serve as baseline, where no nuclear effect and QGP is expected

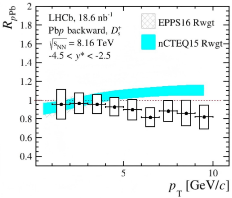
Nuclear modification factor: D mesons

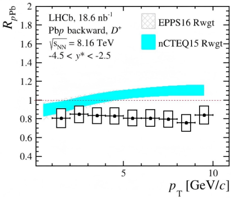
- Nuclear modification factor $R_{p\mathrm{Pb}}$ is defined as:

$$R_{p\mathrm{Pb}}(p_\mathrm{T}, y^*) = \frac{1}{208}\frac{\sigma_{p\mathrm{Pb}}(p_\mathrm{T}, y^*)}{\sigma_{pp}(p_\mathrm{T}, y^*)}$$

- Significant suppression from gluon shadowing at forward rapidity
- Slight difference between hadron species at backward rapidity, hinting at possible final-state effects
- Tension with nPDF predictions at backward rapidity



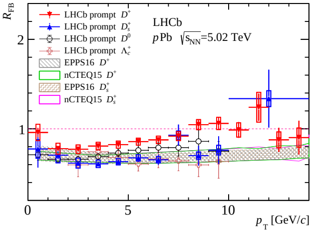




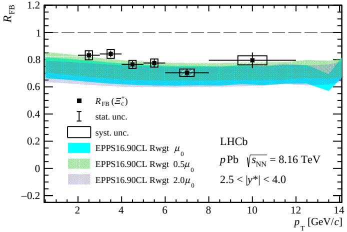
source: JHEP01(2024)070, Phys.Rev.D 110, L031105

Forward-backward asymmetry: D mesons, Λ_c^+, Ξ_c^+

- Forward-backward production ratio as function of p_T is presented



source: JHEP01(2024)070

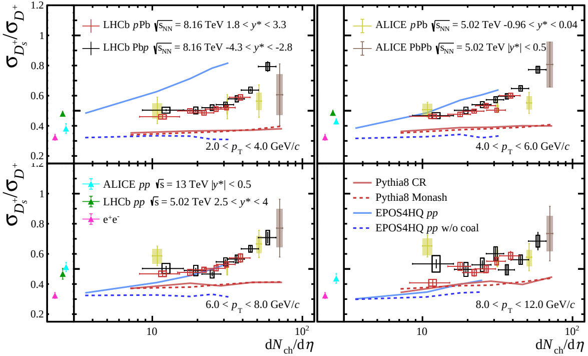


source: Phys.Rev.C 109 (2024) 044901

- Suppression at forward rapidity can be described by nPDF predictions
- Different dependence on p_T found for different hadron species

Strangeness enhancement: D_s^+/D^+

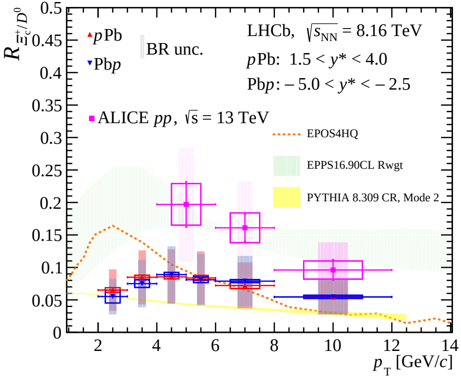
- First observation of strangeness enhancement for charm production in high-multiplicity small systems
- Coalescence needs to be considered for a better description of the data



source: Phys.Rev.D 110 (2024) 3, L031105

Baryon-to-meson ratio: Ξ_c^+ / D^0

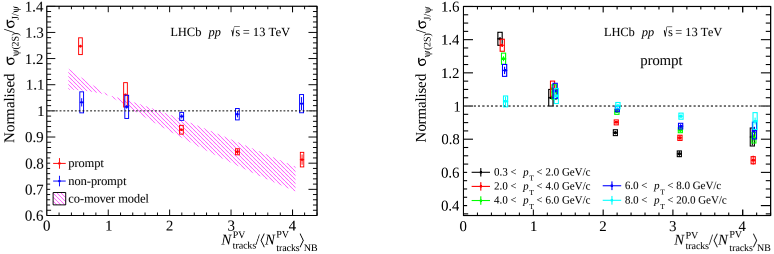
- In high-density medium, modification of hadronization lead to a higher baryon-to-meson ratio
- However, no significant enhancement of charm baryon-to-meson ratio observed
- Dominant uncertainty from branching fraction
- Discrepancy with ALICE result hinting at rapidity dependence



source: Phys.Rev.C 109 (2024) 4, 044901

Charmonia suppression: $\psi(2S)/J/\psi$

- Prompt $\psi(2S)$ over J/ψ ratio found to decrease with multiplicity around charmonium production ($N^{\mathrm{PV}}_{\mathrm{tracks}}$)

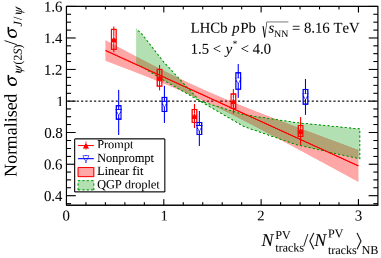


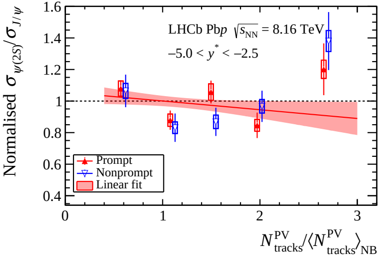
source: JHEP05(2024)243

- Non-prompt charmonia production, only affected by *b*-decay fraction and far away collision center, the ratio found to be consistent
- The $\psi(2S)$ has larger radius and lower binding energy, more easily dissociated
- The $\psi(2S)$ is suppressed more in the low-p_{T} region

Charmonia suppression: $\psi(2S)/J/\psi$

- No significant multiplicity dependence found for non-prompt ratio
- Prompt ratio in forward rapidity consistent with QGP-droplet prediction



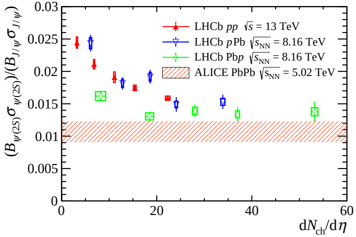


source: arxiv.2506.08624v2

- Prompt ratio decreases with increasing multiplicity in forward rapidity of $p\mathrm{Pb}$ collisions
- No multiplicity dependence found in backward $p\mathrm{Pb}$ collisions

Charmonia suppression: $\psi(2S)/J/\psi$

- Multiplicity dependence of prompt $\psi(2S)$ to J/ψ ratio compared from small to large systems
- Result in $p\mathrm{Pb}$ forward rapidity consistent with that in *pp*, while in backward rapidity is close to that in PbPb collisions
- As system size gets larger, multiplicity dependence converges to PbPb result
- No multiplicity dependence found for prompt ratio in PbPb collisions, consistent with ALICE result at same collision energy
- Regeneration might not be neglected in large systems, $\psi(2S)$ is more easily regenerated than J/ψ



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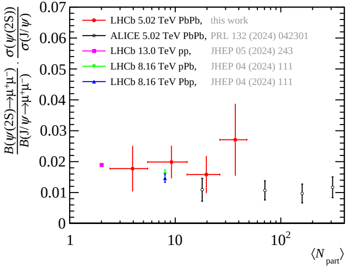
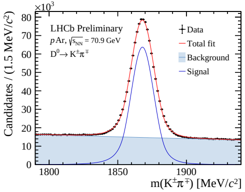
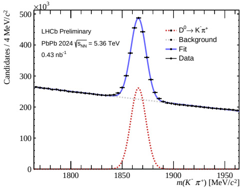


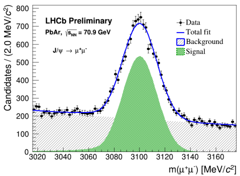
source: arxiv.2411.05669

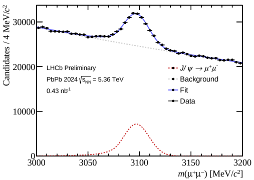
Conclusion and Prospect

- Modification of D-mesons (D^0, D_s^+, D^+, Λ_c) productions and the forward-backward asymmetry indicate that charm production is sensitive to nuclear matter effects
- No enhancement of charm baryon-to-meson ratio (Ξ_c^+/D^0) observed in $\mathrm{Pb}p$ than in $p\mathrm{Pb}$ collisions
- Strangeness enhancement (D_s^+/D^+) and charmonium suppression ($\psi(2S)/J/\psi$) are observed, helps to investigate existence of QGP in high-multiplicity small collision systems
- Multiplicity dependence of excited-to-ground charmonium ratio shows a smooth transition behavior from small to large collision systems
- More results of charm production will come out with newly collected LHCb Run3 data!







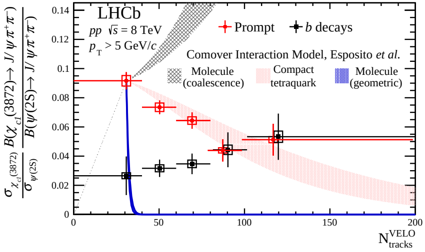


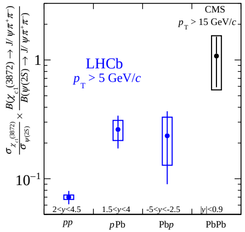
Thanks for your attention!

Q & A

Backup: $\chi_{c1}(3872)/\psi(2S)$

- The prompt $\chi_{c1}(3872)$ to $\psi(2S)$ ratio decrease with multiplicity in *pp* collisions
- Compact tetraquark hypothesis describes the *pp* data better than molecule and conventional charmonium hypothesis



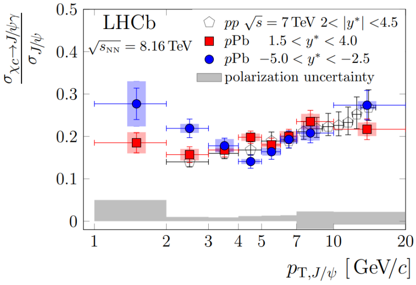


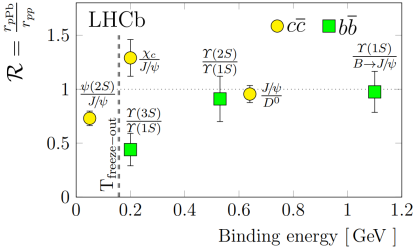
source: Phys.Rev.Lett.126 (2024)24, 242301 source: Phys.Rev.Lett.126 (2021)9, 092001

- Prompt $\chi_{c1}(3872)$ to $\psi(2S)$ ratio increases with increasing system size, indicating the hadronic density in $p\mathrm{Pb}$ collisions allow the quark coalescence become dominant

Backup: $\chi_{c1,c2}/J/\psi$

- No suppression found for χ_c in $p\mathrm{Pb}$ collisions compared to pp collisions
- The non-dissociation of χ_c states suggests a constraint on temperature in $p\mathrm{Pb}$ collisions no more than 180 MeV, the smallest binding energy of χ_c states
- Similar-binding-energy $\Upsilon(3S)$ suppressed, might dissociate due to final-state effects
- The dissociation of $\chi_b(3P)$ can also explain this, which has a binding energy around 47 MeV similar to $\psi(2S)$





source: Phys.Rev.Lett.132(2024)102302