Recent LHCb results on quarkonium production

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On behalf of LHCb Collaboration

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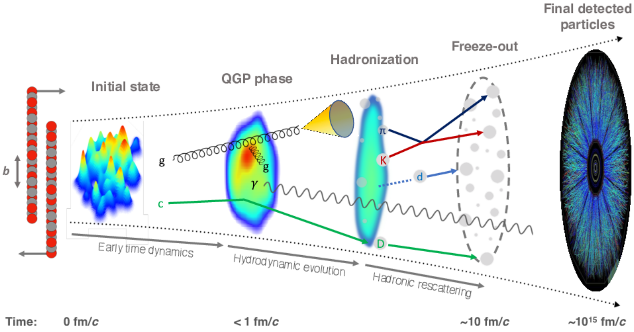
Heavy quark in heavy-ion collisions

- Heavy 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

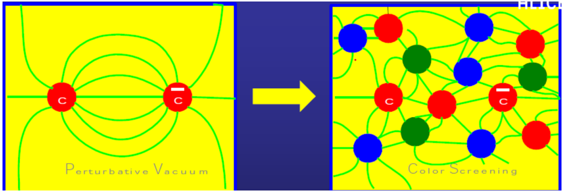
- Nuclear shadowing
- Gluon saturation
- Initial state scatterings

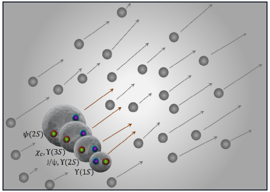
- Color screening
- Comoving effect
- Collectivity
- In-medium energy loss

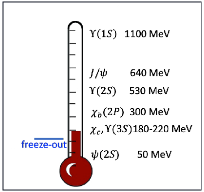
- Modification of hadronization
- Quarkonia regeneration

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



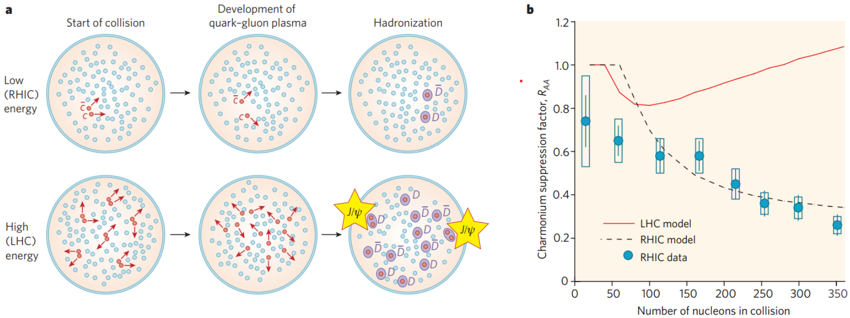




thermometer adapted from: Eur.Phys.J.C 61 (2009) 705-710

Quarkonium regeneration

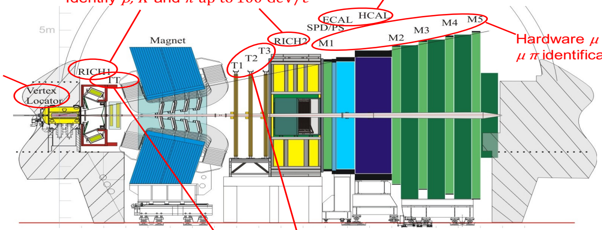
- At high LHC energies:
  - Much more $c\bar{c}$ are produced
  - All charm quarks are produced in hard collisions, $N_{c\bar{c}} = const$
  - All charmonia dissolved in QGP
  - J/ψ produced through statistical regeneration, $N_{J/\psi} \sim N^2_{c\bar{c}}$



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

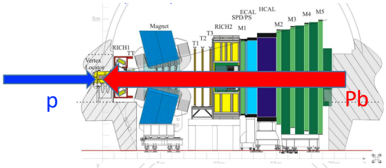


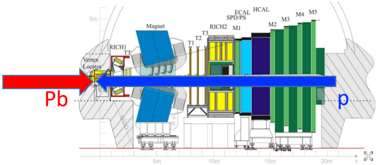
source: JINST 3 (2008) S08005 and IJMPA 30 (2015) 1530022

- 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

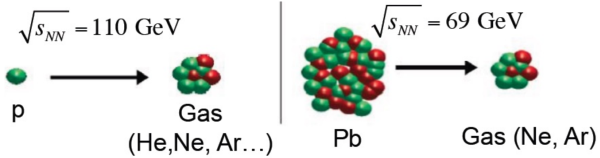
Data set

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





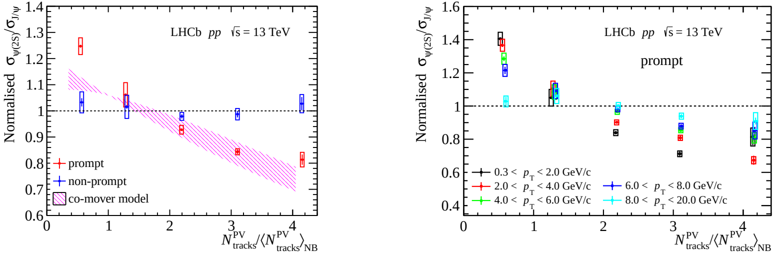
- Fixed-target mode acquired by injecting gases in vertex locator (VELO)



- 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

$\psi(2S)/J/\psi$ in *pp* collisions

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

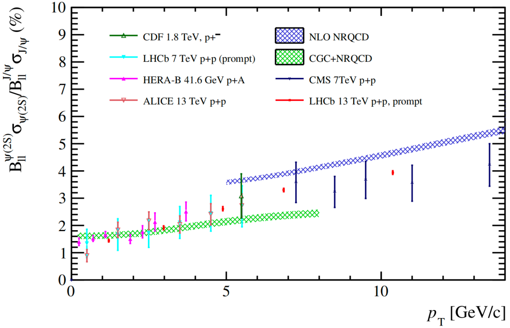


source: JHEP05(2024)243

- 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

$\psi(2S)/J/\psi$ in *pp* collisions

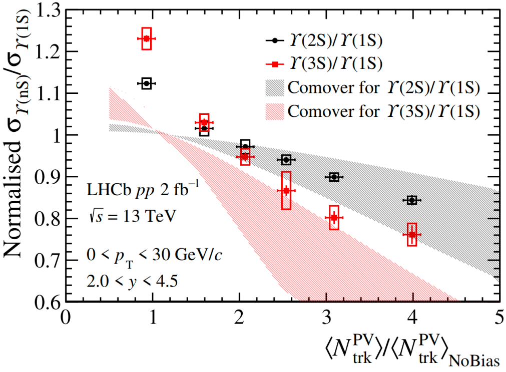
- This measurement cover from low- to high-p_{T} regions
- The p_{T}-dependence agree well with other experiments
- The p_{T}-dependence can be described by NLO NRQCD and CGC+NRQCD in low- and high-p_{T} regions



source: JHEP05(2024)243

$\Upsilon(nS)/\Upsilon(1S)$ in *pp* collisions

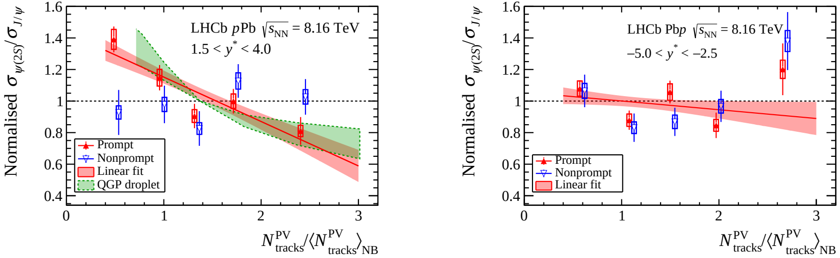
- Multiplicity dependence of $\Upsilon(nS)/\Upsilon(1S)$ show similar results as charmonium
- $\Upsilon(3S)$ is suppressed more than $\Upsilon(2S)$ as multiplicity increases
- Comover effect can not describe the decreasing trend well



source: JHEP05(2025)011

$\psi(2S)/J/\psi$ in pPb collisions

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

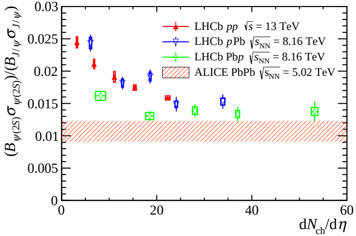


source: JHEP11(2025)169

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

$\psi(2S)/J/\psi$ in different collision systems

- 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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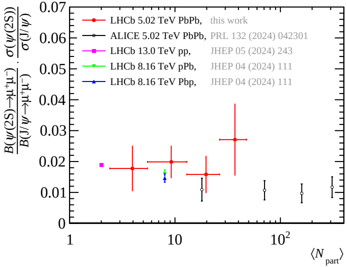
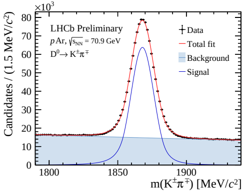
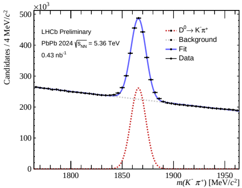


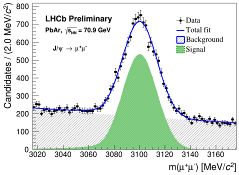
source: arxiv.2411.05669

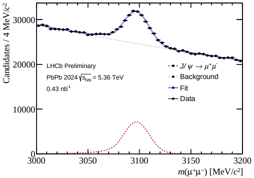
Conclusion and Prospect

- Prompt $\psi(2S)$ is suppressed more than J/ψ in high multiplicity small collision system
- Higher-state Υ suppressed more than ground state $\Upsilon(1S)$ in high multiplicity region
- Multiplicity dependence of excited-to-ground charmonium ratio shows a smooth transition behavior from small to large collision systems
- No multiplicity dependence of prompt $\psi(2S)$ to J/ψ ratio found in large collision system, could result from the competition of regeneration effect
- More results of heavy quarkonium production will come out with newly collected LHCb Run3 data!







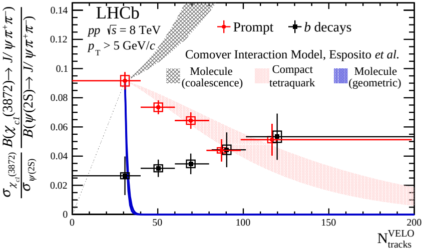


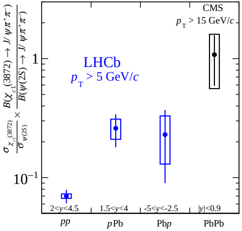
Thanks for your attention!

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



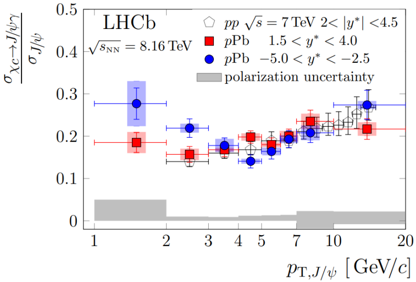


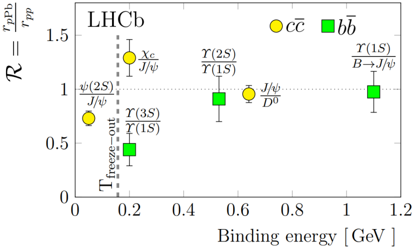
source: Phys.Rev.Lett.126 (2024)24, 242301 source: Phys.Rev.Lett.126 (2021)9, 092001

- 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