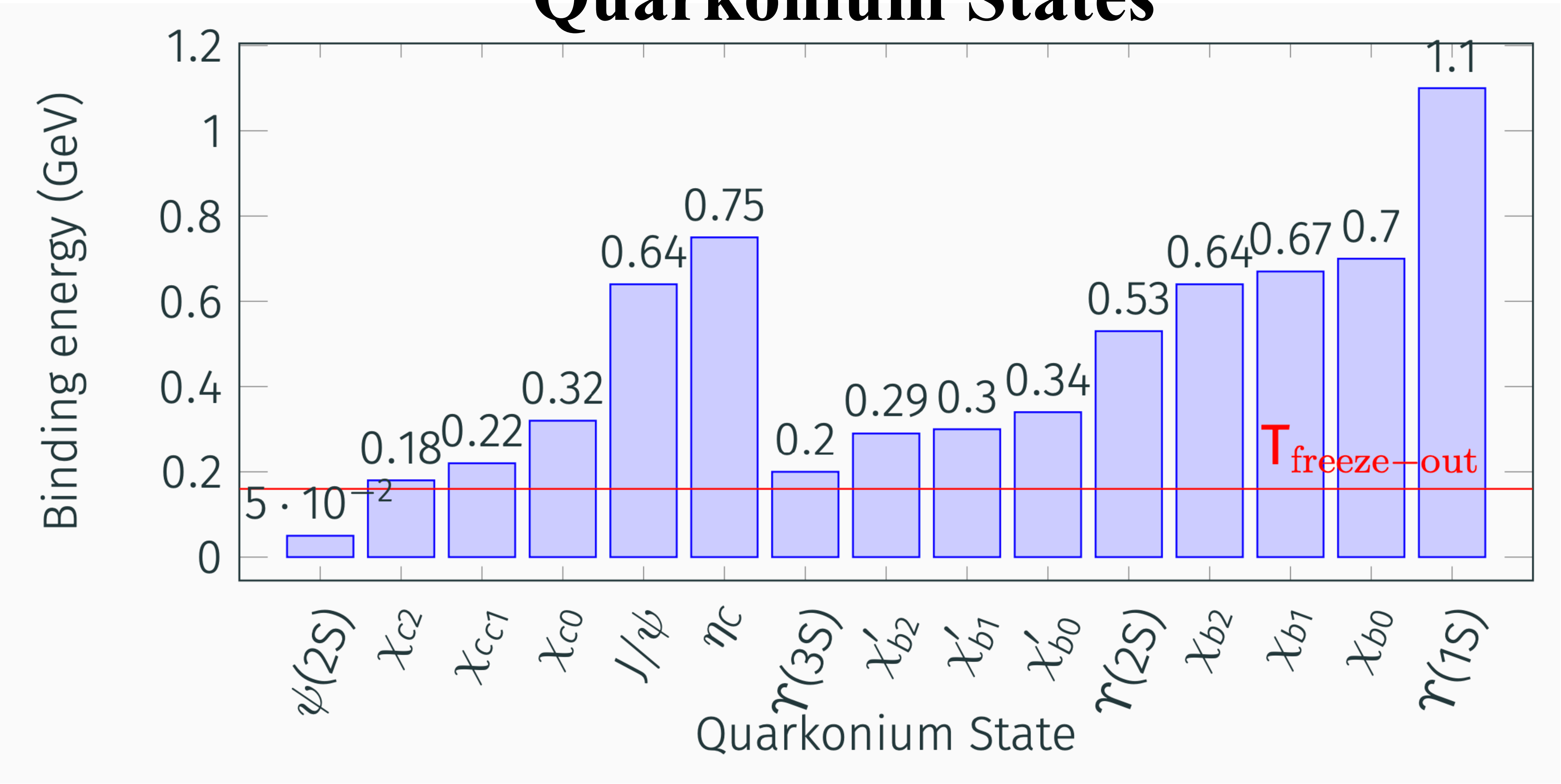
Medium characterization using quarkonia measured by the LHCb.

Cesar Luiz da Silva for the LHCb Collaboration
Los Alamos National Lab

Quarkonia Working Group 2024 – IISER, Mohali, India

Quarkonium States



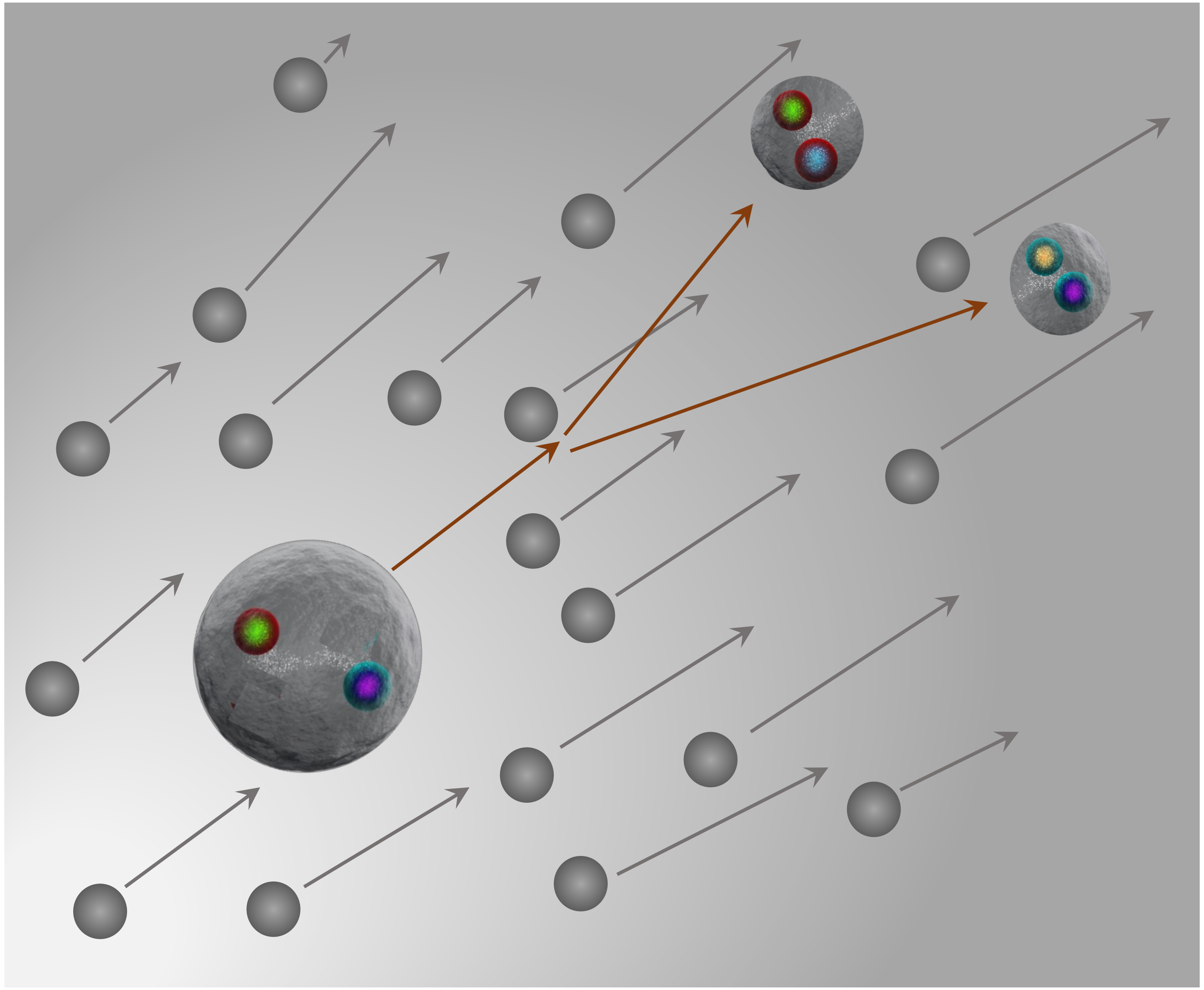
If medium temperature is above the binding energy, the quarkonium state is suppressed.

$T_{freeze\text{-}out}$ ~ 155-160 MeV

Lattice QCD A. Bazavov et al., PLB795 (2019) 15

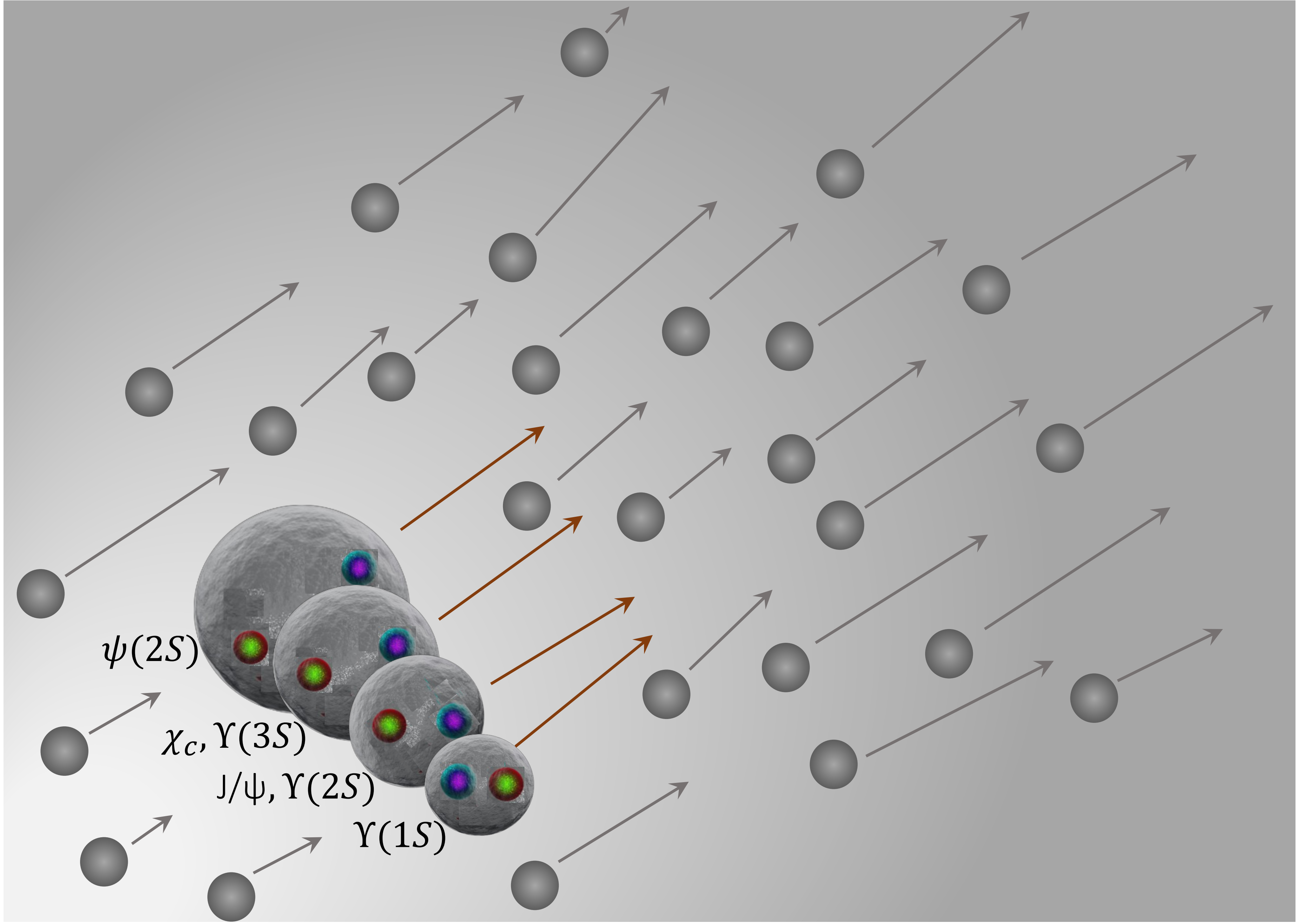
Thermal Model N. Sharma et al. PRC 99 (2019) 044914

Thermal fits to ALICE data F. A. Flor, PLB 834 (2022) 137473



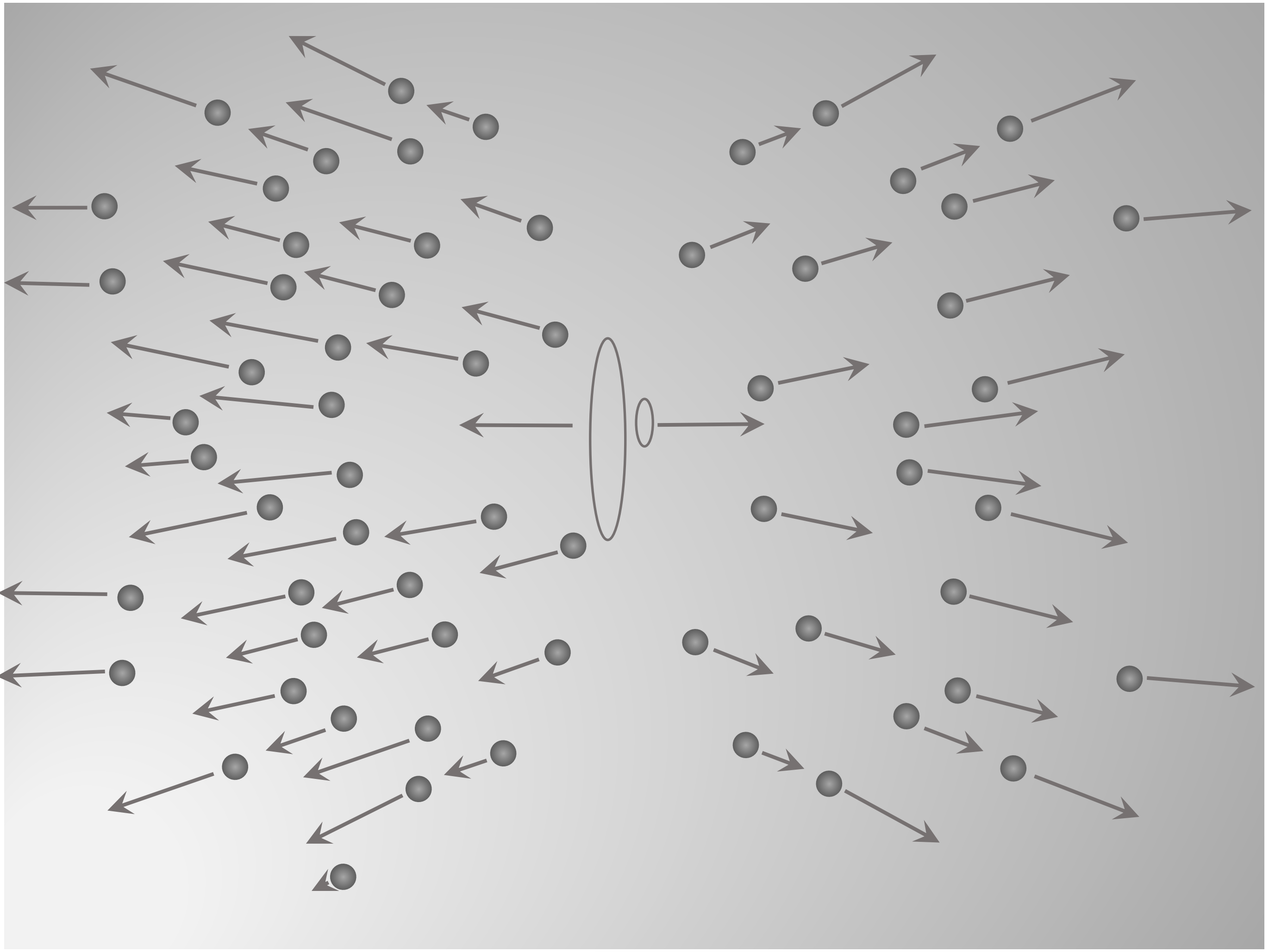
Alternative way to break quarkonium states:

Large quarkonium states can break in high-multiplicity environment when interacting with **co-moving** particles.

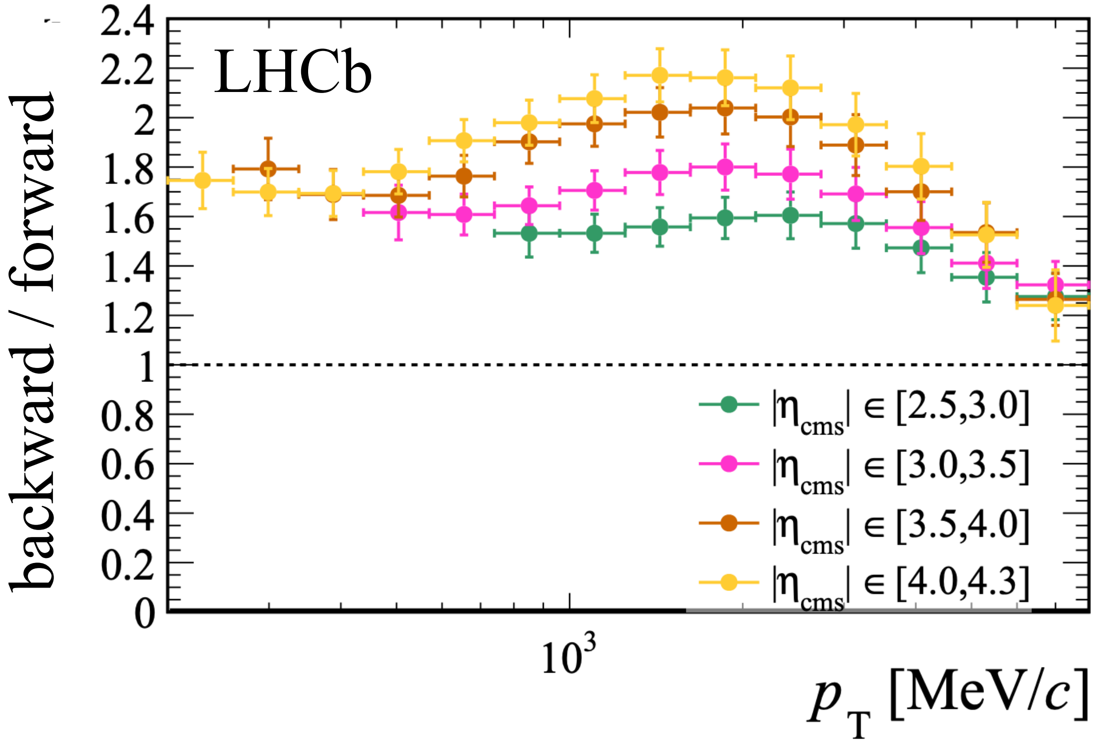


	$r(fm)$
J/ψ	0.50
χ_c	0.72
$\psi(2S)$	0.90
$\Upsilon(1S)$	0.28
χ_b	0.44
$\Upsilon(2S)$	0.56
$\chi_b(2P)$	0.68
$\Upsilon(3S)$	0.78

Non-Relativistic Potential Theory:
Satz, J.Phys.G32:R25 (2006)



Extracted from PRL 128, 142004 (2022)

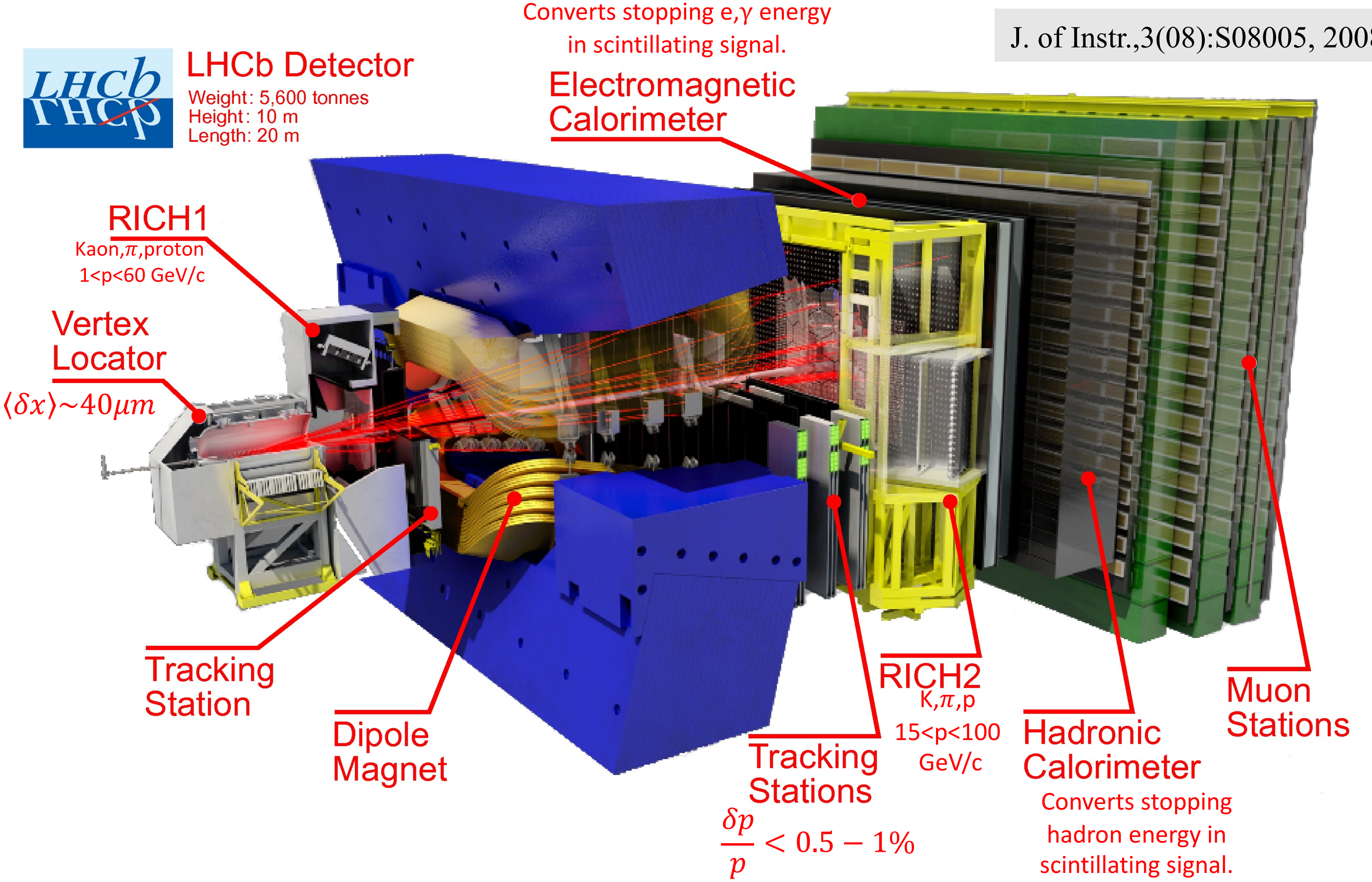


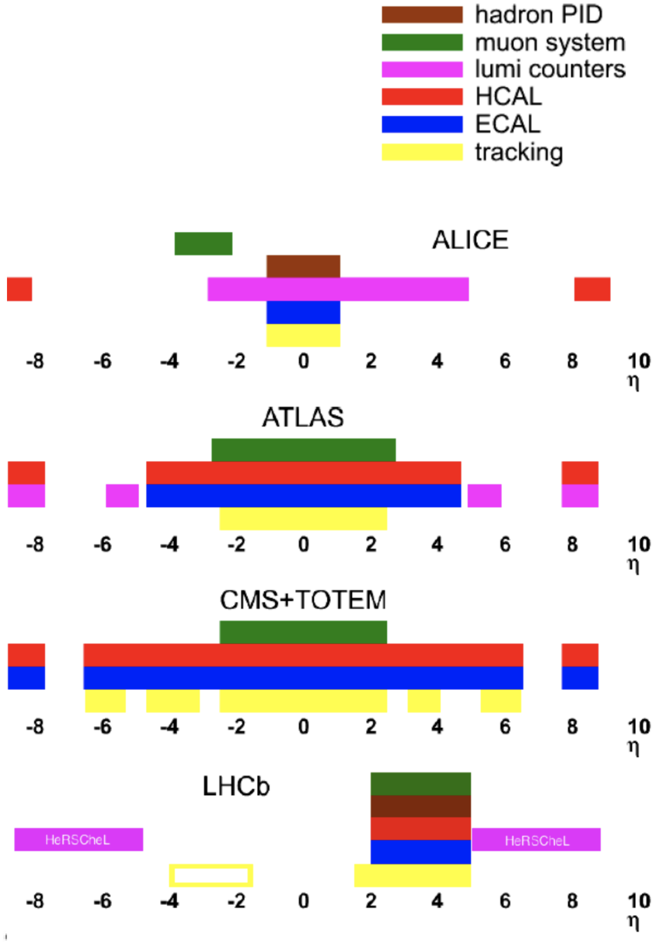
Particle multiplicities are higher at the backward rapidity (A-going direction).

pPb -> proton going to LHCb acceptance (forward rapidity)
Pbp -> lead going to LHCb acceptance (backward rapidity)

The LHC beauty detector

J. of Instr.,3(08):S08005, 2008

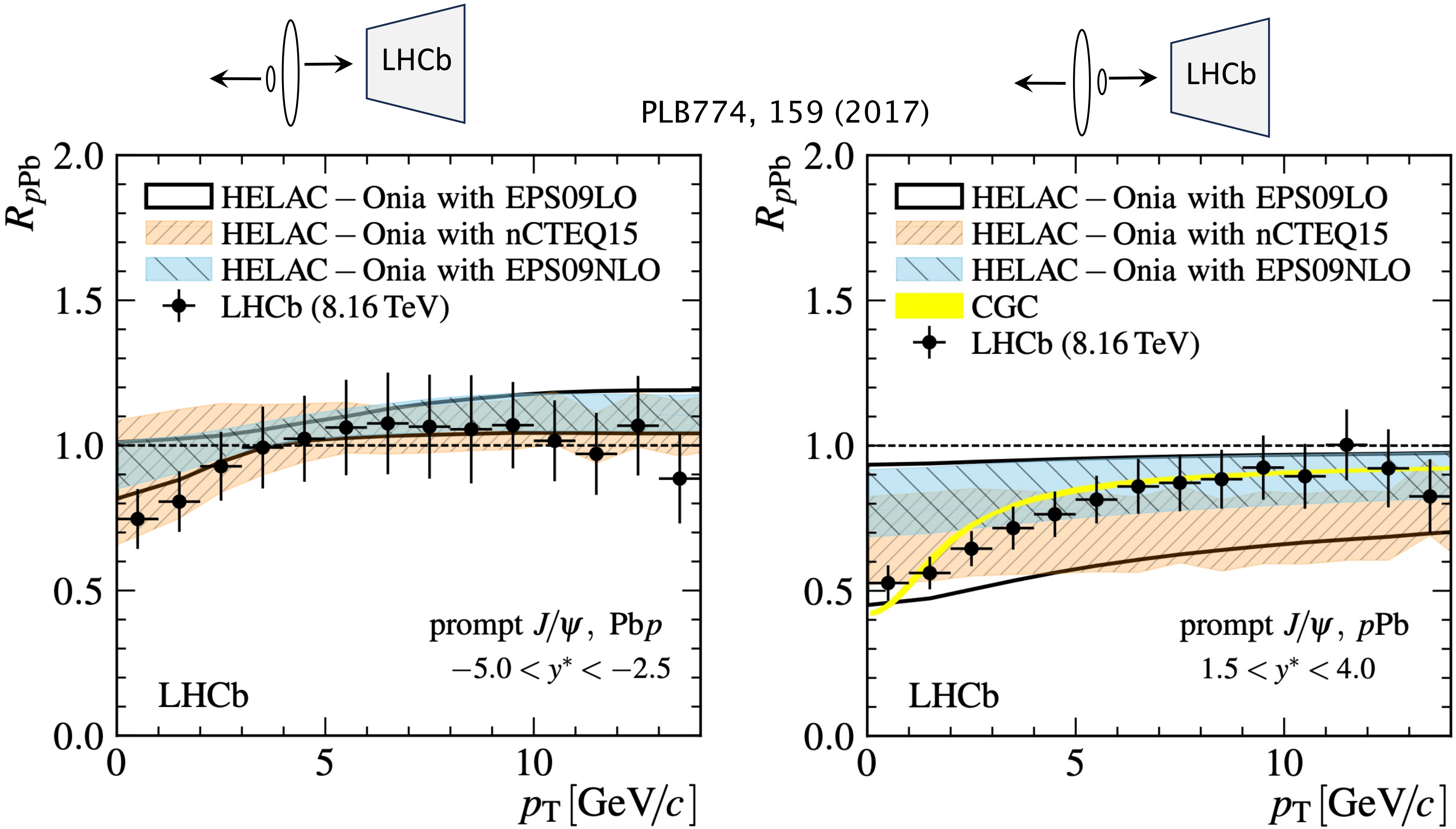




- Dedicated to Flavor Physics
- $e, \mu, \pi, K, p, \gamma$, particle jet identification in 1<p<100 GeV/c
- Unique forward instrumentation for heavy ion physics

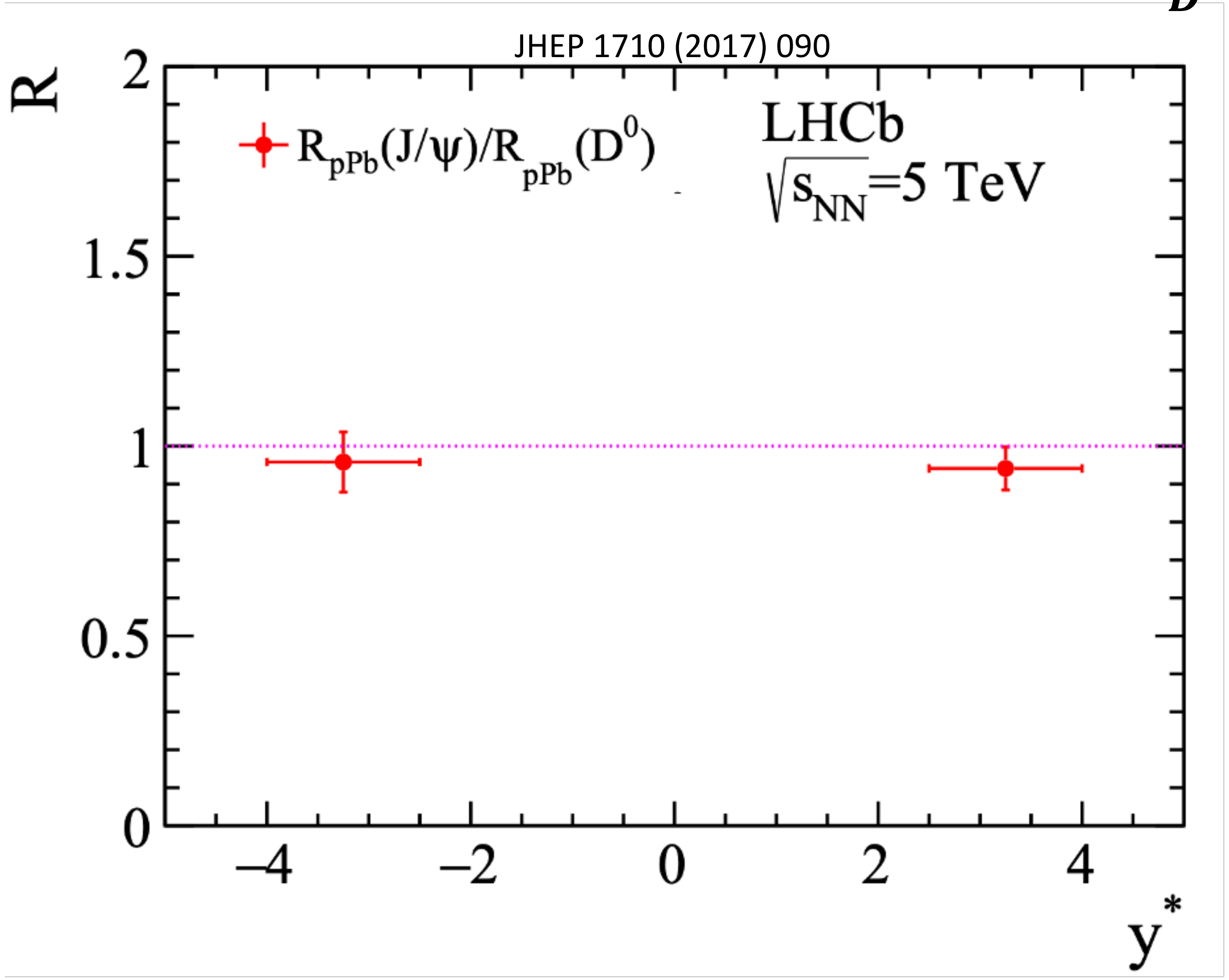
$$R_{pPb} = \frac{\frac{d\sigma_{pPb}}{dp_T}}{A\frac{d\sigma_{pp}}{dp_T}}$$

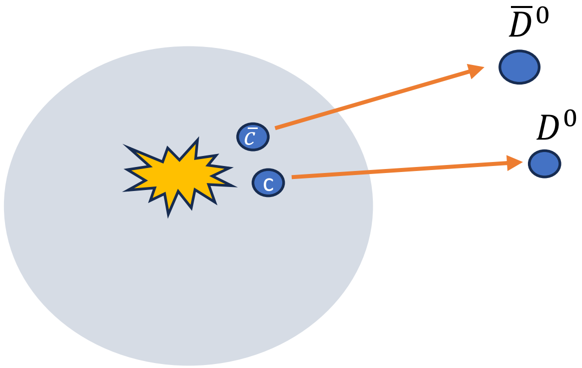
PLB774, 159 (2017)

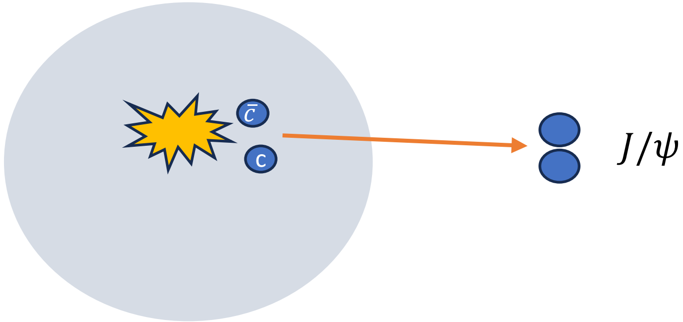


Significant J/ψ suppression in pPb forward rapidity, not much in the backward rapidity.

Nuclear Modification of $\frac{J/\psi}{D^0}$ yield ratio.

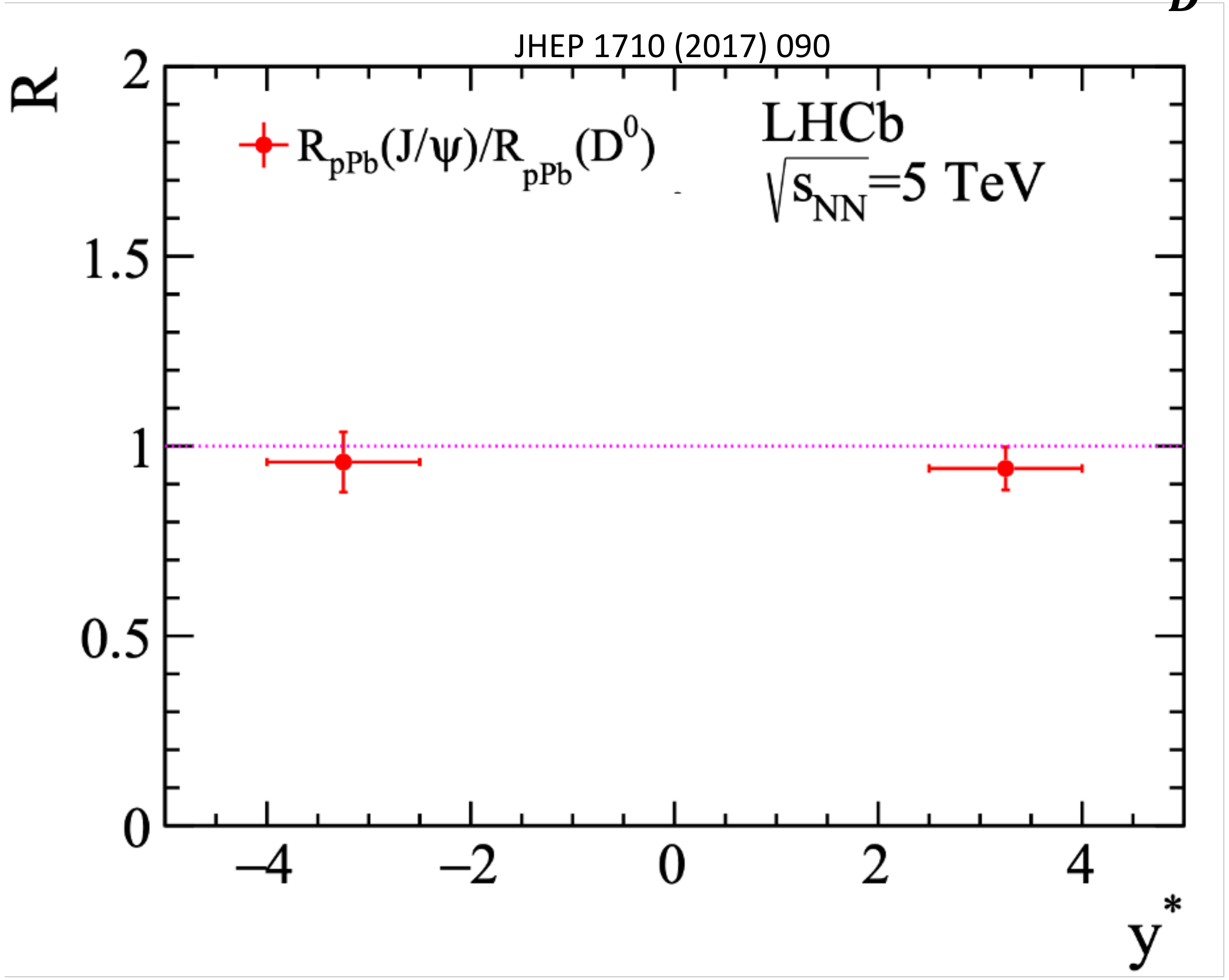


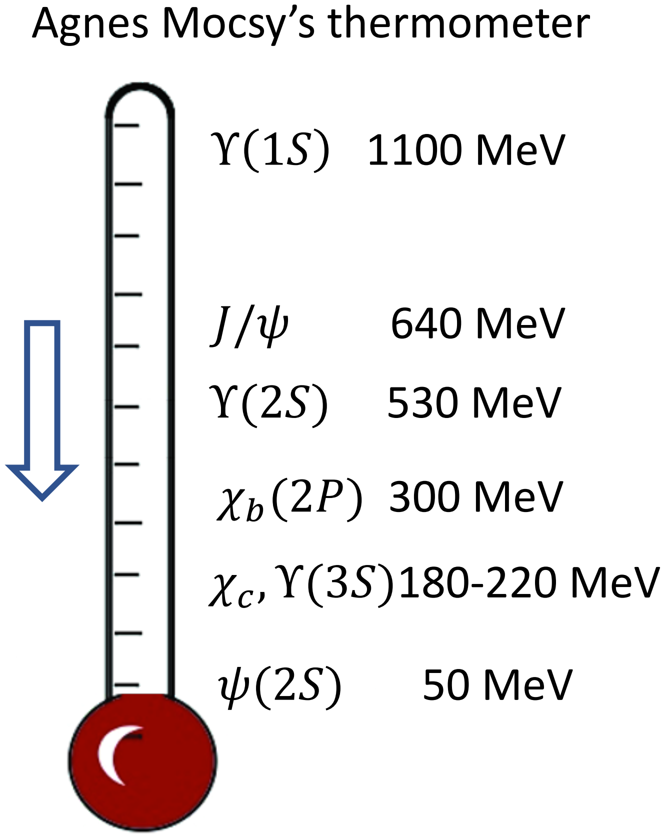




- The p_T integrated J/ψ and D^0 nuclear modifications are similar.
- The common suppression is from Initial-State Effects on the original $c\bar{c}$.

Nuclear Modification of $\frac{J/\psi}{D^0}$ yield ratio.



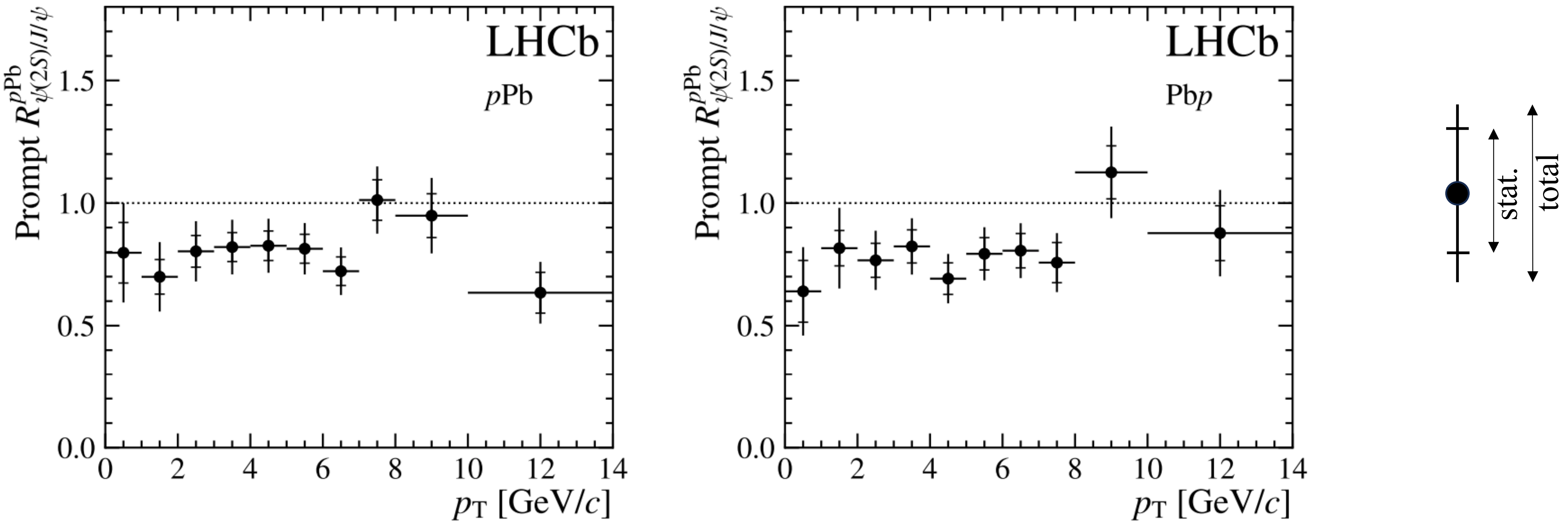


J/ψ is **suppressed** by Initial-State Effects but **not dissociated** by final-state effects.

This observation sets an upper limit on the temperature of the system formed in pPb collisions.

$$R^{p\text{Pb}\,(\text{Pb}p)}_{\psi(2S)/J/\psi} = \frac{R_{p\text{Pb}\,(\text{Pb}p)}(\psi(2S))}{R_{p\text{Pb}\,(\text{Pb}p)}(J/\psi)} = \frac{\left[\frac{\sigma(\psi(2S))}{\sigma(J/\psi)}\right]_{p\text{Pb}\,(\text{Pb}p)}}{\left[\frac{\sigma(\psi(2S))}{\sigma(J/\psi)}\right]_{pp}}$$

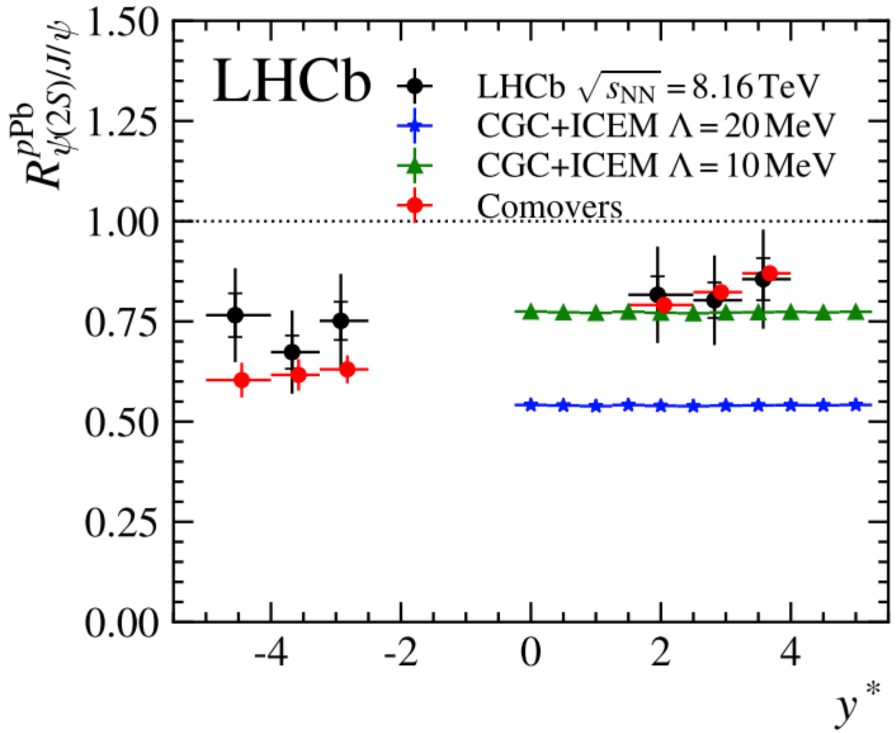
arXiv:2401.11342

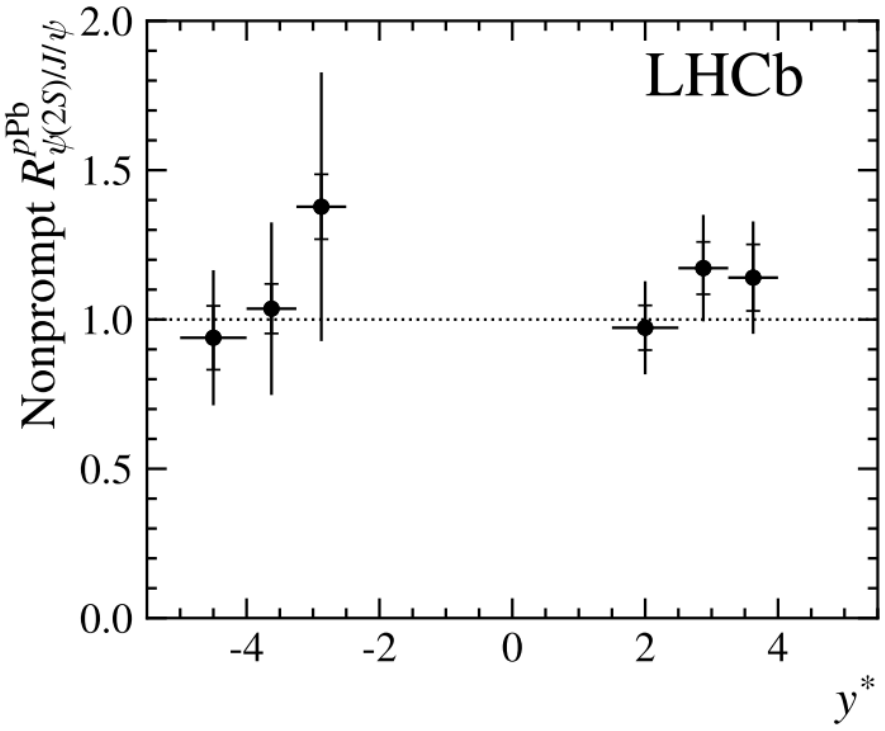


$\psi(2S)$ has stronger suppression than J/ψ indicating that $\psi(2S)$ **is dissociated** in the medium created.

$$R^{p\mathrm{Pb}\,(\mathrm{Pb}p)}_{\psi(2S)/J/\psi} = \frac{R_{p\mathrm{Pb}\,(\mathrm{Pb}p)}(\psi(2S))}{R_{p\mathrm{Pb}\,(\mathrm{Pb}p)}(J/\psi)} = \frac{\left[\frac{\sigma(\psi(2S))}{\sigma(J/\psi)}\right]_{p\mathrm{Pb}\,(\mathrm{Pb}p)}}{\left[\frac{\sigma(\psi(2S))}{\sigma(J/\psi)}\right]_{pp}}$$

arXiv:2401.11342





Additional $\psi(2S)$ suppression only present in the prompt component, consistent with

- comover particle interactions [PLB749, 98 (2015)]
- CGC : Factorization violating soft gluon exchanges PRC97, 014909 (2018)

$$R_{\psi(2S)/J/\psi}^{p\mathrm{Pb}\,(\mathrm{Pb}p)} = \frac{R_{p\mathrm{Pb}\,(\mathrm{Pb}p)}(\psi(2S))}{R_{p\mathrm{Pb}\,(\mathrm{Pb}p)}(J/\psi)} = \frac{\left[\frac{\sigma(\psi(2S))}{\sigma(J/\psi)}\right]_{p\mathrm{Pb}\,(\mathrm{Pb}p)}}{\left[\frac{\sigma(\psi(2S))}{\sigma(J/\psi)}\right]_{pp}}$$

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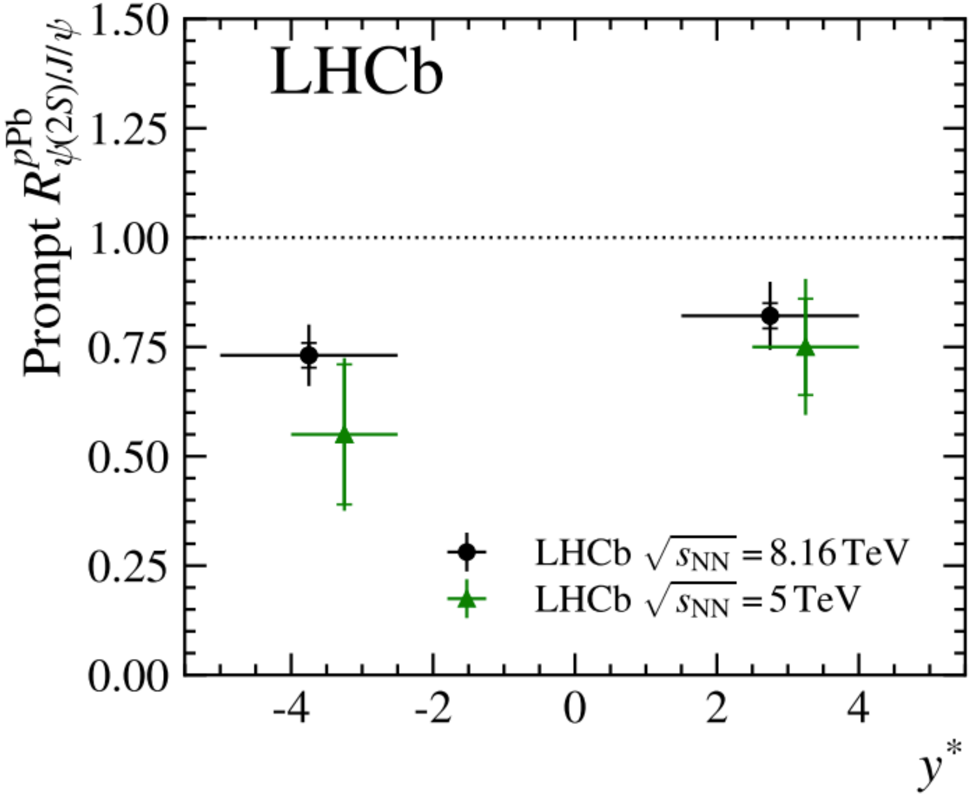
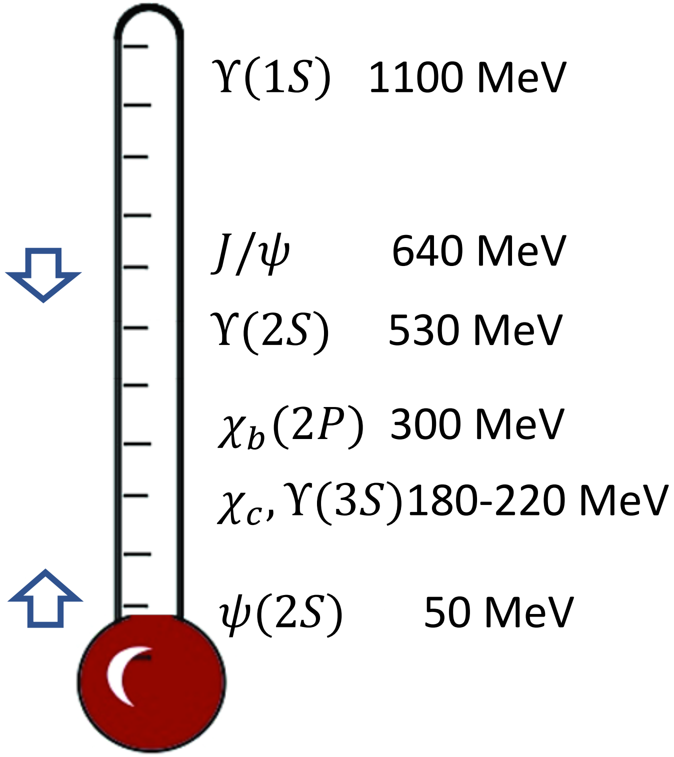




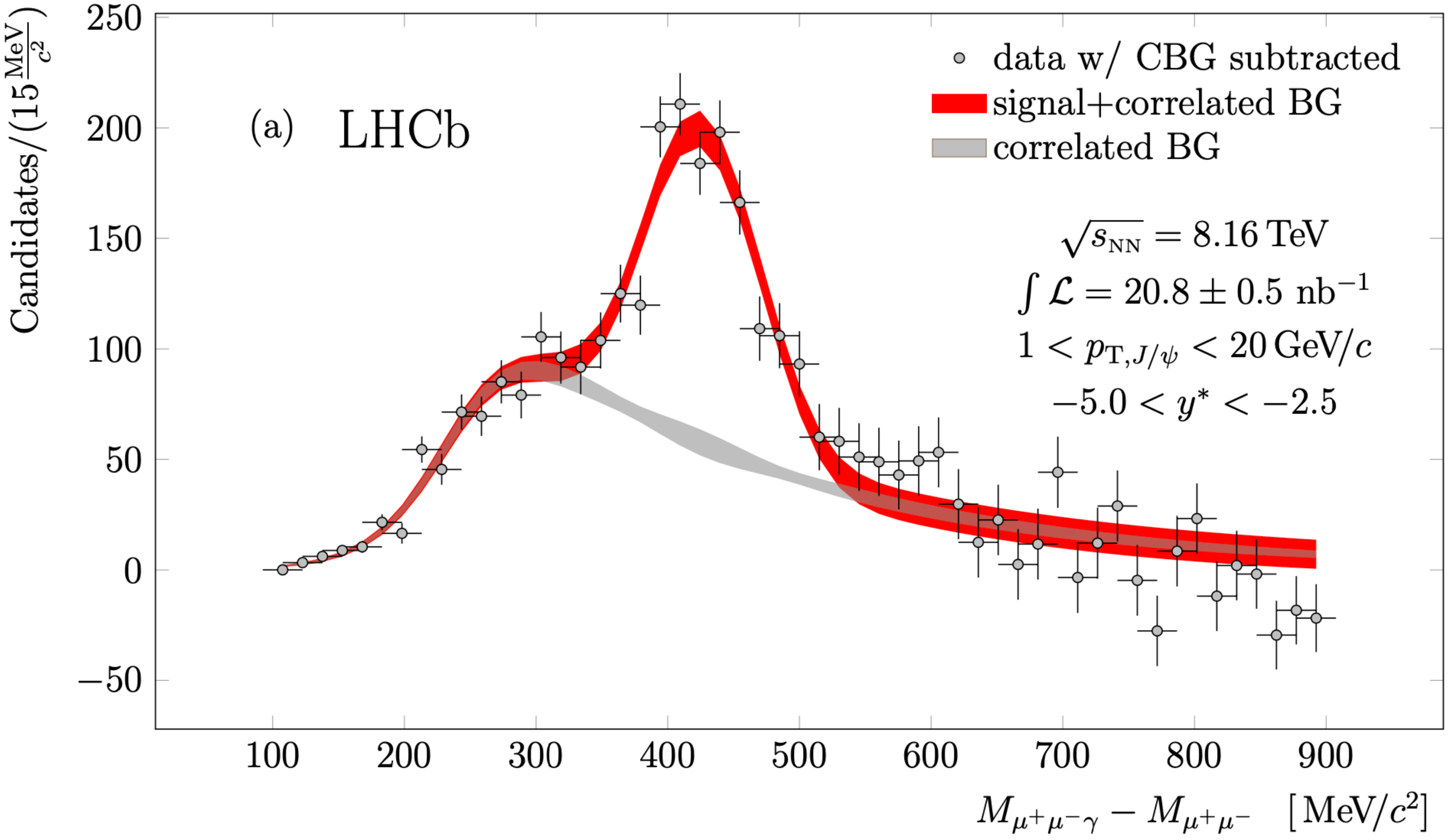
8.16 TeV result more precise and consistent with 5 TeV.

The $\psi(2S)$ dissociation sets a lower limit to the medium temperature.

New χ_c Result

arXiv:2311.01562

Accepted by PRL

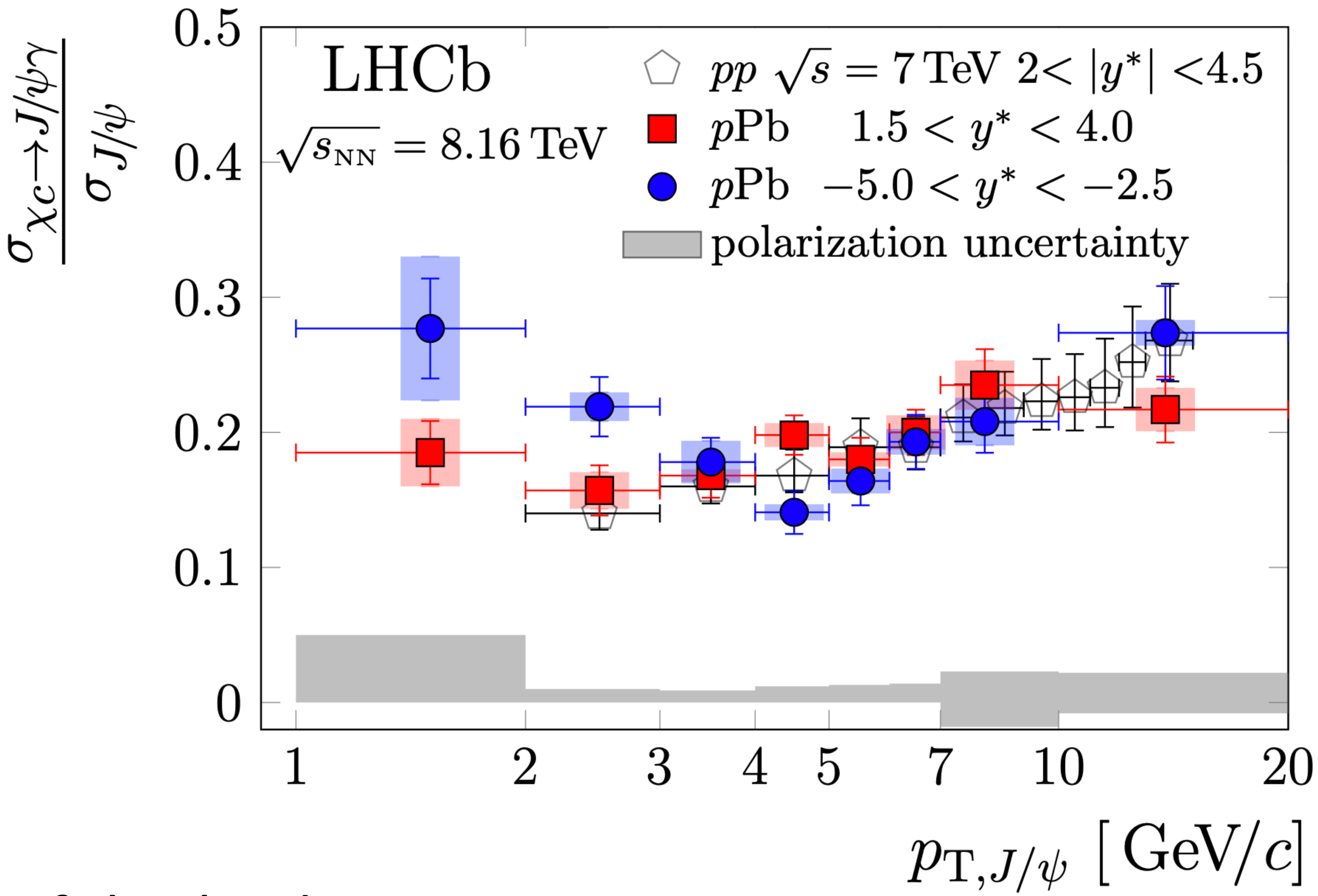


$\chi_{c1} + \chi_{c2}$ measured in the $J/\psi\ \gamma$ decay channel, where the photon ($p_{T,\gamma}$>400 MeV/c) is measured by the ECAL.

Fraction of χ_c decays in prompt J/ψ.

arXiv:2311.01562

Approved by PRL



First result of this kind in LHC.

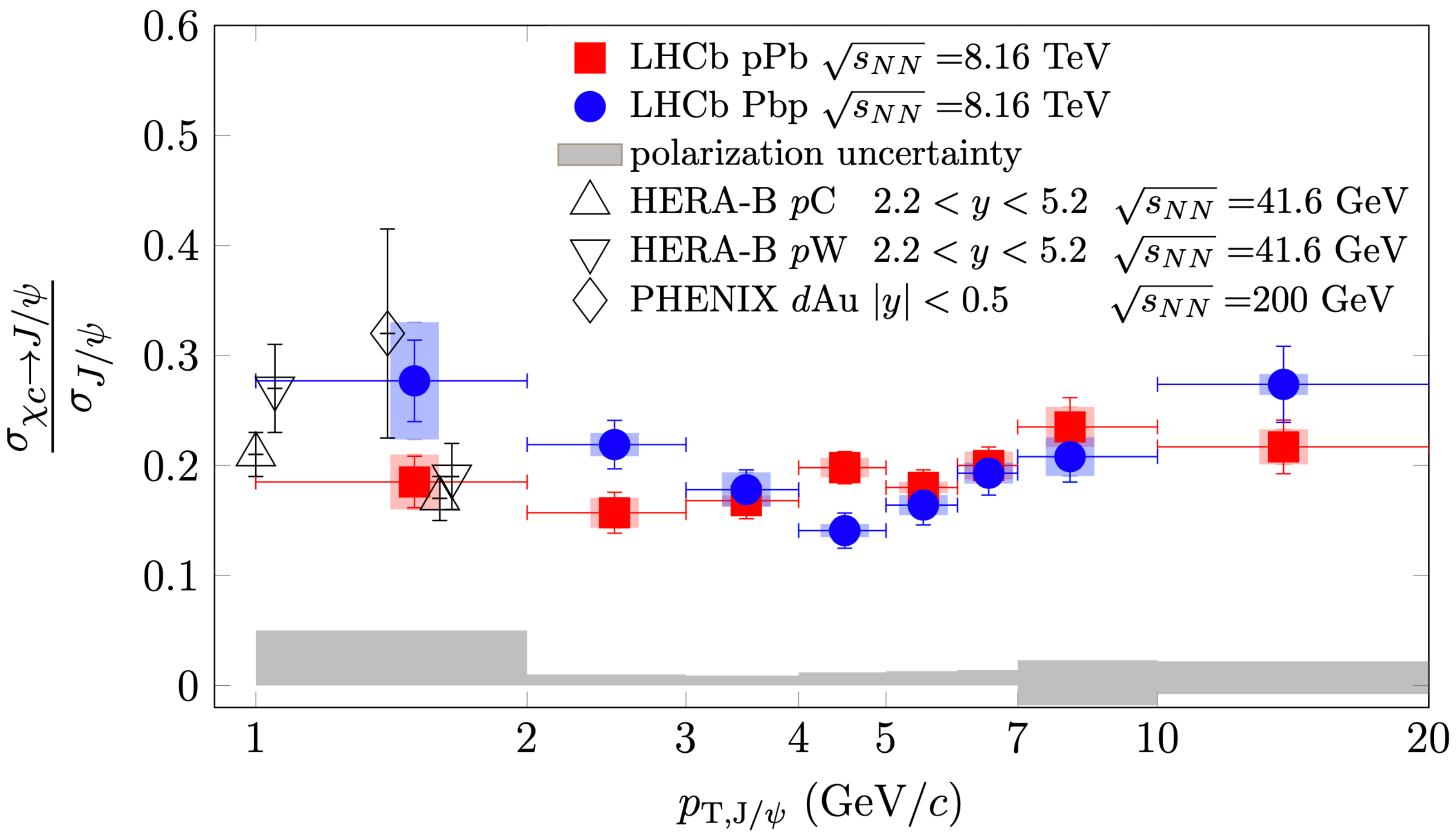
Forward rapidity consistent with *pp* results.

Backward rapidity has a fraction 2.4 σ higher than forward for $p_{T,J/\psi}$<3 GeV/c

Fraction of χ_c decays in prompt J/ψ.

arXiv:2311.01562

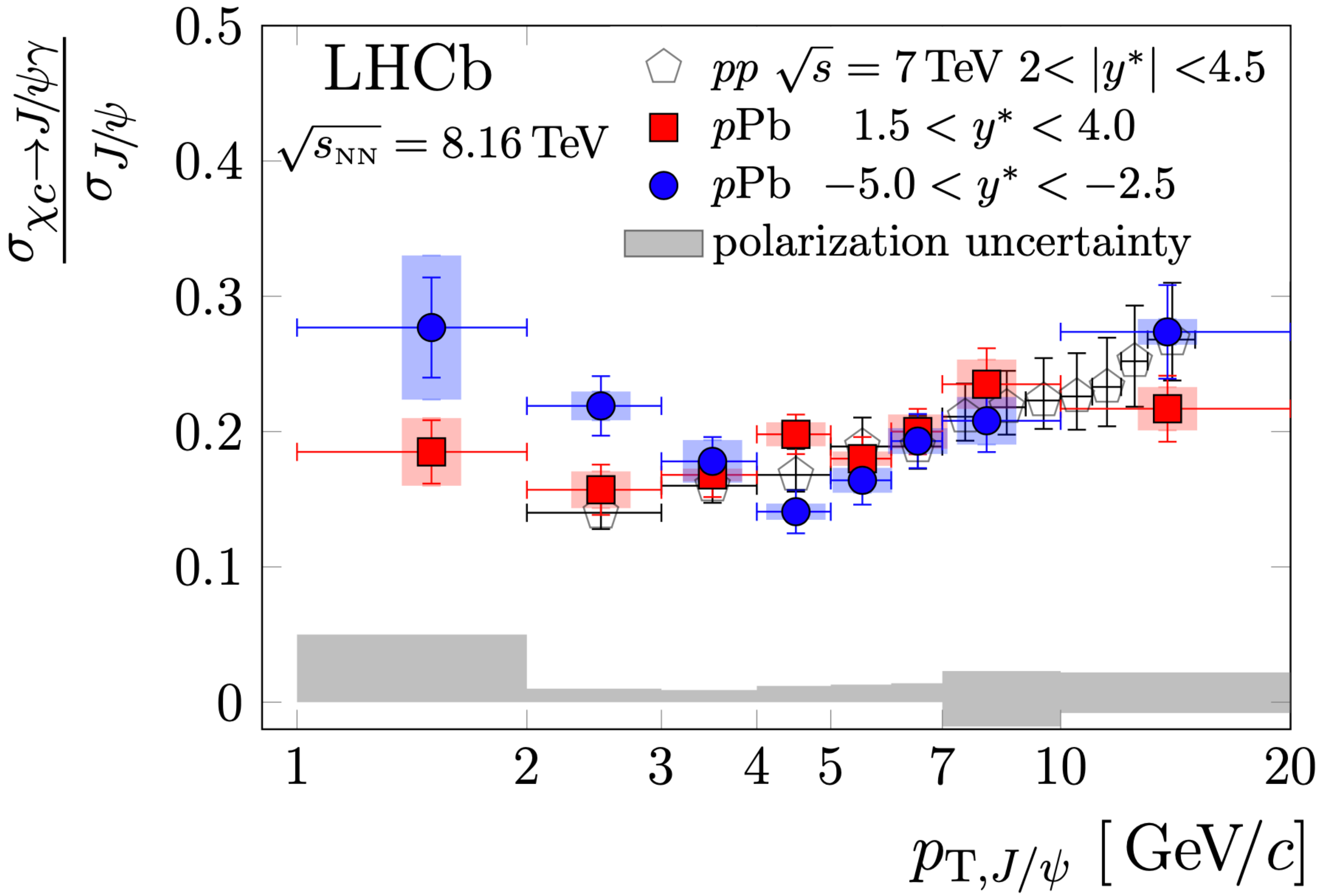
Approved by PRL



Result consistent with lower energy measurements from HERA-B and PHENIX.

Fraction of χ_c decays in prompt J/ψ.

arXiv:2311.01562

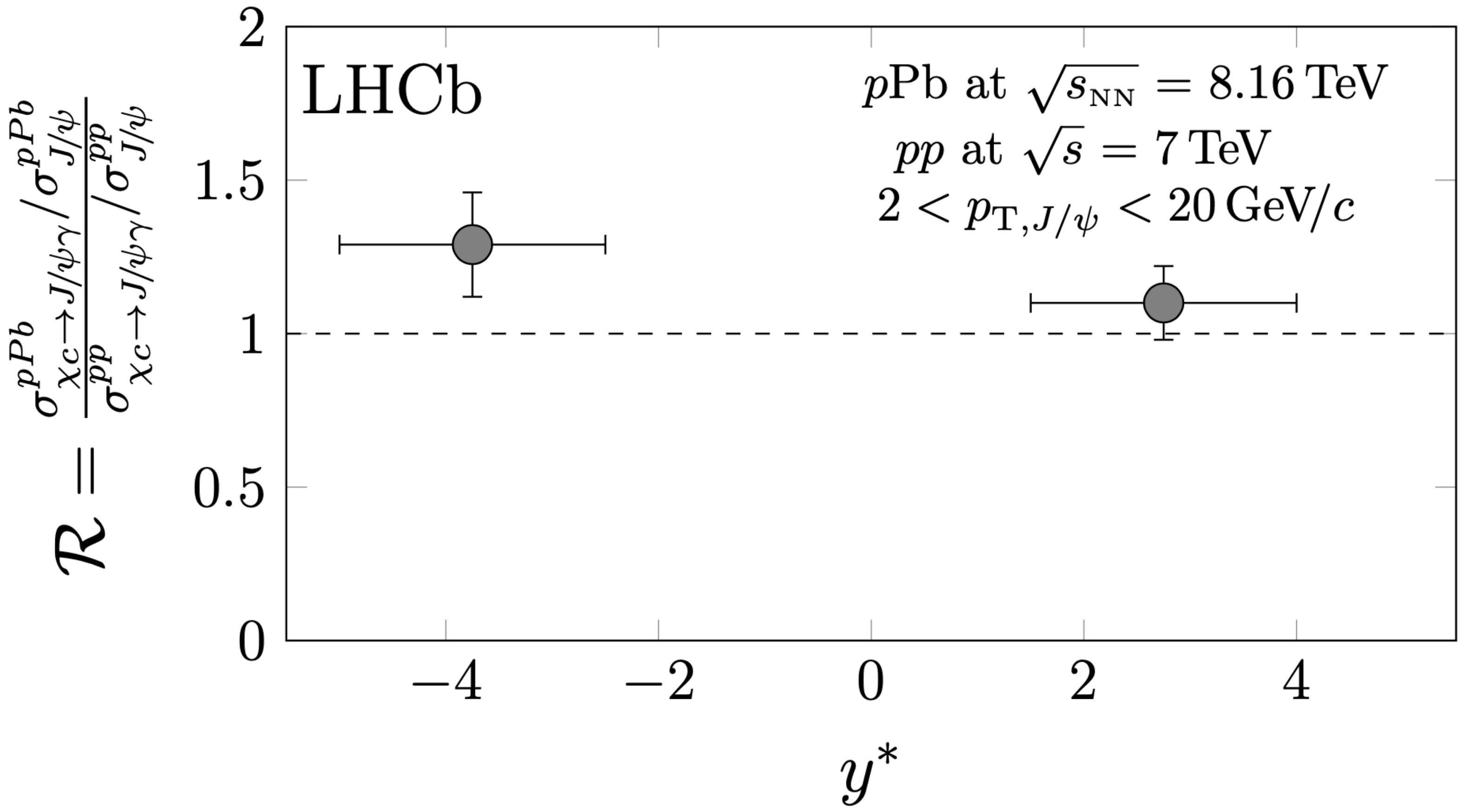


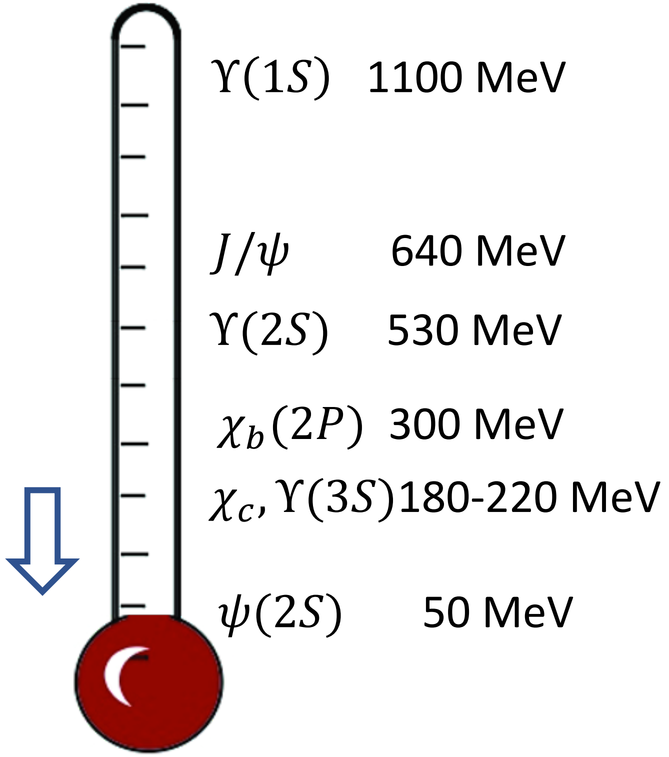
Prompt J/ψ composition:

- Direct J/ψ
- $\chi_c \to J/\psi\,\gamma$ decays
- $\psi(2S) \to J/\psi + X$ decays
- exotics

Apparent larger fraction at backward rapidity consistent with the slightly larger suppression of the $\psi(2S)$ contribution to the prompt J/ψ.

arXiv:2311.01562

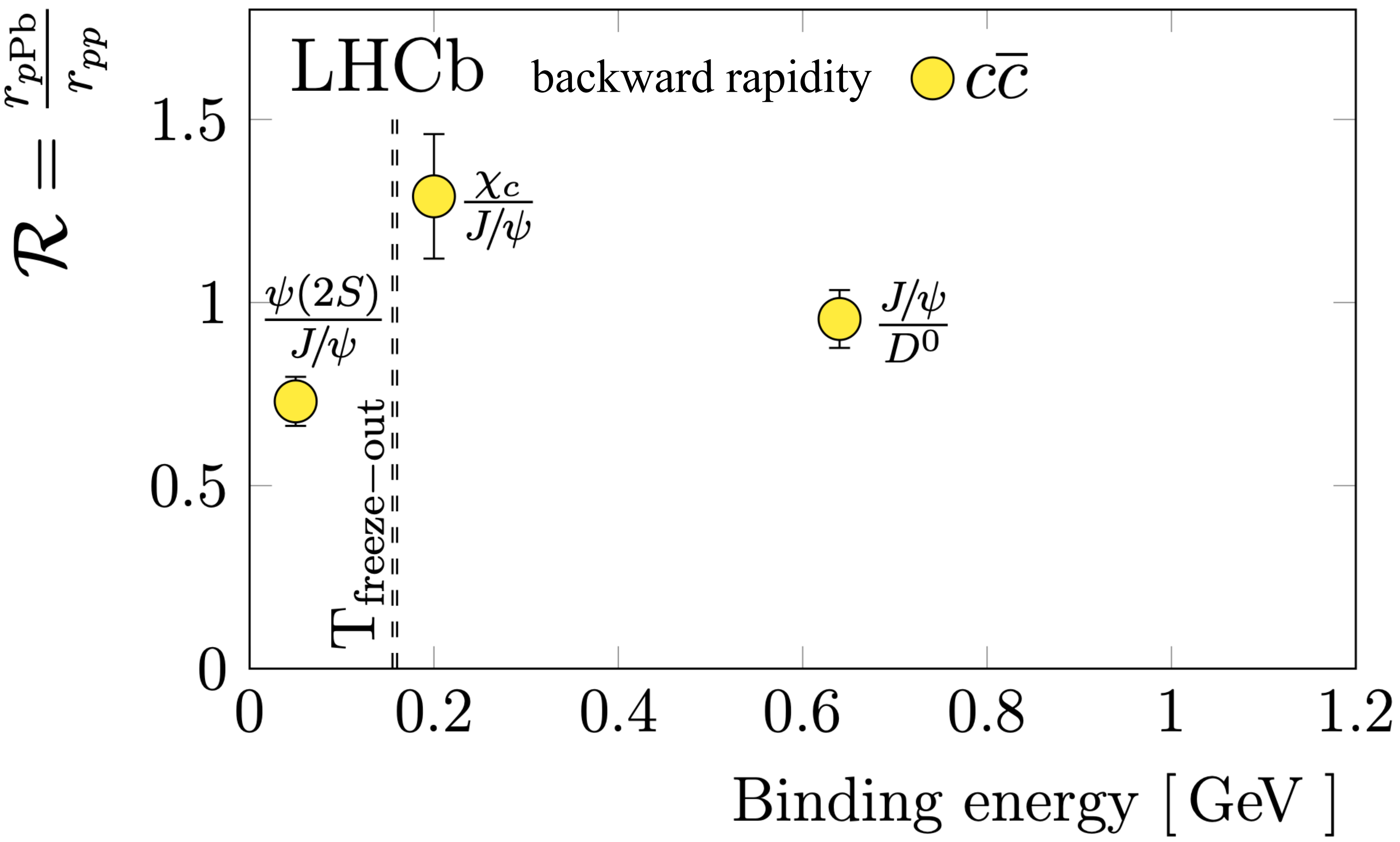




χ_c double ratio consistent with **NO final-state dissociation of χ_c states in pPb collisions** setting a new upper limit for the medium temperature in these colliisons.

Constraints to maximum medium temperature in pPb collisions.

arXiv:2311.01562



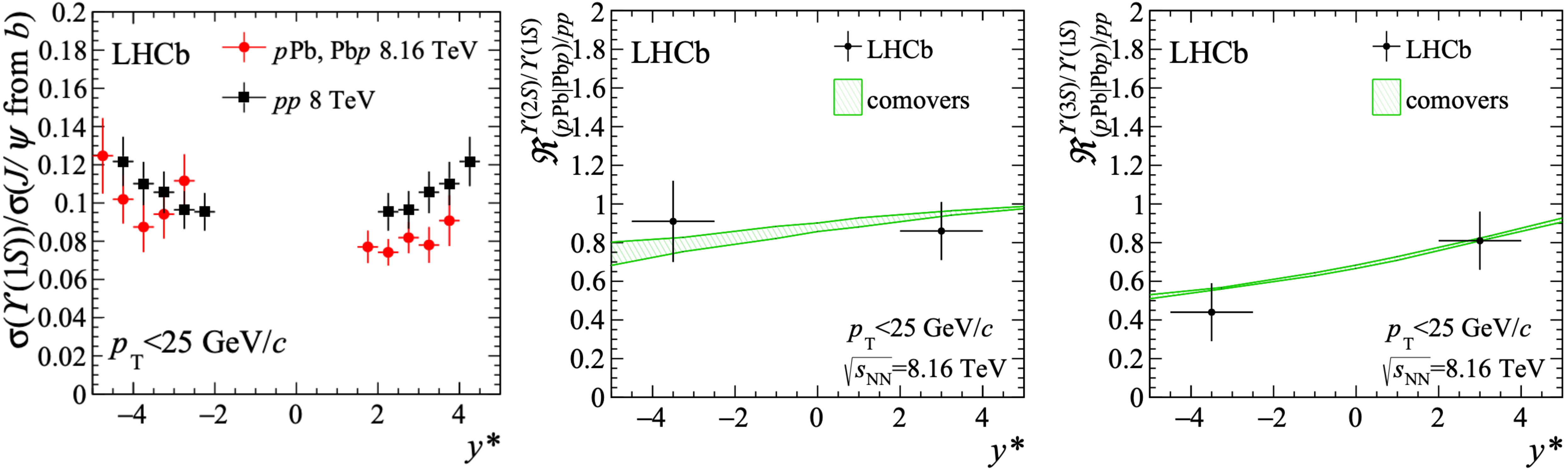
$$r_{pPb}\left(\frac{Q\bar{Q}_1}{Q\bar{Q}_2}\right) = \frac{\sigma_{Q\bar{Q}_1}}{\sigma_{Q\bar{Q}_2}}$$

The medium temperature formed in pPb collisions cannot inhibit the formation of charmonium states with binding energy larger than 180 MeV, just 20 MeV above the estimated freeze-out temperature.

Nuclear modification of bottomonium states ratios.

JHEP11(2018)194

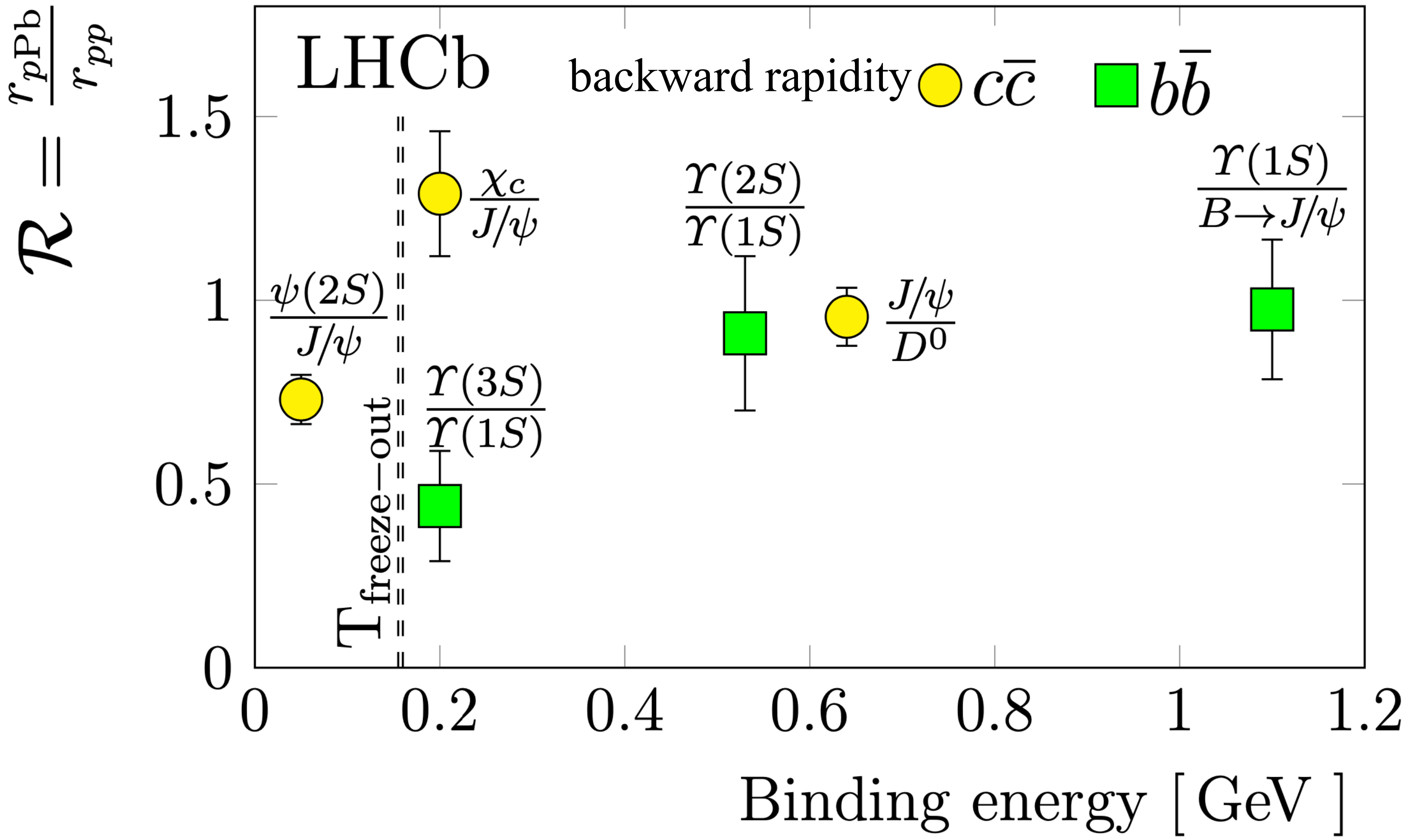
$$\frac{\Upsilon(1S)}{B} \qquad \frac{(\Upsilon(2S)/\Upsilon(1S))^{pPb}}{(\Upsilon(2S)/\Upsilon(1S))^{pp}} \qquad \frac{(\Upsilon(3S)/\Upsilon(1S))^{pPb}}{(\Upsilon(3S)/\Upsilon(1S))^{pp}}$$

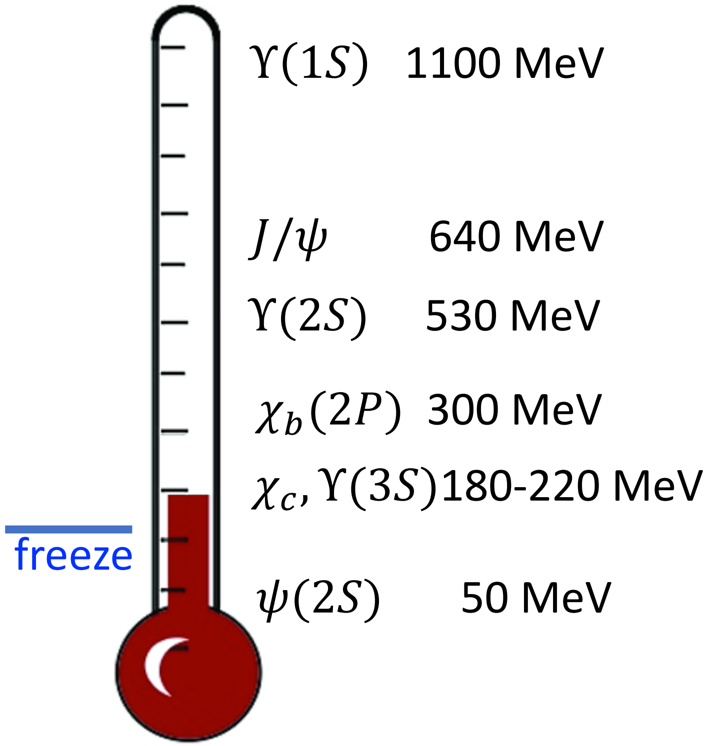


Only $\Upsilon(3S)$ shows a significant dissociation in pPb.

Constraints to maximum medium temperature in pPb collisions.

arXiv:2311.01562

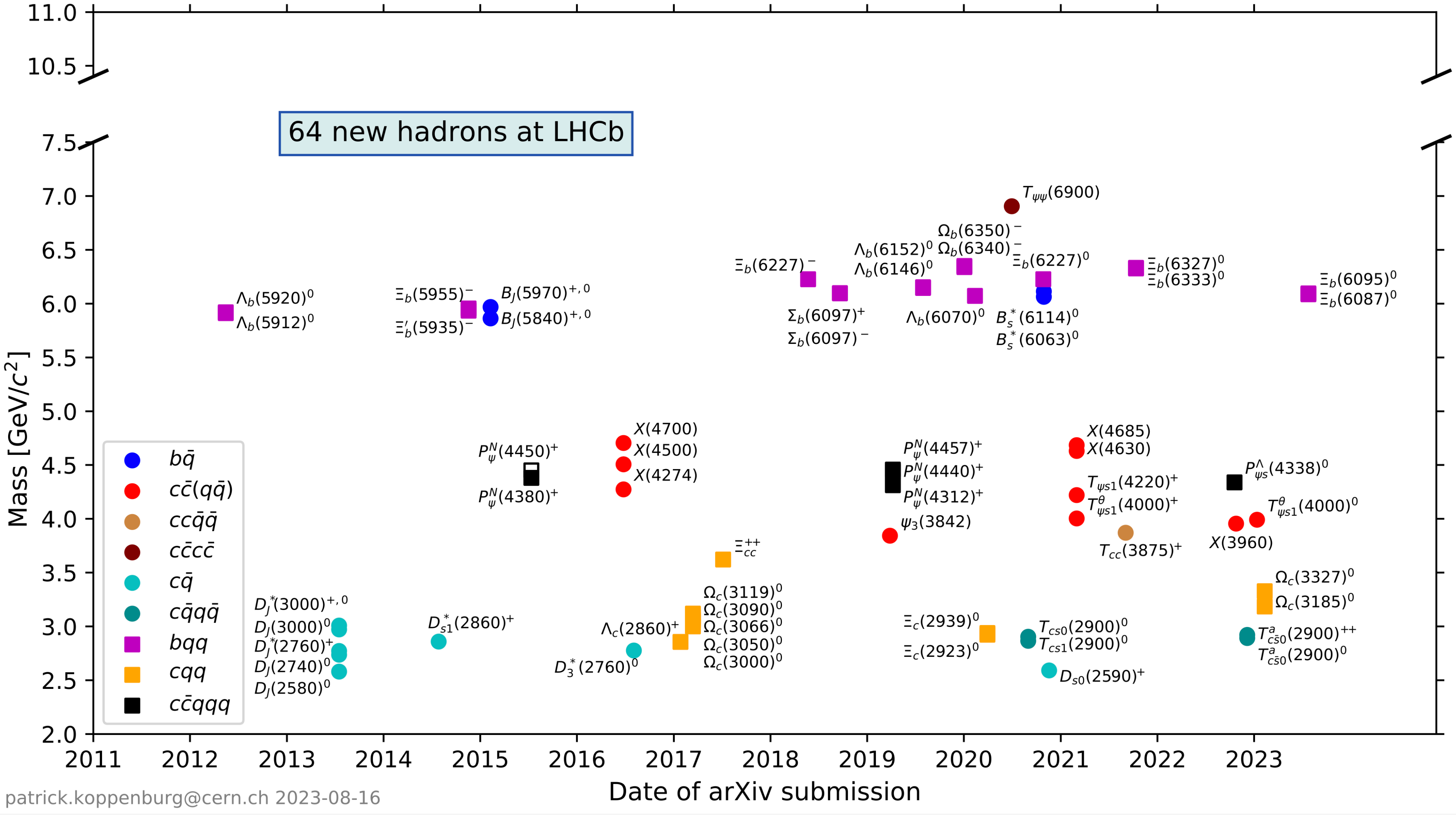


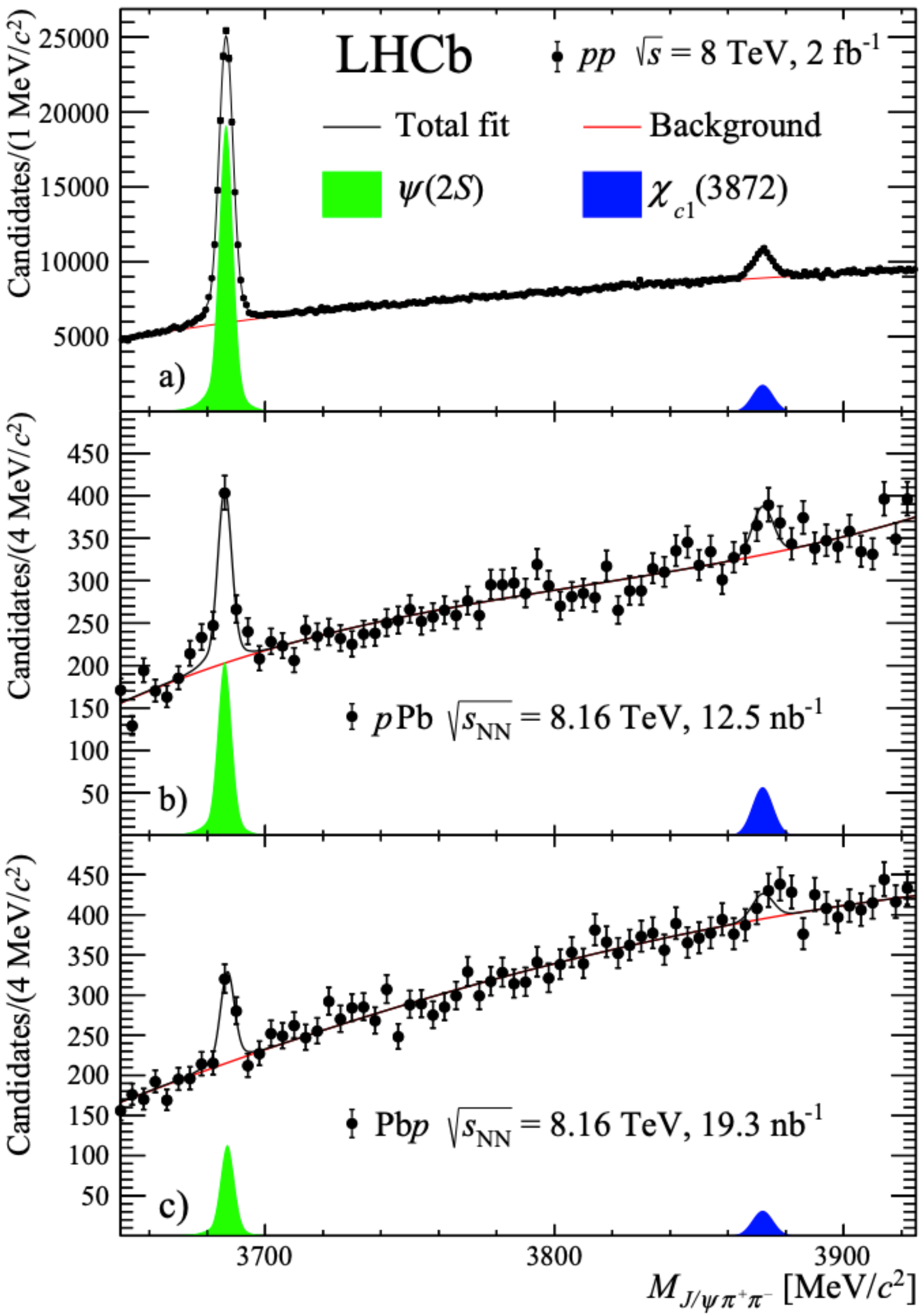


Despite the similar binding energy and size with χ_c, $\Upsilon(3S)$ is dissociated.

Discrepancy can be explained by the 2.9 x larger mass of $\Upsilon(3S)$ relative to χ_c, making its slower moving more suitable to interact with comoving particles. Theoretical input is welcome !!!

Exotic Particles





$\chi_{c1}(3872)$

Measured in the $J/\psi\, \pi^+\pi^-$ decay

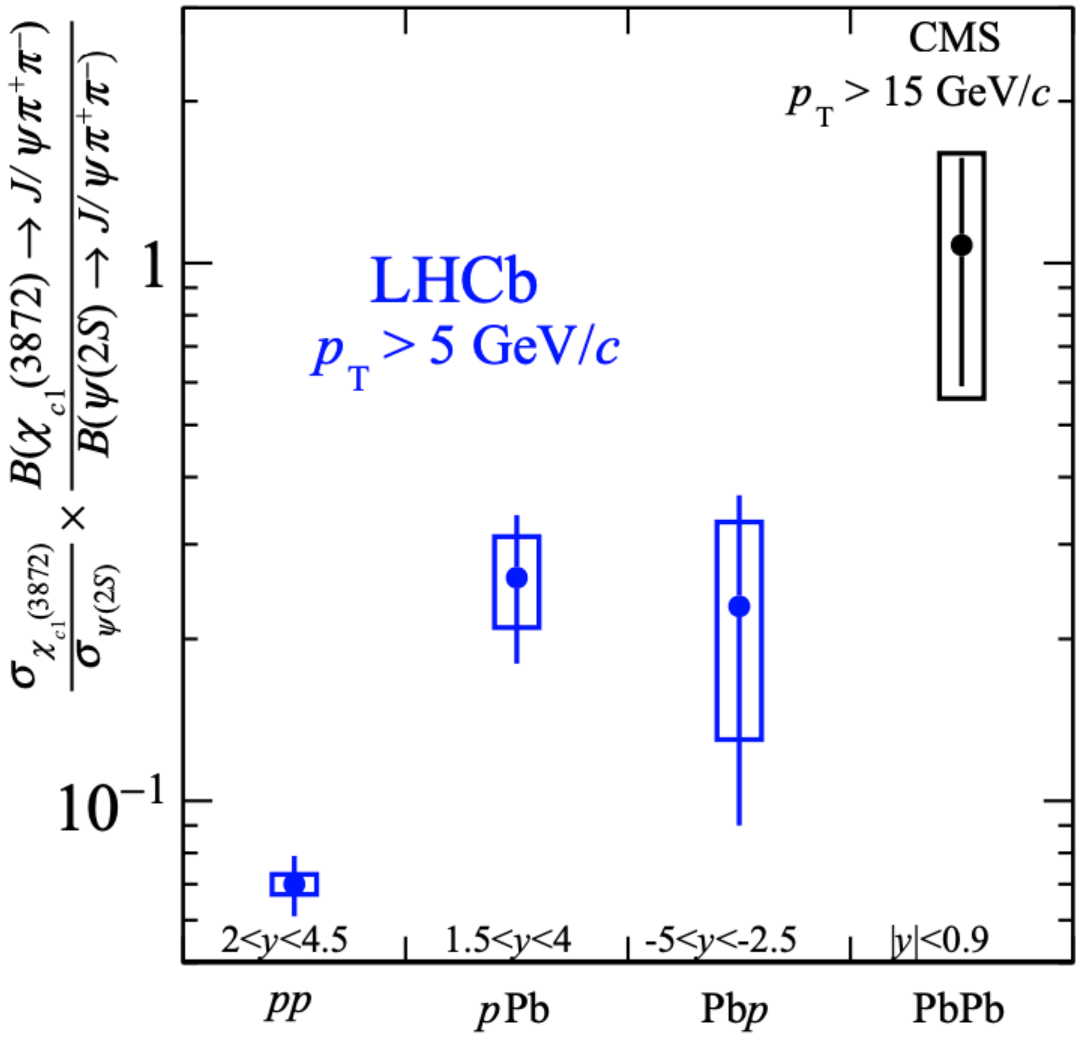
$p_T > 5$ GeV/c

$\chi_{c1}(3872)$ production measured relatively to $\psi(2S)$ in the same decay channel.

arXiv: 2402.14975

$\chi_{c1}(3872)$

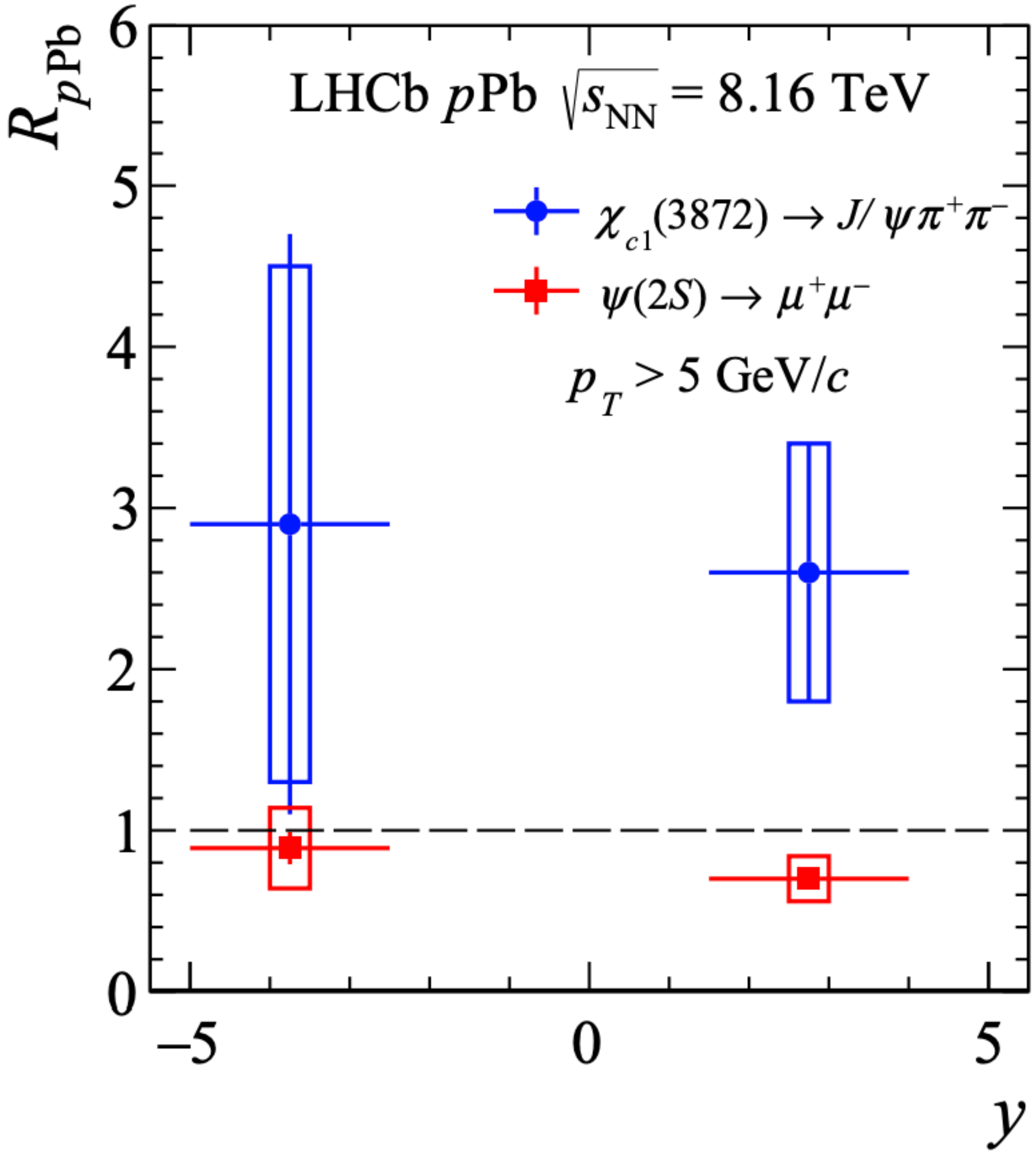
arXiv: 2402.14975



Increasing relative yield in pPb and PbPb collisions.

But uncertainties are still large.

[arXiv: 2402.14975](https://arxiv.org/abs/2402.14975)



$\chi_{c1}(3872)$

First nuclear modification factor measurement of an exotic state.

$\chi_{c1}(3872)$ yield enhancement in nuclear collisions.

Small room for regeneration in pA.

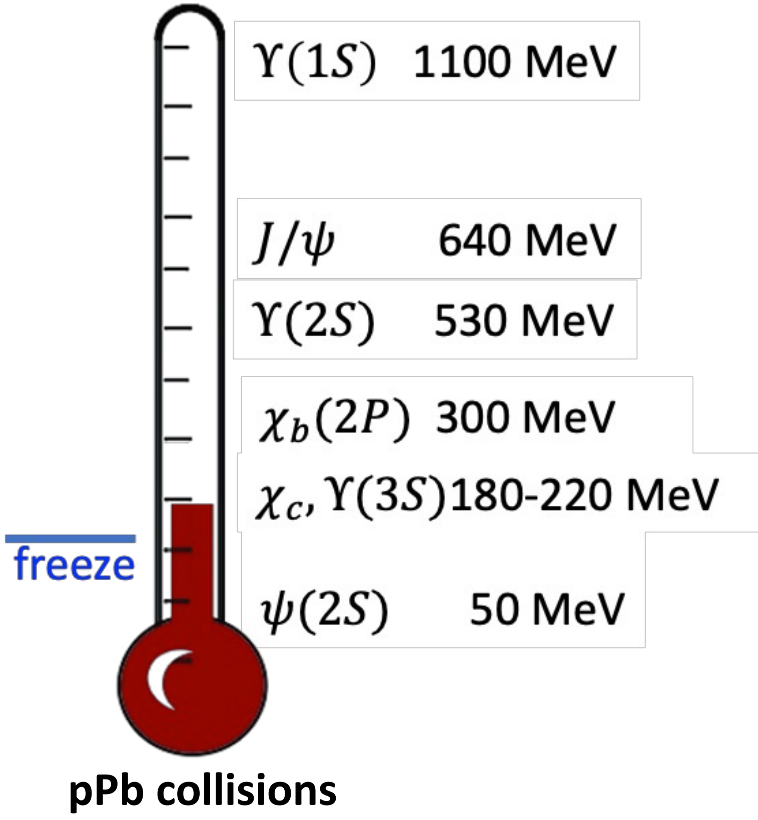
Predicted by a model involving double parton interaction [EPJ Web Conf. 137 (2017) 06004]

Same mechanism of baryon enhancement observed in other probes ?

Take away from pA collisions

- More precise measurement of $\psi(2S)$ final-state dissociation are now available.

- Despite having similar binding energy and sizes, Υ(3S) is dissociated in medium, χ_c is not
  - hot medium in pA would melt both states
  - Υ(3S) state moves slower through medium, making easier to break it by comoving hadrons

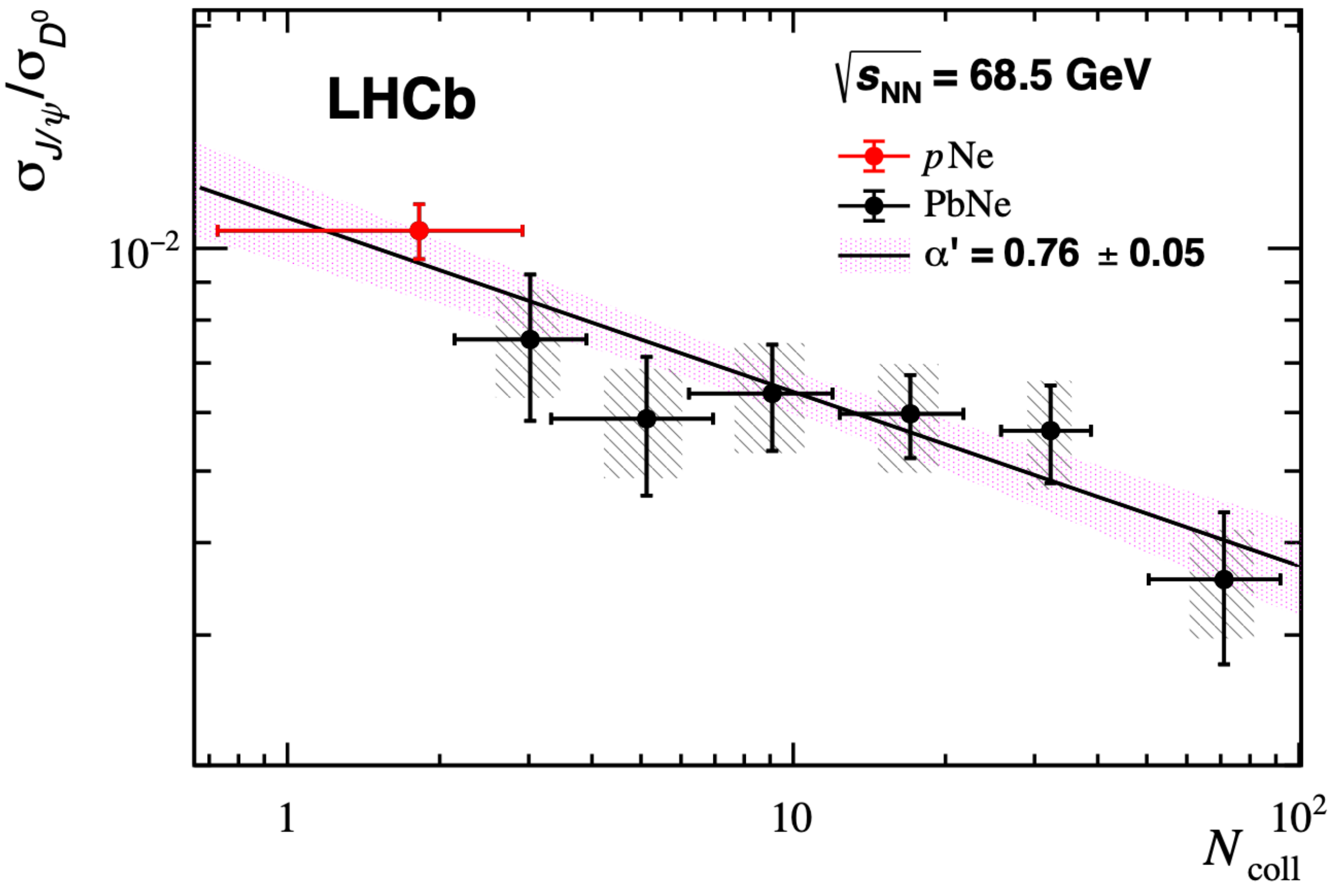


- Observed apparent $\chi_{c1}(3872)$ enhancement in pPb collisions, suggesting an additional production mechanism of tetraquark states in nuclear collisions.

QUARKONIA IN LARGE SYSTEMS

J/ψ in Pb + fixed target collisions (SMOG)

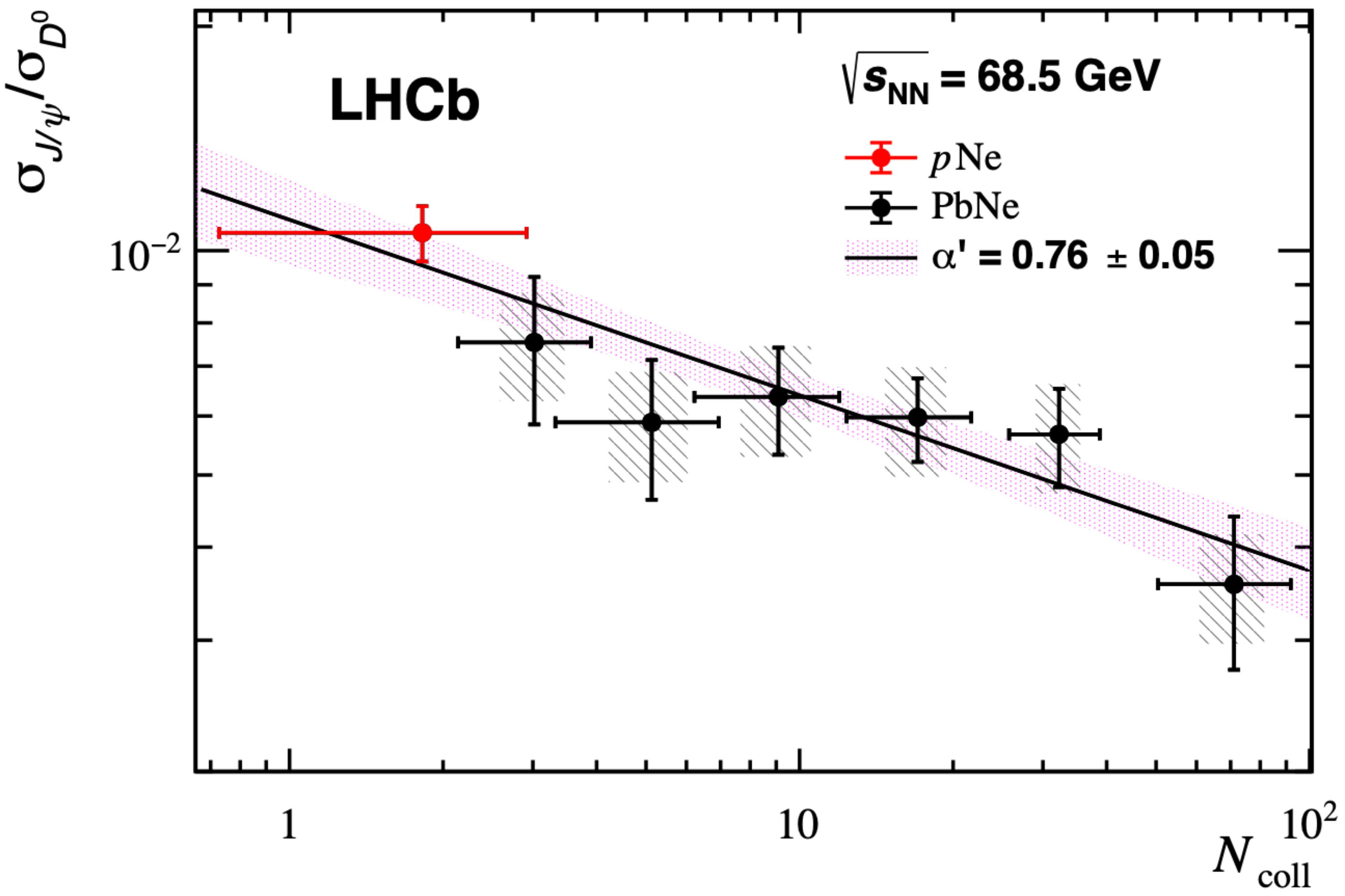
[Eur. Phys. J. C83 (2023) 658]



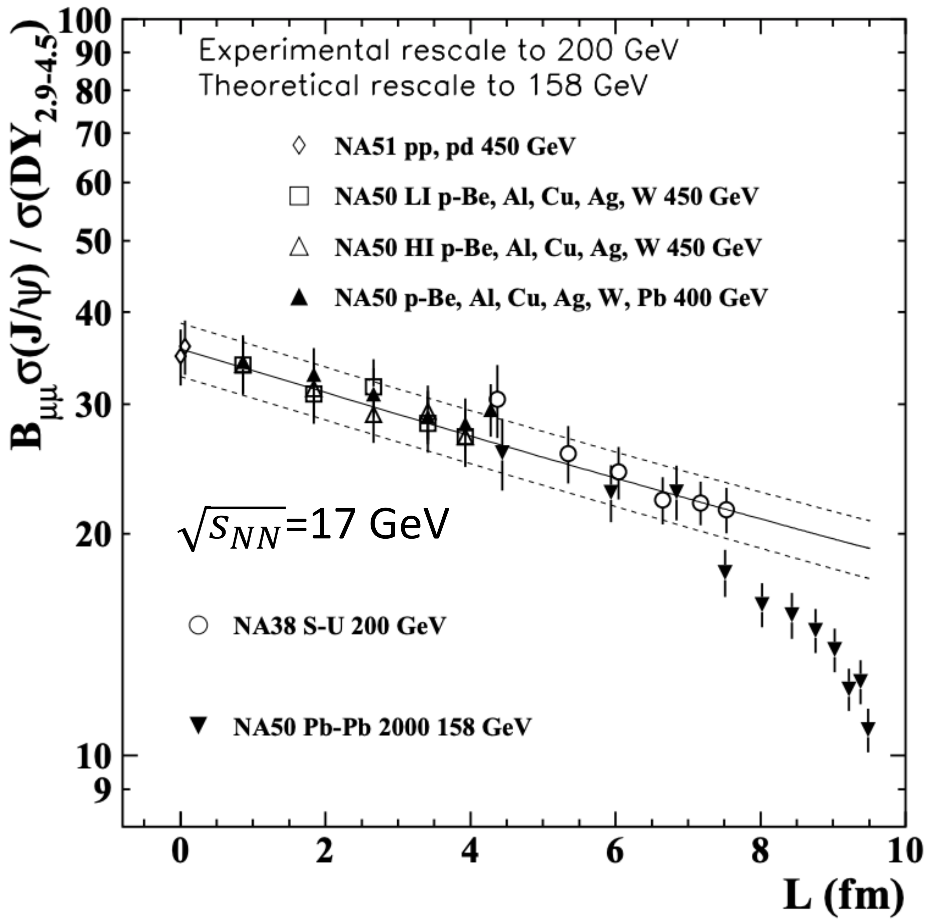
- D^0 used as a proxy for total $c\bar{c}$, but we see Λ_C enhancement with multiplicity which would make this ratio larger with increasing N_{coll}
- Assuming $\sigma_{J/\psi} \propto < N_{coll} >^{\alpha'}$ where α' accounts for nuclear absorption
- No significant charmonium recombination expected at this energy

Comparison with CERN/SPS experiments

Eur. Phys. J. C83 (2023) 658



Eur.Phys.J.C 39 (2005) 335-345

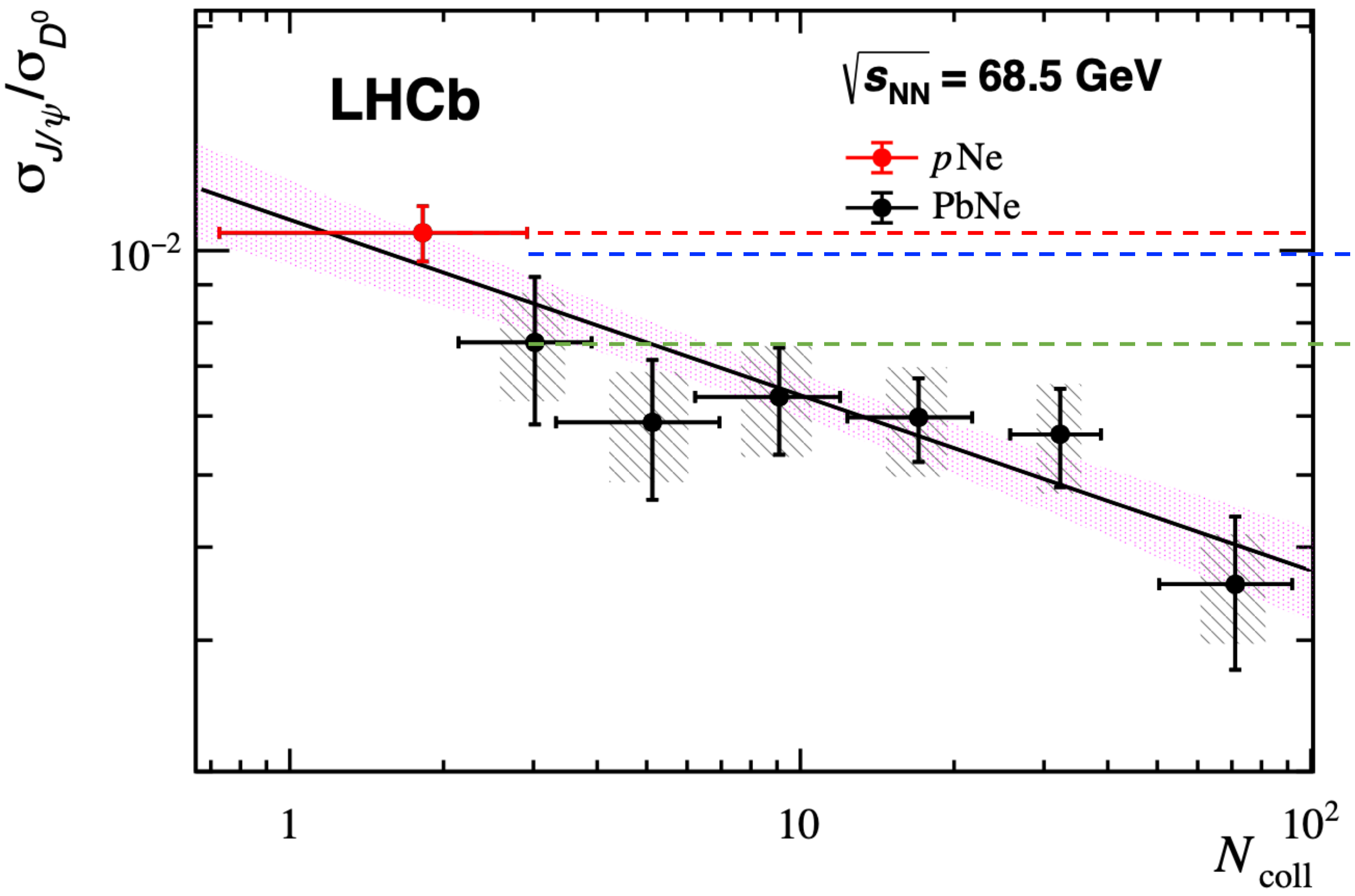


L=average mean path through nucleus

CERN/SPS uses Drell-Yan as initial-state effect reference.
PbNe overlap system size is up to 4 fm.

Sequencial Dissociation

Eur. Phys. J. C83 (2023) 658



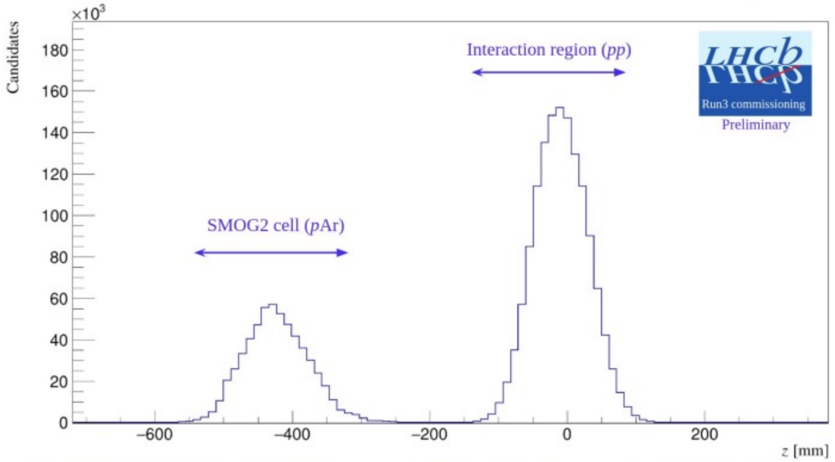
$\psi(2S)$ feed-down turned off

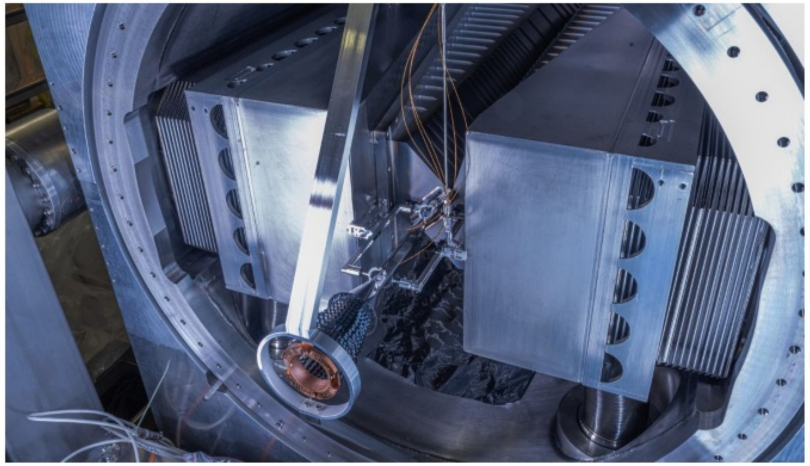
$\psi(2S)+\chi_C$ feed-down turned off

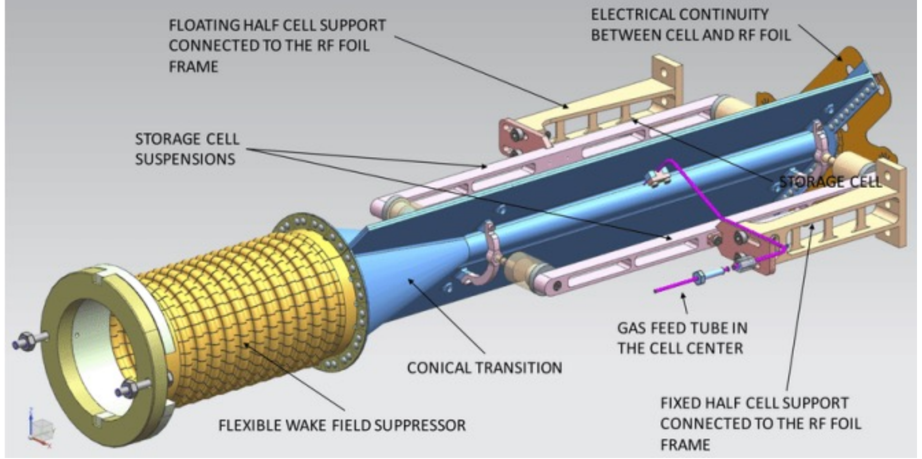
Ratio decreasing consistent with the dissociation of feed-down contributions to J/ψ.
CAVEAT: Not considering the uncertainties in the feed-down contributions.

SMOG2

LHCB-FIGURE-2023-001

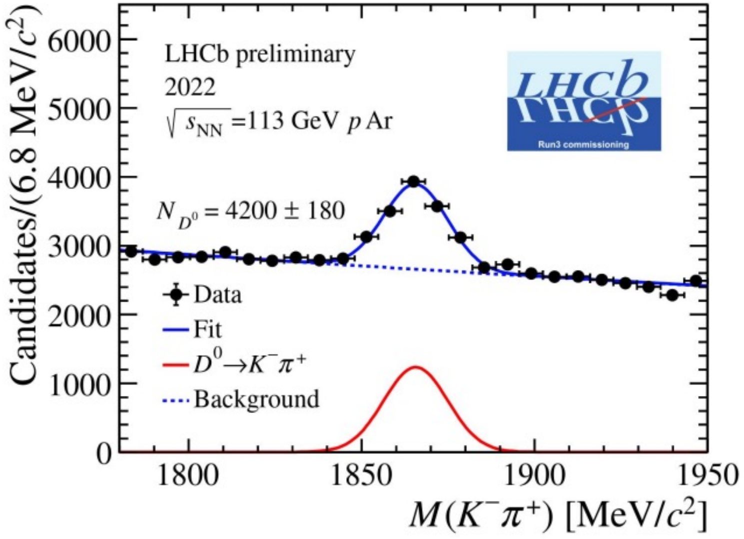


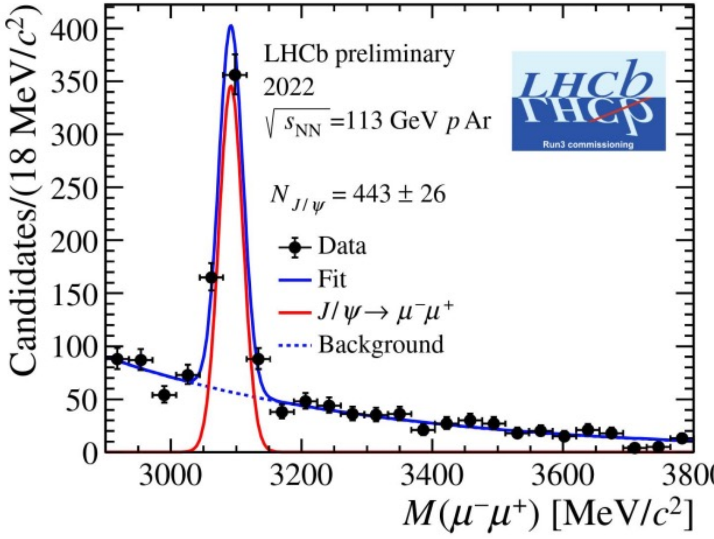




LHCB-FIGURE-2023-008

18 minutes pilot run in 2022





Future gas targets :

- Noble gases : ^{4}He, ^{20}Ne, ^{40}Ar, ^{84}Kr, ^{132}Xe
- and others : H_2, D, N_2, O_2

https://cds.cern.ch/record/2673690/files/LHCB-TDR-020.pdf

Parallel running with pp and PbPb runs.

What to Expect for the Next QWG Meeting ?

- A combination of $(J/\psi, \psi(2S), \chi_c)$ /D^0 ratios vs. N_{coll} in pA and Pb+A from SMOG2. No centrality limitations.

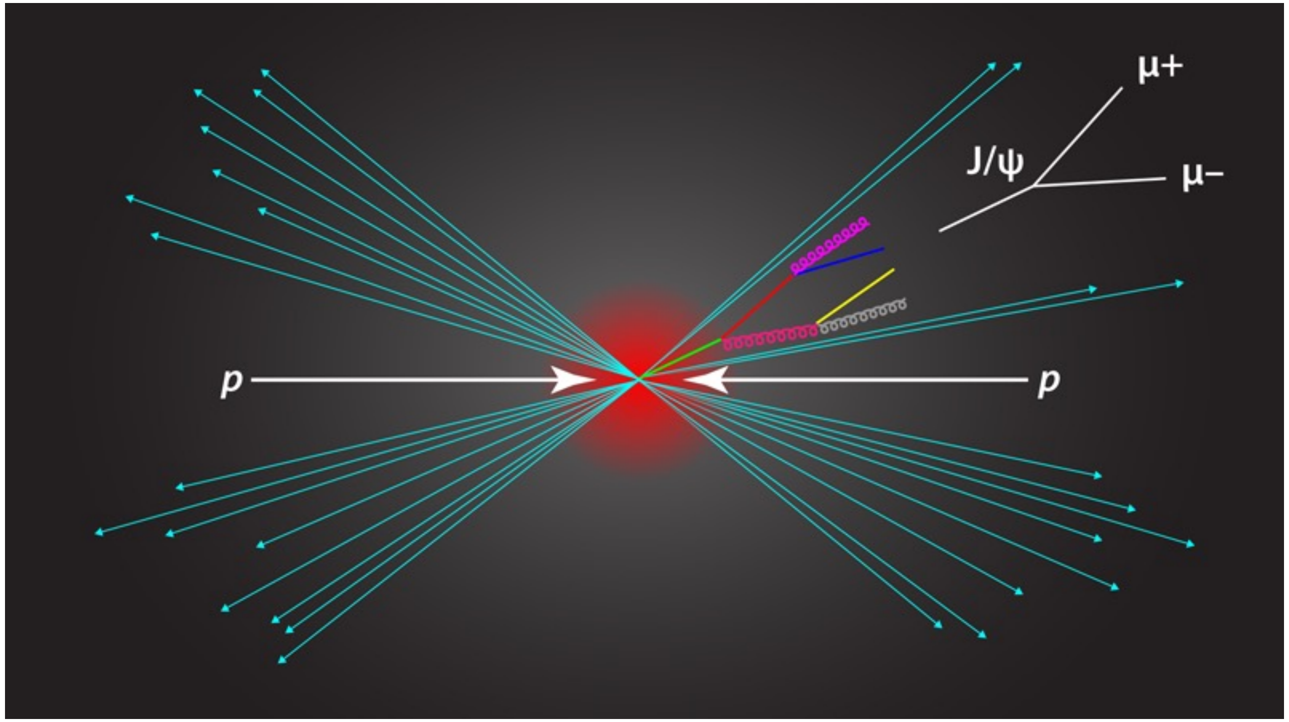
- First charmonium states nuclear modification factors in PbPb collisions (collider mode) reaching centralities up to 30%.

- Perhaps other exotic states in p+A and PbPb collisions.

- A set of measurements providing strong constraints on how hot the medium is created in AA collisions.

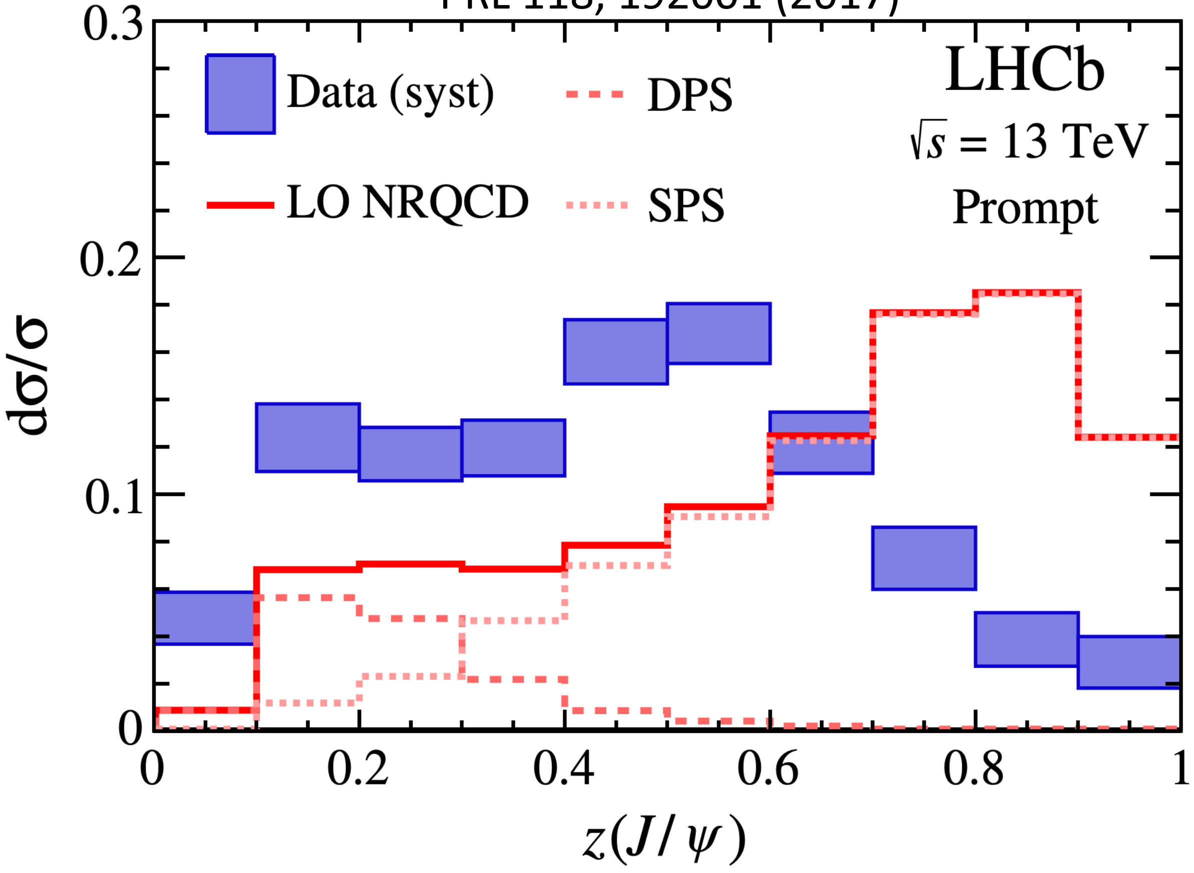
Thank You !!!

EXTRAS



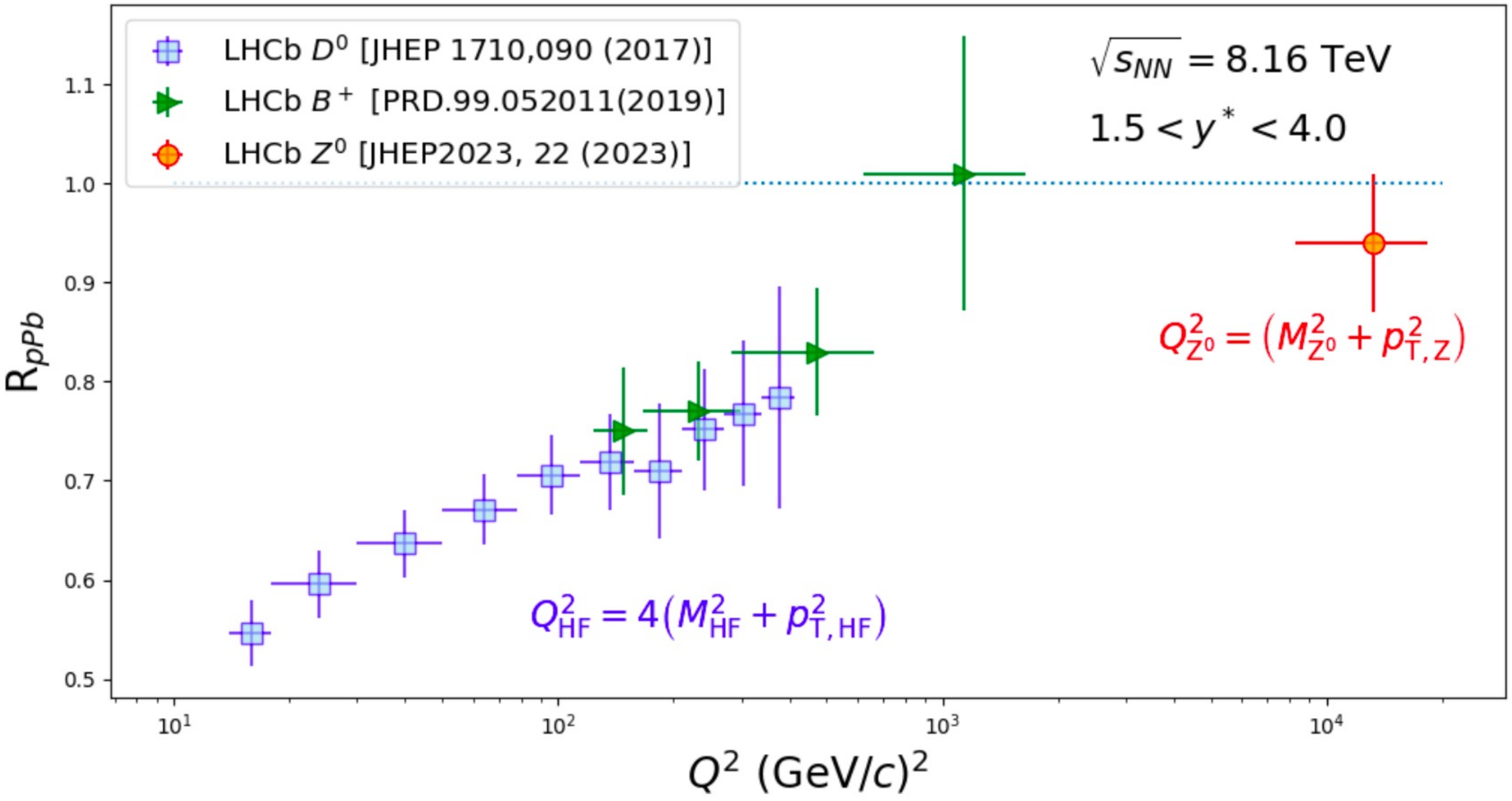
APS/Alan Stonebraker

PRL 118, 192001 (2017)

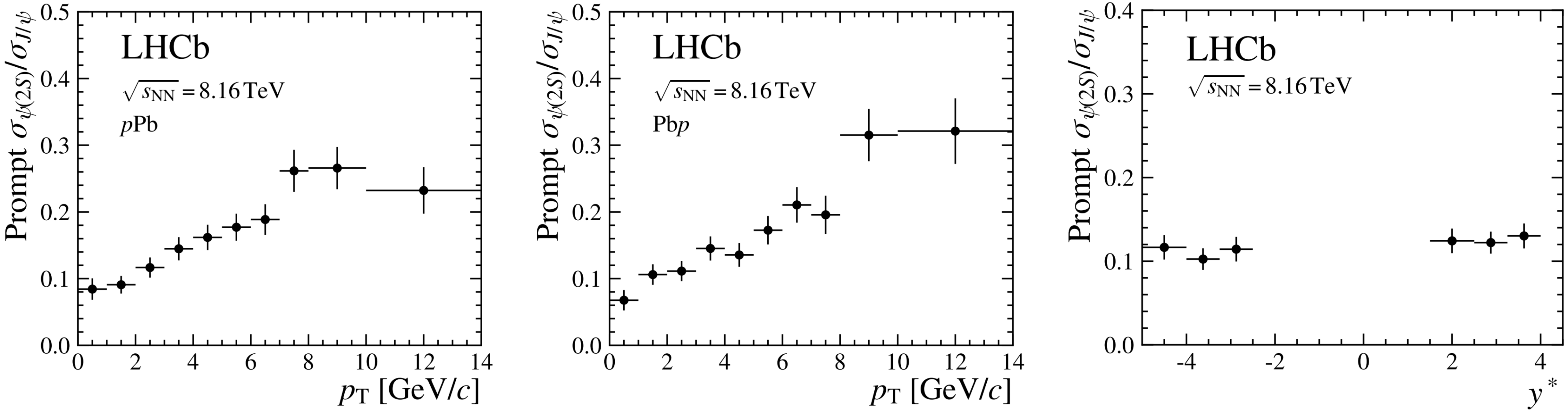


J/psi is mostly formed in jets at LHC.

- Explains why NRQCD cannot simultaneously describe polarization and cross-section
- Explains why J/psi yield increases with local charged particle multiplicity in pp collisions


LHCb D^0 [JHEP 1710,090 (2017)]
LHCb B^+ [PRD.99.052011(2019)]
LHCb Z^0 [JHEP2023, 22 (2023)]
$\sqrt{s_{NN}} = 8.16$ TeV
$1.5 < y^* < 4.0$
$Q^2_{Z^0} = \left(M^2_{Z^0} + p^2_{T,Z}\right)$
$Q^2_{HF} = 4\left(M^2_{HF} + p^2_{T,HF}\right)$
R_{pPb}
Q^2 (GeV/c)^2
1.1
1.0
0.9
0.8
0.7
0.6
0.5
10^1
10^2
10^3
10^4

LHCb-PAPER-2023-024

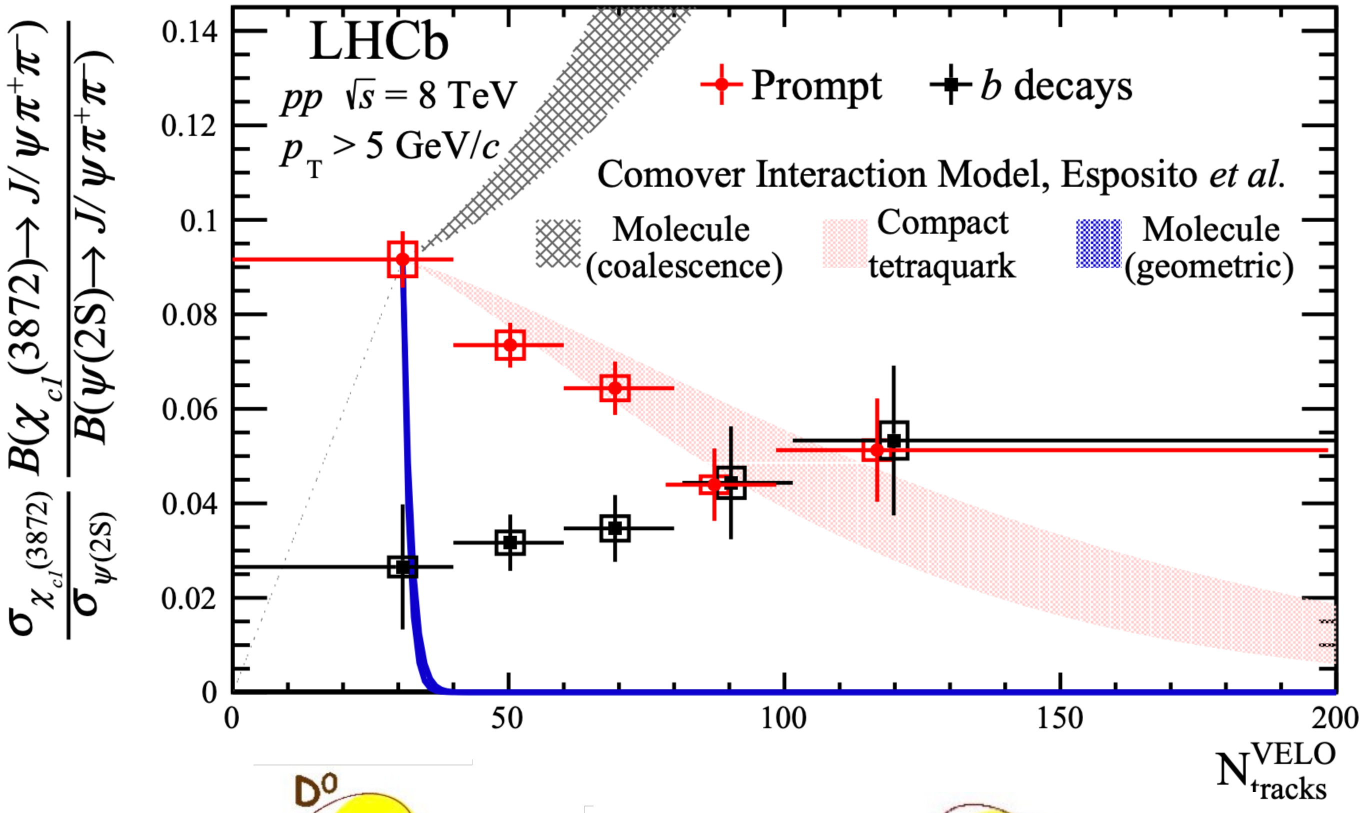


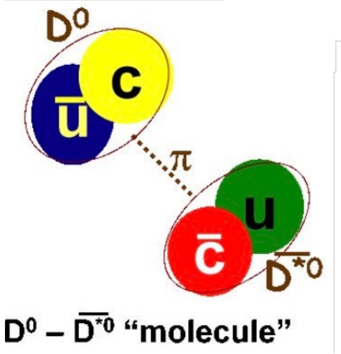
$$\frac{\sigma_{\psi(2S)}}{\sigma_{J/\psi}}$$

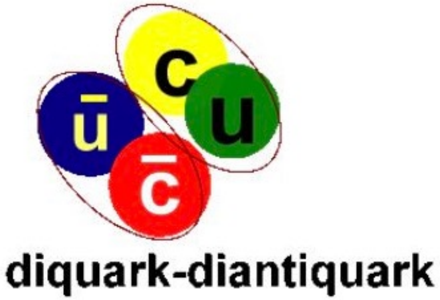
- increases with p_T
- flat in rapidity

$\chi_{c1}(3872)$

PRL126 (2021) 092001







Suppression of $\chi_{c1}(3872)$ relative to $\psi(2S)$ at high multiplicity pp events.

Consistent with dissociation of a compact tetraquark in comoving particles.

Molecular explanation from Bratten