Quarkonium in the quark-gluon plasma: an experimental overview

Roberta Arnaldi
INFN Torino (Italy)

EMMI Featured Talk / GSI-FAIR Colloquium, 16 July 2024

Overview

- ✓ Quarkonium

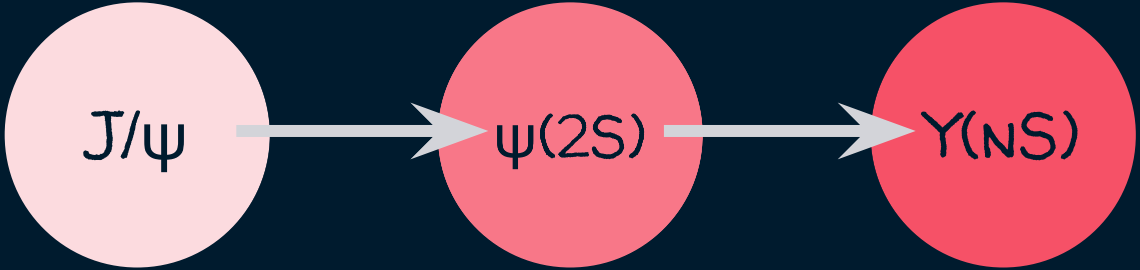
J/ψ → $\psi(2S)$ → $\Upsilon(nS)$

- ✓ as a probe of quark-gluon plasma formation in heavy-ion collisions

pp → pA → AA

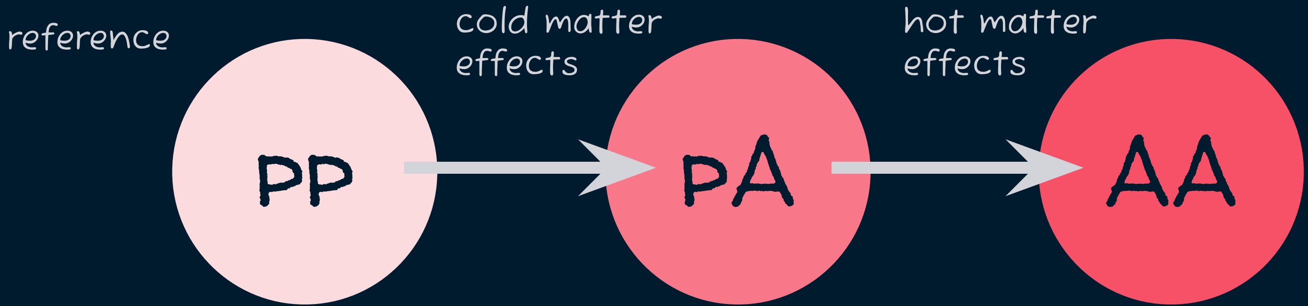
Overview

- ✓ Quarkonium



J/ψ → ψ(2S) → Υ(nS)

- ✓ as a probe of quark-gluon plasma formation in heavy-ion collisions



reference

pp

cold matter effects

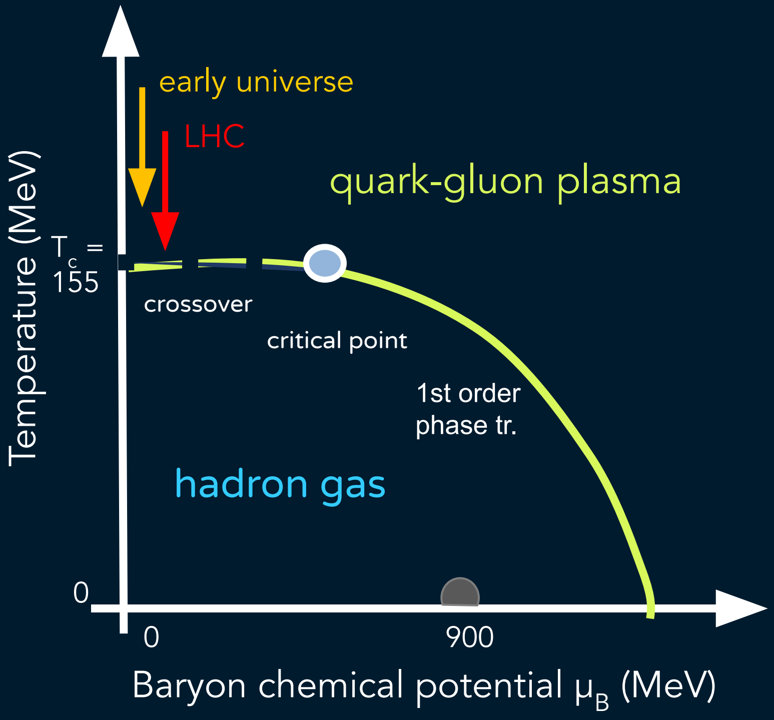
→ pA

hot matter effects

→ AA

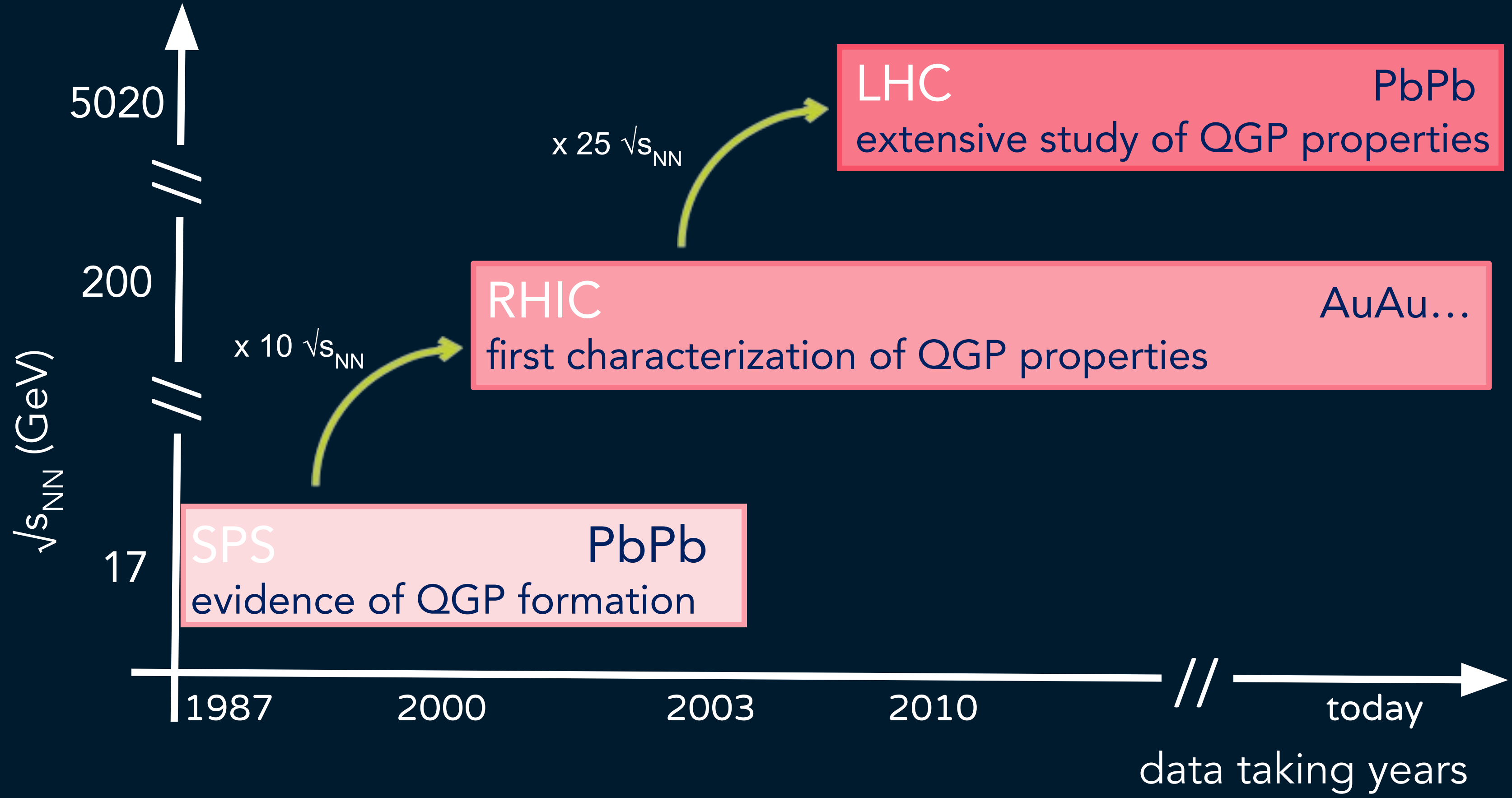
Quark-gluon plasma

Quark-gluon plasma is the QCD state of strongly interacting matter in which quarks and gluons are no more confined into hadrons



- QGP is formed at high temperatures and/or density
- experimentally, these conditions are reached in ultra-relativistic heavy ions collisions

QGP and heavy-ions



LHC PbPb

extensive study of QGP properties

x 25 $\sqrt{s_{NN}}$

RHIC AuAu…

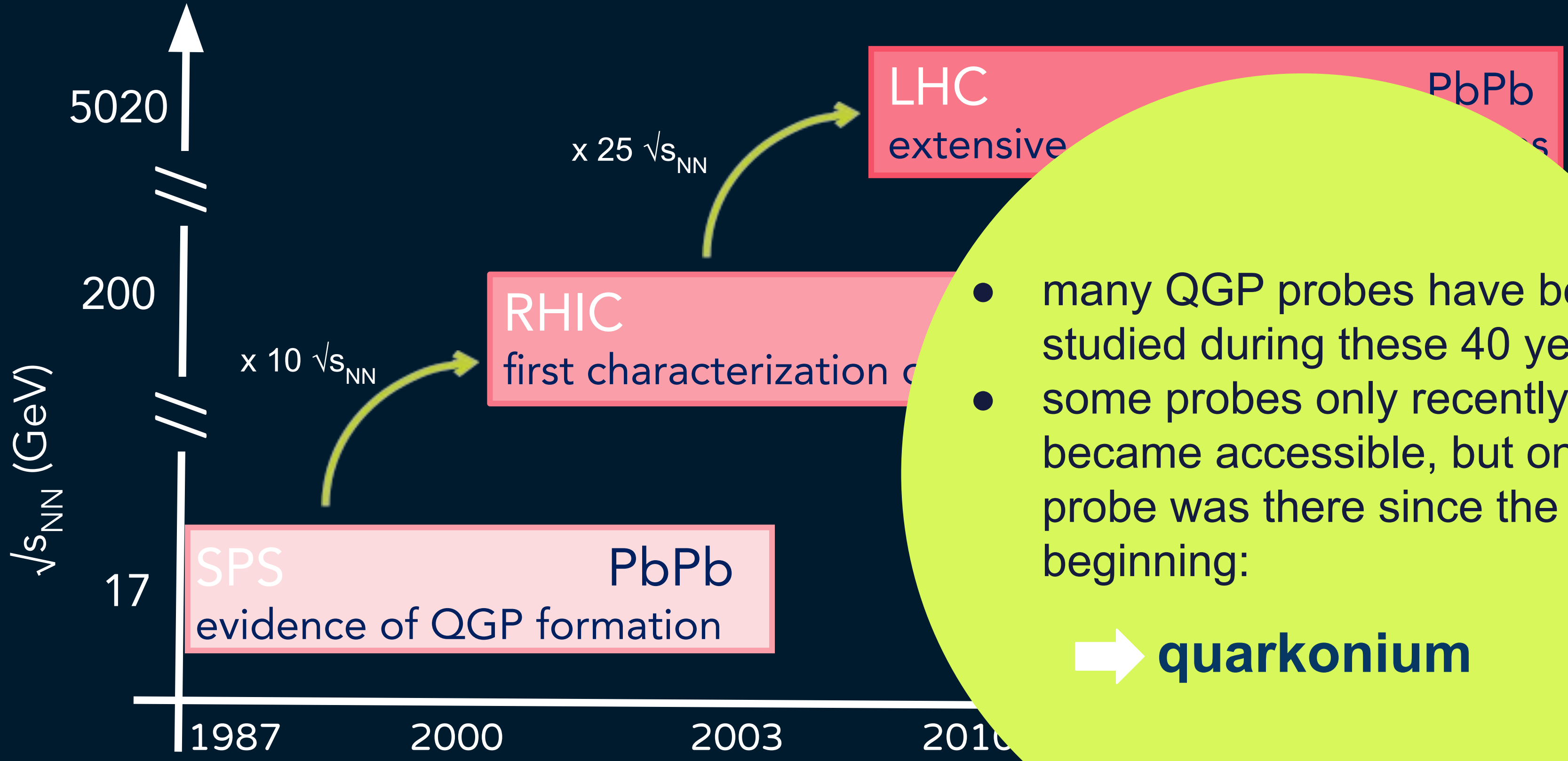
first characterization of QGP properties

x 10 $\sqrt{s_{NN}}$

SPS PbPb

evidence of QGP formation

QGP and heavy-ions



$\sqrt{s_{NN}}$ (GeV)

5020

200

17

x 25 $\sqrt{s_{NN}}$

x 10 $\sqrt{s_{NN}}$

LHC PbPb

extensive

RHIC

first characterization c

SPS PbPb

evidence of QGP formation

1987

2000

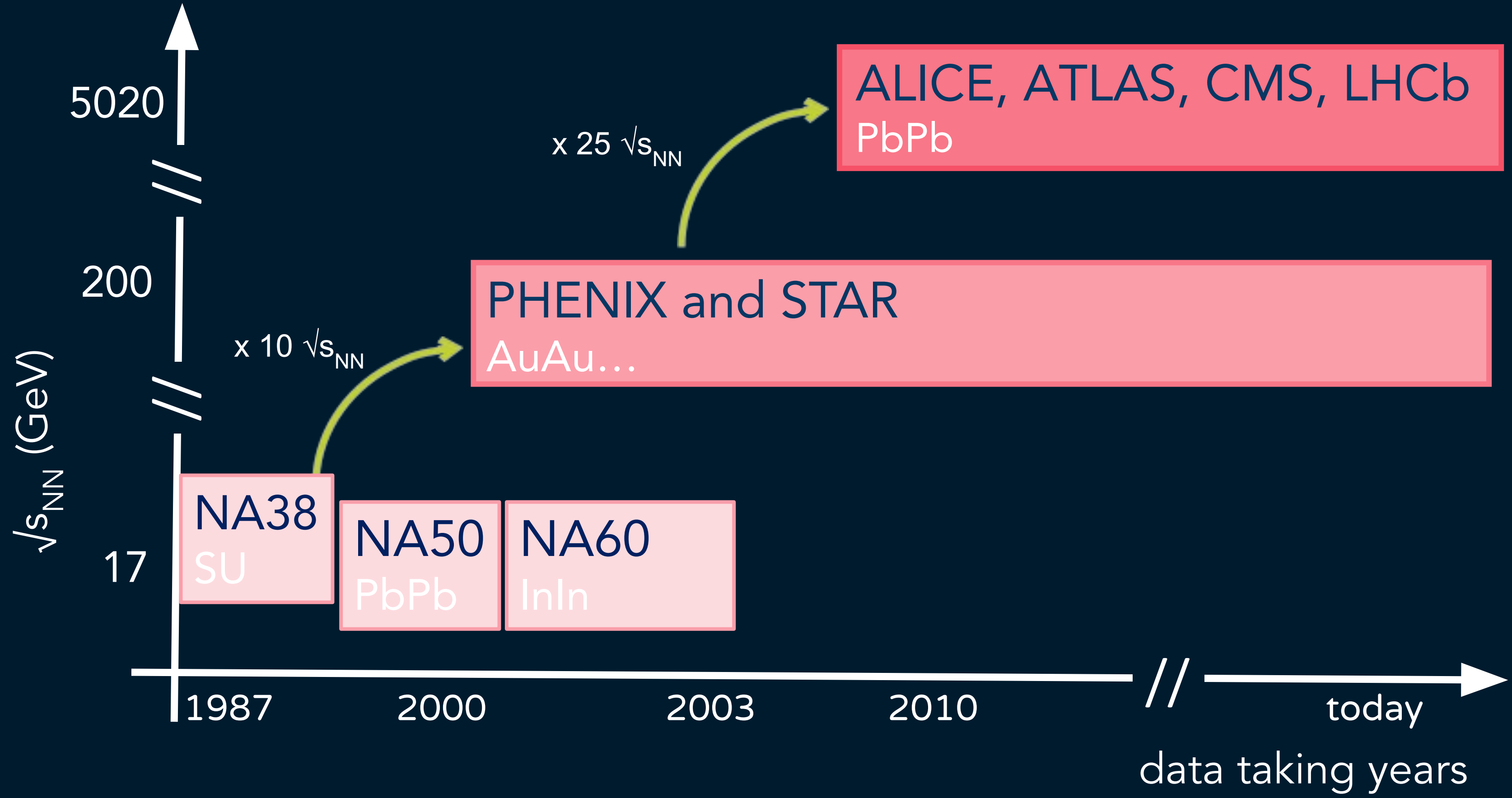
2003

201

- many QGP probes have been studied during these 40 years
- some probes only recently became accessible, but one probe was there since the beginning:

⇨ **quarkonium**

Quarkonium in heavy-ions



ALICE, ATLAS, CMS, LHCb
PbPb

PHENIX and STAR
AuAu…

NA38
SU

NA50
PbPb

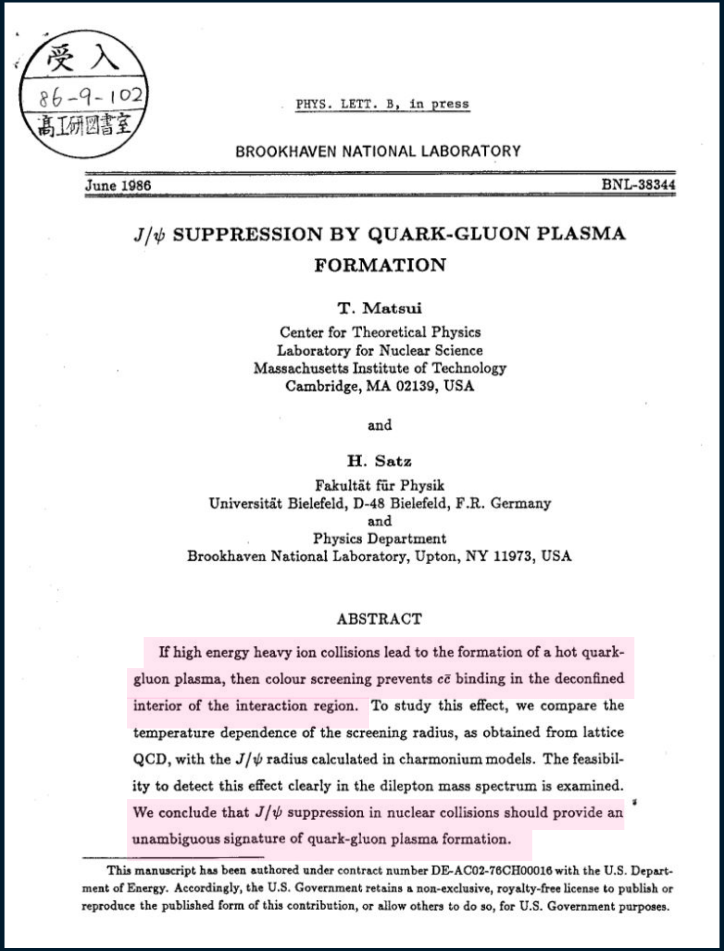
NA60
InIn

Quarkonium and QGP

Heavy quarks produced in the early collision stages

the original idea:
quarkonium production suppressed sequentially via color screening in QGP

T.Matsui, H.Satz, PLB178 (1986) 416
> 3500 citations



PHYS. LETT. B, in press

BROOKHAVEN NATIONAL LABORATORY

June 1986 BNL-38344

J/ψ SUPPRESSION BY QUARK-GLUON PLASMA FORMATION

T. Matsui
Center for Theoretical Physics
Laboratory for Nuclear Science
Massachusetts Institute of Technology
Cambridge, MA 02139, USA

and

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Fakultät für Physik
Universität Bielefeld, D-48 Bielefeld, F.R. Germany
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Physics Department
Brookhaven National Laboratory, Upton, NY 11973, USA

ABSTRACT

If high energy heavy ion collisions lead to the formation of a hot quark-gluon plasma, then colour screening prevents $c\bar{c}$ binding in the deconfined interior of the interaction region. To study this effect, we compare the temperature dependence of the screening radius, as obtained from lattice QCD, with the J/ψ radius calculated in charmonium models. The feasibility to detect this effect clearly in the dilepton mass spectrum is examined. We conclude that J/ψ suppression in nuclear collisions should provide an unambiguous signature of quark-gluon plasma formation.

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Quarkonium and QGP

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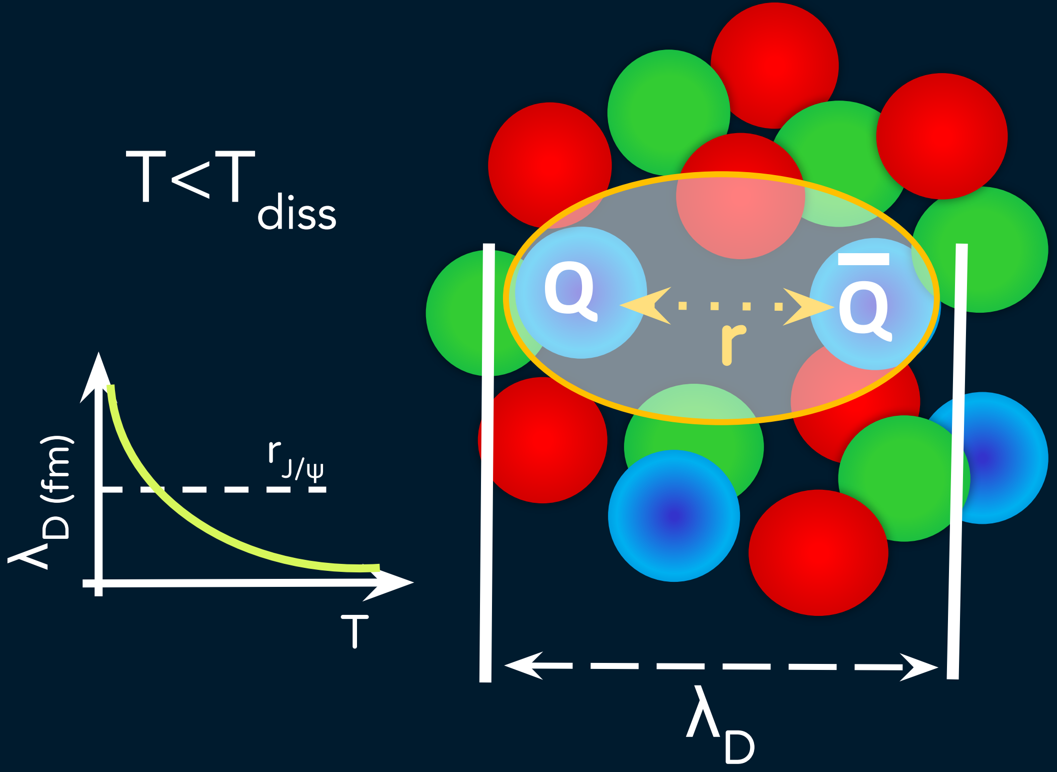

Quarkonium and QGP

Heavy quarks produced in the early collision stages

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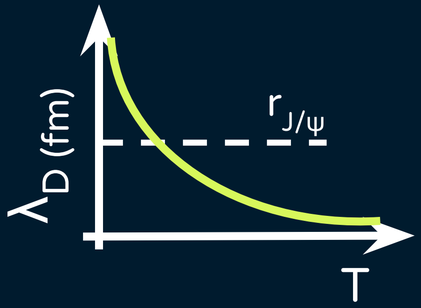
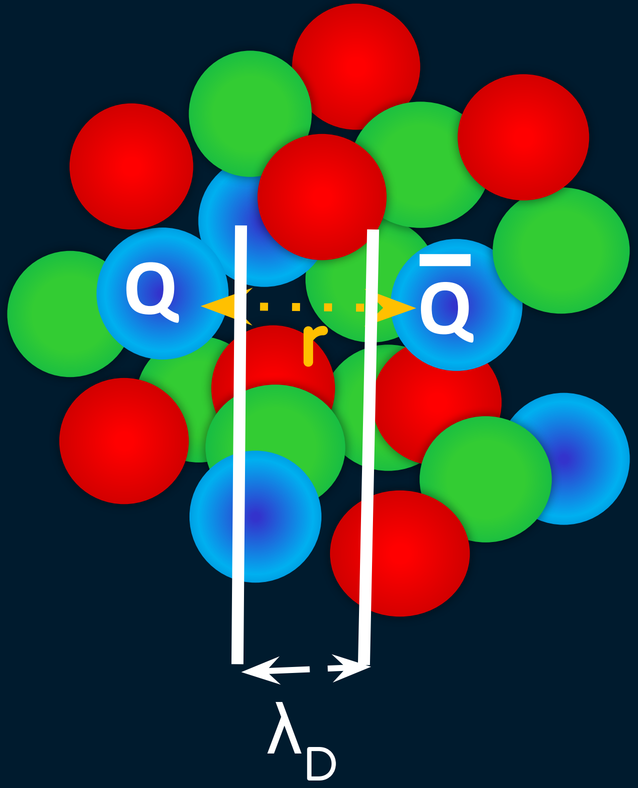
> 3500 citations

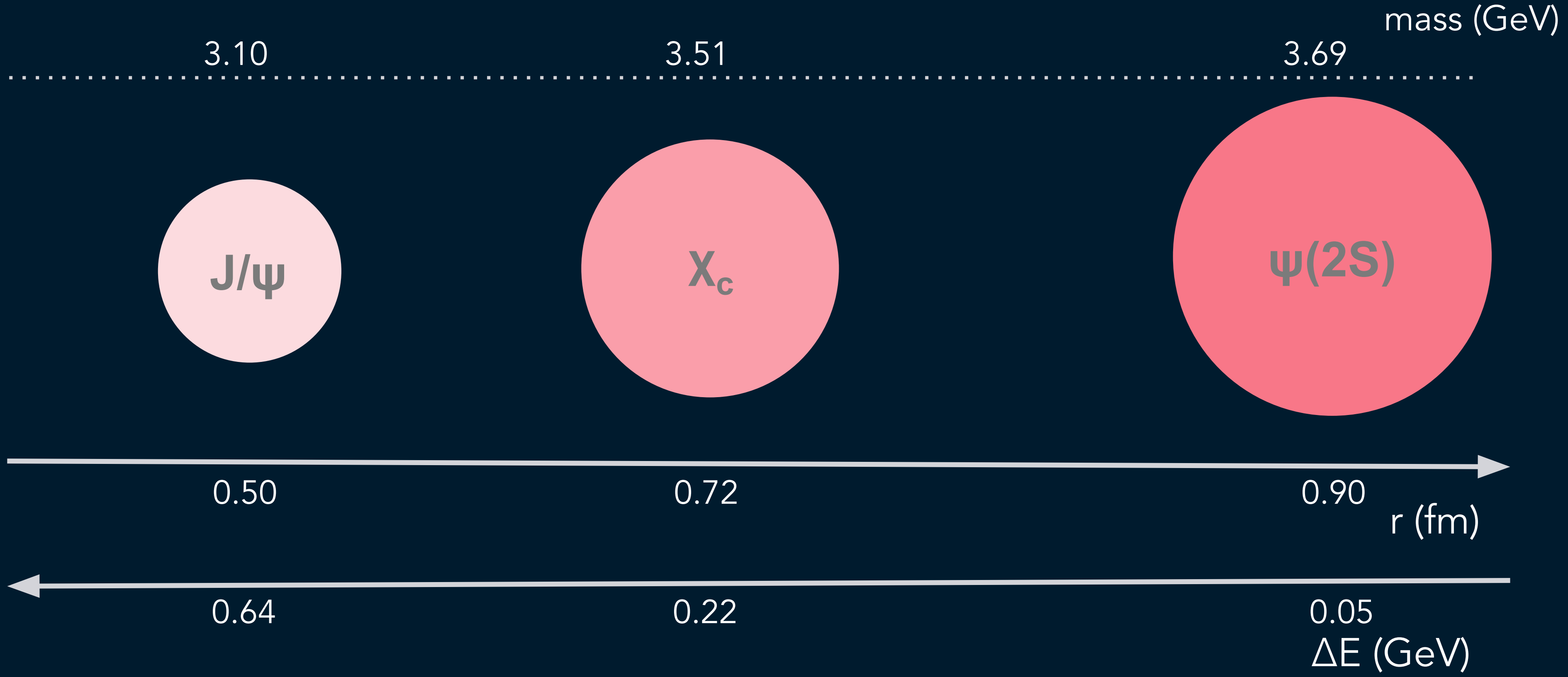
$T>T_{diss}$





Quarkonium states

Quarkonium exists in a large variety of states: charmonium



mass (GeV)

3.10 3.51 3.69

J/ψ

χ_c

ψ(2S)

0.50 0.72 0.90

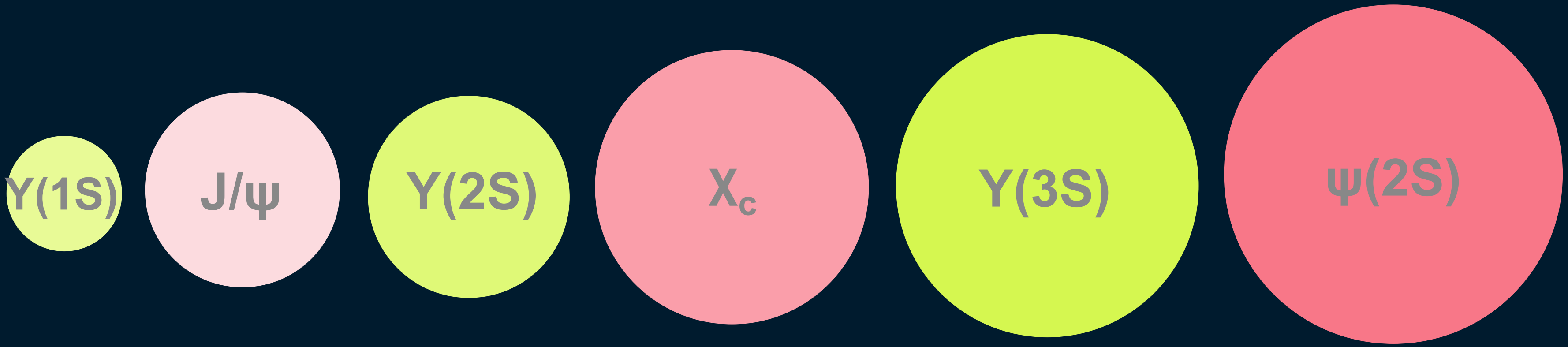
r (fm)

0.64 0.22 0.05

ΔE (GeV)

Quarkonium states

Quarkonium exists in a large variety of states: charmonium and bottomonium



	$\Upsilon(1S)$	J/ψ	$\Upsilon(2S)$	χ_c	$\Upsilon(3S)$	$\psi(2S)$
mass (GeV)	9.46	3.10	10.0	3.51	10.4	3.69
r (fm)	0.28	0.50	0.56	0.72	0.78	0.90
ΔE (GeV)	1.10	0.64	0.54	0.22	0.20	0.05

Sequential melting

the original idea:

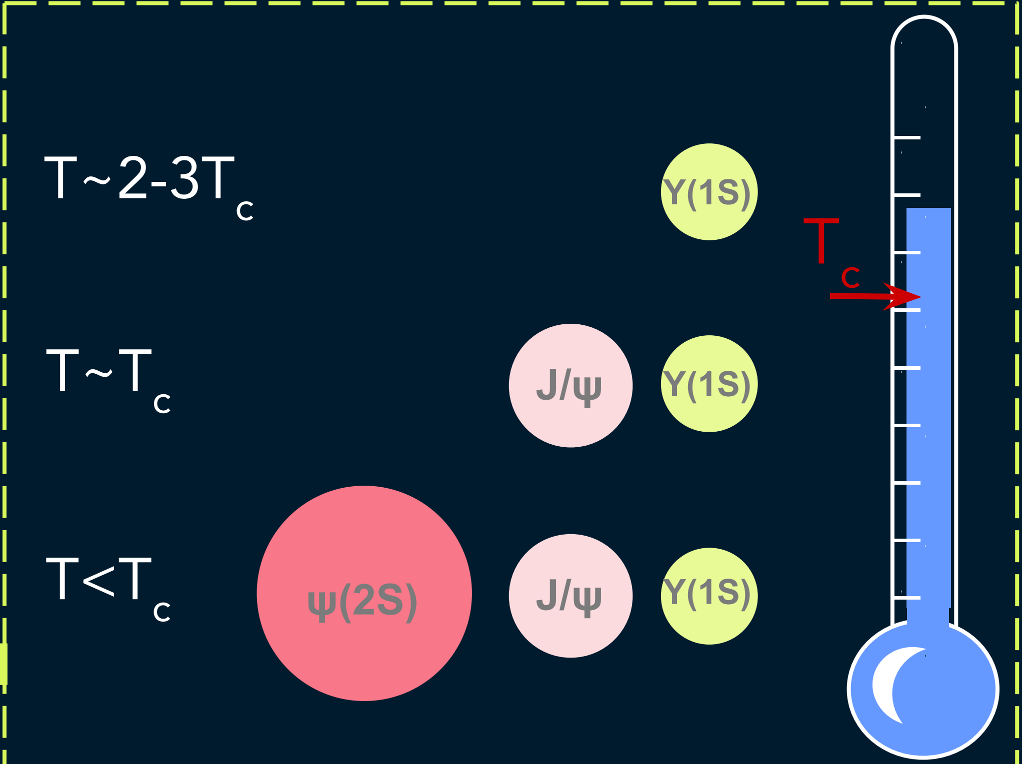
quarkonium production suppressed sequentially via color screening in QGP

T.Matsui, H.Satz, PLB178 (1986) 416

sequential melting:

differences in the quarkonium binding energies lead to a sequential melting with increasing temperature

Digal, Petrecki, Satz PRD 64(2001) 0940150
F. Karsch, D. Kharzeev, H. Satz, PB637 (2006) 75



$T\sim2\text{-}3T_c$ Υ(1S)

$T\sim T_c$ J/ψ Υ(1S)

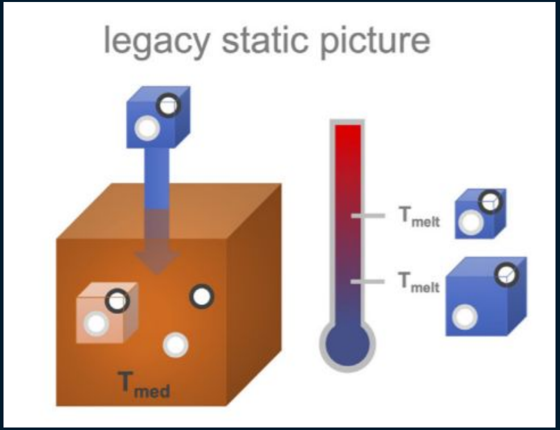
$T<T_c$ ψ(2S) J/ψ Υ(1S)

quarkonium as thermometer of the initial QGP temperature

Quarkonium and QGP

This intuitive suppression picture assumes static in-medium states

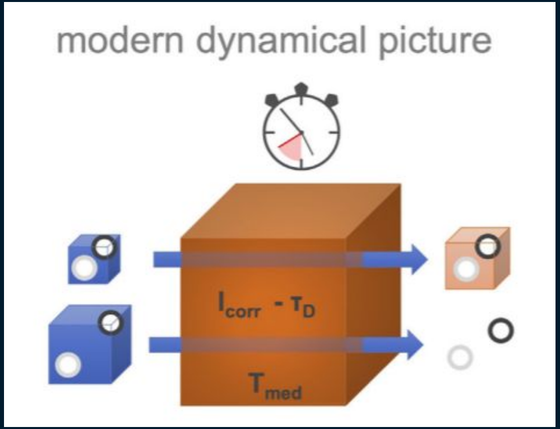
➡ quarkonium as a thermometer of the system



Recent theory developments introduce a dynamical approach

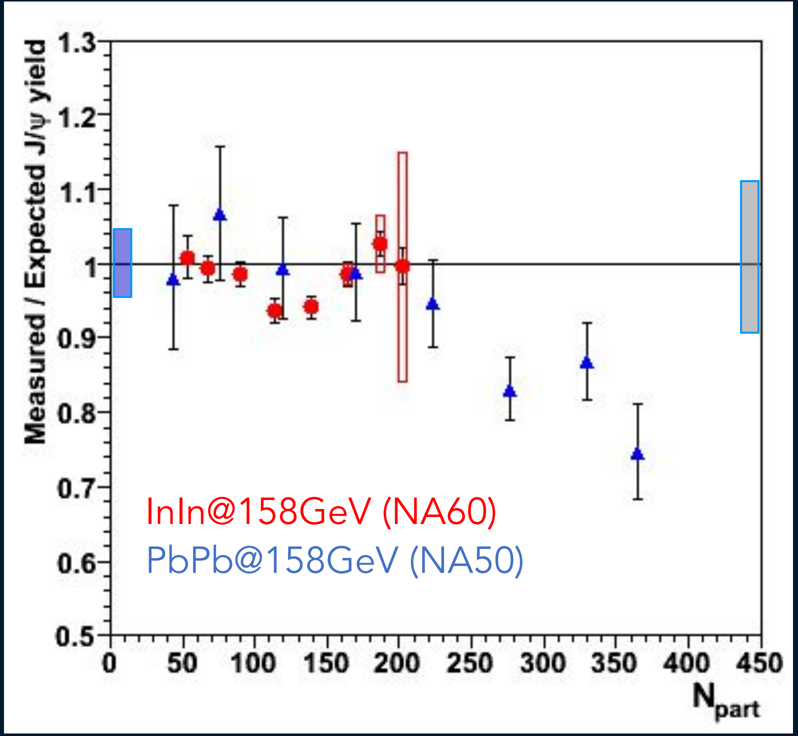
➡ quarkonium survival depends on how strongly it interferes with the medium and on the time spent in the medium

➡ medium as a “sieve” that filters quarkonia, over time, depending on the strength of their binding



A. Rothkopf, Physics Reports 858 (2020)

First charmonium results from SPS



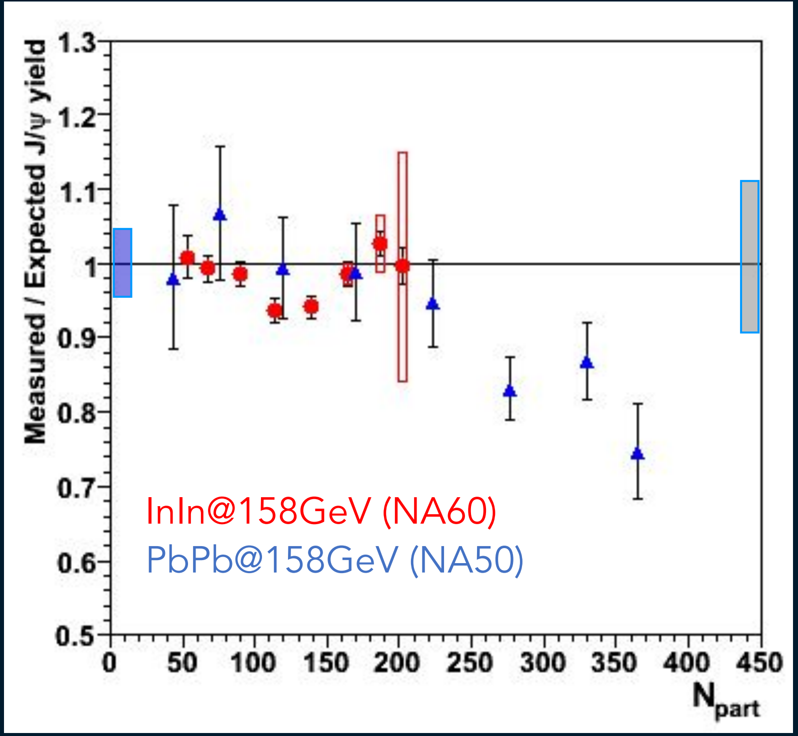
centrality

First observation of J/ψ anomalous suppression in central PbPb collisions

➡ size of J/ψ suppression quantitatively consistent with melting of ψ(2S) and χ_c

B. Alessandro et al., EPJC39 (2005) 335
R. Arnaldi et al., Nucl. Phys. A (2009) 345
R. Arnaldi, P. Cortese, E. Scomparin Phys. Rev. C 81, 014903

First charmonium results from SPS



centrality →

B. Alessandro et al., EPJC39 (2005) 335
R. Arnaldi et al., Nucl. Phys. A (2009) 345
R. Arnaldi, P. Cortese, E. Scomparin Phys. Rev. C 81, 014903

First observation of J/ψ anomalous suppression in central PbPb collisions

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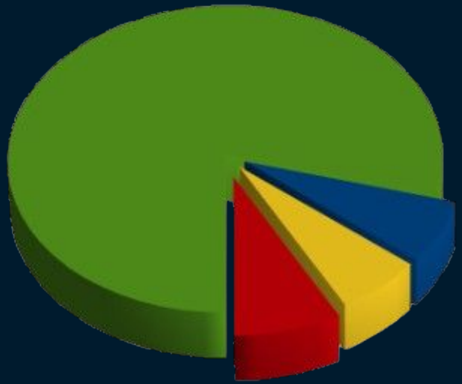
J/ψ feed-down

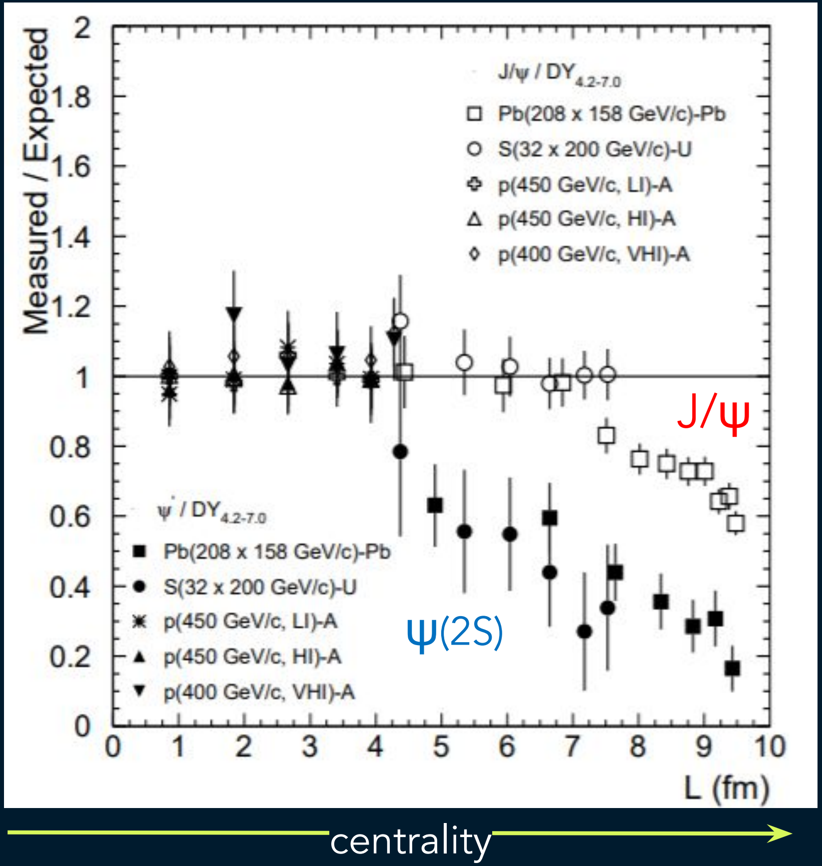


direct ~ 79.5%
from ψ(2S) ~ 6.5%
from χ_{c1}(1P)~ 8%
from χ_{c2}(1P) ~ 6%

(at low p_T)

J.P. Lansberg, Phys. Rept. 889 (2020) 1

First charmonium results from SPS



NA50, EPJC49 (2007)

First observation of J/ψ anomalous suppression in central PbPb collisions

- size of J/ψ suppression quantitatively consistent with melting of ψ(2S) and χ_c

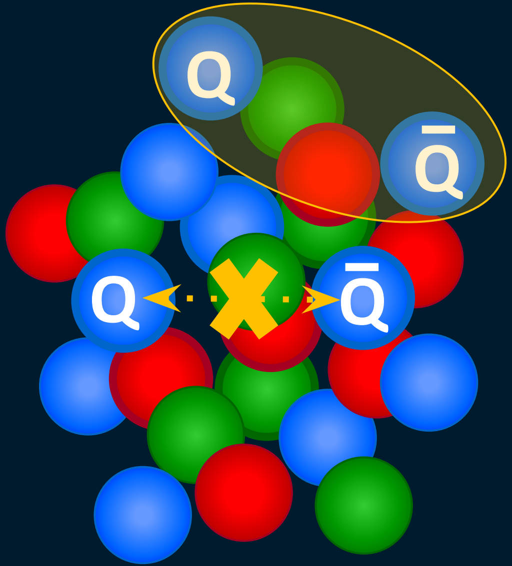
First evidence of sequential suppression

- ψ(2S) anomalous suppression stronger than the J/ψ one

Quarkonium in QGP: recombination

Increasing the energy of the collision the $c\bar{c}$ pair multiplicity increases

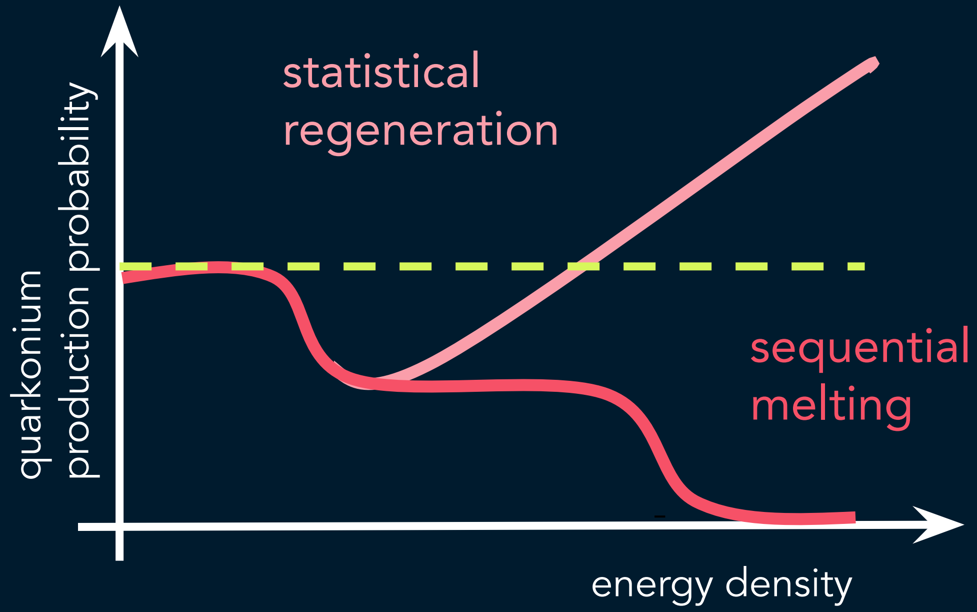
Central AA coll	Ncc	Nbb
SPS, 17 GeV	~0.2	0
RHIC, 200 GeV	~10	~1
LHC, 5.02 TeV	~115	~10



(re)combination:
charmonium production enhanced at hadronization or in QGP

P. Braun-Munzinger, J.Stachel, PLB490(2000)196
R.Thews et al, PRC63:054905(2001)

Quarkonium: hot matter effects



The interplay of these hot matter effects

- suppression
- (re)combination

depends on the

- collision energy
- quarkonium state

Quarkonium: cold matter effects

Quarkonium production can be affected also by cold matter effects (CNM)

➡ the assessment of their size is fundamental to interpret quarkonium AA results

⬇

pA collisions allows us to understand

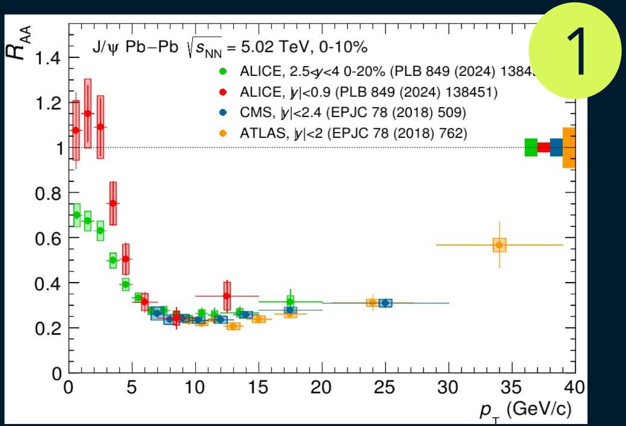
⬆

1) role of the various CNM contributions, whose importance depends on kinematic and energy of the collisions

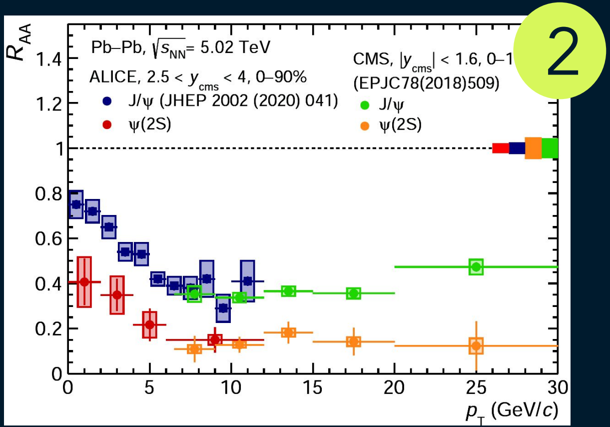
   → shadowing, coherent energy loss, break-up in nuclear matter or via hadronic/partonic comovers

2) presence of possible hot matter effects

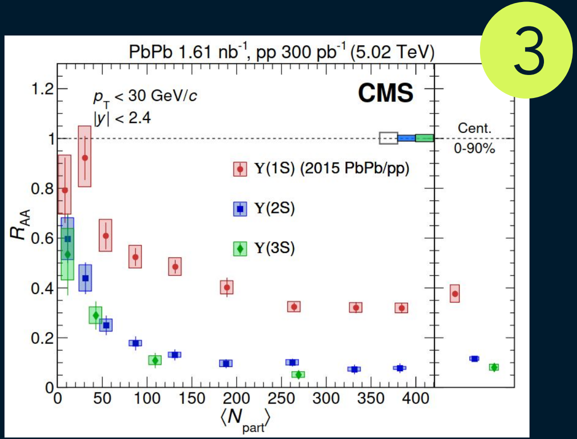
Quarkonium highlights at LHC



J/ψ R_{AA}



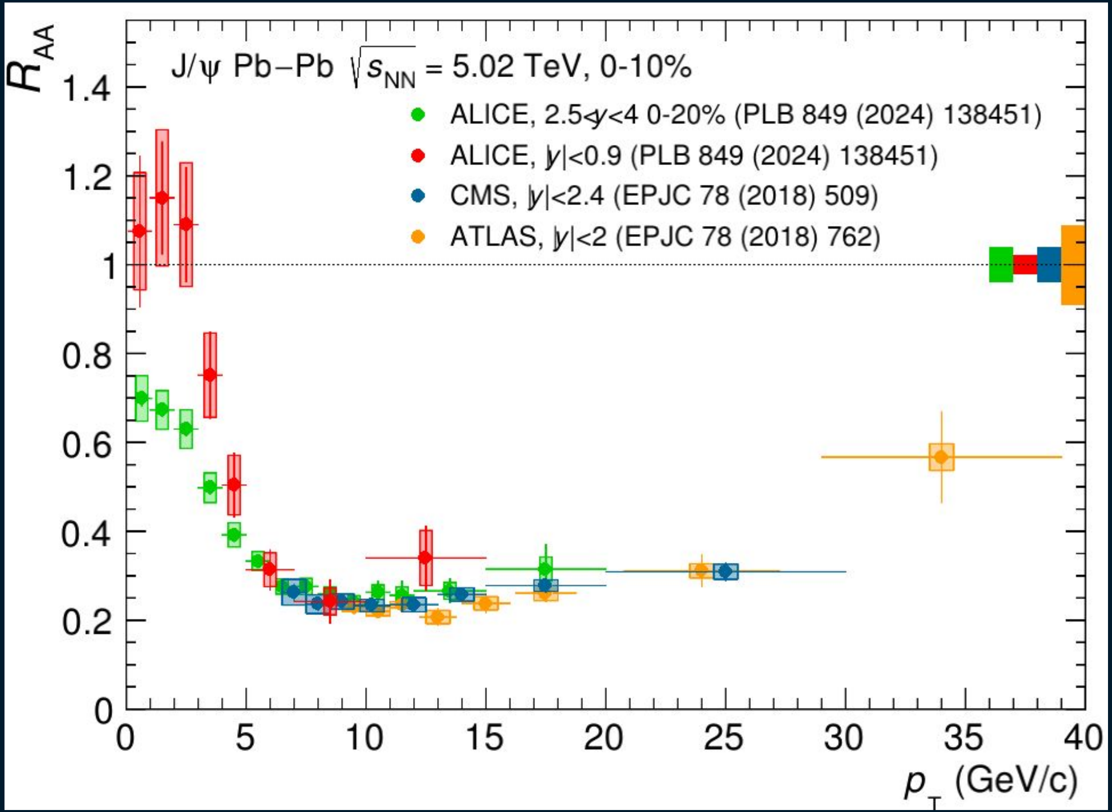
ψ(2S) R_{AA}



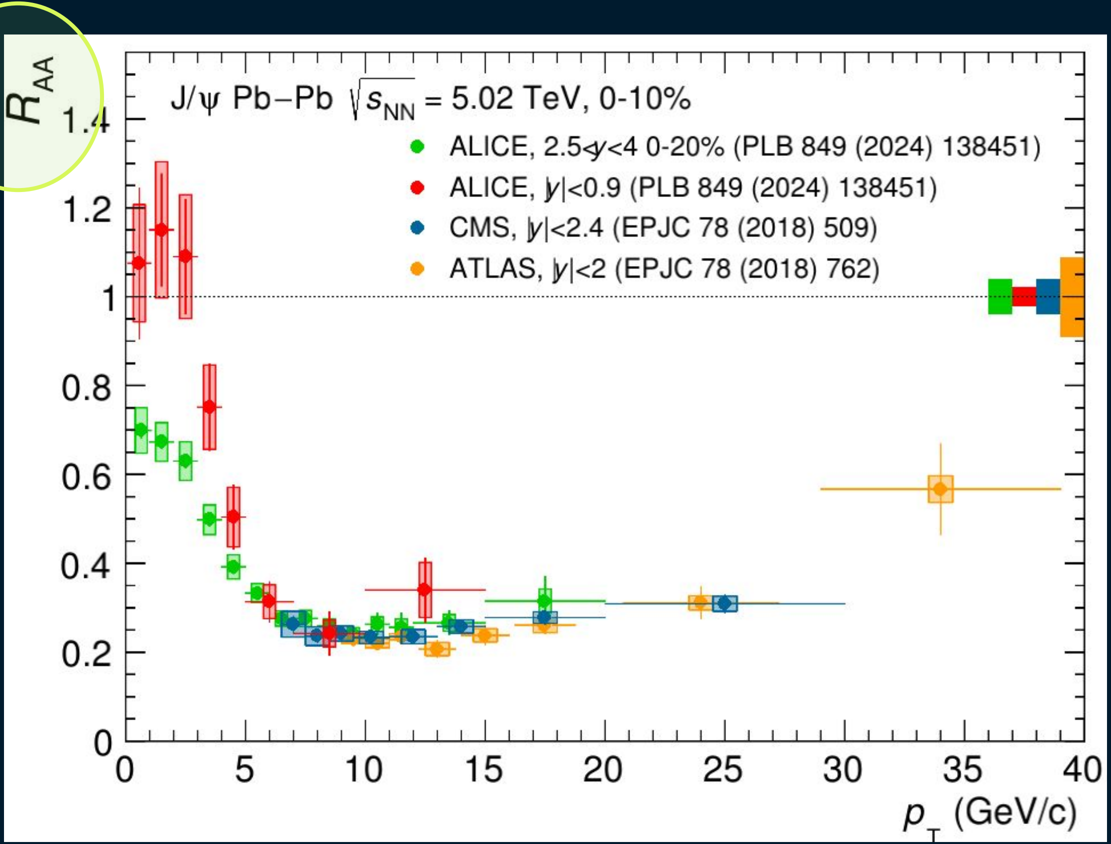
Υ(nS) R_{AA}

J/ψ R_{AA}

1


J/ψ Pb–Pb $\sqrt{s_{NN}}$ = 5.02 TeV, 0-10%
● ALICE, 2.5<y<4 0-20% (PLB 849 (2024) 138451)
● ALICE, |y|<0.9 (PLB 849 (2024) 138451)
● CMS, |y|<2.4 (EPJC 78 (2018) 509)
● ATLAS, |y|<2 (EPJC 78 (2018) 762)
R_{AA}
0
0.2
0.4
0.6
0.8
1
1.2
1.4
0
5
10
15
20
25
30
35
40
p_T (GeV/c)

J/ψ R_{AA}



Nuclear modification factor R_{AA}

Observable: R_{AA}

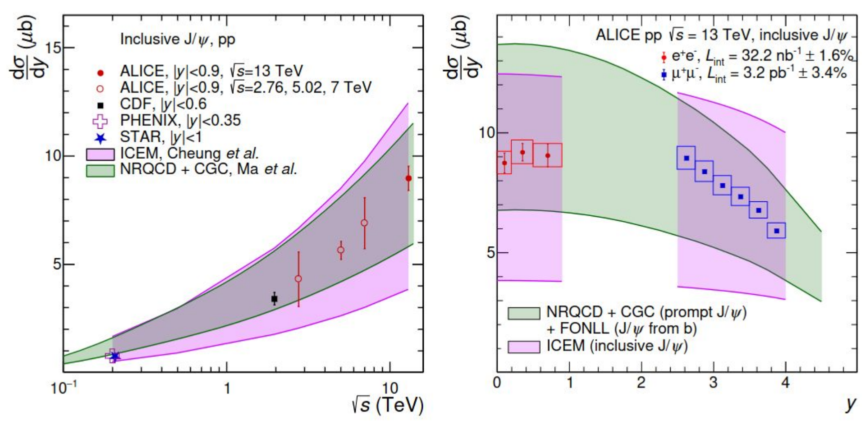
Medium effects are quantified comparing AA particle yield with pp cross section, scaled by a geometrical factor ($\propto N_{coll}$)

$$R_{AA} = \frac{Y_{AA}}{\langle T_{AA} \rangle \sigma_{pp}}$$

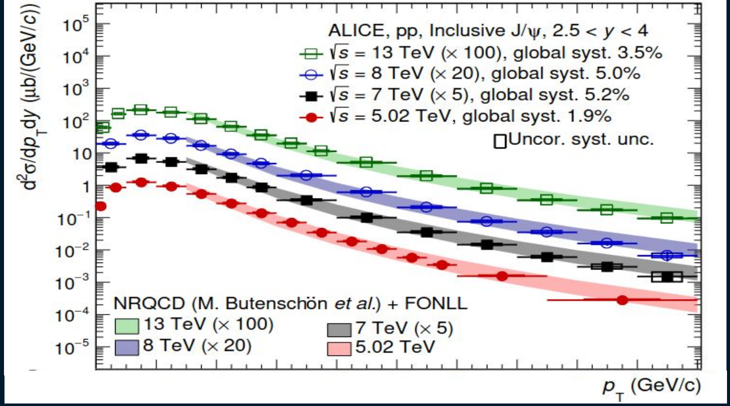
if there are medium effects

$$R_{AA} \neq 1$$

pp reference

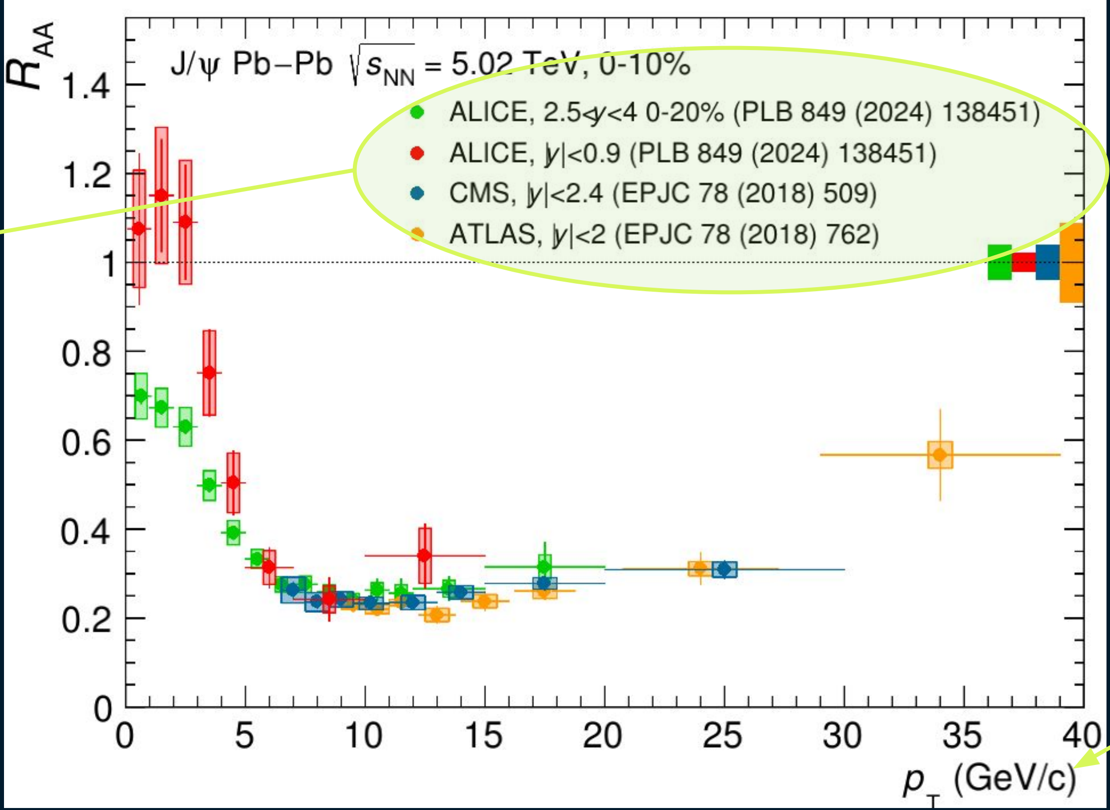


ALICE, Eur. Phys. J. C 81 (2021) 1121



ALICE, Eur. Phys. J. C 83 (2023) 61

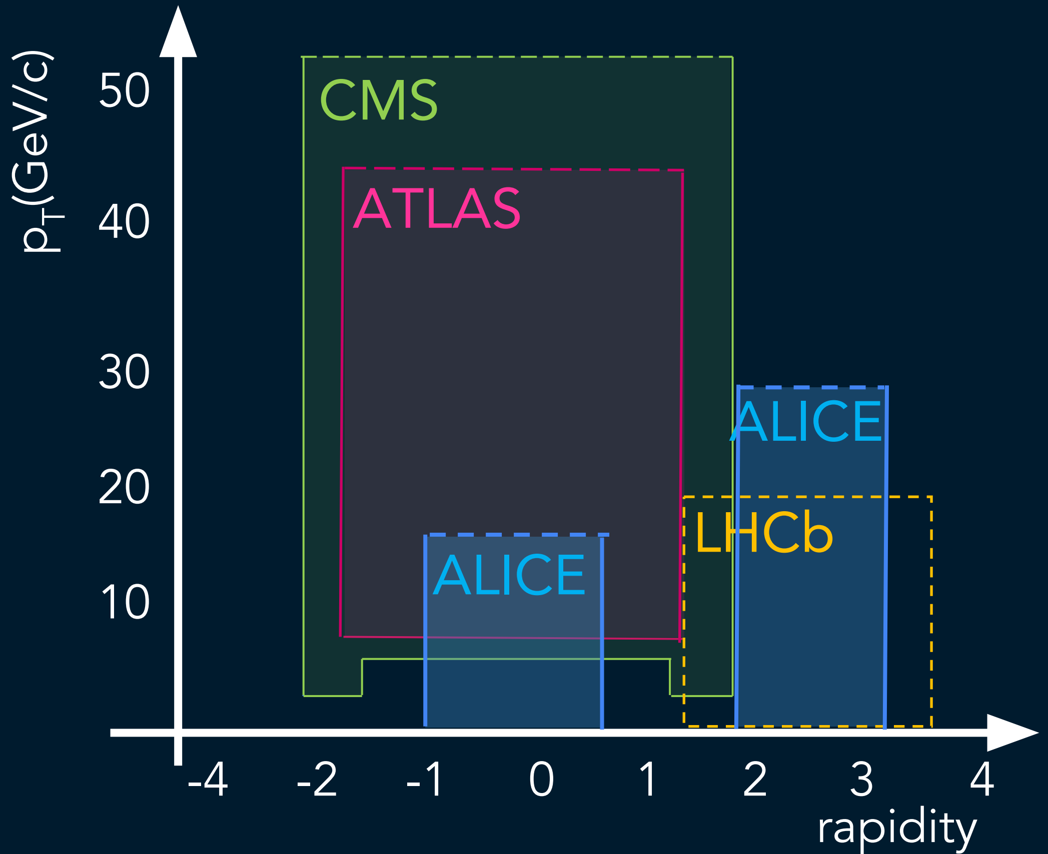
J/ψ R_{AA} vs p_T



complementary results from several LHC experiments

very broad p_T range now accessible

Quarkonium kinematics

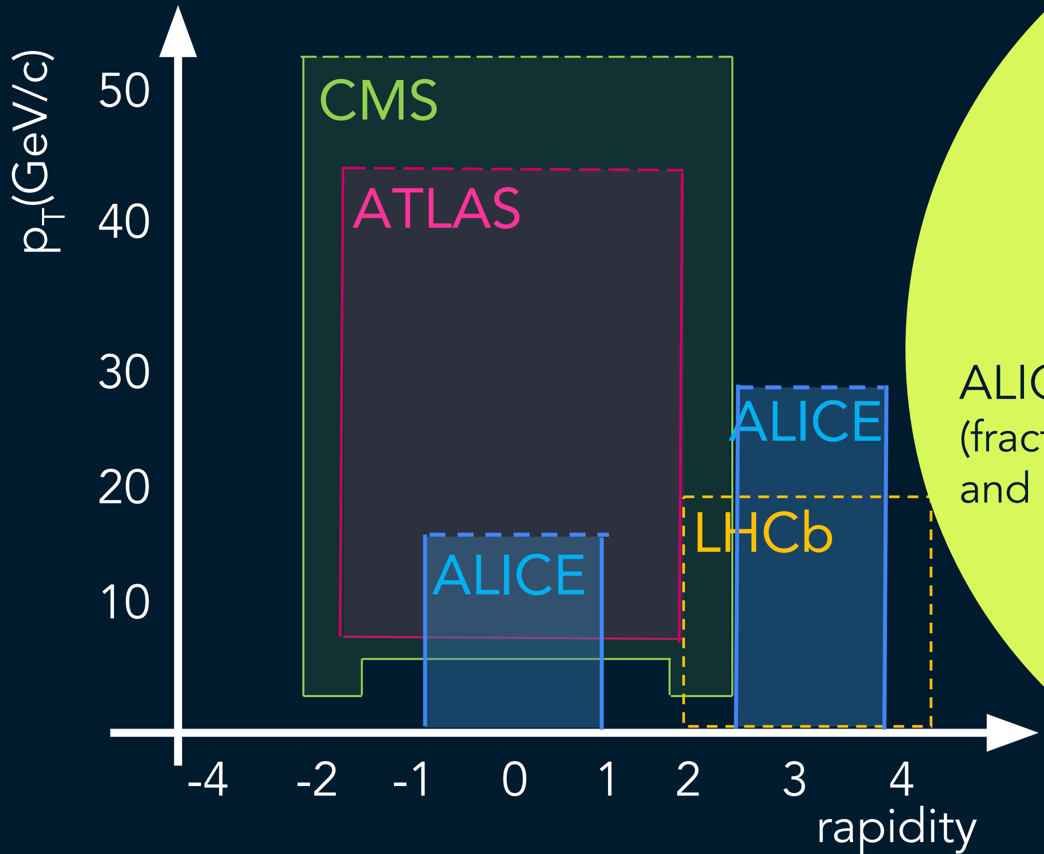


AA (pA for LHCb)

All experiments study quarkonium in its dilepton decay (dimuons and/or dielectrons)

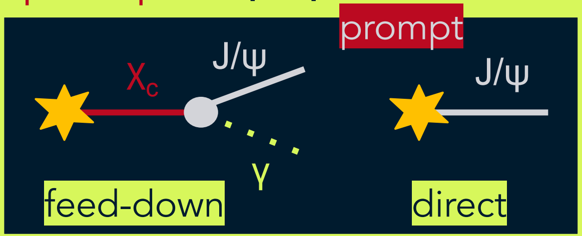
(p_T reach based on the most recent

Quarkonium kinematics

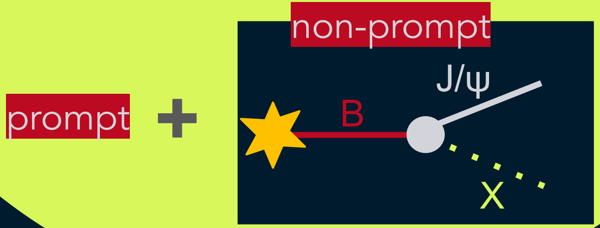


CAVEAT

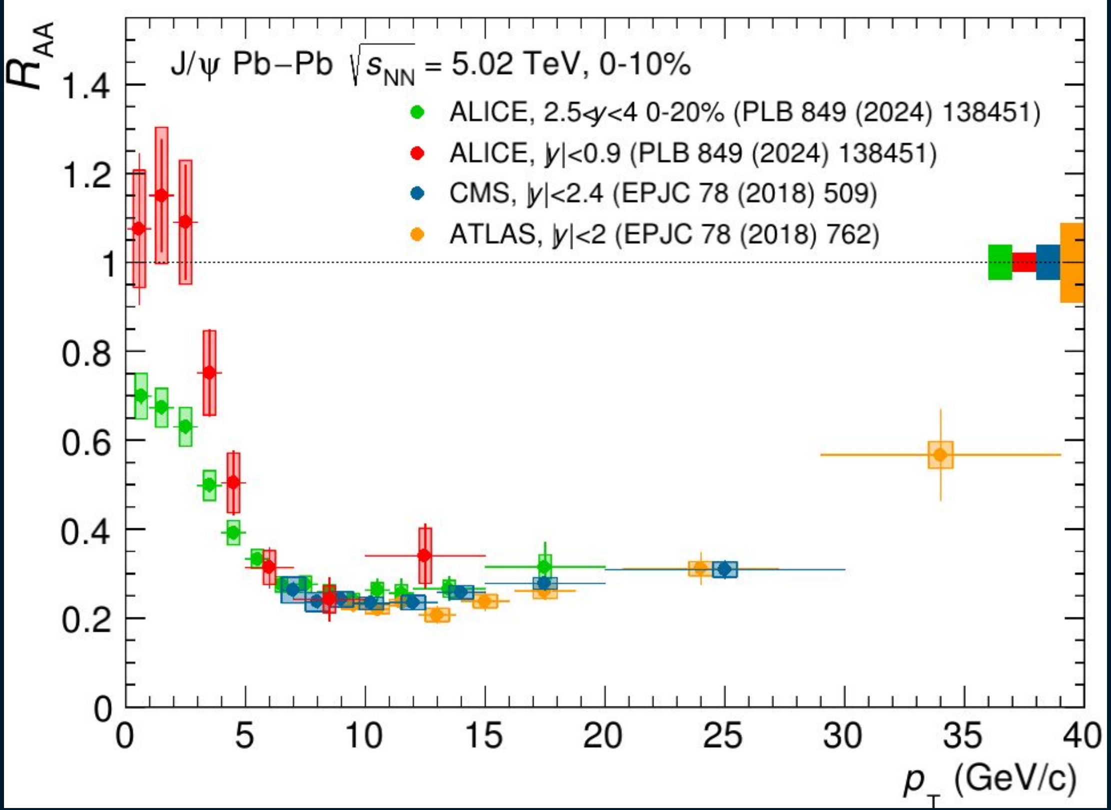
CMS, ATLAS, LHCb results are for prompt J/ψ, ψ(2S)



ALICE results are mainly for inclusive J/ψ (fraction of J/ψ from B is ~10% for p_T < 5 GeV/c and 30% for p_T ~ 10 GeV/c)

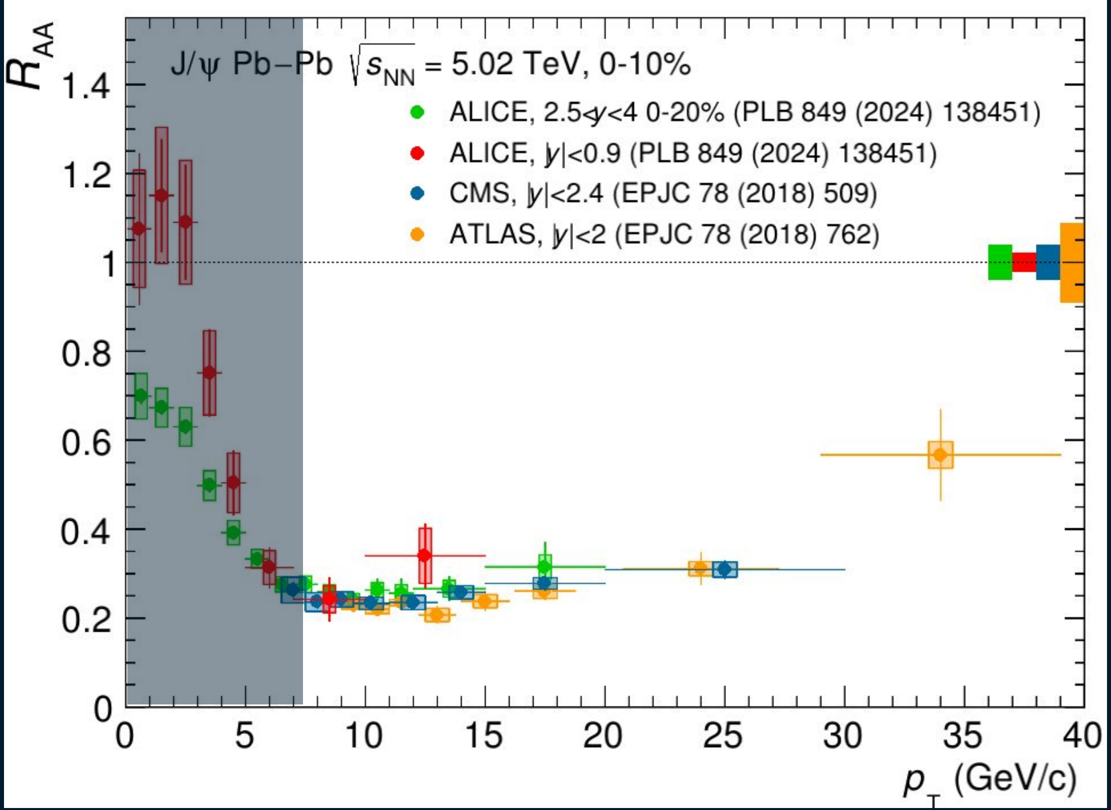


J/ψ R_{AA} vs p_T



low p_T → high p_T → very high p_T

J/ψ R_{AA} vs p_T

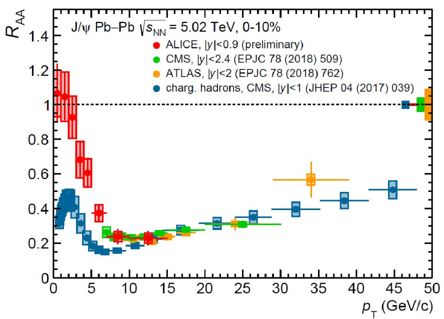


high p_T

- suppression is the dominant process
- similar R_{AA} independent on the rapidity range

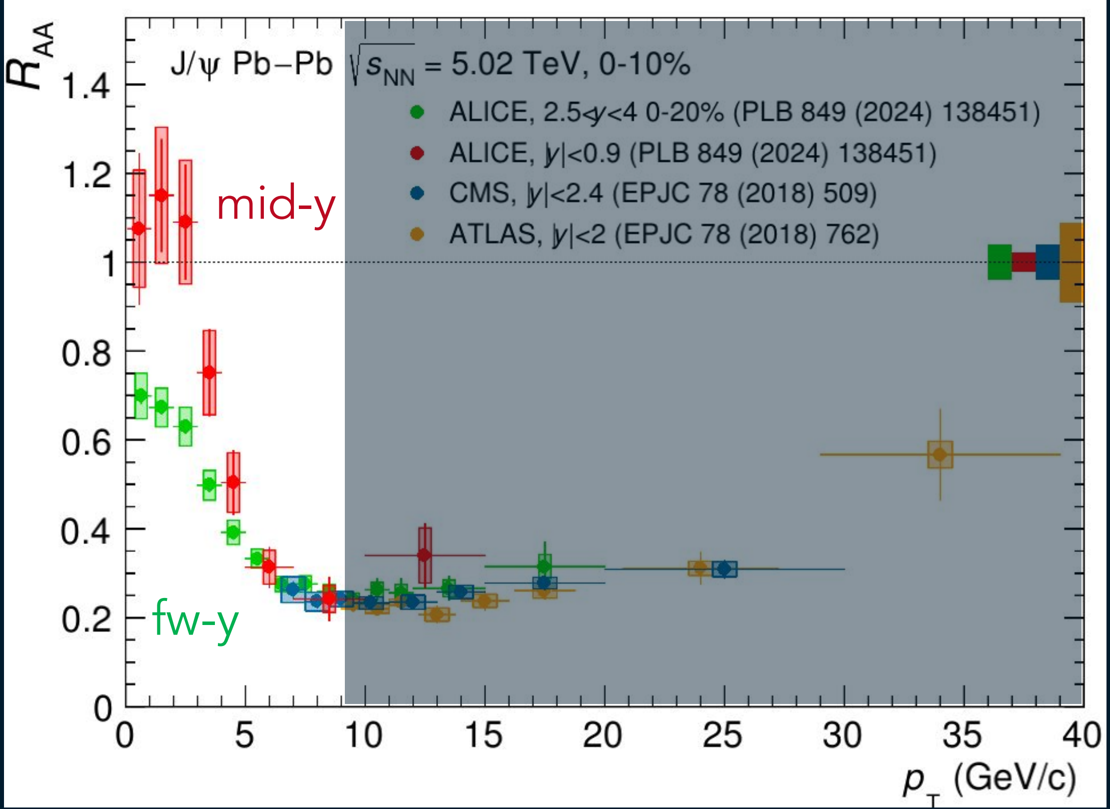
very high p_T

R_{AA} rise due to partonic energy loss as observed for hadrons?



high p_T ⟶ very high p_T

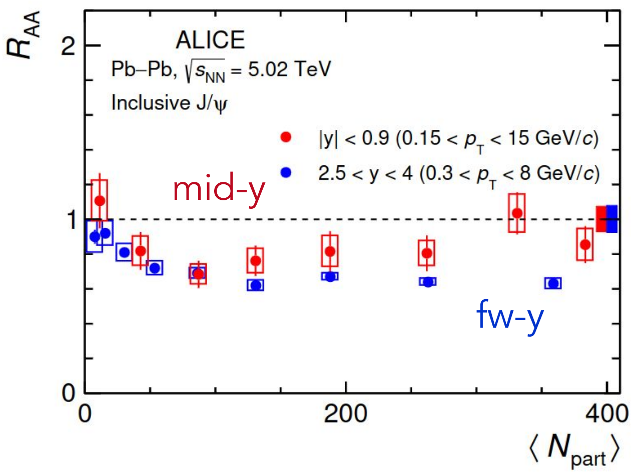
J/ψ R_{AA} vs p_T



low p_T

low p_T

the role of recombination depends on y, reflecting charm p_T and y distributions



ALICE, PLB 849 (2024) 138451

Higher R_{AA} at mid-y wrt fw-y, in central events, as expected from a larger charm quark multiplicity

Theory models

Transport

Macroscopic rate equation including suppression and regeneration in the QGP

Suppression

- computed from modification of charmonium spectral functions, constrained by LQCD validated potentials

Regeneration

- tuned from measured heavy quark yields

X. Du and R. Rapp, NPA 943(2015) 14P.7
P. Zhou et al., PRC89 (2014) 054911

Statistical hadronization

Charmonium yields determined at chemical freeze-out according to their statistical weights

Charm fugacity factor related to charm conservation and based on experimental data on production cross sections

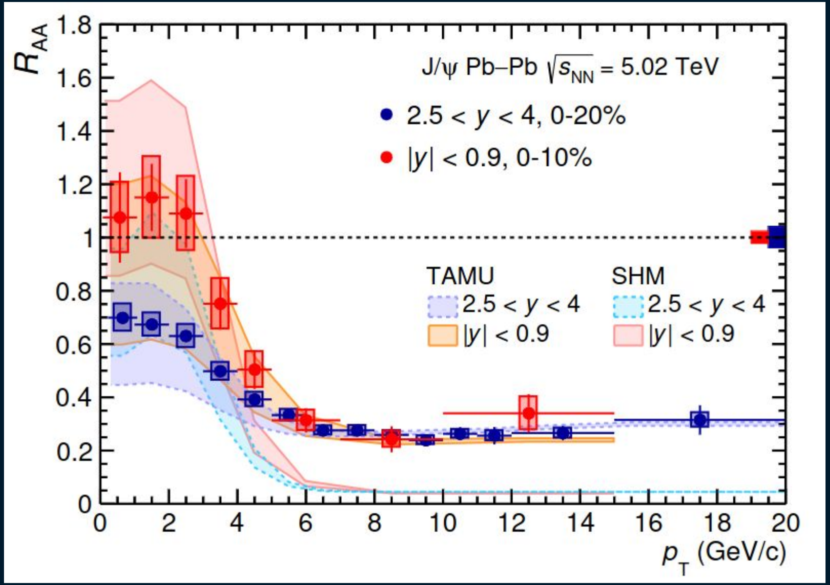
A. Andronic et al., Nature 561 (2018) 321
A. Andronic et al. arXiv:2308.14821 [

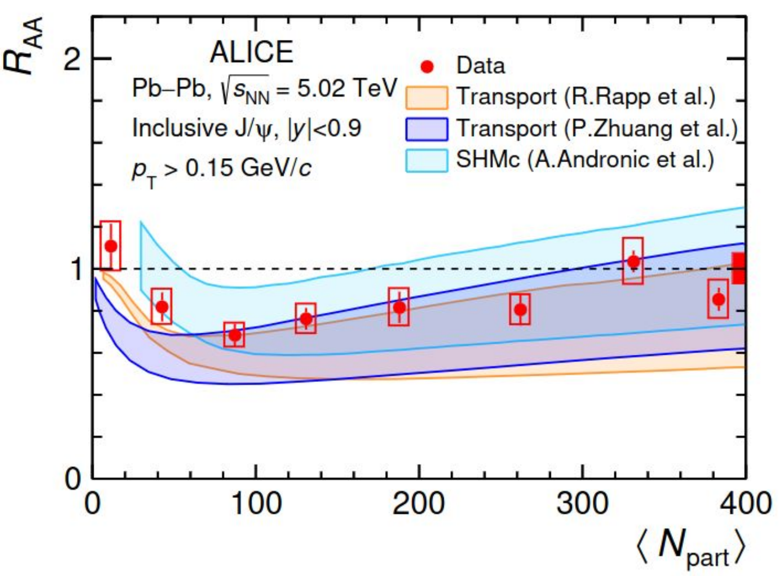
➡ both approaches fairly reproduce LHC experimental results on the J/ψ

Other approaches include “comover” models

E. Ferreiro, PLB 731 (2014) 57

J/ψ R_{AA} vs p_T: comparison to theory





Model uncertainties dominated by

- open charm cross section
- initial state effects (shadowing)

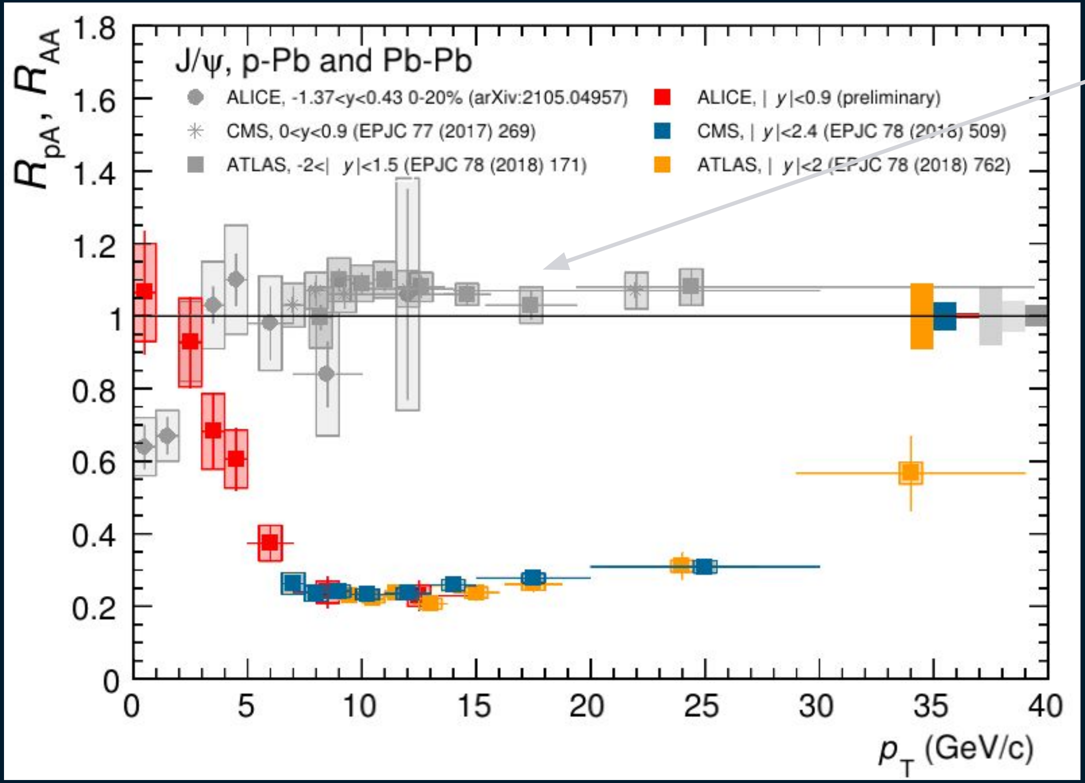
SHM: A. Andronic et al. PLB797 (2019) 134836
Transport: P. Zhuang et al. PRC 89 (2014) 054911
TAMU: R. Rapp et al. PLB664 (2008) 253

suppression+regeneration mechanisms describe the data

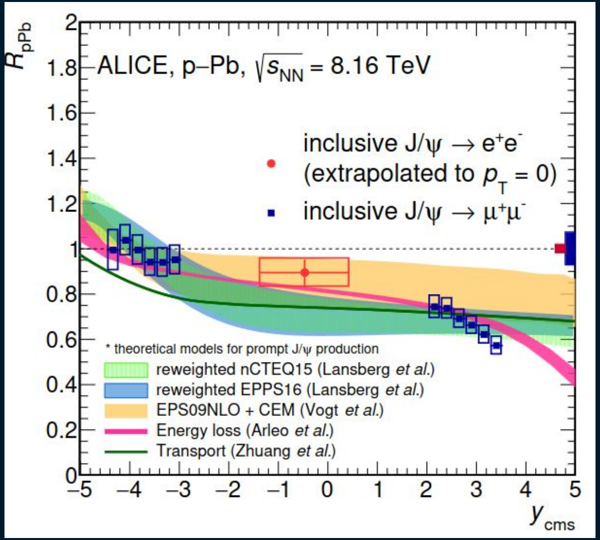
➡ regeneration dominates at low p_T

J/ψ in pA and AA

significant difference between J/ψ R_{pA} and R_{AA} over all the p_T range

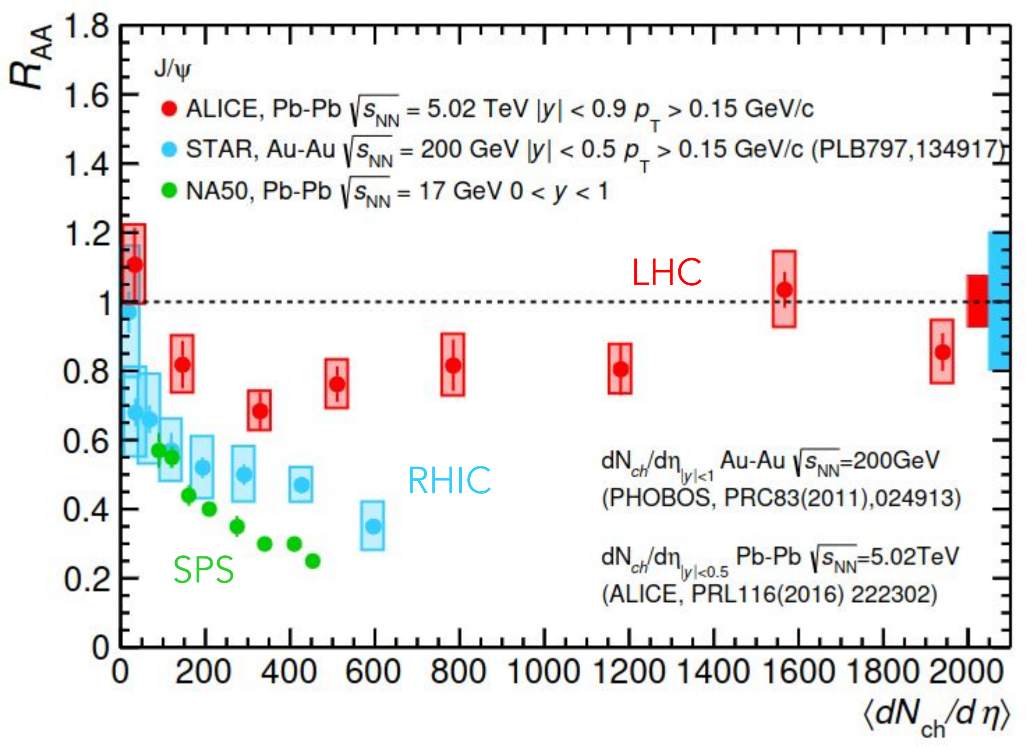


➡ CNM effects (i.e shadowing) not enough to explain the AA result



ALICE, JHEP 07 (2023) 137

J/ψ R_{AA} vs dN/dη



ALICE, arXiv:2211.04384

↑

charged hadron pseudorapidity density at mid-y ~ initial energy density

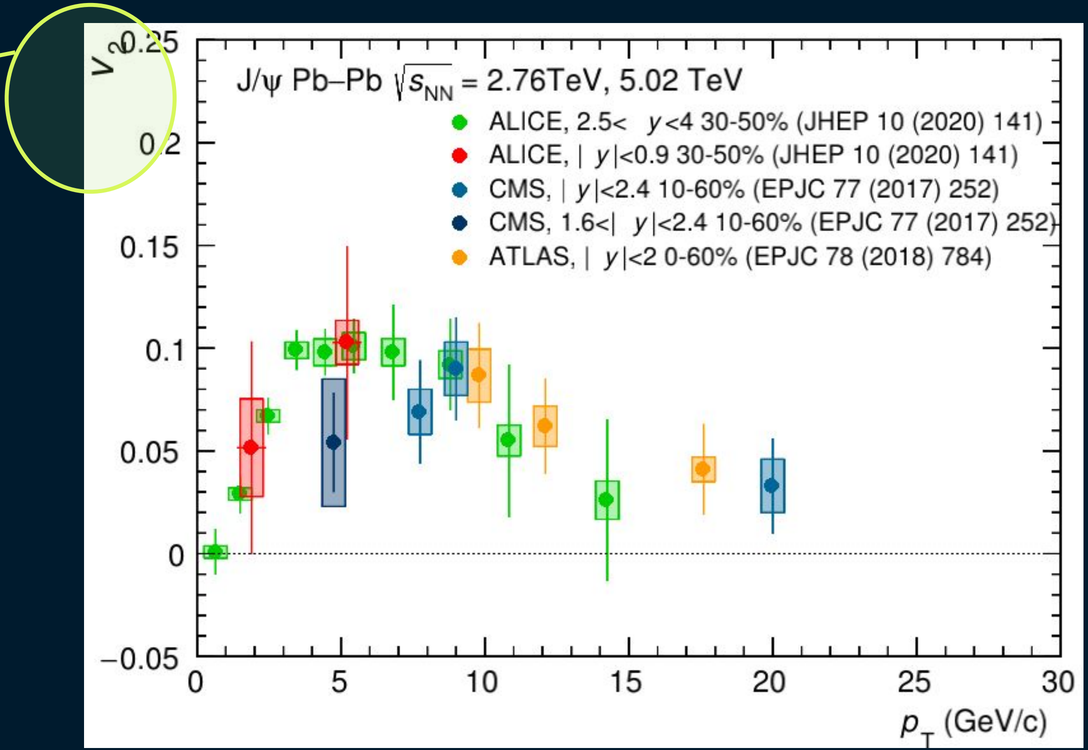
Strong decrease of J/ψ suppression when moving from low to high energy experiments

At LHC, disappearance of suppression effects when going towards central collisions

➡ strong indication of (re)generation effects in the charmonium sector

J/ψ flow

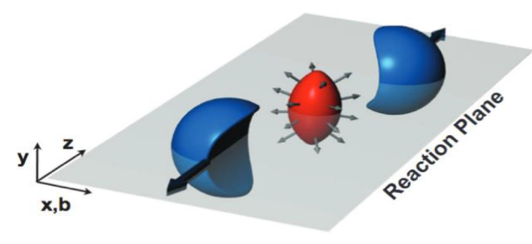
Azimuthal anisotropy v_2



Multiple interactions in the medium convert initial geometric anisotropy into particle momenta anisotropy

→ elliptic flow (v_2) is the 2nd coeff. of the Fourier expansion of the azimuthal distributions of the produced particles, wrt the event plane

$$v_2 = \langle \cos 2(\varphi_{particle} - \Psi_{EP}) \rangle$$



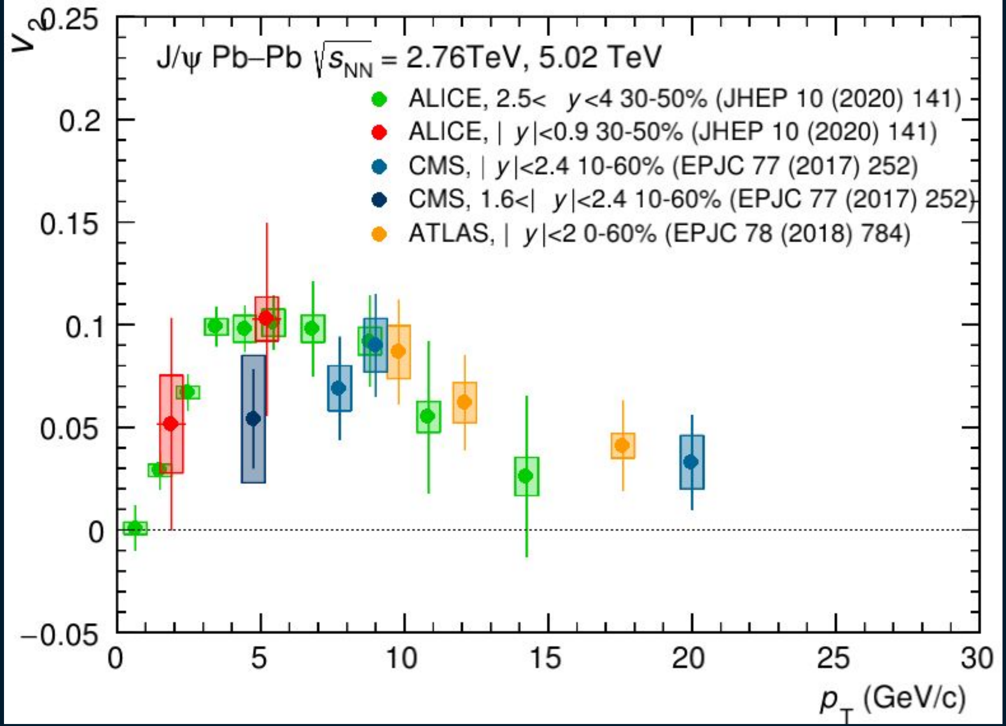
J/ψ flow

v_2 provides complementary information on J/ψ production

➡ J/ψ from recombination should inherit thermalized charm flow

low p_T:
evidence for non-zero flow
(ALICE, 7σ effect in $4<p_T<6$ GeV/c)

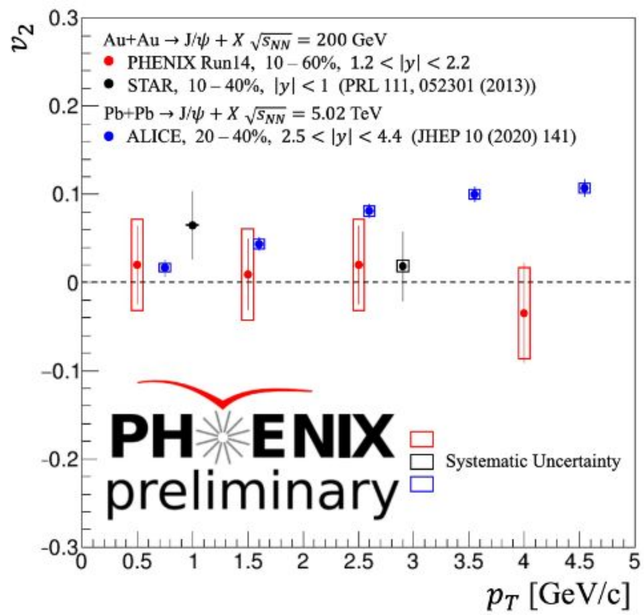
high p_T:
$v_2 \neq 0$ (ATLAS and CMS)

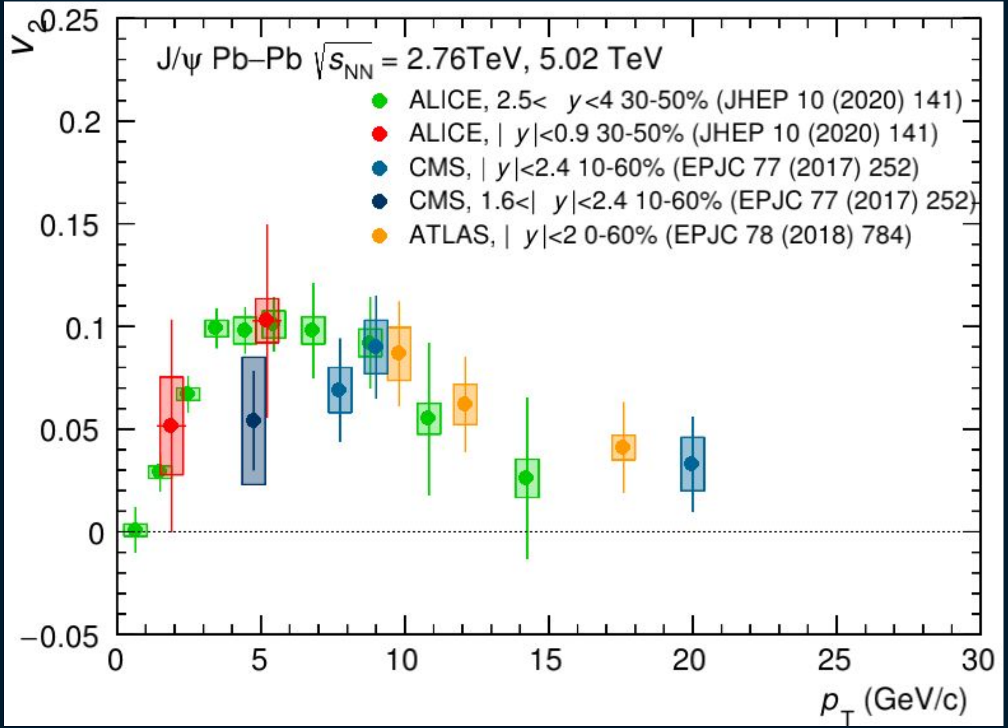


J/ψ v_2 measured up to p_T= 30 GeV/c

J/ψ flow

J/ψ v_2 at RHIC is compatible with 0



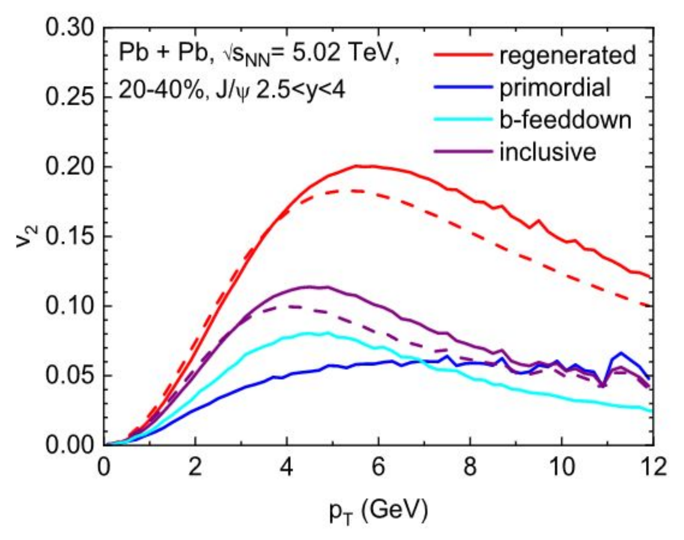


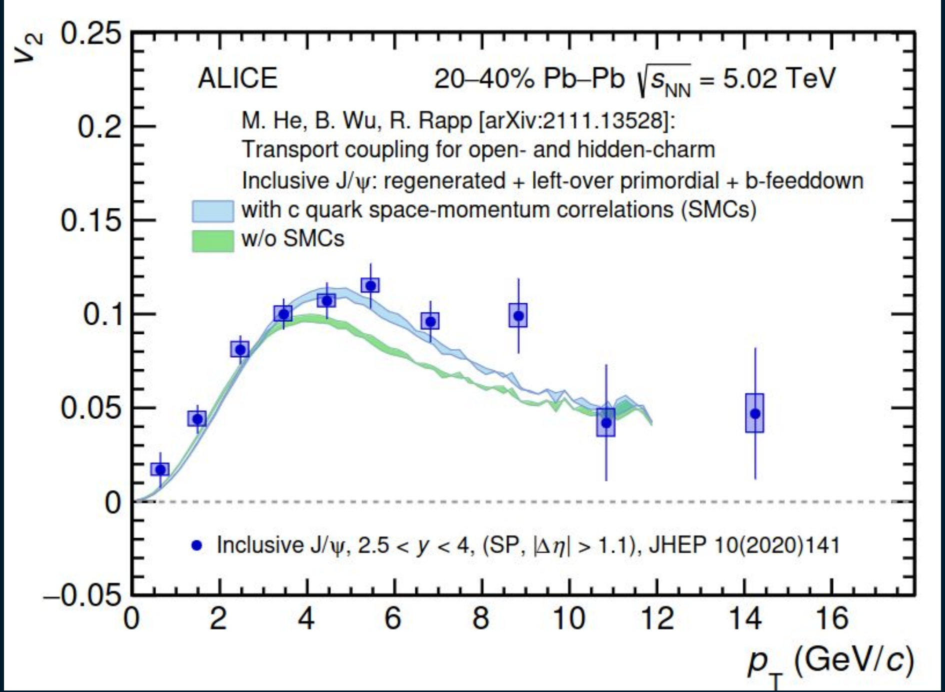
➡ consistent with increase of regeneration contribution from RHIC to LHC energies

J/ψ flow: models comparison

Transport model including (re)combination describe the data over the explored p_T range

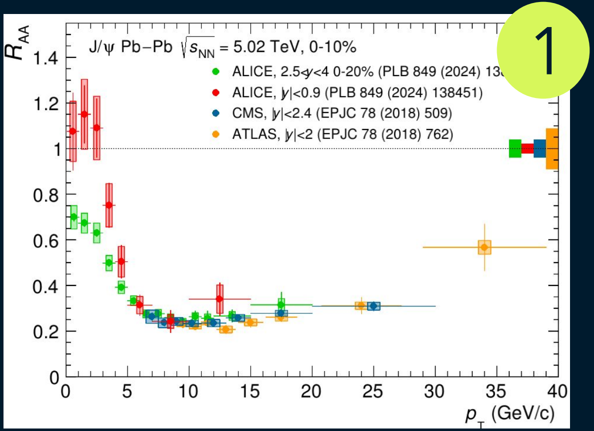
R. Rapp et al. PRL 128, 162301 (2022)



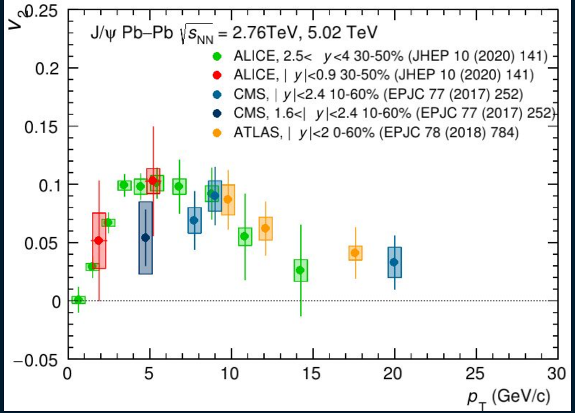


ALICE, arXiv:2211.04384

Quarkonium highlights at LHC



J/ψ R_{AA}



J/ψ v_2

➡ Suppression and recombination mechanisms are at play for J/ψ

➡ Do we observe the sequential suppression in the charmonium sector at LHC?

ψ(2S) vs. J/ψ


ψ(2S)
binding energy
~ 60 MeV

J/ψ
binding energy
~ 640 MeV

Study of ψ(2S) is more challenging wrt J/ψ due to:

✔ ~ 7.5 lower branching ratio to muon pairs

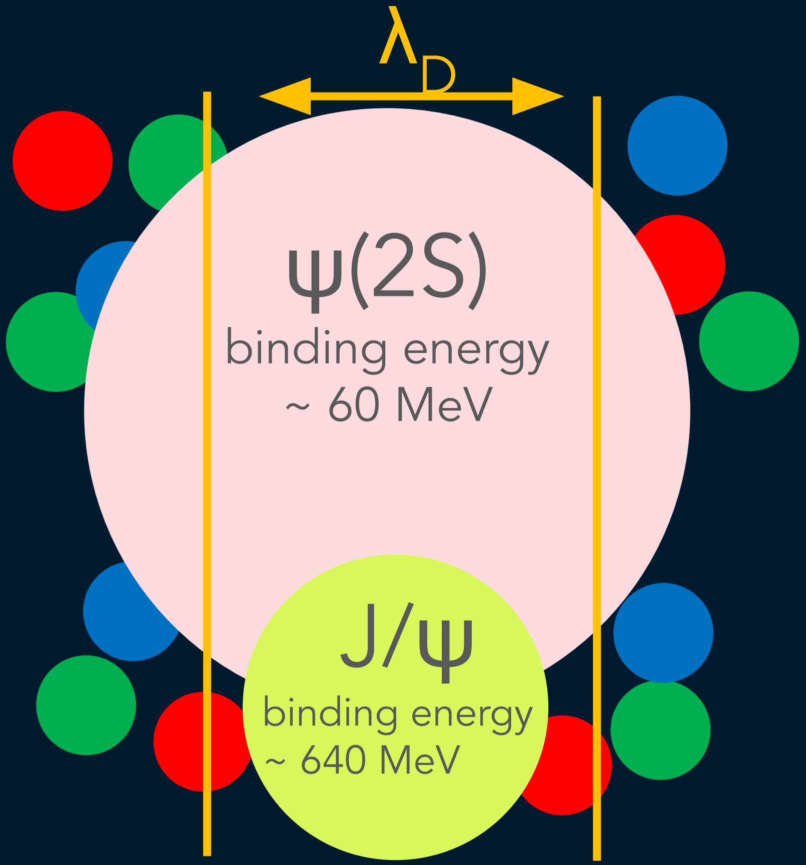
$$BR\ (\psi(2S) \rightarrow \mu^{+}\mu^{-}) = (0.80 \pm 0.06)\ \%$$
$$BR\ (J/\psi \rightarrow \mu^{+}\mu^{-}) = (5.96 \pm 0.03)\ \%$$

✔ ~ 6 times smaller production cross section in pp collisions at LHC energy

$$\sigma_{\psi(2S)} = 0.87 \pm 0.06 \pm 0.10\ \mu b$$
$$\sigma_{J/\psi} = 5.88 \pm 0.03 \pm 0.34\ \mu b$$

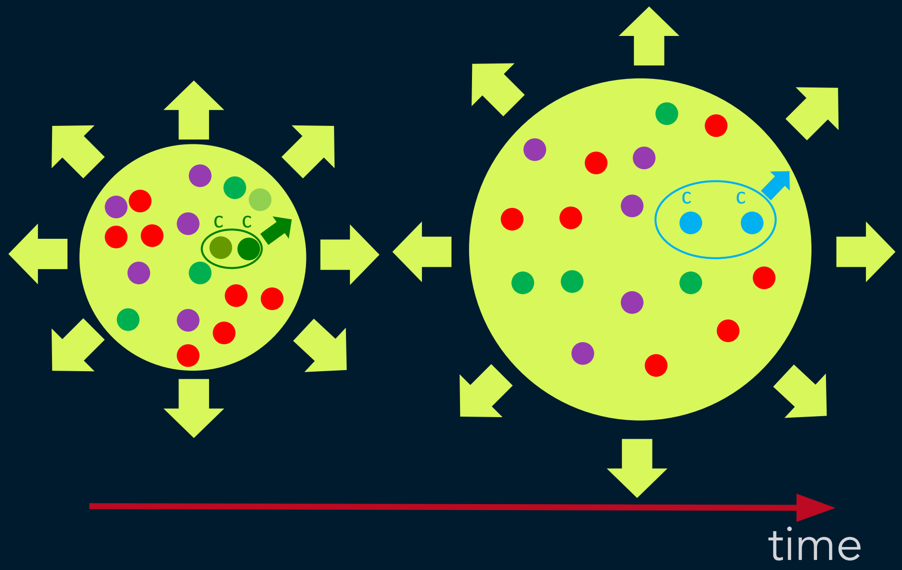
(pp, 5.02 TeV, $2.5<y<4$ ALICE, arXiv:2109.15240)

ψ(2S) vs. J/ψ



Expect much stronger dissociation effects for the weakly bound ψ(2S) state

ψ(2S) vs. J/ψ



➡ What is the impact of recombination on the ψ(2S)?

Larger size charmonium produced later in the evolution of the system

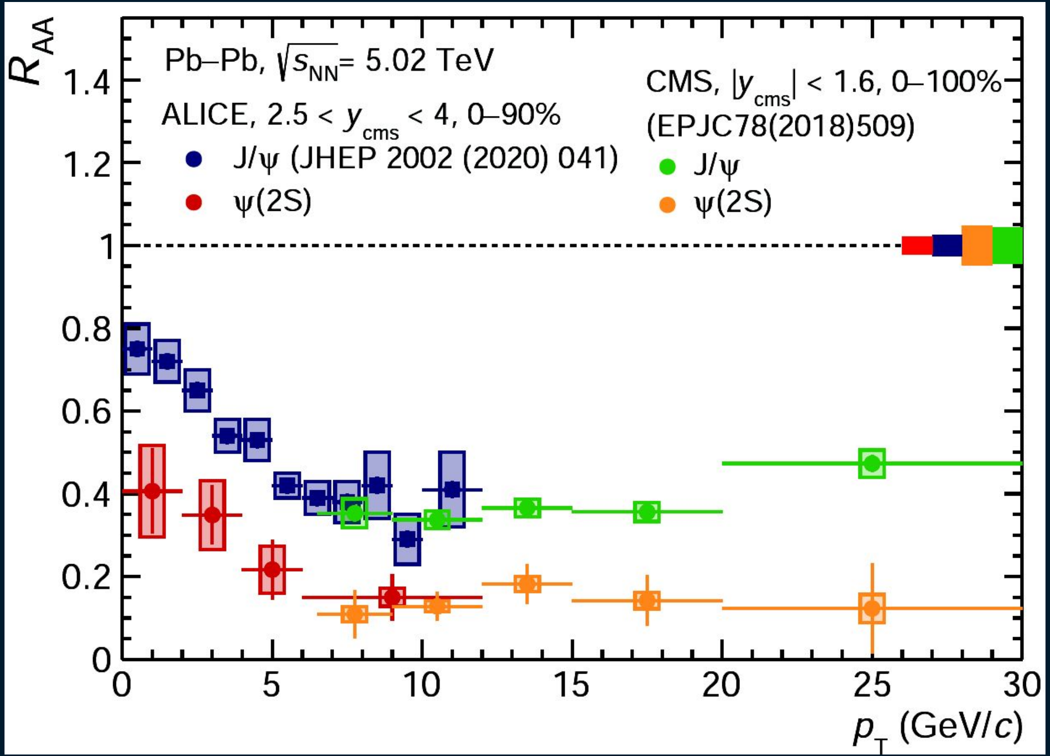
→ recombination at play also when the system is more diluted (even hadronic?)

➡ Comparison between J/ψ and ψ(2S) is an important test for models

ψ(2S) R_{AA}

2

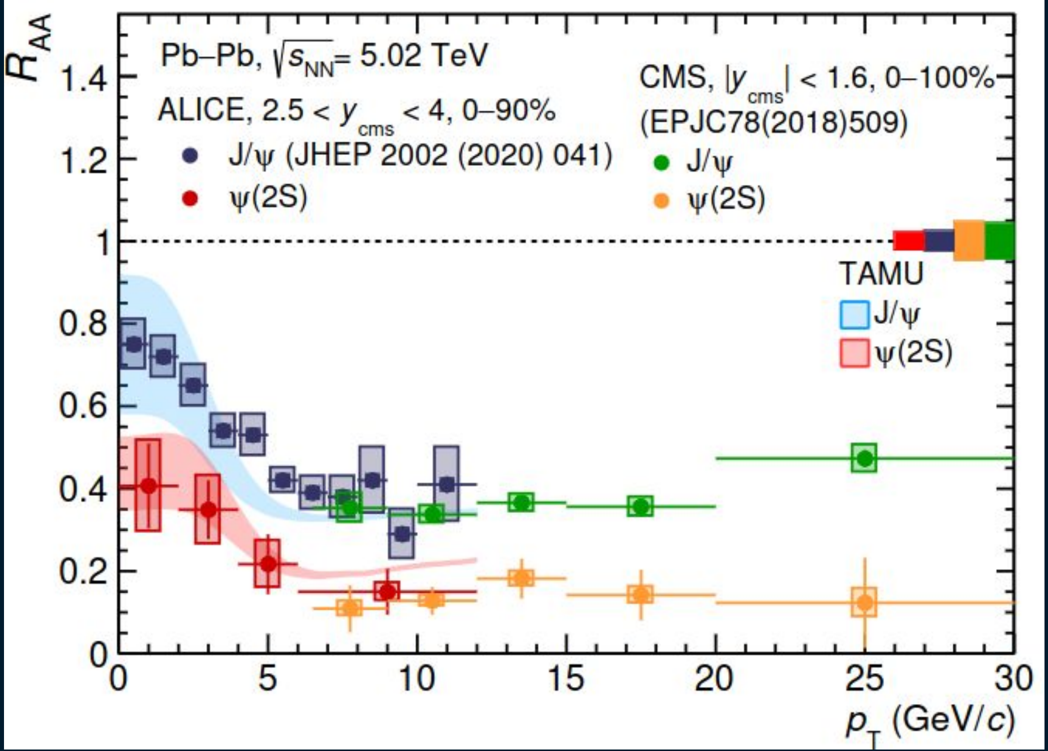
- ✔ Stronger suppression for ψ(2S) compared to J/ψ
  → hint for sequential suppression
- ✔ Increasing trend of R_{AA} at low-p_T for both charmonium states
  → hint of ψ(2S) regeneration
- ✔ Good agreement between CMS and ALICE data in the common p_T range, regardless of the different rapidity coverage

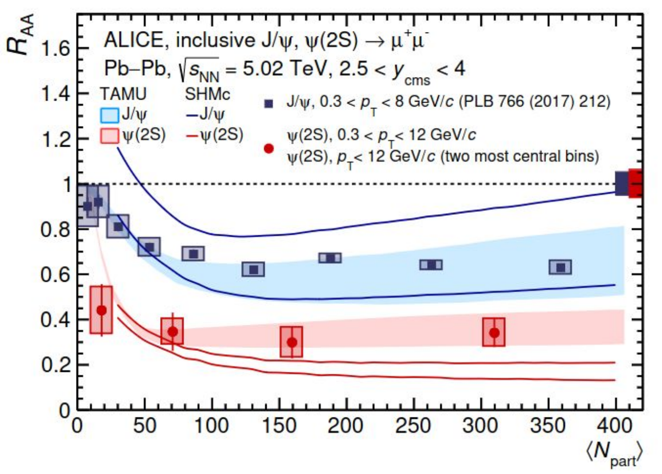


ALICE, PRL 132 (2024) 042301

$\psi(2S)$ R_{AA}: model comparison

- ✔ TAMU model reproduces the results for both J/ψ and $\psi(2S)$
- ✔ SHMc describes J/ψ data but slightly underestimate the $\psi(2S)$ result in central Pb–Pb collisions





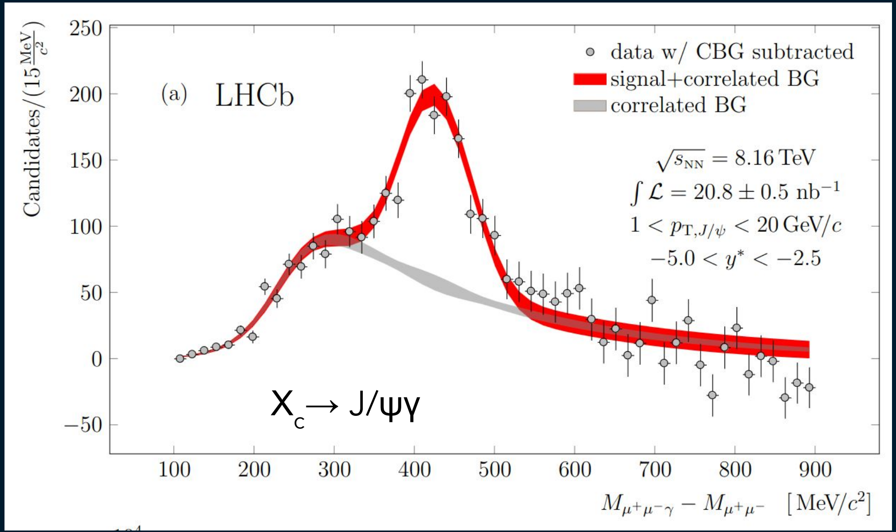
ALICE, PRL 132 (2024) 042301

TAMU: X. Du and R. Rapp, NPA 943 (2015) 147
SHMC: A.Andronic et al. PLB 797 (2019) 134836,
A.Andronic et al. Nature 561 (2018) 321–330

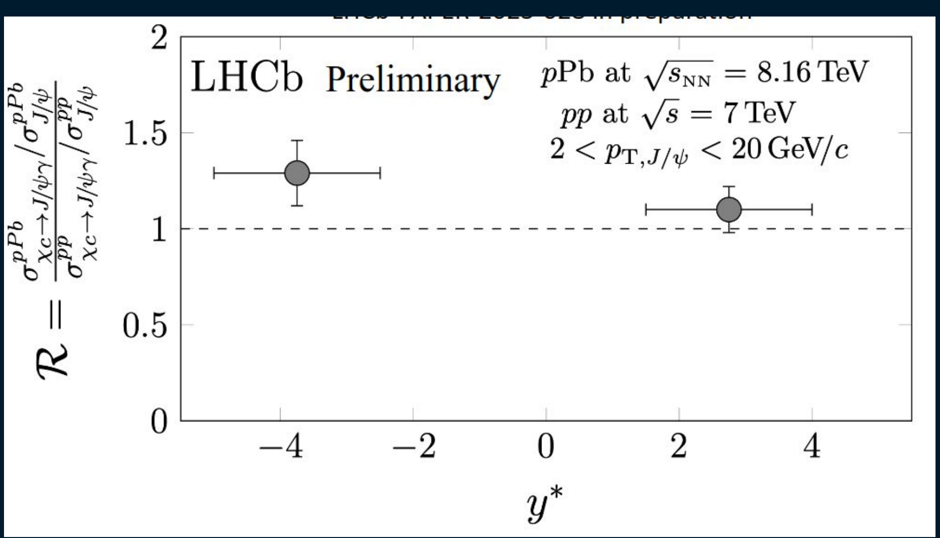
What about χc states?

So far, first χ_c measurements only in pA collisions

$\chi_{c1} + \chi_{c2}$ measured in the J/ψ γ decay channel

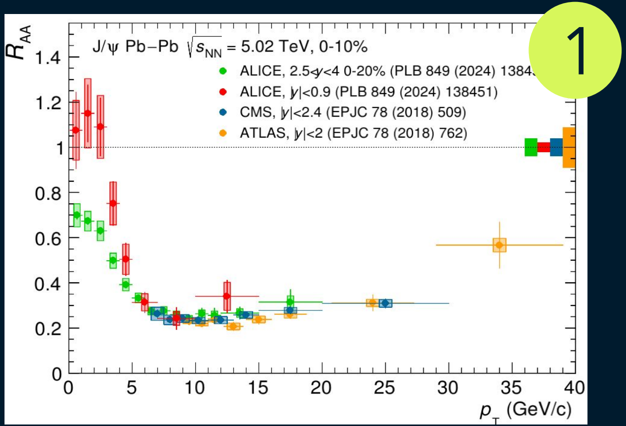


LHCb, PRL 132 (2024) 102302



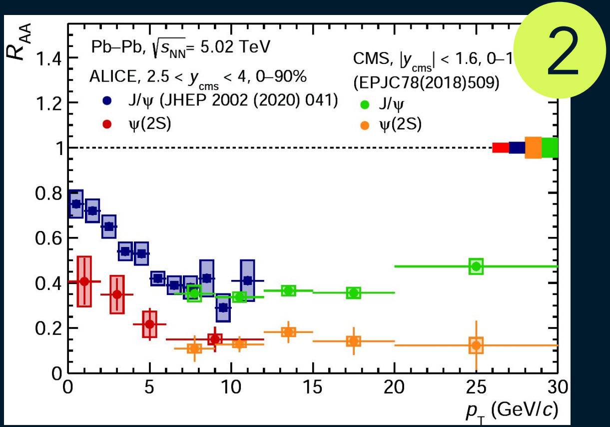
- Double ratio to J/ψ close to unity → no significant final state effects on χ_c in pA, in spite of the weaker binding energy

Quarkonium highlights at LHC



J/ψ R_{AA} and v_2

suppression and recombination mechanisms at play for J/ψ



ψ(2S) R_{AA}

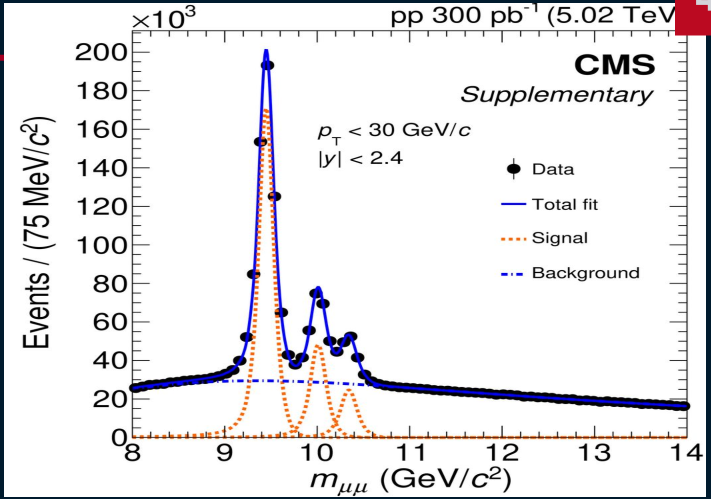
sequential suppression (and recombination) in the charmonium sector

do we observe the sequential suppression also for bottomonium?

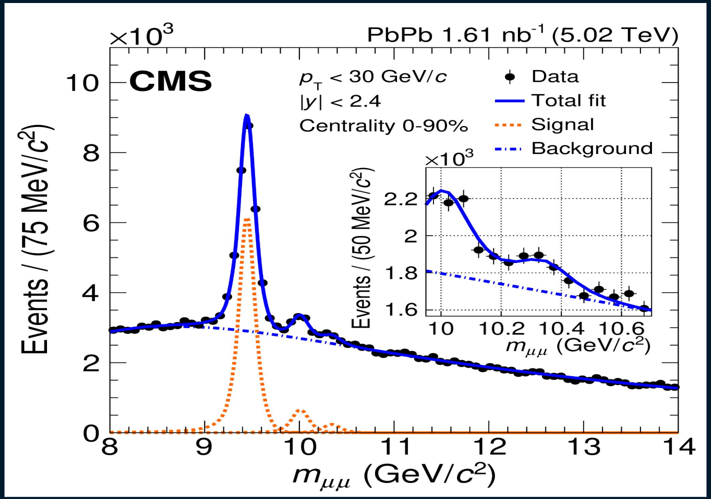
Υ(nS)

- three Υ states with different sensitivity to the medium
- small, but not negligible, BR into dileptons (~2%)

pp



PbPb

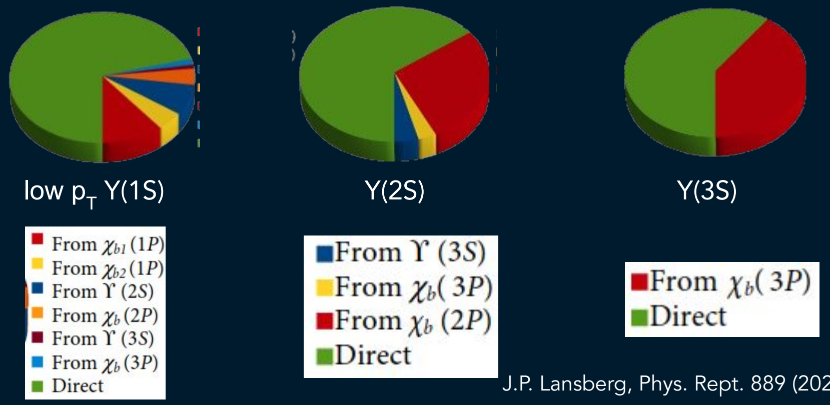


CMS, arXiv:2303.17026

Y(nS)

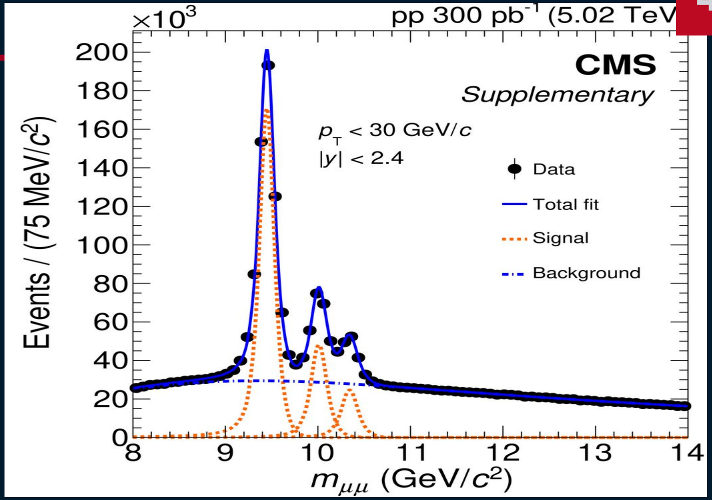
- limited recombination and no B feed down, but large feed down from excited states
  → important for results interpretation

Υ(1S) feed-down

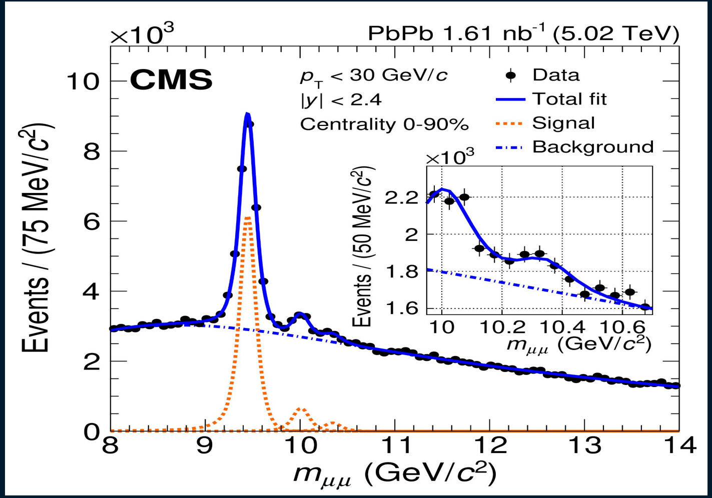


J.P. Lansberg, Phys. Rept. 889 (2020) 1

pp



PbPb



CMS, arXiv:2303.17026

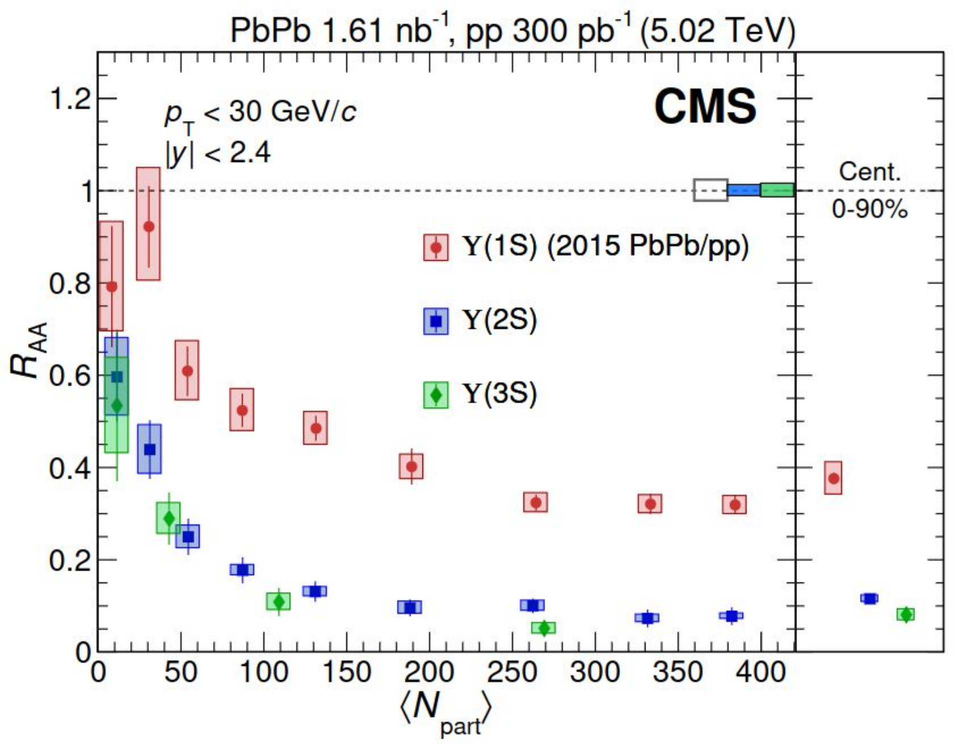
Y(nS) R_{AA} vs centrality

3

- Clear ordering in the sequential suppression of bottomonium

R_{AA} Y(1S) > R_{AA} Y(2S) > R_{AA} Y(3S)

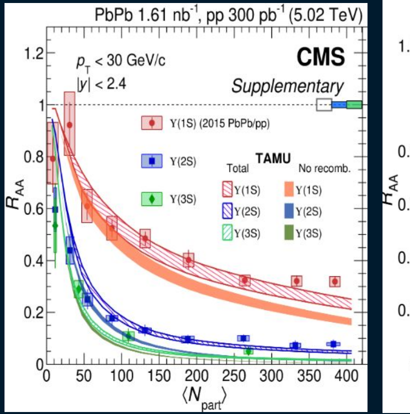
(and first measurement of the Y(3S) in PbPb)



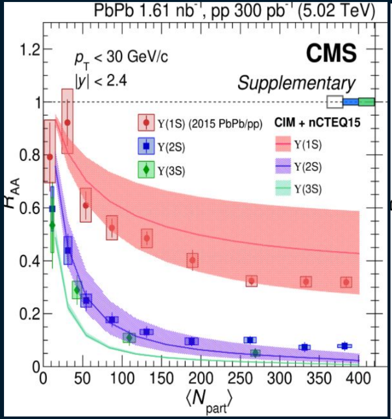
CMS, arXiv:2303.17026

strong centrality suppression for all Y(nS) (factor ~2.5 for Y(1S), ~10 for Y(2S), ~12 for Y(3S)

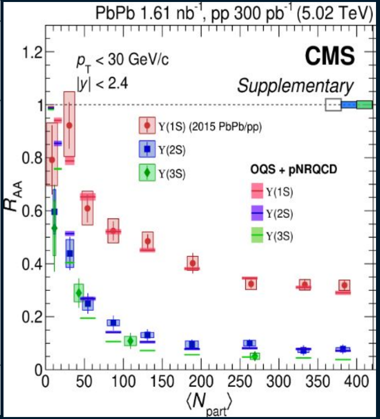
Υ(nS) R_{AA}: model comparison



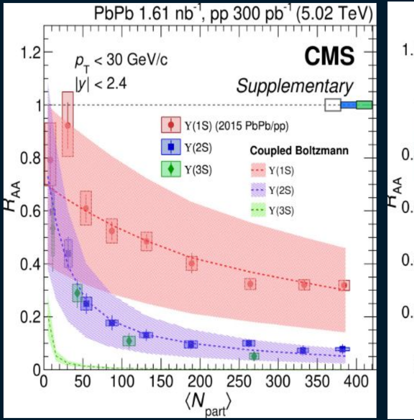
TAMU, PRC 96 (2017) 054901



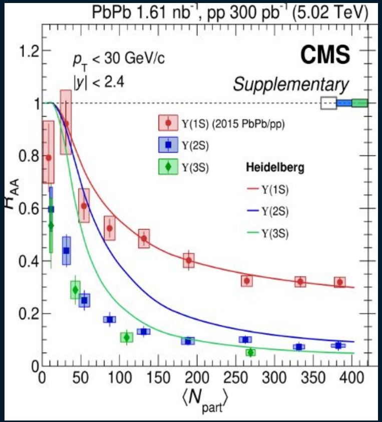
Comovers, JHEP 10 (2018) 094



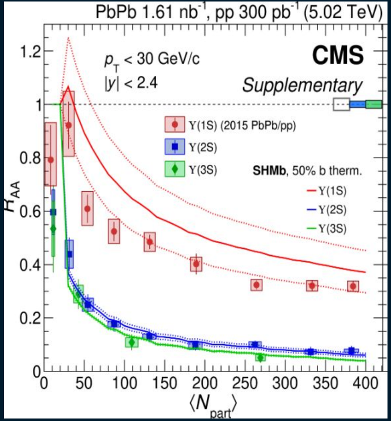
OQS+pNRQCD, PRD 108 (2023) 011502



Coupled Boltzmann,
JHEP01(2021)046



Heidelberg,
IJMPA 35, 2030016 (2020)



SHMb, arXiv:2209.14562v1

➡ Large variety of models

Several approaches can semi-quantitatively reproduce the experimental observations (also the p_T dependence)!

➡ Look more in details into the excited states

Y(nS) R_{AA}: model comparison

TAMU

- kinetic rate equation approach
- includes regeneration, in-medium binding energies, lattice QCD based EOS for fireball evolution

Heidelberg

- screening and gluon dissociation

SHMb

- statistical hadronization of b-quarks
- partial thermalization of b-quarks → arbitrary suppression of beauty pairs at phase boundary
- a thermalization fraction of ~50% of b-quarks explains the bottomonium data at the LHC

OQS + pNRQCD

- open quantum system framework, potential NRQCD approach
- includes quantum regeneration

Comovers

- includes shadowing and break-up from interactions with comoving particles

Coupled Boltzmann

- open quantum system framework, coupled transport equations and EPPS16 nPDF
- includes both correlated and uncorrelated recombination

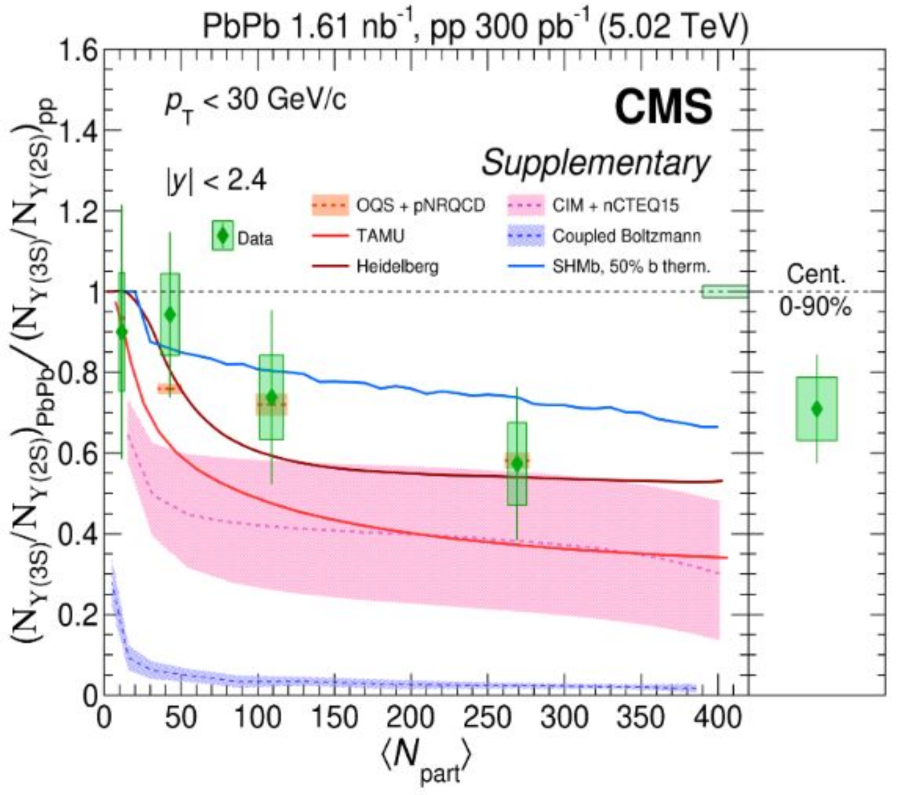
[P. Pujahari, SQM2024]

Double ratio

$$\frac{[\Upsilon(3S)/\Upsilon(2S)]_{\mathrm{PbPb}}}{[\Upsilon(3S)/\Upsilon(2S)]_{\mathrm{pp}}}$$

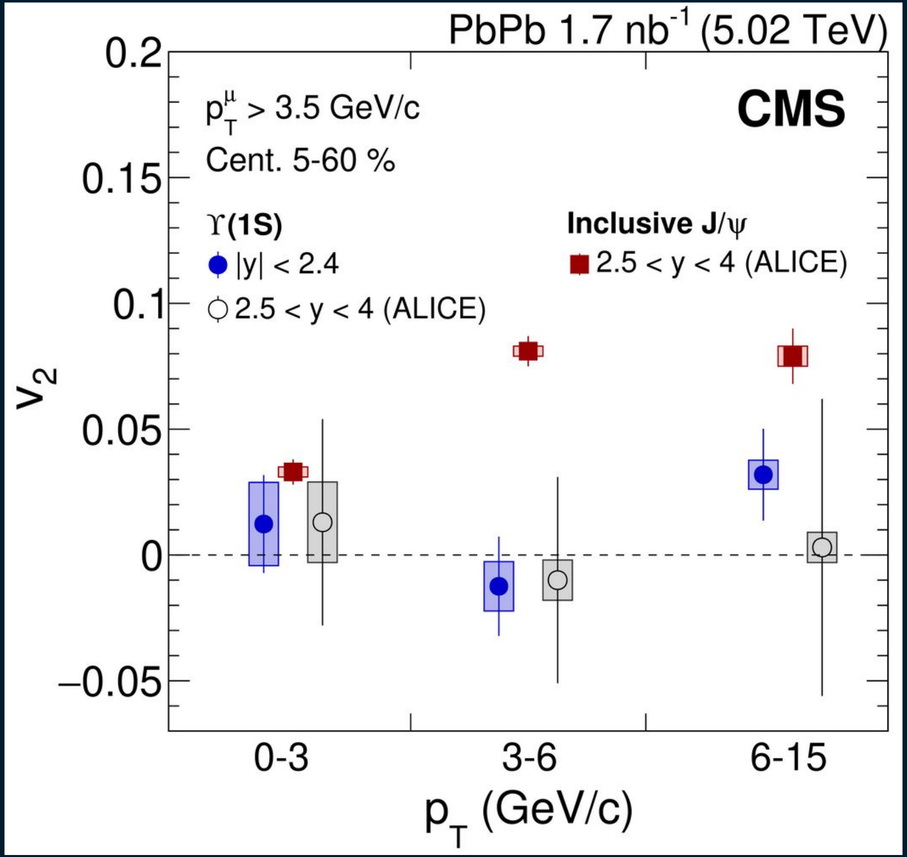
- stronger suppression for Υ(3S) compared to Υ(2S) for more central collisions

- significant differences among models → these data can put constraints on models, in spite of large uncertainties



CMS, arXiv:2303.17026

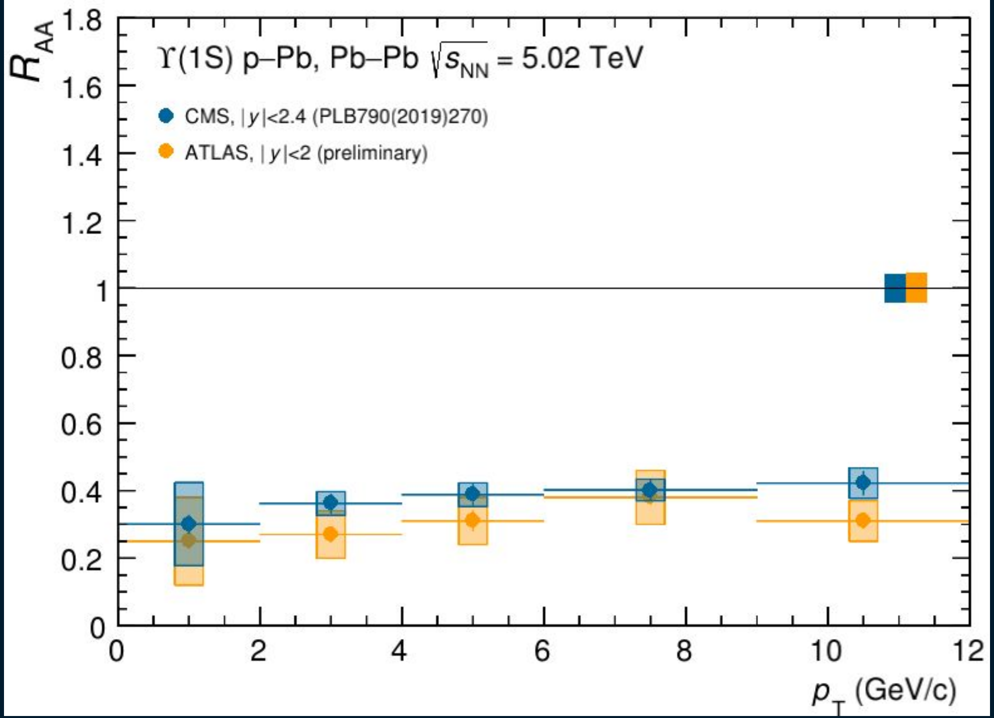
Y(1S) flow



- Y(1S) v_2 closer to 0, even if with large uncertainties in the Y(1S) v_2

suggests smaller recombination role

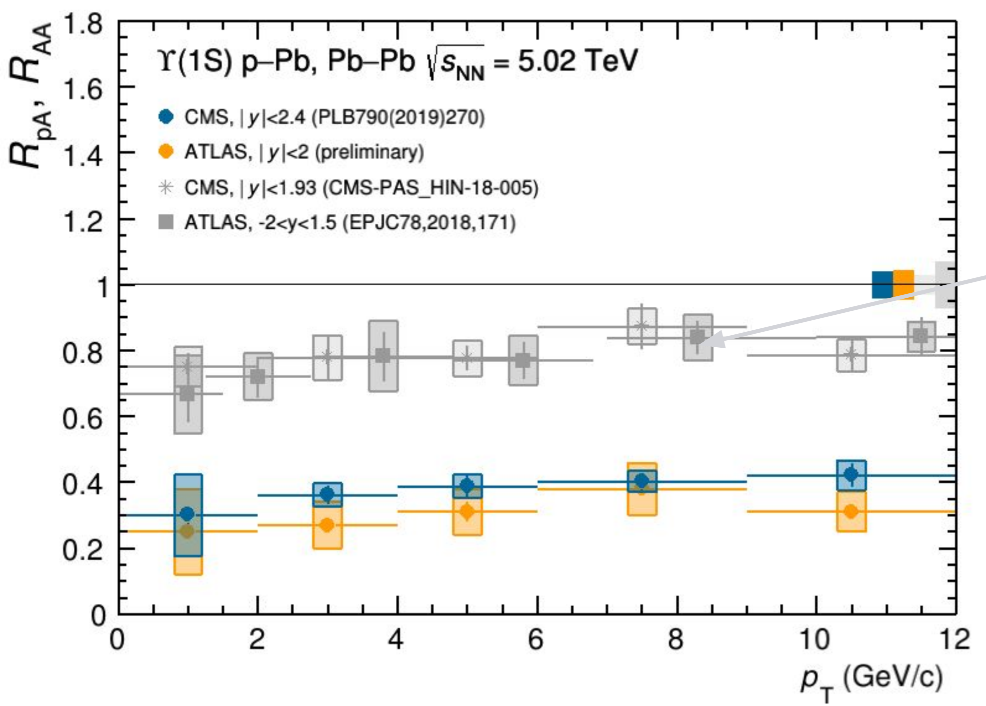
Υ(1S) in pA and AA



Υ(1S) is clearly suppressed in PbPb collisions

Is this strong suppression compatible with the Υ(1S) very large binding energy (~1.1 GeV)?

Y(1S) in pA and AA



ϒ(1S) is clearly suppressed in PbPb collisions

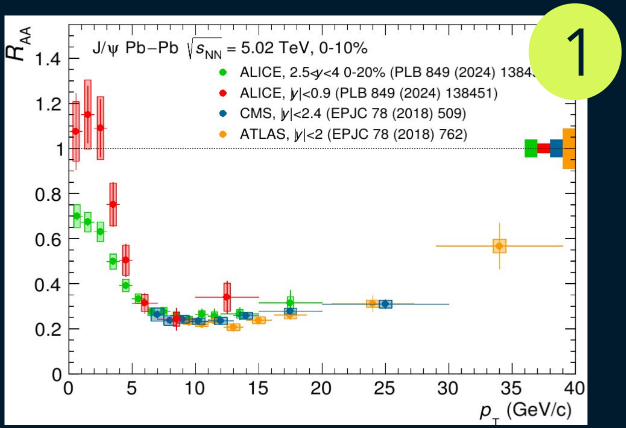
- CNM are not negligible, even if Y(1S) R_{PA} is higher than R_{AA} over the whole p_T range
- 30% of the Y(1S) comes from feed down

⬇

understanding of direct Y(1S) suppression requires a very precise assessment of

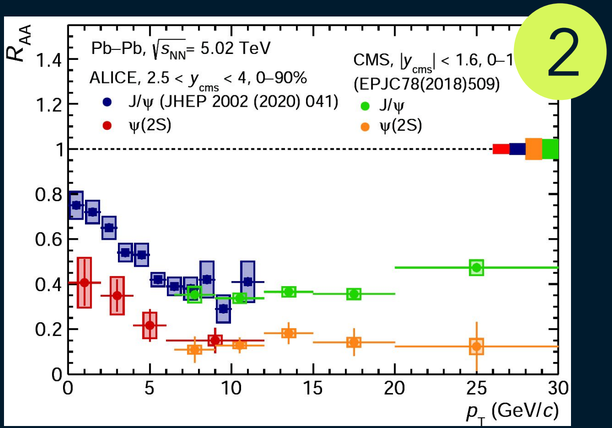
- size of CNM effects
- feed-down from S and P states

Quarkonium highlights at LHC



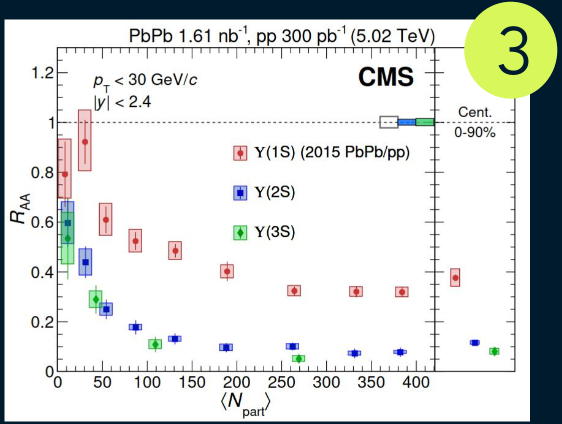
$J/\psi\ R_{AA}$ and v_2

suppression and recombination mechanisms at play for J/ψ



ψ(2S) R_{AA}

sequential suppression (and recombination) in the charmonium sector



Υ(nS) R_{AA}

sequential suppression also observed for bottomonium

More exotic states: X(3872)

- ✔ First observed in 2003 by BELLE
- ✔ Quantum numbers: $J^{PC} = 1^{++}$
- ✔ Nature of this state not yet understood:

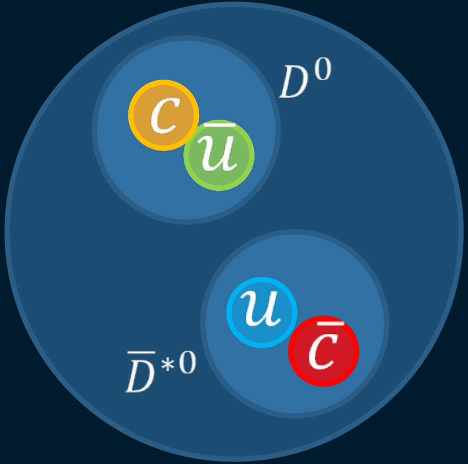
charmonium

wrong mass predicted with $J^{PC} = 1^{++}$

tetraquark

r~0.3fm

D^0–$\bar{D}^{*0}$ MOLECULE



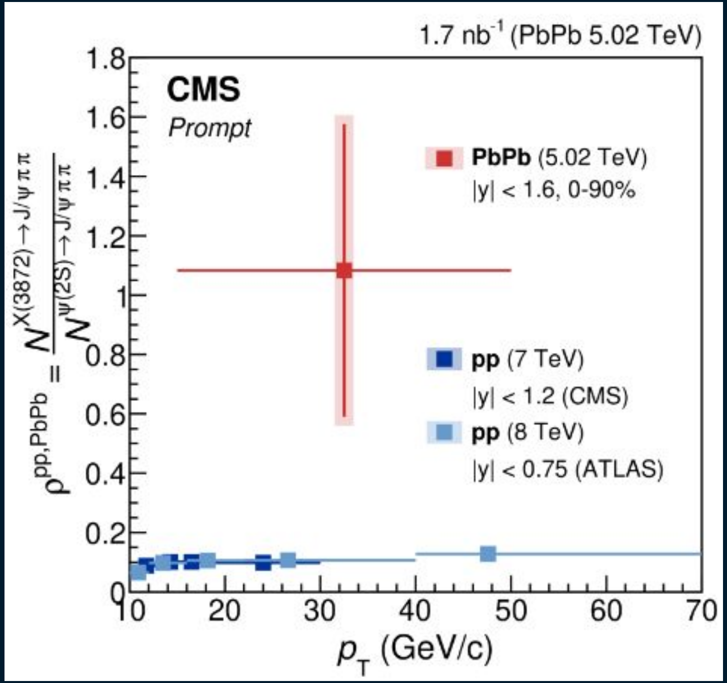
r>5 fm, small binding energy

(Yen-Jie Lee, QM2019)

➡ Can its production in heavy ions provide insight on the X(3872) inner structure?

More exotic states: X(3872)

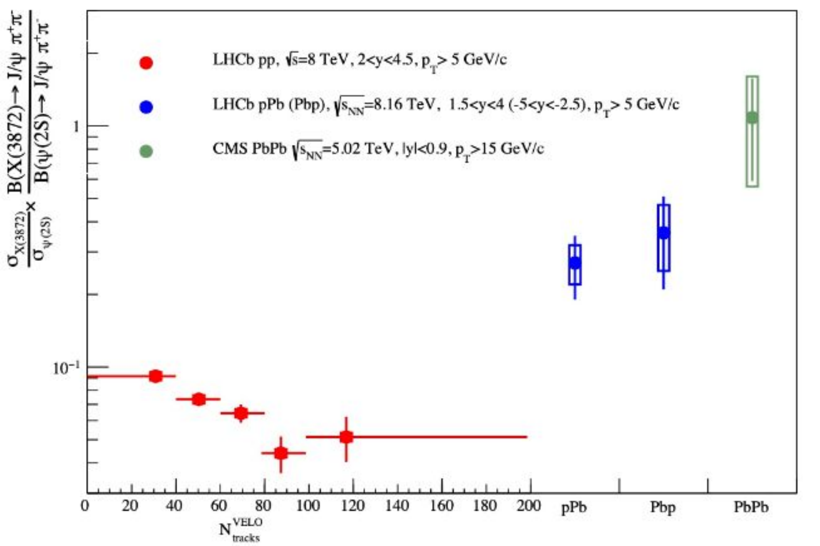
Screening and recombination mechanisms can affect also the X(3872)



CMS, PRL 128 (2022) 3, 032001

Hint of prompt X(3872) to ψ(2S) enhancement in Pb-Pb, at very high p_T ($15<p_T<50$ GeV/c)

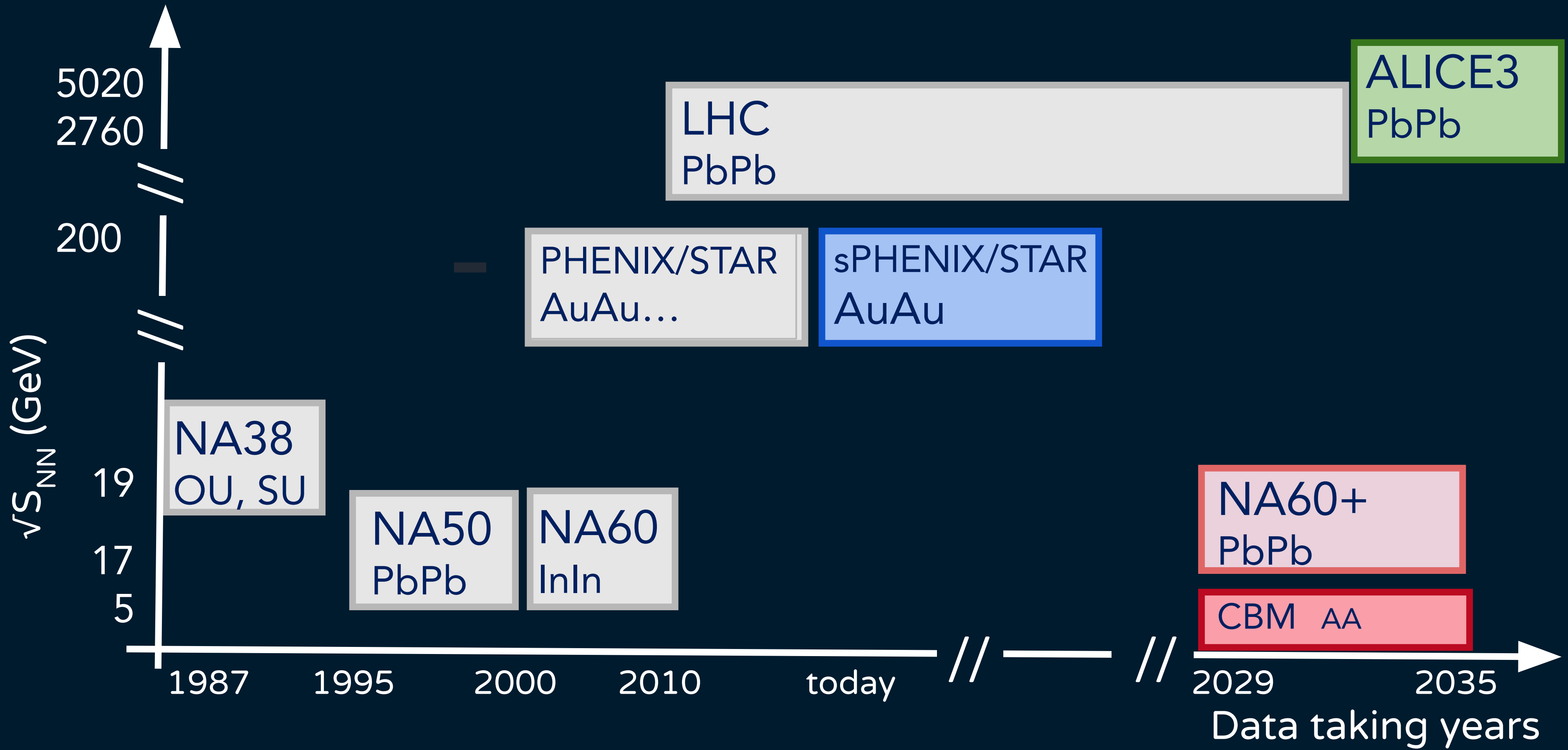
➡ extension to low p_T is crucial!



E. Scomparin, QM2023

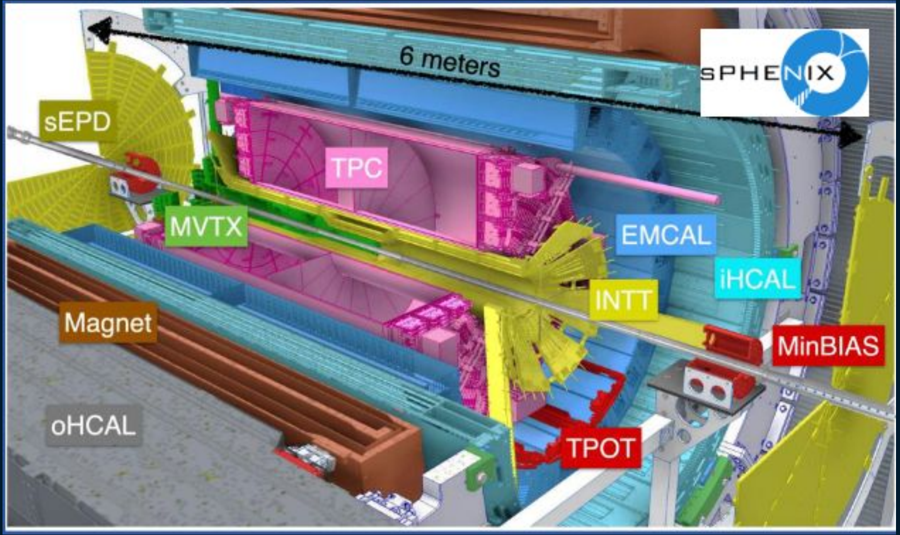
➡ A coherent description from pp to AA is also needed!

What's next?


5020
2760
200
19
17
5
√S_{NN} (GeV)
LHC
PbPb
ALICE3
PbPb
PHENIX/STAR
AuAu…
sPHENIX/STAR
AuAu
NA38
OU, SU
NA50
PbPb
NA60
InIn
NA60+
PbPb
CBM AA
1987
1995
2000
2010
today
2029
2035
Data taking years

sPHENIX @ RHIC

➡ The first "new" heavy-ion experiment since more than a decade



Now taking data at RHIC!

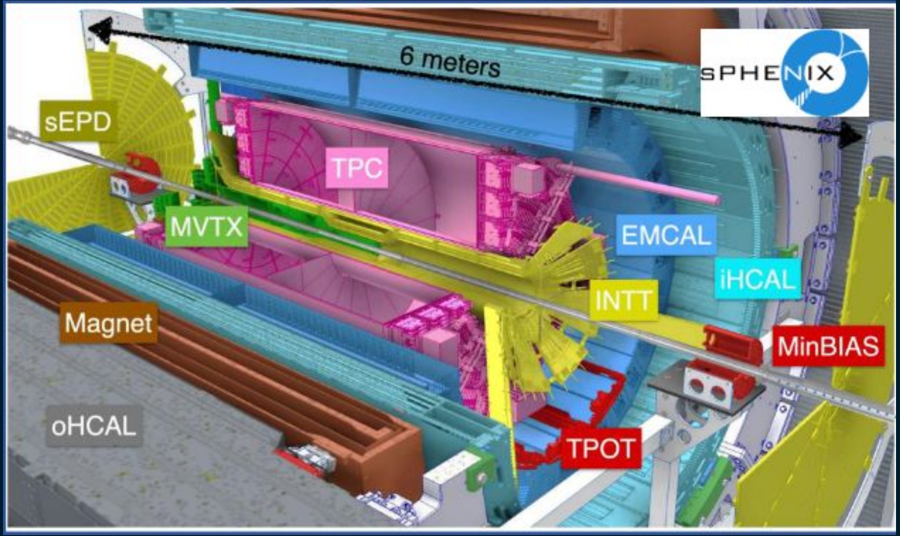
Run24: transversely polarized pp and short AuAu run → finish commissioning, pp program

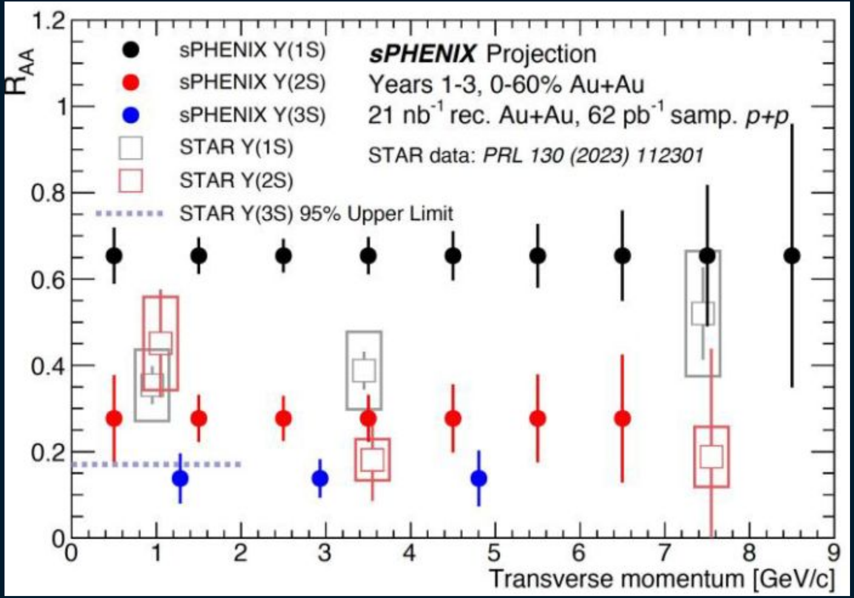
Run25: high-lumi AuAu run → heavy flavour measurements

sPHENIX @ RHIC

➡ The first “new” heavy-ion experiment since more than a decade

Now taking data at RHIC!





Aims to bottomonium precision measurements

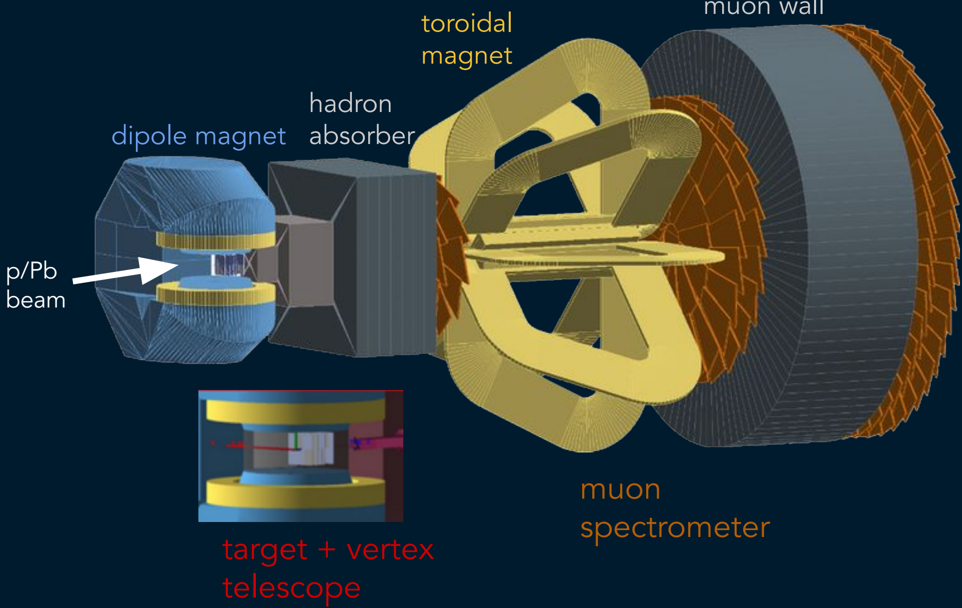
- clear distinction of the three ϒ states
- kinematic range will allow comparison with LHC

NA60+ @ SPS

➡ New fixed-target experiment proposed at CERN SPS

Aims to explore the QCD phase diagram at high baryon chemical potential

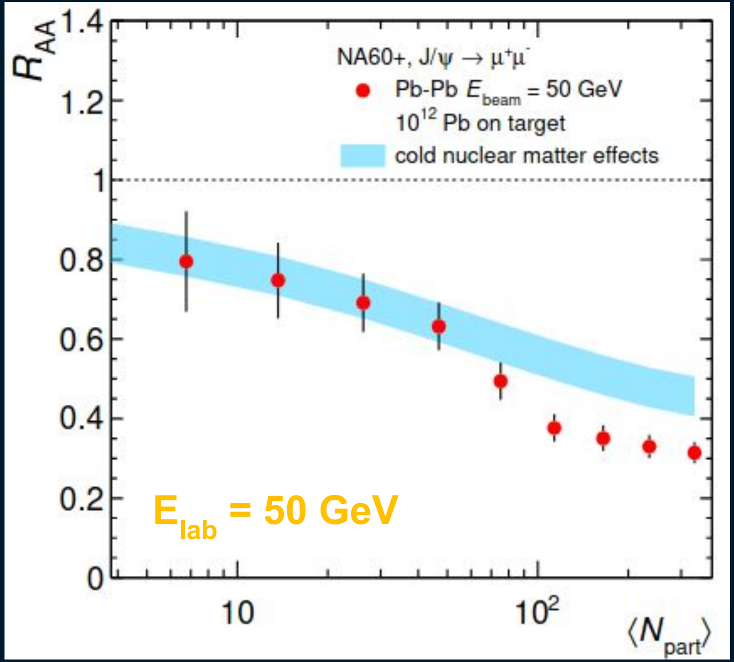
- beam energy scan between $\sqrt{s_{NN}}$ ~ 6 - 17 GeV, exploring the μ_B range ~220 - 550 MeV
- high luminosities (PbPb interactions rates > 10^5 Hz, reachable with 10^6 Pb/s in a fixed target environment)
- aims to data taking in 2029, after LS3

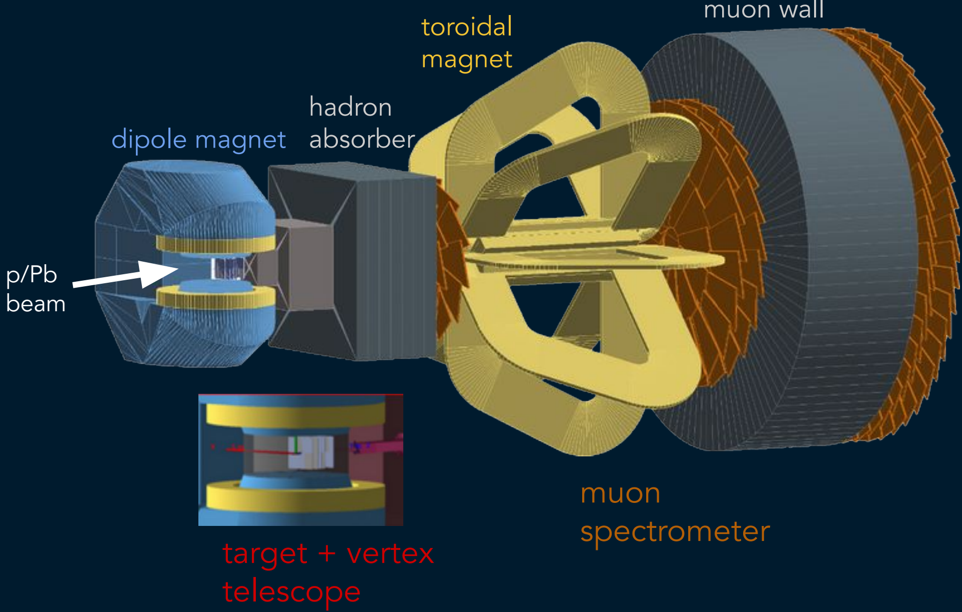


LOI: arXiv:2212.14452

NA60+ @ SPS

- New fixed-target experiment proposed at CERN SPS



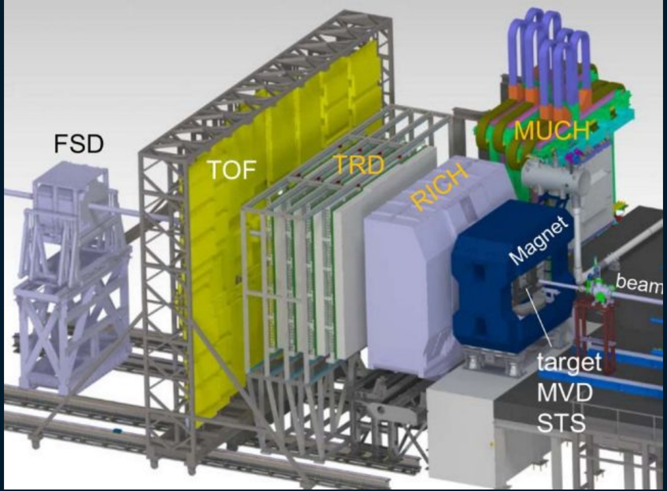


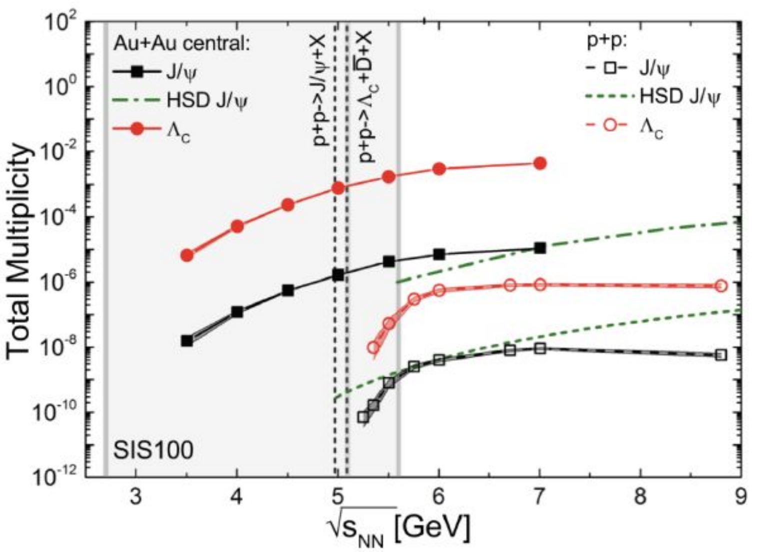
Precise evaluation of J/ψ suppression within reach even at low energy
→ no charmonium results available below top SPS energy ($\sqrt{s_{NN}}$=17 GeV)

CBM @ FAIR

➡ CBM is dedicated to the study of the high μ_B region of the QCD phase diagram

Unprecedented interaction rates up to 10 MHz in HI collisions provide access to rare probes

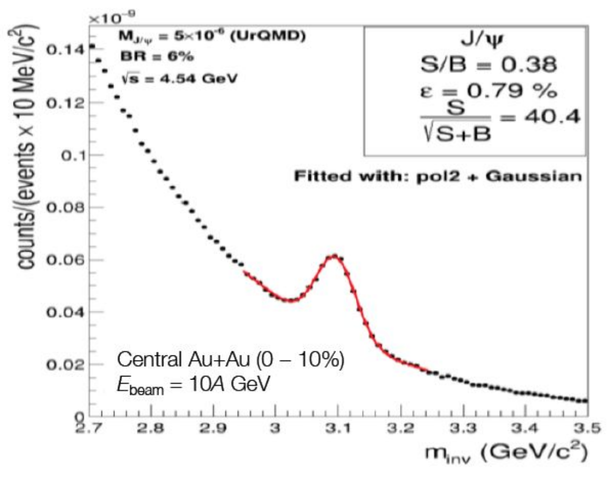


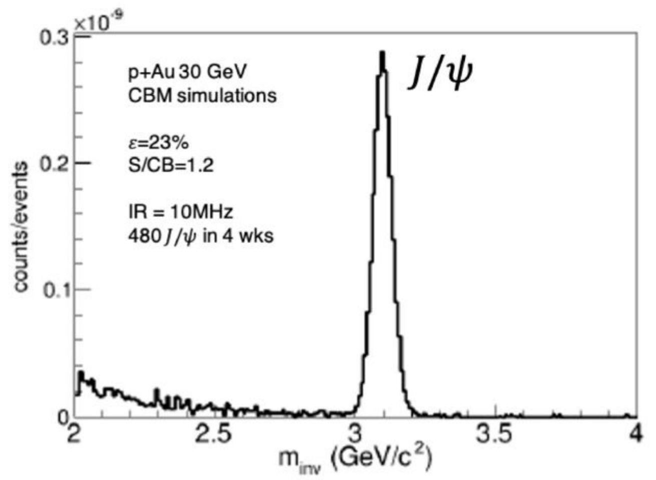


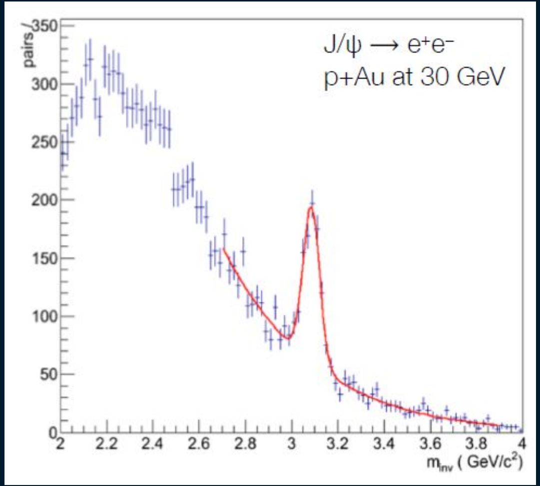
J. Steinheimer et al, Phys. Rev, C95 (2017) 014911

- Sub-threshold production (rare but feasible)
- Production threshold might be exceeded with SIS100 beam of N=Z nuclei
- Both $\mu^+\mu^-$ and e^+e^- decay channels accessible

CBM @ FAIR







J/ψ→μμ

AuAu ~30k J/ψ in 4 weeks at 10 MHz interaction rate
pAu ~500 J/ψ in 4 weeks at 10 MHz interaction rate

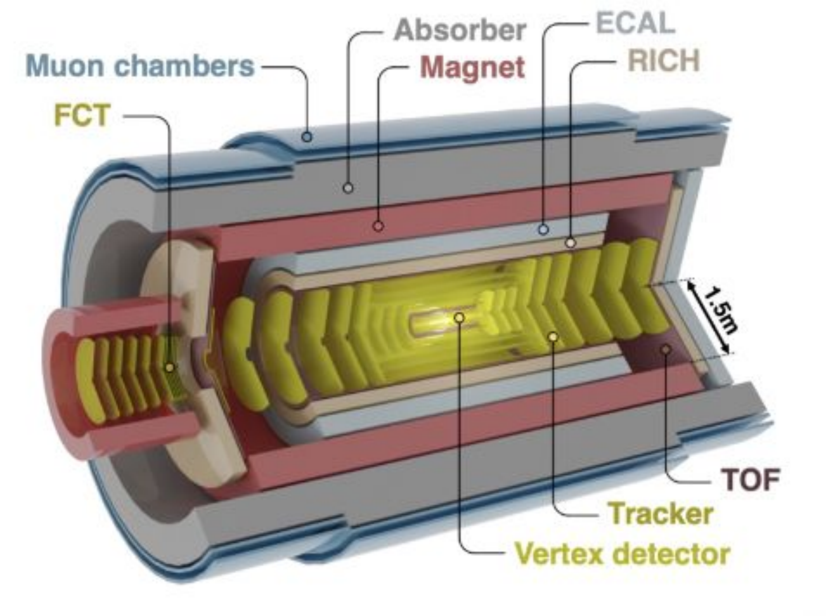
J/ψ→ee

pAu ~450 J/ψ in 4 weeks at 10 MHz int. rate

pA → lower statistics, but very clean signal

ALICE 3

➡ New experiment proposed at LHC after LS4 (2035)



Excellent vertexing, PID and large acceptance

Vertexing precision: ~ 10 µm at p_T = 200 MeV
Acceptance: $|\eta| < 4$ (with particle ID)

High efficiency for reconstruction of

- quarkonium states down to $p_T = 0$
- low energy photons (0.5 GeV and below)

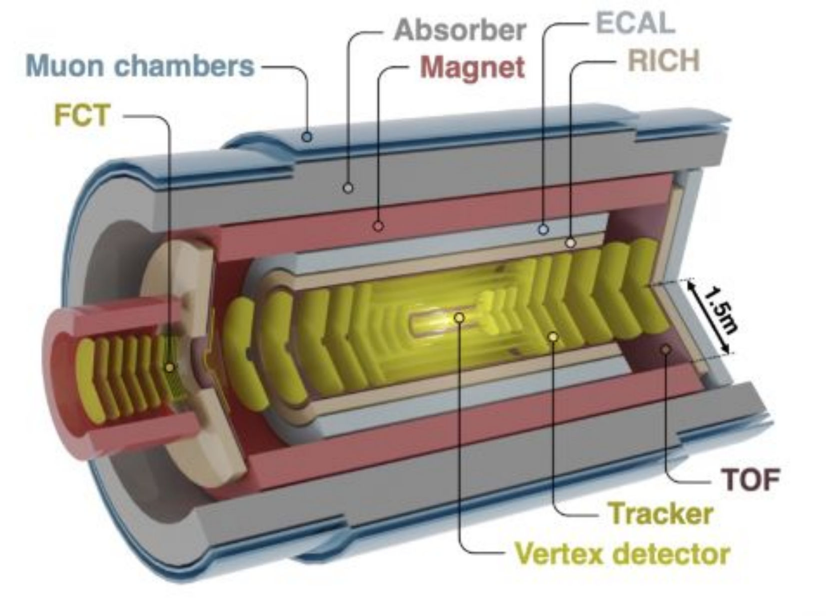
LOI: arXiv:2211.02491

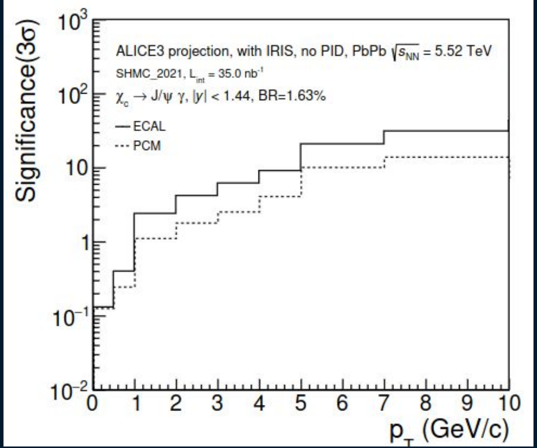
ALICE 3

⇨ New experiment proposed at LHC after LS4 (2035)

Aim at studying quarkonium spectroscopy in QGP

- pseudoscalar (η_c,η_b) and P-wave (χ_c, χ_b) states largely unexplored in heavy-ions
- exotic state as X(3872) not yet measured at low p_T





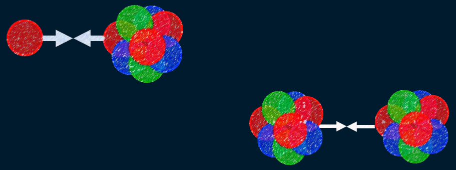
Access

- $\chi_c \to J/\psi\ \gamma$, $\chi_b \to$ ´$\Upsilon\ \gamma$
- $\eta_c \to pp$, $\eta_c \to \Lambda\Lambda$ (performance under study)
- $X(3872) \to J/\psi\ \pi\pi$

Good significance for χ_c down to p_T ~ 2 GeV/c

Conclusions

Very precise quarkonium results are now available, in pA and AA, at several collision energies and over a broad kinematic range



Results from all the LHC experiments show an overall good compatibility in similar kinematic ranges and point to a coherent picture

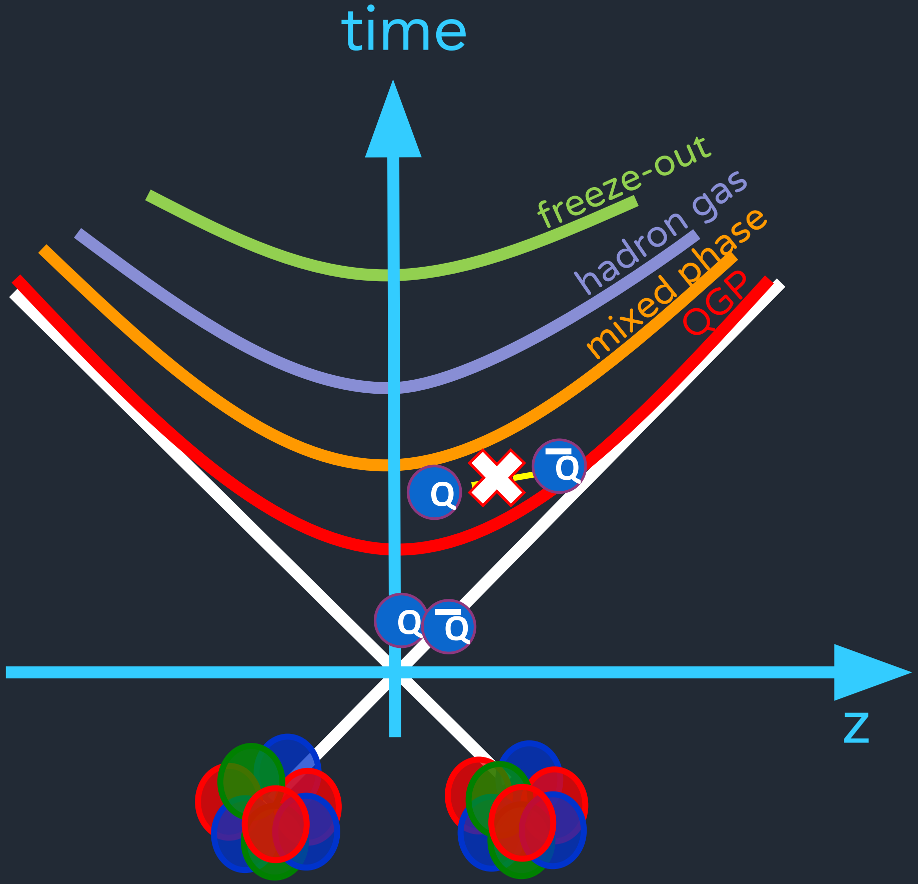
Quarkonium still a very interesting topic after ~40 years!

…with a bright future in front!

Thank you!

Backup

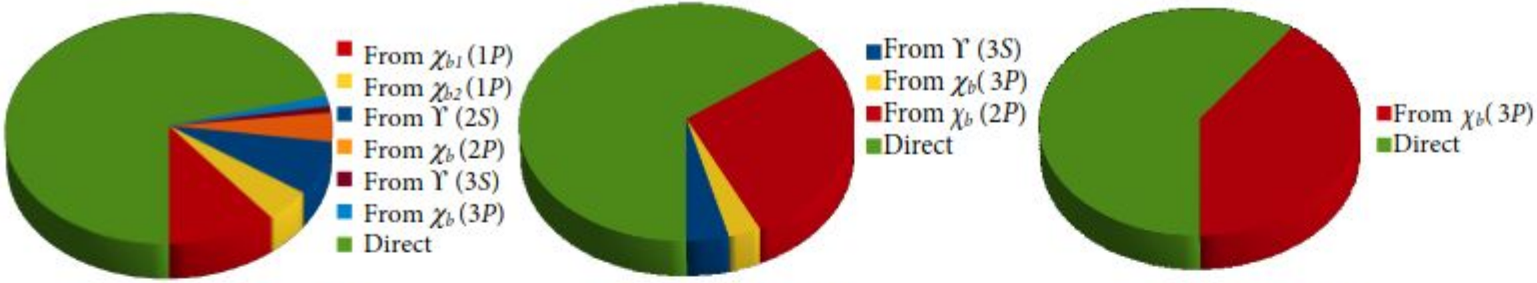
Quarkonium and QGP



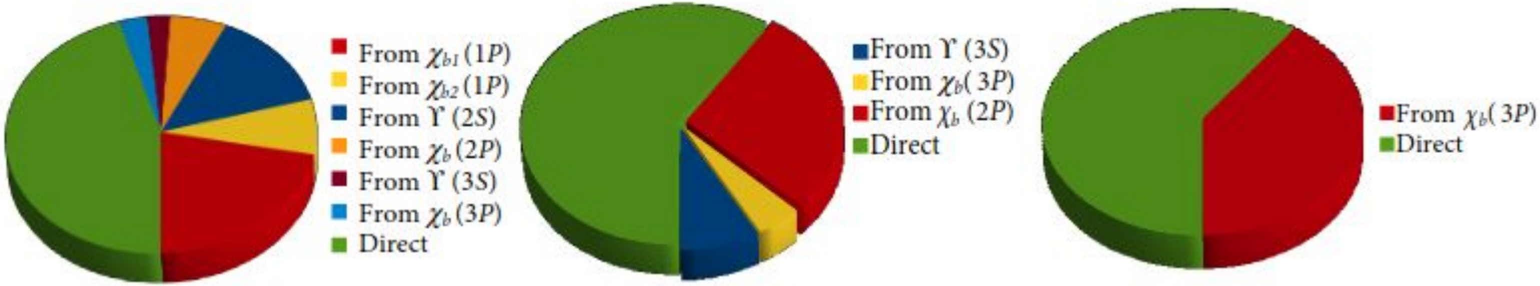
Heavy quarks produced in the early stages of the collisions

the original idea:
quarkonium production suppressed sequentially via color screening in QGP

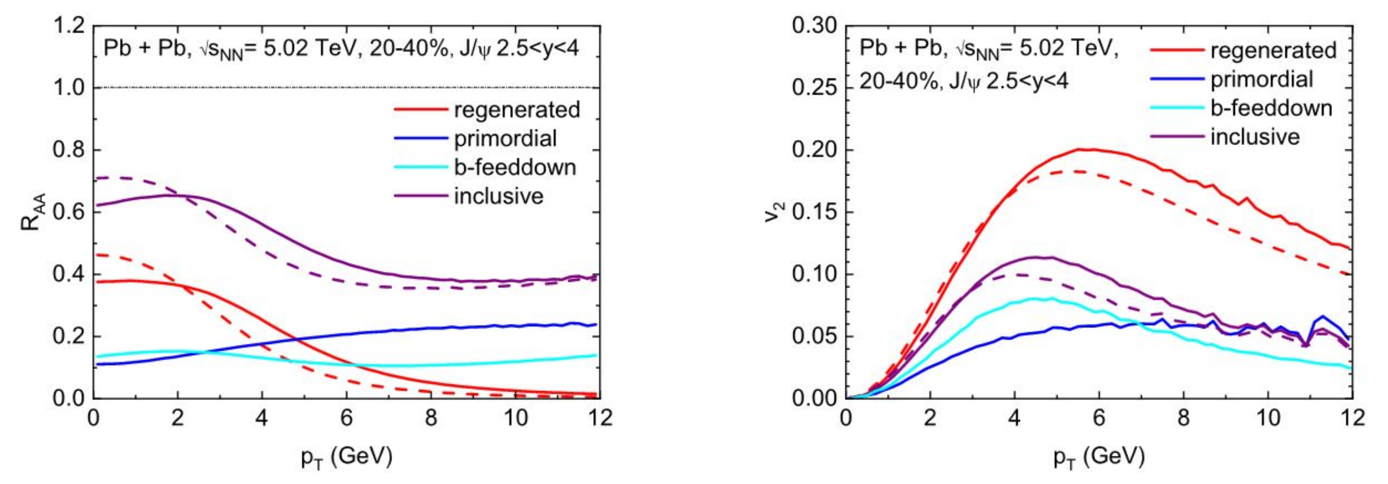
(T.Matsui,H.Satz, PLB178 (1986) 416)
> 3500 citations



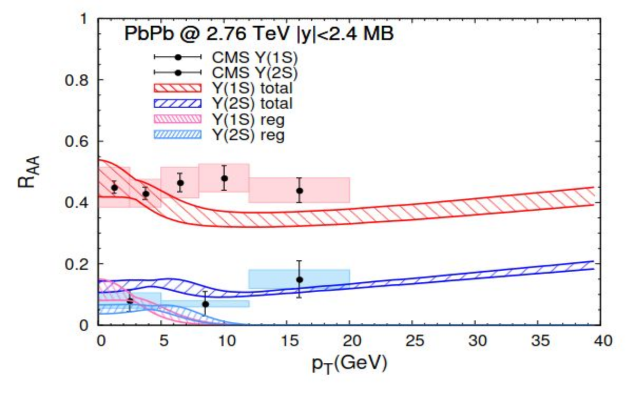
(a) Low P_T $\Upsilon(1S)$ (b) Low P_T $\Upsilon(2S)$ (c) Low P_T $\Upsilon(3S)$

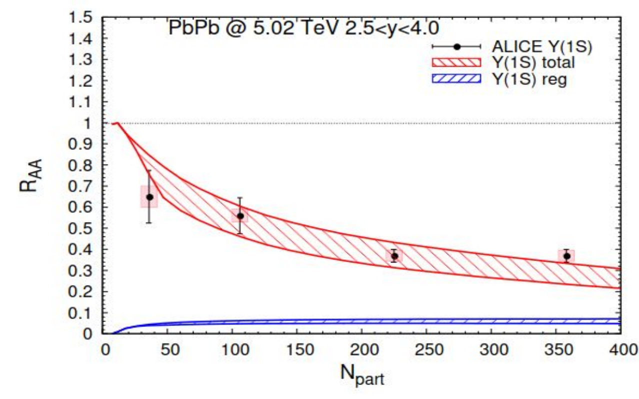


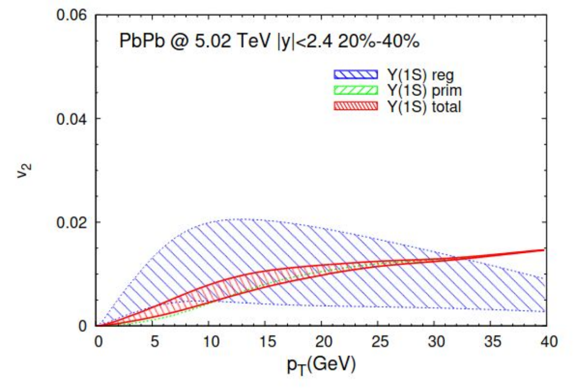
(d) High P_T $\Upsilon(1S)$ (e) High P_T $\Upsilon(2S)$ (f) High P_T $\Upsilon(3S)$

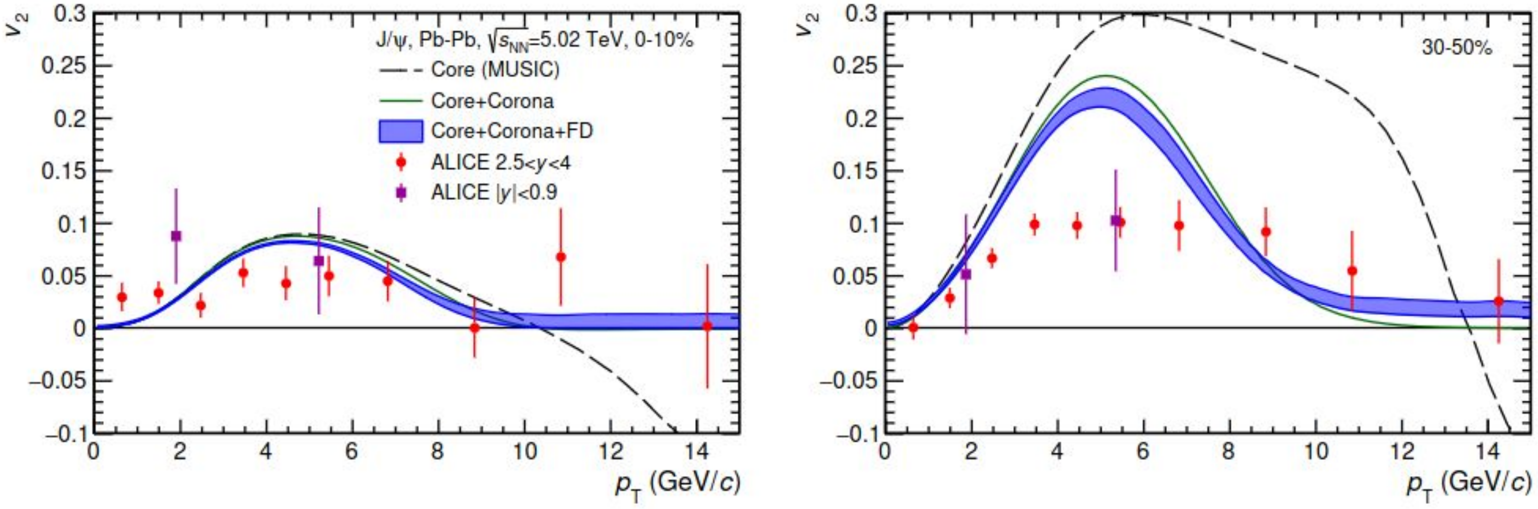


arXiv:1706.08670v2



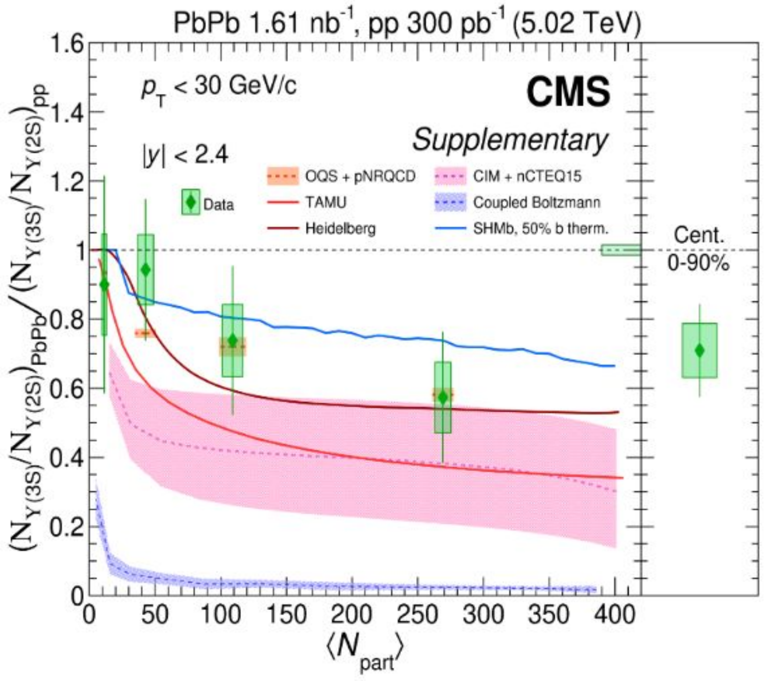


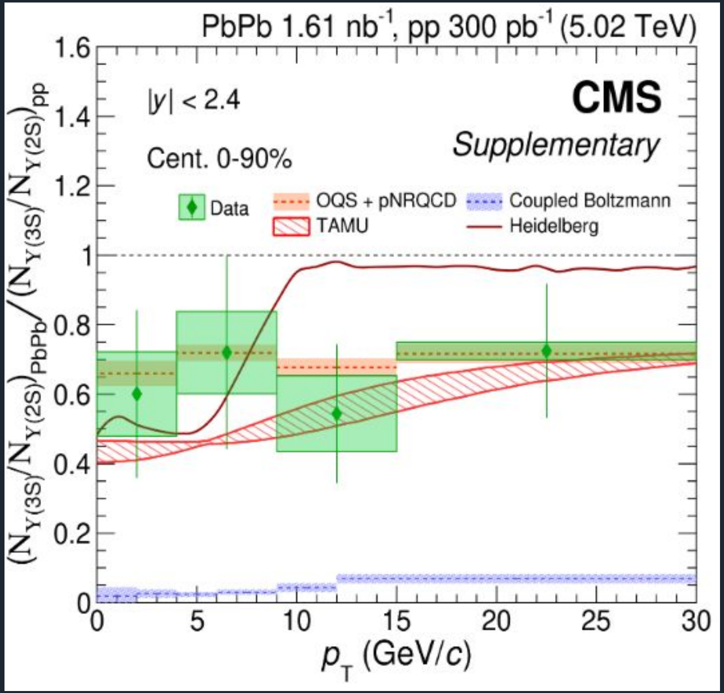



J/ψ, Pb-Pb, $\sqrt{s_{NN}}$=5.02 TeV, 0-10%
Core (MUSIC)
Core+Corona
Core+Corona+FD
ALICE 2.5<y<4
ALICE $|y|$<0.9
30-50%
v_2
0.3
0.25
0.2
0.15
0.1
0.05
0
−0.05
−0.1
0
2
4
6
8
10
12
14
p_T (GeV/c)

Double ratio

$$\frac{[\Upsilon(3S)/\Upsilon(2S)]_{\mathrm{PbPb}}}{[\Upsilon(3S)/\Upsilon(2S)]_{\mathrm{pp}}}$$

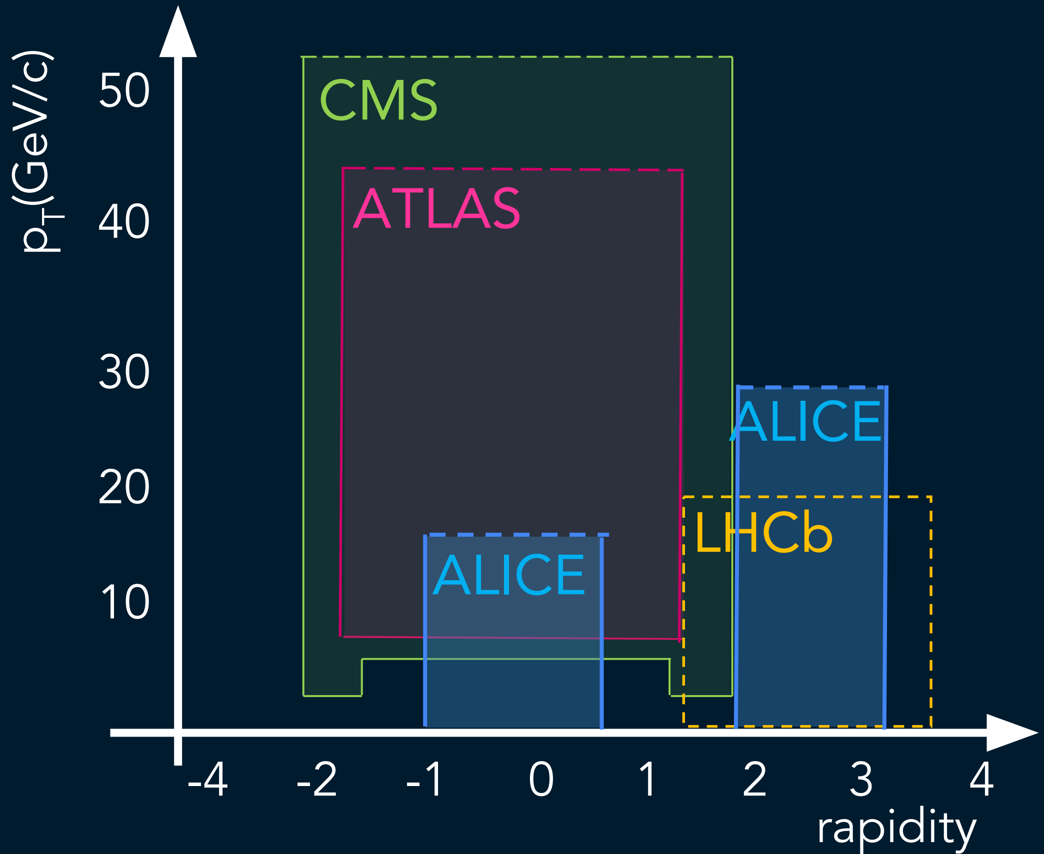




CMS, arXiv:2303.17026

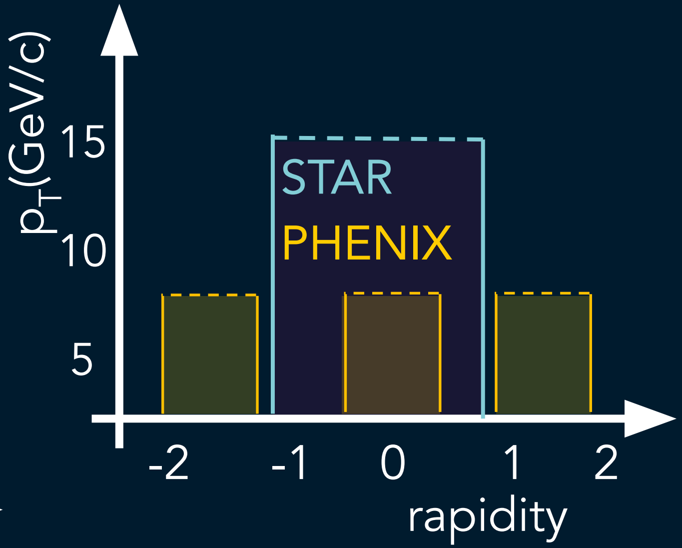
- stronger suppression for ϒ(3S) compared to ϒ(2S) for more central collisions
- significant differences among models → these data can put constraints on models, in spite of large uncertainties

Quarkonium kinematics



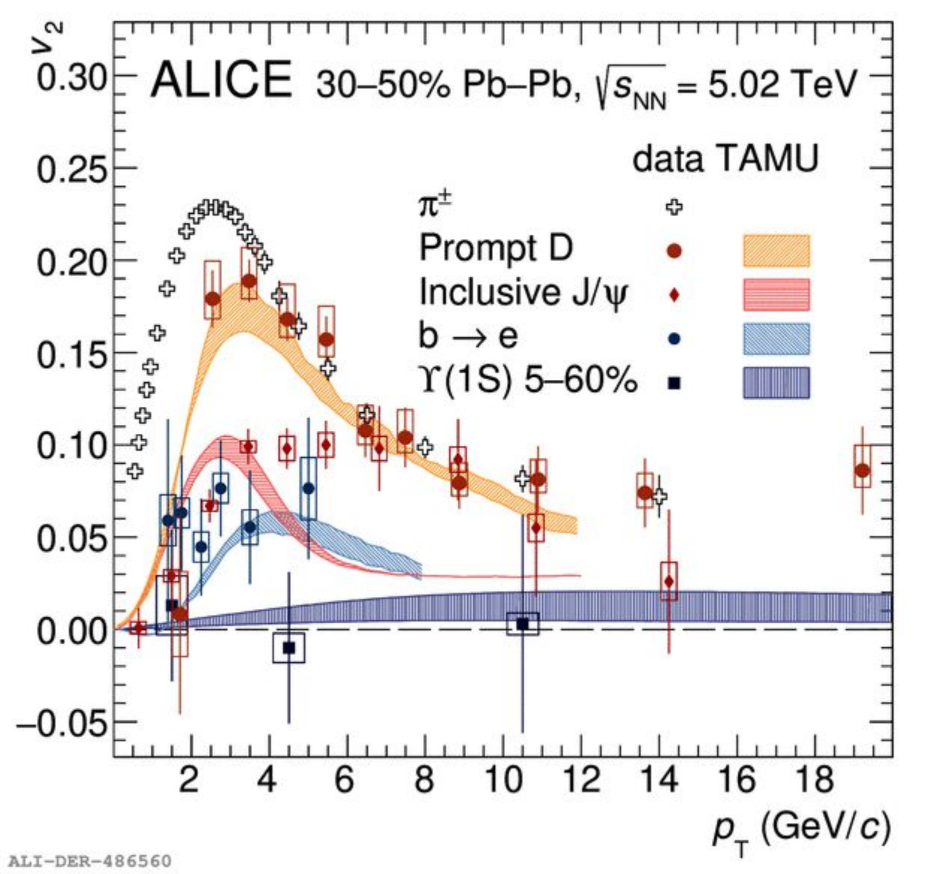
AA (pA for LHCb)

quarkonium studied in their dilepton decay



(p_T reach based on the most recent measurements)

Y flow



Clear ordering:

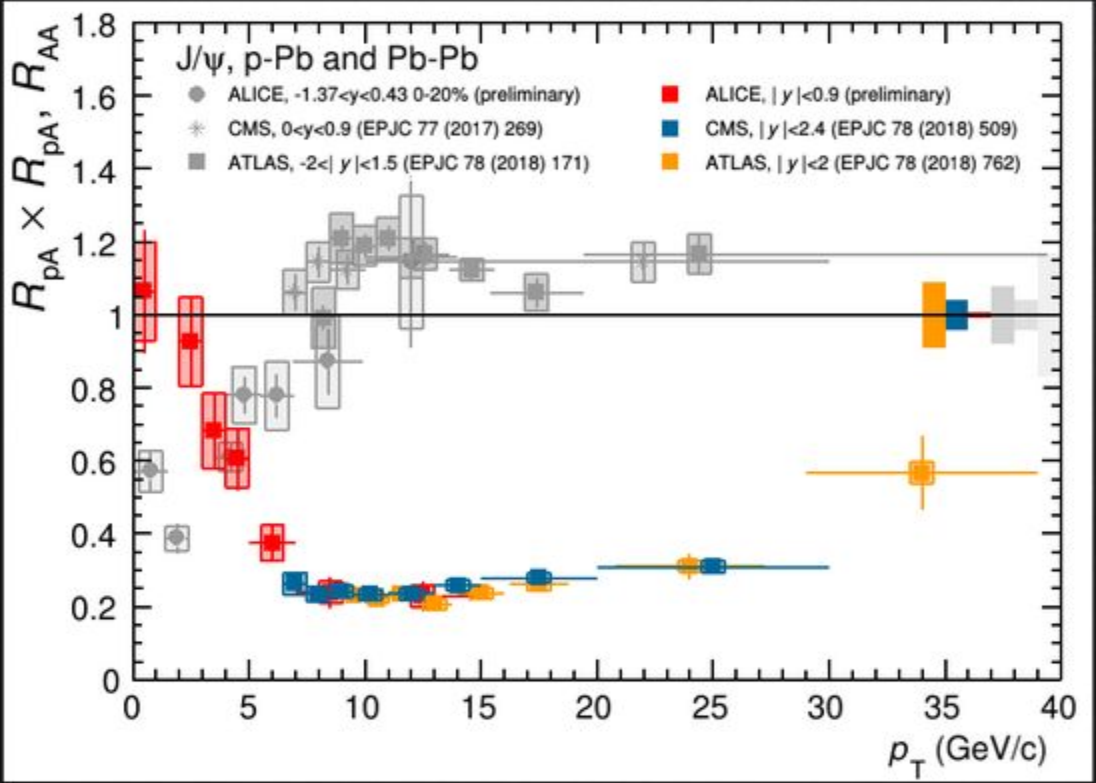
low p_T:

v_2(h) > v_2(D) > v_2(J/ψ) ~ v_2(b) > v_2(ϒ)

high p_T:

v_2(h) ~ v_2(D) ~ v_2(J/ψ)

pA AND AA: J/ψ

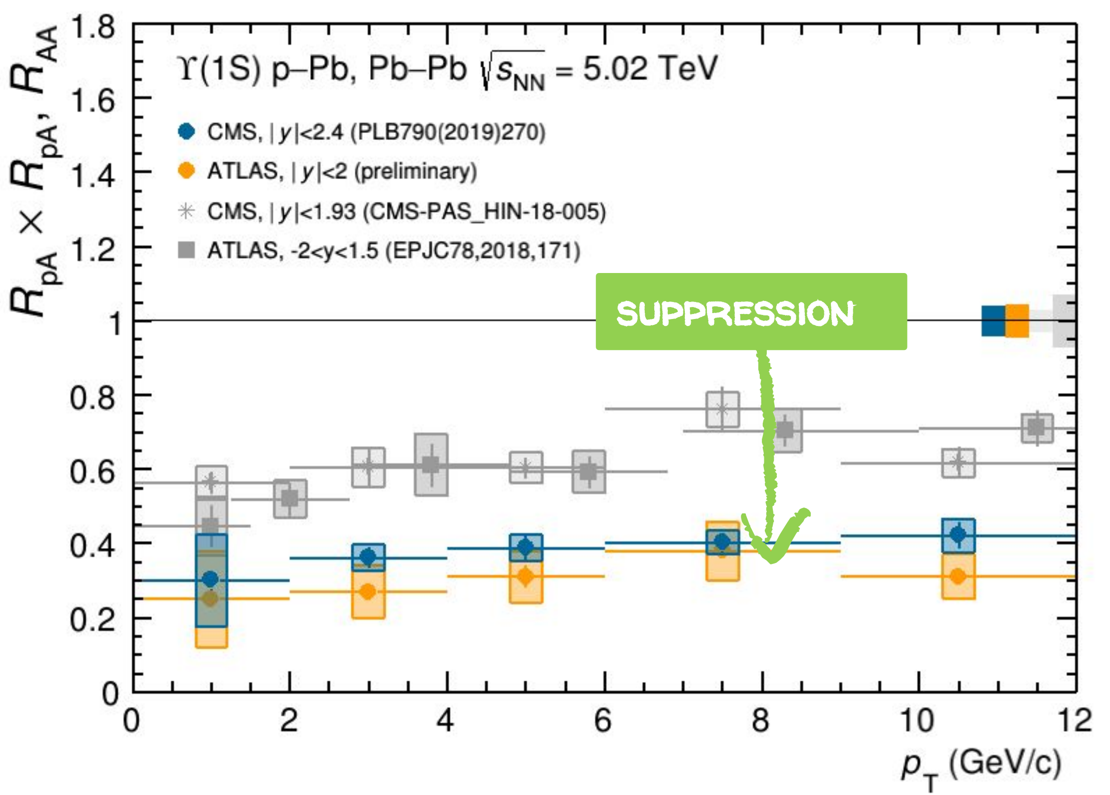


SIGNIFICANT DIFFERENCE BETWEEN J/ψ R_{pA} AND R_{AA} OVER ALL THE p_T RANGE

Under the assumption that shadowing is the main CNM effect at mid-y:

$$R_{AA}^{CNM} = R_{pA}^{2}$$

pA AND AA: Y(1S)



Y(1S) R_{pA} IS HIGHER THAN R_{AA} OVER THE WHOLE Y AND P_T RANGE

IF SHADOWING IS THE MAIN CNM EFFECT AT MID-Y:

$$R_{AA}^{CNM} = R_{pA}{}^2$$

- ✔ SIZEABLE CNM EFFECTS OVER ALL THE P_T RANGE
- ✔ R_{pA} ALWAYS HIGHER THAN R_{AA}, I.E. THERE IS AN ADDITIONAL SUPPRESSION AT ALL P_T ON TOP OF CNM EFFECTS

DIRECT Υ(1S)

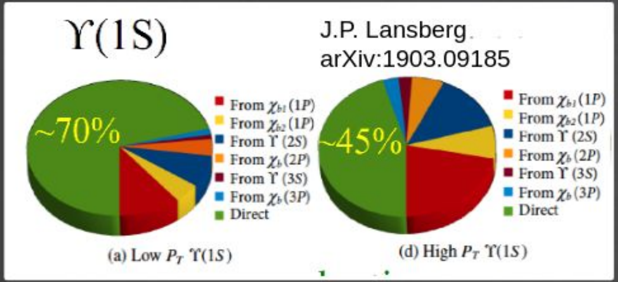
Υ(1S) IS CLEARLY SUPPRESSED IN PBPB COLLISIONS

TO UNDERSTAND IF DIRECT Υ(1S) ARE SUPPRESSED, WE NEED A PRECISE ASSESSMENT OF

- SIZE OF CNM EFFECTS
- FEED-DOWN FROM S AND P STATES

Υ(1S) INCLUSIVE R_{AA} (MID-Y, 0-90%): 0.38 +/- 0.04 (STAT+SYST) (CMS PLB790,270)

FEED-DOWN ~30% AT LOW P_T



J.P. Lansberg
arXiv:1903.09185

(a) Low P_T $\Upsilon(1S)$ (d) High P_T $\Upsilon(1S)$

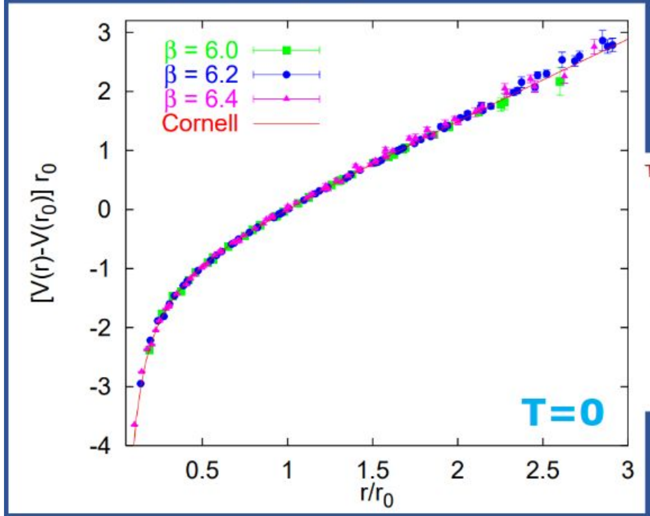
DIRECT Υ(1S) R_{AA}:
0.38/0.7 ~0.54 +/- 0.05
(ASSUMING NO UNCERTAINTY ON FEED-DOWN)

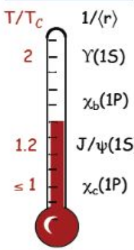
CNM EVALUATED FROM (CMS HIN-2018-005)
R_{pA} = 0.77 +/- 0.07 (STAT+SYST)
→ R_{AA}(CNM) ~ R_{pA}^2 ~0.60 +/- 0.06

OBSERVED Υ(1S) SUPPRESSION COMPATIBLE WITH CNM AND SUPPRESSION OF HIGHER STATES?

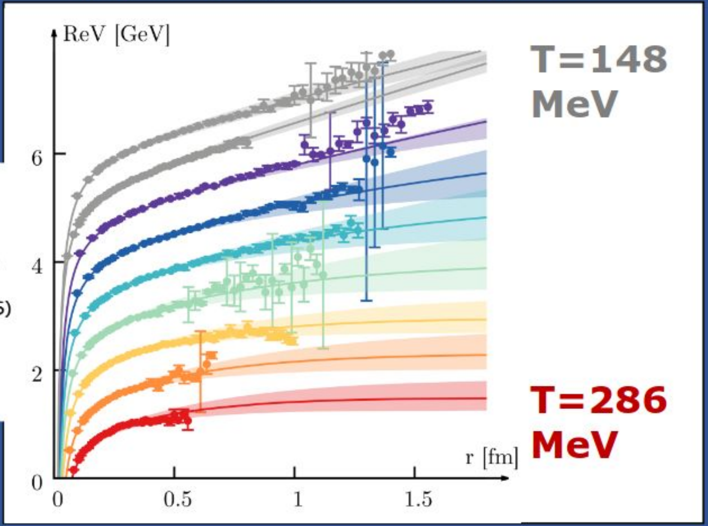
Lattice calculations and potentials

G.S. Bali, Phys. Rep. 343 (2001) 1-136





Lafferty and Rothkopf, Phys. Rev. D 101 (2020) 056010



Potential models provide a faithful reproduction of available lattice data

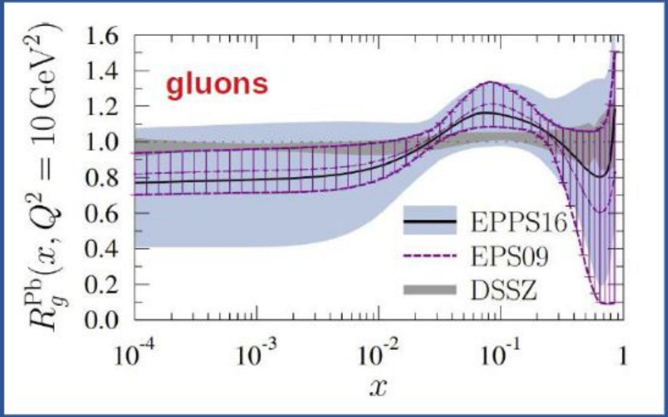
- Gradual transition **from a Cornell to a Debye-screened behaviour** for the (real part of) the potential → **color screening** in a deconfined medium
- Potential also has a finite imaginary part (not shown) → decaying of quark-antiquark correlation due to gluonic damping in the plasma

Quantifying non-QGP effects

- BOTH initial and final state non-QGP effects may lead to a decreased charmonium production
- The relative size depends quite a lot on collision energy (keep in mind for later)

SPS

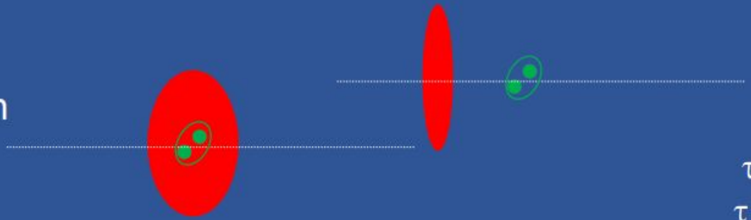
Initial state effects:
moderate anti-shadowing
$x \sim 10^{-1}$ (y=0)



LHC

Initial state effects:
shadowing
$x \sim 10^{-5}$ ($y \sim 3$)
$x \sim 10^{-3}$ (y=0)
$x \sim 10^{-2}$ ($y \sim -3$)

(Final state) CNM effects:
break-up in nuclear matter can be sizeable
$\tau = L/(\beta_z\gamma) \sim 0.5$ fm/c (y=0)

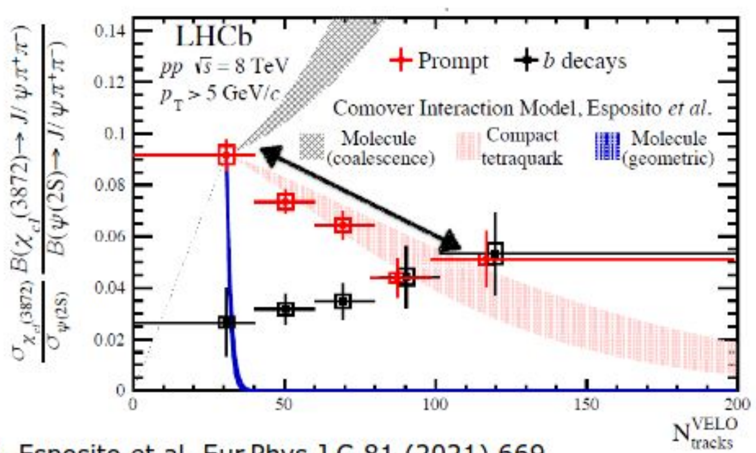


(Final state) CNM effects:
negligible, extremely short crossing time
$\tau = L/(\beta_z\gamma) \sim 7\ 10^{-5}$ fm/c ($y \sim 3$)
$\tau = L/(\beta_z\gamma) \sim 4\ 10^{-2}$ fm/c ($y \sim -3$)

X(3872): yield vs multiplicity in pp

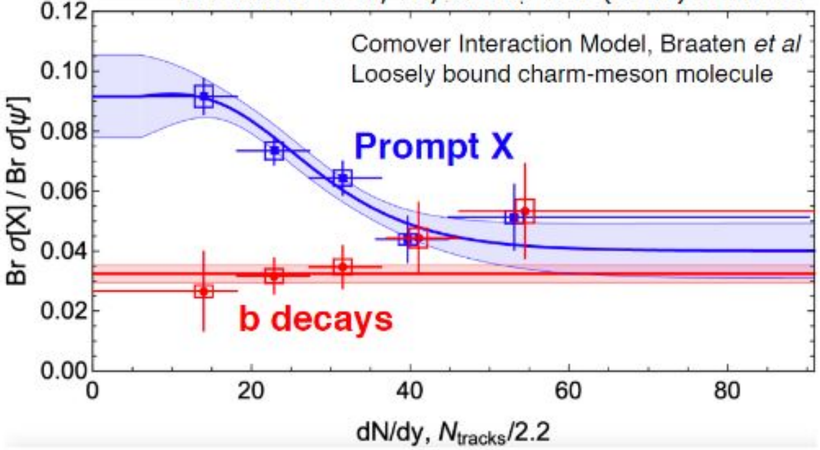
- At the LHC, high-multiplicity pp collisions create a dense hadronic environment
- LHCb studied the **ratio X(3872)/ψ(2S) as a function of hadronic multiplicity**

LHCb, PRL 126 (2021) 092001 (2021)



A. Esposito et al, Eur.Phys.J.C 81 (2021) 669

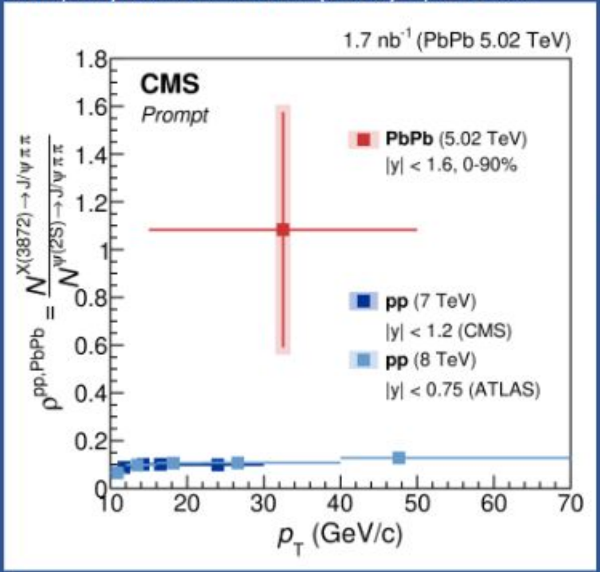
E. Braaten et al., Phys.Rev.D 103 (2021) L071901



- Data described by comover interaction model assuming X(3872) to be a **tetraquark**
  → breakup reaction rate approximated by the geometric cross section
- However, using a different ansatz for CIM can also favour X(3872) being a **molecule**
  → scattering of comoving pions from the charm-meson constituents of X(3872) (no coalescence effects assumed)

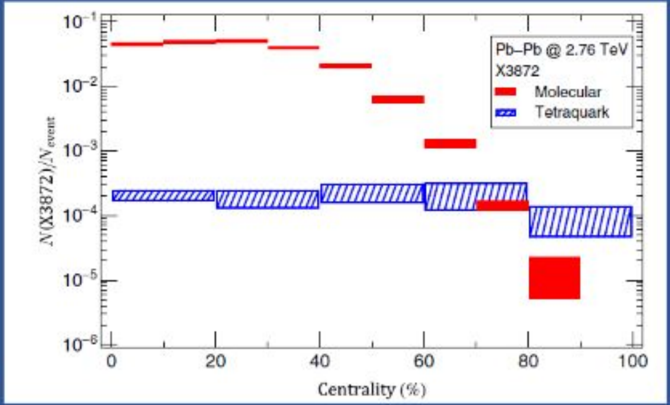
X(3872): first measurement in Pb-Pb

CMS, Phys.Rev.Lett. 128 (2022) 3, 032001

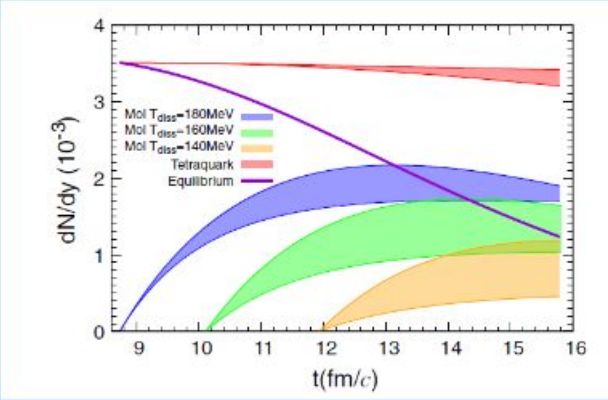


- **Hint of** prompt **X(3872)** to ψ(2S) **enhancement in Pb-Pb,** at very high p_T ($15<p_T<50$ GeV/c)

H. Zhang et al., PRL 126(2021) 012301

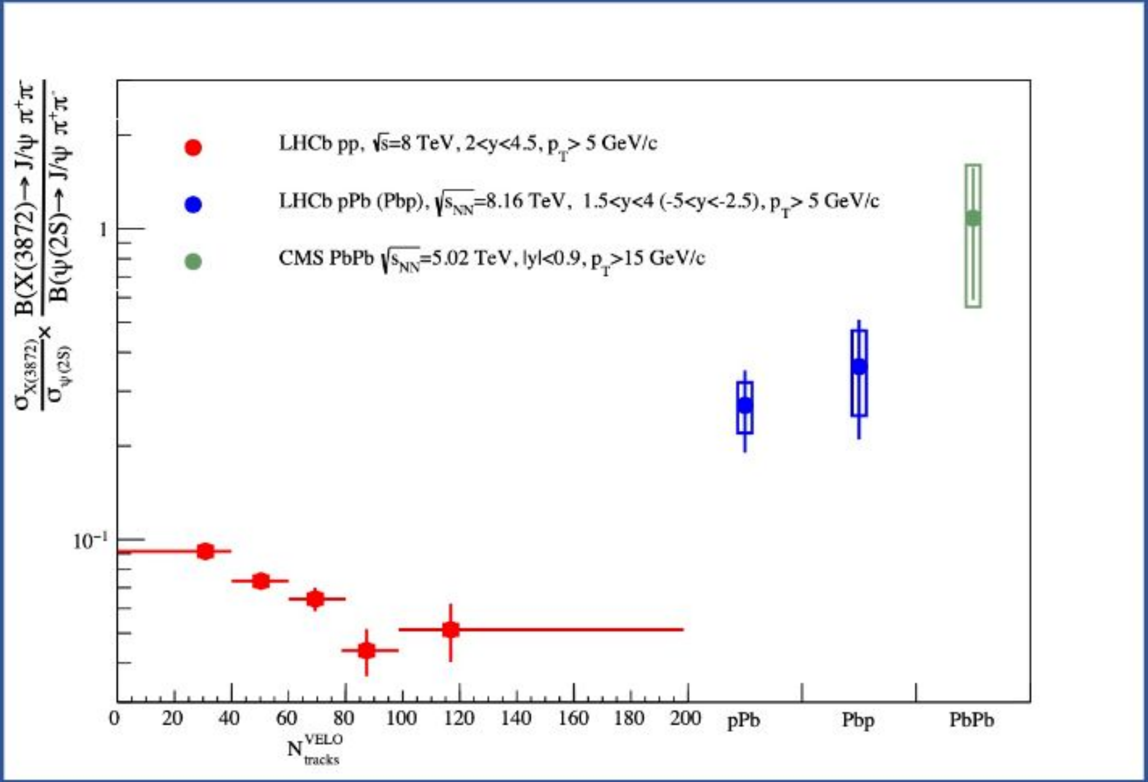


B. Wu et al., EPJA 57(2021) 122



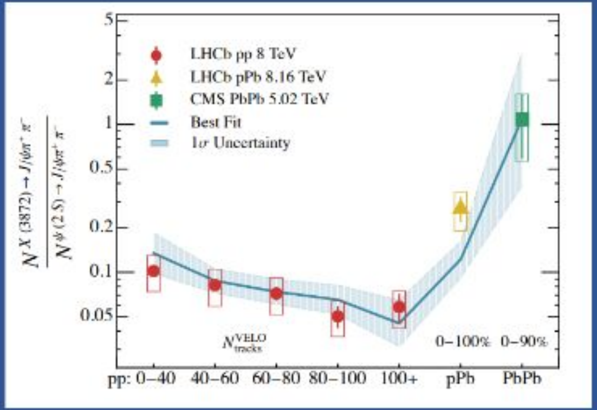
- **Coalescence** model (AMPT): **much larger yields for molecular option**, with strong centrality dependence (ccbar more likely separated in space at freeze-out)
- **Transport** model: **moderate difference between yields**, larger reaction rates associated with the loosely bound molecule structure imply that it is formed later in the fireball evolution than the tetraquark and thus its final yields are generally smaller

X(3872): current experimental status



pp → p-Pb → Pb-Pb

from **suppression** to **enhancement**?



Guo et al., arXiv:2302.03828

First attempts at a coherent description of yields vs system size

- Extension of measurements toward low p_T badly needed → **LHC run 3/4**