Heavy quarks: a (the) golden probe of QGP

E. Scomparin
INFN Torino (Italy)

Quark Matter 2023 Student Day

Heavy quarks: a (the) golden probe of QGP

From the November revolution…

Discovery of a Narrow Resonance in e^+e^- Annihilation*

J.-E. Augustin,† A. M. Boyarski, M. Breidenbach, F. Bulos, J. T. Dakin, G. J. Feldman, G. E. Fischer, D. Fryberger, G. Hanson, B. Jean-Marie,† R. R. Larsen, V. Lüth, H. L. Lynch, D. Lyon, C. C. Morehouse, J. M. Paterson, M. L. Perl, B. Richter, P. Rapidis, R. F. Schwitters, W. M. Tanenbaum, and F. Vannucci‡
Stanford Linear Accelerator Center, Stanford University, Stanford, California 94305

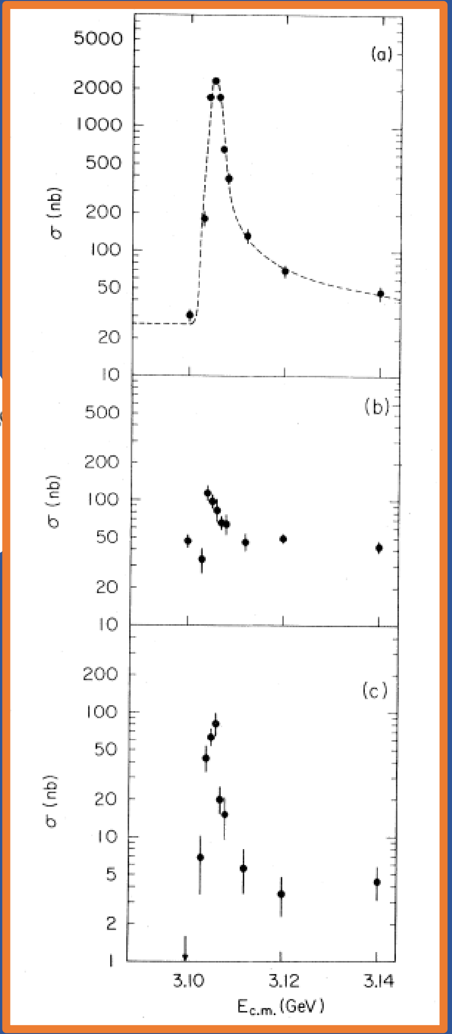
and

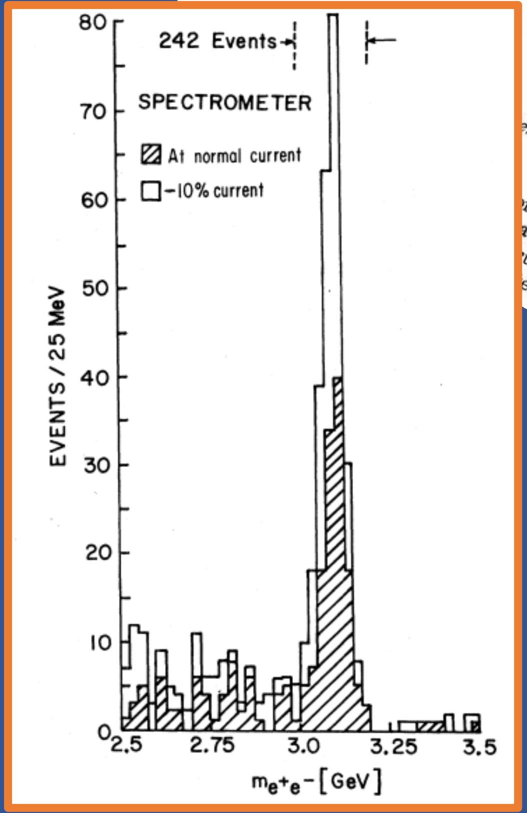
G. S. Abrams, D. Briggs, W. Chinowsky, C. E. Friedberg, G. Goldhaber, R. J. Hollebeek, J. A. Kadyk, B. Lulu, F. Pierre,§ G. H. Trilling, J. S. Whitaker, J. Wiss, and J. E. Zipse
Lawrence Berkeley Laboratory and Department of Physics, University of California, Berkeley, California 9472

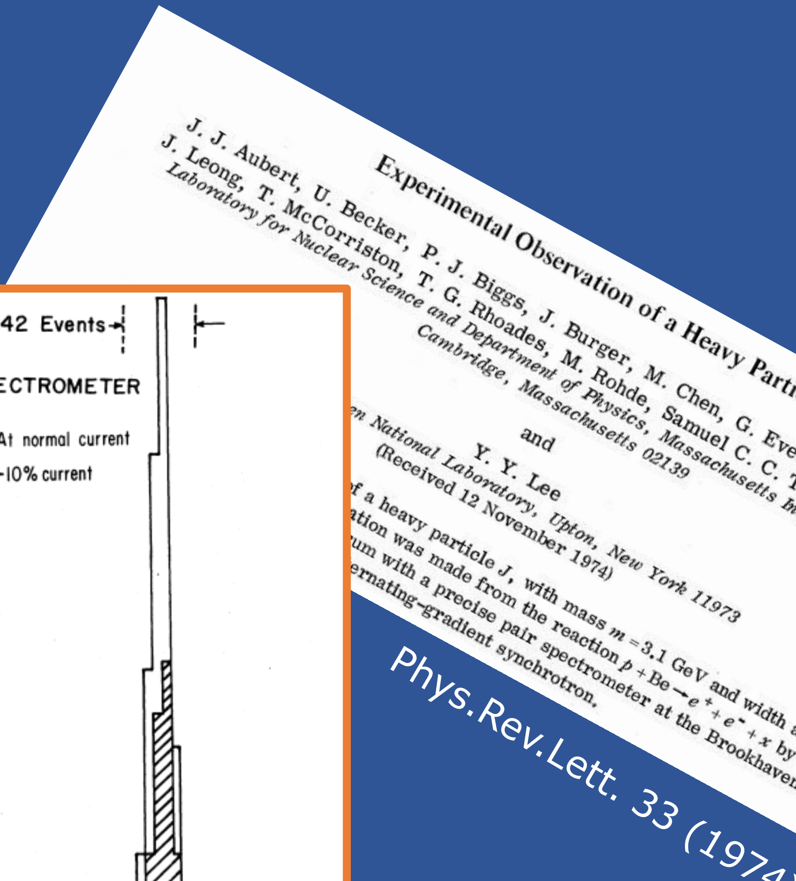
(Received 13 November 1974)

We have observed a very sharp peak in the cross section for $e^+e^- \to$ hadrons, e^+e^-, and possibly $\mu^+\mu^-$ at a center-of-mass energy of 3.105 ± 0.003 GeV. The upper limit to the full width at half-maximum is 1.3 MeV.

Phys.Rev.Lett. 33 (1974) 1406







Experimental Observation of a Heavy Particle J†

J. J. Aubert, U. Becker, P. J. Biggs, J. Burger, M. Chen, G. Everhart, P. Goldhagen, J. Leong, T. McCorriston, T. G. Rhoades, M. Rohde, Samuel C. C. Ting, and Sau Lan Wu
Laboratory for Nuclear Science and Department of Physics, Massachusetts Institute of Technology, Cambridge, Massachusetts 02139

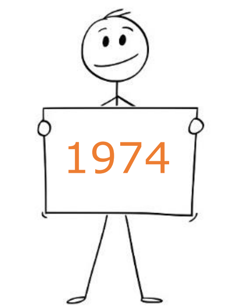
and

Y. Y. Lee
en National Laboratory, Upton, New York 11973

(Received 12 November 1974)

f a heavy particle J, with mass $m = 3.1$ GeV and width ap-
ation was made from the reaction $p + \mathrm{Be} \to e^+ + e^- + x$ by
um with a precise pair spectrometer at the Brookhaven
ernating-gradient synchrotron.

Phys.Rev.Lett. 33 (1974) 1402



Heavy quarks: a (the) golden probe of QGP

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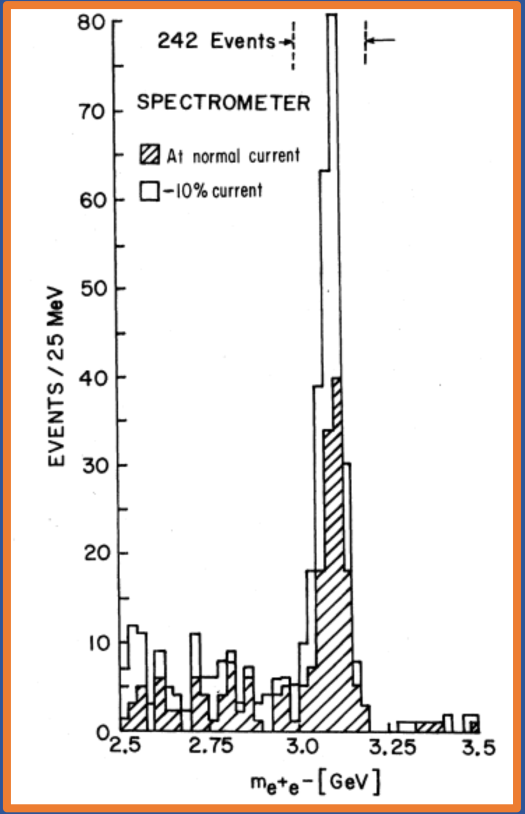


… to the discovery of the J/ψ suppression…

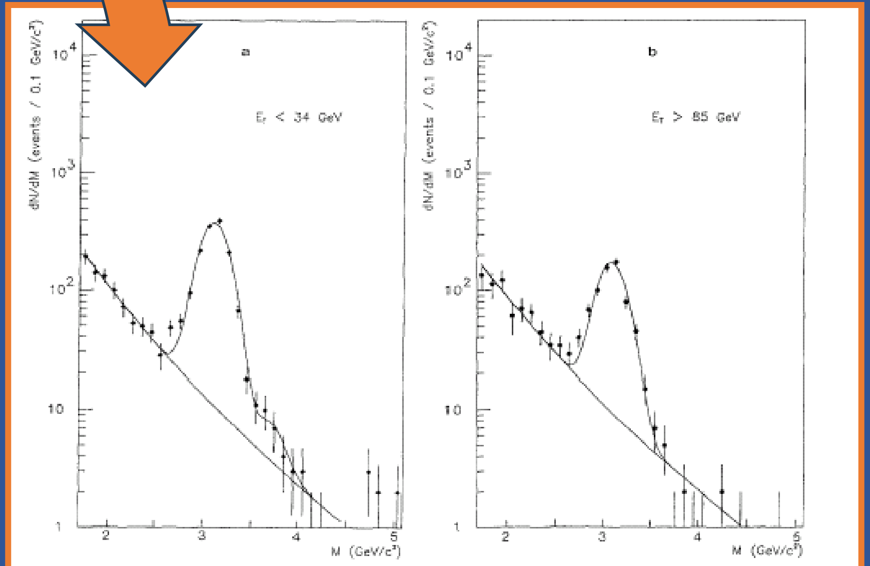
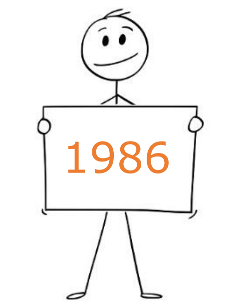


Fig. 5. Mass spectrum and fit of the signal muon pairs in two different E_T bins: $E_T < 34$ GeV (a) and $E_T > 85$ GeV (b).



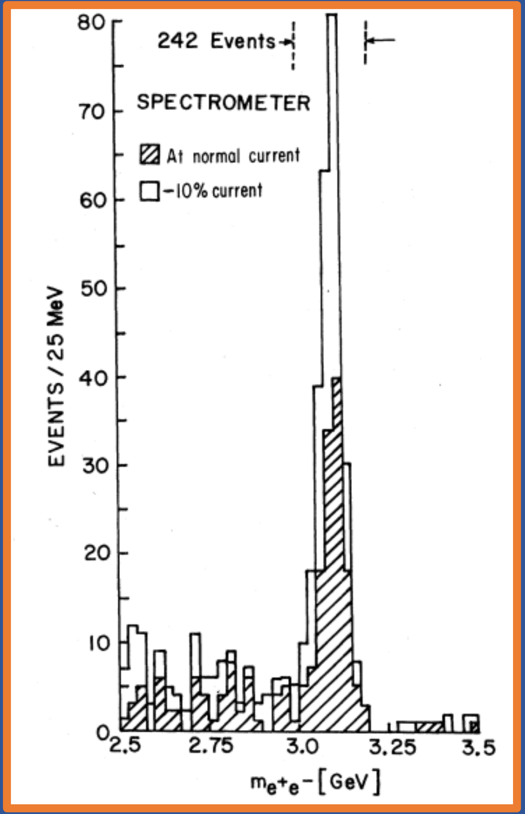
Abstract

The study of oxygen-uranium reactions at 200 GeV/nucleon shows a significant transverse energy dependence of the yield of JΨ's relative to muon pairs produced in the mass continuum. This feature, observed for the first time, is in agreement with predictions from quark-gluon plasma formation, although alternative explanations by hadronic effects cannot be ruled out at this stage.

NA38, PLB220 (1989) 471
NA38, Z. Phys. 38(1988) 117

Heavy quarks: a (the) golden probe of QGP

From the November revolution…



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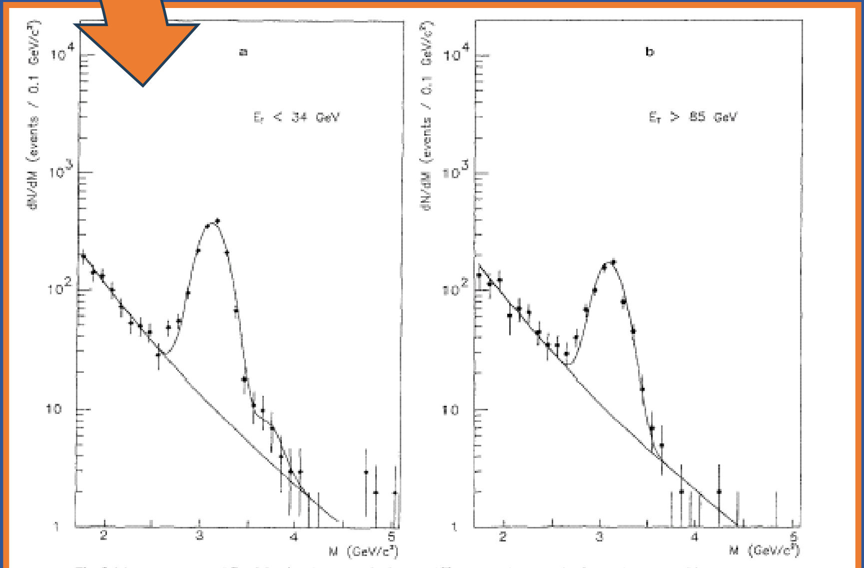
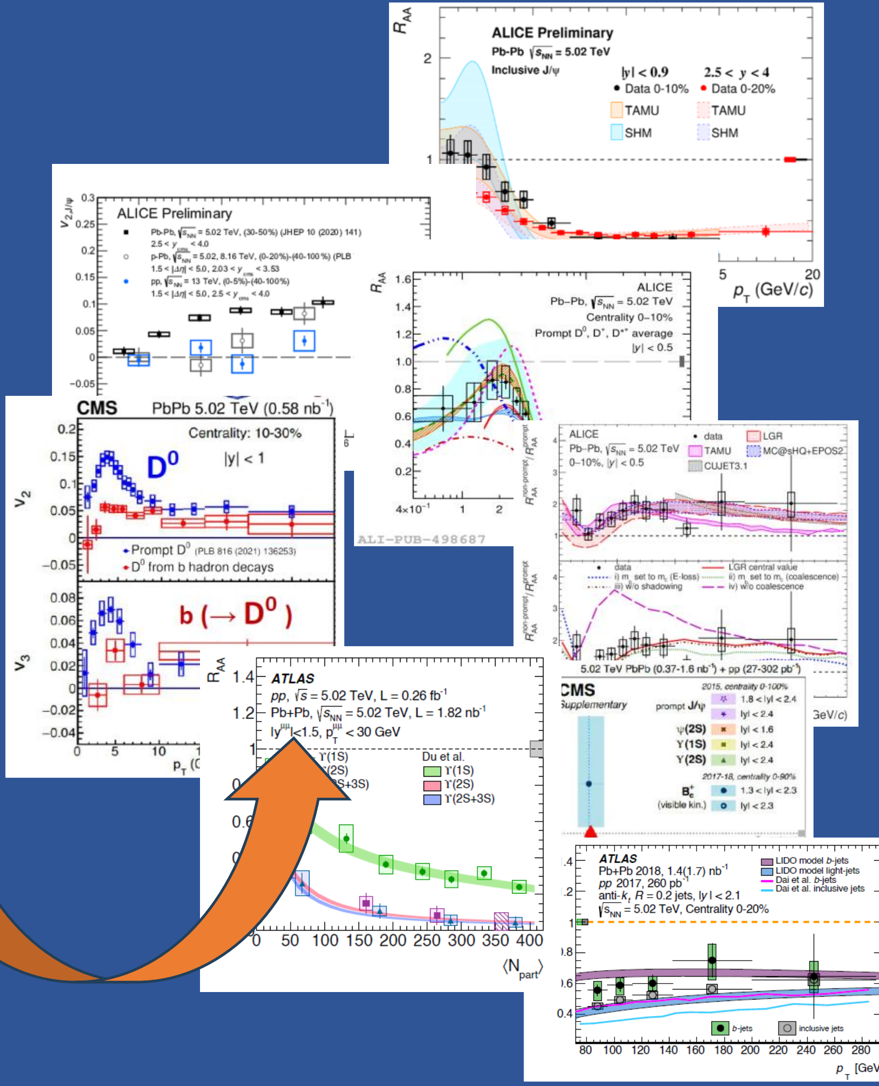


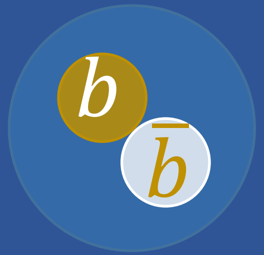
Fig. 5. Mass spectrum and fit of the signal muon pairs in two different E_T bins: $E_T < 34$ GeV (a) and $E_T > 85$ GeV (b).

…to today's precision measurements at collider energies!



Heavy quarks: versatile observables

Υ, χ_b , η_b, …



- (Heavy) Quarkonia: bound states of $c\bar{c}$ and $b\bar{b}$ quarks (no $t\bar{t}$!)
  - Rich spectroscopy
  - Wide range of binding energy
  - Several angular momentum states

J/ψ, χ_c , η_c, …

N.B.: “color” is here used to identify “flavour”!

Heavy quarks: versatile observables

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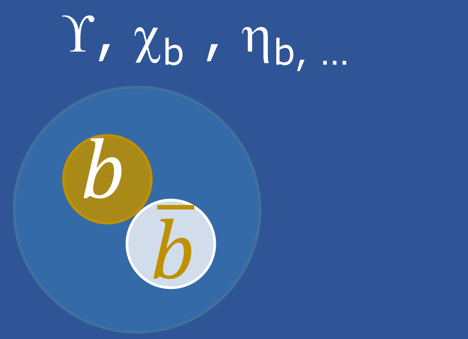
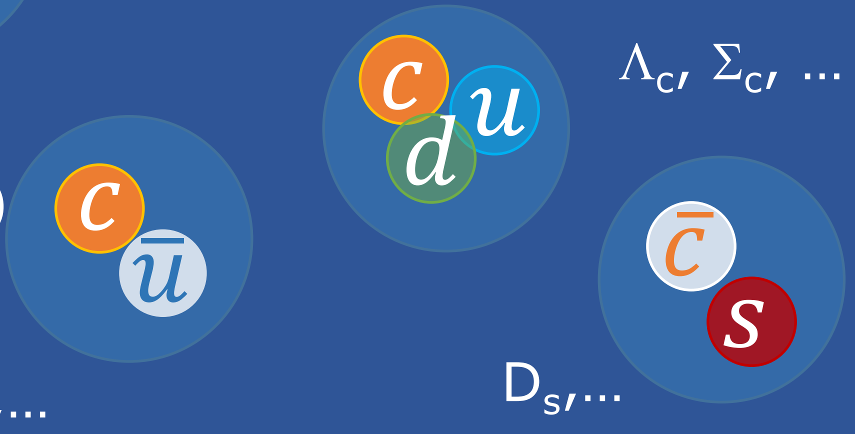
  - Rich spectroscopy
  - Wide range of binding energy
  - Several angular momentum states

- Open heavy flavour hadrons
  - Heavy quark can bind with a light or strange quark(s)
  - Large variety of mesons AND baryons





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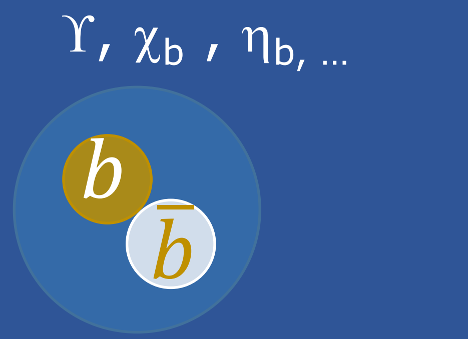
Heavy quarks: versatile observables



- (Heavy) Quarkonia: bound states of $c\bar{c}$ and $b\bar{b}$ quarks (no $t\bar{t}$!)
  - Rich spectroscopy
  - Wide range of binding energy
  - Several angular momentum states

- Open heavy flavour hadrons
  - Heavy quark can bind with a light or strange quark(s)
  - Large variety of mesons AND baryons

- Exotica
  - Beyond qqq and $q\bar{q}$
  - Large number of states (discoveries continue)

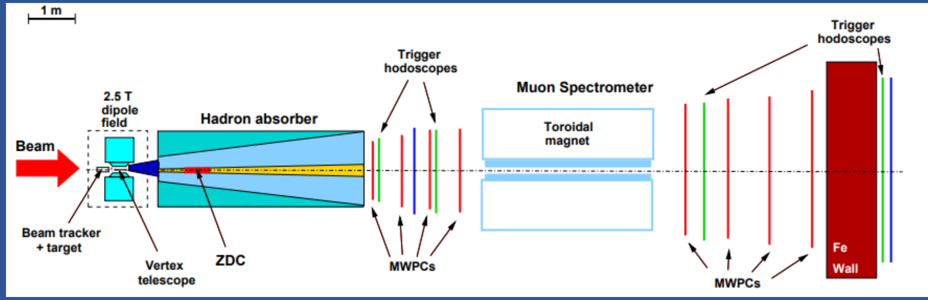
N.B.: “color” is here used to identify “flavour”!

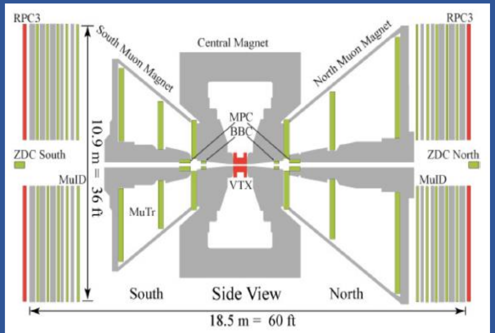
Quarkonia

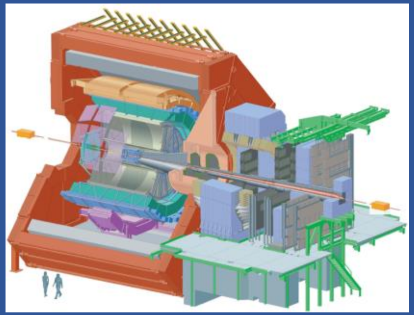
- How were they established as a signature of QGP ?
- Do they retain interest until today ?
- Is there space for further progress ?

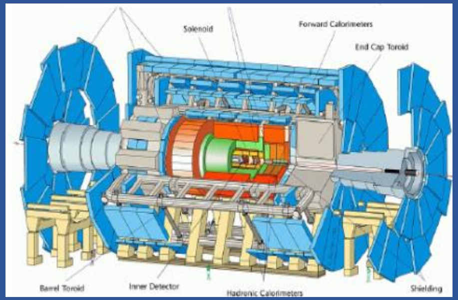
Quarkonia

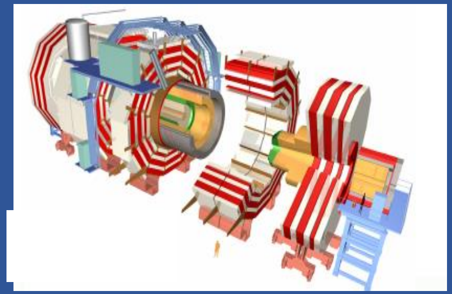
Mostly studied via their **dilepton decay** (muon/electron spectrometers)











- How were they established as a signature of QGP ?
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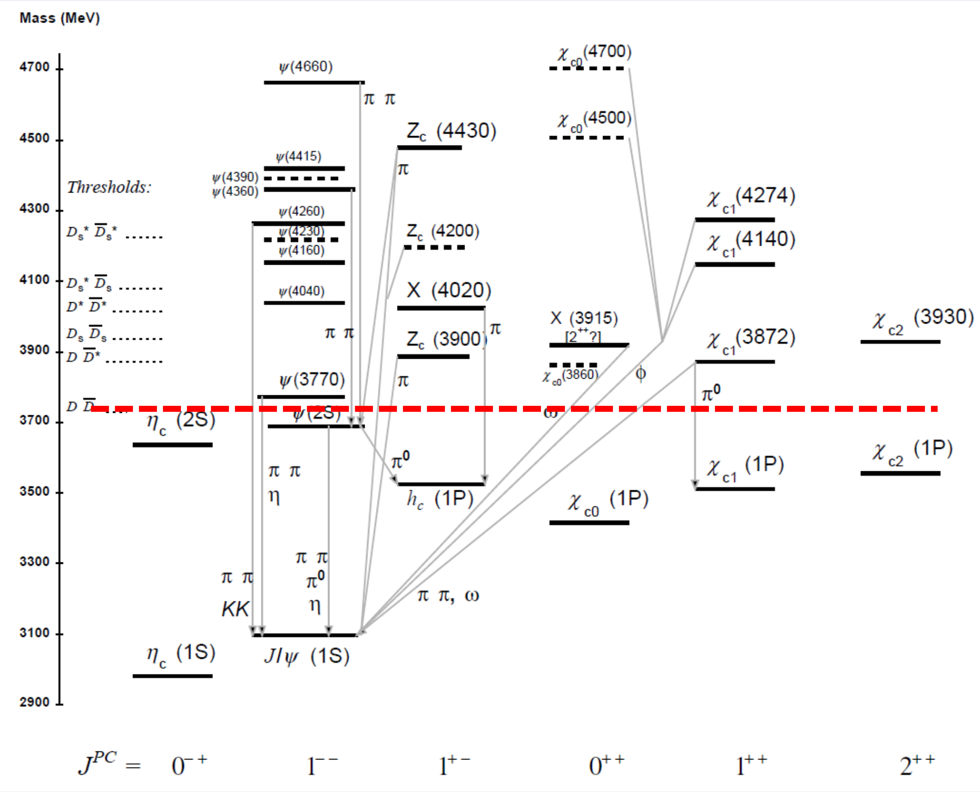
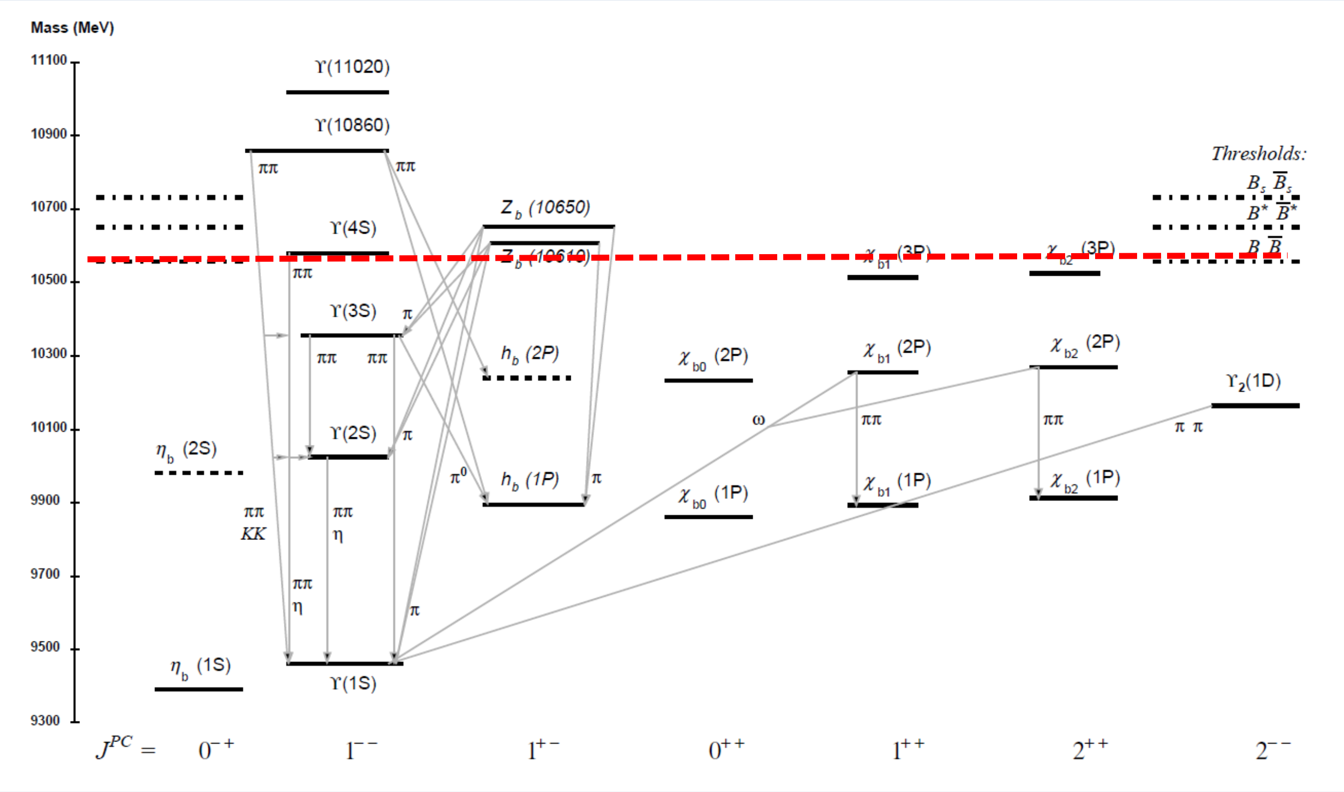
Quarkonium spectroscopy





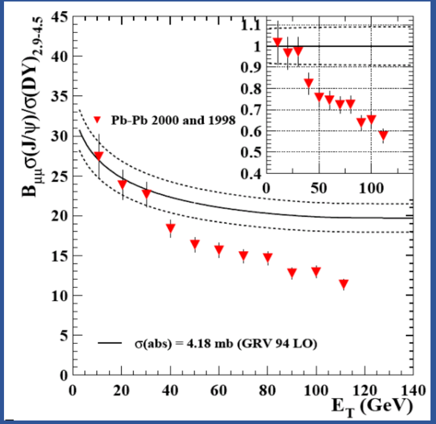
- Below open heavy flavour threshold
  - Extremely **narrow widths** (Γ < 1 MeV for most vector states)
  - Binding energy can be > 1 GeV (Υ(1S))
  - Non-relativistic system → static properties can be explored via Schrodinger equation
  - High-T properties → investigated via lattice QCD

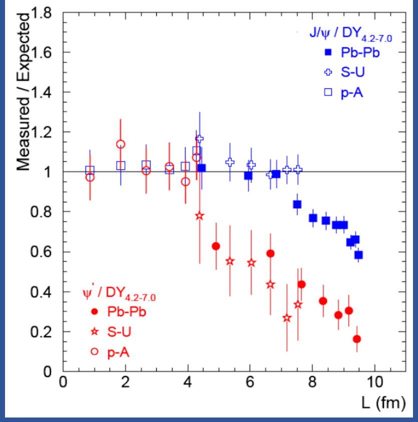
Several discoveries in almost 40 years…

Discovery of **anomalous J/ψ suppression**

Discovery of **sequential charmonium suppression**

} SPS





Several discoveries in almost 40 years…

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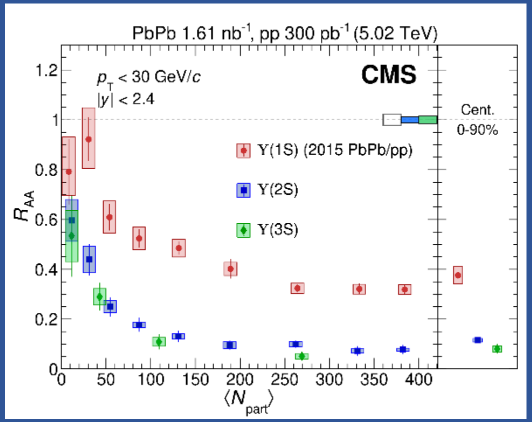
Discovery of **sequential charmonium suppression**

SPS

Discovery of **sequential bottomonium suppression**

LHC



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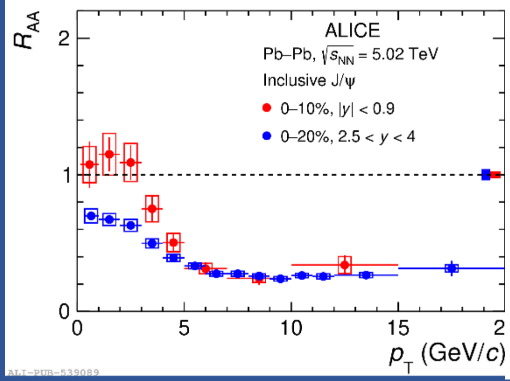
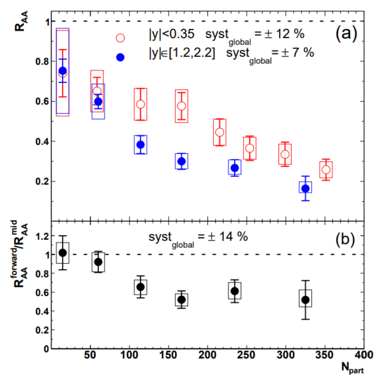
Discovery of **sequential bottomonium suppression** } LHC

Discovery of **J/ψ regeneration** } RHIC LHC





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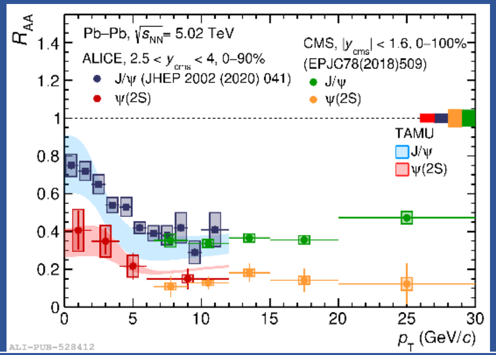
Discovery of **anomalous J/ψ suppression**
Discovery of **sequential charmonium suppression**
} SPS

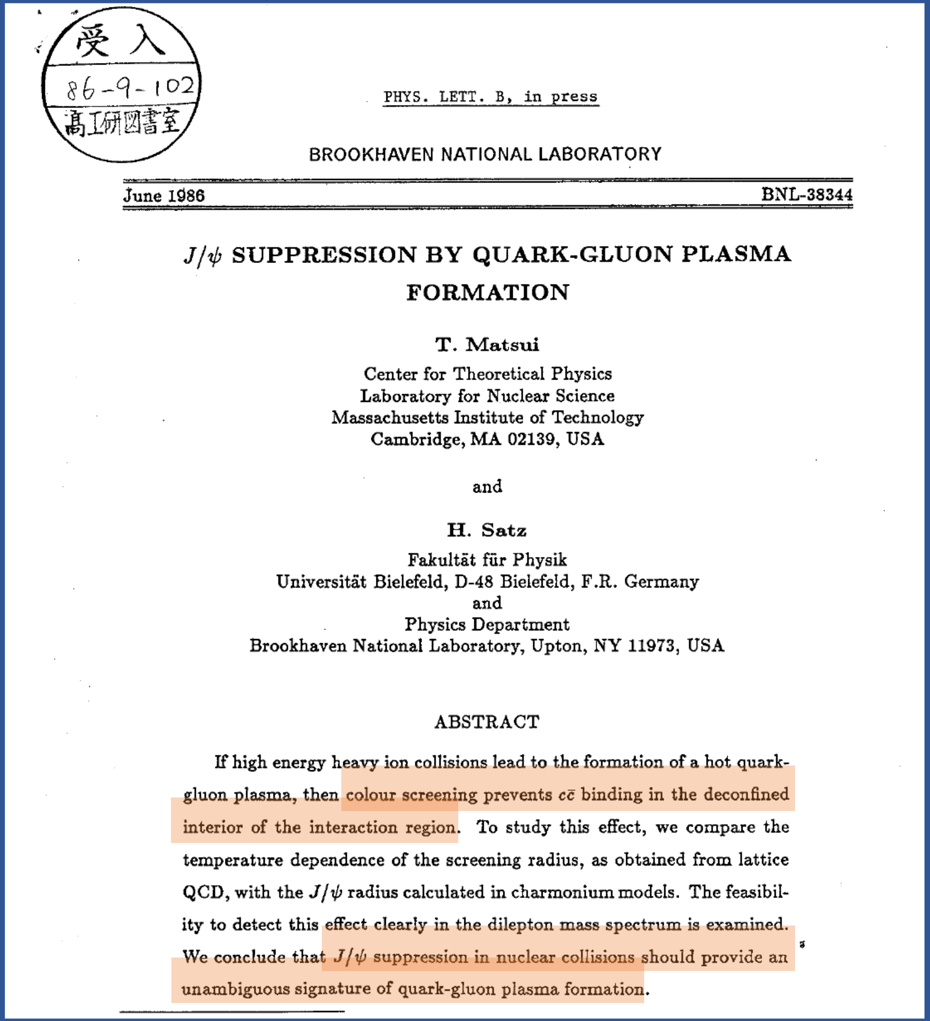
Discovery of **sequential bottomonium suppression** } LHC

Discovery of **J/ψ regeneration** } RHIC, LHC

Observation of **sequential charmonium regeneration** } LHC



The starting point



PHYS. LETT. B, in press

BROOKHAVEN NATIONAL LABORATORY

June 1986 BNL-38344

J/ψ SUPPRESSION BY QUARK-GLUON PLASMA FORMATION

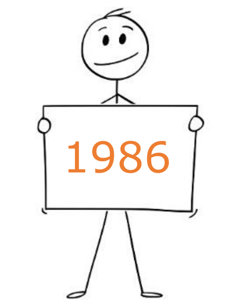
T. Matsui
Center for Theoretical Physics
Laboratory for Nuclear Science
Massachusetts Institute of Technology
Cambridge, MA 02139, USA

and

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

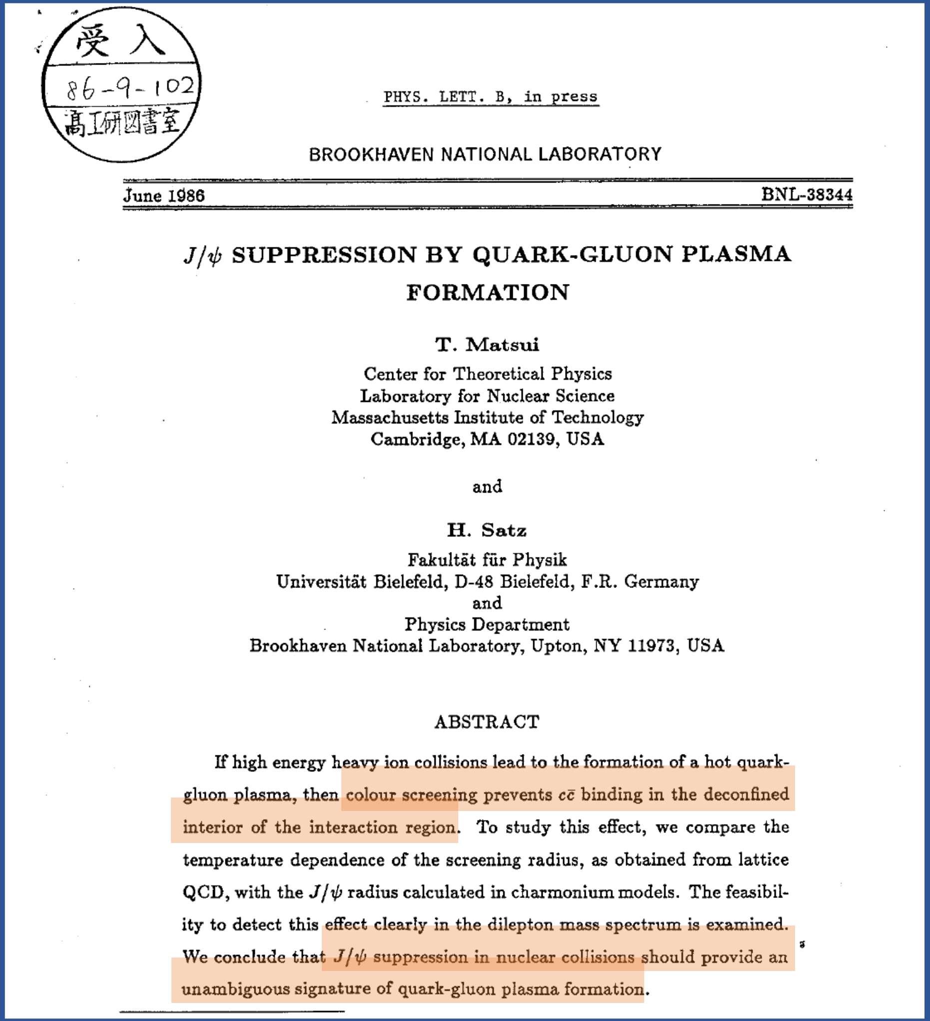
ABSTRACT

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.



From **theory…**

The starting point



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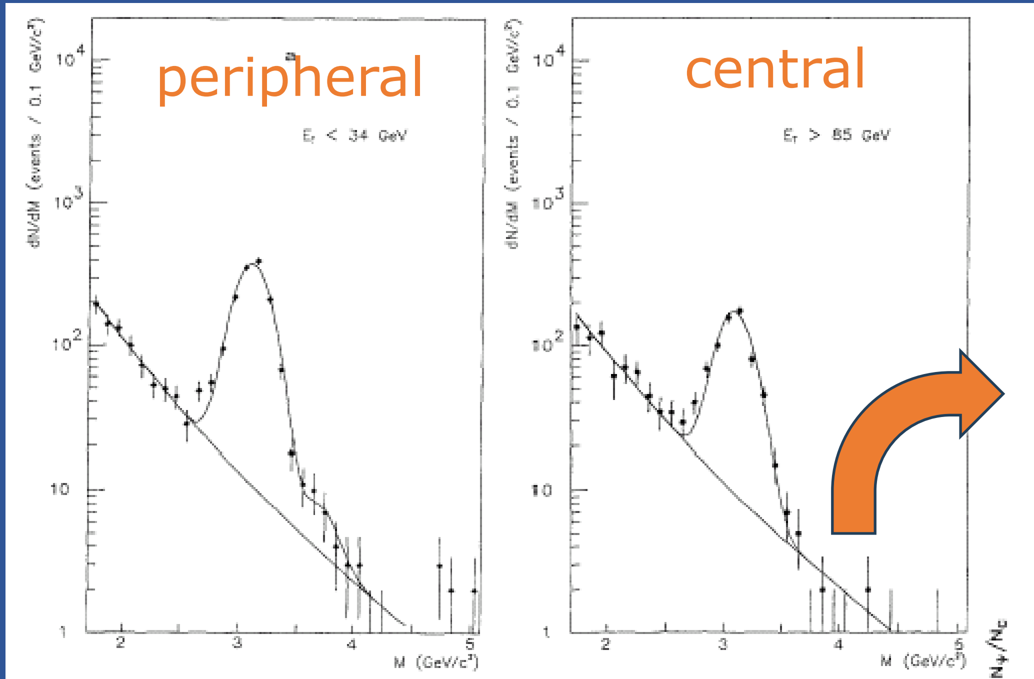

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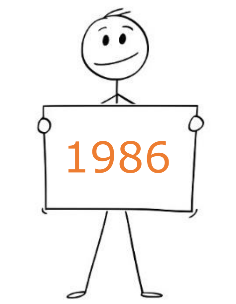
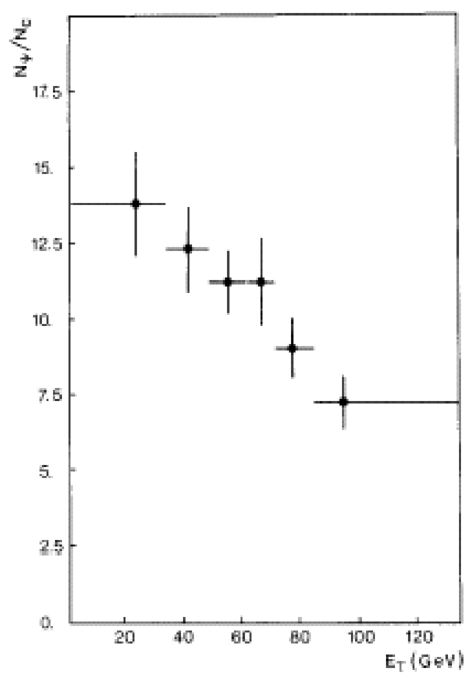
NA38, Z. Phys. 38(1988) 117



Is also ψ(2S) suppressed ?

O-U collisions at $\sqrt{s_{NN}} \sim 20$ GeV
N_ψ/N_c decreases by a factor ~2
from peripheral to central collisions



… to **experiment**

The basic argument

- At T=0 the cc interaction can be described by the potential

$$V(r) = -\frac{\alpha}{r} + kr$$

Coulomb term
$\alpha \sim 0.5$

Confinement term

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- At deconfinement the confinement term vanishes and the Coulomb term is screened

$$V(r) = -\frac{\alpha}{r} e^{-r/\lambda_D(T)}$$

Debye length

The basic argument

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Coulomb term $\alpha \sim 0.5$

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Debye length

- The energy of the system can be written as

$$E = \frac{\vec{p}^2}{2\mu} - \frac{\alpha}{r} e^{-r/\lambda_D}$$

Reduced mass = $m_{cc}/2 \sim 1.5$ GeV

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- Bound state condition can be obtained by minimizing E; one easily gets

$$x(1+x)e^{-x} = \frac{1}{\alpha\mu\lambda_D}$$

$x=r/\lambda_D$

The basic argument

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- Bound state condition can be obtained by minimizing E; one easily gets

$$x(1+x)e^{-x} = \frac{1}{\alpha\mu\lambda_D}$$

$x=r/\lambda_D$

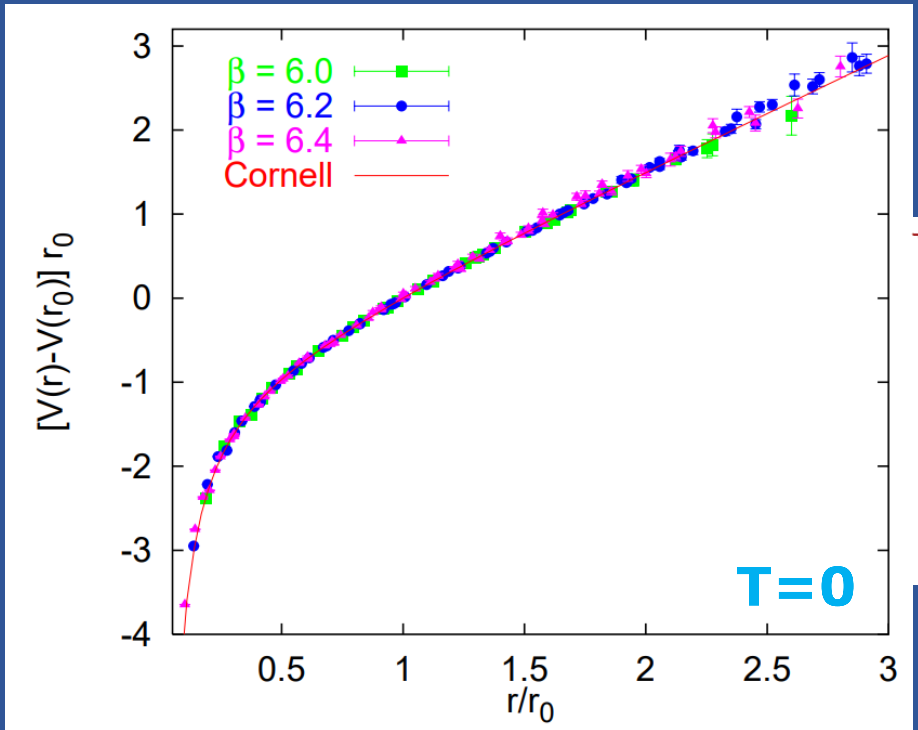
- The above relation does **not** admit solutions if $\frac{1}{0.84\alpha\mu} > \lambda_D$ i.e. $\lambda_D \lesssim 0.6\ \mathrm{fm}$

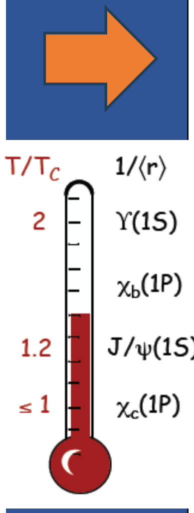
Indications already in the '80s that $\lambda_D \propto T^{-1}$ and **melting conditions** met at T~ 200 MeV

actual λ_D value to be obtained from lattice calculations

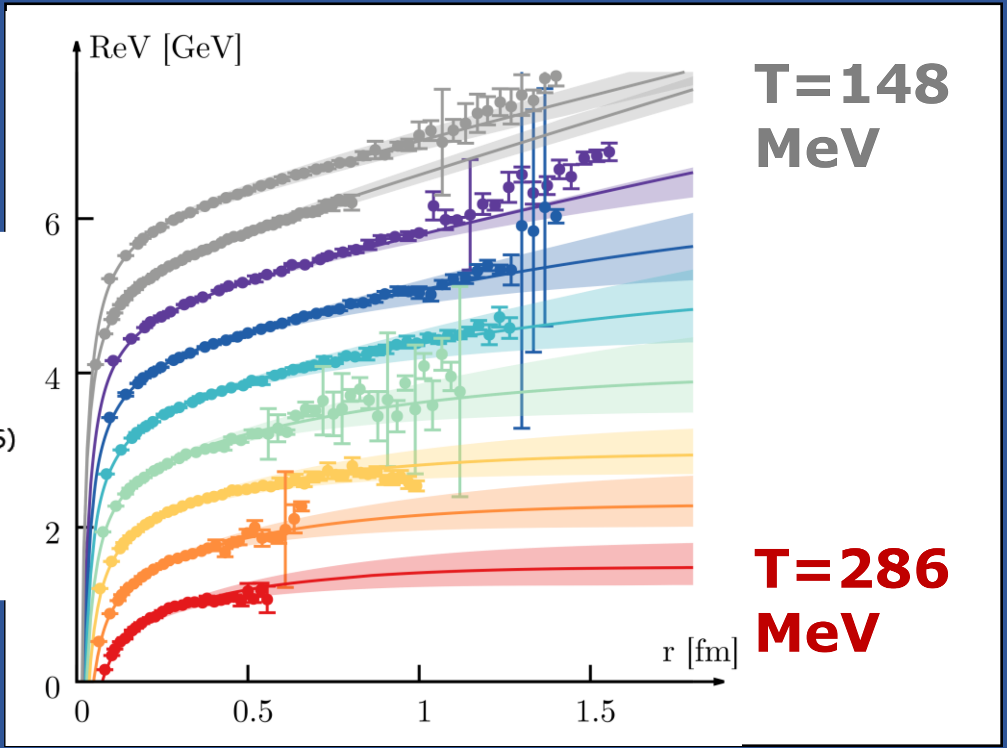
Lattice calculations and potentials

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

Hot debates

From the QM87 summary talk

The most provocative observation, reported by NA 38 [13], was that J/ψ production seems to be suppressed by $\sim 30\%$ in high E_T events. The second provocative

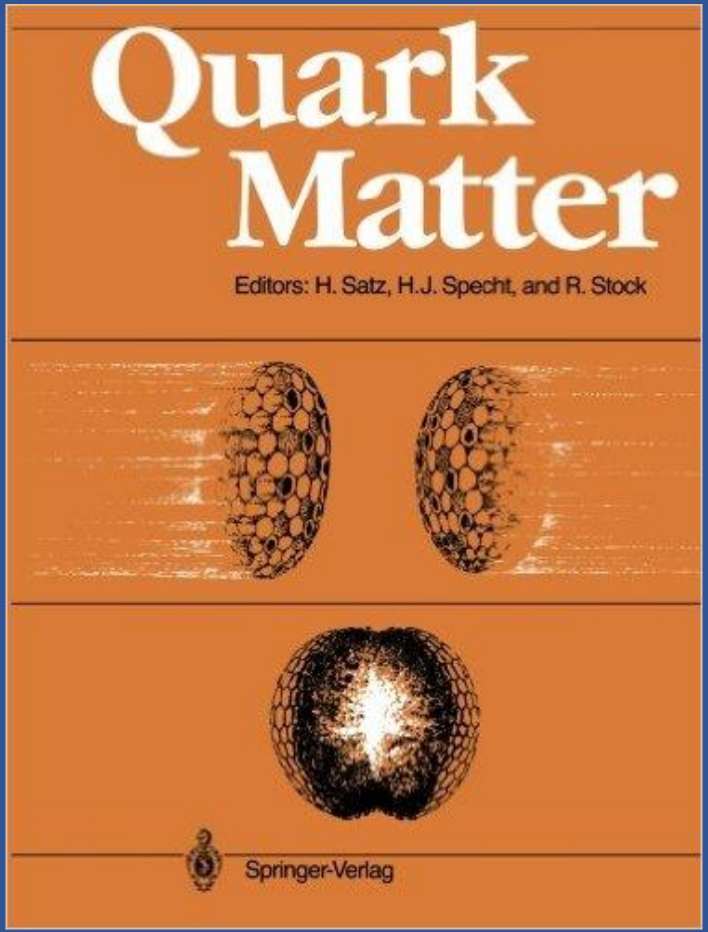
3 Puzzles

3.1 J/Psi suppression

$$N_\psi/N_c = \begin{cases} 9.3 \pm 0.6 & \text{for } E_T < 28 \text{ GeV} \\ 5.9 \pm 0.4 & \text{for } E_T > 50 \text{ GeV.} \end{cases} \quad (10)$$

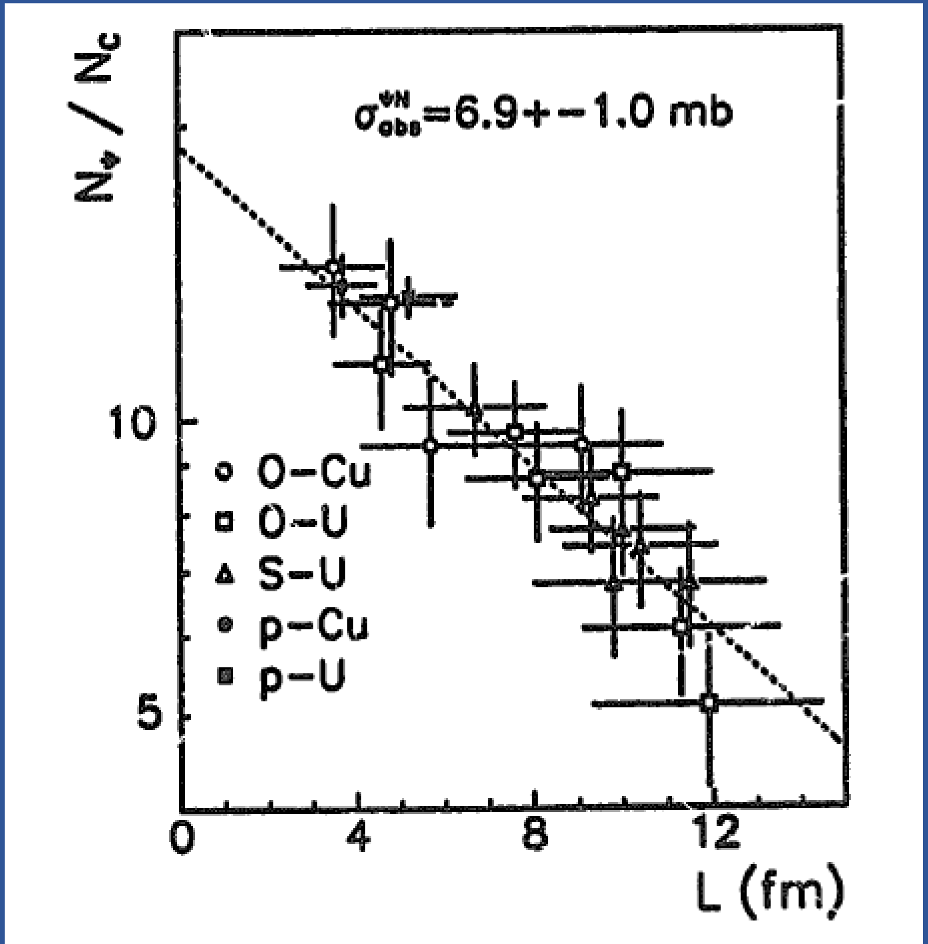
This 30% reduction of ψ production caused the most controversy at Quark Matter '87.

There are naturally several caveats that need further consideration. First, there is the problem of prov-



- ➢ Can **competing sources** of J/ψ dissociation involving hadronic interactions with cold nuclear matter and/or hadronic medium reproduce the observations ?

Where is the Quark-Gluon Plasma ?



C. Gerschel et al., PLB207 (1988)253

Nuclear Physics A544 (1992) 513c–516c
North-Holland, Amsterdam

NUCLEAR PHYSICS A

Comparison of J/ψ-Suppression in Photon, Hadron and Nucleus-Nucleus Collisions : Where is the Quark-Gluon Plasma ?

C. Gerschel[a] and J. Hüfner[b]

p-A collision results imply **significant dissociation cross sections in cold nuclear matter (CNM)**

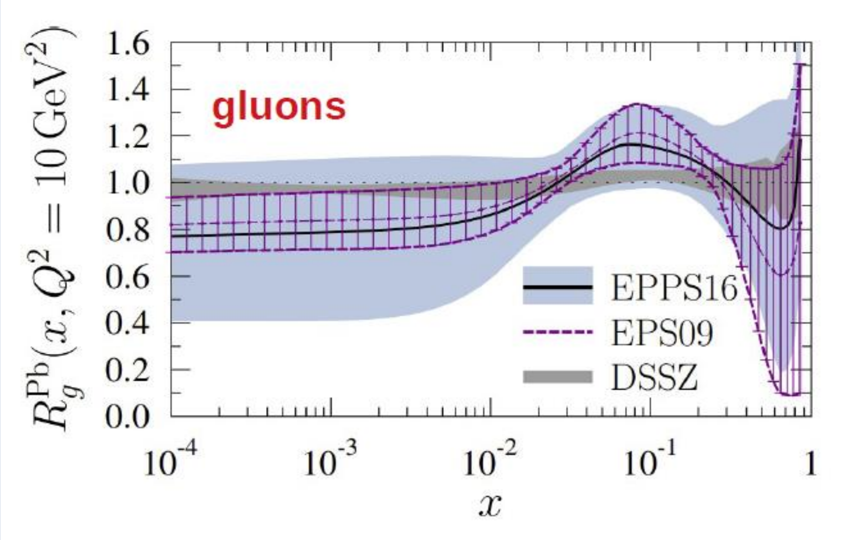
→ Crucial ingredient in the interpretation of the data
→ Stimulated an intense experimental program of p-A studies at both CERN and FNAL

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

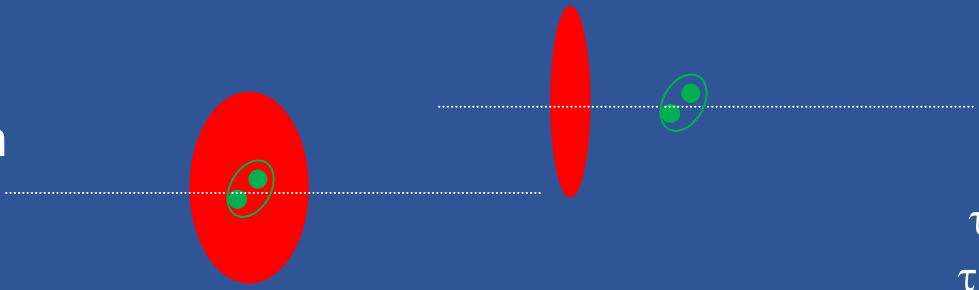
Initial state effects:
moderate anti-shadowing
$x \sim 10^{-1}$ (y=0)



LHC

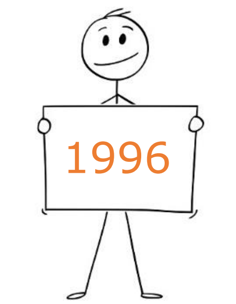
Initial state effects:
shadowing
$x \sim 10^{-5}$ (y~3)
$x \sim 10^{-3}$ (y=0)
$x \sim 10^{-2}$ (y~-3)

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

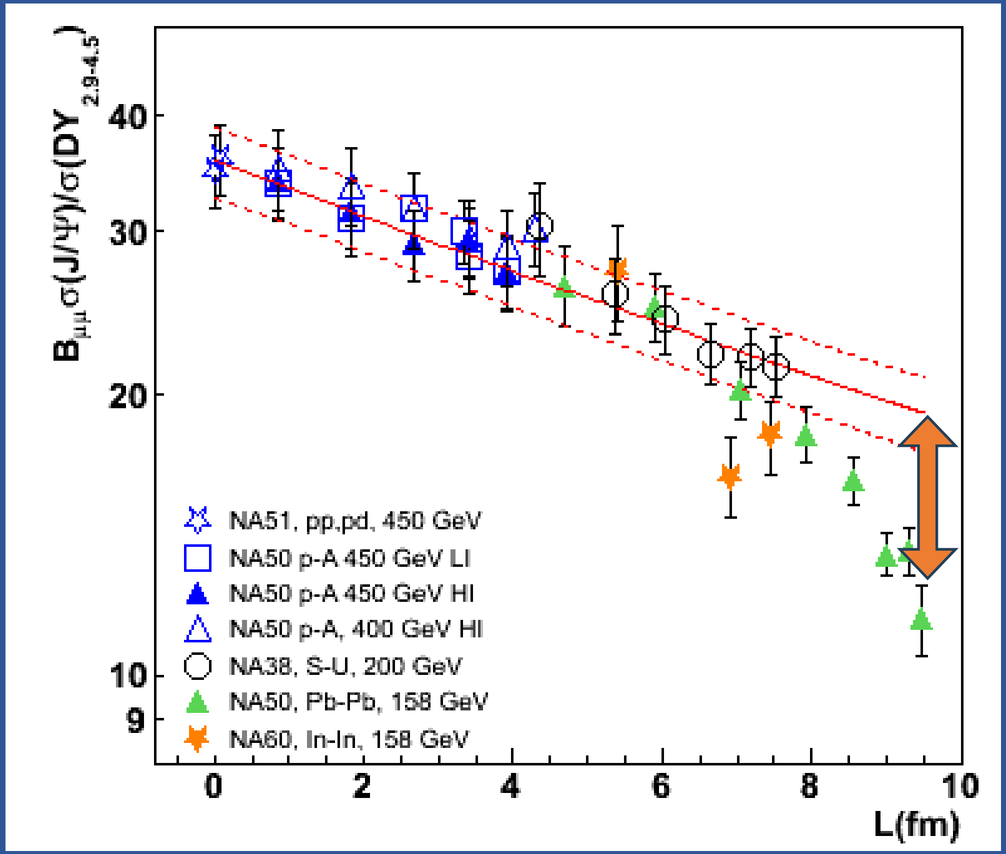


(Final state) CNM effects:
negligible, extremely short crossing time
$\tau = L/(\beta_z\gamma) \sim 7\ 10^{-5}$ fm/c (y~3)
$\tau = L/(\beta_z\gamma) \sim 4\ 10^{-2}$ fm/c (y~-3)

The "anomalous" suppression



NA50, Phys.Lett.B 410 (1997) 337-343



Anomalous suppression

Central Pb-Pb collisions clearly depart from the behaviour of p-A and S-U data, where only CNM is assumed to be present

J/ψ suppression in Pb Pb collisions: a hint of quark-gluon plasma production?

J.P. Blaizot

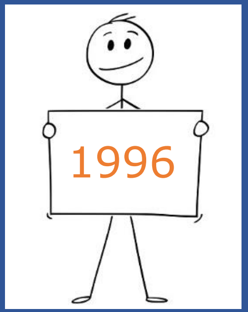
Therefore, it is interesting to speculate whether the new phase of strong absorption may be the quark-gluon plasma.

C.Y. Wong

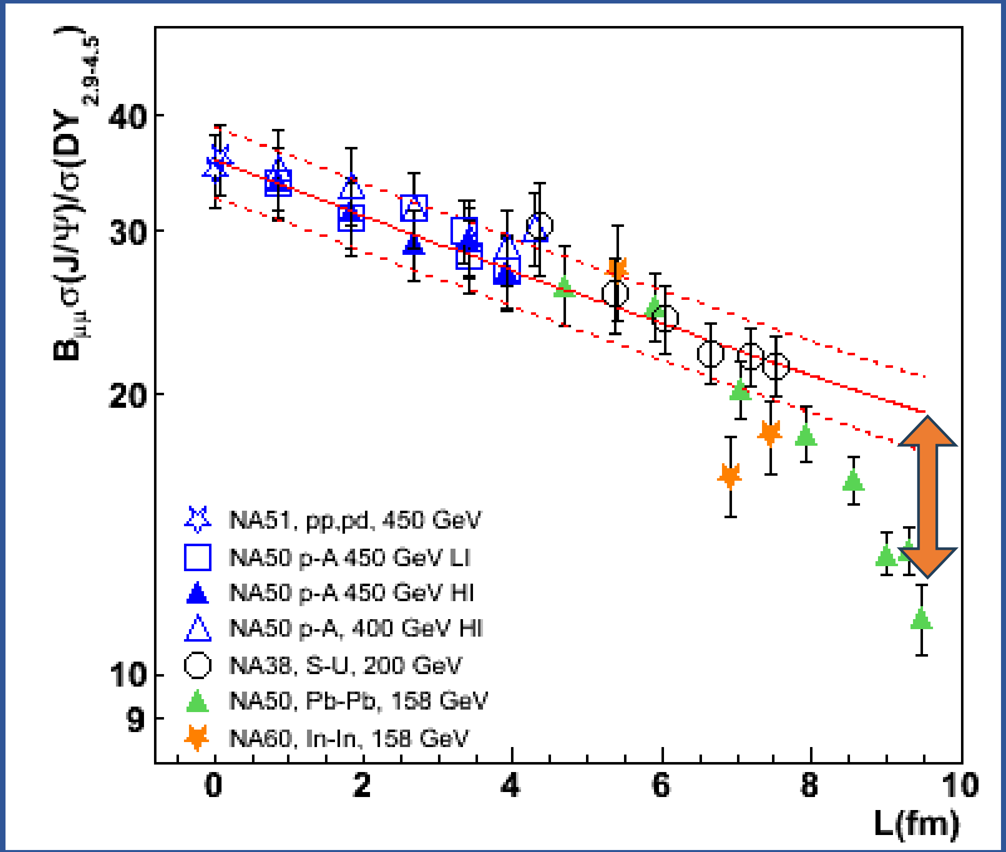
Is this suppression really anomalous? Can we conclude that the quark-gluon plasma is already discovered?

D. Kharzeev

The "anomalous" suppression



NA50, Phys.Lett.B 410 (1997) 337-343

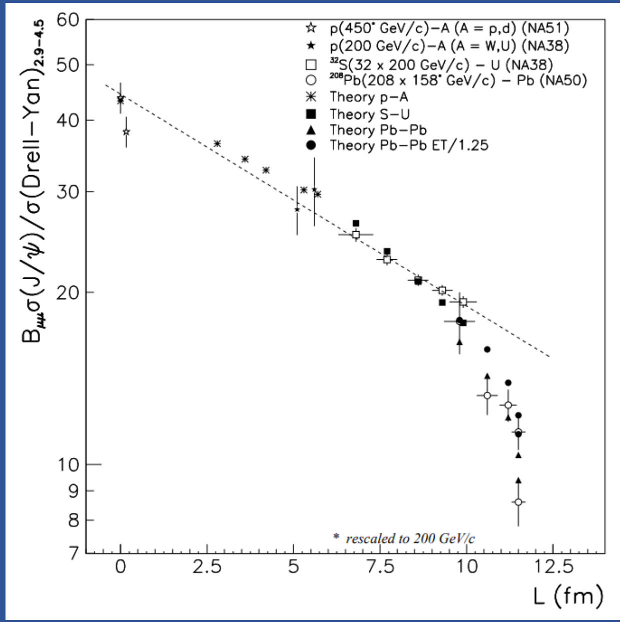


Anomalous suppression

Central Pb-Pb collisions clearly depart from the behaviour of p-A and S-U data, where only CNM is assumed to be present

In conclusion, combining nuclear absorption and final state interaction with co-moving hadrons, we have obtained a reasonable description of the J/ψ and ψ ′ data.

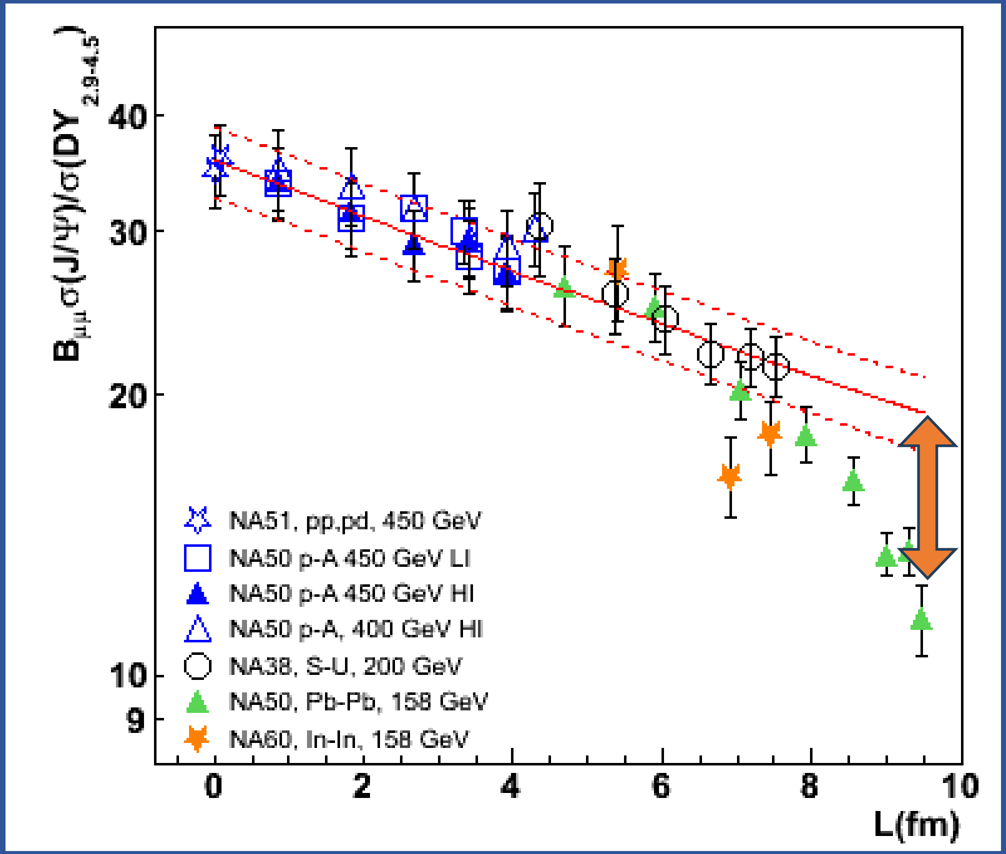
A. Capella



Assuming $\sigma_{\psi\text{-co}} = 0.6$ mb

The “anomalous” suppression

NA50, Phys.Lett.B 410 (1997) 337-343

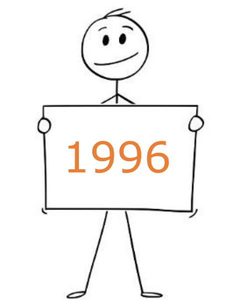


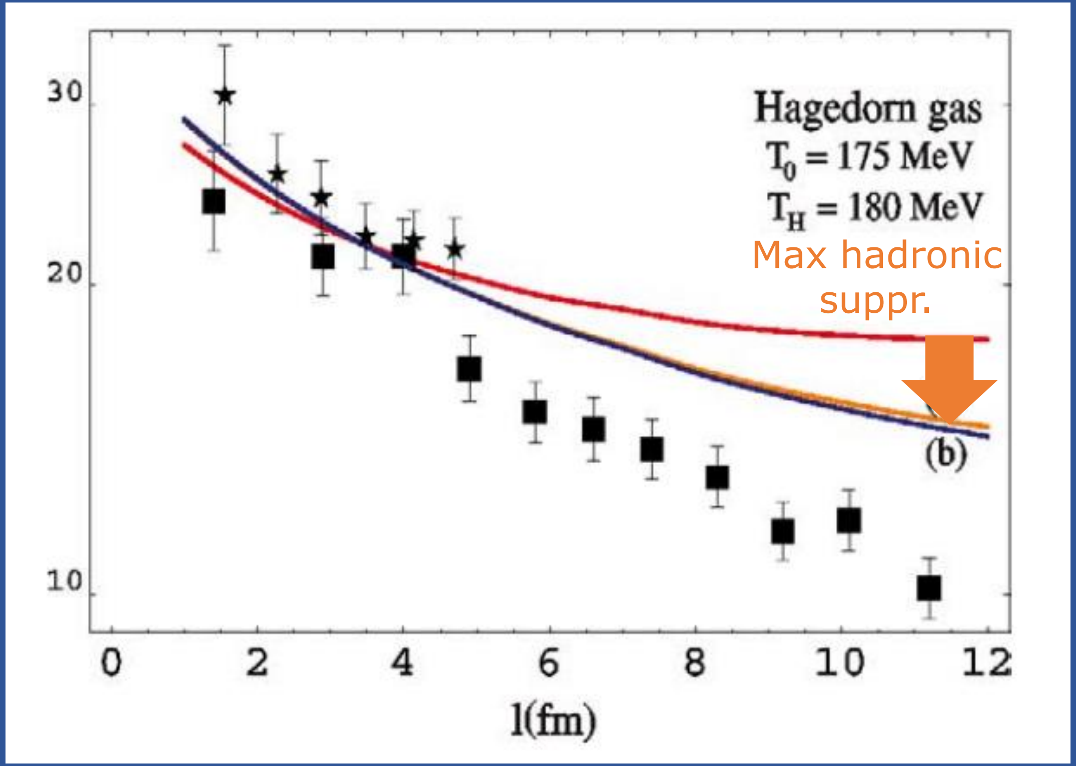
Anomalous suppression

Central Pb-Pb collisions clearly depart from the behaviour of p-A and S-U data, where only CNM is assumed to be present

The dissociation curve cannot become harder, and the prediction falls short from explaining the drop observed by NA50

L. Maiani

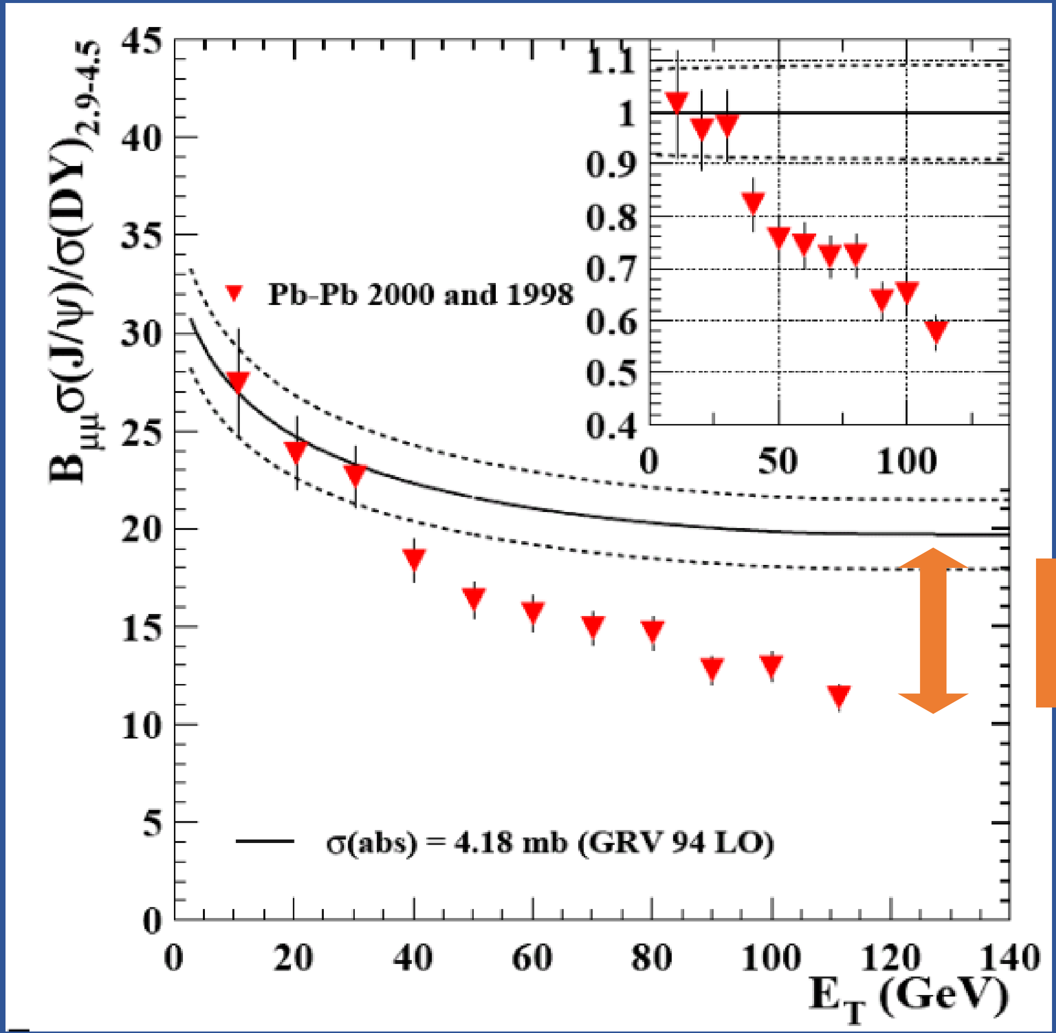




Maiani et al., NP A 748 (2005) 209–225

Feed-down

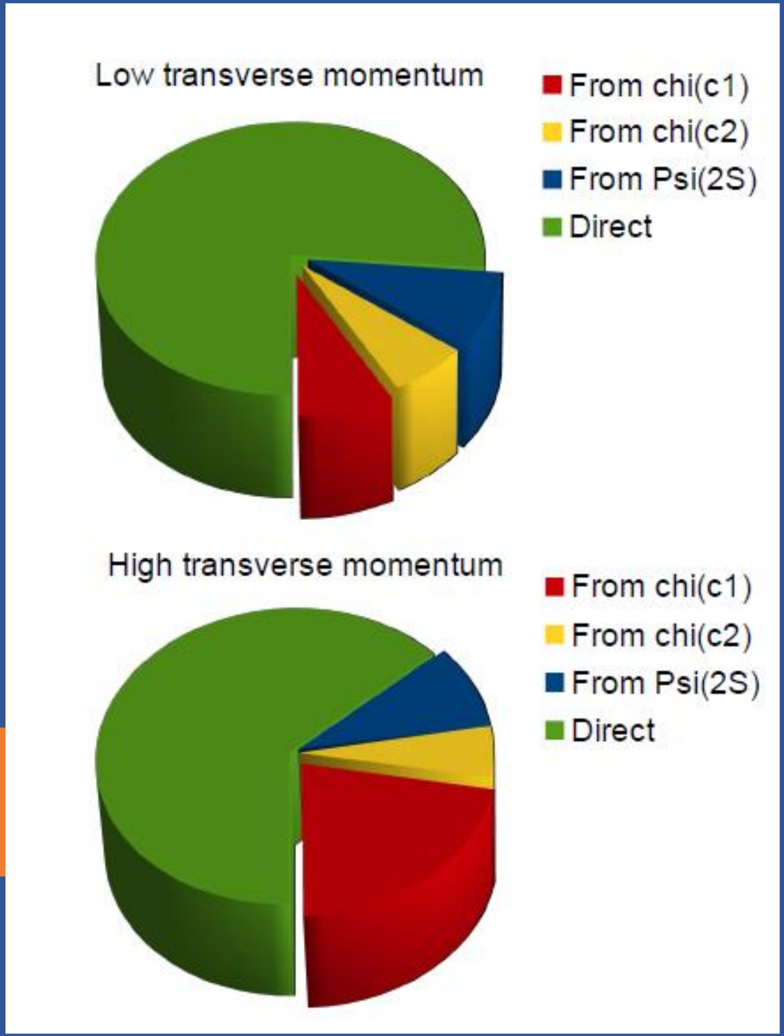
J.P. Lansberg, Phys.Rept. 889 (2020) 1



NA50, Eur.Phys.J.C 39 (2005) 335

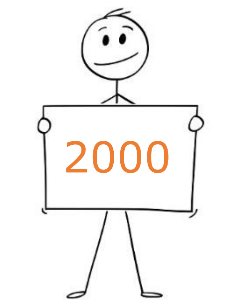
Qualitatively consistent with the contribution of feed-down decays from $\psi(2S)$ and χ_c

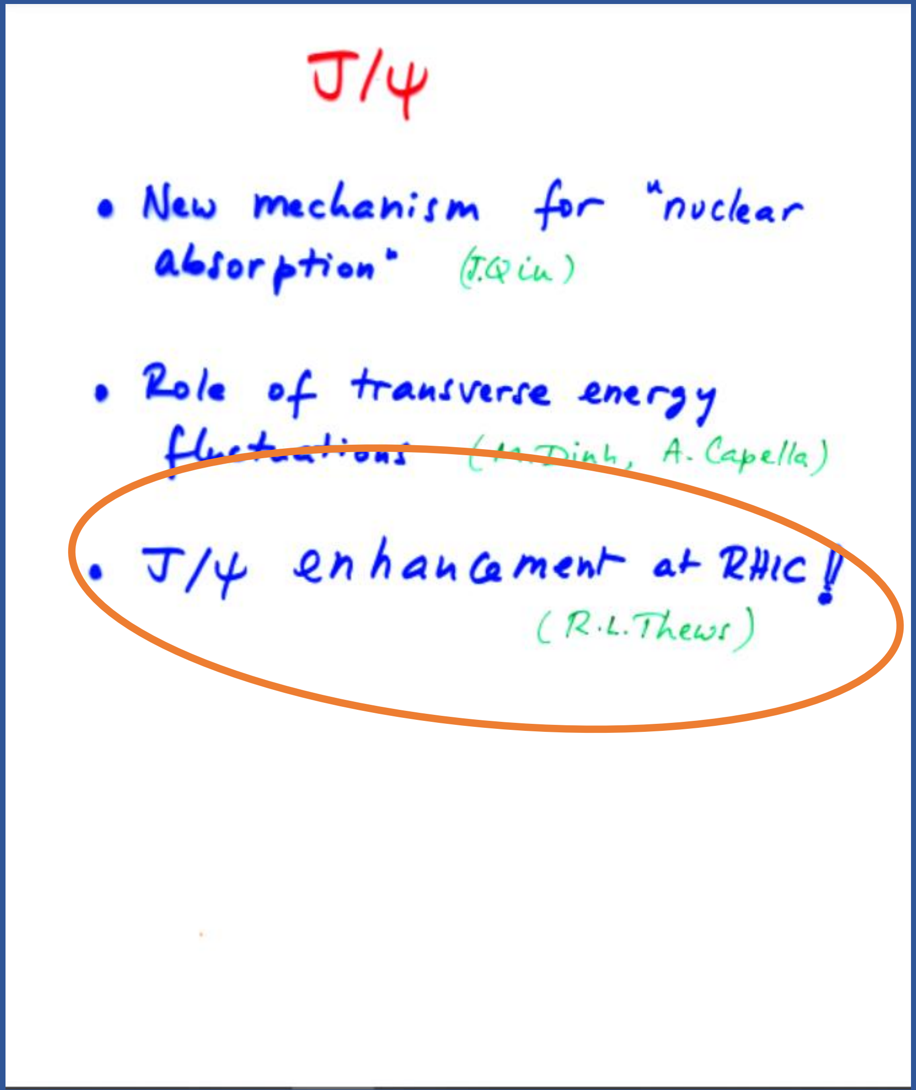
a 30-40% `anomalous' suppression effect



Γ_{10}	$J/\psi(1S)$anything	(61.4 ±0.6) %	← $\psi(2S)$
Γ_{93}	$\gamma J/\psi(1S)$	(1.40±0.05) %	← χ_{c0}
Γ_{93}	$\gamma J/\psi(1S)$	(34.3 ±1.0) %	← χ_{c1}
Γ_{93}	$\gamma J/\psi(1S)$	(19.0 ±0.5) %	← χ_{c2}

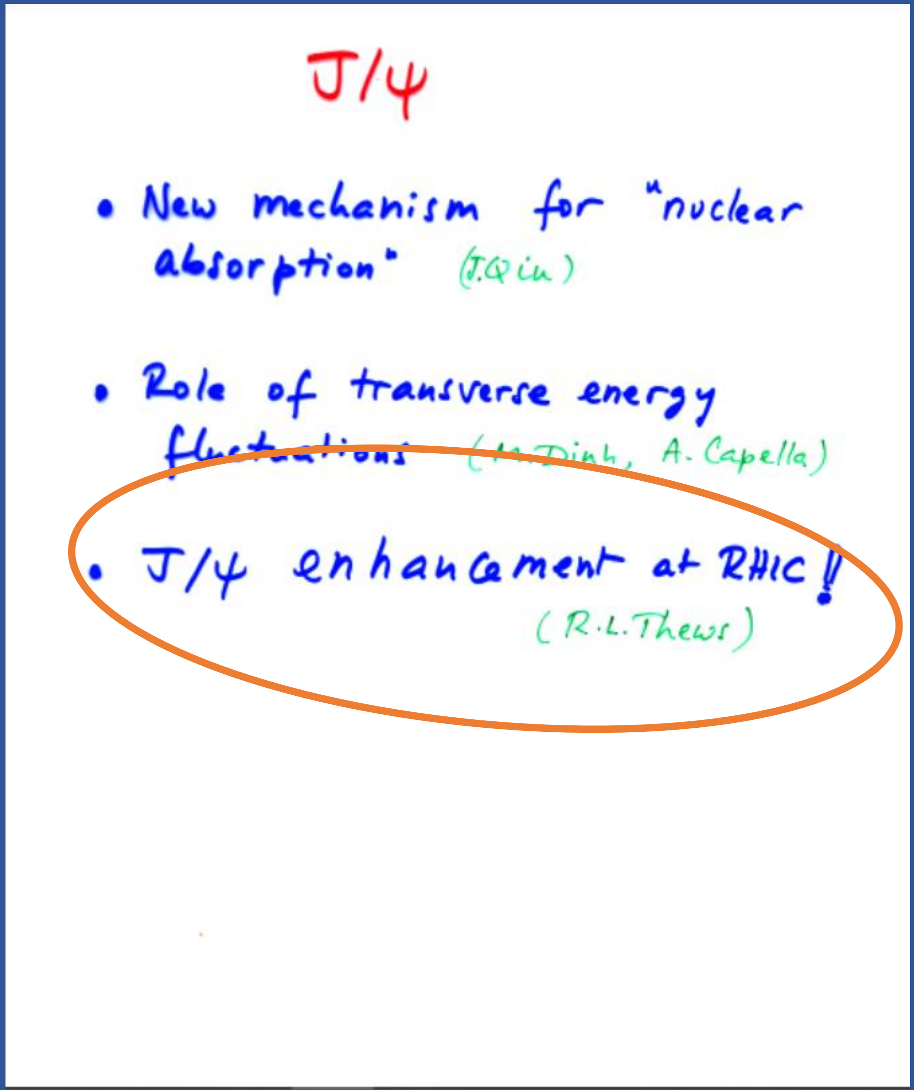
Enter RHIC, big expectations



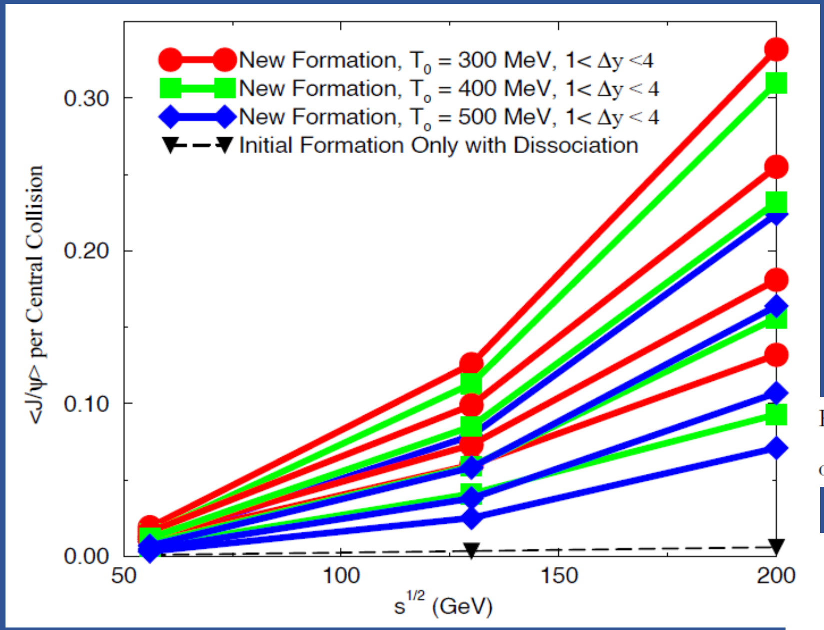


J.P. Blaizot, **QM2001** summary talk

Enter RHIC, big expectations

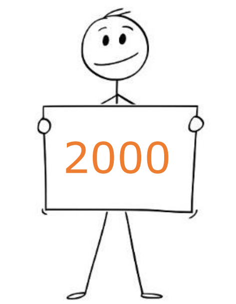


J.P. Blaizot, **QM2001** summary talk



Strong dependence on collision energy

Quadratic dependence on the initial formation rate

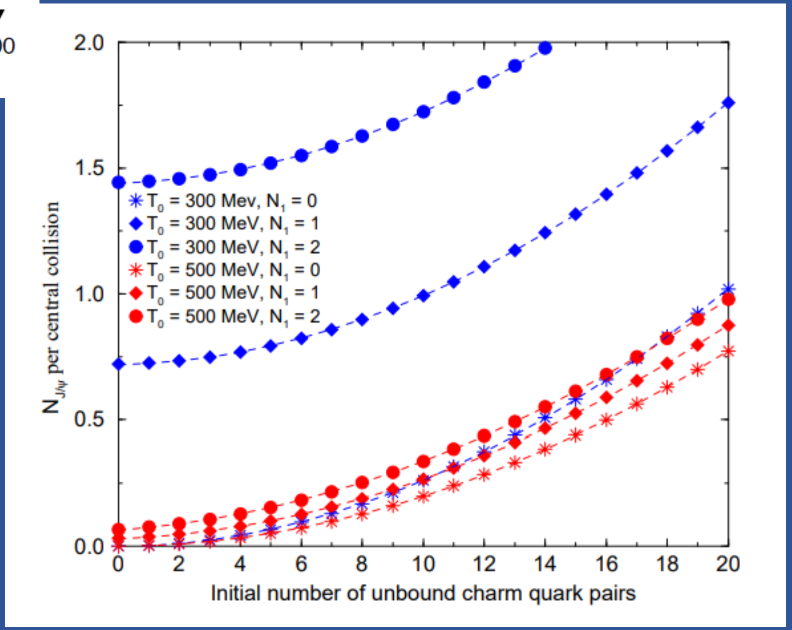


PHYSICAL REVIEW C, VOLUME 63, 054905

Enhanced J/ψ production in deconfined quark matter

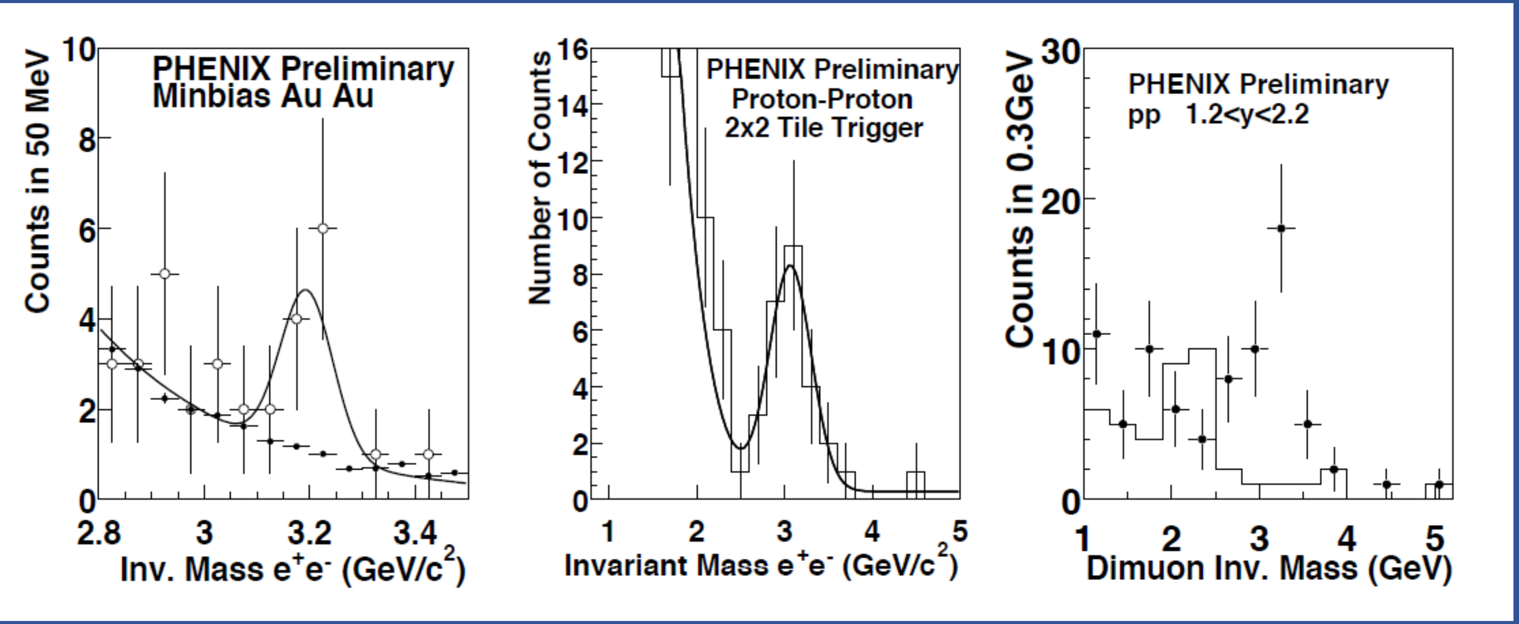
Robert L. Thews, Martin Schroedter, and Johann Rafelski
Department of Physics, University of Arizona, Tucson, Arizona 85721
(Received 29 August 2000; published 23 April 2001)

Experimental observation of such enhanced production would provide evidence for deconfinement unlikely to be compatible with competing scenarios.



Experiment follows theory

T. Frawley, **QM2002**



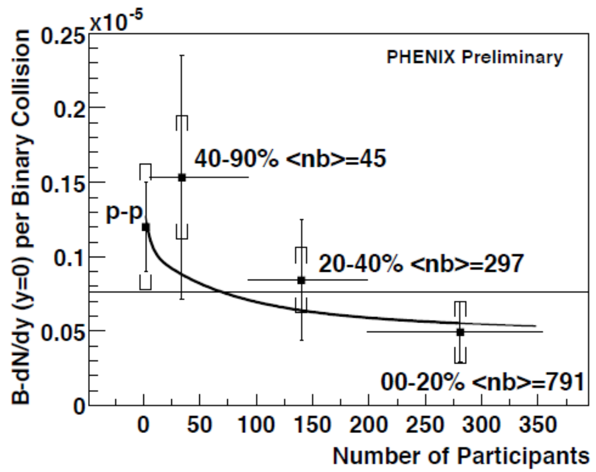
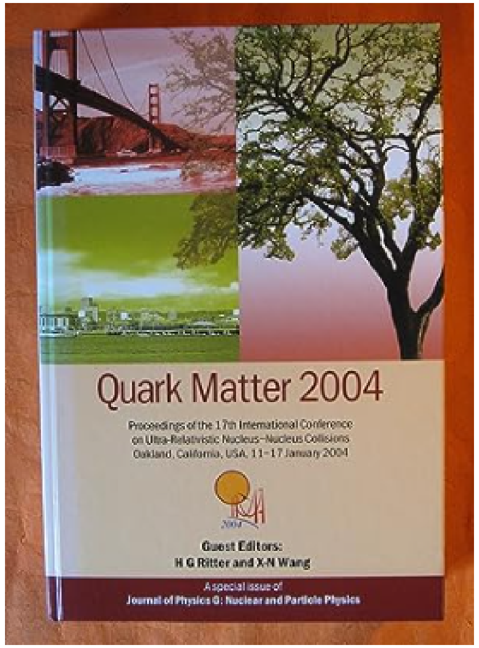


Figure 5. $J/\Psi \to ee$ branching ratio times dN/dy scaled by N_{binary}. The flat line is the best fit binary scaling value. The curve is a normal nuclear absorption model calculation [8].

Rather limited conclusions can be drawn from the data in Fig. 5 because of the large statistical and systematic uncertainties associated with this preliminary analysis. We have

- Collider vs fixed-target: integrating the same luminosity can be tough
  - Fixed target SPS (**2000**): 35 days, 1.2 10^7 Pb/s on a 4mm Pb target → L_{int} ~ 83 nb^{-1}
  - **Total** RHIC Au-Au $\sqrt{s_{NN}}$=200 GeV → L_{int} ~ 130 nb^{-1}

Intermezzo: our literature can be valuable



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Staff

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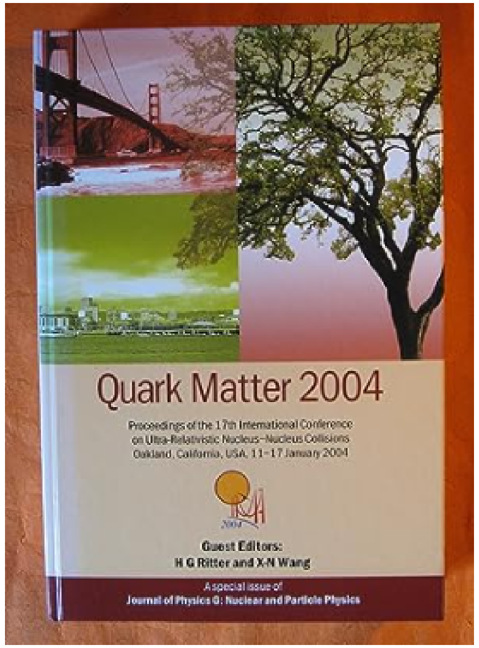
Intermezzo: our literature can be valuable



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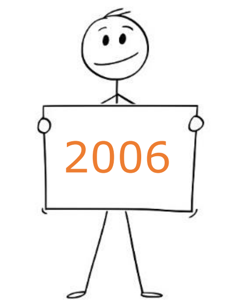
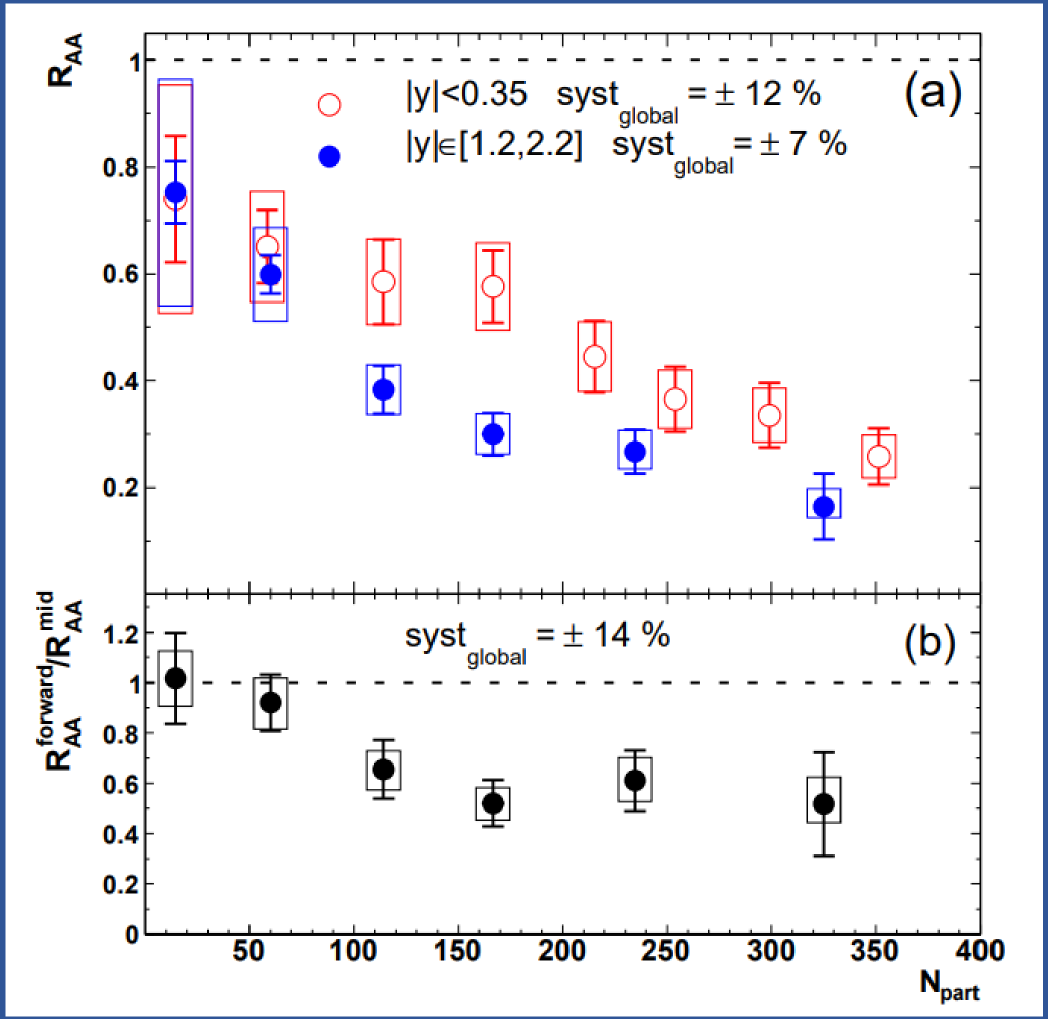
A surprising result

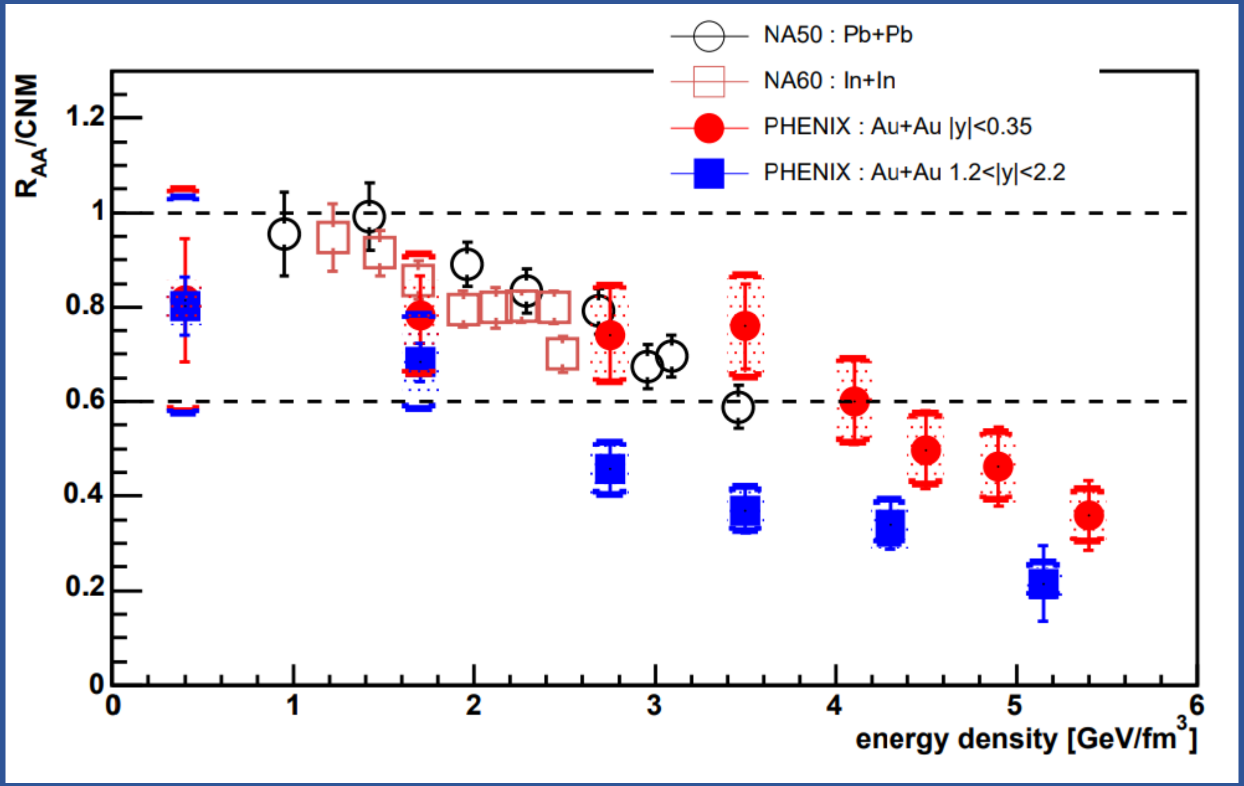




PHENIX, Phys.Rev.Lett.98:232002,2007

- For the first time measurements were performed in **two distinct rapidity ranges**
  - central vs forward y
- Drell-Yan reference becomes unpractical, as high mass dileptons dominated by open HF
  - Use R_{AA}
- Clear hierarchy: J/ψ more suppressed at forward y
  - Difficult to reconcile with the "traditional" suppression scenario
  - Can regeneration effects explain the observations ?

Comparing RHIC and SPS results



PHENIX, J.Phys.G34:S749-752,2007

- RHIC forward-y suppression larger than SPS midrapidity
- RHIC and SPS midrapidity suppression quite similar

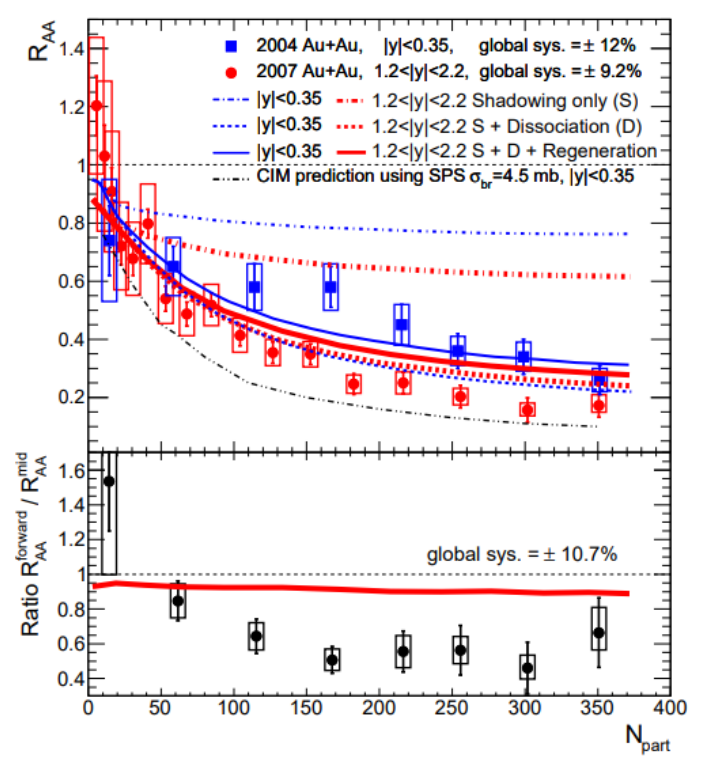
- Is J/ψ suppression stronger at RHIC but regeneration becomes important at midrapidity ?
- Is the similarity of RHIC and SPS midrapidity results a coincidence ?

- Caveat(s)
  - Assumptions in energy density calculations
  - Approximations in evaluation of CNM effects

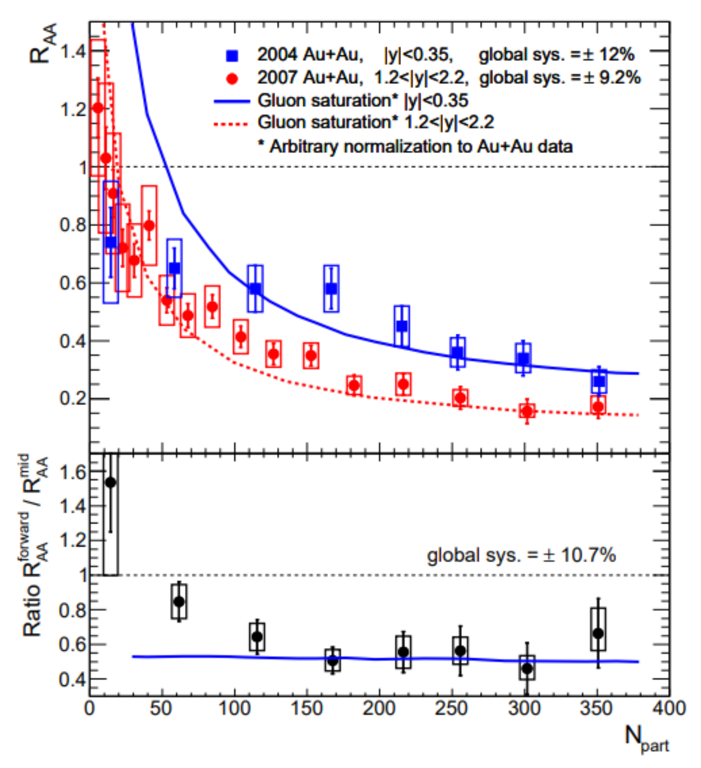
Detailed theory comparisons needed!

PHENIX, Phys. Rev. C **84**, 054912

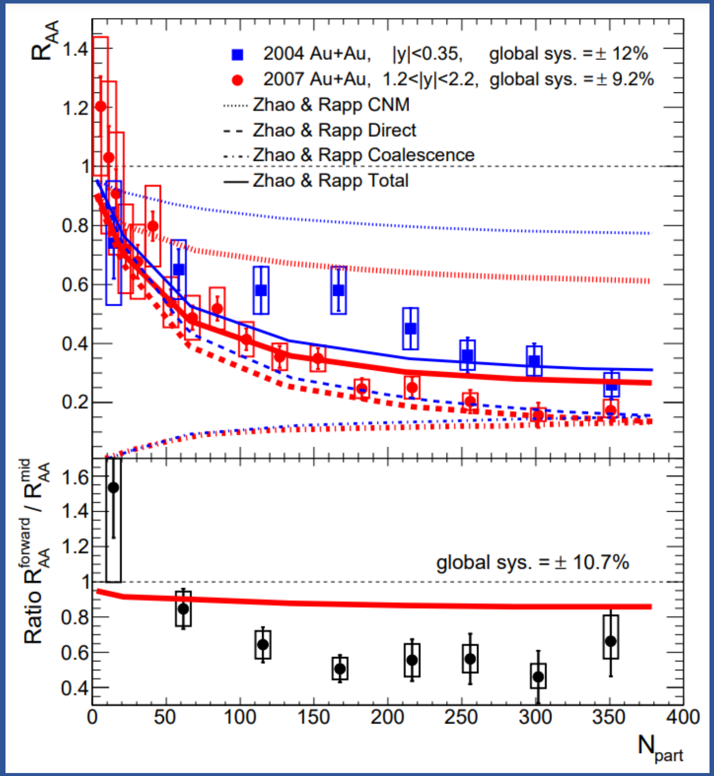
Suppression vs regeneration



Comover interaction model



Gluon saturation model



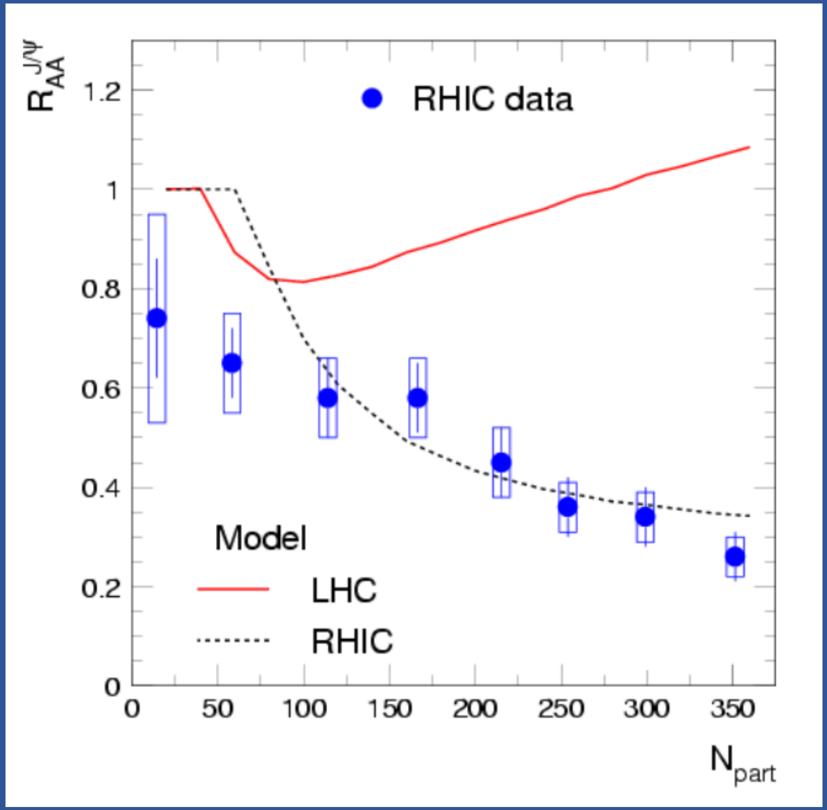
QGP/Hadron gas model

Combination of CNM and hot matter effects represents a tough task for phenomenology

We have presented new and more precise measurements of J/ψ nuclear modification at forward rapidity in Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV. The results confirm our earlier published findings of a larger suppression at forward compared with midrapidity. This, combined with the similar suppression of J/ψ at midrapidity between RHIC and lower energy measurements, remains an outstanding puzzle in terms of a full theoretical description.

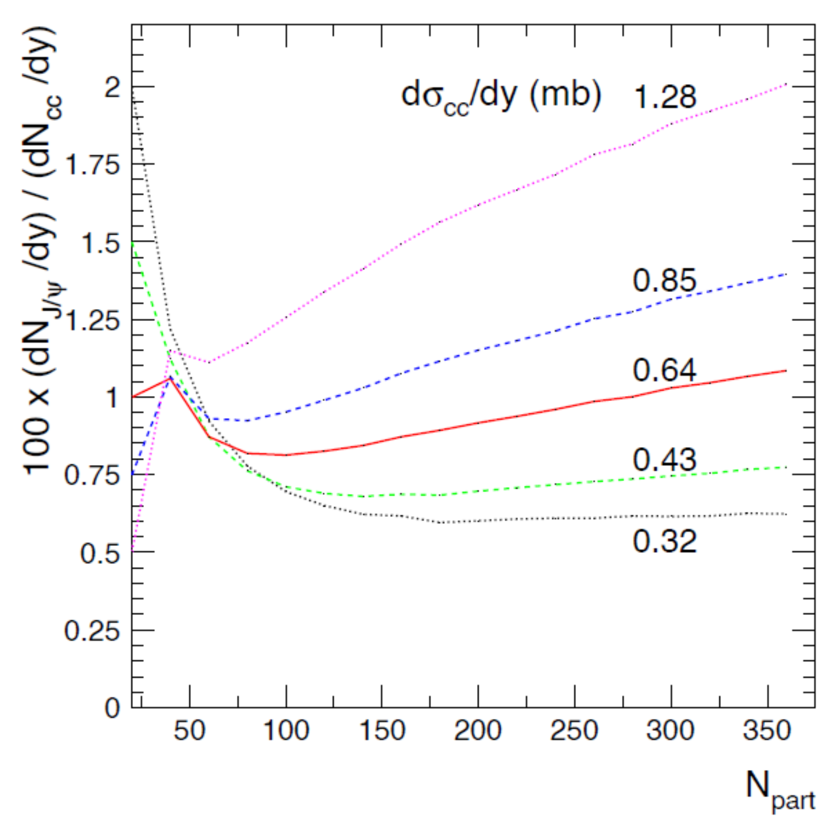
Moving to LHC energy

- Regeneration is an evidence of deconfinement, indications from RHIC experiments, but LHC represents the ideal testing ground → large charm quark multiplicity



Predictions based on the statistical hadronization model

- Charm produced in primary hard collisions
- Total number stays constant
- Thermal equilibration of charm in the QGP
- Quarkonia are **generated** (not regenerated) at T_c

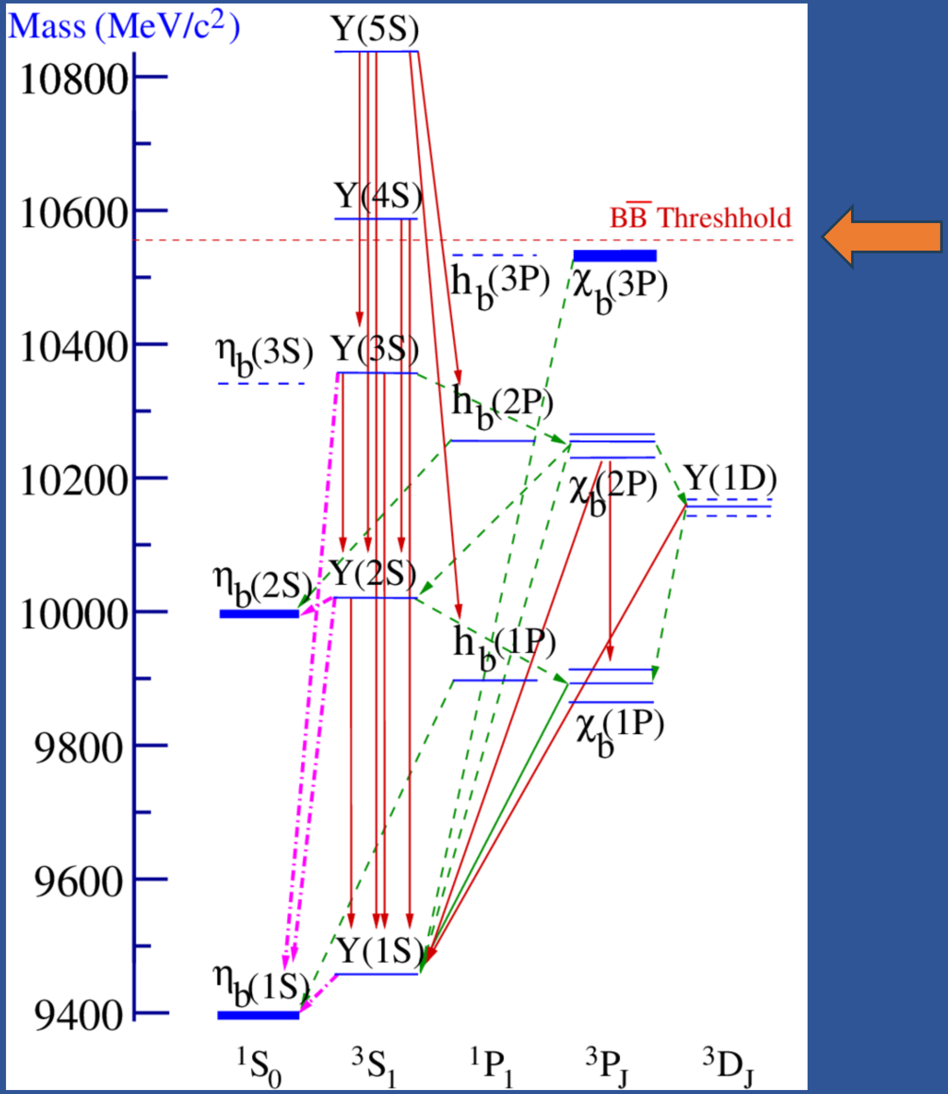


A.Andronic et al., Nucl.Phys.A789:334-356,2007
P. Braun-Munzinger and J. Stachel, PLB490 (2000) 196

Very strong dependence on charm cross section!

…but let's first examine bottomonium

- Below open beauty threshold
  - **Three vector states**, with small but non negligible BR to dileptons (~2%)with extremely different binding energies



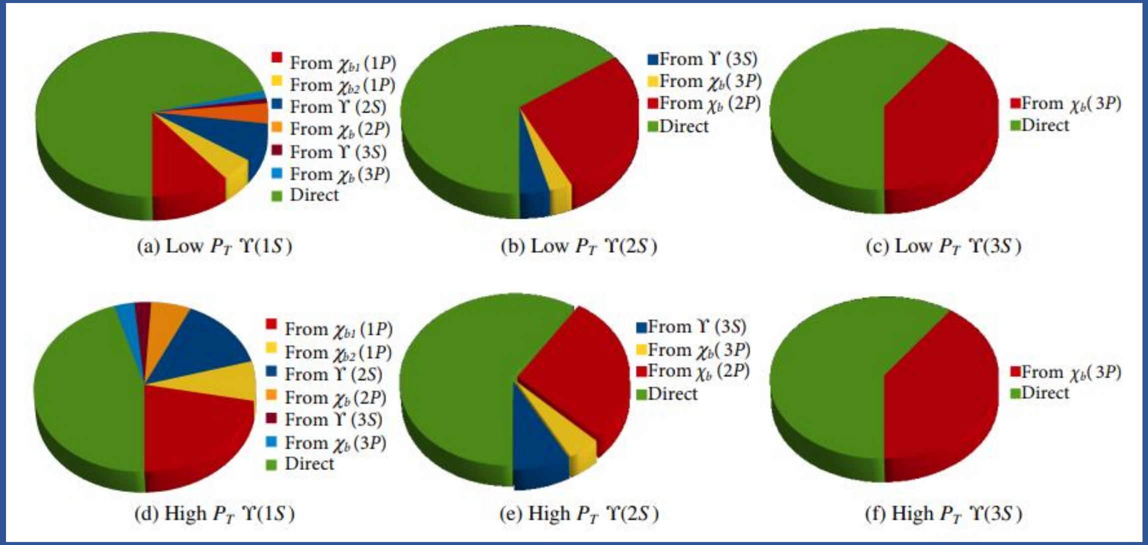
from J.P. Lansberg, Phys. Rep. 889(2020) 1

…but let’s first examine bottomonium

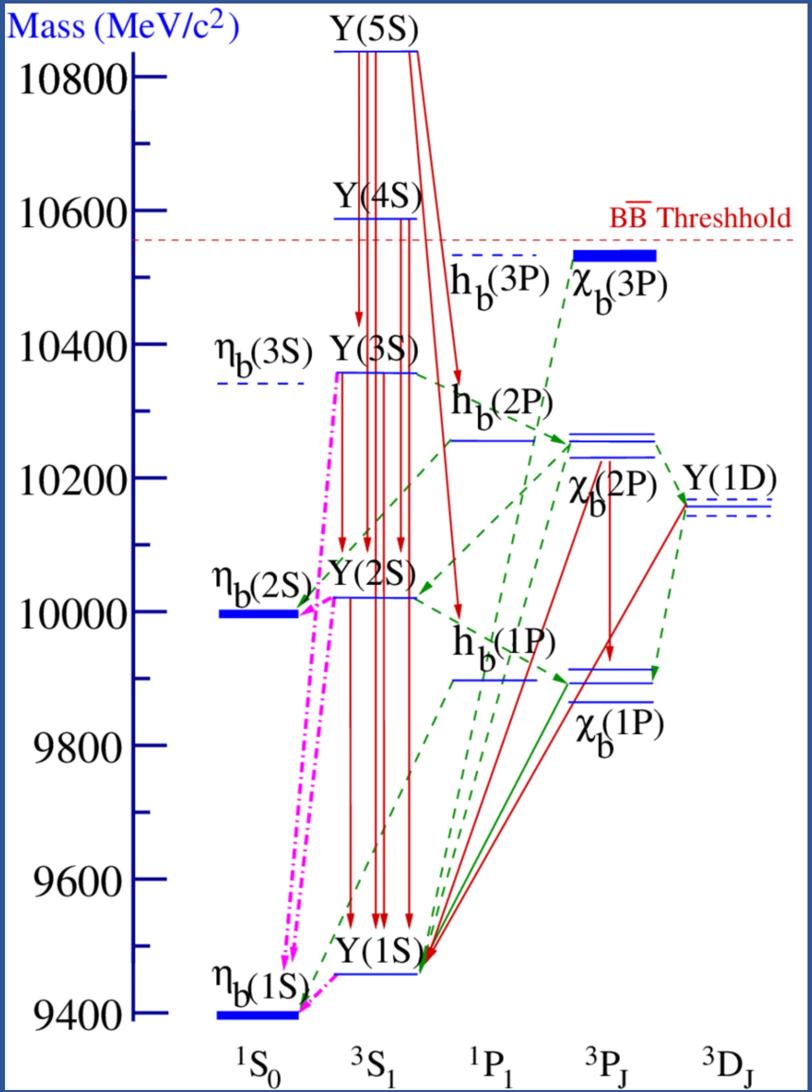
- Below open beauty threshold

  - **Three vector states**, with small but non negligible BR to dileptons (~2%)with extremely different binding energies

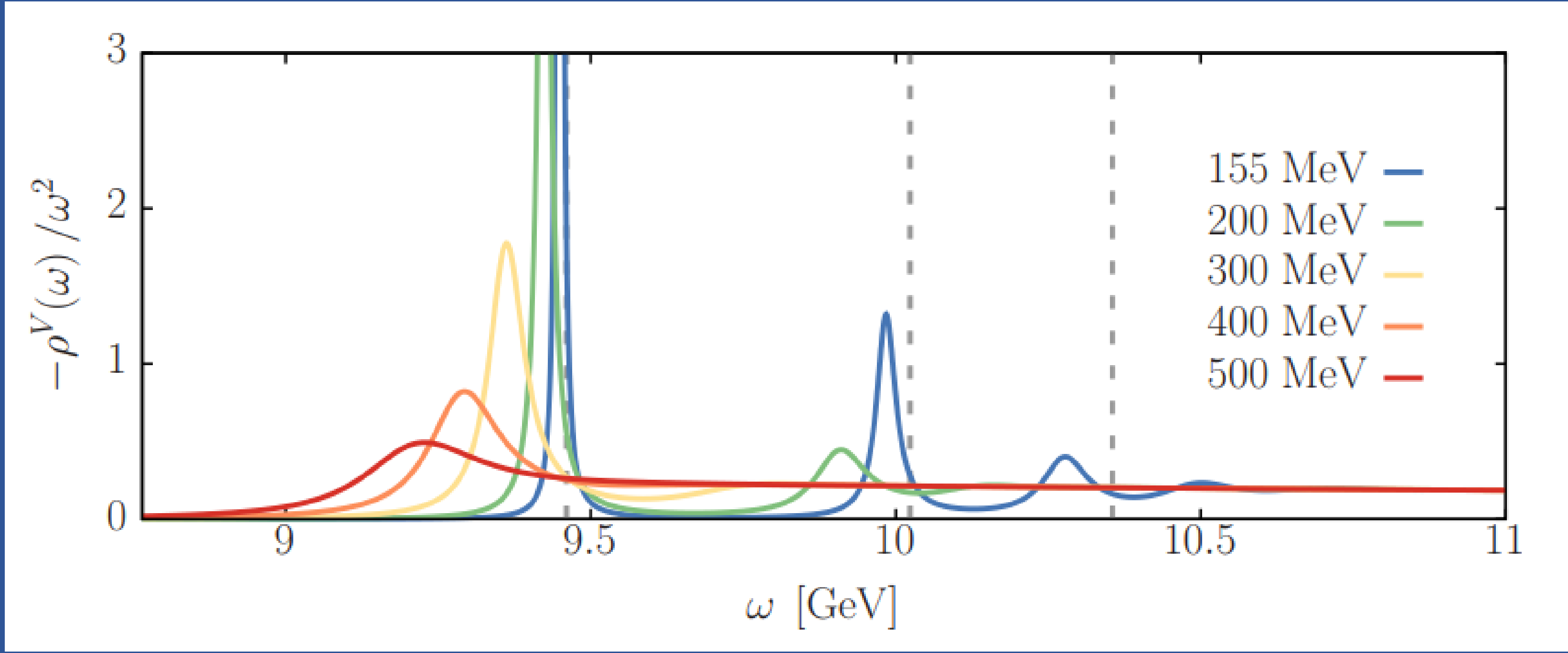
  - Rather complicate feed-down structure, to be considered in the interpretation of the results

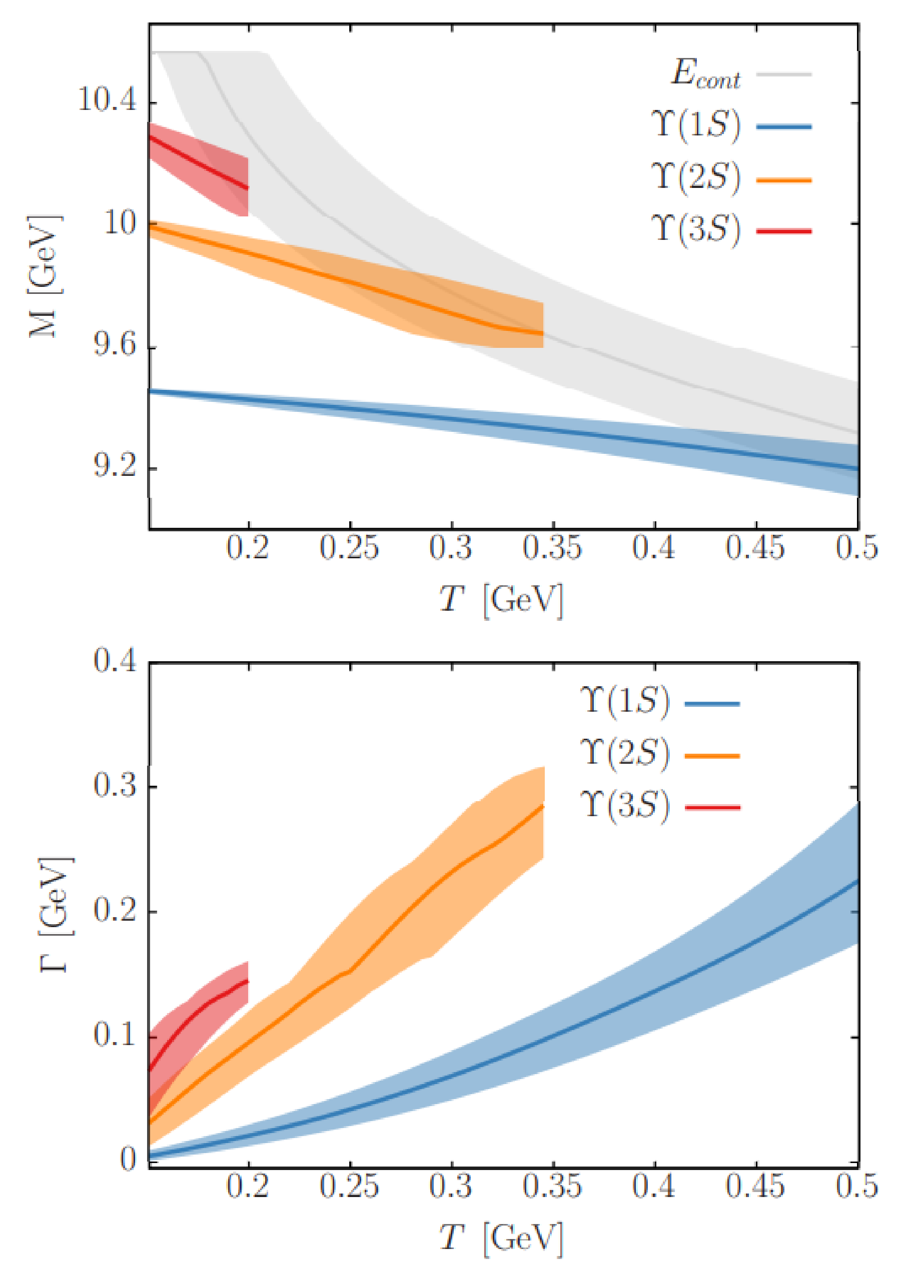


from J.P. Lansberg, Phys. Rep. 889(2020) 1



Modifications of bottomonium properties at T>0

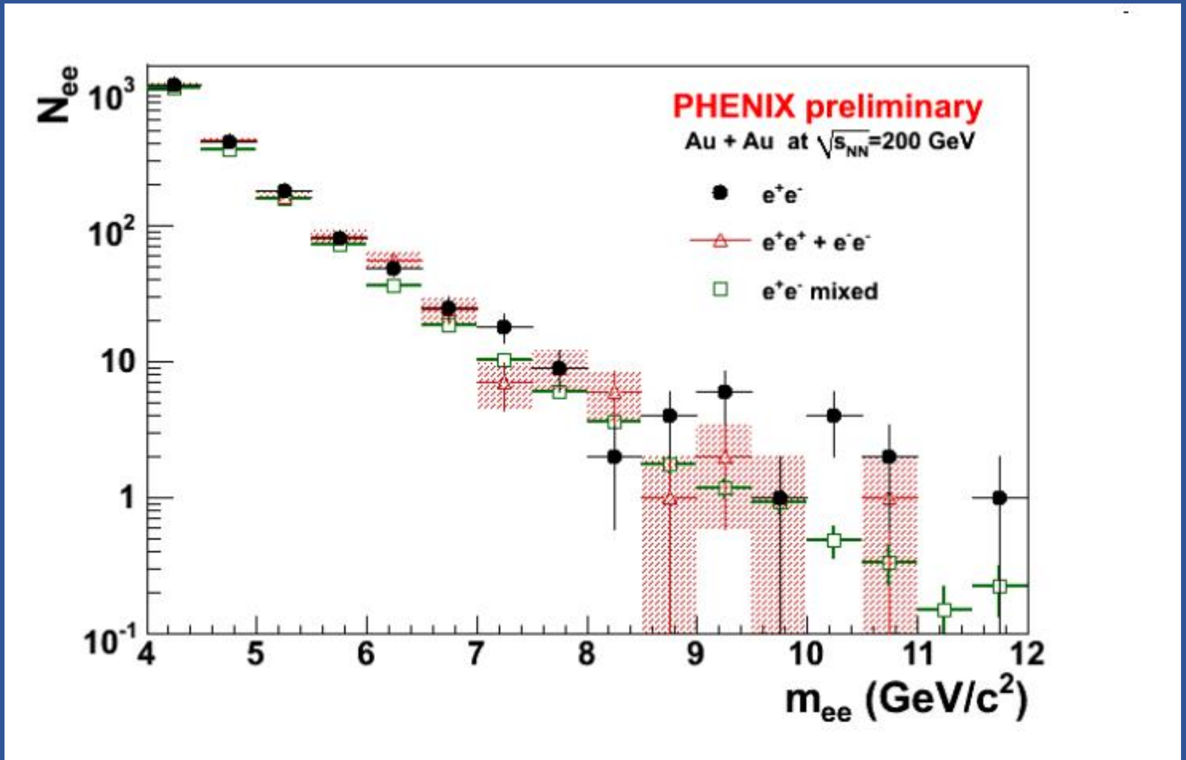


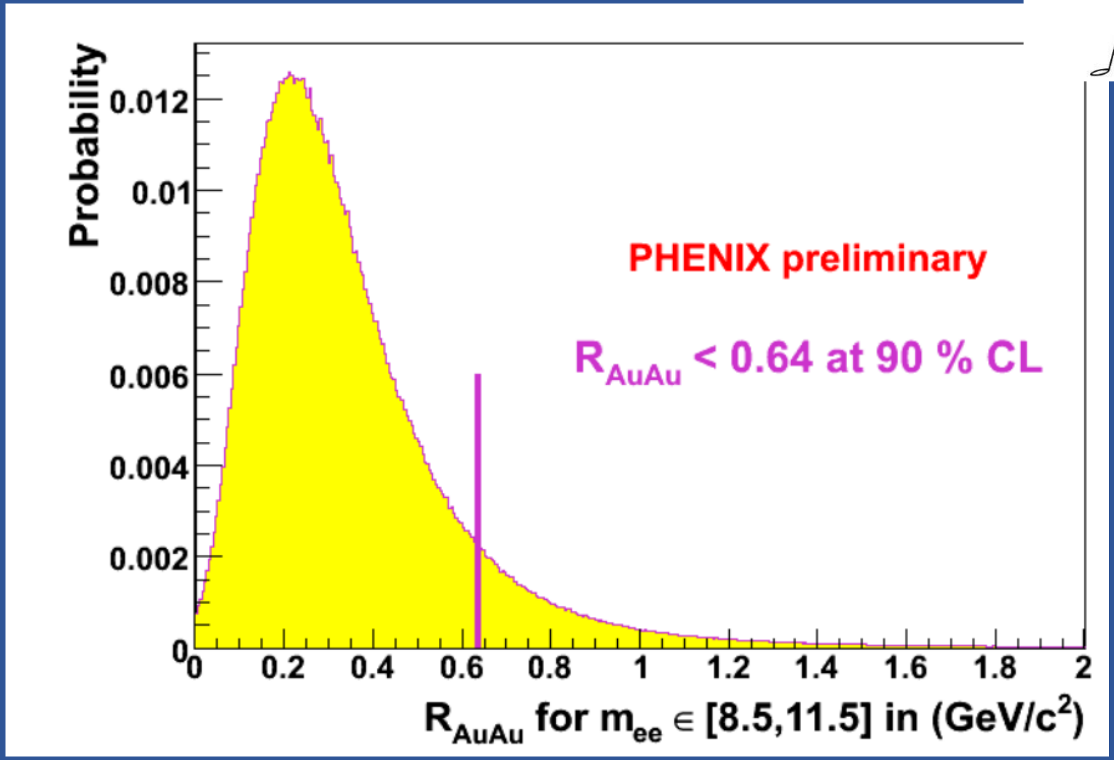


- In-medium peak remnants become "washed out" at **largely different temperatures** (gray line denotes the onset of the continuum)
  → Expect corresponding phenomenology in data

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

First attempts before LHC

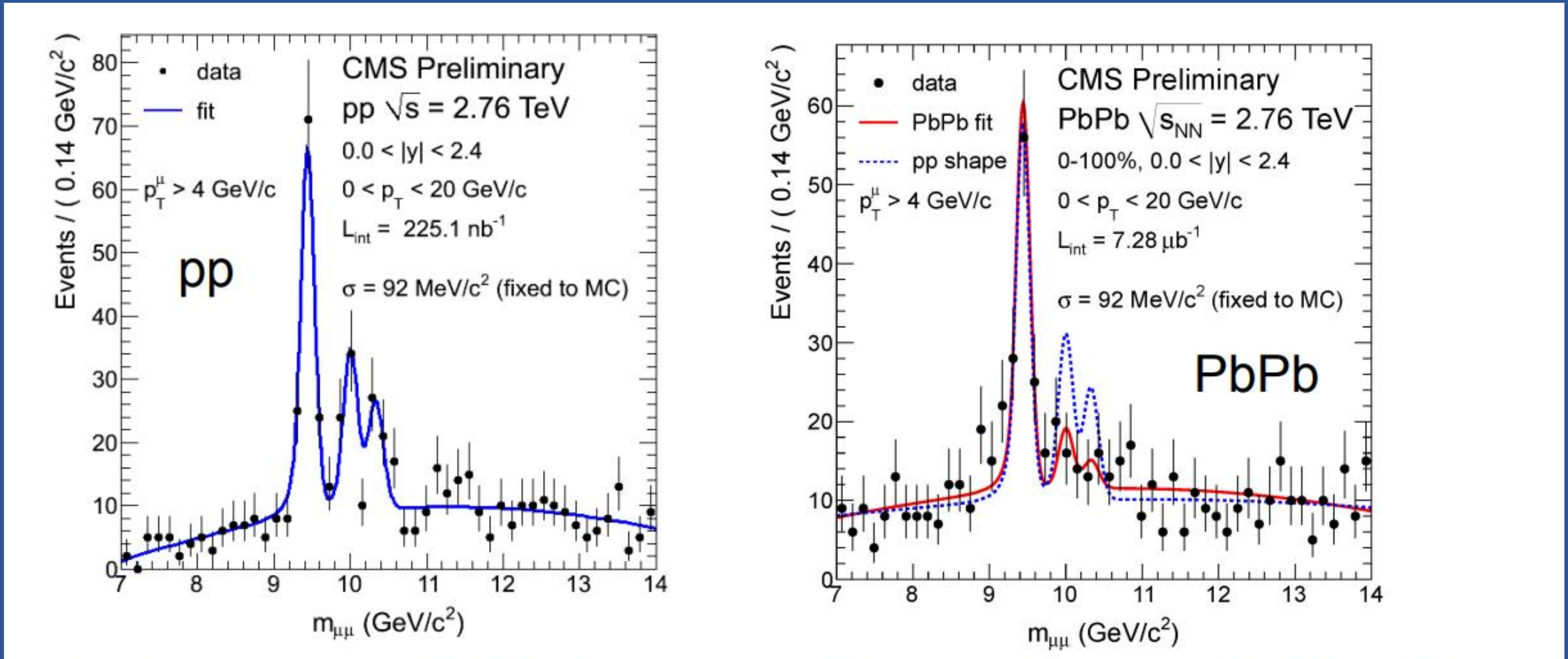




PHENIX, Nucl.Phys.A830:331c-334c,2009

- Large integrated luminosity is needed!
- More accurate results from **STAR** and **PHENIX** came after the LHC start
- Now waiting for **sPHENIX**…

A breakthrough



$$\Upsilon(2S+3S)/\Upsilon(1S)\Big|_{pp} = 0.78^{+0.16}_{-0.14} \pm 0.02$$

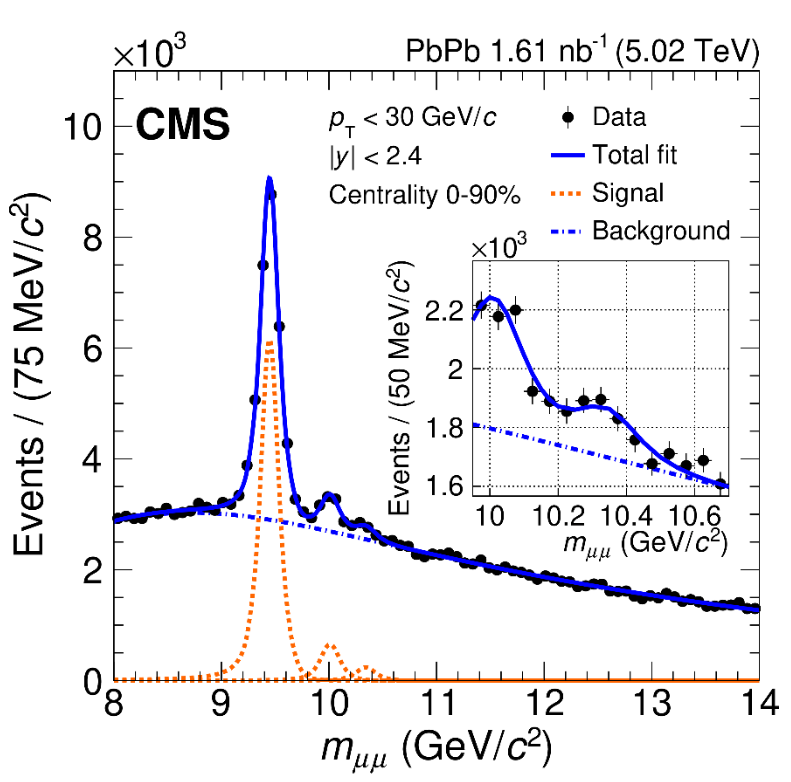
$$\Upsilon(2S+3S)/\Upsilon(1S)\Big|_{PbPb} = 0.24^{+0.13}_{-0.12} \pm 0.02$$

CMS, J. Phys. G38(2011) 124071
CMS, PRL 107 (2011) 052302

First evidence for a **sequential suppression in the bottomonium** sector!

After 10 years…

CMS, arXiv:2303.17026

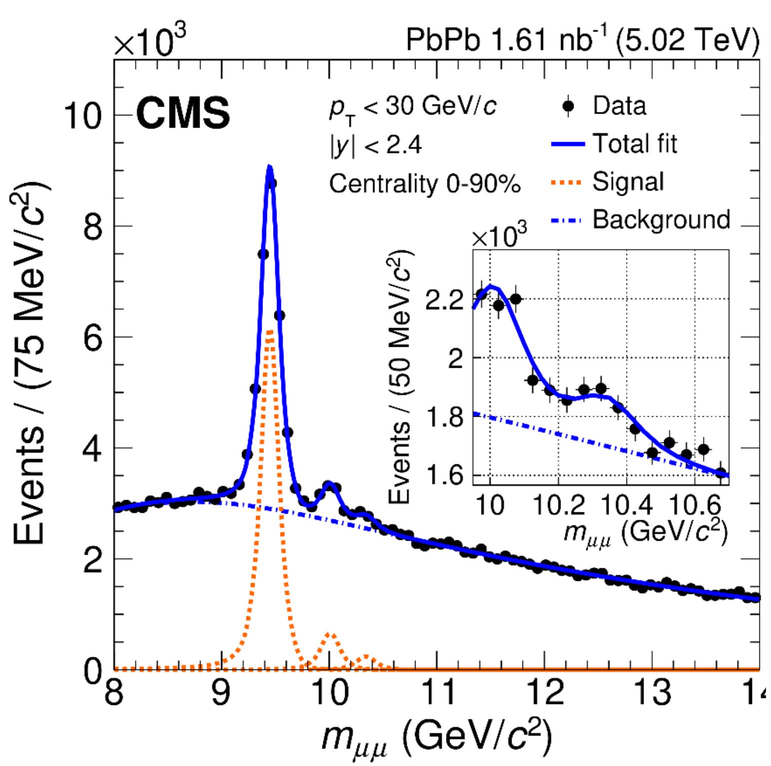


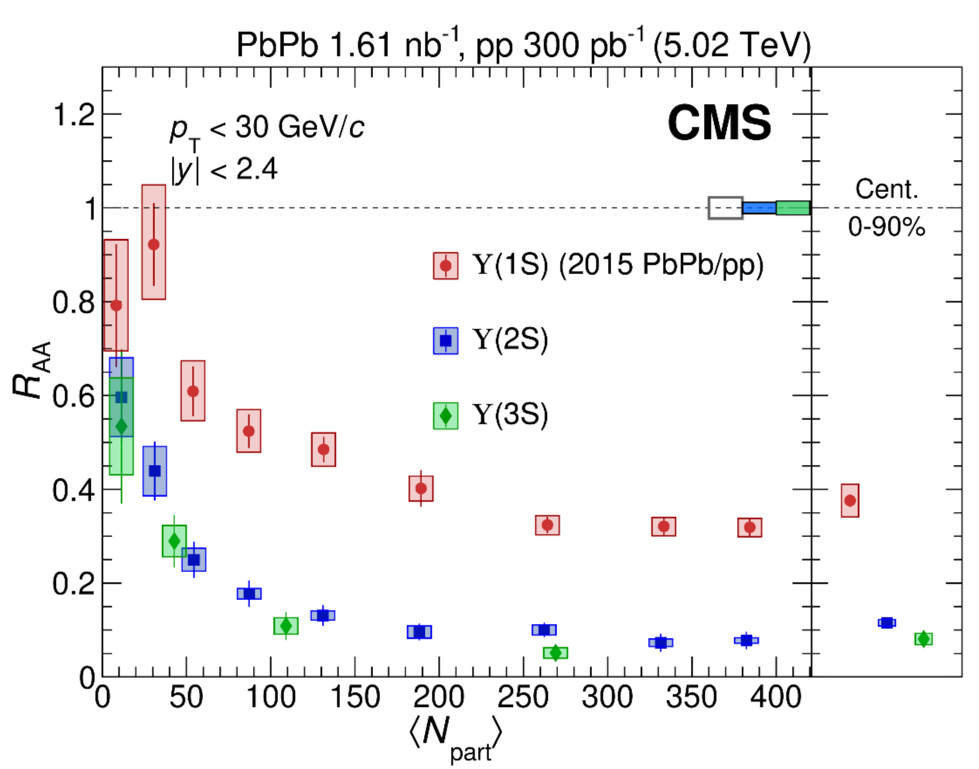
ϒ(3S) measured for the first time in Pb-Pb collisions

After 10 years…

CMS, arXiv:2303.17026

N.B. also the **tightly bound 1S state** is strongly suppressed





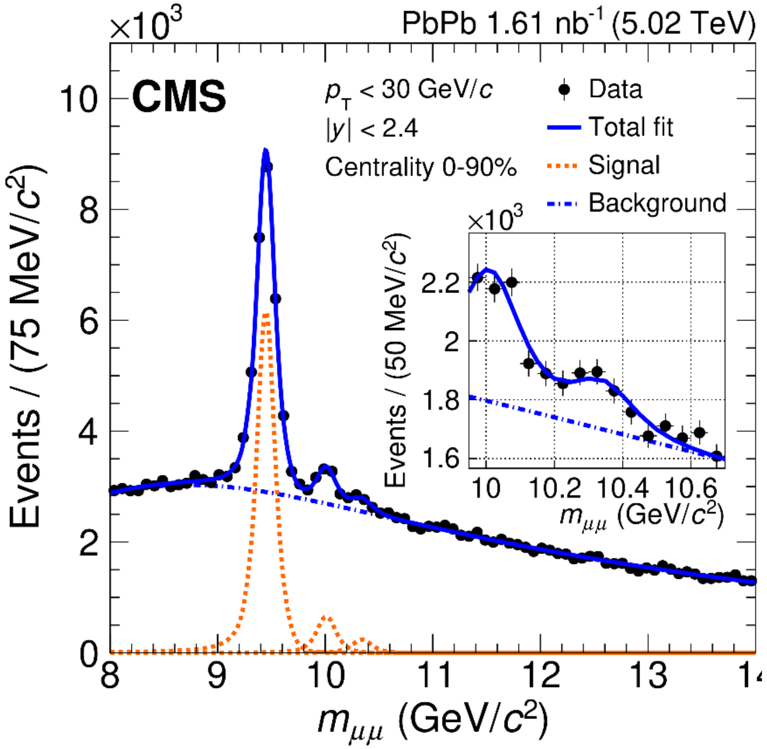
Υ(3S) measured for the first time in Pb-Pb collisions

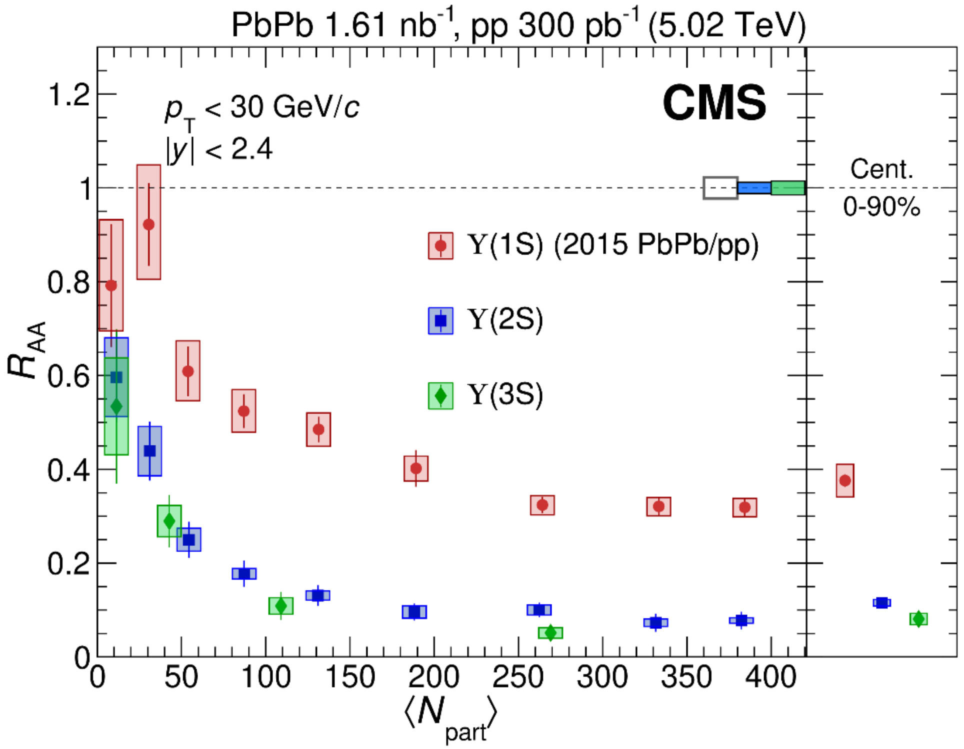
Hierarchy of suppression for the 1S,2S,3S states

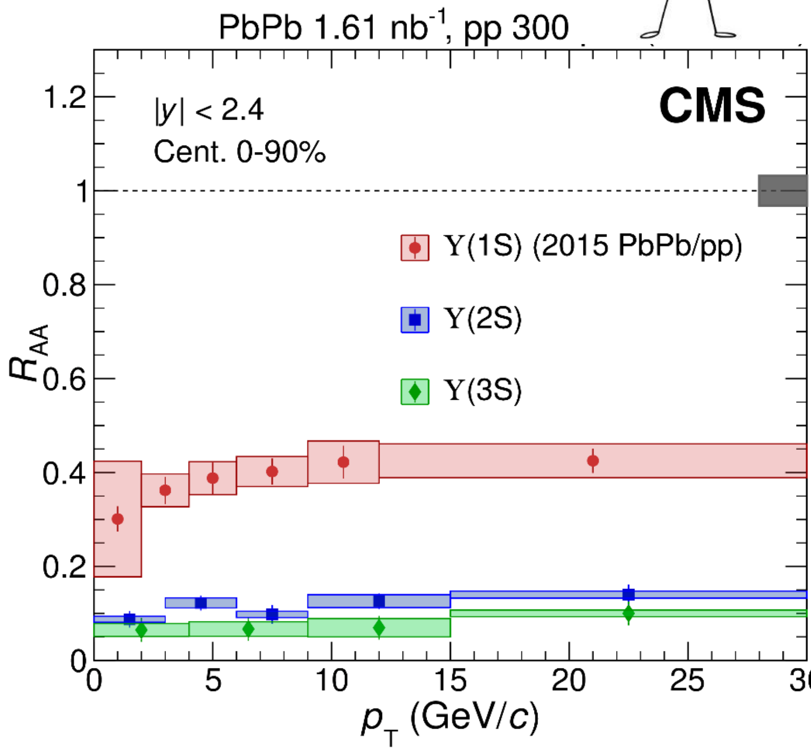
After 10 years...

CMS, arXiv:2303.17026

N.B. also the **tightly bound 1S state** is strongly suppressed





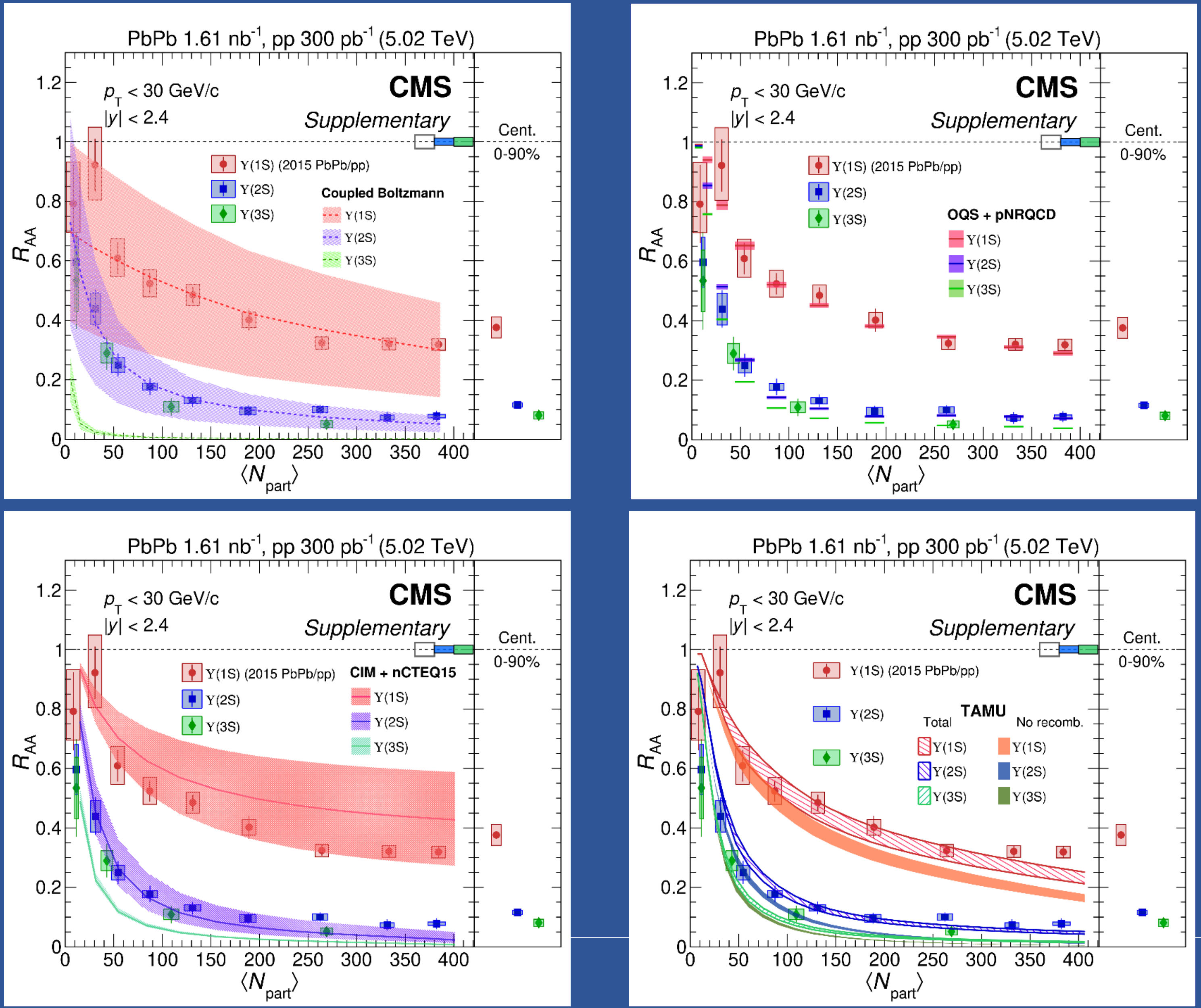


ϒ(3S) measured for the first time in Pb-Pb collisions

Hierarchy of suppression for the 1S,2S,3S states

No appreciable p_T dependence of R_{AA}

Comparisons with theory models

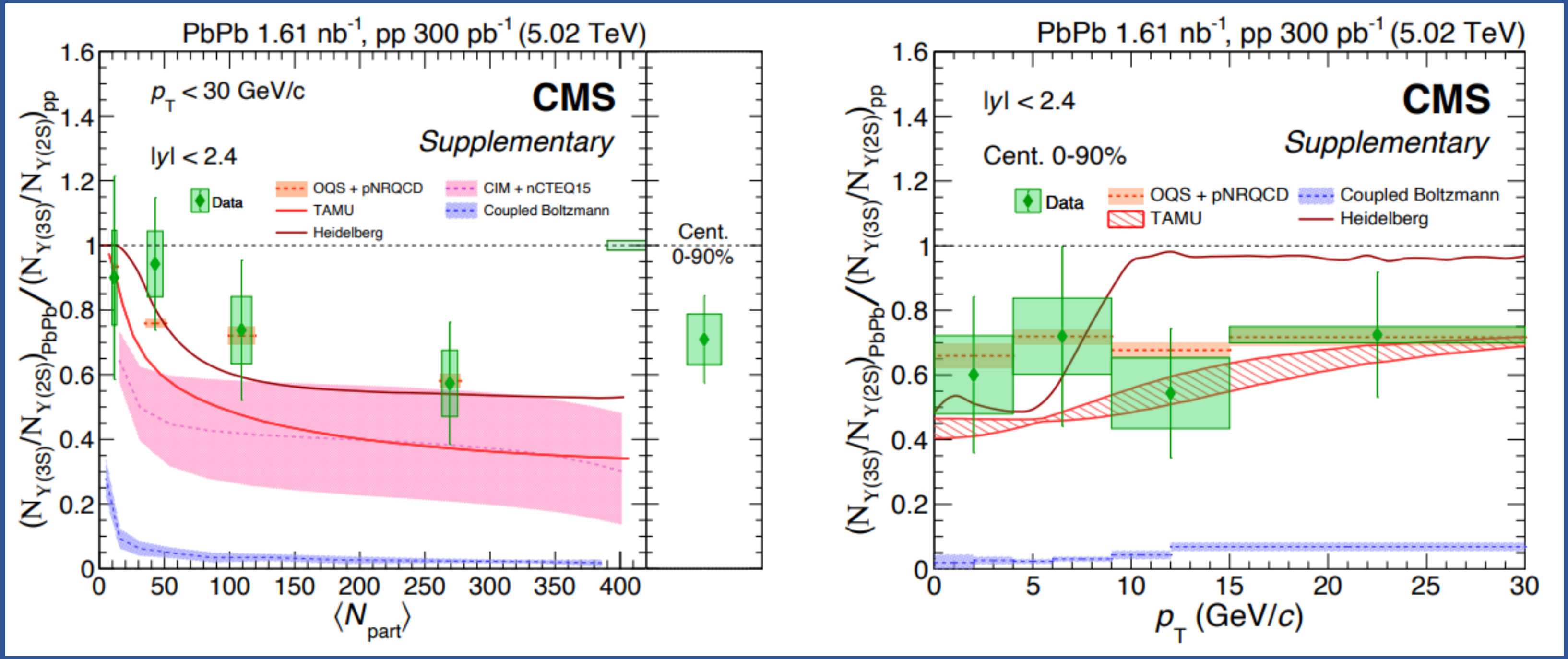


CMS, arXiv:2303.17026

Several approaches are able to reproduce semi-quantitatively the experimental observations! (also the p_T dependence)

Look in more detail at the excited states…

Comparisons with theory models

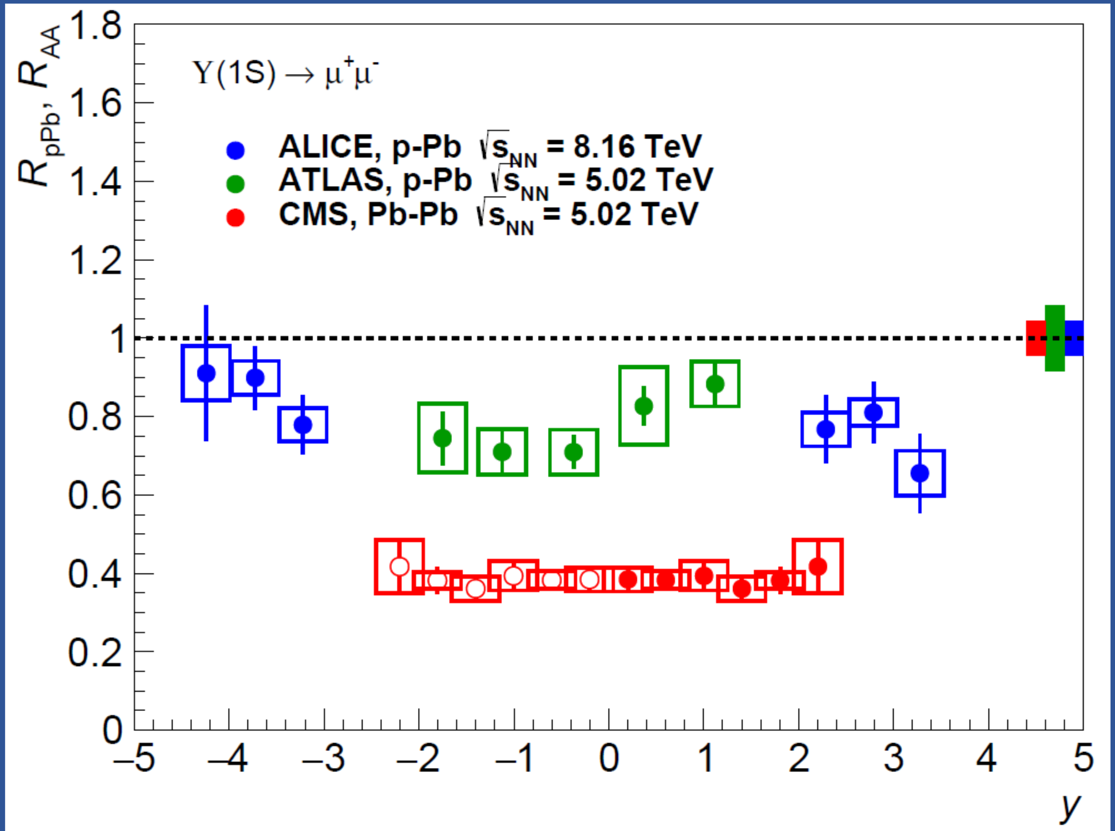


Several approaches are able to reproduce semi-quantitatively the experimental observations! (also the p_T dependence)

Look in more detail at the excited states…

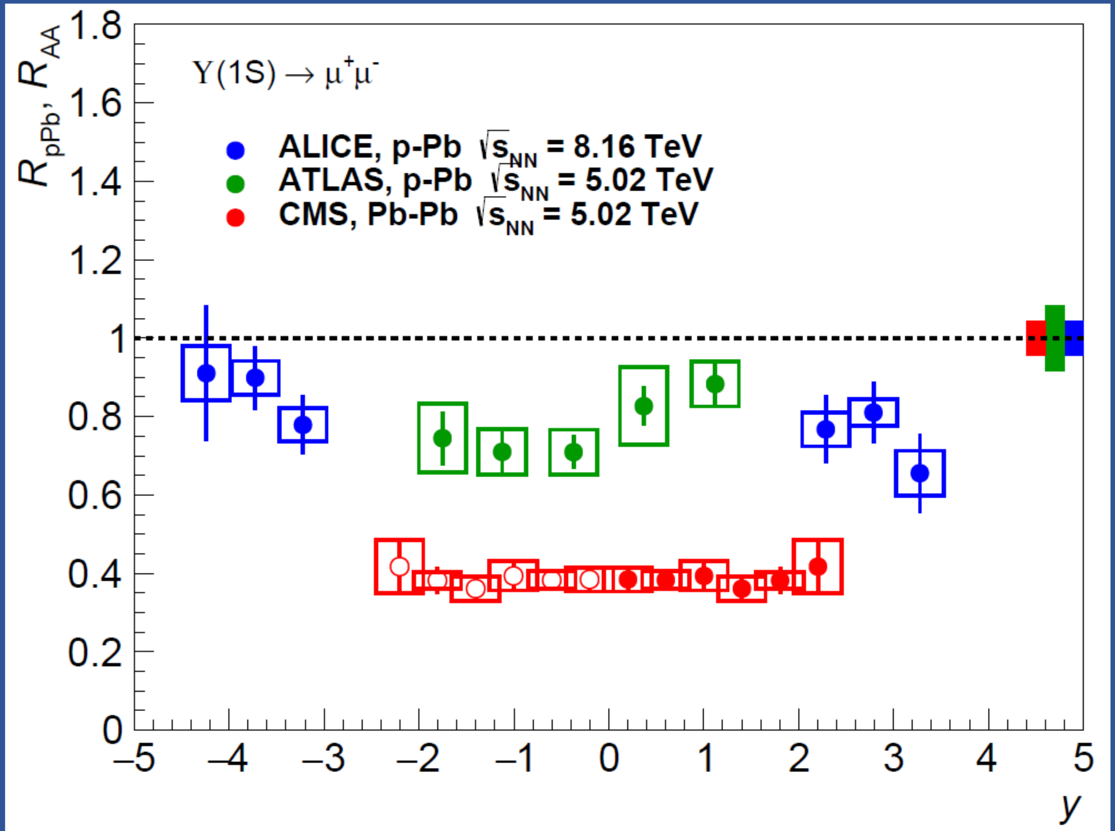
- Y(3S)/Y(2S) double ratio → indication of **stronger suppression for Y(3S),** particularly for central events
- Significant differences among model calculations
- This set of data, in spite of the relatively large uncertainties, poses **strong constraints to the models**

What about CNM effects ?



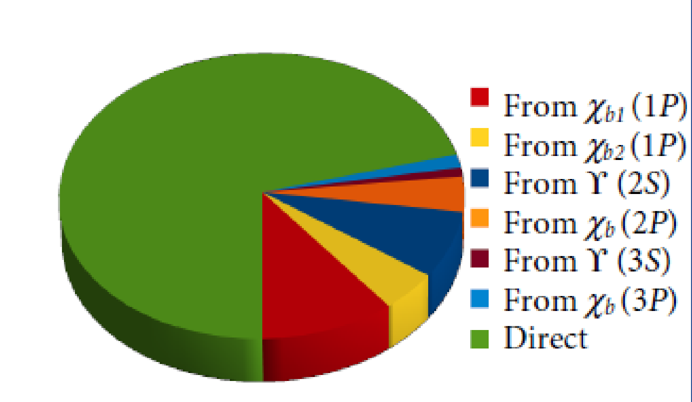
- Is the strong suppression of $\Upsilon(1S)$ “compatible” with its extremely large binding energy (>1 GeV) ?
- Can a fraction of $\Upsilon(1S)$ suppression be due to **non-QGP effects?**

Is Υ(1S) really suppressed ?



CNM effect on Υ(1S)
are shown to be non-negligible

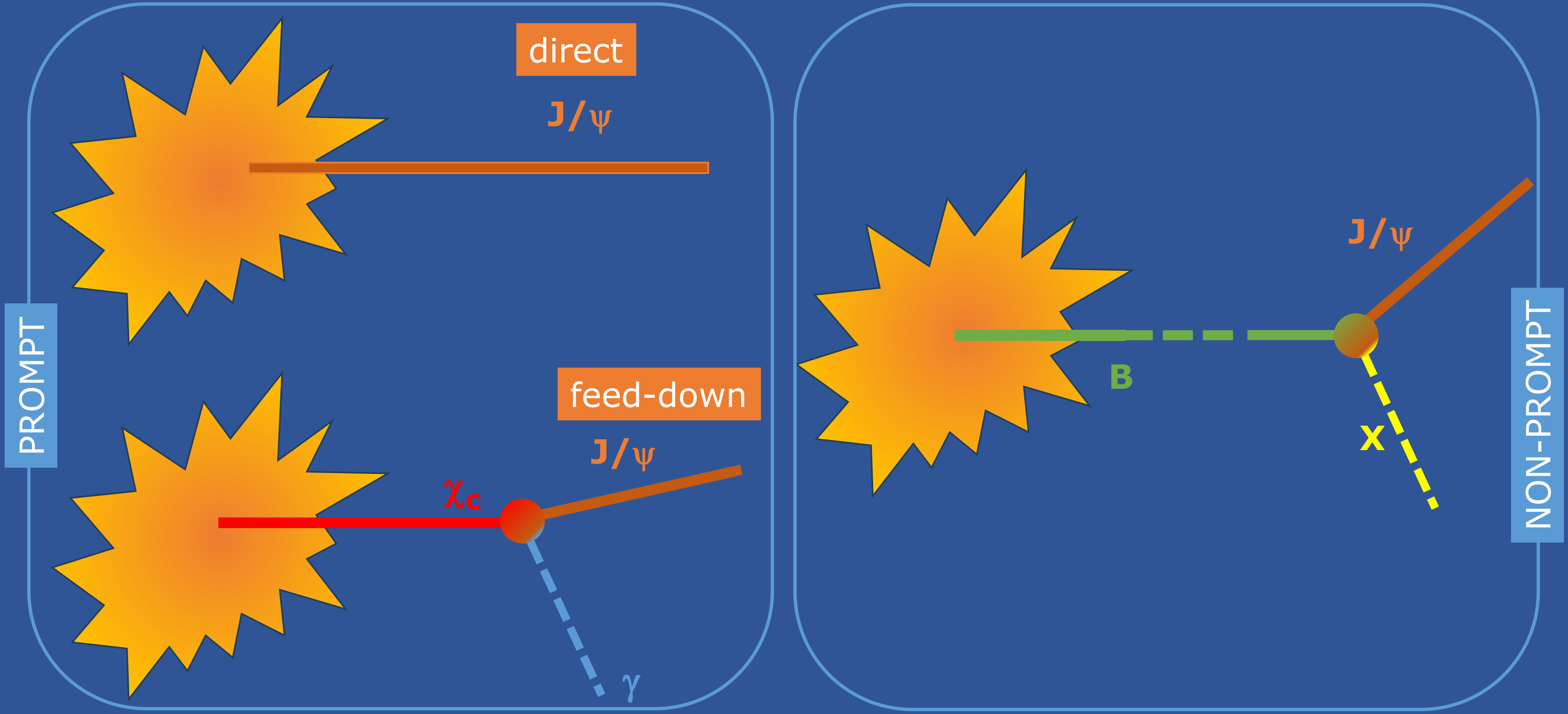
Also considering feed-down effects on Υ(1S) from Υ(2S,3S) and χ_b states



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

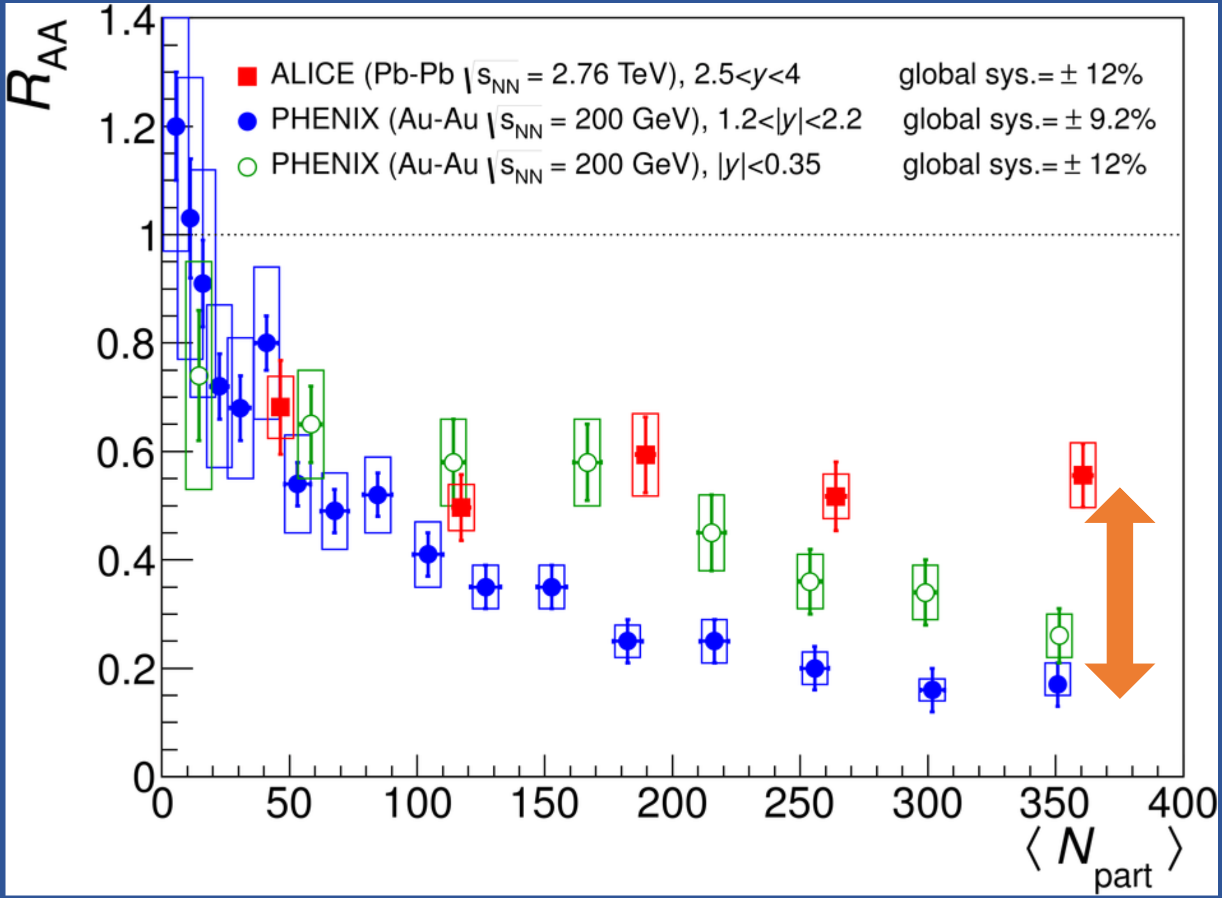
Could the observed **Υ(1S) suppression** be compatible with a **combination of feed-down + CNM effects ?**

Before coming back to charmonia…



Let's come back to charmonia at LHC

- RHIC to LHC: factor >10 in $\sqrt{s_{NN}}$: a **decisive test** of mechanisms at play



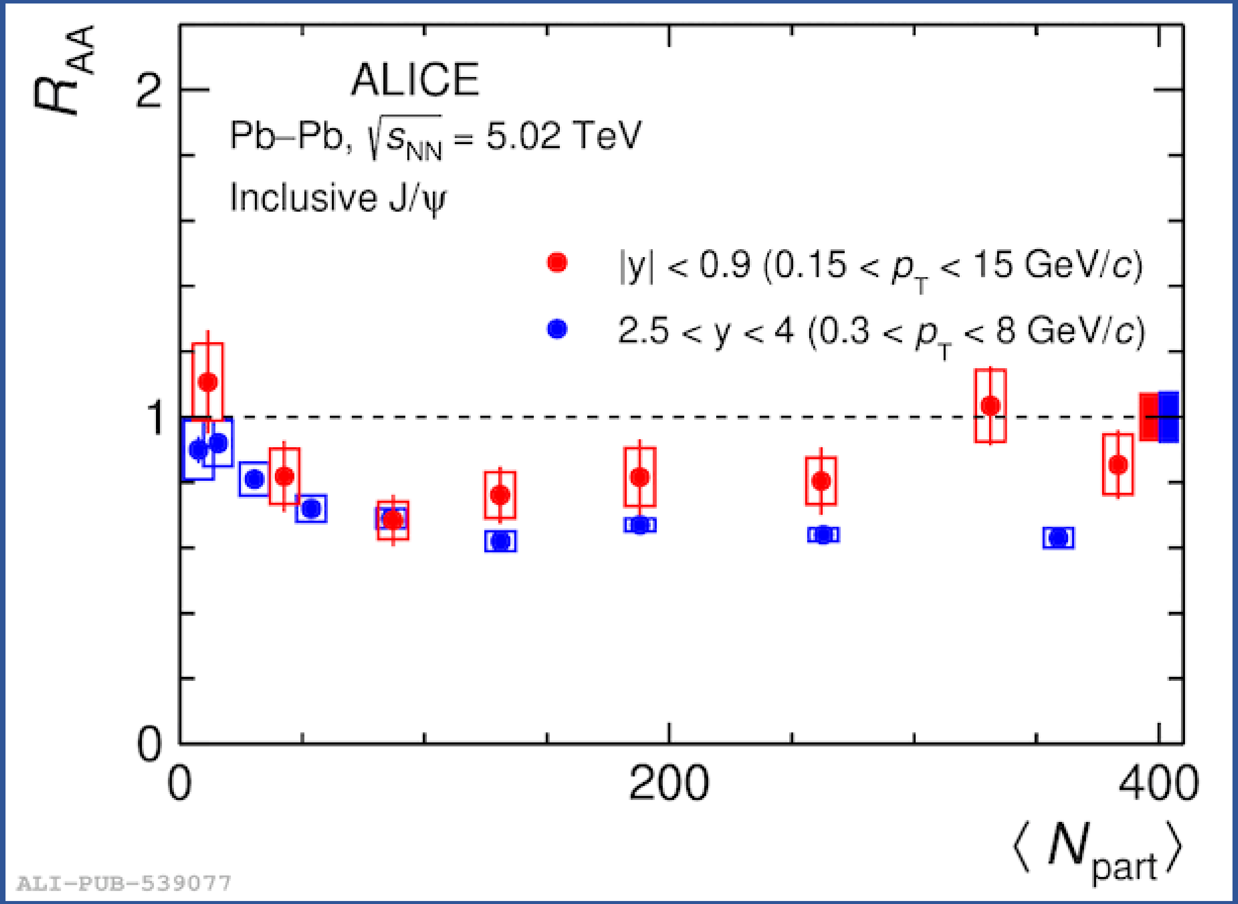
ALICE, PRL 109 (2012) 072301

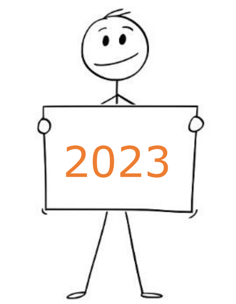
- Central Pb-Pb collisions
  - R_{AA} is **larger by a factor >2** at LHC energy with respect to RHIC
- Forward-y results (muon trigger!)

Smoking gun for **(re)generation effects ?**

After 10 years…

Smoking gun(s) for **(re)generation**

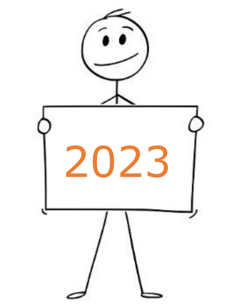


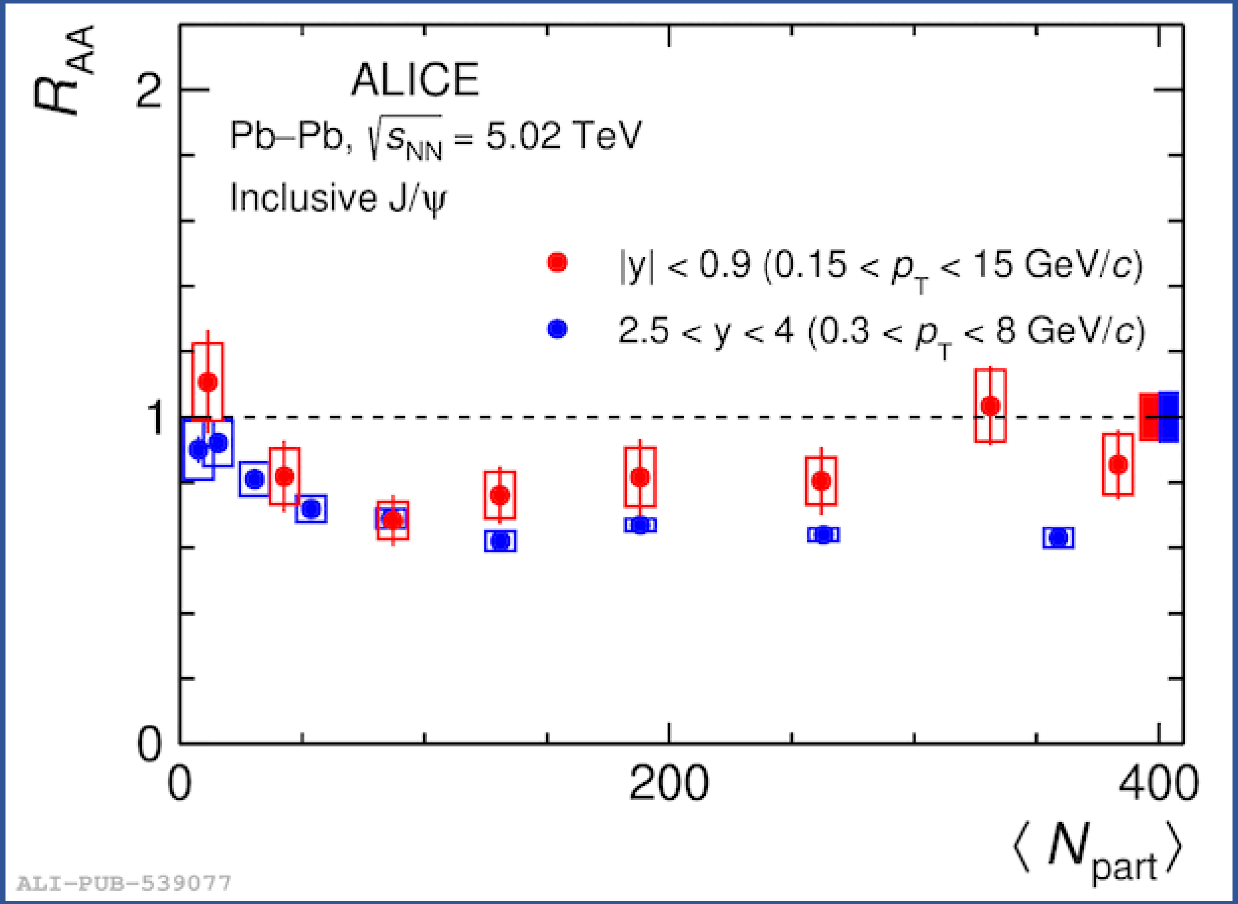


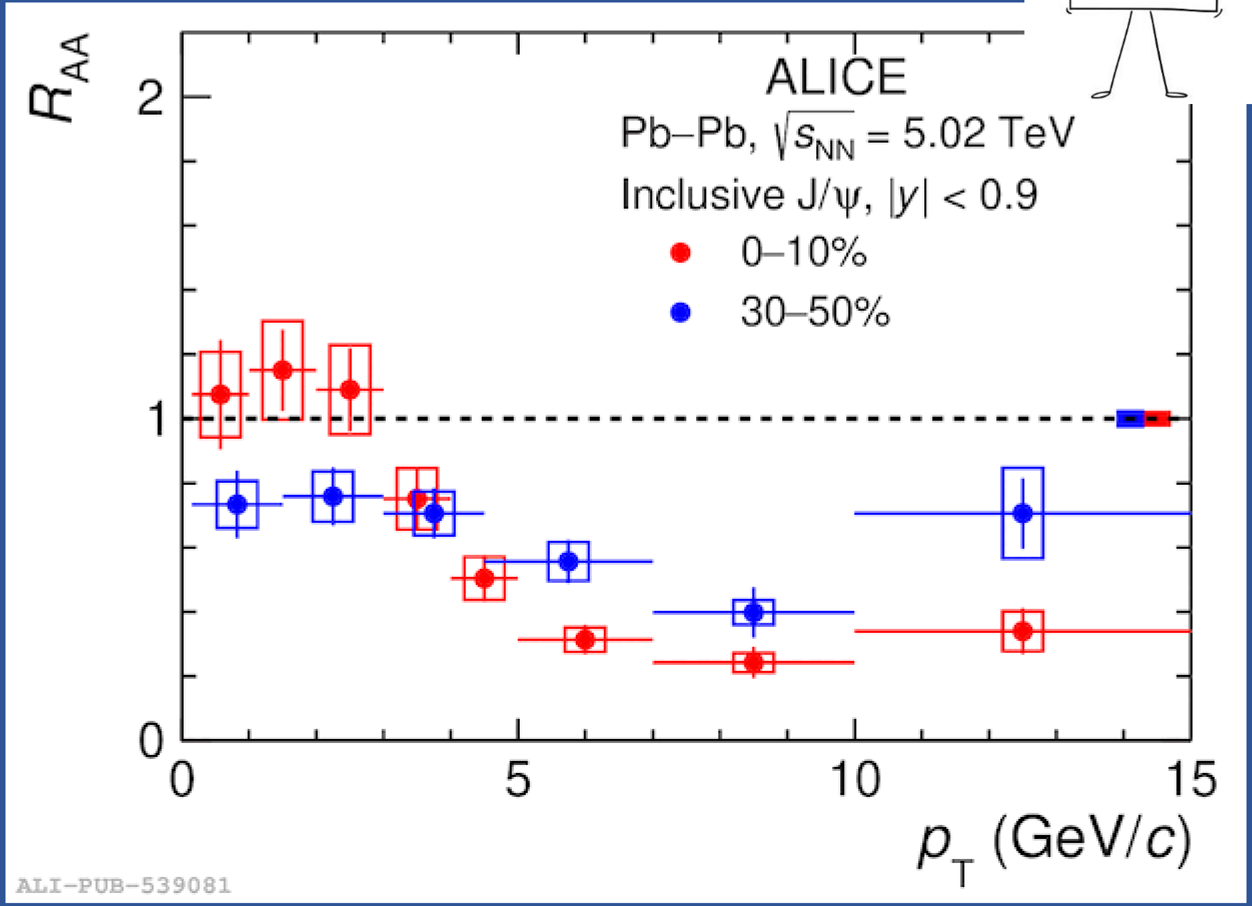
➢ R_{AA} is **larger at midrapidity** ← as expected from a larger charm quark multplicity

After 10 years…

Smoking gun(s) for **(re)generation**







- R_{AA} is **larger at midrapidity** ← as expected from a larger charm quark multplicity
- R_{AA} **increases at low p_T** ← as expected from the charm quark p_T distribution

Theory models: generation vs regeneration

Transport

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

- Macroscopic rate equation including suppression and regeneration in the QGP
- Suppression
  - Calculated starting from modifications of charmonium spectral functions, **constrained by LQCD-validated potentials**
- Regeneration
  - Tuned from measured heavy-quark yields

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

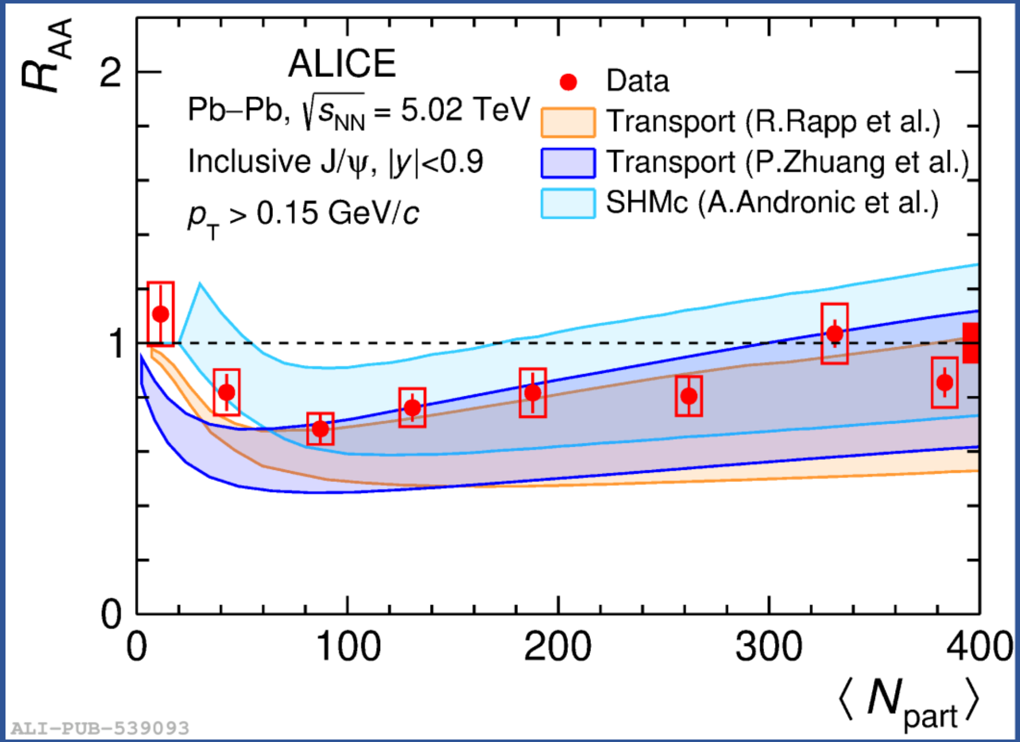
It turns out that both approaches fairly **reproduce LHC experimental results on the J/ψ**

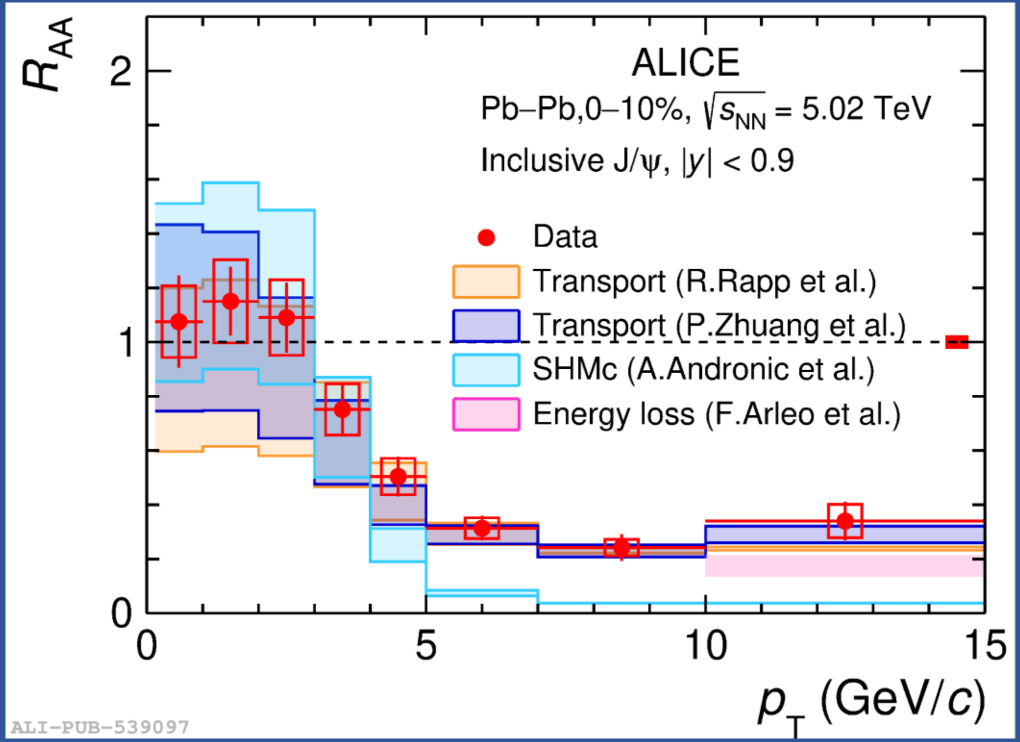
ALICE, Phys. Lett. B 766 (2017) 212

Other approaches exist!
"Comover" models etc.

E. Ferreiro, PLB 731 (2014) 57

Comparisons with theory models

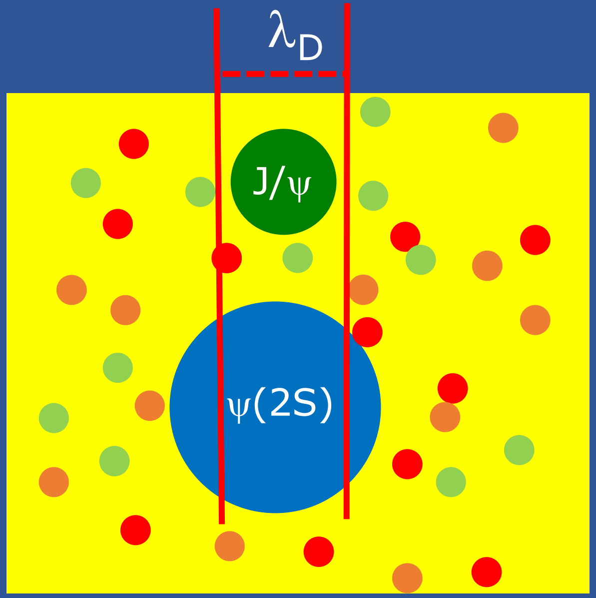




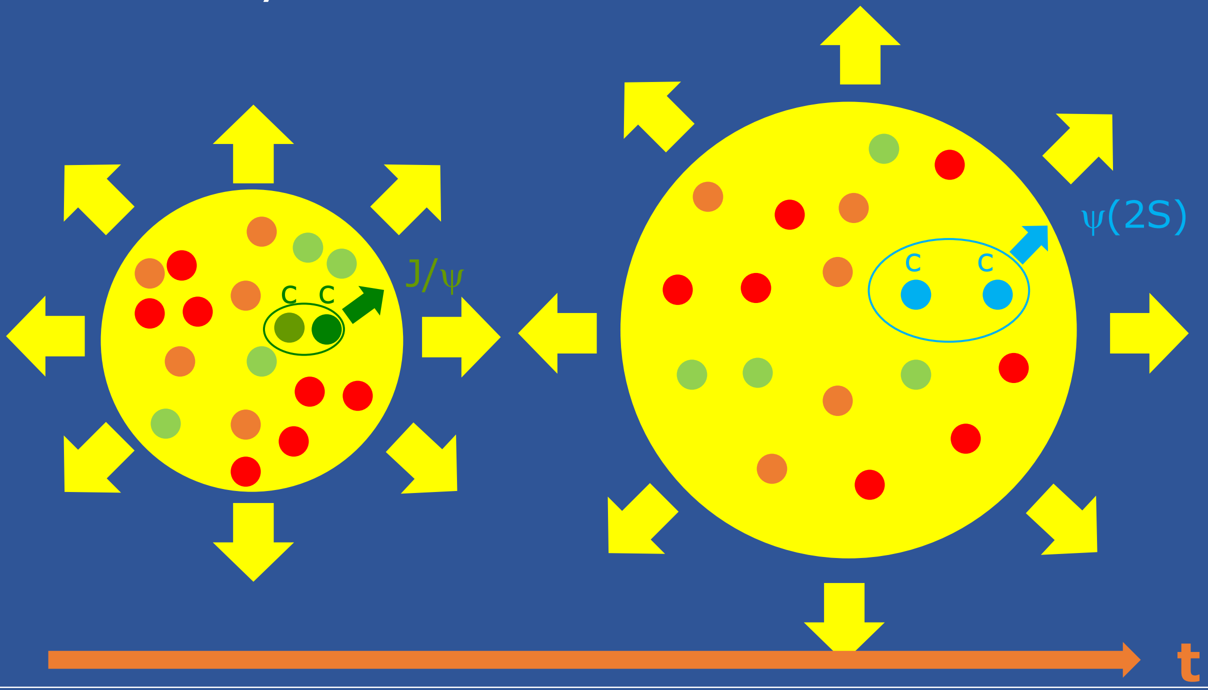
- Model **uncertainties** dominated by
  - Open charm cross section
  - Initial state effects (shadowing)

Sequential regeneration for charmonia at LHC ?

- Binding energy ~$(2m_D - m_\psi)$ → **ψ(2S) ~ 60 MeV, J/ψ ~ 640 MeV**



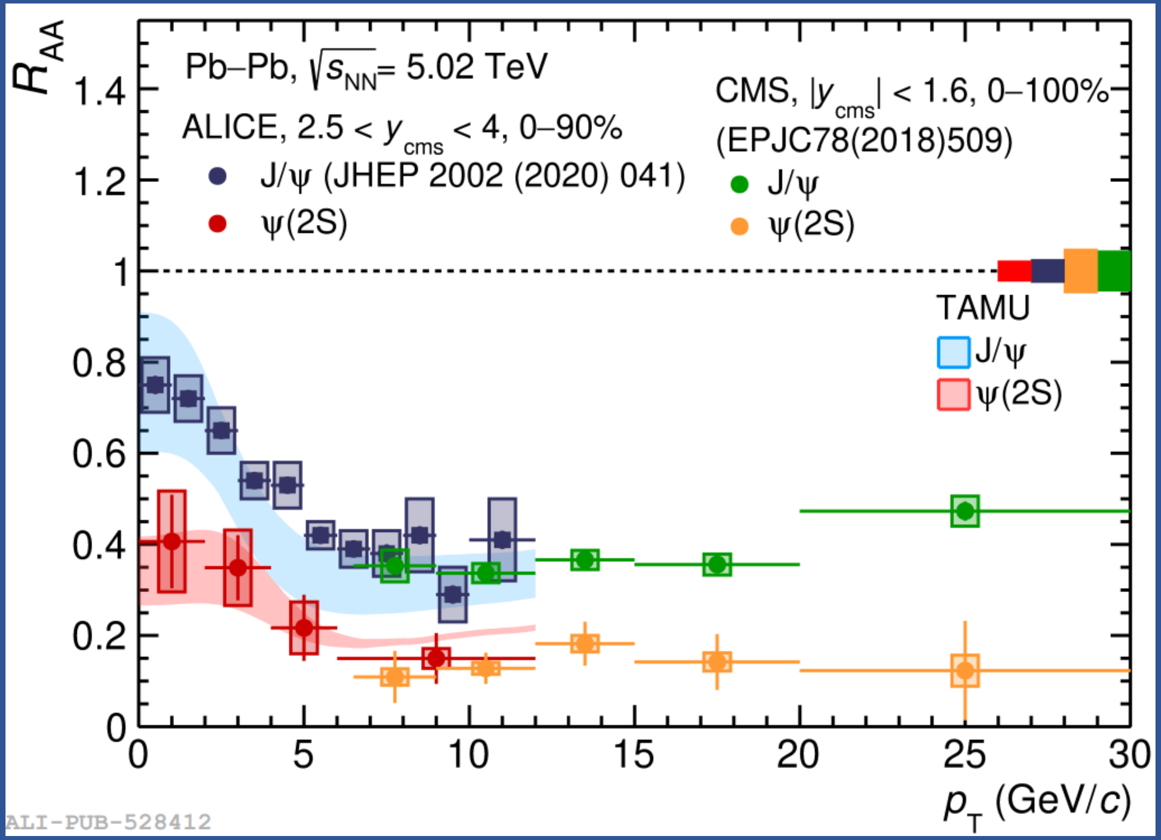
- **Much stronger dissociation effects** for the weakly bound ψ(2S) state already seen at SPS energy
- Effect of re-combination on ψ(2S) could also be important → important when the system is **more diluted ?**



Important test for models!

ψ(2S) at LHC

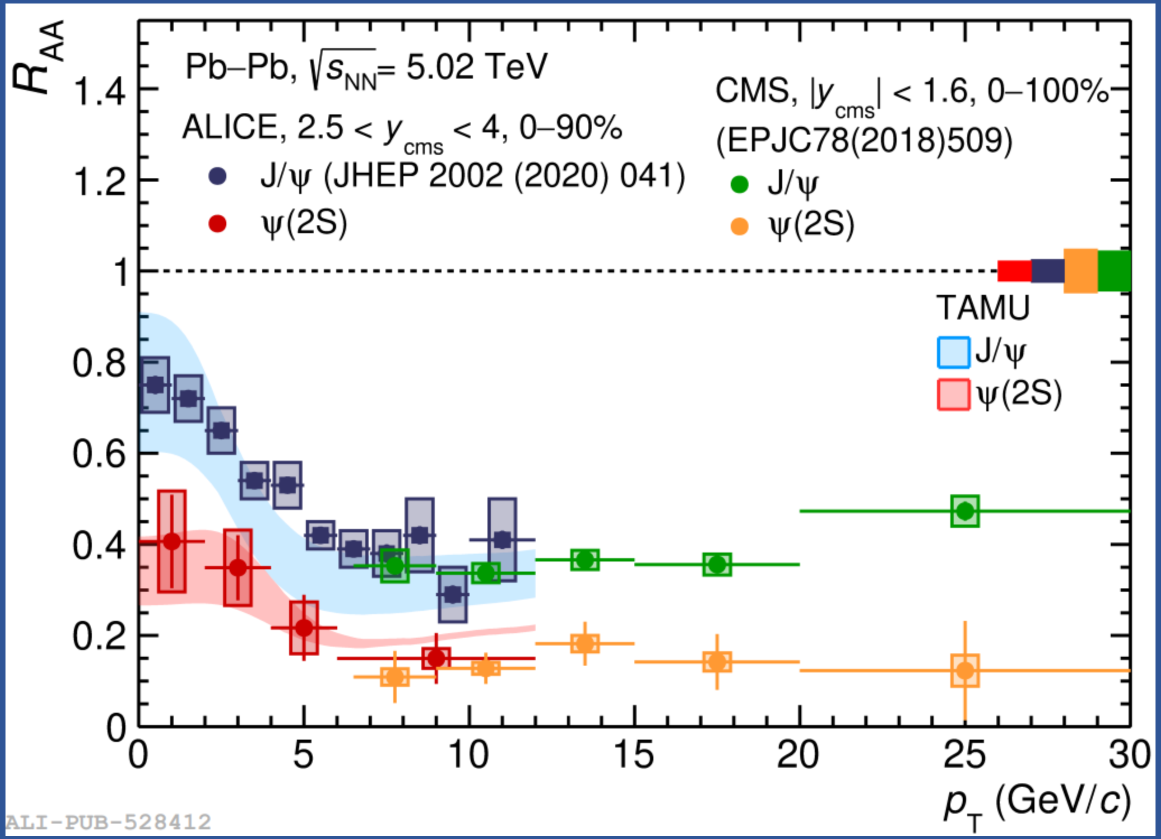
ALICE, arXiv:2210.08893

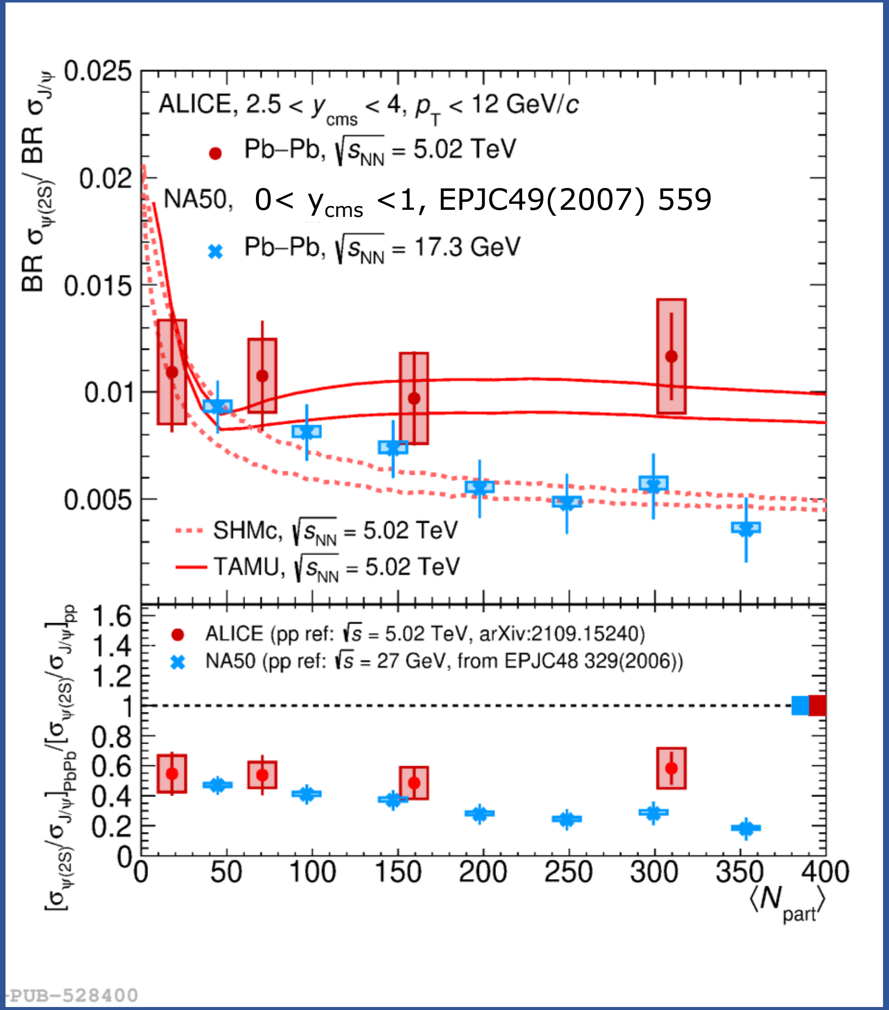


- Two main conclusions
- Indication for an **increase of R_{AA} at low p_T** → "sequential" regeneration ?

ψ(2S) at LHC

ALICE, arXiv:2210.08893

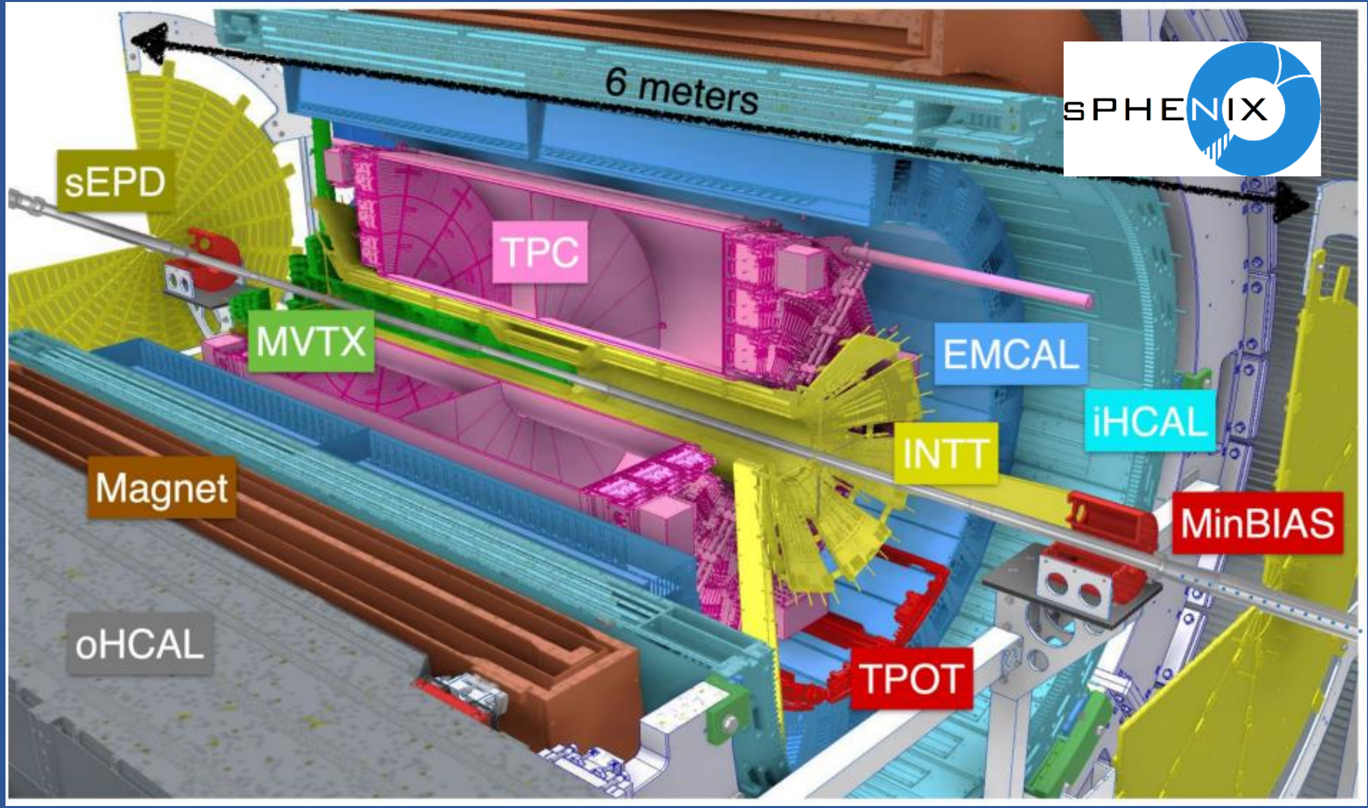




Caveat: **prompt vs inclusive**

- Two main conclusions
- Indication for an **increase of R_{AA} at low p_T** → "sequential" regeneration ?
- First indication for **discrepancy** between transport and statistical approaches → worth investigating!

What remains to be done ? High-energy/low μ_B

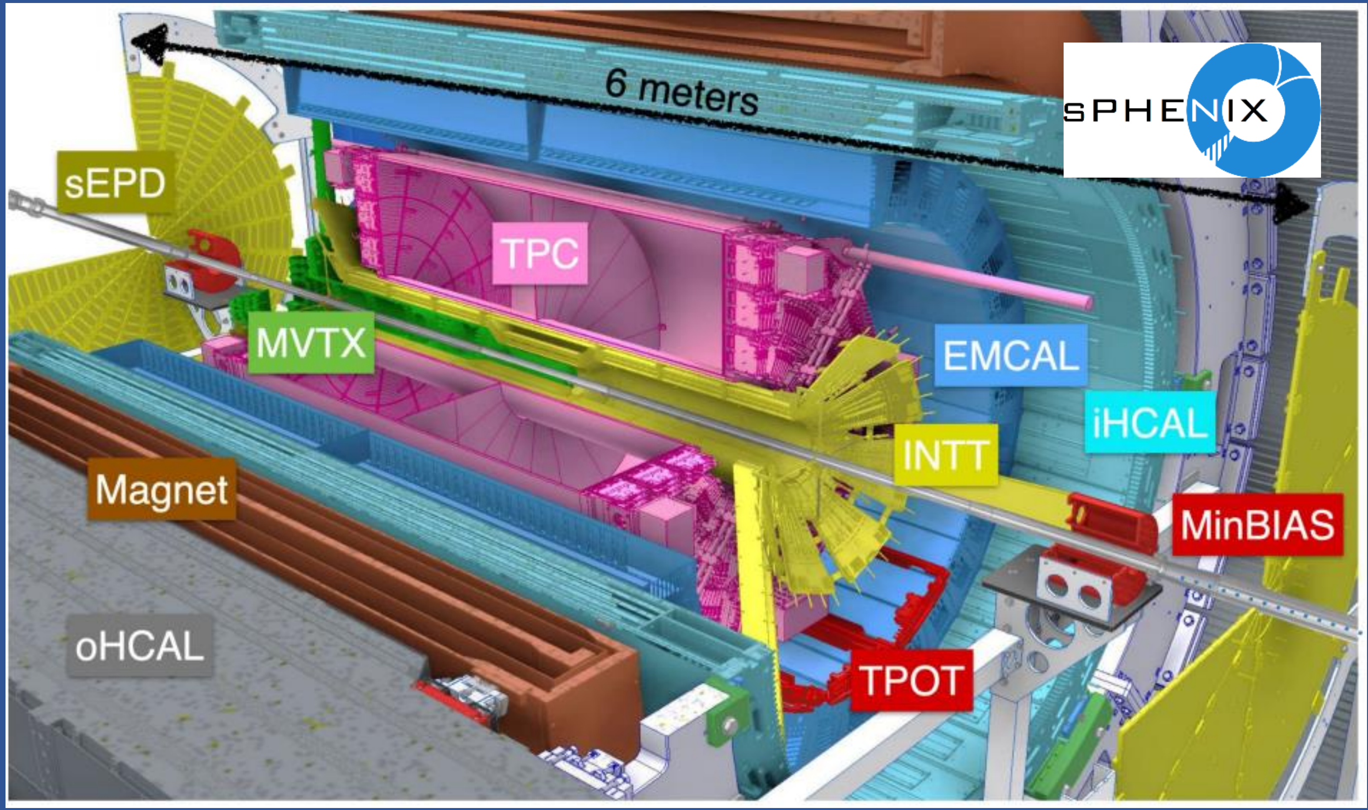


sPHENIX: The first "brand new" heavy-ion experiment since more than a decade

Now taking data!

https://www.sphenix.bnl.gov/

What remains to be done ? High-energy/low μ_B

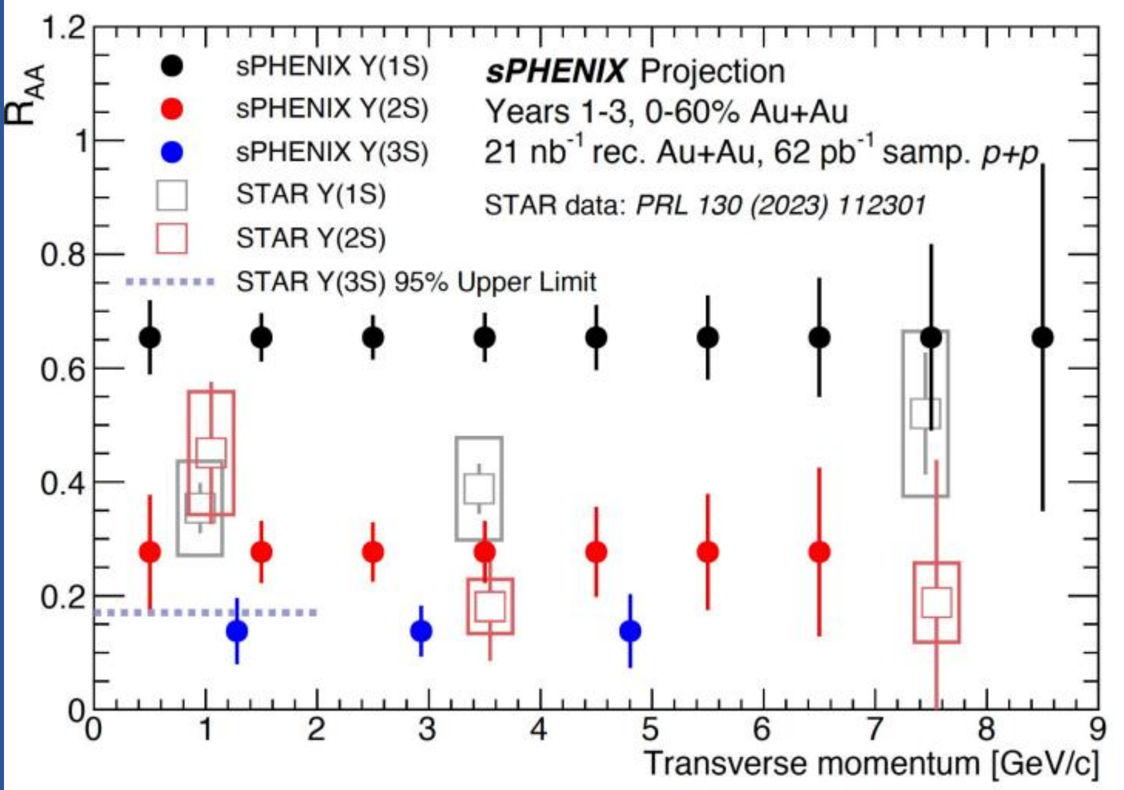


sPHENIX: The first "brand new" heavy-ion experiment since more than a decade

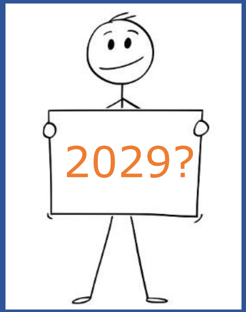
Now taking data!

https://www.sphenix.bnl.gov/

- Clear distinction of three Υ states
- Probing the QGP with color dipoles at three length scales
- Kinematic range allows for **comparison between RHIC and LHC measurements**



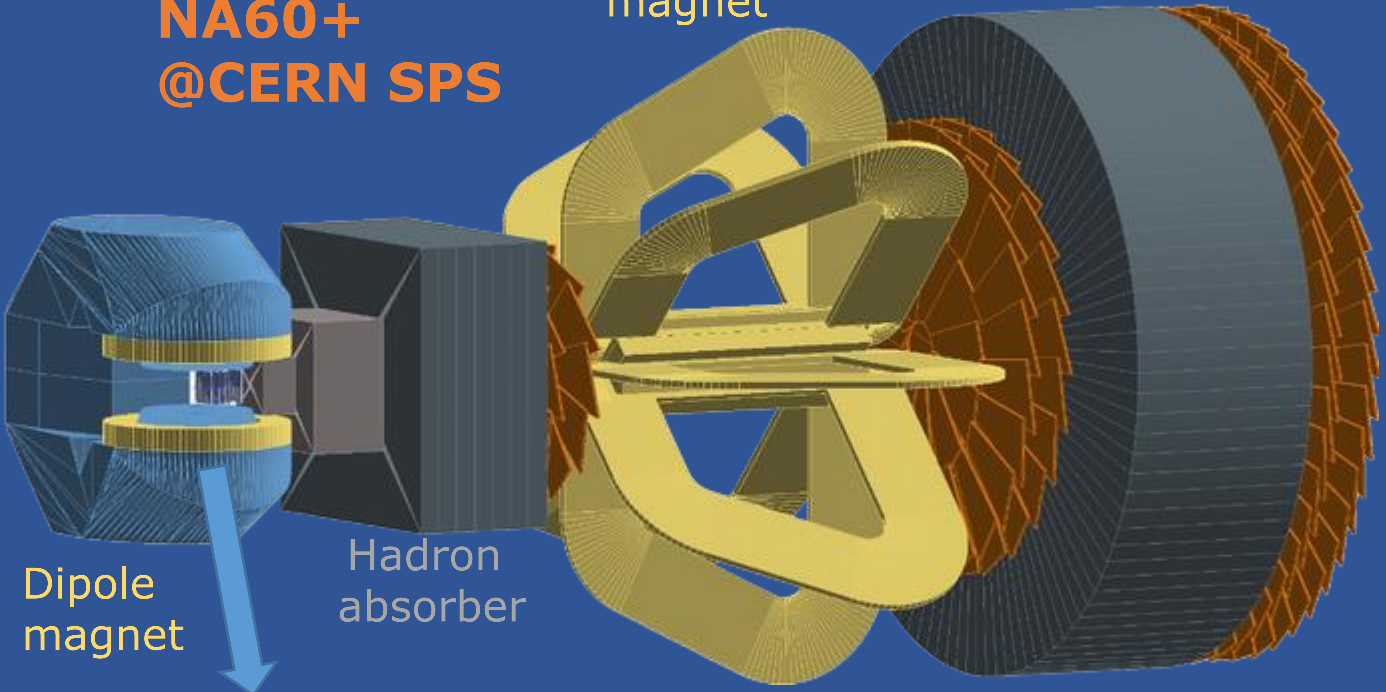
What remains to be done ? Low-energy/high μ_B



NA60+
@CERN SPS

Toroidal magnet

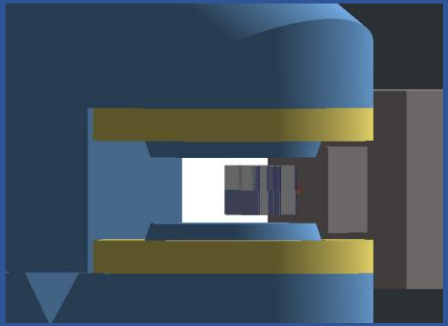
Muon wall



Dipole magnet

Hadron absorber

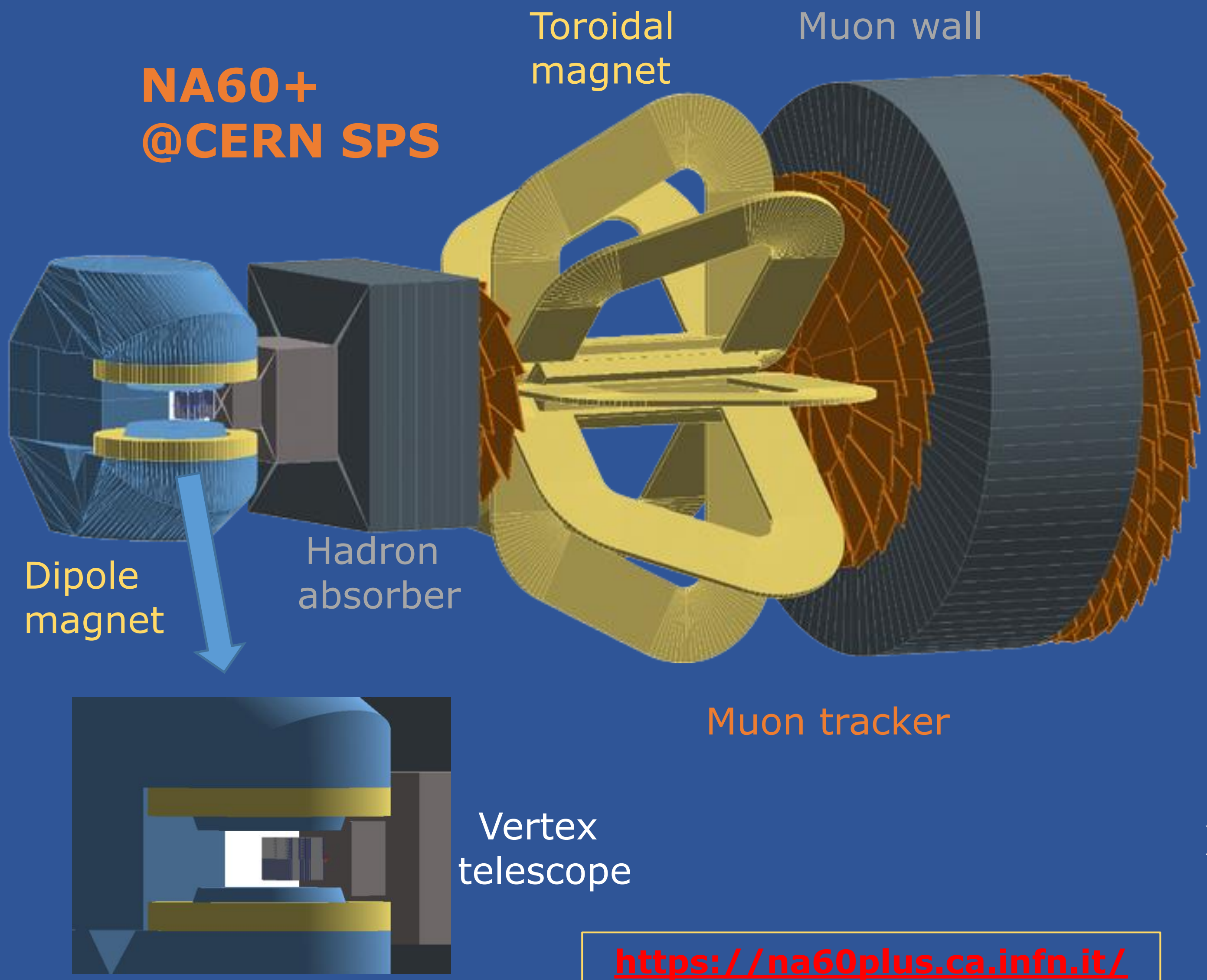
Muon tracker



Vertex telescope

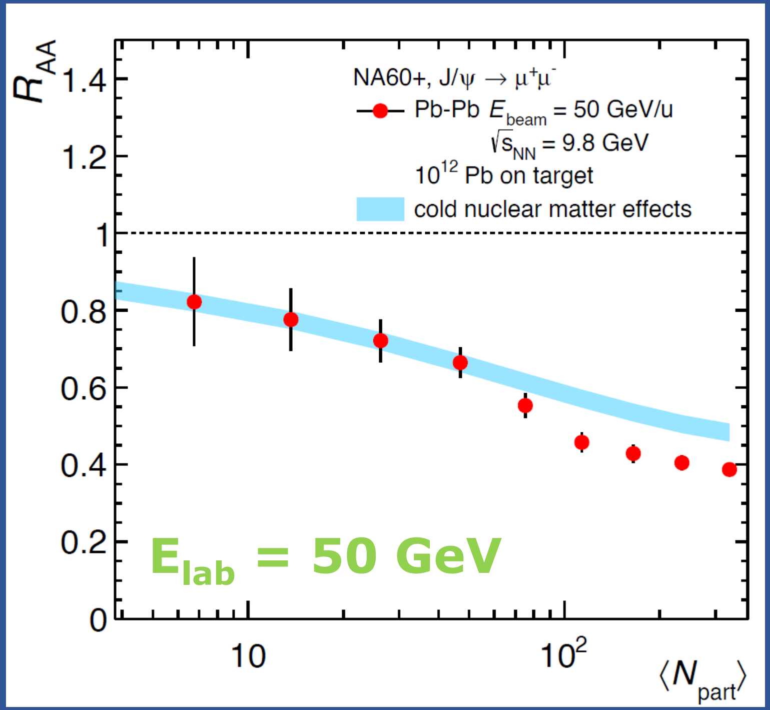
https://na60plus.ca.infn.it/

What remains to be done ? Low-energy/high μ_B



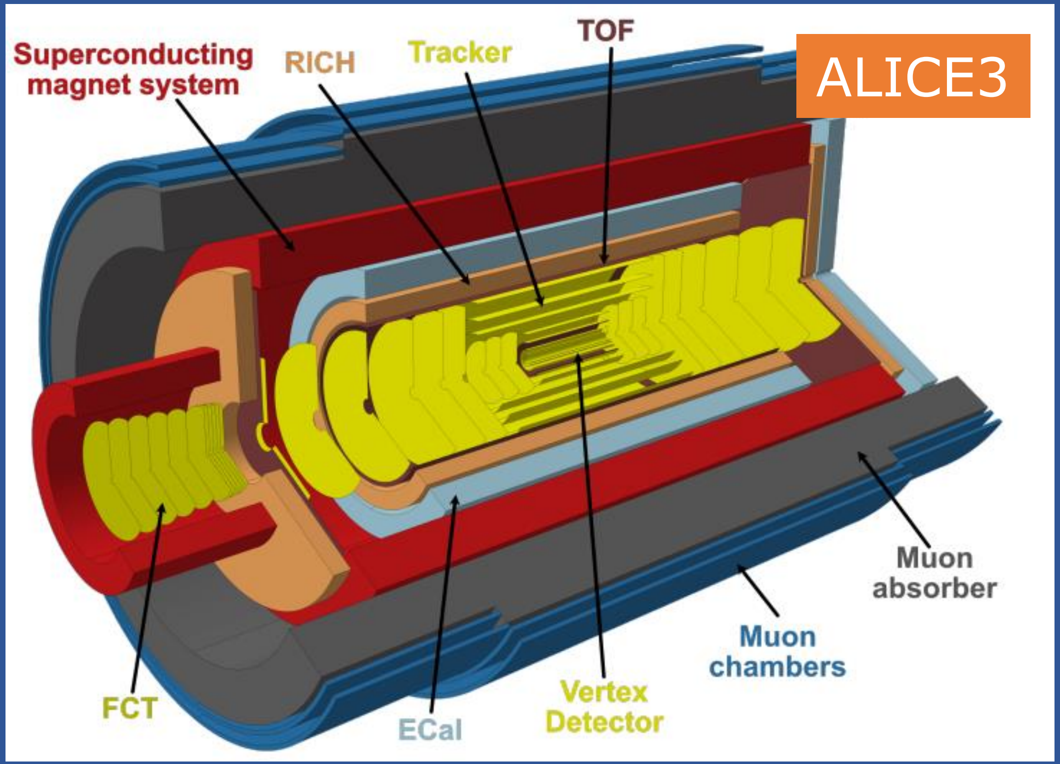
https://na60plus.ca.infn.it/

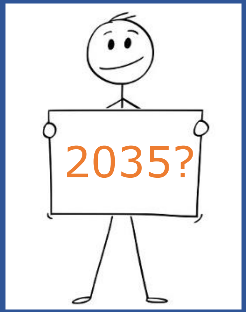
- No charmonium results available below top SPS energy ($\sqrt{s_{NN}}$=17 GeV)



- Study the onset of anomalous suppression and correlate with temperature (thermal dileptons)

What remains to be done ? High-energy/zero μ_B

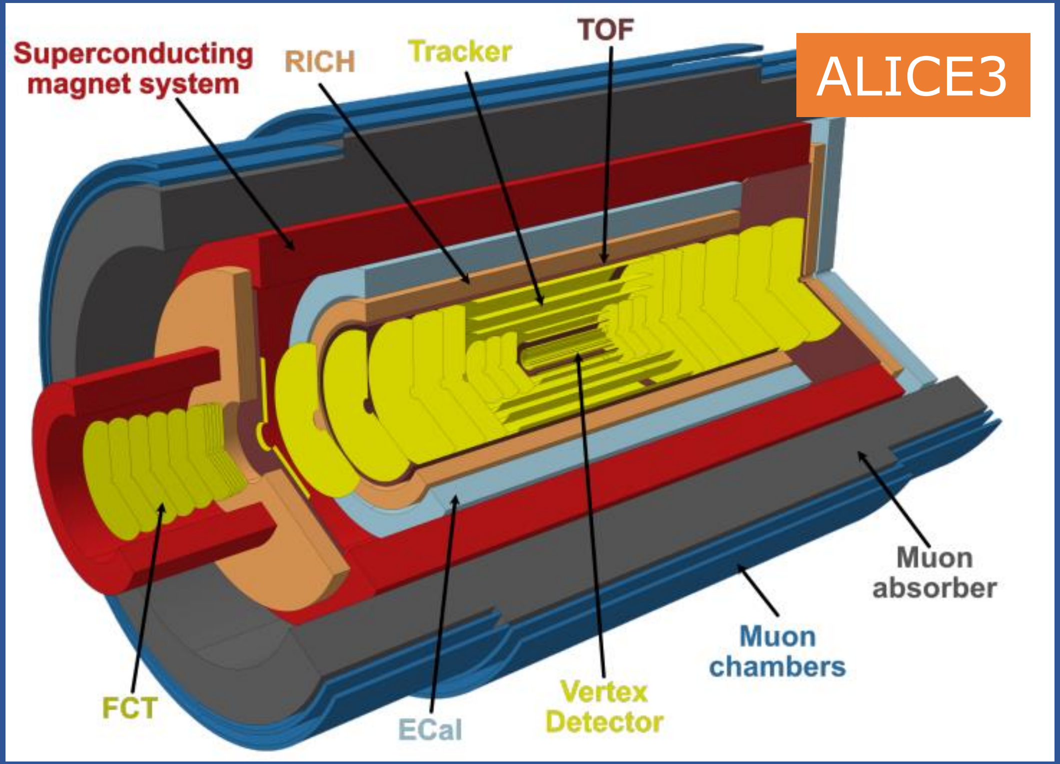




- Unique capabilities for
  - reconstruction of quarkonium states down to $p_T = 0$
  - low energy photons (0.5 GeV and below)

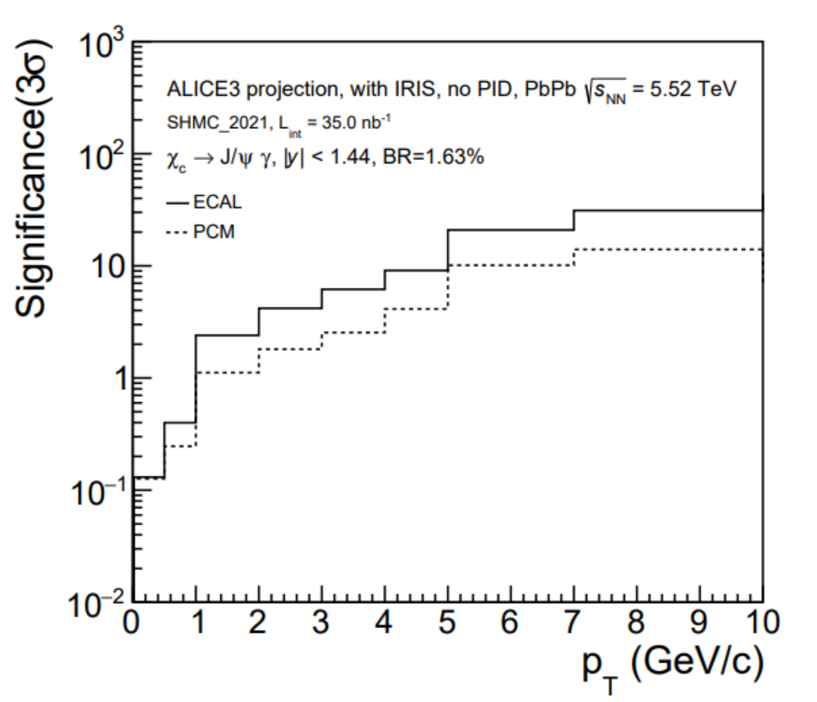
LoI, arXiv:2211.02491

What remains to be done ? High-energy/zero μ_B



- Aim at performing **quarkonium spectroscopy in the Quark-Gluon Plasma**

- Pseudoscalar (η_c,η_b) and P-wave (χ_c,χ_b) states largely unexplored in heavy-ion collisions
- Access
  - $\chi_c \rightarrow J/\psi\ \gamma$, $\chi_b \rightarrow \Upsilon\ \gamma$
  - $\eta_c \rightarrow p\bar{p}$, $\eta_c \rightarrow \Lambda\bar{\Lambda}$ (performance under study)



L_{int} = 35 nb^{-1}

Good significance for χ_c down to $p_T \sim$ 2 GeV/c

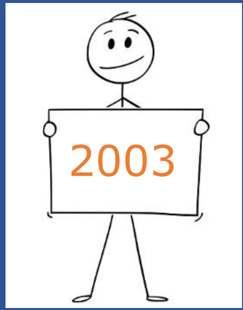
- Unique capabilities for
  - reconstruction of quarkonium states down to p_T = 0
  - low energy photons (0.5 GeV and below)

LoI, arXiv:2211.02491

Exotica

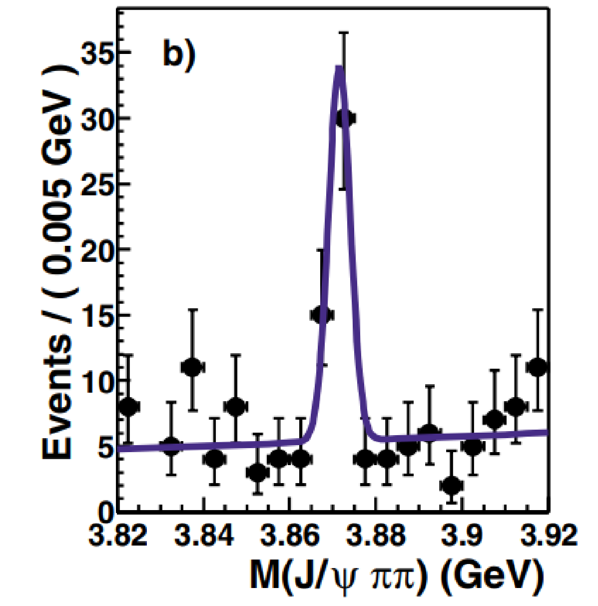
- Can non-$q\bar{q}$/non qqq states tell us something on QGP properties ?
- Can we learn something on their structure by producing them in HI collisions?

Where all started…

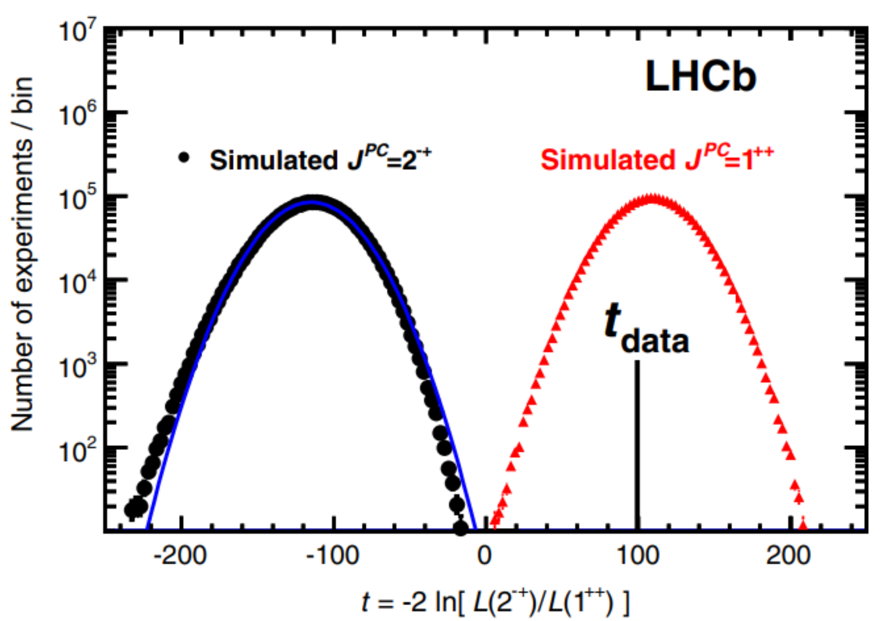


Observation of a Narrow Charmoniumlike State in Exclusive $B^{\pm} \to K^{\pm}\pi^{+}\pi^{-}J/\psi$ Decays

S.-K. Choi *et al.* (Belle Collaboration)
Phys. Rev. Lett. **91**, 262001 – Published 23 December 2003



Among the remaining possibilities are the $\chi_{c1}(2^3P_1)$ charmonium disfavored by the value of the $X(3872)$ mass [34], and unconventional explanations such as a $D^{*0}\bar{D}^0$ molecule [8], tetraquark state [9], or charmonium-molecule mixture [10].

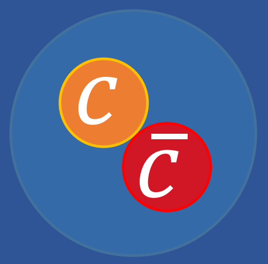


Determination of the $X(3872)$ Meson Quantum Numbers

R. Aaij *et al.* (LHCb Collaboration)
Phys. Rev. Lett. **110**, 222001 – Published 29 May 2013

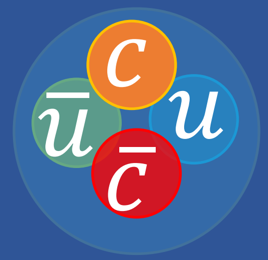
Can HI collisions help us decipher its nature?

charmonium



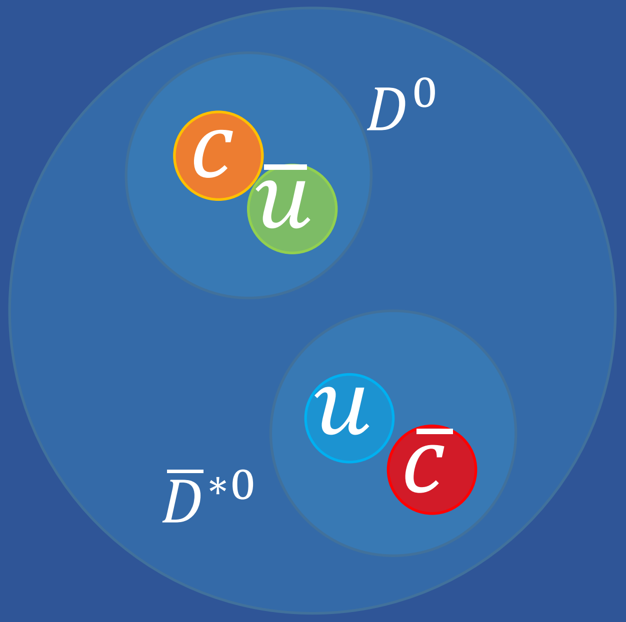
wrong mass
predicted with
$J^{PC} = 1^{++}$

tetraquark



r~0.3fm

D^0-$\bar{D}^{*0}$ molecule

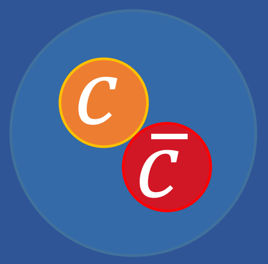


r>5 fm, small binding energy

➢ **Production in a QCD medium** might provide insight on its inner structure?

Can HI collisions help us decipher its nature?

charmonium



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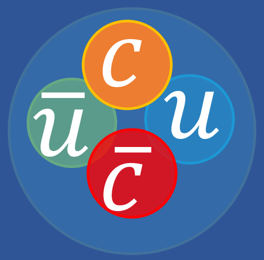

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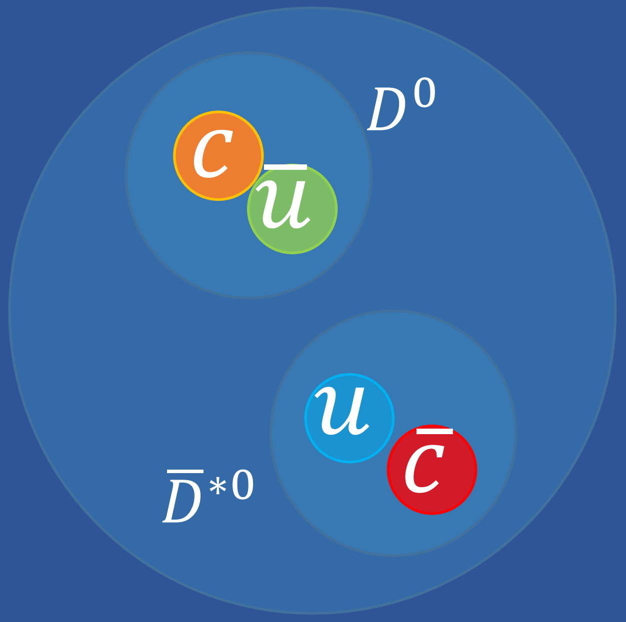

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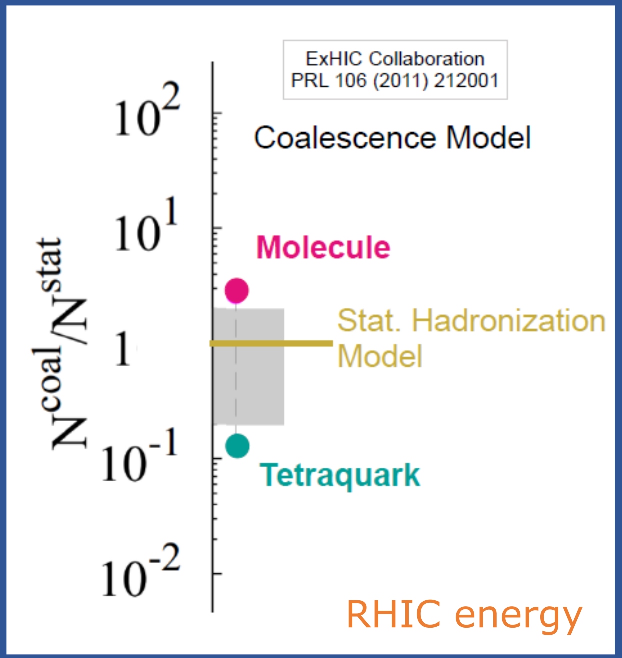


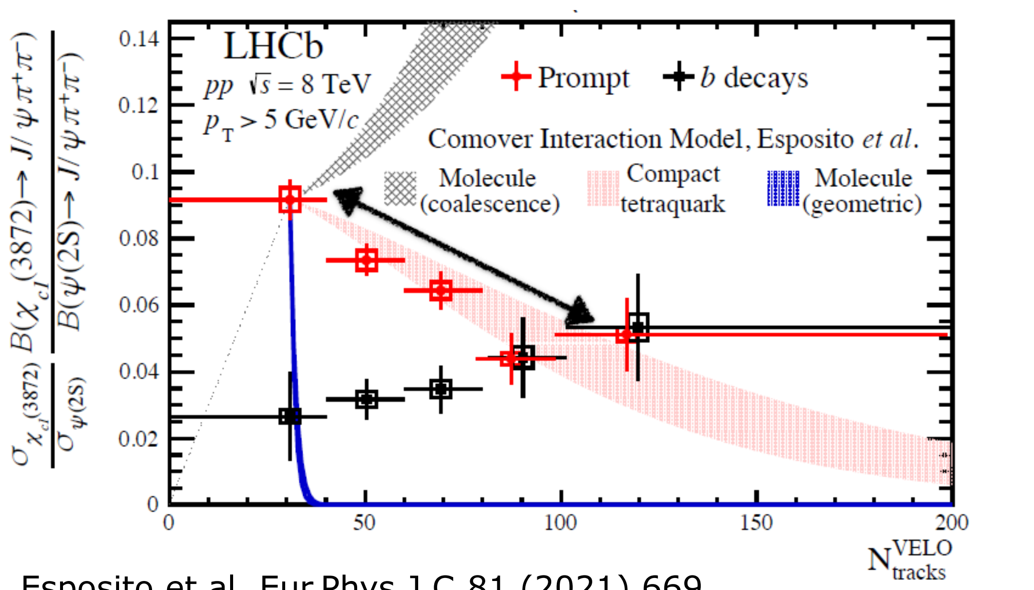
We conclude from the above discussions that the yield of a hadron in relativistic heavy ion collisions reflects its structure and thus can be used as a new method to discriminate the different pictures for the structures of multi-quark hadrons.

- **Production in a QCD medium** might provide insight on its inner structure?
- Early coalescence-based models predicted **lower yields for a compact multiquark state**

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

- Data described by comover interaction model assuming X(3872) to be a **tetraquark**
  → breakup reaction rate approximated by the geometric cross section

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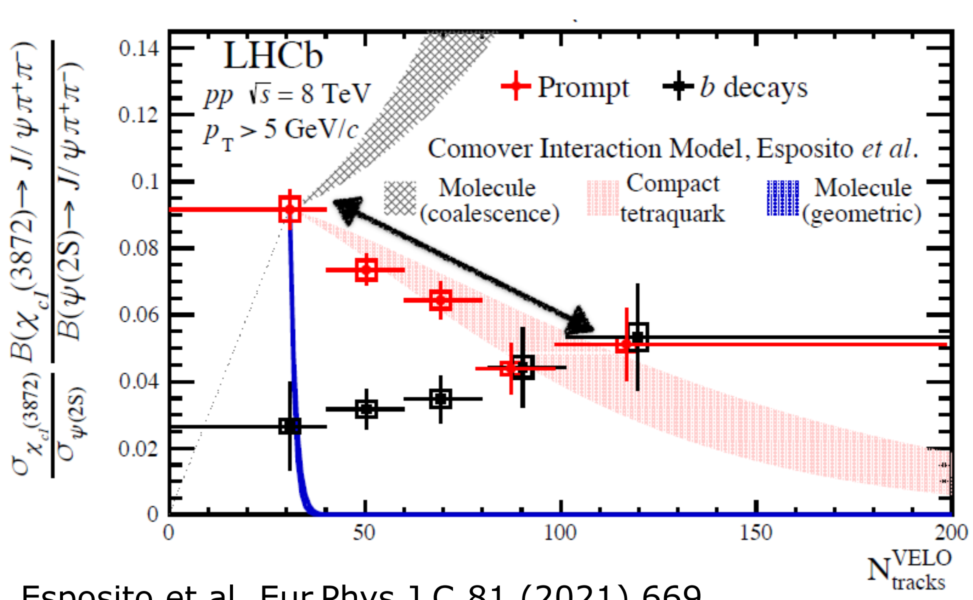
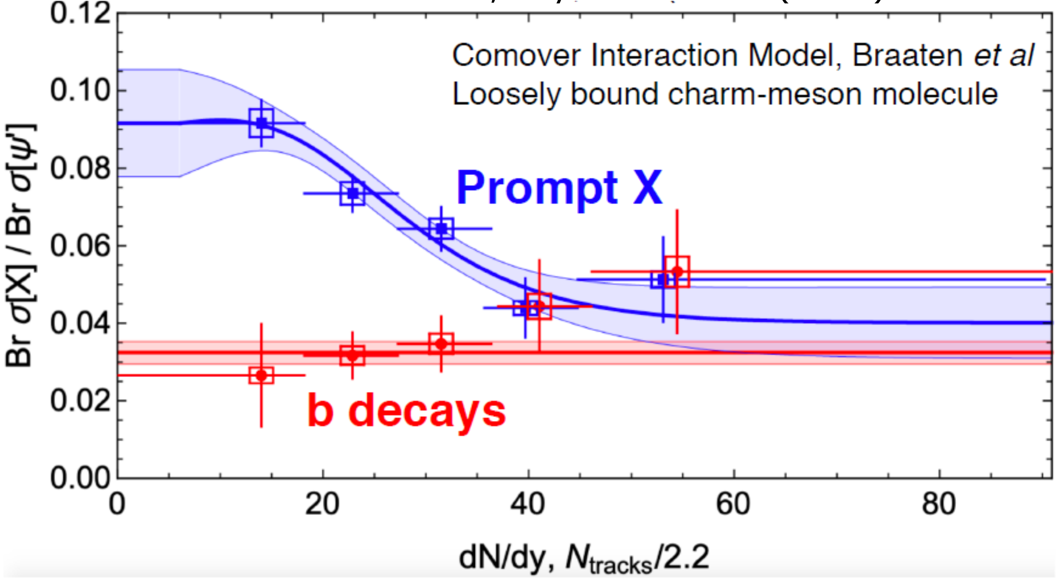
LHCb, PRL 126 (2021) 092001 (2021)



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

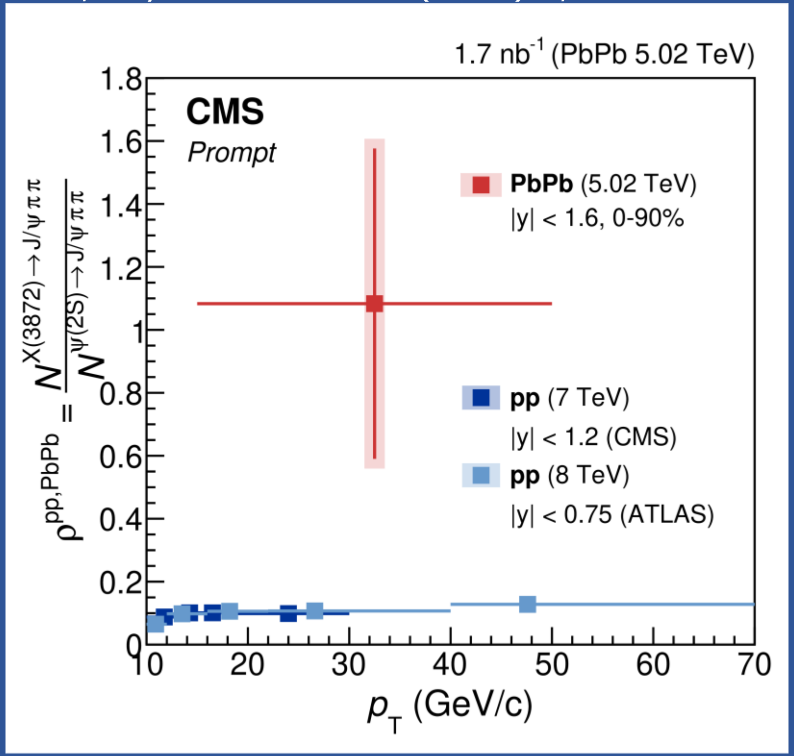
E. Braaten et al., Phys.Rev.D 103 (2021) L071901



- 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)

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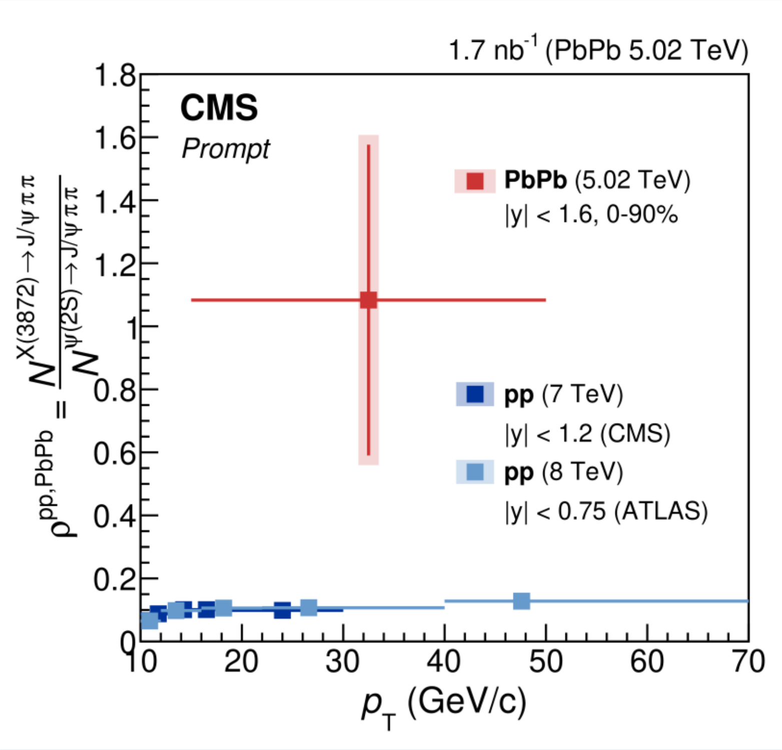

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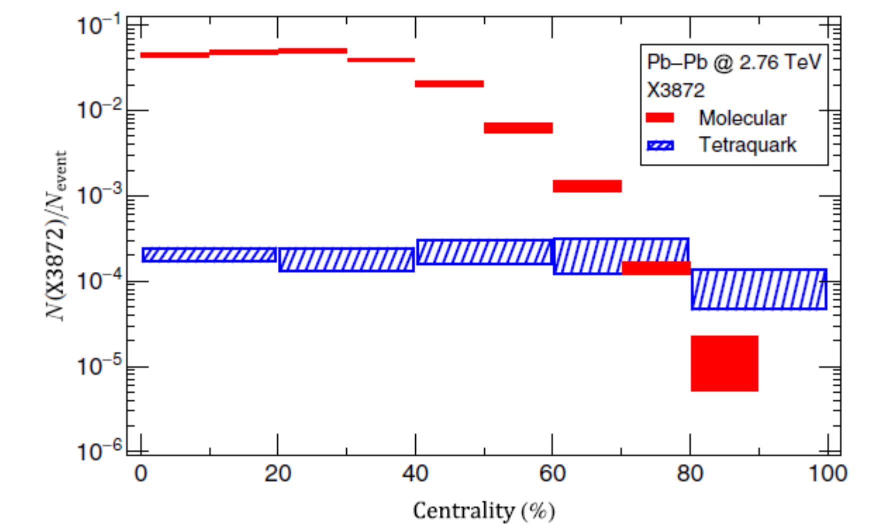
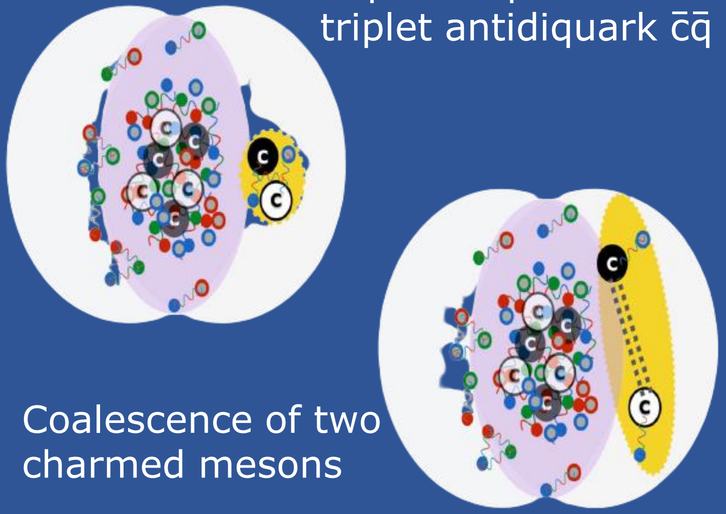
H. Zhang et al., PRL 126(2021) 012301



colored force between a color antitriplet diquark cq and a color triplet antidiquark $\bar{c}\bar{q}$

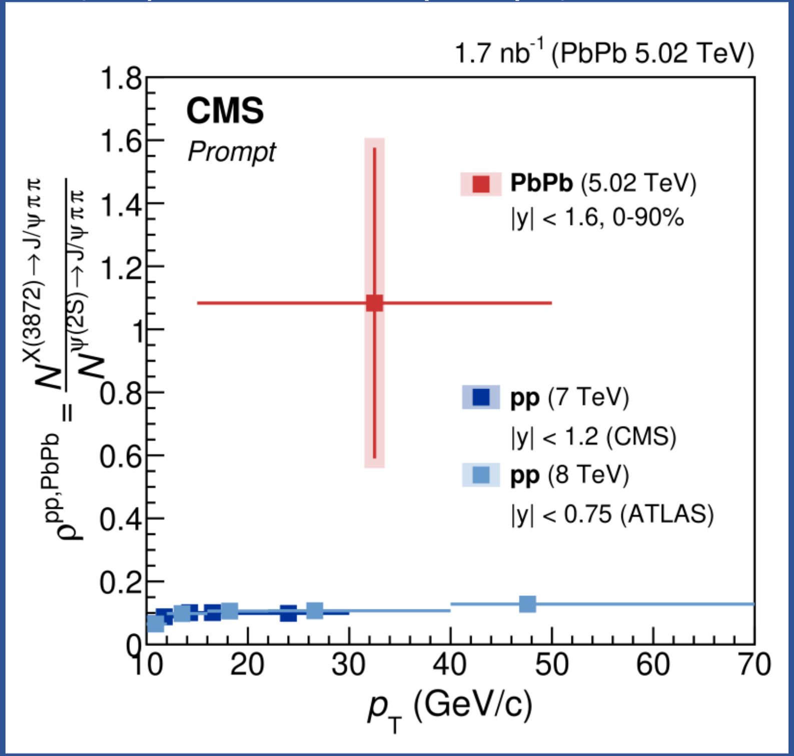


Coalescence of two charmed mesons

➢ **Coalescence** model (AMPT): **much larger yields for molecular option**, with strong centrality dependence (ccbar more likely separated in space at freeze-out)

X(3872): first measurement in Pb-Pb

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



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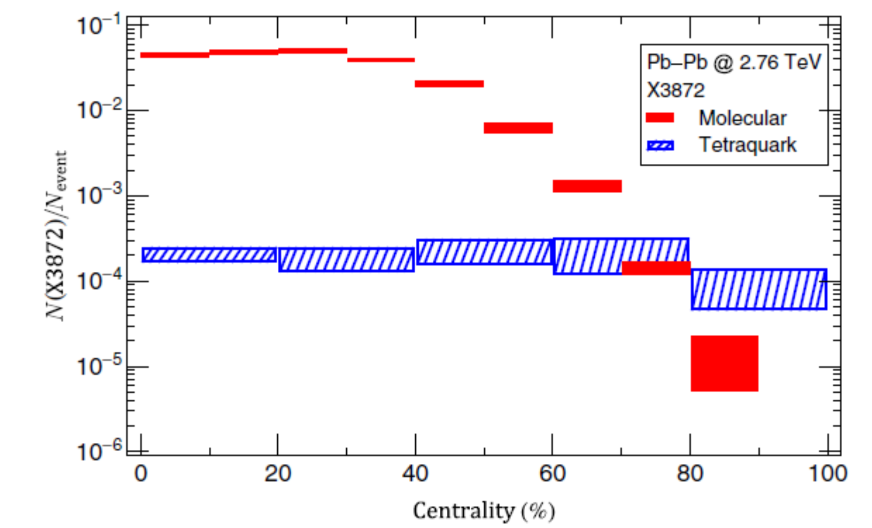
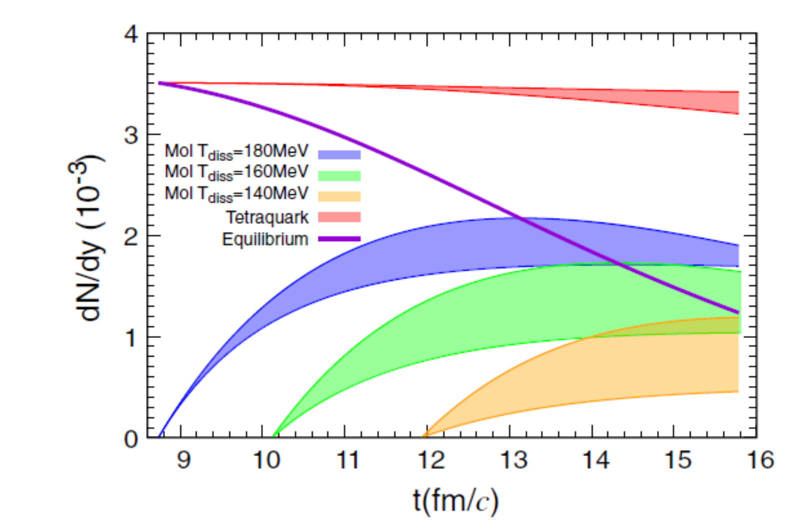
H. Zhang et al., PRL 126(2021) 012301

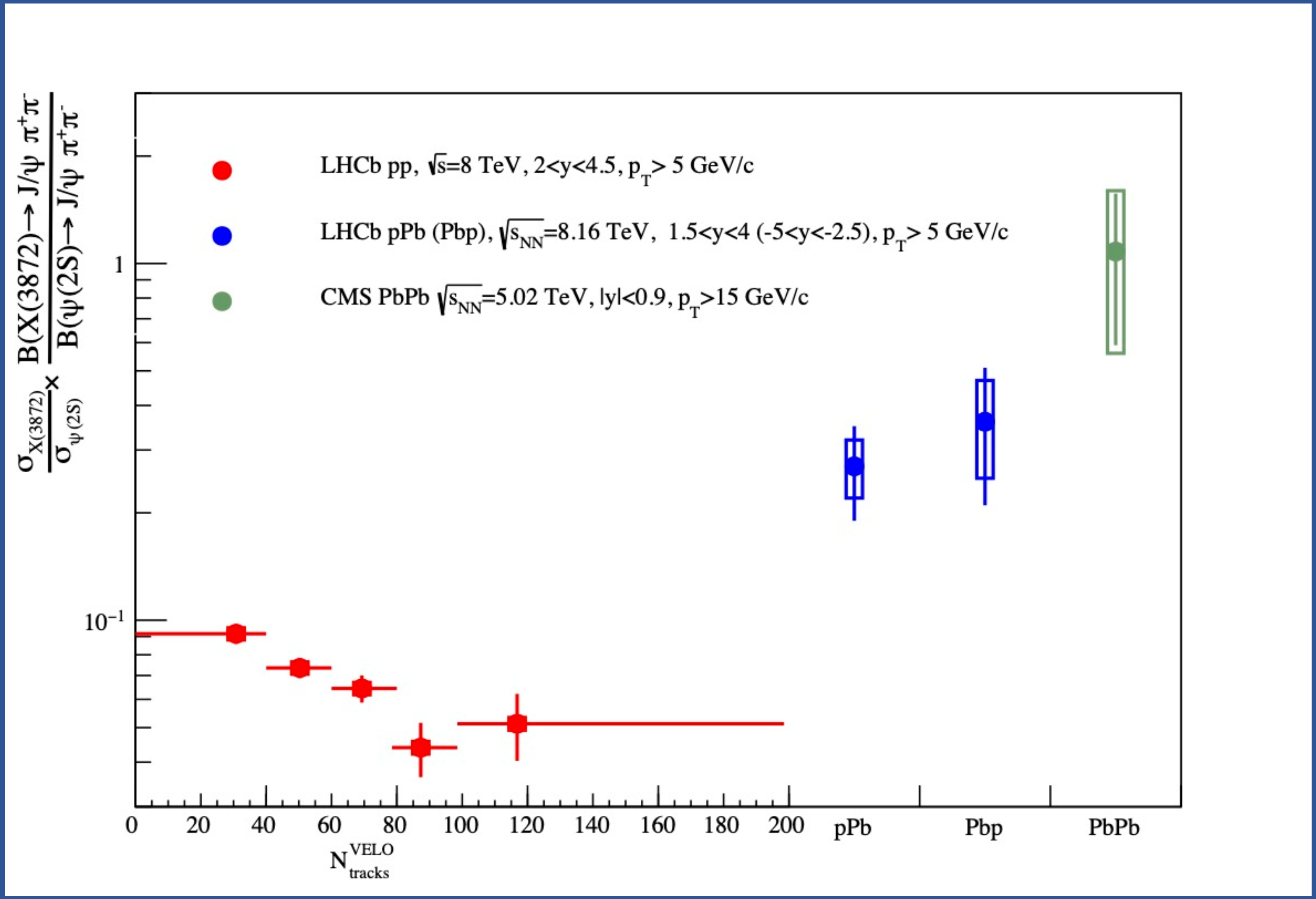


B. Wu et al., EPJA 57(2021) 122



- **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

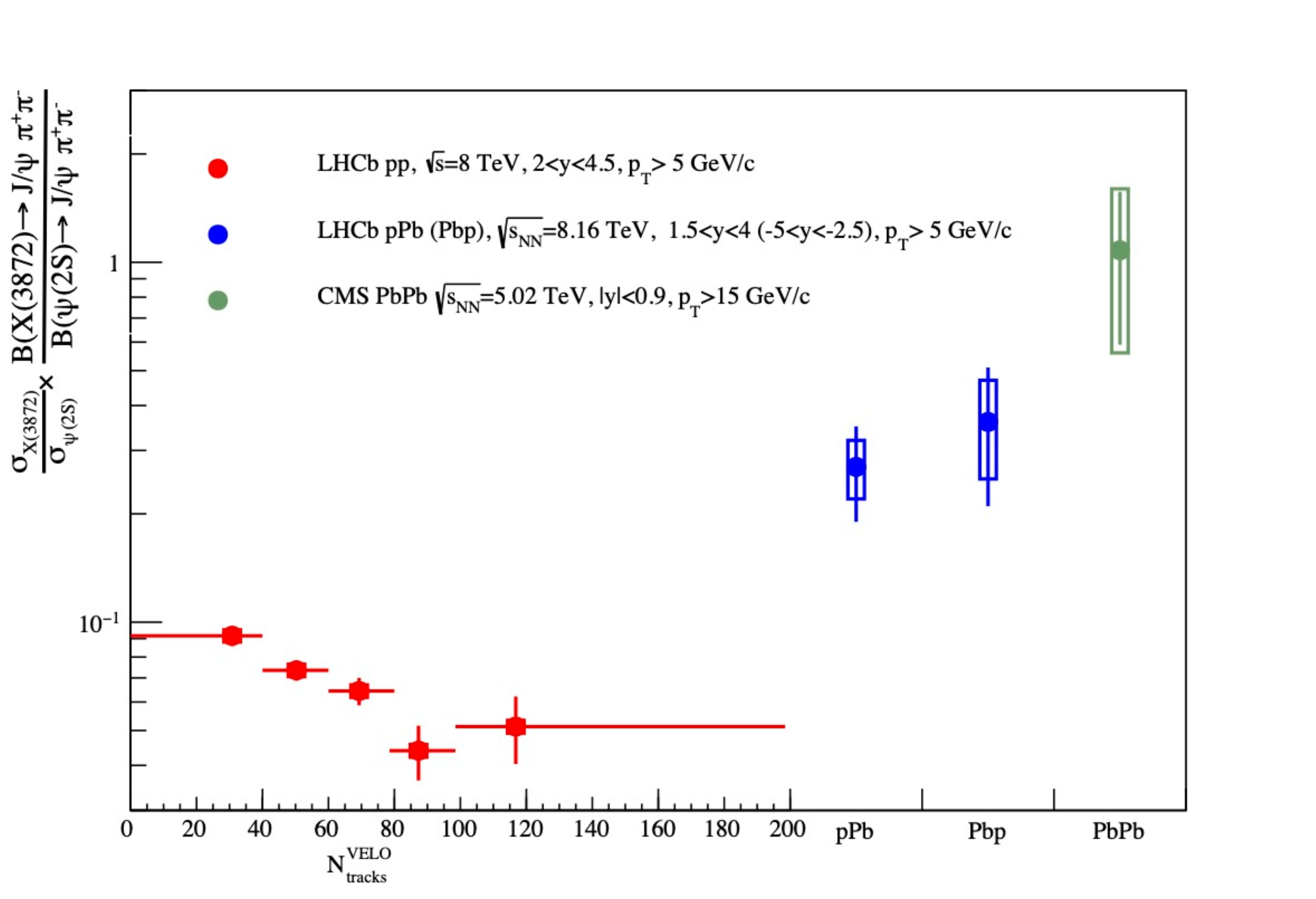


pp → p-Pb → Pb-Pb

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

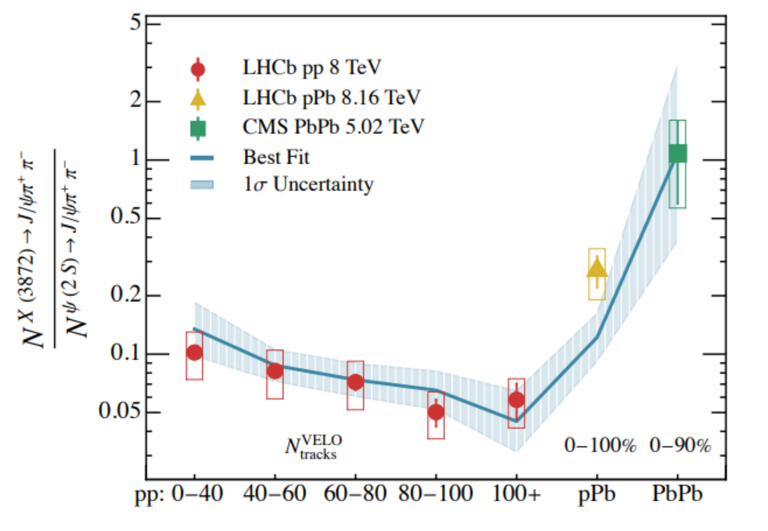
- Extension of measurements toward low p_T badly needed → **LHC run 3/4**

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**

Conclusions

- Heavy quarks: great sensitivity to the medium, spectacular phenomenology!

- Quarkonia
  - Lots of results on vector states
  - P-wave and pseudoscalar states almost completely unexplored
  - B_c needs further investigation
  - Related observables (not covered today): polarization,…

- Exotica
  - Only the surface was scratched
  - Beyond X(3872): T_{cc}^{+}(ccud), X(6900) $(cc\bar{c}\bar{c})$,…

- Open heavy-flavors
  - A world on its own… sorry for not discussing them today!

Looking forward to new exciting results at QM2023

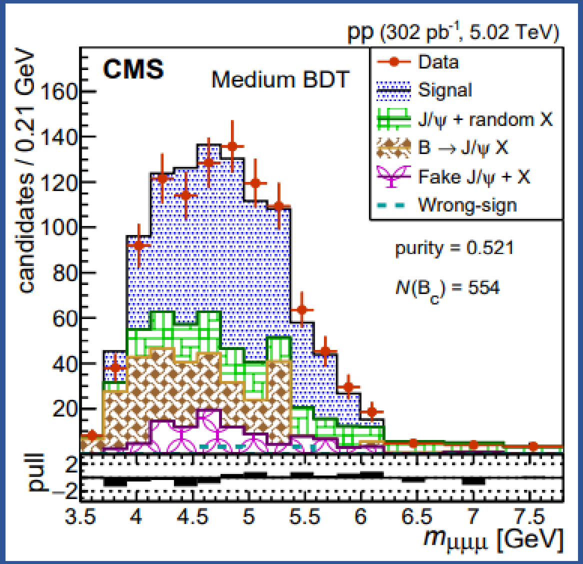
Backup

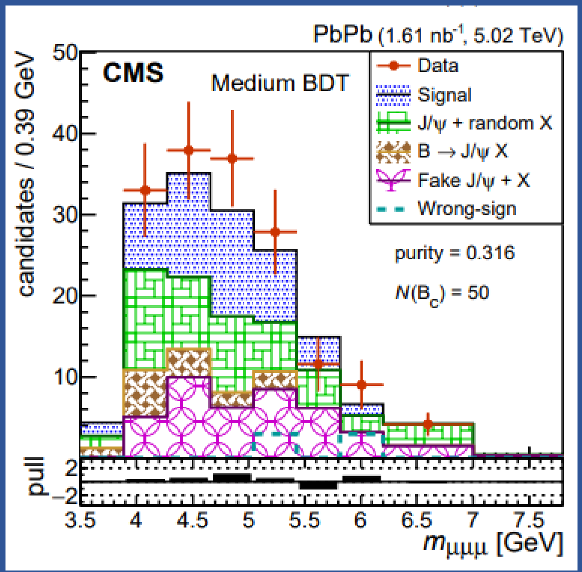
A “hybrid” quarkonium state: B_c^+

- Binding energy intermediate between J/ψ and ϒ(1S), can be dissociated in the QGP
- **Regeneration** effects **could be important** (small σ_{pp}^{Bc}, large charm multiplicity in Pb-Pb)
- Energy loss: study mass and color-charge dependence

- First measurement by CMS in Pb-Pb collisions via **$B_c^+ \rightarrow (J/\psi \rightarrow \mu\mu)\ \mu^+\nu_\mu$** (displaced vertex of 3 muons, with OS pair in the J/ψ region)

✓ Needs good understanding of background in $3.2<M_{\mu\mu}<6.3$ GeV
→ Use **BDT technique**



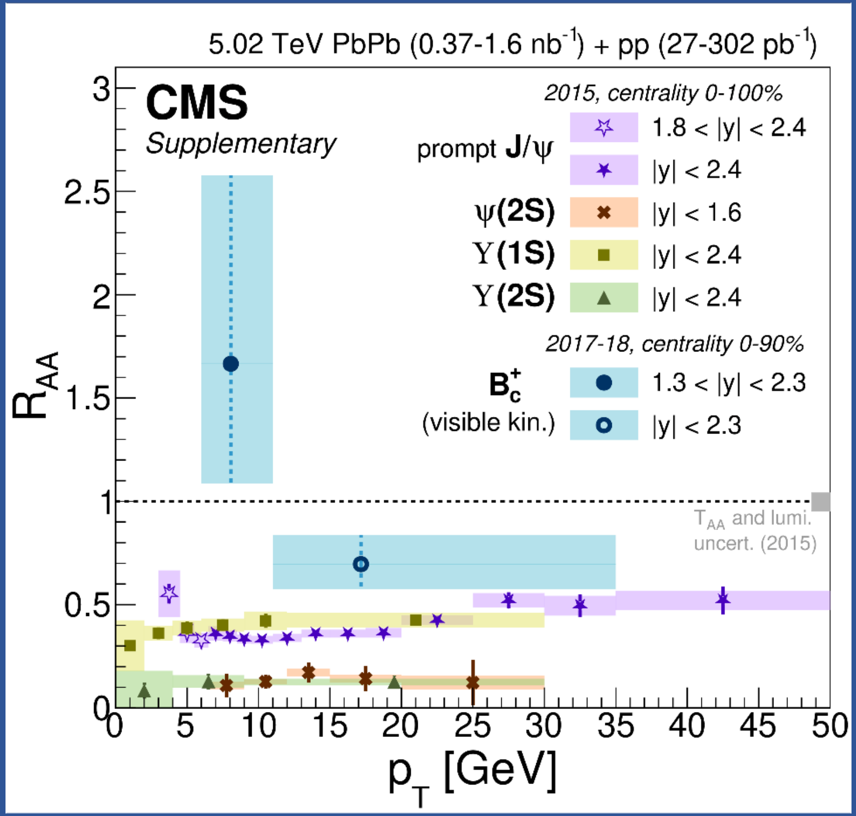


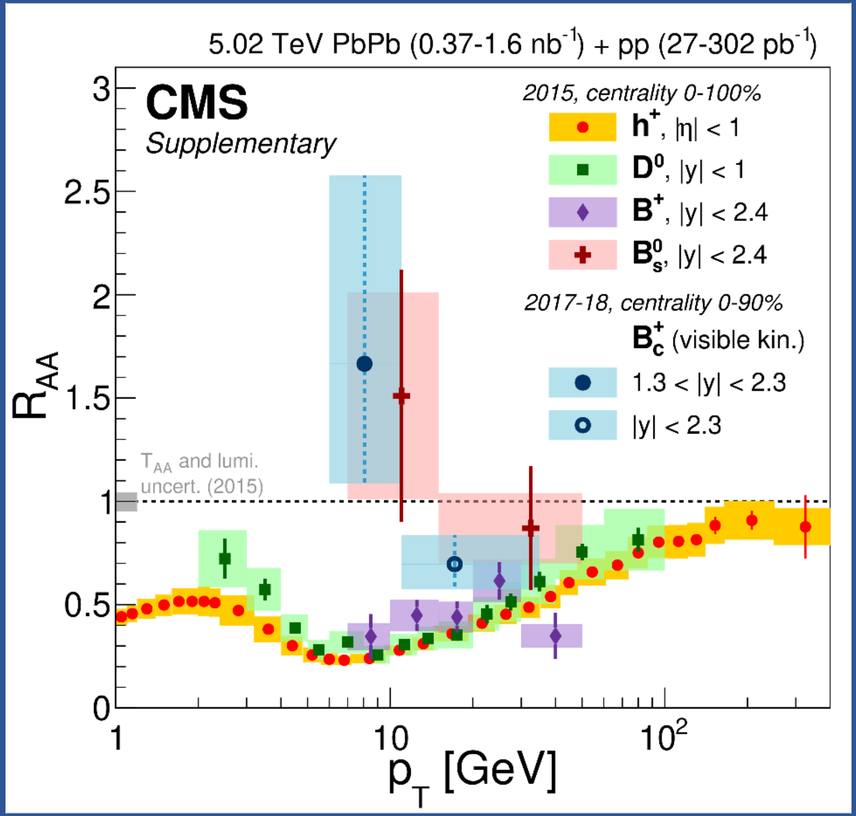
CMS, Phys. Rev. Lett. 128 (2022) 252301

Significance in Pb-Pb well **above 5σ**

Fake J/ψ: OS muons not coming from J/ψ (sidebands)
B decays: B→J/ψ + muon from same vertex (simulation)
J/ψ + random muon

A "hybrid" quarkonium state: B_c^+

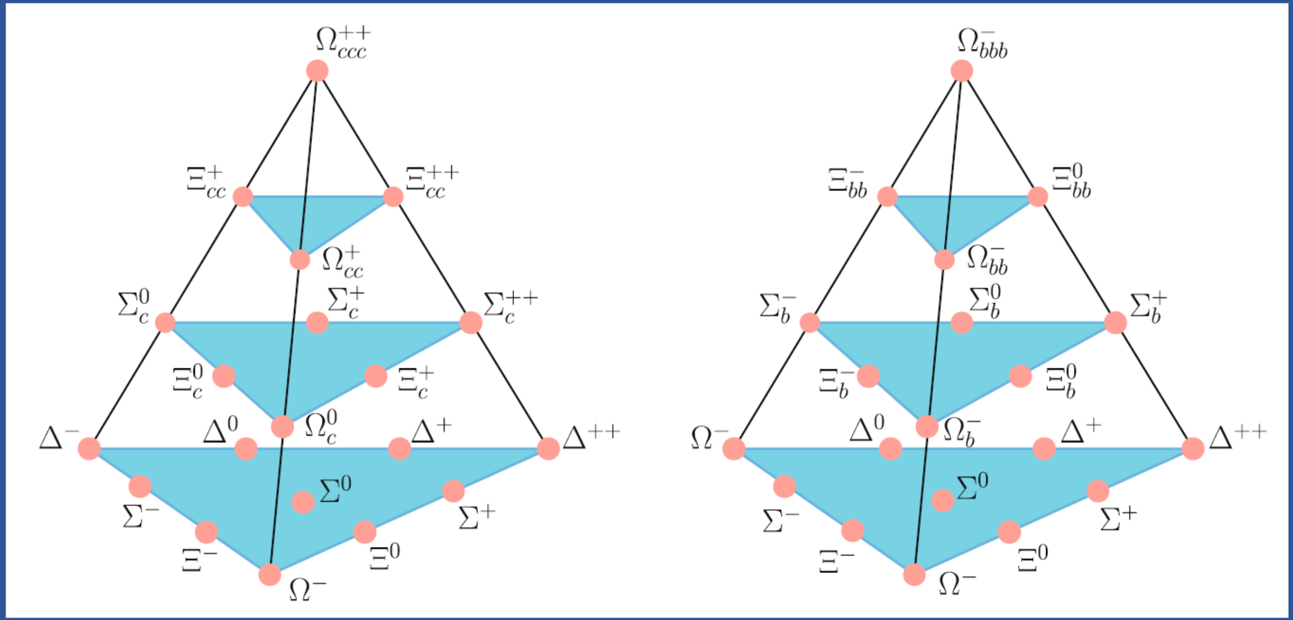




- Reminiscent of **J/ψ behaviour**, but **larger R_{AA}** values
- **High-p_T** region likely sensitive to **energy loss** effects too
- Very promising channel in view of **higher luminosity** data samples

- Hint for a p_T dependence of R_{AA} → from **enhancement to suppression** when increasing p_T (1.6 σ effect)
- Other heavy mesons typically show more suppression, may indicate **recombination** as a significant production effect

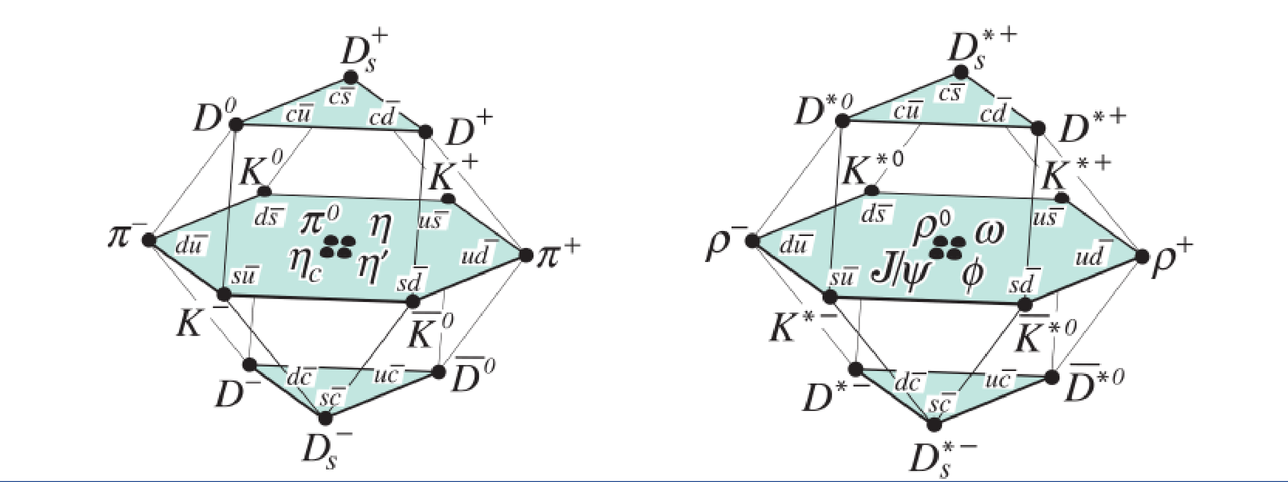
Charm/beauty mesons/baryons



(from Huang et al. EPJC (2021) 81:276

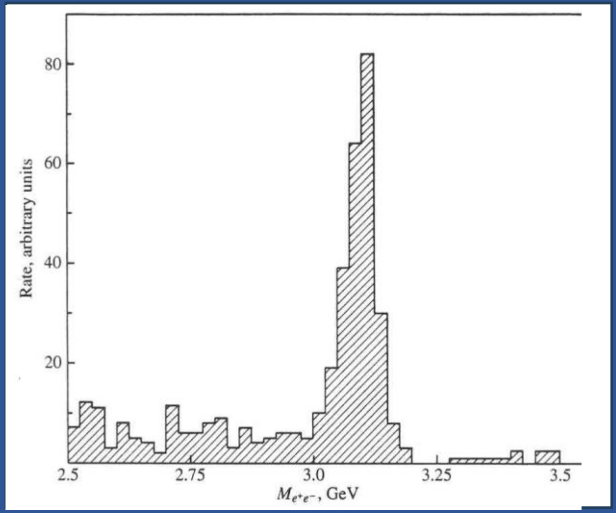
- ➢ Charm and beauty quarks are created in the early stages and probe the QGP phase
  - → Energy loss
  - → Thermalization

- ➢ Give rise to a large variety of particles
- ➢ Investigate hadron formation processes
- ➢ Baryons vs mesons
- ➢ Multi-heavy quark states



Heavy quarks: a (the) golden probe of QGP

From the November revolution…



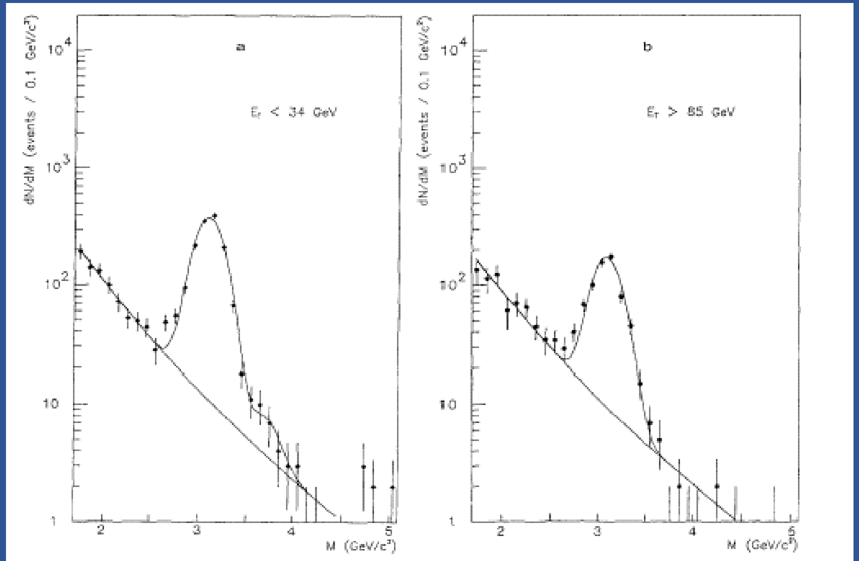
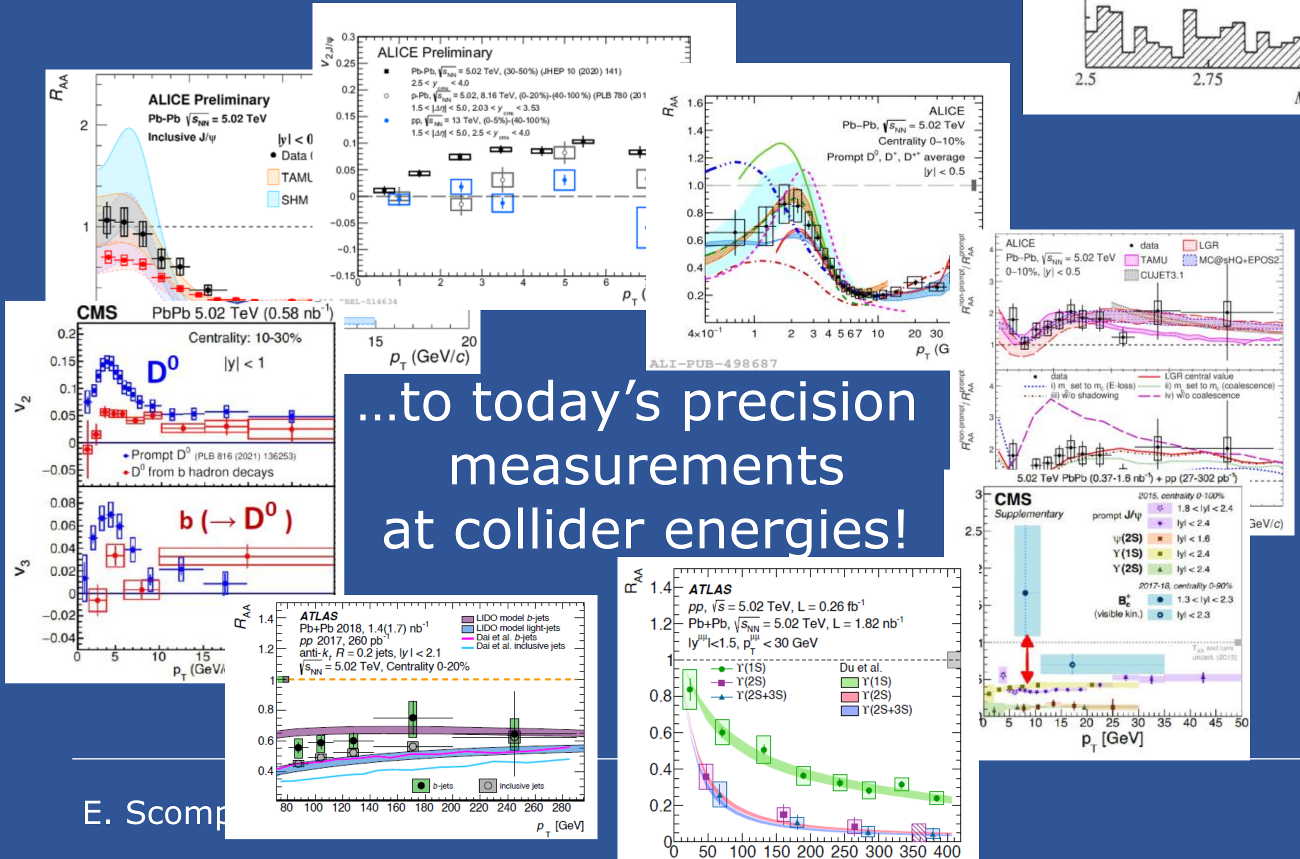


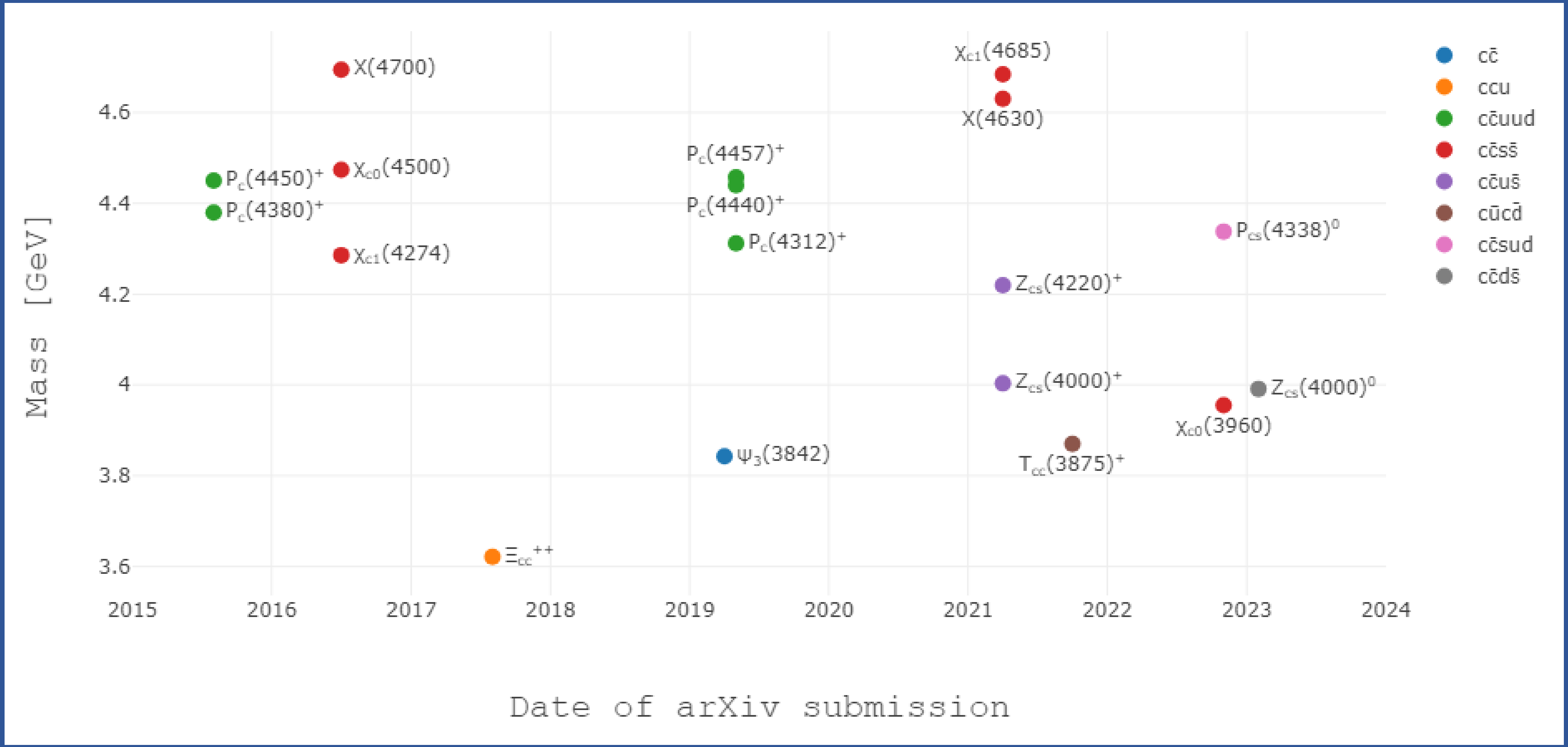
Fig. 5. Mass spectrum and fit of the signal muon pairs in two different E_T bins: $E_T < 34$ GeV (a) and $E_T > 85$ GeV (b).

… to the discovery of the J/ψ suppression…



…to today's precision measurements at collider energies!

Beyond $q\bar{q}$ and qqq



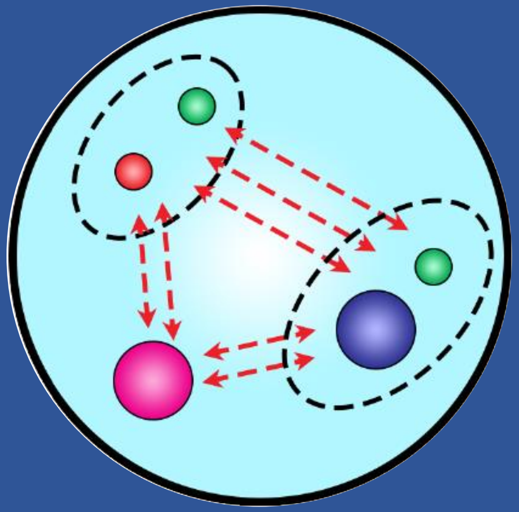
Recent years have seen a flourishing of discoveries of new states that do not fit inside the qqq or qq category

Here the states **discovered by LHCb**

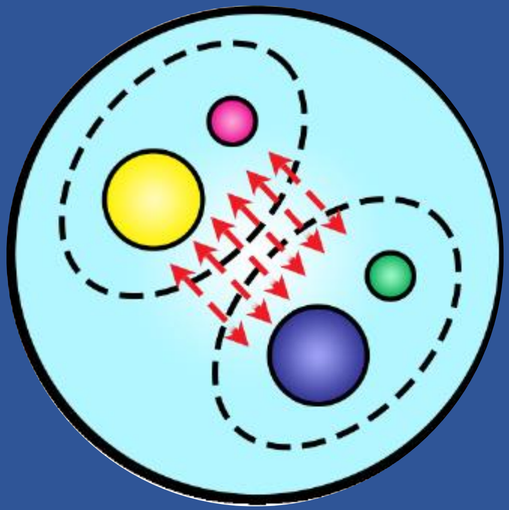
- Strong contributions from **CMS, ATLAS, BELLE, BES III** as well

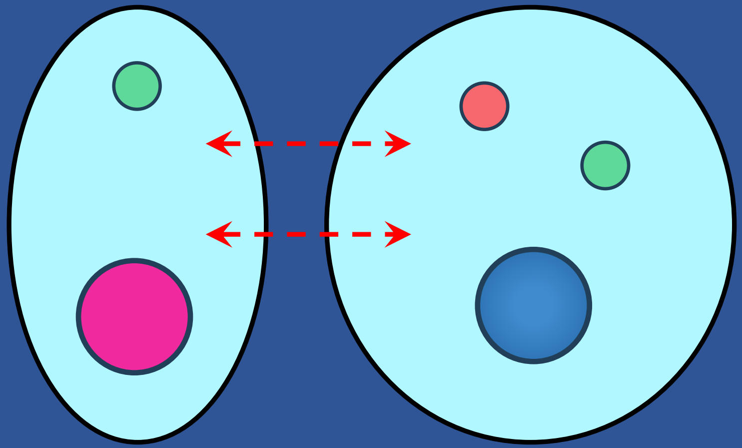
Beyond $q\bar{q}$ and qqq

From Chen et al.,
Rept. Prog. Phys. 86 (2023) no.2, 026201

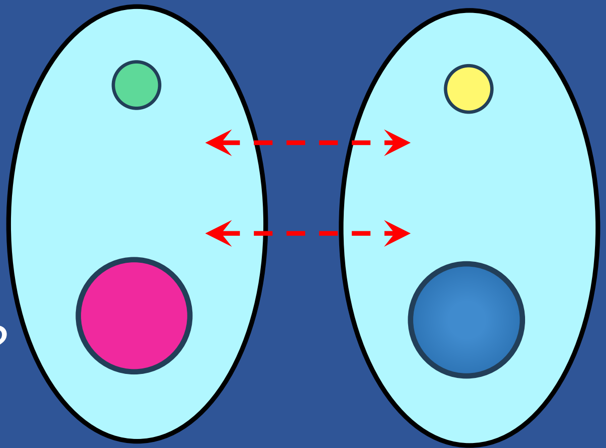


Compact multiquark states are tightly bound by the strong interaction directly, while the **hadronic molecular states** are weakly bound by the residual strong interaction



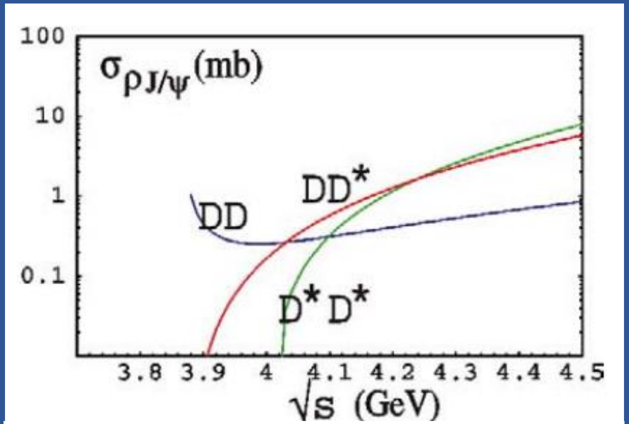


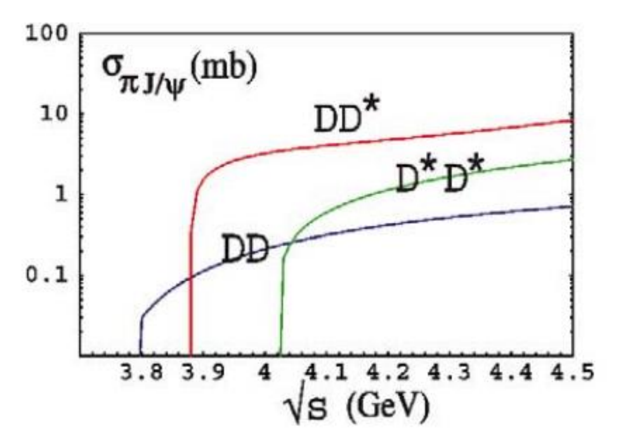
Can we investigate their nature by studying their production in HI collisions?

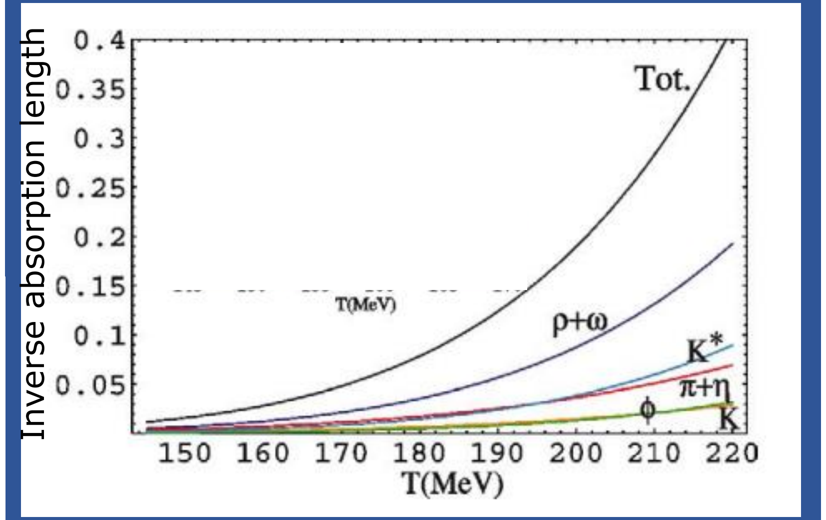


Can hadronic suppression really explain data ?

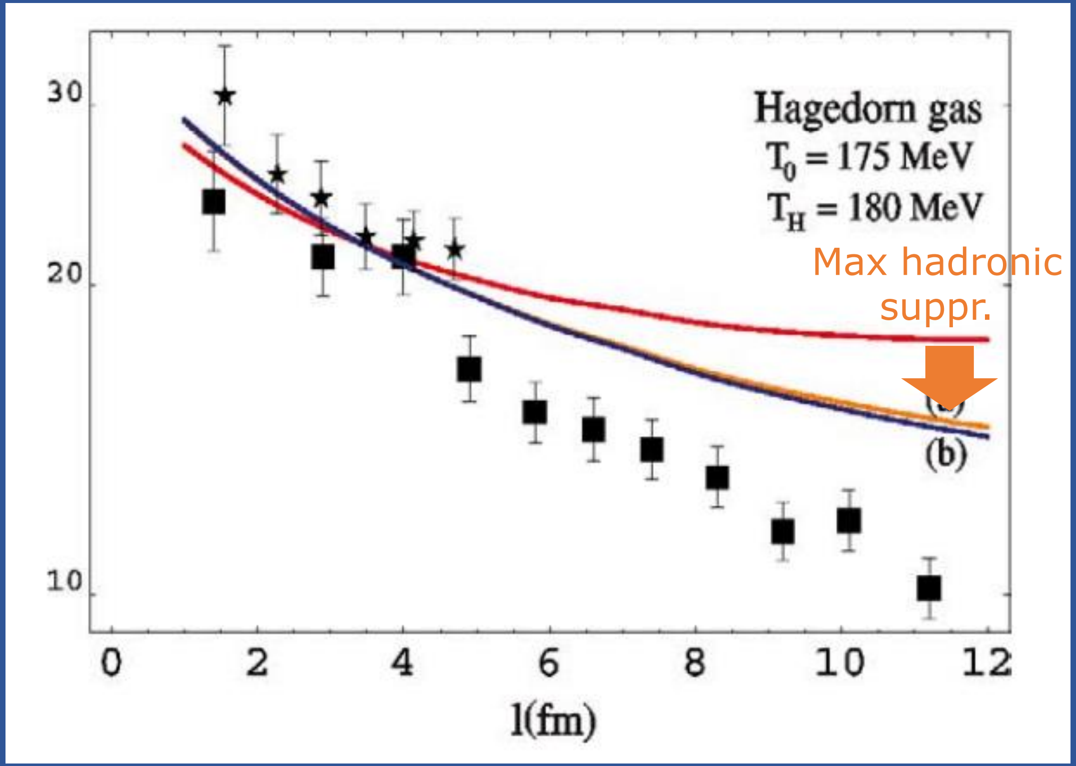
Wild discussions at the time…







Maiani et al., NP A 748 (2005) 209–225



The sharp rise of the degrees of freedom due to the vicinity of the Hagedorn temperature makes so that the temperature of the gas practically does not rise at all, the dissociation curve cannot become harder, and the prediction falls short from explaining the drop observed by NA50.

Sequential suppression…

state	J/ψ	χ_c	ψ'	Υ	χ_b	Υ'	χ'_b	Υ''
mass [GeV]	3.10	3.53	3.68	9.46	9.99	10.02	10.26	10.36
ΔE [GeV]	0.64	0.20	0.05	1.10	0.67	0.54	0.31	0.20
ΔM [GeV]	0.02	-0.03	0.03	0.06	-0.06	-0.06	-0.08	-0.07
r_0 [fm]	0.50	0.72	0.90	0.28	0.44	0.56	0.68	0.78

Binding energy

Resonance size

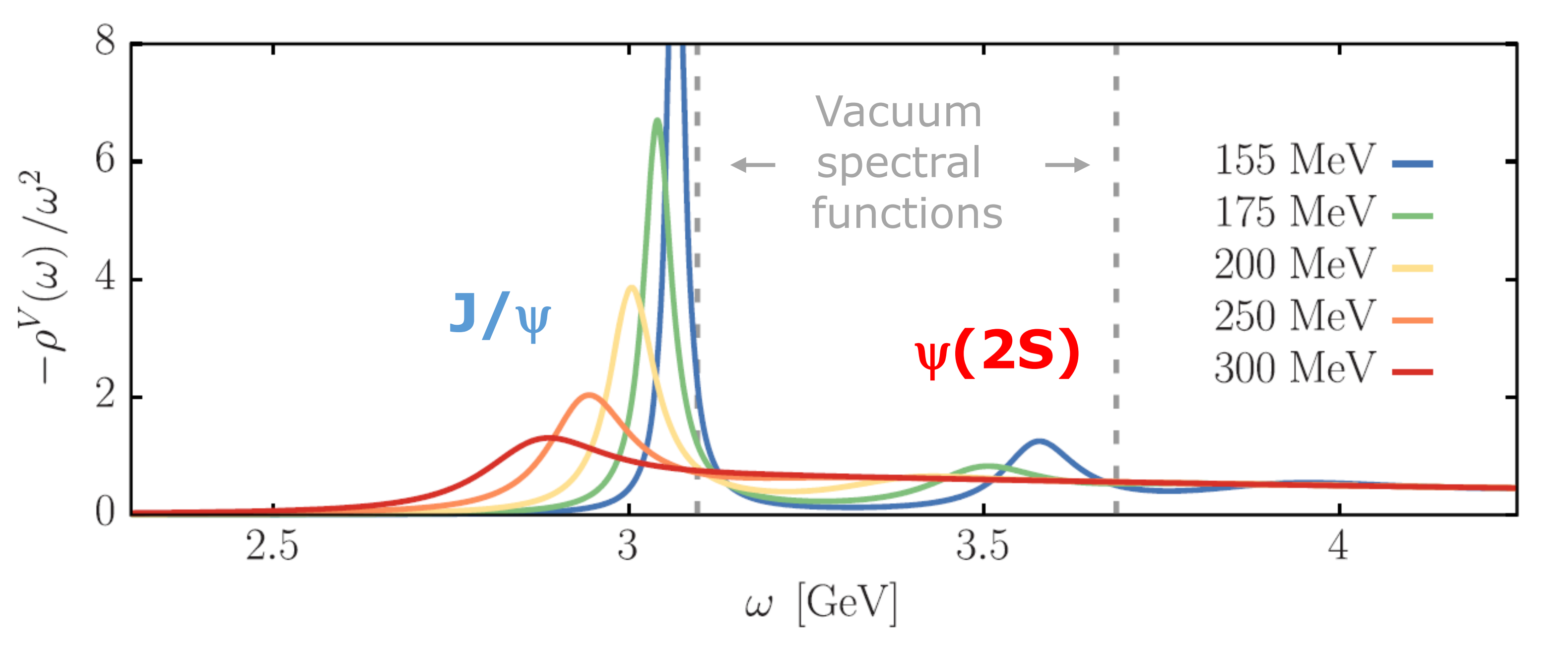
charmonia

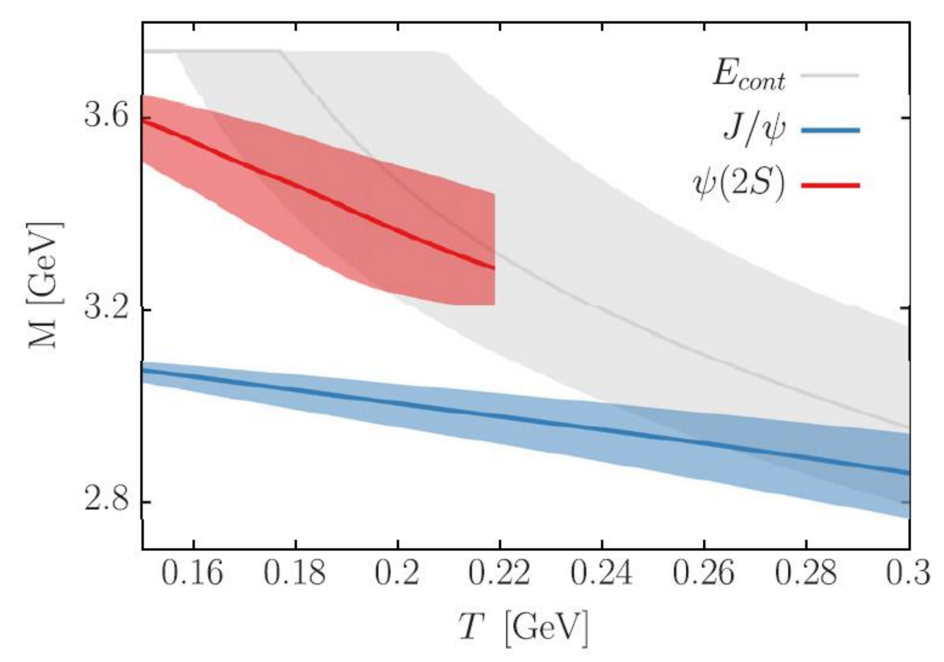
bottomonia

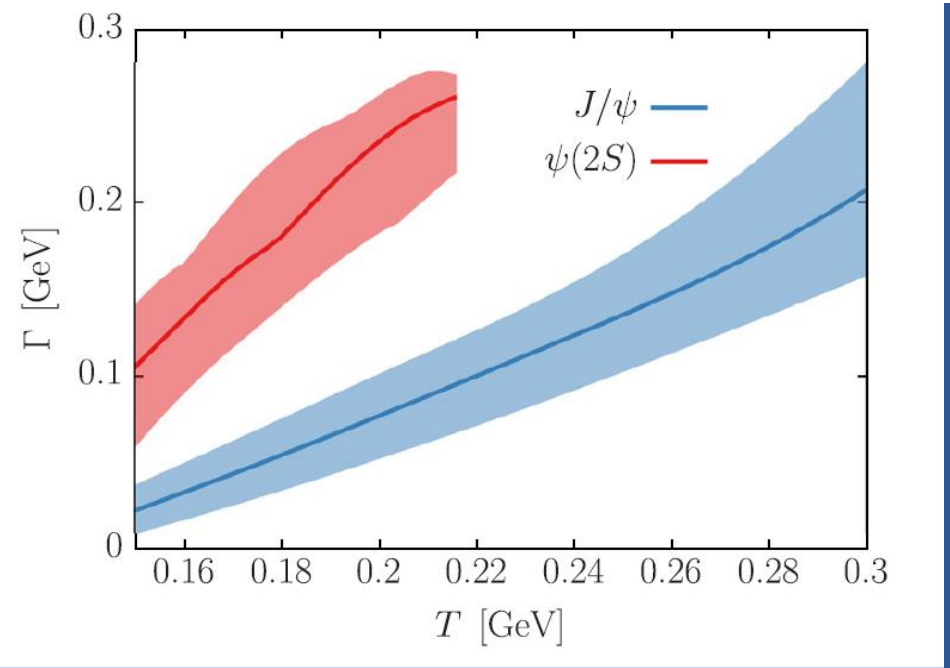
➢ Expect "ordering" in the suppression with weakly bound states more strongly affected

...checked with modern techniques

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

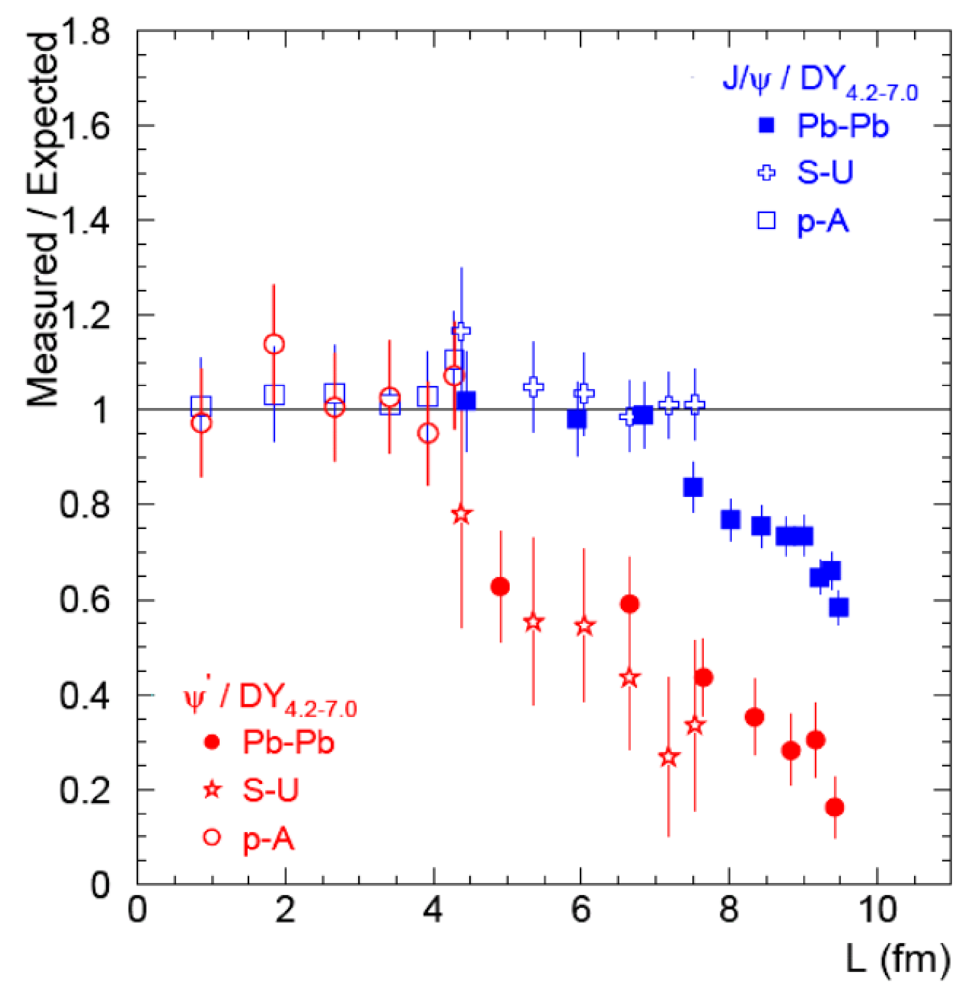






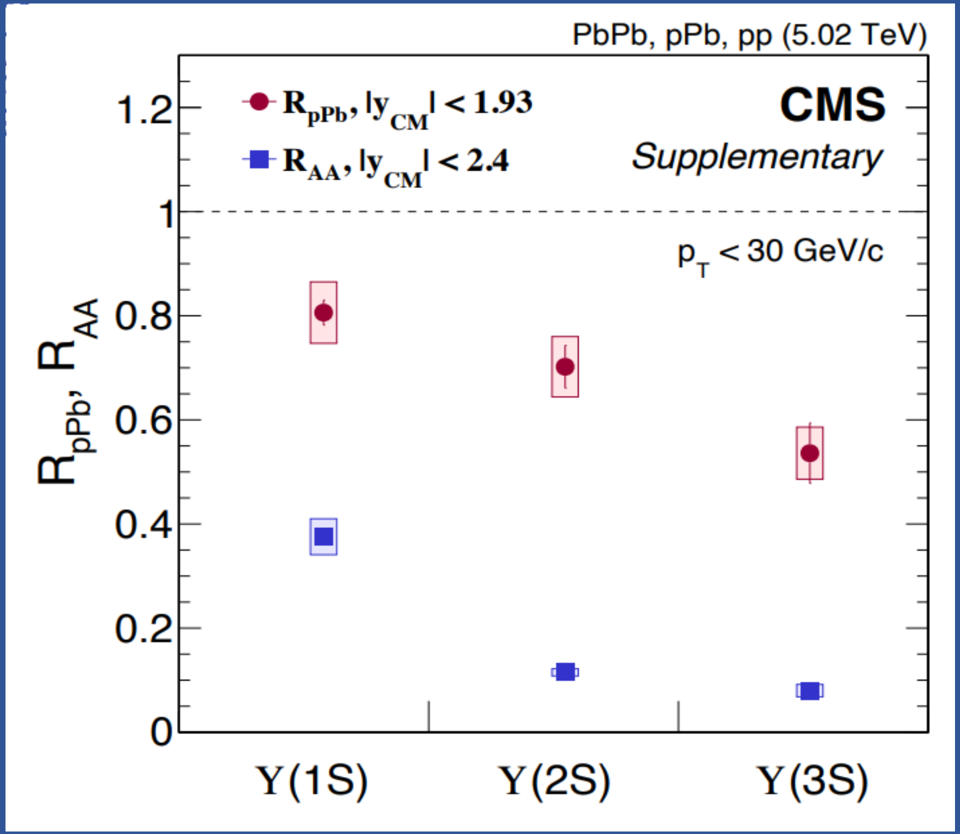
- Strong effects on the **mass AND width** of the charmonium states, with distinctive **differences between J/ψ and ψ(2S)**
- As intuitively expected, the more deeply the state is bound, the less is susceptible to medium effects

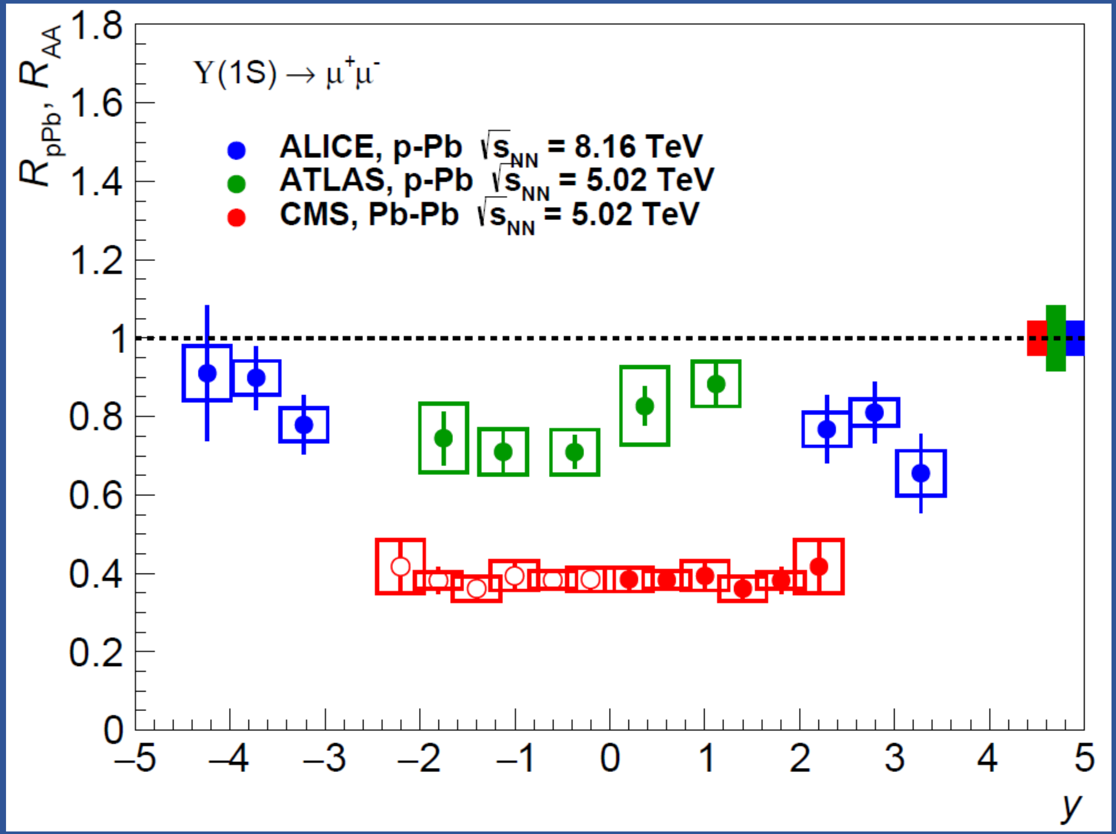
"Sequential" suppression revealed: ψ(2S) vs J/ψ



- With respect to the same reference process
- Having corrected for respective CNM effects, calibrated with p-A data
- ψ(2S) suppression effects turn in for more peripheral events in a given collision system
- The effects are much stronger for ψ(2S) at a given centrality

What about CNM effects ?





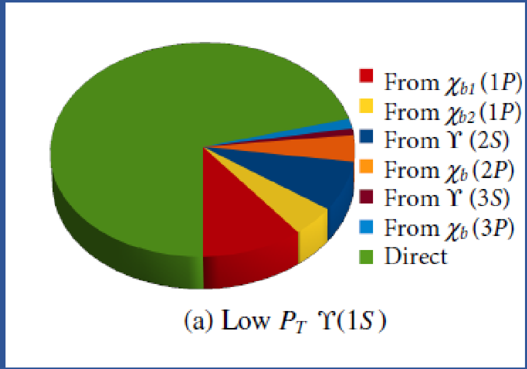
- ➢ Shadowing acts similarly for the three states
- ➢ Are we seeing final state dissociation effects?
- ➢ Nuclear suppression must be negligible
- ➢ Is a **dense system created in p-Pb?**

- ➢ Is the strong suppression of ϒ(1S) "compatible" with its extremely large binding energy (>1 GeV) ?
- ➢ Can a fraction of ϒ(1S) suppression be due to **non-QGP effects?**

Direct Υ(1S) suppression ?

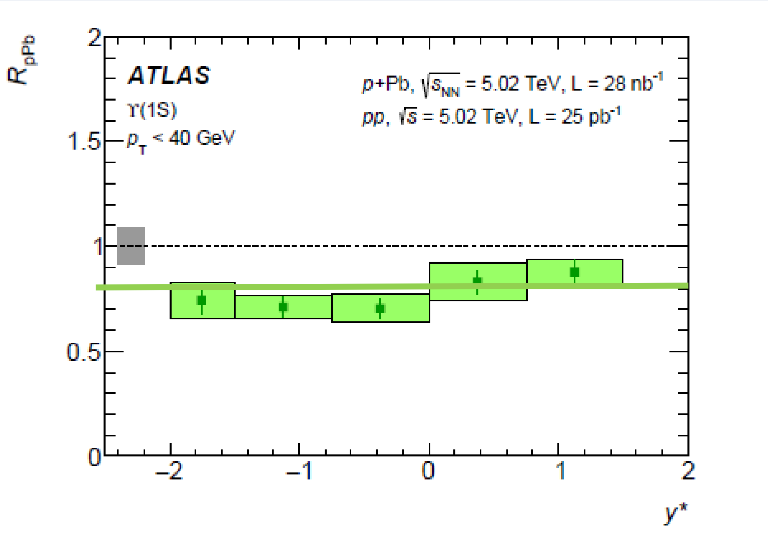
- Two aspects to be considered
  - Non-neligible **CNM effects**
  - **Feed-down** from S and P bottomonium states, with LHCb results implying a ~ 30% effect at (fairly) low p_T in pp

Lansberg, arXiv:1903.09185



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

ATLAS, arxiv:1709.03089



- Consider the Υ(1S) suppression seen by CMS and assume all the remaining Pb-Pb Υ(1S) to be direct

CMS: R_{AA}^{incl} Υ(1S) ~ 0.38

R_{AA}^{direct} Υ(1S) ~ 0.38/0.7 = 0.54

CNM effects: **$(R_{pA})^2 \sim 0.7^2 \sim 0.5$**

The observed **Υ(1S) suppression** could be compatible with a **combination of (i) 2S,3S feed-down + (ii) CNM effects**

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Lansberg, arXiv:1903.09185

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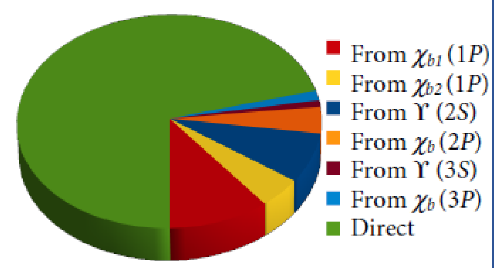

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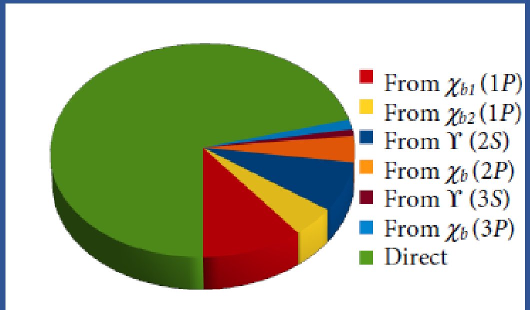

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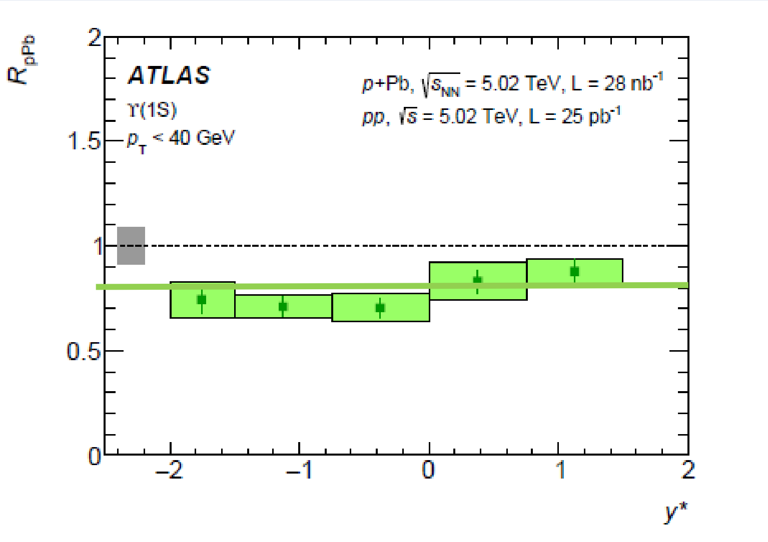

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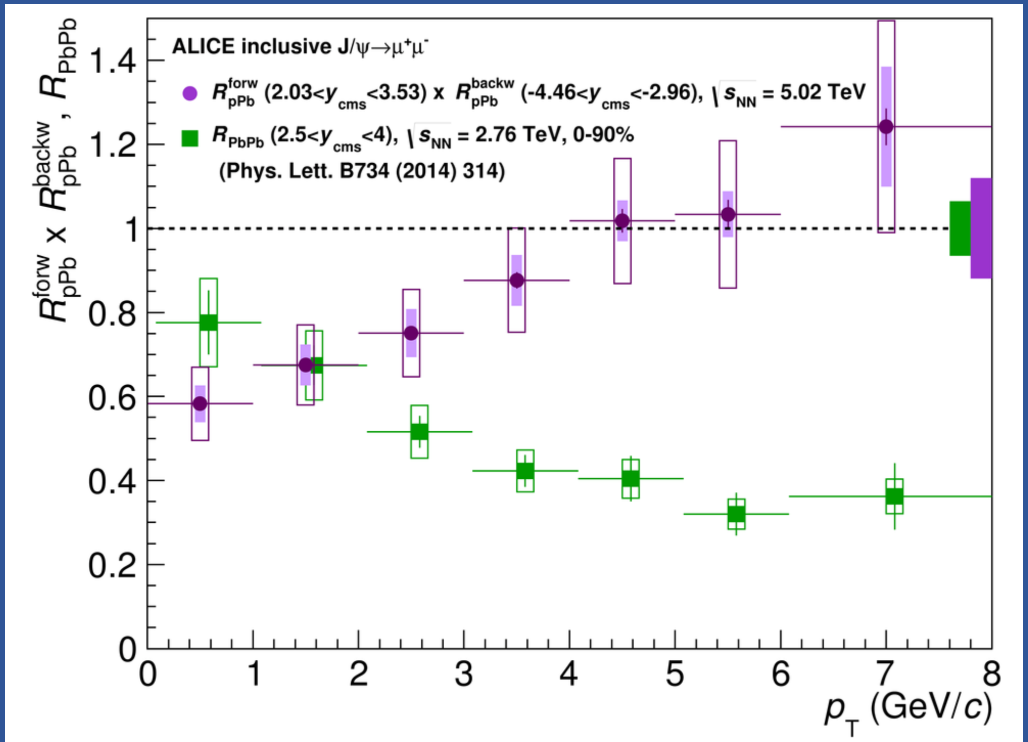
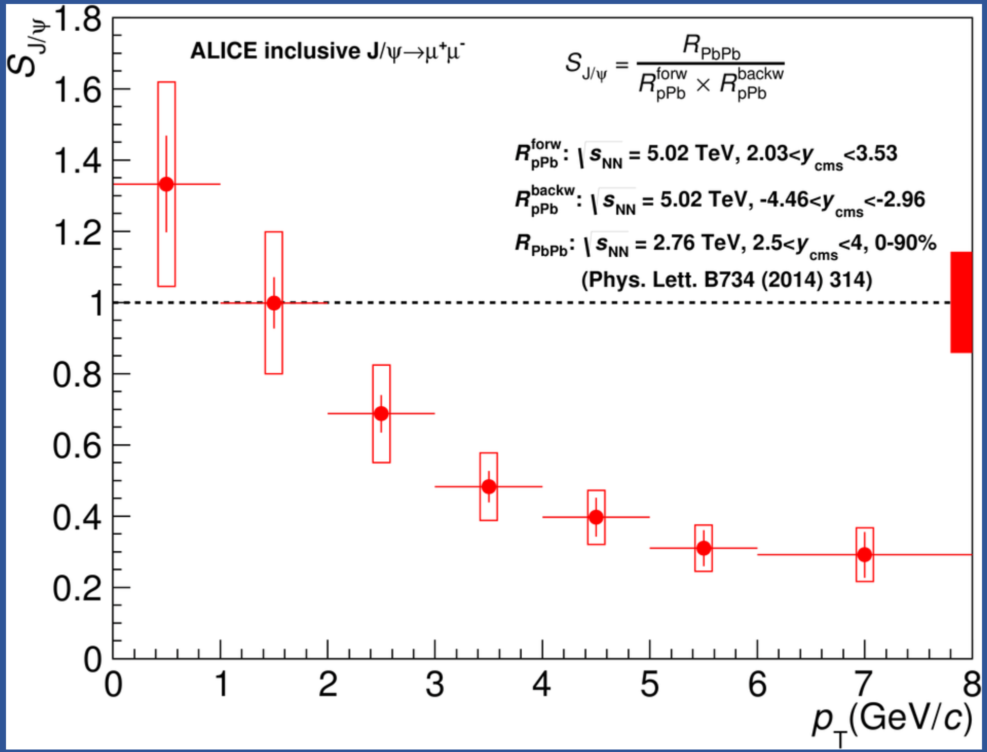
Do non-QGP effects matter ?

- Simple arguments show this is the case



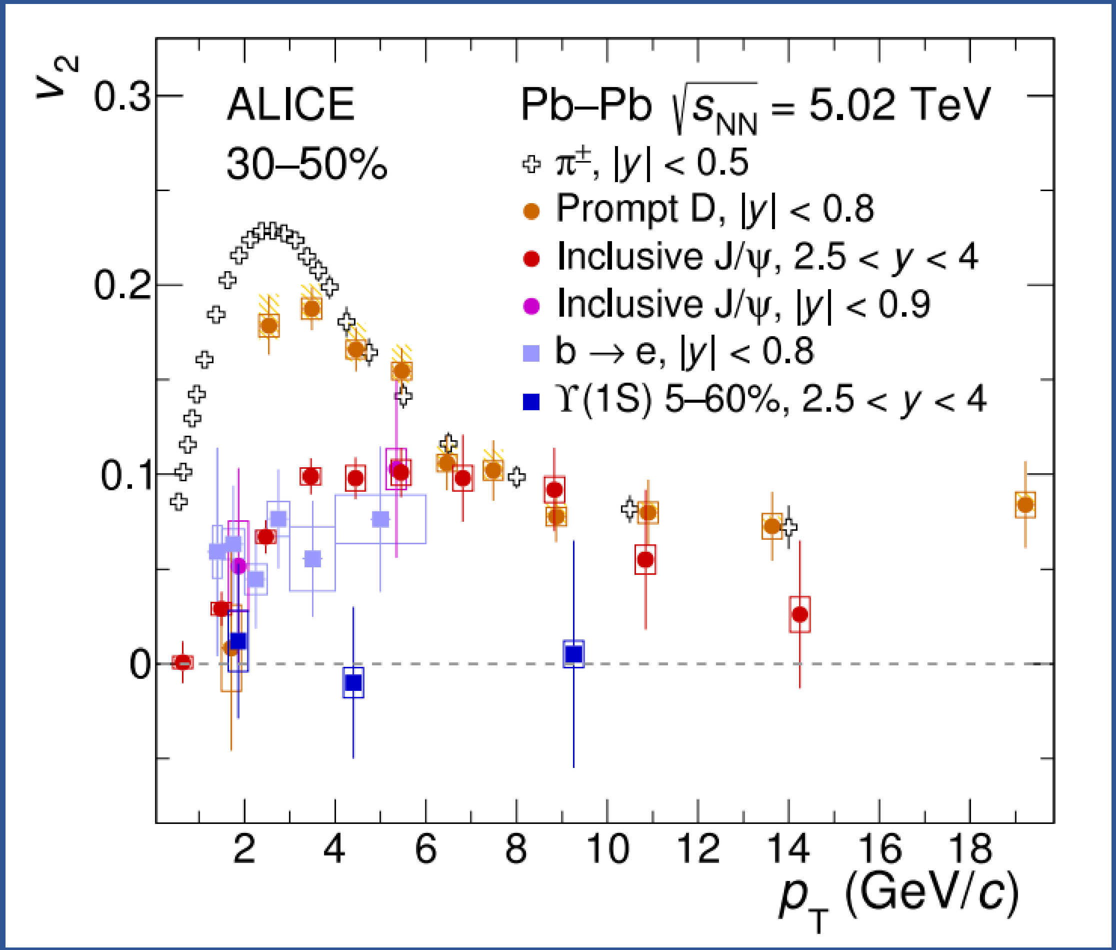


- Compare the measured R_{AA} with the product of backward and forward R_{pPb}

- Strong effect in particular at low p_T
- **J/ψ enhancement!**

Beyond suppression/regeneration → flow

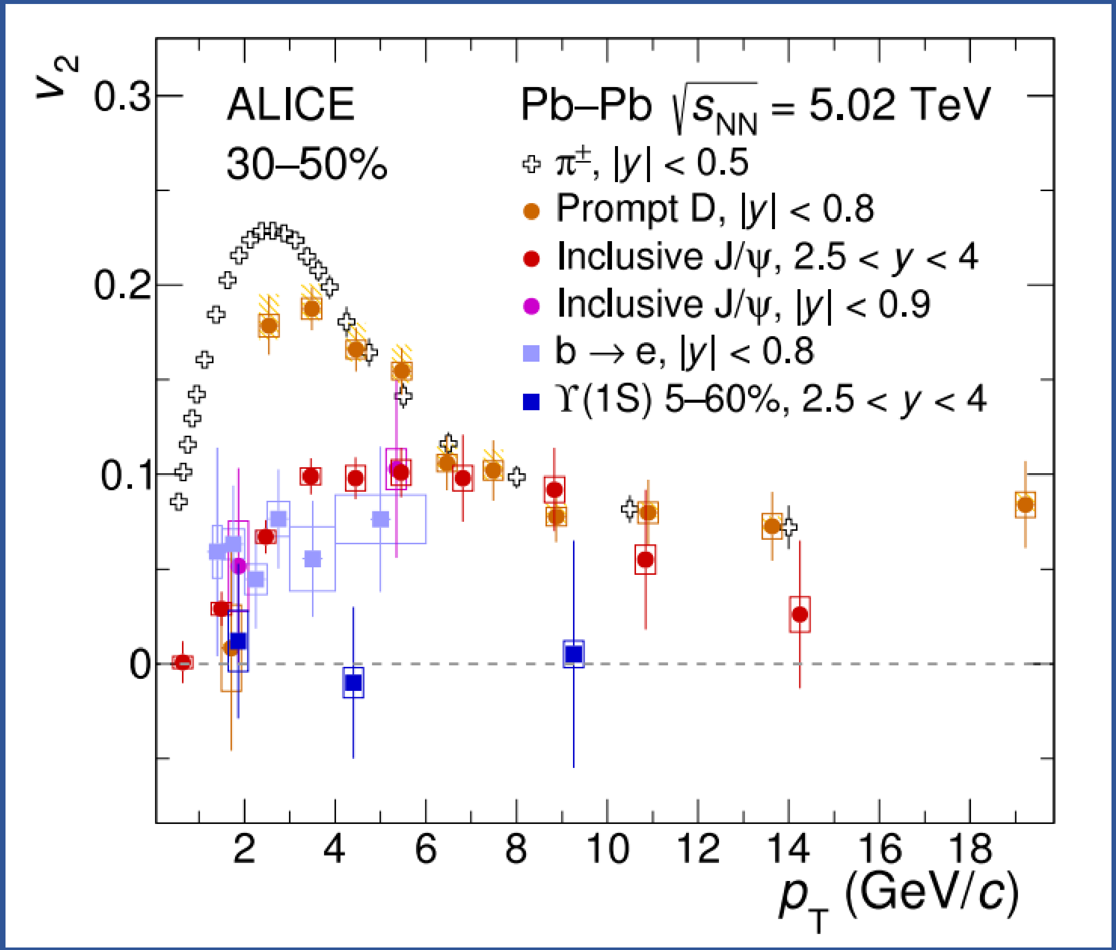
ALICE, arXiv:2211.04384



- **Quark flavour hierarchy** observed in the low-p_T range

Beyond suppression/regeneration → flow

ALICE, arXiv:2211.04384



- **Quark flavour hierarchy** observed in the low-p_T range
- Both open and hidden charm hadrons show a significant amount of anisotropic flow
  → **charm quarks are at least partly thermalised in the QGP medium**

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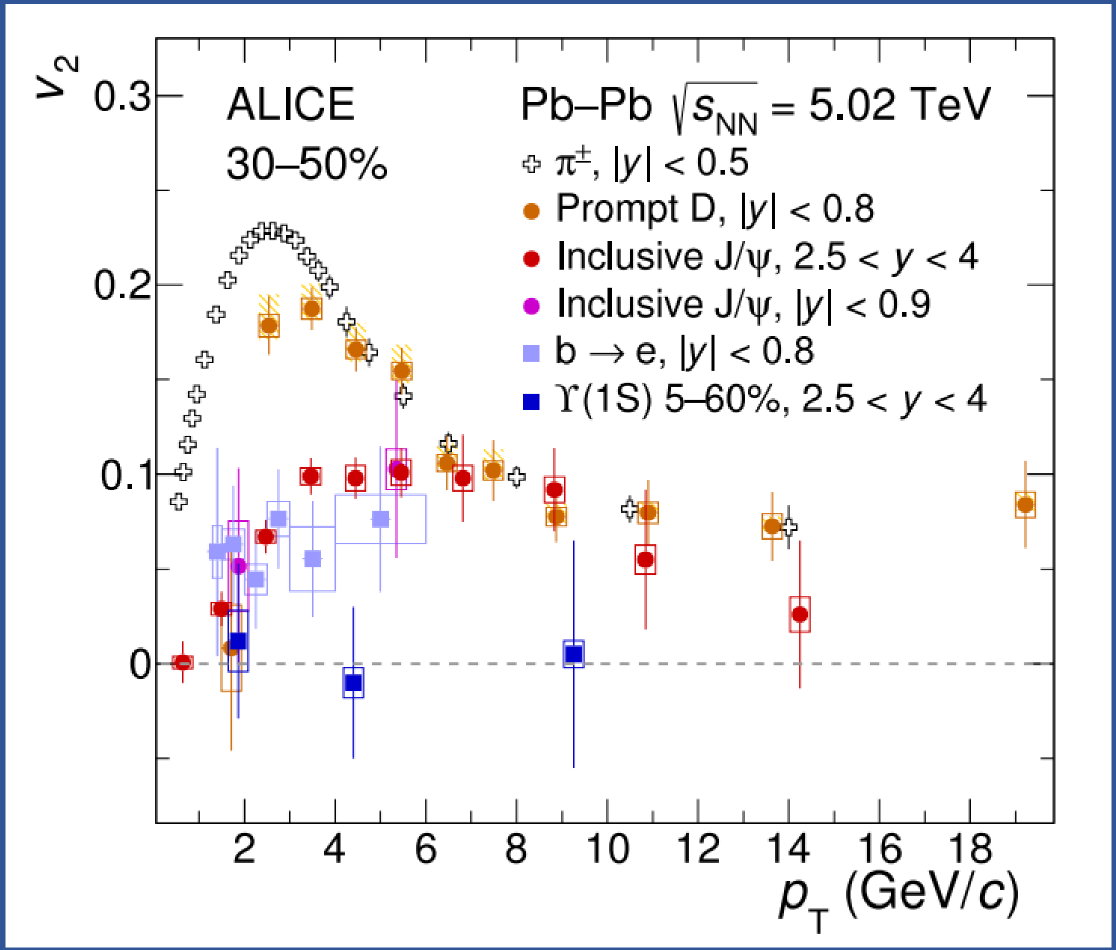

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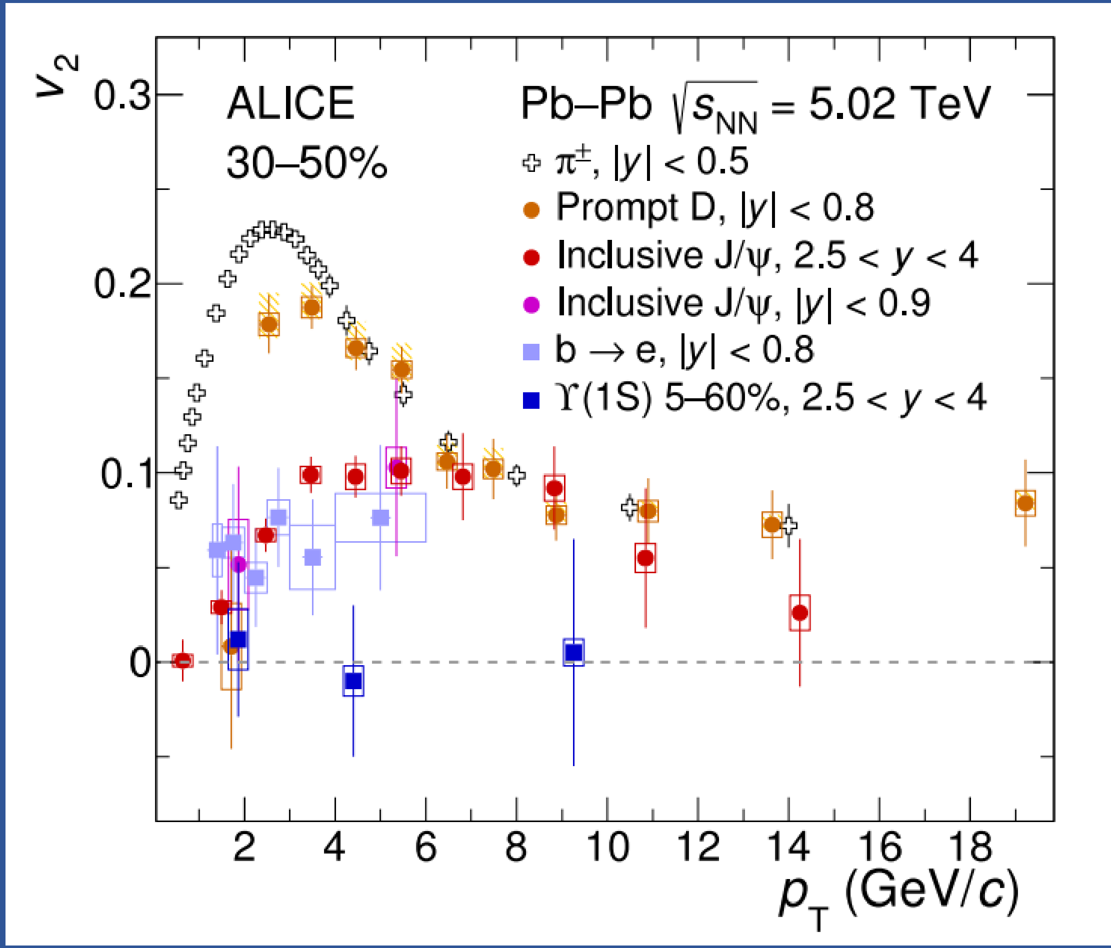

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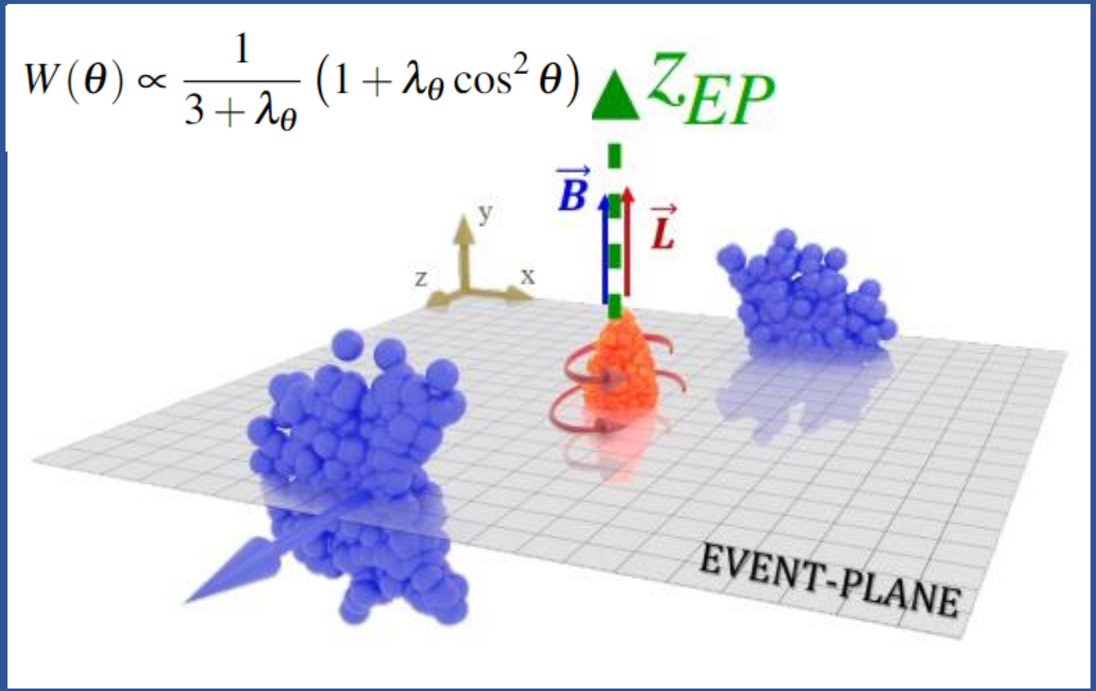
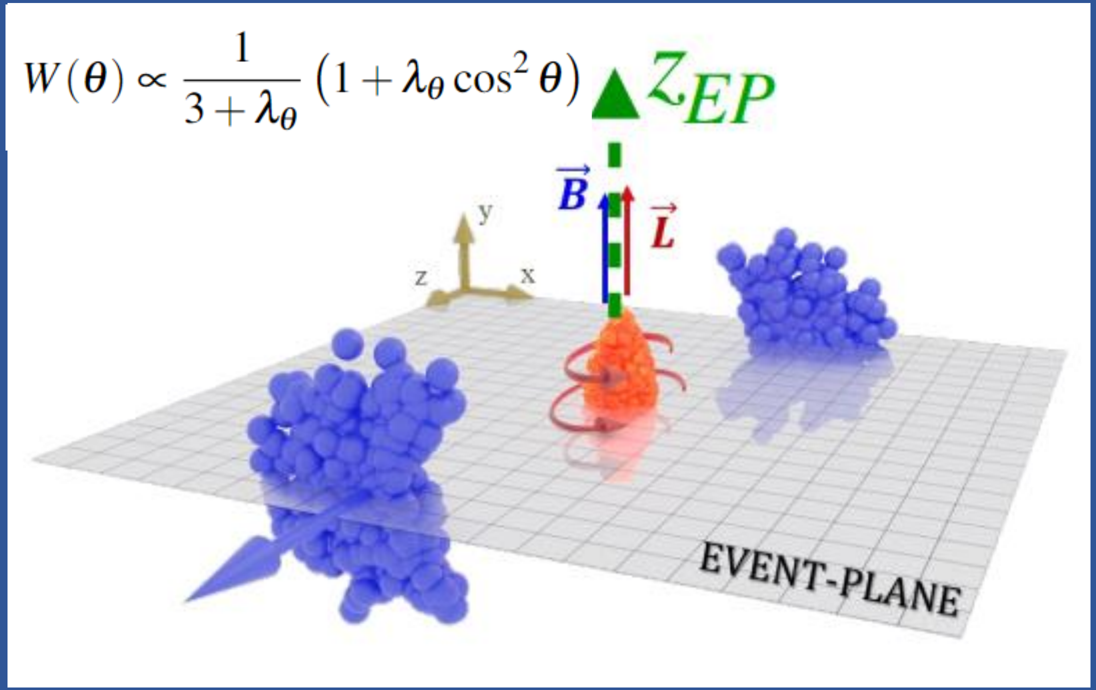
- Both open and hidden charm hadrons show a significant amount of anisotropic flow
  → **charm quarks are at least partly thermalised in the QGP medium**
- Large observed flow supports the scenario of J/ψ formation via **(re)combination**
- Inclusive ϒ(1S)
  - v_2 compatible with **zero** (large uncertainties)
  - Contribution from (re)generation in the beauty sector is small

Beyond suppression/regeneration → polarization

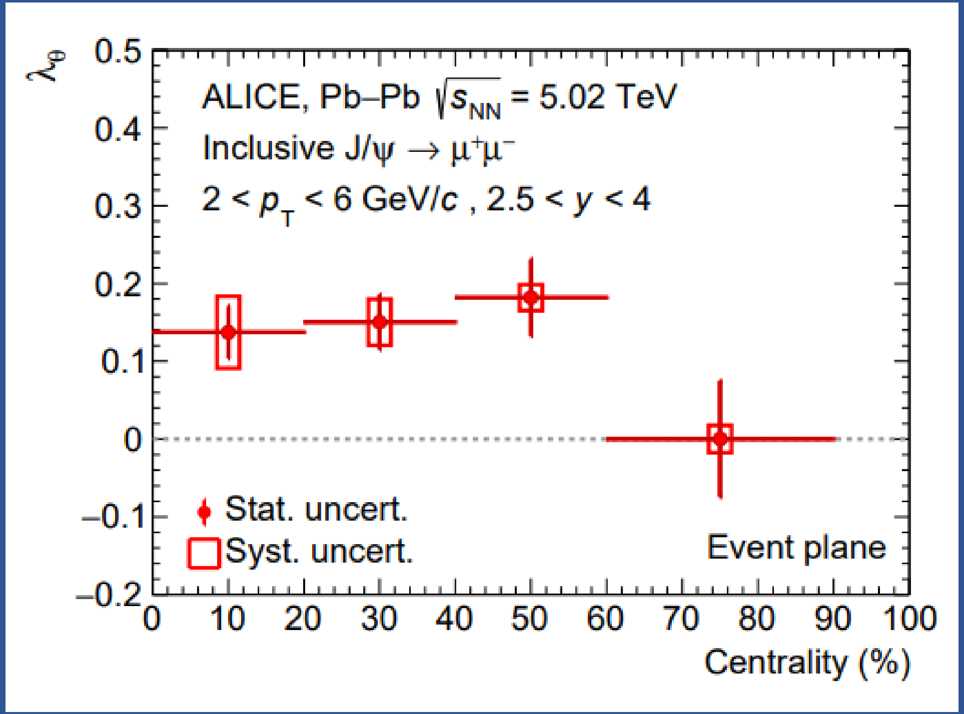


- Large **magnetic field** (B~10^{14} T, τ~1fm/c) and **angular momentum** L (up to 10^{22} s^{-1}) produced in the QGP formation, perpendicular to the event plane

Beyond suppression/regeneration → polarization



ALICE, Phys.Rev.Lett. 131 (2023) 042303



- Large **magnetic field** (B~10^{14} T, τ~1fm/c) and **angular momentum** L (up to 10^{22} s^{-1}) produced in the QGP formation, perpendicular to the event plane

- Small but **significant polarization**
- 3σ effect in the 40-60% centrality range
- Most important at low p_T
- Qualitatively consistent with observations for K* and ϕ

Might be consistent with an effect related to L (B should rather induce a negative polarization)