ATLAS EXPERIMENT PHENIX ALICE CMS STAR LHCb

Overview of Recent Experimental Results on Heavy Quarkonia in QGP

Krista Smith

11th International Conference on Hard and Electromagnetic Probes

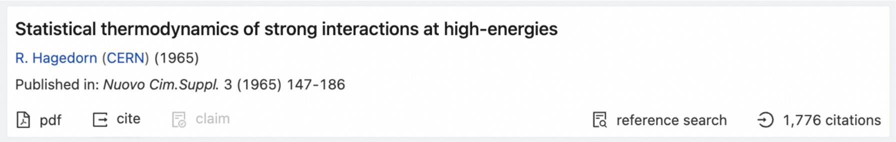
March 30, 2023

2023 HARD PROBES Aschaffenburg

Los Alamos NATIONAL LABORATORY

Brief Timeline

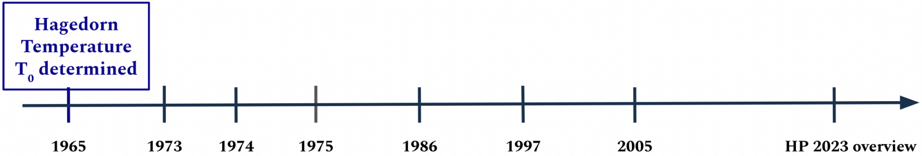
Timeline of Quarkonia Related Events in Heavy-Ion Physics



Statistical thermodynamics of strong interactions at high-energies

R. Hagedorn (CERN) (1965)

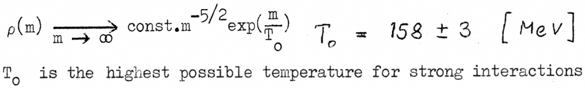
Published in: *Nuovo Cim.Suppl.* 3 (1965) 147-186



Hagedorn Temperature T_0 determined

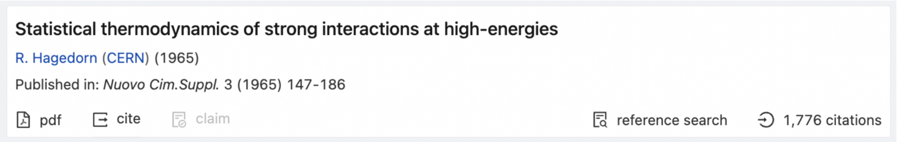
1965 1973 1974 1975 1986 1997 2005 HP 2023 overview

Timeline of Quarkonia Related Events in Heavy-Ion Physics



$$\rho(m) \xrightarrow[m \to \infty]{} \text{const.}\, m^{-5/2} \exp\left(\frac{m}{T_0}\right) \qquad T_0 = 158 \pm 3 \quad [\text{MeV}]$$

T_0 is the highest possible temperature for strong interactions



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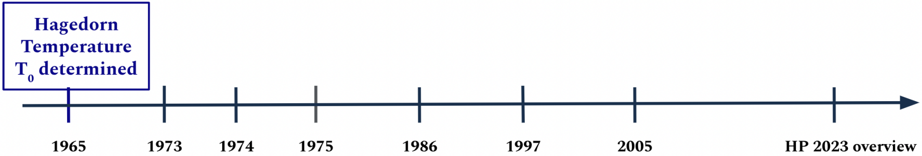
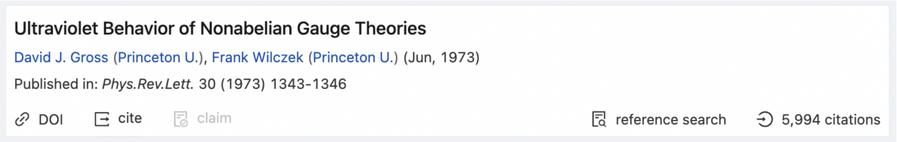


Hagedorn Temperature T_0 determined

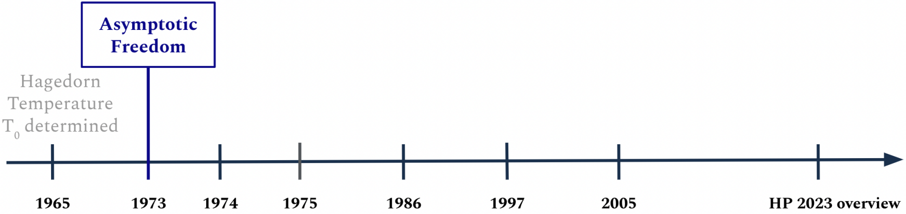
Timeline of Quarkonia Related Events in Heavy-Ion Physics



Ultraviolet Behavior of Nonabelian Gauge Theories

David J. Gross (Princeton U.), Frank Wilczek (Princeton U.) (Jun, 1973)

Published in: *Phys.Rev.Lett.* 30 (1973) 1343-1346



Asymptotic Freedom

Hagedorn Temperature T_0 determined

1965
1973
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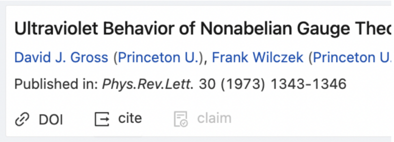
2005
HP 2023 overview

Timeline of Quarkonia Related Events in Heavy-Ion Physics


Ultraviolet Behavior of Nonabelian Gauge Theo

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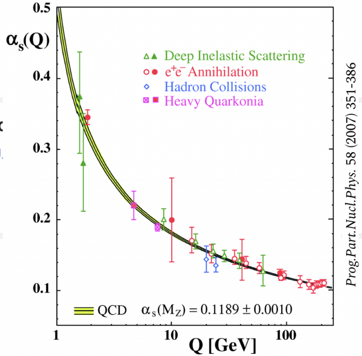
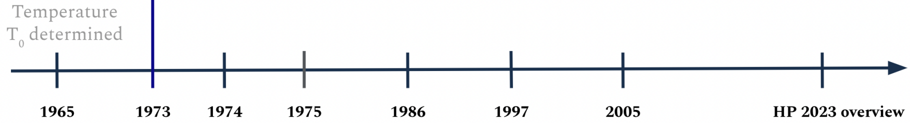


Prog.Part.Nucl.Phys. 58 (2007) 351-386

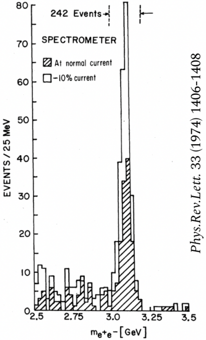
5,994 citations

Asymptotic Freedom

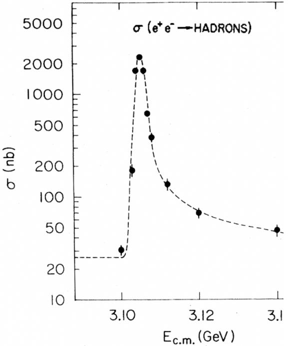
Hagedorn Temperature T_0 determined



Timeline of Quarkonia Related Events in Heavy-Ion Physics

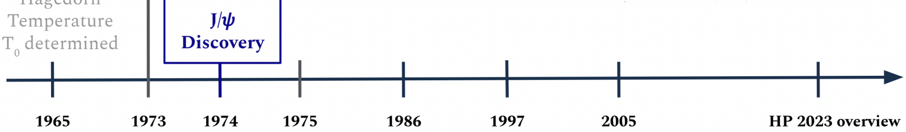


Phys.Rev.Lett. 33 (1974) 1406-1408



Phys.Rev.Lett. 33 (1974) 1404-1406

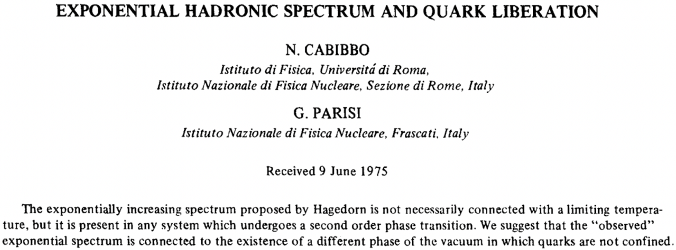
Asymptotic Freedom



Hagedorn Temperature T_0 determined

J/ψ Discovery

Timeline of Quarkonia Related Events in Heavy-Ion Physics



EXPONENTIAL HADRONIC SPECTRUM AND QUARK LIBERATION

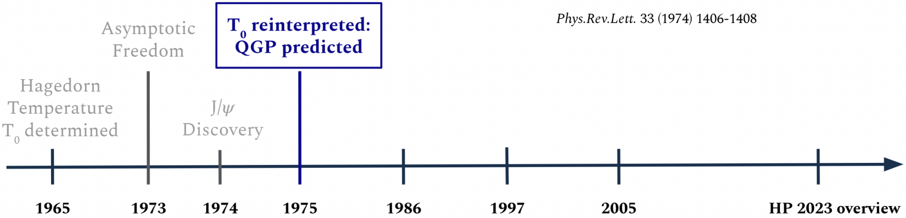
N. CABIBBO
Istituto di Fisica, Universitá di Roma,
Istituto Nazionale di Fisica Nucleare, Sezione di Rome, Italy

G. PARISI
Istituto Nazionale di Fisica Nucleare, Frascati, Italy

Received 9 June 1975

The exponentially increasing spectrum proposed by Hagedorn is not necessarily connected with a limiting temperature, but it is present in any system which undergoes a second order phase transition. We suggest that the "observed" exponential spectrum is connected to the existence of a different phase of the vacuum in which quarks are not confined.

Phys.Rev.Lett. 33 (1974) 1406-1408



Hagedorn Temperature T_0 determined

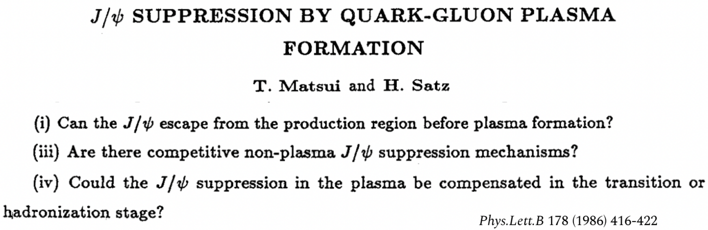
Asymptotic Freedom

J/ψ Discovery

T_0 reinterpreted: QGP predicted

1965 **1973** **1974** **1975** **1986** **1997** **2005** **HP 2023 overview**

Timeline of Quarkonia Related Events in Heavy-Ion Physics



J/ψ SUPPRESSION BY QUARK-GLUON PLASMA FORMATION

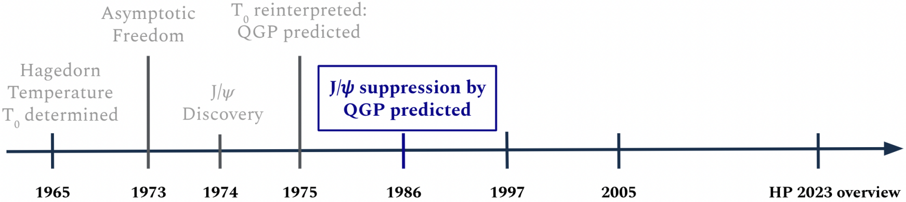
T. Matsui and H. Satz

(i) Can the J/ψ escape from the production region before plasma formation?

(iii) Are there competitive non-plasma J/ψ suppression mechanisms?

(iv) Could the J/ψ suppression in the plasma be compensated in the transition or hadronization stage?

Phys.Lett.B 178 (1986) 416-422



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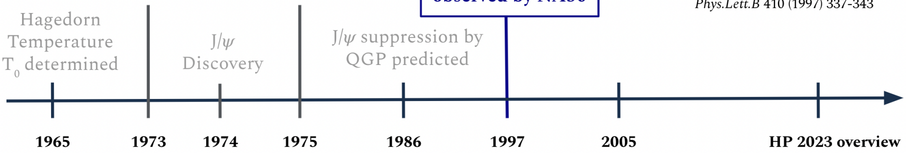
Timeline of Quarkonia Related Events in Heavy-Ion Physics



1965 – Hagedorn Temperature T_0 determined

1973 – Asymptotic Freedom

1974 – J/ψ Discovery

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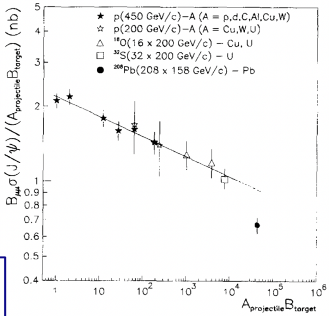
1986 – J/ψ suppression by QGP predicted

1997 – **Anomalous J/ψ suppression observed by NA50**

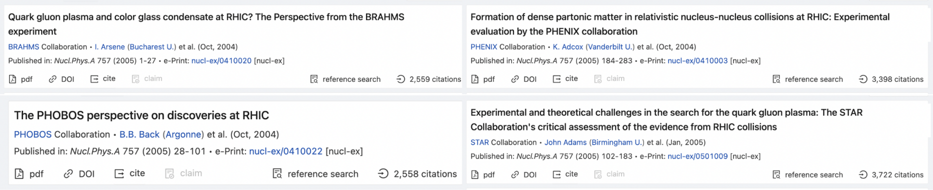
2005

HP 2023 overview



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

Timeline of Quarkonia Related Events in Heavy-Ion Physics

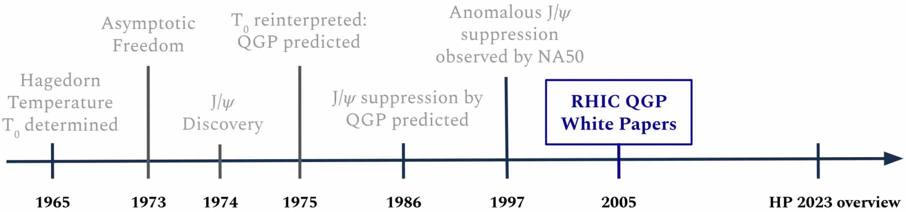


Quark gluon plasma and color glass condensate at RHIC? The Perspective from the BRAHMS experiment
BRAHMS Collaboration • I. Arsene (Bucharest U.) et al. (Oct, 2004)
Published in: *Nucl.Phys.A* 757 (2005) 1-27 • e-Print: nucl-ex/0410020 [nucl-ex]
pdf DOI cite claim reference search 2,559 citations

Formation of dense partonic matter in relativistic nucleus-nucleus collisions at RHIC: Experimental evaluation by the PHENIX collaboration
PHENIX Collaboration • K. Adcox (Vanderbilt U.) et al. (Oct, 2004)
Published in: *Nucl.Phys.A* 757 (2005) 184-283 • e-Print: nucl-ex/0410003 [nucl-ex]
pdf DOI cite claim reference search 3,398 citations

The PHOBOS perspective on discoveries at RHIC
PHOBOS Collaboration • B.B. Back (Argonne) et al. (Oct, 2004)
Published in: *Nucl.Phys.A* 757 (2005) 28-101 • e-Print: nucl-ex/0410022 [nucl-ex]
pdf DOI cite claim reference search 2,558 citations

Experimental and theoretical challenges in the search for the quark gluon plasma: The STAR Collaboration's critical assessment of the evidence from RHIC collisions
STAR Collaboration • John Adams (Birmingham U.) et al. (Jan, 2005)
Published in: *Nucl.Phys.A* 757 (2005) 102-183 • e-Print: nucl-ex/0501009 [nucl-ex]
pdf DOI cite claim reference search 3,722 citations



Hagedorn Temperature T_0 determined — 1965

Asymptotic Freedom — 1973

J/ψ Discovery — 1974

T_0 reinterpreted: QGP predicted — 1975

J/ψ suppression by QGP predicted — 1986

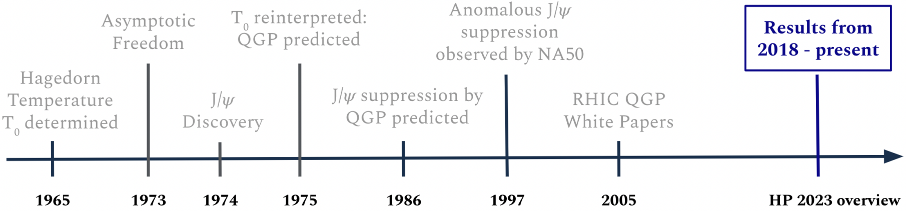
Anomalous J/ψ suppression observed by NA50 — 1997

RHIC QGP White Papers — 2005

HP 2023 overview

Timeline of Quarkonia Related Events in Heavy-Ion Physics

"Prompt and non-prompt J/ψ elliptic flow in Pb+Pb collisions"	*Eur.Phys.J.C* 78 (2018) 9, 784
"J/ψ and D^0 production in PbNe collisions"	arXiv:2211.11652
"$\psi(2S)$ suppression in Pb-Pb collisions"	arXiv:2210.08893
"Observation of the $\Upsilon(3S)$ meson and sequential suppression of Υ states in PbPb collisions"	CMS-PAS-HIN-21-007
"Measurement of inclusive J/ψ suppression in Au+Au collisions"	*Phys.Lett.B* 797 (2019) 134917
"Measurement of $\psi(2S)$ nuclear modification in $p+p$, p+Al and p+Au collisions"	*Phys.Rev.C* 105 (2022) 6, 064912
"Production of Υ mesons in Pb+Pb and $p+p$ collisions"	arXiv:2205.03042
"Observation of Multiplicity Dependent $X_c(3872)$ and $\psi(2S)$ Production in *pp* Collisions"	*Phys.Rev.Lett.* 126 (2021) 9, 092001
"Multiplicity dependence of Υ production at forward rapidity in *pp* collisions"	arXiv:2209.04241
"Nuclear modification of Υ states in pPb collisions"	*Phys.Lett.B* 835 (2022) 137397



1965: Hagedorn Temperature T_0 determined

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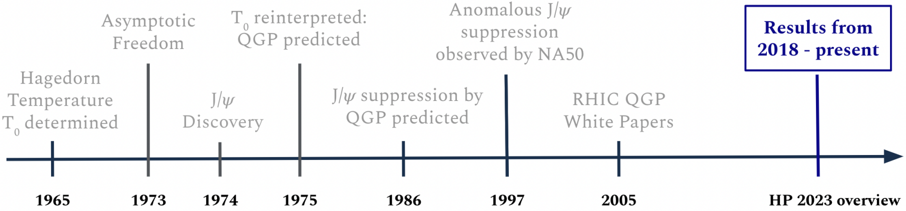
2005: RHIC QGP White Papers

HP 2023 overview: **Results from 2018 - present**

Timeline of Quarkonia Related Events in Heavy-Ion Physics

“Measurement of cold nuclear matter effects for inclusive J/ψ in p+Au collisions”	***Phys.Lett.B*** **825 (2022) 136865**
“Measurement of J/ψ in p+p, p+Al, p+Au, and ^{3}He+Au collisions”	***Phys.Rev.C*** **102 (2020) 1, 014902**
“Correlation of Υ meson production with the underlying event in pp collisions”	**ATLAS-CONF-2022-023**
“Study of coherent charmonium production in ultra-peripheral lead-lead collisions”	**arXiv:2206.08221**
“J/ψ production at midrapidity in p-Pb collisions”	**arXiv:2211.14153**
“Observation of sequential Υ suppression in Au+Au collisions”	***Phys.Rev.Lett.*** **130 (2023) 11, 112301**
“Observation of the B^+_c meson in PbPb and pp collisions”	**CMS-PAS-HIN-20-004**
“Azimuthal anisotropy of muons from charm and bottom hadrons in pp collisions”	***Phys.Rev.Lett.*** **124 (2020) 8, 082301**
“Centrality dependence of J/ψ and ψ(2S) nuclear modification in p-Pb collisions”	***JHEP*** **02 (2021) 002**
“Observation of prompt J/ψ meson elliptic flow in high-multiplicity pPb collisions”	***Phys.Lett.B*** **791 (2019) 172-194**



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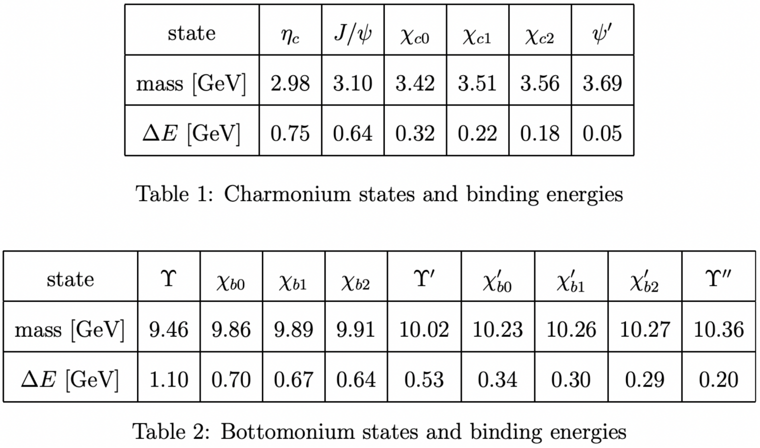
2005 RHIC QGP White Papers

HP 2023 overview **Results from 2018 - present**

Quarkonia: Charmonia & Bottomonia



state	η_c	J/ψ	χ_{c0}	χ_{c1}	χ_{c2}	ψ'
mass [GeV]	2.98	3.10	3.42	3.51	3.56	3.69
ΔE [GeV]	0.75	0.64	0.32	0.22	0.18	0.05

Table 1: Charmonium states and binding energies

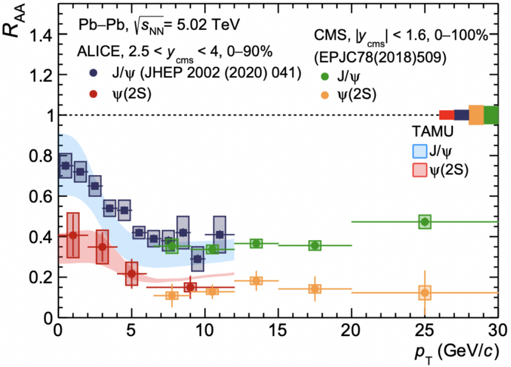
state	Υ	χ_{b0}	χ_{b1}	χ_{b2}	Υ'	χ'_{b0}	χ'_{b1}	χ'_{b2}	Υ''
mass [GeV]	9.46	9.86	9.89	9.91	10.02	10.23	10.26	10.27	10.36
ΔE [GeV]	1.10	0.70	0.67	0.64	0.53	0.34	0.30	0.29	0.20

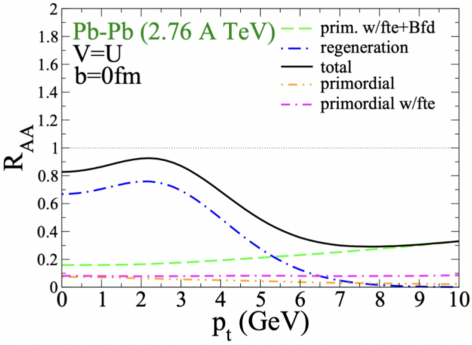
Table 2: Bottomonium states and binding energies

J.Phys.G 32 (2006) R25

Heavy Quarkonia in Large Systems

Charmonia in PbPb Collisions at LHC

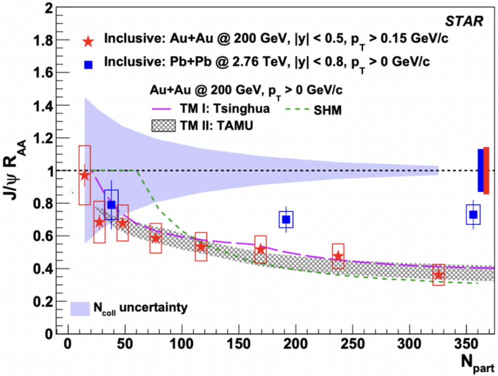


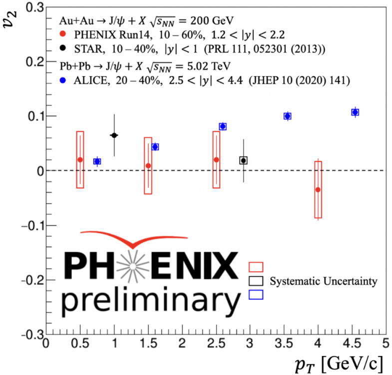


DATA: ARXIV:2210.08893

- J/ψ and ψ(2S) R_{AA} strongly suppressed at high p_T - consistent with CMS results
- Transport Model predictions[1],[2] expect sizeable regeneration at LHC energies
  - $q\bar{q}$ pairs close in phase space can recombine to form a quarkonium state

J/ψ in AA Collisions at RHIC (LHC)

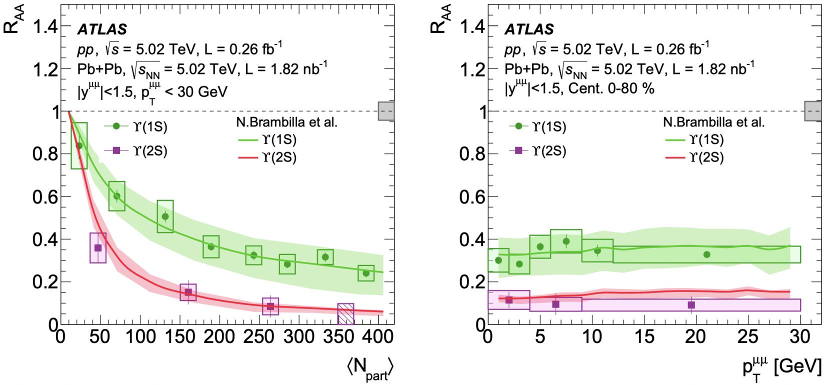




Data: Phys.Lett.B 797 (2019) 134917
Theoretical References: [3],[4],[5]

- STAR J/ψ mid-rapidity R_{AA} shows stronger suppression than ALICE mid-rapidity results
  - Regeneration effects modify charmonia measurements at LHC energies
- At RHIC energies, regeneration not as significant → J/ψ flow consistent with zero

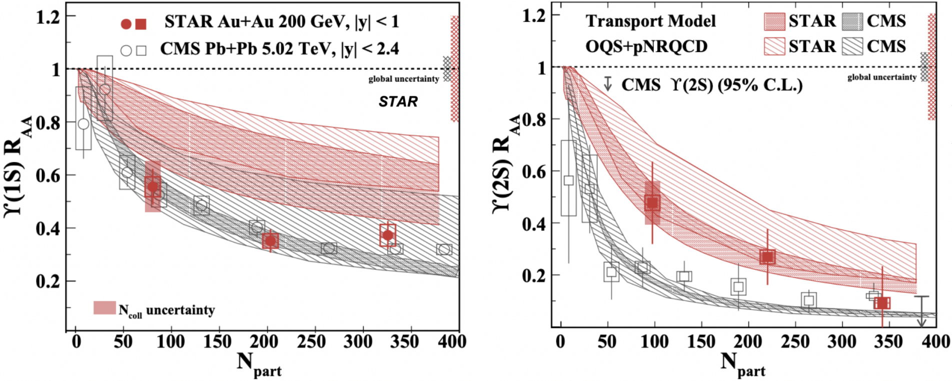
Bottomonia in PbPb Collisions at LHC



Theoretical Reference: [6]
Data: arXiv:2205.03042

- Contributions from regeneration effects expected to be much weaker for Υ states
  - LHC measurements of $\Upsilon(1S)$ R_{AA} much more suppressed than J/ψ R_{AA}
  - Bottomonia shows little dependence on p_T compared to ALICE charmonia results

Bottomonia in AA Collisions at RHIC (LHC)



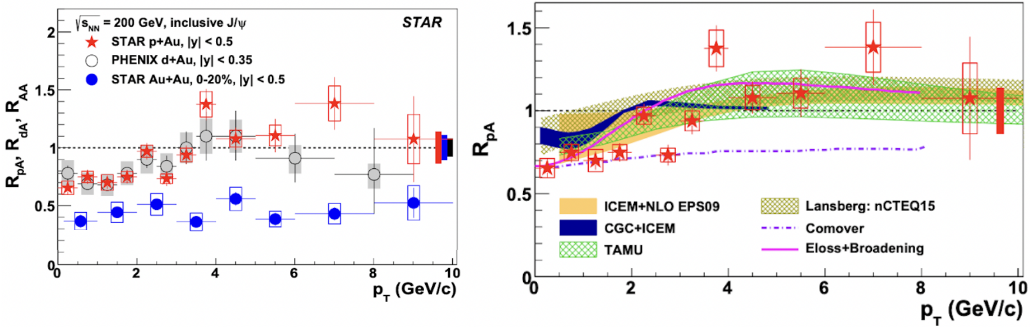
Phys.Rev.Lett. 130 (2023) 11, 112301

Theoretical Reference: [7],[8]

- $\Upsilon(1S)$ suppression very similar at RHIC and LHC energies
  - Possibly due to QGP-related suppression of excited states that decay to Υ(1S)
- Both models include feed-down (Υ(2S), Υ(3S), χ_b) and hot nuclear matter effects

Heavy Quarkonia in Small Systems

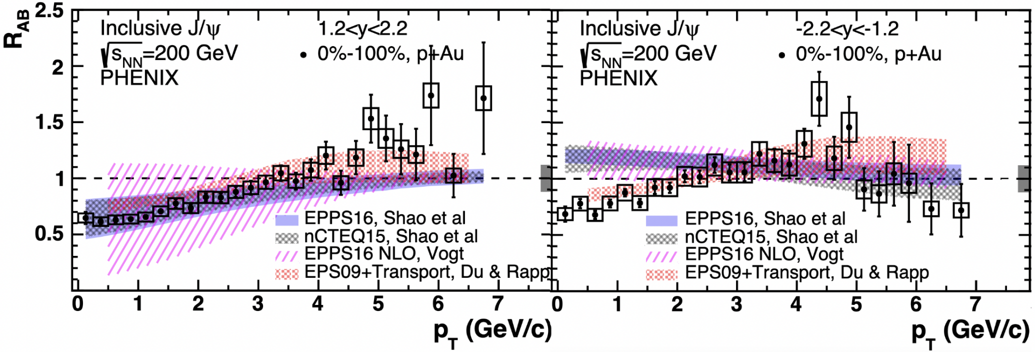
J/ψ in Large & Small Collisions at RHIC



Theoretical Refs: [9],[10],[11],[12],[13],[14]
Phys.Lett.B 825 (2022) 136865

- Mid-rapidity results in AuAu and pAu are compared as a function of p_T
  - Very different p_T dependence observed in the two collision systems
- Inclusive J/ψ measurements in pAu collisions show suppression at low p_T
  - All models appear to describe the suppression reasonably well at low p_T

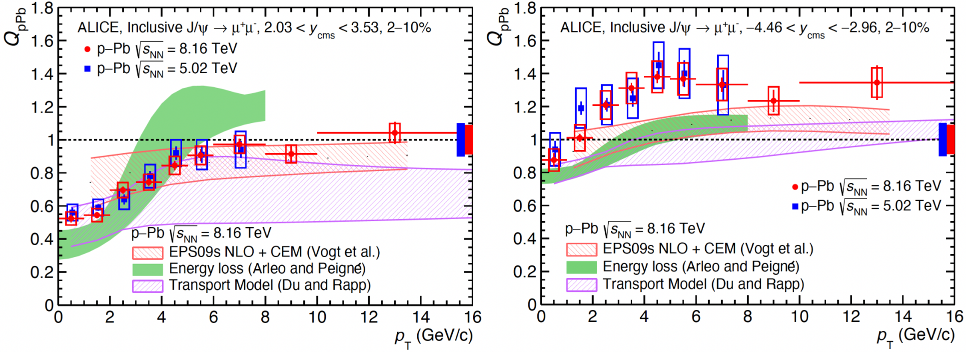
J/ψ in pAu Collisions at RHIC



Phys.Rev.C 102 (2020) 1, 014902

- Nuclear modification at forward, backward rapidity shows similar suppression at low p_T
  - Forward rapidity modification well described by gluon shadowing[15],[16]
- Backward rapidity suppression consistent with Transport Model predictions[12] (includes nuclear absorption effect)

J/ψ in pPb Collisions at LHC

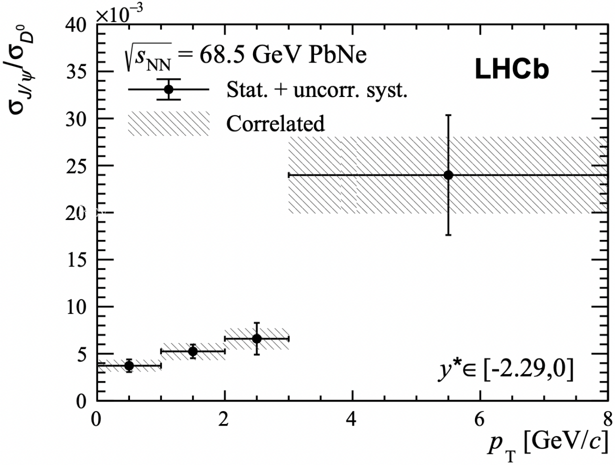


THEORETICAL REFERENCES: [12],[17],[18]
JHEP 02 (2021) 002

- At forward rapidity, similar modification as seen at RHIC - suggests similar mechanism
- Very different modification at backward rapidity - essentially no suppression at low p_T
  - Models predict stronger suppression that what is seen in the data

J/ψ to D^0 Ratio in PbNe Collisions at LHC

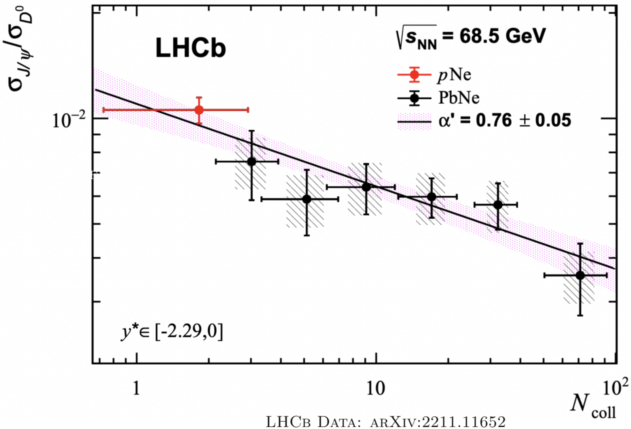
- Data recorded in fixed-target mode at $\sqrt{s_{NN}} = 68.5$ GeV (regeneration effects minimal)
- Strong dependence of J/ψ to D^0 ratio on p_T



LHCb Data: arXiv:2211.11652

J/ψ to D^0 Ratio in PbNe Collisions at LHC

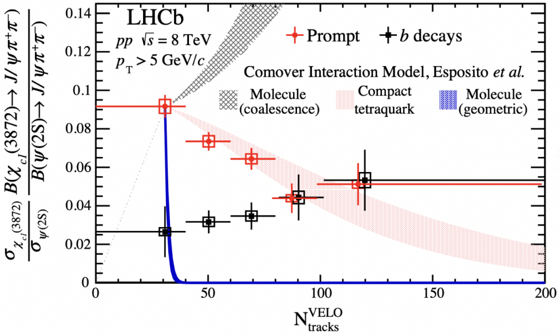
- Data recorded in fixed-target mode at $\sqrt{s_{NN}} = 68.5$ GeV (regeneration effects minimal)
- J/ψ to D^0 ratio shows strong dependence on p_T
- J/ψ(D^0) cross section assumed to scale as $\langle N_{coll} \rangle^{\alpha}$ ($\langle N_{coll} \rangle$)
- Linear falling trend from pNe to central PbNe indicates J/ψ suppression inconsistent with QGP effects

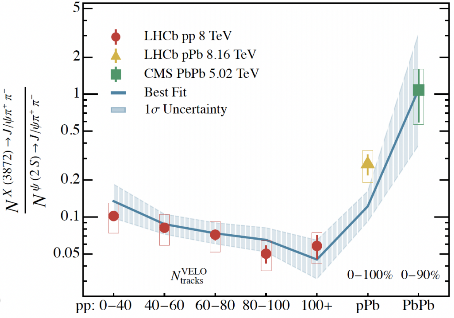


LHCb Data: arXiv:2211.11652

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

$\chi_c(3872)$ to $\psi(2S)$ Ratio in pp Collisions at LHC

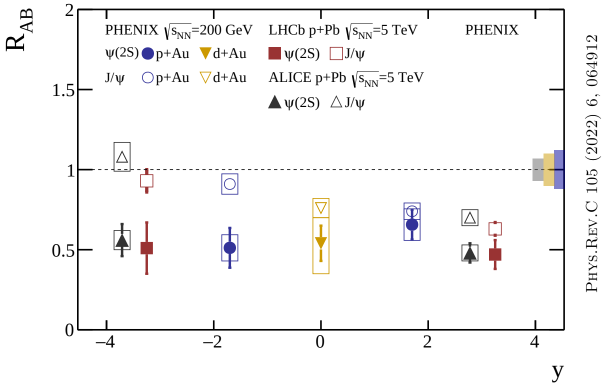




Phys.Rev.Lett. 126 (2021) 9, 092001
Right: arXiv:2202.03863

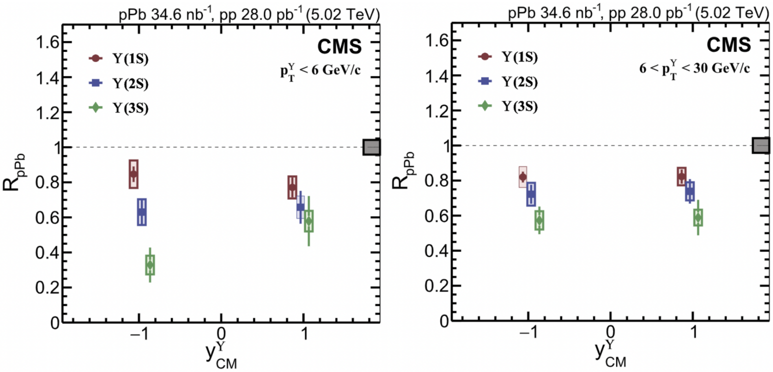
- Ratio of $\chi_c(3872)$ to $\psi(2S)$ shown as a function of charged particle tracks in pp collisions
    - Data best described by Comover Model assuming tetraquark structure[19] $(c\bar{c}q\bar{q})$
- Model on right assumes comovers/regeneration to describe data in different systems[20]

Charmonia in *p*A Collisions at RHIC (LHC)



- J/ψ and ψ(2S) modification similar at forward rapidity
  - Suggests initial state effects dominate charmonium production
- PHENIX, LHCb, and ALICE consistent with final state effects in A-going direction

Bottomonia in pPb Collisions at LHC



Phys.Lett.B 835 (2022) 137397

- $\Upsilon(1S)$, $\Upsilon(2S)$, and $\Upsilon(3S)$ nuclear modification shown at forward and backward rapidity
- At backward rapidity, sequential suppression is less pronounced at high p_T (right)
  - At low p_T (left), significant suppression is seen for $\Upsilon(3S)$ compared to $\Upsilon(1S)$

Conclusion

LARGE SYSTEM COLLISIONS AA

- Results indicate regeneration affects charmonia measurements at LHC energies
- Contributions from regeneration in $\Upsilon(1S)$ measurements appear small, if any
- $\Upsilon(1S)$ modification shows similar suppression as J/ψ modification at RHIC

SMALL SYSTEM COLLISIONS pA

- J/ψ modification versus p_T at backward rapidity suggests different nuclear effects contribute at RHIC compared to LHC energies
- At backward rapidity, higher quarkonia states more suppressed than lower quarkonia states
- If QGP is formed, it does not appear to be dominant effect on J/ψ

Potential Future Measurements

RHIC Collaborations

- Υ measurements from sPHENIX in AuAu collisions
- STAR Υ v_2 in AuAu collisions (?)
- PHENIX $\psi(2S)$ nuclear modification in AuAu collisions (?)

LHC Collaborations

- χ_c nuclear modification or ratios
- χ_b nuclear modification or ratios
- LHC Run3: SMOG fixed target program

Back-Up

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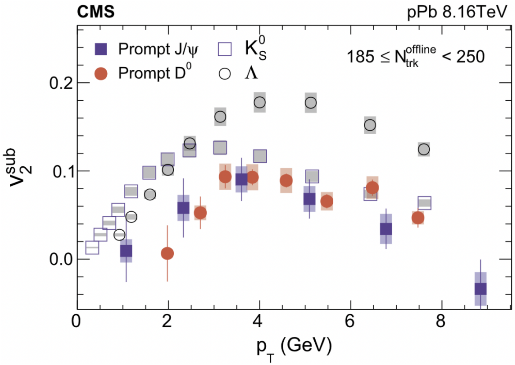
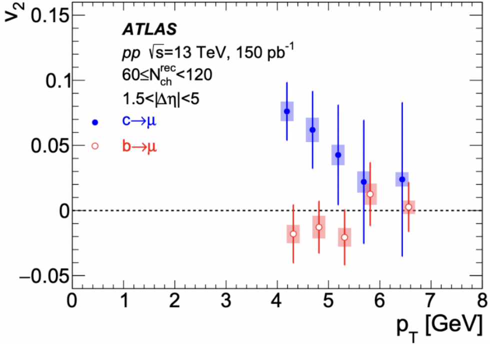
Medium-Assisted Enhancement of $X(3872)$ Production from Small to Large Colliding Systems
arXiv 2302.03828

CMS & ATLAS Elliptic Flow



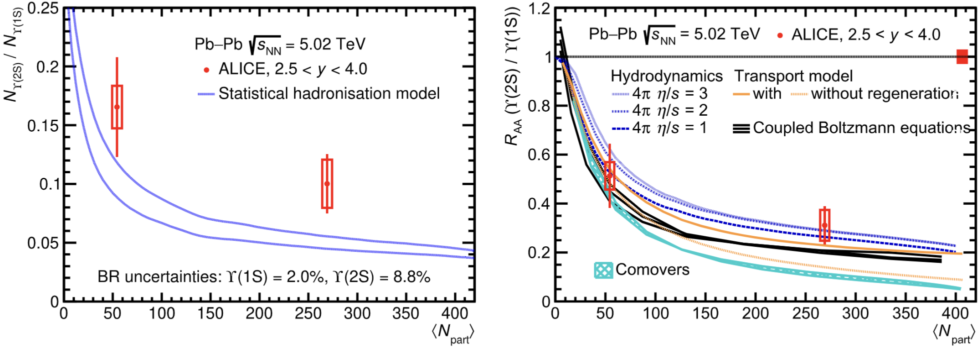


CMS Data: Phys.Lett.B 791 (2019) 172-194

ATLAS Data: Phys.Rev.Lett. 124 (2020) 8, 082301

- Lighter hadrons show collective flow while muons from heavier bottom quarks do not
- Prompt J/ψ (from primary interactions) and muons from charm decays show nonzero v_2
  - Collective behavior of charm quarks in *p*Pb and high multiplicity *pp* collisions

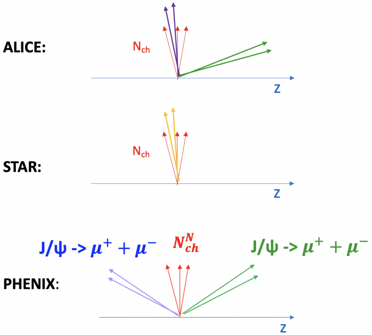
ALICE Bottomonia in PbPb Collisions

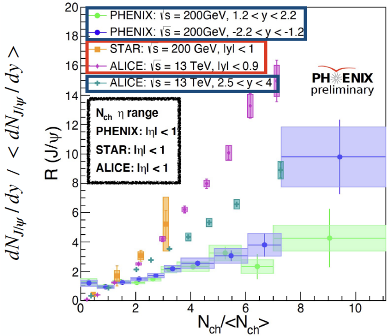


Phys.Lett.B 822 (2021) 136579

- ϒ(2S) to ϒ(1S) ratio of yields (left) and R_{AA} are shown at forward rapidity vs. $\langle N_{part} \rangle$
- Hydrodynamic calculations and the Transport Model with regeneration effects are most consistent with the measured data
    - The suppression is best described by models that include hot nuclear matter effects

Multiplicity Dependent J/ψ Production

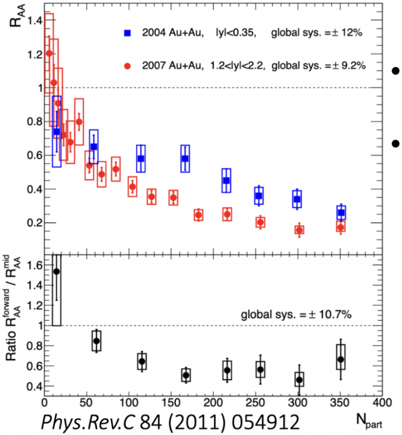




- First measurements of relative J/ψ yields R vs. normalized event charged particle multiplicity $N_{ch}/\langle N_{ch}\rangle$ in pp collisions at $\sqrt{s}$=200 GeV
  - Multiplicity measured in different rapidities (forward, mid, and backward)
- After J/ψ tracks subtracted, PHENIX multiplicity dependence similar at fwd, bkwd y

The J/ψ suppression puzzle

PHENIX



Phys.Rev.C 84 (2011) 054912

- $R_{AA}^{\mathrm{Fwd}} > R_{AA}^{\mathrm{mid}}$, contrary to expectation
- ~20 $c\bar{c}$ pairs in collisions at RHIC (mostly at mid-rapidity)

Can we attribute this significant difference in J/ψ R_{AA} to regeneration of J/ψ from $c\bar{c}$ pairs at mid-rapidity?

Slide credit: Luis Bichon, III (Quark Matter 2022)

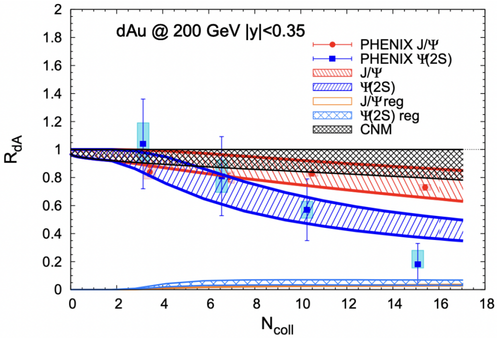
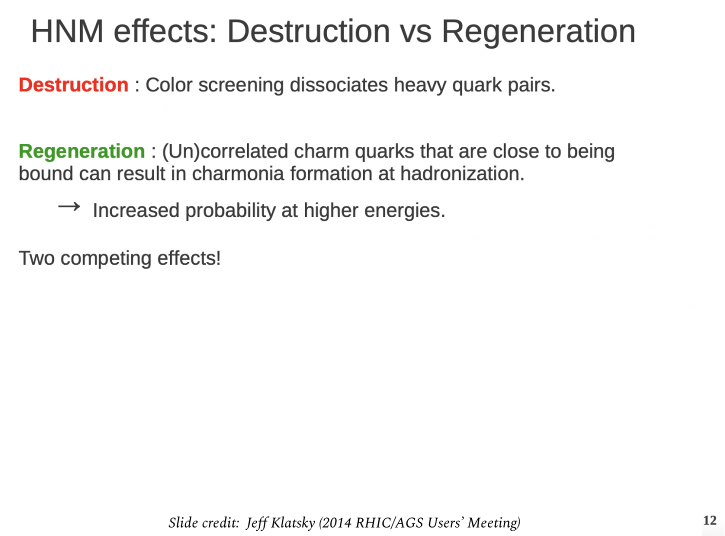


Figure 4.3: Centrality dependent R_{dA} for J/ψ (red bands) and $\psi(2S)$ (blue bands) in 200 GeV d-Au collision, compared with experimental data [120]. The orange (light blue) band is for the J/ψ ($\psi(2S)$) regeneration component. The CNM effect only (black band) represents the uncertainty due to shadowing (via an absorption cross section of 0-2.4 mb) and is the major source of uncertainty for the colored bands.

Image credit: Xiaojian Du (PhD Dissertation, 2019)



HNM effects: Destruction vs Regeneration

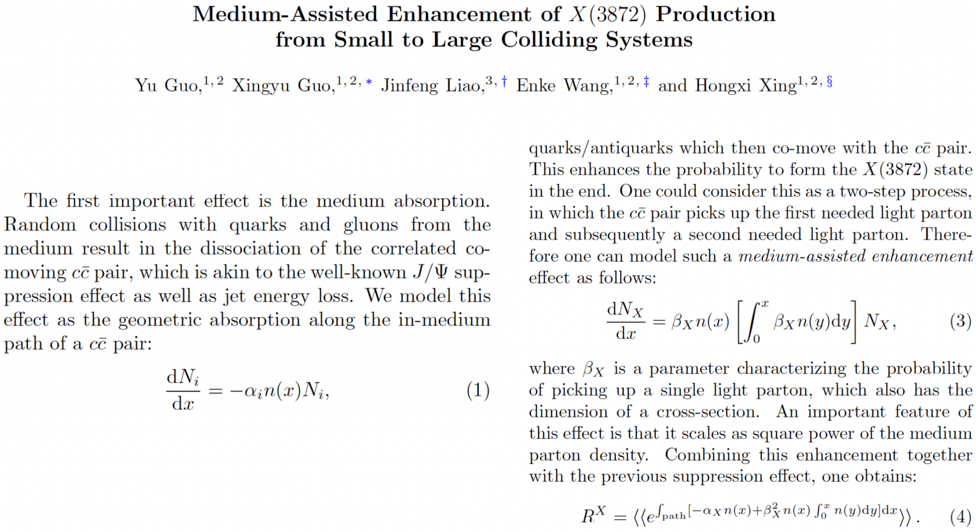
Destruction : Color screening dissociates heavy quark pairs.

Regeneration : (Un)correlated charm quarks that are close to being bound can result in charmonia formation at hadronization.

→ Increased probability at higher energies.

Two competing effects!

Slide credit: Jeff Klatsky (2014 RHIC/AGS Users' Meeting)



Medium-Assisted Enhancement of $X(3872)$ Production from Small to Large Colliding Systems

Yu Guo,[1,2] Xingyu Guo,[1,2,*] Jinfeng Liao,[3,†] Enke Wang,[1,2,‡] and Hongxi Xing[1,2,§]

The first important effect is the medium absorption. Random collisions with quarks and gluons from the medium result in the dissociation of the correlated co-moving $c\bar{c}$ pair, which is akin to the well-known J/Ψ suppression effect as well as jet energy loss. We model this effect as the geometric absorption along the in-medium path of a $c\bar{c}$ pair:

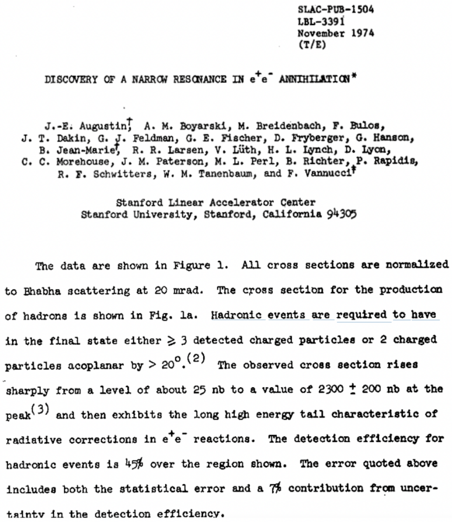
$$\frac{\mathrm{d}N_i}{\mathrm{d}x} = -\alpha_i n(x) N_i, \tag{1}$$

quarks/antiquarks which then co-move with the $c\bar{c}$ pair. This enhances the probability to form the $X(3872)$ state in the end. One could consider this as a two-step process, in which the $c\bar{c}$ pair picks up the first needed light parton and subsequently a second needed light parton. Therefore one can model such a *medium-assisted enhancement* effect as follows:

$$\frac{\mathrm{d}N_X}{\mathrm{d}x} = \beta_X n(x) \left[\int_0^x \beta_X n(y) \mathrm{d}y \right] N_X, \tag{3}$$

where β_X is a parameter characterizing the probability of picking up a single light parton, which also has the dimension of a cross-section. An important feature of this effect is that it scales as square power of the medium parton density. Combining this enhancement together with the previous suppression effect, one obtains:

$$R^X = \langle\langle e^{\int_{\text{path}} [-\alpha_X n(x) + \beta_X^2 n(x) \int_0^x n(y)\mathrm{d}y] \mathrm{d}x} \rangle\rangle . \tag{4}$$



SLAC-PUB-1504
LBL-3391
November 1974
(T/E)

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

The data are shown in Figure 1. All cross sections are normalized to Bhabha scattering at 20 mrad. The cross section for the production of hadrons is shown in Fig. 1a. Hadronic events are required to have in the final state either ≥ 3 detected charged particles or 2 charged particles acoplanar by > 20°.(2) The observed cross section rises sharply from a level of about 25 nb to a value of 2300 ± 200 nb at the peak(3) and then exhibits the long high energy tail characteristic of radiative corrections in e^+e^- reactions. The detection efficiency for hadronic events is 45% over the region shown. The error quoted above includes both the statistical error and a 7% contribution from uncertainty in the detection efficiency.

Color screening and regeneration of bottomonia in high-energy heavy-ion collisions

X. Du,[1] M. He,[2] and R. Rapp[1]

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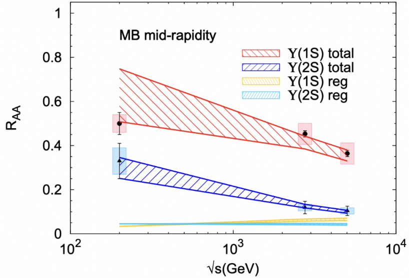
Texas A&M University, College Station, TX 77843-3366, USA
[2] *Department of Applied Physics, Nanjing University of Science and Technology, Nanjing 210094, China*



Phys.Rev.C 96 (2017) 5, 054901

FIG. 30: Excitation function the MB $R_{\rm AA}$ of $\Upsilon(1S)$ and $\Upsilon(2S)$ with TBS compared to STAR [54] and CMS [31, 59, 60] data at mid-rapidity.

Quarkonia Binding Energies

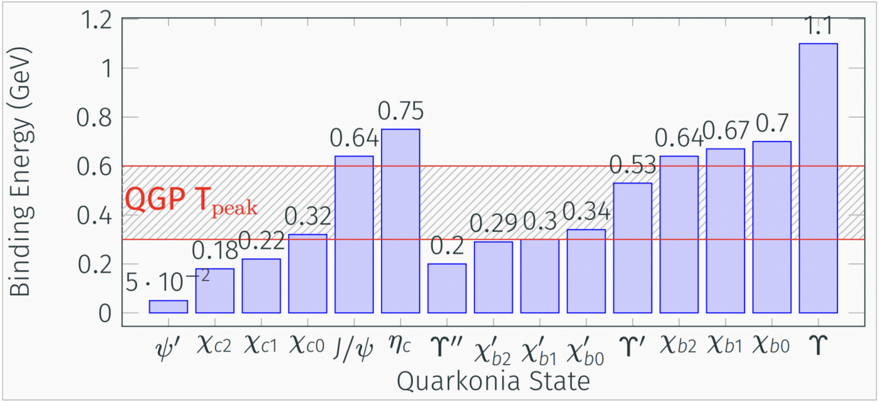
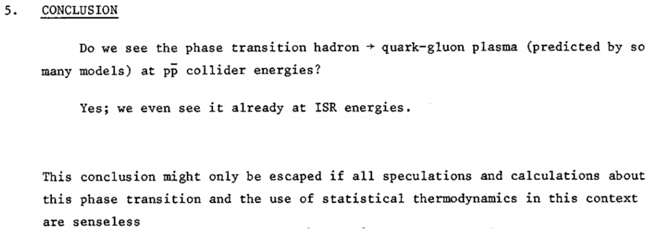


IMAGE CREDIT: C.L. DA SILVA

- Quarkonia binding energies listed according to *J.Phys.G 32 (2006) R25*
- Note the binding energy of $\Upsilon(1S)$ > binding energy of $J/\psi(1S)$

Timeline of Quarkonia Related Events in Heavy-Ion Physics



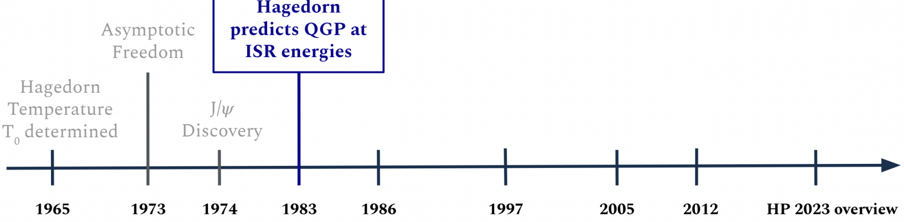
5. CONCLUSION

Do we see the phase transition hadron → quark-gluon plasma (predicted by so many models) at $p\bar{p}$ collider energies?

Yes; we even see it already at ISR energies.

This conclusion might only be escaped if all speculations and calculations about this phase transition and the use of statistical thermodynamics in this context are senseless

Riv.Nuovo Cim. 6N10 (1983) 1-50



Hagedorn predicts QGP at ISR energies

Asymptotic Freedom

Hagedorn Temperature T_0 determined

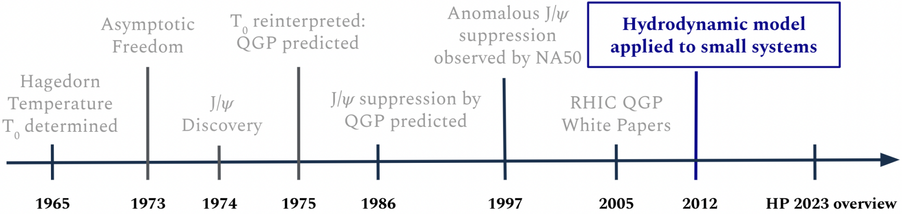
J/ψ Discovery

1965
1973
1974
1983
1986
1997
2005
2012
HP 2023 overview

Timeline of Quarkonia Related Events in Heavy-Ion Physics

> In view of the results in this paper it seems very interesting to look for collective effects in d-Au collisions at $\sqrt{s_N} = 200\text{GeV}$ in RHIC experiments. The multiplicity in central d-Au interactions is similar as in peripheral Au-Au collisions at the same energy. If some stage of collective expansion is present, the large initial eccentricity in a d-Au system should translate into a measurable elliptic flow.

Phys.Rev.C 85 (2012) 014911



1965 Hagedorn Temperature T_0 determined

1973 Asymptotic Freedom

1974 J/ψ Discovery

1975 T_0 reinterpreted: QGP predicted

1986 J/ψ suppression by QGP predicted

1997 Anomalous J/ψ suppression observed by NA50

2005 RHIC QGP White Papers

2012 **Hydrodynamic model applied to small systems**

HP 2023 overview