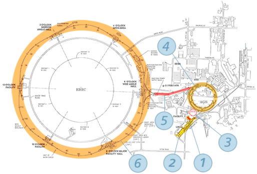
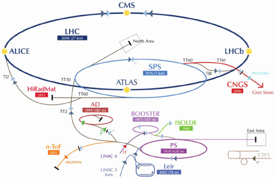




Charmonia in Media

Experimental Results from pp, pA, and AA Collisions

Krista Smith

CHARM Siegen 2023

July 19, 2023

Los Alamos NATIONAL LABORATORY

Introduction

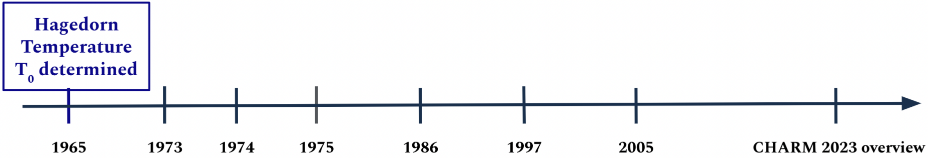
Timeline of Charmonia Related Events in Heavy-Ion Physics

Statistical thermodynamics of strong interactions at high-energies

R. Hagedorn (CERN) (1965)

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

pdf cite claim reference search 1,776 citations



Timeline of Charmonia Related Events in Heavy-Ion Physics

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

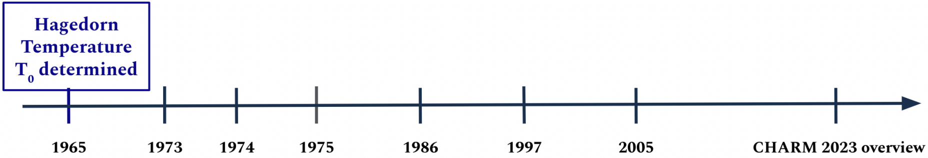
T_0 is the highest possible temperature for strong interactions

Statistical thermodynamics of strong interactions at high-energies

R. Hagedorn (CERN) (1965)

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

pdf cite claim reference search 1,776 citations



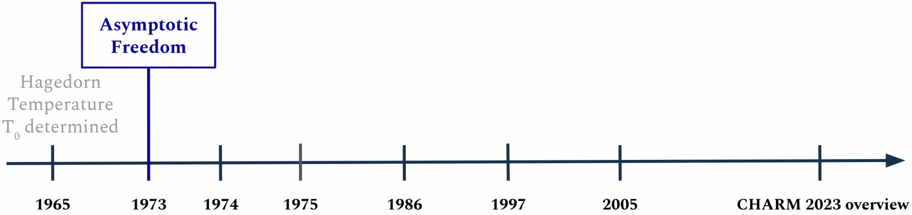
Timeline of Charmonia Related Events in Heavy-Ion Physics

Ultraviolet Behavior of Nonabelian Gauge Theories

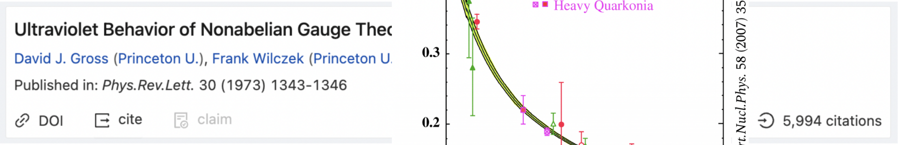
David J. Gross (Princeton U.), Frank Wilczek (Princeton U.) (Jun, 1973)

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

DOI cite claim reference search 5,994 citations



Timeline of Charmonia Related Events in Heavy-Ion Physics


Ultraviolet Behavior of Nonabelian Gauge Theo
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DOI cite claim
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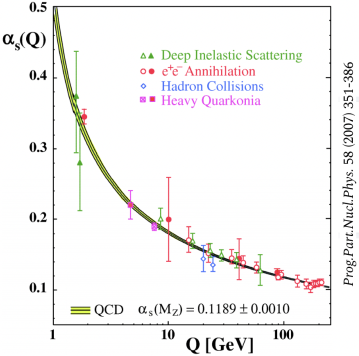
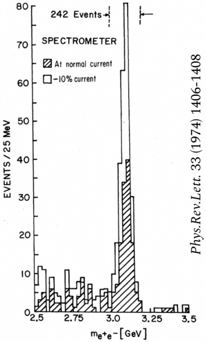


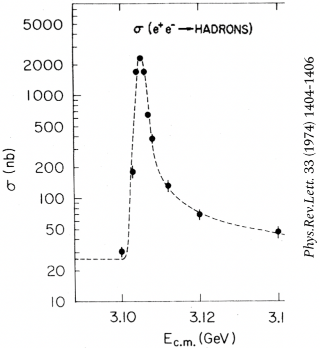
Asymptotic Freedom

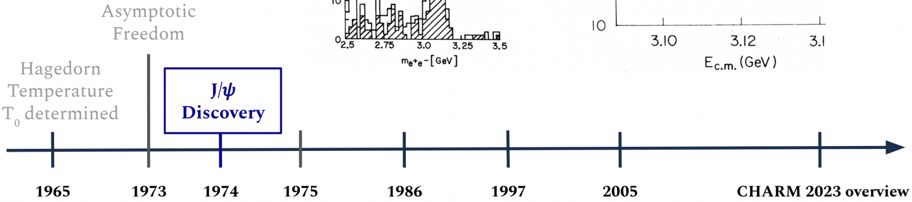
Hagedorn Temperature T_0 determined

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

Timeline of Charmonia Related Events in Heavy-Ion Physics







Timeline of Charmonia Related Events in Heavy-Ion Physics

EXPONENTIAL HADRONIC SPECTRUM AND QUARK LIBERATION

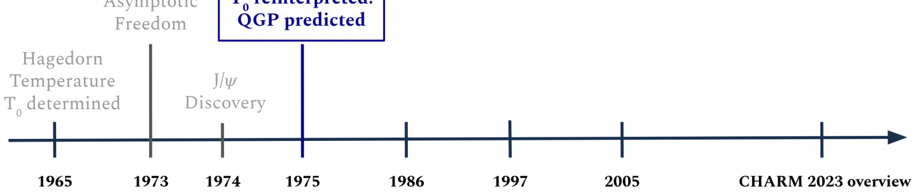
N. CABIBBO
Istituto di Fisica, Universitá di Roma,
Istituto Nazionale di Fisica Nucleare, Sezione di Rome, Italy

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



Timeline of Charmonia Related Events in Heavy-Ion Physics

J/ψ SUPPRESSION BY QUARK-GLUON PLASMA FORMATION

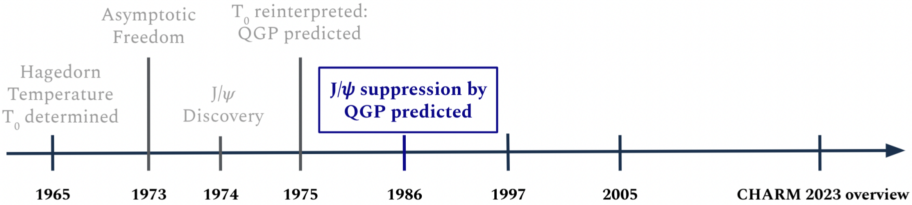
T. Matsui and H. Satz

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

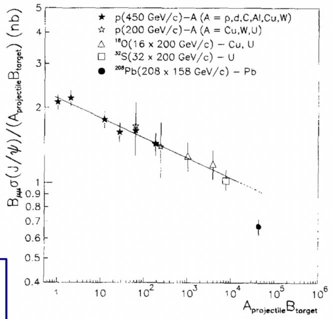
(iii) Are there competitive non-plasma J/ψ suppression mechanisms?

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

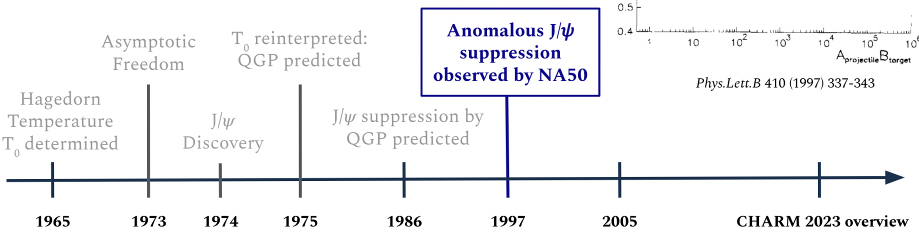
Phys.Lett.B 178 (1986) 416-422



Timeline of Charmonia Related Events in Heavy-Ion Physics



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



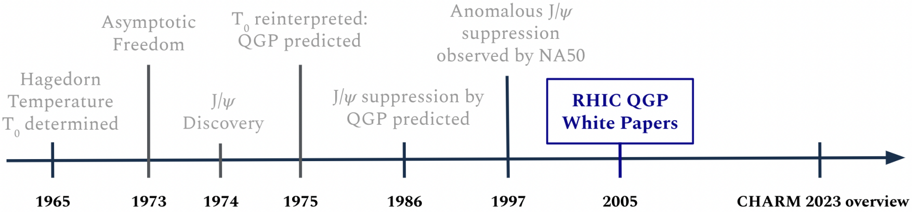
Timeline of Charmonia Related Events in Heavy-Ion Physics

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

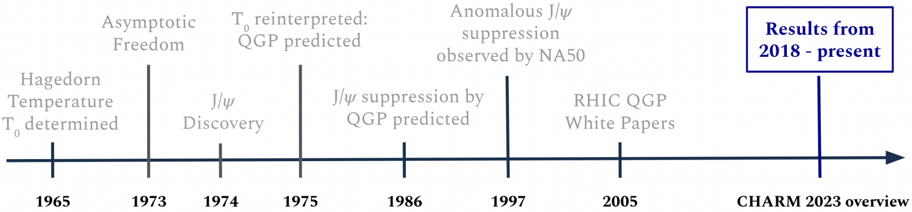
The PHOBOS perspective on discoveries at RHIC
PHOBOS Collaboration • B.B. Back (Argonne) et al. (Oct, 2004)
Published in: *Nucl.Phys.A* 757 (2005) 28-101 • e-Print: nucl-ex/0410022 [nucl-ex]
pdf DOI cite claim reference search 2,558 citations

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



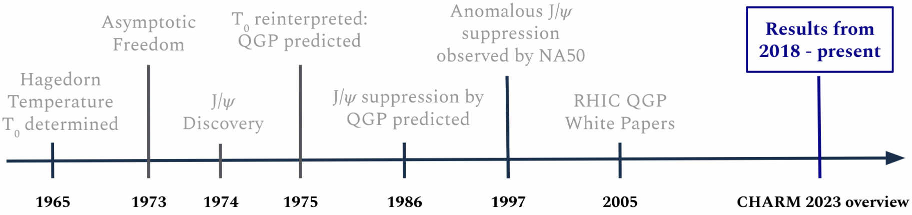
Timeline of Charmonia Related Events in Heavy-Ion Physics

"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**



Timeline of Charmonia Related Events in Heavy-Ion Physics

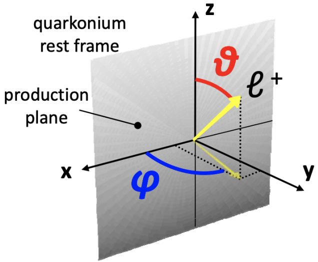
"Measurement of cold nuclear matter effects for inclusive J/ψ in p+Au collisions"	*Phys.Lett.B* 825 (2022) 136865
"Measurement of J/ψ in p+p, p+Al, p+Au, and ^{3}He+Au collisions"	*Phys.Rev.C* 102 (2020) 1, 014902
"Correlation of Υ meson production with the underlying event in *pp* collisions"	ATLAS-CONF-2022-023
"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



Charmonia in pp Collisions

Angular Coefficients

Pedagogical illustration of the decay angular distribution



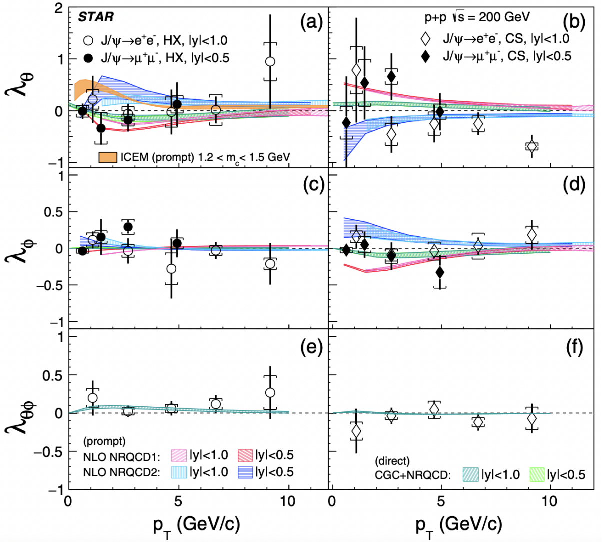
$$W(\cos\theta,\varphi) \propto 1 + \lambda_\theta \cos^2\theta + \lambda_{\theta\varphi} \sin 2\theta \cos\varphi + \lambda_\varphi \sin^2\theta \cos 2\varphi$$

P. Faciolli, Quarkonium in Hot Medium (2009) and Eur. Phys. J. C 69, 657 (2010)

- J/ψ polarization characterized by spin alignment of positively charged decay lepton
- $\lambda_\theta, \lambda_\phi$ and $\lambda_{\theta\phi}$ determined using Helicity, Collins-Soper, or Gottfried-Jackson frames
- $\lambda_\theta = \{+1, 0, -1\} \Rightarrow$ fully transverse, fully zero, or fully longitudinal J/ψ polarization

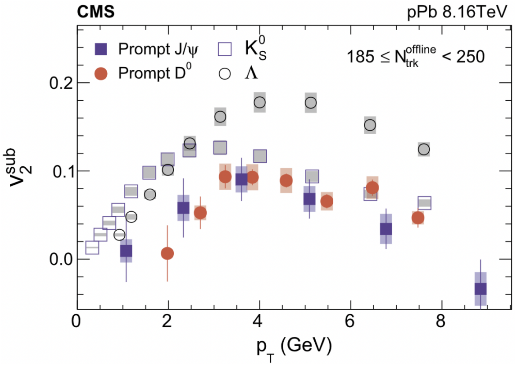
J/ψ Polarization

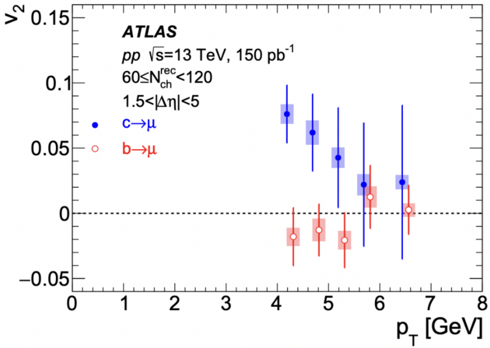
- Left column shows J/ψ polarization parameters λ_θ, λ_ϕ, $\lambda_{\theta\phi}$ in Helicity frame
- Right column shows J/ψ polarization parameters λ_θ, λ_ϕ, $\lambda_{\theta\phi}$ in Collins-Soper frame
  - No meaningful transverse (+1) or longitudinal (-1) J/ψ polarization
  - Although none of the models can be decisively ruled out, the color glass condensate + NRQCD[1] appears to best describe data overall



Phys.Rev.D 102 (2020) 9, 092009

J/ψ & Charm Elliptic Flow in Small Systems

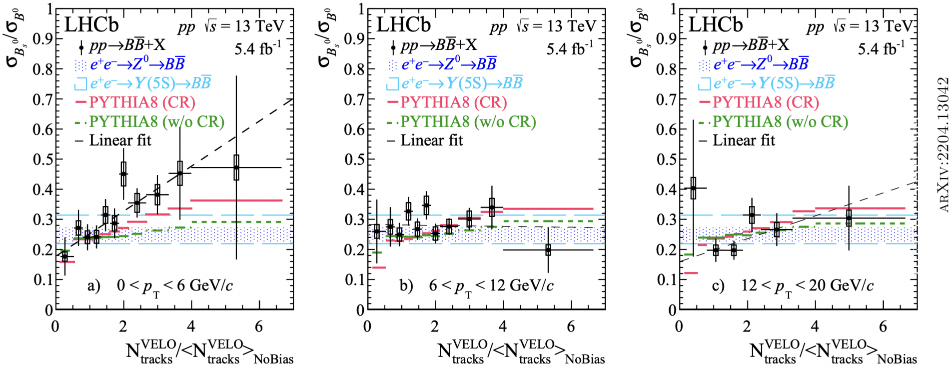




CMS Data: Phys.Lett.B 791 (2019) 172-194
ATLAS Data: Phys.Rev.Lett. 124 (2020) 8, 082301

- 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 pPb and high multiplicity pp collisions

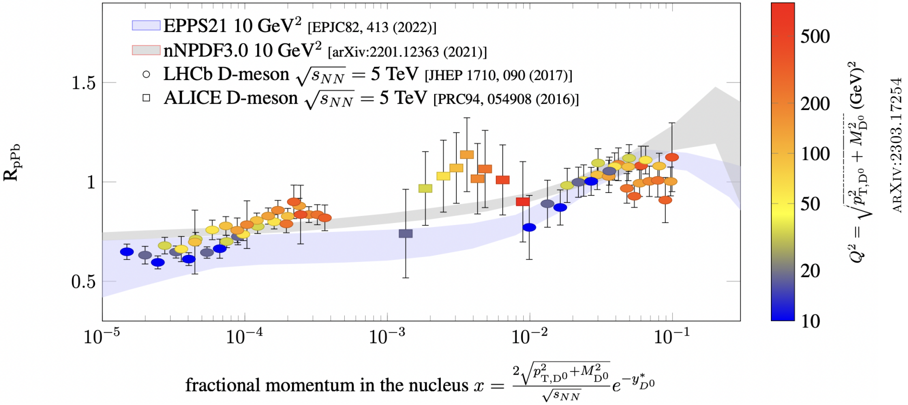
b Quarks in High Multiplicity *pp* Collisions



- $\sigma_{B^0{}_s}$ over σ_{B^0} versus multiplicity shown for different p_T ranges in $\sqrt{s}$ =13 TeV *pp* collisions
- Ratio increases with multiplicity only in the lowest p_T interval ($0 < p_T < 6$ GeV/c)
  - Results consistent with expectations of coalescence and strangeness enhancement

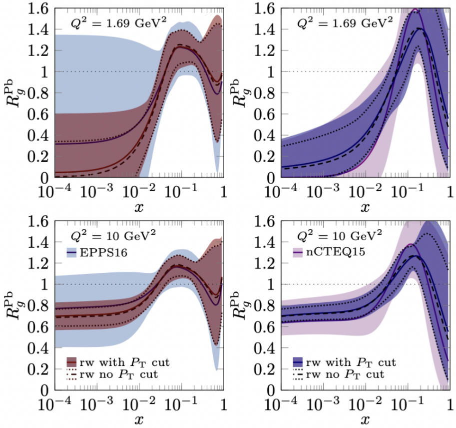
Charmonia in pA Collisions

D-Mesons in pPb Collisions

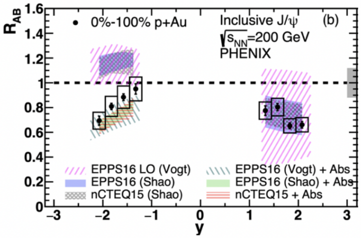


- LHCb and ALICE D-meson nuclear modification plotted as a function of Bjorken-x
  - Data extended now beyond x^{-4} fractional momentum in the nucleus

J/ψ Modification in pAu Collisions



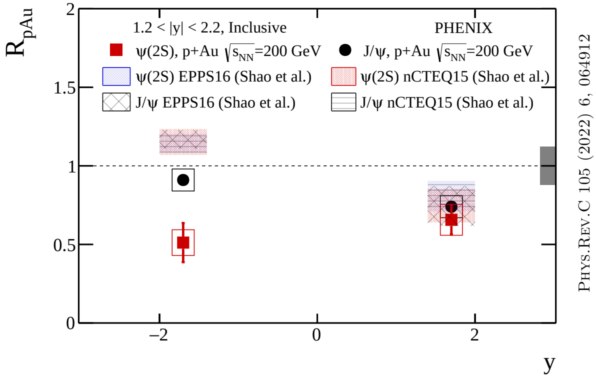
JHEP 05 (2020) 037



Phys. Rev. C 102, 014902

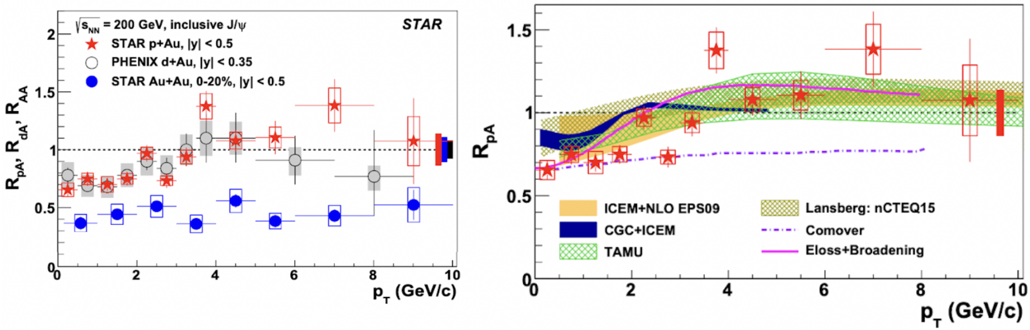
- EPPS16 and nCTEQ15 with and without re-weighted LHCb D-meson data
  - Re-weighted EPPS16 and nCTEQ15 describe PHENIX data well at forward rapidity

Charmonia in pAu Collisions



- At forward rapidity, J/ψ and $\psi(2S)$ modification show similar suppression
    - Data well described by reweighted EPPS16[2] and nCTEQ15[3] shadowing predictions
- At backward rapidity, nPDF effects alone cannot describe $\psi(2S)$ modification

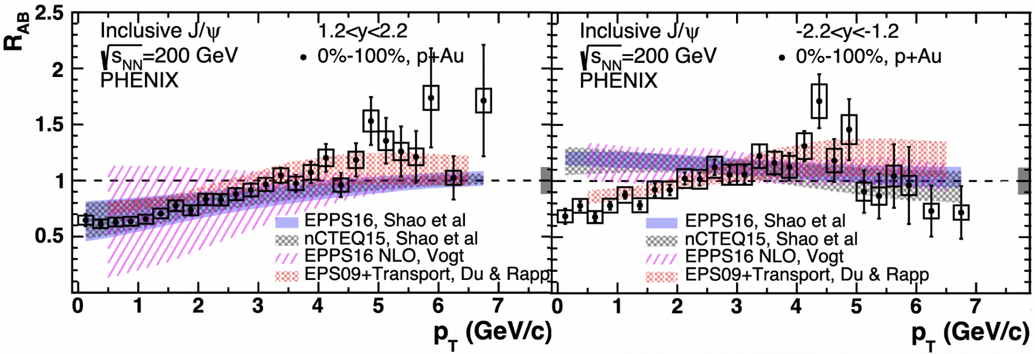
J/ψ in Large & Small Collisions at RHIC



THEORETICAL REFS: [4],[5],[6],[7],[8],[9]
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

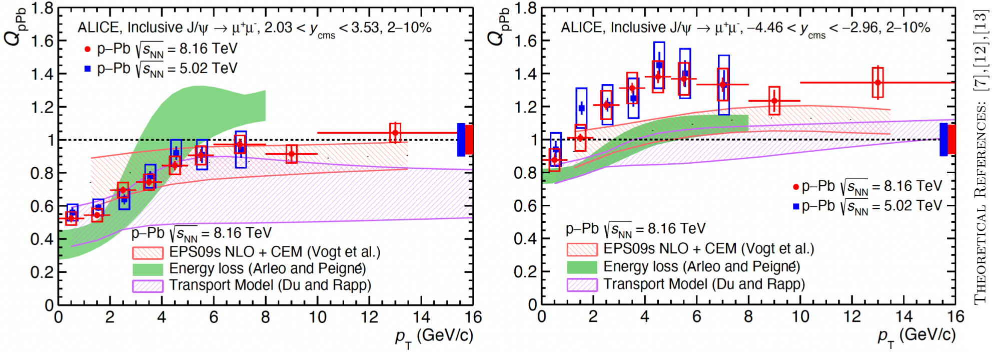
J/ψ in pAu Collisions at RHIC



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[10],[11]
- Backward rapidity suppression consistent with Transport Model predictions[7] (includes nuclear absorption effect)

J/ψ in pPb Collisions at LHC

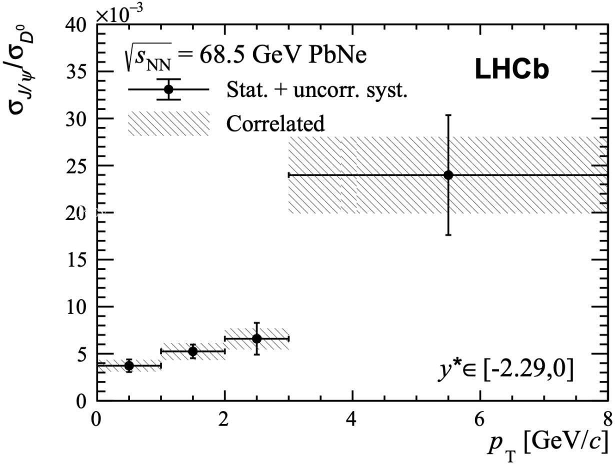


Theoretical References: [7],[12],[13]
JHEP 02 (2021) 002

- 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

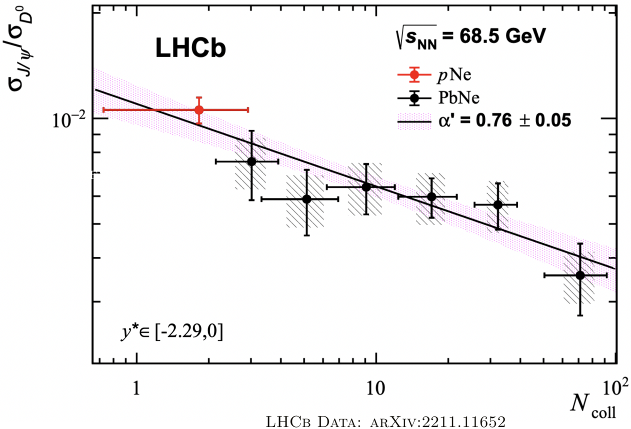
- Data recorded in fixed-target mode at $\sqrt{s_{NN}} = 68.5$ GeV (regeneration effects minimal)
- Strong dependence of J/ψ to D^0 ratio on p_T



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
- $J/\psi(D^0)$ 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

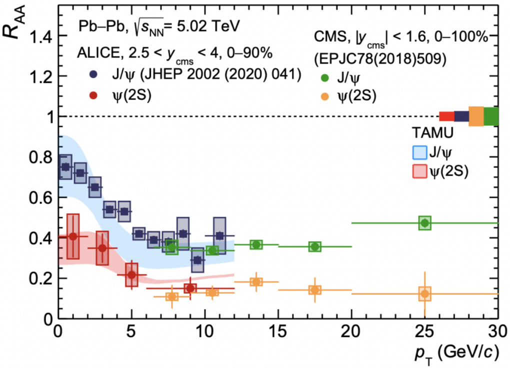


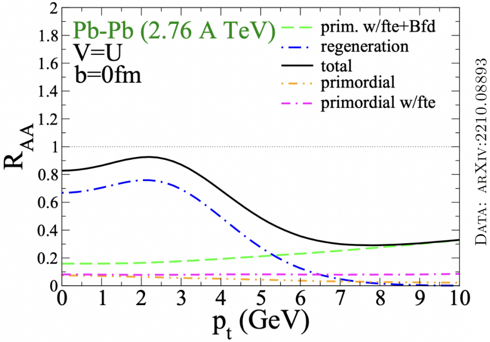
LHCb Data: arXiv:2211.11652

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

Charmonia in AA Collisions

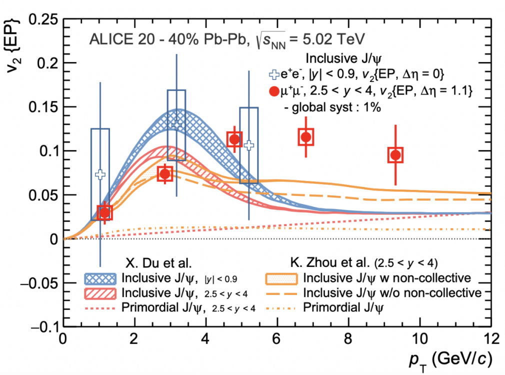
Charmonia in PbPb Collisions

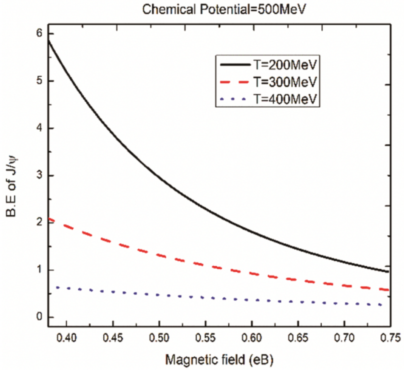




- J/ψ and ψ(2S) R_{AA} strongly suppressed at high p_T - consistent with CMS results
- Transport Model predictions[14],[15] expect sizeable regeneration at LHC energies
    - $q\bar{q}$ pairs close in phase space can recombine to form a quarkonium state

J/ψ Elliptic Flow in PbPb Collisions

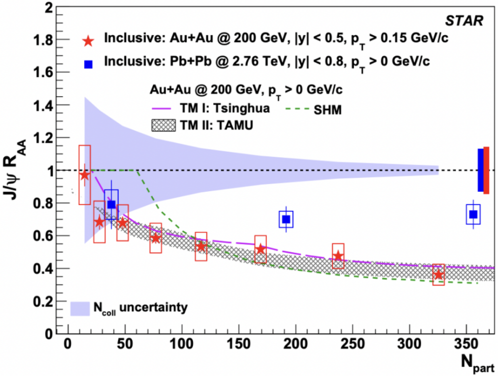


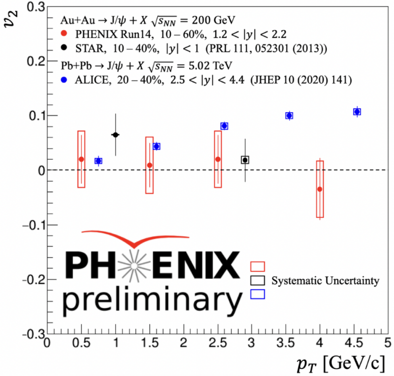


ALICE DATA: Phys.Rev.Lett. 119 (2017) 24, 242301
Theoretical References: [6], [7], [9]

- J/ψ elliptic flow versus p_T in the 20–40% centrality class for $J/\psi \rightarrow \mu^+\mu^-$ and $J/\psi \rightarrow e^+e^-$
  - Nonzero results indicate J/ψ mesons participate in collective flow
- Some studies suggest J/ψ binding energy a function of magnetic field strength

J/ψ in AA Collisions at RHIC (LHC)

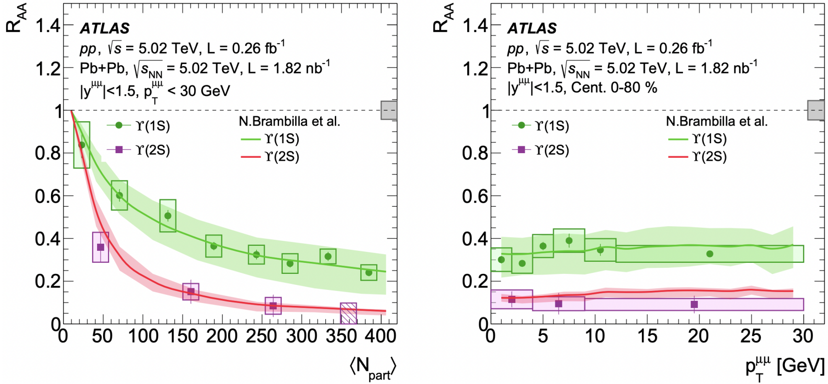




Data: Phys.Lett.B 797 (2019) 134917
Theoretical References: [16],[17],[18]

- 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

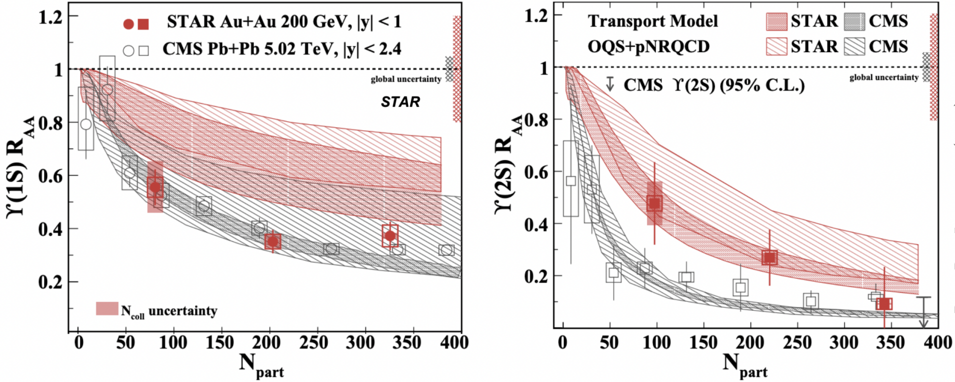
Bottomonia in PbPb Collisions at LHC



Theoretical Reference: [19]
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: [20],[21]

- $\Upsilon(1S)$ 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

Conclusion

Small System Collisions pA

- J/ψ modification versus p_T at backward rapidity suggests different nuclear effects contribute at RHIC compared to LHC energies
- Non-zero charm v_2 observed in pPb and high multiplicity pp collisions
- If QGP is formed, it does not appear to be dominant effect on J/ψ

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

Theory References

[1] Ma, Yan-Qing and Venugopalan, Raju
Comprehensive Description of J/ψ Production in Proton-Proton Collisions at Collider Energies
Phys.Rev.Lett. 113 (2014) 19, 192301

[2] Kusina, Aleksander and Lansberg, Jean-Philippe and Schienbein, Ingo and Shao, Hua-Sheng
Gluon Shadowing in Heavy-Flavor Production at the LHC
Phys.Rev.Lett. 121 (2018) 5, 052004

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Back-Up

Heavy-Ion Experimental Overview

- The primary purpose of the Relativistic Heavy Ion Collider (RHIC) was to detect and characterize the quark gluon plasma (QGP) using data collected from A+A, p+A, and p+p collisions
- This is the main physics goal of the PHENIX, STAR & ALICE Experiments
- In 2005, the experiments at RHIC concluded that the formation of a quark-gluon plasma had been observed
- In particular, strong indicators of the presence of QGP include:
  - Jet quenching
  - **Collective system behavior**
  - **Sequential deconfinement of heavy quark mesons**
  - **Strangeness enhancement**

1. Introduction

Phys.Rept. 458 (2008) 1-171

Contributed by: K. Hencken, M. Strikman, R. Vogt and P. Yepes

In 1924 Enrico Fermi, 23 at the time, proposed the equivalent photon method [1] which treated the moving electromagnetic fields of a charged particle as a flux of virtual photons. A decade later, Weizsäcker and Williams applied the method [2] to relativistic ions. Ultraperipheral collisions, UPCs, are those reactions in which two ions interact via their cloud of virtual photons. The intensity of the electromagnetic field, and therefore the number of photons in the *cloud* surrounding the nucleus, is proportional to Z^2. Thus these types of interactions are highly favored when heavy ions collide. Figure 1 shows a schematic view of an ultraperipheral heavy-ion collision. The pancake shape of the nuclei is due to Lorentz contraction.

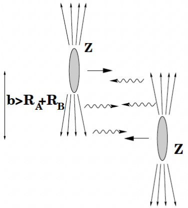
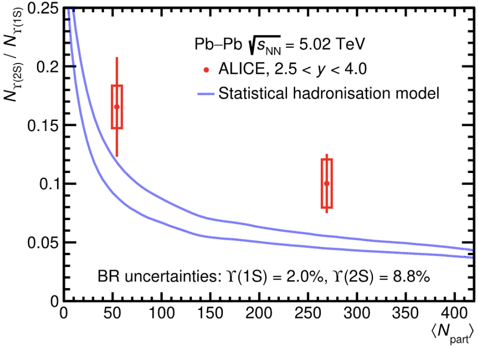
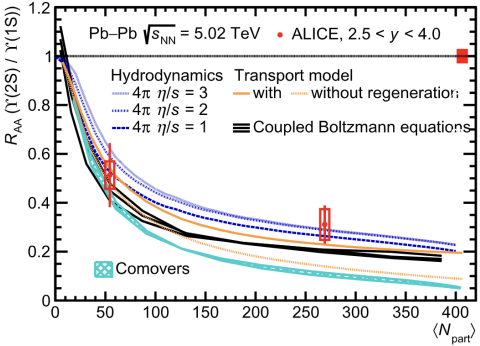


Figure 1. Schematic diagram of an ultraperipheral collision of two ions. The impact parameter, b, is larger than the sum of the two radii, $R_A + R_B$. Reprinted from Ref. [3] with permission from Elsevier.

Bottomonia in PbPb Collisions at LHC





Phys.Lett.B 822 (2021) 136579

- ϒ(2S) to ϒ(1S) ratio of yields (left) and R_{AA} are shown at forward rapidity vs. $\langle N_{\mathrm{part}} \rangle$
- 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

nature physics
LETTERS
PUBLISHED ONLINE: 24 APRIL 2017 | DOI: 10.1038/NPHYS4111
OPEN

Enhanced production of multi-strange hadrons in high-multiplicity proton–proton collisions

ALICE Collaboration†

At sufficiently high temperature and energy density, nuclear matter undergoes a transition to a phase in which quarks and gluons are not confined: the quark–gluon plasma (QGP)[1]. Such an exotic state of strongly interacting quantum chromodynamics matter is produced in the laboratory in heavy nuclei high-energy collisions, where an enhanced production of strange hadrons is observed[2–6]. Strangeness enhancement, originally proposed as a signature of QGP formation in nuclear collisions[7], is more pronounced for multi-strange baryons. Several effects typical of heavy-ion phenomenology have been observed in high-multiplicity proton–proton (pp) collisions[8,9], but the enhanced production of multi-strange particles has not been reported so far. Here we present the first observation of strangeness enhancement in high-multiplicity proton–proton collisions. We find that the integrated yields of strange and multi-strange particles, relative to pions, increases significantly with the event charged-particle multiplicity. The measurements are in remarkable agreement with the p–Pb collision results[10,11], indicating that the phenomenon is related to the final system created in the collision. In high-multiplicity events strangeness production reaches values similar to those observed in Pb–Pb collisions, where a QGP is formed.

equilibrium and can be described using a grand-canonical statistical model[12,13]. In peripheral collisions, where the overlap of the colliding nuclei becomes very small, the relative yields of strange particles to pions decrease and tend toward those observed in pp collisions, for which a statistical-mechanics approach can also be applied[14,15]. Extensions of a pure grand-canonical description of particle production, such as statistical models implementing strangeness canonical suppression[16] and core–corona superposition[17,18] models, can effectively produce a suppression of strangeness production in small systems. However, the microscopic origin of enhanced strangeness production is not known, and the measurements presented in this Letter may contribute to its understanding. Several effects, such as azimuthal correlations and mass-dependent hardening of p_T distributions, which in nuclear collisions are typically attributed to the formation of a strongly interacting quark–gluon medium, have been observed in high-multiplicity pp and proton–nucleus collisions at the LHC[8–11,19–25]. Yet, enhanced production of strange particles as a function of the charged-particle multiplicity density ($dN_{ch}/d\eta$) has so far not been observed in pp collisions. The study of pp collisions at high multiplicity is thus of considerable interest as it opens the exciting possibility of a microscopic understanding of phenomena known from nuclear reactions.

Dissociation Temperature and Magnetic Field

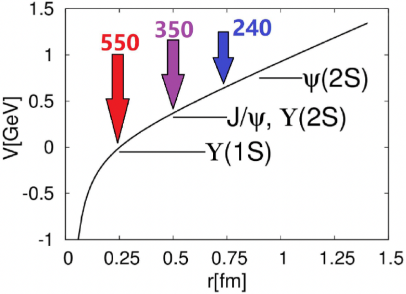


Figure 1.11: The Cornell potential (see Section 1.4) as a function of quarkonium radius. The radii of the J/ψ, $\psi(2S)$, $\Upsilon(1S)$, and $\Upsilon(2S)$ are shown, along with the corresponding melting temperature

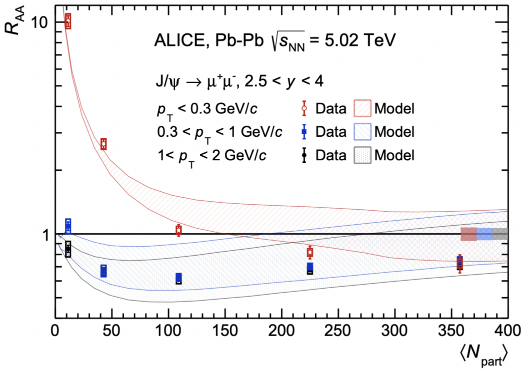
Xiaojian Du. PhD thesis, Texas A-M, 2019.

5 Results and Discussion

In the present work, we have studied the properties of the quarkonia in the presence of strong magnetic field at a constant value of chemical potential. Here we use the Debye mass depending upon the temperature, chemical potential, and magnetic field obtained from the quasiparticle model. It should be noted that we employed the two-loop coupling constant which depends upon the temperature and the chemical potential. For studying the behavior of the magnetic field on the quarkonium states, we use the T=200, 300, and 400 MeV and eB= 0.3, 0.5, and 0.7 GeV^2. However, these values of the temperature and magnetic field are taken arbitrarily for studying the spectra of the heavy quarkonia states.

Indian J.Pure Appl.Phys. 60 (2022) 06, 475-481

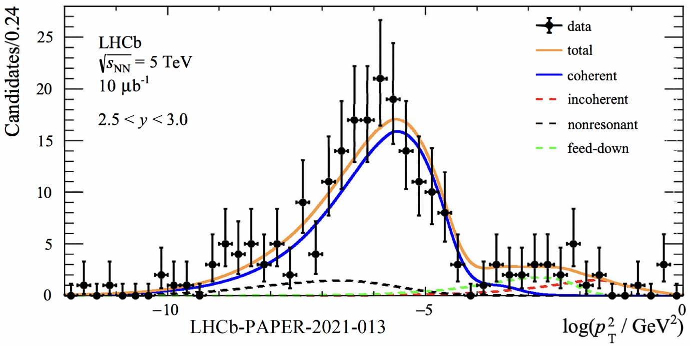
J/ψ Photoproduction in PbPb Collisions

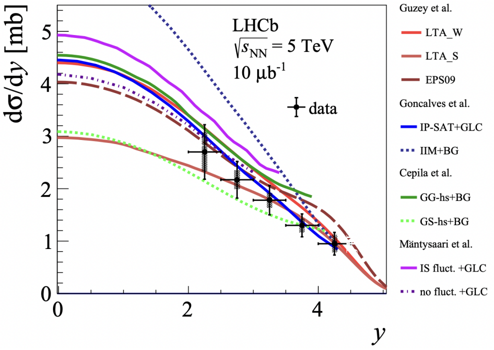


ALICE Data: arXiv:2204.10684
Theoretical Reference: [10]

- Nuclear modification of J/ψ as a function of $\langle N_{\text{part}}\rangle$ in three different p_T ranges
- J/ψ coherent photoproduction expected to be dominant for $p_T < 300$ MeV/c
    - R_{AA} corresponding to coherent photoproduction (red) enhanced in peripheral collisions

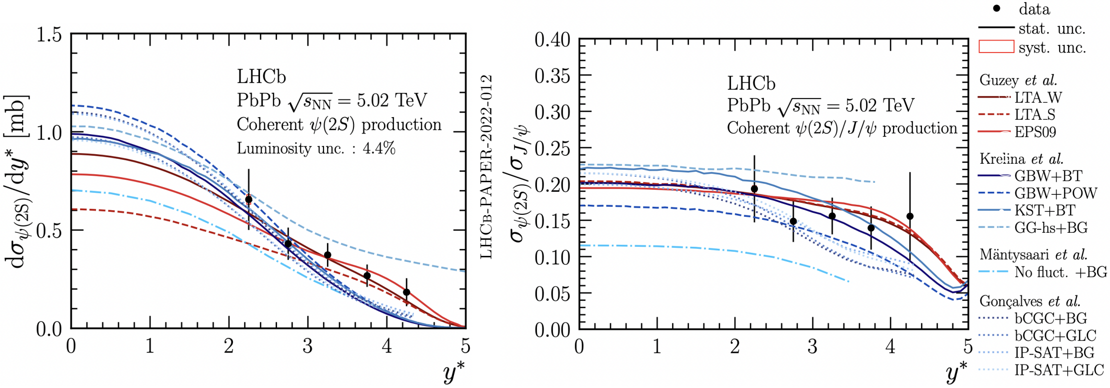
Coherent J/ψ Production in PbPb UPC





- Fit to the log of p_T^2 distribution performed to isolate coherent from incoherent production
- Differential cross-section for coherent J/ψ production decreases as function of y
  - Several of the CGC-based predictions (blue dotted, solid magenta & solid green curves) overestimate the J/ψ production

Coherent $\psi(2S)$ Production in PbPb UPC



- First measurement at LHC for coherent $\psi(2S)$ production at forward rapidity
  - pQCD calculations (red curves) by Guzey *et al.* describe data well at large y
- Ratio of $\psi(2S)$ to J/ψ not as well described by CGC predictions (blue curves)

Measurement of inclusive J/ψ polarization in p+p collisions at $\sqrt{s}$= 200 GeV by the STAR experiment

Model calculations describing the J/ψ production utilize the factorization of the short-distance $c\bar{c}$ production and the long-distance hadronization process [2]. Models differ mainly in the treatment of the non-perturbative formation of J/ψ. One of the early models is the Color Evaporation Model (CEM) [3, 4], which is based on the principle of quark-hadron duality and satisfies all-order factorization. It assumes that every $c\bar{c}$ pair, with an invariant mass below twice the D-meson threshold, evolves into a J/ψ meson with a fixed probability ($F_{J/\psi}$) by randomly emitting or exchanging soft gluons with other color sources. The non-perturbative J/ψ formation is incorpo-

A more sophisticated way to describe the hadronization of heavy quarkonia is based on the effective quantum field theory of non-relativistic QCD (NRQCD) [11]. In addition to the usual expansion in the strong coupling constant (α_s), it also introduces an expansion in the relative velocity between the heavy quarks in the pair. Both the color-singlet and color-octet intermediate $c\bar{c}$ pairs are included in the NRQCD. The hadronization process is incorporated through the assumed universal Long Distance Matrix Elements (LDMEs), which weight the relative contributions of each intermediate state and are extracted from fitting experimental data. The NRQCD

by the CDF Collaboration [16, 17]. To remedy the issue of calculating the $c\bar{c}$ production cross section at low p_{T}, where the collinear factorization formalism may not be applicable, an effort has been made to use the Color Glass Condensate (CGC) effective field theory [18]. Combined with the NRQCD, it describes well the J/ψ cross sections measured in p+p collisions at both RHIC and the LHC [19]. The CGC+NRQCD formalism has also been used to calculate the J/ψ polarization and the results agree well with the LHC measurements at forward rapidities [20]. Continued efforts from both experimental and the-

Phys.Rev.D 102 (2020) 9, 092009

The enhanced production of strange or hidden-strange hadrons in high-energy heavy-ion collisions, as compared to the appropriately scaled $p+p$ collisions, is a direct consequence of the process of chemical equilibration of strange quarks in QGP [11]. Thus, measurement of hadrons containing (anti)strange quarks has been established as a promising method of detecting the QGP. Recently published ratios of strange to nonstrange hadron yields observed at the Large Hadron Collider [12] show a smooth transition from elementary $p+p$ collisions at the higher center-of-mass energy of $\sqrt{s_{NN}} = 7$ TeV, via $p+$Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV, to heavy ion Pb+Pb colli-

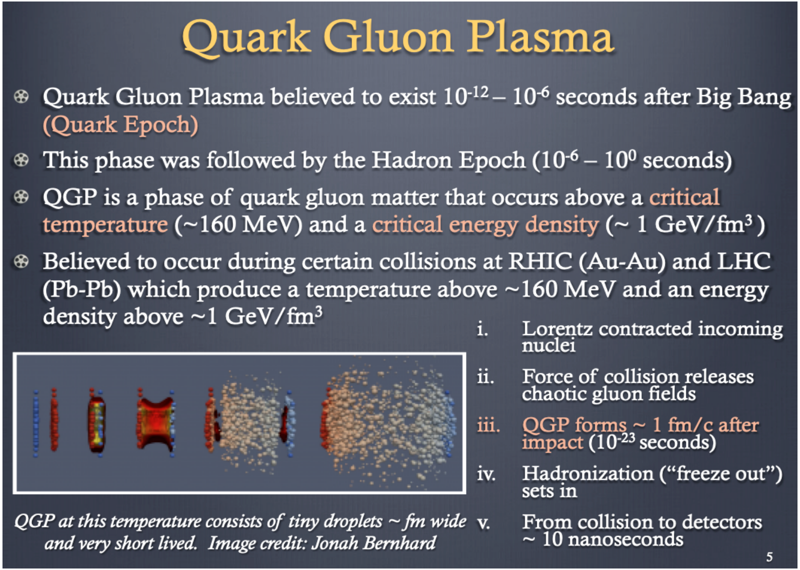
Phys.Rev.C 106 (2022) 1, 014908

Strangeness in Relativistic Heavy Ion Collisions [11]

P. Koch (Cape Town U. and Frankfurt U. and Darmstadt, GSI), Berndt Muller (Cape Town U. and Frankfurt U. and Darmstadt, GSI), Johann Rafelski (Cape Town U. and Frankfurt U. and Darmstadt, GSI) (Feb, 1986)

Published in: *Phys.Rept.* 142 (1986) 167-262

DOI cite claim reference search 1,102 citations


Quark Gluon Plasma
Quark Gluon Plasma believed to exist 10^{-12} – 10^{-6} seconds after Big Bang (Quark Epoch)
This phase was followed by the Hadron Epoch (10^{-6} – 10^{0} seconds)
QGP is a phase of quark gluon matter that occurs above a critical temperature (~160 MeV) and a critical energy density (~ 1 GeV/fm^3)
Believed to occur during certain collisions at RHIC (Au-Au) and LHC (Pb-Pb) which produce a temperature above ~160 MeV and an energy density above ~1 GeV/fm^3
i. Lorentz contracted incoming nuclei
ii. Force of collision releases chaotic gluon fields
iii. QGP forms ~ 1 fm/c after impact (10^{-23} seconds)
iv. Hadronization ("freeze out") sets in
v. From collision to detectors ~ 10 nanoseconds
QGP at this temperature consists of tiny droplets ~ fm wide and very short lived. Image credit: Jonah Bernhard
5

Polarization and cross section of midrapidity J/ψ production in $p+p$ collisions at $\sqrt{s} = 510$ GeV

The spin alignment of a positively charged lepton from a J/ψ decay, commonly known as "polarization," has been measured at the Tevatron [11], RHIC [12, 13], and the Large Hadron Collider [14–17]. Measuring spin alignment provides additional tests for the theory and understanding dominant quarkonium production mechanisms in different kinematic regimes. The J/ψ polarization is measured by fitting the angular distribution of a positively charged lepton, shown in Eq. (1), to data and extracting decay angular coefficients.

$$\frac{dN}{d\Omega} \approx 1 + \lambda_\theta \cos^2\theta + \lambda_{\theta\phi} \sin^2\theta \cos 2\phi + \lambda_\phi \sin 2\theta \cos\phi, \tag{1}$$

where the coefficients λ_θ, $\lambda_{\theta\phi}$, and λ_ϕ are determined most commonly in the helicity (HX) frame [18], Collins-Soper (C-S) frame [19] and Gottfried-Jackson (G-J) frame [20] defined in the J/ψ production plane. Invari-

Phys.Rev.D 102 (2020) 7, 072008

Color-glass condensate

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From Wikipedia, the free encyclopedia

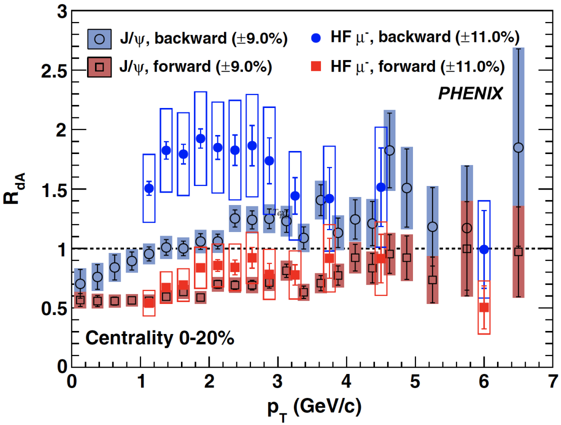
Color-glass condensate (**CGC**) is a type of matter theorized to exist in atomic nuclei when they collide at near the speed of light. During such collision, one is sensitive to the gluons that have very small momenta, or more precisely a very small x_{Bj} Bjorken scaling variable. The small momenta gluons dominate the description of the collision because their density is very large. This is because a high-momentum gluon is likely to split into smaller momentum gluons. When the gluon density becomes large enough, gluon-gluon recombination puts a limit on how large the gluon density can be. When gluon recombination balances gluon splitting, the density of gluons saturate, producing new and universal properties of hadronic matter. This state of saturated gluon matter is called the **color-glass condensate**.[1]

The Color Glass Condensate (CGC) is the description of the properties of saturated gluons in the IMF in the Regge-Gribov limit.

Ann.Rev.Nucl.Part.Sci. 60 (2010) 463-489

Open Heavy Flavor in *d*Au Collisions

- Forward rapidity: J/ψ suppression similar to open charm suppression
  - Consistent with shadowing and/or parton energy loss
- Backward rapidity: J/ψ suppressed relative to open charm
  - Expect open charm to be enhanced by anti-shadowing
  - J/ψ suppression consistent with absorption due to collisions with nucleons in the target
  - Possible contribution also from co-movers



Phys. Rev. Letters 112, 252301

arXiv:1909.01650v2 [nucl-ex] 6 Mar 2020

Measurement of azimuthal anisotropy of muons from charm and bottom hadrons in *pp* collisions at $\sqrt{s}$ = 13 TeV with the ATLAS detector

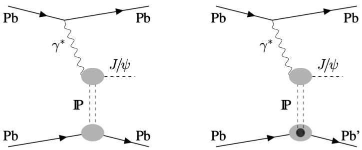
The ATLAS Collaboration

The elliptic flow of muons from the decay of charm and bottom hadrons is measured in *pp* collisions at $\sqrt{s}$ = 13 TeV using a data sample with an integrated luminosity of 150 pb^{-1} recorded by the ATLAS detector at the LHC. The muons from heavy-flavor decay are separated from light-hadron decay muons using momentum imbalance between the tracking and muon spectrometers. The heavy-flavor decay muons are further separated into those from charm decay and those from bottom decay using the distance-of-closest-approach to the collision vertex. The measurement is performed for muons in the transverse momentum range 4–7 GeV and pseudorapidity range $|\eta| < 2.4$. A significant nonzero elliptic anisotropy coefficient v_2 is observed for muons from charm decays, while the v_2 value for muons from bottom decays is consistent with zero within uncertainties.

Coherent J/ψ-meson production in UPCs can be described by the interaction of photons with gluons, identified as a single object with vacuum quantum numbers, which in the Regge theory is referred to as pomeron ($\mathbb{P}$) [1–5]. An illustration of this process is given in Fig. 1. This interaction probes the gluon distribution at a hard momentum transfer Q^2 of about $m^2_{J/\psi}/4$, where $m_{J/\psi}$ is the J/ψ mass [6, 7].[1]

In this paper, a measurement of coherent J/ψ production is reported in lead-lead collisions at a nucleon-nucleon centre-of-mass energy of $\sqrt{s_{\rm NN}} = 5\,\text{TeV}$ collected with the LHCb detector in 2015, corresponding to an integrated luminosity of about $10\,\mu\text{b}^{-1}$. Results of UPC studies have also been reported by RHIC and LHC experiments [8–15]. The forward rapidity range $2.0 < y < 4.5$ covered by the present measurement corresponds to values of the Bjorken variable $x \approx (m_{J/\psi}/\sqrt{s_{\rm NN}})e^{\pm y}$ down to 10^{-5}. At these x values, current uncertainties on the gluon distributions inside the nucleon are sizeable [16, 17], thus new measurements should reduce the uncertainties [18–20].

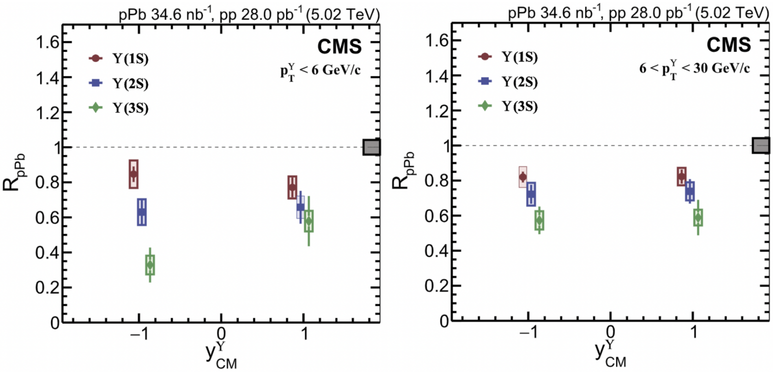
The paper is organised as follows. The LHCb detector and the event selection are described in Sec. 2. The analysis strategy and the systematic uncertainties are discussed in Secs. 3 and 4, respectively. The differential cross-section results for J/ψ production in



JHEP 07 (2022) 117

Figure 1: Illustration of the (left) coherent scatter with the lead nucleus and (right) incoherent interaction with a single nucleon leading to exclusive production of J/ψ mesons in ultraperipheral heavy-ion collisions. The symbol Pb' represents any final state for the nucleus inelastic scattering in the incoherent process.

Bottomonia in pPb Collisions



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 $\Upsilon(1S)$

Polarization Coordinate Frames

The Helicity frame (HX): [9], traditionally used in collider experiments, takes the $\hat{z}$-axis as the spin-1 particle momentum direction.

The Collins-Soper frame (CS): [10], widely used in Drell-Yan measurements, chooses the $\hat{z}$-axis as the difference between the momenta of the colliding partons boosted into the spin-1 particle rest frame. Note that while the original paper [10] and subsequent theoretical studies used colliding parton momenta in their calculations, the colliding hadron momenta are used here, because we do not have information about the parton momenta.

The Gottfried-Jackson frame (GJ): [11], typically used in fixed target experiments, takes the $\hat{z}$-axis as the beam momentum boosted into the spin-1 particle rest frame. At forward angles in a collider environment, the definition of the GJ frame depends heavily on which beam is used in the definition. If the beam circulating in the same direction as the J/ψ momentum is chosen (GJ forward), the resulting $\hat{z}$-axis is nearly collinear with the $\hat{z}$-axis of the HX and CS frames and points in the same direction. In GJ backward frame (beam circulating in the direction opposite to J/ψ momentum is chosen) the $\hat{z}$-axis points in the opposite direction.

Phys. Rev. D 95, 092003 (2017)

- Helicity frame is most commonly used for collider experiments
- Definition of $\hat{z}$ is main difference between coordinate frames