Recent Quarkonia Results in pA and AA Collisions from RHIC

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Quarkonia as Tools 2024

January 10, 2024

Brief Introduction

PHENIX, Past & Present

PHENIX Overview

- **2000–2016**
  PHENIX recorded heavy-ion data at RHIC for 16 years
- **Publications**
  PHENIX has > 200 physics papers published (76 in *Phys. Rev. Lett.*)
- **Presentations/Theses**
  Zenodo contains ∼600 materials
- **Recent Highlights**
  2023 direct photon measurement **BNL News Release**

Data Preservation

- **2021–Present**
  Efforts led by Gabor David, Maxim Potekhin, Christine Nattrass and team of undergraduates at UT Knoxville
- **Publications**
  PHENIX data from 202 publications uploaded to HEPData
- **Recent News**
  BNL News Release on UT Knoxville data preservation efforts

STAR, Present & Future

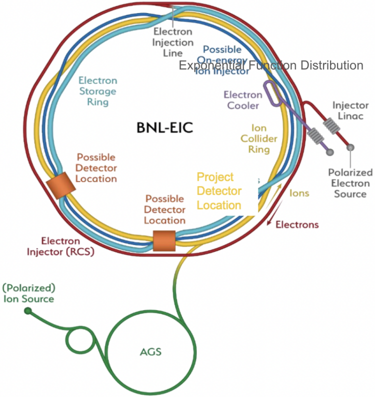
STAR Overview

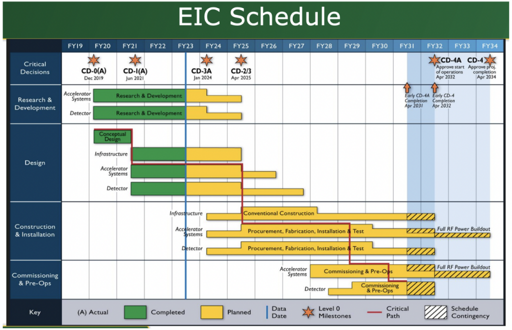
- **2000–2025**
  STAR has been recording heavy-ion data at RHIC for 23 years
- **Publications**
  STAR has > 300 physics papers published (105 in *Phys. Rev. Lett.*)
- **Publication Database**
  Searchable database on **Drupal**
- **Recent Highlights**
  2023 $\Upsilon(1S)$ and $\Upsilon(2S)$ measurement
  BNL News Release

Data Preservation

- **2020–Present**
  Efforts likely began around 2020, when papers published in 2001 were uploaded in early 2020
- **Publications**
  STAR data from 304 publications uploaded to HEPData
- **Present**
  STAR appears to require HEPData for publication (as PHENIX now does)

RHIC & the Electron-Ion Collider



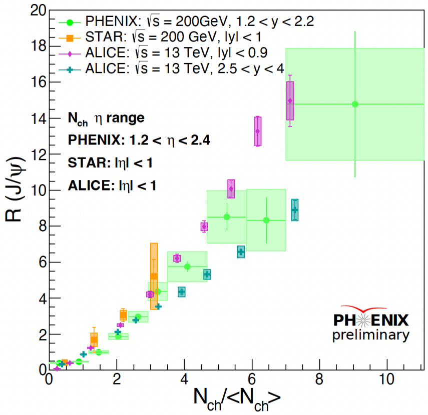


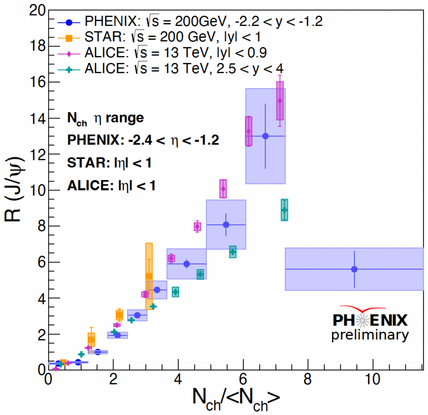
T. Hallman, EIC User Group Meeting July 2023

- RHIC to stop running June 2025 - sPHENIX, STAR expected to complete data taking
- Some EIC construction scheduled to begin in year 2024 (infrastructure, accelerator systems)

Quarkonia in Small Systems

Multiplicity Dependent J/ψ Production

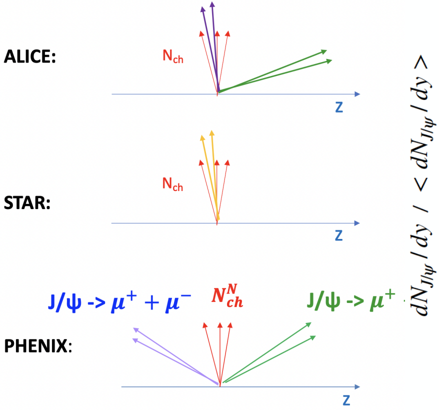


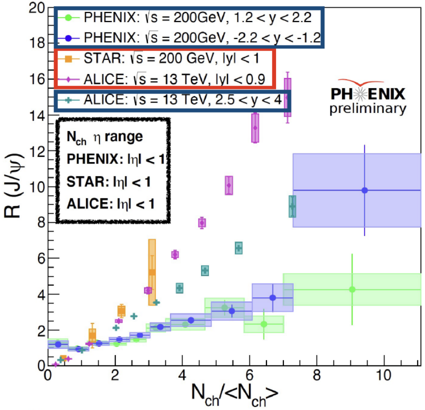


Universe 2023, 9(7), 322

- First PHENIX measurement of relative J/ψ yields R vs. normalized event charged particle multiplicity $N_{ch}/\langle N_{ch}\rangle$ in $p+p$ collisions at $\sqrt{s}$=200 GeV

Multiplicity Dependent J/ψ Production

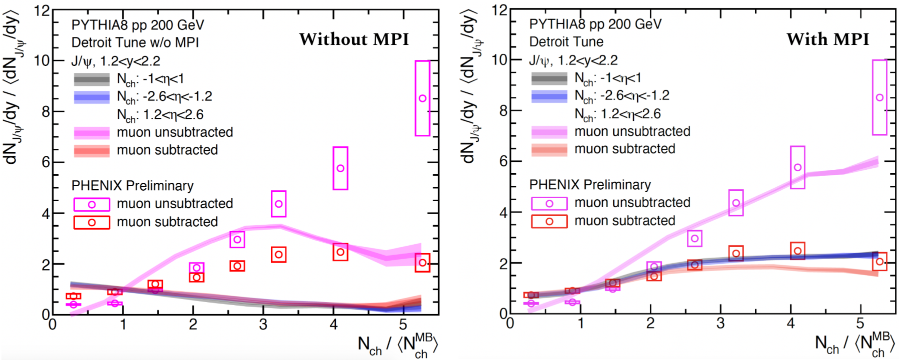




Universe 2023, 9(7), 322

- ◦ **Multiplicity dependent measurements vary based on rapidity of N_{ch}**
- After J/ψ tracks subtracted, PHENIX multiplicity dependence similar at fwd, bkwd rapidity

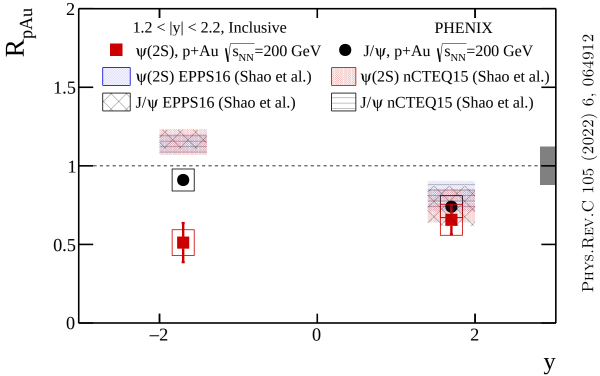
Multiplicity Dependent J/ψ Production



J.Korean Phys.Soc. 82 (2023) 7, 651-657
Eur.Phys.J.C 74 (2014) 8, 3024
Phys.Rev.D 105 (2022) 1, 016011

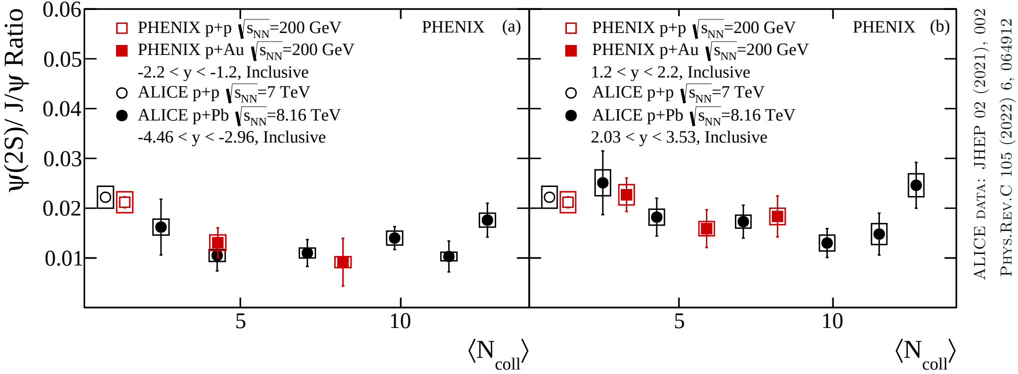
- J/ψ relative yields compared with PYTHIA8 Detroit tune for RHIC energies
- Data is shown for J/ψ multiplicity both before and after J/ψ tracks subtracted
  - **Multi-parton interactions are required to reproduce PHENIX data**

Charmonia in pAu Collisions



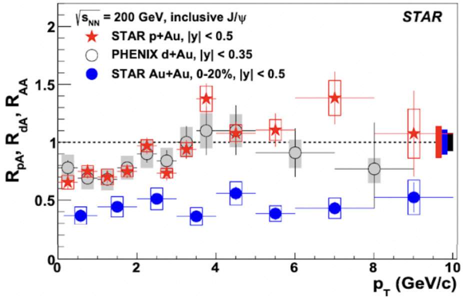
- At forward rapidity, J/ψ and $\psi(2S)$ modification show similar suppression
  - Data well described by EPPS16 and nCTEQ15[1],[2],[3] shadowing predictions
- **At backward rapidity, nPDF effects alone cannot describe ψ(2S) modification**

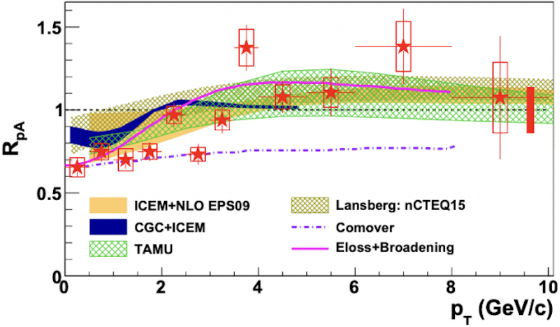
ψ(2S) to J/ψ Ratio at RHIC and LHC



- The ψ(2S) to J/ψ ratio in p+p collisions at RHIC, LHC show no clear energy dependence
- **Comparison of the p+A to p+p ratio strongly suggests final state effects** in p+A collisions at backward rapidity, as initial state effects expected to largely cancel

J/ψ in Large & Small Collisions at RHIC

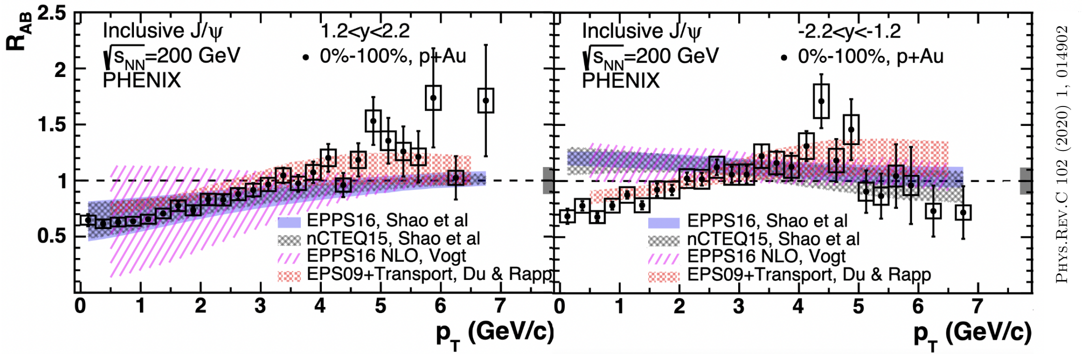




Theoretical Refs: [4],[5],[6],[7],[8],[9]
Phys.Lett.B 825 (2022) 136865

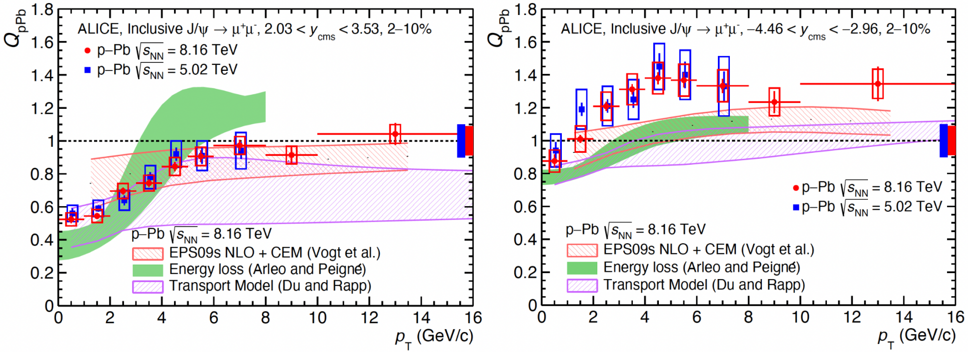
- Mid-rapidity results in AuAu and pAu are compared as a function of p_T
  - **Very different p_T dependence observed in the two collision systems**
- Inclusive J/ψ measurements in pAu collisions show suppression at low p_T
  - All models appear to describe the suppression reasonably well at low p_T

J/ψ in pAu Collisions at RHIC



- **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[12] (includes nuclear absorption effect)

J/ψ in pPb Collisions at LHC

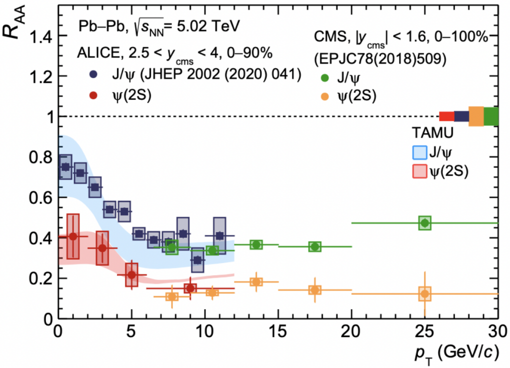


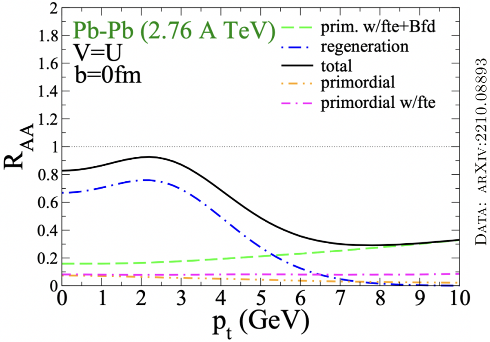
Theoretical References: [12],[13],[14]
JHEP 02 (2021) 002

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

Quarkonia in Large Systems

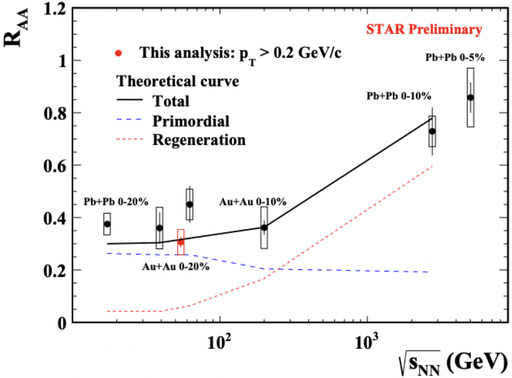
Charmonia in PbPb Collisions at LHC





- J/ψ and $\psi(2S)$ R_{AA} strongly suppressed at high p_T - consistent with CMS results
- **Transport Model predictions[15],[16] expect sizeable regeneration at LHC energies**
  - $q\bar{q}$ pairs close in phase space can recombine to form a quarkonium state

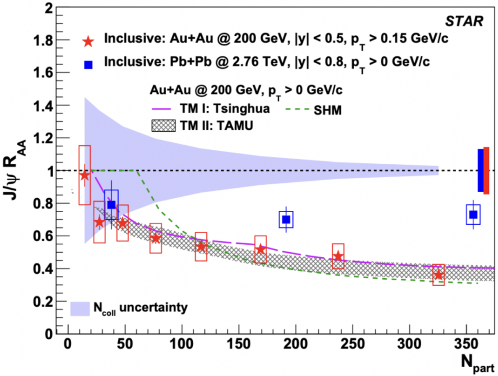
J/ψ Collision Energy Dependence

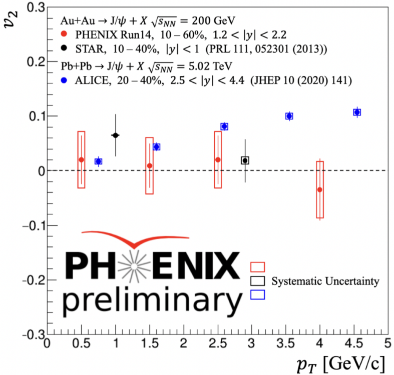


Phys. Lett. B 797 (2019) 134917
Phys. Lett. B 771 (2017) 13-20
Nucl.Phys.A 1005 (2021) 121769
Phys.Lett.B 734 (2014) 314-327

- R_{AA} shown for Au+Au collision energies at RHIC and PbPb collision energies at LHC
  - **Below 200 GeV, no strong energy dependence observed**
- Transport Model[17] with dissociation and recombination effects consistent with the data

J/ψ in AA Collisions at RHIC (LHC)

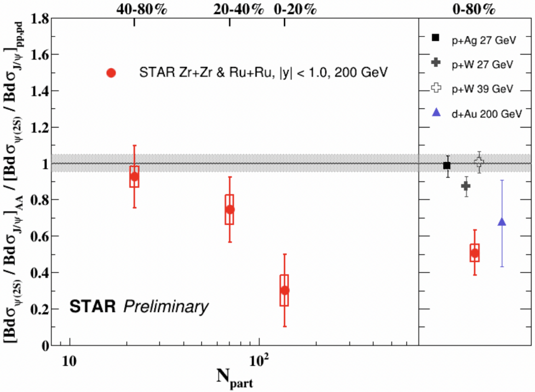




Data: Phys.Lett.B 797 (2019) 134917
Theoretical References: [18],[19],[20]

- 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 $\rightarrow$ J/ψ flow consistent with zero**

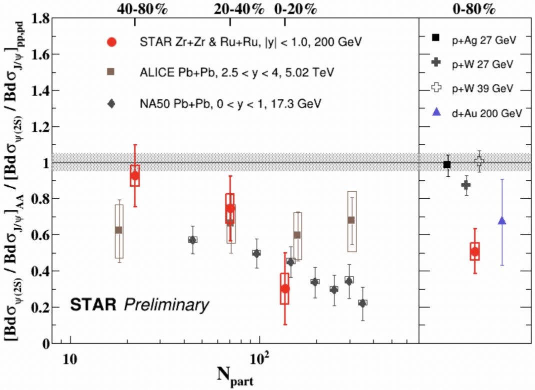
$\psi(2S)$ to J/ψ Ratio in Isobar Collisions



PHENIX: Phys.Rev.Lett. 111 (2013)
NA50: Eur.Phys.J.C 48, (2006)
STAR Run Request HERE

- **First-ever RHIC $\psi(2S)$ to J/ψ ratio in A+A collisions** shown as function of N_{part}
  - Data is compared to centrality integrated measurements from PHENIX and NA50 (p+A)
- Smaller ratio observed in Zr+Zr ($Z = 40$) & Ru+Ru ($Z = 44$) relative to p+A measurements

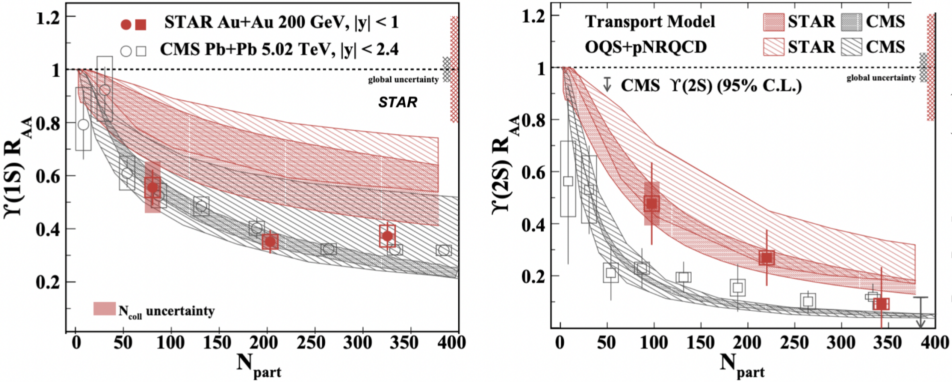
$\psi(2S)$ to J/ψ Ratio in Isobar Collisions



PHENIX: Phys.Rev.Lett. 111 (2013)
NA50: Eur.Phys.J.C 48, (2006)

- Gray shaded band represents averaged $p+p$ experimental data from PHENIX, NA50, and ISR
- STAR $\psi(2S)$ to J/ψ ratio in isobar collisions compared to ALICE and NA50 PbPb data
  - **STAR results follow similar trend as the mid-rapidity SPS measurements**

Bottomonia in Au+Au Collisions



Phys.Rev.Lett. 130 (2023) 11, 11230
Phys.Lett.B 790 (2019) 270-293
Theoretical Reference: [21],[22]

- $\Upsilon(1S)$ **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

Summary

Conclusion

Small System Collisions p+p/A

- Multiplicity dependent J/ψ varies based on η of charged particle tracks
  - PHENIX data well described by PYTHIA Detroit tune with MPI

    $\Longrightarrow$ Evidence for MPI at RHIC energies
- Essentially no low p_T J/ψ suppression at ALICE at backward rapidity

    $\Longrightarrow$ Suggests different effects contribute at RHIC compared to LHC energies

Large System Collisions A+A

- First ever RHIC measurement of ψ(2S) in A+A collisions by STAR

    $\Longrightarrow$ Centrality dependence follows similar trend as SPS measurements
- $\Upsilon(1S)$ suppression very similar at RHIC and LHC energies

    $\Longrightarrow$ Contributions from regeneration in $\Upsilon(1S)$ measurements appear small, if any

Theory References

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Probing impact-parameter dependent nuclear parton densities from double parton scatterings in heavy-ion collisions
Phys. Rev. D 101, 054036

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Gluon Shadowing in Heavy-Flavor Production at the LHC
Phys. Rev. Lett 121, 052004

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Towards an automated tool to evaluate the impact of the nuclear modification of the gluon density on quarkonium, D and B meson production in proton–nucleus collisions
Eur.Phys.J.C 77 (2017) 1, 1

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Impact parameter dependence of the nuclear modification of J/ψ production in dAu collisions at $\sqrt{s_{NN}} = 200$ GeV
Phys.Rev.C 87 (2013) 5, 054910

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Charmonium in Medium: From Correlators to Experiment
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Phys. Lett. B 678 (2009) 72–76

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Phys.Rev.C 82 (2010) 064905

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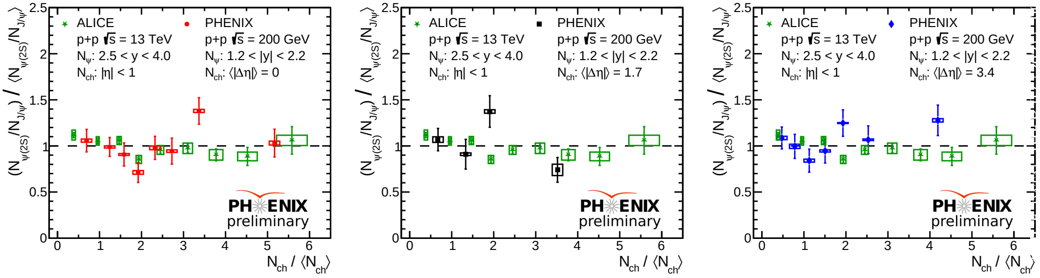
Color Screening and Regeneration of Bottomonia in High-Energy Heavy-Ion Collisions
Phys.Rev.C 96 (2017) 5, 054901

Back-Up

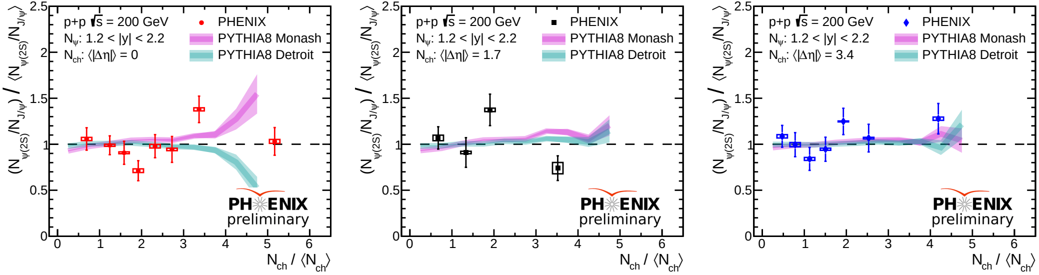
Multiplicity Dependent $\psi(2S)$ to J/ψ



ALICE: JHEP 06 (2023) 147

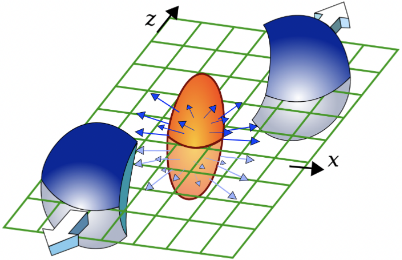
- Multiplicity-dependent studies in small systems provide a testing ground for examining the onset of QGP-like effects
- PHENIX ($\sqrt{s_{NN}}$=200 GeV) and ALICE ($\sqrt{s_{NN}}$=13 TeV) results consistent, with **weak multiplicity dependence more or less consistent with unity**
    - Note that ALICE results have charged particle multiplicity measured at mid-rapidity

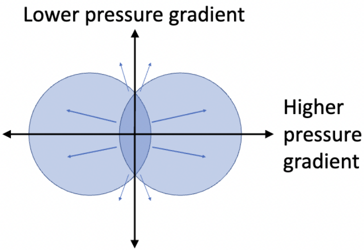
Multiplicity Dependent $\psi(2S)$ to J/ψ



- $\psi(2S)$ to J/ψ ratios shown with particle multiplicity measured in different $|\Delta\eta|$ ranges
- **Co-moving particle or QGP related final state effects appear to be small** in RHIC p+p collisions, with minimal change in ratio with increasing particle multiplicity
  - Overall, both PYTHIA tunes with MPI describe measurements well at lower multiplicity

Azimuthal anisotropy measurements





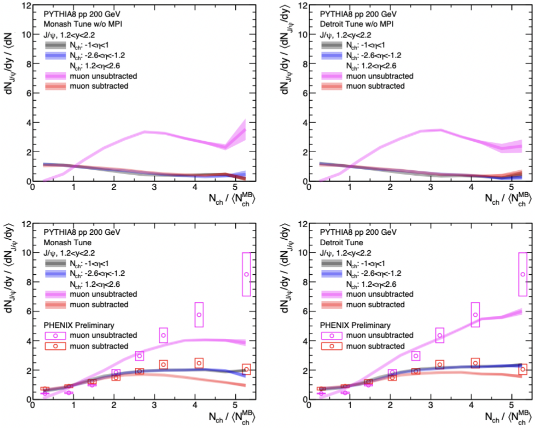
$$\frac{dN}{d\varphi} \propto 1 + \sum_{n=1}^{\infty} 2 v_n \cos n\varphi \qquad v_n = \langle \cos n\varphi \rangle \qquad \varepsilon_n = \frac{\sqrt{\langle r^n \cos n\varphi \rangle + \langle r^n \sin n\varphi \rangle}}{\langle r^n \rangle}$$

- Hydrodynamics translates initial shape (including fluctuations) into final state distribution

R. Belmont, UNCG IS 2021, 10 January 2021 - Slide 3

Credit: Ron Belmont, Initial Stages 2021

3. PHENIX Results - Comparison with PYTHIA8

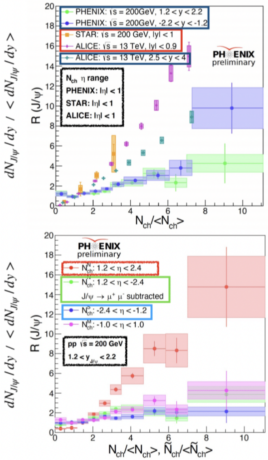


<u>Turn off the MPI effect</u>

- Multiplicity at <u>different acceptances</u> <u>and the same acceptance with subtraction</u> (red): show a <u>decreasing trend</u>
- PYTHIA with MPI can better describe the data
  <u>MPI effect is important at 200 GeV</u>
- Monash Tune for the LHC energies
  Detroit Tune for the RHIC energies
  (**Phys.Rev.D* 105 (2022) 1, 016011)
- J/ψ at forward rapidity ($1.2<y<2.2$)
  Multiplicity at <u>different (other) acceptance</u>: similar multiplicity dependence between two tunes

  Multiplicity at <u>same acceptance</u>: slightly stronger dependence in Detroit Tune at high multiplicity
- Detroit Tune shows a better agreement with the PHENIX results

Credit: Jongho Oh, ICNFP 2023



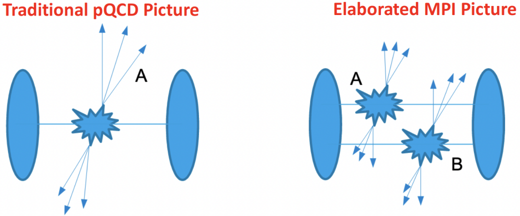
- J/ψ at mid-rapidity:
  Similar dependence between STAR* (200 GeV) and ALICE (13 TeV)
  *Tracks from J/ψ are **included** in multiplicity calculation
- J/ψ at forward rapidity:
  Stronger dependence in ALICE (13 TeV) than PHENIX** (200 GeV)
  Tracks from J/ψ are **excluded in multiplicity calculation

→**Different trends at different rapidity**
rapidity-dependent MPI?
or contribution from J/ψ to multiplicity calculation?

- Measuring J/ψ and multiplicity in the same direction:
  When including tracks from J/ψ,
  the multiplicity dependence becomes stronger
  and comparable with the ALICE results
- Measuring multiplicity in different directions:
  Similar multiplicity dependence

Credit: JongHo Oh, 2022 RHIC/AGS Annual User's Meeting

Multiparton Interactions (MPI)



- Hadronic collider at higher energy enables the phase space for MPI
  - Allow several semi-hard scatterings near the charmonium mass
- Traditional single hard scattering picture is insufficient
  - Typically 4 – 10 scatterings at LHC pp collisions
- MPI: influence charmonium production at high energy hadronic colliders
- Enhance of J/ψ production along with color reconnection model

Credit: Zhaozhong Shi, 2023 Initial Stages

Multiparton Interactions (MPI)

Hard Partonic Scattering: Energetic partons scatter off each other with large momentum transfers. In the traditional pQCD picture, it is simply described as a single hard scattering between two partons in each collision. They can be calculated analytically by pQCD with Feynman diagrams to a very high precision [20]. At RHIC, the $c\bar{c}$ pair production is dominated by gluon–gluon fusion: $gg \to c\bar{c}$.

Multiple Parton Interaction (MPI): MPI is an elaborate paradigm to describe the partonic interaction stage at high-energy colliders at RHIC, Tevatron, and the LHC [21]. According to MPI, one hard scattering, accompanied by several semi-hard interactions, takes place in each collision. All of them need to be included in the partonic scattering amplitudes. At present, high-energy hadronic colliders create more phase space for MPI to occur. Many studies at the LHC suggest MPI should be included to better describe the data [22].

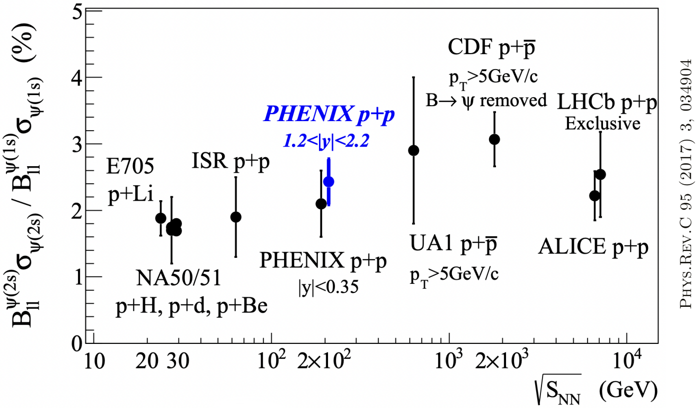
Universe 2023, 9(7), 322

The evidence for MPI comes from high p_T events observed in hadron collisions at the ISR at CERN [1] and later at the Fermilab Tevatron collider[2,3,4]. At lower p_T, underlying event (UE) observables have been measured in $p\bar{p}$ collisions in dijet and Drell-Yan events at CDF in Run I [5] and Run II [6] at center-of-mass energies of $\sqrt{s} = 1.8$ TeV and 1.96 TeV respectively, and in pp collisions at $\sqrt{s} = 900$ GeV in a detector-specific study by CMS [7].

At small transverse momentum MPI have been shown to be necessary for the successful description of the UE in Monte Carlo generators such as PYTHIA [8,9,10] or HERWIG [11,12]. Additionally, MPI are currently invoked to account for observations at hadron colliders that would not be explained otherwise: the cross sections of multi-jet production, the survival probability of large rapidity gaps in hard diffraction, etc. [13]. The wide range of phenomena in which MPI are involved highlights the urgency of a more thorough understanding of these reactions both experimentally and from a theoretical point of view.

arXiv:1111.0469v2

$\psi(2S)$ to J/ψ Ratio in $p+p$ Collisions



- The $\psi(2S)$ to J/ψ ratio in $p+p$ collisions from Tevatron, ISR, SPS, RHIC, and LHC energies
  - Up to 7000 GeV collision energy, no clear energy dependence is observed