LA-UR-22-23138

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Title:	J/psi and psi(2S) production in small systems with PHENIX
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Intended for:	Quark Matter 2022 - 29th International Conference on Ultrarelativistic Nucleus-Nucleus Collisions, 2022-04-04/2022-04-10, 2022-04-04/2022-04-10 (Krakow, Poland)
Issued:	2022-04-05

J/ψ and ψ(2S) Production in Small Systems with PHENIX

Krista Smith
for the PHENIX Collaboration

QUARK MATTER KRAKÓW 2022

Los Alamos NATIONAL LABORATORY

Krista Smith

PHENIX

Los Alamos NATIONAL LABORATORY

Motivation

ψ(2S) Final State Effects in p+A Collisions?

d+Au and p+Pb

- Strong suppression observed for ψ(2S) with respect to J/ψ
  - Would not be expected if only CNM effects are present
  - Reproduced by Co-Movers model - *Phys.Lett.B 749 (2015)*

ψ(2S) Final State Effects in p+A Collisions?

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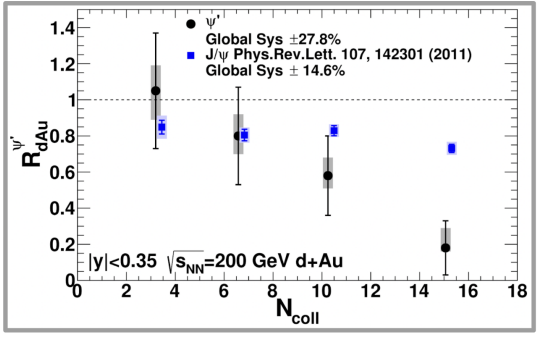

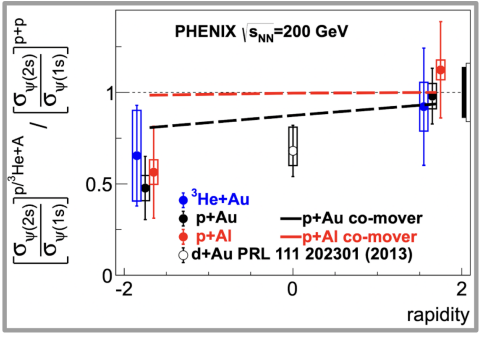

Left: PRL 111 (2013) 20, 202301. Right: PRC 95, 034904 (2017)

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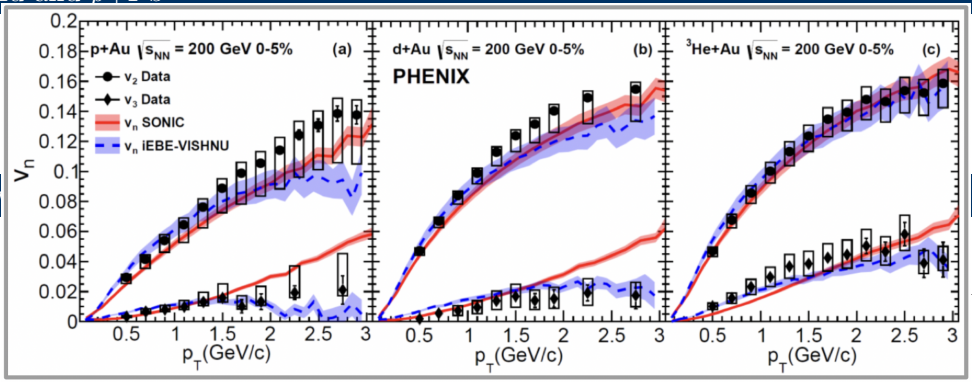
Flow in Small Systems at LHC and RHIC

- Consistent with QGP production in most central collisions

ψ(2S) Final State Effects in p+A Collisions?

d+Au and p+Pb

- Flow



Nature Phys. 15, 214 (2019)

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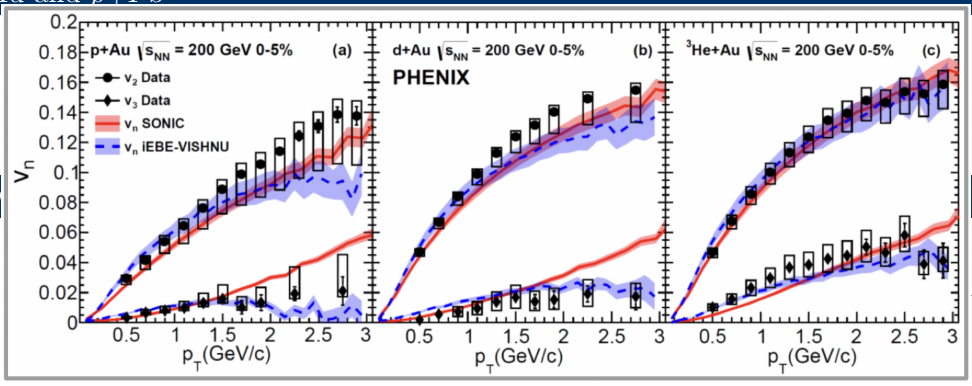

Flow

Nature Phys. 15, 214 (2019)
Results confirmed: PRC 105, 914 024901 (2022)

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Flow in Small Systems at LHC and RHIC

- Consistent with QGP production in most central collisions
  - Transport models extended to small systems and can describe the preferential ψ(2S) suppression

ψ(2S) Final State Effects in p+A Collisions?

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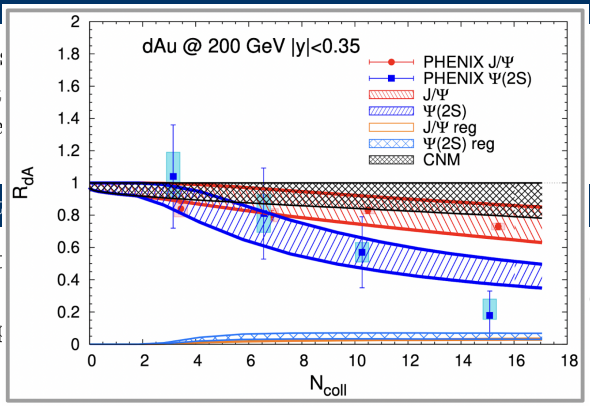

Flow in Small Syst

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JHEP 03 (2019), 015

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Flow in Small Systems at LHC and RHIC

- Consistent with QGP production in most central collisions
  - Transport models can describe the preferential ψ(2S) suppression

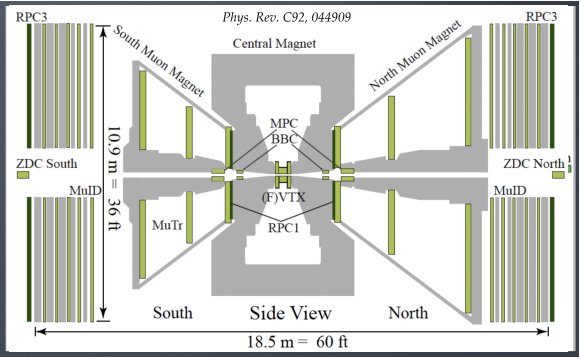
Analysis Motivation

- Look for evidence of final state effects by comparing ψ(2S) with J/ψ

PHENIX Detector: Muon Arms

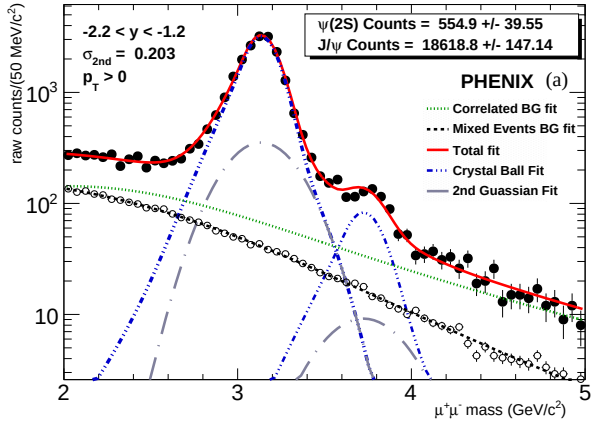
Muon Arms

- rapidity coverage: $1.2 < |y| < 2.2$
- Muon Tracking followed by Muon Identifier
  - Iron and copper absorbers for hadron rejection
- BBC measures collision vertex along beam axis



- All dimuon hits recorded in coincidence with BBC Minimum Bias trigger
- Centrality is measured using the BBC detector in the A-going direction
- PHENIX includes two tracking detectors in Muon Arms: MuTr and FVTX

Reconstructed Dimuon Mass Distribution



- 2015 p+p data set at $\sqrt{s}$ =200 GeV
  - Mixed events background
    - Estimate of combinatorial background
- Correlated background
  - Open heavy flavor, Drell Yan, etc.
- Gaussian fit to high-mass tail
  - MuTr-FVTX misassociated tracks
- J/ψ, ψ(2S) Crystal Ball fits
- Total fit

*Paper submitted to PRC (**arXiv:2202.03863**)*

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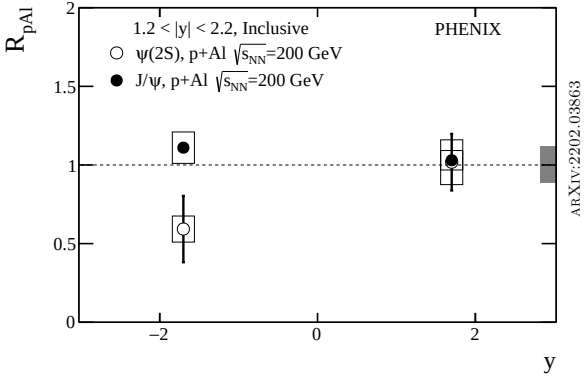
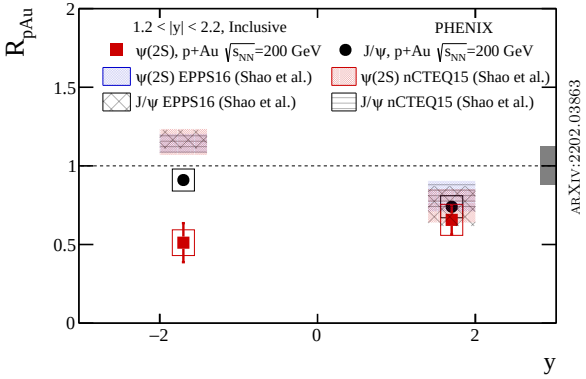
J/ψ and ψ(2S) Results

Charmonia Nuclear Modification in p+Al Collisions



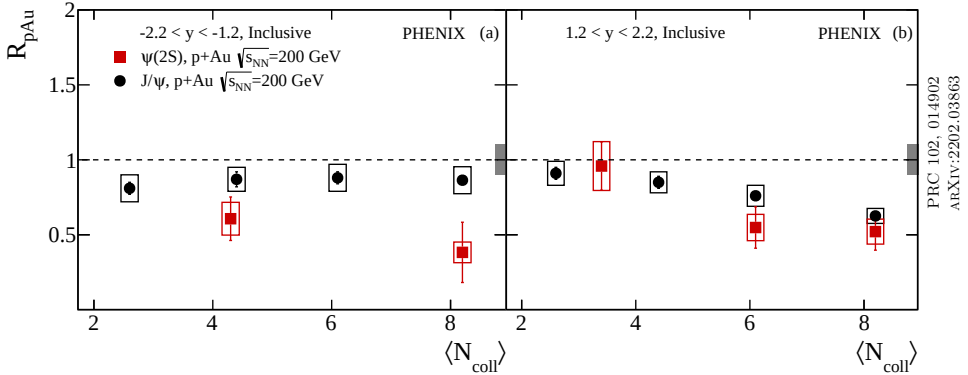
- At forward rapidity, J/ψ and ψ(2S) modification consistent with unity
- At backward rapidity, nuclear absorption cannot explain suppression in ψ(2S) modification
  - ψ(2S) suppression could be due to final state effects, however error bars sizeable

Charmonia Nuclear Modification in p+Au Collisions



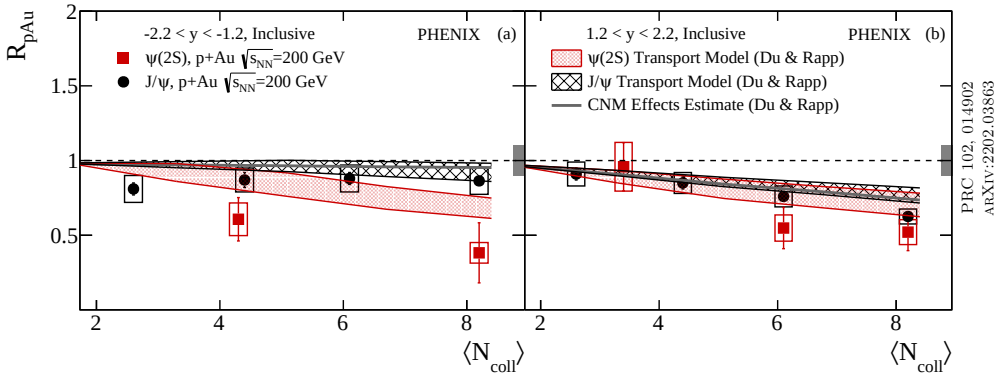
- At forward rapidity, J/ψ and ψ(2S) modification show similar suppression
  - Data well described by EPPS16 and nCTEQ15 shadowing predictions
- At backward rapidity, shadowing effects alone cannot describe ψ(2S) modification

Charmonia Nuclear Modification in p+Au Collisions



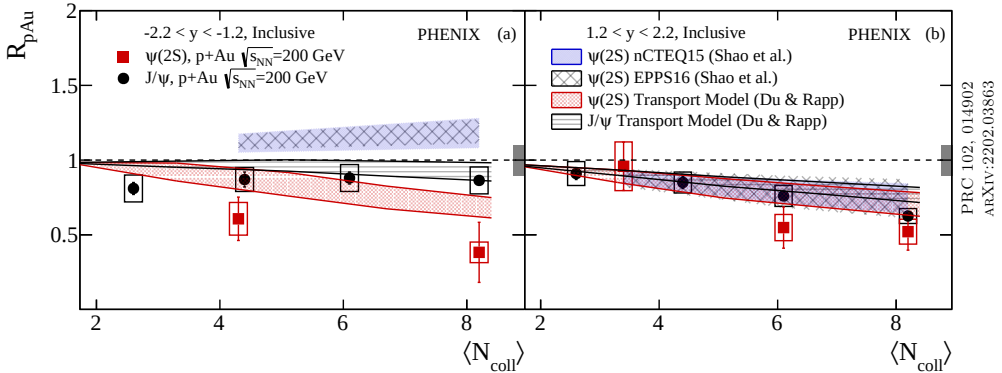
- At forward rapidity, J/ψ and ψ(2S) modification follow similar trend
  - Would be expected if cold nuclear matter effects dominate
- At backward rapidity, clear difference in ψ(2S) modification in most central collisions

Charmonia Nuclear Modification in p+Au Collisions



- Cold nuclear matter estimate shown at both rapidities
- Largest contribution to Transport Model at forward rapidity from EPS09 shadowing
- At backward rapidity, model predicts stronger hot nuclear matter effects for ψ(2S) state

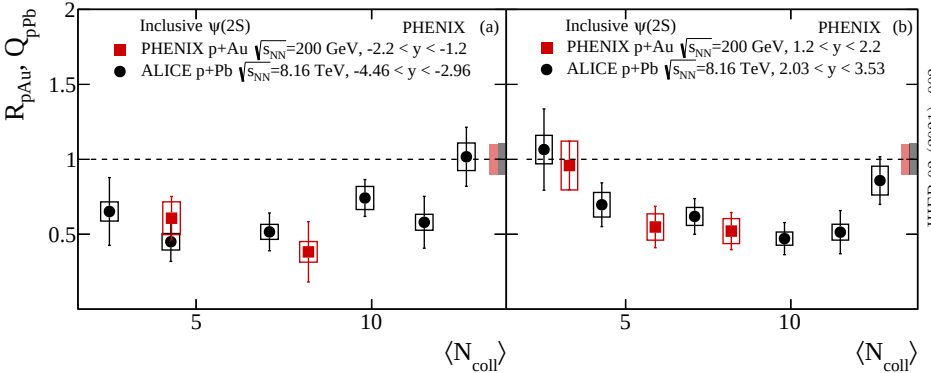
Charmonia Nuclear Modification in p+Au Collisions



PRC 102, 014902
ARXIV:2202.03863

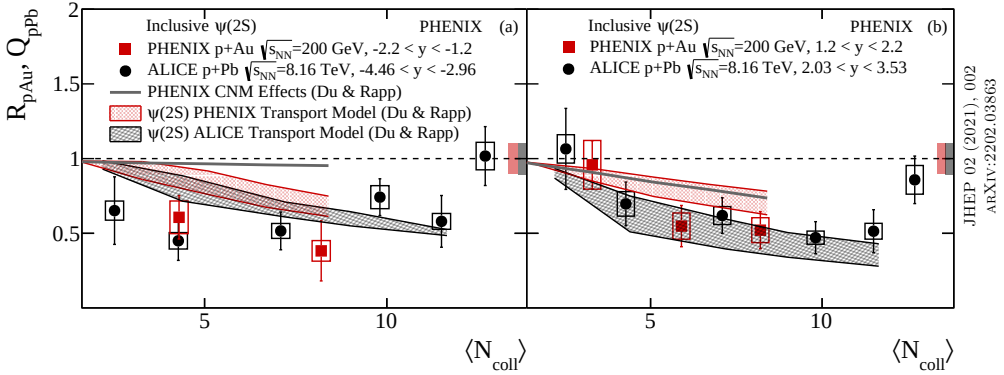
- At forward rapidity, J/ψ and ψ(2S) modification well described by shadowing models
  - Consistent with cold nuclear matter effects
- At backward rapidity, charmonium inconsistent with shadowing effects alone

ψ(2S) Nuclear Modification at RHIC and LHC



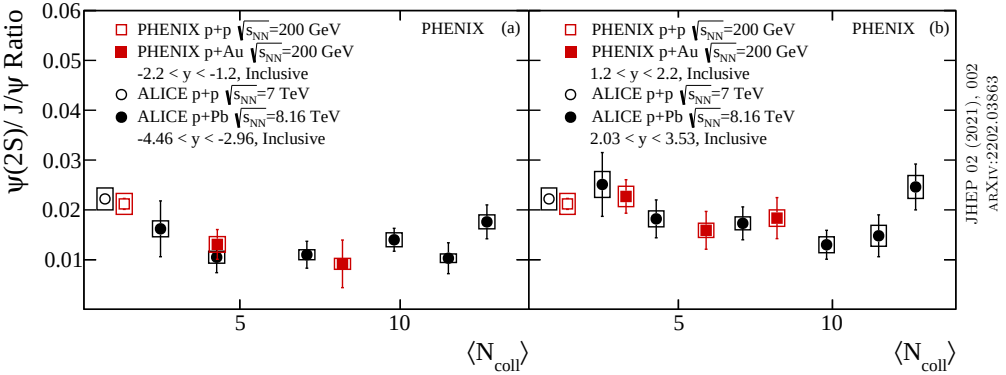
- Initial state effects expected to be different at RHIC and LHC energies
  - Larger mean p_T values at LHC lead to higher Q^2 values; different Bjorken-x probed
- Similar ψ(2S) modification seen between experiments at backward rapidity

ψ(2S) Nuclear Modification at RHIC and LHC



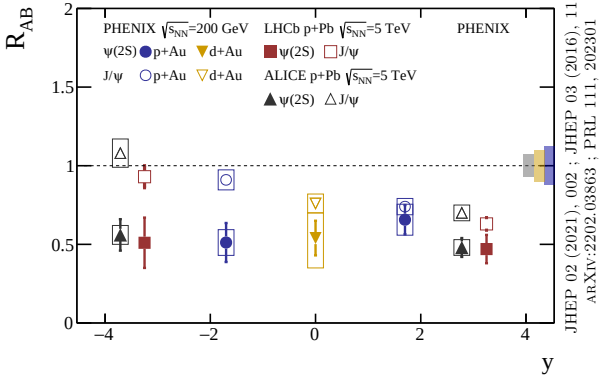
- Initial state effects expected to be different at RHIC and LHC energies
  - Larger mean p_T values at LHC lead to higher Q^2 values; different Bjorken-x probed
- Both transport models at backward rapidity predict similar degree of suppression

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 the presence of final state effects in p+A collisions at backward rapidity, as initial state effects expected to largely cancel

Charmonium Modification at RHIC and LHC



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

Conclusion

1. Nuclear absorption cannot explain $\psi(2S)$ suppression at backward rapidity in p+Al collisions
2. **At forward rapidity, PHENIX J/ψ, ψ(2S) modification consistent with EPPS16, nCTEQ15 shadowing predictions**
3. Final state effects on charmonium states appear very similar at RHIC, LHC energies
4. **Comparison of ψ(2S) to J/ψ ratio in p+A versus p+p collisions strongly suggests presence of final state effects in p+A collisions at backward rapidity**


QM
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KRAKÓW
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29TH INTERNATIONAL
CONFERENCE ON ULTRARELATIVISTIC
NUCLEUS - NUCLEUS COLLISIONS
APRIL 4-10, 2022
KRAKÓW, POLAND

Back-Up

Theory References

[1] Shao, Hua-Sheng
Probing impact-parameter dependent nuclear parton densities from double parton scatterings in heavy-ion collisions
Phys. Rev. D 101, 054036

[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, 052004

[3] Lansberg, Jean-Philippe and Shao, Hua-Sheng
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. C77, 2017

[4] Du, Xiaojian and Rapp, Ralf
In-Medium Charmonium Production in Proton-Nucleus Collisions
JHEP 03, 015

[5] Du, Xiaojian and Rapp, Ralf
Sequential Regeneration of Charmonia in Heavy-Ion Collisions
Nucl. Phys. A943, 2015

Model Overview

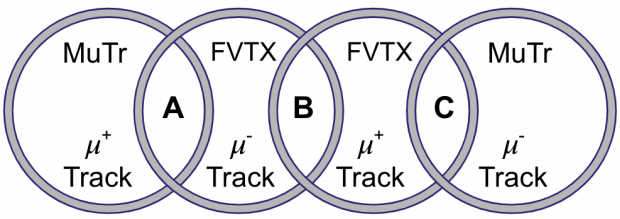
nCTEQ15 and EPPS16 NLO (Shao, et. al.) PRL 121, 052004

- Reweighted using LHC p+Pb data
  - Gives tighter J/ψ constraints
- Centrality integrated only
  - Impact-parameter dependent nPDFs included in PRD 101, 054036

EPS09 NLO + Transport Model (Du & Rapp) JHEP 03, 015

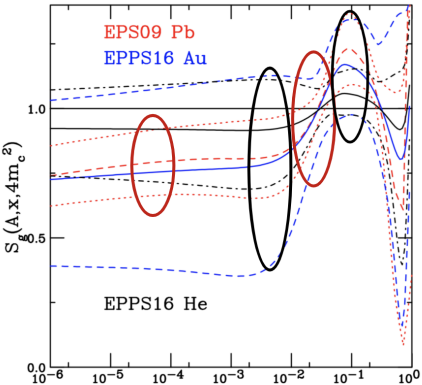
- Includes fireball, MC Glauber for initial conditions
- p_T broadening included
- Backward rapidity: Nuclear absorption added

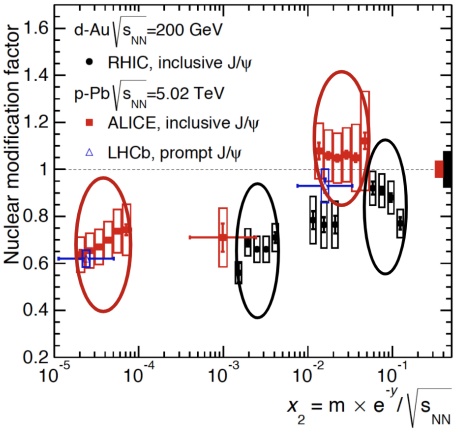
Combining MuTr and FVTX Tracks



- The FVTX detector provides additional space points near the collision vertex
  - Located upstream from hadron absorbers, FVTX improves dimuon mass resolution
- New track reconstruction method for ψ(2S) results at $1.2 < |y| < 2.2$
  - One muon track has momentum determined by the FVTX detector, and the other track has momentum determined by the MuTr detector (A and C)
- For better statistics, at least one track associated with the FVTX was required (A, B, and C)

PHENIX vs. ALICE Bjorken-x

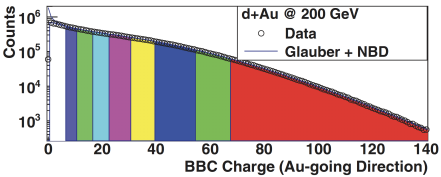


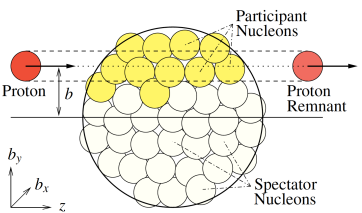


Left: R. Vogt. Right: Eur.Phys.J.C 76 3, 107. Encircled Bjorken-x values not original to either plot.

Centrality Categorization

- Centrality is characterized using the BBC counter, where events are ranked by total charge produced
- However, impact parameter and total number of nucleons involved in a collision cannot be experimentally measured
- A model was developed by Roy Glauber to describe the scattering between high energy composite particles, known as a Glauber Model
  - $\langle N_{coll} \rangle$ average number of binary collisions and depends on average thickness of target
  - c_{BBC} corrects for the bias towards larger charge in the BBC for hard scattering events





Top: Phys. 1019 Rev. C 90, 034902, and bottom, M. Bruinsma (Utrecht U.)

Inclusive ψ(2S) Results in Small Systems

- 2003, 2008 d+Au at $\sqrt{s_{NN}} = 200$ GeV

  PHENIX added 3 new small systems data sets

- 2014 ^{3}He+Au at $\sqrt{s_{NN}} = 200$ GeV
- 2015 p+p, p+Al, p+Au at $\sqrt{s_{NN}} = 200$ GeV

PHENIX has measured inclusive $\psi(2S) \rightarrow \mu^+\mu^-$ nuclear modification in p+Al and p+Au collision systems at $1.2 < |y| < 2.2$.

This analysis builds on recent results of $J/\psi \rightarrow \mu^+\mu^-$ nuclear modification measurements.