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

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for the PHENIX Collaboration

QUARK MATTER KRAKÓW 2022

Los Alamos NATIONAL LABORATORY


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

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)*

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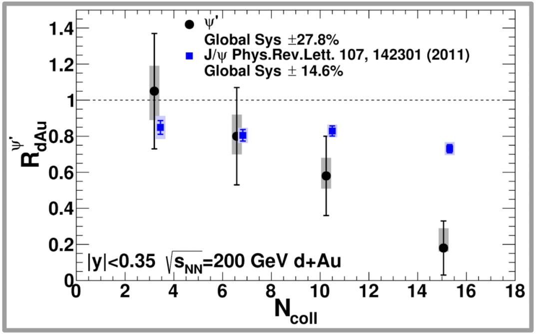

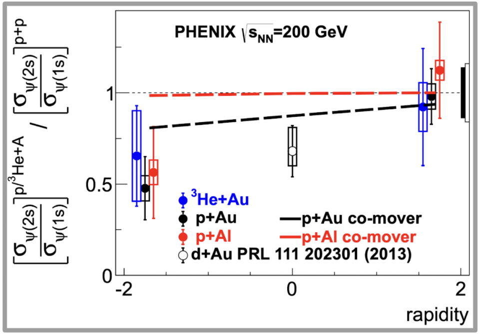

Left: PRL 111 (2013) 20, 202301. Right: PRC 95, 034904 (2017)

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Flow in Small Systems at LHC and RHIC

- Consistent with QGP production in most central collisions

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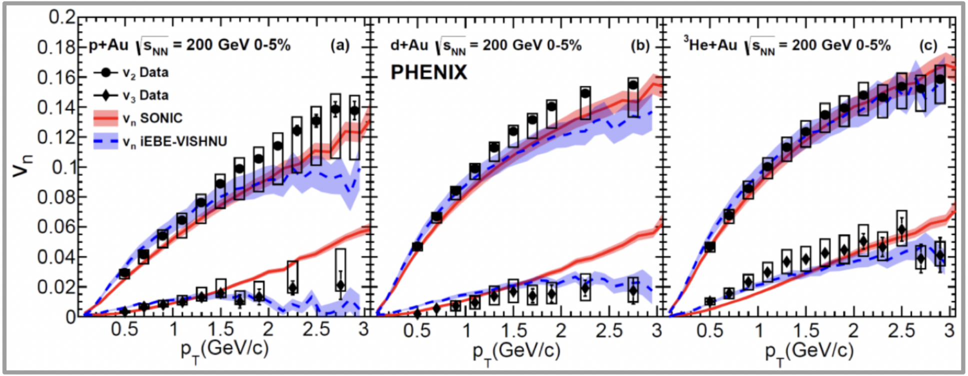

Flow

Nature Phys. 15, 214 (2019)

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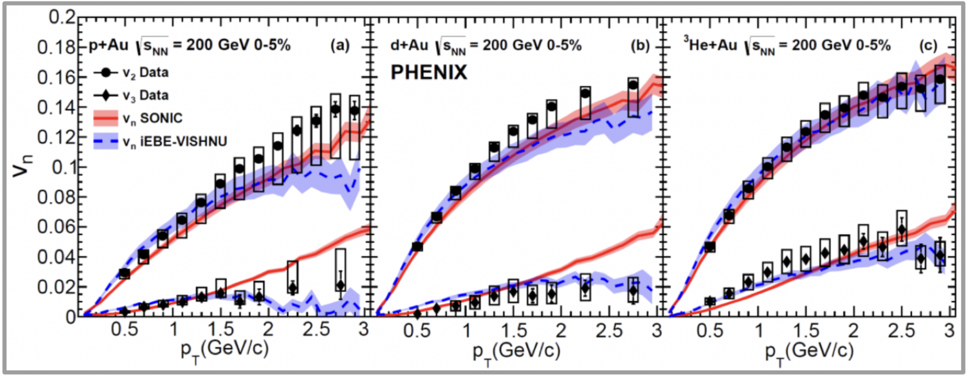

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Results confirmed: PRC 105, 914 024901 (2022)

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

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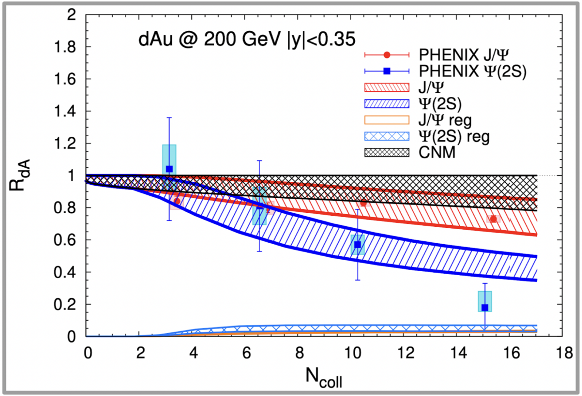

JHEP 03 (2019), 015

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  - Transport models can describe the preferential ψ(2S) suppression

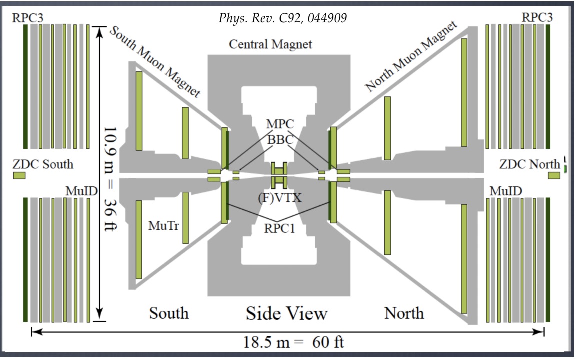
Analysis Motivation

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

PHENIX Detector: Muon Arms

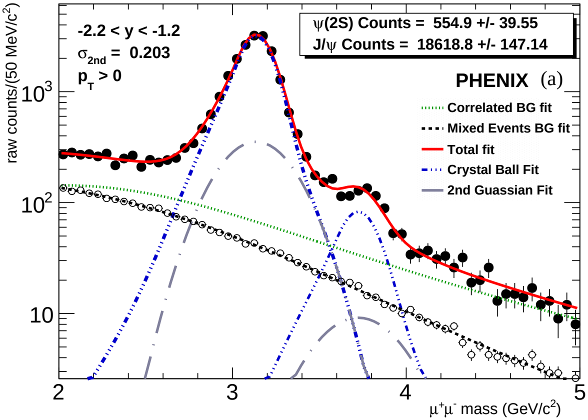
Muon Arms

- 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

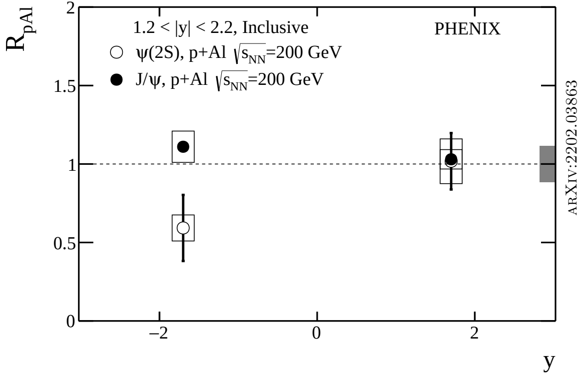


- 2015 p+p data set at $\sqrt{s}$ =200 GeV
- Mixed events background
  - Estimate of combinatorial background
- Correlated background
  - Open heavy flavor, Drell Yan, etc.
- Gaussian fit to high-mass tail
  - MuTr-FVTX misassociated tracks
- J/ψ, $\psi(2S)$ Crystal Ball fits
- Total fit

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

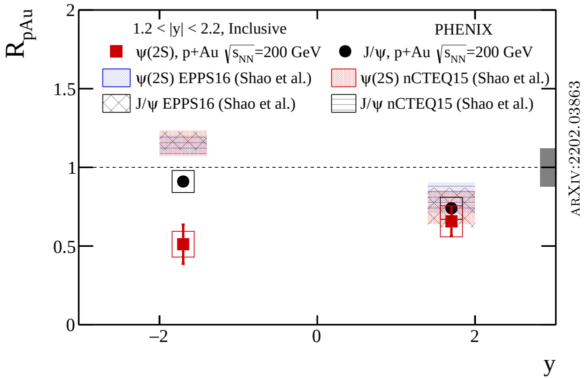
J/ψ and $\psi(2S)$ Results

Charmonia Nuclear Modification in p+Al Collisions



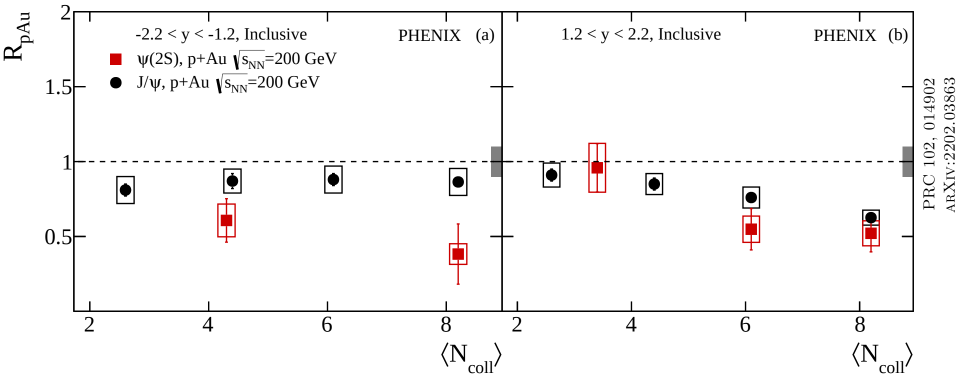
- At forward rapidity, J/ψ and $\psi(2S)$ modification consistent with unity
- At backward rapidity, nuclear absorption cannot explain suppression in $\psi(2S)$ modification
  - $\psi(2S)$ suppression could be due to final state effects, however error bars sizeable

Charmonia Nuclear Modification in p+Au Collisions



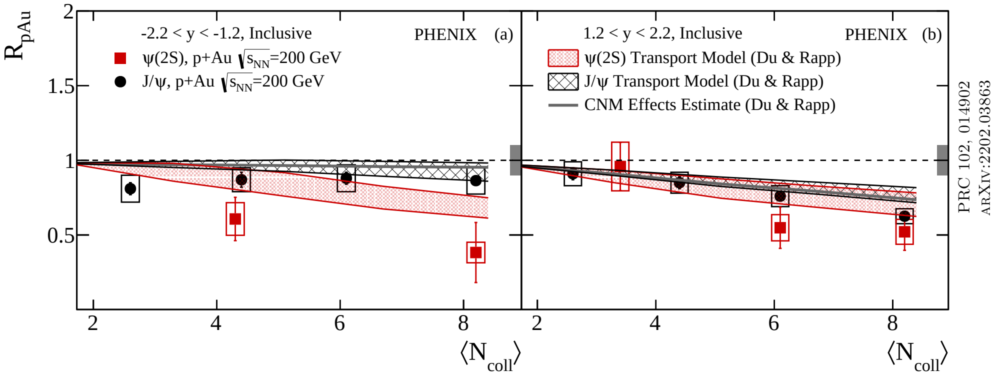
- At forward rapidity, J/ψ and ψ(2S) modification show similar suppression
  - Data well described by EPPS16 and nCTEQ15 shadowing predictions
- At backward rapidity, nPDF effects alone cannot describe ψ(2S) modification

Charmonia Nuclear Modification in p+Au Collisions



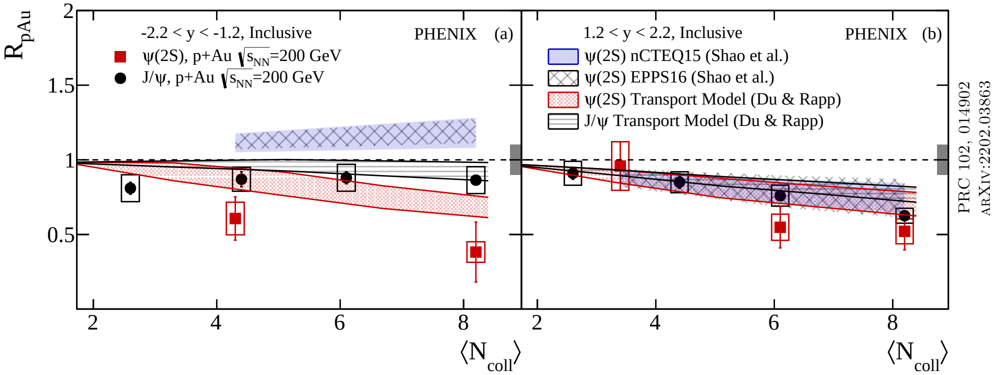
- At forward rapidity, J/ψ and $\psi(2S)$ modification follow similar trend
  - Would be expected if cold nuclear matter effects dominate
- At backward rapidity, clear difference in $\psi(2S)$ modification in most central collisions

Charmonia Nuclear Modification in p+Au Collisions



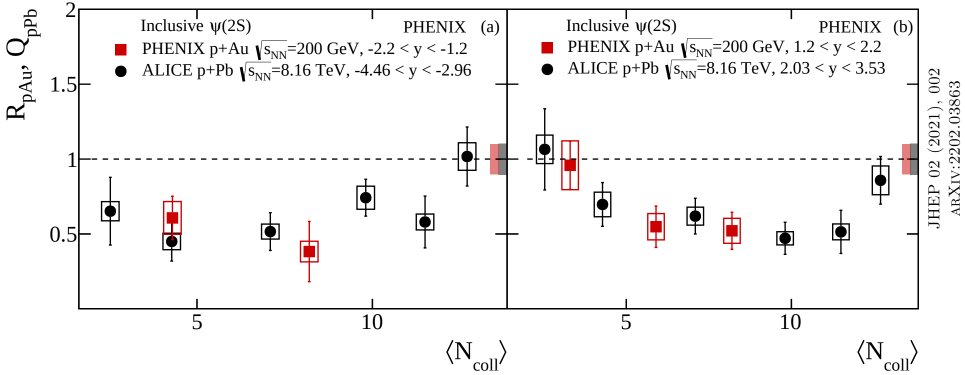
- Cold nuclear matter estimate shown at both rapidities
- Largest contribution to Transport Model at forward rapidity from EPS09 shadowing
- At backward rapidity, model predicts stronger hot nuclear matter effects for $\psi(2S)$ state

Charmonia Nuclear Modification in p+Au Collisions



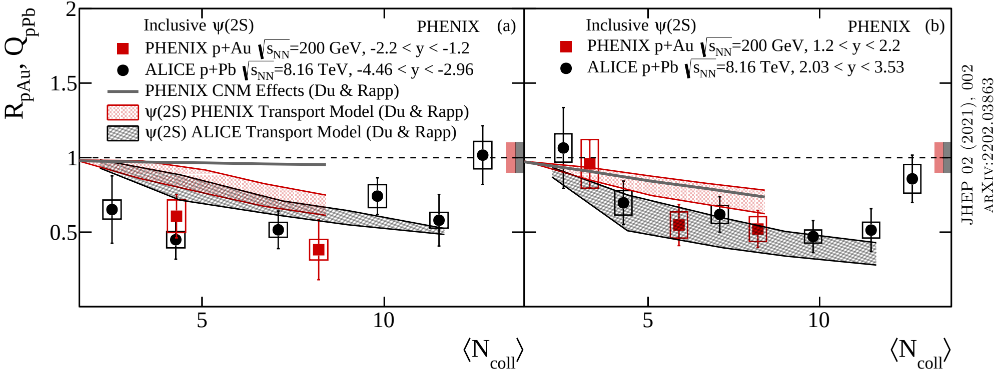
- At forward rapidity, J/ψ and ψ(2S) modification well described by shadowing models
  - Consistent with cold nuclear matter effects
- At backward rapidity, charmonium inconsistent with shadowing effects alone

ψ(2S) Nuclear Modification at RHIC and LHC



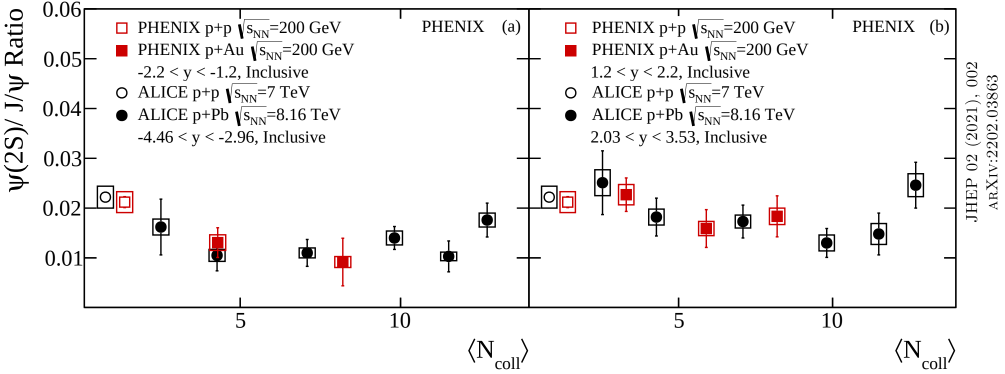
- Initial state effects expected to be different at RHIC and LHC energies
  - Larger mean p_T values at LHC lead to higher Q^2 values; different Bjorken-x probed
- Similar $\psi(2S)$ modification seen between experiments at backward rapidity

ψ(2S) Nuclear Modification at RHIC and LHC



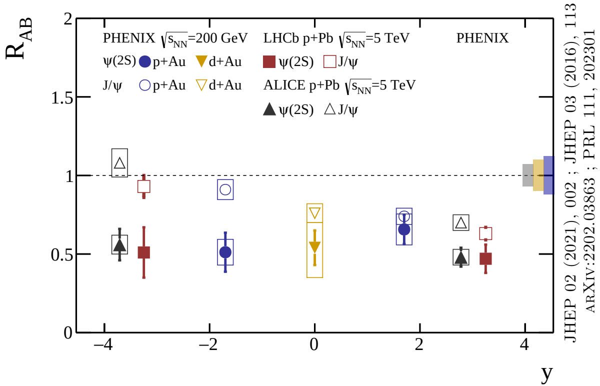
- Initial state effects expected to be different at RHIC and LHC energies
  - Larger mean p_T values at LHC lead to higher Q^2 values; different Bjorken-x probed
- Both transport models at backward rapidity predict similar degree of suppression

$\psi(2S)$ to J/ψ Ratio at RHIC and LHC



- The $\psi(2S)$ 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 ψ(2S) suppression at backward rapidity in p+A 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**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Back-Up

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

[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

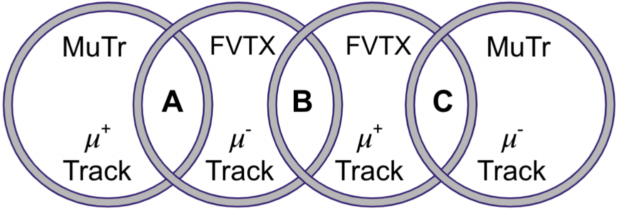
nCTEQ15 and EPPS16 NLO (Shao, et. al.) PRL 121, 052004

- 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

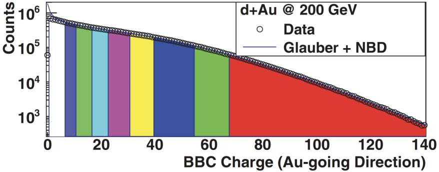
Combining MuTr and FVTX Tracks

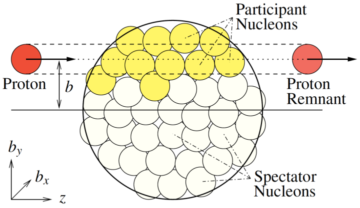


- The FVTX detector provides additional space points near the collision vertex
  - Located upstream from hadron absorbers, FVTX improves dimuon mass resolution
- New track reconstruction method for ψ(2S) results at $1.2 < |y| < 2.2$
  - One muon track has momentum determined by the FVTX detector, and 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)

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.