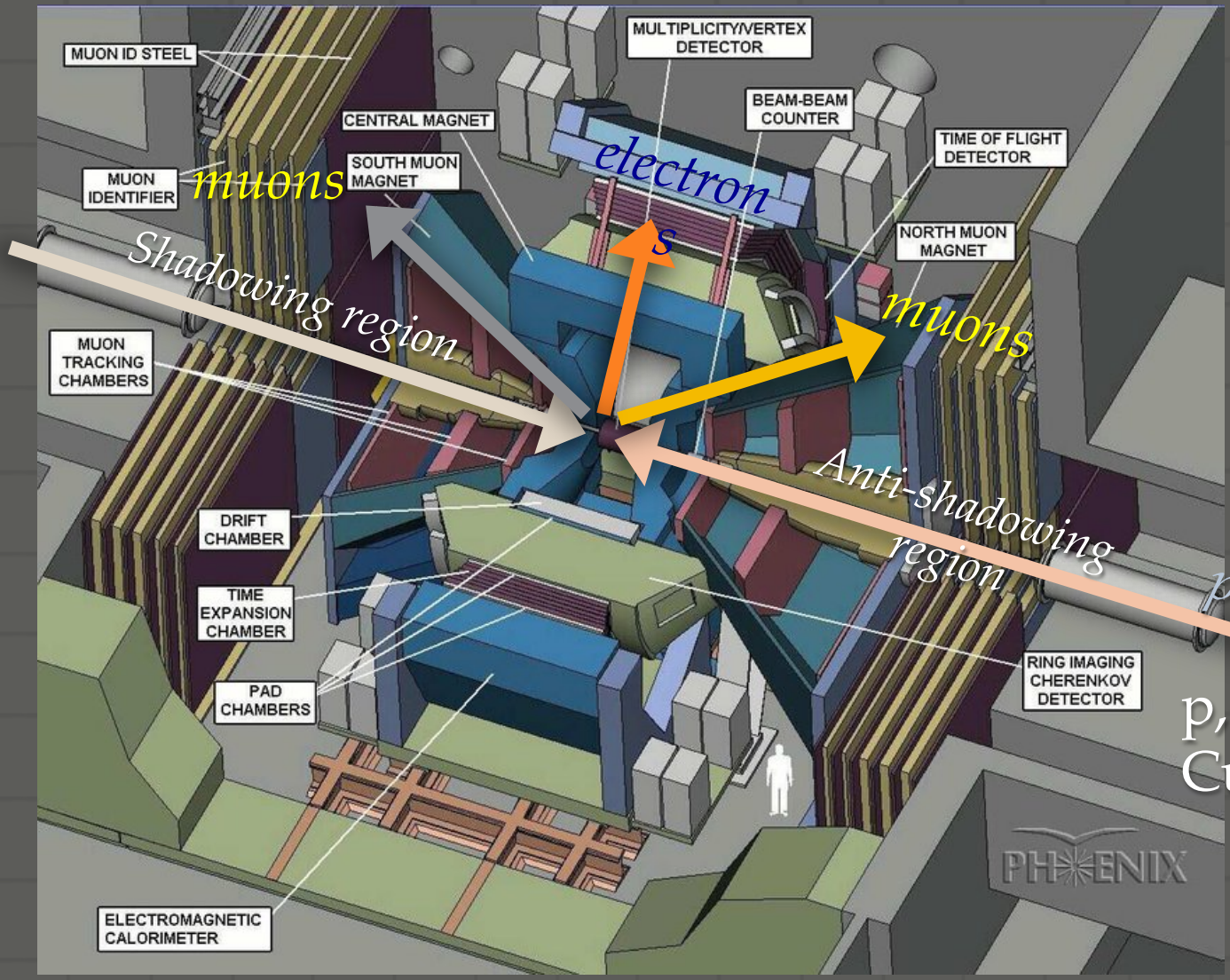
# Quarkonia Measurements from PHENIX

Krista Smith,
Florida State University,
for the PHENIX Collaboration


# PHENIX Detector

target

Al, Cu,
Au, U




projectile

p, d, $^3$He,
Cu, Au, U

# This talk will focus on new p/$^3$He+A results from the muon arms at forward and backward rapidity

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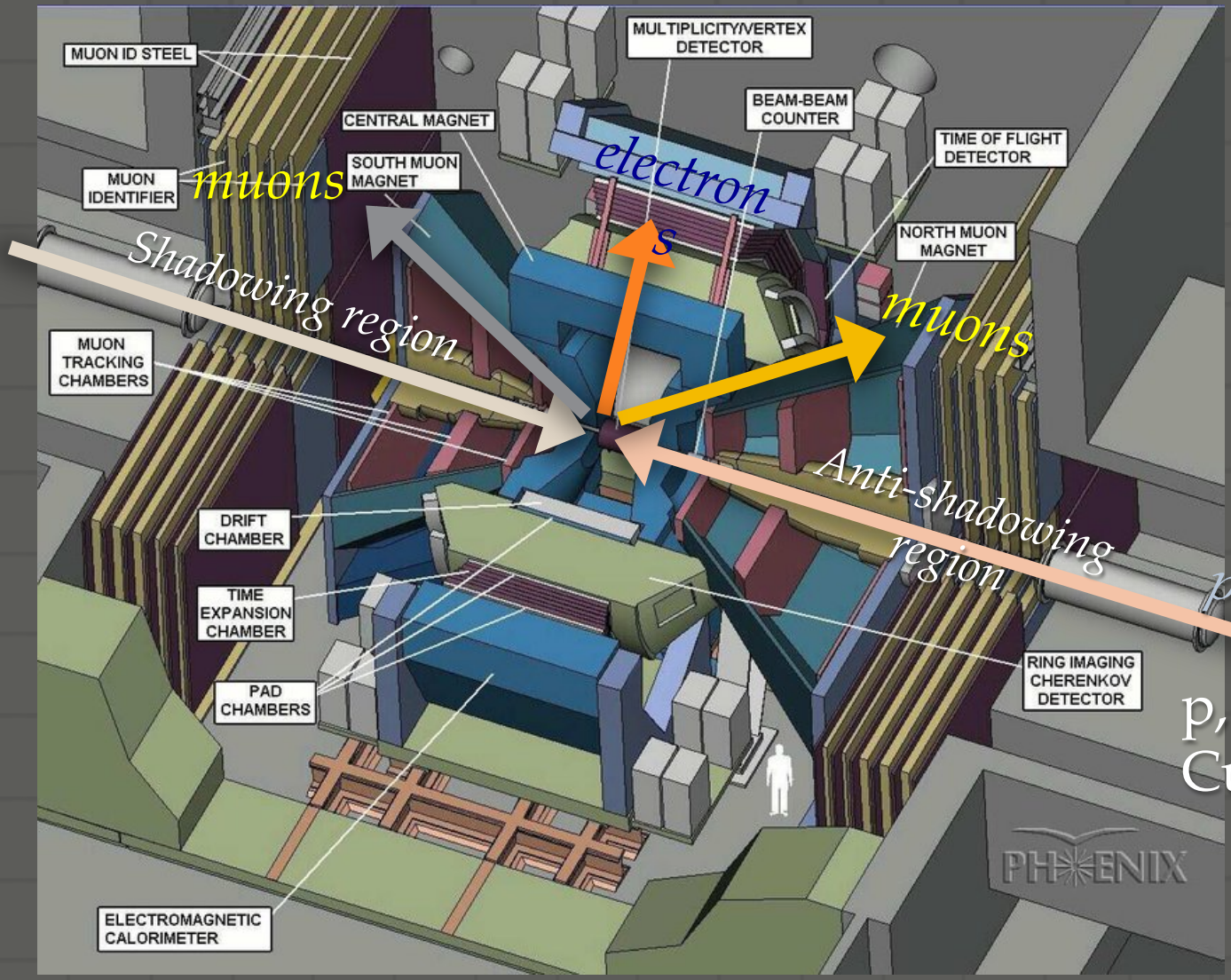
Al, Cu, Au, U




projectile

p, d, $^3$He, Cu, Au, U

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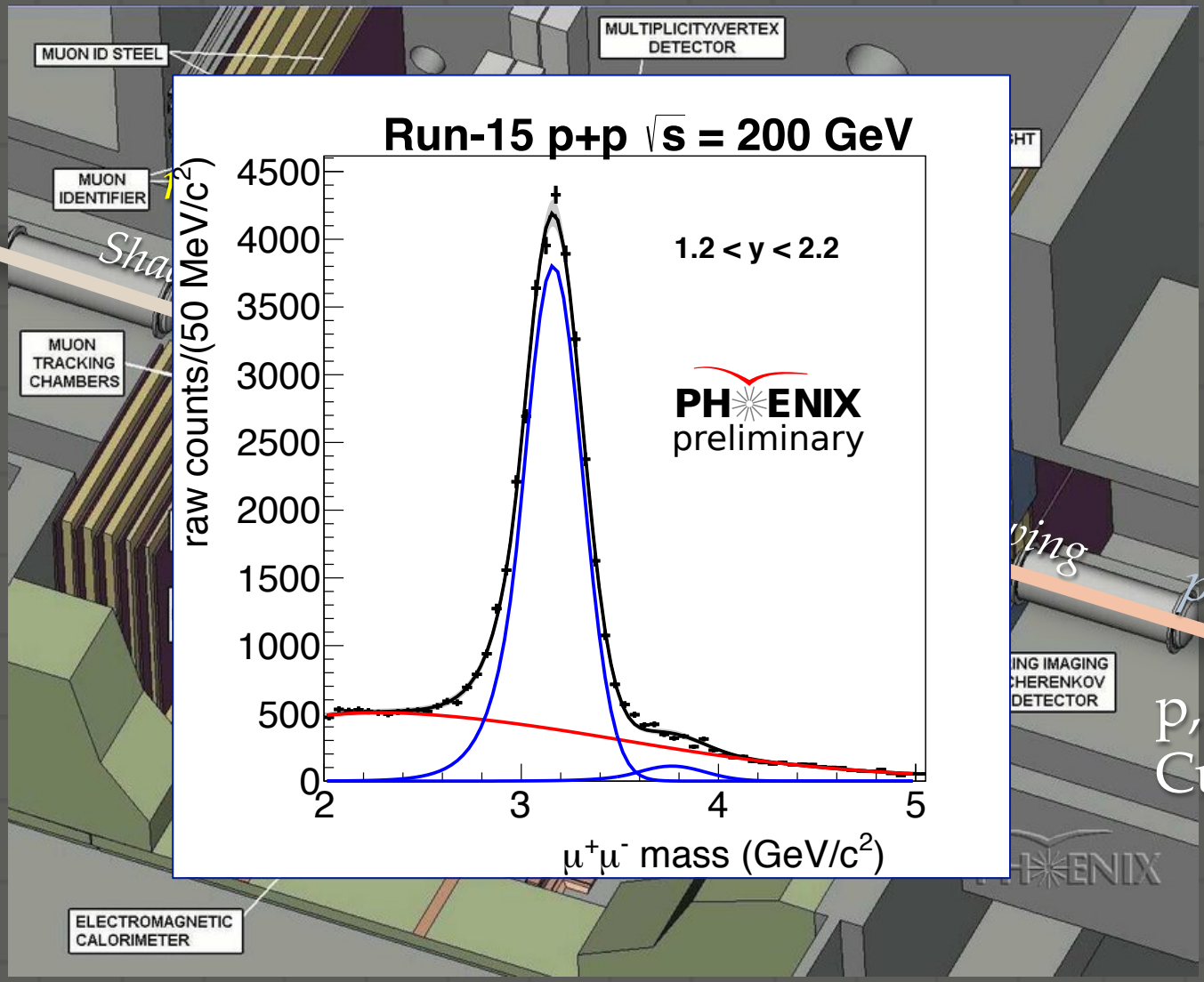


projectile

p, d, $^3$He, Cu, Au, U

# Why Small Systems?

- High luminosity study of d+Au collisions in 2008
- Significant rapidity, centrality and $p_T$ dependent modifications were seen in d+Au collisions, attributed to various Cold Nuclear Matter effects
- However, more recently the question arose whether the QGP is also being formed in small systems
- Led to study of several small systems in 2014 and 2015, including J/$\psi$ production vs. rapidity, centrality and $p_T$

# PHENIX Run History

progresses from larger systems → smaller systems

| Species | Run Year |
|---|---|
| Au+Au | 2001, 2002, 2004, 2007, 2008, 2010, 2011, 2014, 2016 |
| d+Au | 2003, 2008, 2016 |
| Cu+Cu | 2005 |
| U+U | 2012 |
| Cu+Au | 2012 |
| $^{3}$He+Au | 2014 |
| p+Au | 2015 |
| p+Al | 2015 |

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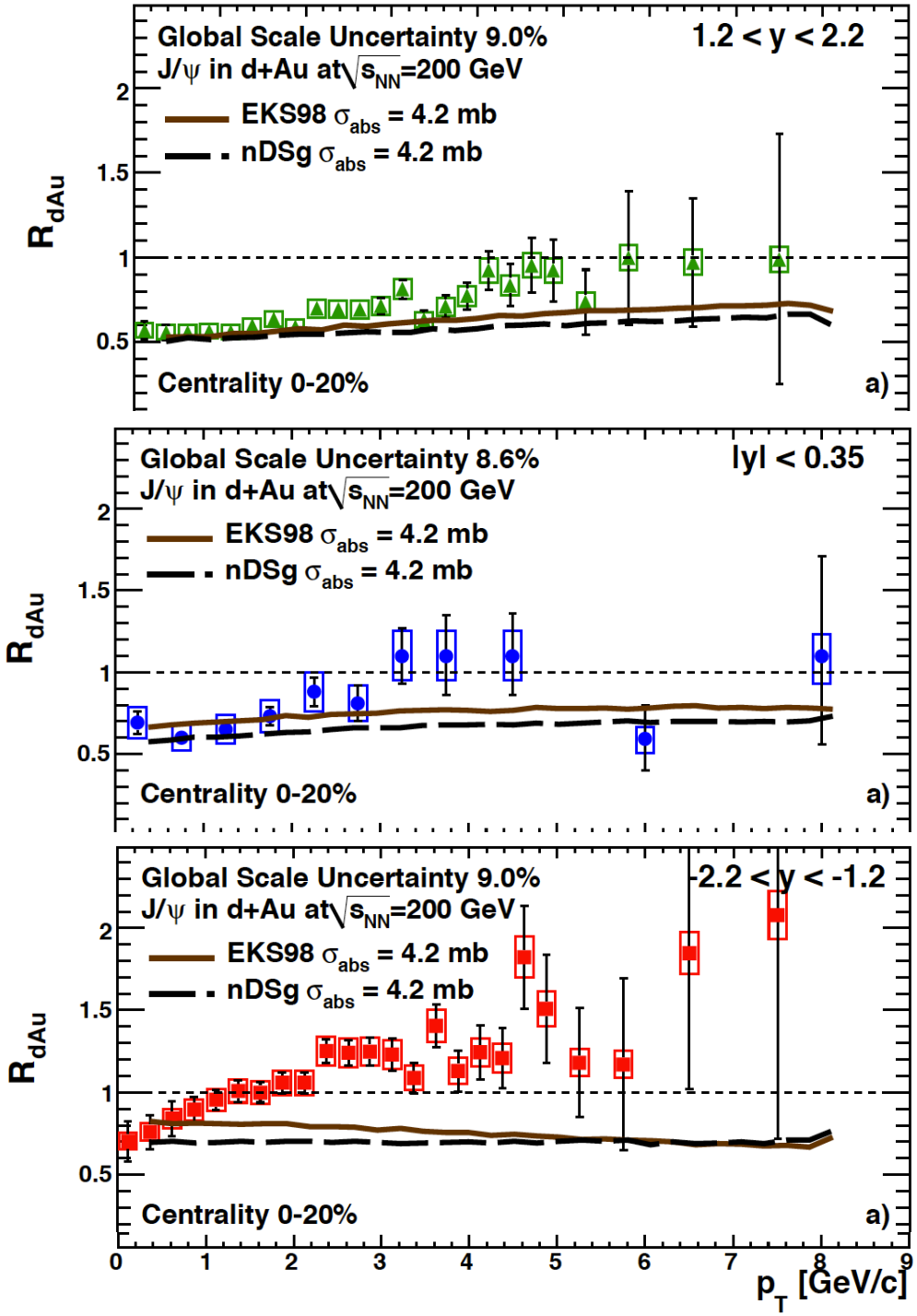
| $^{3}$He+Au | 2014 |
| p+Au | 2015 |
| p+Al | 2015 |




# d+Au (2008 Run) Results

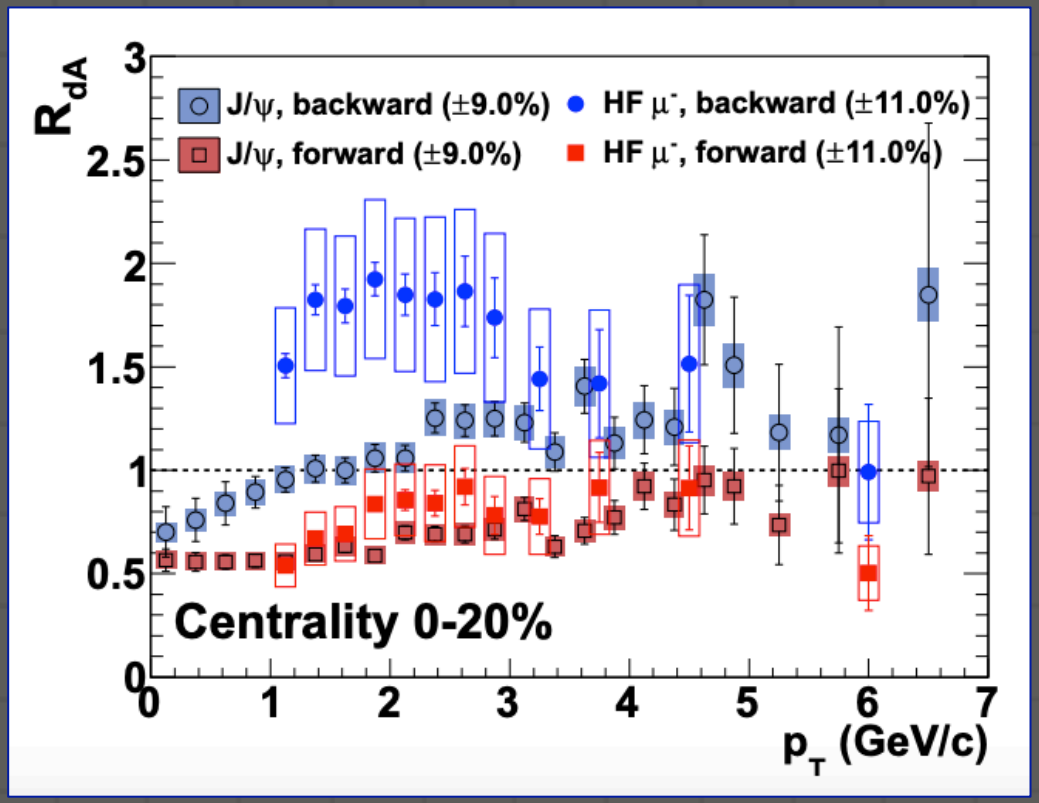
*Phys. Rev. C 87, 034904 (2013)*

- Color screening (final state effect) was not expected to be a factor in d+Au
- Study was intended to show cold nuclear matter effects
- 2008 Run has 30-50 times increase in statistics compared with 2003 Run

*0-20% Centrality Shown*

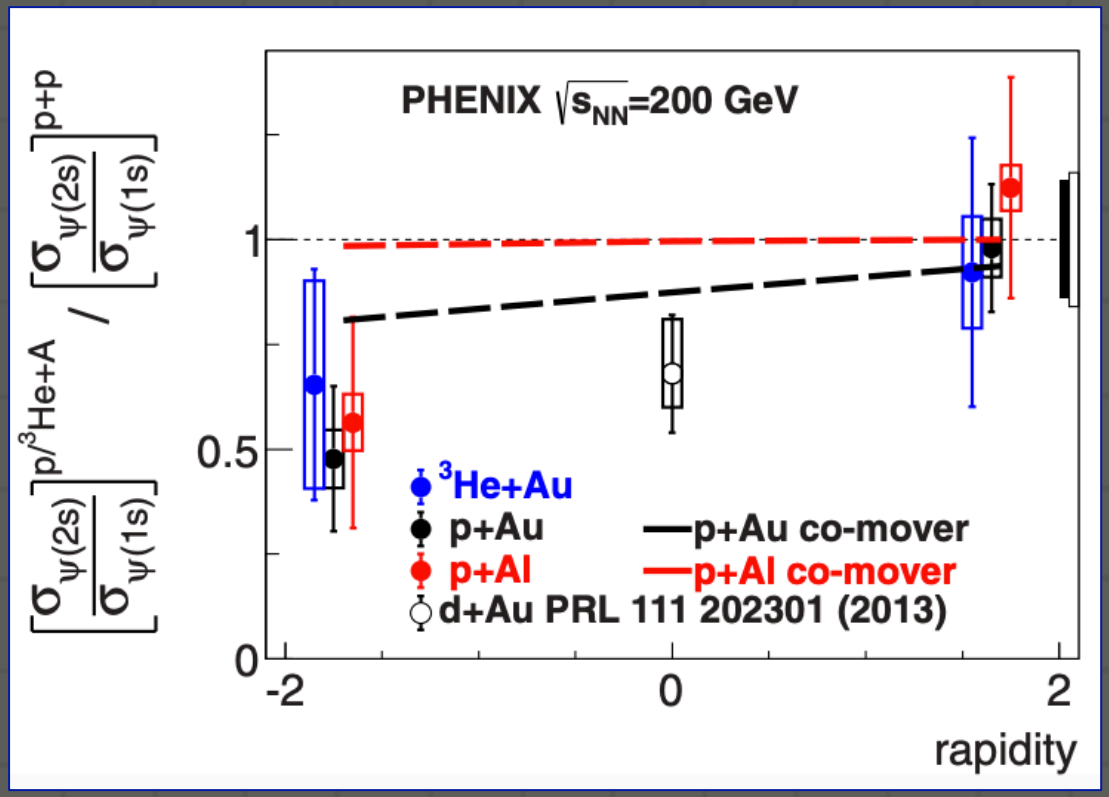
# Comparison with Open Heavy Flavor Production

- 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 break up due to collisions with nucleons in the target
  - Possible contribution also from co-movers in final state




*Phys. Rev. Lett. 112, 252301*

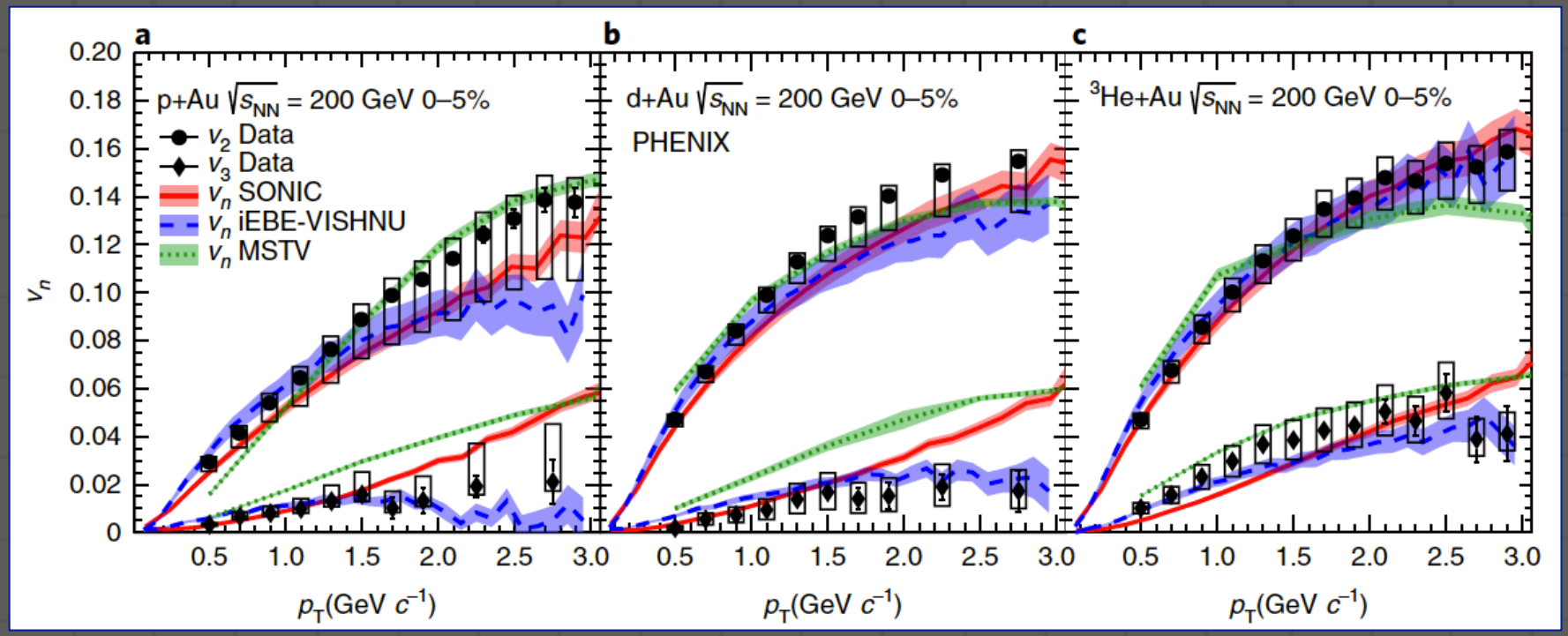
# Also: ψ′ More Suppressed




*Phys. Rev C 95, 034904 (2017)*

- ψ(2s) more strongly suppressed than the J/ψ at backward rapidity for p+Au
- Curves from co-mover model
- Indication of final state effects that differentially suppress weakly bound ψ′ ?

# Evidence of Hydrodynamic Behavior in small systems




*Nature: s41567_018_0360_0*

Most central (0-5%) p+Au, d+Au and $^3$He+Au $v_{2,3}$ measurements consistent with hydrodynamic flow → QGP formed in small systems!

# Comparison of Small Systems Data Sets

d+Au – Run8

$^{3}$He+Au – Run14

p+p – Run15

p+Al – Run15

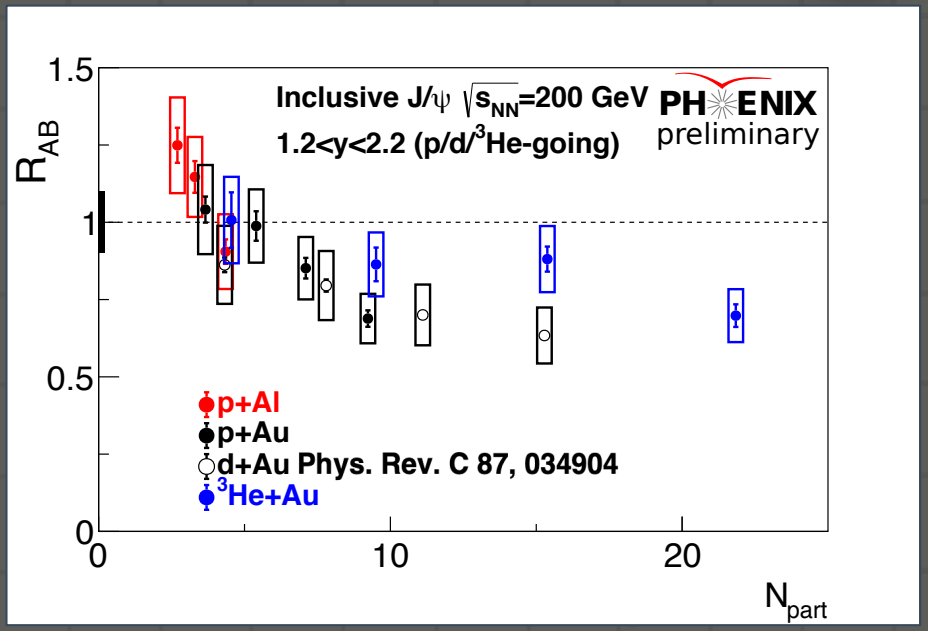
p+Au – Run15

# A Few Comments

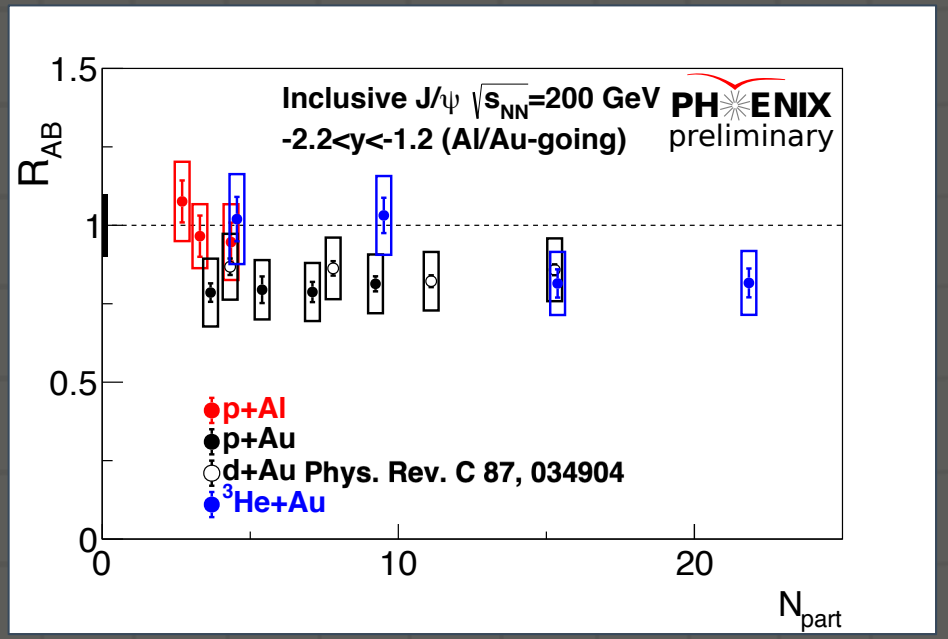
When comparing Run8 d+Au with Run14 $^3$He+Au and Run15 p+Al/Au, we should keep in mind that:

- The 2008 Run had different detector details
- 2008 simulations used GEANT3
- The 2014 and 2015 Runs have the same detector details
- 2014, 2015 simulations used GEANT4
- Some systematics are uncorrelated between old and new data
- Systematics are highly correlated for new data

# $p_T$ Integrated $R_{AA}$ vs. $N_{part}$ small systems

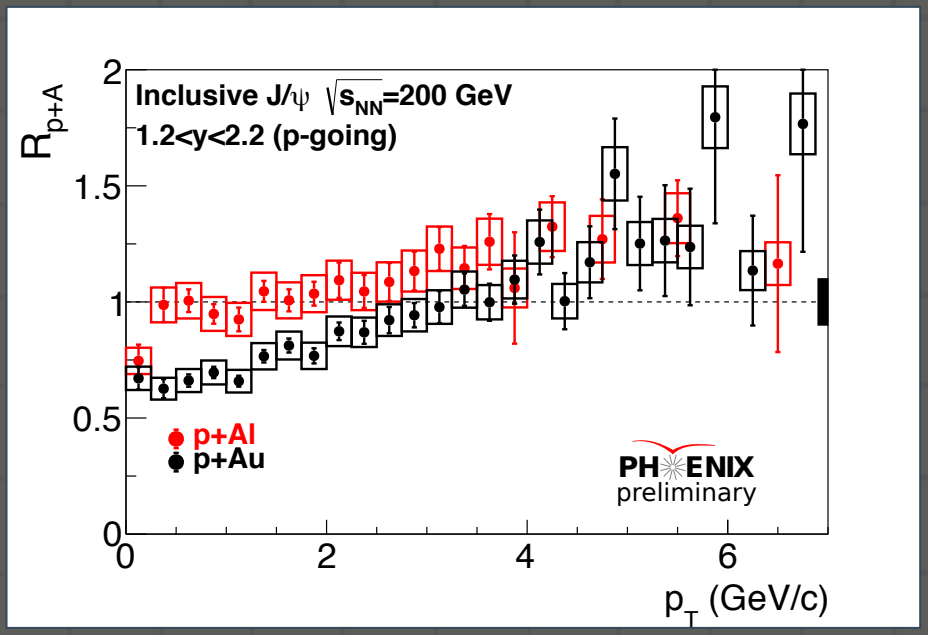



*Forward rapidity*



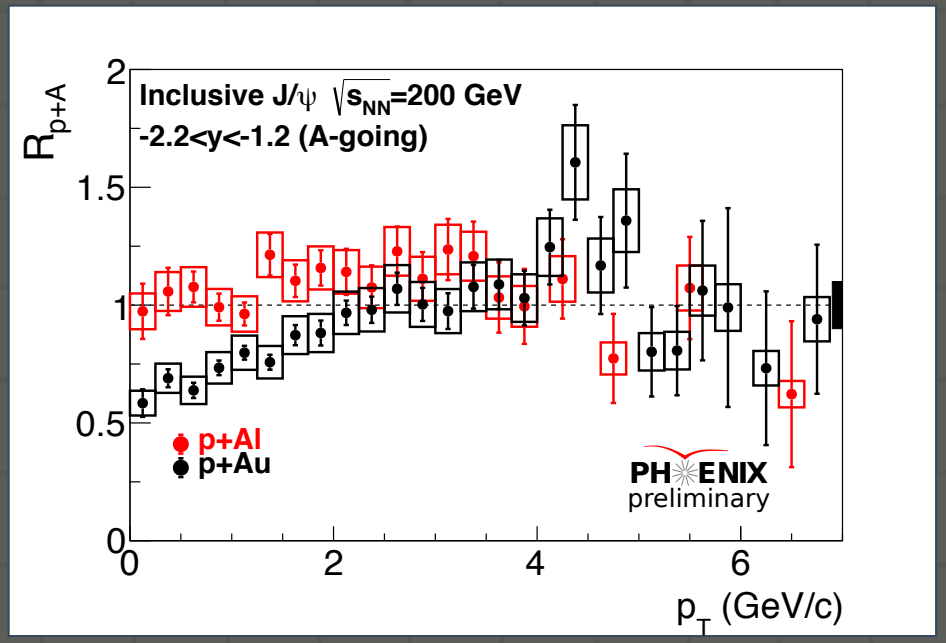

*Backward rapidity*

- p+Al shows little modification
- J/ψ cross section in p/d/$^3$He +Au at forward rapidity decreases wrt p+p cross section as $N_{part}$ increases
- No $N_{coll}$ scaling




*Forward rapidity*

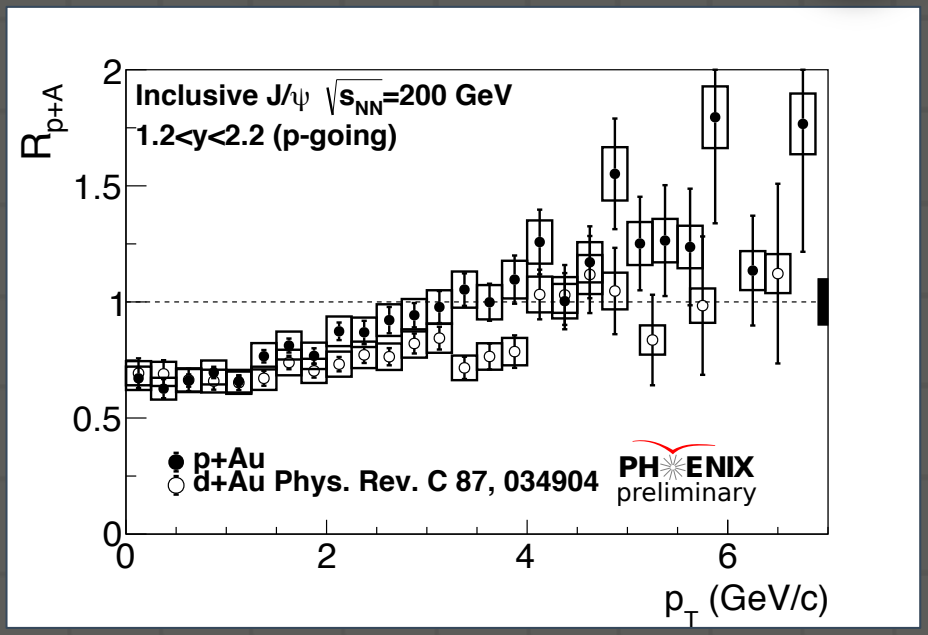
# Centrality Integrated p+Al vs. p+Au




*Backward rapidity*

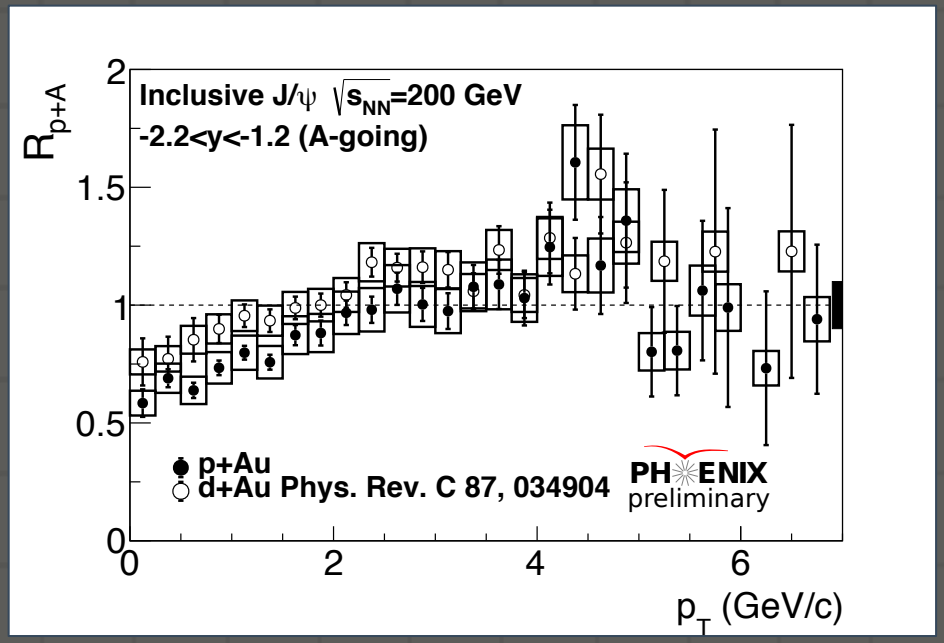
- p+Al shows little modification in either direction
- J/ψ modification in p+Au shows suppression at low $p_T$ in both directions

# Centrality Integrated p+Au vs. d+Au




*Forward rapidity*

- Similar modification at forward rapidity
- Slight difference at backward rapidity, but within systematics



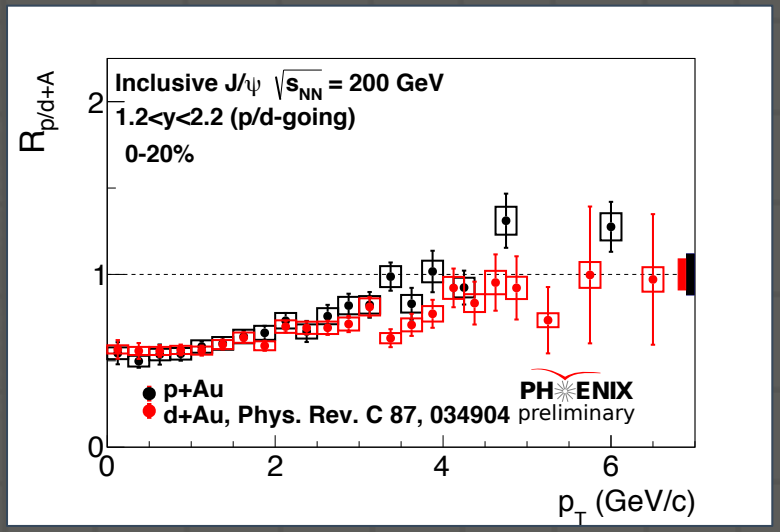

*Backward rapidity*

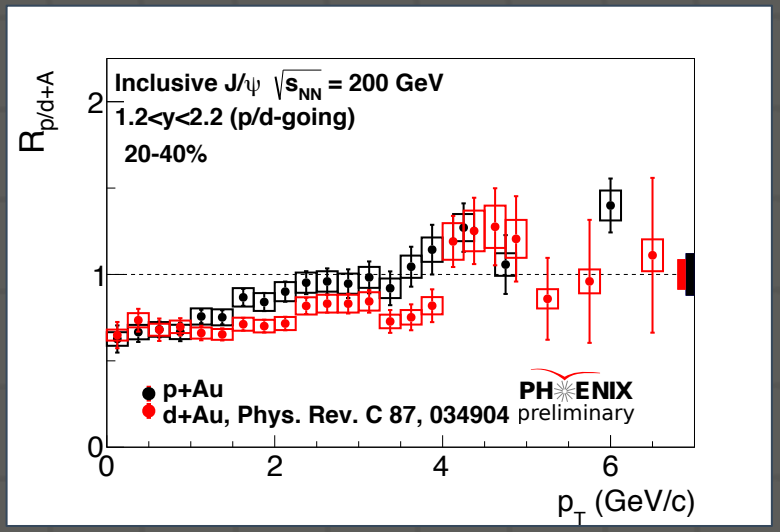
# Centrality Dependence

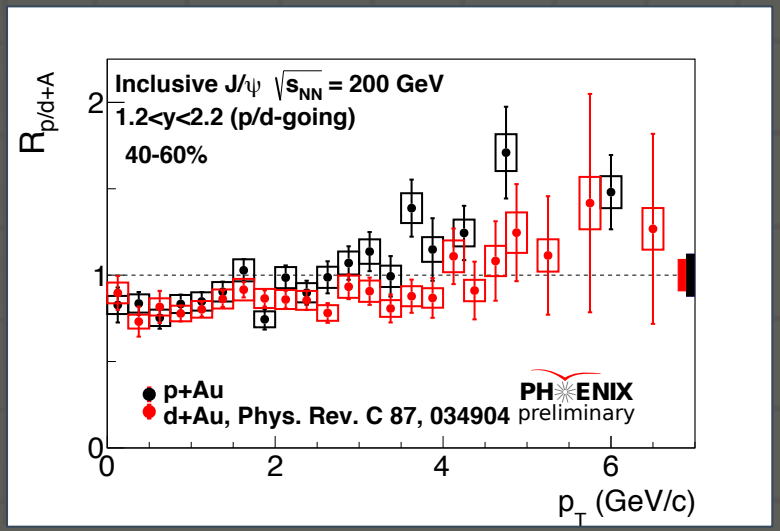
# p+Au vs. d+Au

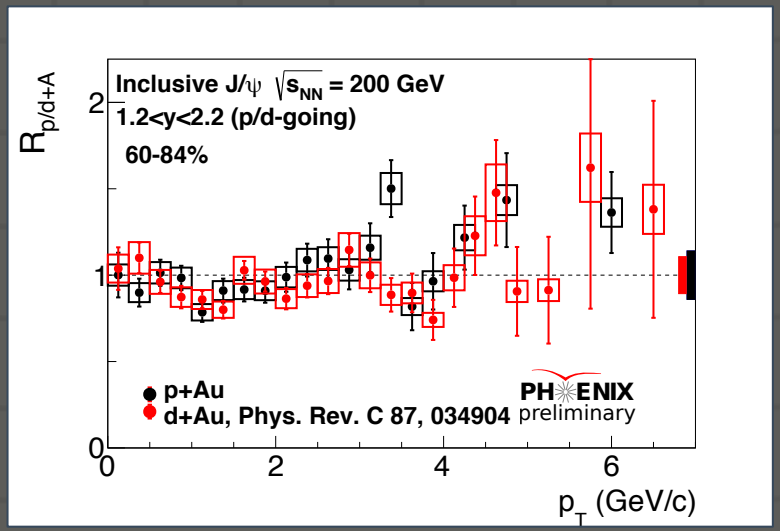
- Again, similar modification at forward rapidity is observed

*Forward Rapidity*



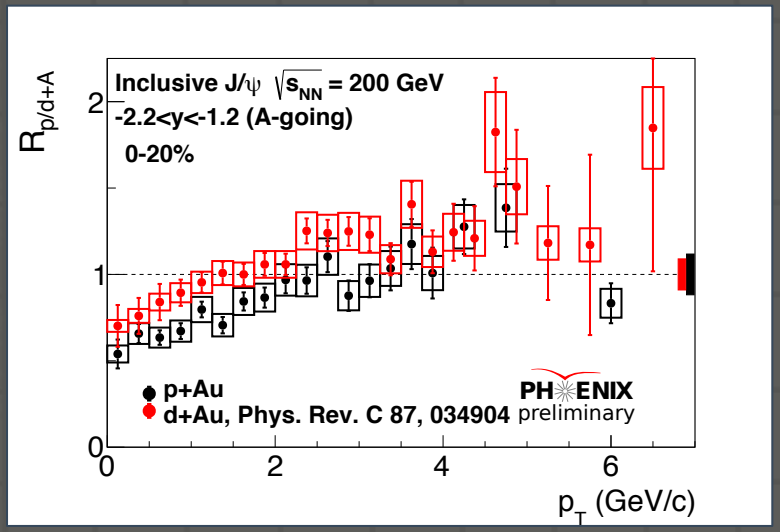



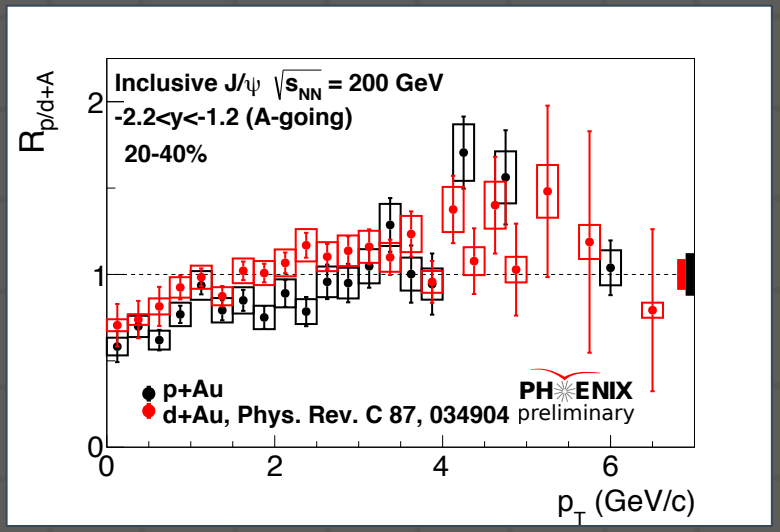



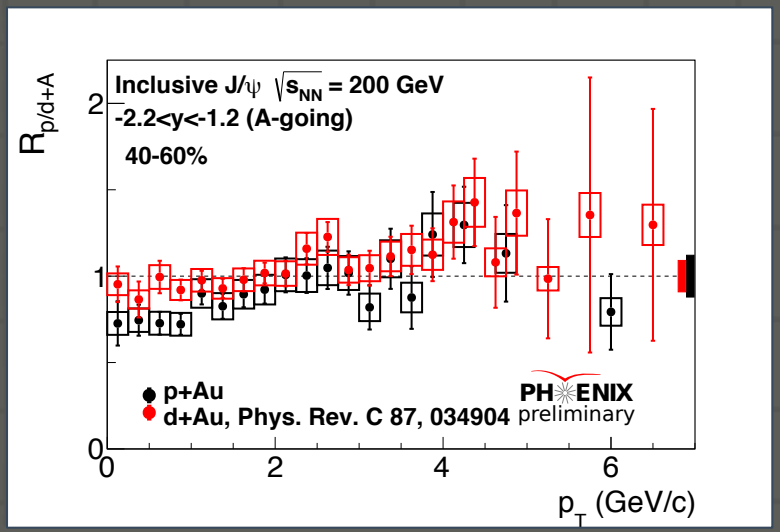
# p+Au vs. d+Au

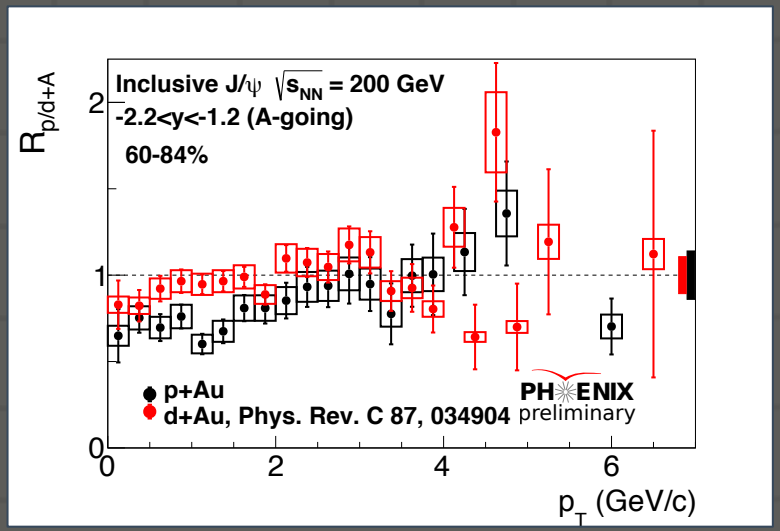
- Again, slight difference at backward rapidity but within systematics

*Backward Rapidity*



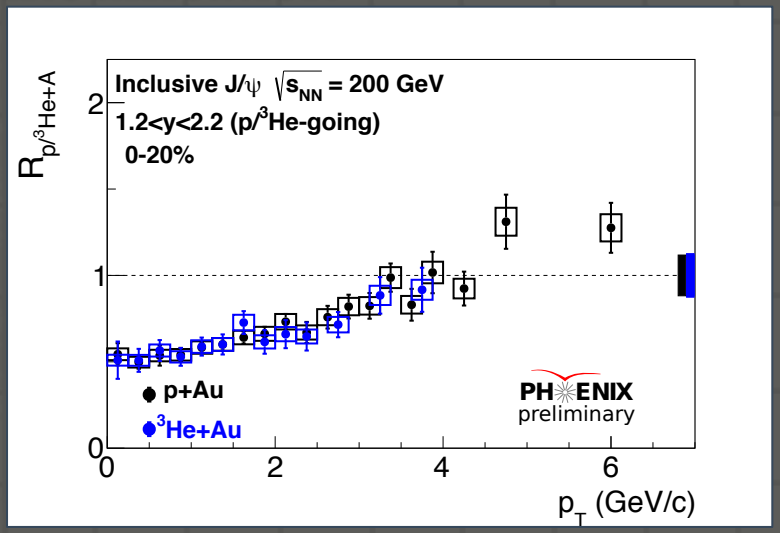



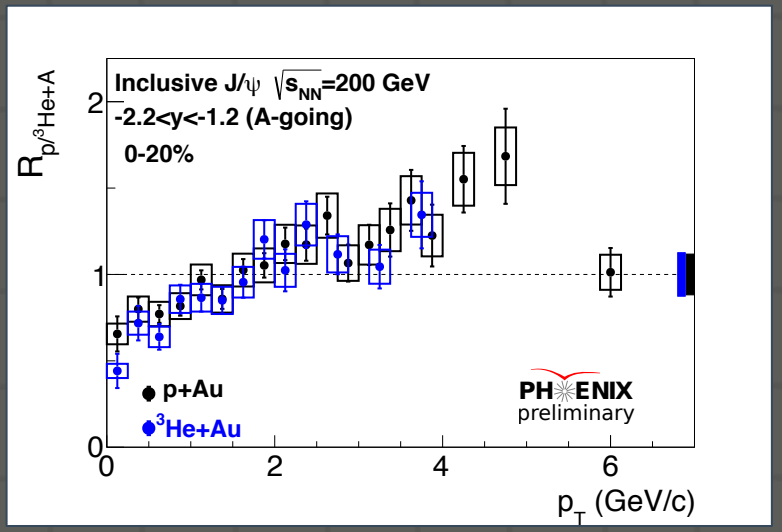



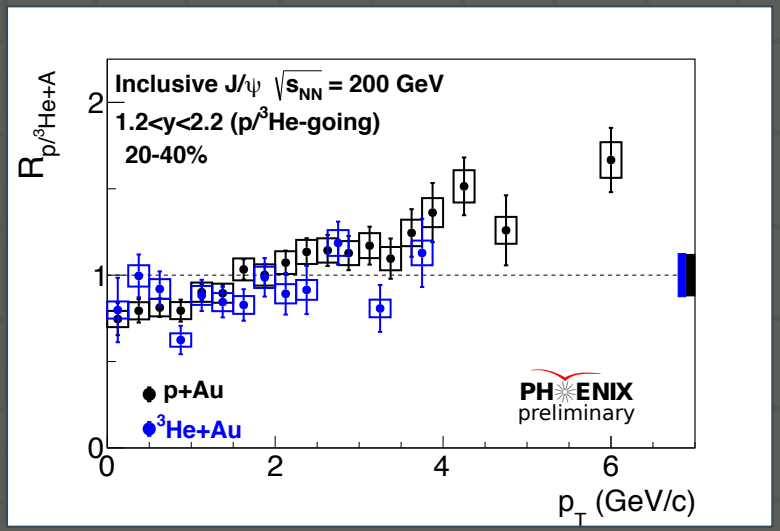
# p+Au vs. $^3$He+Au

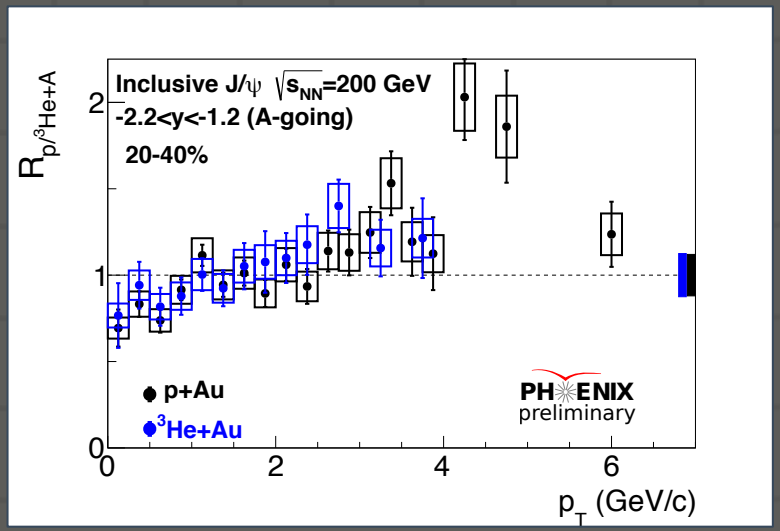
- Very similar modification
- No evidence of final state effects

*Forward Rapidity*



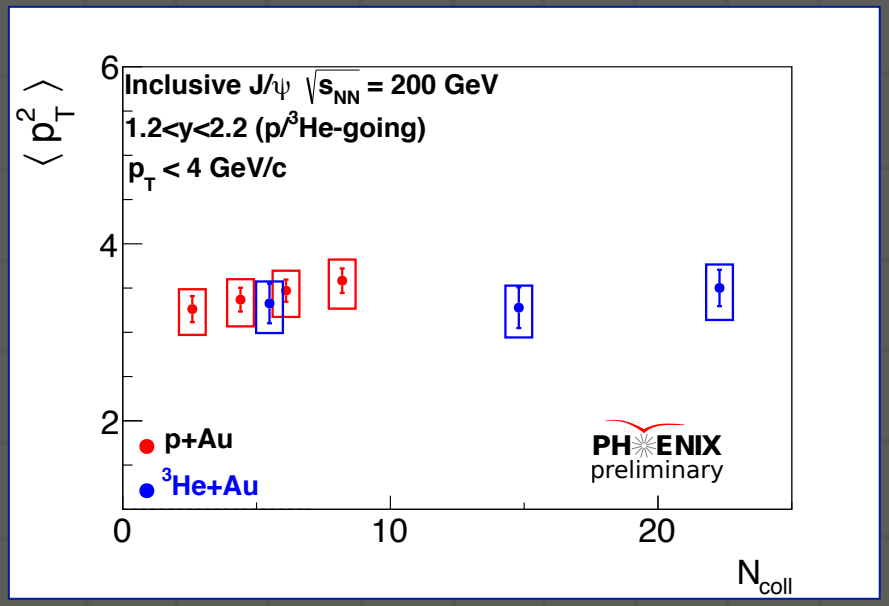



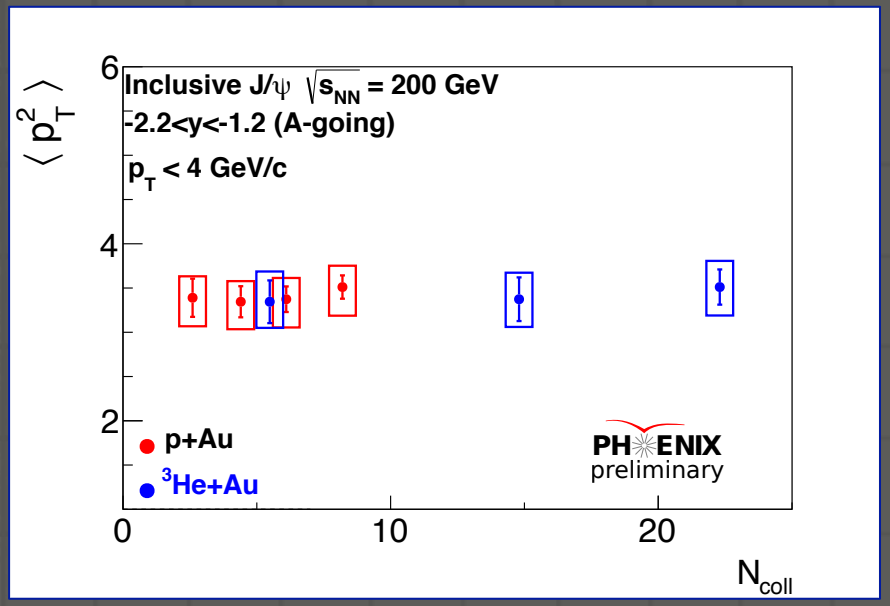



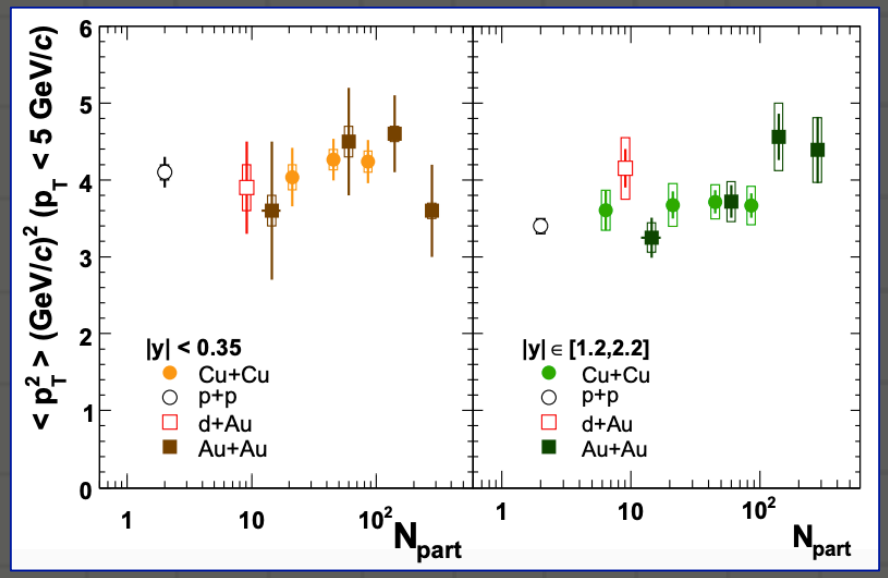




*Backward Rapidity*

# $\langle p_T^2 \rangle$ vs. $N_{coll}$




- $\langle p_T^2 \rangle$ vs. $N_{coll}$ for p+Au and $^3$He+Au show little dependence on centrality
- $\langle p_T^2 \rangle$ vs. $N_{part}$ for Cu+Cu at forward/backward rapidity also shows little dependence

*Phys. Rev. Lett. 101, 122301 (2008)*

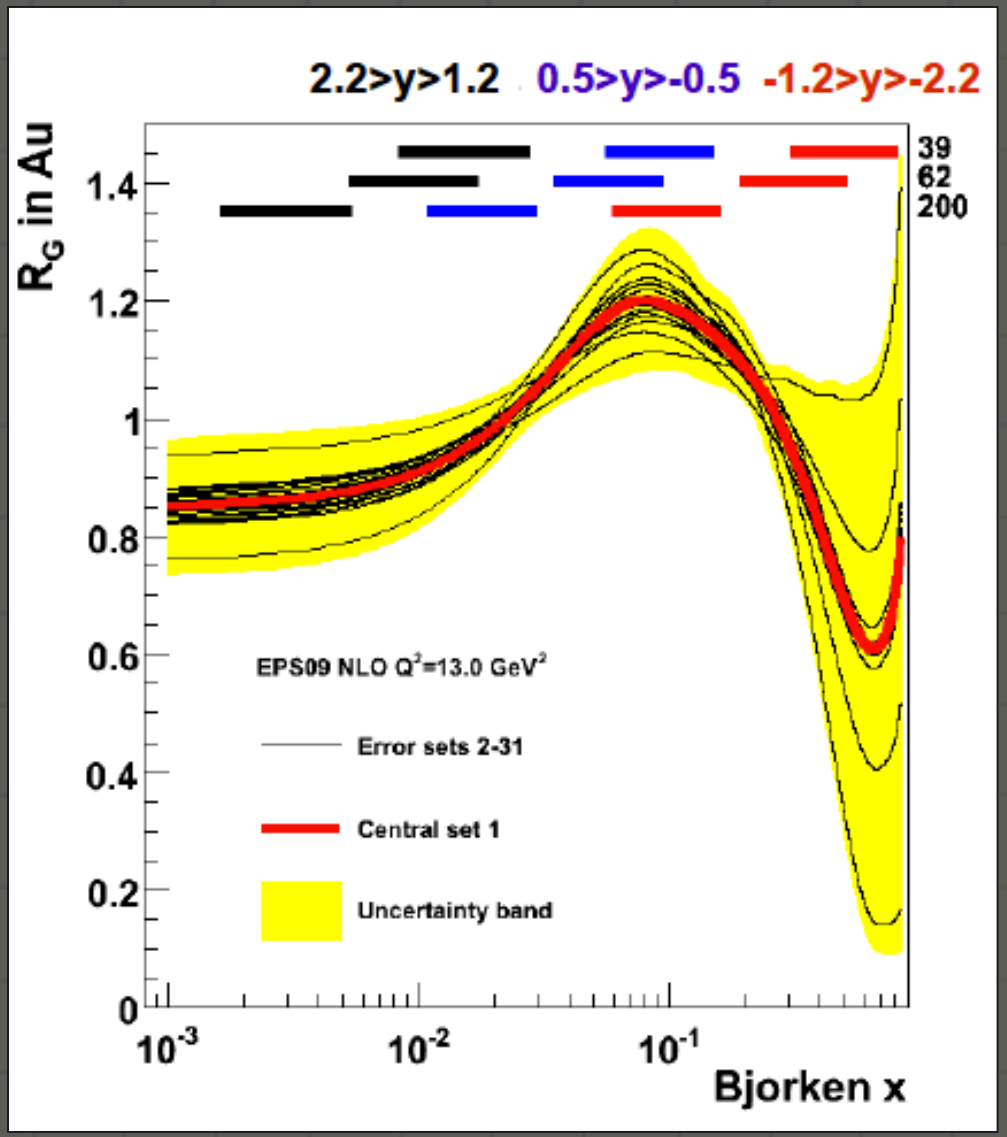
# Summary

- No suppression is observed at low $p_T$ in p+Al
- Suppression observed at low $p_T$ is consistent between p/d/$^3$He +Au
- Centrality integrated $R_{AB}$ for p/d/$^3$He+Au are very similar
  - Would be expected if CNM effects dominate J/$\psi$ production
- Centrality dependent $R_{AB}$ for p/d/$^3$He+Au are very similar
- With this new data, good eyes from theorists are welcome

# Back up

# Gluon Shadowing

- Results in modification of the heavy quark production cross section
- Bars show roughly the Bjorken x range corresponding to PHENIX rapidity intervals at different collision energies for p+Au
- In p+Au collisions, leads to suppression at forward rapidity, enhancement at backward rapidity



# CNM Effects

- Gluon Shadowing/Anti-Shadowing:

  Modification (suppression/enhancement) of heavy quark cross section due to modifications of the gluon structure function

- Parton Energy Loss:

  The projectile gluon experiences multiple scattering while passing through the target before J/ψ production, reducing the rapidity of the J/ψ

- Cronin Effect:

  Modification of the J/ψ $p_T$ distribution due to multiple elastic scattering of partons

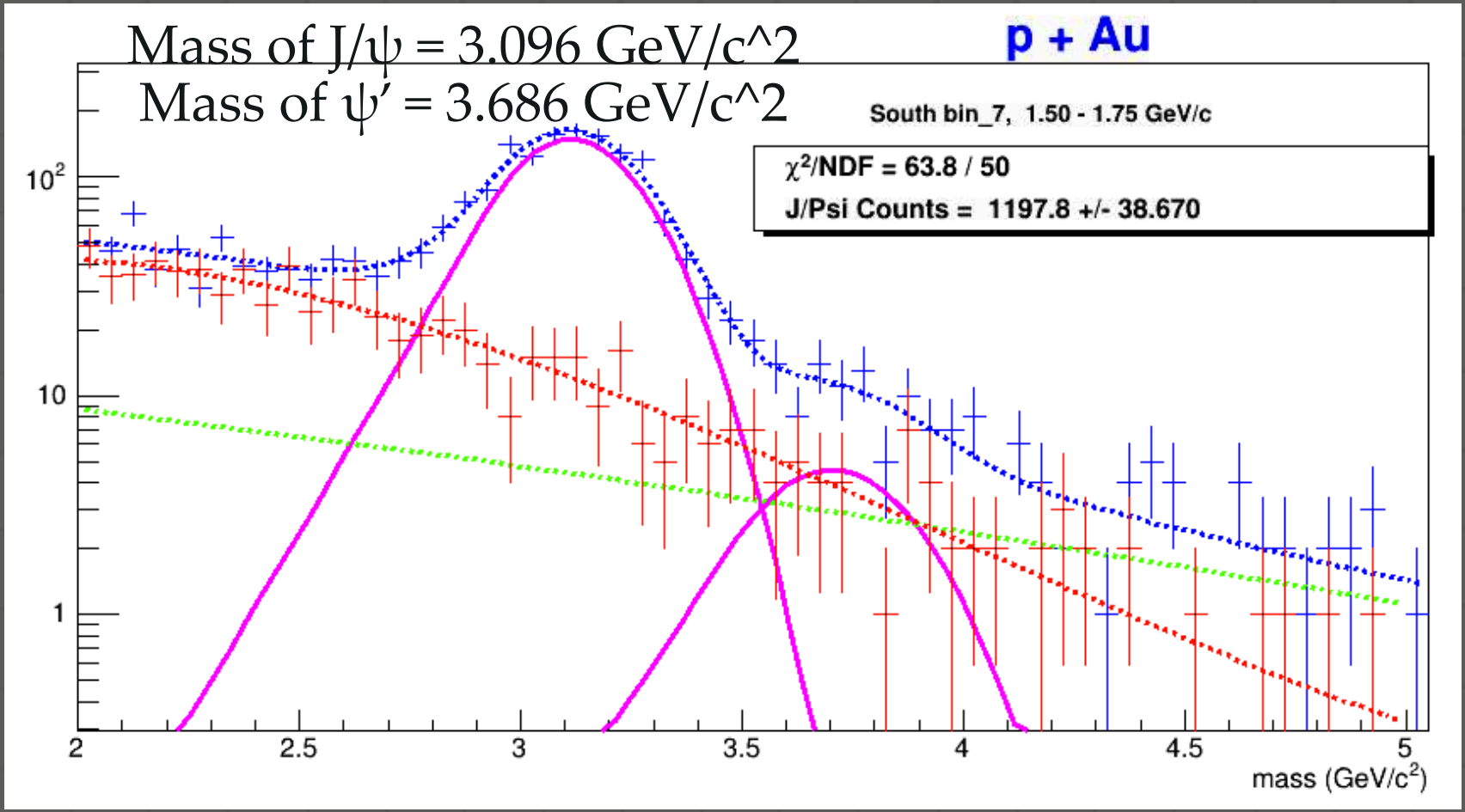
- Nuclear Break-Up:

  The break up of the bound J/ψ (or precursor state) in collisions with other target nucleons that pass through J/ψ production point

- Co-Movers Break-Up:

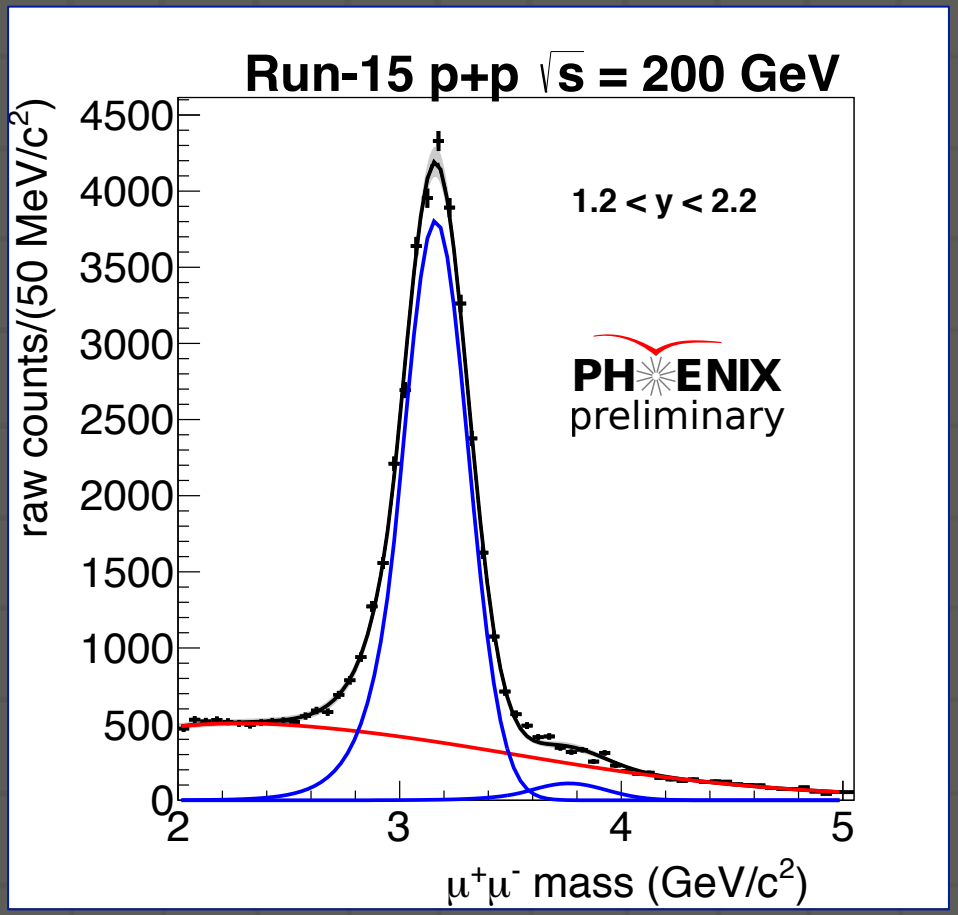
  Final state break up of the J/ψ through interactions with produced partons

# Example Fit


Mass of J/ψ = 3.096 GeV/c^2
Mass of ψ′ = 3.686 GeV/c^2
p + Au
South bin_7, 1.50 - 1.75 GeV/c
χ²/NDF = 63.8 / 50
J/Psi Counts = 1197.8 +/- 38.670
10²
10
1
2
2.5
3
3.5
4
4.5
5
mass (GeV/c²)

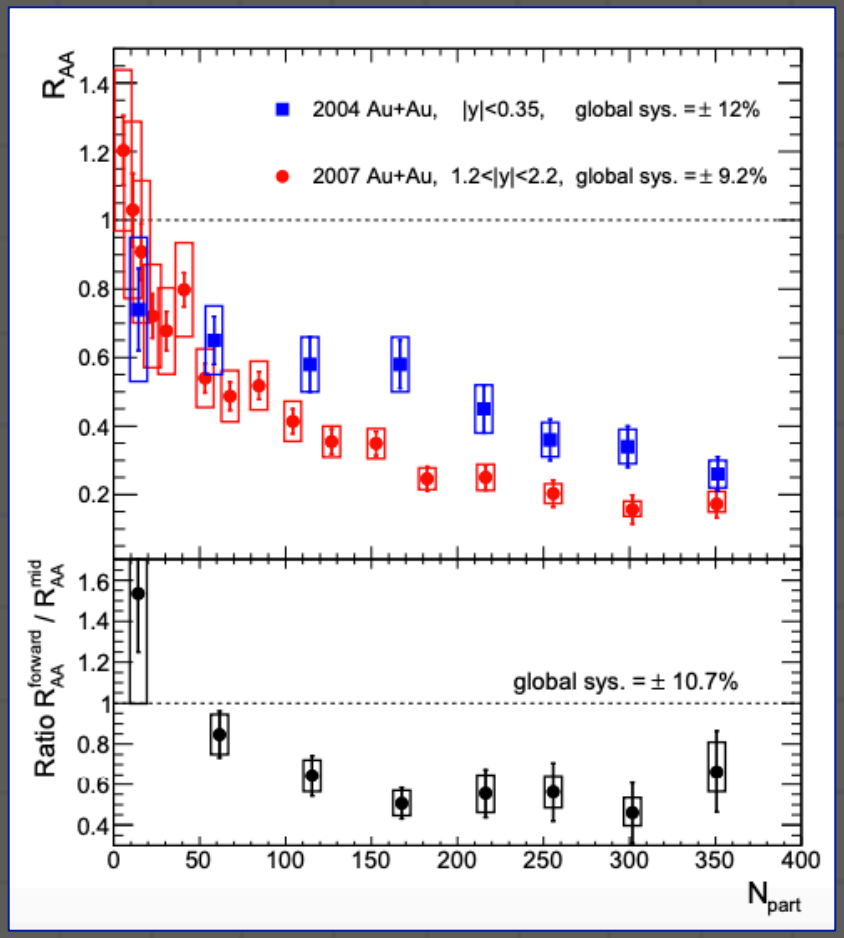
# Motivation to Study J/ψ

- J/ψ are heavy quark mesons, detectable through their di-lepton decays
  - Can be fully reconstructed through their di-lepton decays
- Convenient as a probe of QGP
- Can compare effects across different systems: p+p, p+Au, p+Al, d+Au, $^3$He+Au and Au+Au



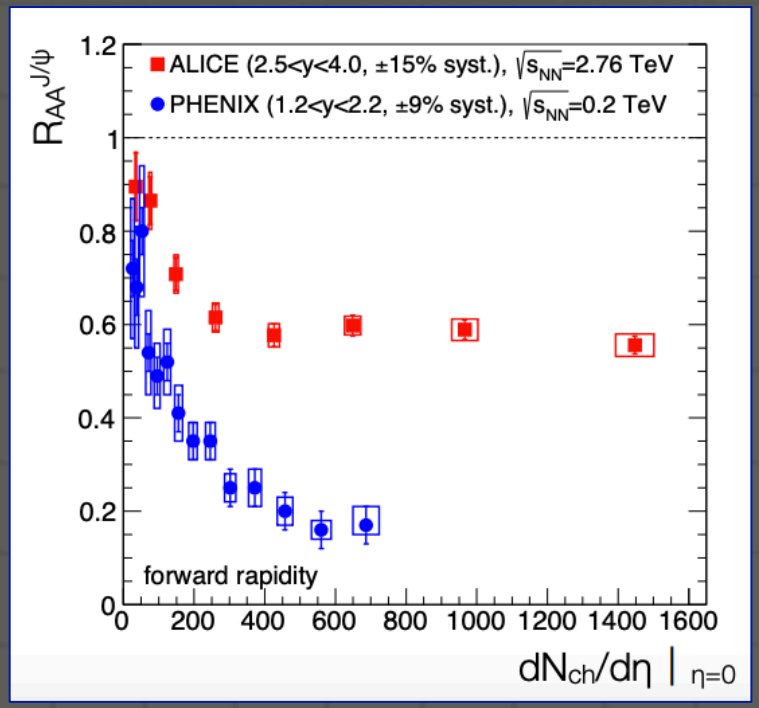
# Large Systems Results

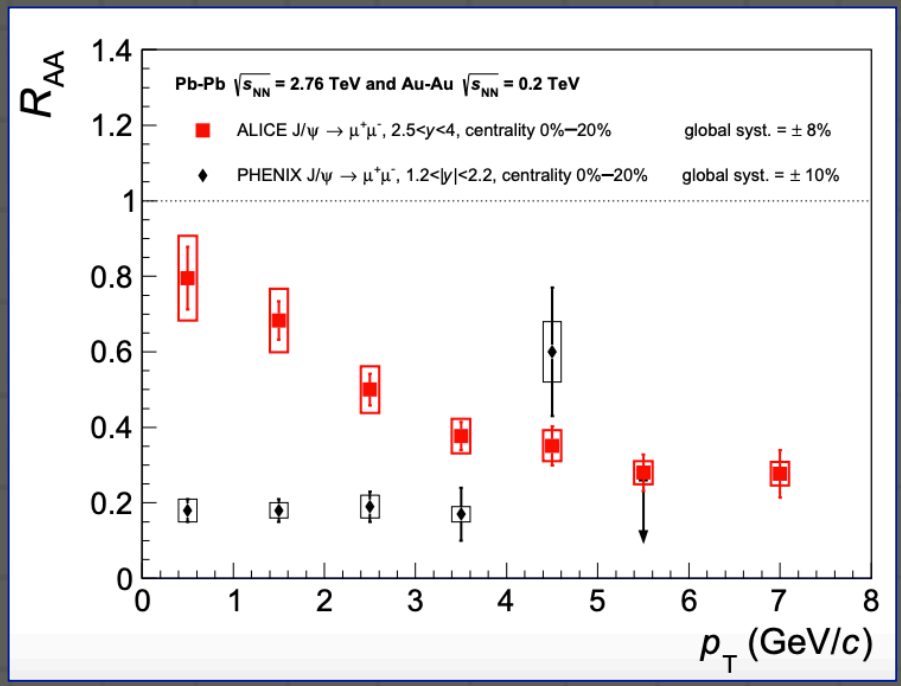
# PHENIX Au+Au vs. ALICE Pb+Pb – Raising the Collision Energy (0.2 → 2.76 TeV)




*Phys. Rev. C 84, 054921 (2011)*

*Int.J.Mod.Phys. A29 (2014) 1430047*



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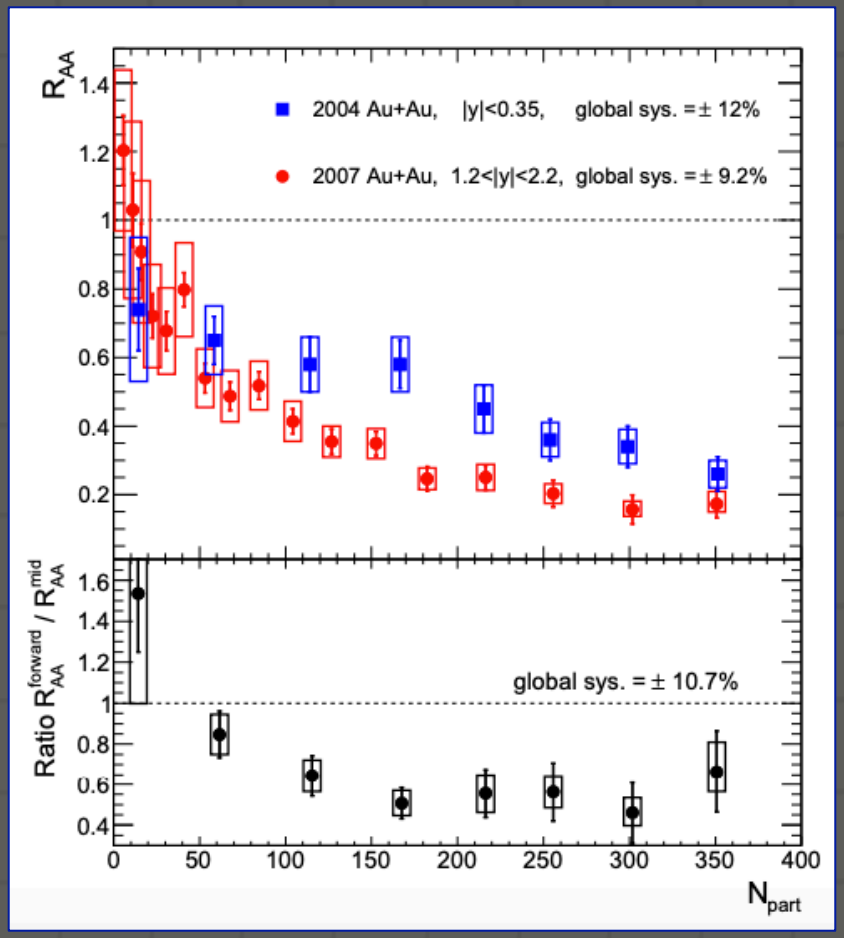
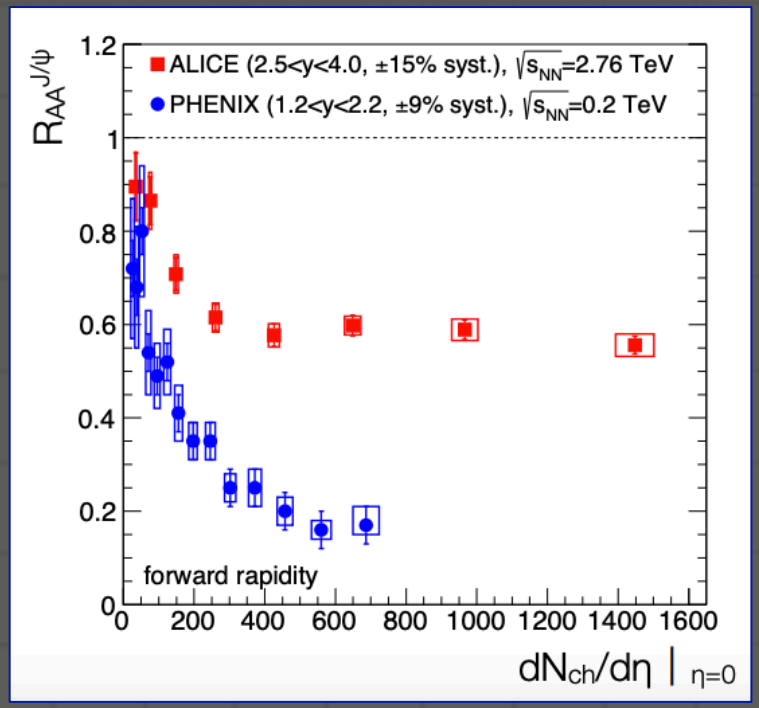
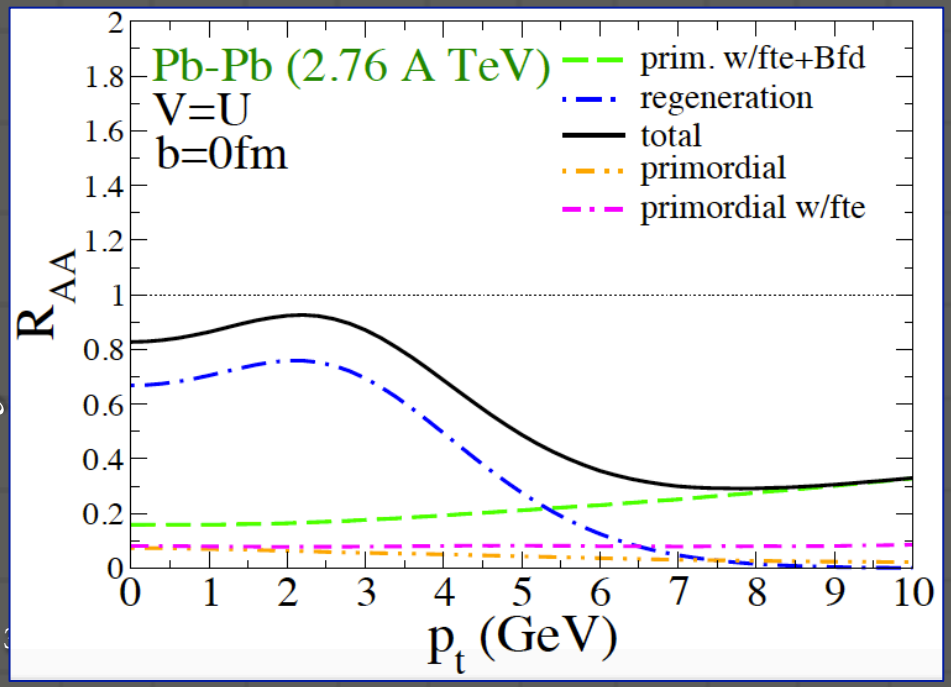



*Phys. Rev. C 84, 054921 (2011)*

*Int.J.Mod.Phys. A29 (2014) 1430047*

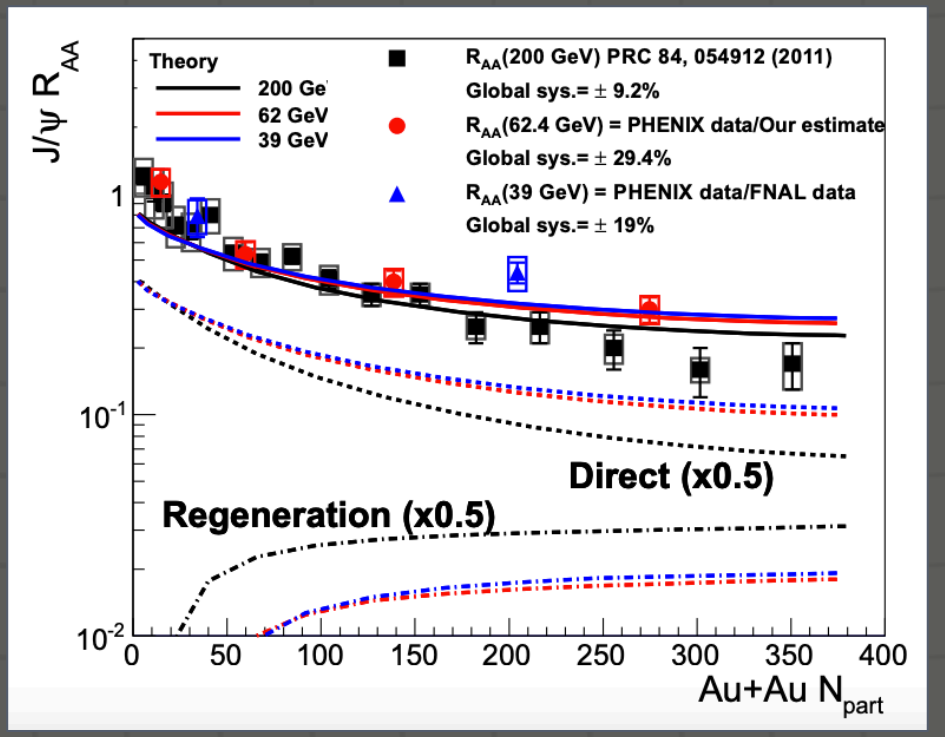



*Nuclear Physics A 859 (2011)*

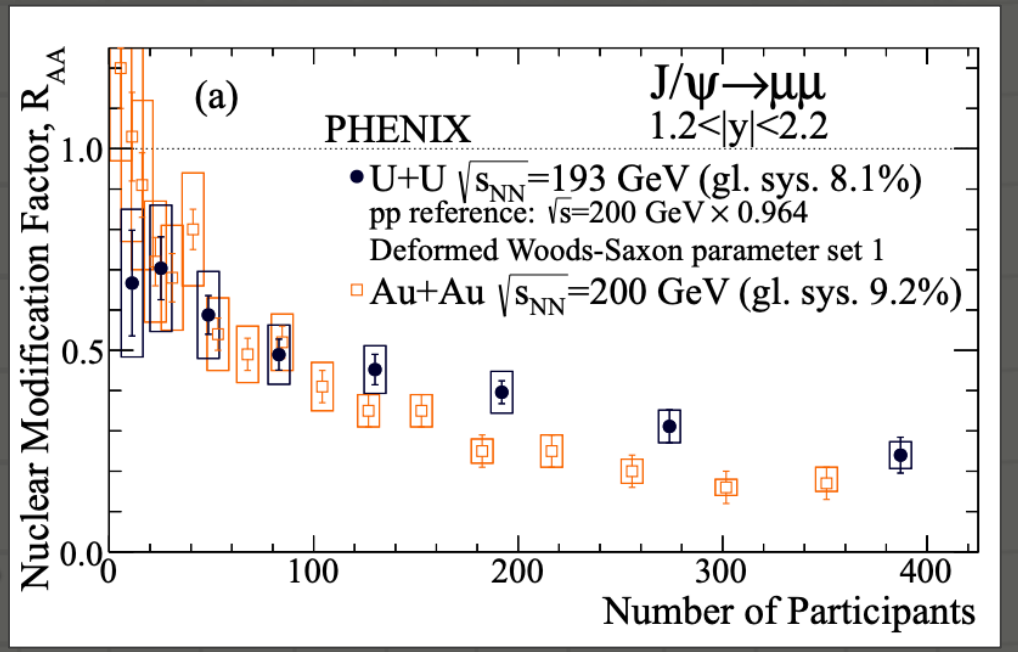


# At RHIC: Larger System vs. Lower Collision Energy

- $R_{AA}$ changes little with:
  - Lower collision energy
    - Decreased energy density
    - Decreased charm production
  - Increased system size
    - Increased energy density
    - Increased charm production
- Consistent with trade off between dissociation due to energy density and coalescence due to larger charm production




*Phys. Rev. C 86, 06409 ( 2012)*




*Phys. Rev. C 93, 034903 (2016)*