Outstanding Results from the PHENIX Experiment at RHIC

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Nuclear Matter Under Extreme Conditions
Erice, Sicily
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The PHENIX Experiment

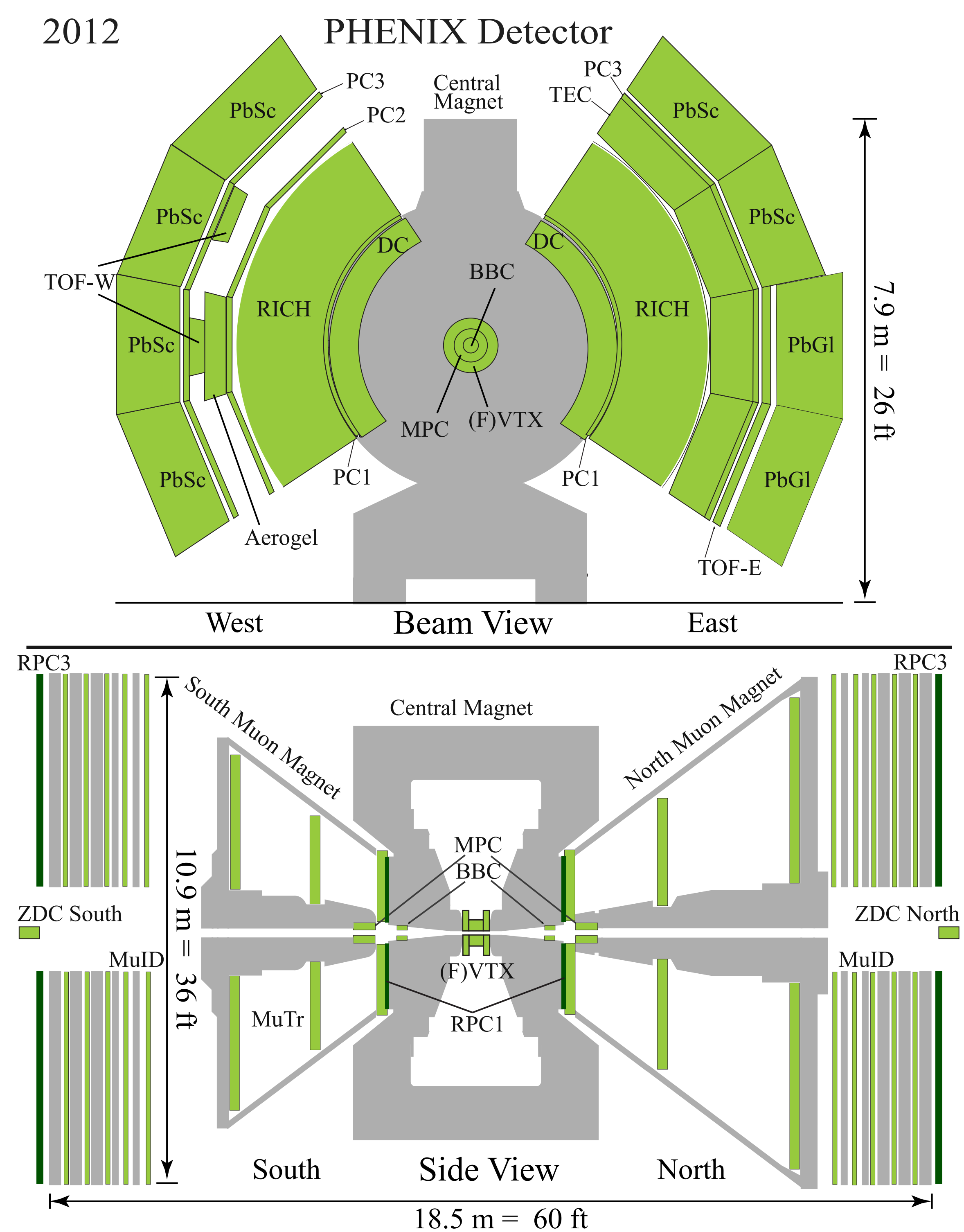
Midrapidity
D, B ➔ $e^{\pm}$
J/ψ ➔ $e^{+}e^{-}$
π^0 ➔ $\gamma\gamma$
direct γ
unidentified charged hadrons
$-0.35 < y < 0.35$
$\Delta\Phi = \pi$

Identified charge hadrons
TOF & Aerogel

Forward/backward rapidity
D, B ➔ $\mu^{\pm}$
J/ψ ➔ $\mu^{+}\mu^{-}$
$-2.2 < y < -1.2$ $1.2<y<2.4$
$\Delta\Phi = 2\pi$

MPC/EX
γ, π^0
forward rapidity

High data rate, no Au+Au triggering
Good triggers in p+p, d,p+A



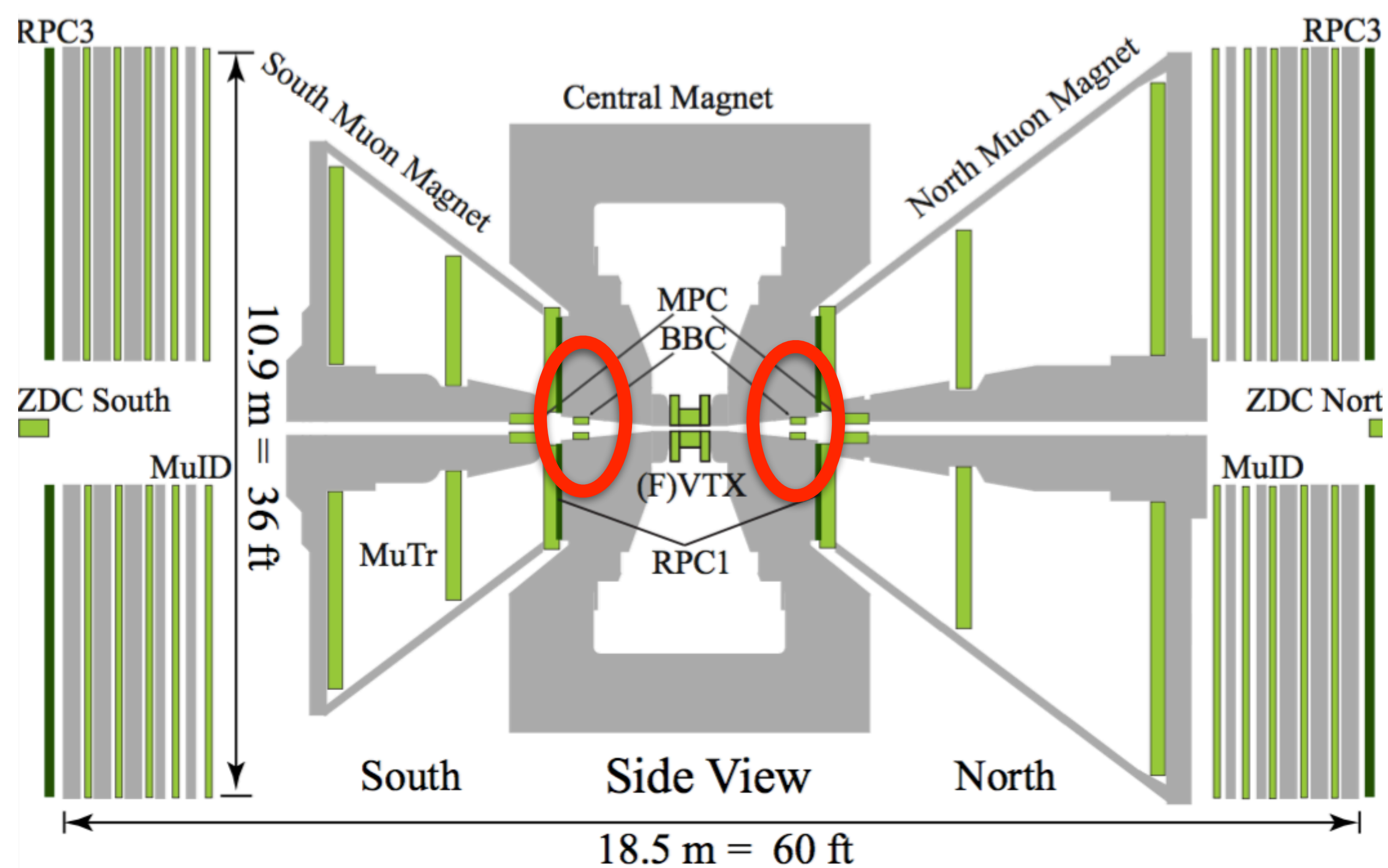
Centrality Measurement

Use the total particle production at large rapidity as a measure of centrality in p+p, p+A, A+A

BBC detector covers 3.1 < $|\eta|$ < 3.9

Centrality corrected for bias due to autocorrelation between hard probe and particle multiplicity at BBC

- Studied by embedding Pythia hard process events in MB collisions



Small System Flow - ^{3}He+Au

PRL 115, 142301 (2015)

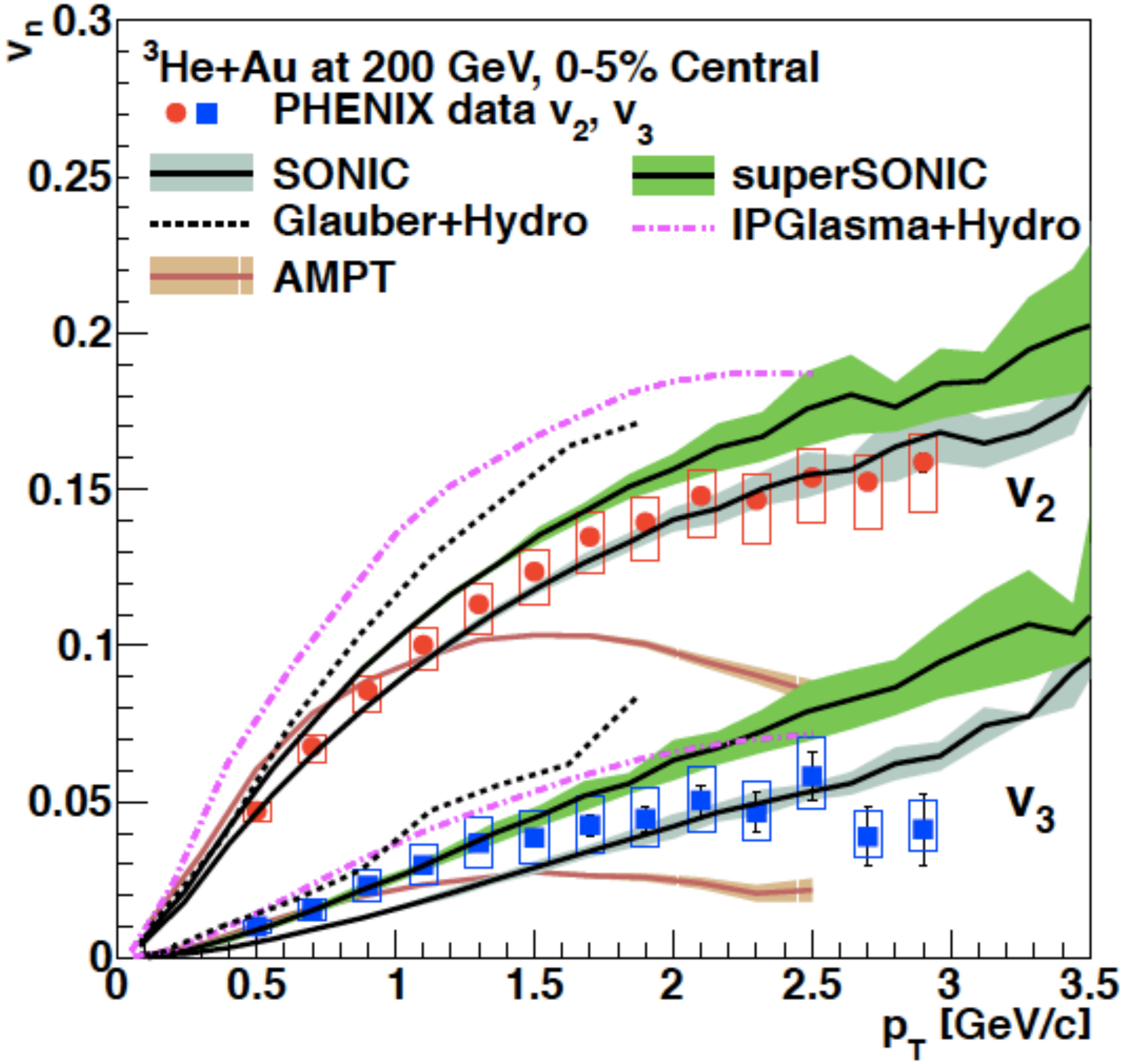
High multiplicity (i.e. very central) collisions in ^{3}He+Au

Measure v_2 and v_3

Good agreement with SONIC

- Glauber MC initial conditions
- Viscous hydrodynamics η/s = 0.08
- Transition to hadronic cascade at T = 170 MeV

Supports initial geometry + hydrodynamic evolution as source of v_n



Perhaps not so surprising for ^{3}He projectile

Event plane determined by FVTX in Au going direction

Small System Flow - p,d,^{3}He+Au

High multiplicity (i.e. very central) collisions in p+Au, d+Au, ^{3}He+Au

Consider v_2 only (v_3 not available for 2008 d+Au measurement)

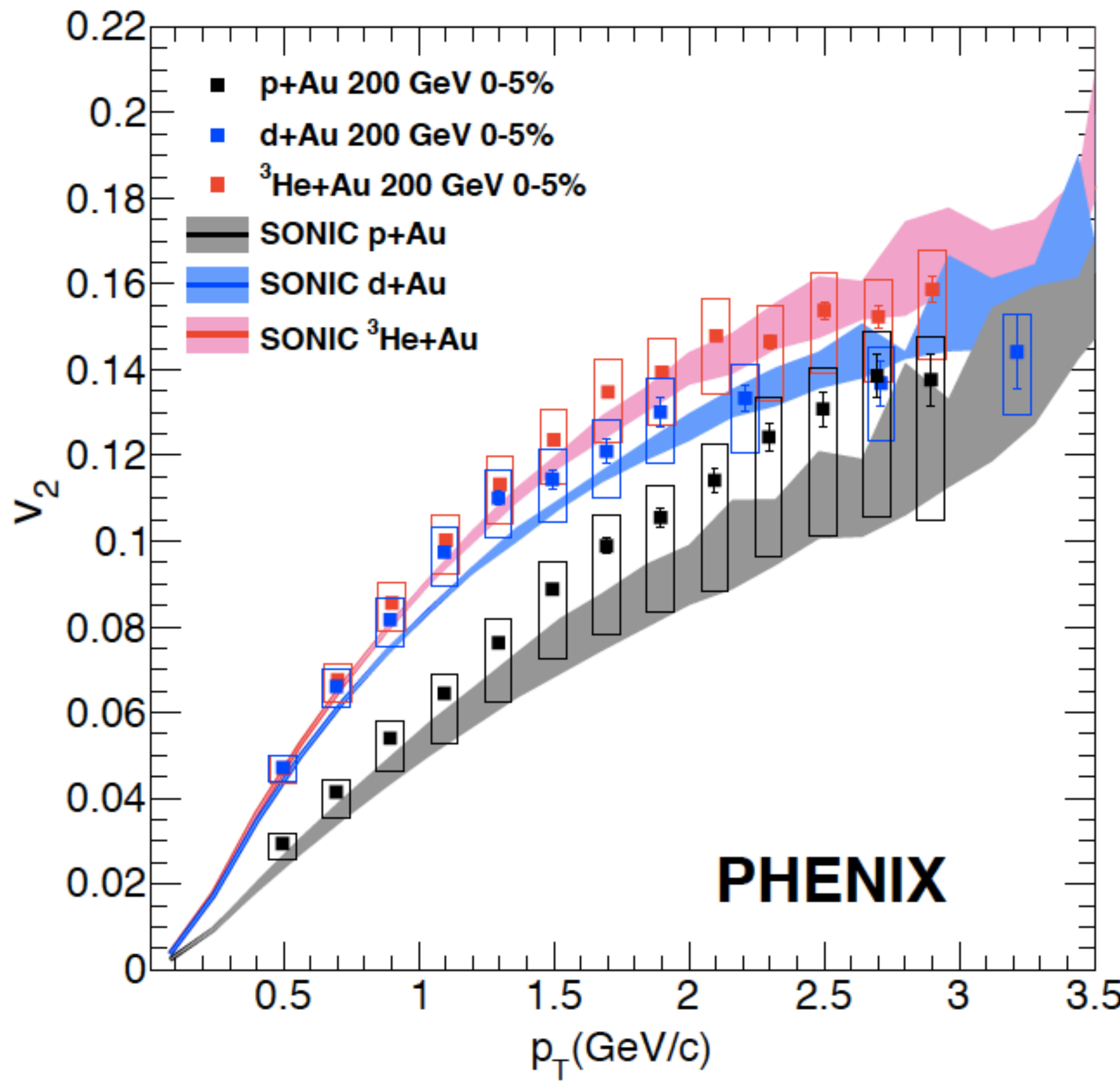
Good agreement with SONIC:

- Glauber MC initial conditions
- Viscous hydrodynamics $\eta/s = 0.08$
- Transition to hadronic cascade at T = 170 MeV

Supports initial geometry + hydrodynamic evolution as source of v_2

Indicates p+Au produces fireball also

PHENIX arXiv:1609.02894



Event plane determined by FVTX in Au going direction

Jets

Jets in d+Au

PHENIX, Phys. Rev. Lett. 116, 122301

MB data (0-100% central) show no modification within uncertainties

R_{dAu} shows significant dispersion with centrality class

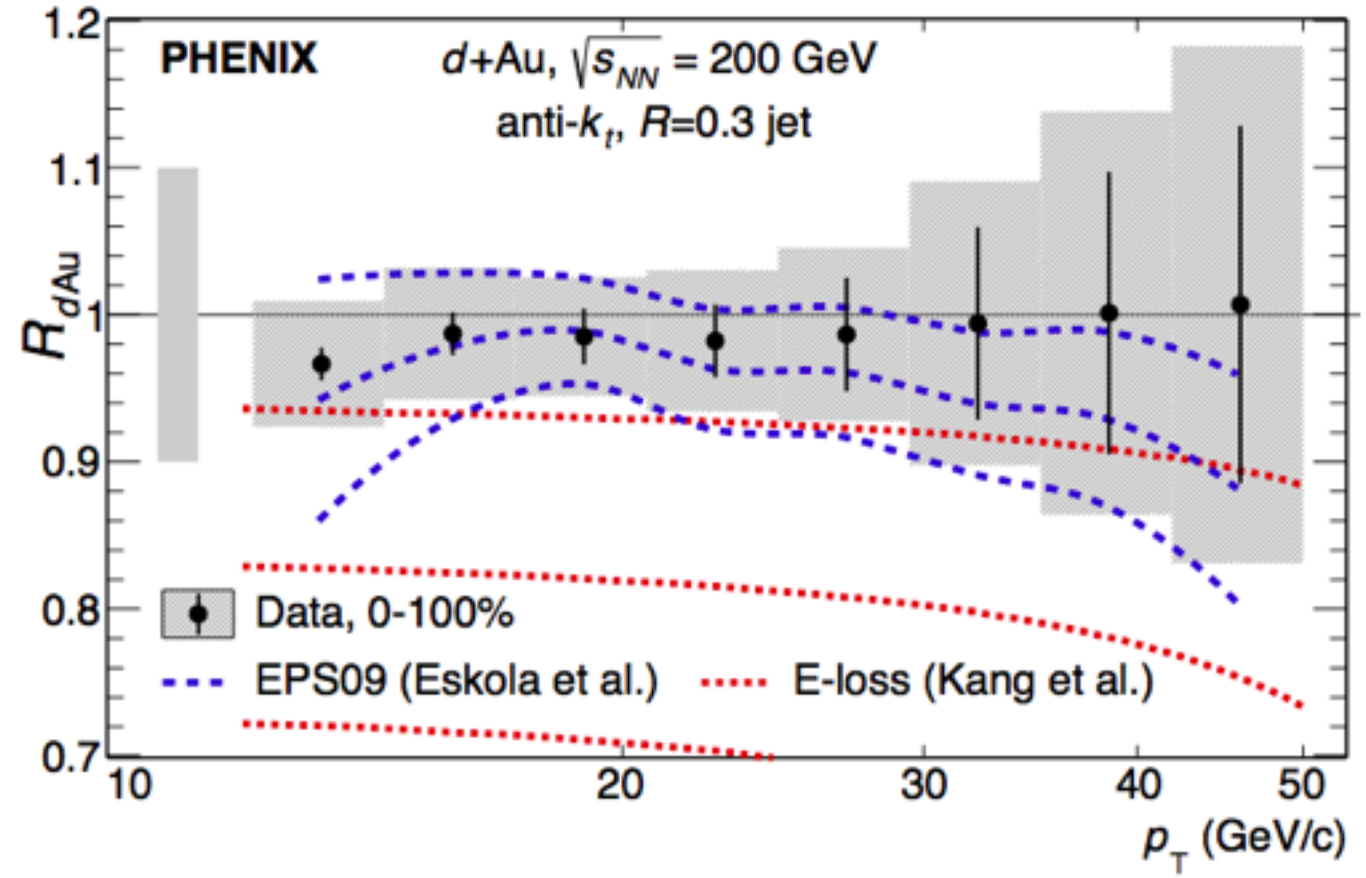
- Suppression for 0-20%
- Enhancement for peripheral classes
- Separation increases with p_T

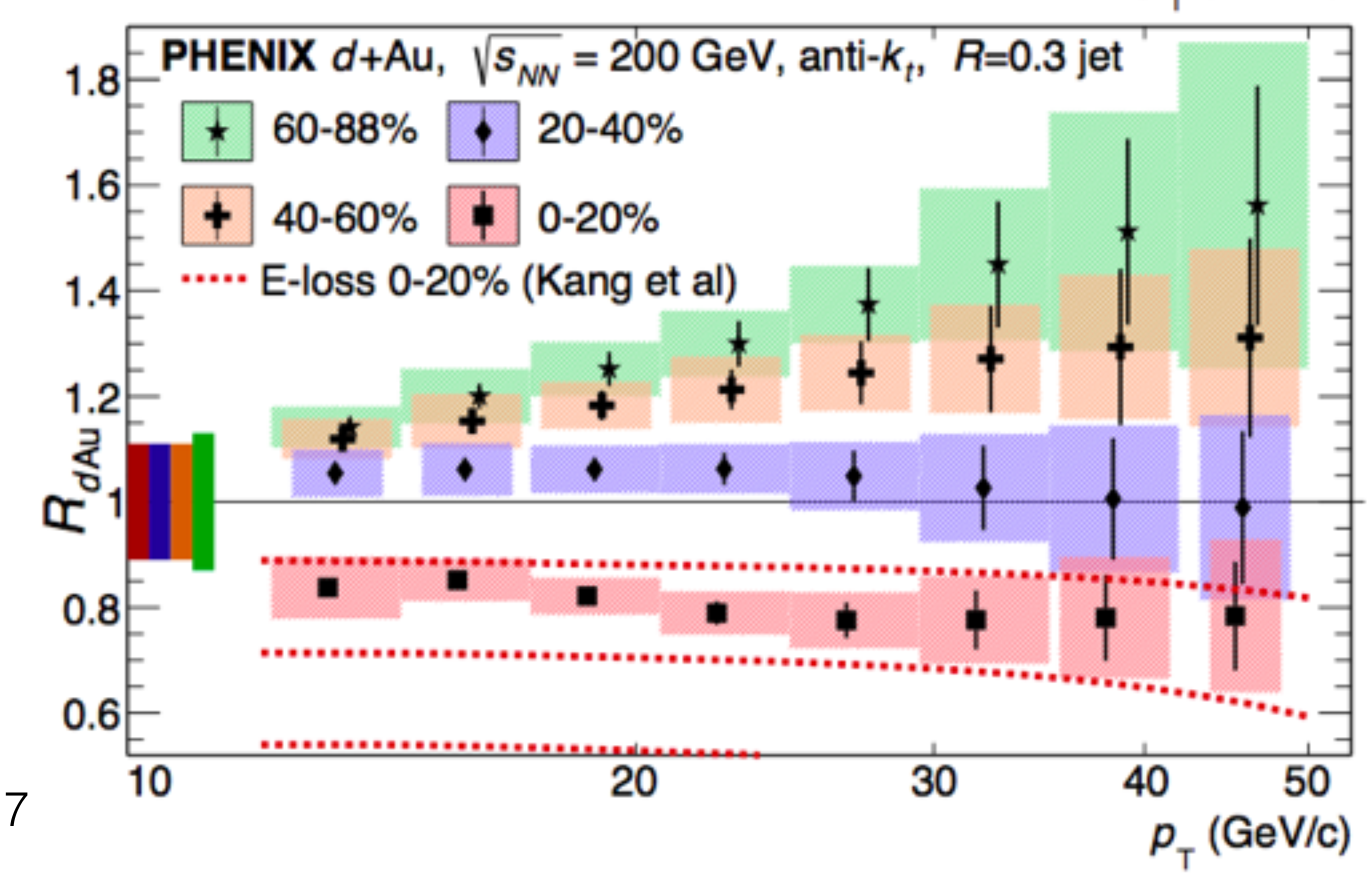
Jet modification in d+Au, or something else?

If it is jet modification, the effects have to exactly cancel when summed over centrality

- Hmm …..

Is it the centrality measurement?





Jets in d+Au - centrality characterization

Centrality category for an event is made from the soft particle production in a different rapidity range from the jet

$$R_{p+A} = (dN^{p+A}/dp_T)/(T_{p+A} d\sigma^{p+p}/dp_T)$$

where the nuclear overlap factor T_{p+A} can be thought of as:

$$T_{p+A}\ d\sigma^{p+p}/dp_T = (N_{coll}/\sigma_{NN})\ d\sigma^{p+p}/dp_T$$

For comparison between data at different centralities, can eliminate some systematic uncertainties by using R_{CP}:

$$R_{CP} = \frac{R_{p+A}^{central}}{R_{p+A}^{peripheral}} = \frac{1/N_{coll}^{central}\ dN^{central}/dp_T}{1/N_{coll}^{peripheral}\ dN^{peripheral}/dp_T}$$

Jets in (p,d)+A - centrality measurement?

Suggested effects on the centrality determination:

Color fluctuations in the internal configuration of the projectile nucleon (Alvioli, Cole, Frankfurt, Perepelitsa, Strikman, Phys. Rev. C93, 011902 (2016))

- Presence of large x_p parton => fewer than average number of partons (Brodsky, Farrar, PRL 31 (1973) 1153)
- => Reduced average cross section
- => Decrease in effective N_{coll} for high x_p collisions

Depletion of the longitudinal energy of the projectile remnant after the removal of a a high x_p parton (Armesto, Gulhan, Milhano, PLB 747, 441 (2015))

Overall x_p dependent suppression in the soft particle multiplicity per-N+N collision (Bzdak, Skokov, Bathe, (2014) arXiv:1408.3156)

Jets in (p,d)+A - centrality measurement?

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Jets in d+Au - proton color fluctuations?

McGlinchey, Nagle, Perepelitsa, PRC 94 (2016) 024915

MC - Glauber model study of p+Au, d+Au, ^{3}He+Au R_{CP}

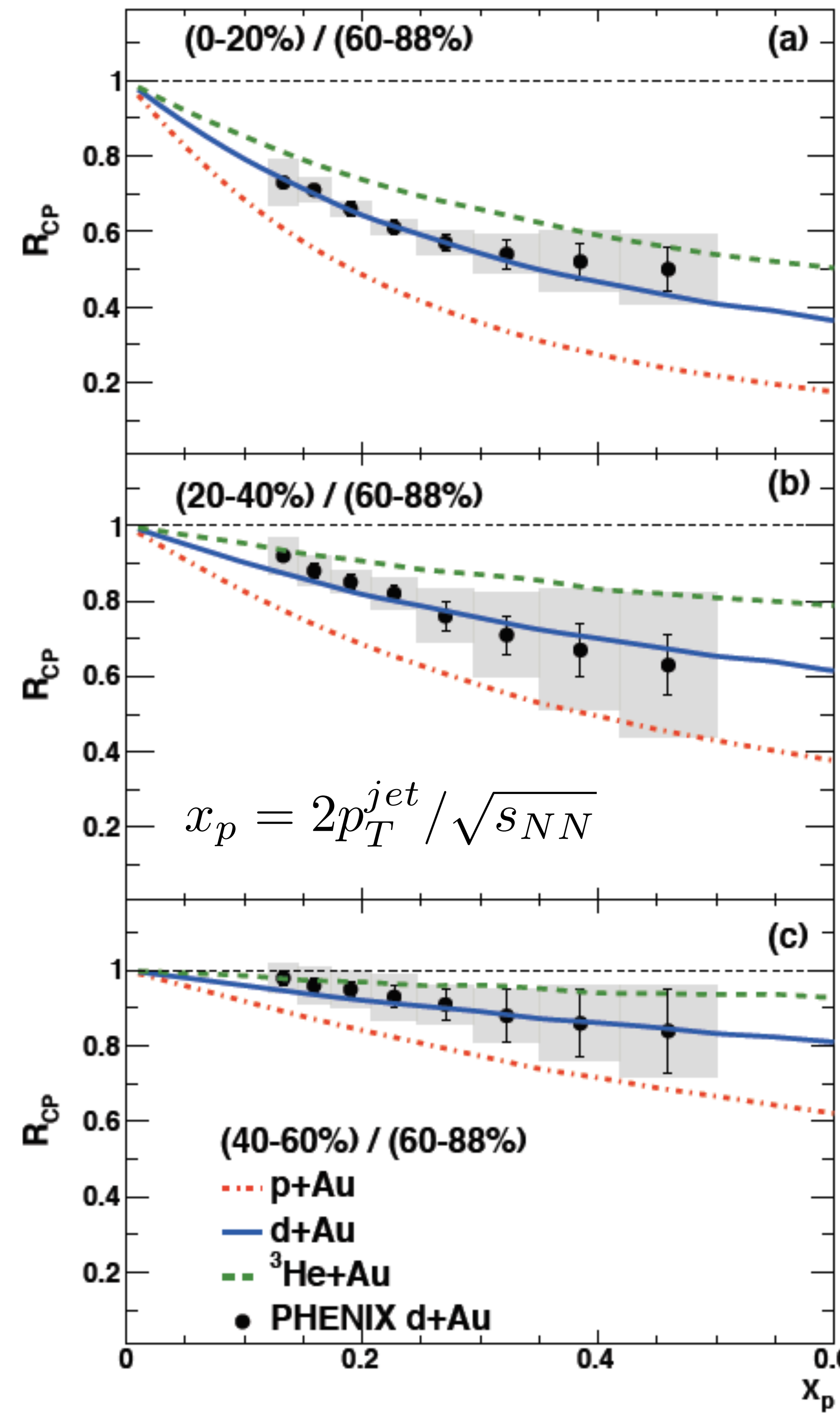
1-parameter description of x_p dependent decrease of σ_{NN}

- Fit to R_{CP} for jets

Convolve particle production with PHENIX centrality framework

Prediction for p+Au, ^{3}He+Au

- data being analyzed now



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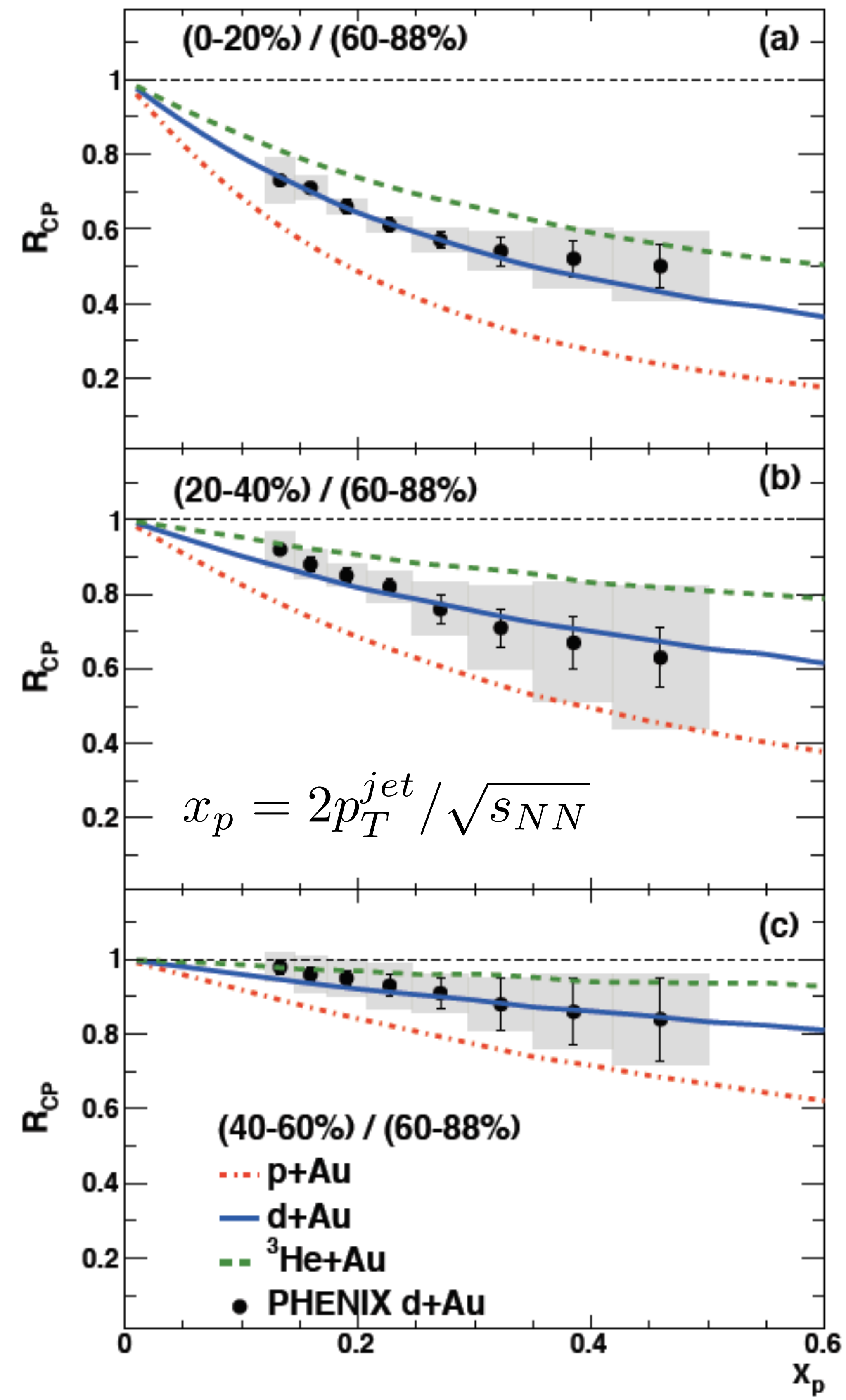
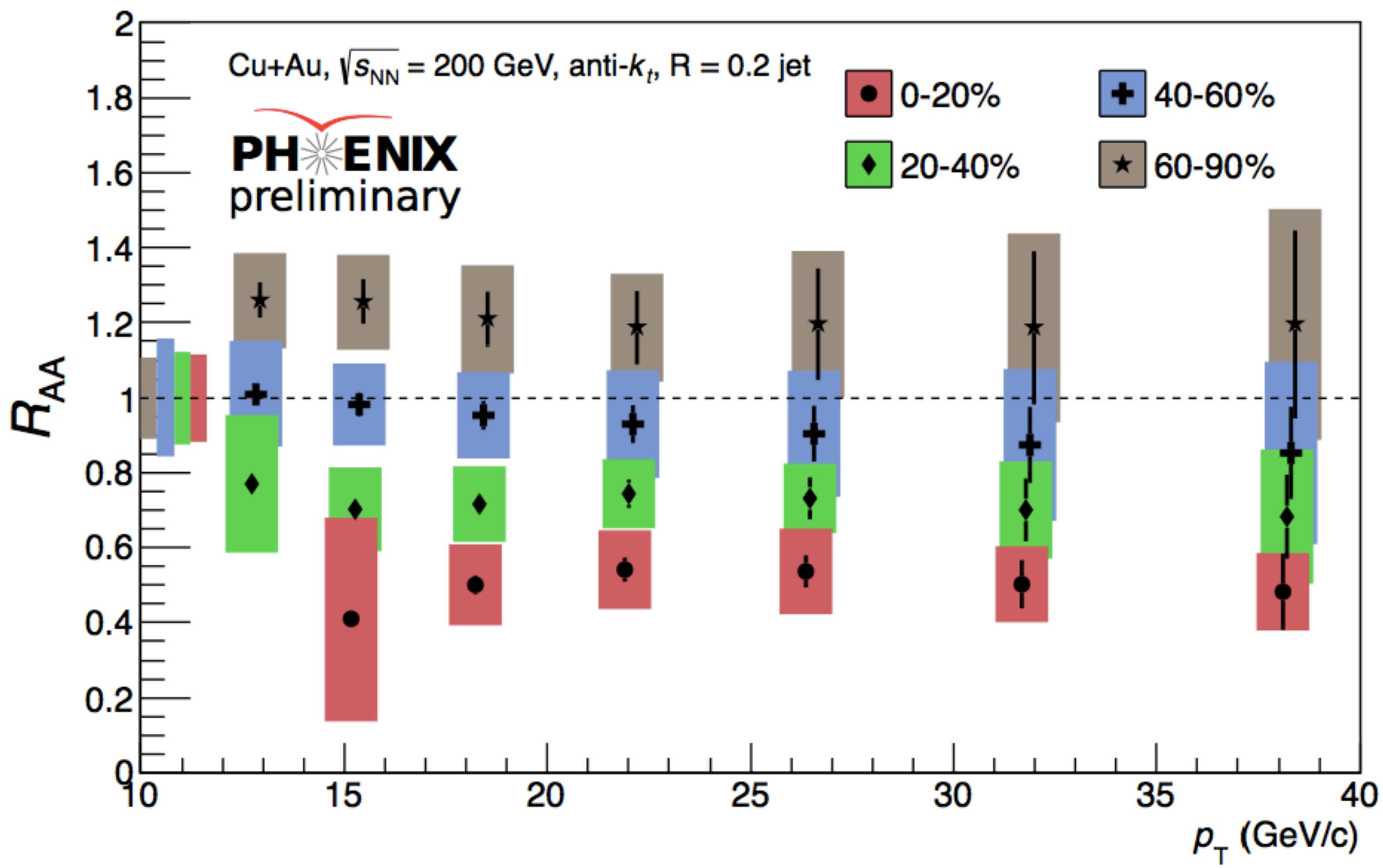
Coming at hard probes: new 3He+Au π^0 data, & comparison with this shrinking proton calculation



Jets in Cu+Au

Similar analysis to d+Au jets
Suppression of x 2 in central collisions
No significant p_T dependence
Enhancement for peripheral events, but not much outside systematic uncertainties

Hot matter suppression



Quarkonia

In-medium Quarkonia Program

Study the screening length in hot matter via:

- Modifications to quarkonia production in A+A collisions
- Relative to the baseline production in p+p collisions
- Correcting for modifications due to production in a nucleus (p,d+A)
    - Traditionally called cold nuclear matter (CNM) effects

Physics is extracted from comparison with theory - so ideally, we would like to:

Vary the temperature of the medium in A+A

- Collision energy (RHIC vs LHC gives wide lever arm)
- Mass of colliding ions
- Collision centrality (but not easy to model)

Vary the type and strength of underlying CNM effects

- Depends on collision energy
- Depends on rapidity

Charmonia - J/ψ

J/ψ in Au+Au Collisions - Rapidity Dependence

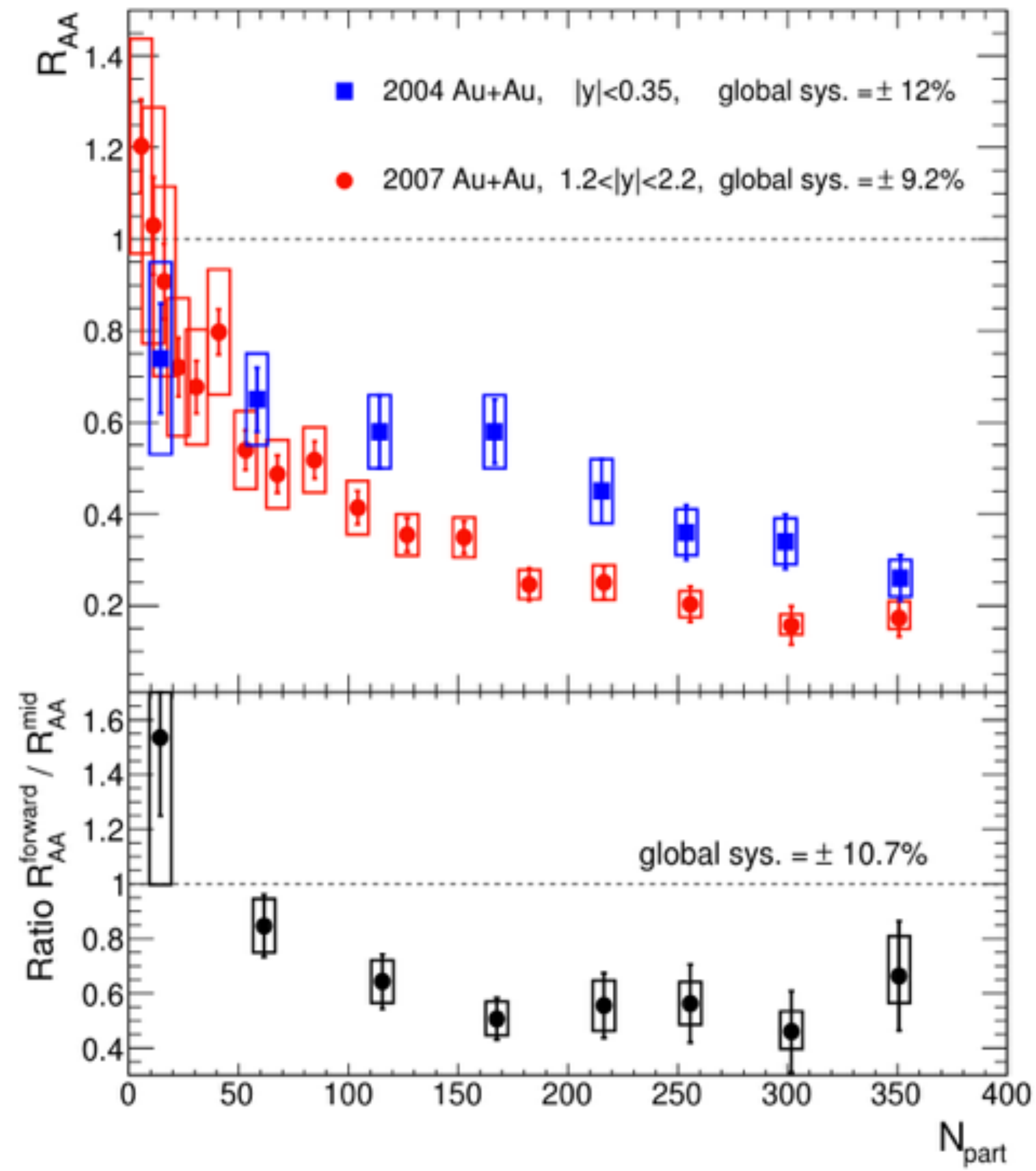
PHENIX 2004 and 2007 data

The suppression is strongest at forward rapidity

- Energy density is slightly smaller at forward rapidity
- But cold nuclear matter effects are different
- Also, underlying charm is smaller at forward rapidity

Question on Saturday: is this caused by cold nuclear matter effects?

- **next slide**

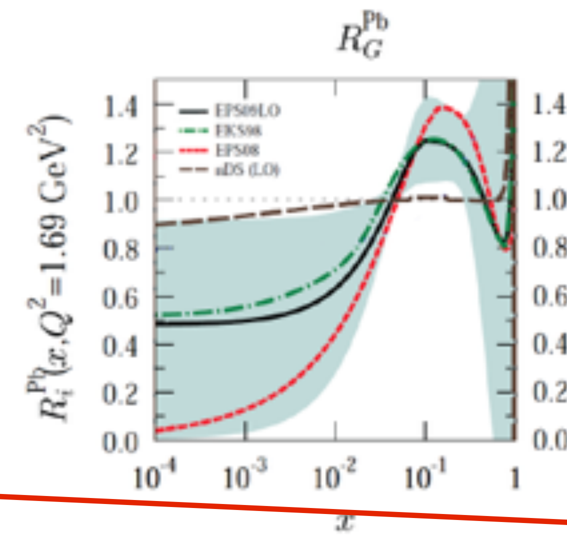


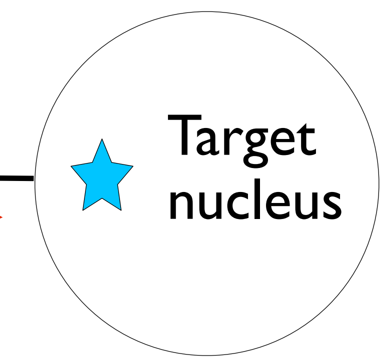
Cold Nuclear Matter Effects

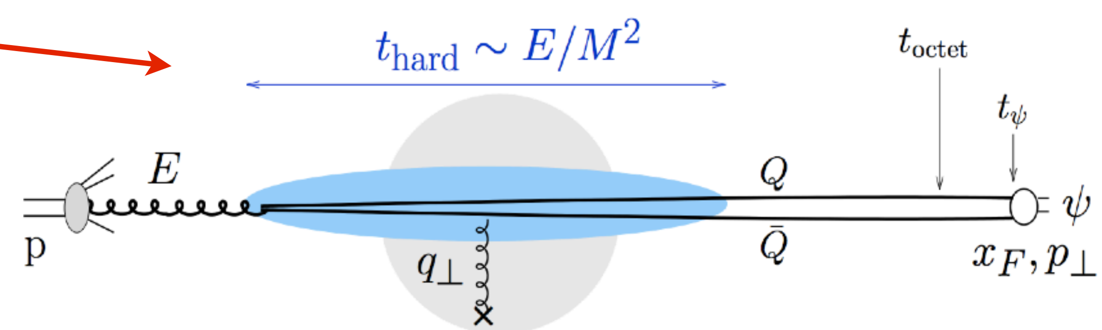
Processes that modify the quarkonia yield in a nuclear target are called cold nuclear matter (CNM) processes

CNM effects include

- Gluon shadowing – parton distributions modified in a nucleus
- Breakup of the precursor J/ψ by collisions with nucleons
- Initial state energy loss of partons in cold nuclear matter
- Cronin effect – multiple elastic scattering of partons







Notes:

- Gluon shadowing affects the underlying charm yield.
- Breakup reduces the **fraction** of charm forming bound charmonium.
- Initial state energy loss changes the rapidity distribution
- Cronin effect modifies only the p_T distribution.

A Note on Time Scales

At 100 GeV/nucleon (200 GeV/nucleon center of mass) the colliding nuclei have γ = 100. Time scales are roughly (in the CM):

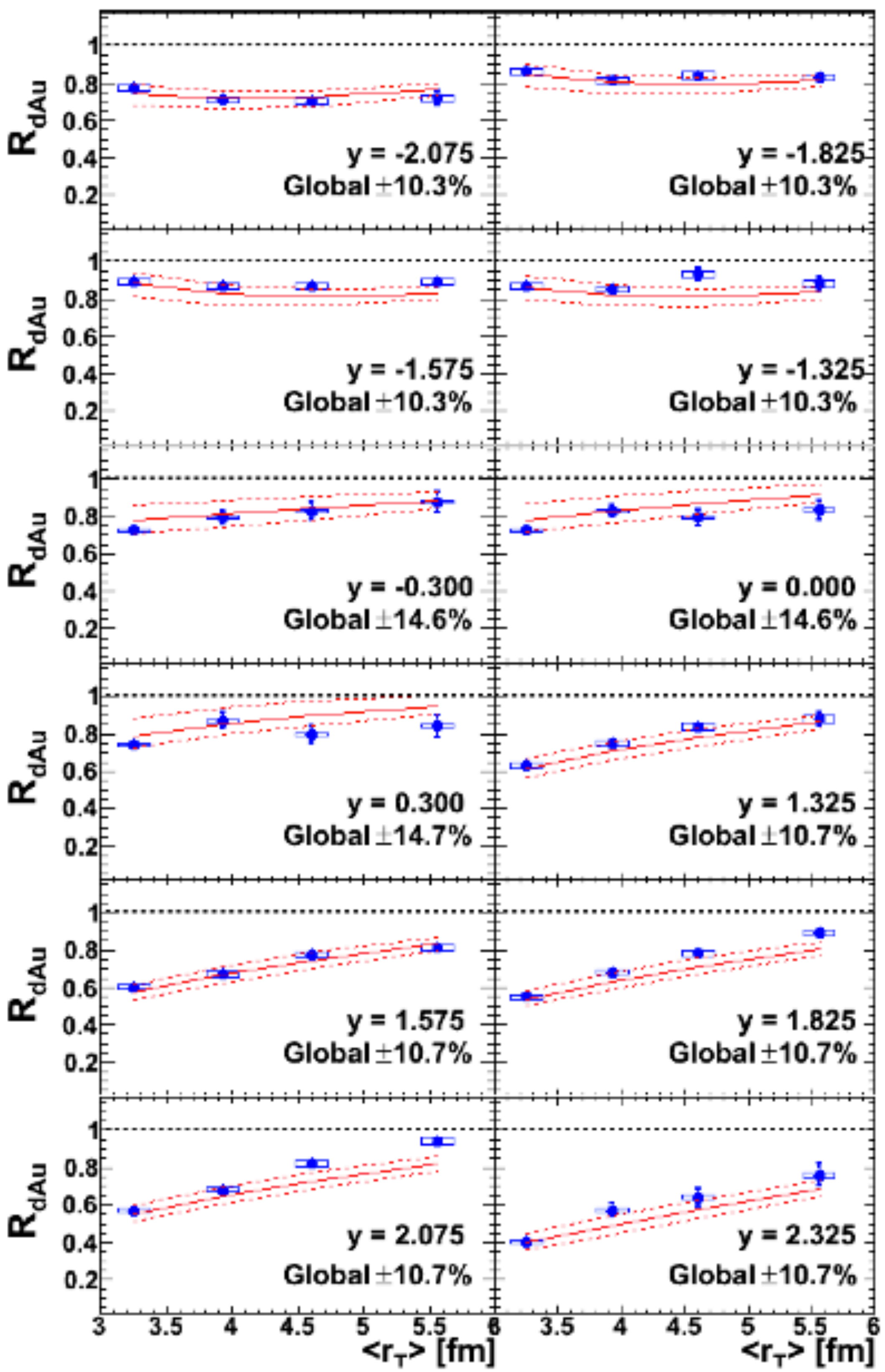
Nuclear crossing time ~ 0.3 fm/c (0.001 fm/c at LHC). CNM effects
J/ψ meson formation time ~ 0.3 fm/c
QGP thermalization time ~ 0.3 to 0.6 fm/c
QGP lifetime ~ 5-7 fm/c
J/ψ lifetime (free space) ~ 2000 fm/c

The creation of the charm pair that evolves into the J/ψ and its modification in the hot medium occur on different time scales. They are often taken as being factorizable.

If so, we can study the cold nuclear matter (CNM) effects using p+A to help understand the initial J/ψ population in A+A.

Cold nuclear matter effects from d + Au

Phys.Rev. C87 (2013) 5, 054910



PHENIX d+Au J/ψ data at 12 rapidities from 2008 run, plotted vs average impact parameter in the Au nucleus

Describe cross sections for d+A data with EPS09 shadowing plus absorption parameter σ_{abs}

- Vary σ_{abs} in a Glauber MC study and compare with data using χ^2

σ_{abs} shows strength of cold nuclear matter suppression **not** due to shadowing

Cold nuclear matter effects from p,d + A

Combine PHENIX d+Au J/ψ data at 12 rapidities, and J/ψ data from 6 fixed target experiments

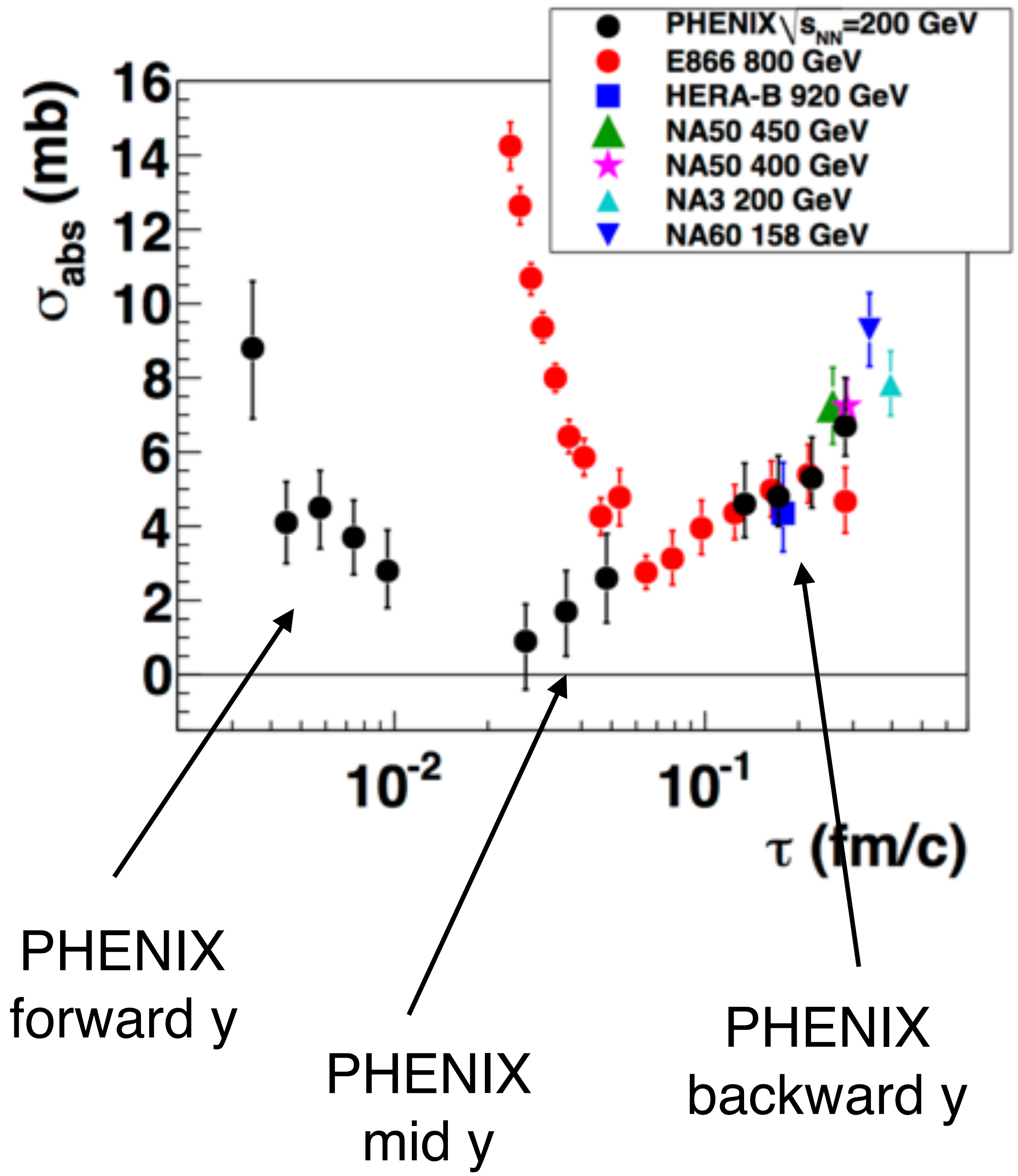
All cross sections parameterized with EKS98 or EPS09 shadowing plus absorption parameter σ_{abs}

Plot absorption parameter vs nuclear crossing time (τ) for p+A or d+Au at 17.3A - 200A GeV CM collision energy

For Au + Au collisions: fold forward & backward rapidity CNM effects together in1.2 < η< 2.2

- Stronger CNM suppression than at mid rapidity

Phys.Rev. C87 (2013) 5, 054910

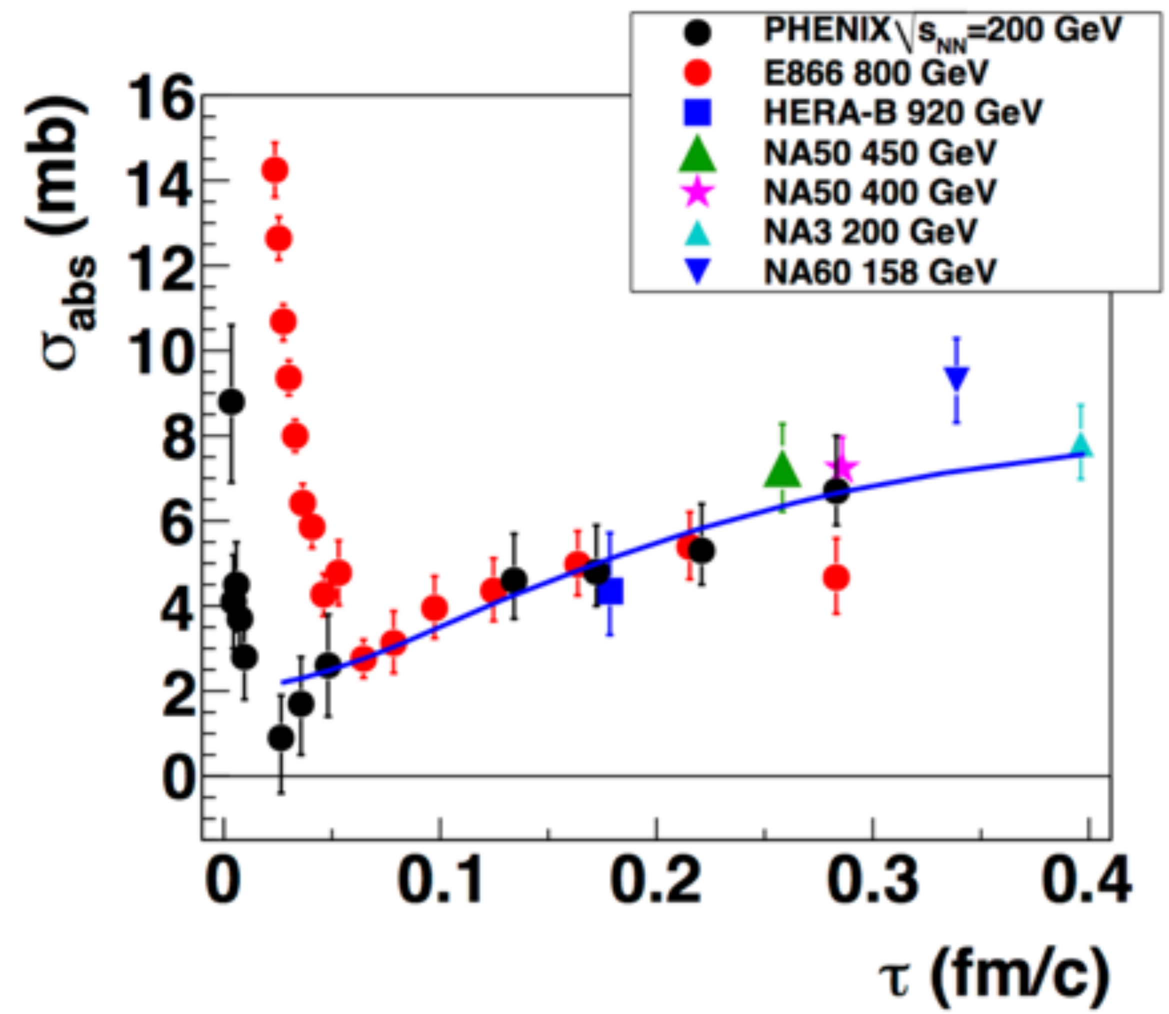


Aside: What is the source of σ_{abs}?

Fit region above τ ~ 0.05 fm/c with model of expanding color neutral meson

- Suggests we really have breakup at backward rapidity (large τ), something else at forward rapidity (small τ)

The suppression at forward rapidity seems to be well explained by energy loss in cold nuclear matter



Phys.Rev. C87 (2013) 5, 054910

J/ψ in Au+Au Collisions

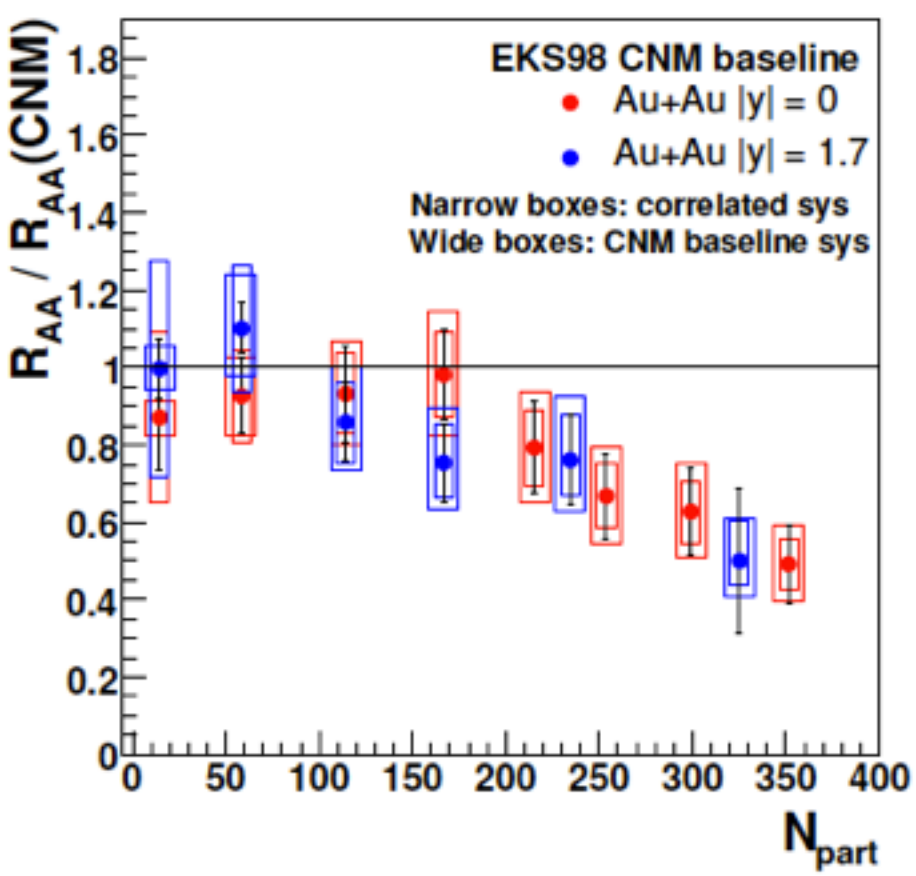
(Early attempt to remove CNM Effects)

Use Glauber model to estimate R_{AA} due to shadowing plus σ_{abs} measured from d+Au data

Divide measured Au+Au R_{AA} at forward/backward and mid rapidity by R_{AA}(CNM) to get estimate of hot matter effect

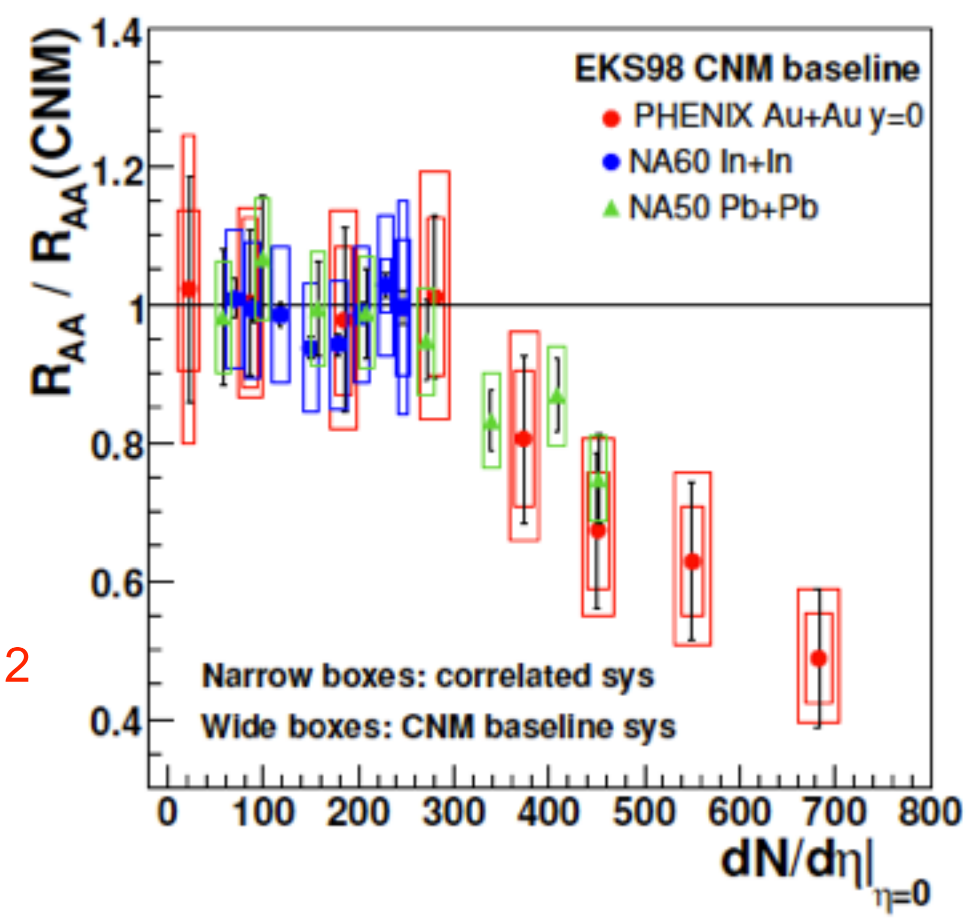
Compare mid rapidity PHENIX Au+Au data with NA60 In+In and NA50 Pb+Pb data after correction for CNM effects

Plot vs particle multiplicity at mid rapidity (used as proxy for energy density)



Quarkonium Working Group report, Eur. Phys. J **C71** (2011) 1534

PHENIX PRC 84 054912 (2011)

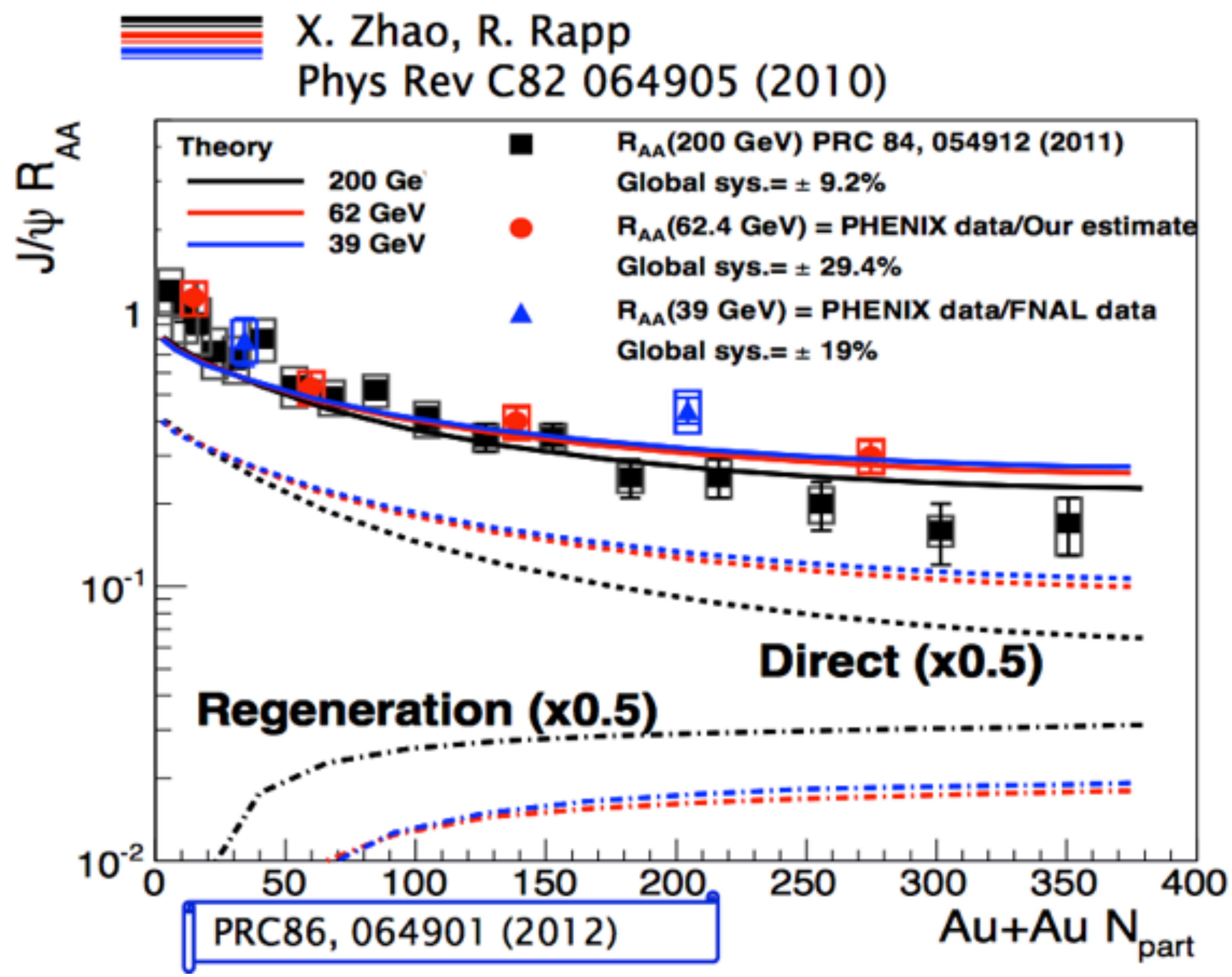


J/ψ in Au+Au collisions - Energy Dependence

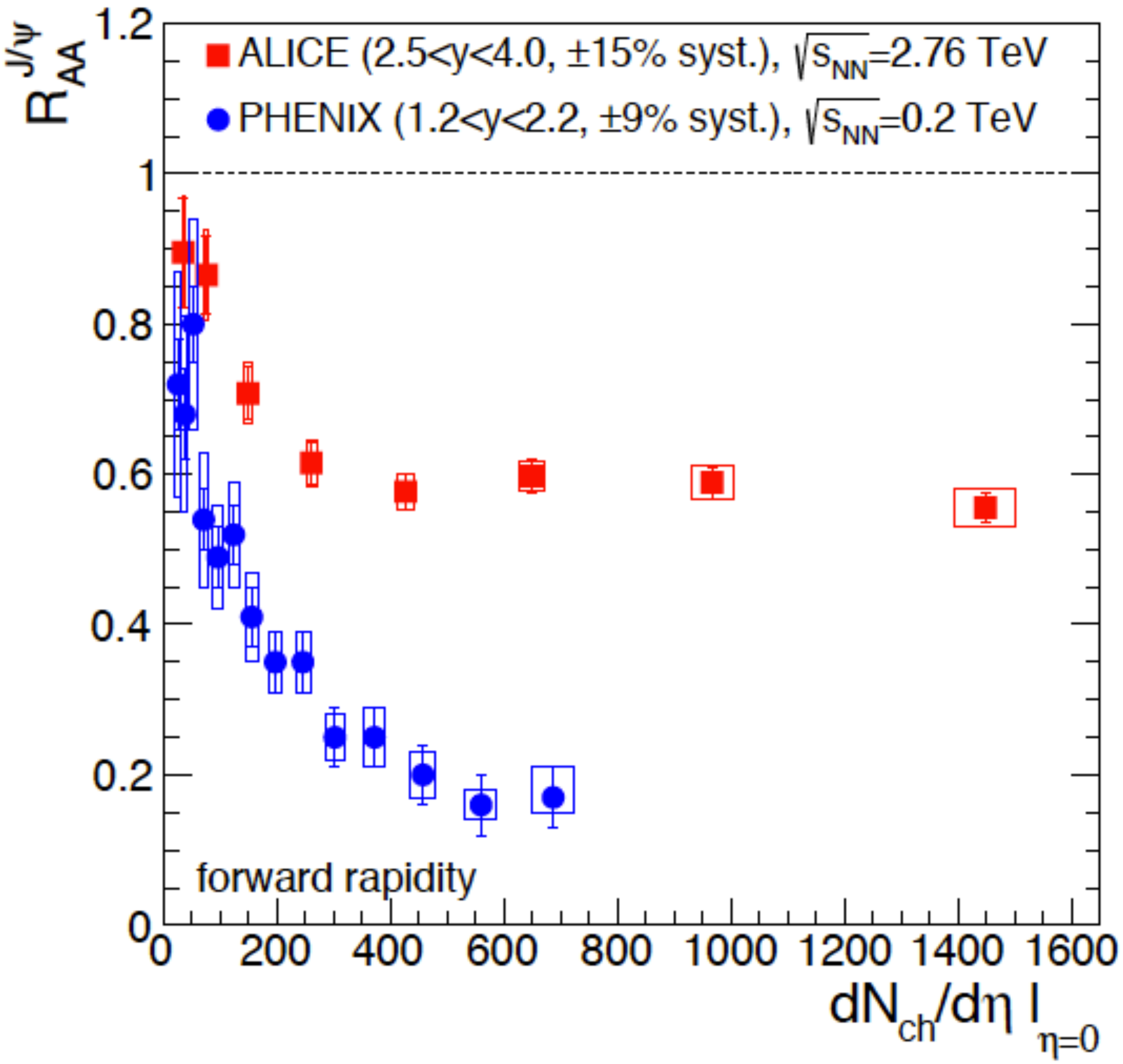
39, 62, 200 GeV at $1.2 < |\eta| < 2.2$
R_{AA} values similar, lowest at 200 GeV

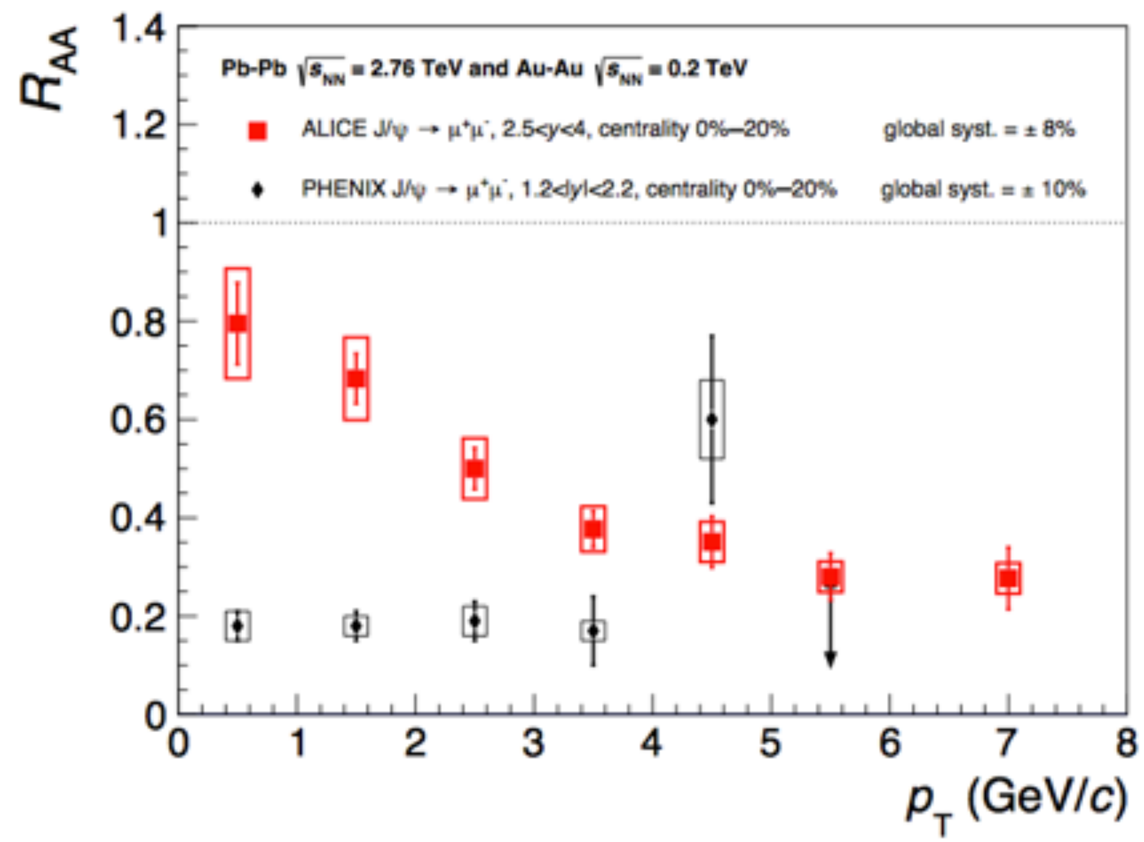
Similarity of R_{AA} at these three energies in the model comes from balance between:

- Increased suppression due to higher energy density
- Increased coalescence due to larger charm production

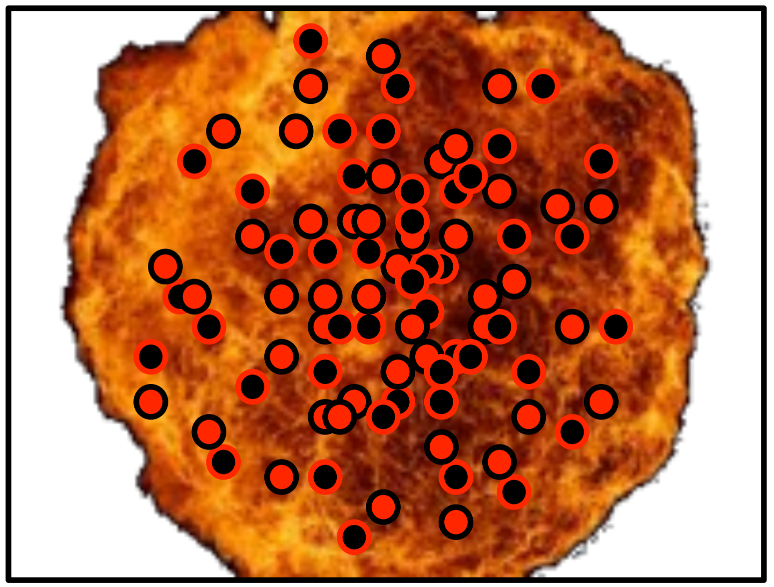


Jump to higher energy - PHENIX vs ALICE J/ψ

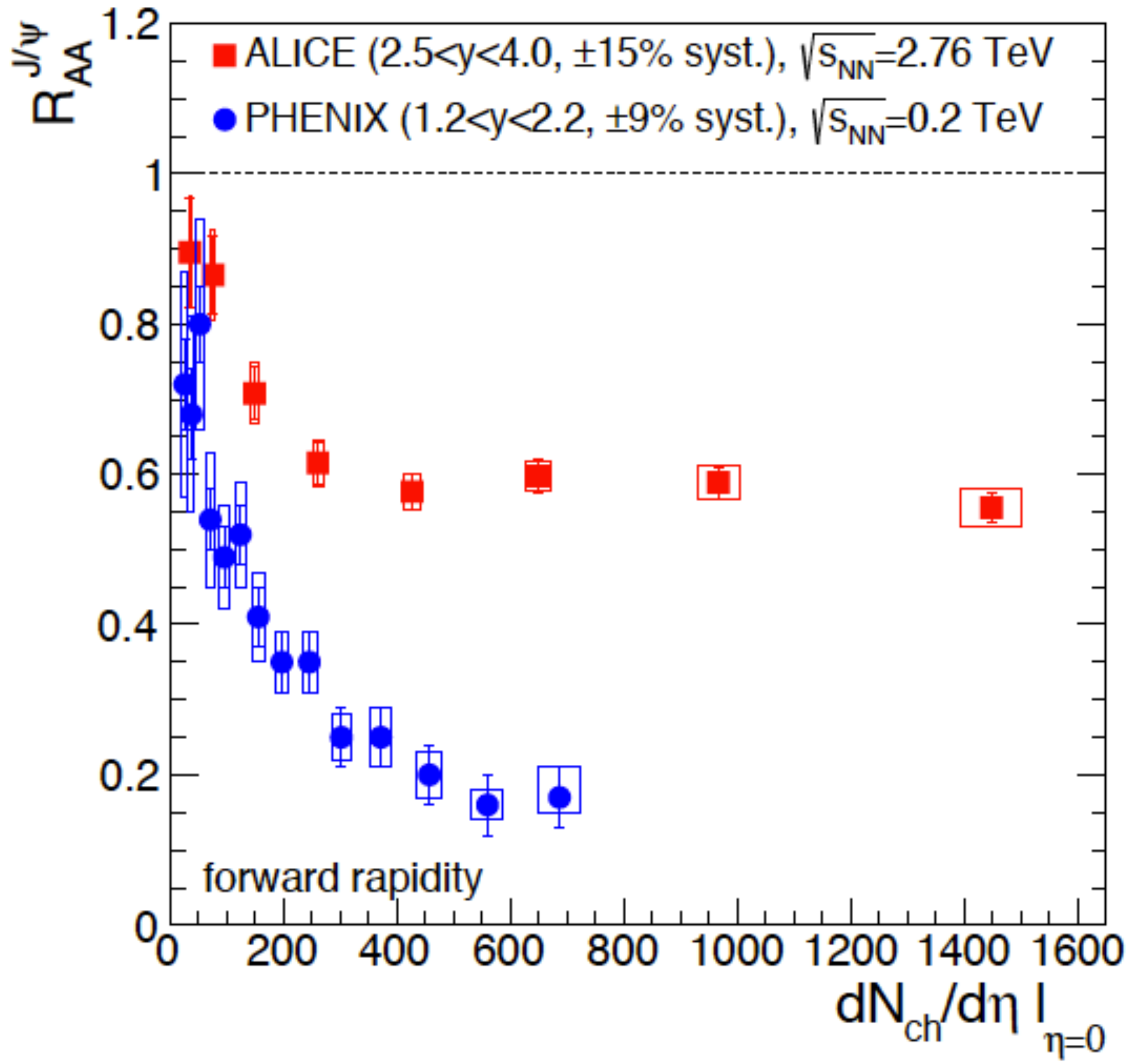


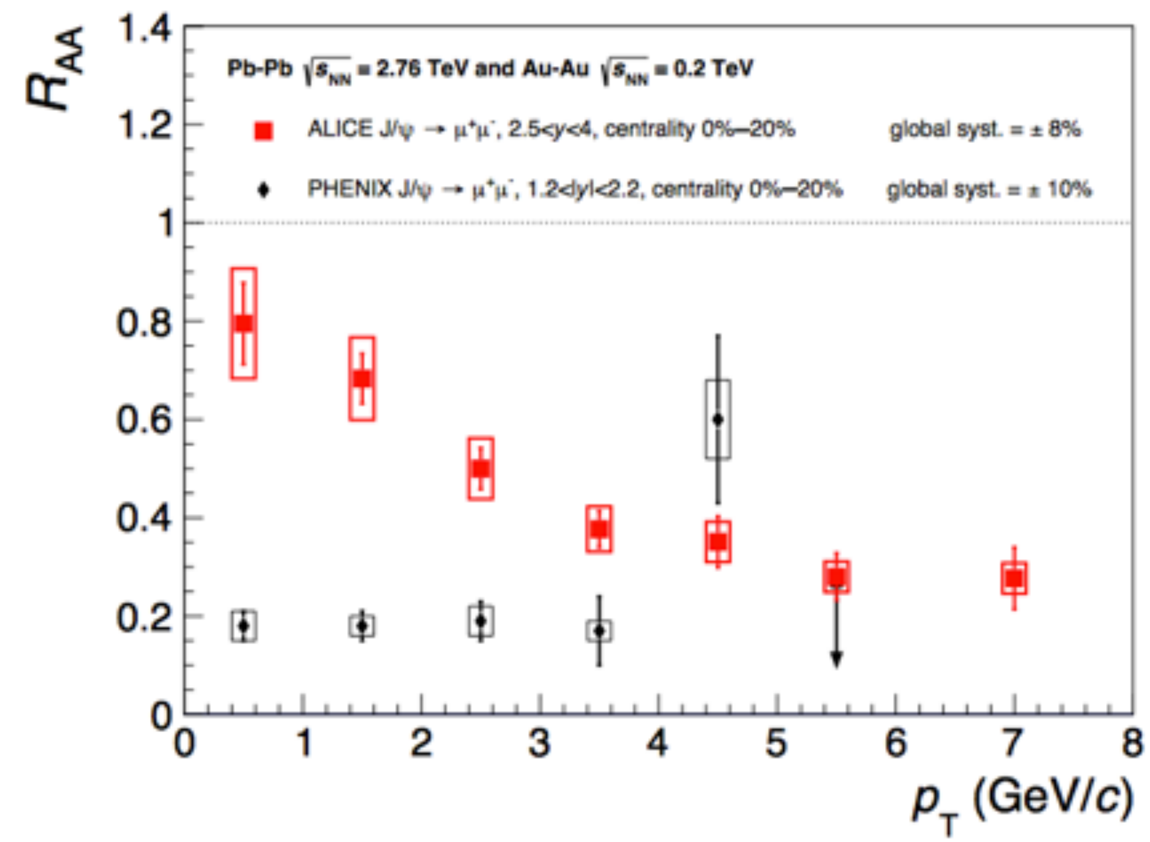


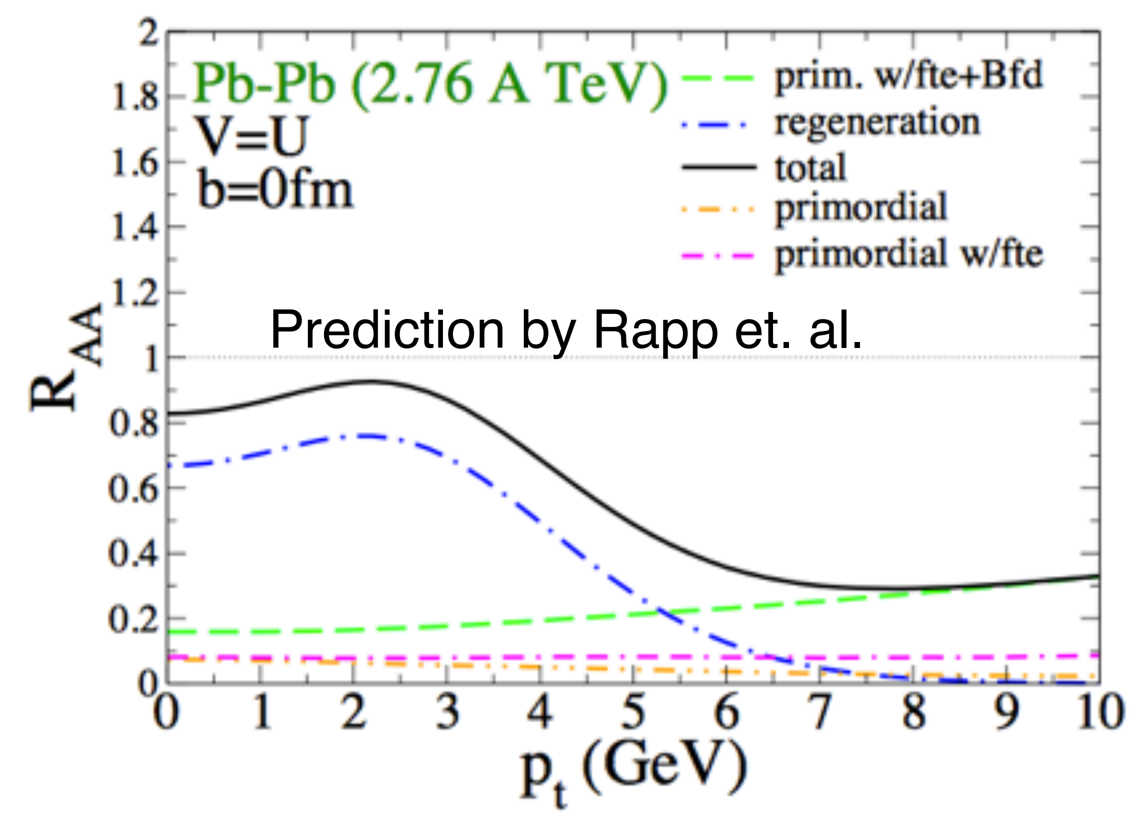
The striking difference in suppression is mostly due to coalescence at LHC, partly due to stronger CNM effects at forward rapidity at RHIC energy.



Jump to higher energy - PHENIX, ALICE J/ψ







The striking difference in suppression is mostly due to coalescence at LHC, partly due to stronger CNM effects at forward rapidity at RHIC energy.

Where does coalescence start to dominate?

U+U collisions allow us to go to higher energy density at RHIC

Central U+U collisions should have:

- 15-20% higher energy density than Au+Au collisions
  - stronger color screening
- Increased charm production from ~ 25% larger N_{coll} values
  - stronger coalescence

J/ψ production in U+U collisions allows us to explore how the trade-off between color screening and coalescence evolves as we increase energy density and charm production

U deformation

Need N_{coll} to get R_{AA} for U+U. Requires a deformed Woods Saxon distribution of the nucleons in the U nucleus

$$\rho = \frac{\rho_0}{1 + exp([r - R']/a)}$$

where

$$R' = R[1 + \beta_2 Y_2^0(\theta) + \beta_4 Y_4^0(\theta)]$$

We considered two parameterizations of the deformation of the U nucleus:

Set 1 (Phys. Lett. B 679, 440 (2009)) - "conventional" description of the U deformation

- The mean radius and diffuseness are taken from electron scattering

Set 2 (Phys. Lett. B 749, 215 (2015)) differs in 2 ways:

- Takes into account the finite radius of the nucleon
- Averages over all orientations of axis-of-symmetry
  - match average radius and diffuseness to values reported from electron scattering

Effect of U deformation model

The parameters for set 1 are significantly different in their surface diffuseness:

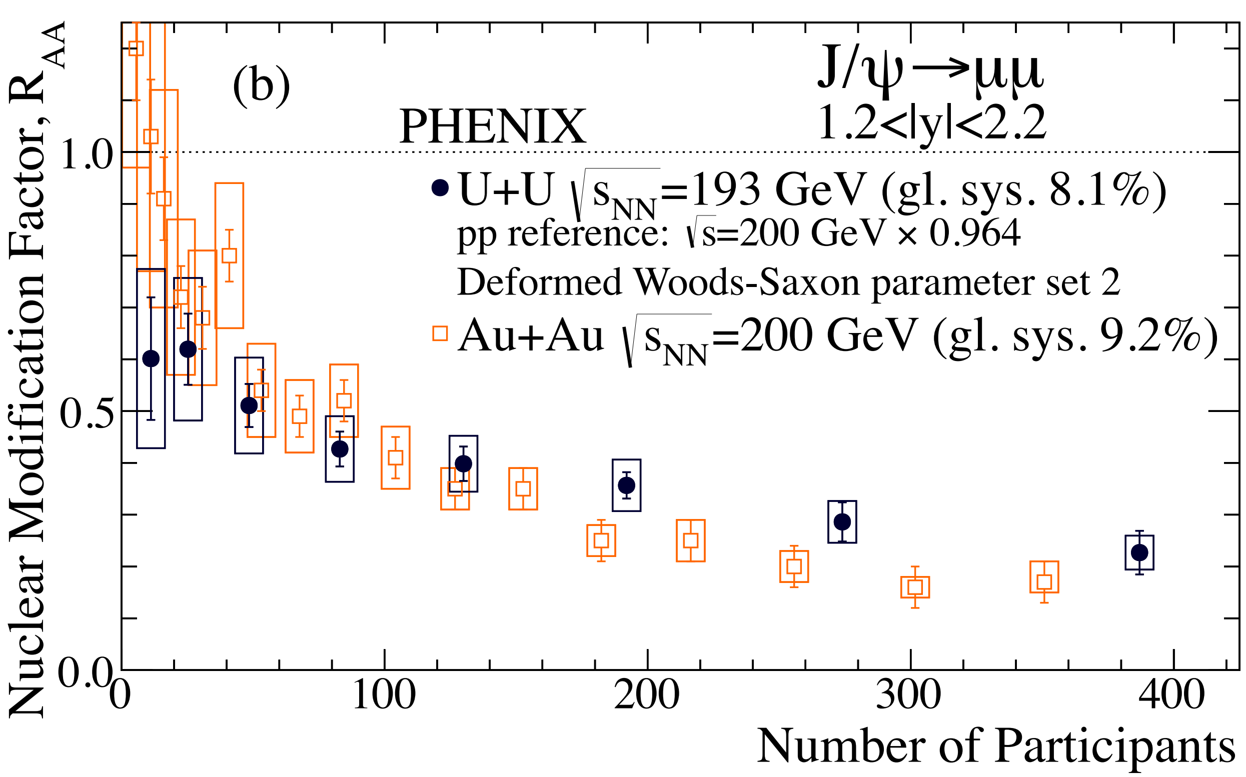
Parameter	set 1	set 2
$R\ (fm)$	6.81	6.86
$a\ (fm)$	0.6	0.42
β_2	0.28	0.265
β_4	0.093	0

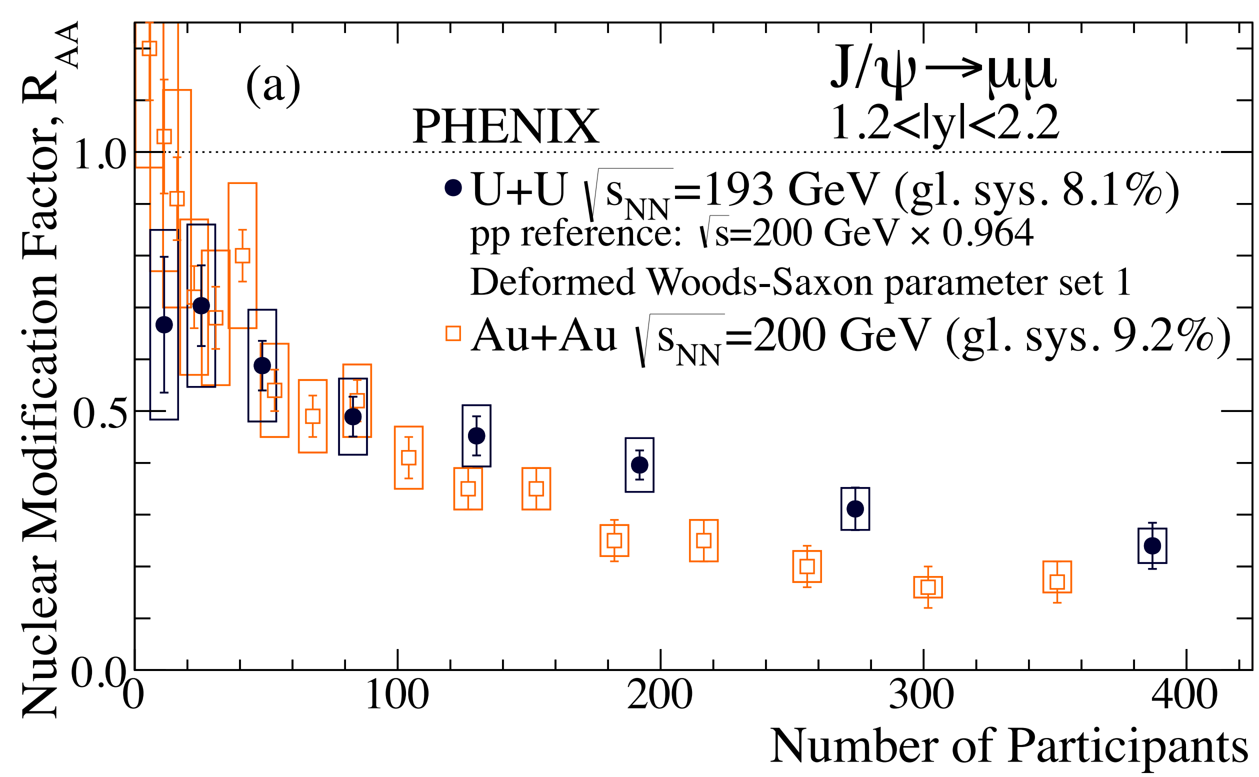
Larger surface diffuseness for set 1 results in a less compact nucleus, a larger reaction cross section by 12%, and N_{coll} values that are smaller by 6 - 15%

Set 2

Phys. Rev. C 93, 034903 (2016)

Set 1





U+U vs Au+Au J/ψ

Take invariant yield ratio:

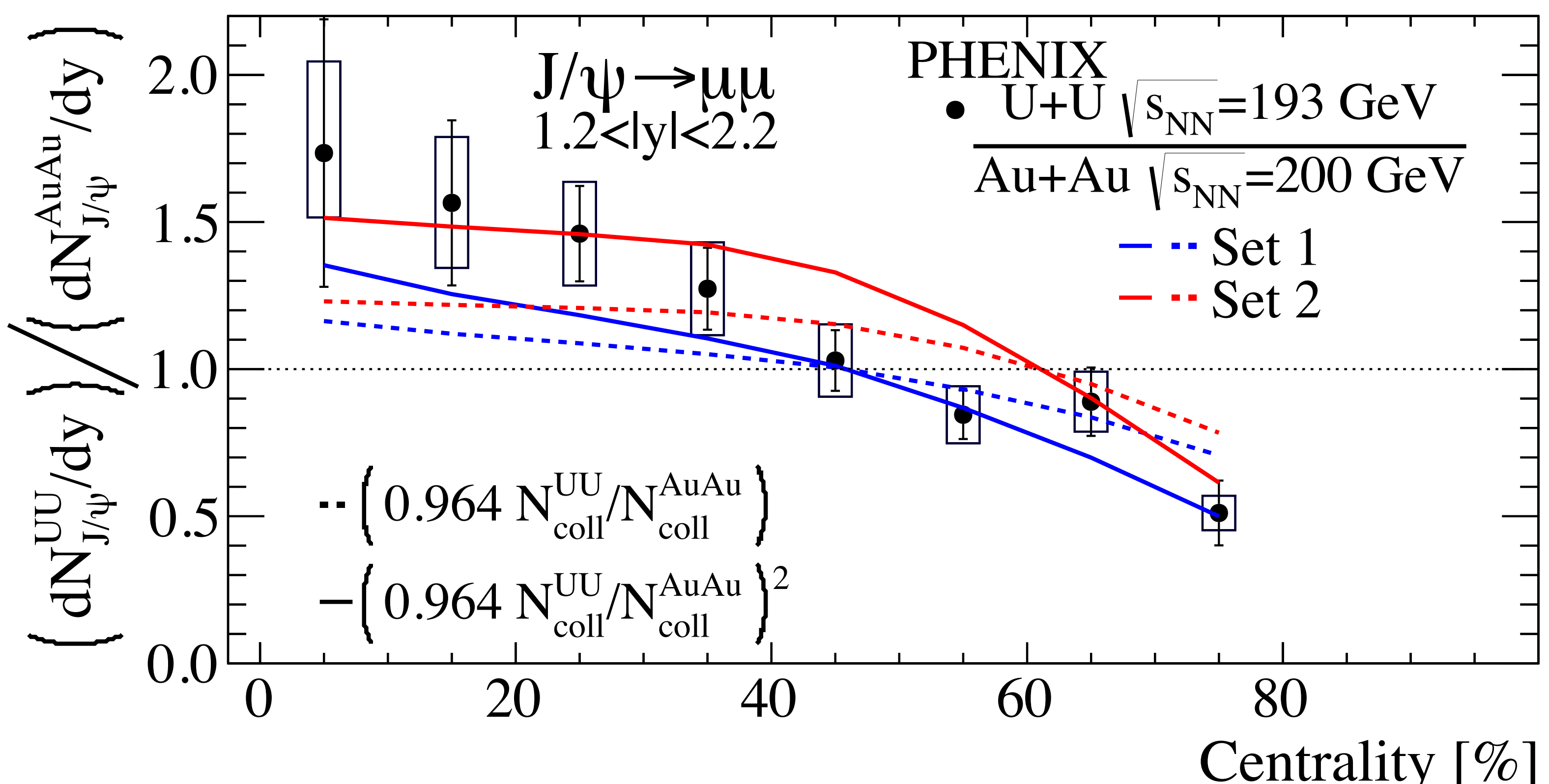
Curves show centrality dependence if J/ψ production scaled with

- N_{coll} (dashed lines)
- N_{coll}^2 (solid lines)

Set 1 (blue) Not much difference

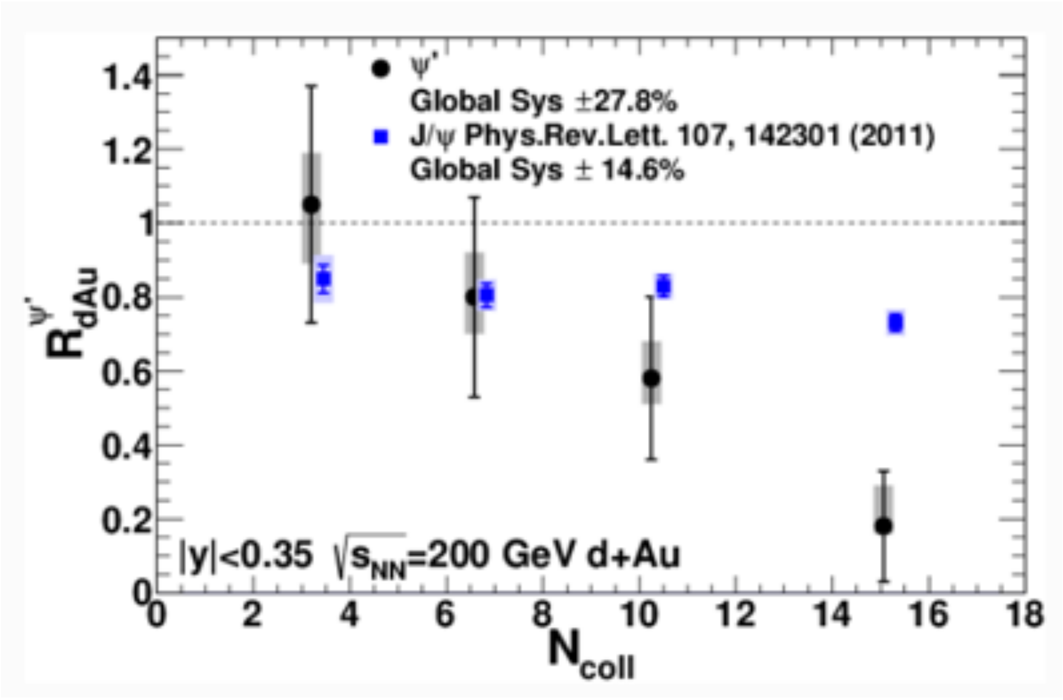
set 2 (red) Favors N_{coll}^2 for central

Phys. Rev. C 93, 034903 (2016)



Charmonia - $\psi(2S)$

d+Au ψ' - mid rapidity



PHENIX R_{dAu} data

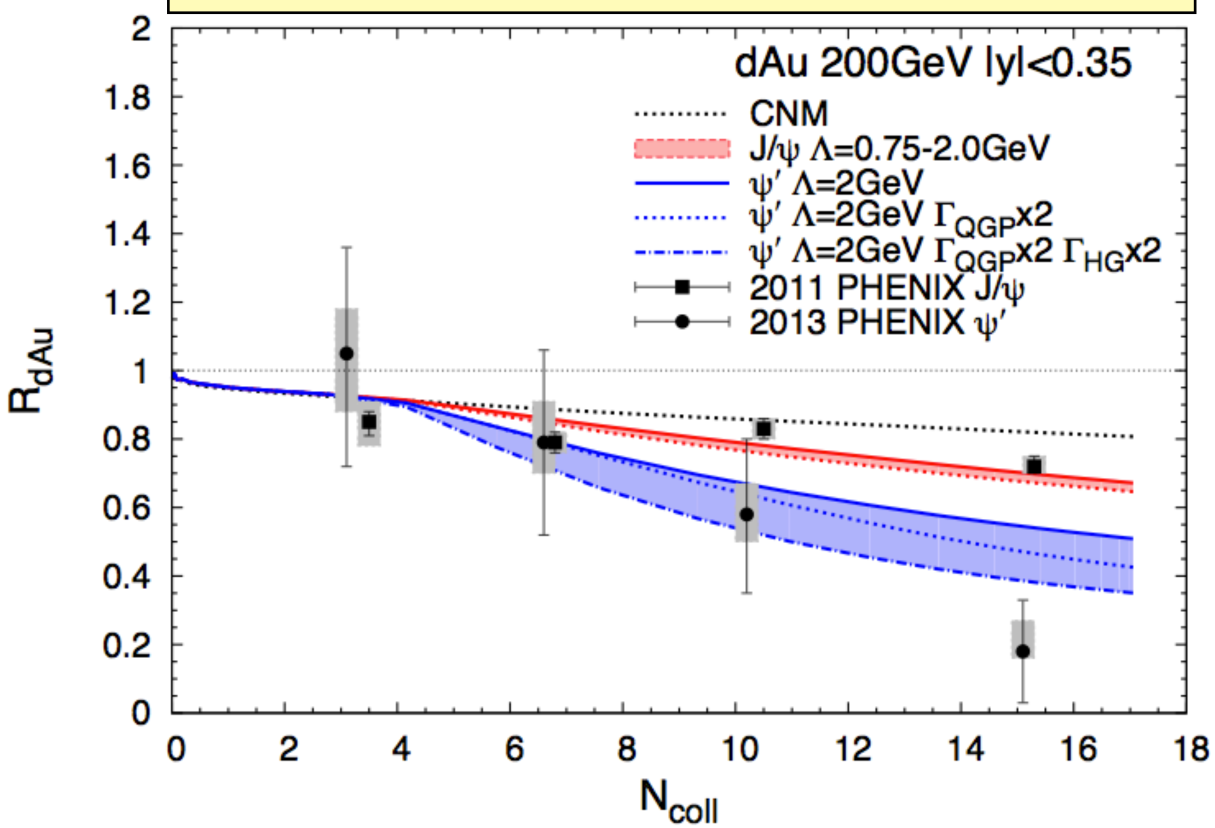
PRL111 (2013) 202301

Too strong for CNM effects:

Interpreted as final state suppression due to effects of co-moving matter on the weakly bound ψ' state

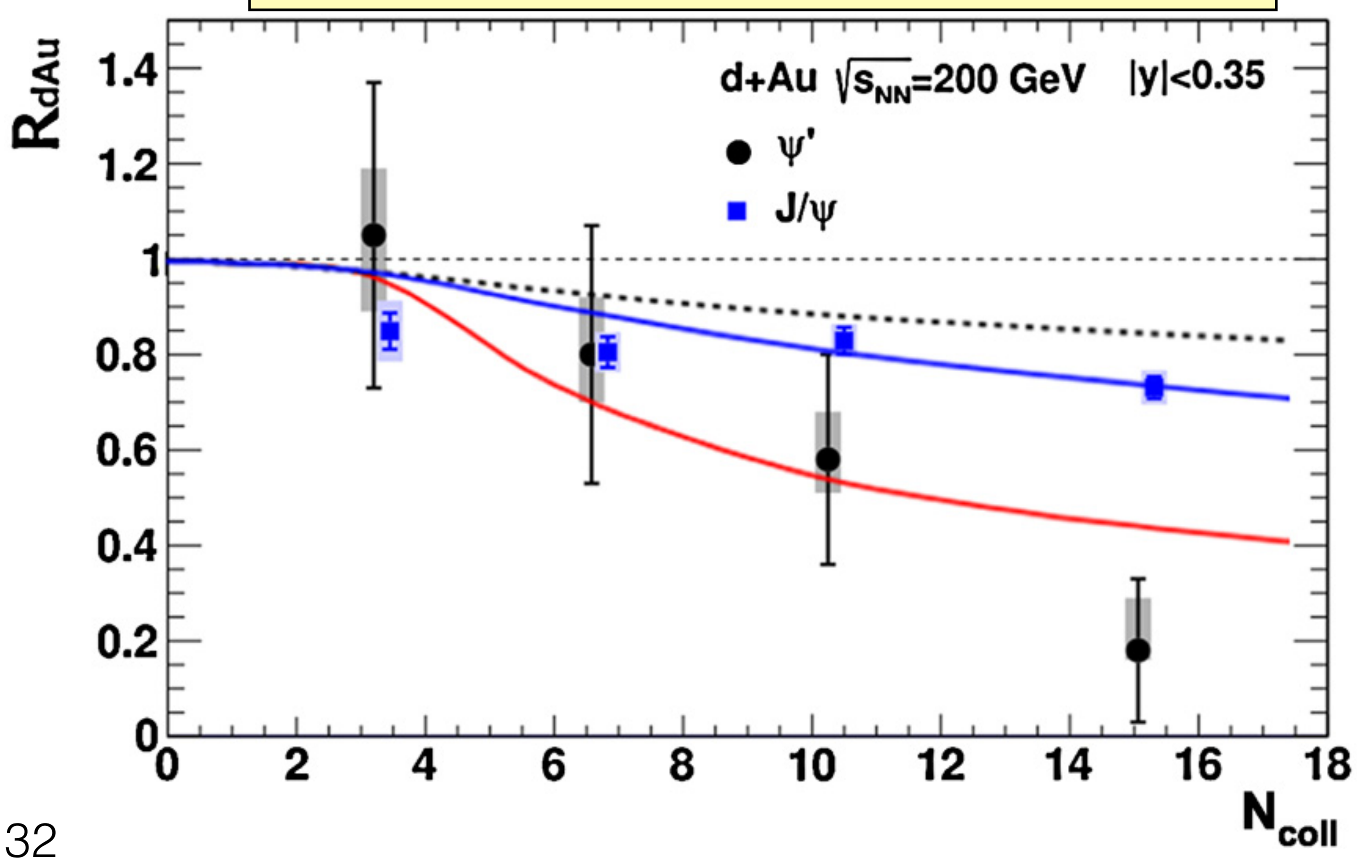
Du & Rapp arXiv:1504.00670

Hadronic gas + QGP in final state



Ferreiro (PLB 749 (2015) 98)

"Comovers" in final state

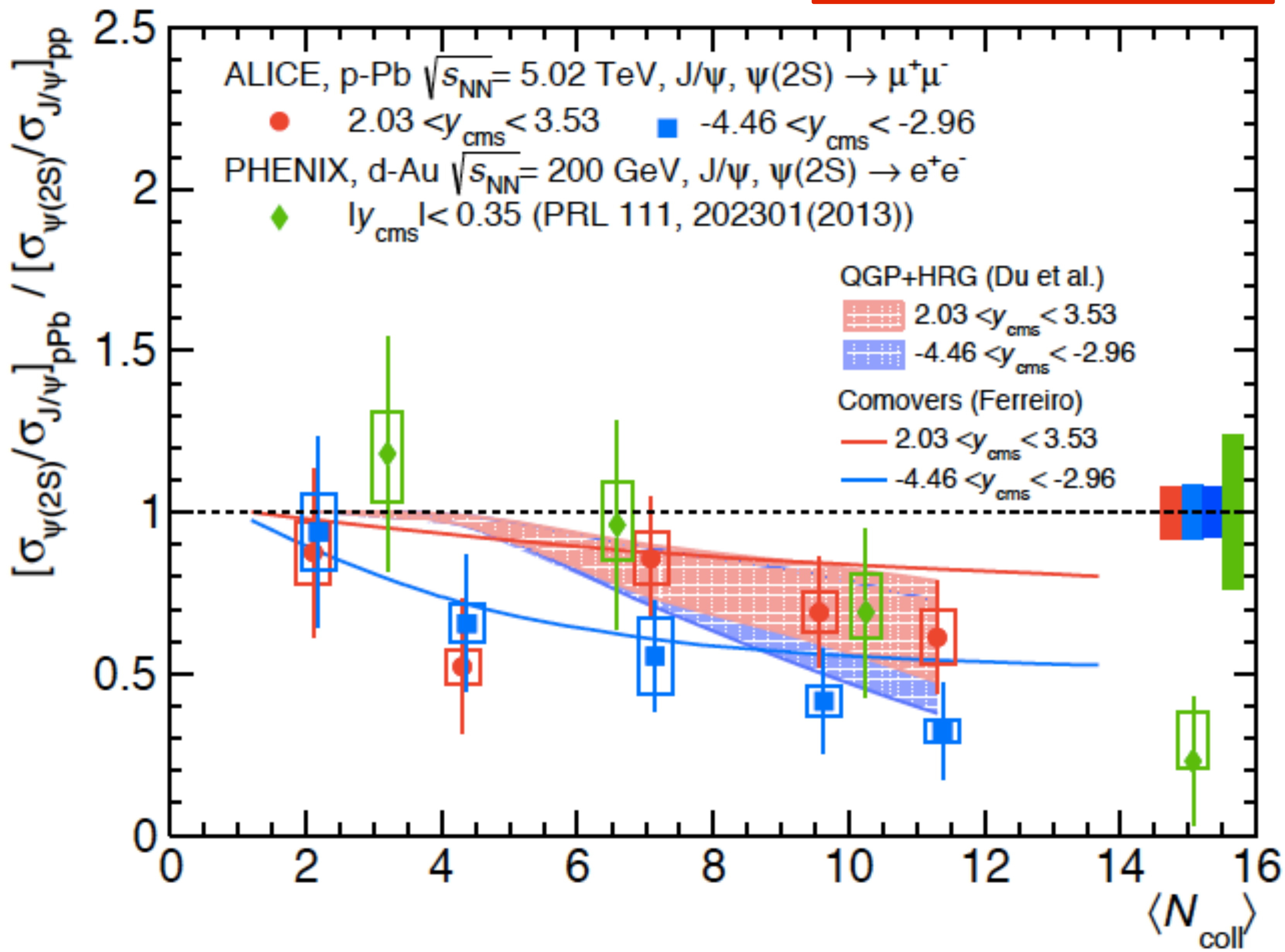


d+Au ψ' - comparison with p+Pb from ALICE

Double ratio has similar dependence on collision centrality at the two very different collision energies

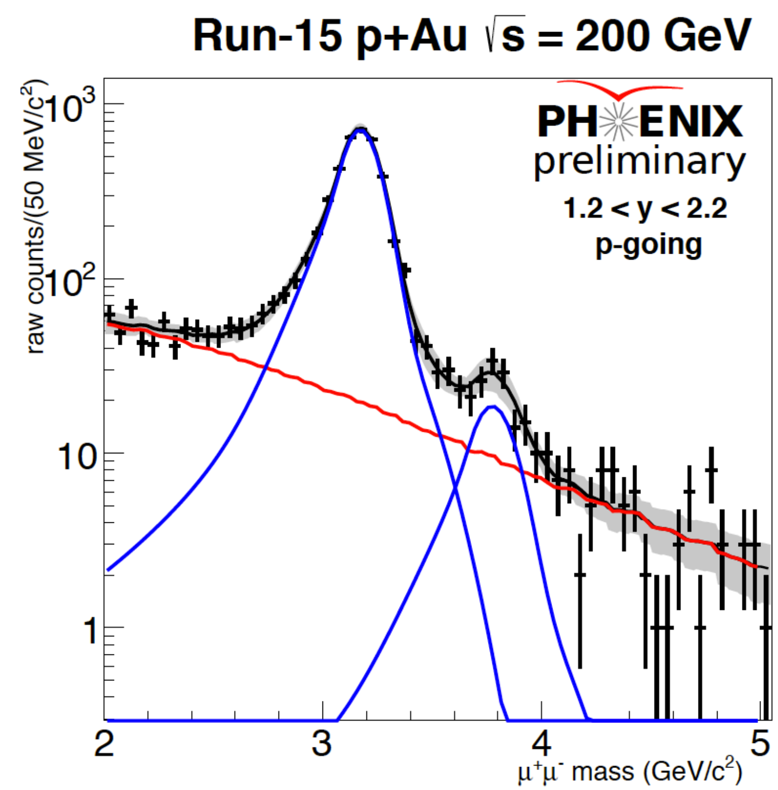
Seems to be explained well by final state models

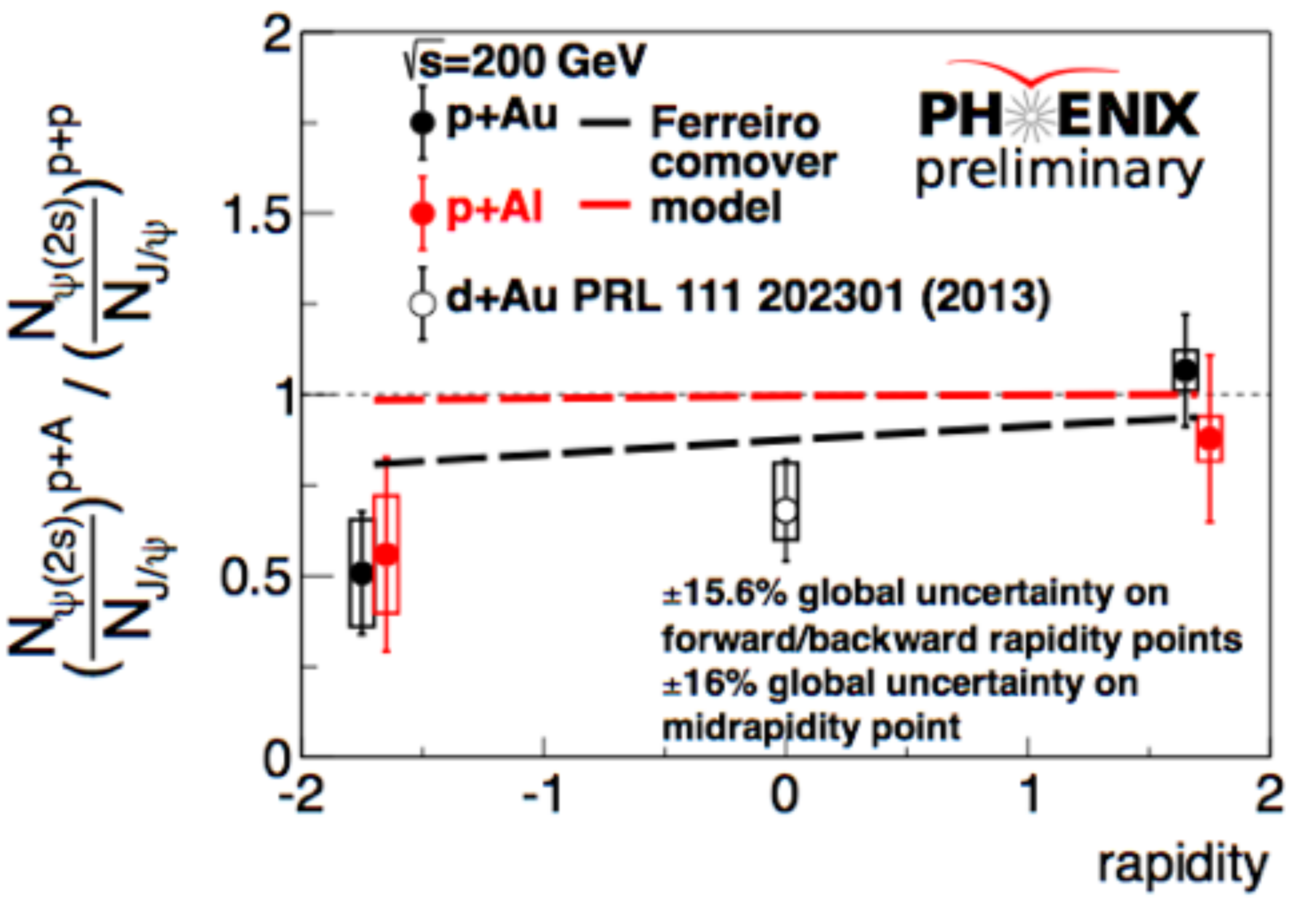
JHEP 06 (2016) 50

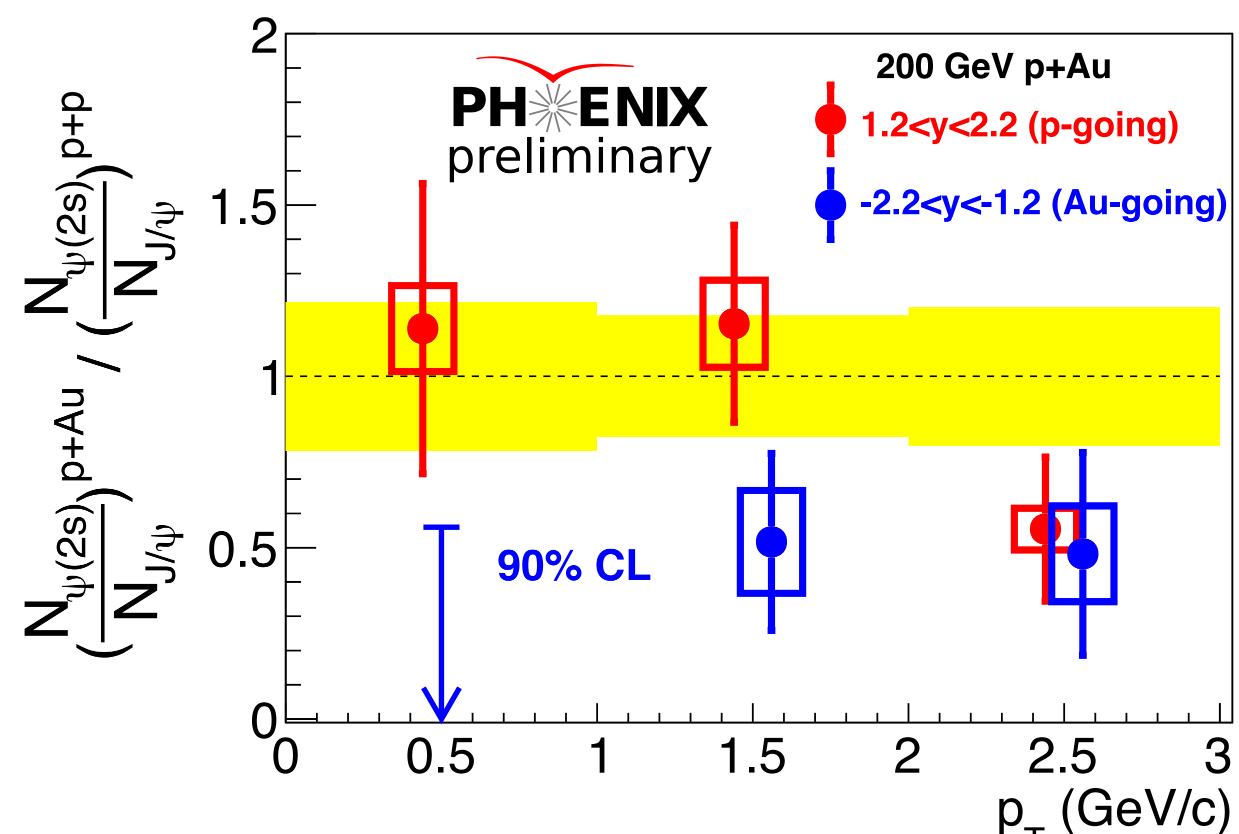


PHENIX p+Al, p+Au ψ’

Add forward/backward rapidity p+Au and p+Al measurements from RHIC 2015 run - strong suppression at backward rapidity, consistent trend with midrapidity







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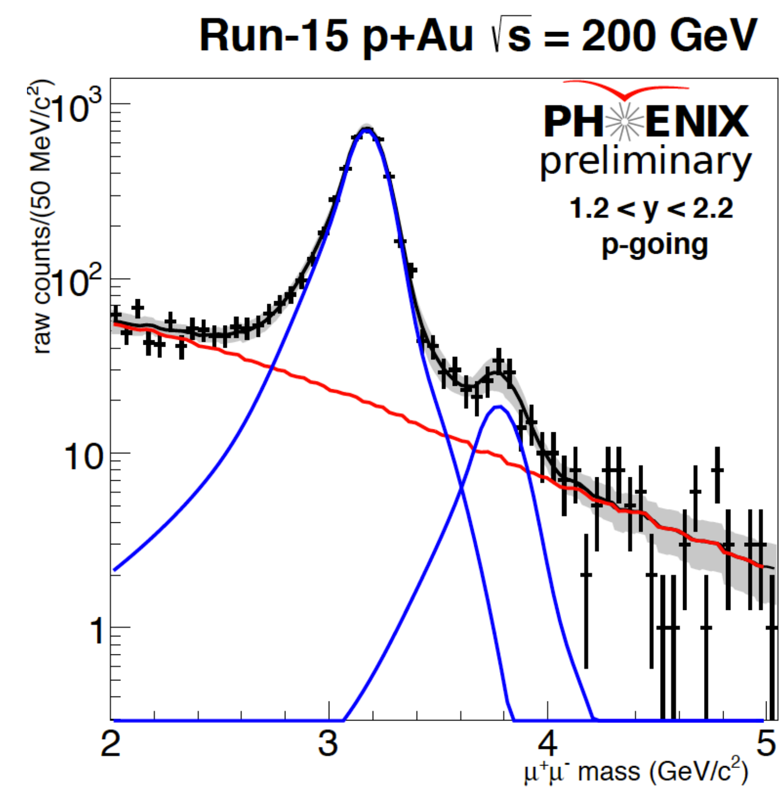
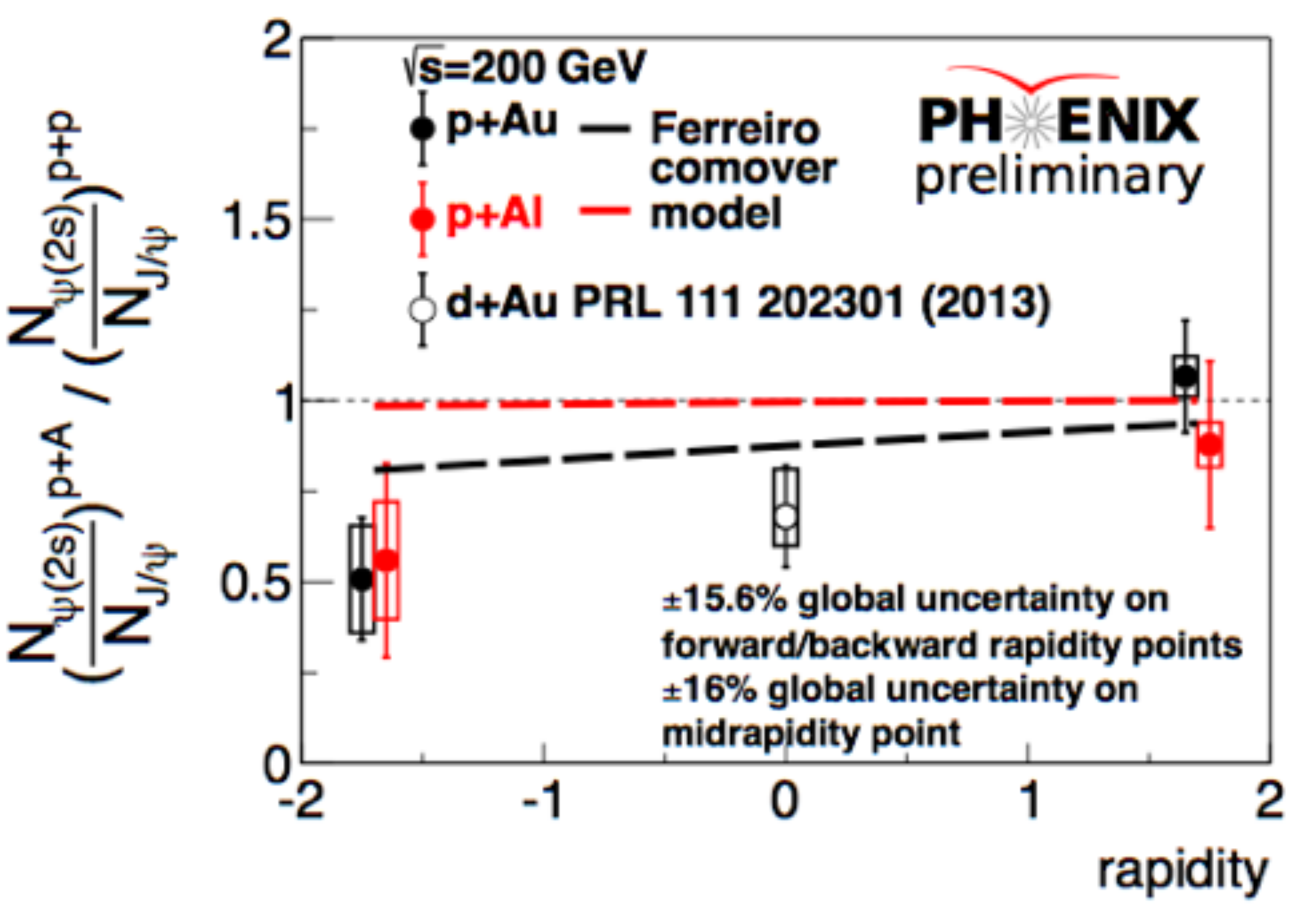
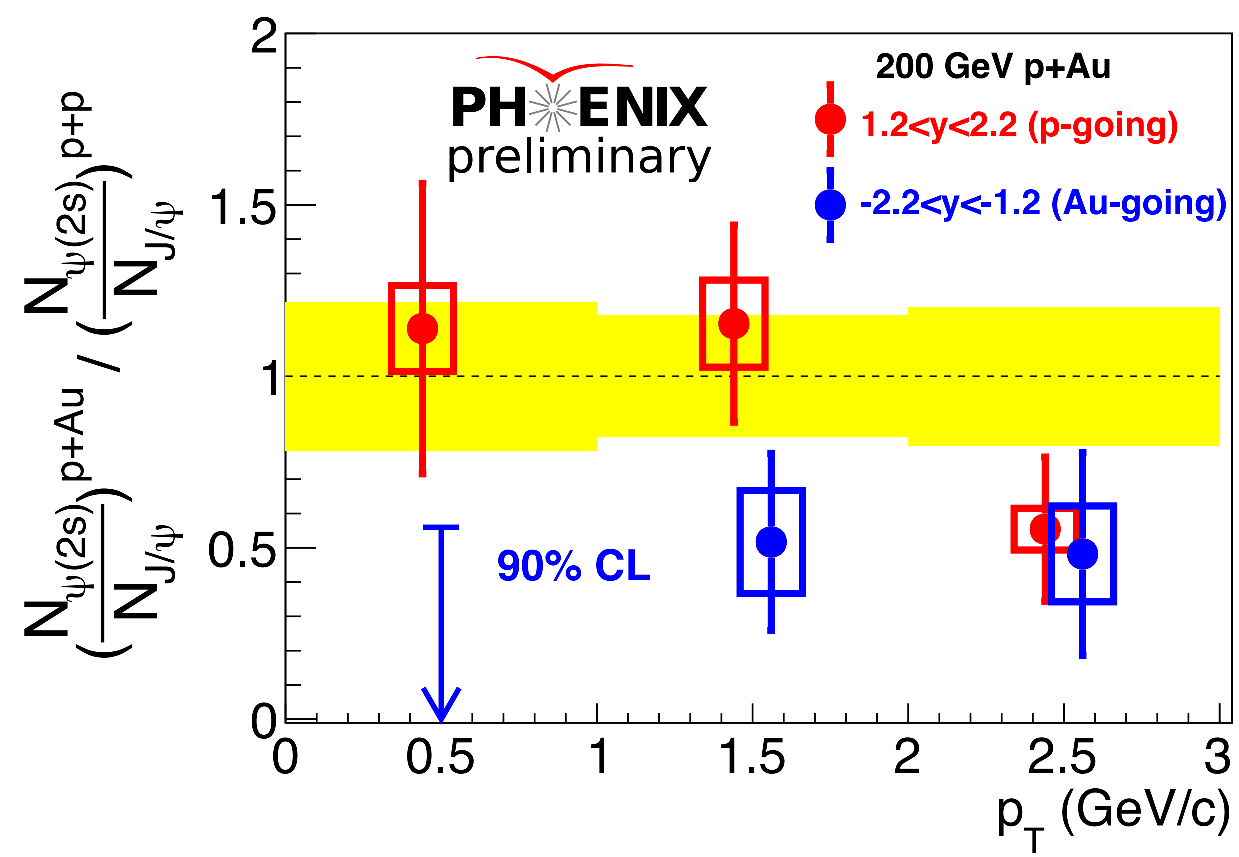


Coming at Hard Probes: Final ψ(2S)/ψ(1S) ratios at forward/backward rapidity in

- p+p, p+Al, p+Au, ^{3}He+Au





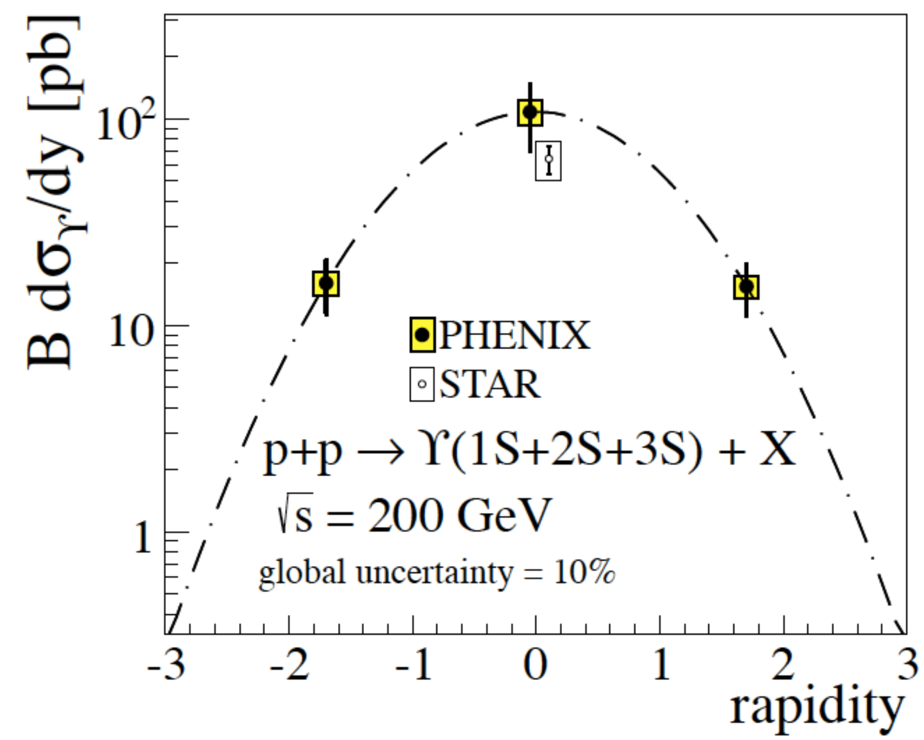
Upsilons

PHENIX Υ(1S+2S+3S) in Au+Au

Statistics starved measurement for PHENIX due to

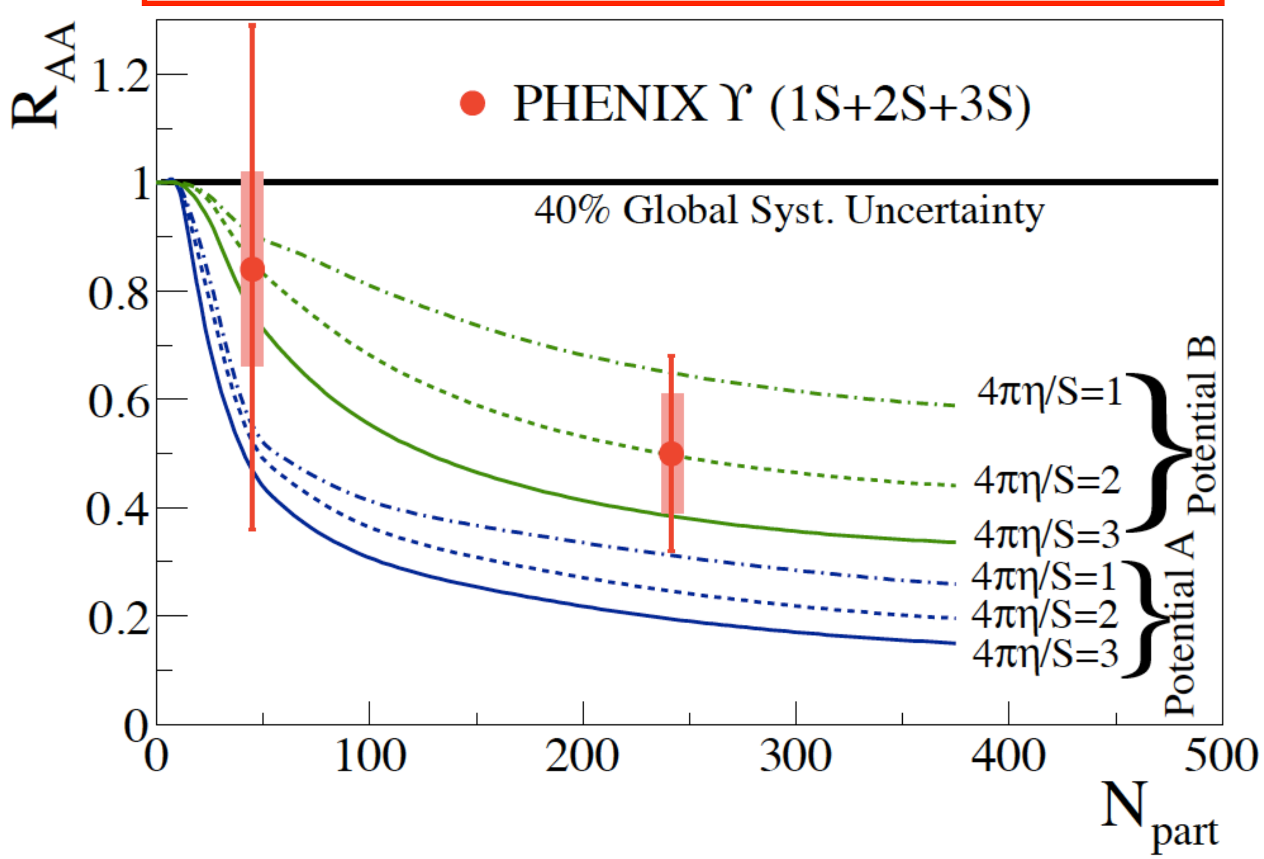
- small acceptance at midrapidity,
- small cross section at forward/ backward rapidity

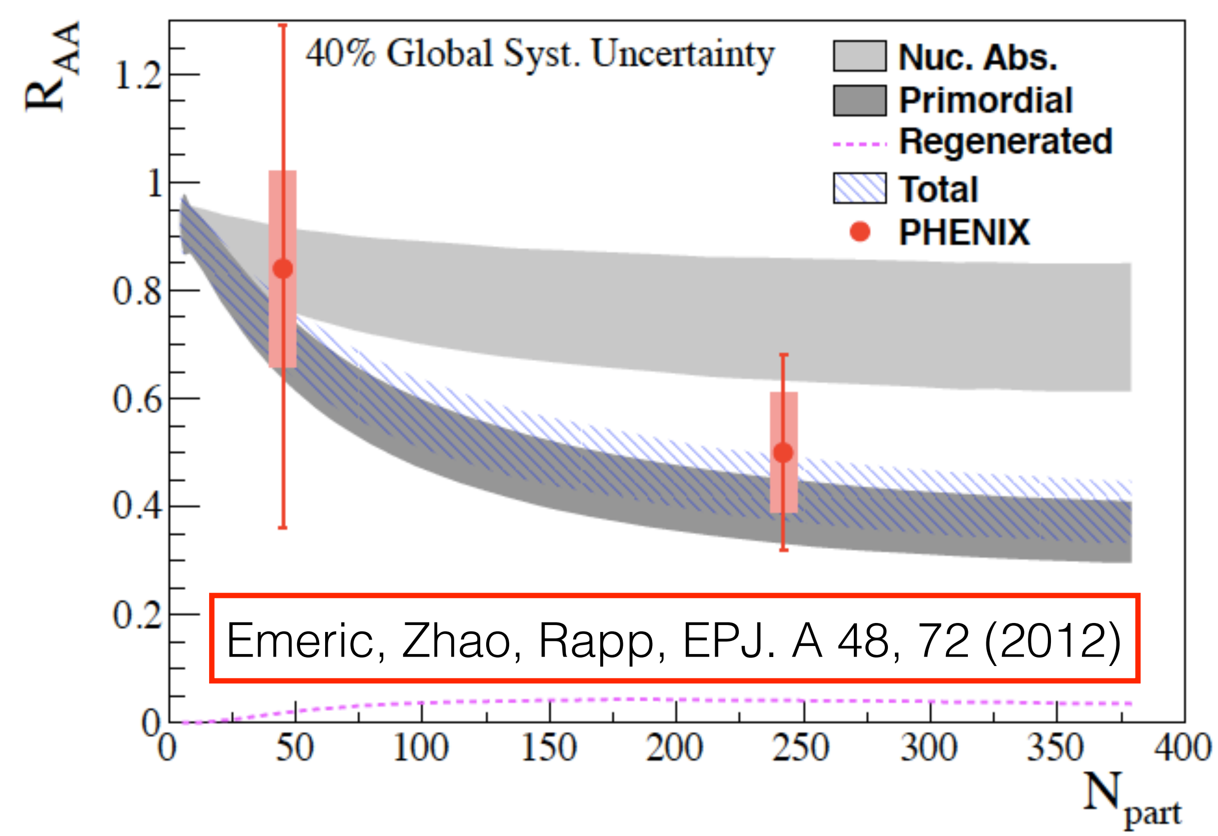
Described by the models, but the data do not provide a strong constraint



PRC 91 (2015) 024913

Strickland, Bazow, Nucl. Phys.A 879, 25 (2012).





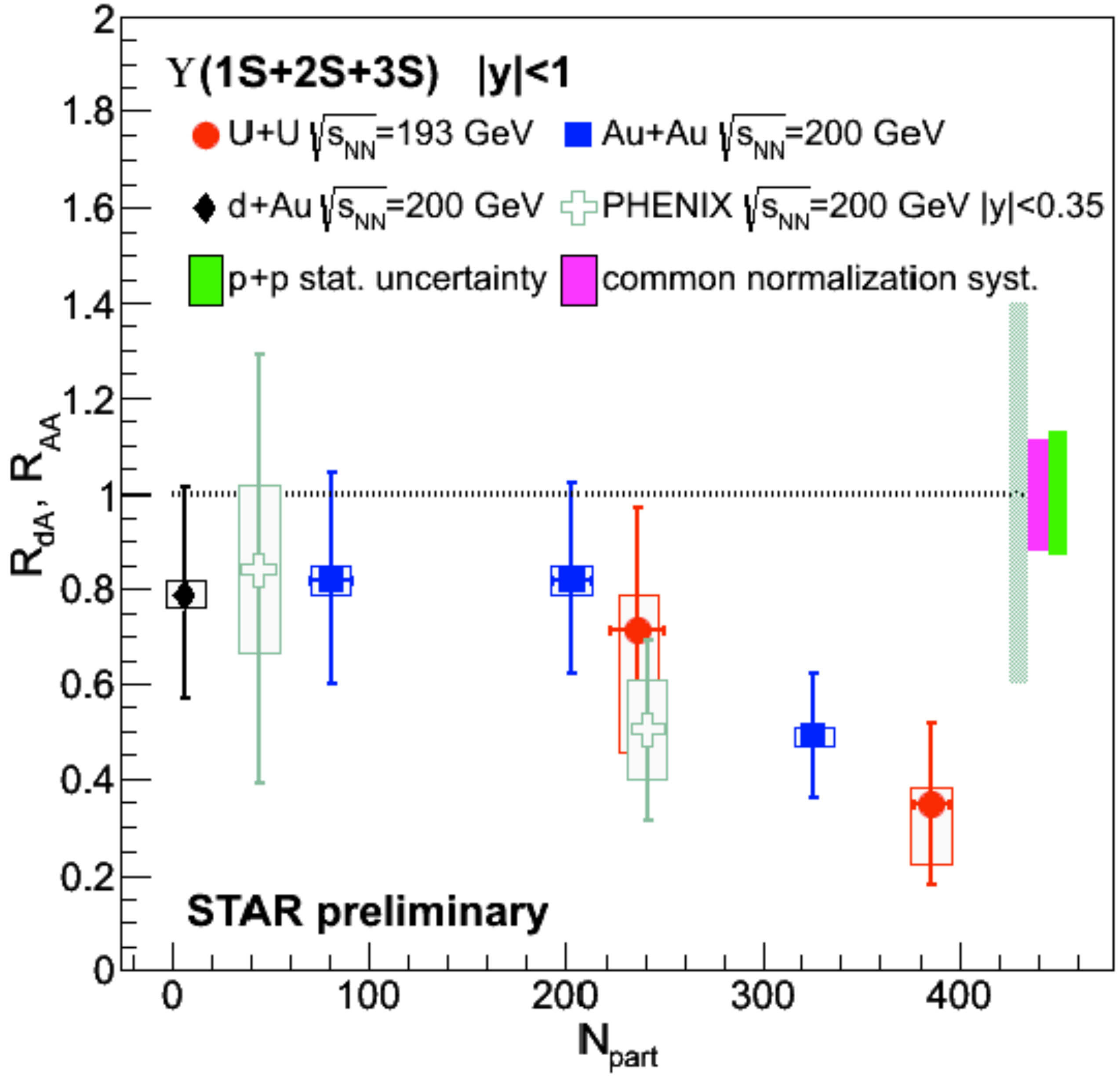
Emeric, Zhao, Rapp, EPJ. A 48, 72 (2012)

Υ(1S+2S+3S) comparisons at RHIC

Υ(1S+2S+3S) for d+Au, U+U and Au+Au

Common trend with N_{part} for suppression in Au+Au (200 GeV) and U+U (193 GeV)

arXiv:1608.06487



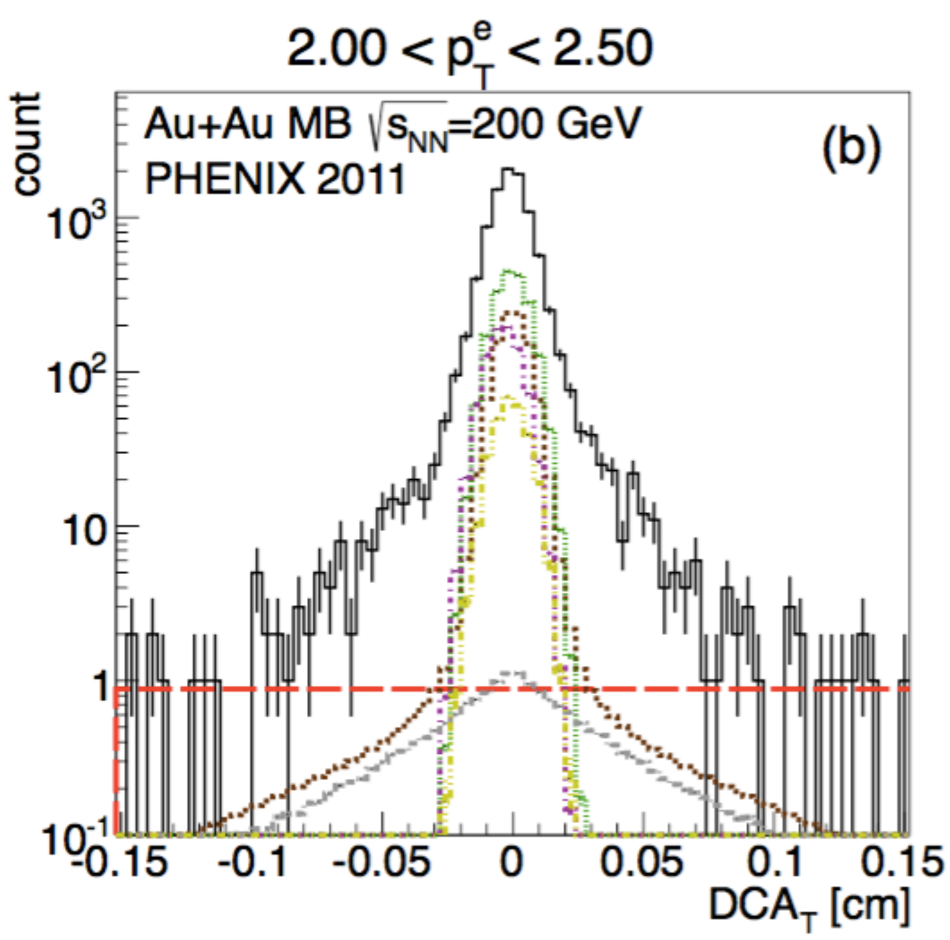
Open Heavy Flavor

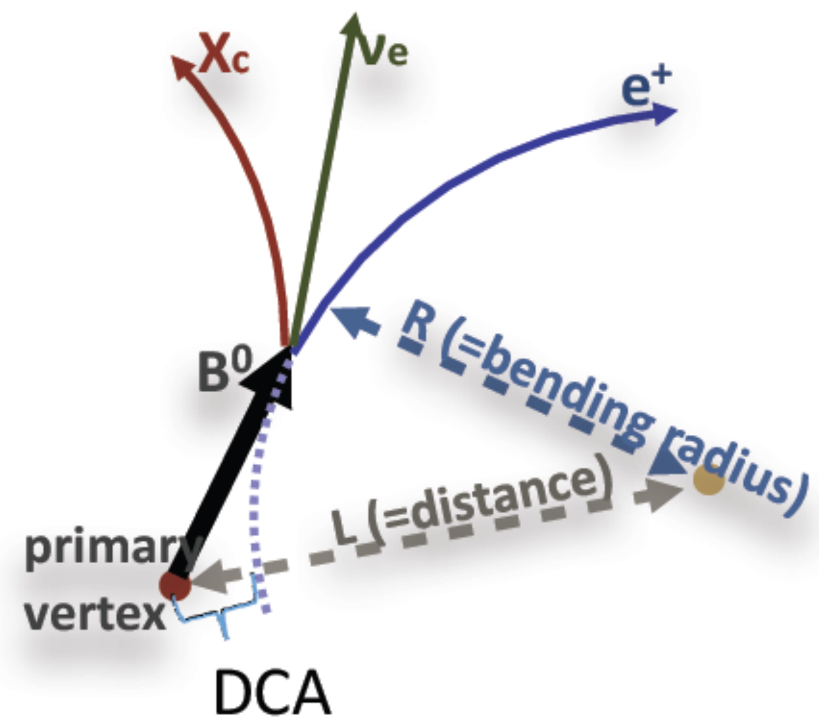
Open Heavy Flavor in Au+Au Collisions

PHENIX uses semi-leptonic decays of heavy quarks

- VTX detector at mid-rapidity + electron ID in central arms
- FVTX detector at forward/backward rapidity + muon ID in muon arms

Heavy quark decays are identified by the displacement of the reconstructed electron track from the event vertex





First results so far only at mid-rapidity, from limited statistics 2011 data set

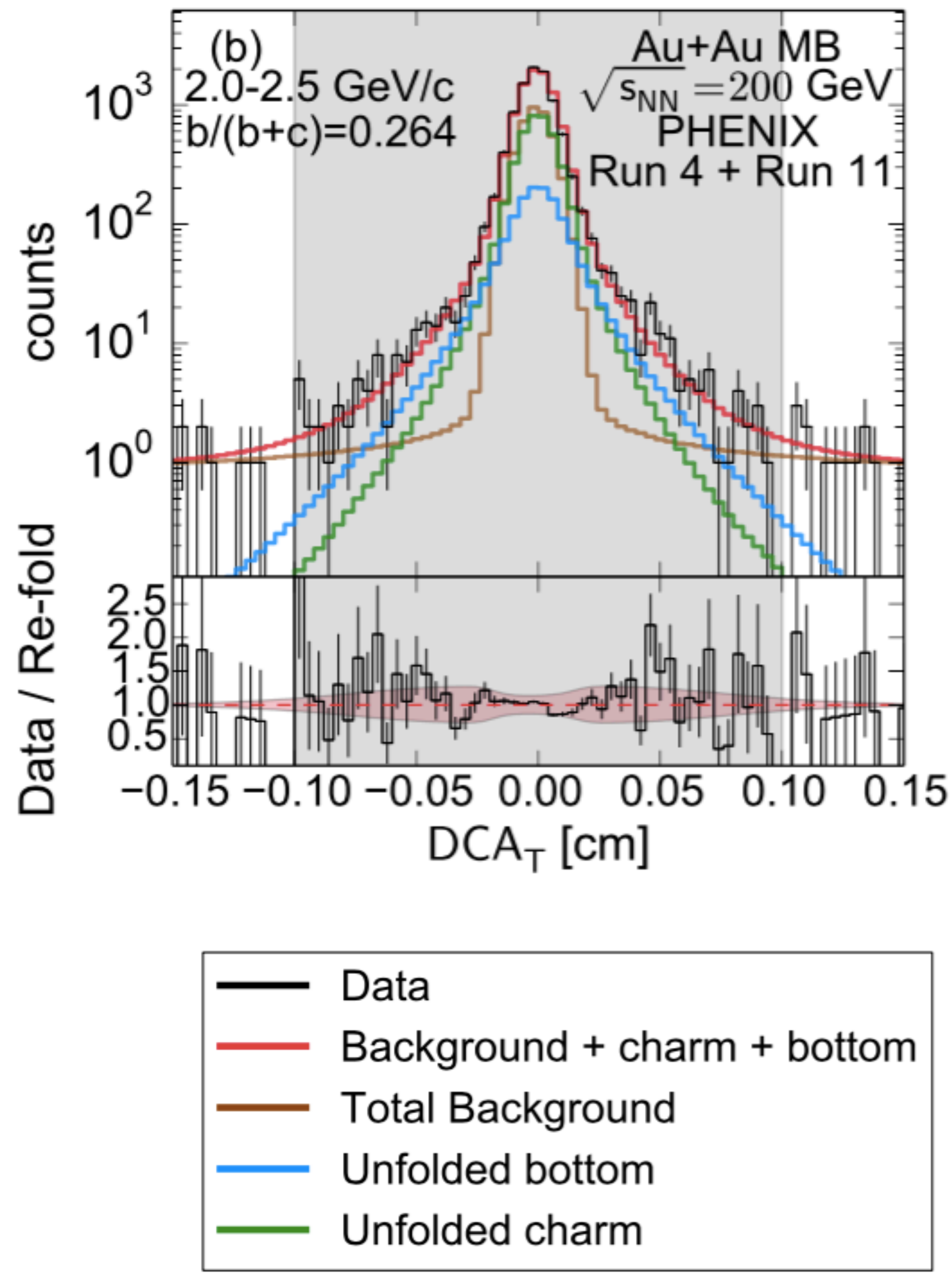
Open Heavy Flavor - procedure

Estimate background contributions

Generate decay matrices relating HF hadron p_T to electron p_T from Pythia
- Assumes rapidity distributions unmodified
- Assumes all ground state charm hadrons experience the same modification
- Assumes all ground state bottom hadrons experience the same modification

HF parent hadron distribution is integrated over all rapidity

Use a Bayesian unfolding technique to extract most likely HF parent hadron p_T distributions from simultaneous fit to measured DCA distributions in 5 pT bins + HF dN/dy vs p_T

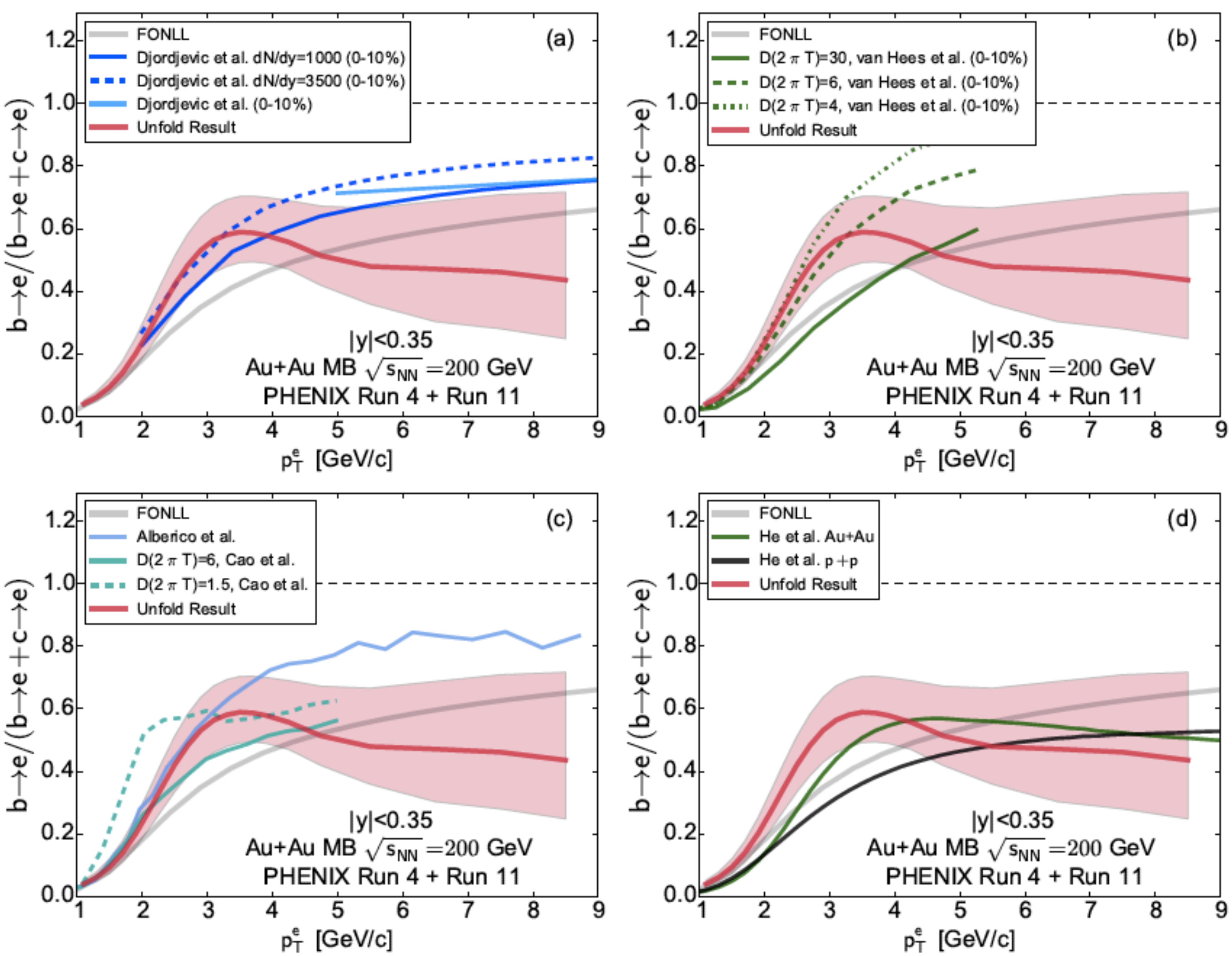


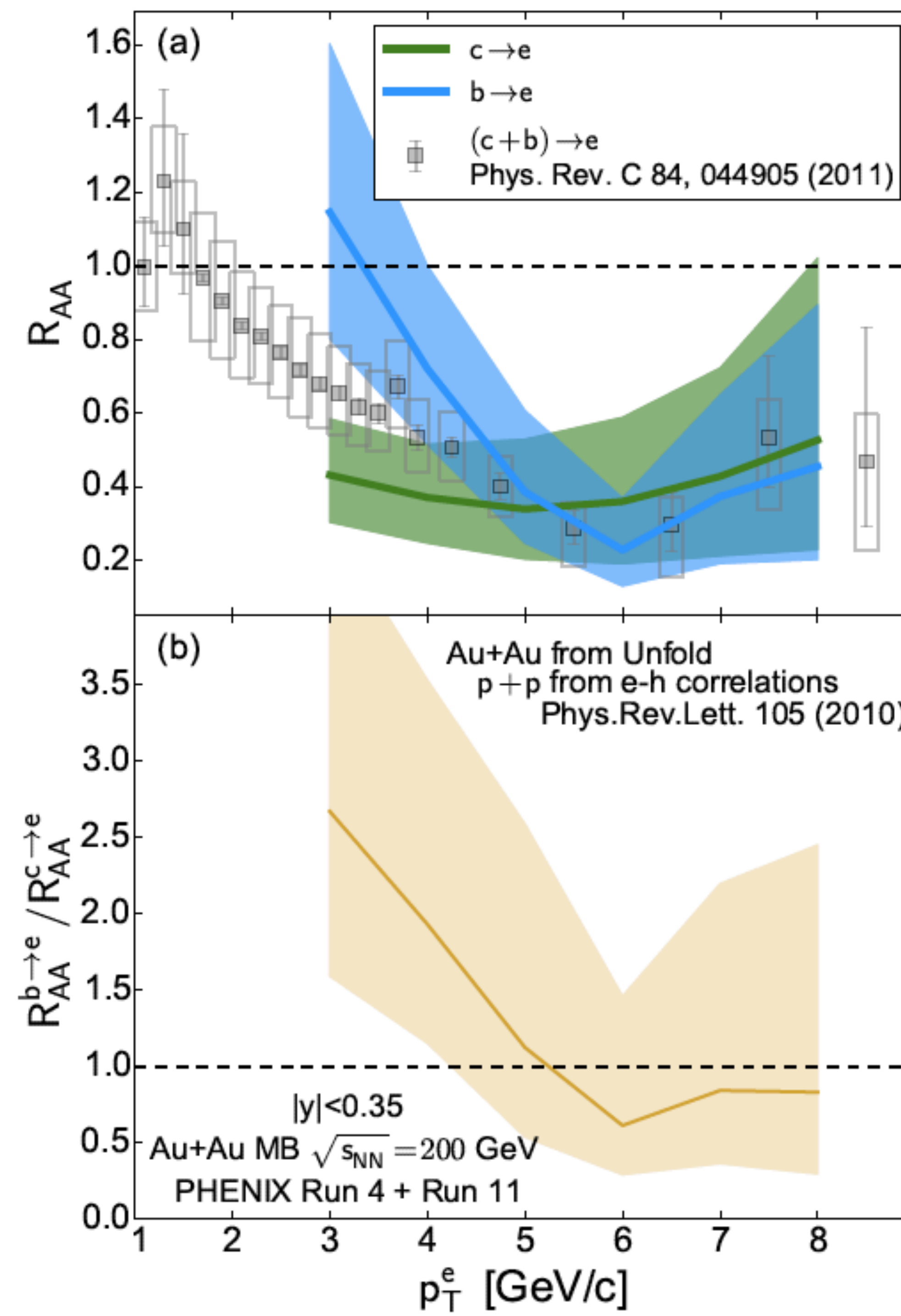
Open Heavy Flavor - results

Extract ratio of b/(c+b) contribution vs p_T of electron, with uncertainty band

Convert to R_{AA} of c and b using measured R_{AA} of HF electrons

Phys. Rev. C 93, 034904





Open Heavy Flavor - Future

Mid-rapidity:

Run 14+16 data to come

- ~ 30 times increase in statistics

Forward rapidity:

FVTX at forward rapidity ($1.2 < |\eta| < 2.2$)

- b and c separation from unfolding single muons

PHENIX had its last run in 2016!

After 16 years of data taking, the PHENIX detector is no more (it is being dismantled this summer)

- Although we have a lot of data to analyze yet!

This is in preparation for the construction of a new experiment at RHIC in the 1008 hall

A new collaboration was formed in December 2015

- Currently known as sPHENIX

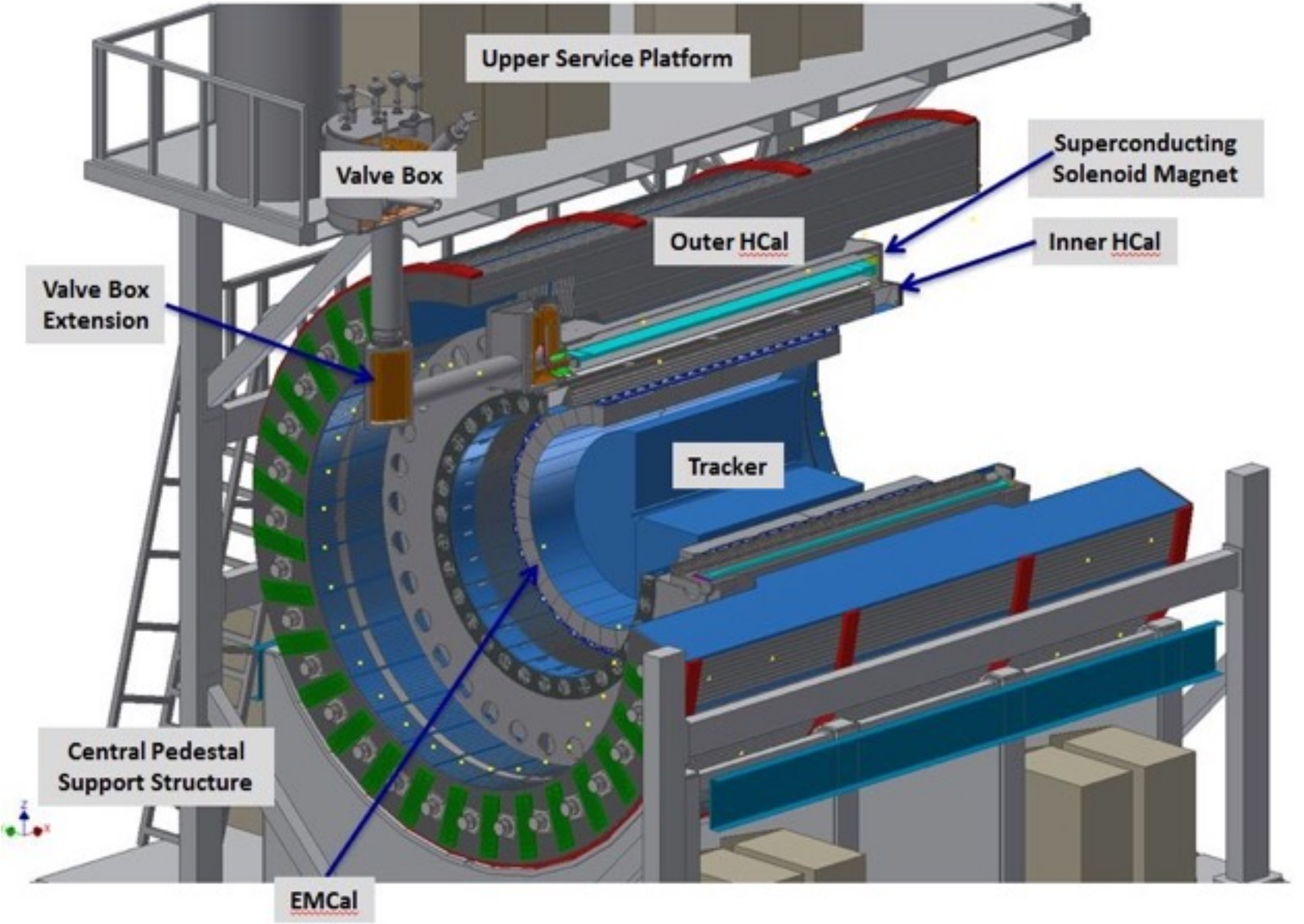
Planned to start data taking in 2022

sPHENIX

Goal: Compact, state of the art jet detector at RHIC

Physics program aimed at:
- Jets
- HF tagged jets
- Upsilons

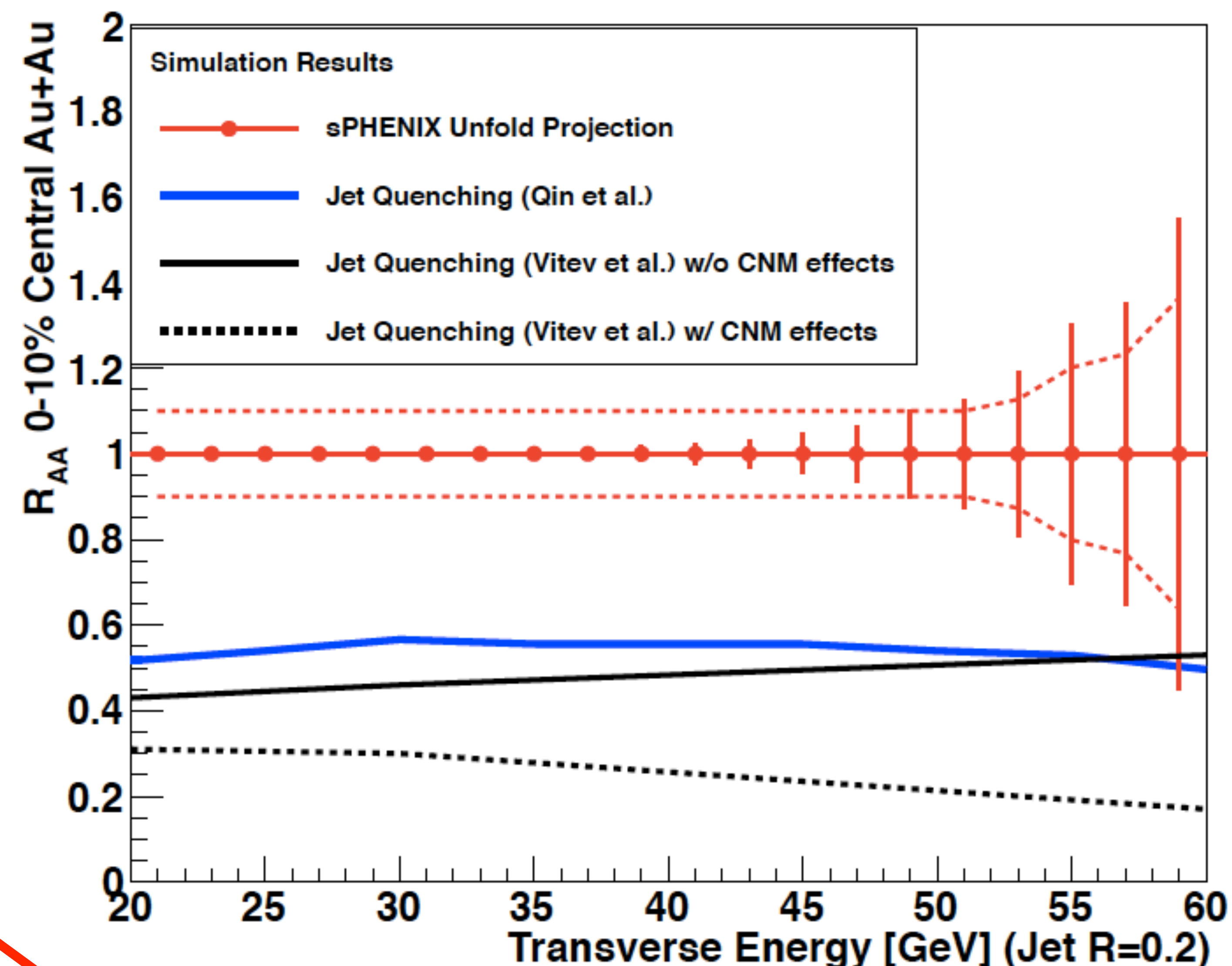
Hermetic detector covering
$-1.1 < \eta < 1.1$
- EM Calorimeter
- Hadronic calorimeter
- Precise vertexing
  - MAPS pixel inner barrel
- Precise tracking
  - intermediate Si strips
  - Compact TPC outer tracker

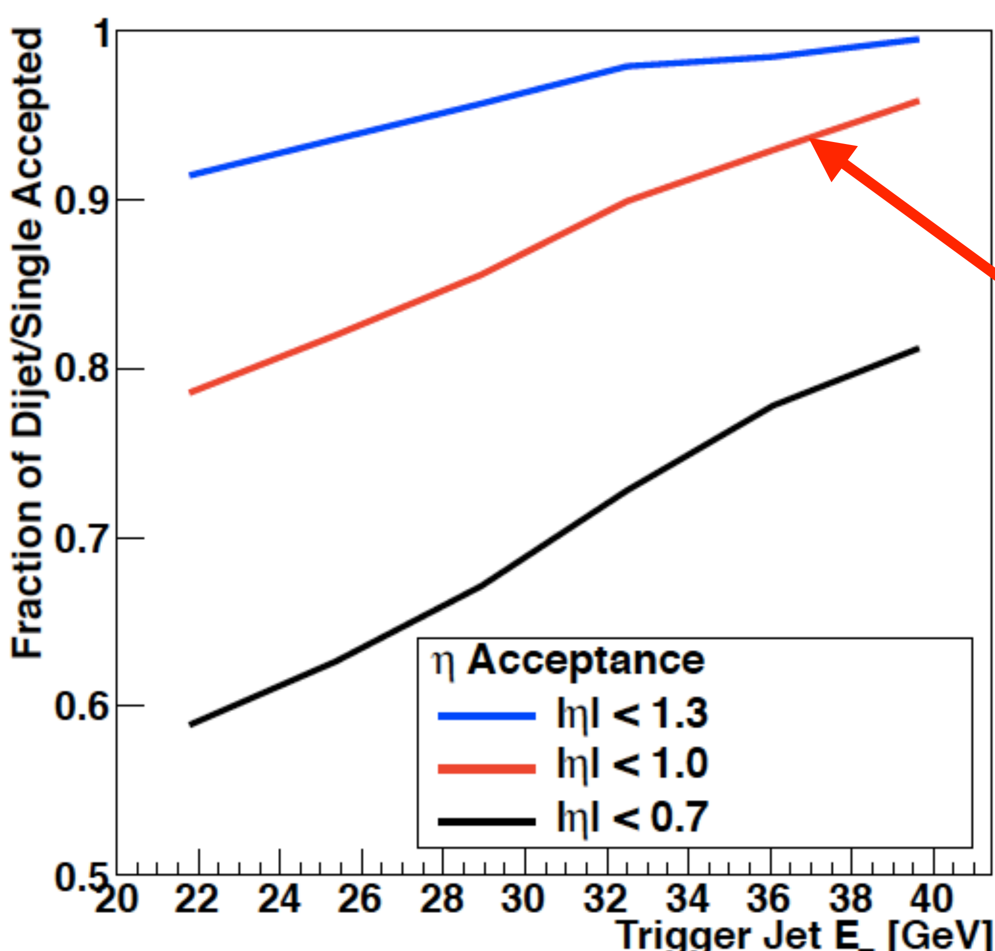


Uses BABAR superconducting solenoid
B = 1.5 T
Data rate for Au+Au collisions = 15 kHz

sPHENIX - jets

Estimated precision of jet R_{AA} vs E_T



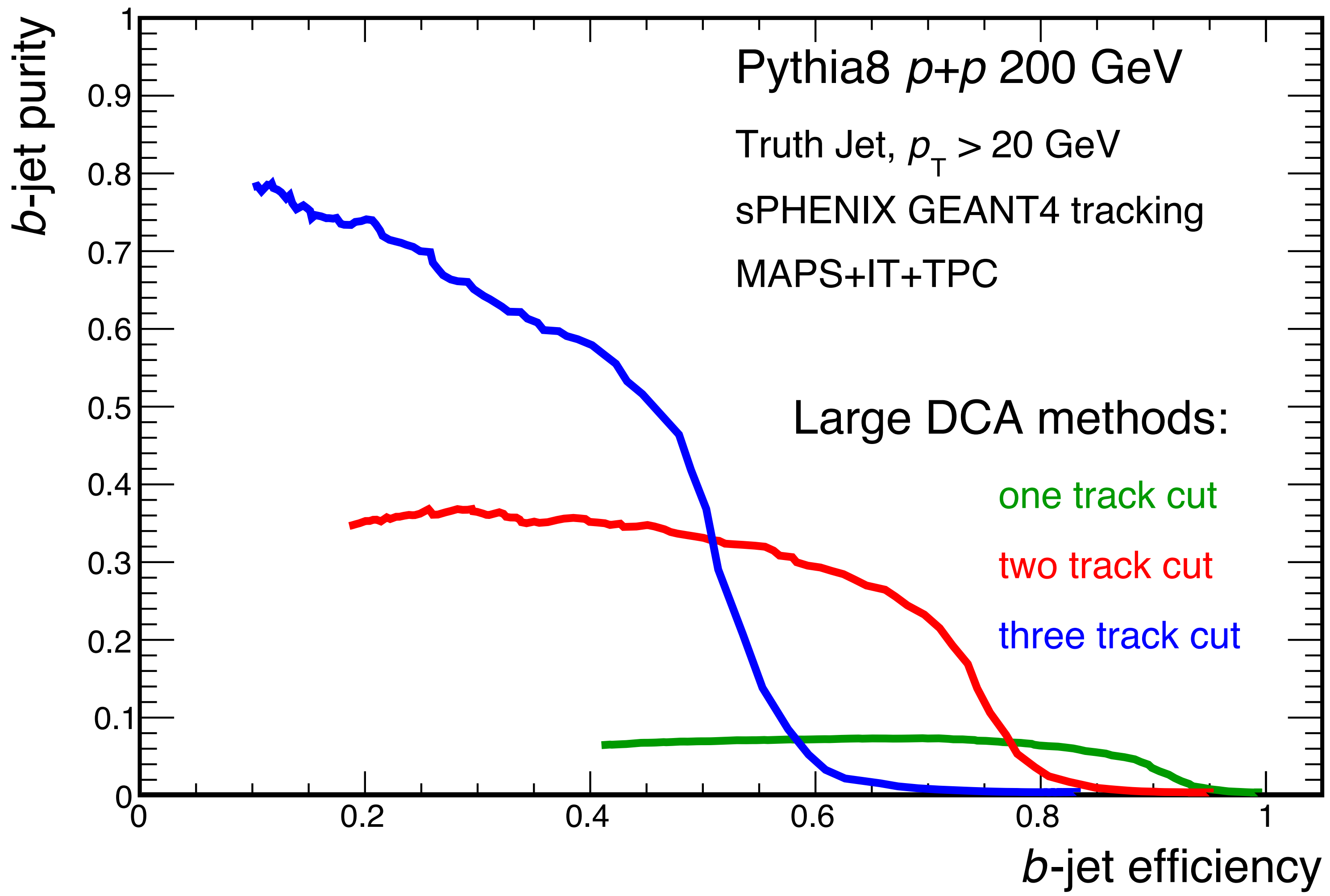


Fraction of dijets in which both jets are within sPHENIX acceptance (red curve)

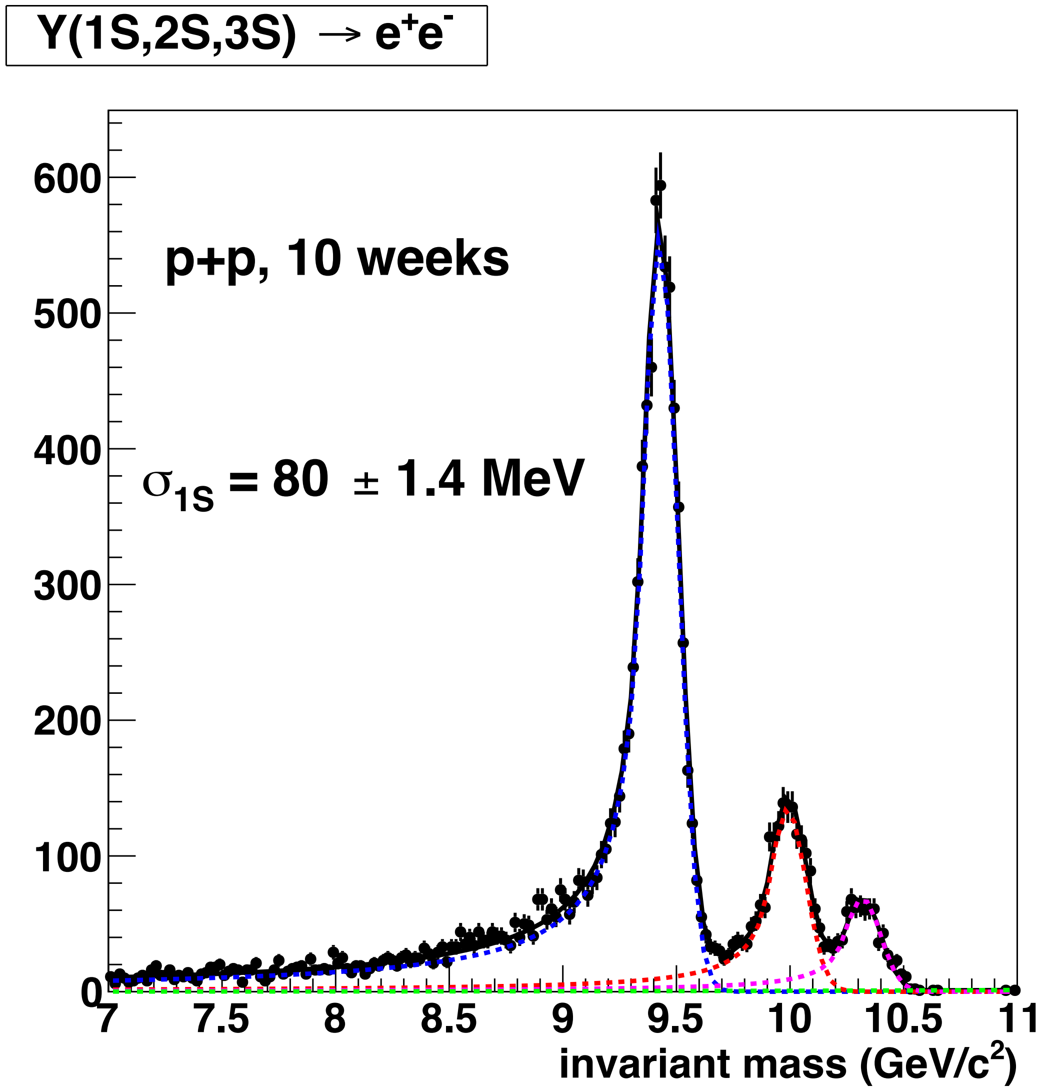
sPHENIX - b-tagged jets

One method for finding jets with a b quark (p+p collisions only so far)
MC study:
Use DCA measurement in the bend plane from inner barrel detector
Require 1, 2 or 3 tracks to be outside DCA cut
Use truth information to extract b-jet efficiency vs purity as DCA cut changes

3 track DCA cut can produce 30% b-jet efficiency at 70% purity

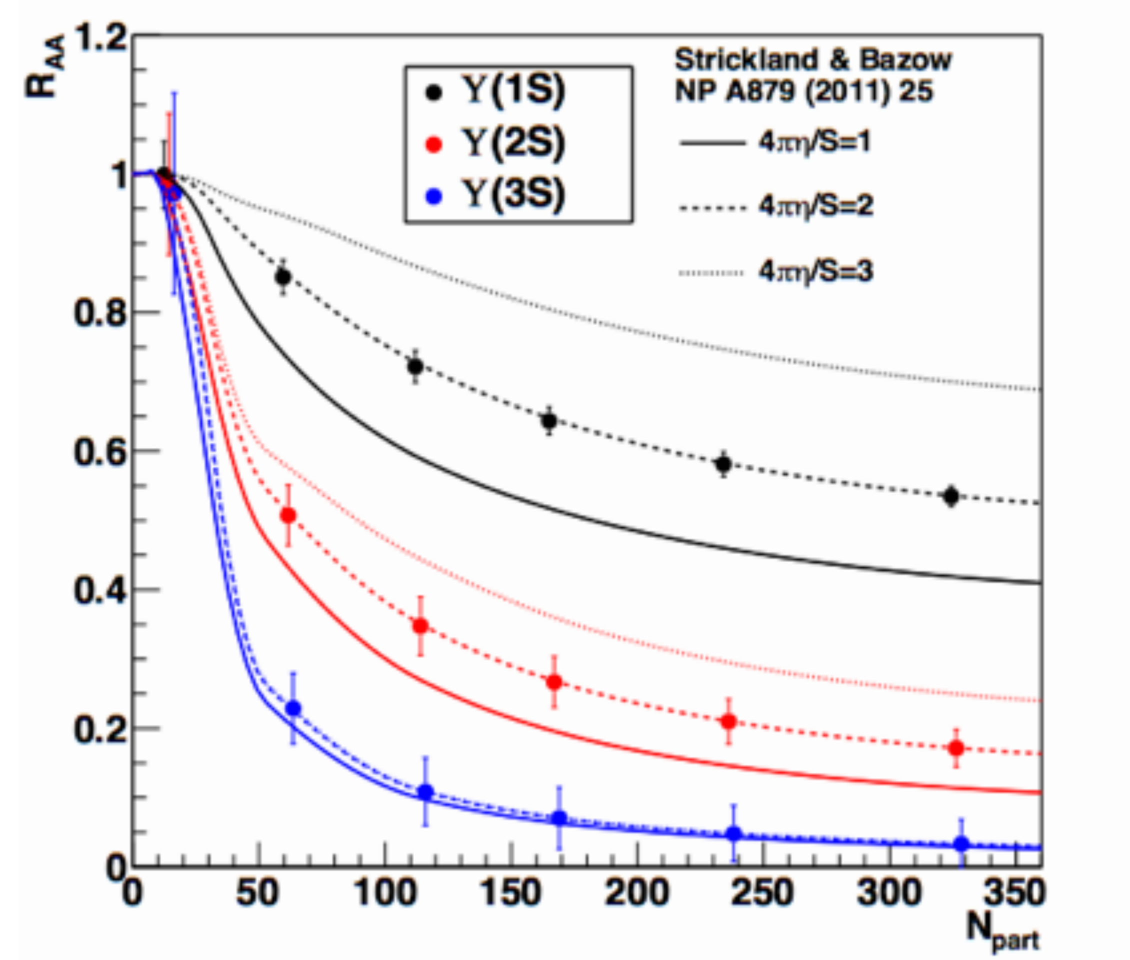


sPHENIX - Upsilons



Use dielectrons
Minimal mass of tracking detector (TPC)
=> good mass resolution
=> minimal radiative tail

Electron identification from EM + hadronic calorimeter => E/p measurement



Expected statistics for R_{AA} assuming model suppression

- 1 year p+p and 1 year Au+Au running

Tim Hallman, RHIC User's Meeting June 2016