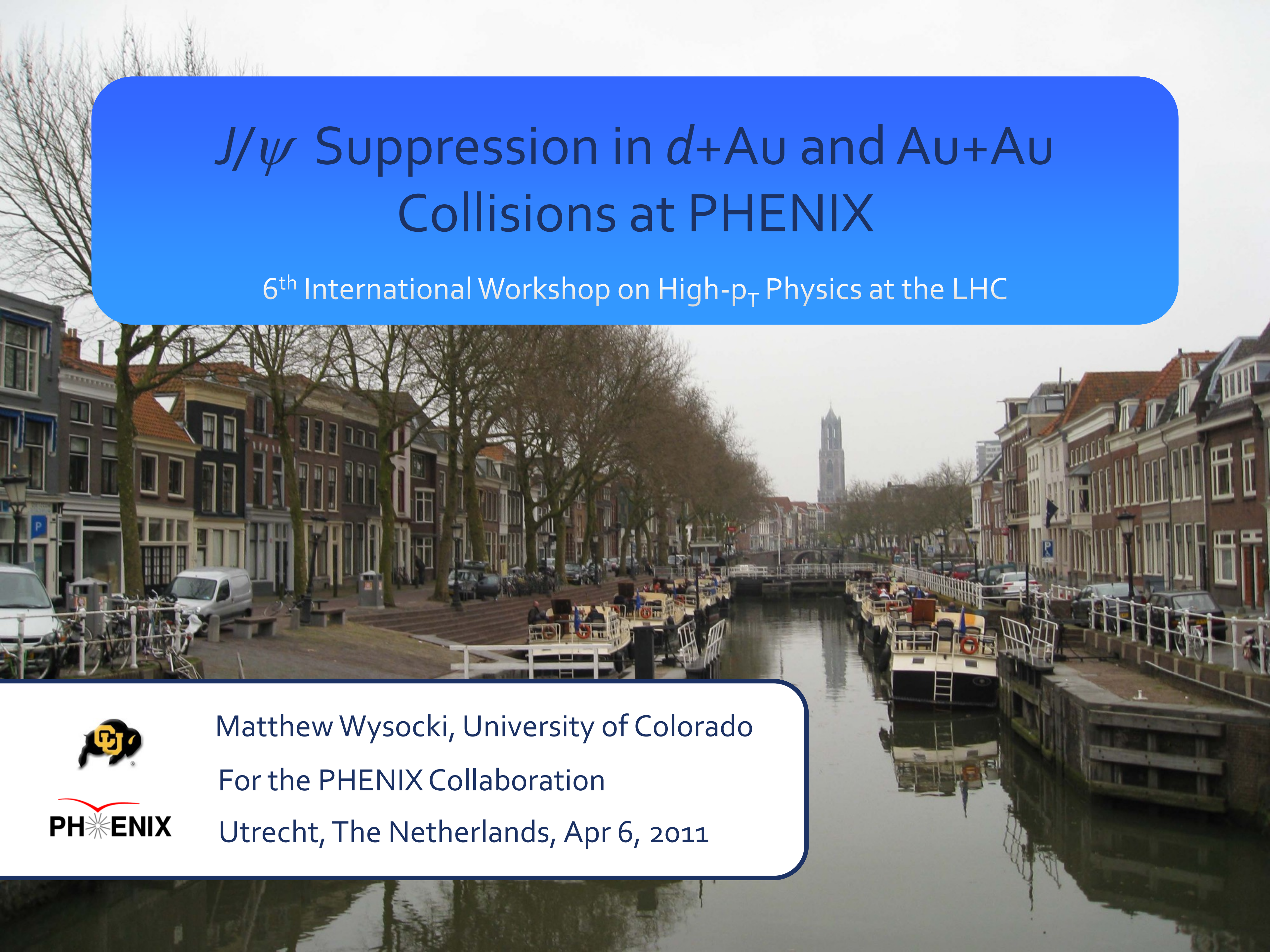
J/ψ Suppression in d+Au and Au+Au Collisions at PHENIX

6th International Workshop on High-p_T Physics at the LHC



Matthew Wysocki, University of Colorado

For the PHENIX Collaboration

Utrecht, The Netherlands, Apr 6, 2011

PHENIX

Recent PHENIX Heavy Flavor Results

There are two recent PHENIX J/ψ publications, and I would like to focus on those today. There are a number of other recent heavy flavor results, several of which I've listed below.

Recent Results:

Non-photonic electrons in *d*+Au

Matt Durham's talk at WWND 2011

Azimuthal correlations of electrons from heavy-flavor decay with hadrons in p+p and Au+Au collisions at sqrt(s_NN)=200 GeV

A. Adare, *et al*, arXiv:1011.1477

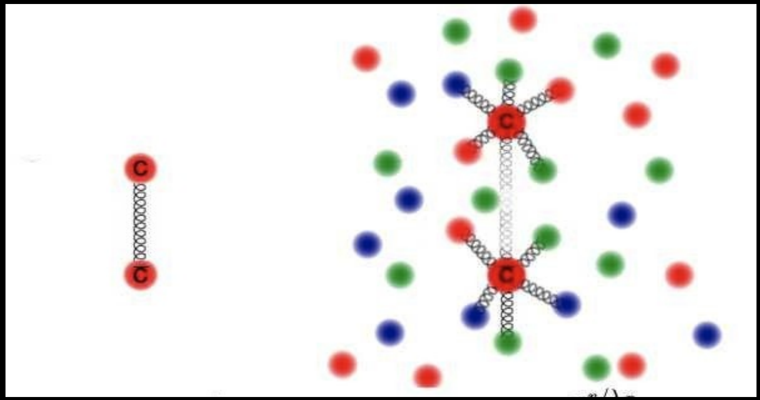
Upsilon R_{dAu} at backward and forward rapidities

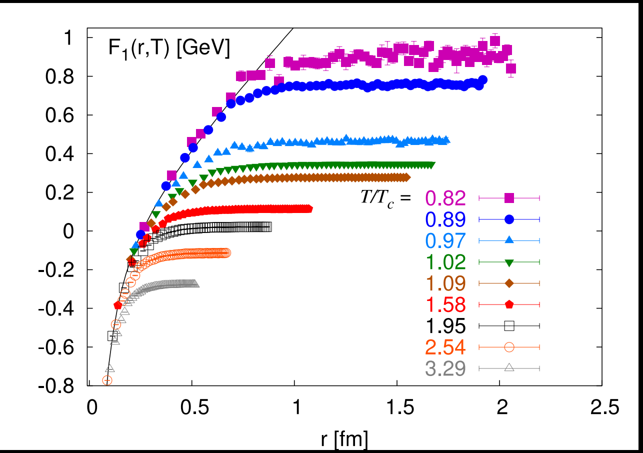
Single muons from heavy flavor decays in Cu+Cu at forward rapidity

J/ψ suppression basics

J/ψ suppression was proposed by Matsui and Satz as a smoking gun signature of the QGP.

Debye screening length of plasma < J/ψ radius





Picture is more complex today with strong cold nuclear matter effects and modification of the hot nuclear suppression due to regeneration.

A Recipe for Suppression

The Ingredients:

CNM effects

shadowing, gluon saturation, nuclear absorption, initial-state parton energy loss

HNM effects

dissociation, regeneration

But what are the proportions???

→ Start by looking at CNM using *d*+Au collisions.

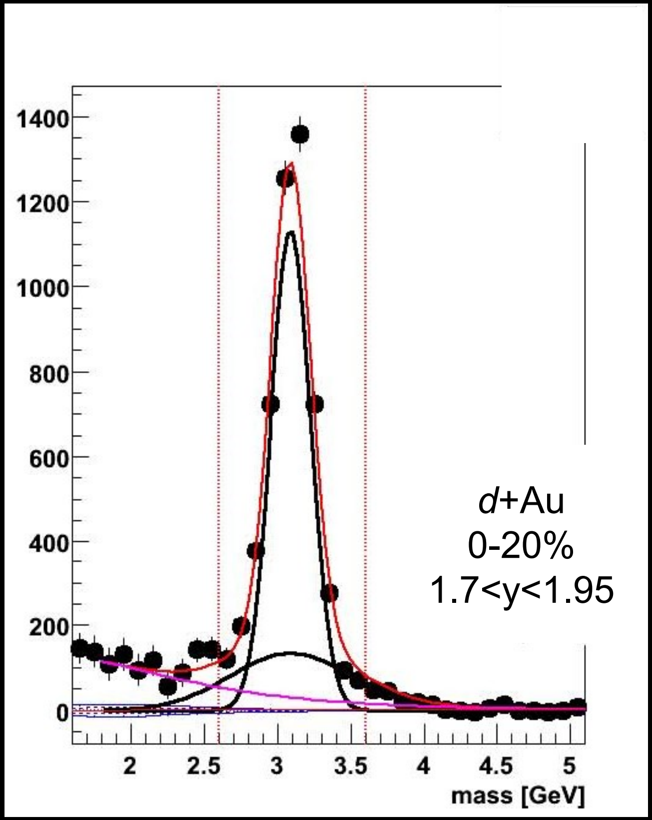
Brand New Results!

PHENIX analyzed new higher-statistics data:

p+*p* in 2006 and 2008
Au+Au in 2007
d+Au in 2008

Smaller uncertainties and finer binning provide better constraints.

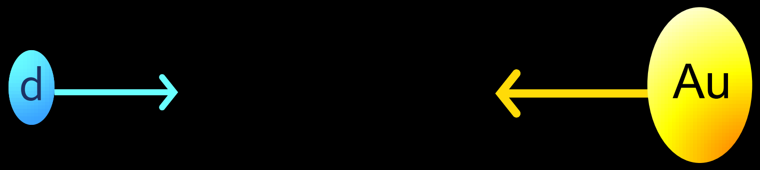
The *d*+Au data in particular represents ~30x the *J/ψ* sample that was recorded during 2003 and used in previous PHENIX *d*+Au analyses.



d+Au - arXiv:1010.1246 (longer paper in preparation)
Au+Au - arXiv:1103.6269 (submitted last week!)

Cold Nuclear Matter Effects

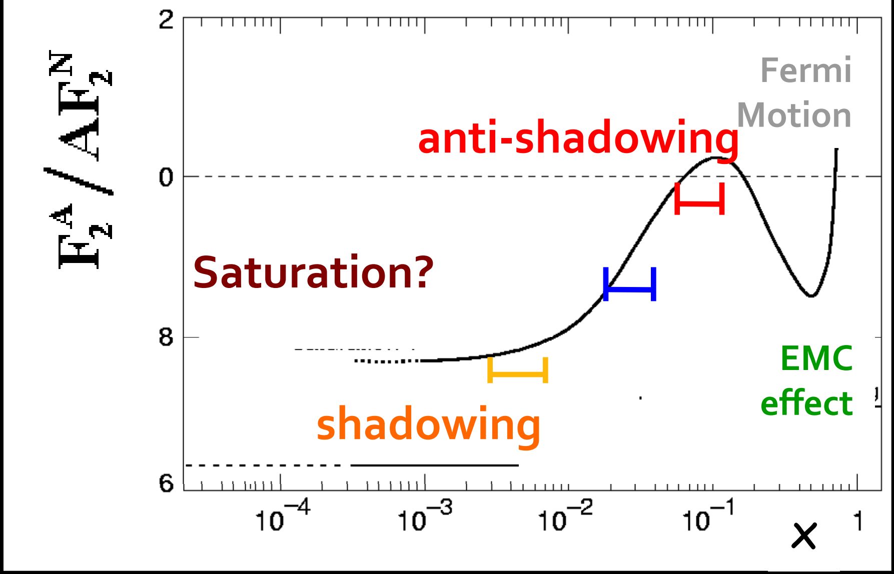
- We want to understand the significant effects that occur without a hot medium, so-called cold nuclear matter effects.
- What goes on in the nucleus is interesting in its own right. Shadowing, anti-shadowing; gluon saturation at low *x*?
- J/ψ from p+A or d+A offer an important test of these effects.
  - g+g → J/ψ dominant process at RHIC



Nuclear modification of PDFs

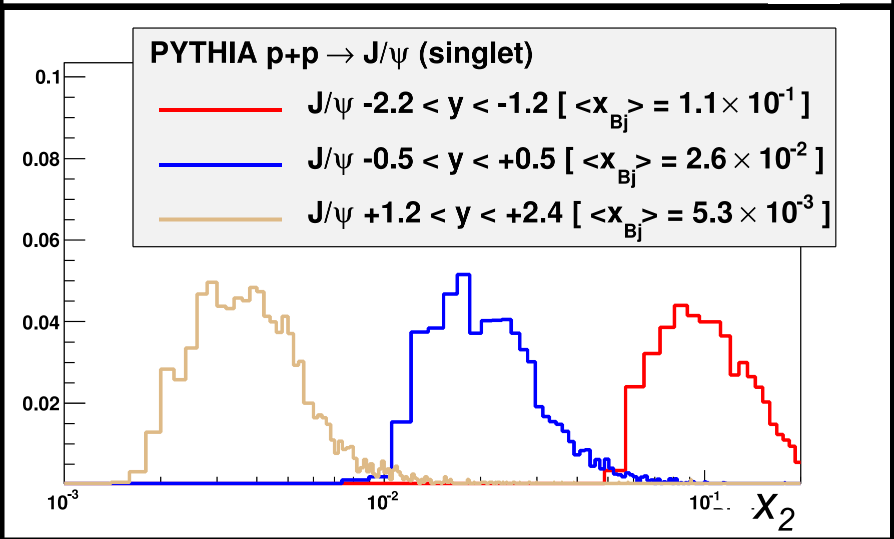
Nuclear PDFs are known to be modified in various *x*-ranges.

- Shadowing, anti-shadowing, EMC effect, etc.



PHENIX probes three ranges of *x* in the gold nucleus, in both the shadowing and anti-shadowing regions, using detectors at:

- forward *y*, *x*~0.005
- mid *y*, *x*~0.03
- backward *y*, *x*~0.1

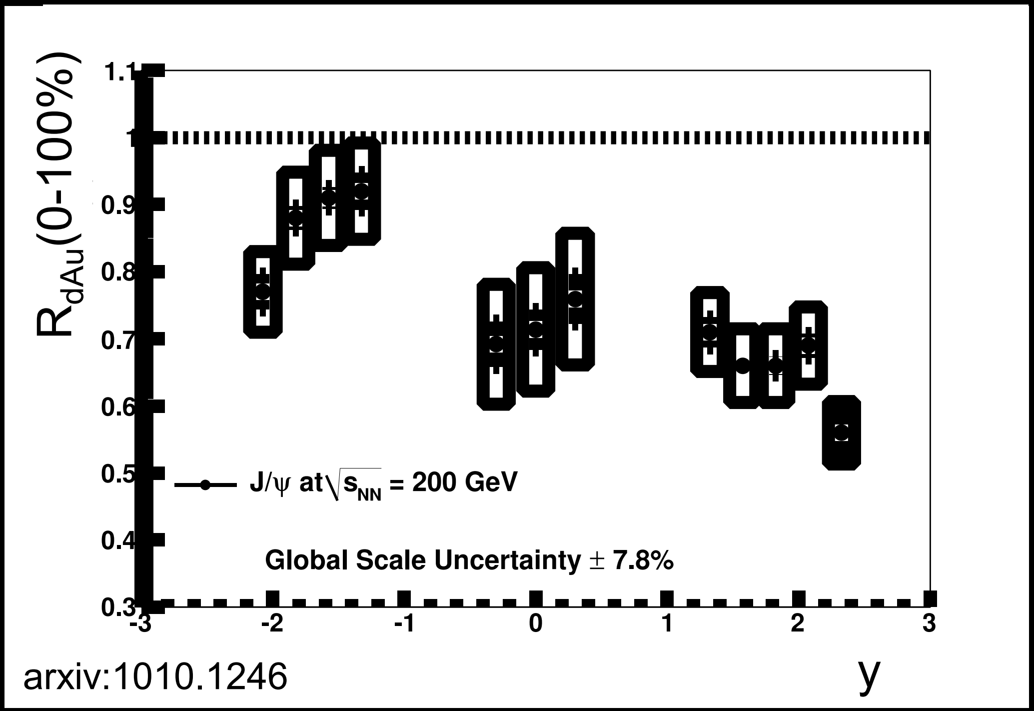


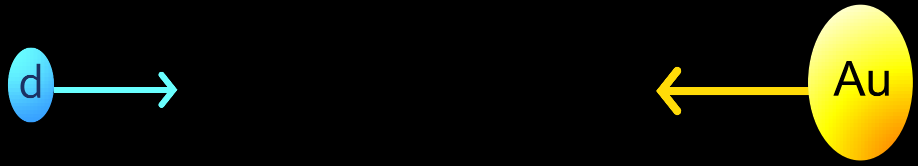
R_{dAu} for minimum bias collisions (new)

$$R_{\mathrm{dAu}} = \frac{1}{N_{\mathrm{coll}}} \frac{dN_{d+Au}/dy}{dN_{p+p}/dy}$$

Significant suppression at mid and forward rapidities.

We compare these data to two model calculations…

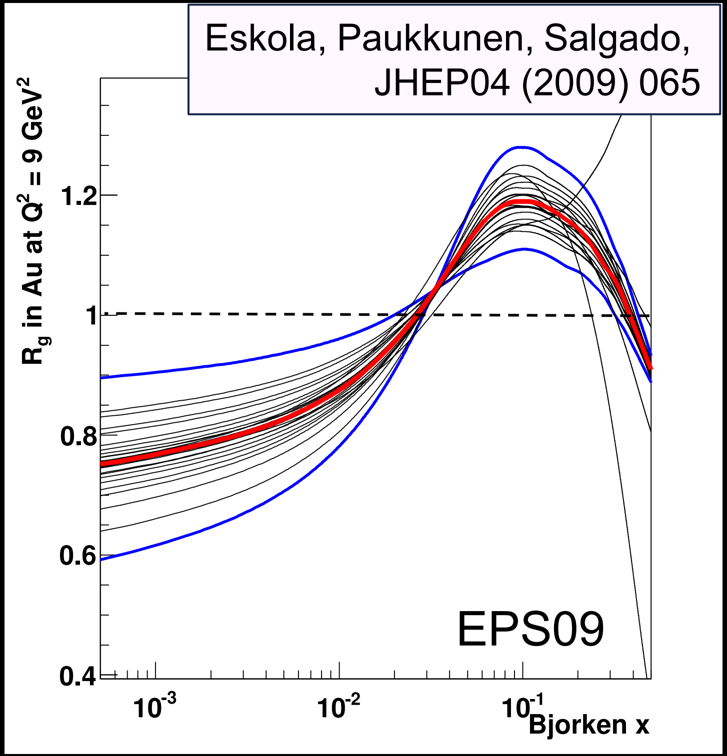




Bars = point-to-point uncorrelated uncertainties
Boxes = point-to-point correlated uncertainties

Calculation I

- R. Vogt calculated for PHENIX the J/ψ production from:
  - EPS09 nPDF with shadowing effects
    - linear dependence on density-weighted longitudinal thickness → impact parameter dependence
    - Fold the provided *b* dist. with PHENIX centrality dists.
    - We compare to both the "best-fit" and maximum-variation EPS09 curves
  - Include $\sigma_{breakup}$ to account for break-up of the $c\bar{c}$ pair while passing through the nucleus.

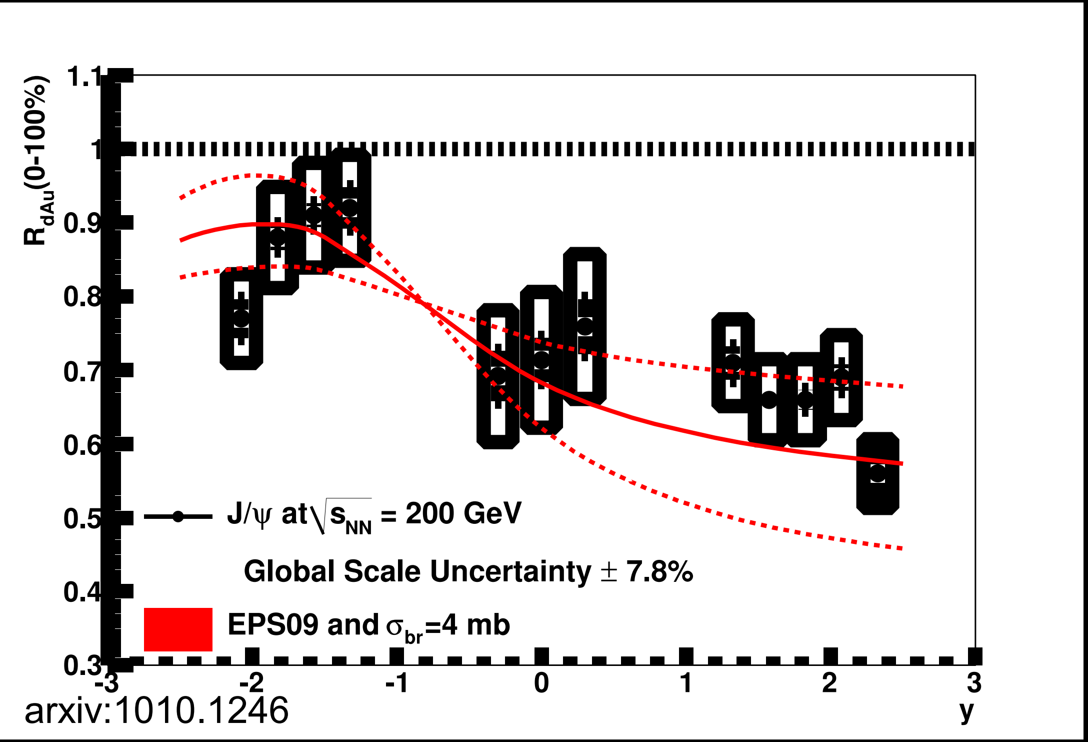


R_{dAu} for minimum bias collisions

Reasonable agreement with EPS09 nuclear PDF + σ_{br} = 4 mb (red curves).

σ_{br} is the only free parameter.

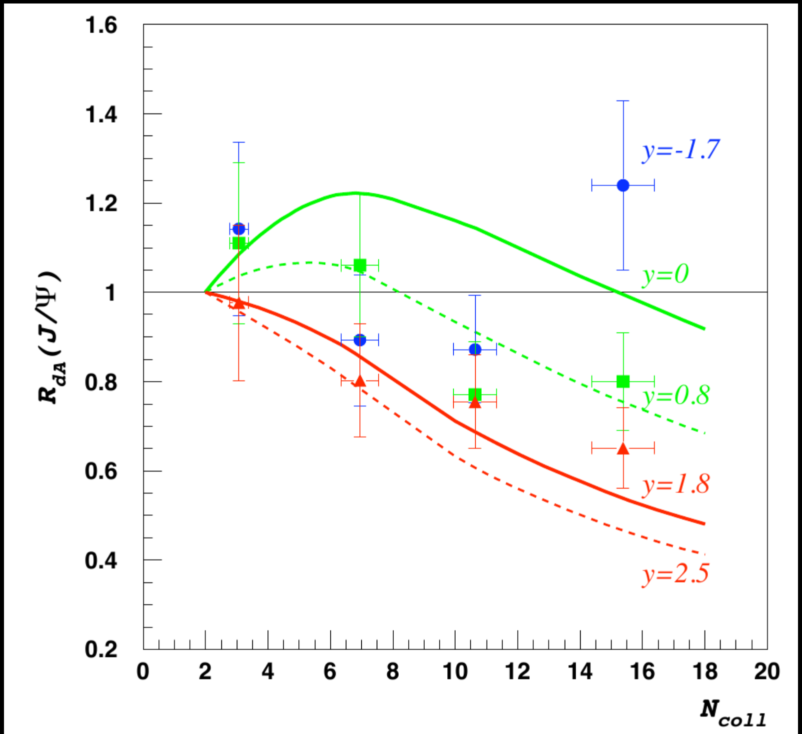
Dashed lines are the maximum variation included in EPS09.



EPS09, as published, is averaged over all *b*, so we would expect decent agreement with R_{dAu}(0-100%).

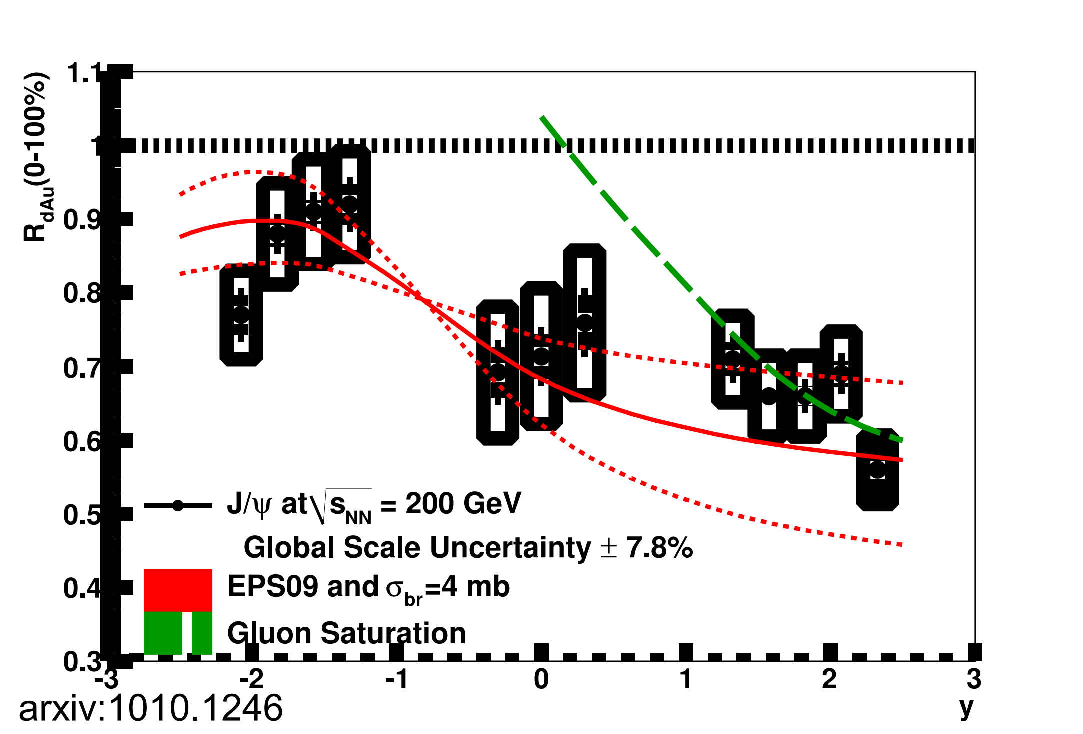
Calculation II

- Kharzeev and Tuchin, Nucl. Phys. A 770 (2006) 40,
  - Include gluon saturation at low x
  - Enhancement from double gluon exchange with nucleus



R_{dAu} for minimum bias collisions

Good agreement at forward rapidity with gluon saturation model of Kharzeev and Tuchin, but deviates from the data quickly as y<1.

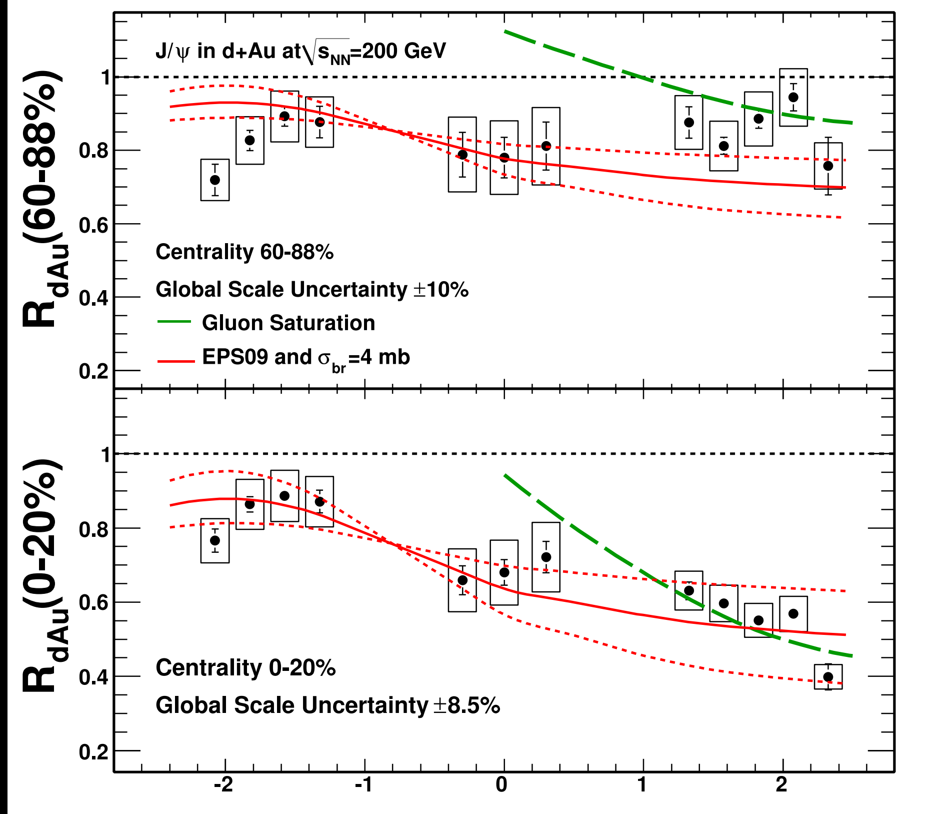


We can break the data down further by dividing events into small and large impact parameter.

R_{dAu} central and peripheral (new)

As can be seen, models including a nuclear-modified PDF and a (fixed) break-up cross section are unable to reproduce the rapidity dependence of R_{dAu} in central and peripheral events with the same $\sigma_{breakup}$.

Gluon saturation again matches the forward rapidity points relatively well, but not mid-rapidity



arxiv:1010.1246

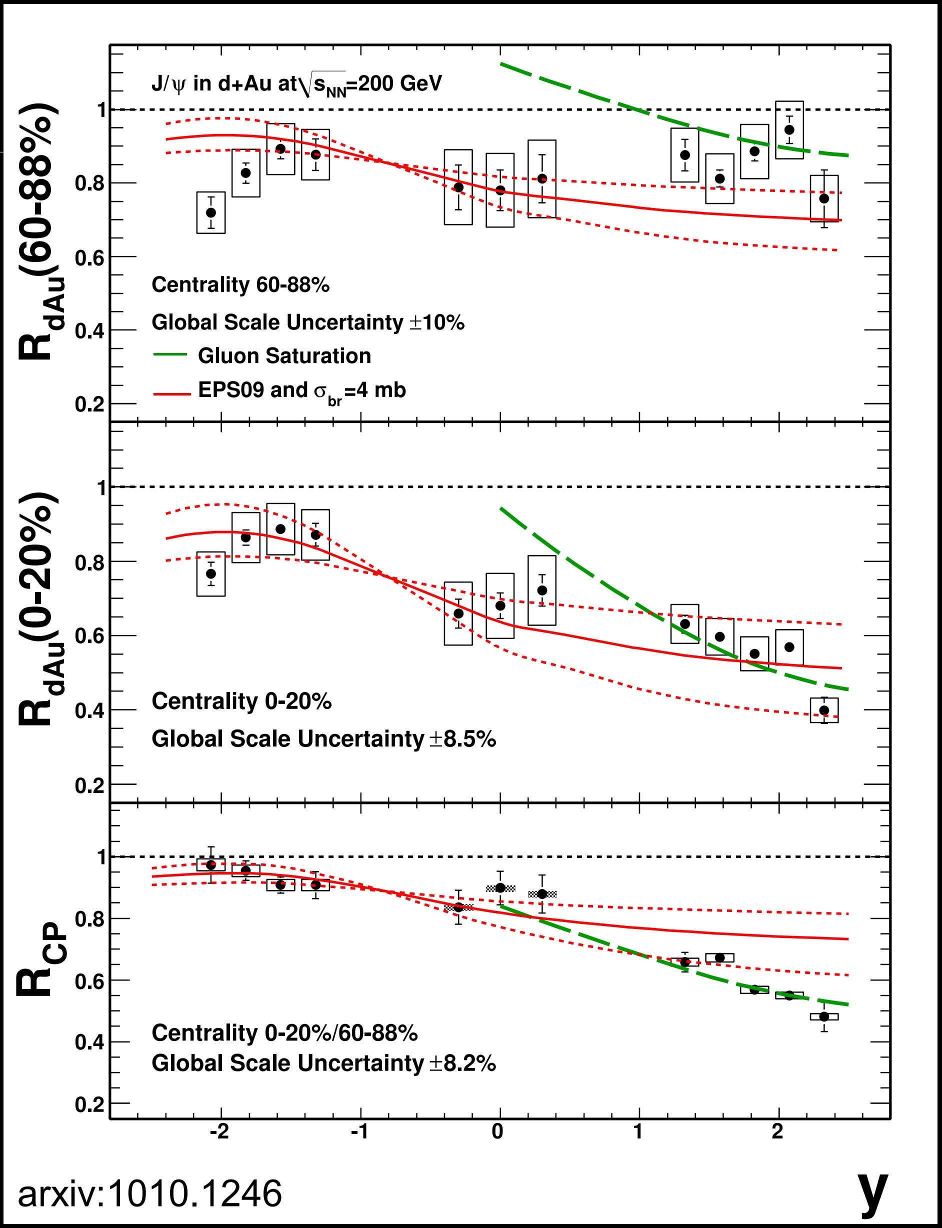
We can further reduce systematics by taking the ratio.

R_{CP} vs. rapidity

$$R_{\mathrm{CP}} = \frac{R_{\mathrm{dAu}}(central)}{R_{\mathrm{dAu}}(peripheral)}$$

R_{CP} has the advantage of cancelling most of the systematic uncertainties.

However, it should not be mistaken for R_{dAu}(central), as R_{dAu}(periph) deviates significantly from unity (ie. $p+p$).

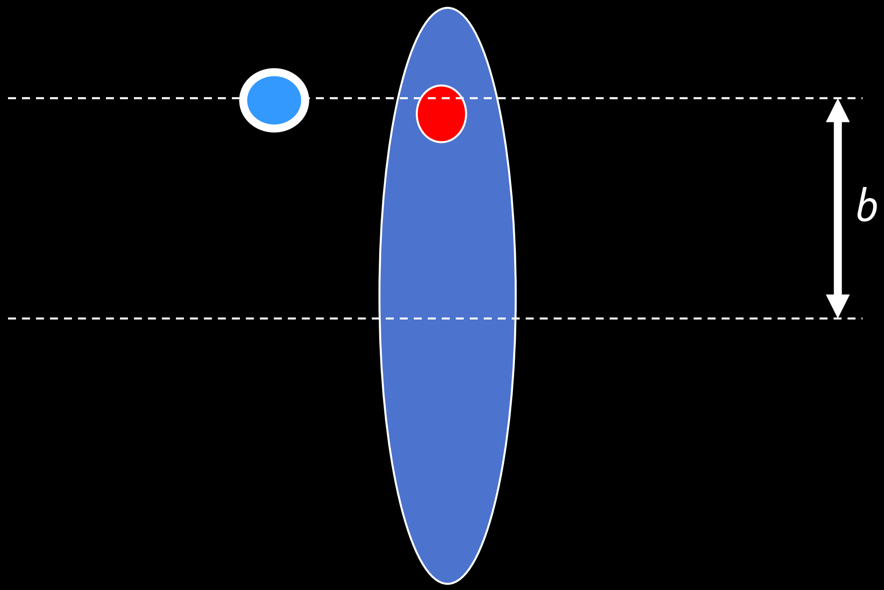


To further examine the centrality and rapidity dependence of R_{dAu}:

1. Start from a Glauber MC of the nucleon-nucleon hit positions.

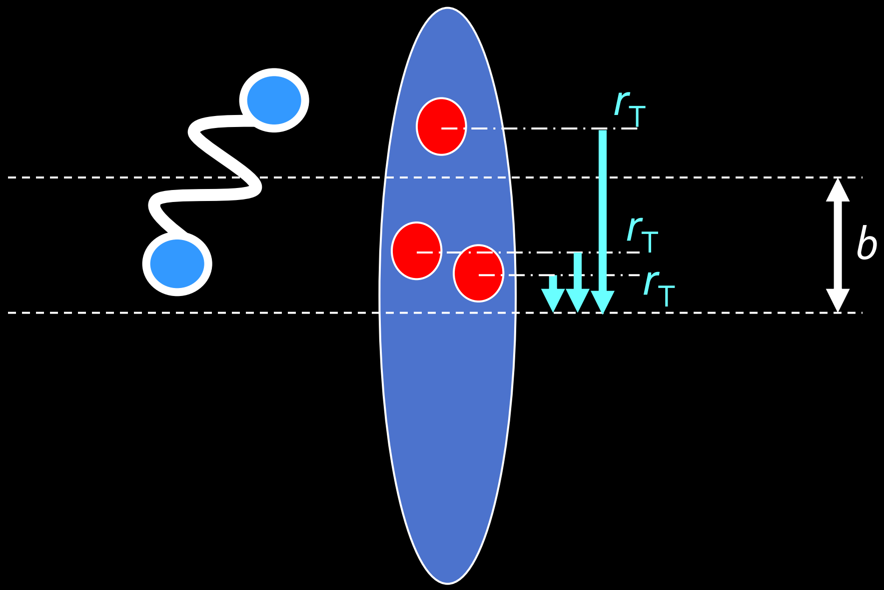
2. Add a simple parameterization based on the longitudinal thickness of the gold nucleus.

p+Au Geometry



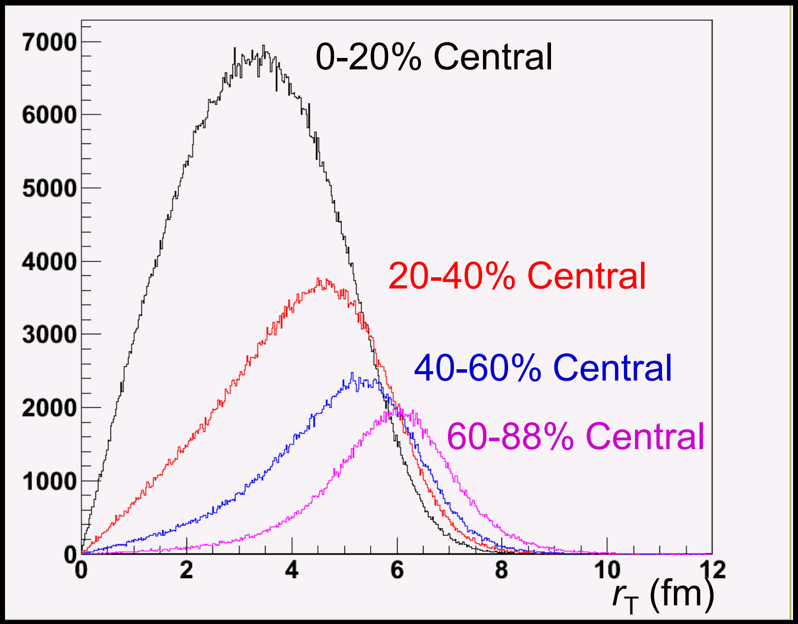
p+Au impact parameter tells us exactly what we want to know, ie. the transverse radius of the *N*-*N* collision(s).

d+Au Geometry

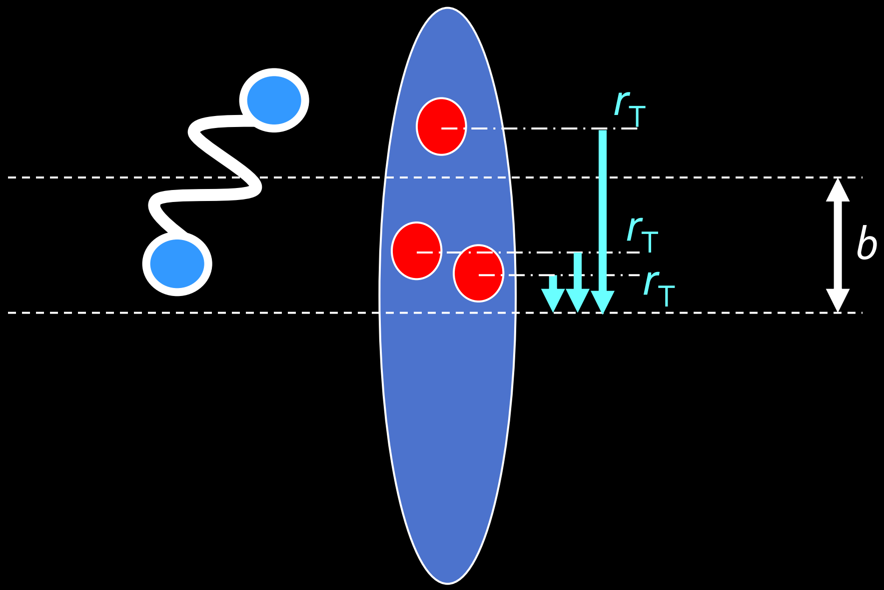


d+Au impact parameter is not as useful as in p+Au, since what we're really interested in is the ***radial positions of all of the struck nucleons***. Call it r_T to differentiate.

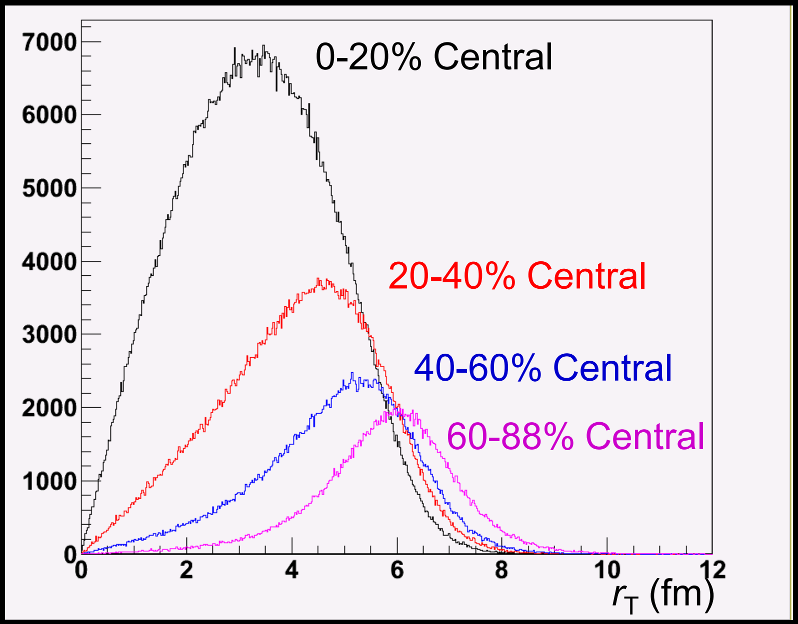
For this event, there are three r_T values (transverse radial positions for the struck gold nucleus nucleons). These are the values in the histograms to the right.



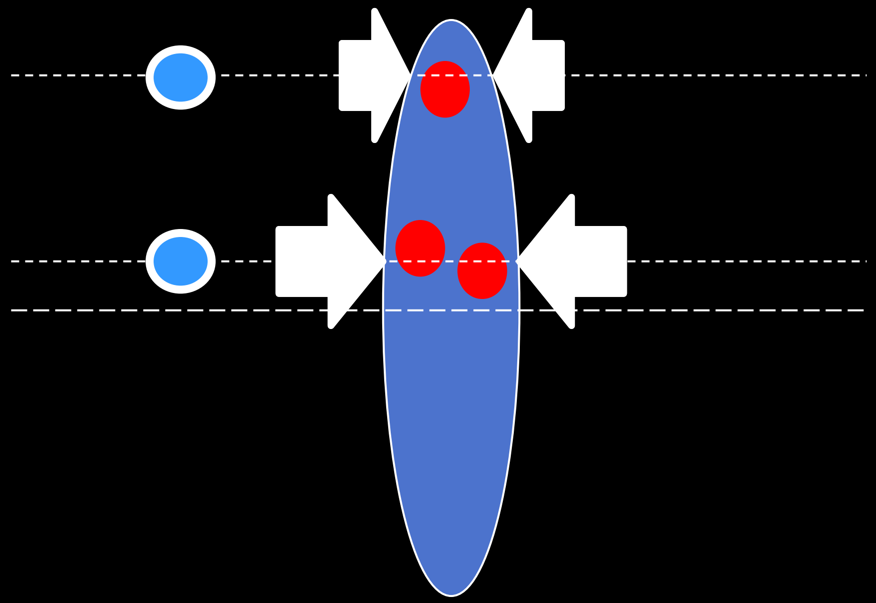
d+Au Geometry



r_T for each binary *N-N* collision in all events



Quantifying the Modification



R_{dAu}(0-100%) tells us the average modification of *J/ψ* from *d*+Au.

R_{CP} tells us the relative difference in modification between the thickest part of the nuclear pancake and the thinnest.

We can combine the average and relative measurements to examine how the absolute modification varies with nuclear longitudinal thickness.

Longitudinal Thickness → Modification

Take CNM effects to depend on the nuclear geometry via density-weighted longitudinal thickness, Λ, of the nucleus, as in Klein and Vogt, nucl-th/0305046.

$$\Lambda(r_T) = \frac{1}{\rho_0}\int dz\,\rho(z, r_T)$$

Use Woods-Saxon for $\rho(z,r_T)$

Several simple modification functions using Λ:

$$M(r_T) = e^{-a\Lambda(r_T)}$$
$$M(r_T) = 1 - a\Lambda(r_T)$$
$$M(r_T) = 1 - a\Lambda(r_T)^2$$

Exponential is usually used for $c\bar{c}$ break-up, while the linear case has been used for parameterizing nPDFs as a function of impact parameter (*eg*. EPS09).

R_{dAu} from geometric modification

Given the r_T-distribution of *NN* collisions and the r_T-dependent modification, it is simple to calculate R_{dAu} for any centrality bin:

$$R_{dAu,i}(a) = \int \underbrace{f_i(r_T)}_{} \underbrace{M(r_T;a)}_{} dr_T$$

r_T dist. of nucleon-nucleon collisions from PHENIX centrality MC

Modification as function of nuclear thickness and a free parameter, *a*

At a fundamental level, we want to study how the modification turns on with centrality.

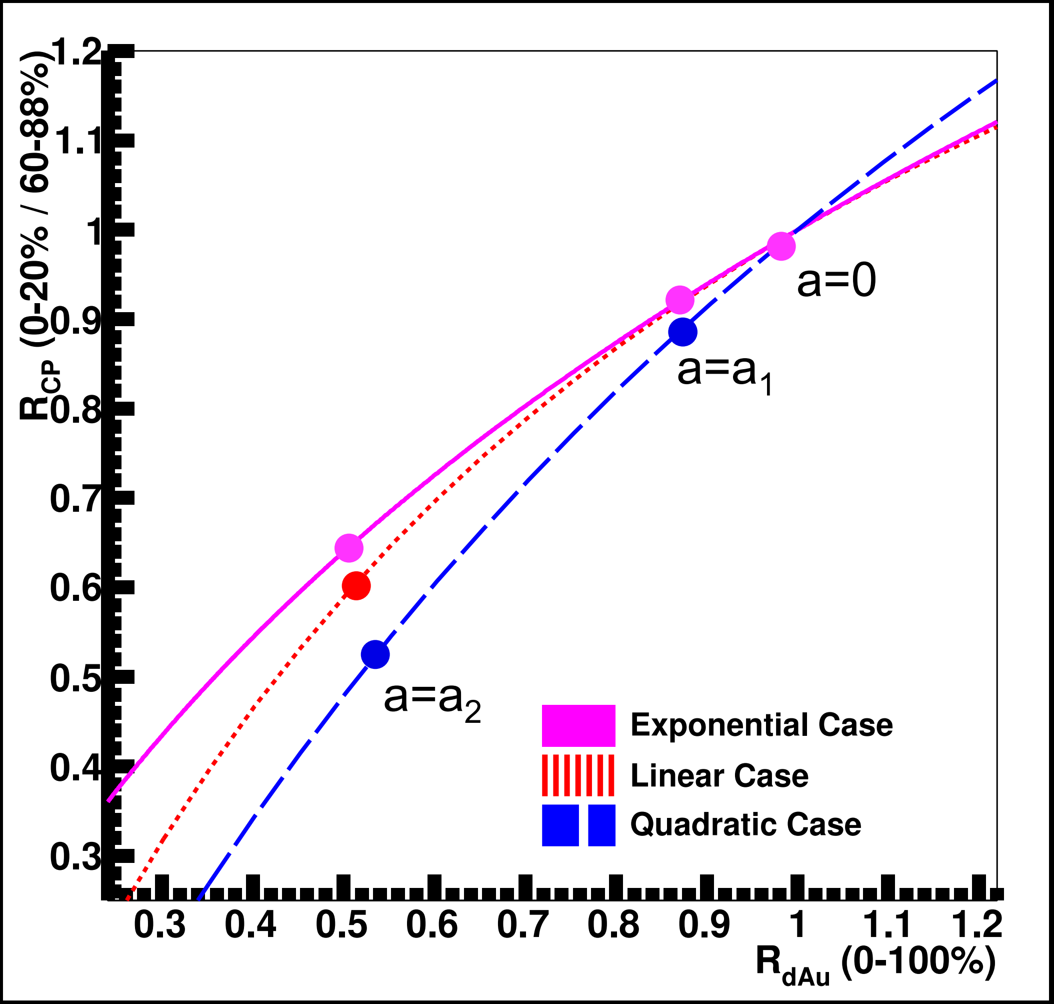
Use R_{dAu}(0-100%) for the *x*-axis. This is the overall level of modification averaged across impact parameters.

Use R_{CP} as *y*-axis. This is relative modification between central & peripheral.

For any value of *a*, we can put a point in the $R_{CP}(a)$ - $R_{dAu}(a)$ plane.

As we vary *a*, we map out one curve for each of our three modification functions $M(r_T)$.

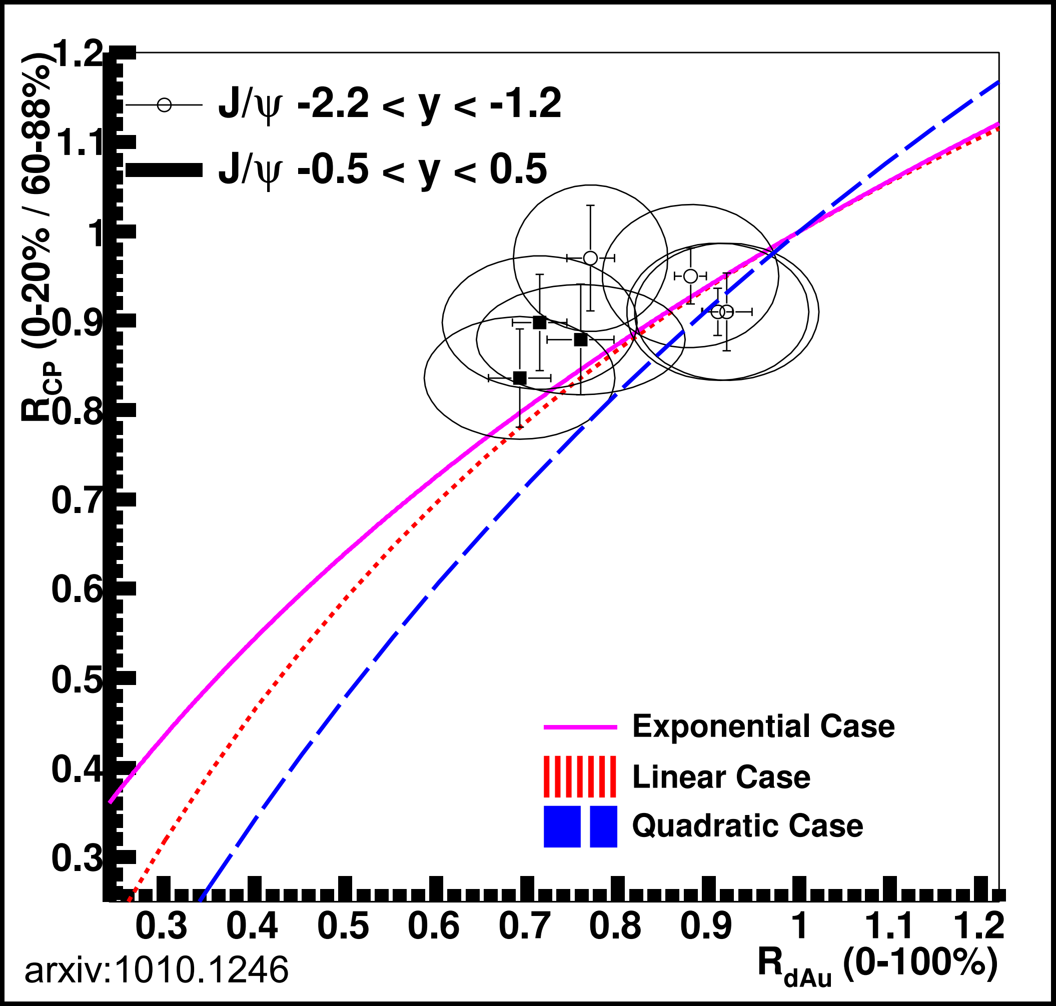
Any model using a particular $M(r_T)$ must follow that curve.



Now add the *d*+Au data points.

Backward and mid-rapidity points agree within uncertainties for the three cases presented here.

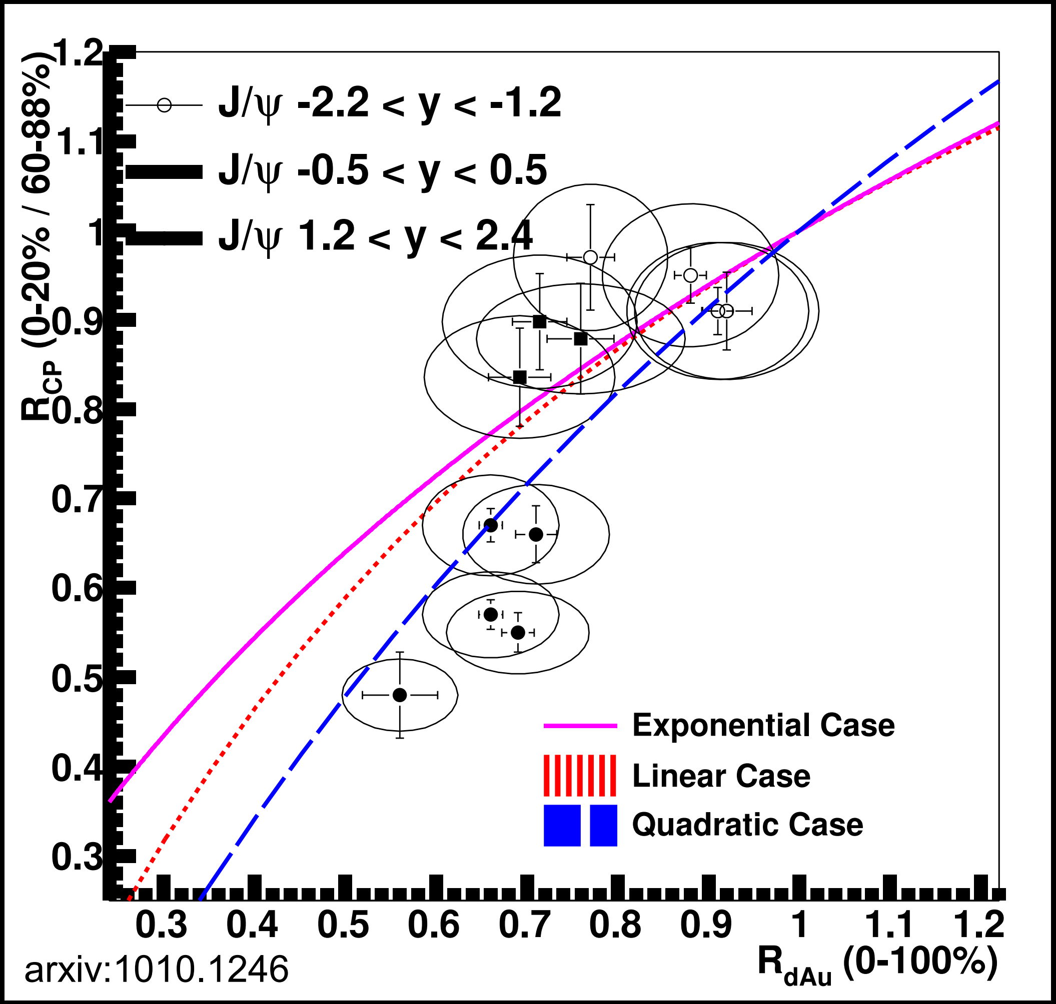
Ellipses = the point-to-point correlated systematics on R_{dAu} and R_{CP}



However, the forward rapidity points require the suppression to be stronger than exponential or linear with the thickness.

This is reflected by the inability of an EPS09(linear) + σ_{br}(exponential) to reproduce the R_{dAu} in both central and peripheral.

The only extra model dependence is the PHENIX centrality calculation, which is included in the systematics on the data.



Summary of CNM

- PHENIX has new *d*+Au → *J/ψ* results with much better statistical precision.
  - Letter with rapidity and centrality distributions submitted to PRL.
  - Longer paper in preparation.

- EPS09 + $\sigma_{breakup}$ cannot reproduce the rapidity- and centrality-dependent R_{dAu} and R_{CP} when EPS09 centrality dependence comes from linear dependence on longitudinal thickness Λ.

- The rate of suppression turn-on requires modification stronger than linear or exponential w/ density-weighted longitudinal thickness.

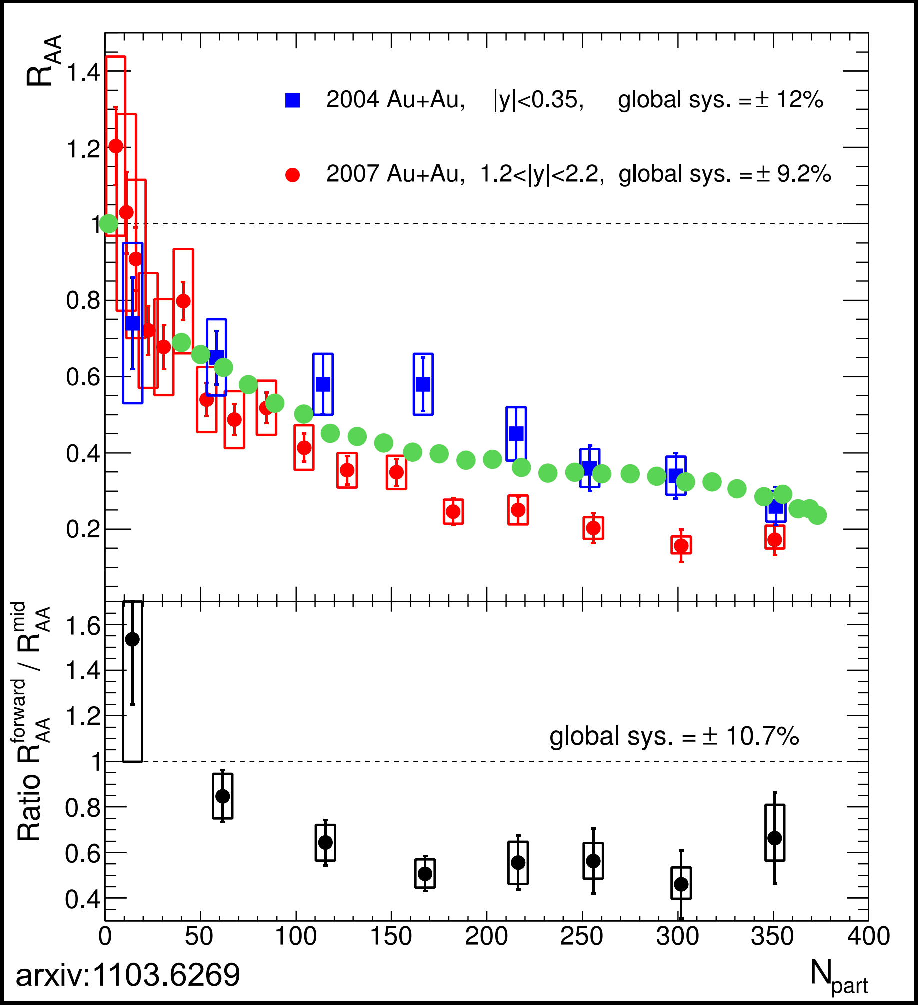
- Additional treatment in Nagle, Frawley, Linden Levy, and Wysocki, **arXiv:1011.4534**

Hot Nuclear Matter

- Now that we have some idea of the CNM effects, let's turn to the HNM.

- New Au+Au R_{AA} at forward rapidity using the 2007 dataset. ~3x increase in J/ψ statistics.

R_{AA} w/ NEW forward data



R_{AA} has the same trend as seen in 2004 data, but now with more bins at N_{part}>200.

<u>The Facts:</u>

Strong suppression in central Au+Au events.

Forward rapidity is more suppressed than midrapidity.

Midrapidity suppression is comparable to that measured at SPS energies.

Questions

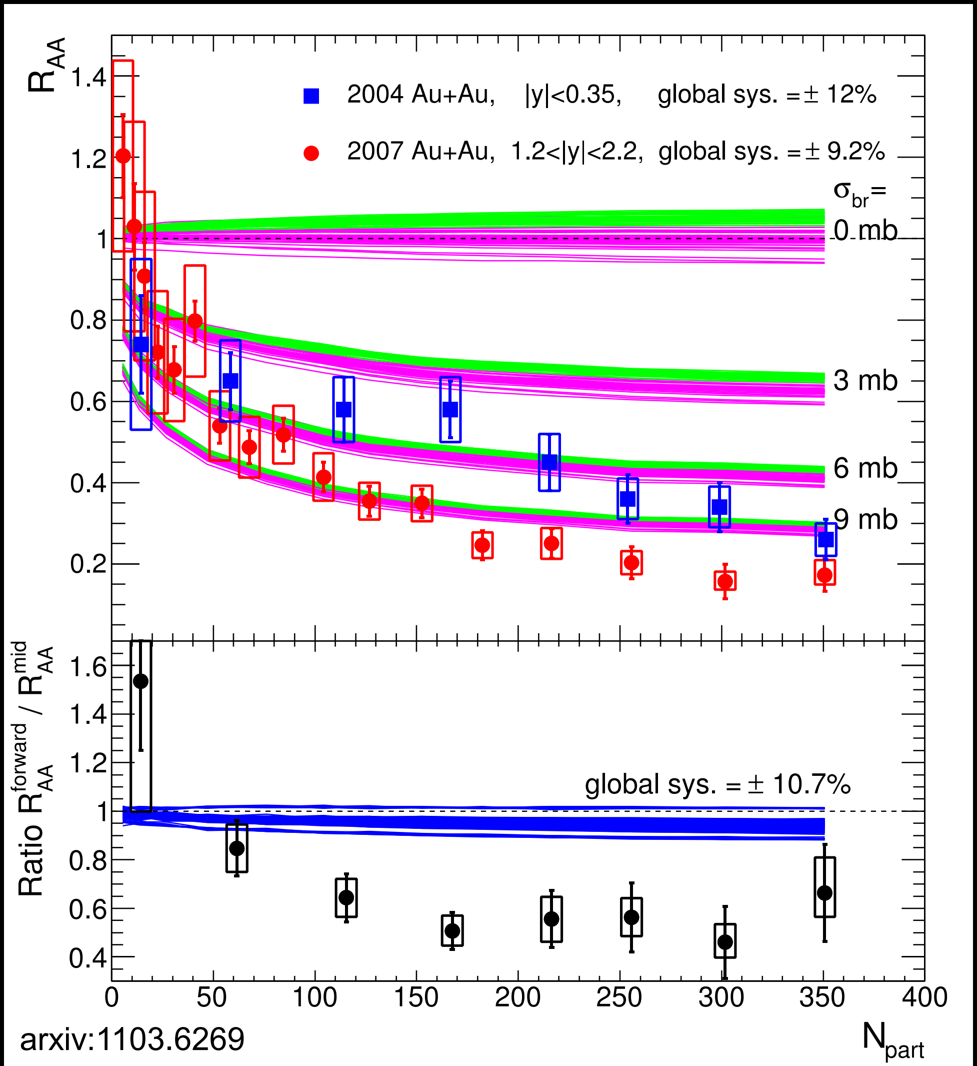
What causes the suppression in central Au+Au events?

1. Why is it similar at midrapidity between different sqrt(s_{NN})?
2. Why is it stronger at forward rapidity?

First we'll look at CNM effects in Au+Au collisions.

Let's project the calculation using EPS09 nPDFs and σ_{br} to Au+Au.

Projection of CNM Effects



Project EPS09 shadowing and σ_{br} to Au+Au

Doesn't reproduce R_{AA} or the ratio between rapidities.

Forward rapidity J/ψs largely come from a high-*x* gluon and a low-*x* gluon, so shadowing effects largely cancel.

Initial-State Parton Energy Loss (d+Au)

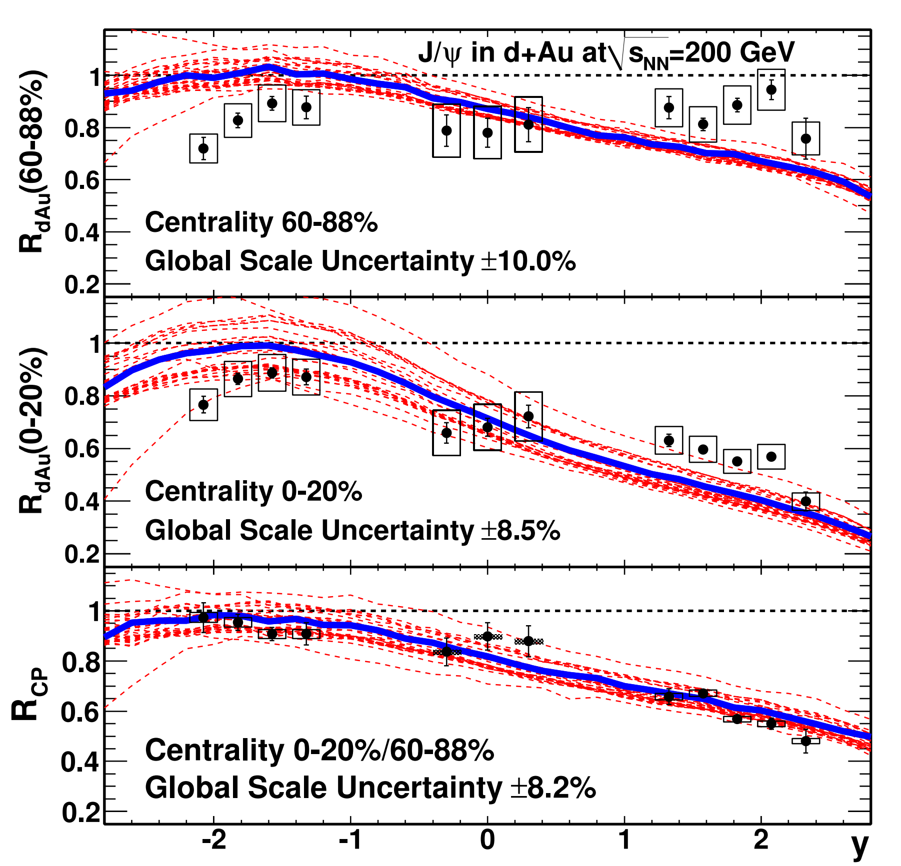
Add in another CNM effect: a simple form of initial-state parton energy loss.

$\Delta E/E \sim 0.05/\text{fm}^2 * L$

Fit R_{CP} w/ to get σ_{br}, using central EPS09 nPDF.

Red lines are other EPS09 nPDFs.

Matches R_{CP} pretty well, but not the separate R_{dAu} at forward or backward rapidity.



Nagle, Frawley, Linden Levy, and Wysocki, **arXiv:1011.4534**

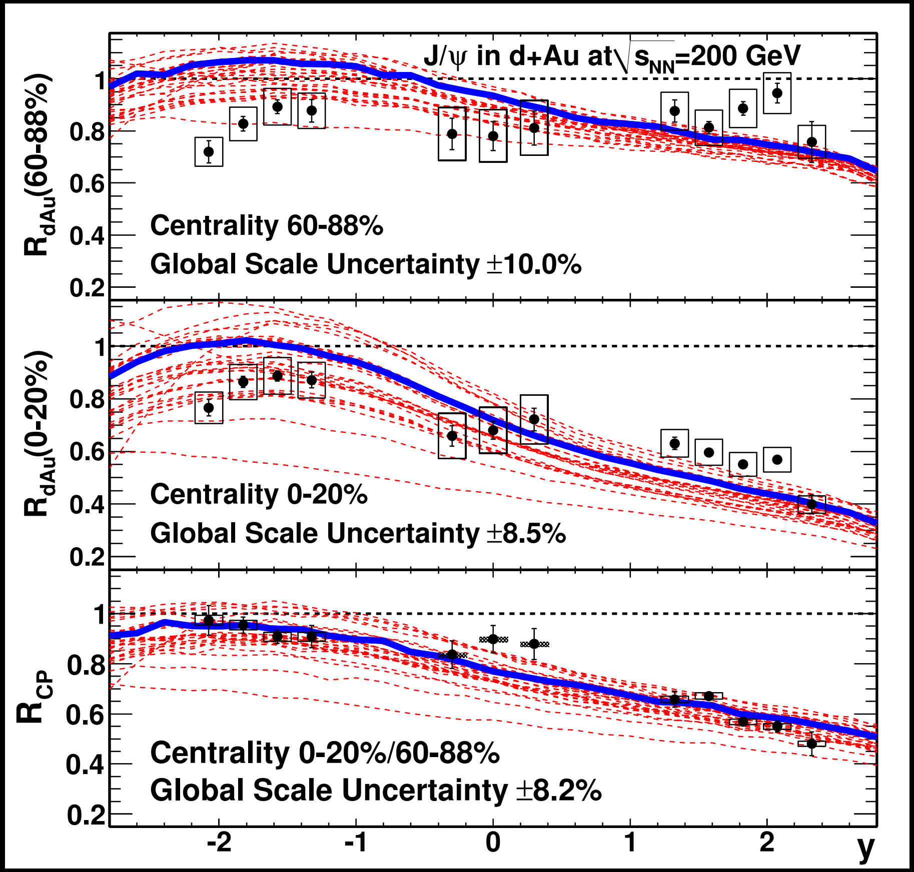
Initial-State Parton Energy Loss (cont)

Now try with L^2 dependence.

$\Delta E/E \sim 0.005/\text{fm}^2 * L^2$

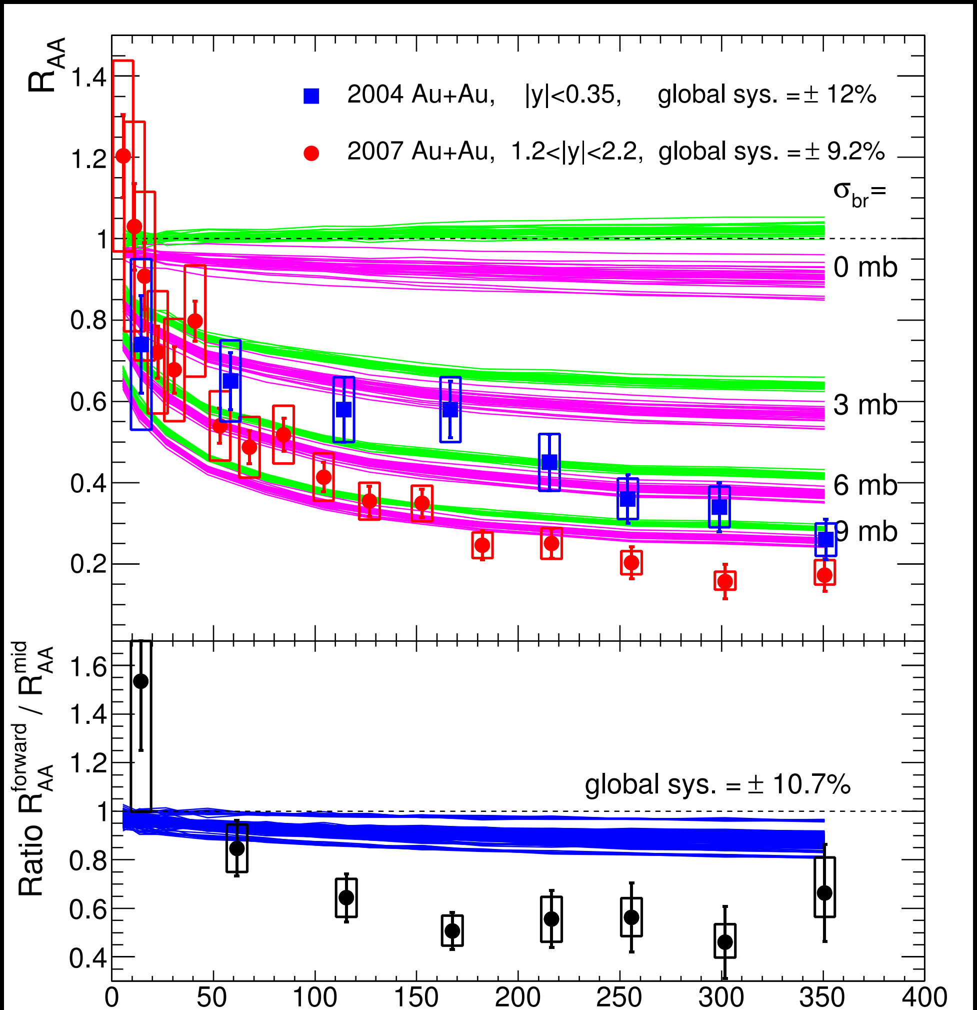
Again, matches R_{CP} pretty well, but not the separate R_{dAu} at forward or backward rapidity.

EPS09 + σ_{br} + initial-state energy loss cannot reproduce the R_{dAu} rapidity/centrality distribution.



Nagle, Frawley, Linden Levy, and Wysocki, **arXiv:1011.4534**

Initial-State Parton Energy Loss (Au+Au)



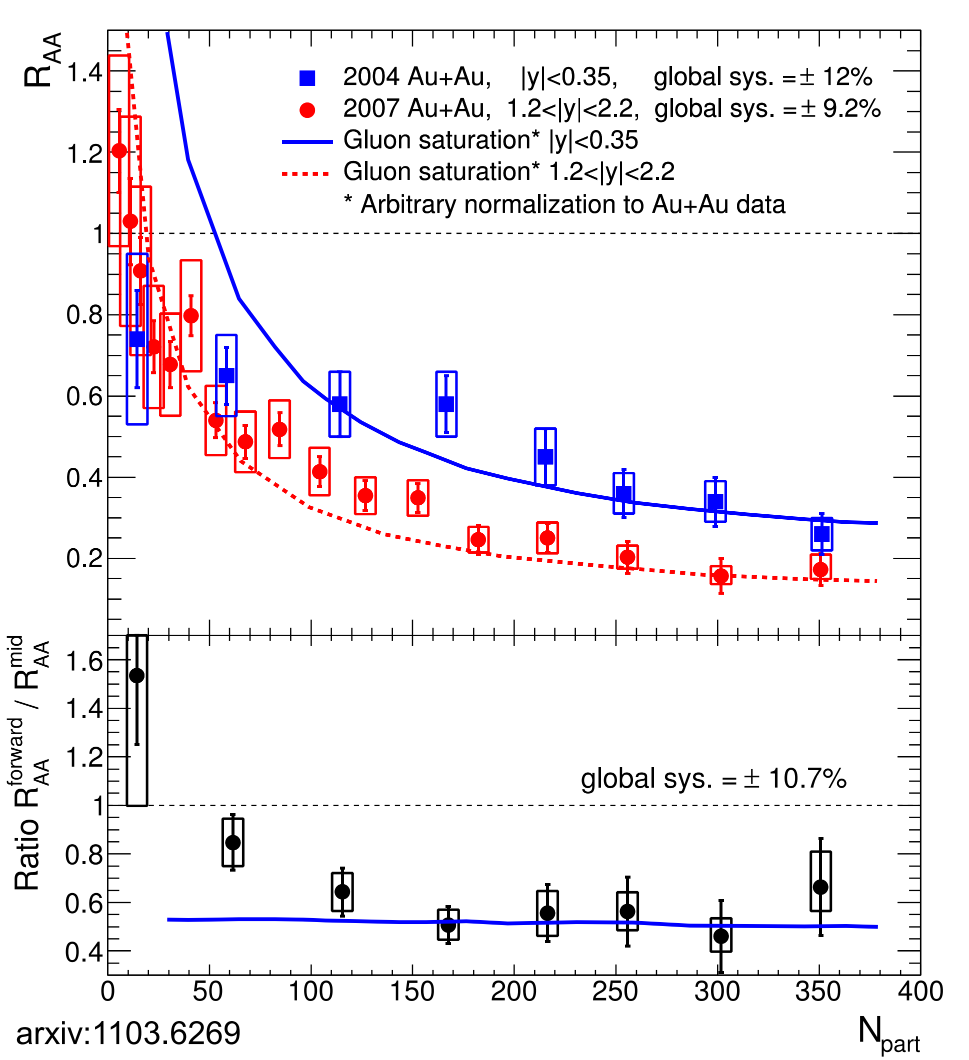
arxiv:1103.6269

Redo the projection to Au+Au now including the energy loss: $\Delta E/E \sim 0.005/\text{fm}^2 * L^2$

Largest effect is at forward rapidity, but even there it is not huge.

Still takes a very large σ_{br} to match the R_{AA}, and the ratio is still > 80%.

Gluon Saturation



Another approach is using gluon saturation as in the CGC combined with double-gluon exchange (which leads to the enhancement in peripheral collisions).

Extension of method from d+Au calculation.

Arbitrarily normalized to R_{AA} data points.

However, matches the ratio of forward/midrapidity very well.

D. Kharzeev, *et al*, Nucl. Phys. A 826, 230 (2009), 0809.2933

Hot Nuclear Matter Effects

- Now that we have some understanding of the CNM effects in Au+Au collisions, we can start looking at HNM effects.

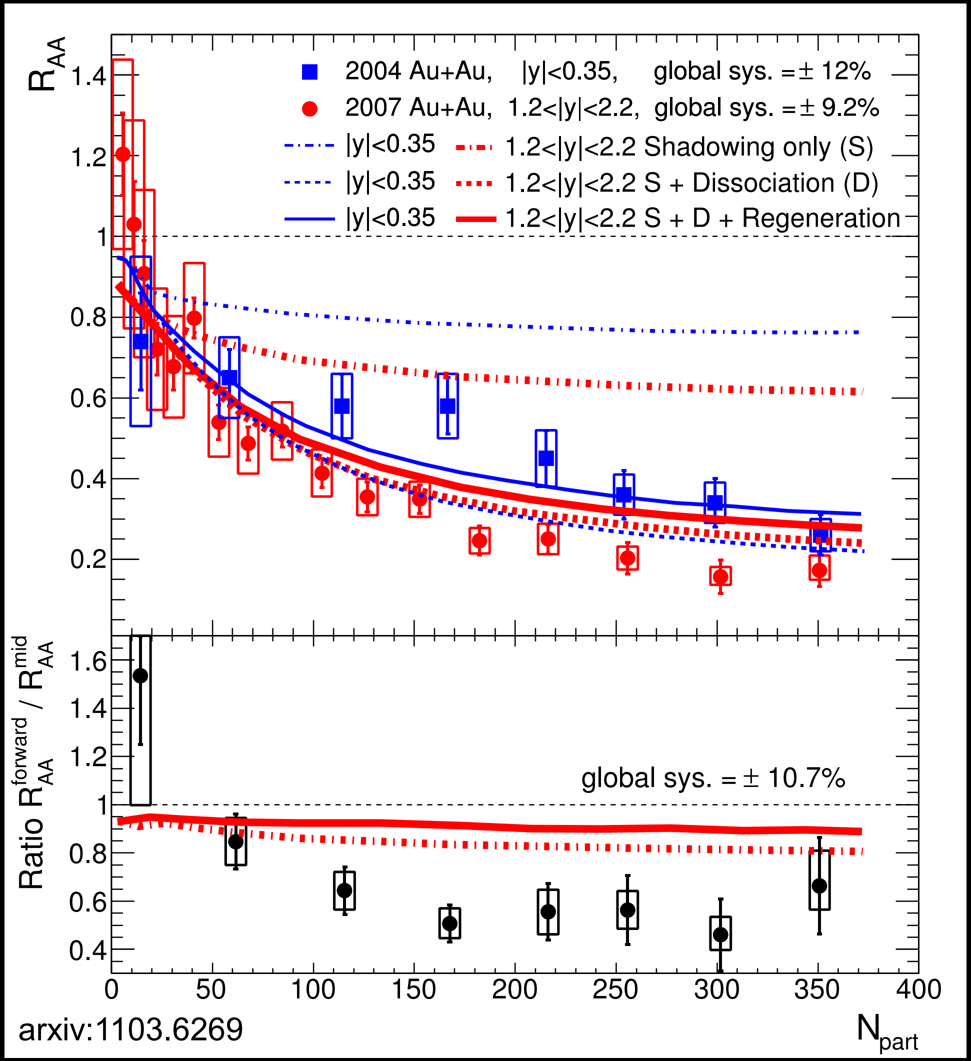
- HNM dissociation will let us match the suppression in central collisions. But what combination of suppression/regeneration will match midrapidity and forward rapidity?

Comover Interaction Model

Combine *x*-dependent nuclear absorption (but σ_{br}=0 at midrapidity) with hot, dissociative comoving medium.

Sort of gets midrapidity R_{AA}, but not the forward rapidity.

Easily seen in the ratio, where HNM effects actually bring it back towards unity.



A. Capella, *et al*, Eur. Phys. J. C 58, 437 (2008), 0712.4331

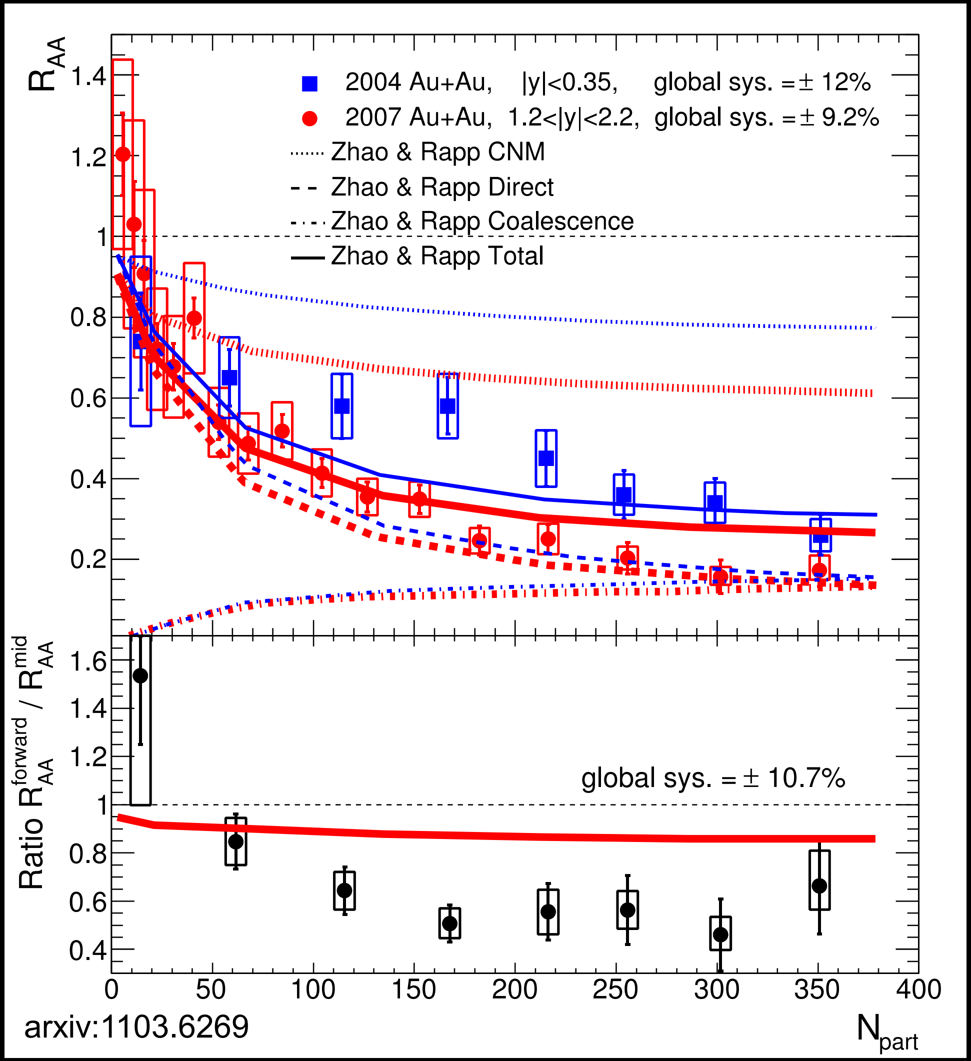
Zhao & Rapp

Now model a QGP phase followed by a hadron gas phase.

Very similar levels of suppression to CIM, just slightly larger HNM suppression at forward rapidity.

* Note how similar the regeneration is between the two rapidities.

Same problem with the forward/midrapidity ratio.

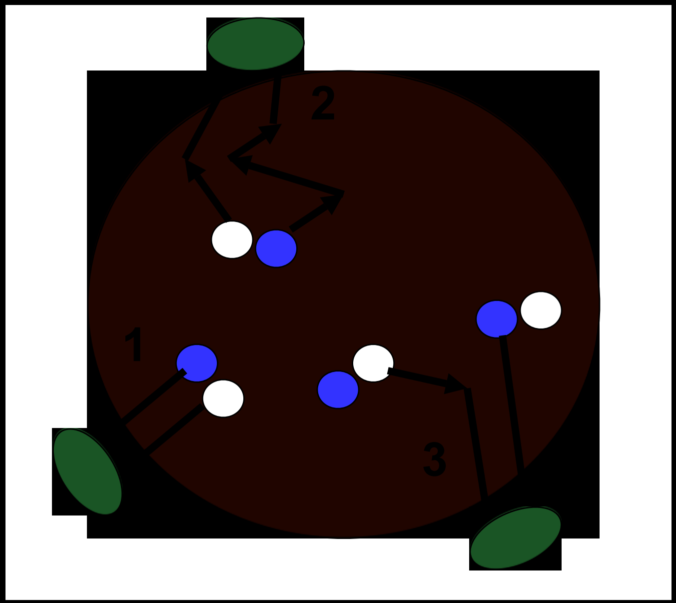


X. Zhao and R. Rapp, Phys. Lett. B 664, 253 (2008), 0712.2407

Regeneration of J/ψs helps reduce the overall amount of suppression.

It does *not* appear to explain the larger suppression at forward rapidity.

Idea was that regeneration would go as N_{ccbar}^2, but this is only true if it is due to off-diagonal pairs (case 3).



Most calculations seem to be dominated by diagonal pairs recombining (case 2), which goes as N_{ccbar}.

Conclusions

1. What causes the suppression in central Au+Au events?
   - CNM effects cannot reproduce the suppression seen in Au+Au (no surprise). Need a full CNM/HNM picture.

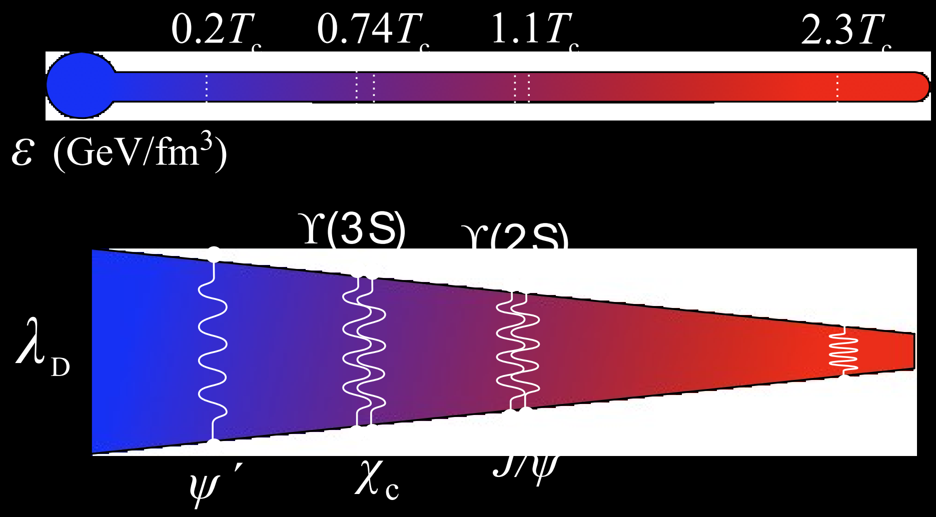
2. Why is R_{AA} similar between different sqrt(s_{NN}) at midrapidity?
   - RHIC appears to have smaller CNM suppression than SPS and more regeneration of J/ψs, so this could balance stronger HNM suppression. Coincidental?

3. Why is it stronger at forward rapidity?
   - CGC might be able to reproduce the forward/midrapidity R_{AA} ratio, while most regeneration calculations do not. Does this imply that it is mostly due to CNM effects?

The Future

- RHIC J/ψ results have helped make the interpretation of SPS results more robust. I think the same will happen with the LHC results and RHIC J/ψ physics.

- PHENIX is expecting to add upsilon measurements and additional charmonium states to our repertoire with our next-generation upgrades.
  - Varying the state changes probes the screening length/temperature.
  - No off-diagonal regeneration for upsilons.
  - CNM effects should be similar across states.



Take-home Message(s)

a) Gluon shadowing does seem to play an important role in d+Au. Whether this includes gluon saturation is still an open question, but at least for the most forward rapidity that would explain the large suppression and geometric dependence of the turn on.

b) Initial state energy loss may play a role, but the nPDF uncertainties and J/ψ production uncertainties preclude a strong conclusion.

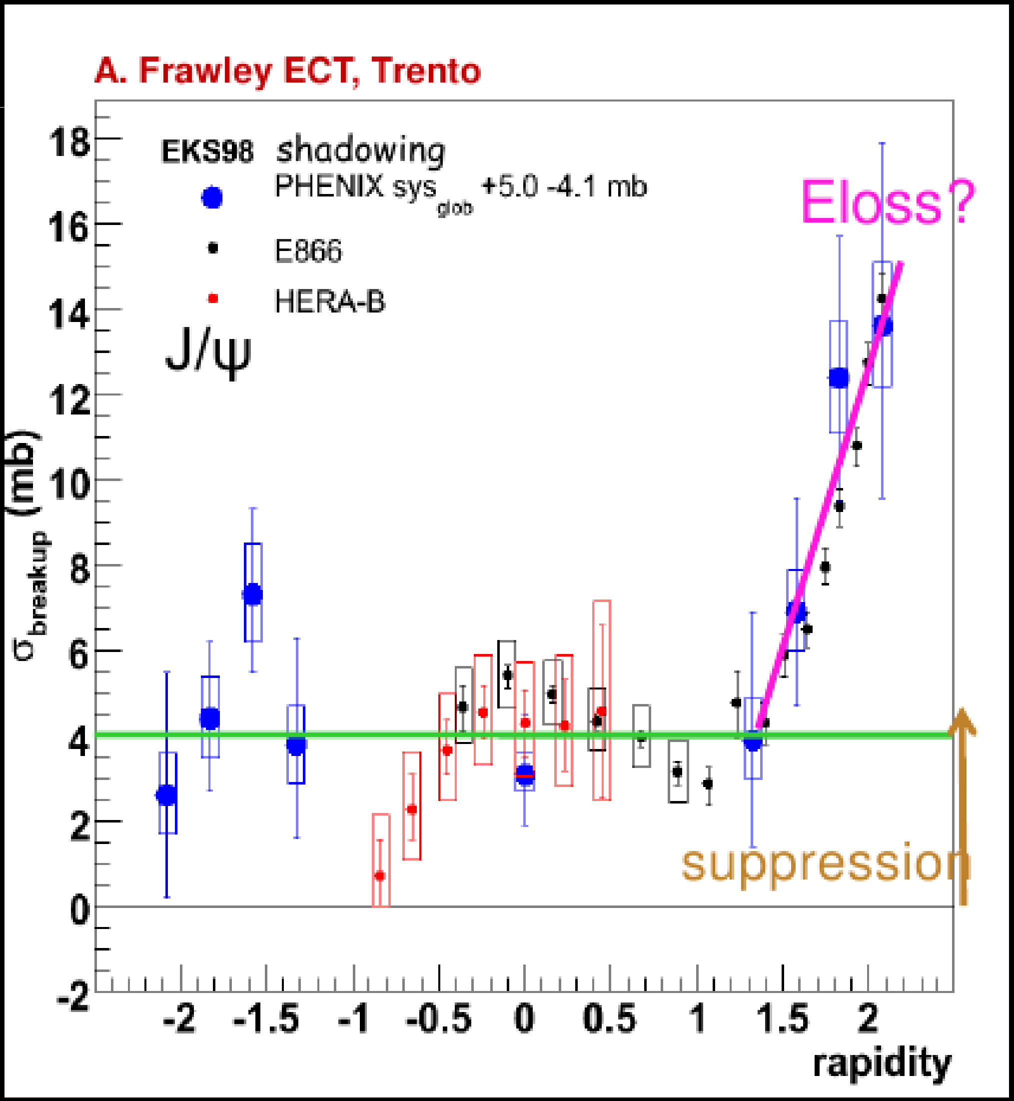
c) Hot nuclear matter effects are confirmed, but we do not divide them out quantitatively because precise description of CNM exists.

d) There is no clear understanding of the larger suppression at forward rapidity -- does not seem to be from recombination as previously proposed. Could be gluon saturation, but that plot showing agreement is deceptive.

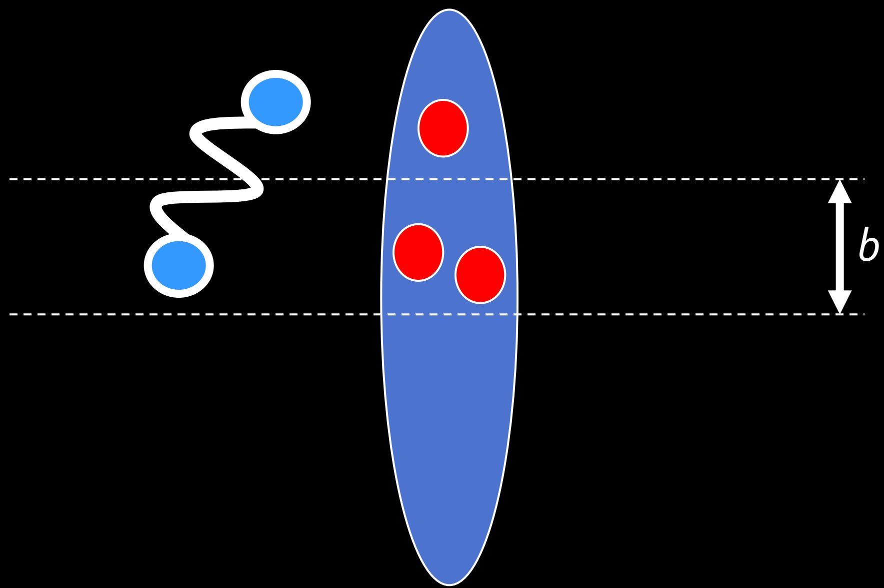
Backup

We discovered a - Rapidity dependence!

- Extract best fit to R_{CP} at a given rapidity versus centrality.
- Based on predictions from R. Vogt.
- Parameterizes all the effect that shadowing is missing.
- Same shape at lower energy (initial state energy loss).



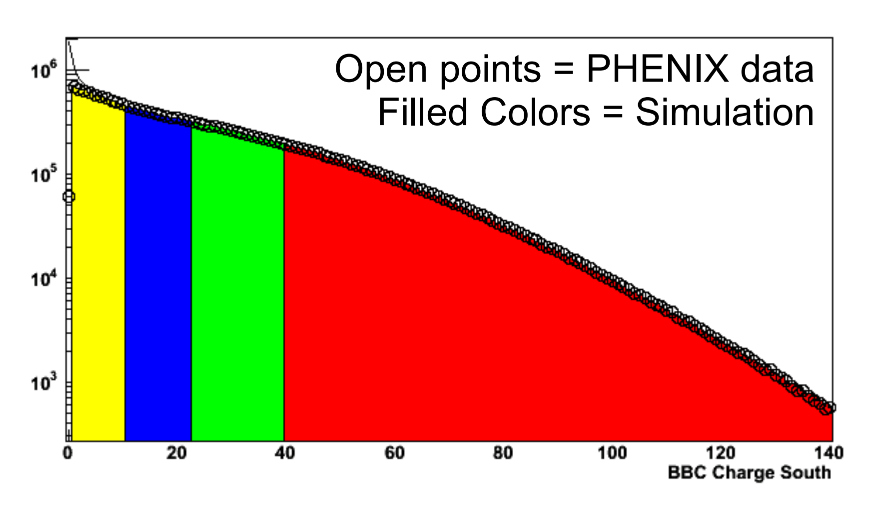
Centrality @ PHENIX



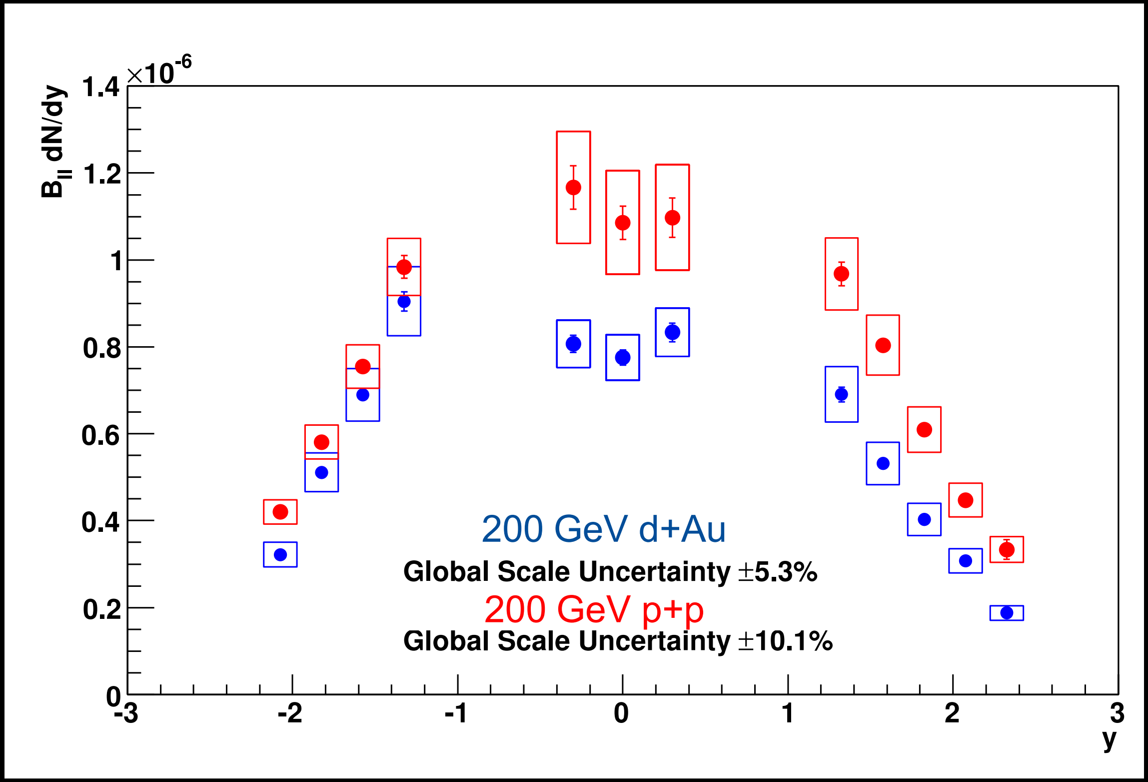
Use BBC charge divided into percentile bins of centrality to classify events. Then use simple Monte Carlo to map this to N_{coll} or impact parameter.

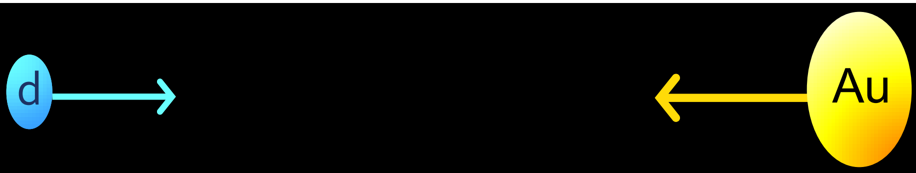
PHENIX currently uses four centrality bins for *d*+Au.

<u>PHENIX *d*+Au Centrality Classes</u>
Includes Glauber Au geometry, deuteron Hulthen wavefunction, event-to-event fluctuations, modeling of PHENIX BBC response and trigger bias, and final event selection.



dN/dy vs. rapidity





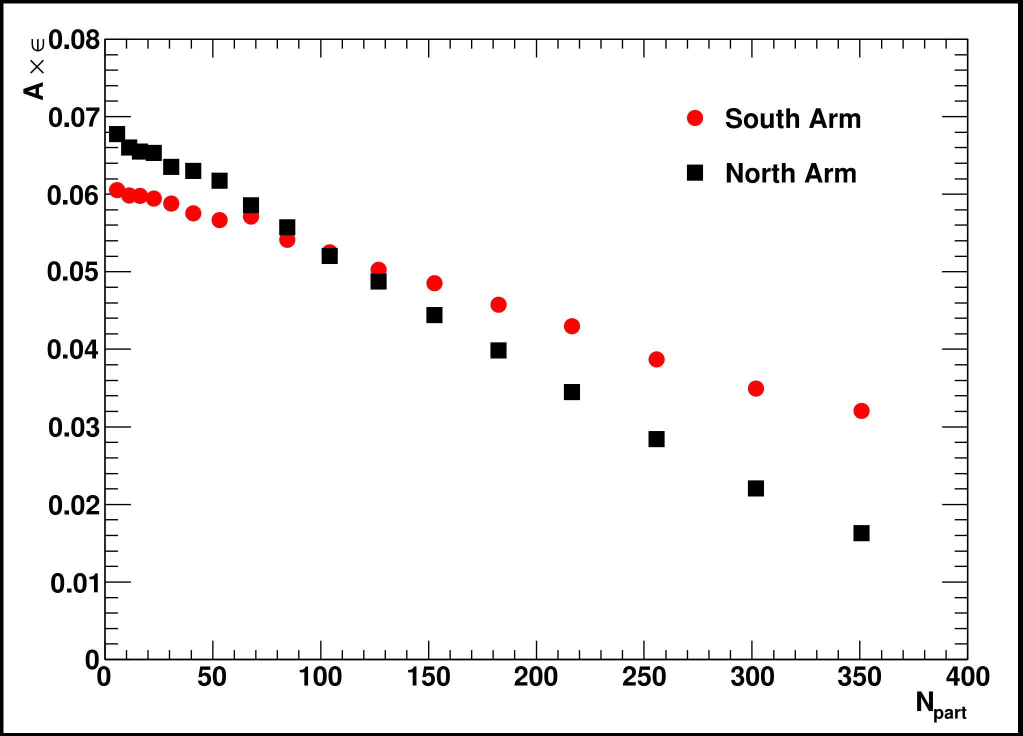
New invariant yields vs. rapidity for *p*+*p* and *d*+Au

- Very small statistical uncertainties
- *d*+Au is scaled by $1/N_{coll}$

Au+Au Reconstruction Efficiency

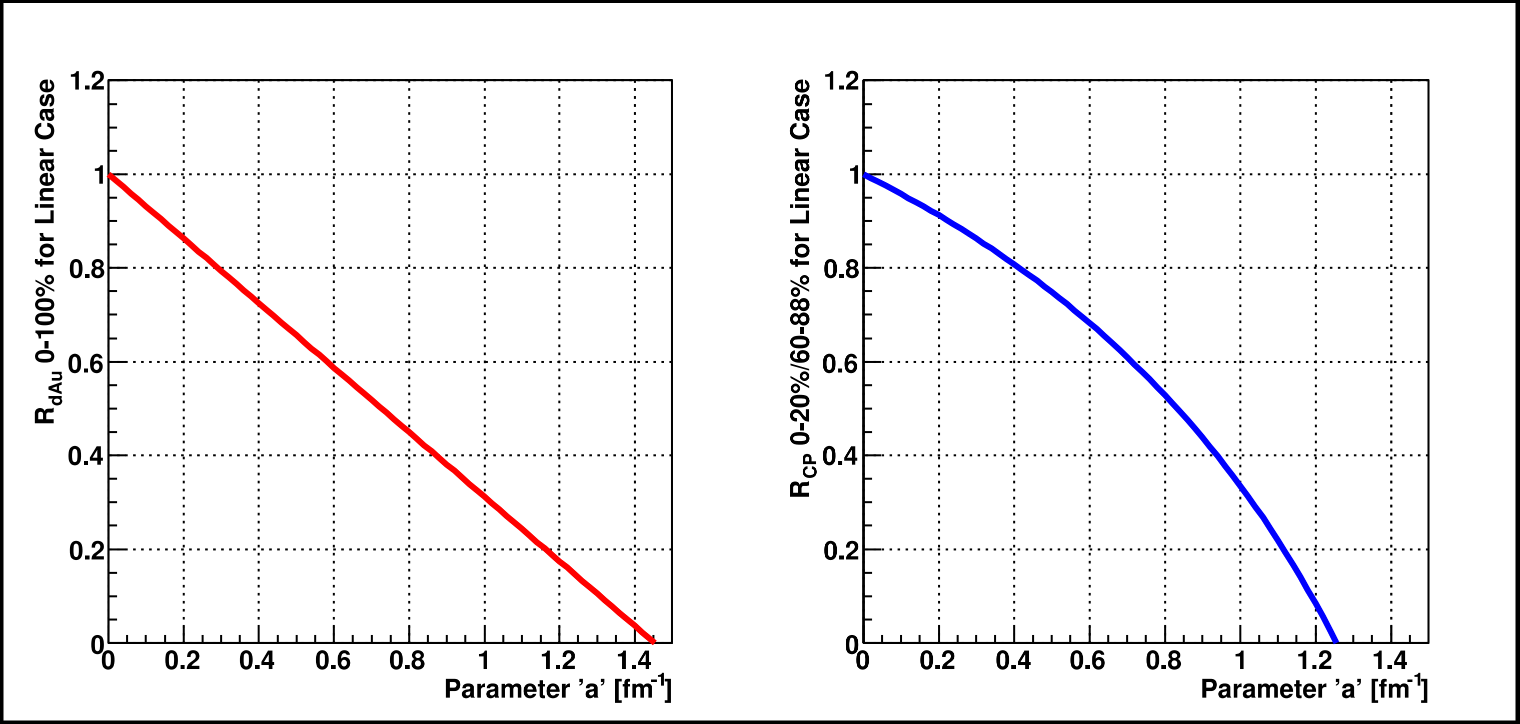
To calculate Au+Au invariant yields, we need to correct by detector acceptance and efficiency.

The two spectrometers are not identical. The North Arm has greater acceptance, but worse occupancy effects.

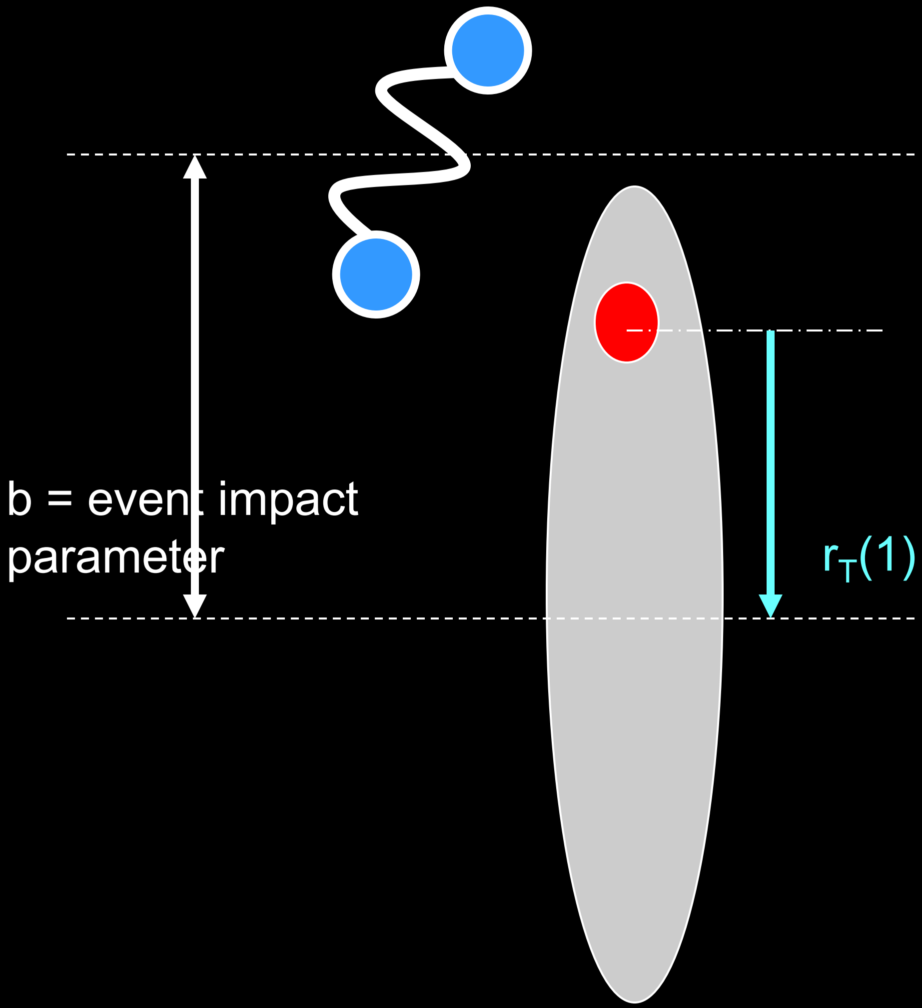


Linear Example

The $R_{dAu}(a)$ for any centrality bin is generated simply by folding $M(r_T)$ with the r_T distribution for a given centrality bin. R_{CP} is simply the ratio of two centrality bins.



d-Au collision

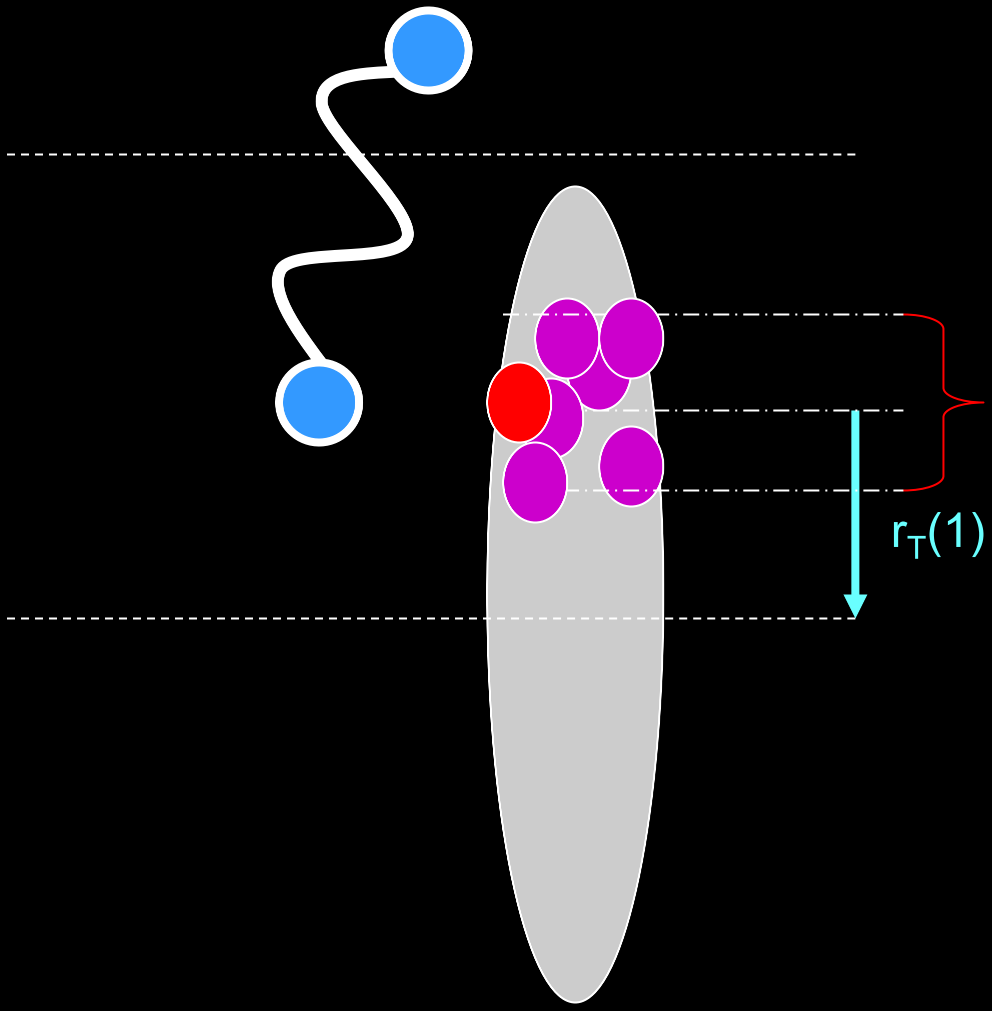


Sometimes only one nucleon from the deuteron hits the Au nucleus.

62% → Peripheral 60-88%
37% → Mid-Peripheral 40-60%
20% → Mid-Central 20-40%
7% → Central 0-20%

We can actually measure this if the missed nucleon is a neutron (in the PHENIX ZDCs)

What about event-to-event fluctuations in $\Lambda(r_T)$?



For each binary collision at rT, count the number of other nucleons in the nucleus inside the tube defined by rT $\pm$ 2 x 0.877 fm

In this example, the **Ntube** = 6.

Perhaps the nuclear modification is related not to the average thickness L(rT), but instead the fluctuating quantity related to **Ntube** defined above.

In the Linear Modification Case, these fluctuations around the average will not matter.
Not exactly true for the non-linear cases.
Also, the difference of the blue solid and dashed raises the question of how localized in rT is the effect (blurred over the size of a nucleon?)