Cold Nuclear Matter Effects on J/ψ Production from PHENIX

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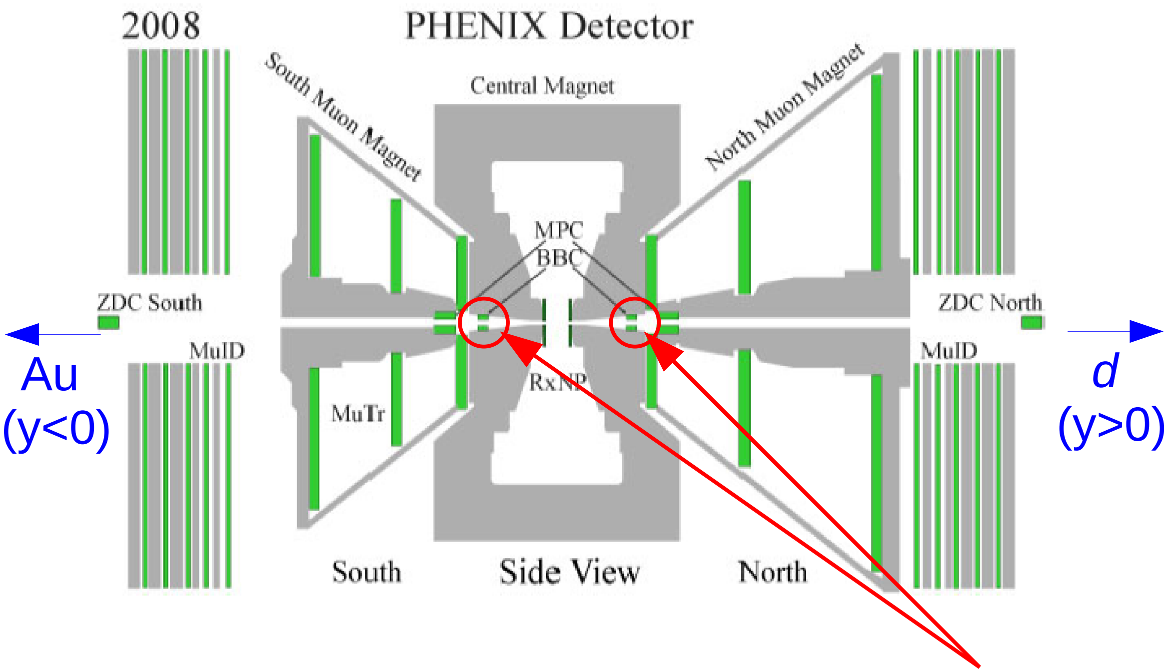
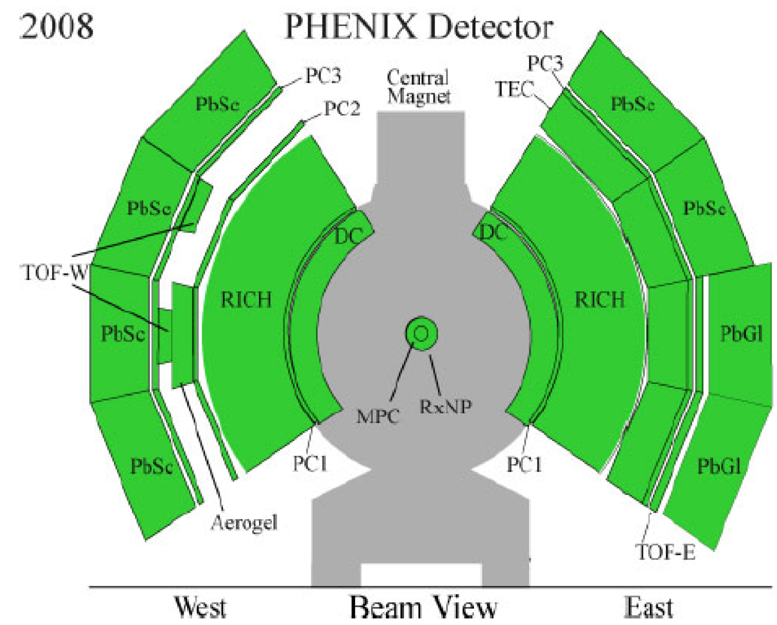
For the PHENIX Collaboration
WWND 2012

The PHENIX Detector

2008 Run





Muon Arms

- Muons
- $1.2<|\eta|<2.4$
- $\Delta\varphi = 2\pi$
- $J/\psi \rightarrow \mu^+\mu^-$

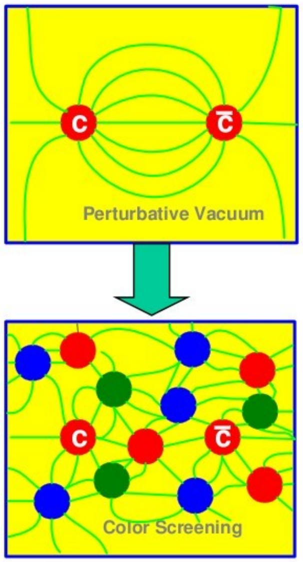
Beam-Beam Counters

- Measure Centrality (impact parameter) as a percentage of BBC charge

Central Arms

- Charged particles
- $\eta<|0.35|$
- $\Delta\varphi = \pi$
- $J/\psi \rightarrow e^+e^-$

Heavy Quarkonia



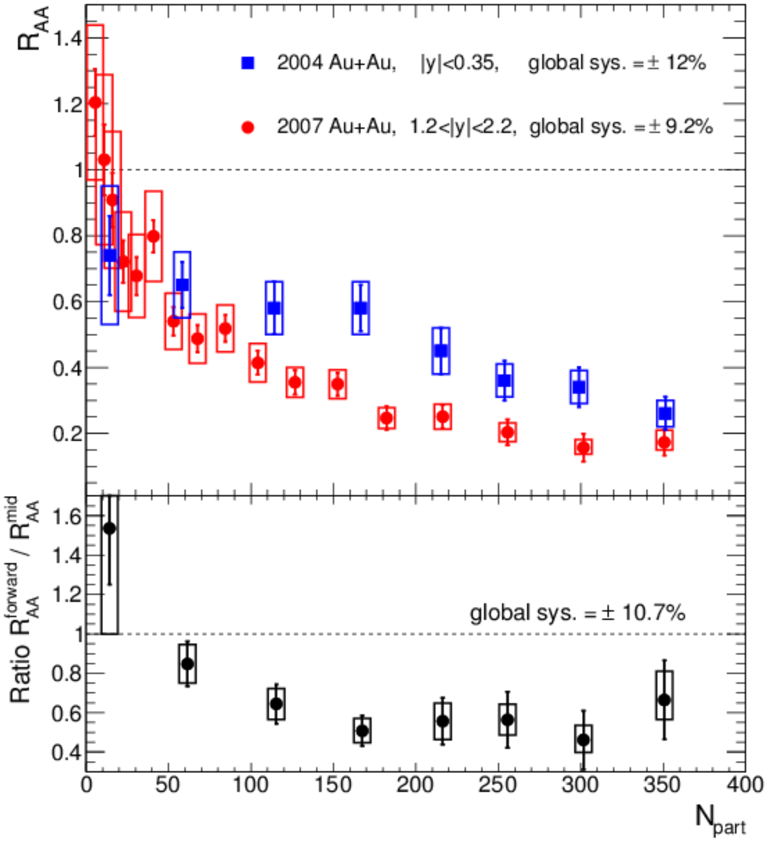
Goal: Measure the screening length in the QGP

Use heavy quarkonia as a tool for measuring this directly.

$$R_{AA} = \frac{dN^{AA}/dy}{dN^{pp}/dy\, N_{Coll}}$$

Understanding A+A results alone is not trivial.

Phys. Rev. C 84, 054912 (2011)



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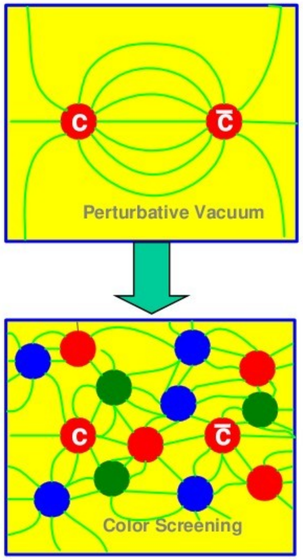

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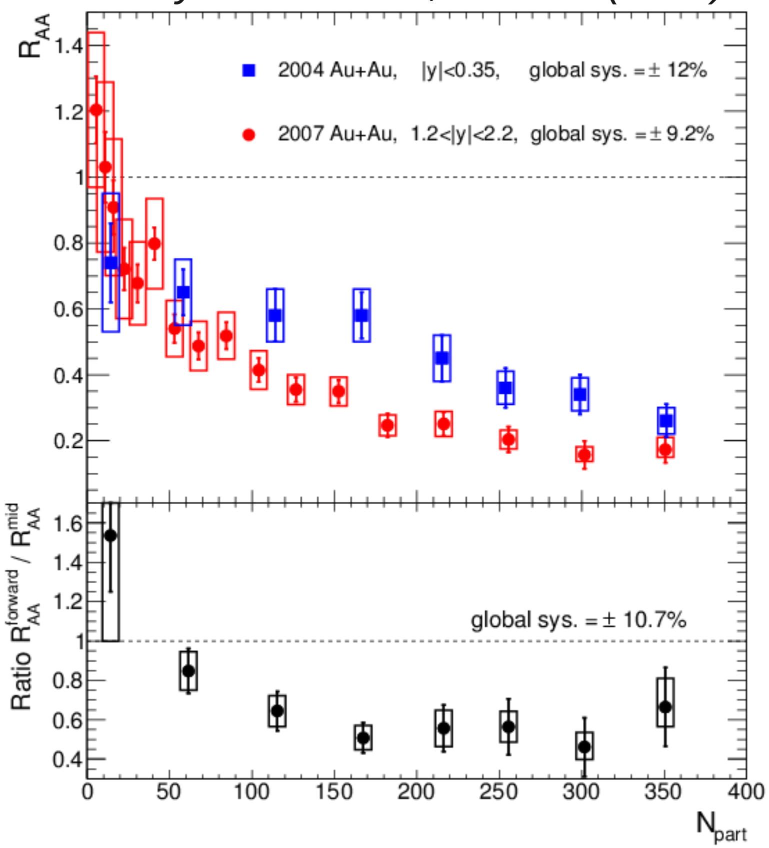


Need to understand our baseline in order to extract hot nuclear matter effects!

Need to not only measure/understand p+p production.

Need to measure/understand Cold Nuclear Matter Effects (effect of producing a J/ψ in a nuclear target)

Understanding our Baseline

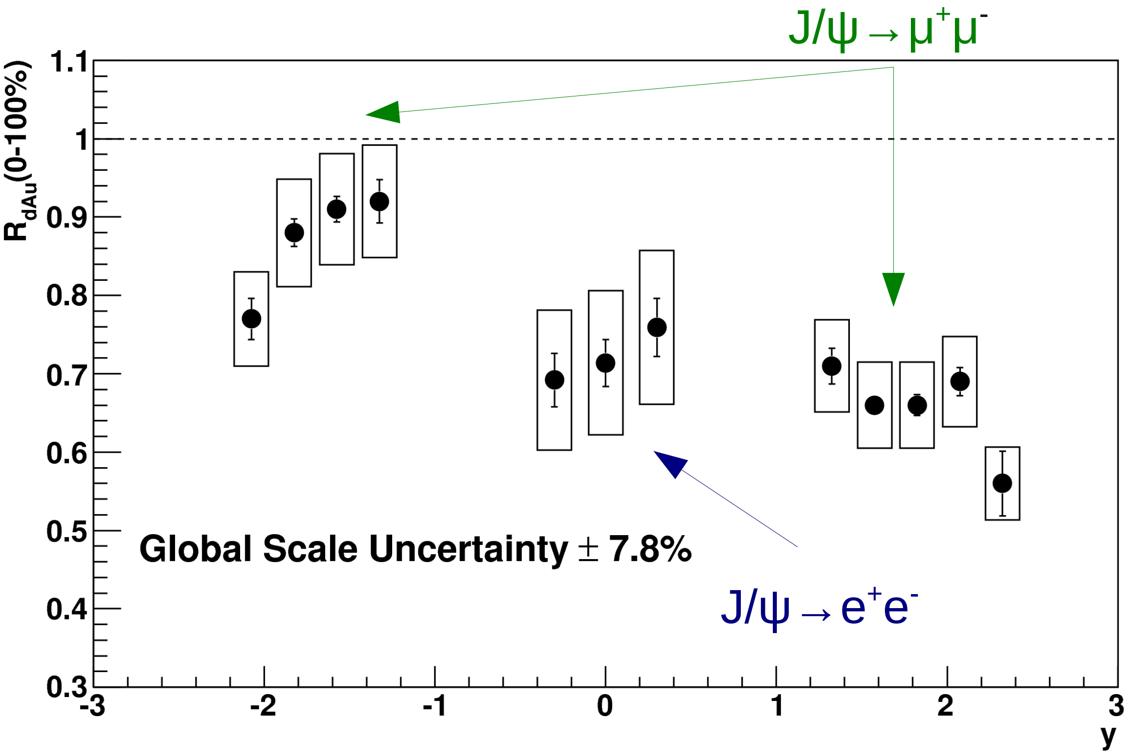
- Large statistics d+Au data taken @ 200 GeV in 2008.
- Allows direct study of Cold Nuclear Matter (CNM) effects.
- Goal: Measure J/ψ production over wide range of kinematics.
  - Rapidity dependence (*Phys. Rev. Lett. 107, 142301 (2011)*).
  - New! p_T dependence (*arXiv:1204.0777*).

Rapidity Dependence of R_{dAu}

- Minimum Bias (centrality integrated) R_{dAu} results as a function of rapidity.
- Shows increasing suppression with increasing rapidity.

$$R_{dAu}(i) = \frac{dN^{dAu}_{J/\psi}/dy(i)}{\langle N_{coll}(i)\rangle dN^{pp}_{J/\psi}/dy}$$

Vertical Error bars – point-to-point uncorrelated errors
Boxes - point-to-point correlated errors

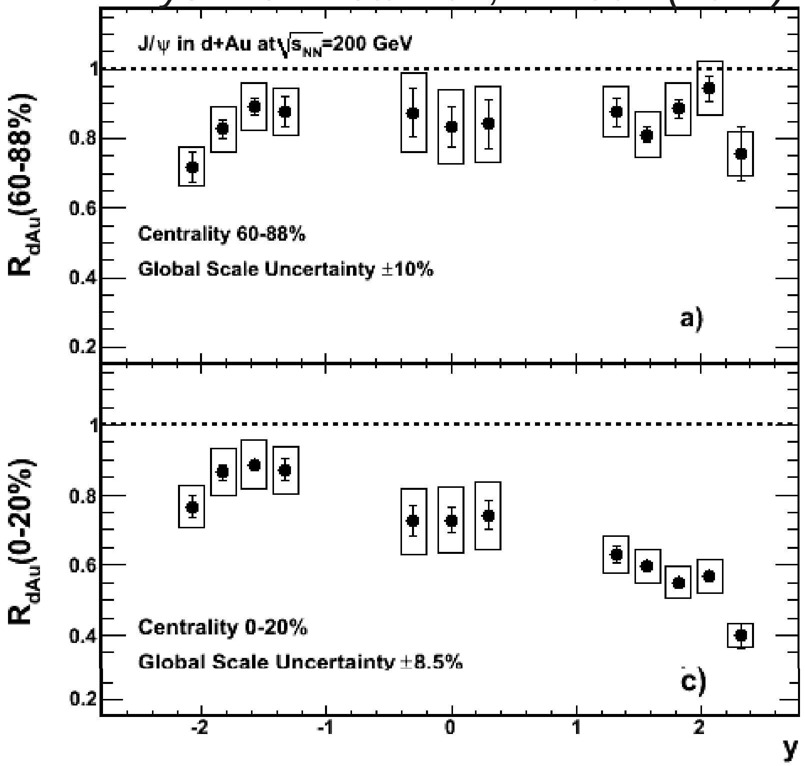


arXiv:nucl-ex/1010.1246

Rapidity Dependence of R_{dAu} II

- **Top** – R_{dAu} vs y for Peripheral events
  - R_{dAu} constant w/ rapidity.
- **Bottom** – R_{dAu} vs y for Central events
  - Stronger suppression at forward rapidity.
  - Similar level of suppression at backward rapidity in central and peripheral events.

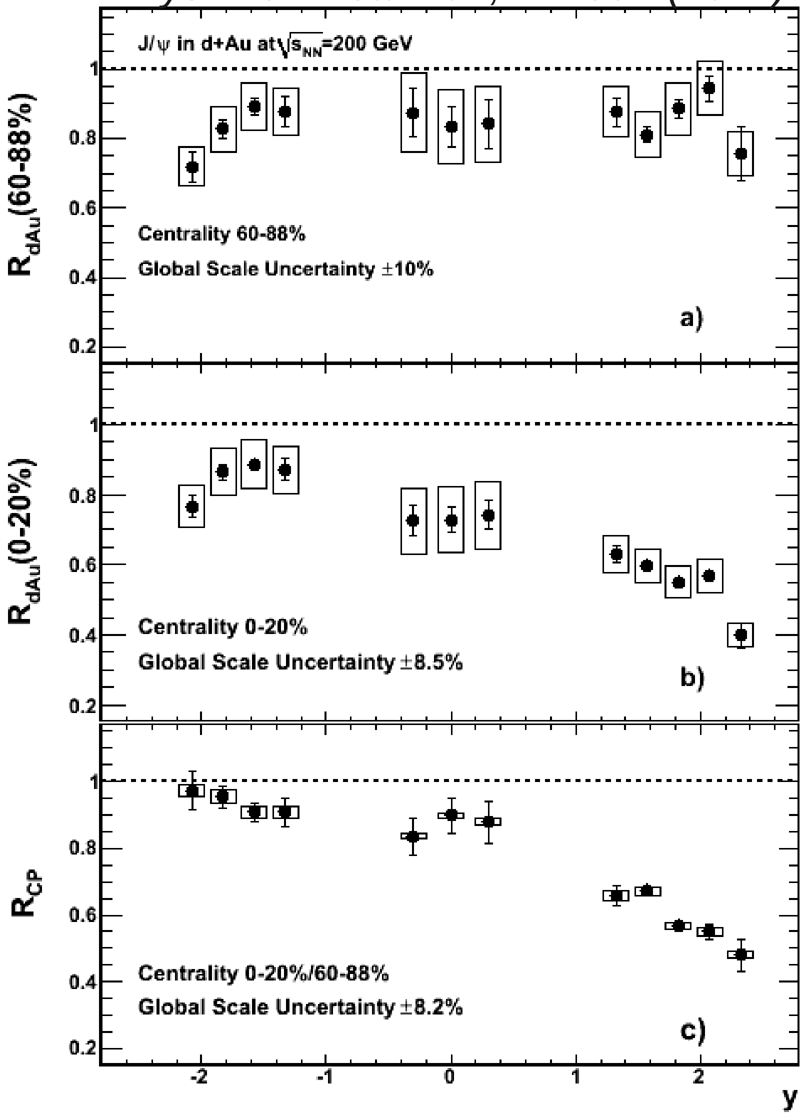
Phys. Rev. Lett. 107, 142301 (2011)



Rapidity Dependence of R_{dAu} III

- Take the ratio of central R_{dAu} (b) to peripheral R_{dAu} (a) → R_{cp}
  - Significant reduction of systematic errors.
  - Describes change in suppression over the nucleus.
  - Strong suppression at forward rapidity.

Phys. Rev. Lett. 107, 142301 (2011)



What can we learn about the geometric dependence of the modification?

A Different Way to Look at the Centrality Dependence

- Use simple geometric model.
- Assume modification is dependent on the nuclear thickness.

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

- Try three simple forms.
  - *Linear:* $M(r_T, a) = 1 - a\Lambda(r_T)$
  - *Quadratic:* $M(r_T, a) = 1 - a\Lambda(r_T)^2$
  - *Exponential:* $M(r_T, a) = e^{-a\Lambda(r_T)}$

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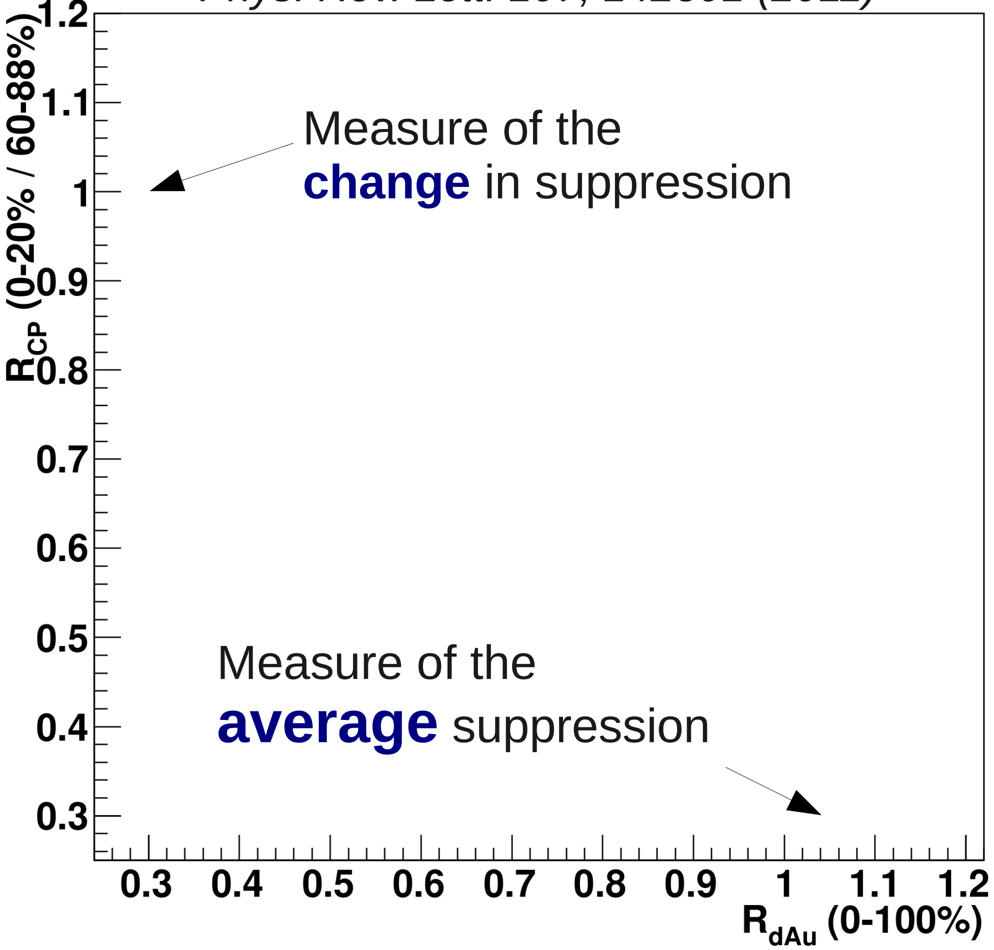

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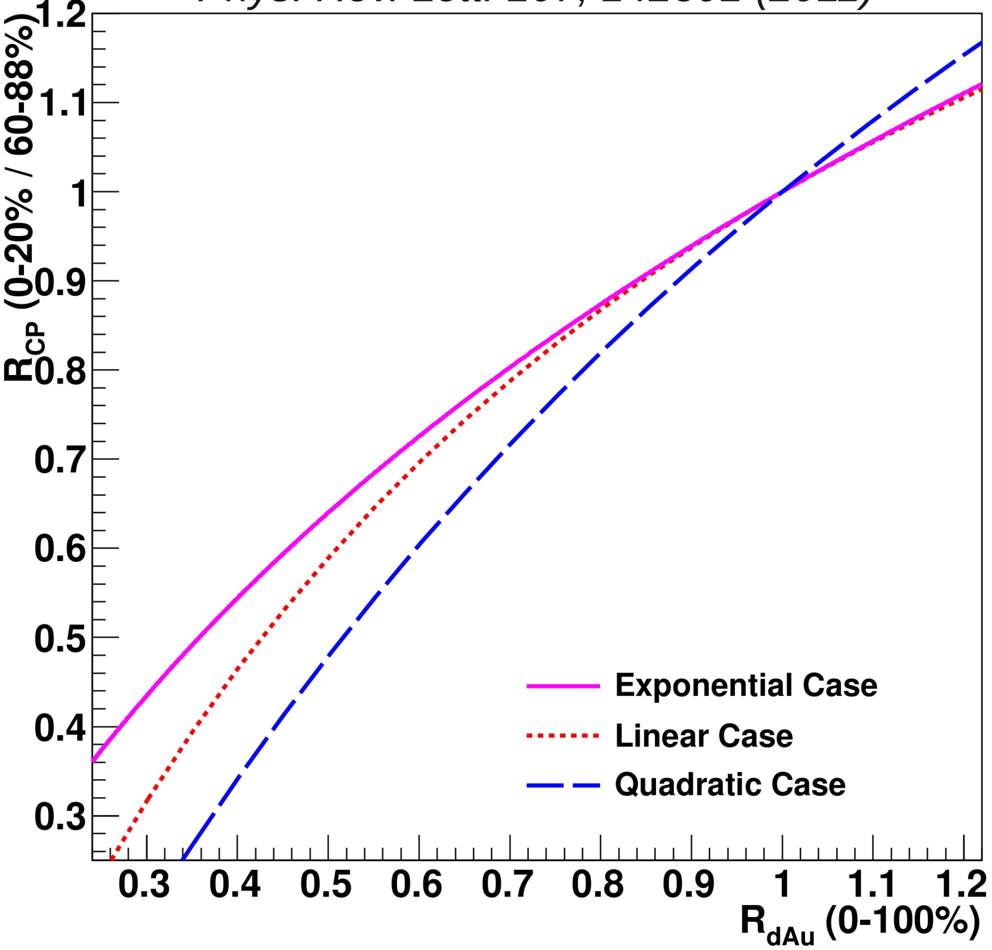
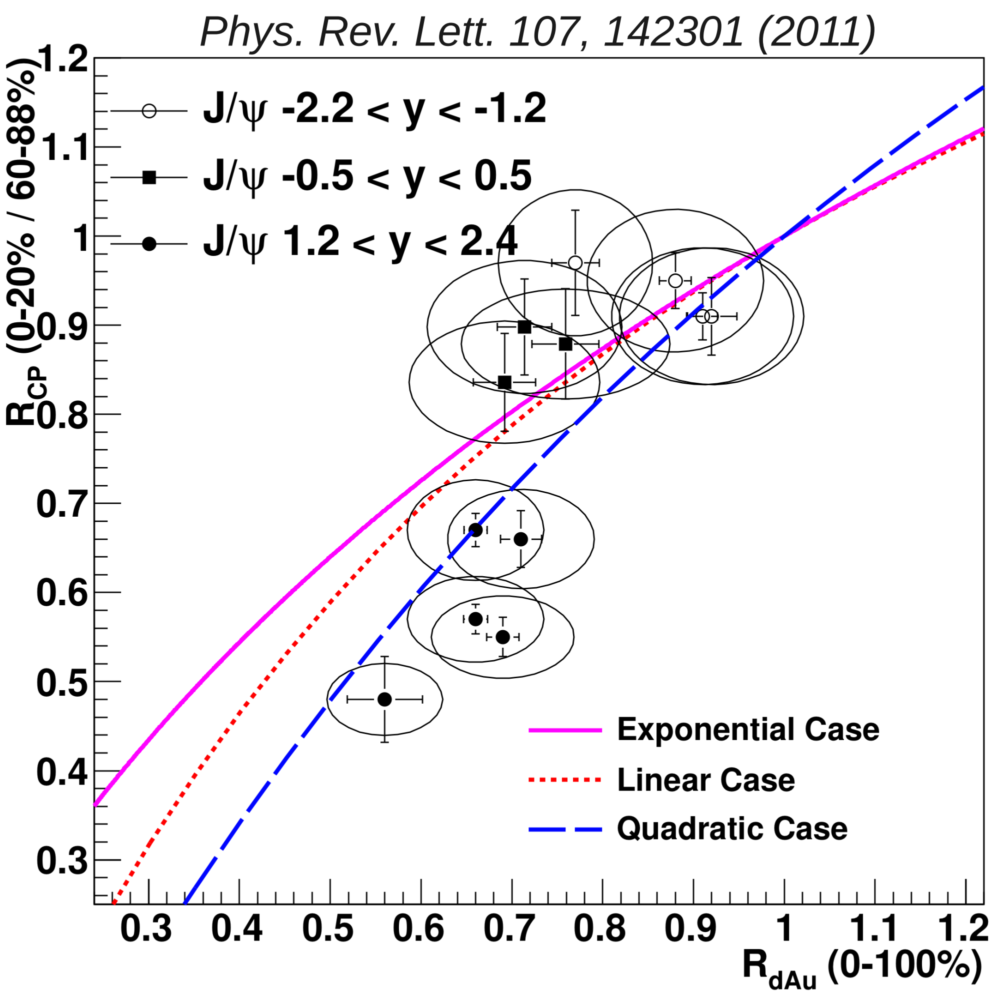
  - *Exponential:* $M(r_T, a) = e^{-a\Lambda(r_T)}$
- Each form maps out a unique curve on this plane.

Phys. Rev. Lett. 107, 142301 (2011)



A Different Way to Look at the Centrality Dependence

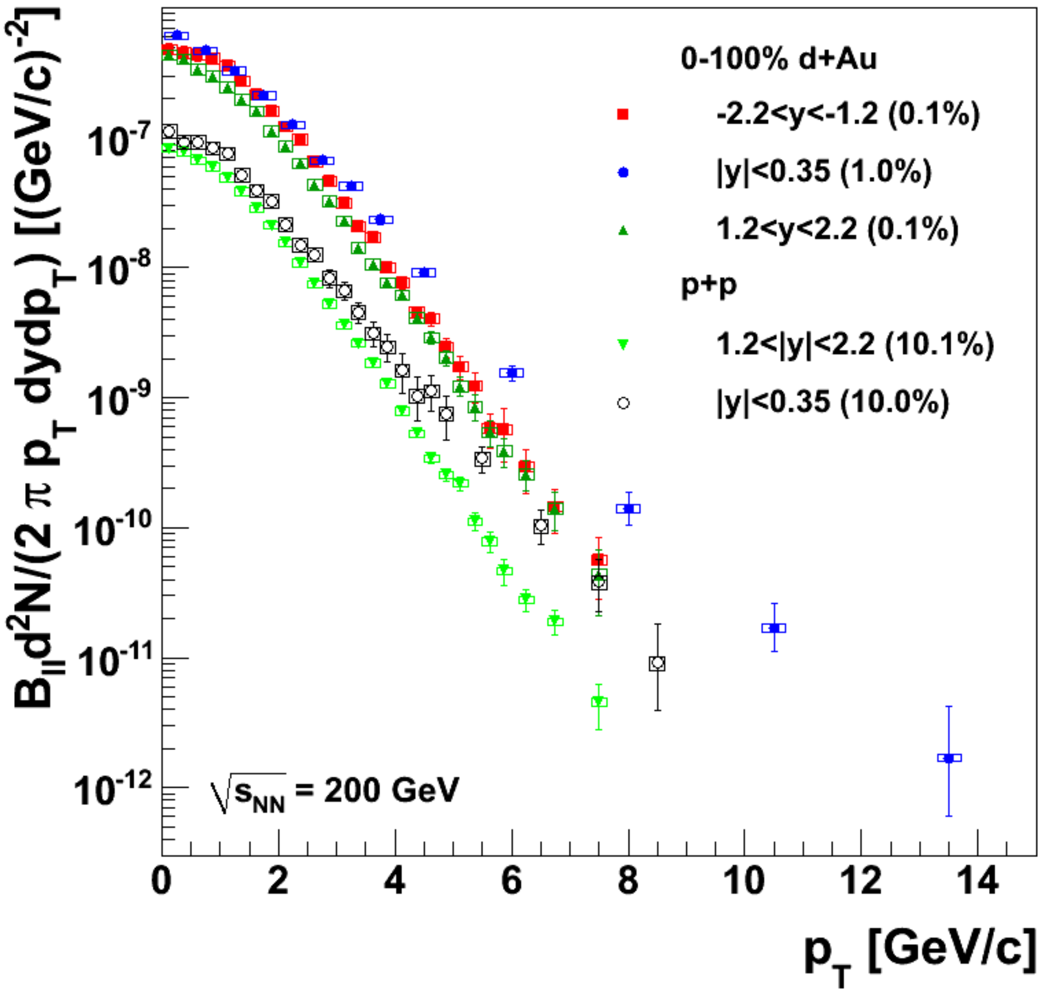
- Backward and mid rapidity data is unable to distinguish between the three cases shown here.
- Forward rapidity data requires stronger than linear or exponential dependence on the thickness.
- Use data to extract thickness dependence!



Vertical(horizontal) bars show point-to-point uncorrelated errors
Ellipses show point-to-point correlated systematic errors

J/ψ p_T Distributions

arXiv:1204.0777

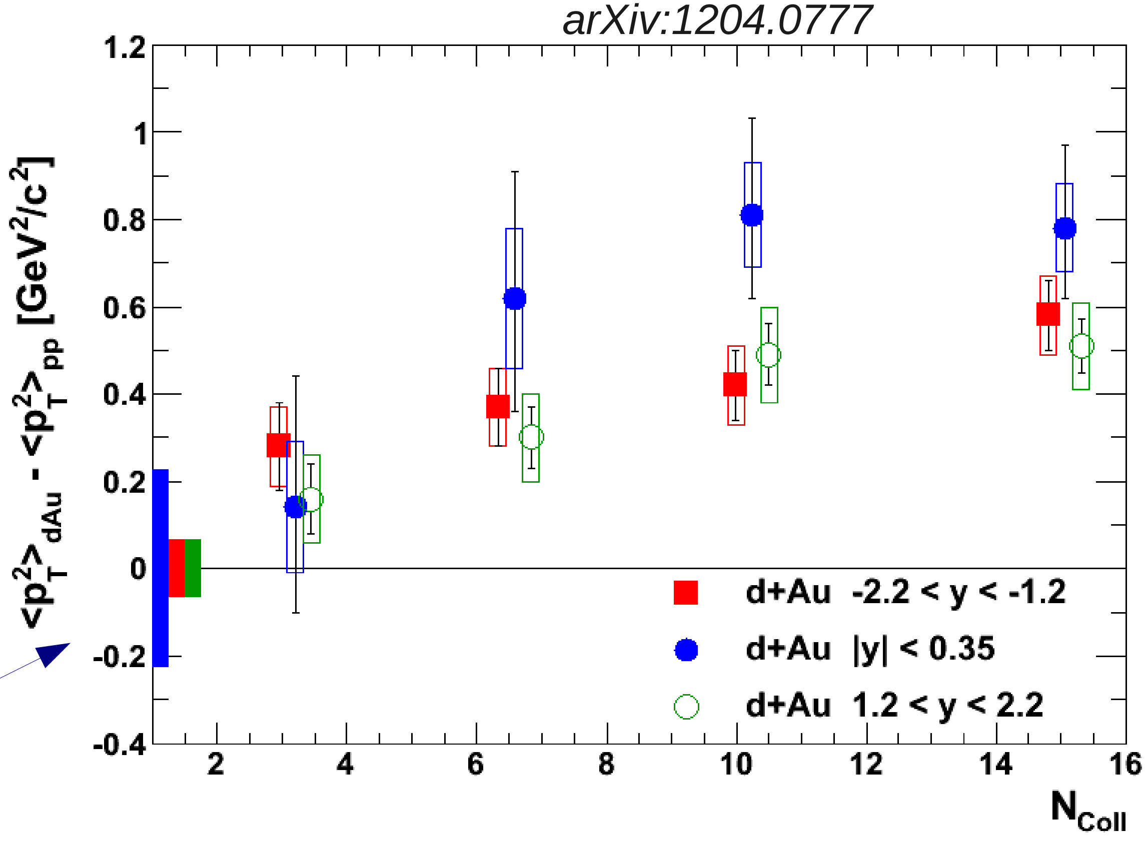


- Minimum bias J/ψ invariant yield vs p_T.
- Integrated over the rapidity of each arm.
- Precise data out to p_T = 8 GeV/c.
- Large improvement over previous d+Au PHENIX results.

$\langle p_T^2 \rangle$ in d+Au

- Extract $\langle p_T^2 \rangle$ numerically from the data at each centrality.
- Subtract the p+p result from the d+Au results.
- Observe broadening in the p_T distribution which increases with increasing N_{coll}.
- Similar at all rapidities within uncertainties.

Colored boxes @ $\Delta\langle p_T^2 \rangle=0$ represent uncertainty on $\langle p_T^2 \rangle_{pp}$

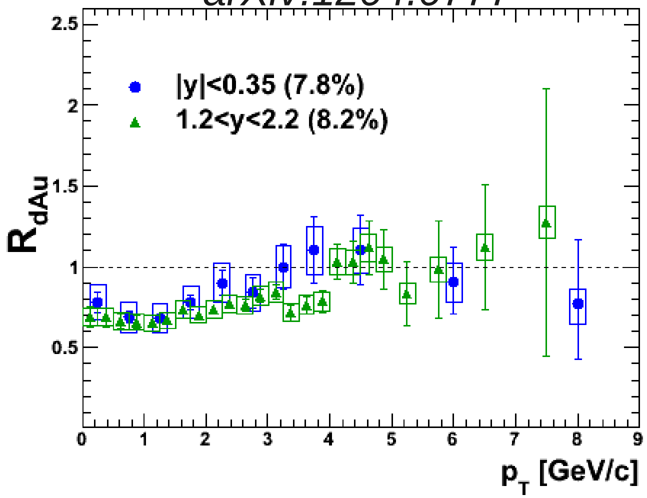


Min Bias p_T Results I

- Minimum bias R_{dAu} vs p_T.
- Similar suppression at mid & forward rapidity.
- Suppression for p_T < 4 GeV/c.
- $R_{dAu} \approx 1$ for p_T > 4 GeV/c.

$$R_{dAu}(i) = \frac{dN^{dAu}_{J/\psi}/dy(i)}{\langle N_{coll}(i)\rangle dN^{pp}_{J/\psi}/dy}$$

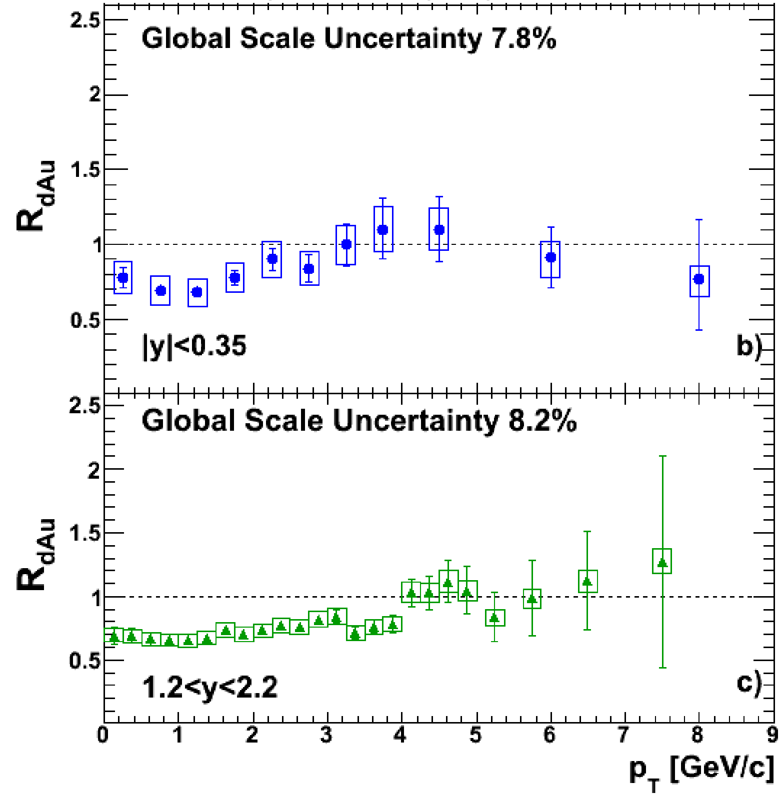
arXiv:1204.0777



Vertical Error bars – uncorrelated uncertainties

Boxes – point-to-point correlated uncertainties.

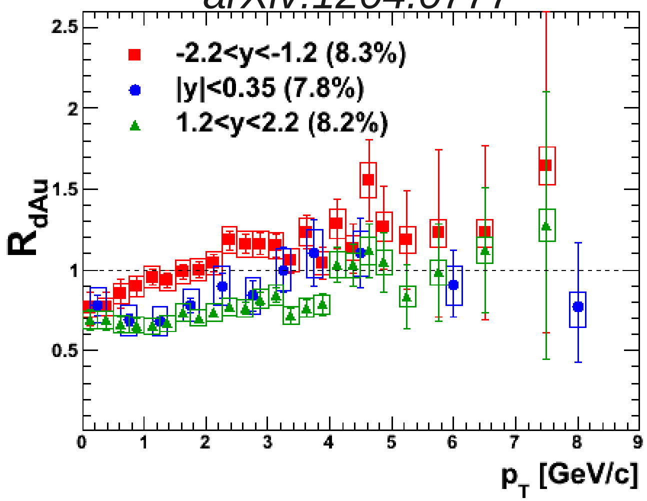
arXiv:1204.0777



Min Bias p_T Results II

- Shape of R_{dAu} p_T distribution different at backward rapidity.
- R_{dAu} > 1 for p_T > 2 GeV/c.

arXiv:1204.0777



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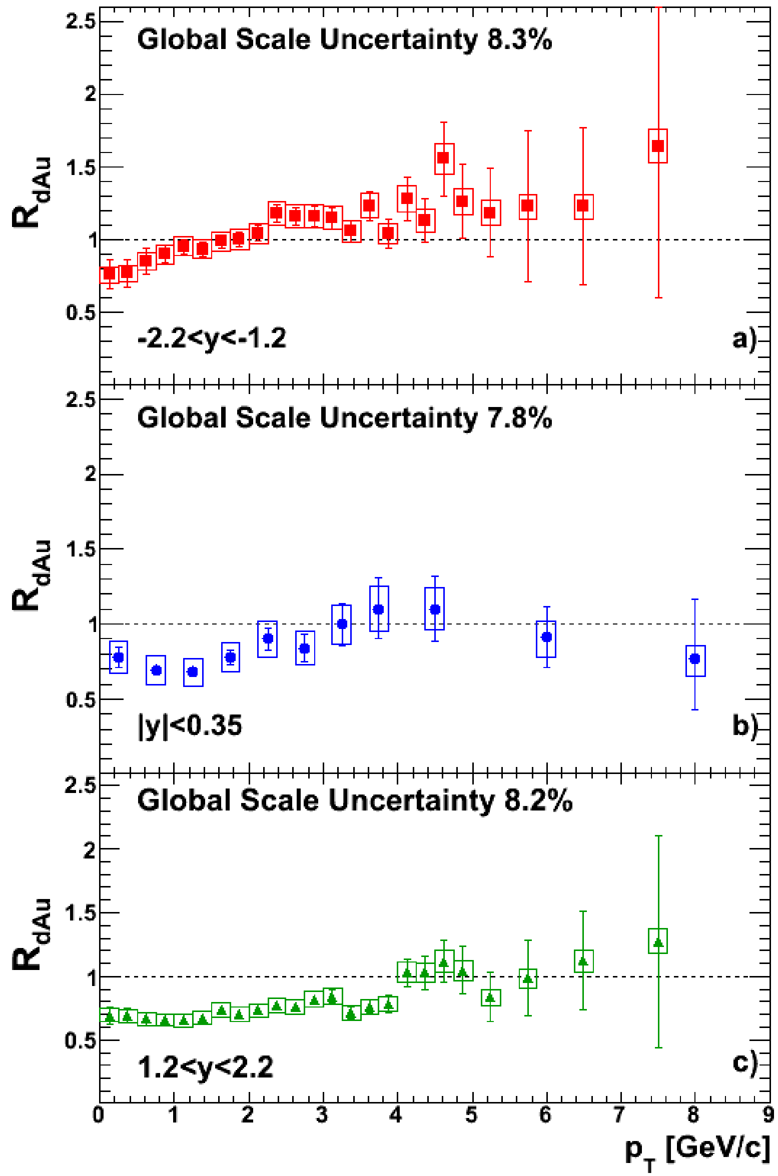


High-p_T R_{dAu}

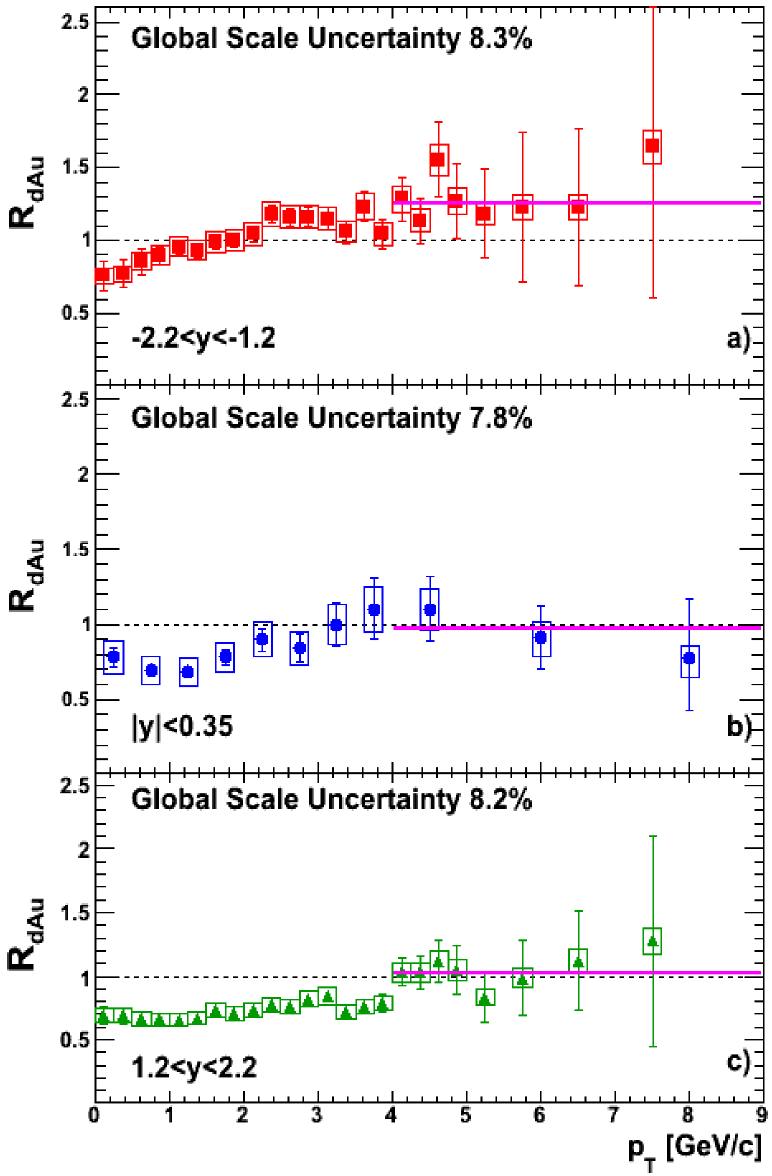
- Fit R_{dAu} w/ constant for p_T>4 GeV/c to find average value.

First quoted uncertainty is the fit uncertainty, second is combined Type B & C systematic from data.

Rapidity	R_{dAu} ($p_T > 4$ GeV/c)
$-2.2 < y < -1.2$	1.27±0.06±0.11
$\lvert y \rvert < 0.35$	0.97±0.14±0.16
$1.2 < y < 2.2$	1.03±0.06±0.11

- R_{dAu} consistent w/ 1 @ mid and forward rapidity.
- R_{dAu} > 1 @ backward rapidity.

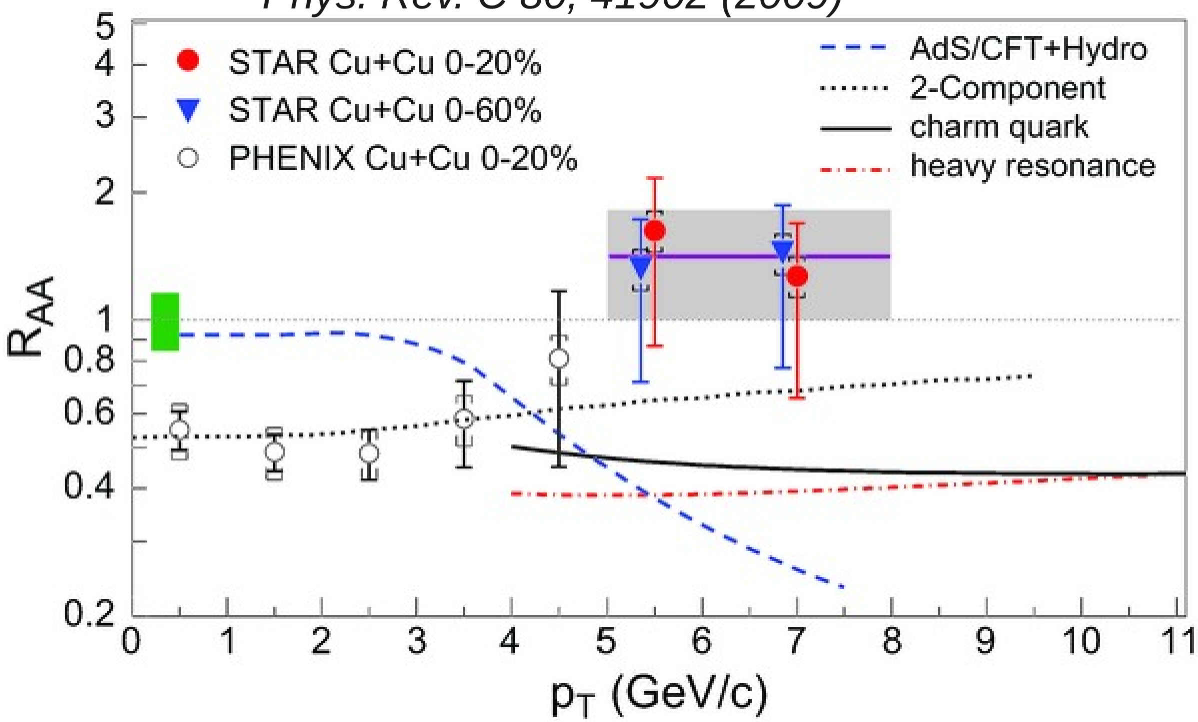
arXiv:1204.0777



High-p_T R_{dAu} Implications

- Propagating R_{dAu} to R_{AA} qualitatively.
- Expect high-p_T $R_{AA} \approx 1$ at midrapidity.
- Forward rapidity R_{AA} is a combination of forward & backward rapidity R_{dAu}.
- Expect high-p_T $R_{AA} \geq 1$ at forward rapidity.
- Need a more detailed understanding of propagation for quantitative results.

Phys. Rev. C 80, 41902 (2009)



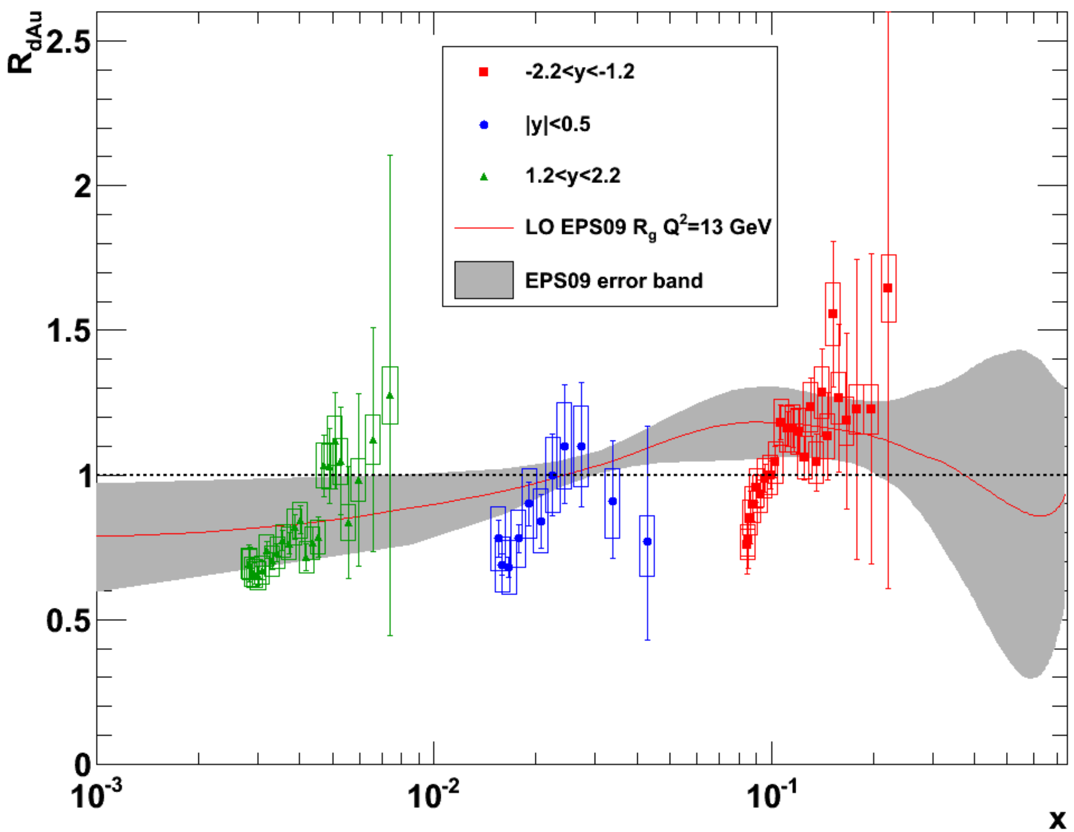
CNM Effects

- **Nuclear Shadowing** – Modification of PDF's for nucleons bound in nuclei.
  - Parametrizations of (mostly) DIS data (ex. EKS98, nDSg, EPS09).
- **Nuclear Break-up** – Break-up of cc pair through collisions with nucleons.
  - Usually parametrized using break-up cross section.
- **Cronin Effect** – Broadening of the pT distribution through scattering of incoming partons.
- **Initial State Energy Loss** – decrease in parton momentum due to soft scatterings while propagating through colliding nucleus.

Nuclear Shadowing (x & Q^2)

- Use $2 \rightarrow 1$ kinematics to get rough idea of the x & Q^2 regions probed by the data.
- Shown with EPS09 nPDF set.

$$x = \frac{\sqrt{M_{J/\psi}^2 + p_T^2}}{\sqrt{s}} e^{-y} \qquad Q^2 = M_{J/\psi}^2 + \langle p_T \rangle^2$$

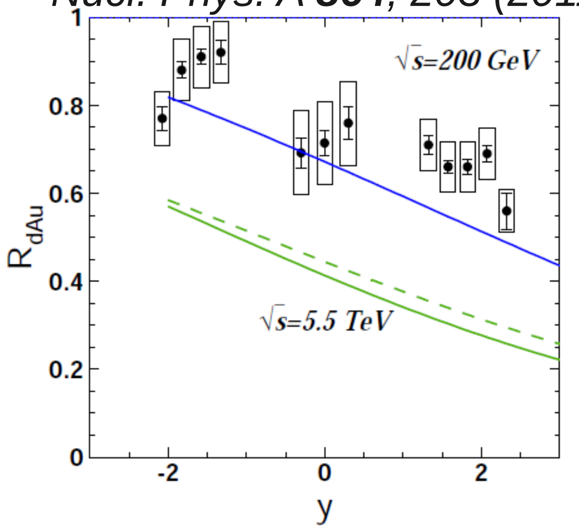


- Forward rapidity – Shadowing region, expect $R_{dAu} < 1$.
- Midrapidity – Transition region.
- Backward rapidity – Anti-shadowing region, expect $R_{dAu} > 1$

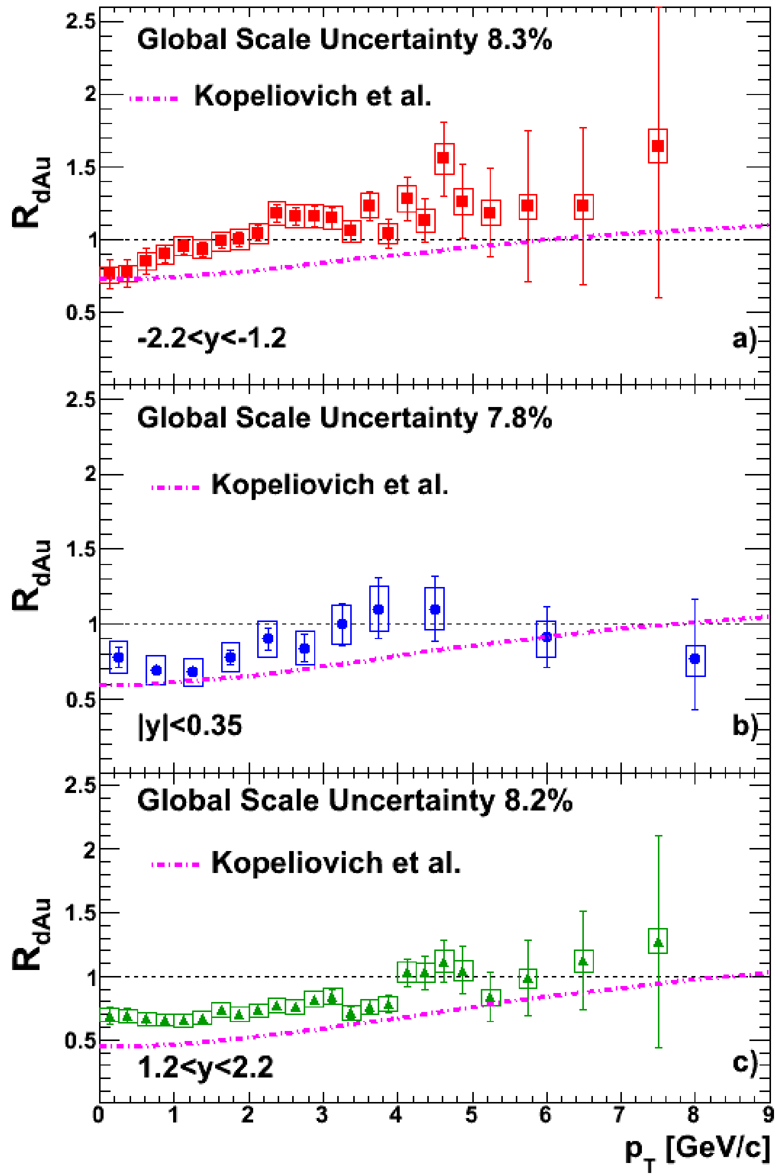
Theory Comparison I

- Calculations from Kopeliovich et al. (*Nucl. Phys. A* ***864***, *203 (2011)*)
- Nuclear Shadowing → nDSg nPDF set.
- Nuclear Break-up → frozen dipole approximation using parametrized break-up cross section from HERA data.
- Includes Cronin Effect.

Nucl. Phys. A ***864***, *203 (2011)*



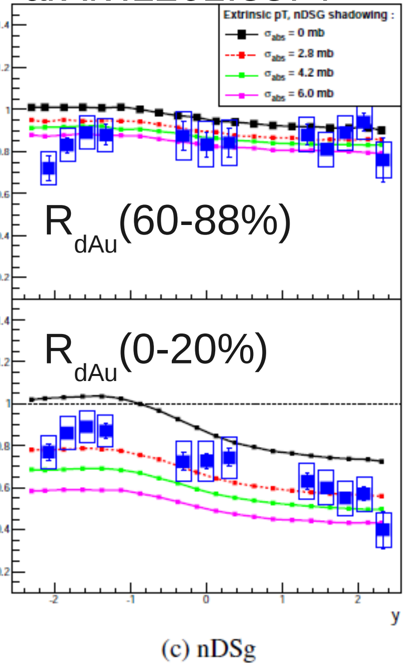
arXiv:1204.0777



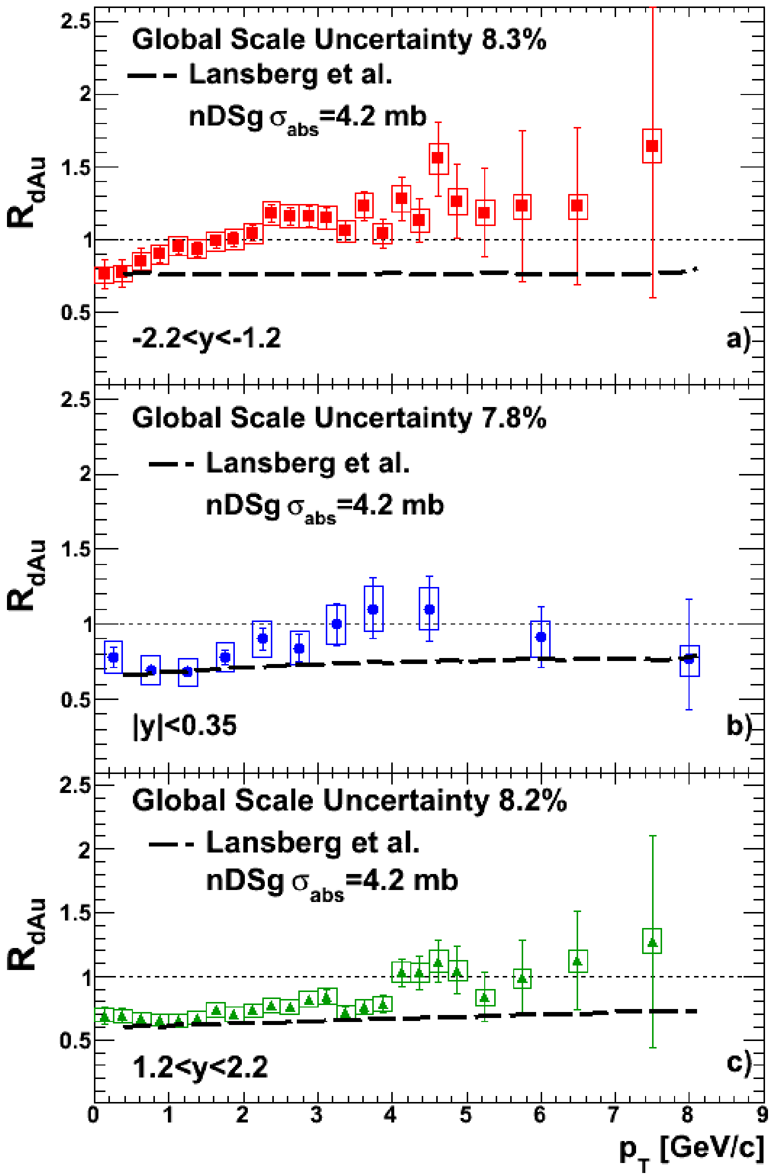
Theory Comparison II

- Calculations from Lansberg et al. (*arXiv:1201.5574*)
- Nuclear Shadowing → nDSg nPDF set.
- Nuclear Break-up → effective σ_{abs} = 4.2 mb
- No Cronin Effect.

arXiv:1201.5574

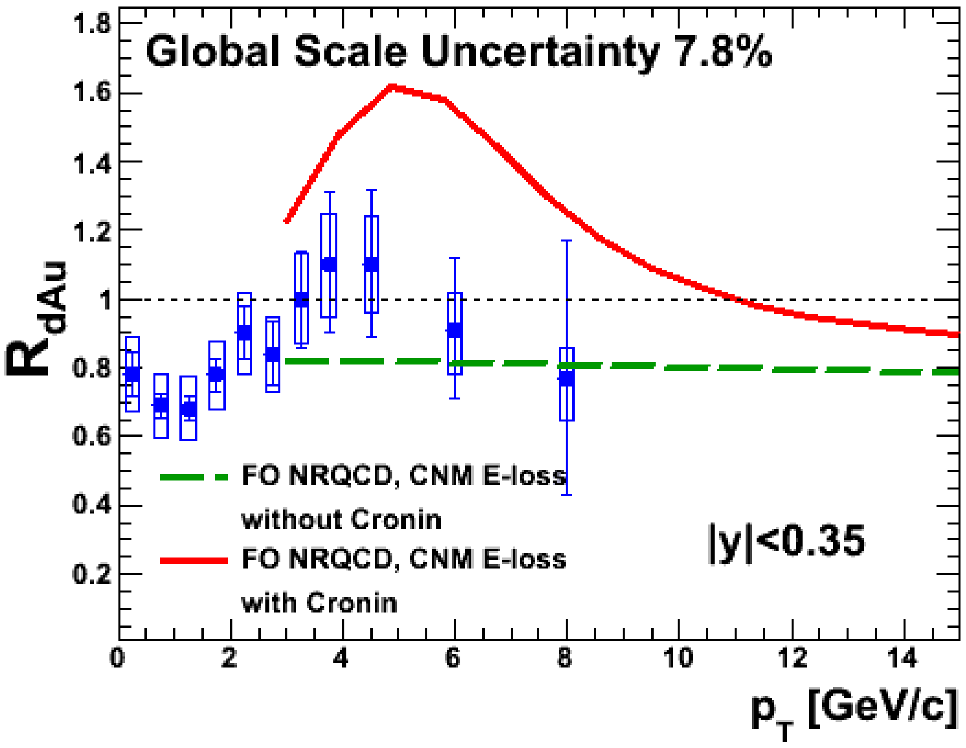


arXiv:1204.0777



Theory Comparison III

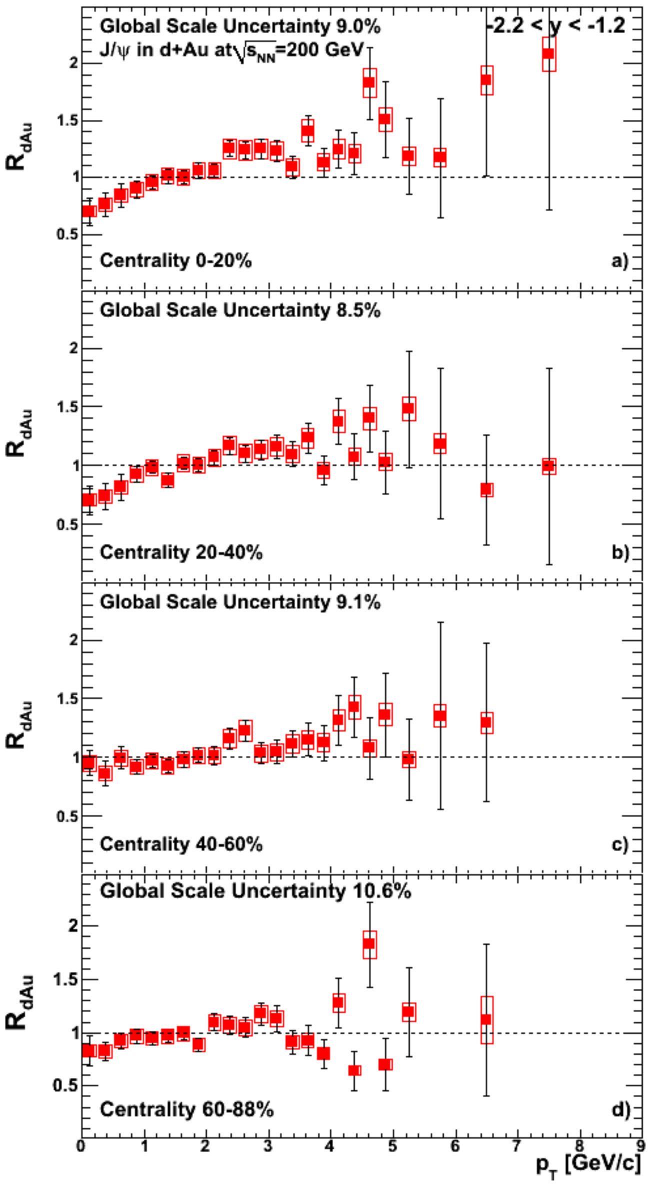
arXiv:1204.0777



- Calculations by Sharma and Vitev (*arXiv:1203.0329*).
- Nuclear Shadowing – EKS98 w/ power suppressed coherent final state scattering
- Includes initial state energy loss.
- Dashed Curve – No Cronin Effect.
- Solid Curve – With Cronin Effect.

Centrality Dependence

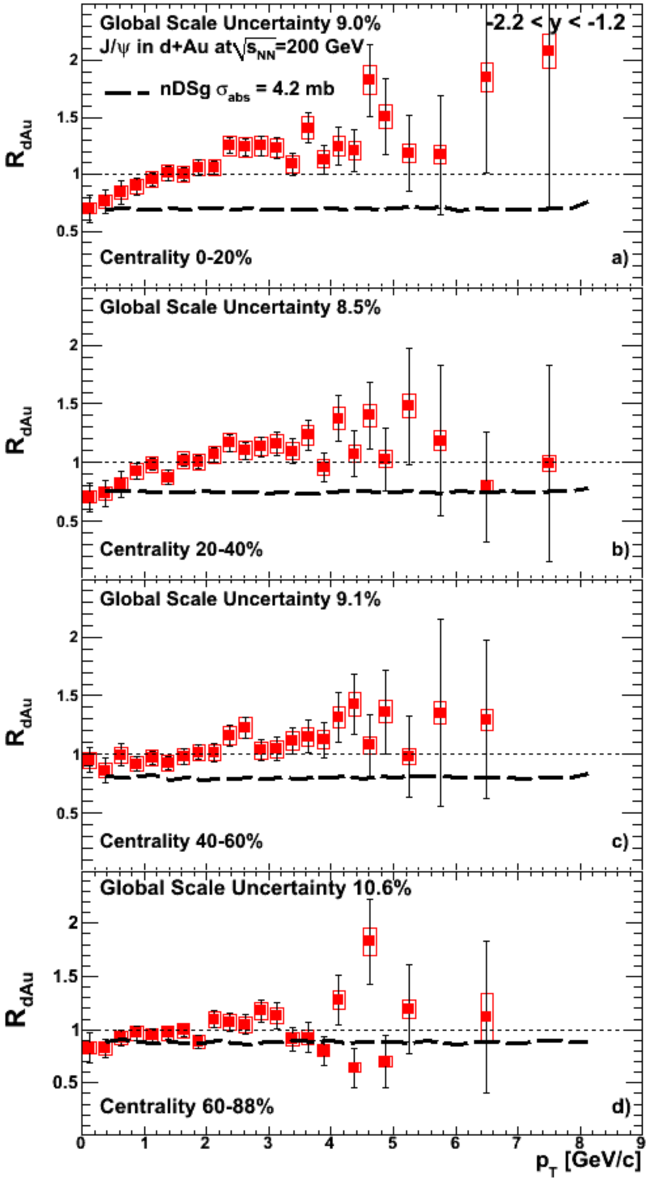
arXiv:1204.0777



- $-2.2 < y < -1.2$
- Suppression is strongest for central collisions at low p_T.
- Shape of R_{dAu} distribution flattens when moving to peripheral events.
- $R_{dAu} \approx 1$ within uncertainties for peripheral collisions.

Centrality Dependence

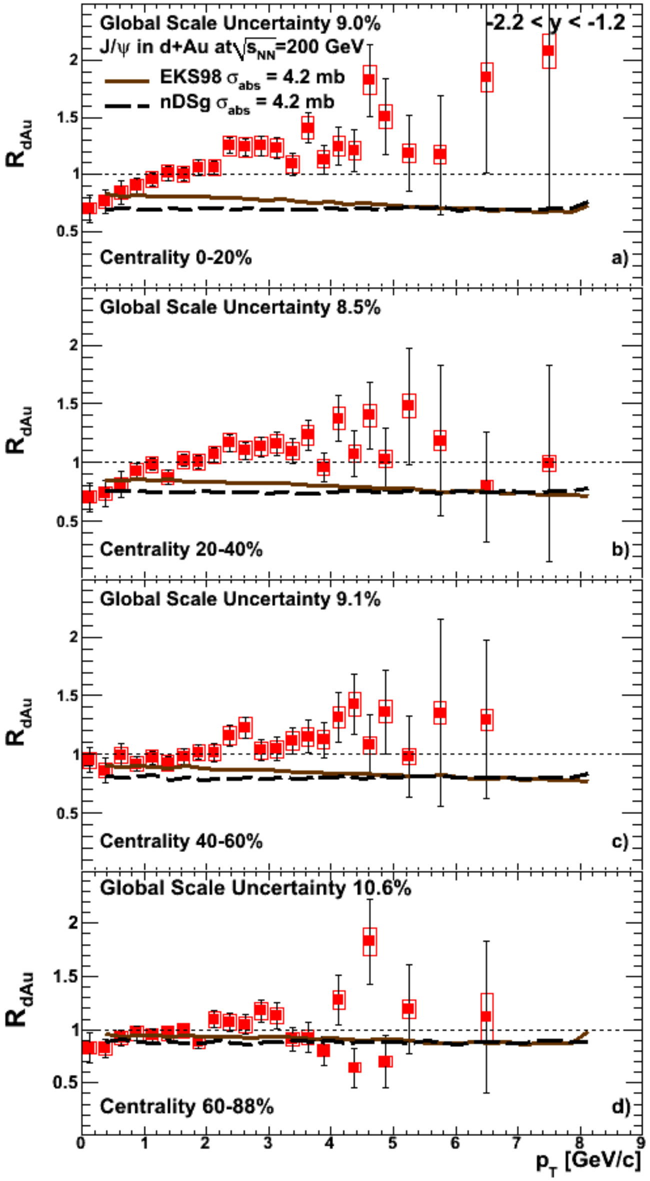
arXiv:1204.0777



- -2.2 < y < -1.2
- Calculations by Lansberg et al.
  - Detailed on previous slide
  - Using nDSg nPDF set.
  - σ_{abs}=4.2 mb.
  - Assume modification is proportional to the density.
- Flat in p_T for all centrality.
- Consistent with peripheral data.
- Disagrees strongly for more central collisions.

Centrality Dependence

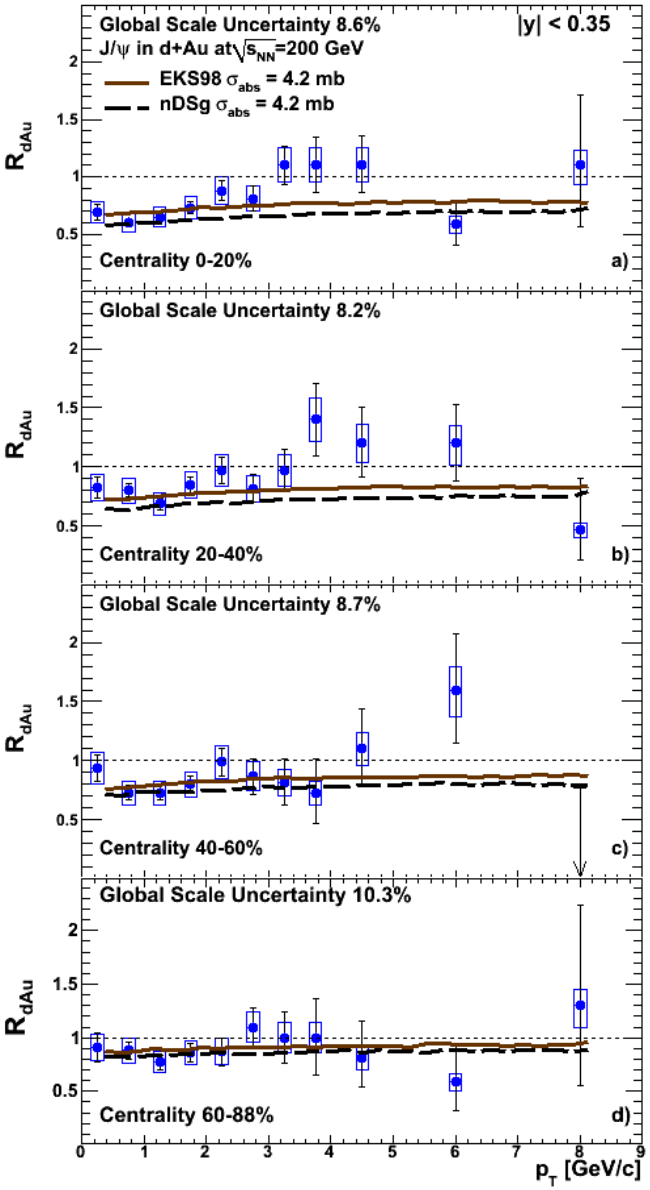
arXiv:1204.0777



- $-2.2 < y < -1.2$
- Calculations by Lansberg et al.
- Add calculations using EKS98 nPDF set.
- Difference in the calculation due to differences in nPDF's only.
- For central collisions calculations show an increase in suppression with increasing p_T.
- Data shows the opposite trend.

Centrality Dependence

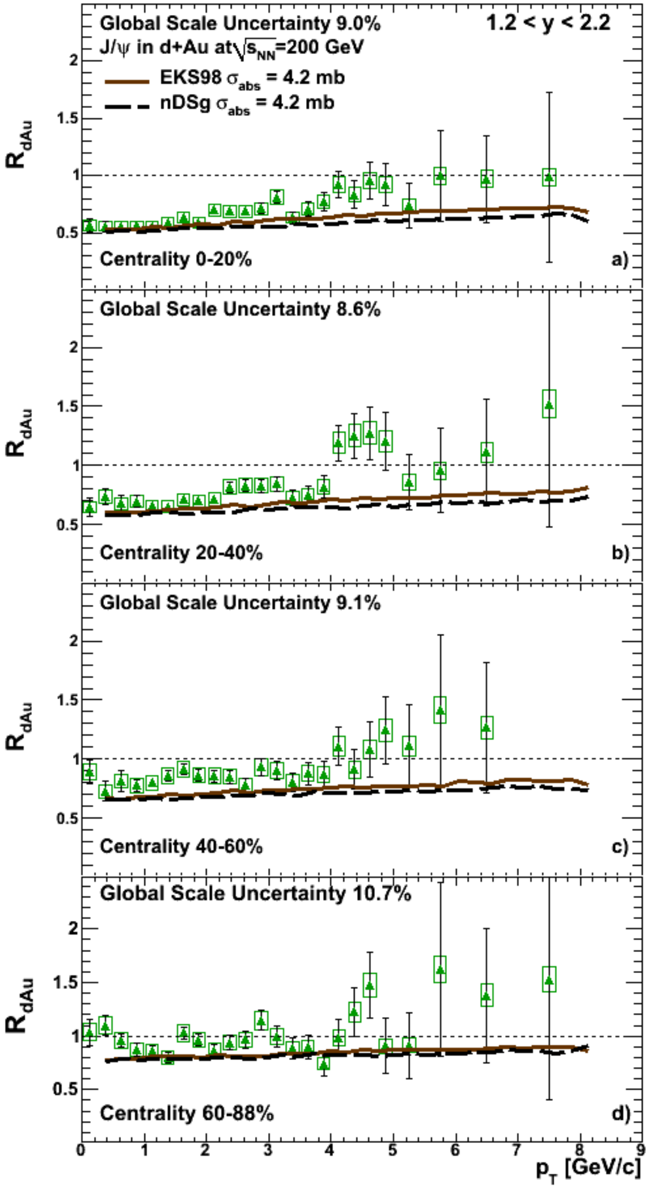
arXiv:1204.0777



- $|y| < 0.35$
- Same set of calculations.
- Calculations w/ EKS98 and nDSg agree in shape, but not overall normalization.
- Relatively good agreement with the data at all p_T & centrality.

Centrality Dependence

arXiv:1204.0777

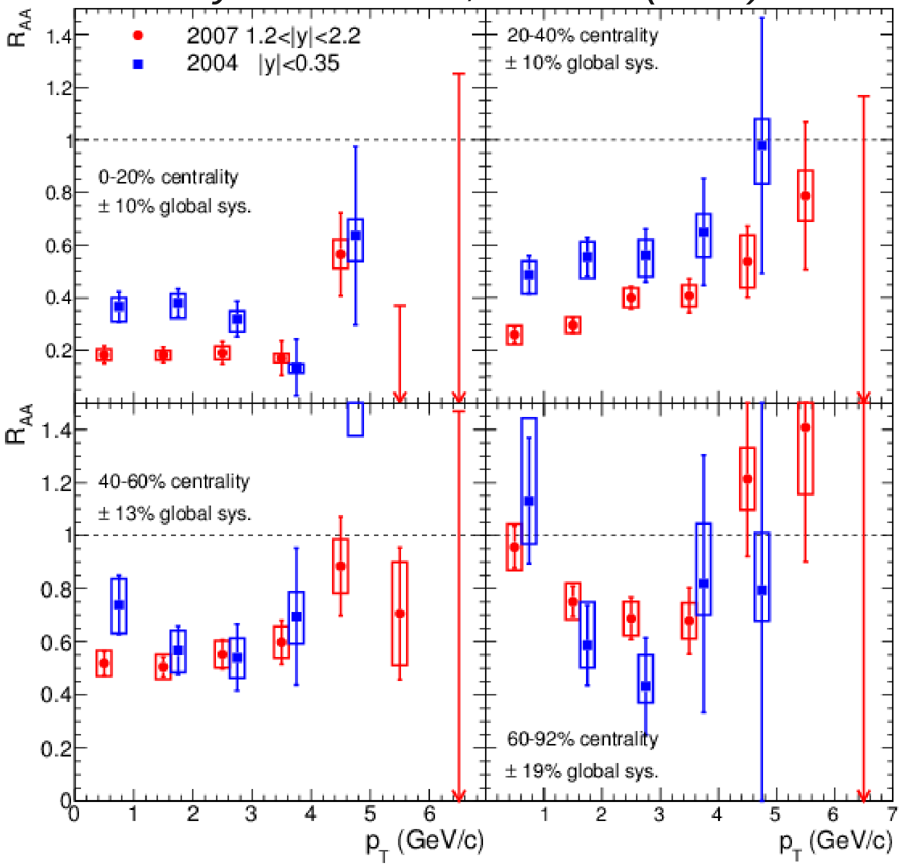


- 1.2 < y < 2.2
- Same set of calculations.
- Calculations w/ EKS98 and nDSg agree in at low p_T, diverge at high-p_T.
- Overall level of suppression over predicted by calculations.

Implications for CNM Effects in A+A

- Midrapidity:
  - R_{dAu} for low $p_T \approx 0.7$ for central collisions.
  - Assuming $R_{AA}=R_{dAu}^2$, $R_{AA}(CNM) \approx 0.5$
  - Observe $R_{AA} \approx 0.4$ for central collisions.
- Forward Rapidity:
  - R_{dAu} for low $p_T \approx 0.6$ @ forward rapidity & 0.8 @ backward rapidity for central collisions.
  - $R_{AA}(CNM) \approx 0.5$
  - Observe $R_{AA} \approx 0.2$ for central collisions.
- Crude estimate, but gives some expectation of CNM effect in A+A.

Phys. Rev. C 84, 054912 (2011)



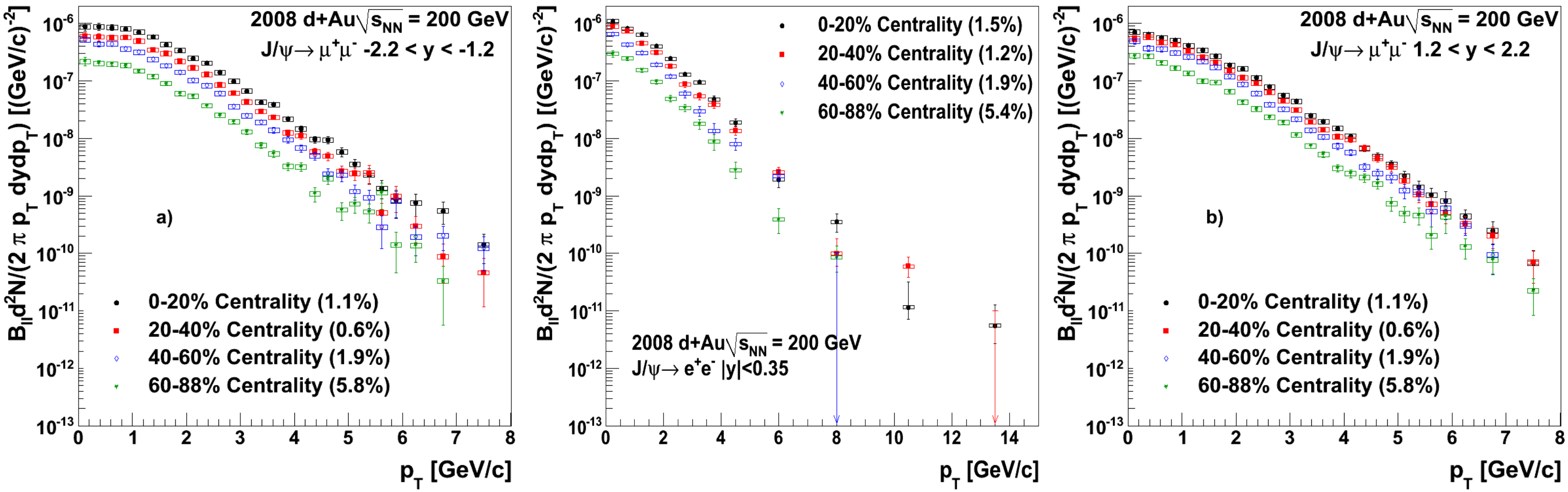
Summary

- PHENIX has made new measurements of the p_T dependence of R_{dAu}.
  - J/ψ measured over p_T, rapidity, and centrality.
- Rapidity dependence is inconsistent with modifications which are linearly or exponentially dependent on the nuclear thickness.
- p_T dependence of R_{dAu} is similar at mid & forward rapidities with a more rapid decrease in suppression with increasing p_T at backward rapidity.
- Average R_{dAu} at high-p_T > 1 at backward rapidity.
- Need a detailed understanding of CNM effects and their propagation to A+A to understand hot nuclear matter effects.

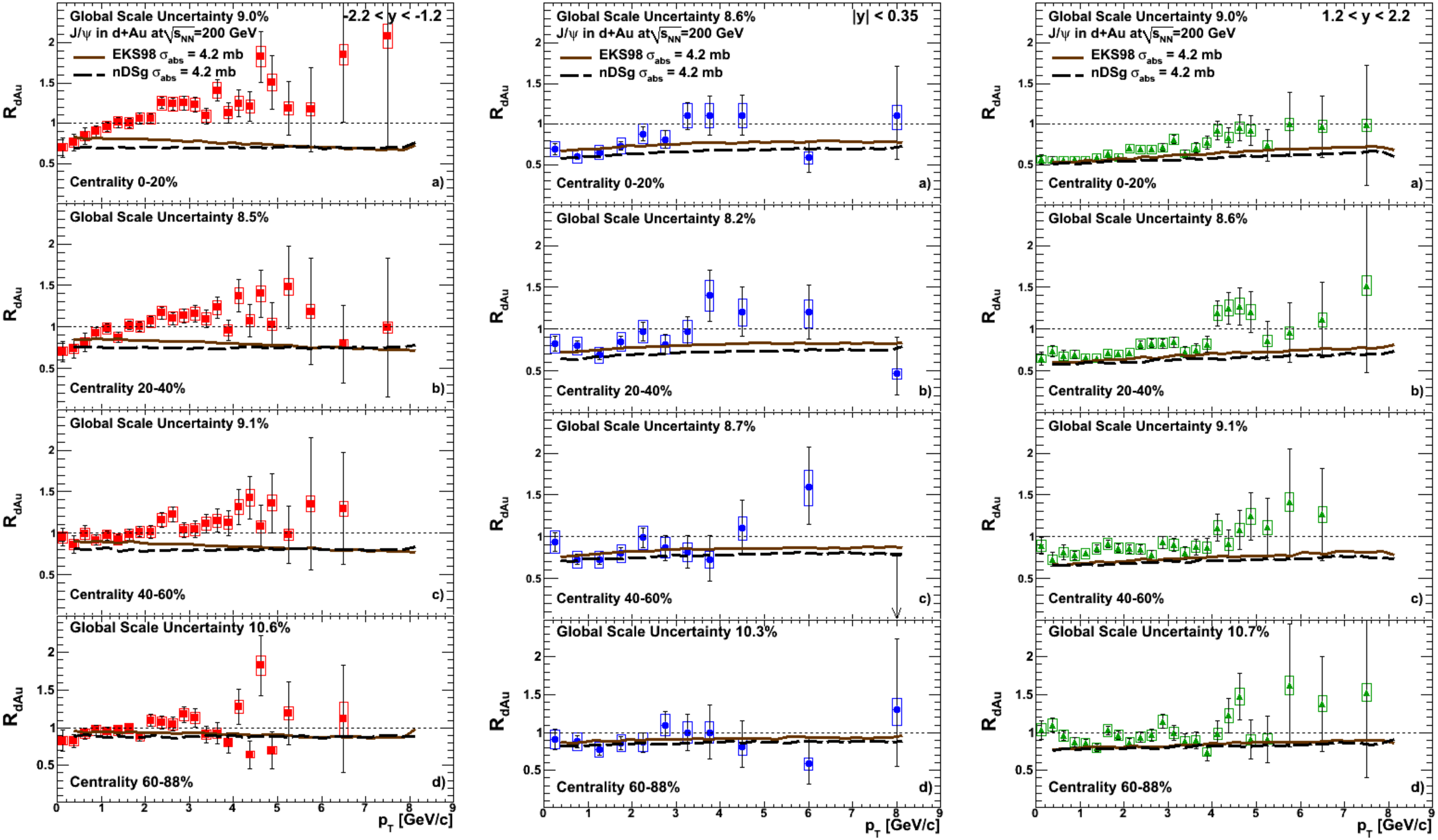
Backup

Centrality Results

- J/ψ invariant yields vs p_T for each centrality.



Centrality Dependence of R_{dAu}



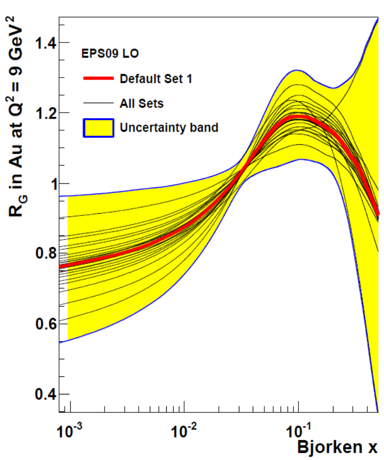
Theoretical Calculations

1) 1st Calculation includes two components.

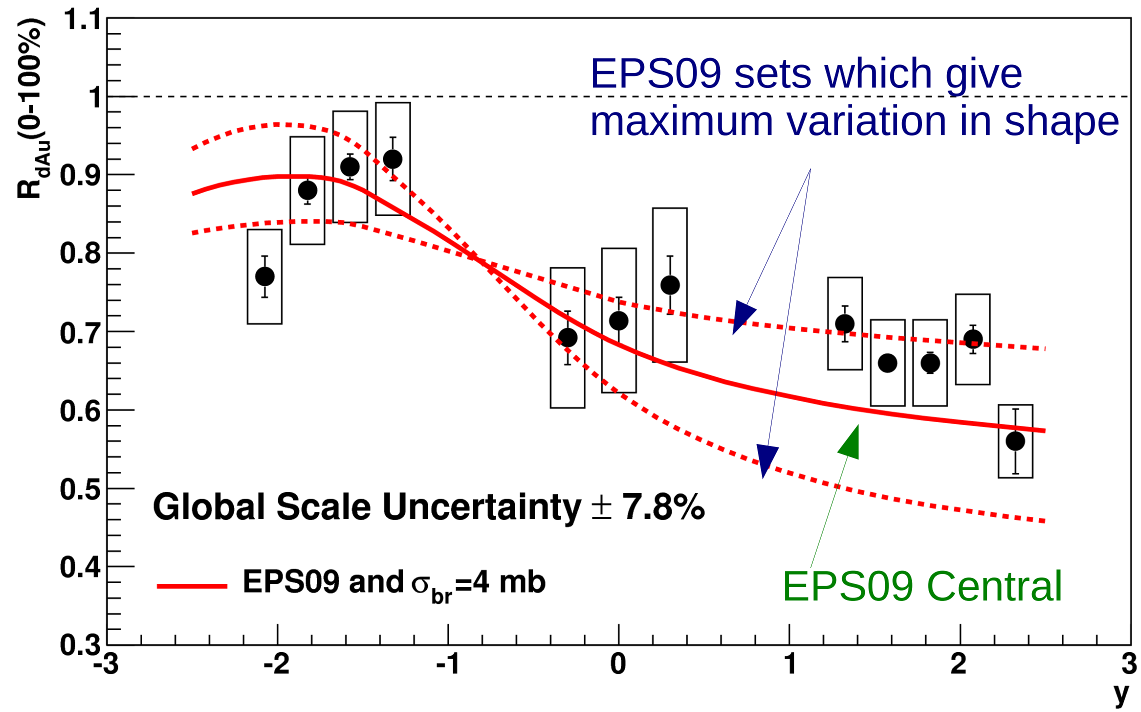
   1) Gluon modification (shadowing) from EPS09 nPDF – parametrization of DIS+pA data.
      - Calculations are modification vs. nucleon impact parameter (r_T) in the Au nucleus.
      - Fold r_T distribution with PHENIX centrality distributions calculated from Glauber MC.

   2) Nuclear Break-up cross section σ_{br} – due to collisions of J/ψ with nucleons
      - σ_{br}=4 mb chosen to match backward rapidity data.

- Shows reasonable agreement over all rapidity, as expected for MB data.



LO EPS09 R_G vs. Bjorken x for Au ← no intrinsic centrality dependence



arXiv:nucl-ex/1010.1246

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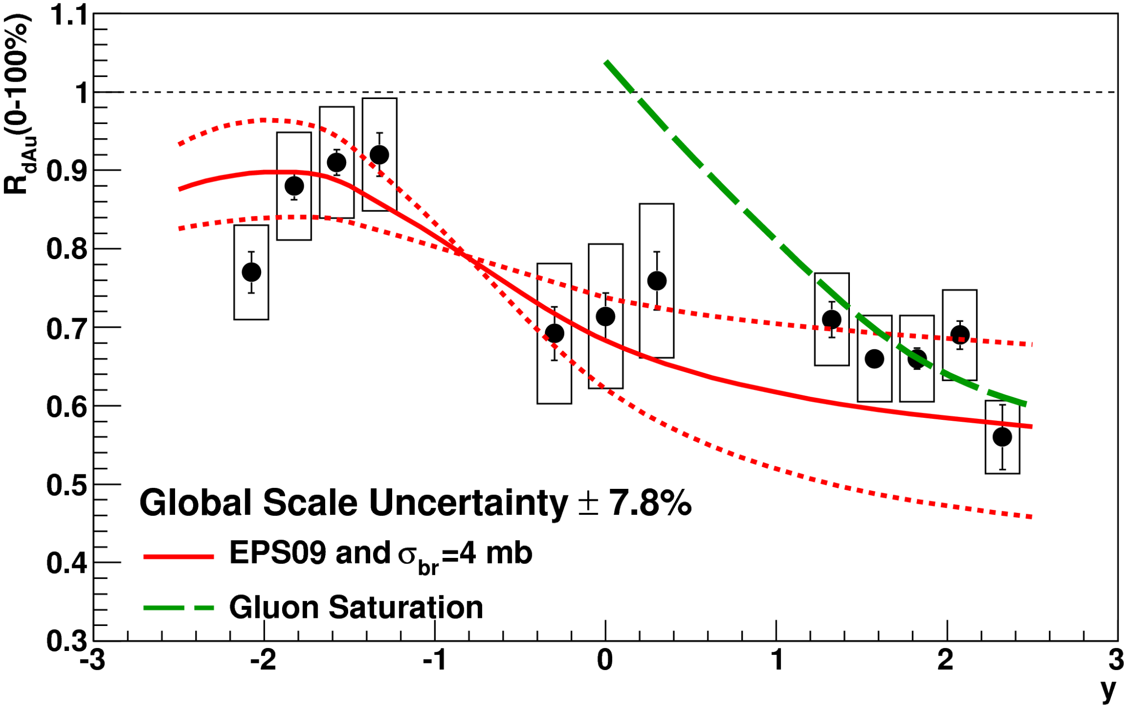
2) Calculation by Kharzeev and Tuchin *(Nucl. Phys. A 770 (2006)40)*

   - Includes Gluon Saturation at low x
   - Shows good agreement @ +y.
   - Unrealistic at backward and mid rapidity.
   - Validity uncertain for peripheral events?

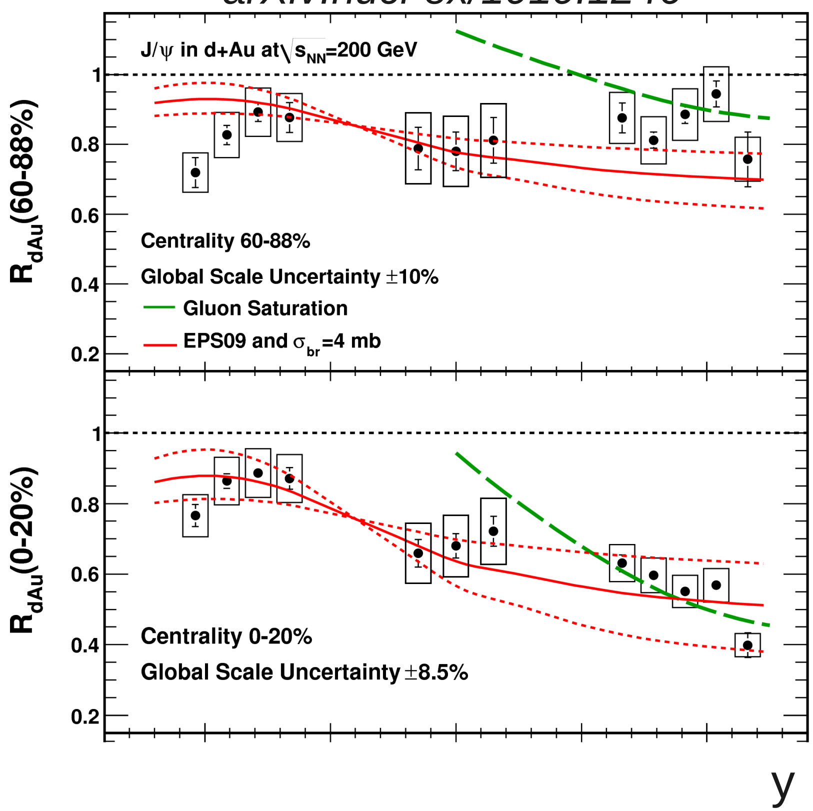


arXiv:nucl-ex/1010.1246

Centrality Dependent R_{dAu}

- Want to investigate centrality (impact parameter) dependence.
  - Divide into percentage bins based on BBC charge (0% - most central, 100% - most peripheral.
- Calculations by the same models as detailed on previous slide.
  - Must introduce centrality dependence into EPS09 – **arbitrarily** choose linear dependence on nuclear thickness (common assumption).
  - Shadowing + break-up does not describe forward rapidity data for peripheral collisions.
  - Gluon saturation model still describes data well at +y.

arXiv:nucl-ex/1010.1246

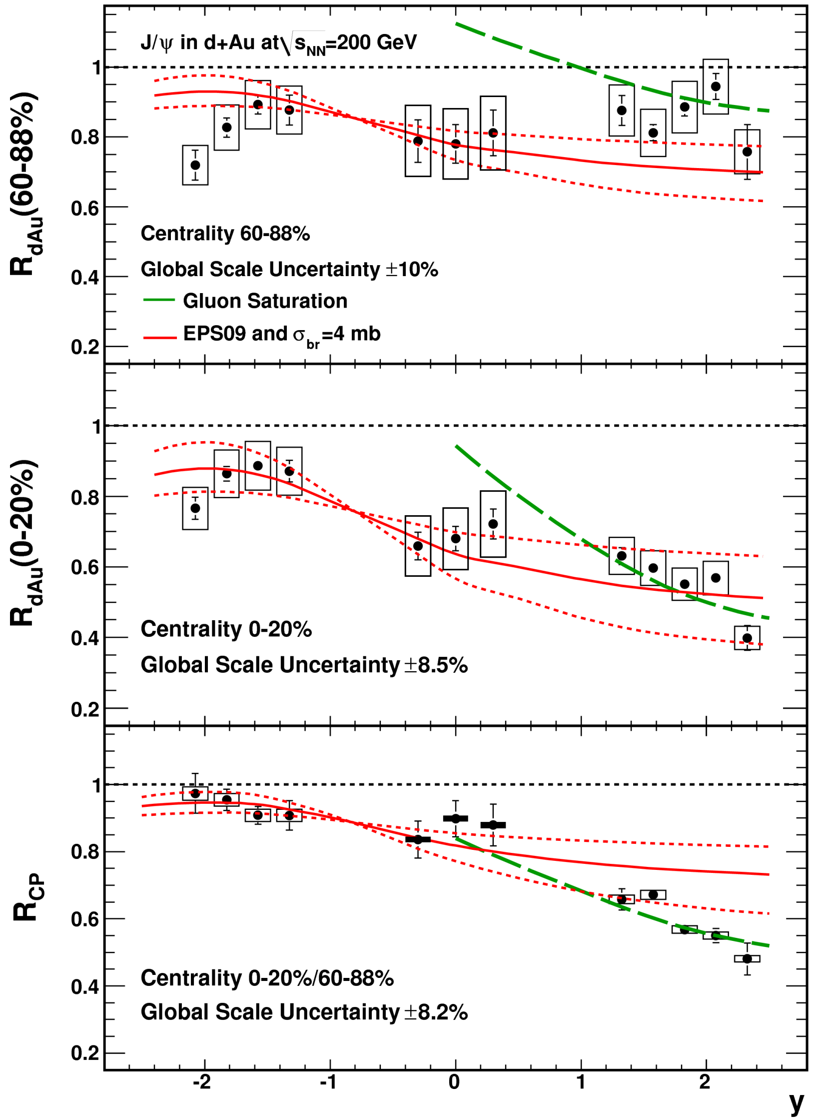


Centrality Dependent R_{dAu}

- Take the ratio of central R_{dAu} to peripheral $R_{dAu} \rightarrow R_{cp}$
  - Significant reduction of systematic errors
  - Shadowing + σ_{br} describes backward & midrapidity well.
  - Failure of Shadowing + σ_{br} to describe R_{cp} at large y seems to be due to poor description of centrality dependence.
  - Gluon saturation model appears to provide a better description of the centrality dependence, although it is not clear how reliable it is for peripheral collisions where there should be less coherent effects.

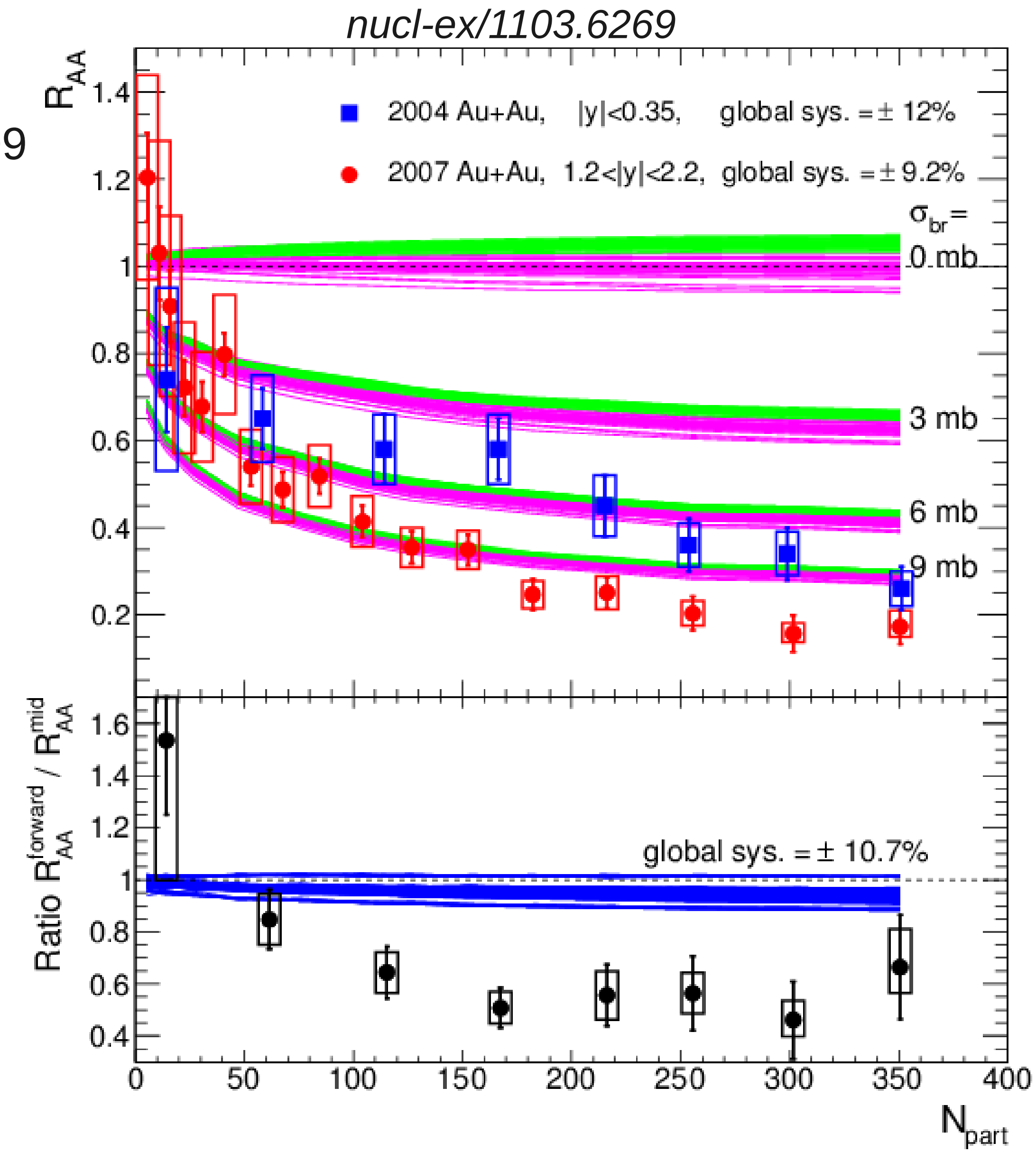
$$R_{cp}(0-20\%) = \frac{R_{dAu}(0-20\%)}{R_{dAu}(60-88\%)}$$

arXiv:nucl-ex/1010.1246



What does this mean for Au+Au?

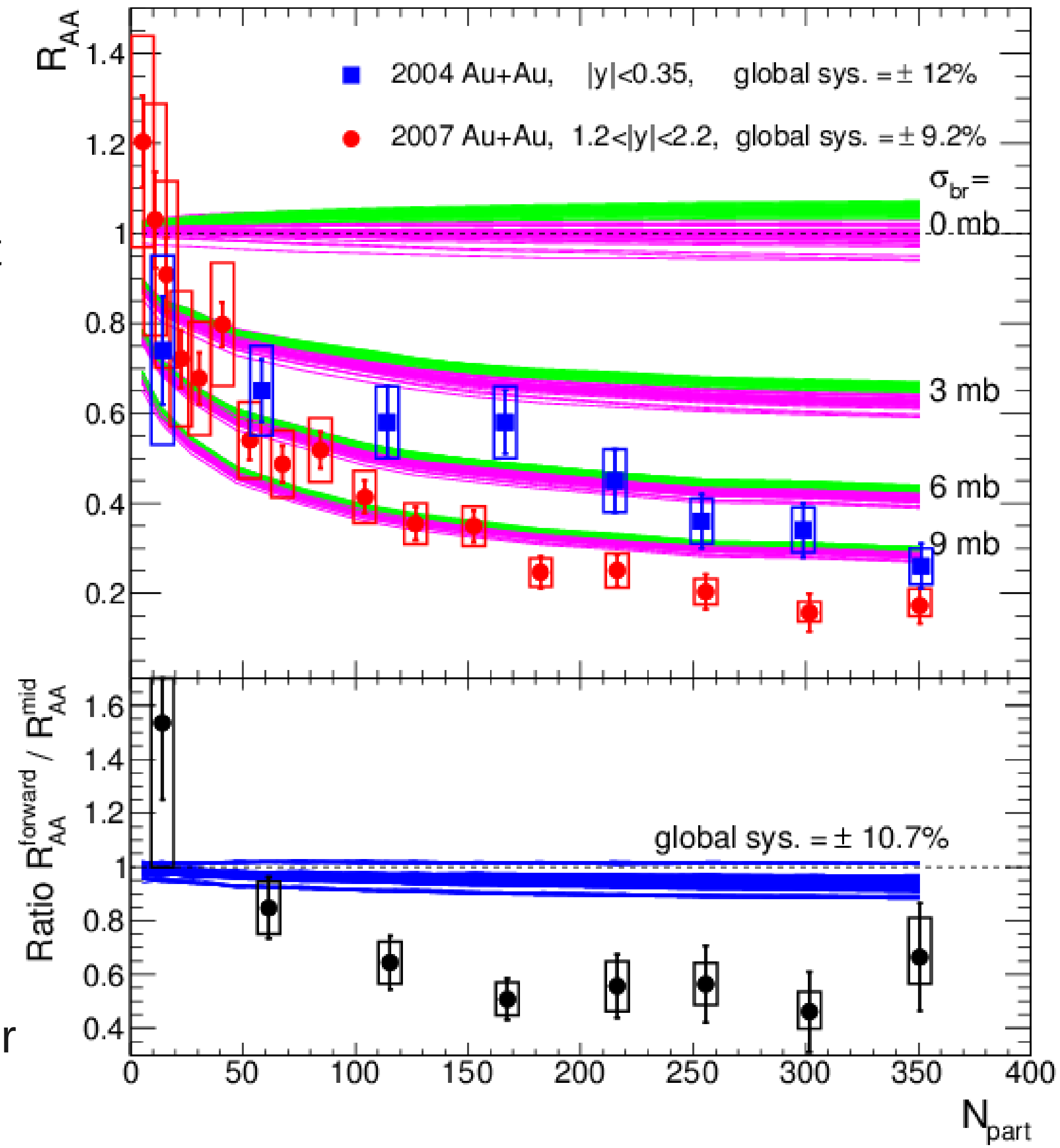
- Calculations show CNM effects extrapolated to Au+Au for (linear) EPS09 + (exponential) nuclear breakup.
- Green curves – predictions for |y|<0.35 for each of 31 EPS09 sets for 0, 3, 6, 9 mb breakup cross sections
- Magenta curves – same as green curves, but for 1.2<|y|<2.2
- Bottom panel shows the ratio of data & CNM predictions.



What does this mean for Au+Au?

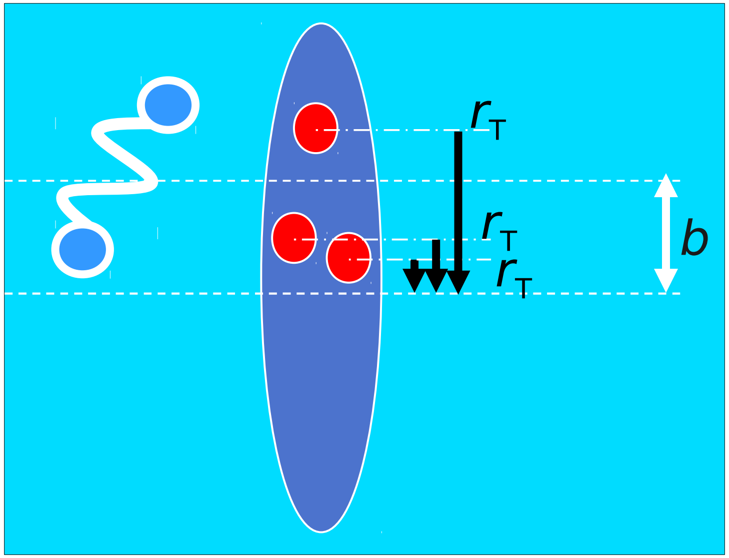
- What do we learn from d+Au:
  - Linear EPS09 w/ a 4mb breakup cs adequately describes backward & midrapidity d+Au data, not sufficient at forward rapidity.
- What does this imply in Au+Au:
  - Suppression at **midrapidity** stronger than expected from d+Au alone.
  - Can not make a similar statement about the forward rapidity data until we understand d+Au at forward y.
  - Linear EPS09 does not explain difference of suppression with rapidity.
- Still, clear evidence of hot nuclear matter effects, although not yet quantifiable.

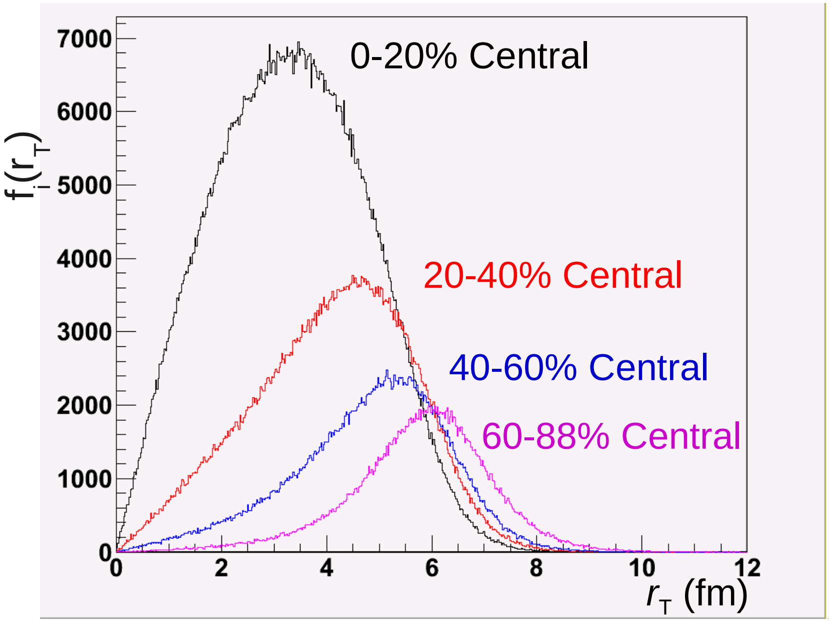
nucl-ex/1103.6269



Simple Geometrical Model

- Would like to understand how the suppression depends on centrality.
- In d+Au relevant parameter is transverse position of the struck nucleon in each N-N collision → r_T
- Use Glauber MC of N-N hit positions in d+Au events to generate r_T distributions.





- Use a simple parametrization of the nuclear modification based on the density weighted longitudinal thickness in the Au nucleus → $\Lambda(r_T)$.

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

Woods-Saxon

← Resulting r_T distributions from MC for PHENIX centrality bins.

R_{dAu} from Geometric Modification

Consider, for example, three functional forms for the nuclear modification vs nuclear thickness at r_T, $\Lambda(r_T)$, with one free strength parameter *a*

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

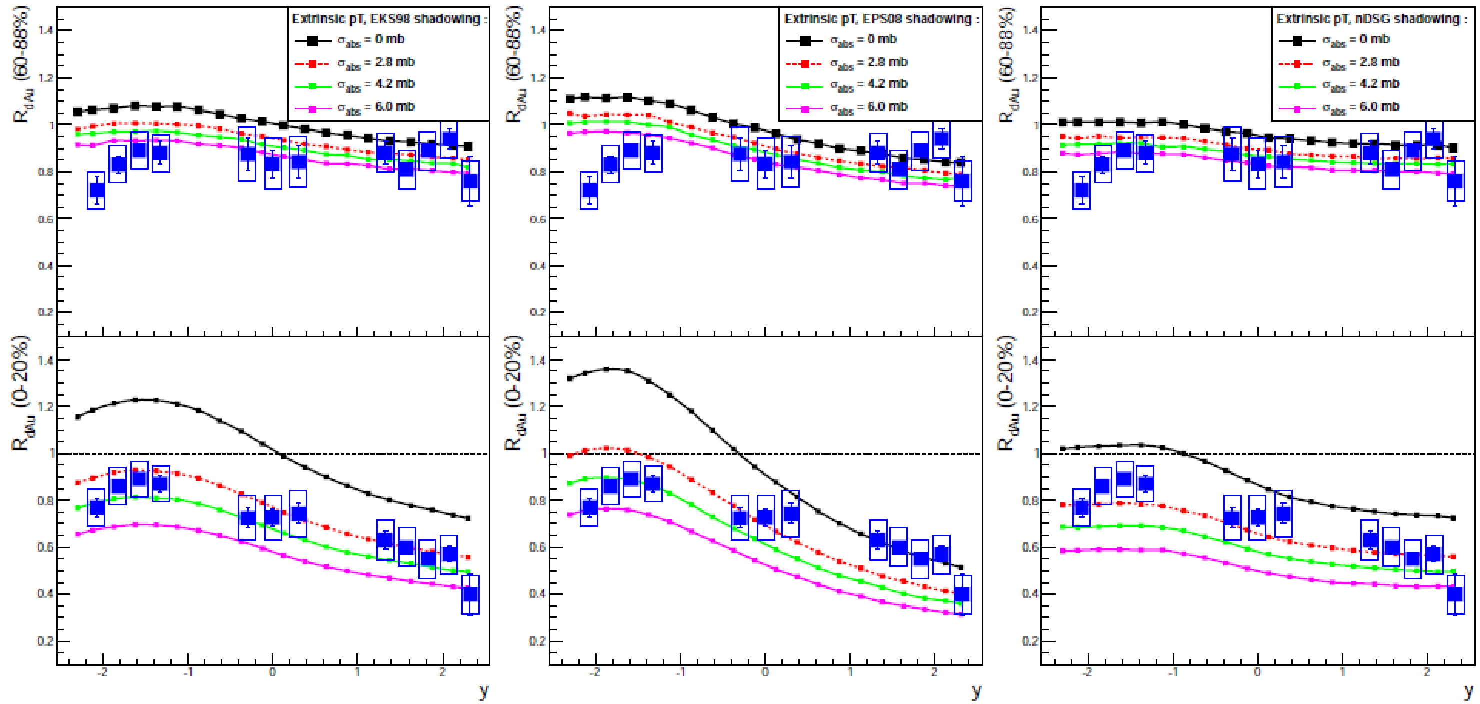
The modification factor R_{dAu} for a given centrality bin (*i*) is then given by

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

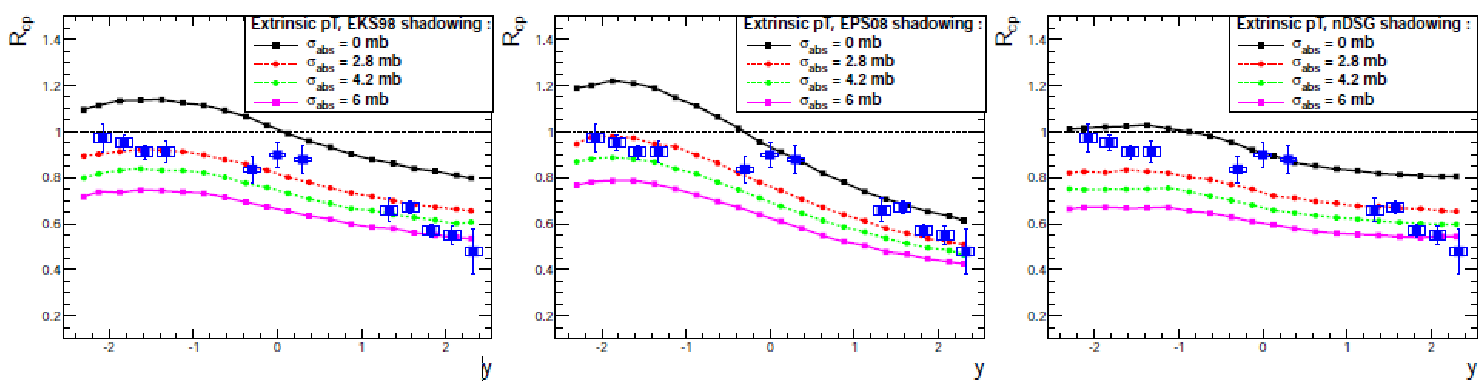
r_T distributions from PHENIX MC

Modification vs $\Lambda(r_T)$ and free parameter *a*

Lansberg Rapidity Comparison



(a) EKS98 (b) EPS08 (c) nDSg



(a) EKS98 (b) EPS08 (c) nDSg

nPDF Comparison