Studying Cold Nuclear Matter at PHENIX

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for PHENIX collaboration

PHENIX

Collision Systems

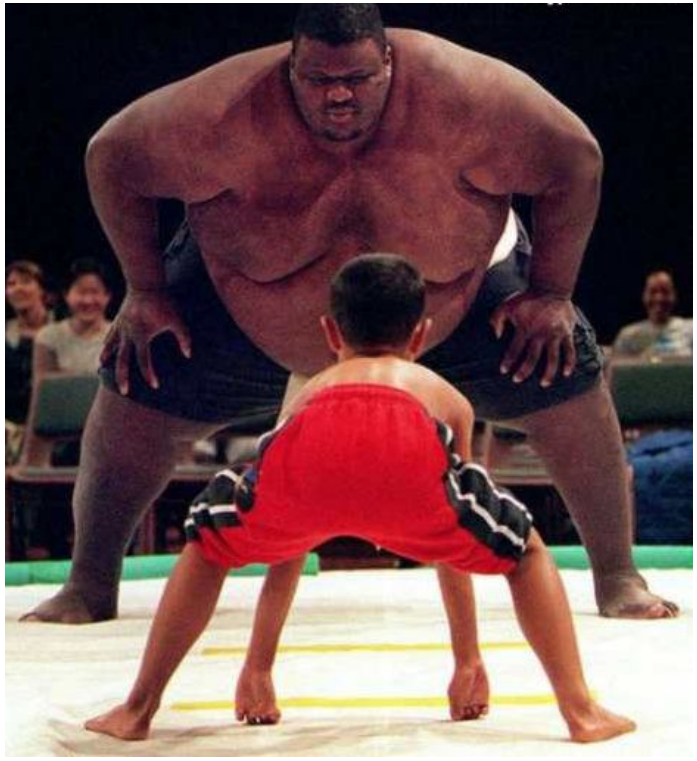
- *p* + *p* collision

  -> Provide the critical test for pQCD calculations of heavy-quark production. Baseline for the study of modification of production in HI collision.

- *p*(*d*) + A collision

  -> Cold nuclear matter (CNM) effects

(parton shadowing, CGC, breakup. See slide 3 & 4).

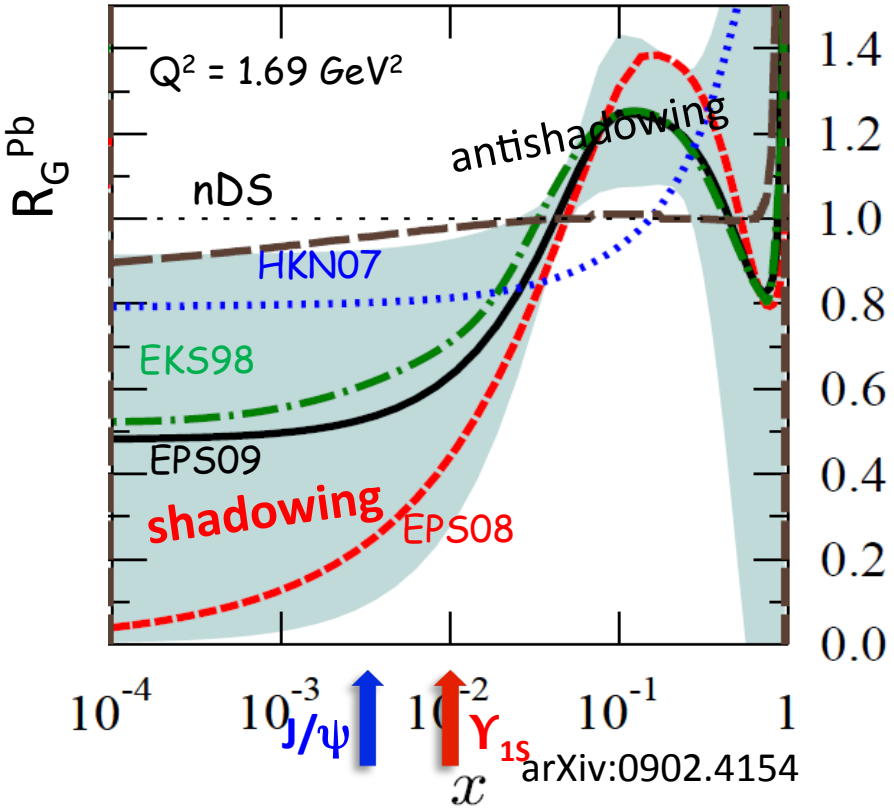


- A + A collision

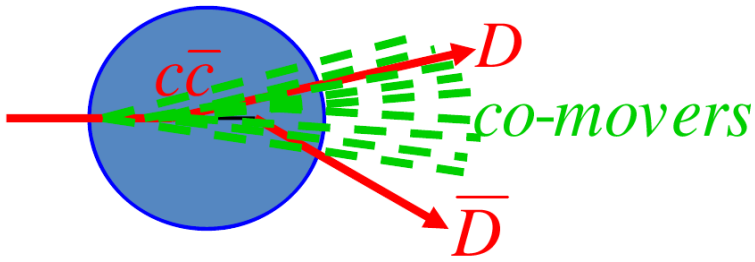
  -> Hot nuclear medium effects + CNM effects.

Cold nuclear matter effects (I)

1. Parton distributions of nucleus are modified. $R_G^A(x,Q^2) = \dfrac{xG_A(x,Q^2)}{AxG_p(x,Q^2)}$



arXiv:0902.4154



2. During propagation, quarkonia get broken up due to inelastic scattering in the nuclear medium.

3. Initial state energy loss.

Cold nuclear matter effects (II)

Gribov, Levin, Ryskin, Mueller, Qiu

4. Saturation criterion

Number of gluon per unit area:

$$\rho \sim \frac{xG_A(x,Q^2)}{\pi R_A^2}$$

Recombination cross section:

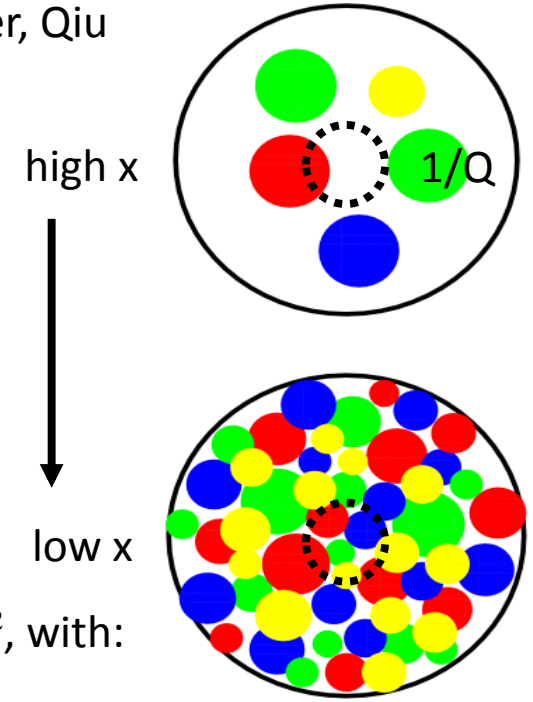
$$\sigma_{gg->g} \sim \frac{\alpha_S}{Q^2}$$

Recombination happens if $\rho\sigma_{gg->g} \gtrsim 1$, i.e. $Q^2 \lesssim Q_S^2$, with:

$$Q_S^2 \sim \frac{\alpha_S xG_A(x,Q_S^2)}{\pi R_A^2} \sim A^{1/3}\frac{1}{x^{0.3}}$$

At saturation, the phase-space density is:

$$\frac{dN_g}{d^2\vec{x}_\perp d^2\vec{p}_\perp} \sim \frac{\rho}{Q^2} \sim \frac{1}{\alpha_S}$$



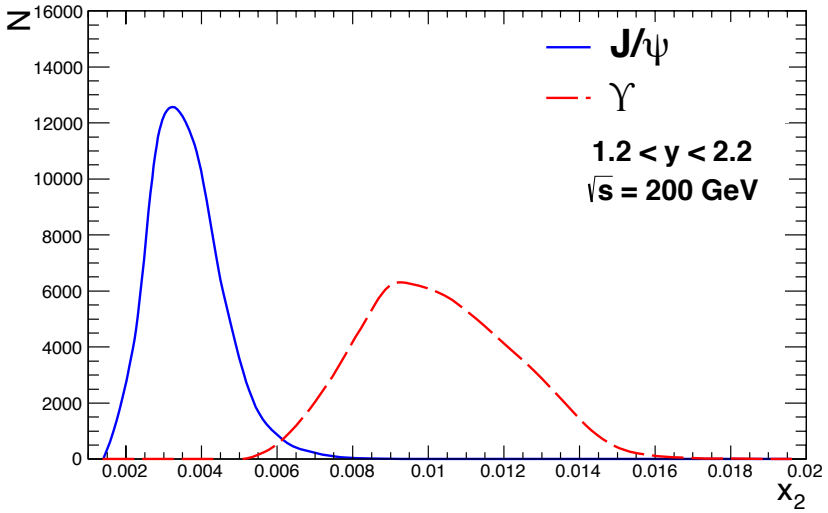
MPC can access low x region.

Probes (I)

1. Quarkonia production.
   - Have different binding energy.
   - Give different kinematics.

	$c\bar{c}$			$b\bar{b}$		
state	J/ψ (1S)	χ_c (1P)	ψ' (2S)	Υ (1S)	Υ (2S)	Υ (3S)
mass [GeV]	3.10	3.53	3.68	9.46	10.02	10.36
radius [fm]	0.25	0.36	0.45	0.14	0.28	0.39
ΔE [GeV]	0.64	0.20	0.05	1.10	0.54	0.20

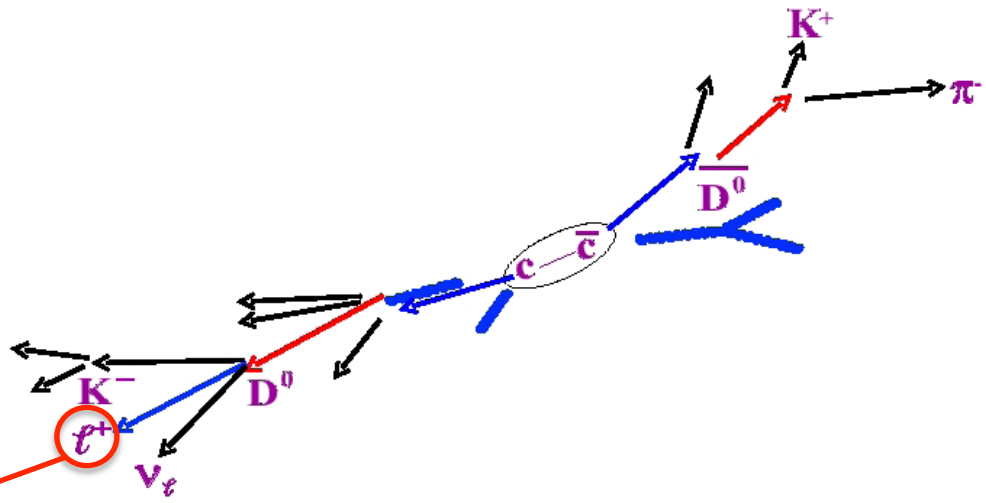
hep-ph/0609197v1 H. Satz



$$x_2 = \frac{m_T}{\sqrt{s}} e^{-y}$$

Fig. x_2 distribution of J/ψ and Υ

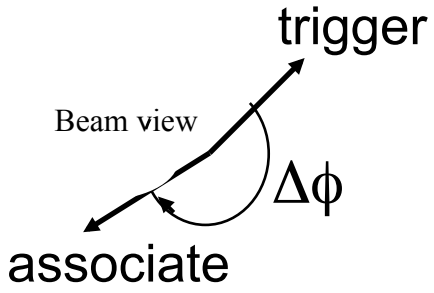
Probes (II)



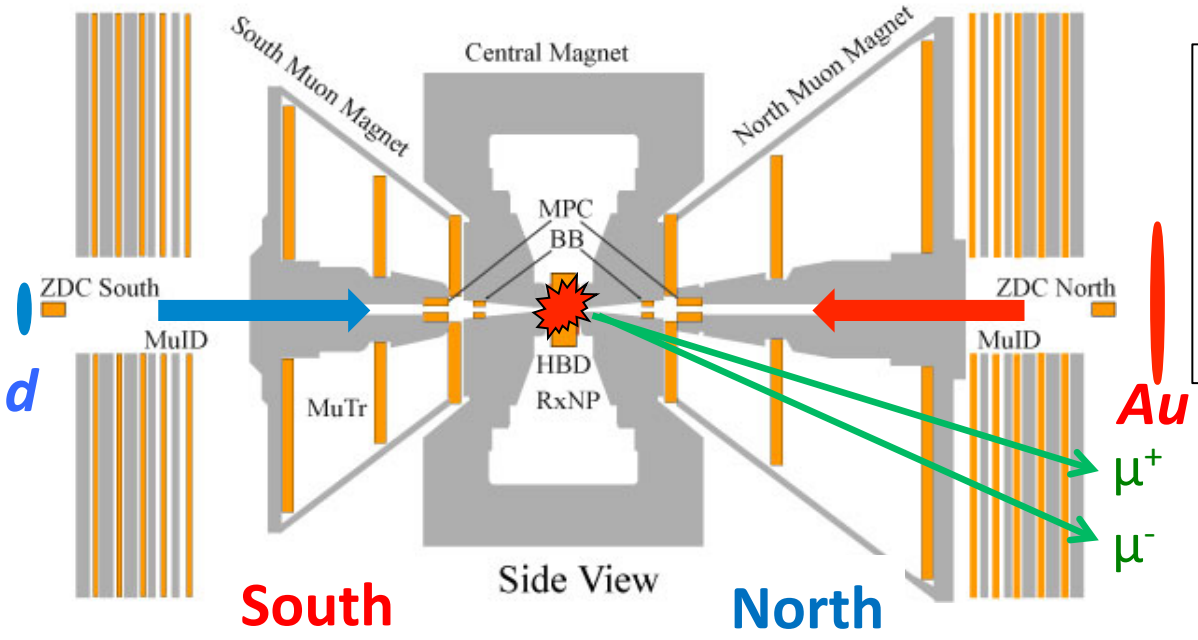
2. Leptons from semi-leptonic decays from heavy flavors (c,b quarks).
   - Charm and bottom quarks are dominantly produced in the early stages of the collision, they experience the complete evolution of the system.

3. Correlated back-to-back hadron pair yields.
   - Reach to low x region and study x-dependence.

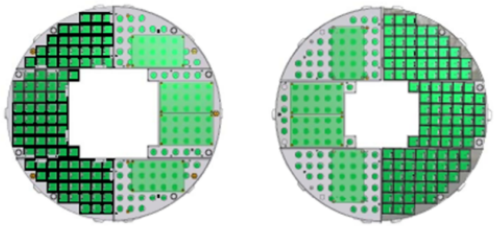
4. Light hadrons and direct photons



PHENIX forward rapidity detectors



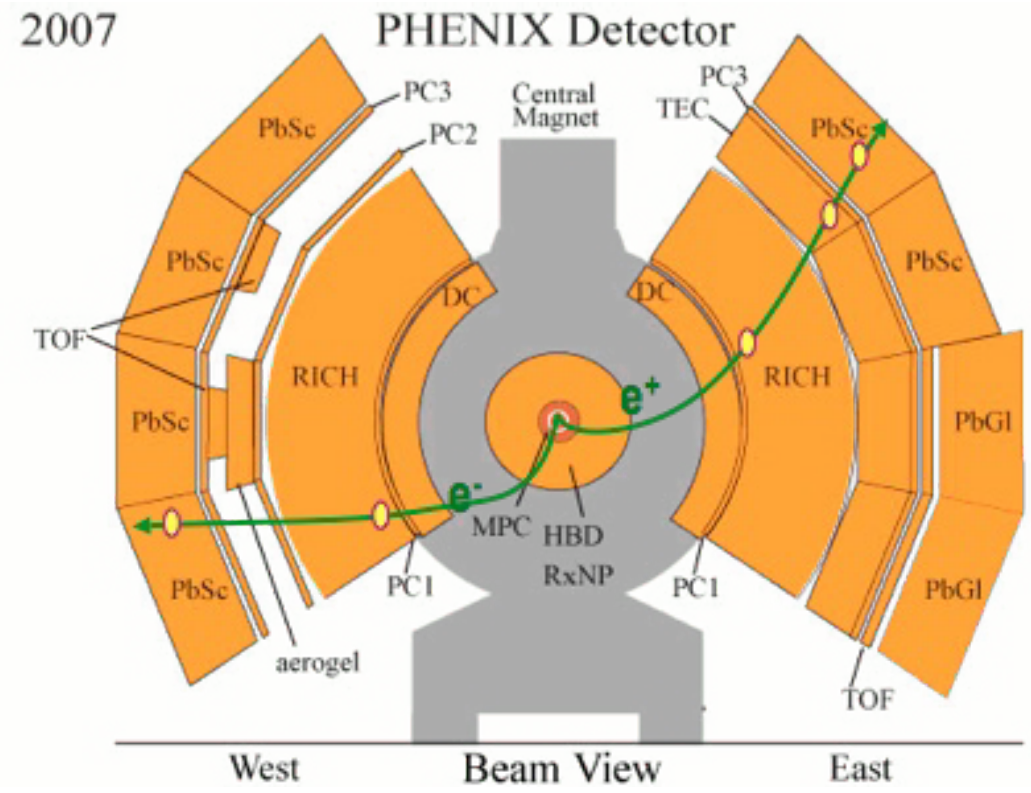
- Muon arm
  D, B -> $\mu^{\pm}$
  Υ, J/ψ, ρ/ω, Φ -> $\mu^{+}\mu^{-}$
  $1.2 < |y| < 2.2$
  $\Delta\Phi = 2\pi$



MPC

- Muon Piston Calorimeter (MPC)
  π^0/η -> photon
  $3.1 < |\eta| < 3.8$, $\Delta\Phi = 2\pi$

PHENIX mid rapidity detectors



- Central arm
  D, B -> $e^{\pm}$
  J/ψ, ϒ -> $e^{+}e^{-}$
  $-0.35 < y < 0.35$
  $\Delta\Phi = \pi$

- Drift chamber + Pad Chamber (momentum measurement)
- Ring Imaging Cherenkov detector (hadron rejection ~ 100)
- Electromagnetic Calorimeter (E/p → hadron rejection ~ 10)

Nuclear modification factors

$$R_{dAu} = \frac{N_{inv}^{dAu} \Big/ \left\langle N_{coll}^{dAu} \right\rangle}{N_{inv}^{pp}}$$

$$R_{CP}^{0-20\%} = \frac{N_{inv}^{0-20\%} \Big/ \left\langle N_{coll}^{0-20\%} \right\rangle}{N_{inv}^{60-88\%} \Big/ \left\langle N_{coll}^{60-88\%} \right\rangle}$$

	pp	dAu (all centralities)	dAu (0-20%)	dAu (60-88%)
N_{coll}	1	7.6 ± 0.4	15.1 ± 1.0	3.2 ± 0.2

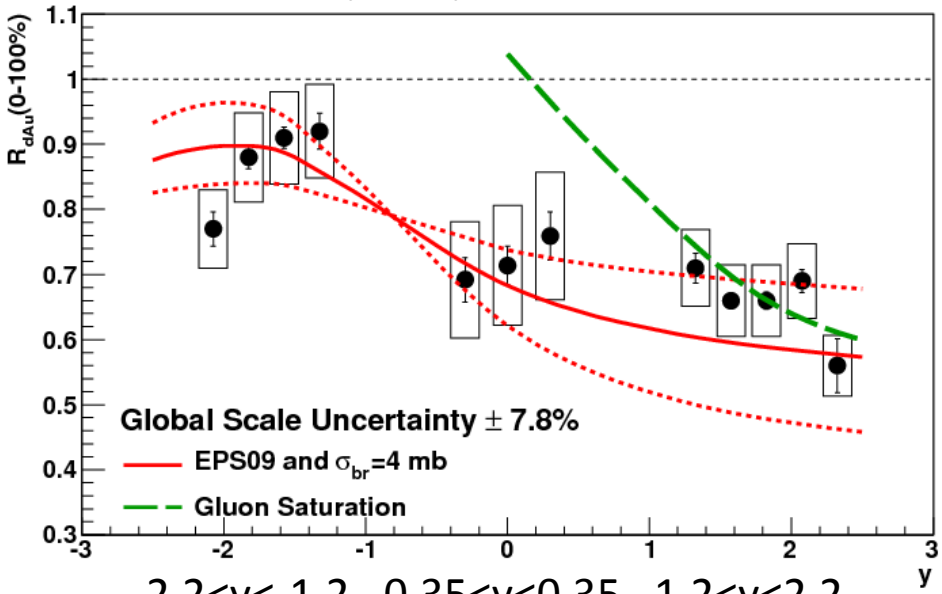
N_{coll} : number of binary (pp) collisions in one HI collision.

- If the production of *d*+Au behaves like in pp,

  $R_{dAu} = R_{cp} = 1$
- If there is suppression, R_{dAu} , $R_{cp} < 1$

J/ψ R_{dAu} rapidity dependence in d+Au

PHENIX:PRL 107(2011) 142301



-2.2<y<-1.2 -0.35<y<0.35 1.2<y<2.2

x ~ 0.1 x ~ 0.03 x ~ 0.005

- Shadowing model, EPS09 + $\sigma_{breakup}$ (red line) = 4 mb
- Dashed lines are the maximum variation.
- Gluon Saturation(green line) Nucl.Phys.A770:40-56,2006
  - Good agreement at forward rapidity
  - Deviates from the data quickly as y<1.

Nuclear thickness, Λ for each N-Au collision

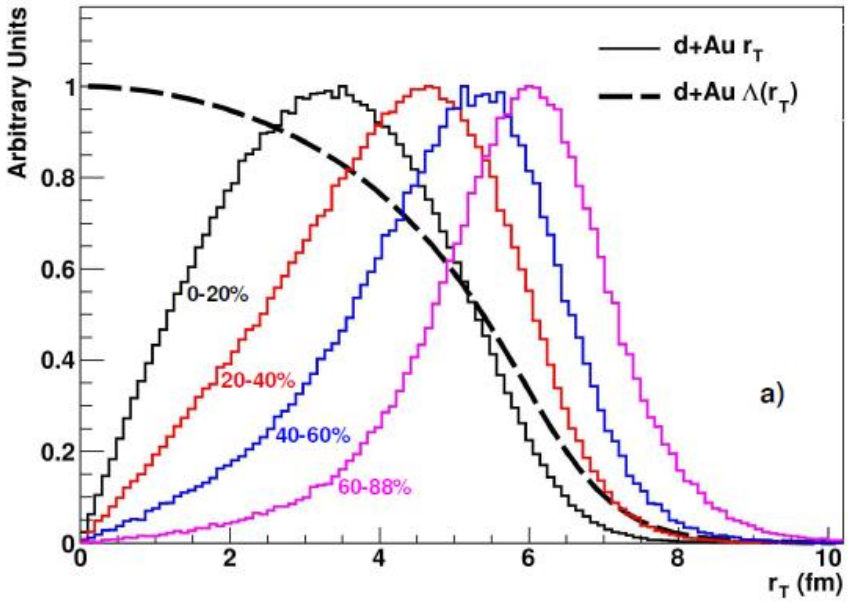
- Assume that CNM effects are related to Λ at the r_T value for each nucleon.

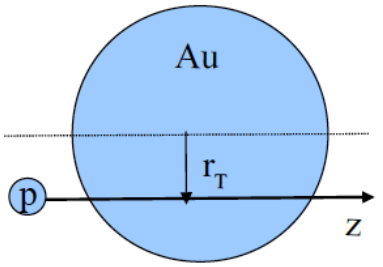
- Define the longitudinal density integrated nuclear thickness, Λ in Au at impact parameter r_T:

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

obtained from a Woods Saxon distribution.

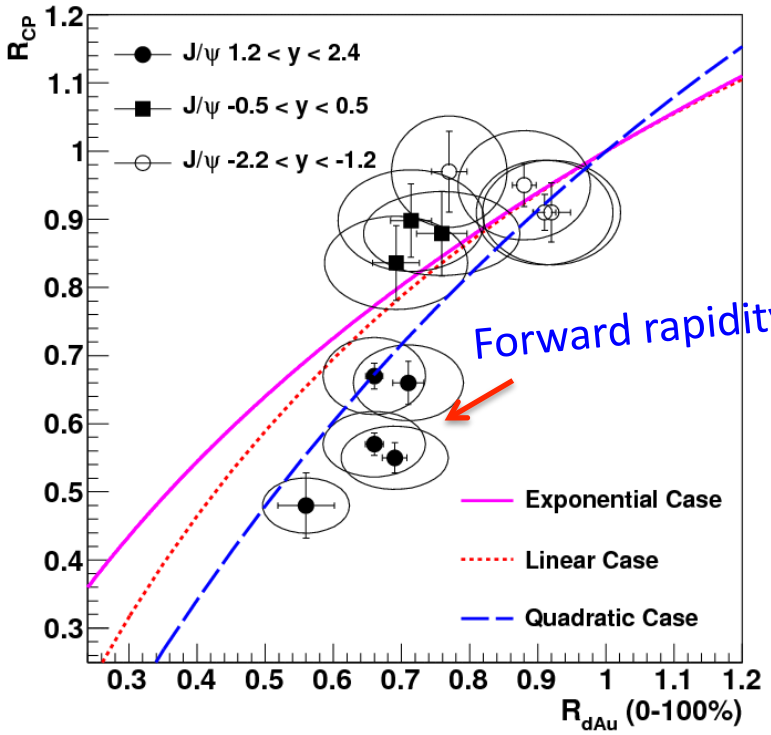
- Use a Glauber calculation to average a postulated CNM effect over the PHENIX centrality bins.





Λ dependence of J/ψ R_{dAu} & R_{CP}

PHENIX:PRL 107(2011) 142301



$R_{CP}(0-20\%)$ vs $R_{dAu}(0-100\%)$

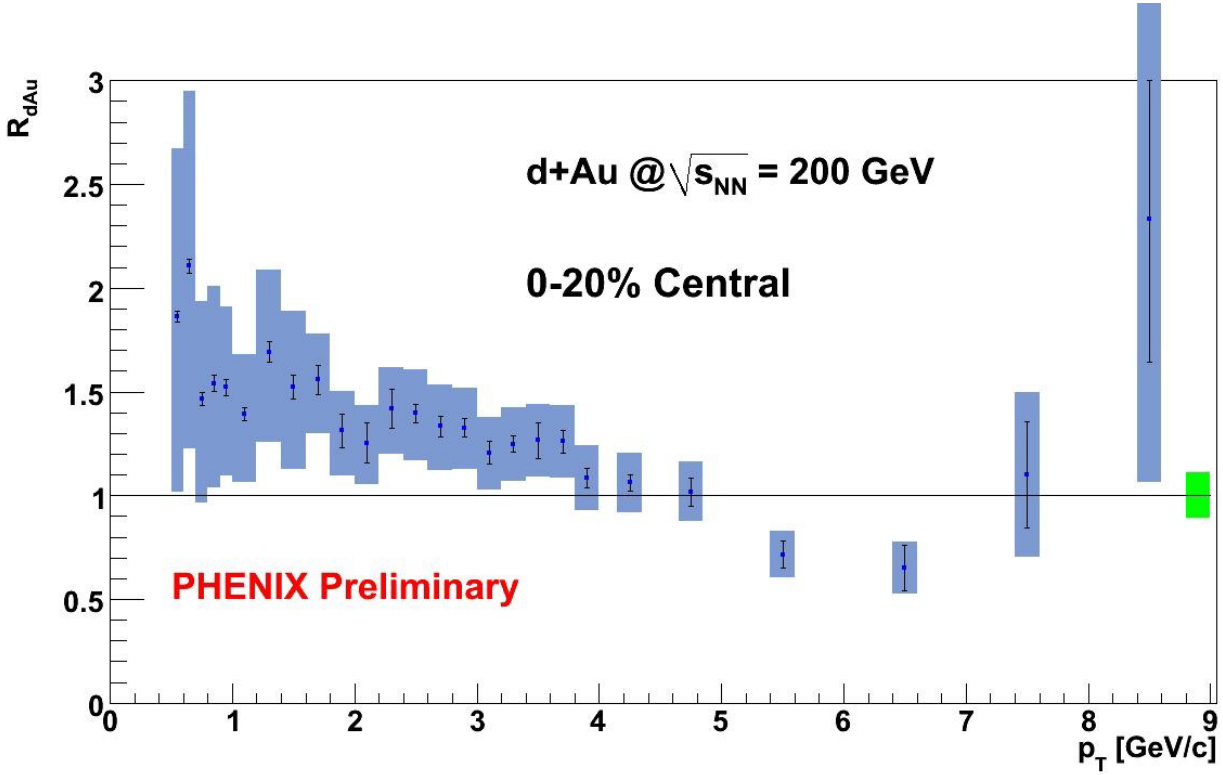
$$Exponentid: M(r_T) = e^{-a\Lambda(r_T)}$$

$$Linear: M(r_T) = 1.0 - a\Lambda(r_T)$$

$$Quadratic: M(r_T) = 1.0 - a\Lambda(r_T)^2$$

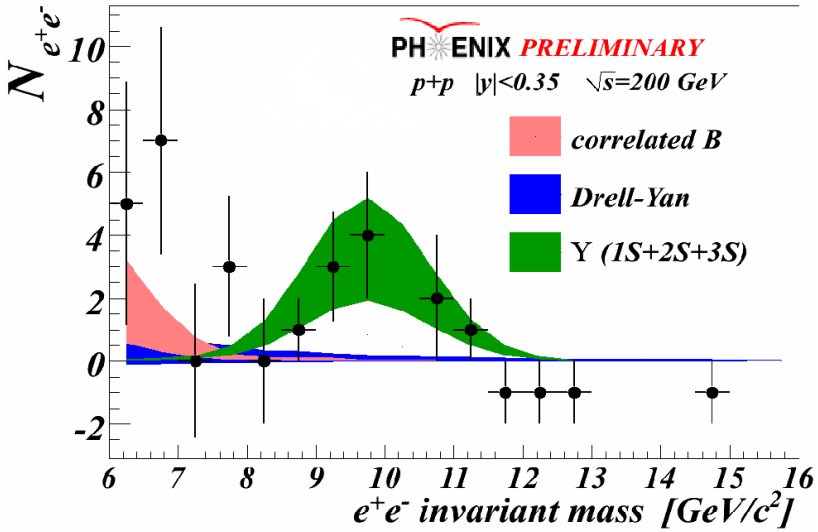
- The forward rapidity data points are barely consistent with even a pure quadratic thickness dependence.

Open heavy flavor R_{dAu}



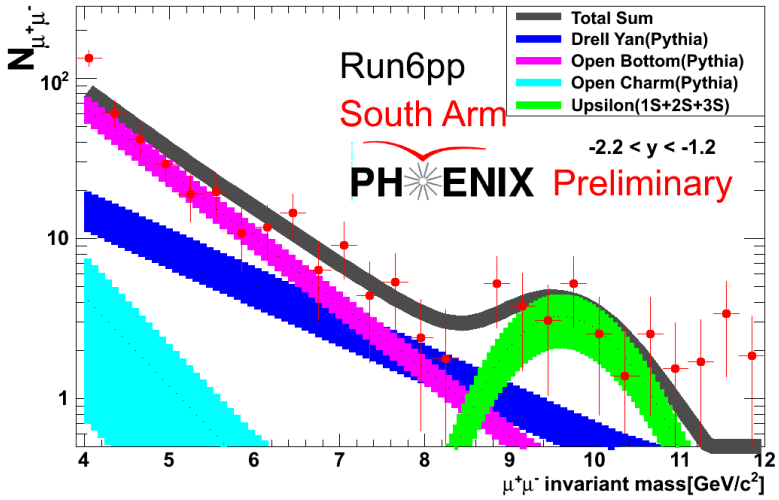
- Semi-leptonic open heavy flavor decay R_{dAu} at y=0.
- Indication of an excess at 1-4 GeV/c, but not far outside the systematics.

ϒ distribution in PHENIX

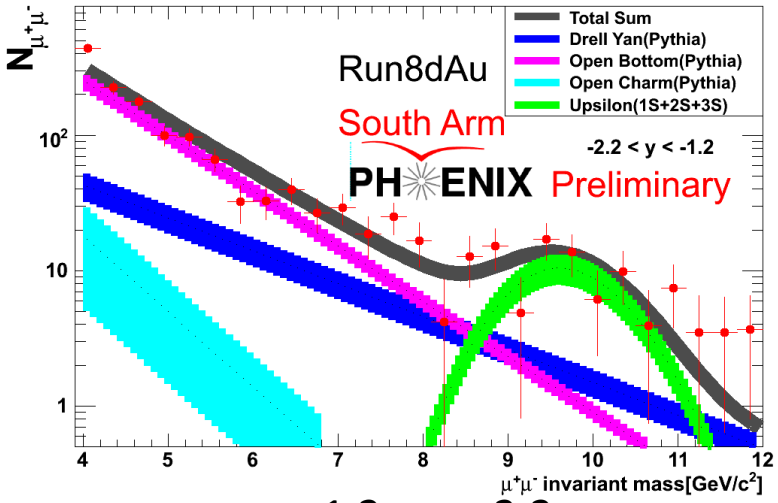


-0.35 < y < 0.35

- Physical backgrounds of Drell-Yan, open charm and open beauty are simulated and subtracted off with corresponding systematic uncertainties.

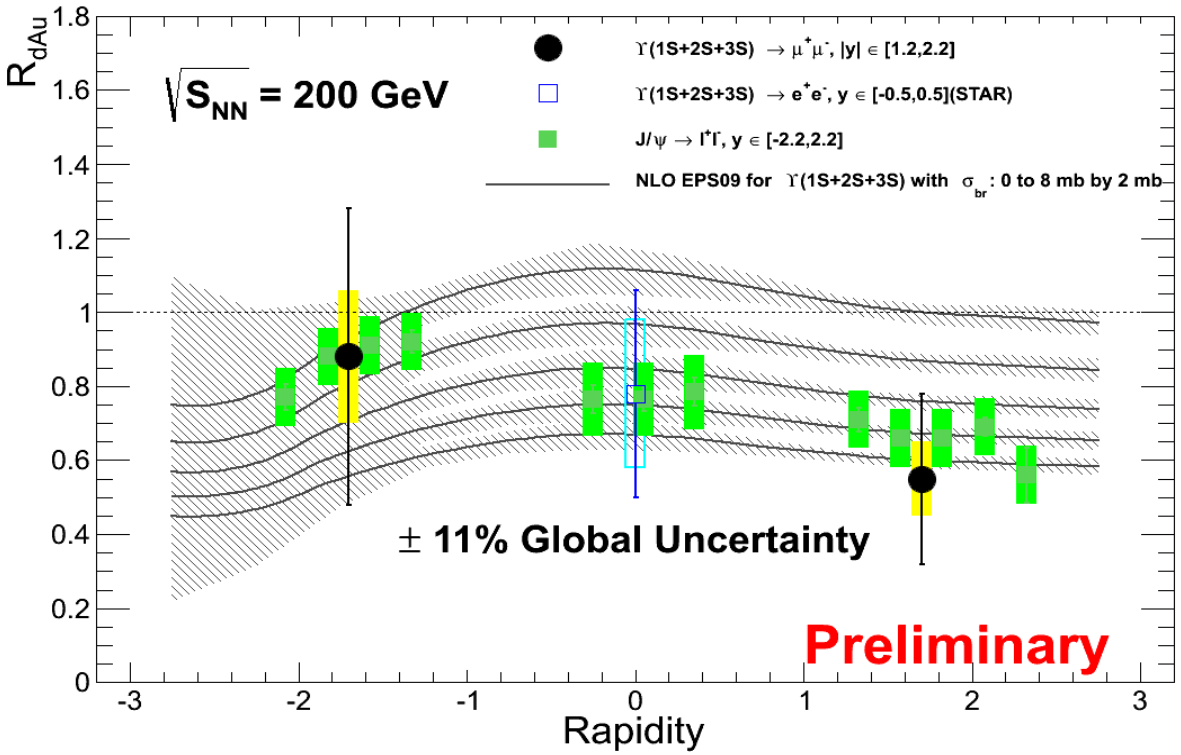


-2.2 < y < -1.2



1.2 < y < 2.2

Υ R_{dAu} rapidity distribution



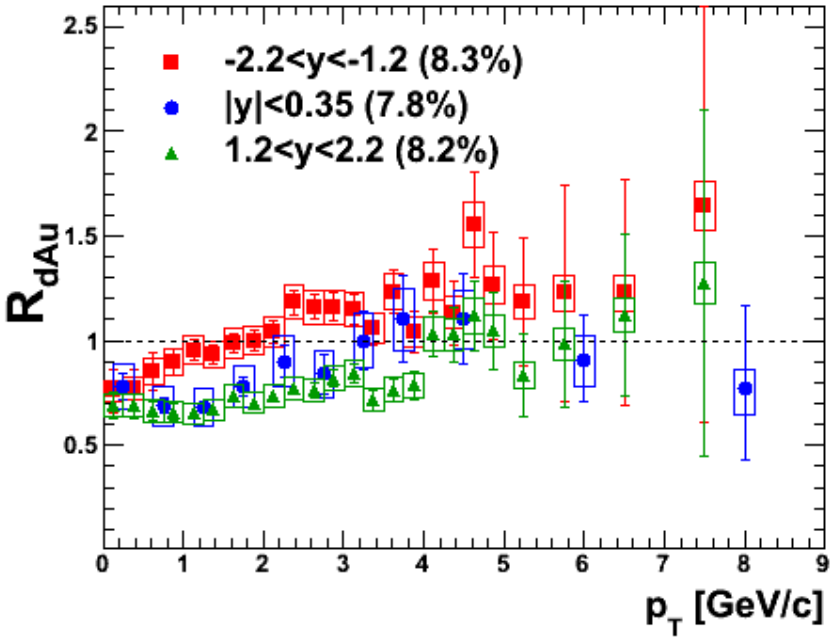
-2.2<y<-1.2
x ~ 0.2

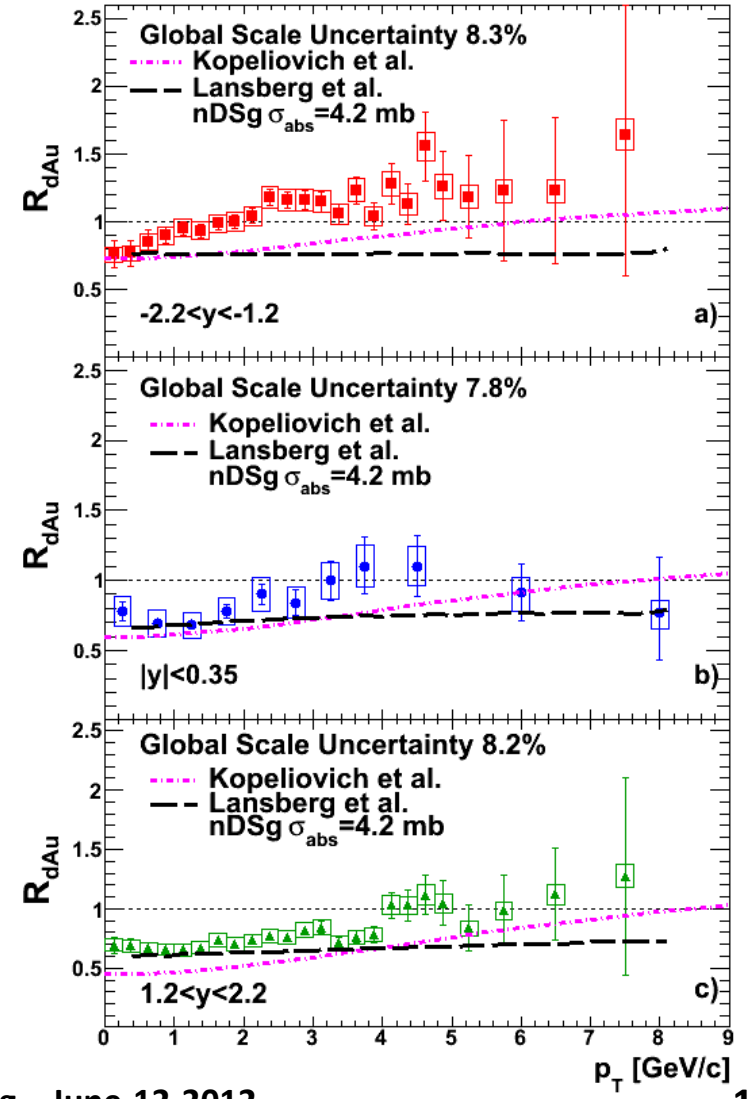
1.2<y<2.2
x ~ 0.01

- Theory curves are from NLO EPS09 + breakup cross sections.
- Shows suppression at forward rapidity.
- Shows similar trend with J/ψ.

J/ψ R_{dAu} vs P_T

arXiv:1204.0777

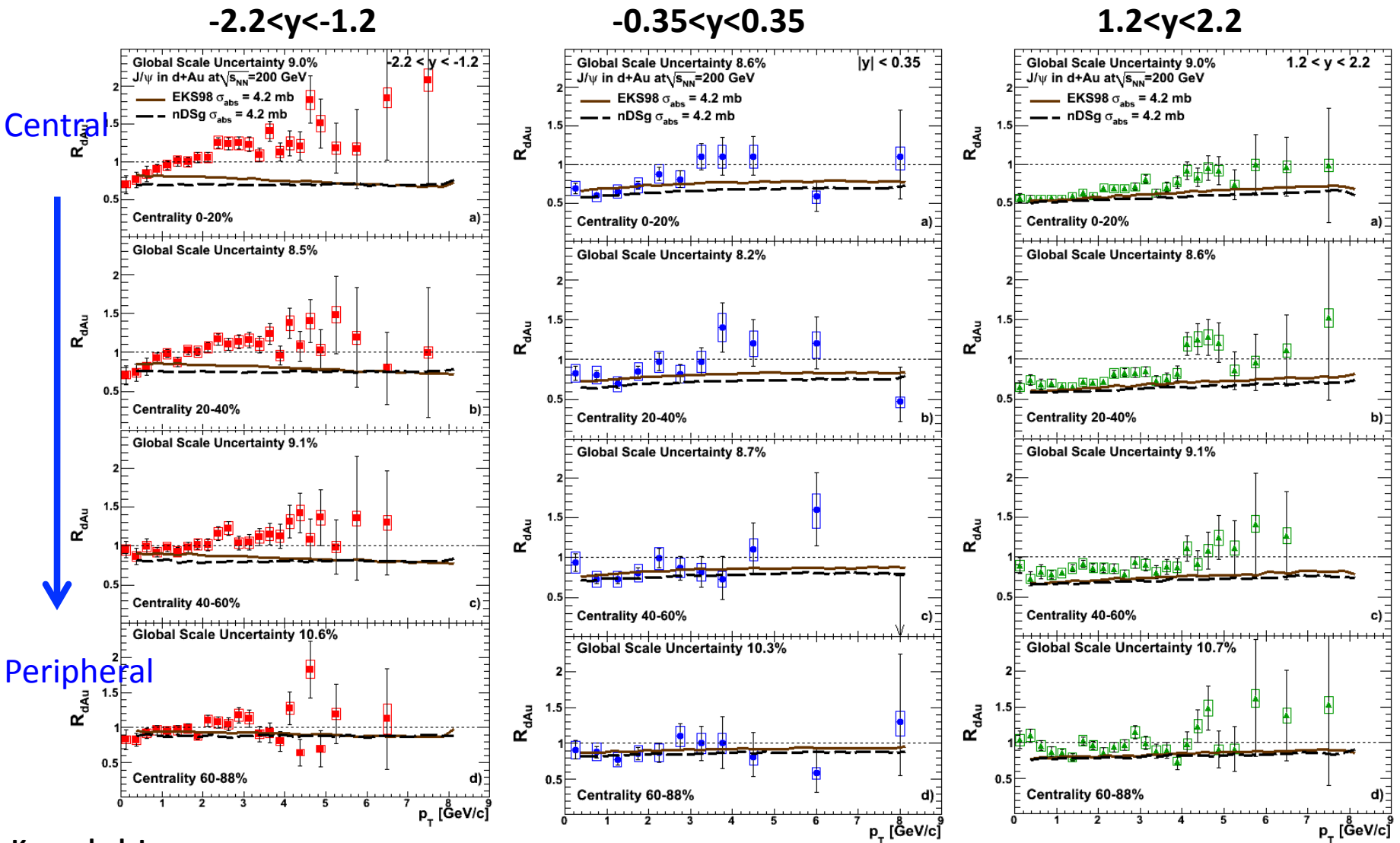




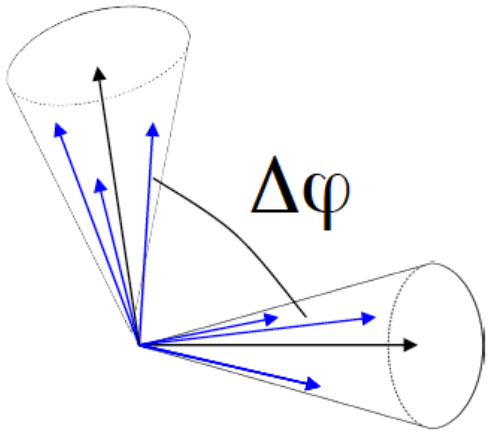
- Both models use nDSg for shadowing.
  The stronger modulation with P_T of Kopeliovich et al. is presumably due to the added Cronin effect (although an effect from the different kinematics assumptions is possible).

- Models do not do well for backward rapidity.

Lansberg et al.-nDSg/EKS98+linear thickness dependence



Back-to-back di-hadron measurement in d+Au



$$J_{dA} = \frac{1}{\langle N_{coll} \rangle} \frac{\sigma_{dA}^{pair} / \sigma_{dA}}{\sigma_{pp}^{pair} / \sigma_{pp}}$$

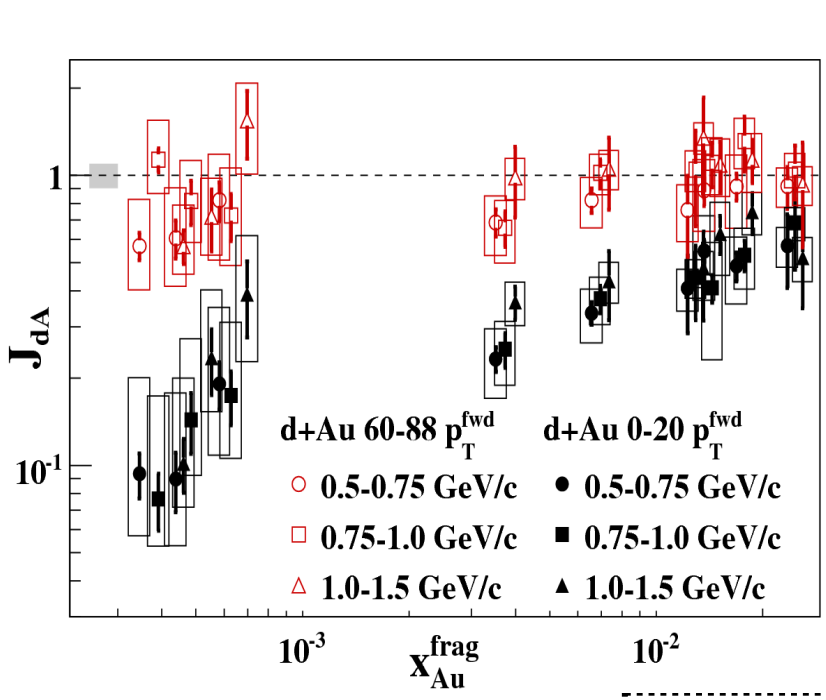
Caveats:

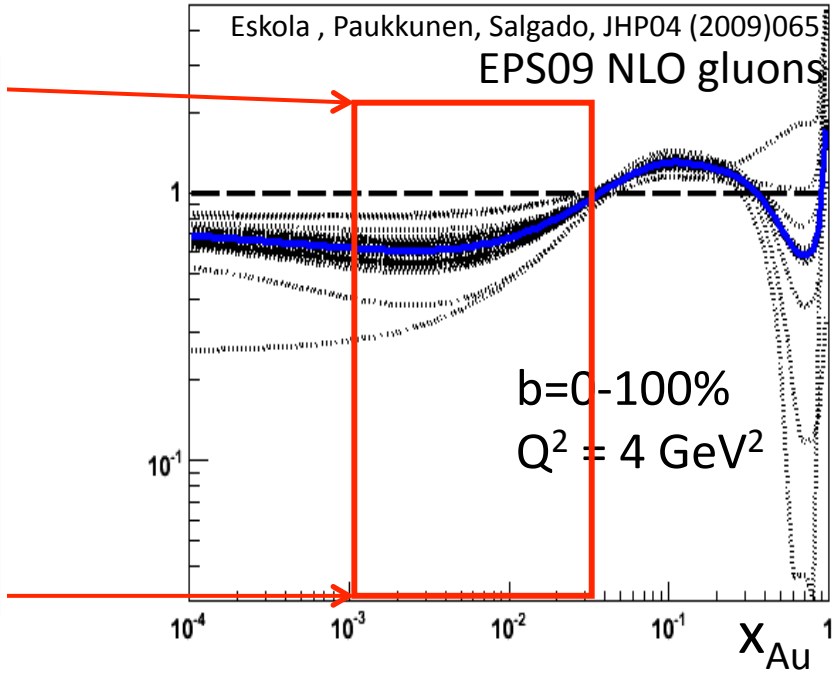
1. Low P_T (but back-to-back peak is selected)
2. Di-Hadrons not di-jets (but ok if fragmentation unmodified)

We do not know Bjorken x in the Au nucleus unless the two hadrons carry all of the parton energy. Instead, use:

$$x_{Au}^{frag} = \frac{< p_{T1} > e^{-\eta_1} + < p_{T2} > e^{-\eta_2}}{\sqrt{S_{NN}}}$$

Large Suppression in Central d+Au





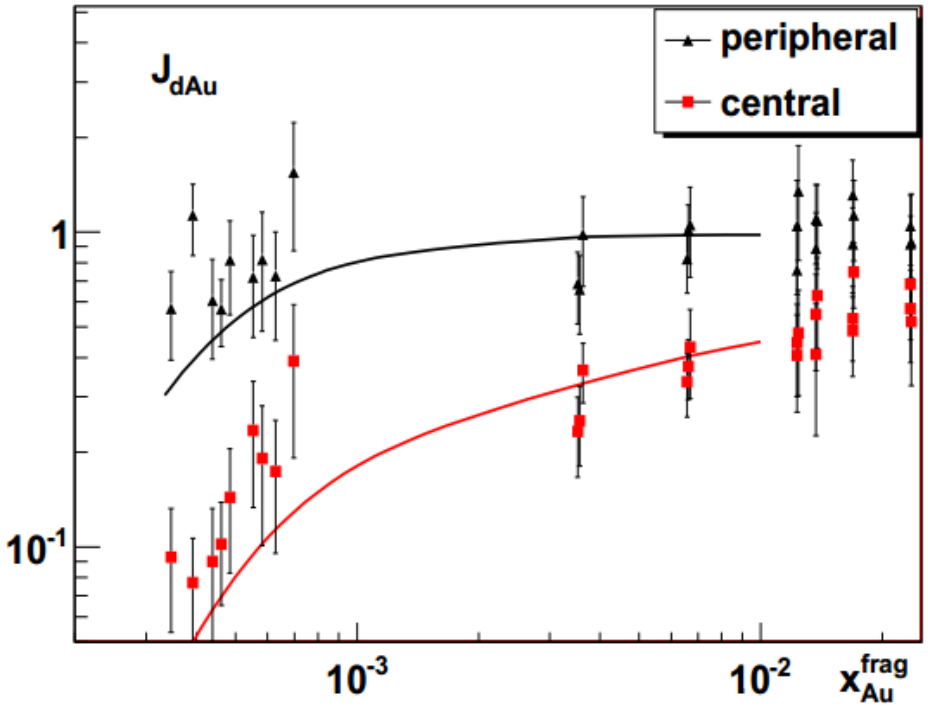
$$J_{dA} = \frac{\sigma_{dAu}^{pairs} / \sigma_{dAu}}{\langle N_{coll} \rangle \sigma_{pp}^{pairs} / \sigma_{pp}} \propto \frac{f_d^a(x_d) \otimes f_{Au}^b(x_{Au}) \otimes \hat{\sigma}^{ab \to cd} \otimes D(z_c, z_d)}{f_p^a(x_p) \otimes f_p^b(x_p) \otimes \hat{\sigma}^{ab \to cd} \otimes D(z_c, z_d)}$$

High x, mostly quarks, $\frac{f_d^a(x_d)}{f_p^a(x_p)}$ week effect

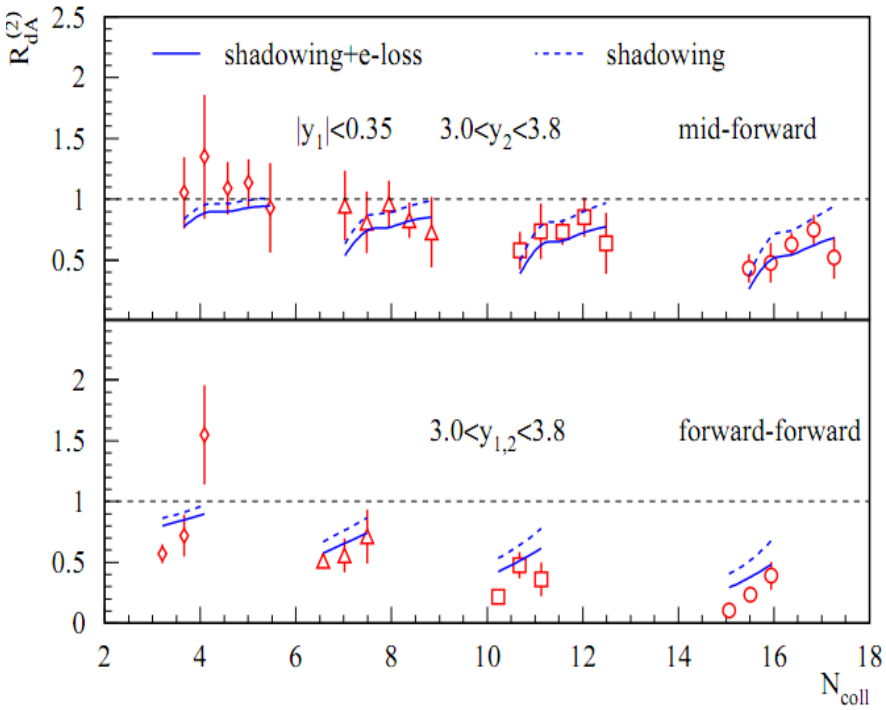
Low x, mostly gluons $\rightarrow J_{dA} \leftrightarrow R_G^{Au}$

CGC vs "pQCD" Approach

Stasto, Xiao, Yuan [arxiv:1109.1817]



Kang, Vitev, Xing [arxiv:1112.6021]



- Left: CGC saturation approach.
- Right: Perturbative approach incorporates ISI and FSI for momentum imbalance (multiple scattering broadening), plus energy loss and coherent power corrections.
- Win-win scenario? Either saturation is found, or one can extract $g_{Au}(x)$.

Summary and near Future

Open heavy flavor:

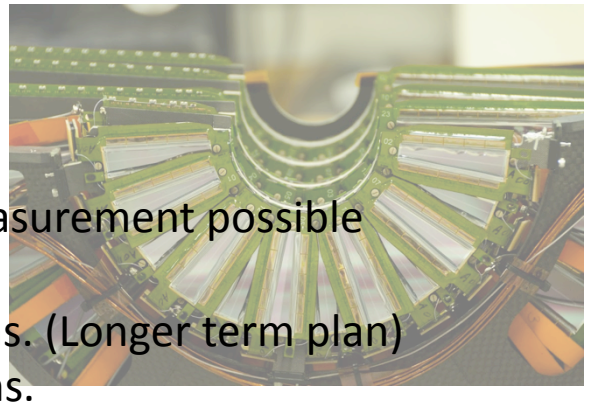
- No suppression for 1-5 GeV/c, likely some enhancement.

Quarkonia:

- J/ψ R_{dAu}, R_{CP} are inconsistent with models which has several dependences on nuclear thickness over the full rapidity and centrality.
- Models with nDSg for shadowing do not explain well for backward rapidity at J/ψ R_{dAu} vs P_T.
- Y(1S+2S+3S) are suppressed at forward rapidity – similar to J/ψ.

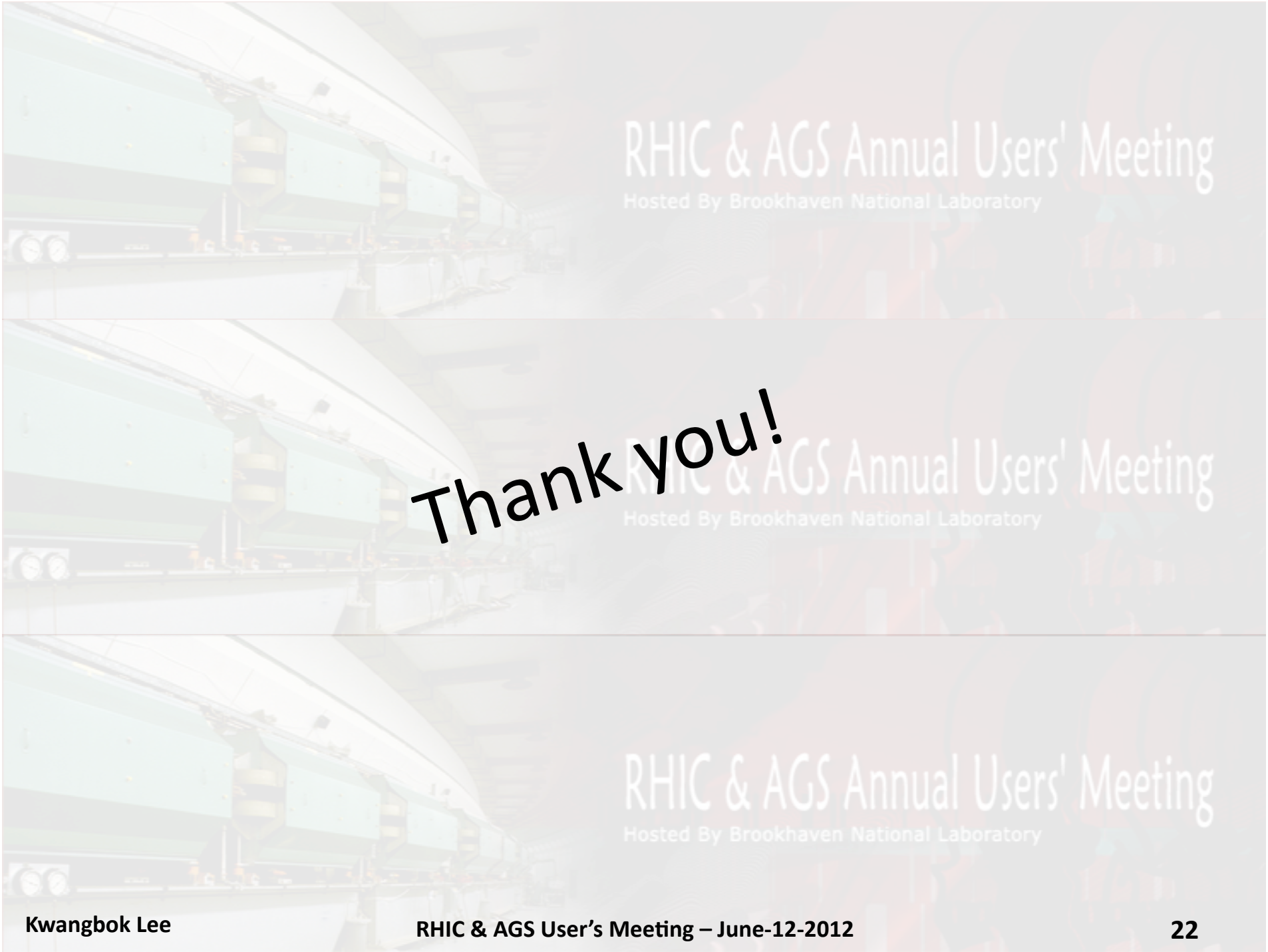
Forward/forward and forward/mid dihadrons:

- Forward/forward dihadrons shows strong suppression at lower x, mostly due to the gluon.
- Described by CGC or pQCD approach.



Near Future

- VTX/FVTX would make Drell-Yan, charm/bottom and ψ' measurement possible with improved mass resolution and vertex measurement.
- The MPC-EX upgrade would measure forward direct photons. (Longer term plan)
- Would give another proves to access initial effects of partons.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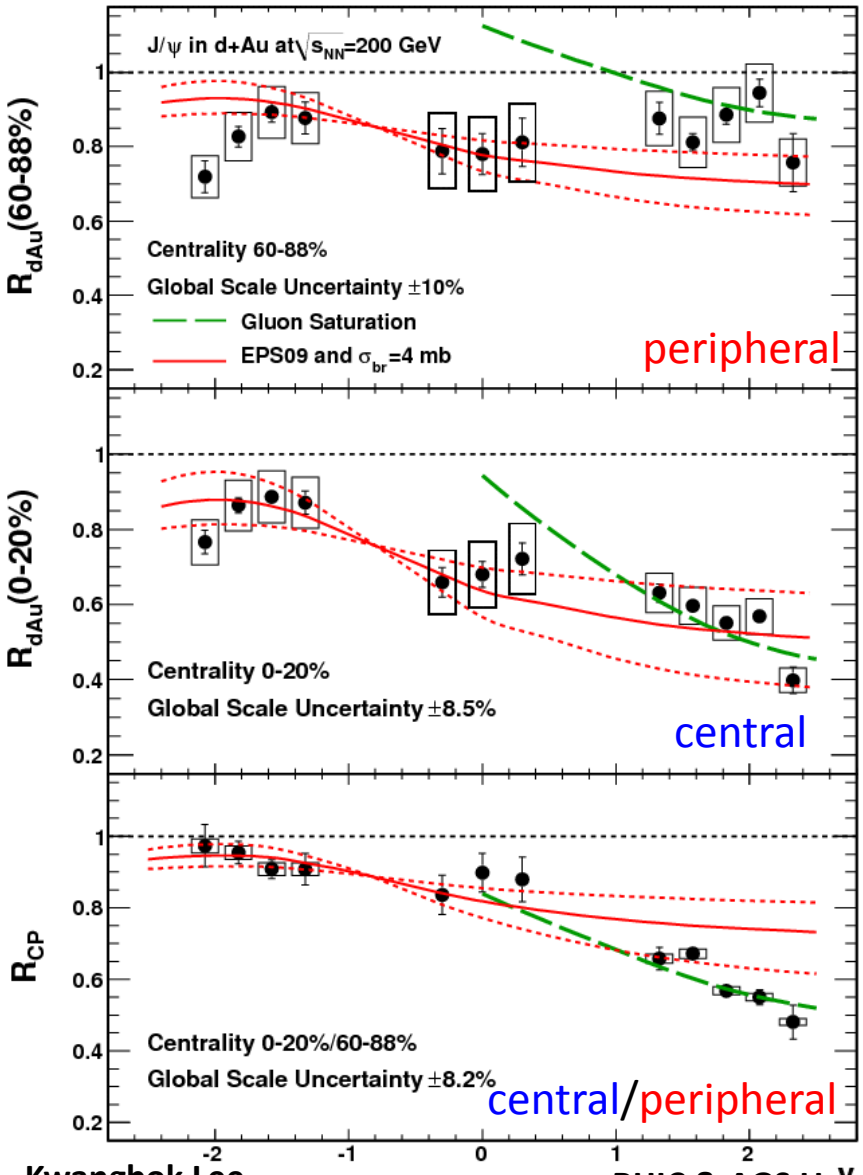
J/ψ R_{dAu} centrality & R_{cp}



- EPS09(linear) + fixed Breakup cross section(exponential) for central and peripheral collisions.
- Forward rapidity data inconsistent with a linear dependence on thickness.
- Expect the nuclear effects are dependent on the geometric thickness through the gold nucleus.

- Need to consider modification stronger than linear or exponential dependence on density-weighted longitudinal thickness like quadratic.

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

arXiv:1010.1246