Cold Nuclear Matter Absorption

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based on:
Lourenco, RV, and Wöhri, JHEP 0902 (2009) 014
McGlinchy, Frawley and RV, Phys. Rev. C 87 (2013) 054910

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Cold Matter Effects on Heavy Flavor Production

Production cross section in a pA collision

$$\sigma_{pA}(S,m^2) = \sum_{i,j=q,\overline{q},g} \int_{4m_Q^2/S}^{1} \frac{d\tau}{\tau} \int d^2b\, dz\, d\epsilon\, dx_1\, dx_2\, \delta(x_1x_2-\tau)\delta(x'_F-x_F-\delta x_F(\epsilon))\delta(x'_F-x_1+x_2)$$
$$\times P(\epsilon)\, S_A^{\rm abs}(\vec{r},z)\, f_i^p(x_1,\mu_F^2) F_i^A(x'_1,\mu_F^2,\vec{b},z)\, \widehat{\sigma}_{ij}(s,m^2,\mu_F^2,\mu_R^2)$$

In AA collisions, the proton PDF would be replaced by that of the nucleus

Survival probability for absorption of a (proto)charmonium state in nuclear matter

$S_A^{\rm abs}(b,z) = \exp\left\{-\int_z^\infty dz'\rho_A(b,z')\sigma_{\rm abs}(z-z')\right\}$

$P(\epsilon)$ **is energy loss probability that modifies the** x_F **of the produced** J/ψ **state**

Nuclear parton densities

$$F_i^A(x,Q^2,\vec{b},z) = \rho_A(s) S^i(A,x,Q^2,\vec{b},z) f_i^p(x,Q^2)\ ; \quad s=\sqrt{b^2+z^2}\ ; \quad \rho_A(s) = \rho_0 \frac{1+\omega(s/R_A)^2}{1+\exp[(s-R_A)/d]}$$

S^i **is shadowing parameterization for parton** i, *e.g.* **EPS09, EPPS16**

With no nuclear modifications, $S^i(A,x,Q^2,\vec{r},z) \equiv 1$

S. Klein and R. V. initially assumed shadowing proportional to nuclear thickness.
later raised to power n **for PHENIX d+Au**

EPS09s parameterization keeps powers $n = 1\cdots 4$ **for** A**-independent coefficients**

$$S^i(A,x,Q^2,\vec{b},z) = 1 - (1 - S^i(A,x,Q^2)\,)\left(\frac{T_A^n(b)}{a(n)}\right)$$

If onset of shadowing is like a step function with a radius R **and diffuseness** d

$$S^i(A,x,Q^2,\vec{b},z) = 1 - \left(\frac{1-S^i(A,x,Q^2)}{a(R,d)(1+\exp((b-R)/d))}\right)$$

Interplay of Shadowing and Absorption

Depending on x values probed, shadowing can enhance or reduce absorption cross section needed to describe data

Absorption alone always gives less than linear A dependence ($\alpha < 1$)

For SPS energies, $17.3 \leq \sqrt{S} \leq 29$ GeV, rapidity range covered is in EMC and antishadowing region, $\alpha > 1$ with no absorption

Adding shadowing to absorption in the SPS energy region requires a larger absorption cross section is needed to maintain agreement with data

For $\sqrt{S} \geq 38$ GeV, x in shadowing regime, thus $\alpha < 1$ with shadowing alone in forward region, reducing needed absorption cross section to $\sigma_{\rm abs} \sim 0$ at the LHC

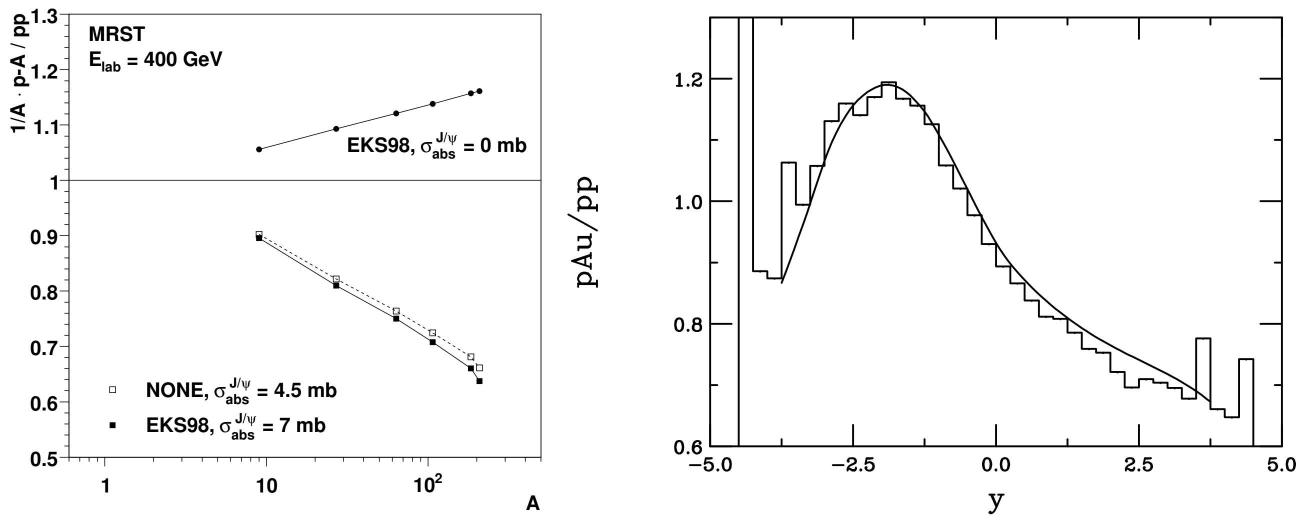

Figure 2: (Left) Illustration of the interplay between shadowing and absorption. [C. Lourenco, H. K. Woehri and RV, JHEP 0902 (2009) 014.] (Right) Comparison of LO and NLO shadowing ratios.

Energy Dependence of $\sigma_{\rm abs}^{J/\psi}$

At midrapidity, systematic decrease of absorption cross section with center of mass energy, independent of shadowing, trend continues at RHIC and above

$\sigma_{\rm abs}^{J/\psi}(y_{\rm cms} = 0)$ extrapolated to 158 GeV is significantly larger than measured at 450 GeV, underestimating "normal nuclear absorption" in SPS heavy-ion data

Calculations confirmed by NA60 pA measurements at 158 GeV showing stronger absorption with L

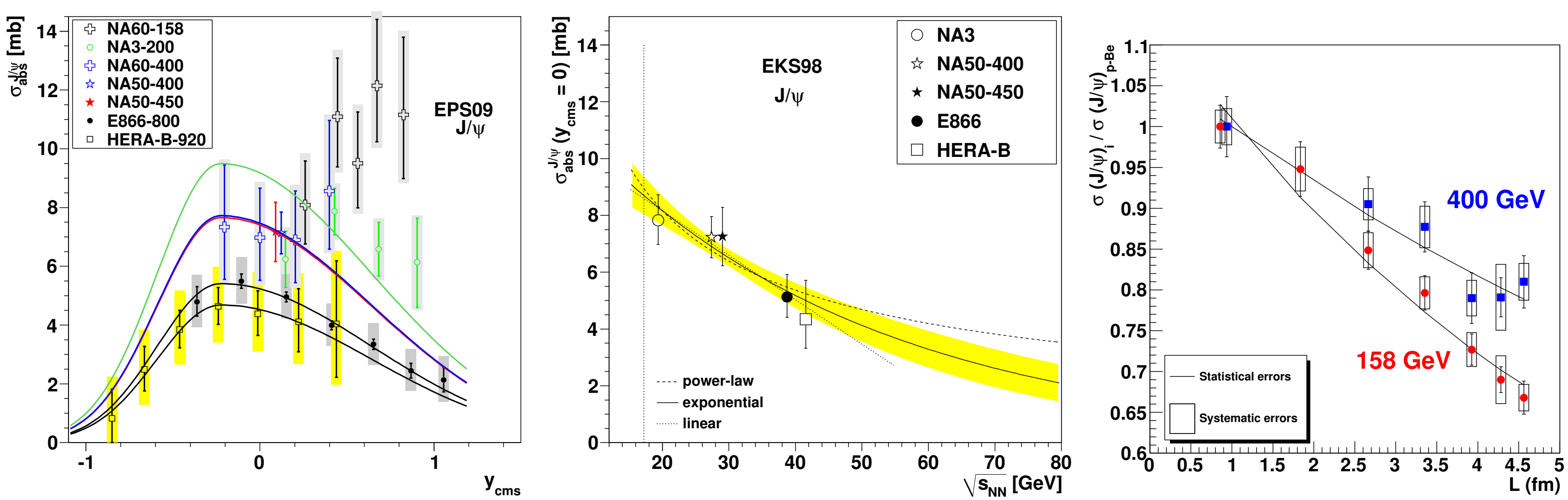

Figure 3: Left: Dependence of $\sigma_{\rm abs}^{J/\psi}$ on $y_{\rm cms}$ for all available data sets including EPS09 shadowing. The shape of the curves is fixed by the E866 and HERA-B data. [Lourenço, RV, Wöhri] Middle: The extracted energy dependence of $\sigma_{\rm abs}^{J/\psi}$ at midrapidity for power law (dashed), exponential (solid) and linear (dotted) approximations to $\sigma_{\rm abs}^{J/\psi}(y = 0, \sqrt{s_{NN}})$ using the EKS98 shadowing parameterization with the CTEQ61L parton densities. The band around the exponential curve indicates the uncertainty in the extracted cross sections at $x_F \sim 0$ from NA3, NA50 at 400 and 450 GeV, E866 and HERA-B. The vertical dotted line indicates the energy of the Pb+Pb and In+In collisions at the CERN SPS. [Lourenço, RV, Wöhri] Right: The J/ψ cross section ratios for pA collisions at 158 GeV (circles) and 400 GeV (squares), as a function of L, the mean thickness of nuclear matter traversed by the J/ψ.

Effective $\sigma_{\rm abs}$ Decreases with $\sqrt{s}$

Once data corrected for shadowing effects, dependence of effective absorption cross section on center of mass energy is visible; should be negligible at LHC energies

In backward region, quarkonium states should be fully formed within the target

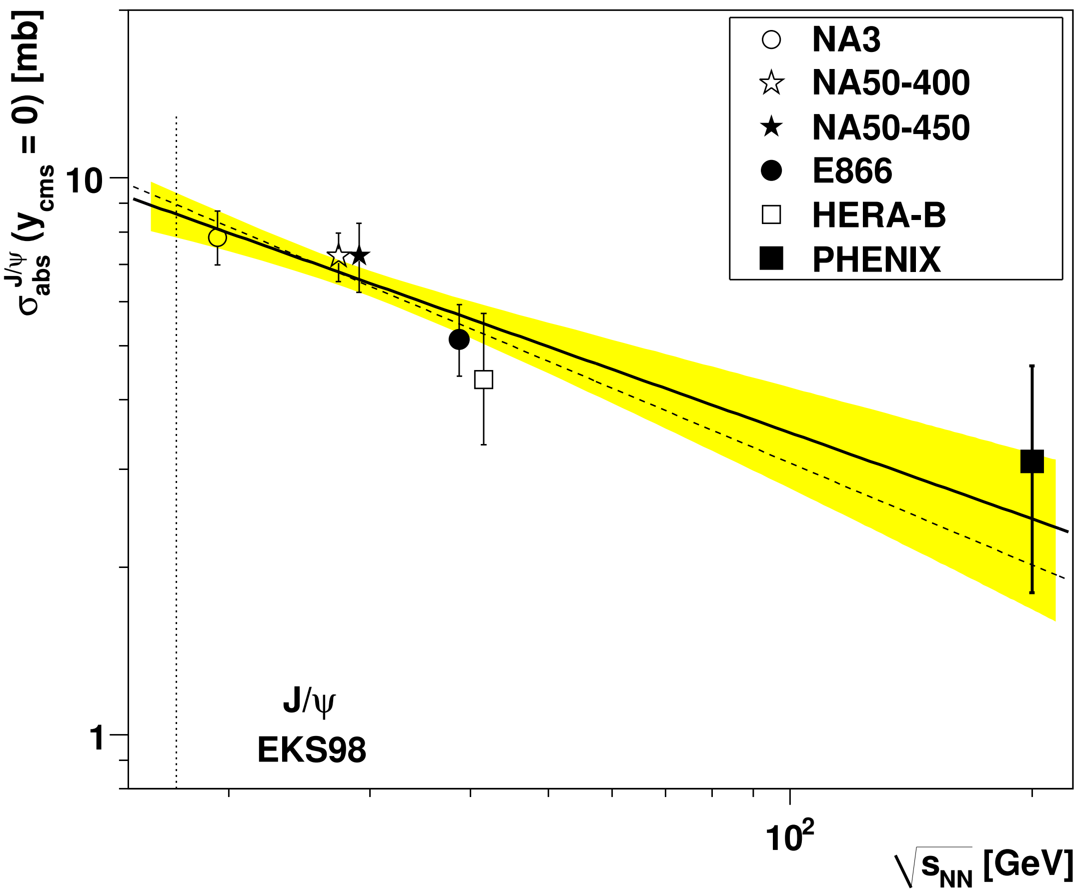

Figure 4: At midrapidity, the effective absorption cross section decreases as a function of energy. (Modified from Lourenco, Wohri and RV.)

$\sigma_{\rm abs}$ Grows with Time $c\bar{c}$ Spends Traversing Nucleus

Mid- and backward rapidity J/ψ at $\sqrt{s_{NN}} = 200$ GeV (longer $\tau = L/\gamma$) dominated by conversion of color octet $c\bar{c}$ pair to color singlet J/ψ by gluon emission

$$\sigma_{\rm abs}(\tau) = \sigma_1 \left(\frac{\sqrt{s}}{10\ GeV}\right)^{0.4} \left(\frac{r_{c\bar{c}}(\tau)}{r_{{\rm J}/\psi}}\right)^2 \qquad r_{c\bar{c}}(\tau) = r_0 + v_{c\bar{c}}\tau \text{ for } r_{c\bar{c}}(\tau) < r_\psi$$

Difference at forward rapidity (shorter τ) where conversion occurs outside target

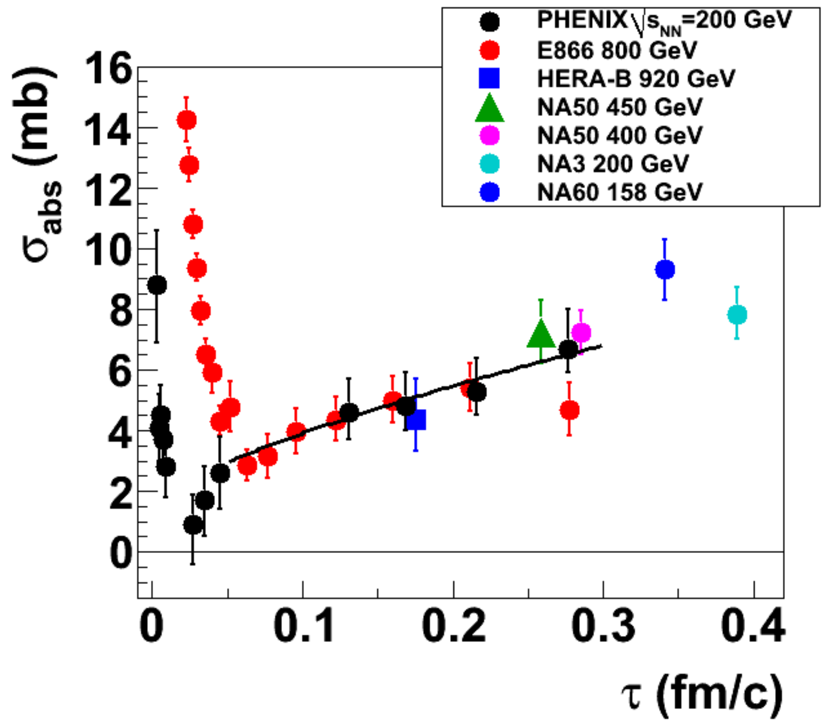

Figure 5: The effective $c\bar{c}$ breakup cross section as a function of the proper time spent in the nucleus, τ. The values were extracted from PHENIX $\sqrt{s_{NN}} = 200$ GeV d+Au data after correction for shadowing using EPS09 and from fixed-target p+A data measured by E866 at 800 GeV, by HERA-B at 920 GeV, by NA50 at 450 GeV and 400 GeV, by NA3 at 200 GeV, and by NA60 at 158 GeV. In all fixed-target cases, the EKS98 parameterization was used. The curve is calculated based on octet-to-singlet conversion inside the nucleus. [D. McGlinchey, A. D. Frawley and RV, Phys. Rev. C **87** (2013) 054910.]

Study of J/ψ Centrality Dependence of CNM

RHIC minimum bias (impact-parameter integrated shadowing) d+Au data agrees with EPS09 shadowing and 4 mb absorption cross section

The R_{CP} ratio does not agree with the impact-parameter dependent shadowing calculation at forward rapidity because the peripheral result is overestimated

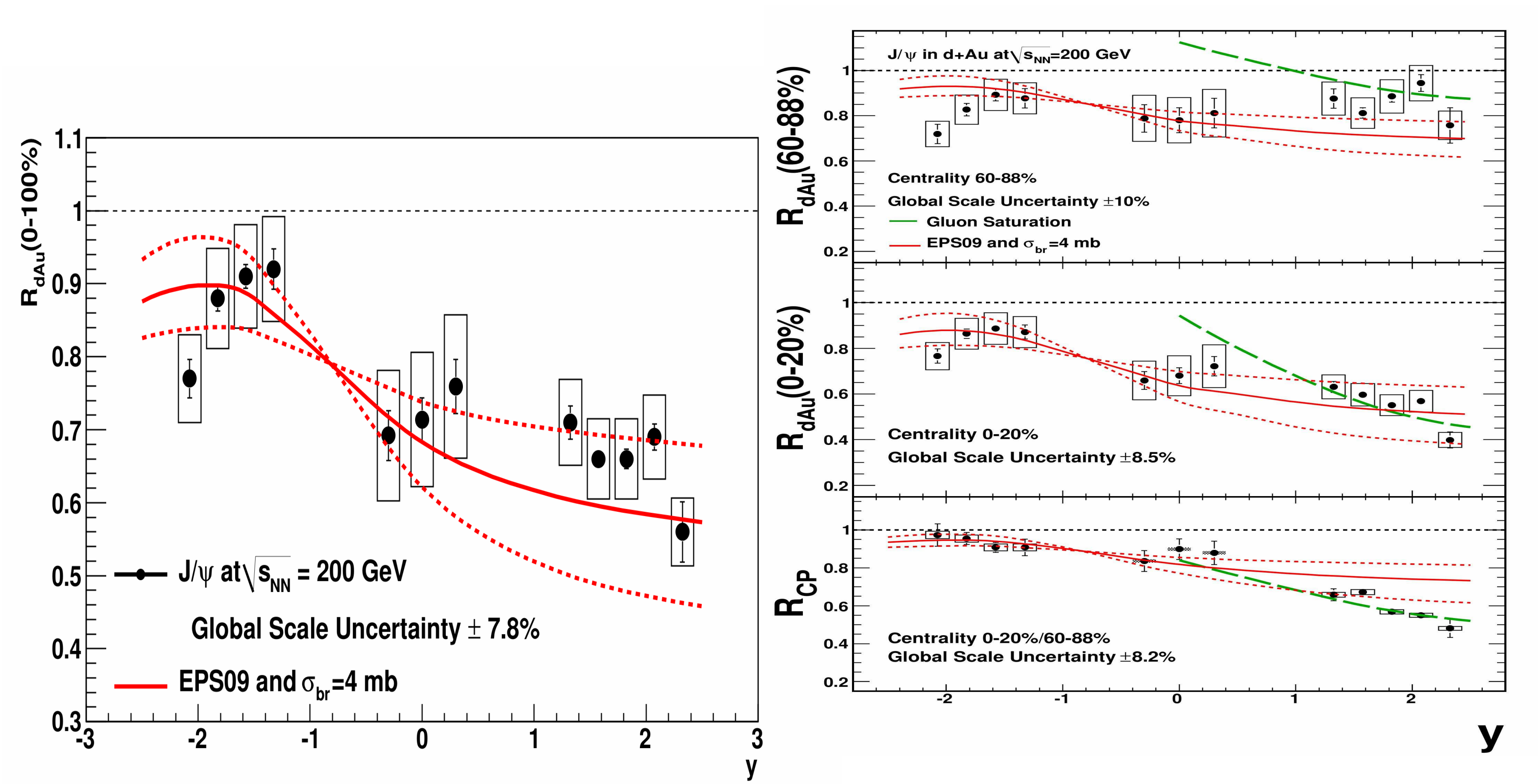

Figure 6: The PHENIX data compared to calculations of EPS09 shadowing including uncertainties and a constant absorption cross section of 4 mb. Left: the minimum bias result. Right: Including impact-parameter dependent shadowing in the 60 − 88% centrality (top) and 0 − 20% centrality (middle) bins. The lower panel shows the central-to-peripheral ratio. The dashed curves shows a gluon saturation calculation.

Centrality Dependence CNM on J/ψ in d+Au Collisions

$$\text{Path Length Dependence}\ \ S^i_\rho(A,x,Q^2,\vec{r},z) = 1 + N_\rho(S^i(A,x,Q^2)-1)(T_A(\vec{r})/T_A(0))^n$$

$$\text{Step function Behavior}\ \ S^i_\theta(A,x,Q^2,r_T) = 1 - (\frac{1-S^i(A,x,Q^2)}{a(R,d)})/(1+\exp(r_T-R)/d))\ ,$$

Shadowing appears to be concentrated in core of Au nucleus

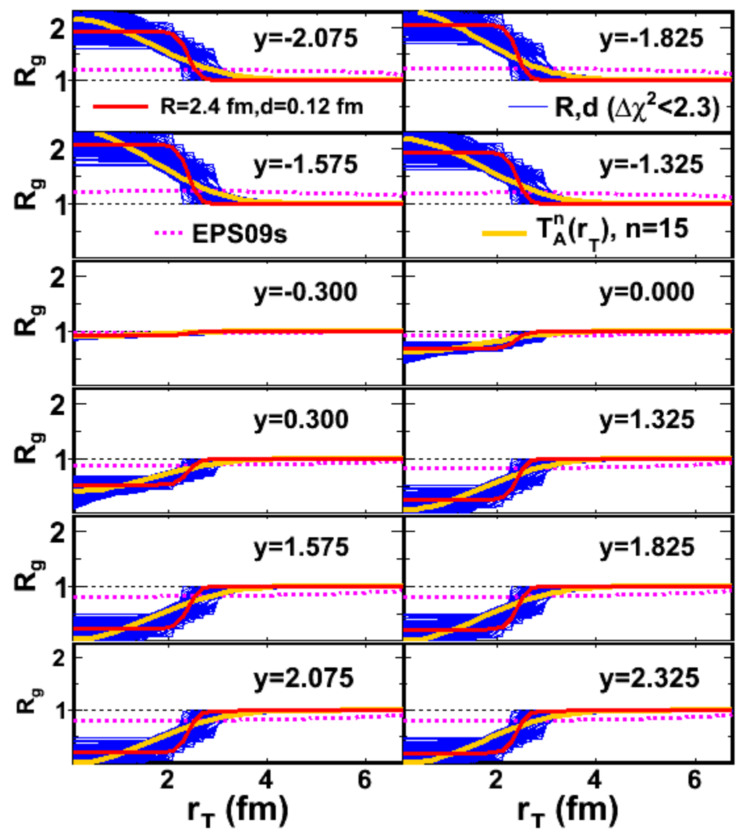

Figure 7: **Transverse radius dependence of gluon shadowing ratio R_g (based on EPS09 NLO) for the PHENIX d+Au rapidity bins. The results compare b-dependence based on path length through the nucleus, $T_A(b)$, and a sharp surface with radius and diffuseness parameters.**

Dependence of Absorption Cross Section on Rapidity and Nuclear Gluon Density Dependence

Effective $\sigma_{\rm abs}$ is a function of rapidity, essentially independent of centrality, exponential absorption has significantly different centrality dependence than shadowing

Forward rise could be due to energy loss effects at larger x_F; backward enhancement in $\sigma_{\rm abs}$ could be related to formation time effects

Smaller difference between EPS09s and ALICE data at the LHC, likely shadowing occurs over more of the nuclear profile, not just the core, at higher energy

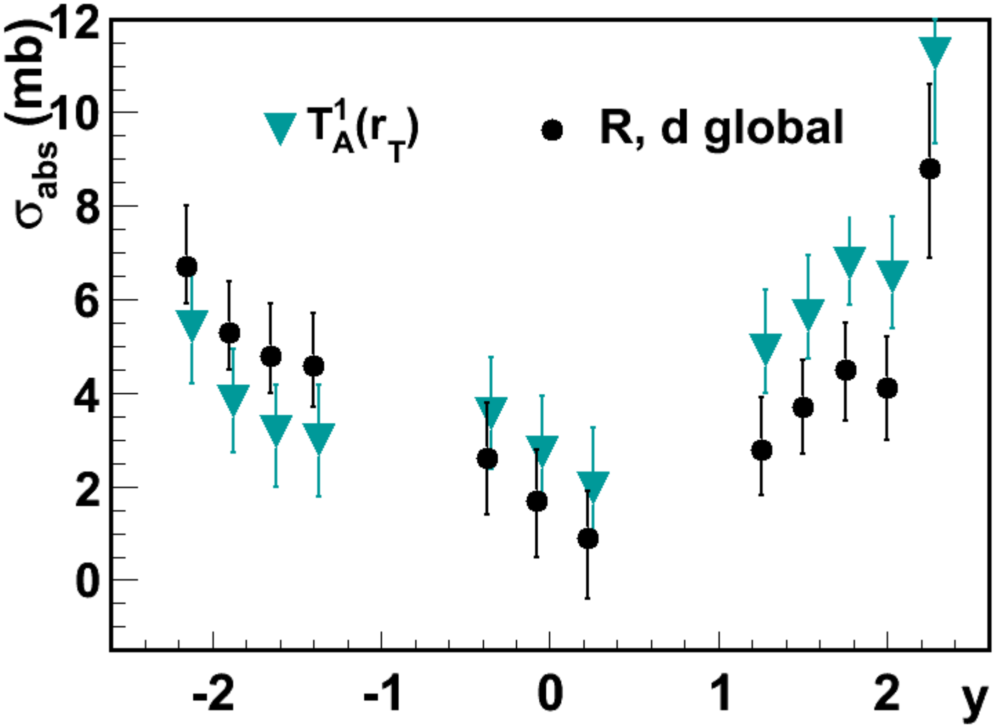

Figure 8: **The rapidity dependence of $\sigma_{\rm abs}$ for two assumptions about shadowing centrality dependence. (McGlinchey *et al.*)**