Improving the J/ψ Production Baseline in *pp* and d+Au Interactions at RHIC and the LHC

R. Vogt and R. E. Nelson (LLNL and UC Davis)
A. D. Frawley and D. McGlinchey (FSU)

We assess the theoretical uncertainties on the inclusive J/ψ production cross section in the Color Evaporation Model using values for the charm quark mass, renormalization and factorization scales obtained from a fit to the charm production data. We use our new results to provide improved baseline comparison calculations at RHIC. We also study the rapidity, and centrality dependence of cold nuclear matter effects on J/ψ production in the CEM.

To Improve J/ψ Baseline in CEM, Start with Open Charm

Charm production parameters based on the FONLL fiducial parameter set: $m = 1.5 \pm 0.2$ GeV, $\mu_{R,F}/m$ with $0.5 \leq \mu_{R,F}/m \leq 2$ and $0.5 \leq \mu_R/\mu_F \leq 2$ with $\{(\mu_F/m, \mu_R/m)\} = \{(1,1), (2,2), (0.5,0.5), (1,0.5), (2,1), (0.5,1), (1,2)\}$ results in large uncertainties at collider energies. Since the same set is used to calculate J/ψ production in the CEM, when this fiducial set is used, the uncertainty on the J/ψ cross section is such that a finite lower bound cannot be set.

To reduce the large uncertainties, we start with NLO total cross section,

$$\sigma_{AB}(\sqrt{s}, m^2) = \sum_{i,j=q,\bar{q},g} \int dx_1\, dx_2\, f_i^p(x_1, \mu_F^2)\, f_j^p(x_2, \mu_F^2)\, \widehat{\sigma}_{ij}(\hat{s}, m^2, \mu_F^2, \mu_R^2) \, ,$$

the highest order with a complete calculation available. We fit the factorization, μ_F, and renormalization, μ_R, scale parameters to the total charm cross section data from fixed-target experiments and RHIC based on $m = 1.27 \pm 0.09$ GeV, the PDG value. The uncertainty band is calculated based on the mass and scale differences added in quadrature,

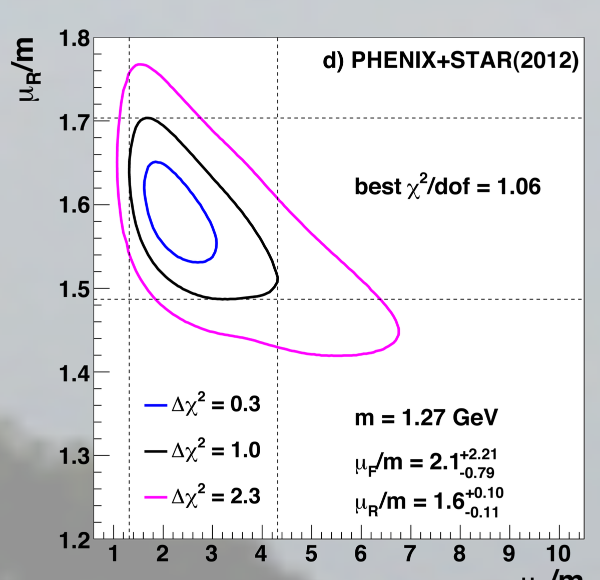
$$\sigma_{\rm max} = \sigma_{\rm cent} + \sqrt{(\sigma_{\mu,{\rm max}} - \sigma_{\rm cent})^2 + (\sigma_{m,{\rm max}} - \sigma_{\rm cent})^2} \, ,$$

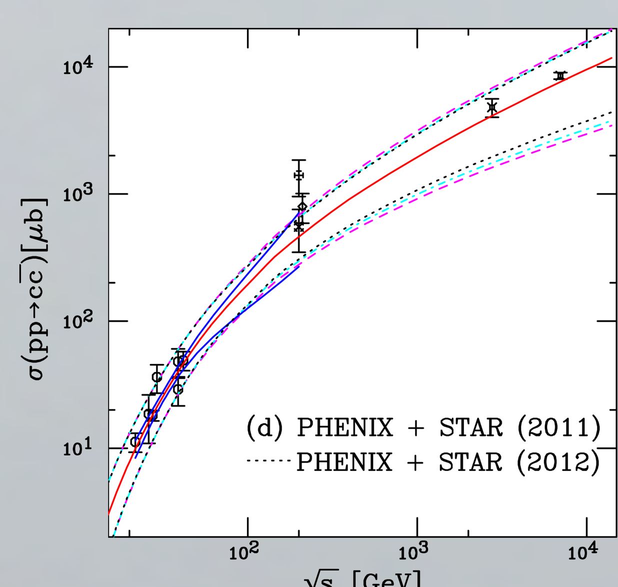
$$\sigma_{\rm min} = \sigma_{\rm cent} - \sqrt{(\sigma_{\mu,{\rm min}} - \sigma_{\rm cent})^2 + (\sigma_{m,{\rm min}} - \sigma_{\rm cent})^2} \, ,$$

The fit results are shown in the table. Our final results are calculated with the more recent STAR data.

Fitted Data	μ_F/m	μ_R/m	χ^2/DOF
fixed-target only	$1.1^{+1.00}_{-0.40}$	$1.6^{+0.13}_{-0.08}$	1.03
+ PHENIX	$1.6^{+1.53}_{-0.56}$	$1.6^{+0.09}_{-0.13}$	1.03
+ STAR (2004)	$2.8^{+2.73}_{-1.35}$	$1.6^{+0.14}_{-0.10}$	1.53
+ STAR (2011)	$2.1^{+2.55}_{-0.85}$	$1.6^{+0.11}_{-0.12}$	1.16
+ STAR (2012)	$2.1^{+2.21}_{-0.79}$	$1.6^{+0.10}_{-0.11}$	1.06

Table 1: The factorization, μ_F/m, and renormalization, μ_R/m, scale uncertainties obtained by fitting subsets of the total charm cross section data with $m = 1.27$ GeV.





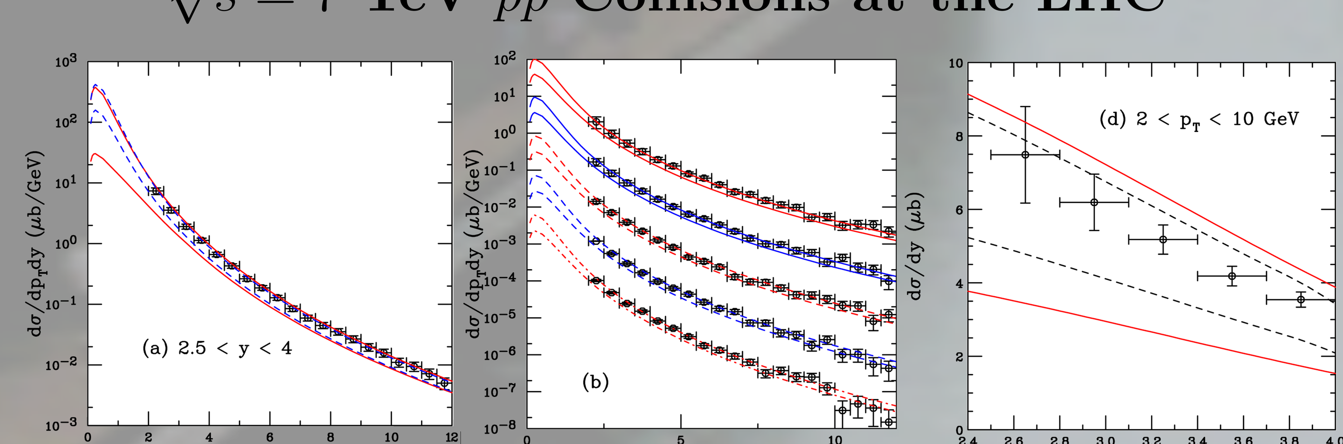
(Left) The χ^2/dof contours for fits including fixed target data as well as the PHENIX and STAR 2012 charm cross sections in 200 GeV pp collisions. The best fit values are given for the furthest extent of the $\Delta\chi^2 = 1$ contours. (Right) The energy dependence of the charm total cross section obtained from fits including the STAR 2011 cross section but excluding the STAR 2004 cross section compared to data. The best fit values are given for the furthest extent of the $\Delta\chi^2 = 1$ contours. The central value of the fit is given by the solid red curve while the dashed magenta curves and dot-dashed cyan curves show the extent of the corresponding uncertainty bands. The dashed curves outline the most extreme limits of the band. The dotted black curves show the difference between the uncertainty bands with the 2011 and 2012 STAR results while the solid blue curves in the range $19.4 \leq \sqrt{s} \leq 200$ GeV represent the uncertainty obtained from the extent of the $\Delta\chi^2 = 2.3$ contour on the left.

The fits are very sensitive to the factorization scale. The fixed-target data require a rather small value of μ_F/m but fail to agree well with collider data. Including PHENIX alone does not give enough tension to the RHIC data while the old STAR cross section required a larger than physical value, $\mu_F/m \sim 3$. The value of μ_F/m changes the slope of the energy dependence. The lower limit of the cross section is more sensitive to μ_F/m than the upper limit because the gluon density is more affected by μ_F/m at lower scales.

The result is not very sensitive to the renormalization scale which is, in fact, rather tightly constrained by the data since it moves the total cross section up and down by a factor.

The predicted LHC cross sections at $\sqrt{s} = 2.76$ and 7 TeV, not included in the fit, are in quite good agreement with the data.

Comparison to Heavy Flavor Decays in $\sqrt{s} = 7$ TeV pp Collisions at the LHC



Our calculations are compared with the ALICE inclusive single muon data from heavy flavor decays at $\sqrt{s} = 7$ TeV. (a) Comparison of the single lepton p_T distributions in the rapidity interval $2.5 < y < 4$ at $\sqrt{s} = 7$ TeV calculated with the FONLL set for charm (solid red) and the fitted set with $m = 1.27$ GeV (dashed black). (b) The contributions to the p_T distributions in (a) divided into rapidity bins, from top to bottom: $2.5 < y < 2.8$ (solid red); $2.8 < y < 3.1$ (solid blue); $3.1 < y < 3.4$ (dashed red); $3.4 < y < 3.7$ (dashed blue); and $3.7 < y < 4$ (dot-dashed red). The top curves are shown at their calculated value, the others are scaled down by successive factors of 10 to separate them. (d) The sum of the contributions to the rapidity distribution are compared with the FONLL set for charm (solid red) and that with $m = 1.27$ GeV (dashed black).

Quarkonium Production in the Color Evaporation Model

The quarkonium production cross section is some fraction, F_C, of all $Q\overline{Q}$ pairs below the $H\overline{H}$ threshold where H is the lowest mass heavy-flavor hadron. Thus the CEM cross section is simply the $Q\overline{Q}$ production cross section with a cut on the pair mass but without any constraints on the final-state color or spin. Color is 'evaporated' through an unspecified process which does not change the momentum. The additional energy needed to produce heavy-flavored hadrons when $\sqrt{\hat{s}} < 2m_H$, is nonperturbatively obtained from the color field in the interaction region.

The direct production cross section of quarkonium state C is

$$\sigma_C^{\rm CEM}(s_{_{NN}}) = F_C \sum_{i,j} \int_{4m^2}^{4m_H^2} ds \int dx_1\, dx_2\, f_i^p(x_1, \mu_F^2)\, f_j^p(x_2, \mu_F^2)\, \hat{\sigma}_{ij}(\hat{s}, \mu_F^2, \mu_R^2) \, .$$

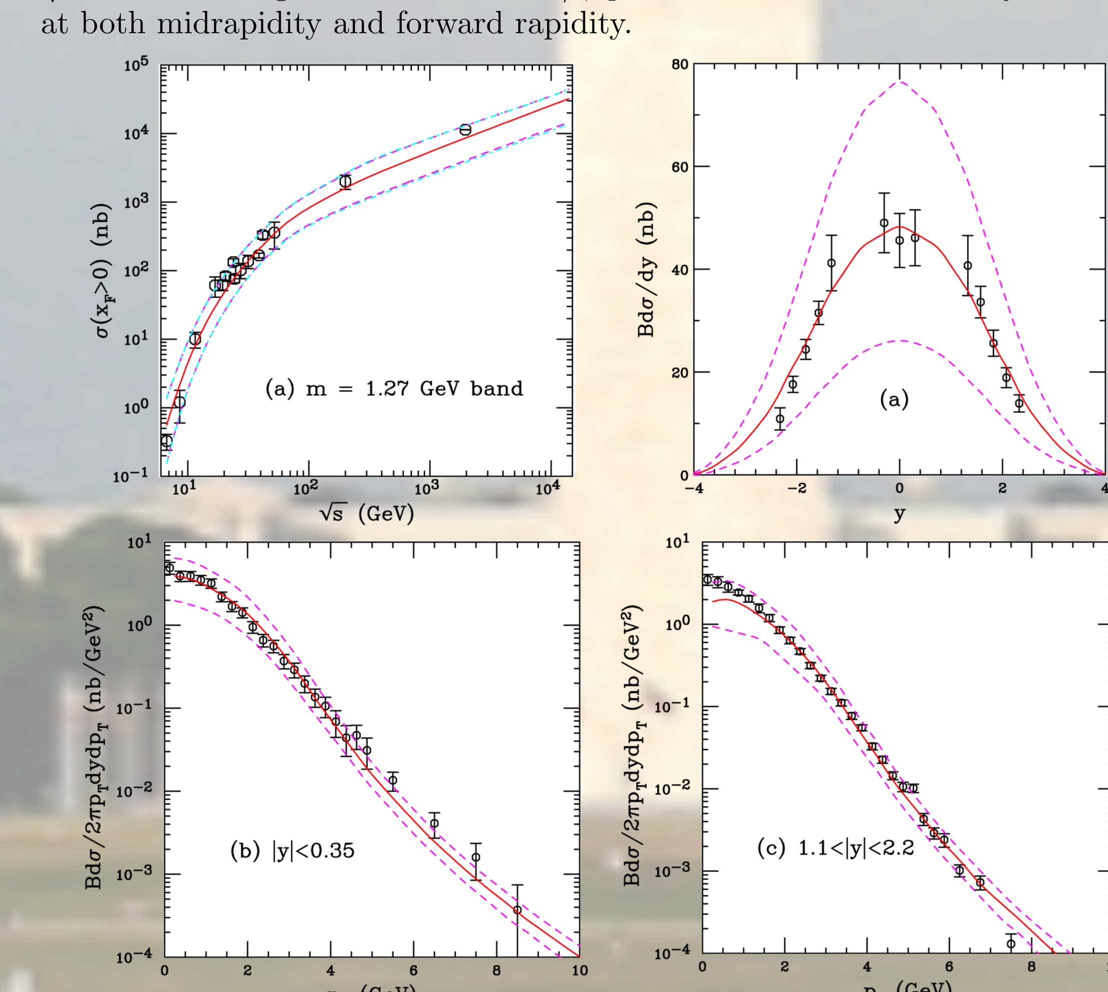
The fraction F_C must be universal so that, once it is fixed by data, the direct quarkonium production ratios should be constant as a function of $\sqrt{s}$, y and p_T.

The data we use to obtain F_C for the J/ψ are from the compilation by Maltoni. The data range from fixed-target experiments with center-of-mass energy $6.8 \leq \sqrt{s} \leq 41.6$ GeV to collider energies at $\sqrt{s} = 52$, 63 and 200 GeV. Our final value of F_C is based on the total cross section data with only p, Be, Li, C, and Si targets to avoid uncertainties due to ignoring any cold nuclear matter effects.

We include transverse momentum broadening, convoluting the Gaussian function $g_p(k_T)$,

$$g_p(k_T) = \frac{1}{\pi \langle k_T^2 \rangle_p} \exp(-k_T^2/\langle k_T^2 \rangle_p) \, ,$$

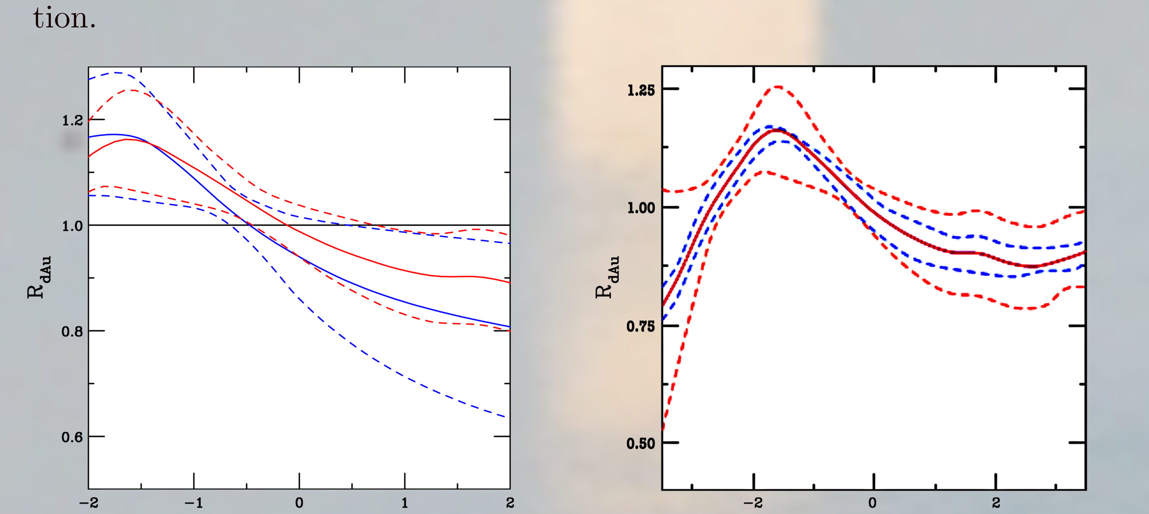
with the parton densities for both hadrons, assuming the x and k_T dependencies in the initial partons completely factorizes. We use $\langle k_T^2 \rangle_p = 1$ GeV^2 for pp collisions The effect of the intrinsic k_T on the J/ψ p_T distribution decreases as $\sqrt{s}$ increases because the average p_T also increases with $\sqrt{s}$. However, the value of $\langle k_T^2 \rangle$ may increase. We find that $\langle k_T^2 \rangle = 1 + (1/12) \ln(\sqrt{s}/20) \approx 1.19$ GeV^2 at $\sqrt{s} = 200$ GeV agrees well with the J/ψ p_T distributions measured by PHENIX at both midrapidity and forward rapidity.



(upper left) The uncertainty band on the forward J/ψ cross section calculated based on the $c\bar{c}$ parameter fit with $m = 1.27$ GeV. The dashed magenta curves and dot-dashed cyan curves show the extent of the corresponding uncertainty bands. The dashed curves outline the most extreme limits of the band. The J/ψ rapidity distribution (upper right) and the midrapidity (lower left) and forward rapidity (lower right) p_T distributions and their uncertainties are compared to PHENIX pp measurements at $\sqrt{s} = 200$ GeV. The correlated and uncorrelated systematic errors are added in quadrature. No additional scaling factor has been applied. The solid red curve shows the central value while the dashed magenta curves outline the uncertainty band. A $\langle k_T^2 \rangle$ kick of 1.19 GeV^2 is applied to the p_T distributions.

Including Cold Nuclear Matter Effects

Cold matter effects are important for quarkonium production in d+Au collisions at RHIC. We have considered two here: nuclear shadowing, an initial state effect, momentum fraction x and scale dependent, and an effective nuclear absorption cross section which breaks up the J/ψ after formation. The absorption cross section parameterizes the amount of cold matter effect left over after shadowing is accounted for. We use the EPS09 NLO shadowing parameterization.



(Left) The difference between LO and NLO gluon shadowing with EPS09 parameterization reflected in the J/ψ ratio $R_{dAu}(y)$. (Right) The variation of $R_{dAu}(y)$ with the 31 EPS09 NLO parameter sets (red) compared to the mass and scale variations calculated with the central EPS09 NLO set (blue). With the new charm cross section fits, the scale dependence is smaller than the shadowing dependence.

Centrality Dependence of Shadowing

Nuclear shadowing is expected to be dependent upon impact parameter. The spatial dependence is usually taken to be proportional to the parton path length through the nucleus

$$M_{\rm shad}(A, x, \mu_F^2, r_T) = 1 - \left(\frac{1 - R_g(x, \mu_F^2)}{a(n)} \right) T_A^n(r_T)$$

where n is an integer, usually assumed to be unity and $a(n)$ is a normalization factor adjusted so that integration over all values of r_T gives the average EPS09 central NLO shadowing result at x and μ_F^2. Recent PHENIX results showed that the impact parameter dependence was stronger than the naive linear assumption. A r_T-dependent analysis by Eskola and collaborators showed that a sum up to $n = 4$ was necessary for a consistent, A-independent result with a dependence slightly stronger than the $n = 1$ assumption.

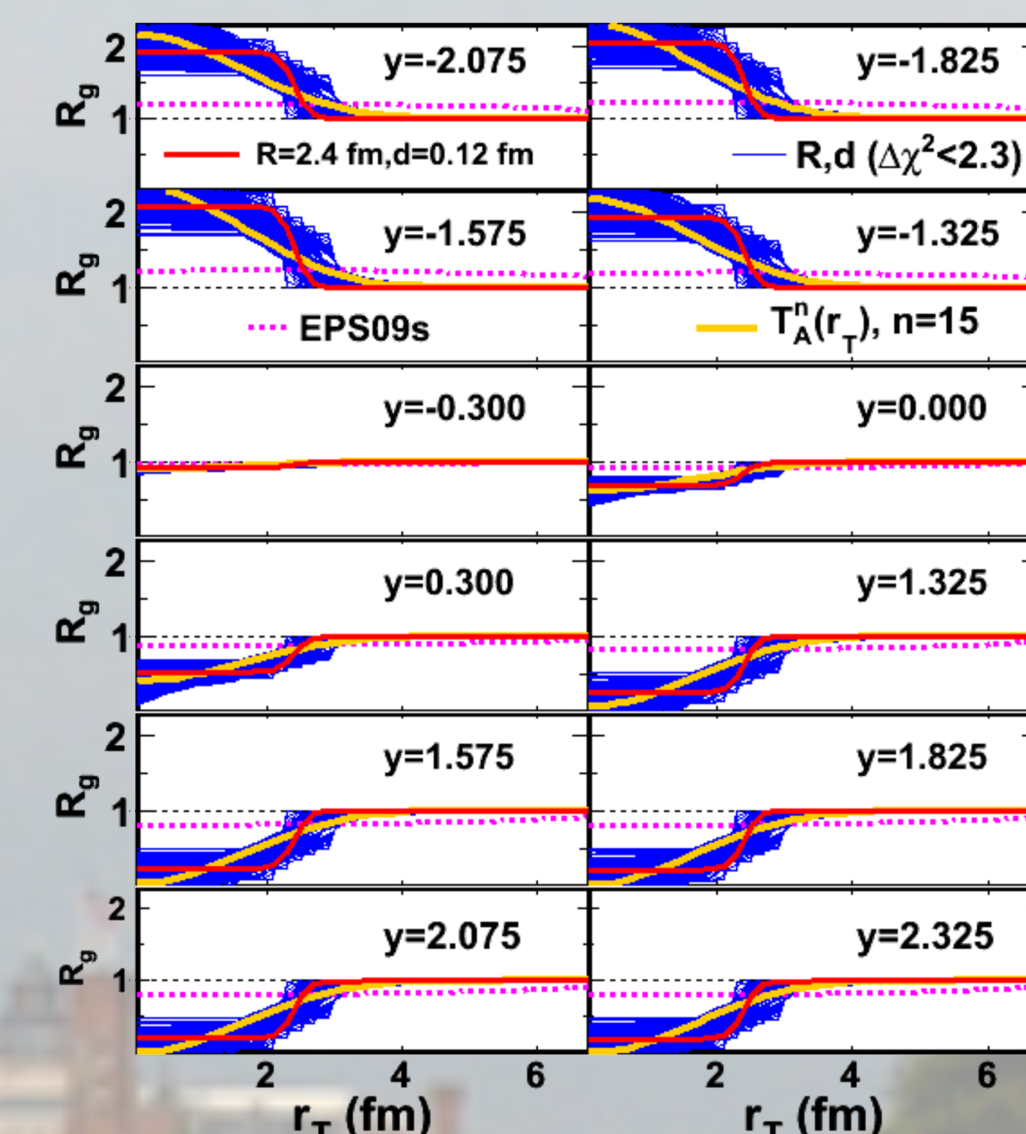
We fit the PHENIX d+Au centrality dependent data and found that a power $n = 15$ was required to fit the PHENIX data with a single value of n. The difference between the measured R_{dAu} and that calculated with EPS09 NLO was made up by introducing a rapidity-dependent absorption cross section $\sigma_{\rm abs}$.

Such strong centrality dependence suggests that a sharp turn on,

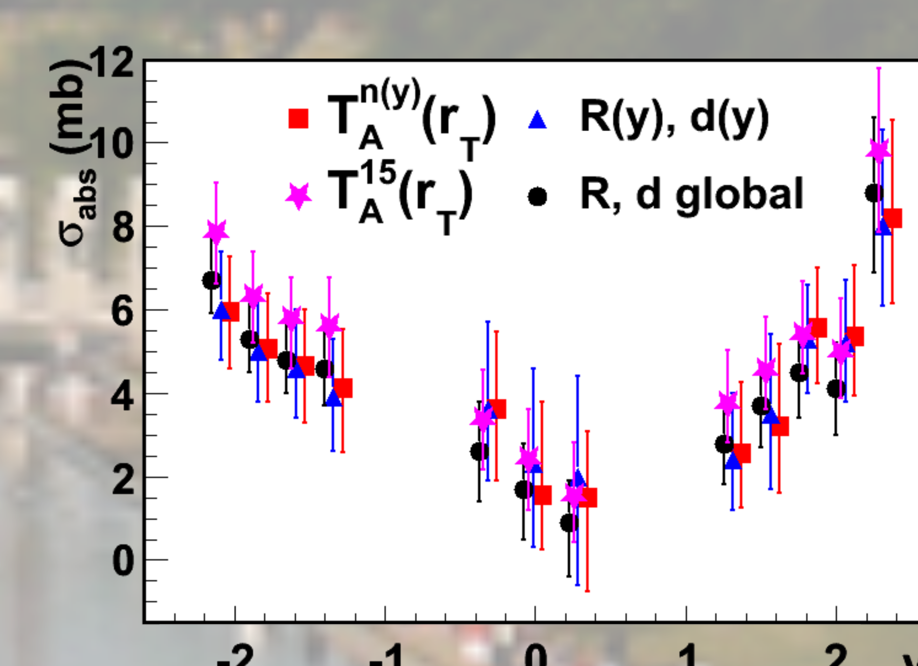
$$M_{\rm shad}(x, \mu_F^2, r_T) = 1 - \left(\frac{1 - R_g(x, \mu_F^2)}{a(R, d)} \right) / (1 + \exp[(r_T - R)/d]) \, ,$$

where R is a 'hot spot' radius parameter and d is the diffuseness of the onset of shadowing, may be more appropriate. A global fit gives $R = 2.4$ fm and $d = 0.12$ fm.

In all cases, the onset is significantly sharper than either that predicted by Eskola and collaborators or the $n = 1$ assumption.



The gluon modification factor R_g at each rapidity measured by PHENIX in 200 GeV d+Au collisions from the best fit global values of R and d (solid red line). We also show the results for values of R and d within the $\chi^2 = 2.3$ fit contour (thin blue lines). The modification from the best fit global analysis of $T_A^n(r_T)$ ($n = 15$) is shown in the solid orange line. The dashed magenta line is the recently released EPS09s impact parameter dependence.



The optimum values and uncertainties on $\sigma_{\rm abs}$ for $M_{\rm shad}(T_A^n)$ with $n(y)$ and $n = 15$ and the 'hot spot' parameterization, $M_{\rm shad}(R, d)$ with $R(y)$, $d(y)$ and global values of R and d. For clarity, the rapidity values for each fit are slightly offset.

Summary

We have obtained a new parameter set for the analysis of open charm and charmonium production, narrowing the uncertainties on the calculations. The results agree well with present data.

We have also made a preliminary study of the cold nuclear matter effects at NLO with this parameter set.

Finally, we have investigated the centrality dependence of shadowing in d+Au collisions at RHIC. We find a much stronger centrality dependence both than previously assumed and with the new EPS09s dependence. This result is in accord with the 'hot spot' assumption akin to saturation effects. However, since we find the same behavior at backward rapidity, the results suggest that shadowing effects are concentrated in the nuclear core rather than throughout the nuclear volume.

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