

Quantifying Cold Nuclear Matter Effects on J/ψ production at RHIC

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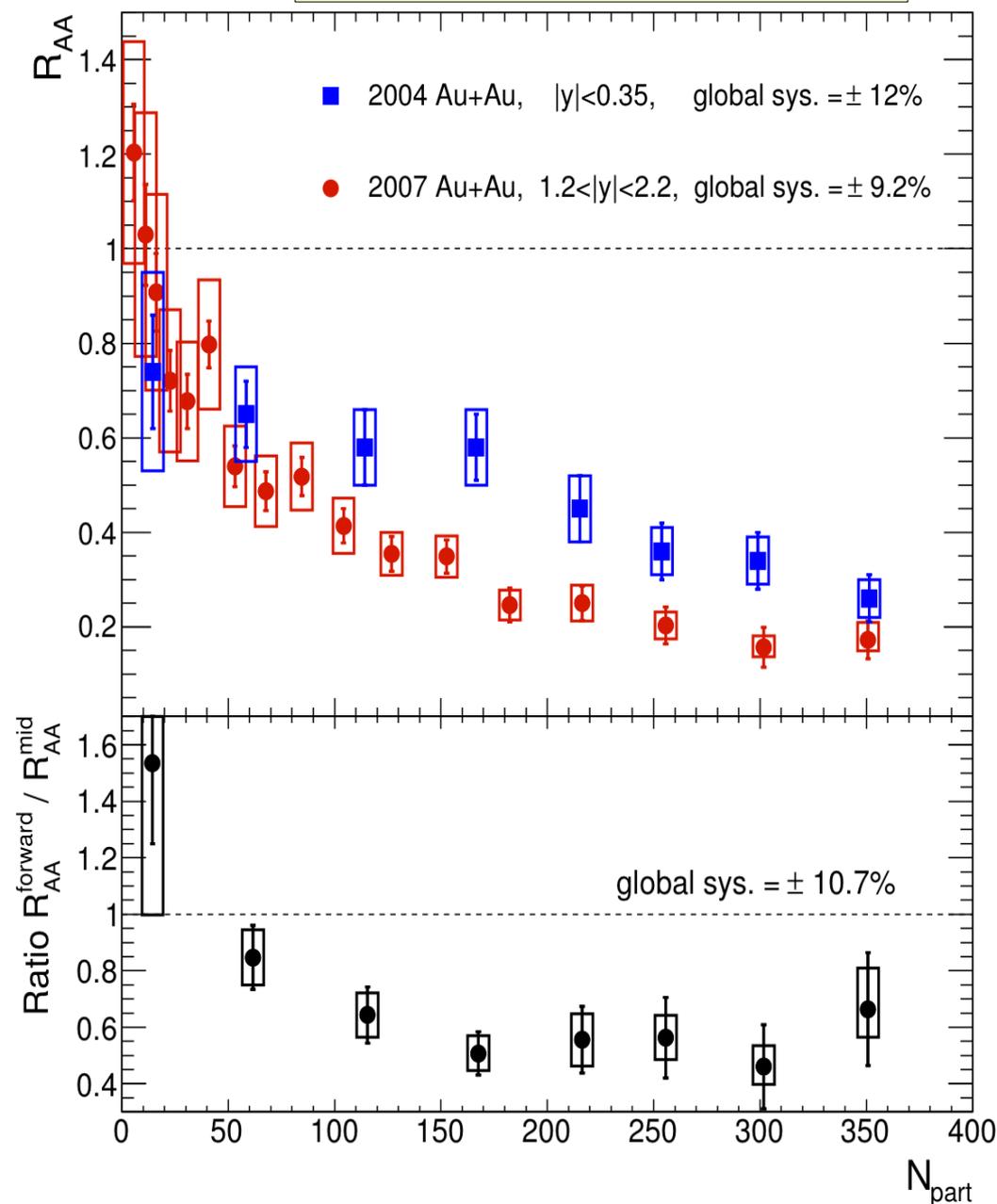
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PHENIX has J/ψ data from $\sqrt{s_{NN}}=200$ GeV Au+Au collisions in the rapidity ranges $|y|<0.5$ and $1.2<|y|<2.2$.

Shown here are the midrapidity data from Run 4. The forward-backward rapidity data are recently released Run 7 results.

The stronger suppression at forward rapidity is a well known result.

We have been working for some time now on quantifying the **cold nuclear matter contributions** to the Au+Au R_{AA} .

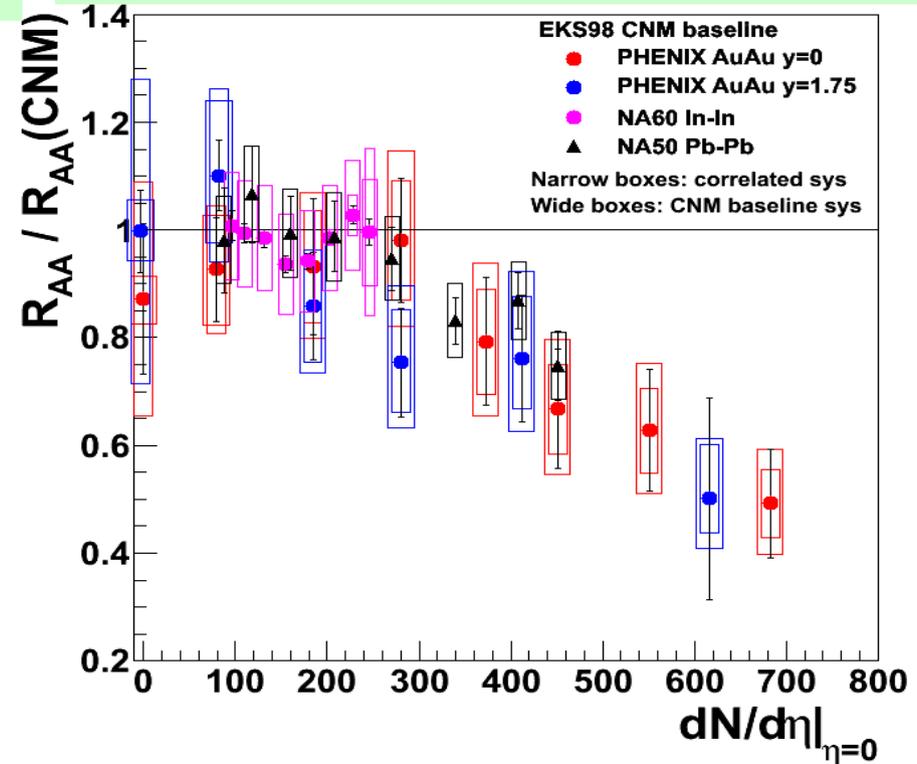
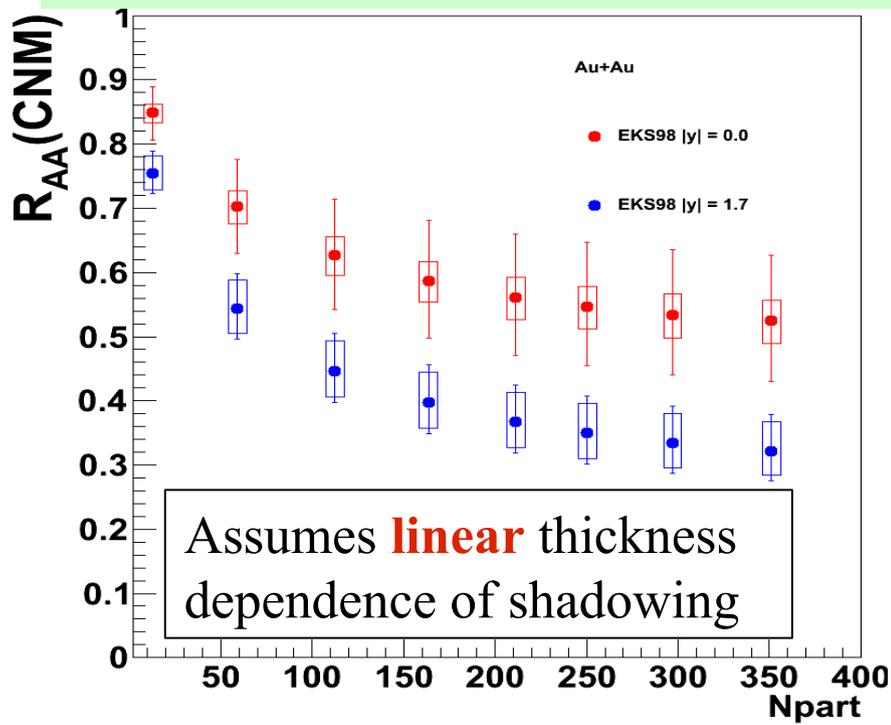


History: Cold nuclear matter R_{AA} – first attempts

Both PHENIX d+Au and NA60 p+A data at 158 GeV have been used to estimate cold nuclear matter contributions to R_{AA} .

Predicted Au+Au CNM R_{AA} from Glauber model, R. Vogt EKS98 calculation + σ_{breakup} fitted to preliminary PHENIX d+Au R_{CP} (Frawley, INT 2009)

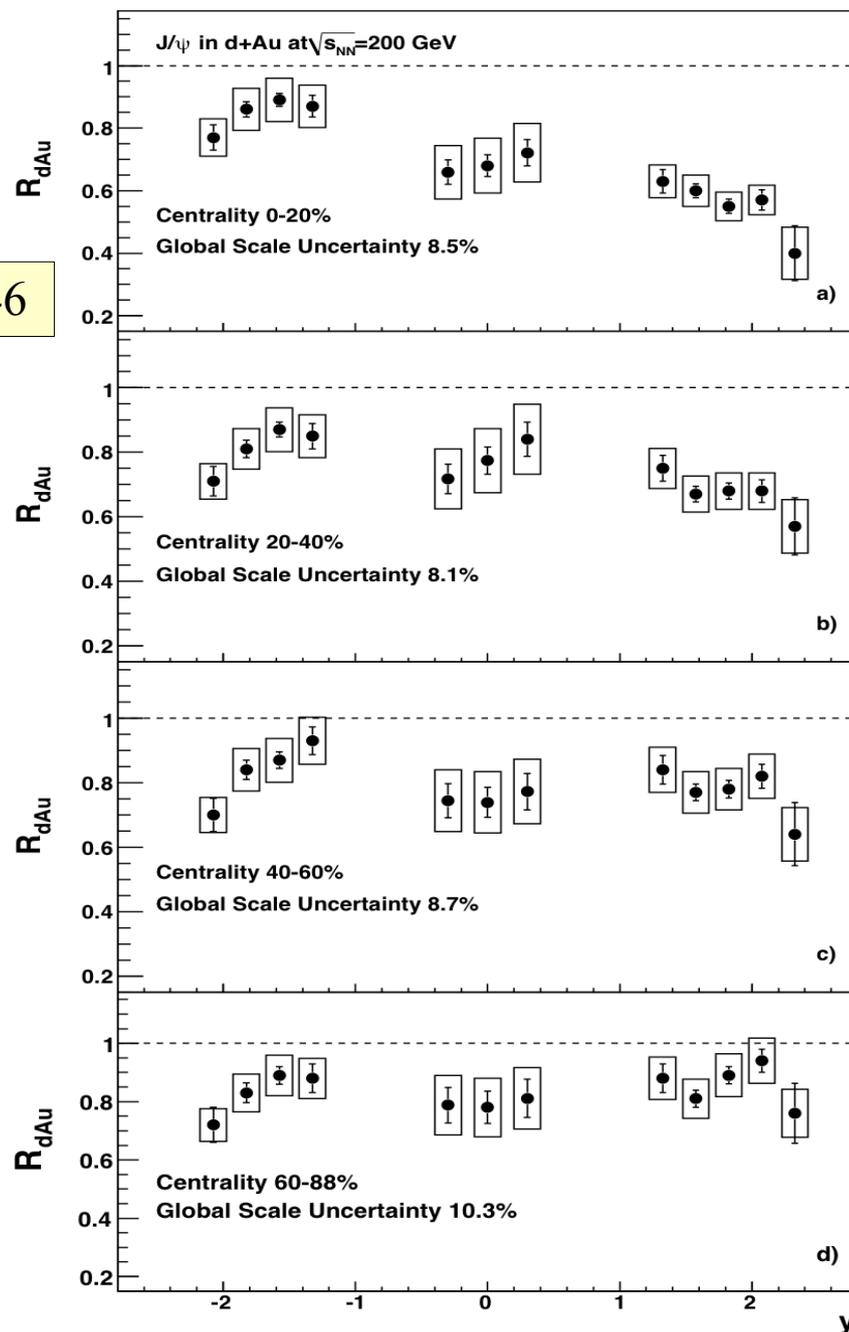
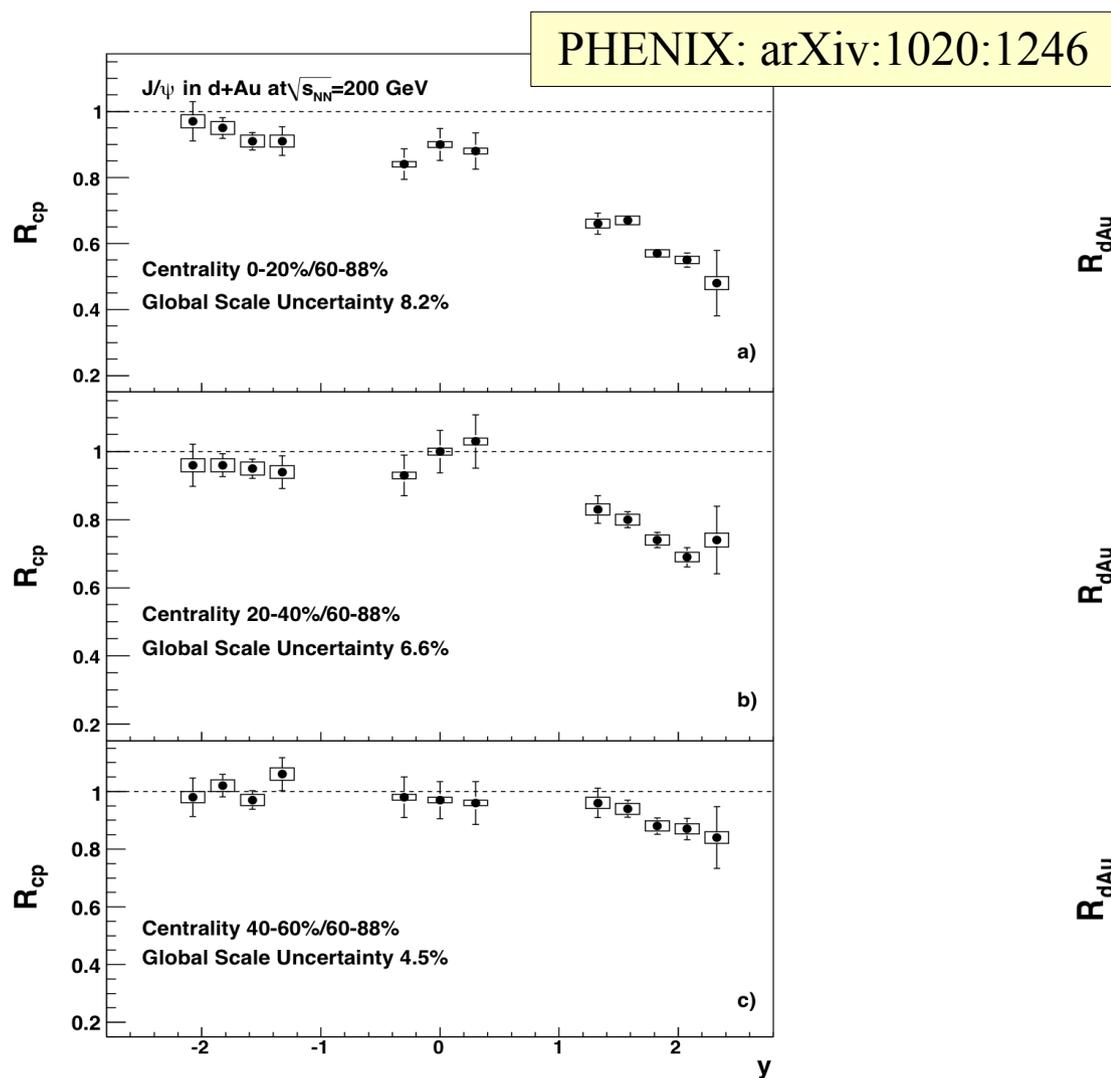
Comparison of PHENIX Au+Au $R_{AA}/R_{AA}(\text{CNM})$ with similar data from NA60 for In-In and Pb-Pb (NA60, arXiv:0907.5004) plotted vs multiplicity.



The PHENIX data used for this were preliminary R_{CP} data

PHENIX run 8 d+Au data set

Final PHENIX d+Au J/ψ results from Run 8 are now released. These provide R_{dAu} vs rapidity in four centrality bins.



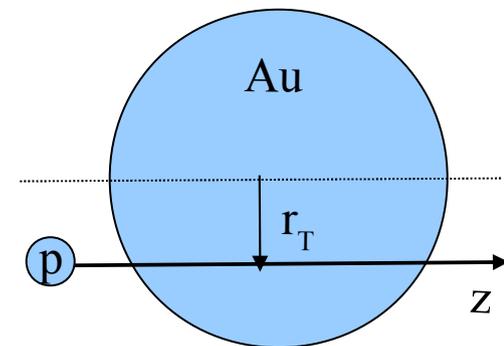
Define nuclear thickness

I need to define the longitudinal density integrated nuclear thickness in Au at impact parameter r_T . It has units fm^{-2} :

$$\Lambda(r_T) = \int dz \rho(z, r_T)$$

Where z is the longitudinal distance in the projectile direction and $\rho(z, r_T)$ is the nuclear density at z and r_T , obtained from a Woods Saxon distribution.

To calculate the effect of σ_{br} , **start the integral** at z_I , the production point for the J/ψ precursor.



A surprising result

R_{dAu} (0-100%) vs R_{CP} (0-20%/60-98%) at 12 rapidities.

PHENIX: arXiv:1020:1246

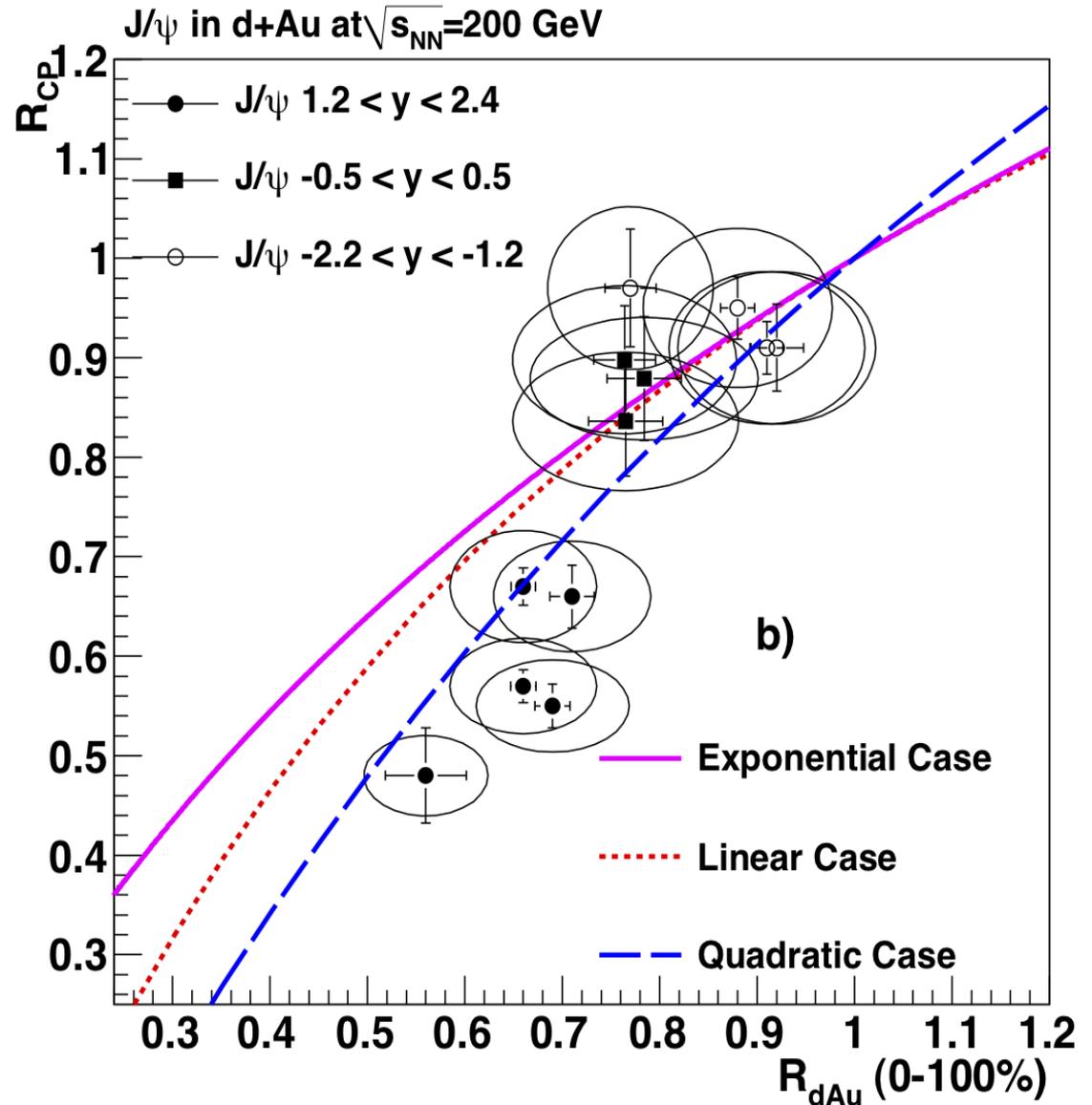
Simple mathematical forms for the modification vs nuclear thickness, in a Glauber model.

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

$$M(r_T) = 1 - a\Lambda(r_T)$$

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

The forward rapidity data points are not consistent with even a pure quadratic thickness dependence.

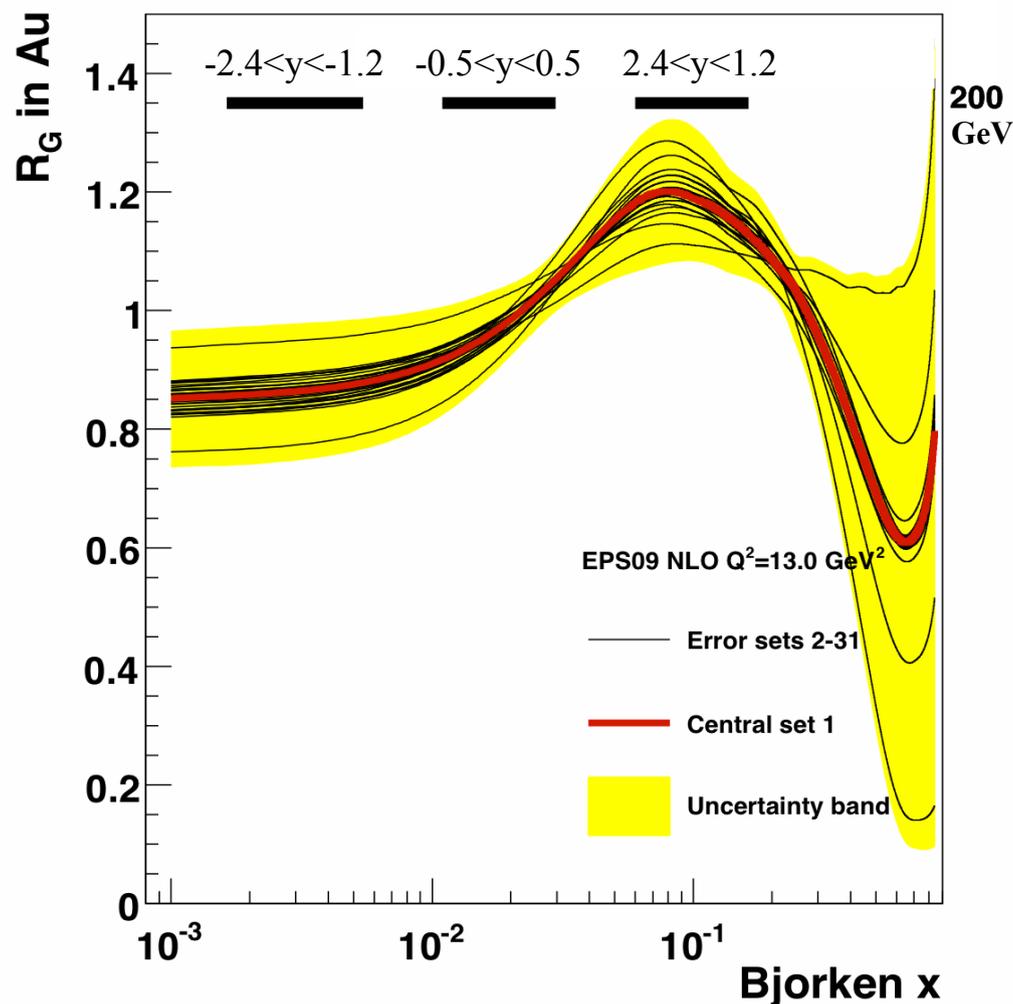


Shadowing: R_G for J/ψ production at RHIC

EPS09 **gluon** modification vs x at $Q^2 = 13$ ($M^2 + \langle p_T \rangle^2$ for the J/ψ).

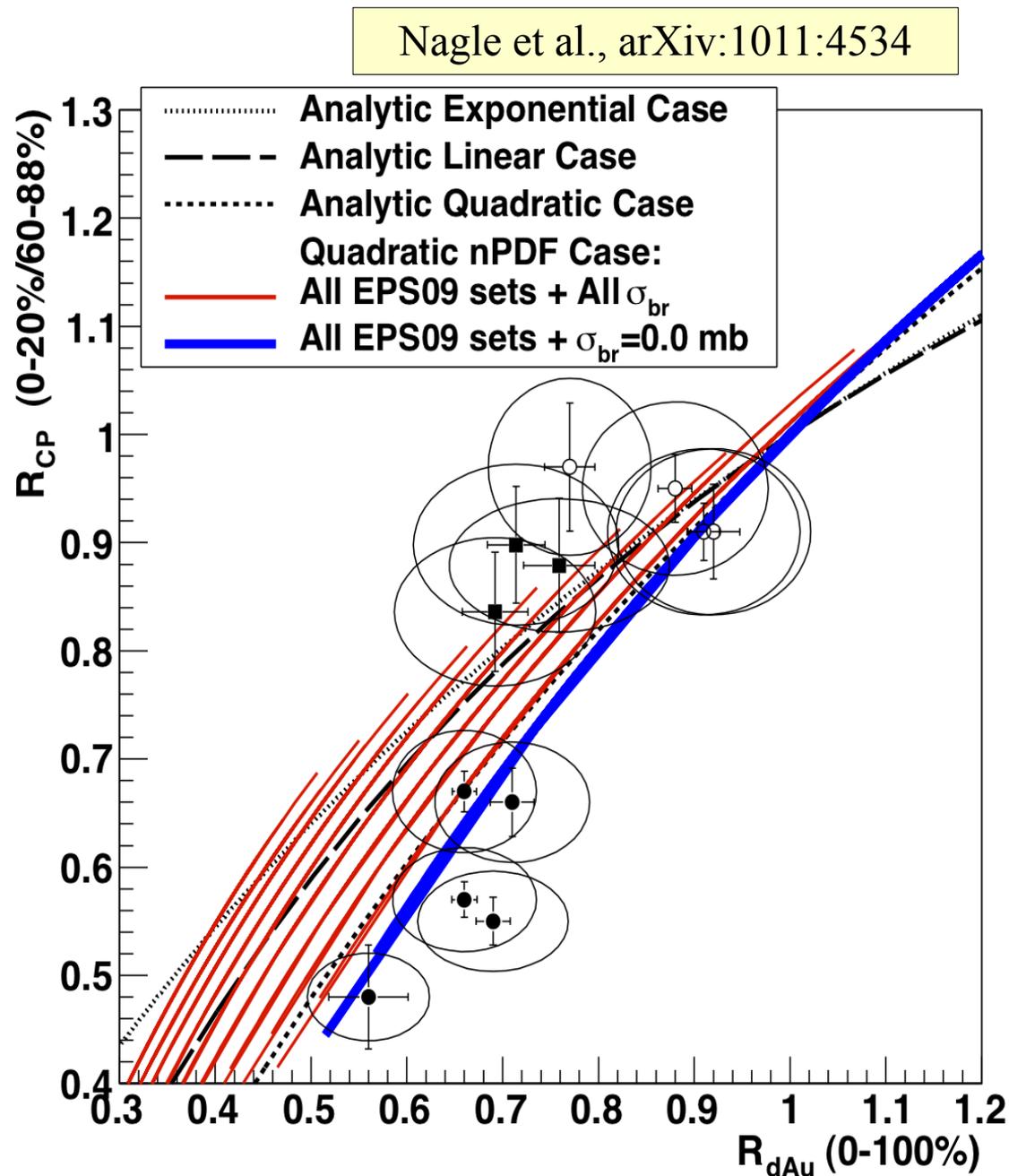
It will be important later to know that the input DIS and $p+A$ data have no impact parameter information - **the modification is averaged over the nucleus.**

The approximate **x ranges** sampled by PHENIX at 200 GeV are shown.



This shows a calculation using EPS09 with a quadratic thickness dependence plus breakup cross sections varying from **0-20 mb** in 2 mb steps.

A significant breakup cross section worsens agreement with the data at $y > 1.2$.



How to proceed?

Explore what the data want by fitting the centrality dependence **independently** at all 12 rapidities.

At each rapidity, try a shadowing power of **1-50**, and optimize σ_{br} for each power.

$$M(r_T) = 1 - aA(r_T)^n$$

Where the normalization factor a is set to produce the EPS09 modification when integrated over all centrality.

Choose the power and σ_{br} to minimize χ^2 .

Assign an **uncertainty** corresponding to where χ^2 increases by 1.

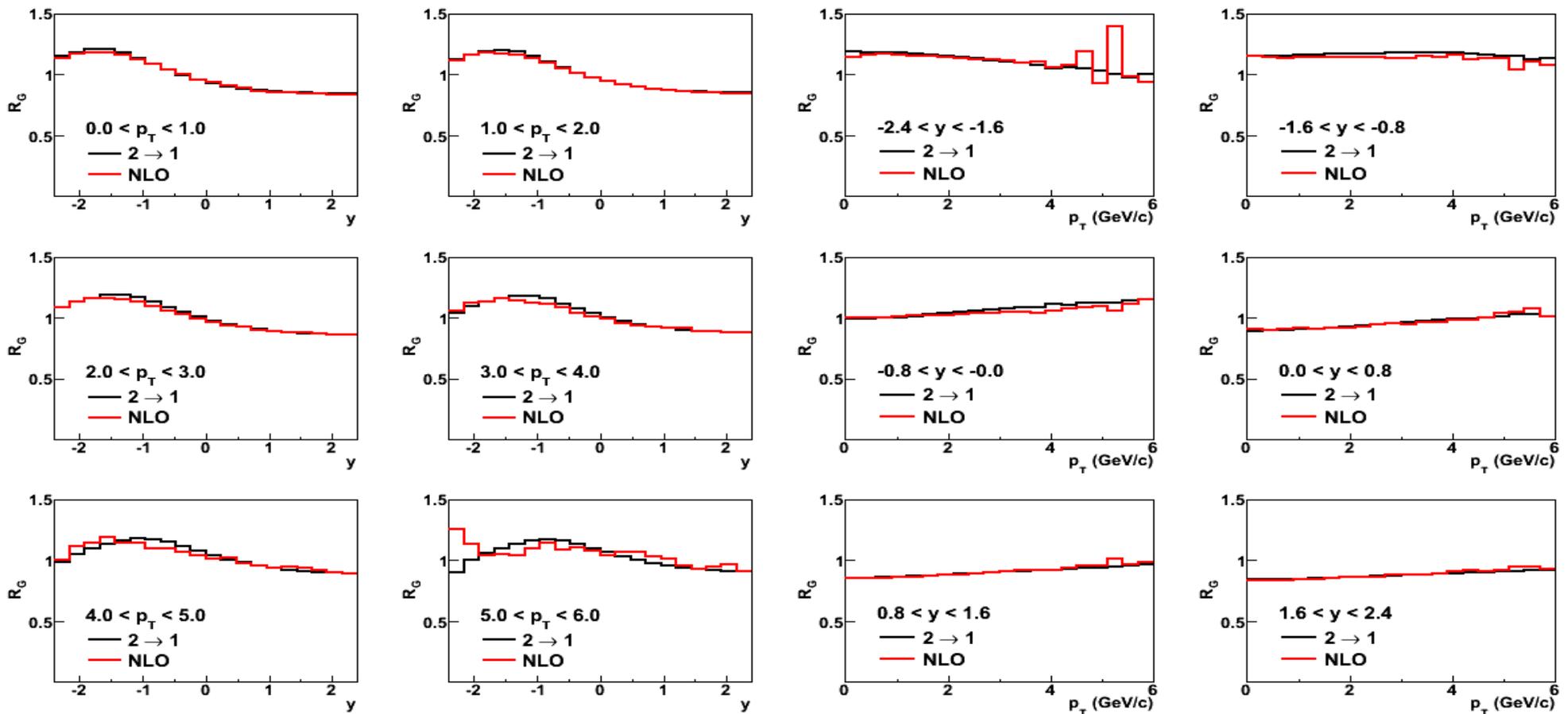
How to get x_2 and Q^2 for EPS09?

We assume **2→1 kinematics**.

Not quite correct - but R_G obtained with x_2 and Q^2 from an NLO calculation by Ramona is very similar.

$$x_2 = \frac{\sqrt{M_J^2 + p_T^2}}{\sqrt{s_{NN}}} e^{-y}$$

$$Q^2 = M_{J/\psi}^2 + p_T^2$$

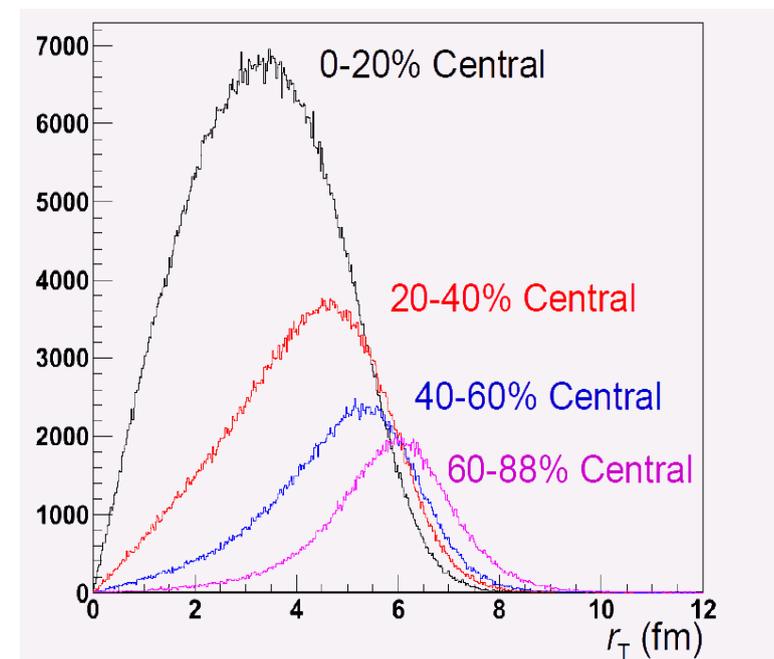
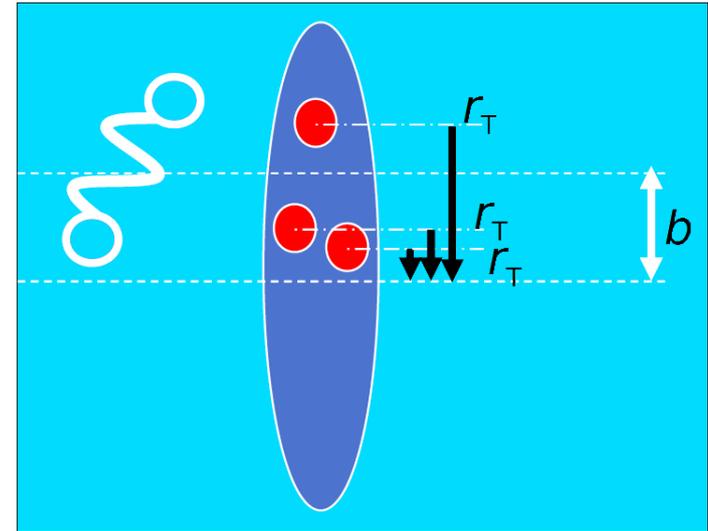


Fit the d+Au data using a Glauber model

Implement **shadowing** + σ_{br} nuclear modification in a Glauber model of the d+Au collision:

- Throw a d+Au collision
- Assign it to a **centrality** bin
- For each NN collision:
 - Use r_T to calculate the “thickness” Λ
 - Choose p_T from the p+p distribution.
 - Calculate x_2 and Q^2 for each p_T, y
 - Use Λ to get shadowing
 - Use $\Lambda(z_1)$ to calculate breakup
- Calculate the average R_{dAu} at each y

Can then vary σ_{br} to **optimize** χ^2 .



A comment on fitting

For fitting the centrality dependence we use a modified χ^2 that takes into account both the statistical and systematic uncertainties of the data. For a sum over **centrality bins i** , we use:

$$\bar{\chi}^2 = \sum \frac{[R_{dAu_i} + \epsilon_{B_i} \sigma_{B_i} + \epsilon_C \sigma_{C_i} - \mu_i(n, \sigma_{br})]^2}{\sigma_{A_i}} + \epsilon_B^2 + \epsilon_s^2 + \epsilon_C^2$$

$$\bar{\sigma}_{A_i} = \sigma_{A_i} \frac{(y_i + \epsilon_{B_i} \sigma_{B_i} + \epsilon_C \sigma_{C_i})}{y_i}$$

$$\epsilon_{B_i} = \epsilon_B + \epsilon_s$$

σ_A = point-to-point uncorrelated
 σ_B = point-to-point correlated
 σ_A = global systematic

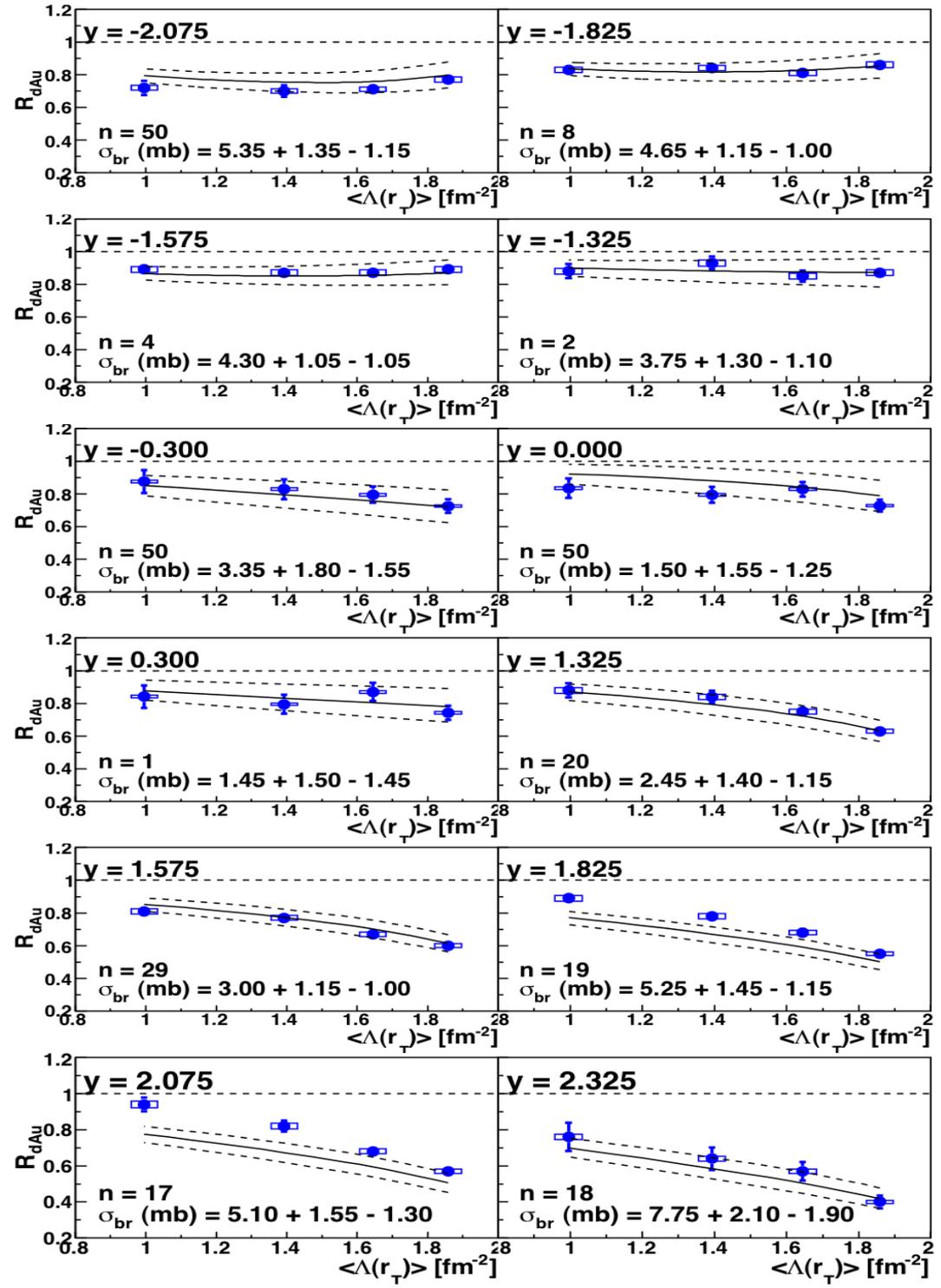
Where R_{dAu_i} is the data point, $\sigma_{A_i(B_i, C_i)}$ are the type A(B,C) uncertainties on the data point, $\mu_i(n, \sigma_{br})$ is the model calculation for the trial values of n and σ_{br} .

The fit procedure includes moving the data points by a fraction $\epsilon_{B(C)}$ of the systematic uncertainties $\sigma_{B(C)}$. A penalty of $\epsilon_{B(C)}^2$ is taken whenever this is done. The quantity ϵ_s accounts for possible correlations/anti-correlations in the type B systematic.

Fits at all 12 rapidities

Note that because of the way the **systematic uncertainties** are included in the modified χ^2 , it is possible that the best fit will be offset from the data points vertically.

The global uncertainty is $\sim 10\%$.



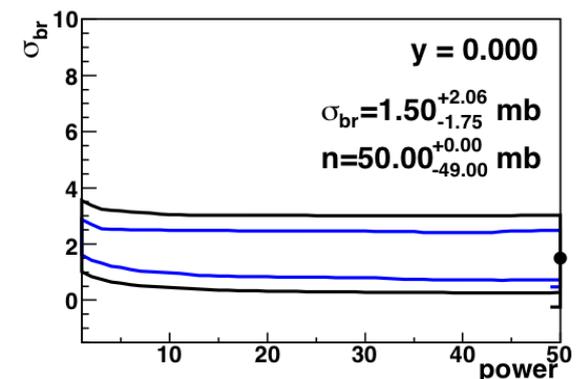
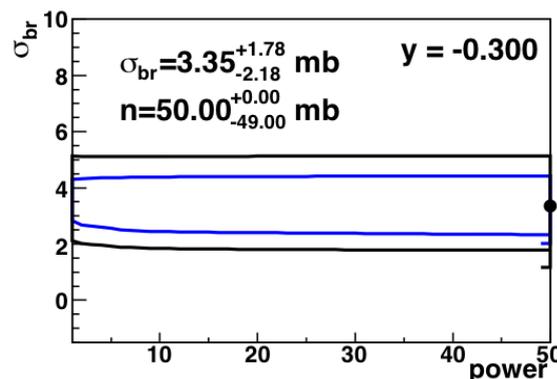
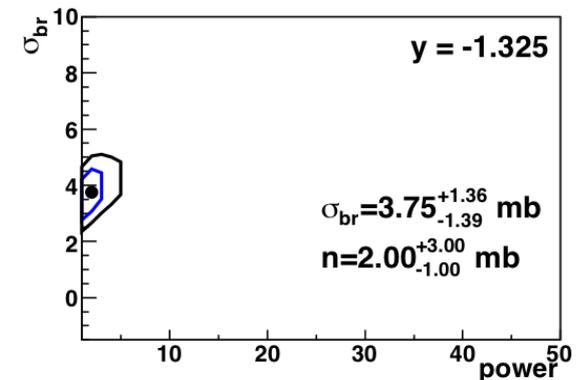
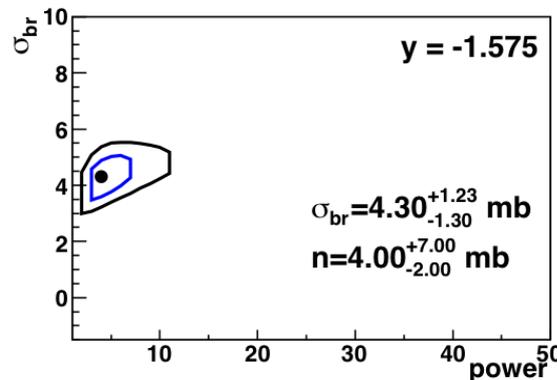
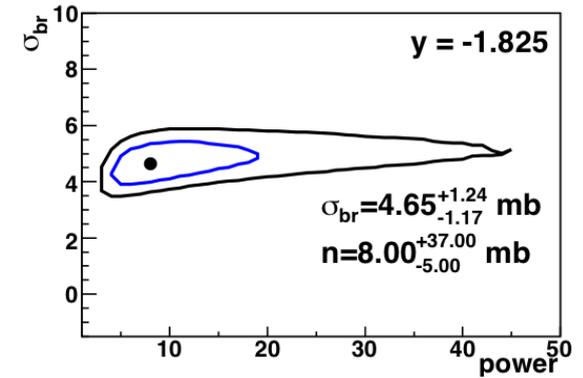
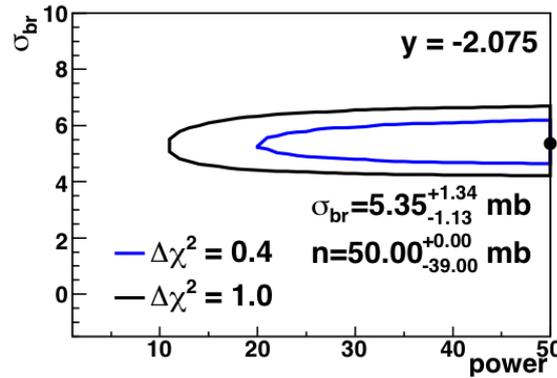
Contours of the modified χ^2 ($y \leq 0$)

The point shows the optimum combination of σ_{br} and n at each rapidity.

The black contour line corresponds to $\Delta\chi^2 = 1$.

The **uncertainties** quoted on each parameter correspond to the maximum extent of the $\Delta\chi^2 = 1$ line for that parameter.

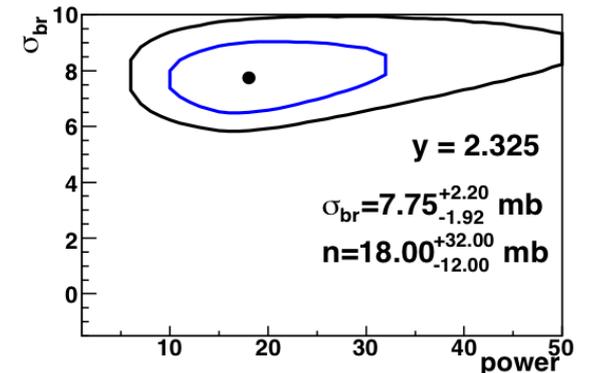
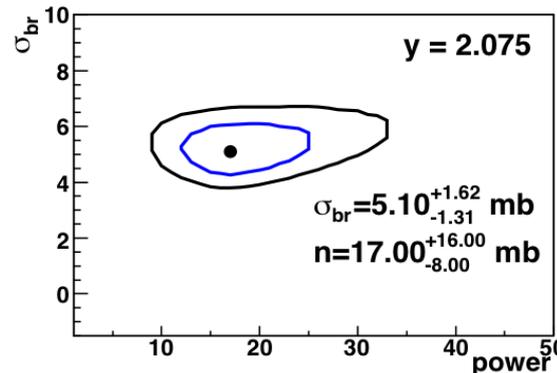
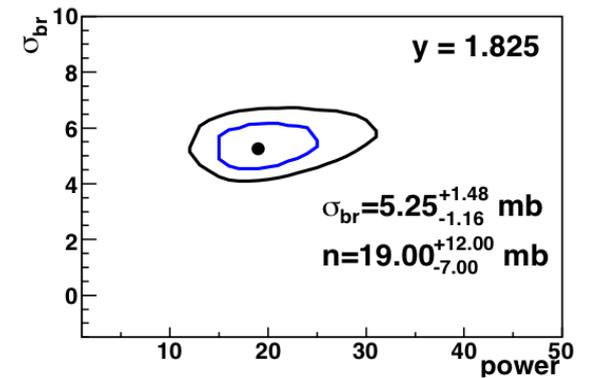
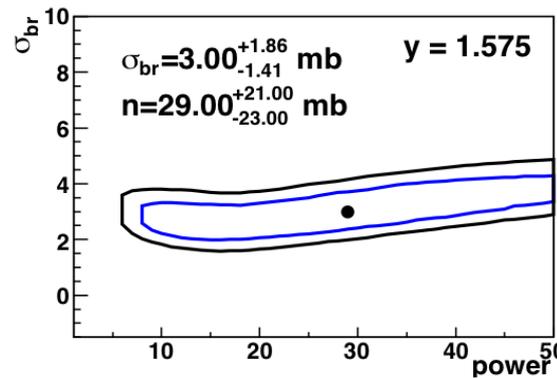
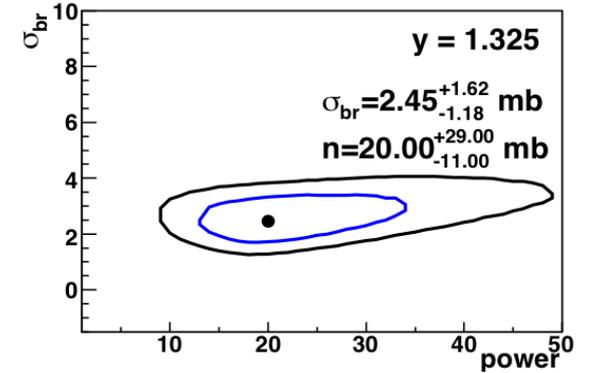
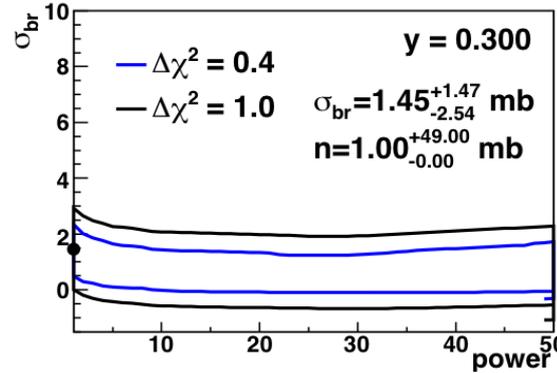
The EPS09 modification is relatively small at mid rapidity, and thus the power is poorly defined there.



Contours of the Modified χ^2 ($y > 0$)

Again, the EPS09 modification is relatively small at mid rapidity, and thus the power is not well defined there.

But a large shadowing power is preferred at all forward rapidities.



Summary of the best fit parameters

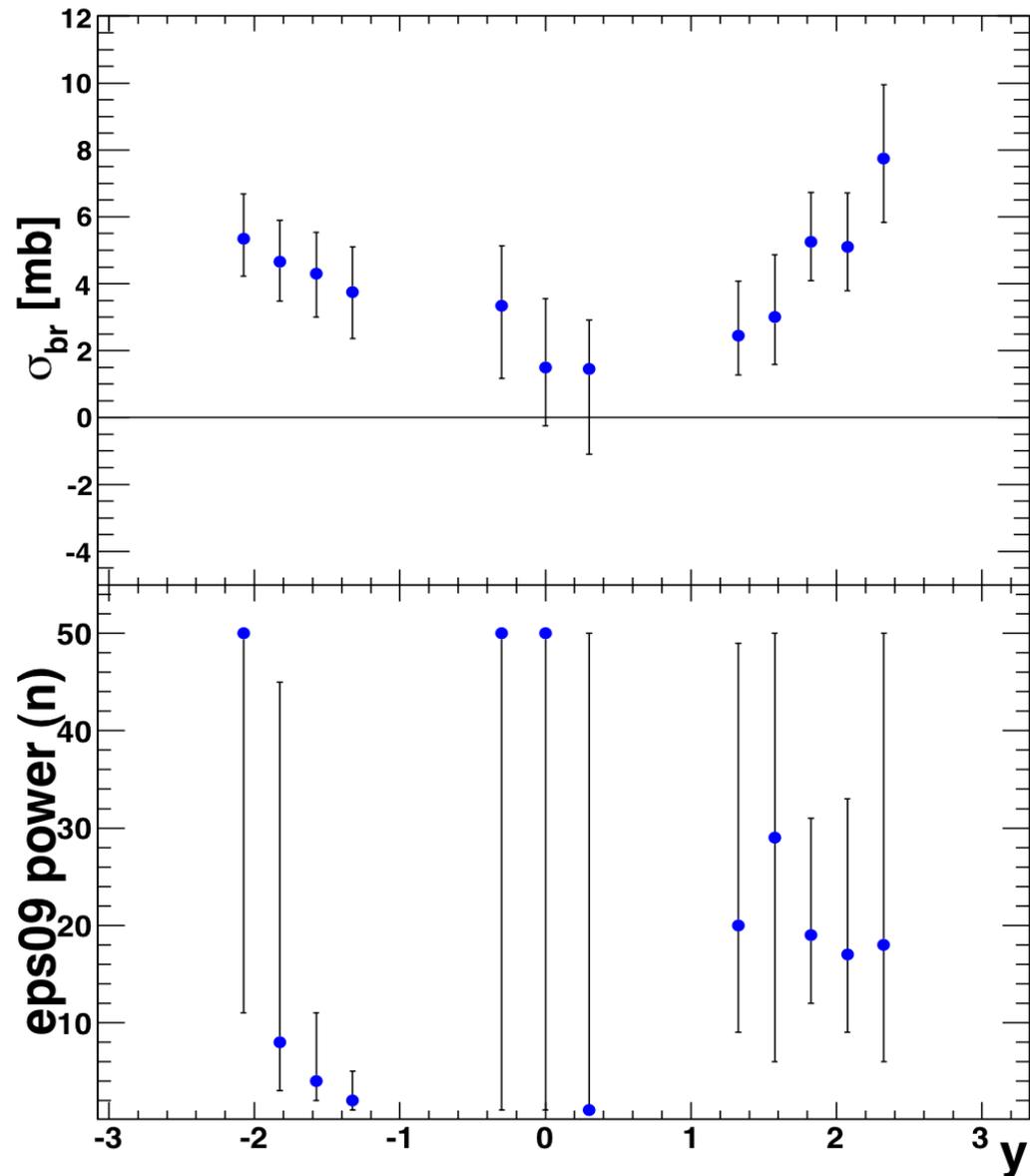
Optimum values for σ_{br} and the power n vs rapidity.

Uncertainties are the $\Delta\chi^2 = 1$ maximum extent.

The mid rapidity σ_{br} values of ~ 2 mb are consistent with previous estimates.

It is interesting that σ_{br} **increases** at forward and backward rapidity.

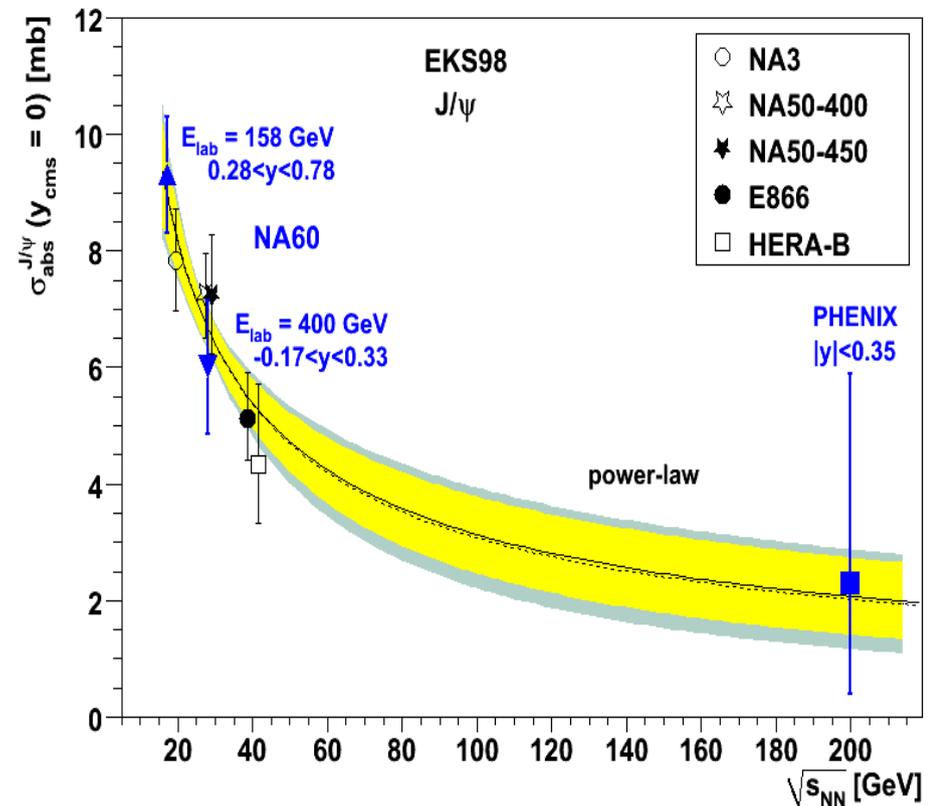
Later, we will see this is true even if n is forced to be the same at all y values.



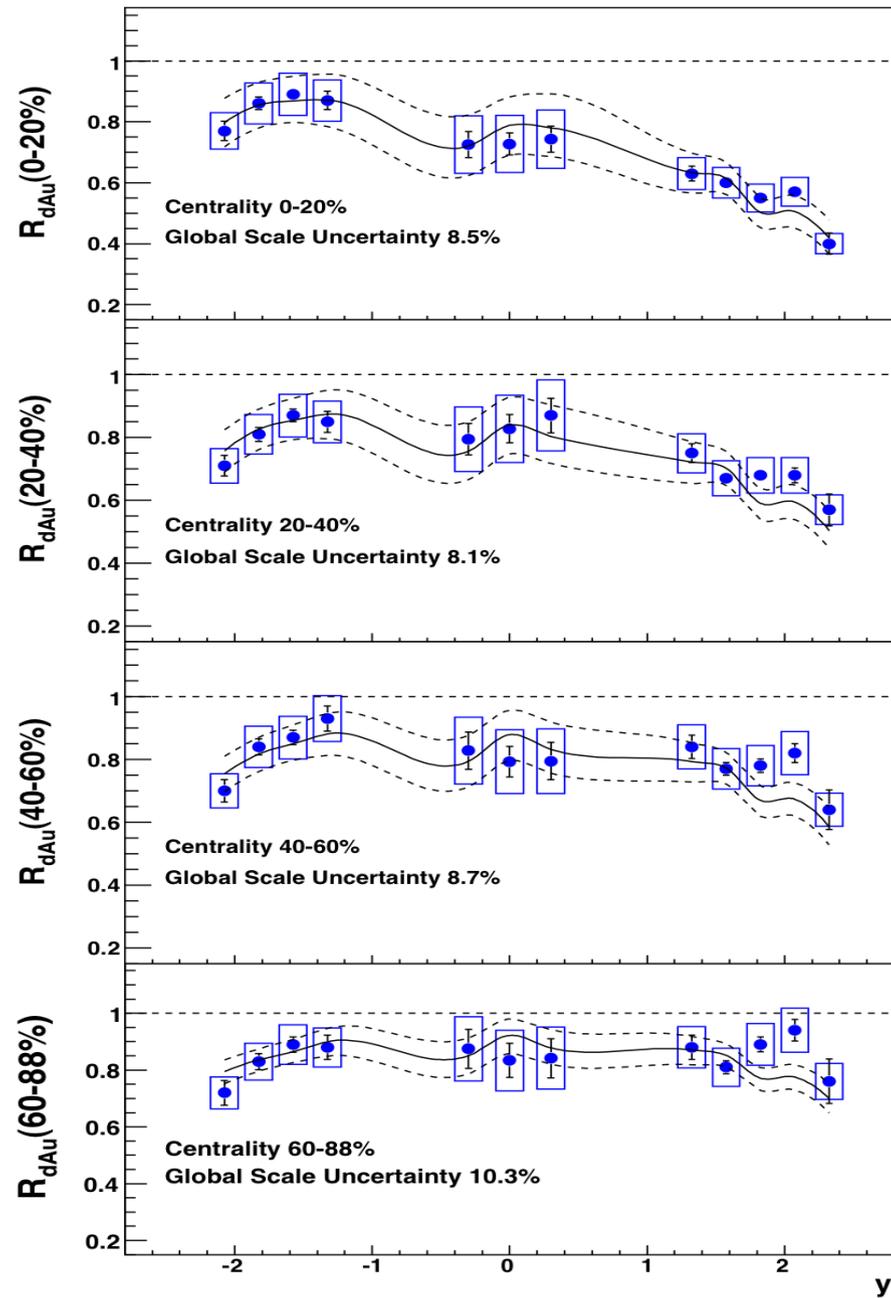
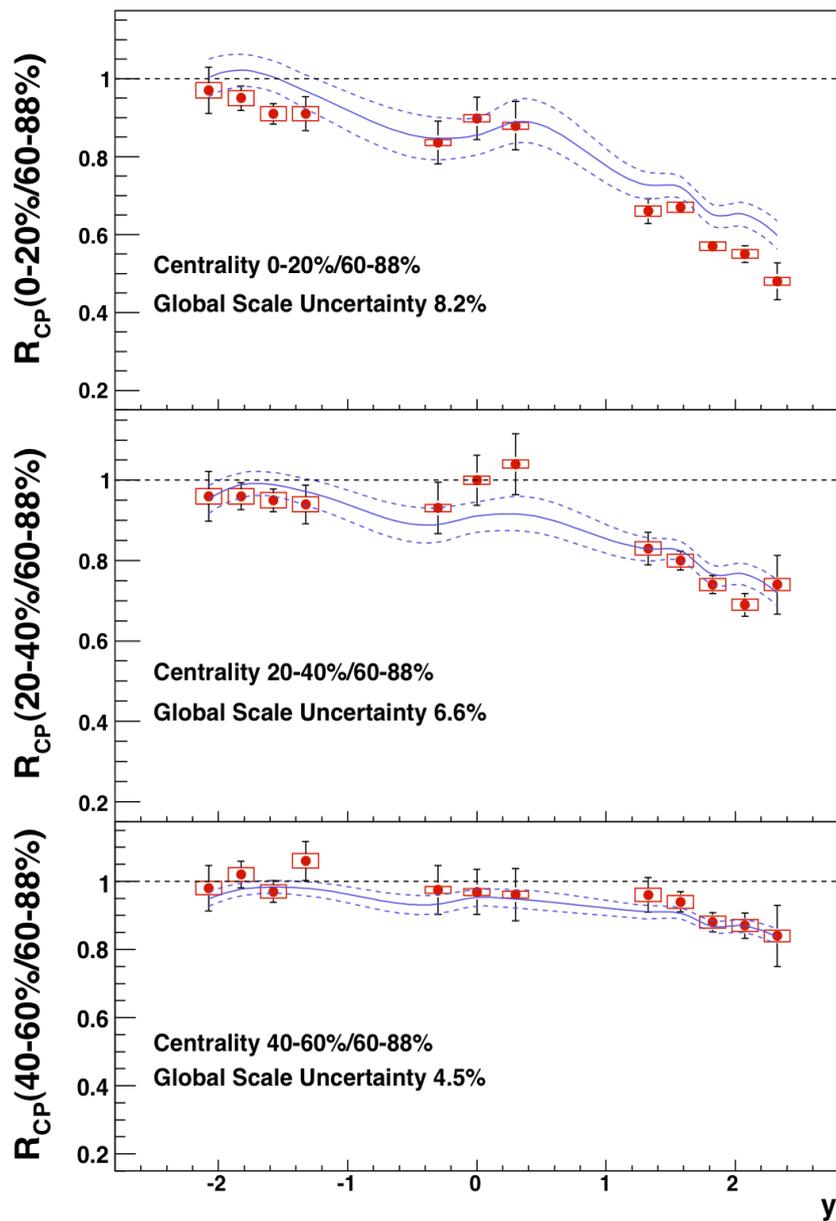
Cross section systematics

The breakup cross sections obtained here at midrapidity are consistent with the systematic behavior observed at lower energy.

y	σ_{br} (mb)
-0.3	3.35 (+ 1.8 – 2.2)
0.0	1.50 (+ 2.1 – 1.8)
+0.3	1.45 + (1.5 - 2.5)



Description of the data



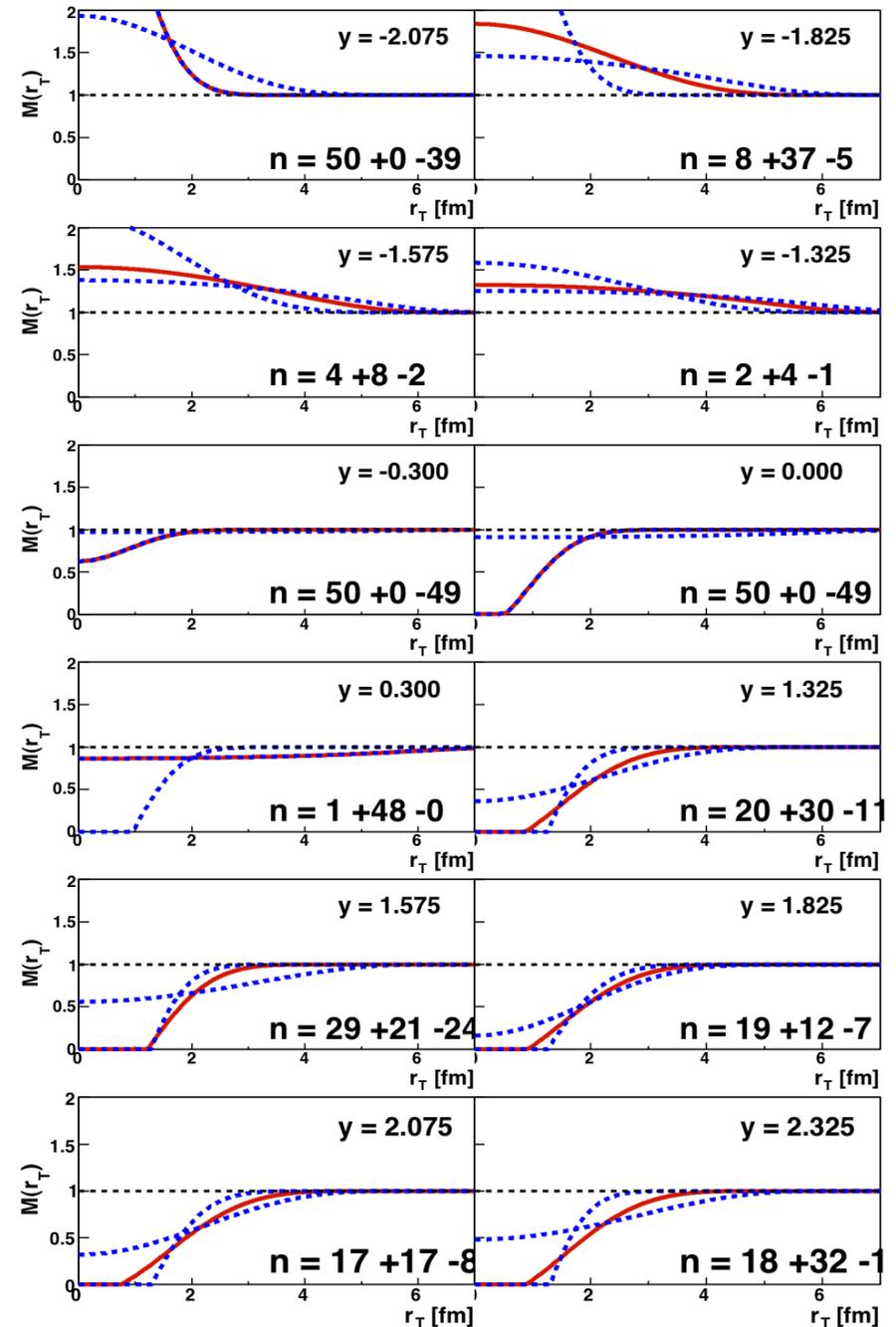
Shadowing modification vs r_T from the fit results

The red curve is the EPS09 shadowing modification calculated from the **best fit value of n**.

The blue curves show the fitting **uncertainty limits**.

Where shadowing is strong, the modification turns on suddenly at $r_T \sim 3-4$ fm.

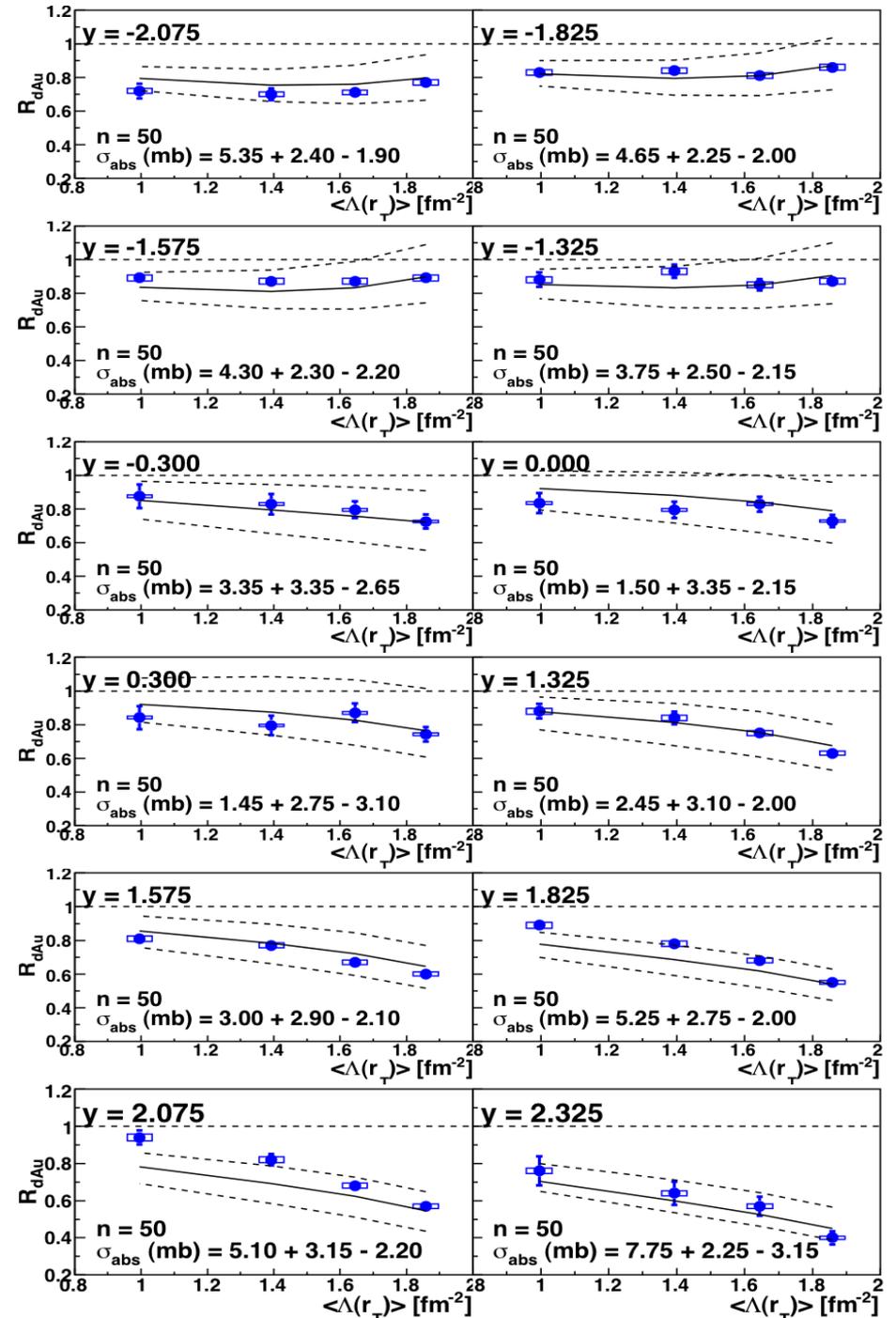
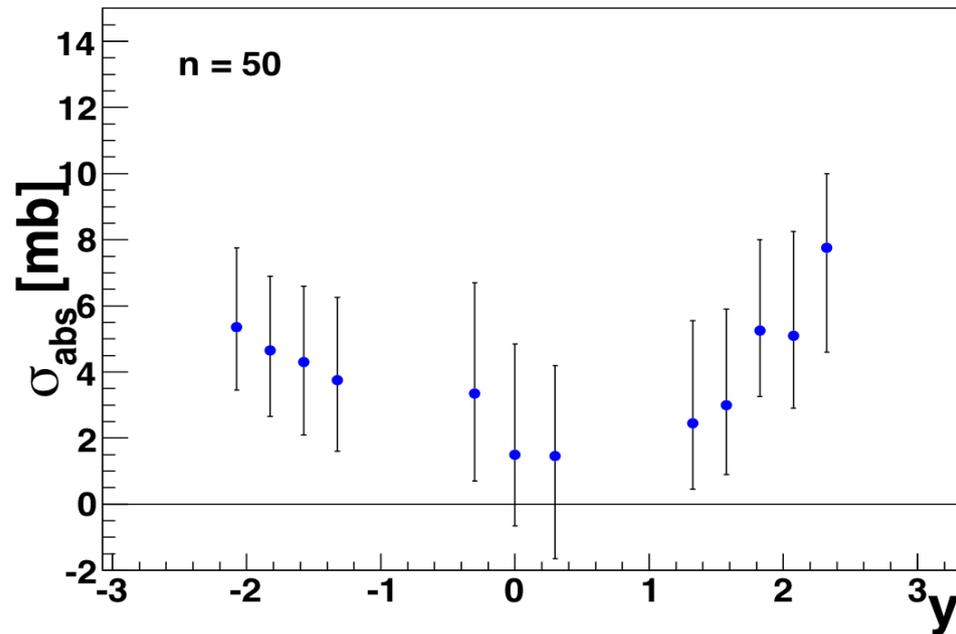
Note that at **midrapidity** there are strong effects at very small values of $r_T < 2$ fm. But the fit is **insensitive to n** in this region, as the uncertainty band shows.



Fit to all 12 rapidities with a **common** shadowing power 20

This results in a good description of the data. The overall χ^2 is minimum for $n = 50$, but is **good for all $n \gtrsim 15$** .

The σ_{br} values are similar to the fits with n optimized at each rapidity, albeit with larger uncertainties.



Discussion of R_{dAu} results

The χ^2 contour plots show the need for a highly **nonlinear** onset of shadowing with nuclear thickness at forward and backward rapidity.

The calculated modifications with uncertainty are very large at forward and backward rapidity for $r_T < 4$ fm, and very weak at larger r_T .

At midrapidity, the shadowing is weak, and hence the power is essentially undefined.

A single shadowing power of **$n > 15$** provides a reasonably good description of all of the data, suggesting the possibility that shadowing effects have similar turn-on behavior vs r_T at all rapidities.

The cross sections have a **minimum at midrapidity**, rising at forward and backward rapidity. Could this be a consequence of the model of the shadowing? Of other physics?

Using the fit parameters in calculations

We want to calculate some R_{dAu} and R_{AA} values integrated over each of the three PHENIX arms. However the x and Q^2 values vary significantly across the widths of the three PHENIX arms.

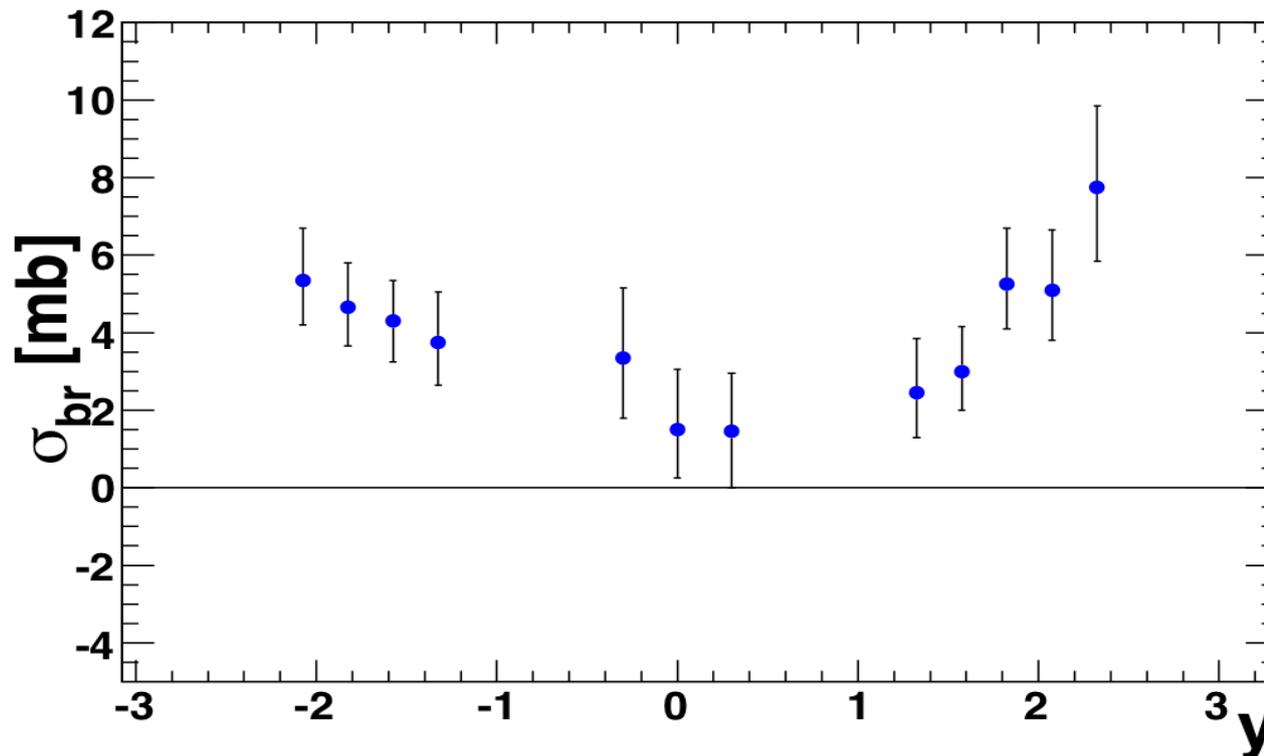
This is taken into account by using the independent fit results from the **twelve narrow rapidity bins** and calculating the modification averaged over each arm using the **measured** rapidity dependence for the J/ψ from p+p collisions for the narrow rapidity bins.

The modification is calculated at the center of each narrow rapidity bin (this is valid if there is approximately linear behavior across the narrow bin).

The p_T distribution within each arm is taken from the p+p distribution integrated over that arm, since no difference is observed, within statistics, within an arm.

Uncertainty propagation in calculations

When using the fit parameters in a glauber calculation, we treat the uncertainties as follows: we take as our “model” the one with the best fit shadowing power, and we take as the uncertainty in σ_{br} the values at $\Delta\chi^2 = 1$ for that power. This gives the uncertainties shown here, which are the ones propagated into any quantity calculated with the fit parameters.

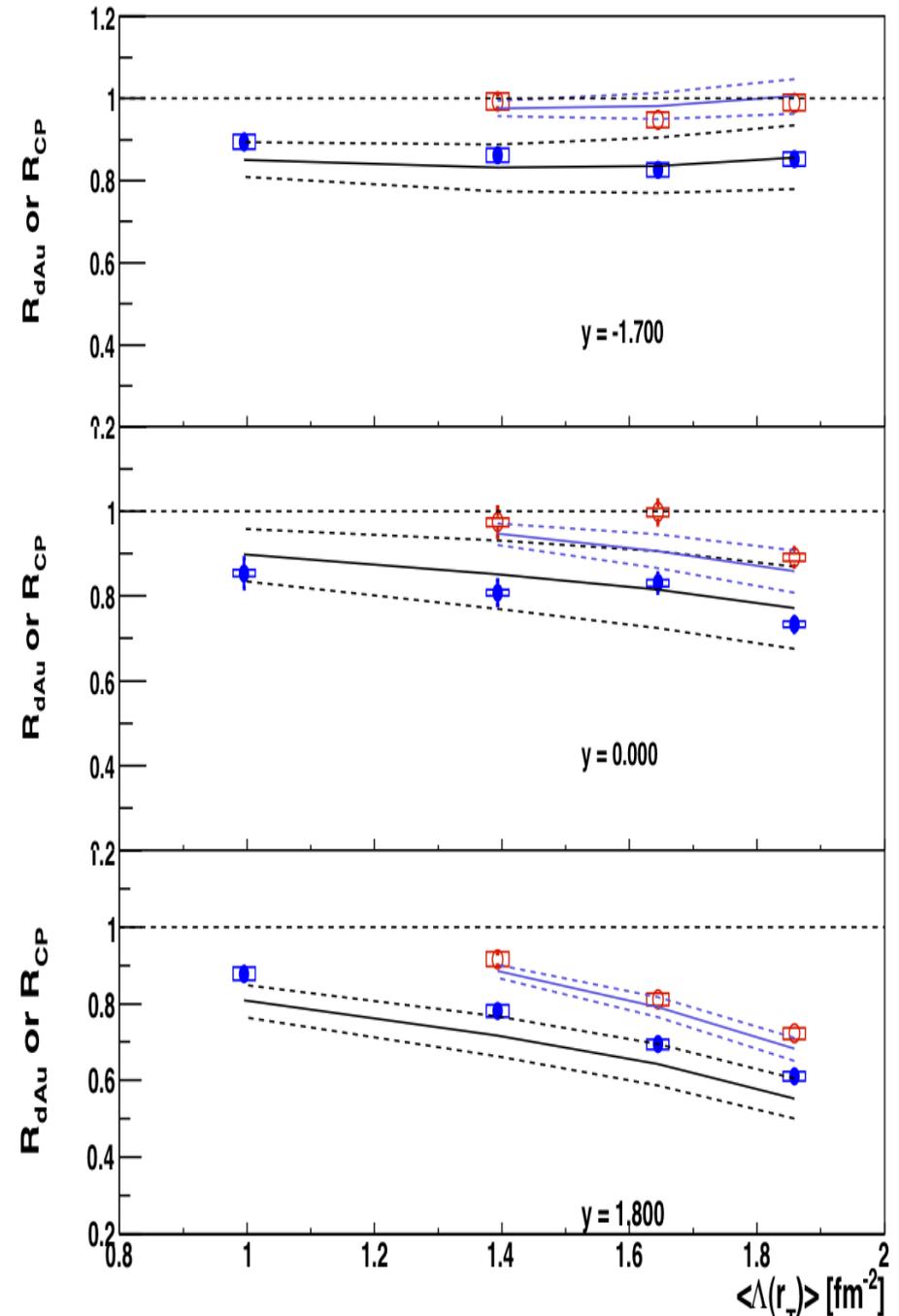


d+Au centrality dependence for three arms

The centrality dependence of R_{dAu} calculated from the **best fit** parameters, and integrated over each of the three arms using the procedure outlined in the last two slides.

The calculated values of R_{CP} are also compared with the data.

This shows that the description of the arm-integrated d+Au data is good.



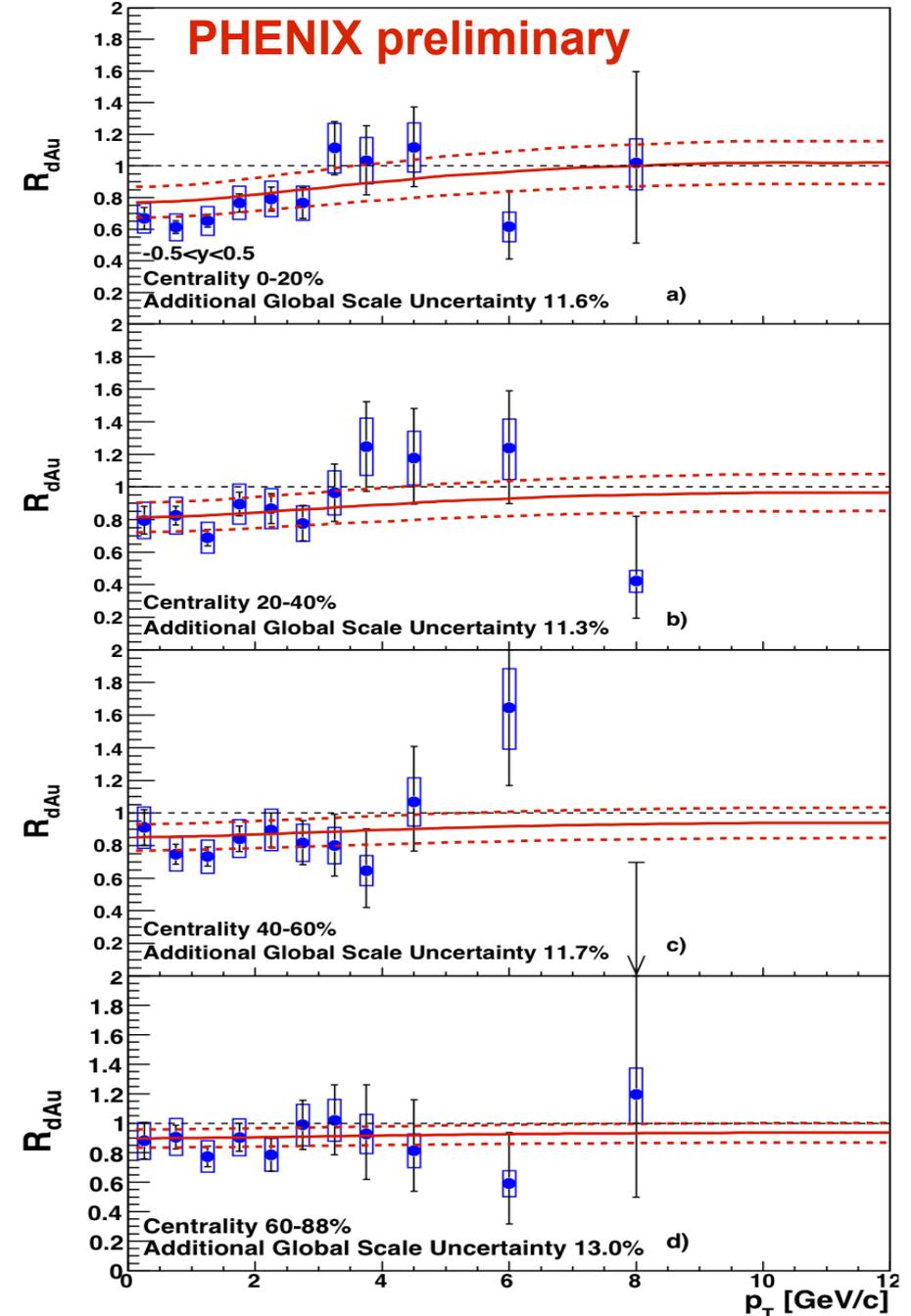
d+Au p_T dependence for the central arm

The p_T dependence of R_{dAu} calculated from the best fit parameters and integrated over the central arm, compared with the PHENIX preliminary central arm R_{dAu} .

Note that the p_T dependence of R_{dAu} here is a **prediction** of the model. No d+Au p_T information is used in the fitting (p+p p_T dependence only).

There are no data from PHENIX yet showing the p_T dependence at forward or backward rapidity.

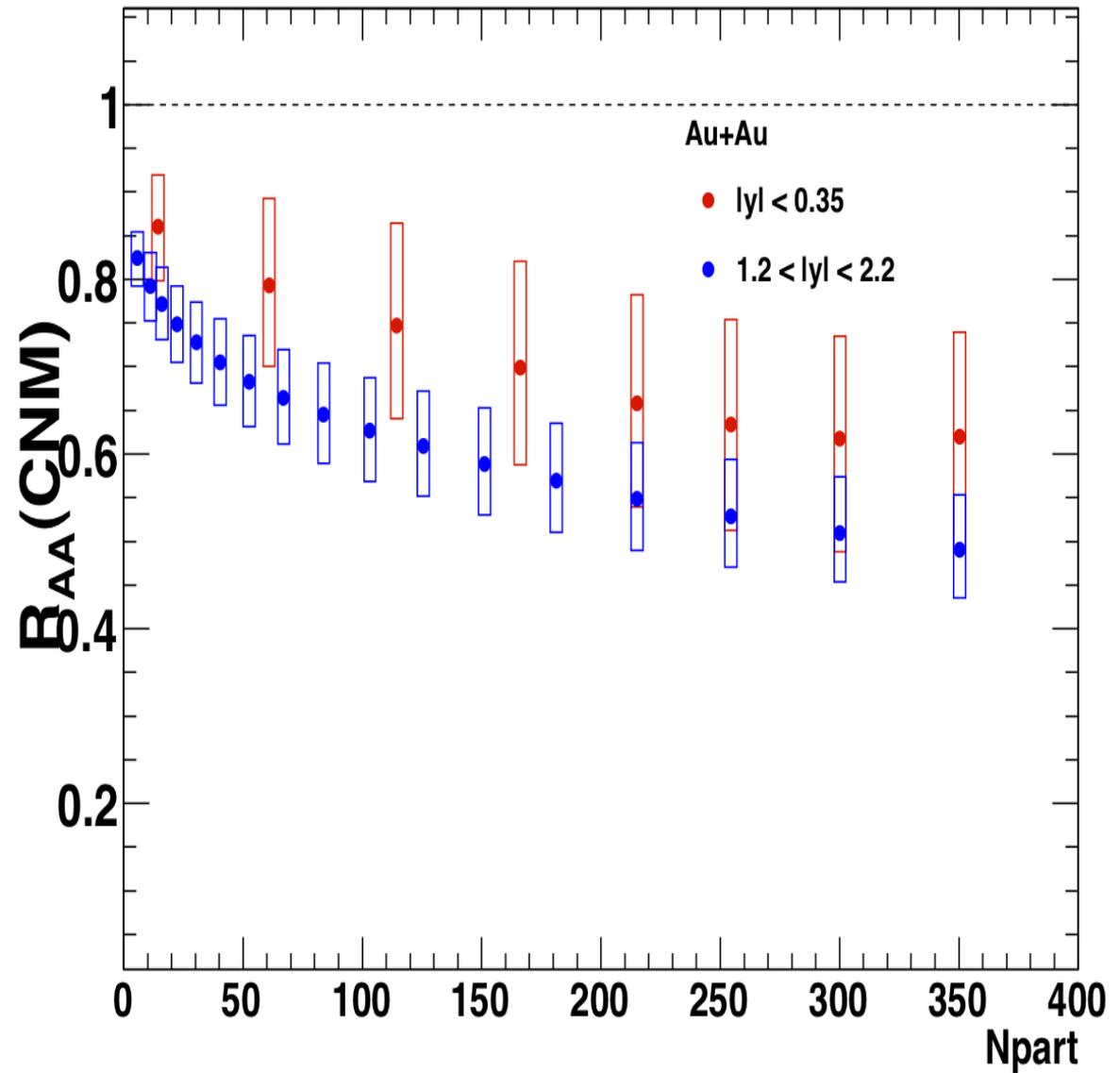
The p_T dependence here comes entirely from EPS09.



Calculating $R_{AA}(\text{CNM})$

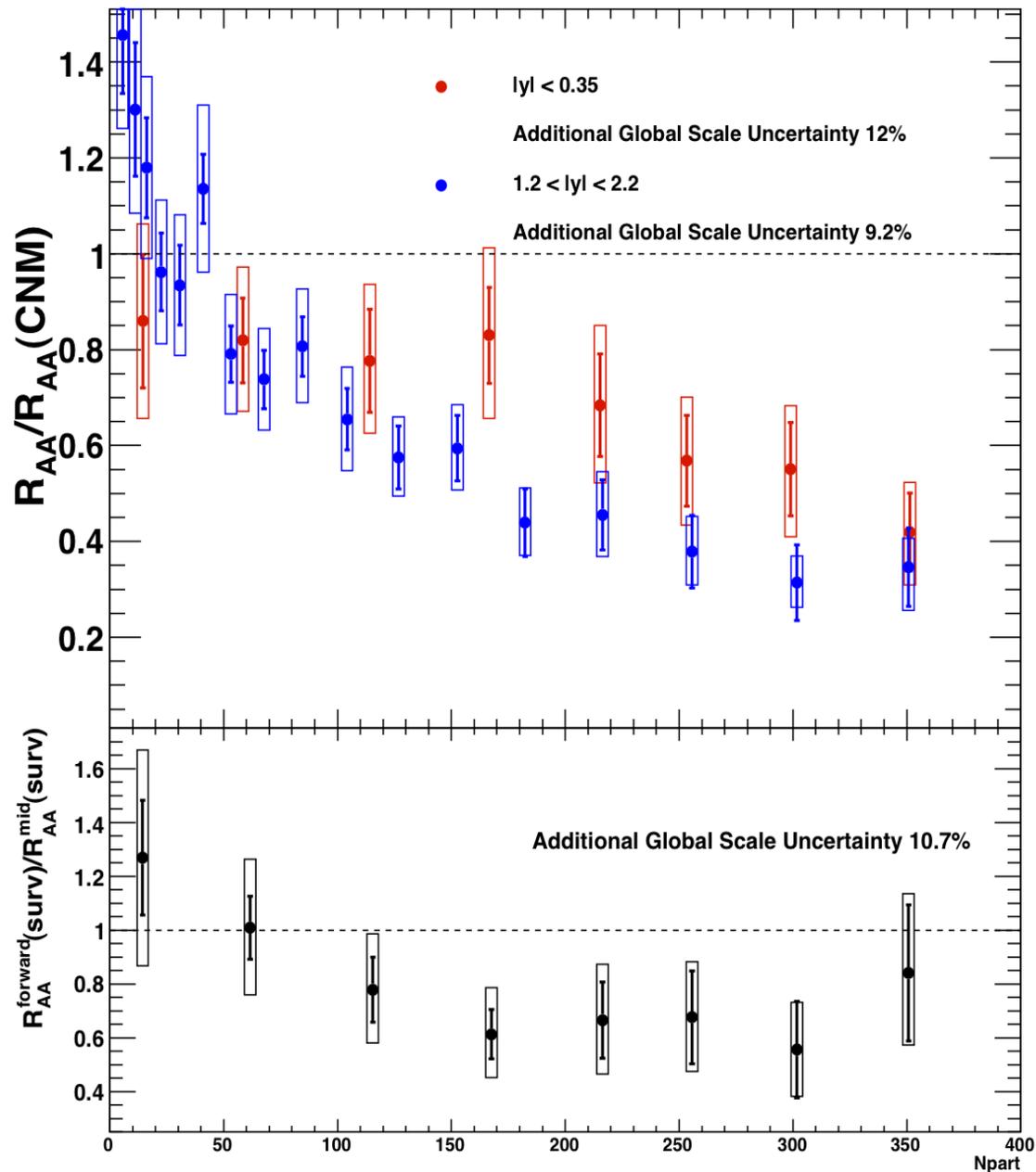
Now we can take the d+Au fit results and put them into a Au+Au Glauber model, to get the CNM contributions to the R_{AA} .

The fit uncertainties in σ_{br} are propagated to the result as a systematic uncertainty (box).



The PHENIX R_{AA} data divided by the estimated $R_{AA}(\text{CNM})$ values.

Unlike earlier estimates using EKS98 to fit the PHENIX preliminary R_{CP} data with an assumption of a linear thickness dependence, the mid and forward/backward rapidity ratios do not agree closely.



Discussion of $R_{AA}(\text{CNM})$

Estimated CNM effects on the J/ψ for Au+Au give:

R_{AA} of 0.62 in central collisions at $y=0$

R_{AA} of 0.5 in central collisions at $y=1.7$

$R_{AA}/R_{AA}(\text{CNM}) \sim 42\%$ ($y=0$) and $\sim 35\%$ ($y=1.7$) for most central point.

$R_{AA}/R_{AA}(\text{CNM})$ for $y=0$ agrees reasonably well with the earlier estimates (using EKS98 and fits to the preliminary R_{CP} data):

– most central point now 42%, was previously 50%.

They should agree, since shadowing is weak at midrapidity and the linear thickness dependence assumption should not have made much difference.

Comparison for $y=1.7$ is more difficult, since the Au+Au data are new and have **much** smaller uncertainties, greater centrality reach. The new and old estimates are consistent within uncertainties – the new estimates seem lower. The linear thickness dependence assumption used in the old estimates is not justified, **so they should not be expected to agree.**

Comment on RHIC vs LHC results

The most central ALICE J/ψ R_{AA} measurement at $y = 2.5-4$ sits at ~ 0.5 .

The **CNM corrected** R_{AA} for the RHIC data at $y = 1.2-2.4$ is ~ 0.35 .

The ALICE R_{AA} value will certainly **increase** once it is corrected for CNM effects, probably by a larger factor than the RHIC data.

It seems very likely that the R_{AA} for central collisions at LHC will be **higher than at RHIC** after both are corrected for CNM effects.

For the purpose of **correcting for CNM effects** on the Au+Au J/ψ R_{AA} , the **midrapidity** case may be better, because the effects of shadowing are minimal there, and the fitted breakup cross section is smallest also. Thus the correction is smaller.

At forward/backward rapidity, shadowing effects are more significant – even though the shadowing and antishadowing **mostly cancel each other**, the details matter. Also, the fitted breakup cross section is larger at forward and backward rapidity, making the correction larger.

Therefore, while the forward and backward rapidity R_{dAu} measurements obviously have very interesting physics implications, the more boring midrapidity region may be the best place to get the CNM correction for Au+Au.