Parameterizing Cold Nuclear Matter Effects at RHIC

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International Workshop on Heavy Quarkonium 2011
GSI, Germany
10/4/2011

Cold Nuclear Matter Effects

- Effects due to the presence of a nuclear target.
- Not yet well understood at RHIC.
- Two common sources:
  - Modification of PDFs for protons bound in a nucleus – shadowing.
    - Taken from nPDFs which provide modifications to the PDFs averaged over the entire nucleus.
  - Break-up of J/ψ's (or cc precursor) through collisions with nucleons – nuclear break-up.
- Inseparable from hot nuclear matter (QGP) effects using A+A collisions alone.
- Use p+A (d+Au at RHIC) to isolate these effects.
  - Use some model or parametrization to propagate p+A results to A+A collisions.

PHENIX d+Au Conclusions

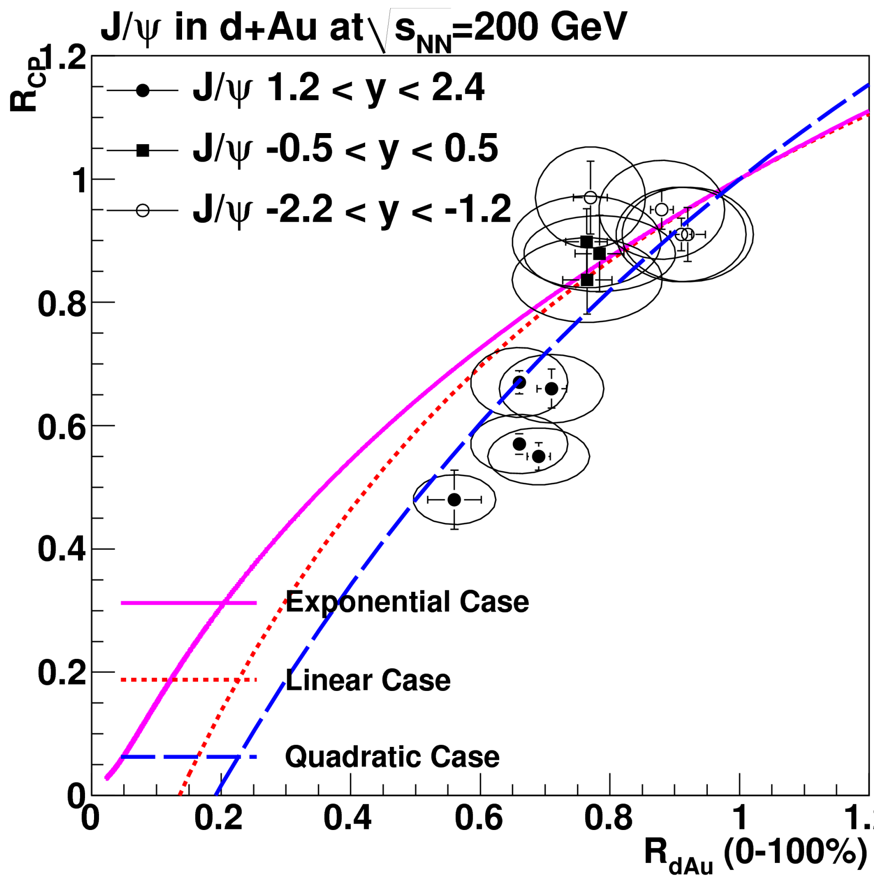
- Assume simple functional forms of the modification vs $\Lambda(r_T)$.

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

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

- Fold these functions with r_T distributions from Glauber.
- Here R_{CP}(0-20%/60-88%) vs R_{dAu}(0-100%) is plotted w/ the functional forms of the modification.
- Purely tests the geometric dependence of the data.
- Forward rapidity data is inconsistent with even quadratic thickness dependence.

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

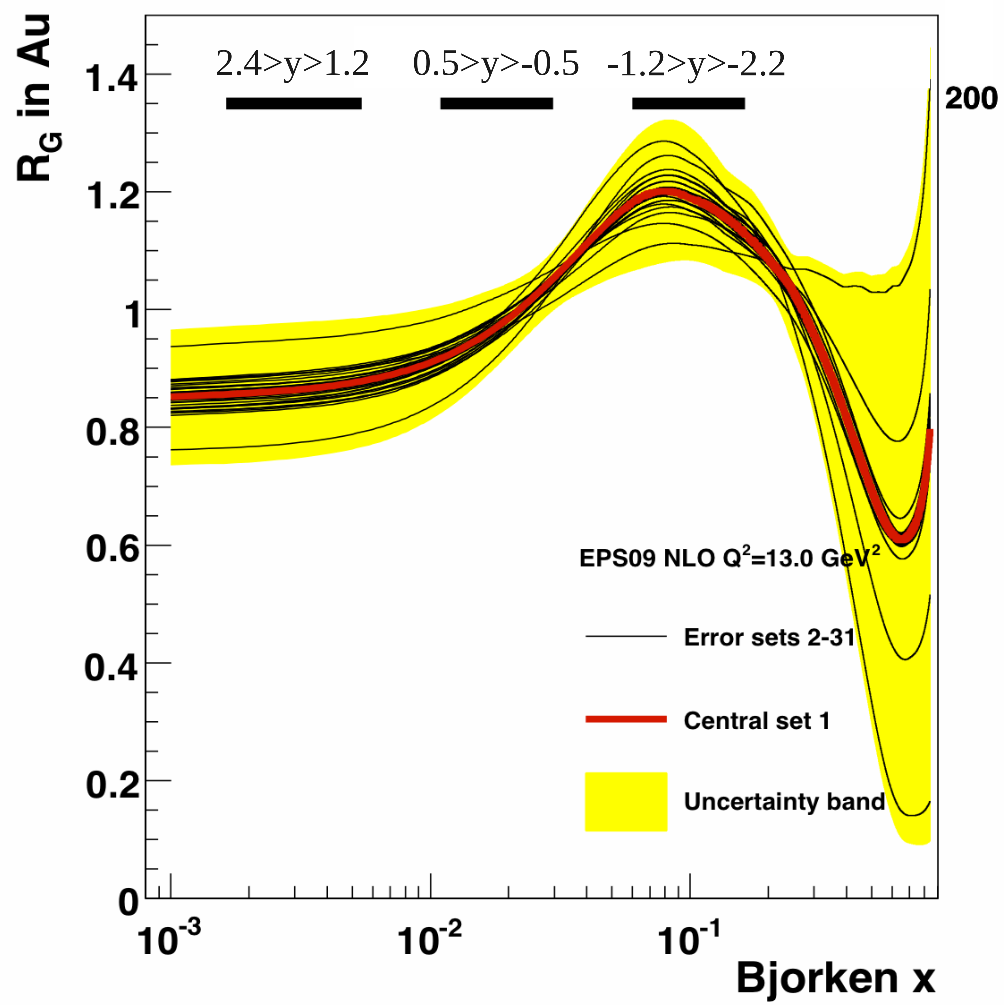


Where to go From Here

- Use the data to constrain the thickness dependence.
- Assume CNM effects consist only of shadowing + nuclear break-up.
- Shadowing:
  - Use EPS09 nPDF set (NLO) – gives average suppression.
  - Assume modification vs thickness is: $M_{shad}(r_T) = 1 - a\Lambda(r_T)^n$
  - Allow n to vary between 1-50. $\Lambda(r_T) = \int dz\,\rho(r_T, z)$
  - a is normalized to the EPS09 modification integrated over all centrality.
  - This thickness dependence is somewhat arbitrary.
- Nuclear break-up
  - Assume modification vs thickness is: $M_{br}(r_T) = e^{-\sigma_{br}\Lambda(r_T, z_1)}$
  - Allow σ_{br} to vary. $\Lambda(r_T, z_1) = \int_{z_1}^{\infty} dz\,\rho(r_t, z)$
  - z_1 is the production point of the precursor J/ψ in the Au nucleus.

EPS09

- At RHIC, J/ψ production dominated by gluons – use EPS09 gluon modification (R_G).
- Shown for Q^2 of 13 (M^2 + $\langle p_T \rangle^2$ for J/ψ) GeV.
- x regions relevant to PHENIX @ 200 GeV shown as black bars.
- Remember: EPS09 determined mainly from DIS data, and is averaged over the nucleus.

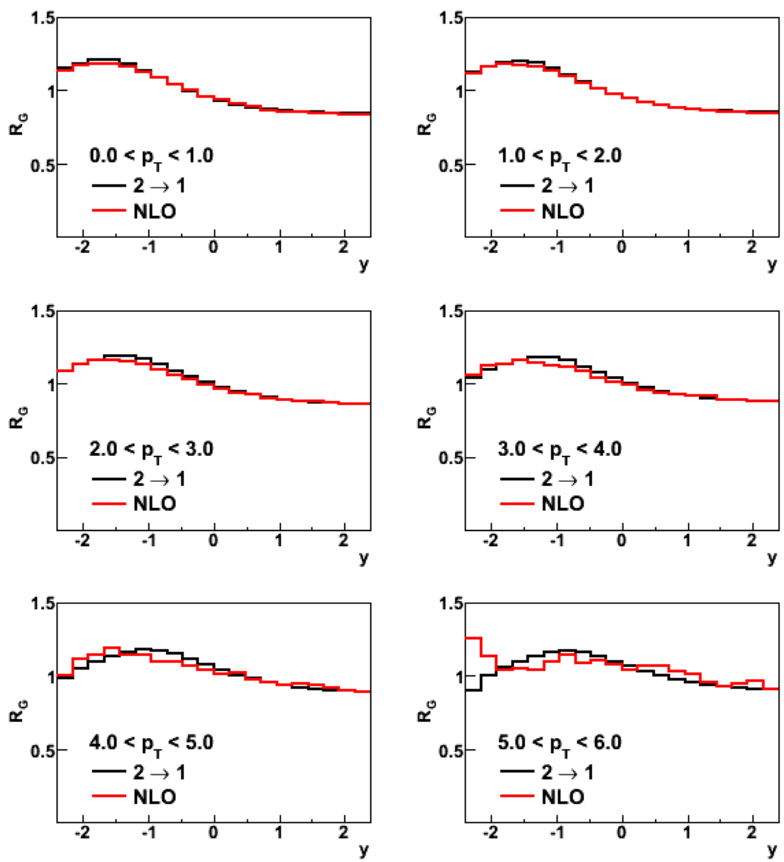


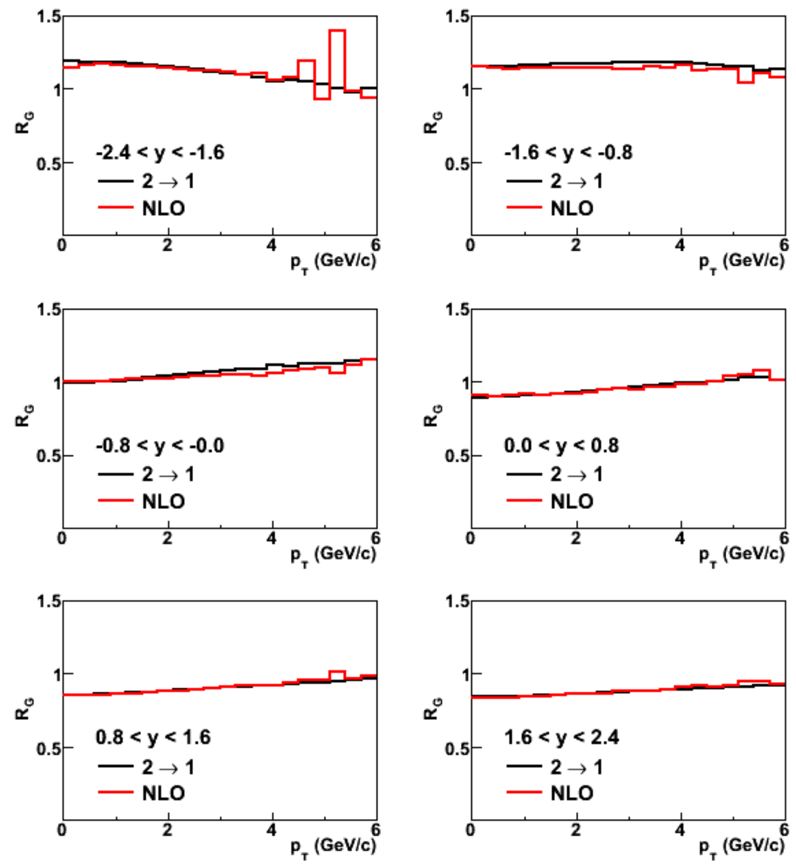
Determining x and Q^2

- Assume 2→1 kinematics.
- Not quite right, but R_G extracted using x and Q^2 from NLO framework from Ramona compare well.

$$x_2 = \frac{\sqrt{M_{J/\psi}^2 + p_T^2}}{\sqrt{s_{NN}}} e^{-y}$$

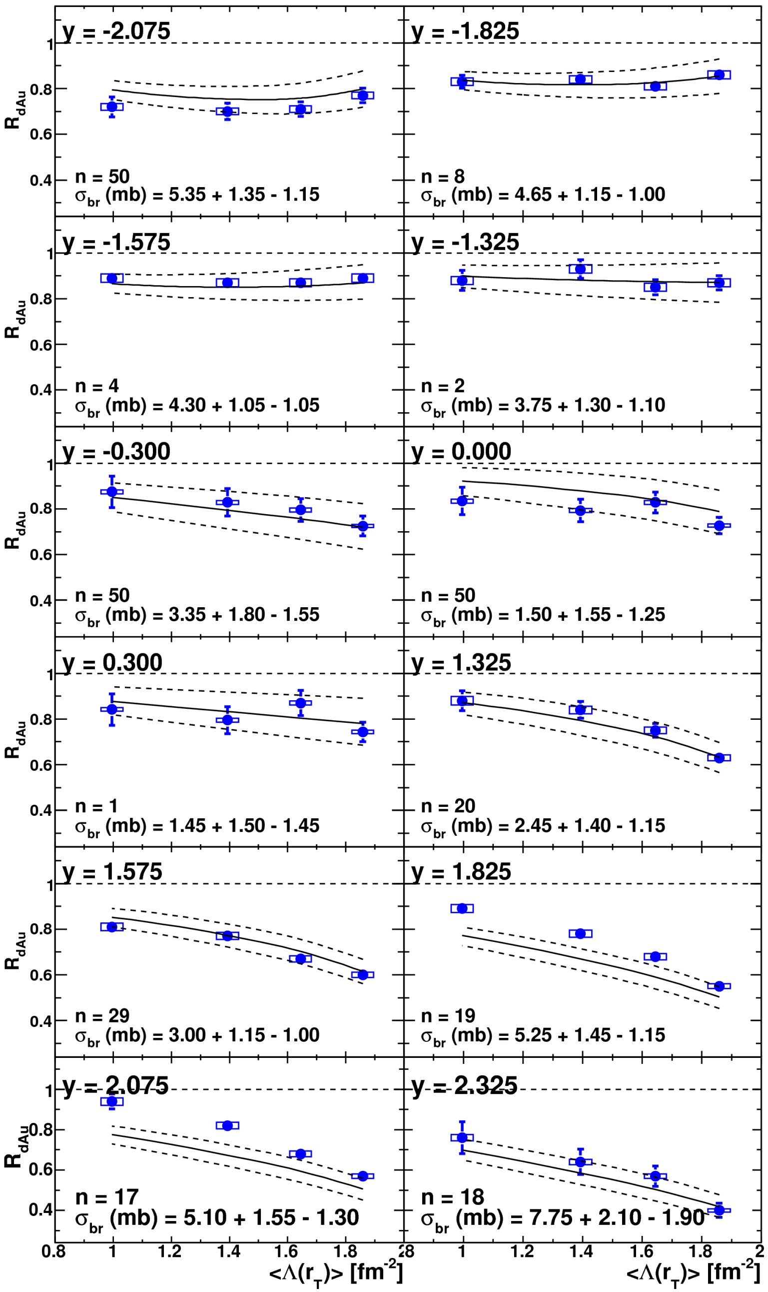
$$Q^2 = M_{J/\psi}^2 + p_T^2$$





Fits to R_{dAu}

- Calculate R_{dAu} using a Glauber model.
- Use a modified χ^2 to find the optimum n & σ_{br} independently for each y.
  - The modified χ^2 takes into account the statistical & systematic uncertainties on the data.
- Results plotted versus the average nuclear thickness.
- Because the systematic uncertainties are included in the fit, the best-fit line may be offset from the data points.
  - Global uncertainty ~10-15% not shown in plots.



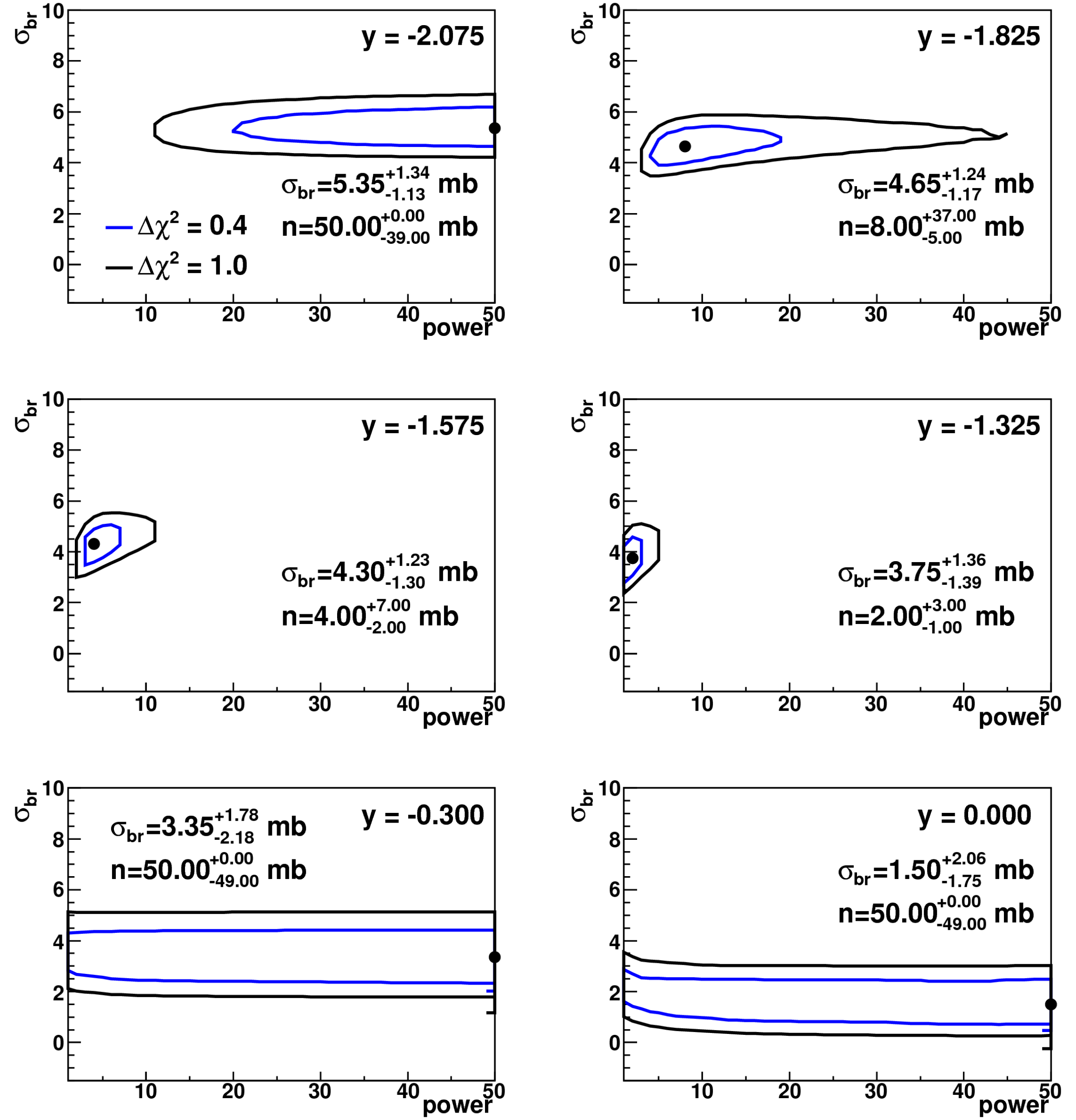
Blue points: PHENIX R_{dAu} data.

Solid line: optimum n & σ_{br} values.

Dashed lines: $\Delta\chi^2=1$ limits on σ_{br} for the optimum n.

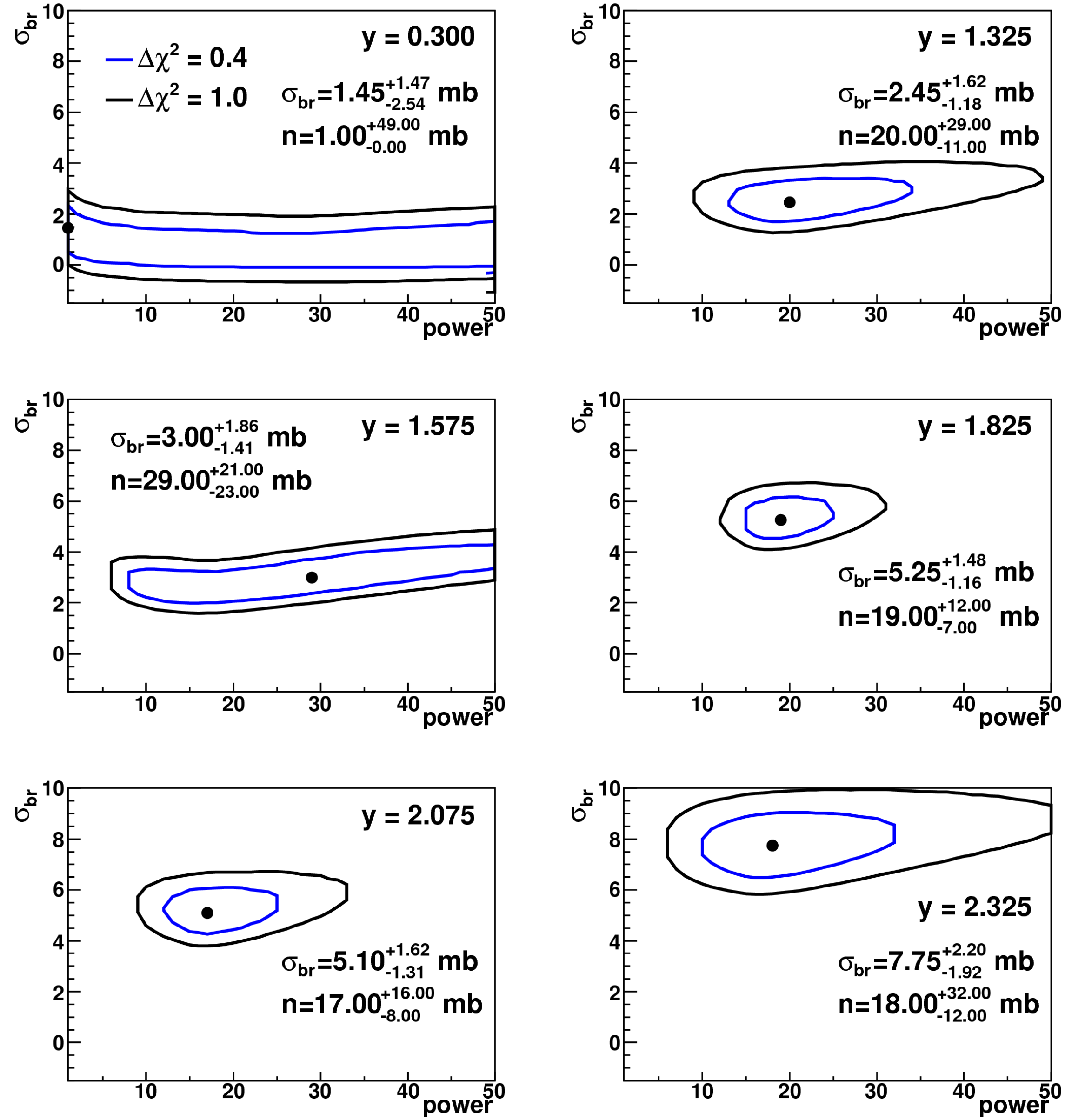
χ^2 Contours (y<0)

- Visualize the results by plotting the χ^2 contours.
  - Best fit is indicated by the point.
  - Black curve is $\Delta\chi^2$=1.
- Quoted uncertainties on n & σ_{br} represent the max extent of the $\Delta\chi^2$=1 curve for that parameter.
- The χ^2 contours at midrapidity are broad because the EPS09 modification is small.
- Break-up and shadowing essentially decoupled.



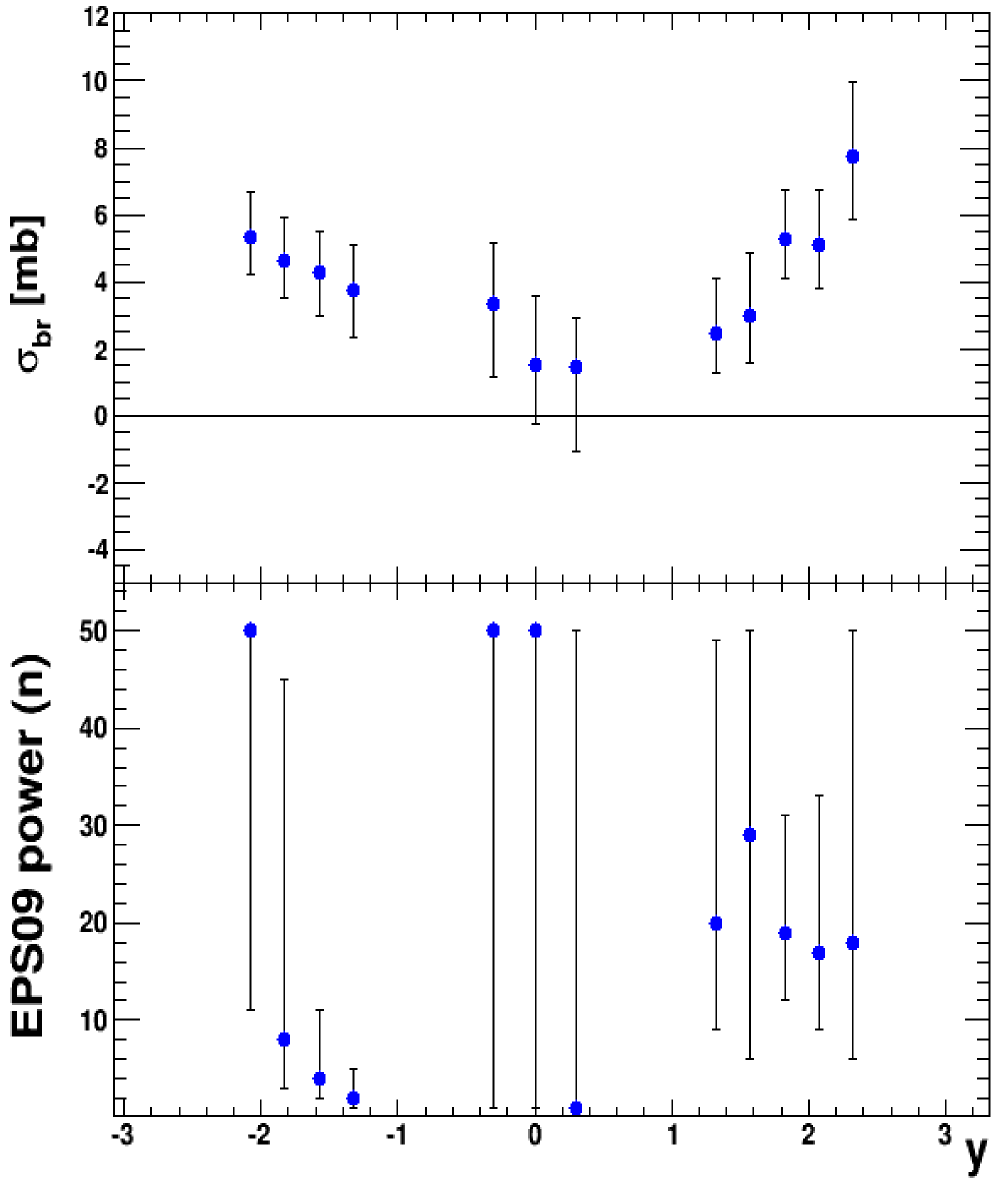
X^2 Contours (y>0)

- Visualize the results by plotting the χ^2 contours.
  - Best fit is indicated by the point.
  - Black curve is $\Delta\chi^2$=1.
- Quoted uncertainties on n & σ_{br} represent the max extent of the $\Delta\chi^2$=1 curve for that parameter.
- The χ^2 contours at midrapidity are broad because the EPS09 modification is small.
- Break-up and shadowing essentially decoupled.
- Forward rapidity consistently requires a higher power.



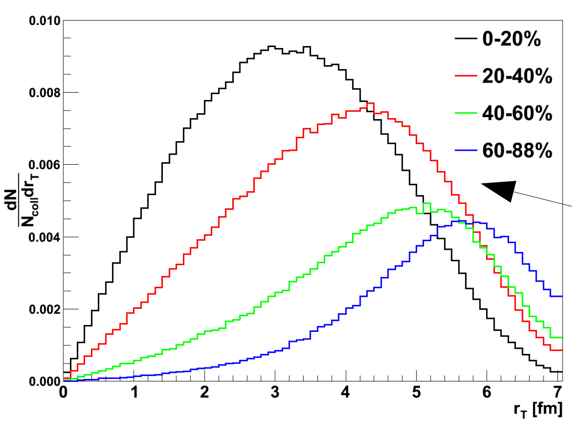
Best Fit Parameters vs. Rapidity

- Best fit n & σ_{br} values plotted vs rapidity.
- Uncertainties represent the width of the $\Delta\chi^2=1$ contour in that parameter.
- **σ_{br} increases** as you move to backward/forward rapidity.
- **Large n** required at forward and far backward rapidity.



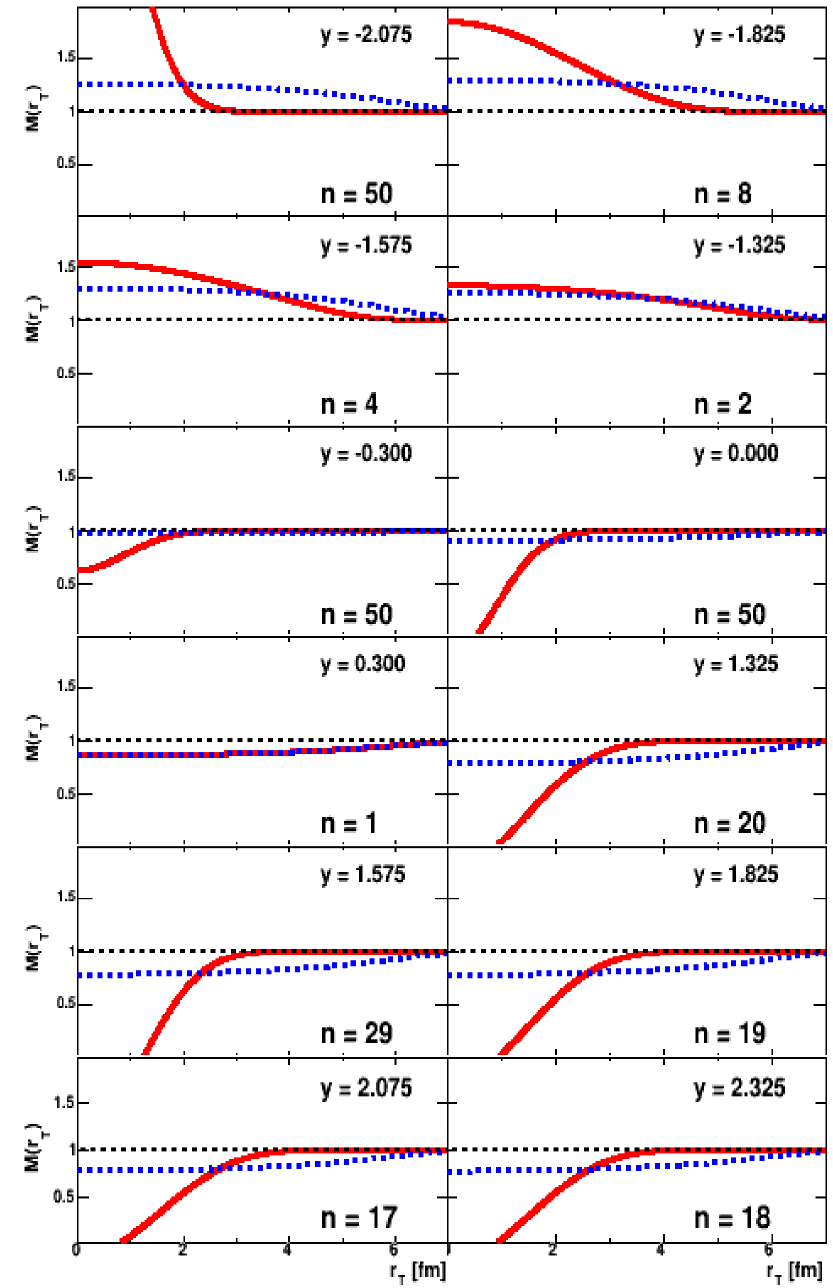
Shadowing vs r_T

- What do these high powers mean?
- Plot only shadowing vs r_T.
  - Red curves: best fit powers.
  - Blue curve: n=1.
- Where the modification is strong, turns on suddenly at r_T~3-4 fm.
- This is very different than linear!
- Remember that the data does not probe a well-defined, unique r_T range!



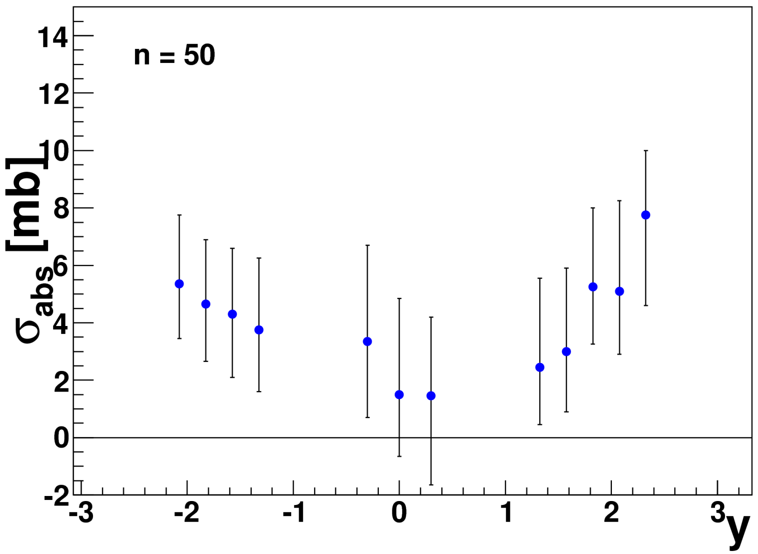
r_T distributions of PHENIX centrality bins.

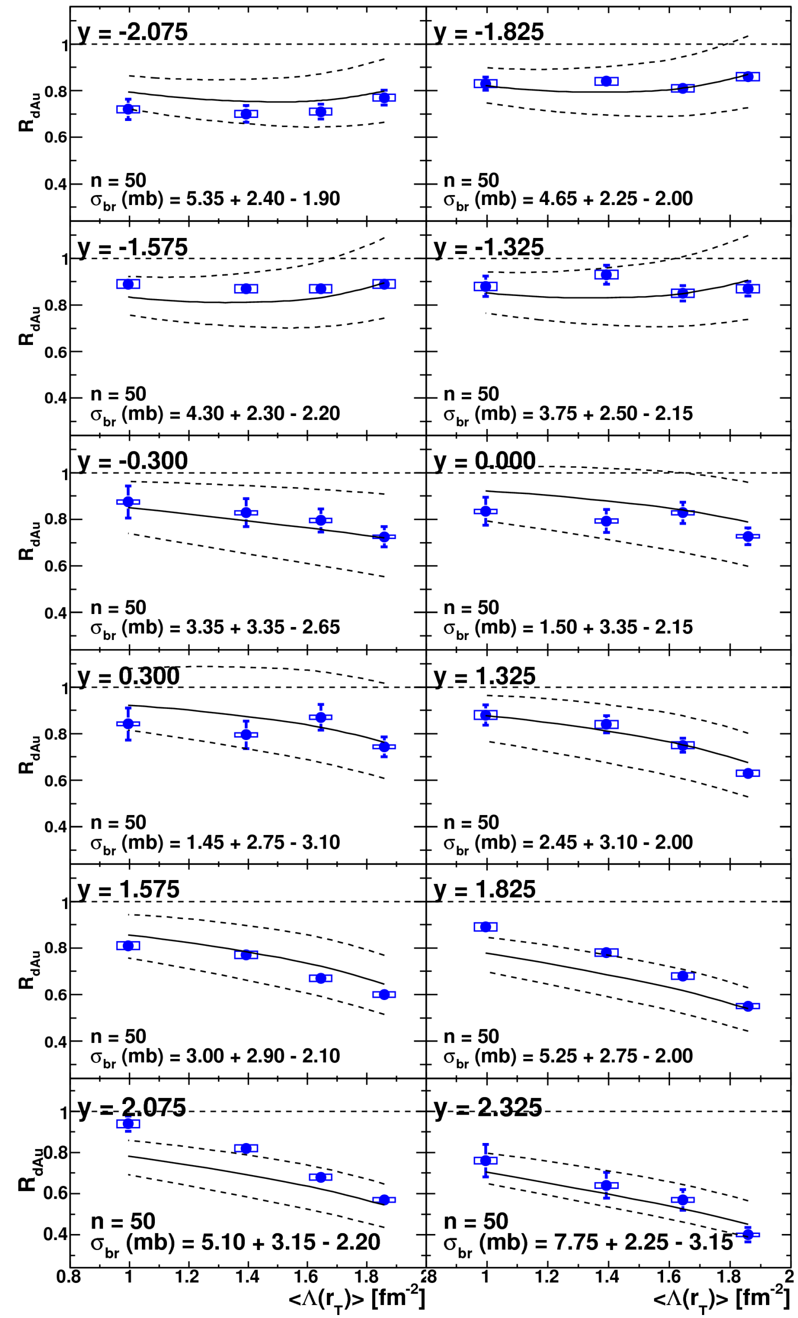
$<r_T>$(0-20%) = 3.23 fm
$<r_T>$(20-40%) = 3.87 fm
$<r_T>$(40-60%) = 4.53 fm
$<r_T>$(60-88%) = 5.40 fm



Fitting all Rapidities with a Common Power

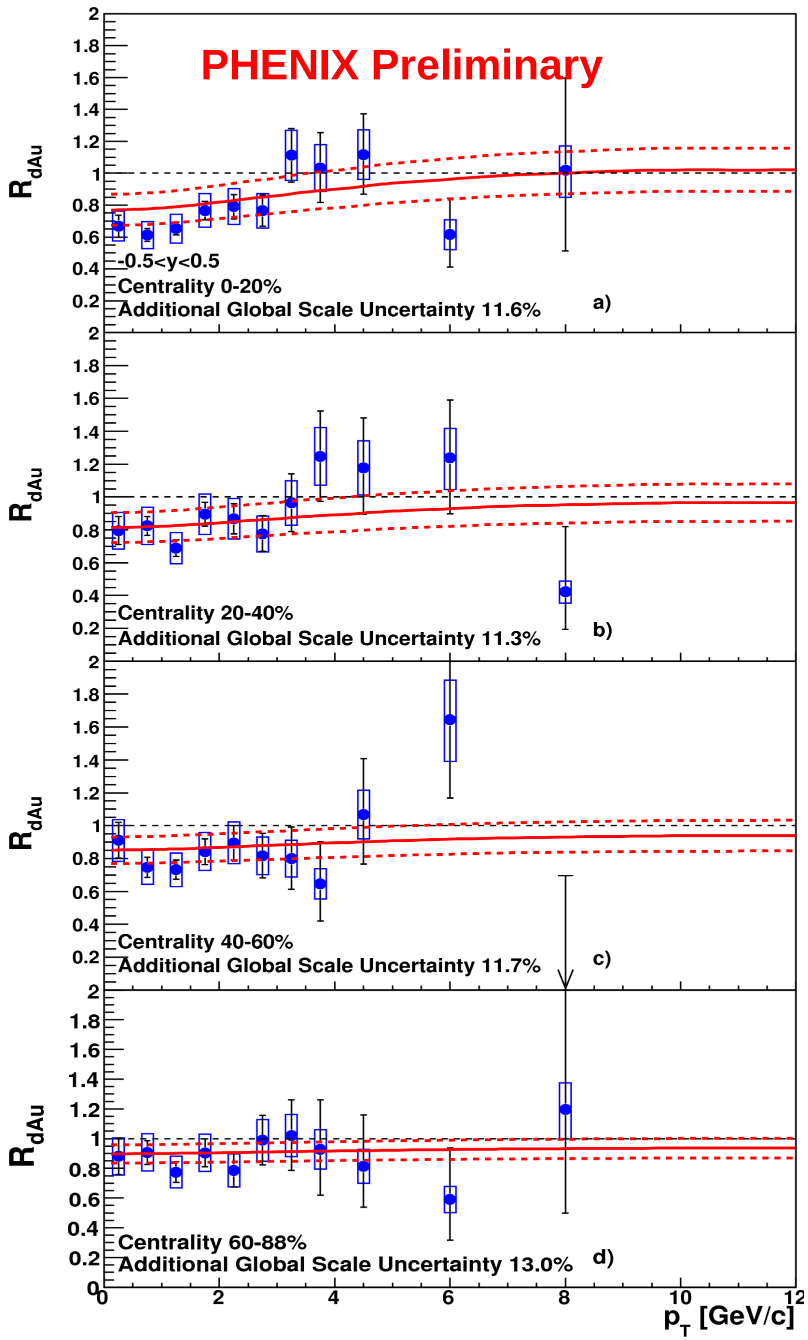
- Try fitting the data with a **constant n** value across all rapidities.
- Minimum χ^2 occurs for n=50, but good for all n ≥ 15.
- The σ_{br} values are similar across rapidity with larger uncertainty.
- Unable to truly distinguish between common/independent power with current uncertainties.





Bonus: R_{dAu} p_T Dependence

- We can also extract the p_T dependence of R_{dAu} from this method using the best-fit n & σ_{br} values and the integrating over rapidity using the measured PHENIX J/ψ p+p y distribution.
- This is a prediction of the p_T dependence, as no d+Au p_T information has been introduced (only p+p p_T information is used).
- p_T dependence comes entirely from EPS09.
- Currently, only preliminary R_{dAu} at midrapidity is available.
- Shows good agreement with the data.

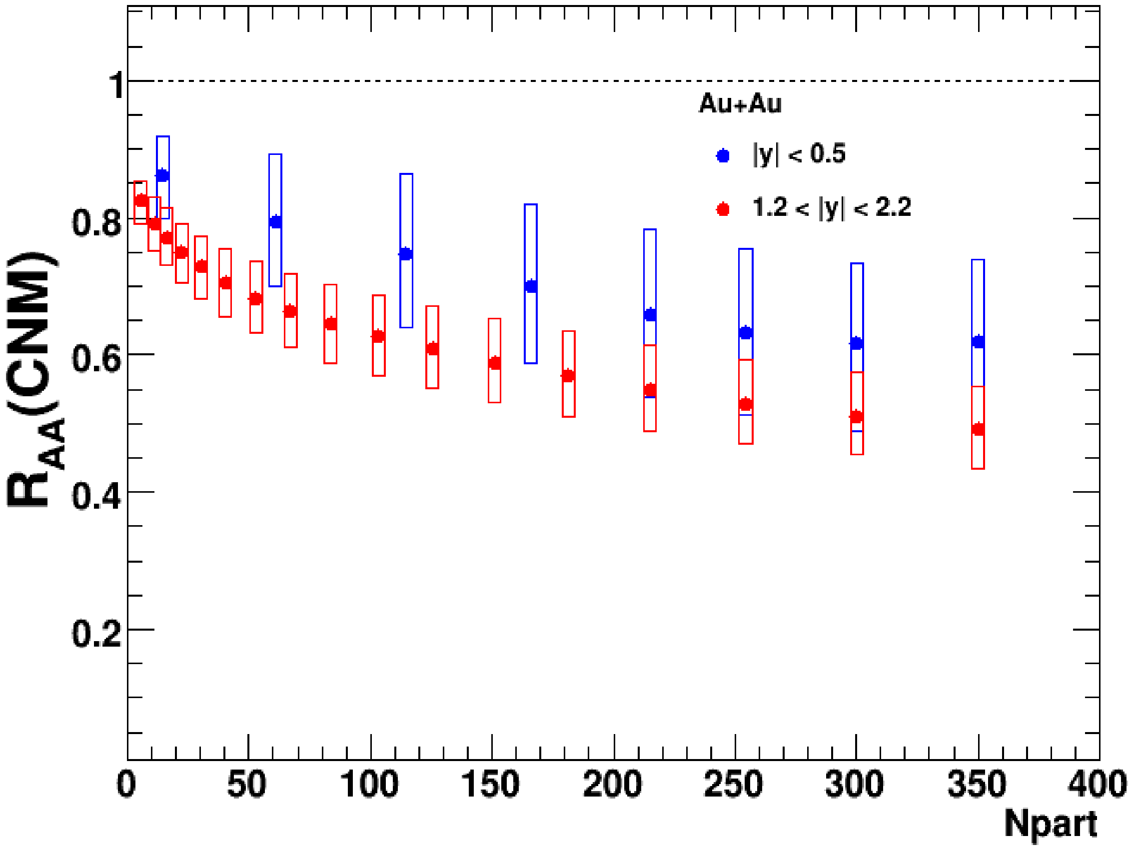


Summary of R_{dAu} Results

- Results indicate a highly nonlinear shadowing is required at backward/forward rapidity.
- This produces shadowing which is very strong for r_T < 4 fm, and very weak for r_T > 4 fm.
- Midrapidity is insensitive to the power due to the current errors on the measurements and the small amount of shadowing present.
- A single shadowing power of $n > 15$ provides a good description of the data, indicating the shadowing may have a similar centrality dependence at all rapidity.
- The σ_{br} is smallest at midrapidity and increases when moving to either backward or forward rapidity.
- Calculation in good agreement with the preliminary PHENIX R_{dAu} vs. p_T data.

R_{AA}(CNM)

- Use a Glauber model of Au+Au collisions following the same recipe as the d+Au calculations.
- Use best-fit n & σ_{br} values from all 12 independent y fits.
- The error on σ_{br} is propagated as a systematic uncertainty (boxes around the points).

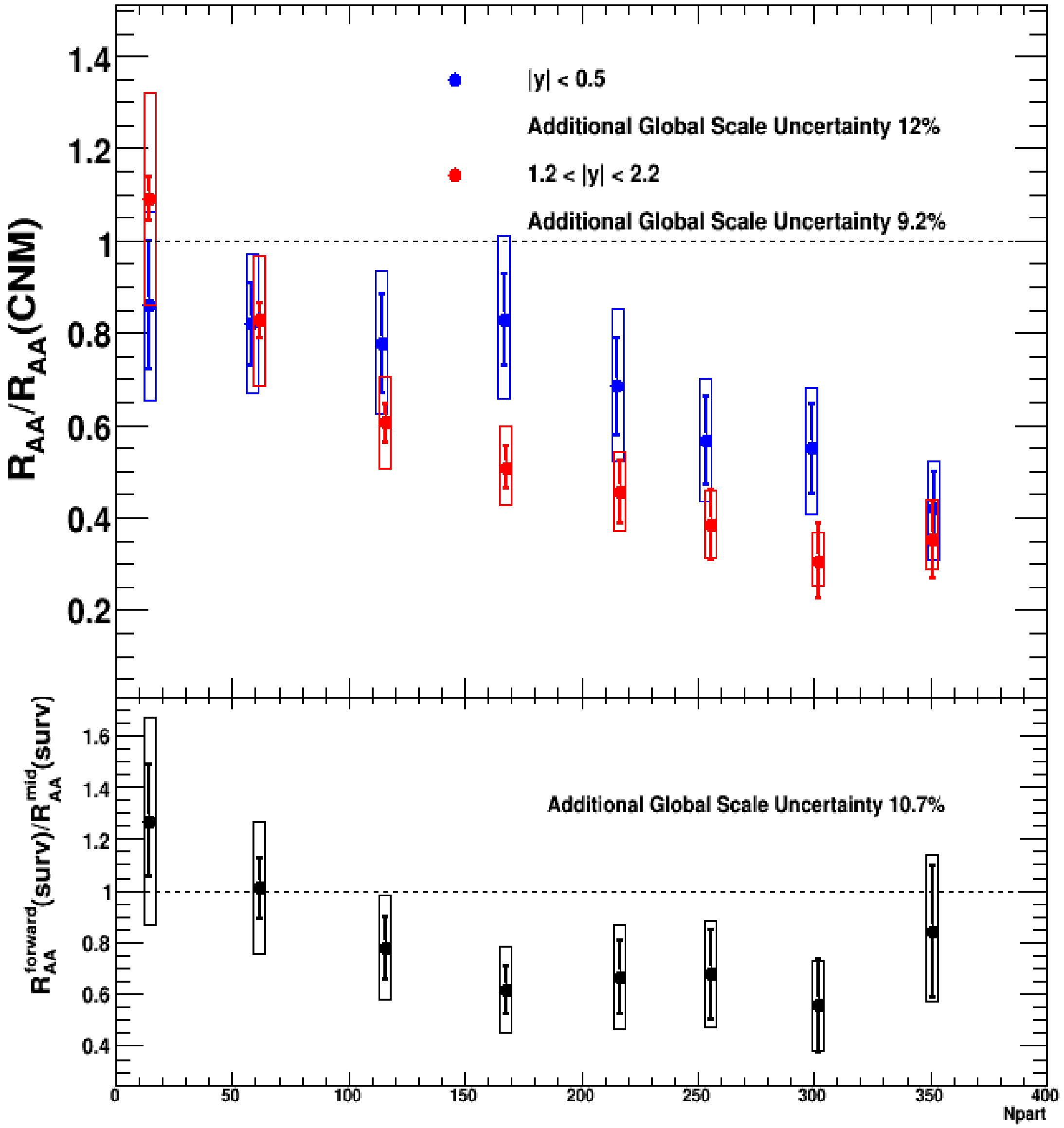


R_{AA}(CNM) ~ 0.62 for central events at midrapidity.

R_{AA}(CNM) ~ 0.49 for central events at forward rapidity.

R_{AA}/R_{AA}(CNM)

- Divide the PHENIX R_{AA} data by the R_{AA}(CNM) predictions.
- Significant suppression beyond CNM effects.
- Discrepancy between mid/forward rapidity remains.
  - Avg ratio forward/mid ~0.68 for N_{part} > 150



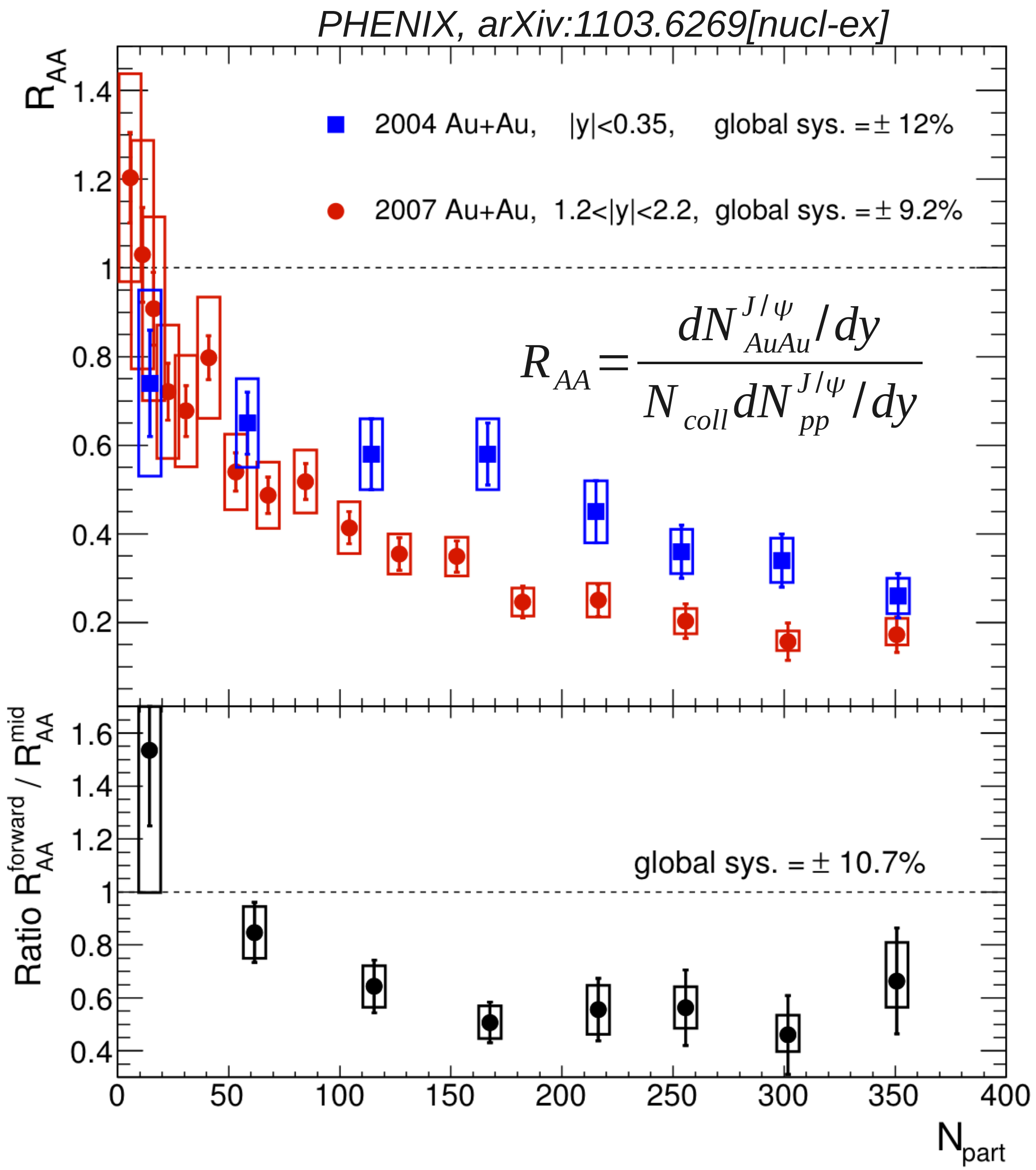
R_{AA}(CNM) Conclusions

- Projected cold nuclear matter R_{AA} baseline is significant!
- R_{AA}/R_{AA}(CNM) < 1, shows suppression beyond CNM.
  - ~58% @ y=0 and ~65% @ y=1.7 for central events.
- Still a first look at the R_{AA} result, more work to be done.

Thank You!

RHIC J/ψ Puzzle

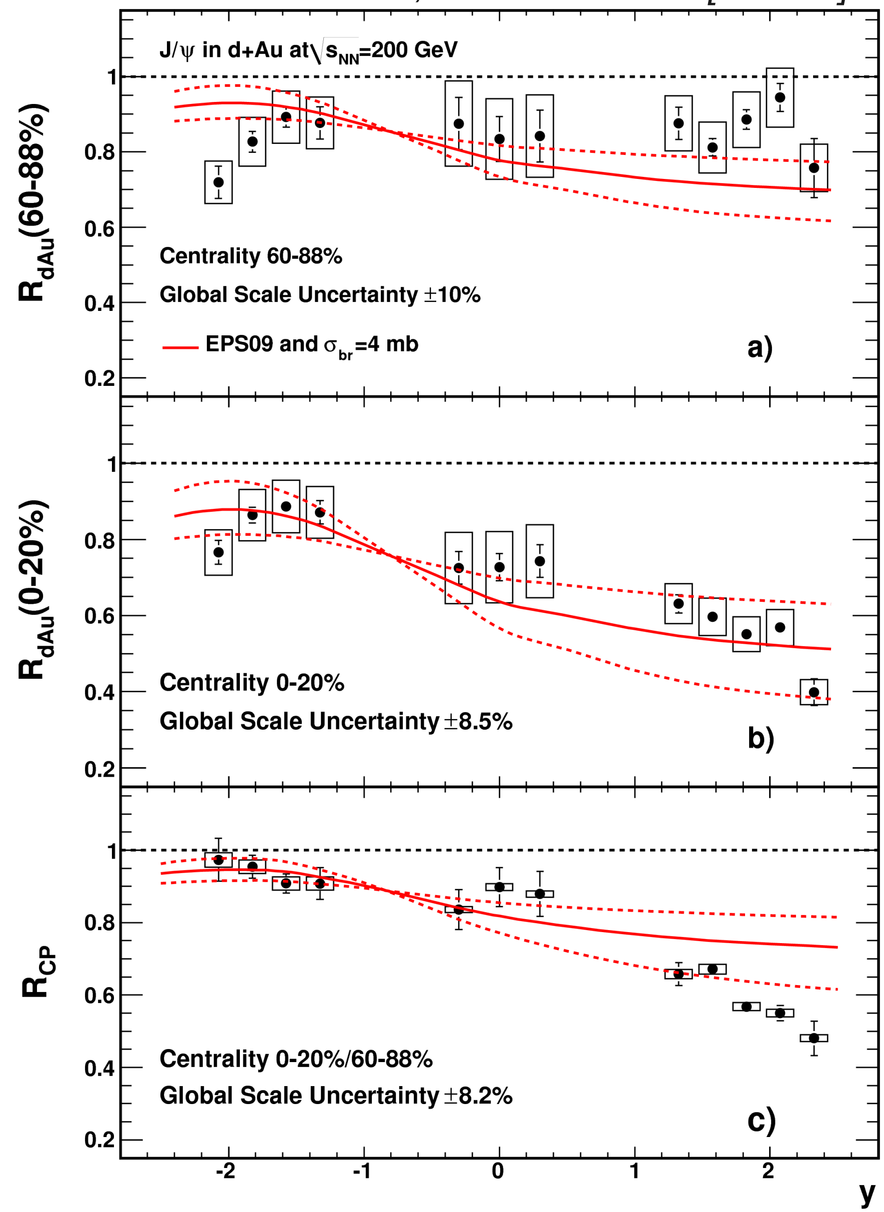
- Use quarkonia to probe screening length in QGP.
- PHENIX has J/ψ data at 200 GeV Au+Au collisions.
  - |y|<0.5 from 2004 RHIC run.
  - 1.2<|y|<2.2 from 2007 RHIC run (recently released *arXiv:1103.6269[nucl-ex]*).
- Suppression is stronger at forward rapidity than midrapidity?
- R_{AA} is believed to include effects due to a nuclear target, termed **cold nuclear matter effects**.



PHENIX d+Au Conclusions (I)

- Compare data with calculation including shadowing + σ_{br}=4 mb.
  - Shadowing from EPS09 nPDF set, which only provides the modification averaged over the entire nucleus.
  - Assume that shadowing is linearly dependent on the thickness of the nucleus.
  - Solid line – central EPS09 set.
  - Dashed lines – EPS09 sets which cause the maximum variation in shape.
- Calculation does not reproduce the centrality dependence of the forward rapidity data.

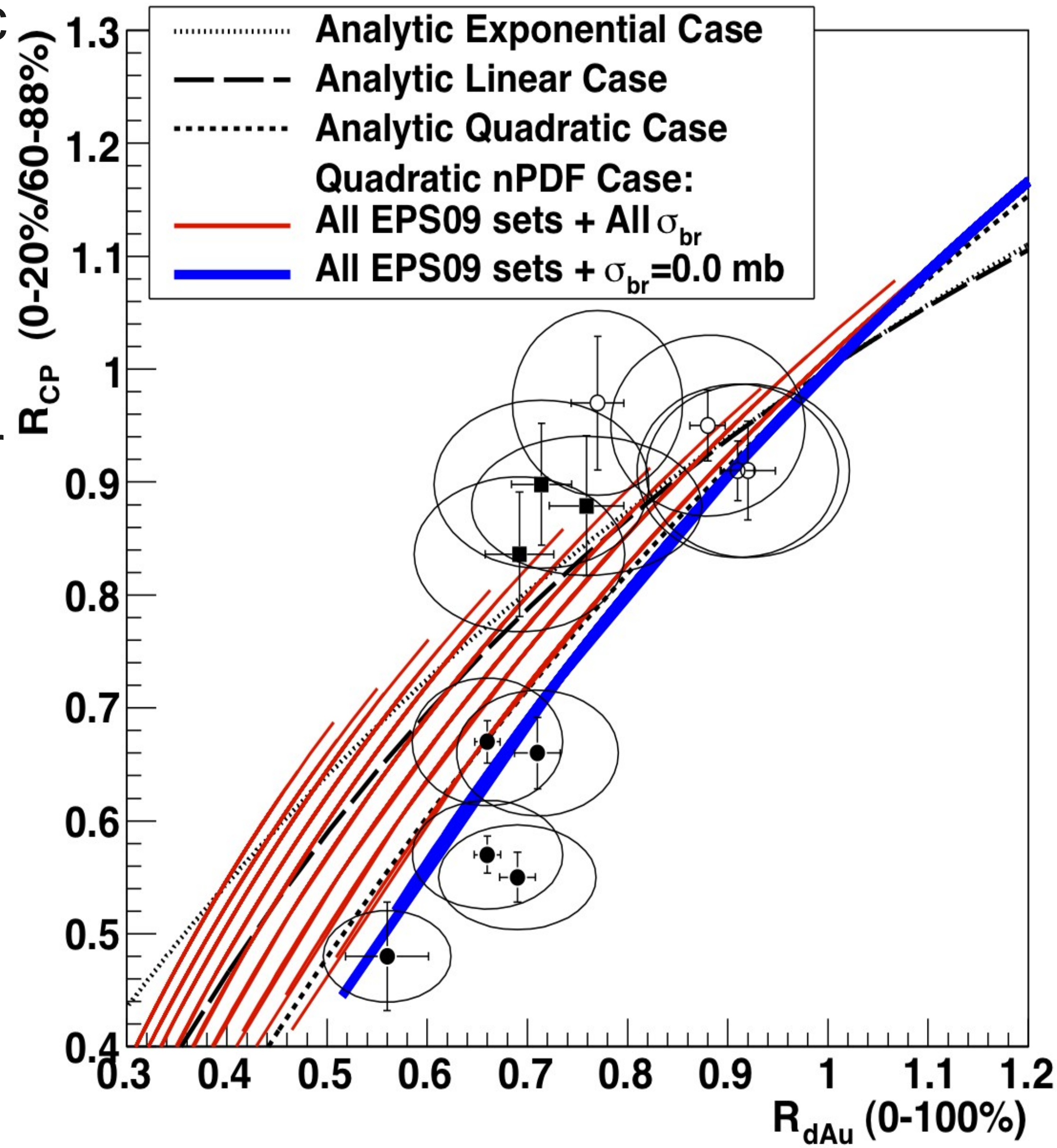
PHENIX, arXiv:1010.1246[nucl-ex]



R_{cp} vs R_{dAu} for EPS09 + σ_{br}

- Includes EPS09 w/ quadratic thickness dependence + σ_{br} from 0-20 in 2 mb steps.
- Also includes density fluctuations.
- Adding (exponential) nuclear breakup makes the agreement at forward rapidity worse.

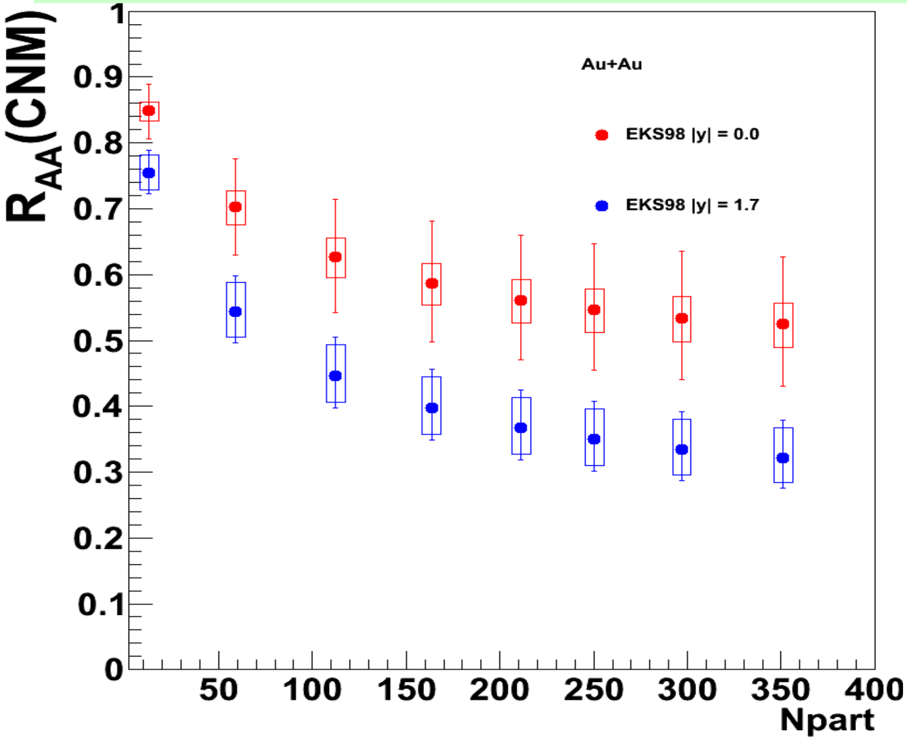
Nagle et al. arxiv:1011.4534



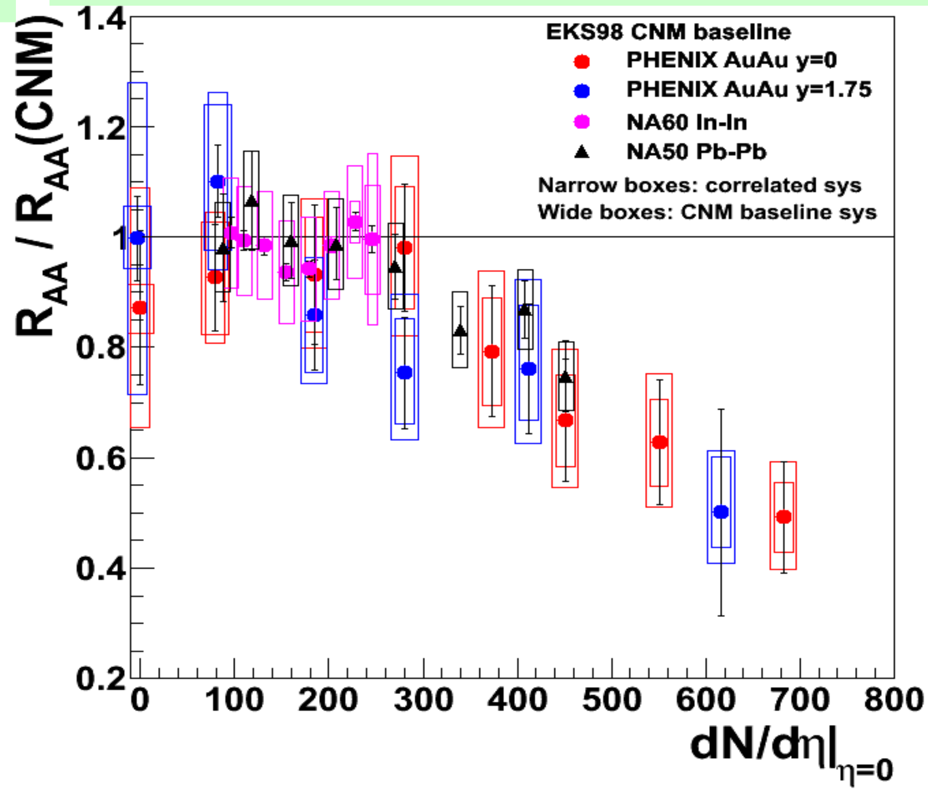
Previous CNM Estimates

Using PHENIX preliminary R_{cp} results from QM2009

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



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



More on Fitting

Use a modified χ^2 fitting procedure which includes the systematic uncertainties on the data. For k centrality bins:

$$\tilde{\chi}^2 = (\sum_{i=1}^{k} \frac{[R_{dAu_i} + \epsilon_{B_i}\sigma_{B_i} + \epsilon_C \sigma_{C_i} - \mu_i(n, \sigma_{br})]^2}{\bar{\sigma}_{A_i}}) + \epsilon_B{}^2 + \epsilon_s{}^2 + \epsilon_C{}^2,$$

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

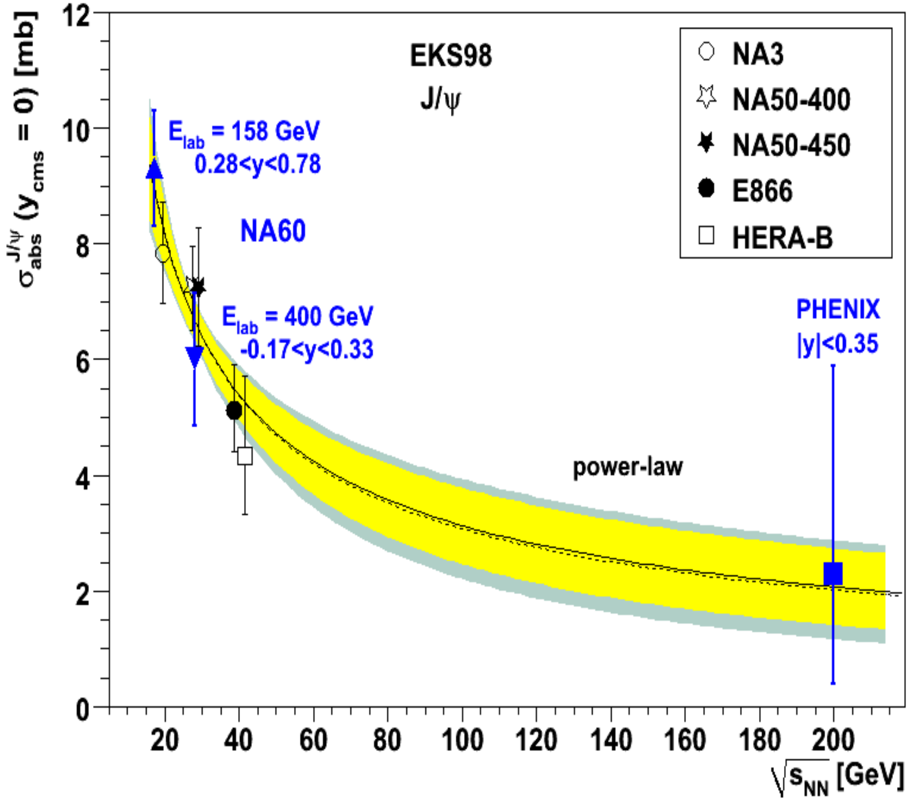
$$\epsilon_{B_i} = \epsilon_B + \epsilon_s \left(1 - 2 \frac{\langle \Lambda(r_T) \rangle_i - \langle \Lambda(r_T) \rangle_0}{\langle \Lambda(r_T) \rangle_N - \langle \Lambda(r_T) \rangle_0} \right),$$

Where *i* indicates the centrality bin, $\sigma_{B(C)}$ are the type B(C) uncertainties, $\mu_i(n,\sigma_{br})$ is the model prediction for the given n and σ_{br} value, $\varepsilon_{B(C)}$ are the fractions by which the type B(C) errors move, and ε_s governs the amount of correlation in the type B erros.

σ_{br} as a Function of Collision Energy

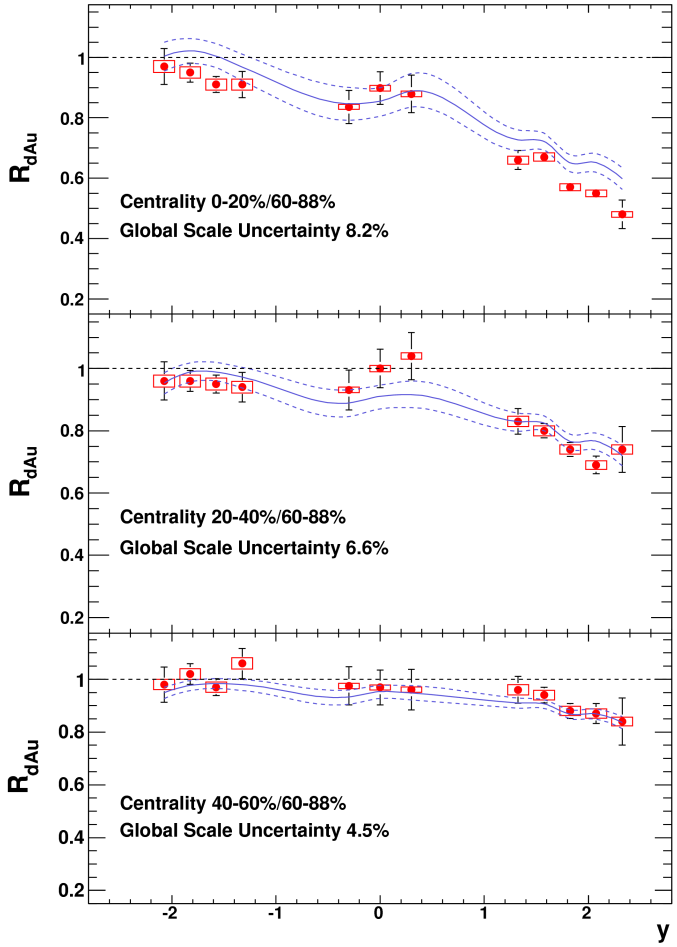
- Fitted σ_{br} values are consistent with the trend observed at lower energies.

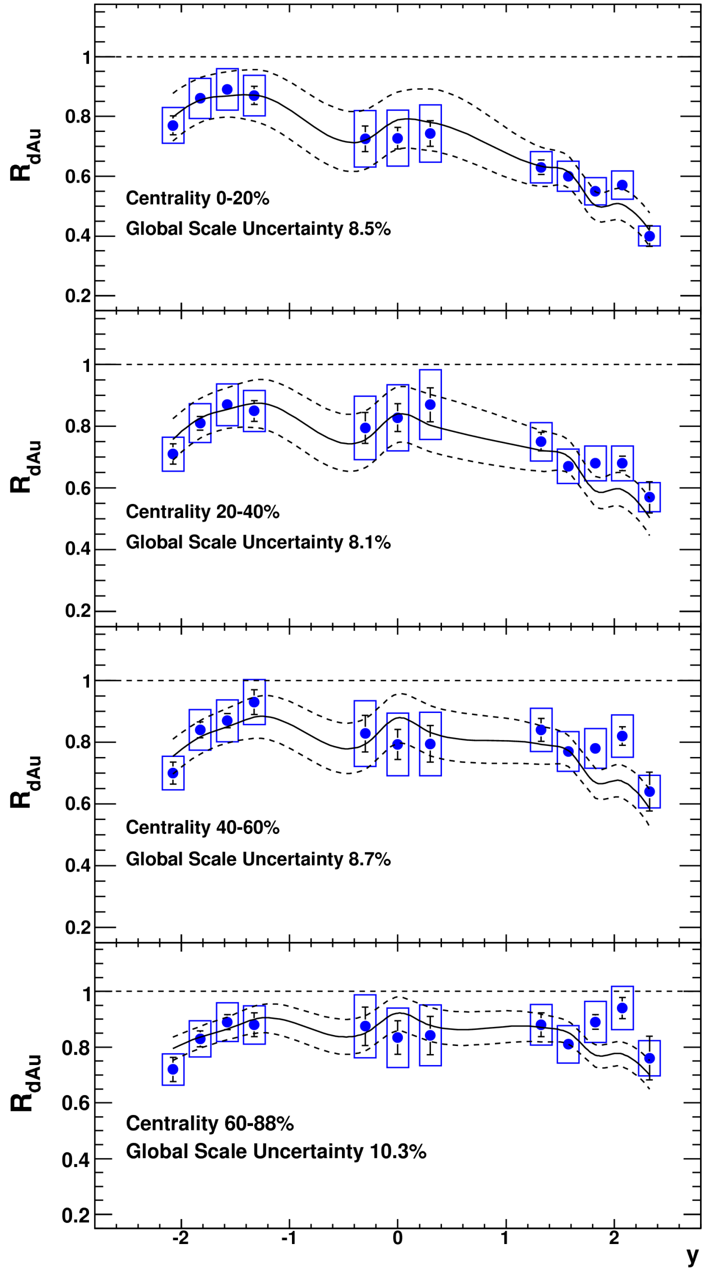
y	σ_{br} (mb)
-0.3	3.35 (+ 1.8 – 2.2)
0.0	1.50 (+ 2.1 – 1.8)
+0.3	1.45 + (1.5 - 2.5)



Fits vs Rapidity

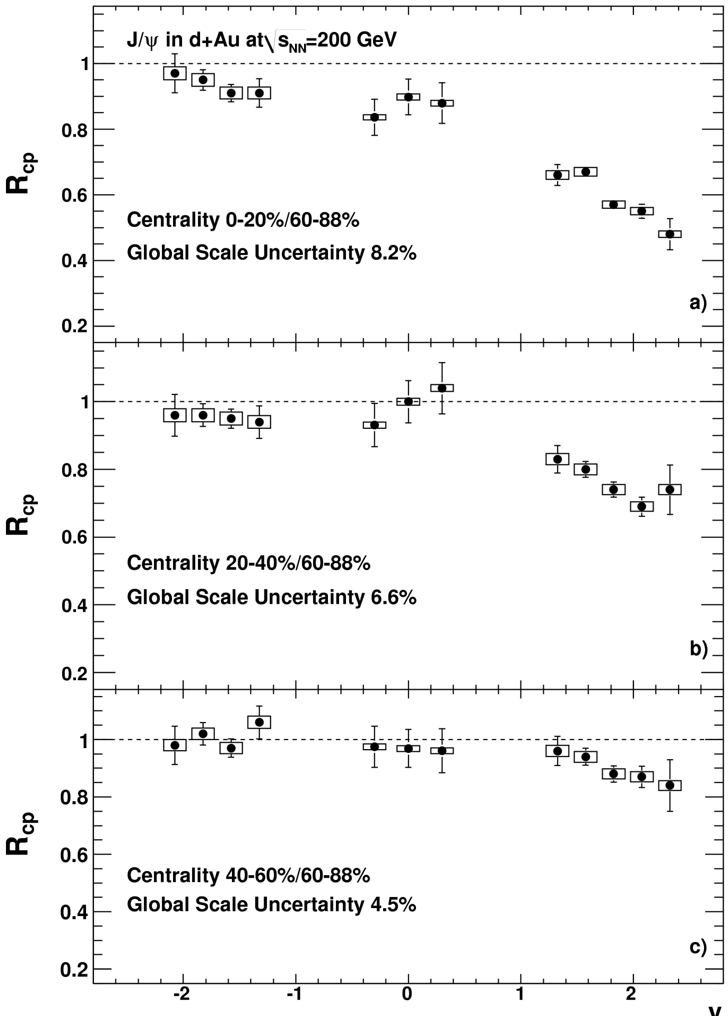
- Using the best-fit n & σ_{br} values from the independent fits to each rapidity.





PHENIX d+Au Results

- PHENIX R_{dAu} results from 2008 RHIC run are now available @ 12 rapidities and in 4 centrality bins. (*arXiv:1010.1246[nucl-ex]*)

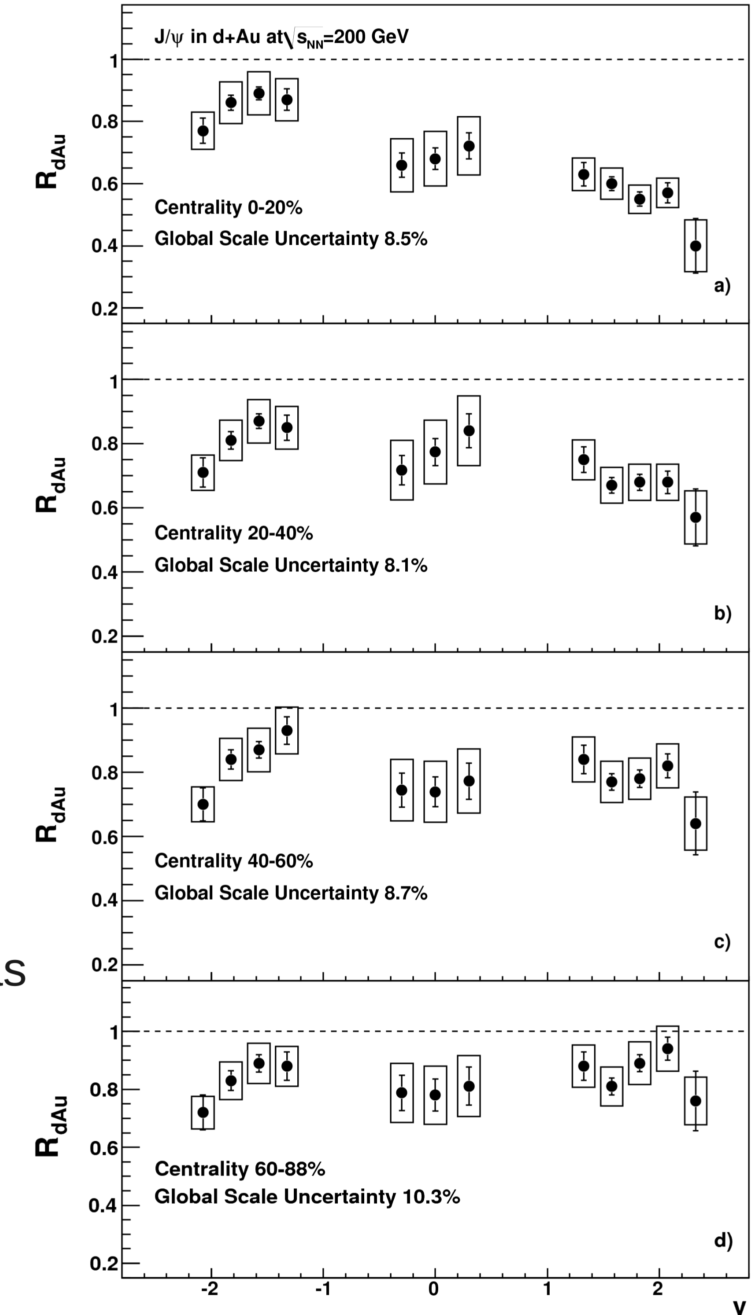


PHENIX, arXiv:1010.1246[nucl-ex]

$$R_{dAu}=\frac{dN^{J/\psi}_{dAu}/dy}{N_{coll}\,dN^{J/\psi}_{pp}/dy}$$

$$R_{CP}=\frac{R_{dAu}(i)}{R_{dAu}(60-88)}$$

Centrality is defined as a percentage of the charge collected in PHENIX BBC detectors.
0% - most central.
88% most peripheral.

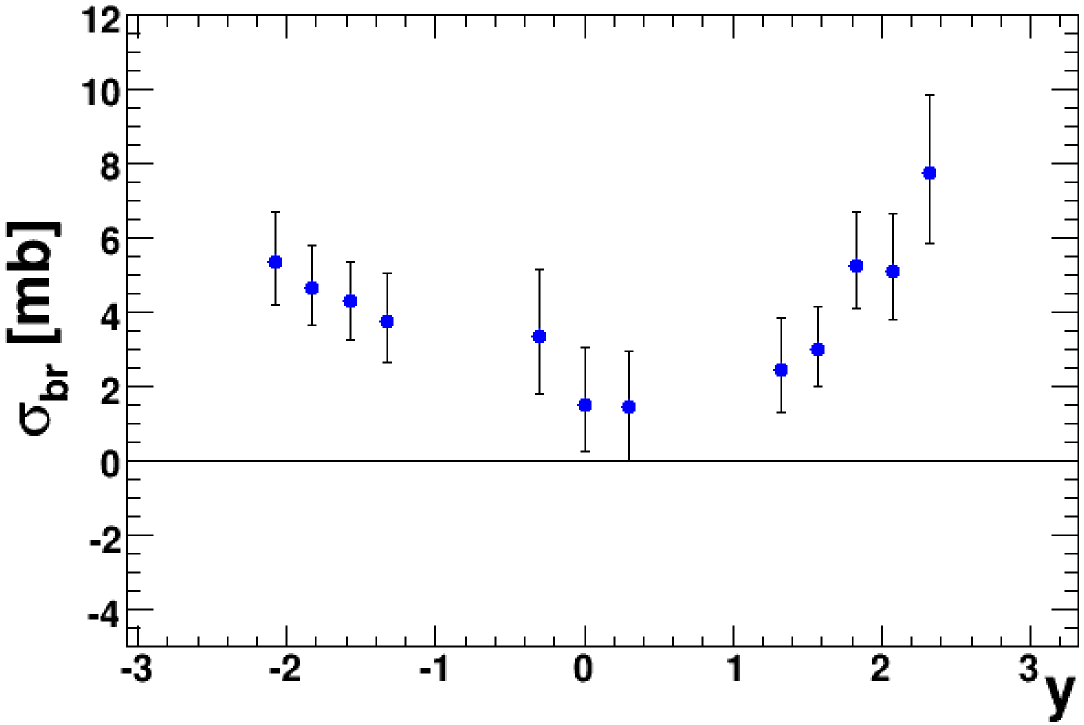


Implementing the Model

- Implement shadowing + break-up in a Glauber model of d+Au collisions.
  - Generate a d+Au event.
  - Determine the centrality bin it belongs to.
  - For each nucleon-nucleon collision in a d+Au event:
    - Calculate $\Lambda(r_T, z_1)$ and use it to calculate M_{br} for a given σ_{br}.
    - Calculate $\Lambda(r_T)$.
    - Choose a p_T based on the measured p+p J/ψ p_T distributions.
    - Calculate x and Q^2 for the given y and p_T.
    - Calculate M_{shad} for a given n.
    - Calculate the total modification, $M_{shad} * M_{br}$.
  - $R_{dAu}(y, n, \sigma_{br})$ is then the total modification averaged over all d+Au events which fall into the given centrality bin.

Integrating the Results over Rapidity

- The PHENIX R_{AA} data is integrated over the full rapidity range of each arm.
- Before projecting our results to R_{AA}, check that rapidity integration in R_{dAu}.
- Use the results from the finely binned, 12 rapidity case, integrate using the measured J/ψ p+p y distribution.
- For uncertainties use the $\Delta\chi^2=1$ values for the best fit power (shown below)

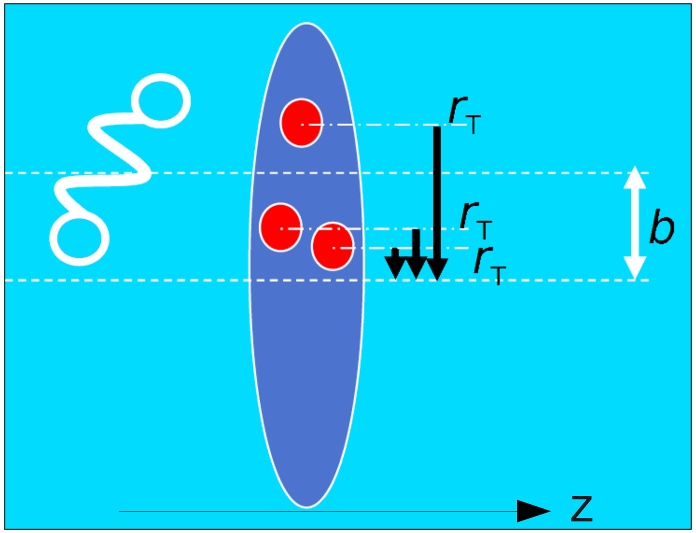


PHENIX d+Au Conclusions (I)

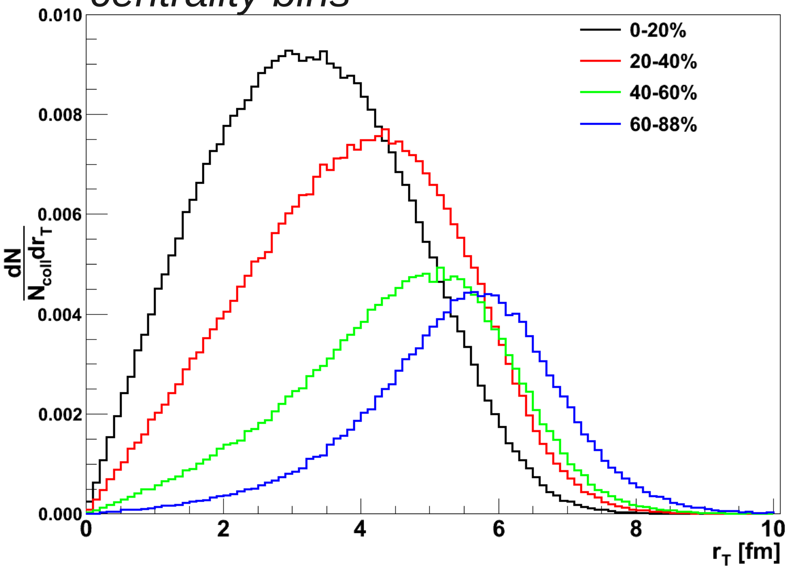
- EPS09 with an assumed linear dependence on the thickness of the nucleus + σ_{br}=4 mb did not reproduce the PHENIX data at forward rapidity.
- PHENIX used a simple geometric model of the modification in d+Au to investigate centrality dependence.
- Use a Glauber model to generate r_T distributions for each centrality bin
  - r_T - transverse position of the struck nucleon in the Au nucleus.
- Use a parametrization of the nuclear modification based on the density-weighted nuclear thickness in the Au nucleus → $\Lambda(r_T)$ [nucleons/fm^2]

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

← Woods-Saxon distribution

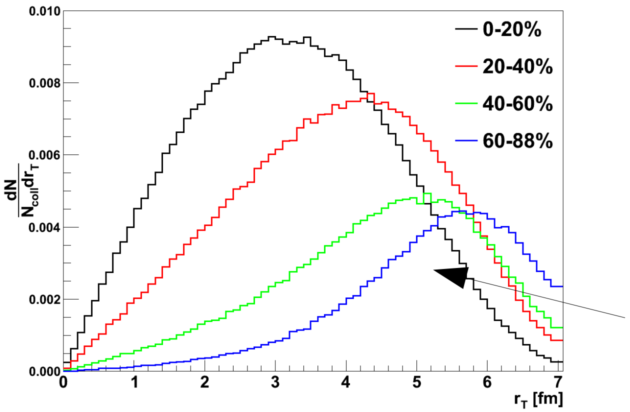


r_T distributions for the PHENIX centrality bins



Shadowing vs r_T

- What do these high powers mean?
- Plot only shadowing vs r_T.
  - Red curves: best fit powers.
  - Blue curves: best fit power limits.
- Where the modification is strong, turns on suddenly at r_T~3-4 fm.
- Remember that the data does not probe a well-defined, unique r_T range!



$<r_T>$(0-20%) = 3.23 fm
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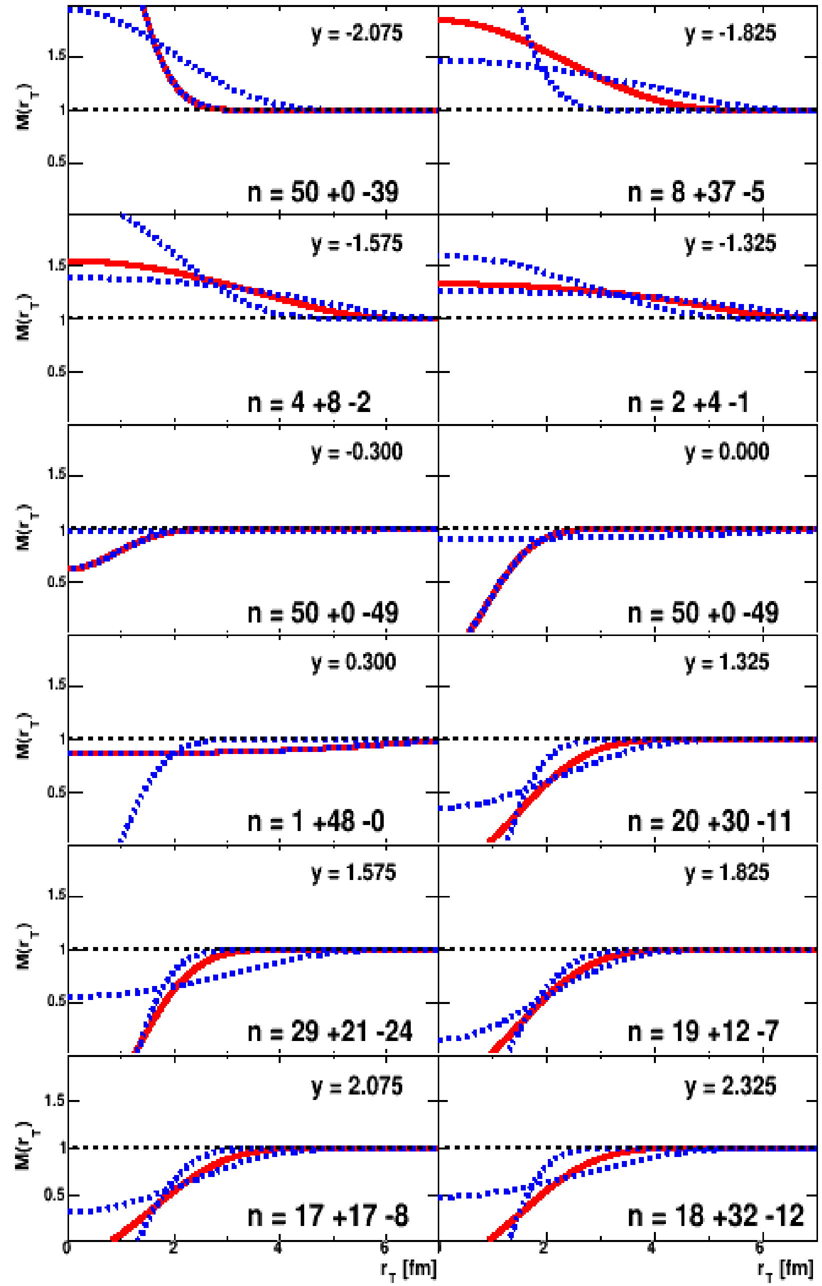

Integrating the Results over Rapidity

- Results using the best fit n & σ_{br} values at each of the 12 rapidities, integrated over y using the measured PHENIX J/ψ p+p y distribution.
- Results are in good agreement with the arm integrated R_{dAu}.
- Also shown are the R_{CP} data points and curves.