"The emergence of QCD is a wonderful example of the evolution from farce to triumph" David Gross, from his Nobel Lecture

Recent Results on d+Au Collisions from PHENIX

Richard Seto

for the

PHENIX

Experiment

RHIC/AGS User's meeting

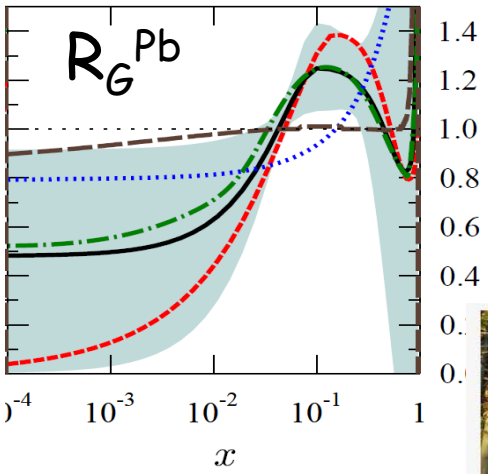
Jun 6, 2009

Outline

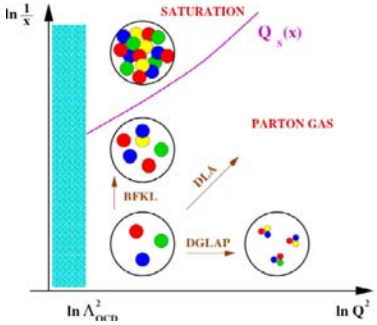
- d+Au collisions
  - forward hadrons
  - forward J/ψ
- a sort of Non Sequitur
  - An estimate of the NDOF (effective)
- Conclusions

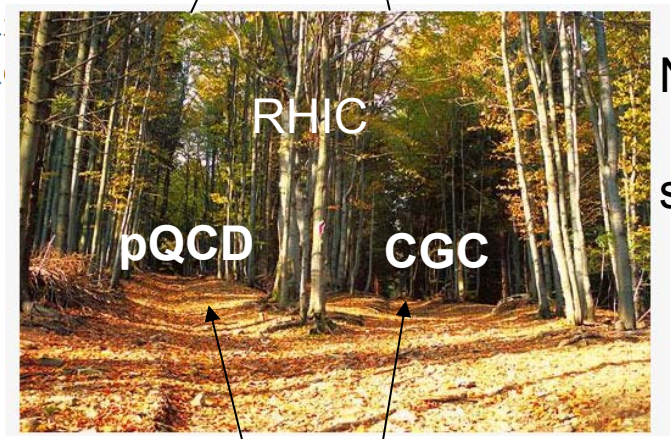
slides shamelessly stolen from
Tony Frawley, Mike Leitch,
Beau Meredith, Mickey Chiu,….

dAu QCD: Two roads diverged in a yellow wood



will the two ever meet?

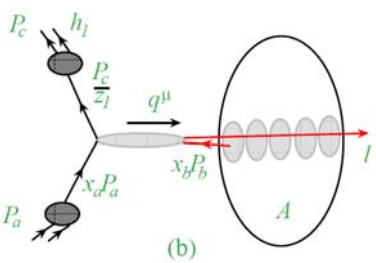




Nucleus Gluon low-x blob =
Classical E_{color} field
soup it up with quantum corrections

Clear "simple" theory in one framework – works at "low" x $<10^{-2}$

To be useful, one has to use a model



consideration of various phenomena
often a menu
consider LT, HT
initial state ms,….

QCD

Are these really two different paths?
Or are they really two different views same forest?

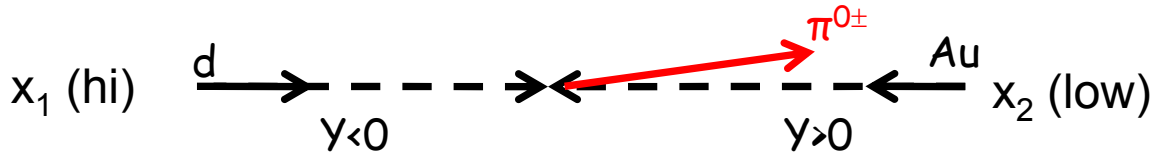
d+Au – forward hadrons I

π^0s and correlations

Predictions - forward

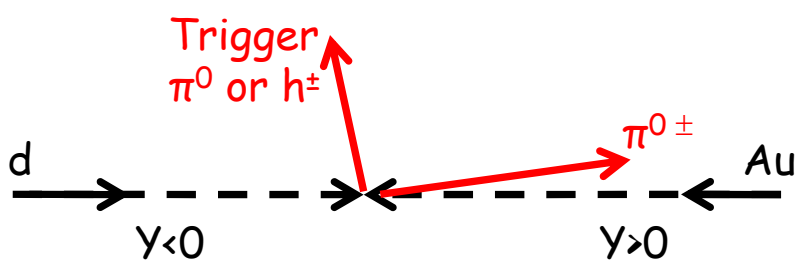
- pQCD
- Colored Glass

single particles



- suppression of forward hadrons
- suppression of forward hadrons

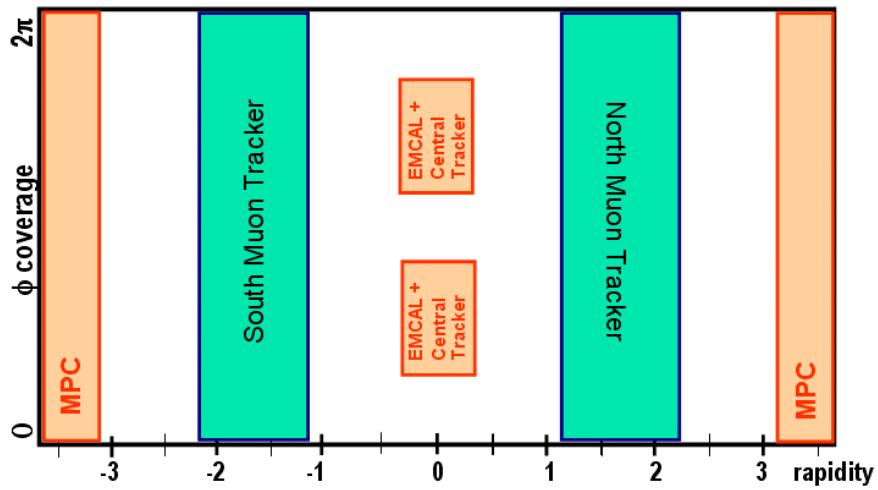
Correlations

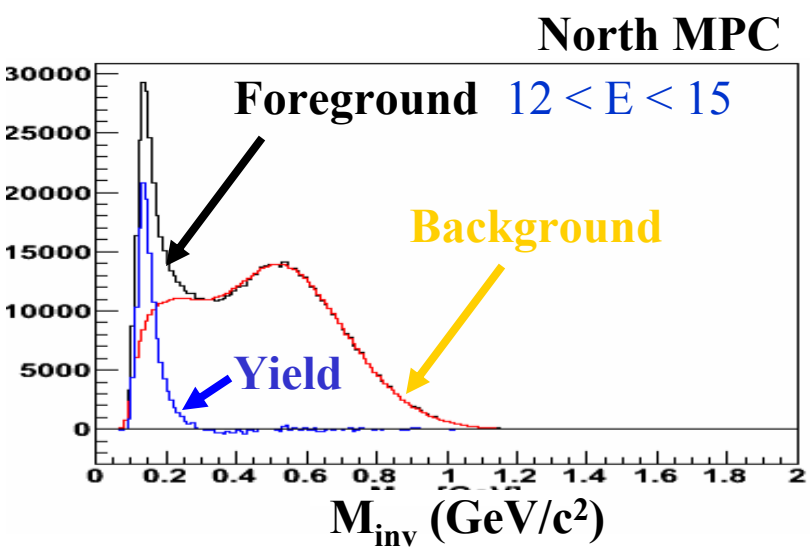


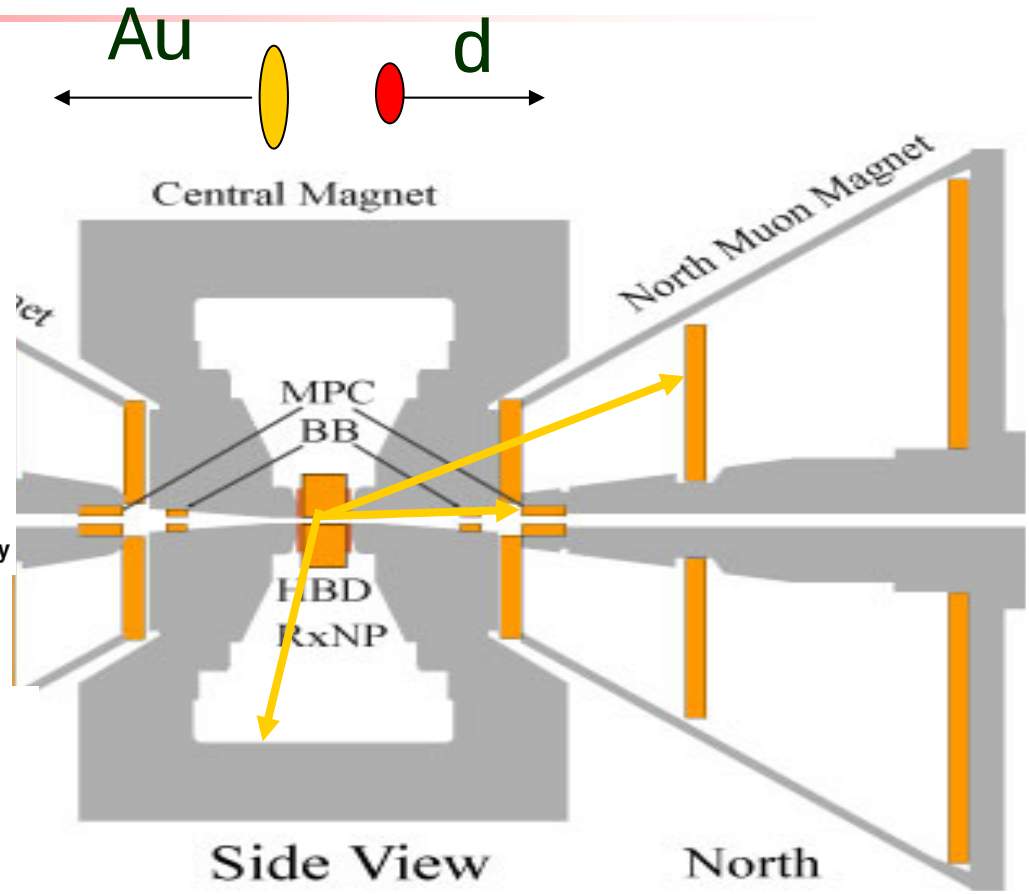
- Widening of correlation
- Yields Reduced

- Widening of correlation
- Yields being calculated (C. Marquet)

How does PHENIX see this stuff?







The MPC can reliably detect pions (via $\pi^0 \rightarrow \gamma\gamma$) up to *17* GeV in energy

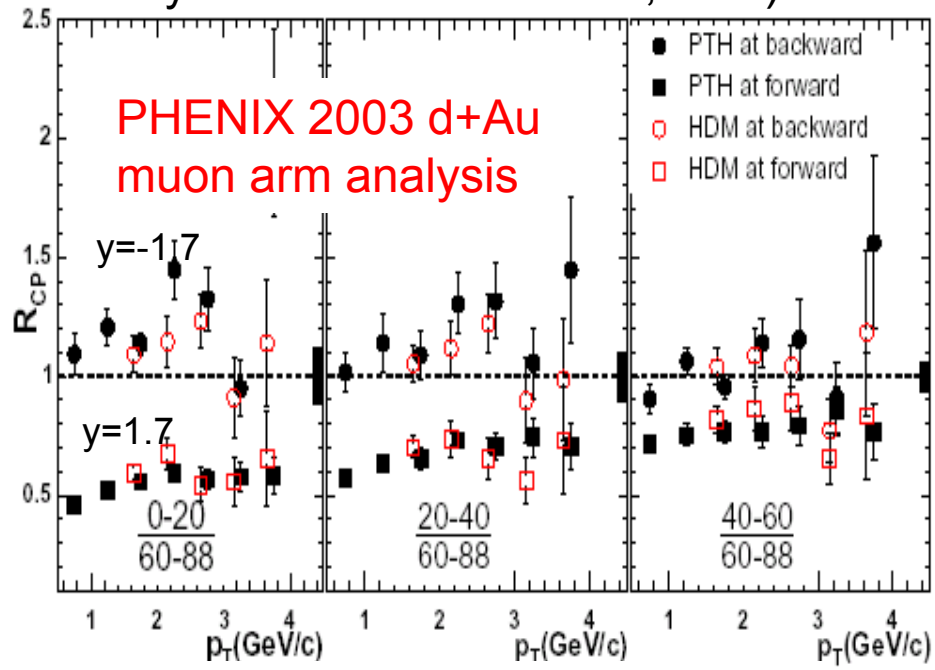
➔ *pT* max ~ *1.7* GeV/c

To go to higher *pT*, use single clusters in the calorimeter

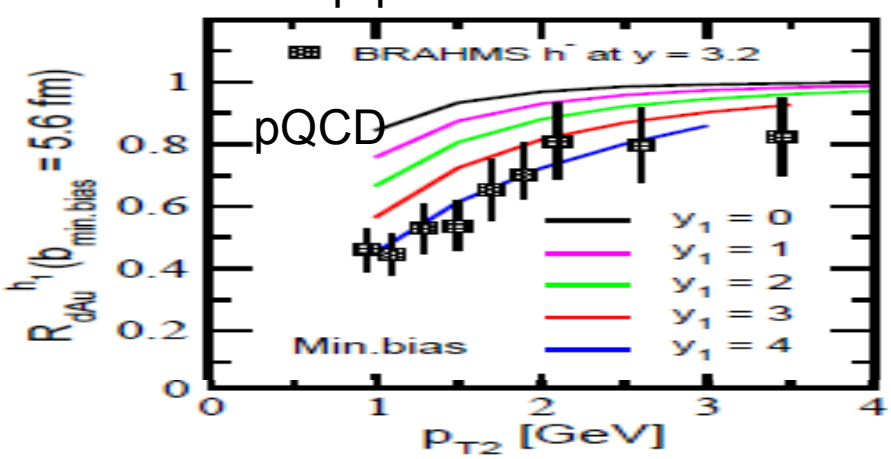
Rcp,RdAu

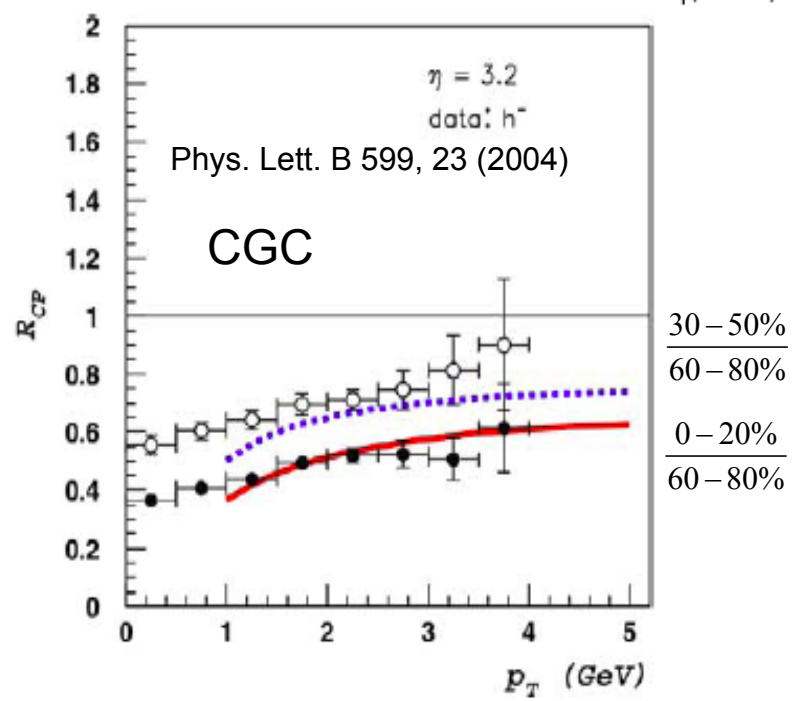
- Suppression of forward particles
  - muon analysis
- consistent among all expts

Phys.Rev.Lett.94:082302,2005).



hep-ph/0405068v2



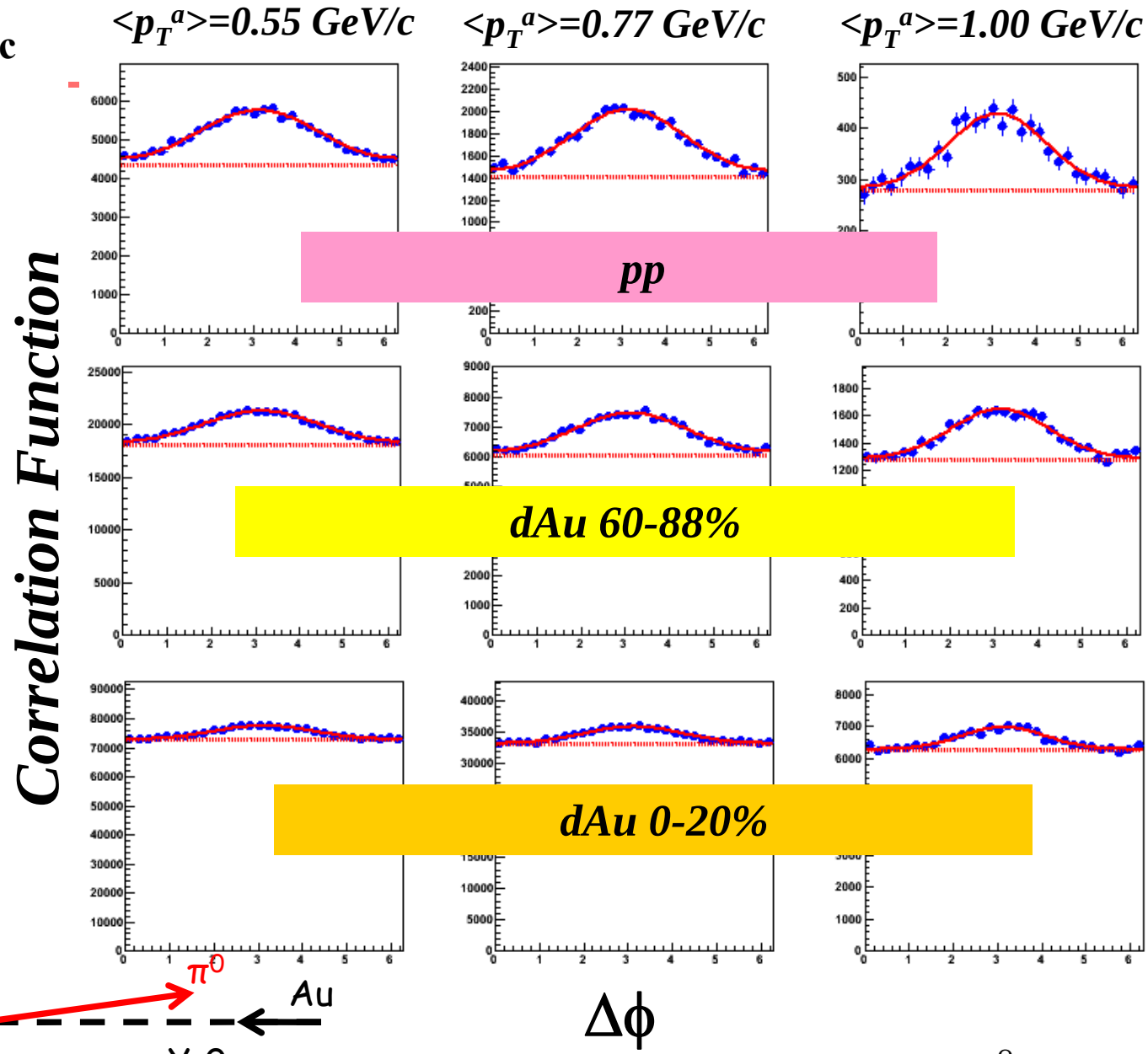


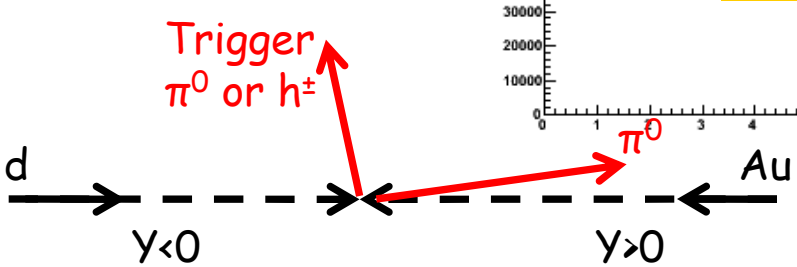
Correlations: $h^{+/-}$ (trigger,central)/π^0 (associate,forward)

1.0 < p_T^t < 2.0 GeV/c

for all plots

MPC+central arm

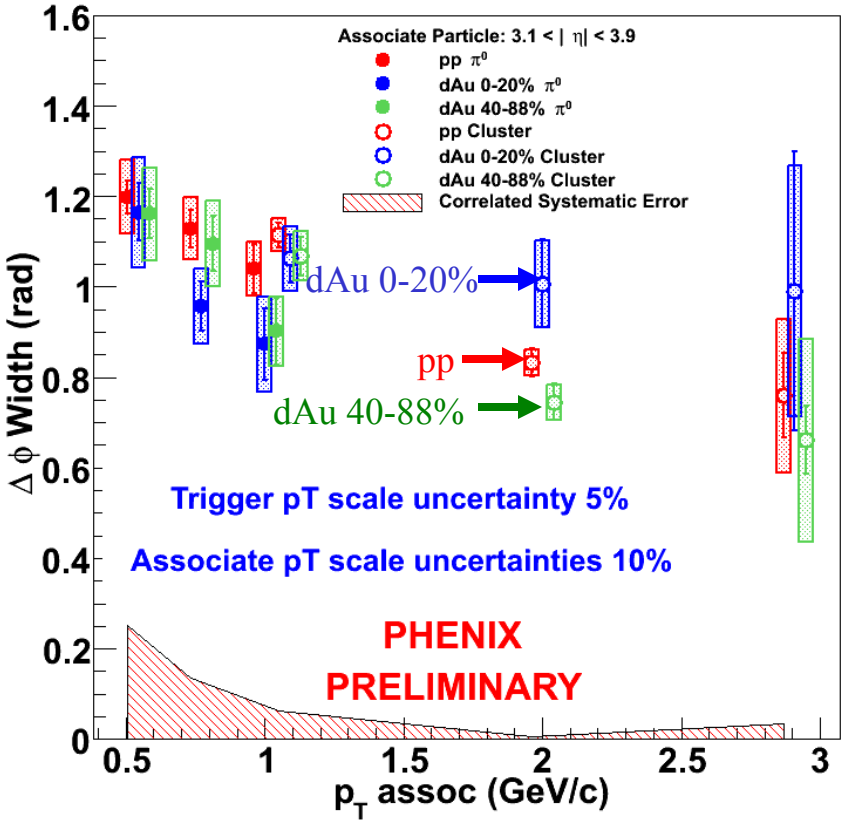




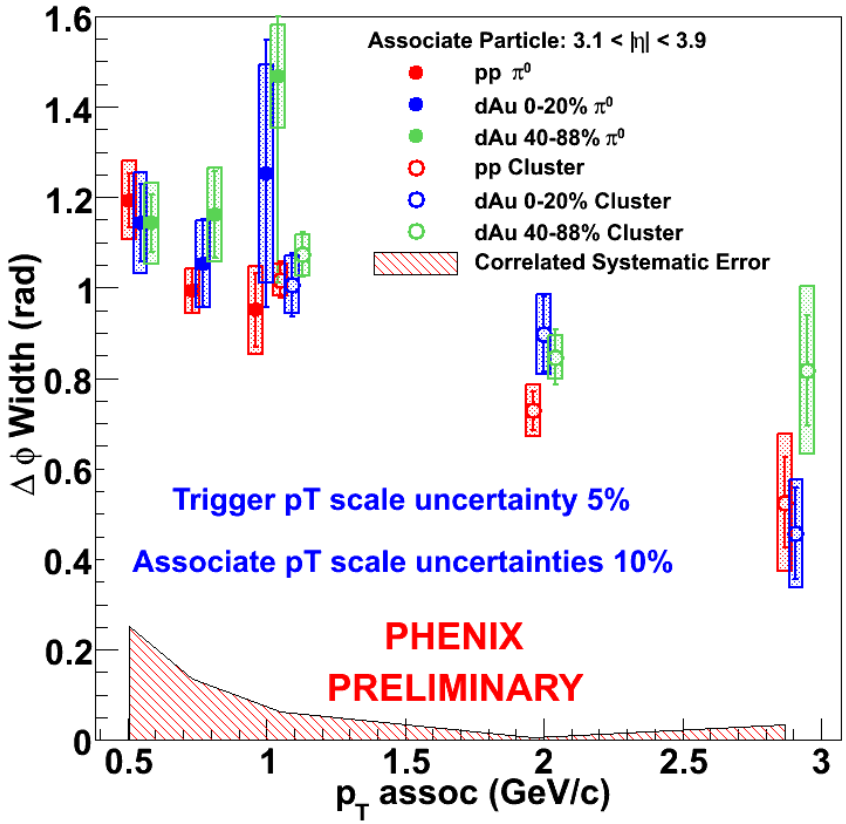
Forward/Central Correlation Widths

- No significant changes in correlation width between pp and dAu within experimental uncertainties expect r,g,b(widest)

Trigger π^0: $|\eta| < 0.35$, $2.0 < p_T < 3.0$ GeV/c

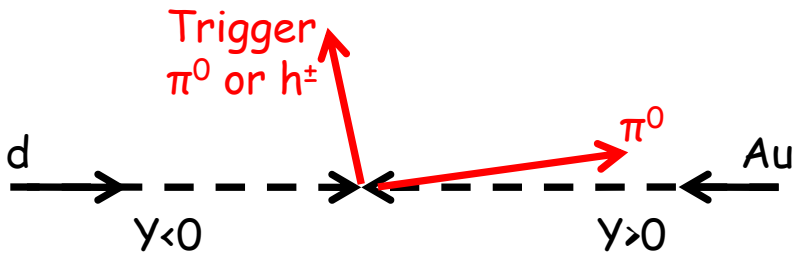


Trigger π^0: $|\eta| < 0.35$, $3.0 < p_T < 5.0$ GeV/c



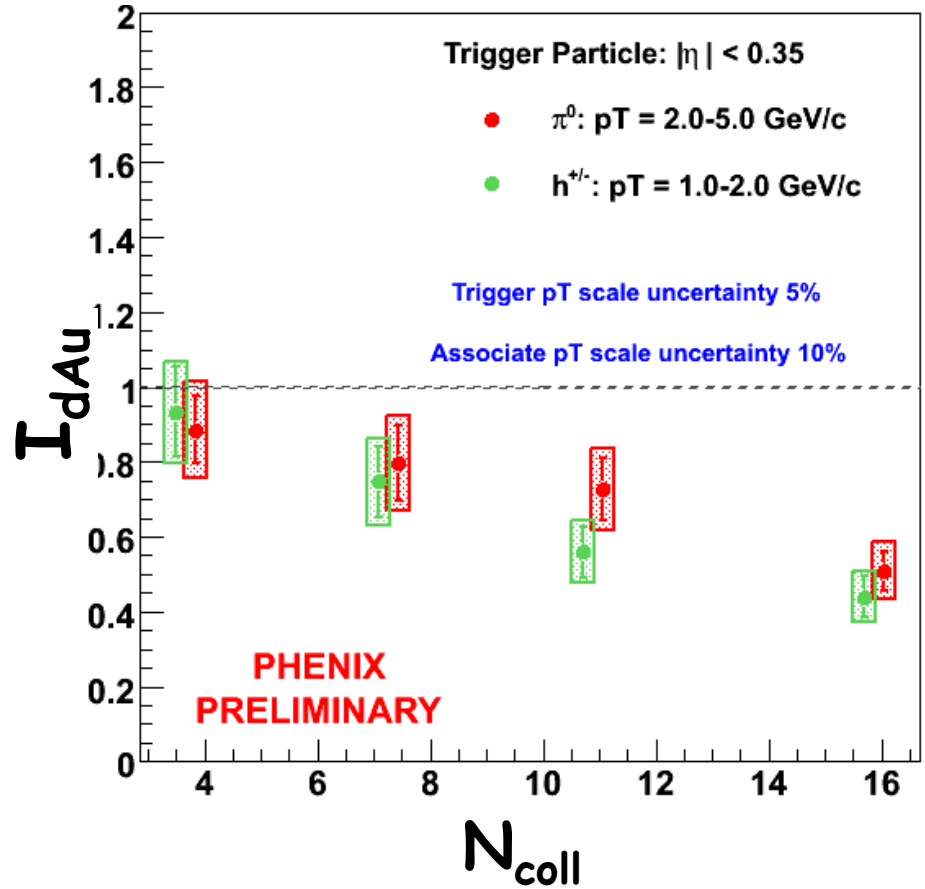
Rapidity-separated hadron correlations in d+Au

$$I_{dAu} = \frac{N^{pair}_{d+Au}\left[(\eta=3.5)+(\eta=0)\right] / N^{trig}_{d+Au}(\eta=0)}{N^{pair}_{p+p}\left[(\eta=3.5)+(\eta=0)\right] / N^{trig}_{p+p}(\eta=0)}$$



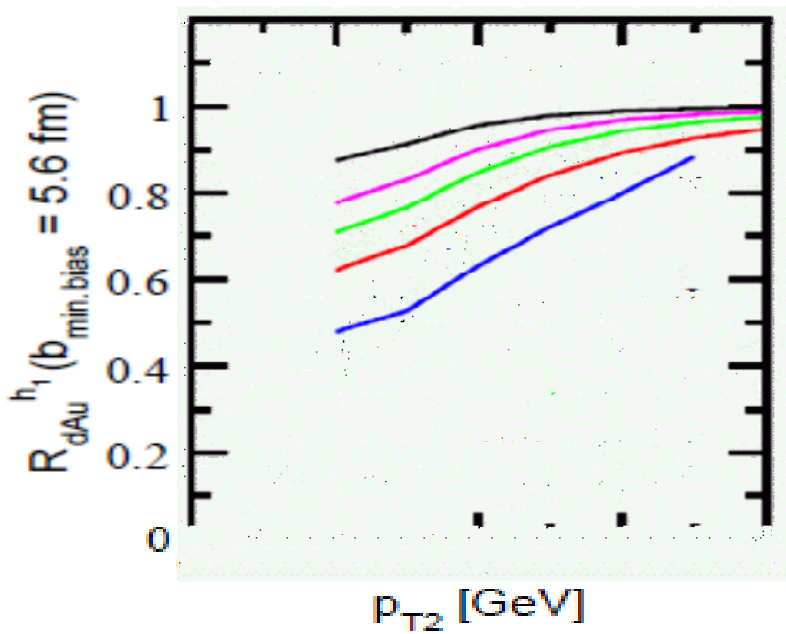
I_{dAu} suppressed at forward rapidity for more central collisions

Associate π^0: 3.1<η<3.9 p_T = 0.45-1.59 GeV

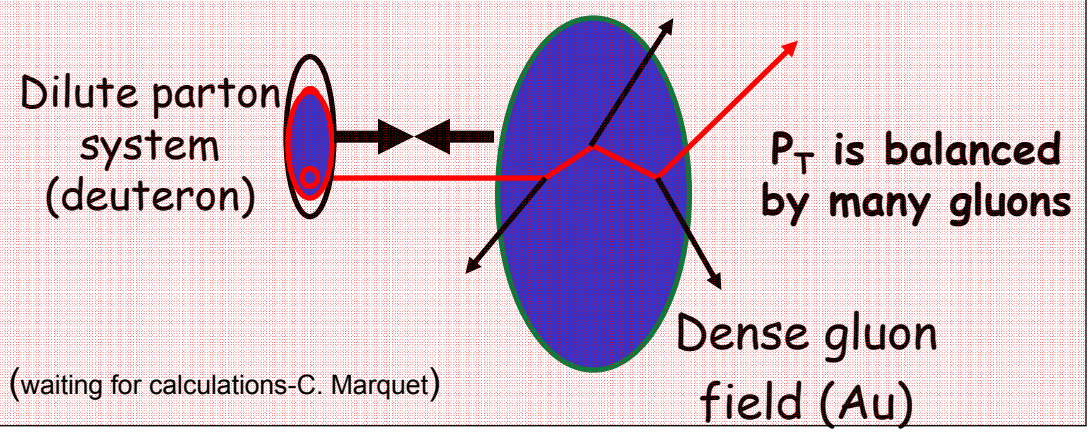


Rapidity-separated hadron correlations in d+Au
what does a pQCD and CGC model predict?

shadowing (non-LT) gives suppression of pairs wrt to singles
Vitev, hep-ph/0405068v2



Mono-jets in the gluon saturation (CGC) picture give suppression of pairs per trigger and some broadening of correlation
Kharzeev, NPA 748, 727 (2005)



(waiting for calculations-C. Marquet)

Conclusions

- forward (1<y<3) R_{dAu} suppressed (run-3 Muon arm analysis)
- Correlation Analysis: Trigger on central arm look at MPC (3<y<4)
  - Width not dependent Centrality within errors
  - I_{dAu} suppressed for more central d+Au
- So what?
  - Waiting for predictions on I_{dAu} from CGC
  - Many pre (post) dictions of the pQCD and CGC are similar
    - Are they really different theories? or different approximations applicable in different regions? - can we see them meet in the middle?

dAu – forward hadrons II

J/ψ - an attempt to understand

Cold Nuclear matter effects

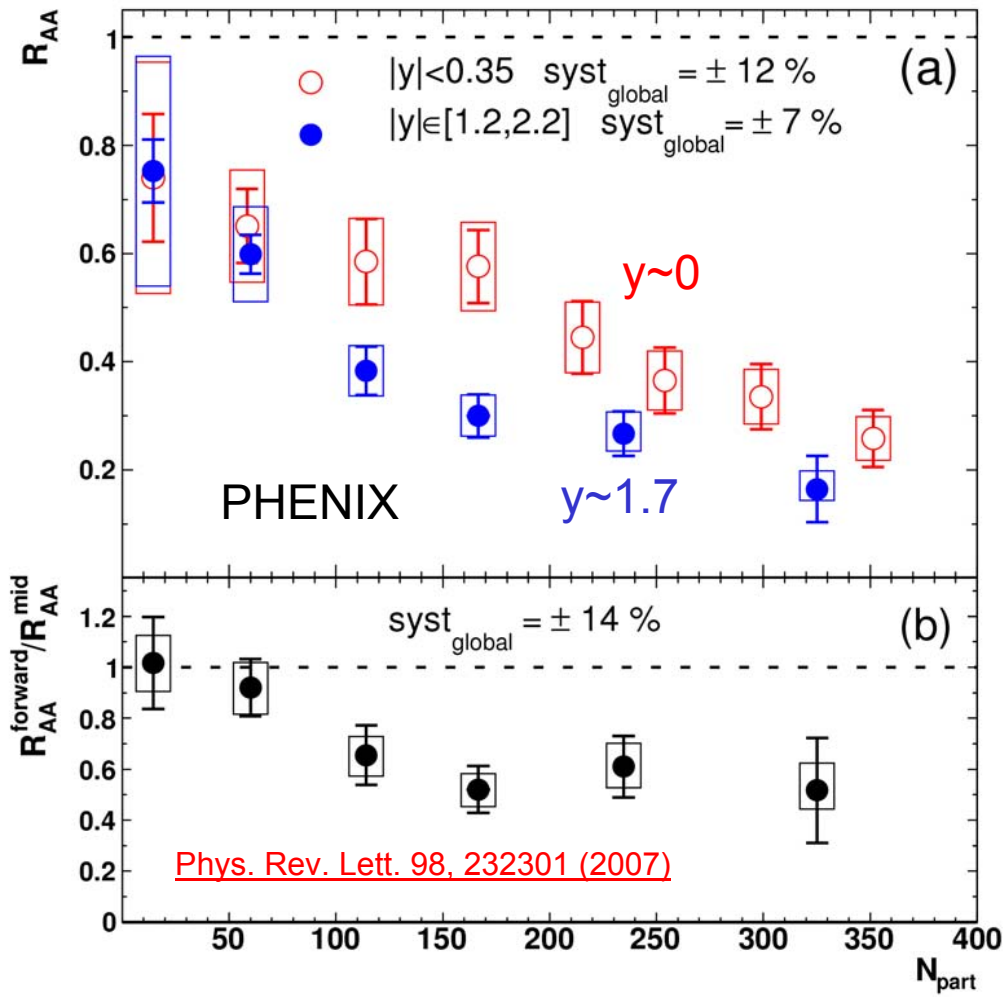
Tony Frawley, Mike Leitch, Ramona Vogt,
Alex Levy, Jamie Nagle, Darren McGlinchey

for more details see http://www.ect.it/

Au+Au R_{AA} - A "high y anomaly" (just kidding)

The stronger Au+Au suppression at forward/backward rapidity has generated considerable interest.

But what is the expected suppression due to **cold nuclear matter effects**?

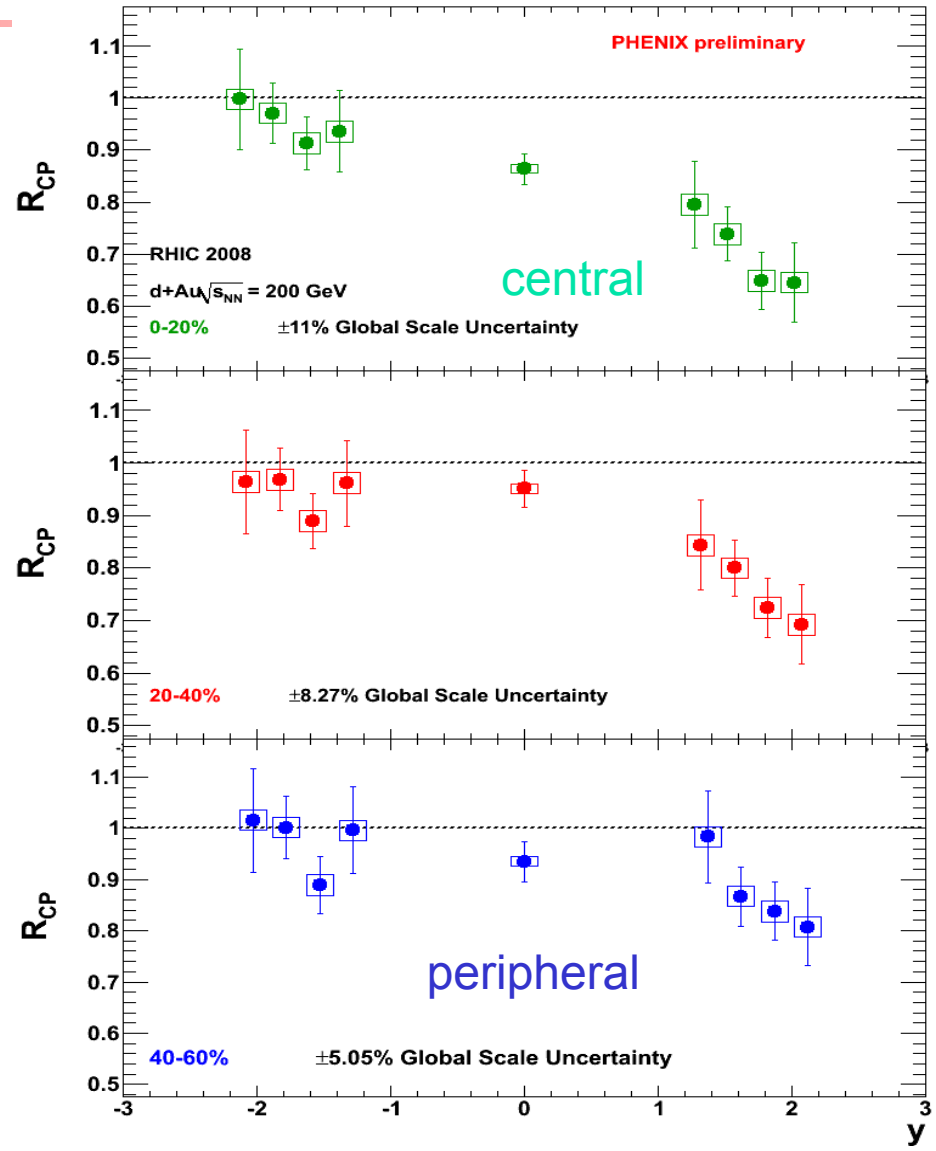


d+Au R_{CP}

The first results for d+Au from Run 8, shown at QM09.

Four centrality bins to make three R_{CP} points:

$$R_{CP} = \frac{\frac{dN}{dy}(0-20, 20-40, 40-60)}{\frac{dN}{dy}(60-80)}$$

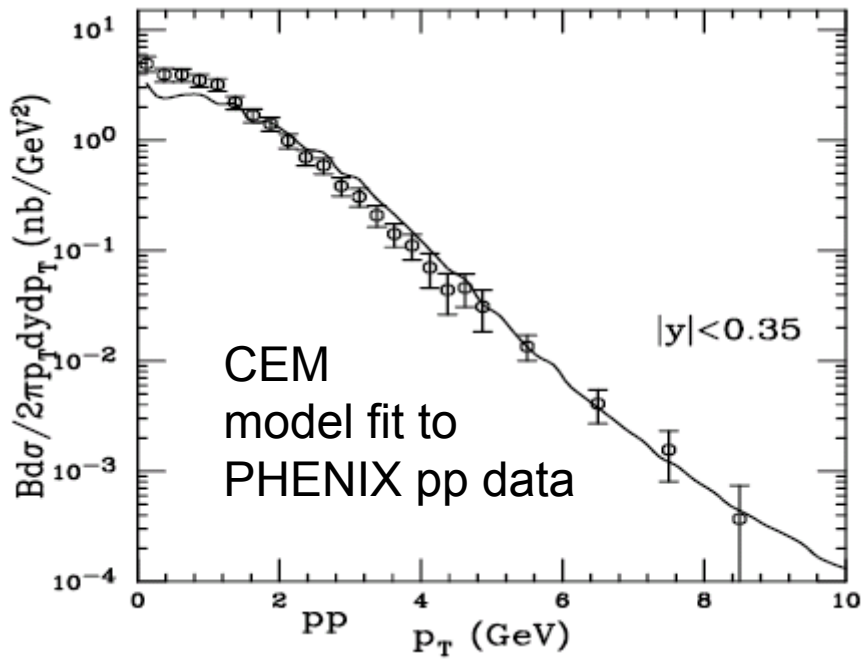


Fitting the Run 8 d+Au R_{CP}

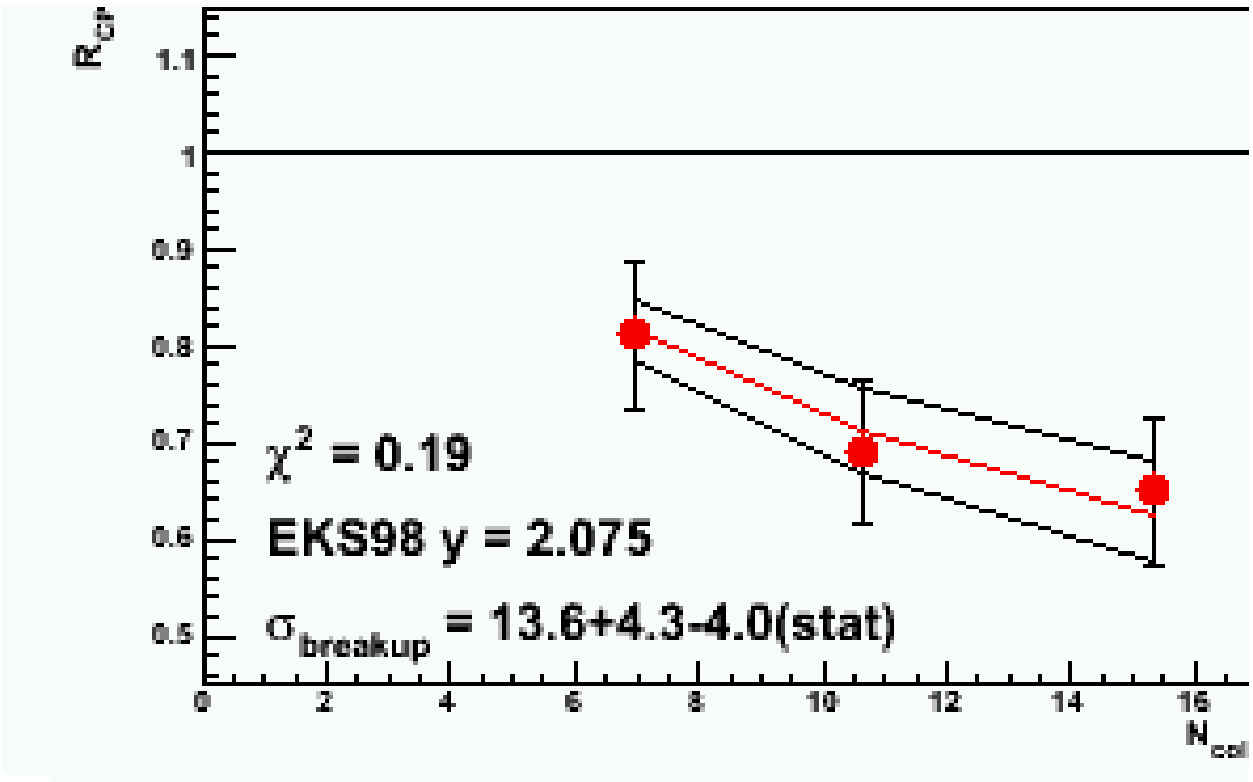
- **parameterize** d+Au R_{CP}
  - ➔ obtain AuAu R_{AA} with p+A physics divided out.

- Fit R_{CP} vs centrality **at each y** using calculations of R_{dAu} vs b
  - Color Evaporation Model (model of Ramona Vogt)
  - shadowing PDF's – EKS98 and nDSg are used here.
  - $\sigma_{breakup}$ for J/ψ **is allowed to vary with y**

- Convert R_{dAu} vs impact parameter to R_{dAu} vs centrality
  - use Glauber model

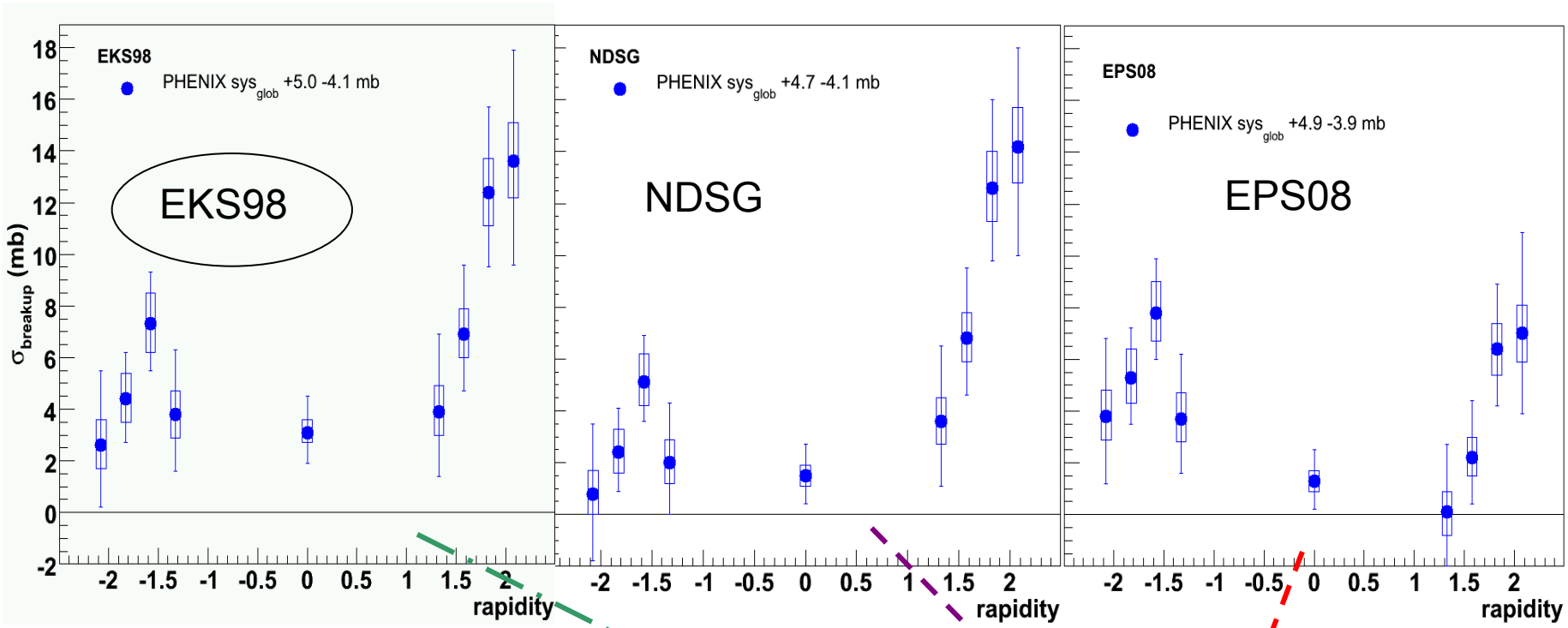


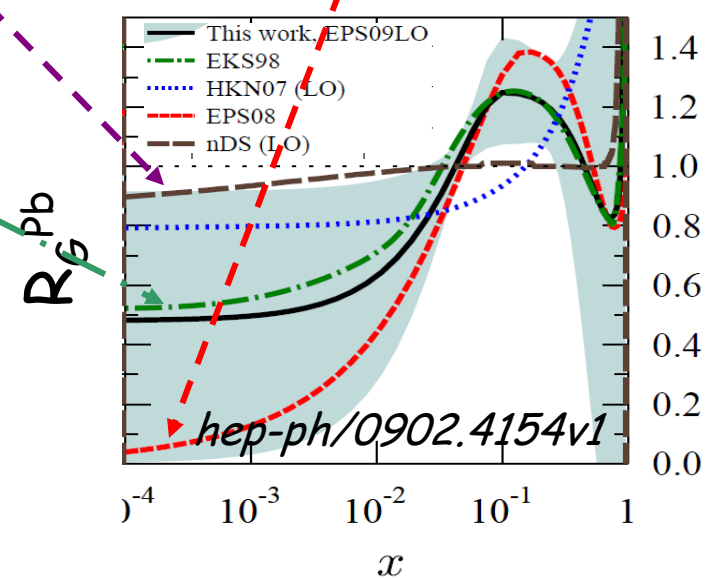
Fits to d+Au R_{CP} – example for EKS98



Au going -y ⟷ +y deuteron going

$\sigma_{breakup}$ vs y from d+Au R_{CP} fits with EKS98 and nDSg

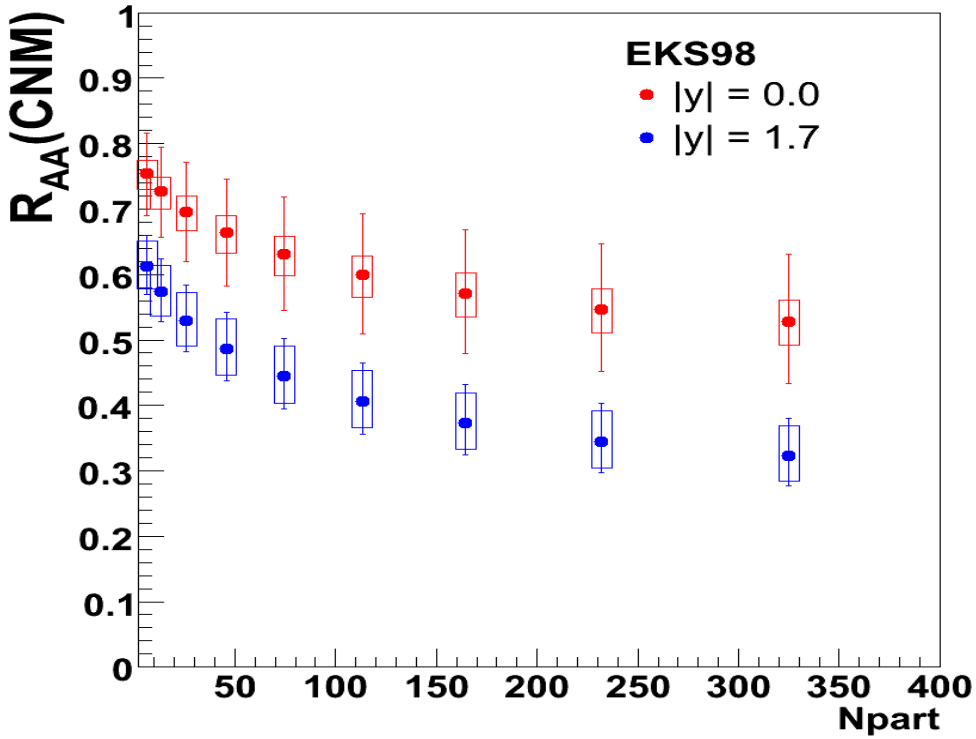




$\sigma_{breakup}$ Dependent on PDF shadowing model

$\sigma_{breakup}$
effective cross section which might indicate physics not in the model (e.g. initial state dE/dx…)

Cold Nuclear Matter RAA for heavy ions



Now estimate R_{AA}(CNM) using the results from the dAu R_{CP} fits and a Glauber model

In the Glauber calculation:

Each nuclear collision is placed in a centrality bin according to Npart.

For each nucleon-nucleon collision:

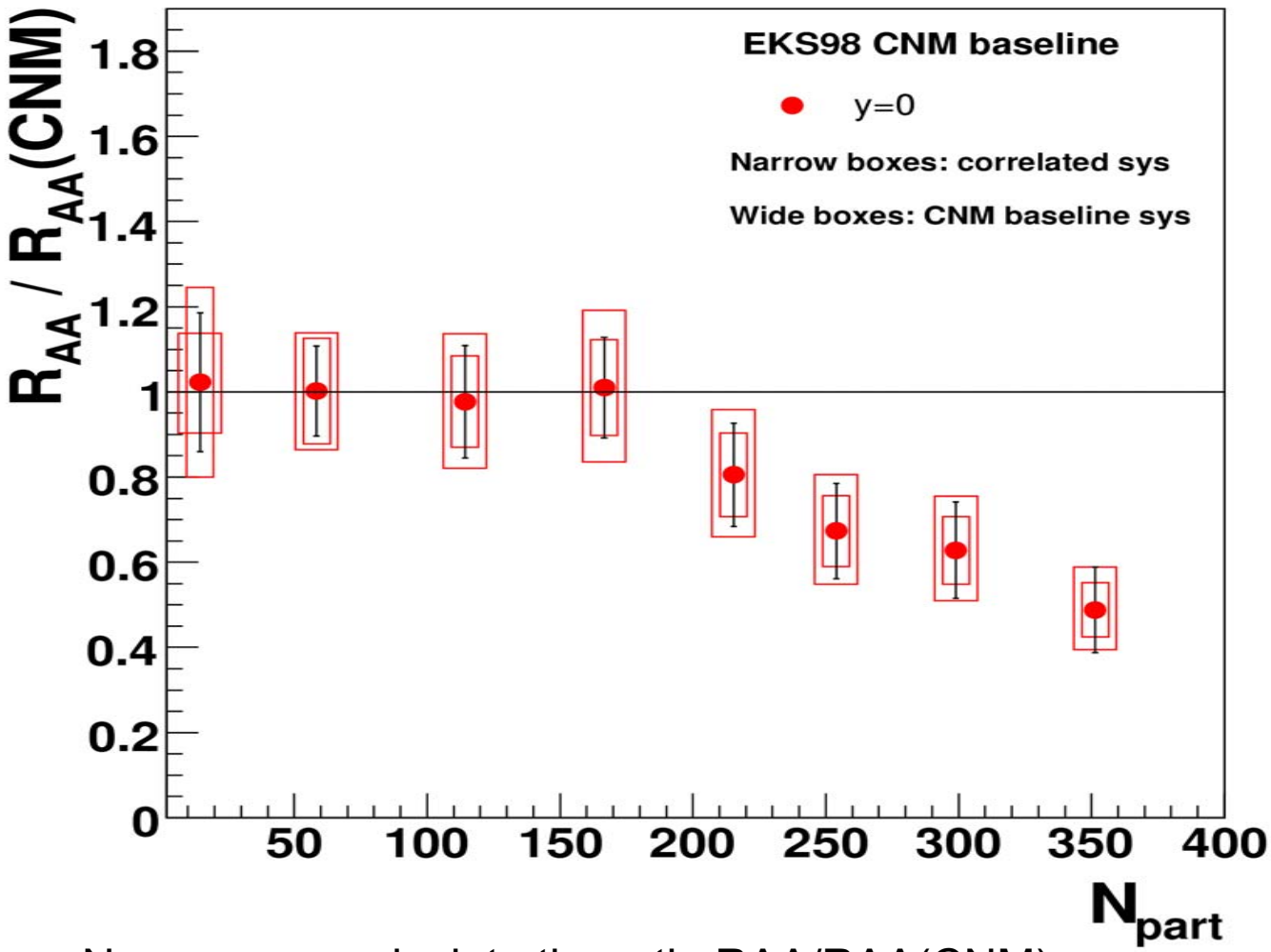
Determine impact parameter b1 of nucleon 1 in its target nucleus.

Determine impact parameter b2 of nucleon 2 in its target nucleus.

Add to the accumulated RAA: RdAu(b1,y=0) * RdAu(b2,y=0)

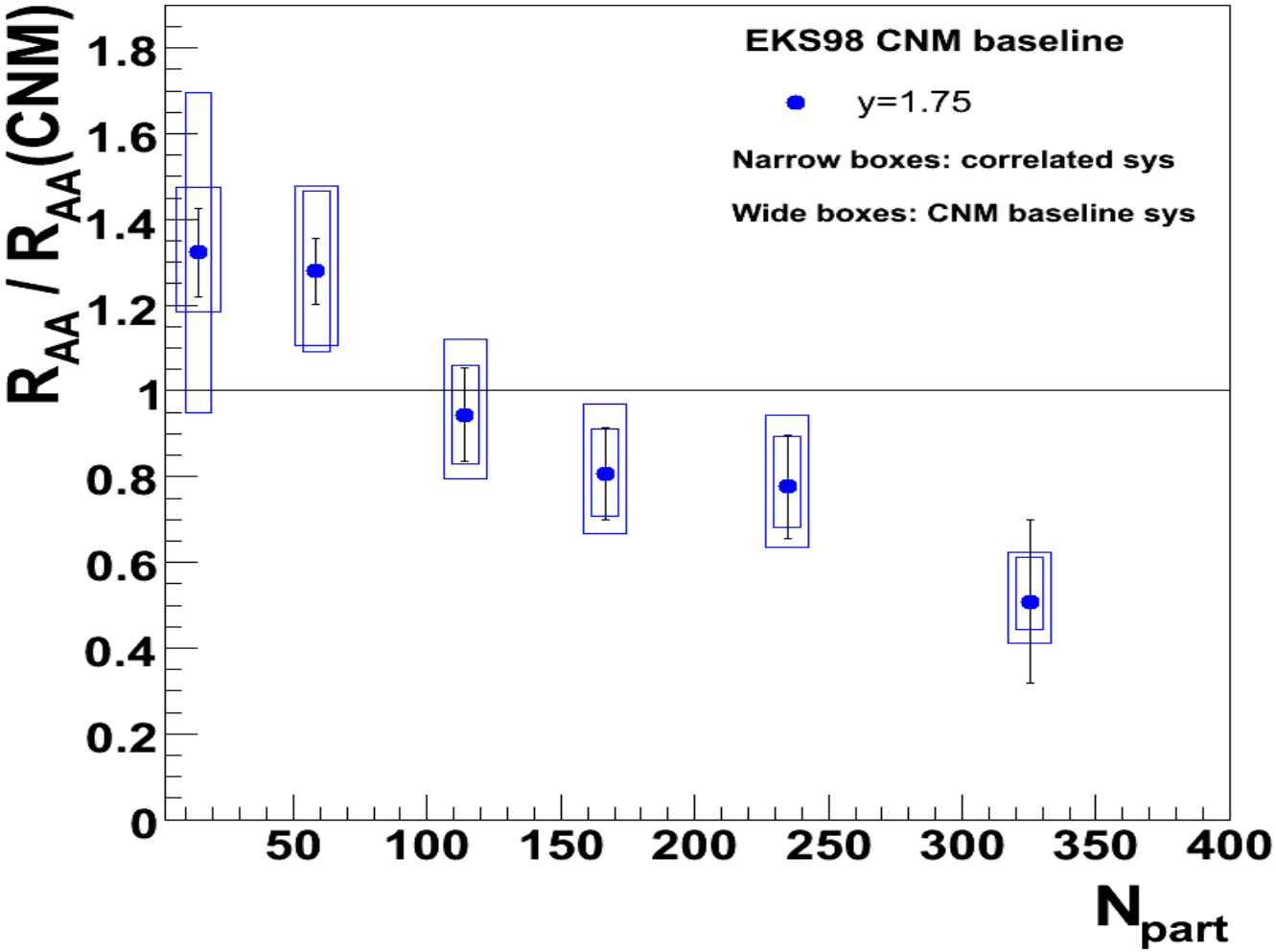
Add to the accumulated RAA: RdAu(b1,y=-1.75) * RdAu(b2,y=1.75)

Heavy ion "survival probability" at y=0 (EKS example)

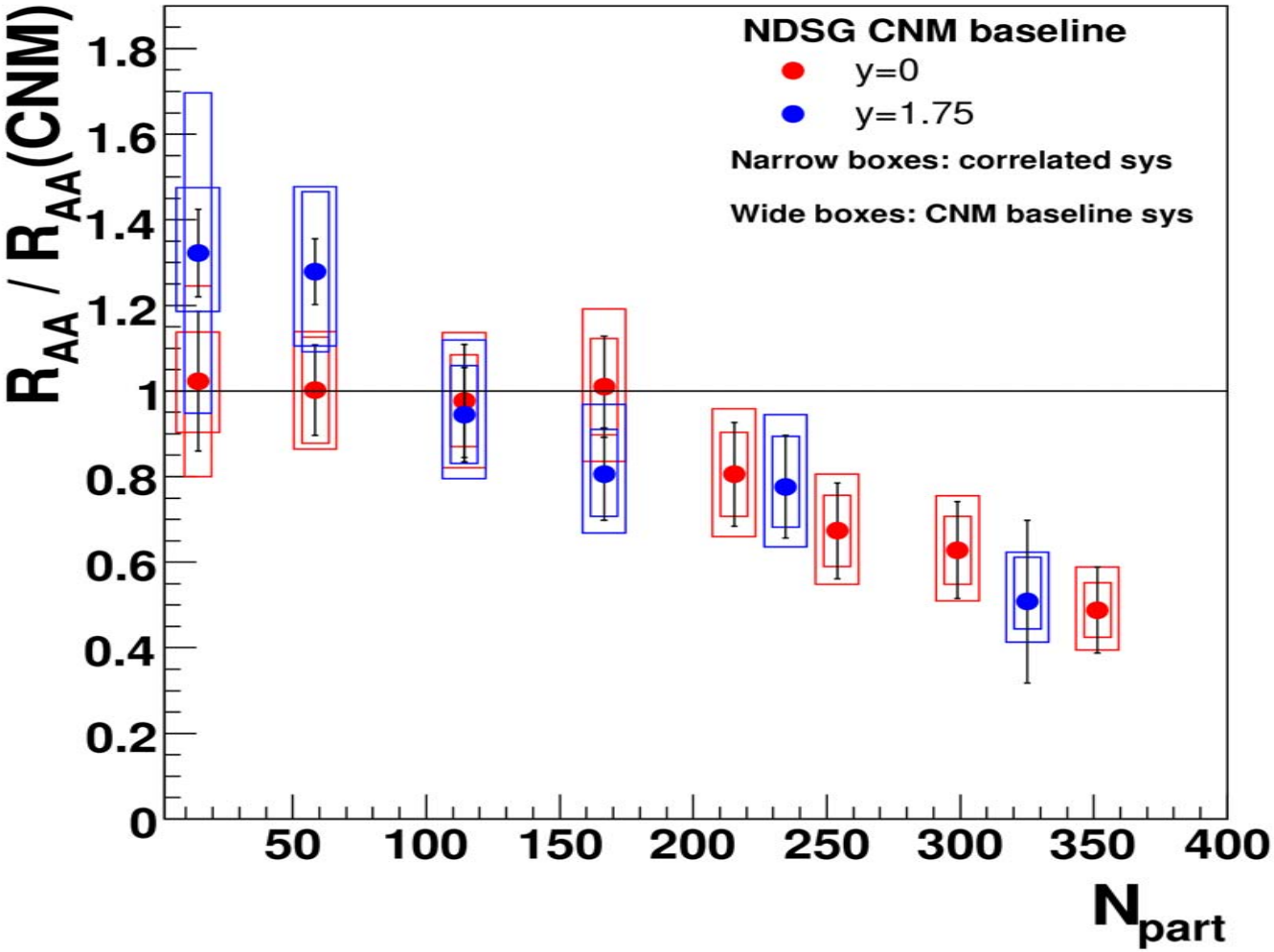


Now we can calculate the ratio RAA/RAA(CNM)

Heavy ion "survival probability" at |y| = 1.7 (EKS example)

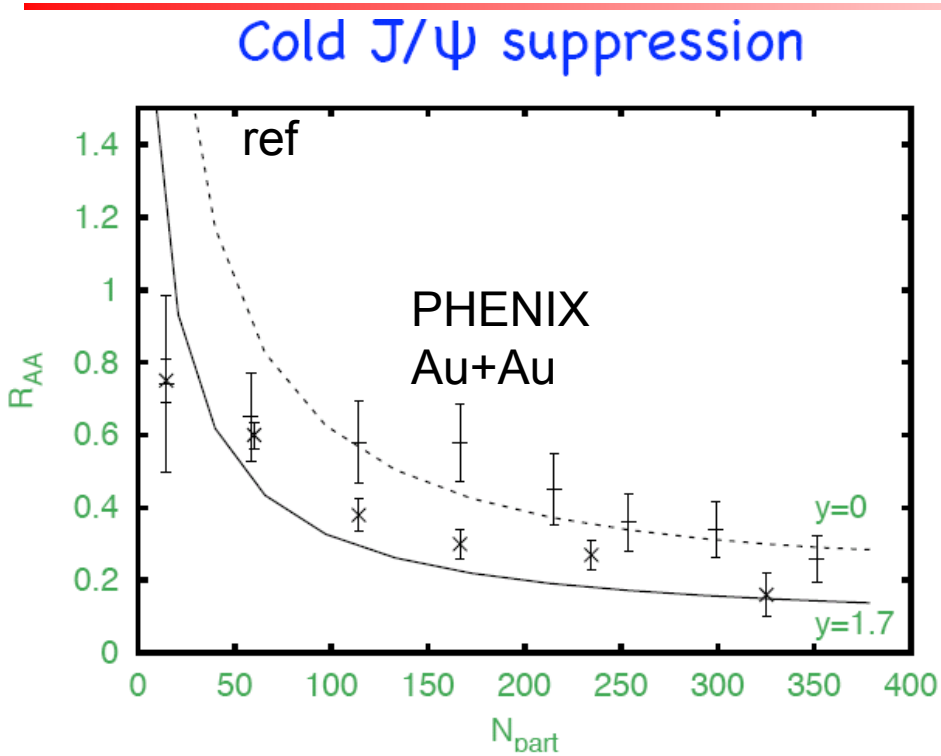


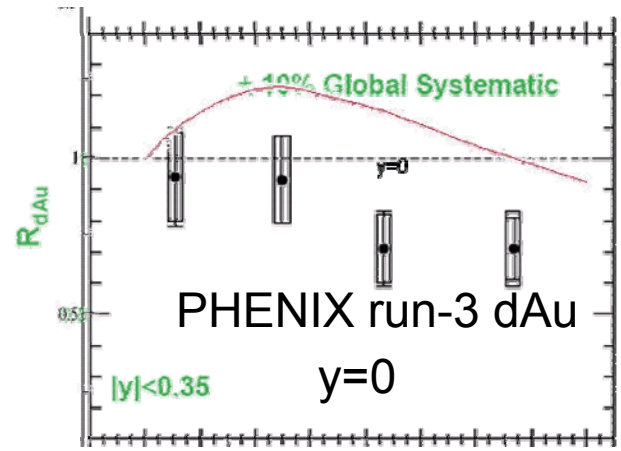
Heavy ion "survival probability" - EKS98 parameterization

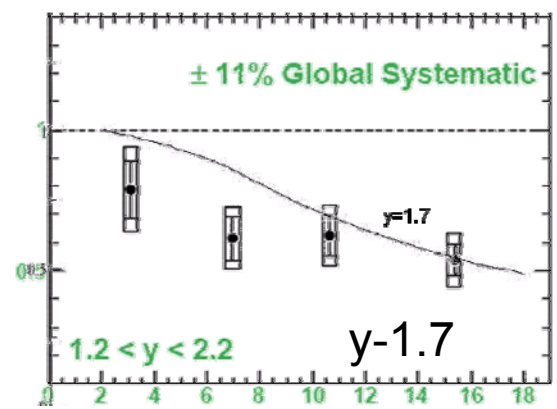


CNM effects explain the high y anomaly?

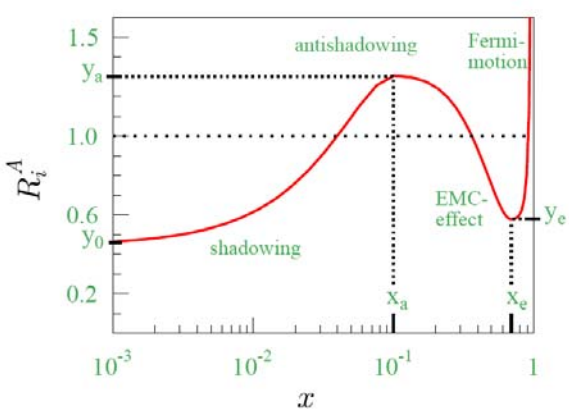
what about the CGC?







Question – what about the ~ high x part of the PDF? Is there anti-shadowing



but does it fit dAu?

Note: from private communication
dAu model too crude, new results coming

Summary

The RAA(CNM) estimated from the fits to the RdAu data show significantly stronger suppression at |y|=1.7 than at y=0.

The PHENIX d+Au data at 200 GeV shows a **rapid rise** in the **effective $\sigma_{breakup}$** at forward rapidity. (same trend at SPS energies)

The measured suppression **beyond** the estimated R_{AA}(CNM) values, presumably due to **hot nuclear matter** effects, seems to be very similar at y=0 and |y|=1.7 at about 50%.

An attempt to estimate NDOF(effective)

really its

ε/T^4, $3s/4T^3$

Preliminaries : thermo

melt the hadrons and liberate quark and gluon DOF?

Energy density (entropy density) for "g" massless d.o.f. (bosons)

$$\varepsilon = g\frac{\pi^2}{30}T^4 \qquad TS = \varepsilon + p \Rightarrow \qquad s = g\left(\frac{4}{3}\right)\frac{\pi^2}{30}T^3$$

$$\varepsilon = 3\cdot\frac{\pi^2}{30}T^4$$

Hadronic Matter: quarks and gluons confined
For T ~ 200 MeV, **3** pions with spin=0

$$\varepsilon = \left\{2_s\cdot 8_g + \frac{7}{8}\cdot 2_s\cdot 2_a\cdot 2_f(3)\cdot 3_c\right\}\frac{\pi^2}{30}T^4$$

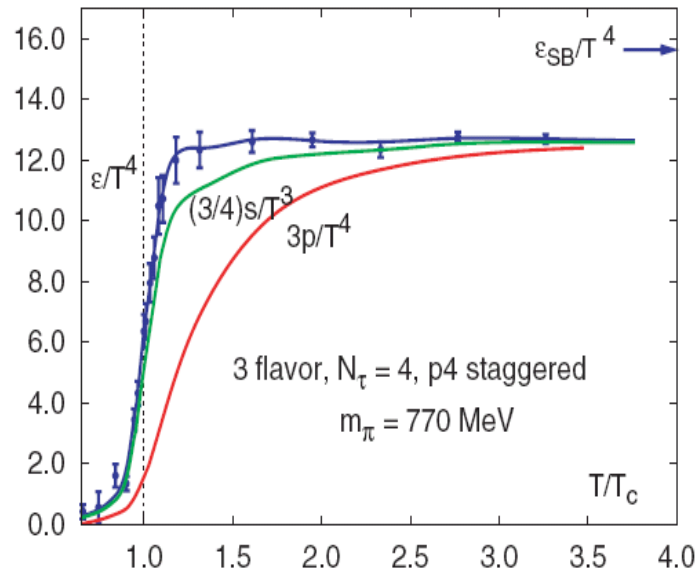
$$\varepsilon = 37(48)\cdot\frac{\pi^2}{30}T^4$$

Ndof~37 (48) !

Quark Gluon Matter:
8 gluons;
2(3) quark flavors,
antiquarks,
2 spins, 3 colors

Looking at ε/T^4, $3s/4T^3$ aka $NDOF_{effective}$

- PHENIX
  - energy density (E_T)
  - T (photons)
  - entropy (dN/dy)
- Can we make a rough estimate from data of ε/T^4, $3s/4T^3$ ~NDOF ?
- sQGP $\Rightarrow$ but we can look at the lattice for guidance



strategy~ fit ε, s, T as functions of τ
get τ from flow considerations

ref – see Muller, Rajagopal hep-ph/0502174
Enterria, Peressounko nucl-th/0503054

what do we expect?

3 flavors

16 (ndof=48)

12.5 (ndof=38)

10 (ndof=30)

for 2 flavors

12 (ndof=37)

9.5 (ndof=29)

7.5 (ndof=23)

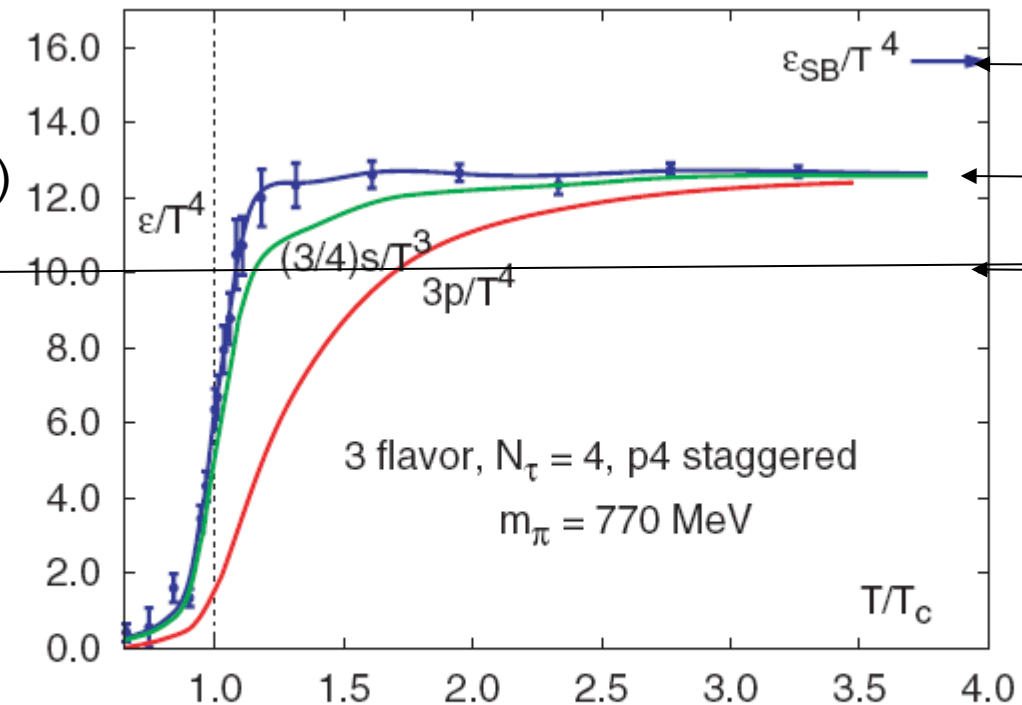


Figure 1 $\varepsilon(T)/T^4$, $P(T)/T^4$, and $s(T)/T^3$ for three light flavors of quarks on the lattice. SB, massless Bose field.

$$9.5\frac{30}{\pi^2} = 29 = ndof\,(effective)$$

37=ndof(effective, 3 flavor)

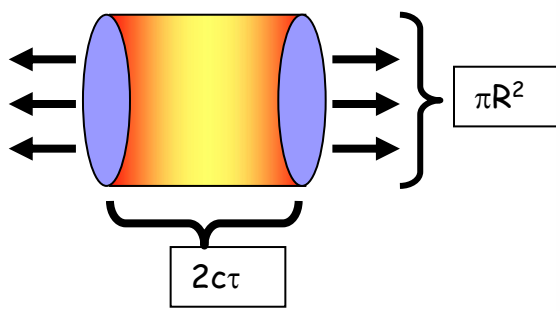
Expectaions								
	ndof(sb)	e/T^4(s	3s/4T^3(sb)	e/T^4(la	3s/4T^3(	ndof(effective)	3s/4T^3(near T	ndof(effective)
3 flavor	48	16.00	16	12.5	12.5	38.0	10.00	30.4
2 flavor	37	12.00	12	9.5	9.5	28.9	7.50	22.8

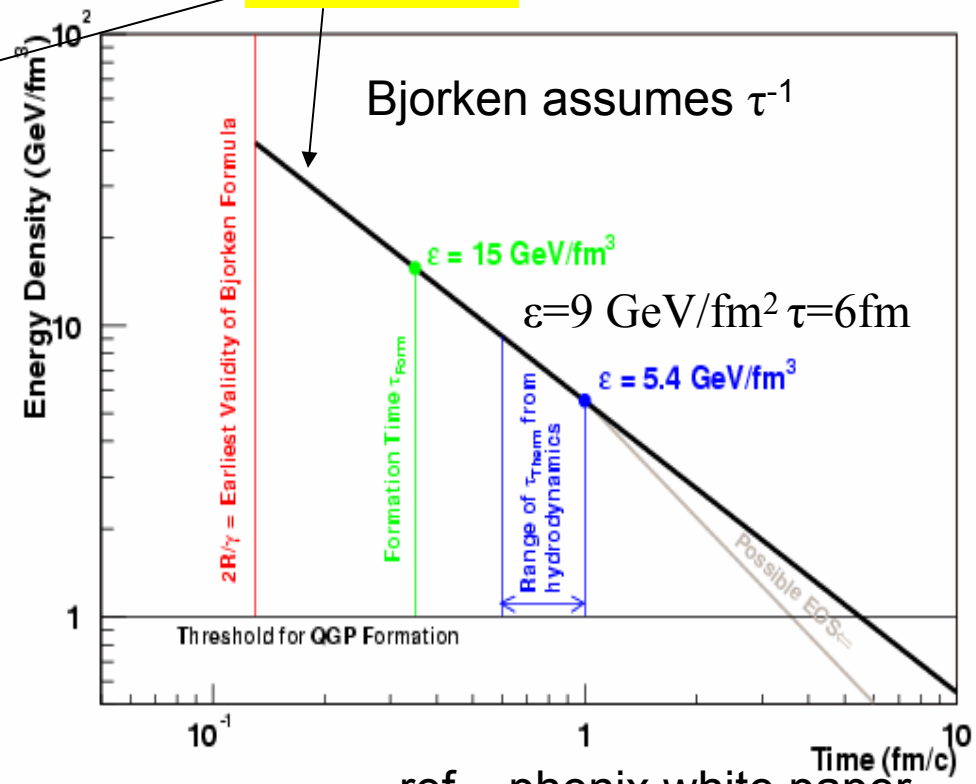
the data: Energy Density

$\varepsilon(\tau) \sim \tau^{-1}$

$$\varepsilon_{Bj} = \frac{1}{\pi R^2}\frac{1}{2c\tau}\left(2\frac{dE_T}{dy}\right)$$

R~6.3fm



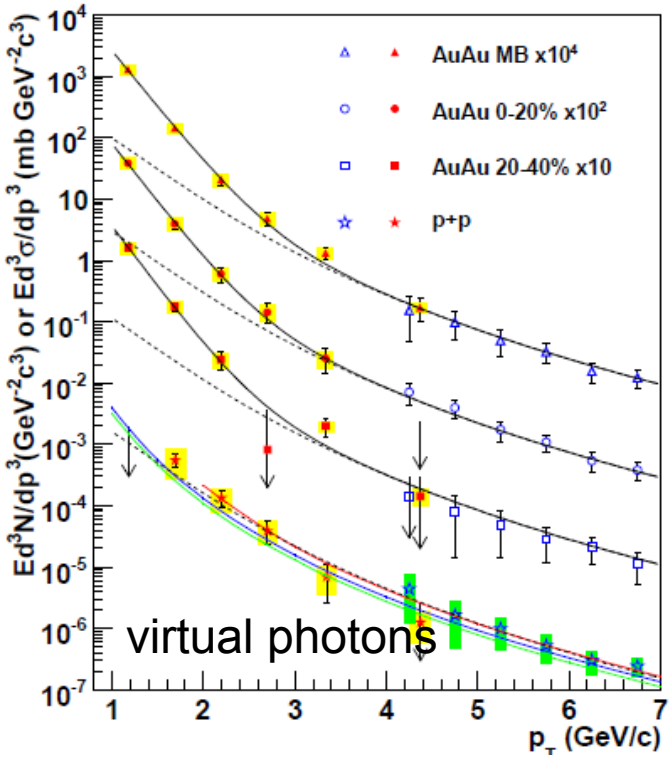


ref – phenix white paper

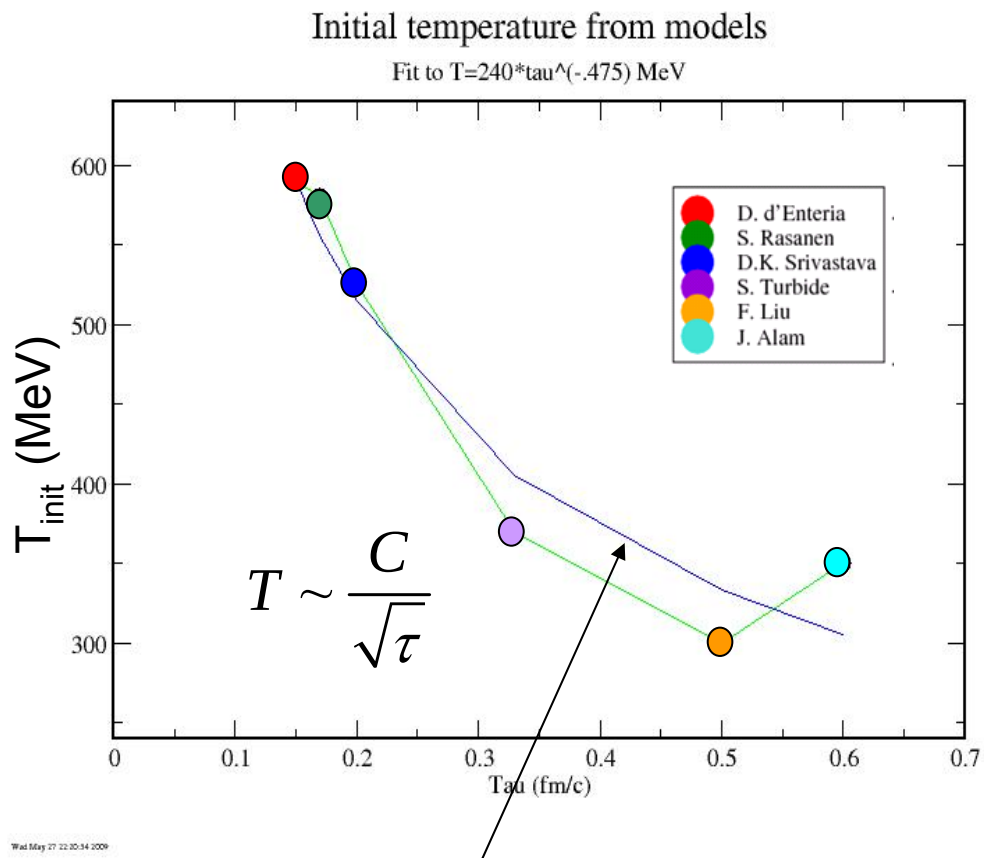
PHENIX: Central Au-Au yields

$$\left\langle \frac{dE_T}{d\eta} \right\rangle_{\eta=0} = 606 \pm 2\,GeV \quad \Rightarrow \quad \left\langle \frac{dE_T}{dy} \right\rangle_{y=0} = 760\,GeV$$

The data: Temperature - Photons



arXiv:0804.4168v1 [nucl-ex]



- Fit to the p_T slope in central collisions yields

T_{avg} = 221 ±23 ±18 MeV

fit to

$$T(GeV) = 0.240\tau^{-.475}\ GeV$$

The rough calculation
$NDOF_{effective}$ using ε/T^4 $3s/4T^4$

central

$$NDOF = \frac{30\varepsilon}{\pi^2 T^4} = \frac{1}{\pi R^2}\frac{1}{c\tau}\left(\frac{dE_T}{dy}\right)\frac{30(\hbar c)^3}{\pi^2 T^4} =$$

$$\frac{1}{\pi(6.6\,fm)^2}\frac{1}{\tau(\,fm)}(758GeV)\frac{30\,(0.197\,GeV\;\;fm)^3}{\pi^2(0.240\tau^{-.475}\;GeV)^4} = C\tau^{0.9}$$

$$NDOF = 39\tau^{0.9} \qquad dEt/dy = 760 \quad R = 6.6 = 1.18*(351/2)^{1/3}$$

$$s = \frac{7.9}{\pi R^2}\frac{1}{c\tau}\left(\frac{dN_{ch}}{d\eta}\right)$$

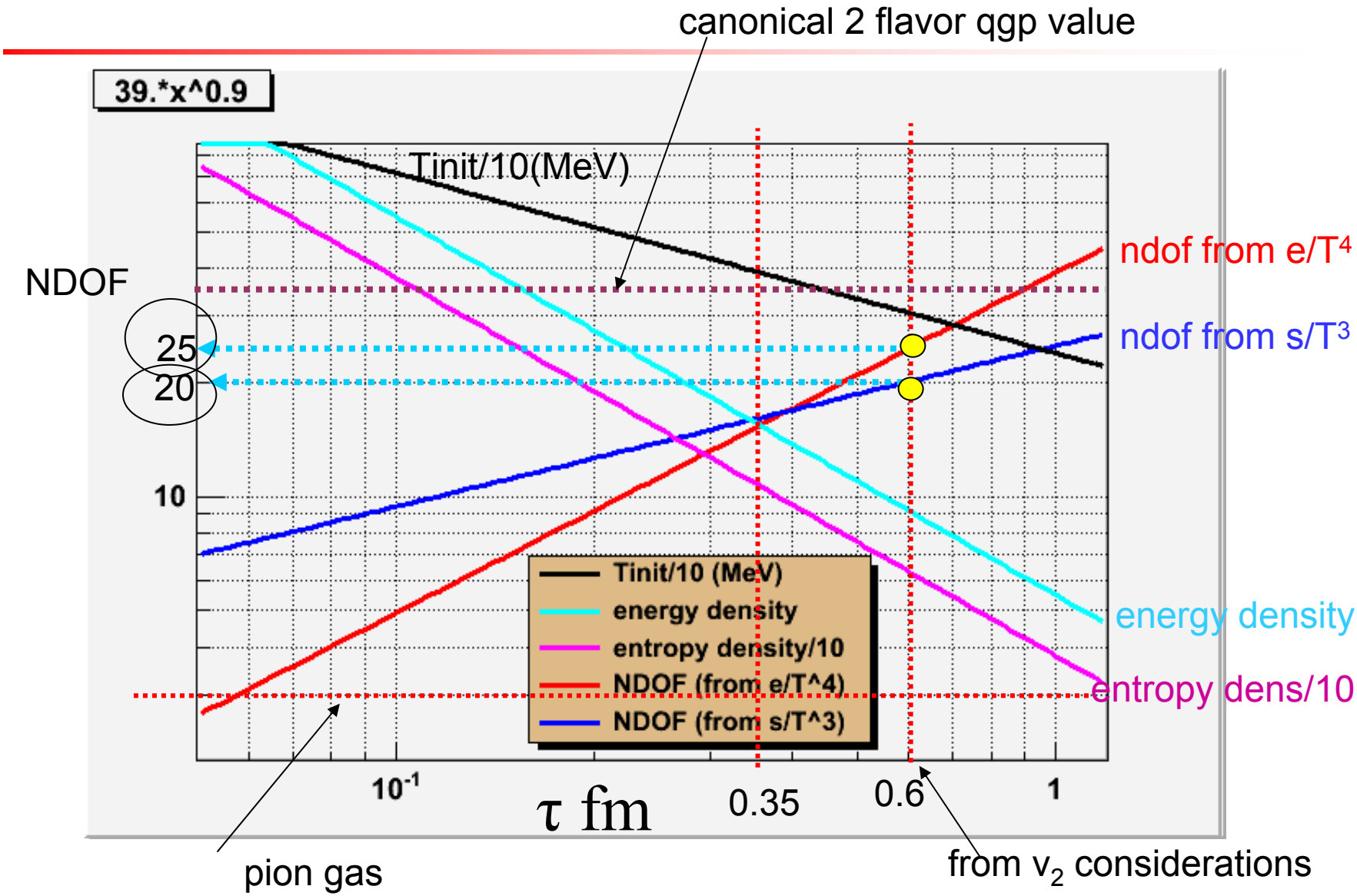
from 1.1*7.25/1.04
hep-ph/0502174
nucl-th/0501028
PLB 289, 132 (1992)

$$NDOF = \frac{45s}{2\pi^2 T^3} = \frac{7.9}{\pi R^2}\frac{1}{c\tau}\left(\frac{dN_{ch}}{d\eta}\right)\frac{45\,(0.197\,GeV\;\;fm)^3}{2^2\pi^2(0.3\,GeV)^3} =$$

$$\frac{7.9}{\pi R^2}\frac{1}{c\tau}\left(\frac{dN_{ch}}{d\eta}\right)\frac{45\,(0.197\,GeV\;\;fm)^3}{2^2\pi^2(0.240\tau^{-.475}\;GeV)^3} = C\tau^{0.425}$$

$$NDOF = 25\tau^{0.425} \qquad dN/d\eta = 758 \quad R = 6.6 = 1.18*(350/2)^{1/3}$$

Now plot NDOF(effective) vs τ



remember the expectations for 2 flavor QCD is 29(from e/T^4) and 23(from s/T^3)

What do we learn?

- Pretty hard to get NDOF(effective)=3 (i.e. need τ <0.1 fm)
- For reasonable τ ~0.35 to 1 fm (0.6 from v2 considerations) get NDOF= 25 using ε/T^4 and 20 using s/T^3
- a wQGP predicts NDOF=37. If you use the lattice we see a value of 29 using ε/T^4 . The entropy rises slower so right at Tc, NDOF(effective) would start out at about 23

- So:
  - a) we see a ε/T^4 and s/T^3 consistent (within the errors of this rough calculation) with the lattice
  - d) its much greater than 3

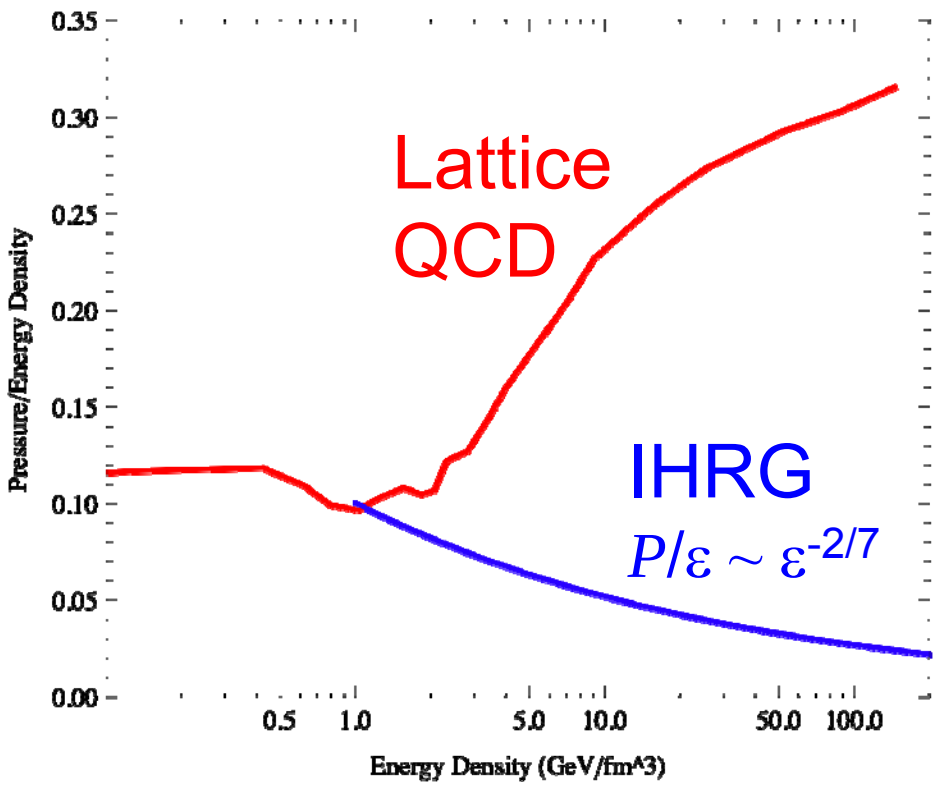
- This is a VERY rough estimate. Caveats about a hadron gas. But pressure arguments may be able to help
  - if the NDOF came from hadrons i.e. it would be the high mass stuff, then it would take a longer to equilibrate. But we have tau~0.6. also p/energy density from the lattice rises with energy density, as does our v2 – but it a hadron gas, a lot of the energy would be taken up in the mass (they particles would be moving slower, and the pressure would be less as compared to the energy density as the energy density rose

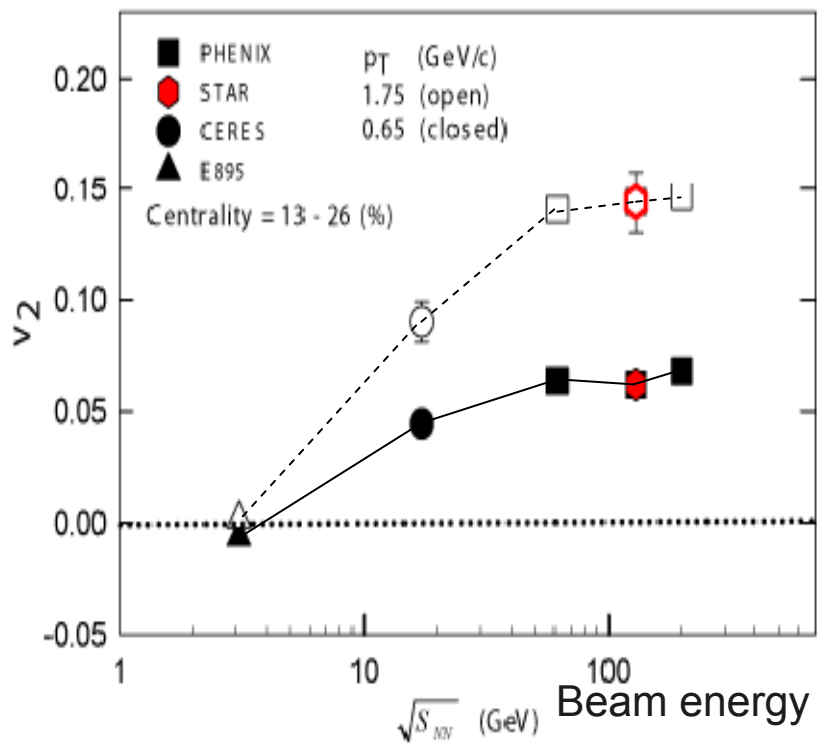
The final summary

- Both pQCD models and CGC seem to be able to explain our forward hadrons, correlations, and the J/psi
  - We do not however, see the broadening expected in the correlations analysis
    - not sensitive yet because of errors?
    - triggering?
- In a very preliminary investigation, CNM effects appear to explain the additional suppression seen at higher y. This will need to be pursued and checked
- A crude estimate of ε/T^4 and $3s/4T^4$ as a count of the effective NDOF, appears to be consistent with lattice calculations and greater than the pion gas value of 3.

- The future
  - As has been said – we are not beginning to be able to make quantitative statements about the sQGP
  - A measurement of the gluon PDF's in nuclei will be crucial to limit experimental uncertainties
  - Clear theoretical guidance would be nice – i.e. measureable signatures distinguishing models
  - Upgrades for PHENIX (HBD, VTX, FVTX, FOCAL) and high luminosity running will be to open new avenues for study

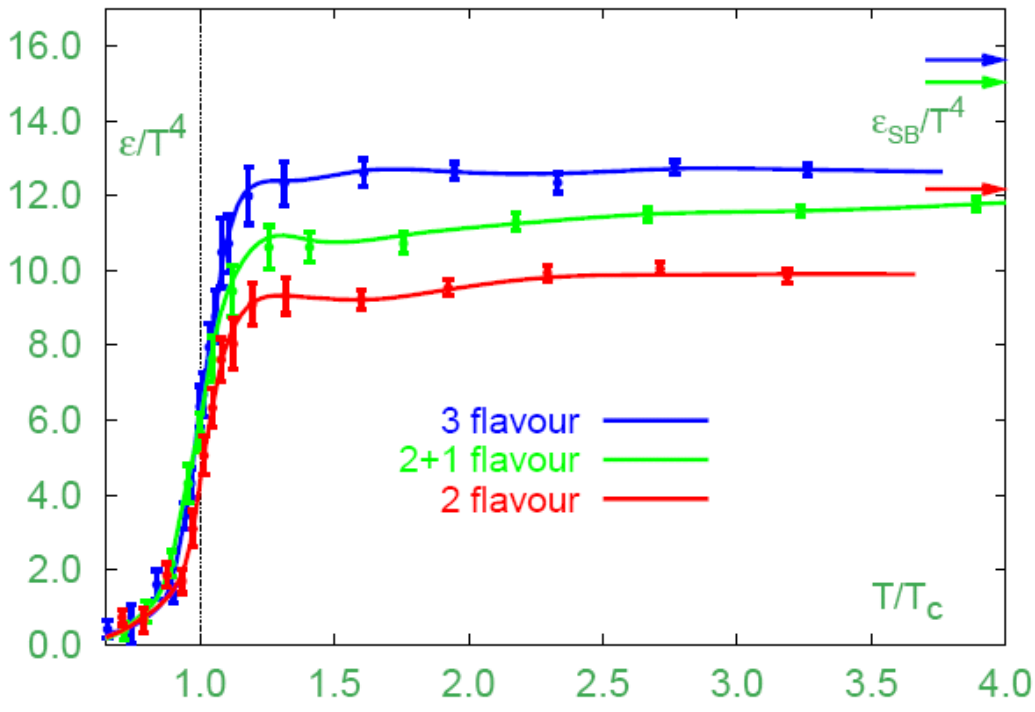
Pressure effects *increase* with energy density





A. Bazavov et al. (HotQCD), arXiv:0903.4379 [hep-lat]

Phys Rev Lett 94, 232302

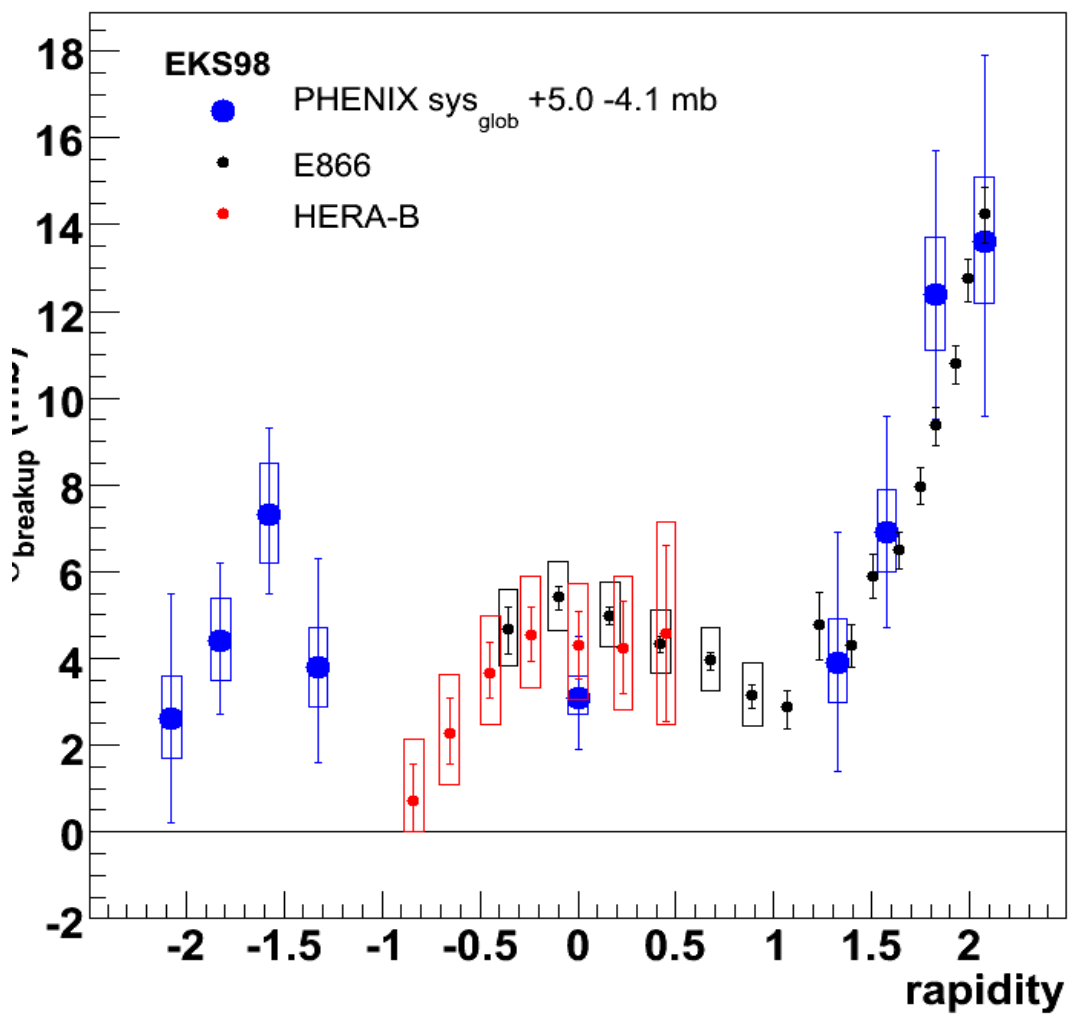

16.0
14.0
12.0
10.0
8.0
6.0
4.0
2.0
0.0
ε/T4
εSB/T4
3 flavour
2+1 flavour
2 flavour
T/Tc
1.0
1.5
2.0
2.5
3.0
3.5
4.0

Comparison with lower energy data – EKS98 fits

Lourenco, Vogt and Woehri (JHEP 02 (2009) 014) published the effective breakup cross section vs y from fits to E866 and HERA-B data.

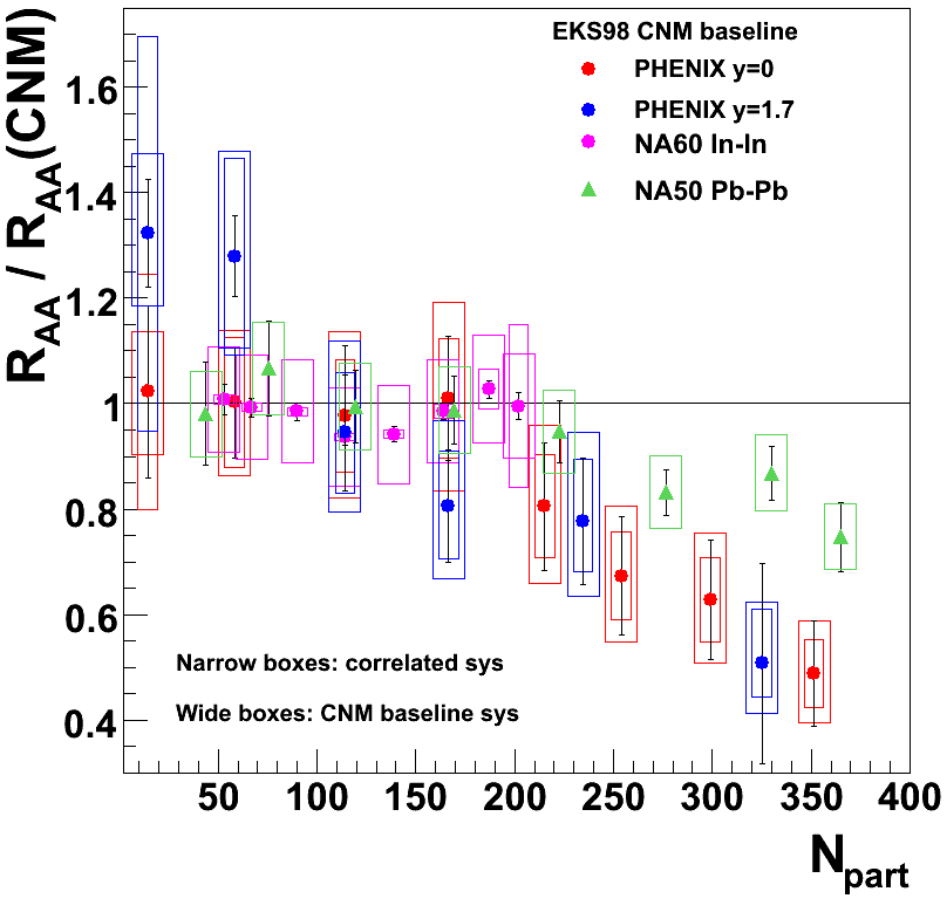
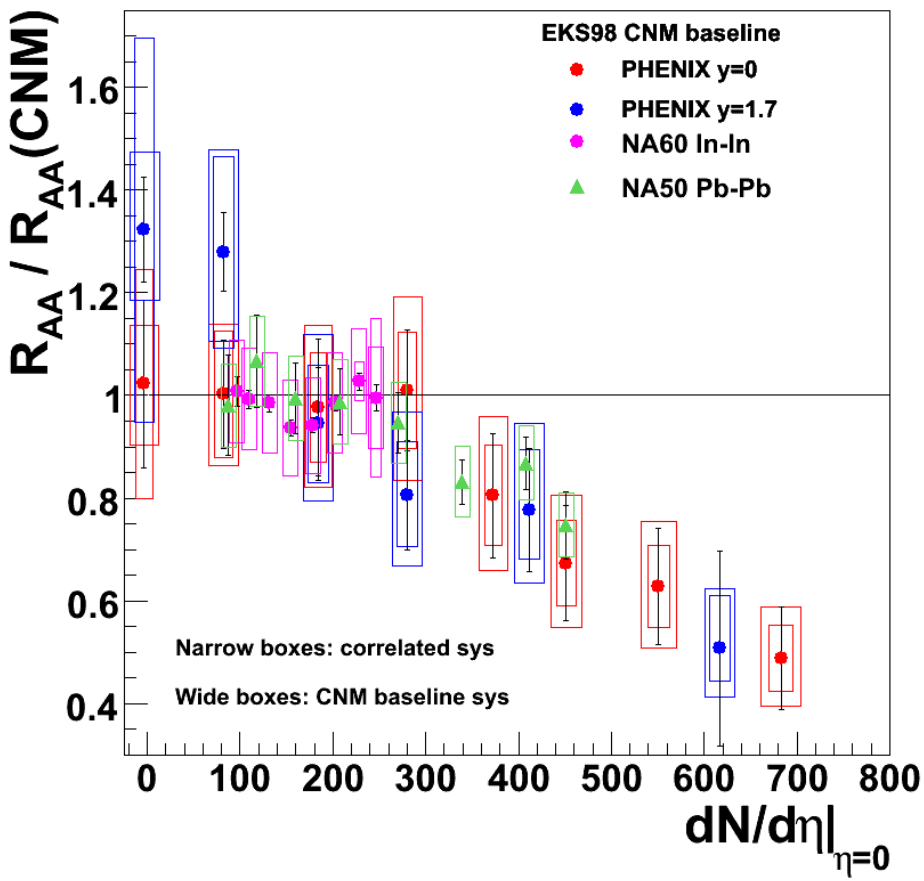
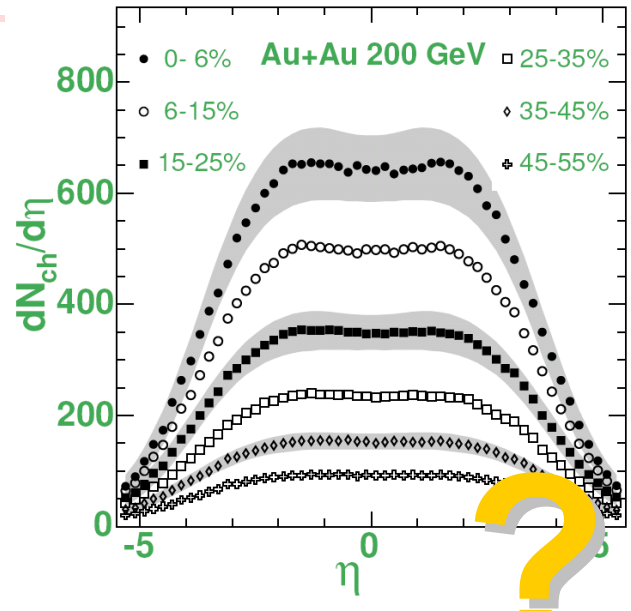
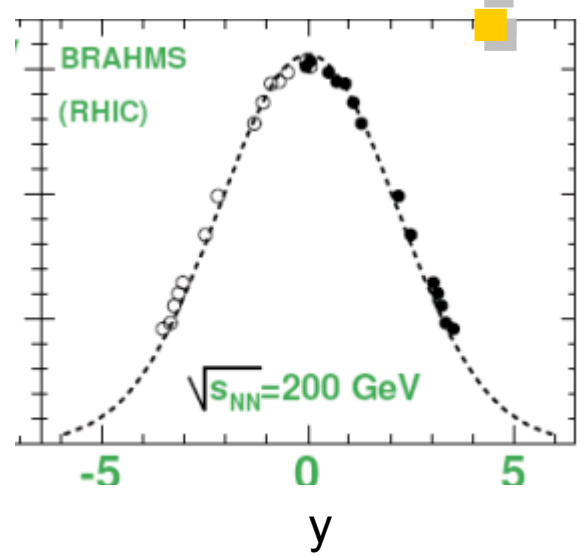
Our results from 200 GeV are shown here compared with their results for the EKS98 case.

For **y > 1.2** the 200 GeV data follow the trend observed at lower energy remarkably closely!



Any connections to NA50, NA60?

Roberta Analdi (ECT trento)



Plot now vs dN/dη ~ ε