Energy Dependence of Energy Loss in Au+Au Collisions at PHENIX

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PHENIX R_{AA} in low – energy scan

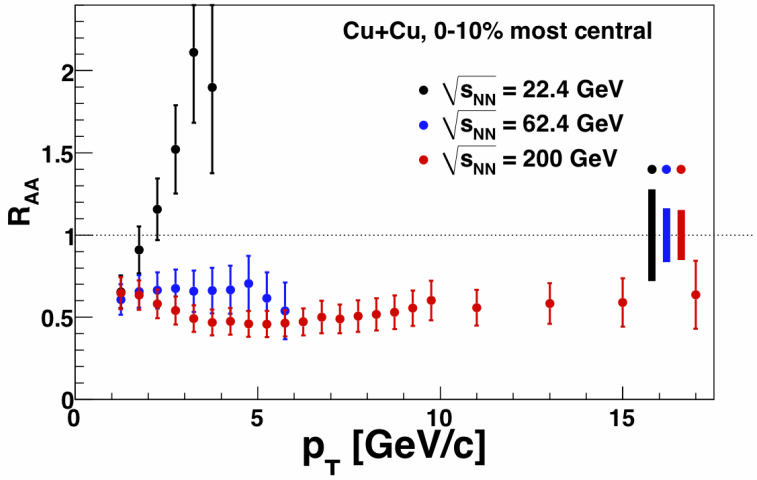
In Au+Au at 200 GeV:

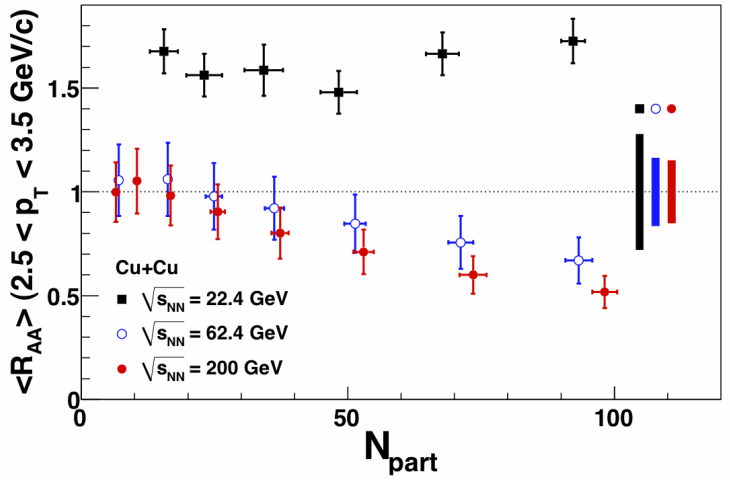
- Strong suppression (x5) in central Au+Au coll.
- No suppression in peripheral Au+Au coll.
- No suppression (Cronin enhancement) in control d+Au exp.

Convincing evidence for the **final state partonic** interaction - emergence of **sQGP**

Cu+Cu energy scan:

- **Significant suppression** at $\sqrt{s_{NN}}$ = 200 and 62.4 GeV
- **Moderate enhancement** at $\sqrt{s_{NN}}$ = 22.4 GeV



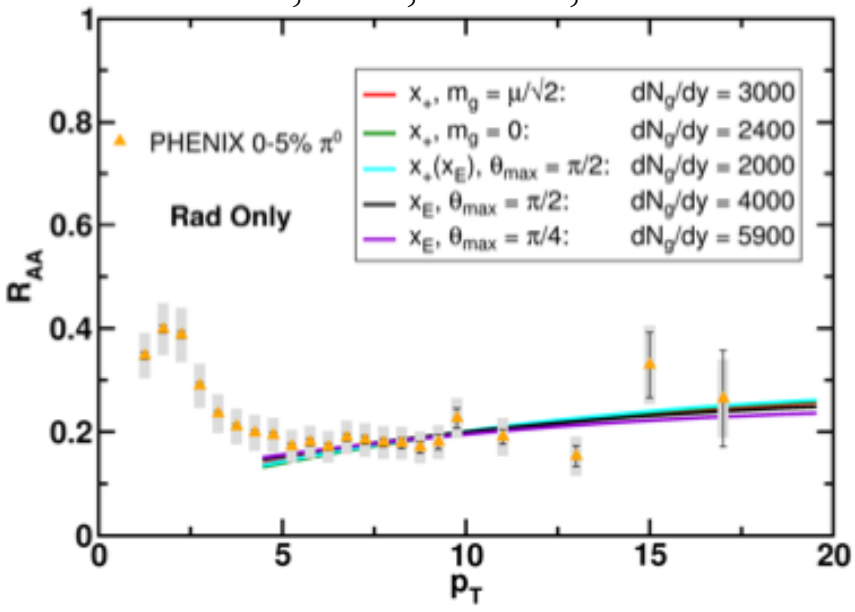


Energy – Loss in HI – Theory Models

In principle four different theory classes of models:

- Opacity expansion (GLV): *Gyulassy, Levai,. Vitev, PLB538, 2002*
- Multiple soft scattering (BDMPS-Z-ASW): *Wiedemann, NPB588, 2000*
- Higher-twist (HT): *Guo, Wang, PRL. 85, 3591, 2000*
- Thermal field theory (AMY): *Arnold, Moore, Yaffe, JHEP 11, 001(2000)*

Horowitz, Cole, *PRC81*, 024909



1. The data do not discriminate between different models
2. Theoretical models has large uncertainties:
   - Energy density (differs by factors).
   - Different transport coefficients.
   - Collinear approximation violations.
   - Different values of strong coupling α_S

How can the experiment help to constrain the models?

Systematic study of the π^0 suppression

It is natural to ask where the **onset** of such massive suppression is in terms of:

- **Different colliding energies**
  - Low-energy scan (observe region between SPS – RHIC)

- **Different system sizes**
  - Centrality dependence of the same colliding ions
  - Different size of the colliding ions (Cu, Au)

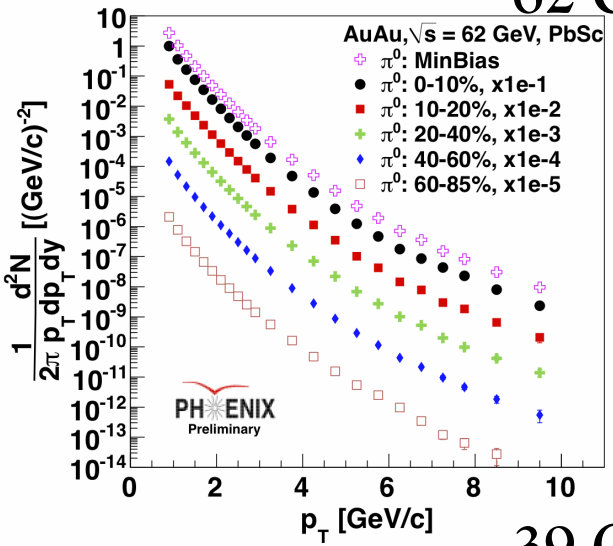
Year	System	Energy [GeV]
2005	Cu+Cu	200
	Cu+Cu	62.4
	Cu+Cu	22.4
……	…..	……
2010	Au+Au	62.4
	Au+Au	39.0
2011	Au+Au	19.5

PRL101, 162301

NEW results – subject of this talk

π^0 invariant yields of the Au+Au at 62.4 and 39 GeV

62 GeV



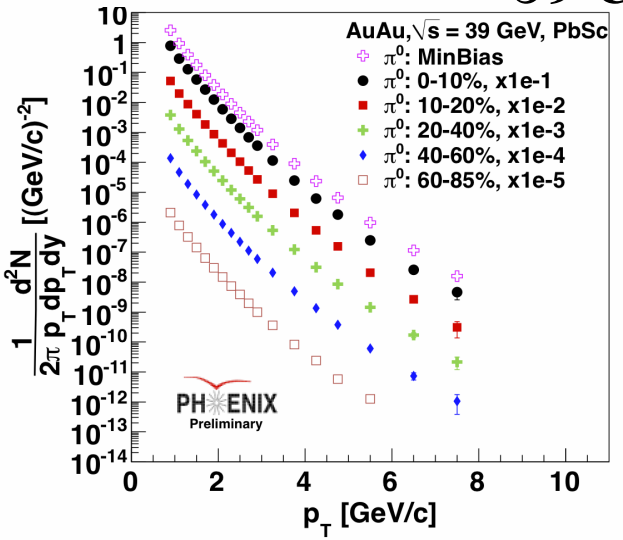
The scale-less theory from pQCD:

$$E\frac{d^3\sigma}{dp^3} \propto \frac{1}{p_T^4}$$

To lower √s the contribution from other processes are larger:

- Running $\alpha(Q^2)$
- PDF evolution
- k_T smearing
- Higher-twist phenomena

39 GeV



The minimum bias spectra are fitted with a power-law shape function for $p_T > 4$ GeV/c :

$$f(x) = \frac{A}{(p_T)^n},$$

n_{200GeV} = 8.1 ± 0.03

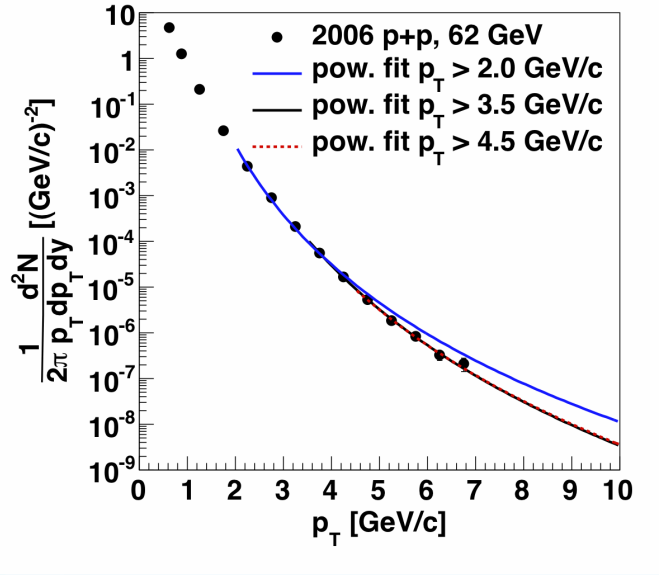
n_{62GeV} = 10.9 ± 0.03

n_{39GeV} = 12.1 ± 0.1

Nuclear Modification Factor

- For the R_{AA} the p+p reference from same experiment is vital. External reference will increase systematic errors.
  - 62.4 GeV p+p data is available from PHENIX, however **only up to** $p_T < 7$ GeV/c (heavy-ion up to 10 GeV/c)
  - 39.0 GeV p+p data is **not yet available** from PHENIX,
    - Because of that we used fix target p+p experiment at Tevatron, E0706 ($\sqrt{s} = 39$ GeV, PRD68: 052001, 2003).

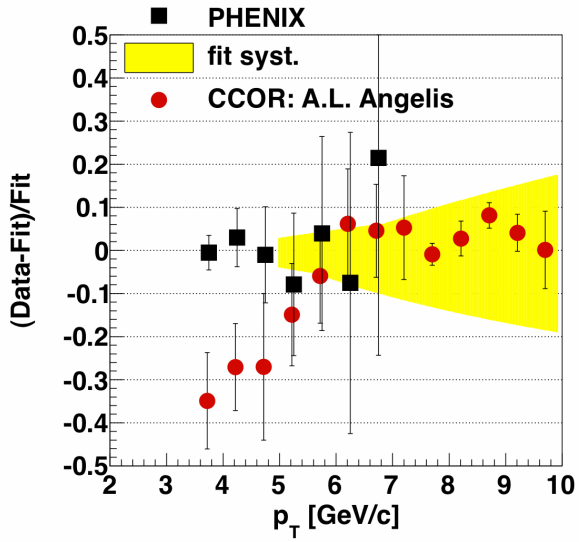
62.4 GeV p+p reference extrapolation



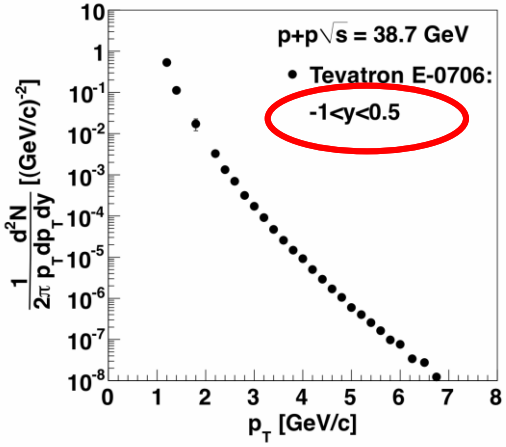
- Data from PHENIX are available up to p_T < 7 GeV/c
- To extrapolate to higher p_T points power-law function was used:
  - The limit of the fits is vital

  --> systematic errors.

- The systematic uncertainty is calculated from the errors of the power-law fit
- It agrees well with the CCOR data (ISR) in p_T 7-10 GeV/c region

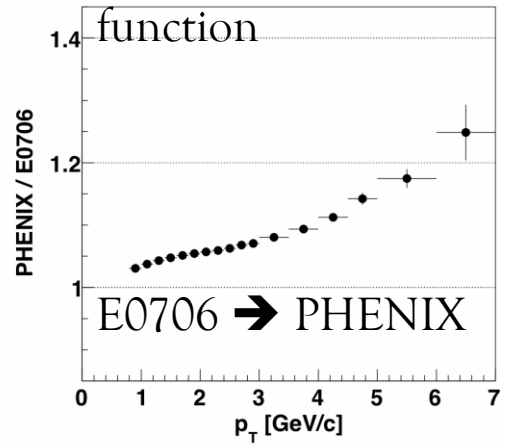


39 GeV p+p reference

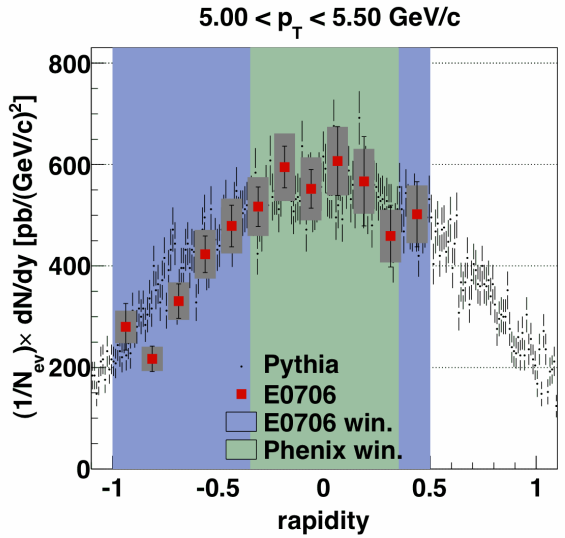


- p+p data measured only in fix-target experiment by E0706 at Tevatron with 800 GeV beam energy. **(Phys.Rev.D68:052001,2003)**
- The E0706 has different rapidity acceptance -1.0 < y < 0.5 (PHENIX |y|<0.35).

Acceptance correction function



- Acceptance correction based on PYTHIA8 simulation.
- The systematic uncertainty of the correction function is calculated based on data to PYTHIA8 comparison.

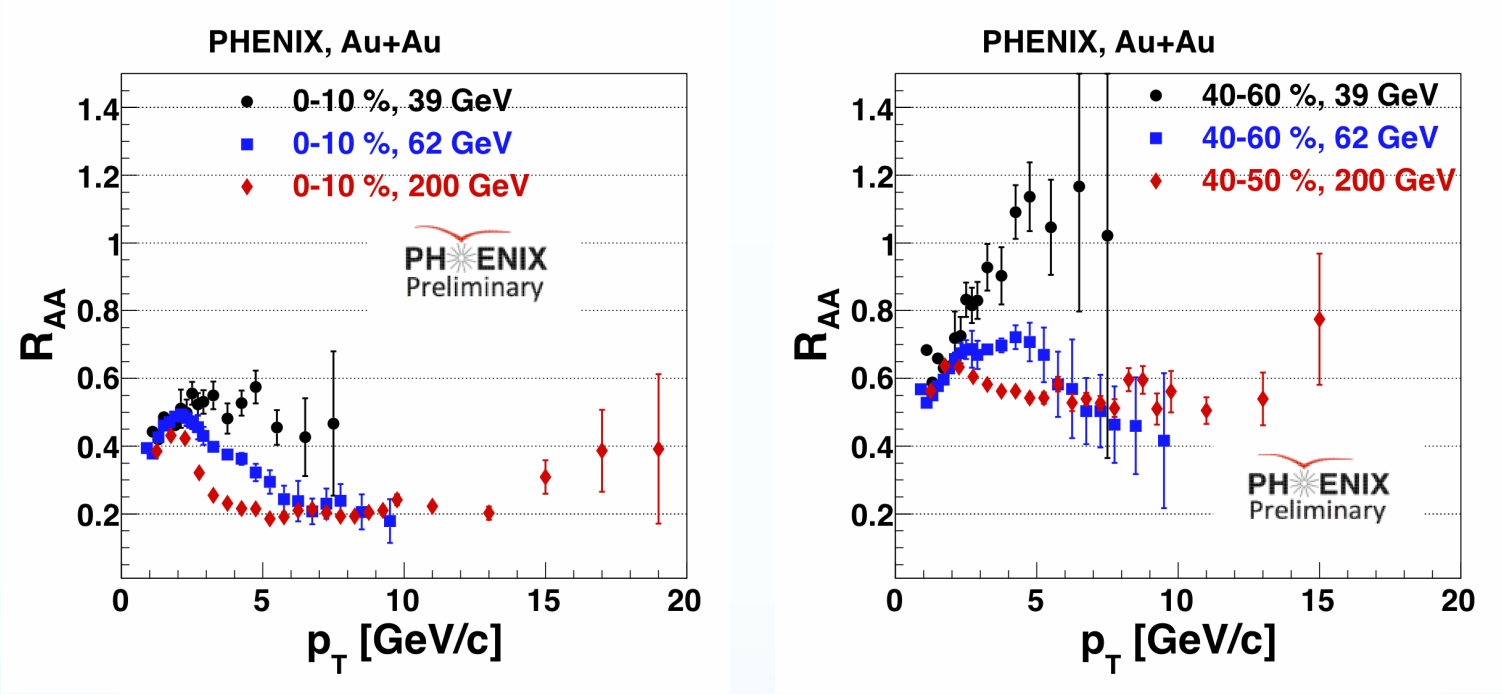


Nuclear Modification Factor

$$R_{AA}(p_T) = \frac{d^2N^{AA} / dp_T d\eta}{\langle N_{binary} \rangle d^2N^{pp} / dp_T d\eta}$$

- 39 GeV: with external reference from E0706, Tevatron
- 62 GeV: PHENIX reference with extrapolation to higher p_T.

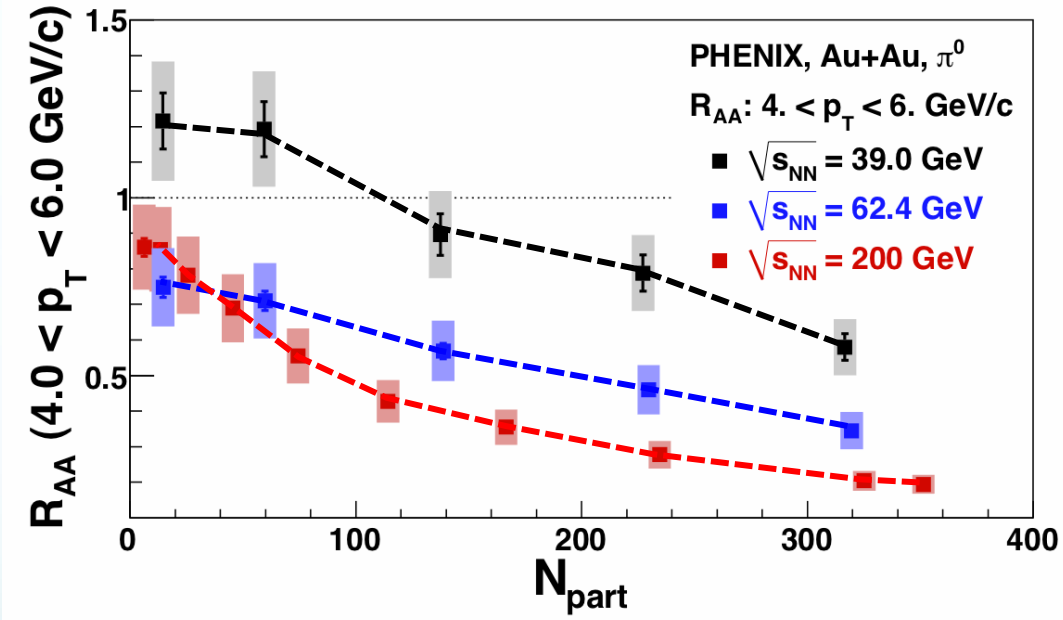
R_{AA} in Au+Au at 39 and 62 GeV



π^0 R_{AA} as a function of p_T in PHENIX at $\sqrt{s_{NN}}$ = **39**, 62 and 200 GeV.

- Still strong suppression (factor of 2) at most central $\sqrt{s_{NN}}$ = 39 GeV.
- R_{AA} from $\sqrt{s_{NN}}$ = 62 GeV data is comparable with R_{AA} from $\sqrt{s_{NN}}$ = 200 GeV for p_T 6 >GeV/c
- In peripheral $\sqrt{s_{NN}}$ = 62 and 200 GeV are suppressed, but the $\sqrt{s_{NN}}$ = 39 GeV is not suppressed

p_T averaged R_{AA}



R_{AA} evolution in Au+Au at $\sqrt{s_{NN}}$ = 39, 62 and 200 GeV:

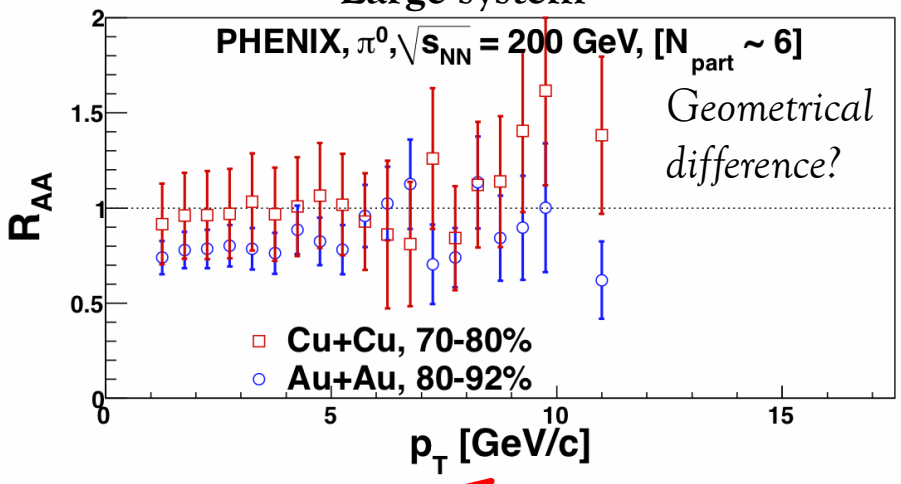
- 62-200 GeV large **suppression**
- 39 GeV shows suppression only in N_{part}>100

In higher p_T ranges, the 62 GeV points are comparable to the 200 GeV points in all centralities.

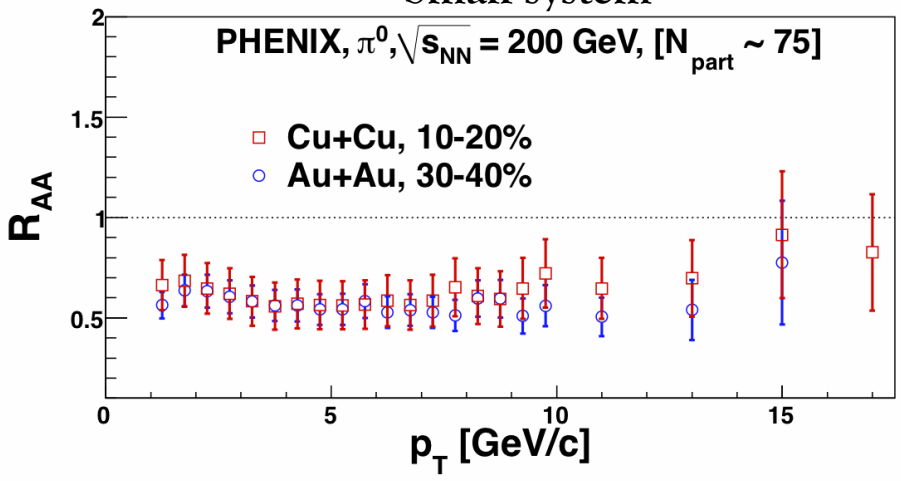
The lines are just to guide the eyes over the points.

System size dependence

Large system

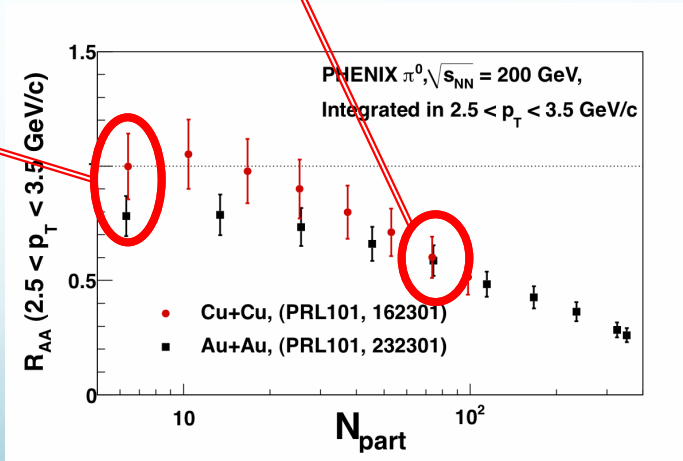


Small system

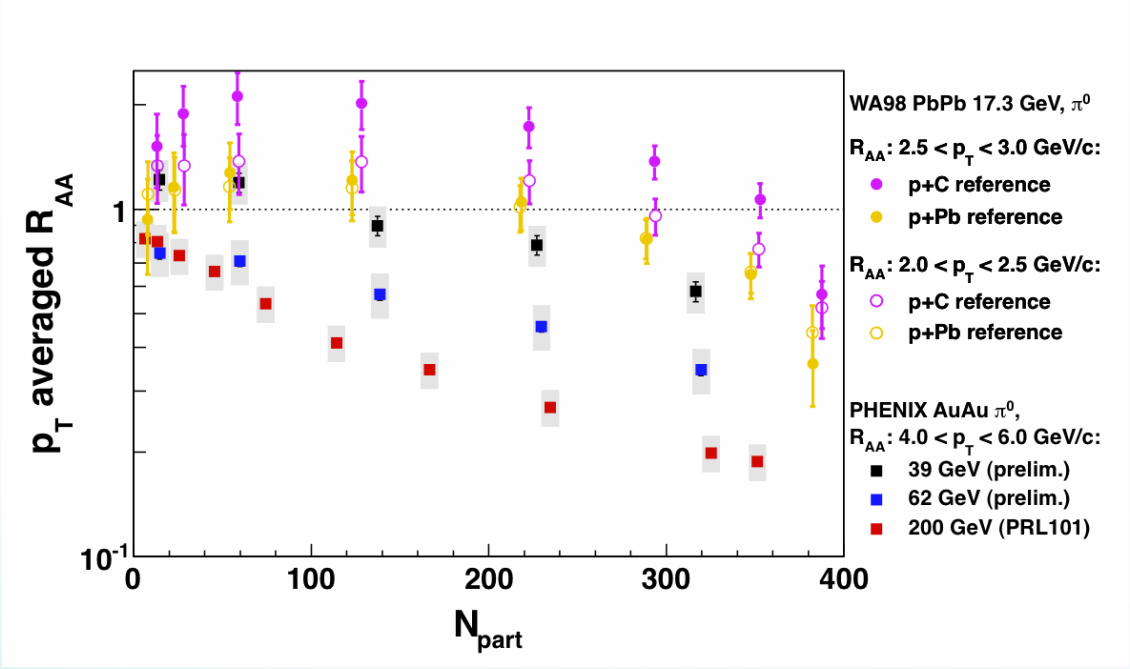


The R_{AA} was measured with different heavy ions collisions (Au and Cu):

- In Cu+Cu at same energy we see less suppression as compared to Au+Au system.
- The centrality dependence of Cu+Cu with respect to the Au+Au shows enhancement in lower N_{part}.



Comparison with recent SPS R_{AA}



- In previous experiment at WA98 we see only (PRL 100 (2008), 242301) suppression at "ultra"-central (0-1%) collisions of Pb+Pb.
- The x_T is overlapping between the SPS and RHIC intervals.
- The "onset" of the energy loss is dependent on system size and collision energy.
- The energy loss is present in lower energies also.

The magenta closed circles are the most comparable with the PHENIX results, as they have the smaller system (p+C) for reference.

The "onset" of the suppression depends on collision energy and centrality or system size (and p_T)

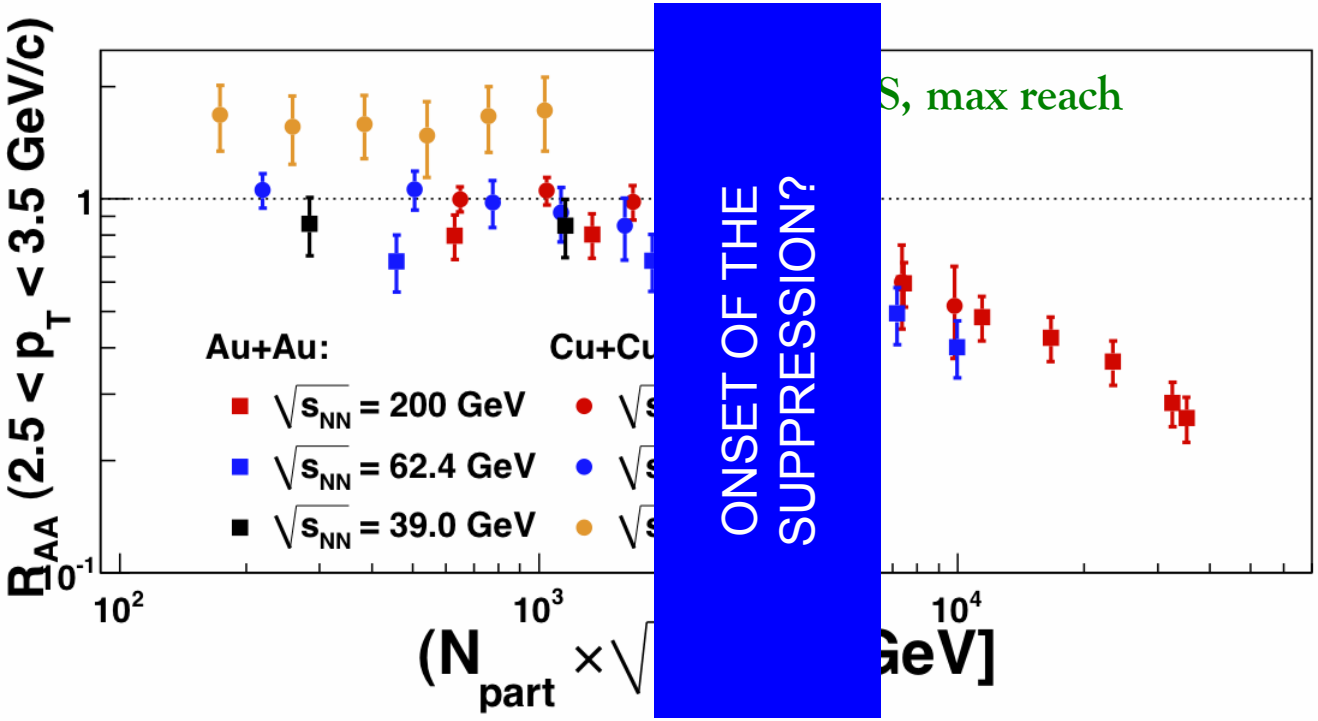
All π^0 R_{AA}

Total energy available of the collision:

$$E_{AA} \approx \left(N_{part} \cdot \sqrt{s_{NN}}\right)/2$$

System size:

- **Circles: Cu+Cu**
- **Squares: Au+Au**

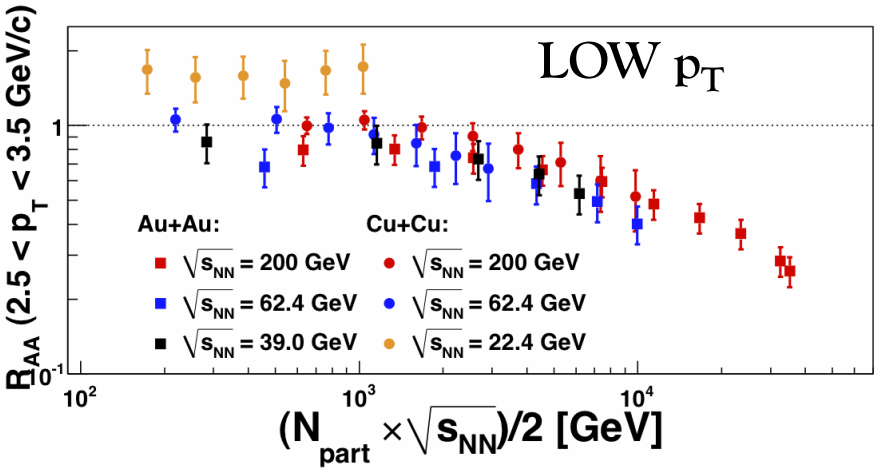


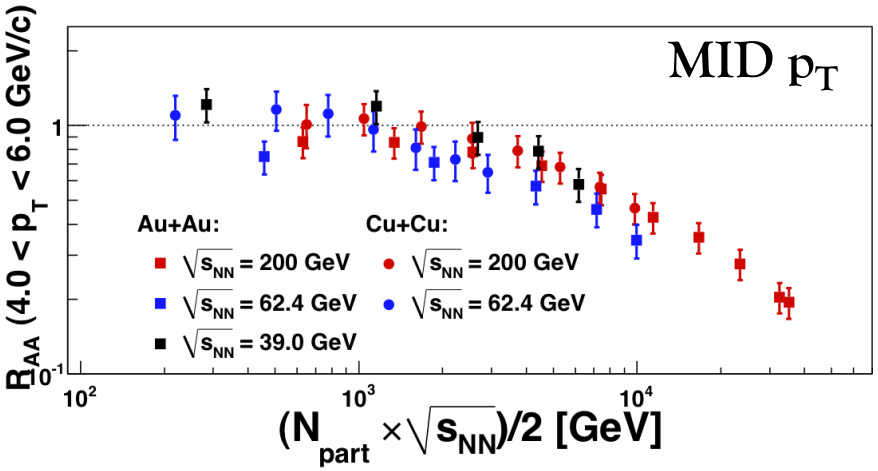
The R_{AA} values seems to have the same trend.

SPS, max reach: 2 × 208(Pb) × 17.3 GeV ($\sqrt{s_{NN}}$)/2 = 3598.4 GeV

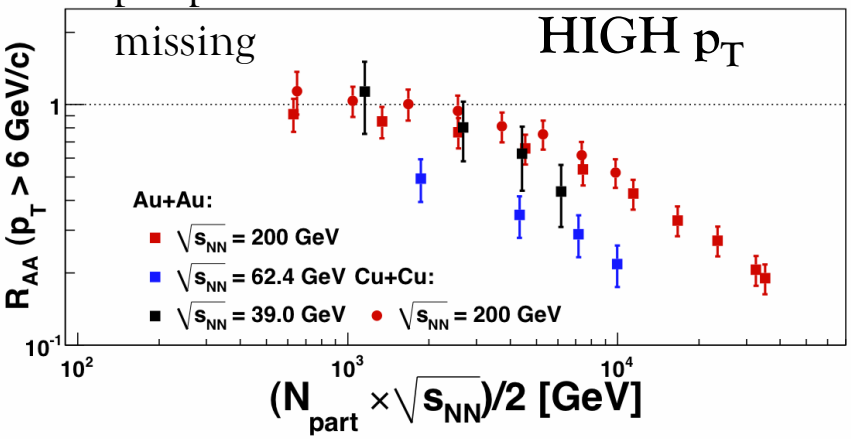
E_{AA} = 2 – 5 TeV

E_{AA} dependence on p_T





periph. data missing



In higher p_T the scaling does not work.

shadowing? Bjorken energy density?

Summary and Outlook

- The systematic study of the π^0 suppression:
  - The R_{AA} 62 and 200 are comparable in higher p_T (> 6GeV/c)
  - The R_{AA} in 39 GeV collision shows a large suppression (2x)
  - The Cu+Cu and Au+Au R_{AA} are are similar in same N_{part}.
  - The averaged R_{AA} at 39 GeV collision bellow 1 when N_{part}>100.
- The "onset" of the suppression varies with collision energy and system size.
  - The total energy of the system gives fairly good scaling of the R_{AA}, however it breaks down at high-p_T region.
- Stay tuned: 19.6 GeV AuAu, 27 GeV AuAu

References of PHENIX data:

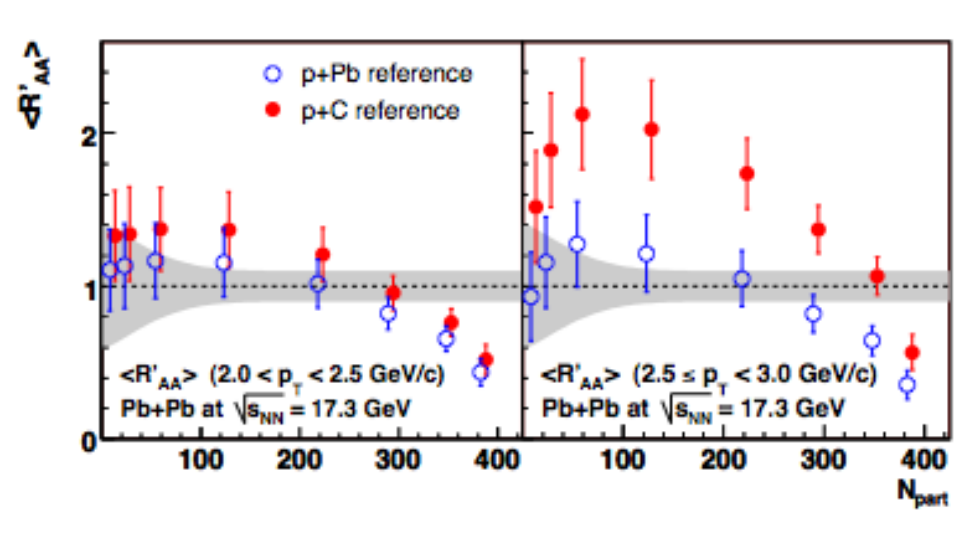
Cu+Cu results, π^0 (22.4-200 GeV): Phys. Rev. Lett.101, 162301 (2008)

Au+Au results, π^0 at 200 GeV: Phys. Rev. Lett. 101, 232301 (2008)

Thank you for your attention

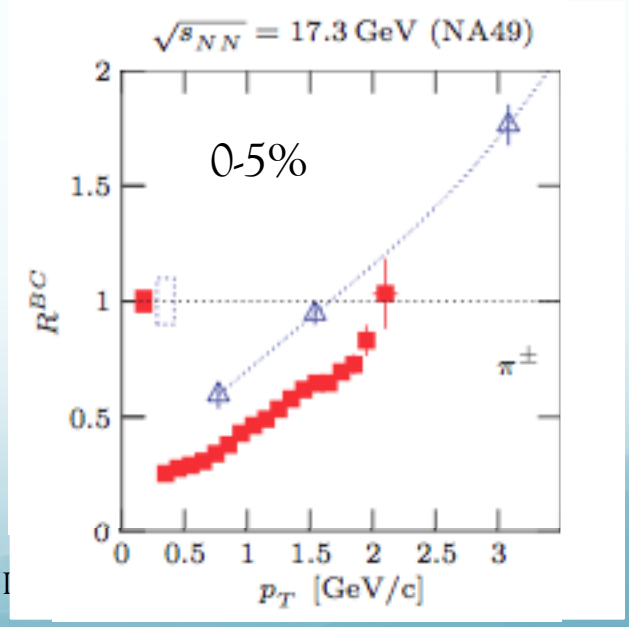
Backup

New SPS results (from 2008)



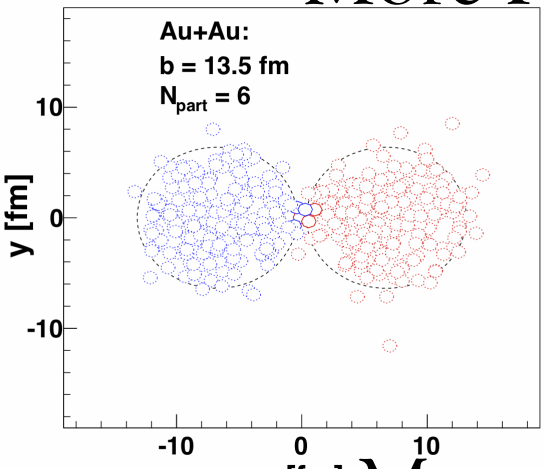
WA98 results:
Phys.Rev.Lett. 100 (2008) 242301
- No p+p reference,
- p+C : $N_{coll} \approx 1.7$
- Suppression in "ultra-central" collisions only (0-1%).
- In Npart < 100 same "constant" behavior as CuCu 22 GeV.

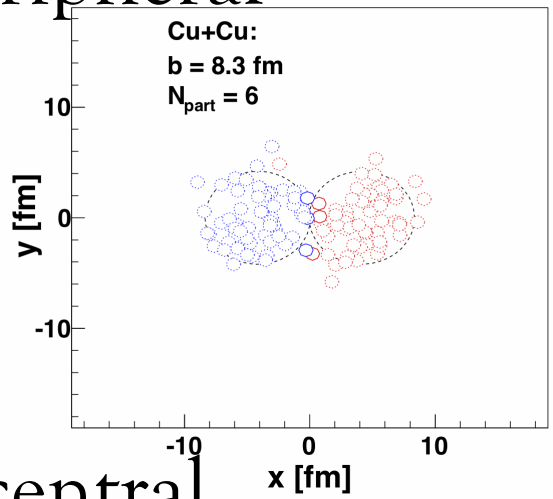
NA49: (charged hadrons)
- There is a slight suppression in the most central collision for the RAA results.
- The "suppression" is still within the systematic errors of the data.
- Point-by-point systematic errors are not shown...



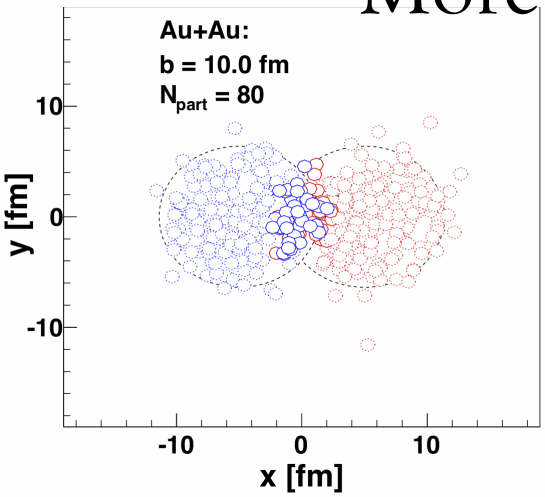
Supportive slide with Glauber MC (to backup)

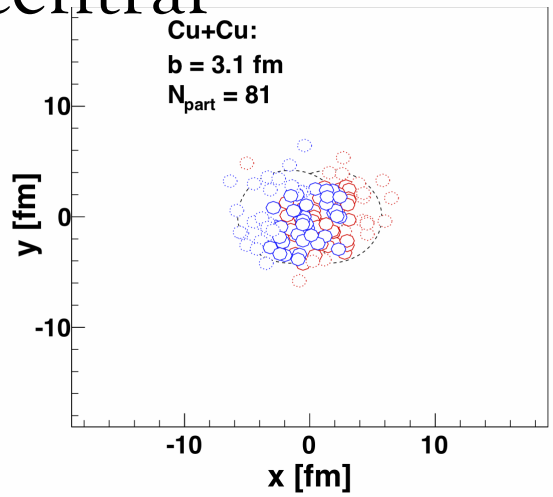
More Peripheral



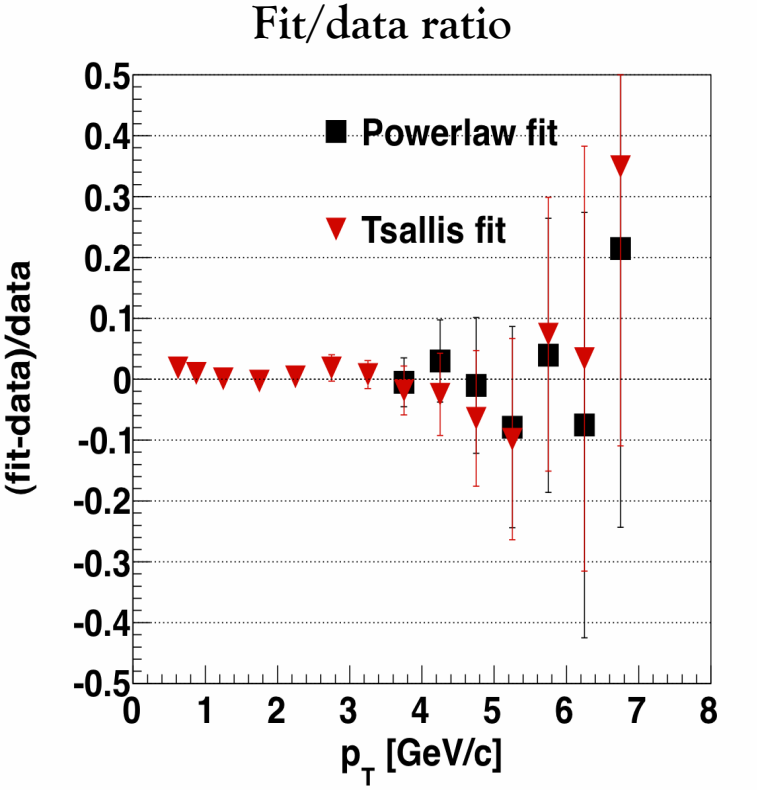


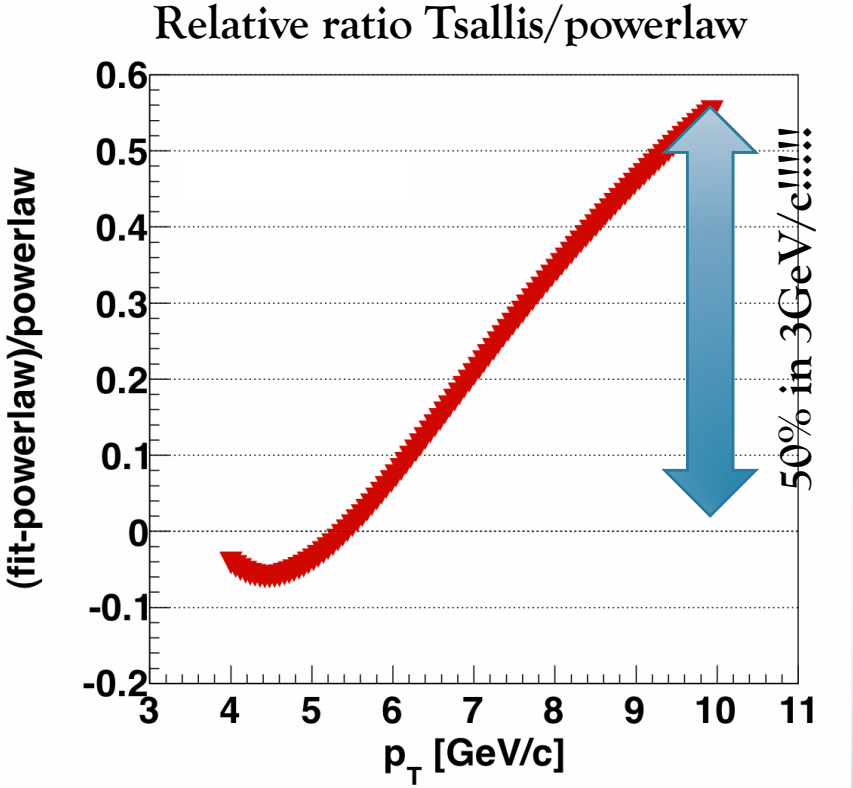
More central

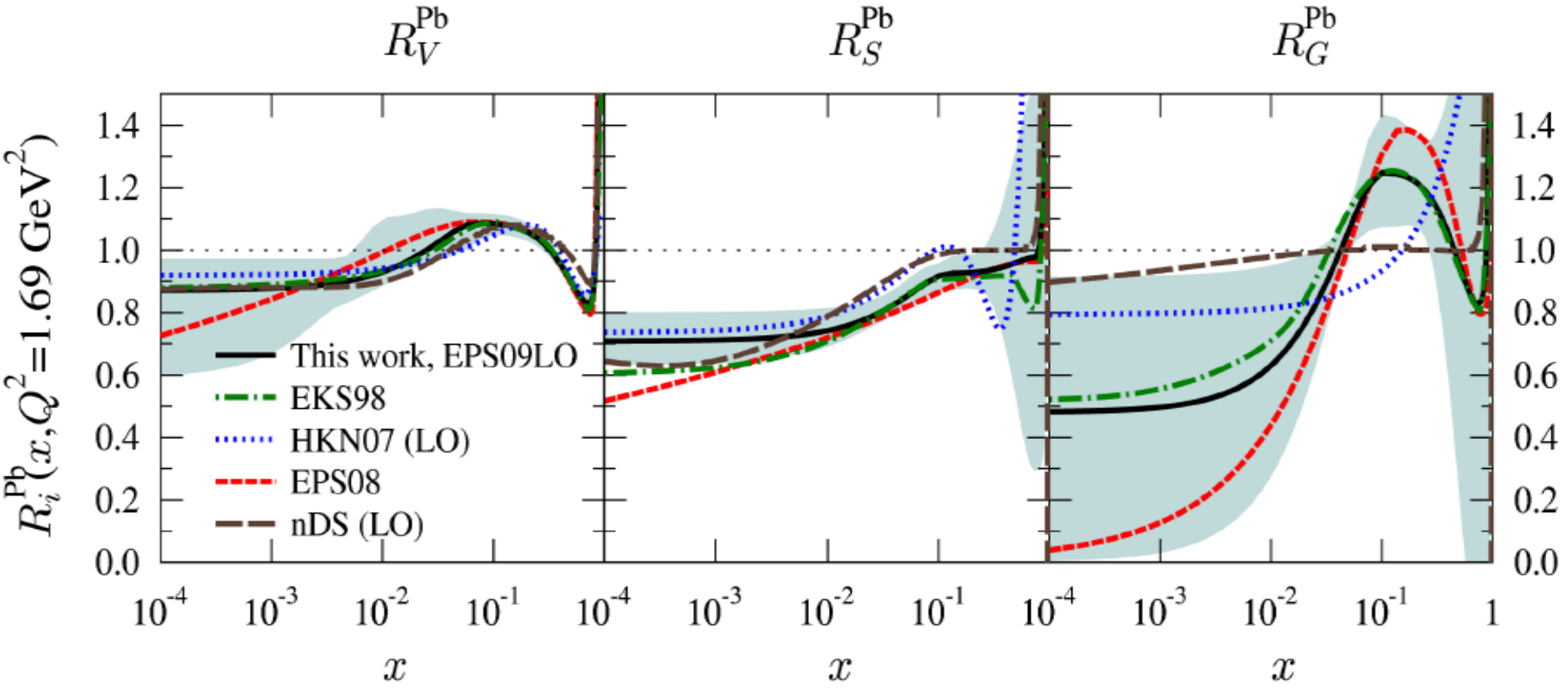




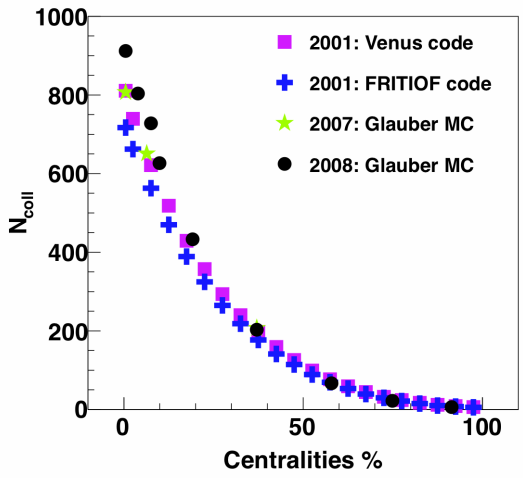
62.4 GeV p+p: powerlaw VS. Tsallis






R_V^{Pb}
R_S^{Pb}
R_G^{Pb}
$R_i^{Pb}(x,Q^2=1.69\ GeV^2)$
This work, EPS09LO
EKS98
HKN07 (LO)
EPS08
nDS (LO)
x

WA98 suspicion



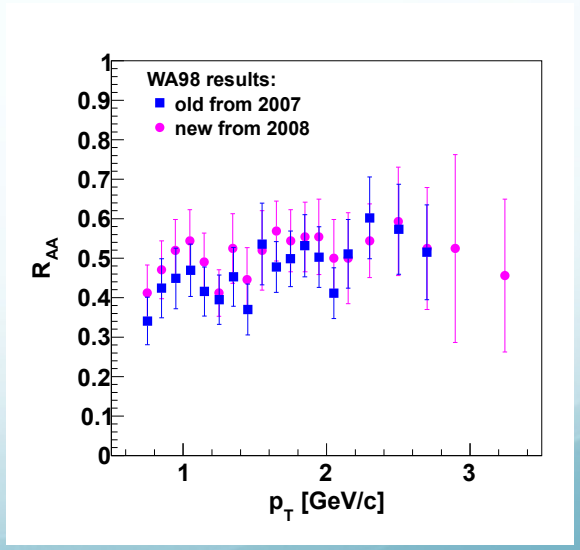
The WA98 published their Glauber model results from 2001-2008 period:

- In last year there was a 15% increase in from 2007 to 2008 numbers

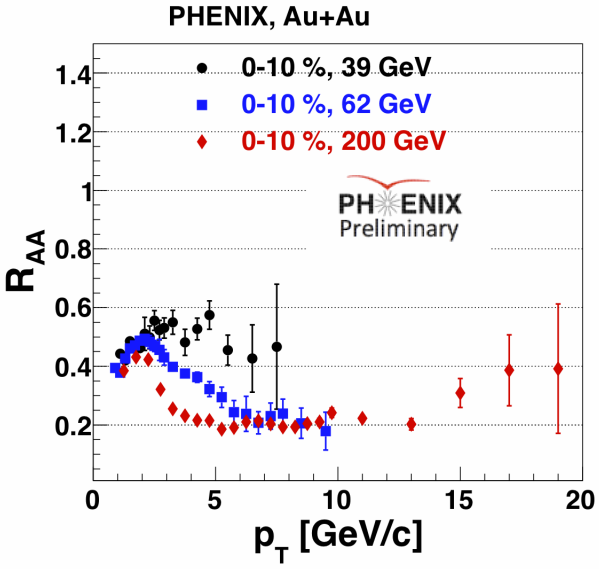
Simple equation:

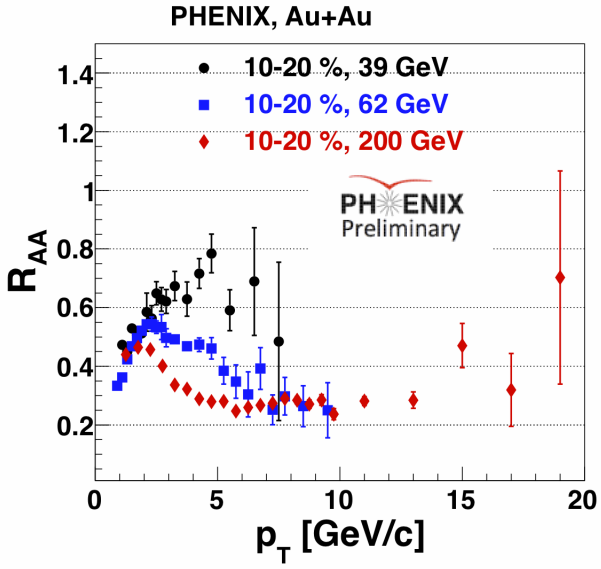
$$R_{AA} = \frac{Yield^{AuAu}}{N_{coll} \square Yield^{pp}}$$

1. If the yields of the Au+Au and p+p collisions are fixed, increasing the Ncoll will decrease the RAA value.
2. However:

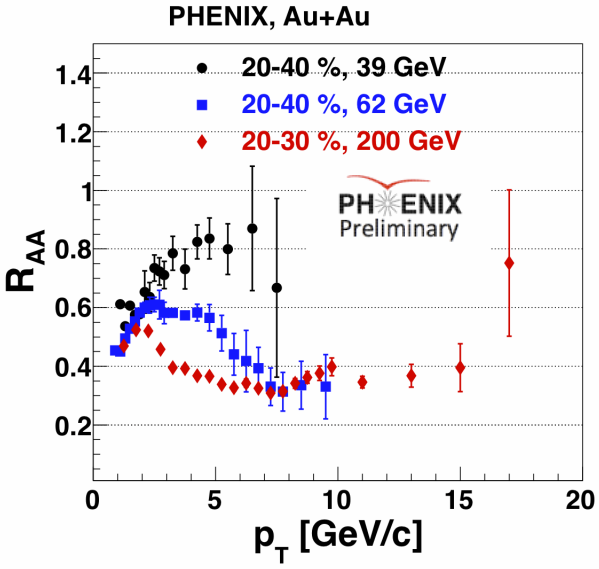


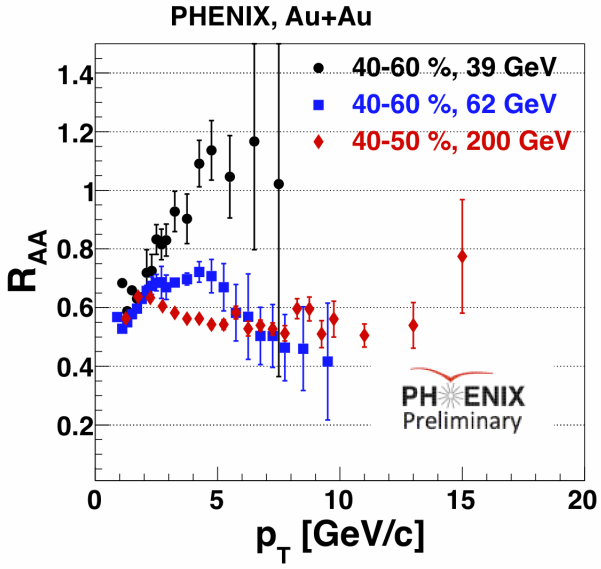
PHENIX

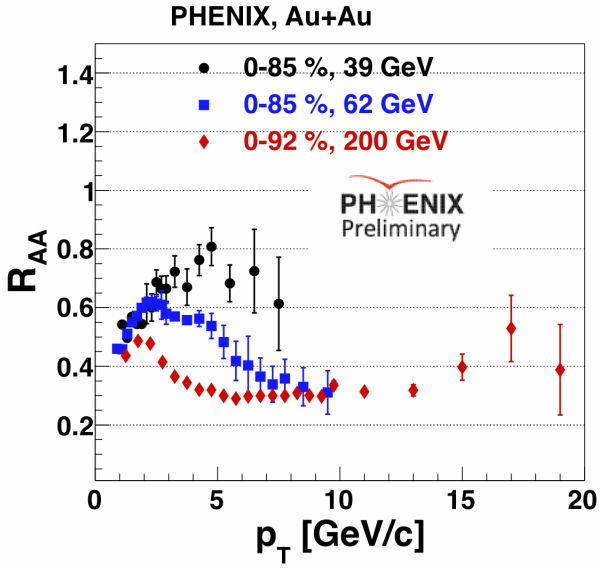


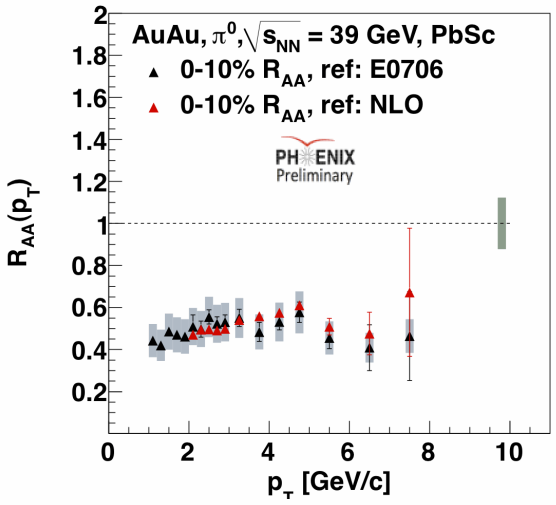


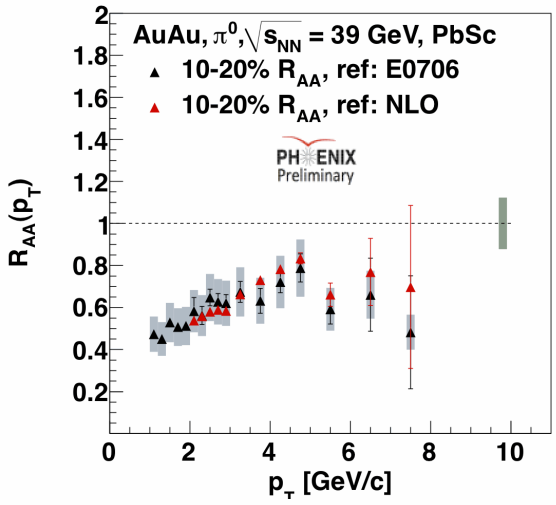
Minimum Bias








AuAu, π^0, $\sqrt{s_{NN}}$ = 39 GeV, PbSc
0-10% R_{AA}, ref: E0706
0-10% R_{AA}, ref: NLO
PHENIX Preliminary
$R_{AA}(p_T)$
p_T [GeV/c]


AuAu, π^0, $\sqrt{s_{NN}}$ = 39 GeV, PbSc
10-20% R_{AA}, ref: E0706
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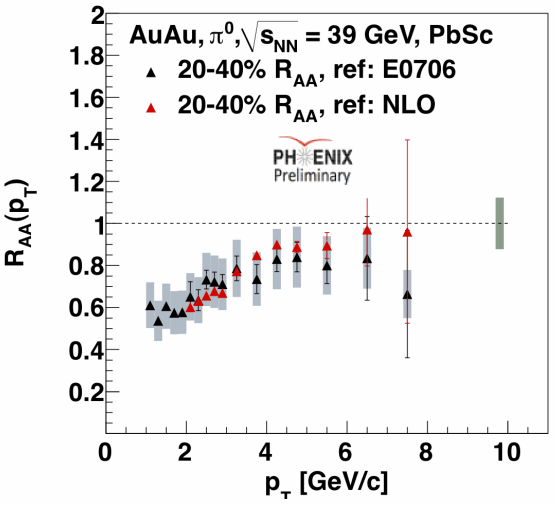
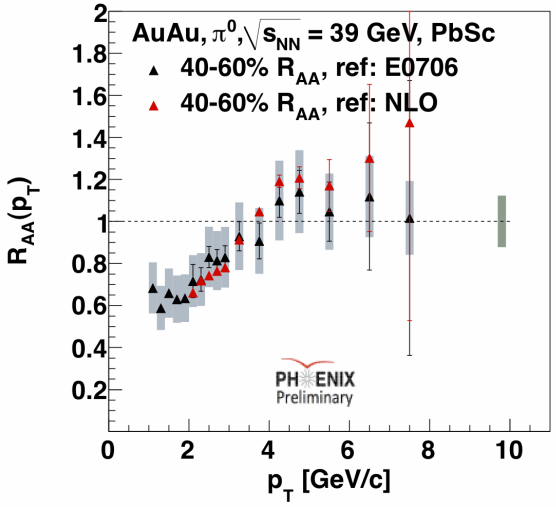
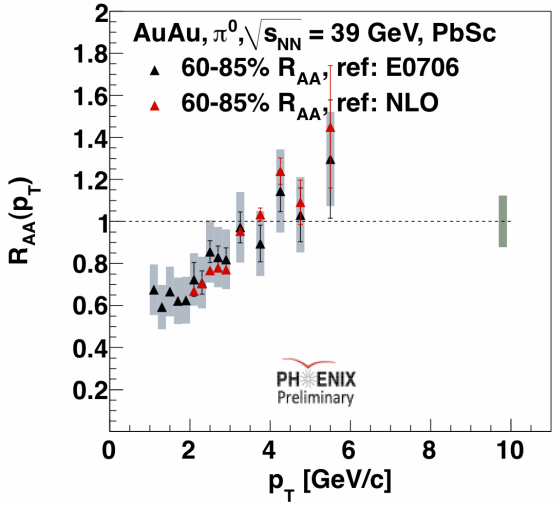
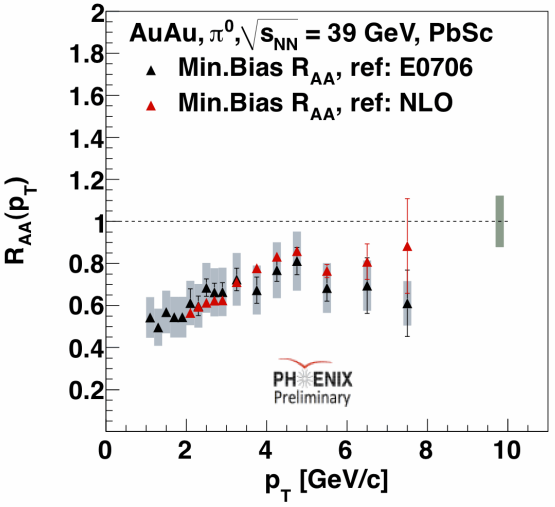
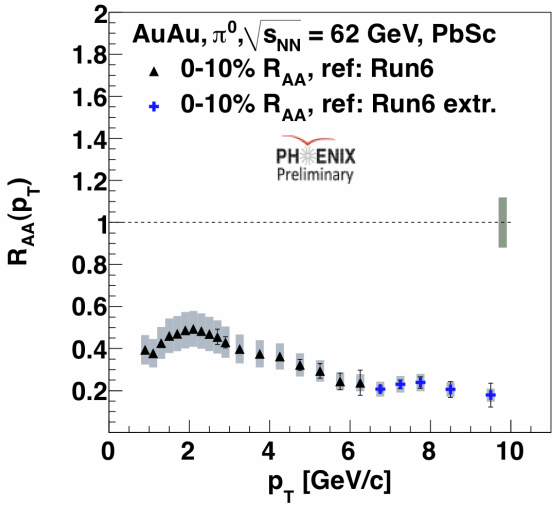
PHENIX Preliminary
$R_{AA}(p_T)$
p_T [GeV/c]

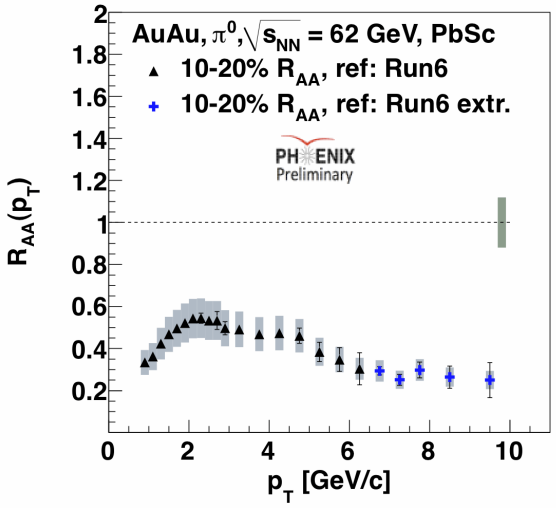

AuAu, π^0, $\sqrt{s_{NN}}$ = 39 GeV, PbSc
20-40% R_{AA}, ref: E0706
20-40% R_{AA}, ref: NLO
PHENIX Preliminary
$R_{AA}(p_T)$
p_T [GeV/c]

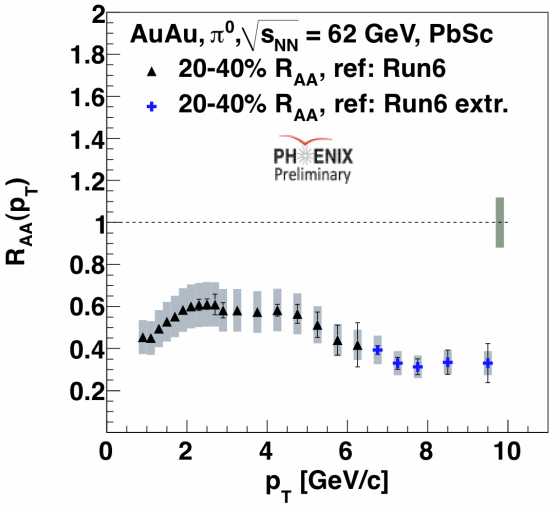

AuAu, π^0, $\sqrt{s_{NN}}$ = 39 GeV, PbSc
40-60% R_{AA}, ref: E0706
40-60% R_{AA}, ref: NLO
PHENIX Preliminary
$R_{AA}(p_T)$
p_T [GeV/c]

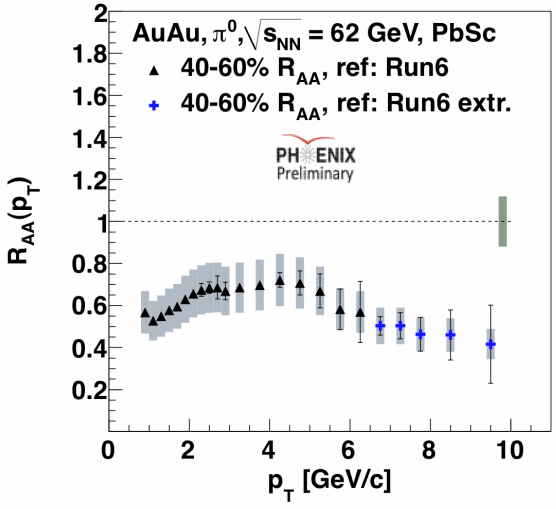

AuAu, π^0, $\sqrt{s_{NN}}$ = 39 GeV, PbSc
60-85% R_{AA}, ref: E0706
60-85% R_{AA}, ref: NLO
PHENIX Preliminary
$R_{AA}(p_T)$
p_T [GeV/c]

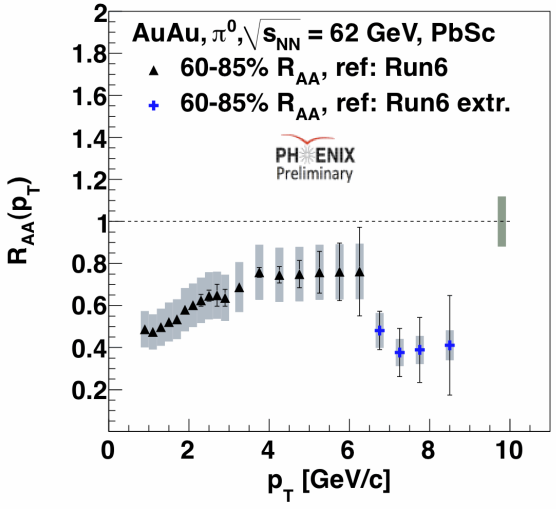

AuAu, π^0, $\sqrt{s_{NN}}$ = 39 GeV, PbSc
Min.Bias R_{AA}, ref: E0706
Min.Bias R_{AA}, ref: NLO
PHENIX Preliminary
$R_{AA}(p_T)$
p_T [GeV/c]

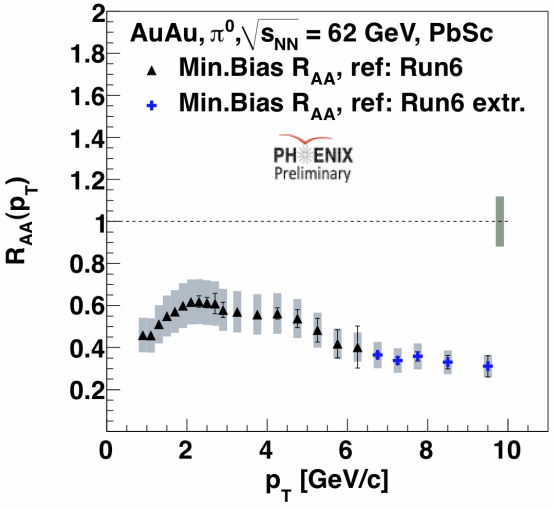

AuAu, π^0, $\sqrt{s_{NN}}$ = 62 GeV, PbSc
0-10% R_{AA}, ref: Run6
0-10% R_{AA}, ref: Run6 extr.
PHENIX Preliminary
$R_{AA}(p_T)$
p_T [GeV/c]

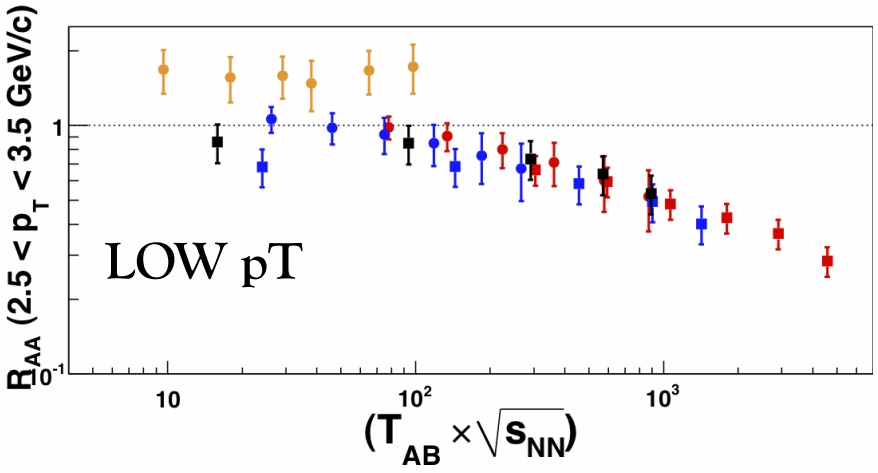

AuAu, π^0, $\sqrt{s_{NN}}$ = 62 GeV, PbSc
10-20% R_{AA}, ref: Run6
10-20% R_{AA}, ref: Run6 extr.
PHENIX Preliminary
$R_{AA}(p_T)$
p_T [GeV/c]

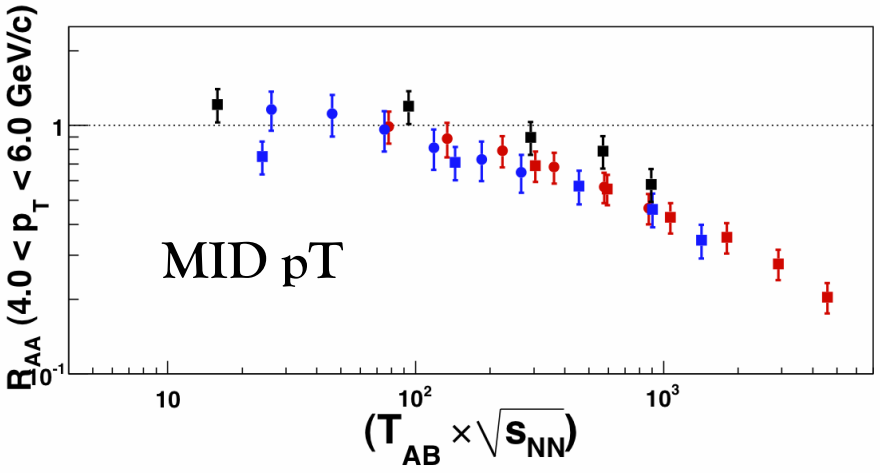

AuAu, π^0, $\sqrt{s_{NN}}$ = 62 GeV, PbSc
20-40% R_{AA}, ref: Run6
20-40% R_{AA}, ref: Run6 extr.
PHENIX Preliminary
$R_{AA}(p_T)$
p_T [GeV/c]

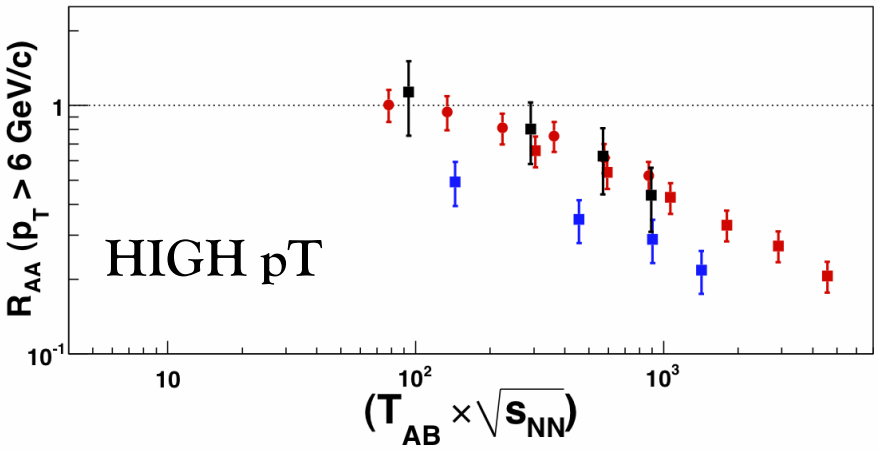

AuAu, π^0, $\sqrt{s_{NN}}$ = 62 GeV, PbSc
40-60% R_{AA}, ref: Run6
40-60% R_{AA}, ref: Run6 extr.
PHENIX Preliminary
$R_{AA}(p_T)$
p_T [GeV/c]


AuAu, π^0, $\sqrt{s_{NN}}$ = 62 GeV, PbSc
60-85% R_{AA}, ref: Run6
60-85% R_{AA}, ref: Run6 extr.
PHENIX Preliminary
$R_{AA}(p_T)$
p_T [GeV/c]

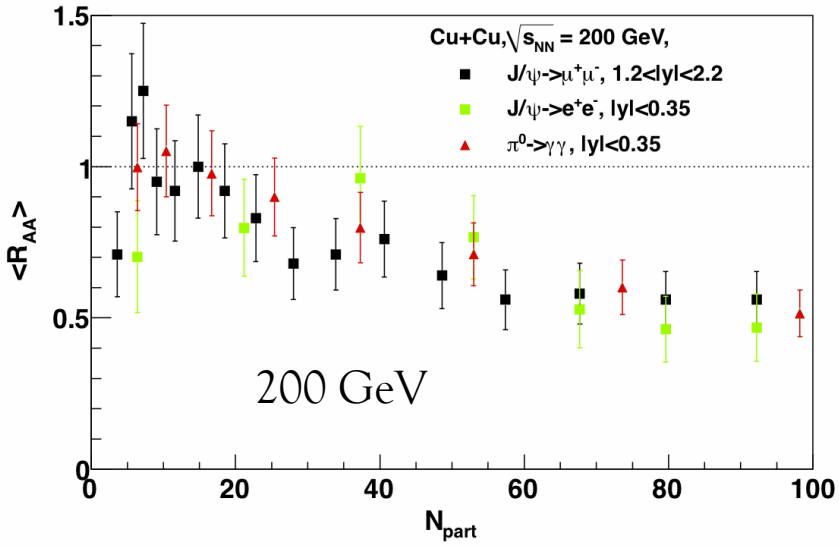

AuAu, π^0, $\sqrt{s_{NN}}$ = 62 GeV, PbSc
Min.Bias R_{AA}, ref: Run6
Min.Bias R_{AA}, ref: Run6 extr.
PHENIX Preliminary
$R_{AA}(p_T)$
p_T [GeV/c]

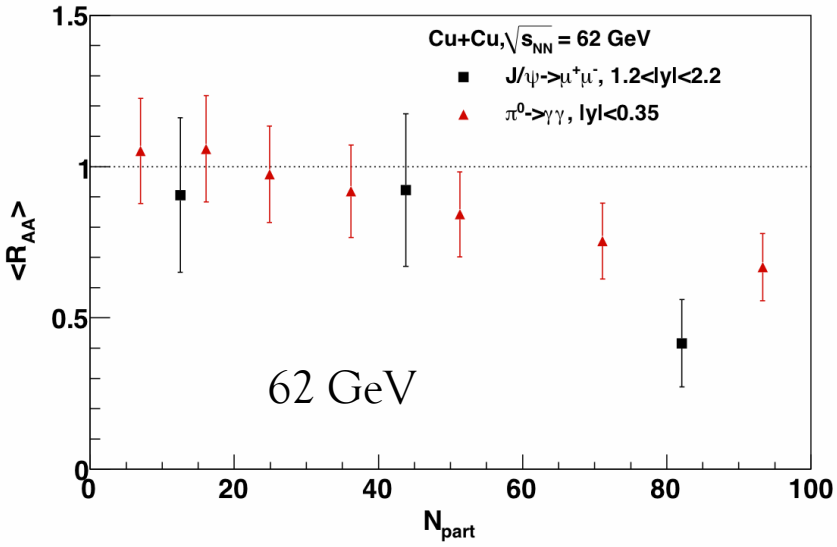

LOW pT
R_{AA} (2.5 < p_T < 3.5 GeV/c)
$(T_{AB} \times \sqrt{s_{NN}})$

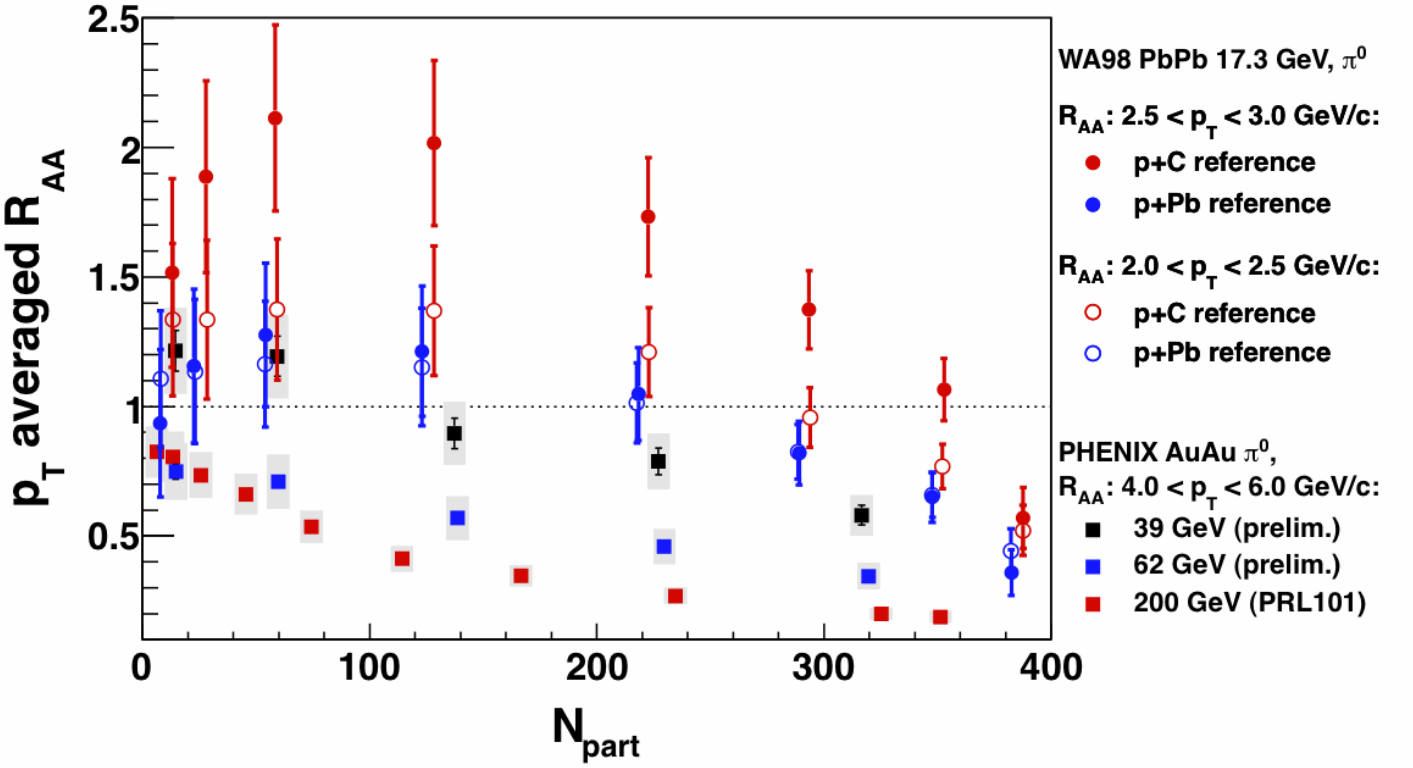

MID pT
R_{AA} (4.0 < p_T < 6.0 GeV/c)
$(T_{AB} \times \sqrt{s_{NN}})$


HIGH pT
R_{AA} (p_T > 6 GeV/c)
$(T_{AB} \times \sqrt{s_{NN}})$

Suppression of Light- and Heavy-quarks






2.5
2
1.5
1
0.5
0
100
200
300
400
p_T averaged R_{AA}
N_{part}
WA98 PbPb 17.3 GeV, π^0
R_{AA}: 2.5 < p_T < 3.0 GeV/c:
p+C reference
p+Pb reference
R_{AA}: 2.0 < p_T < 2.5 GeV/c:
p+C reference
p+Pb reference
PHENIX AuAu π^0,
R_{AA}: 4.0 < p_T < 6.0 GeV/c:
39 GeV (prelim.)
62 GeV (prelim.)
200 GeV (PRL101)