Particle production at different scales in p_T

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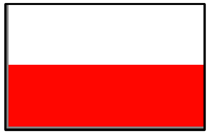
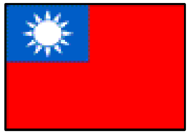
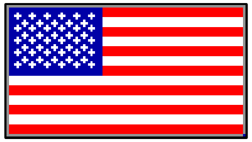
RHIC/AGS users' meeting, June 7, 2006

PHOBOS collaboration (June 2006)

Burak Alver, Birger Back, Mark Baker, Maarten Ballintijn, Donald Barton, Russell Betts, Richard Bindel, Wit Busza (Spokesperson), Zhengwei Chai, Vasundhara Chetluru, Edmundo García, Tomasz Gburek, Kristjan Gulbrandsen, Clive Halliwell, Joshua Hamblen, Ian Harnarine, Conor Henderson, David Hofman, Richard Hollis, Roman Hołyński, Burt Holzman, Aneta Iordanova, Jay Kane, Piotr Kulinich, Chia Ming Kuo, Wei Li, Willis Lin, Constantin Loizides, Steven Manly, Alice Mignerey, Gerrit van Nieuwenhuizen, Rachid Nouicer, Andrzej Olszewski, Robert Pak, Corey Reed, Eric Richardson, Christof Roland, Gunther Roland, Joe Sagerer, Iouri Sedykh, Chadd Smith, Maciej Stankiewicz, Peter Steinberg, George Stephans, Andrei Sukhanov, Artur Szostak, Marguerite Belt Tonjes, Adam Trzupek, Sergei Vaurynovich, Robin Verdier, Gábor Veres, Peter Walters, Edward Wenger, Donald Willhelm, Frank Wolfs, Barbara Wosiek, Krzysztof Woźniak, Shaun Wyngaardt, Bolek Wysłouch

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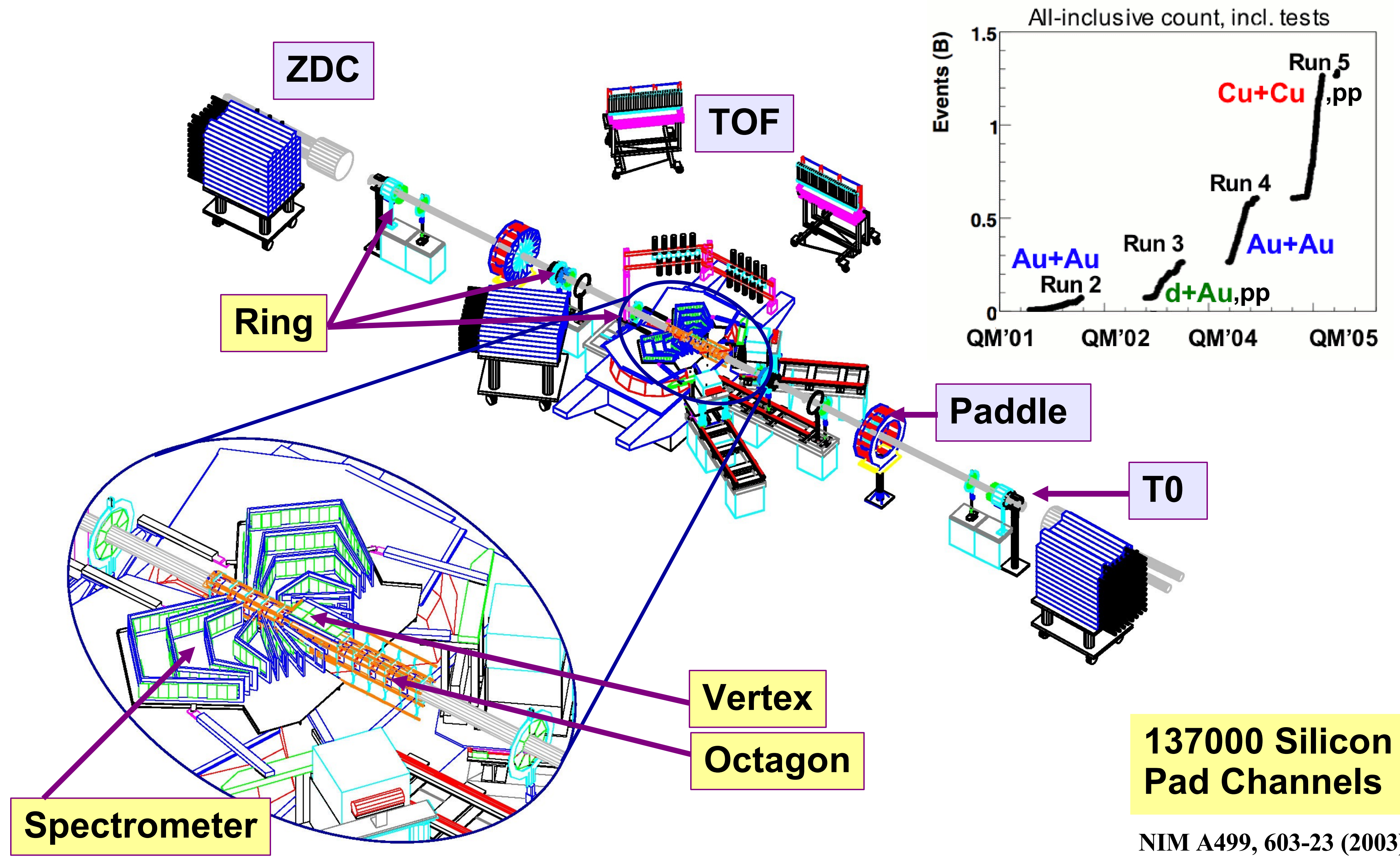
NATIONAL CENTRAL UNIVERSITY, TAIWAN
UNIVERSITY OF MARYLAND

BROOKHAVEN NATIONAL LABORATORY
MASSACHUSETTS INSTITUTE OF TECHNOLOGY
UNIVERSITY OF ILLINOIS AT CHICAGO
UNIVERSITY OF ROCHESTER

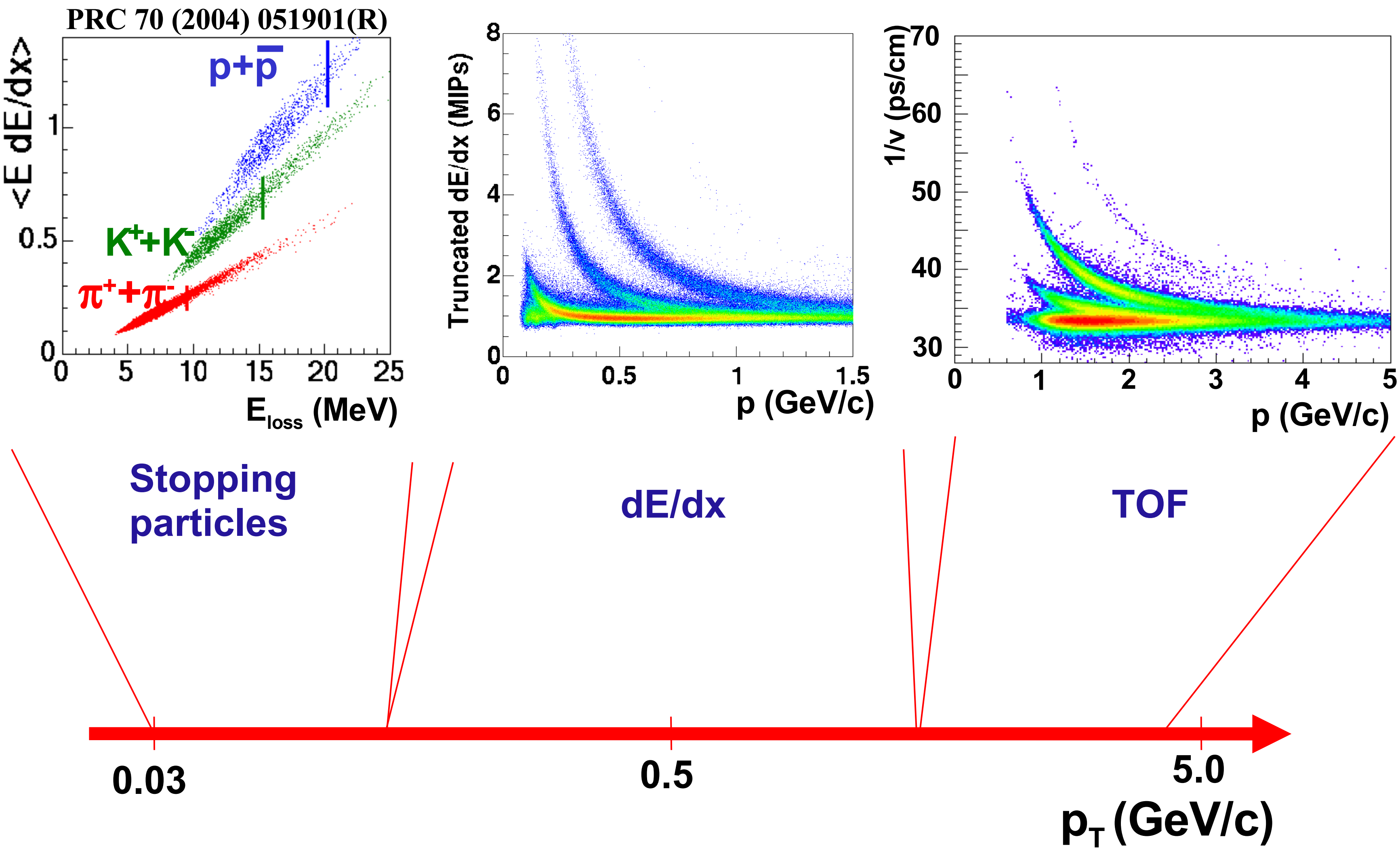
PHOBOS experiment



137000 Silicon Pad Channels

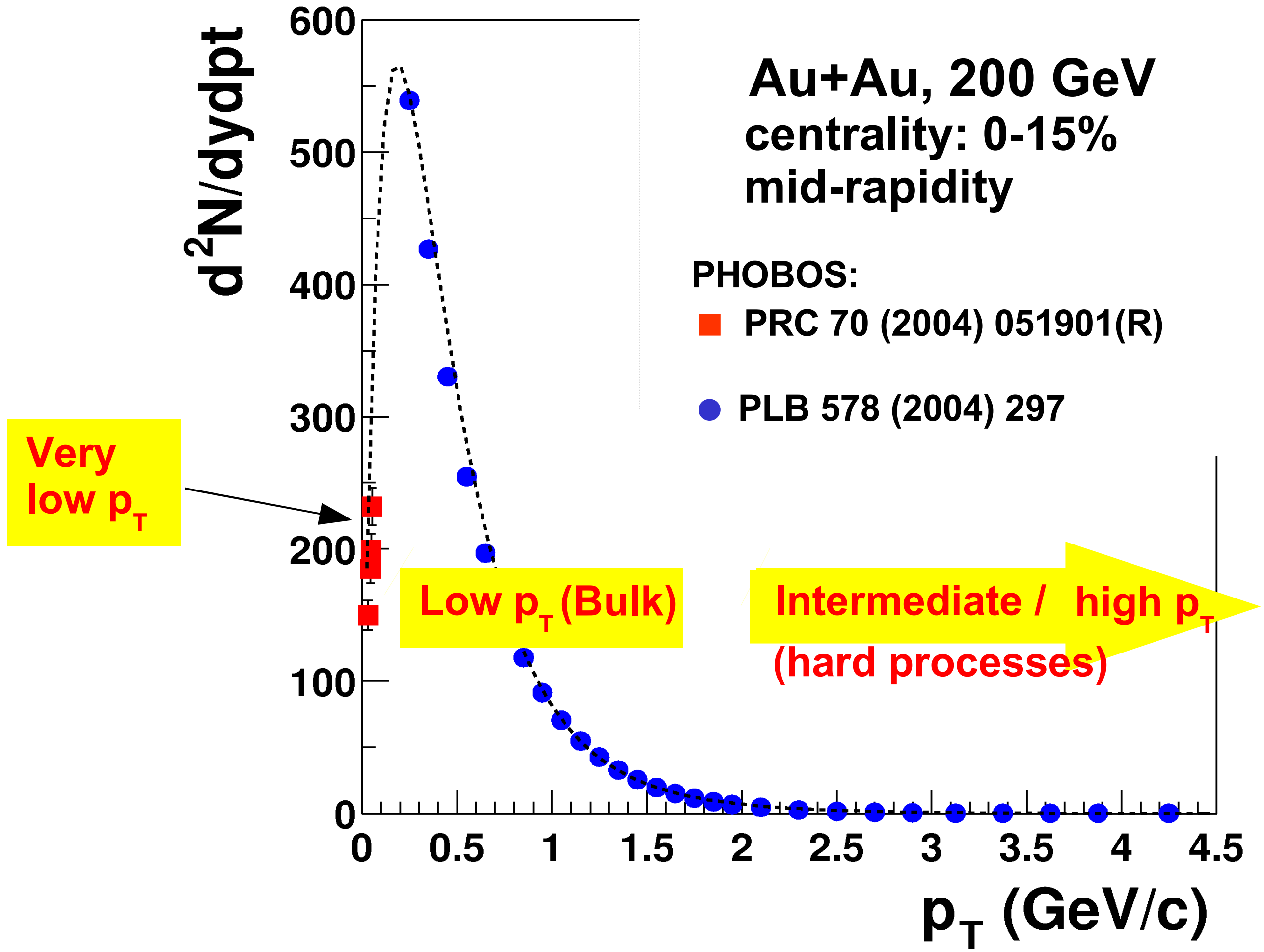
NIM A499, 603-23 (2003)

PHOBOS PID capabilities



Particle ID from low to high p_T

Particle production at various p_T scales



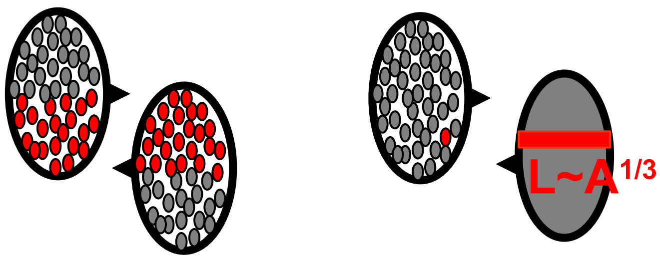
Particle production dominated by

Volume, eg. participants (N_{part})

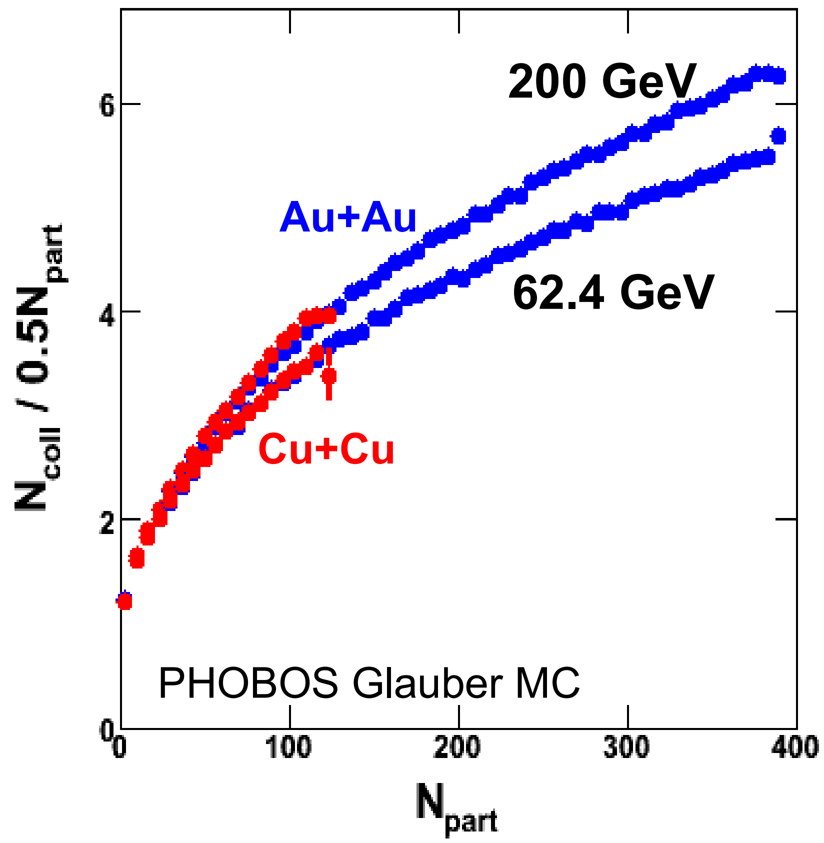
Binary NN-collisions (N_{coll})

External parameters

- Collision centrality relates to
  - #Participants (N_{part})
  - #NN-collisions (N_{coll})

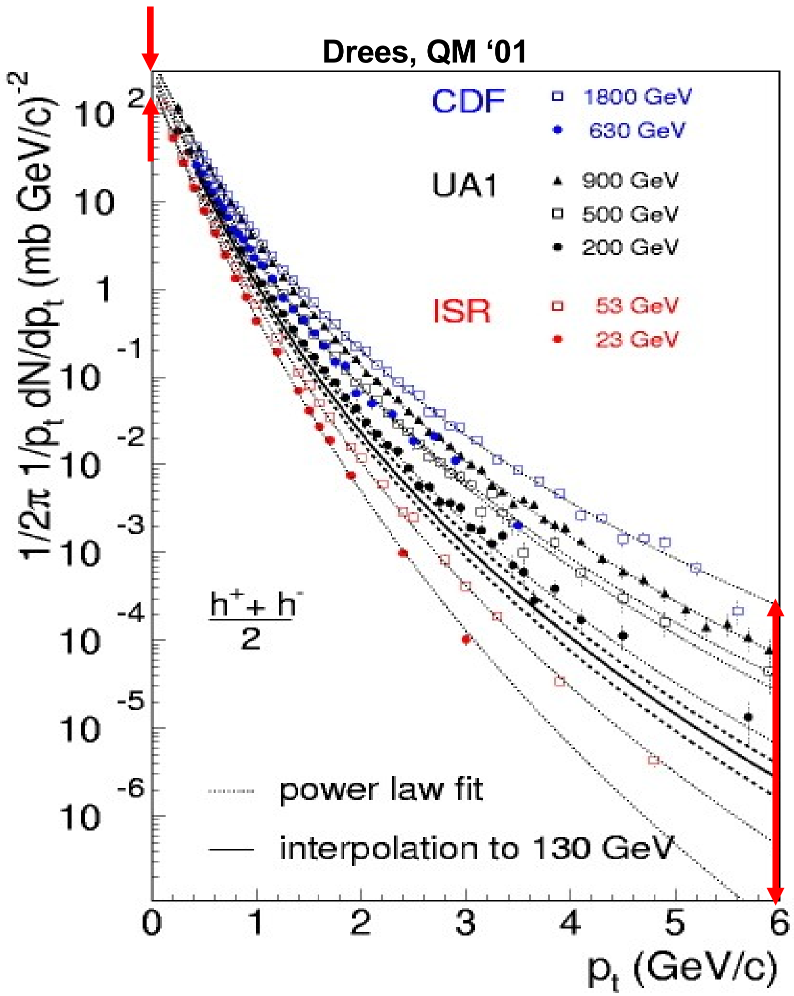


$N_{part} \sim A$ $N_{coll} \sim A^{4/3}$



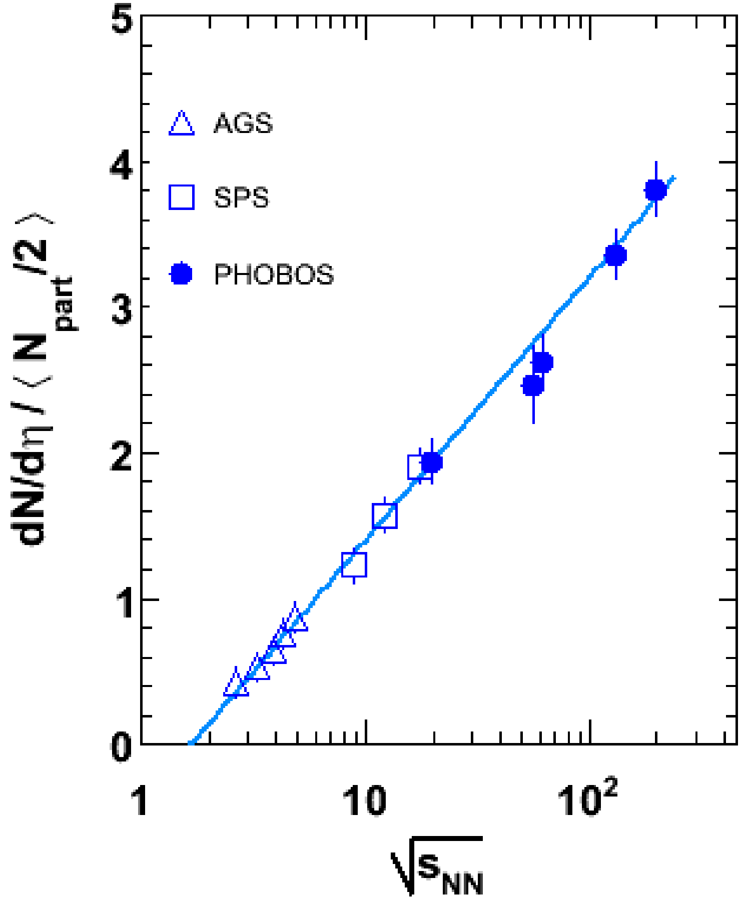
External parameters (2)

- Collision energy controls
  - Ratio of hard to soft processes



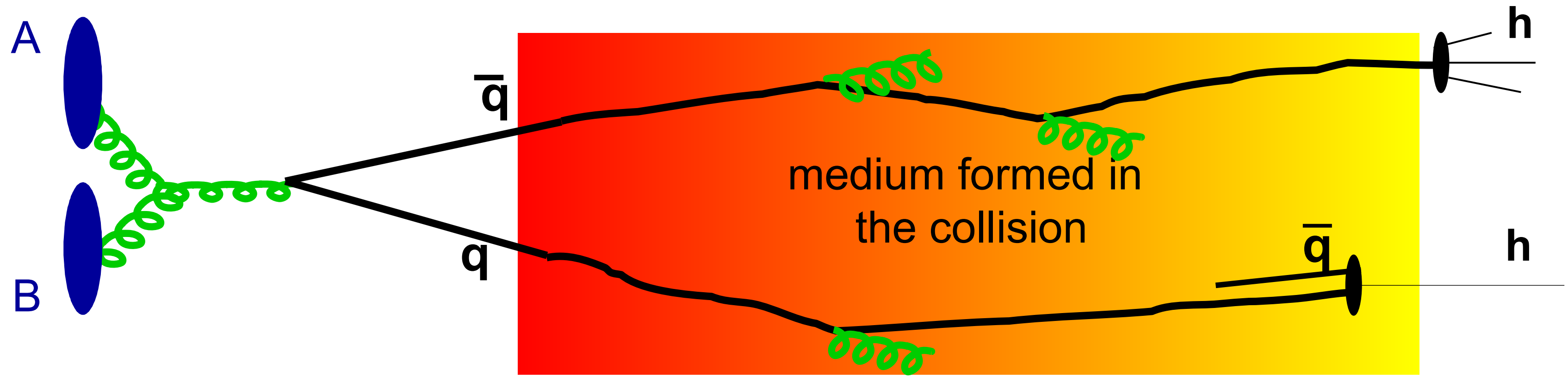
External parameters (3)

- Collision energy controls
  - Ratio of hard to soft processes
  - Mid-rapidity particle density



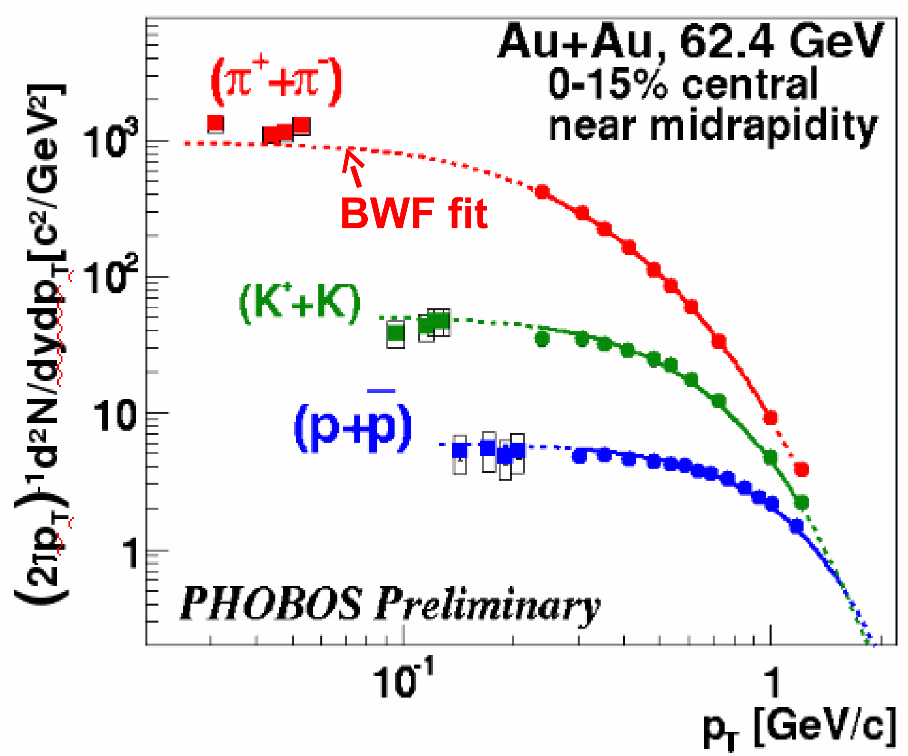
(Increase also with centrality, not shown)

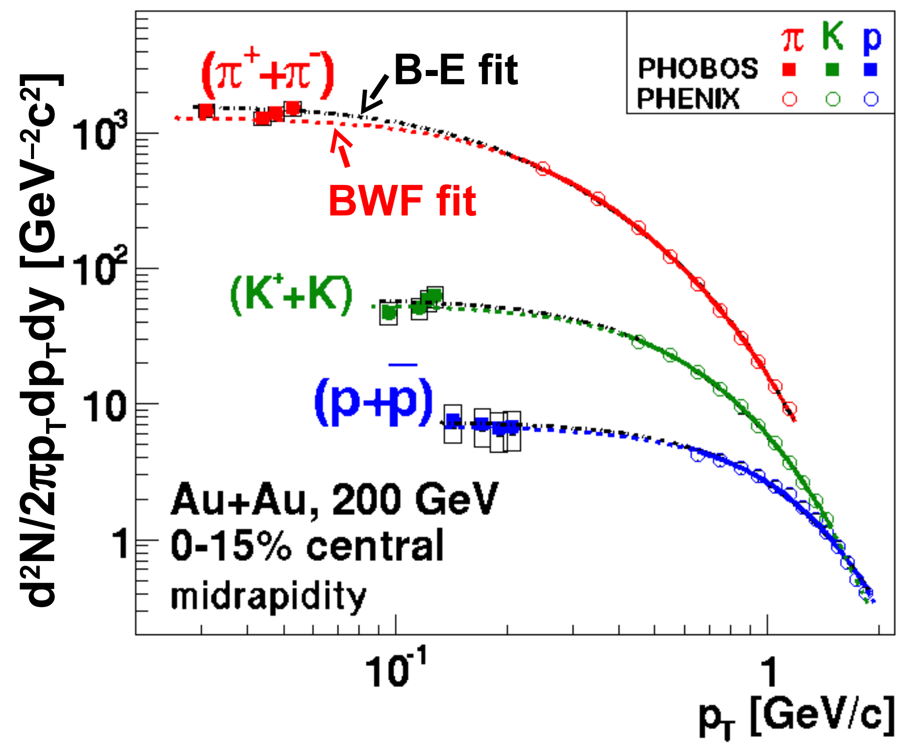
Usage of hard probes in different systems



- System comparison
  - To disentangle initial from final state effects (dAu)
  - To study density vs geometry effects (Au, Cu)
  - Needs a calibrated baseline (pp)
    - Also peripheral A+A collisions are used

Properties of the medium





In a large volume + weakly interacting system, one expects the development of particles with long wavelengths.

PHOBOS WhitePaper

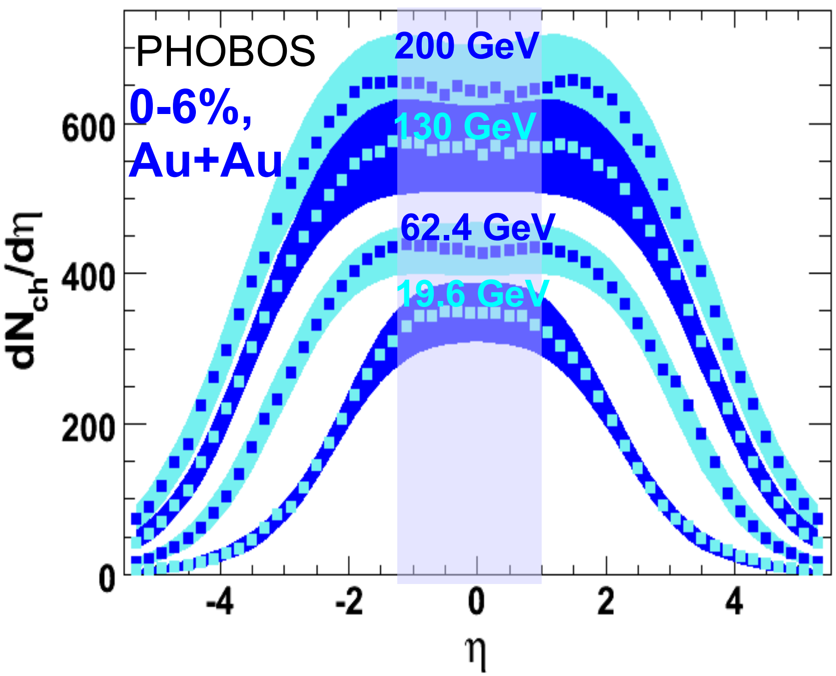
No evidence of enhanced particle production at very low p_T

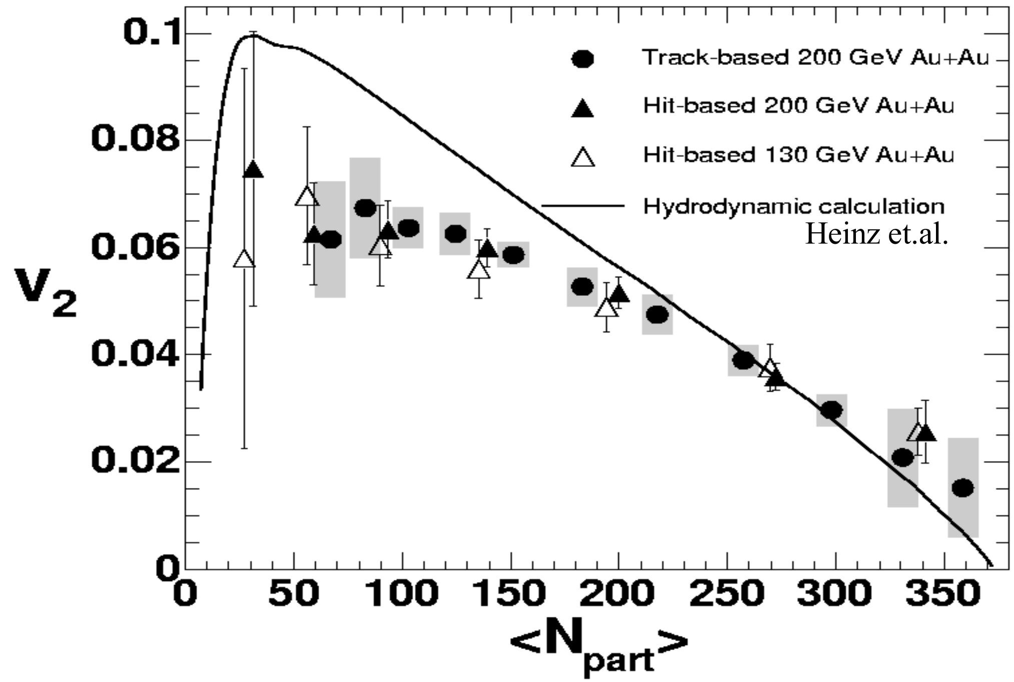
constraints → <E>

200 GeV PHOBOS: PRC 70, 051901 (R) (2004)
200 GeV PHENIX: PRC 69, 034909 (2004)
62.4 GeV PHOBOS prel. : QM05, nucl-ex/0510039

For details and fit params, see G.Veres, SQM'06

Properties of the medium (2)





$$\epsilon = \frac{\langle E \rangle \times dN/d\eta \times \text{corr}}{\pi R^2 \ \text{X} \ (0.1 - \text{few}) \ \text{fm}}$$

At 200 GeV:

$\epsilon > 3$ GeV/fm^3

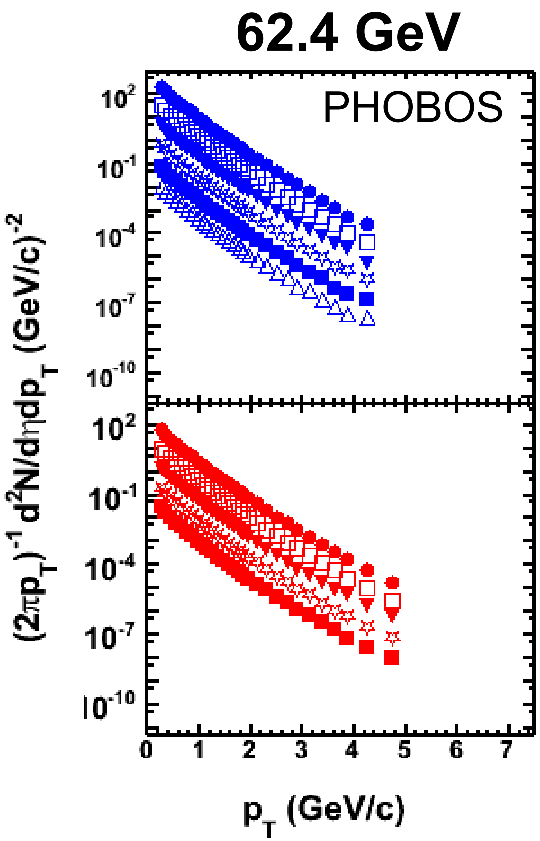
PHOBOS WhitePaper

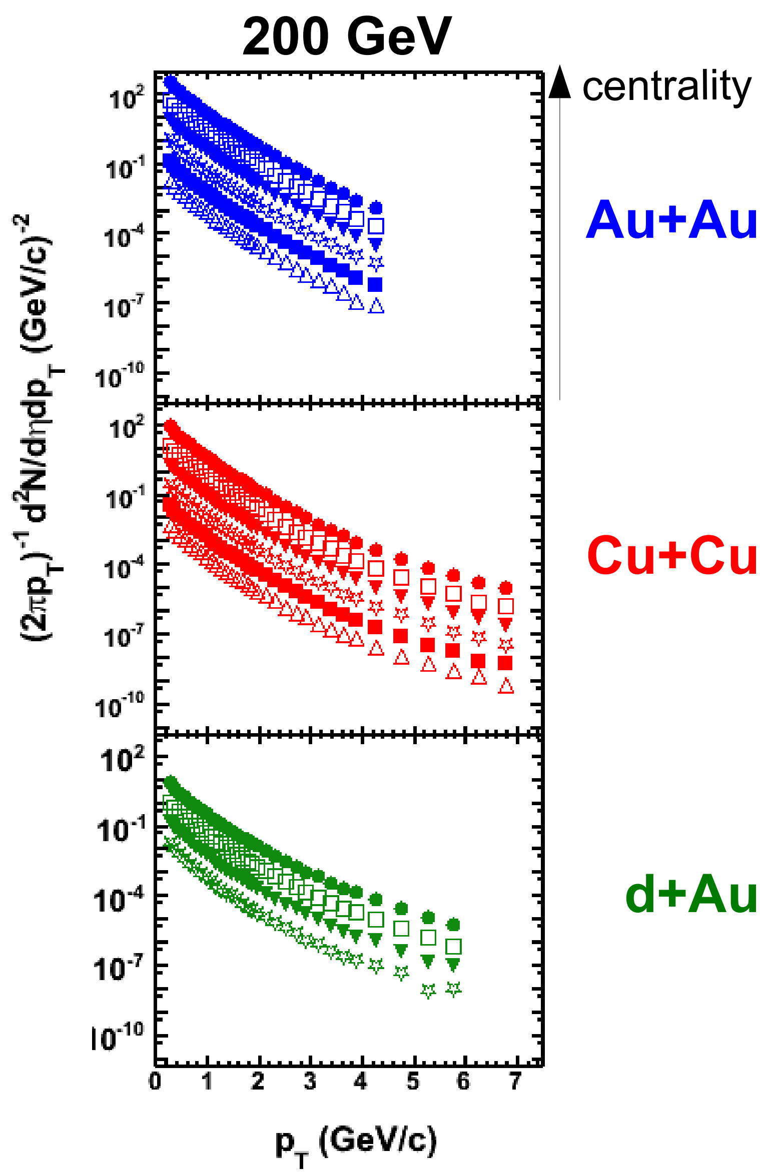
Strongly interacting medium
with extremely high energy density

WhitePaper: NPA, 757 28 (2005)
v_2 Au+Au: PRL 94, 122303 (2005)
v_2 Cu+Cu (prel.): QM05, nucl-ex/0510042

Charged hadron p_T-spectra (near mid-rapidity)

0.2<η<1.4

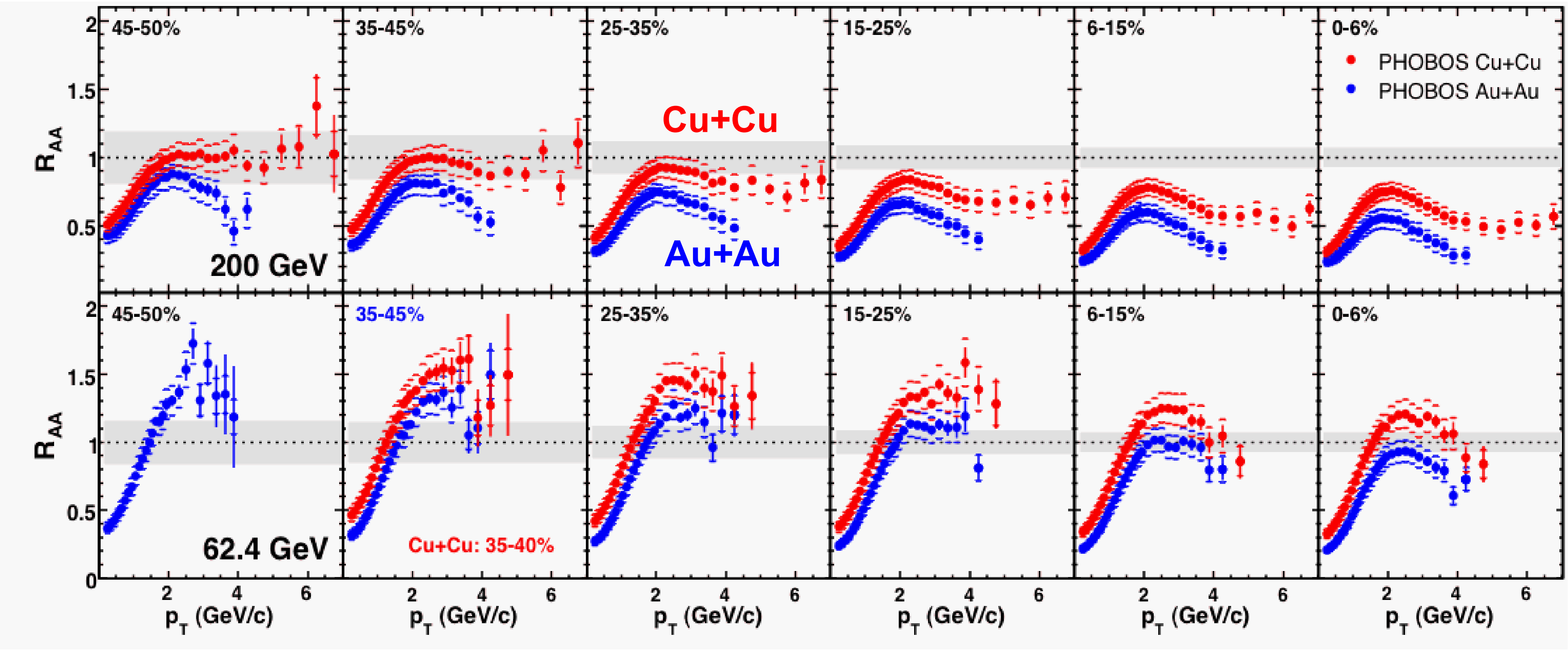




Au+Au: PRL 94, 082304 (2005),
PLB 578, 297 (2004)
Cu+Cu: PRL 96, 212301 (2006)
d+Au: Phys. Rev. Lett. 91, 072302 (2003)

R_{AA} in Au+Au and Cu+Cu at 62.4 and 200 GeV

0.2<η<1.4



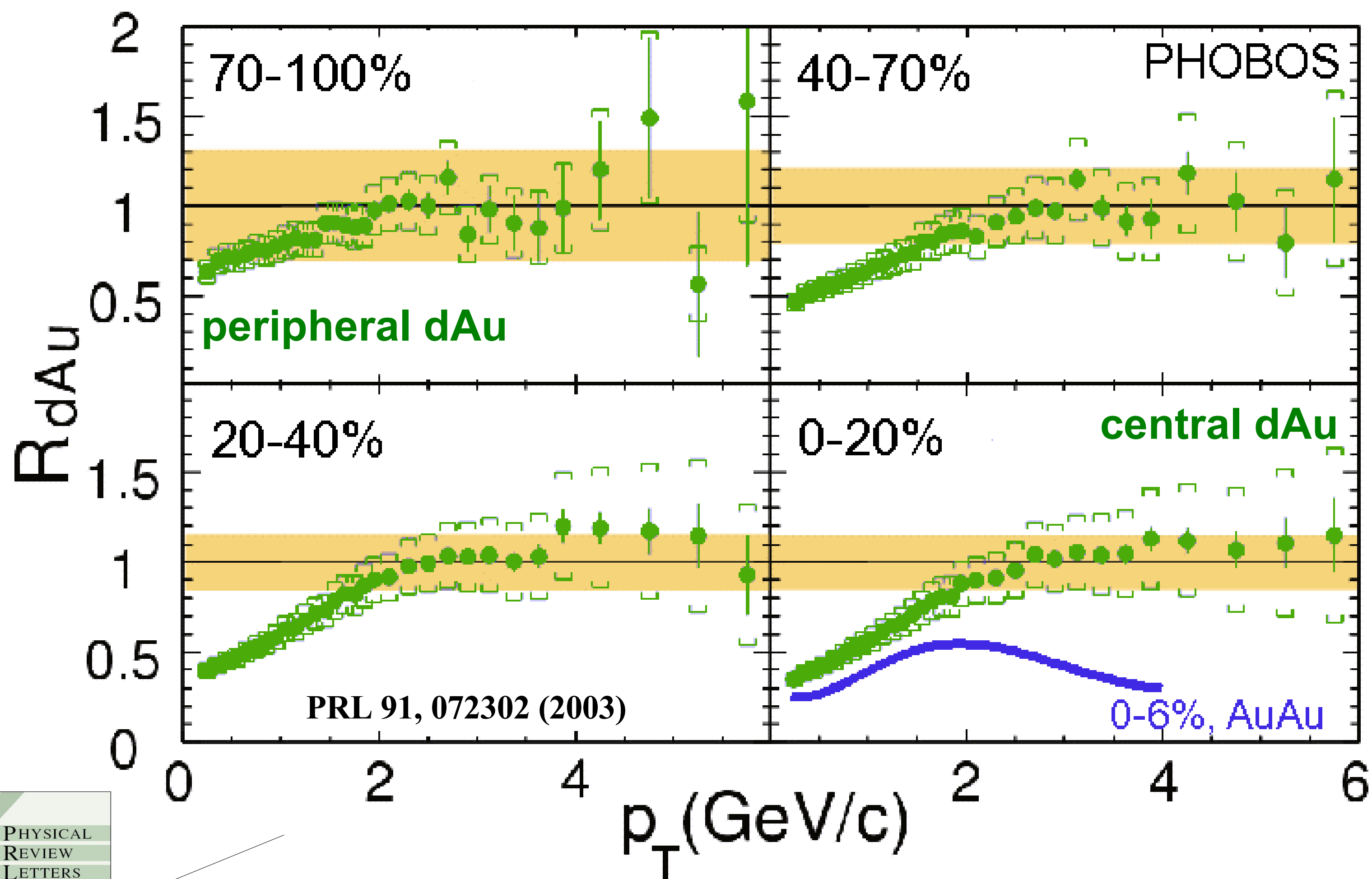
Large suppression of leading particles wrt. binary scaling

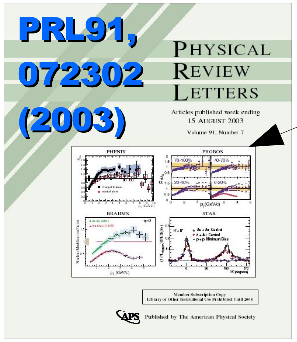
Au+Au: PRL 94, 082304 (2005), PLB 578, 297 (2004)
Cu+Cu: PRL 96, 212301 (2006)
p+p̄, 200 GeV: UA1 -2.5<η<2.5 (acc. correction with PYTHIA)
p+p, 63 GeV: SFM 0.5<y<1 (acc. correction with PYTHIA)

$$R_{AA} = \frac{\sigma_{pp}^{inel}}{\langle N_{coll} \rangle} \frac{d^2 N_{AA}/dp_T d\eta}{d^2 \sigma_{p\bar{p}}/dp_T d\eta}$$

R_{dAu} vs centrality at 200 GeV

0.2<η<1.4



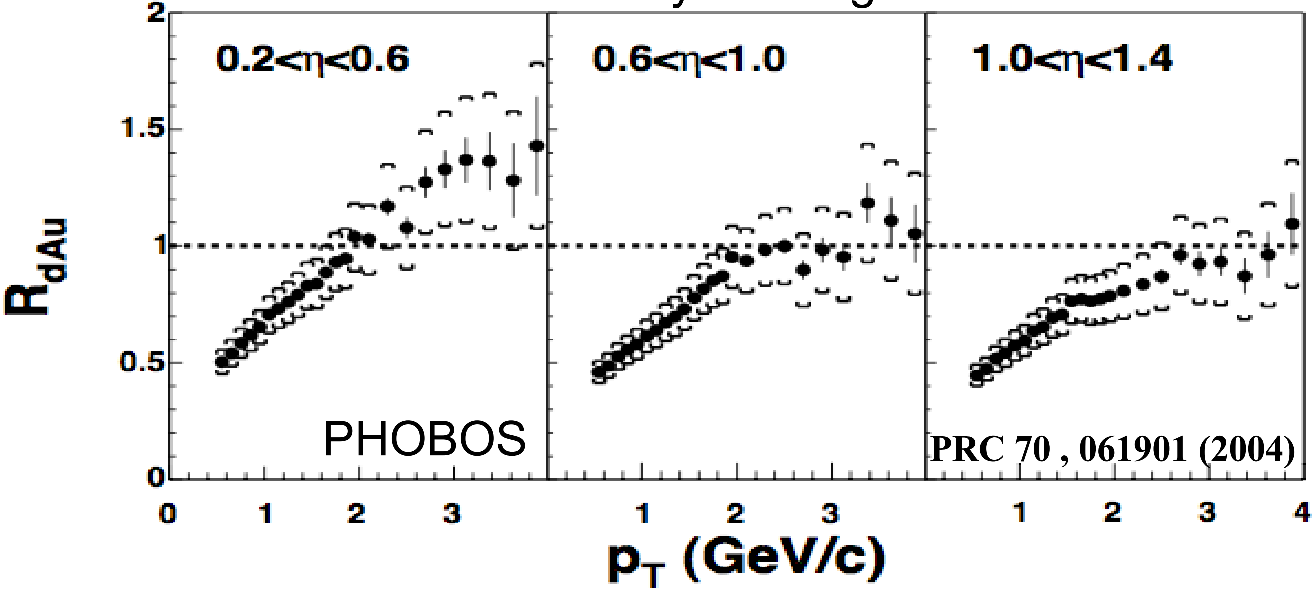


Jet quenching is final state effect

$$R_{dAu} = \frac{\sigma^{inel}_{p\overline{p}}}{\langle N_{coll} \rangle} \frac{d^2N_{dAu}/dp_T d\eta}{d^2\sigma(\mathrm{UA1})_{p\overline{p}}/dp_T d\eta}$$

R_{dAu} as a function of η

- all centrality bins together -



Gradual suppression with η

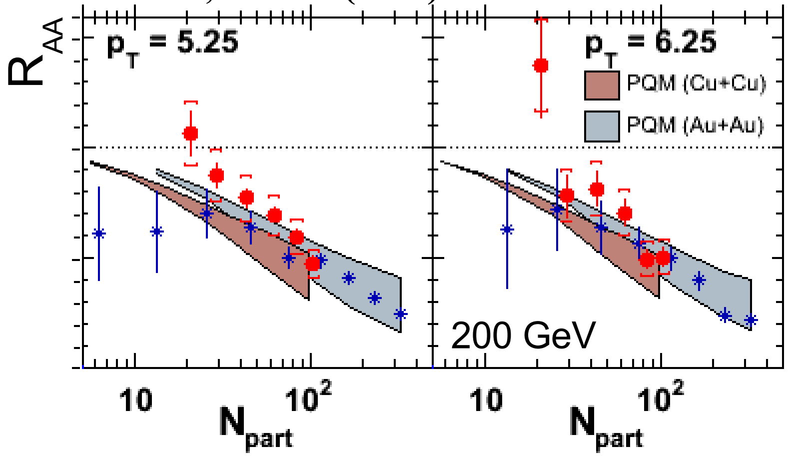
Room for CGC might be at forward η (but beware of backward η)

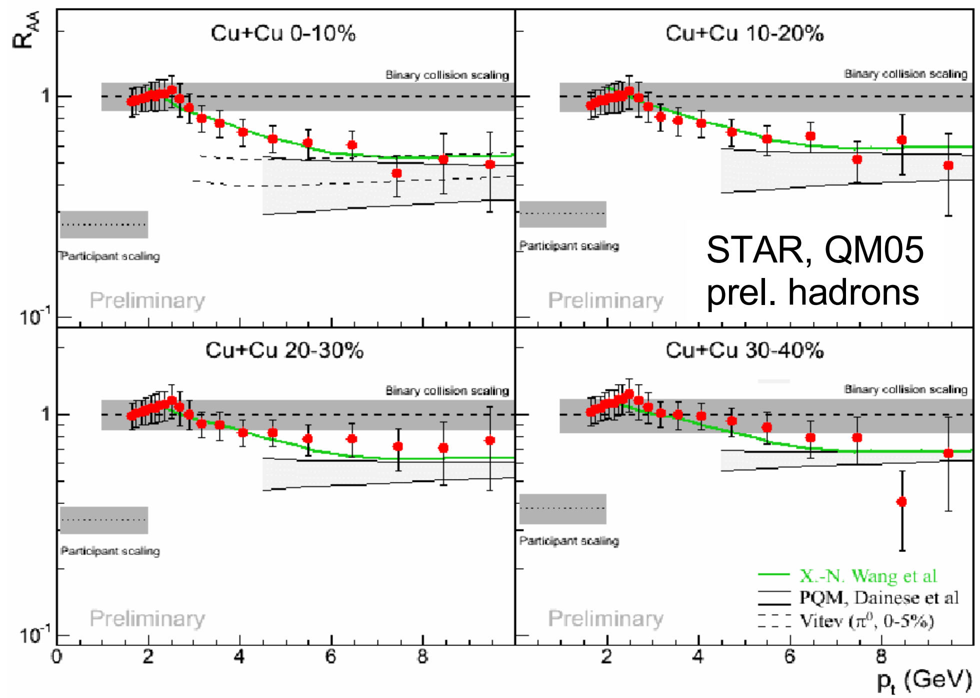
Jet quenching at mid-rapitidy is a final state effect

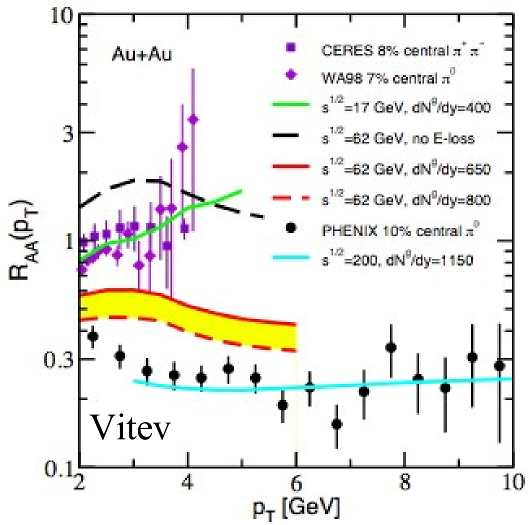
Note, that all our suppression plots are for **0.2<η<1.4**

Models for final-state suppression

PRL 96, 212301 (2006)

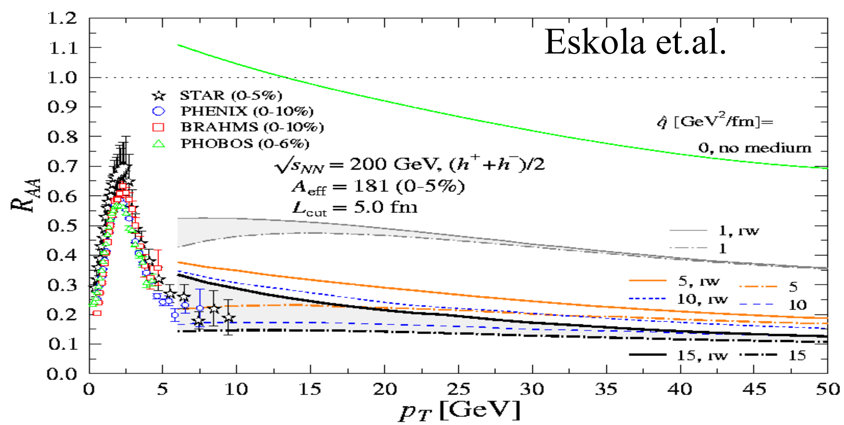




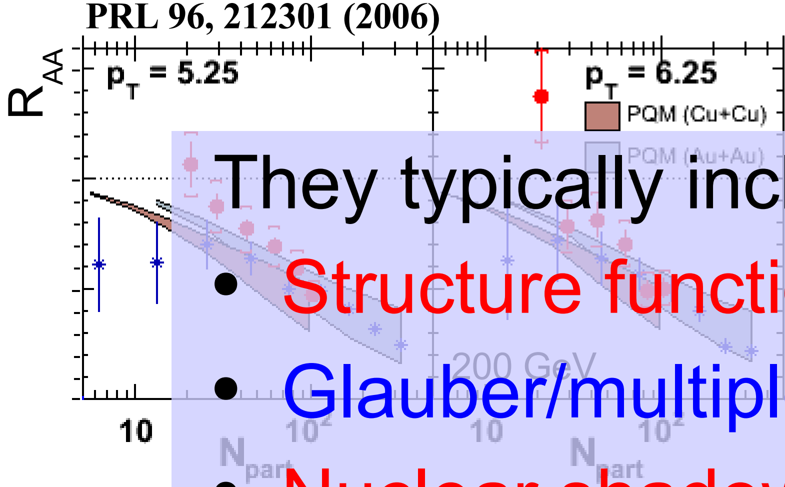


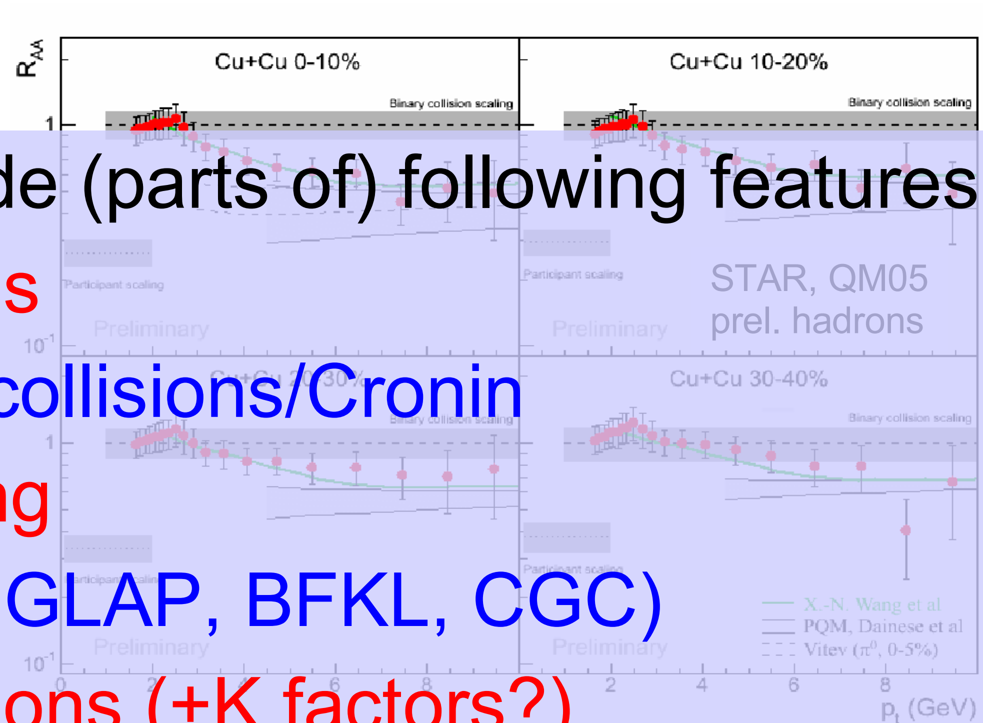
Models describe suppression quite well

Eskola et.al.: NPA 747, 511 (2005)
PQM: EPJC 38, 461 (2005)
Vitev: hep-ph/0603010, PLB 606, 303 (2005)
Wang: nucl-th/0511001
(plus many others)



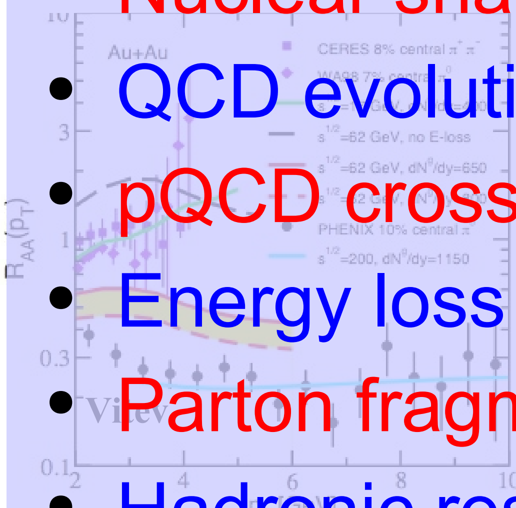
Models for suppression at high p_T



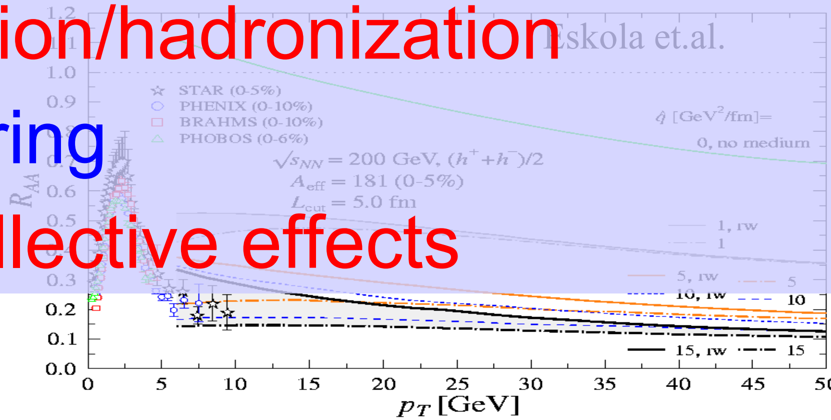


They typically include (parts of) following features

- Structure functions
- Glauber/multiple collisions/Cronin
- Nuclear shadowing
- QCD evolution (DGLAP, BFKL, CGC)
- pQCD cross-sections (+K factors?)
- Energy loss in medium (radiational/collisional)
- Parton fragmentation/hadronization
- Hadronic rescattering
- Expansion and collective effects



Models describe suppression quite well



Eskola et.al.: NPA 747, 511 (2005)
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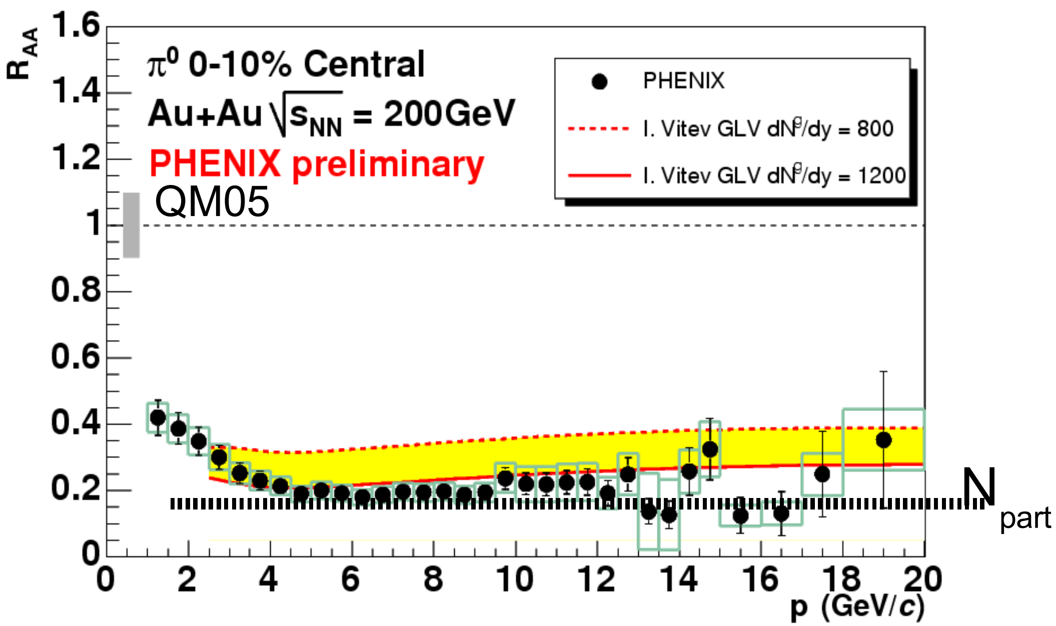
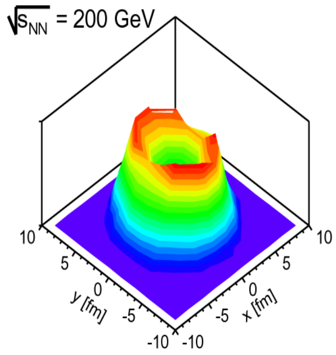
Wang: nucl-th/0511001
(plus many others)

Maximal suppression in central collisions





N_{part} scaling:

MAXIMAL jet quenching?

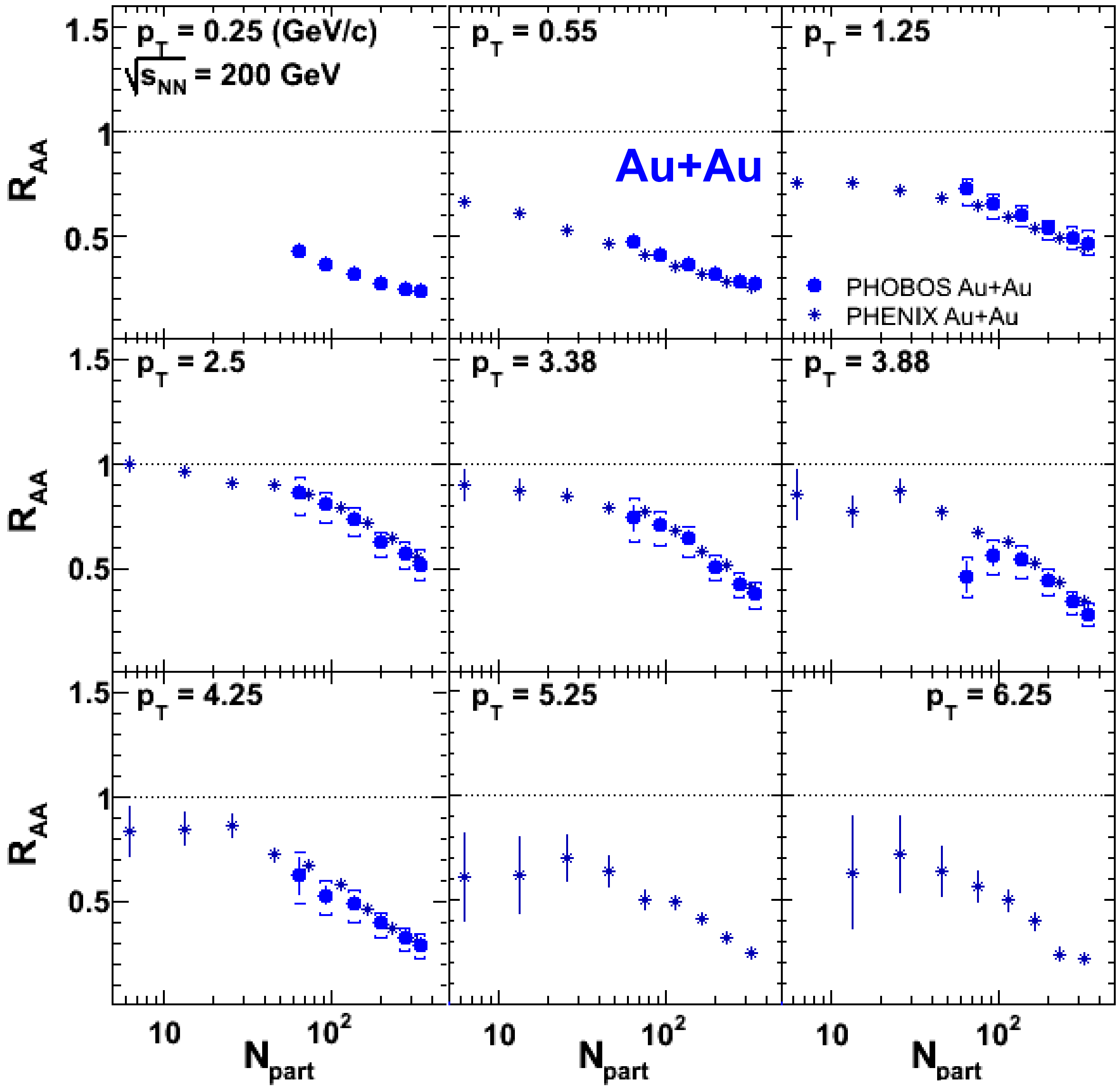
N_{coll} * S / V ~ N_{part}

Is approximate N_{part} scaling reached by accident?

Scaling rules

Go back one step and see
if data gives us more constraints!

Yields vs N_{part} at 200 GeV

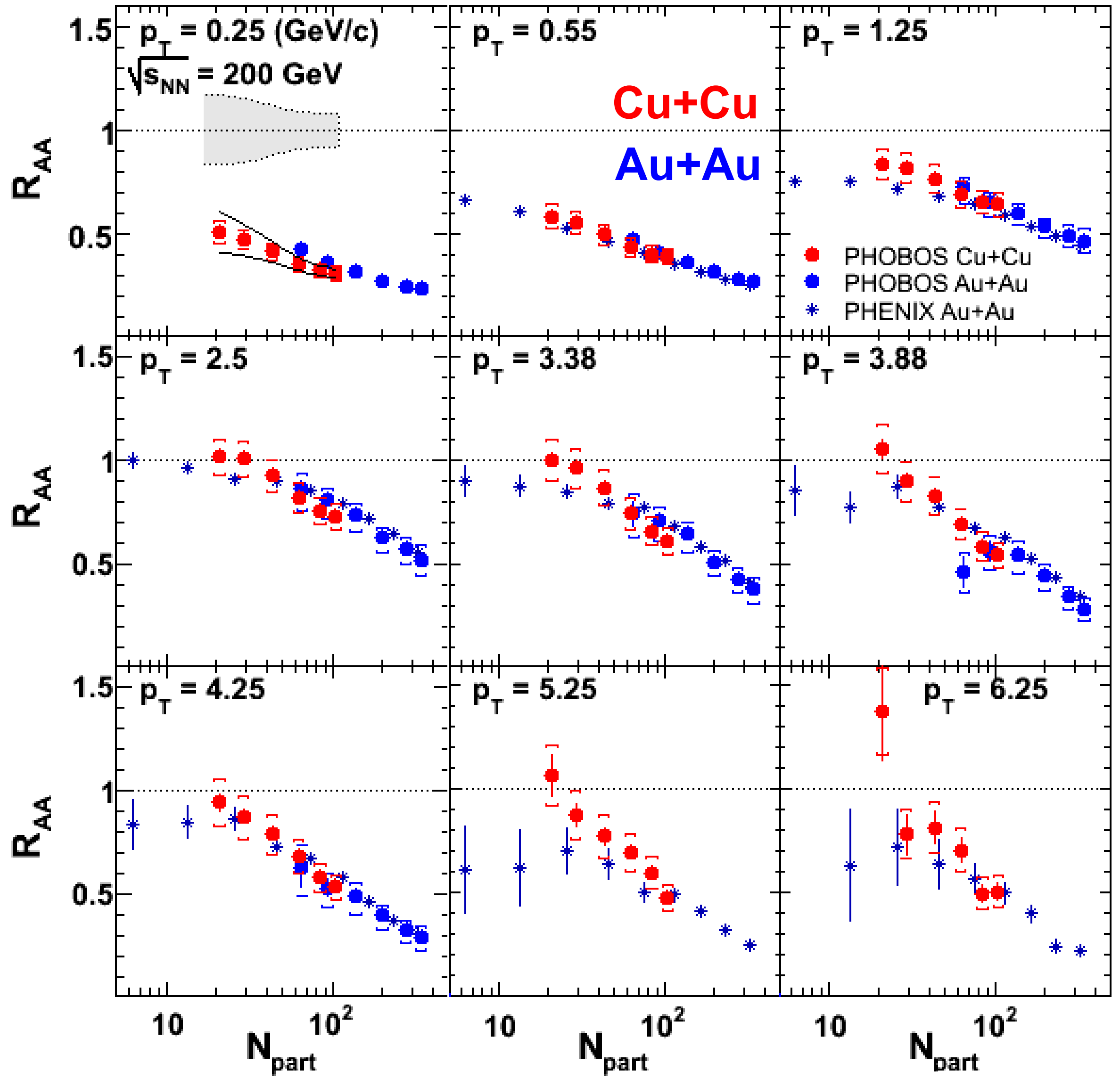


0.2<η<1.4

Au+Au: PRL 94, 082304 (2005), PLB 578, 297 (2004)
Phenix: PLB 561, 82 (2003), PRC 69, 034910 (2004)
Cu+Cu: PRL 96, 212301 (2006)
p+p̄: UA1 -2.5<η<2.5 (acc. correction with PYTHIA)

$$R_{AA} = \frac{\sigma_{p\bar{p}}^{inel}}{\langle N_{coll} \rangle} \frac{d^2 N_{AA}/dp_T d\eta}{d^2 \sigma_{p\bar{p}}/dp_T d\eta}$$

Yields vs N_{part} at 200 GeV



0.2<η<1.4

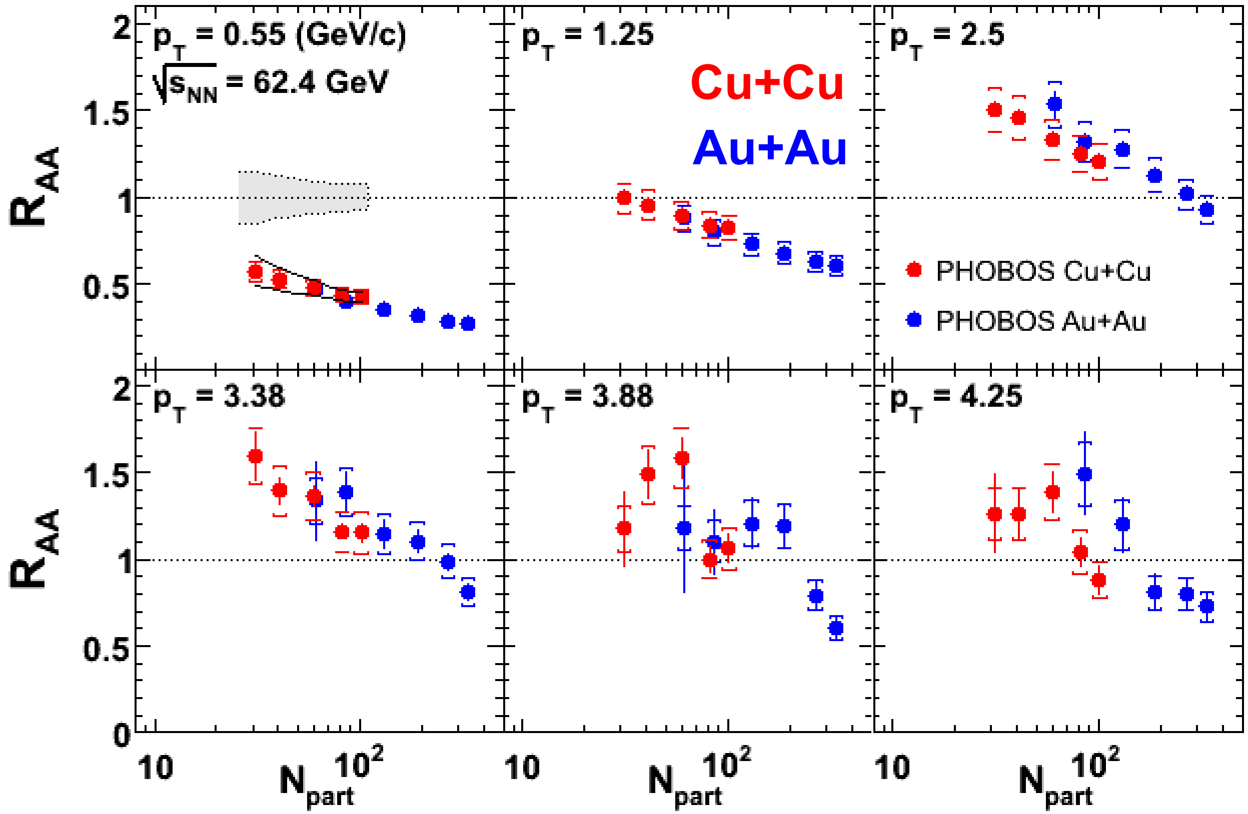
System-size scaling observed!

Au+Au: PRL 94, 082304 (2005), PLB 578, 297 (2004)
Phenix: PLB 561, 82 (2003), PRC 69, 034910 (2004)
Cu+Cu: PRL 96, 212301 (2006)
$p+\bar{p}$: UA1 -2.5<η<2.5 (acc. correction with PYTHIA)

$$R_{AA} = \frac{\sigma_{p\bar{p}}^{inel}}{\langle N_{coll} \rangle} \frac{d^2 N_{AA}/dp_T d\eta}{d^2 \sigma_{p\bar{p}}/dp_T d\eta}$$

Yields vs N_{part} at 62 GeV

0.2<η<1.4



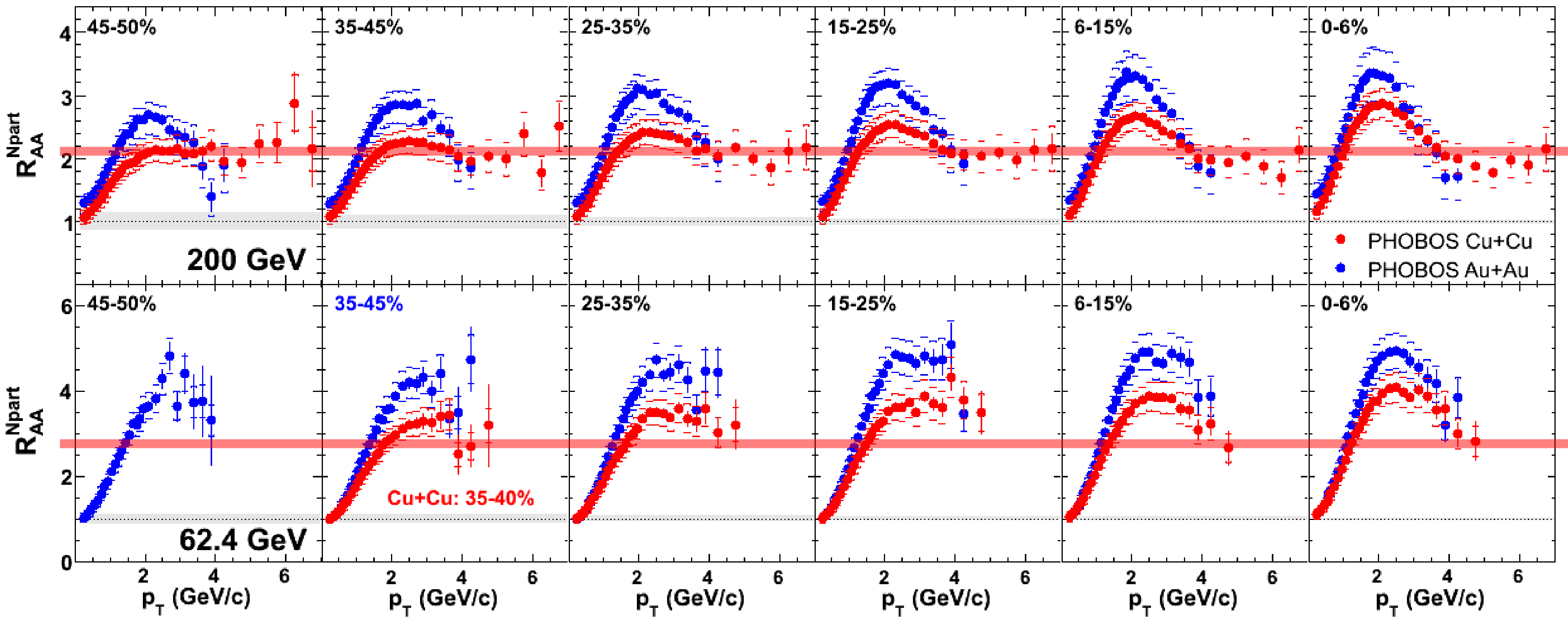
System-size scaling observed!

Au+Au: PRL 94, 082304 (2005)
Cu+Cu: PRL 96, 212301 (2006)
p+p: SFM 0.5<y<1 (acc. correction with PYTHIA)

$$R_{AA} = \frac{\sigma_{pp}^{inel}}{\langle N_{coll} \rangle} \frac{d^2 N_{AA}/dp_T d\eta}{d^2 \sigma_{pp}/dp_T d\eta}$$

R_{AA}^{Npart} in Au+Au and Cu+Cu at 200 GeV

0.2<η<1.4



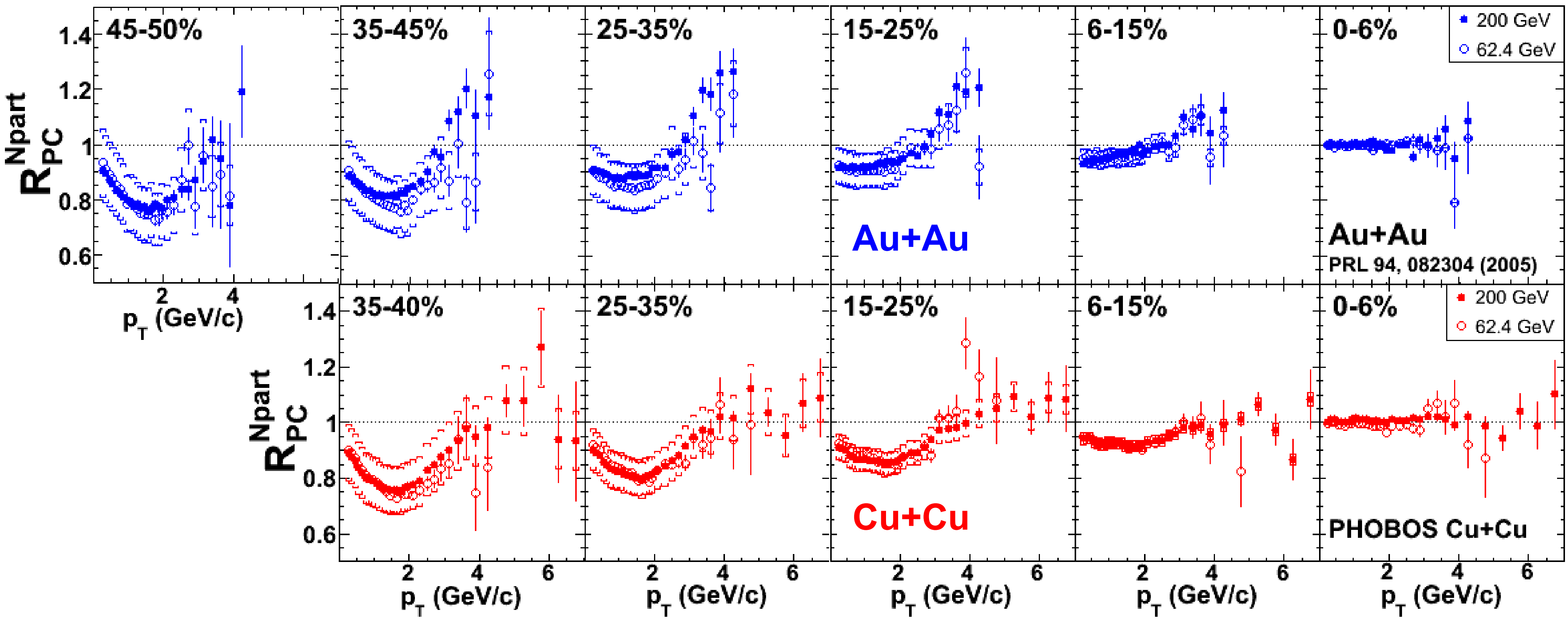
Yields normalized by N_{part} less centrality-dependent

$$R_{AA}^{N_{part}} = \frac{\sigma_{p\bar{p}}^{inel}}{\langle N_{part}/2\rangle} \frac{d^2 N_{AA}/dp_T d\eta}{d^2\sigma_{p\bar{p}}/dp_T d\eta}$$

Au+Au: PRL 94, 082304 (2005)
Cu+Cu: PRL 96, 212301 (2006)

Factorization in bins of p_T

Normalized for central events



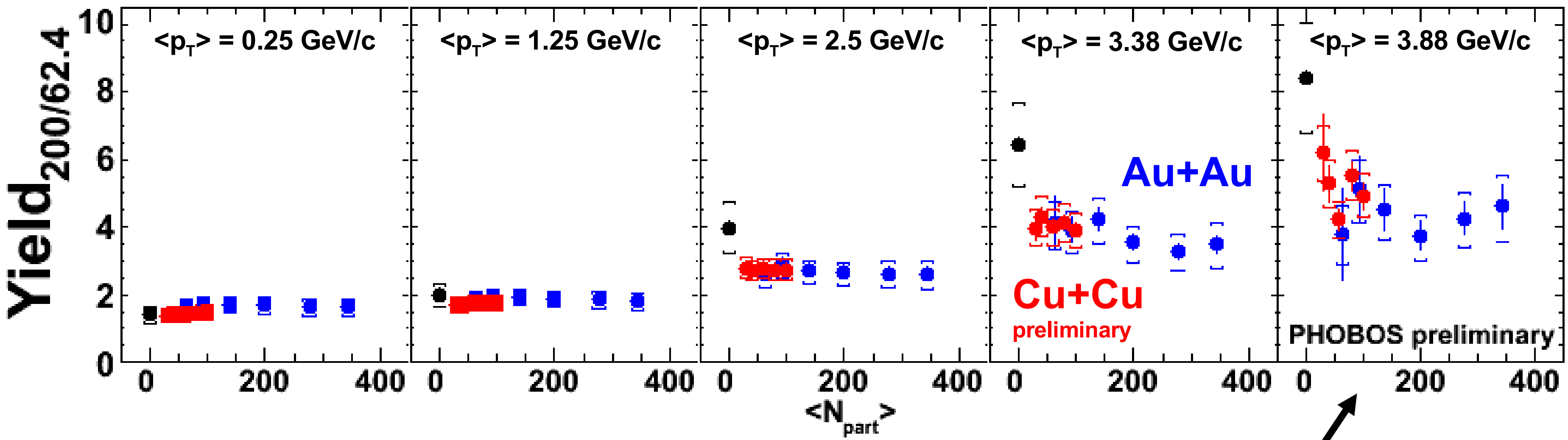
Same shape evolution from central to peripheral at 200 GeV and 62 GeV

Au+Au: PRL 94, 082304 (2005)
Cu+Cu: PRL 96, 212301 (2006)

$$R_{PC}^{N_{part}} = \frac{\langle N_{part}^{0-6\%} \rangle}{\langle N_{part} \rangle} \frac{d^2 N_{AA}/dp_T d\eta}{d^2 N_{AA}^{0-6\%}/dp_T d\eta}$$

Factorization in bins of p_T (2)

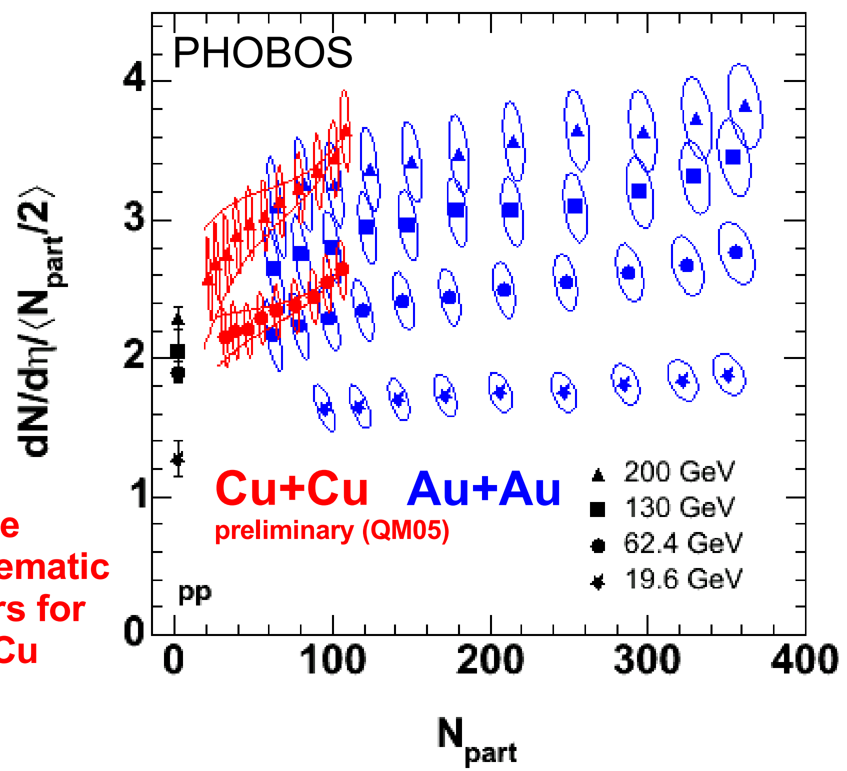
Ratio of charged hadron yields in 200 GeV to 62 GeV



Energy/centrality factorization up to $p_T \approx 4$ GeV/c for $N_{part} > 40$

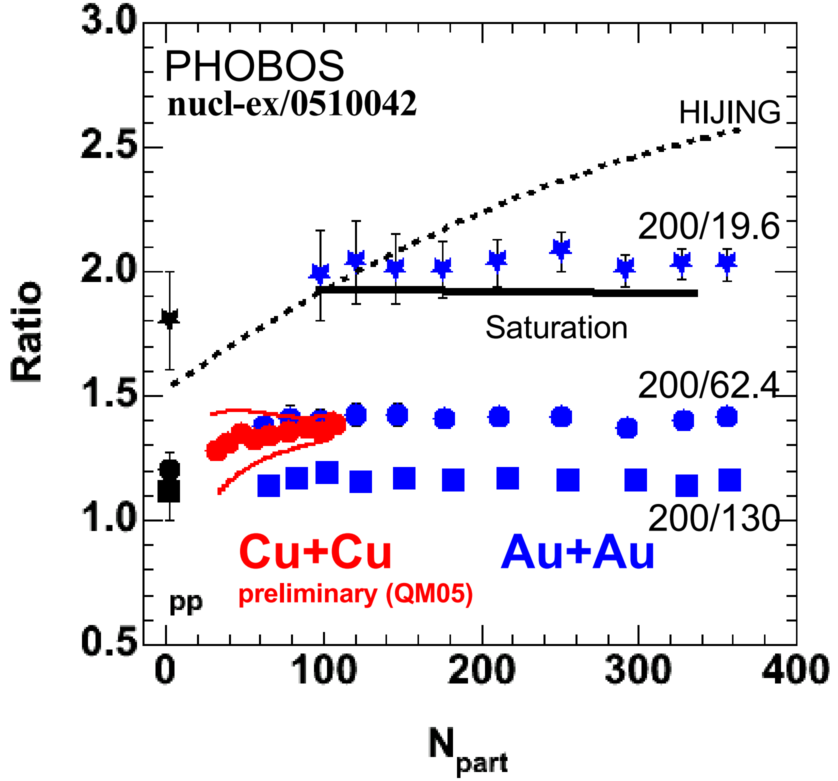
Au+Au: PRL 94, 082304 (2005)
Cu+Cu: PRL 96, 212301 (2006)

Factorization of energy and centrality



Large systematic errors for Cu+Cu

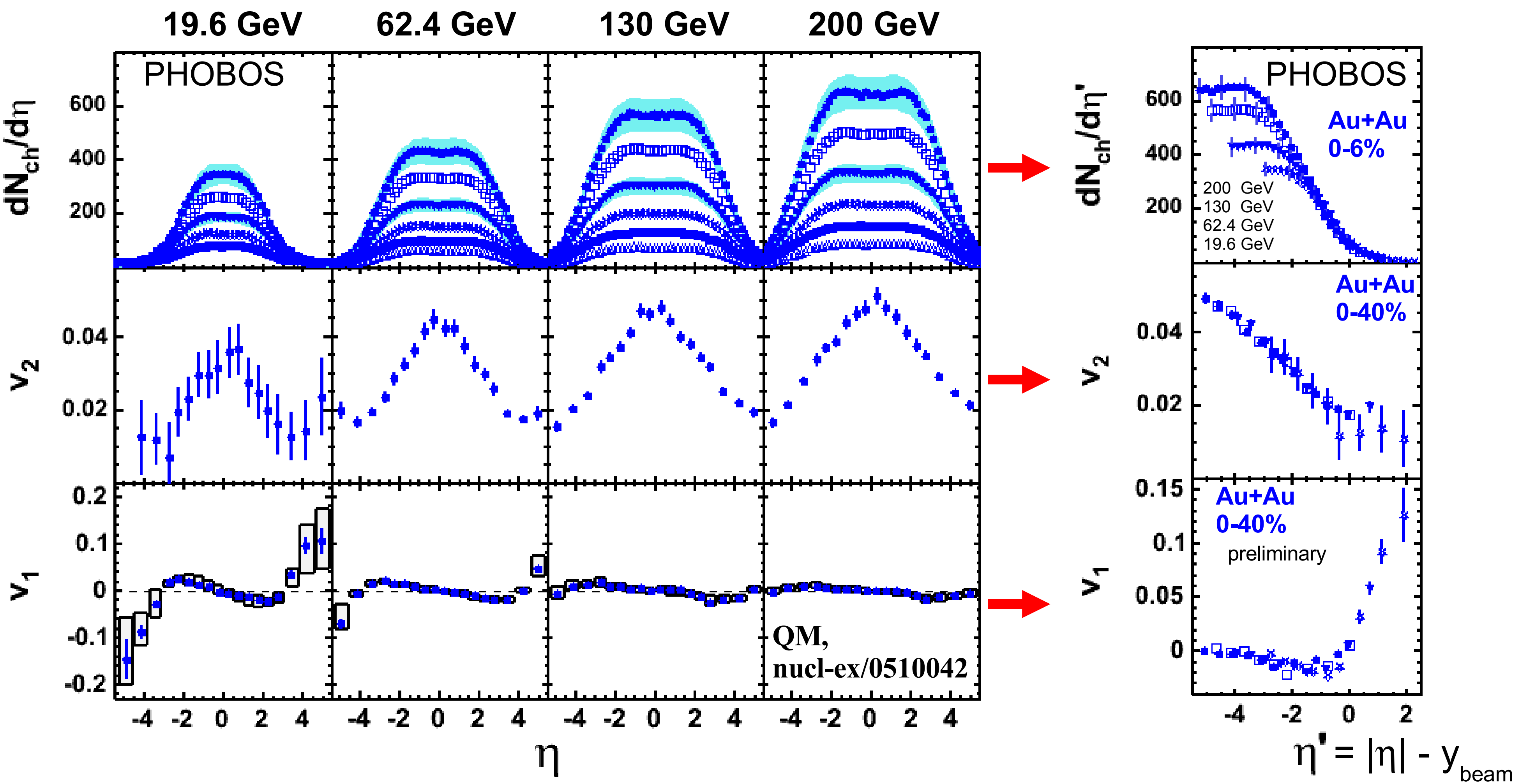
Ratio of dN/dη @ η=0 relative to 200 GeV vs centrality



Factorization of energy and centrality due to initial state effect?

Au+Au: Phys. Rev. C70, 021902(R) (2004)
62.4 GeV Au+Au: nucl-ex/0509034 (sub.to PRC)
Cu+Cu (preliminary): QM, nucl-ex/0510042

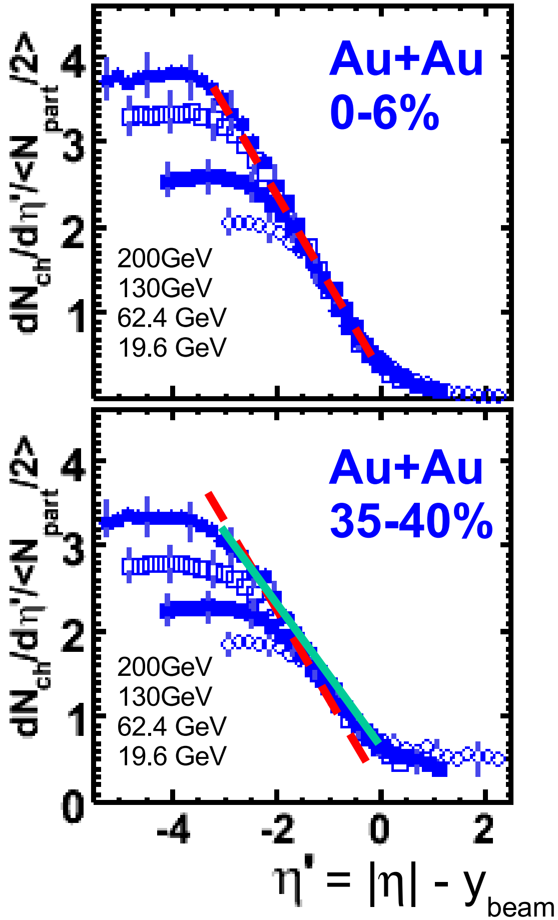
Limiting fragmentation (Au+Au)



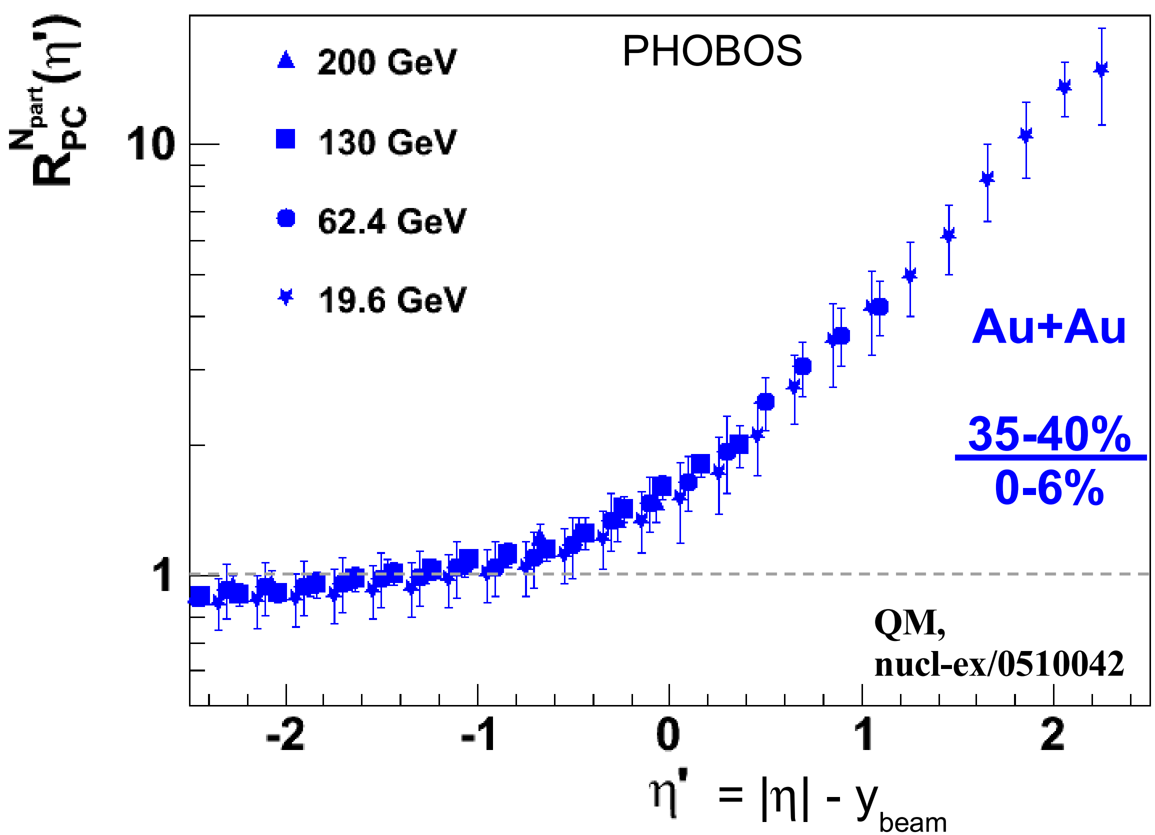
"Extended Longitudinal Scaling" of all longitudinal distributions

(same for Cu+Cu collisions)

Factorization of longitudinal dynamics



Ratio of 0-6% and 35-40% centrality bins, each normalized by N_{part}



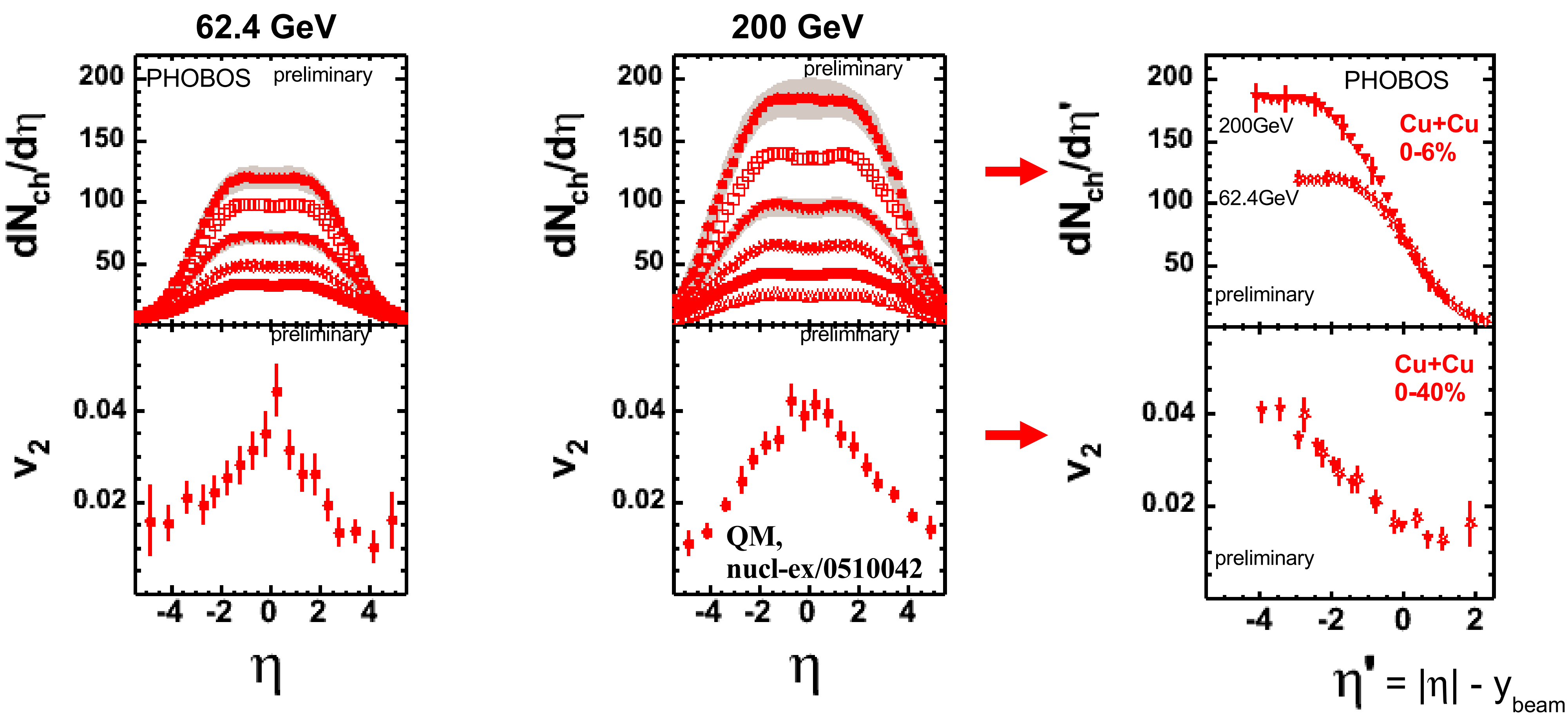
$R_{PC}^{N_{part}}$ is energy independent!

Summary

- Low-p_T measurements (bulk)
  - Strongly interacting system with non hadronic dof
- High-p_T measurements (probes)
  - Opaque medium in Au+Au and Cu+Cu collisions
  - At mid-rapidity, jet quenching is final state effect
  - Magnitude, energy and centrality dependence are calculable
- Study of energy and system-size dependence
  - Data at all p_T (PHOBOS range) have common features
  - Factorization of energy and centrality dependence
    - in transverse and longitudinal direction

Backup

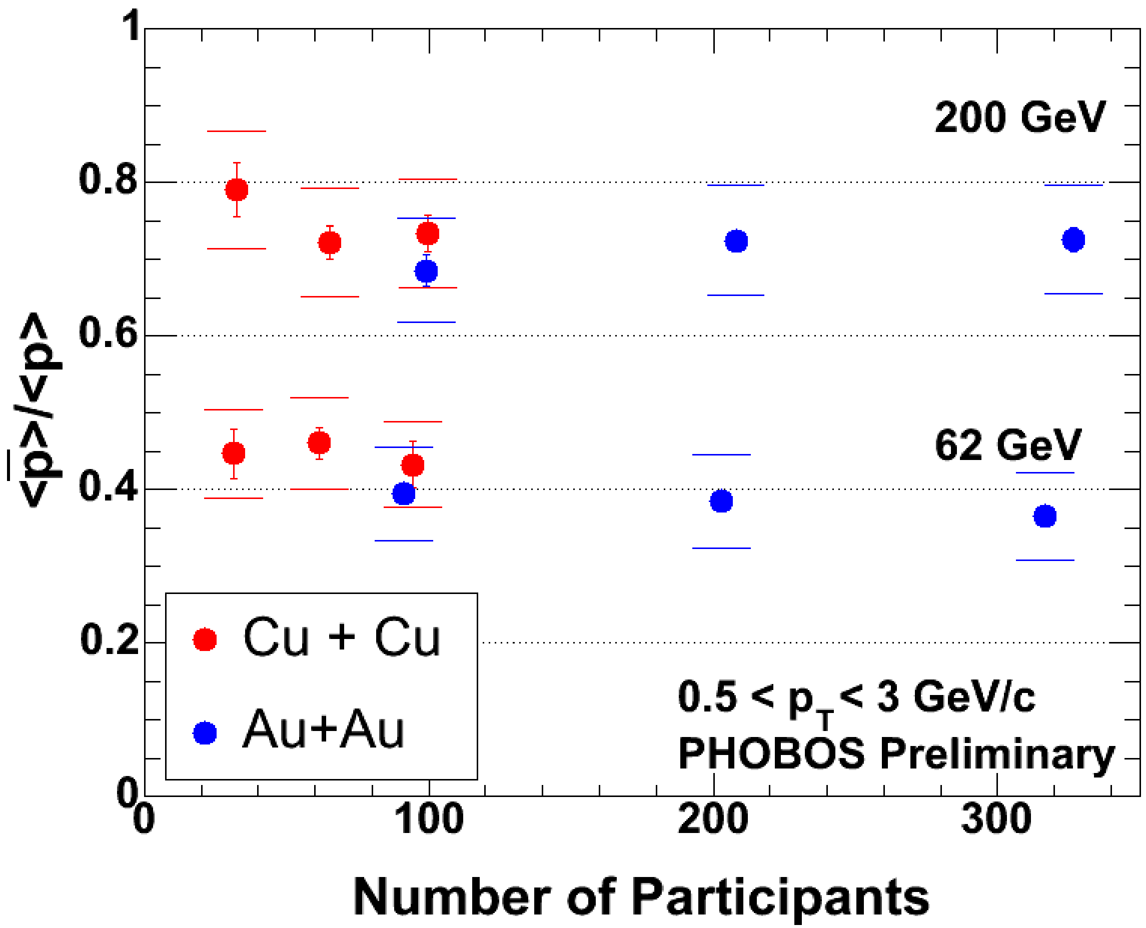
Limiting fragmentation (Cu+Cu)



'Extended Longitudinal Scaling' also seen in Cu+Cu
Persists from p+p to Au+Au over large range in η'

QM, nucl-ex/0510042

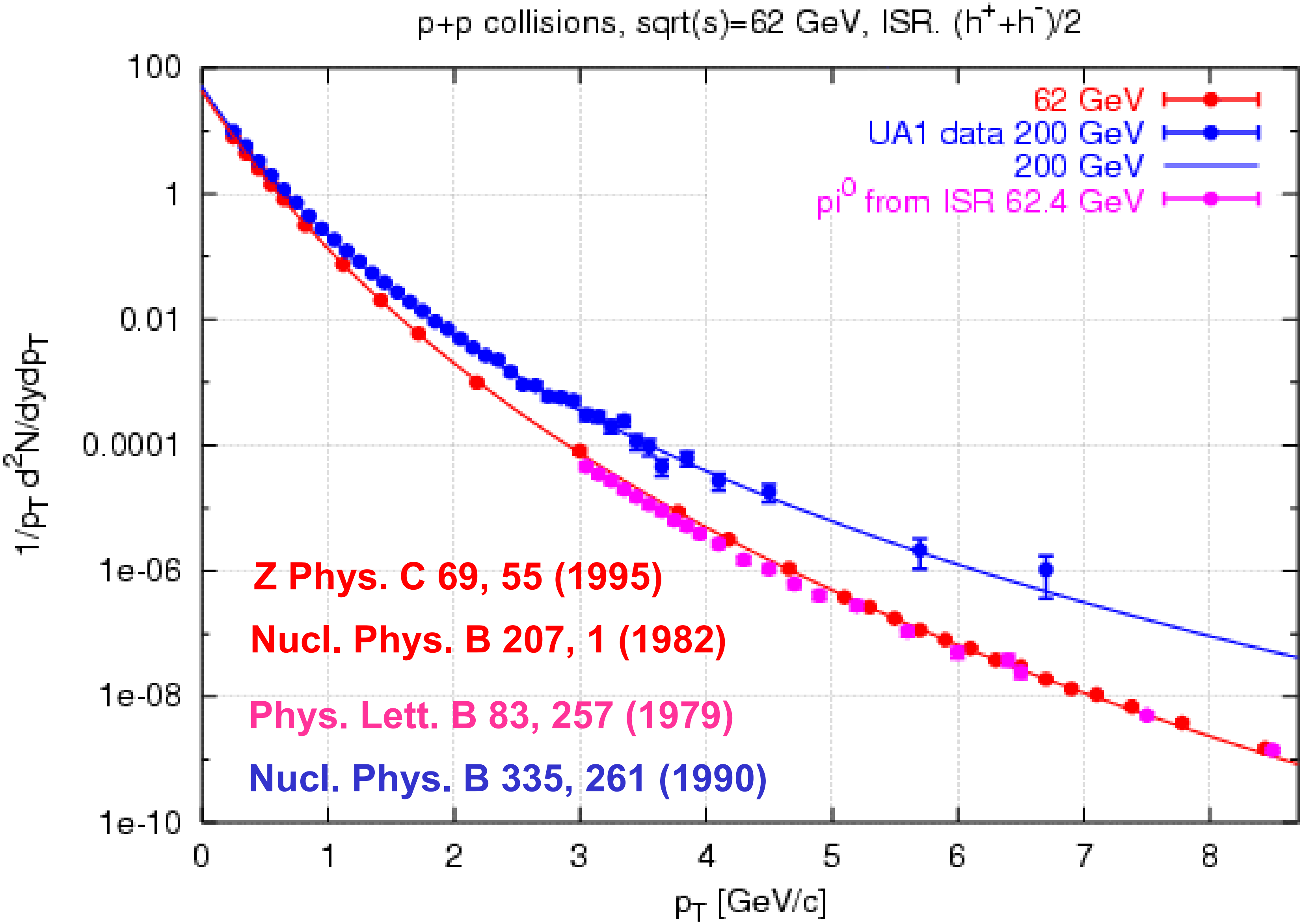
Anti-proton/proton ratio



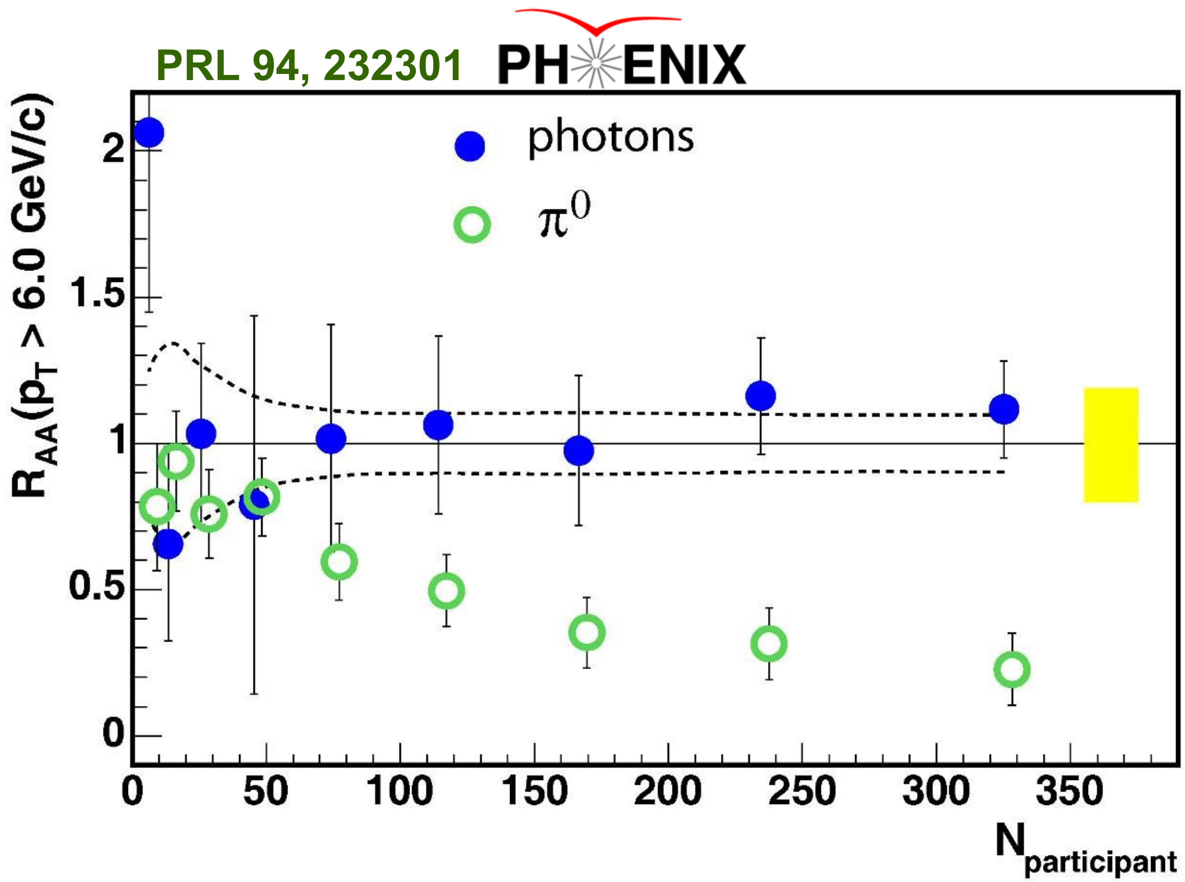
Anti-p/p ratio very similar in Cu+Cu and Au+Au

QM, nucl-ex/0510042

p+pbar(p) reference at 62.4 and 200 GeV

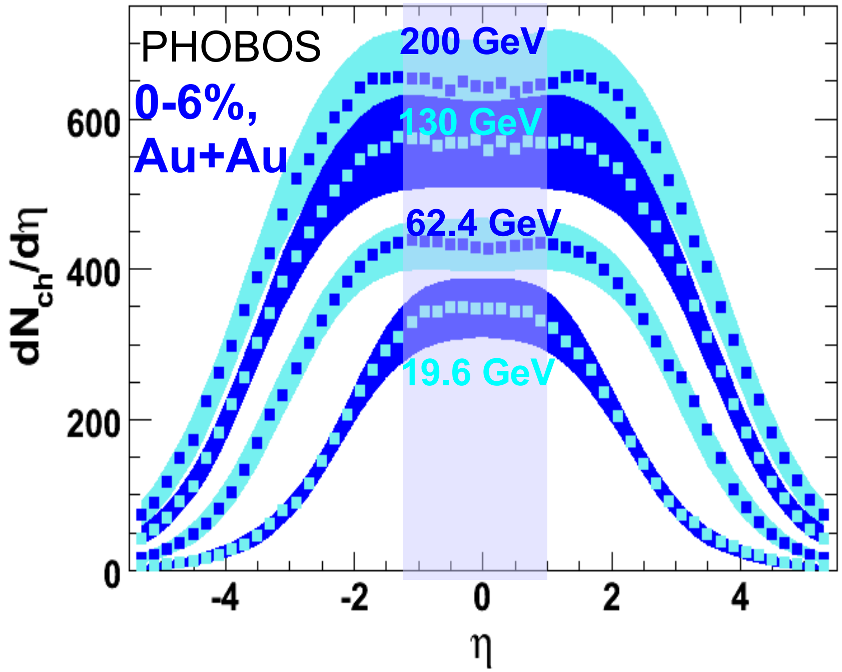


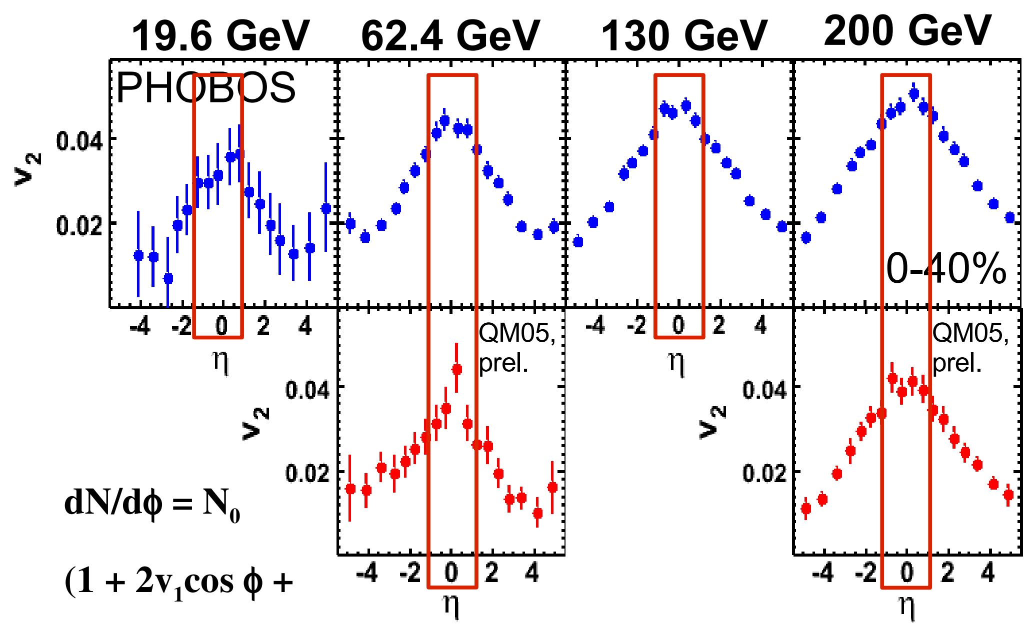
Direct Photon R_{AA} from PHENIX



$$R_{AA} = \frac{dN_{AA}^{\pi^0} / dp_T}{\langle T_{AA} \rangle_f \, d\sigma_{NN}^{\pi^0} / dp_T}$$

Properties of the medium (2)





$dN/d\phi = N_0$

$(1 + 2v_1 \cos\phi +$

$2v_2 \cos(2\phi) + \ldots)$

At 200 GeV:

ϵ >3 GeV/fm^3

$$\epsilon = \frac{\langle E \rangle \text{ x } dN/d\eta \text{ x corr}}{\pi R^2 \text{ X } (0.1 - \text{few}) \text{ fm}}$$

PHOBOS WhitePaper

Strongly interacting medium
with extremely high energy density

WhitePaper: NPA, 757 28 (2005)
v_2 Au+Au: PRL 94, 122303 (2005)
v_2 Cu+Cu (prel.): QM05, nucl-ex/0510042