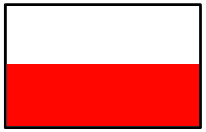
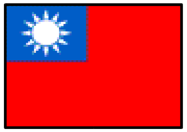
The state of matter at PHOBOS

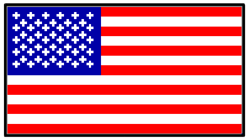
Recent results from PHOBOS

Gerrit van Nieuwenhuizen
For the PHOBOS collaboration
SQM 2004
Capetown, September 14, 2004

The PHOBOS Collaboration







Birger Back, Mark Baker, Maarten Ballintijn, Donald Barton, Russell Betts, Abigail Bickley, Richard Bindel, Wit Busza (Spokesperson), Alan Carroll, Zhengwei Chai, Patrick Decowski, Edmundo García, Tomasz Gburek, Nigel George, Kristjan Gulbrandsen, Clive Halliwell, Joshua Hamblen, Adam Harrington, Michael Hauer, Conor Henderson, David Hofman, Richard Hollis, Roman Hołyński, Burt Holzman, Aneta Iordanova, Jay Kane, Nazim Khan, Piotr Kulinich, Chia Ming Kuo, Willis Lin, Steven Manly, Alice Mignerey, Gerrit van Nieuwenhuizen, Rachid Nouicer, Andrzej Olszewski, Robert Pak, Inkyu Park, Heinz Pernegger, Corey Reed, Christof Roland, Gunther Roland, Joe Sagerer, Helen Seals, Iouri Sedykh, Wojtek Skulski, Chadd Smith, Maciej Stankiewicz, Peter Steinberg, George Stephans, Andrei Sukhanov, Marguerite Belt Tonjes, Adam Trzupek, Carla Vale, Sergei Vaurynovich, Robin Verdier, Gábor Veres, Peter Walters, Edward Wenger, Frank Wolfs, Barbara Wosiek, Krzysztof Woźniak, Alan Wuosmaa, Bolek Wysłouch

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BROOKHAVEN NATIONAL LABORATORY
MASSACHUSETTS INSTITUTE OF TECHNOLOGY
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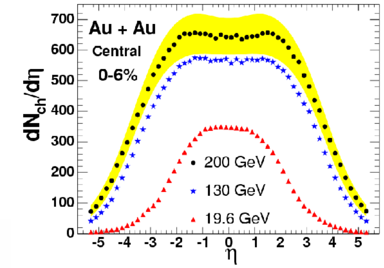
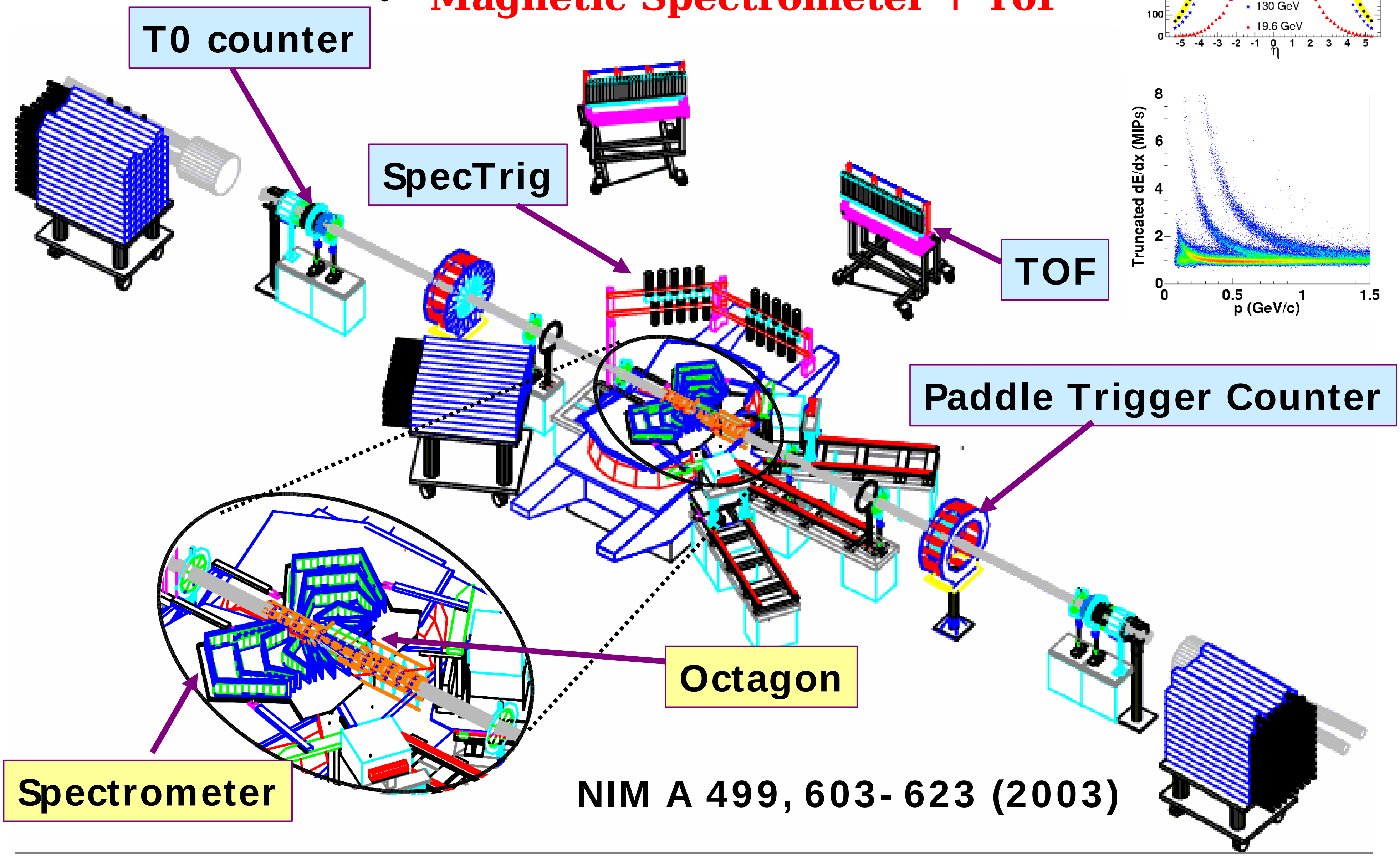
UNIVERSITY OF ROCHESTER

The 2004 PHOBOS detector

- **4-π Multiplicity Detector**
- **Magnetic Spectrometer + ToF**





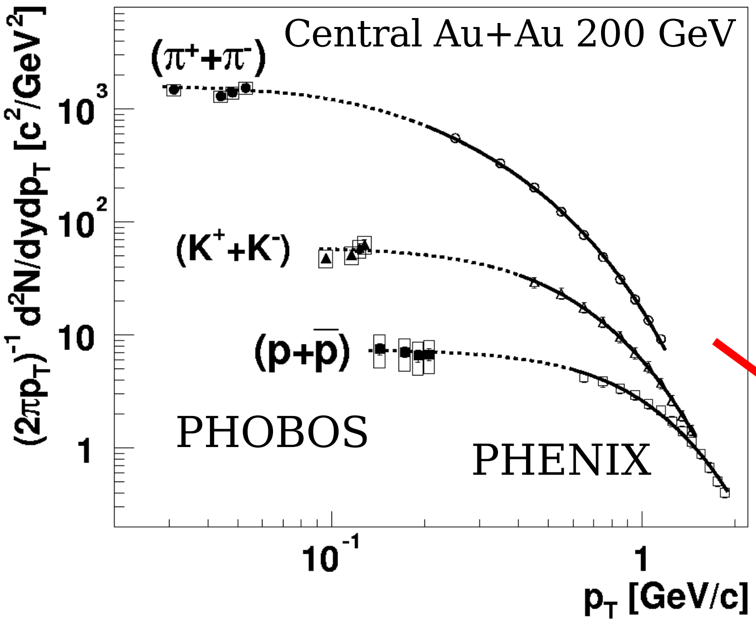
NIM A 499, 603-623 (2003)

The PHOBOS dataset so far

RHIC Run	Colliding System and $\sqrt{s_{NN}}$		Dates of PHOBOS Data Taking	Total Events (M)
1	Au+Au	56 GeV	6/13/00–6/16/00	1.8*
	Au+Au	130 GeV	8/15/00–9/4/00	4.3
2	Au+Au	130 GeV	7/8/01	0.044
	Au+Au	200 GeV	7/20/01–11/24/01	34
	Au+Au	19.6 GeV	11/25/01–11/26/01	0.76*
	p+p	200 GeV	12/28/01–1/25/02	23
3	d+Au	200 GeV	1/6/03–3/23/03	146
	p+p	200 GeV	4/13/03–5/24/03	50
4	Au+Au	200 GeV	1/5/04–3/24/04	215
	Au+Au	62.4 GeV	3/24/04–4/2/04	22
	p+p	200 GeV	4/18/04–5/14/01	28

5 different collision energies
3 different collision systems

Initial system: Energy density

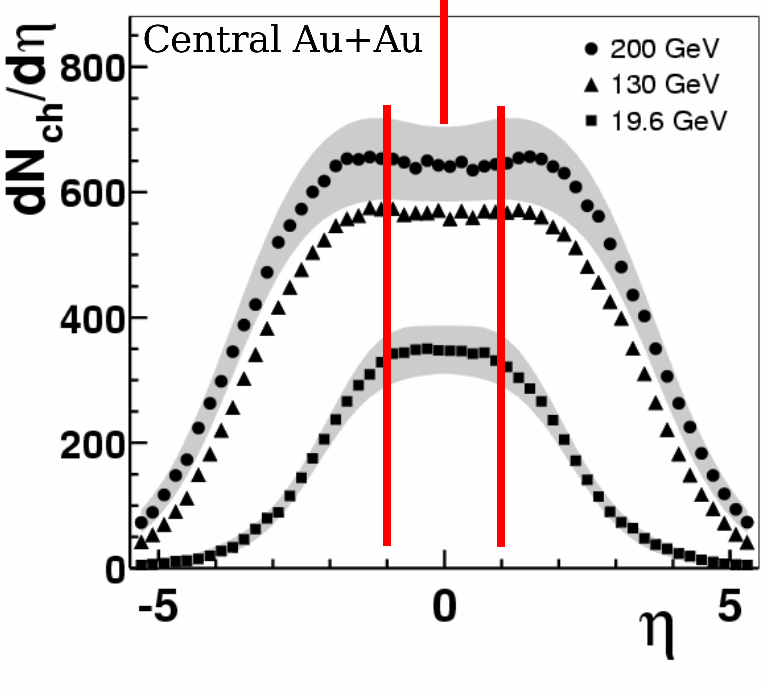


$$E_{tot} = 2E_{part}\ dN_{ch}/d\eta|_{|\eta|<1}\ f_{neutral}\, f_{4\pi}$$

$f_{neutral} \to 1.5$, $f_{4\pi} \to 1.3$

$E_{part} \sim 600$ MeV

$\boxed{E_{tot} \sim 1600 \text{ GeV}}$



$dN_{ch}/d\eta|_{|\eta|<1} \sim 650$

Transverse area ~ 150 fm^2 (Au)

Longitudinal size ~ 2 – 4 fm

(Bjorken 1 fm/c   flow 1-2 fm/c)

$\boxed{\text{Volume} \lesssim 600 \text{ fm}^3}$

(and expanding)

Initial system: Energy density

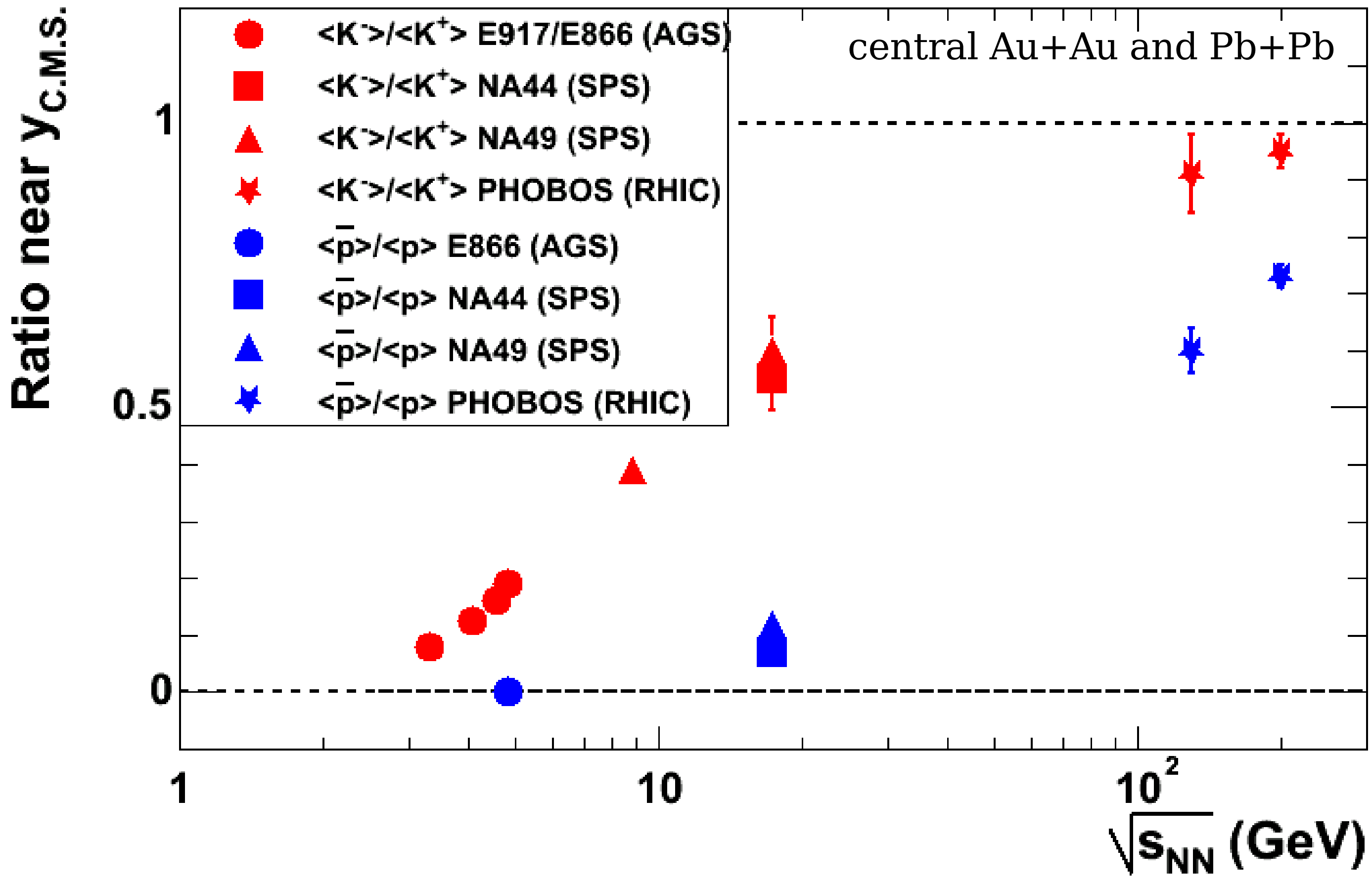
For central Au+Au at 200 MeV the approximately equilibrated system will have an energy density of

$$\gtrsim 3 \text{ GeV/fm}^3$$

Even this conservative estimate is already 6 times higher than the energy density inside a nucleon and 20 times higher than the energy density inside the nucleus
This estimate is also at least 2 times higher than the energy density reached at SPS

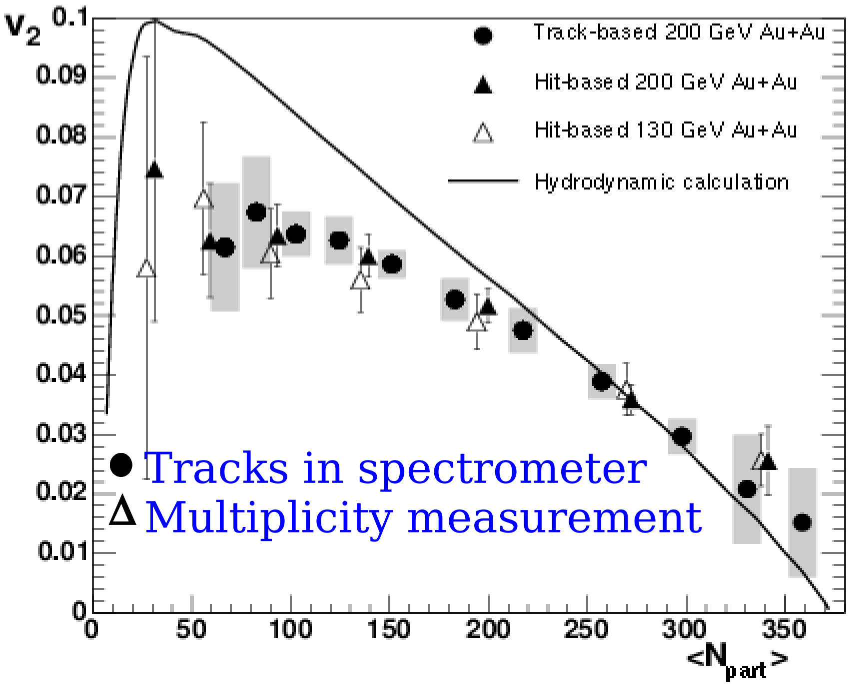
$\boxed{\text{The created system cannot be described appropriately in terms of \underline{simple} hadronic degrees of freedom}}$

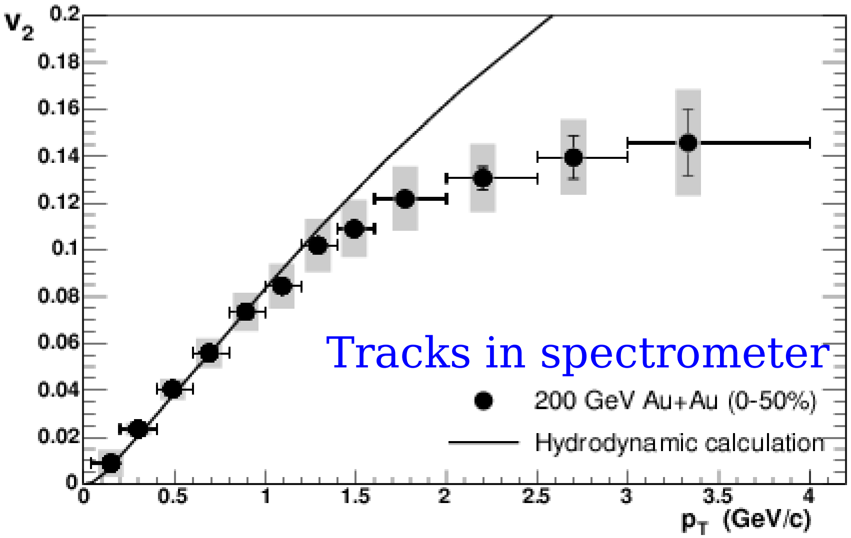
Baryon chemical potential



From the deduced baryon chemical potential of 27 MeV for Au+Au at 200 MeV (which is an order of magnitude lower than the baryon chemical potential for the SPS Pb+Pb at 17.2 GeV) it is clear that we are approaching a net baryon free regime

Strongly interacting medium: Elliptic flow





Over a large range of centrality and transverse momentum the elliptic flow signal is strong

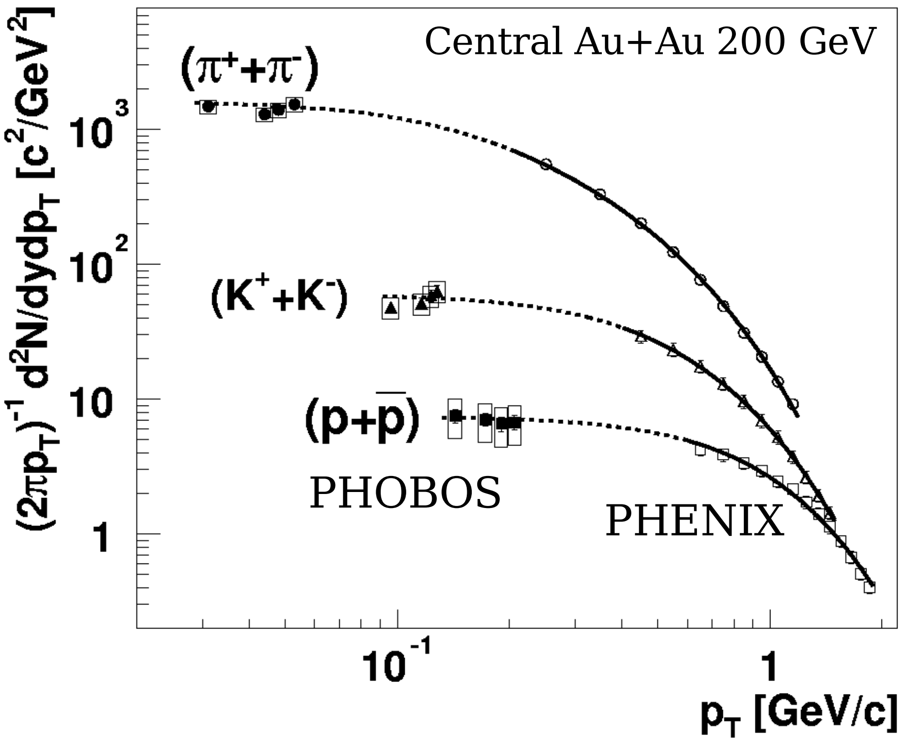
The signal is very close to what can be expected from a relativistic hydrodynamical calculation

Strong interactions in initial overlap zone to imprint the initial shape on the elliptic flow signal

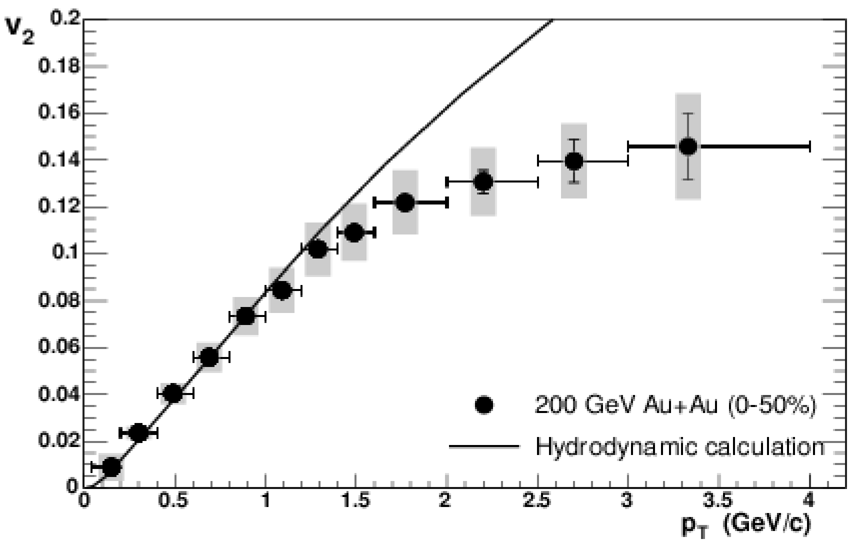
Interactions must happen at early times, otherwise the expansion will wash out the initial overlap shape

< 2 fm/c

Strongly interacting medium: Low Pt



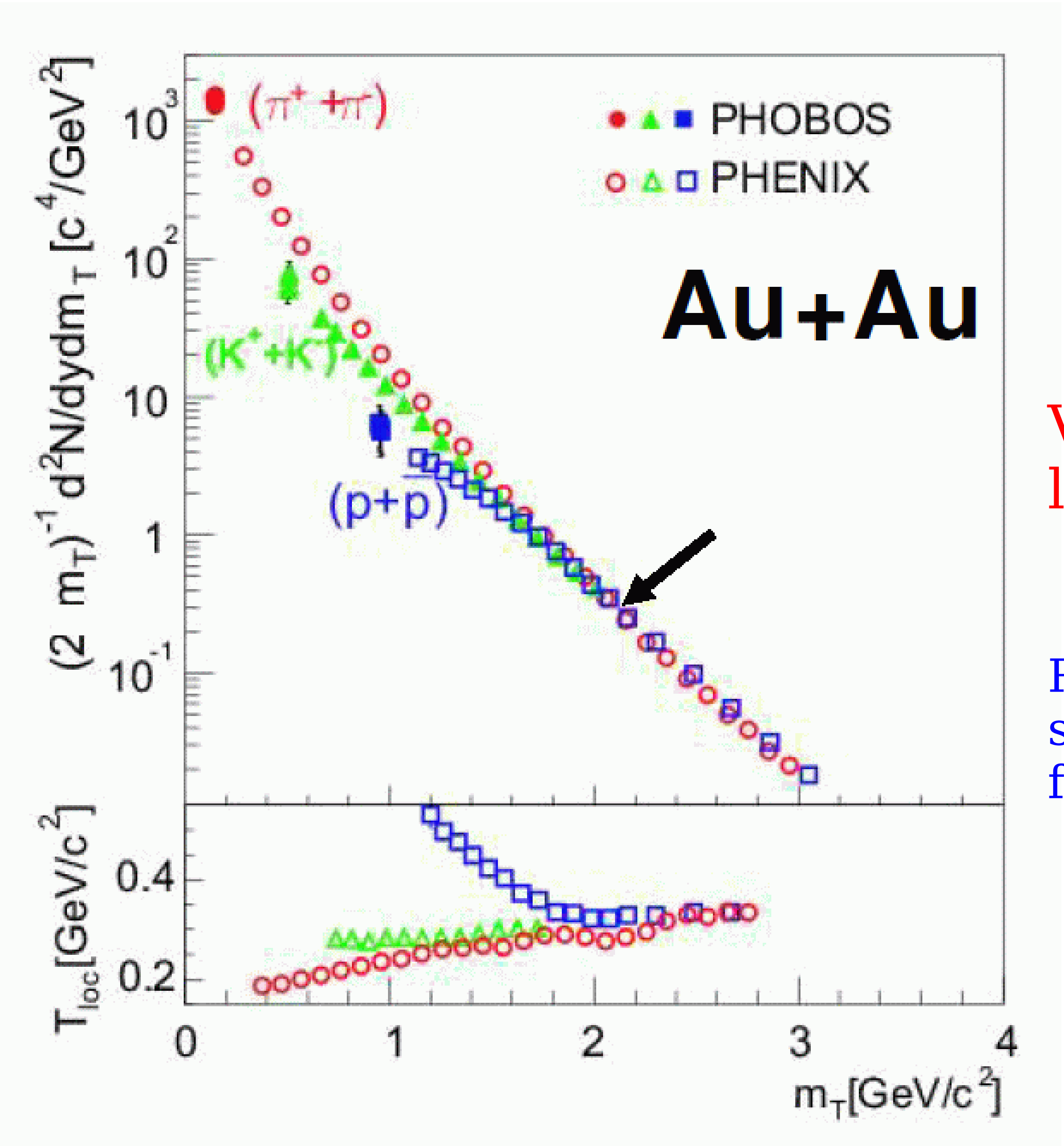
There is no excess of low Pt particles as one would expect from a weakly interacting medium (note: measuring this excess was one of the major PHOBOS baseline physics objectives)



Even at low Pt the elliptic flow signal remains relativily strong

No coherent production of low Pt particles as they get 'accelerated' by the strong interactions with the high energy density medium

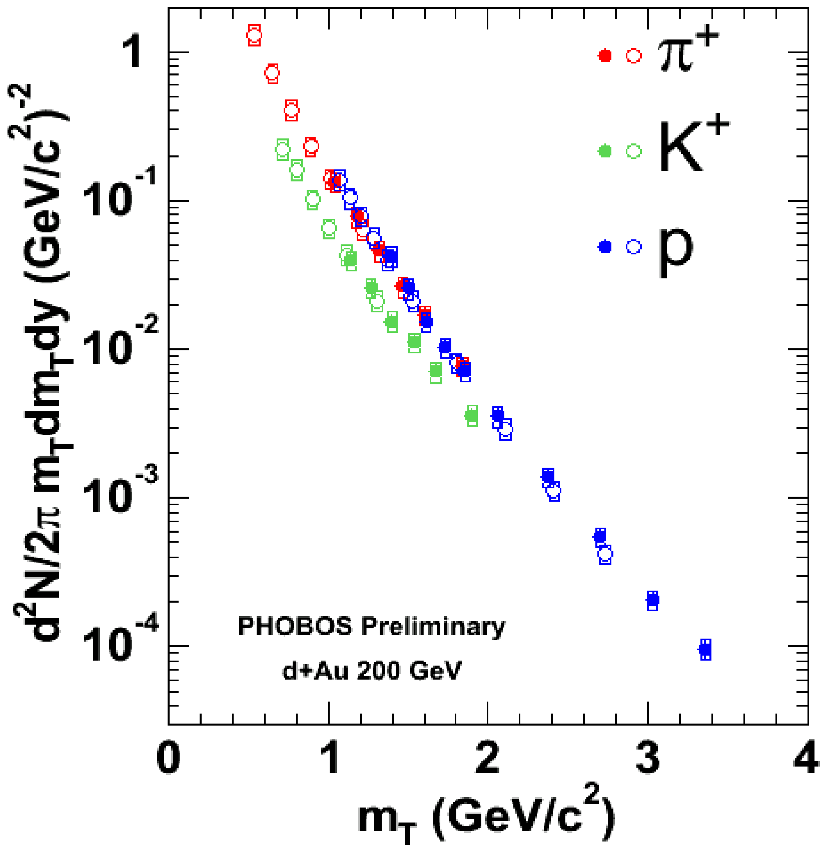
m_T scaling in Au+Au at 200 GeV

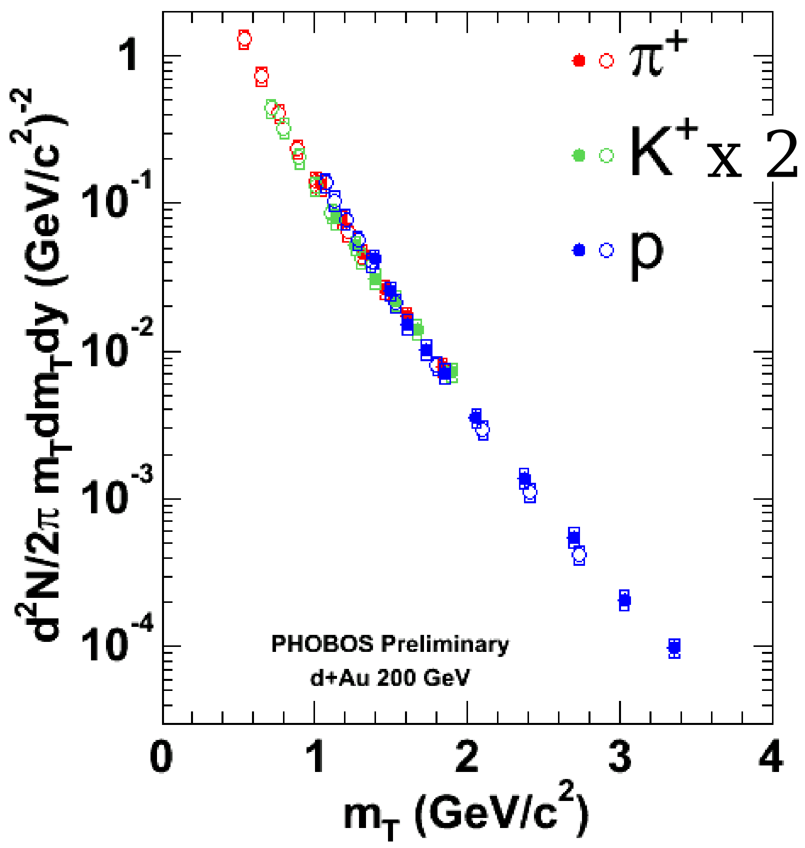


Violation of m_T scaling at low transverse mass

Rapid expansion of the system, i.e. strong radial flow???

m_T scaling in d+Au at 200 GeV

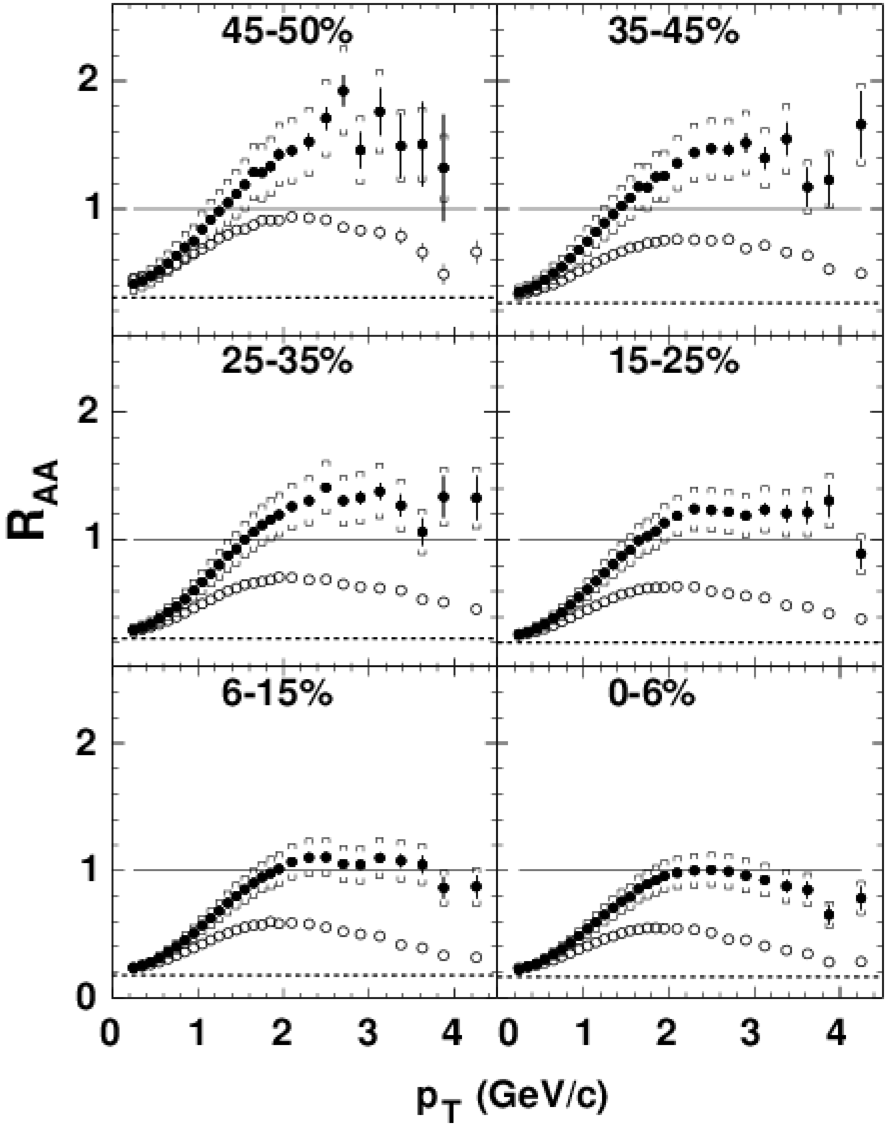




No feeddown correction
15% scale uncertainty

No violation of tranverse mass scaling observed in d+Au at 200 GeV

Strongly interacting medium: High Pt Au+Au at 200 and 62.4 GeV



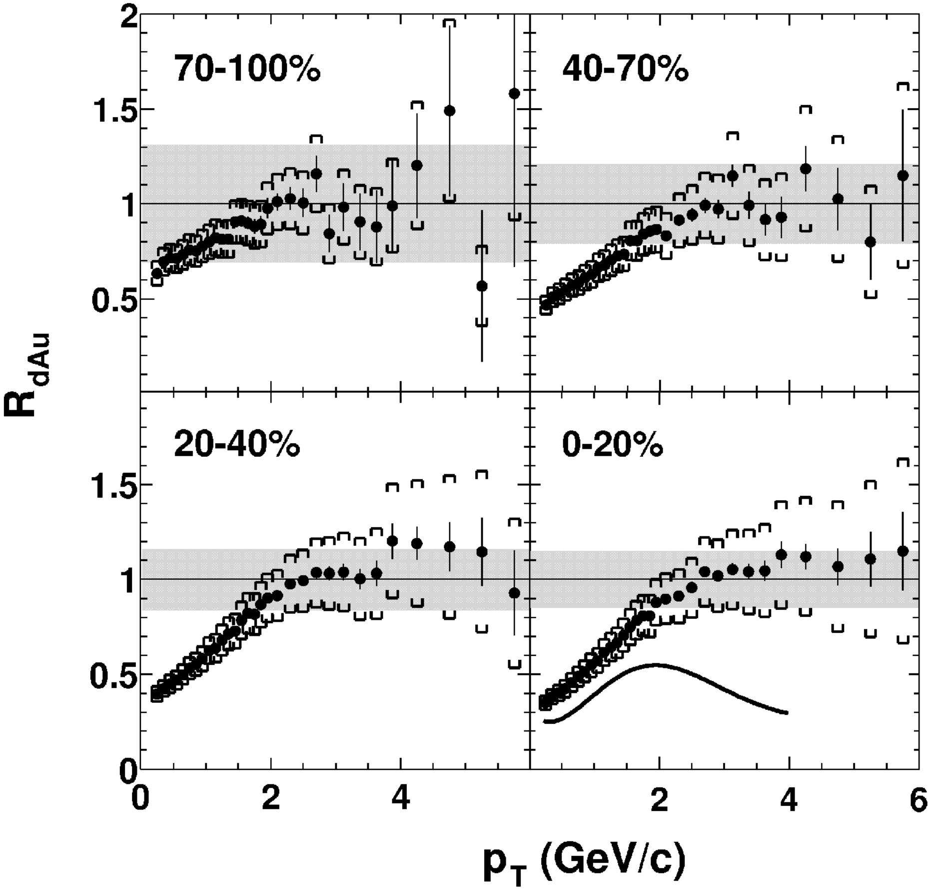
$$R_{AA} = \frac{\sigma_{pp}^{inel}}{\langle N_{coll} \rangle} \frac{d^2 N_{AA}/dp_T d\eta}{d^2\sigma_{pp}/dp_T d\eta}$$

How effective is each binary collision for inducing a hard scattering process?

Au+Au at 200 GeV shows a strong suppression of high Pt particles
At 62.4 GeV there seems to be less suppression, but this could be because of the interplay of the Cronin effect, radial flow, suppression, etc.

Is high Pt suppression an initial or a final state effect?

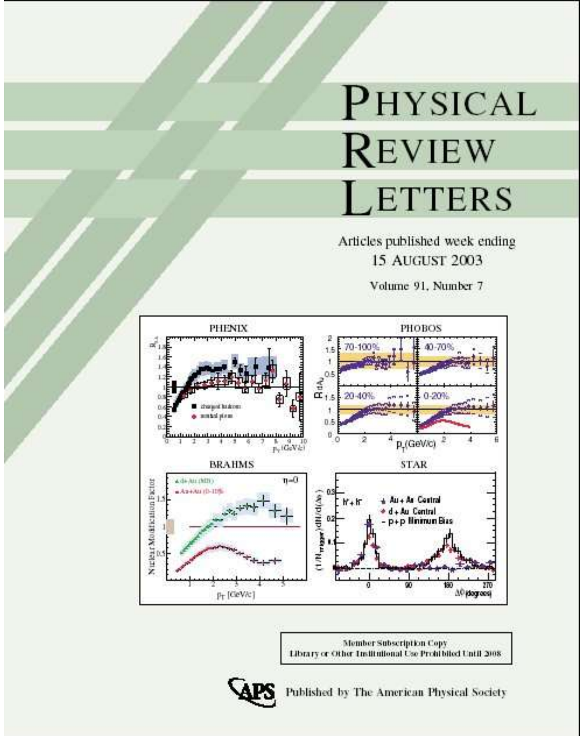
Strongly interacting medium: High Pt d+Au at 200 GeV



d+Au at 200 GeV shows no high Pt suppression

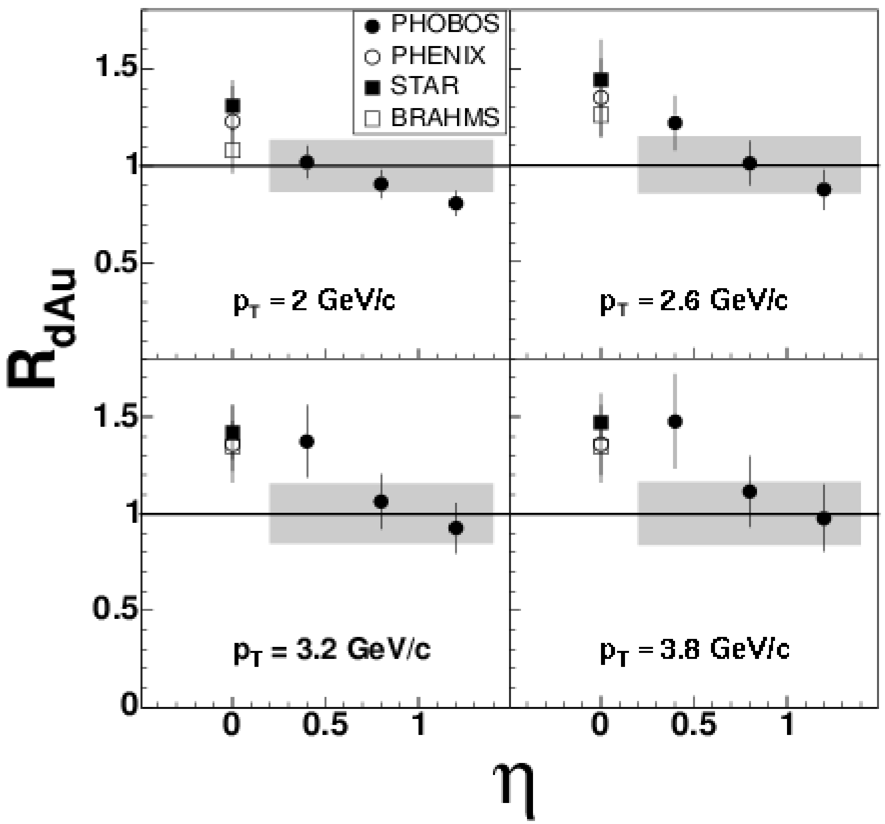
The high Pt suppression in Au+Au is a final state effect

With high certainty the suppresion of high Pt particles in Au+Au is caused by their strong interaction with the high energy density medium



A word of caution

A difference was found between the strength of the nuclear modification factor for d+Au between PHOBOS and the other RHIC experiments



Recent BRAHMS and PHOBOS results indicate that this difference is caused by the

η dependence of R_{dAu}

(very recent STAR and PHENIX results point to the same explanation)

Strongly interacting high energy density medium

Strong elliptic flow signal observed

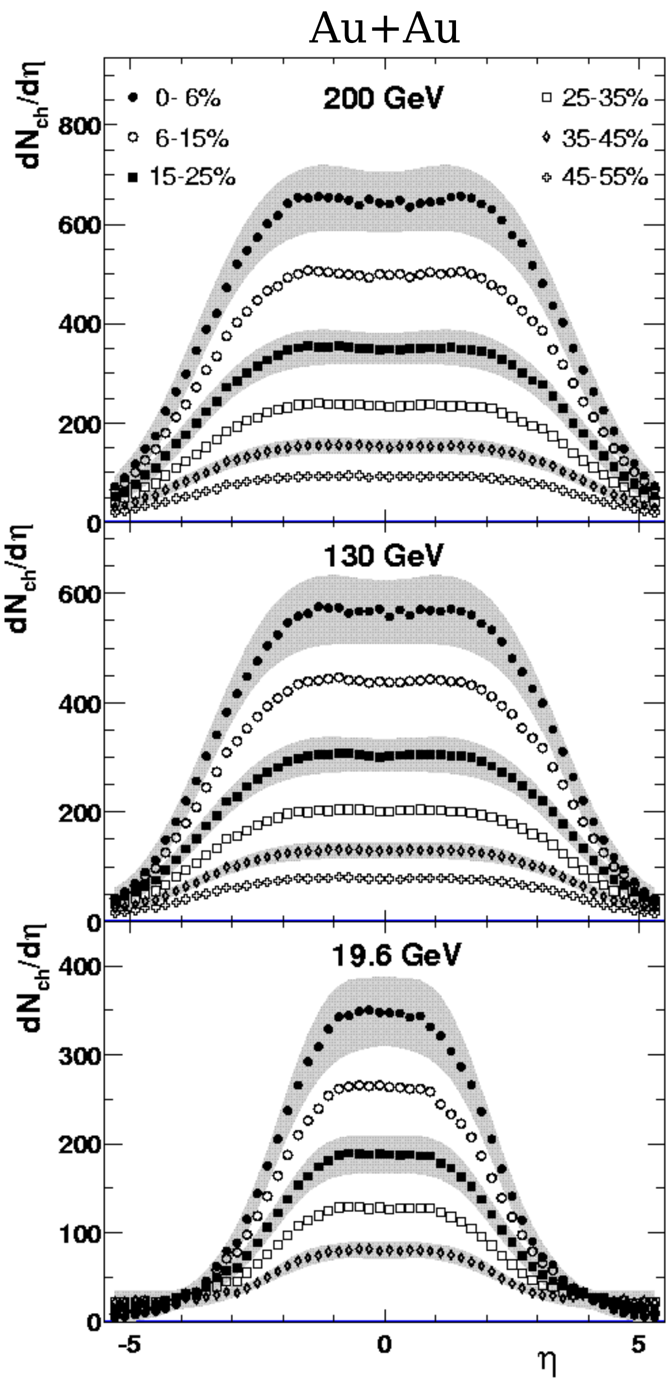
No low transverse momentum particle excess

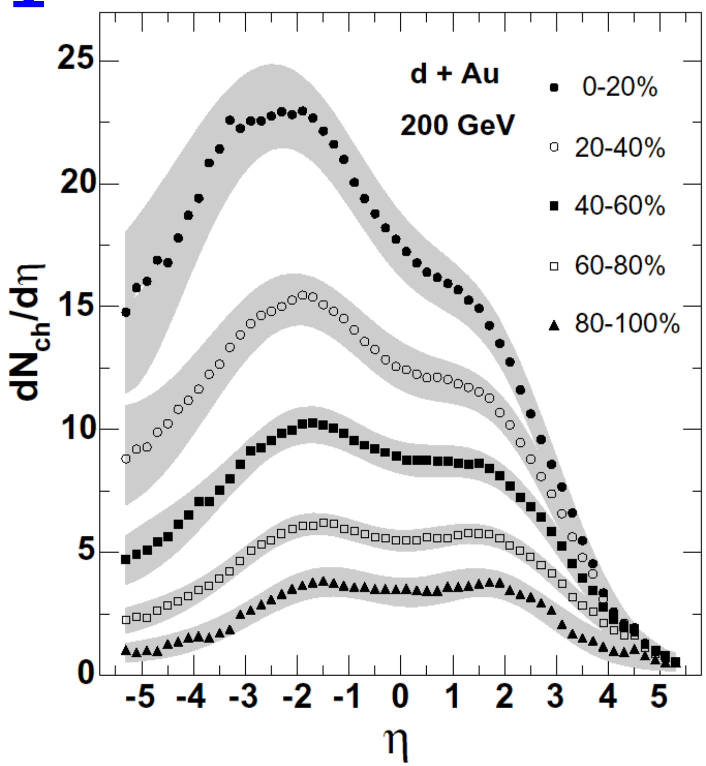
Close to reaching net baryon-free regime

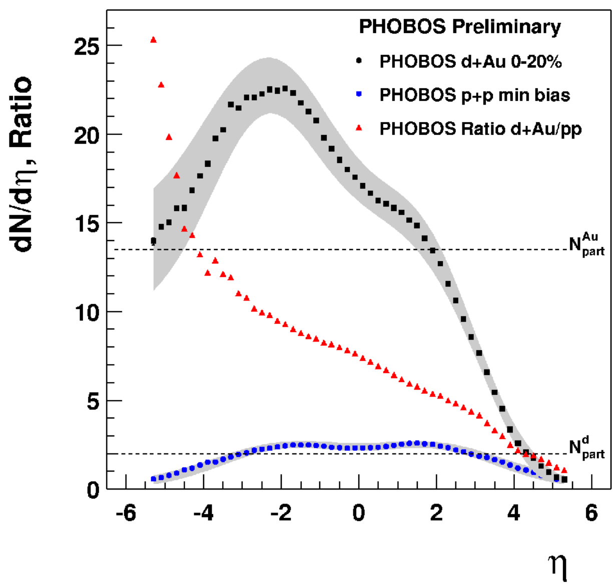
High Pt suppresion through final state interactions

Strong evidence for the creation of a very high energy density, relativily net baryon-free, medium which cannot simply be described in terms of hadrons and whose constituents experience significant interactions with each other

Scaling behaviours of particle production

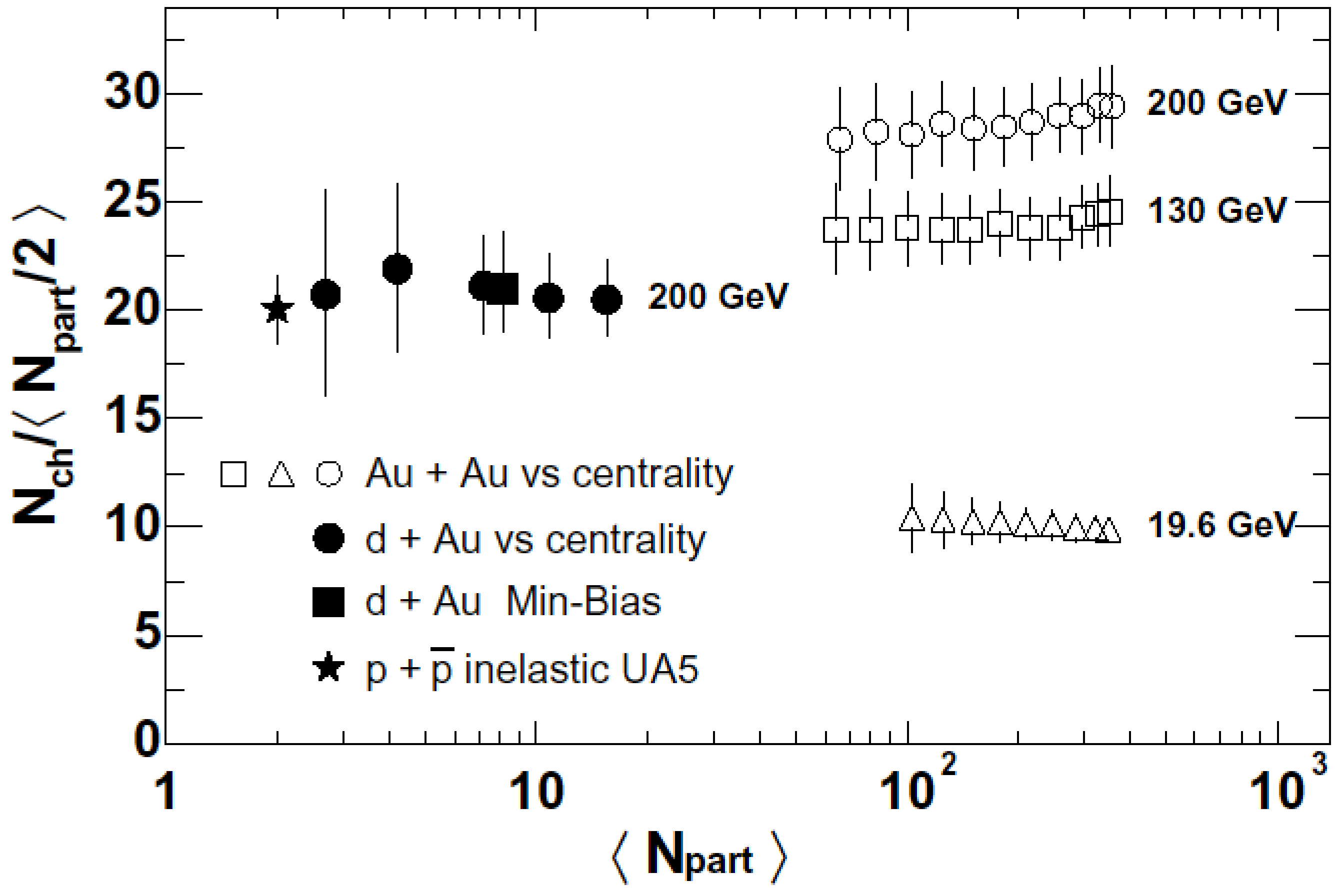






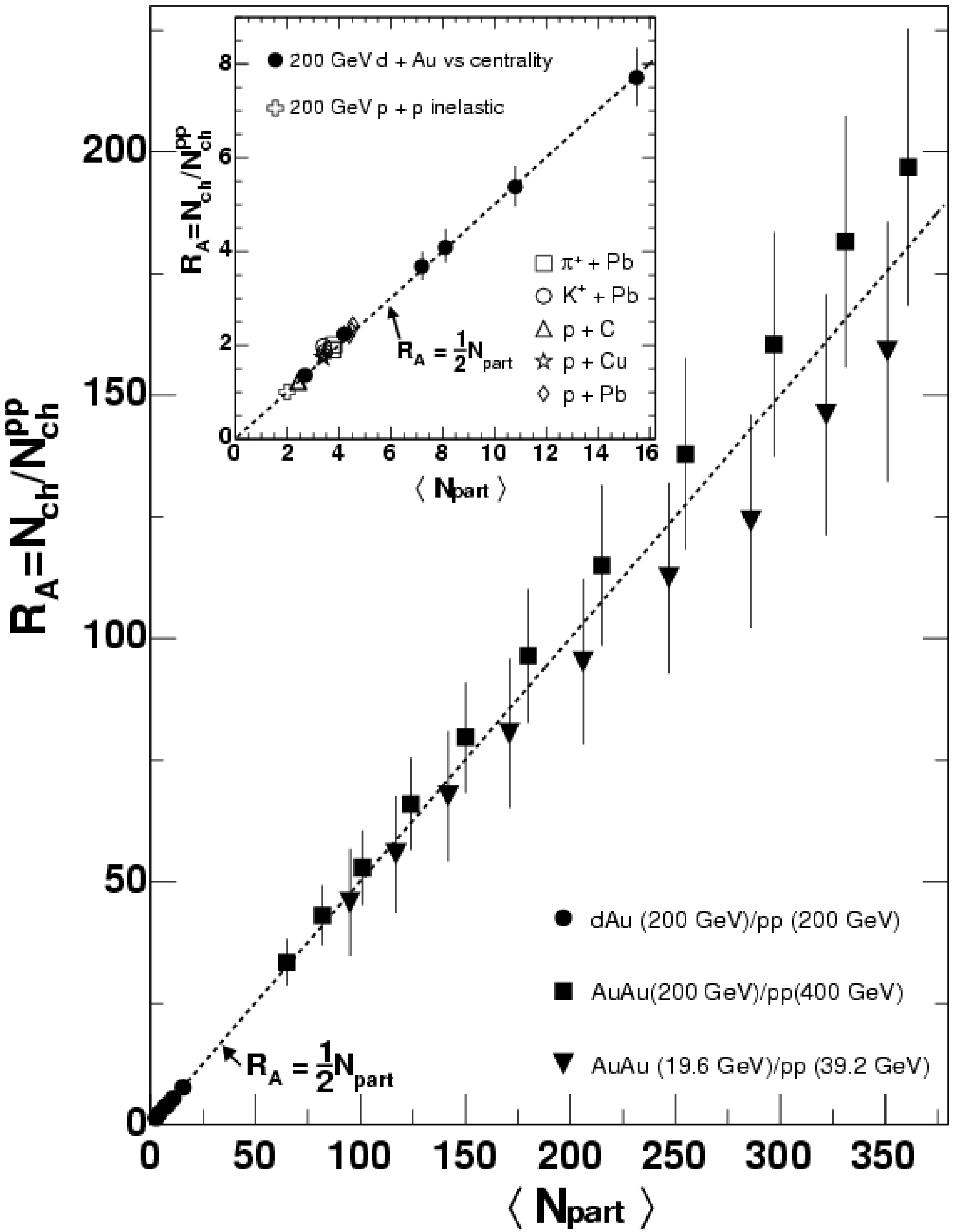
Let's play with the extensive dataset that we have accumulated

Centrality dependence of total multiplicity



Total charged particle multiplicity is proportional to the number of participant pairs and is proportional to the number of participating nucleons in Au+Au at the three energies shown

Centrality dependence of total multiplicity



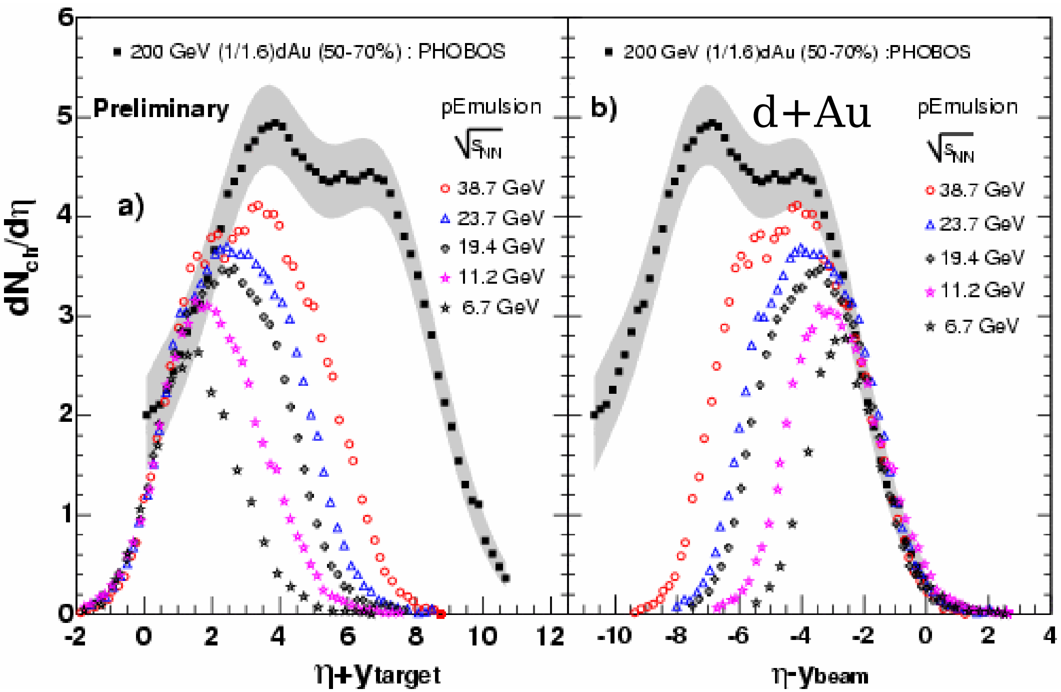
Many different systems and beam energies

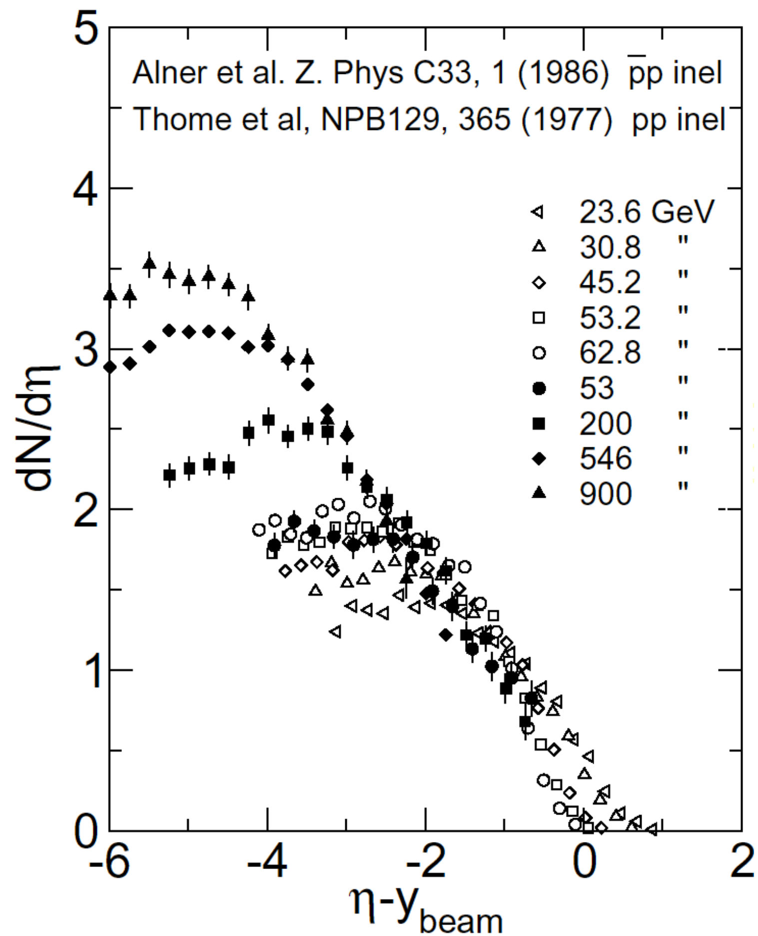
Normalize to charged particle multiplicity of p+p with 'appropriate' energy

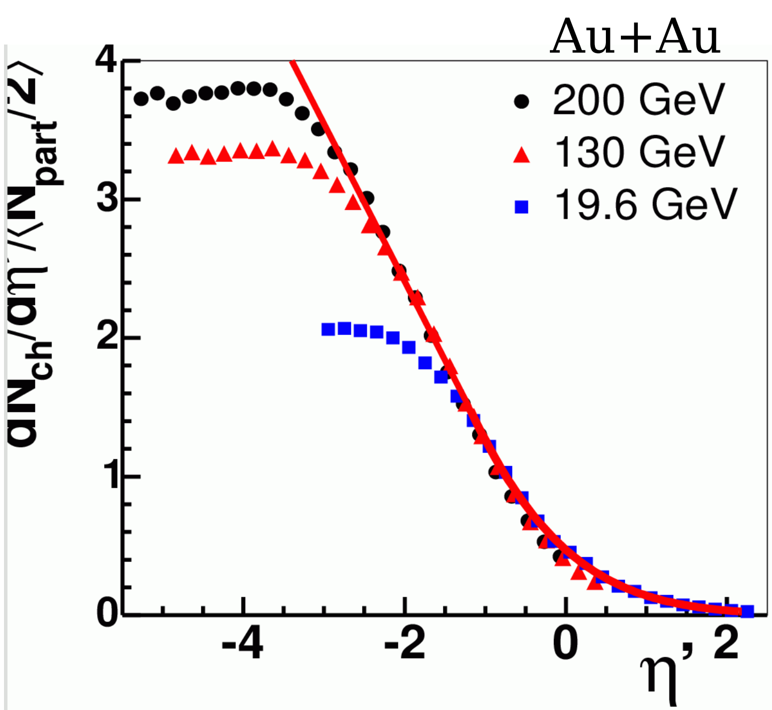
'Appropriate' means to take effective energy of p+p to compensate for energy taken away by leading proton

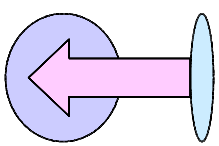
Participant scaling for a wide variety of systems and for beam energies from below 10 GeV upto full RHIC energy

Longitudinal scaling: Charged particle distributions



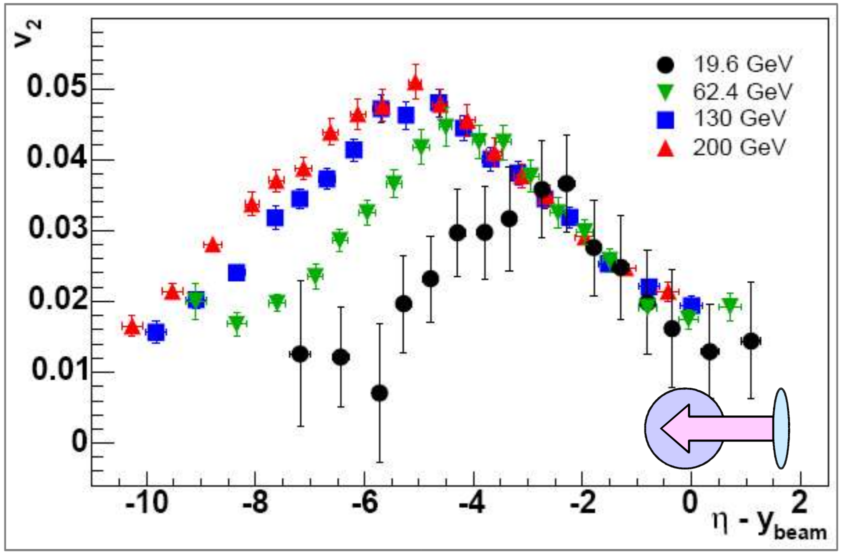


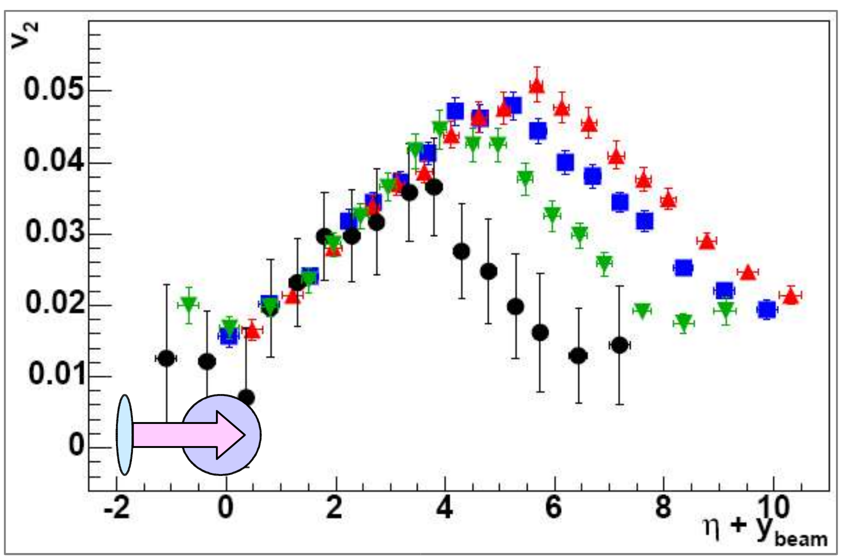




Like pp also d+Au and Au+Au exhibits extensive longitudinal scaling
(limiting fragmentation)

Longitudinal scaling: Flow



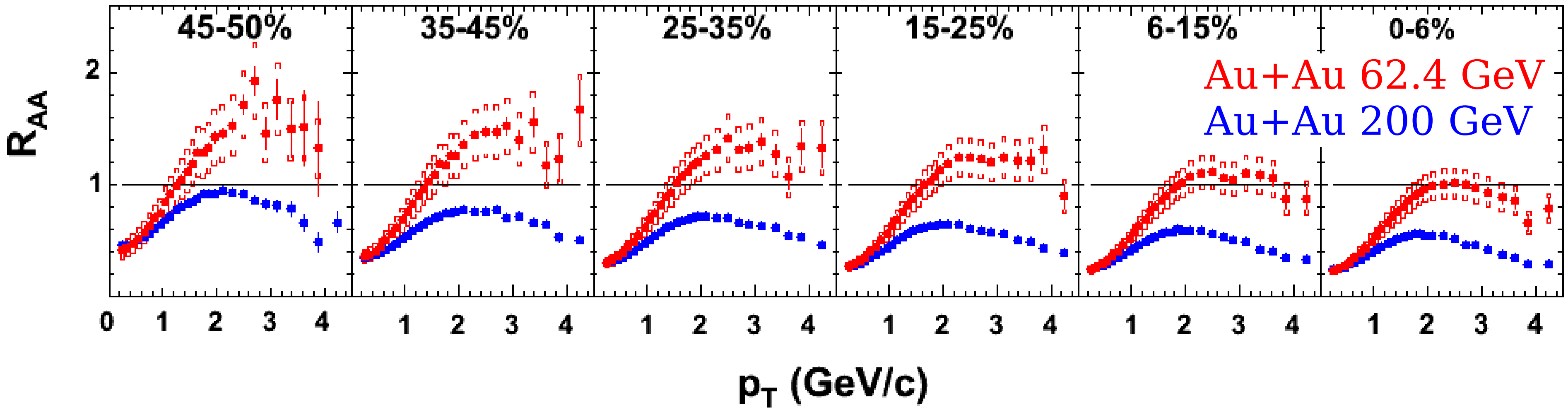


Elliptic flow shows a limiting behaviour reminiscent of the limiting behaviour for charged particle production

Since elliptic flow is believed to originate early in the collision (< 2 fm/c) this longitudinal scaling probably also happens relativily early in the collision

The triangle shape of the distributions (lack of a boost invariant plateau) will be a challenge to explain
(note: in the final particle **rapidity** distributions there is also no boost invariant plateau visible)

Nuclear modification factor: R_{AA}

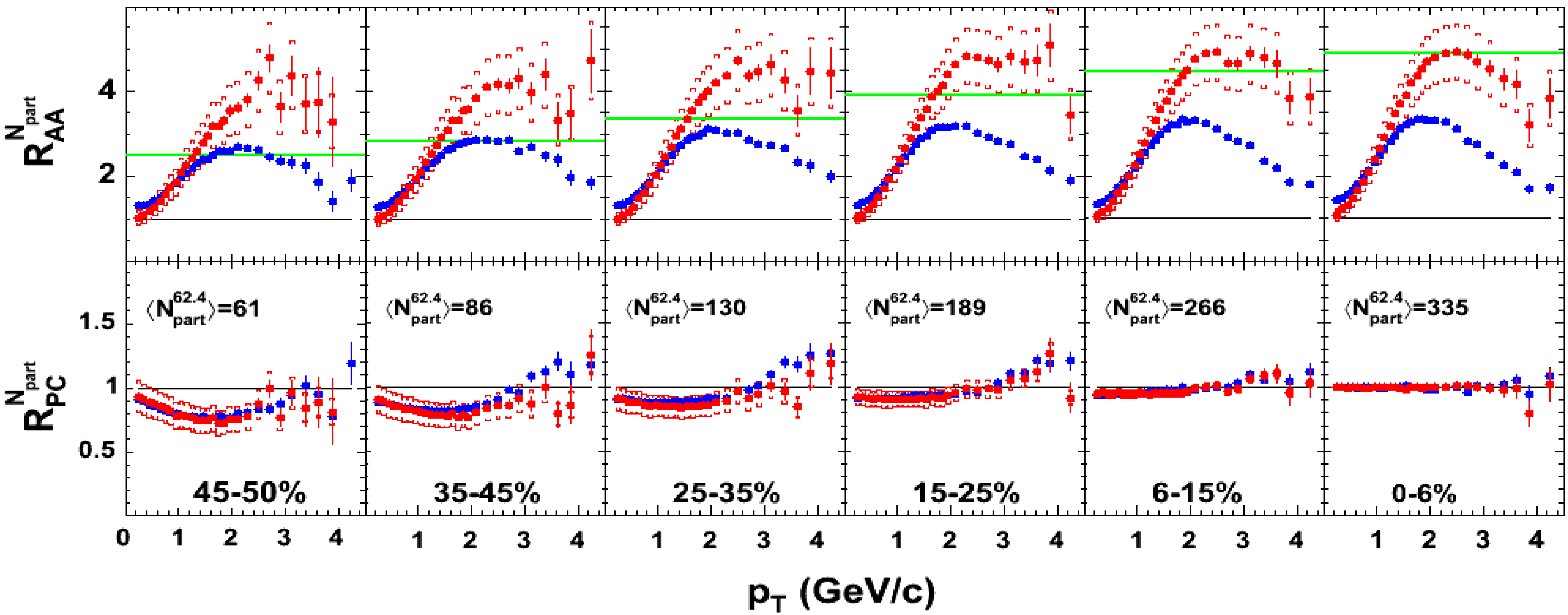


$$R_{AA} = \frac{\sigma_{pp}^{inel}}{\langle N_{coll} \rangle} \frac{d^2 N_{AA}/dp_T d\eta}{d^2 \sigma_{pp}/dp_T d\eta}$$

Since participant scaling works so well for charged particle production, change binary collision scaling to participant scaling

$R_{AA}^{N_{part}}$

Au+Au 62.4 GeV
Au+Au 200 GeV

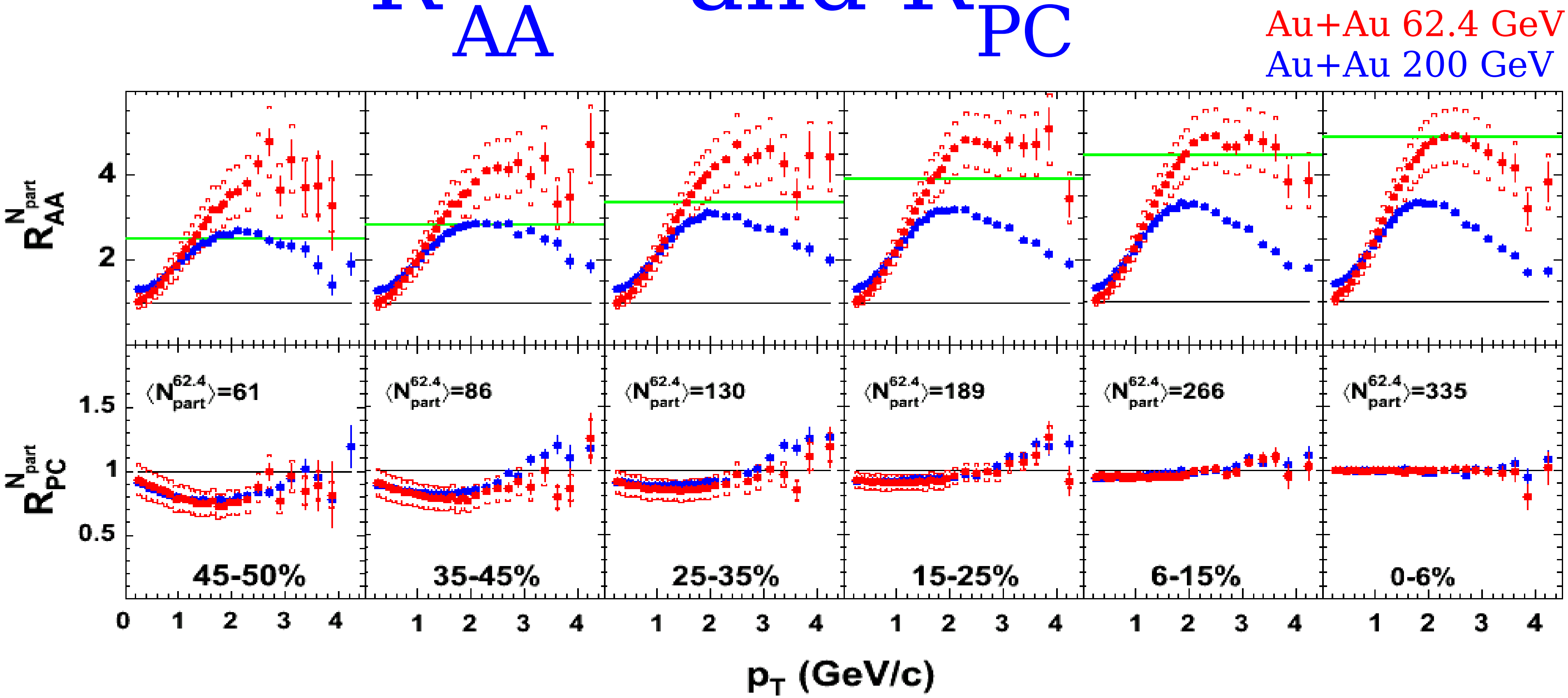


$R_{AA}^{N_{part}}$ has become almost independent of centrality

Divide by the most central distributions to study the shape evolution in more detail

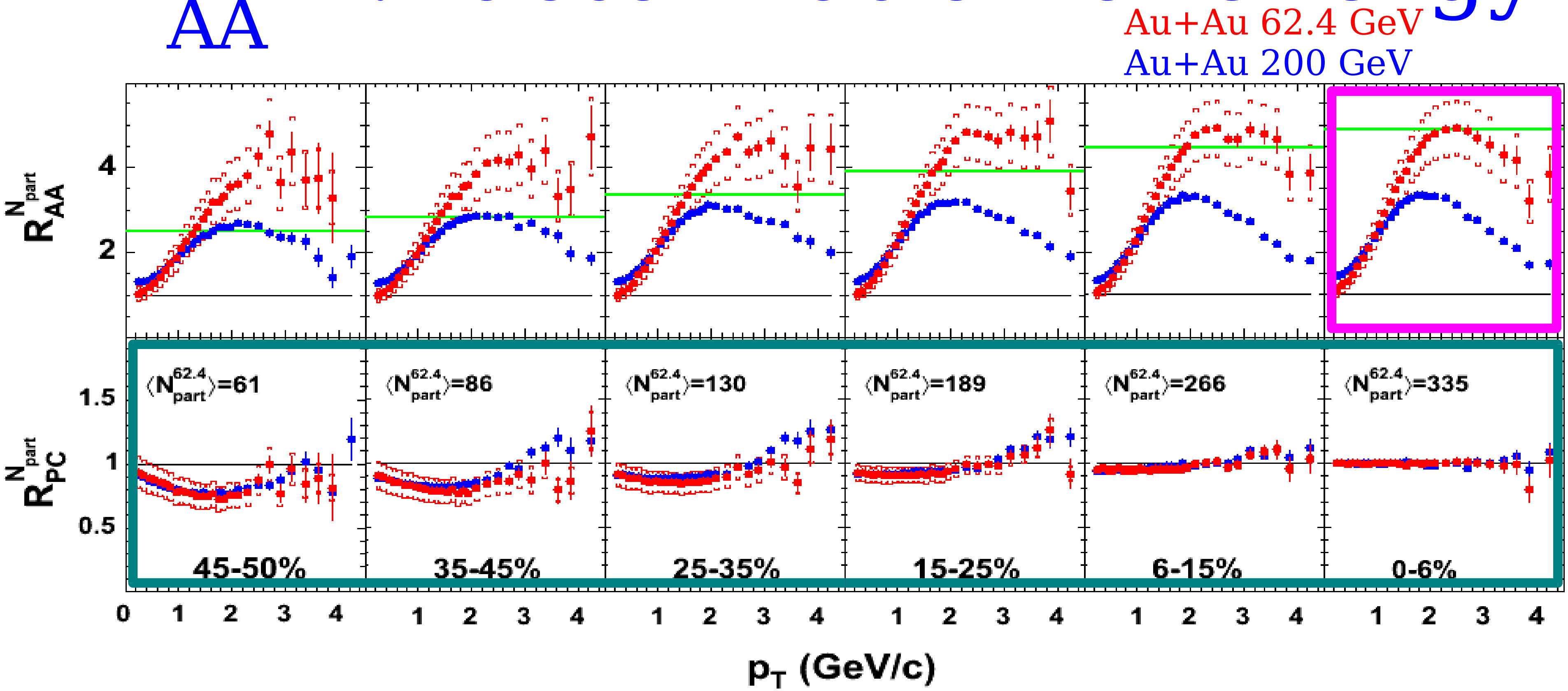
$$R_{PC}^{N_{part}} = \frac{\langle N_{part}^{0-6\%} \rangle}{\langle N_{part} \rangle} \frac{d^2 N_{AA}/dp_T d\eta}{d^2 N_{AA}^{0-6\%}/dp_T d\eta}$$

$R_{AA}^{N_{part}}$ and $R_{PC}^{N_{part}}$



$R_{PC}^{N_{part}}$ has become practically energy independent!

$R_{AA}^{N_{part}}$:Factorization of energy



$$R_{AA}^{N_{part}} = \boxed{R_{PC}^{N_{part}}(N_{part}, p_T)} \times \boxed{R_{AA}^{N_{part}^{0-6\%}}(\sqrt{s_{NN}}, p_T)}$$

Energy independent
Weak function of
(N_{part}, p_T)

Centrality
independent shape

Summary

Extreme high energy densities

Strong interactions

Close to net baryon-free

Participant scaling

Extensive longitudinal scaling

Factorization of energy- and centrality dependence

Conclusion

We have discovered a strongly interacting medium with extremely high energy density whose description in terms of simple hadronic degrees of freedom is not appropriate

We have discovered that much of the data can be expressed in terms of simple scaling rules which suggest the existence of strong global constraints or some kind of universality in the mechanism of the production of hadrons in high energy collisions

http://www.phobos.bnl.gov/Publications/PublicDocuments/PhobosWhitePaper.pdf (.ps)