JINR Joint Institute for Nuclear Research

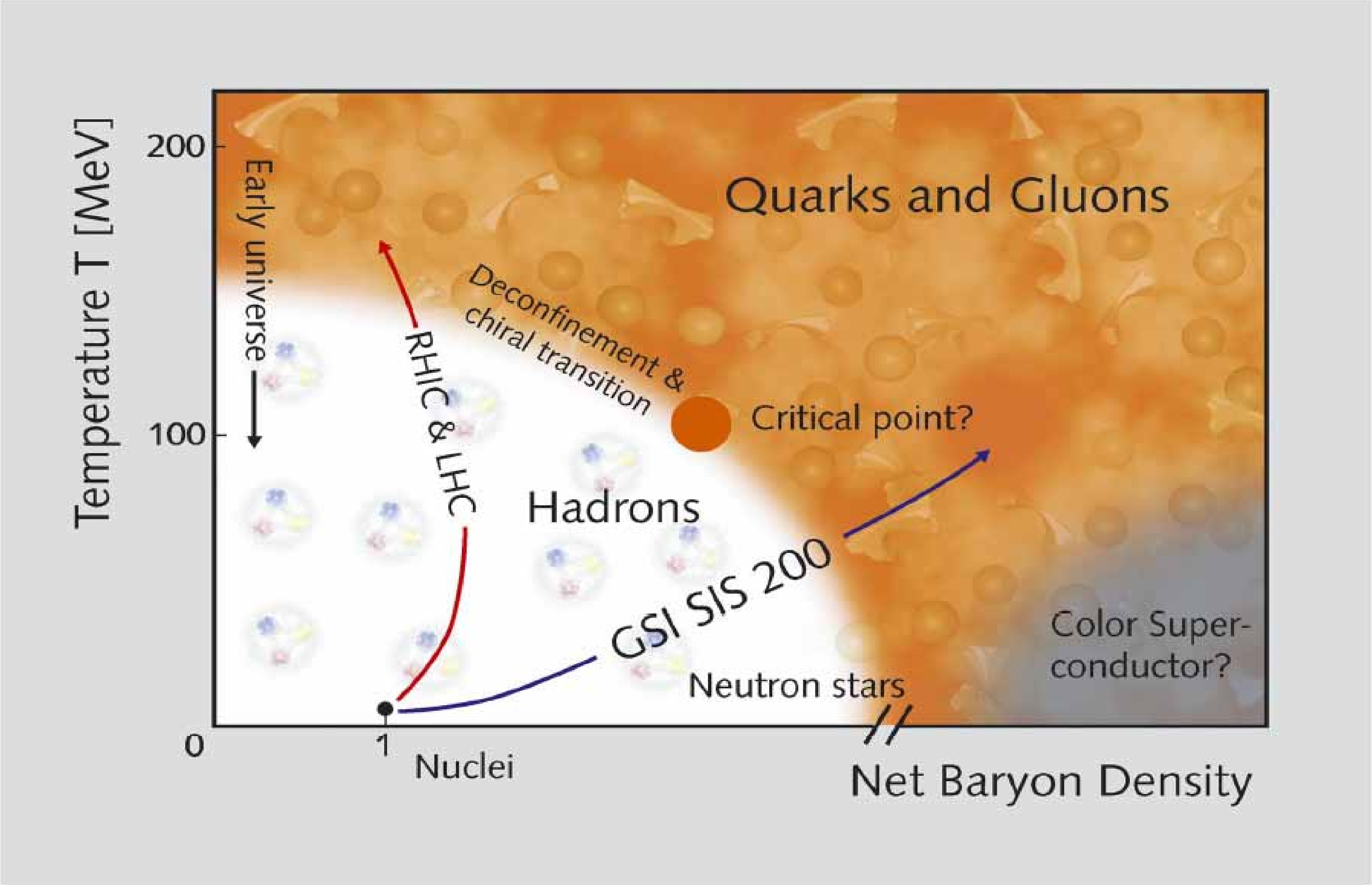
Search for the mixed phase of strongly interacting matter at the JINR Nuclotron

A.N. Sissakian and A.S. Sorin

(on behalf of the working group)

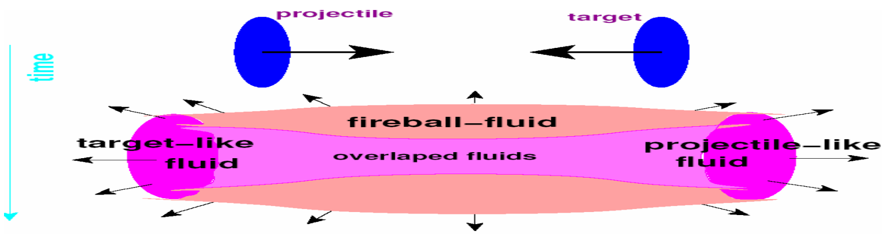
ROUND TABLE DISCUSSION, JINR (Dubna) July 7 - 9, 2005

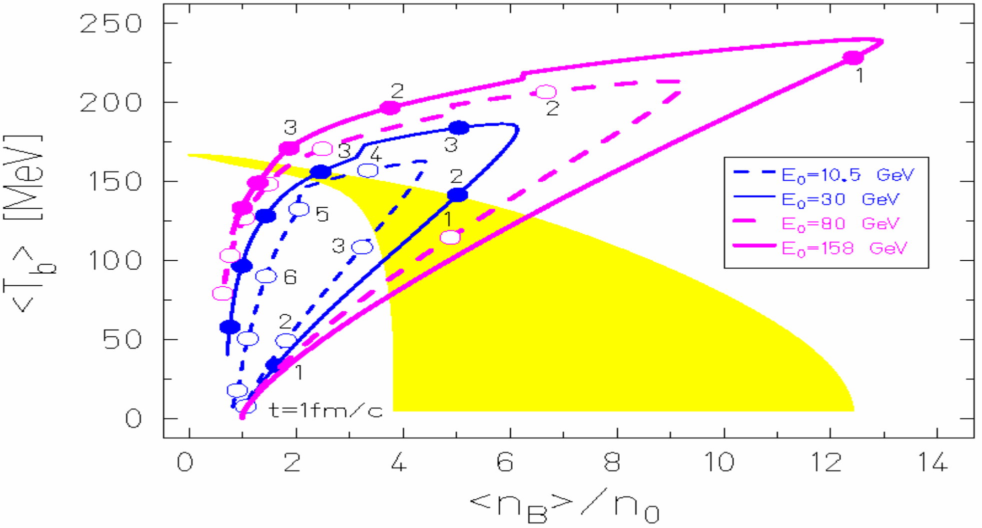
Phases of strongly interacting matter

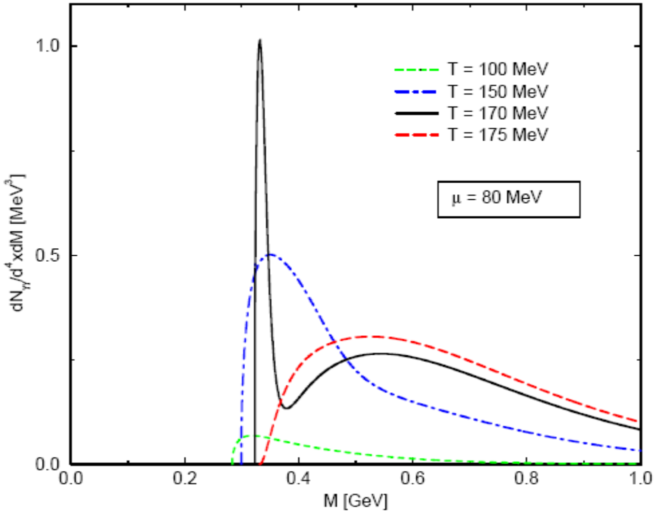


Simulations of Heavy-Ion Collisions: Relativistic 3-fluid hydrodynamic model for the energy range: a few to 200 *A GeV.*

Y.Ivanov,V.Russkikh,V.Toneev







$\pi\pi \rightarrow \gamma\gamma$

M.Volkov, E.Kuraev,D .Blaschke, G.R¨opke, S.Schmidt,

PLB(1998)

Proposal for FAIR GSI: consider the anomalous peak in the two-photon spectrum as a signal of the mixed phase formation and, therefore, a tool to identify the critical point in the QCD phase diagram. **D.Blaschke, A.Sissakian, A.Sorin, M.Suleymanov** (On physical programme at FAIR, 5th Workshop on the scientific cooperation between German research centres and JINR, Dubna, 17-19 January 2005, http://cv.jinr.ru/BMBF_05/index.html).

$$\sigma \rightarrow \pi\pi \quad \sigma \rightarrow \gamma\gamma$$
$$\Gamma_\sigma = 600 - 1000 MeV$$
$$M_\sigma = 400 - 1200 MeV$$

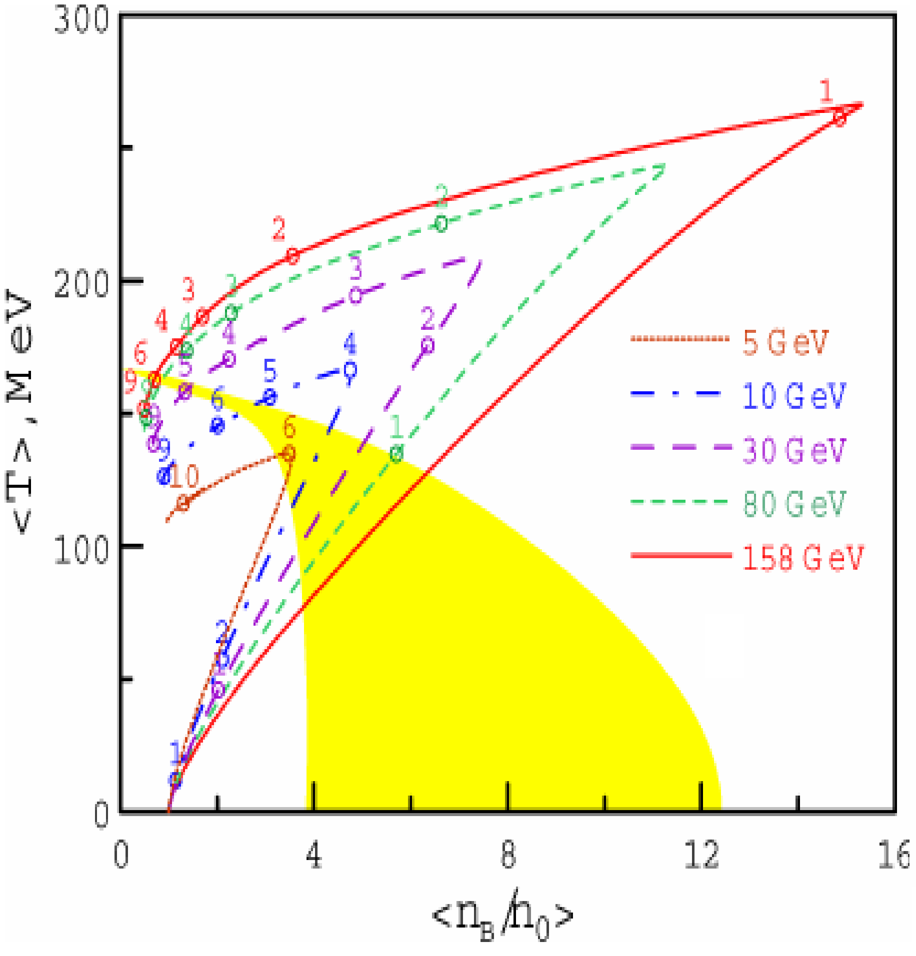
The number of anomalous two-photon events in the narrow invariant mass region M_2gamma ~ M_sigma(mu_c, T_c) can be considered as a "clock" for the duration of the mixed phase.

Problems of SPS and RHIC: huge background from neutral pion decays complicates identification of this signal. Privilege of FAIR: higher densities entail lower critical temperatures → lower background!

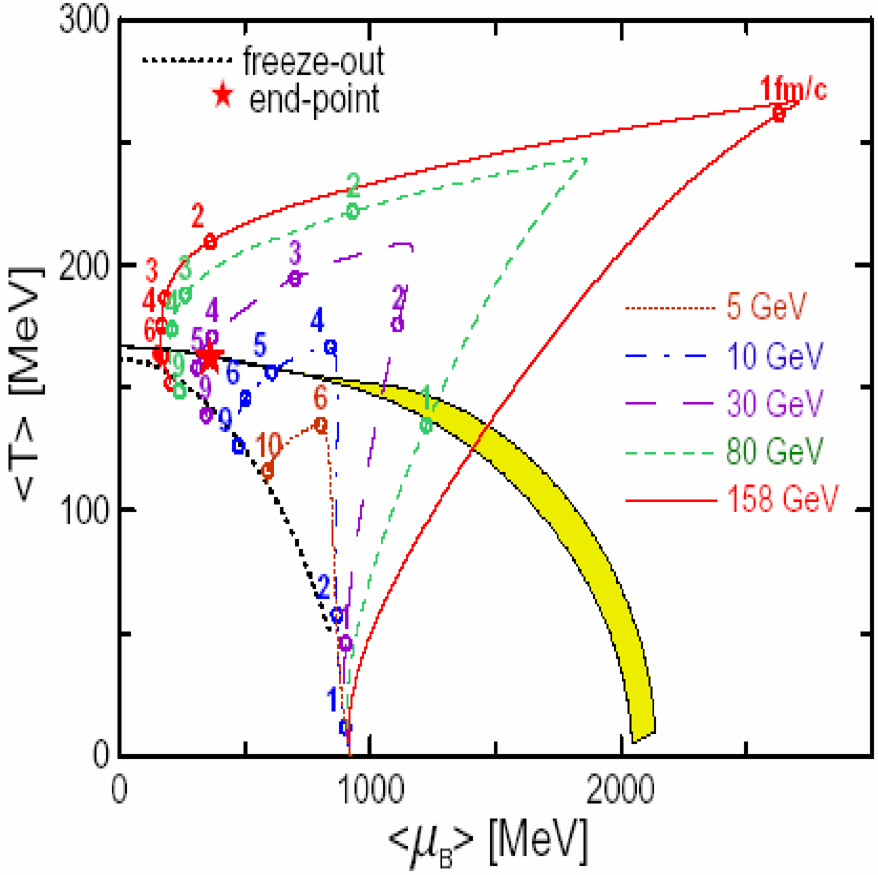
What about the JINR Nuclotron?

Nuclotron: E ~ 5 GeV/nucleon, heavy nuclei A ~ 200

With light quarks



With heavy quarks



V.Toneev, Talk at the CBM Collaboration Meeting
March 9-12, 2005, GSI,Darmstadt,
http://www.gsi.de/documents/DOC-2005-Mar-871.pdf

Y.Ivanov,V.Russkikh,V.Toneev,
Relativistic Heavy-Ion Collisions within 3-Fluid Hydrodynamics: Hadronic Scenario, nucl-th/0503088 (March 31 2005)

Nothing seems to change drastically between GSI and AGS as far as the hadronic observables are concerned!?

We could agree with this statement if GLOBAL observables are considered (average multiplicities, rapidity, transverse spectra, and so on ...). However it might be not the case for more delicate haracteristics.

Heavy ion collisions from Bevalak to SIS

The Day Before Yesterday

BEVALAK: 2 AGeV

The investigation of the properties of compressed hadronic matter

Yesterday

AGS: 11 AGeV

The study of hadronic matter at several times normal nuclear density.

Today

SPS: 20 – 160 AGeV (NA49 experiments).

NUCLOTRON: 5 AGeV

Search for the mixed phase of strongly interacting matter.

SIS: 1-2 AGeV

The study of electron-positron pair emission in relativistic heavy ion collisions (HADES)

Tomorrow

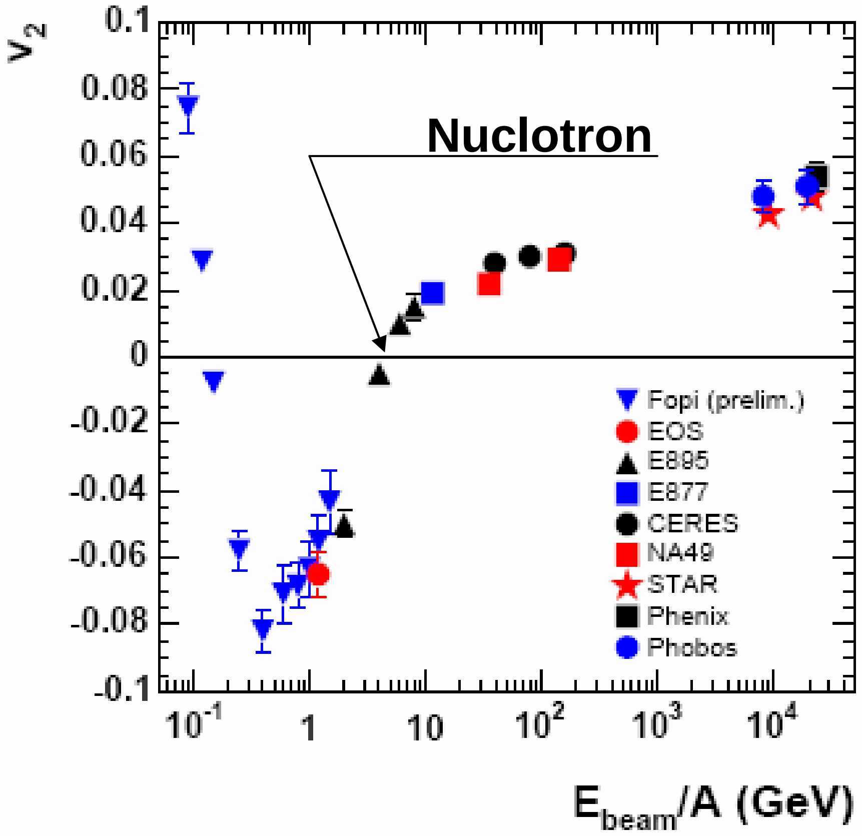
SIS (FAIR GSI): 10 – 30 GeV/nucl

Compressed Baryonic Matter (CBM)

In particular, the excitation function of the elliptic flow (v_2-coefficient) exhibits some structure and changes the sign JUST at the Nuclotron energy of about 5 GeV/nucleon.

Elliptic Flow

$$dN/d\phi \propto [1+2v_1 \cos(\phi)+2v_2 \cos(2\phi)]$$

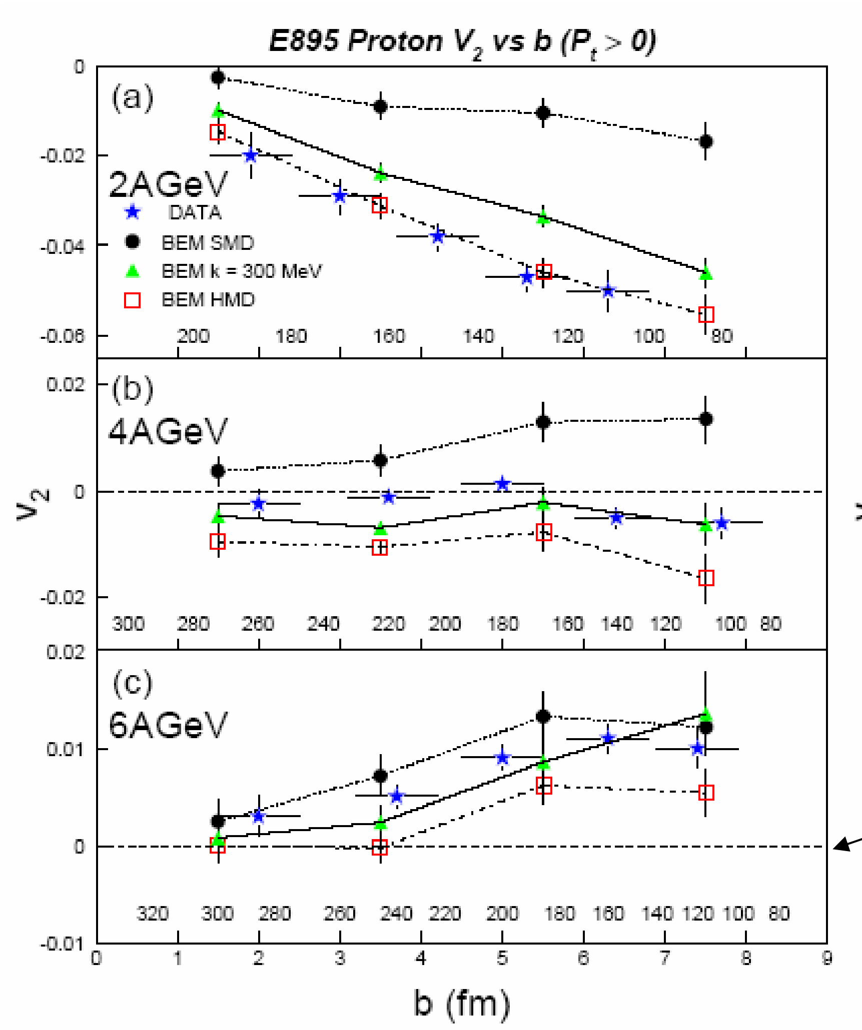


Presently available data for the elliptic flow coefficient v2 (near midrapidity,integrated over p_T), for √s from SIS /Bevalac via AGS and SPS to RHIC.

R. Stock, nucl-ex/0405007

At the Nuclotron energy range v_2 strongly depends on the collision energies.
V_2 is sensitive to the EOS and space-time evolution.
Its measurement at the Nuclotron energy will be extremely important!

Remarkable structure in v_2 versus centrality.



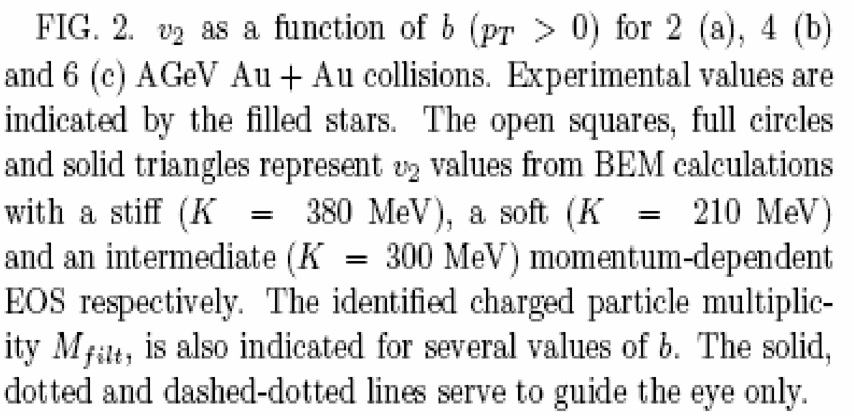


FIG. 2. v_2 as a function of b ($p_T > 0$) for 2 (a), 4 (b) and 6 (c) AGeV Au + Au collisions. Experimental values are indicated by the filled stars. The open squares, full circles and solid triangles represent v_2 values from BEM calculations with a stiff ($K = 380$ MeV), a soft ($K = 210$ MeV) and an intermediate ($K = 300$ MeV) momentum-dependent EOS respectively. The identified charged particle multiplicity M_{filt}, is also indicated for several values of b. The solid, dotted and dashed-dotted lines serve to guide the eye only.

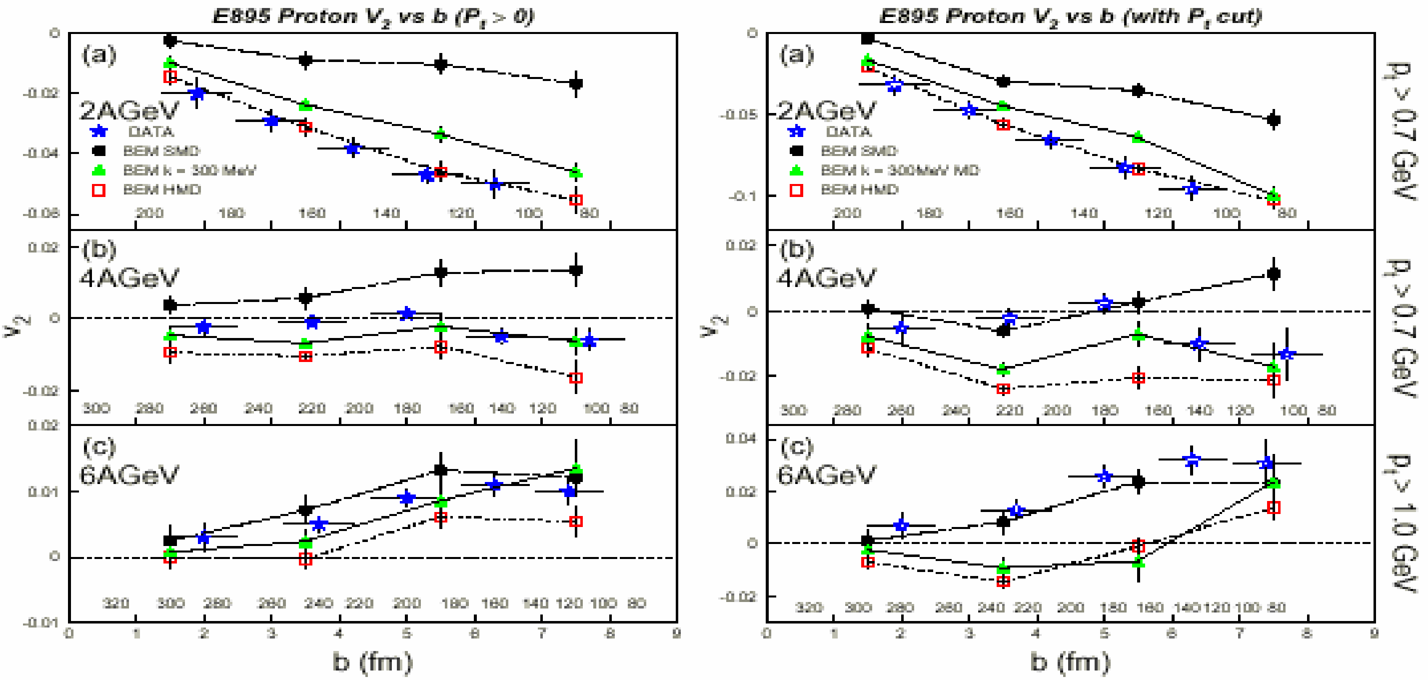
Nuclotron

P. Chung et al. Differential Elliptic Flow in 2 - 6 AGeV Au + Au Collisions: A New Constraint for the Nuclear Equation of State, nucl- ex/ 0112002.

Boltzmann Equation Model
BEM which assumes a soft (K = 210 MeV), a stiff (K = 380 MeV) and an intermediate (K = 300 MeV) EOS respectively (K is the nuclear matter compressibility).

$dN/d\phi \propto [1+2v_1\cos(\phi)+2v_2\cos(2\phi)]$

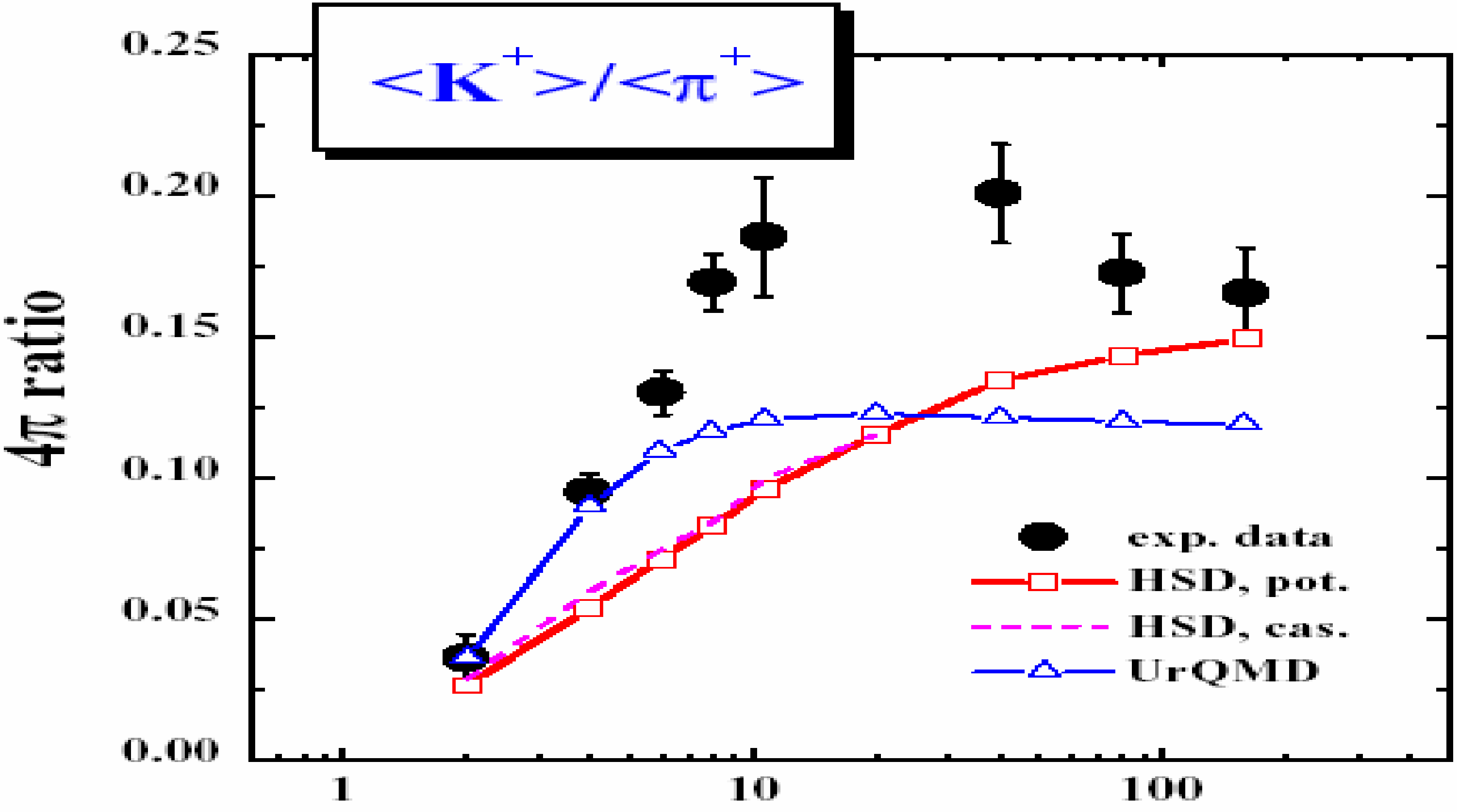
BNL E895 Collaboration has studied the proton elliptic flow as a function of impact-parameter **b**, for two transverse momentum cuts in 2 - 6 AGeV Au + Au collisions (AGS).



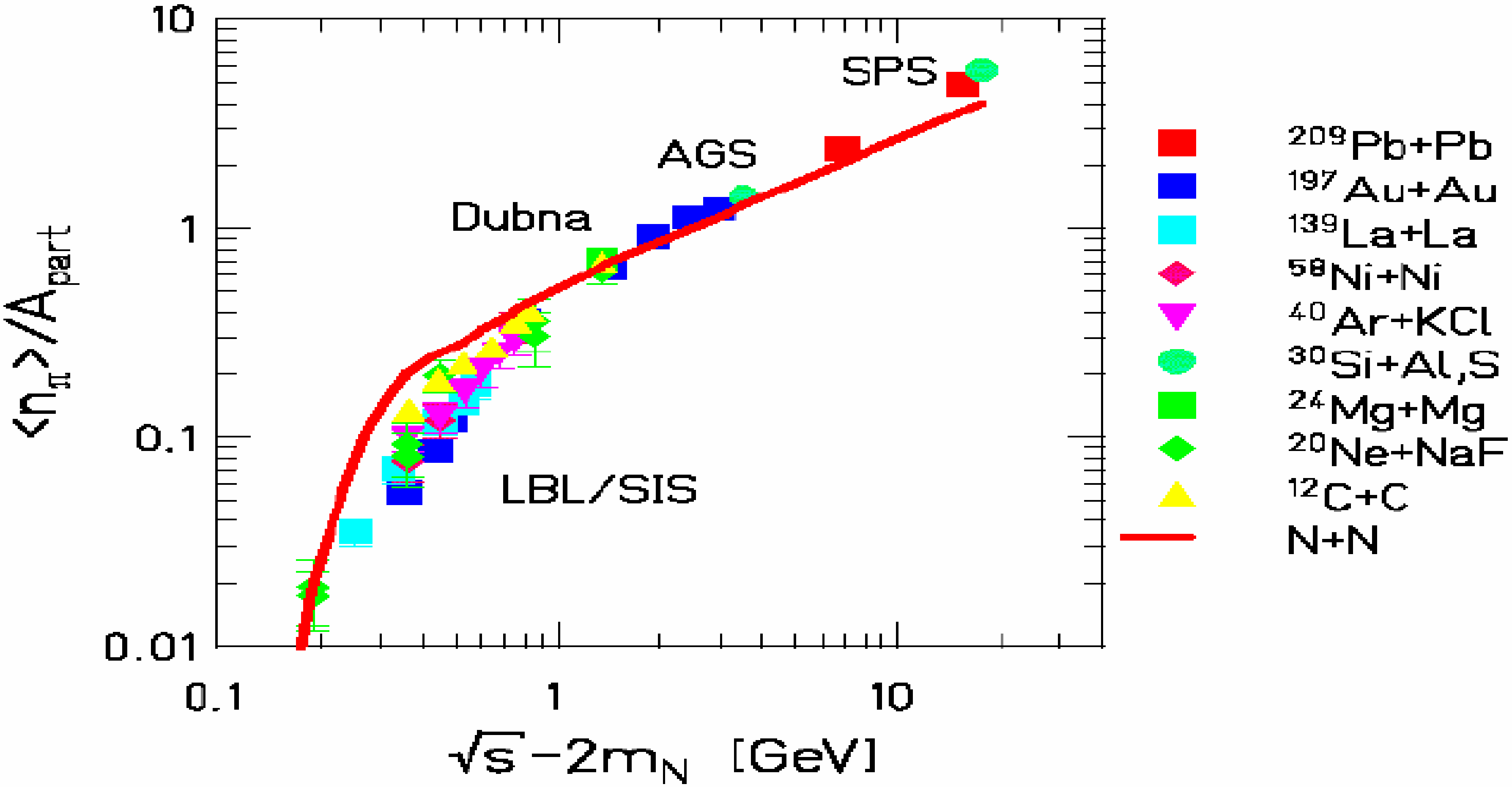
P. Chung et al. Differential Elliptic Flow in 2 - 6 AGeV Au + Au Collisions: A New Constraint for the Nuclear Equation of State, nucl- ex/ 0112002.

The elliptic flow shows an essentially linear dependence on b (for 1.5 < b < 8 fm) with a negative slope at 2 AGeV, a positive slope at 6 AGeV and a near zero slope at 4 AGeV. These dependencies serve as an important constraint for discriminating between various EOS for high density nuclear matter, and they provide important insights on the interplay between collision geometry and the expansion dynamics.

Moreover, even global characteristics are not completely explained by modern transport theory (UrQMD, HSD models). While average pion and kaon multiplicities are well reproduced at SIS and SPS energies, the above-mentioned models essentially underestimate kaon/pion ratio in the Nuclotron-AGS energy domain.



H. Weber, E. L. Bratkovskaya, W. Cassing, H. Stoecker, nucl-th/0209079



Pion multiplicity per participating nucleon for nucleus-nucleus (symbols) and nucleon-nucleon collisions (solid line) as function of available energy in nucleon-nucleon collisions (taken from [P. Senger and H. Ströbele, J. Phys. G: Nucl. Part. Phys. 25 (1999) R59].)

As became clear at the last years, excited nuclear matter near the phase transition boundary line behaves like a liquid rather than a gas, both from hadron and quark sides, see, e.g. the following references:

1. E.V.Shuryak and I.Zahed, "Towards the theory of binary bound states in the quark-gluon plasma", hep-ph/0403127,
2. E.V.Shuryak and I.Zahed, "Rethinking on properties of the quark-gluon plasma at $T\sim T_c$", hep-ph/0307267,
3. G.E.Brown, Ch,-H.Lee and M.Rho, "A new state of matter at high temperature as "sticky molasses", hep-ph/0402207,
4. D.N. Voskresensky, Hadron Liquid with a Small Baryon Chemical Potential at Finite Temperature, Nucl.Phys. A744 (2004) 378 [hep-ph/0402020,
5. E.Shuryak, Why does the Quark-Gluon Plasma at RHIC behave as a nearly ideal fluid, Prog.Part.Nucl.Phys. 53 (2004) 273-303, hep-ph/0312227,
6. Masakiyo Kitazawa, Teiji Kunihiro, Yukio Nemoto, Non-Fermi Liquid Behavior Induced by Resonant Diquark-pair Scattering in Heated Quark Matter, hep-ph/0505070,
7. Masakiyo Kitazawa, Teiji Kunihiro, Yukio Nemoto, Quark Spectrum near Chiral Transition Points, hep-ph/0505106,
8. G.E. Brown, B.A. Gelman, M. Rho, What hath RHIC wrought? nucl-th/0505037.

It is hardly to say now that we understand properly physics in this energy range, both experimentally and theoretically. We hope that the JINR Nuclotron facilities could contribute into solving the related problems.

Search for the mixed phase of strongly interacting matter at the JINR Nuclotron

Perspective theoretical and experimental researches

1. Researching the hadron properties in hot and/or dense baryonic matter.

2. Analyzing multiparticle hadron interactions, targeted to the development of new statistical treatment as well as codes for space-time evolution of heavy nuclei collisions at high energies.

3. **Studying the system size, lifetime, freeze-out duration, expansion time in the HBT analysis (noticeable volume expansion is expected if the mixed phase is formed), scanning in atomic number and energy;**

4. **Analyzing the energy and centrality dependences of the pion, hadron resonances and strange particle multiplicities, and the ratio of their yields, together with the transverse momentum, including K-, K*- and phi-meson spectra as well as manifestation of baryon repulsion effects on hadron abundances;**

5. **Studying di-leptons (electron and muon pairs) production (in-medium modification of hadron properties at high baryon densities);**

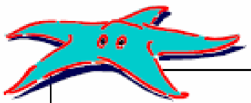
6. **Studying the behaviour of angular correlations and radial, directed as well as elliptic fows (their different behaviour as compared to hadron-hadron interactions is expected)**

7. **Analyzing fuctuations of multiplicities, electric charge and transverse momenta for secondary particles (their energy dependences could give information on the phase transition range)**

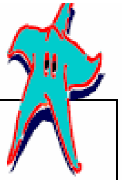
8. **Analyzing nuclear fragments characteristics versus the centrality (change of behaviour comparing to the peripheral collisions is expected), universality of nuclear fragmentation.**

9. **Energy and atomic number scanning for all characteristics of central heavy nuclei collisions (this might allow one to obtain information on the equation of state of strongly interacting matter in the transition area), difference between central collisions of light nuclei and peripheral heavy ion collisions.**

1. Researching the hadron properties in hot and/or dense baryonic matter. A spectral change is expected, first of all of the sigma-meson as the chiral partner of pions, which characterizes a degree of chiral symmetry violation and could play a role of a "signal" of its restoration.



T. Hatsuda (U. Tokyo), NATO ARW, Yalta,Crimea,2005



Broad "σ" in the vacuum :

$\Gamma_\sigma \sim m_\sigma$ *by* $\sigma \to \pi\pi$

$|\sigma\rangle \sim |\sigma_B\rangle + |\pi\pi\rangle + \cdots$

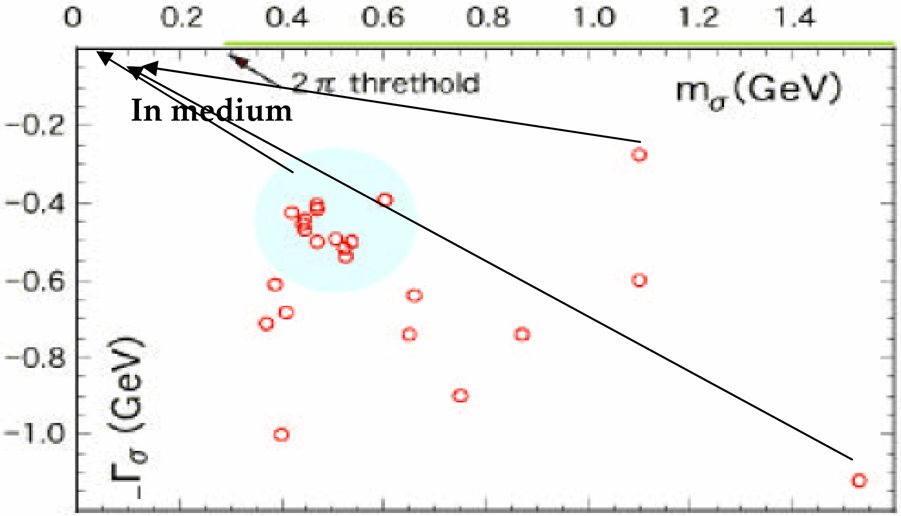
↔

Sharp "σ" in the medium :

- $\Gamma_\sigma \to 0$ *as* $m_\sigma \to 2m_\pi$
- *strong* $\pi\pi$ *attraction near threshold*

Kunihiro and T.H, Phys. Rev. Lett. 55 ('85) 158.
Phys. Lett. B185 ('87) 304.

PDG ('04) f_0 (600) or σ

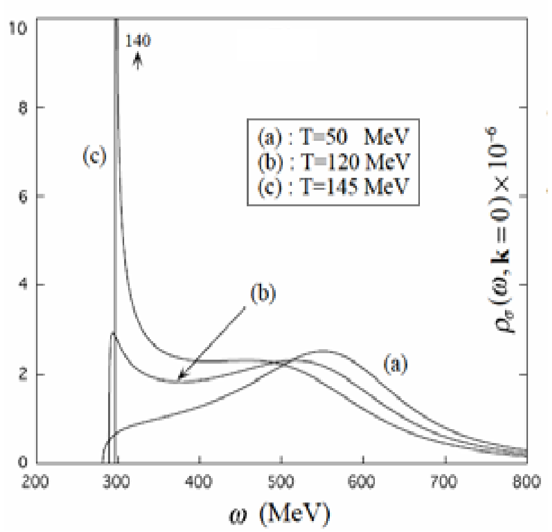


Normal density
and zero tempeature

$m_\sigma = \text{Re}\sqrt{s_{\text{pole}}}$
$-\Gamma_\sigma = 2\,\text{Im}\sqrt{s_{\text{pole}}}$

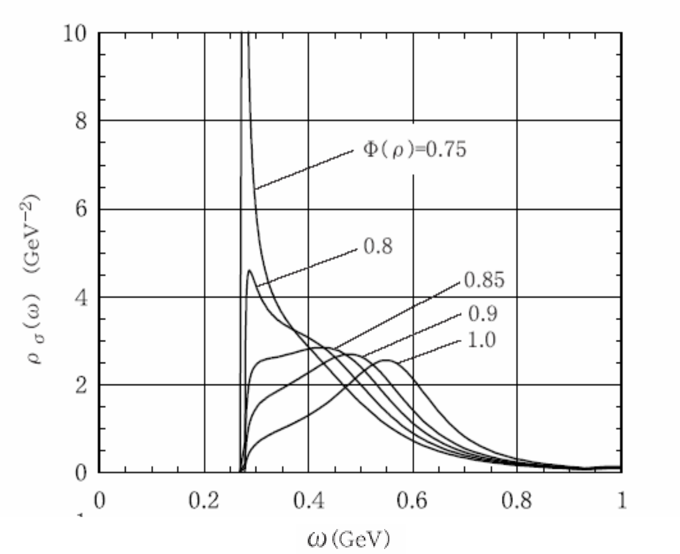
Chiral restoration and scalar meson : $\langle \bar{q}q \rangle \to 0$

Finite temperature

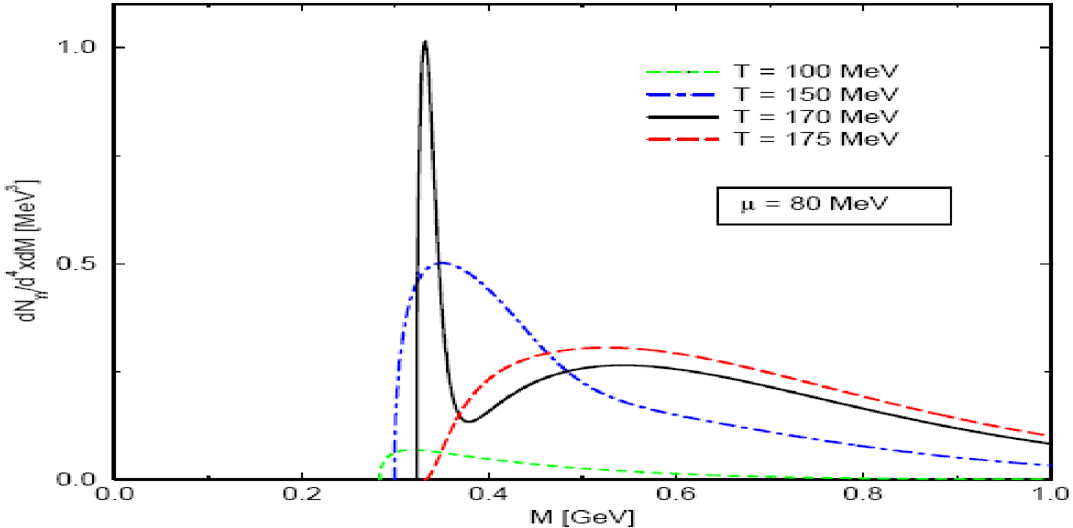


Chiku and Hatsuda, PRD58 (‘98)
Volkov et al., PLB424 (‘98)

Finite density



Hatsuda, Kunihiro and Shimizu, PRL82 (’99)



M.Volkov, E.Kuraev, D.Blaschke, G.R¨opke, S.Schmidt, PLB(1998)

2 πproduction experiments: missing attraction

Composite ratio :

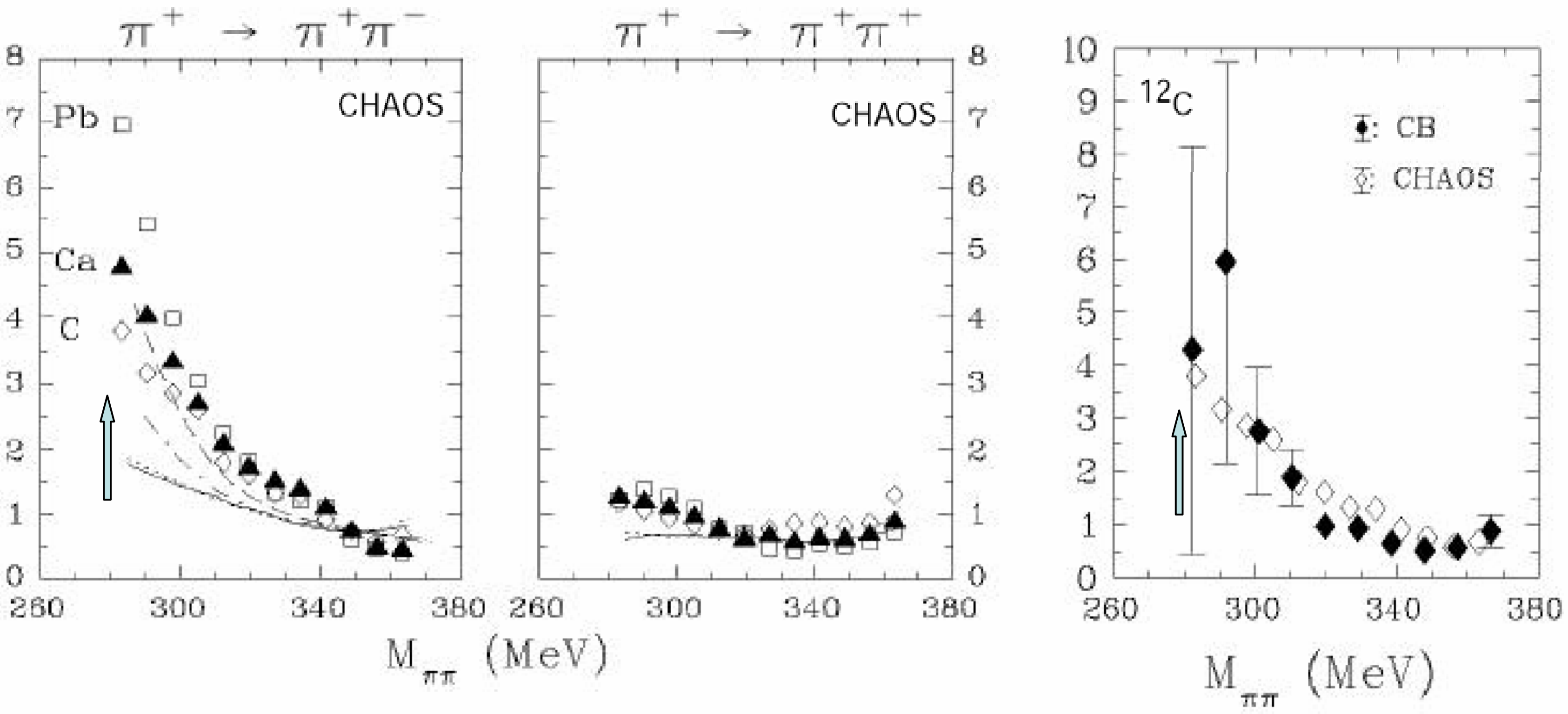
$$C^A_{\pi\pi} = \frac{\sigma^A(M_{\pi\pi})}{\sigma^A_T} \Big/ \frac{\sigma^N(M_{\pi\pi})}{\sigma^N_T}$$

- $\pi^+A \rightarrow \pi\pi A'$ $p_{\pi+}$=399 MeV/c

  CHAOS, PRL 77(’96), Nucl. Phys. A677 (’00)
- $\pi^-A \rightarrow \pi\pi A'$ $p_{\pi-}$=408 MeV/c

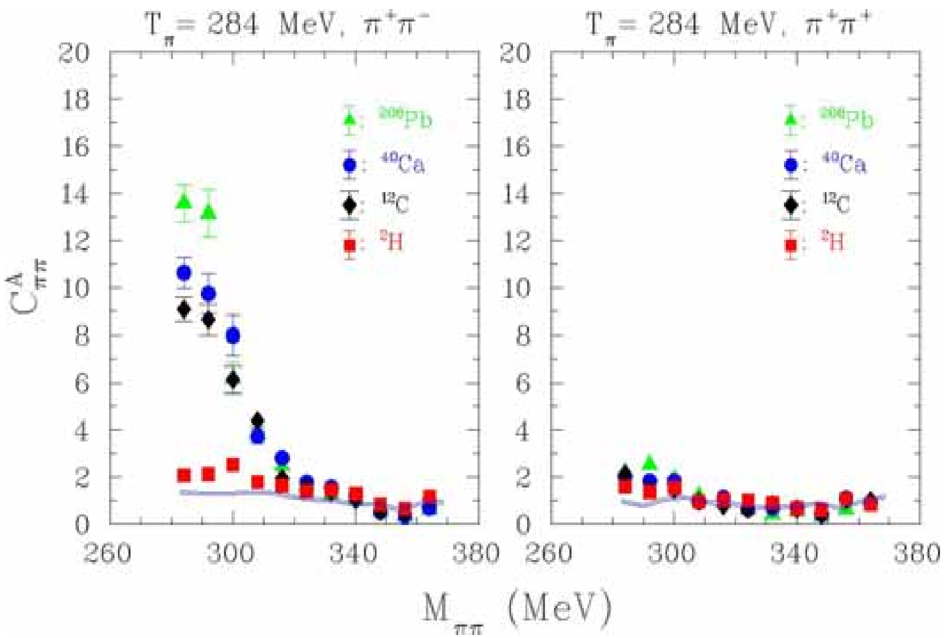
  Crystal Ball, PRL 85 (’00)
- $\gamma A \rightarrow \pi\pi A'$ E_γ=400-460 MeV

  TAPS, PRL 89 (’02)



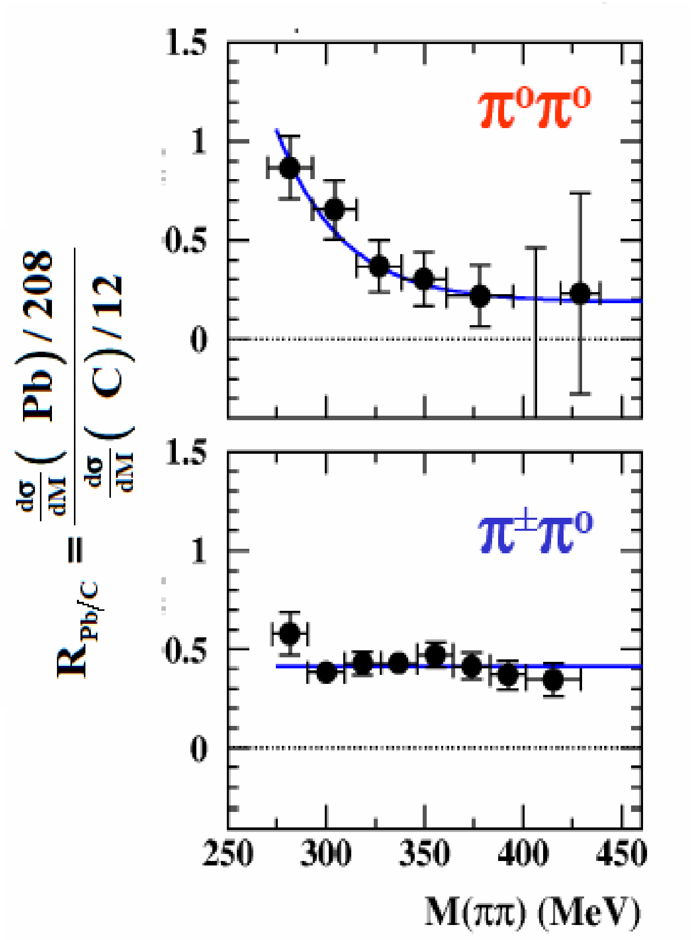
Camerini et al, Phys.Rev.C64 (’01)

CHAOS update

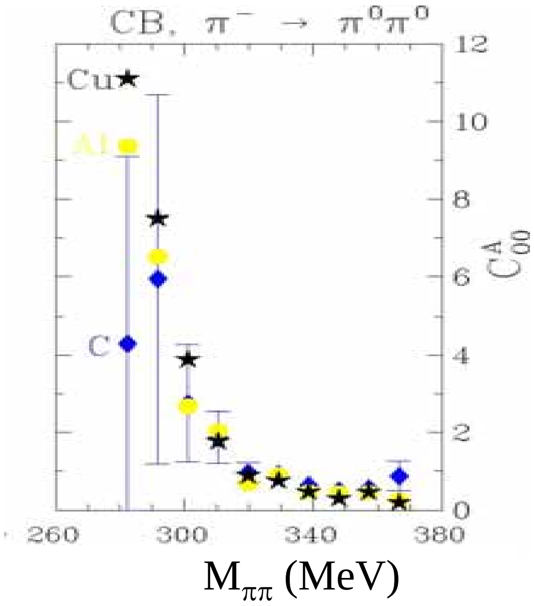


Chiral 05 workshop at RIKEN
http://chiral05.riken.jp/
N. Grion (CHAOS), S. Shadmand (TAPS)

TAPS update



CB update

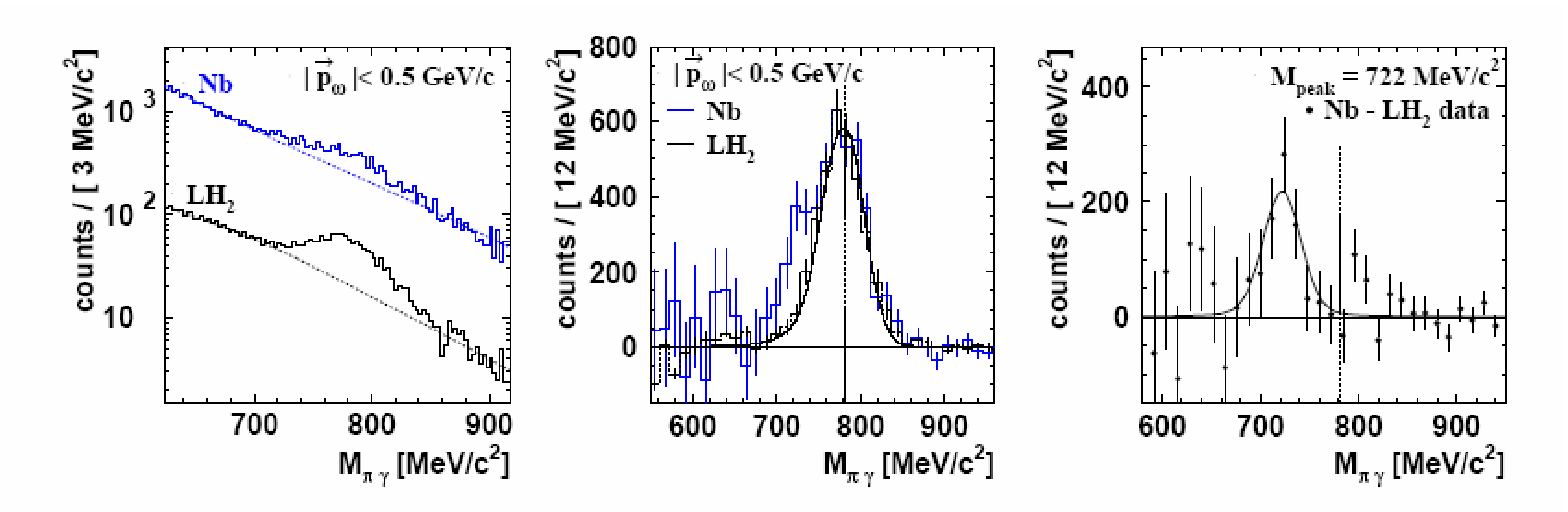


CBELSA/TAPS Collaboration,
“FIRST OBSERVATION OF IN-MEDIUM MODIFICATIONS OF THE OMEGA MESON”, nucl-ex/0504010

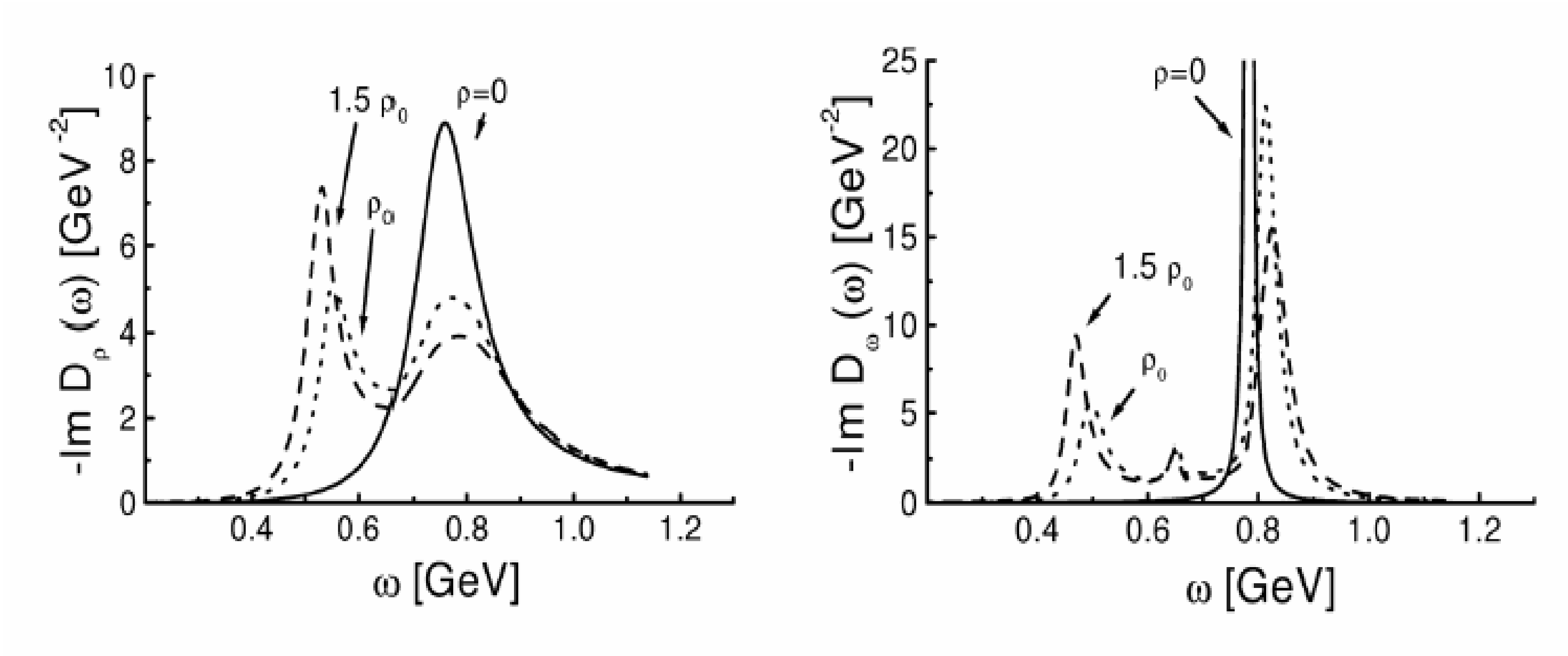
ELSA tagged photon facility in Bonn

$$\gamma + A \rightarrow \omega + X \rightarrow \pi^0\gamma + X'$$

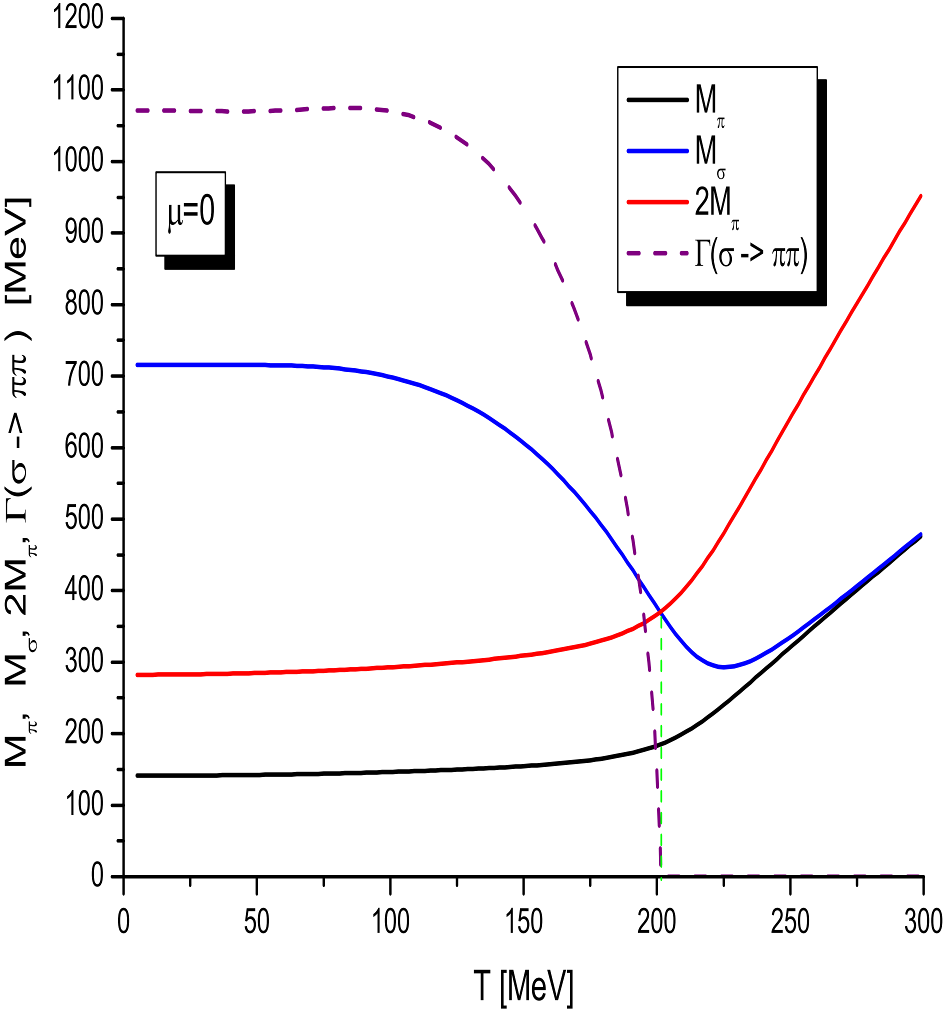
$E\gamma$=0.64-2.53 GeV

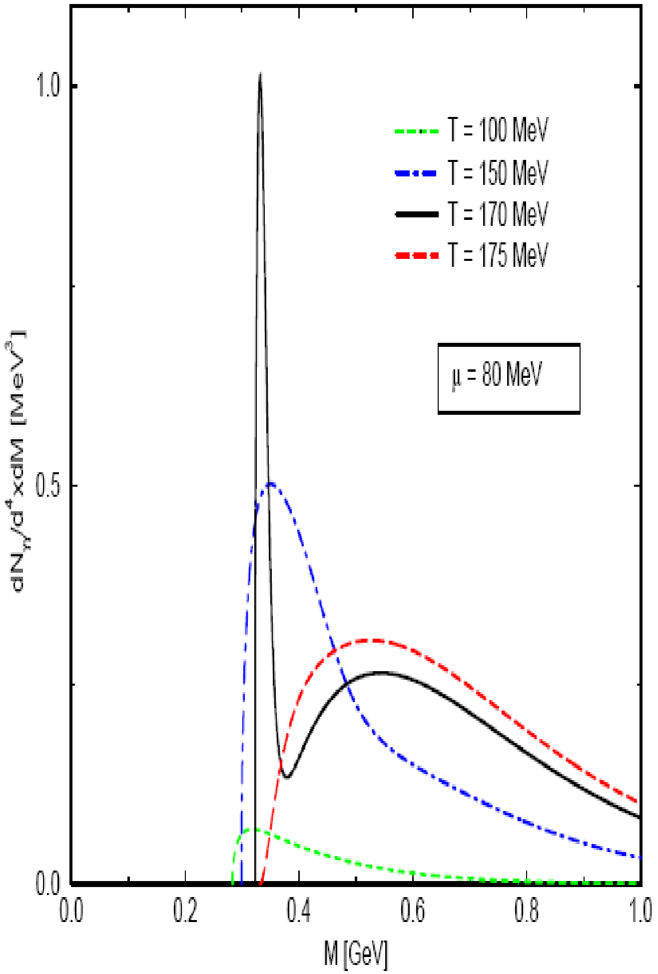


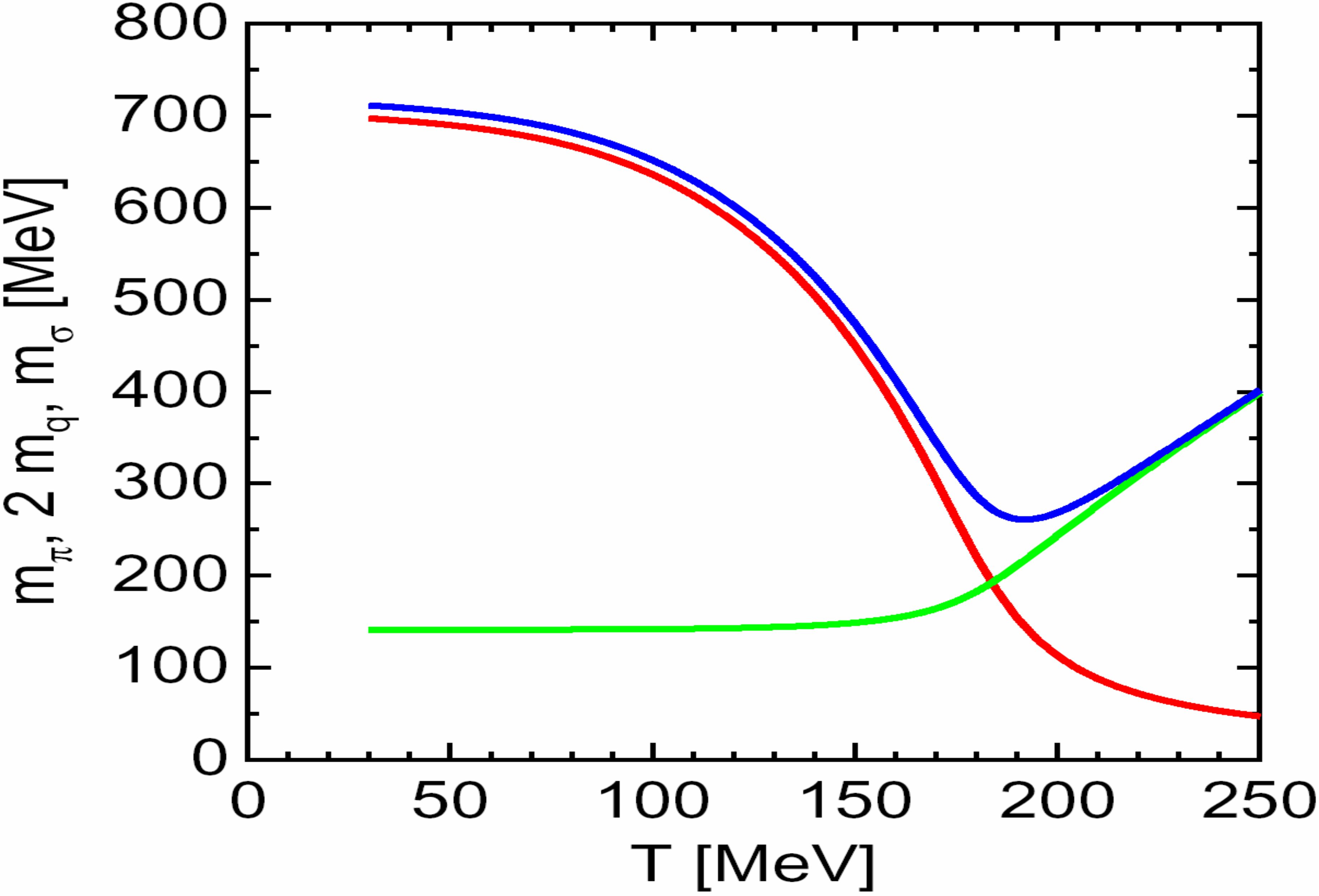
Left panel: Inclusive $\pi^0\gamma$ invariant mass spectra for ω momenta less than 500 MeV/c. Upper histogram: Nb data, lower histogram: LH_2 target reference measurement. The dashed lines indicate fits to the respective background.Center panel: $\pi^0\gamma$ invariant mass for the Nb data (solid histogram) and LH_2 data (dashed histogram) after background subtraction. The error bars show statistical uncertainties only. The solid curve represents the simulated lineshape for the LH_2 target. Right panel: In-medium decays of ω mesons along with a Voigt fit to the data. The vertical line indicates the vacuum ω mass of 782 MeV/c².

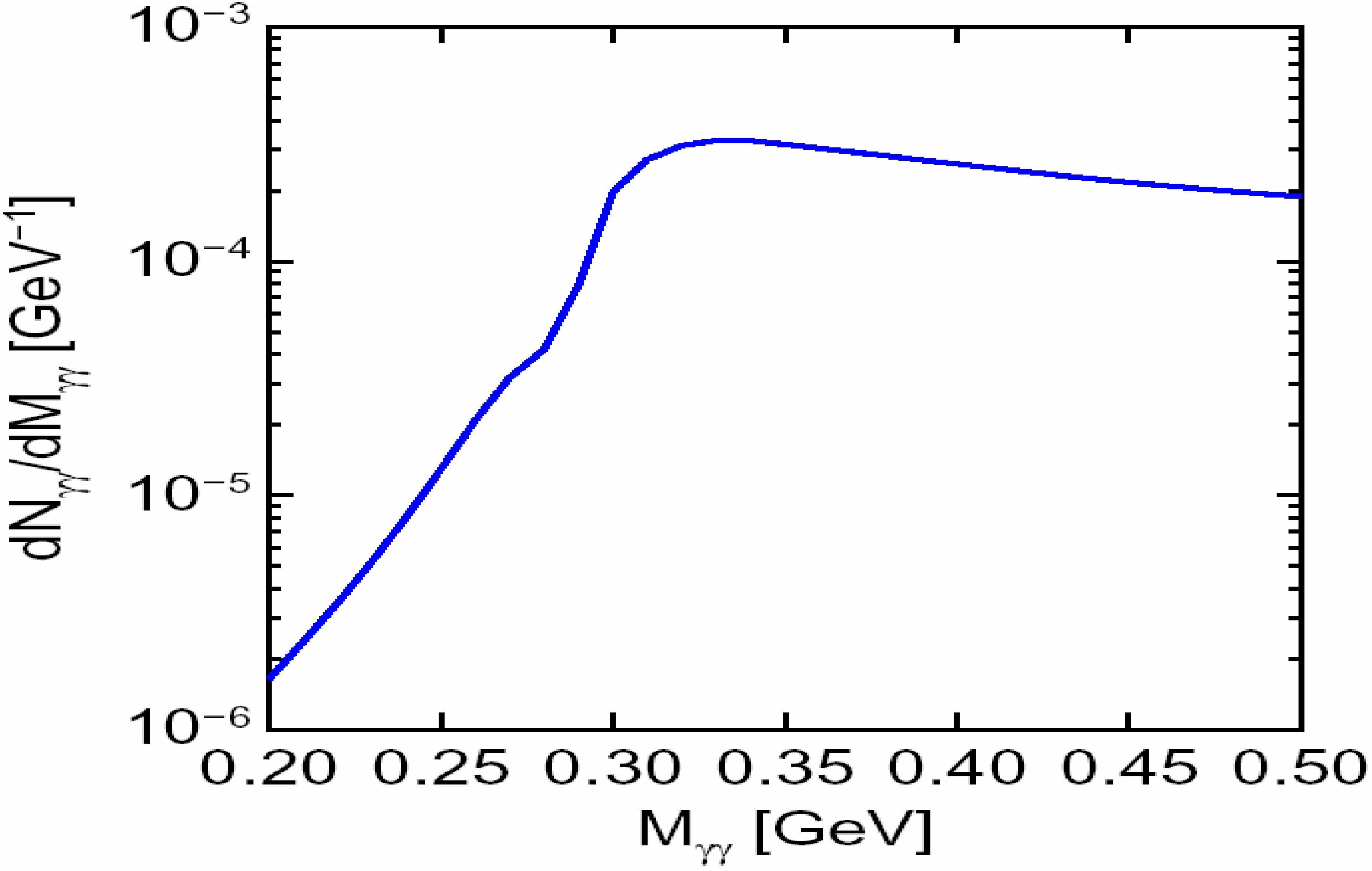


The ρ (left) and ω (right) spectral functions in vacuum and in nuclear matter at densities $\rho = \rho_0$ and $\rho = 1.5\ \rho_0$, obtained in a model that describes meson-nucleon scattering data at energies near the vector meson threshold [B. Friman, M. Lutz and G. Wolf, In Proc. Int. Workshop on Gross Properties of Nuclei and Nuclear Excitations, Hirschegg, Austria, 2000, p. 161]

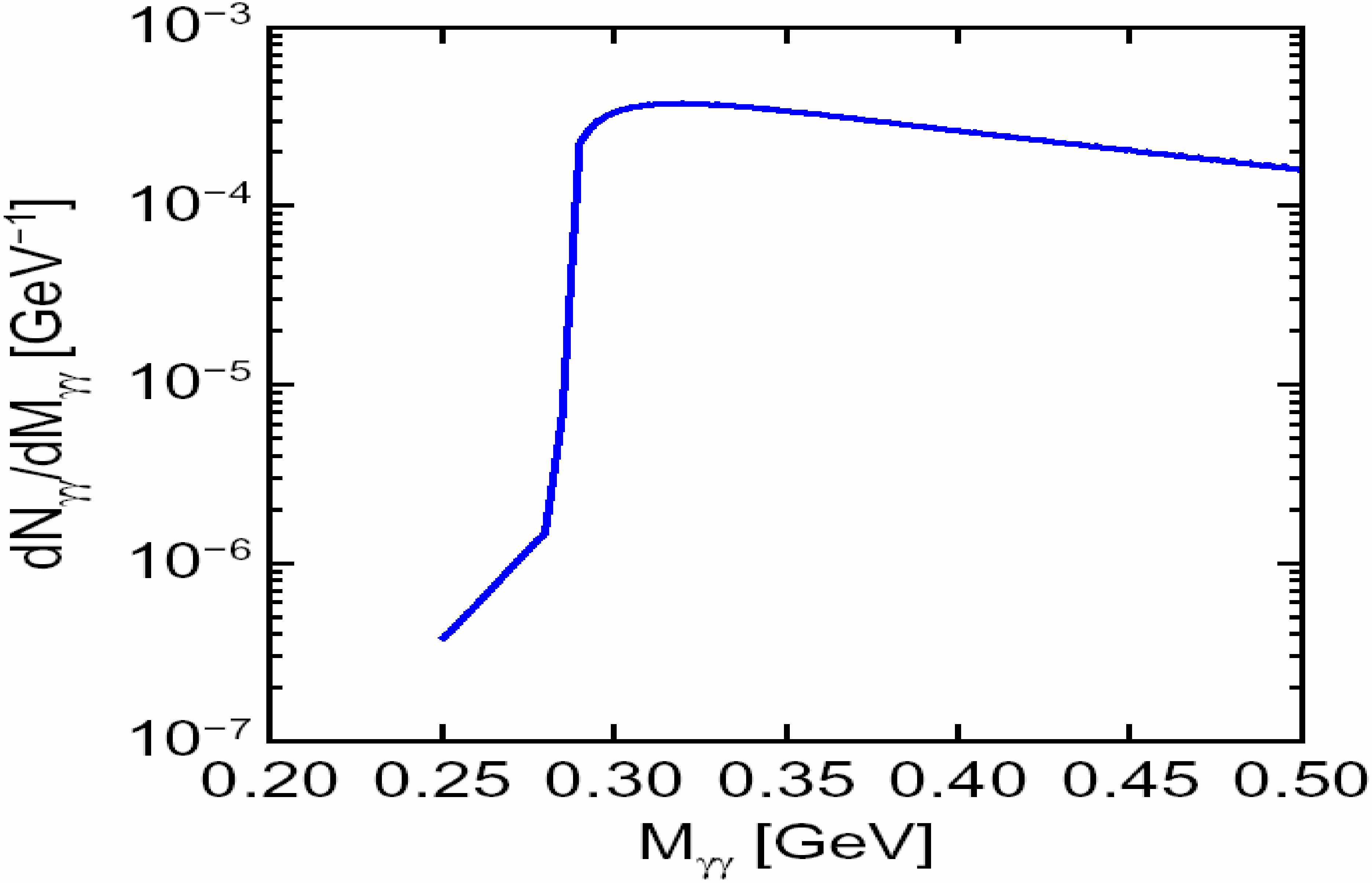

μ=0
M_π
M_σ
$2M_\pi$
$\Gamma(\sigma \to \pi\pi)$
M_π, M_σ, $2M_\pi$, $\Gamma(\sigma \to \pi\pi)$ [MeV]
T [MeV]
0
100
200
300
400
500
600
700
800
900
1000
1100
1200
0
50
100
150
200
250
300


T = 100 MeV
T = 150 MeV
T = 170 MeV
T = 175 MeV
μ = 80 MeV
$dN_{\pi\pi}/d^4x dM$ [MeV^3]
M [GeV]
0.0
0.5
1.0
0.0
0.2
0.4
0.6
0.8
1.0


m_π, 2 m_q, m_σ [MeV]
T [MeV]
0
100
200
300
400
500
600
700
800
0
50
100
150
200
250



sigma → 2γ, π+π- → 2γ,



sigma → 2γ, π+π- → 2γ,

3. Studying the system size, lifetime, freeze-out duration, expansion time in the HBT analysis (noticeable volume expansion is expected if the mixed phase is formed), scanning in atomic number and energy;

The correlation femtoscopy exploits particle correlations at small relative velocities, and is widely used to study space-time characteristics of the production processes (see,e.g., reviews {M.I.Podgoretsky, Sov. J. Part. Nucl. 20 (1989) 266; B. Lorstad, J.Mod.Phys. A4 (1989) 2861;D.H.~Boal et al., Rev. Mod. Phys. 62 (1990) 553;U.A.Wiedemann and U.Heinz, Phys.Rept. 319, 145 (1999);T.Csorgo, Heavy Ion Phys. 15, 1 (2002); R.Lednicky, Phys. At. Nucl. 67 (2004) 72.} Particularly, in heavy ion collisions, two-particle Bose-Einstein interferometry has been used in many sophisticated analyses tracing the dynamical evolution of the hadronic freeze-out hypersurface.

There is substantial experience accumulated in JINR in the field of particle correlations. In particular **{R.Lednicky, V.L.Lyuboshitz, Sov.J.Nucl.Phys. 35 (1982) 770; Proc. CORINNE 90,Nantes, France, 1990 (ed. D.Ardouin, World Scientific, 1990) p. 42; Heavy Ion Physics 3 (1996) 1.}** is one of the pioneering papers calculating the effect of final state interaction on particle correlations, including finite size effects on correlations of nonidentical particles. Also our novel correlation technique **{R.Lednicky, V.L.Lyuboshitz, B.Erazmus, D.Nouais, Phys.Lett. B373 (1996) 30.}** becomes a promising tool for a study of the relative space—time asymmetries in particle production.

4. Analyzing the energy and centrality dependences of the pion, hadron resonances and strange particle multiplicities, and the ratio of their yields, together with the transverse momentum, including K-, K*- and phi-meson spectra as well as manifestation of baryon repulsion effects on hadron abundances.

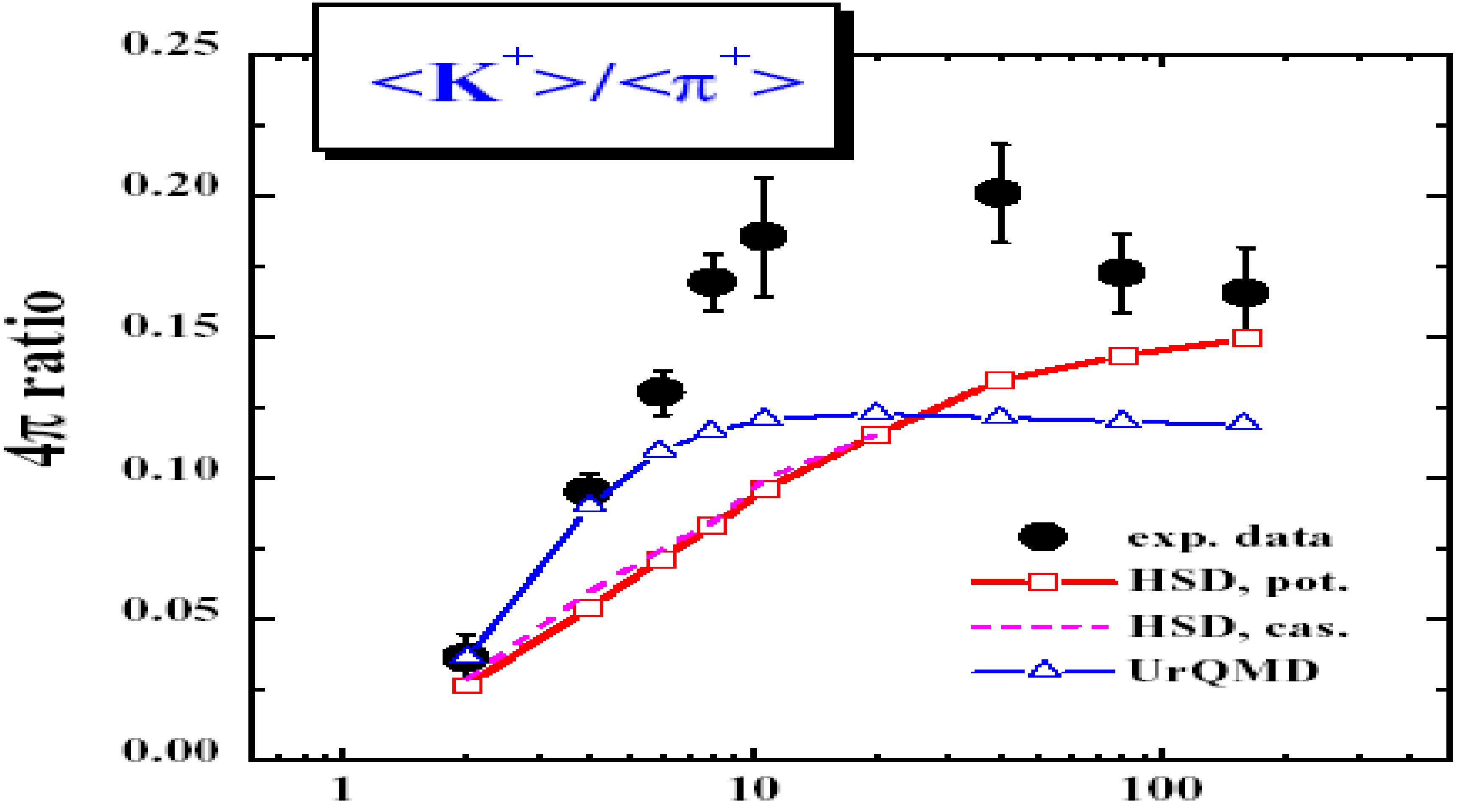
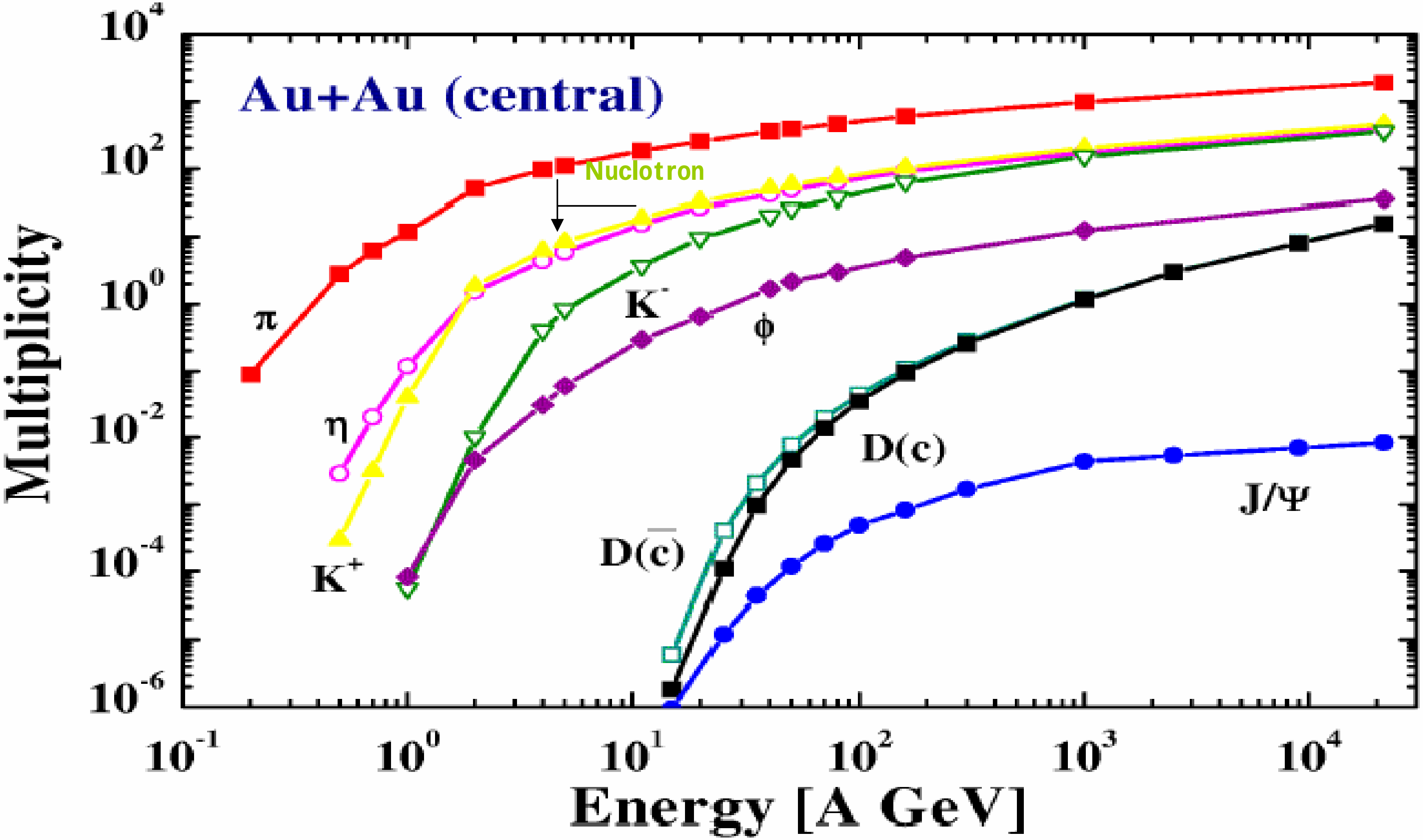


Fig. 6 of the paper nucl-th/0209079



The average number of mesons produced per central Au+Au collision (multiplicity) as function of the incident beam energy. The calculation was performed with the HSD transport code. No in-medium mass modification was taken into account (taken from [W. Cassing, E. Bratkovskaya, A. Sibirtsev, Nucl. Phys. A 691 (2001) 745]).

Hadron Production

$E_{beam} = 5$ AGeV, $Au + Au$, (JINR)

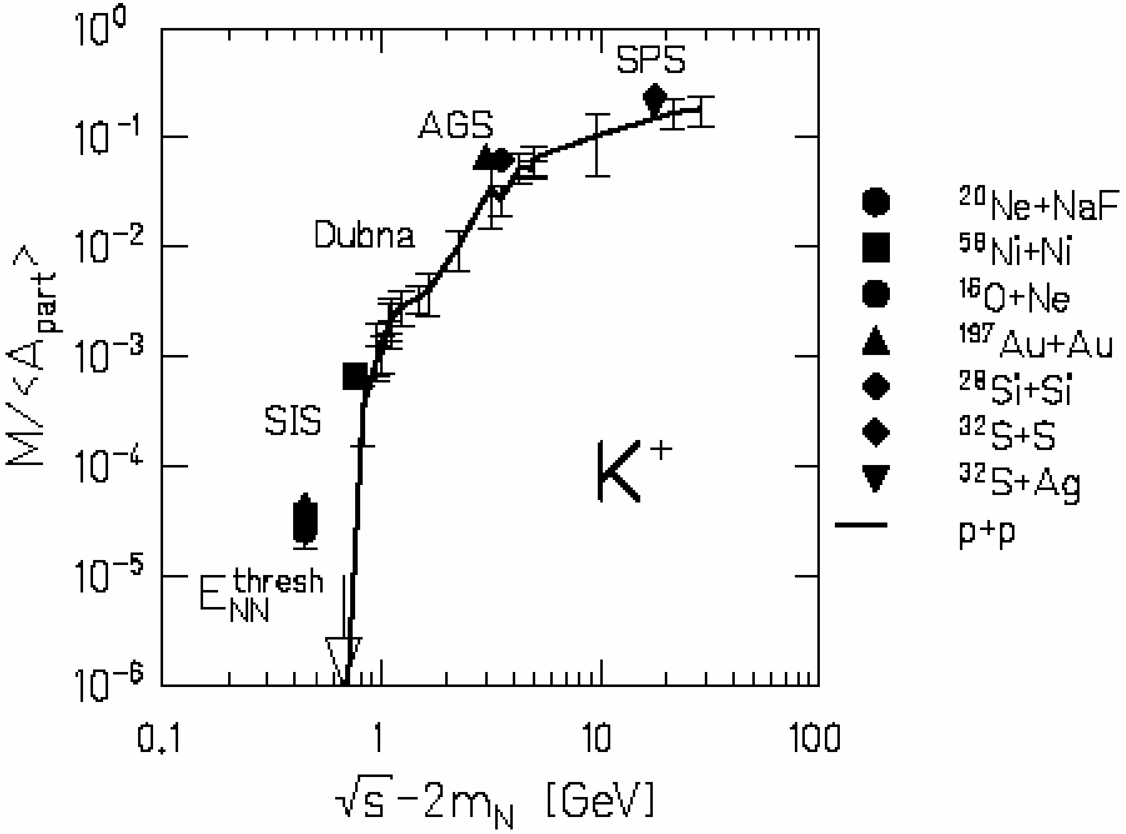
Canonical Strangeness Hadron Gas Model

$S = 0, Q, B = const$

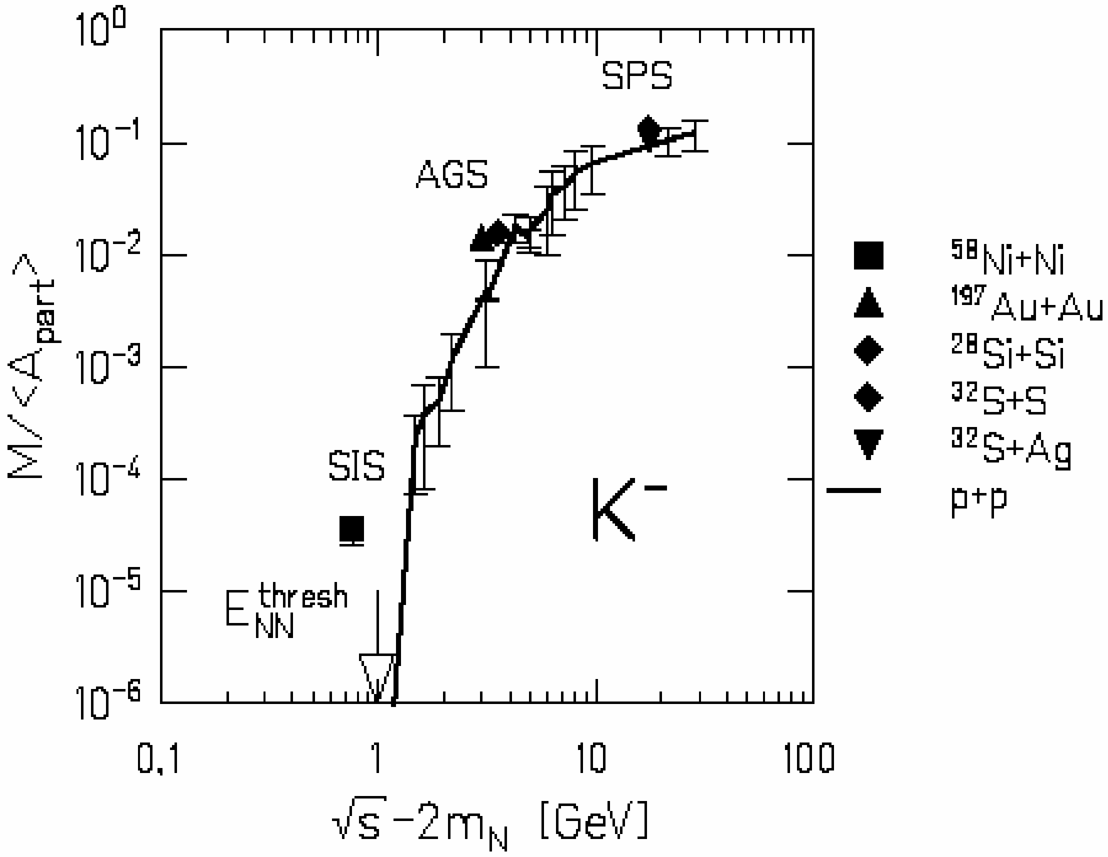
[Toneev & Parvan, J.Phys.G:NPP 31(2005)583]

$\sqrt{s}$,GeV	T,MeV	μ_B,MeV	μ_Q,MeV	V,fm^3
3.575	80.4	693.5	-14.1	9365

K^+/π^+	K^-/π^-	π^-/π^+	K^-/K^+
0.139	0.0071	1.43	0.073
K^+	$K^+_{(prim)}$	K^-	$K^-_{(prim)}$
6.98	6.64	0.51	0.45
π^+	$\pi^+_{(prim)}$	π^-	$\pi^-_{(prim)}$
50.29	31.48	71.78	44.7
$\pi^0_{(prim)}$	$\eta_{(prim)}$	$p_{(prim)}$	$\Delta(1232)_{(prim)}$
38.62	1.02	149.53	50.1



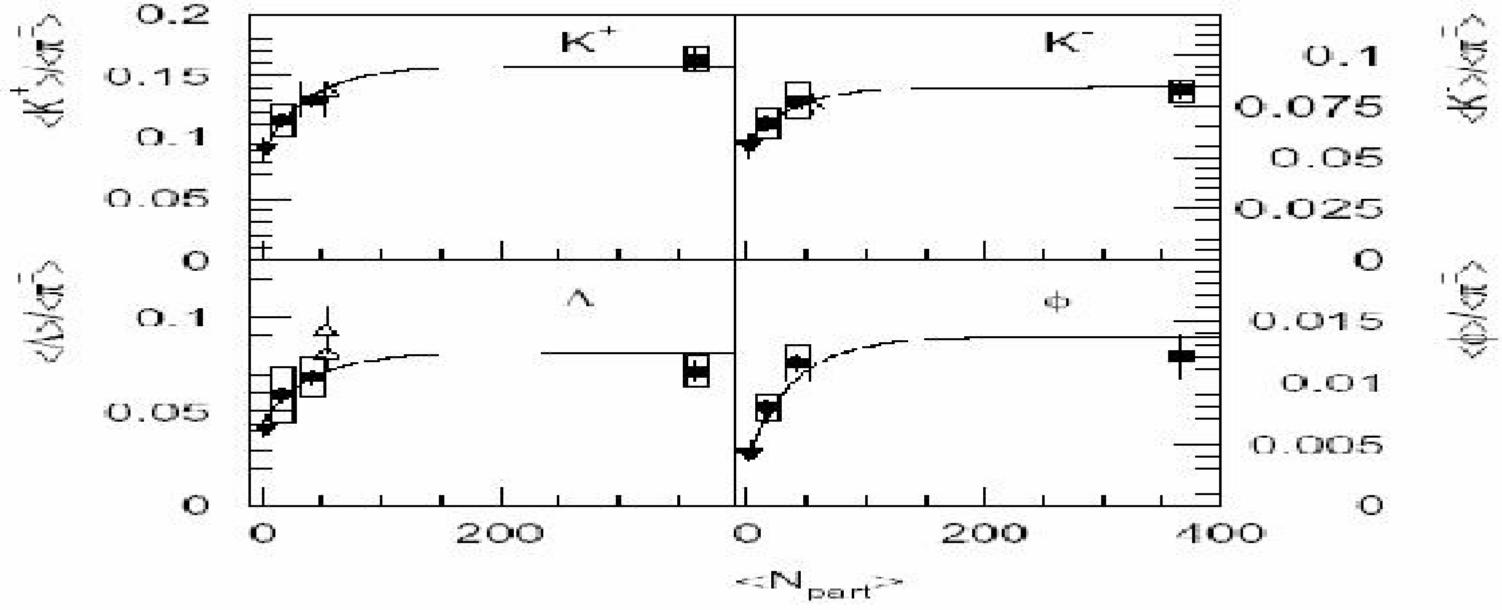
K + multiplicity per average number of participants for A+A (full symbols) and p+p collisions (solid line with error bars) as a function of the energy available in the nucleon-nucleon system. **P. Senger and H. Str¨obele: nucl- ex/ 9810007**



K $^-$ multiplicity per average number of participants for A+A (full symbols) and p+p collisions (solid line with error bars) as a function of the energy available in the nucleon-nucleon system. **P. Senger and H. Str¨obele: nucl- ex/ 9810007**

NA49 Collaboration SPS **Strangness production**

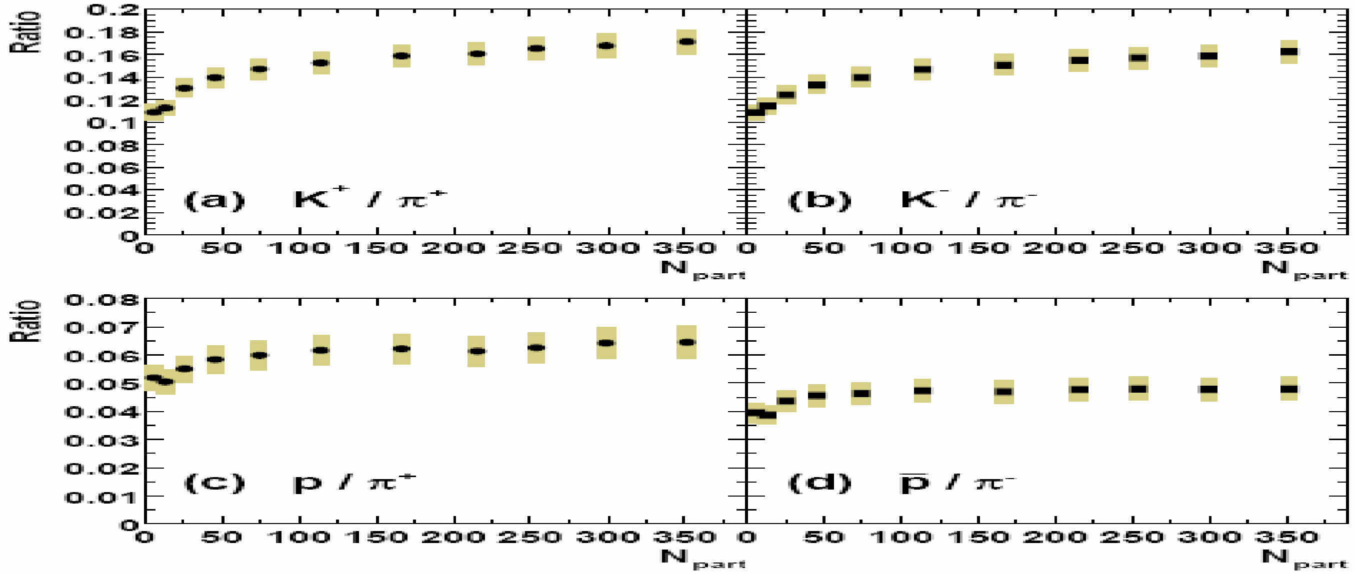
C.Alt, et al, System-size dependence of strangeness production in nucleus-nucleus collisions at $\sqrt{s_{NN}}$=17.3 GeV , Phys.Rev.Lett. 94 (2005) 052301



Experimental ratios of $\langle K^+\rangle$,$\langle K^-\rangle$,φ, and Λ to $\langle\pi^\pm\rangle$ plotted as a function of system size (▼ p+p, C+C and Si+Si, ● S+S, ■ Pb+Pb).Statistical errors are shown as error bars,systematic errors if available as rectangular boxes.The curves are shown to guide the eye and represent a functional form a - b exp($-\langle N_{part}\rangle$ /40). At $\langle N_{part}\rangle$=60 they rise to about 80%of the difference of the ratios between N_{part} =2 and 400.

RHIC

Phenix Collaboration



Centrality dependence of particle production ratios for

(a) $K+/\pi+$,

(b) $K-/\pi-$,

(c) $p/\pi+$, and

(d) antip$/\pi-$

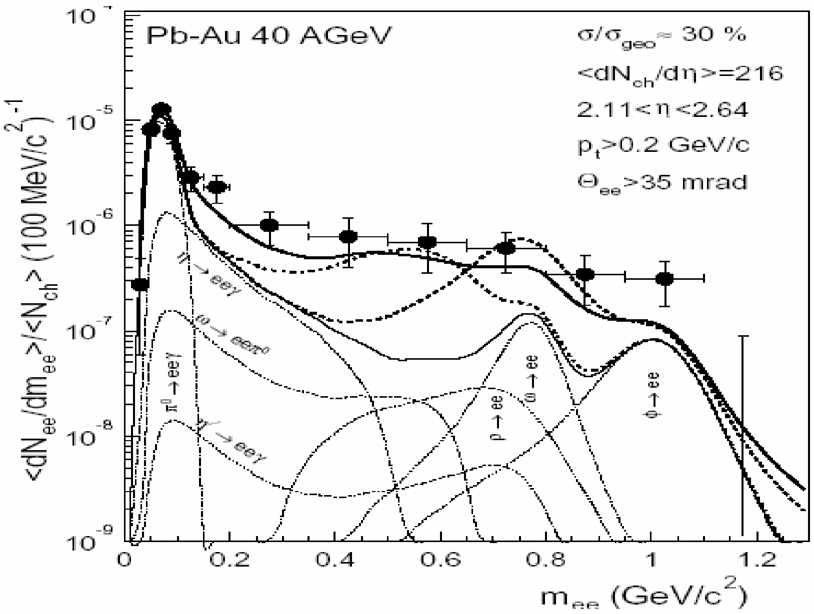
in Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV

[S. S. Adler, et al., Phys. Rev. Lett. 91 (2003) 182301.].

5. Studying di-leptons (electron and muon pairs) production (in-medium modification of hadron properties at high baryon densities)

CERN SPS Colloboration: D.Adamova´ et al., Enhanced Production of Low-Mass Electron-Positron Pairs in 40 AGeV Pb-Au Collisions at the CERES/NA45 experiment, nucl-ex/0209024.

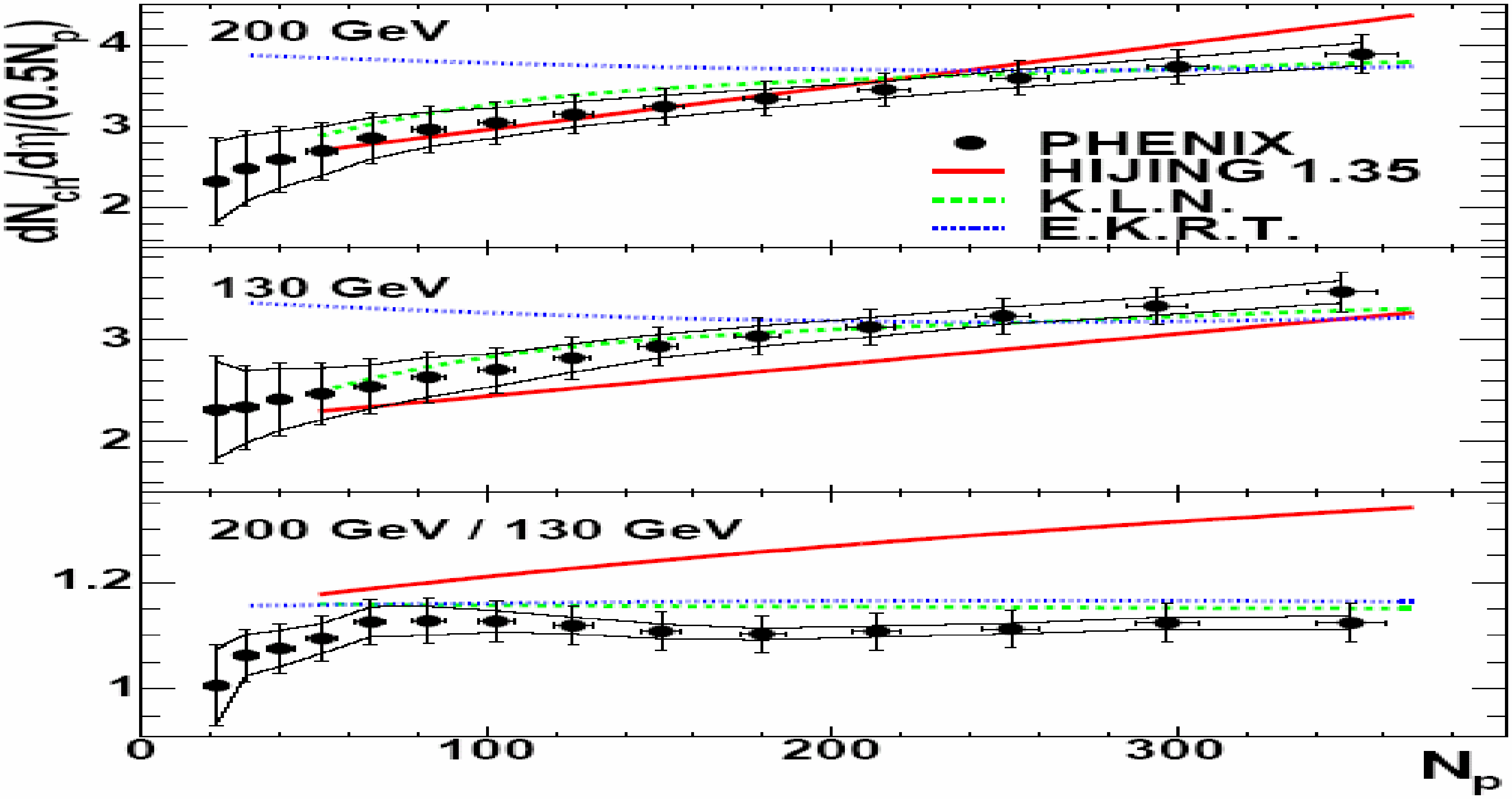
Measurements of low-mass electron-positron pairs in Pb-Au collisions at the SPS beam energy of 40 AGeV. The pair yield integrated over the range of invariant masses $0.2<m \leq .1$ GeV/c^2 is enhanced over the expectation from neutral meson decays by a factor of 5.9 ± 1.5(stat.) $\pm$ 1.2(syst. data) $\pm$ 1.8(syst. meson decays), somewhat larger than previously observed at the higher energy of 158 AGeV. It may be linked to chiral symmetry restoration and support the notion that the in-medium modifications of the ρ are more driven by baryon density than by temperature.



Inclusive e^+e^- mass spectrum, compared to the hadron decay cocktail (thin solid; individual contributions thin dotted) and to theoretical model calculations based on $\pi^+\pi^-$ annihilation with an unmodified ρ (thick dashed), an in-medium dropping mass ρ (thick dashed-dotted) and an in-medium spread ρ width (thick solid). The model calculations contain the cocktail, but without the ρ to avoid double counting. The low-mass tail of the cocktail ρ is due to the inclusion of a $\pi^+\pi^-$phase space correction. The (weaker) tails of the ω and φ are caused by electron bremsstrahlung.

Centrality experiments

Studying a dependence of characteristics of nuclear-nuclear interactions on the centrality is an important experimental way of obtaining information on phases of strongly interacting matter formed during the collision evolution. It is expected that new structures - changes in the behaviour, will show up in these characteristics due to phase transitions.



Multiplicity per participant nucleon pair, as a function of the centrality, for $\sqrt{s_{NN}}$ =130 GeV and 200 GeV Au+Au collisions as measured in PHENIX (A. Bazilevsky, Nucl. Phys. A715 (2003) 486).

Suggestions

1. π+π- → 2γ,
   our estimates at the Nuclotron energy:
   π+π- → 2γ / background = 10^{-4} -- 10^{-5}.

   Example (WA80, SPS CERN): S+Au, 200 GeV/nucl.,

   eta → 2γ / background = 7 10^{-4}.

Our task to observe (π+π- → 2γ)-signal is a more complicated problem.

2. Statistical fluctuations in relativistic systems. It seems that the JINR Nuclotron is a unique possibility to investigate this problem: we will create a statistical relativistic system and all its particles can be detected event-by-event!

3. For these investigations we will need a very high statistics. This can give us a possibility to observe the productions of very rare particles (for example, threshold and sub-threshold production of multistrange baryons with uss-, dss-, sss-quark content).

Preliminary Collaboration

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Collaboration, suggestions, and remarks are welcome!