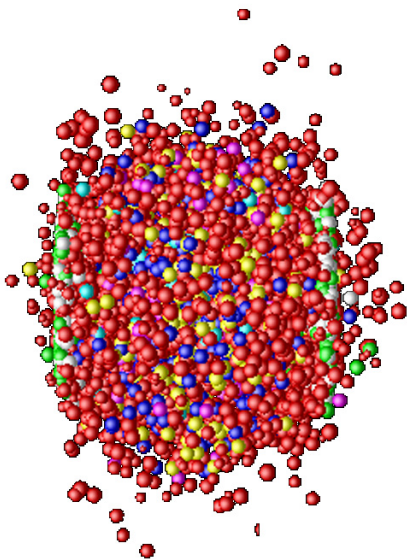


PHSD transport calculations

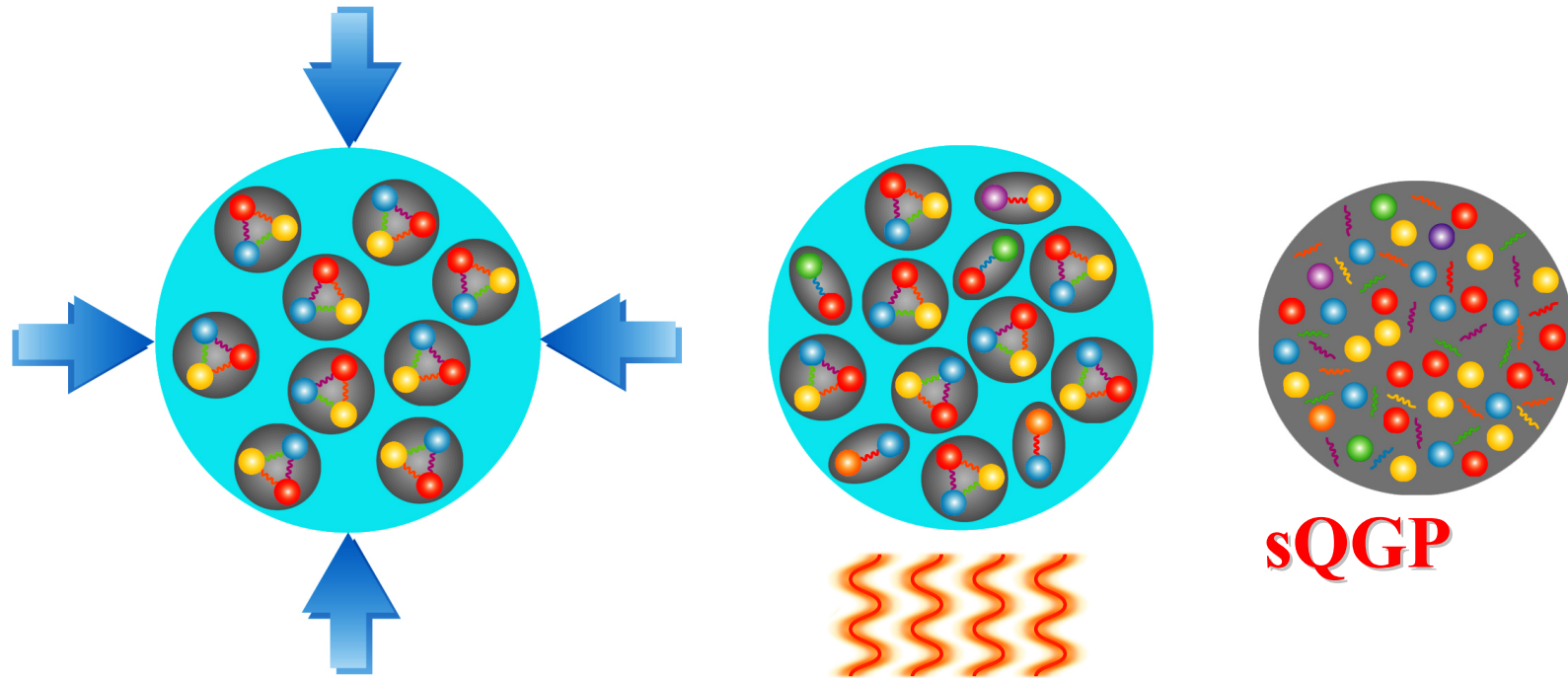
Wolfgang Cassing

Elena Bratkovskaya
ITP Frankfurt

GSI 09.03.2009



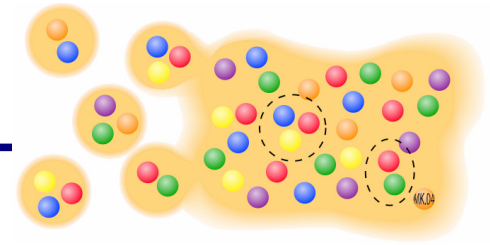
Compressing and heating hadronic matter:



Questions:

- What are the **transport properties** of the **sQGP**?
- How may the **hadronization** (partons \rightarrow hadrons) occur?

From hadrons to partons



In order to study of the **phase transition** from hadronic to partonic matter – **Quark-Gluon-Plasma** – we need a **consistent dynamical description with**

- explicit **parton-parton interactions** (i.e. between quarks and gluons)
- explicit **phase transition** from hadronic to partonic degrees of freedom
- **QCD equation of state (EoS)** for the partonic phase

Transport theory: off-shell Kadanoff-Baym equations for the Green-functions $G_h^<(x,p)$ in phase-space representation for the **partonic** and **hadronic** phase



Parton-Hadron-String-Dynamics (PHSD)

QGP phase described by input from the

Dynamical QuasiParticle Model (DQPM)



The Dynamical QuasiParticle Model (DQPM)

Spectral functions for **partonic degrees of freedom** (g, q, q_{bar}):

$$\rho(\omega) = \frac{\gamma}{E} \left(\frac{1}{(\omega - E)^2 + \gamma^2} - \frac{1}{(\omega + E)^2 + \gamma^2} \right)$$

gluon mass:
$$M^2(T) = \frac{g^2}{6} \left((N_c + \frac{1}{2}N_f) T^2 + \frac{N_c}{2} \sum_q \frac{\mu_q^2}{\pi^2} \right)$$

quark mass:
$$\gamma_g(T) = N_c \frac{g^2 T}{4\pi} \ln \frac{c}{g^2} \quad N_c = 3$$

quark width:
$$\mathcal{J}^d(\mathbf{L}) = \frac{\mathcal{J}M^c}{M_s^c - \int \mathcal{G}_s \mathbf{L}} \int \mathcal{W} \frac{\mathcal{G}_s}{c}$$

with $E^2(\mathbf{p}) = \mathbf{p}^2 + M^2 - \gamma^2$

Peshier, PRD 70 (2004) 034016;
 Peshier, Cassing, PRL 94 (2005) 172301;
 Cassing, NPA 791 (2007) 365; NPA 793 (2007)

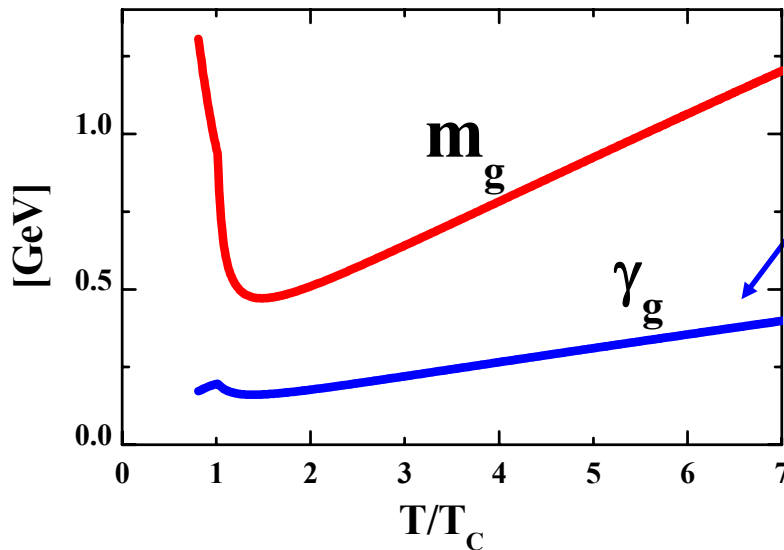
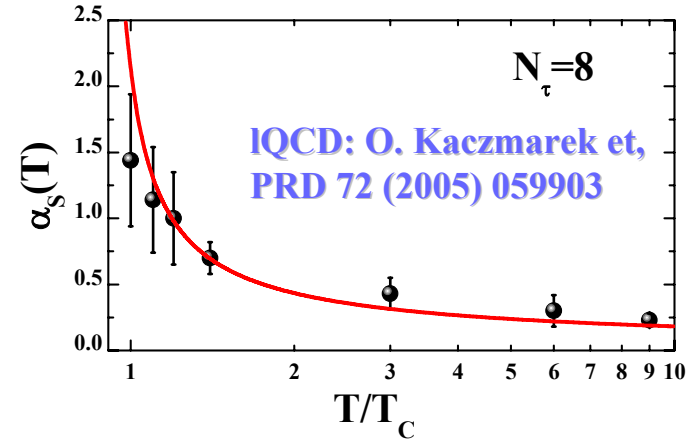
The running coupling g^2

$$g^2(T/T_c) = \frac{48\pi^2}{(11N_c - 2N_f) \ln(\lambda^2(T/T_c - T_s/T_c)^2)}$$

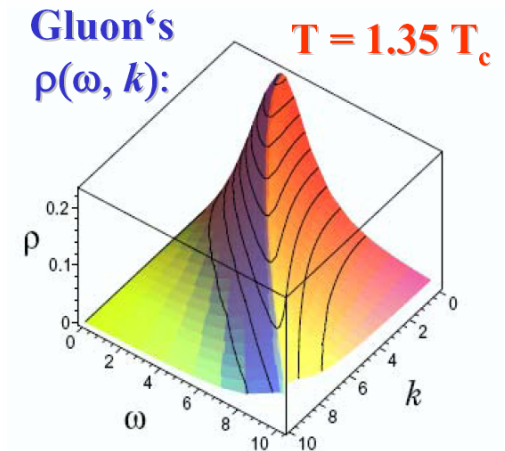
3 parameters: $T_s/T_c=0.46$; $c=28.8$; $\lambda=2.42$

fit to lattice (IQCD) entropy density:

→ quasiparticle properties ($N_f=3$; $T_c = 0.185$ GeV)



large width for
gluons
(and quarks)!



DQPM thermodynamics ($N_f=3$)

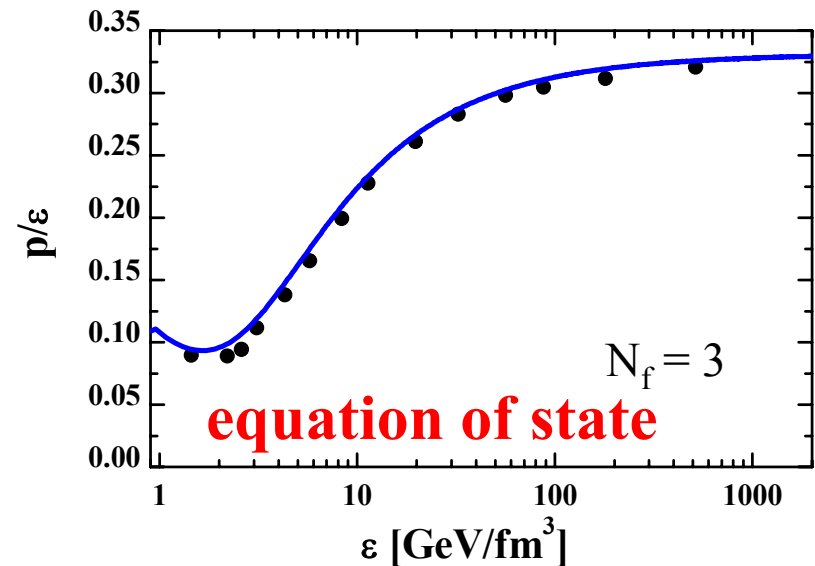
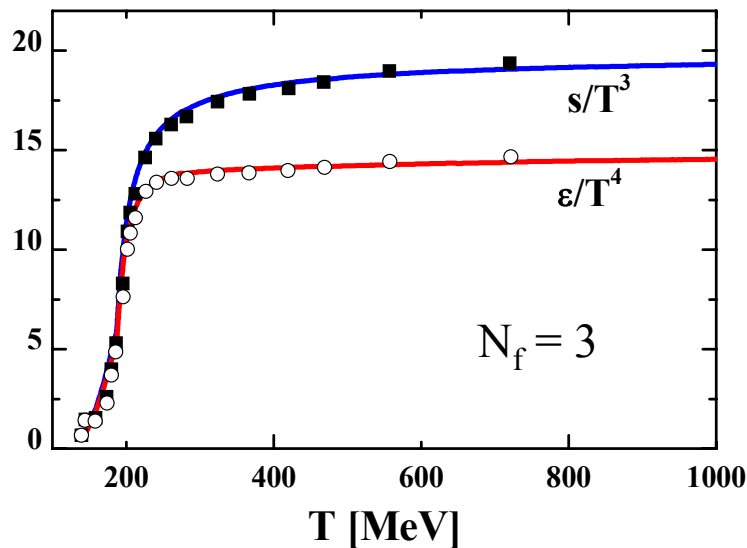
Thermodynamics: entropy $s = \frac{\partial P}{\partial T}$ \rightarrow pressure P

energy density: $\epsilon = Ts - P$

interaction measure:

$$W(T) := \epsilon(T) - 3P(T) = Ts - 4P$$

IQCD: M. Cheng et al.,
PRD 77 (2008) 014511



cf. V. D. Toneev, Heavy Ion Phys. 8 (1998) 83

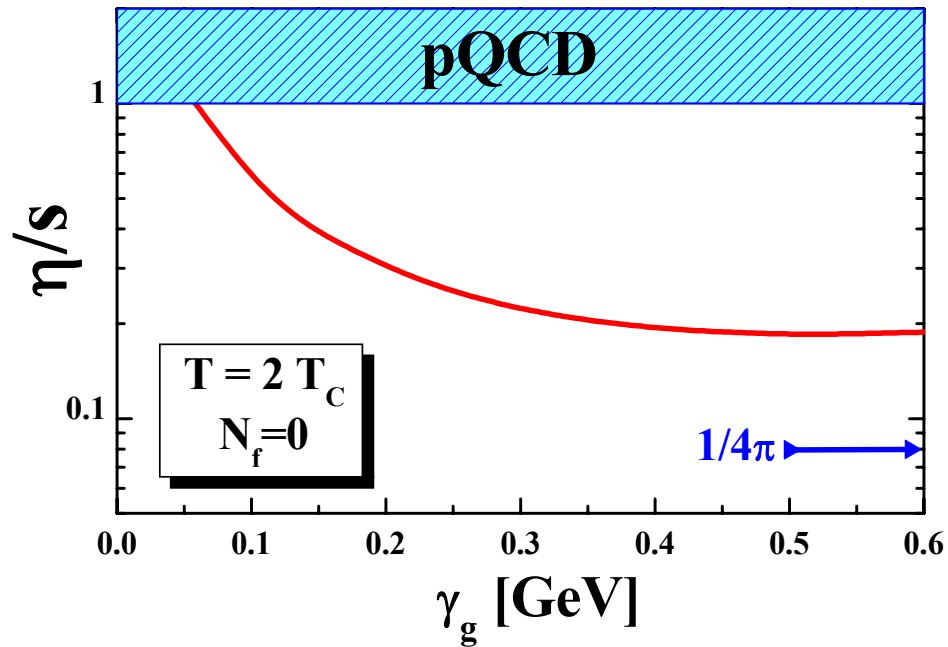
DQPM gives a ,perfect‘ description of IQCD results !

Transport properties of hot glue

Why do we need broad quasiparticles?

viscosity ratio to entropy density:

$$\eta^{\text{DQP}} = -\frac{d_g}{60} \int \frac{d\omega}{2\pi} \frac{d^3 p}{(2\pi)^3} \frac{\partial n}{\partial \omega} \rho^2(\omega) [7\omega^4 - 10\omega^2 p^2 + 7p^4].$$



→ otherwise η/s will be too high!

Time-like and space-like quantities

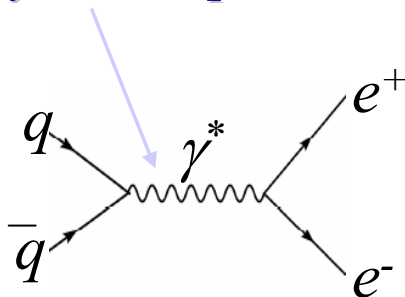
some short-hand notations (useful for all single-particle quantities):

$$\tilde{\text{Tr}}_{\mathbf{g}}^{\pm} \dots = d_{\mathbf{g}} \int \frac{d\omega}{2\pi} \frac{d^3 p}{(2\pi)^3} 2\omega \rho_{\mathbf{g}}(\omega) \Theta(\omega) n_{\text{B}}(\omega/T) \Theta(\pm P^2) \dots \quad \text{gluons}$$

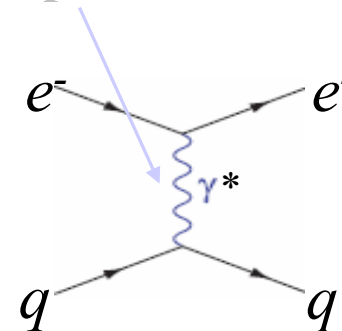
$$\tilde{\text{Tr}}_q^{\pm} \dots = d_q \int \frac{d\omega}{2\pi} \frac{d^3 p}{(2\pi)^3} 2\omega \rho_q(\omega) \Theta(\omega) n_{\text{F}}((\omega - \mu_q)/T) \Theta(\pm P^2) \dots \quad \text{quarks}$$

$$\tilde{\text{Tr}}_{\bar{q}}^{\pm} \dots = d_{\bar{q}} \int \frac{d\omega}{2\pi} \frac{d^3 p}{(2\pi)^3} 2\omega \rho_{\bar{q}}(\omega) \Theta(\omega) n_{\text{F}}((\omega + \mu_q)/T) \Theta(\pm P^2) \dots \quad \text{antiquarks}$$

Time-like: $\Theta(+P^2)$: particles may decay to real particles or interact

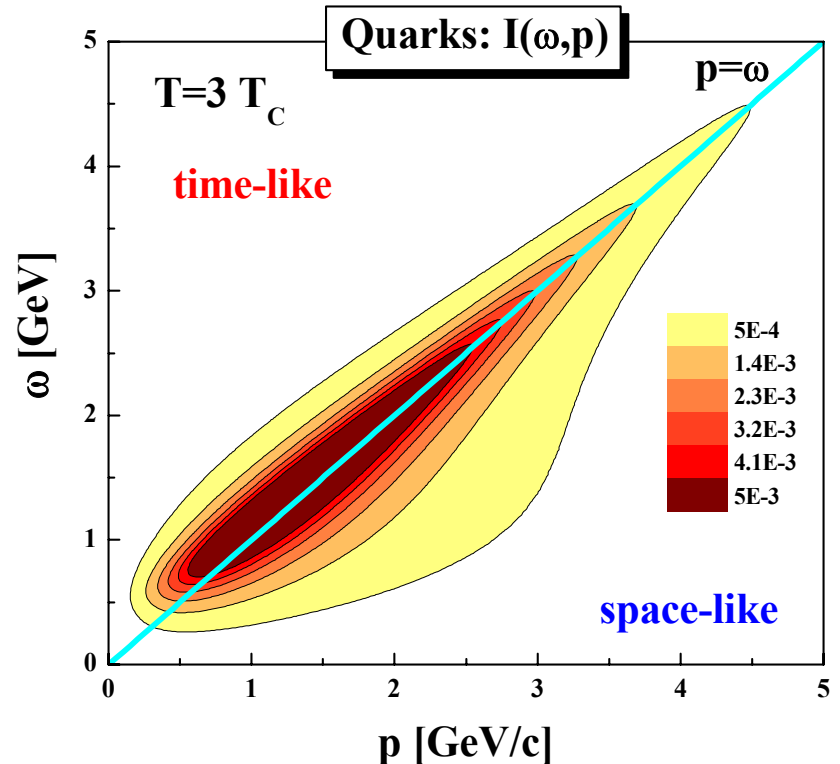
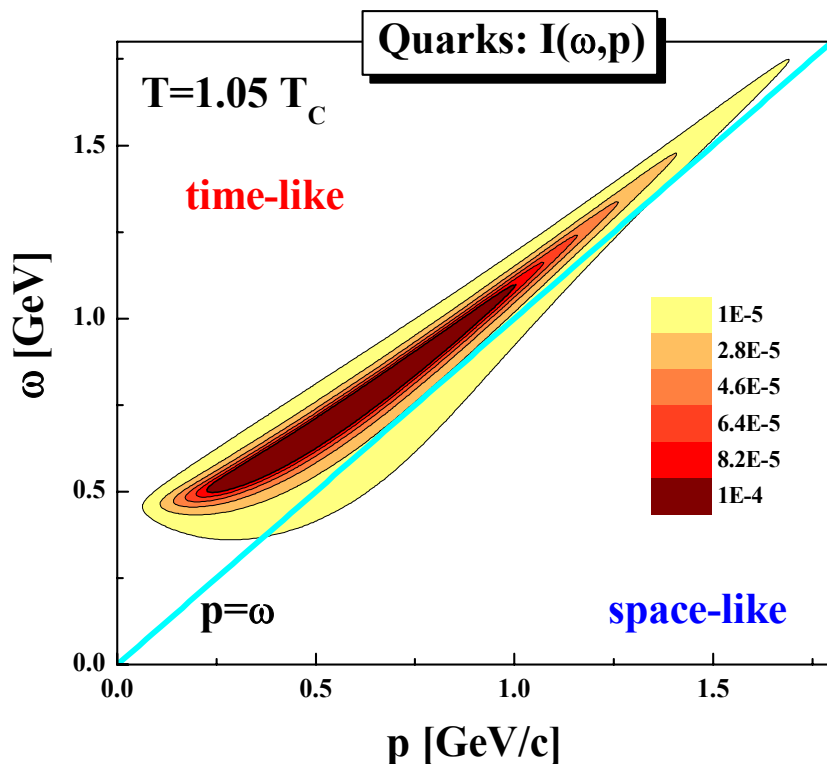


Space-like: $\Theta(-P^2)$: particles are virtual and appear as exchange quanta in interaction processes of real particles



Differential quark ,density‘

Example:
$$I(\omega, p) = \frac{d_q}{2\pi^3} p^2 \omega \rho(\omega, p^2) n_F((\omega - \mu_q)/T)$$



→ **Large space-like contributions for broad quasiparticles !**

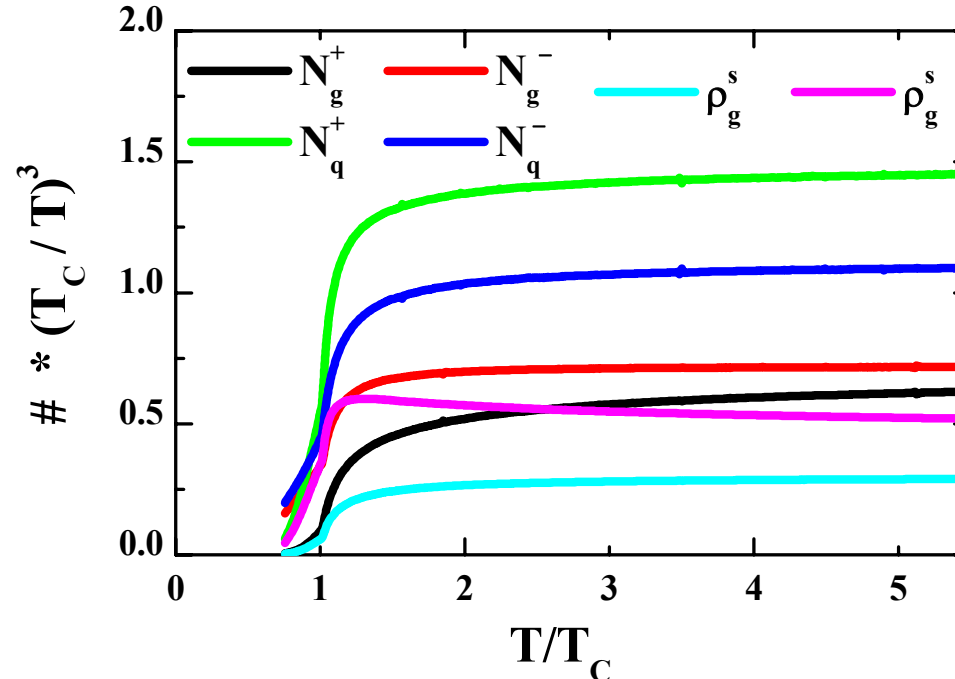
Time-like and 'space-like' densities

'densities':

$$N_g^\pm(T) = \tilde{T}r_g^\pm 1, \quad N_q^\pm(T) = \tilde{T}r_q^\pm 1, \quad N_{\bar{q}}^\pm(T) = \tilde{T}r_{\bar{q}}^\pm 1$$

scalar densities:

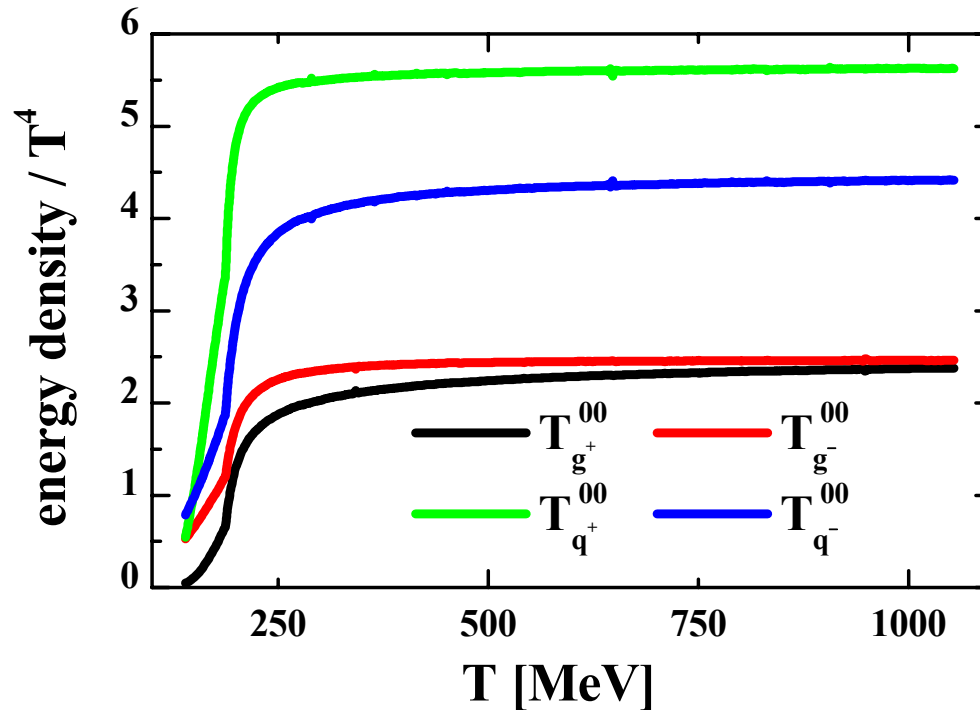
$$N_g^s(T) = \tilde{T}r_g^+ \left(\frac{\sqrt{P^2}}{\omega} \right), \quad N_q^s(T) = \tilde{T}r_q^+ \left(\frac{\sqrt{P^2}}{\omega} \right), \quad N_{\bar{q}}^s(T) = \tilde{T}r_{\bar{q}}^+ \left(\frac{\sqrt{P^2}}{\omega} \right)$$



→ more virtuell (space-like) than time-like gluons
but more time-like than virtuell quarks !

Time-like and 'space-like' energy densities

$$T_{00,x}^{\pm}(T) = \tilde{T}_{r_x^{\pm}} \omega \quad \mathbf{x}: \text{gluons, quarks, antiquarks}$$



→ space-like energy density dominates for gluons;

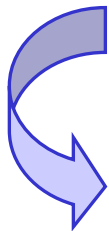
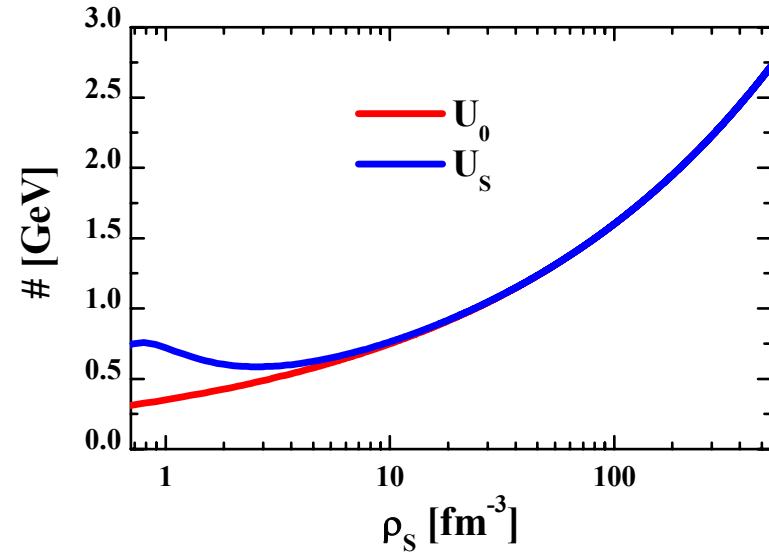
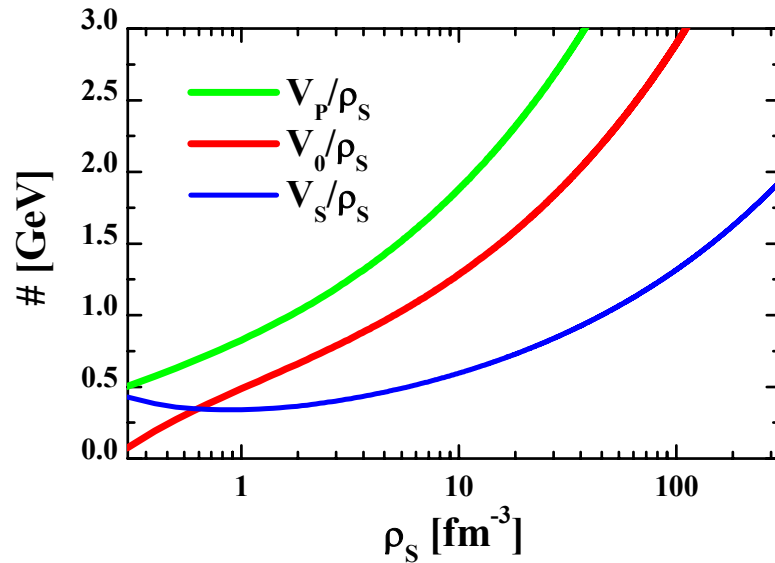
→ space-like parts are identified with potential energy densities!

Potential energy versus scalar parton density

potential energy: $V := T_{00,g}^- + T_{00,q}^- + T_{00,\bar{q}}^- = \tilde{V}_{gg} + \tilde{V}_{qq} + \tilde{V}_{qg}$

$\mathbf{P} = \langle \mathbf{P}_{xx} \rangle - V_s + V_0$

$\epsilon = \langle p_0 \rangle + V_s + V_0$



mean fields: $U_s = dV_s/d\rho_s$ $U_0 = dV_0/d\rho_0$ **→ PHSD**

Summary of part I

- **The dynamical quasiparticle model (DQPM) well matches IQCD (with only 3 parameters) !**
- **DQPM allows to extrapolate to finite quark chemical potentials**
- **DQPM separates lime-like quantities from space-like (interaction) regions (needed for off-shell transport)**
- **DQPM provides mean-fields for gluons and quarks as well as effective 2-body interactions → PHSD**

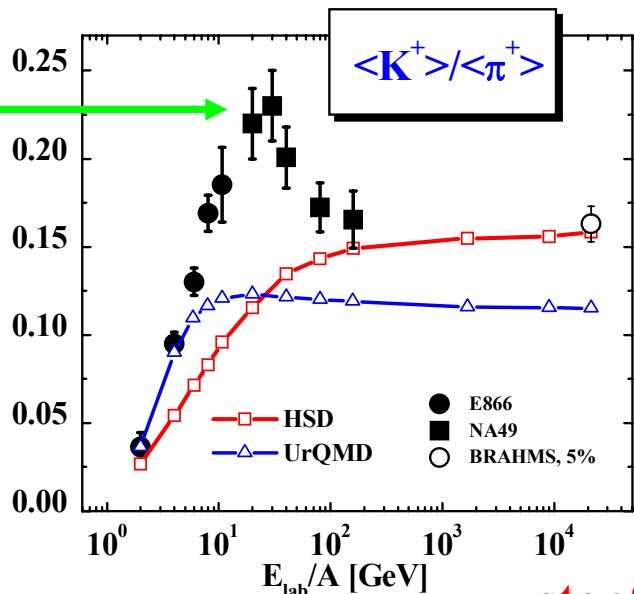


Hadron-string transport models versus observables: the actual problem

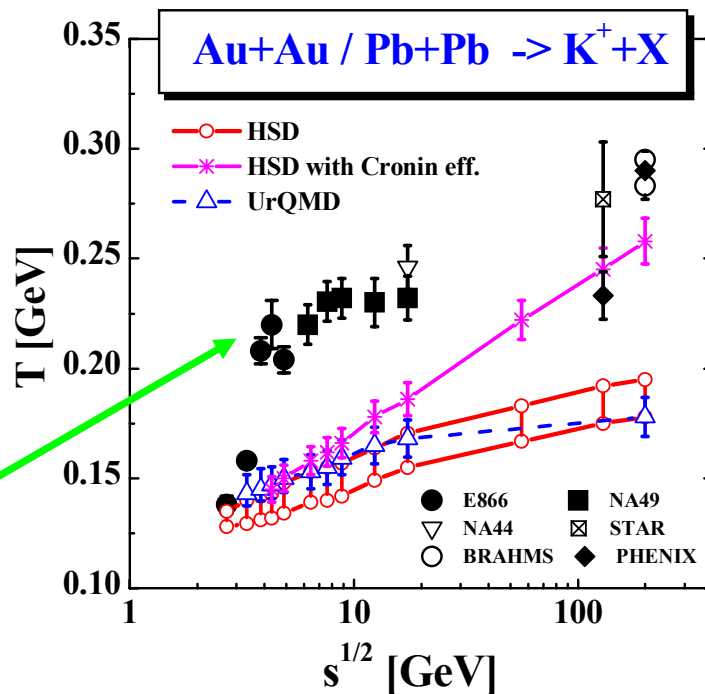
Strangeness signals of the QGP

E.B. et al., PRC69 (2004) 054907

,horn' in K^+/π^+



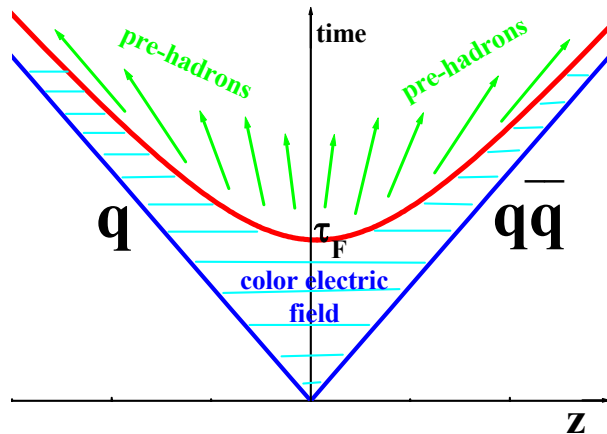
,step' in slope T



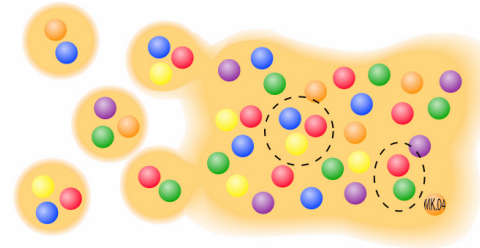
Exp. data are not reproduced in terms of the hadron-string picture
 \Rightarrow evidence for nonhadronic degrees of freedom !? \rightarrow PHSD ?

I. PHSD: basic concepts

1. Initial A+A collisions – off-shell HSD: string formation and decay to pre-hadrons

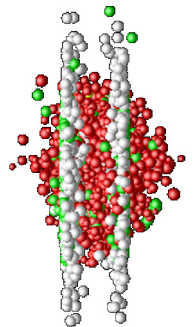
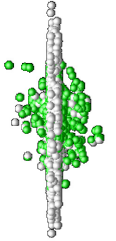


Strings – excited color singlet states
($qq - q$) or ($q - q\bar{q}$)
(in HSD: pre-hadrons = hadrons under
formation time $\tau_F \sim 0.8 \text{ fm}/c$)

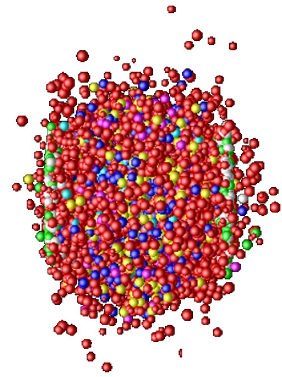


2. Fragmentation of pre-hadrons into quarks:

dissolve all new produced secondary hadrons to **partons** (and
attribute a random color **c**) using the spectral functions from the
Dynamical QuasiParticle Model (DQPM) approximation to lQCD
-- 4-momentum, flavor and color conservation --



II. PHSD: partonic phase



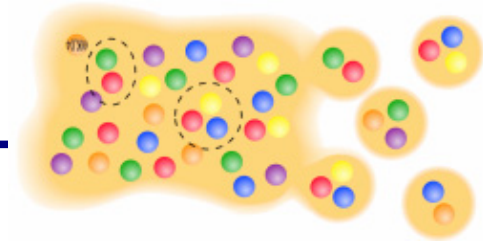
3. Partonic phase:

- Degrees of freedom:
quarks and gluons (= ,dynamical quasiparticles‘) (+ hadrons)
- Properties of partons:
off-shell spectral functions (width, mass) defined by DQPM
- EoS of partonic phase: from lattice QCD (fitted by DQPM)

- **elastic parton-parton interactions:**
using the effective cross sections from the DQPM
- **inelastic parton-parton interactions:**
 - ✓ quark+antiquark (flavor neutral) \Leftrightarrow gluon (colored)
 - ✓ gluon + gluon \Leftrightarrow gluon (possible due to large spectral width)
 - ✓ quark + antiquark (color neutral) \Leftrightarrow hadron resonances

Note: inelastic reactions are described by Breit-Wigner cross sections determined by the spectral properties of constituents (q, q_{bar}, g) !
- **parton propagation:**
with self-generated potentials U_q, U_g

III. PHSD: hadronization



Based on DQPM: massive, off-shell quarks and gluons with broad spectral functions hadronize to off-shell mesons and baryons:

gluons \rightarrow **q + qbar** **q + qbar** \rightarrow **meson**
q + q + q \rightarrow **baryon**

Hadronization happens:

- when the effective interactions become attractive \Leftarrow from DQPM
- for parton densities $1 < \rho_P < 2.2 \text{ fm}^{-3}$:

Note: **nucleon:** parton density $\rho_P^N = N_q / V_N = 3 / 2.5 \text{ fm}^3 = 1.2 \text{ fm}^{-3}$
meson: parton density $\rho_P^m = N_q / V_m = 2 / 1.2 \text{ fm}^3 = 1.66 \text{ fm}^{-3}$

Parton-parton recombination rate = probability to form bound state during fixed time-interval Δt in volume ΔV :

$$\frac{d^4P}{\Delta V \Delta t} \Rightarrow \frac{1}{\Delta V} \sum_{i,j \in \Delta V} \text{flux} \cdot |V_{q\bar{q}}(\rho_P)|^2 \quad \Leftarrow \text{from DQPM and recomb. model}$$

Matrix element $|V_{q\bar{q}}(\rho_P)|^2$ increases drastically for $\rho_P \rightarrow 0 \Rightarrow \frac{d^4P}{\Delta V \Delta t} \Big|_{\rho_P \rightarrow 0} \rightarrow \infty$
 \Rightarrow **hadronization successful !**

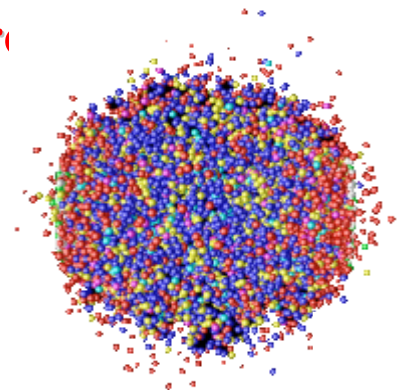
IV. PHSD: hadronization

Conservation laws:

- ❖ **4-momentum conservation** → invariant mass and momentum of meson
 - ❖ **flavor current conservation** → quark-antiquark content of meson
 - ❖ **color + anticolor** → **color neutrality**
-
- large parton masses → dominant production of vector mesons or baryon resonances (of finite/large width)
 - **resonance state (or string)** is determined by the weight of its **spectral function** at given invariant mass M
 - hadronic resonances are propagated in HSD (and finally decay to the groundstates by emission of pions, kaons, etc.) → **Since the partons are massive the formed states are very heavy (strings) → entrance in the hadronization phase !**

5. Hadronic phase:

hadron-string interactions → off-shell transport in HSD



V. PHSD: Hadronization details

Local off-shell transition rate: (meson formation)

$$\begin{aligned} \frac{dN_m(x, p)}{d^4x d^4p} &= Tr_q Tr_{\bar{q}} \delta^4(p - p_q - p_{\bar{q}}) \delta^4\left(\frac{x_q + x_{\bar{q}}}{2} - x\right) \\ &\times \omega_q \rho_q(p_q) \omega_{\bar{q}} \rho_{\bar{q}}(p_{\bar{q}}) |v_{q\bar{q}}|^2 W_m(x_q - x_{\bar{q}}, p_q - p_{\bar{q}}) \\ &\times N_q(x_q, p_q) N_{\bar{q}}(x_{\bar{q}}, p_{\bar{q}}) \delta(\text{flavor, color}). \end{aligned}$$



using

$$Tr_j = \sum_j \int d^4x_j d^4p_j / (2\pi)^4$$

W_m : Gaussian in phase space

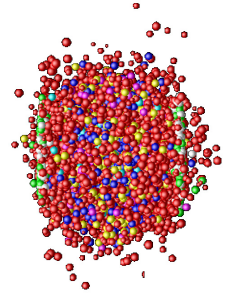
$$\sqrt{\langle r^2 \rangle} = 0.66 \text{ fm}$$

Cassing, E.B., PRC 78 (2008) 034919

Cassing, EPJ ST (2009)

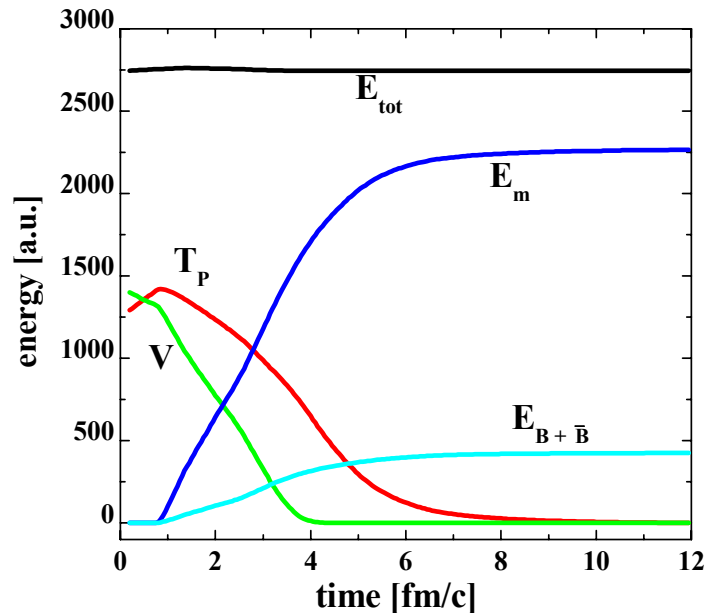
Expanding partonic fireball I

Initial condition: Partonic fireball at temperature $1.7 T_c$ with ellipsoidal gaussian shape in coordinate space

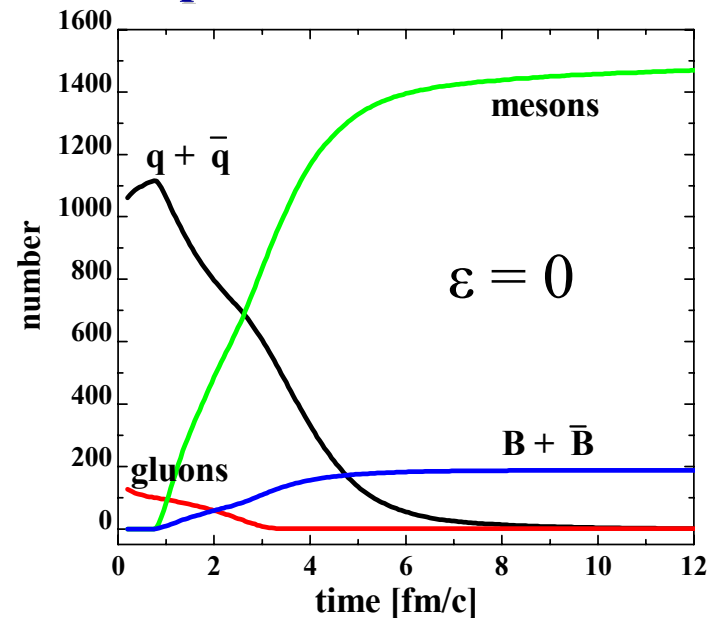


eccentricity: $\varepsilon = (\sigma_y^2 - \sigma_x^2) / (\sigma_y^2 + \sigma_x^2)$

energy conservation



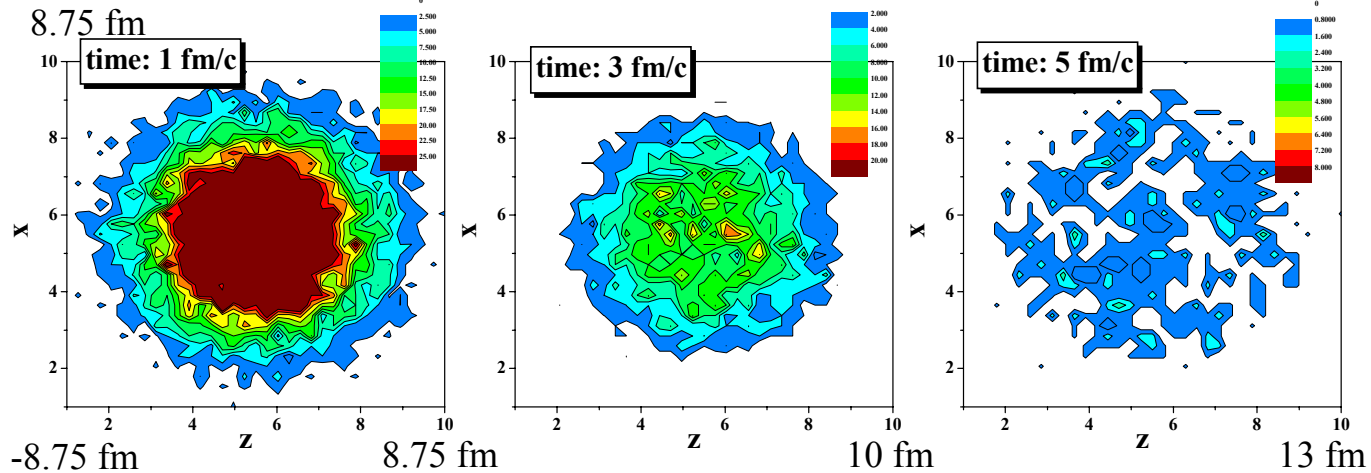
partons and hadrons



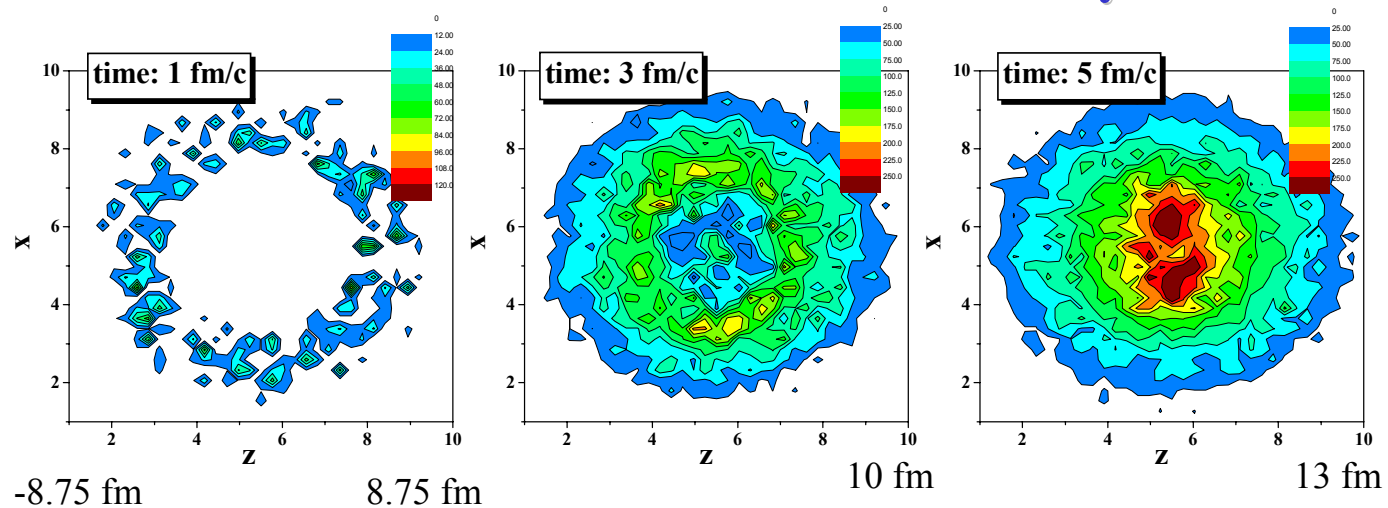
More hadrons in the final state than initial partons !

Expanding fireball II

Time-evolution of parton density at $y=0$



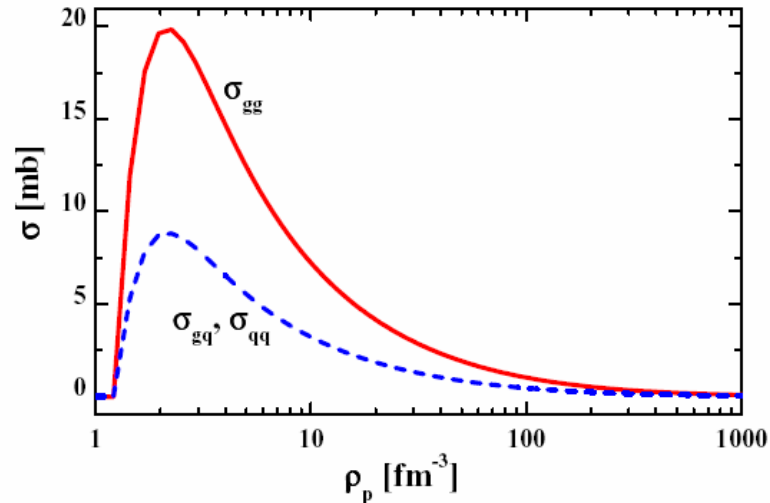
Time-evolution of hadron density



expanding grid: $\Delta z(t) = \Delta z_0(1 + at)$!

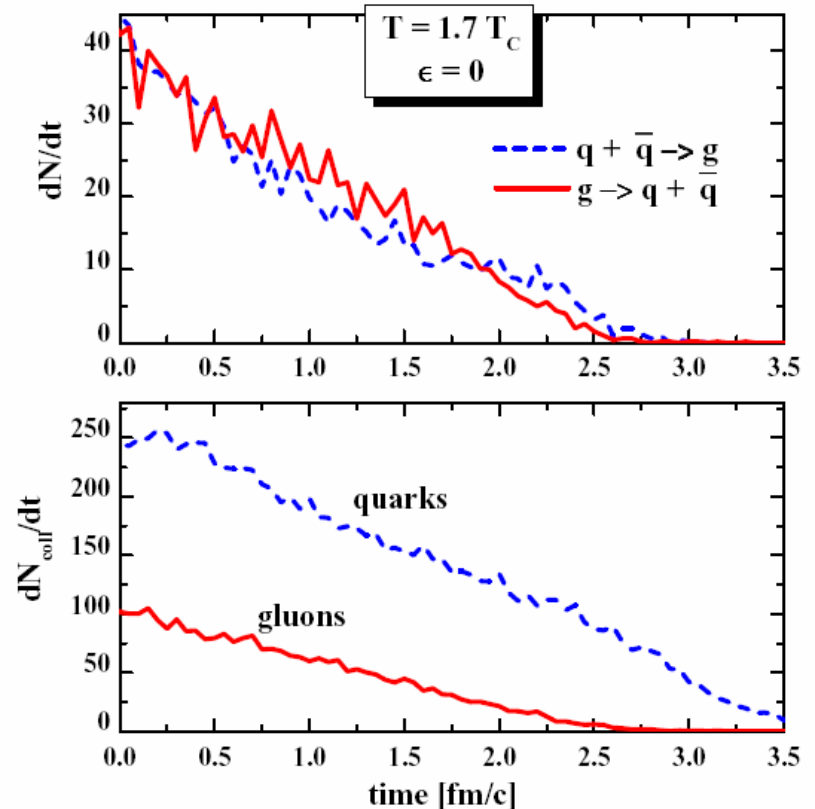
Dynamical information

effective cross sections from the DQPM
versus parton density



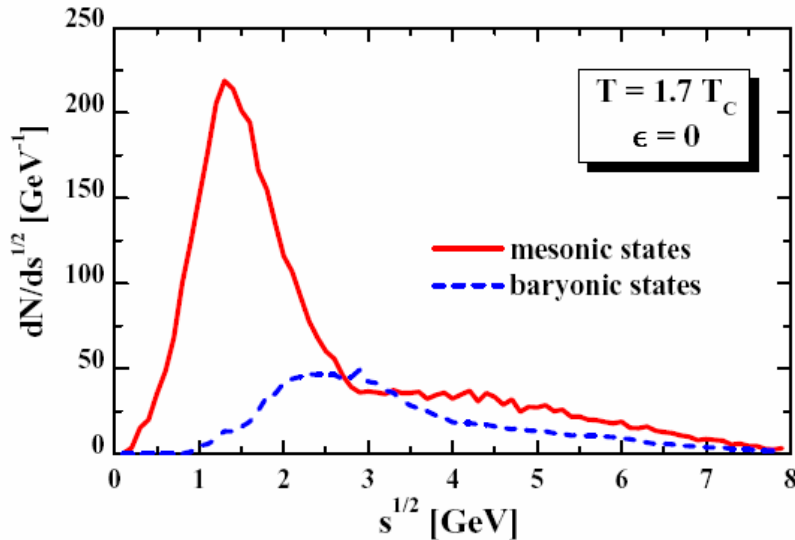
become low at high parton density
but interaction rate slightly increases
with parton density!

gluon decay rate to $q+q\bar{q}$
roughly equal to glue
formation rate



Expanding fireball III - hadronization

mass distributions for color neutral ,mesons‘ and ,baryons‘ after parton fusion: (rotating color dipoles)



These ,prehadrons‘ decay according to JETSET to 0-, 1-, 1+ mesons and the baryon octet/decouplet

Comparison of particle ratios with the statistical model (SM):

	p/π^+	Λ/K^+	K^+/π^+
PHSD	0.086	0.28	0.157
SM $T = 160$ MeV	0.073	0.22	0.179
SM $T = 170$ MeV	0.086	0.26	0.180

TABLE I: Comparison of particle ratios from PHSD with the statistical model (SM) [31] for $T = 160$ MeV and 170 MeV.

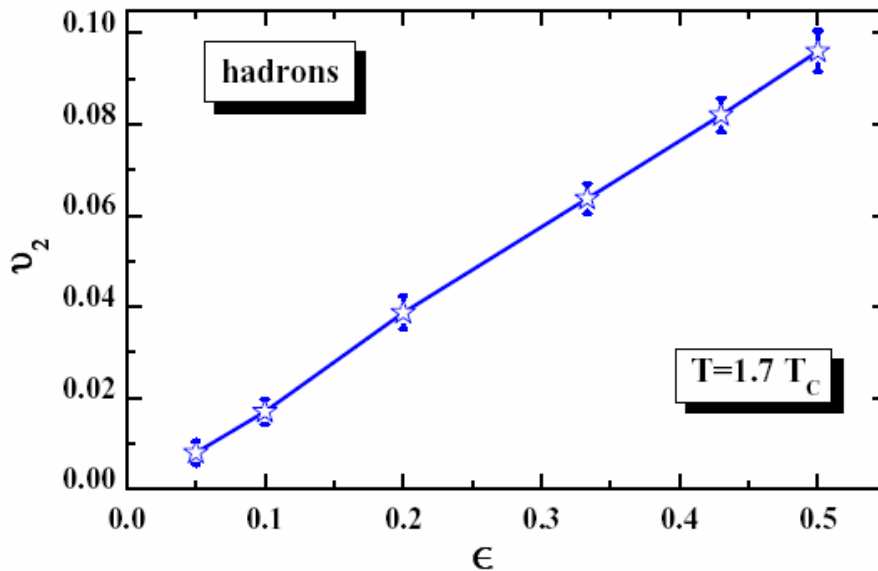
Expanding fireball IV – collective aspects

Elliptic flow v_2 is defined by an anisotropy in momentum space:

$$v_2 = (p_x^2 - p_y^2)/(p_x^2 + p_y^2)$$

Initially: $v_2 = 0 \rightarrow$ study final v_2 versus initial eccentricity ϵ !

$$\epsilon = (\sigma_y^2 - \sigma_x^2)/(\sigma_y^2 + \sigma_x^2)$$



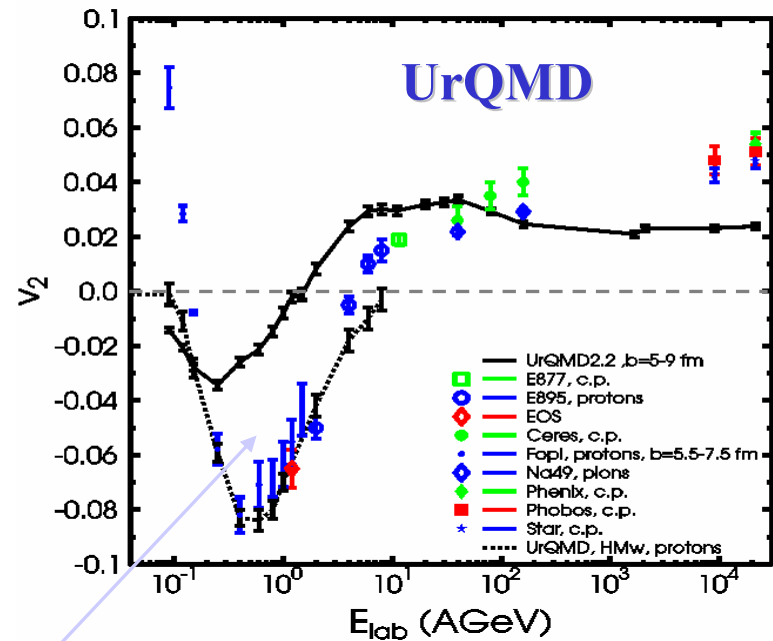
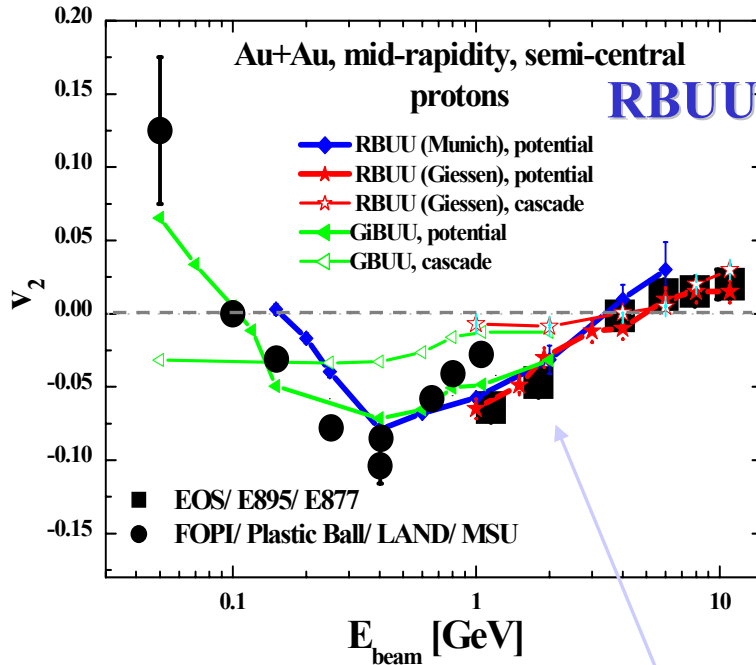
$v_2/\epsilon = \text{const.}$
indicates ideal hydrodynamic
flow !

This is expected since η/s is
very small in the DQPM

Reminder: Collective flow: v_2 excitation functions

v_2 excitation functions from string-hadronic transport models :

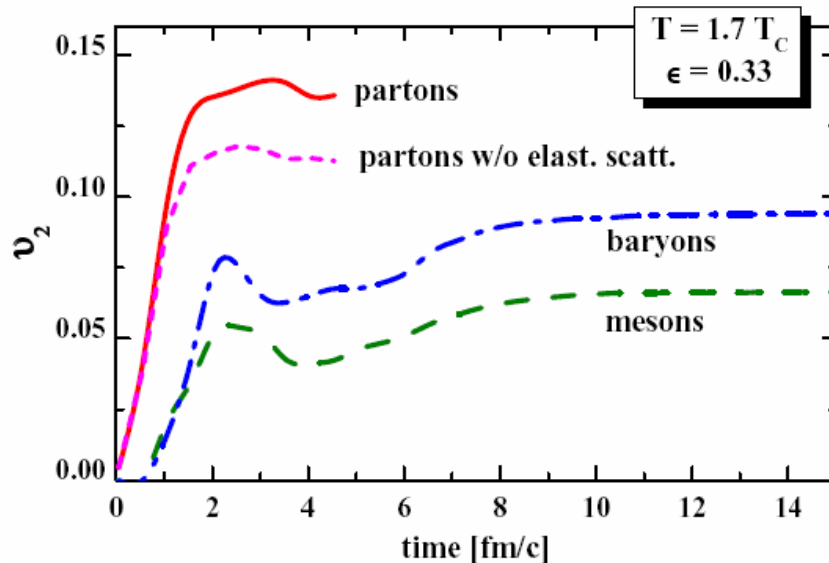
charged particles, $|\eta| < 0.1$



- Proton v_2 at low energy shows sensitivity to the nucleon potential.
- Cascade codes fail to describe the exp. data.
- v_2 is determined by attractive/repulsive potentials !

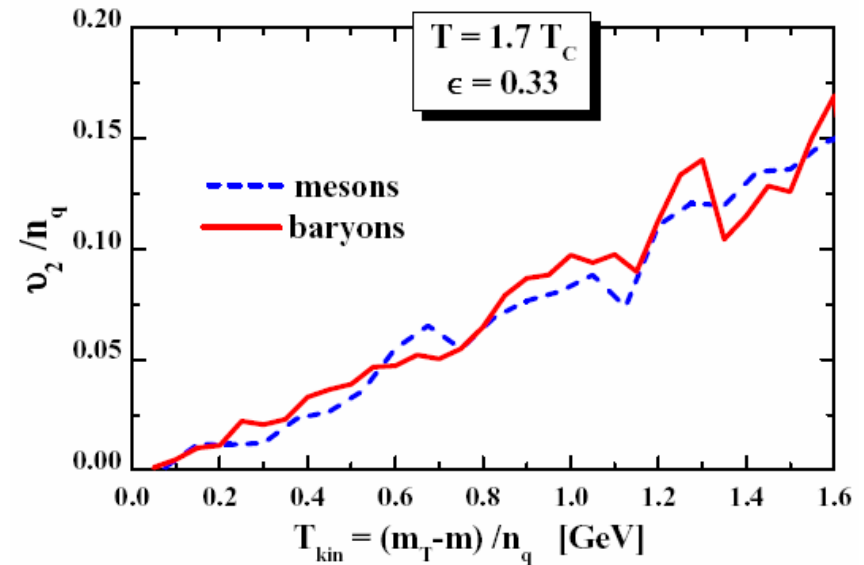
Expanding fireball V - differential elliptic flow

Time evolution of v_2 :



parton v_2 is generated also by the repulsive partonic forces !

Quark number scaling v_2/n_q :

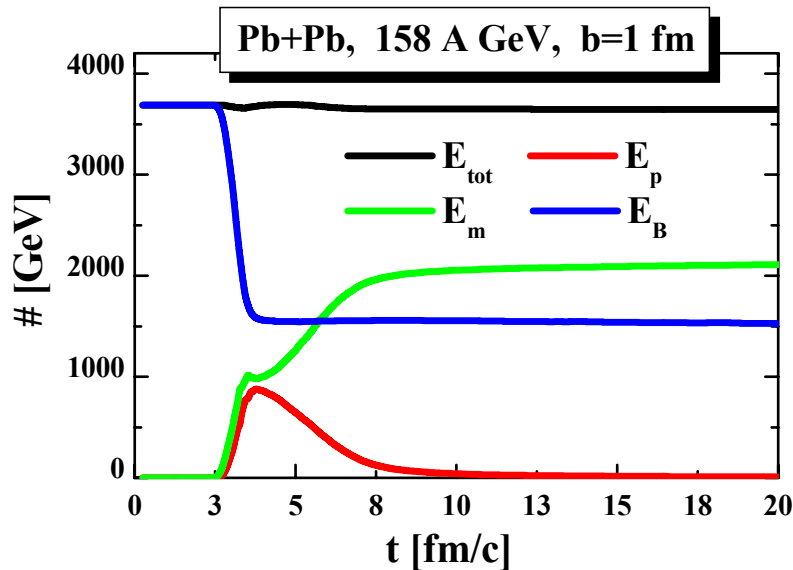


meson to baryon v_2 suggests quark number scaling !

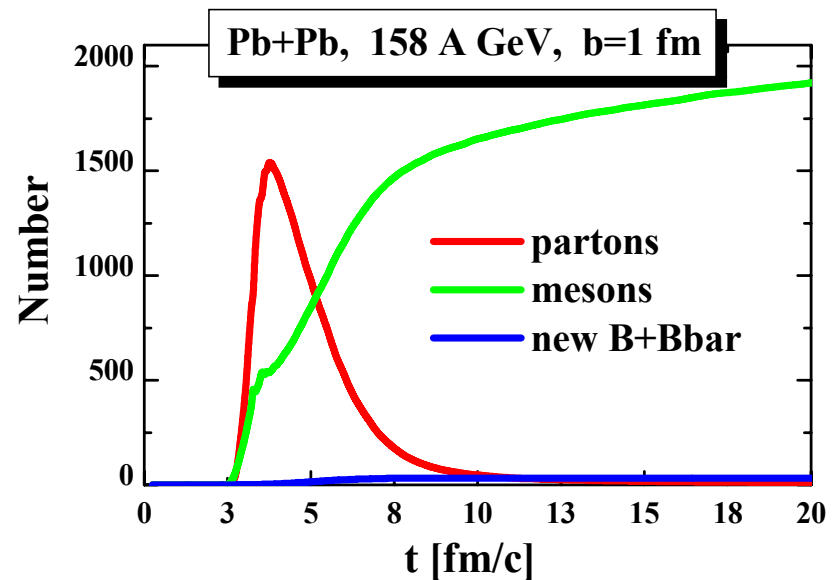
Application to nucleus-nucleus collisions

central Pb + Pb at 158 A GeV

energy balance



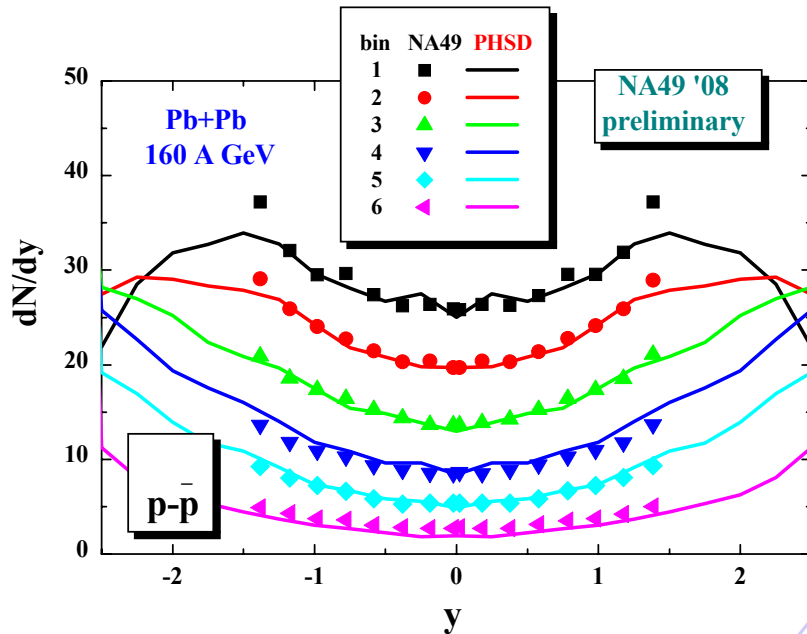
particle balance



only about 40% of the converted energy goes to partons;
the rest is contained in the ,large‘ hadronic corona!

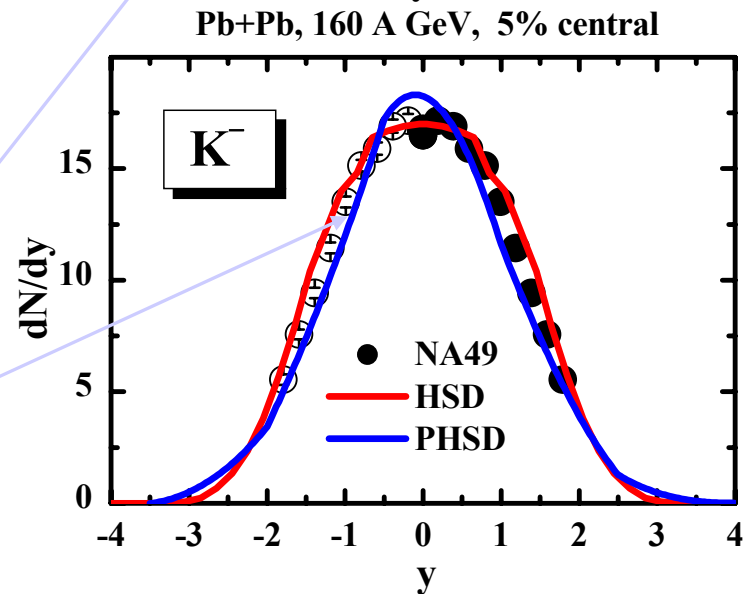
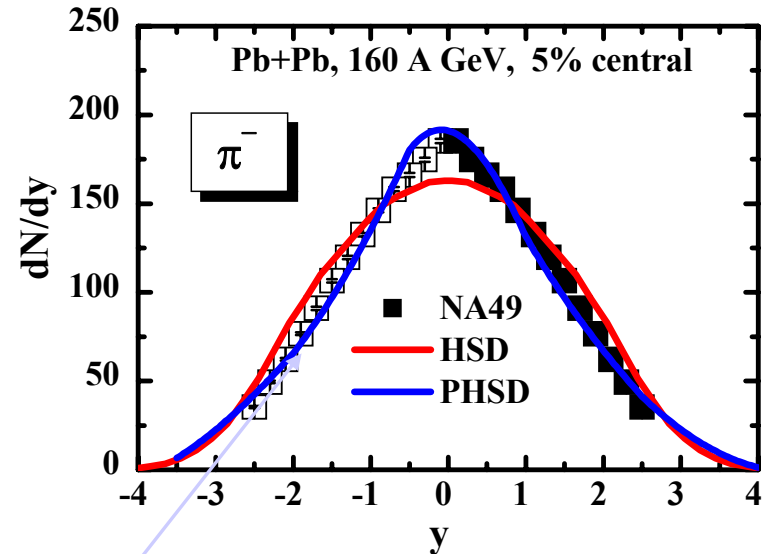
Rapidity distributions

proton stopping



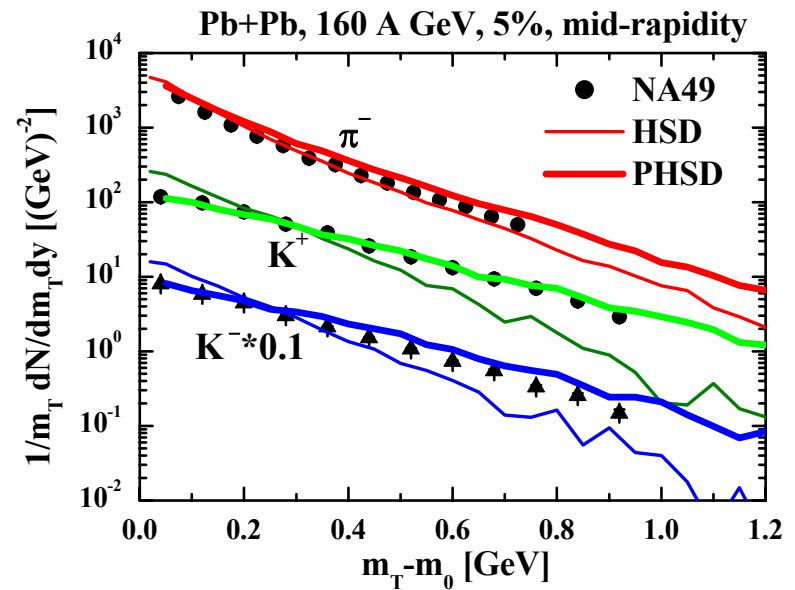
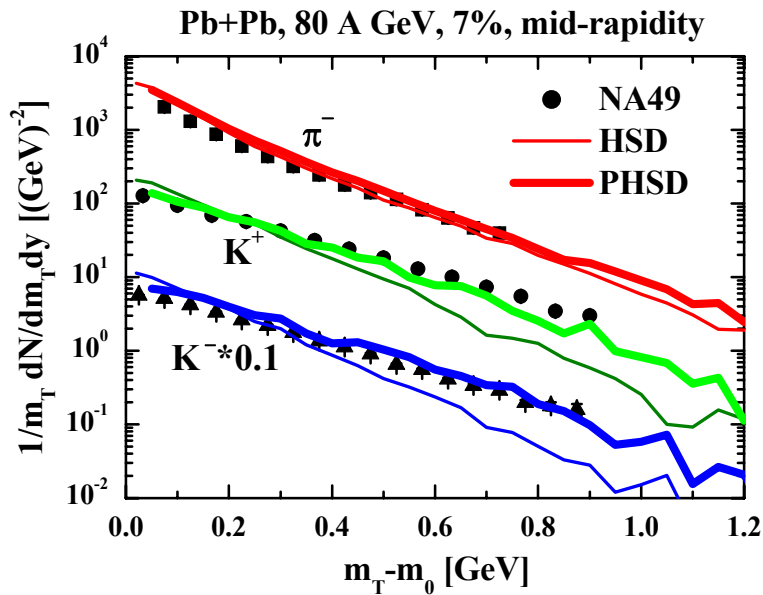
→ looks not bad !

✓ pions and kaons dN/dy
become more narrow !



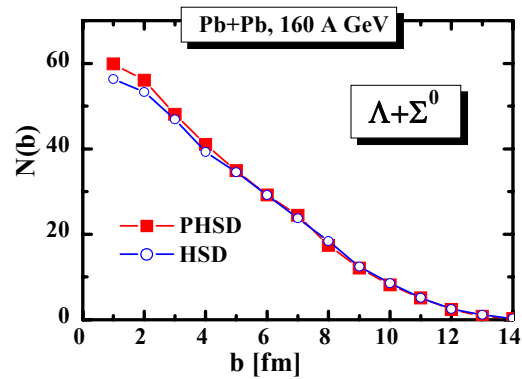
Transverse mass spectra

Central Pb + Pb at top SPS energies



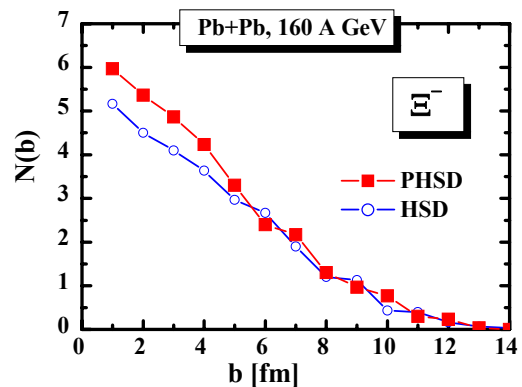
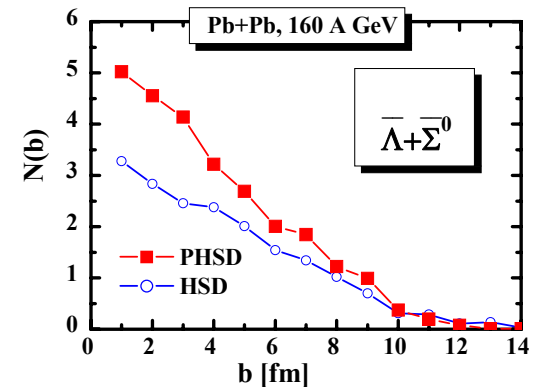
→ PHSD seems to work better than HSD !

Strange and antistrange baryons at 160 A GeV

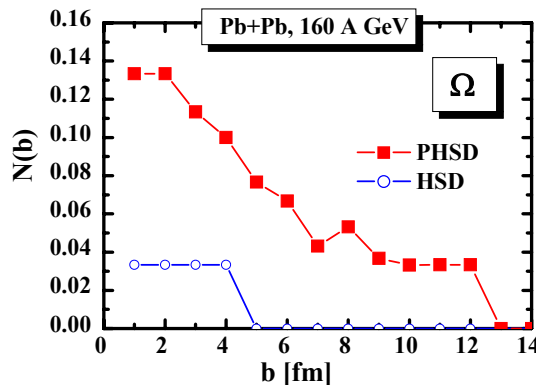
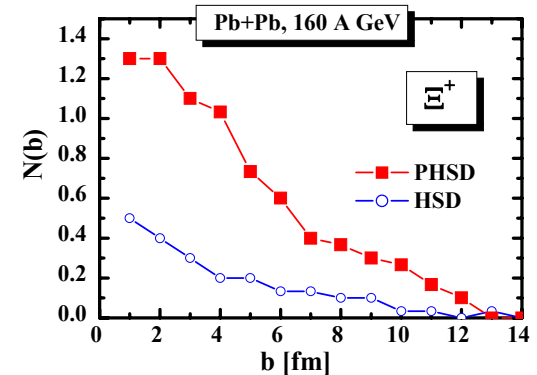


PHSD:

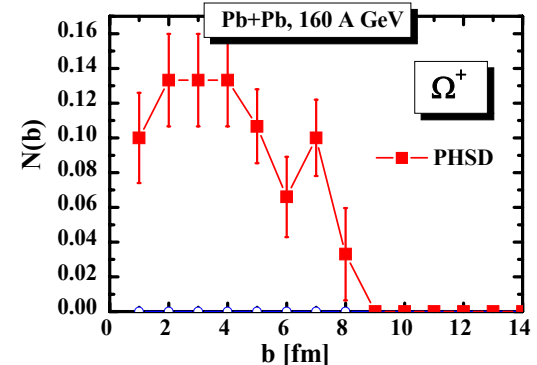
Slightly more Λ and Ξ
but much more Ω 's !!



Antibaryons (r.h.s.) are
substantially enhanced !

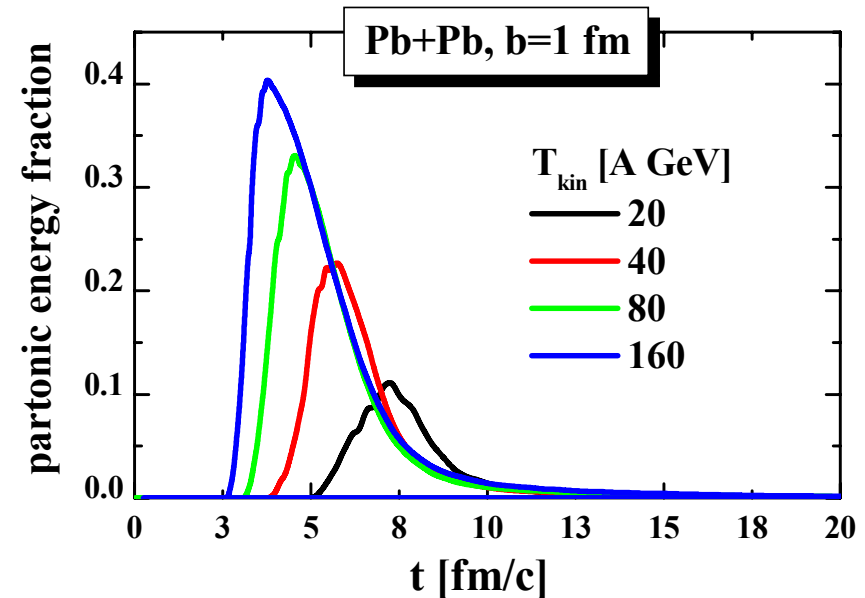
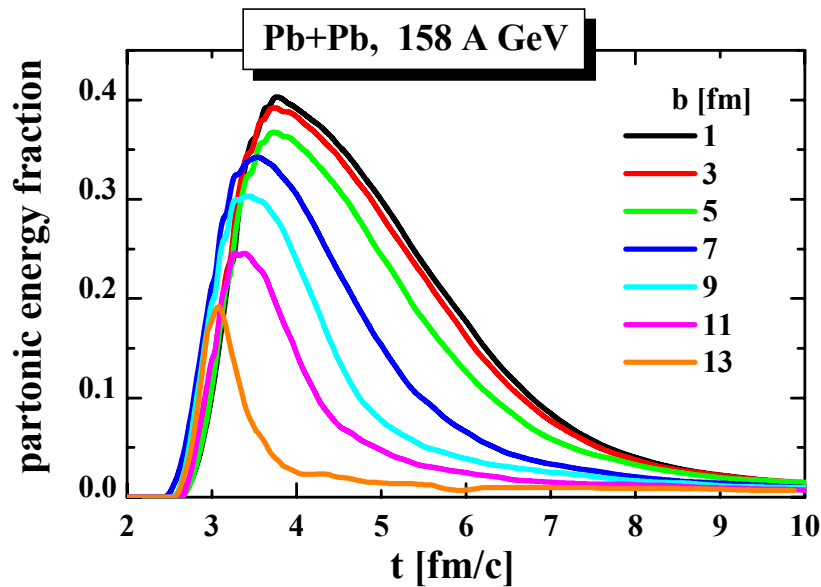


Note:
present statistics
drastically need
improvement !



Perspectives at FAIR energies

partonic energy fraction vs centrality and energy



→ Dramatic decrease of partonic phase with decreasing energy and centrality !

Summary of part II

- PHSD provides a consistent description of **off-shell parton dynamics in line with IQCD**; the repulsive mean fields generate transverse flow
- The dynamical **hadronization** in PHSD yields particle ratios close to the (GC) statistical model at a temperature of about 170 MeV
- The **elliptic flow v_2** scales with the initial eccentricity in space as in ideal hydrodynamics
- The Pb + Pb data at **top SPS energies** are rather well described within PHSD including **baryon stopping**, **strange antibaryon enhancement** and **meson m_T slopes**
- At **FAIR energies** PHSD gives practically the same results as HSD (except for **strange antibaryons**) when the IQCD EoS (where the phase transition is always a cross-over) is used

Open problems

- Is the **critical energy/temperature** provided by the IQCD calculations **sufficiently accurate**?
- How to describe a **first-order phase transition** in transport ?
- How to describe **parton-hadron interactions** in a **‘mixed’ phase**?

Thanks

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