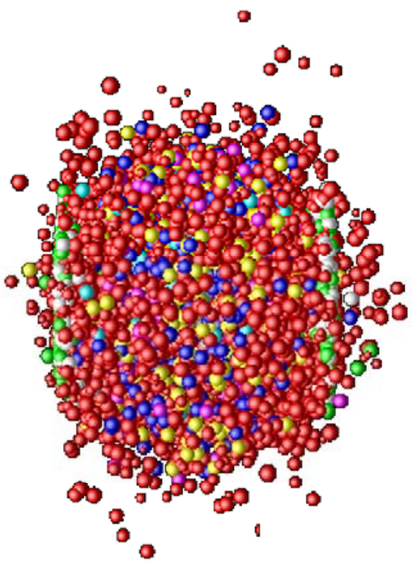
Institut für
Theoretische Physik I

JUSTUS-LIEBIG-
UNIVERSITÄT
GIESSEN

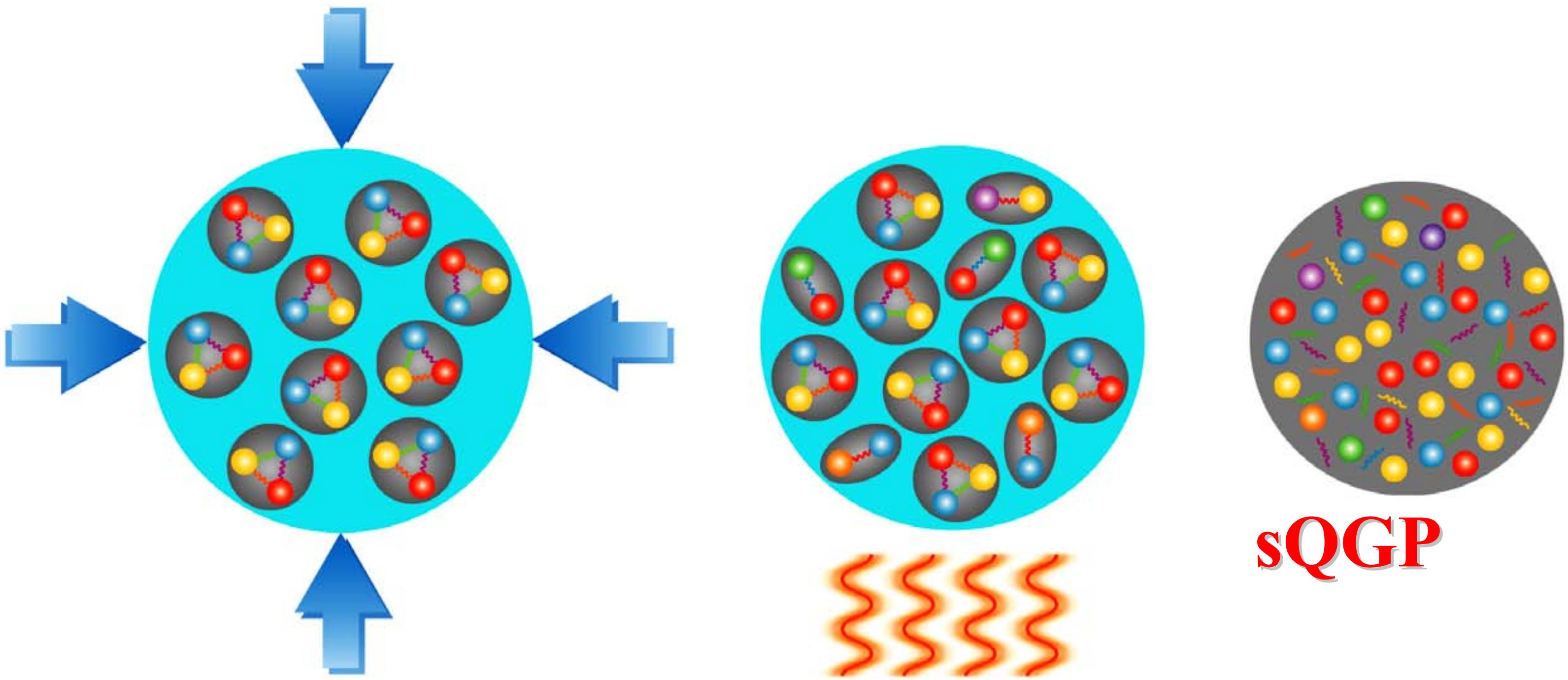
Covariant transport approach for strongly interacting partonic systems



Wolfgang Cassing

Jamaica, 03.01.2010

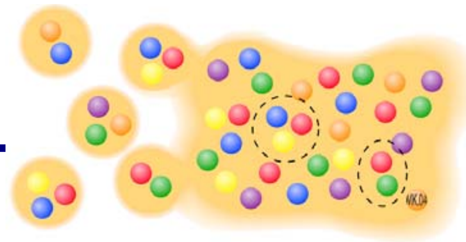
Compressing and heating hadronic matter:



Questions:

- **What are the transport properties of the sQGP?**
- **How may the hadronization (partons → hadrons) occur?**
- **Where do we see traces of parton dynamics in HIC?**

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:

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

gluon width:

$$\gamma_g(T) = N_c \frac{g^2 T}{4\pi} \ln\frac{c}{g^2}$$

$N_c = 3$

quark width:

$$\gamma_q(T) = \frac{N_c^2 - 1}{2N_c}\frac{g^2 T}{4\pi} \ln\frac{c}{g^2}$$

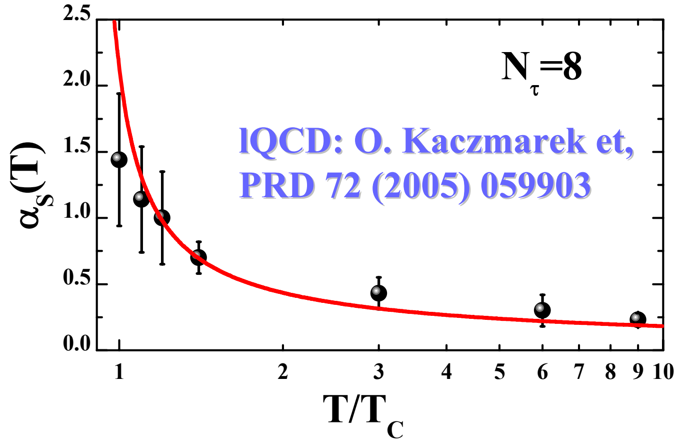
with $E^2(\mathbf{p}) = \mathbf{p}^2 + M^2 - \gamma^2$

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

The running coupling g^2

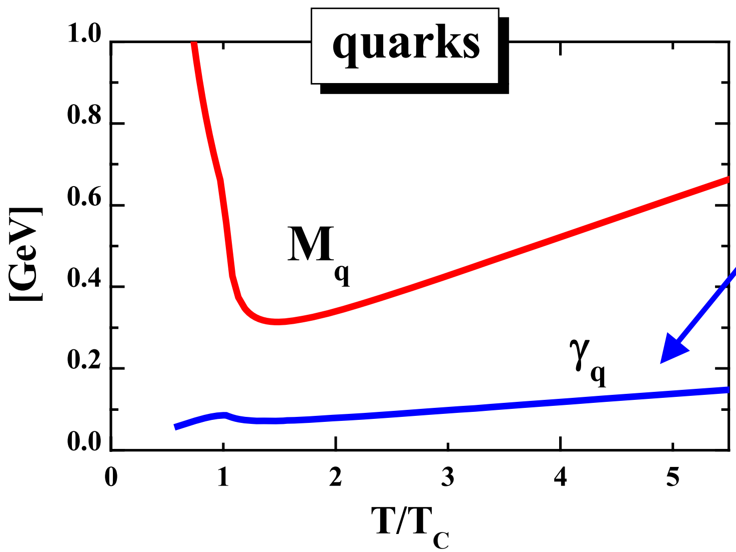
$$g^2(T/T_c) = \frac{48\pi^2}{(11N_c - 2N_f)\ln(\lambda^2(T/T_c - T_s/T_c)^2}$$

3 parameters: T_s/T_c=0.46; c=28.8; λ=2.42

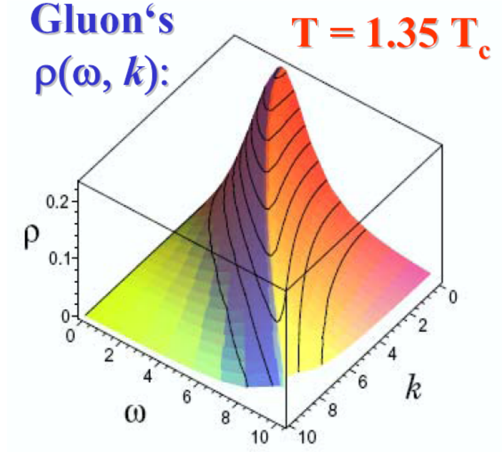


fit to lattice (lQCD) entropy density:

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



large width for gluons and quarks !



DQPM thermodynamics (N_f=3)

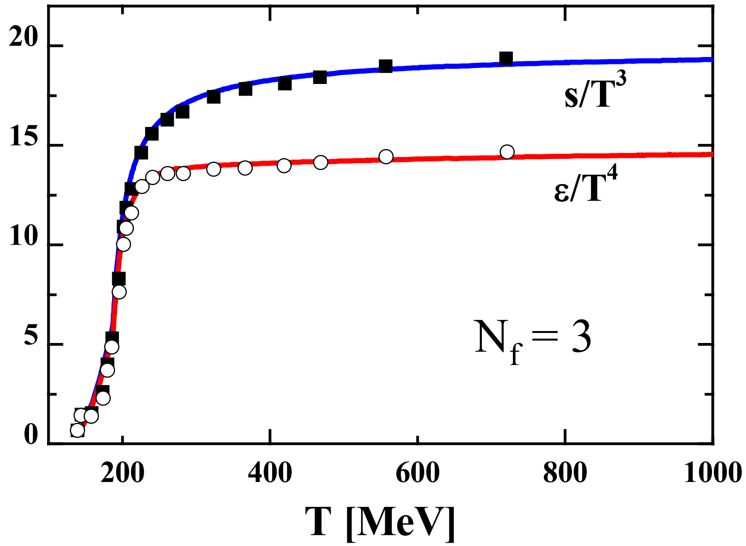
Thermodynamics: entropy $s = \frac{\partial P}{dT}$ → pressure P

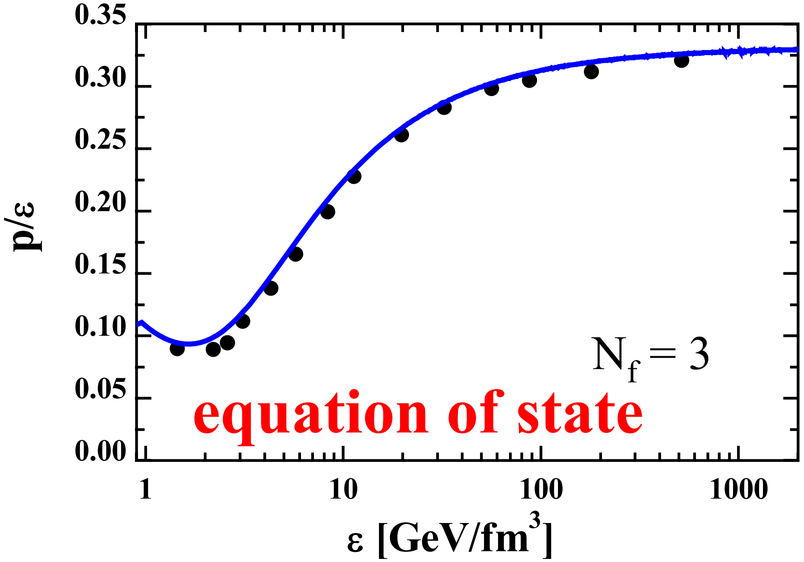
energy density: $\epsilon = Ts - P$

interaction measure:

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

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





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

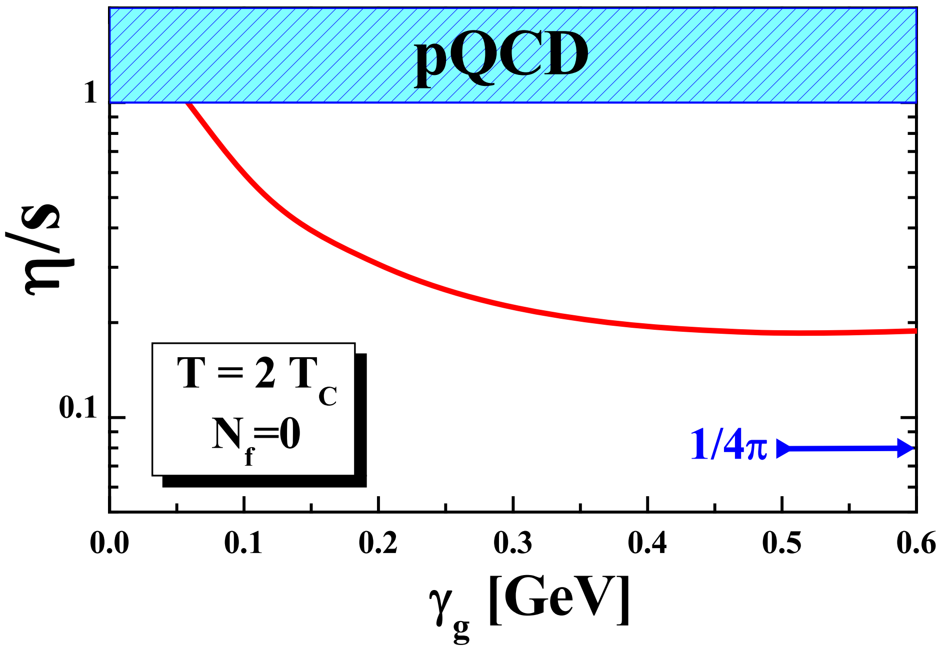
DQPM gives a ‚perfect' description of lQCD results !

Transport properties of hot glue

Why do we need broad quasiparticles?

shear viscosity ratio to entropy density:

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



→ otherwise η/s will be too high!

Time-like and space-like quantities

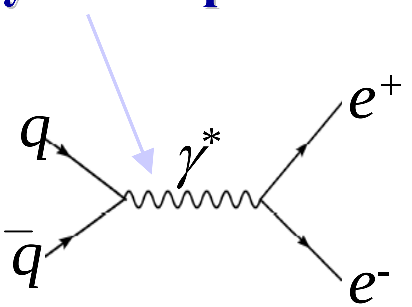
some short-hand notations (useful for all single-particle quantities):

$$\tilde{\mathrm{Tr}}_{\mathbf{g}}^{\pm} \cdots = \mathbf{d_g} \int \frac{\mathbf{d}\omega}{\mathbf{2}\pi} \frac{\mathbf{d^3 p}}{(\mathbf{2}\pi)^{\mathbf{3}}}\, \mathbf{2}\omega\, \rho_{\mathbf{g}}(\omega)\ \mathbf{\Theta}(\omega)\ \mathbf{n_B}(\omega/\mathbf{T})\ \mathbf{\Theta}(\pm \mathbf{P^2}) \cdots$$ gluons

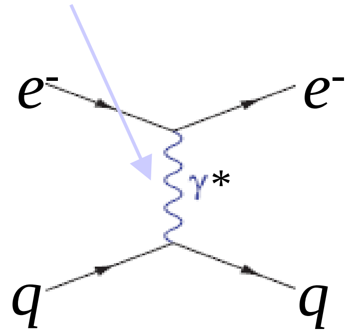
$$\tilde{\mathrm{Tr}}_{q}^{\pm} \cdots = d_q \int \frac{d\omega}{2\pi} \frac{d^3 p}{(2\pi)^3}\, 2\omega\, \rho_q(\omega)\ \Theta(\omega)\ n_F((\omega - \mu_q)/T)\ \Theta(\pm P^2) \cdots$$ quarks

$$\tilde{\mathrm{Tr}}_{\bar{q}}^{\pm} \cdots = d_{\bar{q}} \int \frac{d\omega}{2\pi} \frac{d^3 p}{(2\pi)^3}\, 2\omega\, \rho_{\bar{q}}(\omega)\ \Theta(\omega)\ n_F((\omega + \mu_q)/T)\ \Theta(\pm P^2) \cdots$$ antiquarks

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



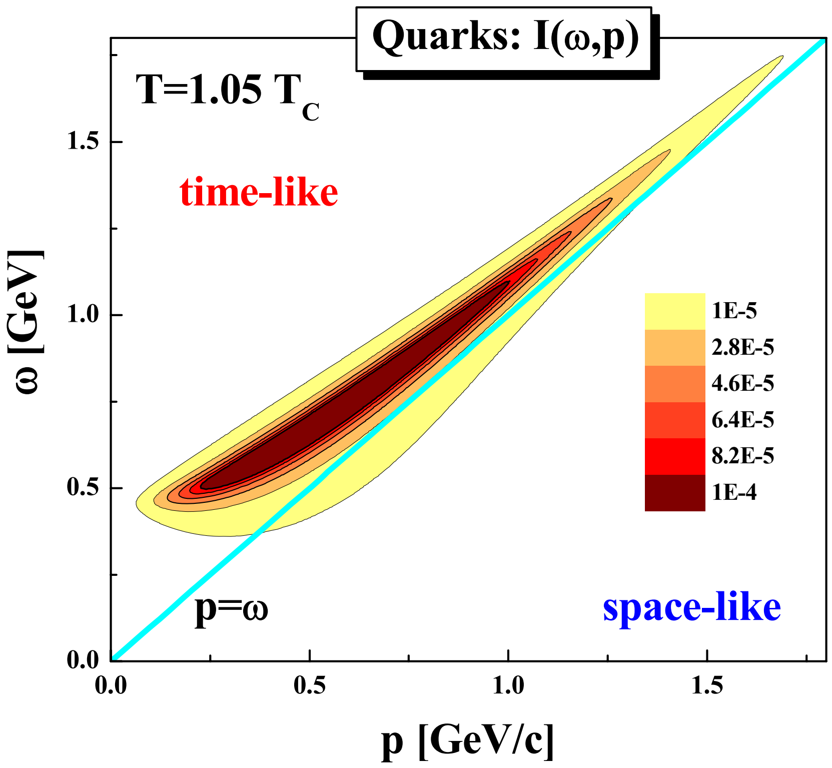
Space-like: $\Theta(-P^2)$: particles are virtuell and appear as exchange quanta in interaction processes of real particles

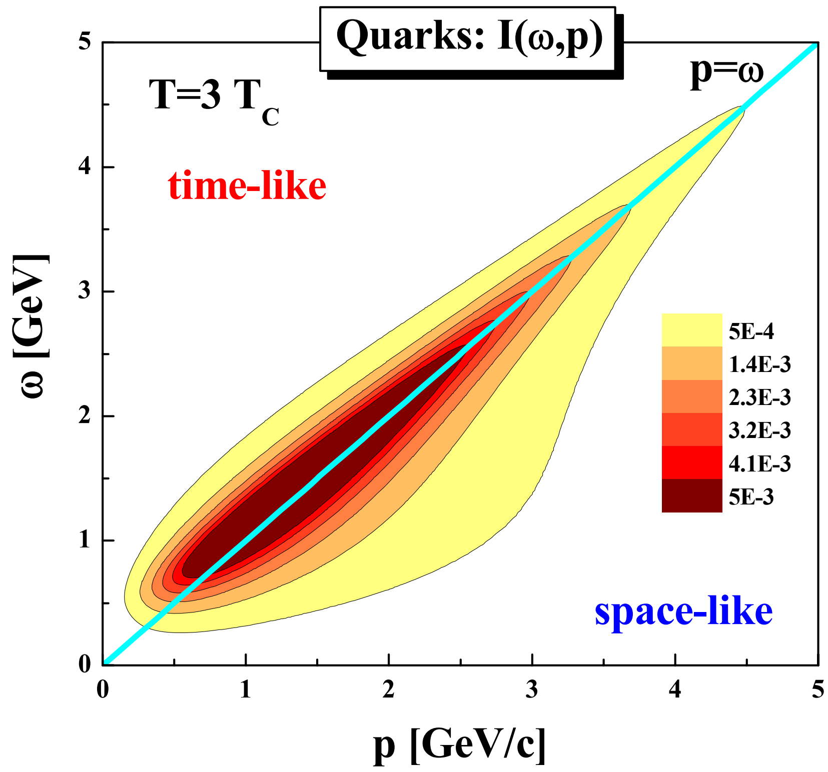


Cassing, NPA 791 (2007) 365: NPA 793 (2007)

Differential quark ‚density'

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





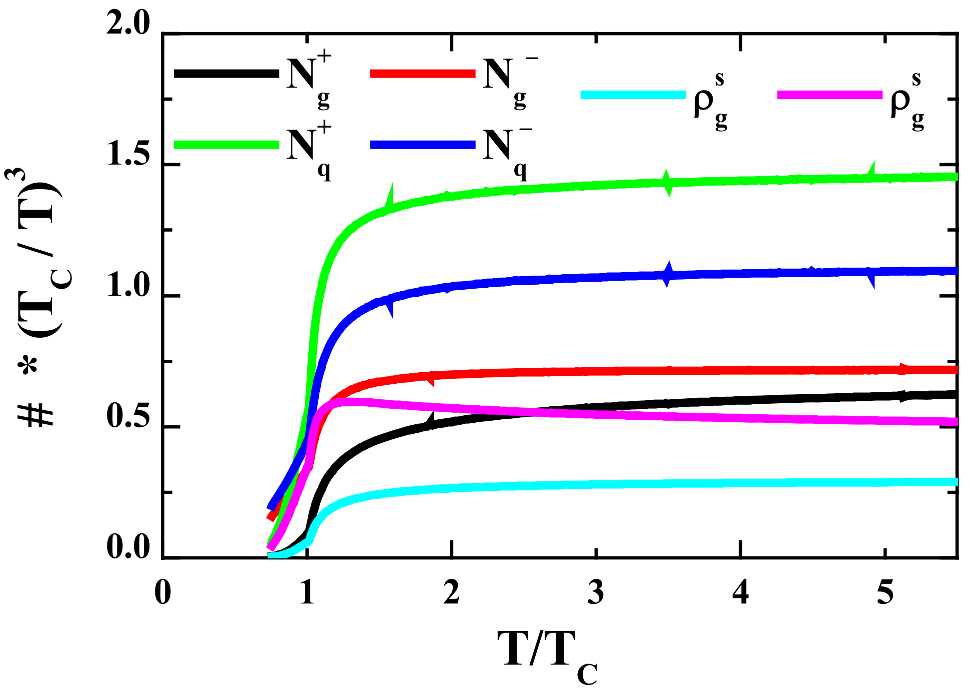
→ **Large space-like contributions for broad quasiparticles !**

Cassing, NPA 791 (2007) 365: NPA 793 (2007)

Time-like and ‚space-like' densities

‚densities': $N_g^{\pm}(T) = \tilde{\mathrm{Tr}}_g^{\pm}\, 1, \qquad N_q^{\pm}(T) = \tilde{\mathrm{Tr}}_q^{\pm}\, 1, \qquad N_{\bar{q}}^{\pm}(T) = \tilde{\mathrm{Tr}}_{\bar{q}}^{\pm}\, 1$

scalar densities: $N_g^{s}(T) = \tilde{\mathrm{Tr}}_g^{+} \left(\frac{\sqrt{P^2}}{\omega}\right), \quad N_q^{s}(T) = \tilde{\mathrm{Tr}}_q^{+} \left(\frac{\sqrt{P^2}}{\omega}\right), \quad N_{\bar{q}}^{s}(T) = \tilde{\mathrm{Tr}}_{\bar{q}}^{+} \left(\frac{\sqrt{P^2}}{\omega}\right)$



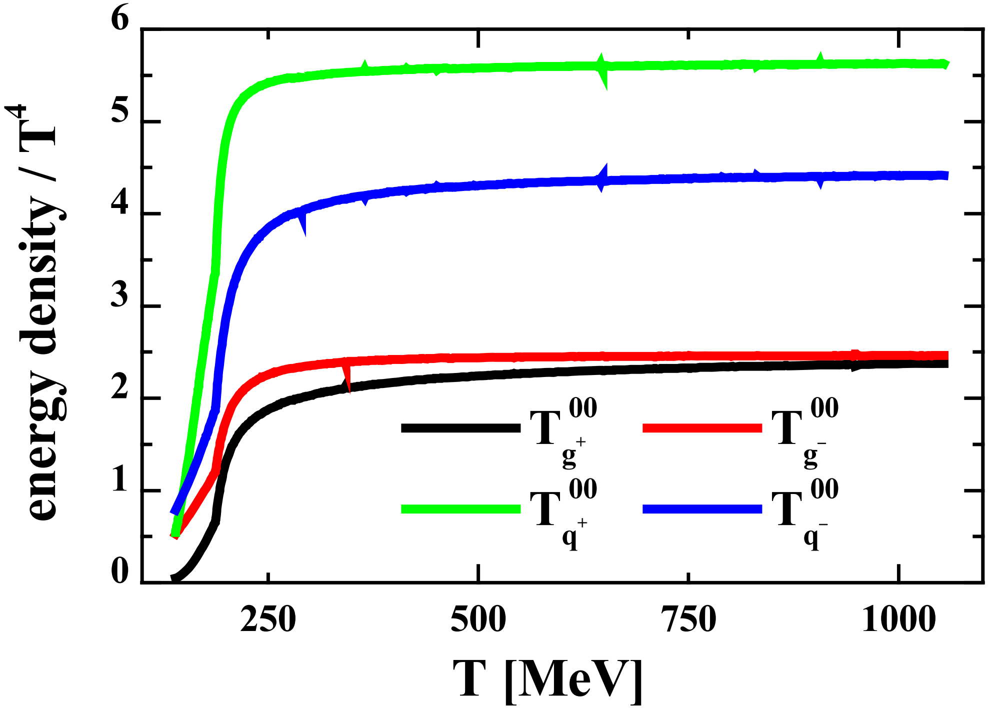
→more virtuell (space-like) than time-like gluons

but more time-like than virtuell quarks !

Time-like and ‚space-like' energy densities

$$\mathrm{T}^{\pm}_{00,\mathrm{x}}(\mathrm{T}) = \tilde{\mathrm{T}}\mathrm{r}^{\pm}_{\mathrm{x}}\ \omega$$

x: gluons, quarks, antiquarks



→ **space-like energy density dominates for gluons;**

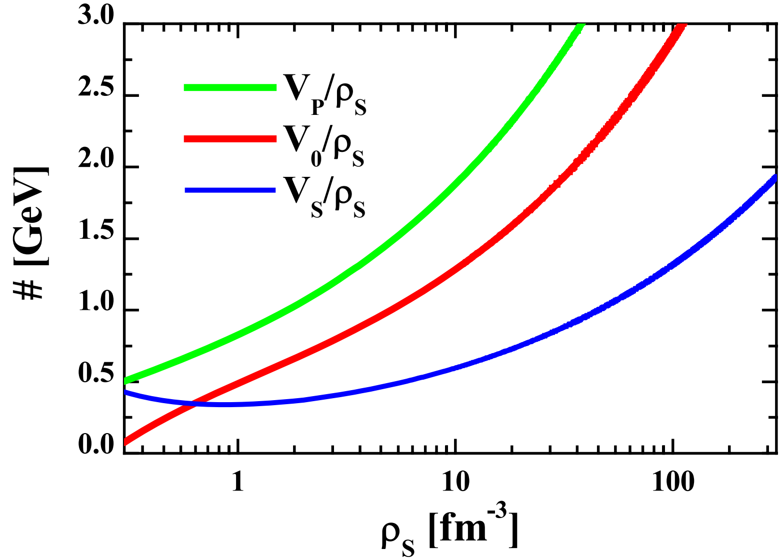
→ **space-like parts are identified with potential energy densities!**

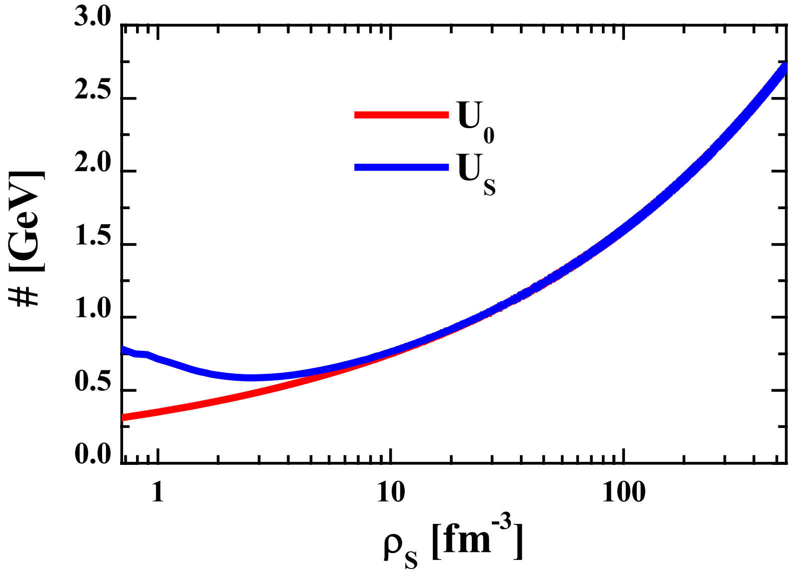
Potential energy versus scalar parton density

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

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

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





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

Summary of part I

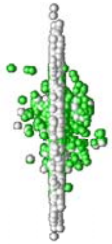
- The dynamical quasiparticle model (DQPM) well matches lQCD (with only 3 parameters) !

- DQPM allows to extrapolate to finite quark chemical potentials

- DQPM separates lime-like quantities from space-like (interaction) regions (needed for off-shell transport)

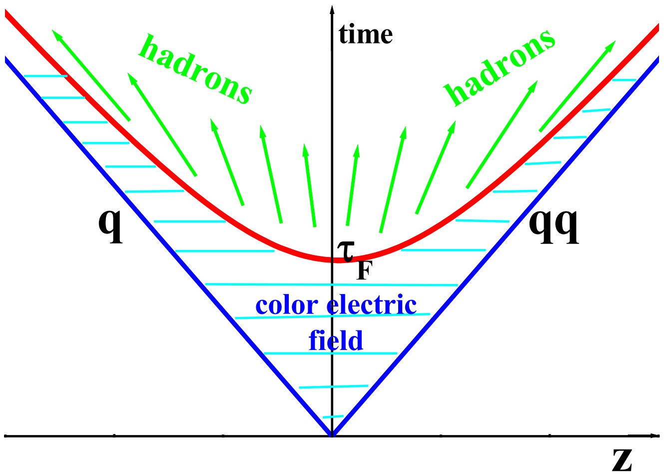
- DQPM provides mean-fields for gluons and quarks as well as effective 2-body interactions → PHSD

I. PHSD: basic concepts



1. Initial A+A collisions – off-shell HSD:

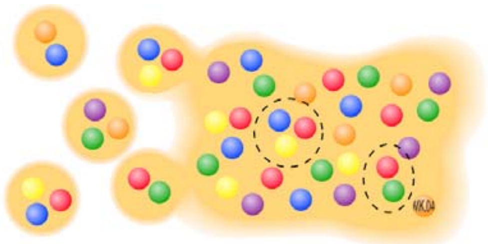
string formation and decay to pre-hadrons

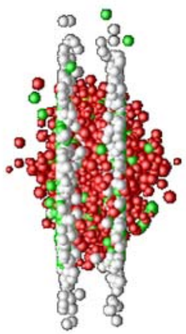


Strings – excited color singlet states

(qq - q) or (q – qbar)

(in HSD: pre-hadrons = hadrons under formation time $\tau_F \sim 0.8$ fm/c)



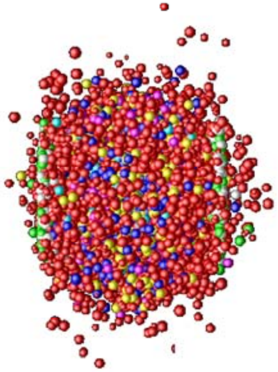


2. Fragmentation of pre-hadrons into quarks:

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:

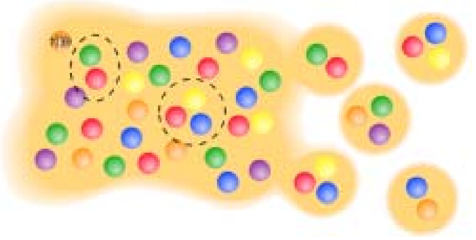
- Degrees of freedom:
  quarks and gluons (= ‚dynamical quasiparticles‘) (+ hadrons
- Properties of partons:
  off-shell spectral functions (width, mass) defined by DQPM
- EoS of partonic phase: from lattice QCD (fitted by DQPM)

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

Cassing, Bratkovskaya, PRC 78 (2008) 034919
Cassing, EPJ ST 168 (2009) 3

III. PHSD: hadronization



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

gluons → q + qbar **q + qbar → meson**
q + q + q → baryon

Hadronization happens:

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

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

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

$$\frac{d^4P}{\Delta V \Delta t} \Rightarrow \frac{1}{\Delta V} \sum_{i,j \in \Delta V} flux \bullet |V_{q\bar{q}}(\rho_P)|^2$$

<= from DQPM and recomb. model

Matrix element $|V_{q\bar{q}}(\rho_P)|^2$ **increases drastically for** $\rho_P \to 0$ => $\frac{d^4P}{\Delta V \Delta t}\Big|_{\rho_P \to 0} \to \infty$

=> **hadronization successful !**

IV. PHSD: hadronization

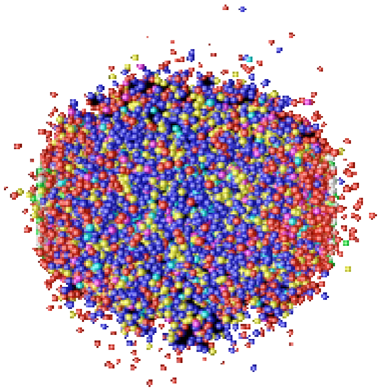
Conservation lows:

- 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) → entr 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)

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

using

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

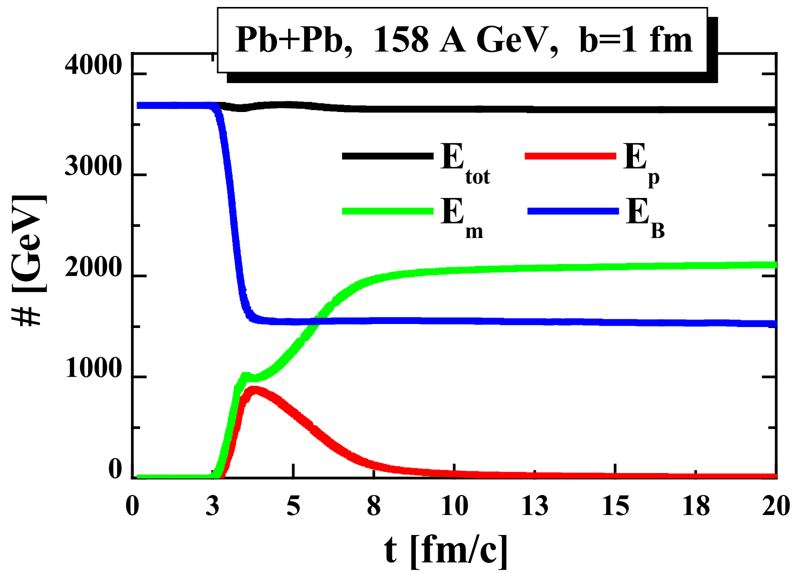
W_m: Gaussian in phase space $\sqrt{< r^2 >} = 0.66 \text{ fm}$

Cassing, Bratkovskaya, PRC 78 (2008) 034919
Cassing, EPJ ST 168 (2009) 3

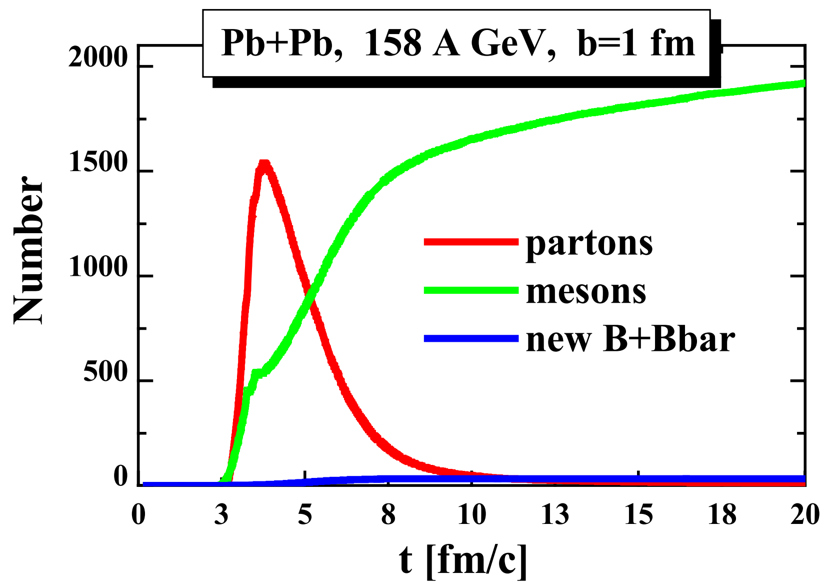
Application to nucleus-nucleus collisions

central Pb + Pb at 158 A GeV

energy balance



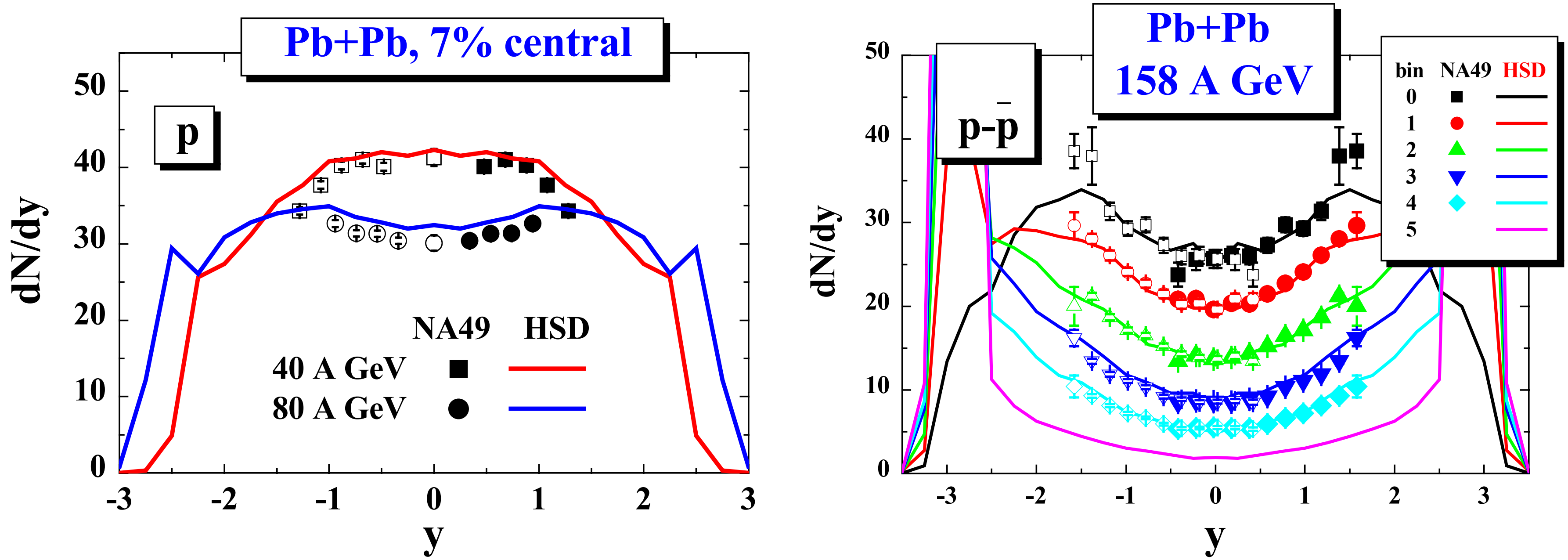
particle balance



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

W.C., E.L.B.: NPA 831 (2009) 215

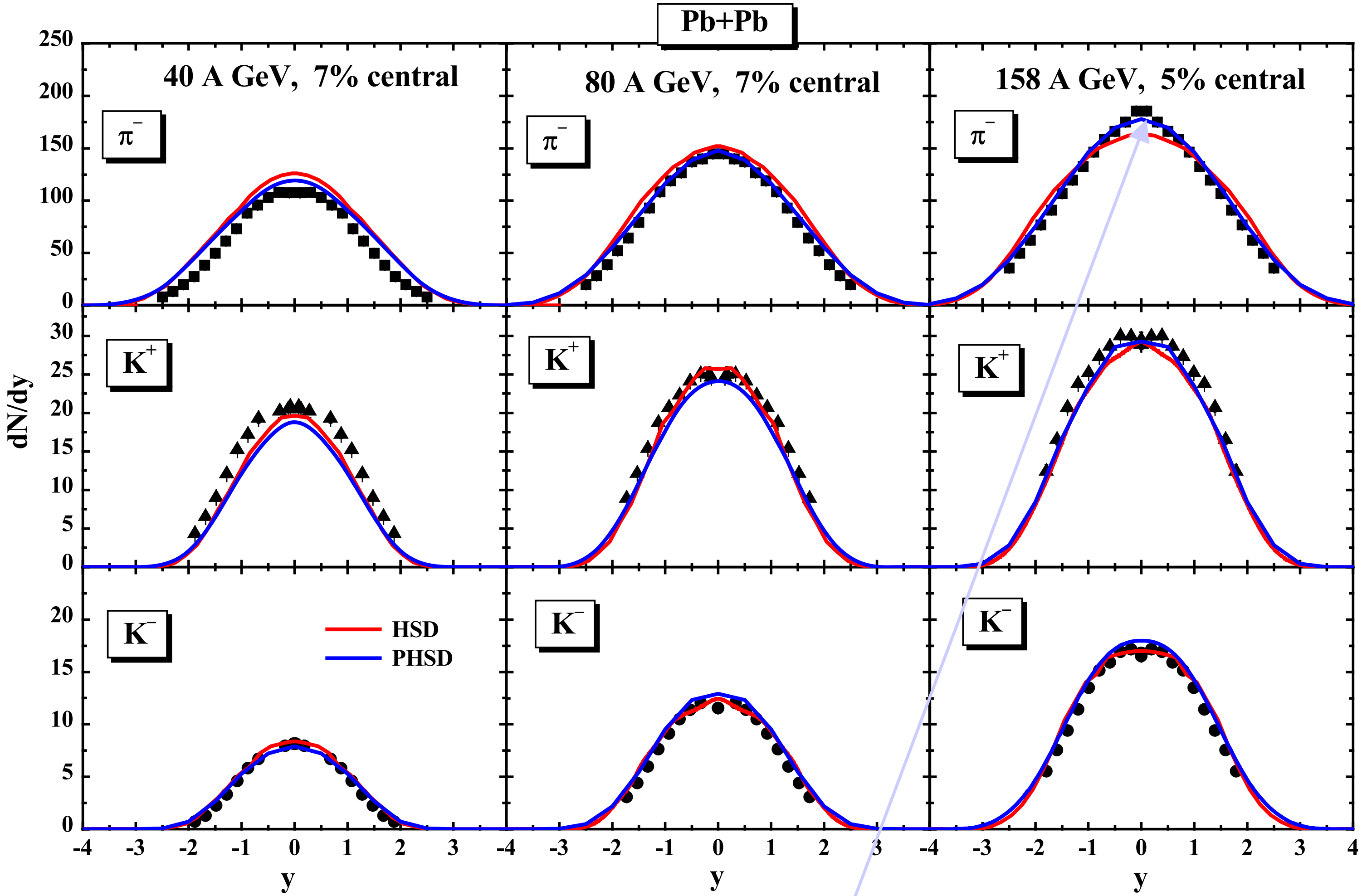
Proton stopping at SPS



➔looks not bad in comparison to NA49,
but not sensitive to parton dynamics!

Cassing & Bratkovskaya, NPA 831 (2009) 215

Rapidity distributions of π, K⁺, K⁻

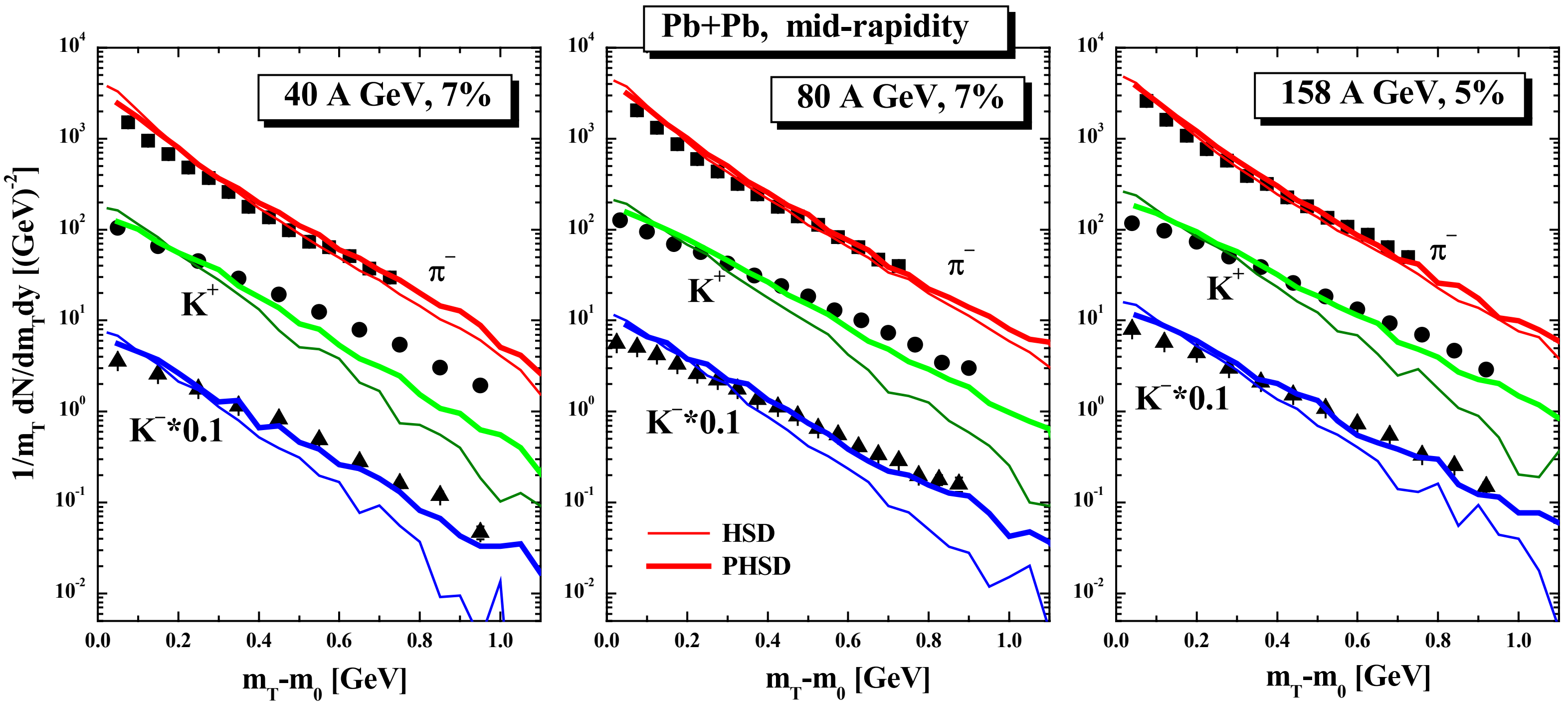


➔ **pion and kaon rapidity distributions become slightly narrower**

Cassing & Bratkovskaya, NPA 831 (2009) 215

PHSD: Transverse mass spectra at SPS

Central Pb + Pb at SPS energies

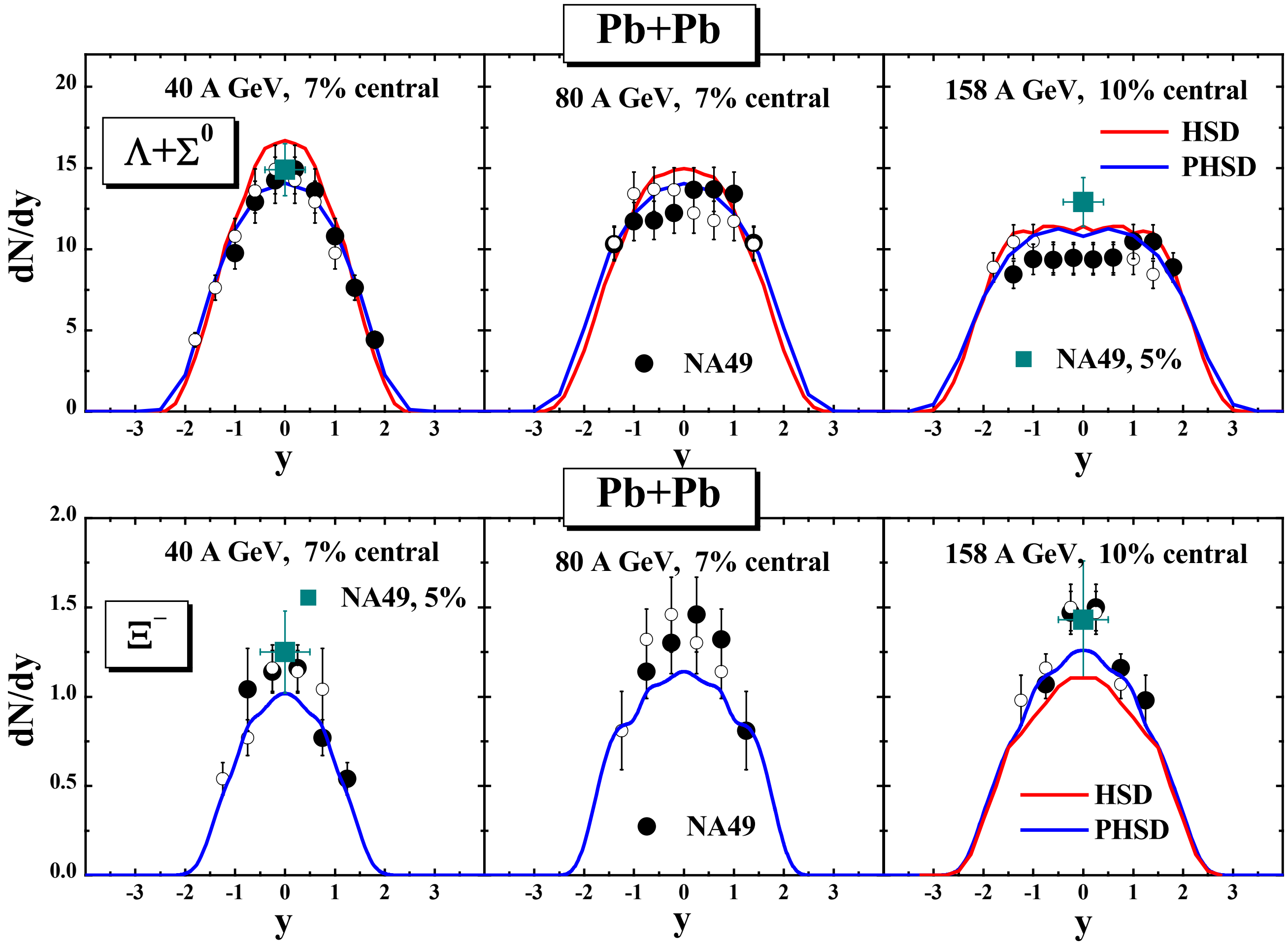


☺ PHSD gives harder spectra and works better than HSD at top SPS energies

☹ However, at low SPS (and FAIR) energies the effect of the partonic phase is NOT seen in rapidity distributions and m_T spectra

Cassing & Bratkovskaya, NPA 831 (2009) 215

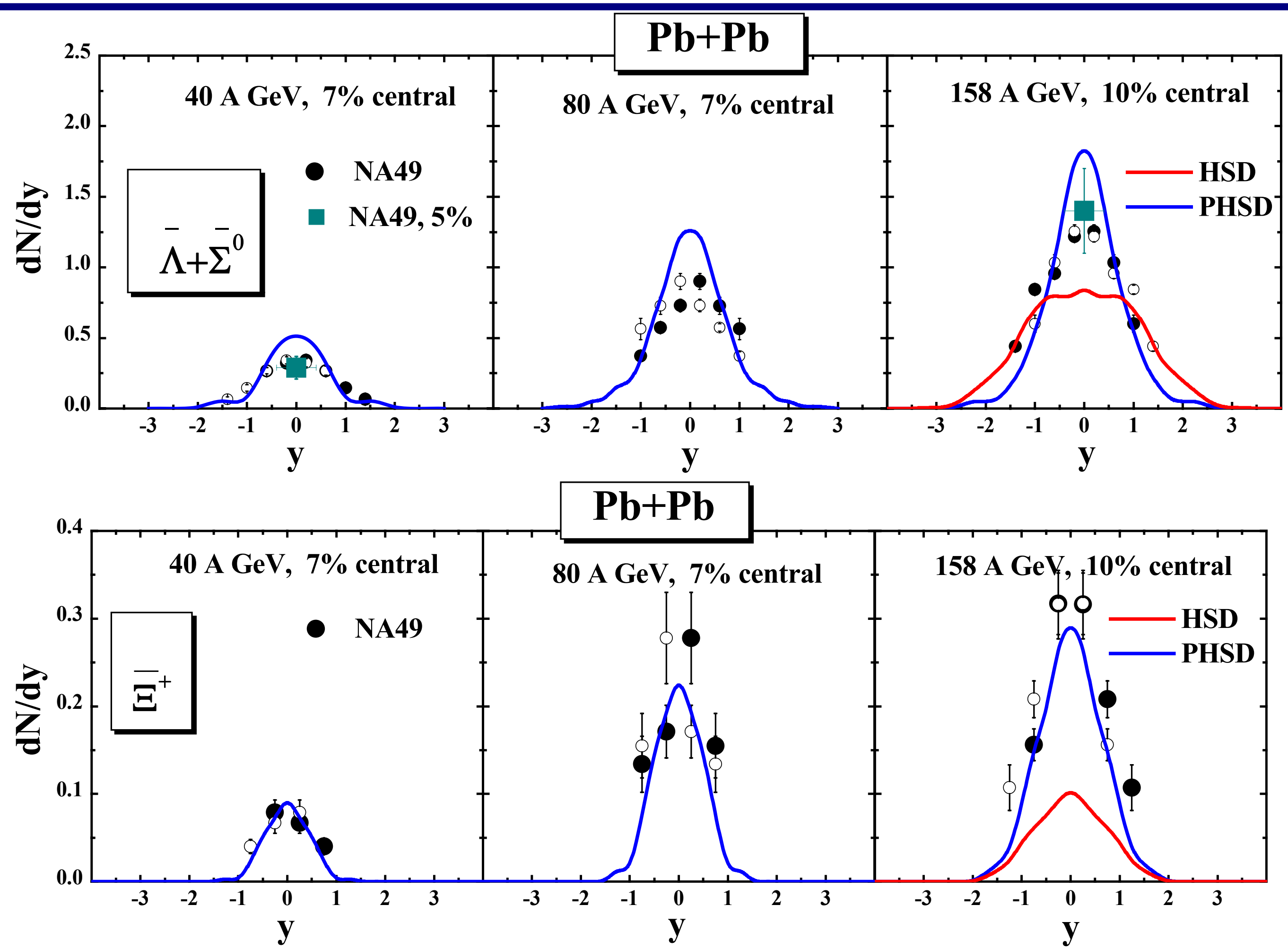
Rapidity distributions of strange baryons



➔ **similar to HSD, reasonable agreement with data**

Cassing & Bratkovskaya, NPA 831 (2009) 215

Rapidity distributions of (multi-)strange antibaryons



strange antibaryons

$\bar{\Lambda}+\bar{\Sigma}^0$

multi-strange antibaryon

$\bar{\Xi}^+$

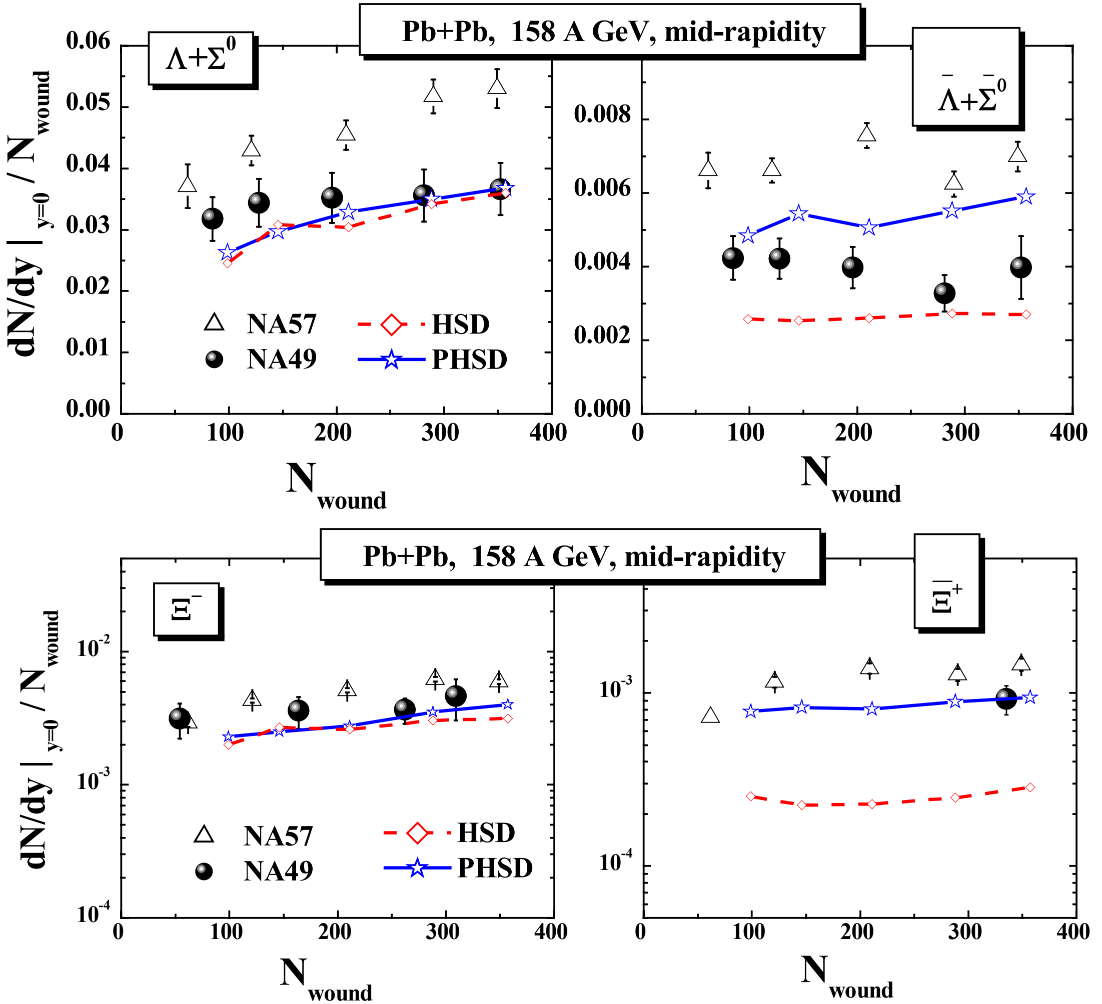
➔ enhanced production of (multi-) strange anti-baryons in PHSD

Cassing & Bratkovskaya, NPA 831 (2009) 215

Centrality distributions of (multi-)strange (anti-)baryons

strange baryons $\Lambda+\Sigma^0$

strange antibaryons $\bar{\Lambda}+\bar{\Sigma}^0$



multi-strange baryon Ξ^-

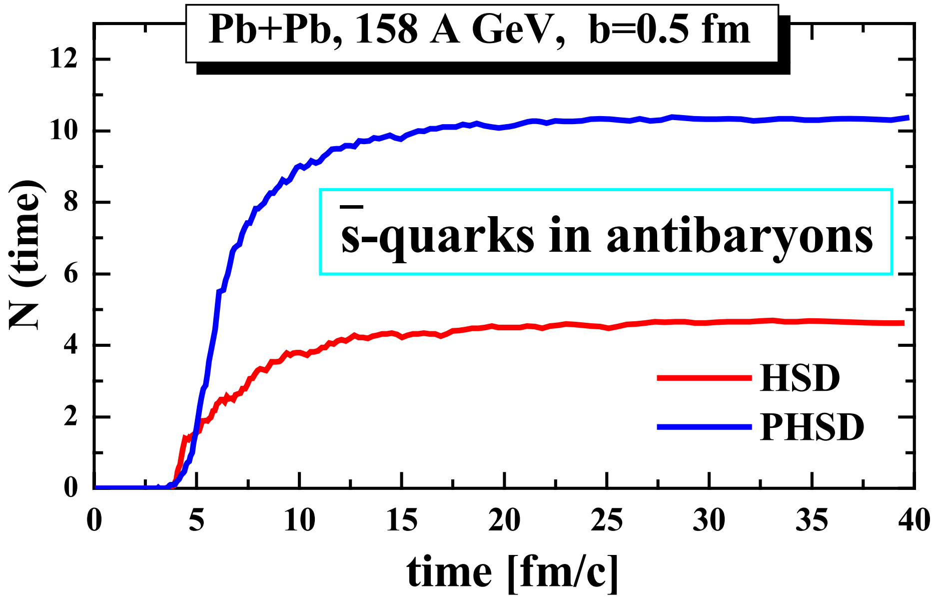
multi-strange antibaryon $\bar{\Xi}^+$

➔ enhanced production of (multi-) strange antibaryons in PHSD

Cassing & Bratkovskaya, NPA 831 (2009) 215

Number of s-bar quarks in hadronic and partonic matter

Number of s-bar quarks in antibaryons for central Pb+Pb collisions at 158 A GeV from PHSD and HSD

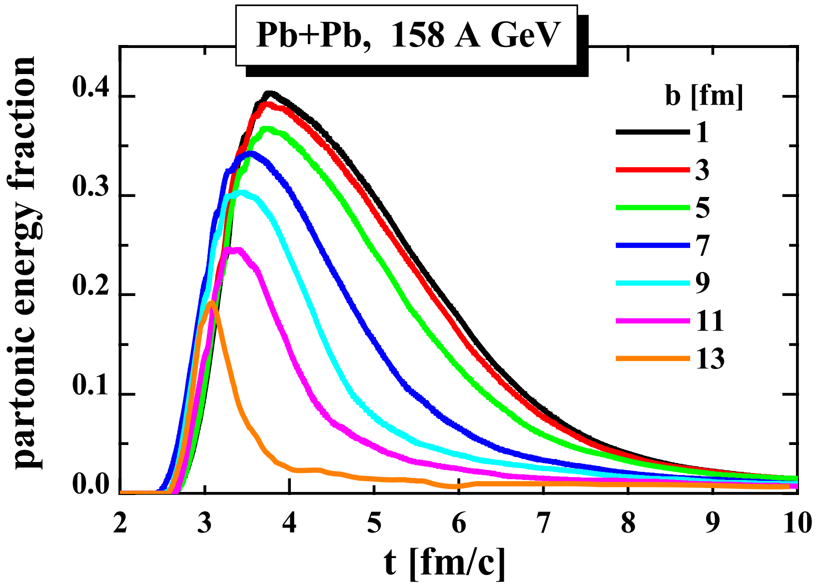


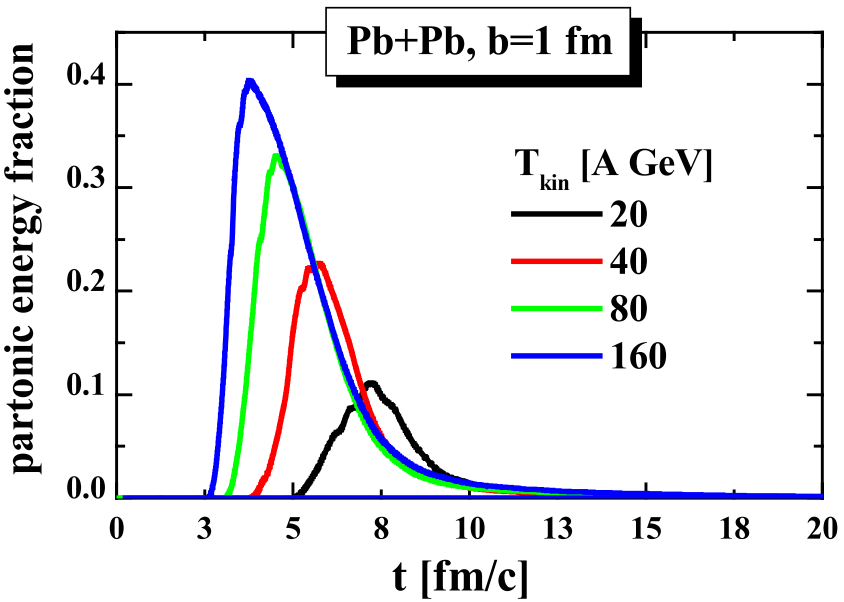
➔ **significant effect on the production of (multi-)strange antibaryons due to a slightly enhanced s-sbar pair production in the partonic phase from massive time-like gluon decay and a larger formation of antibaryons in the hadronization process!**

Cassing & Bratkovskaya, NPA 831 (2009) 215

Perspectives at FAIR energies

partonic energy fraction vs centrality and energy





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

Cassing & Bratkovskaya, NPA 831 (2009) 215

Summary of part II

- **PHSD provides a consistent description of off-shell parton dynamics in line with lQCD; 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 lQCD EoS (where the phase transition is always a cross-over) is used**

Open problems

- Is the critical energy/temperature provided by the lQCD calculations sufficiently accurate?

- How to describe a first-order phase transition in transport ?

- How to describe parton-hadron interactions in a ‚mixed' phase?

Thanks

in particular to

Elena Bratkovskaya
(dynamical hadronization and application to A+A reactions)

Sascha Juchem
(off-shell transport)

Andre Peshier
(DQPM)

and the numerous theoretical and experimental friends and colleagues !