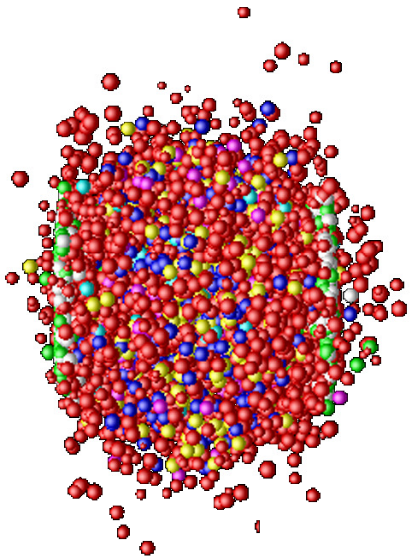
Institut für
Theoretische Physik I
JUSTUS-LIEBIG-UNIVERSITÄT GIESSEN

The hadronization problem in transport approaches



Wolfgang Cassing

Heraklion
31.08.2011
NeD-Symposium

PHSD

From lattice QCD to parton dynamics

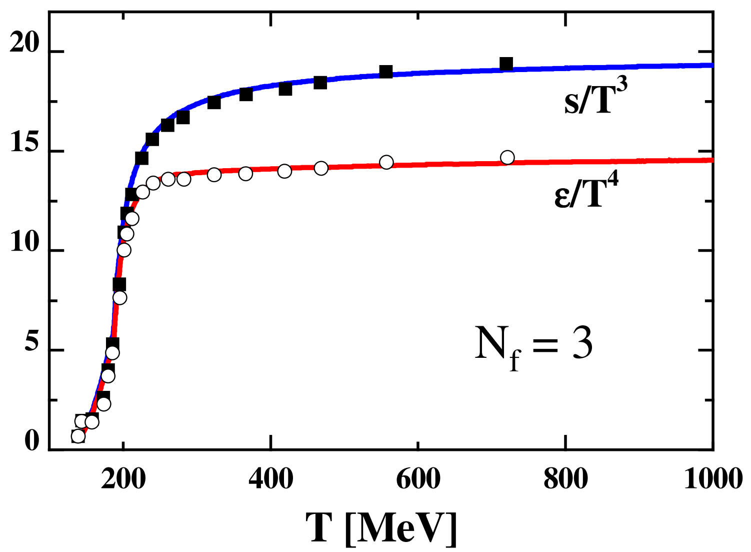
Thermodynamics: entropy $s = \frac{\partial P}{dT}$ → pressure P

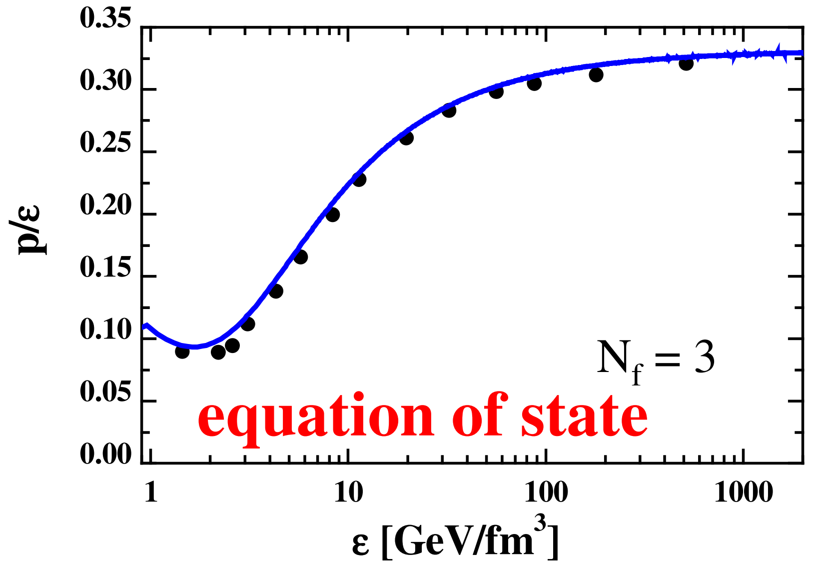
energy density: $\epsilon = Ts - P$

interaction measure:

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

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





What are the effective degrees-of-freedom? → 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 $E^2(p) = p^2 + M^2 - \gamma^2$

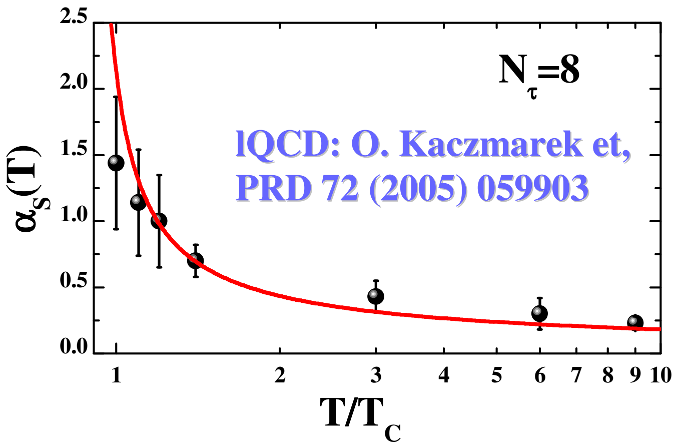
A. Peshier, PRD 70 (2004) 034016

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

The running coupling g^2

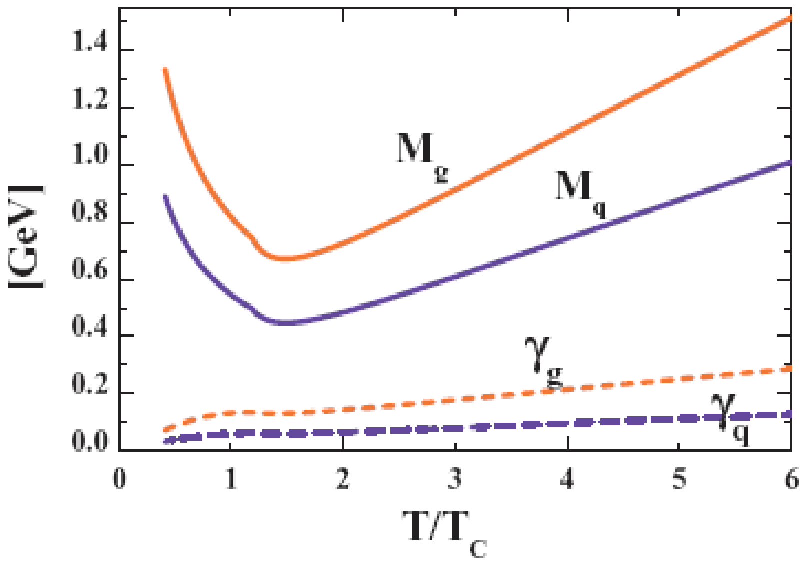
$$g^2(T/T_c) = \frac{48\pi^2}{(11N_c - 2N_f)\ln(\lambda^2(T/T_c - T_s/T_c)^2}$$

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

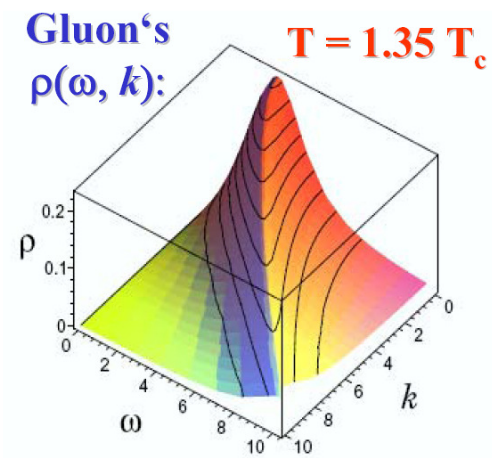


fit to lattice (lQCD) entropy density:

→ quasiparticle properties ($N_f=3$; T_c = 0.16 GeV)



finite width for gluons and quarks !



DQPM thermodynamics (N_f=3)

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

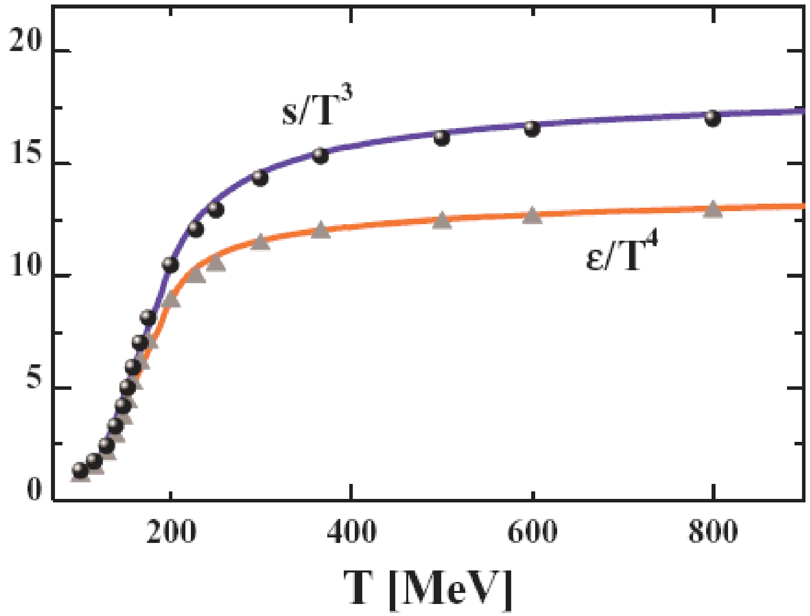
energy density: $\epsilon = Ts - P$

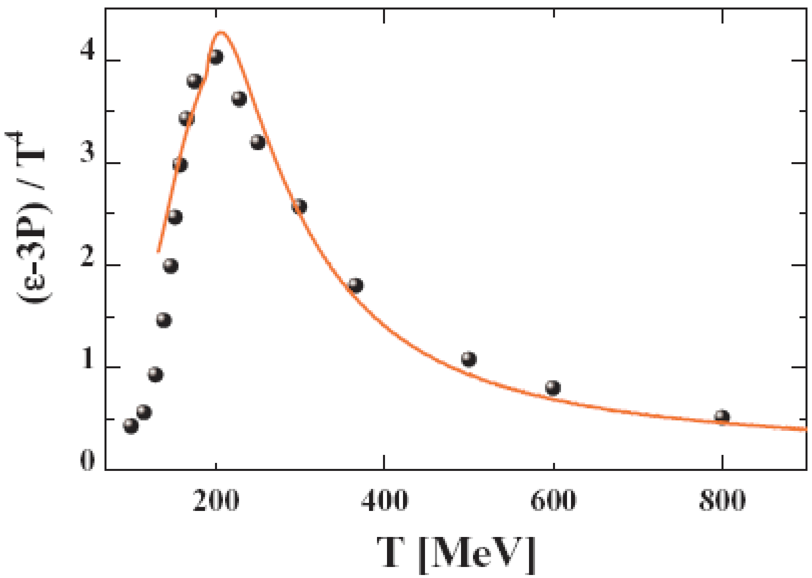
interaction measure:

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

$N_f = 3$

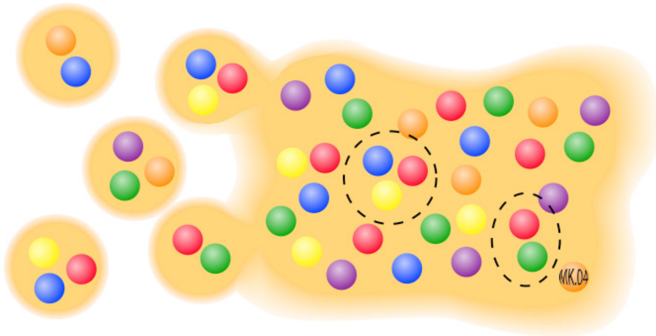
lQCD: Fodor & Katz, (2009)





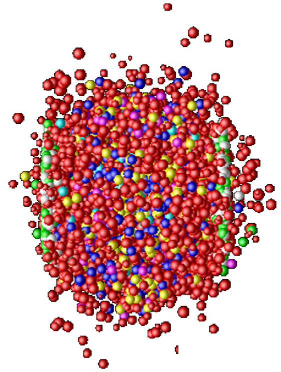
DQPM gives a ‚perfect' description of lQCD results !

Transport description of the partonic and hadronic phase



Parton-Hadron-String-Dynamics (PHSD)

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 (or 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

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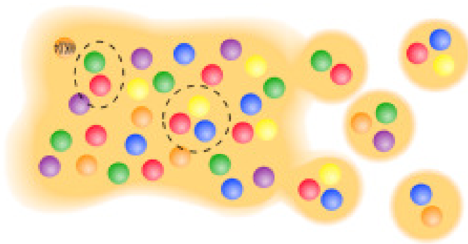
III. PHSD: hadronization



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 states 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 $\rho_P \to 0$ => $\frac{d^4P}{\Delta V \Delta t} |_{\rho_P \to 0} \to \infty$
=> hadronization successful !

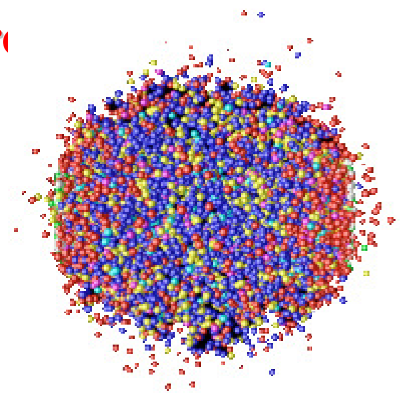
IV. PHSD: hadronization

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) → 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 $\sqrt{< r^2 >} = 0.66$ fm

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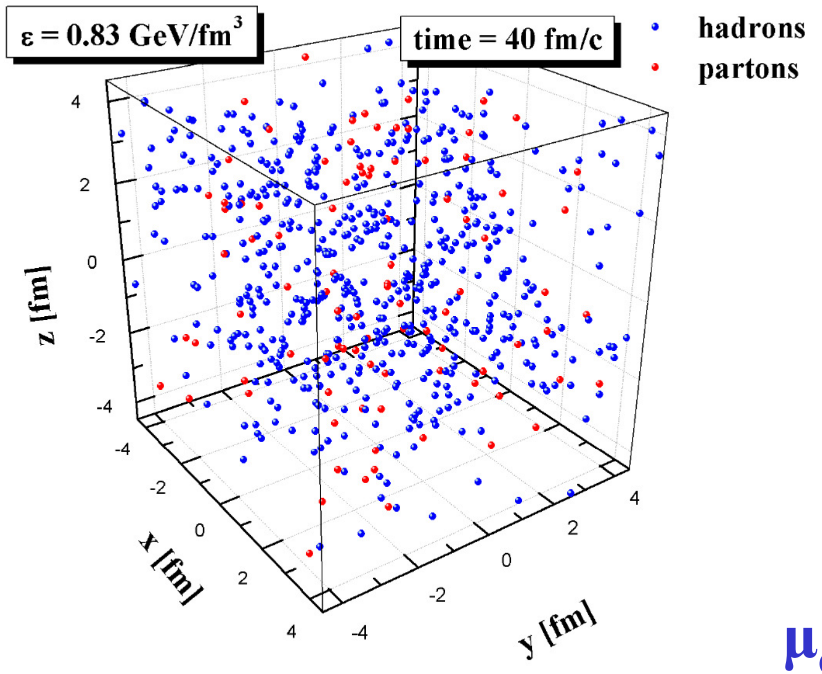
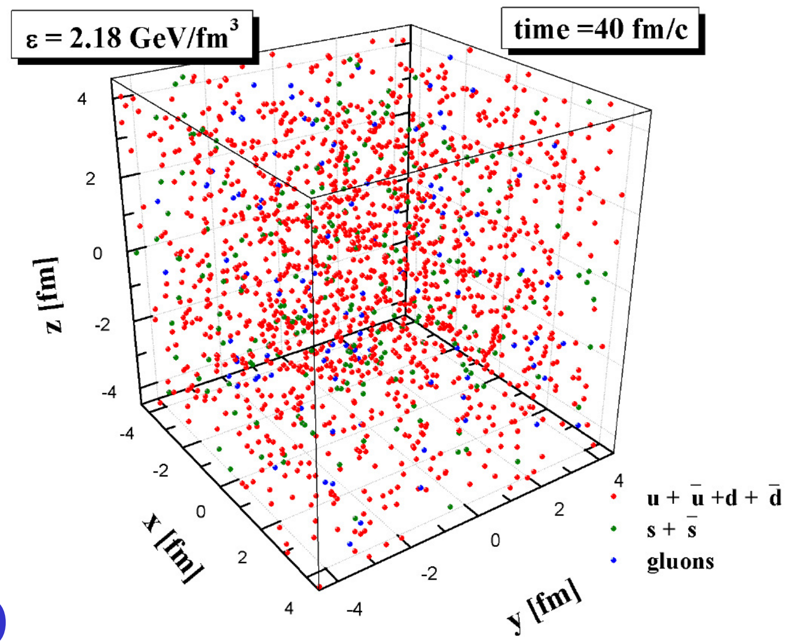
Systems in a finite box – periodic boundary cond.

Initialize the system with some number of partons and 4-momentum distributions in line with the DQPM
→ energy density $\varepsilon = E/V$ and chemical potential μ_q

Evolve the system in time until equilibrium is achieved !





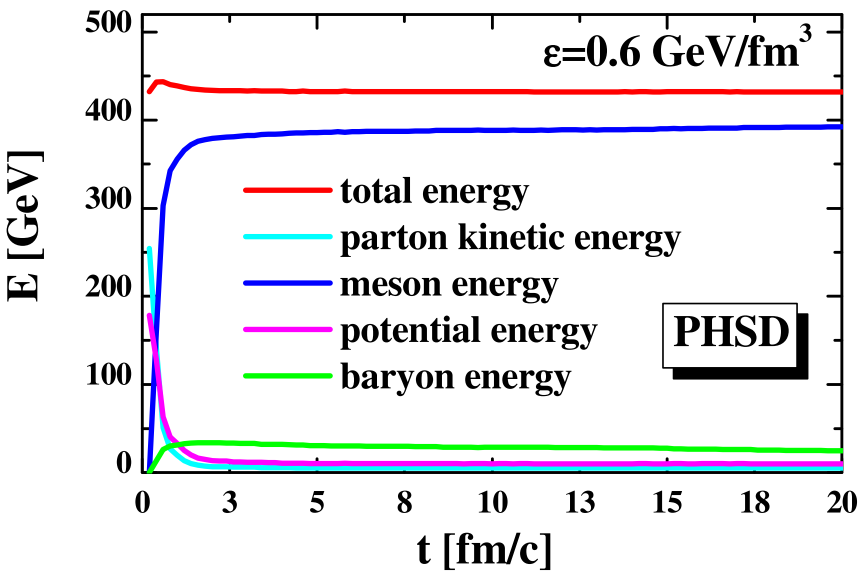
$\mu_q = 0$

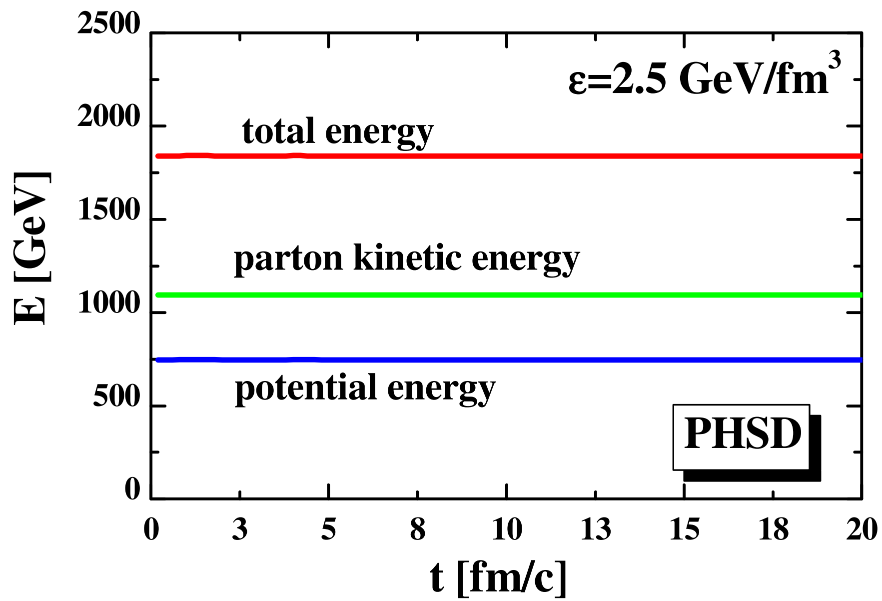
Note: the volume is divided into 9^3 cells of size 1 fm^3 !

Systems in a finite box – energy partitions

The system evolves very differently for $\varepsilon < \varepsilon_c$ and $\varepsilon > \varepsilon_c$

$\varepsilon_c = 1.2$ GeV/fm^3

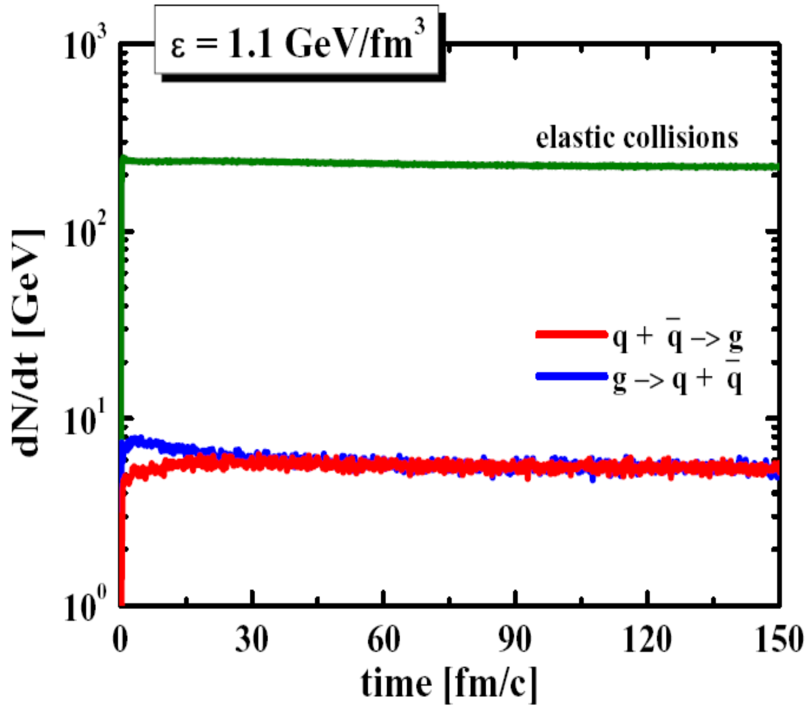


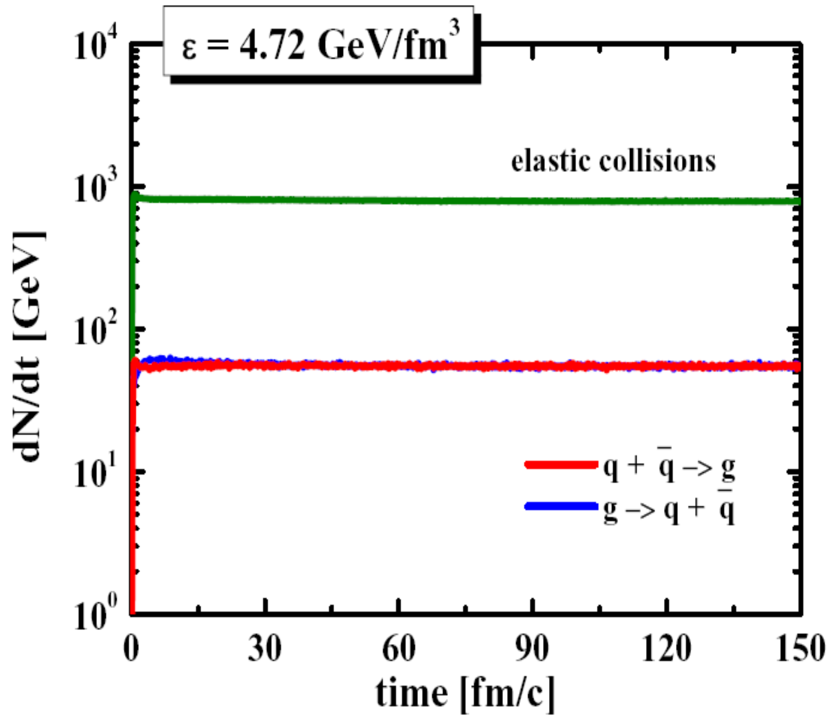


See talk by Vitalii Ozvenchuk next week!

Systems in a finite box – reaction rates

Partonic interaction rates: $\varepsilon_c = 0.5$ GeV/fm^3



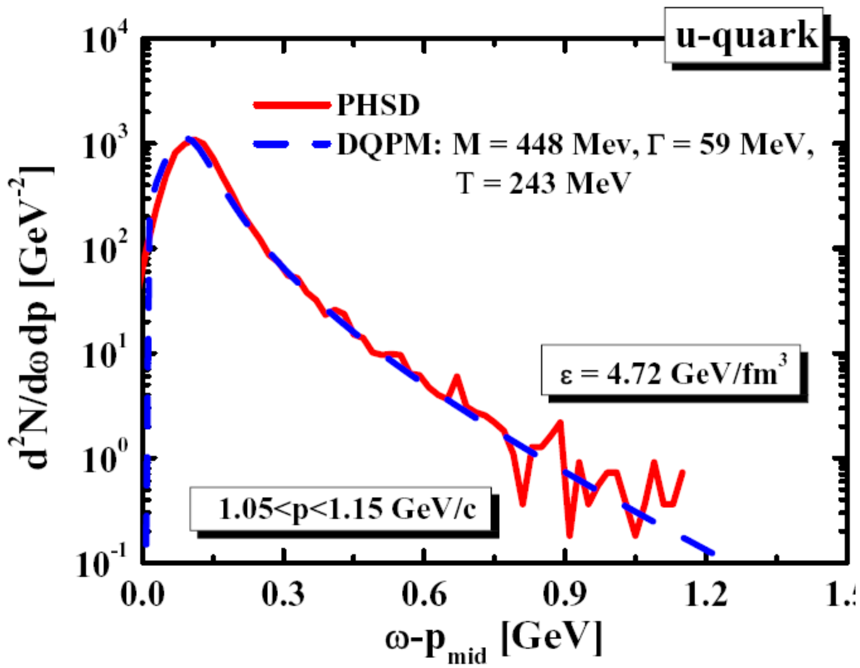


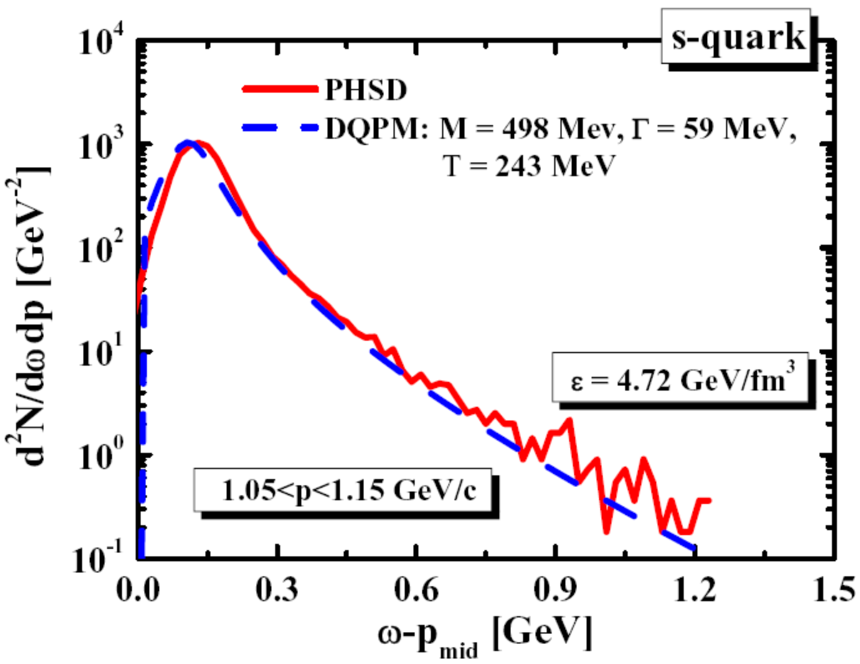
Detailed balance is established in equilibrium !

See talk by Vitalii Ozvenchuk next week!

Systems in a finite box – dynamical equilibrium

Equilibrium distributions of u- and s-quarks

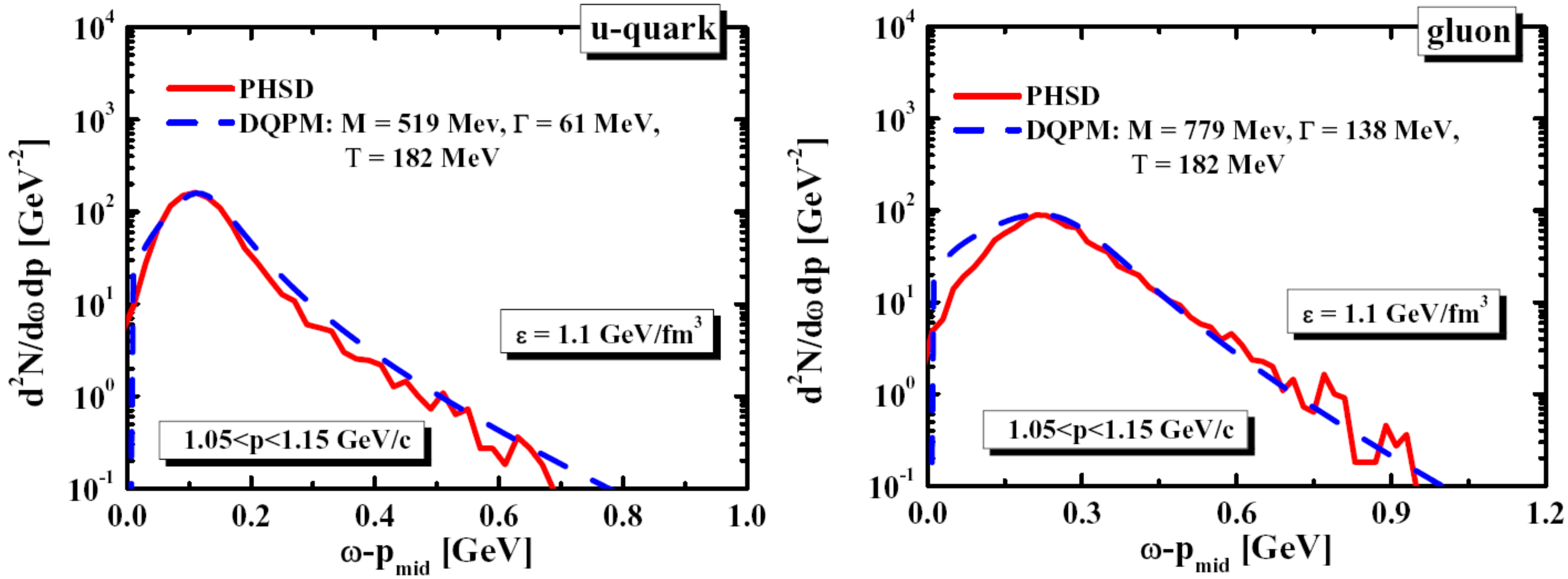




Good match between PHSD and the DQPM! $\varepsilon = 4.72$ GeV/fm^3

Systems in a finite box – dynamical equilibrium

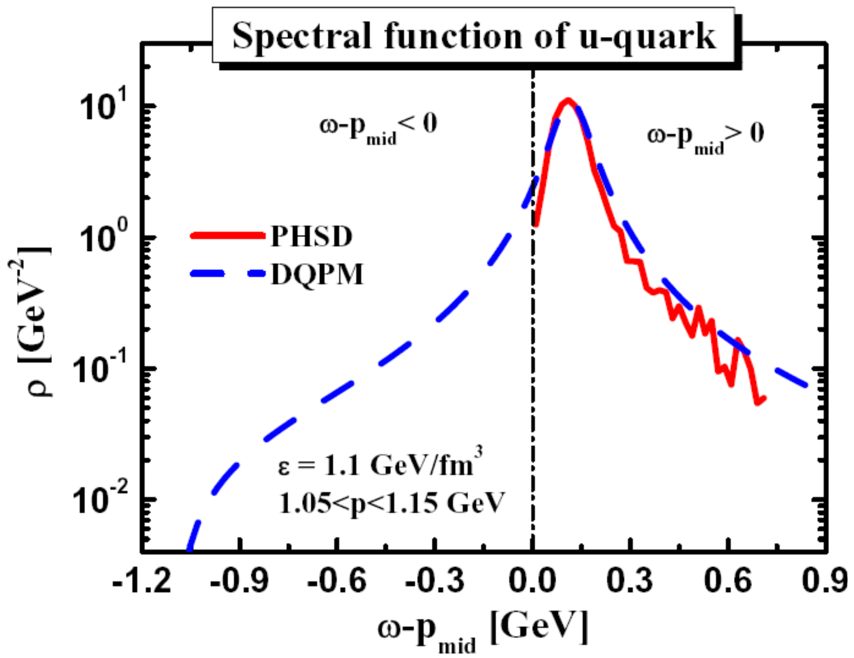
Equilibrium distributions of u-quarks and gluons

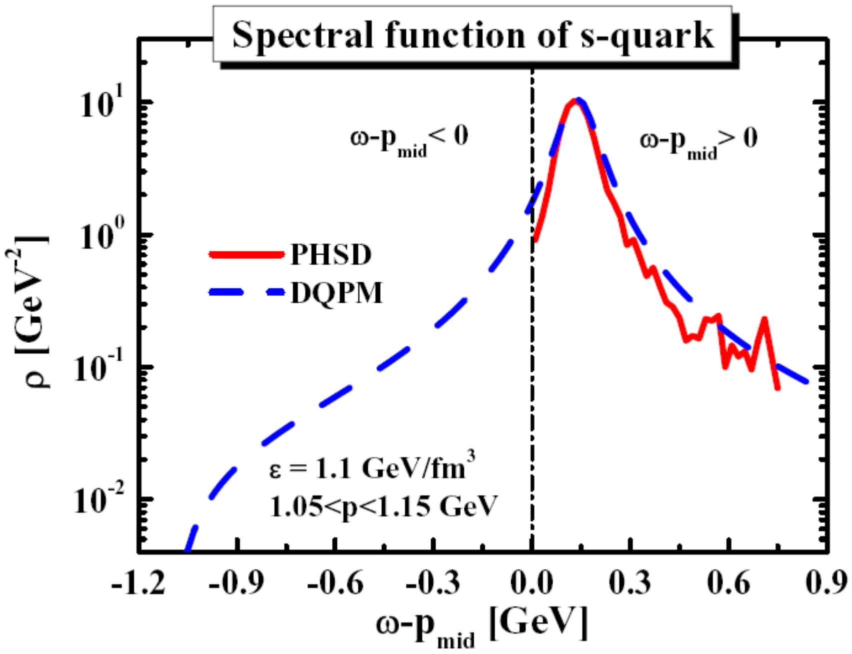


Good match between PHSD and the DQPM! $\varepsilon = 1.1\ \mathrm{GeV/fm^3}$

Systems in a finite box – spectral functions

Equilibrium spectral functions of u- and s-quarks



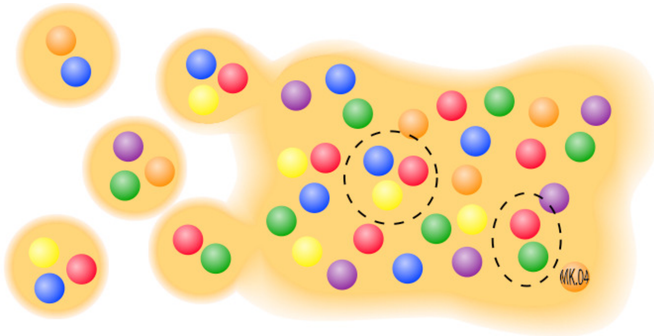


Good match between PHSD and the DQPM! $\varepsilon = 1.1$ GeV/fm^3

Note: PHSD propagates only time-like partons!

See talk by Vitalii Ozvenchuk next week!

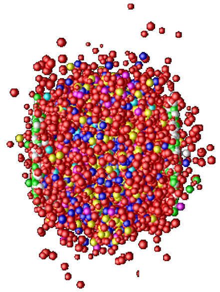
Transport description of hadronization



Parton-Hadron-String-Dynamics (PHSD)

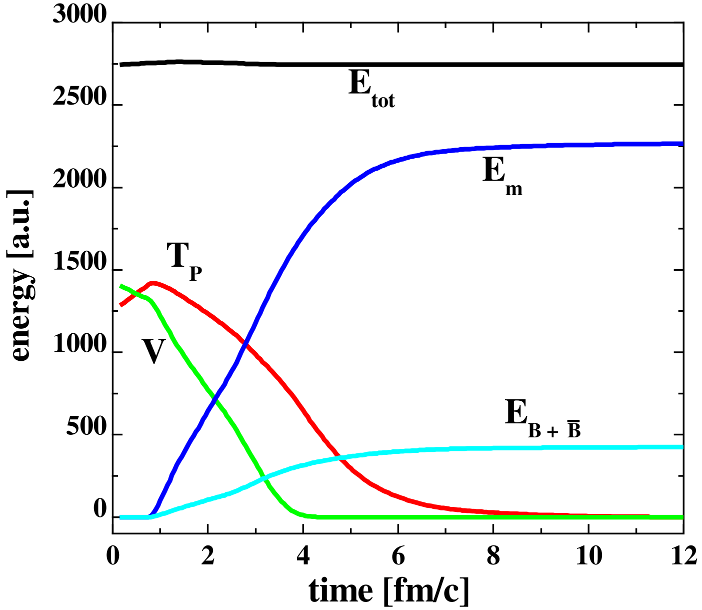
Expanding partonic fireball I

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

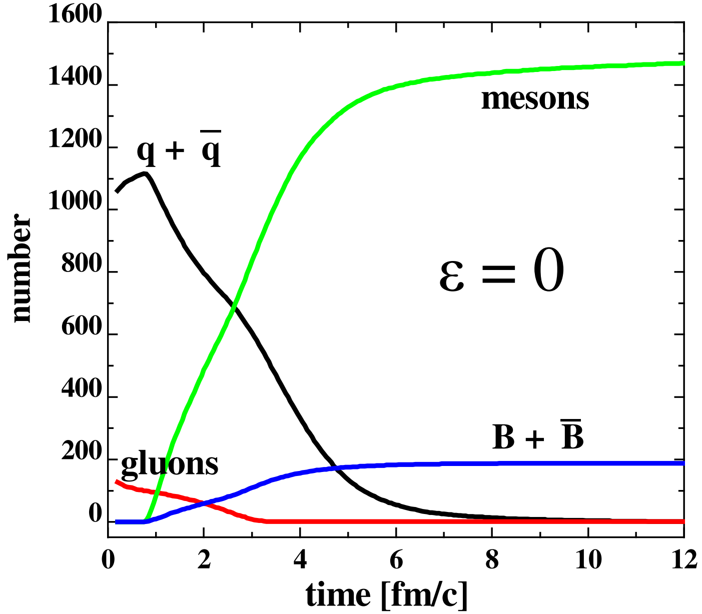


Eccentricity: $\varepsilon = (\sigma_y^2 - \sigma_x^2)/(\sigma_y^2 + \sigma_x^2)$

energy conservation



partons and hadrons



More hadrons in the final state than initial partons !

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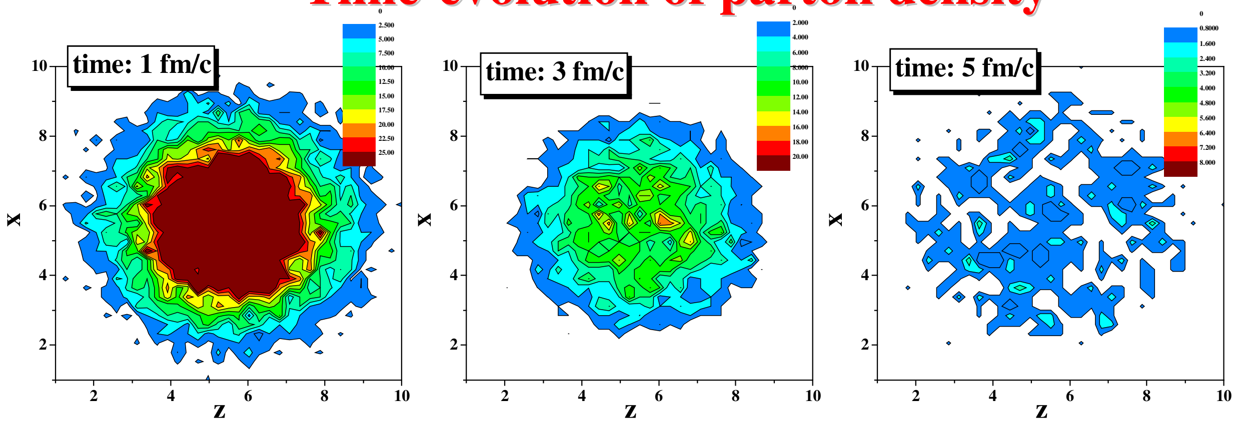
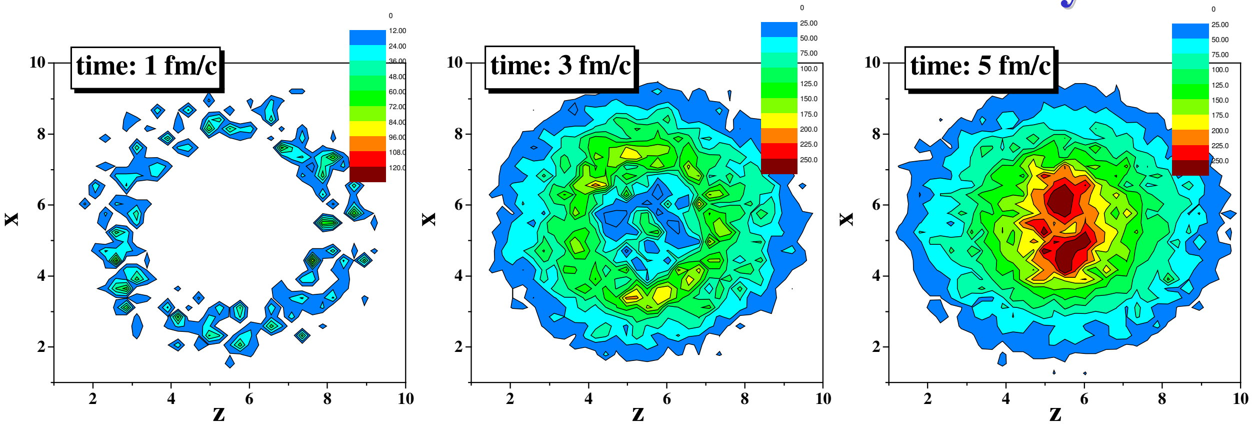
PHSD: Expanding fireball II

Time-evolution of parton density



Time-evolution of hadron density

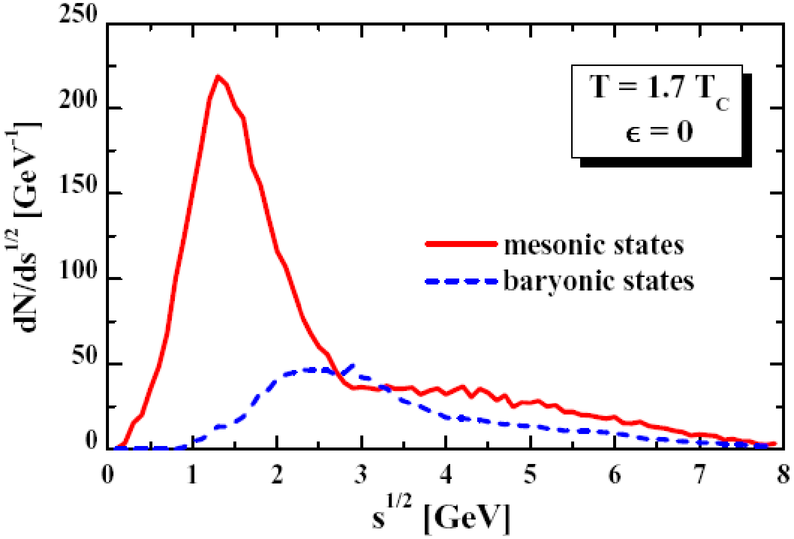


Expanding grid: $\Delta z(t) = \Delta z_0(1+a\ t)$!

PHSD: spacial phase ‚co-existence' of partons and hadrons, but NO interactions between hadrons and partons (since it is a cross-over)

Hadronization details

mass distributions for color neutral ‚mesons' and ‚baryons' after parton fusion:



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

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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.

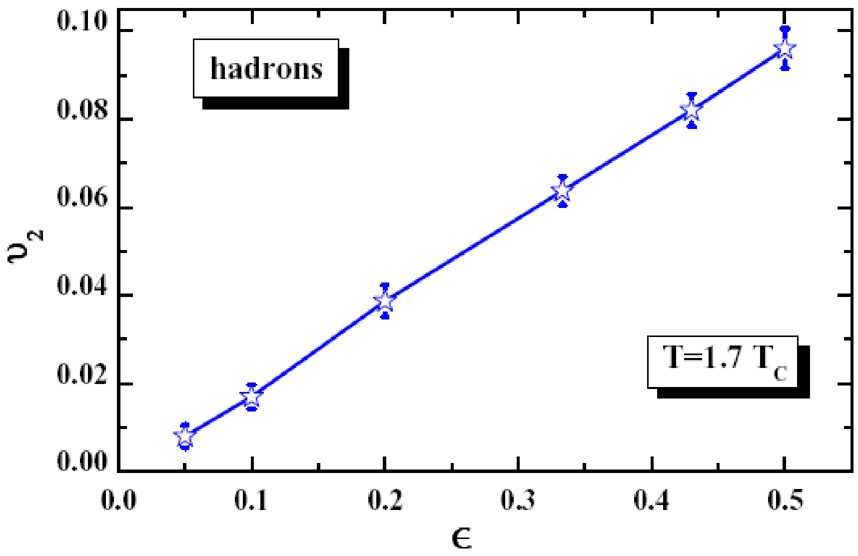
Expanding fireball III – collective aspects

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: $v_2 = 0$ → study final v_2 versus eccentricity ε !

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



v_2/ε = const.
indicates ideal hydrodynamic flow !

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

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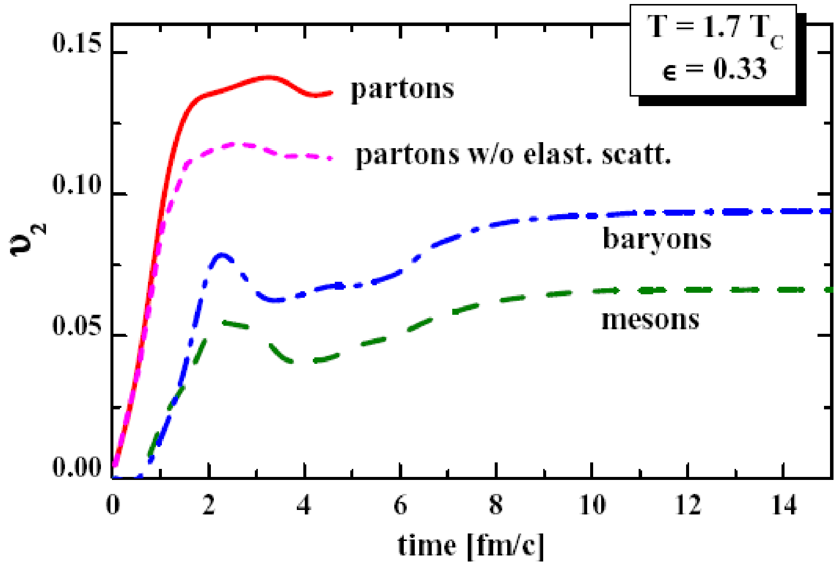
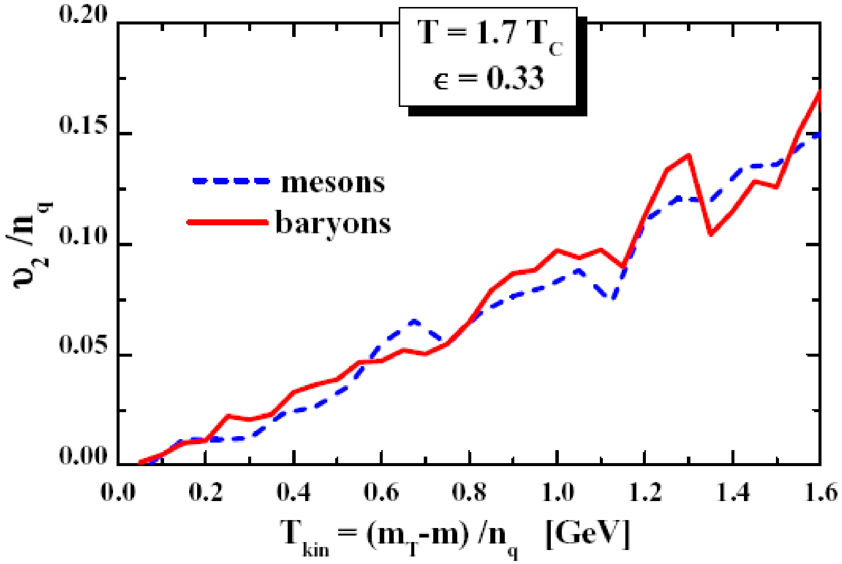
Expanding fireball IV: Differential elliptic flow

time evolution of v_2:



quark number scaling v_2/n_q:



parton v_2 is generated also by the repulsive partonic forces !

meson to baryon v_2 indicates quark number scaling !

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Summary

- The dynamical quasiparticle model (DQPM) defines the transport input for PHSD in line with lQCD!

- PHSD provides a consistent description of off-shell parton dynamics; the repulsive mean fields generate 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 scaled elliptic flow of mesons and baryons is approximately the same as a function of the scaled transverse kinetic energy, but is smaller than the parton $v_2(p_T)$!

Thanks to

Elena Bratkovskaya
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Volodya Konchakovski
Olena Linnyk
Jaakko Manninen
Vitalii Ozvenchuk

PHSD

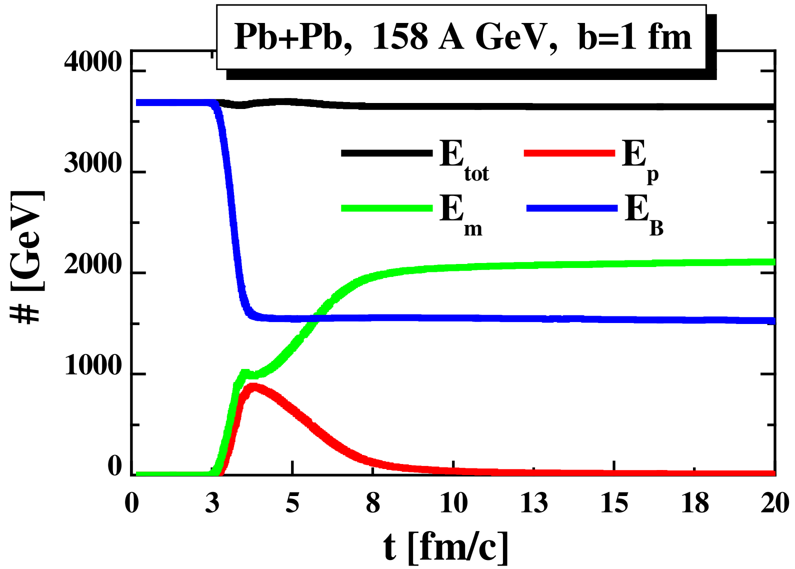
HSD & PHSD Team

HIC for FAIR
Helmholtz International Center

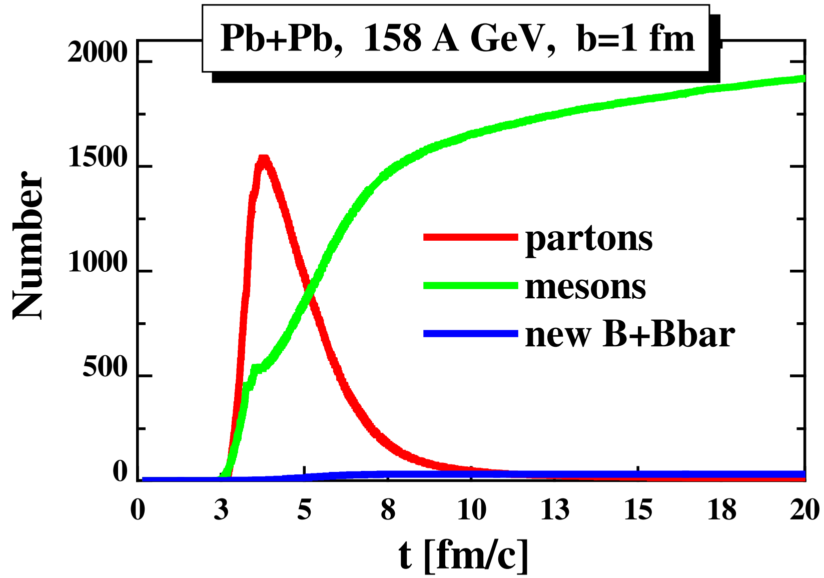
Application to nucleus-nucleus collisions

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!

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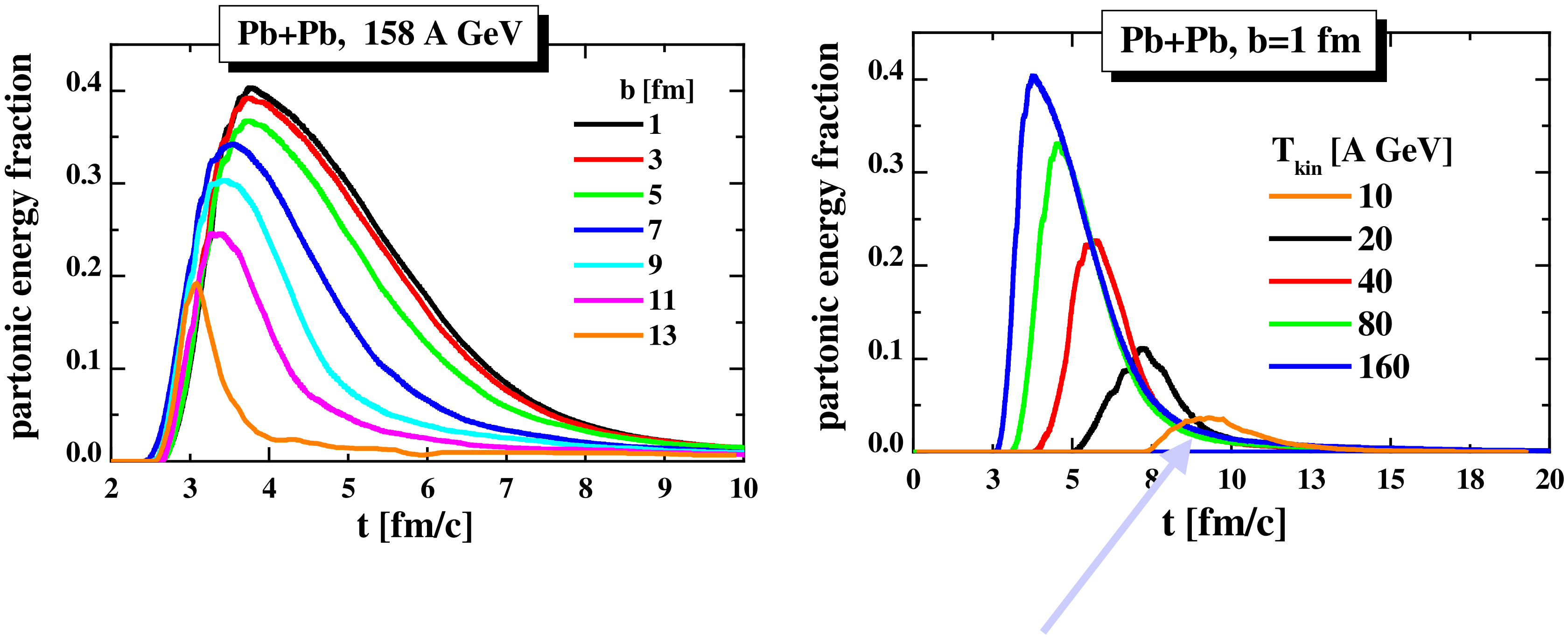
Partonic phase at SPS/FAIR/NICA energies

partonic energy fraction vs centrality and energy



Dramatic decrease of partonic phase with decreasing energy and centrality

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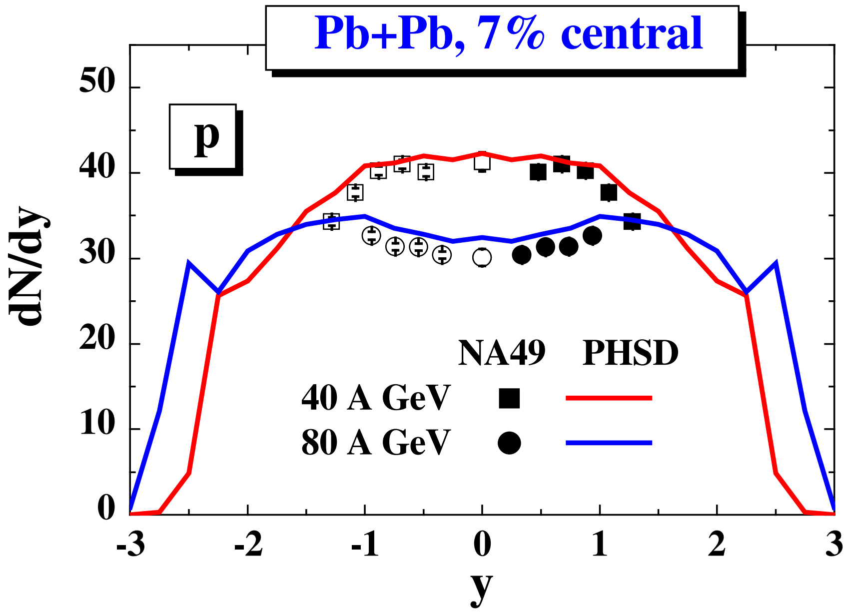
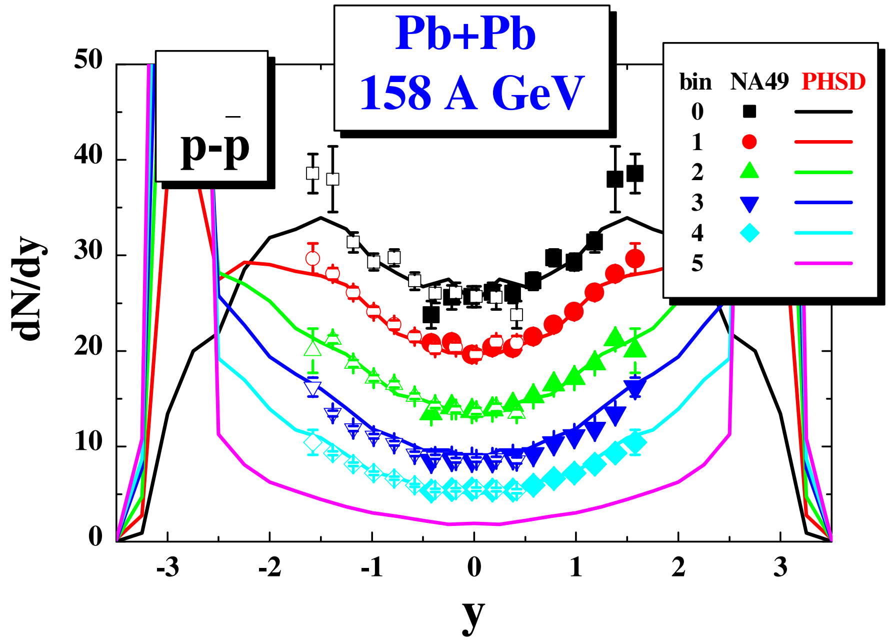
Proton stopping at SPS





➔looks not bad in comparison to NA49 data,
but not sensitive to parton dynamics (PHSD = HSD)!

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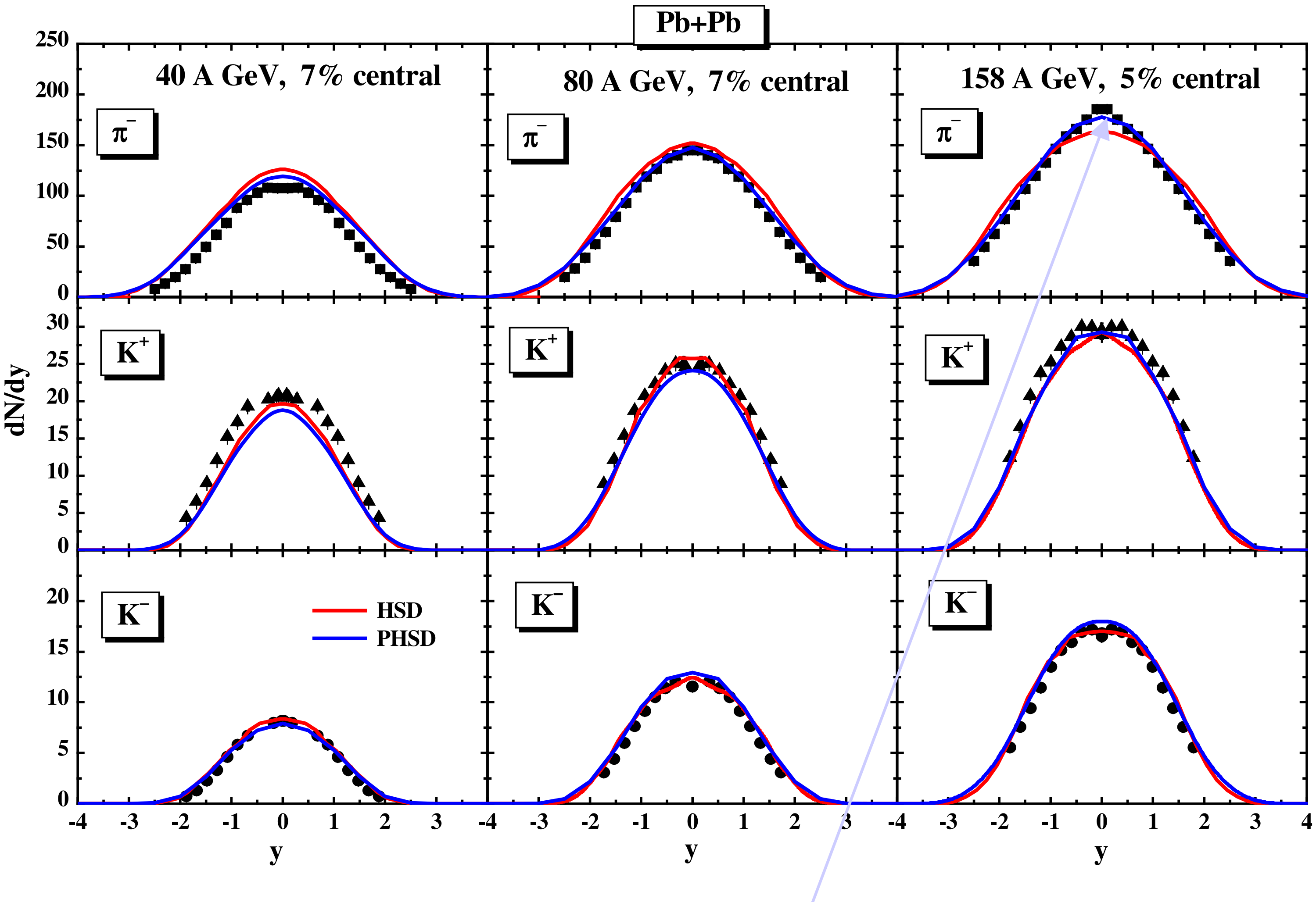
Rapidity distributions of π, K⁺, K⁻



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

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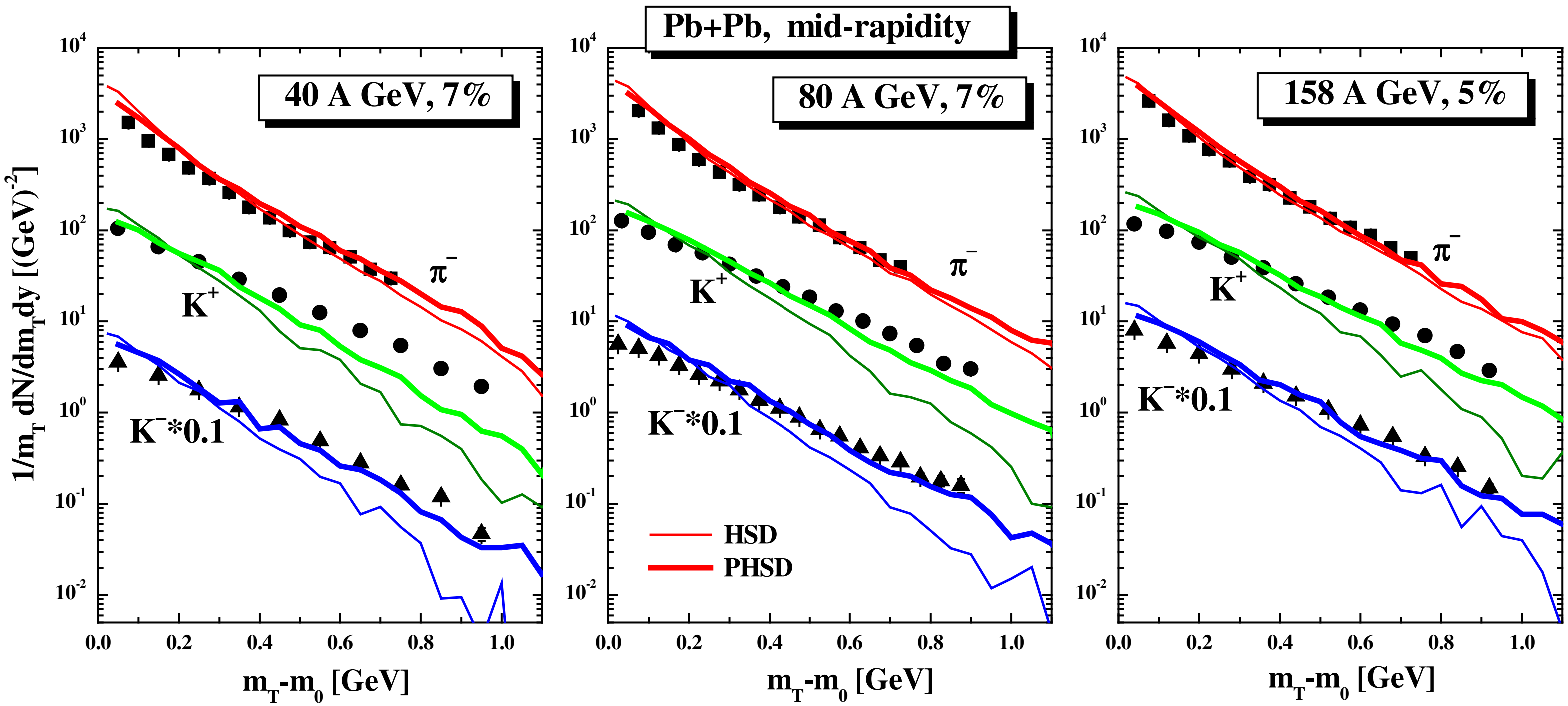
PHSD: Transverse mass spectra at SPS

Central Pb + Pb at SPS energies



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

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

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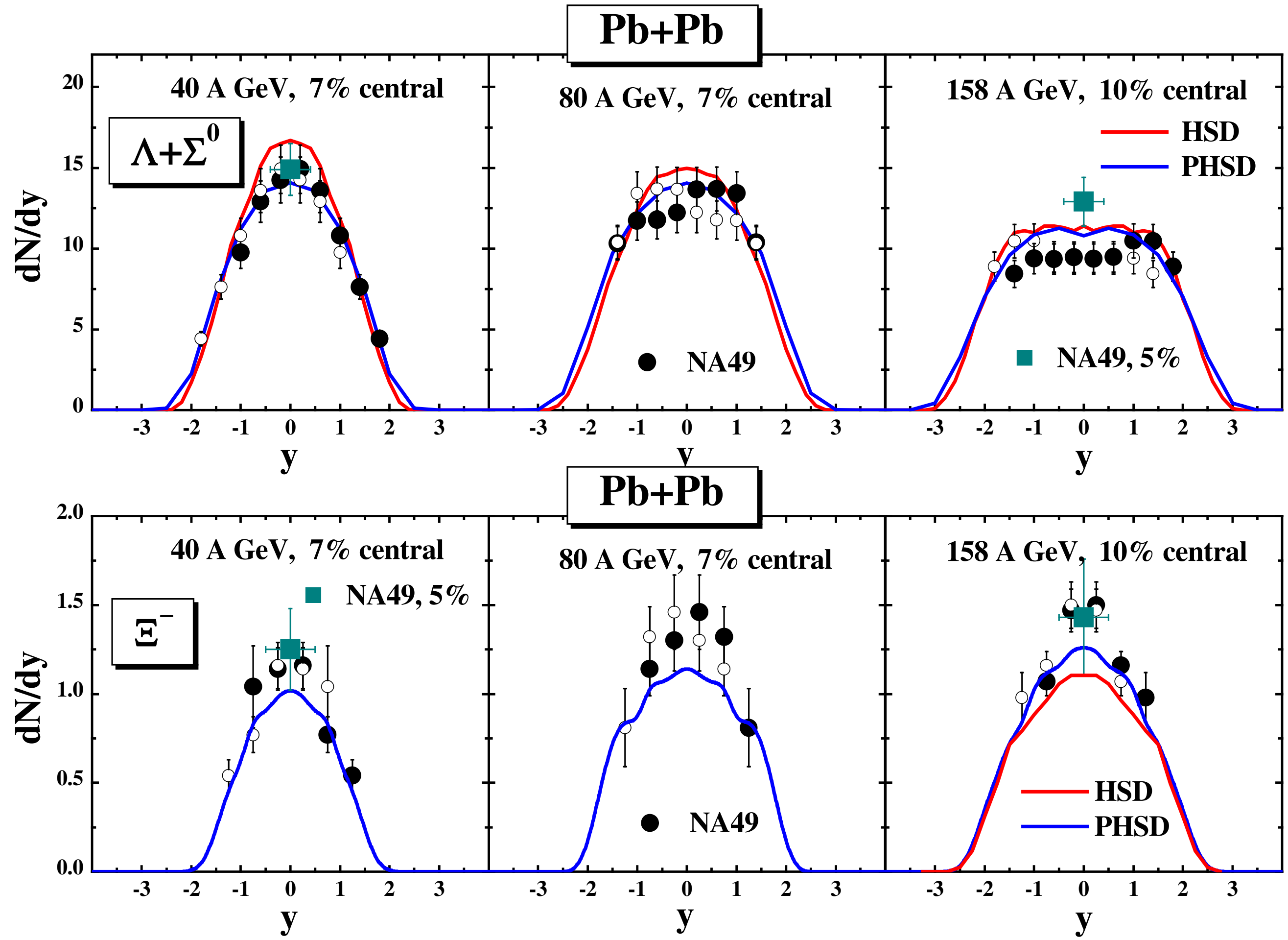
Rapidity distributions of strange baryons



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

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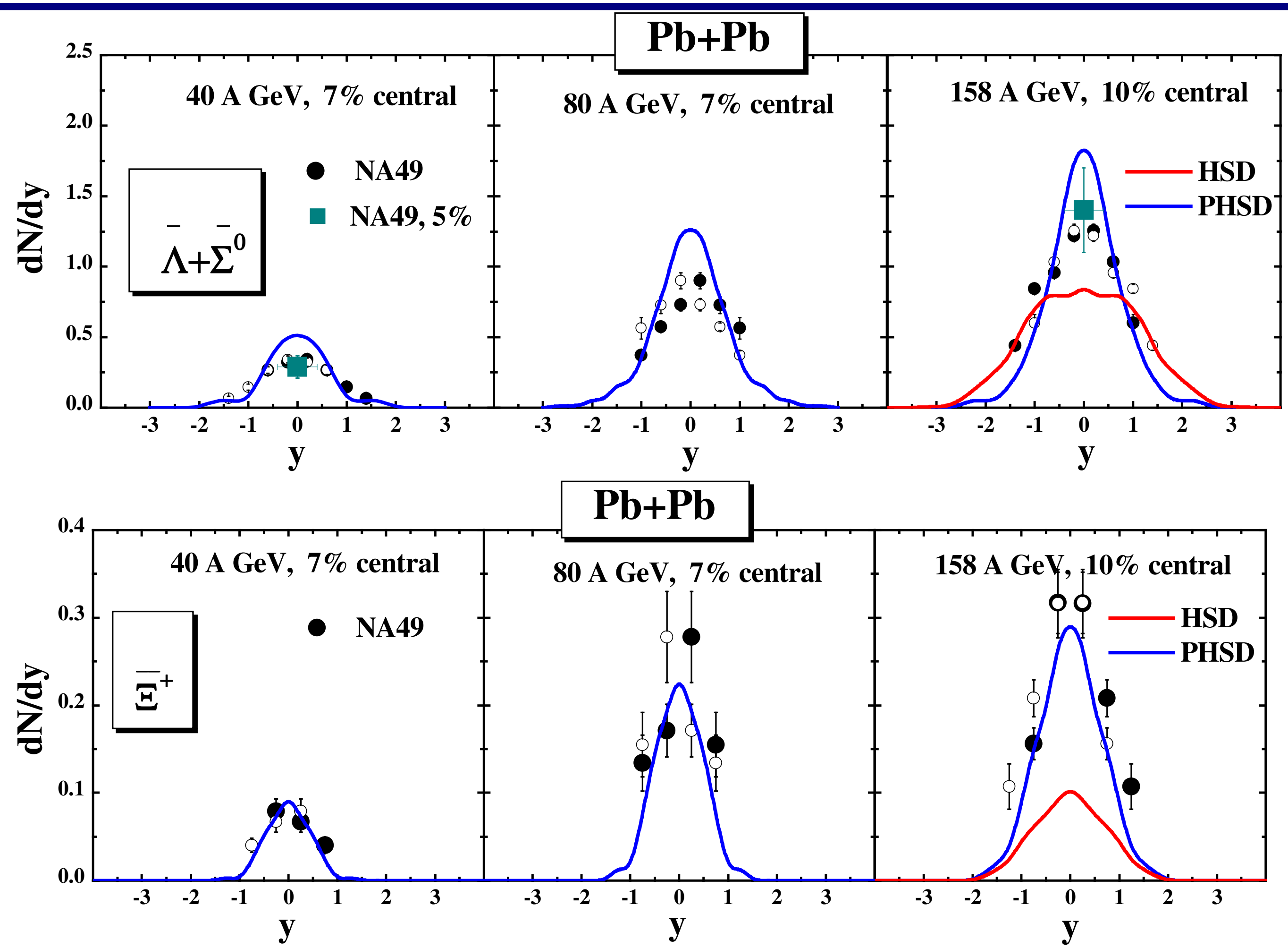
Rapidity distributions of (multi-)strange antibaryons



strange antibaryons

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

multi-strange antibaryon

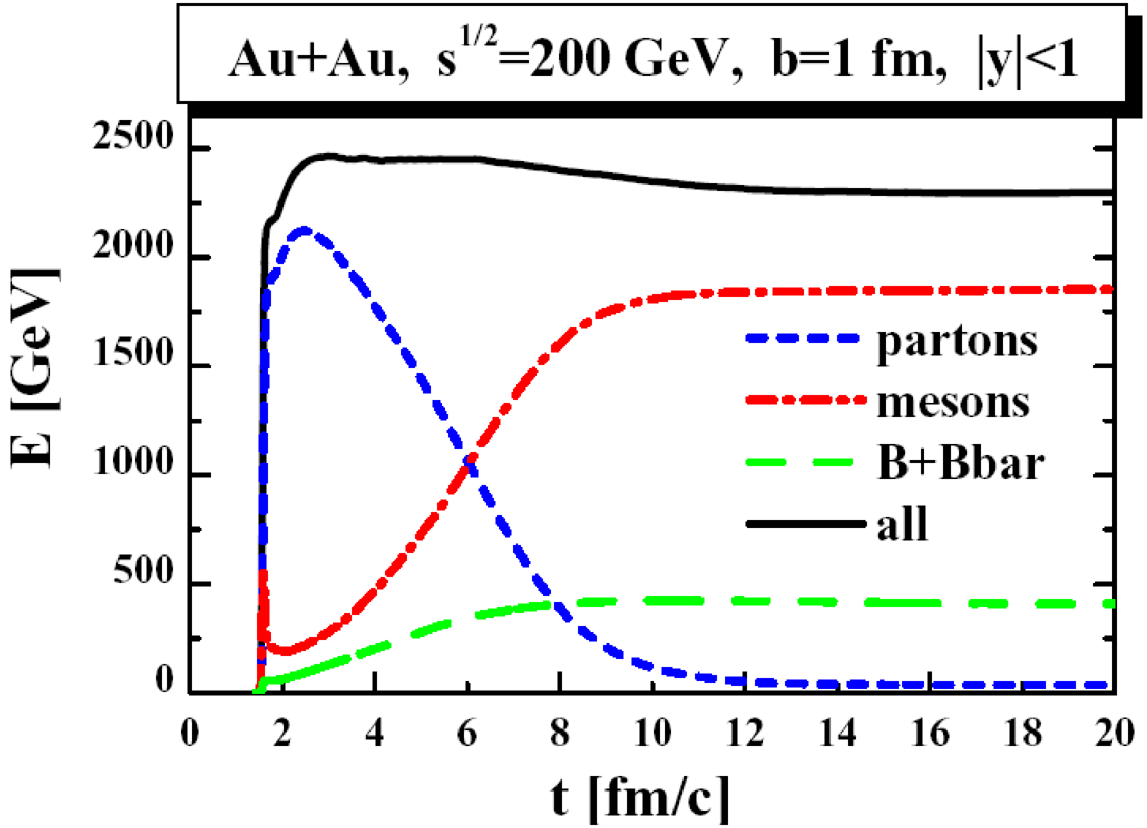
$\bar{\Xi}^+$

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

Cassing & Bratkovskaya, NPA 831 (2009) 215

RHIC energies

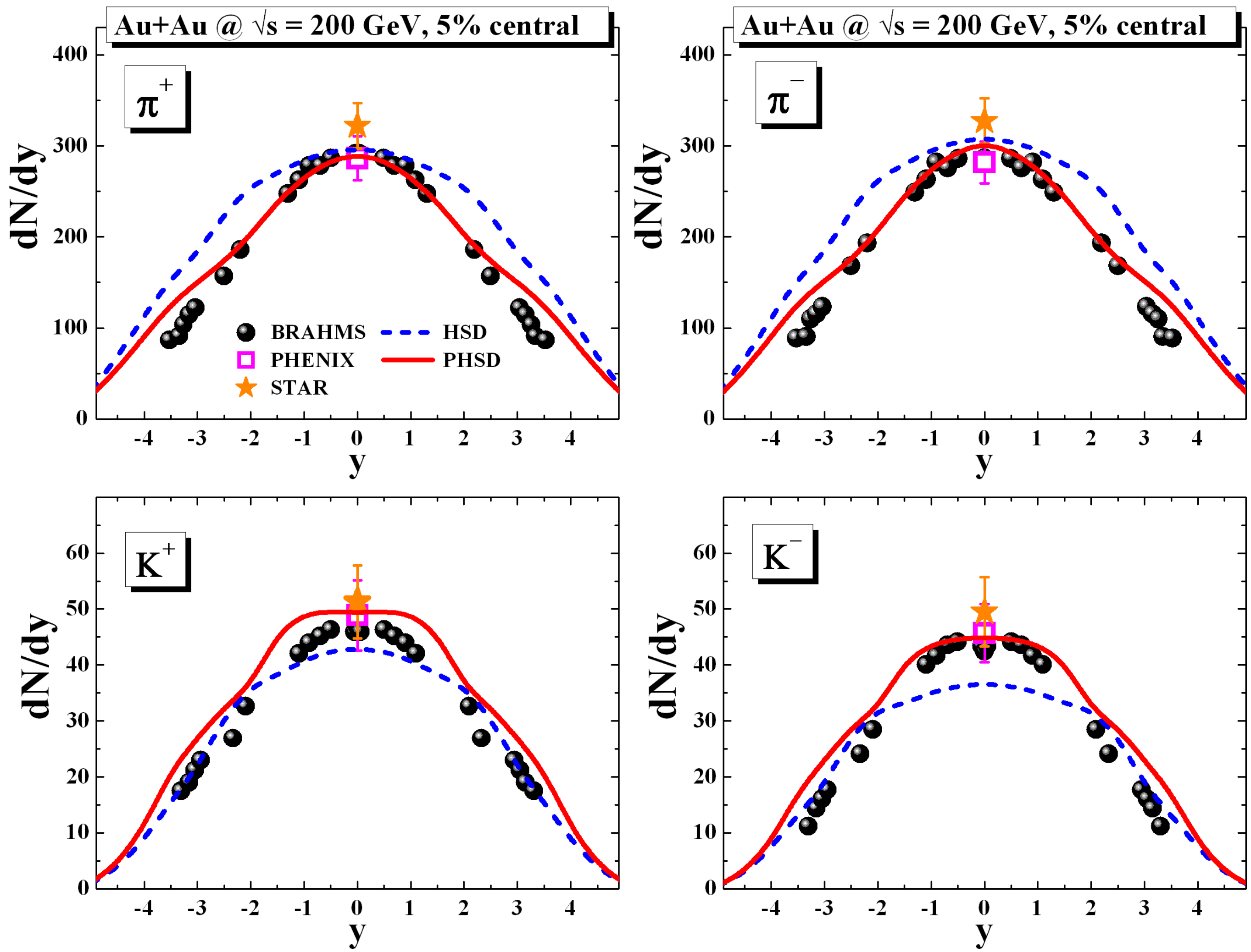
Energy decomposition in central Au + Au collisions at midrapidity:



➔ Up to 85% is partonic energy ! Hadrons dominate after a few fm/c .

E. Bratkovskaya, W. Cassing, V. Konchakovski, O. Linnyk, NPA 856 (2011) 162

Rapidity distributions in central Au+Au at RHIC

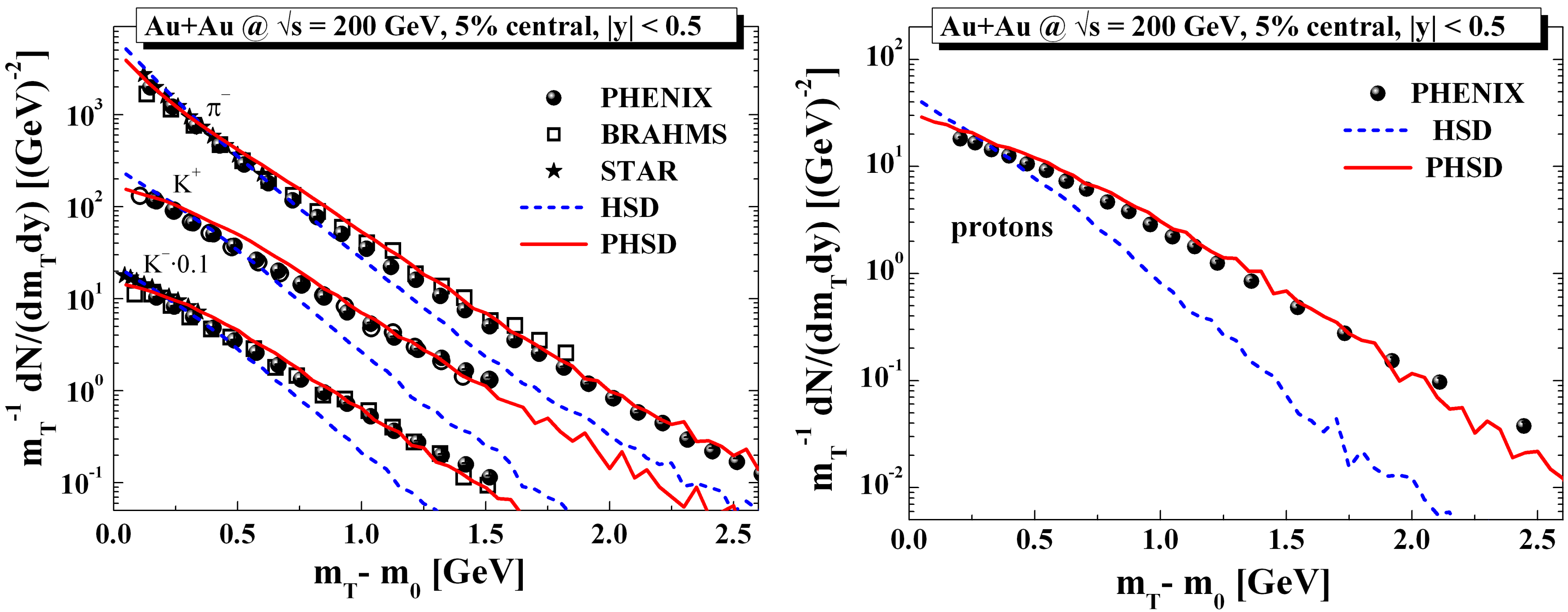


➔ **reasonable description of the data from BRAHMS, STAR, PHENIX!**

E. Bratkovskaya, W. Cassing, V. Konchakovski, O. Linnyk, NPA 856 (2011) 162

Transverse mass distributions in central collisions

Au+Au at midrapidity |y| < 0.5



➔ PHSD gives harder spectra and works better than HSD at RHIC

Note: In PHSD the protons at midrapidity stem from hadronization of quarks.

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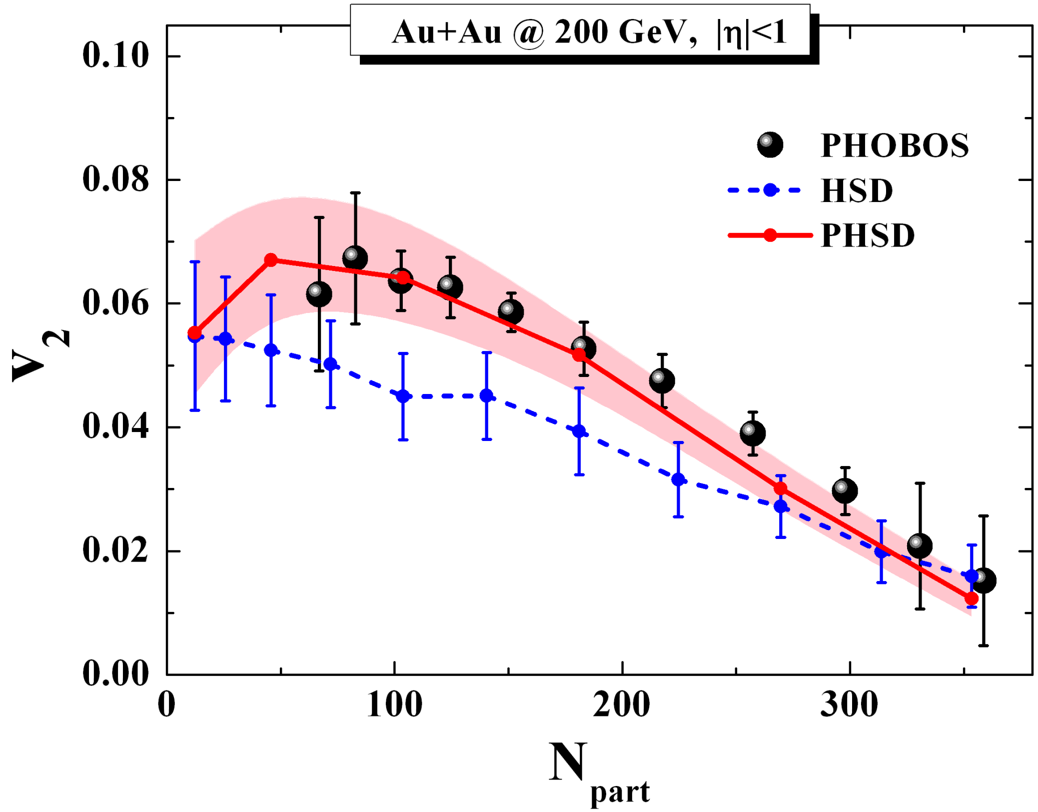
Elliptic flow versus centrality in PHSD

Au+Au at midrapidity |η| < 1



- enhancement of v_2 due to the partonic interactions
- v_2 from PHSD is larger relative to HSD (in line with the data from PHOBOS)

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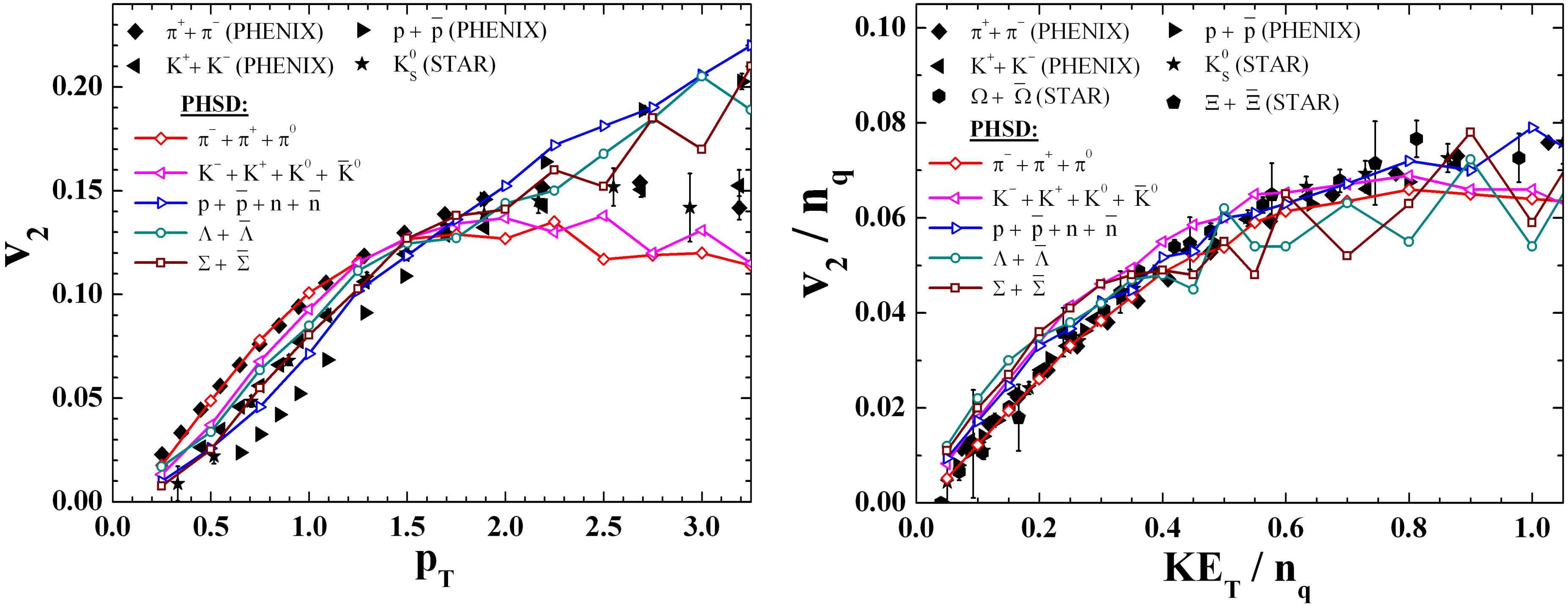
Elliptic flow scaling



- The mass splitting at low p_T is approximately reproduced as well as the meson-baryon splitting for $p_T > 2$ GeV/c !
- The scaling of v_2 with the number of constituent quarks n_q is roughly in line with the data .

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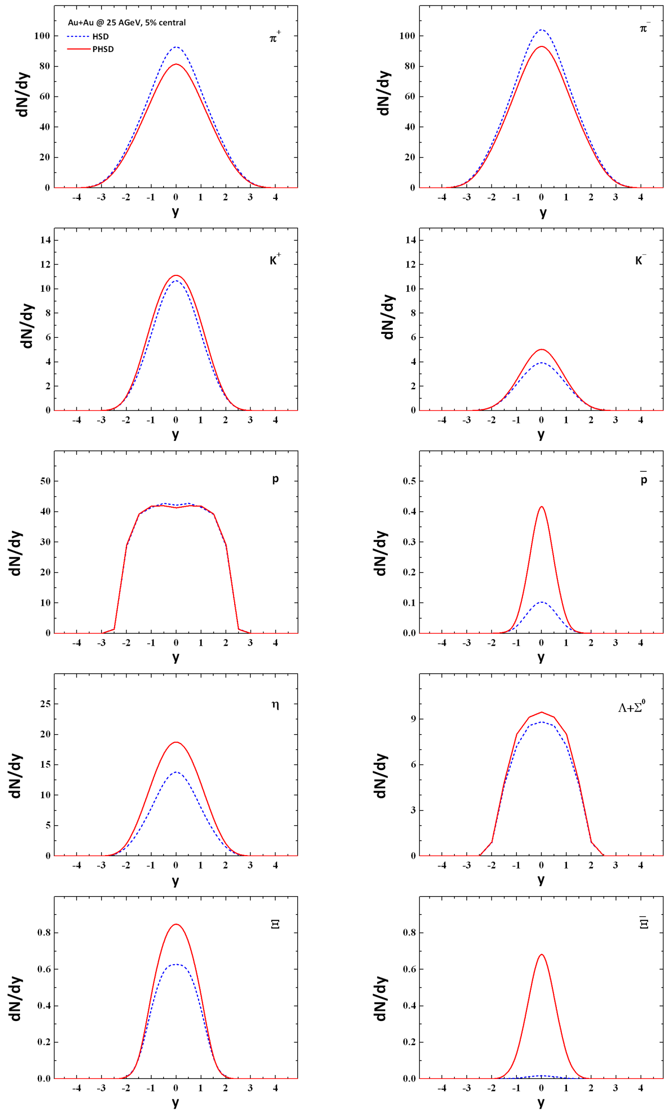
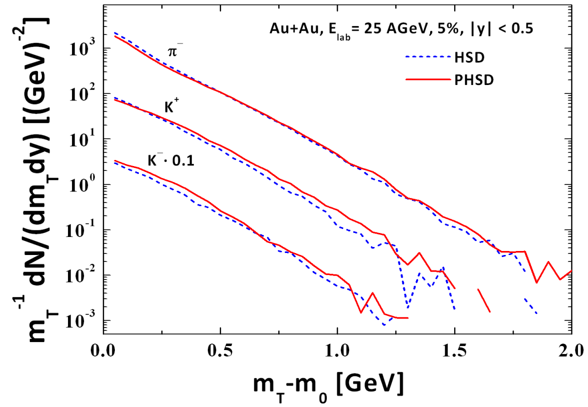
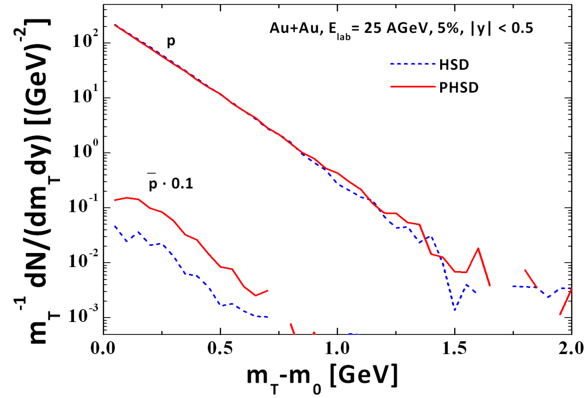
FAIR energies

PHSD: Au+Au @ 25 AGeV



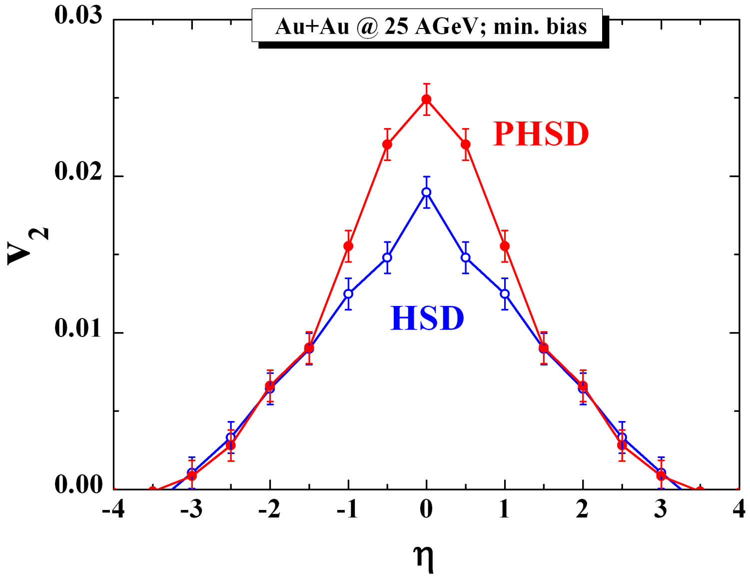
PHSD: Au+Au @ 25 AGeV

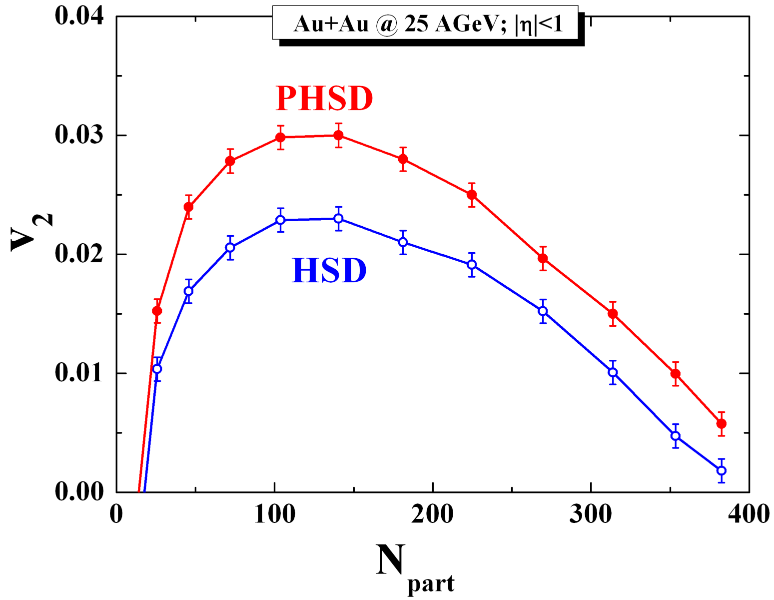


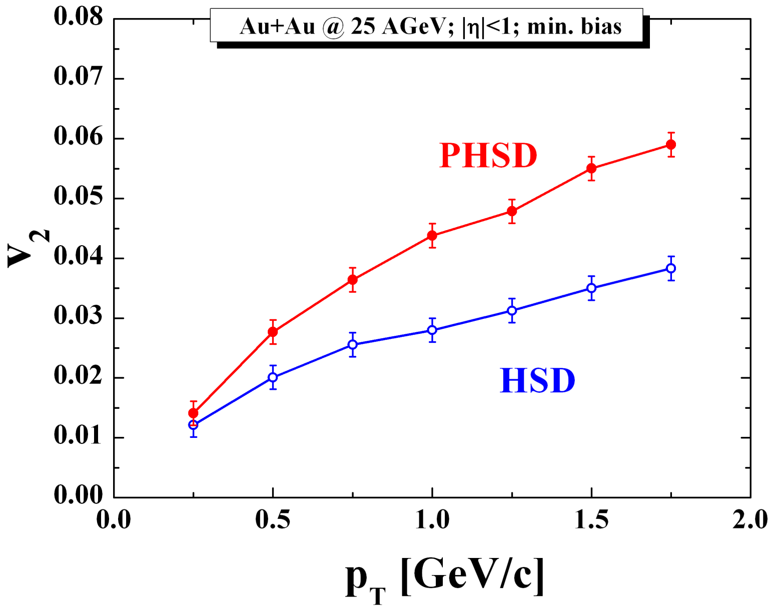


PHSD gives less pions but more kaons and strange baryons than HSD and especially strange antibaryons !

Elliptic flow at FAIR energies



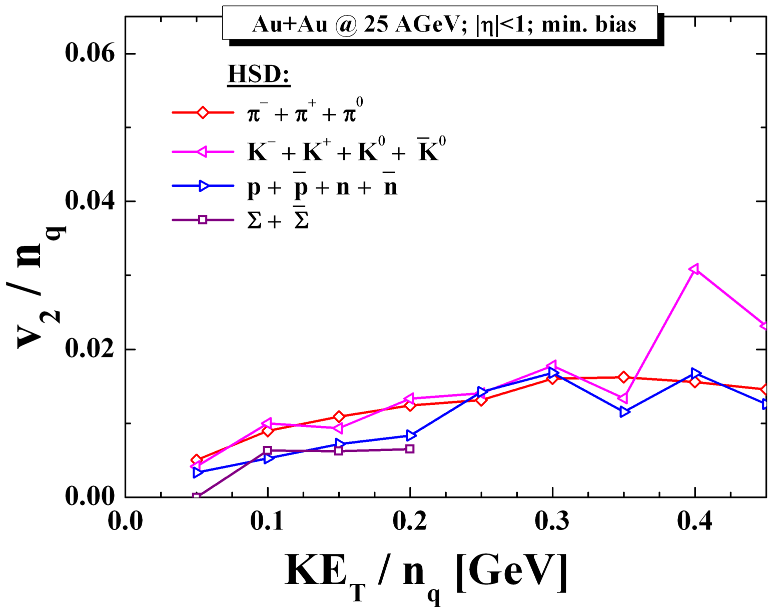




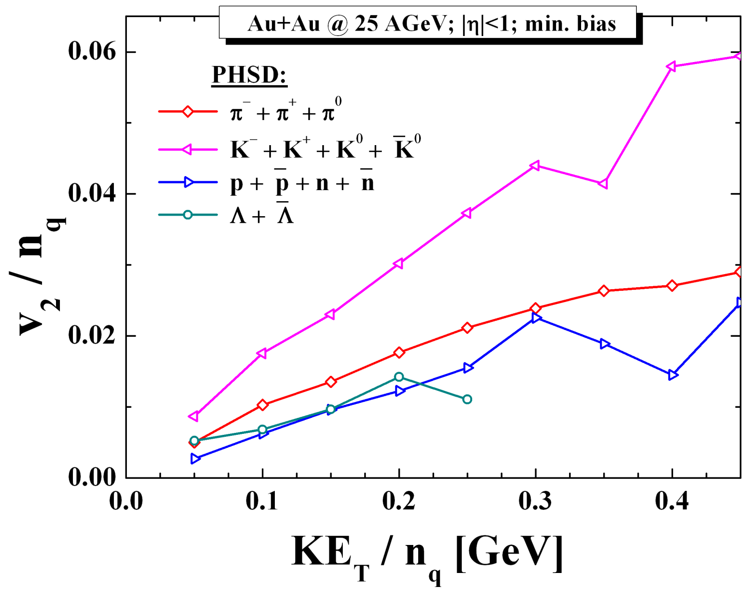
PHSD gives a larger elliptic flow than HSD essentially at midrapidity about a factor of 2 smaller than at RHIC energies !

Quark number scaling at FAIR energies

HSD



PHSD



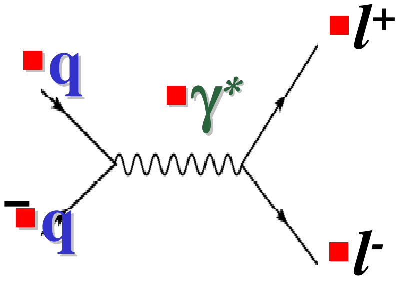
does not work for HSD and PHSD !

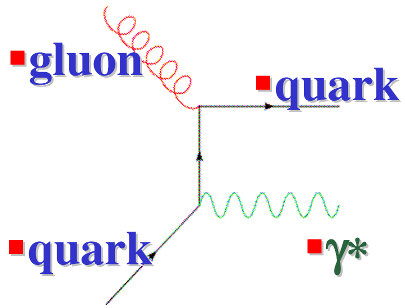
Dilepton emission probes 2-particle correlations in contrast to 1-particle distributions

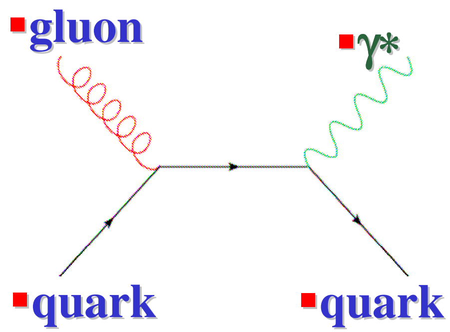
- **Example:** dilepton measurements access spectral functions of the particles, i.e. their interaction rates and decay properties

- **Hadronic channels included:**
  - direct and Dalitz decays of π_0, η, η‘, ρ, ω, ϕ, J/Ψ, Ψ‘
  - correlated D+D_{bar} pairs
  - radiation from secondary mesons ($\pi + \pi$, $\pi + \rho$, $\pi + \omega$, $\rho + \rho$, $\pi + a_1$)

- **Partonic channels (e.g.):**



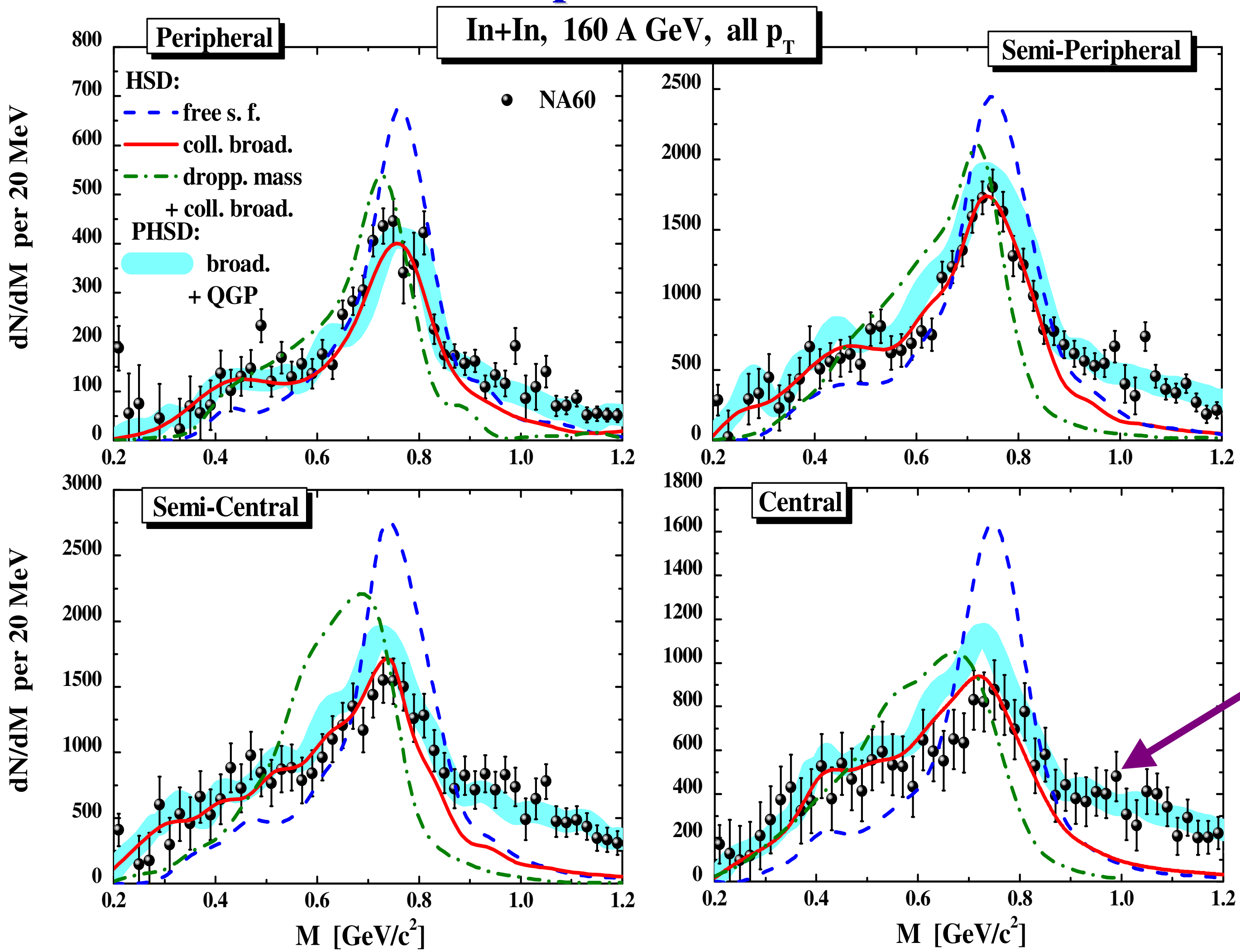




O. Linnyk, JPG 38 (2011)

NA60: the sQGP shines already at SPS

- Implementation of the cross sections into the PHSD transport approach
  -> comparison to the NA60 data:

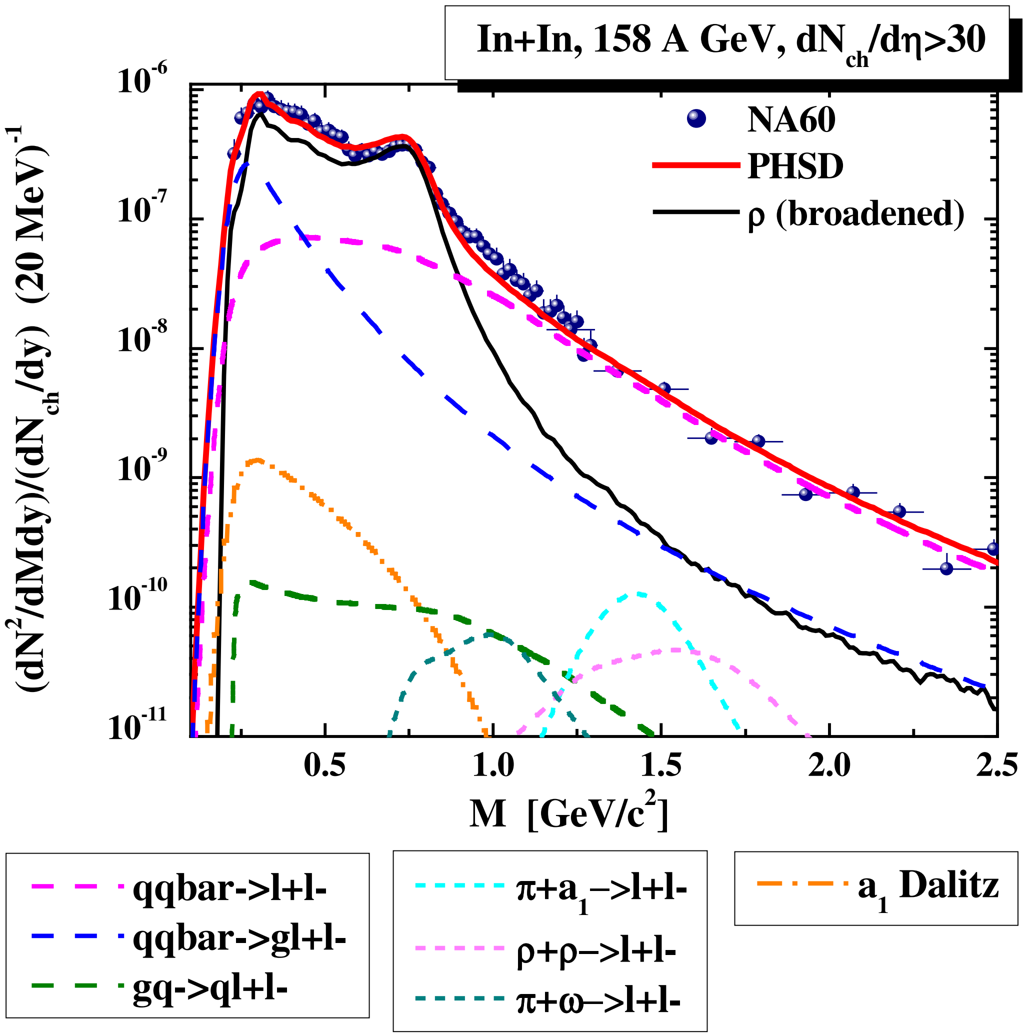


- NA60 data favor the in-medium scenario with collisional broadening

- High mass tail in PHSD is of partonic origin.

- E. Bratkovskaya, W. Cassing, O. L., PLB 670 (2009) 428

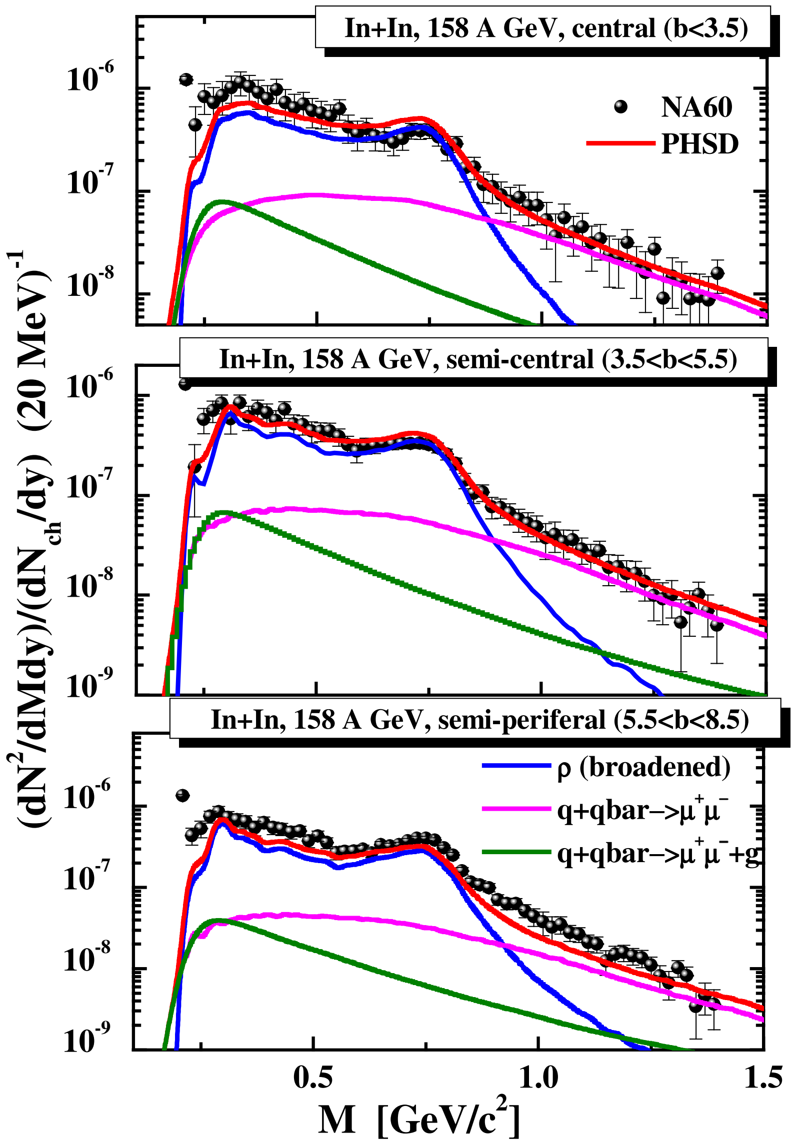
Acceptance corrected NA60 data



- Mass region above 1 GeV is dominated by partonic radiation !

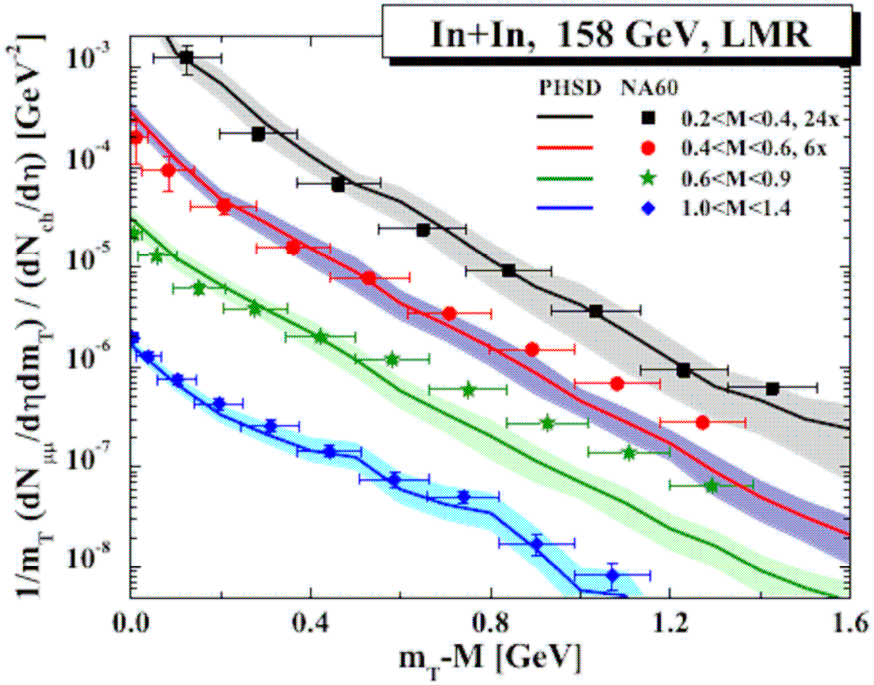
E.L. Bratkovskaya, NPA 855 (2011) 133

Centrality dependent NA60 data

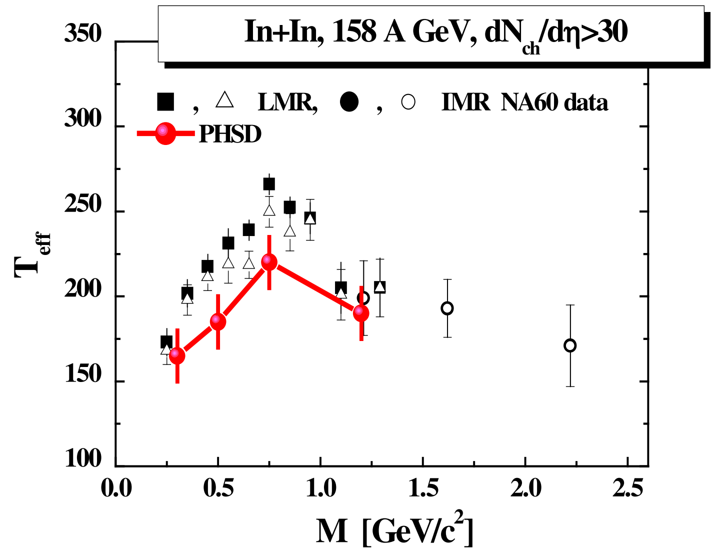


Dominant rho-channel at low and quark annihilation at intermediate masses !

NA60: m_T spectra



- **Inverse slope parameter T_{eff} for dilepton spectra vs NA60 data**



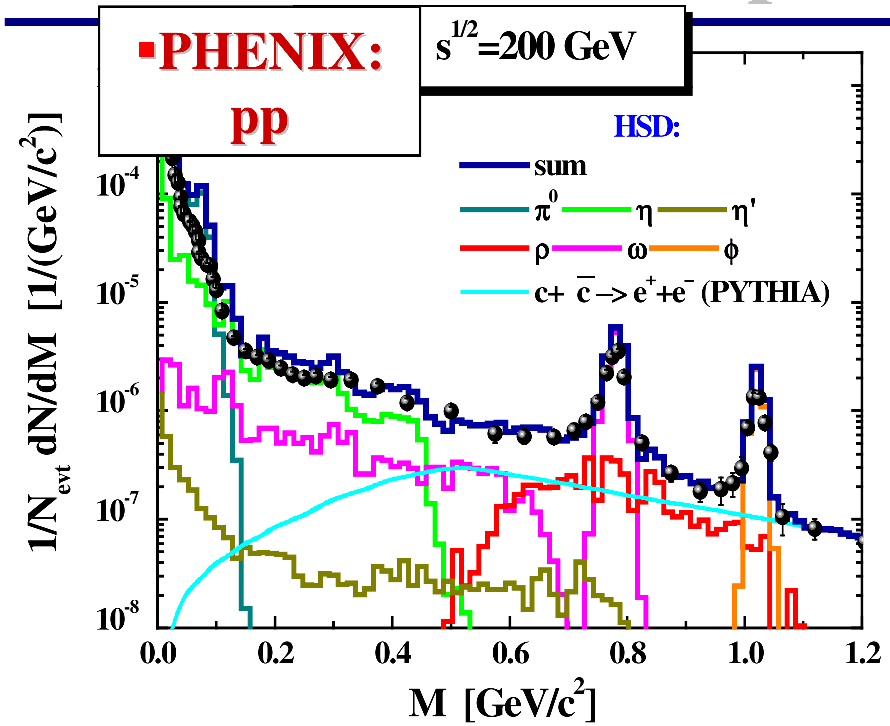
Evolution of the inverse slope parameter T_{eff} with mass is roughly reproduced!

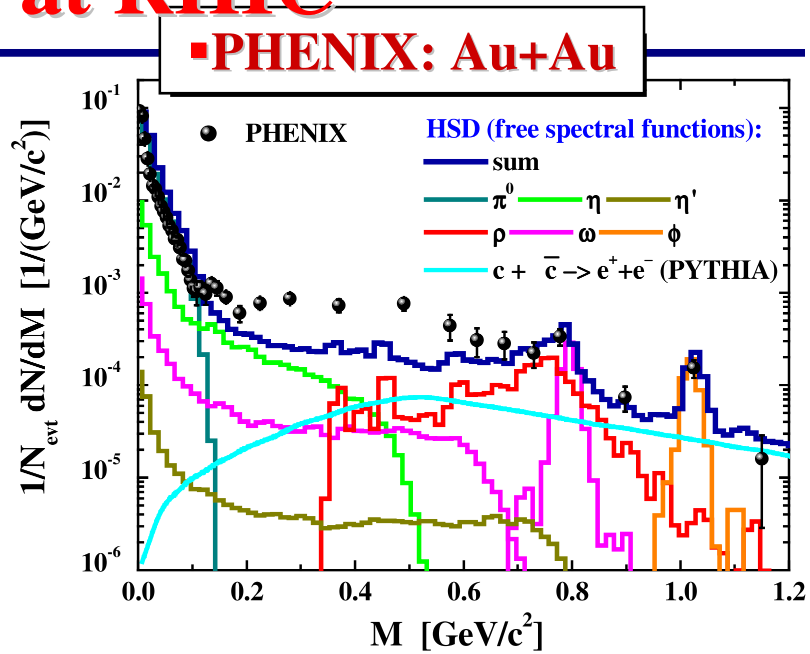
- **Conjecture:**

- **spectrum from sQGP is softer than from hadronic phase since quark-antiquark annihilation occurs dominantly before the collective radial flow has developed (cf NA60)!**

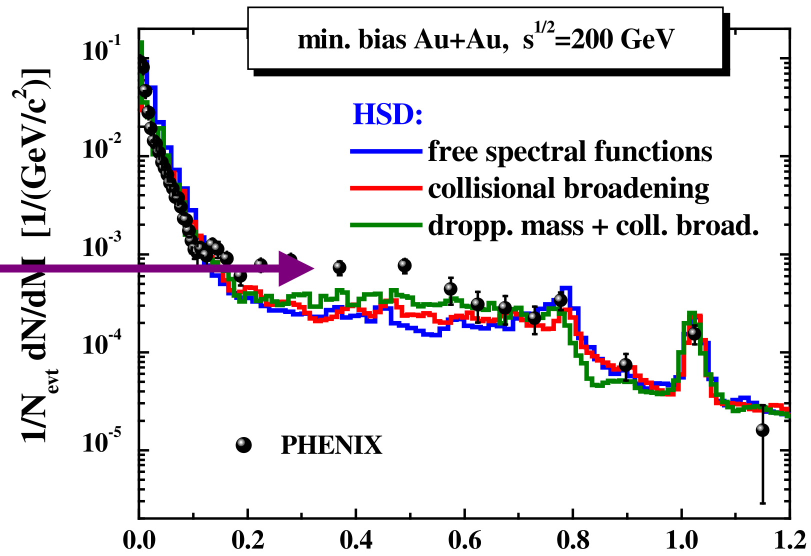
O. Linnyk et al., PRC (2011)

HSD: Dileptons at RHIC



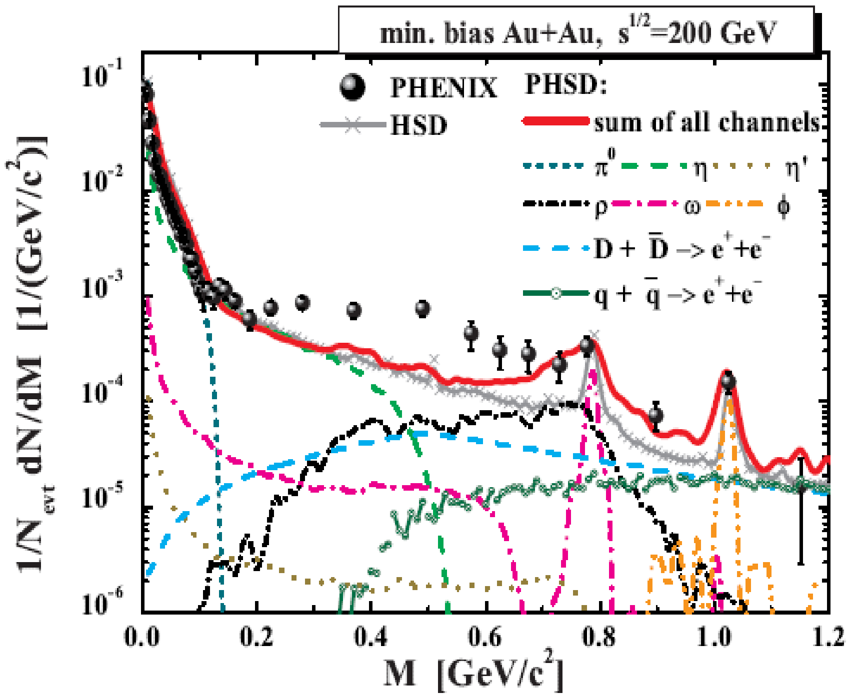


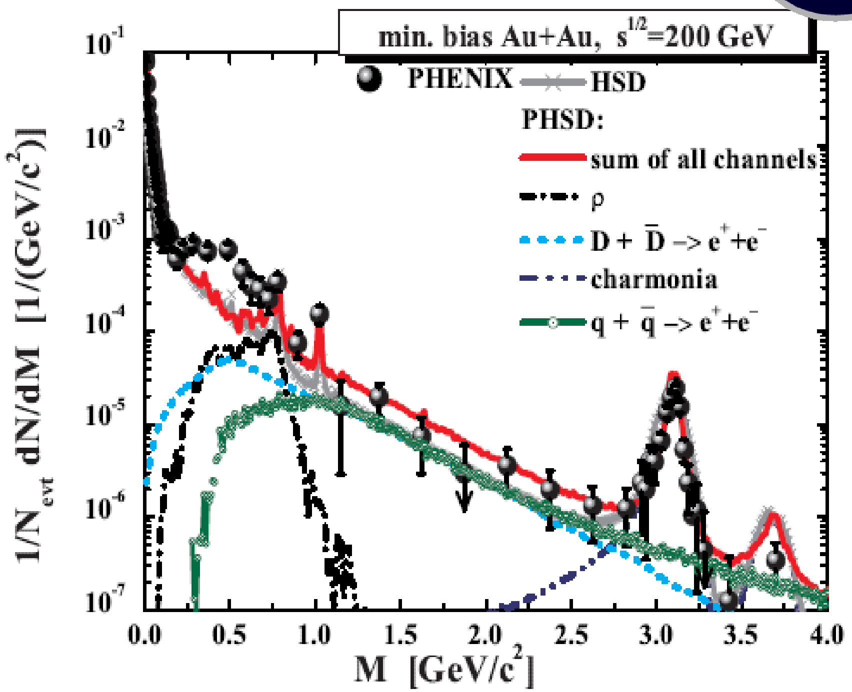
▪Standard in-medium effects of vector mesons (compatible with the NA60 and CERES data at SPS) do not explain the large enhancement observed by PHENIX in the invariant mass from 0.2 to 0.5 GeV in Au+Au collisions at $s^{1/2}$=200 GeV relative to pp collisions !



▪E. Bratkovskaya, W. Cassing, O. L., PLB 670 (2009) 428

PHENIX: min. bias

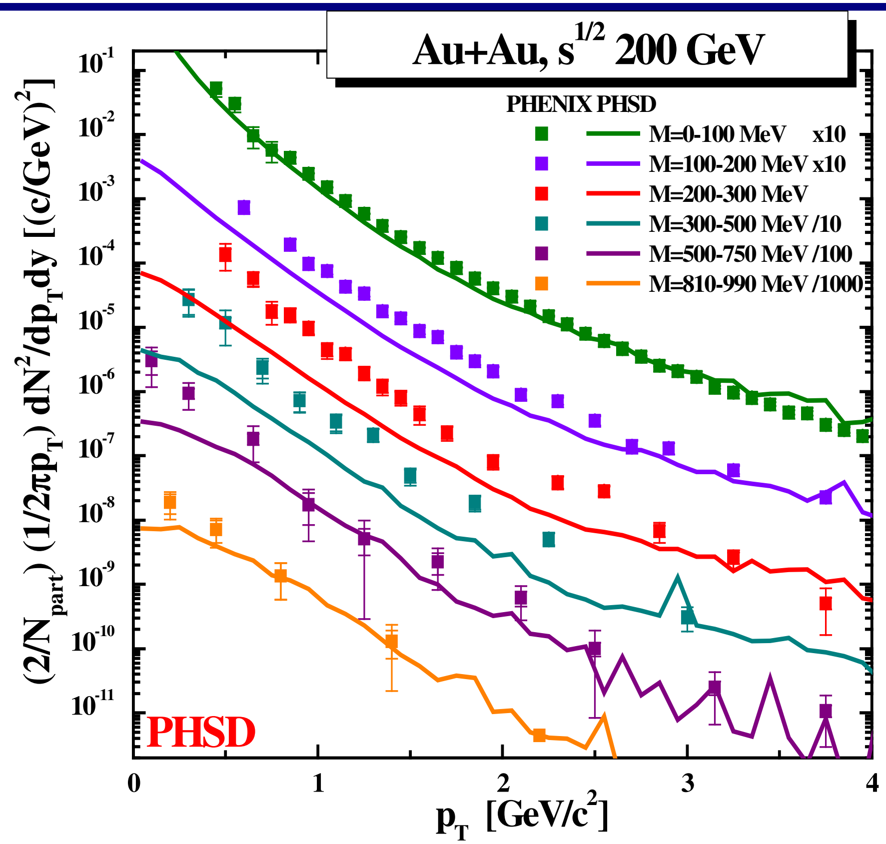




- Radiation from hadrons in HSD and PHSD is essentially the same.
- The excess over the considered mesonic sources for M=0.15-0.6 GeV is not explained by the QGP radiation as incorporated presently in PHSD.
- The partonic channels fill up the discrepancy between the hadronic contributions and the data for M>1 GeV.

O. Linnyk et al., PRC (2011)

PHENIX: p_T spectra



- The lowest and highest mass bins are described very well !
- Underestimation of data for 100<M<750 MeV consistent with dN/dM above
- The 'missing source' is located at low p_T !

•Agreement slightly better than the cocktail calculations due to the dynamics and production by secondary hadronic sources ($\pi+\pi \rightarrow \rho \rightarrow e^+e^-$).

Summary on parton dynamics

- PHSD provides a consistent description of off-shell parton dynamics in line with a lattice QCD equation of state and incorporates dynamical hadronization in line with conservation laws as well as entropy production!

- 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 (will be also seen at top FAIR energies)

- PHSD also provides a reasonable description of the rapidity spectra and meson and proton m_T slopes for Au+Au collisions at the top RHIC energy.

- The collective properties as expressed in terms of the elliptic flow v_2 are reasonably reproduced by PHSD contrary to HSD calculations.

- The quark-number scaling of v_2 holds fairly well in PHSD at RHIC but no longer at FAIR energies !

Conclusions on dileptons

- The dilepton data from NA60 at SPS energies are better described within off-shell PHSD, if a collisional broadening of vector mesons is assumed.
- The yield of dilepton pairs at masses above 1 GeV indicates the presence of the strongly interacting QGP and is described by the interactions of dynamical quasiparticles.
- Neither the incorporated hadronic nor partonic sources account for the enhancement observed by PHENIX in the invariant mass from 0.2 to 0.6 GeV in central Au+Au collisions at $s^{1/2}$=200 GeV (relative to pp collisions) !