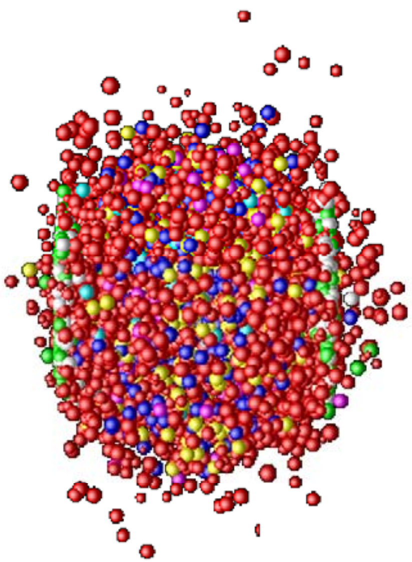
Institut für
Theoretische Physik I

JUSTUS-LIEBIG-UNIVERSITÄT GIESSEN

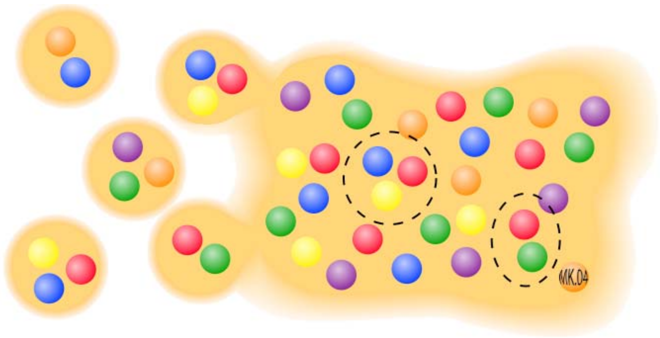
Dynamical hadronization within PHSD



Wolfgang Cassing

Villasimius
23.09.2010

Transport description of the partonic and hadronic phase



Parton-Hadron-String-Dynamics (PHSD)

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

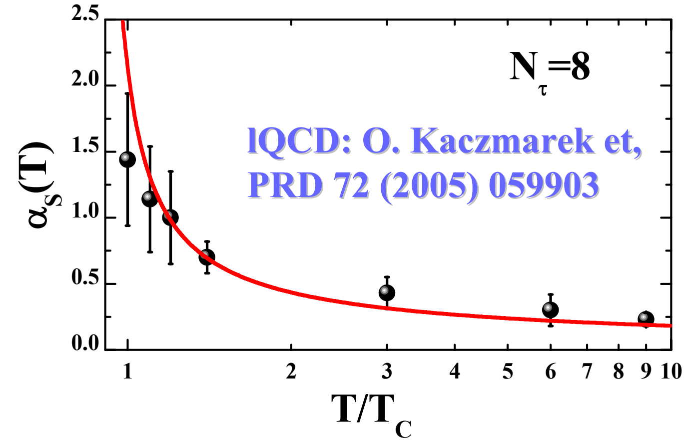
A. Peshier, PRD 70 (2004) 034016

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

The running coupling g^2

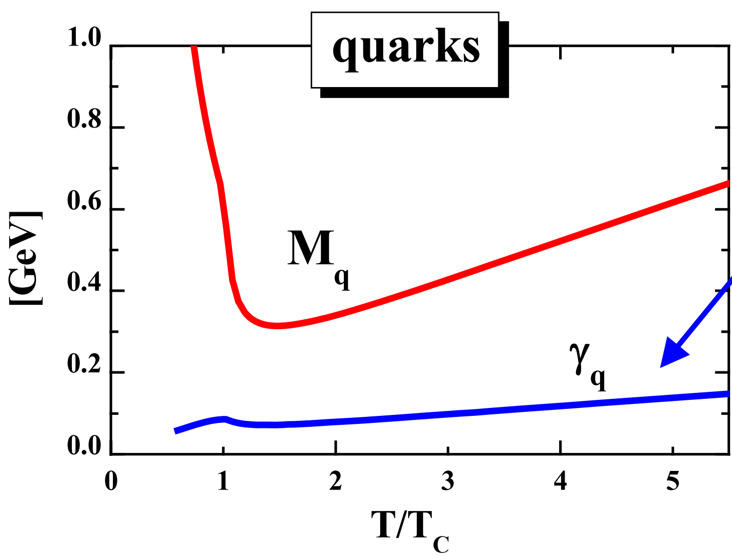
$$g^2(T/T_c) = \frac{48\pi^2}{(11N_c - 2N_f)\ln(\lambda^2(T/T_c - T_s/T_c)^2}$$

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

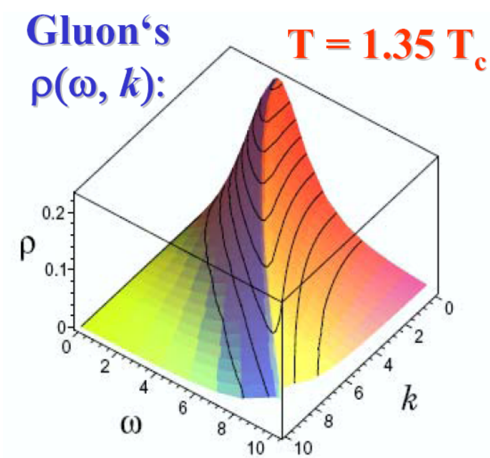


fit to lattice (lQCD) entropy density:

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



large width for gluons and quarks !



DQPM thermodynamics (N_f=3)

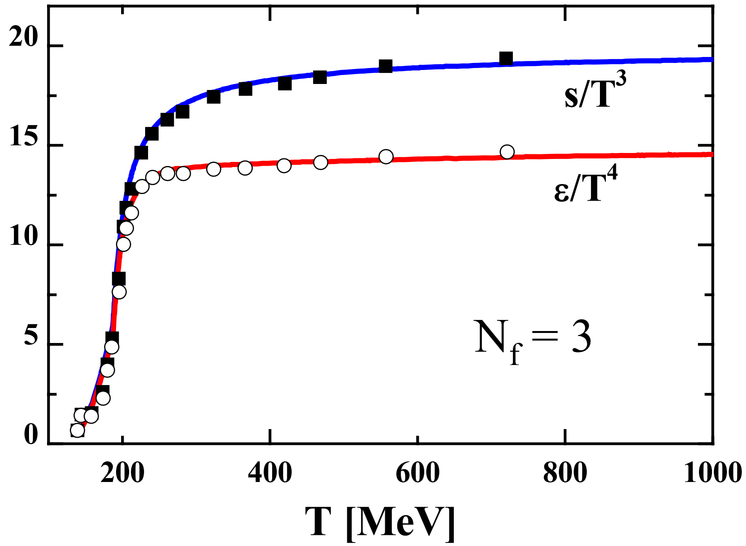
Thermodynamics: **entropy** $s = \frac{\partial P}{dT}$ → **pressure P**

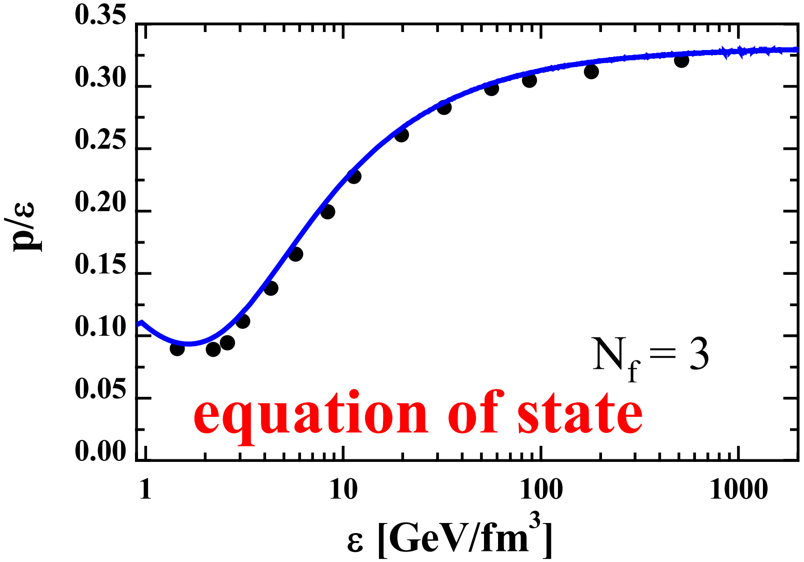
energy density: $\epsilon = Ts - P$

interaction measure:

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

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

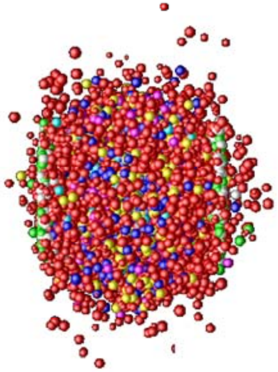




cf. V. D. Toneev, Heavy Ion Phys. 8 (1998) 83

DQPM gives a ‚perfect' description of lQCD results !

II. PHSD: partonic phase



3. Partonic phase:

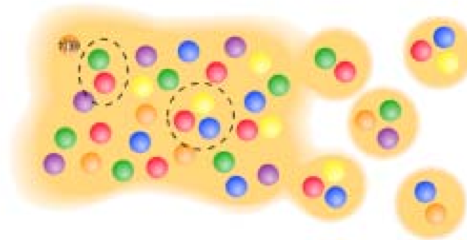
- Degrees of freedom:
  quarks and gluons (= ‚dynamical quasiparticles') (+ hadrons
- Properties of partons:
  off-shell spectral functions (width, mass) defined by DQPM
- EoS of partonic phase: from lattice QCD (or DQPM)

- **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 vector potentials U_q, U_g

Casssing, 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 $1 < \rho_P < 2.2\ \mathrm{fm}^{-3}$:

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

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

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

<= from DQPM and recomb. model

Matrix element $|V_{q\bar{q}}(\rho_P)|^2$ increases drastically for $\rho_P \to 0$ => $\left.\frac{d^4P}{\Delta V \Delta t}\right|_{\rho_P \to 0} \to \infty$
=> hadronization successful !

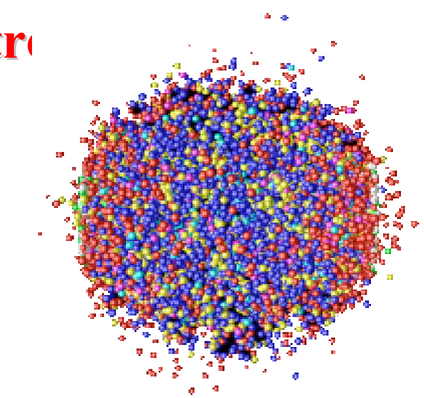
IV. PHSD: hadronization

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 $\sqrt{< r^2 >} = 0.66 \text{ fm}$

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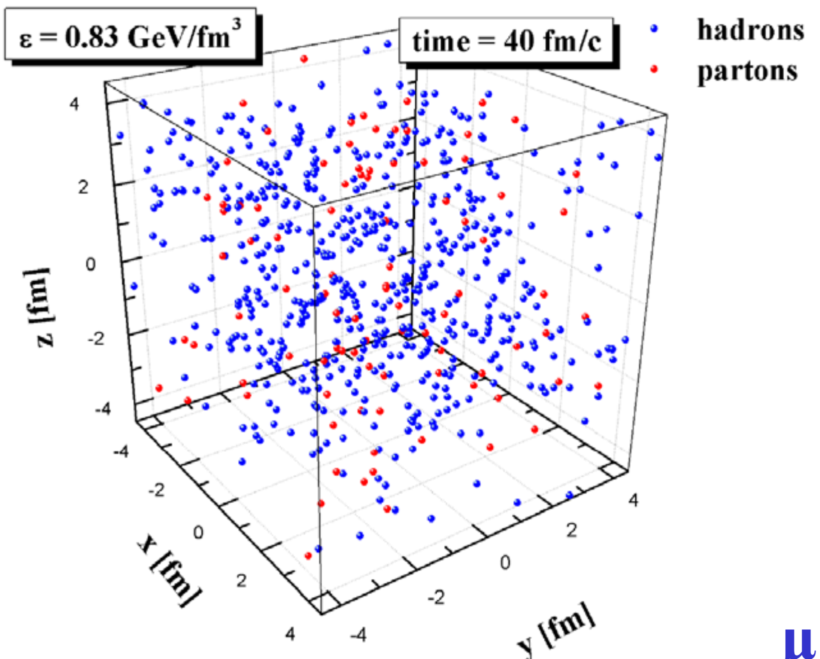
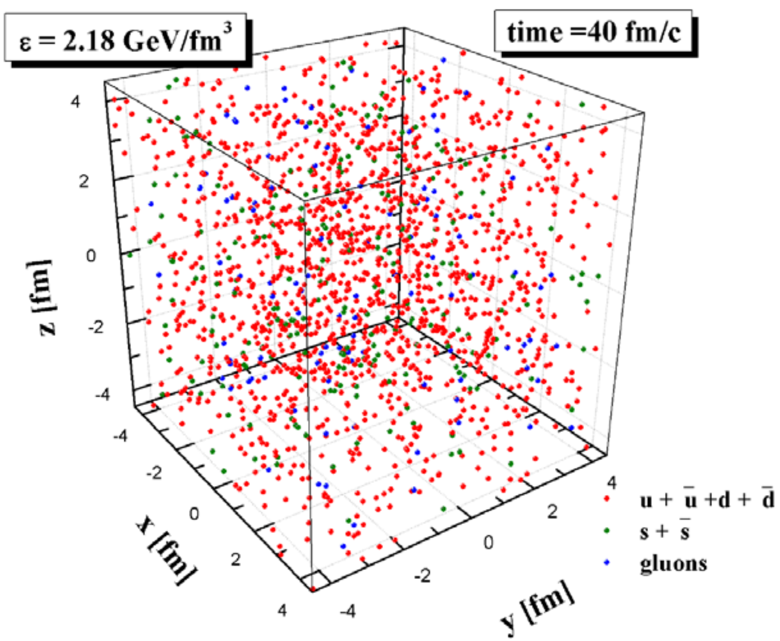
Systems in a finite box – periodic boundary cond.

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 !





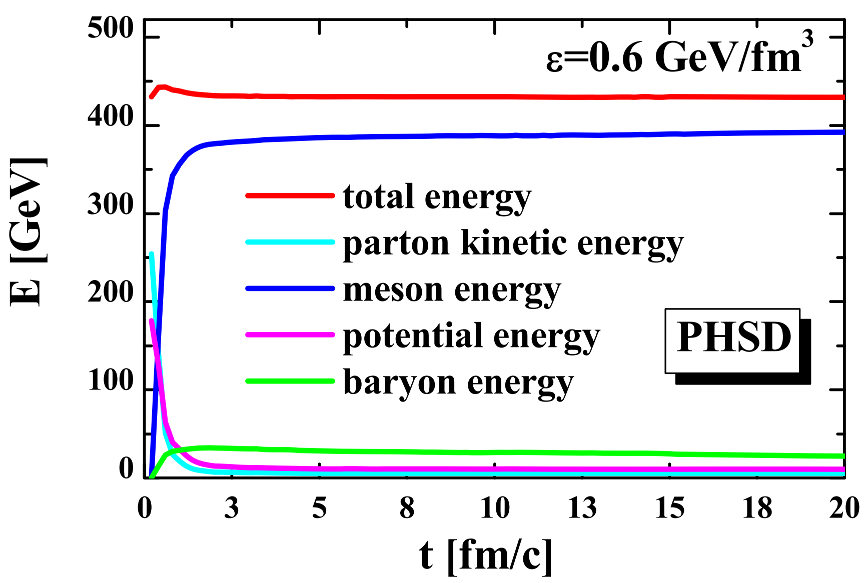
$\mu_q = 0$

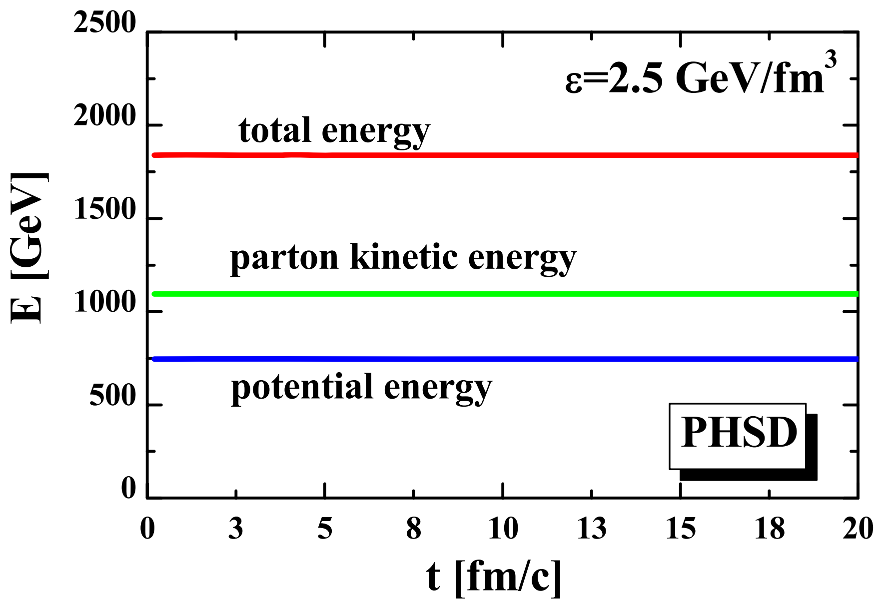
Note: the volume is divided into 9^3 cells of size 1 fm^3 !

Systems in a finite box – energy partitions

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

$$\varepsilon_c = 1.2 \text{ GeV/fm}^3$$

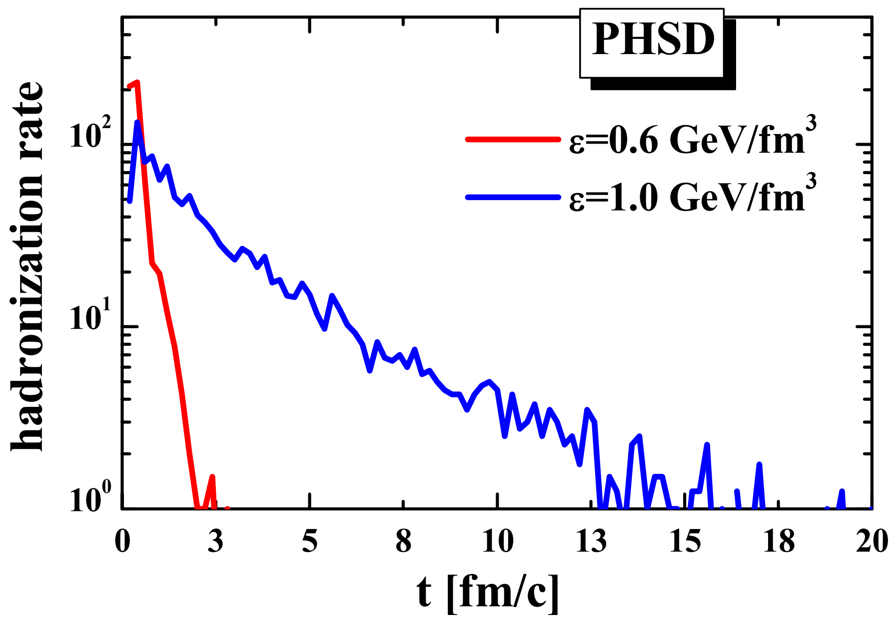


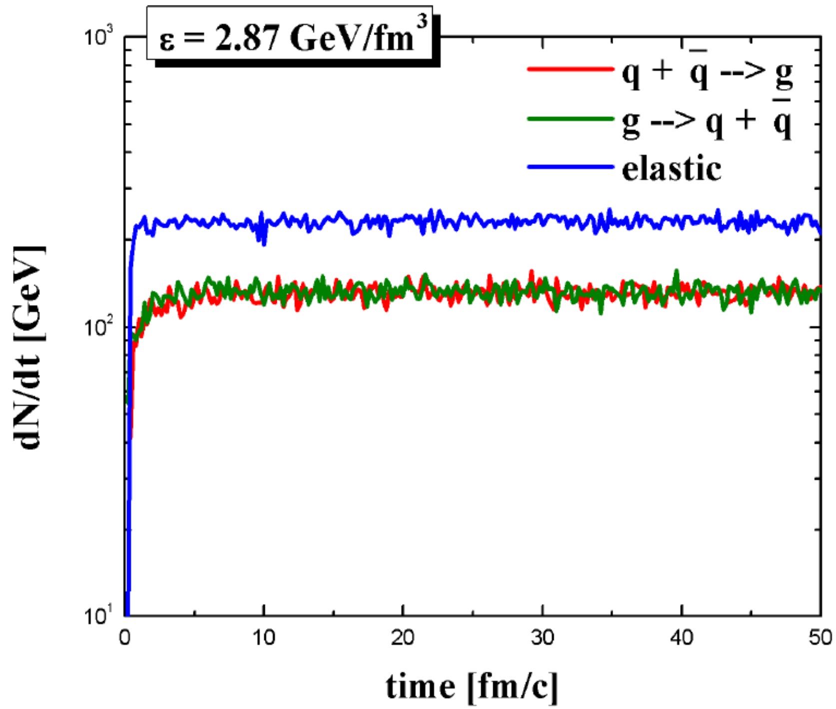


Systems in a finite box – reaction rates

Hadron formation and partonic interaction rates:

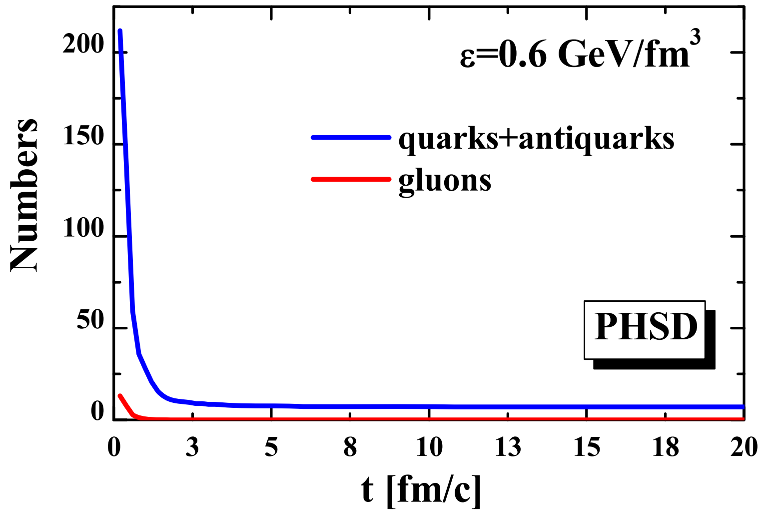
$\varepsilon_c = 1.2$ GeV/fm^3

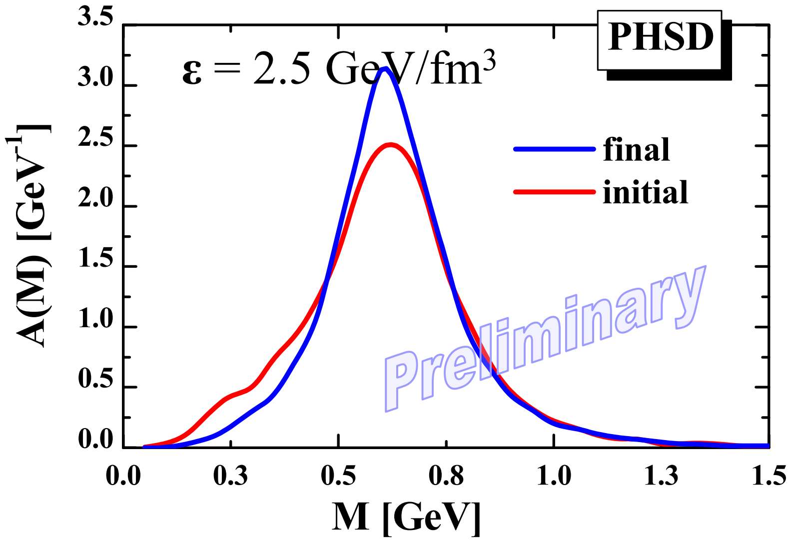


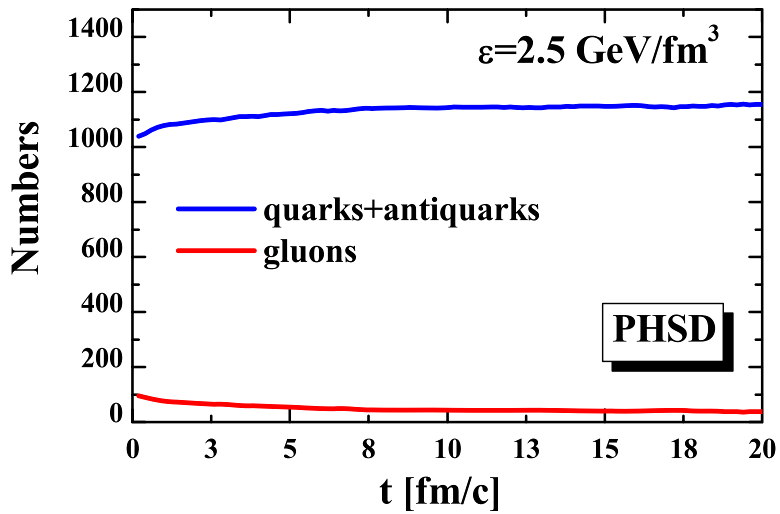


Detailed balance is established in equilibrium !

Systems in a finite box – dynamical equilibrium





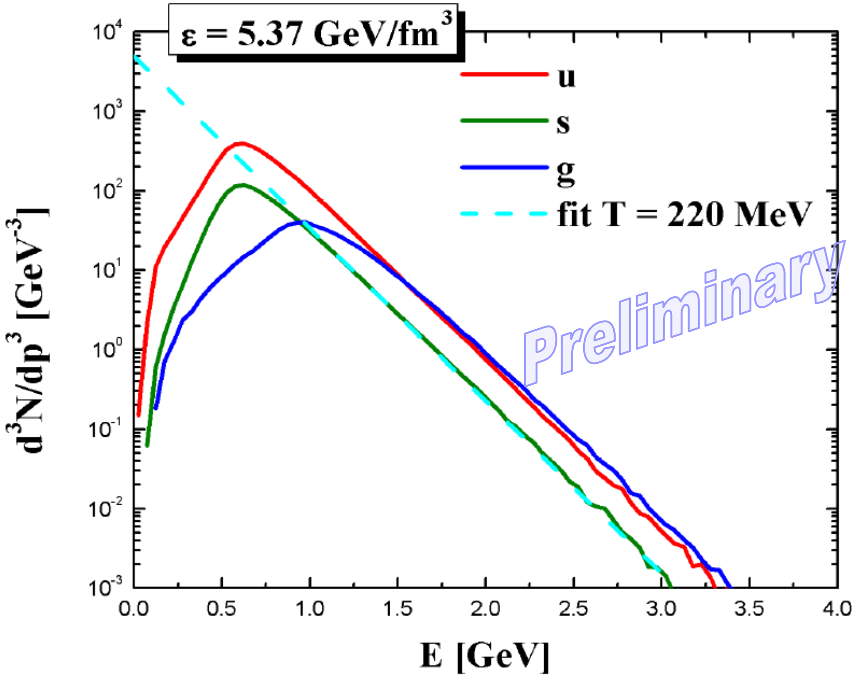


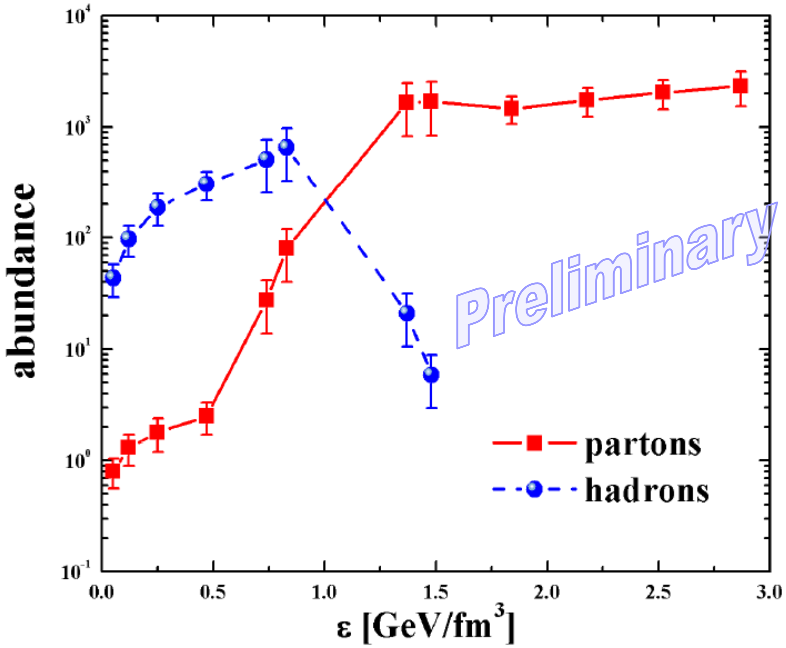
The equilibrium state of the dynamical evolution slightly deviates from the DQPM model

Systems in a finite box

Energy spectra become thermal → temperature T

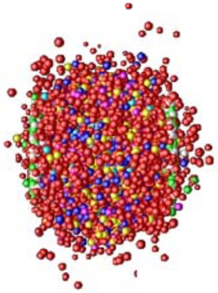
change of degrees of freedom with energy density ε :





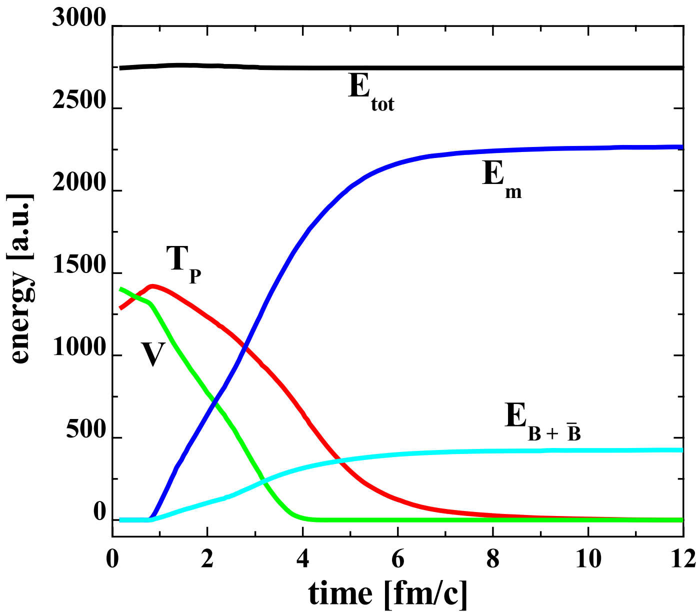
Expanding partonic fireball I

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

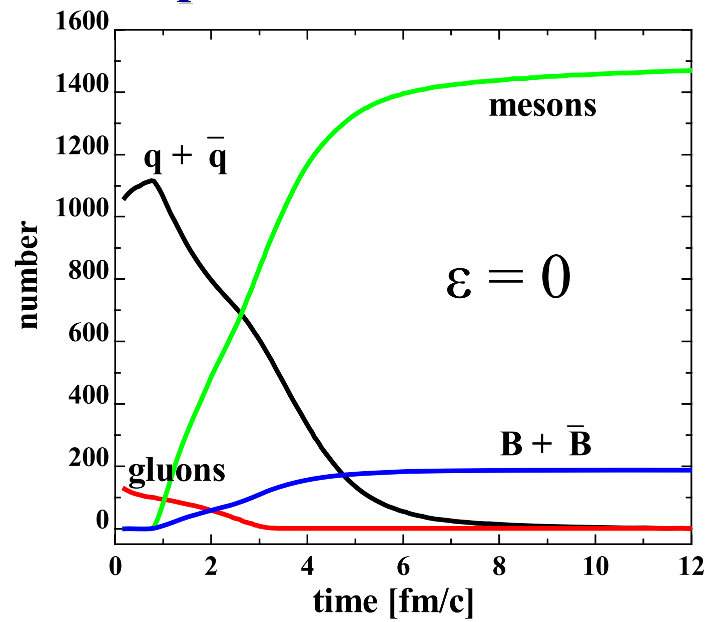


Eccentricity: $\varepsilon = (\sigma_y^2 - \sigma_x^2)/(\sigma_y^2 + \sigma_x^2)$

energy conservation



partons and hadrons



More hadrons in the final state than initial partons !

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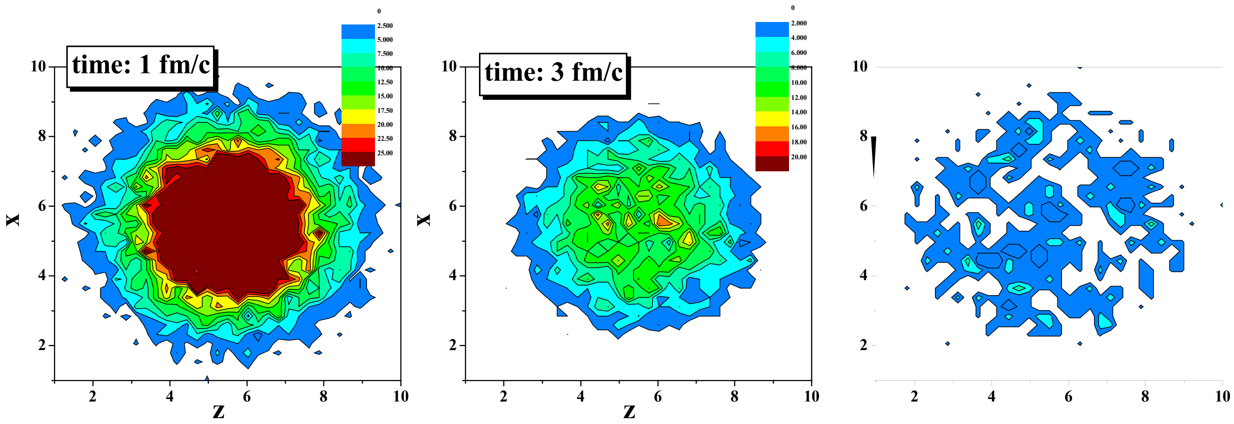
PHSD: Expanding fireball II



Summary

- The dynamical quasiparticle model (DQPM) defines the transport input for PHSD !
- 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
Sascha Juchem
Olena Linnyk
Volodya Konchakovski

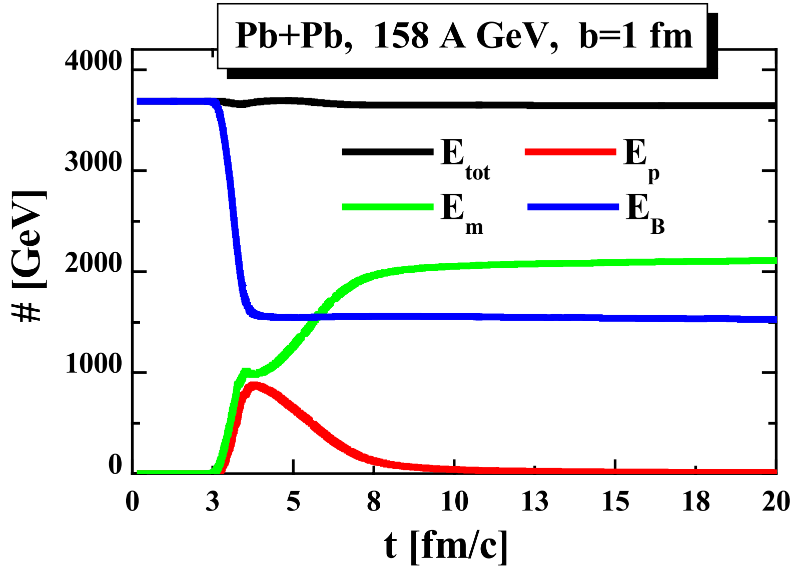
HSD & PHSD Team

and the numerous friends and colleagues !

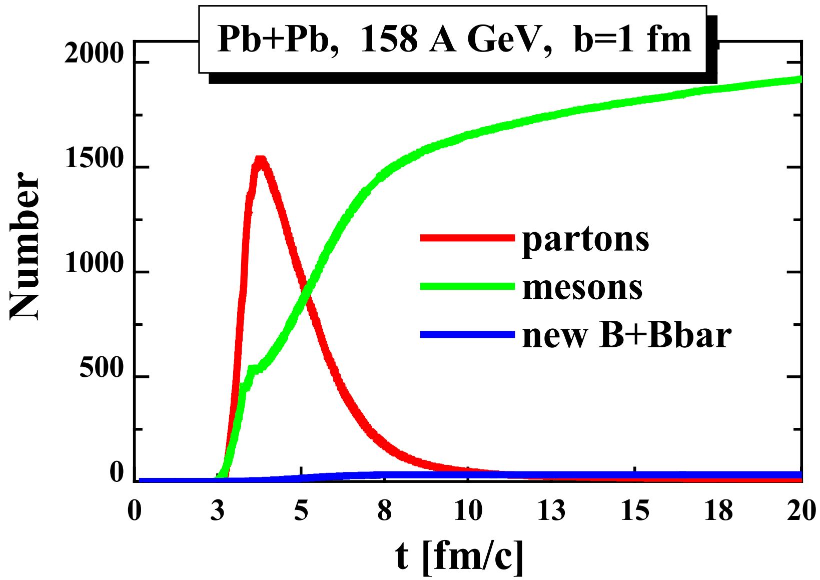
Application to nucleus-nucleus collisions

central Pb + Pb at 158 A GeV

energy balance



particle balance

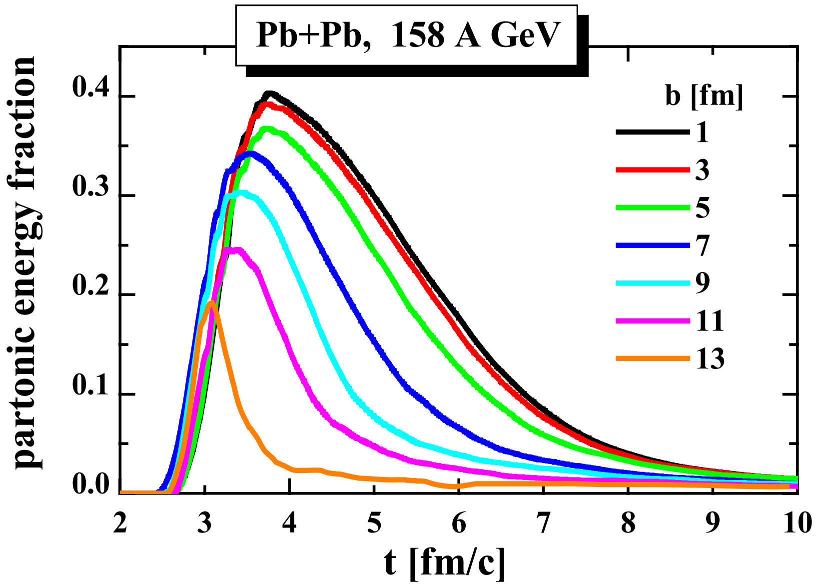


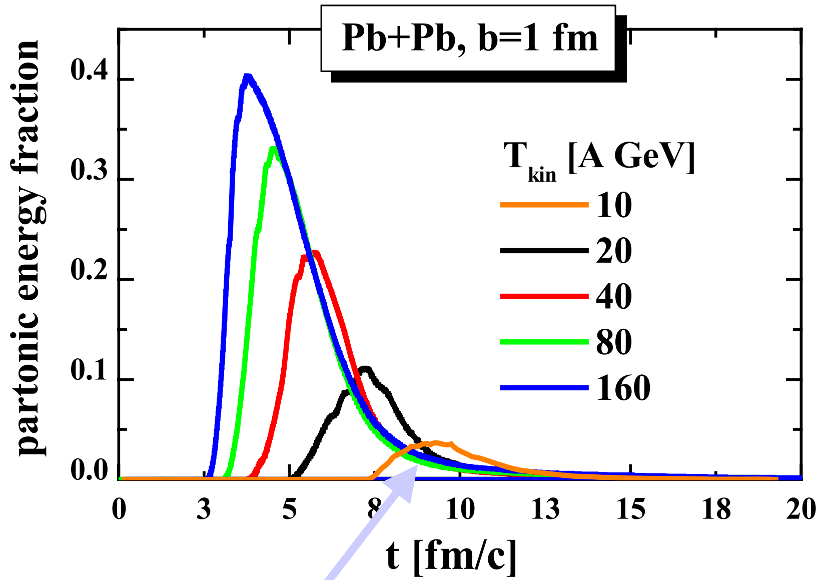
only about 40% of the converted energy goes to partons;
the rest is contained in the ‚large' hadronic corona!

Cassing & Bratkovskaya, NPA 831 (2009) 215

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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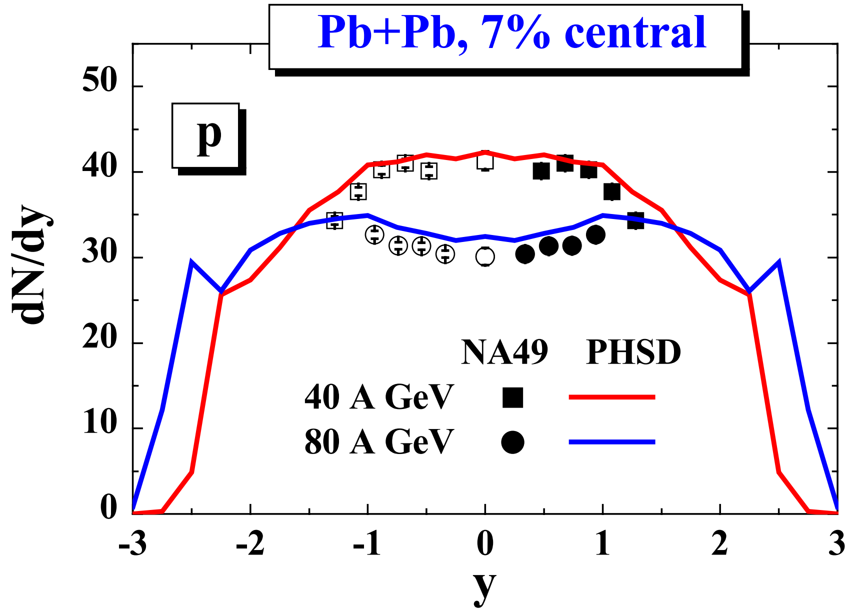
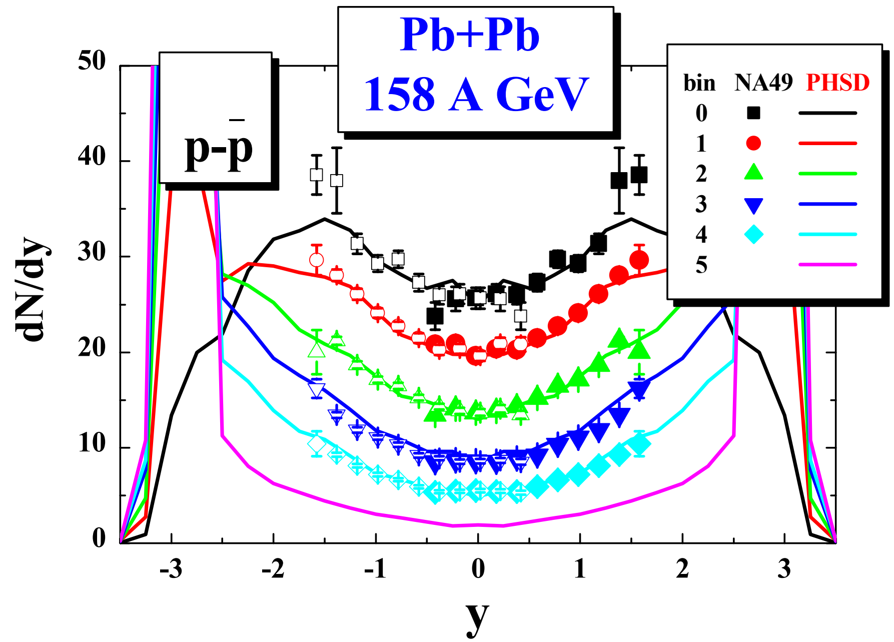
Proton stopping at SPS





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

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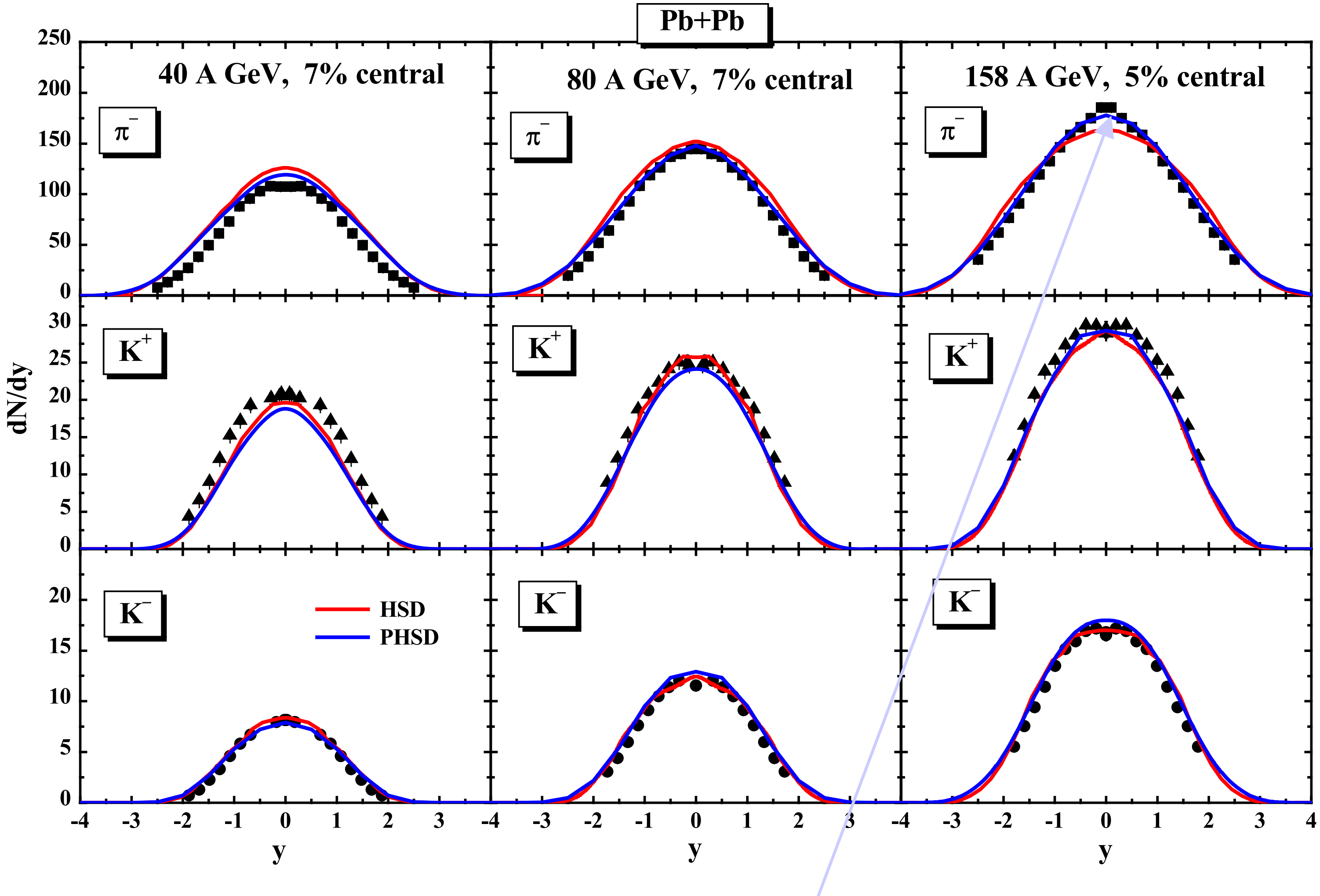
Rapidity distributions of π, K^+, K^-



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

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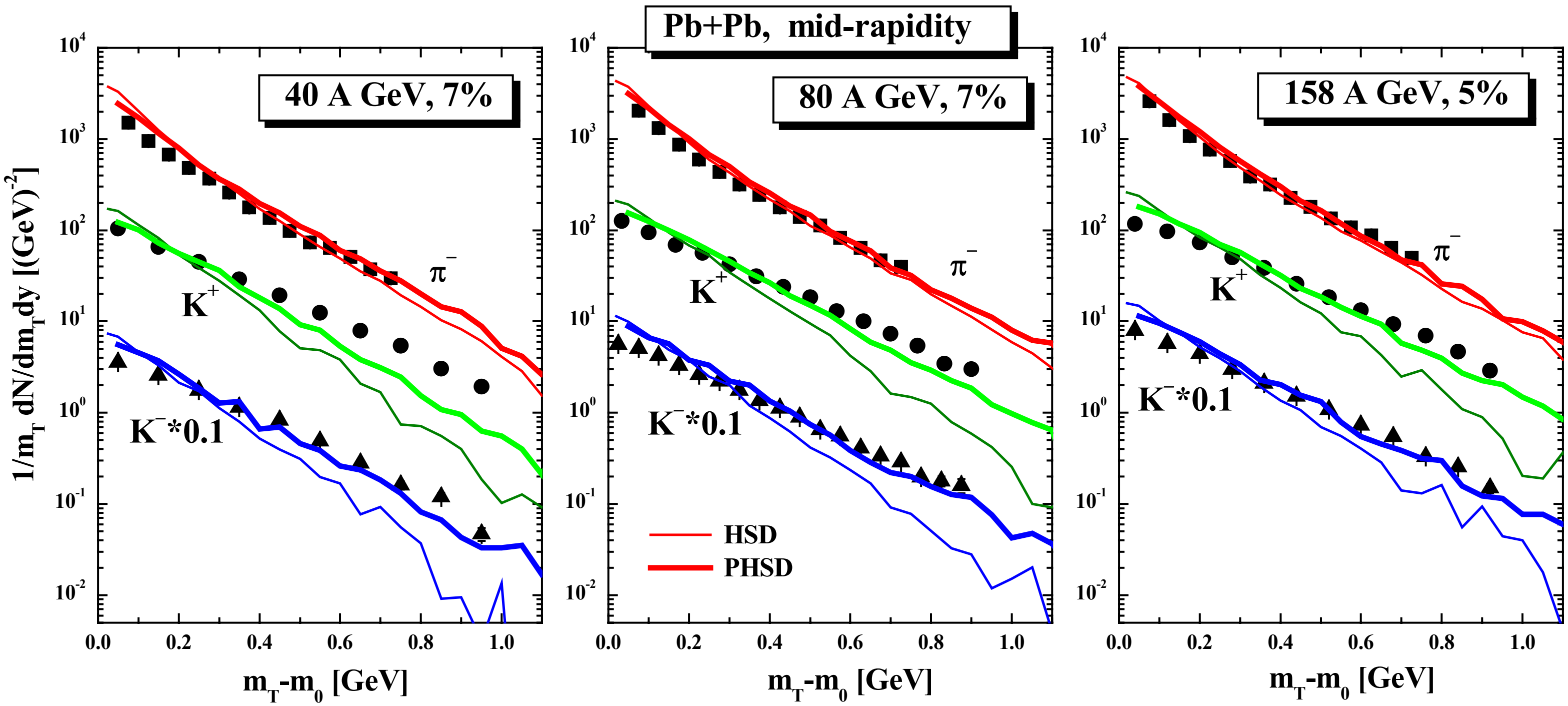
PHSD: Transverse mass spectra at SPS

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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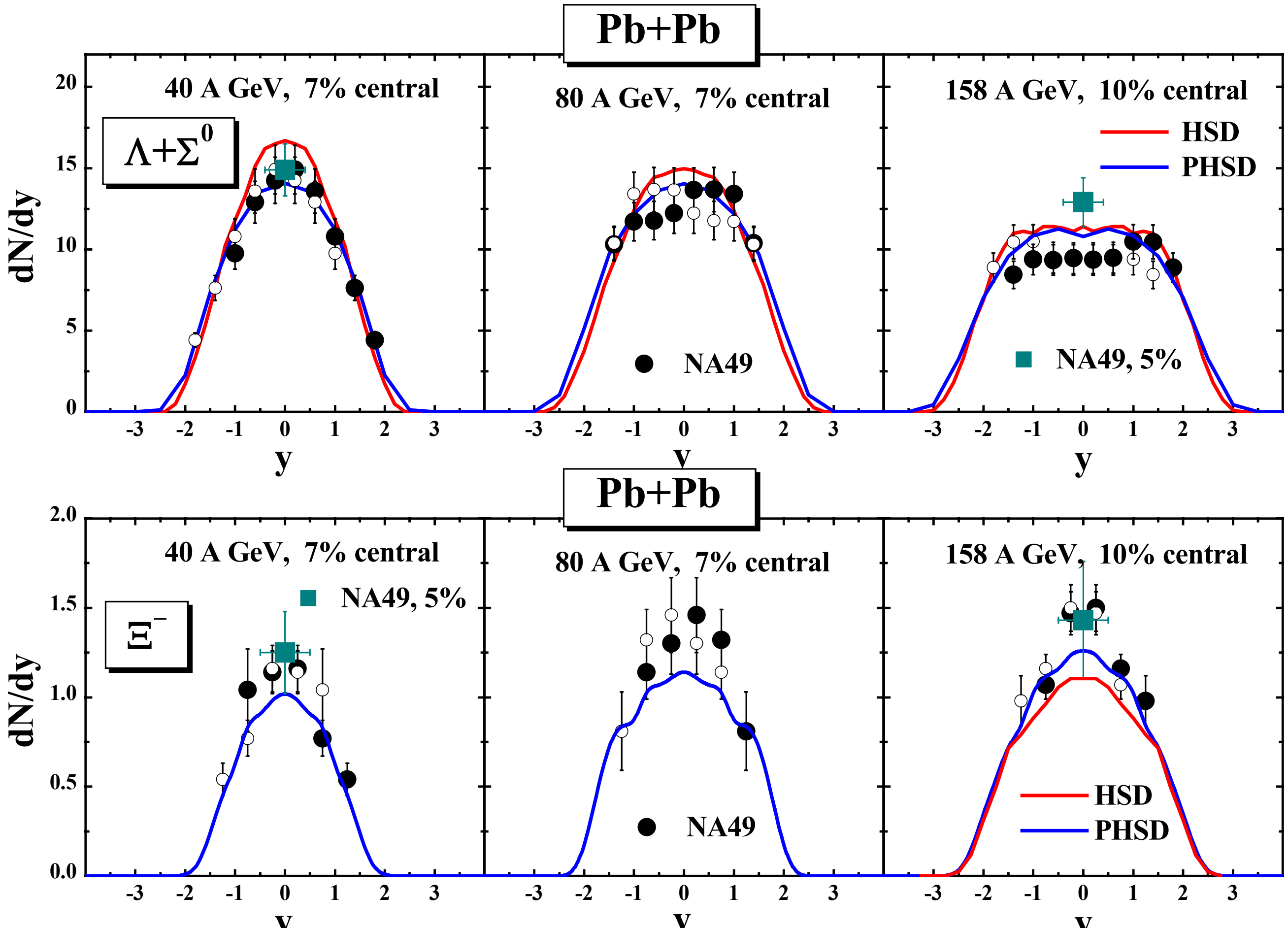
Rapidity distributions of strange baryons



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

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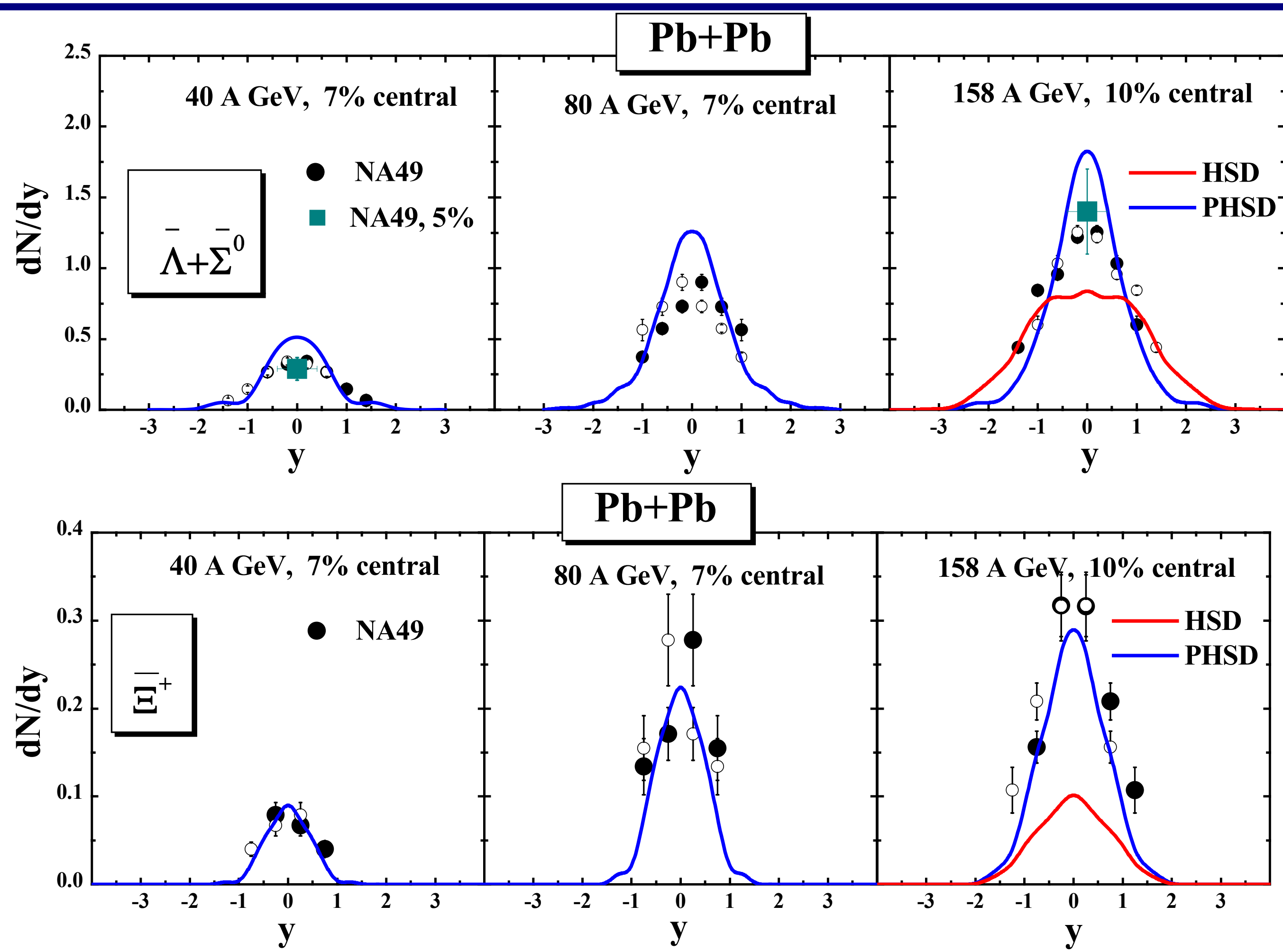
Rapidity distributions of (multi-)strange antibaryons



strange antibaryons

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

multi-strange antibaryon

$\bar{\Xi}^+$

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

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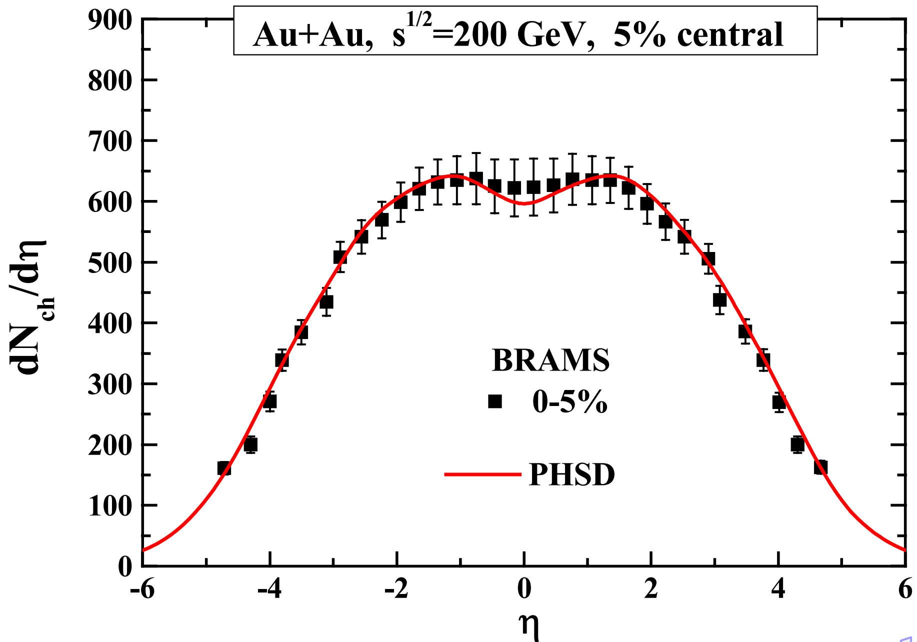
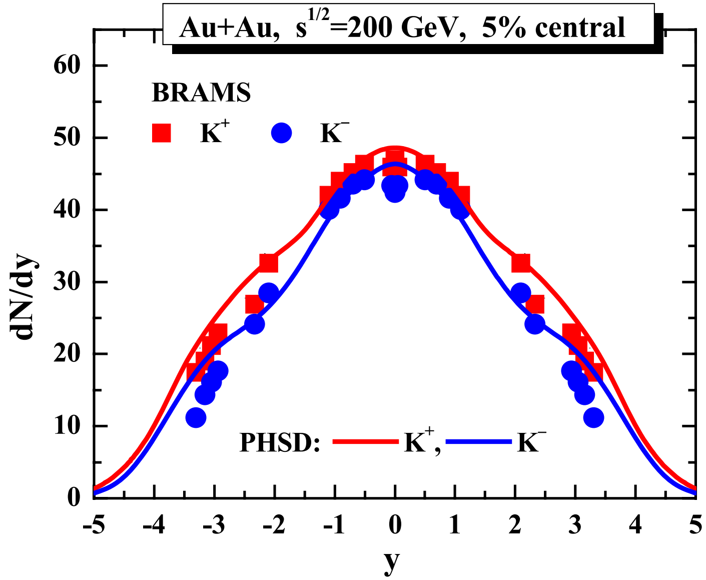
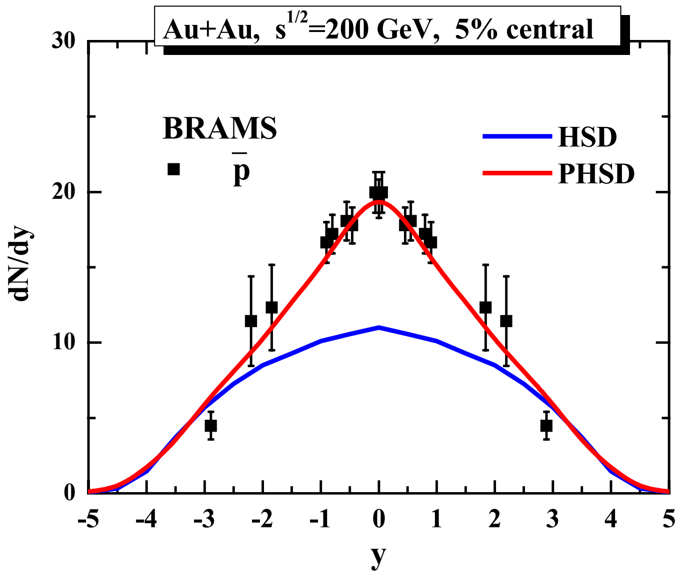
PHSD: rapidity spectra at RHIC



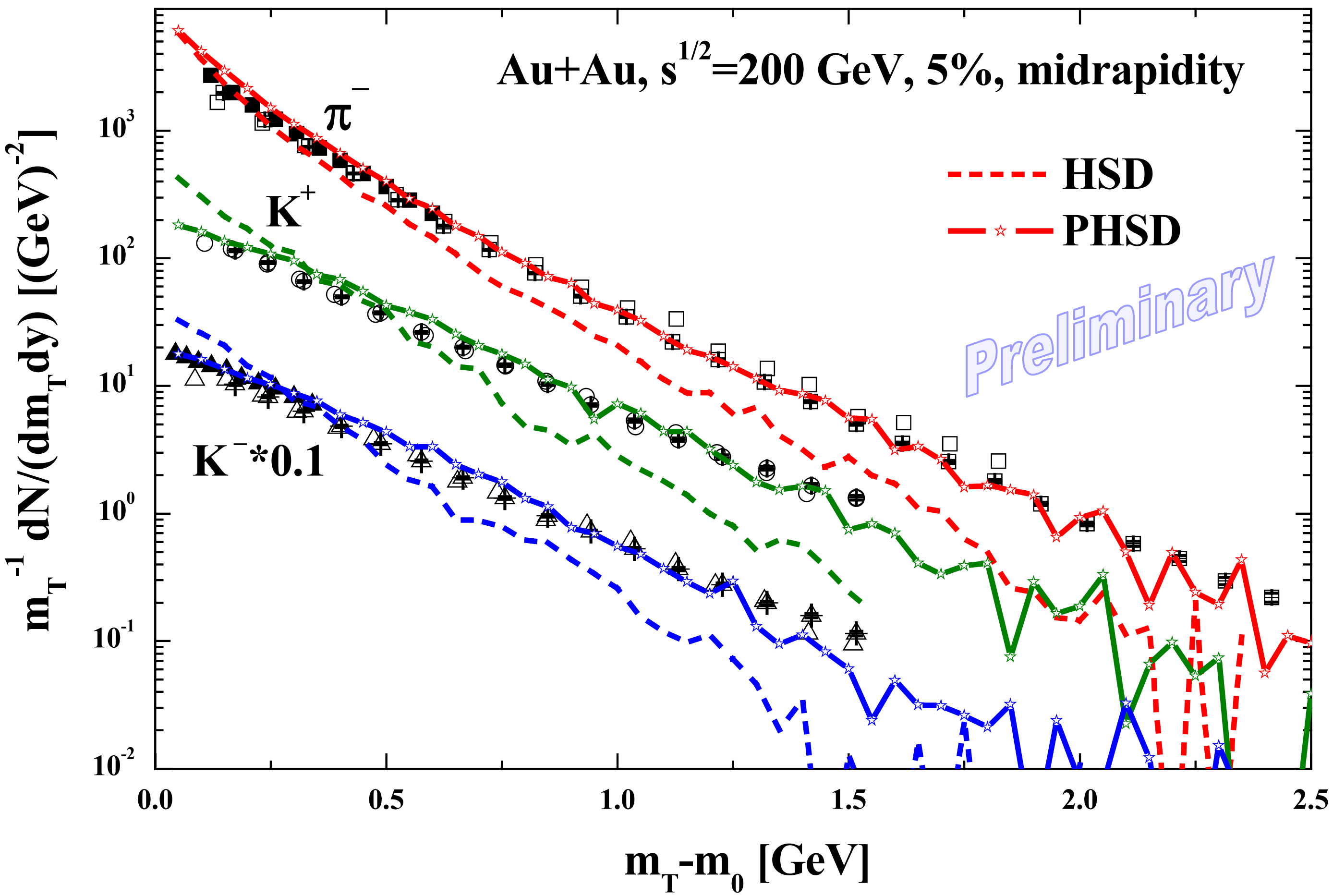




PHSD gives a reasonable description of the rapidity spectra also at RHIC

looks actually too good to be true!

PHSD: Transverse mass spectra at RHIC

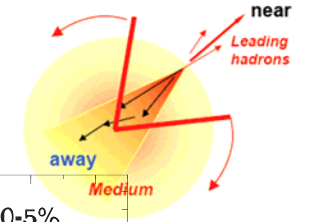


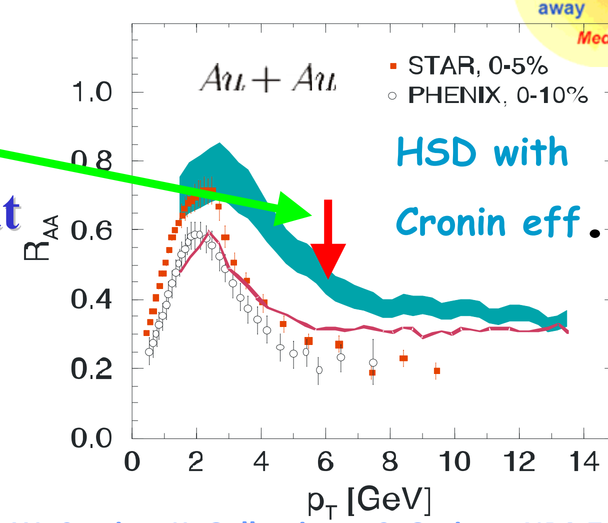
PHSD gives harder spectra and works better than HSD at RHIC

looks actually too good to be true!

High p_T suppression signals of QGP:

The attenuation of high p_T-hadrons (R_{AA}) is well reproduced in the hadron-string approach for non-central Au+Au collisions at top RHIC energies, however, the hadron-string model doesn't provide enough high p_T suppression for central Au+Au !

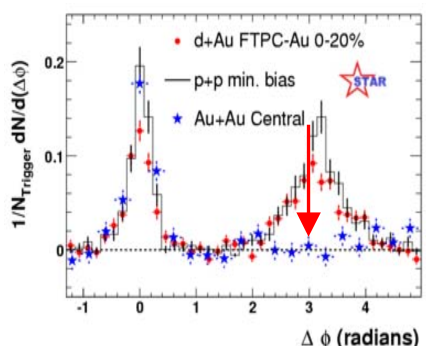


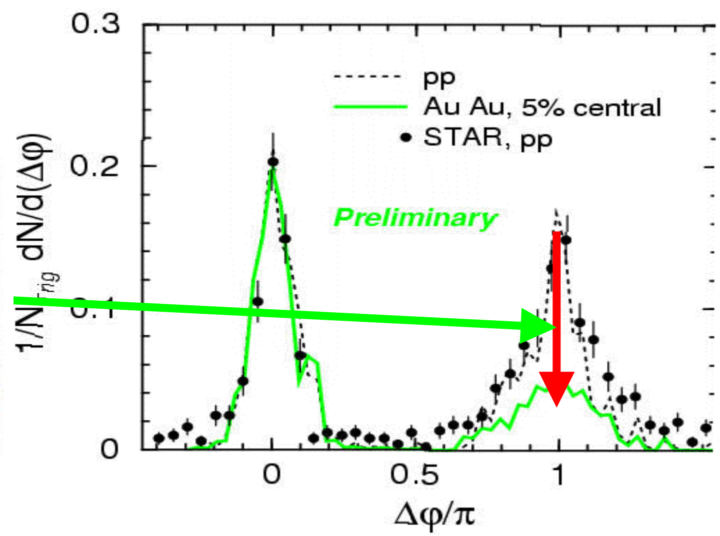


W. Cassing, K. Gallmeister, C. Greiner, NPA 735 (2004) 277

Jet suppression signals of QGP:

STAR observed very strong away-side jet suppression which is NOT reproduced in the hadron-string picture

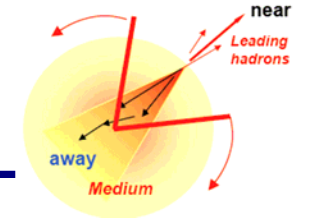




=> evidence for strong nonhadronic interactions in the early phase of the reaction!

W. Cassing, K. Gallmeister and C. Greiner, J.Phys.G30 (2004) S801; NPA 748 (2005) 241

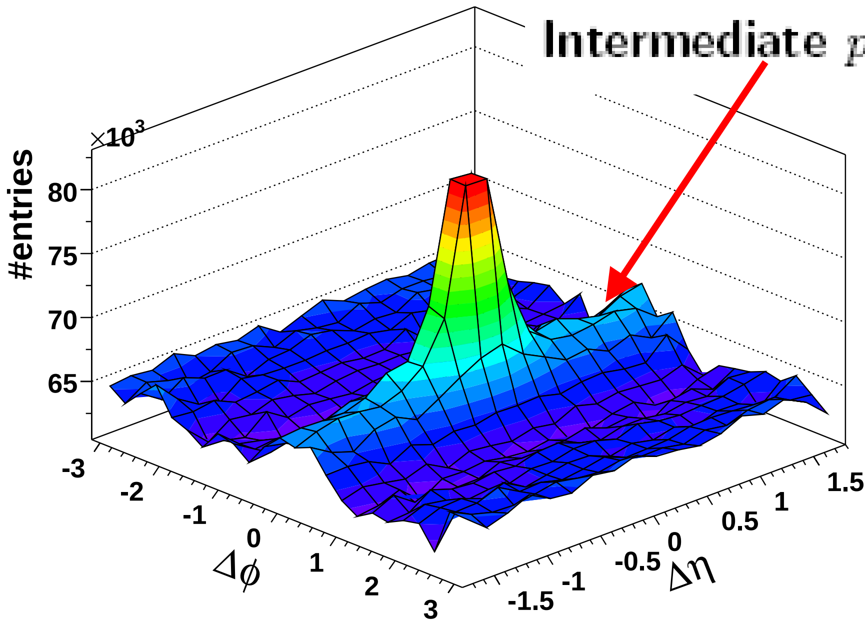
New exp. data: ϕ–η angular correlations



STAR
arXiv:0808.4096

PHOBOS
arXiv:0903.2811

Intermediate p_T: near-side ridge



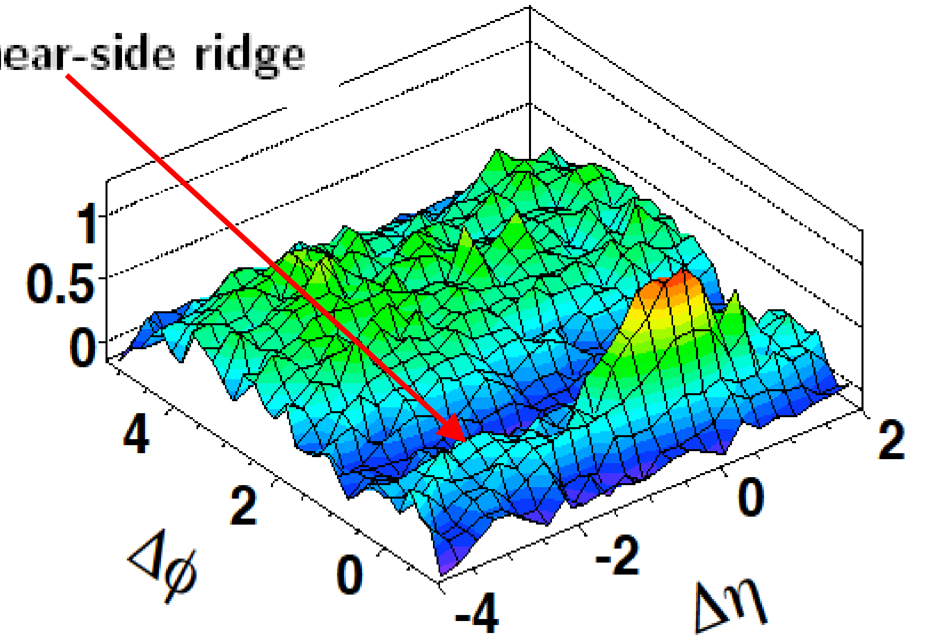
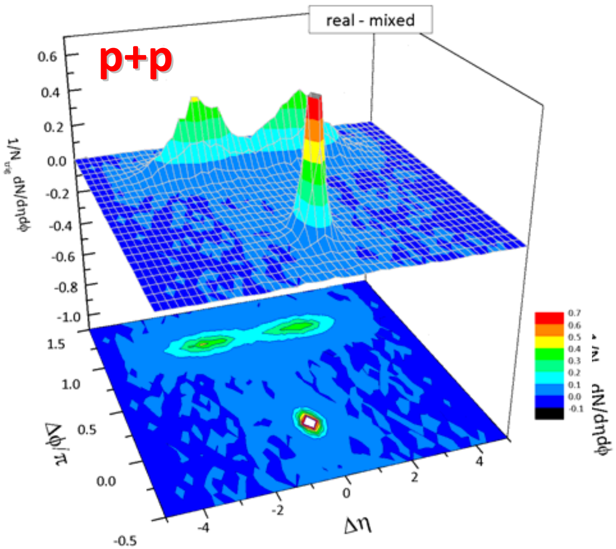


Fig. 1. (Color on-line) Preliminary associated particle distributions in $\Delta\eta$ and $\Delta\phi$ with respect to the trigger hadron for associated particles with 2 GeV/c < p_T^{assoc} < p_T^{trig} in 0-12% central Au+Au collisions. Two different trigger p_T selections are shown: 3 < p_T^{trig} < 4 GeV/c (upper panel) and 4 < p_T^{trig} < 6 GeV/c (lower panel). No background was subtracted.

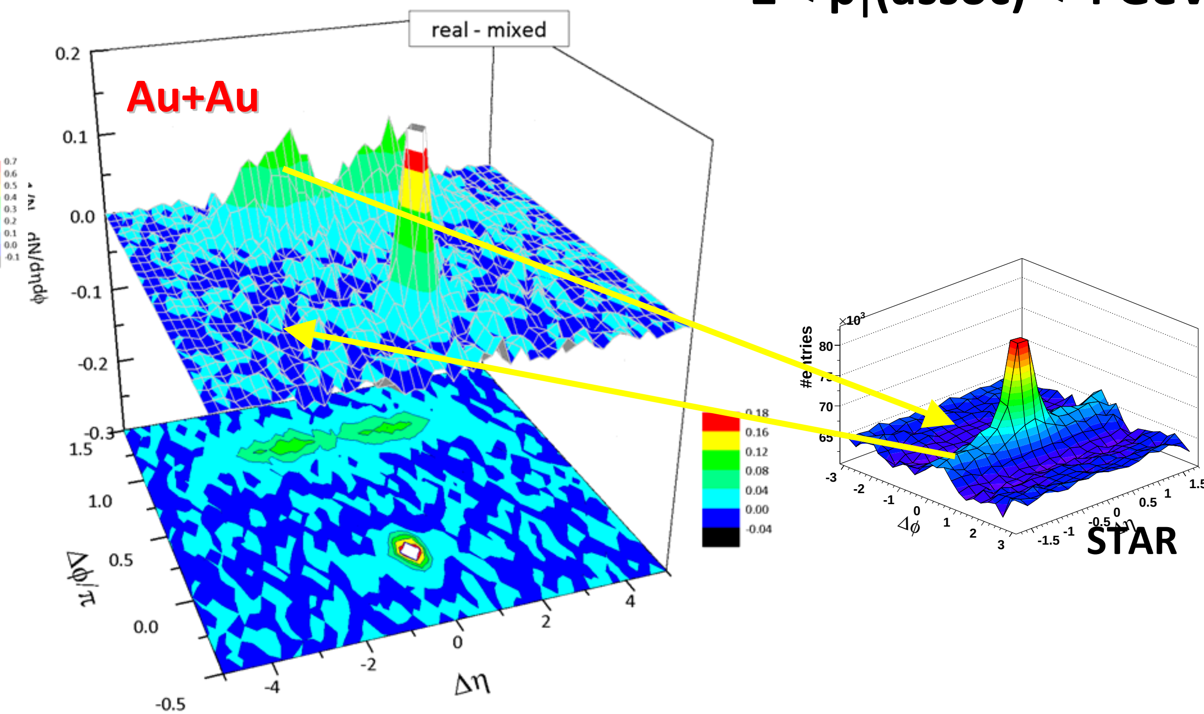
FIG. 2: (color online) Per-trigger correlated yield with p_T^{trig} > 2.5 GeV/c as a function of $\Delta\eta$ and $\Delta\phi$ for $\sqrt{s}$ and $\sqrt{s_{NN}}$=200 GeV (a) PYTHIA p+p and (b) PHOBOS 0-30% central Au+Au collisions. (c) Near-side yield integrated

I: High p_T particle correlations in HSD vs. STAR data



Real-Mixed distribution

STAR: High p_T:
p_T(trig) > 4 GeV/c
2 < p_T(assoc) < 4 GeV



HSD vs. STAR:

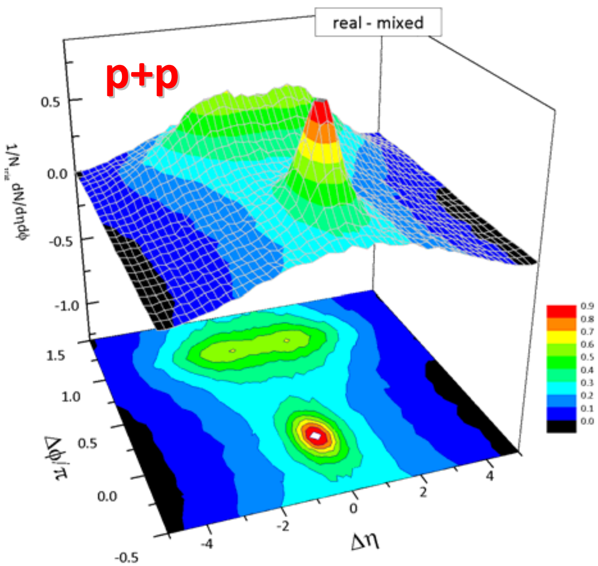
- **away side structure is suppressed in Au+Au collisions in comparison to p+p, however, HSD doesn‘t provide enough high p_T suppression to reproduce the STAR Au+Au data**
- **near-side ridge structure is NOT seen in HSD!**

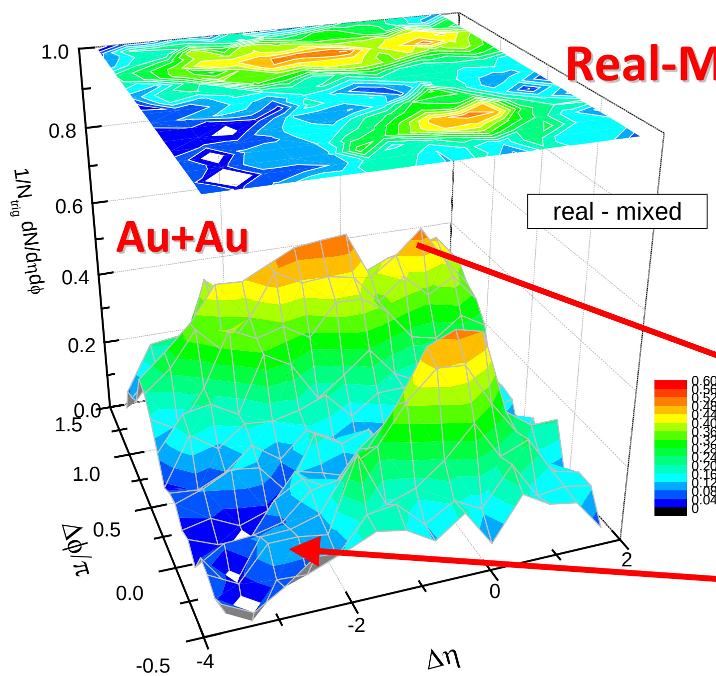
V. Konchakovski et al., PRC in press

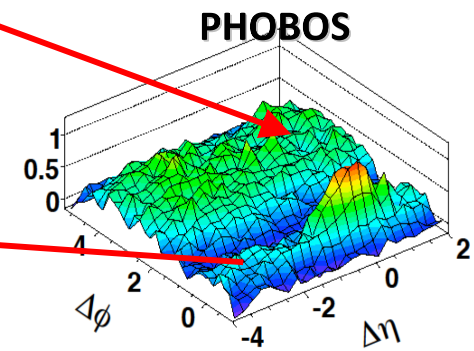
II: Intermediate p_T particle correlations in HSD vs. PHOBOS data

PHOBOS: Intermediate p_T:

p_T(trig) > 2.5 GeV/c; 0.02 < p_T(assoc) < 2.5 GeV







HSD vs. PHOBOS:

- **away side structure is suppressed in Au+Au collision in comparison to p+p, however, HSD doesn‘t provide enough high p_T suppression to reproduce the PHOBOS Au+Au data**
- **near-side ridge structure is NOT seen in HSD!**

V. Konchakovski et al., PRC in press

Summary II

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

- new exp. data from the STAR and PHOBOS collaborations show a near-side ridge structure in the $\phi-\eta$ angular correlations which is not reproduced in the HSD model

- STAR and PHOBOS observe a very strong away-side jet suppression which is NOT reproduced in the hadron-string picture

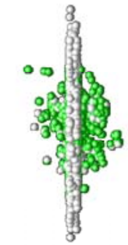
=> evidence for strong nonhadronic interactions in the early phase of the reaction ?!

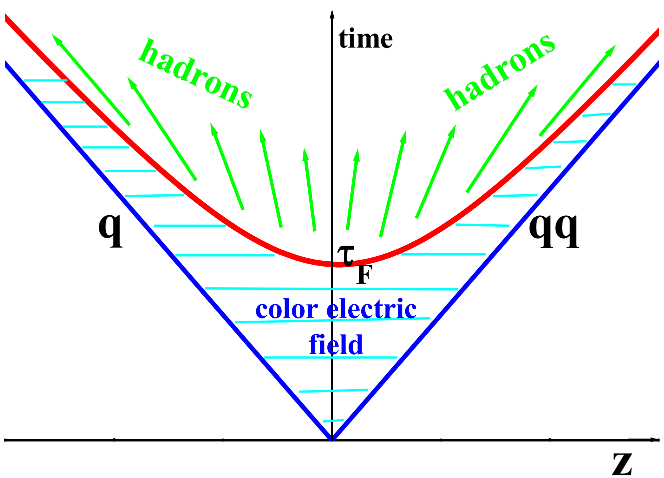
Just let's see what PHSD thinks about the issue!

I. PHSD: basic concepts

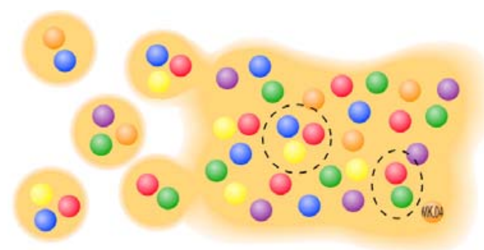
1. Initial A+A collisions – off-shell HSD:

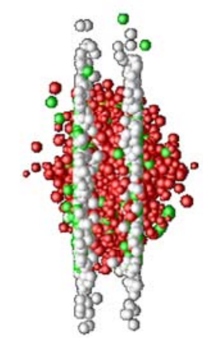
string formation and decay to pre-hadrons





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 --

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