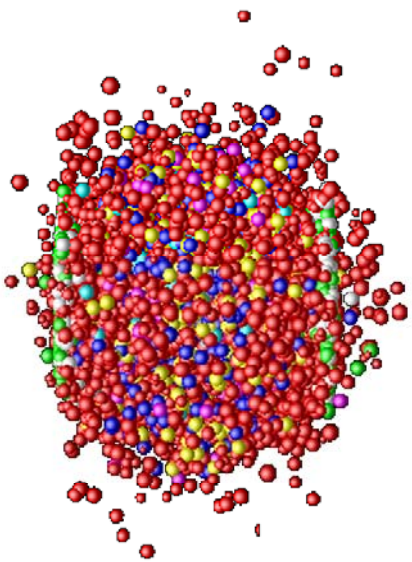
Institut für Theoretische Physik I

JUSTUS-LIEBIG-UNIVERSITÄT GIESSEN

Parton/hadron transport in relativistic nucleus-nucleus collisions



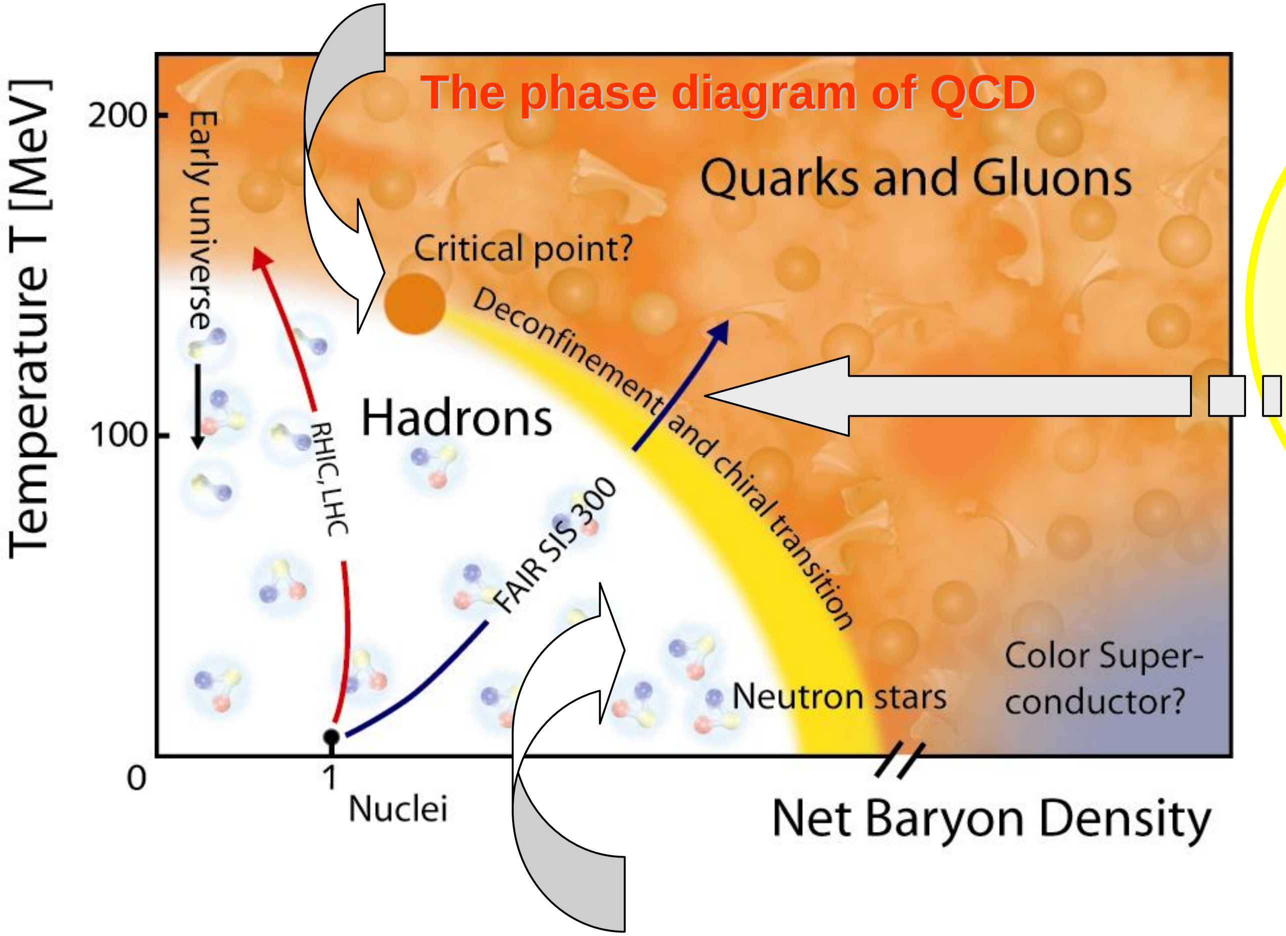
Wolfgang Cassing

GSI 14.04.2010

PHSD

The holy grail:

- Search for the critical point



- Study of the phase transition from hadronic to partonic matter – Quark-Gluon-Plasma

- Study of the in-medium properties of hadrons at high baryon density and temperature

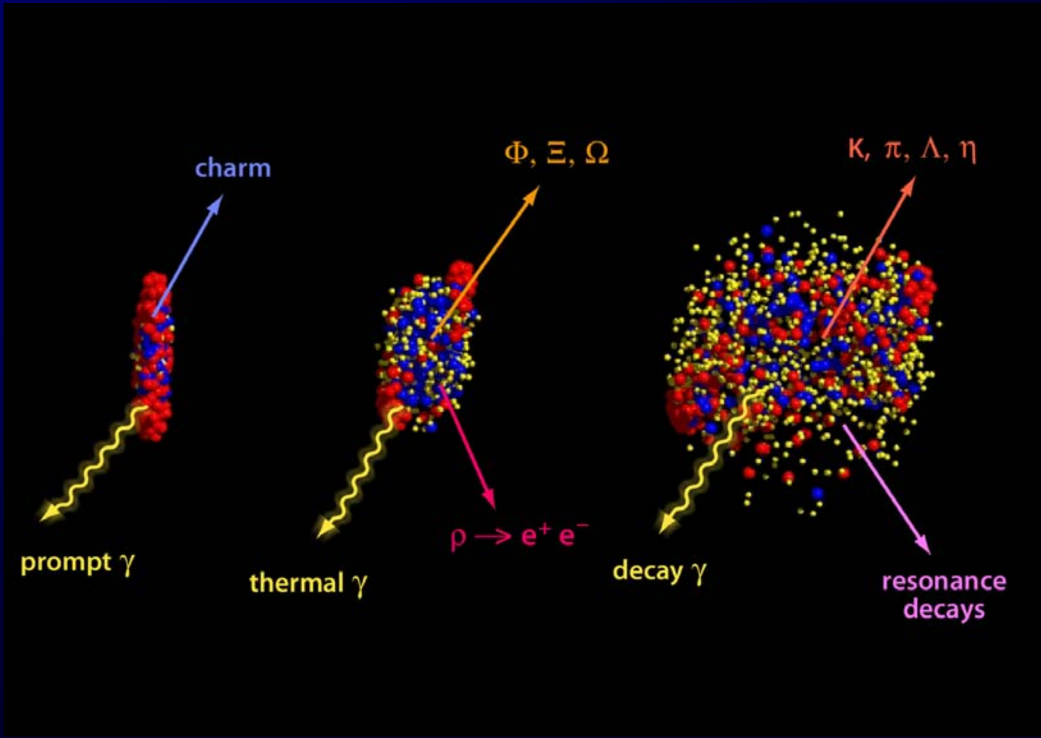
Signals of the phase transition:

- Multi-strange particle enhancement in A+A
- Charm suppression
- Collective flow (v_1, v_2)
- Thermal dileptons
- Jet quenching and angular correlations
- High p_T suppression of hadrons
- Nonstatistical event by event fluctuations and correlations
- ...

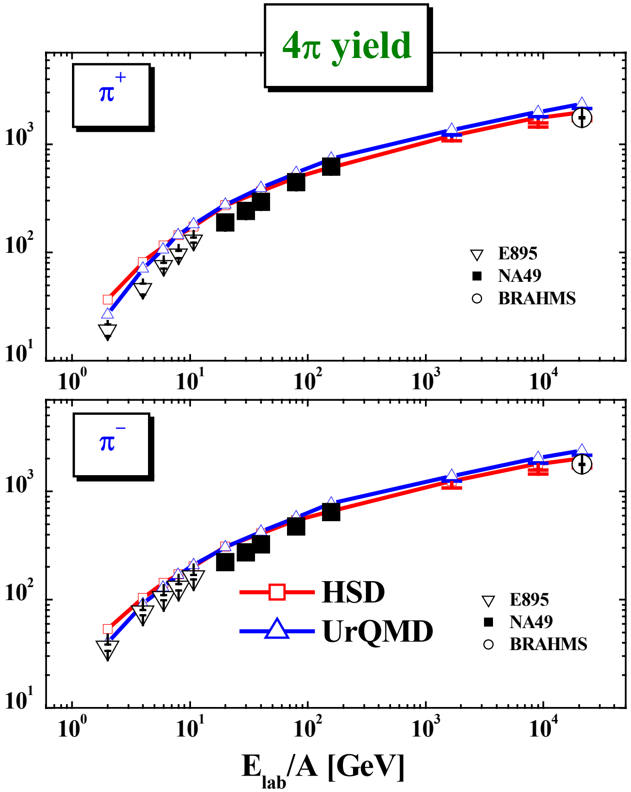
Experiment: measures final hadrons and leptons

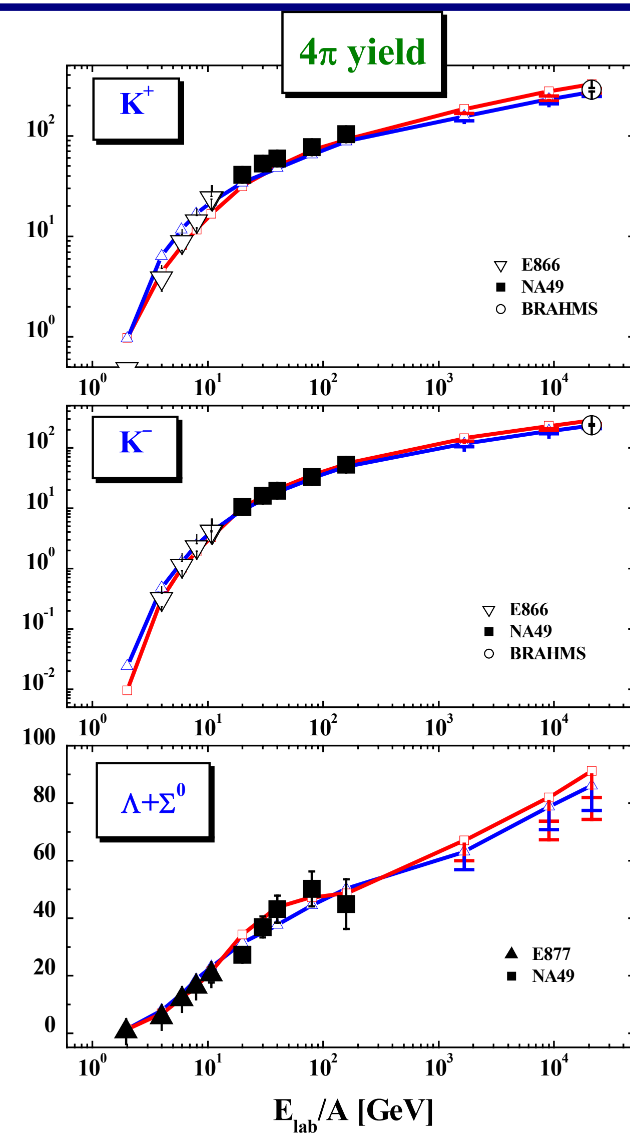
How to learn about physics from data?

Compare with theory!



Hadron-string transport models versus observables





Reasonable description of strangeness by HSD and UrQMD 2.0 (deviations < 20%)

works very well,

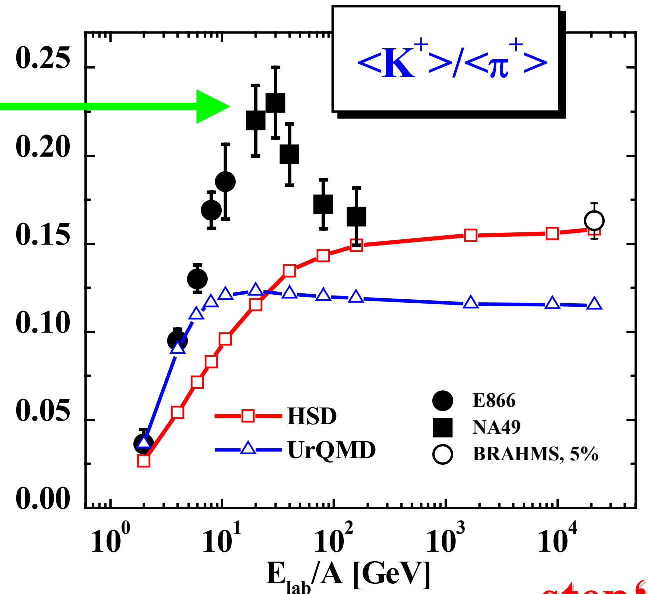
but where do we fail ?

PRC 69 (2004) 032302

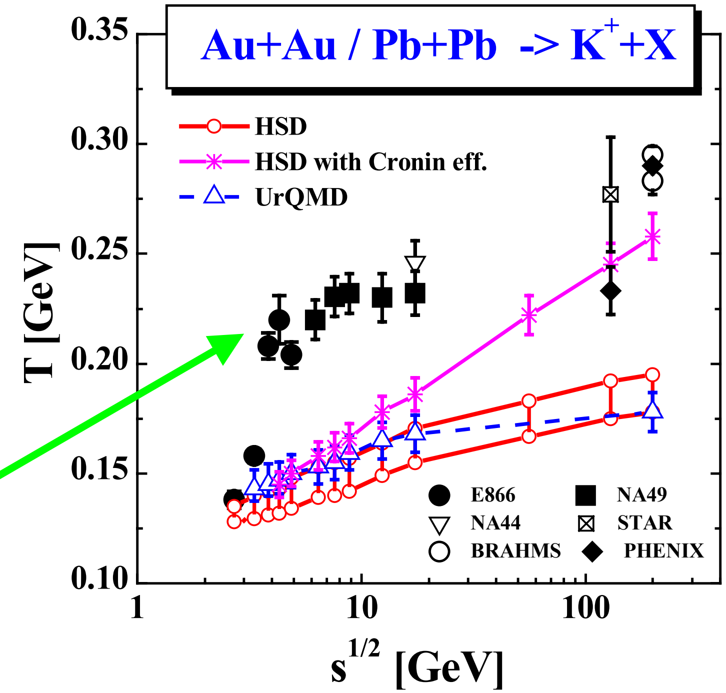
Hadron-string transport models versus observables

- **Strangeness signals of QGP**

,horn' in K^+/π^+



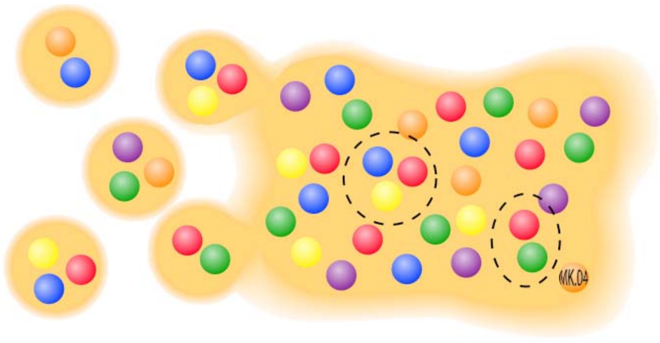
,step' in slope T



Exp. data are not reproduced in terms of the hadron-string picture
=> evidence for nonhadronic degrees of freedom

PRC 69 (2004) 032302

Transport description of the partonic and hadronic phase



Parton-Hadron-String-Dynamics (PHSD)

From hadrons to partons

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

- explicit parton-parton interactions (i.e. between quarks and gluons)!
- + explicit phase transition from hadronic to partonic degrees of freedom
- lQCD EoS for partonic phase => phase transition is always a cross-over

Transport theory: off-shell Kadanoff-Baym equations for the Green-functions $S^{<}_{h}(x,p)$ in phase-space representation with the partonic and hadronic phase

Parton-Hadron-String-Dynamics (PHSD)

W. Cassing, E. Bratkovskaya, PRC 78 (2008) 034919;
NPA831 (2009) 215;
W. Cassing, EPJ ST 168 (2009) 3

QGP phase described by input from the

Dynamical QuasiParticle Model (DQPM)

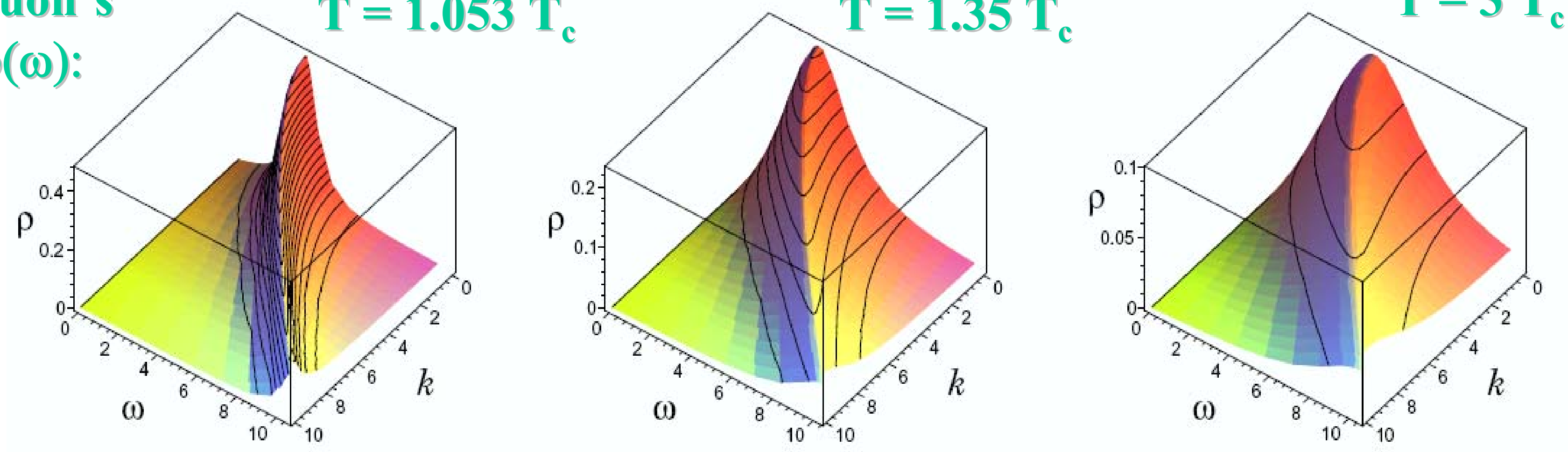
A. Peshier, W. Cassing, PRL 94 (2005) 172301;
Cassing, NPA 791 (2007) 365: NPA 793 (2007)

The Dynamical QuasiParticle Model (DQPM)

- **Interacting quasiparticles :**
  massive quarks and gluons
  with spectral functions

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

Gluon's $\rho(\omega)$:



plot from A. Peshier

- **DQPM well matches lQCD**
- **DQPM provides mean-fields for gluons and quarks as well as effective 2-body interactions and gives transition rates for the formation of hadrons → PHSD**

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

DQPM thermodynamics (N_f=3)

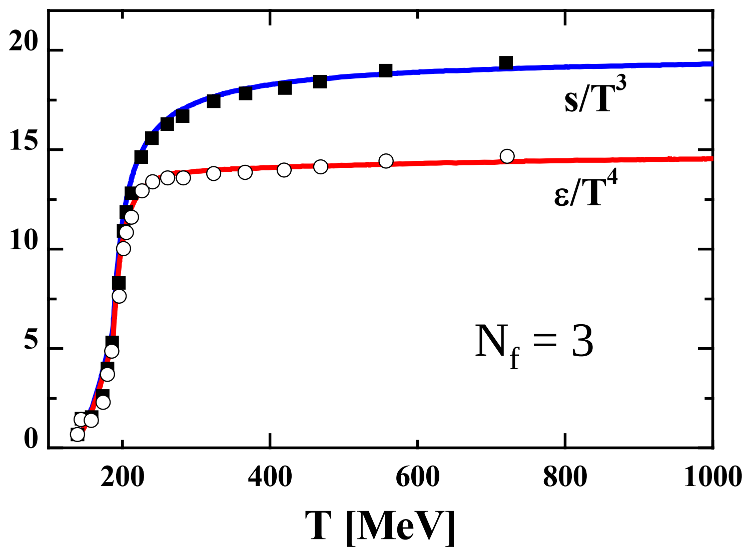
Thermodynamics: **entropy** $s = \frac{\partial P}{dT}$ → **pressure P**

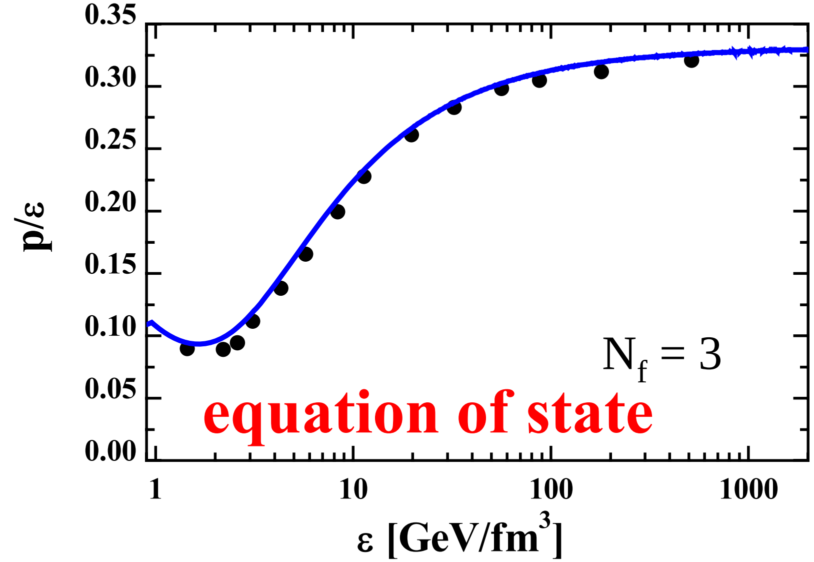
energy density: $\epsilon = Ts - P$

interaction measure:

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

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

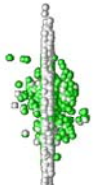




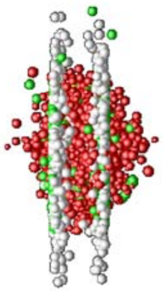
cf. V. D. Toneev, Heavy Ion Phys. 8 (1998) 83

DQPM gives a ‚perfect' description of lQCD results !

PHSD - basic concepts



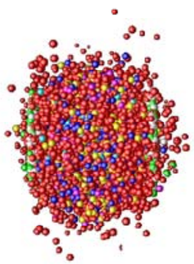
Initial A+A collisions – HSD: string formation and decay to pre-hadrons



Fragmentation of pre-hadrons into quarks: using the quark spectral functions from the Dynamical QuasiParticle Model (DQPM) approximation to QCD

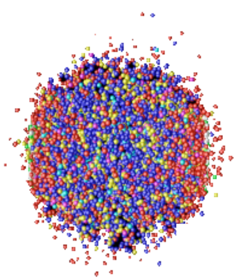
DQPM: Peshier, Cassing, PRL 94 (2005) 172301;
Cassing, NPA 791 (2007) 365: NPA 793 (2007)

Partonic phase: quarks and gluons (= ‚dynamical quasiparticles') with off-shell spectral functions (width, mass) defined by the DQPM



elastic and inelastic parton-parton interactions: using the effective cross sections from the DQPM

- ✓ q + qbar (flavor neutral) <=> gluon (colored)
- ✓ gluon + gluon <=> gluon (possible due to large spectral width)
- ✓ q + qbar (color neutral) <=> hadron resonances

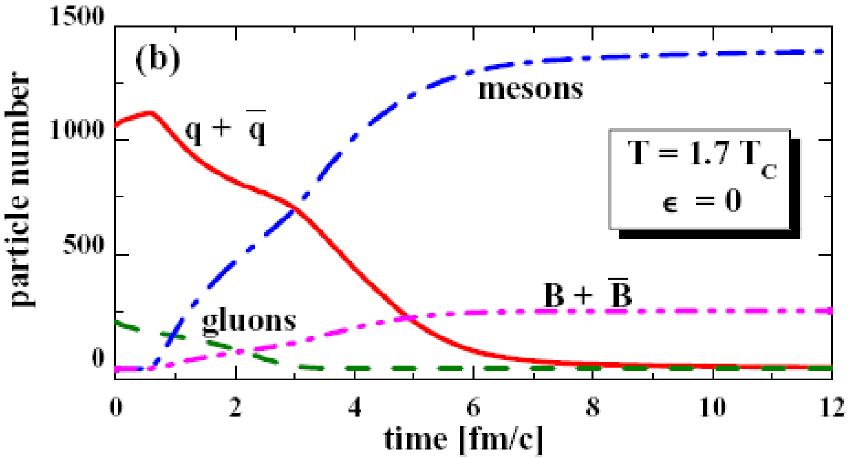


Hadronization: based on DQPM - massive, off-shell quarks and gluons with broad spectral functions hadronize to off-shell mesons and baryons:
gluons → q + qbar; q + qbar → meson (or string);
q + q +q → baryon (or string) (strings act as ‚doorway states' for hadrons)

Hadronic phase: hadron-string interactions – off-shell HSD

PHSD: hadronization

E.g. time evolution of the partonic fireball at initial temperature 1.7 T_c at μ_q=0 →



Consequences: ☺

- Hadronization: q+q_{bar} or 3q or 3q_{bar} fuse to color neutral hadrons (or strings) which furtheron decay to hadrons in a microcanonical fashion, i.e. obeying all conservation laws (i.e. 4-momentum conservation, flavor current conservation) in each event!

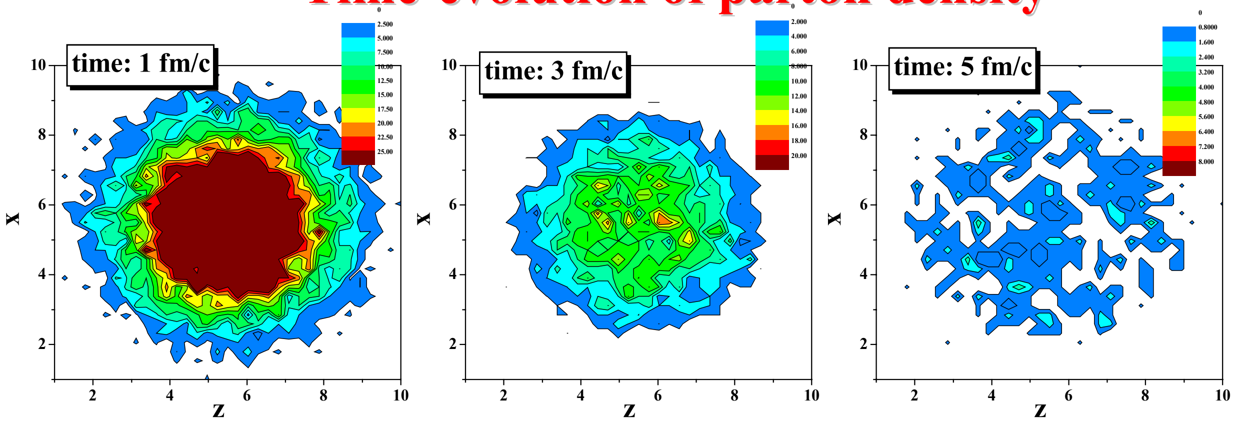
- Hadronization yields an increase in total entropy S (i.e. more hadrons in the final state than initial partons) and not a decrease as in the simple recombination models!

- Off-shell parton transport roughly leads a hydrodynamic evolution of the partonic system

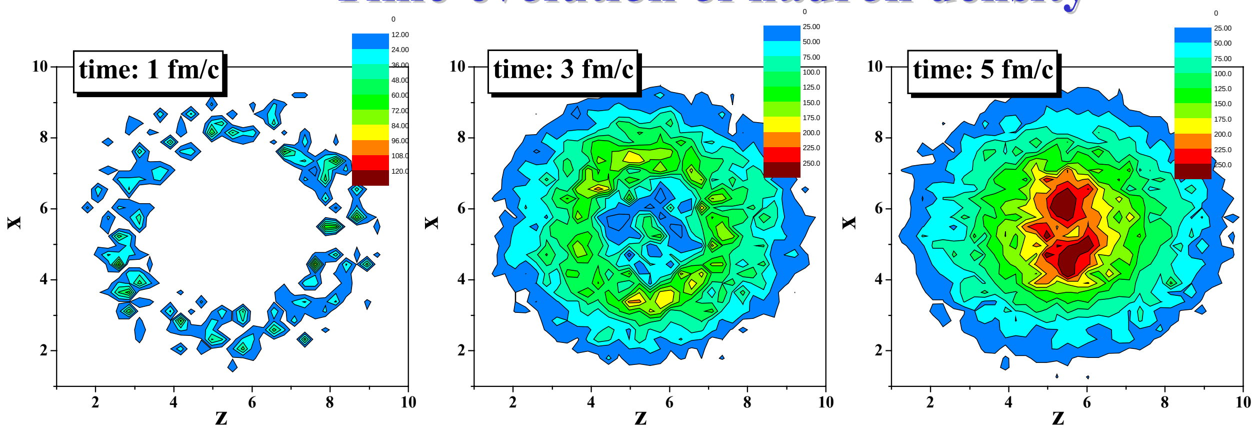
W. Cassing, E. Bratkovskaya, PRC 78 (2008) 034919;
NPA831 (2009) 215;
W. Cassing, EPJ ST 168 (2009) 3

PHSD: Expanding fireball II

Time-evolution of parton density



Time-evolution of hadron density



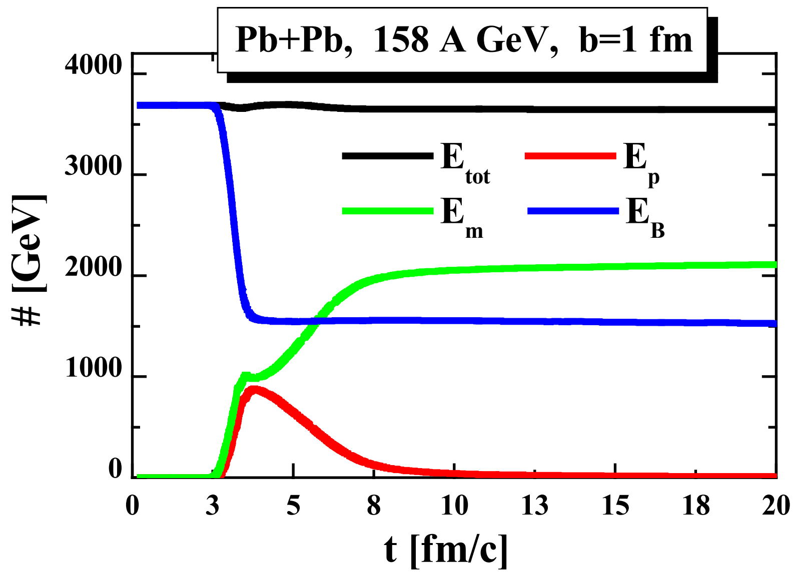
Expanding grid: $\Delta z(t) = \Delta z_0(1+a\ t)$!

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

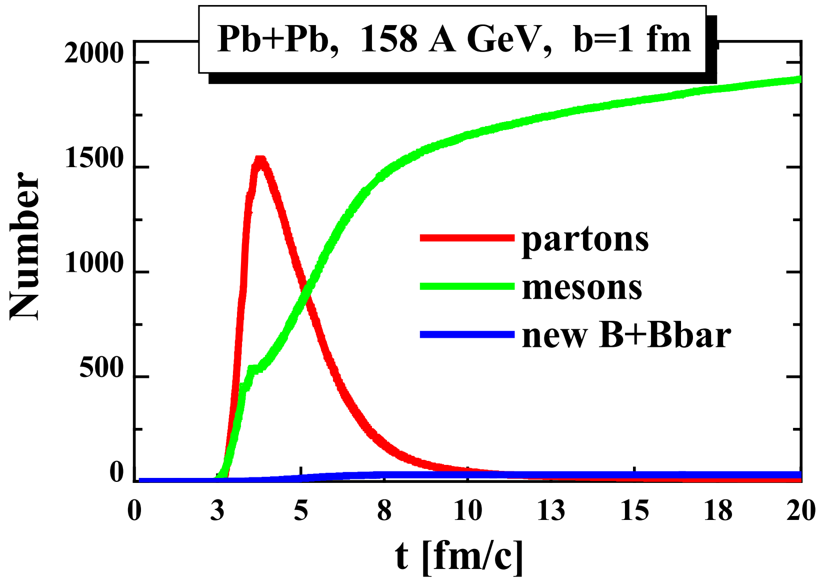
Application to nucleus-nucleus collisions

central Pb + Pb at 158 A GeV

energy balance



particle balance

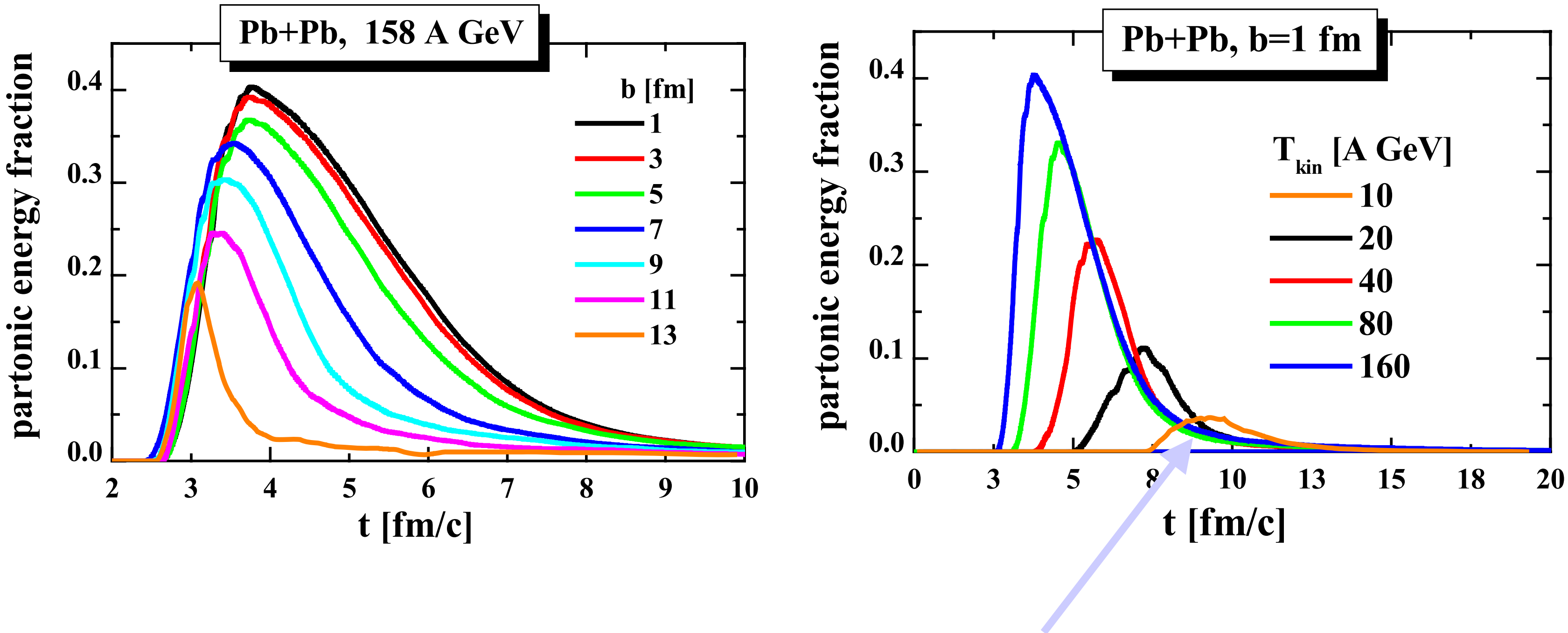


only about 40% of the converted energy goes to partons;
the rest is contained in the ‚large' hadronic corona!

Cassing & Bratkovskaya, NPA 831 (2009) 215

Partonic phase at SPS/FAIR/NICA energies

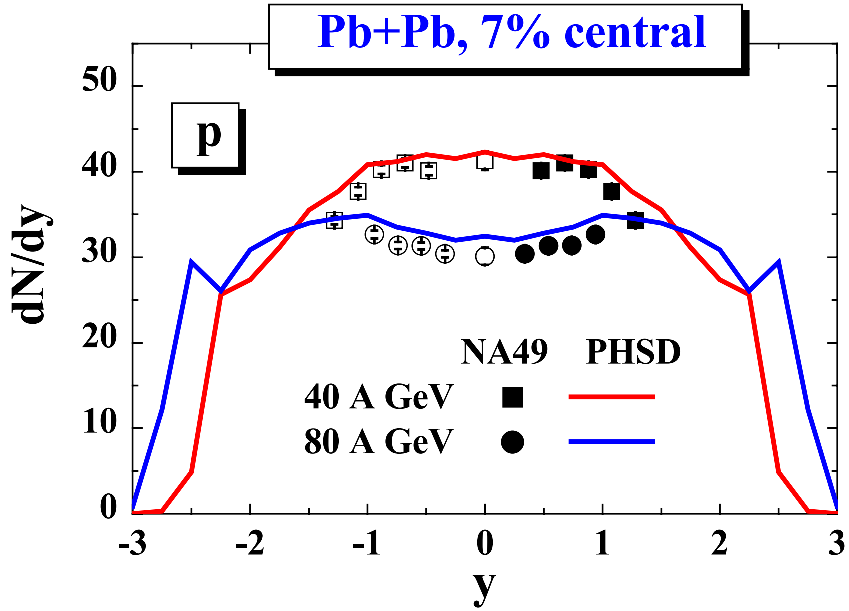
partonic energy fraction vs centrality and energy

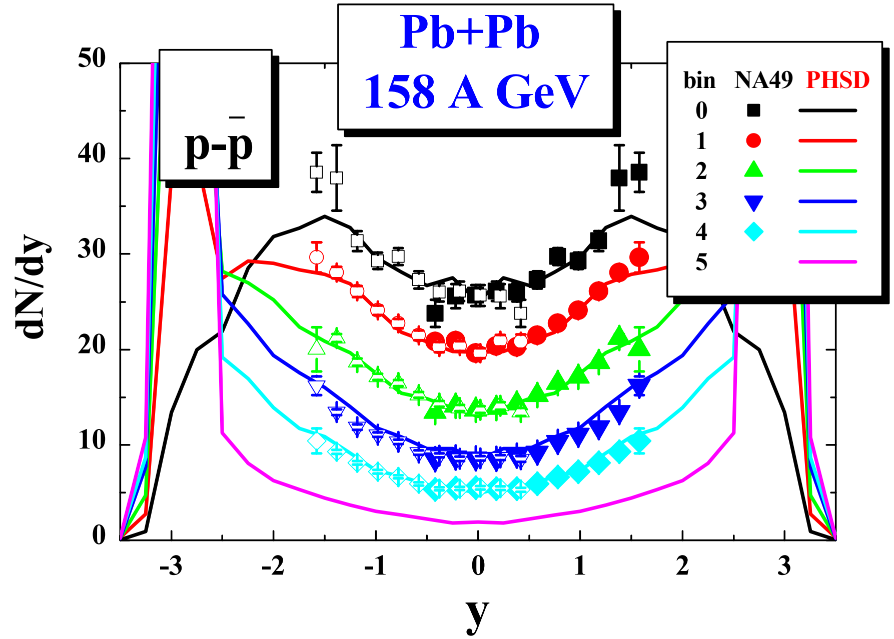


Dramatic decrease of partonic phase with decreasing energy and centrality

Cassing & Bratkovskaya, NPA 831 (2009) 215

Proton stopping at SPS

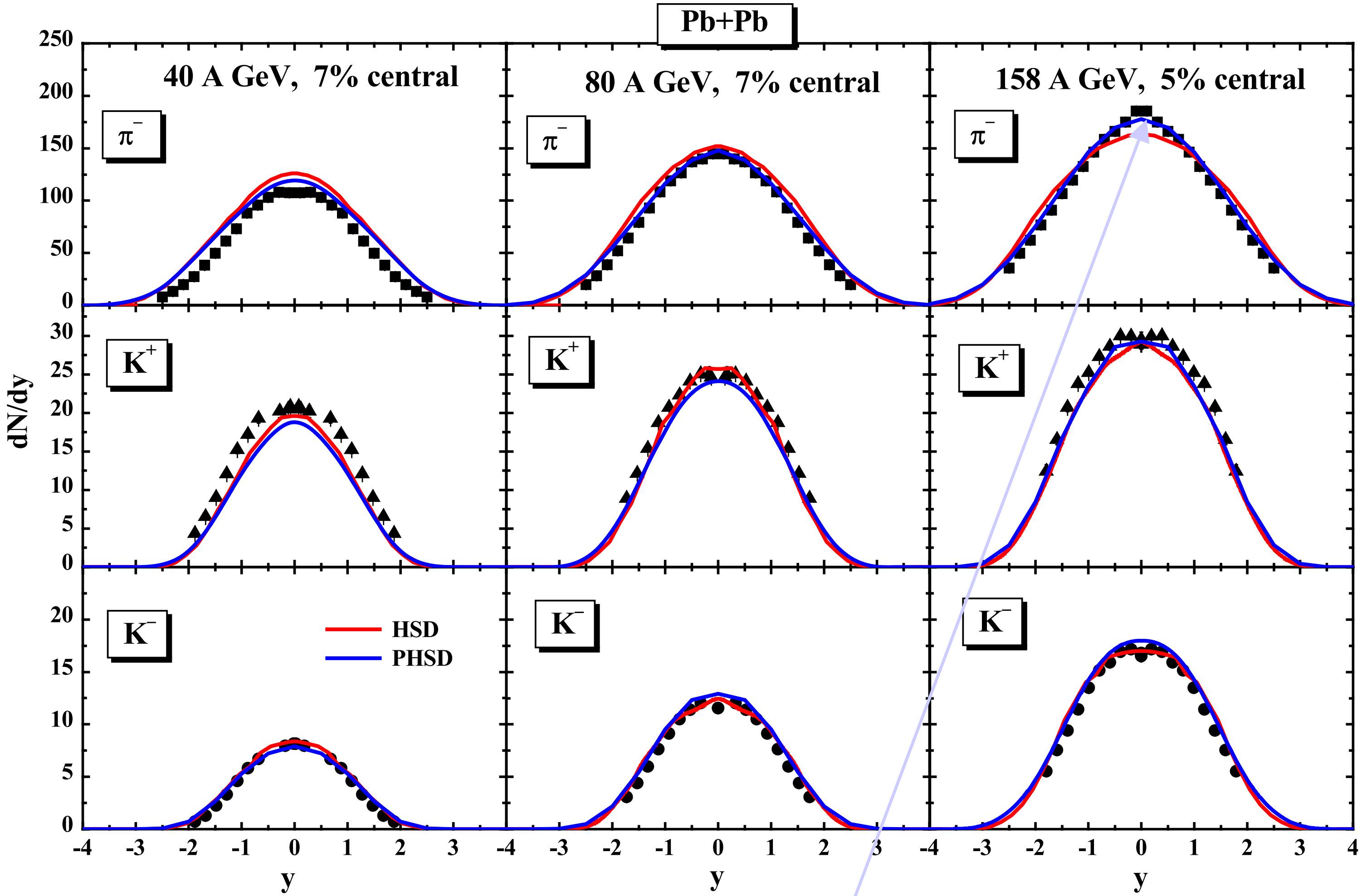




➔looks not bad in comparison to NA49 data,
but not sensitive to parton dynamics (PHSD = HSD)!

Cassing & Bratkovskaya, NPA 831 (2009) 215

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

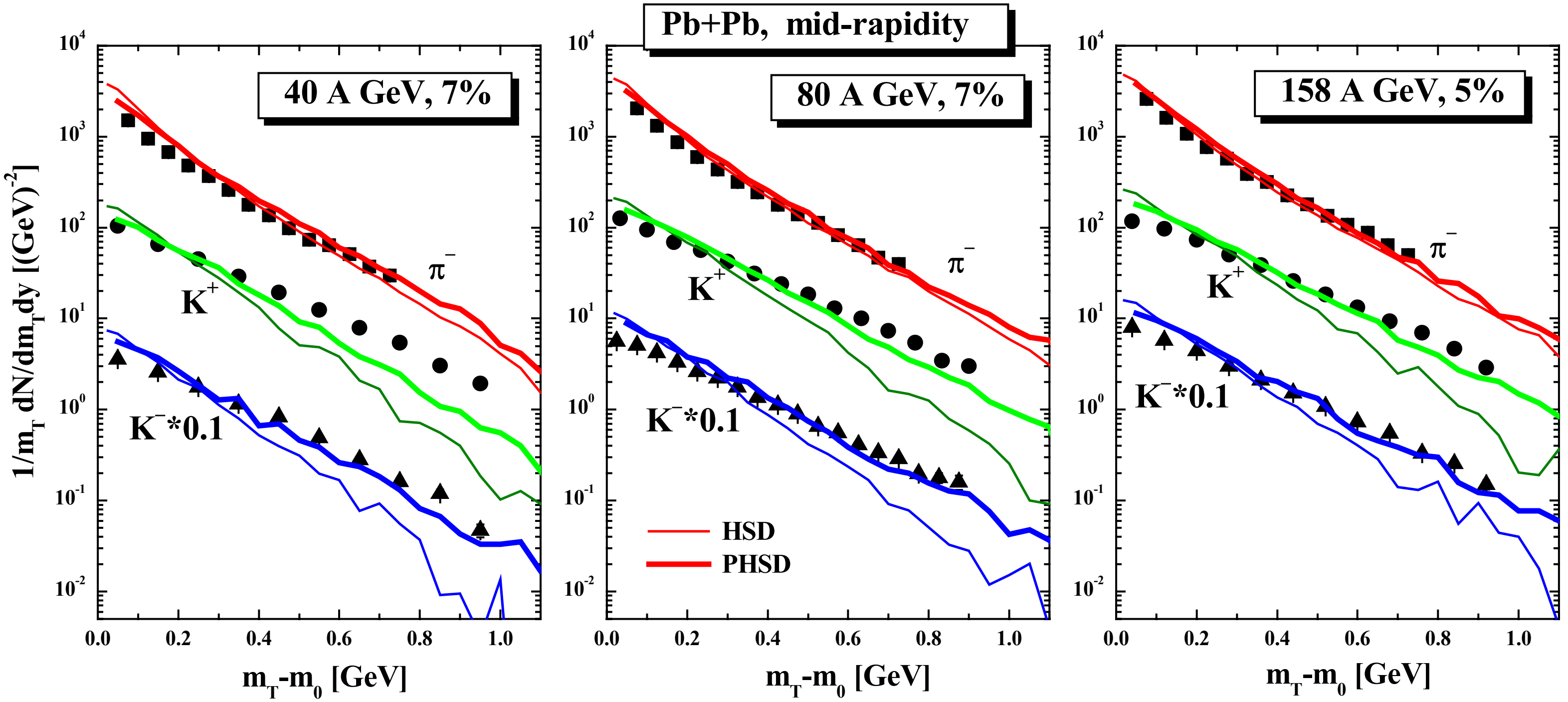


➔ pion and kaon rapidity distributions become slightly narrower

Cassing & Bratkovskaya, NPA 831 (2009) 215

PHSD: Transverse mass spectra at SPS

Central Pb + Pb at SPS energies

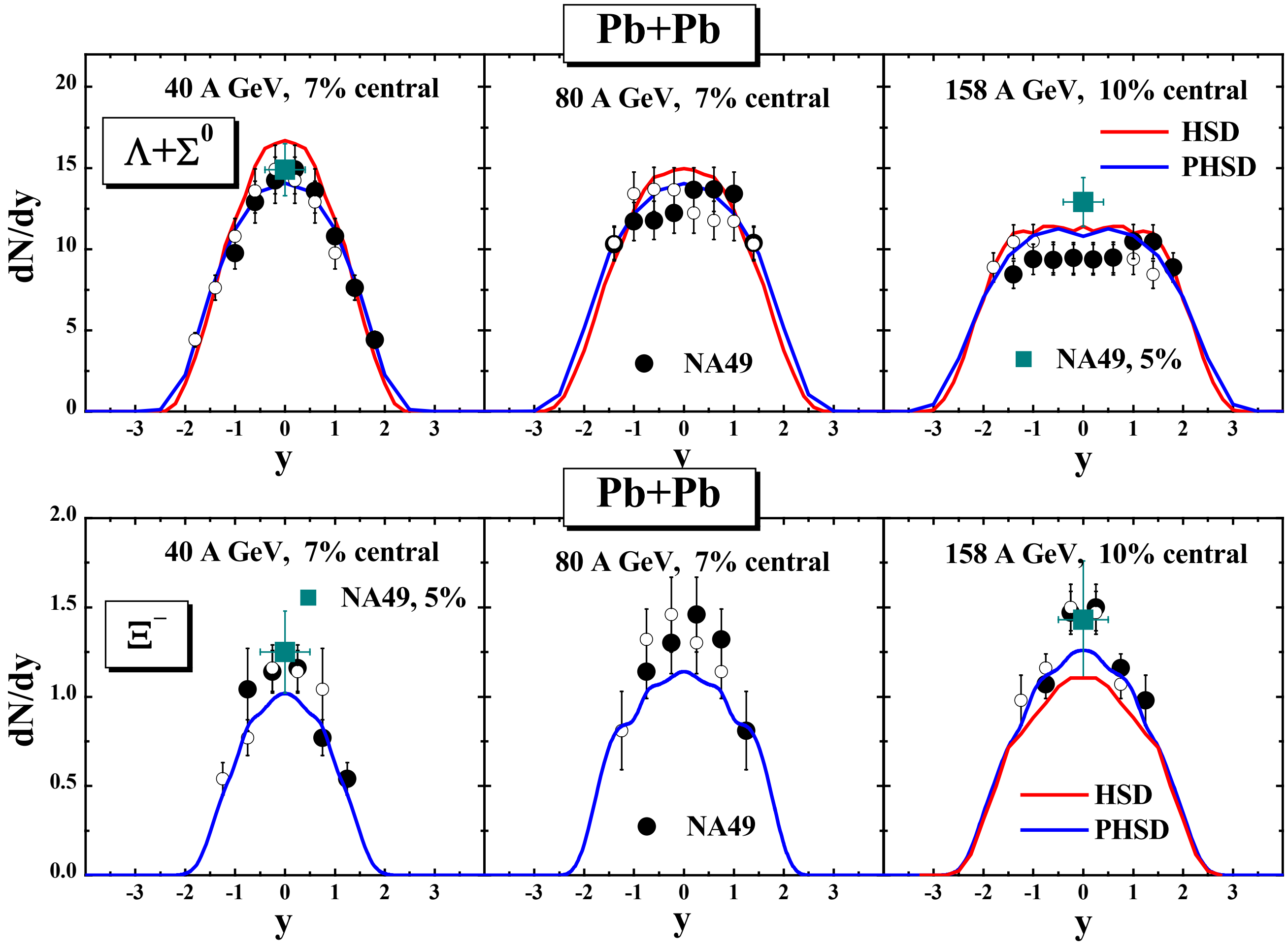


☺ PHSD gives harder spectra and works better than HSD at SPS (and top FAIR) energies

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

Cassing & Bratkovskaya, NPA 831 (2009) 215

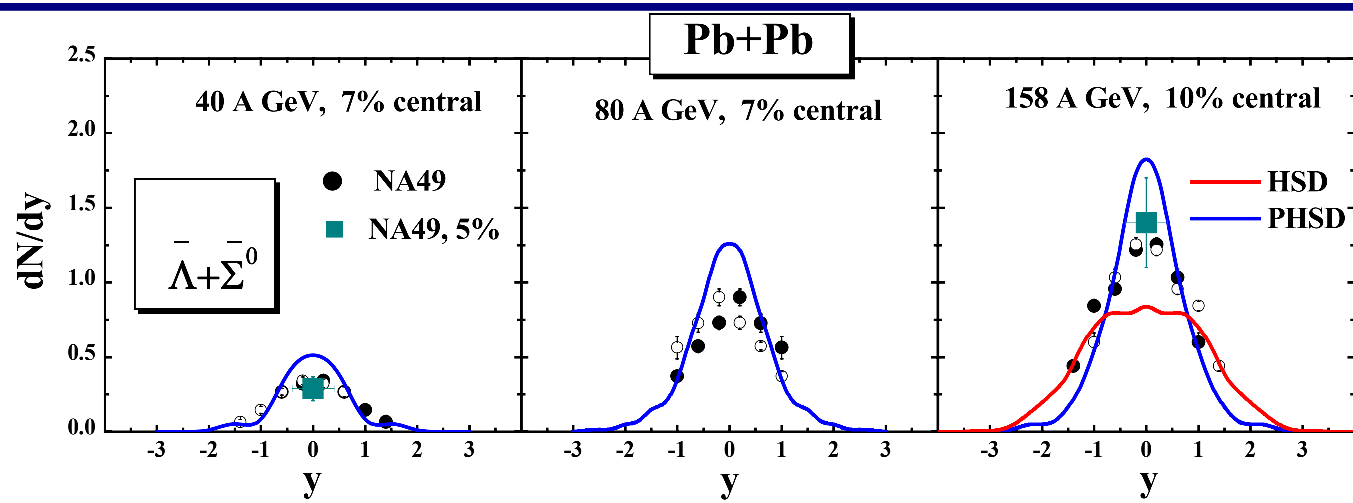
Rapidity distributions of strange baryons



➔ PHSD similar to HSD, reasonable agreement with data

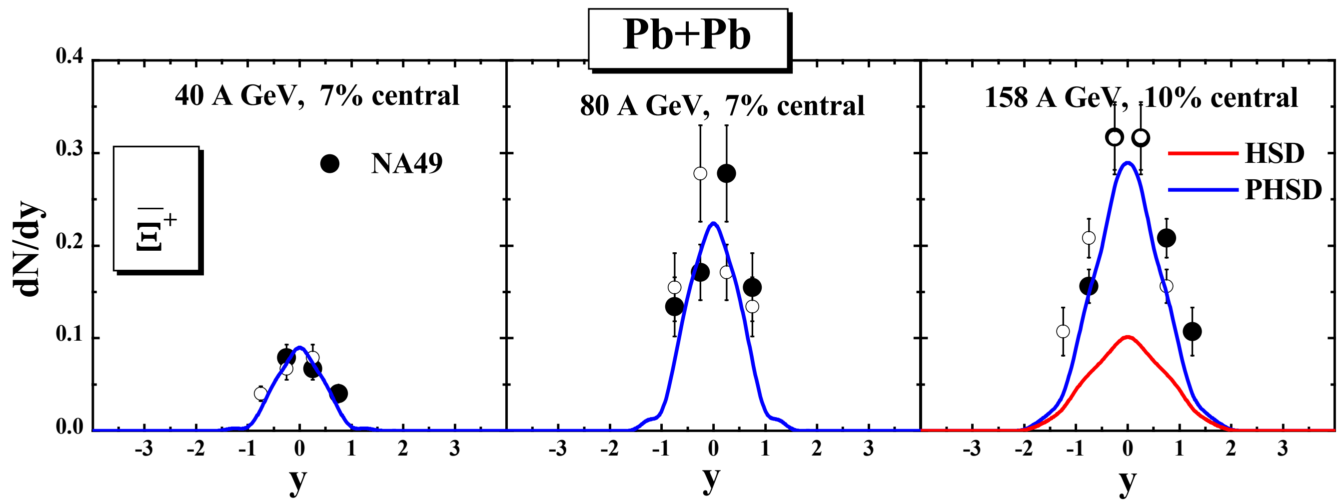
Cassing & Bratkovskaya, NPA 831 (2009) 215

Rapidity distributions of (multi-)strange antibaryons



strange antibaryons

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



multi-strange antibaryon

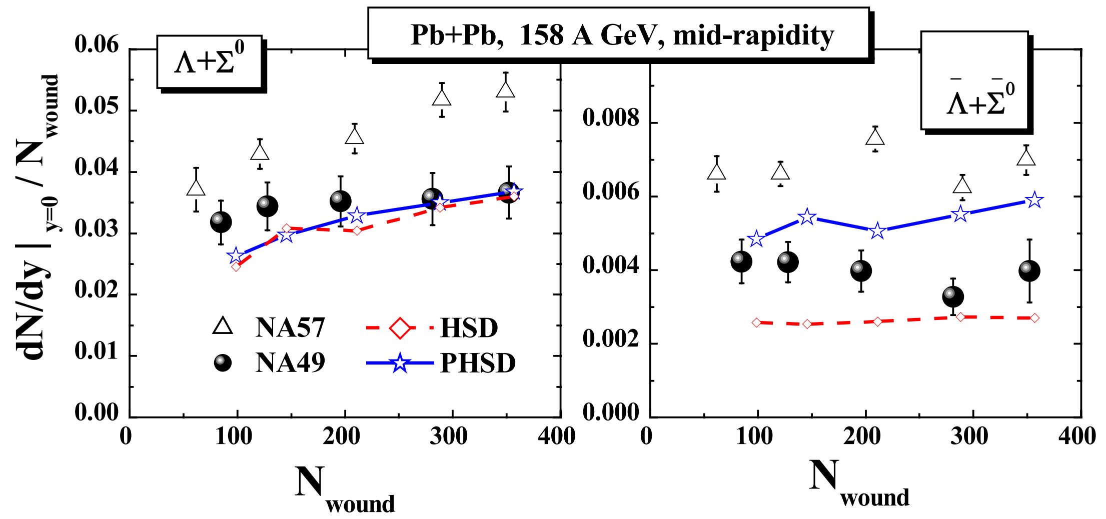
$\bar{\Xi}^+$

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

Cassing & Bratkovskaya, NPA 831 (2009) 215

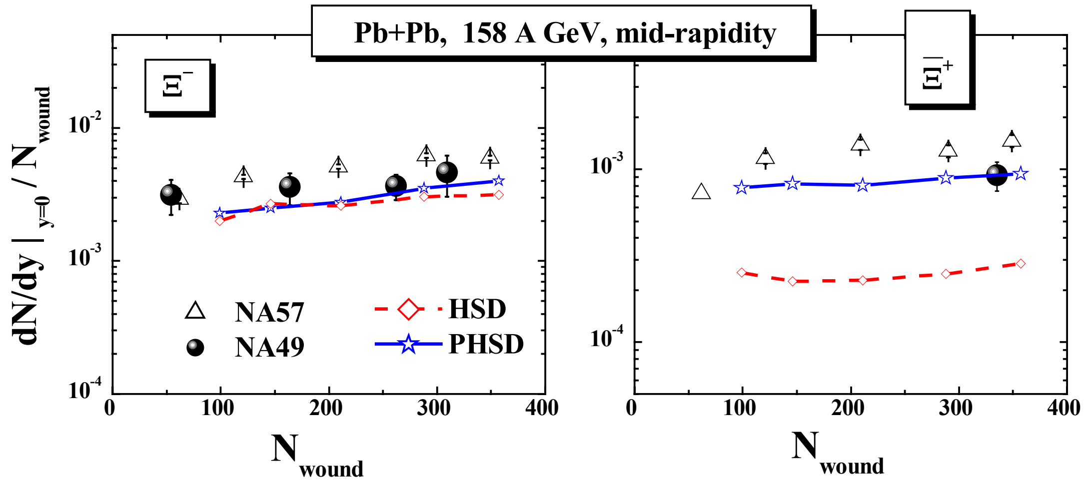
Centrality dependence of (multi-)strange (anti-)baryons

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

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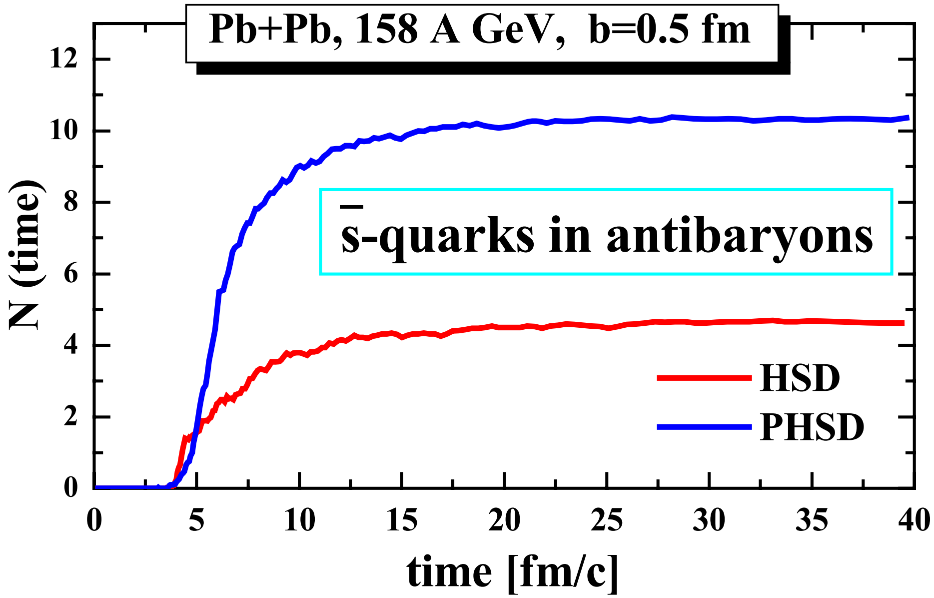
Number of s-bar quarks in hadronic and partonic matter

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

Summary I

- Some exp. data are not well reproduced in terms of the hadron-string picture => evidence for nonhadronic degrees of freedom

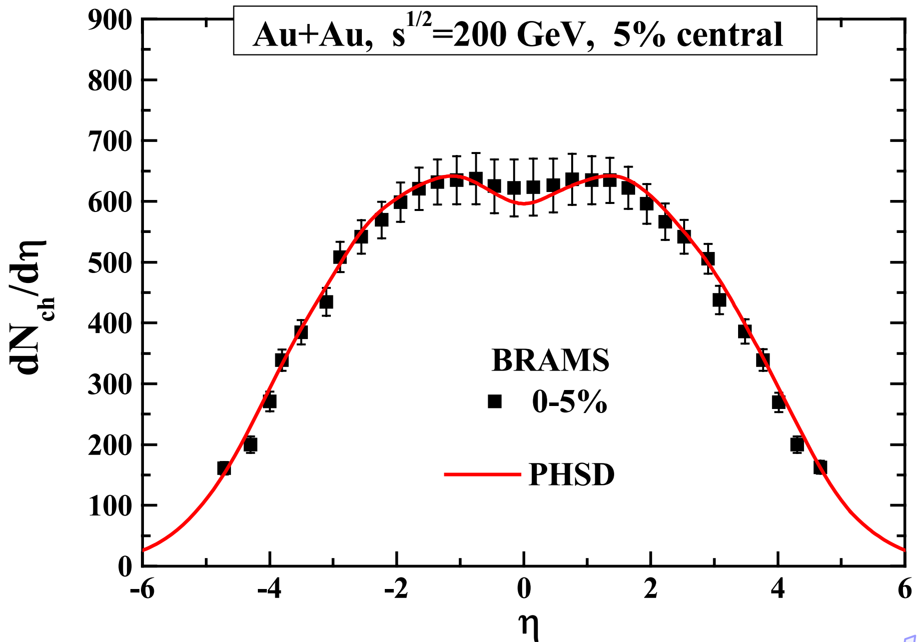
- PHSD provides a consistent description of off-shell parton dynamics in line with a lattice QCD equation of state

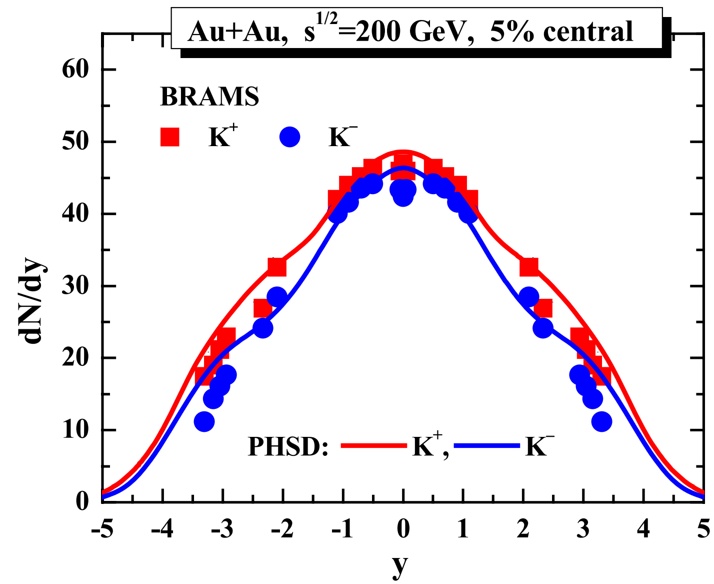
- The Pb + Pb data at top SPS energies are rather well described within PHSD including baryon stopping, strange antibaryon enhancement and meson m_T slopes (will be also seen at top FAIR energies)

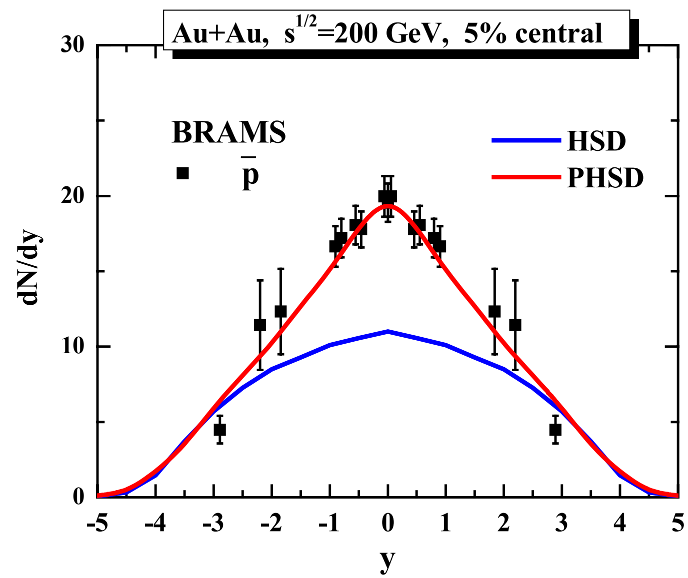
- At low SPS energies PHSD gives practically the same results as HSD (except for strange antibaryons) when the lQCD EoS (where the phase transition is always a cross-over) is used

➔ Is the matter at low SPS a ‚mixed phase‘ of hadrons and partons?

PHSD: rapidity spectra at RHIC





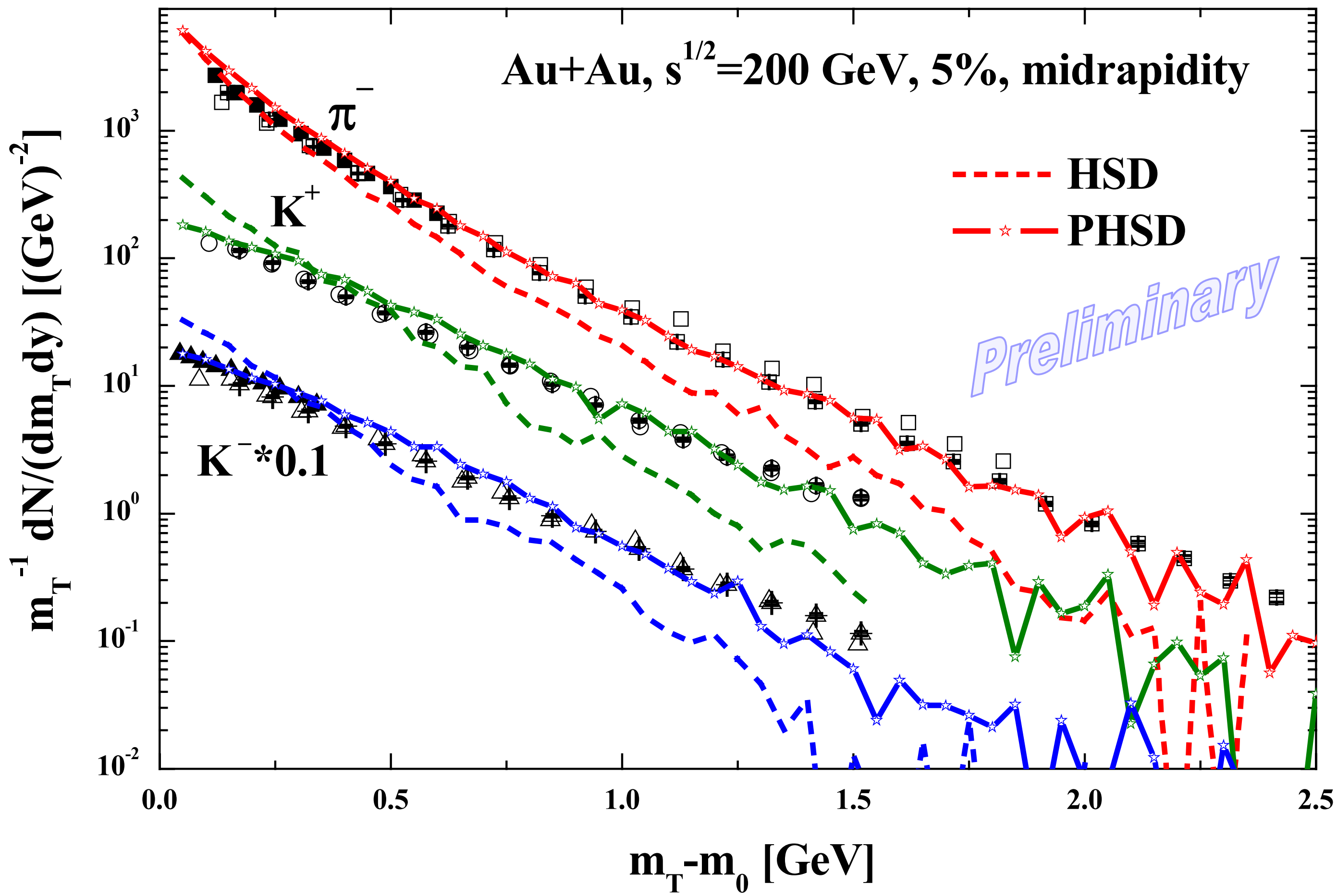


Preliminary

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

looks actually too good to be true!

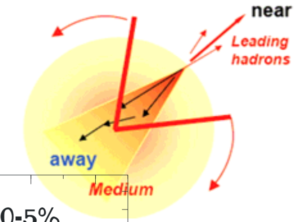
PHSD: Transverse mass spectra at RHIC



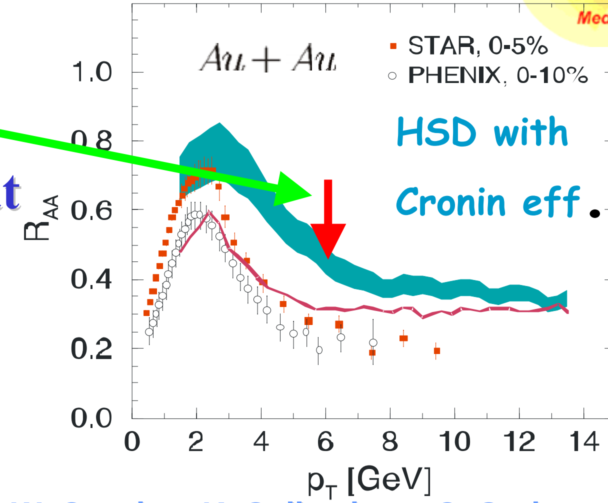
PHSD gives harder spectra and works better than HSD at RHIC

looks actually too good to be true!

High p_T suppression signals of QGP:



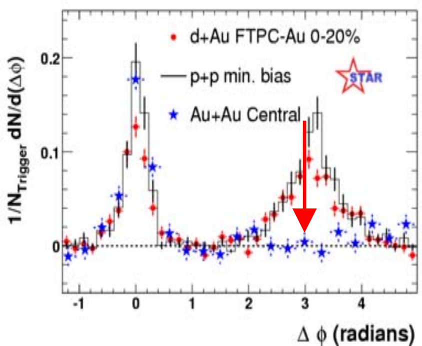
The attenuation of high p_T-hadrons (R_{AA}) is well reproduced in the hadron-string approach for non-central Au+Au collisions at top RHIC energies, however, the hadron-string model doesn‘t provide enough high p_T suppression for central Au+Au !

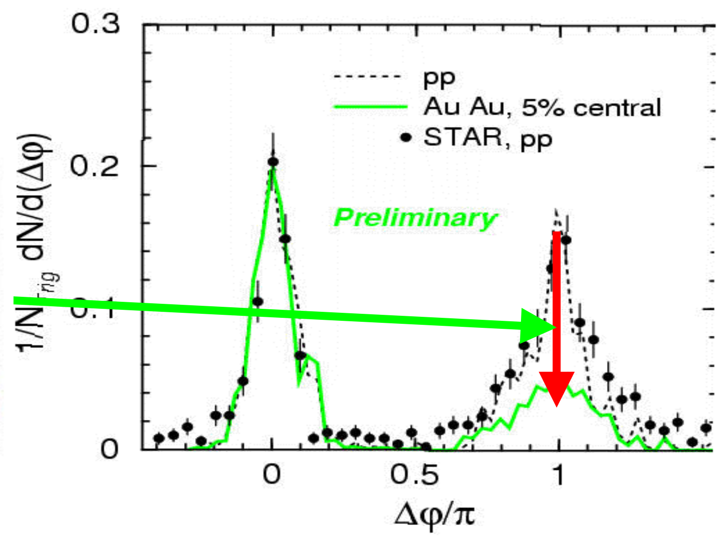


W. Cassing, K. Gallmeister, C. Greiner, NPA 735 (2004) 277

Jet suppression signals of QGP:

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

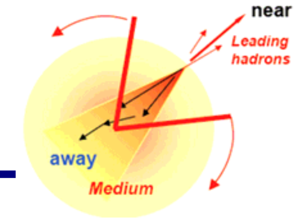




=> evidence for strong nonhadronic interactions in the early phase of the reaction!

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

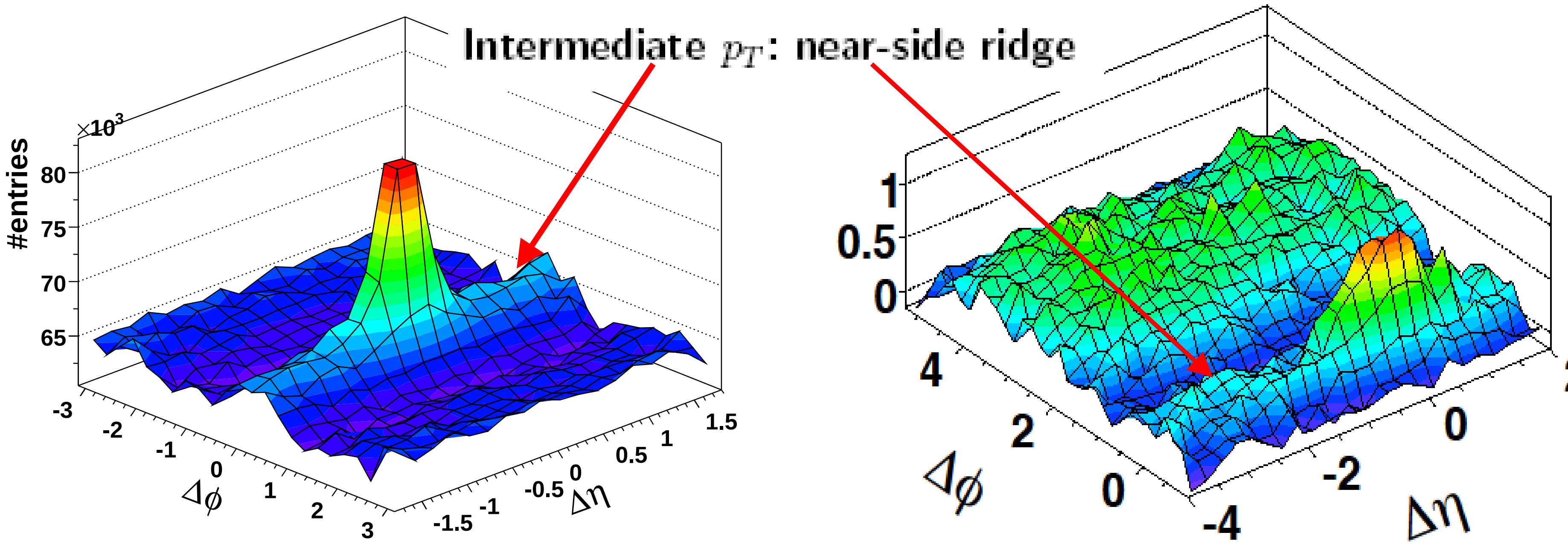
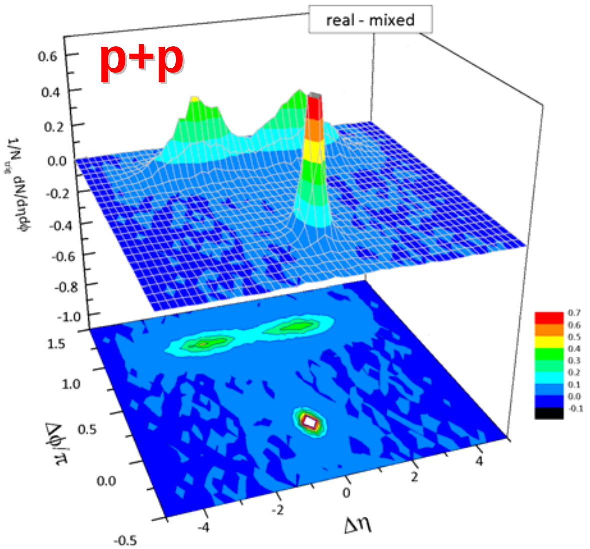


Fig. 1. (Color on-line) Preliminary associated particle distributions in $\Delta\eta$ and $\Delta\phi$ with respect to the trigger hadron for associated particles with 2 GeV/c $< p_T^{assoc} < p_T^{trig}$ in 0-12% central Au+Au collisions. Two different trigger p_T selections are shown: $3 < p_T^{trig}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

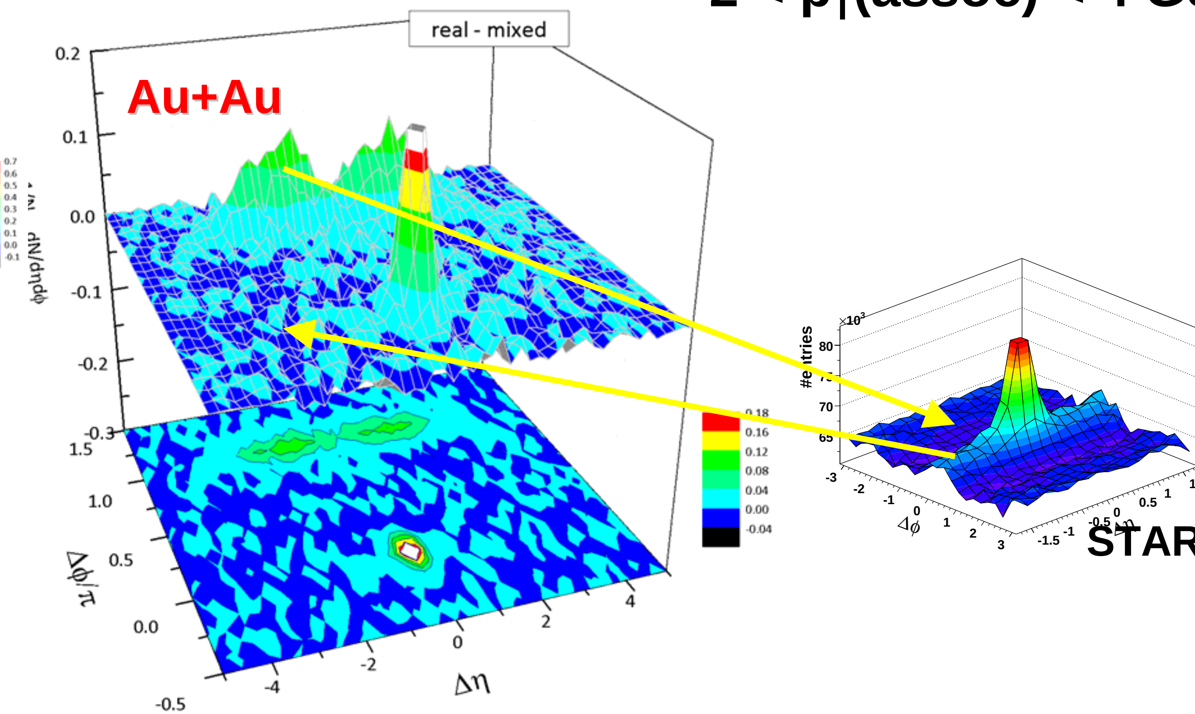
FIG. 2: (color online) Per-trigger correlated yield with $p_T^{trig} > 2.5$ GeV/c as a function of $\Delta\eta$ and $\Delta\phi$ for $\sqrt{s}$ and $\sqrt{s_{NN}}$=200 GeV (a) PYTHIA p+p and (b) PHOBOS 0-30% central Au+Au collisions. (c) Near-side yield integrated

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

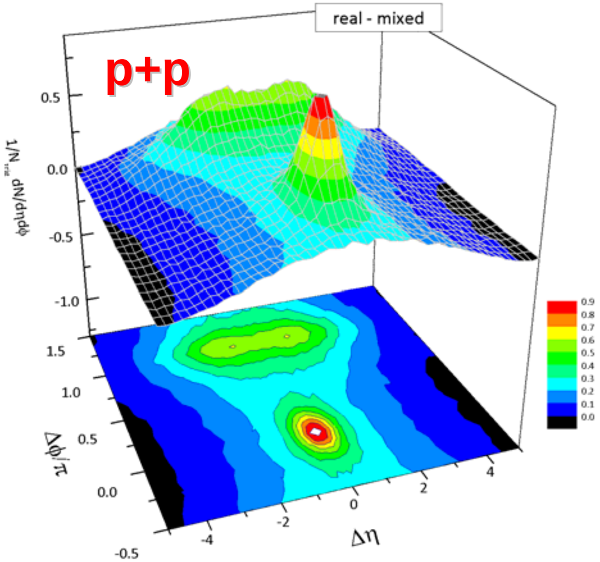


HSD vs. STAR:

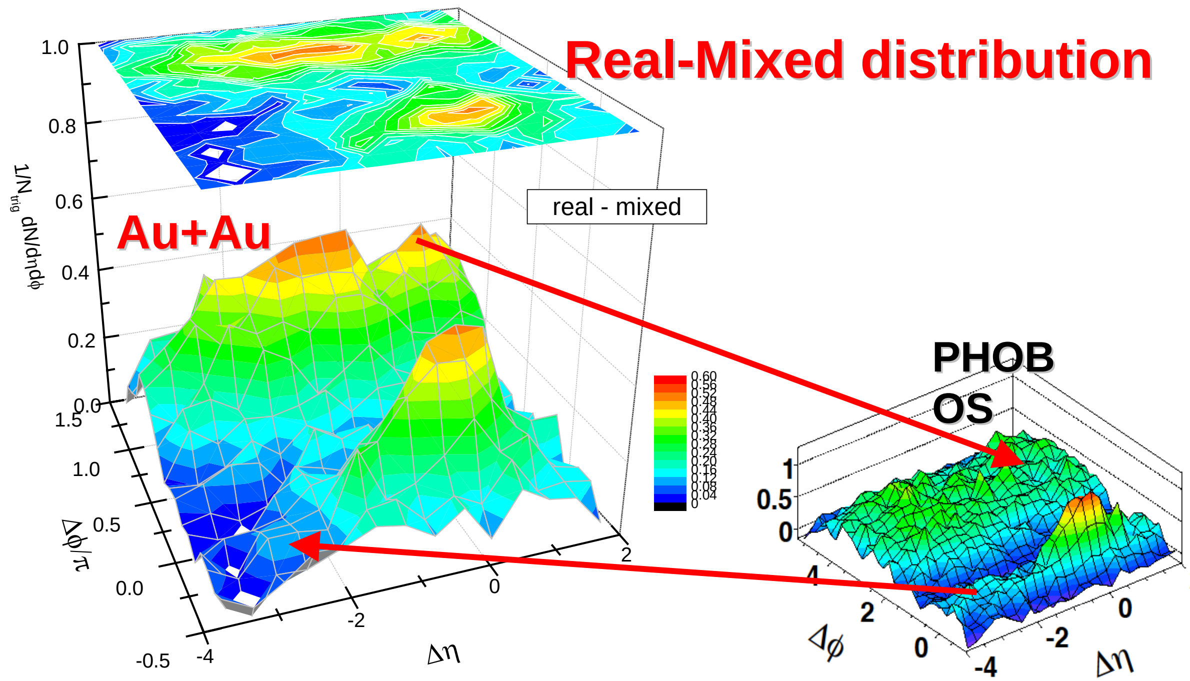
- **away side structure is suppressed in Au+Au collisions in comparison to p+p, however, HSD doesn't provide enough high p_T suppression to reproduce the STAR Au+Au data**
- **near-side ridge structure is NOT seen in HSD!**

V. Konchakovski

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

Summary II

- PHSD provides a reasonable description of the rapidity spectra and meson m_T slopes for Au+Au collisions at 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!

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