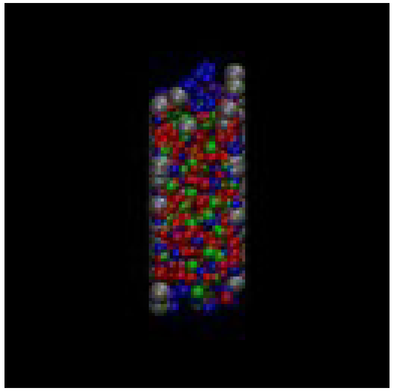
Institut für
Theoretische Physik I

JUSTUS-LIEBIG-
UNIVERSITÄT
GIESSEN

Strange antibaryons and directed flow from $\sqrt{s}$= 4 - 200 GeV

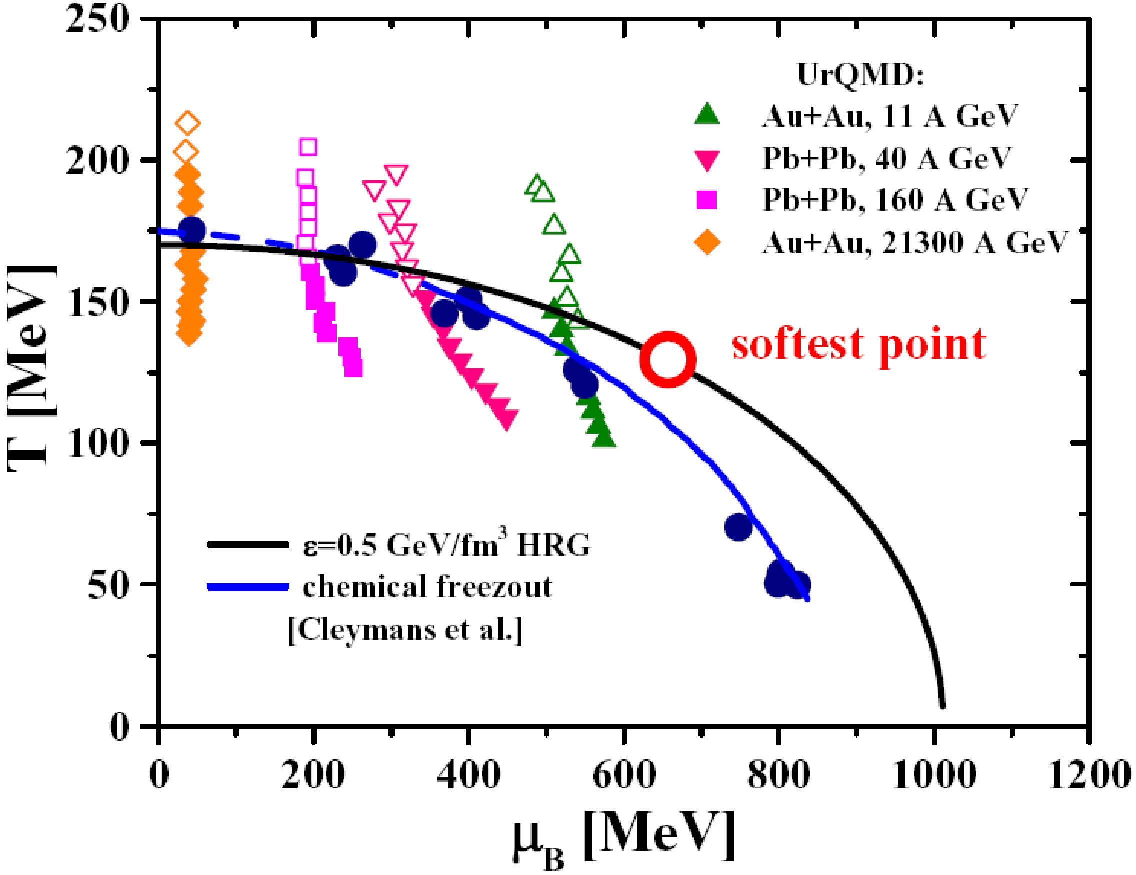
Wolfgang Cassing



CBM Physics Workshop
09.04.2014

PHSD

Lattice QCD <--> transport <--> experiment



hunting for the softest point in the equation of state

Strange baryons at low energies

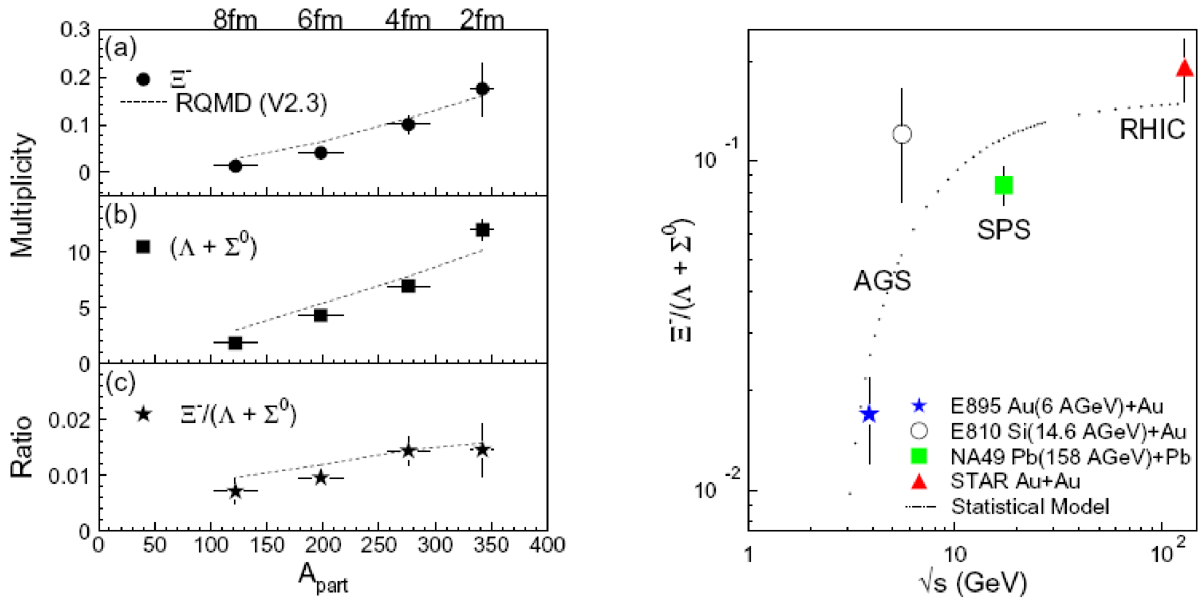


Fig. 3.13 a.) Centrality dependence of Ξ and $\Lambda+\Sigma$ yields, as well as $\Xi/(\Lambda+\Sigma)$ ratio for 6 A GeV Au+Au collisions in comparison to RQMD calculations, b.) Excitation function of $\Xi/(\Lambda+\Sigma)$ ratio based on E810, E895, NA49 and RHIC data (from [115]).

have been a challenge since long !

Au+Au data at 11.6 A GeV suggest

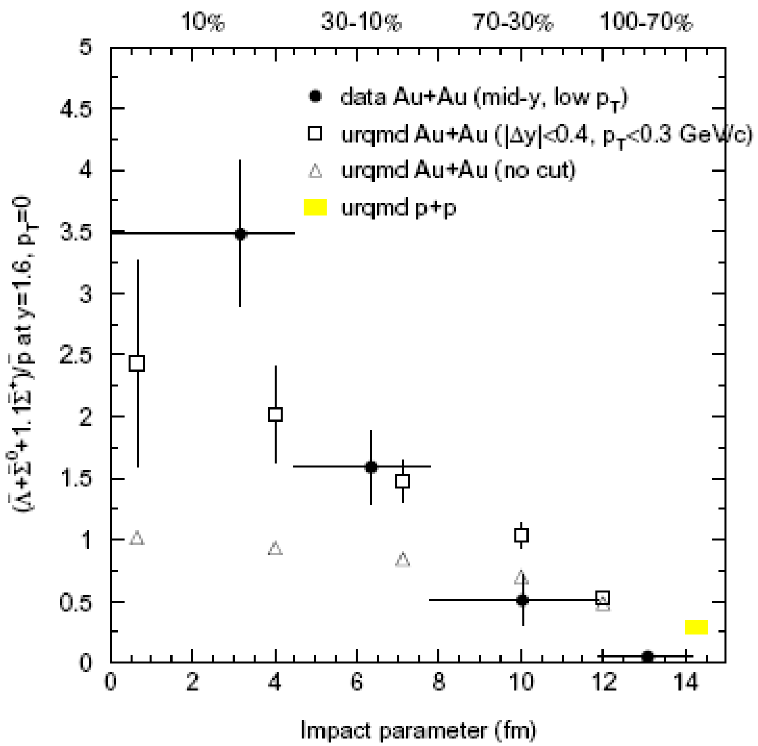
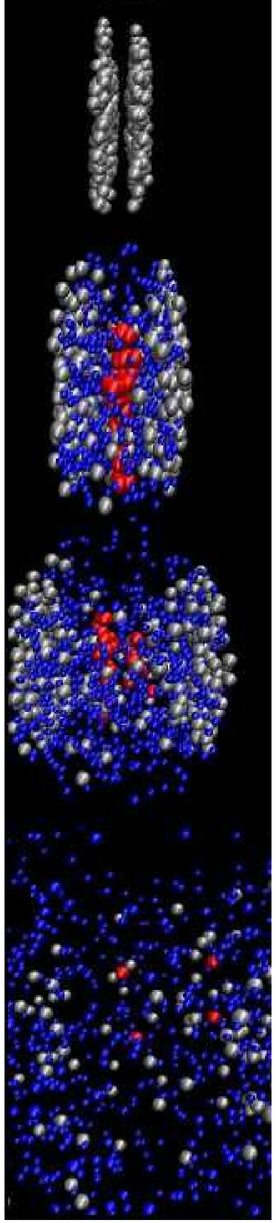


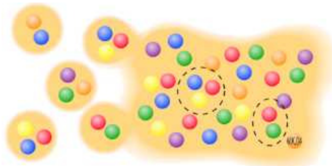
Fig. 3.14 Measurements of the $\overline{\Lambda}/\overline{p}$ ratio at mid-rapidity and low p_T as a function of impact parameter compared to UrQMD calculations (from [109]).

strong enhancement of antistrange quarks with increasing centrality ?



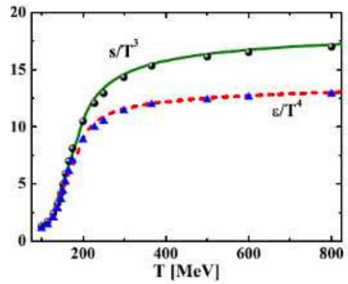
Parton Hadron String Dynamics

I. From hadrons to QGP:



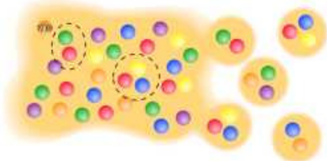
- Initial A+A collisions:
  - string formation in primary NN collisions
  - strings decay to pre-hadrons (*B* - baryons, *m* – mesons)
- Formation of QGP stage by dissolution of pre-hadrons into massive colored quarks + mean-field energy based on the Dynamical Quasi-Particle Model (DQPM) which defines quark spectral functions, masses $M_q(\varepsilon)$ and widths $\Gamma_q(\varepsilon)$ + mean-field potential U_q at given ε – local energy density (related by lQCD EoS to T - temperature in the local cell)

QGP phase:
$\varepsilon > \varepsilon_{critical}$



II. Partonic phase - QGP:

- quarks and gluons (= ‚dynamical quasiparticles') with off-shell spectral functions (width, mass) defined by the DQPM
- in self-generated mean-field potential for quarks and gluons U_q, U_g from the DQPM
- EoS of partonic phase: ‚crossover' from lattice QCD (fitted by DQPM)
- (quasi-) elastic and inelastic parton-parton interactions: using the effective cross sections from the DQPM



III. Hadronization: based on DQPM

- massive, off-shell (anti-)quarks with broad spectral functions hadronize to off-shell mesons and baryons or color neutral excited states - ‚strings' (strings act as ‚doorway states' for hadrons)

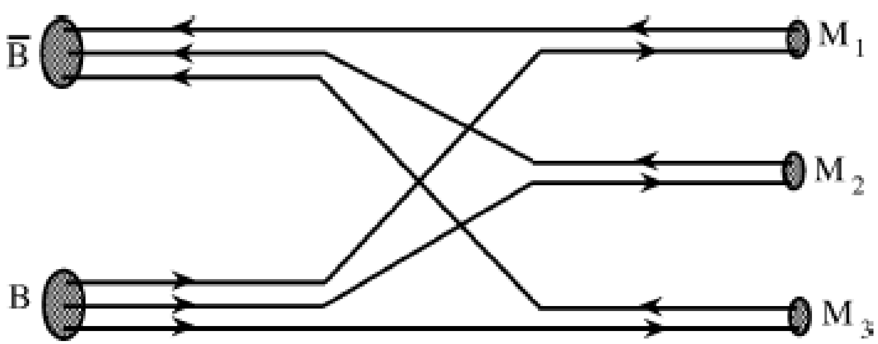
IV. Hadronic phase: hadron-string interactions – off-shell HSD

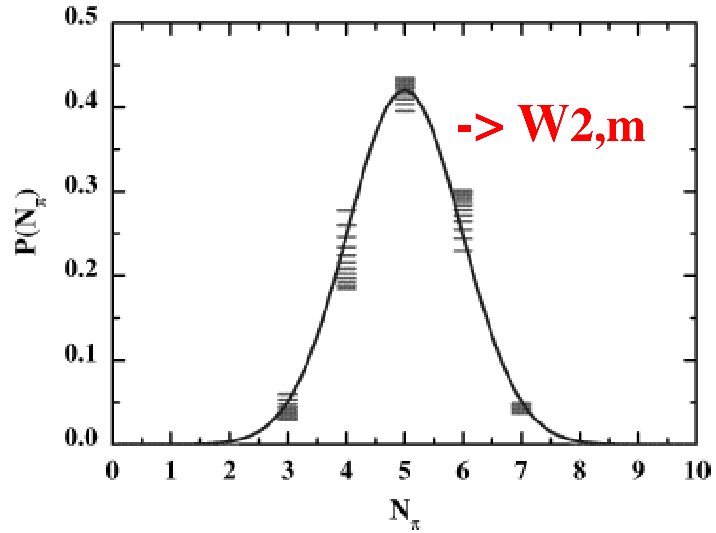
DQPM: Peshier, Cassing, PRL 94 (2005) 172301; Cassing, NPA 791 (2007) 365: NPA 793 (2007)

W. Cassing, E. Bratkovskaya, PRC 78 (2008) 034919; NPA831 (2009) 215; EPJ ST 168 (2009) 3; NPA856 (2011) 162.

Antibaryons in HSD/PHSD

W. Cassing / Nuclear Physics A 700 (2002) 618–646

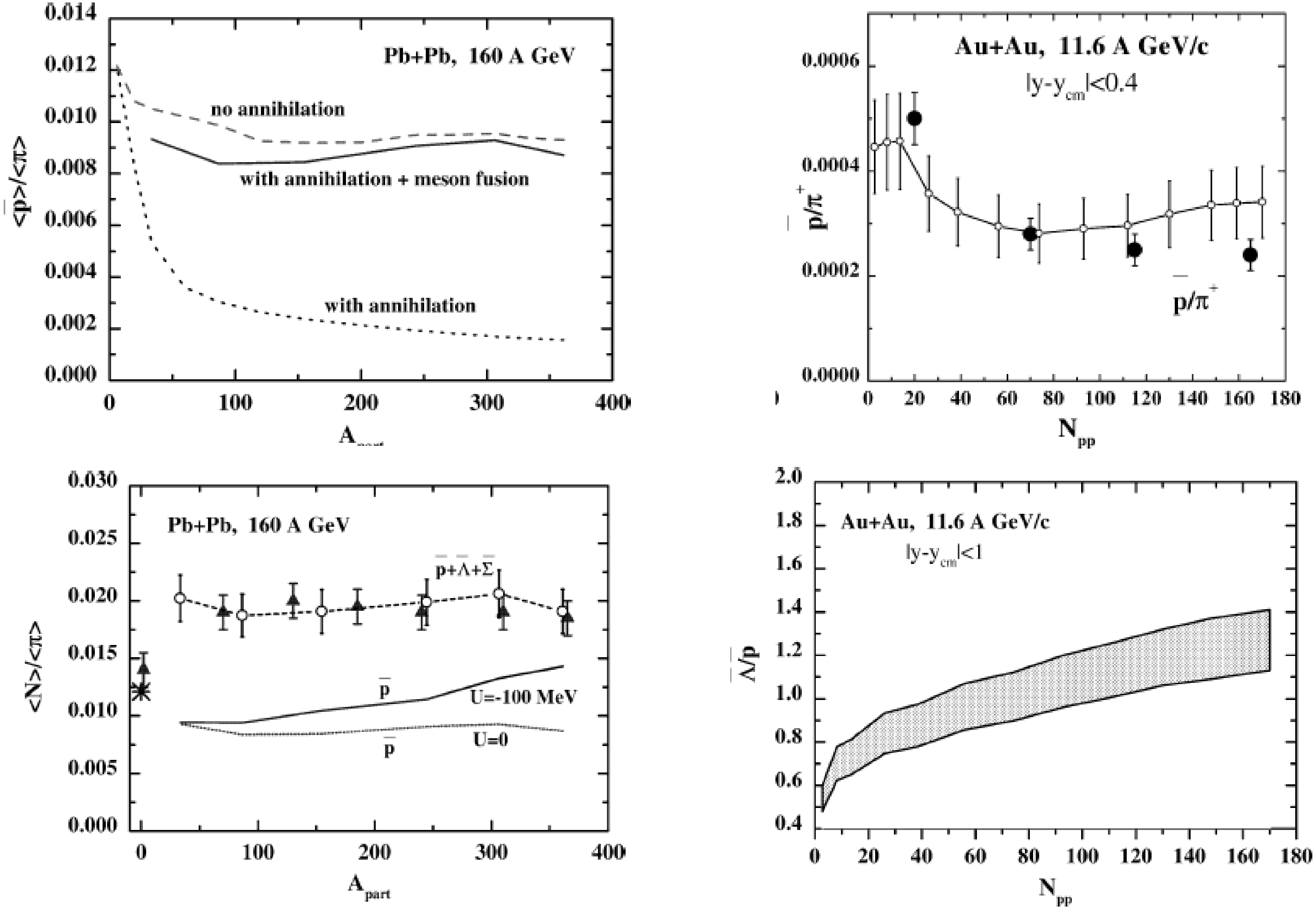




Annihilation vs. regeneration by detailed balance !

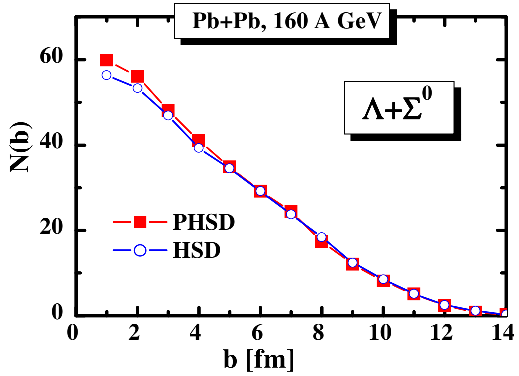
$$\frac{dN_{\text{coll}}[m \text{ mesons} \to B\overline{B}]}{dt\, dV} = \sum_{i,j} \sum_{\lambda_m} \left(\frac{1}{(2\pi)^3}\right)^m \int \left(\prod_{k=3}^{m+2} \frac{d^3 p_k}{2E_k}\right) W_{2,m}(\sqrt{s}; i, j, \lambda_m) \times R_2\left(P^\mu = \sum_{k=3}^{m+2} p_k^\mu; M_1, M_2\right) \prod_{k=3}^{m+2} f_k(x, p_k),$$

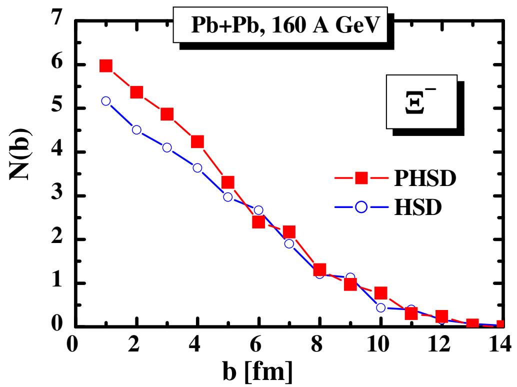
Previous results from HSD

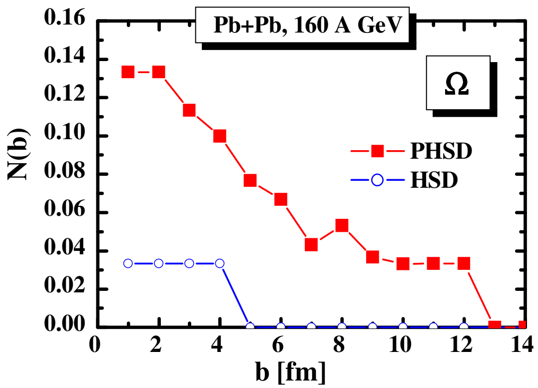


show strong impact of the multi-meson channels at top SPS energies in HSD !

Strange and antistrange baryons at 160 A GeV







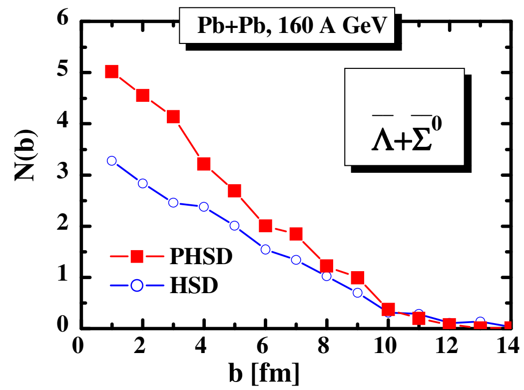
PHSD:

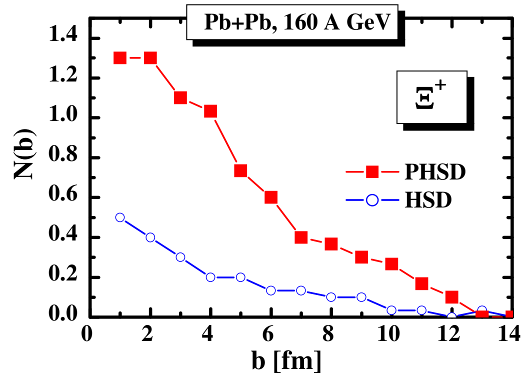
Slightly more Λ and Ξ but much more Ω's !!

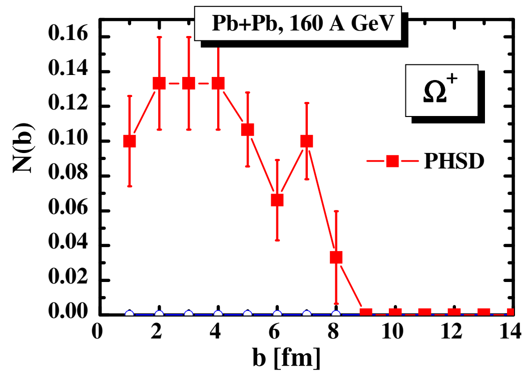
Antibaryons (r.h.s,) are substantially enhanced !

Note:

present statistics drastically need improvement !

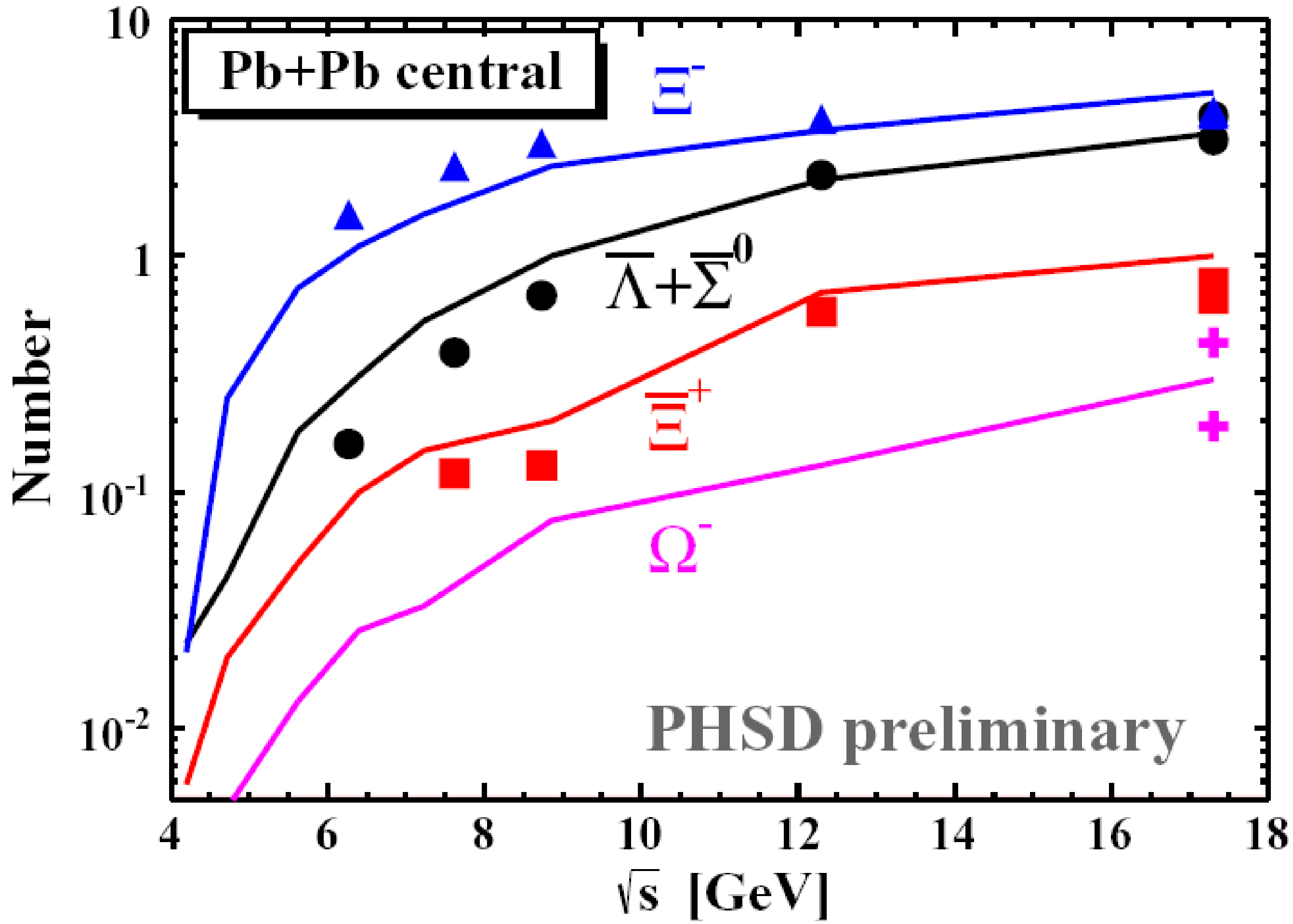






CBM 2009

What about lower energies ?

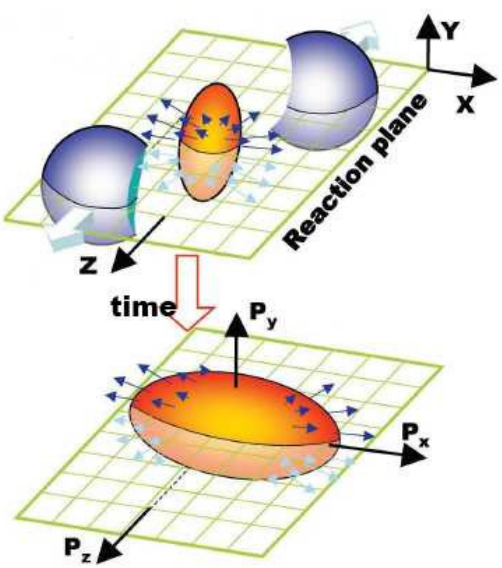


The trend with increasing centrality is enhanced at lower energies !

Anisotropy coefficients

Non central Au+Au collisions :

- interaction between constituents leads to a pressure gradient => spatial asymmetry is converted to an asymmetry in momentum space => collective flow

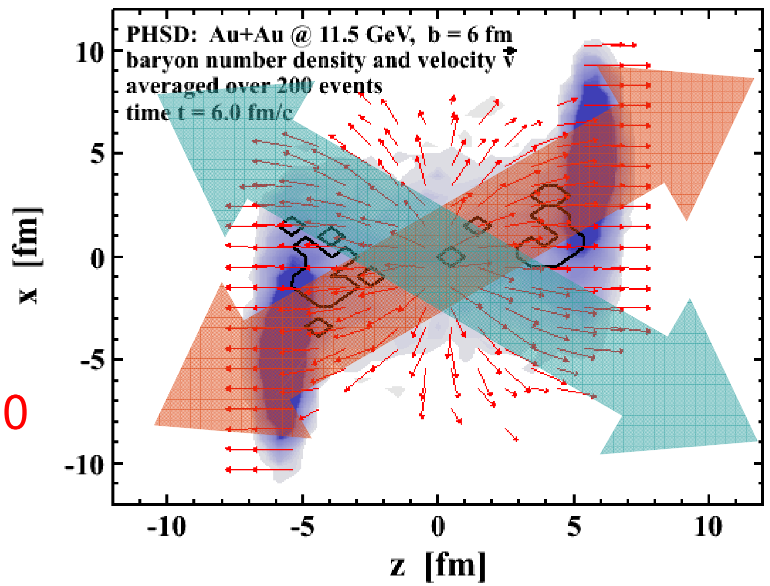


$$\frac{dN}{d\varphi} \propto \left(1 + 2\sum_{n=1}^{+\infty} v_n \cos[n(\varphi - \psi_n)]\right)$$

$$v_n = \langle \cos n(\varphi - \psi_n) \rangle, \quad n = 1,2,3..,$$

v_1: directed flow
v_2: elliptic flow
v_3: triangular flow.....

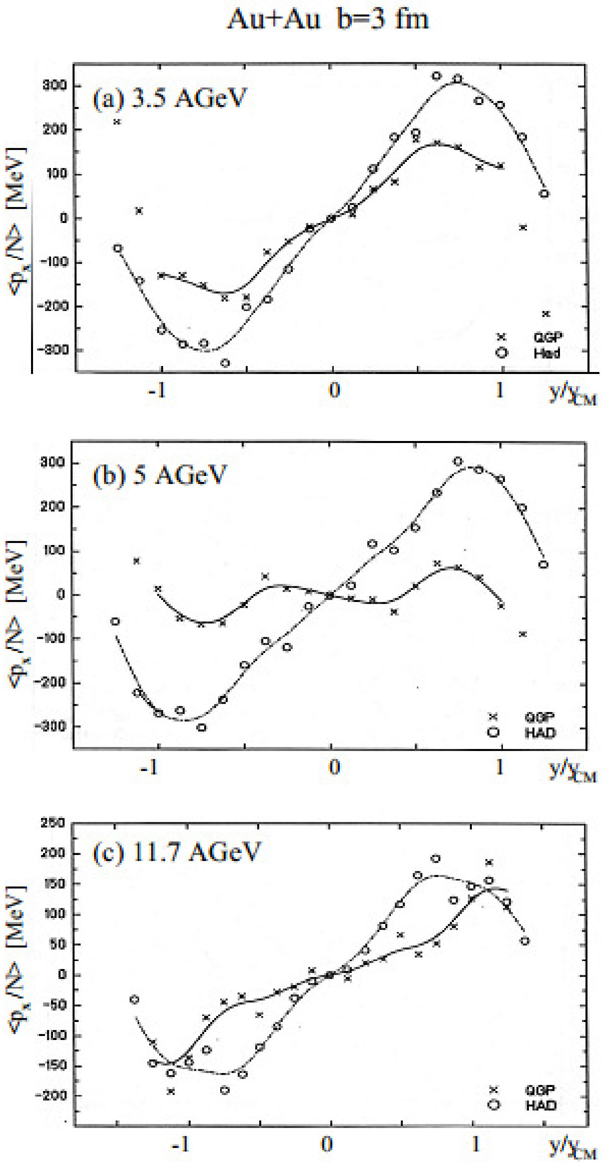
$$v_1 = \left\langle \frac{p_x}{p_T} \right\rangle, \quad v_2 = \left\langle \frac{p_x^2 - p_y^2}{p_x^2 + p_y^2} \right\rangle$$



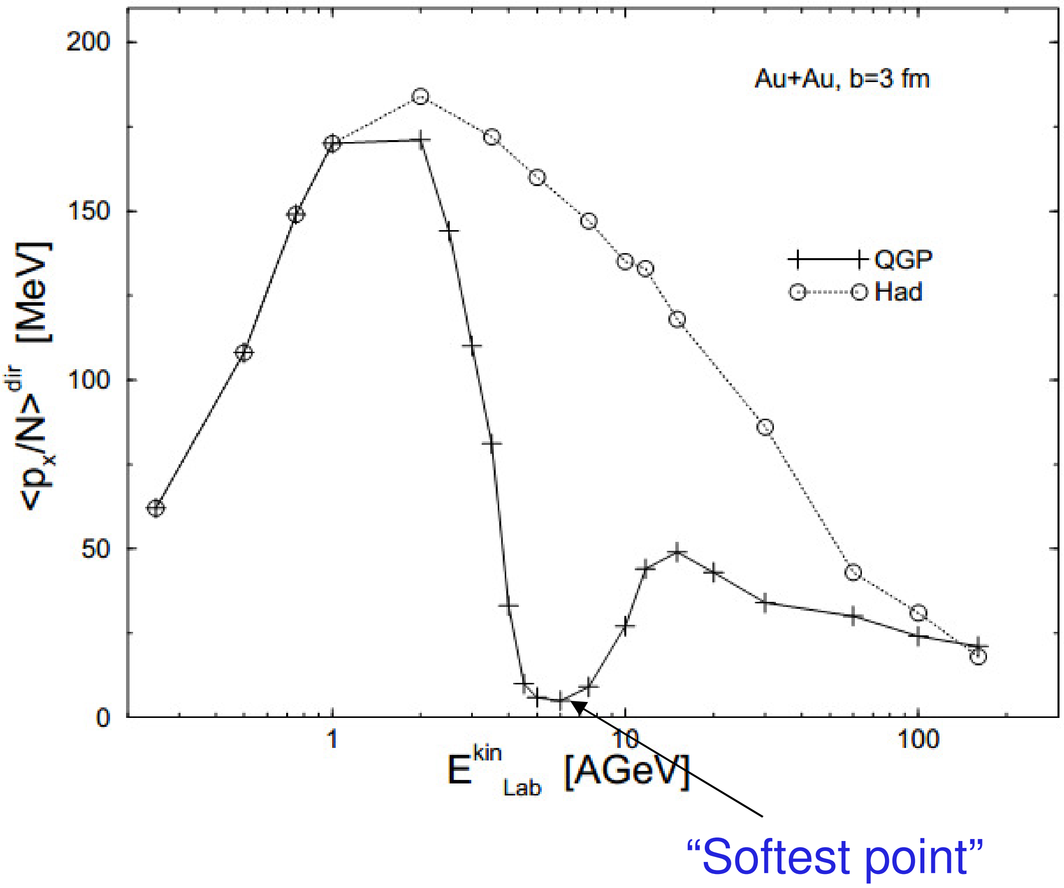
Directed flow $v_1 > 0$

"Antiflow" $v_1 < 0$
"third flow component"

Direct flow and Quark–Gluon Plasma



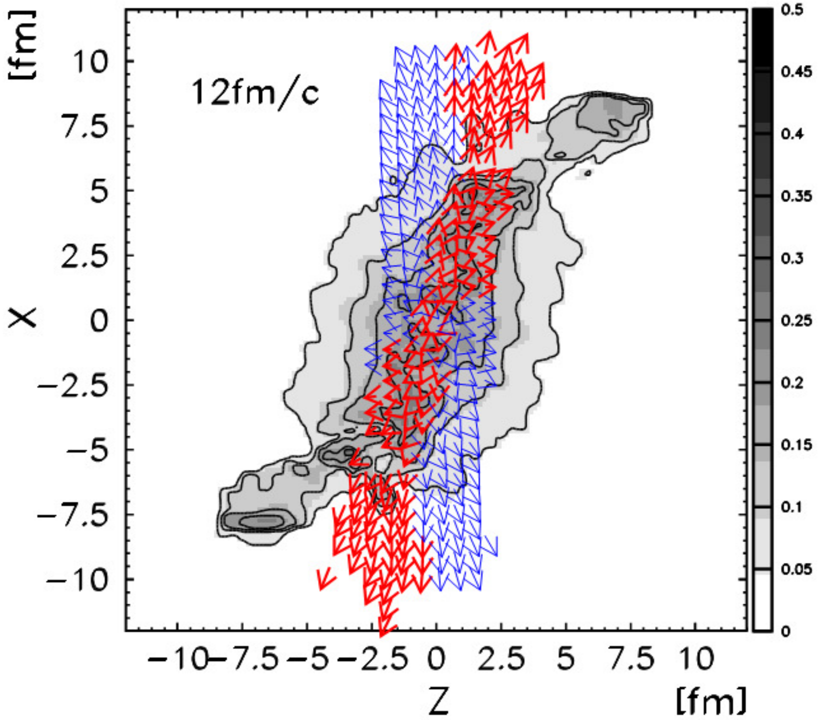
$$\langle p_x/N \rangle^{dir} = \frac{1}{N} \int_{-y_{CM}}^{y_{CM}} \mathrm{d}y \, \langle p_x/N \rangle(y) \, \frac{\mathrm{d}N}{\mathrm{d}y} \, \mathrm{sgn}(y)$$

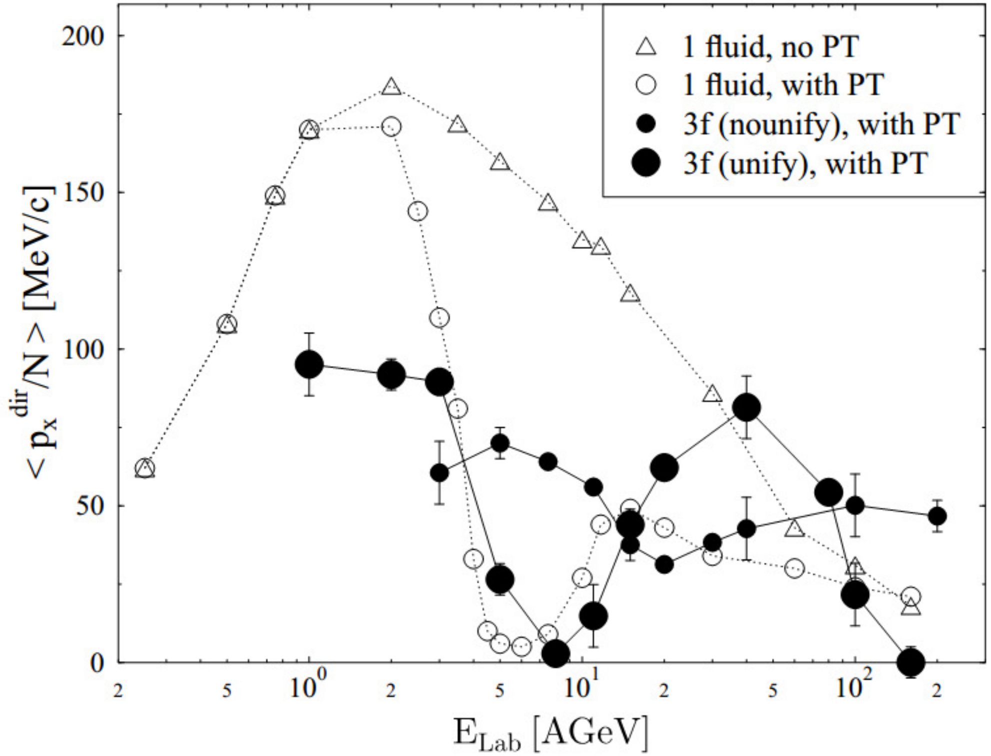


D.H. Rischke, Y. Pursun, J.A. Maruhn, H. Stoecker, W. Greiner, Heavy Ion Phys. 1, 309 (1995)

Antiflow of nucleons at the softest point of the EoS

Au+Au (8 AMeV)



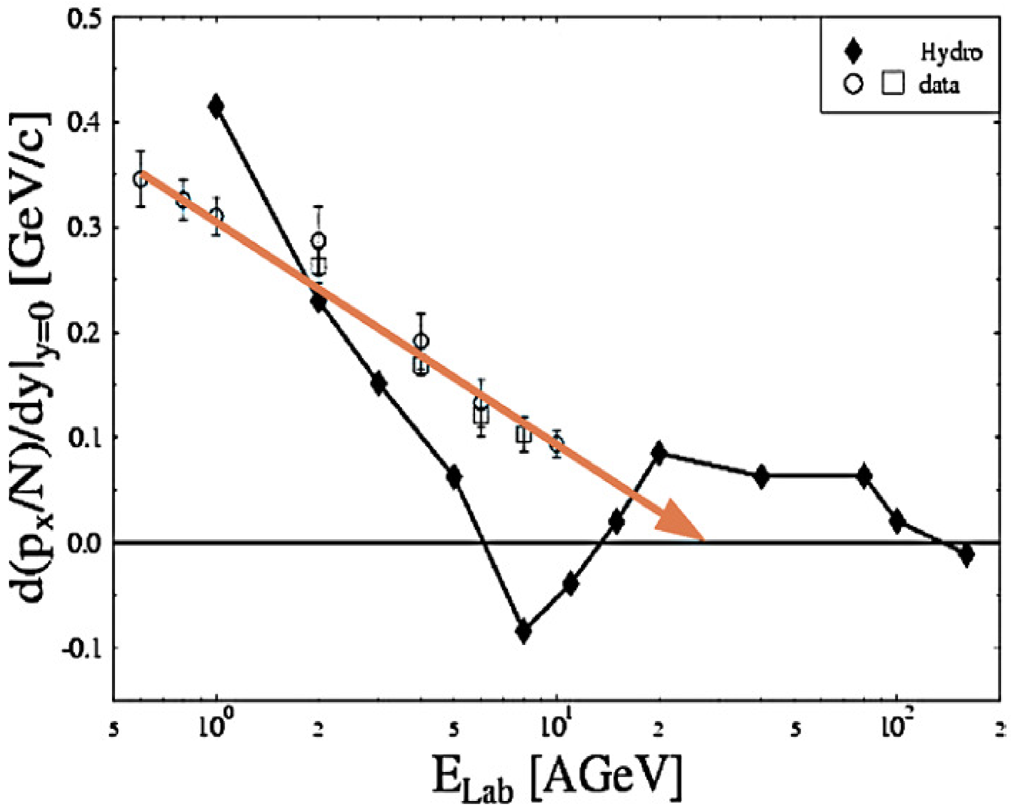


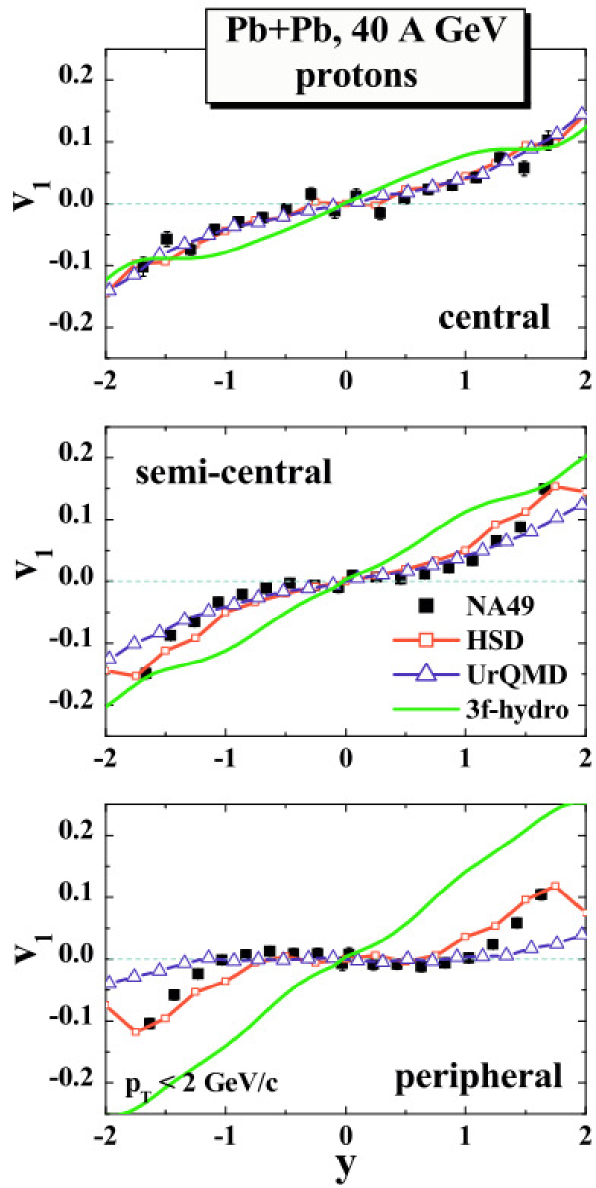
EoS is softened either by a phase transition to the QGP or by the creation of resonances and string-like excitations

J. Brachmann, S. Soff, A. Dumitru, Y. Stoecker, J.A. Maruhn, W. Greiner, L.V. Bravina, D.H. Rischke, Phys. Rev. C61 (2000) 024909

Collective flow signals of the Quark–Gluon Plasma

H. Stöcker, Nucl. Phys. A 750, 121 (2005)

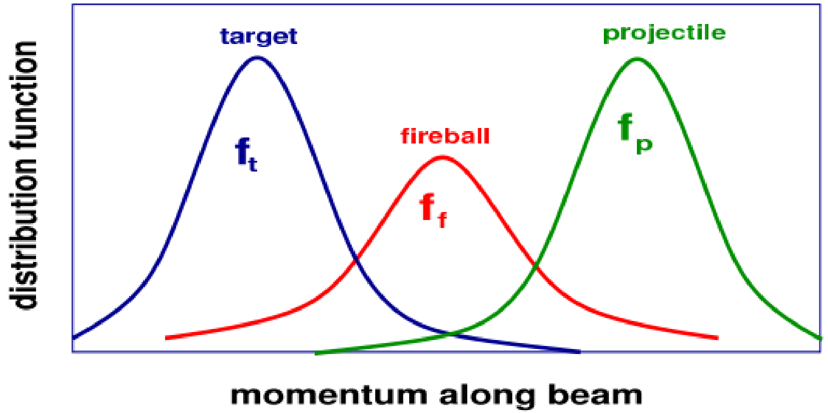




- Early hydro calculation predicted the “softest point” at E_{lab}= 8 AGeV
- A linear extrapolation of the data (arrow) suggests a collapse of flow at E_{lab}= 30 AGeV

3-Fluid Dynamics

Produced particles populate mid-rapidity
$\Rightarrow$ fireball fluid



Target-like fluid: $\partial_\mu J_t^\mu = 0$ $\quad \partial_\mu T_t^{\mu\nu} = -F_{tp}^\nu + F_{ft}^\nu$

Leading particles carry bar. charge $\quad$ exchange/emission

Projectile-like fluid: $\partial_\mu J_p^\mu = 0$, $\quad \partial_\mu T_p^{\mu\nu} = -F_{pt}^\nu + F_{fp}^\nu$

Fireball fluid: $J_f^\mu = 0$, $\quad \partial_\mu T_f^{\mu\nu} = F_{pt}^\nu + F_{tp}^\nu - F_{fp}^\nu - F_{ft}^\nu$

Baryon-free fluid $\quad$ Source term $\quad$ Exchange

The source term is delayed due to a formation time $\tau \sim 1$ fm/c

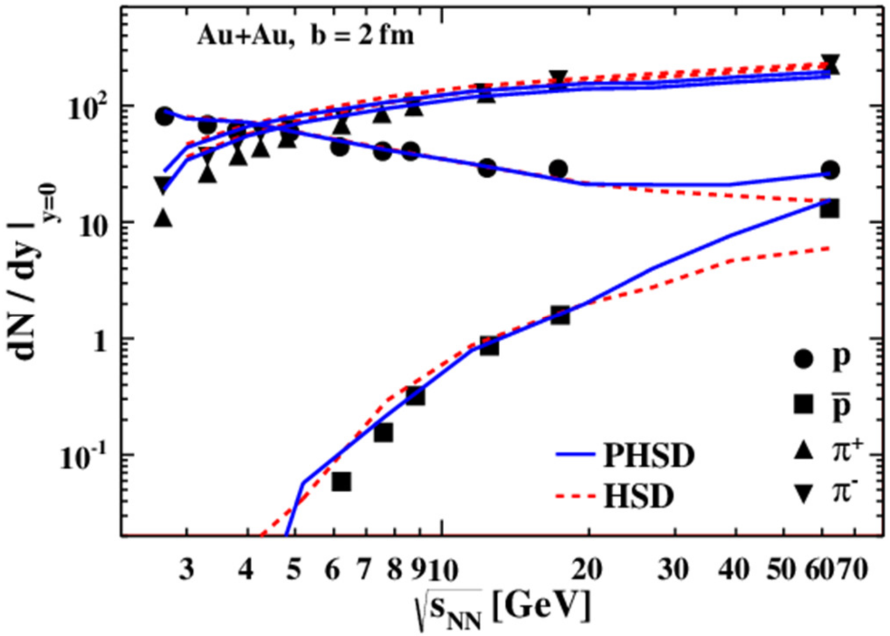
Total energy-momentum conservation:

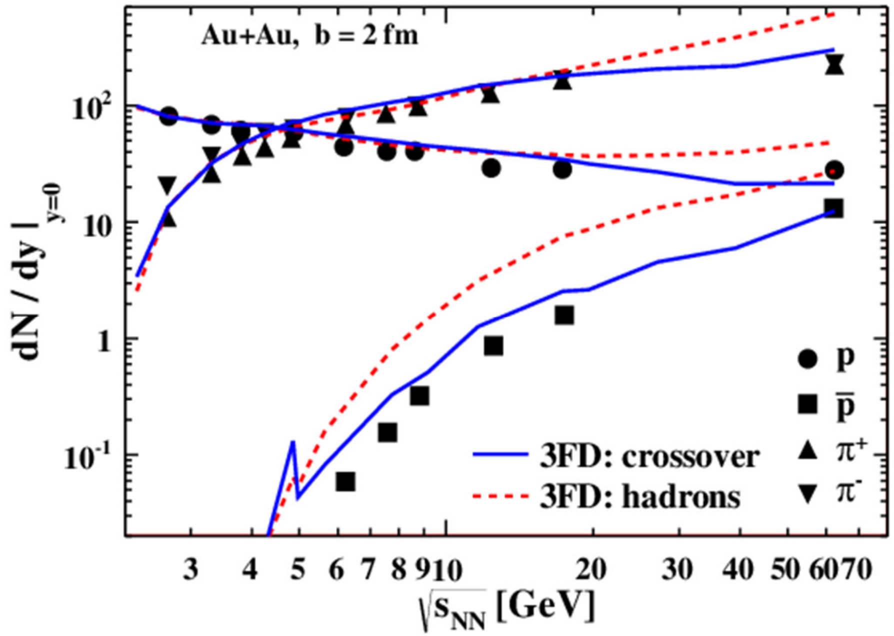
$$\partial_\mu (T_p^{\mu\nu} + T_t^{\mu\nu} + T_f^{\mu\nu}) = 0$$

Yu.B. Ivanov, V.N. Russkikh and V.D. Toneev, Phys. Rev. C73, 044904 (2006)

HSD/PHSD vs 3FD: multiplicities at midrapidity

3-Fluid Dynamics



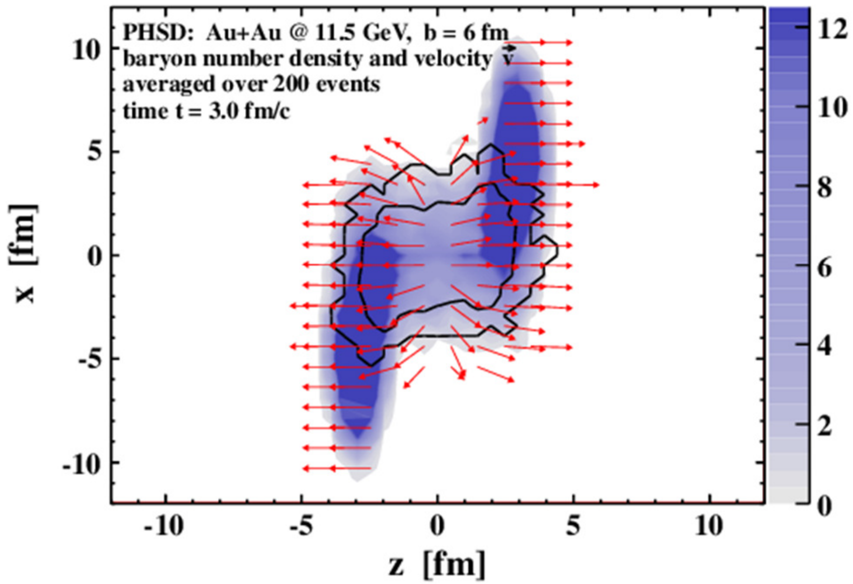


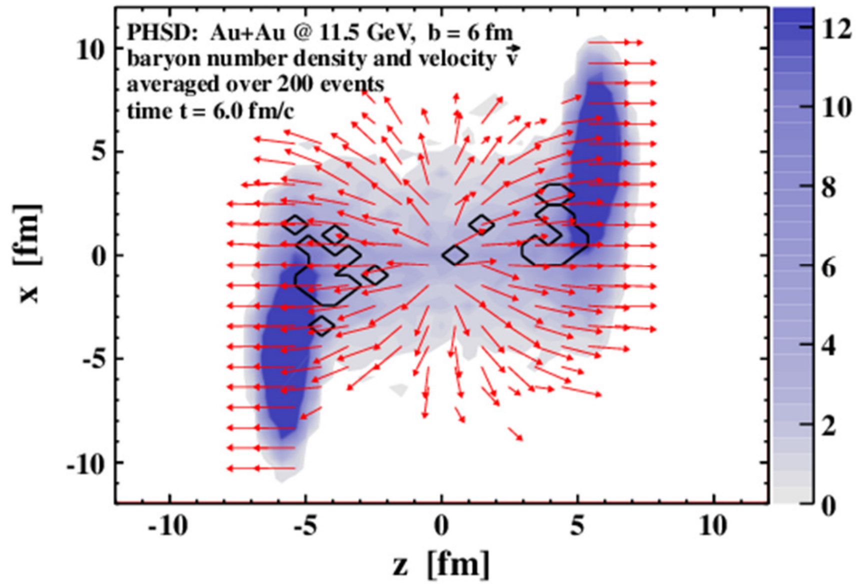
- Both transport and hydro approaches work reasonably fine
- Deviation from the data appear at √s > 20 GeV for the hadronic cases (HSD)

A. Andronic, P. Braun-Munzinger and J. Stachel, Nucl. Phys. A772, 167 (2006)

PHSD: snapshot of the reaction plane

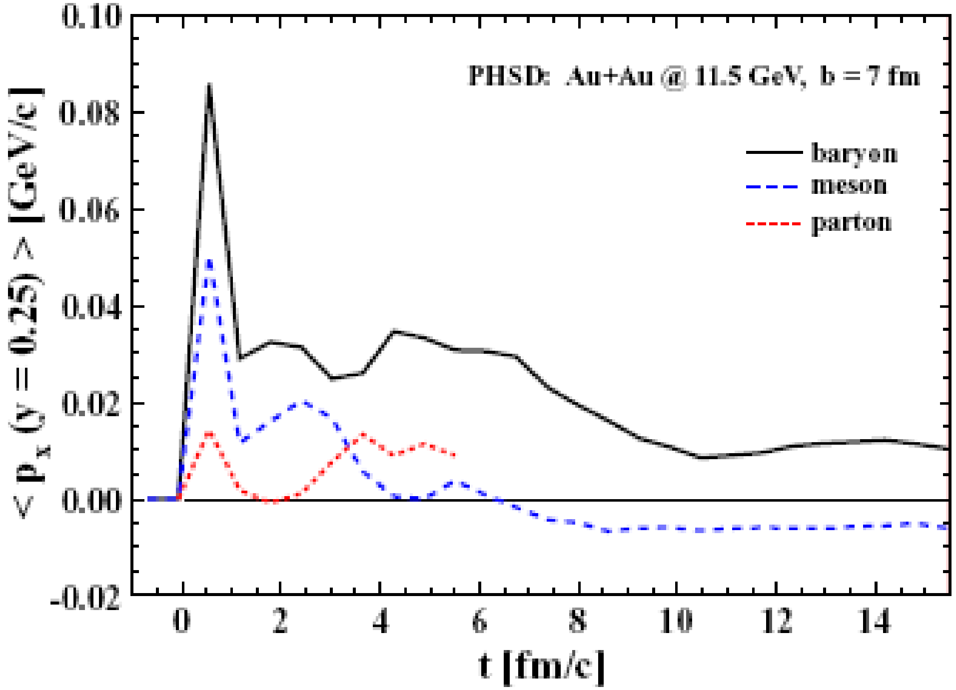
t = 3 fm/c **11.5 GeV** t = 6 fm/c





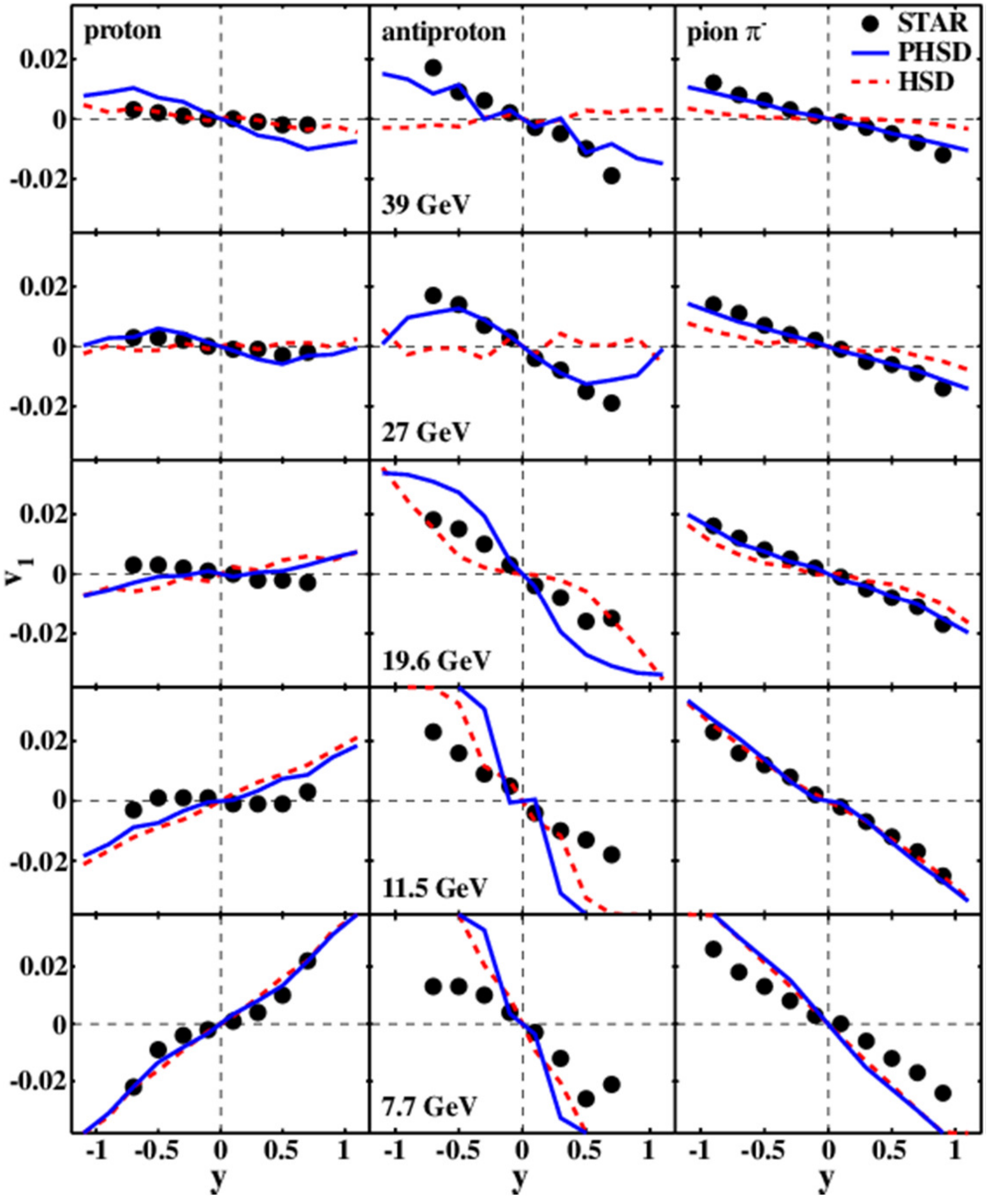
- Color scale: baryon number density
- Black levels: parton density 0.6 and 0.01 fm^{-3}
- Red arrows: local velocity of baryon matter

PHSD: time evolution of $<p_x>$ at y = +0.25



- **Averaged over ~ 80 000 collisions**
- **Directed flow v_1 is formed at an early stage of the nuclear interaction.**
- **Baryons finally reach a positive v_1 while mesons turn to a negative value of v_1**

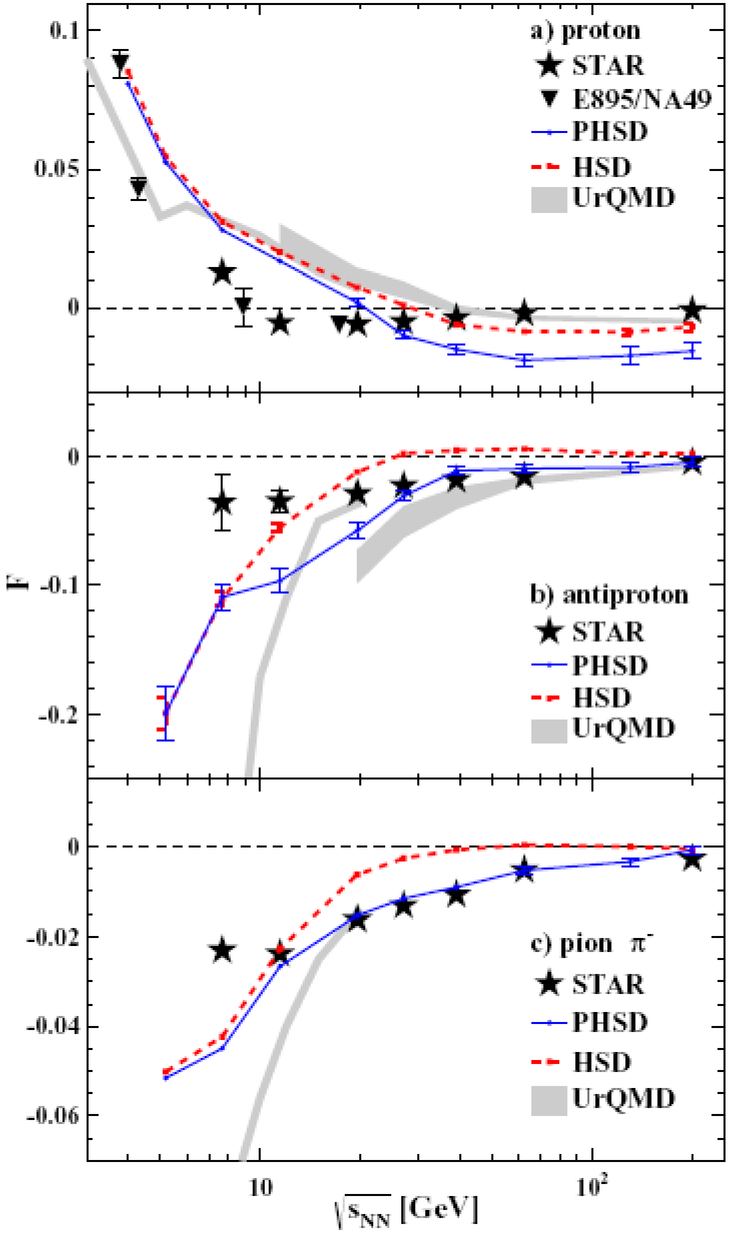
Directed flow from PHSD and HSD



- Both models HSD and PHSD reproduce the general trends of the recent STAR data
- Protons and pions are reasonably described by both models
- Antiprotons in PHSD are produced dominantly from hadronization at the highest energies
- PHSD and HSD coincide at lower energies => dominance of hadronic matter and hadronic reaction channels (absorption and recreation)

STAR Collaboration, arXiv:1401.3043

PHSD: Characteristic slopes of $v_1(y)$



- The slope of $v_1(y)$ at midrapidity:

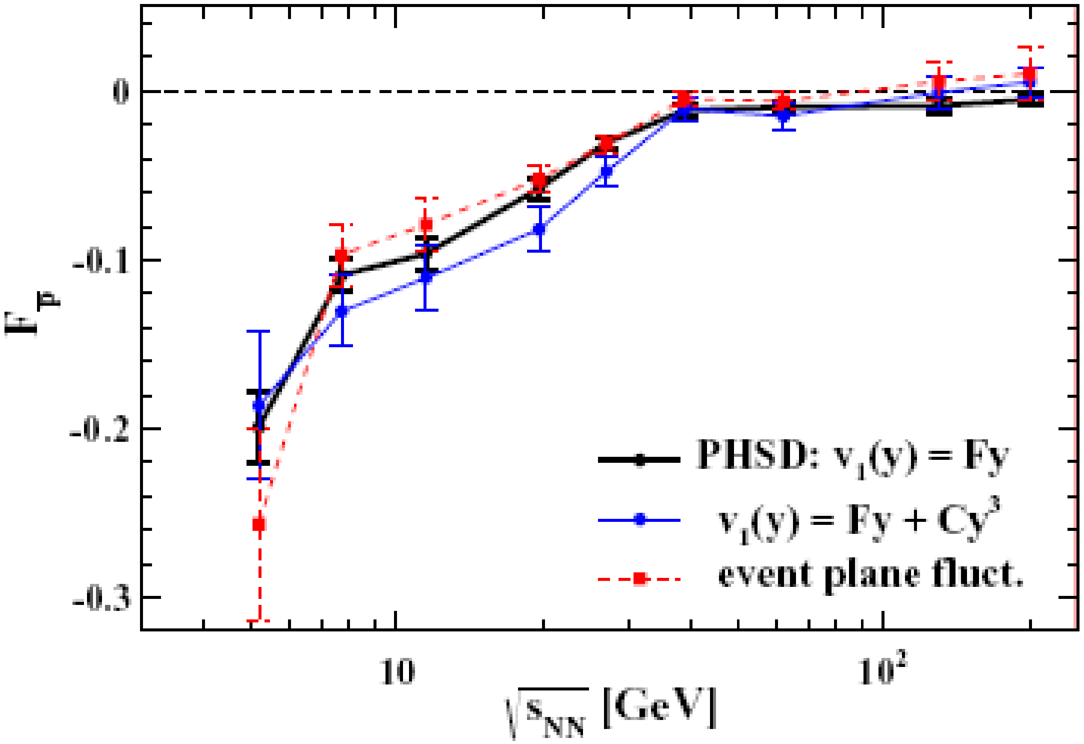
$$F = \left.\frac{dv_1}{dy}\right|_{y=0}$$

is used to characterize directed flow

- Fit $v_1(y) = Fy$ in the rapidity window -0.5 < y < 0.5
- Proton slopes are in qualitative agreement but overestimate STAR data at 5 < √s < 15 GeV; HSD is close to UrQMD
- PHSD/HSD works reasonable due to inclusion of inverse processes for antiproton annihilation
- Partonic phase clearly seen in the pion directed flow at higher energies!

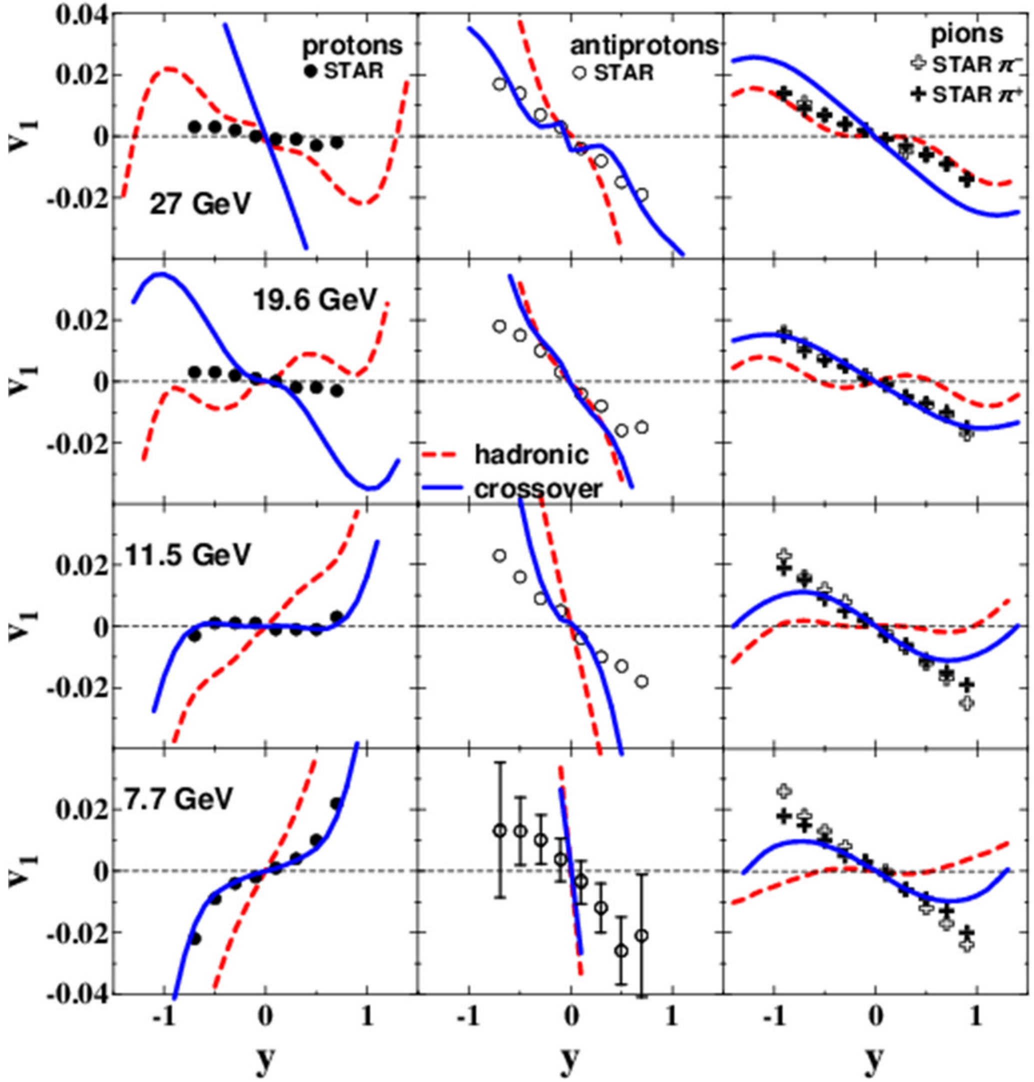
STAR Collaboration, arXiv:1401.3043

Stability of the slopes



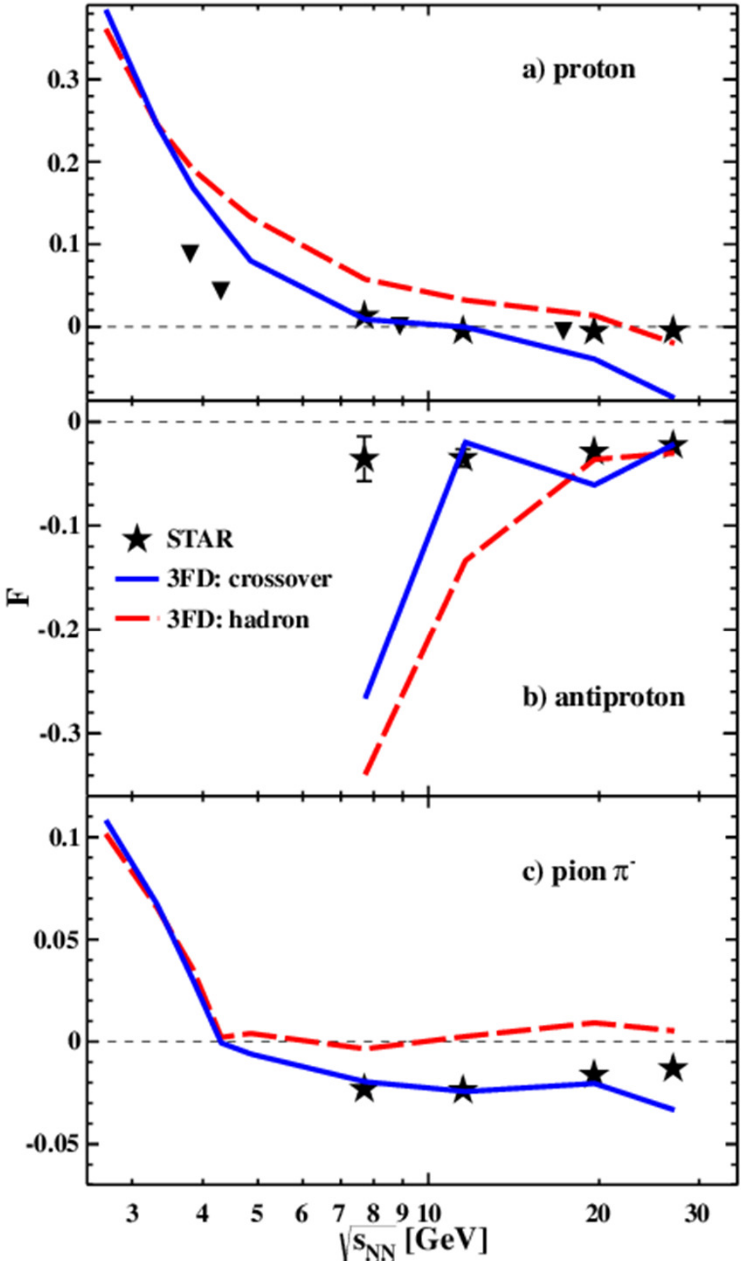
- Fluctuations of the experimentally determined event plane do not change the result.
- Addition of a cubic term to the fit $v_1(y) = Fy + Cy^3$ gives similar results

3FD: directed flow vs. EoS



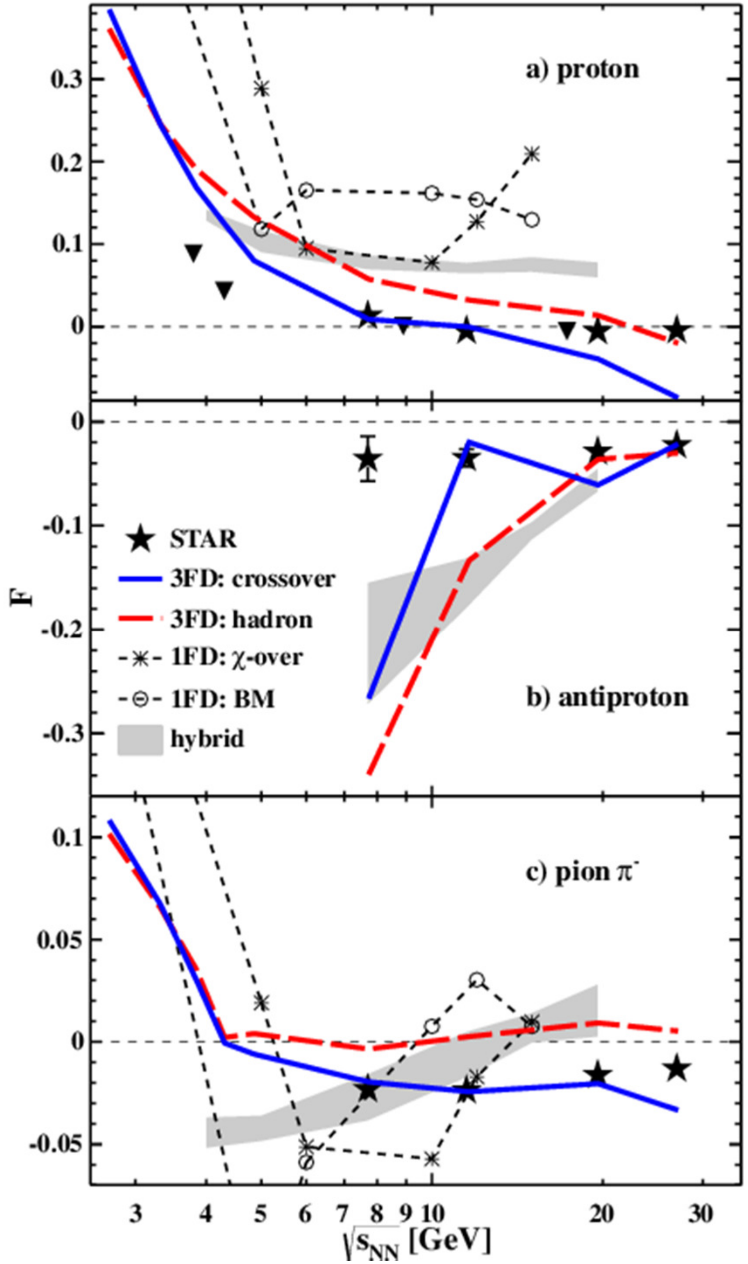
- Description of the STAR $v_1(y)$ is not very well and relatively worse than by PHSD
- Crossover EoS agrees better with the experimental data than the pure hadronic EoS

3FD: excitation function of v_1 slopes



- 3-Fluid Dynamic approach (3FD) gives reasonable results for proton and pion slopes of v_1 and fails at 7.7 GeV for antiprotons
- Discrepancies between 3FD model and STAR data are smaller in case of a crossover

3FD: comparison with 1F-hydro and hybrid models

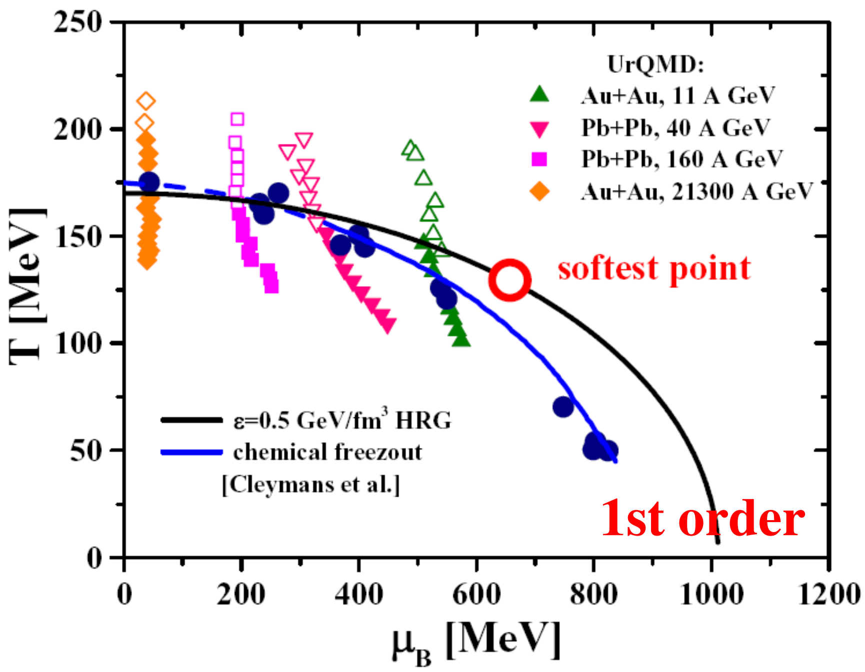


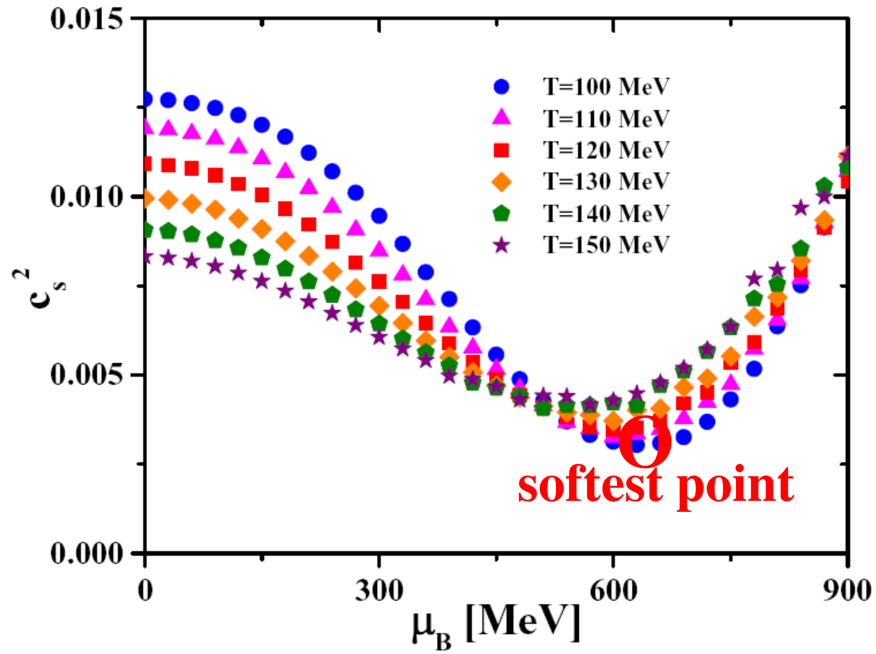
- 3-Fluid Dynamic approach (3FD) gives reasonable results for proton and pion slopes of v_1 and fails at 7.7 GeV for antiprotons
- Discrepancies between 3FD model and STAR data are smaller in case of a crossover
- Recent hydrodynamical and hybrid (hydro+kinetic) results are shown for comparison

J. Steinheimer, J. Auvinen, H. Petersen, M. Bleicher and H. Stöcker, [1402.7236]

New thoughts about the phase diagram ?

Matching the DQPM with the HRG





=> Softest point should be at higher baryon chemical potential !

T. Steinert et al., in preparation

Summary I – directed flow

- The microscopic Parton-Hadron-String-Dynamics (PHSD) transport approach reproduces the general trends in the $v_1(y)$ excitation functions
in the energy range $\sqrt{s}$ =7.7-39 GeV and leads to an almost quantitative agreement for protons, antiprotons and pions especially at higher energies. We don't see any "wiggle-like" structures as expected by early hydro calculations but see a softening of the EoS in the BES range.

- The PHSD results differ from those of HSD where no explicit partonic degrees of freedom are incorporated. A comparison of both microscopic models has provided detailed information on the effect of parton dynamics on the directed flow (especially for pions).

- Inclusion of antiproton annihilation into several mesons as well as the inverse processes in HSD/PHSD help to reproduce antiproton directed flow at lower energies.

- 3-Fluid Dynamic approach (3FD) gives reasonable results for proton and pion slopes of v_1 but fails at 7.7 GeV for antiprotons

- Crossover transition agrees better with the experiment than the pure hadronic EoS

Summary II – multistrange antibaryons

- Inclusion of antiproton annihilation into several mesons as well as the inverse processes in HSD/PHSD help to reproduce antibaryon yields at lower energies.
- Enhancement of multi-strange antibaryons with increasing centrality and decreasing bombarding energy within PHSD relative to HSD.
- Indications for the softest point in the EoS at higher baryon chemical potential than assumed before!
- The heavy-ion dynamics close to the softest point is not well understood in all models! Strong parton-hadron reactions in the crossover or mixed phase?

CBM should find out!

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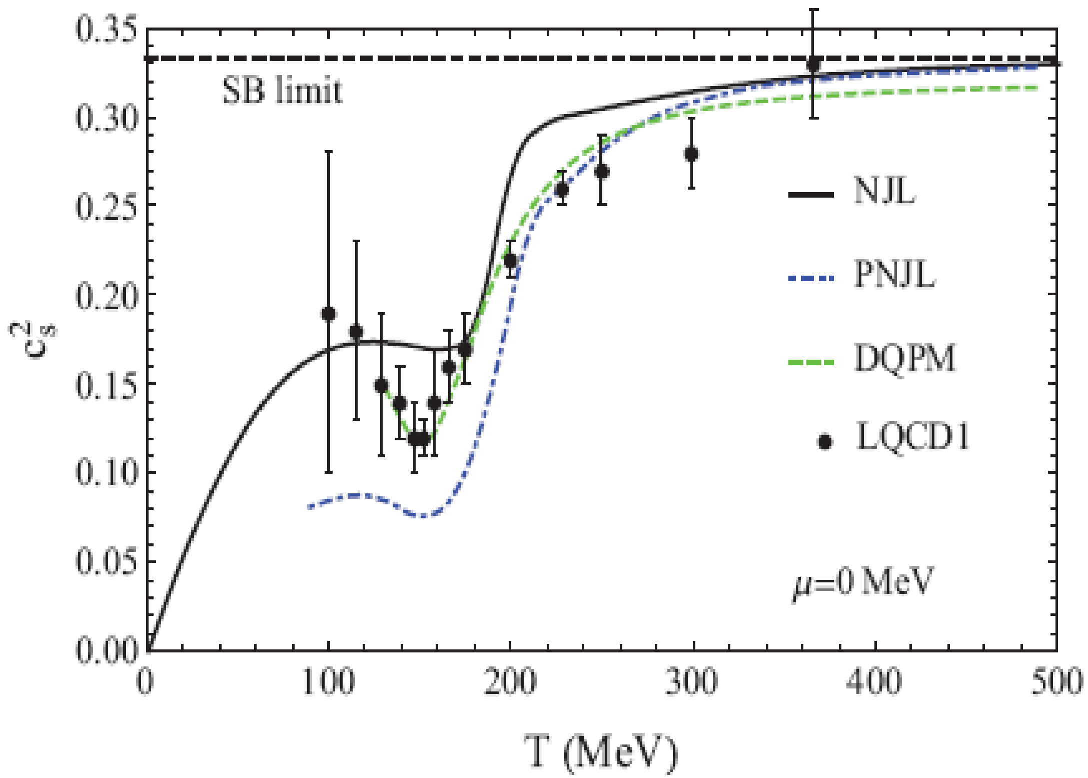
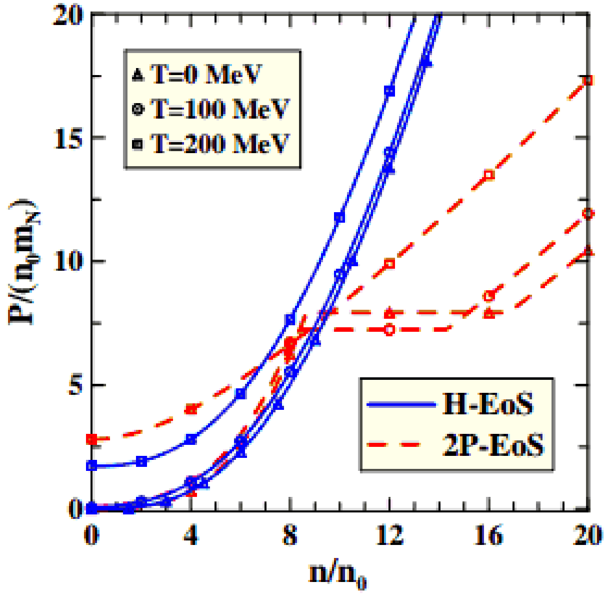
Backup



0.35
0.30
0.25
0.20
0.15
0.10
0.05
0.00
0
100
200
300
400
500
SB limit
NJL
PNJL
DQPM
LQCD1
μ=0 MeV
c_s^2
T (MeV)

Physical Input

- Equation of State (EoS)



Hadronic EoS (H-EoS)

[Galitsky and Mishustin, Sov. J. Nucl. Phys. **29**, 181 (1979)]

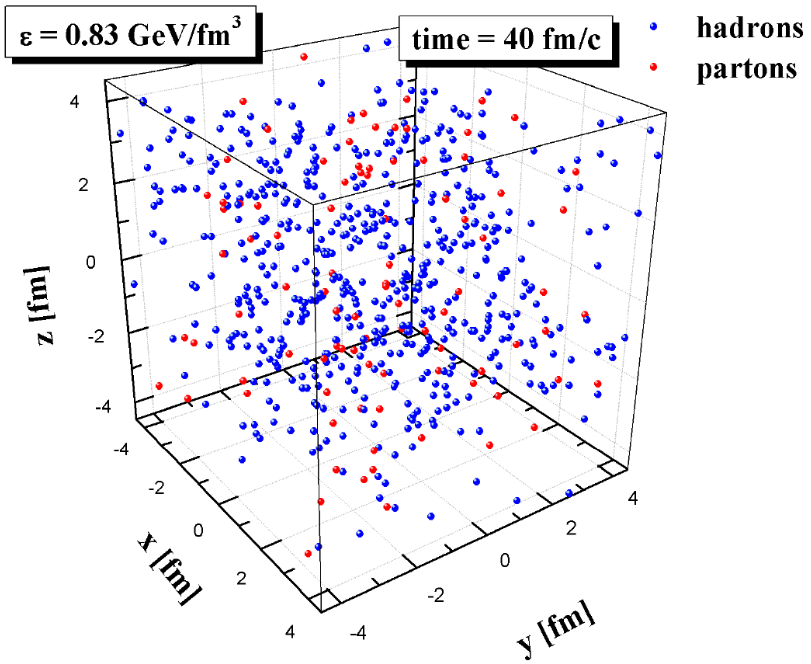
1st-order transition to QGP (2P-EoS)

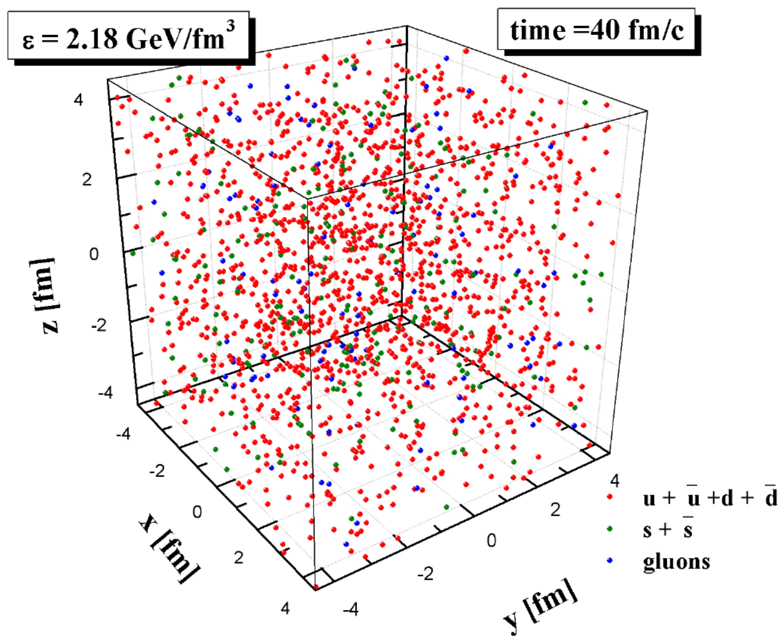
[Khvorostukhin, Skokov, Redlich, Toneev, EPJ **C48**, 531 (2006)]

Phase transition $\Longrightarrow$ **EoS softening** (in dense baryon matter)

- Freeze-out energy-density: $\varepsilon_{frz} = 0.4$ GeV/fm^3
- Friction: estimated and tuned
- Formation Time: τ= 2 fm/c for H-EoS and τ= 0.33 fm/c for 2P-EoS
- Coalescence coefficients for fragments

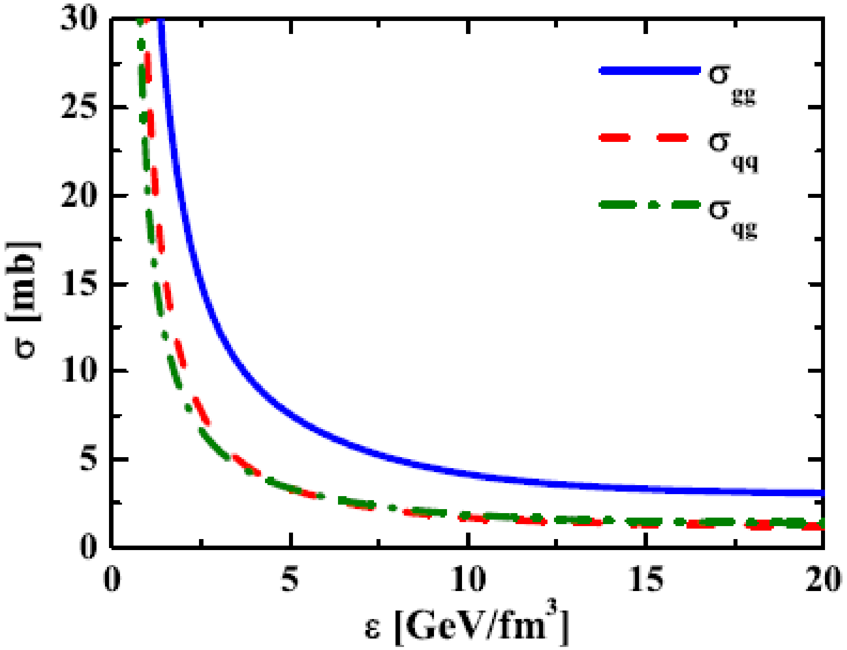
PHSD in the box





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

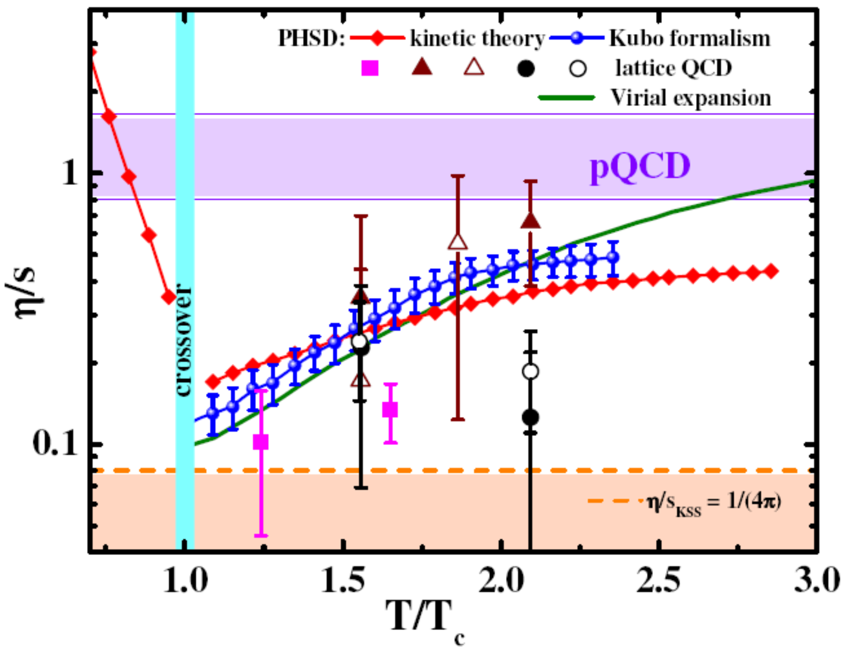
Transport coefficients



$$\eta = \frac{1}{T}\int d^3r \int_0^\infty dt \langle \pi^{xy}(\mathbf{0},0)\pi^{xy}(\mathbf{r},t)\rangle.$$

Cross sections in PHSD

$$\pi^{xy}(\mathbf{r},t) \equiv T^{xy}(\mathbf{r},t) = \int \frac{d^3p}{(2\pi)^3}\frac{p^x p^y}{E} f(\mathbf{r},\mathbf{p};t).$$



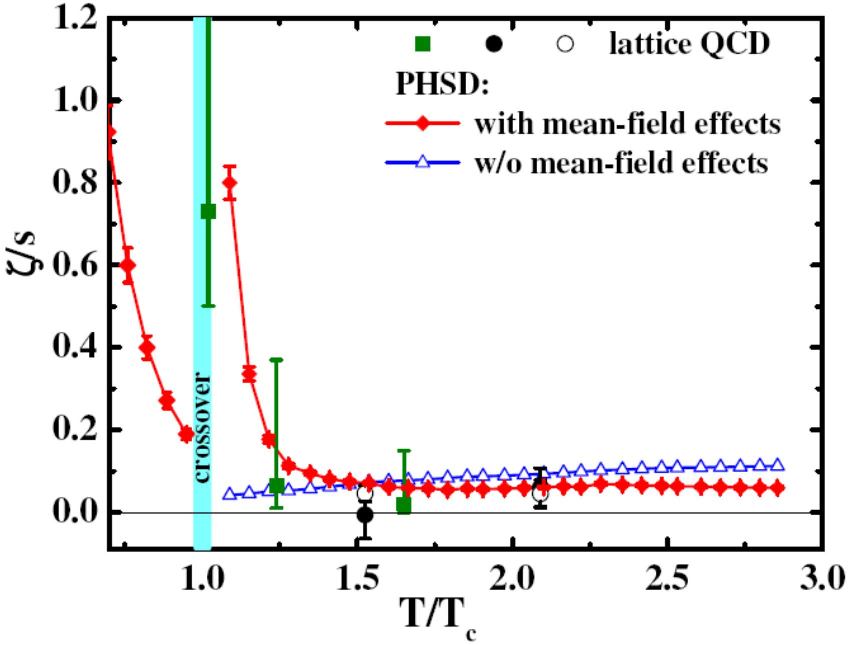
Shear viscosity shows a minimum close to Tc !

V. Ozvenchuk et al., PRC87(2013)064903

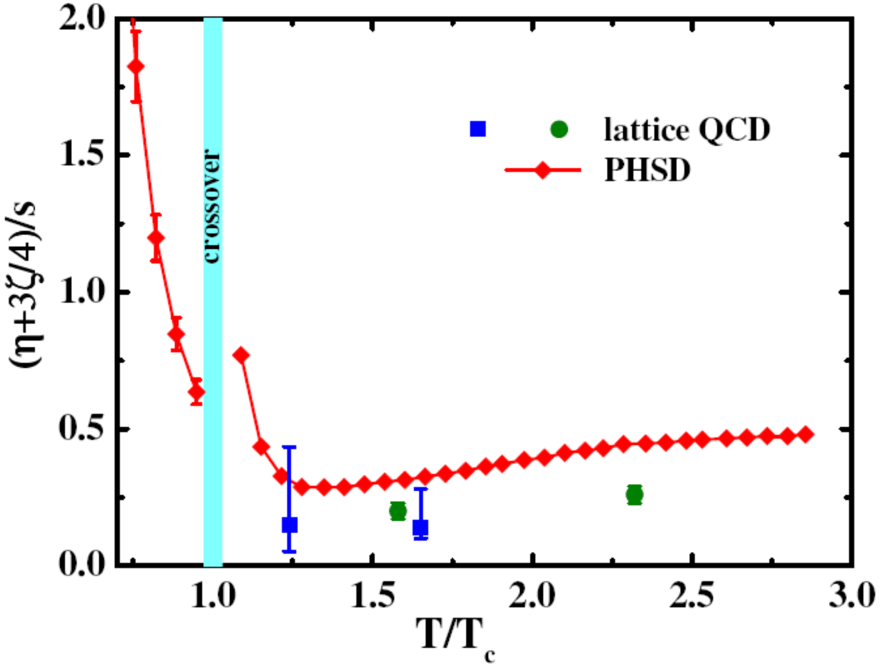
Bulk viscosity

$$\zeta = \frac{1}{T}\sum_a \int \frac{d^3p}{(2\pi)^3} \frac{\tau_a(E_a)}{E_a^2} f_a^{eq}(E_a/T) \times \left[\left(\frac{1}{3} - v_s^2\right)|\mathbf{p}|^2 - v_s^2\left(m_a^2 - T^2\frac{dm_a^2}{dT^2}\right)\right]^2$$

in comparison to lQCD



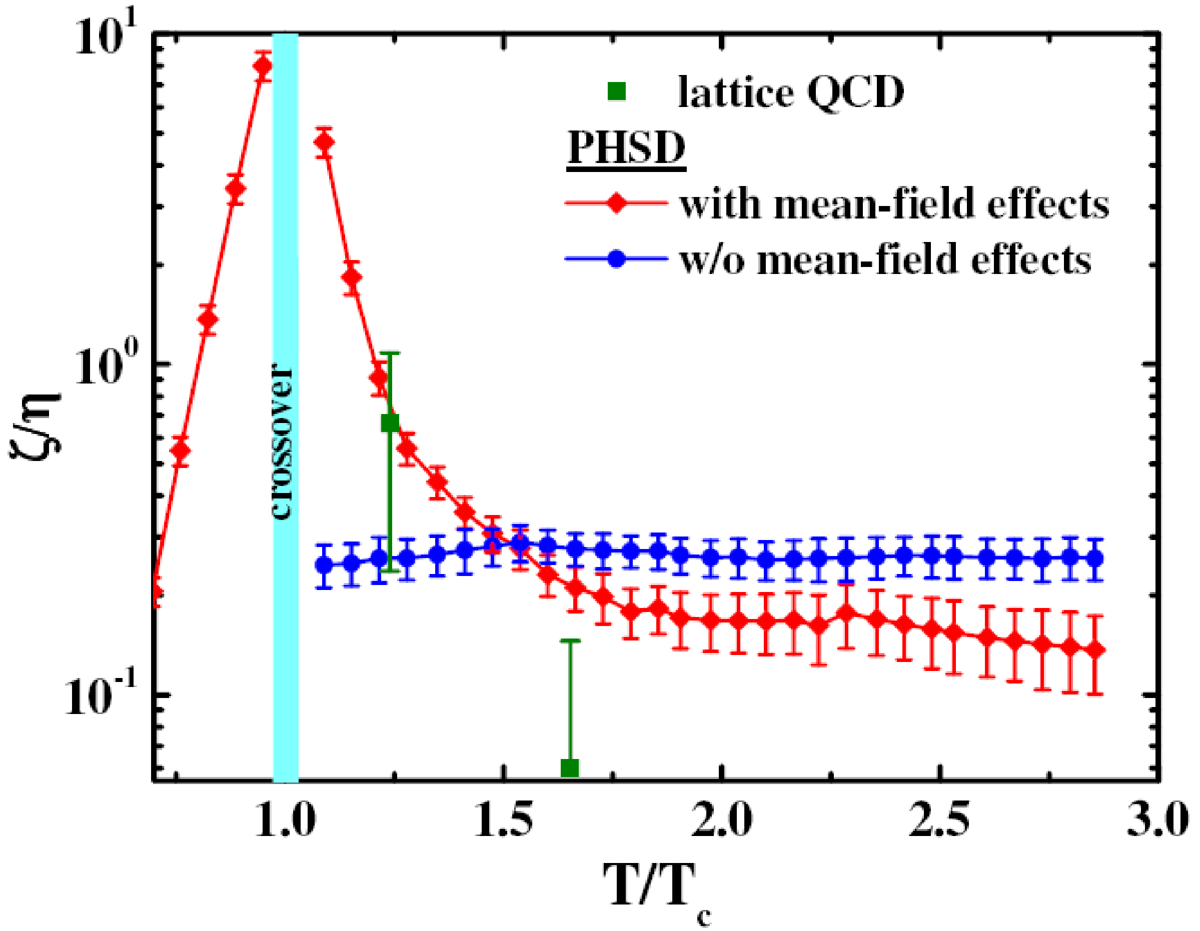
specific sound



shows a maximum close to Tc

V. Ozvenchuk et al., PRC87(2013)064903

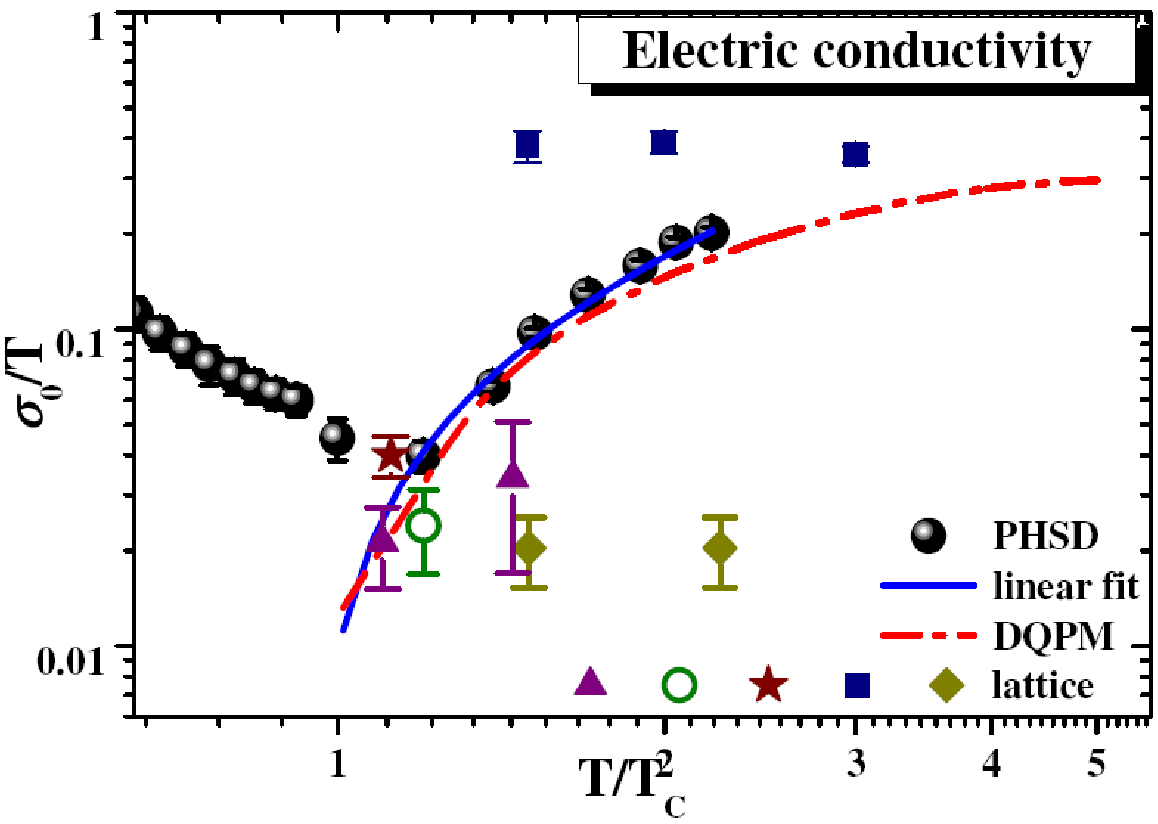
bulk/shear versus temperature T



pronounced maximum at Tc !

V. Ozvenchuk et al., PRC87(2013)064903

electric conductivity



relaxation time approach:

$$\frac{\sigma_0(T)}{T} \approx \frac{2}{9}\frac{e^2 n_q(T)}{M_q(T)\Gamma_q(T)T}$$

W. Cassing et al., PRL 110(2013)182301