Institut für Theoretische Physik

JUSTUS-LIEBIG-UNIVERSITÄT GIESSEN

Phys.Rev. C90 (2014) 014903

Directed flow in HIC within PHSD transport and 3FD hydro

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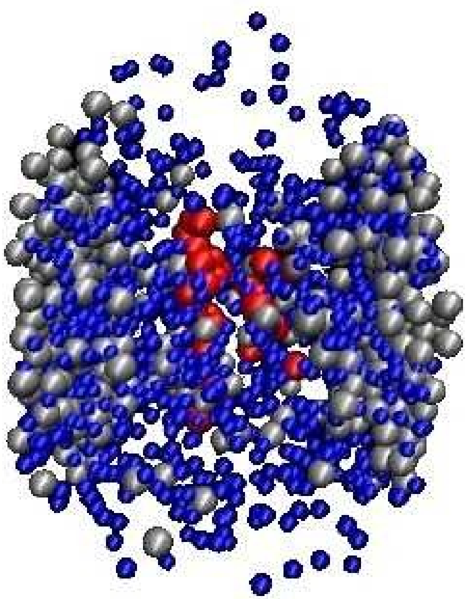
Yury Ivanov
Alessia Palmese
Vyacheslav Toneev

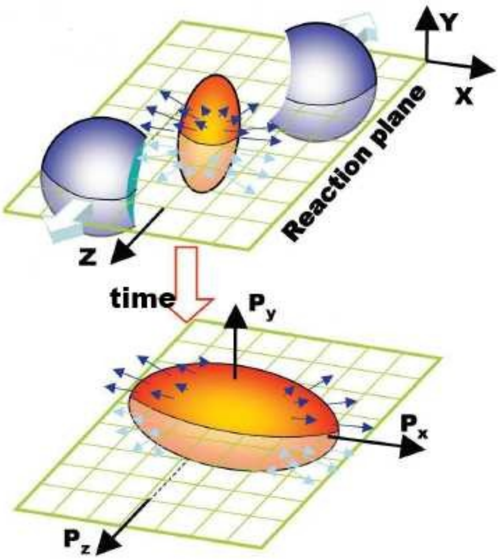


Hot Quarks 2014
Las Negras, Andalucia, Spain
24 September 2014

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**



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

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

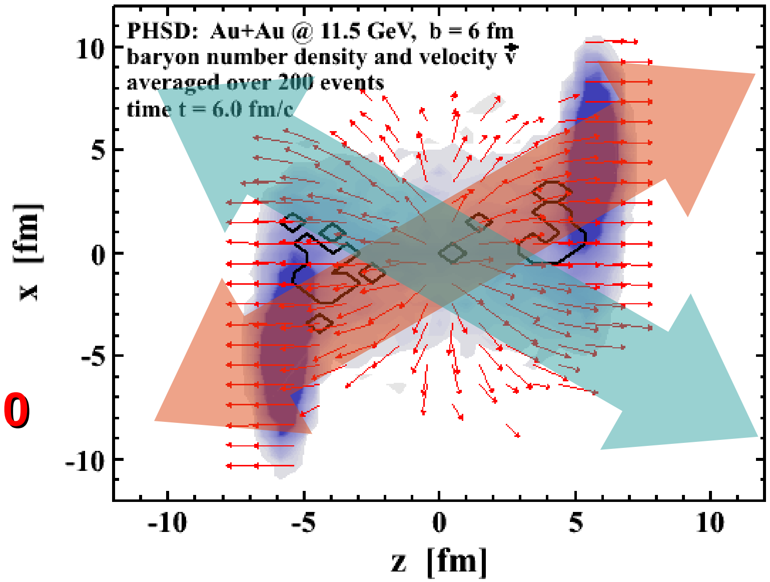
v_1: directed flow

v_2: elliptic flow

v_3: triangular flow…..

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

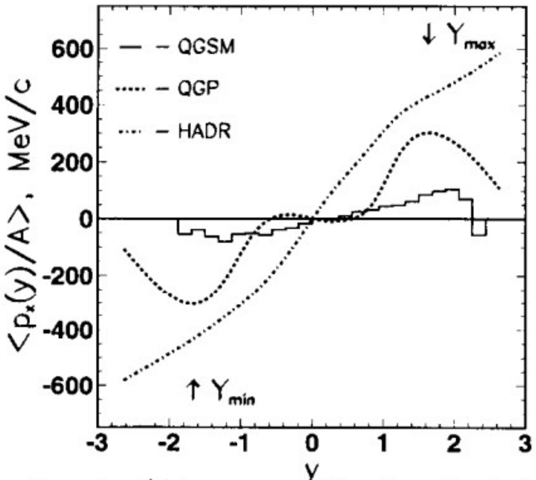
Directed flow $v_1 > 0$



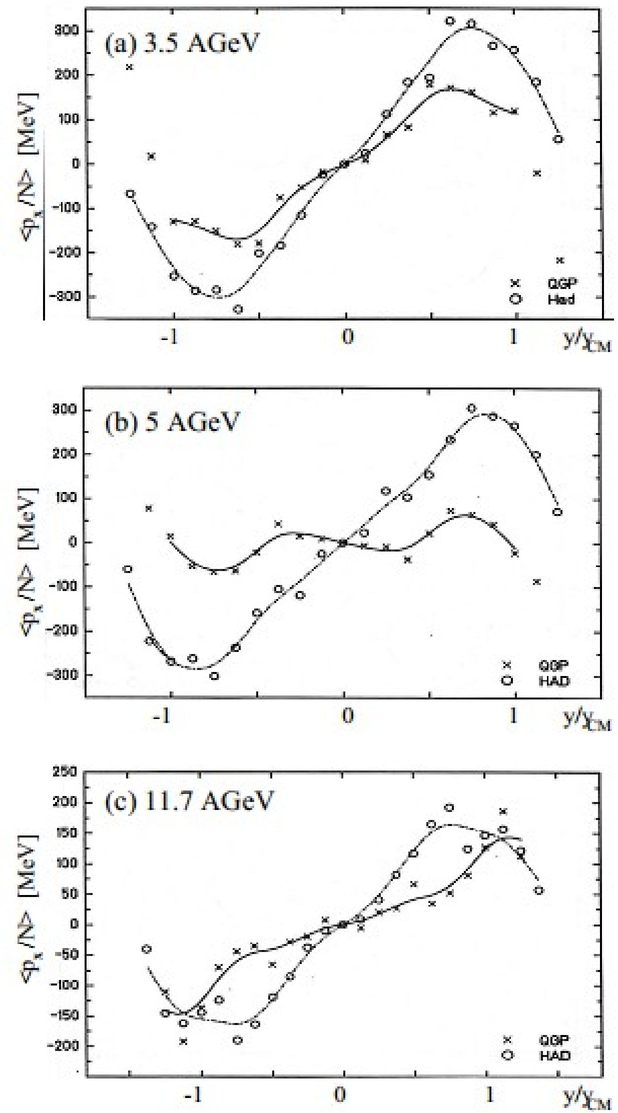
"Antiflow" $v_1 < 0$

"third flow component"

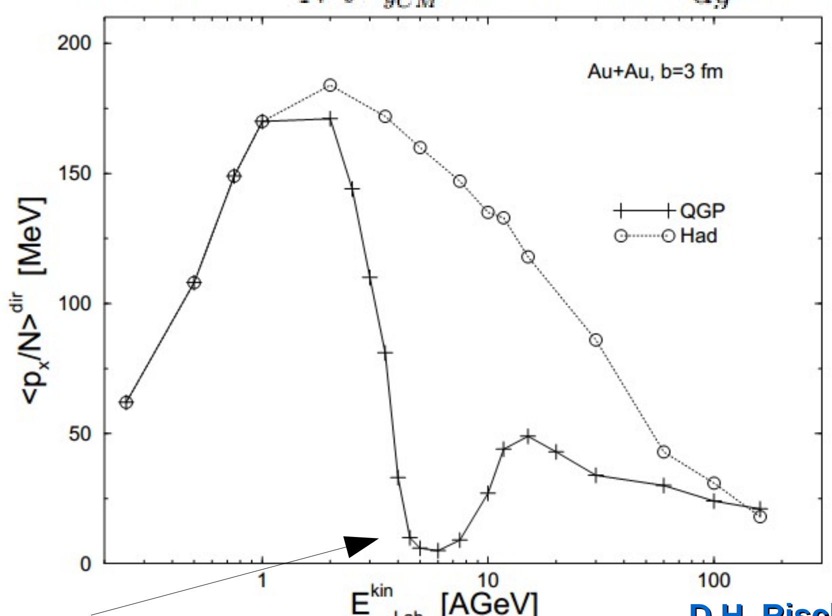
Direct flow and Quark–Gluon Plasma



L.V. Bravina, L.P. Csernai,
P. Levai, N.S. Amelin, D. Strottman,
Nucl. Phys. A566 (1994) 461



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

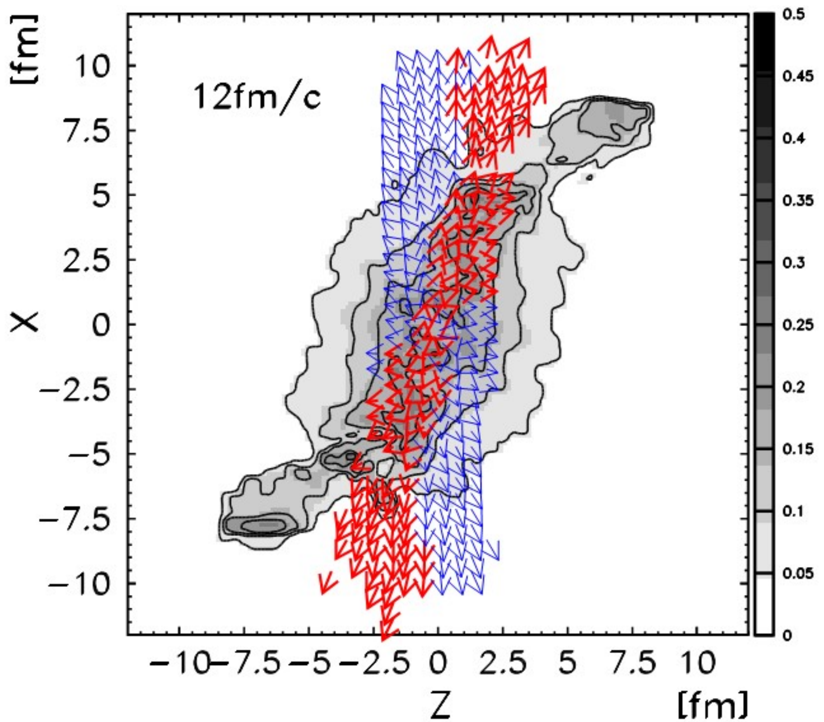


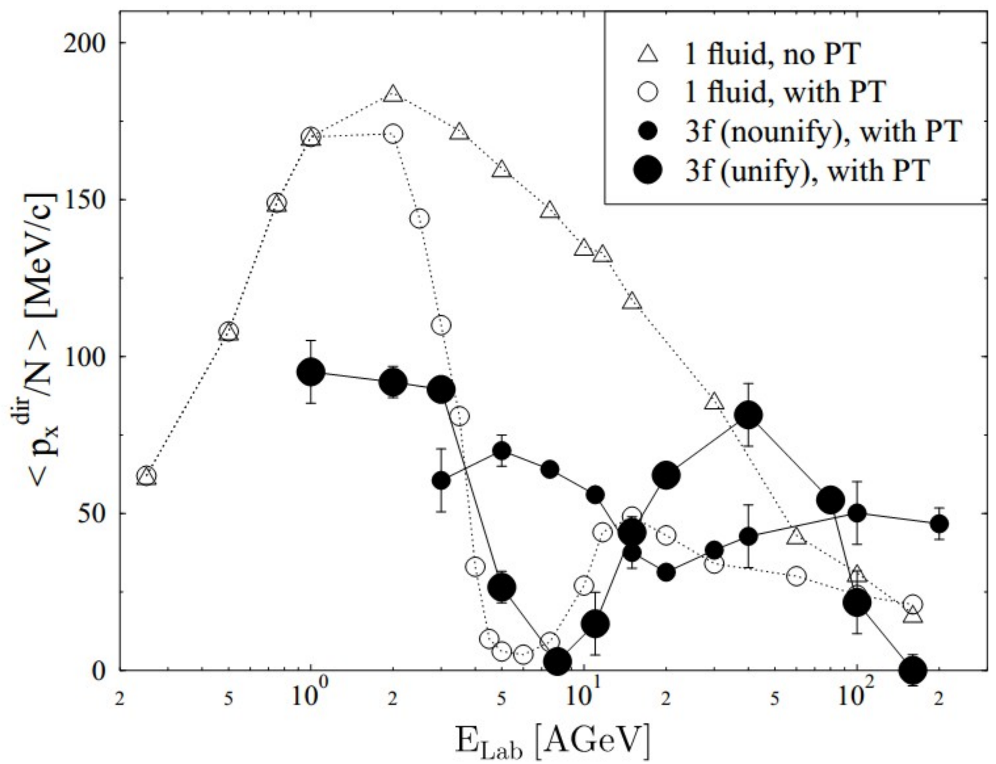
"Softest point"

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 AGeV)



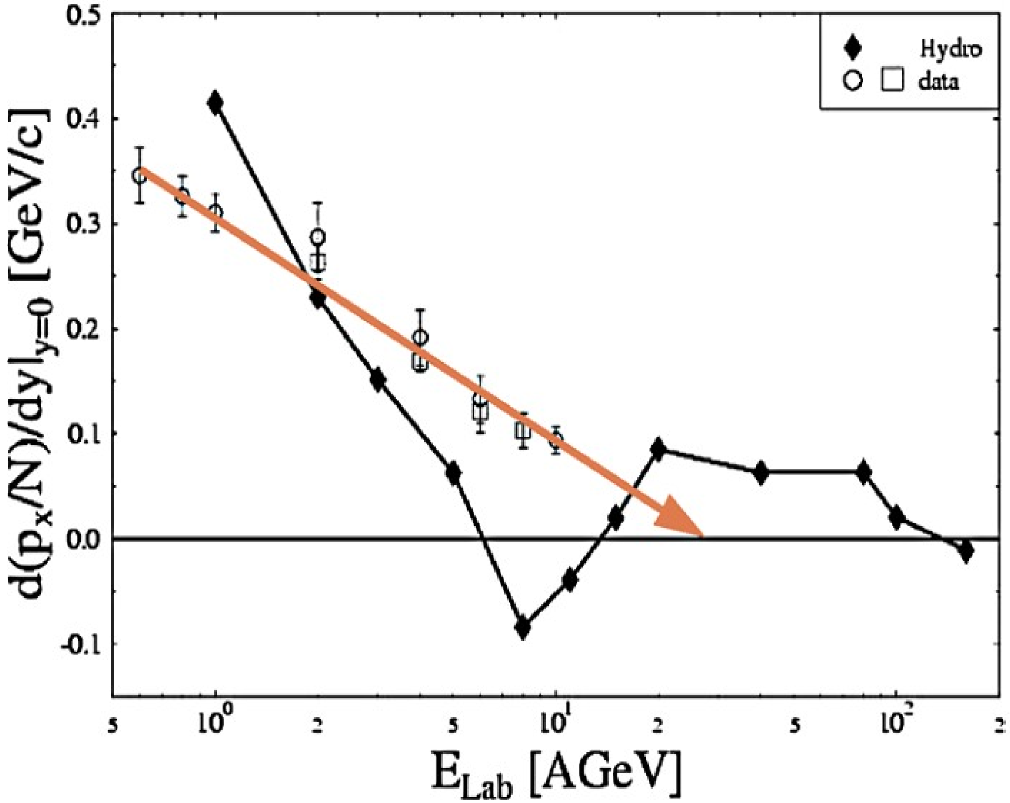


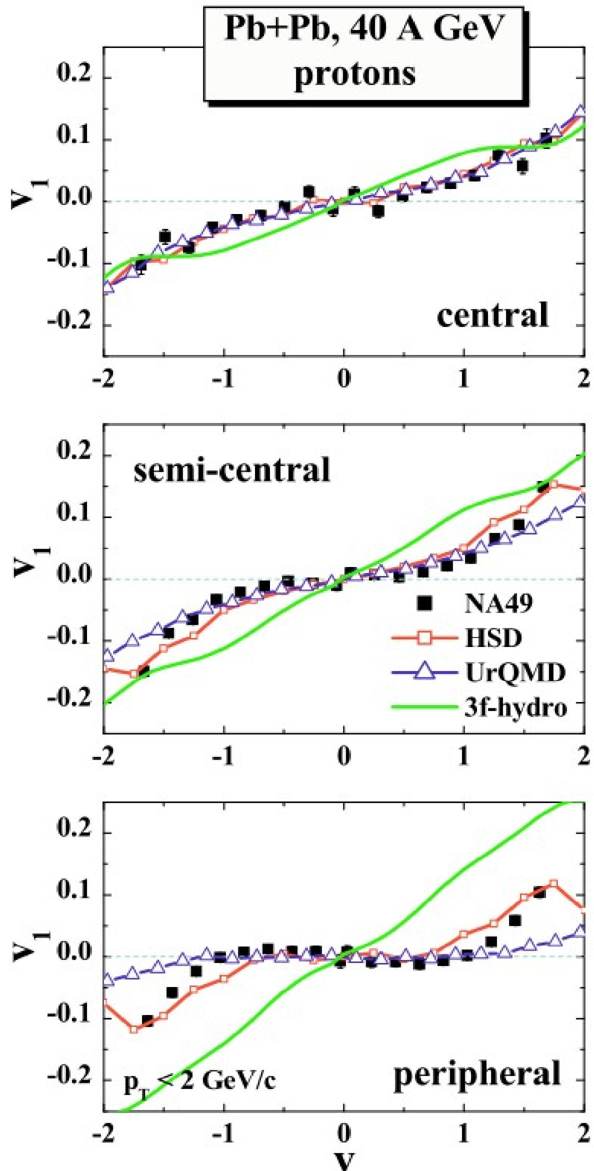
EoS is softened either by a phase transition to QGP, or by the creation of resonances and string-like excitations

J. Brachmann, S. Soff, A. Dumitru, H. 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

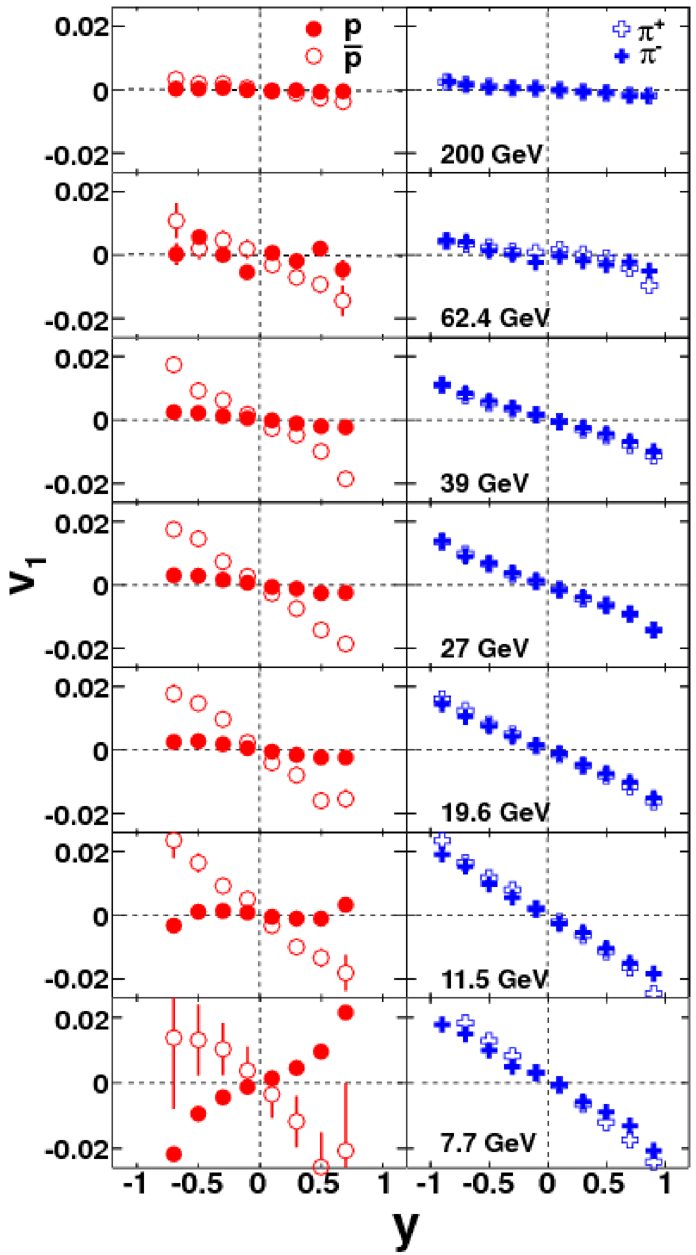
H. Stöcker, Nucl. Phys. A 750, 121 (2005)

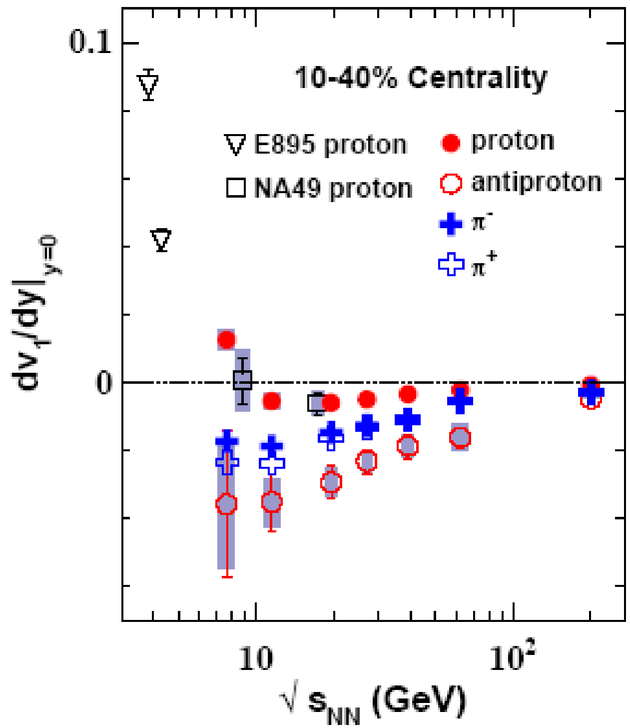




- Early hydro calculation predicted the "softest point" at E_{lab} = 8 AGeV
- A linear extrapolation of the data (arrow) suggests a collapse of flow at E_{lab} = 30 AGeV

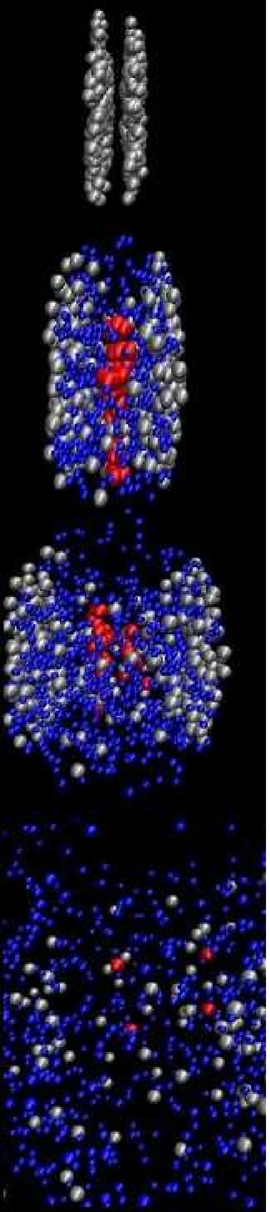
Recent measurements of v_1 of identified hadrons





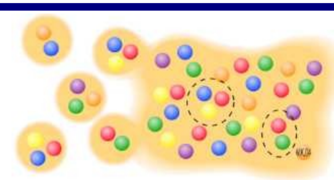
measured distributions are smooth !

STAR Collaboration, PRL 112 (2014) 162301



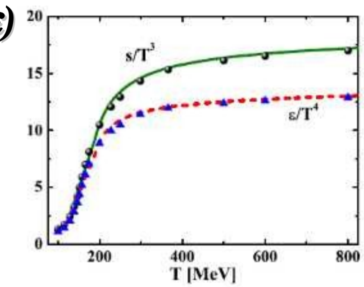
Parton Hadron String Dynamics

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

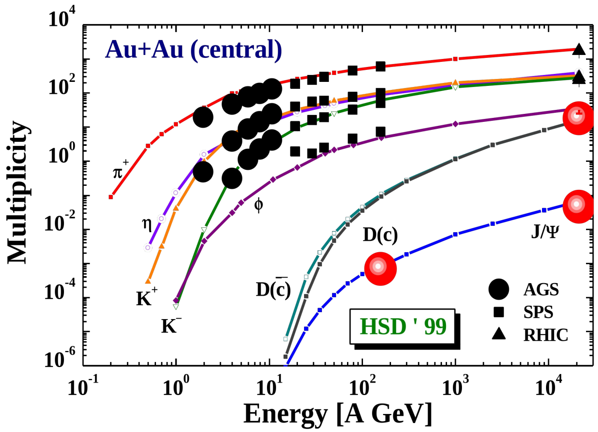
- **massive, off-shell (anti-)quarks** with broad spectral functions hadronize to **off-shell mesons and baryons or color neutral excited states - ‚strings'** (strings act as ‚doorway states' for hadrons)

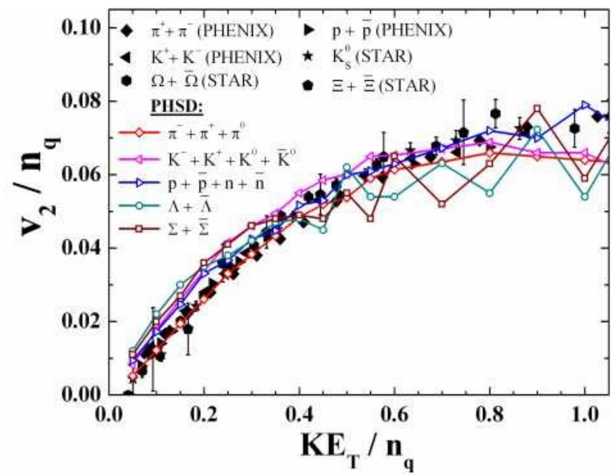
IV. Hadronic phase: hadron-string interactions – off-shell HSD

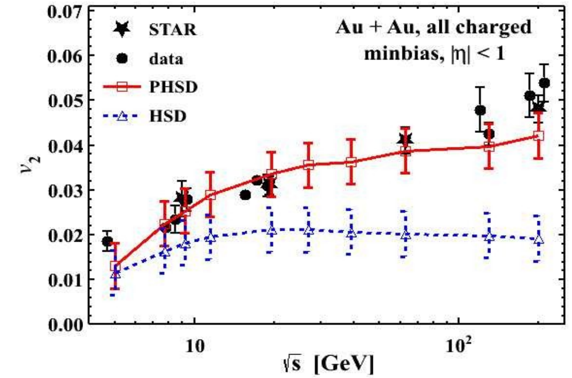
DQPM: Peshier, Cassing, PRL 94 (2005) 172301;
Cassing, NPA 791 (2007) 365: NPA 793 (2007)

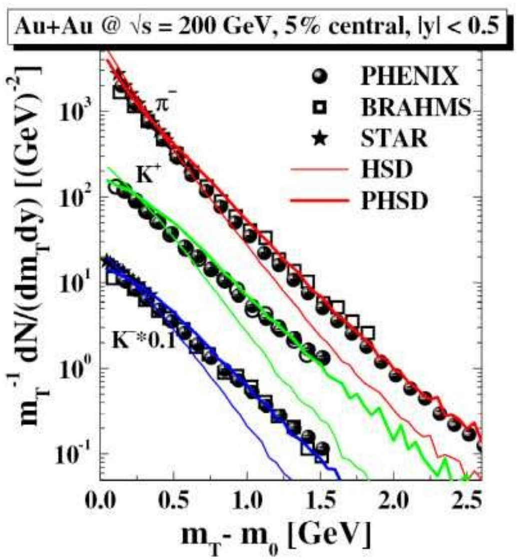
W. Cassing, E. Bratkovskaya, PRC 78 (2008) 034919;
NPA831 (2009) 215; EPJ ST 168 (2009) 3; NPA856 (2011) 162.

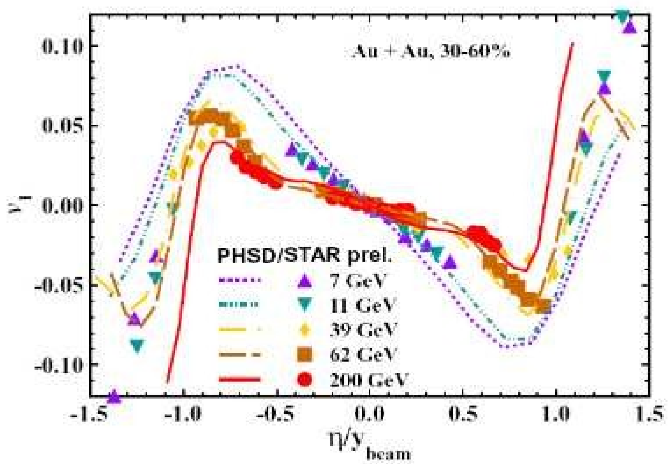
PHSD for HIC from AGS to RHIC (highlights)

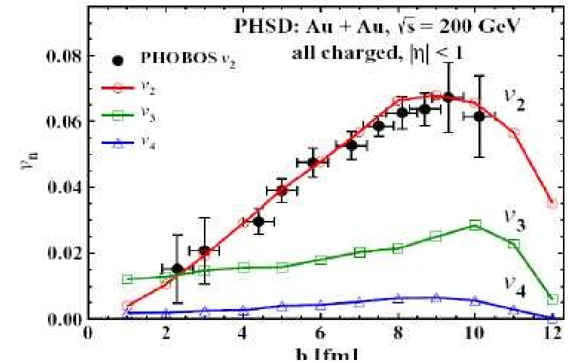


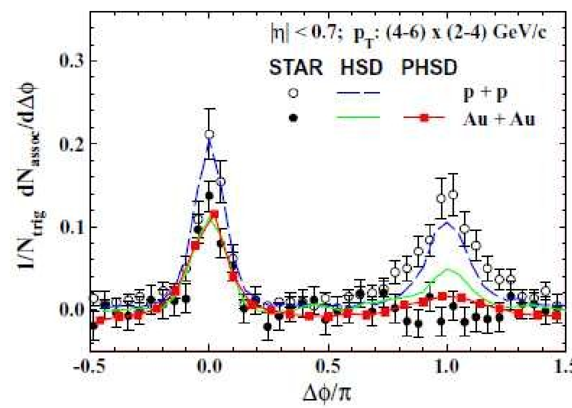








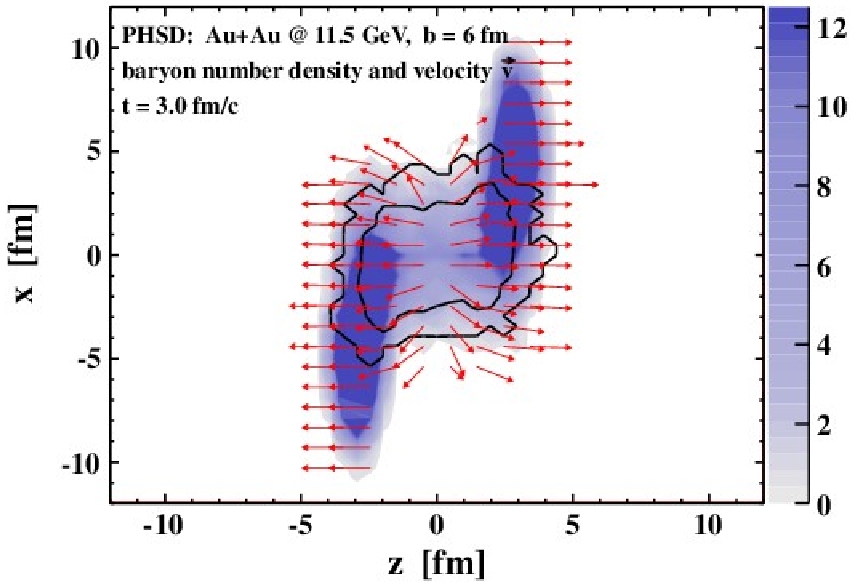




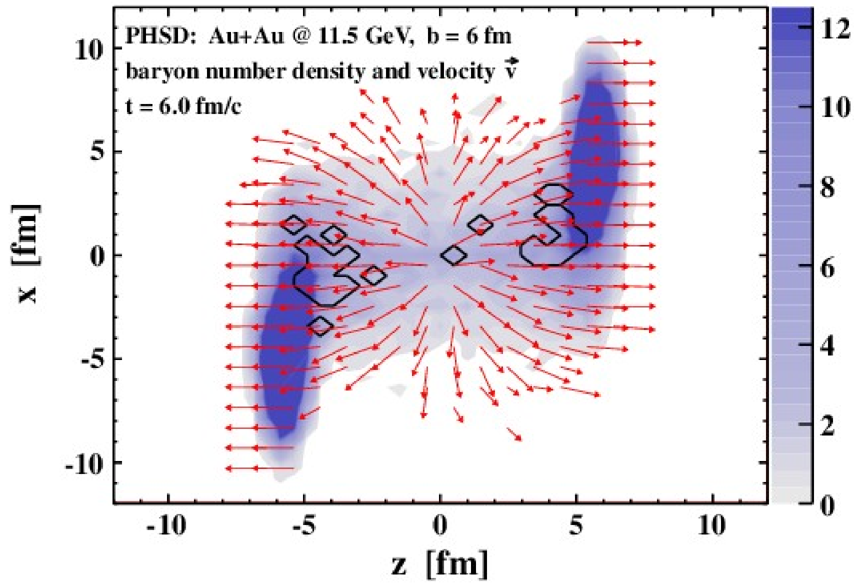
PHSD provides a consistent description of HIC dynamics

PHSD: snapshot of the reaction plane

t = 3 fm/c

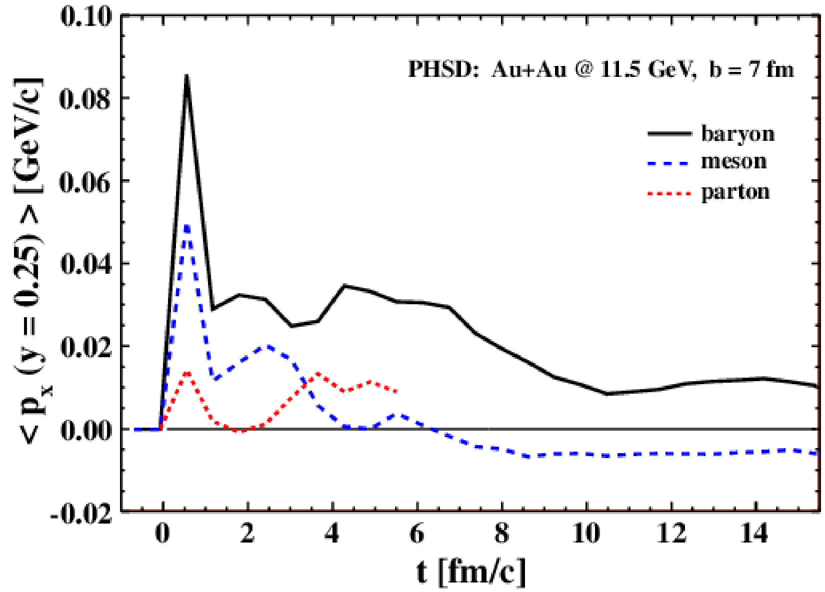


t = 6 fm/c



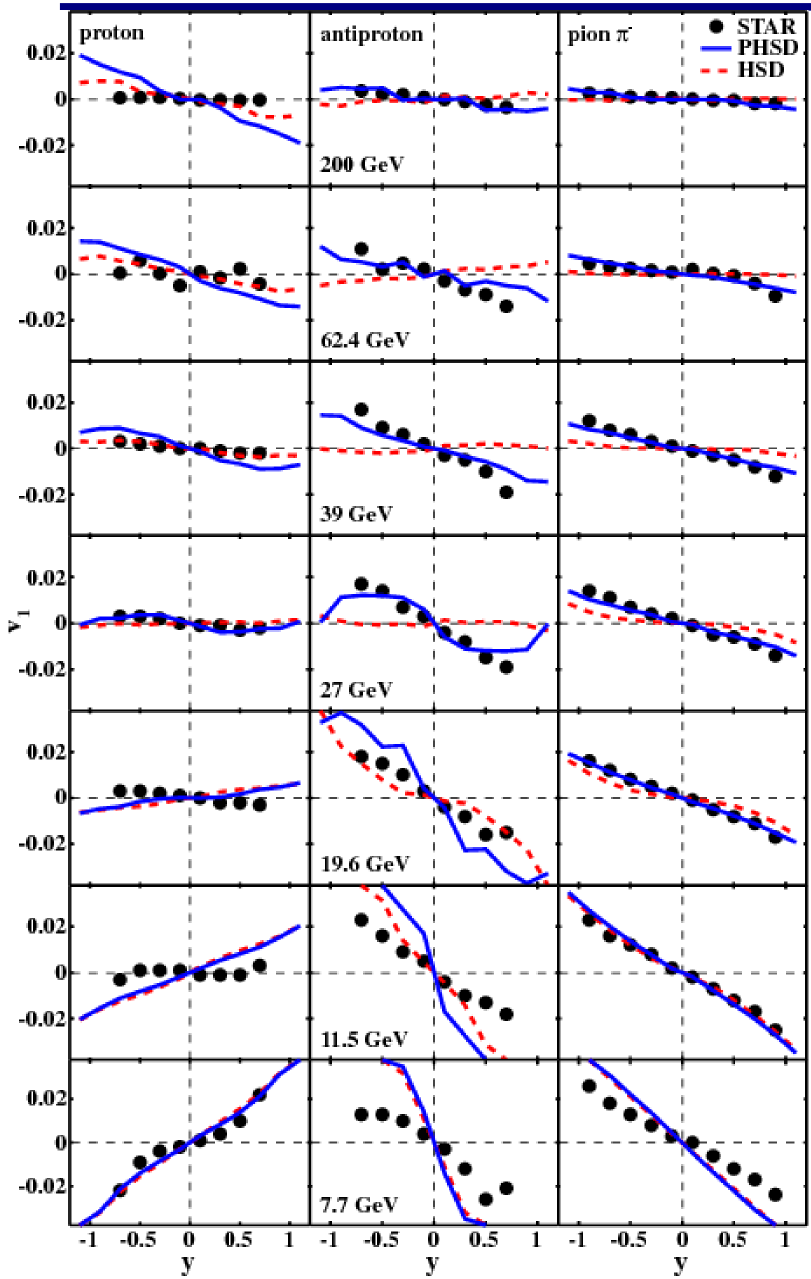
- Color scale: baryon number density
- Black levels: parton density 0.6 and 0.01 fm^{-3}
- Red arrows: local velocity of baryon matter

PHSD: $<p_x>$ at y = +0.25



- Averaged over ~ 80 000 collisions
- Directed flow v_1 is formed at an early stage of the nuclear interaction.
- Baryons are reaching positive and mesons – negative value of v_1

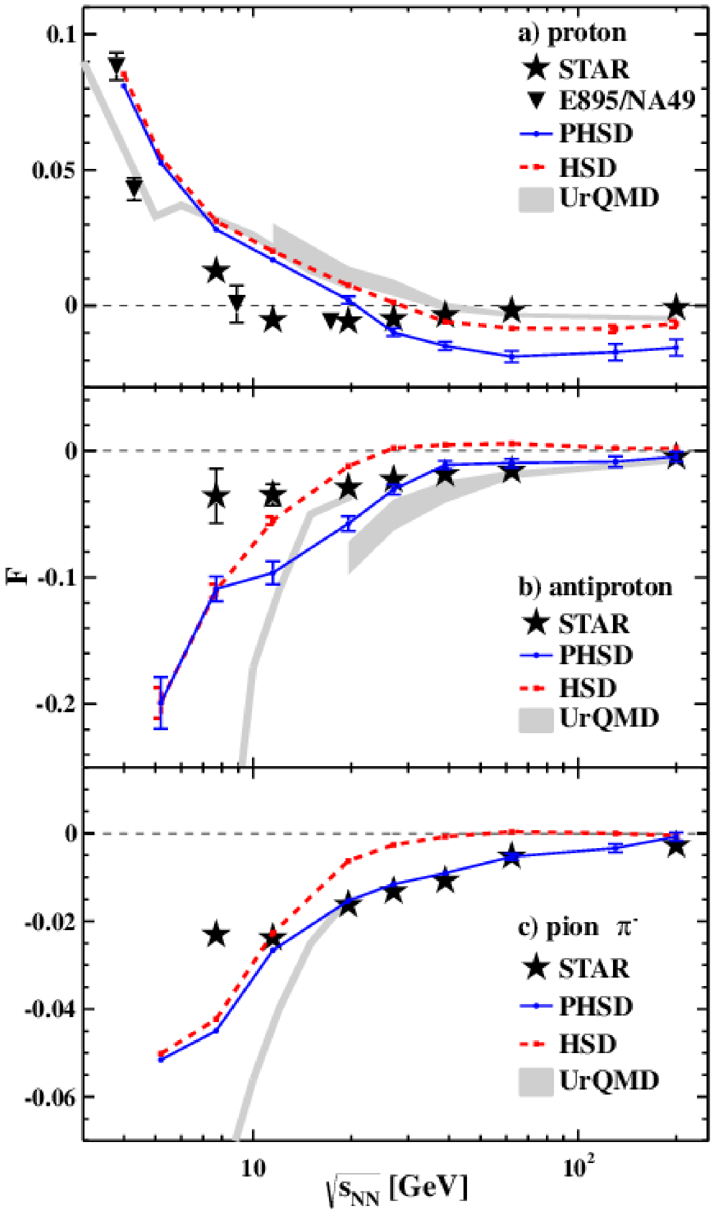
Directed flow from PHSD and HSD



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

STAR Collaboration, PRL 112 (2014) 162301

PHSD: Characteristic slope 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 $v_1(y) = Fy$ was used in the rapidity window $-0.5 < y < 0.5$

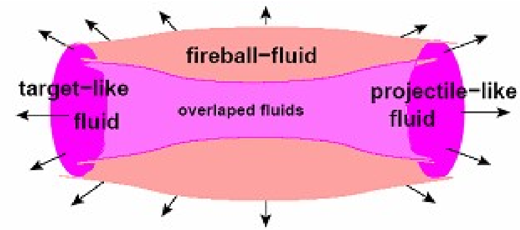
- Proton slopes are in qualitative agreement but overestimate STAR data at $5 < \sqrt{s} < 15$ GeV;
  HSD is close to UrQMD

- UrQMD fail to reproduce pion and antiproton slopes

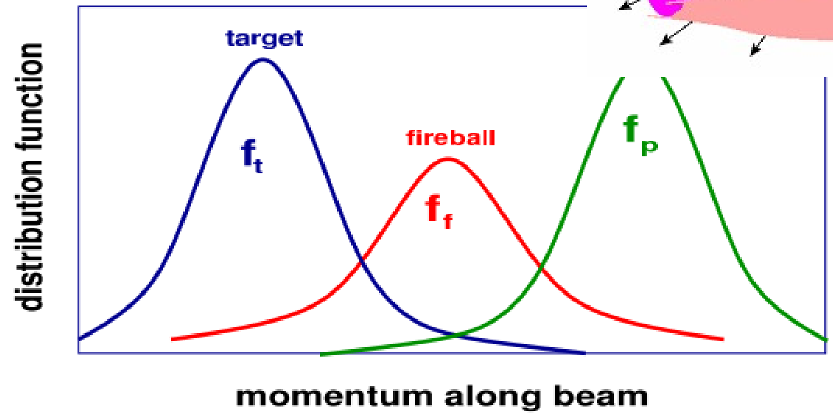
- PHSD/HSD work better due to including of inverse processes for antiproton annihilation

STAR Collaboration, PRL 112 (2014) 162301
UrQMD J. Steinheimer, J. Auvinen, H. Petersen, M. Bleicher and H. Stöcker, PRC89 (2014) 054913

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

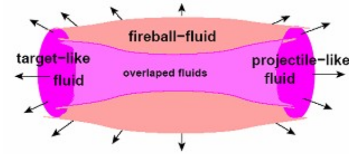
The source term is delayed due to a formation time $\tau \sim 1$ fm/c

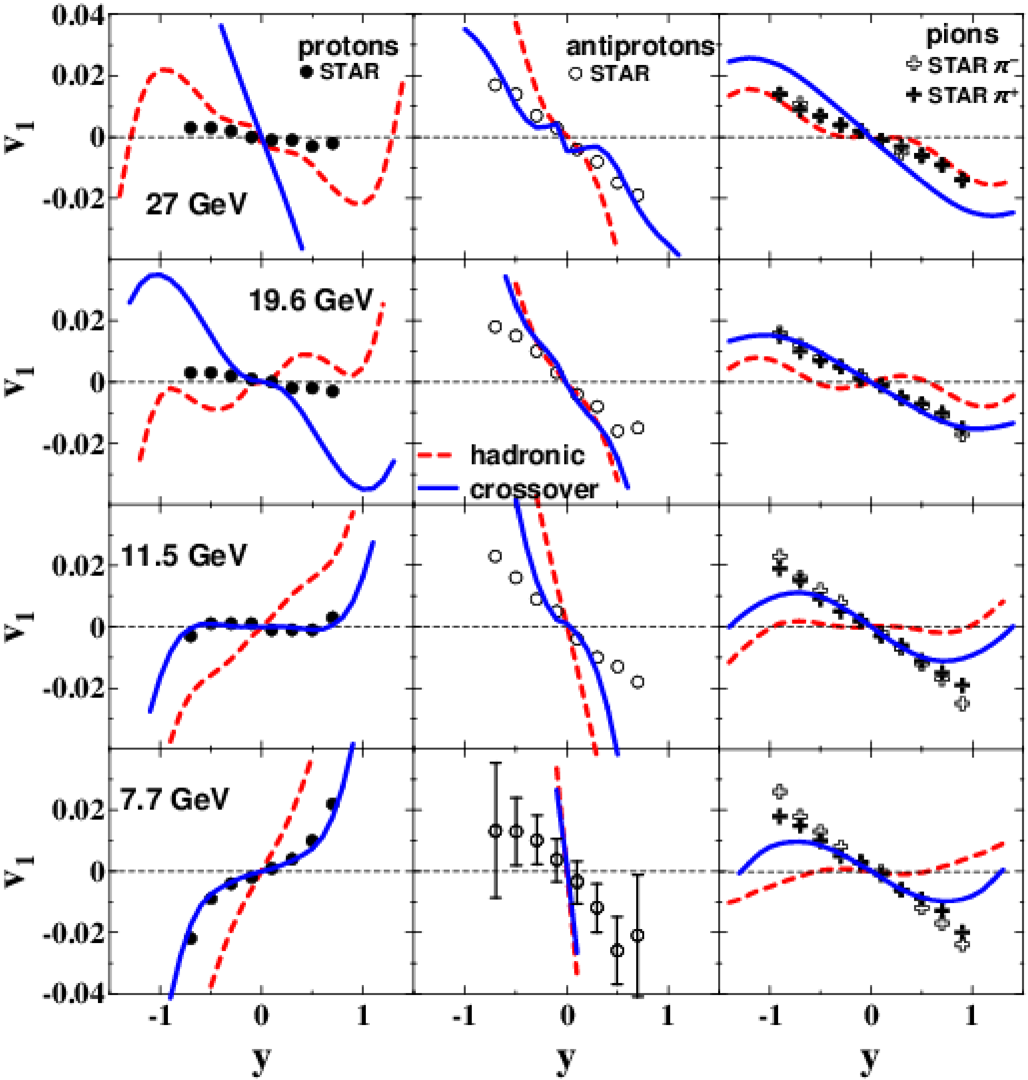
Total energy-momentum conservation:

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

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

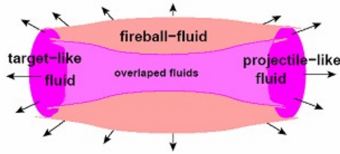
3FD: directed flow vs. EoS

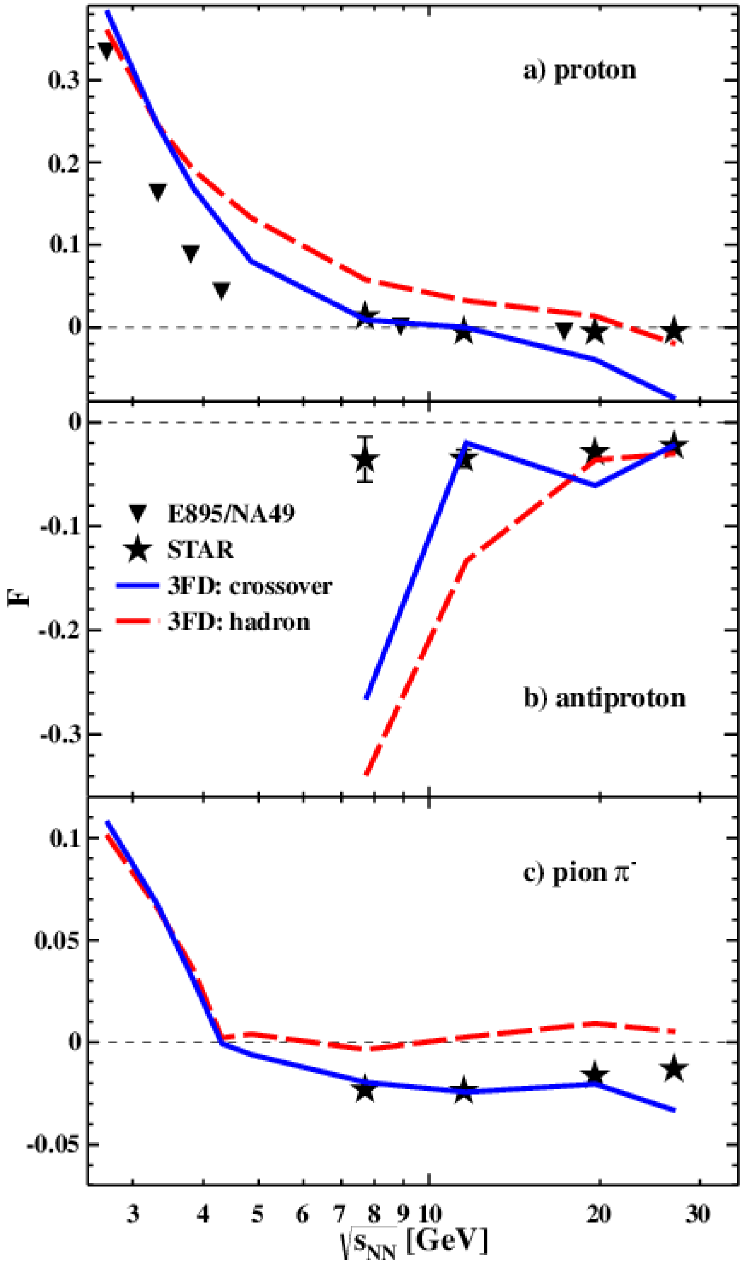




- **Description of the STAR $v_1(y)$ is not very well and relatively worse then by the PHSD**
- **Crossover EoS agrees better with the experiment then the pure hadronic EoS**

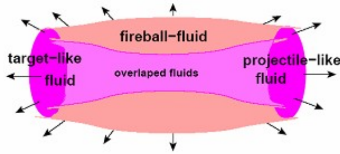
3FD: excitation function of v_1 slopes

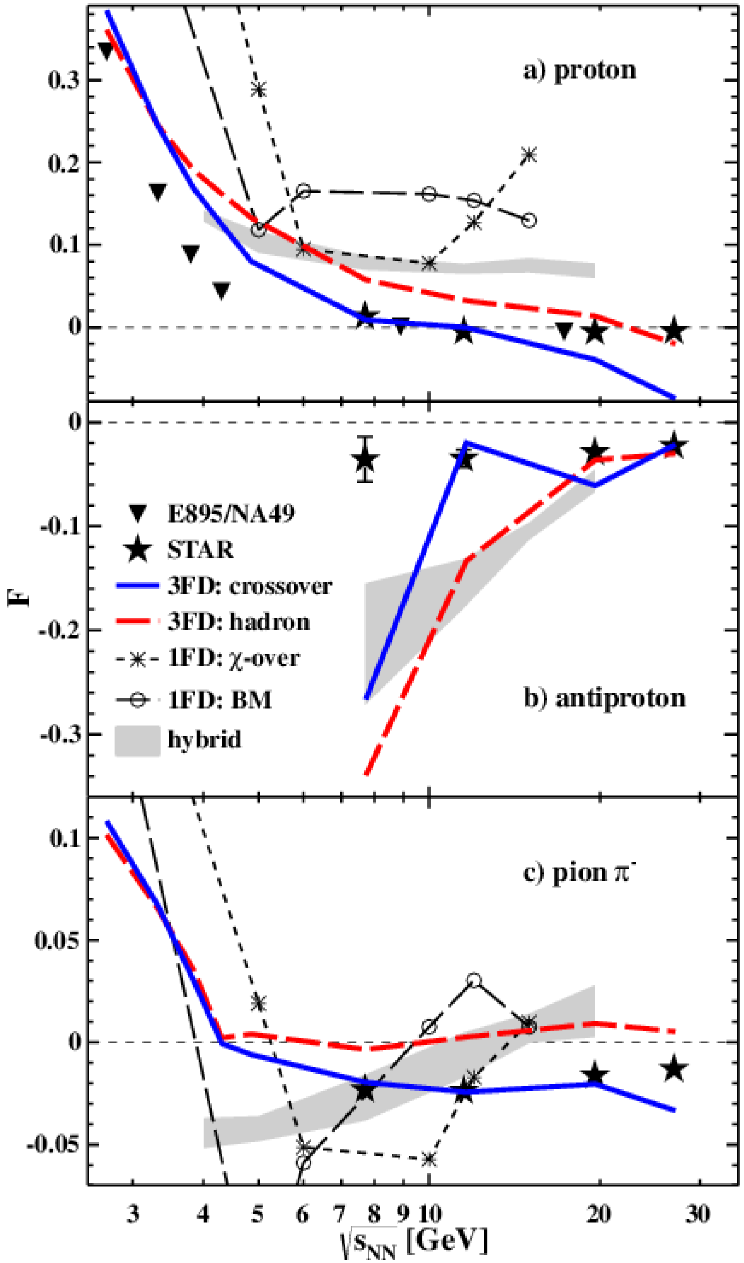




- **3-Fluid Dynamic approach (3FD) gives reasonable results for proton and pion slopes of v_1 and fail at 7.7 GeV for antiprotons**
- **Discrepancies between 3FD model and STAR data are smaller in case of crossover**

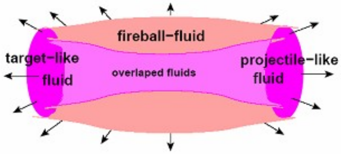
3FD: excitation function of v_1 slopes





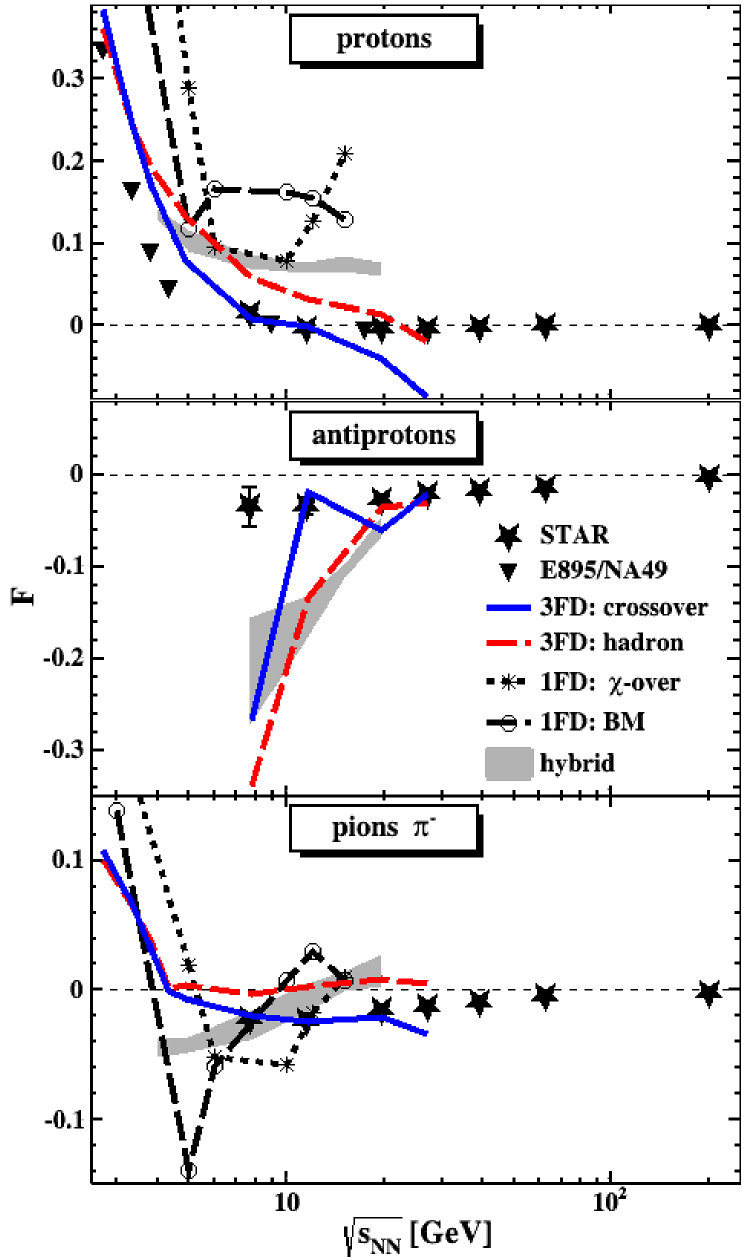
- 3-Fluid Dynamic approach (3FD) gives **reasonable results** for proton and pion slopes of v_1
  and fail at 7.7 GeV for antiprotons
- Discrepancies between 3FD model and STAR data are smaller in case of **crossover**
- Resent **hydrodynamical** and **hybrid** (hydro+kinetic) results are shown in comparison
- Give worse description of data for both chiral x-over and Bag Model (BM) EoS

J. Steinheimer, J. Auvinen, H. Petersen, M. Bleicher and H. Stöcker, PRC89 (2014) 054913

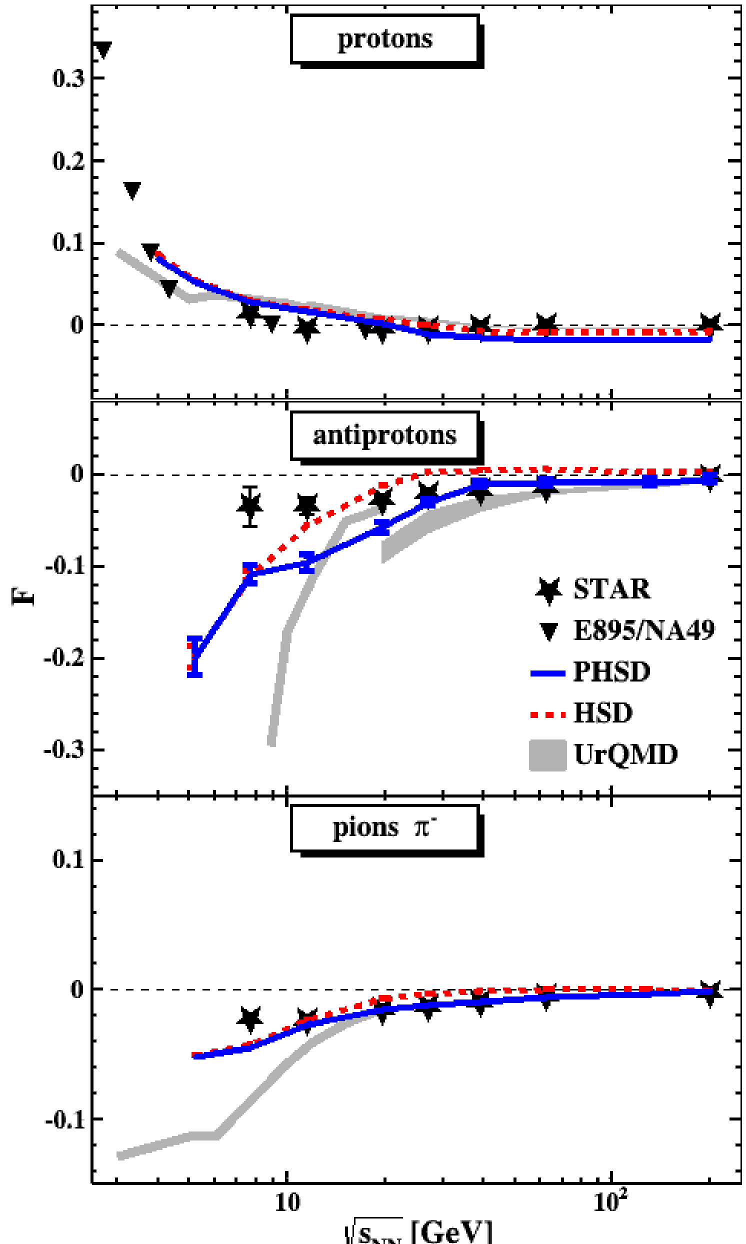


fireball−fluid
target−like
fluid
overlaped fluids
projectile−like
fluid

3FD vs PHSD

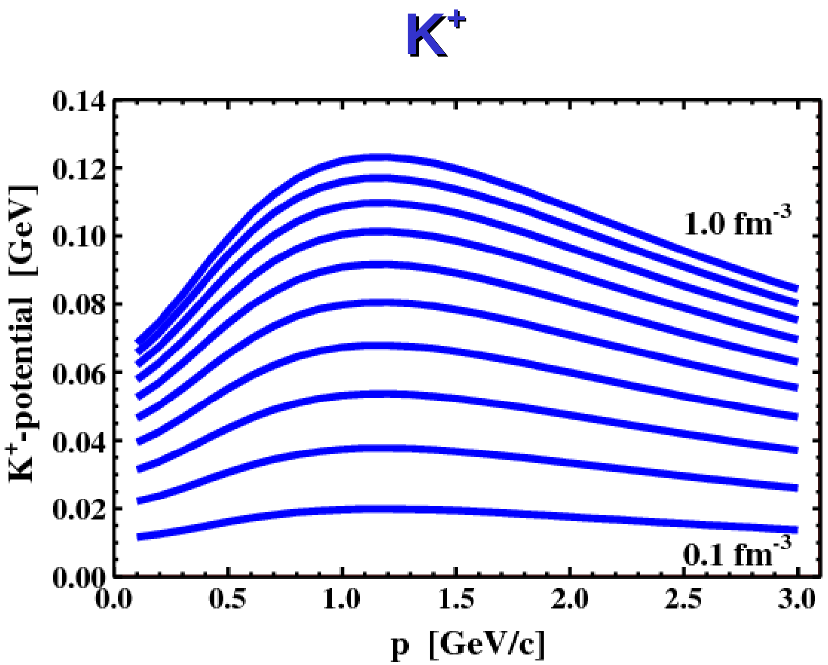


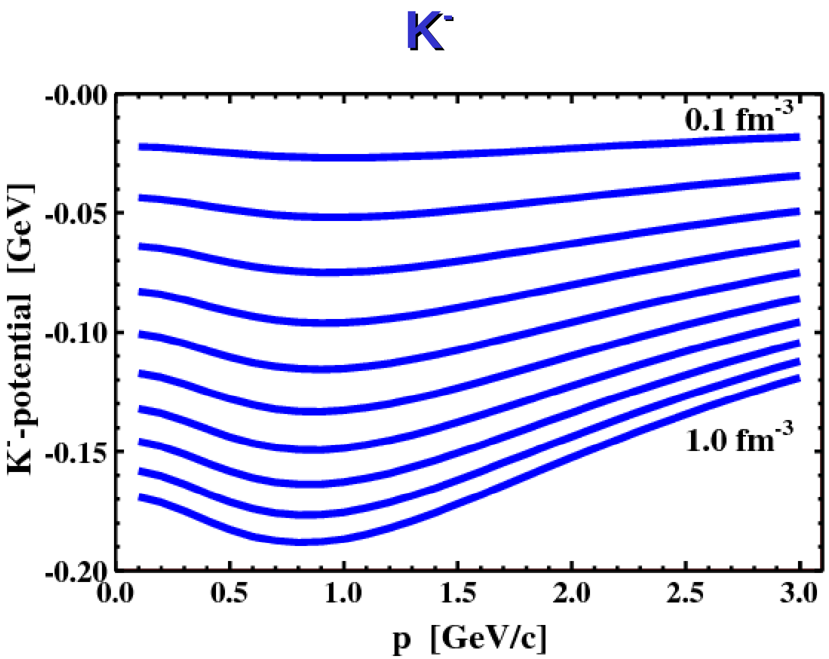
protons
antiprotons
pions π⁻
STAR
E895/NA49
3FD: crossover
3FD: hadron
1FD: χ-over
1FD: BM
hybrid
F
√s_NN [GeV]



protons
antiprotons
pions π⁻
STAR
E895/NA49
PHSD
HSD
UrQMD
F
√s_NN [GeV]

Kaon potentials





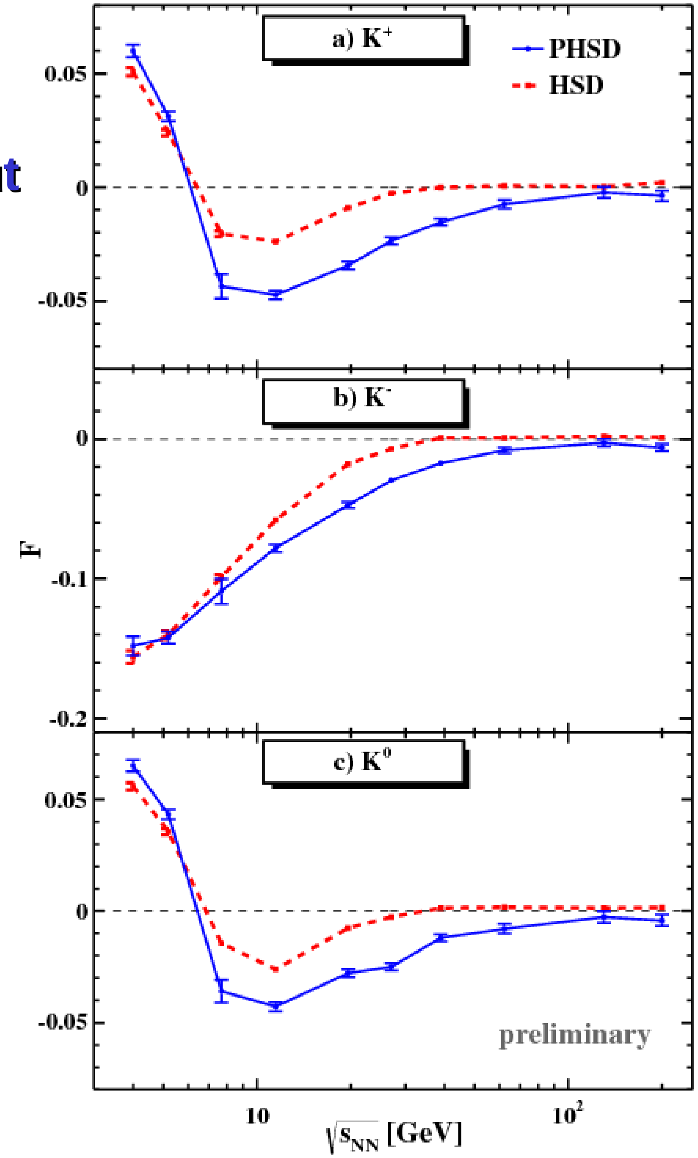
Dispersion relation $$\omega_K^2(\vec{p},\rho)=\pm\frac{3}{4}\frac{\omega}{f_K^2}\rho_N+p^2+m_K^2-\frac{\Sigma_{KN}}{f_K^2}\rho_s$$

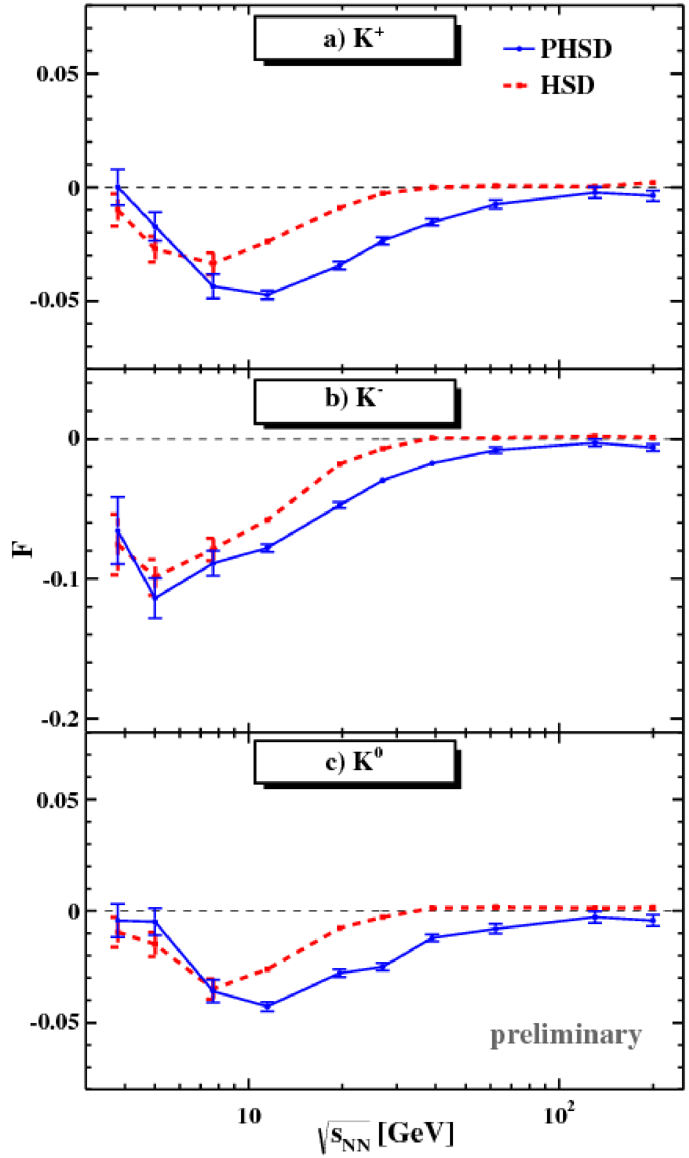
Kaon potential $$U_K(\vec{p},\rho)=\omega_K(\vec{p},\rho)-\sqrt{p^2+m_K^2}$$

L.Tolos, A.Ramos, A.Polls, PRC65 (2002) 054907;
W.Cassing, L.Tolos, E.L.Bratkovskaya, A.Ramos, NPA727 (2003) 59;
W.Cassing, V.P.K, A. Palmese, V.D. Toneev, E.L. Bratkovskaya [1408.4313]

Sensitivity of v1 to kaon potentials

without





with pot

W.Cassing, V.P.K, A. Palmese, V.D. Toneev, E.L. Bratkovskaya [1408.4313]

Summary

- The microscopic Parton-Hadron-String-Dynamics (PHSD) transport approach reproduces the general trend in the $v_1(y)$ excitation function in the energy range $\sqrt{s}$ =7.7-200 GeV. We don't see any "wiggle-like" irregularities as expected by early hydro calculations.

- The PHSD results differ from those of HSD where no 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.

- Inclusion of antiproton annihilation into several mesons as well as inverse processes in HSD/PHSD help to reproduce antiproton directed flow (in contrast to UrQMD).

- 3-Fluid Dynamic approach (3FD) gives reasonable results for proton and pion slopes of v_1 and fail at 7.7 GeV for antiprotons, which is better then the resent hydrodynamical and hybrid (hydro+kinetic) results.

- Crossover agrees better with the experiment then the pure hadronic EoS

- Sizeable effect of momentum dependent mean-fields on directed flows

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Wolfgang Cassing
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Viacheslav Toneev
Vadim Voronyuk

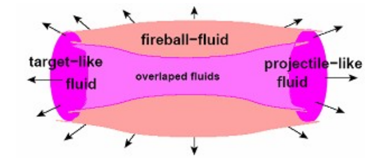
BITP, Kiev University:
Mark Gorenstein

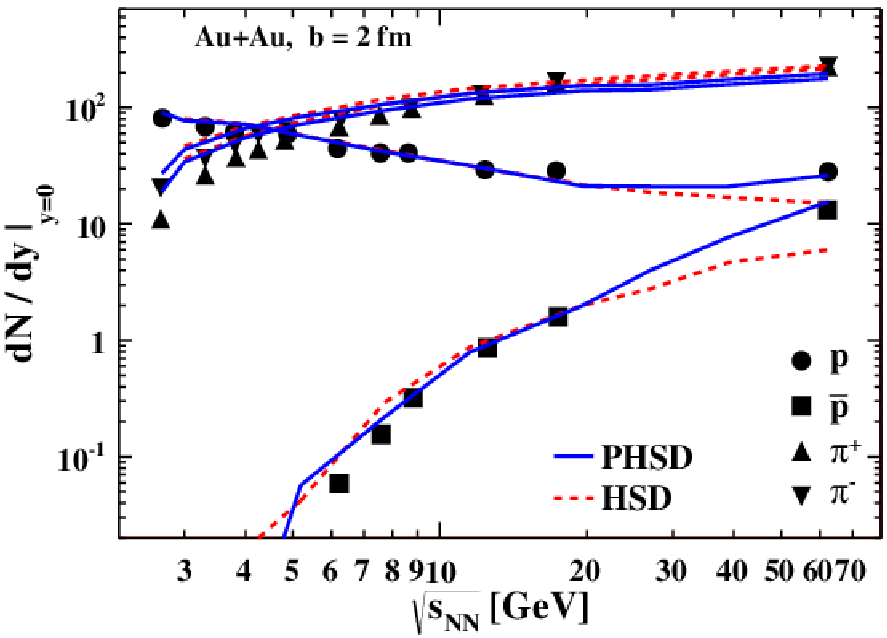
Barcelona University:
Laura Tolos
Angel Ramos

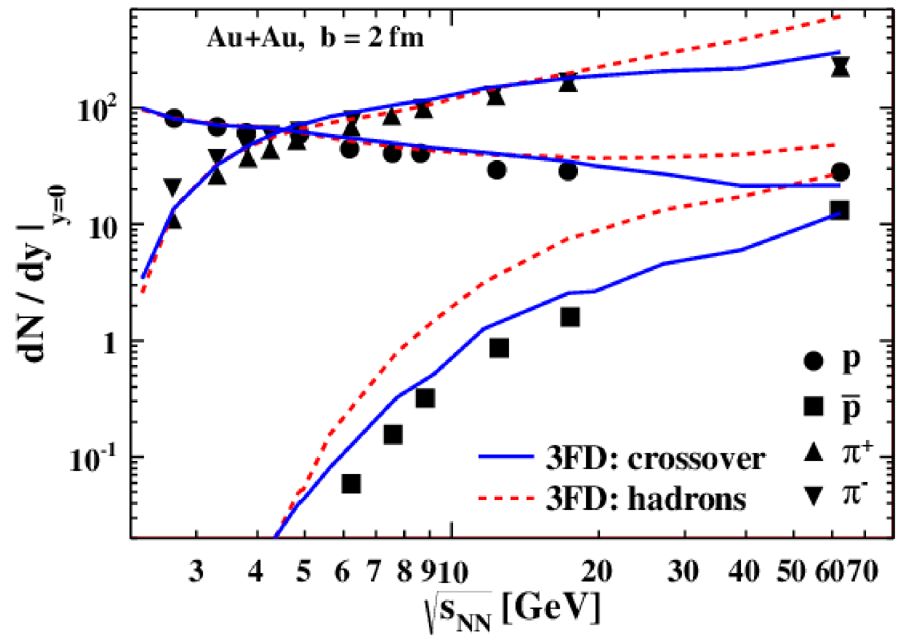
University Rio de Janeiro
Takeshi Kodama

Backup

PHSD vs 3FD: multiplicities



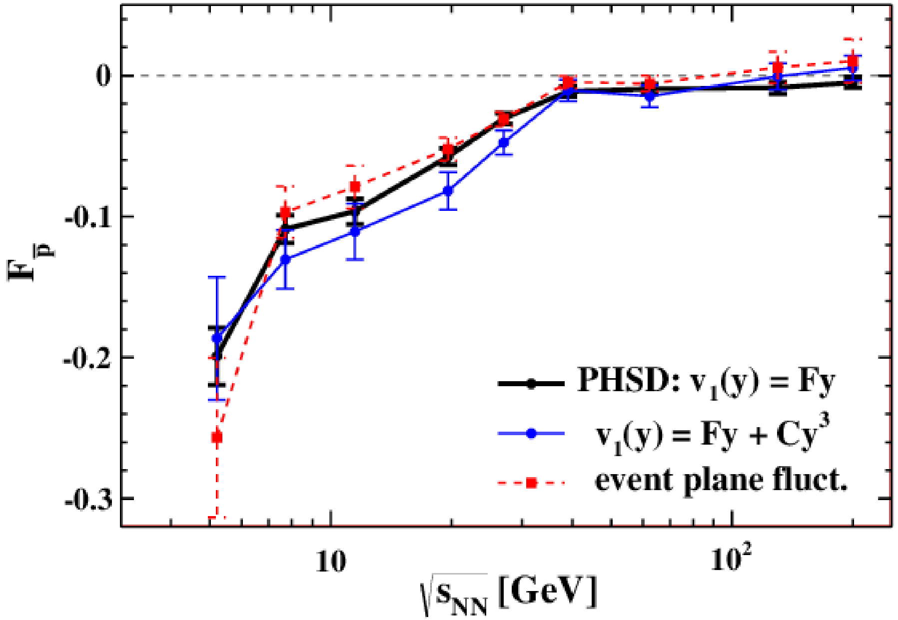




- **Both transport and hydro approach work reasonably fine**
- **Deviation from the data appear at $\sqrt{s}$ > 20 GeV for the hadronic cases**

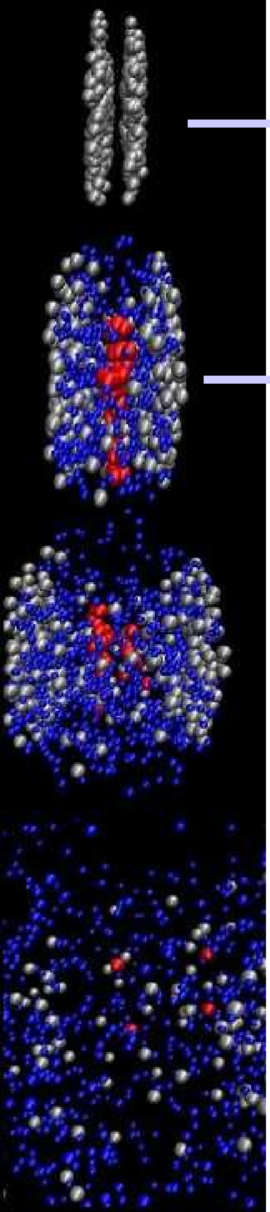
A. Andronic, P. Braun-Munzinger and J. Stachel, Nucl. Phys. A772, 167 (2006)

Stability of the obtained slopes

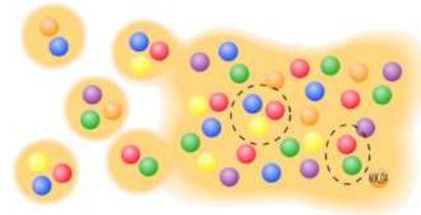


- Fluctuation of determined experimentally event plane doesn't change the result.
- Addition of cubic term to the fit $v_1(y) = Fy + Cy^3$ gives similar result but increase uncertainties.

Parton Hadron String Dynamics I



I. From hadrons to QGP:



- **Initial A+A collisions** – as in HSD:
  - string formation in primary NN collisions
  - string decay to pre-hadrons (*B* - baryons, *m* - mesons)

- **Formation of QGP stage by dissolution of pre-hadrons**
  (all new produced secondary hadrons)
  into **massive colored quarks + mean-field energy**

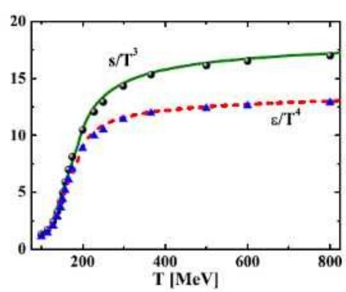
QGP phase:
$\varepsilon > \varepsilon_{critical}$

$$B \to qqq,\ \ m \to q\bar{q} \quad \forall \quad U_q$$

based on the **Dynamical Quasi-Particle Model (DQPM)** which defines **quark spectral functions,** i.e. masses $M_q(\varepsilon)$ and widths $\Gamma_q(\varepsilon)$

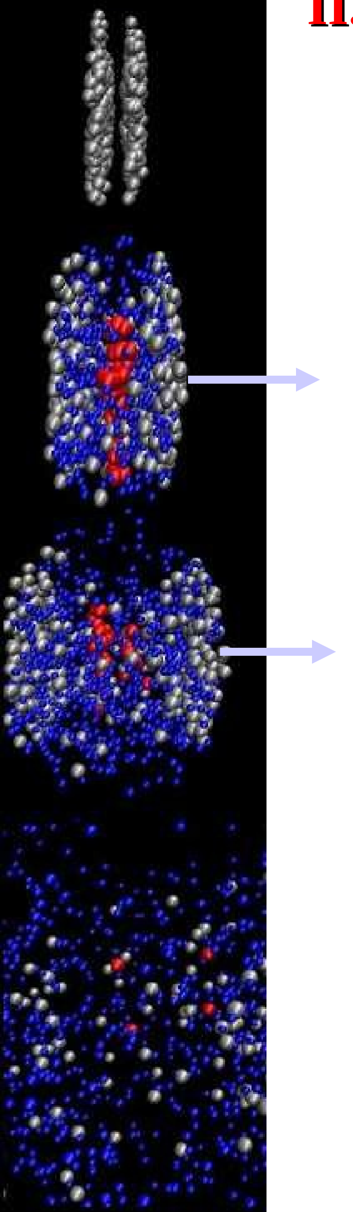
\+ **mean-field potential** U_q at given ε – local energy density

(ε related by lQCD EoS to T - temperature in the local cell)



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

Parton Hadron String Dynamics II



II. Partonic phase - QGP:

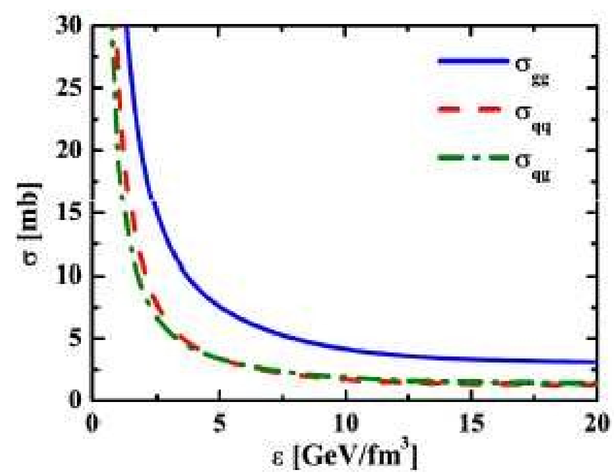
quarks and gluons (= ‚dynamical quasiparticles‘)
with off-shell spectral functions (width, mass) defined by the DQPM

- **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

- **(quasi-) elastic collisions:**

$$q+q \to q+q \qquad g+q \to g+q$$
$$q+\bar{q} \to q+\bar{q} \qquad g+\bar{q} \to g+\bar{q}$$
$$\bar{q}+\bar{q} \to \bar{q}+\bar{q} \qquad g+g \to g+g$$



- **inelastic collisions:**

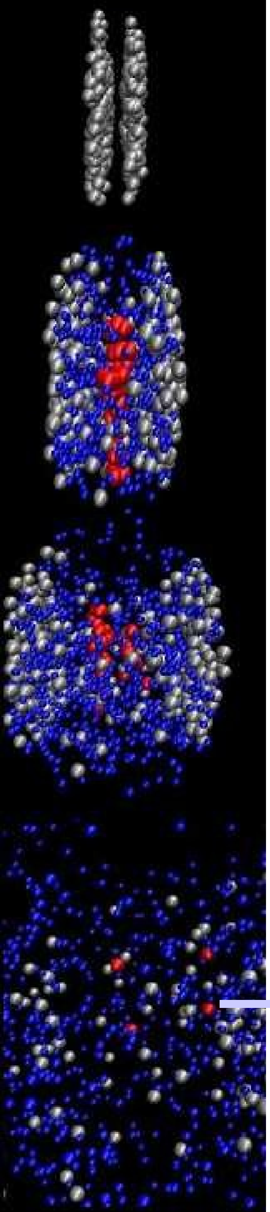
(Breight-Wigner cross sections)

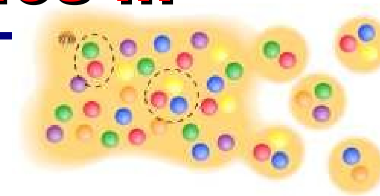
$$\left\{ \begin{array}{l} q+\bar{q} \to g \\ g \to q+\bar{q} \end{array} \right.$$

$$\left. \begin{array}{l} \cancel{q+\bar{q} \to g+g} \\ \cancel{g \to g+g} \end{array} \right\}$$

suppressed (<1%) due to the large mass of gluons

Parton Hadron String Dynamics III





III. Hadronization:

- **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)

$$\boxed{\begin{array}{l} g \to q+\bar{q}, \qquad q+\bar{q} \leftrightarrow meson\ ('\,string\,')\\ \qquad\qquad\quad q+q+q \leftrightarrow baryon\ ('\,string\,') \end{array}}$$

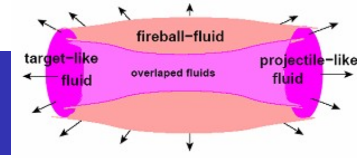
- Local covariant off-shell transition rate for q+qbar fusion
  ➔ meson formation:

$$\frac{dN^{q+\bar{q}\to m}}{d^4x\, d^4p} = Tr_q Tr_{\bar{q}}\, \delta^4(p-p_q-p_{\bar{q}})\, \delta^4\!\left(\frac{x_q+x_{\bar{q}}}{2}-x\right) \delta(flavor, color)$$

$$\cdot N_q(x_q,p_q)\, N_{\bar{q}}(x_{\bar{q}},p_{\bar{q}}) \cdot \omega_q \rho_q(p_q) \cdot \omega_{\bar{q}} \rho_{\bar{q}}(p_{\bar{q}}) \cdot |M_{q\bar{q}}|^2\, W_m\!\left(x_q-x_{\bar{q}},\, p_q-p_{\bar{q}}\right)$$

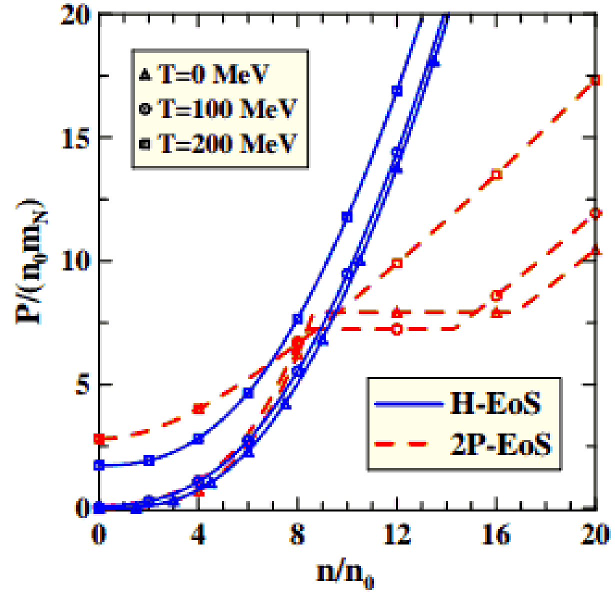
- $N_j(x,p)$ is the phase-space density of parton j at space-time position x and 4-momentum p
- W_m is the phase-space distribution of the formed ‚pre-hadrons‘ (Gaussian in phase space)
- $|M_{qq}|^2$ is the effective quark-antiquark interaction from the DQPM

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



Physical Input

- Equation of State (EoS)



Hadronic EoS (H-EoS)

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

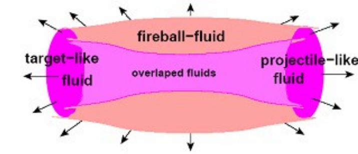
1st-order transition to QGP (2P-EoS)

[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: $\tau=$ 2 fm/c for H-EoS and $\tau=$ 0.33 fm/c for 2P-EoS
- Coalescence coefficients for fragments

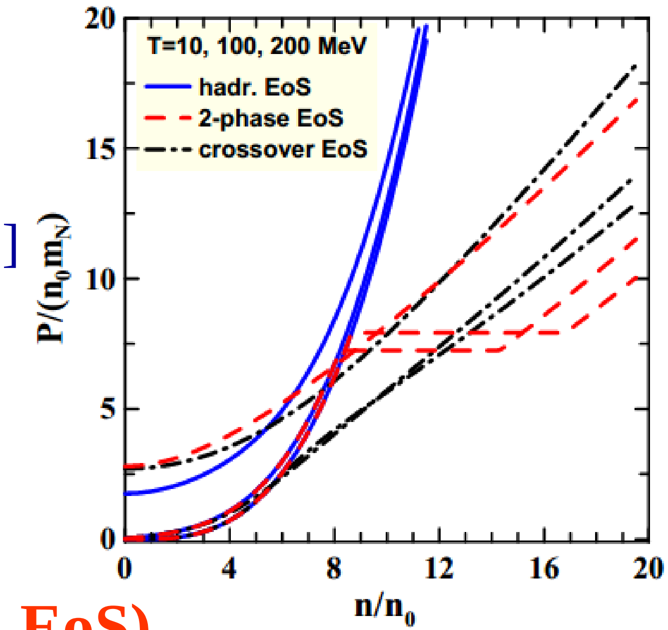
Physical input



Equation of state (EoS)

Hadronic EoS (hadr-EoS)

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



Crossover EoS

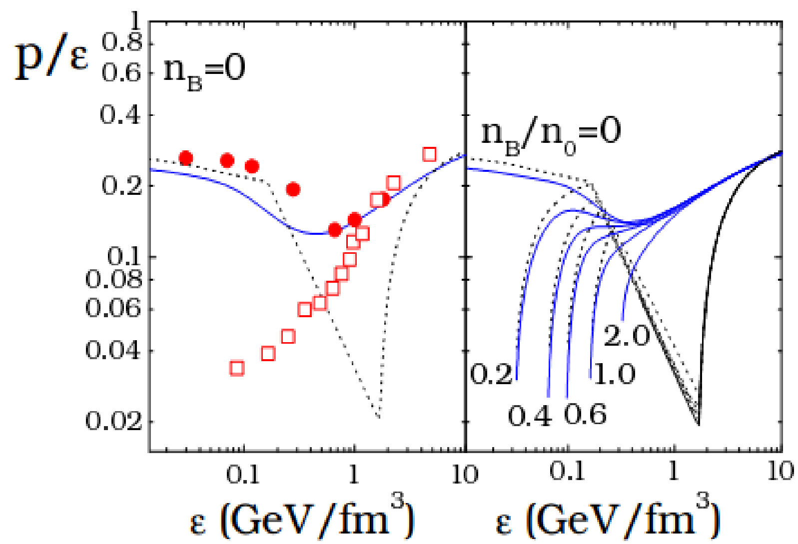
[Khvorostukhin, Skokov, Redlich, Toneev, EPJ, **C48**, 571 (2006)]

1st-order phase transition to QGP (2ph-EoS)

[Khvorostukhin, et al.,, EPJ, **C48**, 571 (2006)]

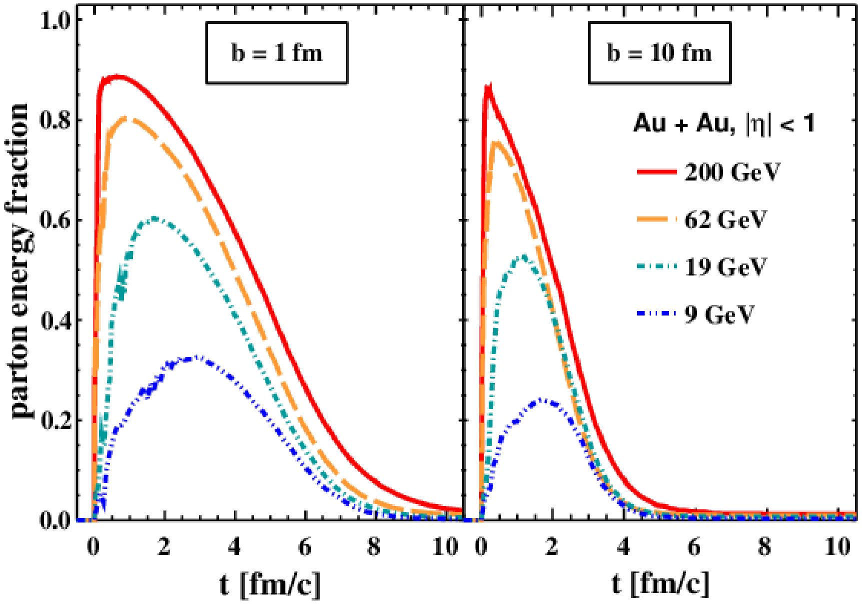
Phase transition ↔ EoS softening

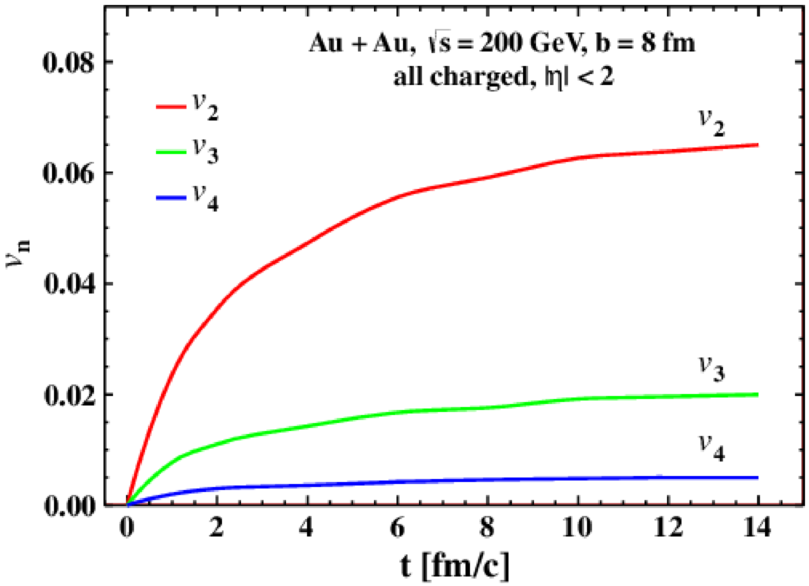
(in dense baryon matter)



- Freeze-out energy density: ε_{frz} =0.4 GeV/fm³
- Friction: estimated and tuned
- Formation time: τ=2 fm/c for H-EoS and τ=0.33 fm/c for 2ph-EoS

Formation of flow

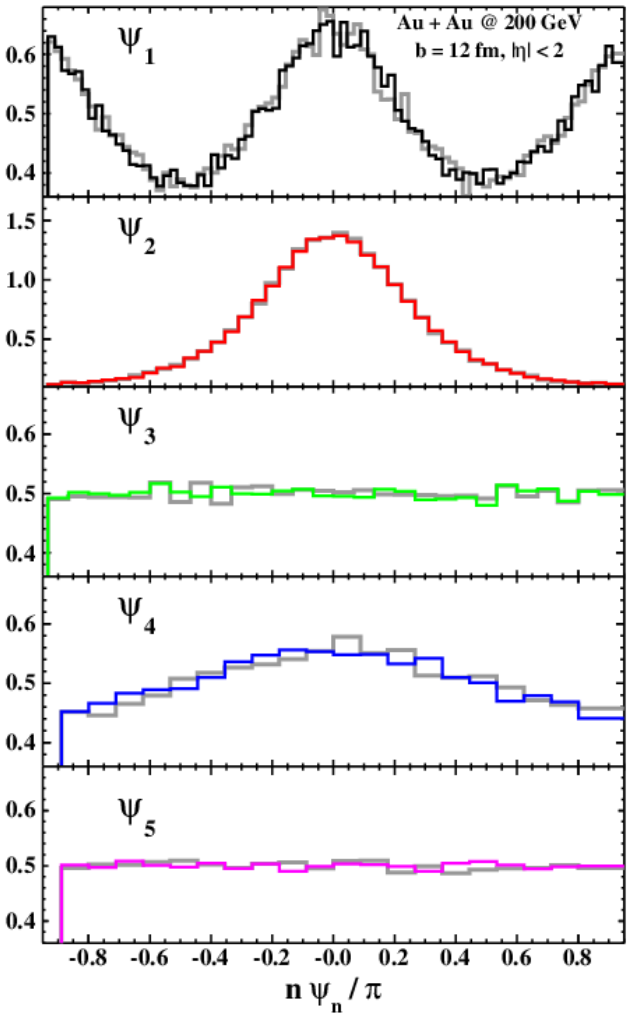




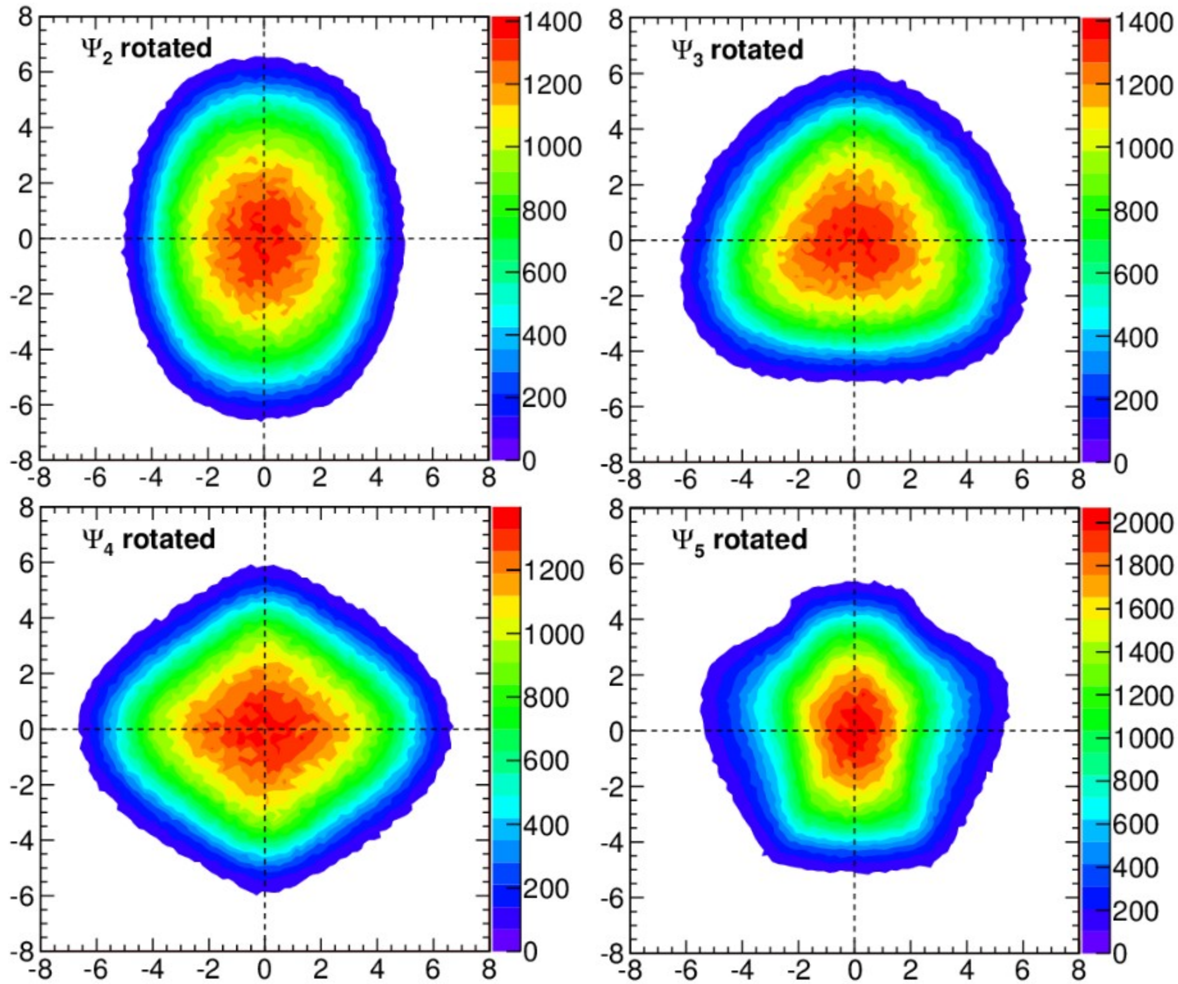
- Relative number of partons does not depend much on centrality.
- In peripheral collisions the duration of the partonic phase is short.
- Collective flow is formed mainly during the partonic phase.

Phys. Rev. C85, 044922 (2012)

Final angular distribution in p-space



Event plane distributions:
even – peaked,
odd – flat.



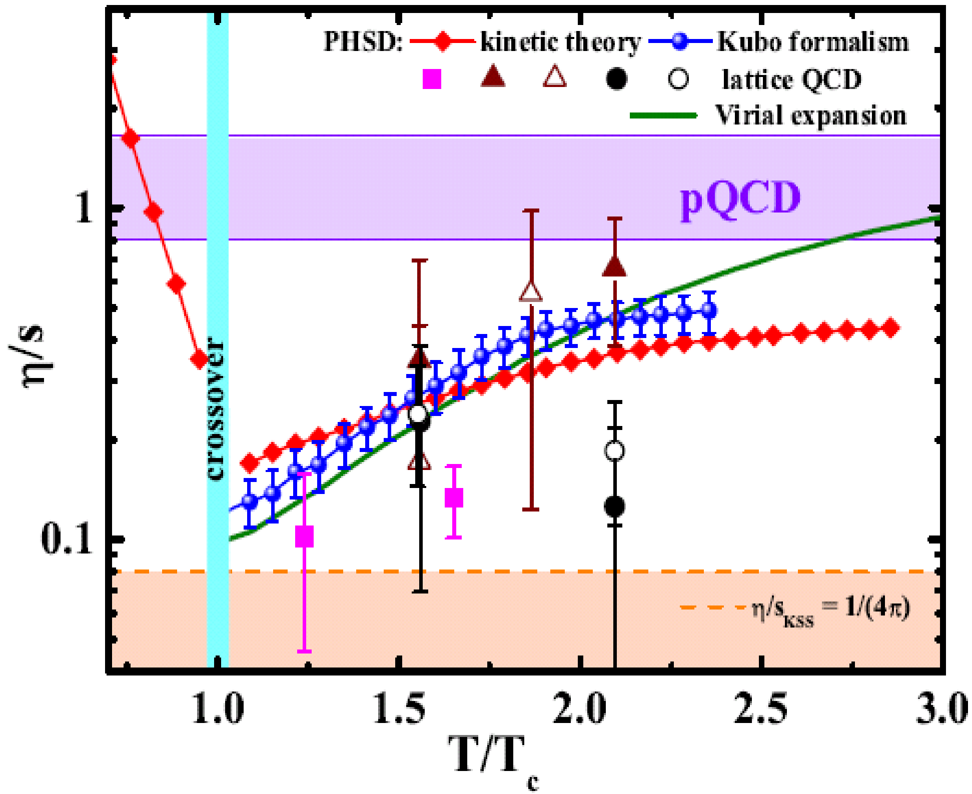
Au+Au collisions
rotated to different event planes.

S. Voloshin, arXiv: 1111.7241

Shear viscosity

η/s using **Kubo formalism** and the **relaxation time approximation** (‚kinetic theory‘)

- **$T=T_C$:** η/s shows **a minimum (~0.1)** close to the critical temperature
- **$T>T_C$:** QGP - **pQCD limit** at higher temperatures
- **$T<T_C$:** fast increase of the ratio η/s for **hadronic matter**➔
  - lower interaction rate of hadronic system
  - smaller number of degrees of freedom (or entropy density) for hadronic matter compared to the QGP



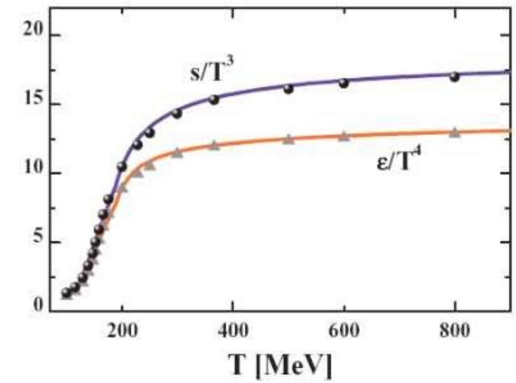
QGP in PHSD = strongly-interacting liquid

V. Ozvenchuk et al., Phys. Rev. C 87 (2013) 024901
V. Ozvenchuk et al., Phys. Rev. C 87 (2013) 064903

The Dynamical QuasiParticle Model (DQPM)

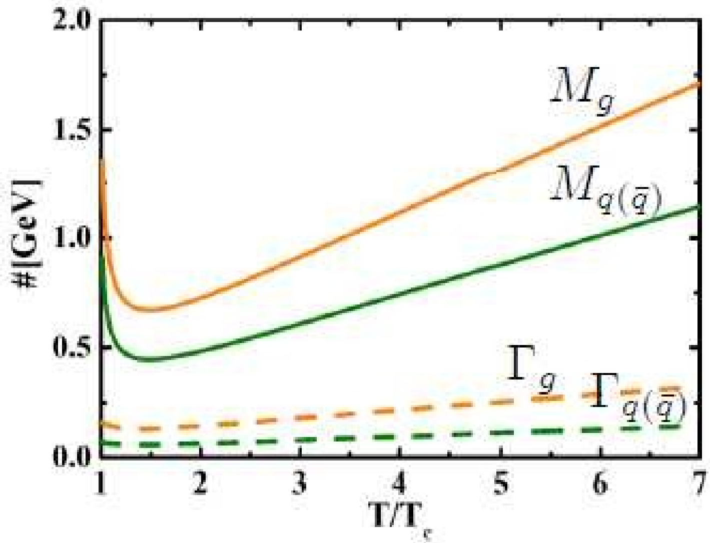
- **fit to lattice (lQCD) results** (e.g. entropy density)

  * BMW lQCD data S. Borsanyi et al., JHEP 1009 (2010) 073



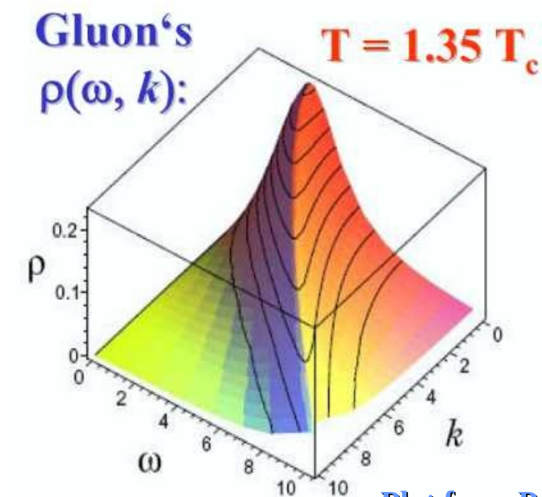
➔ Quasiparticle properties:

- **large width and mass for gluons and quarks**



T_C=158 MeV

ε_C=0.5 GeV/fm³



Plot from Peshier, PRD 70 (2004) 034016

- **DQPM matches well lattice QCD**
- **DQPM provides mean-fields (1PI) for gluons and quarks as well as effective 2-body interactions (2PI)**
- **DQPM gives transition rates for the formation of hadrons ➔ PHSD**

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

The Dynamical QuasiParticle Model (DQPM)

Properties of **interacting quasi-particles:** **massive quarks and gluons** (g, q, q_{bar}) with **Lorentzian spectral functions :**

$$\rho_i(\omega, T) = \frac{4\omega\Gamma_i(T)}{\left(\omega^2 - p^2 - M_i^2(T)\right)^2 + 4\omega^2\Gamma_i^2(T)} \qquad (i = q, \bar{q}, g)$$

- **Modeling of the quark/gluon masses and widths → HTL limit at high T**
  - **quarks:**

    mass: $$M^2_{q(\bar{q})}(T) = \frac{N_c^2 - 1}{8N_c} g^2 \left(T^2 + \frac{\mu_q^2}{\pi^2}\right)$$

    width: $$\Gamma_{q(\bar{q})}(T) = \frac{1}{3}\frac{N_c^2 - 1}{2N_c}\frac{g^2 T}{8\pi}\ln\left(\frac{2c}{g^2} + 1\right)$$

  - **gluons:**

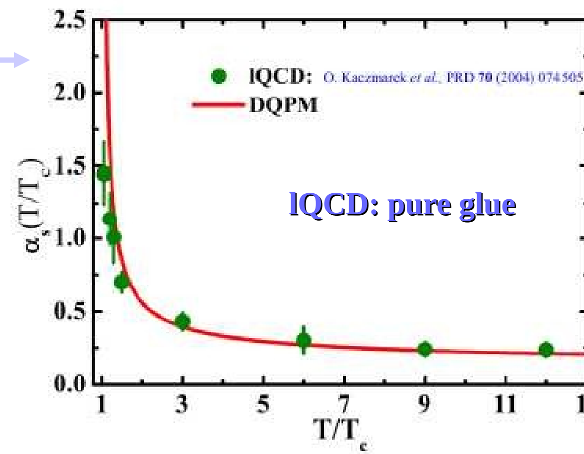
    $$M_g^2(T) = \frac{g^2}{6}\left(\left(N_c + \frac{N_f}{2}\right)T^2 + \frac{N_c}{2}\sum_q \frac{\mu_q^2}{\pi^2}\right)$$

    $$\Gamma_g(T) = \frac{1}{3}N_c\frac{g^2 T}{8\pi}\ln\left(\frac{2c}{g^2} + 1\right)$$

$N_c = 3$, $N_f = 3$

  - **running coupling** (pure glue):

$$\alpha_s(T) = \frac{g^2(T)}{4\pi} = \frac{12\pi}{(11N_c - 2N_f)\ln[\lambda^2(T/T_c - T_s/T_c)^2]}$$



- **fit to lattice (lQCD) results** (e.g. entropy density)

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

  (for pure glue N_f=0)

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

Dynamical QuasiParticle Model (DQPM):

DQPM describes **QCD** properties in terms of **„resummed" single-particle Green's functions** – in the sense of a two-particle irreducible (2PI) approach:

Gluon propagator: $\Delta^{-1} = P^2 - \Pi$ gluon self-energy: $\Pi = M_g^2 - i2\Gamma_g\omega$

Quark propagator: $S_q^{-1} = P^2 - \Sigma_q$ quark self-energy: $\Sigma_q = M_q^2 - i2\Gamma_q\omega$

- the resummed properties are specified by **complex self-energies** which depend on temperature:

 -- the **real part of self-energies** (Σ_q, Π) describes a **dynamically generated mass** (M_q,M_g);

-- the **imaginary part** describes the **interaction width** of partons (Γ_q, Γ_g)

- **space-like part of energy-momentum tensor $T_{\mu\nu}$** defines the potential energy density and the **mean-field potential** (1PI) for quarks and gluons

- **2PI framework** guaranties a consistent description of the system **in- and out-of equilibrium** on the basis of **Kadanoff-Baym equations**

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