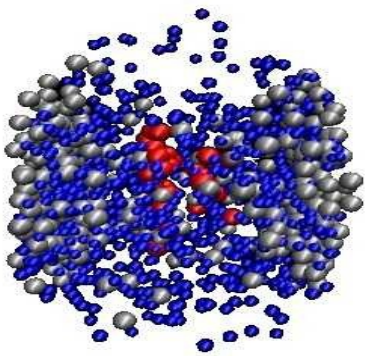
Institut für Theoretische Physik

HIC for FAIR Helmholtz International Center

JUSTUS-LIEBIG-UNIVERSITÄT GIESSEN

Directed flow in heavy-ion collisions from PHSD transport approach



Alessia Palmese

Wolfgang Cassing

Dubna, 10.07.2015

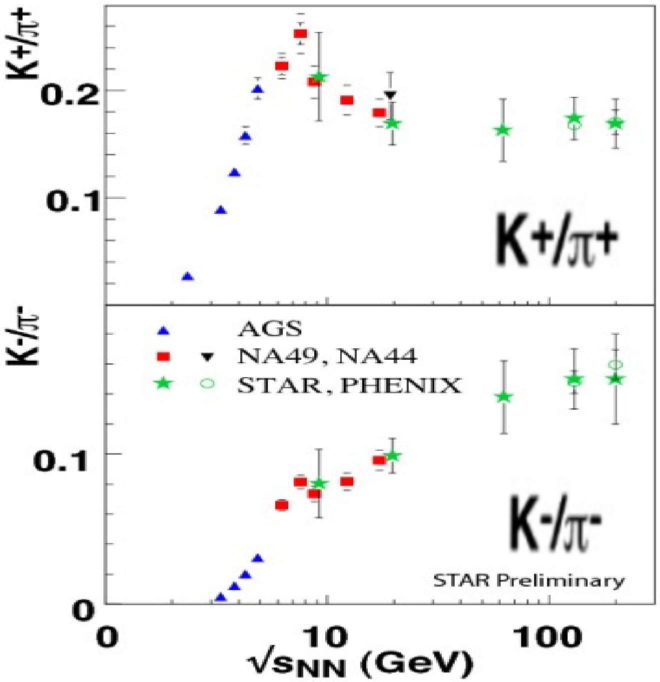
Strangeness in Quark Matter 2015

SQM DUBNA 2015

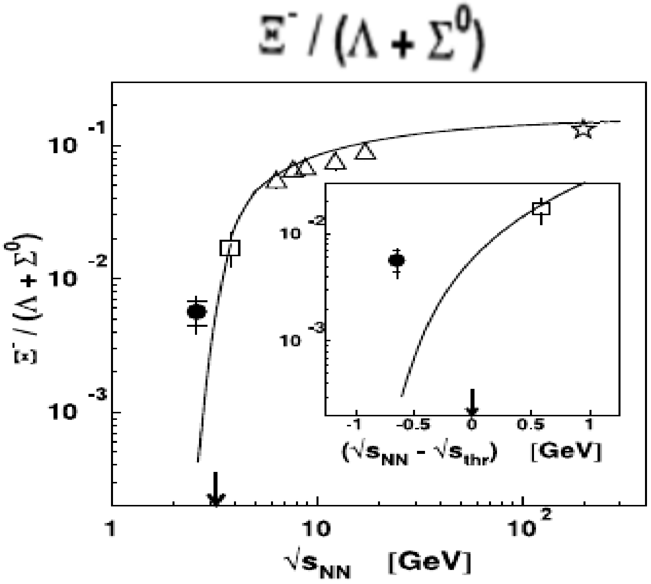
JINR JOINT INSTITUTE FOR NUCLEAR RESEARCH

Motivation

Strangeness observables are still not well understood!



M.M. Aggarwal et al. [STAR Collaboration], arXiv:1007.2613 (2010).

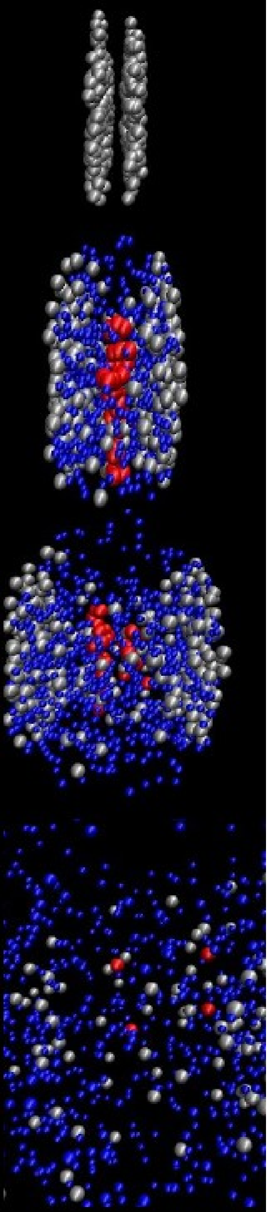


G.Agakishiev et al. [HADES Collaboration], Phys. Rev. Lett. 103, 132301 (2009).

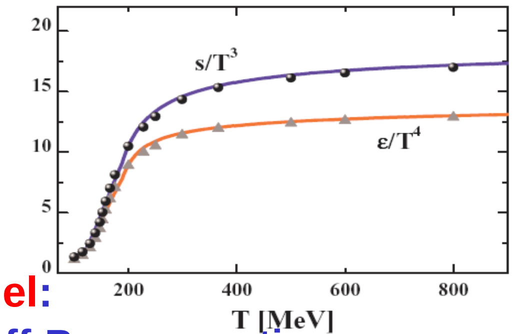
Low energy scan (NICA, FAIR, RHIC) is going to provide us new information!

Which is the role played by the Kaon potential?

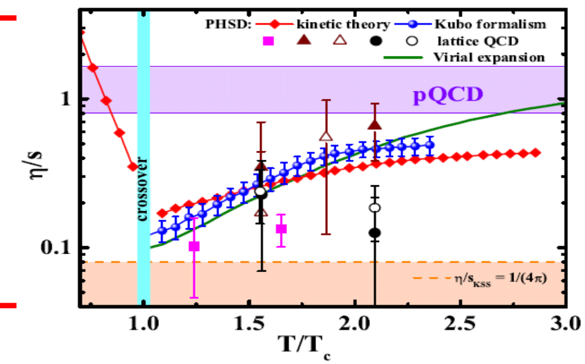
Parton Hadron String Dynamics



- Microscopic description of the heavy-ion collision with full time evolution:
  transition from hadrons to partons;
  lattice QCD EoS;
  dynamical hadronization and hadronic rescattering.



- Non-equilibrium relativistic off-shell transport model:
  based on the 1st order gradient expansion of Kadanoff-Baym equations



Applicable to describe strongly-interacting liquids as well as gases!

- Off-shell hadronic collision dynamics and mean fields

High energy inelastic hadron-hadron collisions are described by the FRITIOF string model (including PYTHIA) whereas low energy hadron-hadron collisions are modelled based on experimental cross sections.

- QGP phase by the Dynamical Quasi-Particle Model which matches lattice QCD.

Strongly interacting quasi-particles massive quarks and gluons (g, q, q_{bar}) with sizeable collisional widths in self-generated mean-field potential.

Talks by Elena Bratkovskaya and Pierre Moreau

W. Cassing, E. Bratkovskaya, PRC 78 (2008) 034919; NPA831 (2009) 215, W. Cassing, EPJ ST 168 (2009) 3
W. Cassing, E.L. Bratkovskaya, Nucl.Phys. A831 (2009) 215; E.L.Bratkovskaya et al, NPA856 (2011) 162

Directed Flow: <p$_x$> and v$_1$

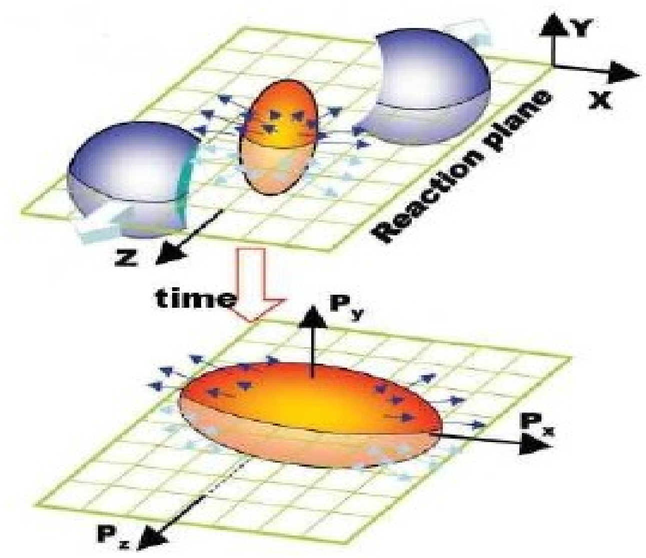
First type of collective motion to be identified among fragments of HIC.

It represents the deflection of the produced particles in the reaction plane.

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

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

$$v_1 = \left\langle \frac{p_x}{p_T} \right\rangle$$



Non central collisions!

Interaction between constituents

Pressure gradient

Spatial asymmetry

Asymmetry in momentum space

Collective transverse motion

Time Evolution of the Directed Flow

Protons:

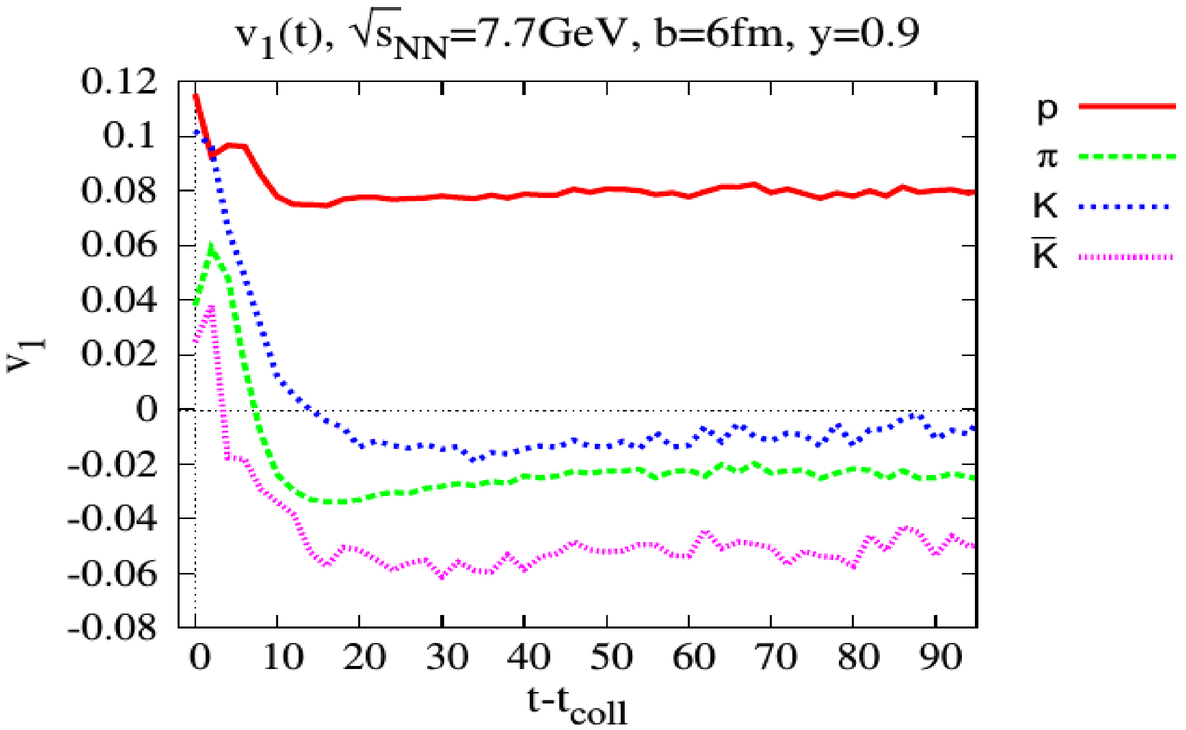
Normal flow

is established in the **early stage** of the collision and marginally distorted during the evolution.

Mesons:

Antiflow

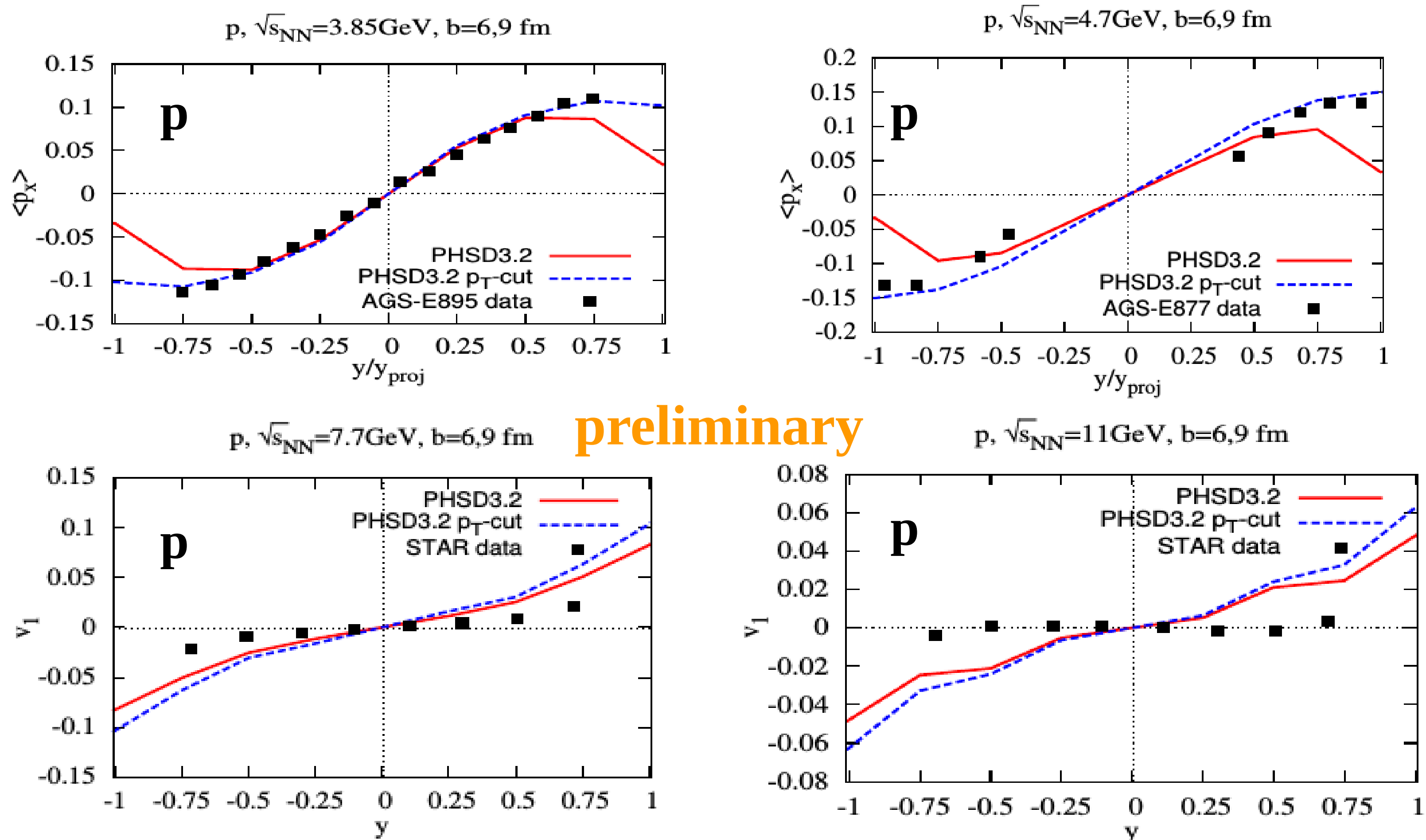
is sensitive to **rescattering** of hadrons.



N.B.: PHSD as transport approach includes intrinsically a screening of long range interactions.

Proton flow in Au+Au collisions

The **proton flow** has an **S-shape ,** but is approximately **linear at midrapidity**.
The $\mathbf{P_T}$ **cut** deflects the tails of the flow.

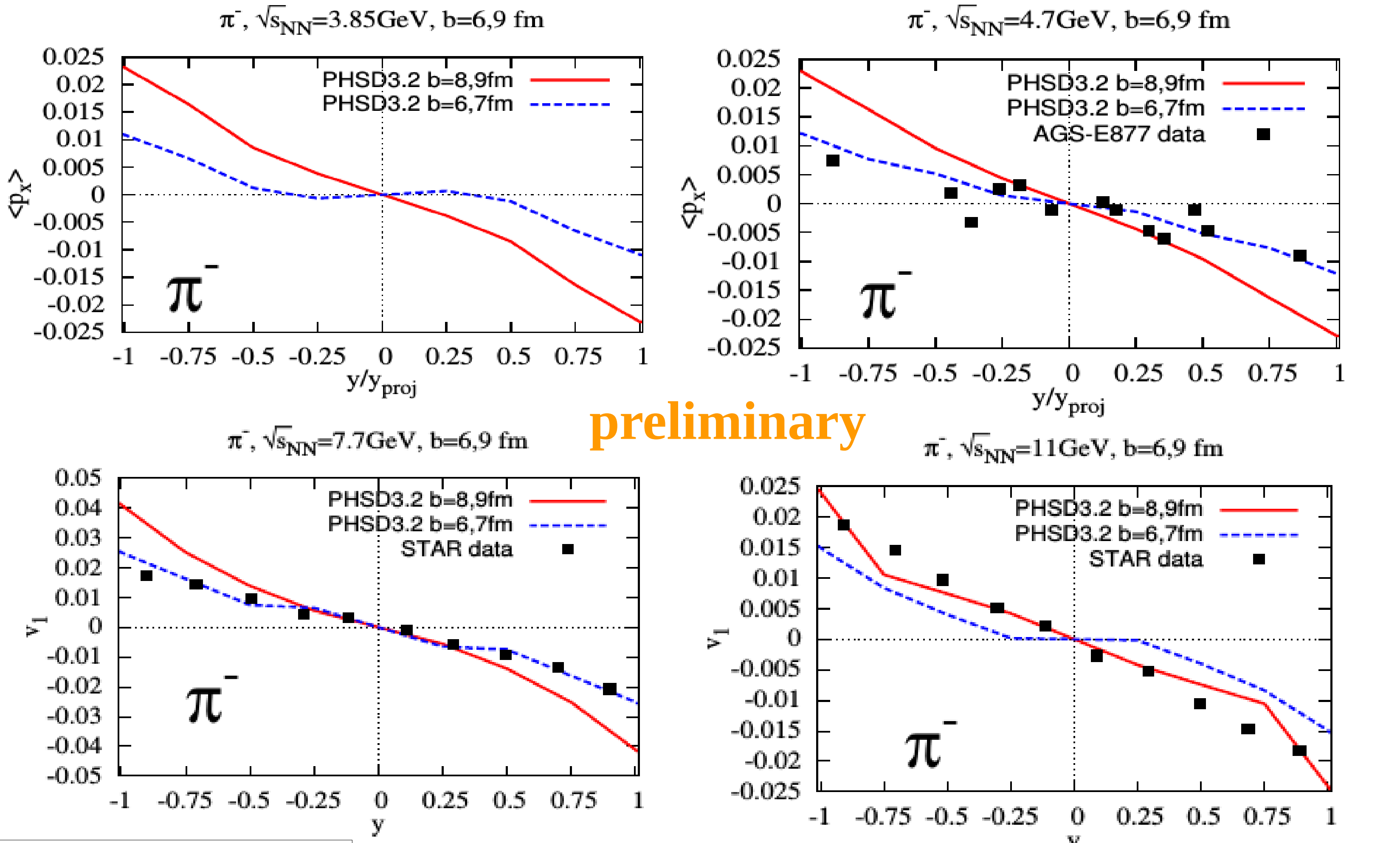


AGS data: P_y >0.3GeV
STAR data: 0.4GeV< P_T <2GeV

Data E895: H. Liu et al. (E895 Collab.), Phys. Rev. Lett. 84, 5488 (2000).
Data E877: J. Barrette et al. (E877 Collab.), Phys. Rev. C 55, 1420 (1997); 56, 3254 (1997).
Data STAR: L. Adamczyk et al. (STAR Collab.), Phys. Rev. Lett. 112, 162301 (2014).

Pion antiflow in Au+Au collisions

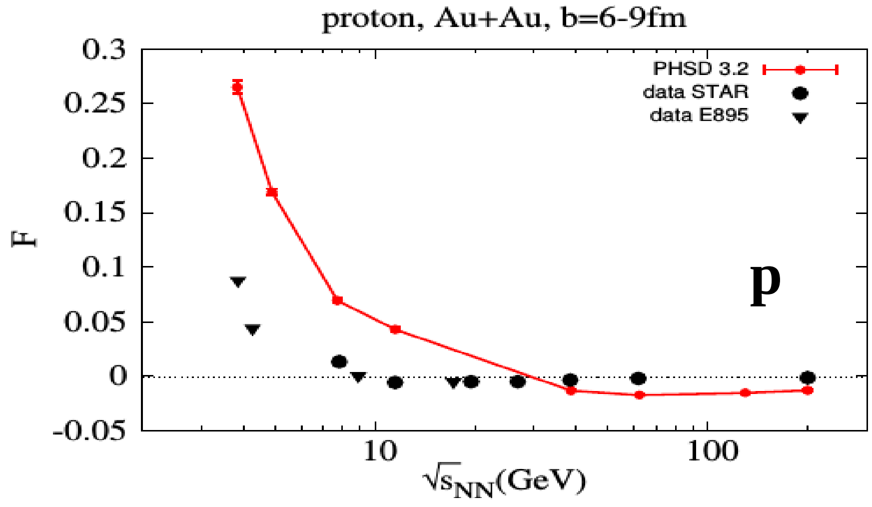
The **antiflow of pions** presents a **flattening** at midrapidity.
This flattening disappears with increasing **impact parameter**.



STAR data: P_T >0.2GeV, P<1.6GeV
midcentral centrality class: 10-40%

Data E877: J. Barrette et al. (E877 Collab.), Phys. Rev. C 55, 1420 (1997); 56, 3254 (1997).
Data STAR: L. Adamczyk et al. (STAR Collab.), Phys. Rev. Lett. 112, 162301 (2014).

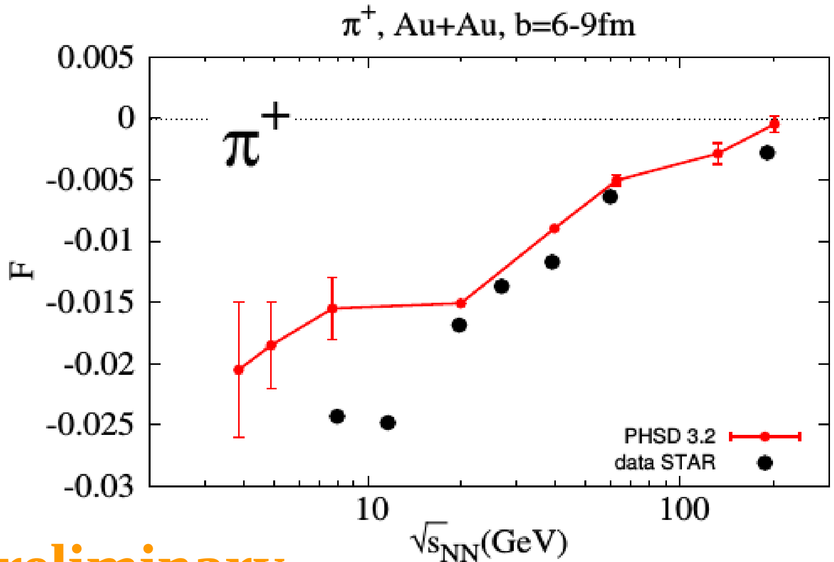
Directed Flow: Slope F

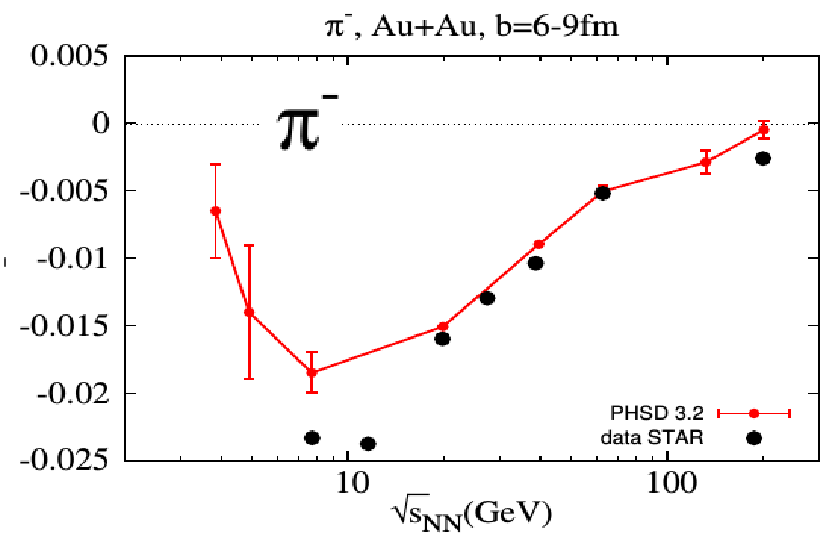


Fitting procedure:

$\mathbf{v_1(Y)=F\,Y}$ at midrapidity

and $\mathbf{v_1(Y)=F\,Y + C\,Y^3}$ for $|Y|<1$.





preliminary

Kaon Potentials

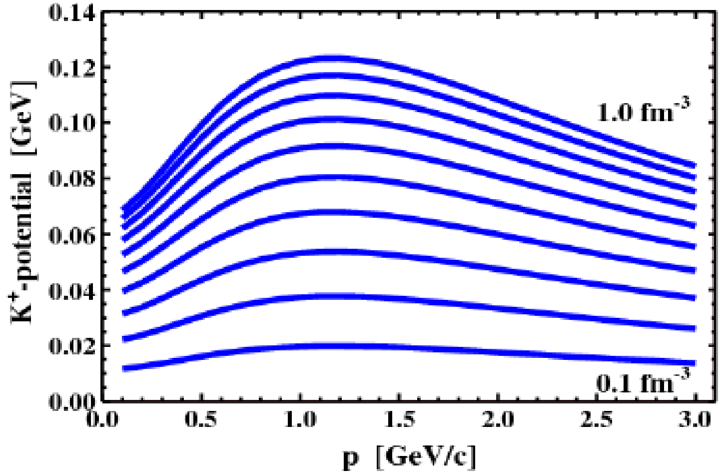
G-Matrix theory

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

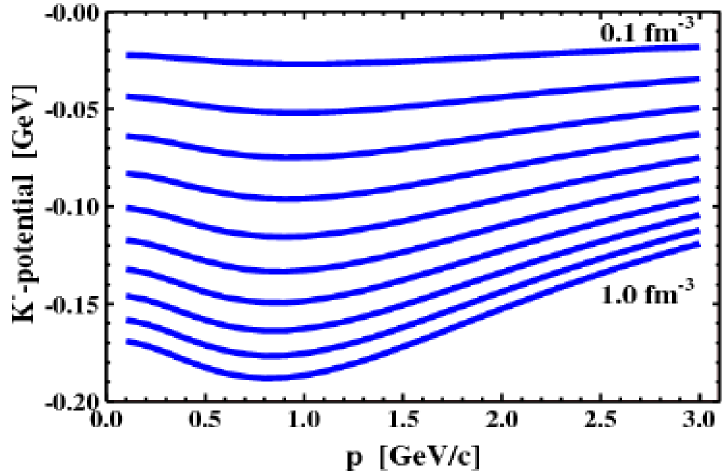
Dispersion relation $$\omega_K^2(\vec{p},\rho) = \pm\frac{3}{4}\frac{\omega}{f_K^2}\rho_N + p^2 + m_K^2 - \frac{\Sigma_{KN}}{f_K^2}\rho_s$$

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

K Repulsive

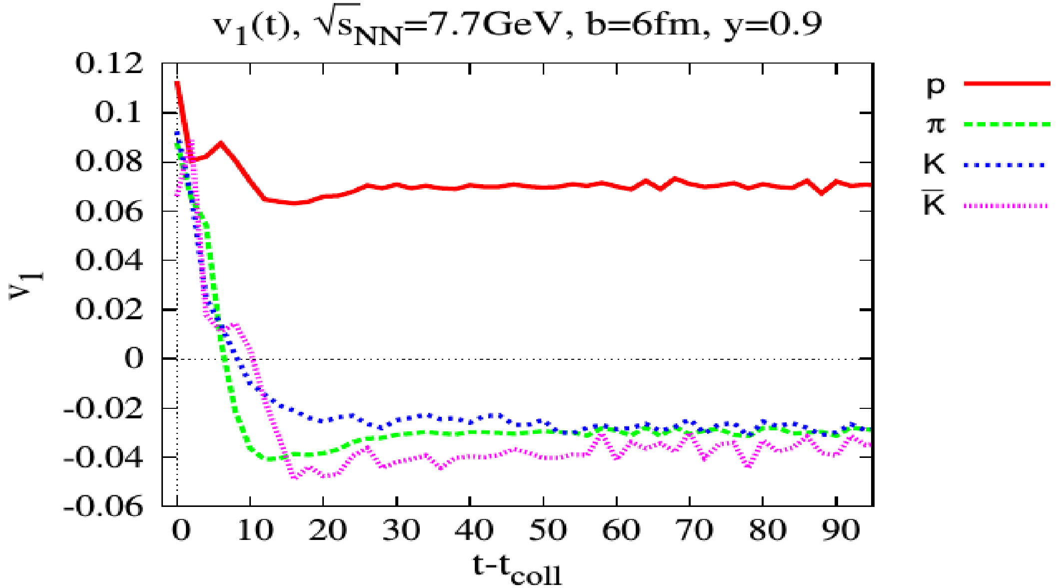


$\overline{\text{K}}$ attractive



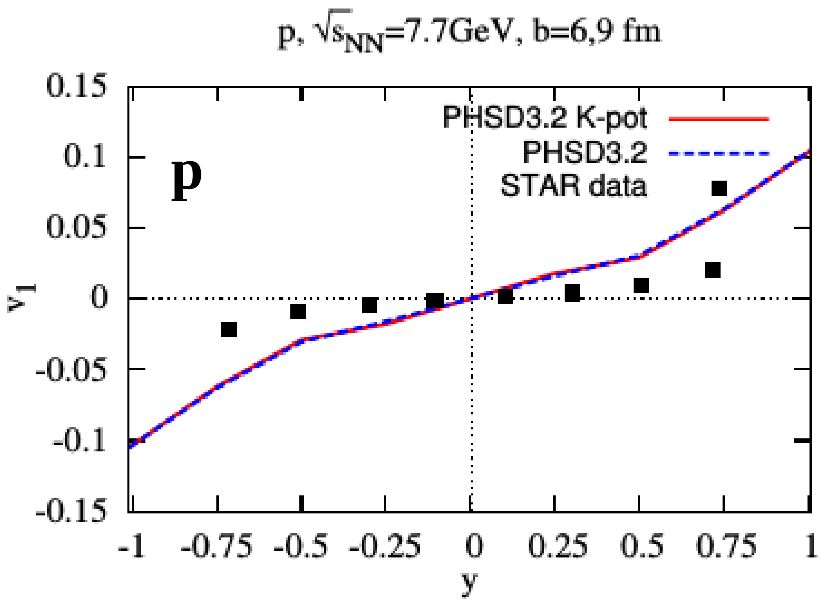
Potentials are density- and momentum-dependent.
PHSD explores these potentials in collisions up to $3\rho_0$.

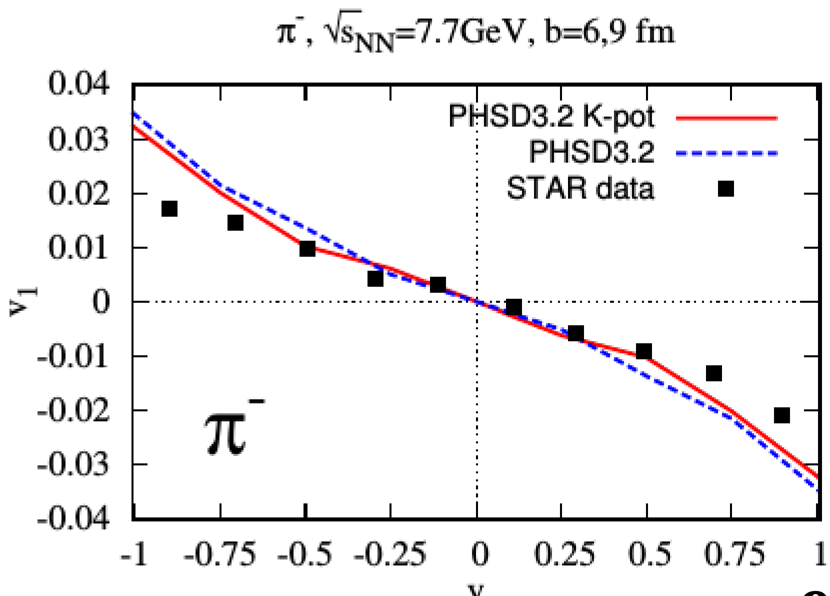
Directed flow with Kaon Potential



The time evolution of the flow does not change with the inclusion of the potentials.

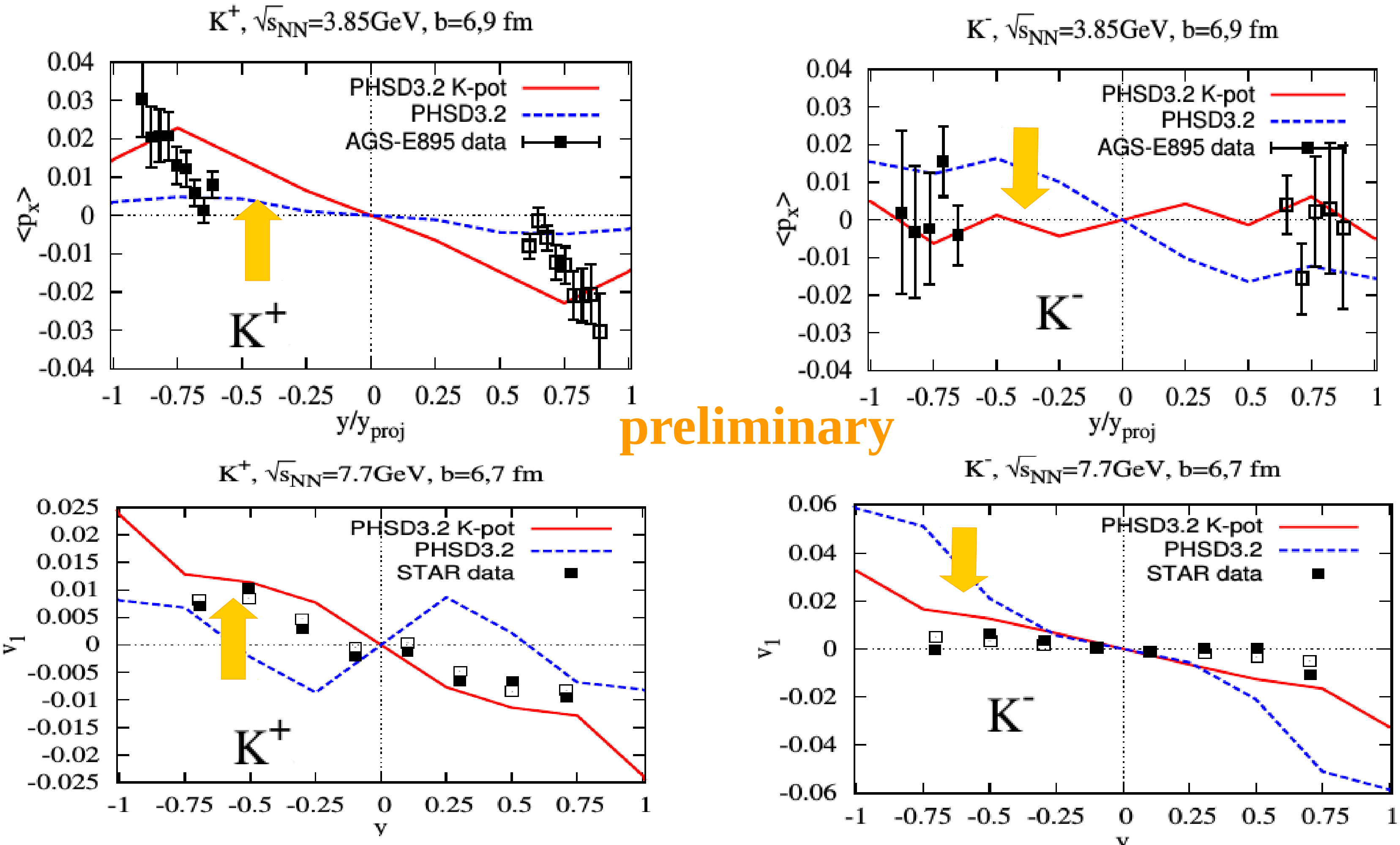
The **non-strange particles flow** is not deflected introducing the Kaon potential.





Kaon antiflow in Au+Au collisions

The **antiflow of Kaons** is sensitive to the potential!

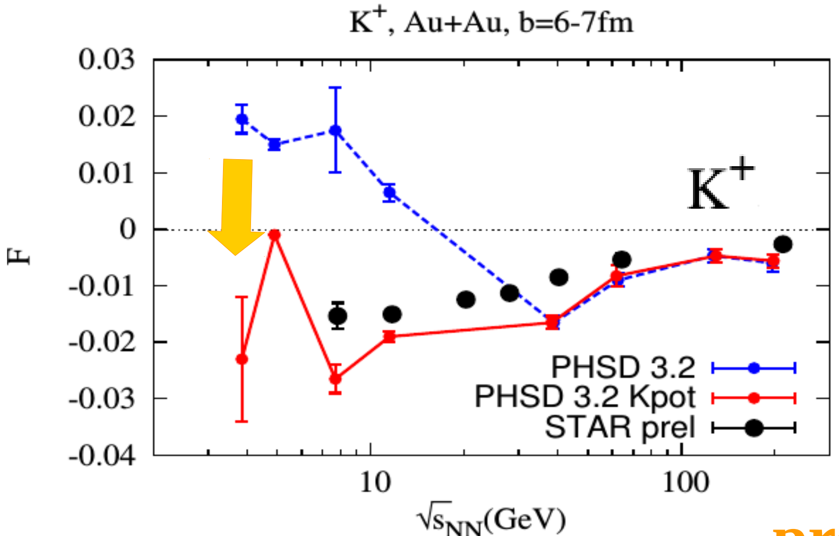


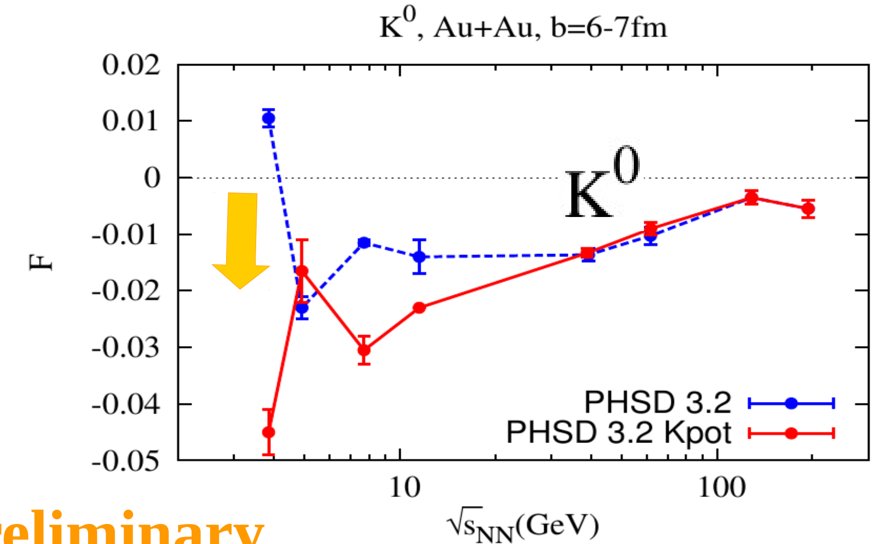
AGS data: P_T <0.3GeV
STAR data: P_T >0.2GeV, P<1.6GeV

Data E895: C. Pinkenburg et al. (E895 Collab.), arXiv: nucl-ex/0104025(2001).
Data STAR: Y. Pandit et al. (STAR Collab.), arXiv:1505.03933 (2015).

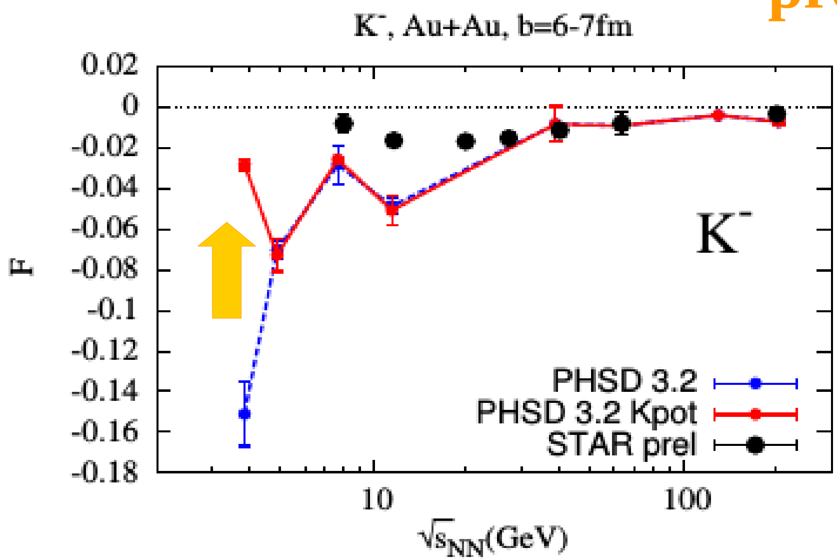
Kaon Directed Flow slope F

Fitting procedure: $\mathbf{v_1(Y)=F\,Y}$ at midrapidity and $\mathbf{v_1(Y)=F\,Y + C\,Y^3}$ for $|Y|<1$.





preliminary



Kaon potential → **Change of the sign of the flow**

AntiKaon potential → **Flatter Antiflow**

With increasing energy the flow vanishes and there is no more relevant role of the potentials.

Summary

- Directed Flow is established at the **early stage** of the collisions but the mesons flows are sensitive to **rescattering** of hadrons.
- Directed Flow is sensitive to **P_T cuts** and value of the **impact parameter**.
- **Directed Flow is a probe to study the Kaon Potentials in the medium!**

We look forward for low energy-scan!

Thanks for your attention!

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Vadym Voronyuk
Laura Tolos
Angel Ramos

Back up slides

Directed Flow: $\langle p_x \rangle$ and v1

Spatial asymmetry and asymmetry in momentum space

v_1: directed flow

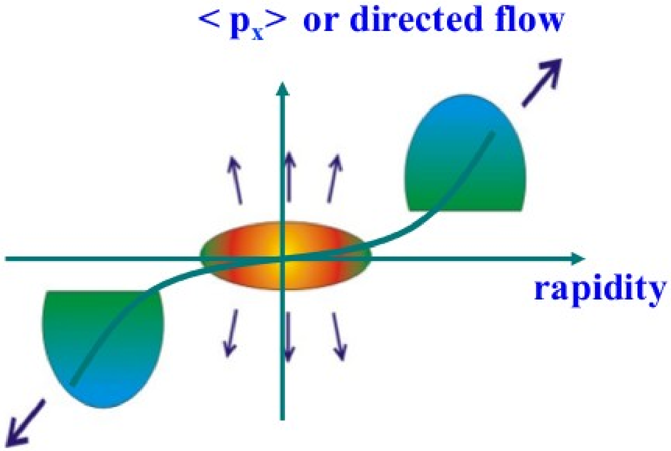
v_2: elliptic flow

v_3: triangular flow.....

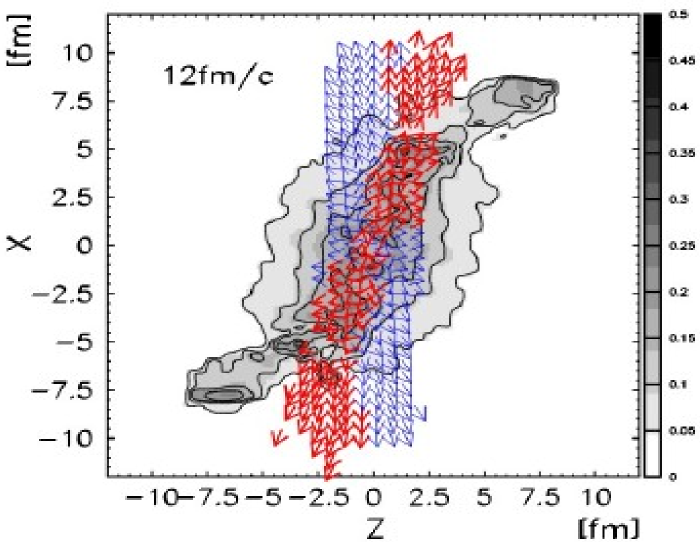
$$\frac{dN}{d\varphi} \propto \left(1 + 2\sum_{n=1}^{+\infty} v_n \cos\left[n(\varphi - \psi_n)\right]\right)$$

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

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



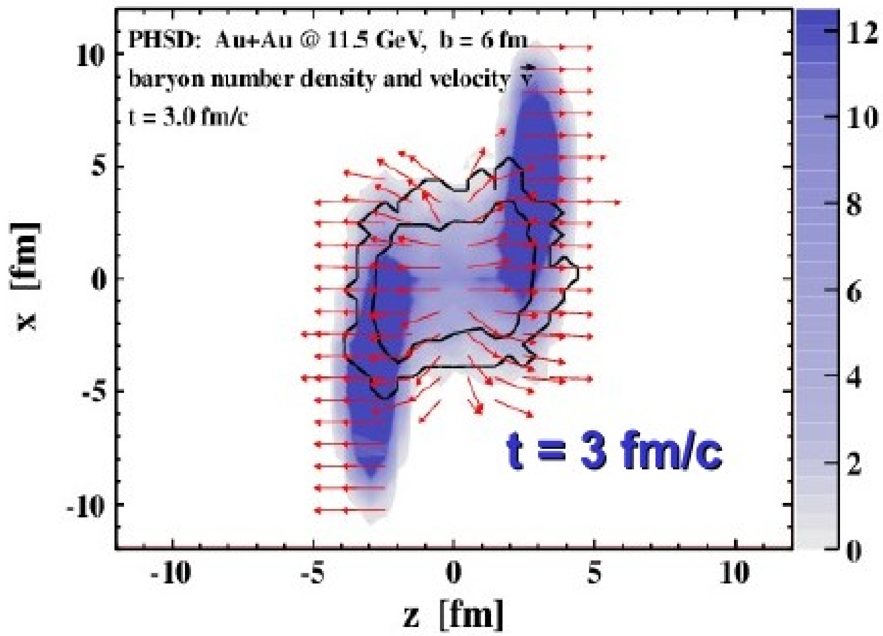
Collective transverse motion: $\langle \mathbf{p}_x \rangle$ and $\mathbf{v}_1$

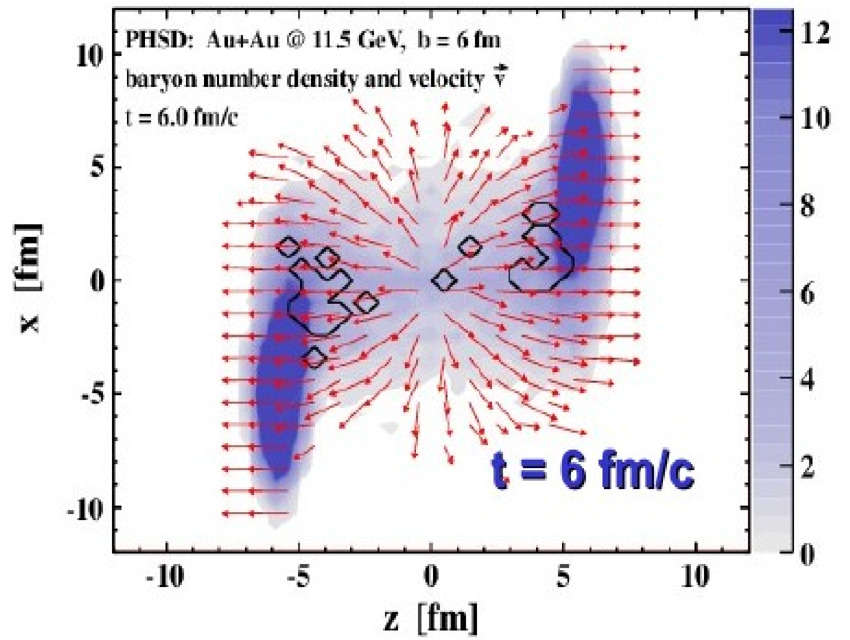


$d\langle p_x \rangle/dY$, $dV_1/dY > 0$ "normal flow"

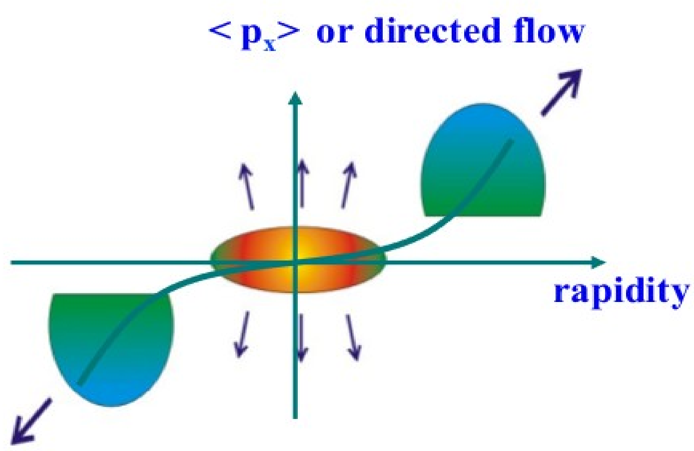
$d\langle p_x \rangle/dY$, $dV_1/dY < 0$ "antiflow"

Snapshot of the reaction plane





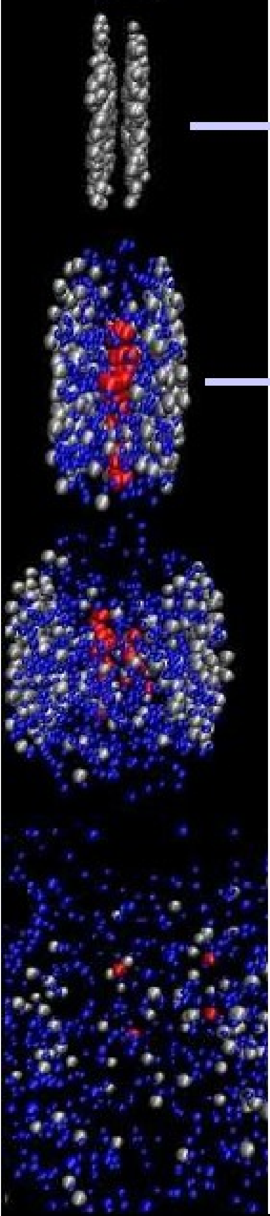
V. Konchakovski, W. Cassing, Yu. Ivanov, V. Toneev, PRC90 (2014) 014903.



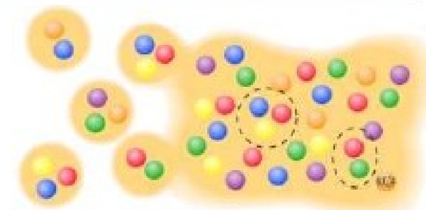
$d<p_x>/dY$, $dV_1/dY > 0$ "normal flow"

$d<p_x>/dY$, $dV_1/dY < 0$ "antiflow"

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**

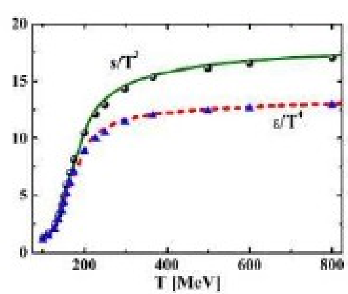
QGP phase:
$\varepsilon > \varepsilon_{critical}$

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

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

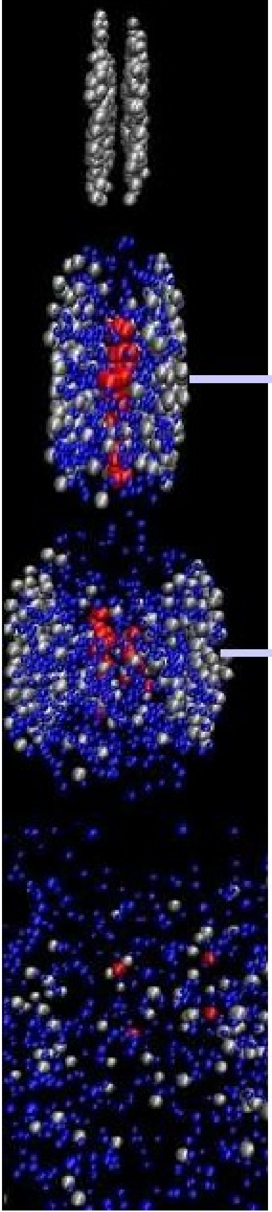
\+ **mean-field potential** U_q at given ε – local energy density

(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

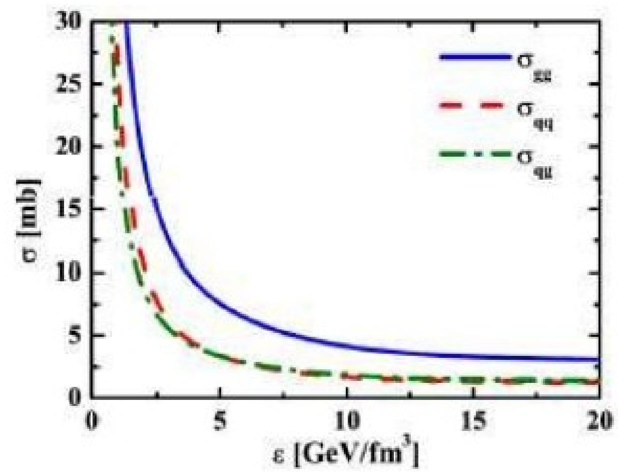
- ❑ in **self-generated mean-field potential** for quarks and gluons U_q, U_g from the DQPM
- ❑ **EoS of partonic phase: ‚crossover‘ from lattice QCD** (fitted by DQPM)
- ❑ **(quasi-) elastic and inelastic** parton-parton interactions:
using the effective cross sections from the DQPM

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

$$q+q \rightarrow q+q \qquad g+q \rightarrow g+q$$

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

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

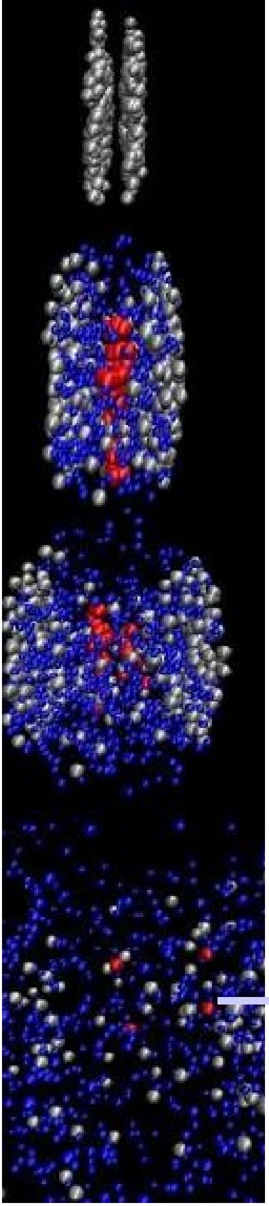


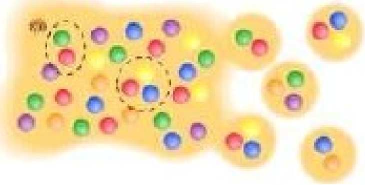
- **inelastic collisions:**
(Breight-Wigner cross sections)

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

$$\left. \begin{array}{l} q+\bar{q} \rightarrow g+g \\ g \rightarrow g+g \end{array} \right\}$$ 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)**

$$g \to q+\bar{q}, \qquad q+\bar{q} \leftrightarrow meson \ ('string')$$
$$q+q+q \leftrightarrow baryon \ ('string')$$

- **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

Boltzmann equation -> off-shell transport

$$\left(\frac{\partial}{\partial t} + \vec{v}_1\cdot\nabla_{\vec{r}} + \frac{\vec{K}}{m}\cdot\nabla_{\vec{v}_1}\right) f_1 = \int d\Omega \int d\vec{v}_2\, \sigma(\Omega)\,|\vec{v}_1 - \vec{v}_2| \left(f_1' f_2' - f_1 f_2\right)$$

GENERALIZATION

(First order gradient expansion of the Wigner-transformed Kadanoff-Baym equations)

drift term **Vlasov term** **backflow term** **collision term = ‚loss' term - ‚gain' term**

$$\diamond\{P^2 - M_0^2 - Re\Sigma^{ret}_{XP}\}\{S^<_{XP}\} - \diamond\{\Sigma^<_{XP}\}\{ReS^{ret}_{XP}\} = \frac{i}{2}\left[\Sigma^>_{XP} S^<_{XP} - \Sigma^<_{XP} S^>_{XP}\right]$$

Backflow term incorporates the off-shell behavior in the particle propagation

! vanishes in the quasiparticle limit $A_{XP} = 2\pi\,\delta(p^2-M^2)$

Propagation of the Green's function $iS^<_{XP}=A_{XP} f_{XP}$, which carries information not only on the number of particles, but also on their properties, interactions and correlations

$$A_{XP} = \frac{\Gamma_{XP}}{(P^2 - M_0^2 - Re\Sigma^{ret}_{XP})^2 + \Gamma^2_{XP}/4}$$

$$\diamond\{F_1\}\{F_2\} := \frac{1}{2}\left(\frac{\partial F_1}{\partial X_\mu}\frac{\partial F_2}{\partial P^\mu} - \frac{\partial F_1}{\partial P_\mu}\frac{\partial F_2}{\partial X^\mu}\right)$$

Γ_{XP} – width of spectral function = reaction rate of a particle (at phase-space position XP)

W. Cassing , S. Juchem, NPA 665 (2000) 377; 672 (2000) 417; 677 (2000) 4451