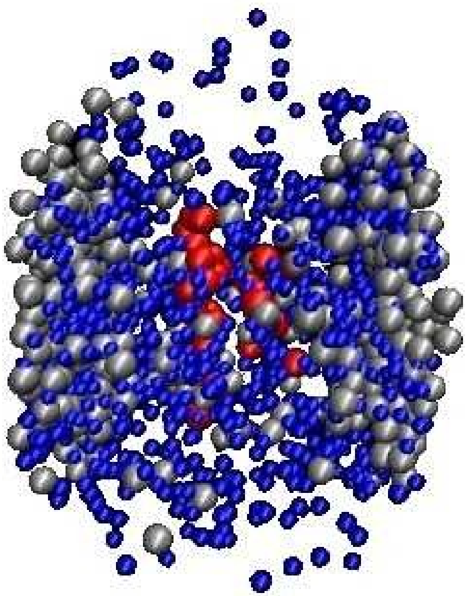
Institut für Theoretische Physik

JUSTUS-LIEBIG-UNIVERSITÄT GIESSEN

Directed flow in heavy-ion collisions from PHSD transport approach



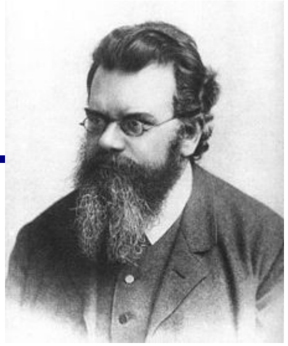
Volodya Konchakovski
Wolfgang Cassing
Alessia Palmese
Vyacheslav Toneev
Vadim Voronyuk

Lunch Club Seminar
ITP, Giessen
29 Oktober 2014

The menue

- Generalized transport theory
- Parton properties at temperatures $T > T_c$
- The PHSD approach
- Directed flow of hadrons in the BES program
- Directed flow at FAIR energies
- Directed flow in asymmetric reactions at RHIC
- Summary

Semi-classical BUU equation


Ludwig Boltzmann

Boltzmann -Uehling-Uhlenbeck equation (non-relativistic formulation)

- propagation of particles in the **self-generated Hartree-Fock mean-field potential** *U(r,t)* with an on-shell **collision term:**

$$\frac{\partial}{\partial t} f(\vec{r},\vec{p},t) + \frac{\vec{p}}{m}\vec{\nabla}_{\vec{r}} f(\vec{r},\vec{p},t) - \vec{\nabla}_{\vec{r}} U(\vec{r},t)\vec{\nabla}_{\vec{p}} f(\vec{r},\vec{p},t) = \left(\frac{\partial f}{\partial t}\right)_{coll}$$

collision term: elastic and inelastic reactions

$f(\vec{r},\vec{p},t)$ is the **single-particle phase-space distribution function**

- probability to find the particle at position *r* with momentum *p* at time *t*

Self-generated **Hartree-Fock mean-field potential:**

$$U(\vec{r},t) = \frac{1}{(2\pi\hbar)^3}\sum_{\beta_{occ}}\int d^3r'\, d^3p\, V(\vec{r}-\vec{r}\,',t)\, f(\vec{r}\,',\vec{p},t) + (\textit{Fock term})$$

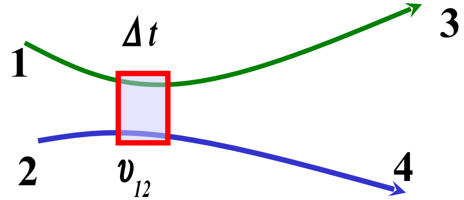
Collision term for 1+2→3+4 (for fermions) :

$$I_{coll} = \frac{4}{(2\pi)^3}\int d^3p_2\, d^3p_3 \int d\Omega\, |v_{12}|\, \delta^3(\vec{p}_1+\vec{p}_2-\vec{p}_3-\vec{p}_4)\cdot \frac{d\sigma}{d\Omega}(1+2\rightarrow 3+4)\cdot P$$

Probability including **Pauli blocking of fermions:**

$$P = f_3 f_4 (1-f_1)(1-f_2) \; - \; f_1 f_2 (1-f_3)(1-f_4)$$

Gain term: 3+4→1+2 (underlining the first term) — **Loss term: 1+2→3+4** (underlining the second term)



Dynamical description of strongly interacting systems

Semi-classical BUU ➔ solution for weakly interacting systems of particles

How to describe **strongly interacting systems?!**

Quantum field theory ➔
Kadanoff-Baym dynamics for resummed(!) single-particle Green functions $S^<$

$$\hat{S}_{0x}^{-1}\, S_{xy}^{<} = \Sigma_{xz}^{ret} \odot S_{zy}^{<} + \Sigma_{xz}^{<} \odot S_{zy}^{adv}$$

(1962)

Green functions $S^<$/self-energies Σ:

Integration over the intermediate space-time

$$iS_{xy}^{<} = \eta \langle \{ \Phi^{+}(y) \Phi(x) \} \rangle$$

$$iS_{xy}^{>} = \langle \{ \Phi(y) \Phi^{+}(x) \} \rangle$$

$$iS_{xy}^{c} = \langle T^{c} \{ \Phi(x) \Phi^{+}(y) \} \rangle \quad - causal$$

$$iS_{xy}^{a} = \langle T^{a} \{ \Phi(x) \Phi^{+}(y) \} \rangle \quad - anticausal$$

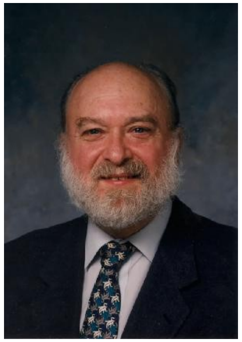
$$S_{xy}^{ret} = S_{xy}^{c} - S_{xy}^{<} = S_{xy}^{>} - S_{xy}^{a} \quad - retarded$$

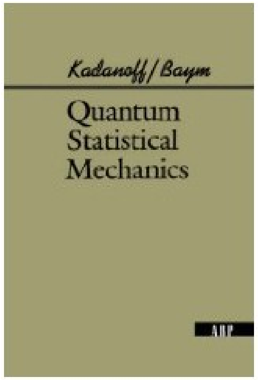
$$S_{xy}^{adv} = S_{xy}^{c} - S_{xy}^{>} = S_{xy}^{<} - S_{xy}^{a} \quad - advanced$$

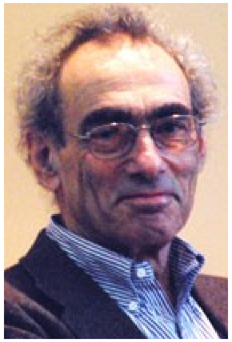
$$\hat{S}_{0x}^{-1} \equiv -(\partial_x^{\mu} \partial_{\mu}^{x} + M_0^2)$$

$$\eta = \pm 1 (bosons / fermions)$$

$$T^{a}(T^{c}) - (anti-)time-ordering\ operator$$


Leo Kadanoff




Gordon Baym

From Kadanoff-Baym equations to generalized transport equations

After the first order gradient expansion of the Wigner transformed Kadanoff-Baym equations and separation into the real and imaginary parts one gets:

Generalized transport equations (GTE):

drift term — Vlasov — backflow term — collision term = 'loss' term - 'gain' term

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

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

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

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

Spectral function:

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

$\Gamma_{XP} = -Im\,\Sigma^{ret}_{XP}$ – width of spectral function

= reaction rate of particle (at phase-space position XP)

4-dimensional generalization of the Poisson-bracket:

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

W. Cassing , S. Juchem, NPA 665 (2000) 377; 672 (2000) 417; 677 (2000) 445

Extended testparticle off-shell equations of motion

W. Cassing , S. Juchem, NPA 665 (2000) 377; 672 (2000) 417; 677 (2000) 445

Employ testparticle Ansatz for the real valued quantity $i\,S^<_{XP}$ -

$$F_{XP} = A_{XP} N_{XP} = i\,S^<_{XP} \sim \sum_{i=1}^{N} \delta^{(3)}(\vec{X} - \vec{X}_i(t))\ \delta^{(3)}(\vec{P} - \vec{P}_i(t))\ \delta(P_0 - \epsilon_i(t))$$

insert in generalized transport equations and determine equations of motion !

General testparticle off-shell equations of motion for the time-like particles:

$$\frac{d\vec{X}_i}{dt} = \frac{1}{1-C_{(i)}} \frac{1}{2\epsilon_i} \left[2\,\vec{P}_i + \vec{\nabla}_{P_i} Re\Sigma^{ret}_{(i)} + \frac{\epsilon_i^2 - \vec{P}_i^2 - M_0^2 - Re\Sigma^{ret}_{(i)}}{\Gamma_{(i)}} \vec{\nabla}_{P_i} \Gamma_{(i)} \right],$$

$$\frac{d\vec{P}_i}{dt} = -\frac{1}{1-C_{(i)}} \frac{1}{2\epsilon_i} \left[\vec{\nabla}_{X_i} Re\Sigma^{ret}_i + \frac{\epsilon_i^2 - \vec{P}_i^2 - M_0^2 - Re\Sigma^{ret}_{(i)}}{\Gamma_{(i)}} \vec{\nabla}_{X_i} \Gamma_{(i)} \right],$$

$$\frac{d\epsilon_i}{dt} = \frac{1}{1-C_{(i)}} \frac{1}{2\epsilon_i} \left[\frac{\partial Re\Sigma^{ret}_{(i)}}{\partial t} + \frac{\epsilon_i^2 - \vec{P}_i^2 - M_0^2 - Re\Sigma^{ret}_{(i)}}{\Gamma_{(i)}} \frac{\partial \Gamma_{(i)}}{\partial t} \right],$$

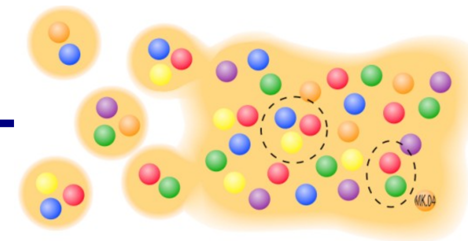
with $F_{(i)} \equiv F(t, \vec{X}_i(t), \vec{P}_i(t), \epsilon_i(t))$

$$C_{(i)} = \frac{1}{2\epsilon_i} \left[\frac{\partial}{\partial \epsilon_i} Re\Sigma^{ret}_{(i)} + \frac{\epsilon_i^2 - \vec{P}_i^2 - M_0^2 - Re\Sigma^{ret}_{(i)}}{\Gamma_{(i)}} \frac{\partial}{\partial \epsilon_i} \Gamma_{(i)} \right]$$

-> determined by complex retarded selfenergies !

DQPM

From hadrons to partons



In order to study the **phase transition** from hadronic to partonic matter – **Quark-Gluon-Plasma** – we **need a consistent non-equilibrium (transport) model with**

- explicit **parton-parton interactions** (i.e. between quarks and gluons) beyond strings!
- explicit **phase transition** from hadronic to partonic degrees of freedom
- **lQCD EoS** for partonic phase

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

Dynamical QuasiParticle Model (DQPM)

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

DQPM The Dynamical QuasiParticle Model

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

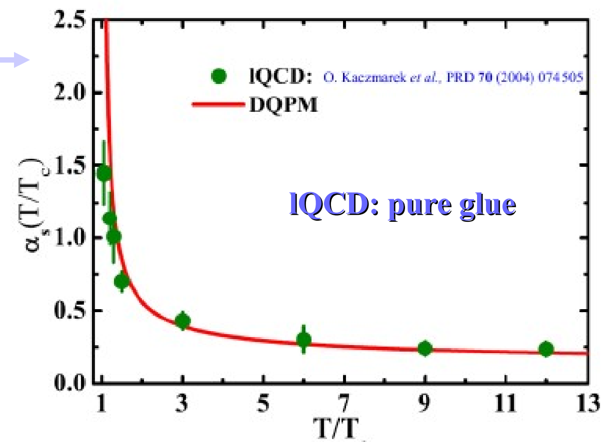
$$(i = q, \bar{q}, g) \qquad \rho_i(\omega, T) = \frac{4\omega\Gamma_i(T)}{\left(\omega^2 - \vec{p}^2 - M_i^2(T)\right)^2 + 4\omega^2\Gamma_i^2(T)}$$

- 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):

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



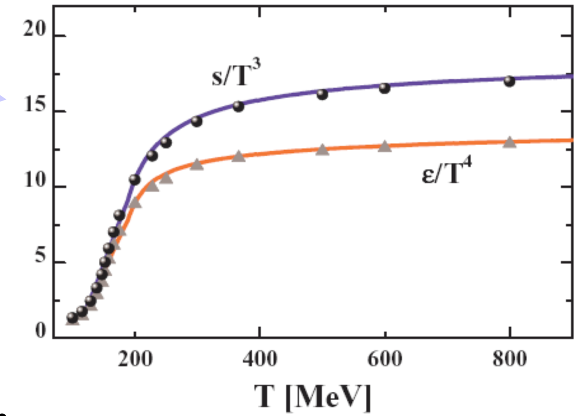
- fit to lattice (lQCD) results (e.g. entropy density) with 3 parameters: T_s/T_c=0.46; c=28.8; λ=2.42 (for pure glue N_f=0)

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

DQPM The Dynamical QuasiParticle Model

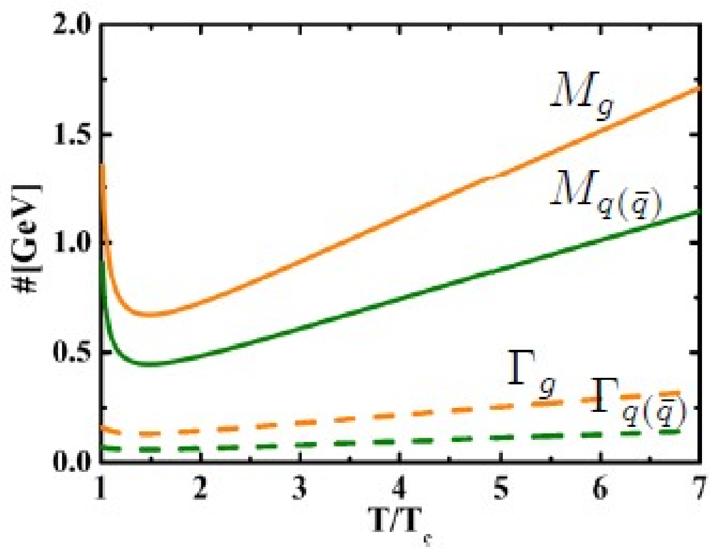
- fit to lattice (lQCD) results (e.g. entropy density)

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



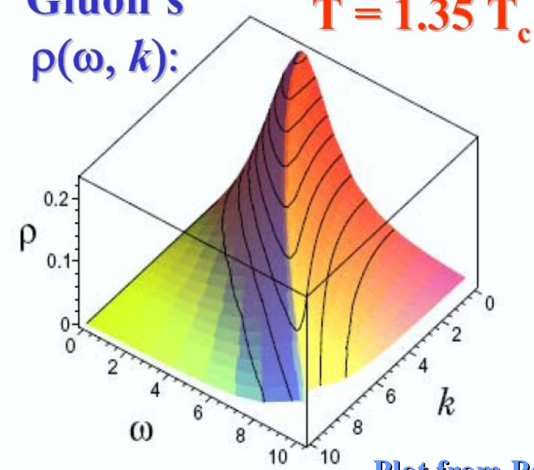
→ **Quasiparticle properties:**

- large width and mass for gluons and quarks



T_C=158 MeV
ε_C=0.5 GeV/fm^3

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

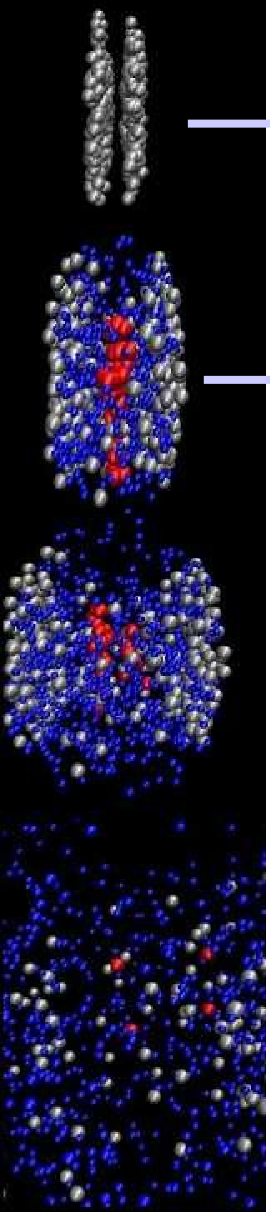


Plot from Peshier, PRD 70 (2004) 034016

- 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)

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

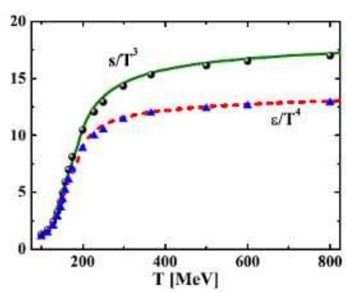
QGP phase: $\varepsilon > \varepsilon_{critical}$

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

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

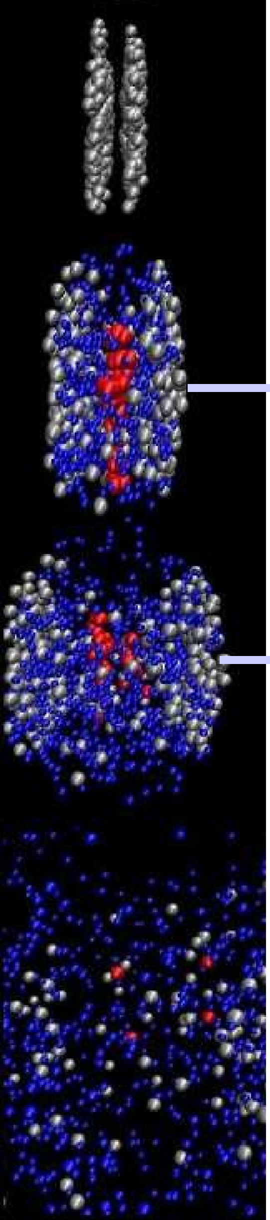
+ **mean-field potential** U_q at given ε – local energy density

(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.

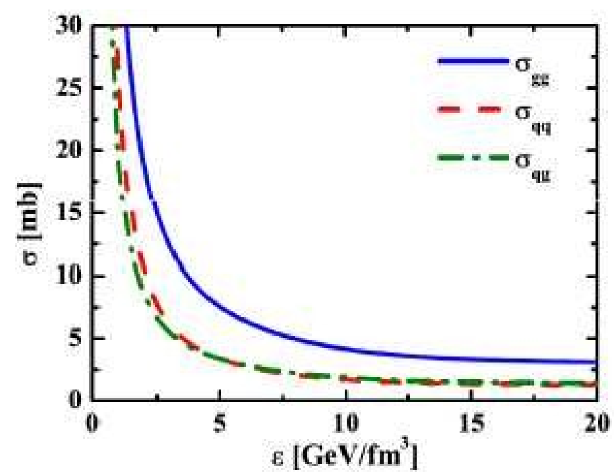
Parton Hadron String Dynamics II



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:**

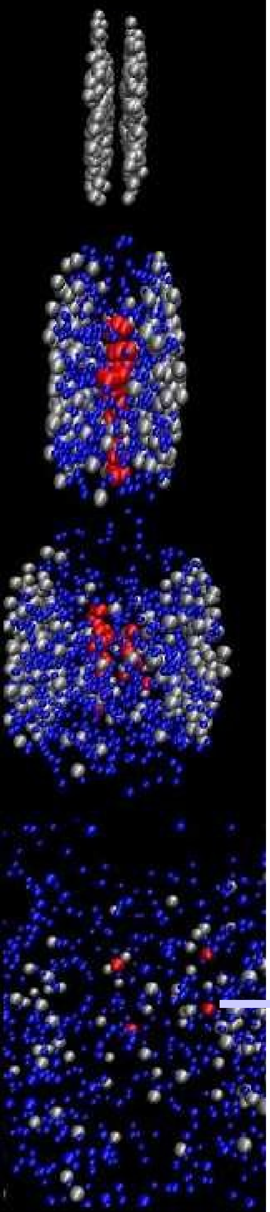
$$q+q \to q+q \qquad g+q \to g+q$$
$$q+\bar{q} \to q+\bar{q} \qquad g+\bar{q} \to g+\bar{q}$$
$$\bar{q}+\bar{q} \to \bar{q}+\bar{q} \qquad g+g \to g+g$$

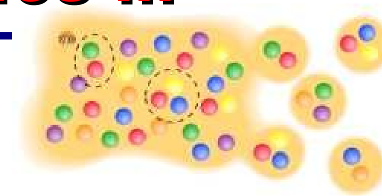
- **inelastic collisions:**
  (Breight-Wigner cross sections)

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

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

$$g \rightarrow q + \bar{q}, \quad q + \bar{q} \leftrightarrow meson \ ('string')$$

$$q + q + q \leftrightarrow baryon \ ('string')$$

- **Local covariant off-shell transition rate for q+qbar fusion**

➔ meson formation:

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

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

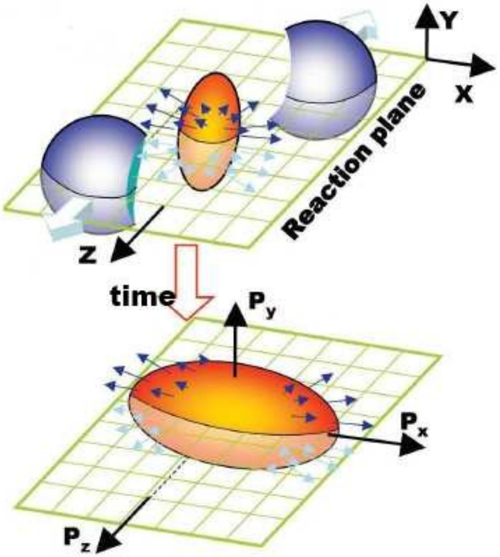
- **$N_j(x,p)$ is the phase-space density of parton j at space-time position x and 4-momentum p**
- **W_m is the phase-space distribution of the formed ‚pre-hadrons‘ (Gaussian in phase space)**
- **$|M_{qq}|^2$ is the effective quark-antiquark interaction from the DQPM**

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

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**



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

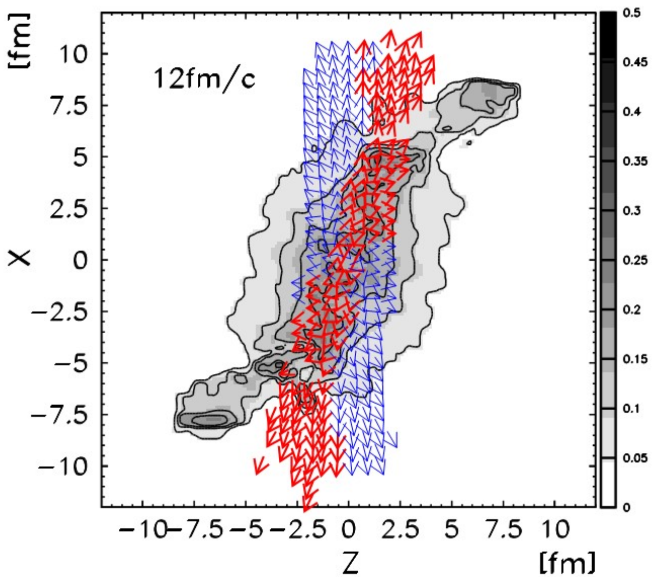
$$v_n = \langle \cos n(\varphi - \psi_n) \rangle, \quad n = 1,2,3..,$$

v_1: directed flow

v_2: elliptic flow

v_3: triangular flow…..

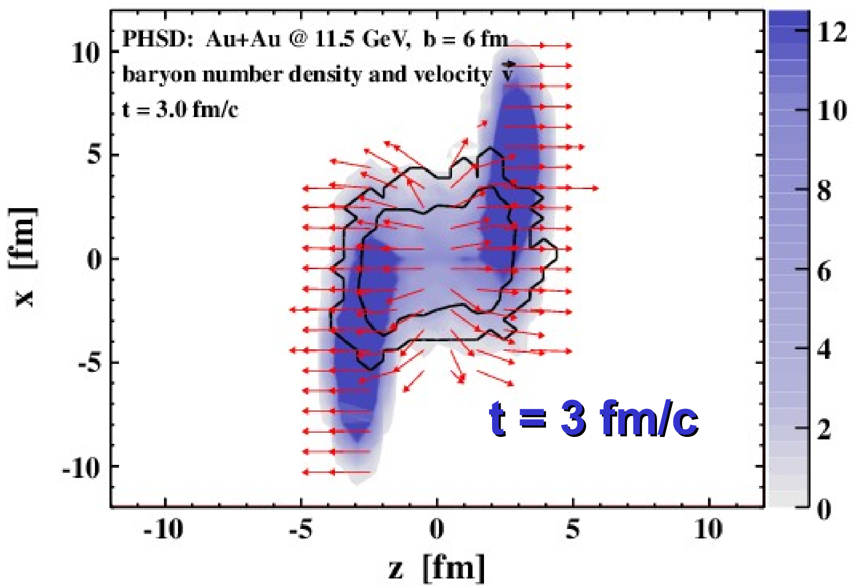
$$v_1 = \left\langle \frac{p_x}{p_T} \right\rangle, \quad v_2 = \left\langle \frac{p_x^2 - p_y^2}{p_x^2 + p_y^2} \right\rangle$$

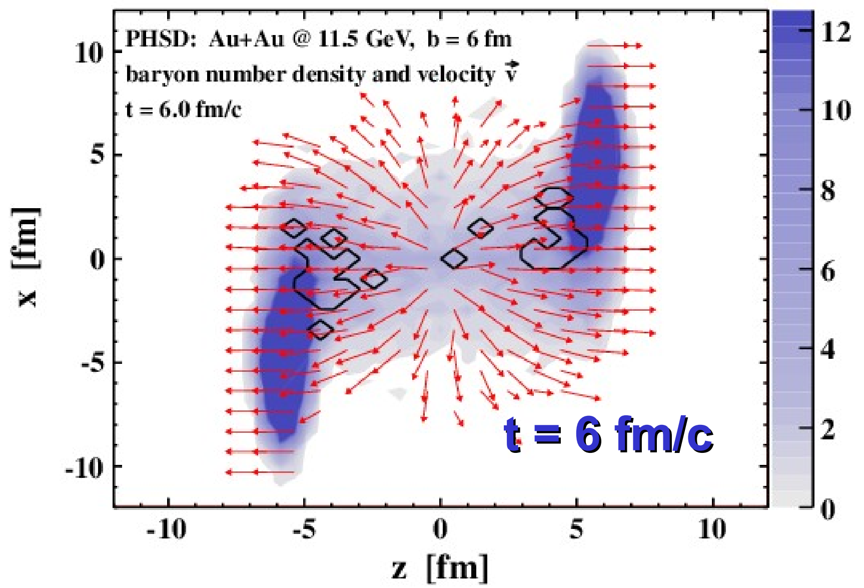


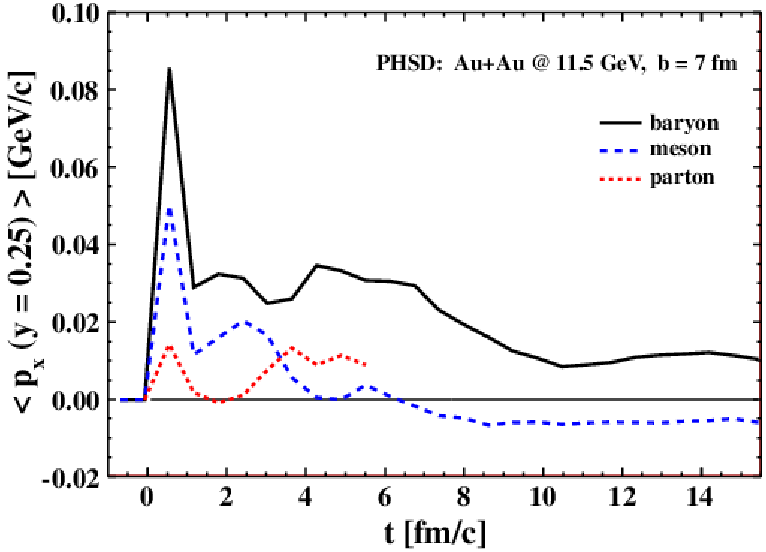
Directed flow $v_1 > 0$
"normal flow"

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

PHSD: snapshot of the reaction plane





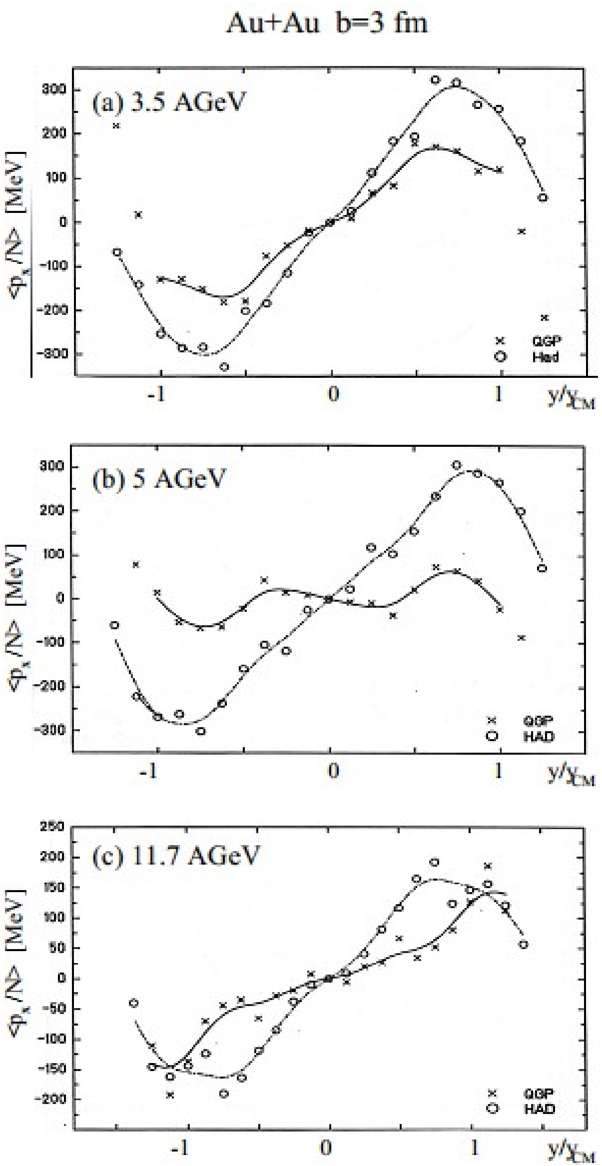


Color scale: baryon number density
Black levels: **QGP**- parton density 0.6 and 0.01 fm^{-3}
Red arrows: local velocity of baryon matter

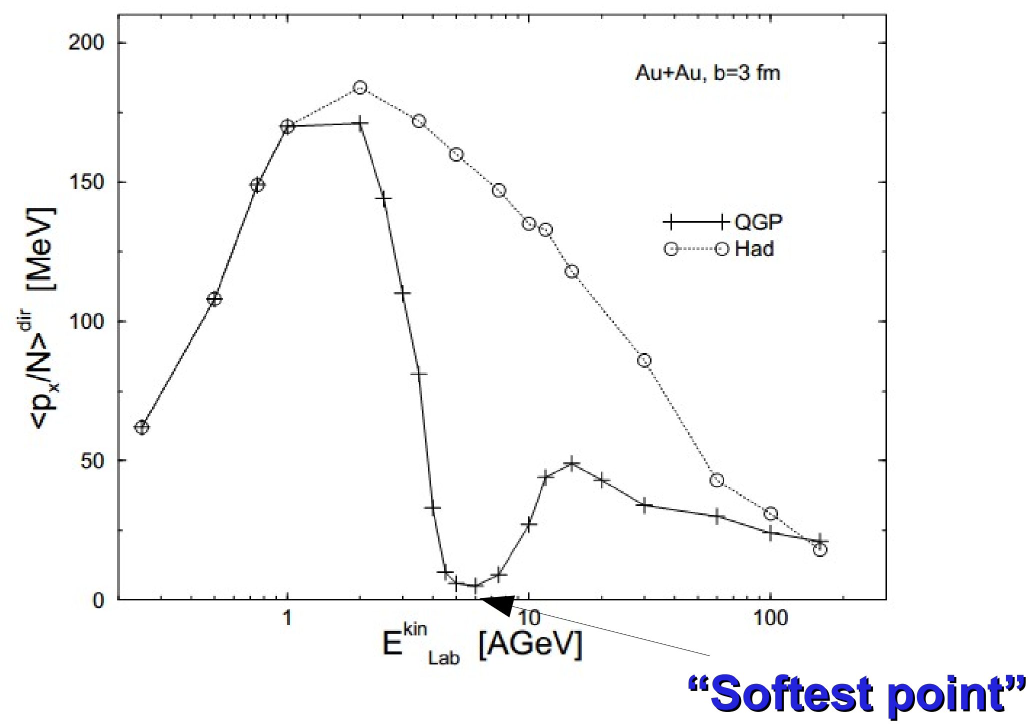
Baryons are reaching **positive** and **mesons – negative** value of v_1

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

Direct flow and Quark–Gluon Plasma



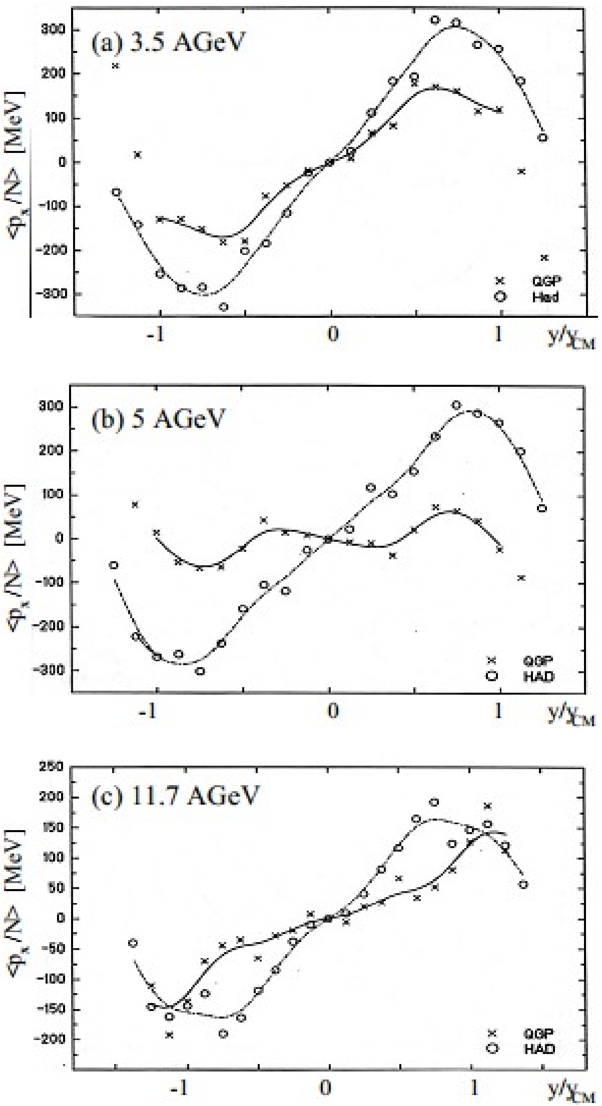
$$\langle p_x/N \rangle^{dir} = \frac{1}{N} \int_{-y_{CM}}^{y_{CM}} \mathrm{d}y \, \langle p_x/N \rangle(y) \, \frac{\mathrm{d}N}{\mathrm{d}y} \, \mathrm{sgn}(y)$$



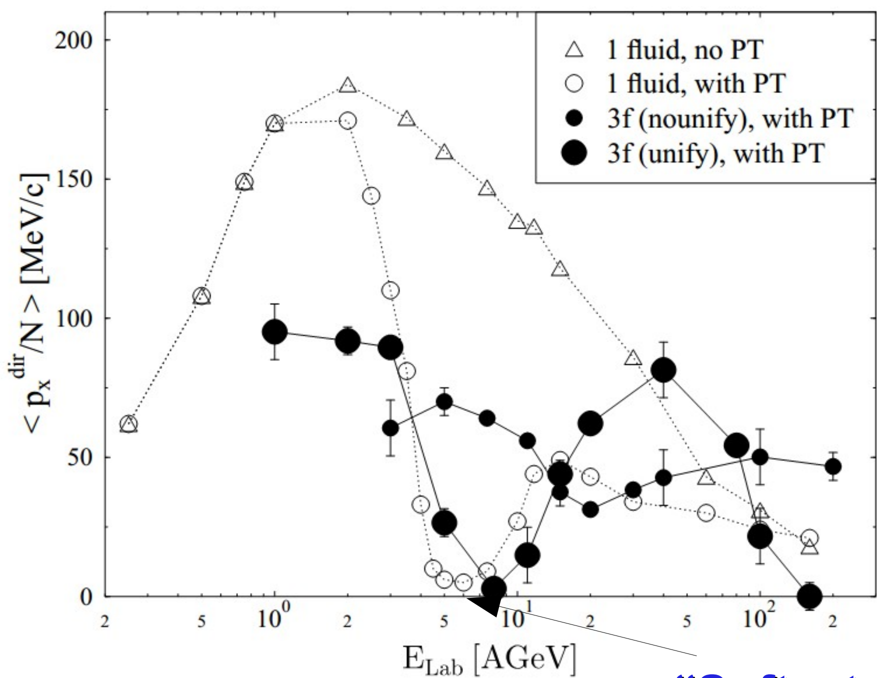
D.H. Rischke, Y. Pursun, J.A. Maruhn, H. Stoecker, W. Greiner, Heavy Ion Phys. 1, 309 (1995)

Direct flow and Quark–Gluon Plasma

Au+Au b=3 fm



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



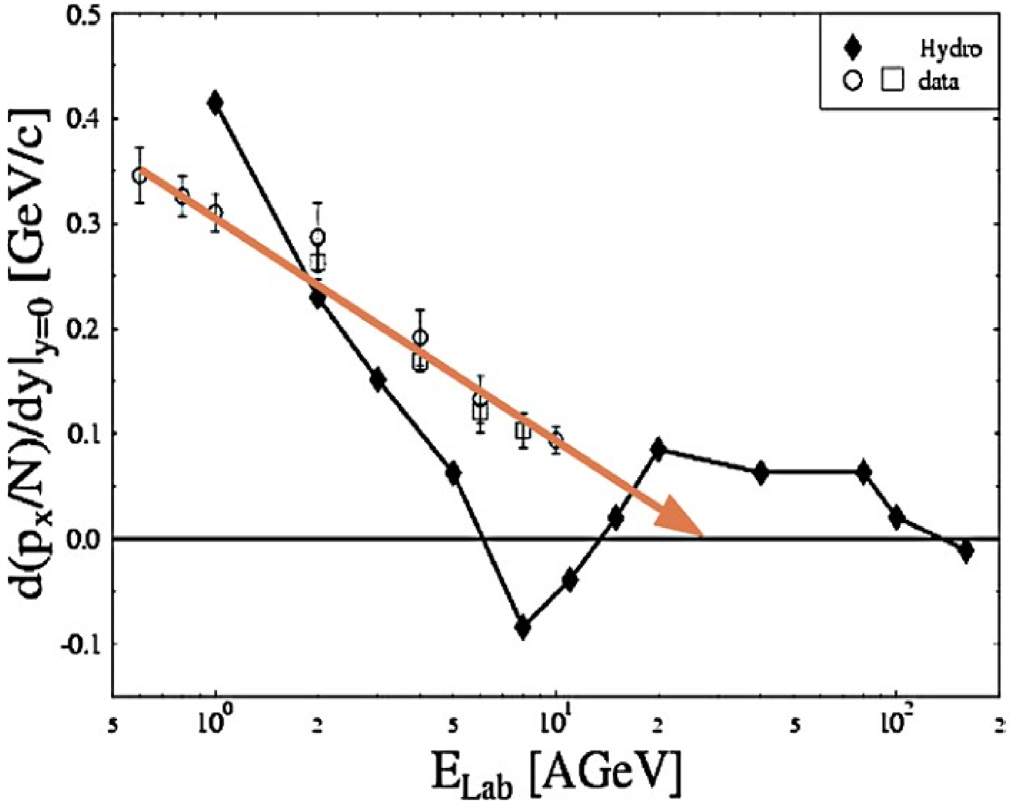
"Softest point"

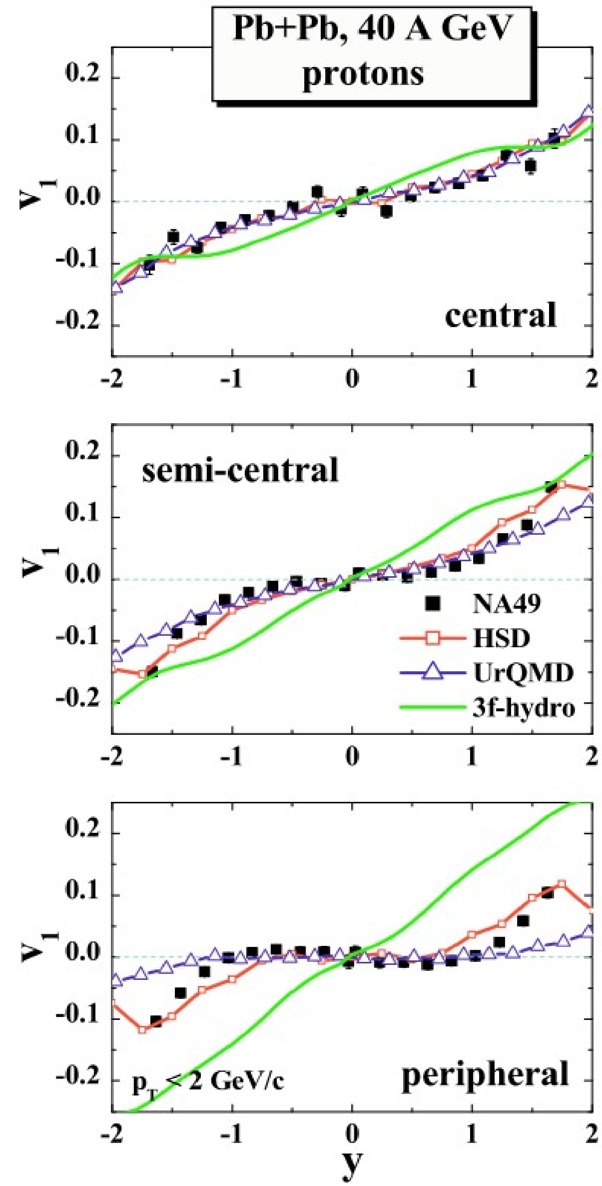
D.H. Rischke, Y. Pursun, J.A. Maruhn, H. Stoecker, W. Greiner, Heavy Ion Phys. 1, 309 (1995)

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

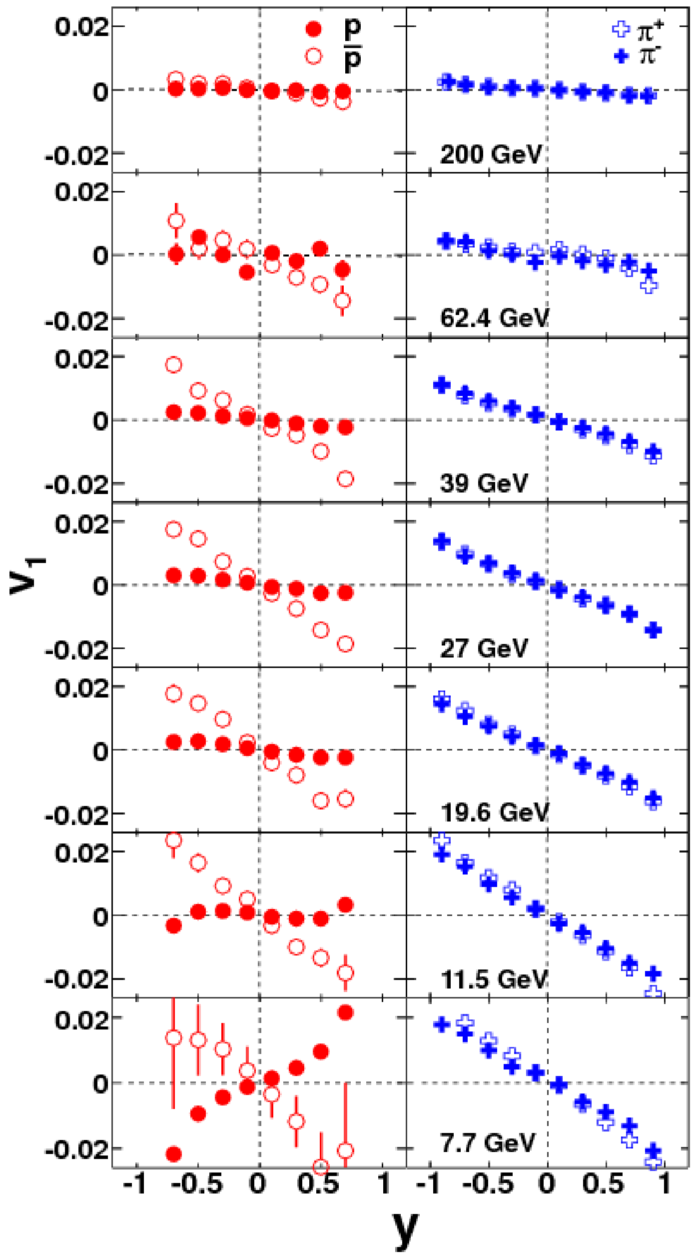
H. Stöcker, Nucl. Phys. A 750, 121 (2005)

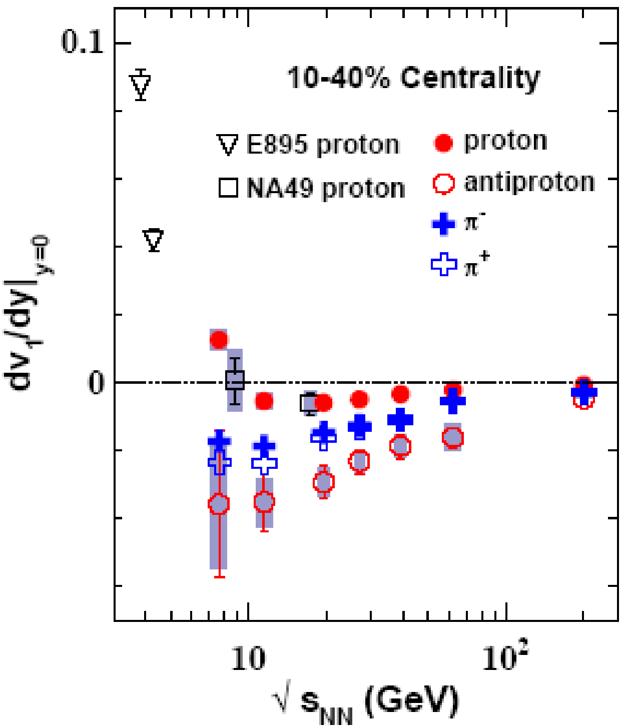




- Early hydro calculation predicted the "softest point" at E_{lab} = 8 AGeV
- A linear extrapolation of the data (arrow) suggests a collapse of flow at E_{lab} = 30 AGeV

Recent measurements of v_1 of identified hadrons

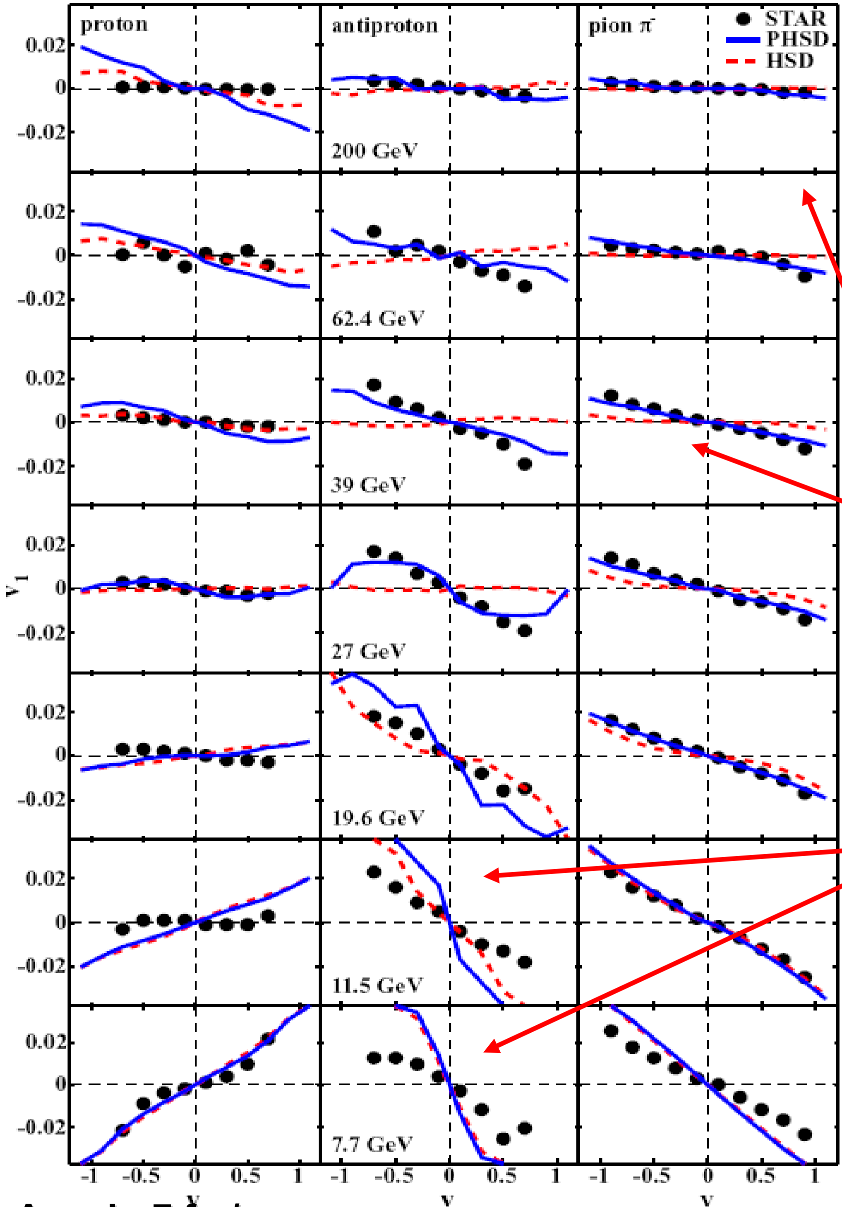




measured distributions are smooth !

STAR Collaboration, PRL 112 (2014) 162301

Directed flow from PHSD and HSD

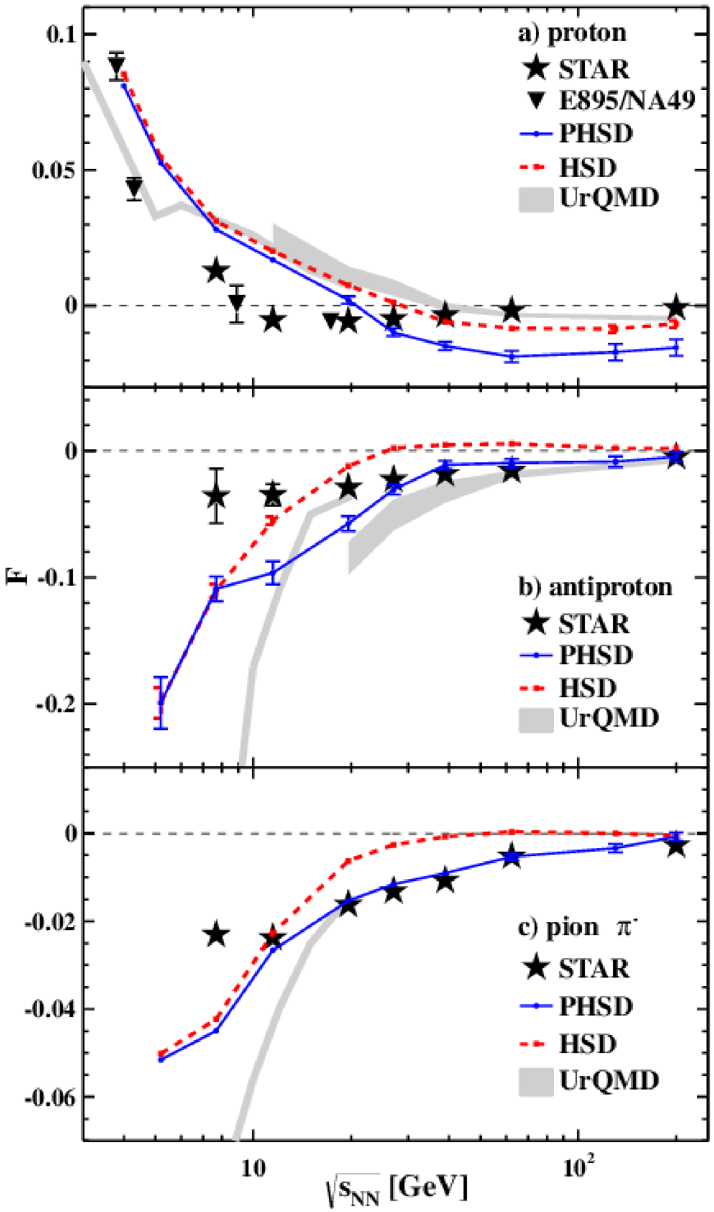


Au+Au, b=7 fm/c

- **Models:**
  * HSD (red) – warning: NO hadronic potentials, cascade mode!
  * PHSD (blue) – repulsive parton potential
- Antiprotons in PHSD are produced dominantly from hadronization at highest energies; multi-meson fusion reactions are important for the v_1 at low energies!
- higher energies ➔ influence of QGP
  lower energies ➔ dominance of hadronic matter and hadronic reaction channels (absorption and recreation)
- Discrepancies at low energy – indication for the influence of hadronic potentials (cf. AMPT results)

V. Konchakovski, W. Cassing, Yu. Ivanov, V. Toneev, PRC 90 (2014) 014903
STAR Collaboration, PRL 112 (2014) 162301

PHSD: Characteristic slope of $v_1(y)$



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

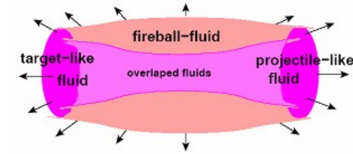
$$F = \left. \frac{dv_1}{dy} \right|_{y=0}$$

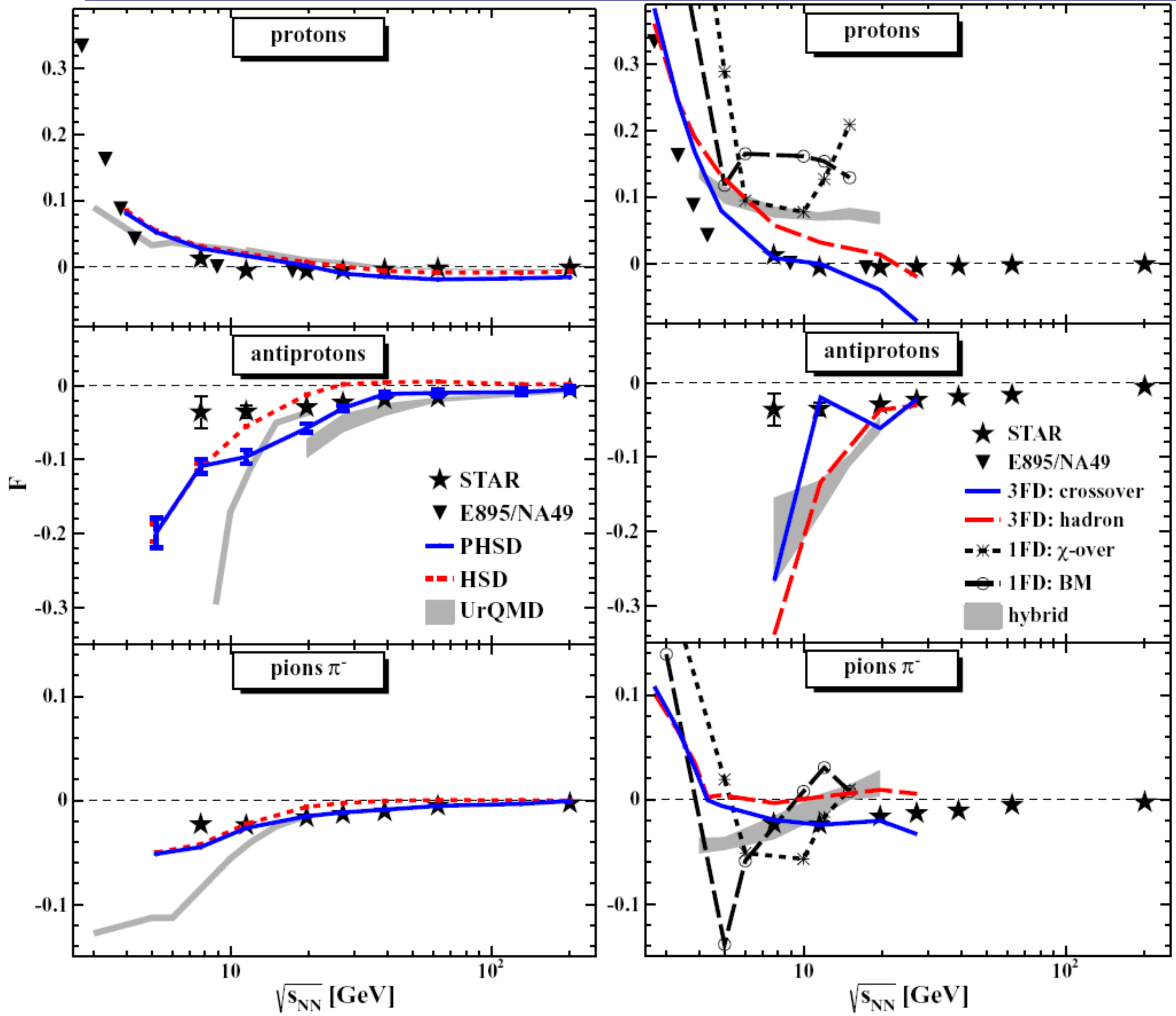
is used to characterize directed flow

- 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
- Better description of pion and antiproton slopes then UrQMD 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

Excitation function of v_1 slopes





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

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

Models:

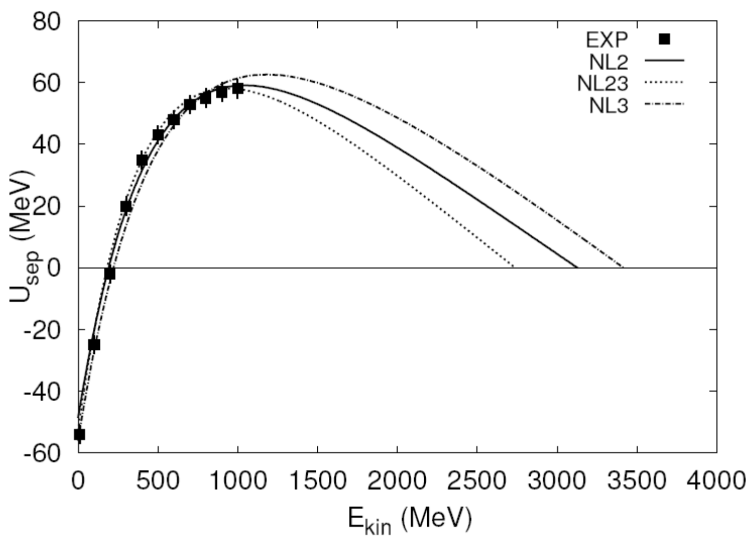
- HSD, PHSD
- 3D-Fluid Dynamic approach (3FD)
- UrQMD
- Hybrid-UrQMD
- 1FD-hydro with chiral cross-over and Bag Model (BM) EoS

➔ smooth crossover?!

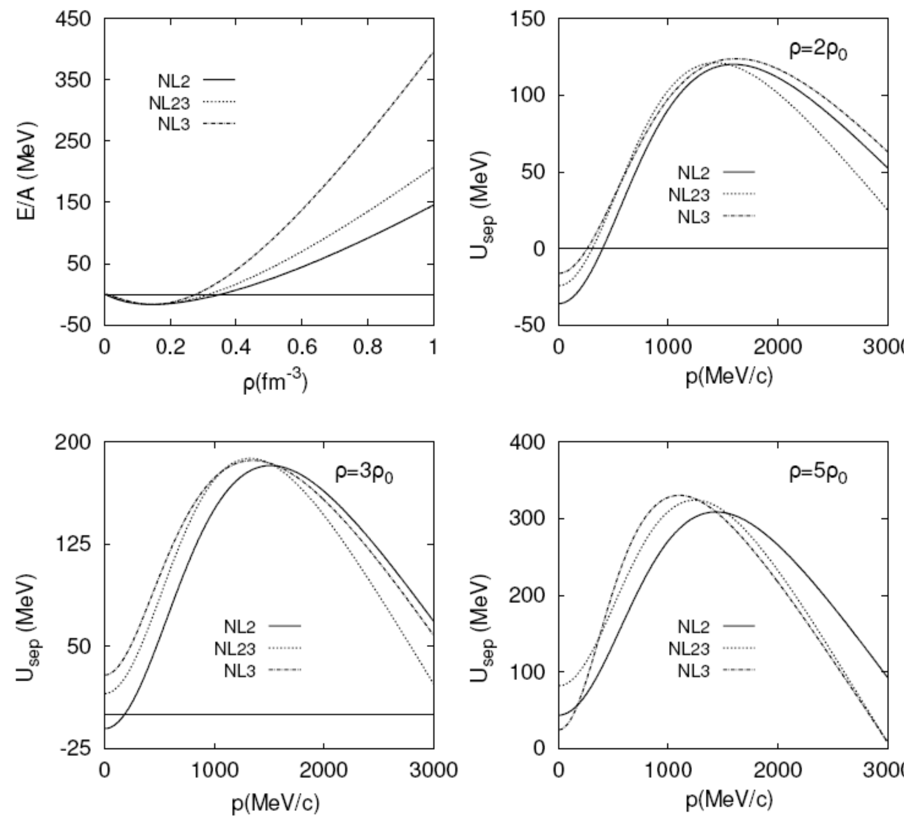
STAR Collaboration, PRL 112 (2014) 162301
PHSD/HSD and 3D-fluid hydro: V. Konchakovski, W. Cassing, Yu. Ivanov, V. Toneev, PRC 90 (2014) 014903
Hybrid/UrQMD/Hydro: J. Steinheimer, J. Auvinen, H. Petersen, M. Bleicher, H. Stöcker, PRC 89 (2014) 054913

What is known from the AGS on nucleon potentials?

Fix **momentum dependence** of **nucleon potential** by proton-nucleus scattering for normal nuclear density:

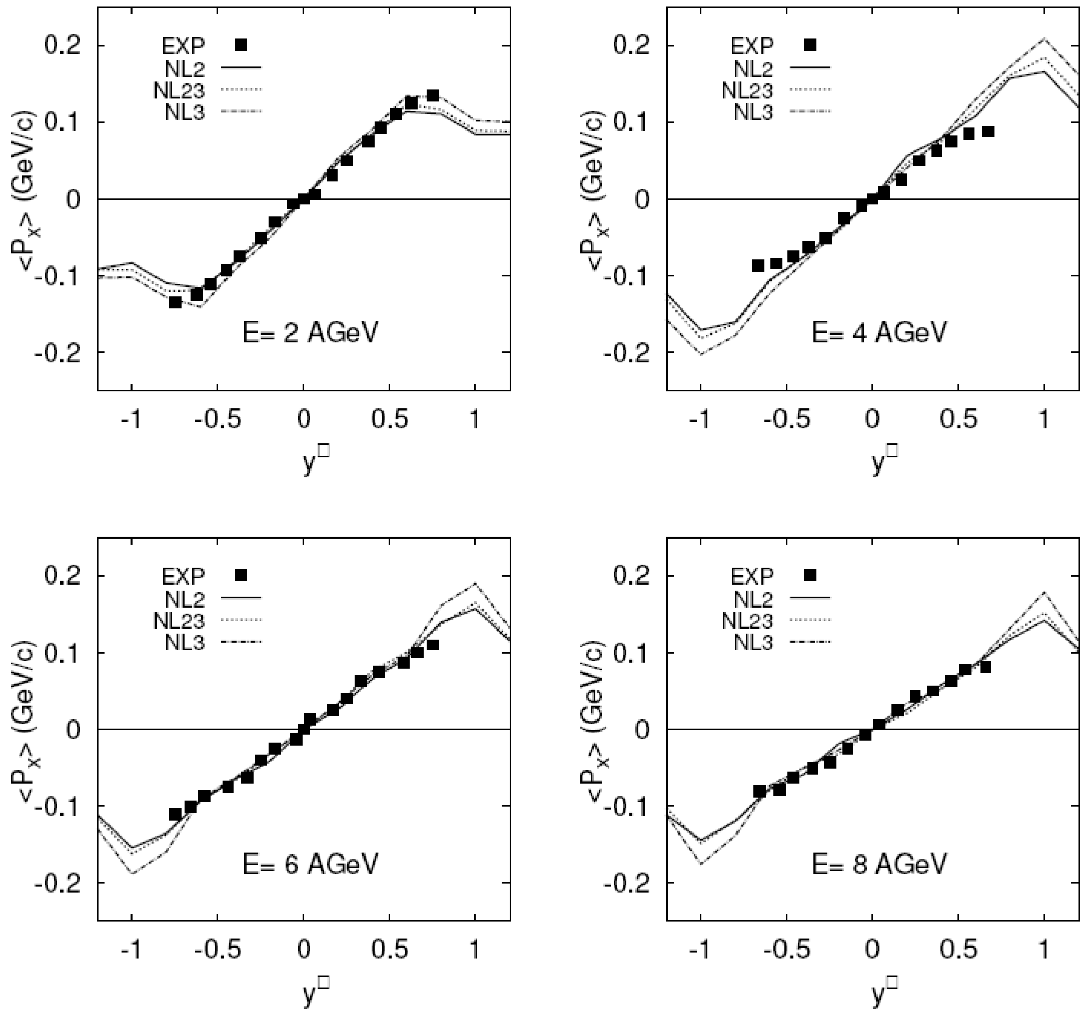


Employ also different EoS:



P.K. Sahu, W. Cassing, NPA 712 (2002) 357

Directed proton flow Px from Au+Au collisions

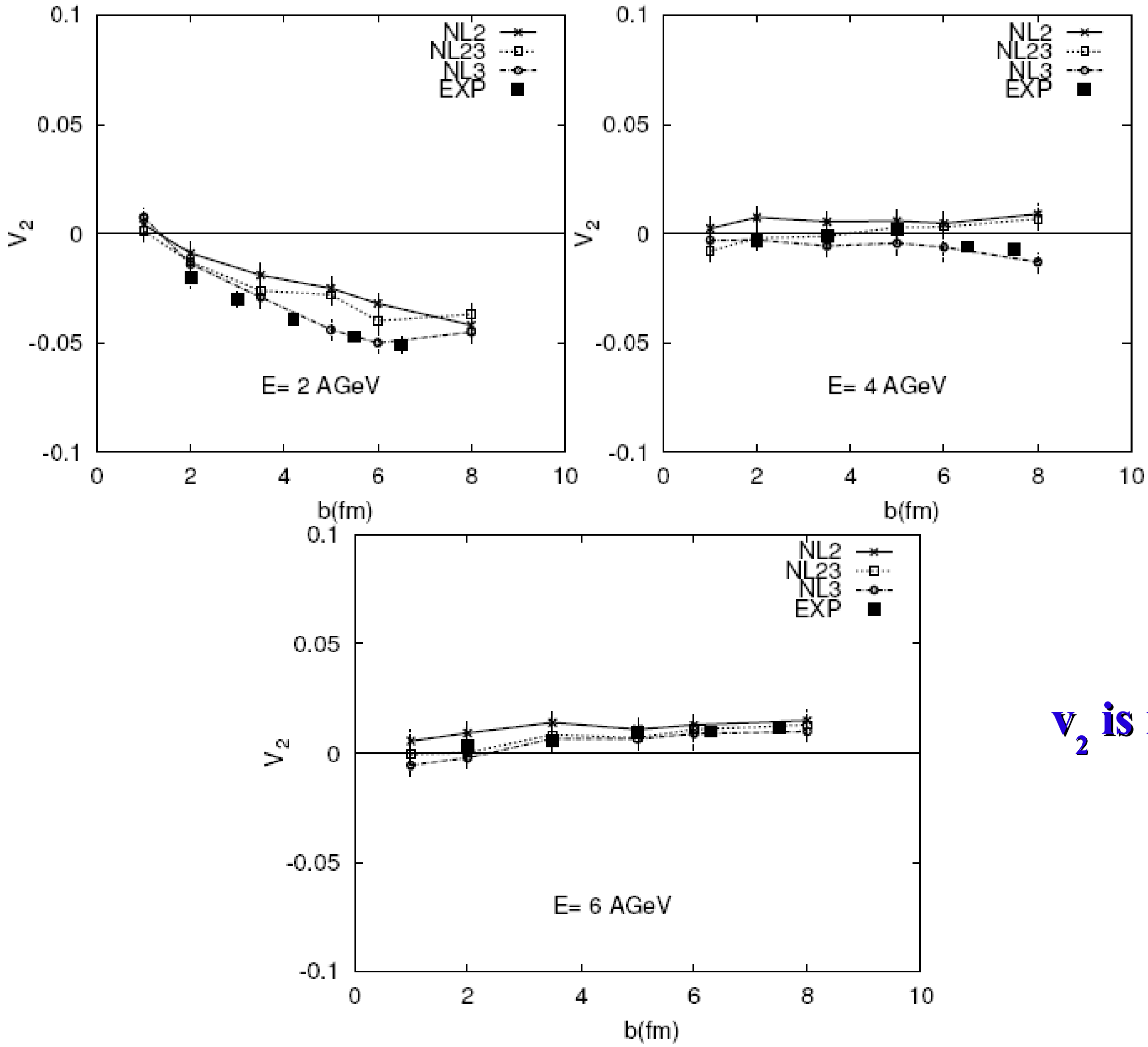


is sensitive to momentum dependent nucleon potentials

but does not constrain the EoS

P.K. Sahu, W. Cassing, NPA 712 (2002) 357

Elliptic proton flow v2 at the AGS



v_2 is more sensitive to the EoS

P.K. Sahu, W. Cassing, NPA 712 (2002) 357

JAM calculations for directed flow

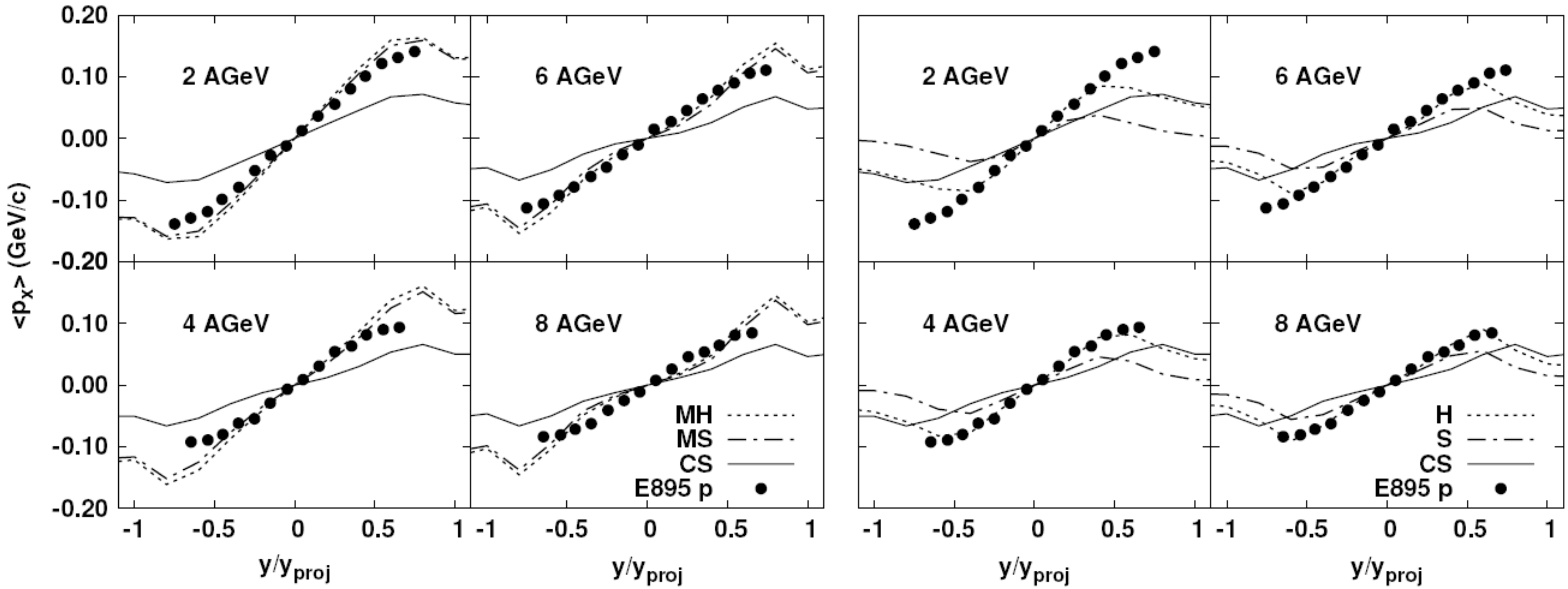
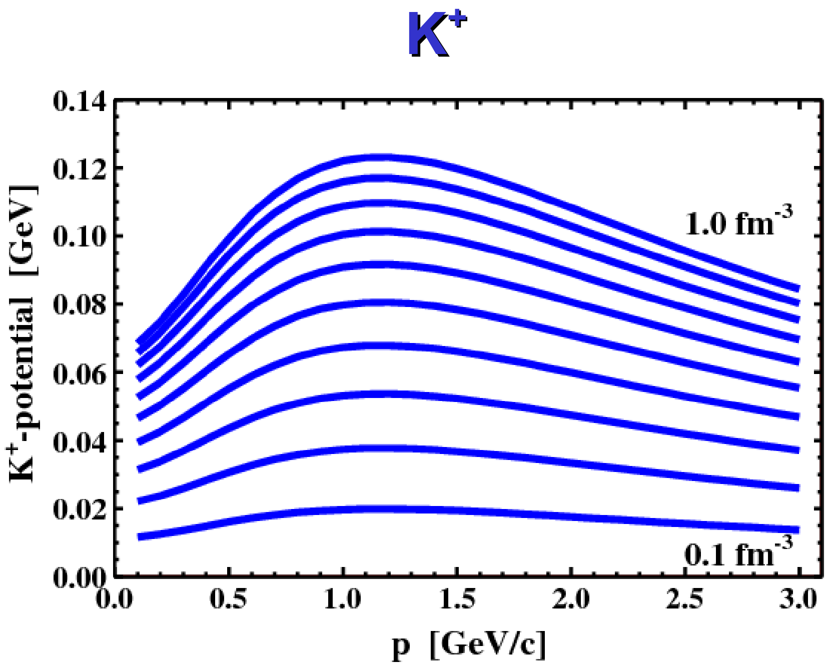


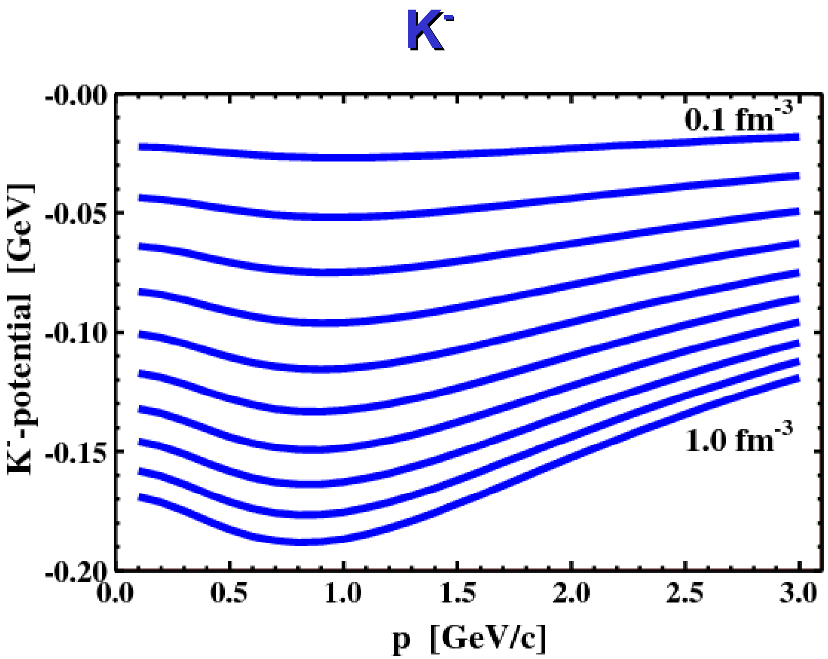
FIG. 2. Sideward flows $\langle p_x \rangle$ of protons in mid-central Au+Au collisions at (2–8)A GeV are compared with the AGS-E895 data [20]. Curves show the calculated results of cascade with momentum-dependent hard or soft mean field (MH or MS, left-hand panels), cascade with momentum-independent mean field (H or S, right-hand panels), and cascade without mean field (CS). The experimental data are shown in both the left and the right panels.

give the same information

M. Isse, A. Ohnishi, N. Otuka, P.K. Sahu, Y. Nara, PRC 72 (2005) 064908

Kaon potentials



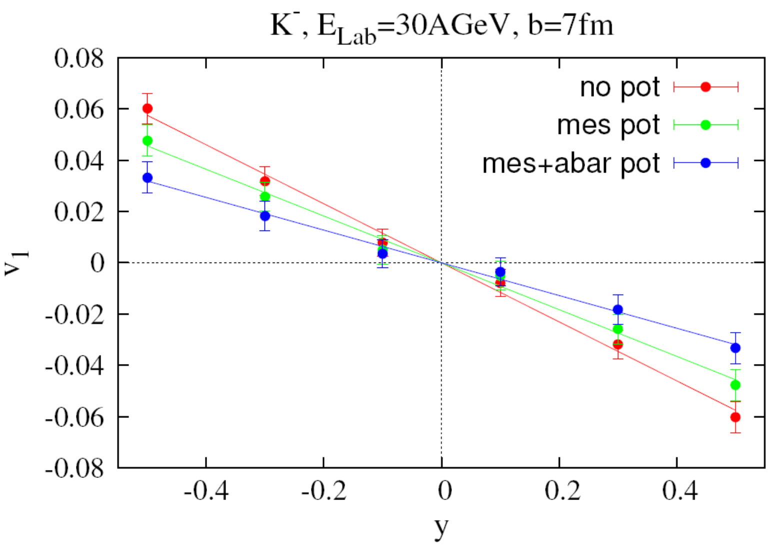


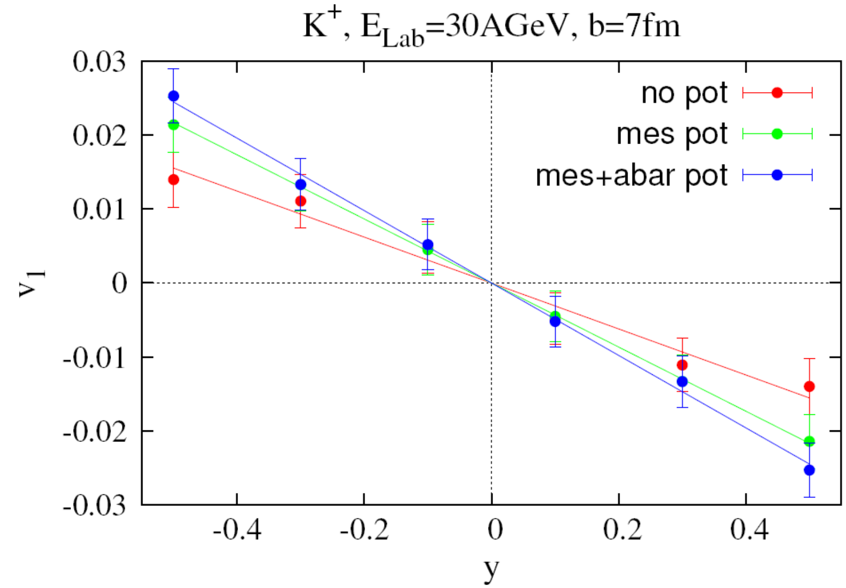
Dispersion relation $\omega_K^2(\vec{p},\rho) = \pm\frac{3}{4}\frac{\omega}{f_K^2}\rho_N + p^2 + m_K^2 - \frac{\Sigma_{KN}}{f_K^2}\rho_s$

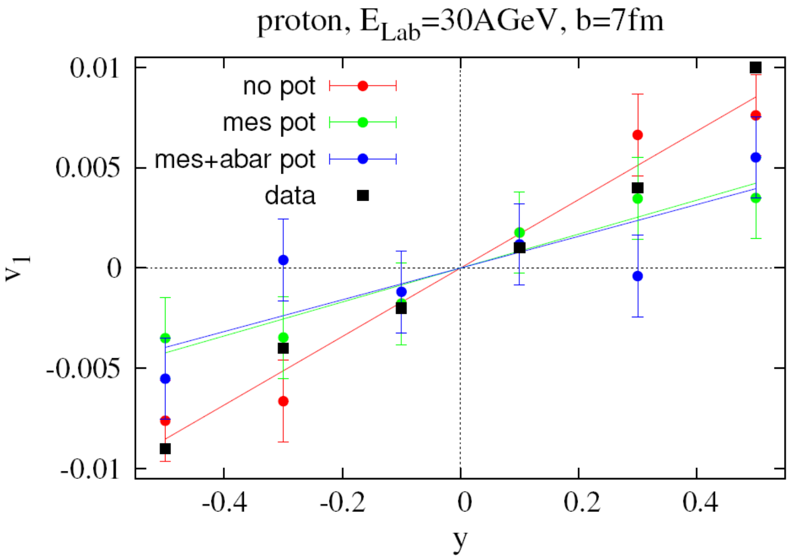
Kaon potential $U_K(\vec{p},\rho) = \omega_K(\vec{p},\rho) - \sqrt{p^2 + m_K^2}$

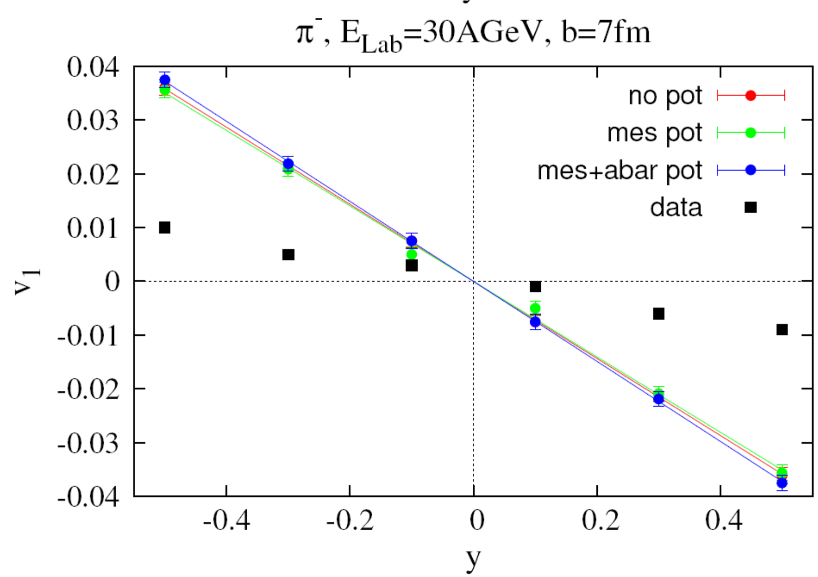
L.Tolos, A.Ramos, A.Polls, PRC65 (2002) 054907;
W.Cassing, L.Tolos, E.L.Bratkovskaya, A.Ramos, NPA727 (2003) 59;
W.Cassing, VK, A. Palmese, V.D. Toneev, E.L. Bratkovskaya [1408.4313]

Sensitivity to hadron potentials at 30 A GeV



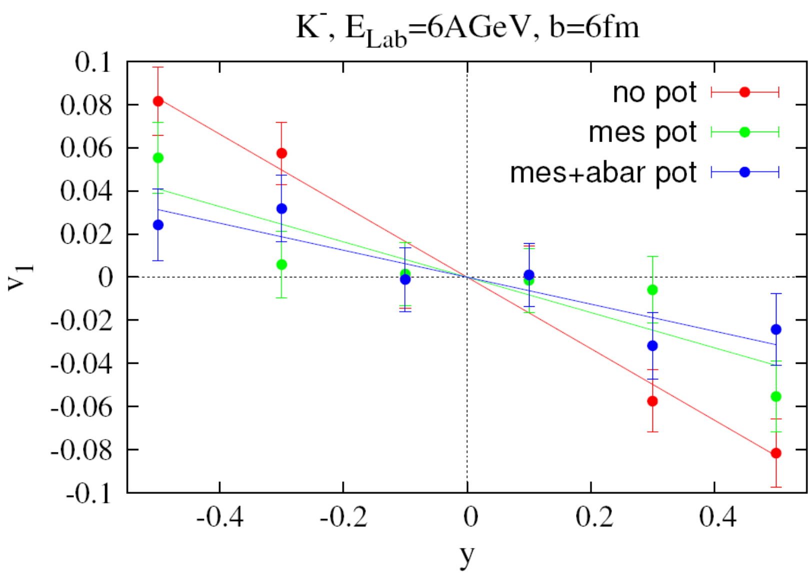


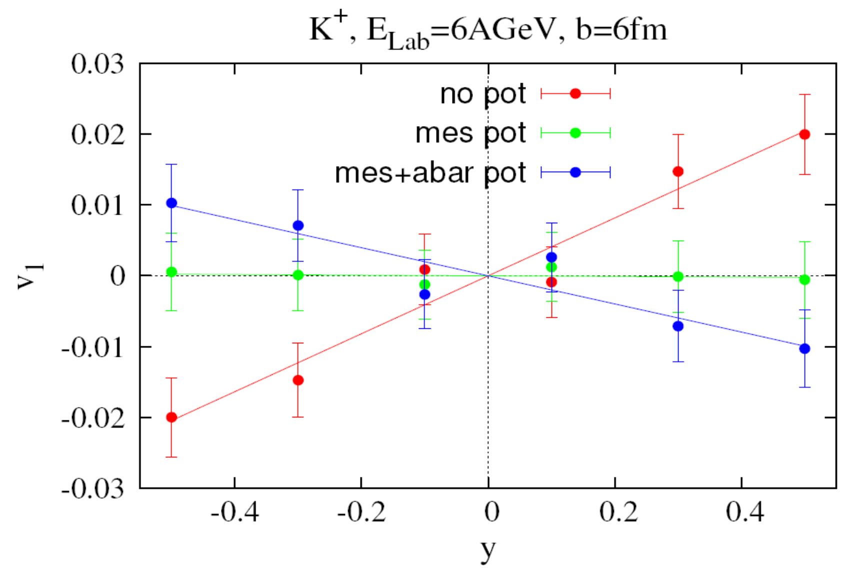


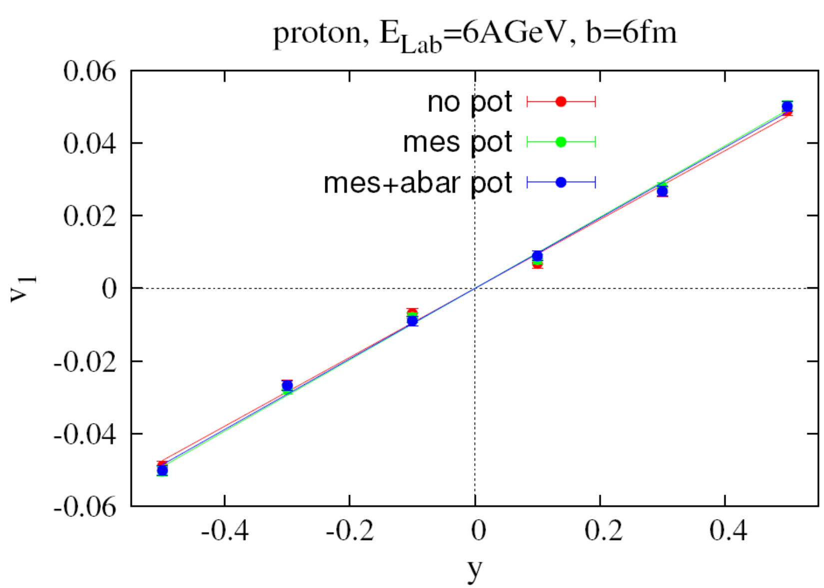


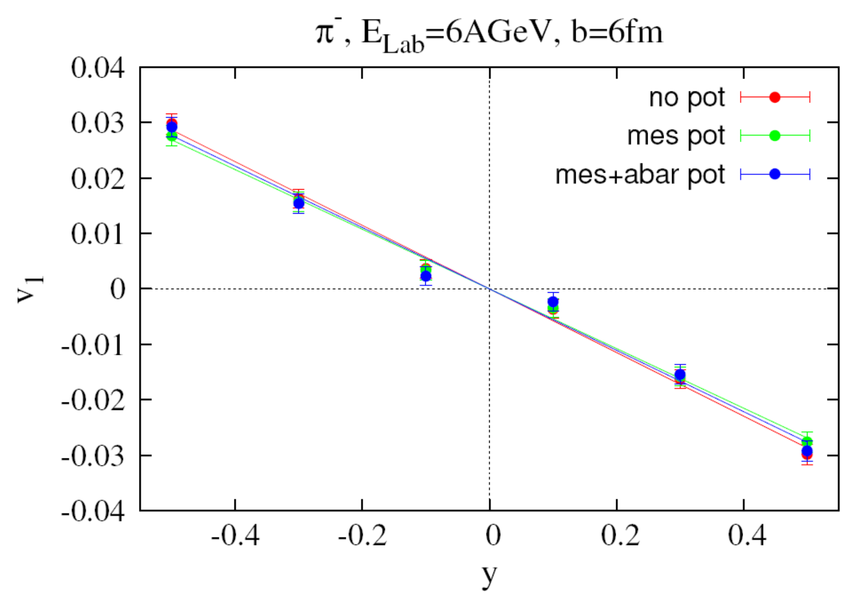
A.Palmese et al., preliminary

Sensitivity to hadron potentials at 6 A GeV





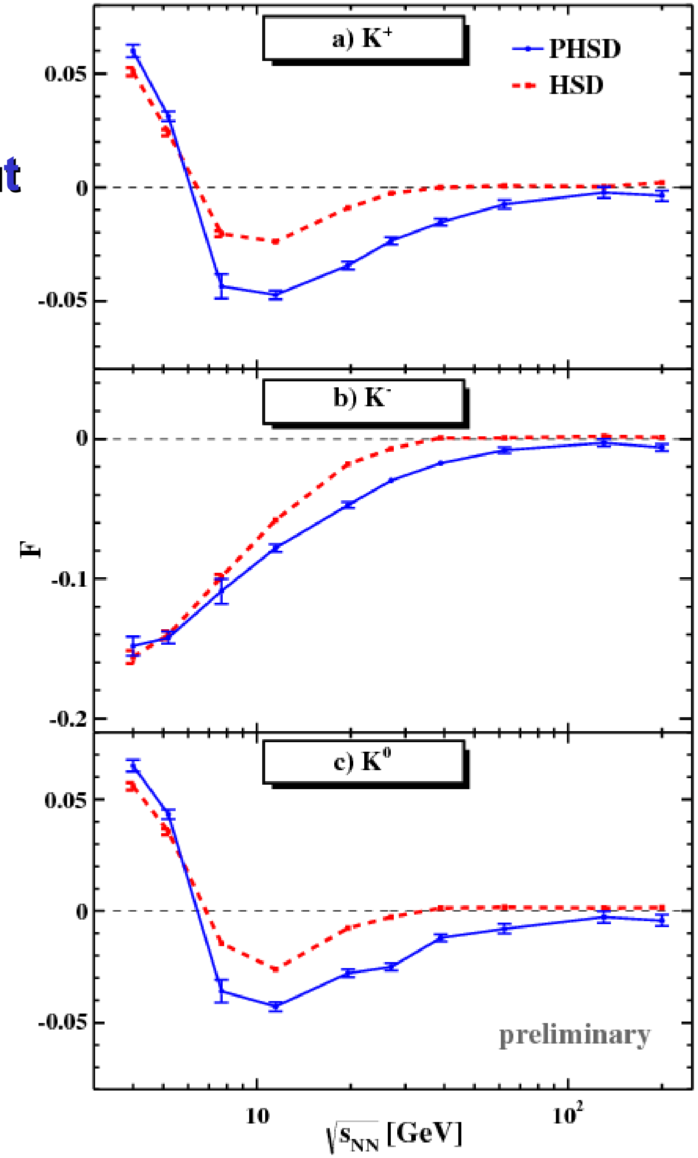




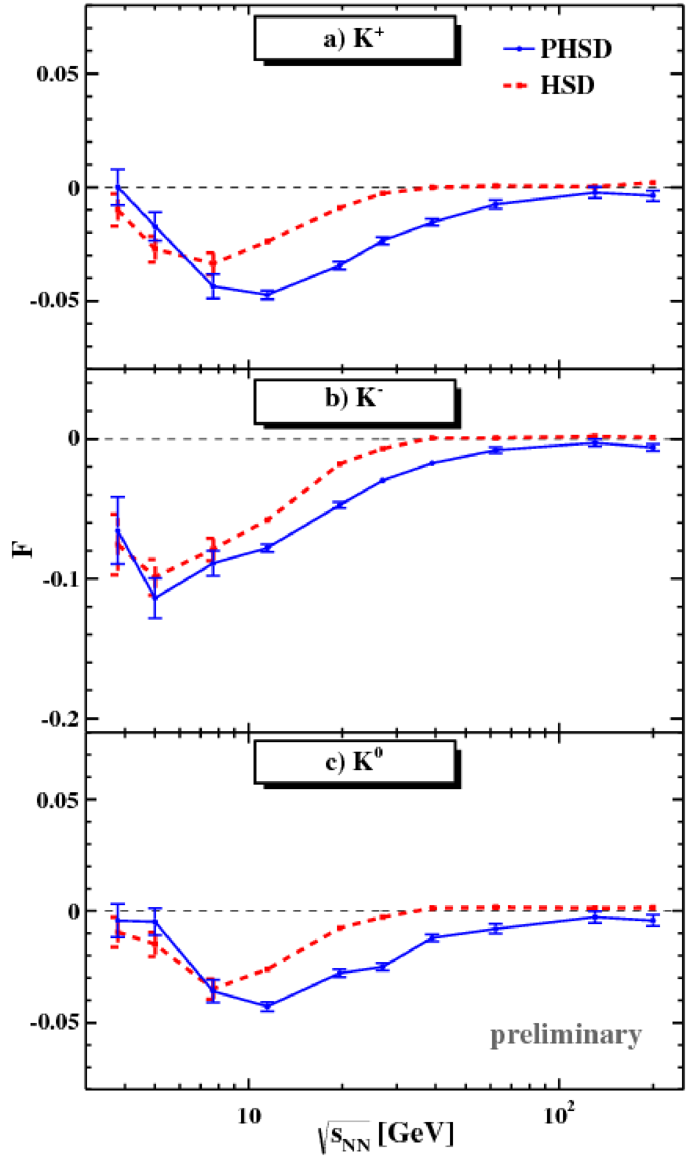
A.Palmese et al., preliminary

Sensitivity of v_1 to kaon potentials

without



with pot



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

Transport model with electromagnetic field

The Boltzmann equation is the basis of QMD like models:

$$\{\frac{\partial}{\partial t} + \dot{\vec{r}} \cdot \vec{\nabla}_r + \dot{\vec{p}} \cdot \vec{\nabla}_p\} \; f(\vec{r},\vec{p},t) = I_{coll}(f, f_1, ... f_N)$$

Generalized on-shell transport equations in the presence of electromagnetic fields can be obtained formally by the substitution:

$$\dot{\vec{r}} \to \frac{\vec{p}}{p_0} + \vec{\nabla}_p U \;,$$

$$\dot{\vec{p}} \to -\vec{\nabla}_r U + e\vec{E} + e\vec{v} \times \vec{B}$$

$$\{\frac{\partial}{\partial t} + \left(\frac{\vec{p}}{p_0} + \vec{\nabla}_{\vec{p}}\, U\right)\vec{\nabla}_{\vec{r}} - \left(\vec{\nabla}_{\vec{r}}\, U - e\vec{E} - e\vec{v} \times \vec{B}\right)\vec{\nabla}_{\vec{p}}\;\} \; f(\vec{r},\vec{p},t) = I_{coll}(f, f_1, ... f_N)$$

$$U \sim Re(\Sigma^{ret})/2p_0$$

A general solution of the wave equations is as follows

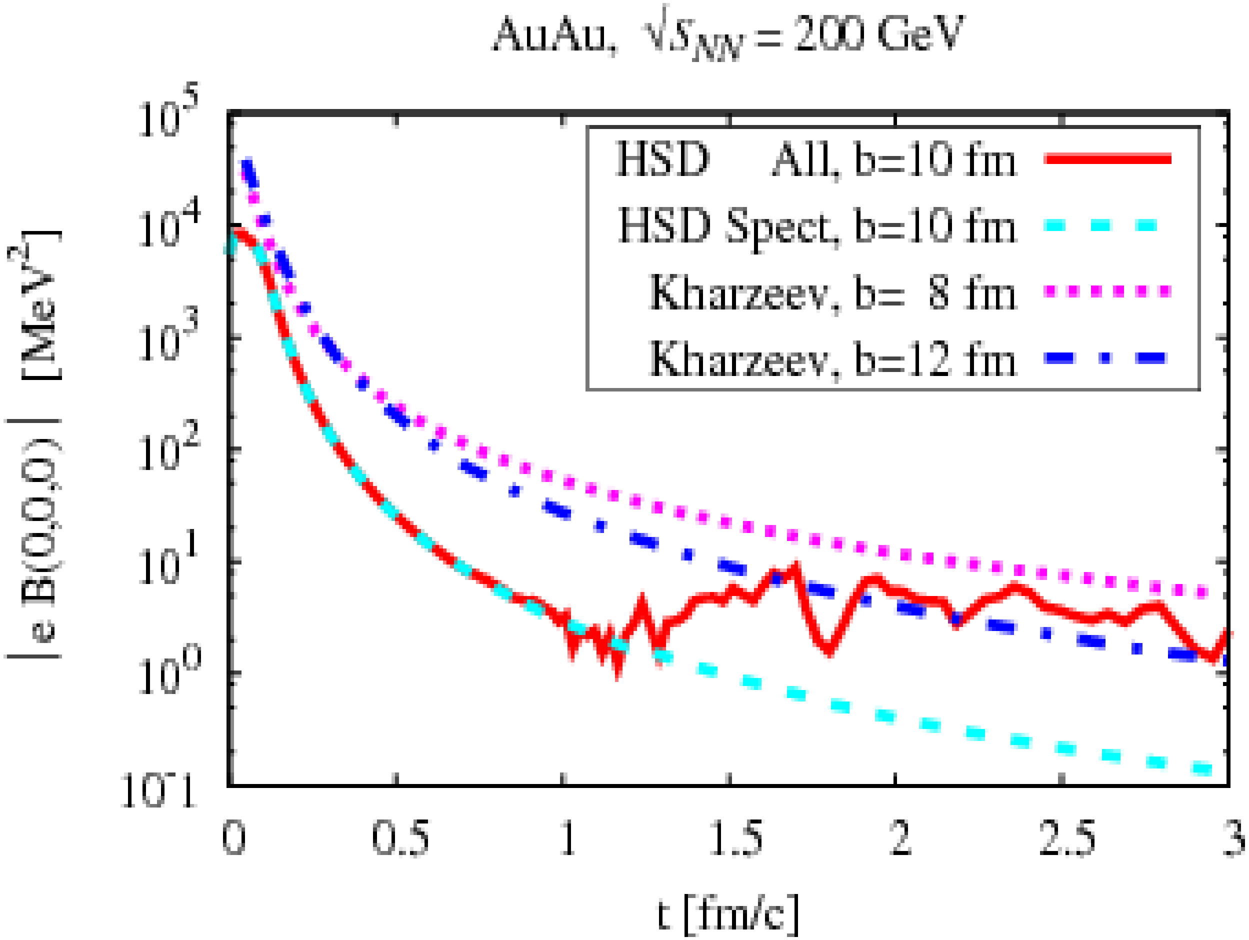
$$\vec{A}(\vec{r},t) = \frac{1}{4\pi}\int \frac{\vec{j}(\vec{r'},t')\;\delta(t - t' - |\vec{r} - \vec{r'}|/c)}{|\vec{r} - \vec{r'}|}\; d^3r'dt'$$

$$\Phi(\vec{r},t) = \frac{1}{4\pi}\int \frac{\rho(\vec{r'},t')\;\delta(t - t' - |\vec{r} - \vec{r'}|/c)}{|\vec{r} - \vec{r'}|}\; d^3r'dt'$$

$$\begin{cases} \vec{B} = \vec{\nabla} \times \vec{A} \\ \vec{E} = -\vec{\nabla}\Phi - \frac{\partial \vec{A}}{\partial t} \end{cases}$$

For point-like particles $\rho(\vec{r},t) = e\;\delta(\vec{r} - \vec{r}(t));\quad \vec{j}(\vec{r},t) = e\;\vec{v}(t)\;\delta(\vec{r} - \vec{r}(t))$ $\quad \vec{\nabla} \times \vec{A} \to LW\,eq.$

Time dependence of eB_y



D.E. Kharzeev et al.,
Nucl. Phys. A803, 227 (2008)

Collision of two infinitely thin layers (pancake-like)

V.Voronyuk, et al.,
PRC83 (2011) 054911

- **Until t~1 fm/c the induced magnetic field is defined by spectators only.**
- **Maximal magnetic field is reached during nuclear overlapping time Δt~0.2 fm/c, then the field goes down exponentially.**

Electric and magnetic fields at RHIC

magnetic fields   electric fields

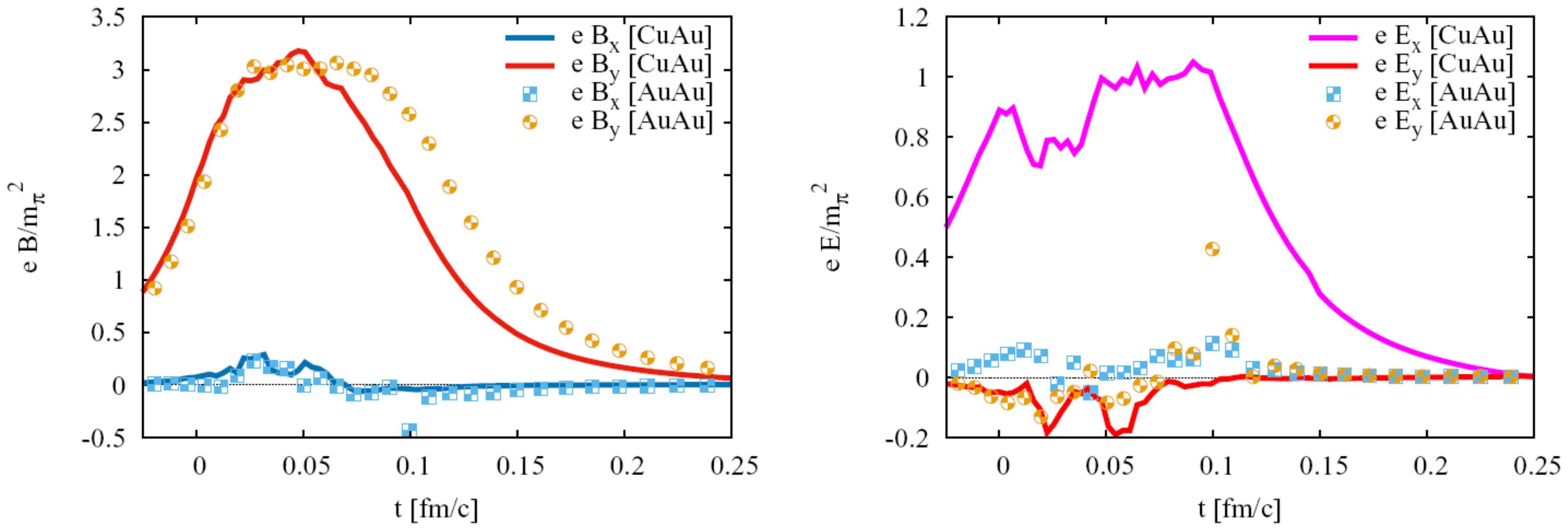


FIG. 1. Time evolution of event-averaged components of the magnetic (l.h.s.) and electric (r.h.s.) fields in the center of the overlap region of colliding Cu+Au (solid lines) and Au+Au (dotted lines) systems at $\sqrt{s_{NN}}$ =200 GeV and b = 7 fm. The distributions are averaged over 70 events.

E-field in reaction plane E_x is much larger for Cu+Au!

V. Voronyuk, V.D. Toneev, S.A. Voloshin, W. Cassing [1410.1402]

Electric field induced by spectators at RHIC

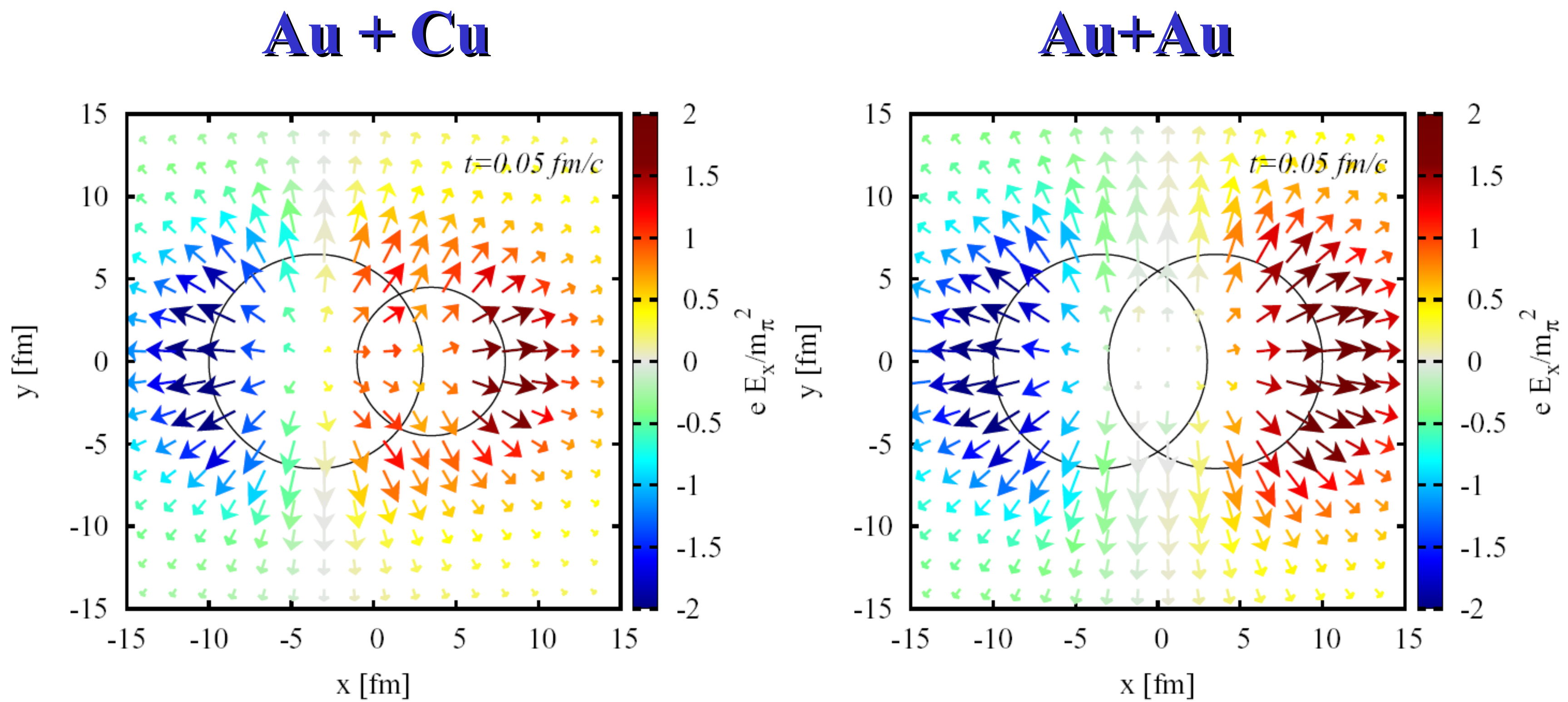
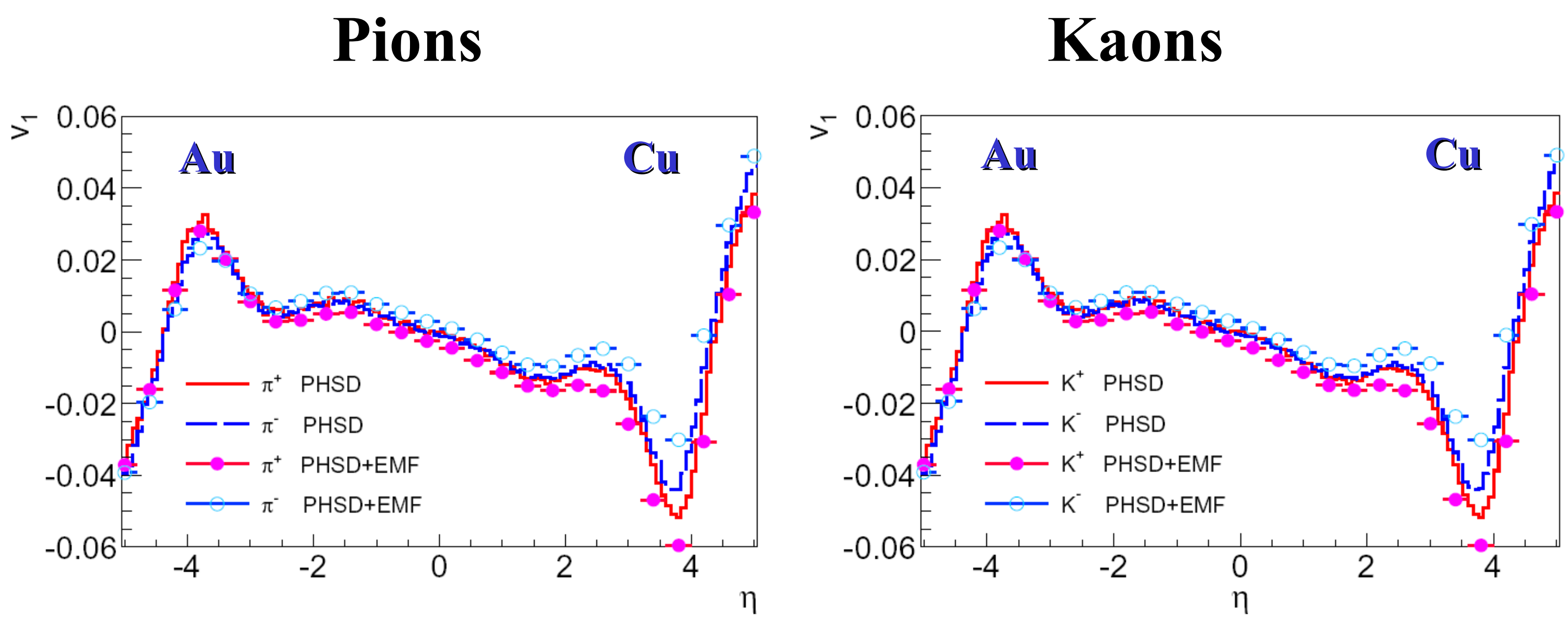


FIG. 2. Event-averaged electric field in the transverse plane for a Cu+Au (left panel) and Au+Au (right panel) collision at 200 GeV at time t =0.05 fm/c for the impact parameter b =7 fm. Each vector represents the direction and magnitude of the electric field at that point.

V. Voronyuk, V.D. Toneev, S.A. Voloshin, W. Cassing [1410.1402]

Impact on charged pion and kaon directed flow



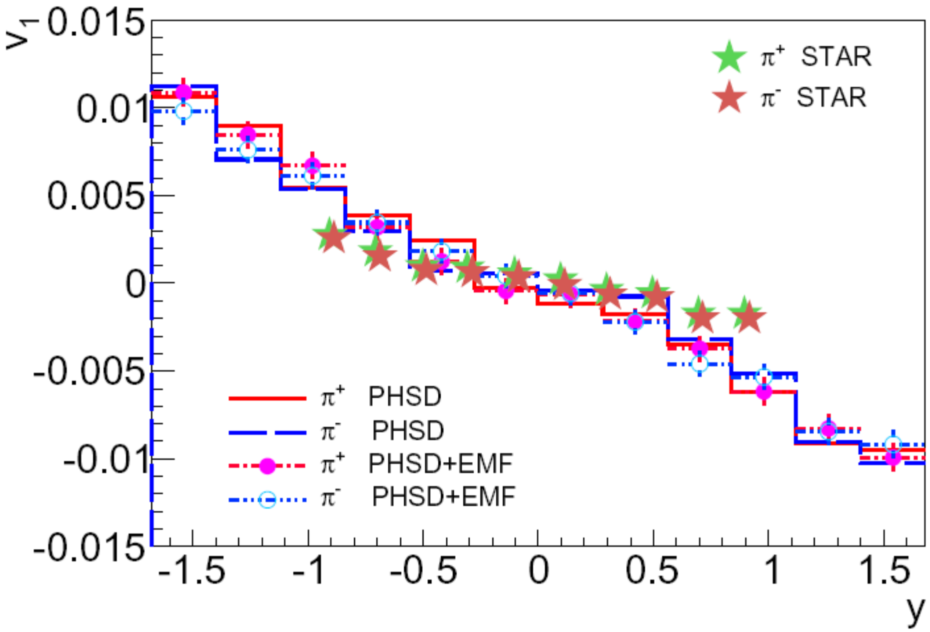
Shift in directed flow between the different charge states!

This scenario assumes presence of charges very early.

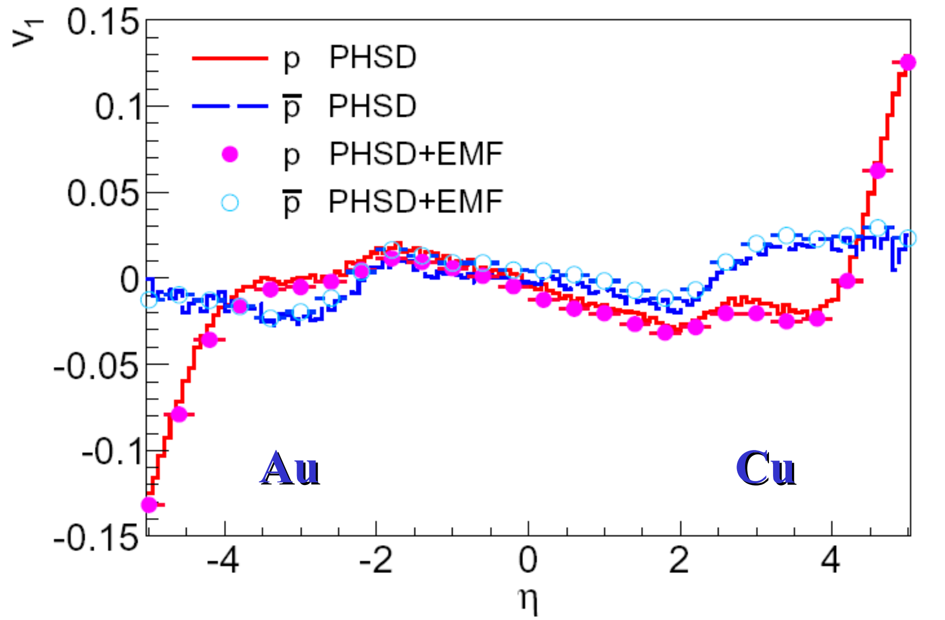
V. Voronyuk, V.D. Toneev, S.A. Voloshin, W. Cassing [1410.1402]

Impact on charged baryon directed flow

$\pi^{\pm}$ in Au+Au @ STAR



p, $\bar{p}$ in Cu+Au



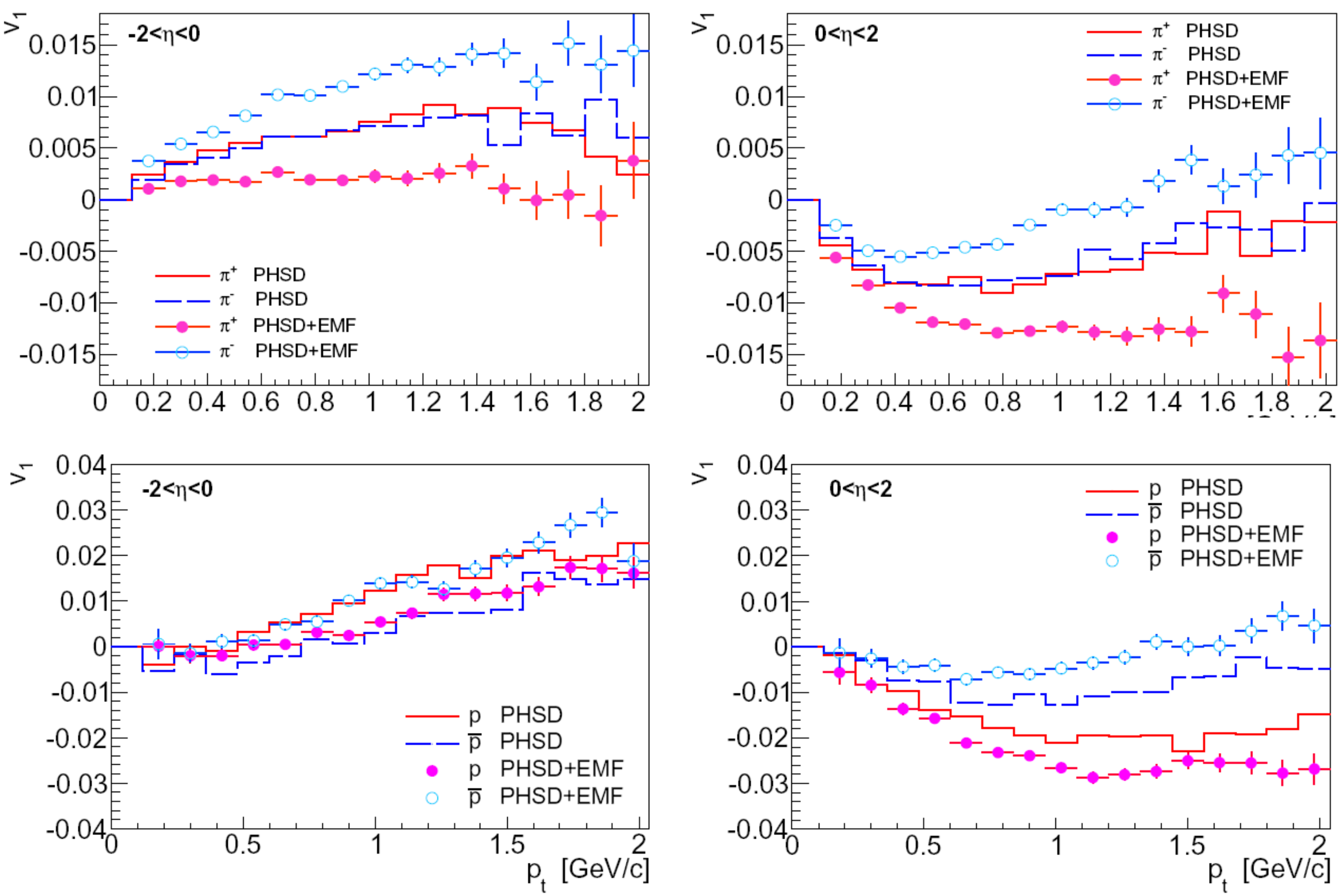
Shift in directed flow between the different charge states!

Asymmetry in the pseudorapidity distribution between p and $\bar{p}$.

V. Voronyuk, V.D. Toneev, S.A. Voloshin, W. Cassing [1410.1402]

Directed flow versus transverse momentum

backward **Au+Cu** **forward**



pions

protons

Significantly different p_T dependences !

V. Voronyuk, V.D. Toneev, S.A. Voloshin, W. Cassing [1410.1402]

Summary

- The PHSD reproduces the general trends in the $v_1(y)$ excitation functions in the energy range $\sqrt{s}$ =7.7-200 GeV but differs from HSD results 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 multi-meson fusion processes in HSD/PHSD help to reproduce antiproton directed flow at lower energies.

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

- Sizeable effect of momentum dependent mean-fields on directed flows at FAIR/NICA energies

- Directed flow of oppositely charged hadrons is sensitive to the very early charges in mass asymmetric collisions (like Cu+Au), i.e. to the early presence of quarks and antiquarks (or gluons)

PHSD group

FIAS & Frankfurt University
Elena Bratkovskaya
Hamza Berrehrah
Daniel Cabrera
Taesoo Song
Andrej Ilner

Giessen University
Wolfgang Cassing
Olena Linnyk
Volodya Konchakovski
Thorsten Steinert
Alessia Palmese

External Collaborations

SUBATECH, Nantes University:
Jörg Aichelin
Christoph Hartnack
Pol-Bernard Gossiaux
Vitalii Ozvenchuk
Rudy Marty

Texas A&M University:
Che-Ming Ko

JINR, Dubna:
Viacheslav Toneev
Vadim Voronyuk

BITP, Kiev University:
Mark Gorenstein

Barcelona University:
Laura Tolos
Angel Ramos

University Rio de Janeiro
Takeshi Kodama