Institut für
Theoretische Physik

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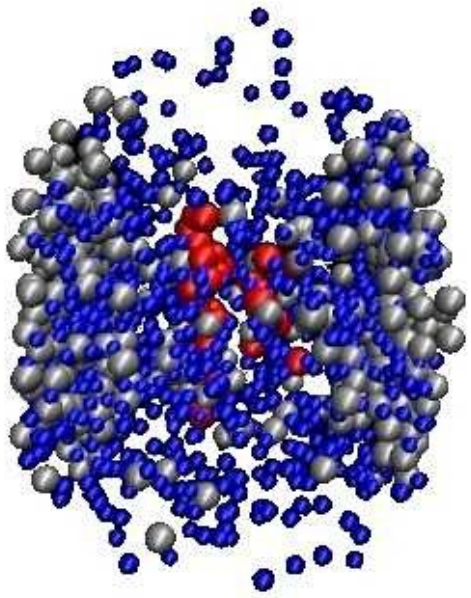
GIESSEN

arXiv:1404.2765

Directed flow from the PHSD transport approach



Volodya Konchakovski
Wolfgang Cassing
Yury Ivanov
Vyacheslav Toneev

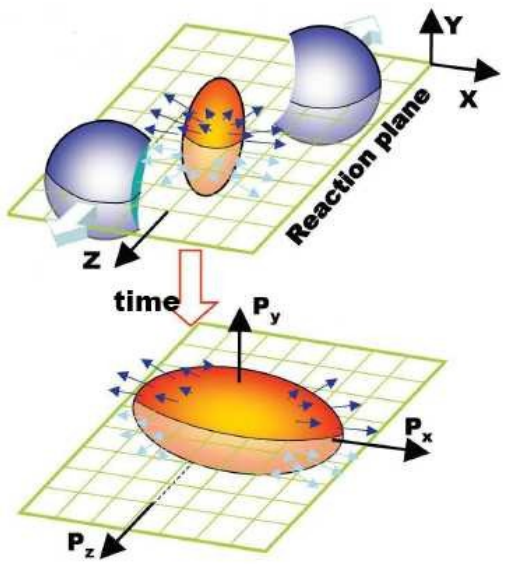
NeD & TURIC 2014
Hersonissos, Crete, Greece
11 June 2014

PHSD

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**

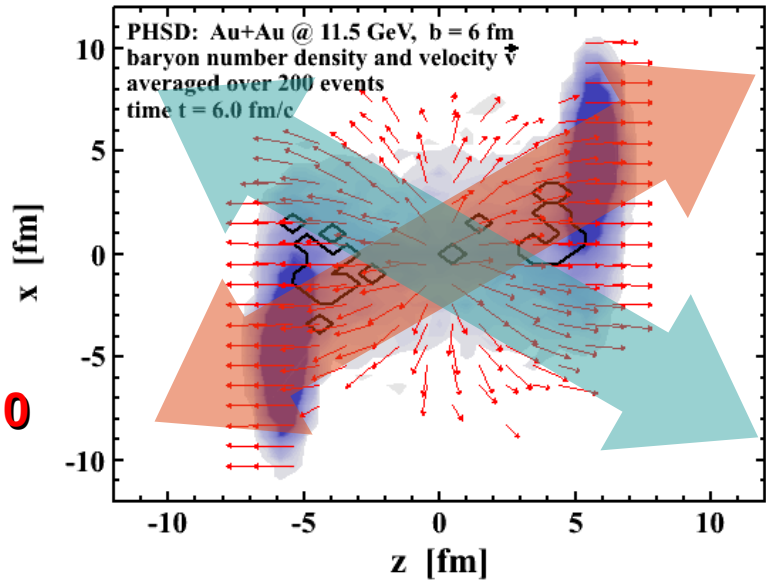


$$\frac{dN}{d\varphi} \propto \left(1 + 2\sum_{n=1}^{+\infty} v_n \cos\left[n(\varphi - \psi_n)\right]\right)$$

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

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

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

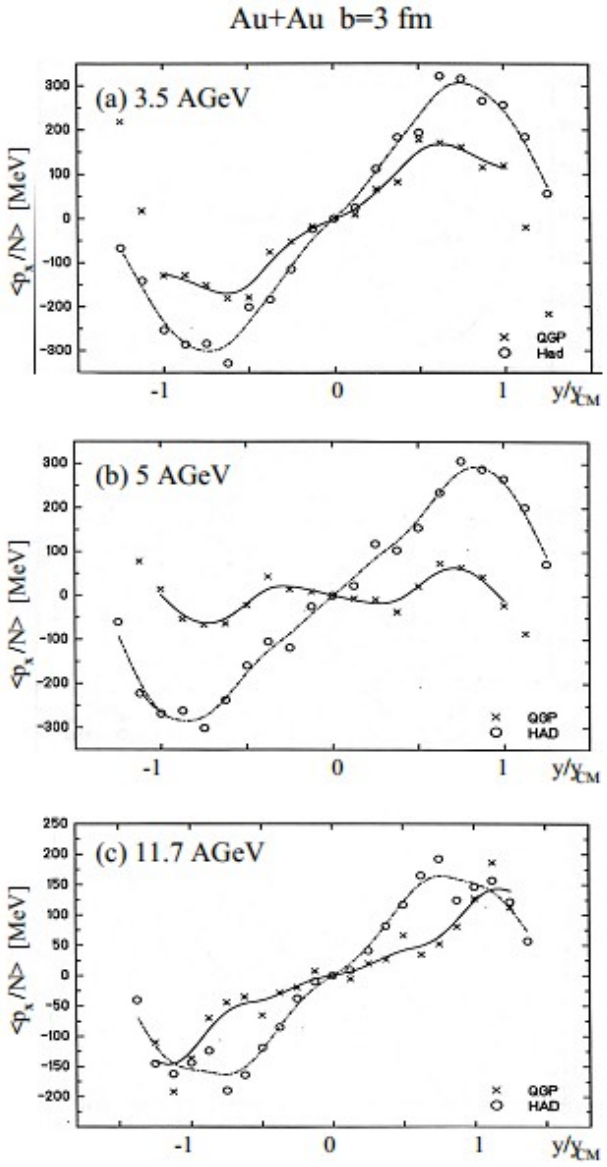


Directed flow $v_1 > 0$

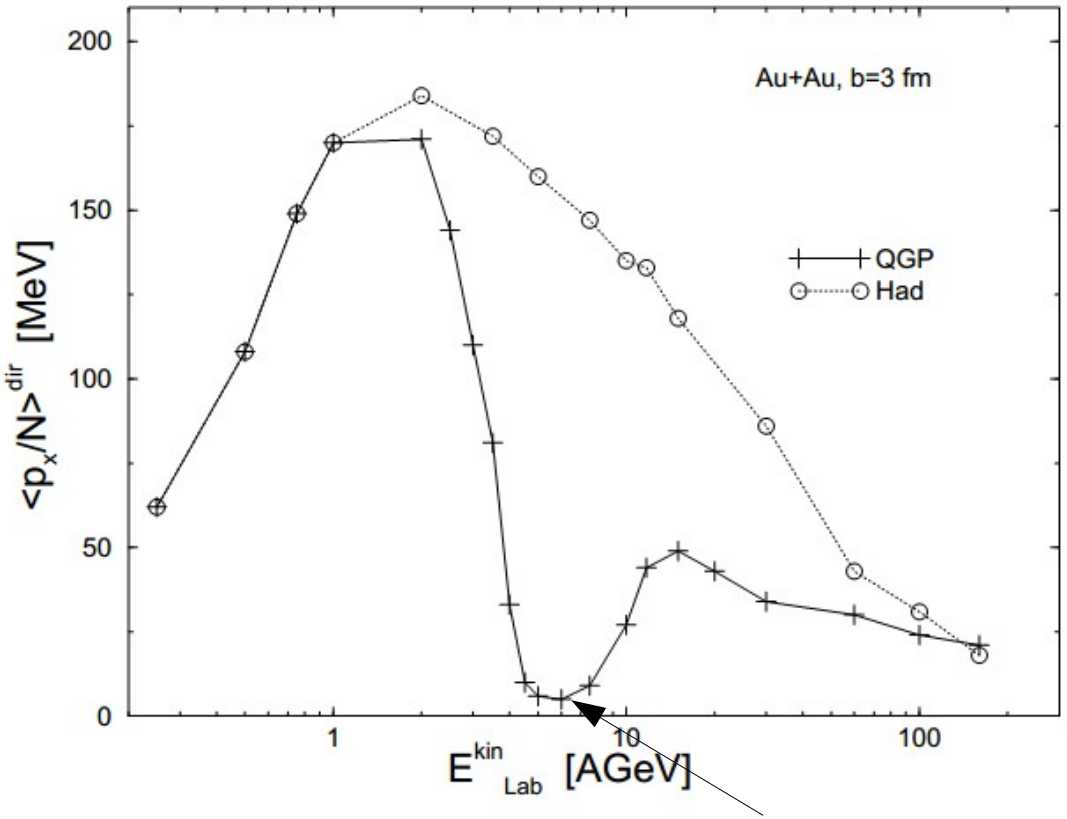
"Antiflow" $v_1 < 0$

"third flow component"

Direct flow and Quark–Gluon Plasma



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

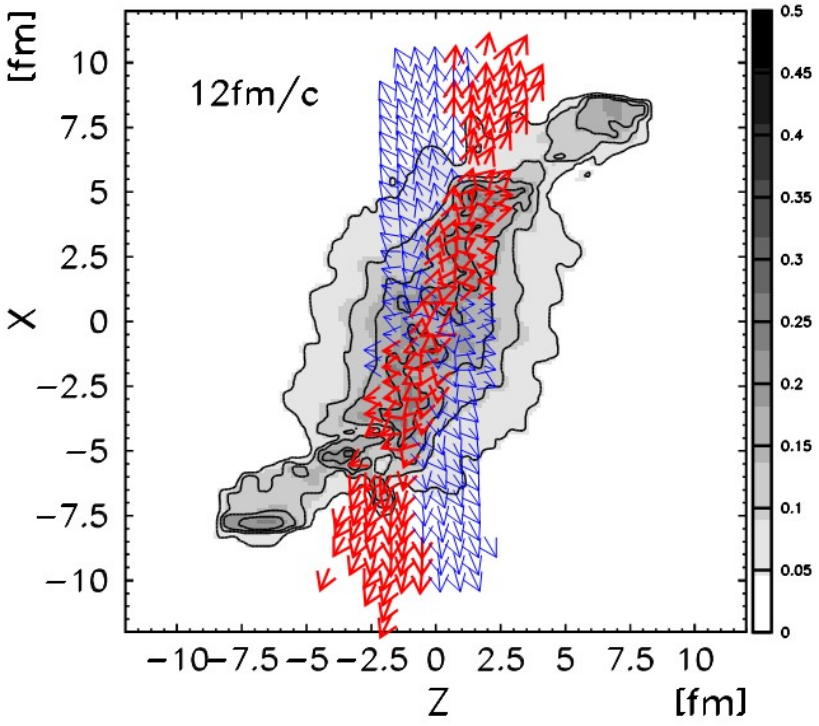


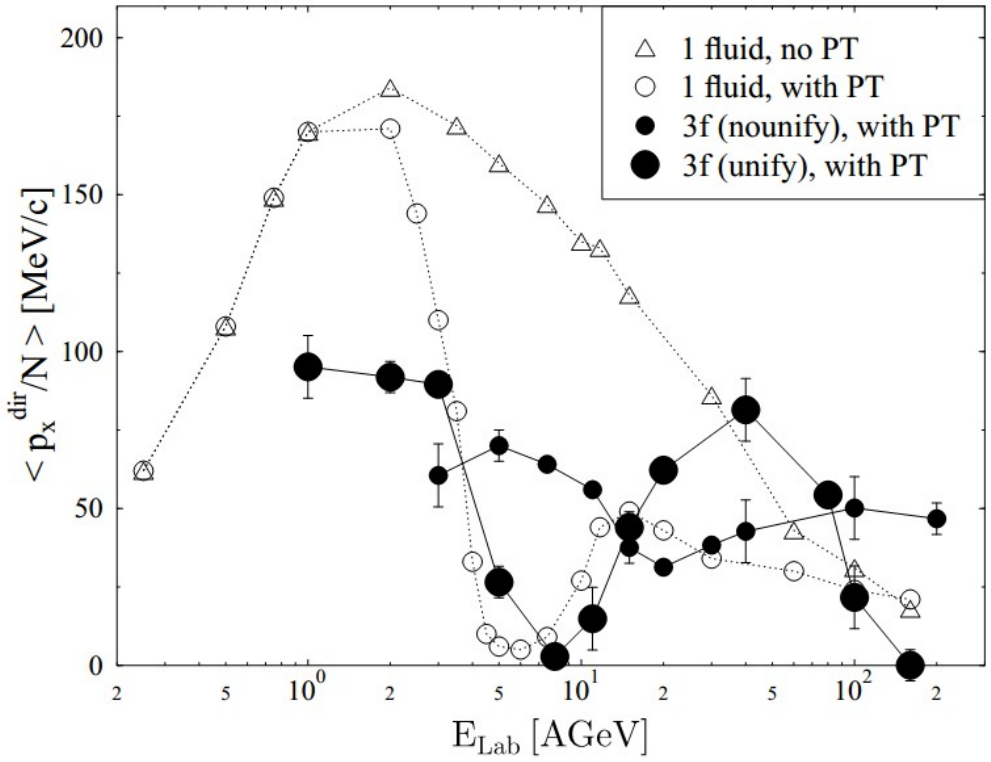
"Softest point"

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 AMeV)



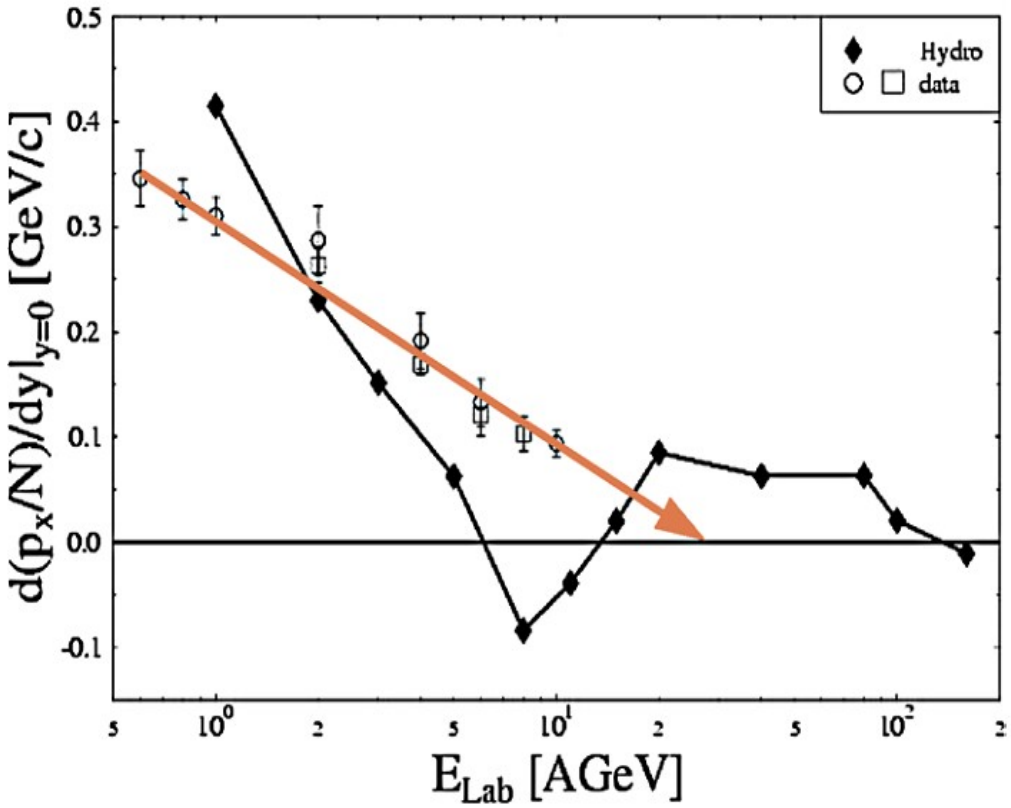


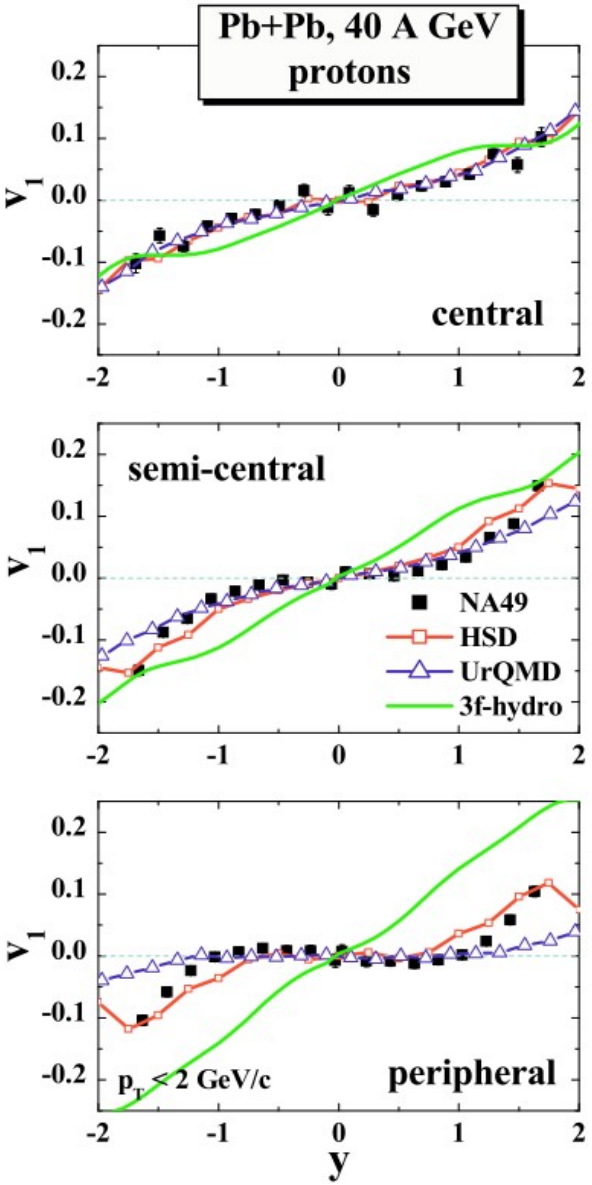
EoS is softened either by a phase transition to QGP,
or by the creation of resonances and string-like excitations

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

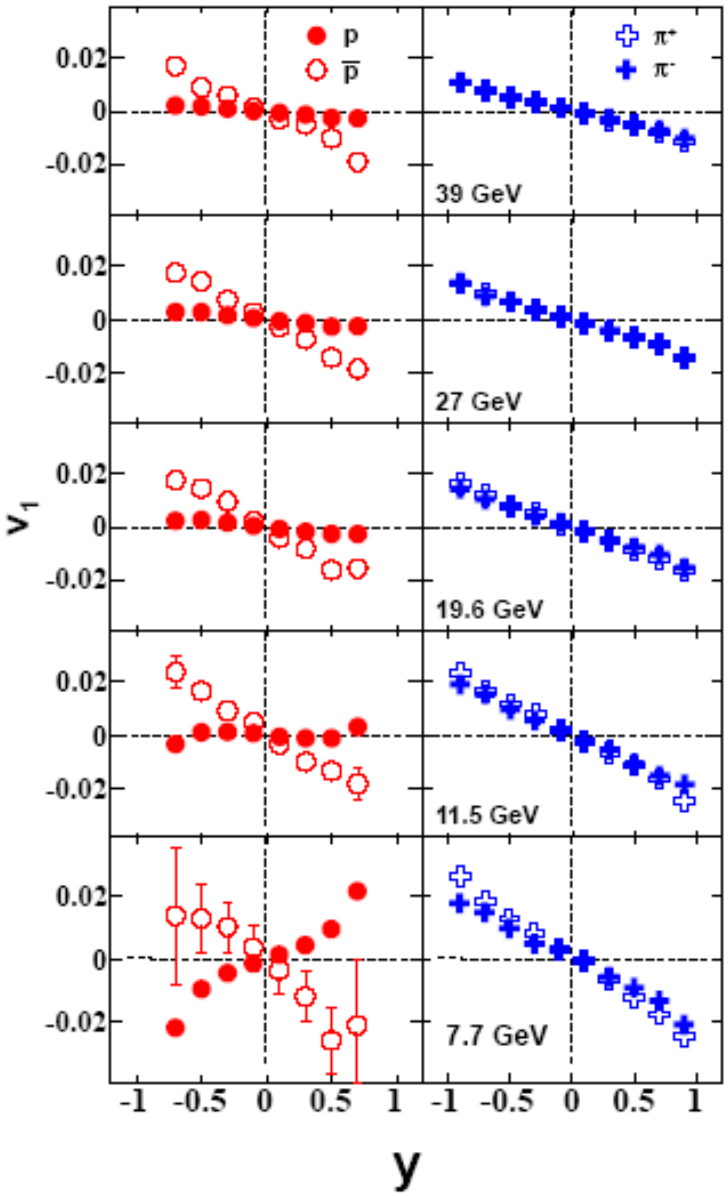
H. Stöcker, Nucl. Phys. A 750, 121 (2005)

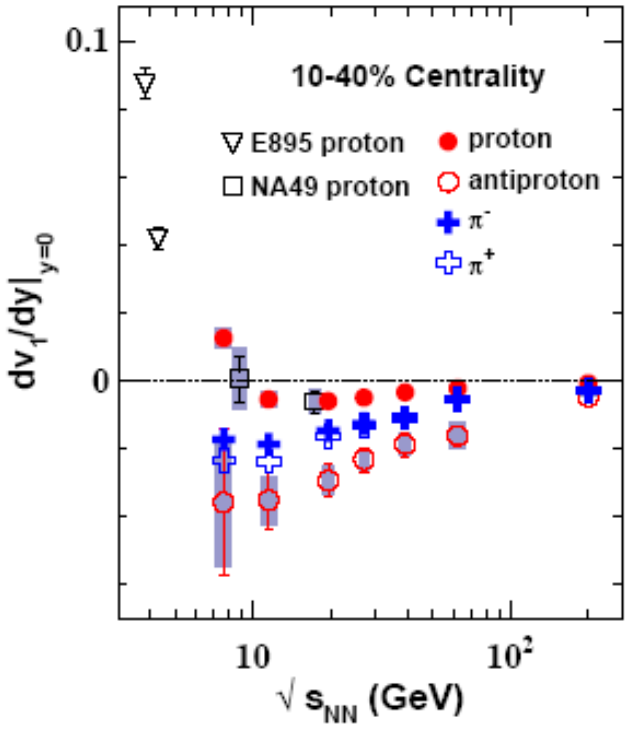




- Early hydro calculation predicted the "softest point" at E_{lab} = 8 AGeV
- A linear extrapolation of the data (arrow) suggests a collapse of flow at E_{lab} = 30 AGeV

Recent measurements of v_1 of identified hadrons



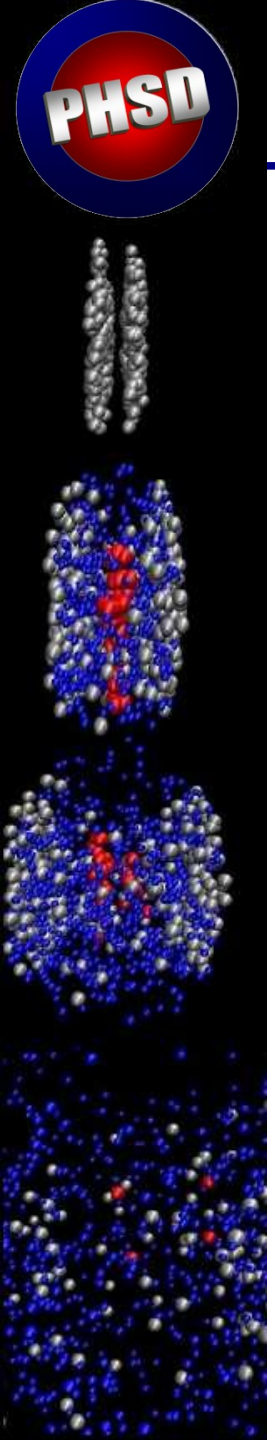


- measured distributions are smooth

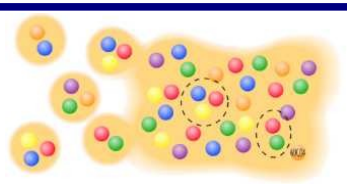
Statistical errors are shown and systematic bars are shaded

STAR collaboration, arXiv:1401.3043

Parton Hadron String Dynamics

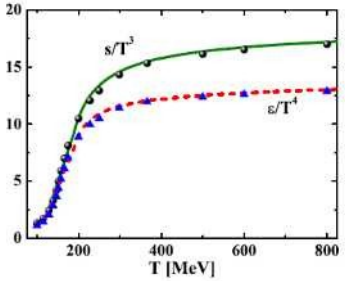


I. From hadrons to QGP:



- **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

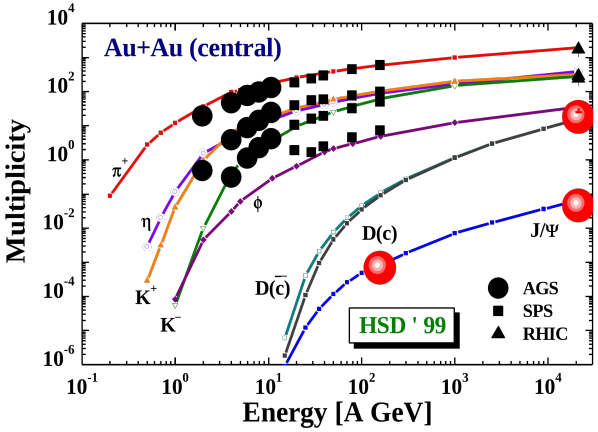
- **massive, off-shell (anti-)quarks** with broad spectral functions hadronize to **off-shell mesons and baryons or color neutral excited states - ‚strings‘ (strings act as ‚doorway states‘ for hadrons)**

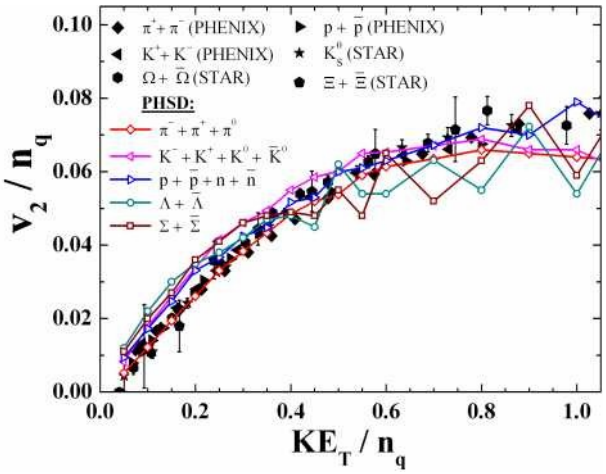
IV. Hadronic phase: hadron-string interactions – off-shell HSD

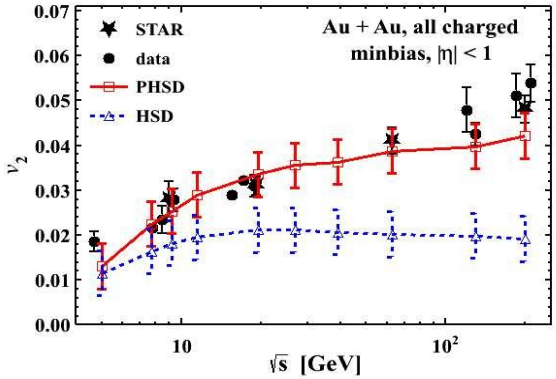
DQPM: Peshier, Cassing, PRL 94 (2005) 172301; Cassing, NPA 791 (2007) 365: NPA 793 (2007)

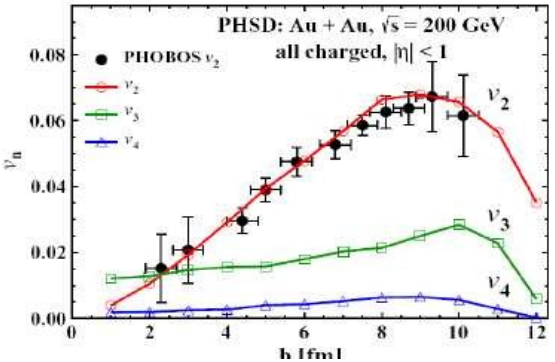
W. Cassing, E. Bratkovskaya, PRC 78 (2008) 034919; NPA831 (2009) 215; EPJ ST 168 (2009) 3; NPA856 (2011) 162.

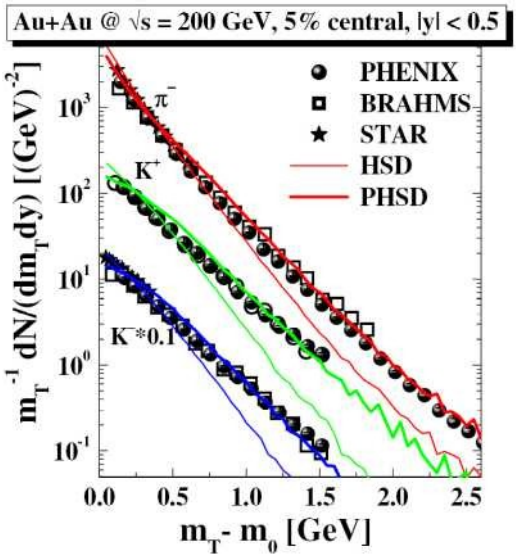
PHSD for HIC from AGS to RHIC (highlights)

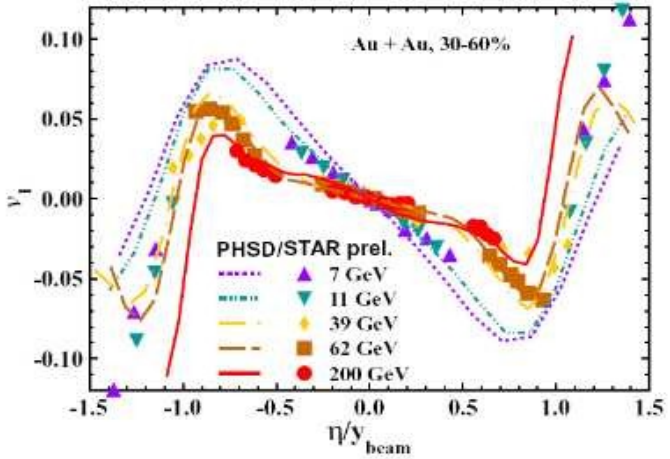


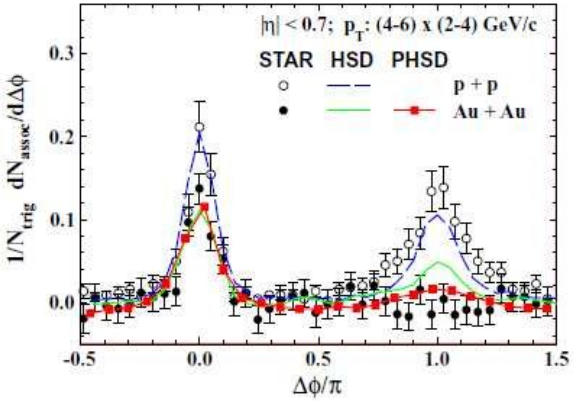








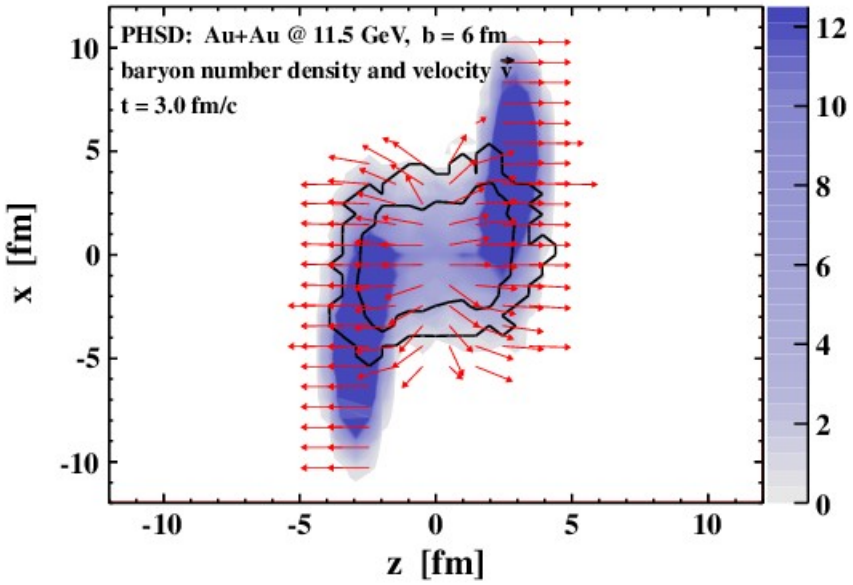




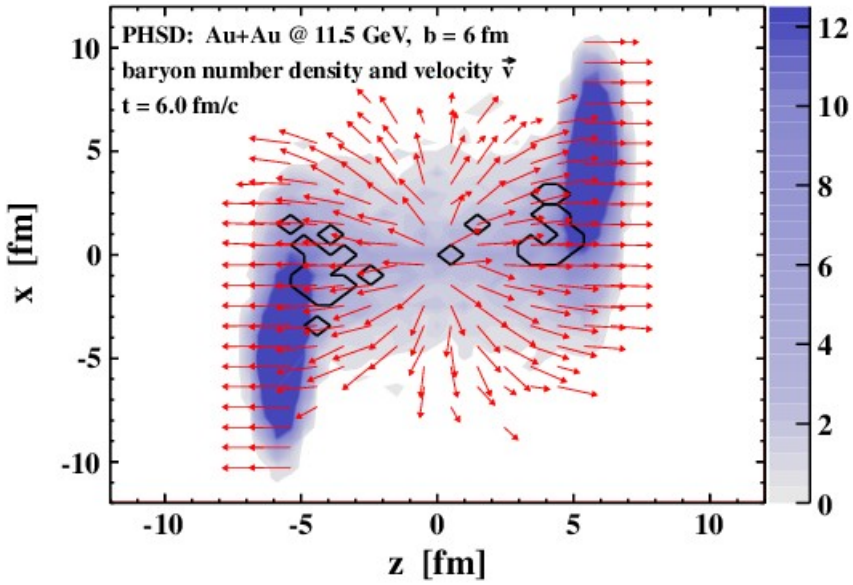
PHSD provides a consistent description of HIC dynamics

PHSD: snapshot of the reaction plane

t = 3 fm/c

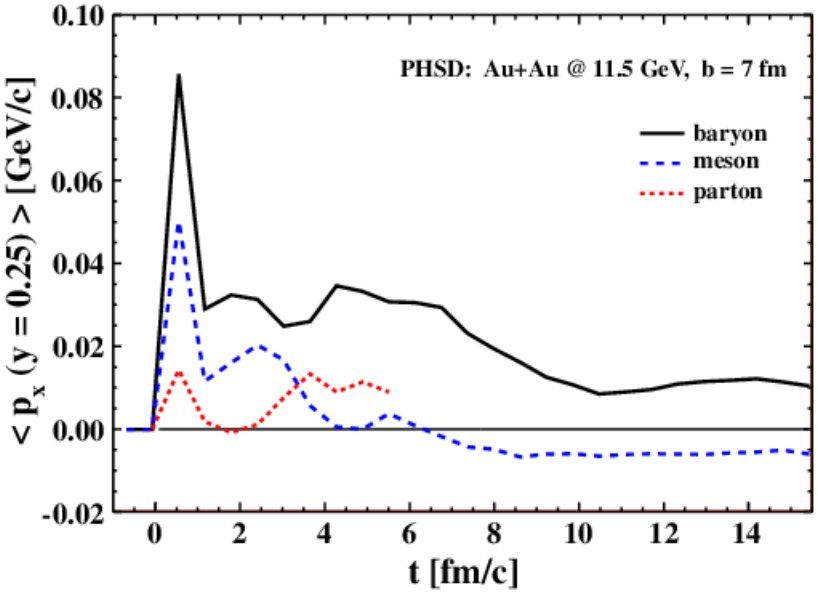


t = 6 fm/c



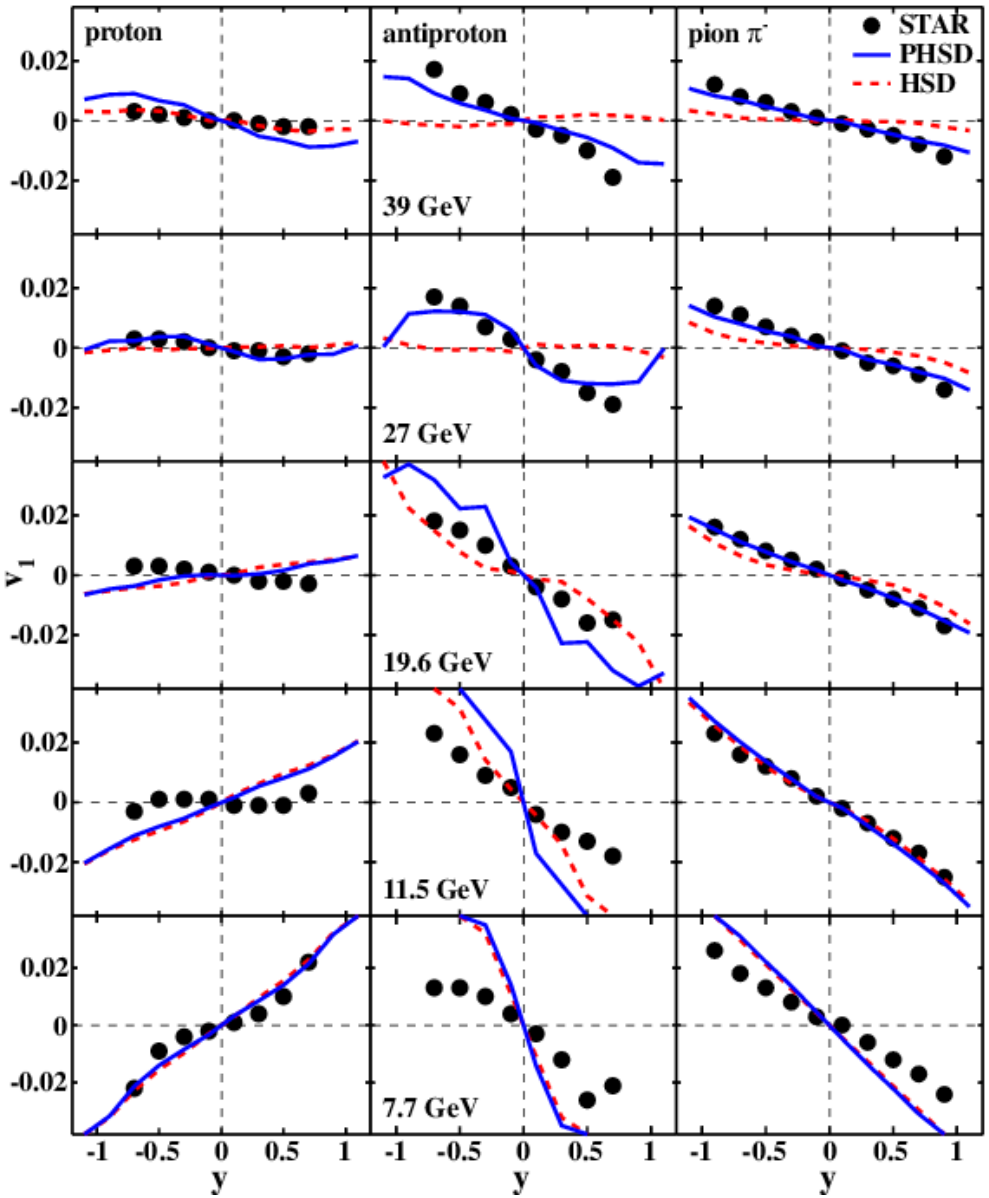
- **Color scale: baryon number density**
- **Black levels: parton density 0.6 and 0.01 fm^{-3}**
- **Red arrows: local velocity of baryon matter**

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

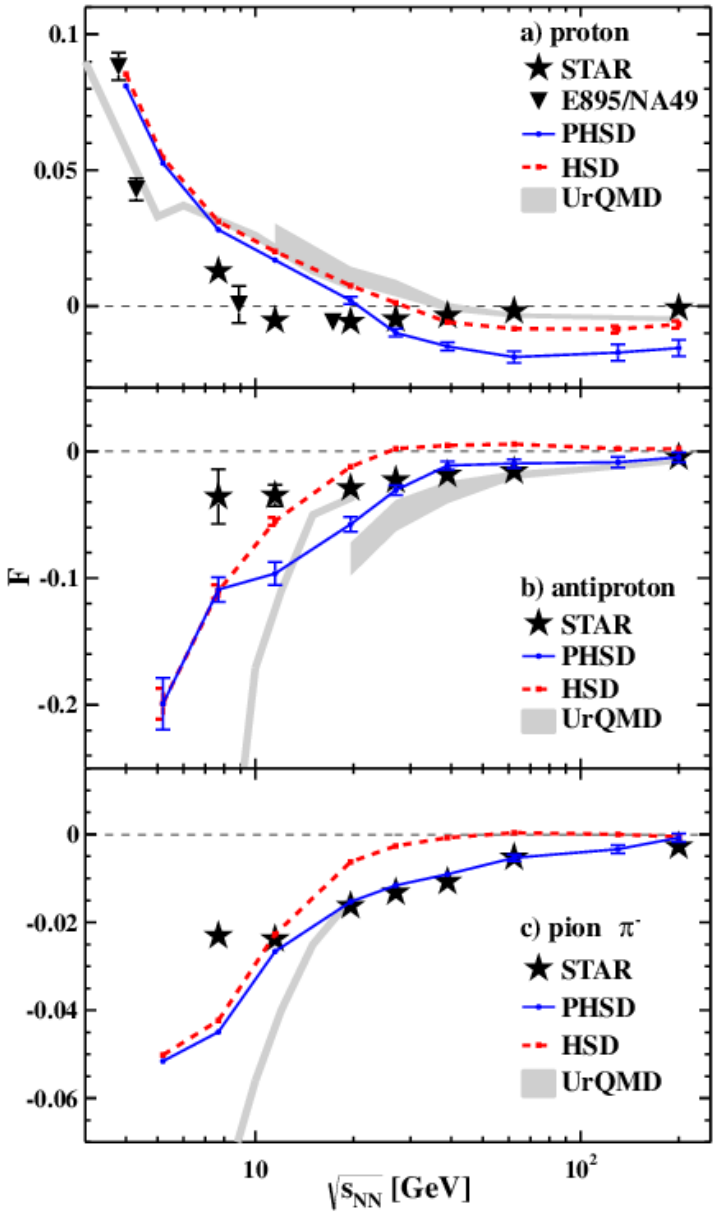
Directed flow from PHSD and HSD



- 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, arXiv:1401.3043

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

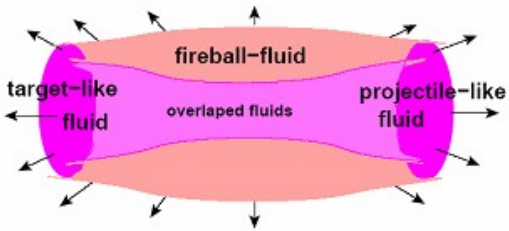
- UrQMD fail to reproduce pion and antiproton slopes

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

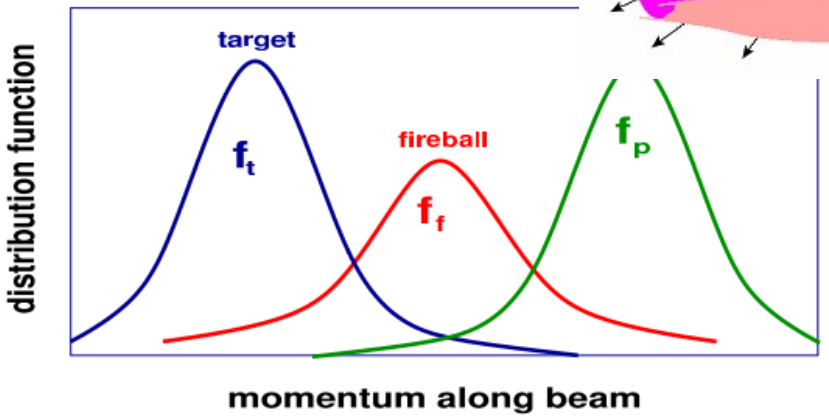
STAR Collaboration, arXiv:1401.3043

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

3-Fluid Dynamics



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



Target-like fluid: $\partial_\mu J_t^\mu = 0$ Leading particles carry bar. charge $\partial_\mu T_t^{\mu\nu} = -F_{tp}^\nu + F_{ft}^\nu$ exchange/emission

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

Fireball fluid: $J_f^\mu = 0,$ Baryon-free fluid $\partial_\mu T_f^{\mu\nu} = F_{pt}^\nu + F_{tp}^\nu - F_{fp}^\nu - F_{ft}^\nu$ Source term Exchange

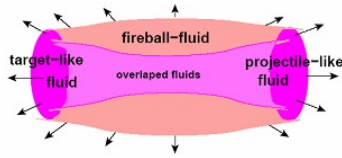
The source term is delayed due to a formation time $\tau \sim 1$ fm/c

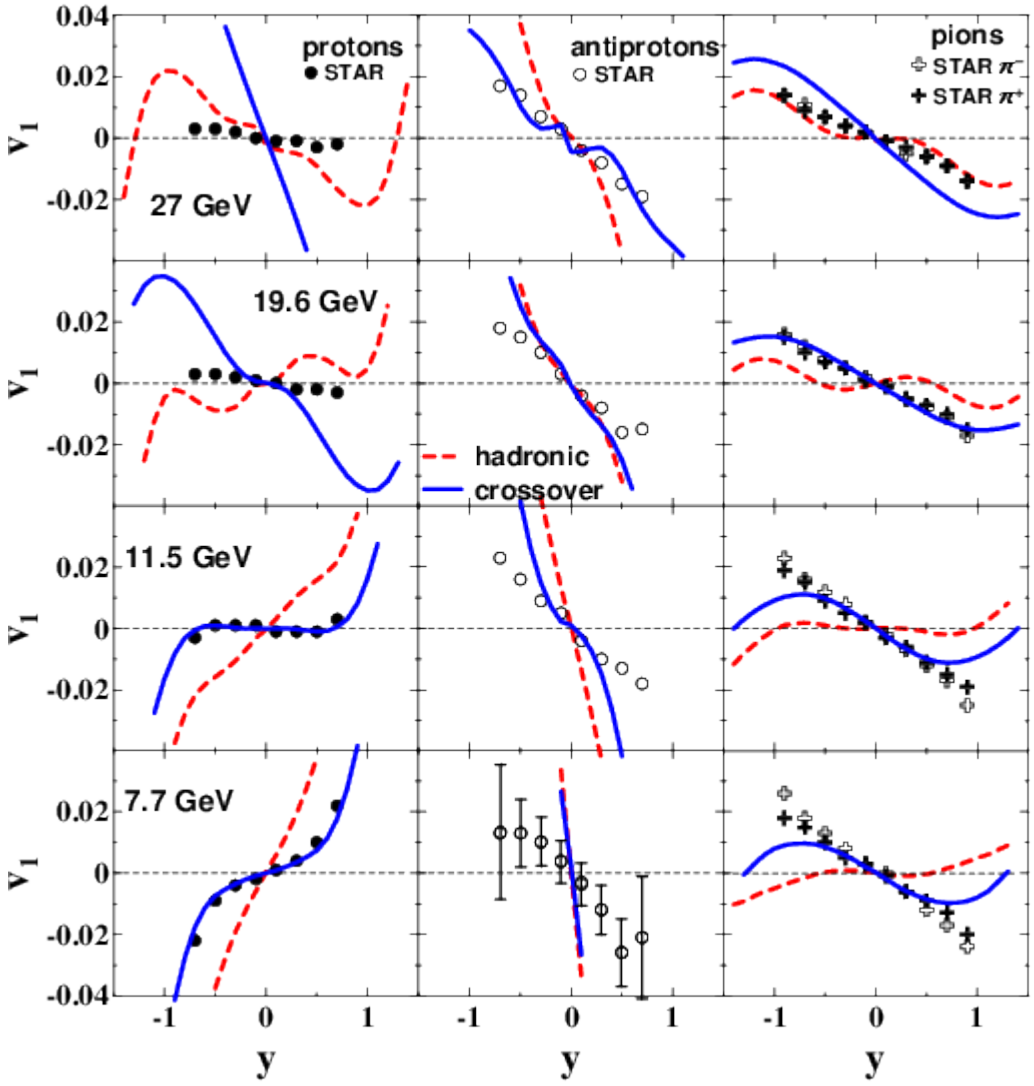
Total energy-momentum conservation:

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

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

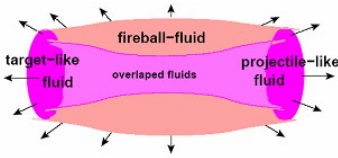
3FD: directed flow vs. EoS

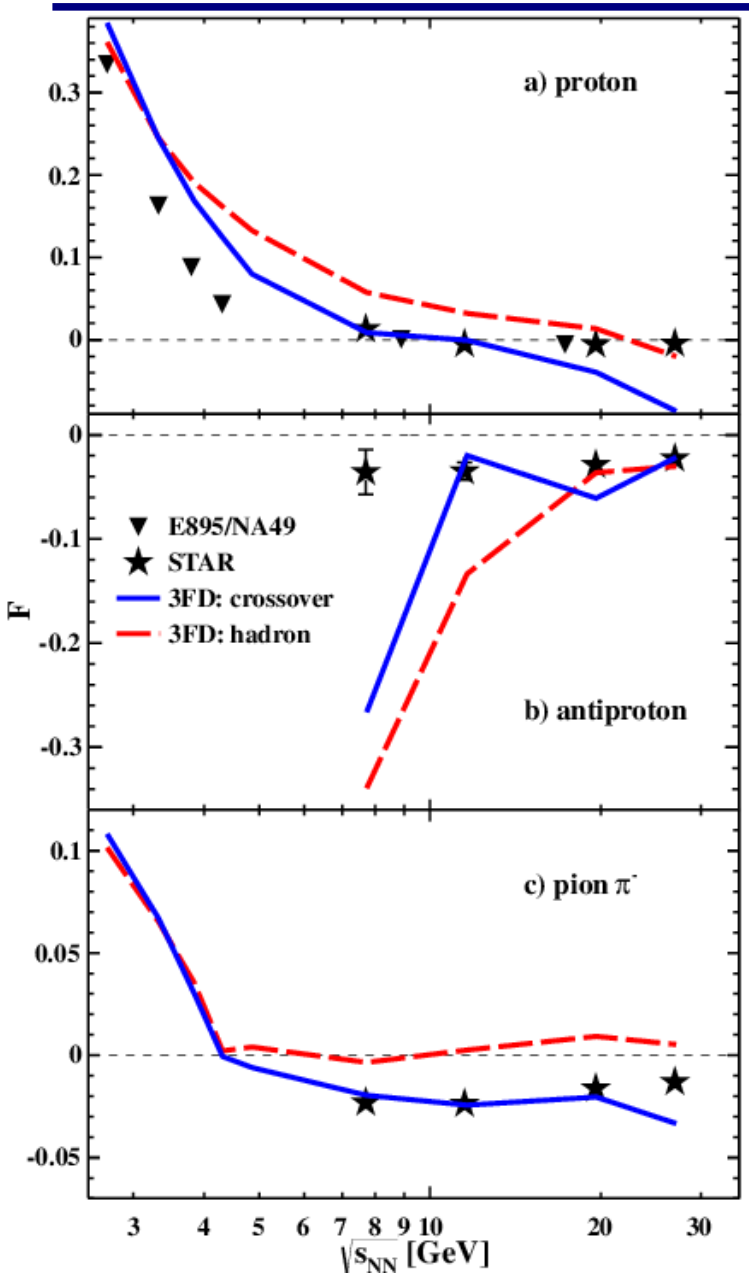




- Description of the STAR $v_1(y)$ is not very well and relatively worse then by the PHSD
- Crossover EoS agrees better with the experiment then the pure hadronic EoS

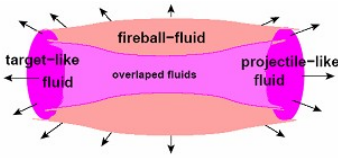
3FD: excitation function of v_1 slopes

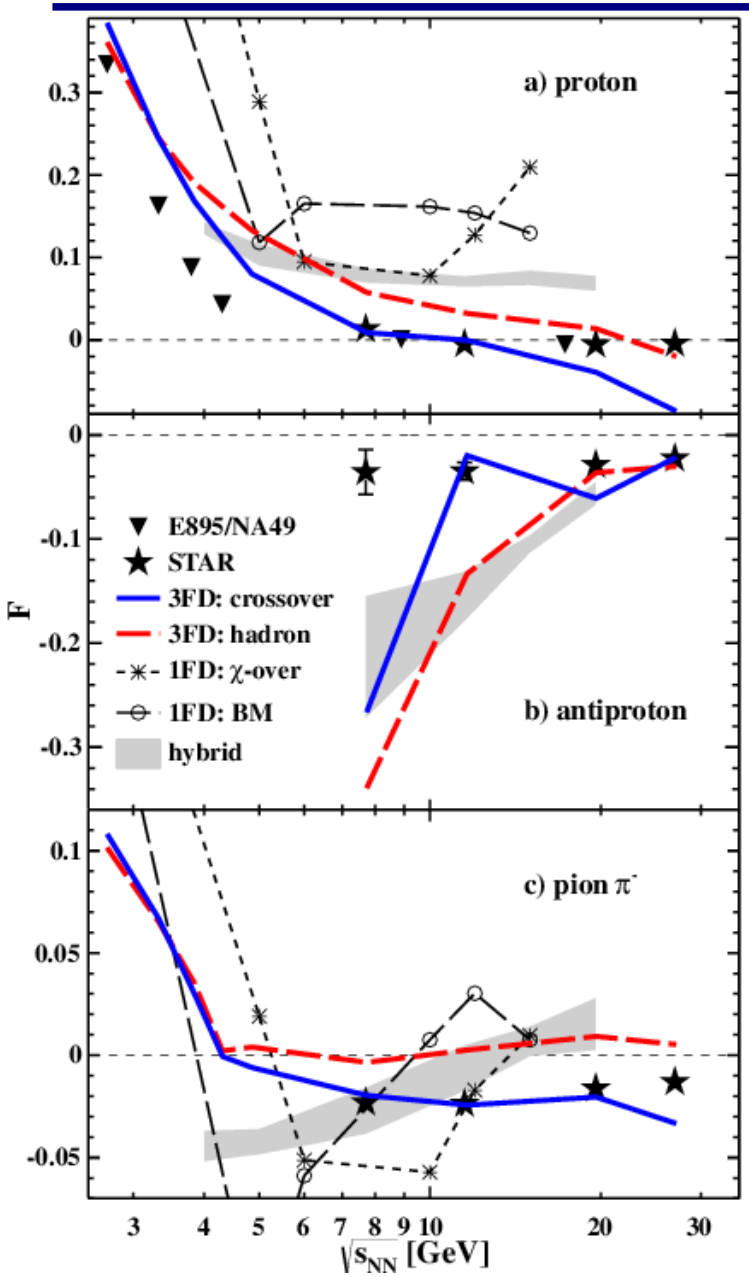




- 3-Fluid Dynamic approach (3FD) gives reasonable results for proton and pion slopes of v_1 and fail at 7.7 GeV for antiprotons
- Discrepancies between 3FD model and STAR data are smaller in case of crossover

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, [1402.7236]

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 $\sqrt{s}$ =7.7-39 GeV and leads to an almost quantitative agreement for protons, antiprotons and pions especially at higher energies. We don't see any "wiggle-like" 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

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