Particularities of the directed flow in the NICA energy range

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XXII Baldin ISHEPP
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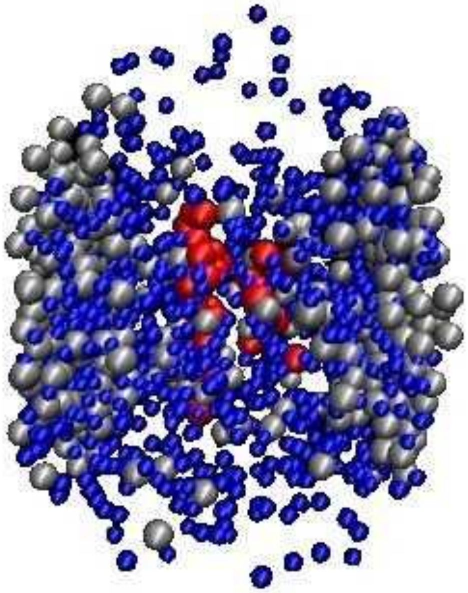
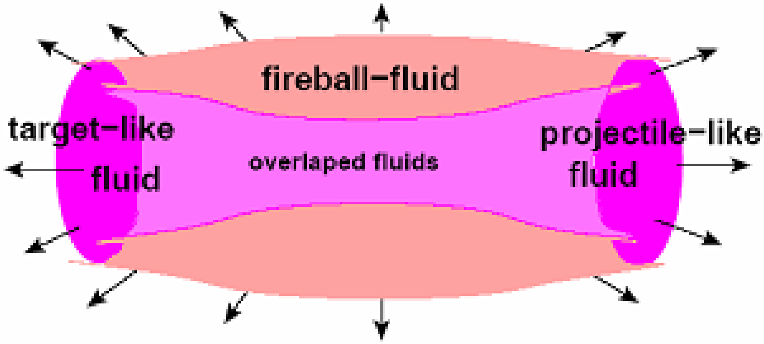
Content



- Prehistory of the directed flow in HIC
- New STAR results on the directed flow v_1
- Analysis of v_1 in the kinetic PHSD model
- Analysis of v_1 in hydrodynamic 3FD model
- Charge-depended directed flow in asymmetric collisions
- Conclusions



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

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

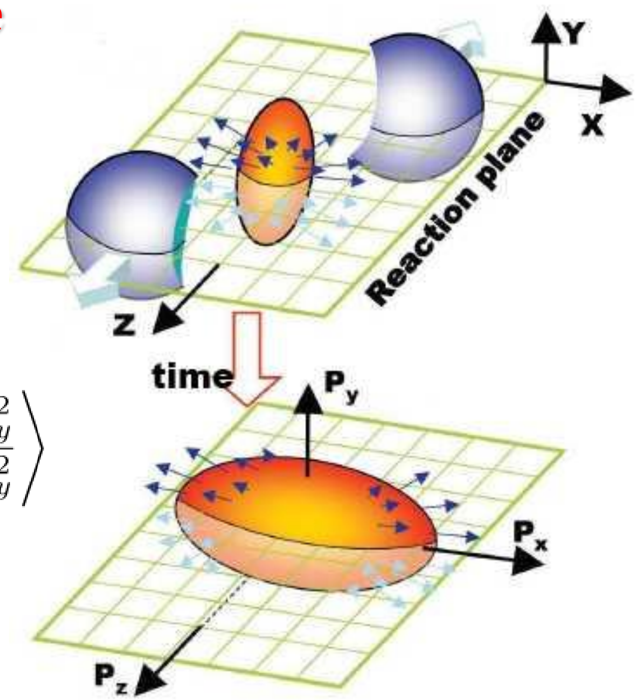
$$v_n = \langle \cos n(\varphi - \psi_n) \rangle, \quad n = 1,2,3..,$$

v_1: directed flow

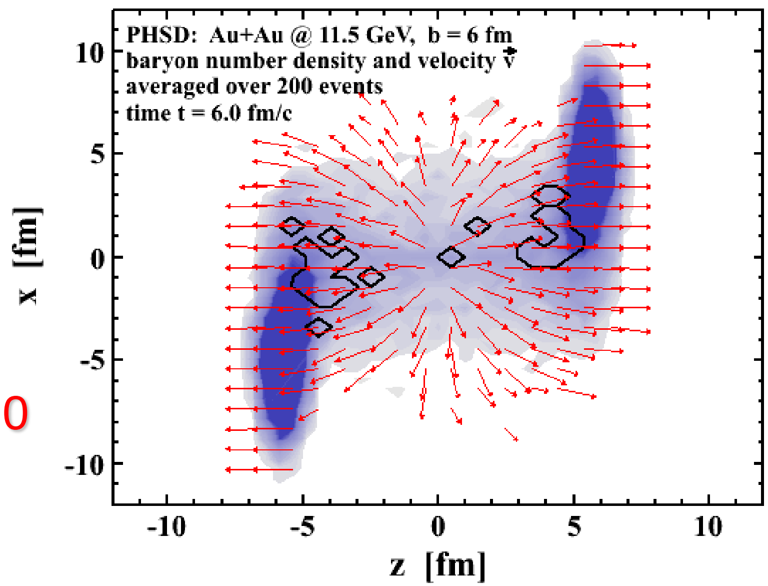
v_2: elliptic flow

v_3: triangular flow…..

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



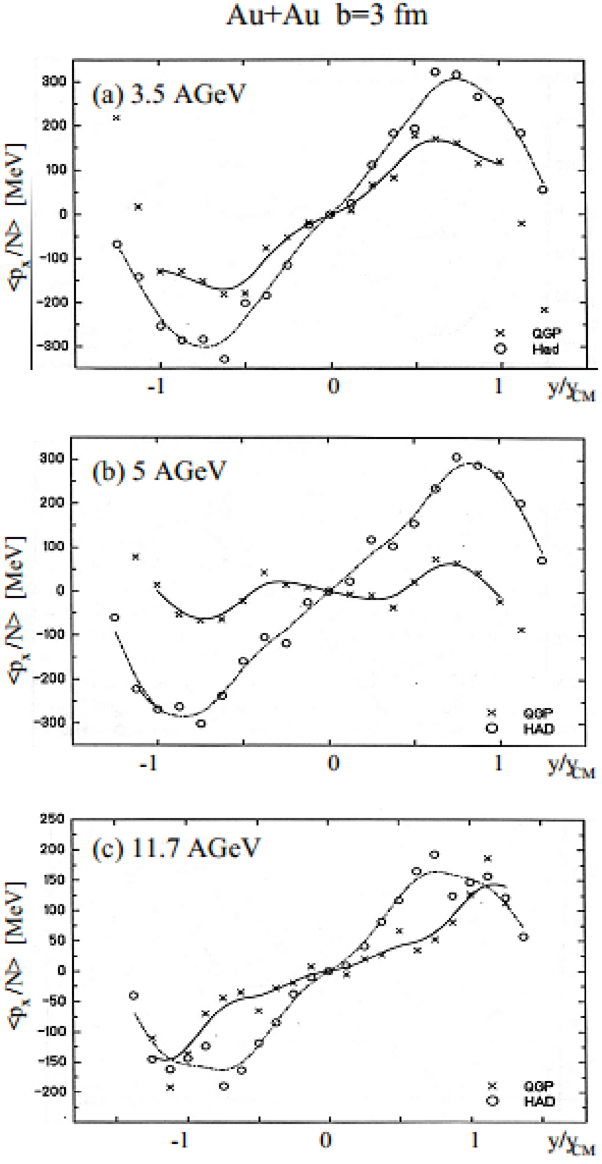
<px (y) / N>



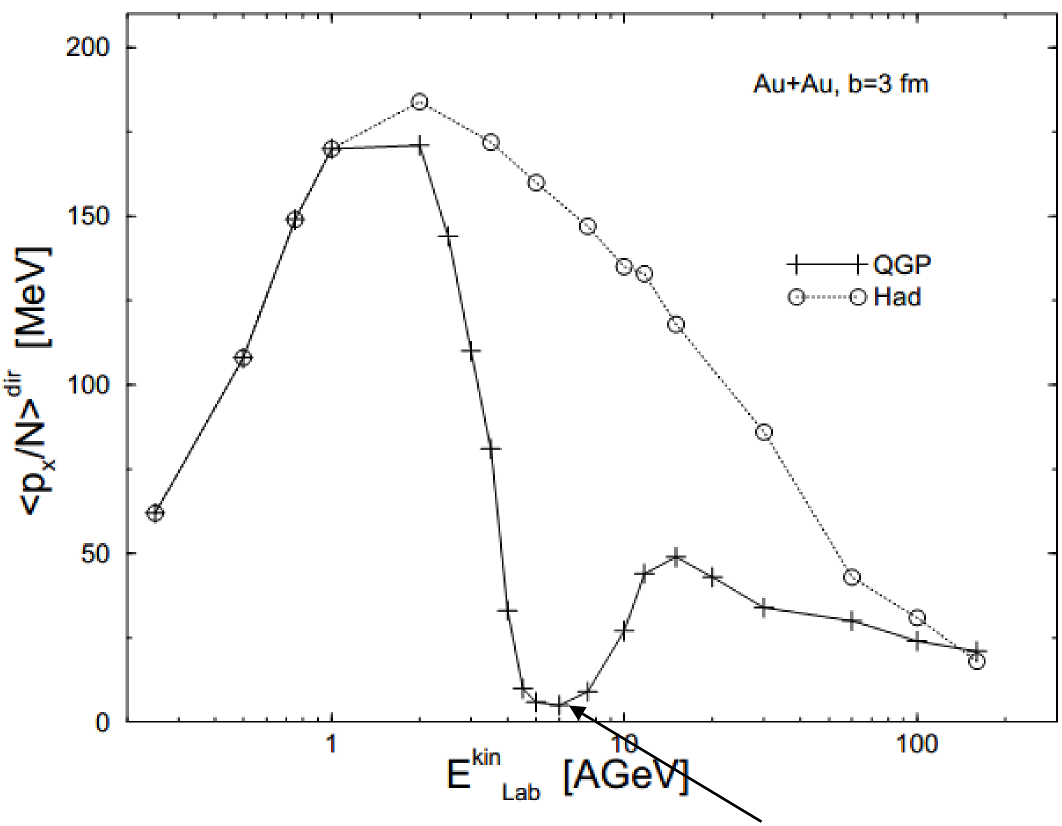
Directed flow $v_1 > 0$

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

Direct flow and Quark–Gluon Plasma



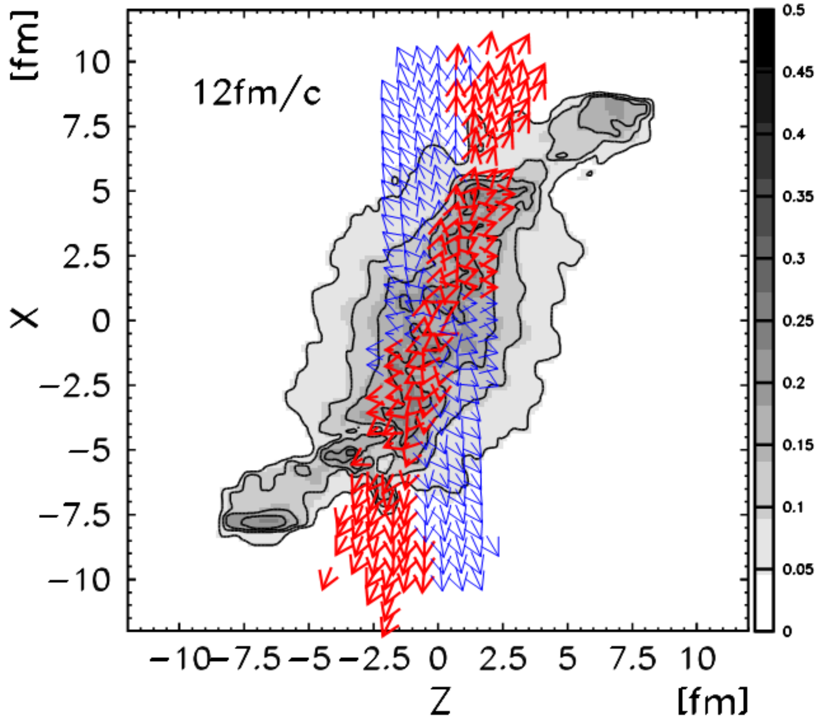
$$\langle p_x/N\rangle^{dir} = \frac{1}{N}\int_{-y_{CM}}^{y_{CM}} \mathrm{d}y\ \langle p_x/N\rangle(y)\ \frac{\mathrm{d}N}{\mathrm{d}y}\ \mathrm{sgn}(y)$$

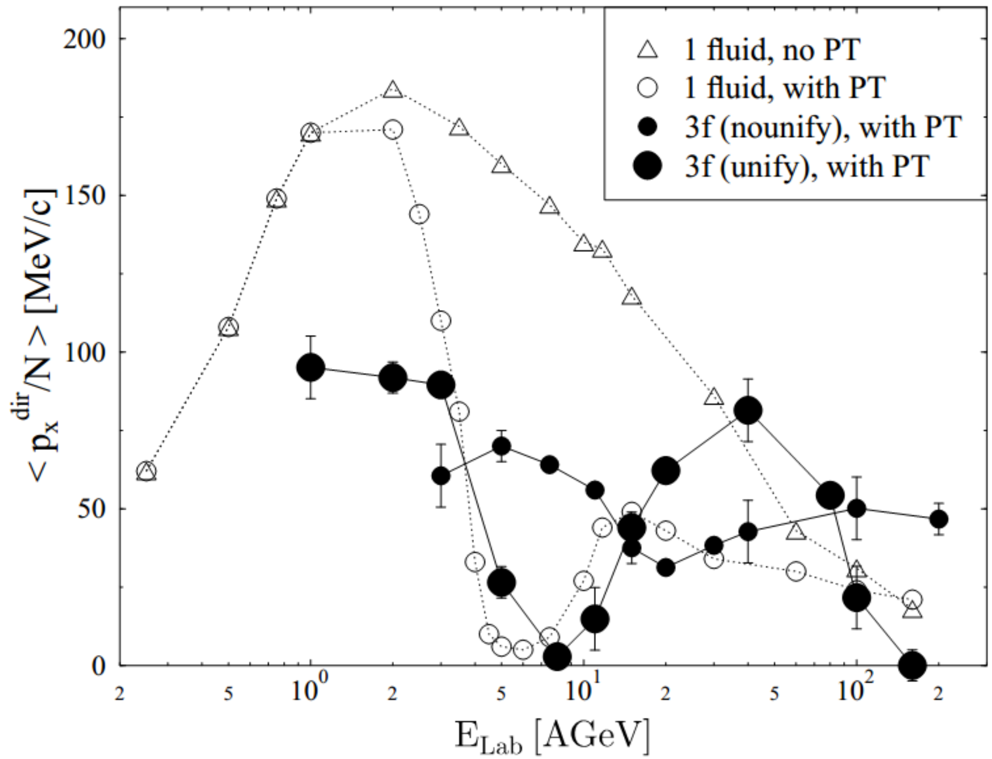


D.H. Rischke, Y. Pursun, J.A. Maruhn, H. Stoecker, W. Greiner, Heavy Ion Phys. **1**, 309 (1995)

Antiflow of nucleons at the softest point of the EoS

Au+Au (8 AGeV)

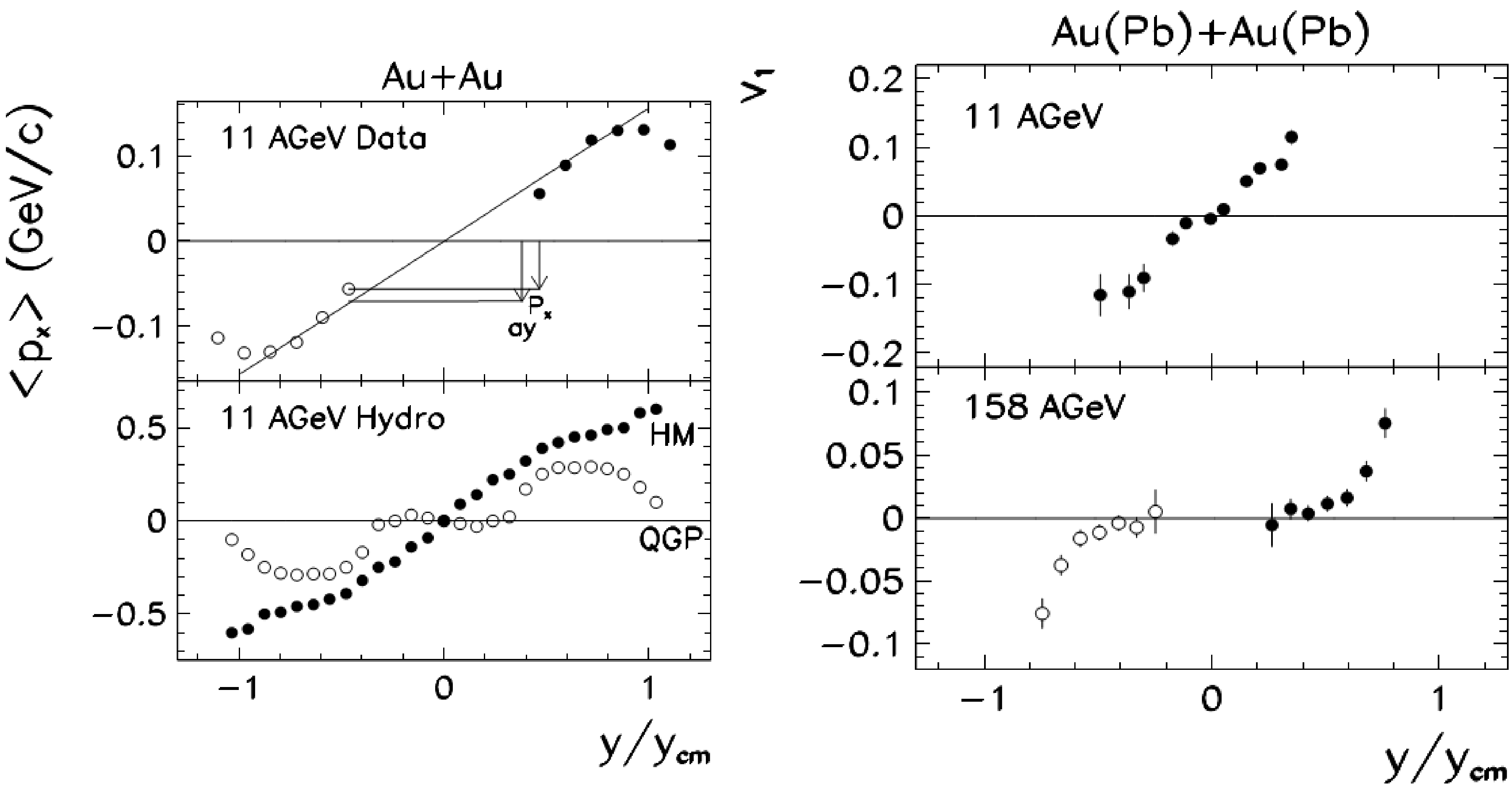




EoS is softened either by a phase transition to QGP,
or by the creation of resonances and string-like excitations

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

Third flow component as QGP signal

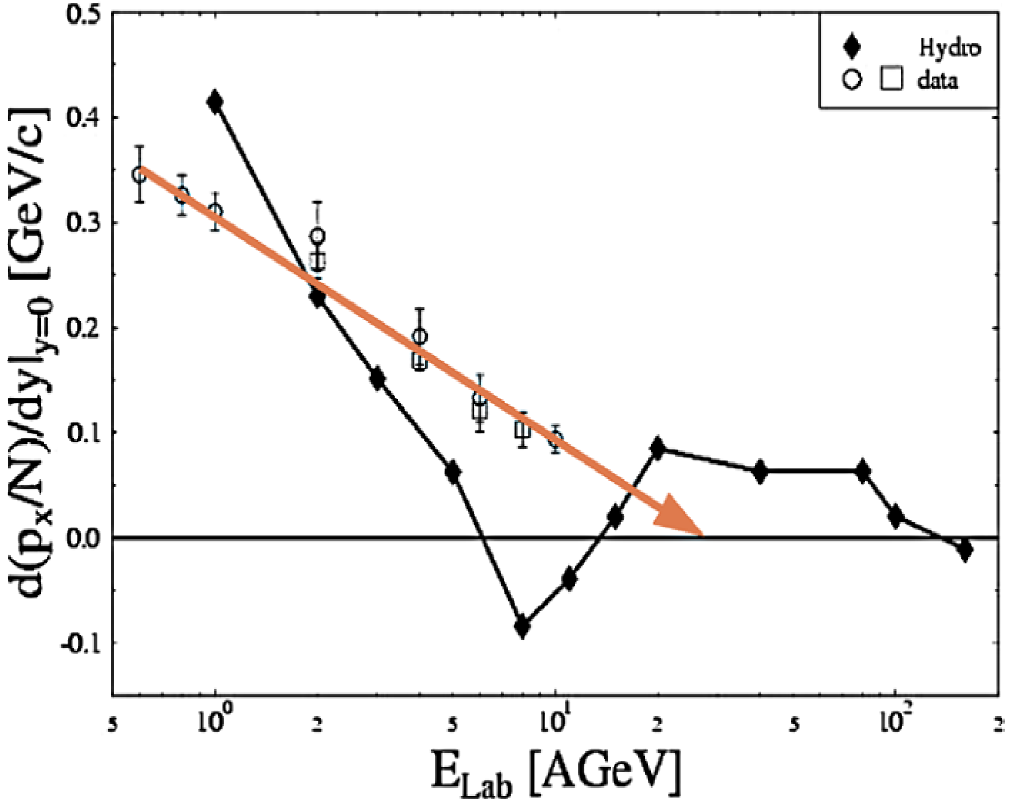


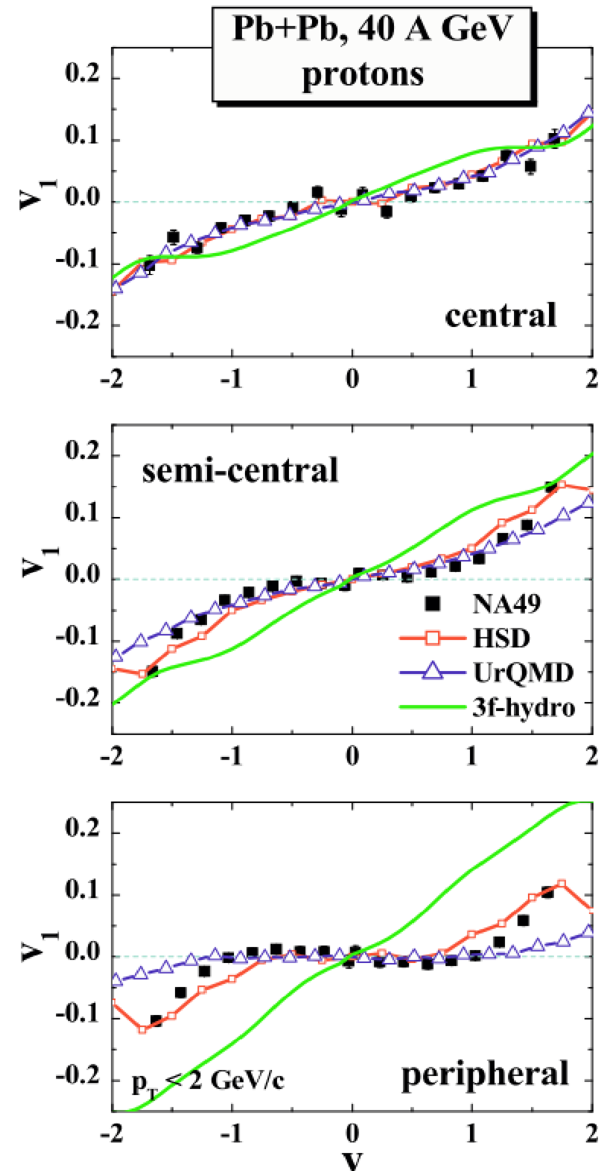
The effect shows up in the reaction plane as enhanced emission which is orthogonal to the directed flow.

L.P. Csernai and D. Roehrich, Phys. Lett. B458, 454 (1999) .

Collective flow signals of the Quark–Gluon Plasma

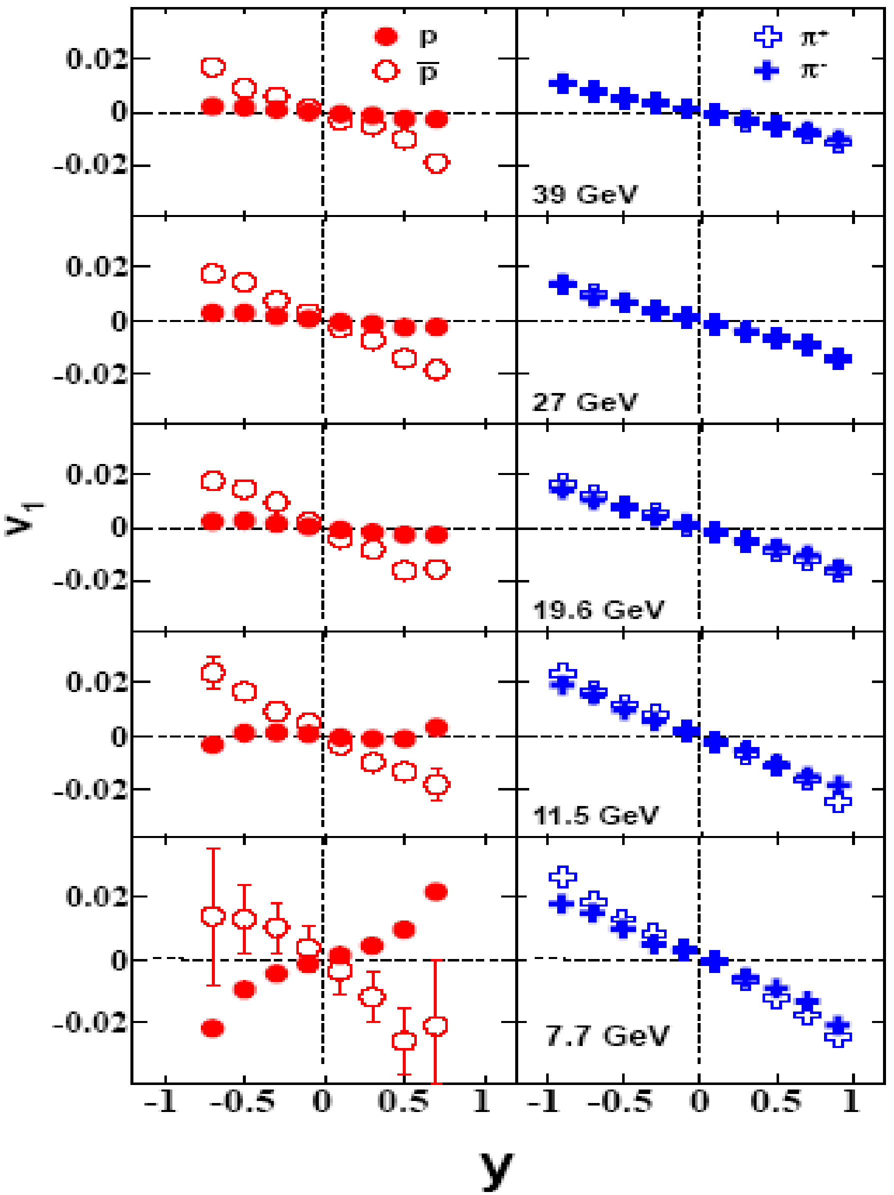
H. Stöcker, Nucl. Phys. A **750**, 121 (2005)

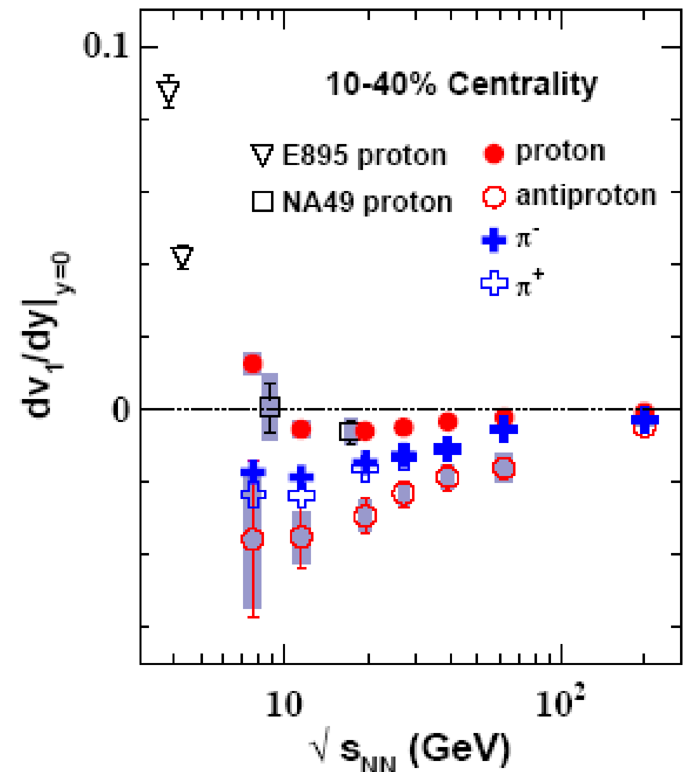




- Early hydro calculation predicted the "softest point" at E_{lab}= 8 AGeV
- A linear extrapolation of the data (the arrow) suggests a collapse of flow at E_{lab}≈ 30 AGeV

Recent measurements of v_1 of identified hadrons



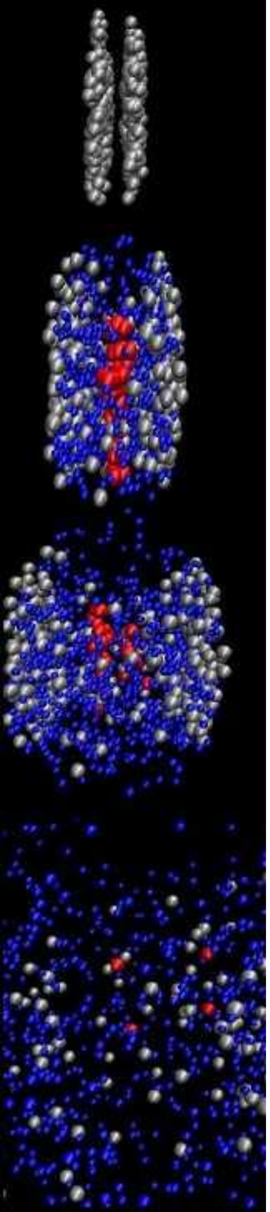


● measured distributions are smooth

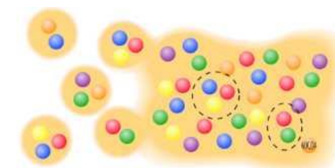
Statistical errors are shown and systematic bars are shaded

STAR Collaboration, PRL **112**, 162301 (2014)

Parton Hadron String Dynamics



I. From hadrons to QGP: (Kadanoff-Baym eqs.)



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

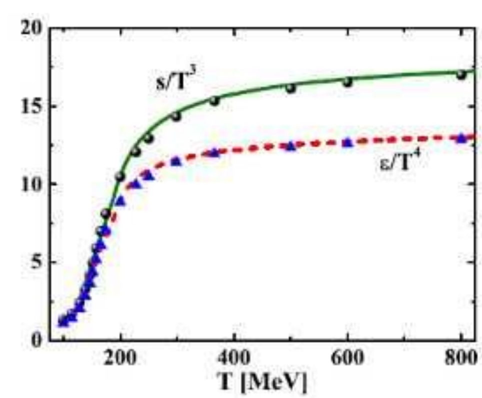
- Formation of QGP stage by dissolution of pre-hadrons into massive colored quarks + mean-field energy based on the Dynamical Quasi-Particle Model (DQPM)

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

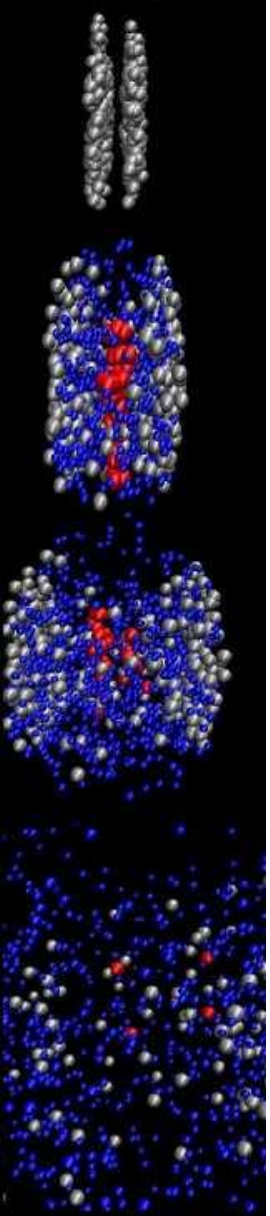
which defines quark spectral functions, masses $M_q(\varepsilon)$ and widths $\Gamma_q(\varepsilon)$ + mean-field potential U_q at given ε – local energy density (related by lQCD EoS to *T* - temperature in the local cell)

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.



Parton Hadron String Dynamics



II. Partonic phase - QGP:

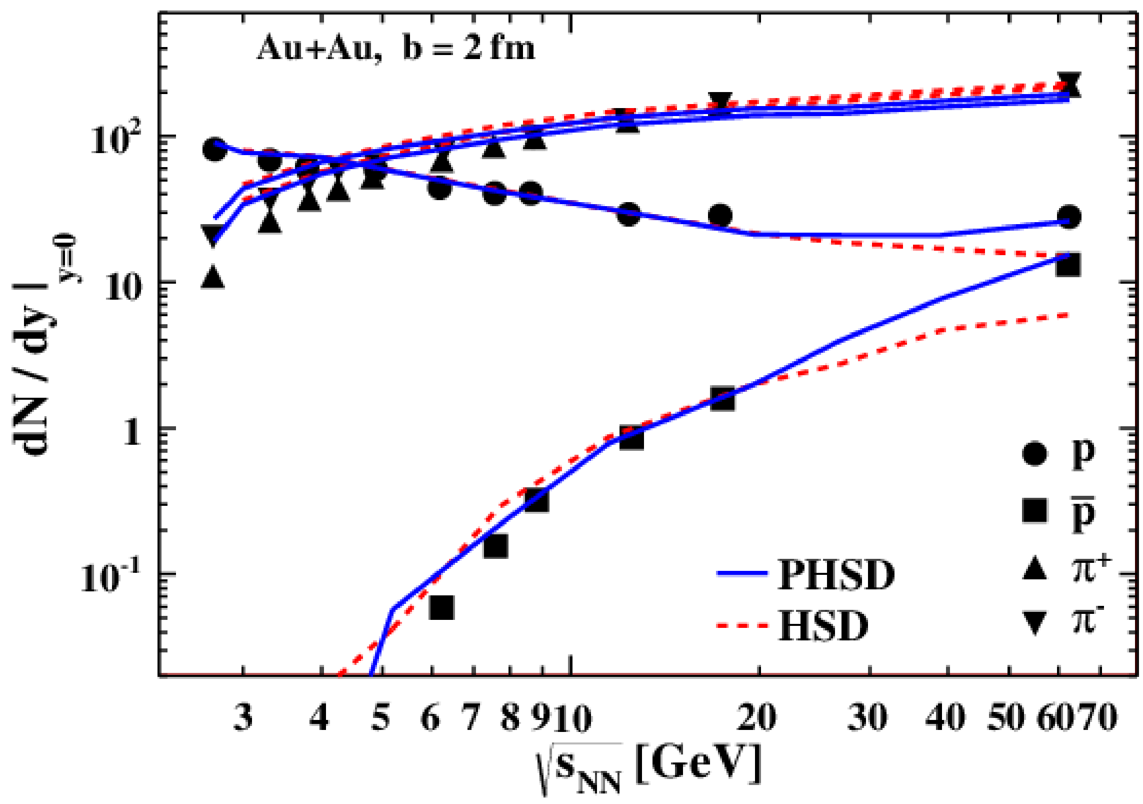
- in self-generated mean-field potential for quarks and gluons U_q, U_g from the DQPM
- EoS of partonic phase: ‚crossover' from lattice QCD (fitted by DQPM)
- (quasi-) elastic and inelastic parton-parton interactions:
  using the effective cross sections from the DQPM
- quarks and gluons (= ‚dynamical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

PHSD: multiplicities at midrapidity

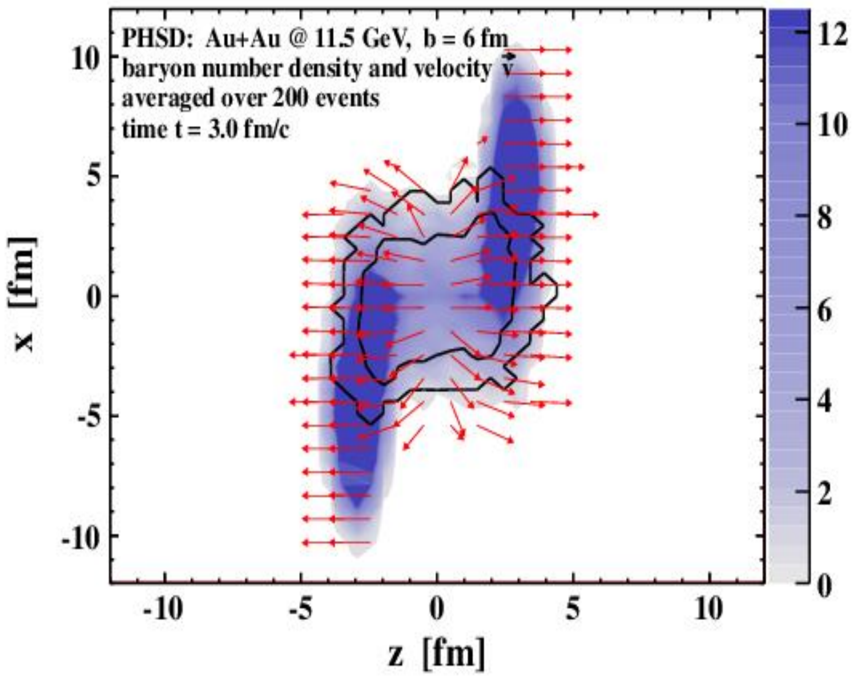


- Transport approach works reasonably good
- Deviations from the data appear for HSD at $\sqrt{s}$ > 20 GeV

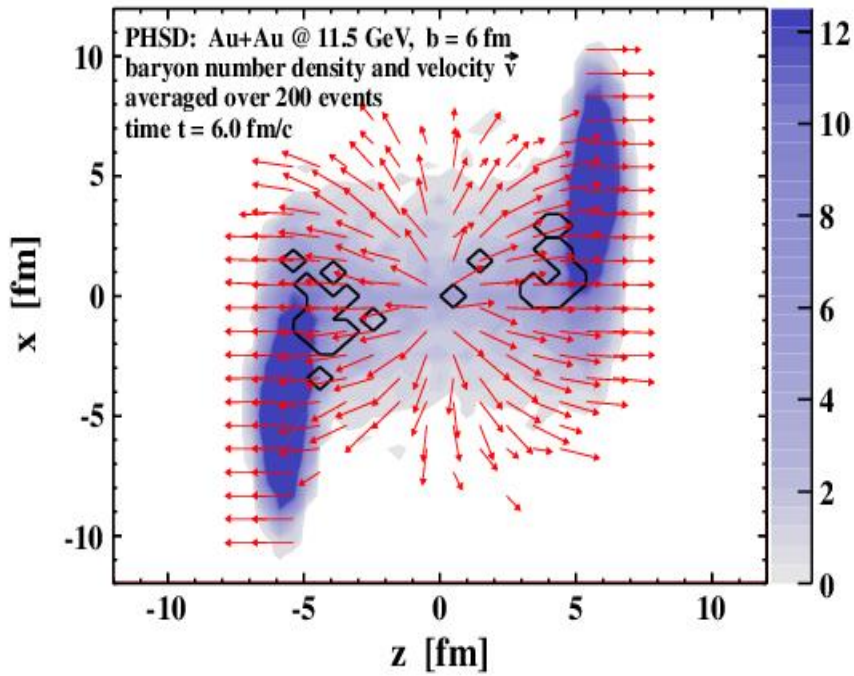
A. Andronic, P. Braun-Munzinger and J. Stachel, Nucl. Phys. **A772,** 167 (2006)

PHSD: snapshot of the reaction plane

t = 3 fm/c

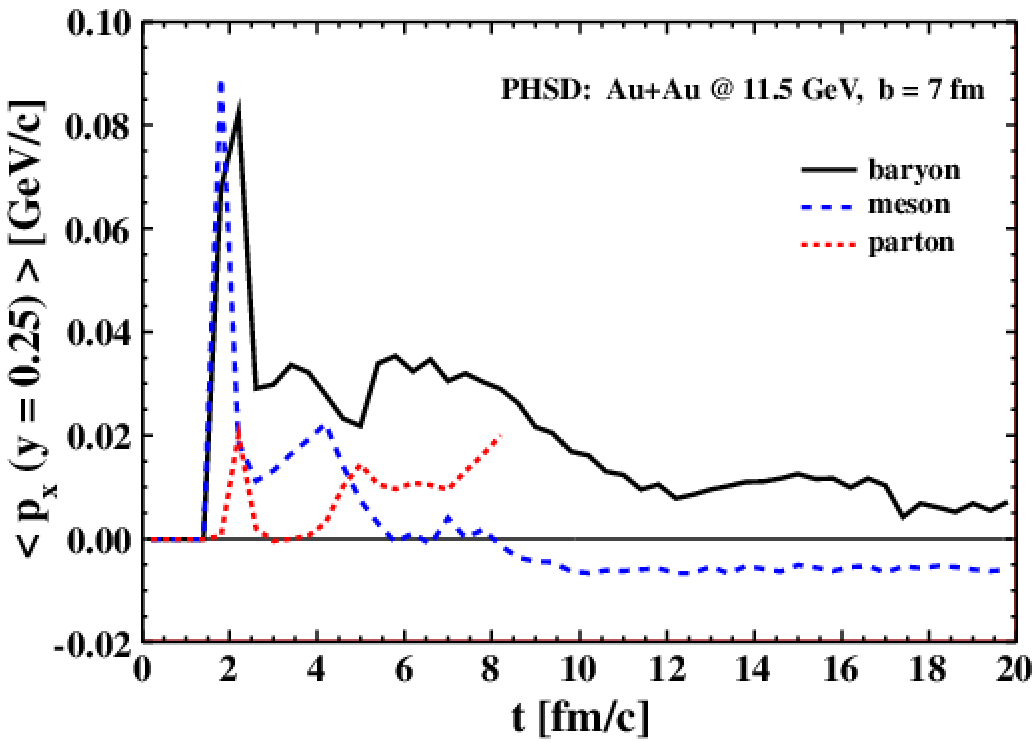


t = 6 fm/c



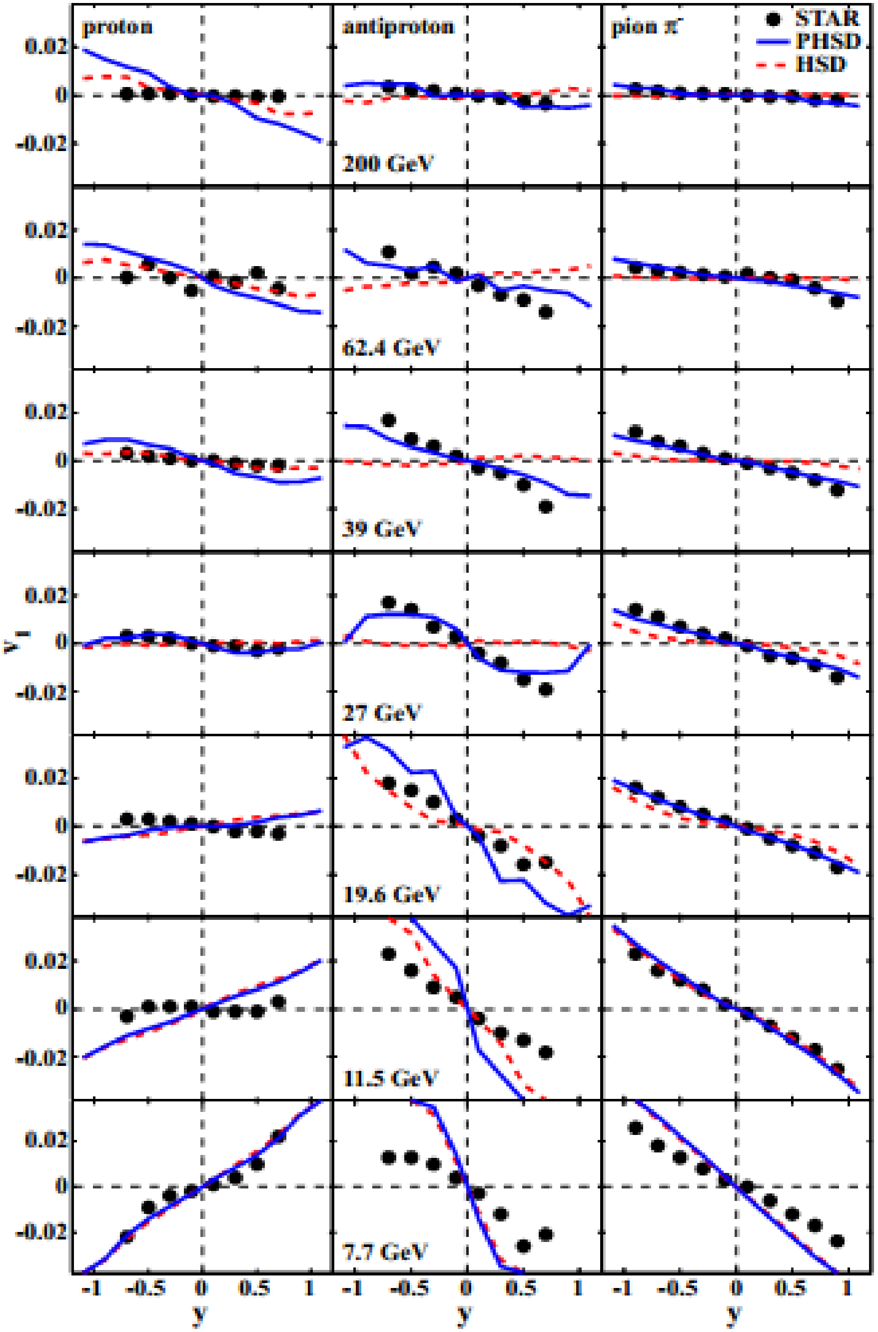
- Color scale: baryon number density
- Black levels: parton density 0.6 and 0.01 fm^{-3}
- Red arrows: local velocity of baryon matter

PHSD: <p_x / N> 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

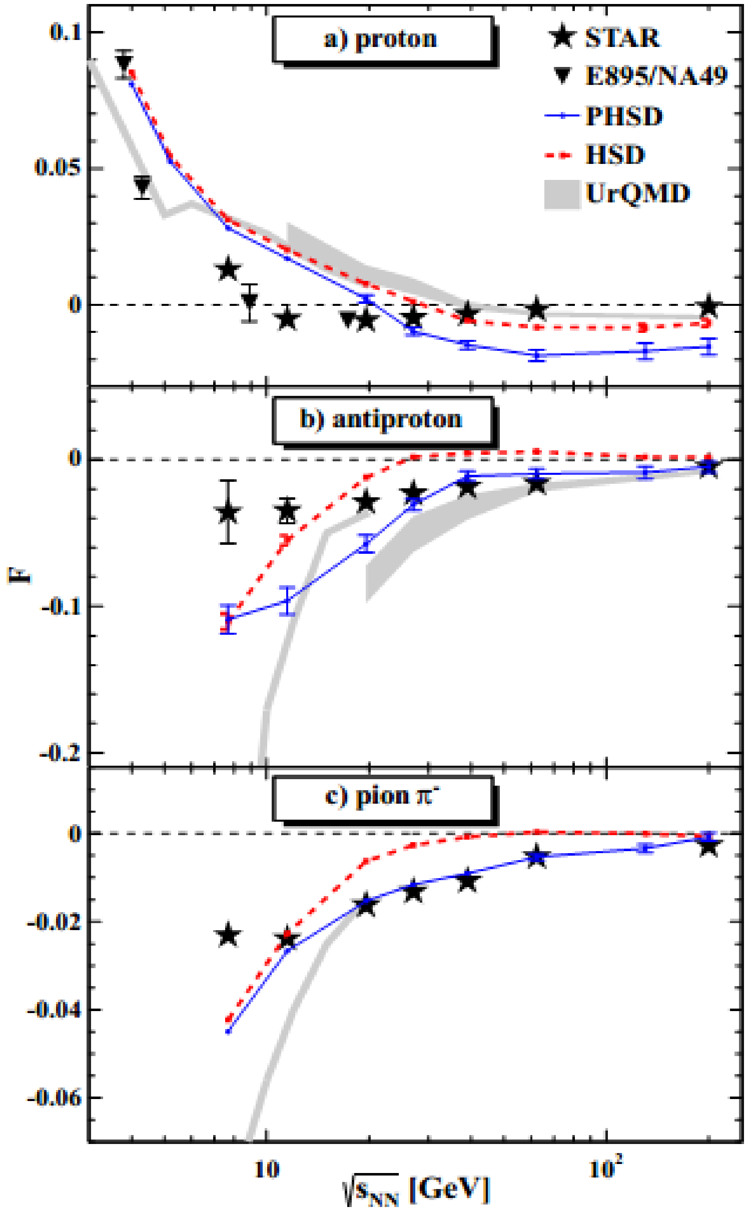
Directed flow from PHSD/HSD



- Both models HSD and PHSD reproduce general trends of recent 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**, 162301 (2014)

PHSD: Characteristic slope of $v_1(y)$



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

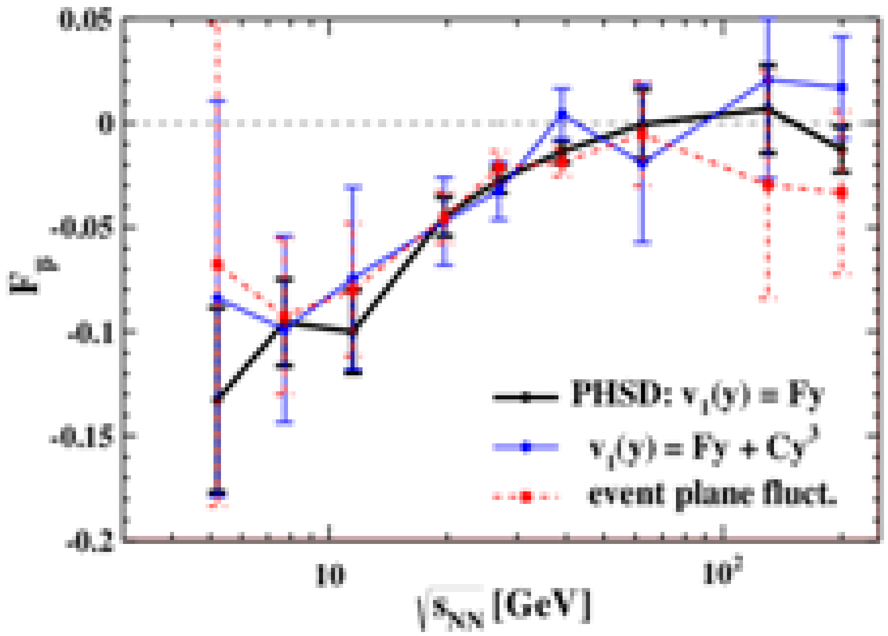
$$F = \left.\frac{dv_1}{dy}\right|_{y=0}$$

is used to characterize the 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 the STAR data at $7 < \sqrt{s} < 15$ GeV; HSD results are close to UrQMD
- UrQMD model fails to reproduce pion and antiproton slopes
- PHSD/HSD work better due to including inverse processes for antiproton annihilation

STAR Collaboration, PRL **112**, 162301 (2014)

Stability of the obtained slopes



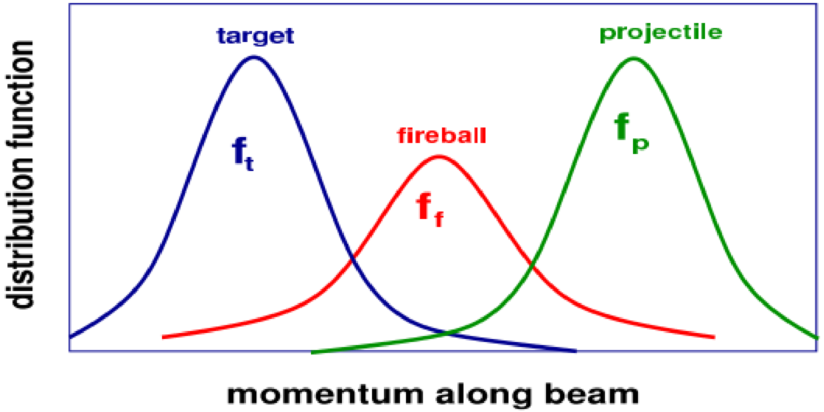
- Fluctuation of determined experimentally event plane doesn't change the result.
- Addition of cubic term to the fit $v_1(y) = Fy + Cy^3$ gives similar result but increase uncertainties.

3-Fluid Dynamics

Produced particles populate mid-rapidity

$\Rightarrow$ fireball fluid

$$f(x,p) = \sum_{j}^{M} f_j(x,p)$$



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:

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

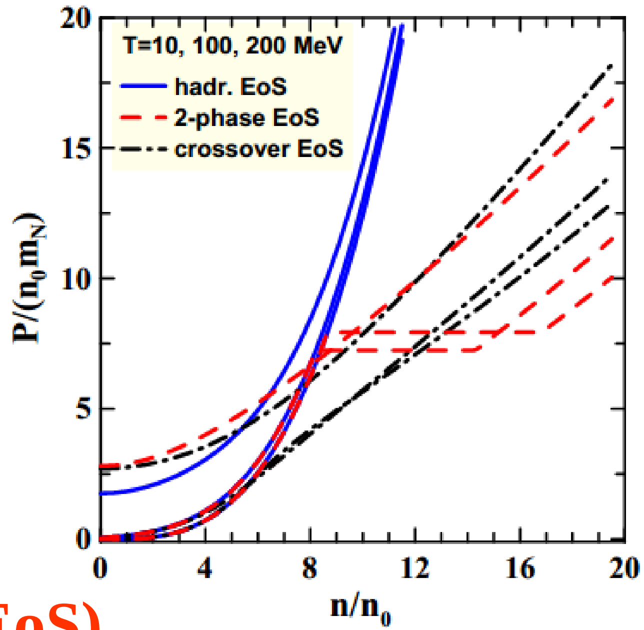
Yu.B. Ivanov, V.N. Russkikh and V.D. Toneev, Phys. Rev. **C73**, 044904 (2006)

Physical input

Equation of state (EoS)

Hadronic EoS (hadr-EoS)

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

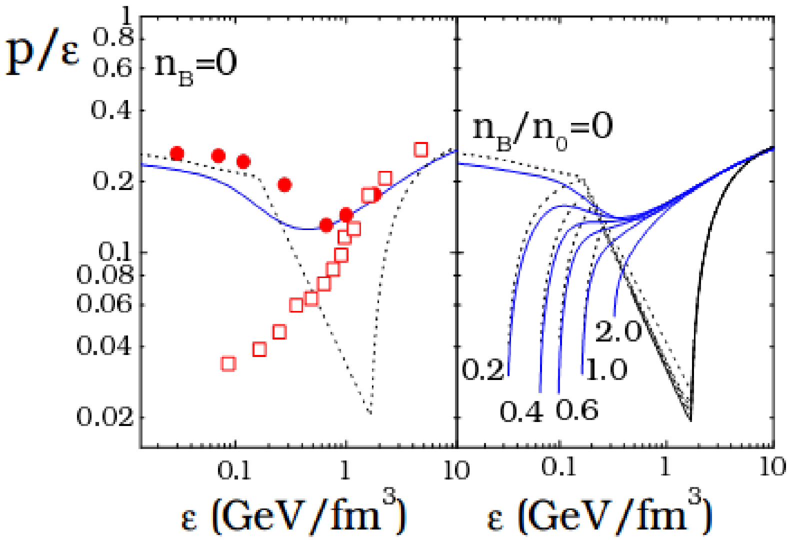


Crossover EoS

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

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

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

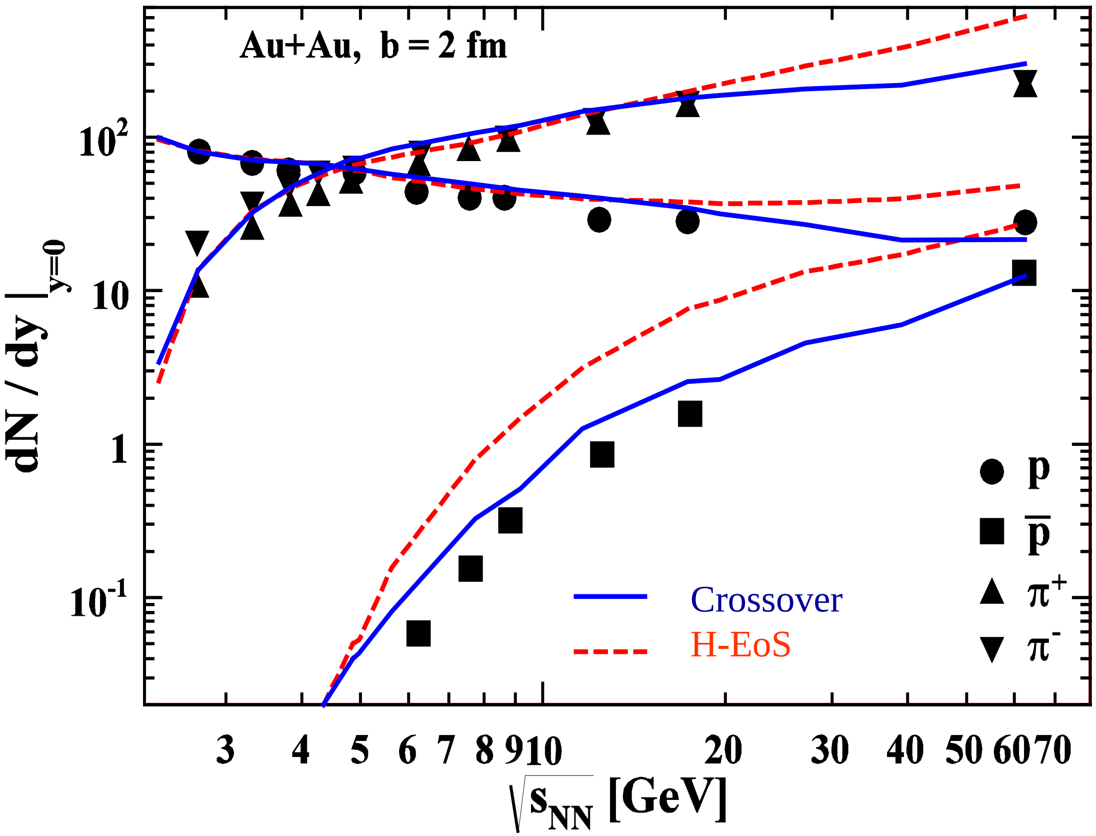


Phase transition ↔ EoS softening

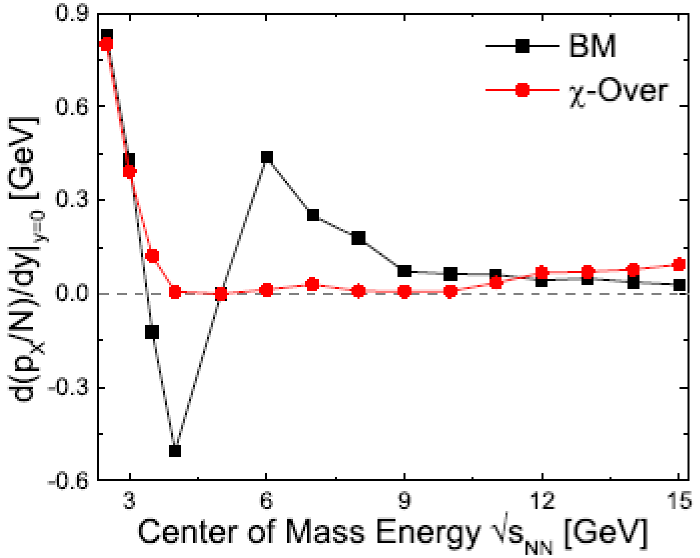
(in dense baryon matter)

- Freeze-out energy density: ε_{frz} =0.4 GeV/fm^3
- Friction: estimated and tuned
- Formation time: τ=2 fm/c for H-EoS and τ=0.33 fm/c for 2ph-EoS

3FD: multiplicities at midrapidity



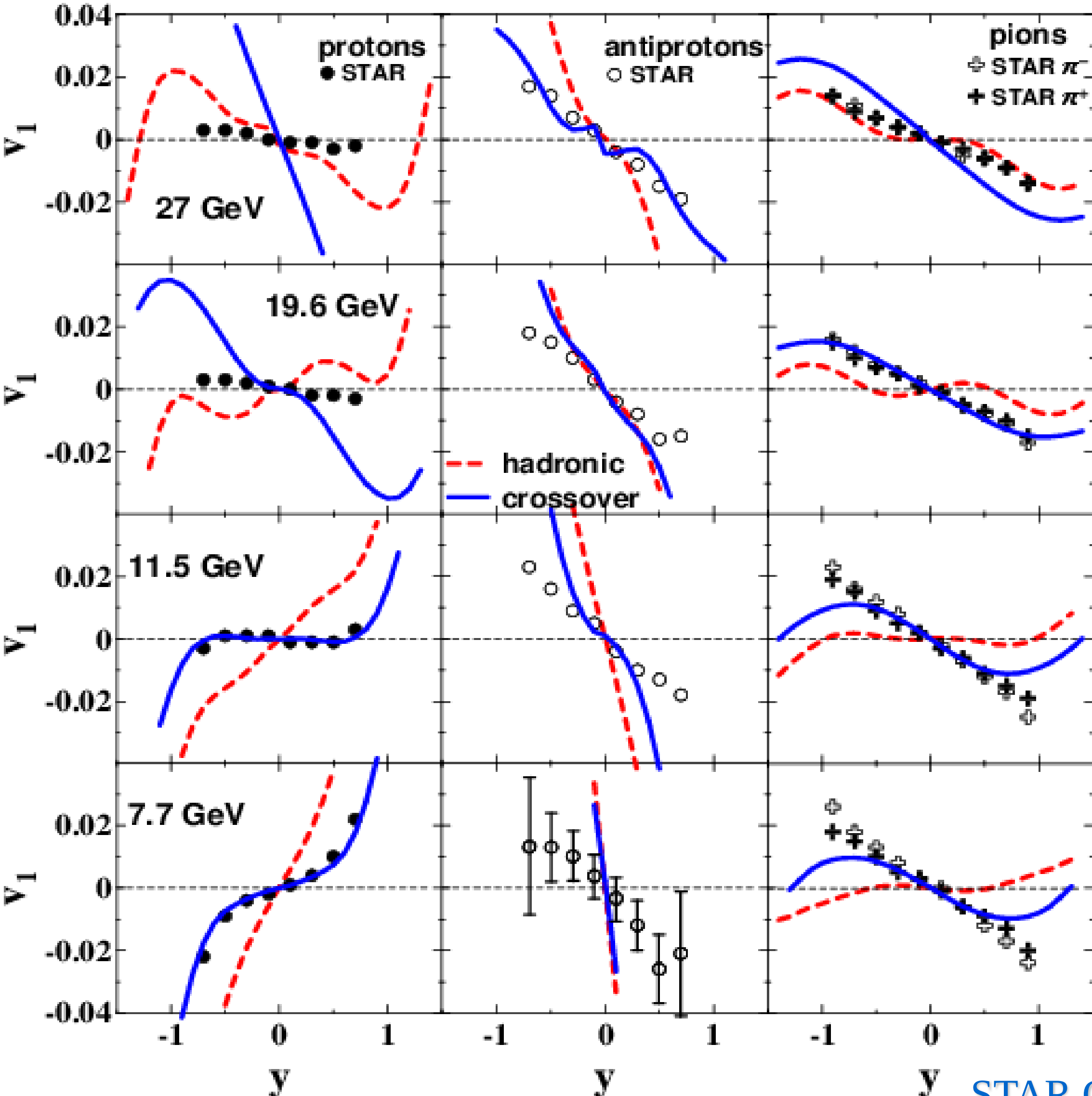
A. Andronic, P. Braun-Munzinger and J. Stachel, Nucl. Phys. **A772,** 167 (2006)



arXiv:1402.7236

- Hydro approach works reasonably good
- Deviations from data appear for H-EoS at √s > 20 GeV and antiproton yield is overestimated regularly. Crossover is OK.

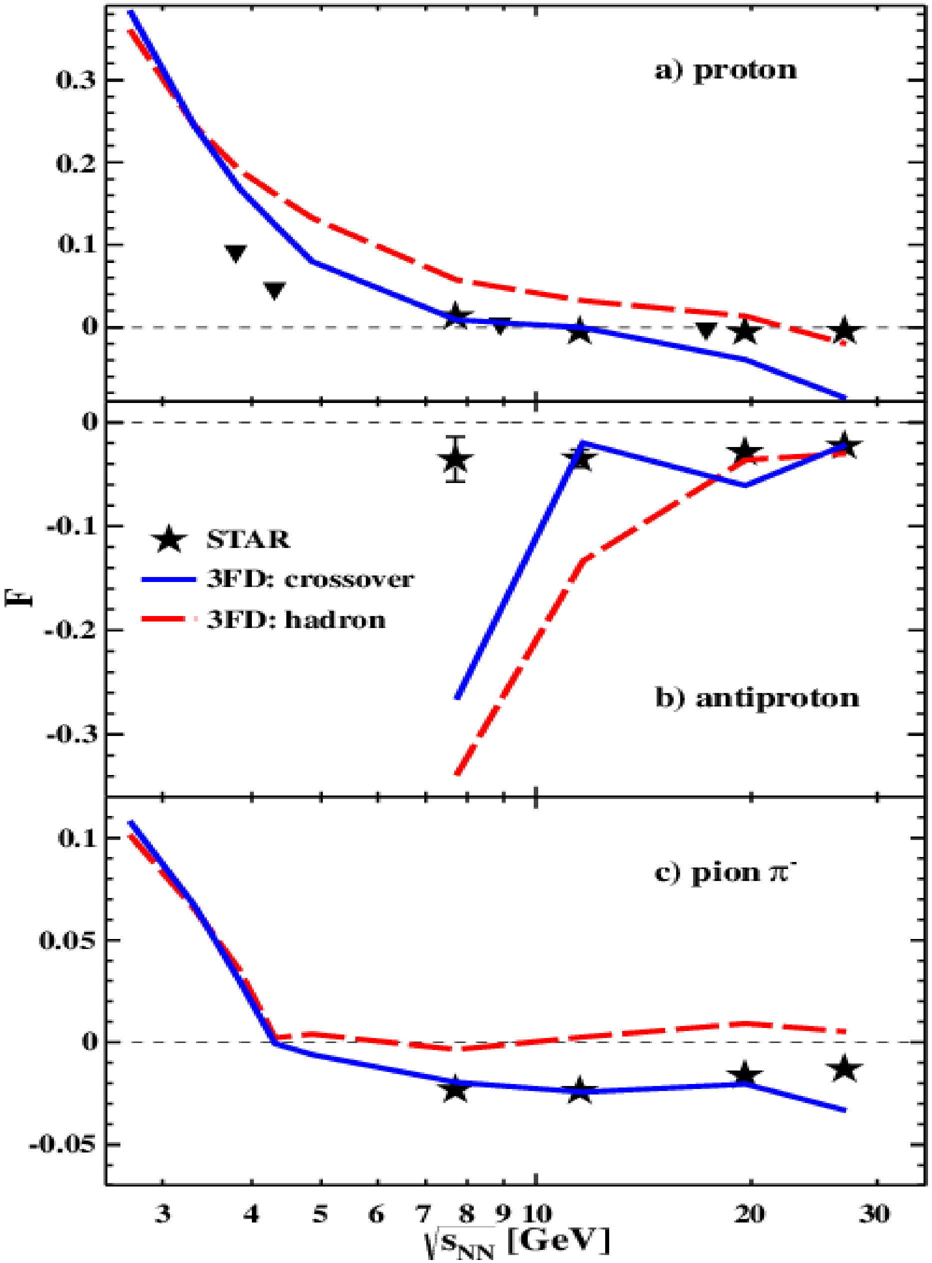
3FD: directed flow vs. EoS



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

STAR Collaboration, PRL **112**, 162301 (2014)

3FD: excitation function of v_1 slopes

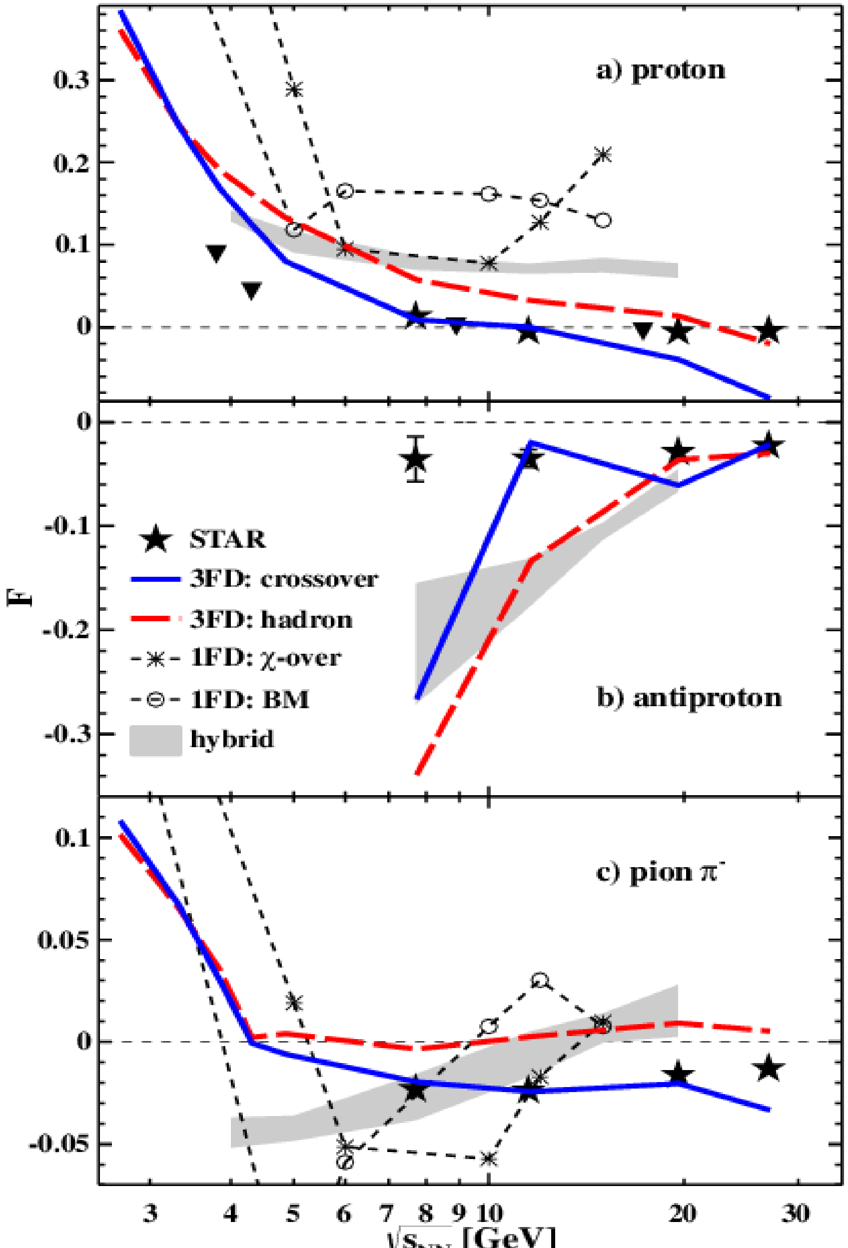


3-Fluid Dynamics

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

STAR Collaboration, PRL **112**, 162301 (2014)

3FD: comparison with other models

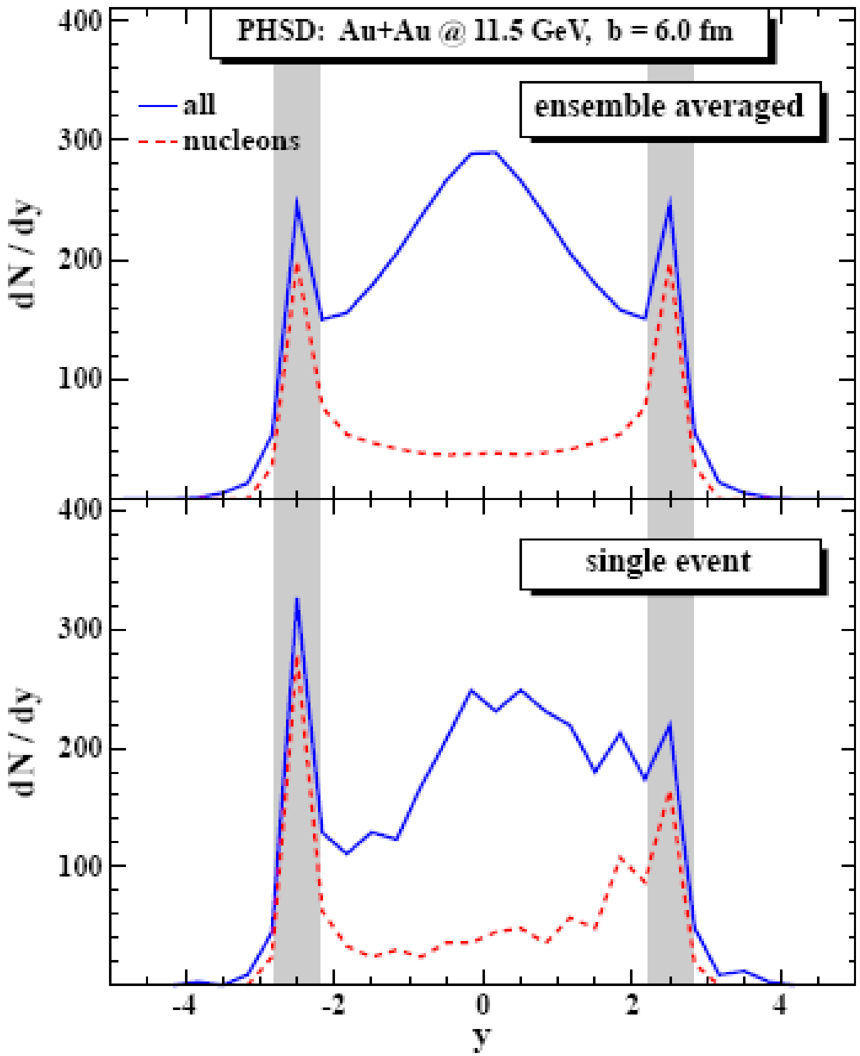


3-Fluid Dynamics

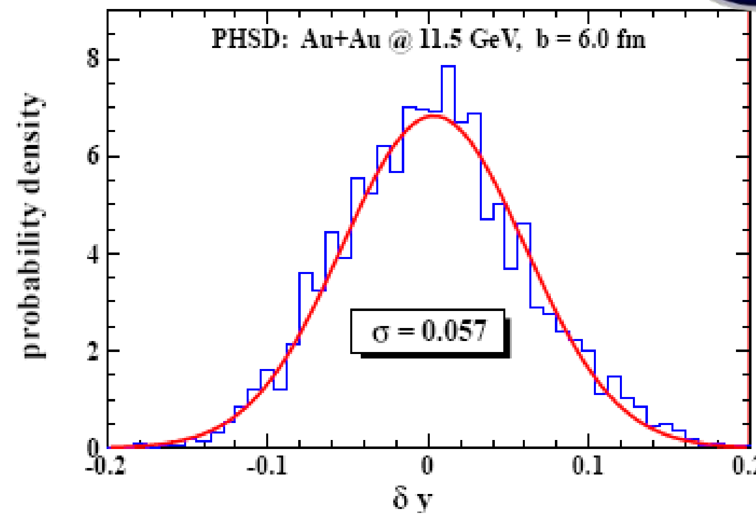
- 3-Fluid Dynamic approach (3FD) gives reasonable results for proton and pion slopes of v_1 and fails at 7.7 GeV for antiprotons
- Discrepancies between 3FD model and STAR data are smaller in case of crossover.
- Recent hydrodynamical and hybrid (hydro+kinetic) results are shown in comparison with [1].
- They fail to reproduce data by an order of magnitude for both chiral χ and Bag Model (BM) EoS.

[1] J. Steinheimer, J. Auvinen, H. Petersen, M. Bleicher, H. Stöcker, Phys. Rev. **C89**, 054913 (2014).

c.m. longitudinal rapidity fluctuation



Y.Cheng et al., Phys. Rev. **C84,** 014901 (2011)



$$P(\delta y_{cm}) = \frac{1}{\sigma\sqrt{2\pi}} \exp(-\frac{\delta y_{cm}^2}{2\sigma^2})$$

$$v_1^{fl} = \int_{-\infty}^{\infty} v_1(y - \delta y_{cm})\ P(\delta y_{cm})\ d\delta y_{cm}$$

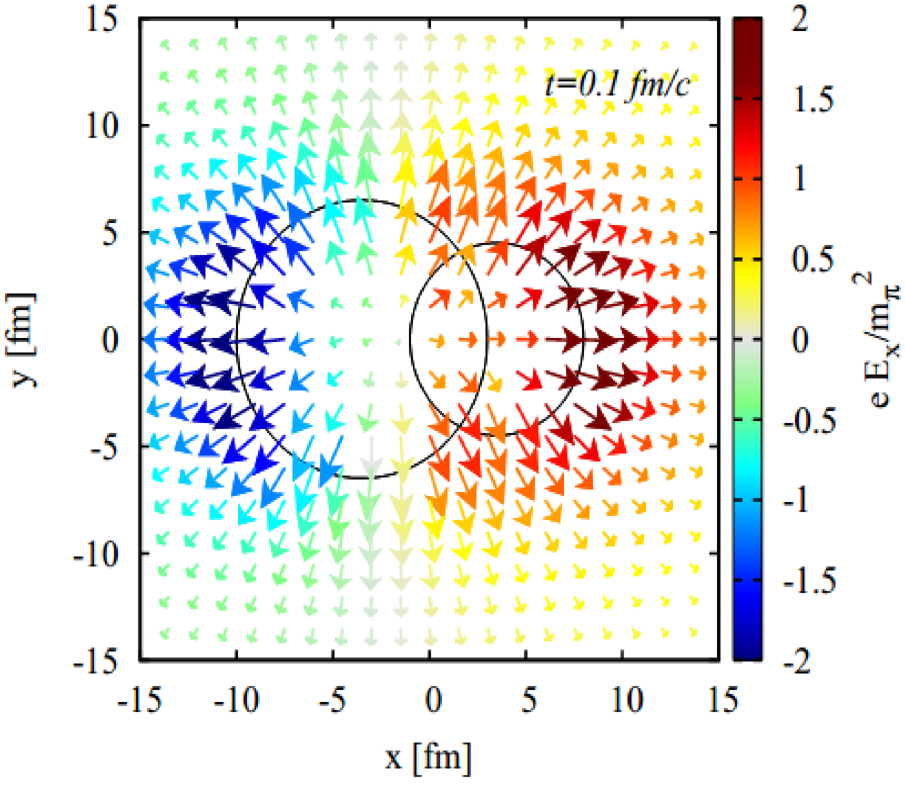
$$v_1(y - \delta y_{cm}) = F(y - \delta y_{cm}) + C(y - \delta y_{cm})^3$$

$$v_1^{fl} = F + 3C\langle(\delta y_{cm})^2\rangle y + Cy^3$$

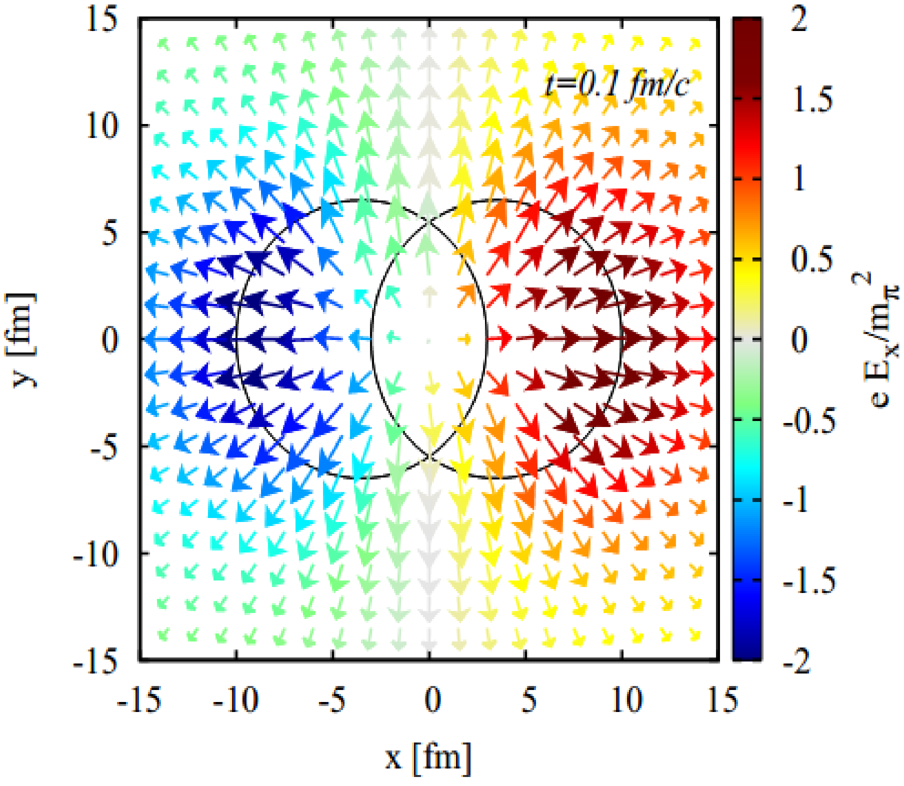
Influence of c.m. rapidity fluctuation on the slope of v_1 distribution is negligible

Electric field E_x in the transverse plane

Cu+Au (200 GeV)



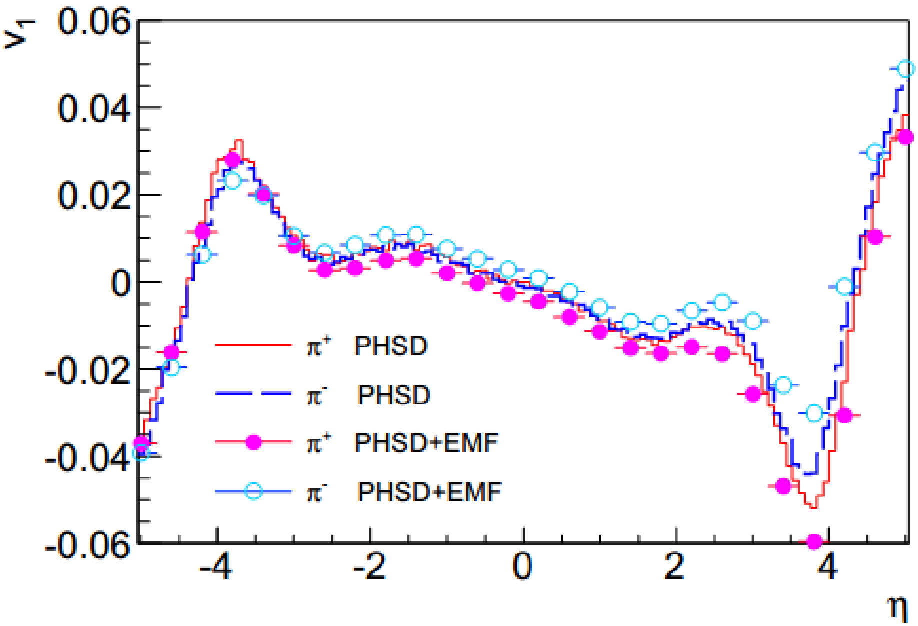
Au+Au (200 GeV)

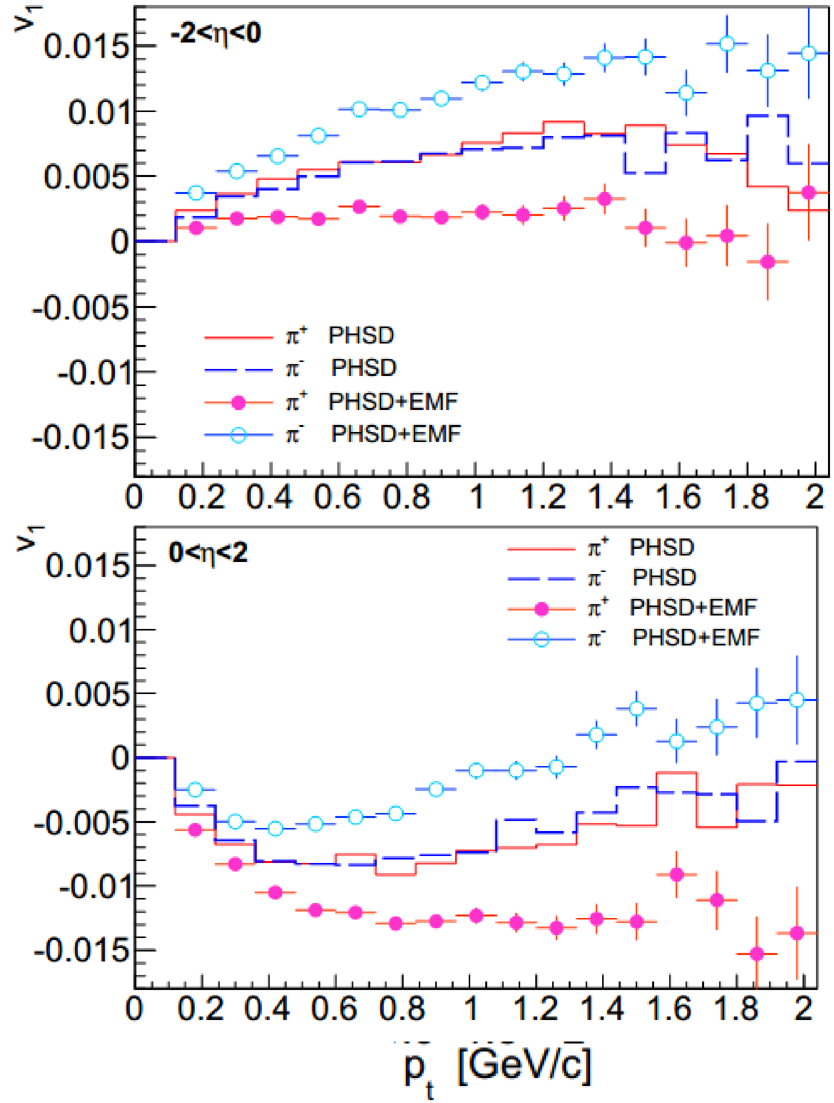


In the overlapping region of asymmetric peripheral collisions a finite electric current appears to be directed from the heavy nuclei to light one.

Charge-dependent distributions of v_1

Cu+Au (200 GeV)





Distributions for the same hadron masses but opposite electric charges are splitted and this can be observable !

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 2ph EoS hydro calculations.

- Inclusion of antiproton annihilation into several mesons as well as inverse processes (the detail balance principle !) in HSD/PHSD helps 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 fails at 7.7 GeV for antiprotons, which nevertheless is much better than the recent hydrodynamics and hybrid (hydro+kinetic) results.

- The whole body of experiment data agrees better with crossover EoS rather than with pure hadronic or 2ph ones.

- The use of charge-dependent v_1 is a very promising tools.

- Application to MPD ($\sqrt{s}$<11.5 GeV) and BM@N (E_{lab}<4.5 A·GeV) ("horn" ?)

I am thankful to

Wolfgang Cassing (Giessen)
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