From cold to hot nuclear matter

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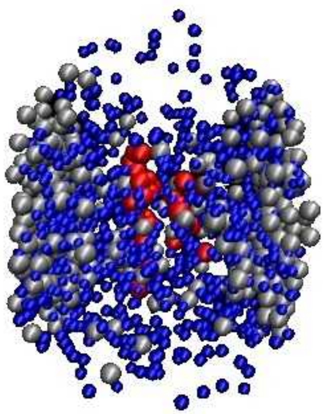
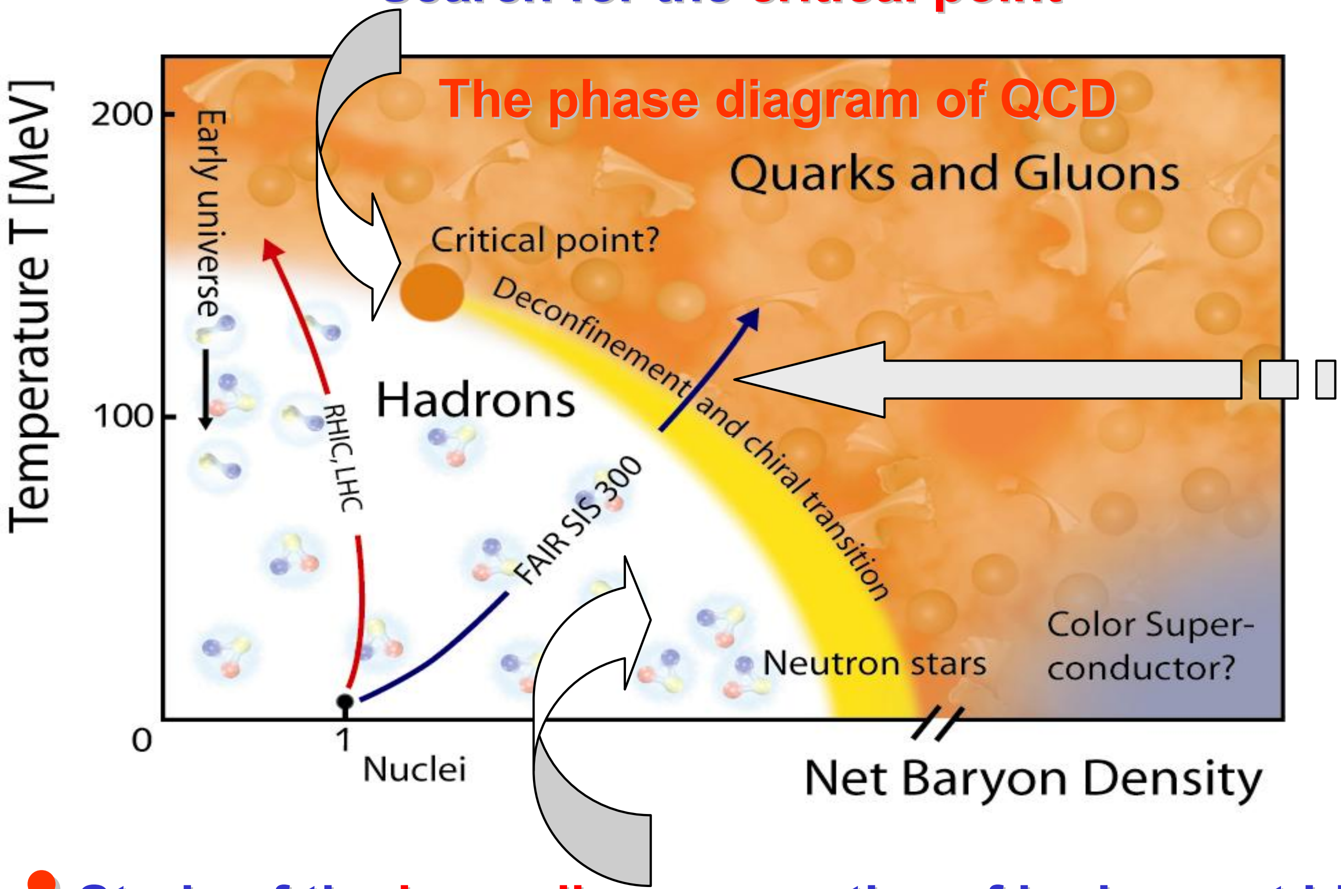


3nd Caribbean Symposium on Cosmology, Gravitation, Nuclear and Astroparticle Physics – STARS2013, May 4 – 6, 2013, Havana

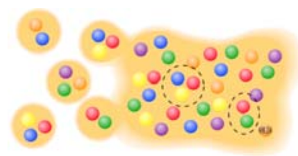
4th International Symposium on Strong Electromagnetic Fields and Neutron Stars – SMFNS2013, May 7 – 10, 2013, Varadero

The ‚holy grail' of heavy-ion physics:

- **Search for the critical point**



- **Study of the phase transition from hadronic to partonic matter – Quark-Gluon-Plasma**



- **Study of the in-medium properties of hadrons at high baryon density and temperature**

The goal: to study the properties of strongly interacting matter under extreme conditions from a microscopic point of view

Realization: dynamical many-body transport models

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:**

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

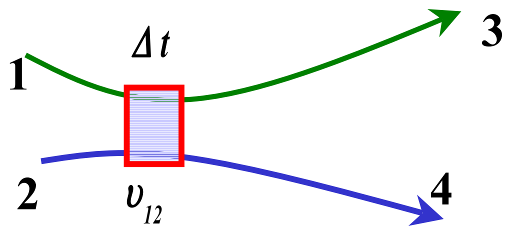
- **Collision term** for 1+2→3+4 (let's consider fermions) :

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

Probability including Pauli blocking of fermions:

$$P = \underbrace{f_3 f_4 (1-f_1)(1-f_2)}_{\text{Gain term: }3+4\rightarrow 1+2} \; - \; \underbrace{f_1 f_2 (1-f_3)(1-f_4)}_{\text{Loss term: }1+2\rightarrow 3+4}$$

Gain term: 3+4→1+2 Loss term: 1+2→3+4



Theoretical description of 'in-medium effects'

In-medium effects = changes of particle properties in the hot and dense baryonic medium; example – vector mesons, strange mesons

Many-body theory:

Strong interaction ➔ large width = short life-time
➔ broad spectral function ➔ quantum object

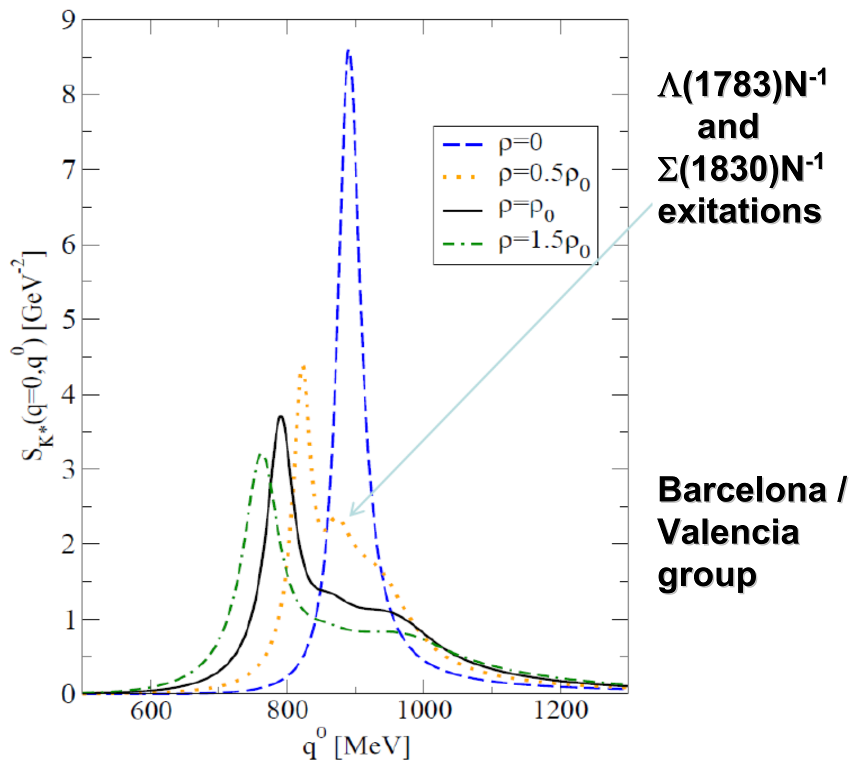
- **How to describe the dynamics of broad strongly interacting quantum states in transport theory?**

❑ **semi-classical BUU**

first order gradient expansion of quantum Kadanoff-Baym equations

❑ **generalized transport equations**

Kbar* spectral function



Barcelona / Valencia group

Dynamical description of strongly interacting systems

- **Semi-classical on-shell BUU:** applies for small collisional width, i.e. for a 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)

Integration over the intermediate spacetime

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

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

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

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

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

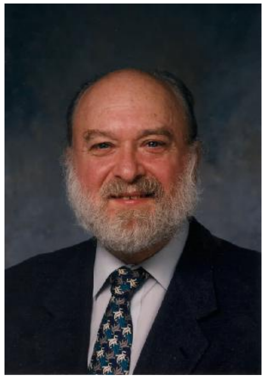
$$S_{xy}^{ret} = S_{xy}^{c} - S_{xy}^{<} = S_{xy}^{>} - S_{xy}^{a} \quad - retarded$$

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

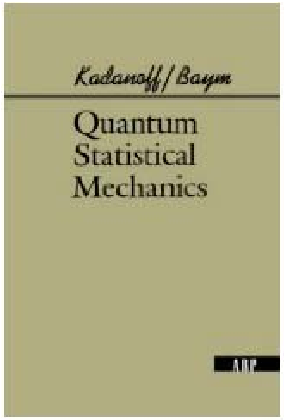
$$\hat{S}_{0x}^{-1} \equiv -(\partial_x^{\mu} \partial_{\mu}^{x} + M_0^2)$$

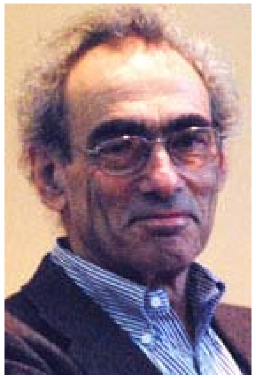
$$\eta = \pm 1 (bosons \,/\, fermions)$$

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



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 term — backflow term — collision term = 'gain' - 'loss' 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 $A_{XP} \to \delta(p^2-M^2)$

- 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:

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

$\Gamma_{XP} = -Im\Sigma^{ret}_{XP} = 2p_0\Gamma$ – 'width' of spectral function

= reaction rate of particle (at space-time position X)

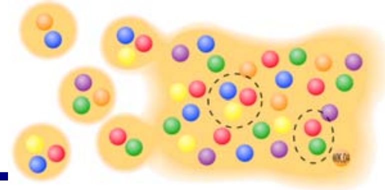
4-dimentional generalizaton of the Poisson-bracket:

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

- Life time $\tau = \frac{\hbar c}{\Gamma}$

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

From SIS to LHC: from hadrons to partons



The goal: to study of the phase transition from hadronic to partonic matter and properties of the Quark-Gluon-Plasma from microscopic origin

➔ need a consistent non-equilibrium transport model

- with explicit parton-parton interactions (i.e. between quarks and gluons)
- explicit phase transition from hadronic to partonic degrees of freedom
- lQCD EoS for partonic phase (‚crossover' at μ_q=0)

- 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)**

QGP phase described by

Dynamical QuasiParticle Model (DQPM)

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

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

Dynamical QuasiParticle Model (DQPM) - Basic ideas:

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 (U_q, U_g)

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

A. Peshier, W. 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 :

$$A_i(\omega,T) = \frac{4\omega\Gamma_i(T)}{\left(\omega^2 - \vec{p}^2 - M_i^2(T)\right)^2 + 4\omega^2\Gamma_i^2(T)}$$

$$(i = q, \bar{q}, g)$$

- **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:**

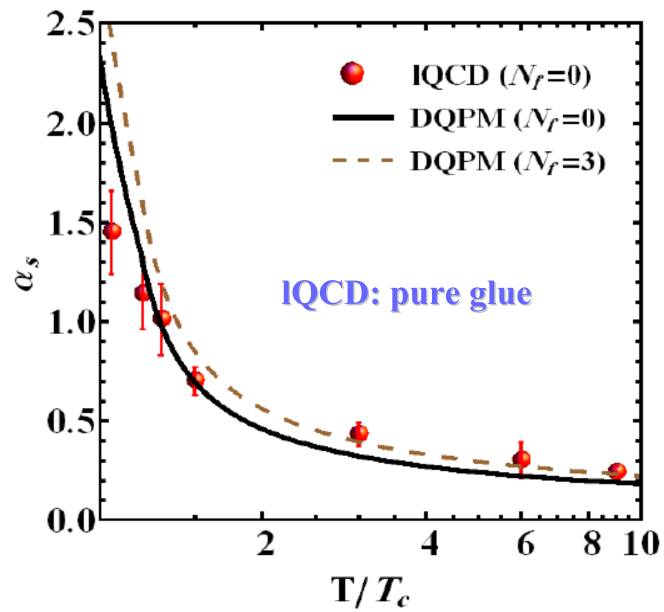
$M_g^2(T) = \frac{g^2}{6}\left(\left(N_c + \frac{N_f}{2}\right)T^2 + \frac{N_c}{2}\sum_q \frac{\mu_q^2}{\pi^2}\right)$

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

$N_c = 3$, $N_f = 3$

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

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



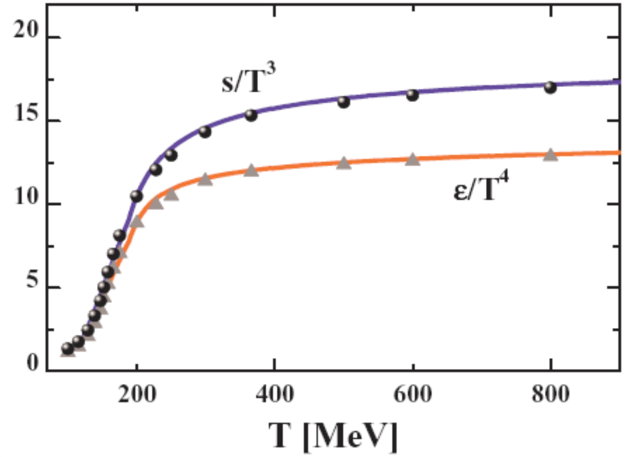
❑ **fit to lattice (lQCD) results (e.g. entropy density)**

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)

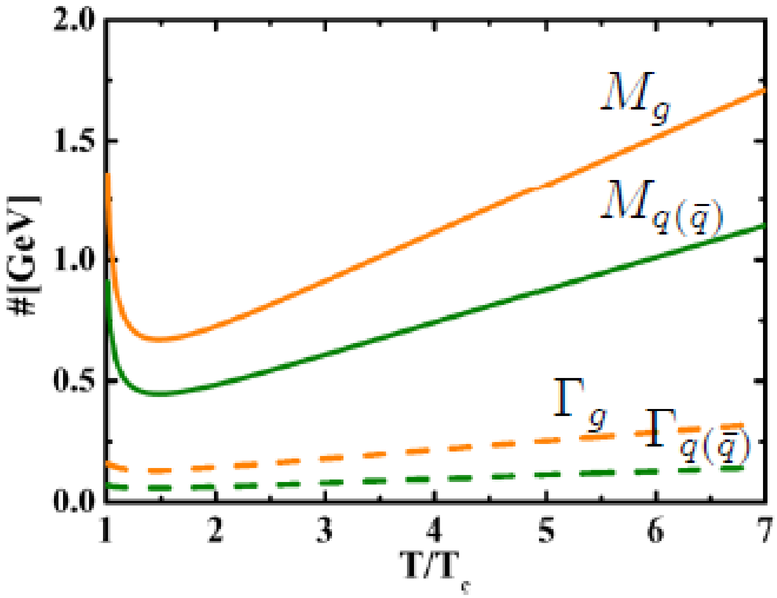
The Dynamical QuasiParticle Model (DQPM)

- **fit to lattice (lQCD) results (e.g. entropy density)**
  - * BMW lQCD data S. Borsanyi et al., JHEP 1009 (2010) 073

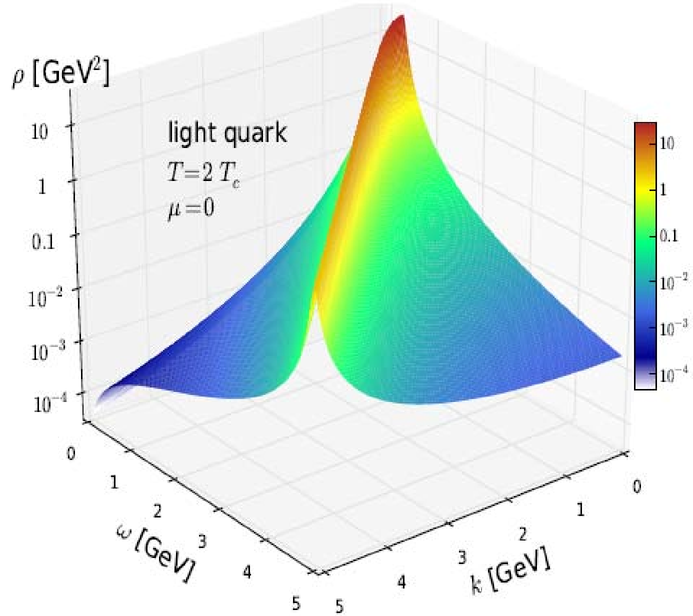


→ **Quasiparticle properties:**

- large width and mass for gluons and quarks



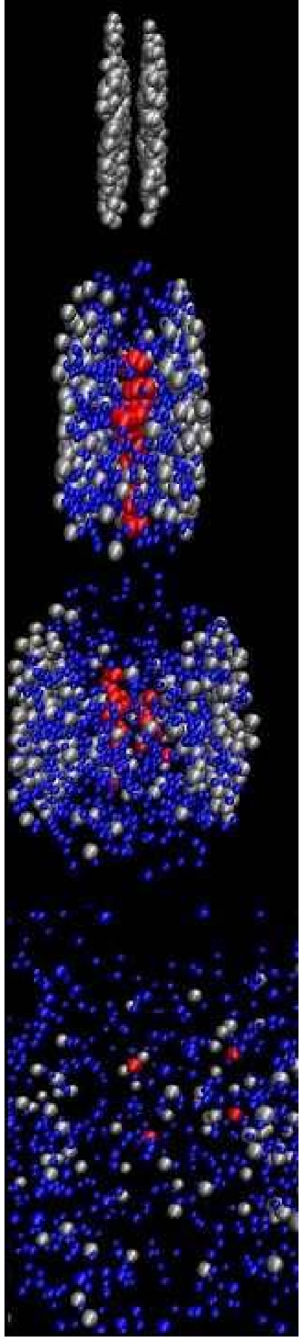
T_C=158 MeV
ε_C=0.5 GeV/fm^3



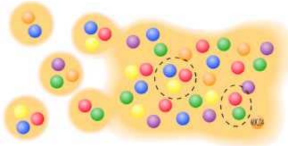
- DQPM matches well lattice QCD
- DQPM provides mean-fields (1PI) for gluons and quarks as well as effective 2-body interactions (2PI)
- DQPM gives transition rates for the formation of hadrons → PHSD

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

Parton Hadron String Dynamics

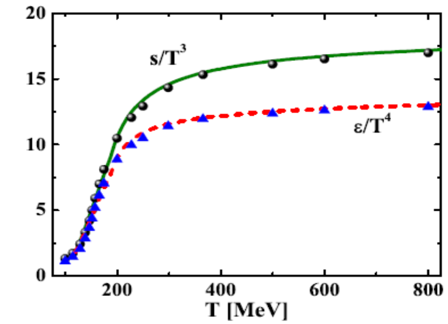


I. From hadrons to QGP:



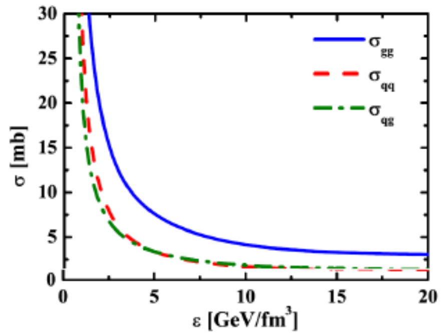
QGP phase:
$\varepsilon > \varepsilon_{critical}$

- 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)



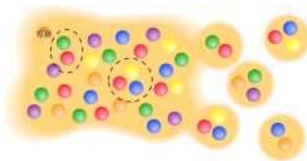
II. Partonic phase - QGP:

- 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
- 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

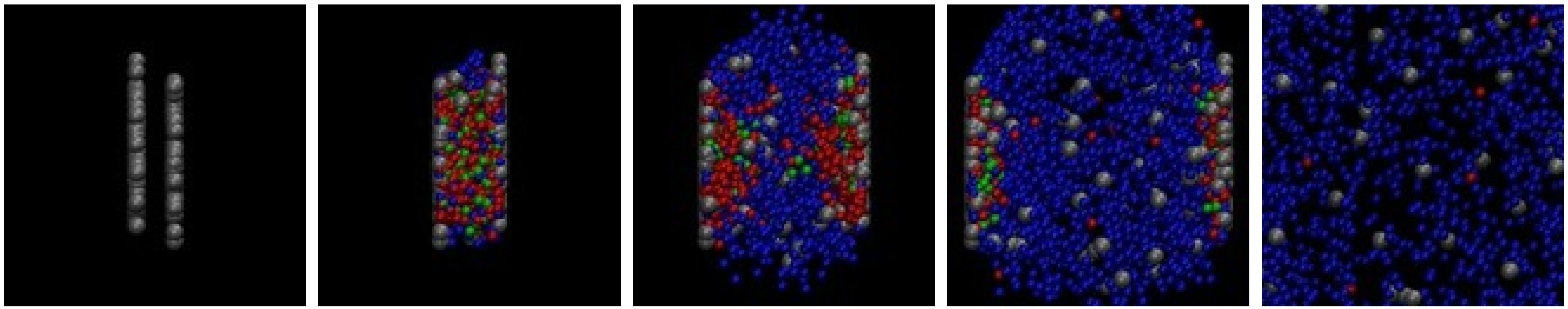
- massive, off-shell (anti-)quarks with broad spectral functions hadronize to off-shell mesons and baryons or color neutral excited states - ‚strings‘ (strings act as ‚doorway states‘ for hadrons)



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

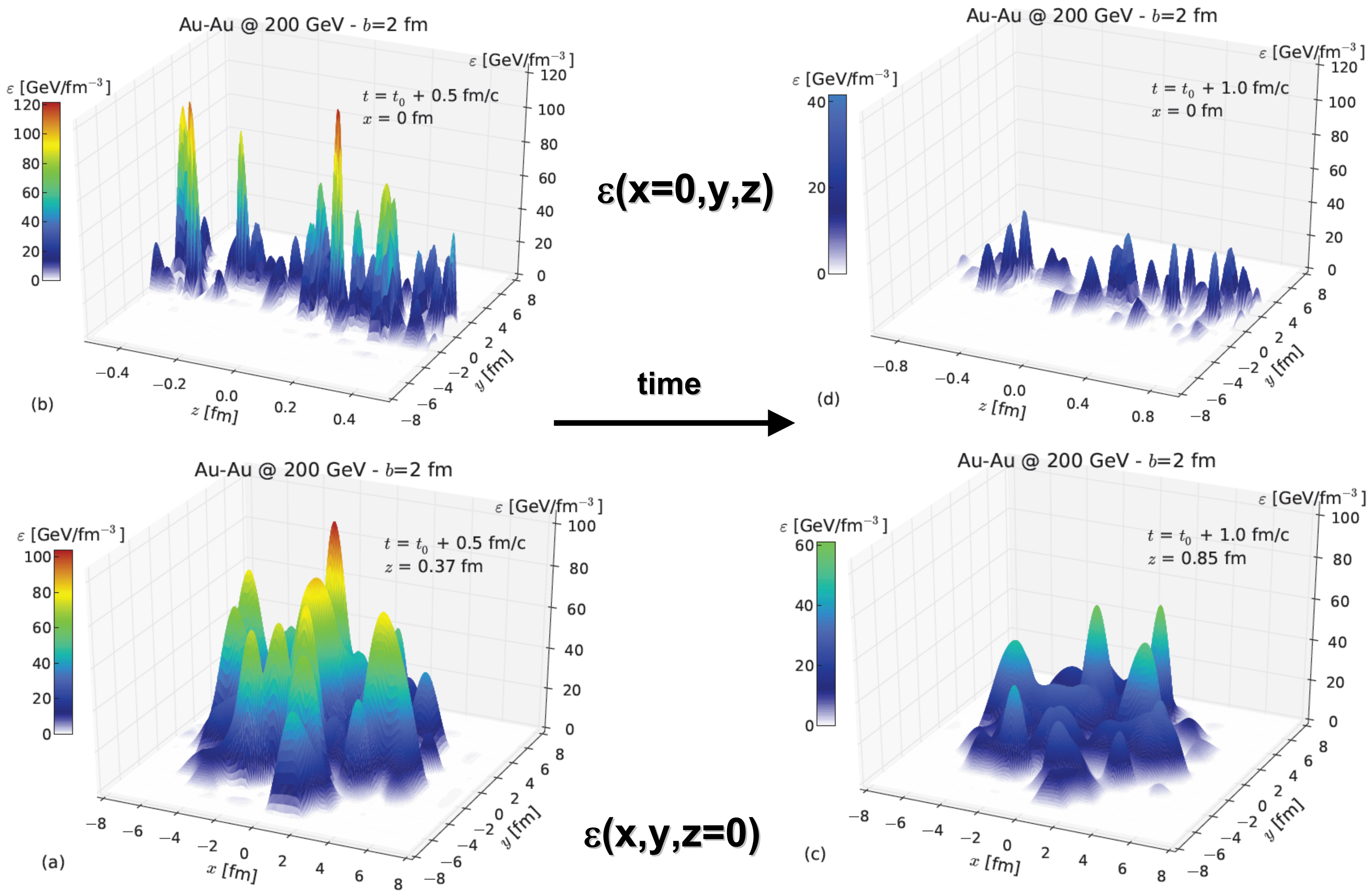
W. Cassing, E. Bratkovskaya, PRC 78 (2008) 034919;
NPA831 (2009) 215; EPJ ST 168 (2009) 3; NPA856 (2011) 162.

‚Bulk‘ properties in Au+Au



Time evolution of energy density

PHSD: 1 event Au+Au, 200 GeV, b = 2 fm

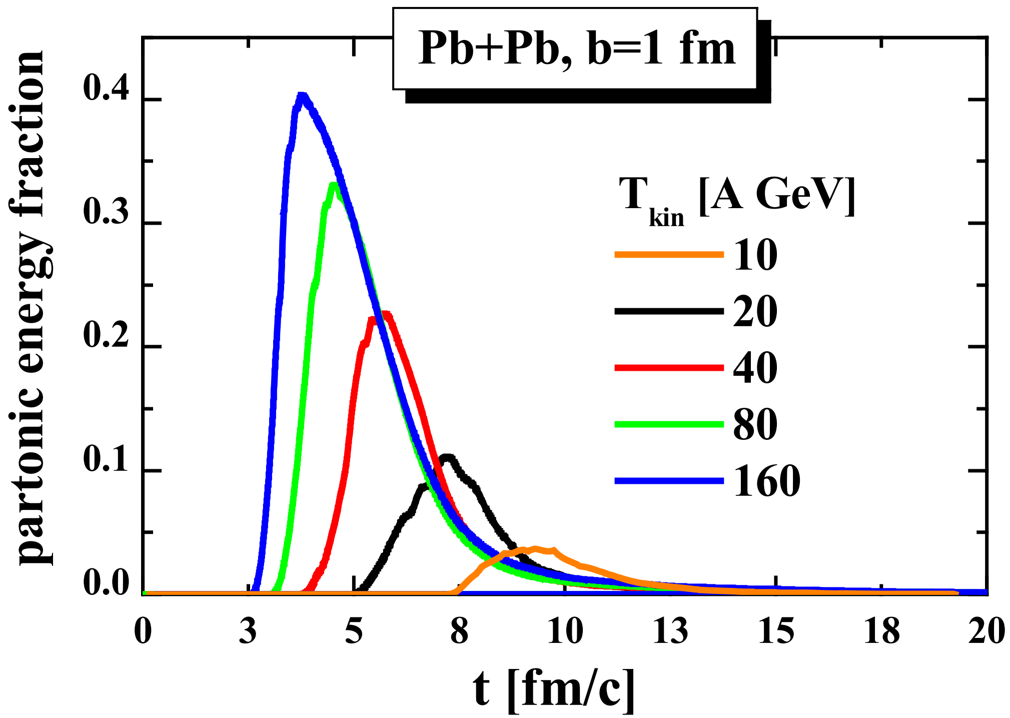


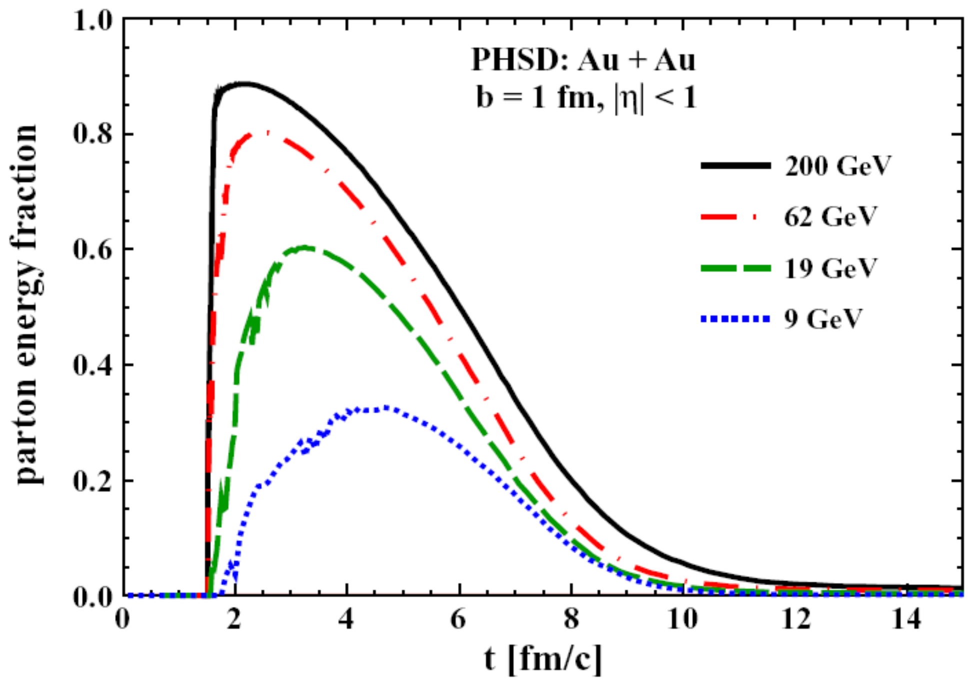
ΔV: Δx=Δy=1fm, Δz=1/γ fm

R. Marty et al, 2014

Partonic energy fraction in central A+A

Time evolution of the partonic energy fraction vs energy





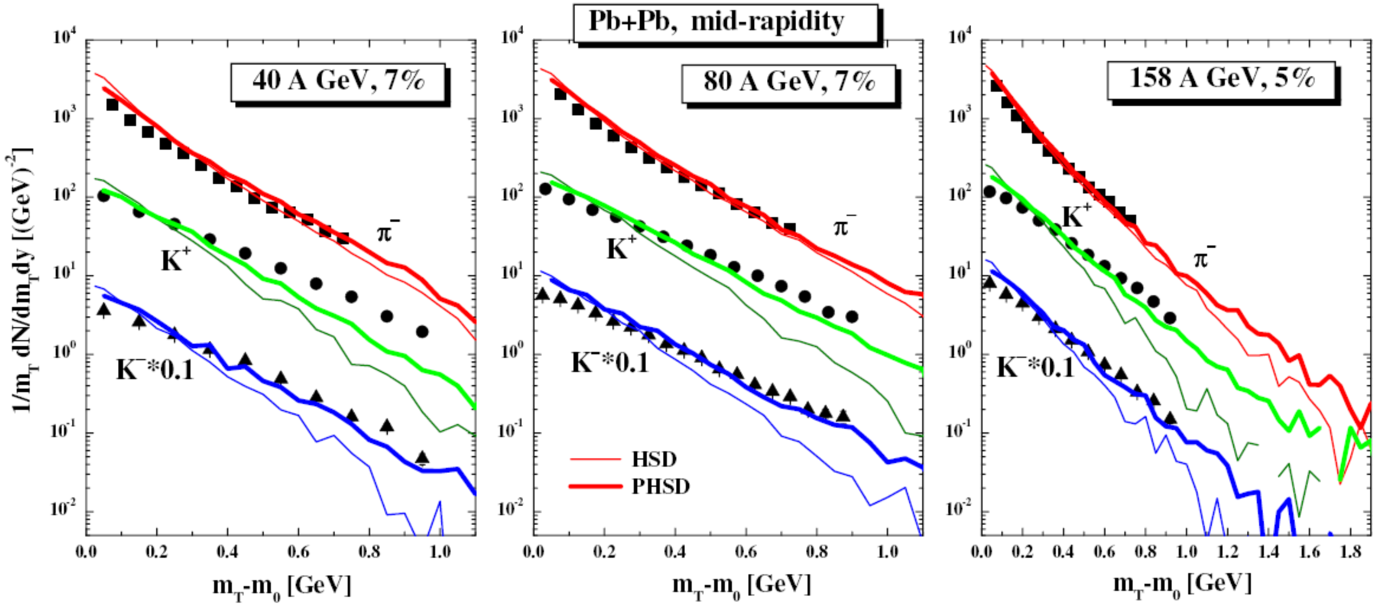
- Strong increase of partonic phase with energy from AGS to RHIC

- SPS: Pb+Pb, 160 A GeV: only about 40% of the converted energy goes to partons; the rest is contained in the large hadronic corona and leading partons
- RHIC: Au+Au, 21.3 A TeV: up to 90% - QGP

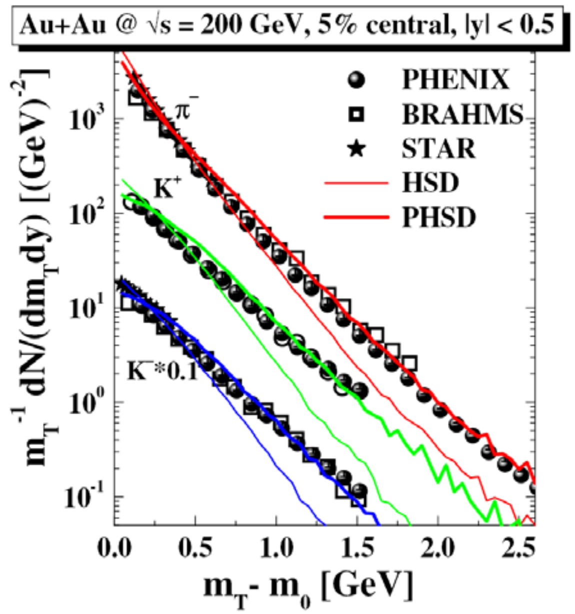
W. Cassing & E. Bratkovskaya, NPA 831 (2009) 215
V. Konchakovski et al., Phys. Rev. C 85 (2012) 011902

Transverse mass spectra from SPS to RHIC

Central Pb + Pb at SPS energies



Central Au+Au at RHIC

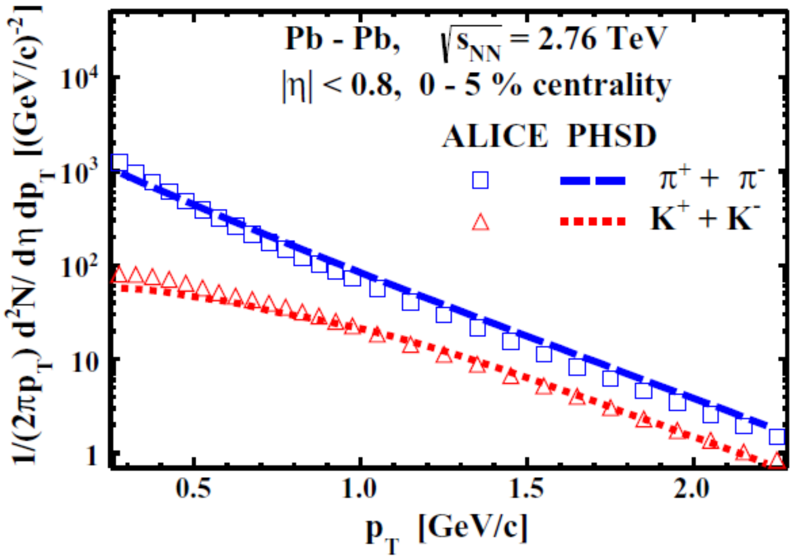


- PHSD gives harder m_T spectra and works better than HSD (wo QGP) at high energies – RHIC, SPS (and top FAIR, NICA)
- however, at low SPS (and low FAIR, NICA) energies the effect of the partonic phase decreases due to the decrease of the partonic fraction

W. Cassing & E. Bratkovskaya, NPA 831 (2009) 215
E. Bratkovskaya, W. Cassing, V. Konchakovski, O. Linnyk, NPA856 (2011) 162

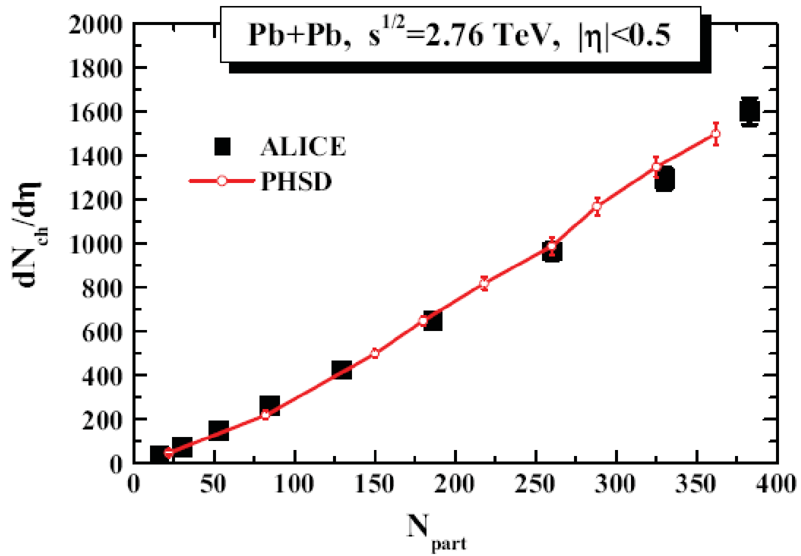
p_T spectra for Pb+Pb from PHSD at LHC

Low p_T spectra of pions and kaons



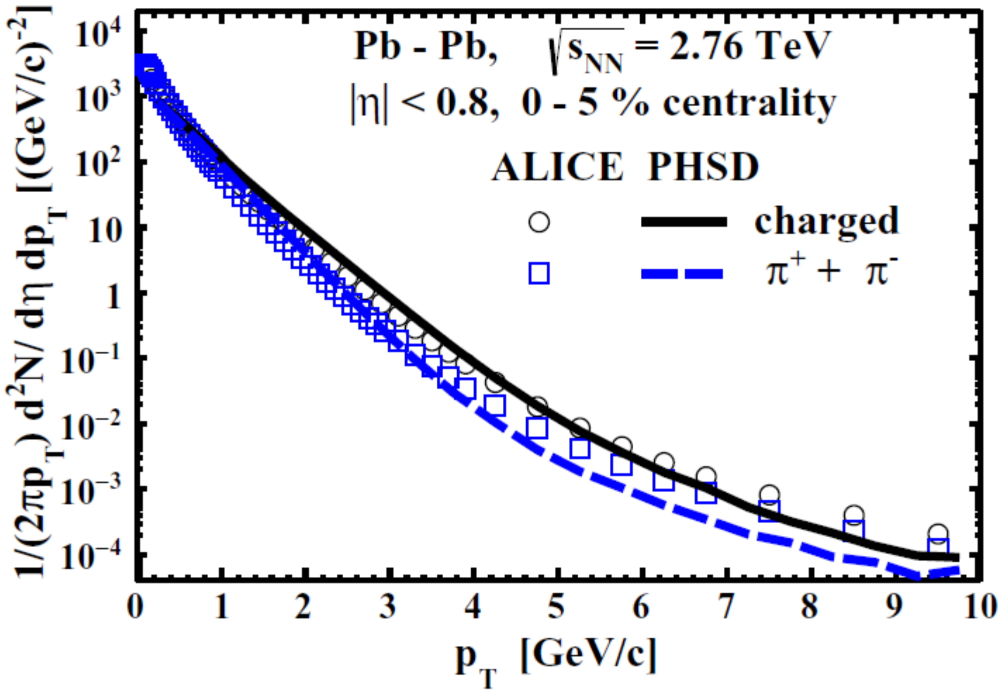
Charged particle multiplicity vs centrality

PHSD: Phys.Rev. C87 (2013) 014905; arXiv:1208.1279



p_T spectra of charged hadrons and pions

central Pb+Pb at $s^{1/2}$=2.76 TeV



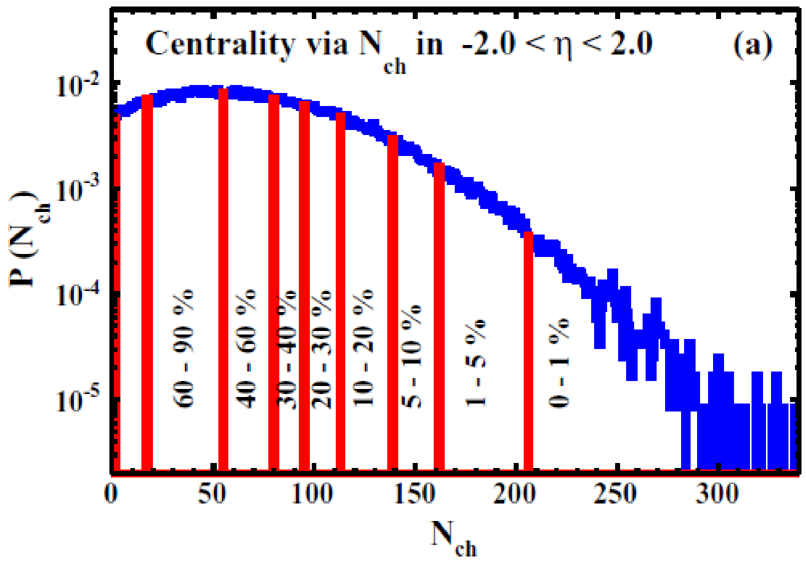
➔ PHSD reproduces ALICE data on Pb+Pb

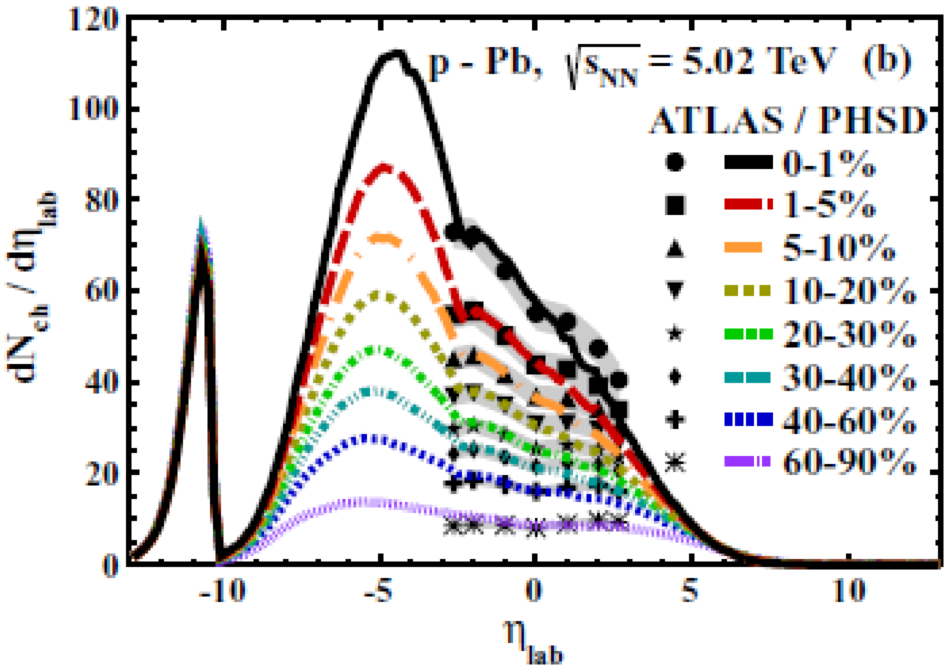
V. Konchakovski, W. Cassing, V. Toneev, arXiv:1411.5534

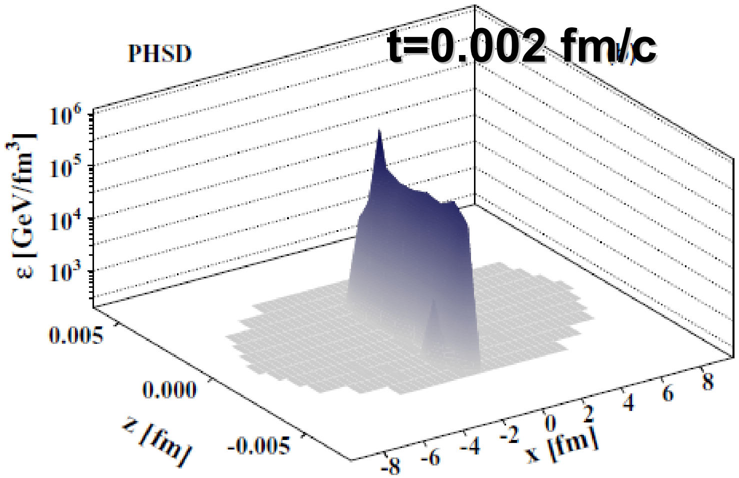
‚Cold‘ nuclear matter at LHC

❑ Great surprize → evidence for the creation of ‚QGP‘ in p+Pb collisions !

Centrality dependence of η_{lab} spectra of charged hadrons p+Pb at $s^{1/2}$=5.02 TeV





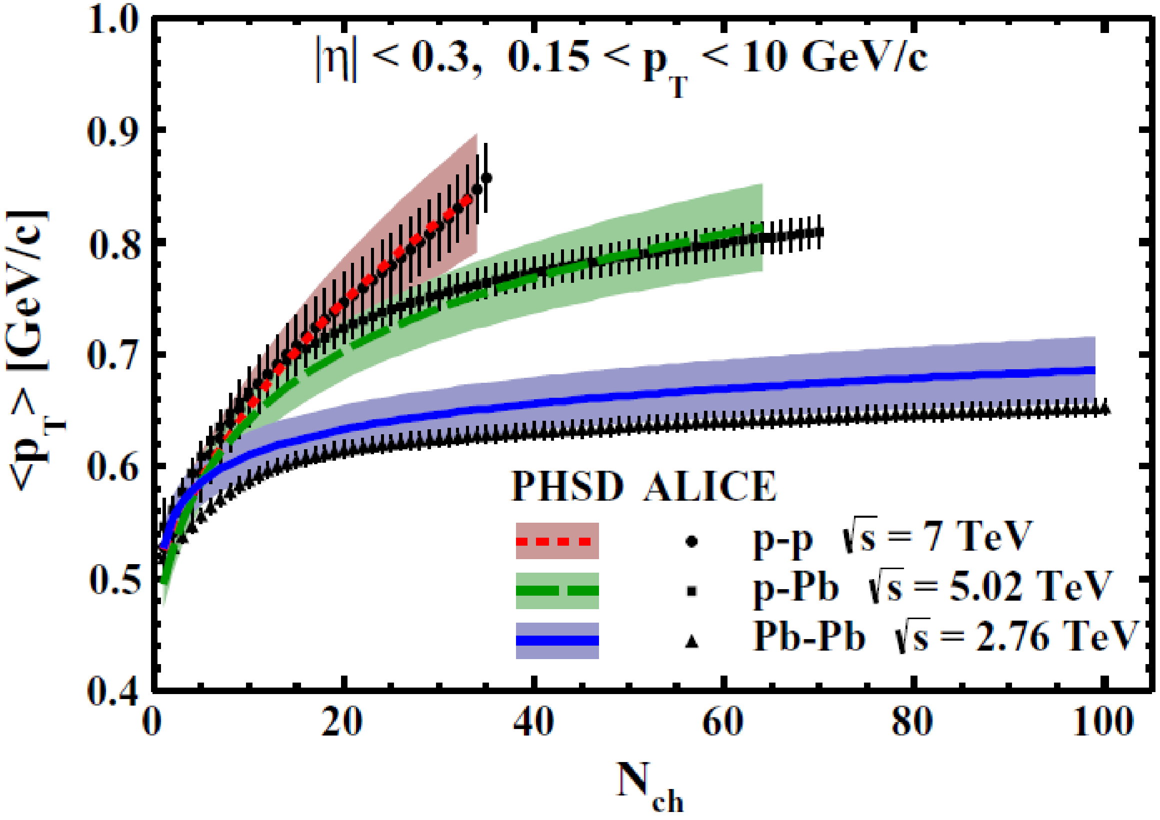


Energy density in p+Pb is very high,
up to ε~10^5 GeV/fm^3 ⇔ comparable with HIC!

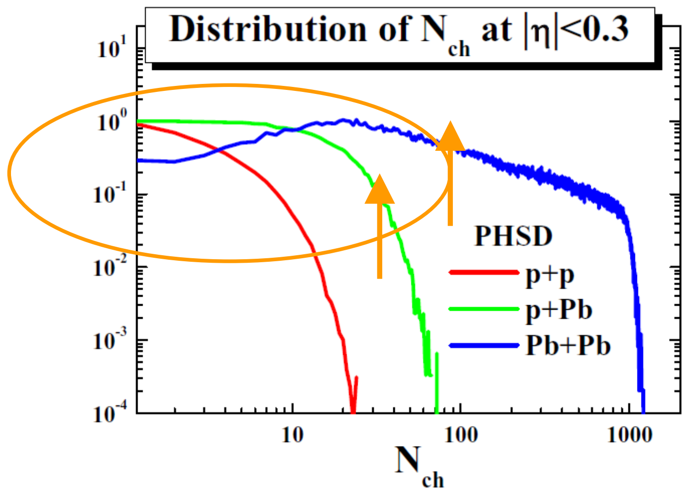
V. Konchakovski, W. Cassing, V. Toneev, arXiv:1411.5534

Correlations of mean p_T vs N_{ch} at LHC

Mean p_T of charged hadrons at midrapidity vs N_{ch}



➔ probe only narrow part of the total phase space for |η|<0.3 ➔ large influence of correlations!



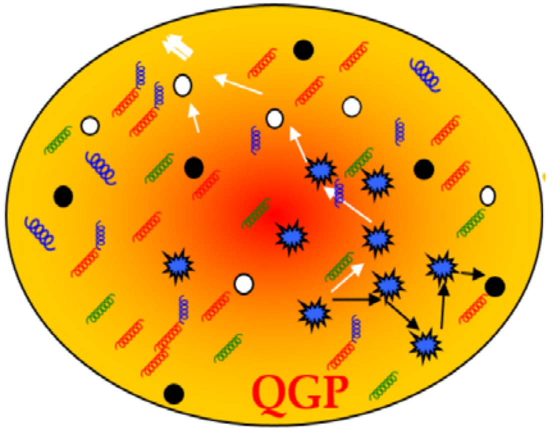
- Mean p_T spectra of p+p and p+Pb are identical at low N_{ch} since N_{coll}~1-2 similar to pp
- The origin for the ‚hierarchy' of mean p_T at larger N_{ch} :

  N_{coll} >>1 ➔ summation of multiple (soft) collisions

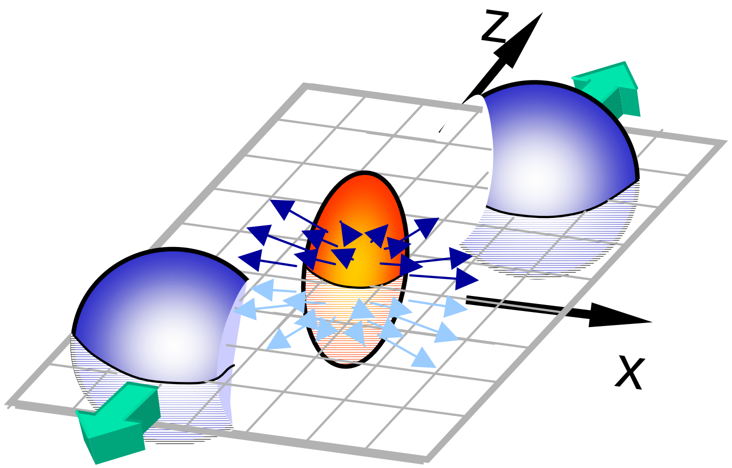
V. Konchakovski, W. Cassing, V. Toneev, arXiv:1411.5534

Messages from the study of particle spectra

- PHSD gives harder m_T spectra than HSD (without QGP) at high energies – LHC, RHIC, SPS
- at RHIC and LHC the QGP dominates the early stage dynamics
- at low SPS (and low FAIR, NICA) energies the effect of the partonic phase decreases
- ‚cold' nuclear matter at LHC → creation of QGP in p+Pb



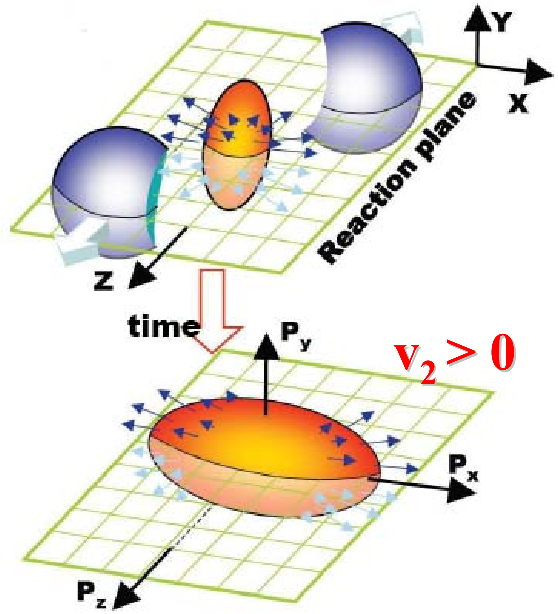
Collective flow, anisotropy coefficients (v_1, v_2, ...) in A+A



Anisotropy coefficients

Non central Au+Au collisions :

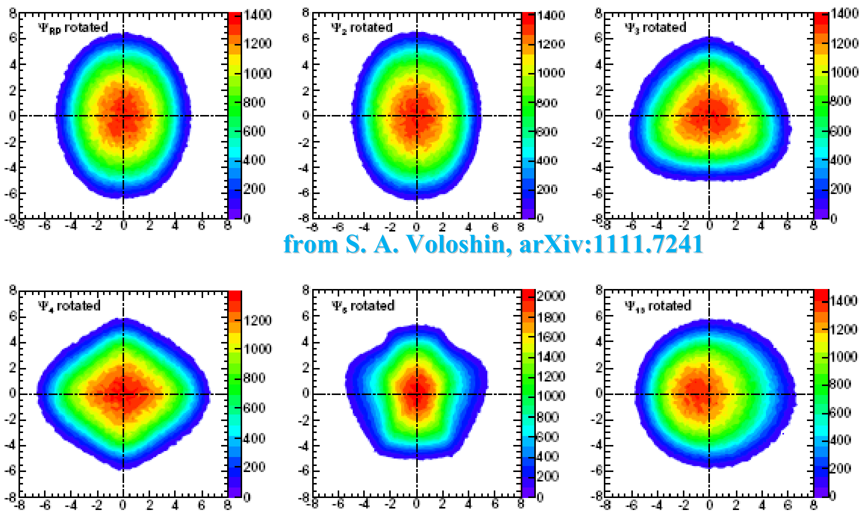
- interaction between constituents leads to a **pressure gradient** → **spatial asymmetry** is converted to an **asymmetry in momentum space** → **collective flow**



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

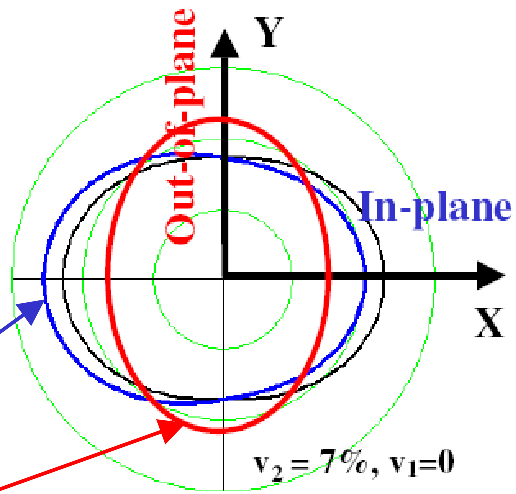
$$v_n = \left\langle \cos n\left(\varphi - \psi_n\right)\right\rangle, \quad n = 1,2,3..,$$

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



from S. A. Voloshin, arXiv:1111.7241

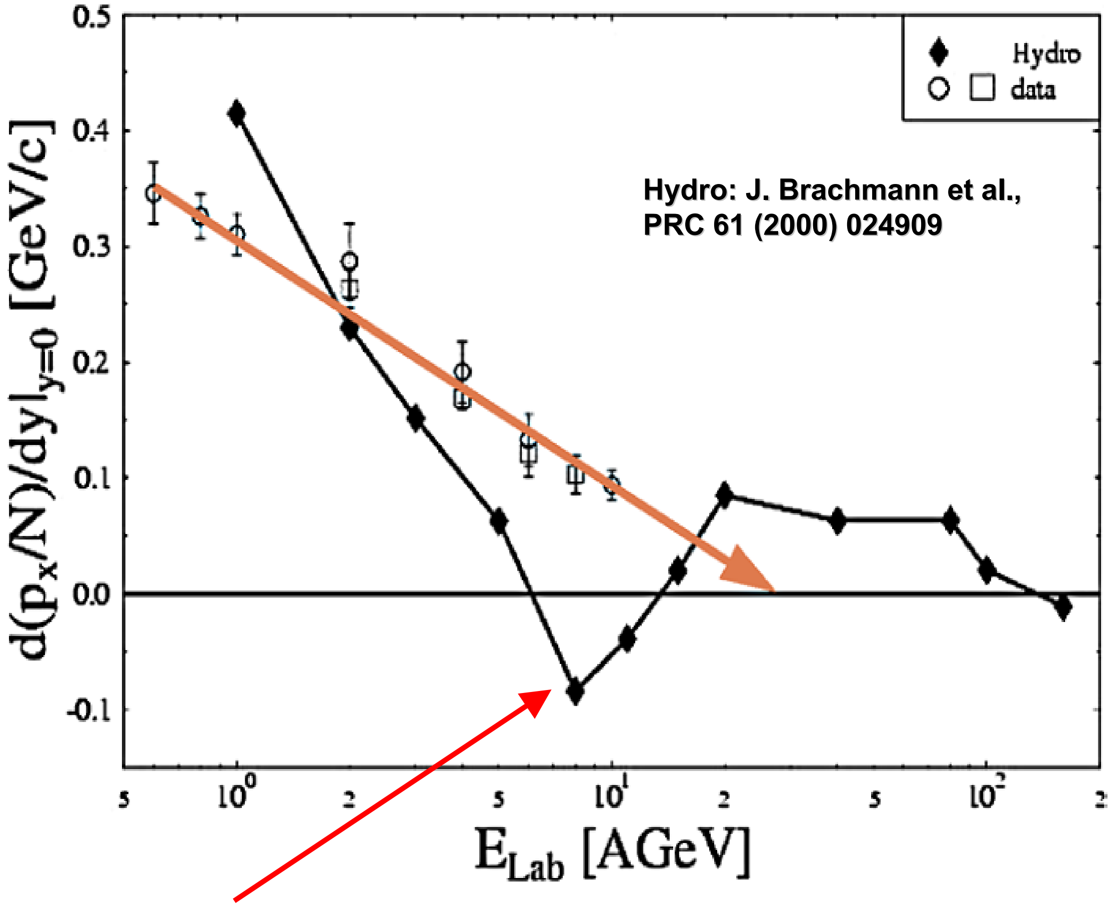
v_1: directed flow
v_2: elliptic flow
v_3: triangular flow

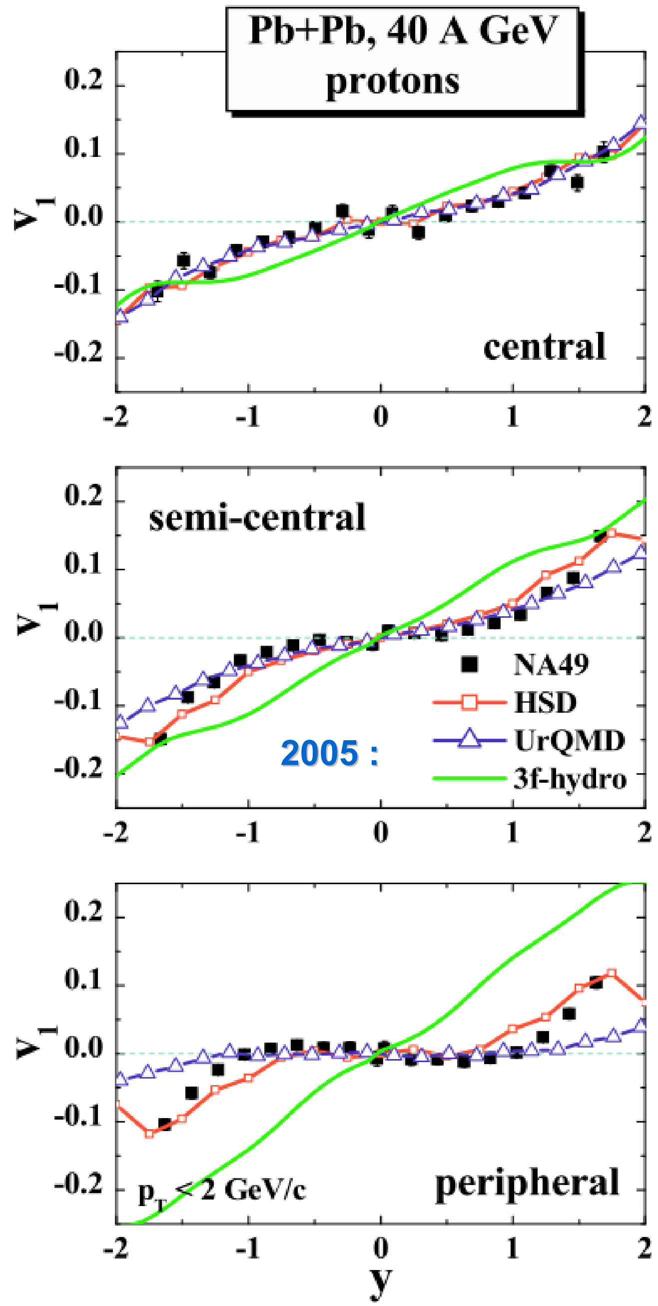


$v_2 > 0$ indicates in-plane emission of particles
$v_2 < 0$ corresponds to a squeeze-out perpendicular to the reaction plane (out-of-plane emission)

Directed flow signals of the Quark–Gluon Plasma?

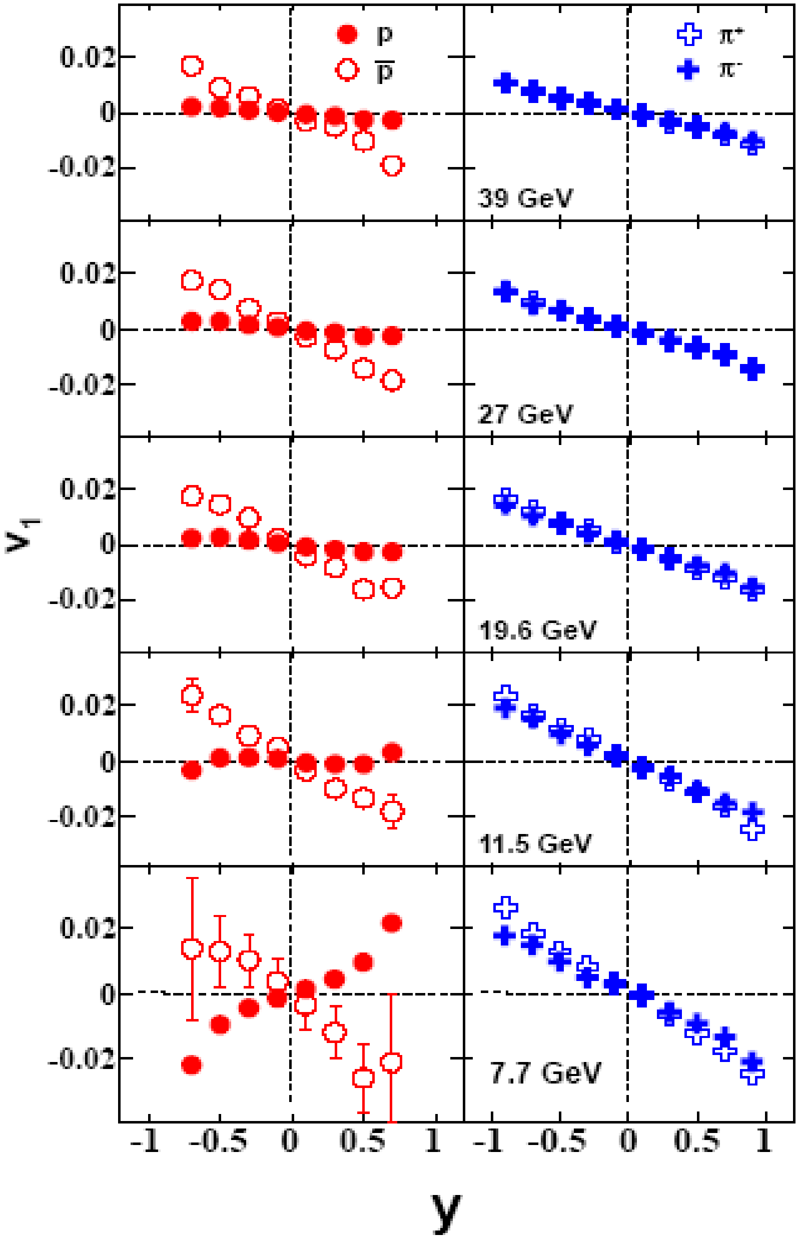
From H. Stöcker, Nucl. Phys. A 750, 121 (2005)





- **Early ideal 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**

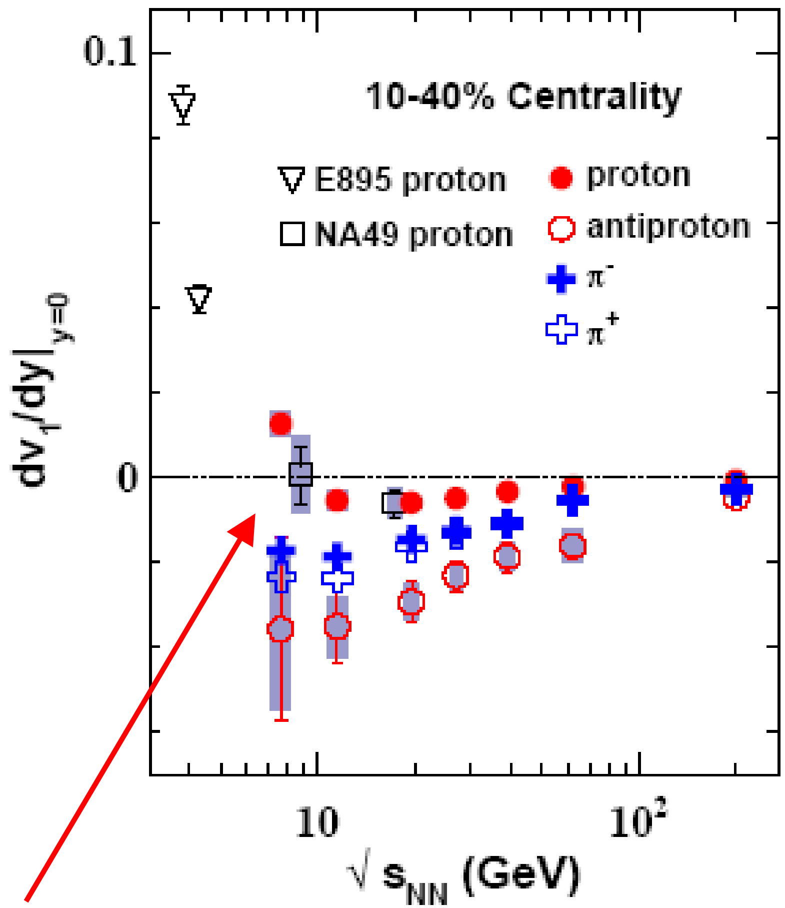
Recent STAR measurements of v_1 of identified hadrons



Slope of $v_1(y)$ at midrapidity:

$$F = \frac{d\upsilon_1}{dy}\Big|_{y=0}$$

STAR collaboration, PRL 112, 162301 (2014)

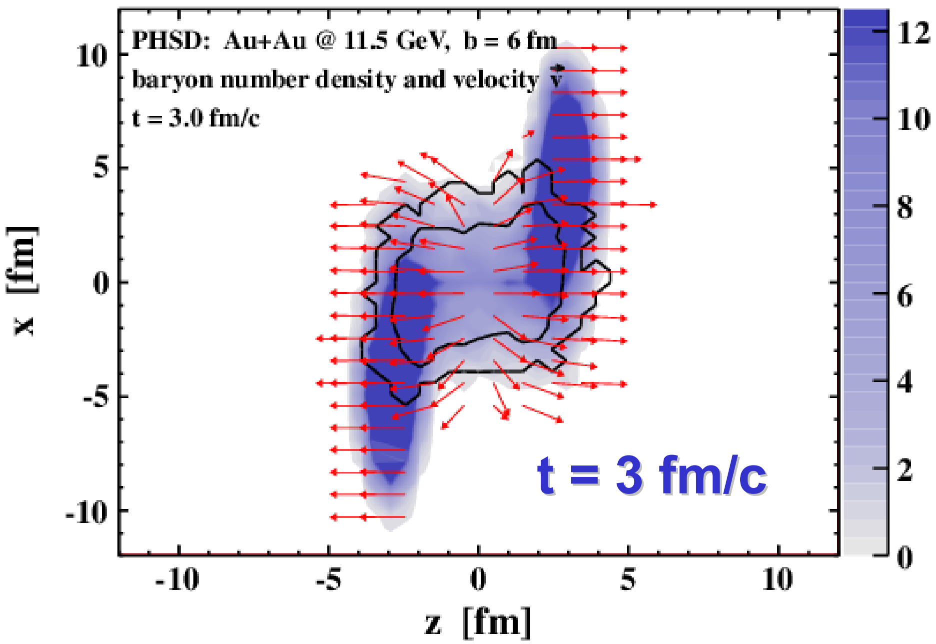


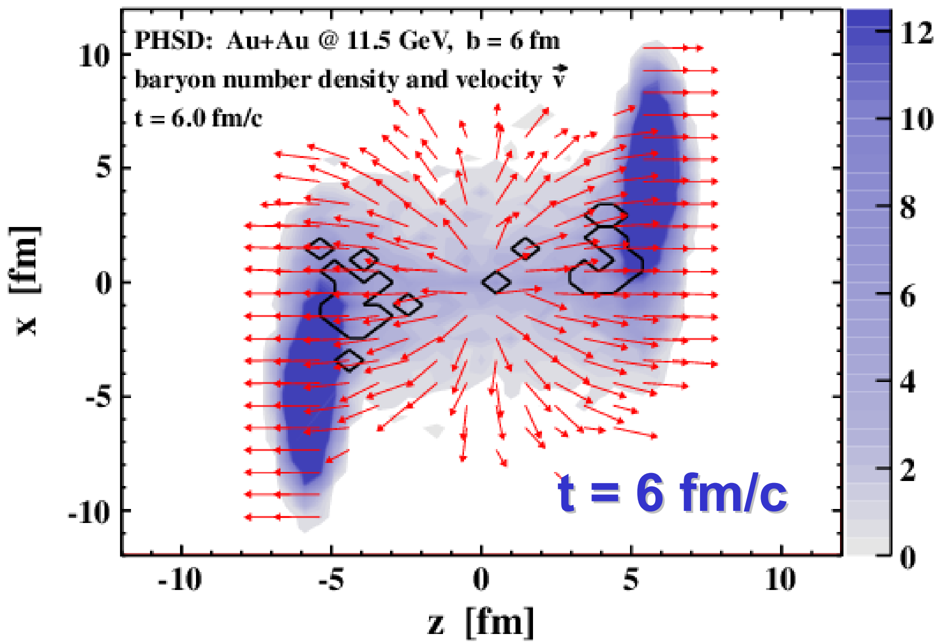
- (Net-)proton v_1 slope at midrapidity changes sign at $\sqrt{s_{NN}}$ ~10 GeV

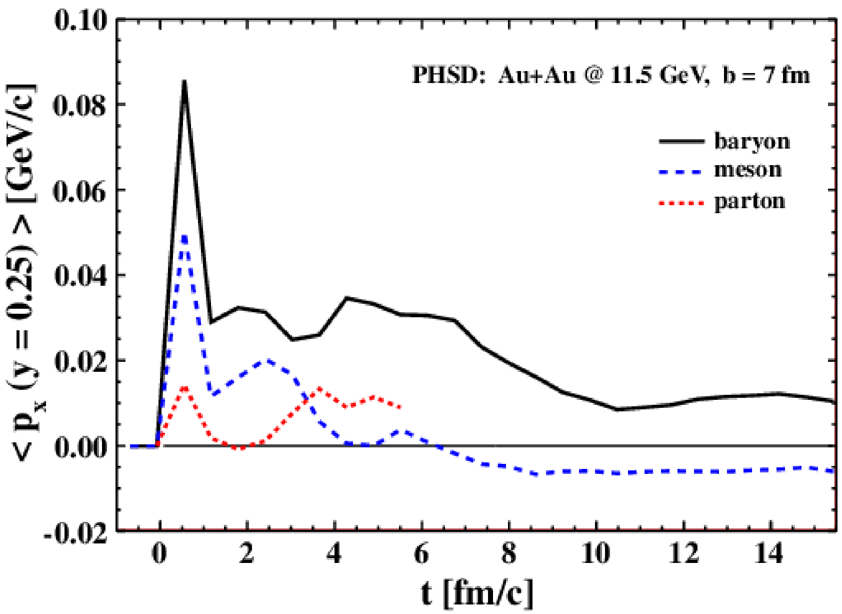
➔ EOS softest point ?
(1st order phase transition ?)

➔ measured y-distributions are smooth !

PHSD: snapshot of the reaction plane at 11 A GeV







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

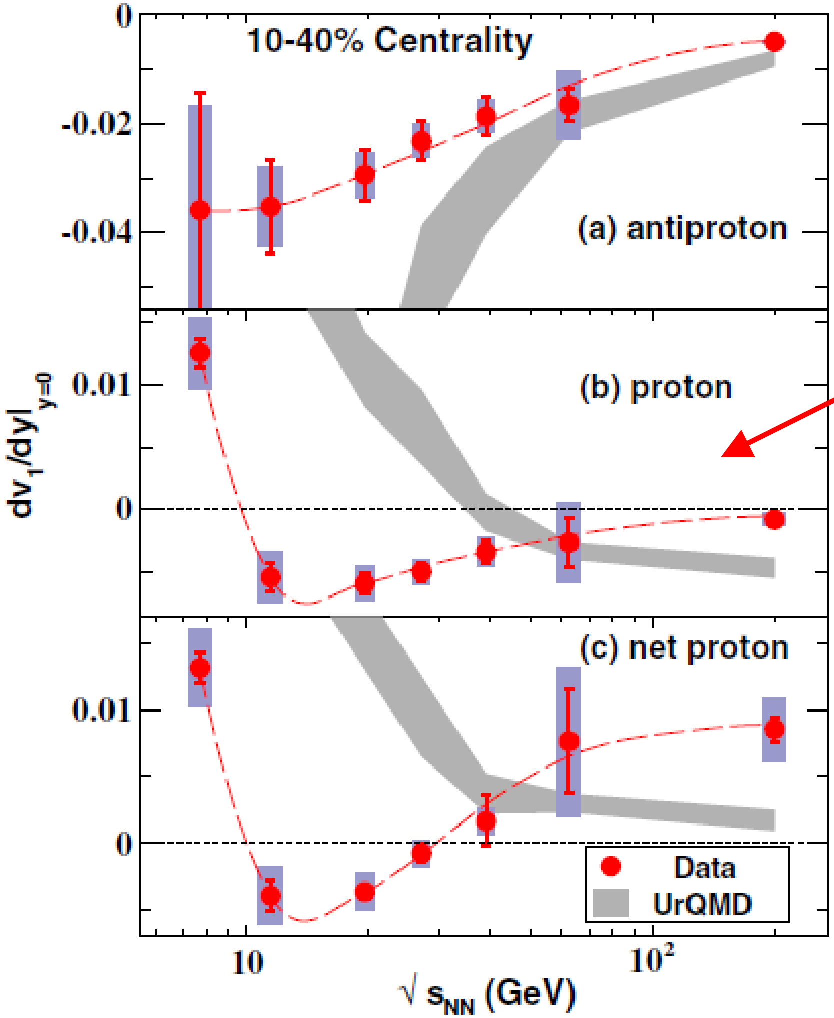
- **Directed flow v_1 is formed at an early stage of the nuclear interaction**

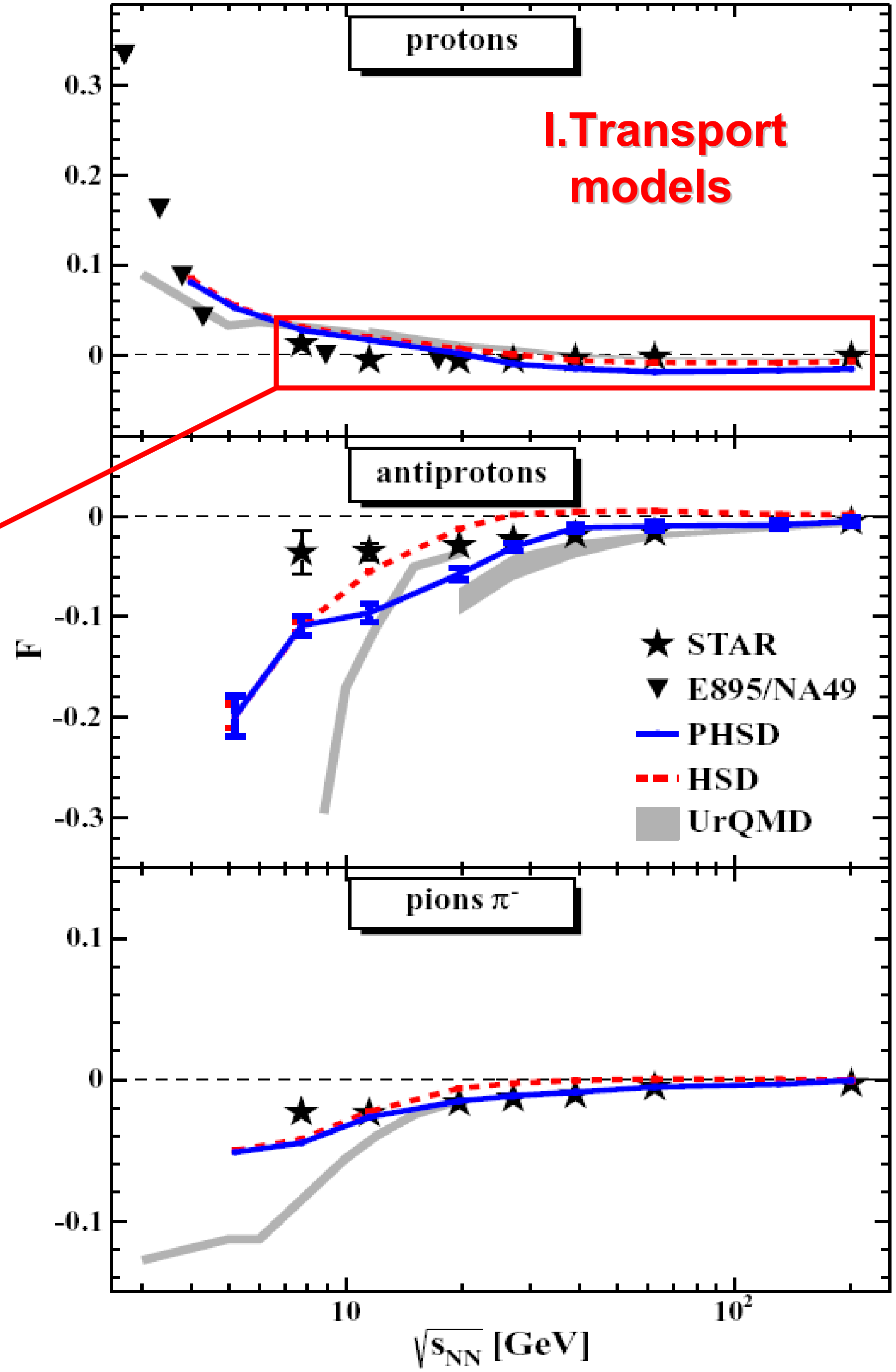
- **Baryons are reaching positive and mesons – negative value of v_1**

V. Konchakovski, W. Cassing, Yu. Ivanov, V. Toneev, PRC(2014), arXiv:1404.2765

Excitation function of v_1 slopes at midrapidity

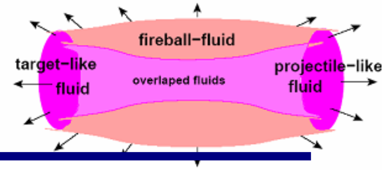
The slope of $v_1(y)$ at y=0: $F = \frac{d\upsilon_1}{dy}\big|_{y=0}$

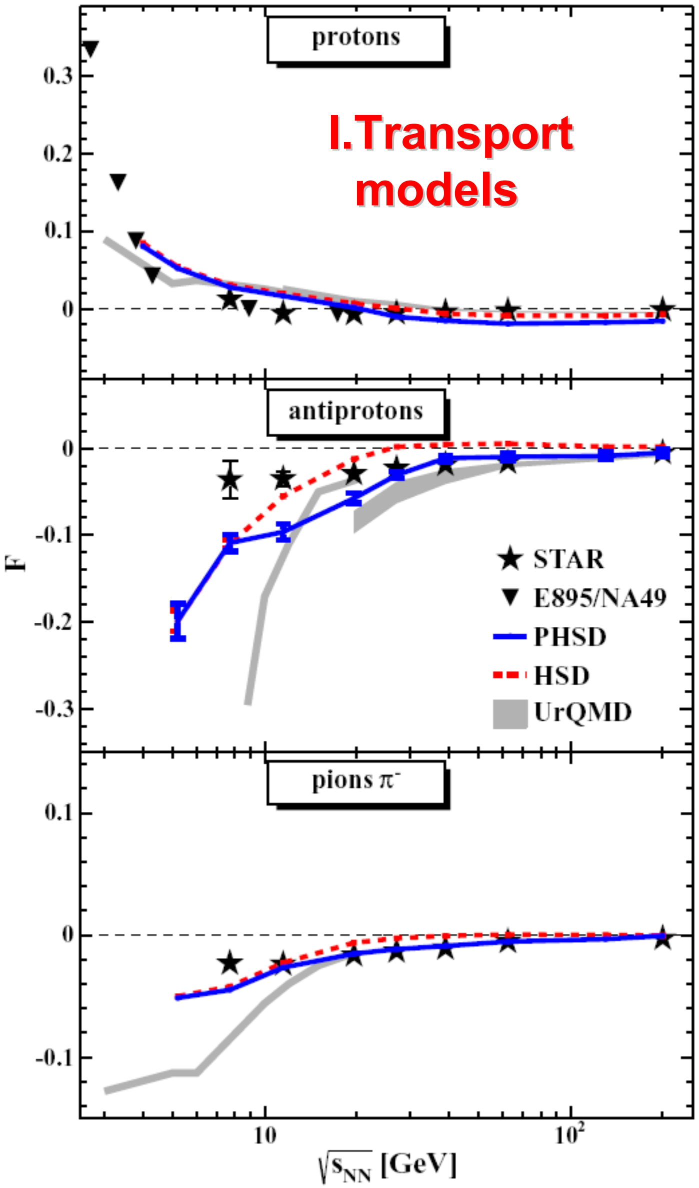


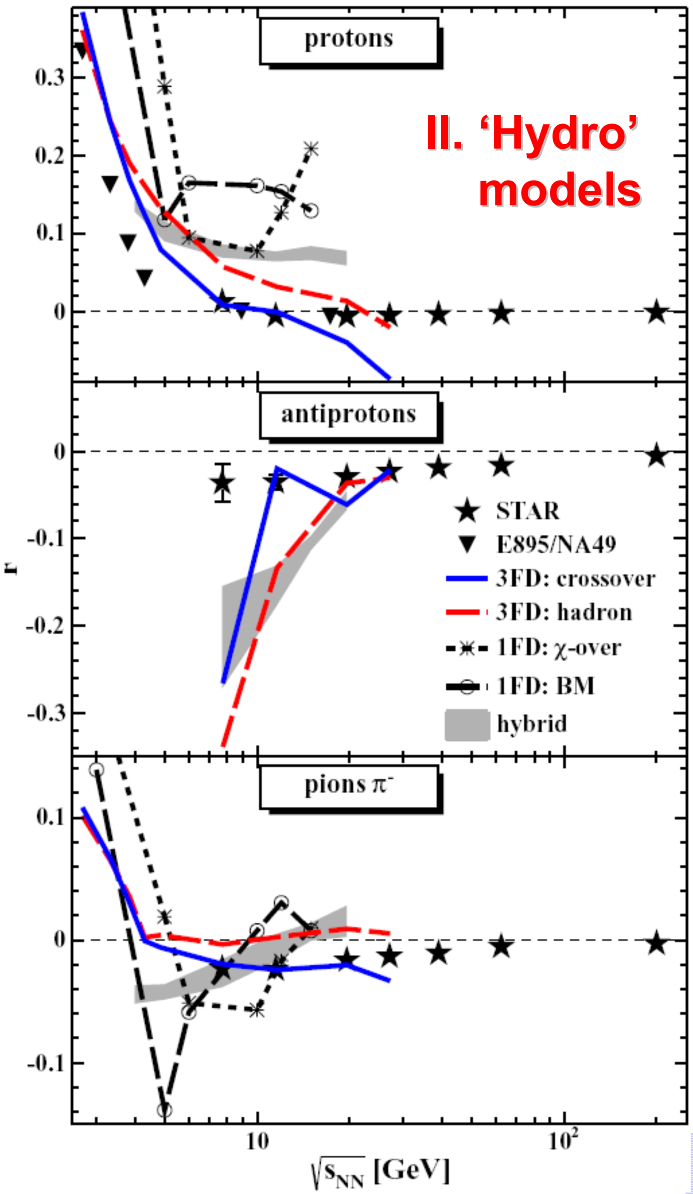


STAR Collaboration, PRL 112, 162301 (2014)
PHSD/HSD : V. Konchakovski et al., PRC90 (2014) 14903
UrQMD: J. Steinheimer et al., PRC 89 (2014) 054913

Excitation function of v_1 slopes







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

$$F = \frac{d\upsilon_1}{dy}\Big|_{y=0}$$

Models:

I. Transport models:
HSD, PHSD, UrQMD

II. 'Hydro' models:

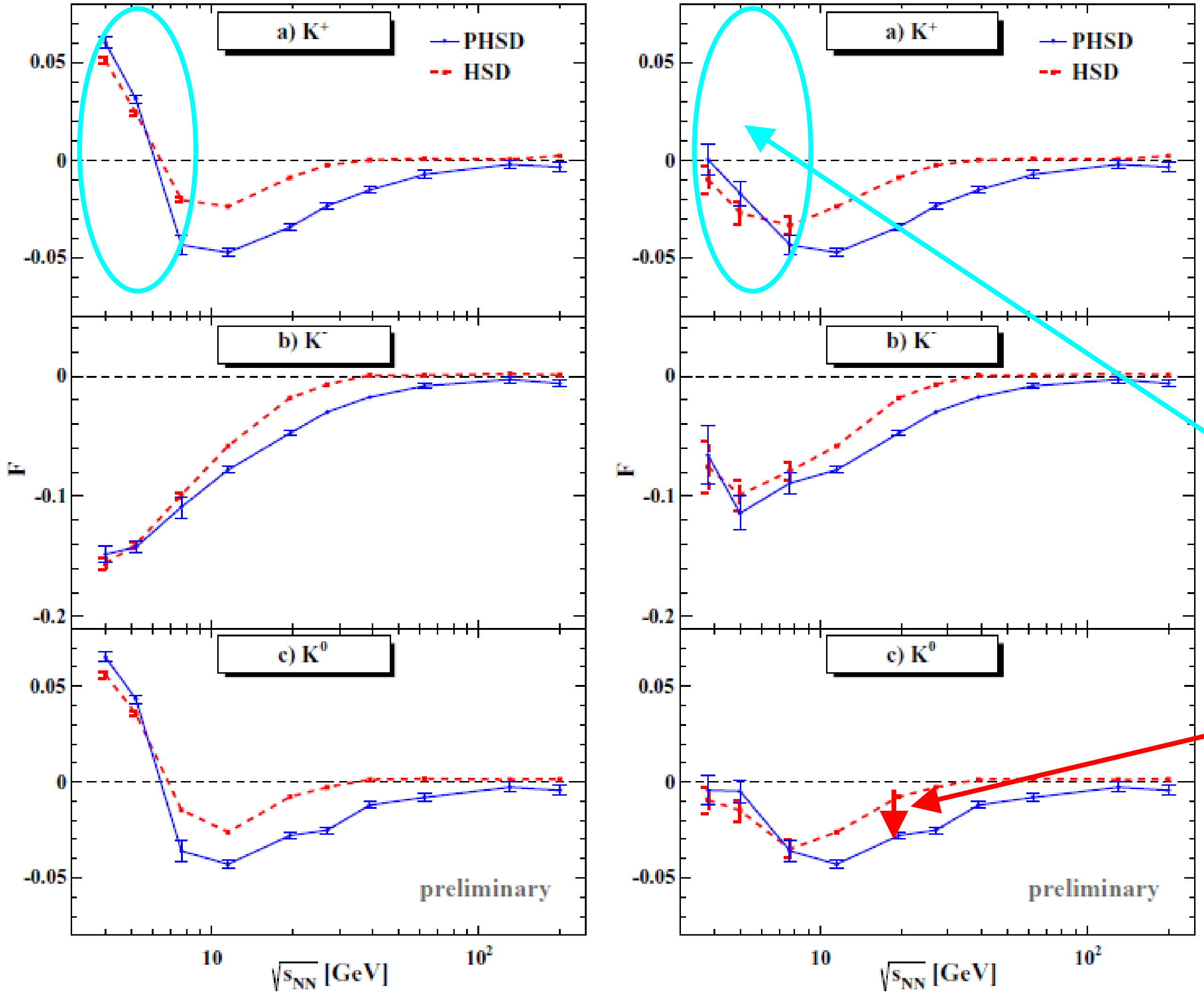
- **3D-Fluid Dynamic approach (3FD)**
- **1FD-hydro with chiral cross-over (χ) and Bag Model (BM) EoS**
- **Hybrid-UrQMD with BM and χ-EoS (shaded arria)**

➔ smooth crossover?!

STAR Collaboration, PRL 112, 162301 (2014)
PHSD/HSD and 3D-fluid hydro: V. Konchakovski, W. Cassing, Yu. Ivanov, V. Toneev, PRC90 (2014) 14903
Hybrid/UrQMD/Hydro: J. Steinheimer, J. Auvinen, H. Petersen, M. Bleicher, H. Stöcker, PRC 89 (2014) 054913

Excitation function of v_1 slopes of K,Kbar

Without K, Kbar potential | **Including K, Kbar potential:**



$$U_K(\mathrm{p},\rho_N) = \omega_K(\rho_N,\mathrm{p}) - \sqrt{\mathrm{p}^2 + m_K^2}$$

From **G-matrix**: L. Tolós et al, PRC 65, 054907 (2002)

Potential: attractive for K^-, repulsive for K^+

U_K - relevant for $\rho_B < 3\rho_0$

➔ Strong influence of (anti-) kaon **potential** at low energies!

➔ at high energies – **partonic interactions** are important (differences between HSD and PHSD)

- v_1 slopes of K, Kbar at midrapidity – sensitive to the dynamics!

PHSD/HSD: W. Cassing, V. P. Konchakovski, A. Palmese, V. D. Toneev, and E. L. Bratkovskaya, arXiv:1408.4313

Messages from the directed flow v_1 analysis

- The PHSD reproduces the general trends in the $v_1(y)$ excitation functions in the energy range $\sqrt{s}$ =7.7-200 GeV.
  We don't see any "wiggle-like" structures as expected by early hydro calculations but see a softening of the EoS in the BES range.

- The PHSD results differ from those of HSD 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.

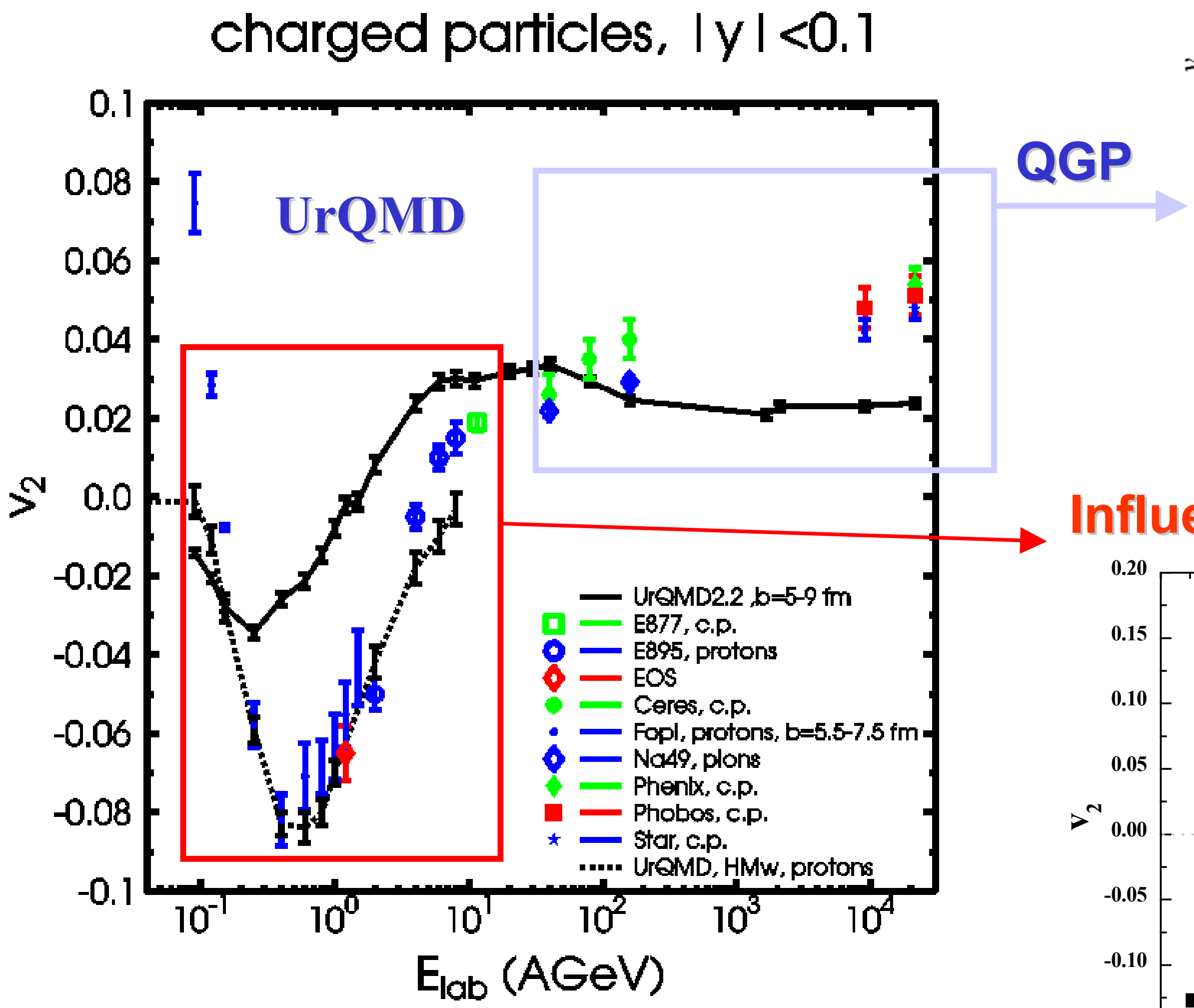
- 3-Fluid Dynamic approach (3FD) gives reasonable results for proton and pion slopes of v_1 but fails at 7.7 GeV for antiprotons

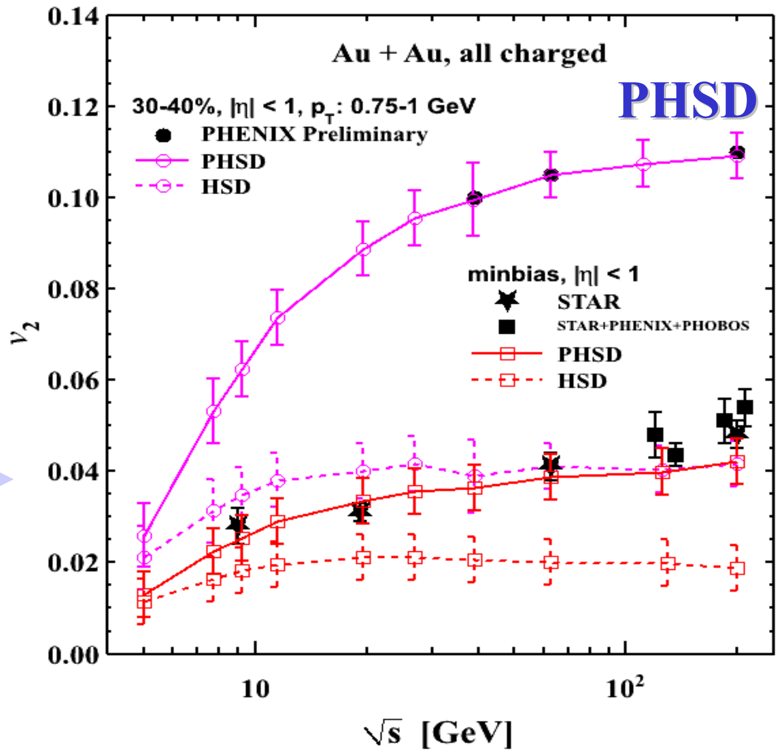
- Crossover transition agrees better with the experimental data than a pure hadronic EoS

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

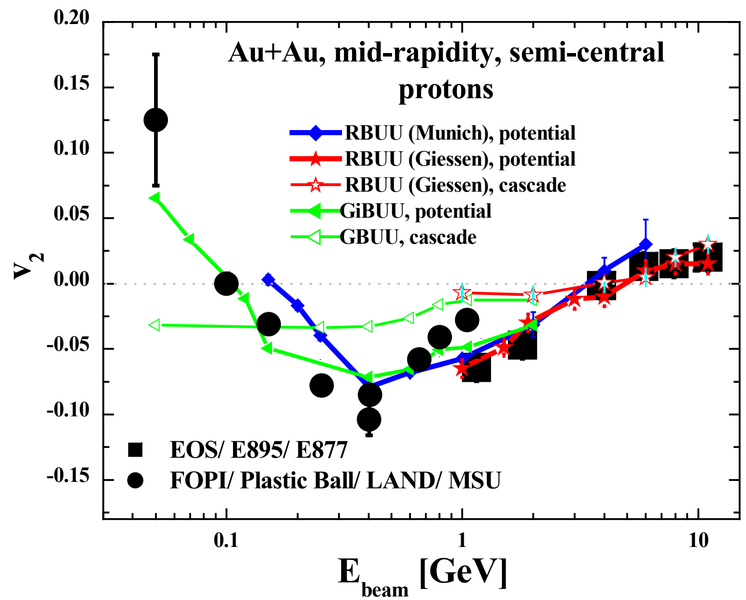
Collective flow: v_2 excitation functions

The excitation function for v_2 of charged particles from string-hadron transport models :





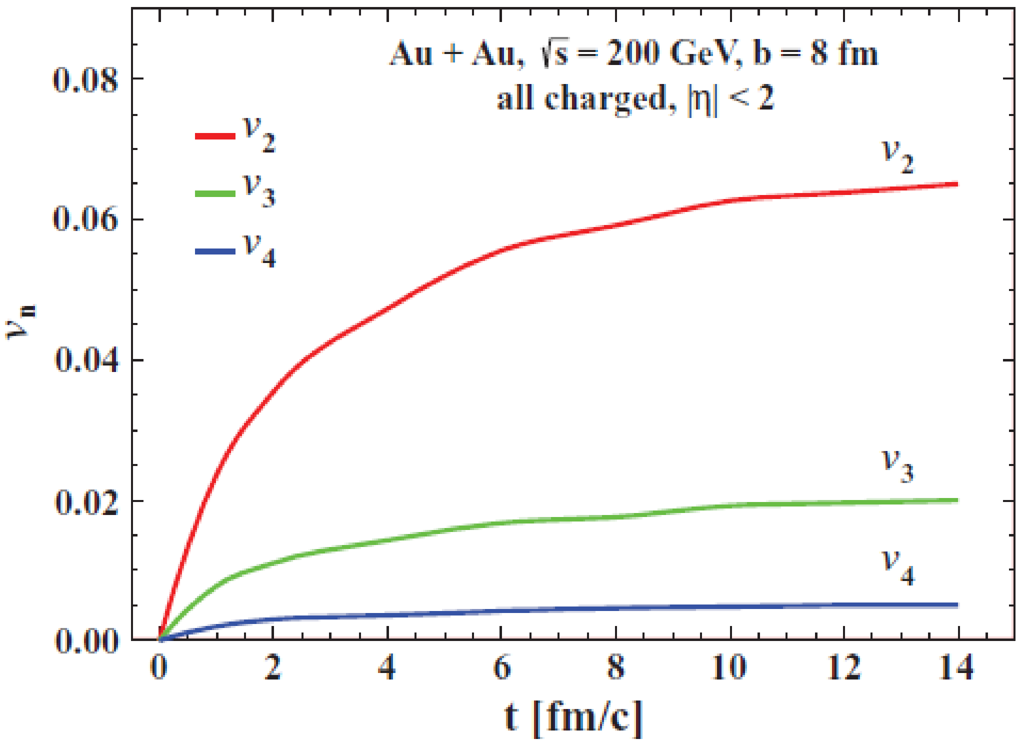
Influence of hadron potentials → EoS



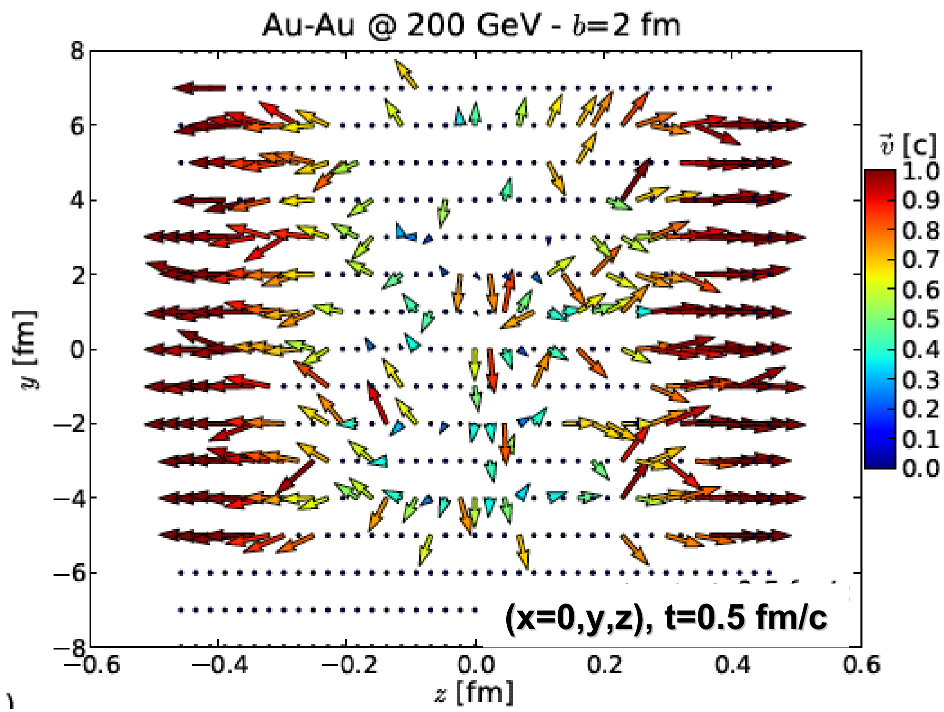
Development of azimuthal anisotropies in time

Au + Au collisions at $s^{1/2}$ = 200 GeV

❑ **Time evolution of v_n for b = 8 fm**



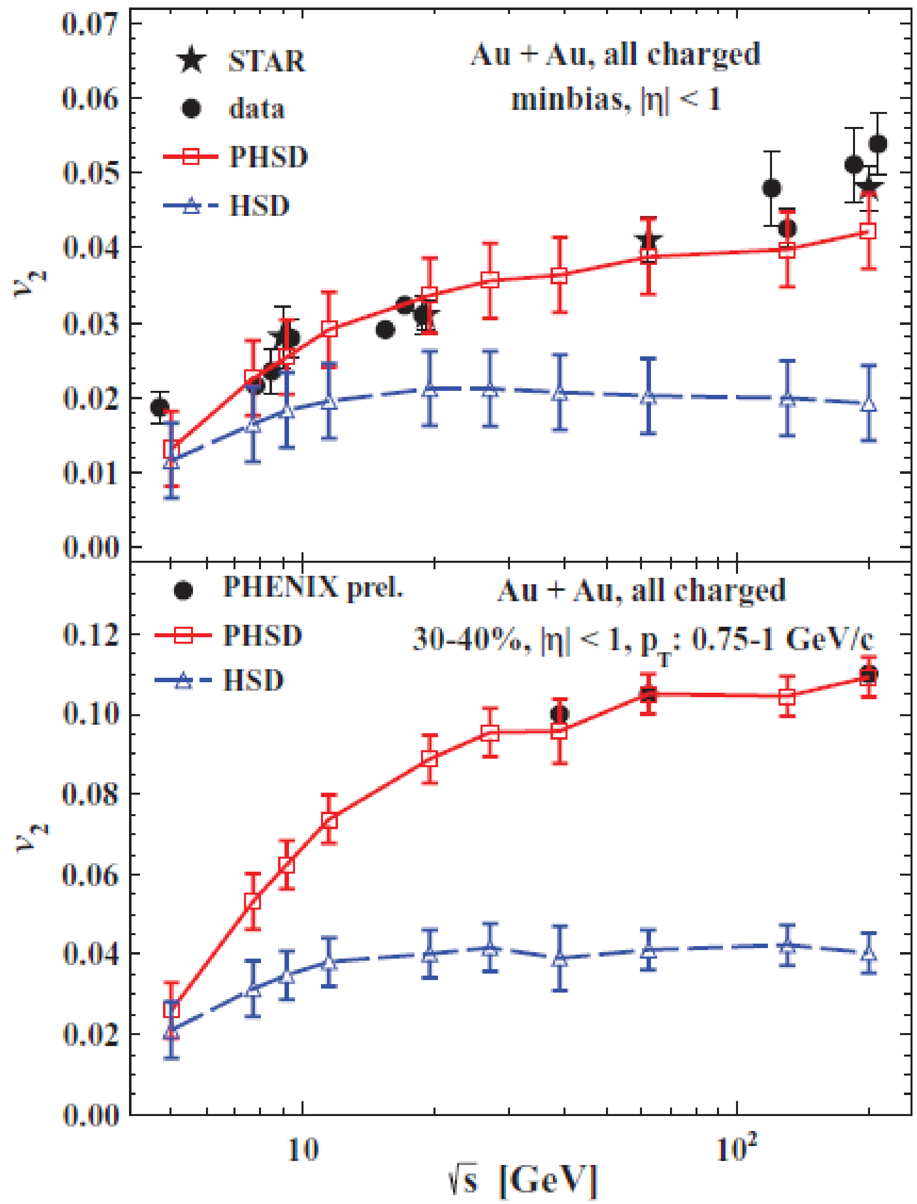
❑ **Flow velocity for b = 2 fm (x=0,y,z), t=0.5 fm/c**

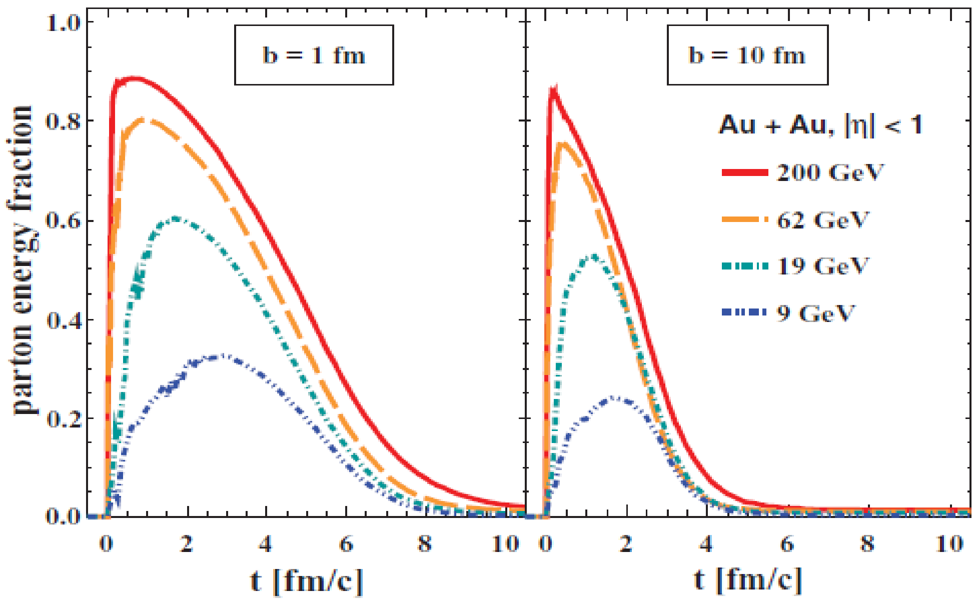


■ **Flow coefficients reach their asymptotic values by the time of 6–8 fm/c after the beginning of the collision**

V. Konchakovski, E. Bratkovskaya, W. Cassing, V. Toneev, V. Voronyuk, Phys. Rev. C 85 (2012) 011902

Elliptic flow v_2 vs. collision energy for Au+Au

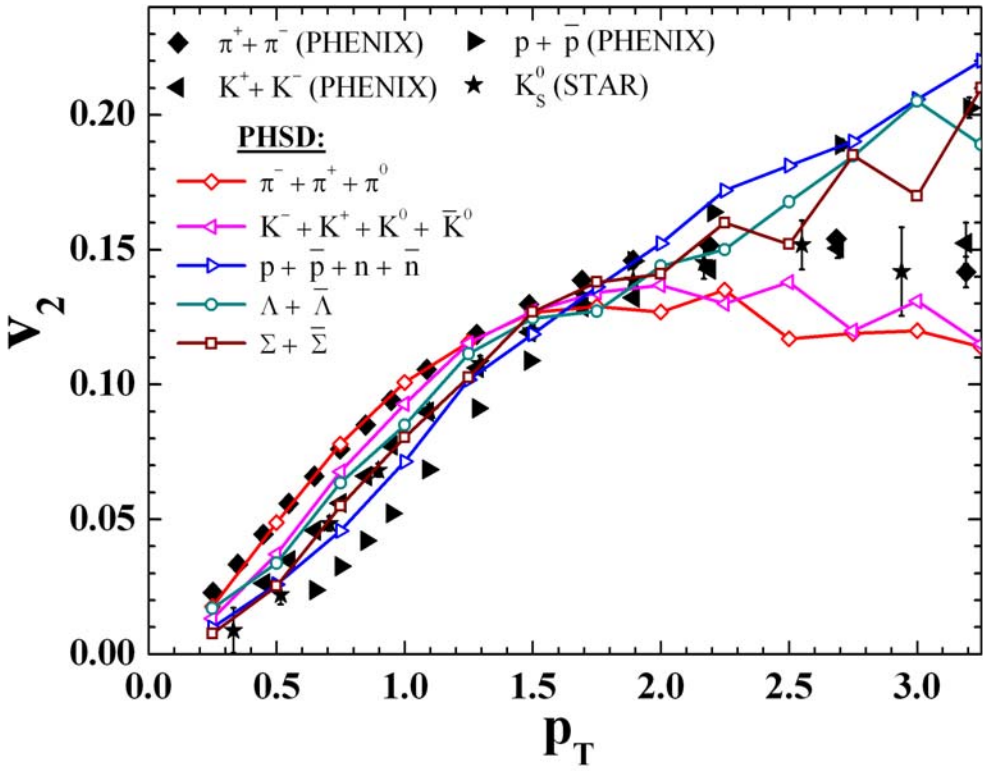


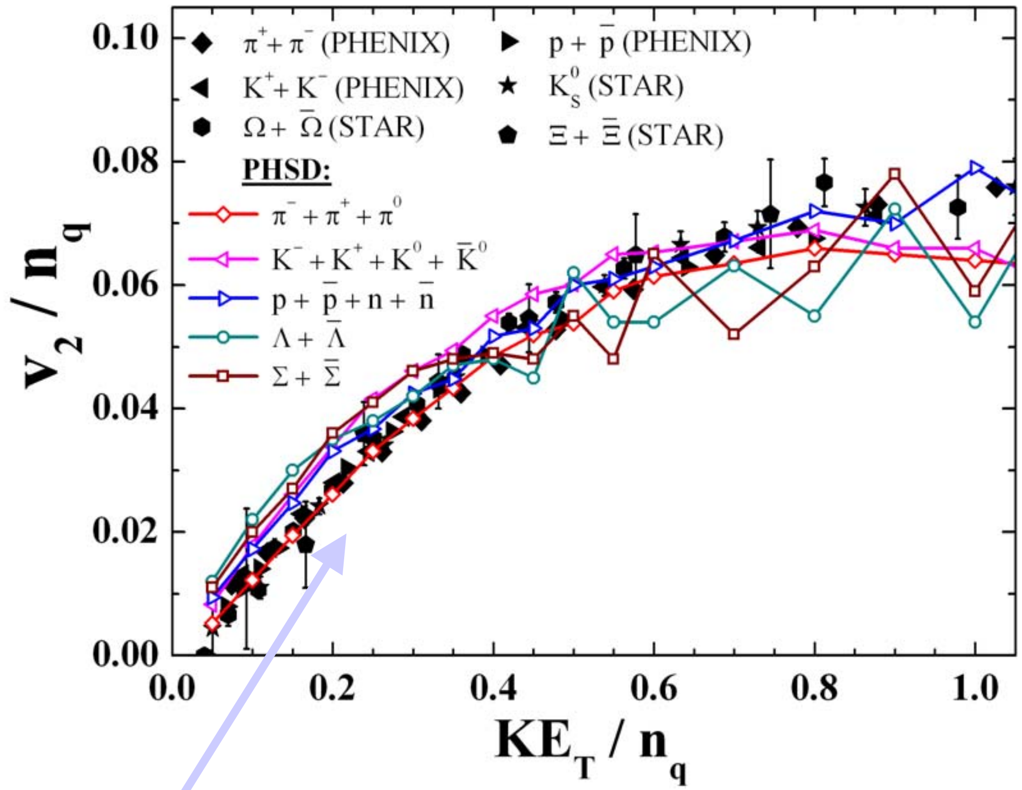


- v_2 in PHSD is larger than in HSD due to the repulsive scalar mean-field potential $U_s(\rho)$ for partons
- v_2 grows with bombarding energy due to the increase of the parton fraction

V. Konchakovski, E. Bratkovskaya, W. Cassing, V. Toneev, V. Voronyuk, Phys. Rev. C 85 (2012) 011902

Elliptic flow scaling at RHIC

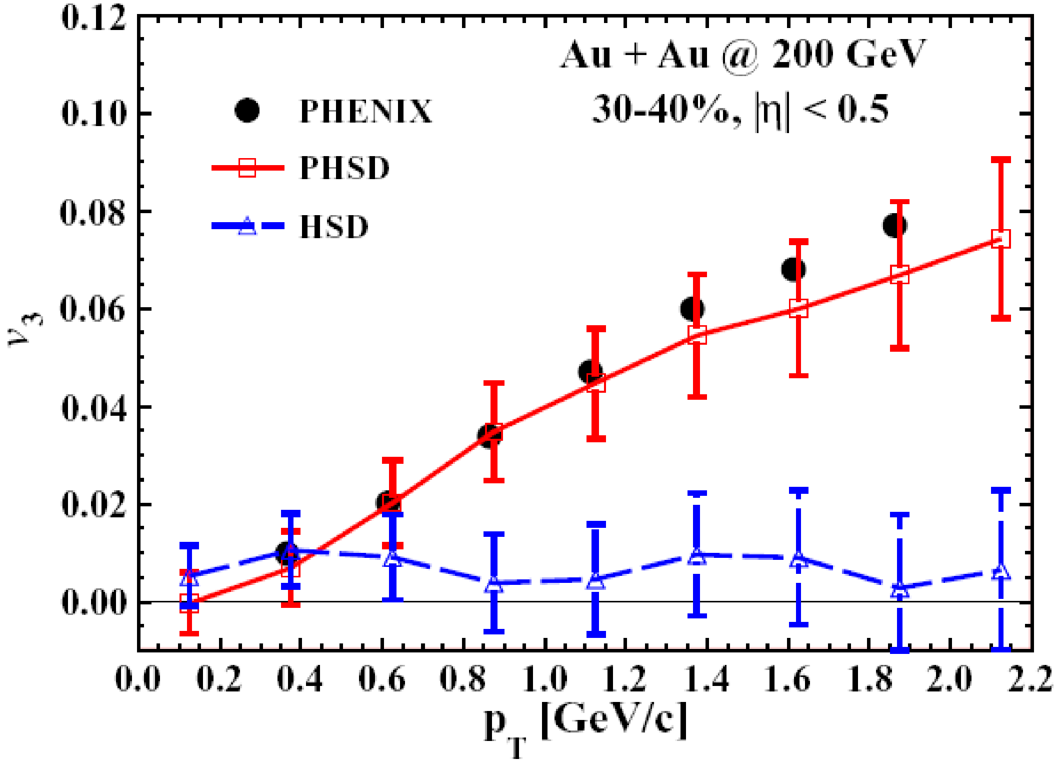




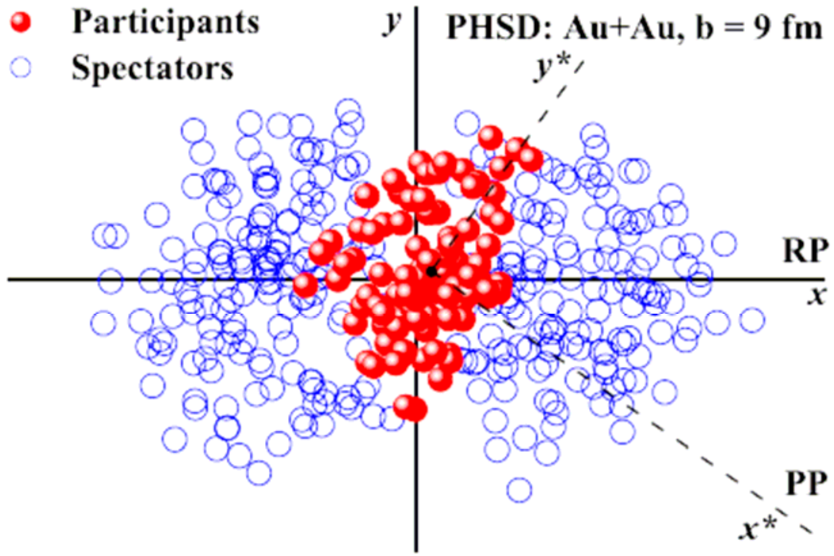
- The **mass splitting at low p_T** is approximately reproduced in PHSD as well as the **meson-baryon splitting for p_T > 2 GeV/c**
- The **scaling of v_2 with the number of constituent quarks n_q** is roughly in line with the data

E. Bratkovskaya, W. Cassing, V. Konchakovski, O. Linnyk, NPA856 (2011) 162

Transverse momentum dependence of triangular flow at RHIC



triangular flow

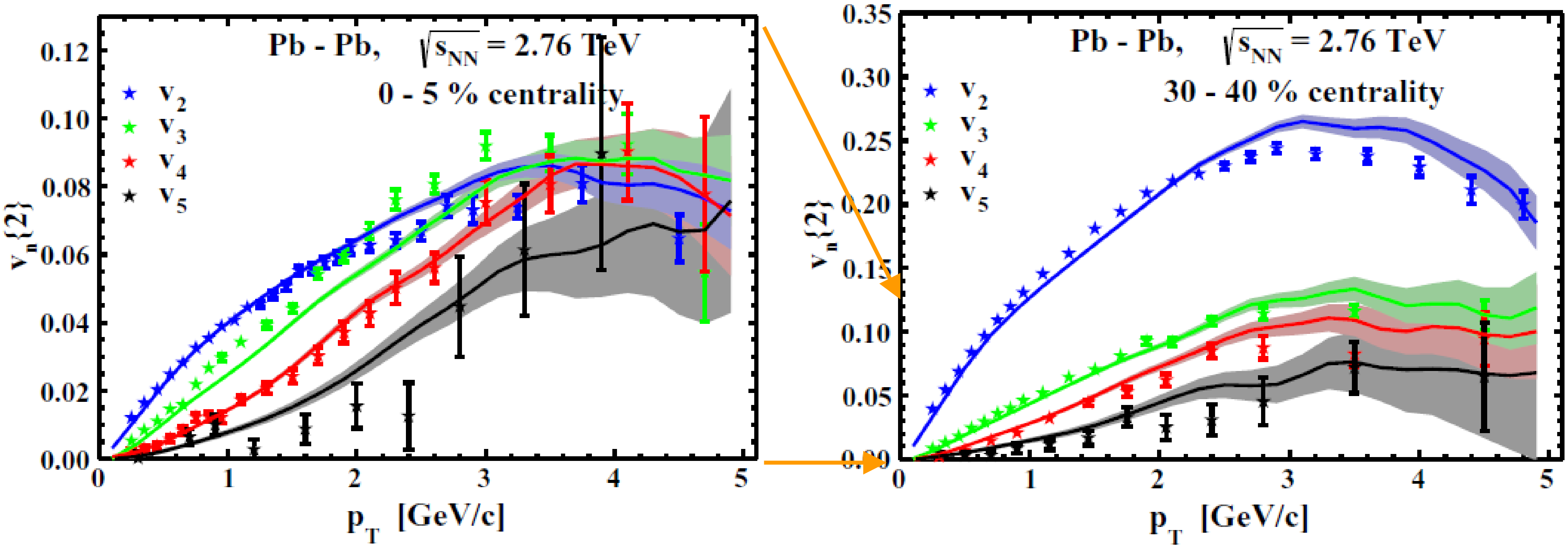


- HSD (without QGP) shows a flat p_T distribution
- PHSD shows an increase of v_3 with p_T

➔ v_3 : needs partonic degrees of freedom !

V. Konchakovski, E. Bratkovskaya, W. Cassing, V. Toneev, V. Voronyuk, Phys. Rev. C 85 (2012) 044922

V_n (n=2,3,4,5) of charged particles from PHSD at LHC



symbols – ALICE

PRL 107 (2011) 032301

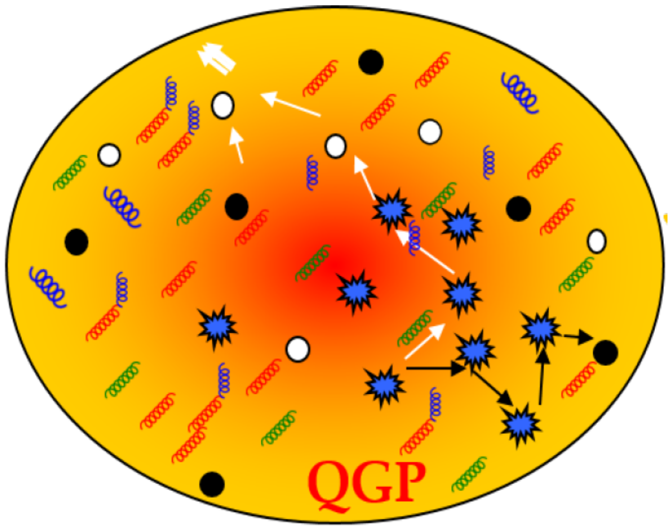
lines – PHSD (e-by-e)

- PHSD: increase of v_n (n=2,3,4,5) with p_T
- v_2 increases with decreasing centrality
- v_n (n=3,4,5) show weak centrality dependence

V. Konchakovski, W. Cassing, V. Toneev, arXiv:1411.5534

Messages from the study of anisotropy coefficients V_n

- **Anisotropy coefficients v_n (n=2,3,4,5,...) as a signal of the QGP:**
- **quark number scaling of v_2 at ultrarelativistic energies – signal of deconfinement**
- **growing of v_2 with energy – partonic interactions generate a larger pressure than the hadronic interactions**
- **v_n, n=3,4,5.. – sensitive to QGP**



Thanks to: PHSD group

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

Giessen University
Wolfgang Cassing
Olena Linnyk
Volodya Konchakovski
Thorsten Steinert
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GOETHE UNIVERSITÄT FRANKFURT AM MAIN
FIAS Frankfurt Institute for Advanced Studies
Bundesministerium für Bildung und Forschung
DFG Deutsche Forschungsgemeinschaft
PHSD
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Subatech
TEXAS A&M UNIVERSITY
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UAB Universitat Autònoma de Barcelona