FIAS Frankfurt Institute for Advanced Studies

HIC for FAIR Helmholtz International Center

GOETHE UNIVERSITÄT FRANKFURT AM MAIN

Theory and HPC

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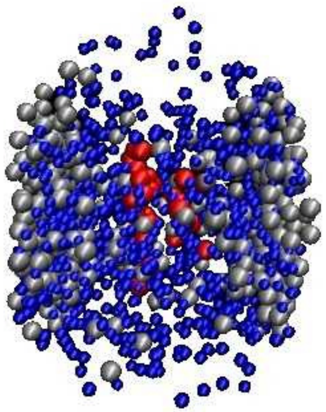


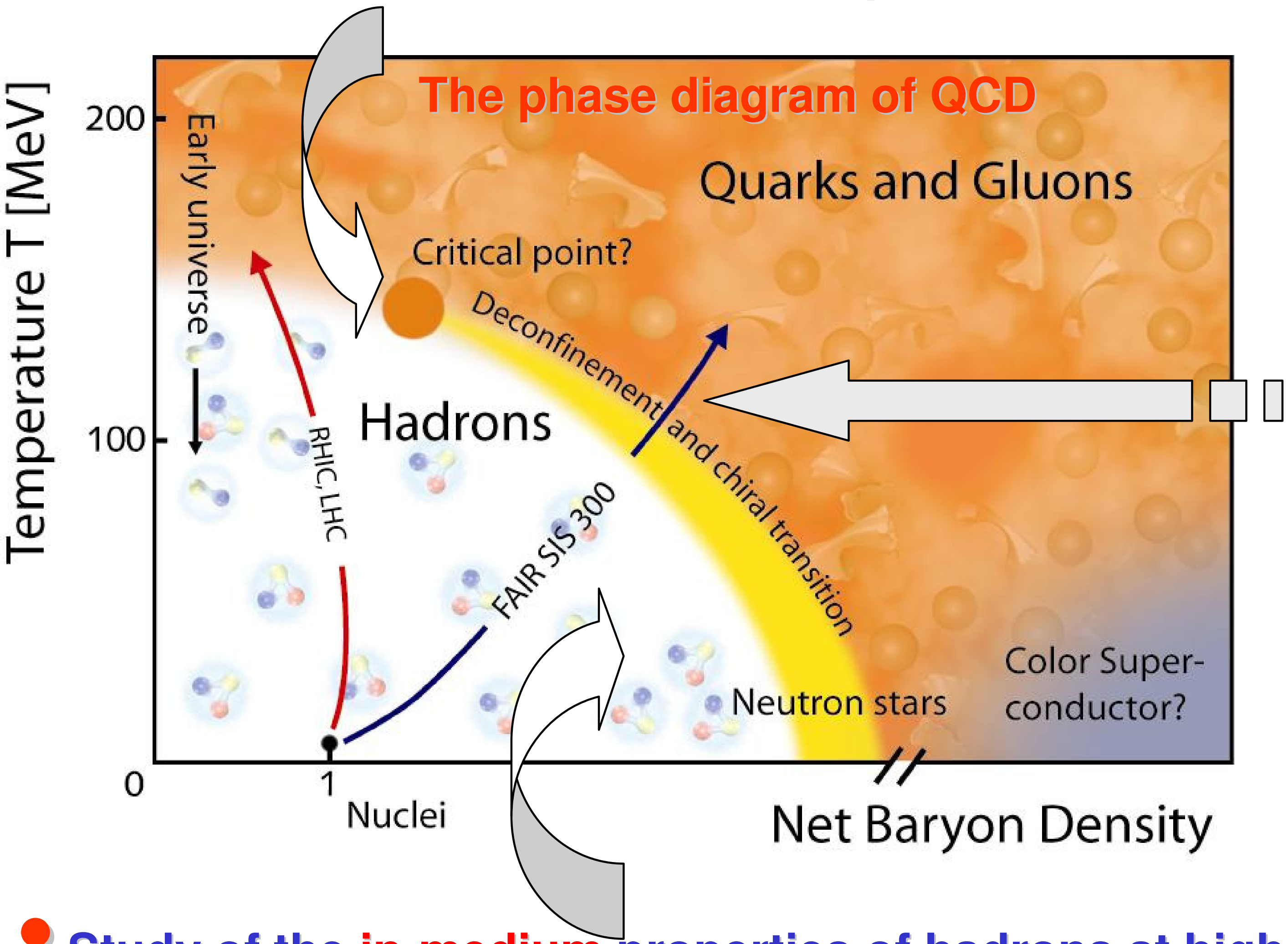
***HIC for FAIR Physics Day: HPC Computing,
FIAS, Frankfurt am Main***

11 November 2014

PHSD

The holy grail of heavy-ion physics:

- Search for the critical point



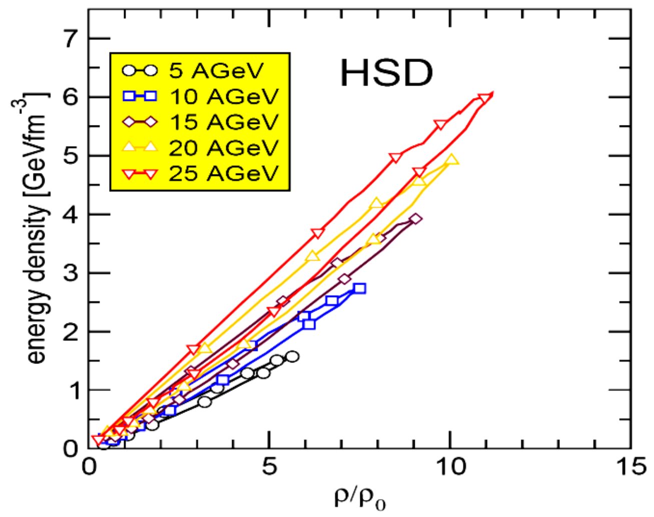
- Study of the phase transition from hadronic to partonic matter – Quark-Gluon-Plasma

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

Physics at FAIR

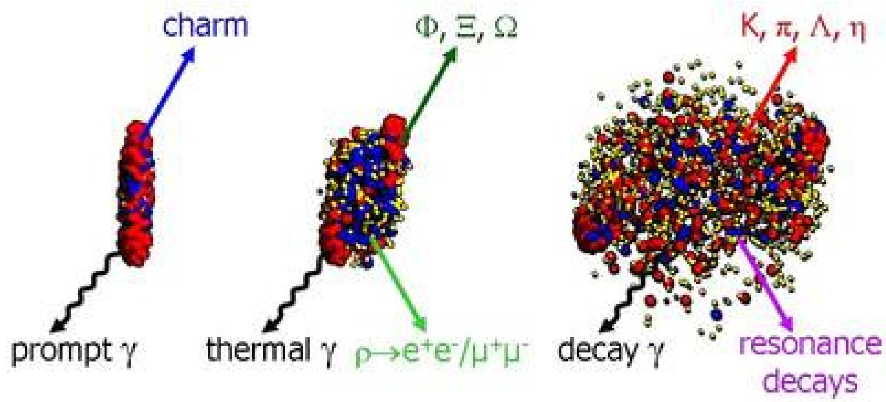
FAIR energies are well suited to study dense and hot nuclear matter :

- a phase transition to QGP
- in-medium effects of hadrons
- chiral symmetry restoration



Way to study:

Experimental energy scan of different observables in order to find an ‚anomalous' behavior by comparing with theory

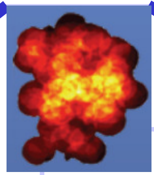


➔ Dynamical models of HIC!

Dynamical models for HIC

Macroscopic

hydro-models:
- description of QGP and hadronic phase by hydrodanamical equations for fluid
- assumption of local equilibrium
- EoS with phase transition from QGP to HG
- initial conditions (e-b-e, fluctuating)



ideal
(Jyväskylä,SHASTA, TAMU, …)

viscous
(Romachkke,(2+1)D VISH2+1, (3+1)D MUSIC,…)

fireball models:
- no explicit dynamics: parametrized time evolution (TAMU)

‚Hybrid‘
QGP phase: hydro with QGP EoS
- hadronic freeze-out: after burner - hadron-string transport model

(‚hybrid‘-UrQMD, EPOS, …)

Microscopic

Non-equilibrium microscopic transport models – based on many-body theory

Hadron-string models
(UrQMD, IQMD, HSD, QGSM …)

Partonic cascades
pQCD based
(Duke, BAMPS, …)

Parton-hadron models:
- QGP: pQCD based cascade
- massless q, g
- hadronization: coalescence

(AMPT, HIJING)

PHSD
- QGP: lQCD EoS
- massive quasi-particles (q and g with spectral functions) in self-generated mean-field
- dynamical hadronization
- HG: off-shell dynamics

(applicable for strongly interacting systems)

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

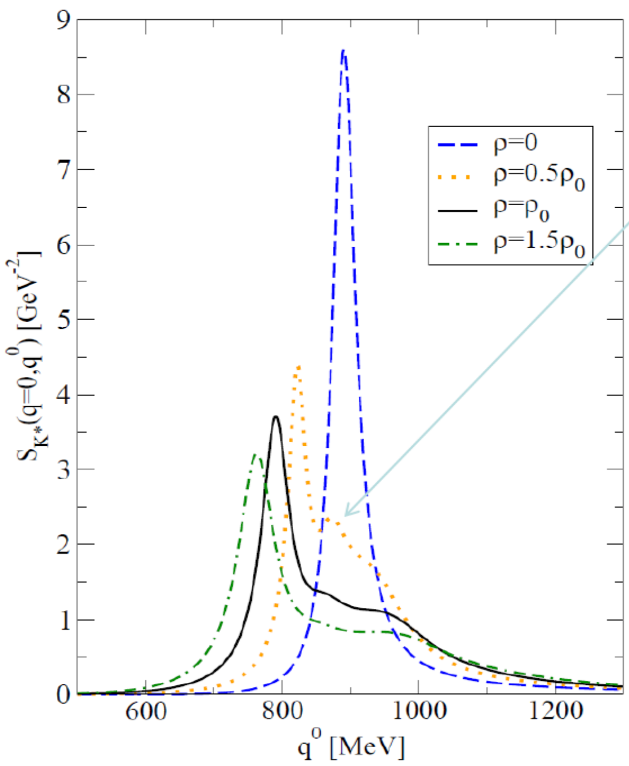
- **How to describe the dynamics of broad strongly interacting quantum states in transport theory?**

- ❑ **semi-classical BUU**

  first order gradient expansion of quantum Kadanoff-Baym equations

- ❑ **generalized transport equations**

Kbar* spectral function



Λ(1783)N^{-1} and Σ(1830)N^{-1} exitations

Barcelona / Valencia group

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:

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

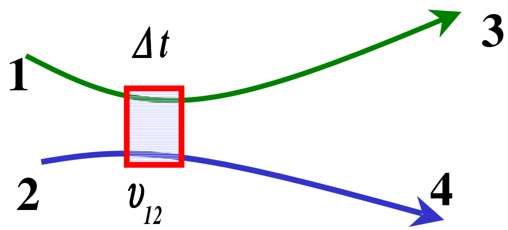
- Collision term for 1+2→3+4 (let's consider fermions) :

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

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 — Loss term: 1+2→3+4



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 $S^<$

(1962)

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

Integration over the intermediate spacetime

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

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

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

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

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

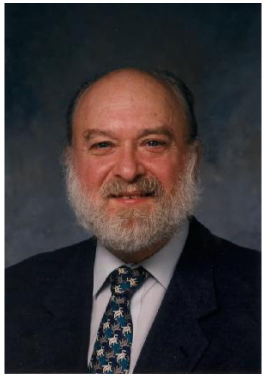
$$S_{xy}^{ret} = S_{xy}^{c} - S_{xy}^{<} = S_{xy}^{>} - S_{xy}^{a} \quad - retarded$$

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

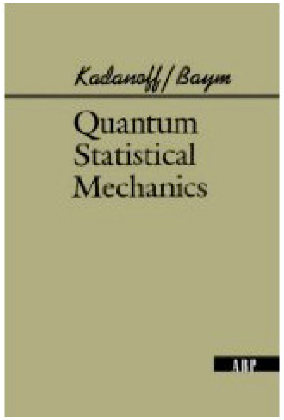
$$\hat{S}_{0x}^{-1} \equiv -(\partial_x^{\mu}\partial_{\mu}^{x} + M_0^2)$$

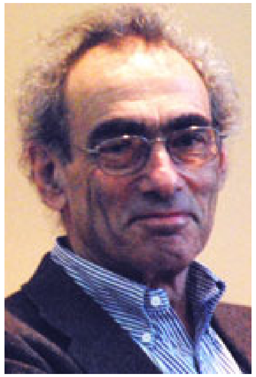
$$\eta = \pm 1 (bosons \,/\, fermions)$$

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



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 $A_{XP} \rightarrow \delta(p^2-M^2)$

- 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:

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

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

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

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

Collision term in off-shell transport models

Collision term for reaction 1+2->3+4:

$$I_{coll}(X,\vec{P},M^2) = Tr_2 Tr_3 Tr_4 A(X,\vec{P},M^2) A(X,\vec{P}_2,M_2^2) A(X,\vec{P}_3,M_3^2) A(X,\vec{P}_4,M_4^2)$$

$$|G((\vec{P},M^2)+(\vec{P}_2,M_2^2) \to (\vec{P}_3,M_3^2)+(\vec{P}_4,M_4^2))|^2_{\mathcal{A},\mathcal{S}} \; \delta^{(4)}(P+P_2-P_3-P_4)$$

$$[\, N_{X\vec{P}_3M_3^2}\, N_{X\vec{P}_4M_4^2}\, \bar{f}_{X\vec{P}M^2}\, \bar{f}_{X\vec{P}_2M_2^2} \;-\; N_{X\vec{P}M^2}\, N_{X\vec{P}_2M_2^2}\, \bar{f}_{X\vec{P}_3M_3^2}\, \bar{f}_{X\vec{P}_4M_4^2} \,]$$

‚gain' term ‚loss' term

with $\bar{f}_{X\vec{P}M^2} = 1 + \eta\, N_{X\vec{P}M^2}$ and $\eta = \pm 1$ for bosons/fermions, respectively.

The trace over particles 2,3,4 reads explicitly

for fermions

$$Tr_2 = \sum_{\sigma_2,\tau_2} \frac{1}{(2\pi)^4} \int d^3P_2 \frac{dM_2^2}{2\sqrt{\vec{P}_2^2 + M_2^2}}$$

for bosons

$$Tr_2 = \sum_{\sigma_2,\tau_2} \frac{1}{(2\pi)^4} \int d^3P_2 \frac{dP_{0,2}^2}{2}$$

additional integration

The transport approach and the particle spectral functions are fully determined once the in-medium transition amplitudes G are known in their off-shell dependence!

In-medium transition rates: G-matrix approach

Need to know in-medium transition amplitudes G and their off-shell dependence

$$|G((\vec{P},M^2)+(\vec{P}_2,M_2^2)\rightarrow(\vec{P}_3,M_3^2)+(\vec{P}_4,M_4^2))|^2_{\mathcal{A},\mathcal{S}}$$

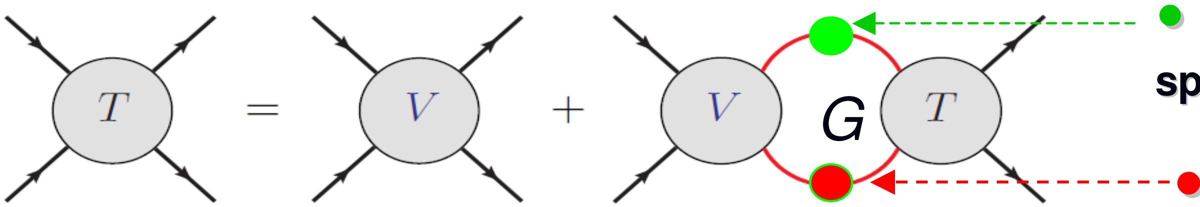
↓

Coupled channel G-matrix approach

Transition probability :

$$P_{1+2\rightarrow 3+4}(s)=\int d\cos(\theta)\ \frac{1}{(2s_1+1)(2s_2+1)}\sum_i\sum_\alpha\ G^\dagger G$$

with G(p,ρ,T) - G-matrix from the solution of coupled-channel equations:



Meson selfenergy and spectral function

Baryons: Pauli blocking and potential dressing

- $\mathcal{T}_{ij}(\rho,T) = V_{ij} + V_{il}\ G_l(\rho,T)\ \mathcal{T}_{lj}(\rho,T)$

For strangeness:
D. Cabrera, L. Tolos, J. Aichelin, E.B., arXiv:1406.2570; W. Cassing, L. Tolos, E.B., A. Ramos, NPA727 (2003) 59

Collision width in off-shell transport model

- **Total width** = collision width + decay width : $\Gamma = \Gamma_{coll} + \Gamma_{dec}$

In the **vacuum**: $\Gamma = \Gamma_{dec}$

- **Example: Collision width Γ_{coll}** for 1+2->3+4 process – defined from the **loss term** of the collision integral I_{coll}:

(similar for the n<->m reactions!)

$$-I_{coll}(loss) = \Gamma_{coll}(X,\vec{P},M^2)N_{X\vec{P}M^2}$$

$$\Gamma_{XP} = -Im\Sigma^{ret}_{XP} = 2p_0\Gamma$$

$$\Gamma_{coll}(X,\vec{P},M^2) = Tr_2 Tr_3 Tr_4\ A(X,\vec{P},M^2)A(X,\vec{P}_2,M_2^2)A(X,\vec{P}_3,M_3^2)A(X,\vec{P}_4,M_4^2)$$

$$\times |G((\vec{P},M^2)+(\vec{P}_2,M_2^2)\to(\vec{P}_3,M_3^2)+(\vec{P}_4,M_4^2))|^2_{AS}\ \delta^{(4)}(P+P_2-P_3-P_4)N_{X\vec{P}_2M_2^2}\bar{f}_{X\vec{P}_3M_3^2}\bar{f}_{X\vec{P}_4M_4^2}$$

- **Collision width is defined by all possible interactions in the local cell**

! Assumptions used in transport calculations for V-mesons (to speed up calculations):

- Collision width in **low density approximation:** $\Gamma_{coll} = \gamma\,\rho <\upsilon\,\sigma_{VN}^{tot}>$
- replace $<\upsilon\,\sigma_{VN}^{tot}>$ by averaged value G=const: $\Gamma_{coll} = \gamma\,\rho\,G$

(Works well – cf. low density approximation vs. the full dynamical calculation of Γ_{Coll} in Ref. E.B., NPA696 (2001) 761)

Mean-field potential in off-shell transport model

- **Many-body theory:** Interacting relativistic particles have a **complex self-energy:**

$$\Sigma_{XP}^{ret} = Re\Sigma_{XP}^{ret} + i\, Im\Sigma_{XP}^{ret}$$

The neg. imaginary part $\Gamma_{XP} = -Im\Sigma_{XP}^{ret} = 2p_0\Gamma$ is related via $\Gamma = \Gamma_{coll} + \Gamma_{dec}$

to the inverse livetime of the particle $\tau \sim 1/\Gamma$.

- The **collision width** Γ_{coll} is determined from the **loss term** of the collision integral I_{coll}

- By **dispersion relation** we get a contribution to the **real part of self-energy**:

$$Re\Sigma_{XP}^{ret}(p_0) = P\int_0^\infty dq \frac{Im\Sigma_{XP}^{ret}(q)}{(q-p_0)}$$

that gives **a mean-field potential U_{XP}** via: $$Re\Sigma_{XP}^{ret}(p_0) = 2p_0 U_{XP}$$

→ the **complex self-energy** relates in a self-consistent way to the self-generated mean-field potential and collision width (inverse lifetime)

Detailed balance on the level of 2<->n: treatment of multi-particle collisions in transport approaches

W. Cassing, NPA 700 (2002) 618

Generalized collision integral for *n <->m* reactions:

$$I_{coll} = \sum_n \sum_m I_{coll}[n \leftrightarrow m]$$

$$I^i_{coll}[n \leftrightarrow m] =$$
$$\frac{1}{2} N^m_n \sum_\nu \sum_\lambda \left(\frac{1}{(2\pi)^4}\right)^{n+m-1} \int \left(\prod_{j=2}^{n} d^4p_j \;\; A_j(x,p_j)\right) \left(\prod_{k=1}^{m} d^4p_k \; A_k(x,p_k)\right)$$
$$\times A_i(x,p) \; W_{n,m}(p,p_j;i,\nu \mid p_k;\lambda) \; (2\pi)^4 \; \delta^4(p^\mu + \sum_{j=2}^{n} p^\mu_j - \sum_{k=1}^{m} p^\mu_k)$$
$$\times [\tilde{f}_i(x,p) \prod_{k=1}^{m} f_k(x,p_k) \prod_{j=2}^{n} \tilde{f}_j(x,p_j) - f_i(x,p) \prod_{j=2}^{n} f_j(x,p_j) \prod_{k=1}^{m} \tilde{f}_k(x,p_k)].$$

$\tilde{f} = 1 + \eta f$ **is Pauli-blocking or Bose-enhancement factors; η=1 for bosons and η=-1 for fermions**

$W_{n,m}(p,p_j;i,\nu \mid p_k;\lambda)$ **is a transition probability**

➔ huge CPU!

Antibaryon production in heavy-ion reactions

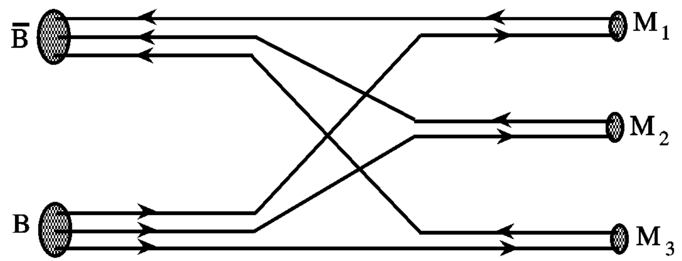
W. Cassing, NPA 700 (2002) 618

Multi-meson fusion reactions

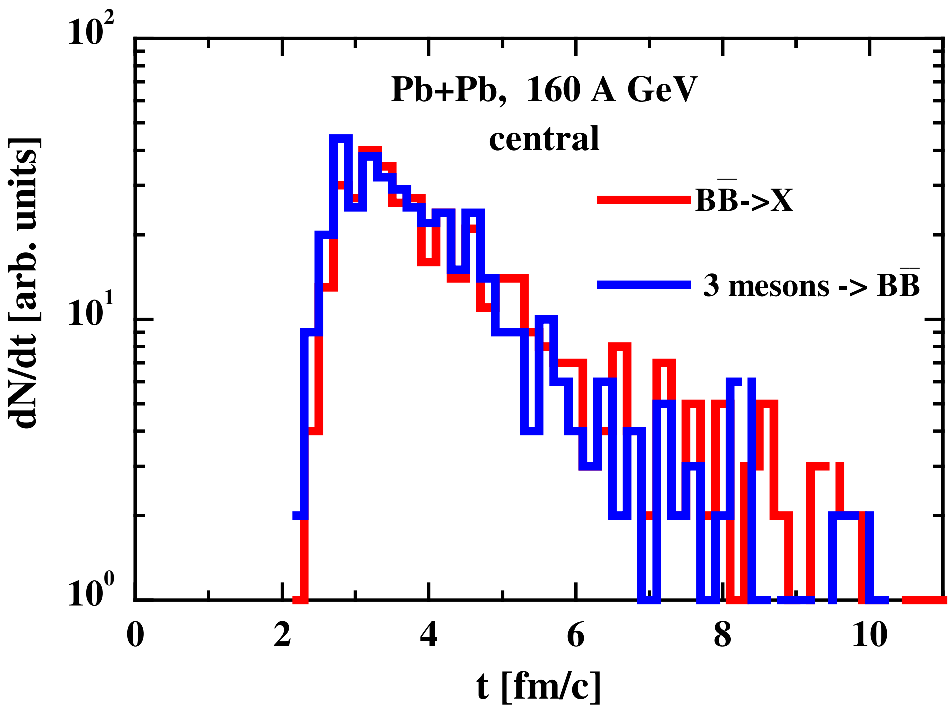
$m_1+m_2+...+m_n \leftrightarrow B+\bar{B}$ B+Bbar

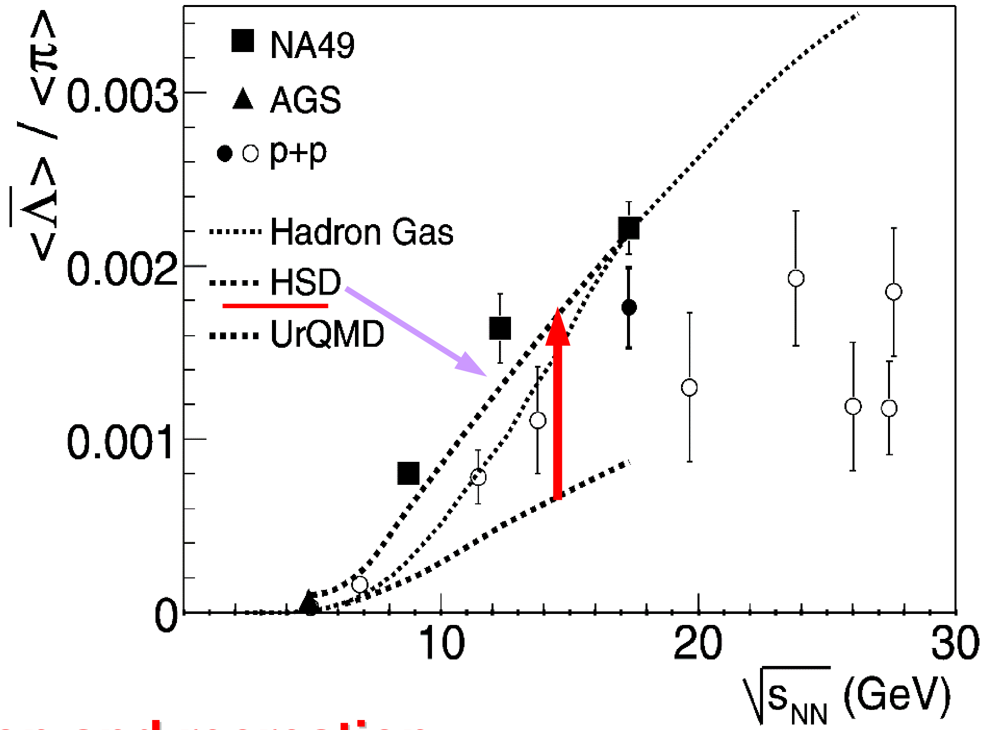
(m=π,ρ,ω,..)

- important for antiproton, antilambda dynamics !



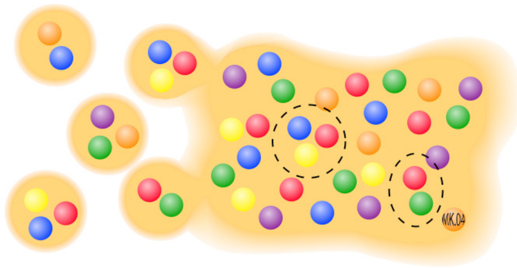
2<->3





→ approximate equilibrium of annihilation and recreation

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)

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 :

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

- **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:**

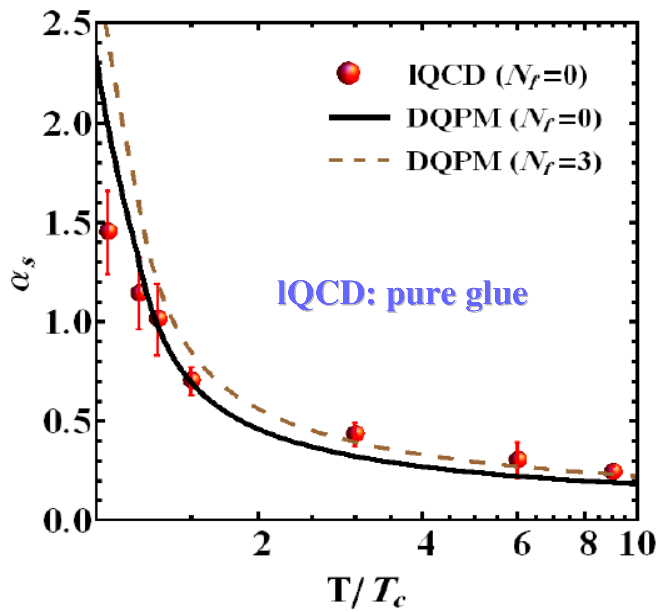
    $M_g^2(T) = \frac{g^2}{6}\left(\left(N_c + \frac{N_f}{2}\right)T^2 + \frac{N_c}{2}\sum_q \frac{\mu_q^2}{\pi^2}\right)$

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

$N_c = 3$, $N_f = 3$

  - **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)**

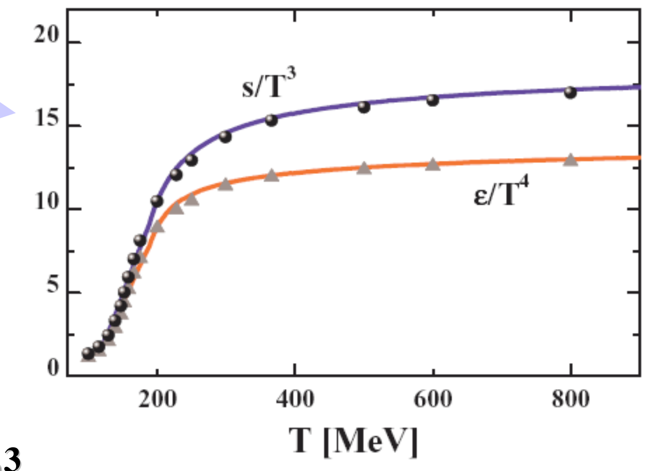
  with 3 parameters: T_s/T_c=0.46; c=28.8; λ=2.42
  (for pure glue N_f=0)

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

The Dynamical QuasiParticle Model (DQPM)

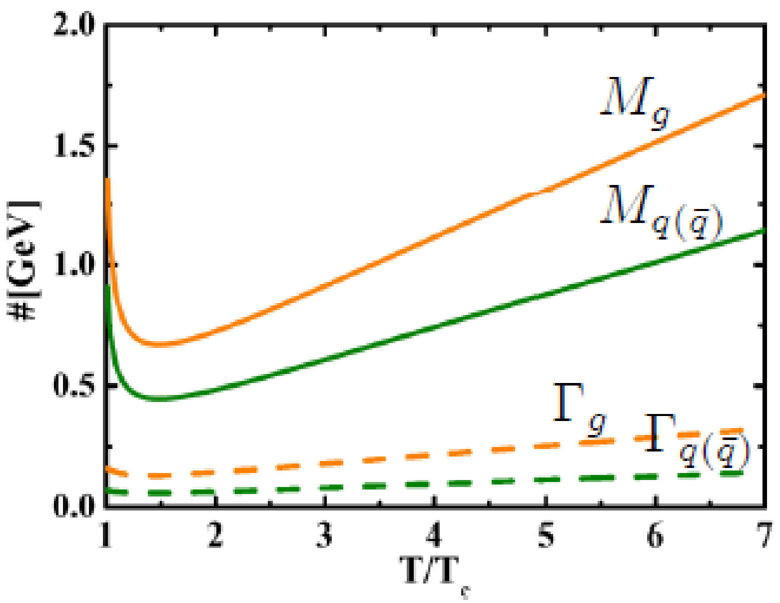
➢ **fit to lattice (lQCD) results (e.g. entropy density)**

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

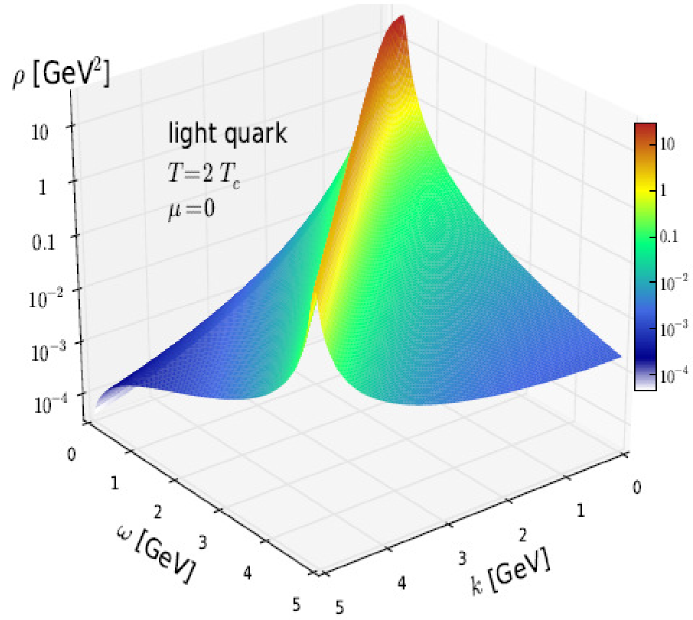


➔ **Quasiparticle properties:**

■ **large width and mass for gluons and quarks**



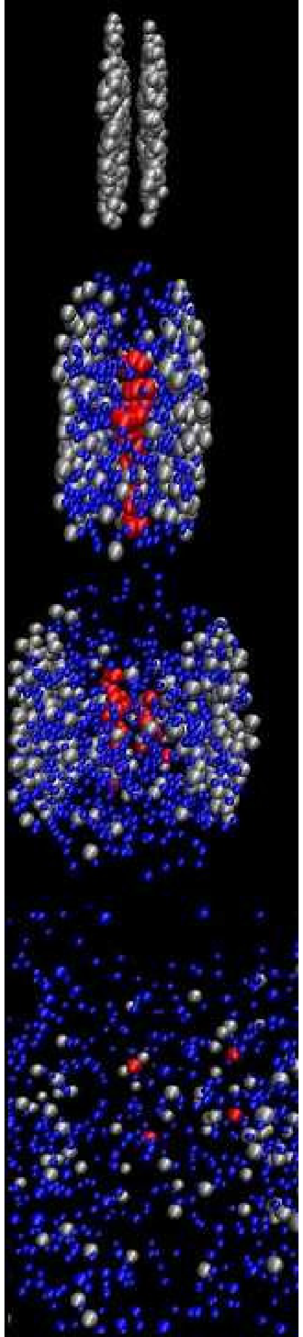
T_C=158 MeV
ε_C=0.5 GeV/fm^3



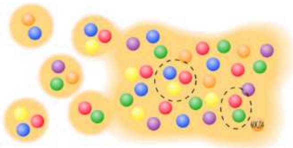
- **DQPM matches well lattice QCD**
- **DQPM provides mean-fields (1PI) for gluons and quarks as well as effective 2-body interactions (2PI)**
- **DQPM gives transition rates for the formation of hadrons → PHSD**

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

Parton Hadron String Dynamics

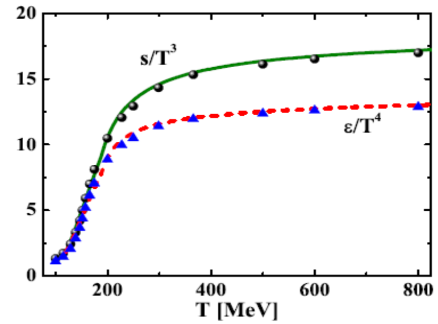


I. From hadrons to QGP:



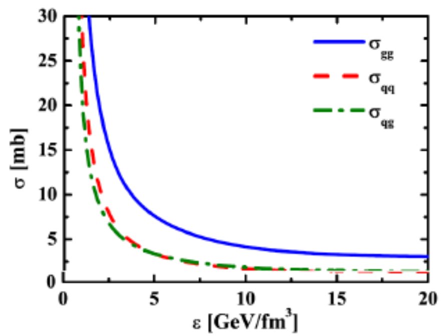
QGP phase:
$\varepsilon > \varepsilon_{critical}$

- 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)



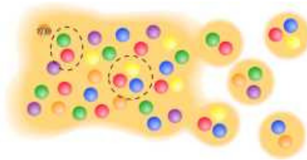
II. Partonic phase - QGP:

- 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

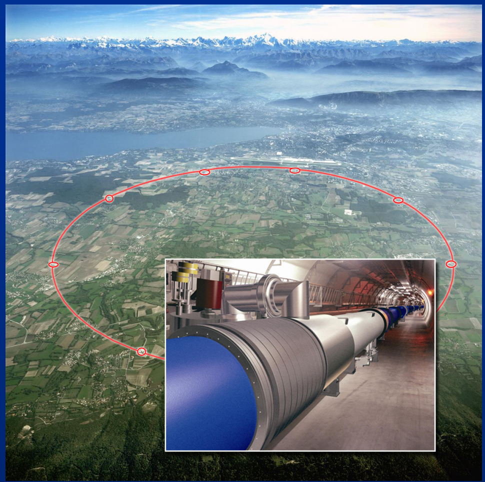
- massive, off-shell (anti-)quarks with broad spectral functions
  hadronize to off-shell mesons and baryons or color neutral excited states - ‚strings' (strings act as ‚doorway states' for hadrons)

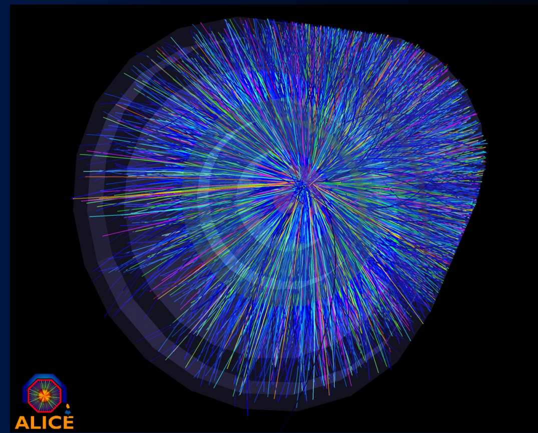


IV. Hadronic phase: hadron-string interactions – off-shell HSD

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

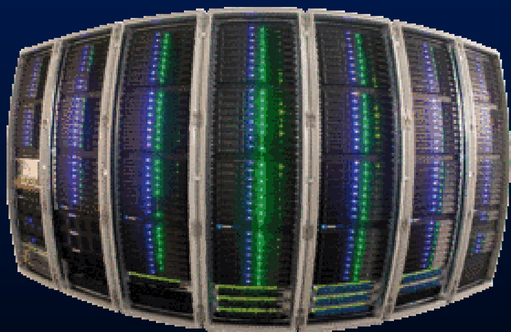
PHSD – ‚femto‘ accelerator

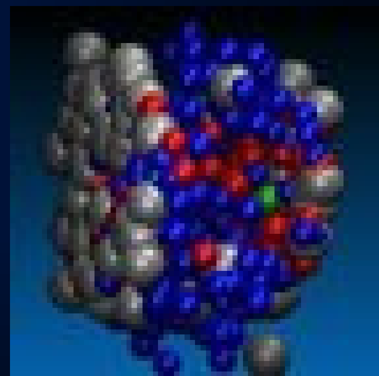




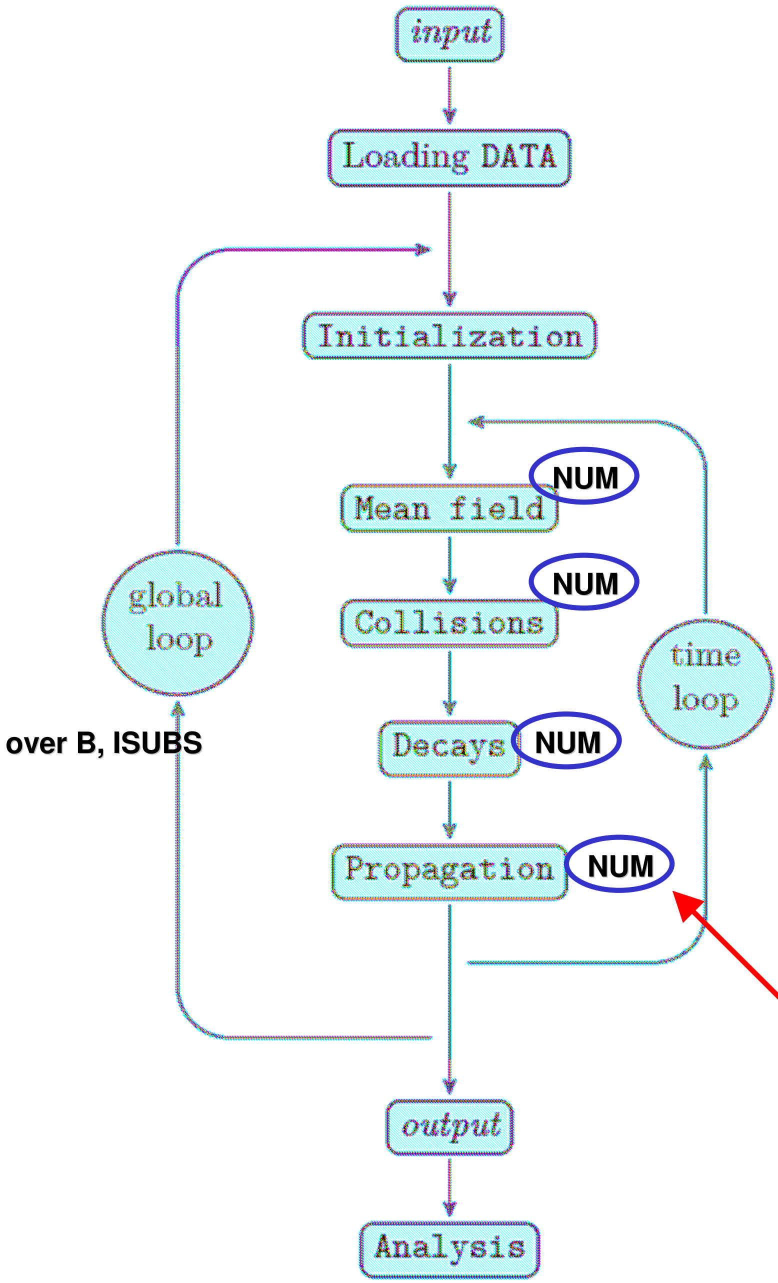
PHSD

Center for Scientific Computing Frankfurt





PHSD code: structure



Input file (*input*) for Au+Au @ 200 GeV - 30-40%

197,	MASSTA:	target mass
79,	MSTAPR:	protons in target
197,	MASSPR:	projectile mass
79,	MSPRPR:	protons in projectile
21300.,	ELAB:	lab energy per nucleon
8.7,	BMIN:	minimal impact parameter [fm]
8.7,	BMAX:	maximal impact parameter [fm]
1.,	DBIMP:	impact parameter step [fm]
25,	NUM:	number of parallel events
1,	ISUBS:	number of subsequent runs
4567,	ISEED:	initial random seed [integer]
0,	ICHARM:	charm degrees of freedom =0 no, =1 yes
0,	IDILEPT:	=0 no dileptons, =1 electron pair, =2 muon pair
0,	ICQ:	=0 free, =1 drop. mass, =2 broad., =3 drop.+broad.
1,	IGLUE:	=1 with partons, =0 w/o partons — **HSD mode**
40.,	FINALT:	final time of calculation [fm/c]
0,	IHARD:	=1 compute hard collisions, =0 no
10,	ILOW:	output level

PHSD is the parallel ensembles code!!!

loop over NUM – parallel ensembles or ‚events‘:

- ❑ **needed for the smooth description of the mean-field properties as energy density or baryon density**

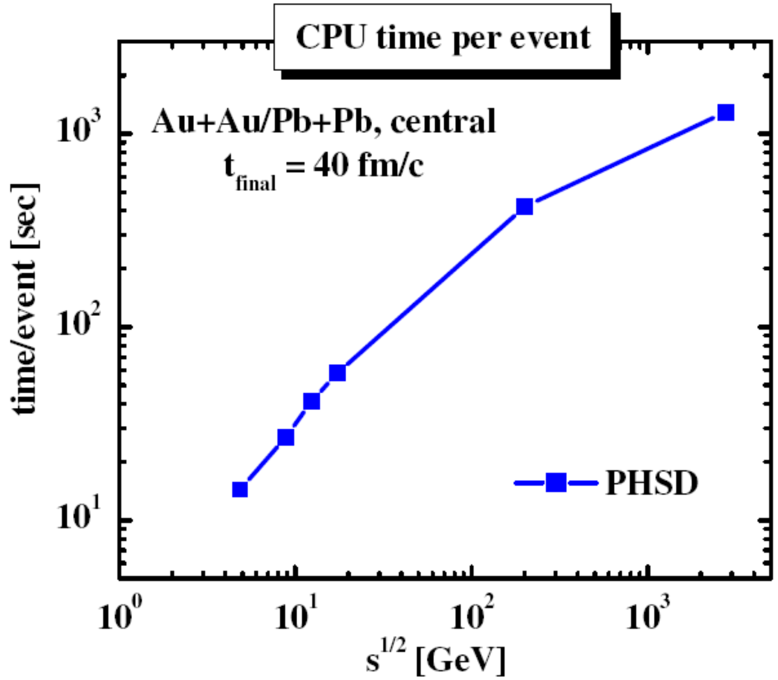
➔ **possible parallelization**

PHSD running time ←→ HPC

PHSD mode: Au+Au/Pb+Pb, central, t_{final} = 40 fm/c

Elab, AGeV	$S^{1/2}$, GeV	CPU time, h	NUM	CPU time/NUM
10.7	4.86	0.2	50	14.4sec
40	8.86	0.75	100	27sec
80	12.4	1.15	100	41.4sec
158	17.3	0.8	50	57.6sec
21300	200	1.75	15	7min
4060000	2760	1.8	5	21.6min

from V. Konchakovski

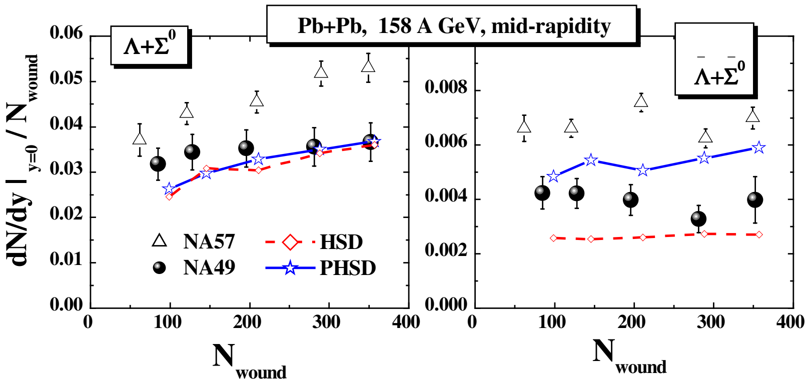


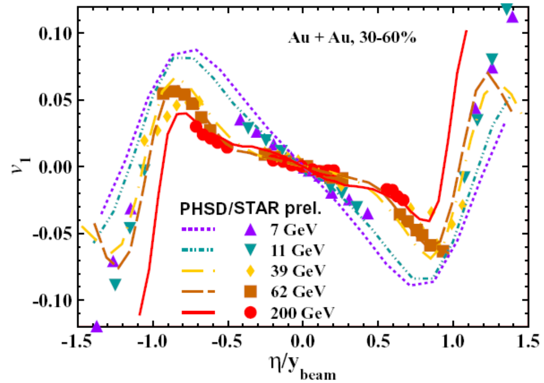
NUM – the number of parallel ensembles/events

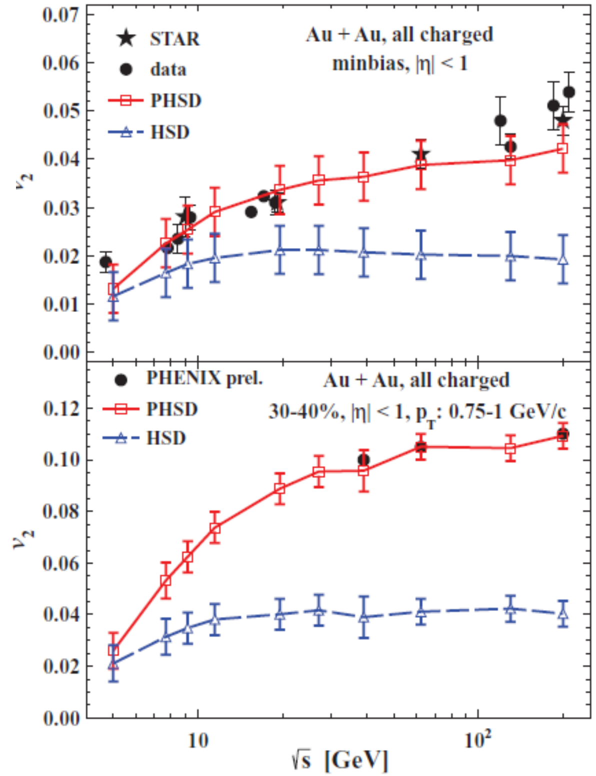
→ CPU time per event grows with energy
→ PHSD mode (for RHIC, LHC) – more time consuming than HSD

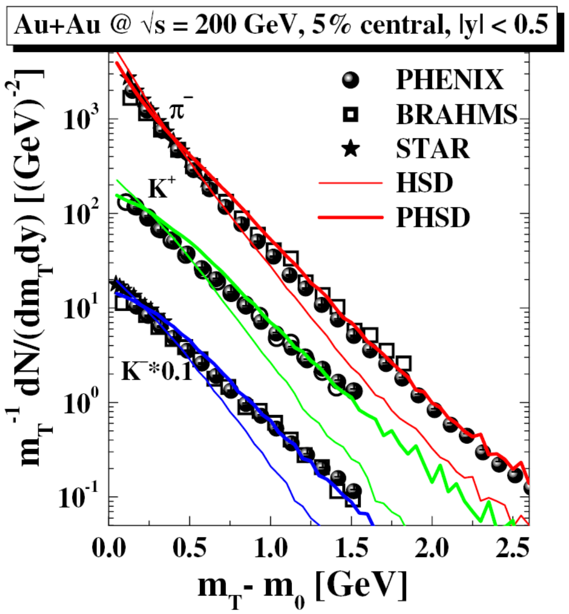
PHSD is the open source code for the FAIR experiments:
http://fias.uni-frankfurt.de/~brat/PHSD/index4.html

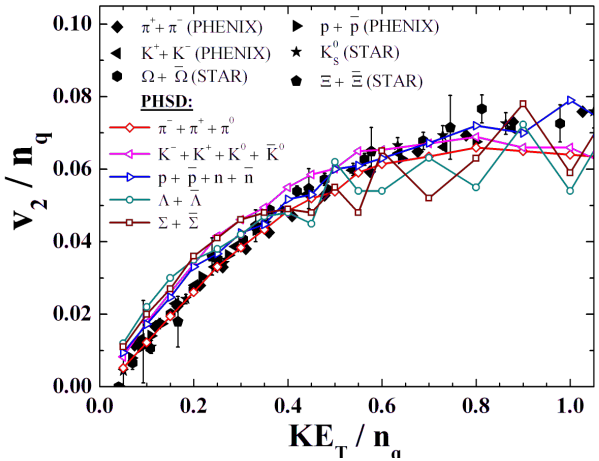
PHSD for HIC (highlights)

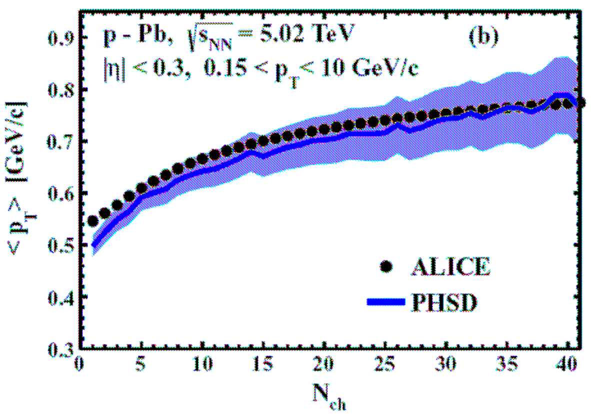


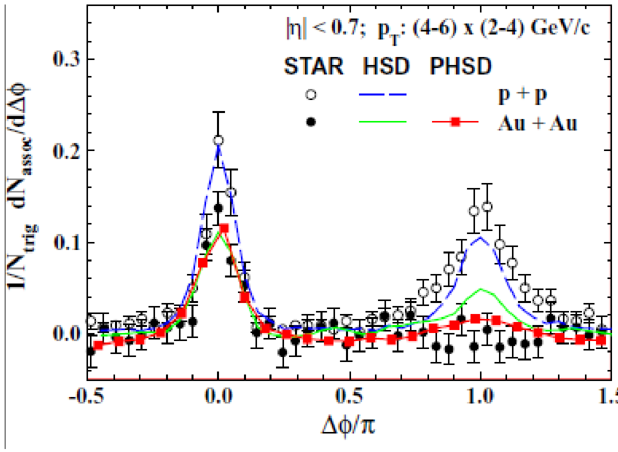












- **PHSD** provides a consistent description of p+A and HIC dynamics

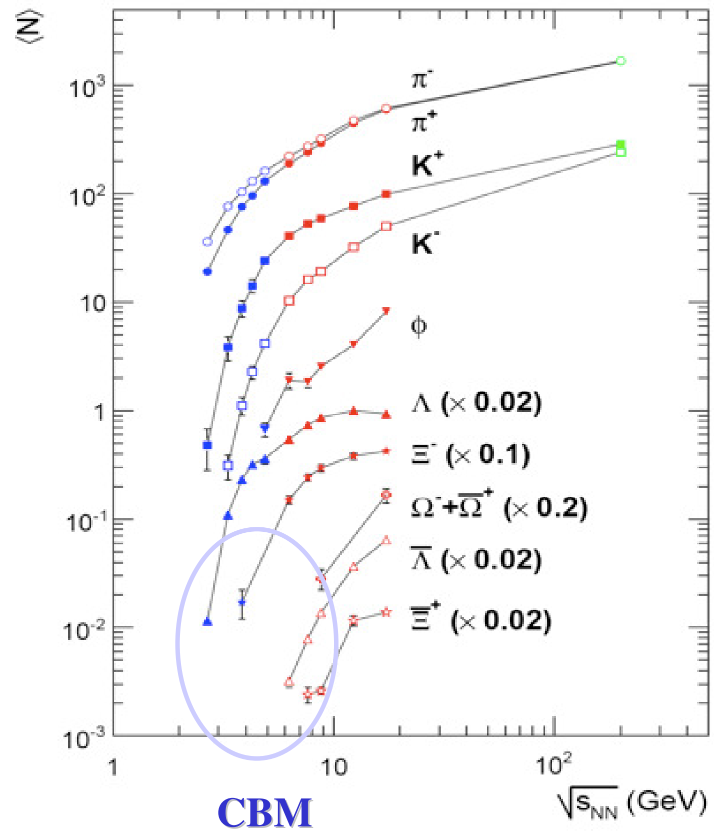
The most CPU costly observables
(some examples)

(Multi-)strange particles in Au+Au

Multi-strange baryon production

Multi-strange hyperons (Ξ, Ω) are promising probes to study:

- in-medium effects at low bombarding energy
- QGP properties at high energy density



❑ **Elementary production:**

$$p + p \rightarrow \Sigma^- K^+ K^+ p \qquad (E_{beam} > 3.7 \text{ GeV})$$

$$p + p \rightarrow \Omega^- K^+ K^+ K^0 p \qquad (E_{beam} > 7.0 \text{ GeV})$$

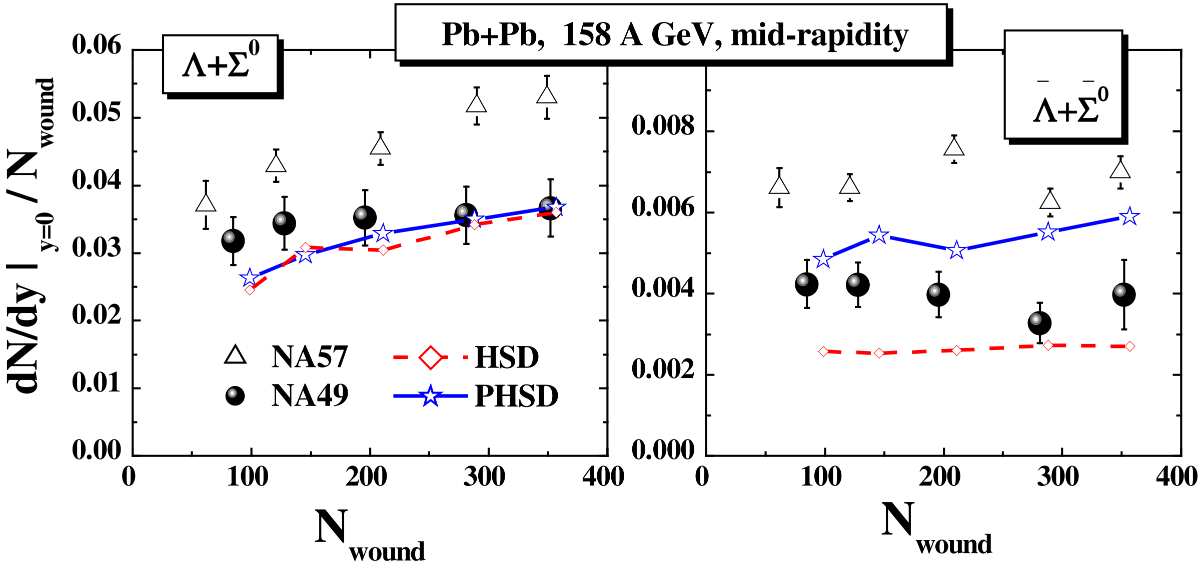
❑ In **heavy-ion reactions**: sub-threshold channels, e.g. $p + p \rightarrow K^+ \Lambda p$ ➜

➜ $\Lambda + \Lambda \rightarrow \Xi^- p$ ➜ $\Lambda + \Xi^- \rightarrow \Omega^- + n$

Production through these channels highly depends on baryon density (and it‘s fluctuations)

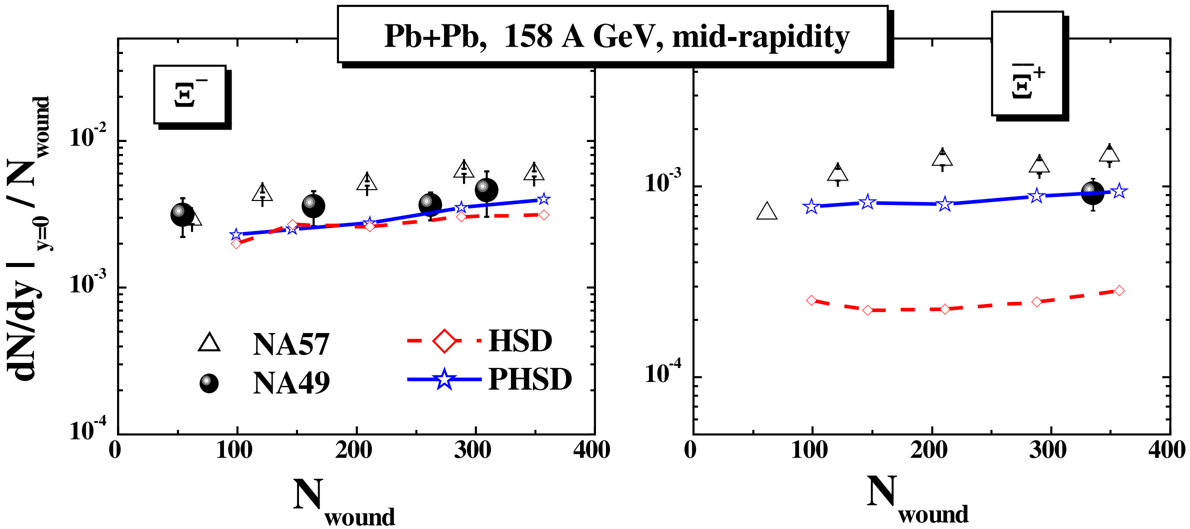
Centrality dependence of (multi-)strange (anti-)baryons

strange baryons $\Lambda+\Sigma^0$



strange antibaryons $\bar{\Lambda}+\bar{\Sigma}^0$

multi-strange baryon Ξ^-

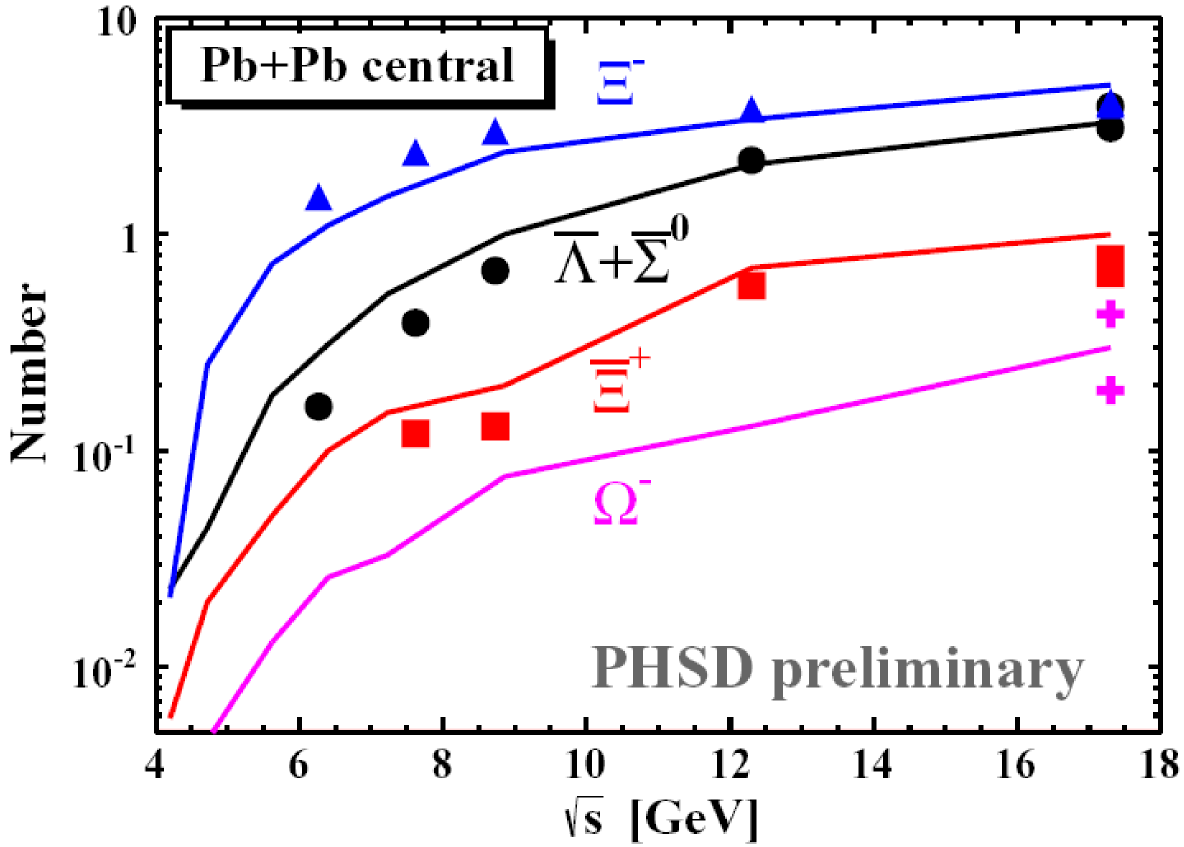


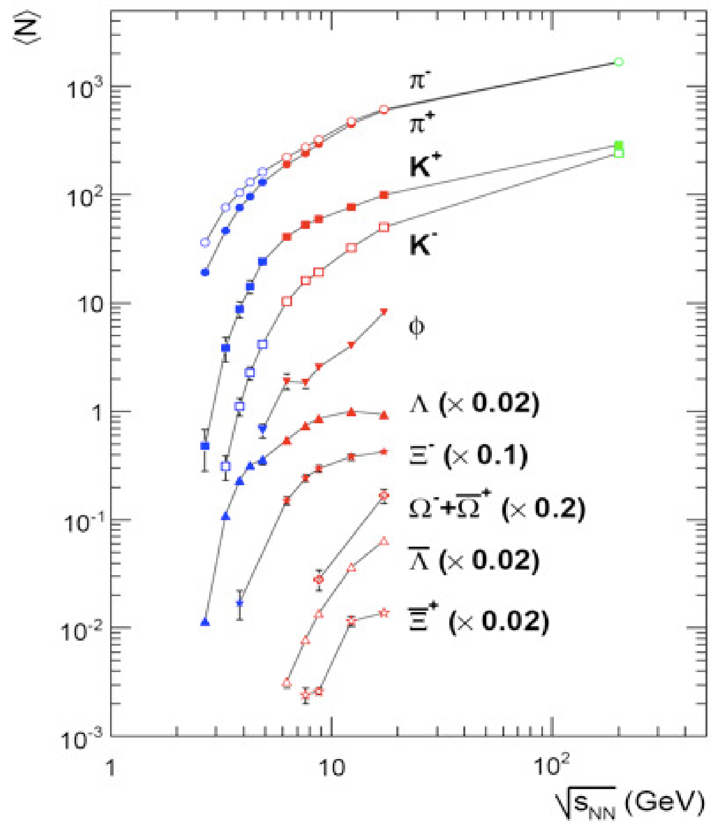
multi-strange antibaryon $\bar{\Xi}^+$

➔ enhanced production of (multi-) strange antibaryons in PHSD

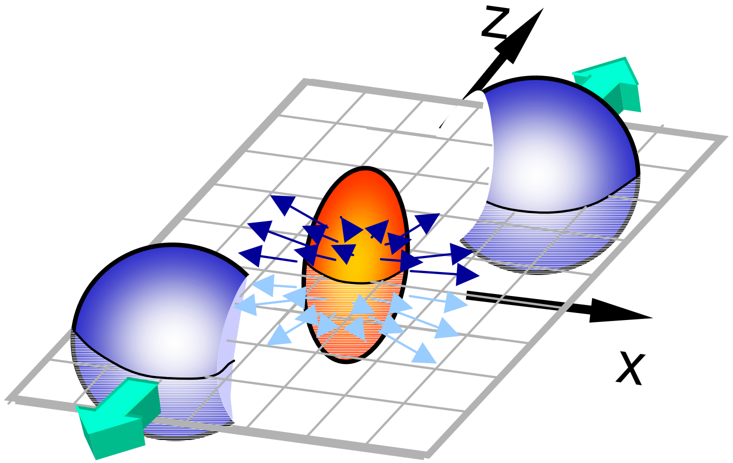
Cassing & Bratkovskaya, NPA 831 (2009) 215

Exitation function of (multi-)strange (anti-)baryons





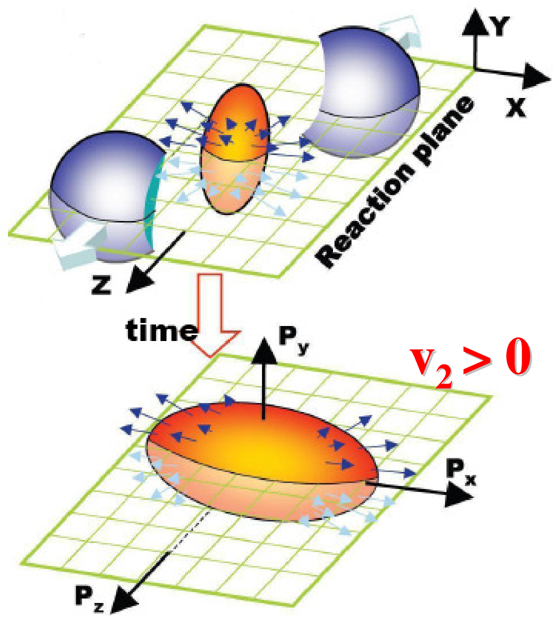
Collective flow: anisotropy coefficients (v_1, v_2, v_3, v_4) in A+A



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**



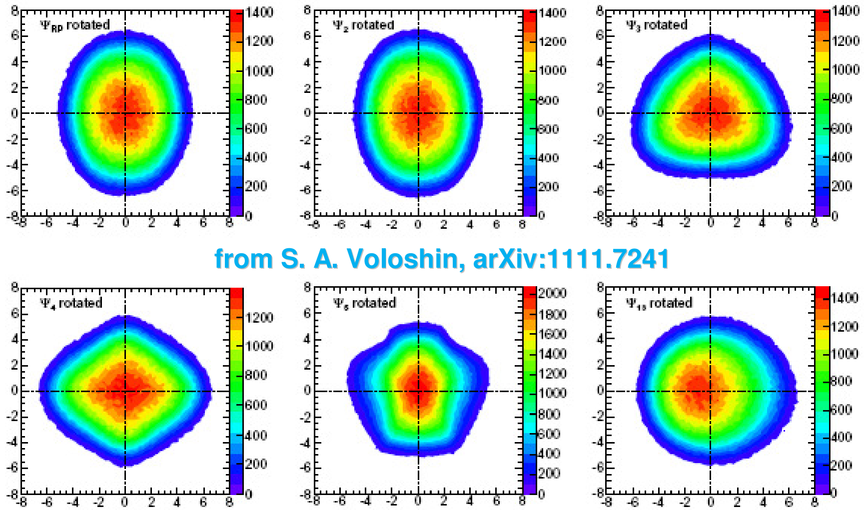
$$\frac{dN}{d\varphi} \propto \left(1 + 2\sum_{n=1}^{+\infty} v_n \cos\left[n(\varphi - \psi_n)\right]\right)$$

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

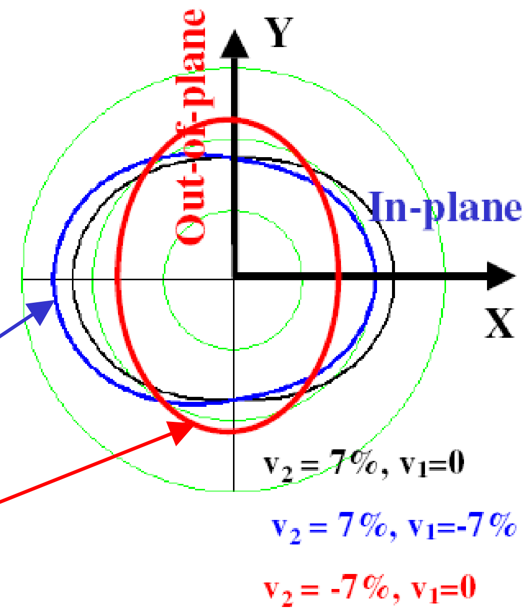
v_1: directed flow

v_2: elliptic flow

v_3: triangular flow…..



from S. A. Voloshin, arXiv:1111.7241

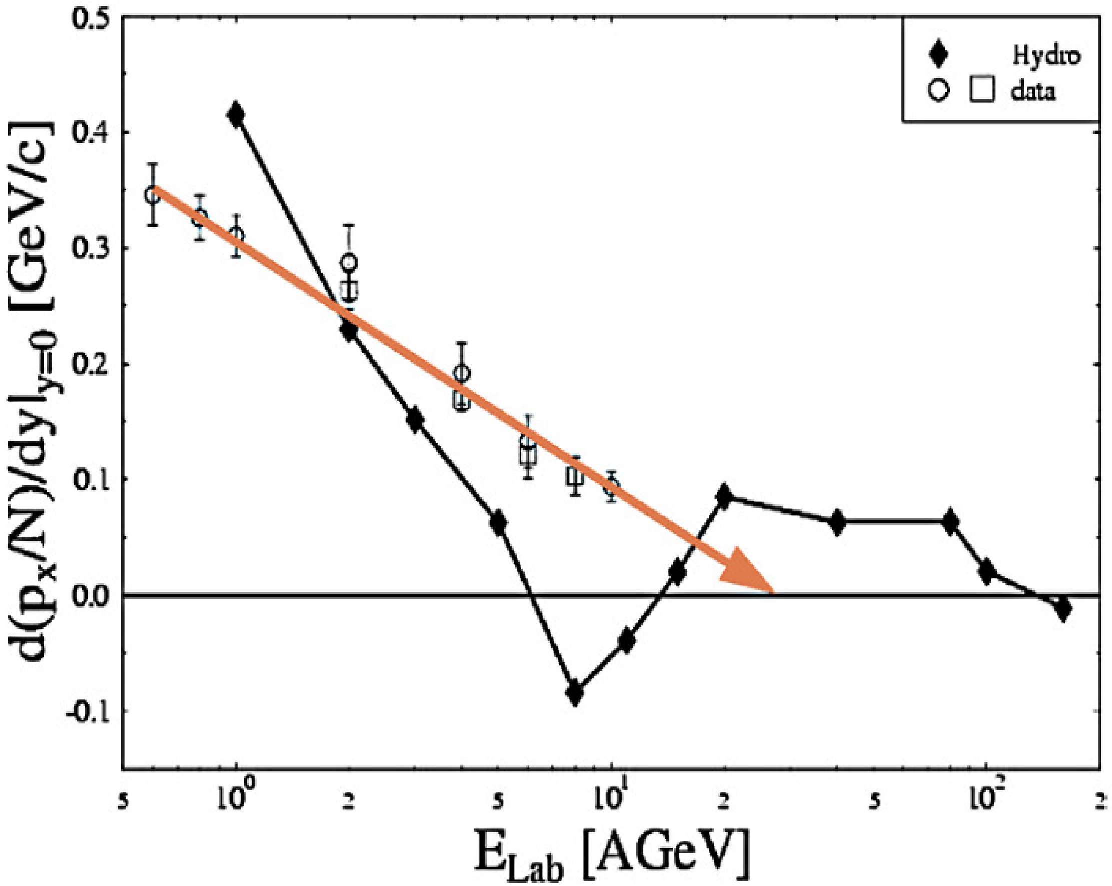


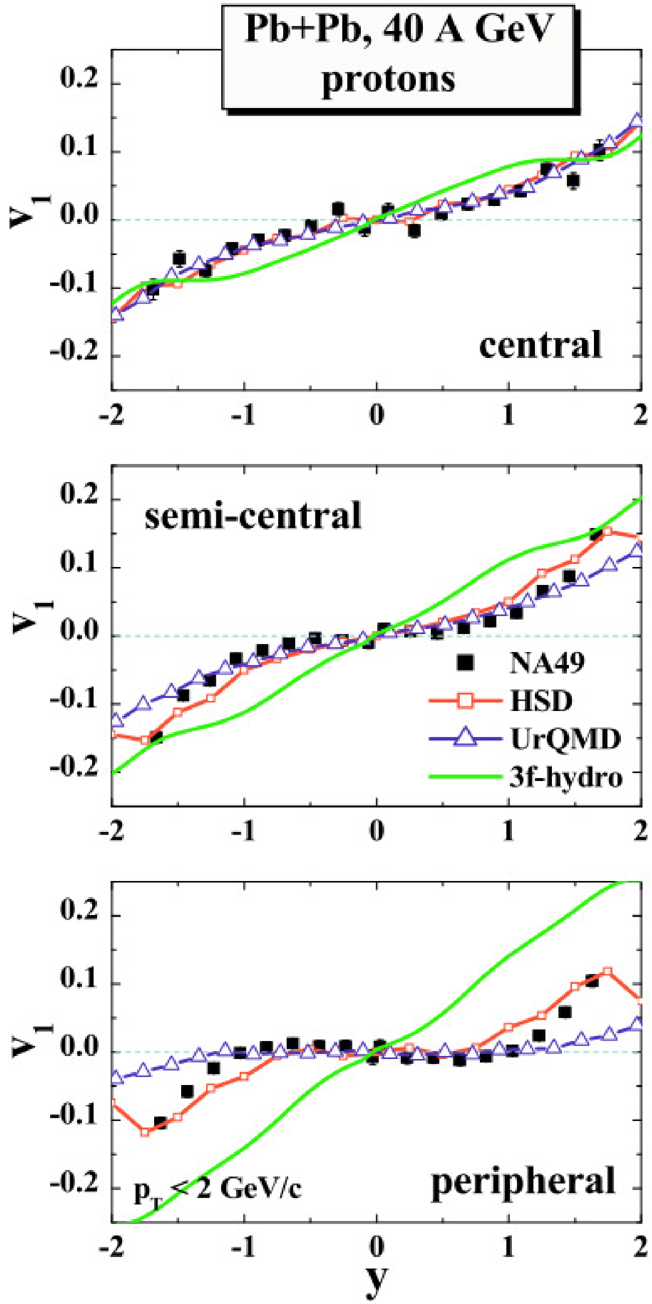
$v_2 > 0$ indicates **in-plane** emission of particles

$v_2 < 0$ corresponds to a **squeeze-out** perpendicular to the reaction plane (**out-of-plane** emission)

Directed flow signals of the Quark–Gluon Plasma

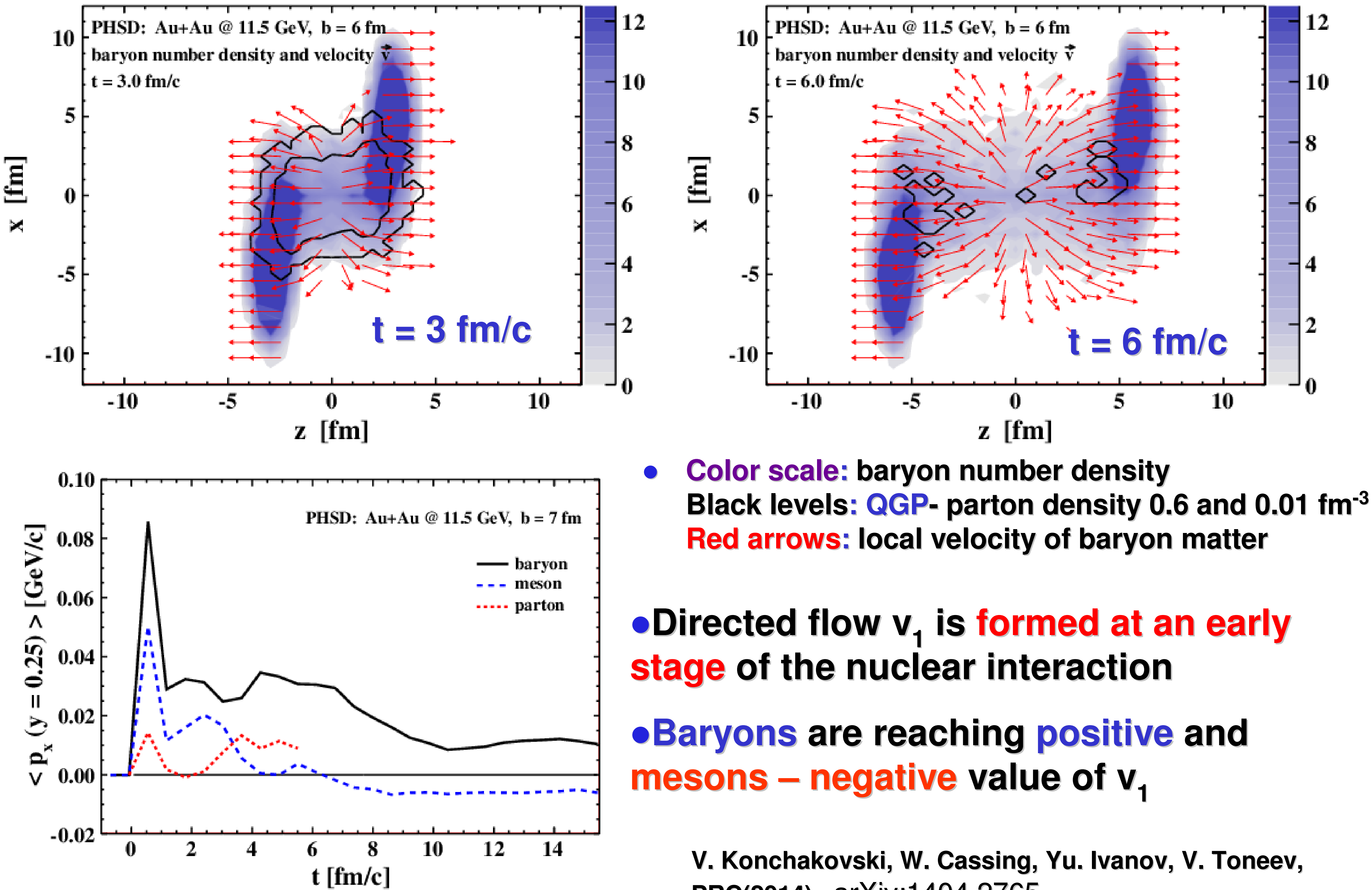
H. Stöcker, Nucl. Phys. A 750, 121 (2005)





- 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

PHSD: snapshot of the reaction plane



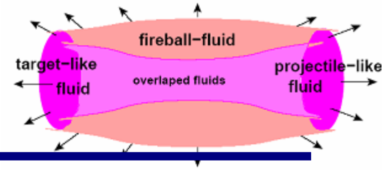
- **Color scale:** baryon number density
  Black levels: QGP- parton density 0.6 and 0.01 fm^{-3}
  Red arrows: local velocity of baryon matter

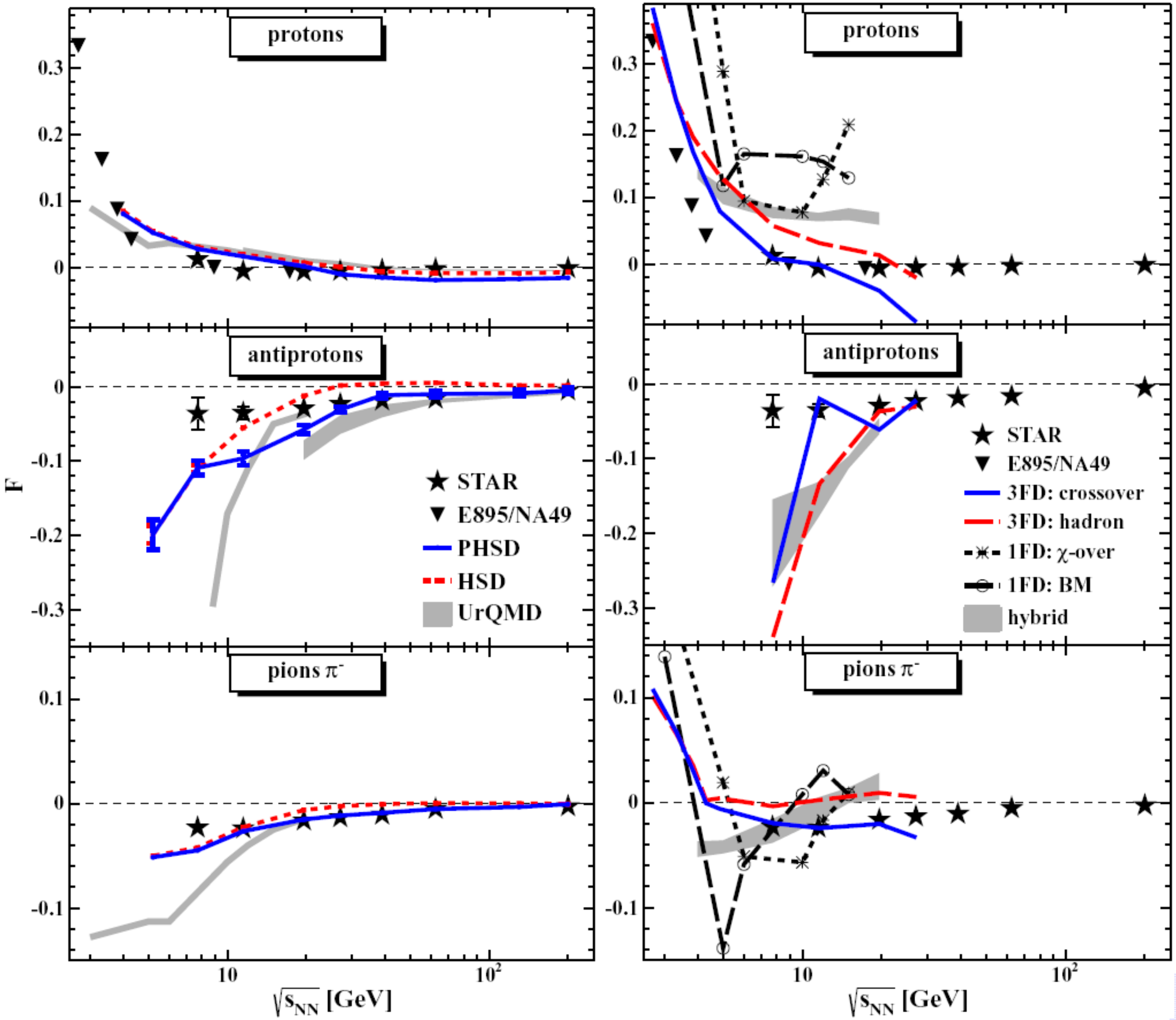
- **Directed flow v_1 is formed at an early stage of the nuclear interaction**

- **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





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

$$F = \frac{dv_1}{dy}\Big|_{y=0}$$

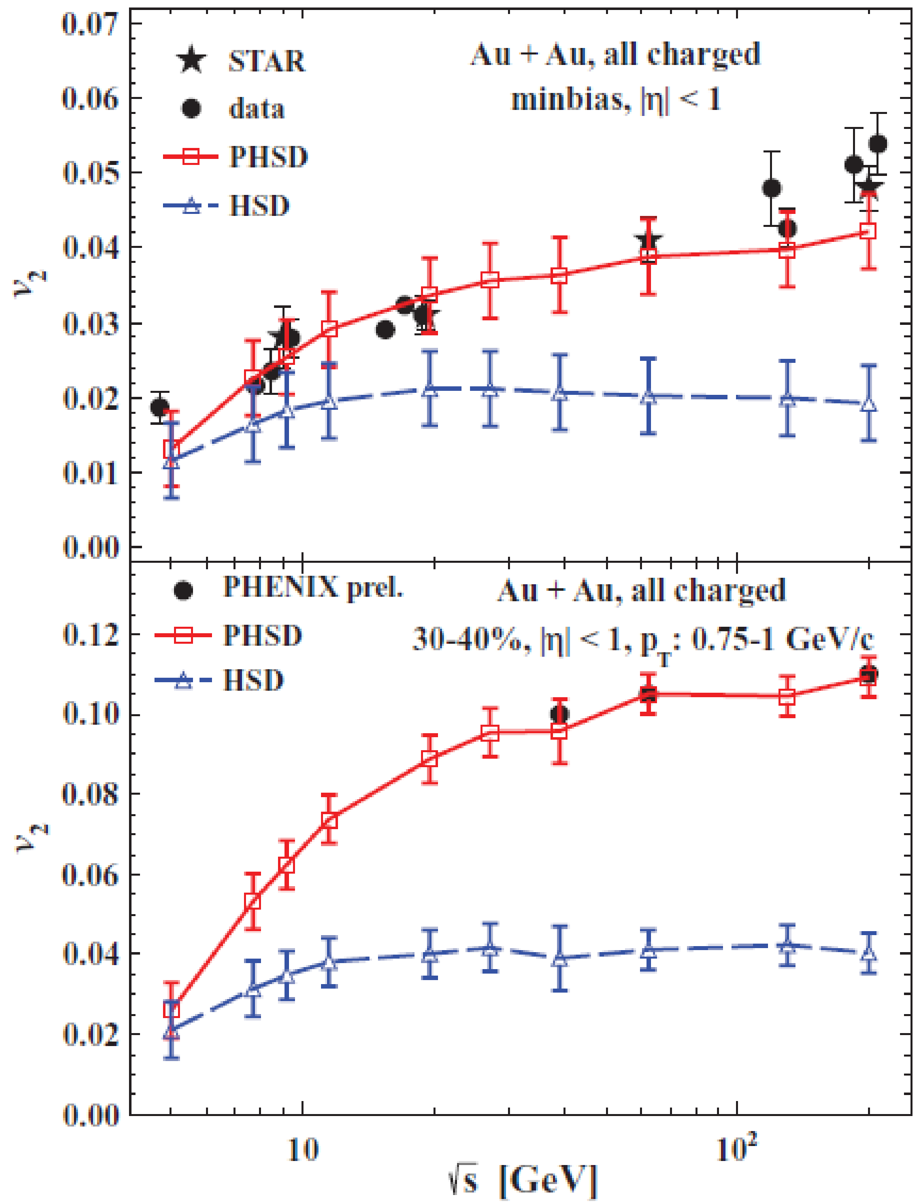
Models:

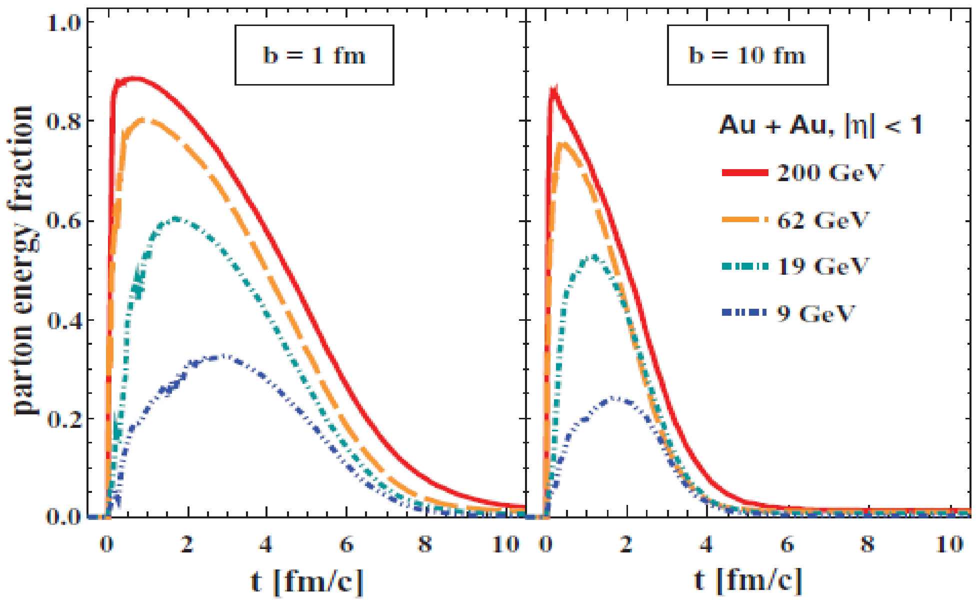
- **HSD, PHSD**
- **3D-Fluid Dynamic approach (3FD)**
- **UrQMD**
- **Hybrid-UrQMD**
- **1FD-hydro with chiral cross-over and Bag Model (BM) EoS**

➔ smooth crossover?!

STAR Collaboration, arXiv:1401.3043
PHSD/HSD and 3D-fluid hydro: V. Konchakovski, W. Cassing, Yu. Ivanov, V. Toneev, PRC(2014), arXiv:1404.2765
Hybrid/UrQMD/Hydro: J. Steinheimer, J. Auvinen, H. Petersen, M. Bleicher, H. Stöcker, PRC 89 (2014) 054913

Elliptic flow v_2 vs. collision energy for Au+Au

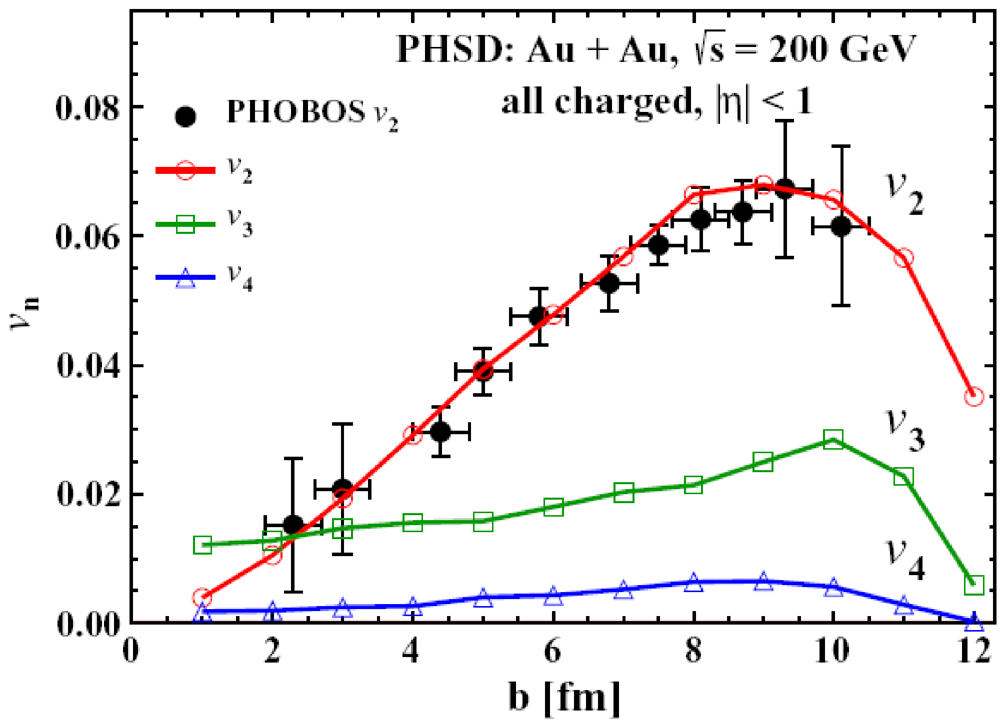


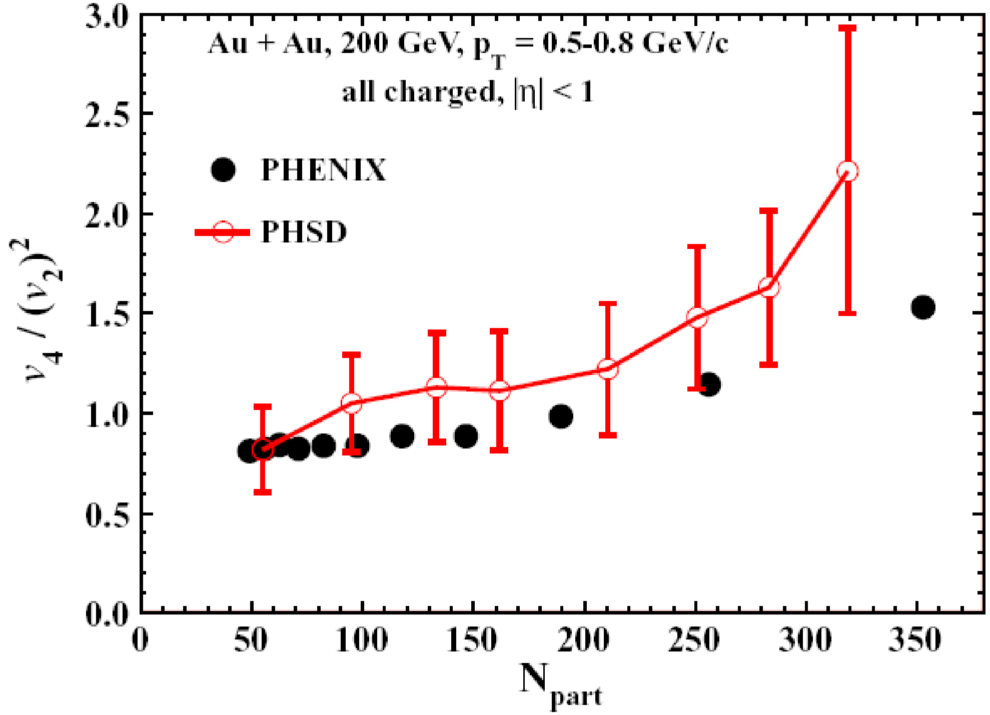


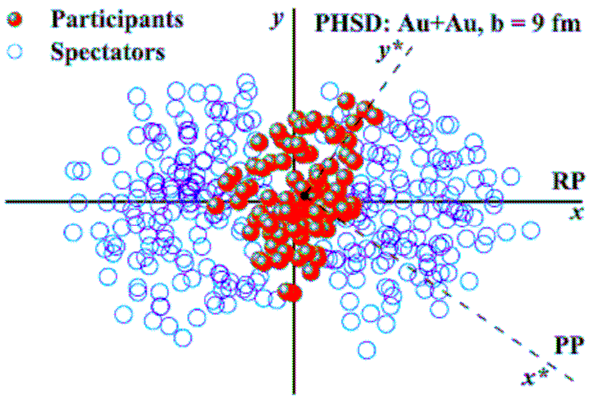
- v_2 in PHSD is larger than in HSD due to the repulsive scalar mean-field potential $U_s(\rho)$ for partons
- v_2 grows with bombarding energy due to the increase of the parton fraction

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

Flow coefficients versus centrality at RHIC







- increase of v_2 with impact parameter but flat v_3 and v_4

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

Fluctuations and correlations

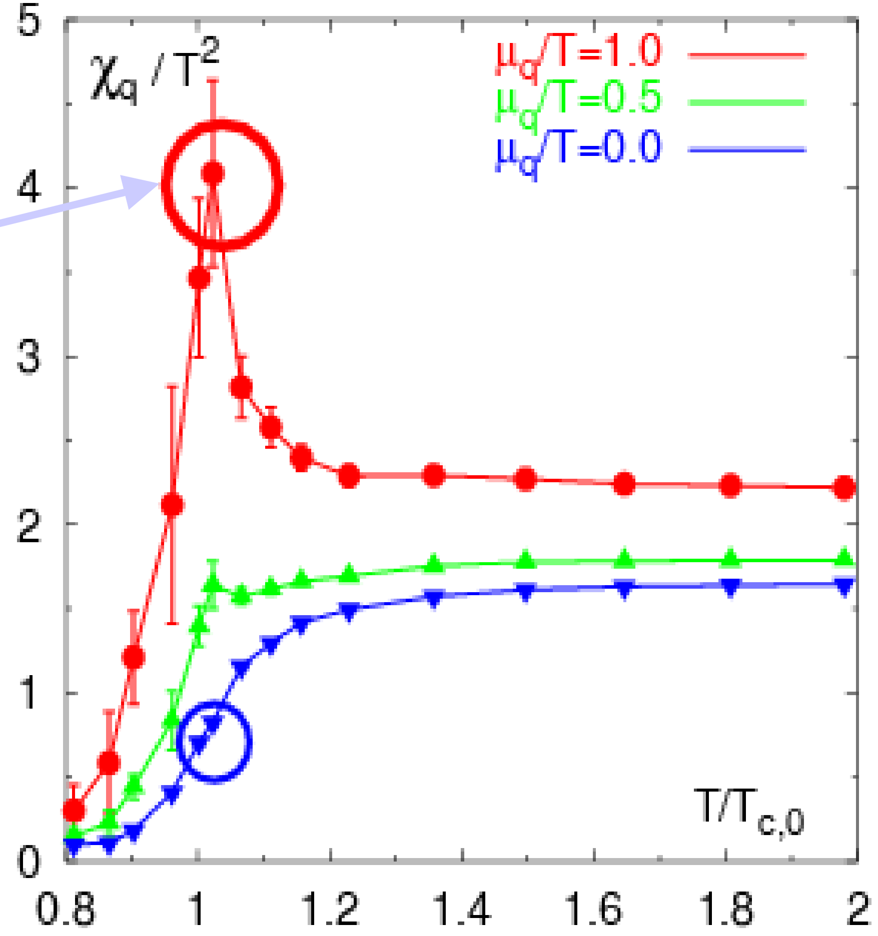
Lattice QCD: Critical Point

Fluctuations of the quark number density (susceptibility) at $\mu_q>0$

[F. Karsch et al.]

$$\frac{\chi_q}{T^2} = \left[\frac{\partial^2}{\partial(\mu_q/T)^2} \frac{P}{T^4} \right]_{T_{fixed}}$$

Lattice QCD predictions:
χ_q (quark number density fluctuations) will diverge at the critical chiral point =>



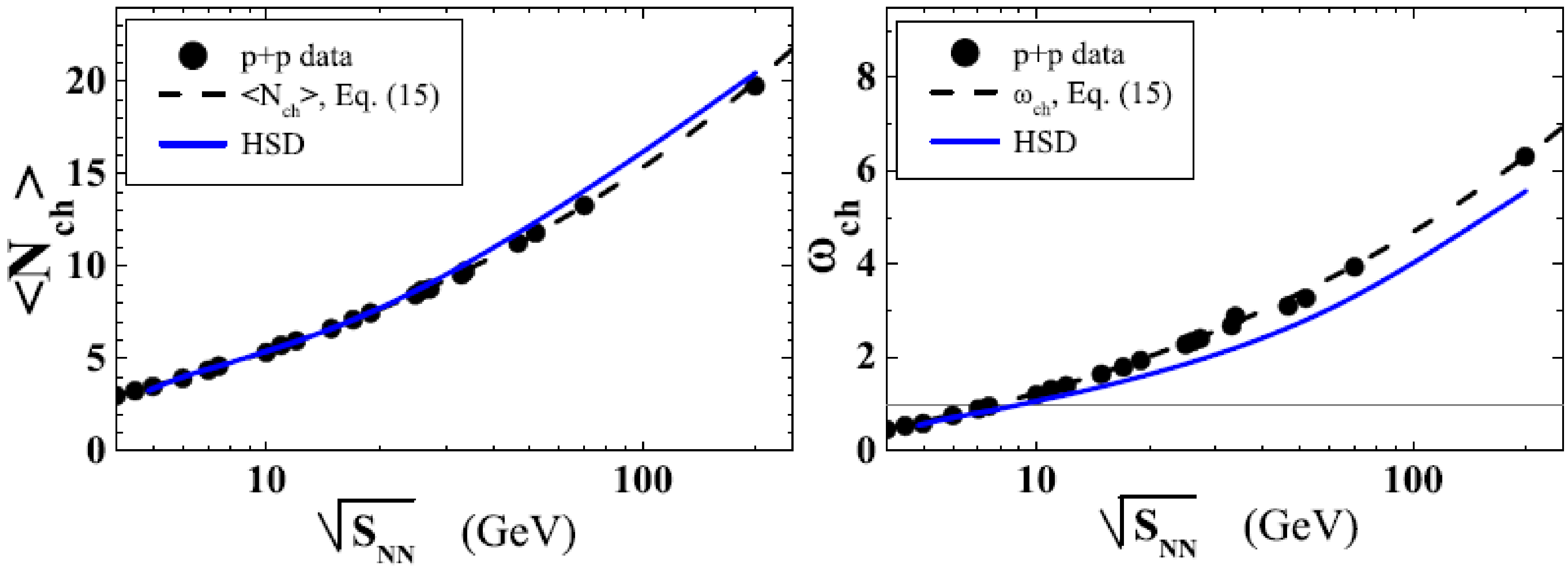
Experimental observation – look for non-monotonic behavior of the observables near the critical point :

- **baryon number fluctuations**
- **charge number fluctuations**
- **multiplicity fluctuations**
- **particle ratio fluctuations (K/π, K/p, ...)**
- **mean p_T fluctuations**
- **2 particle correlations**
- **...**

Multiplicity fluctuations in p+p

- **Scaled variance - multiplicity fluctuations in some acceptance (charge, strangeness, etc.):**

$$\omega = \frac{Var(N)}{\langle N \rangle} = \frac{\langle N^2 \rangle - \langle N \rangle^2}{\langle N \rangle}$$

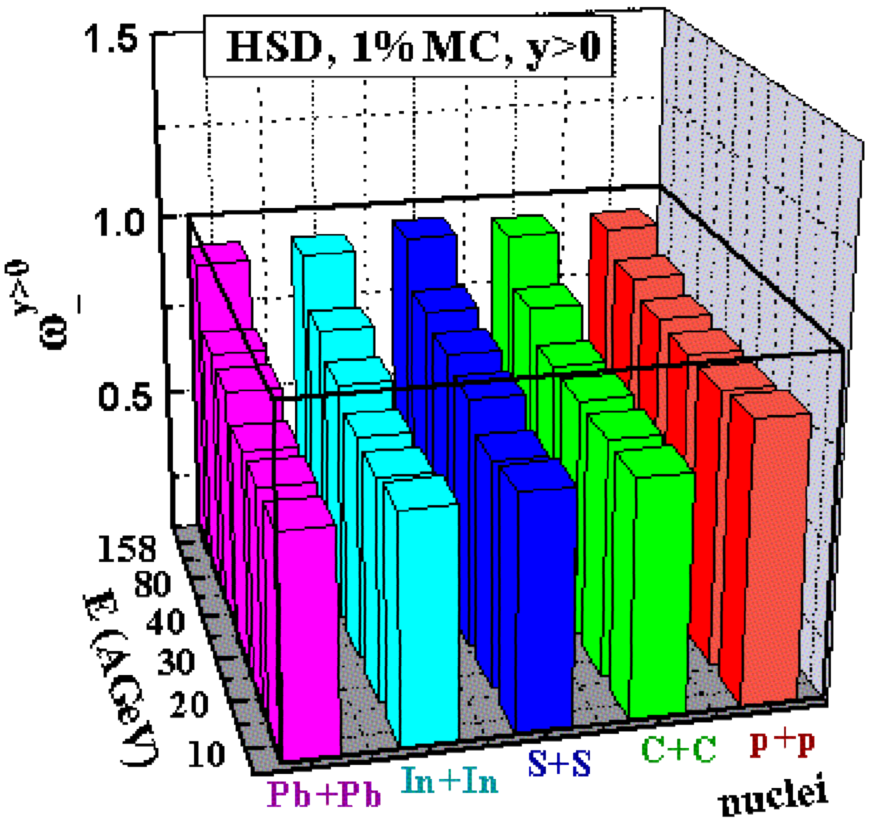


❑ **The excitation functions of N_{ch} and charge multiplicity fluctuations ω_{ch} from HSD are approximately in line with experimental data**

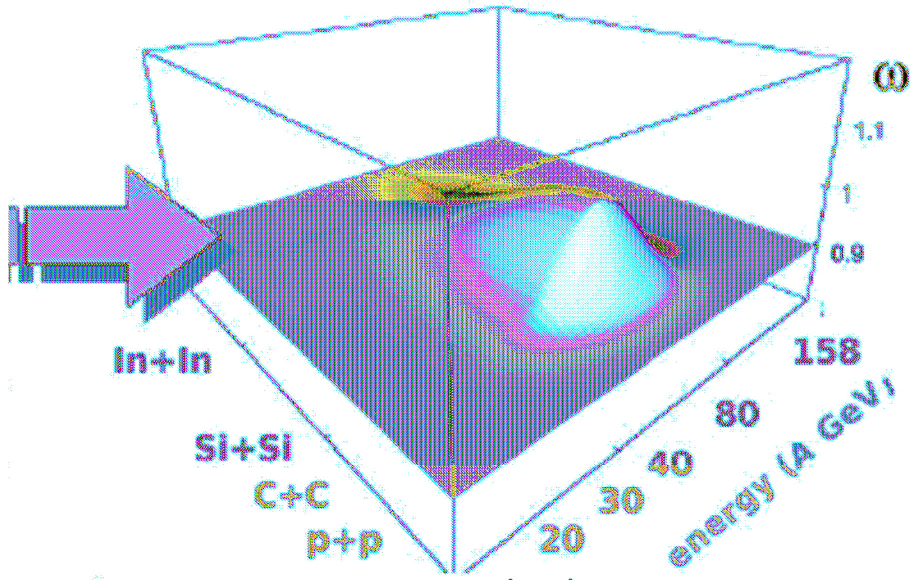
Multiplicity fluctuations in HSD: 1%MC

Konchakovski, Lungwitz, Gorenstein, Bratkovskaya, Phys. Rev. C78 (2008) 024906

rapidity y>0



❑ Multiplicity fluctuations for 1%MC practically do not depend on atomic mass for y>0 and only slightly grow with increasing collision energy.

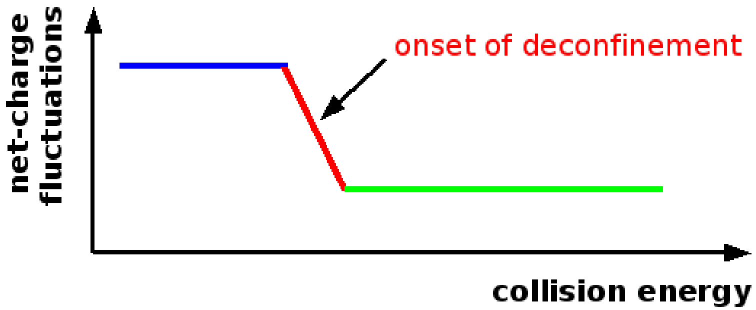


Gazdzicki, PoS CPOD2006:016

❑ HSD (and UrQMD) show a plateau on top of which the SHINE Collaboration expects to find increasing multiplicity fluctuations as a "signal" for the critical point !

Charge fluctuations

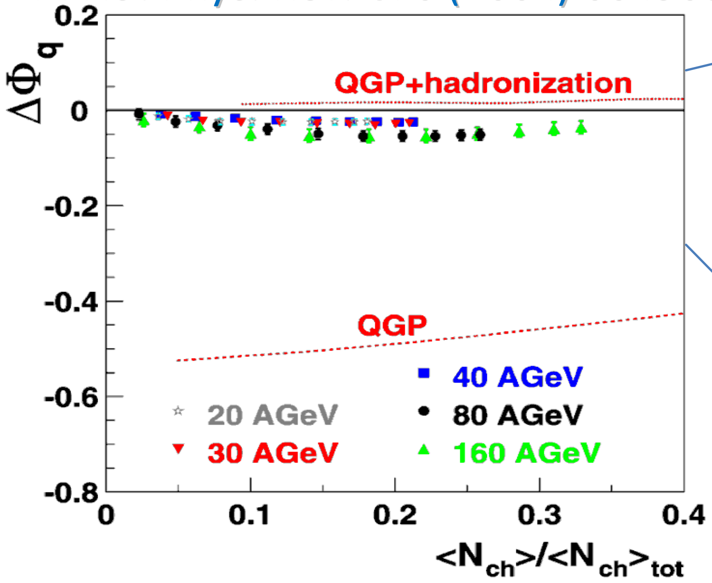
❑ sensitive to the **EoS** at the early stage of the collision and to its changes in the deconfinement phase transition region



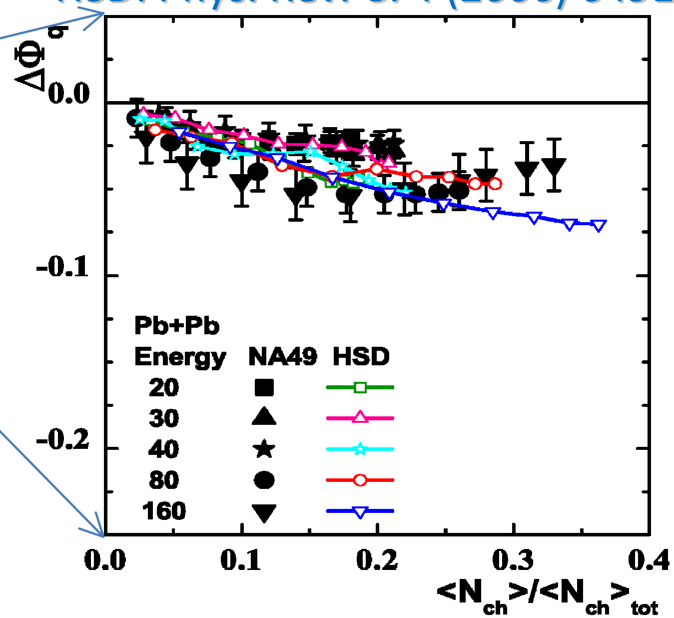
Jeon, Koch, PRL85 (2000) 2076
Asakawa, Heinz, Muller PRL85 (2000) 2072

❑net-charge fluctuations are smaller in QGP than in a hadron gas

NA49: Phys. Rev. C70 (2004) 064903

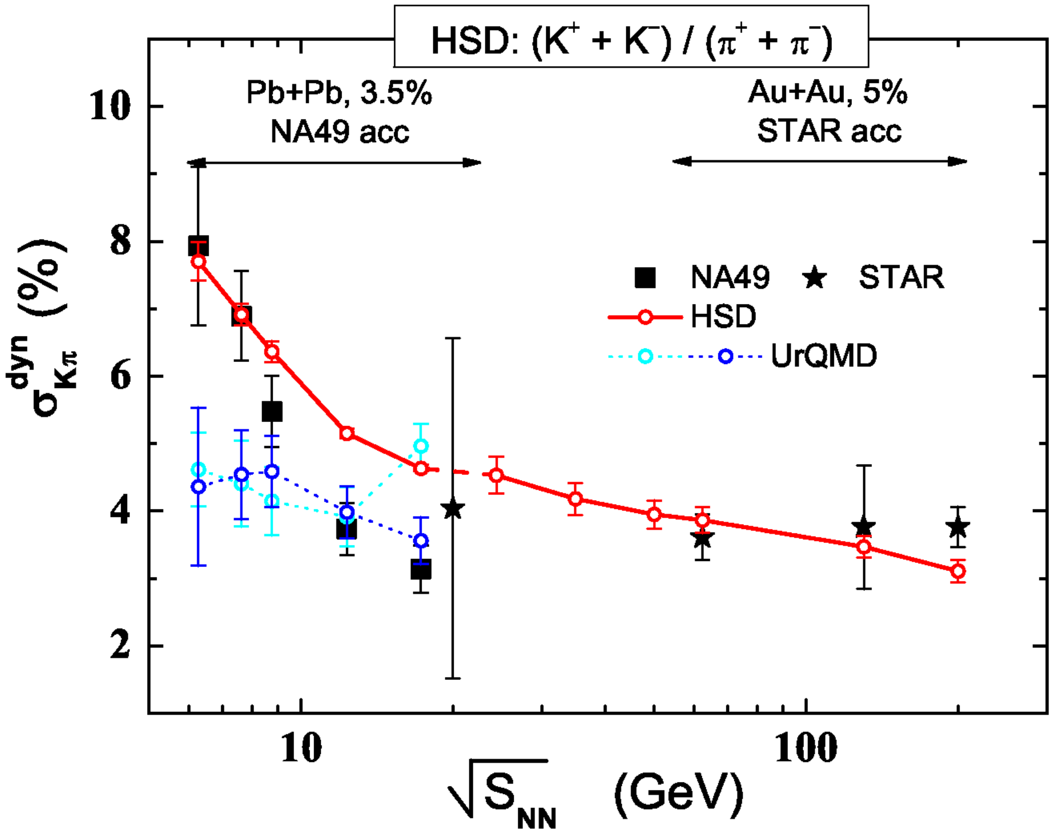


HSD: Phys. Rev. C74 (2006) 64911



❑The **decay of resonances** strongly modifies the initial QGP fluctuations!

K/π-ratio fluctuations: Transport models vs Data



$$\sigma^2 \equiv \frac{\langle \Delta (N_A/N_B)^2 \rangle}{\langle N_A/N_B \rangle^2}$$

- In GCE for ideal Boltzman gas:

$$\sigma^2 = \frac{1}{\langle N_A \rangle} + \frac{1}{\langle N_B \rangle}$$

• **Exp. data show a plateau from top SPS up to RHIC energies and an increase towards lower SPS energies**

➔ evidence for a critical point at low SPS energies ?

• **but the HSD (without QGP!) results shows the same behavior ➔**

• **K/π-ratio fluctuation is driven by hadronic sources ➔ No evidence for a critical point in the K/π ratio ?**

• **K/π ratio fluctuation is sensitive to the acceptance!**

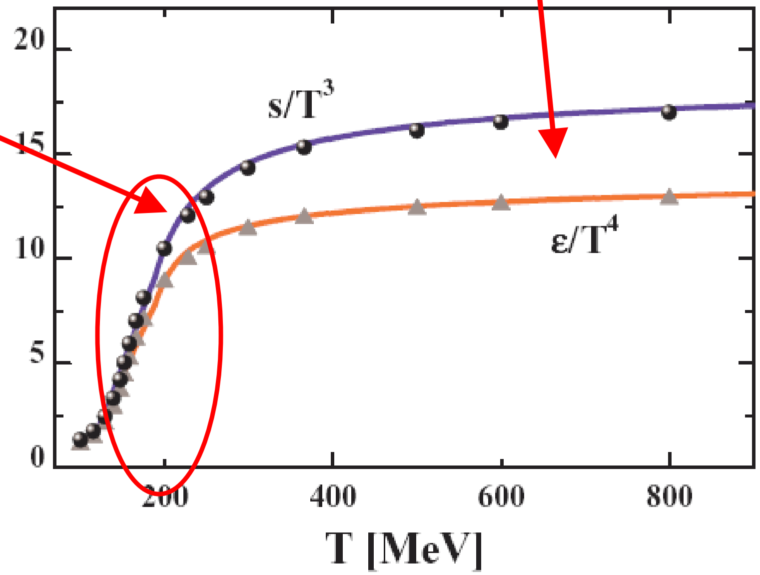
HSD: Phys. Rev. C 79 (2009) 024907
UrQMD: J. Phys. G 30 (2004) S1381, PoS CFRNC2006,017
NA49: 0808.1237
STAR: 0901.1795

Outlook - Perspectives

What is the stage of matter close to T_c and large μ:

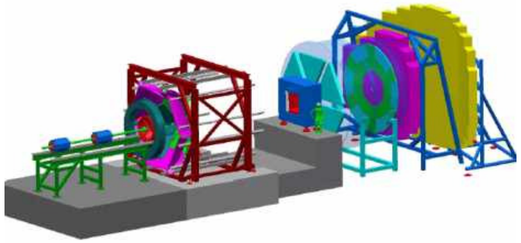
- ❑ 1st order phase transition?
- ❑ ‚Mixed' phase = interaction of partonic and hadronic degrees of freedom?

Lattice EQS for m=0
➔ ‚crossover' , $T > T_c$



Open problems:

- How to describe a **first-order phase transition in transport models?**
- How to describe parton-hadron interactions in **a ‚mixed' phase?**



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