Description of strongly interacting nuclear matter within a microscopic off-shell transport approach

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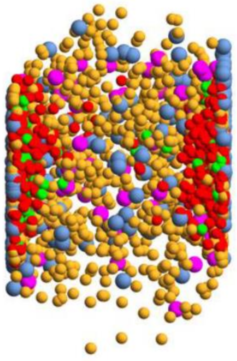
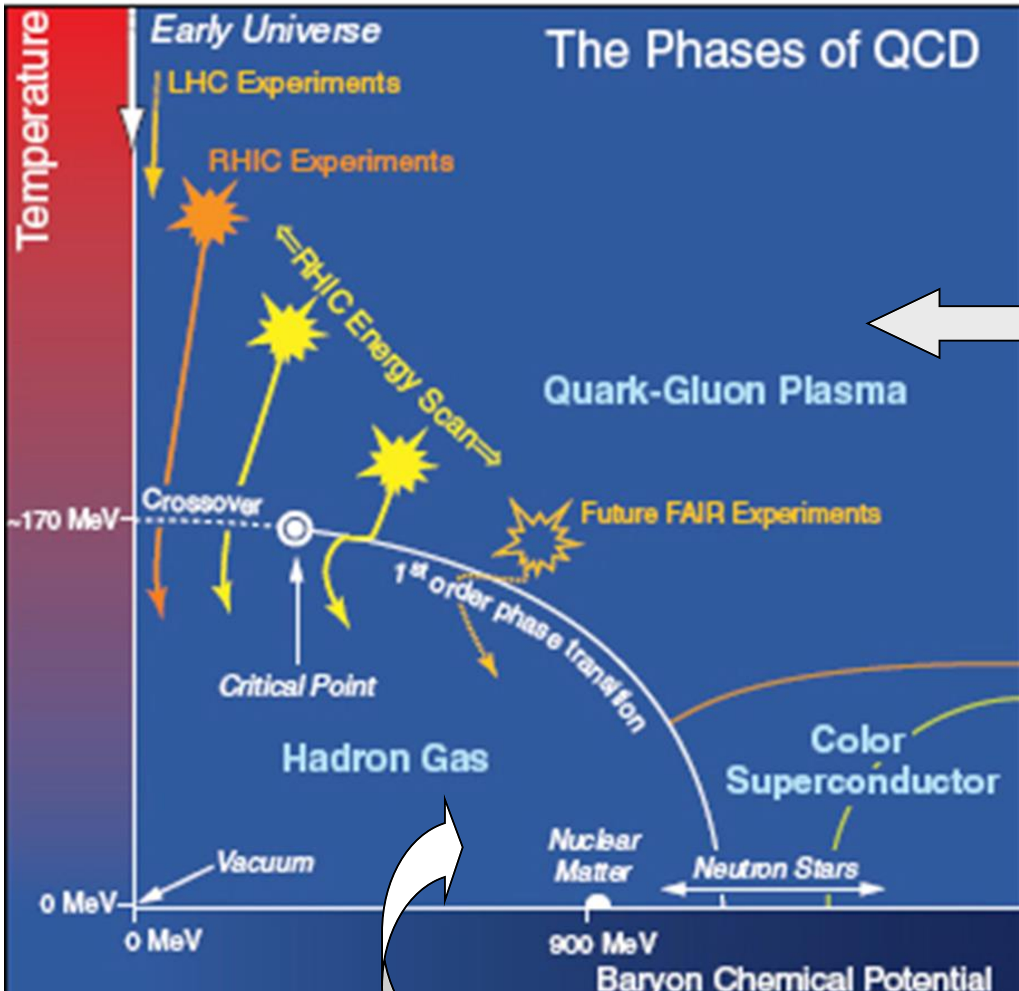
for the PHSD group



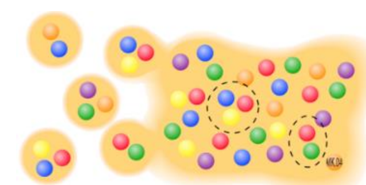
Workshop 'Challenges to Transport Theory for Heavy-Ion Collisions',
ECT, Trento, Italy, May 20-24, 2019*

The ‚holy grail' of heavy-ion physics:



The phase diagram of QCD

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



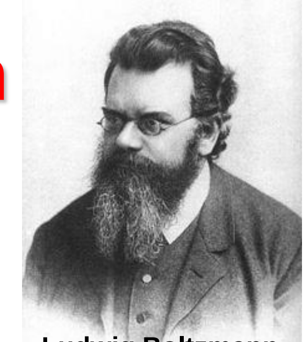
- Search for the critical point
- Search for signatures of chiral symmetry restoration
- Study of the in-medium properties of hadrons at high baryon density and temperature

Dynamical description of heavy-ion collisions

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

Realization:
to develop a dynamical many-body transport approach
1) applicable for strongly interacting systems,
which includes:
2) phase transition from hadronic matter to QGP
3) chiral symmetry restoration

History: 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:**

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

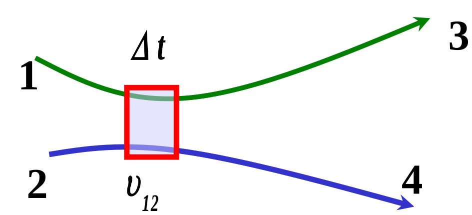
- **Collision term for 1+2→3+4 (let‘s consider fermions) :**

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

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**



History: developments of relativistic transport models

Low energy HIC ⟹ High energy HIC

Non-relativistic semi-classical BUU

⟹ Relativistic transport models

'Relativistic Vlasov-Uehling-Uhlenbeck model for heavy-ion collisions'
Che-Ming Ko, Qi Li, Phys.Rev. C37 (1988) 2270

'Covariant Boltzmann-Uehling-Uhlenbeck approach for heavy-ion collisions'
Bernhard Blaettel, Volker Koch, Wolfgang Cassing, Ulrich Mosel, Phys.Rev. C38 (1988) 1767

'Relativistic BUU approach with momentum dependent mean fields'
T. Maruyama, B. Blaettel, W. Cassing, A. Lang, U. Mosel, K. Weber, Phys.Lett. B297 (1992) 228

'The Relativistic Landau-Vlasov method in heavy ion collisions'
C. Fuchs, H.H. Wolter, Nucl.Phys. A589 (1995) 732

. . .

Covariant transport equation

- Covariant relativistic on-shell BUU equation :

  from many-body theory by connected Green functions in phase-space + mean-field limit for the propagation part (VUU)

$$\left\{ \left(\Pi_\mu - \Pi_\nu (\partial_\mu^p U_V^\nu) - m^* (\partial_\mu^p U_S^\nu)\right) \partial_x^\mu + \left(\Pi_\nu (\partial_\mu^x U_V^\nu) + m^* (\partial_\mu^x U_S^\nu)\right) \partial_p^\mu \right\} f(x,p) = I_{coll}$$

$$I_{coll} \equiv \sum_{2,3,4} \int d2\; d3\; d4\; [G^+ G]_{1+2 \to 3+4}\; \delta^4(\Pi + \Pi_2 - \Pi_3 - \Pi_4)$$

$$d2 \equiv \frac{d^3 p_2}{E_2}$$

$$\times \{ f(x,p_3)\; f(x,p_4)\; (1 - f(x,p))\; (1 - f(x,p_2))$$

Gain term $3+4 \rightarrow 1+2$

$$- f(x,p)\; f(x,p_2)\; (1 - f(x,p_3))\; (1 - f(x,p_4)) \}$$

Loss term $1+2 \rightarrow 3+4$

where $\partial_\mu^x \equiv (\partial_t, \vec{\nabla}_r)$

$m^*(x,p) = m + U_s(x,p)$ - effective mass

$\Pi_\mu(x,p) = p_\mu - U_\mu(x,p)$ - effective momentum

$U_s(x,p)$, $U_\mu(x,p)$ are scalar and vector part of particle self-energies

$\delta(\Pi_\mu \Pi^\mu - m^{*2})$ – mass-shell constraint

W. Ehehalt, W. Cassing, Nucl. Phys. A 602 (1996) 449

Dynamical transport model: collision terms

- BUU eq. for different particles of type *i=1,…n*

$$Df_i \equiv \frac{d}{dt} f_i = I_{coll}\left[f_1, f_2, ..., f_n\right]$$

Drift term=Vlasov eq. collision term

$$i: \quad Baryons: \; p, n, \Delta(1232), N(1440), N(1535), ..., \Lambda, \Sigma, \Sigma^*, \Xi, \Omega; \; \Lambda_C$$

$$Mesons: \; \pi, \eta, K, \bar{K}, \rho, \omega, K^*, \eta', \phi, a_1, ..., D, \bar{D}, J/\Psi, \Psi', ...$$

➔ coupled set of BUU equations for different particles of type *i=1,…n*

$$\begin{cases} Df_N = I_{coll}\left[f_N, f_\Delta, f_{N(1440)}, ..., f_\pi, f_\rho, ...\right] \\ Df_\Delta = I_{coll}\left[f_N, f_\Delta, f_{N(1440)}, ..., f_\pi, f_\rho, ...\right] \\ ... \\ Df_\pi = I_{coll}\left[f_N, f_\Delta, f_{N(1440)}, ..., f_\pi, f_\rho, ...\right] \\ ... \end{cases}$$

Elementary hadronic interactions

Consider all possible interactions – eleastic and inelastic collisions - for the sytem of *(N,R,m)*, where *N*-nucleons, *R*- resonances, *m*-mesons, and resonance decays

Low energy collisions:

- binary 2←→2 and 2←→3(4) reactions
- 1←→2 : formation and decay of baryonic and mesonic resonances

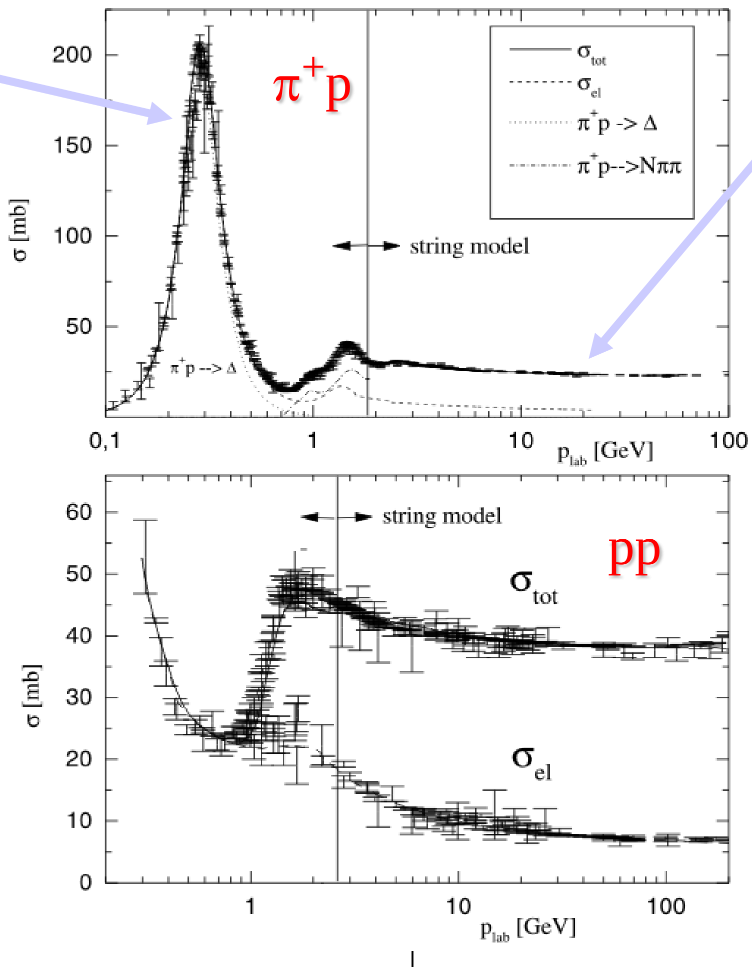
BB ←→ B´B´
BB ←→ B´B´m
mB ←→ m´B´
mB ←→ B´
mm ←→ m´m´
mm ←→ m´ . . .

Baryons:

B = p, n, Δ(1232), N(1440), N(1535), ...

Mesons:

M = π, η, ρ, ω, φ, ...



High energy collisions:

(above $s^{1/2}$~2.5 GeV)

Inclusive particle production:

BB→X , mB→X, mm→X

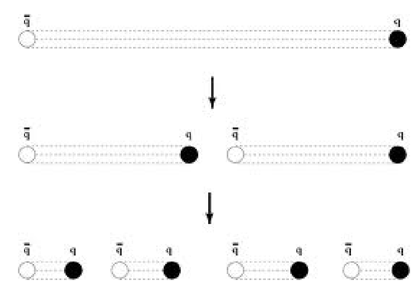
X =many particles

described by

string formation and decay

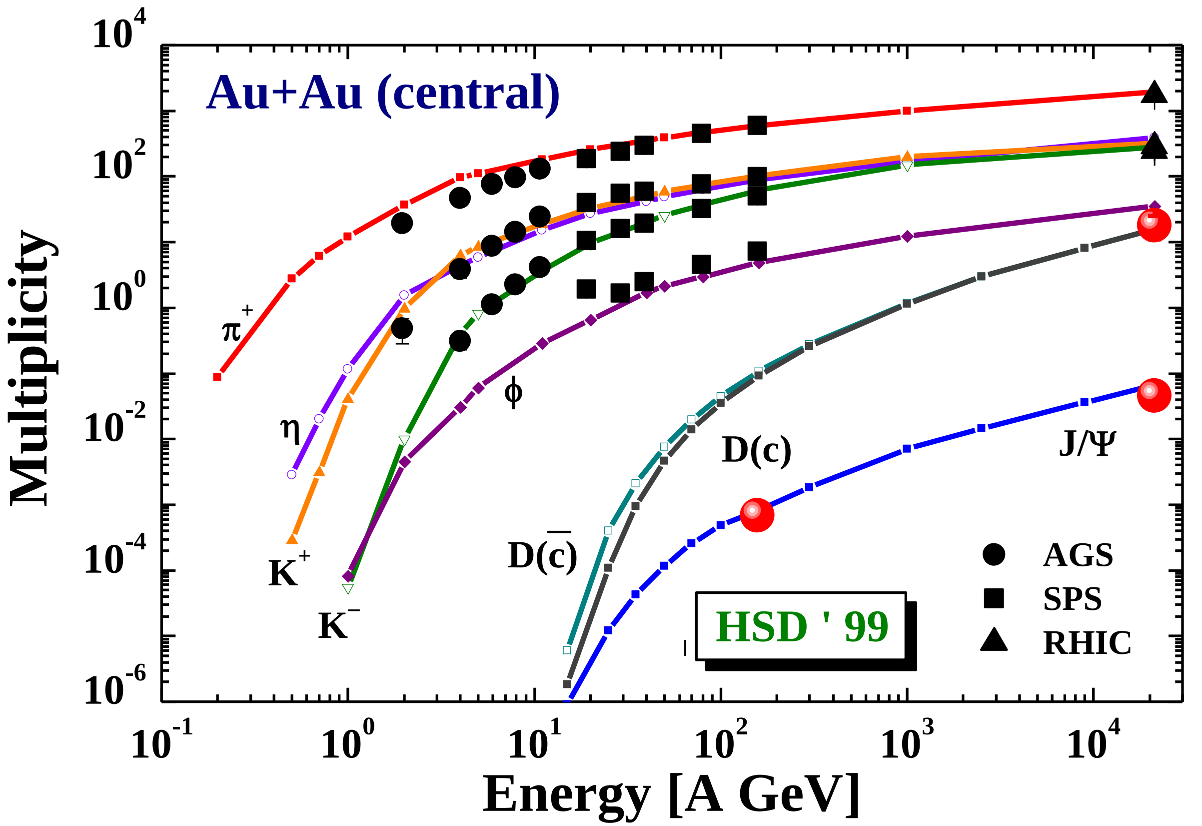
(string = excited color singlet states *q-qq*, *q-qbar*)

using LUND string model



Hadron-String-Dynamics – a microscopic transport model for heavy-ion reactions

- very good description of particle production in pp, pA, pA, AA reactions
- unique description of nuclear dynamics from low (~100 MeV) to ultrarelativistic (>20 TeV) energies



HSD predictions from 1999; data from the new millenium

W. Cassing, E.B., Phys.Rept. 308 (1999) 65

From weakly to strongly interacting systems

In-medium effects (on hadronic or partonic levels!) = changes of particle properties in the hot and dense medium

Examples: hadronic medium - vector mesons, strange mesons
QGP – dressing of partons

Many-body theory:
Strong interaction → large width → broad spectral function → quantum object

Semi-classical on-shell BUU: applies for small collisional width, i.e. for a weakly interacting systems of particles

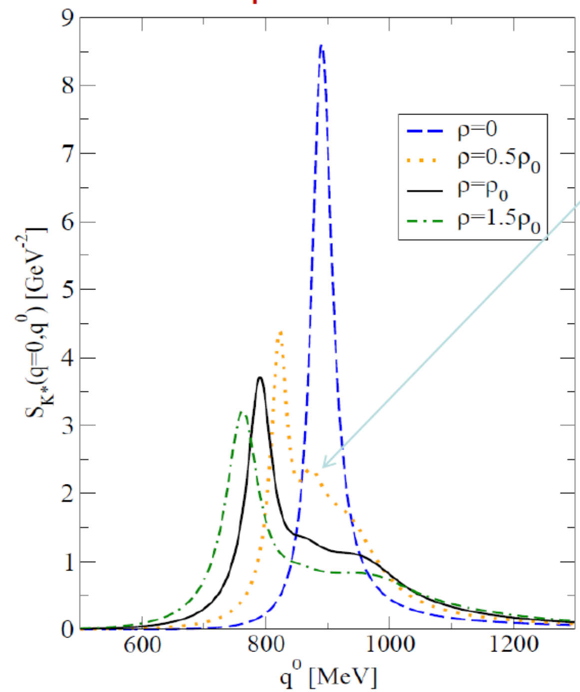
> ▪ **How to describe the dynamics of broad strongly interacting quantum states in transport theory?**

- ❑ **semi-classical BUU**

  first order gradient expansion of quantum Kadanoff-Baym equations

- ❑ **generalized transport equations based on Kadanoff-Baym dynamics**

Kbar* spectral function



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

Barcelona / Valencia group

Dynamical description of strongly interacting systems

Quantum field theory ➔

Kadanoff-Baym dynamics **for resummed single-particle Green functions $S^<$**

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

(1962)

Integration over the intermediate spacetime

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

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

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

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

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

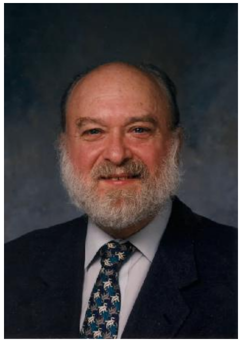
$$S^{ret}_{xy} = S^c_{xy} - S^<_{xy} = S^>_{xy} - S^a_{xy} \quad - retarded$$

$$S^{adv}_{xy} = S^c_{xy} - S^>_{xy} = S^<_{xy} - S^a_{xy} \quad - advanced$$

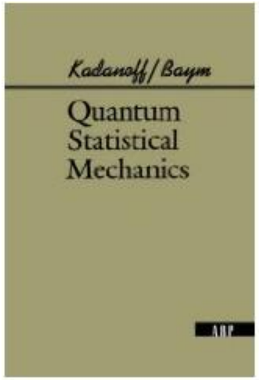
$$\hat{S}^{-1}_{0x} \equiv -(\partial^\mu_x \partial^x_\mu + M_0^2)$$

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

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



Leo Kadanoff



Gordon Baym

1st application for spacially homodeneous system with deformed Fermi sphere:
P. Danielewicz, Ann. Phys. 152, 305 (1984); … H.S. Köhler, Phys. Rev. 51, 3232 (1995); …

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

$$\diamond\{P^2 - M_0^2 - Re\Sigma_{XP}^{ret}\}\{S_{XP}^{<}\} - \diamond\{\Sigma_{XP}^{<}\}\{ReS_{XP}^{ret}\} = \frac{i}{2}\left[\Sigma_{XP}^{>}S_{XP}^{<} - \Sigma_{XP}^{<}S_{XP}^{>}\right]$$

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})

Botermans-Malfliet (1990)

- Spectral function:

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

$\Gamma_{XP} = -Im\,\Sigma_{XP}^{ret} = 2\,p_0\Gamma$ – ‚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 !

➔ Generalized testparticle Cassing's 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:

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

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

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

‚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

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

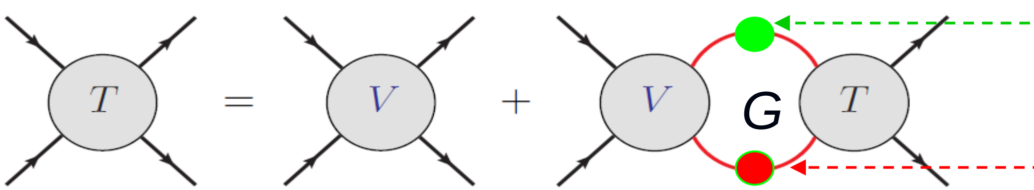
↓

Coupled channel G-matrix approach

Transition probability :

$$P_{1+2\to3+4}(s) = \int d\cos(\theta) \, \frac{1}{(2s_1+1)(2s_2+1)} \sum_i \sum_\alpha \, G^\dagger G$$

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**

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

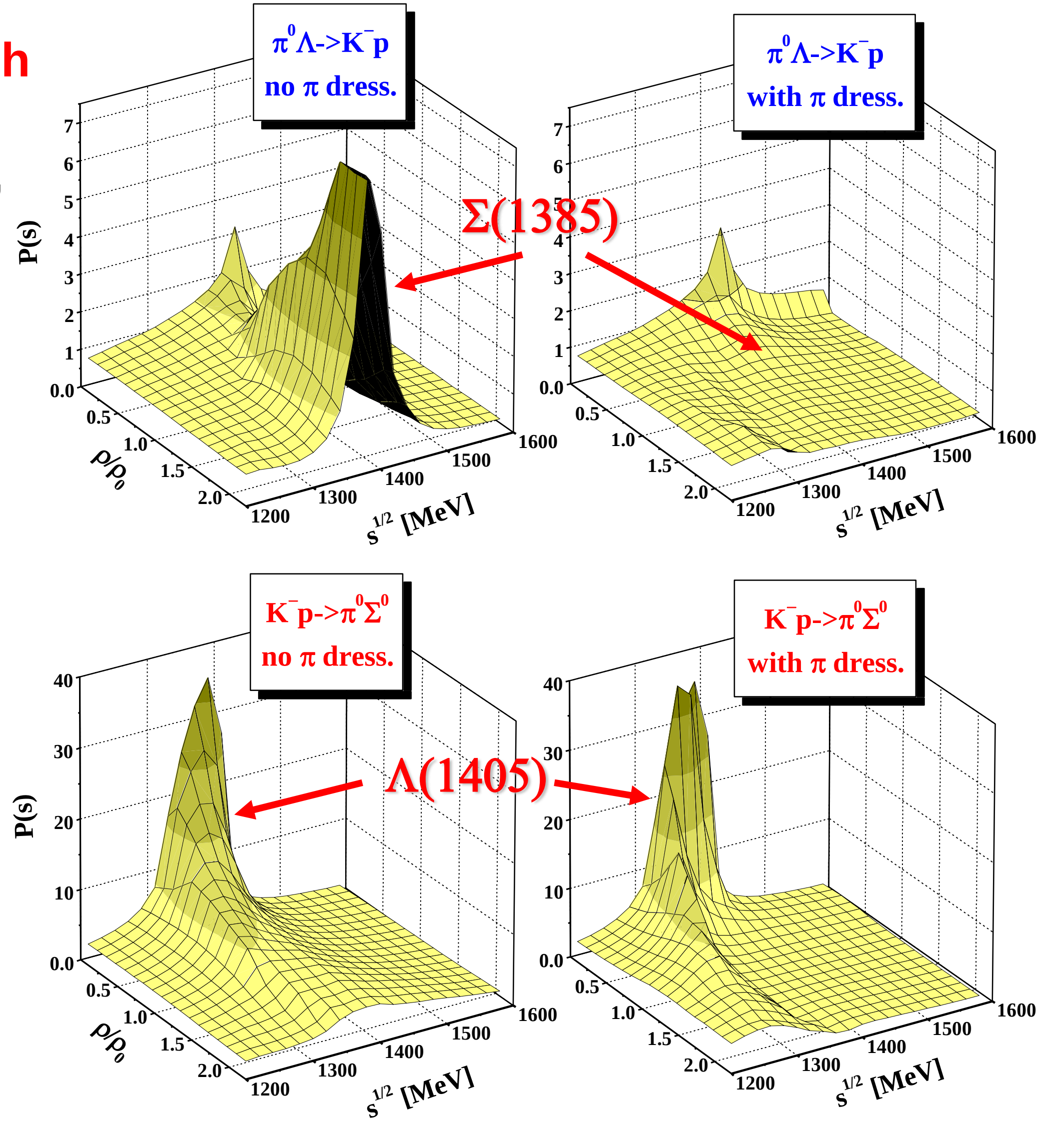
For strangeness:

D. Cabrera, L. Tolos, J. Aichelin, E.B., PRC C90 (2014) 055207; W. Cassing, L. Tolos, E.B., A. Ramos, NPA727 (2003) 59

Transition probabilities for $\pi Y \leftrightarrow K^- p$ ($Y = \Lambda,\Sigma$)

L. Tolos et al., NPA 690 (2001) 547

Coupled-channel G-matrix approach provides in-medium transition probabilities for different channels, e.g. $\pi Y \leftrightarrow K^- p$ ($Y = \Lambda,\Sigma$)



- **With pion dressing:**
  $\Lambda(1405)$ and $\Sigma(1385)$ melt away with baryon density

- **K^- absorption/production from πY** collisions are strongly suppressed in the nuclear medium

- πY is the **dominant channel** for K^- production in heavy-ion collisions !

W. Cassing, L. Tolos, E.L.B., A. Ramos, NPA 727 (2003) 59

Mean-field potential in off-shell transport models

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

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

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

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

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

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

which gives a mean-field potential U_{XP} via: $Re\,\Sigma^{ret}_{XP}(p_0) = 2p_0 U_{XP}$

➔ The complex self-energy relates in a self-consistent way to the self-generated mean-field potential and collision width

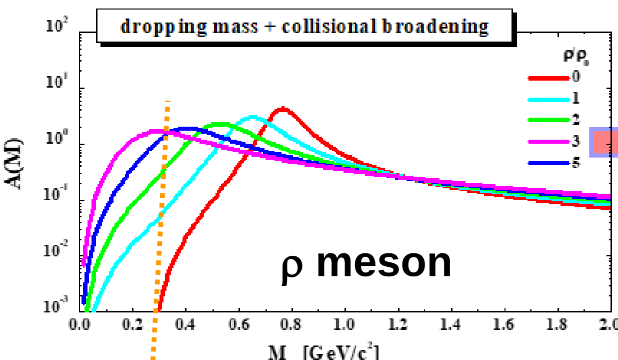
In-medium
$\rho >> \rho_0$

Off-shell vs. on-shell transport dynamics

Time evolution of the mass distribution of ρ and ω mesons for central C+C collisions (b=1 fm) at 2 A GeV for dropping mass + collisional broadening scenario

$$A(M,p,\rho) = \frac{2}{\pi} \frac{M^2 \Gamma_{tot}(M,p,\rho)}{(M^2 - M_0^2 - Re\Sigma^{ret}) + \left(M\Gamma_{tot}(M,p,\rho)\right)^2},$$

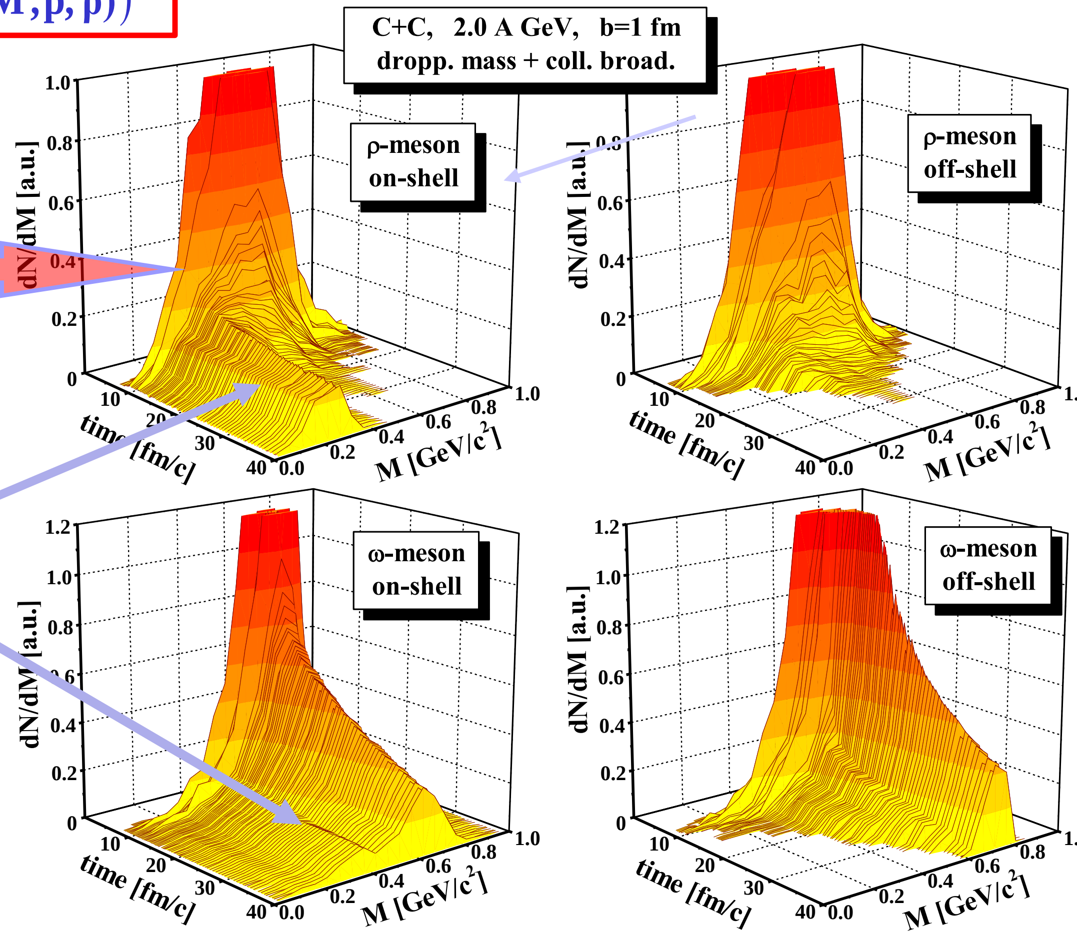
width $\Gamma \sim -Im\, \Sigma^{ret}/M$



On-shell BUU:
low mass ρ and ω mesons live forever (and shine ‚fake' dileptons)!

The off-shell spectral function becomes on-shell in the vacuum dynamically by propagation through the medium!

On-shell | Off-shell



E.L.B. &W. Cassing, NPA 807 (2008) 214

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**

Antibaryon production in heavy-ion reactions

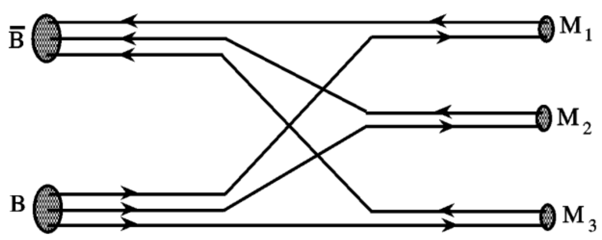
Multi-meson fusion reactions

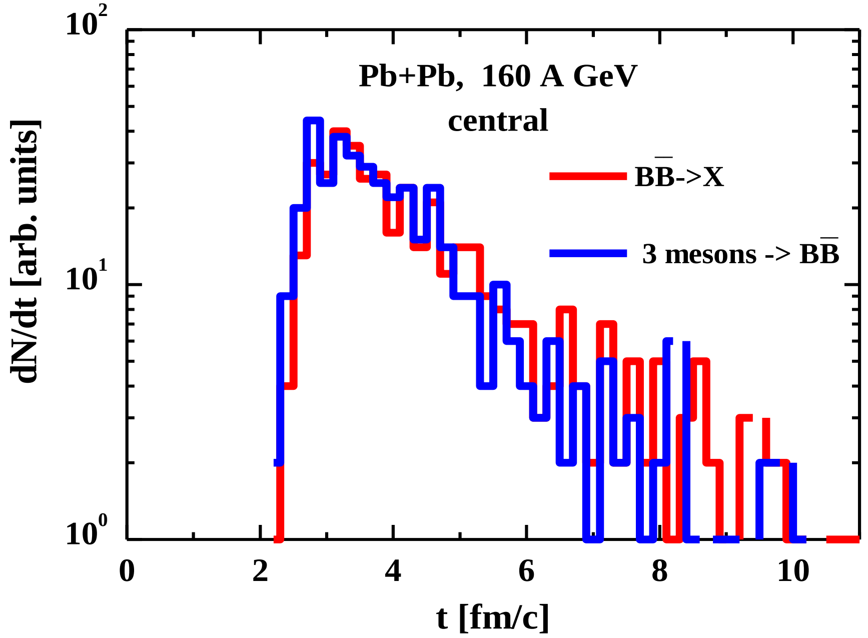
$m_1+m_2+...+m_n \leftrightarrow B+Bbar$

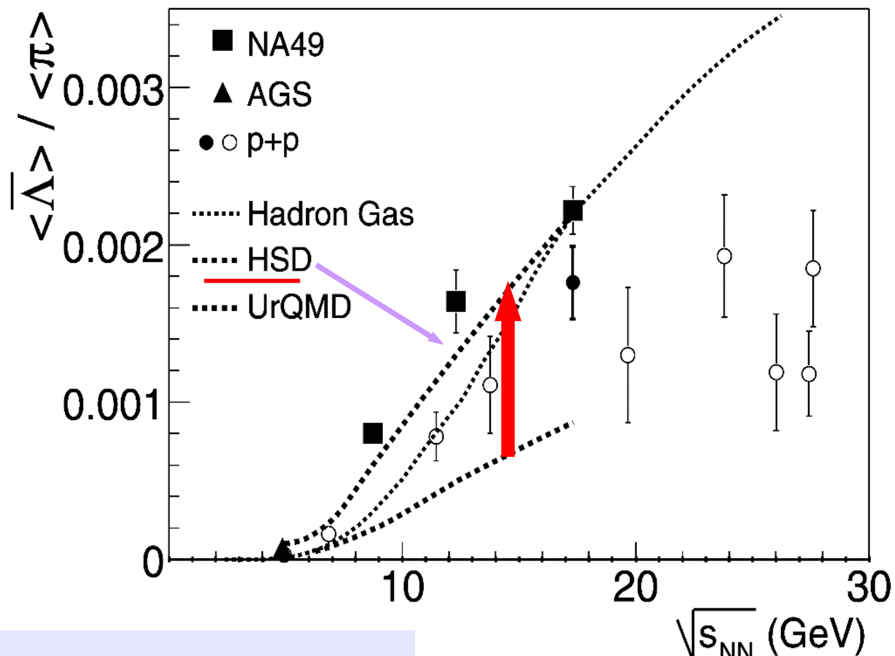
m=π,ρ,ω,.. B=p,Λ,Σ, Ξ, Ω,... (>2800 channels)

W. Cassing, NPA 700 (2002) 618
E. Seifert, W. Cassing, PRC 97, 024913 (2018); PRC 97, 044907 (2018)

- important for anti-baryon (anti-p, anti-Λ, anti-Ξ, anti-Ω) dynamics !

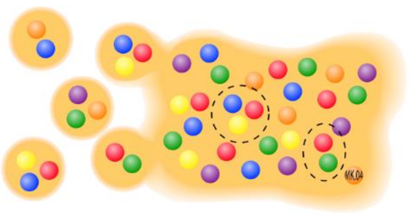






→ approximate equilibrium of annihilation and recreation

Goal: microscopic transport description of the partonic and hadronic phase



Problems:

- How to model a QGP phase in line with lQCD data?
- How to solve the hadronization problem?

Ways to go:

pQCD based models:

- QGP phase: pQCD cascade
- hadronization: quark coalescence

➔ AMPT, HIJING, BAMPS

‚Hybrid' models:

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

➔ Hybrid-UrQMD

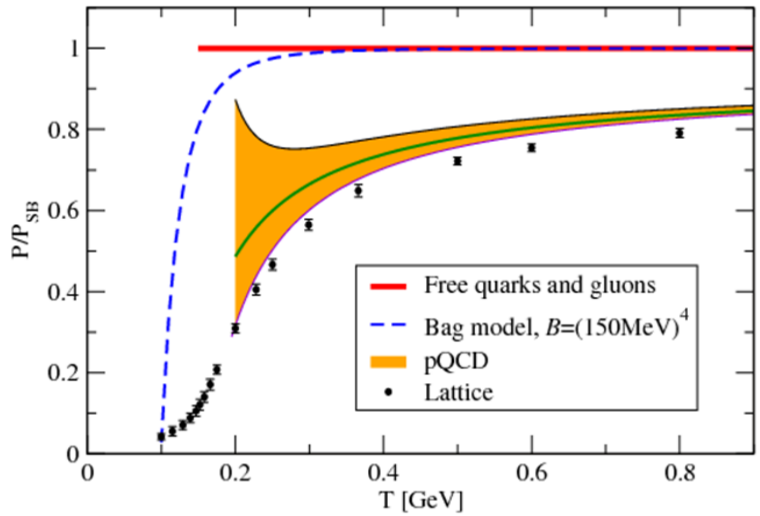
- microscopic transport description of the partonic and hadronic phase in terms of strongly interacting dynamical quasi-particles and off-shell hadrons

➔ PHSD

Degrees-of-freedom of QGP

❖ lQCD gives QGP EoS at finite μ_B

! need to be interpreted in terms of degrees-of-freedom



Non-perturbative QCD ← pQCD

pQCD:

- weakly interacting system
- massless quarks and gluons

Thermal QCD
= QCD at high parton densities:

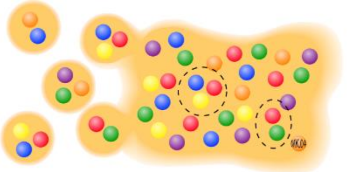
- strongly interacting system
- massive quarks and gluons

➔ quasiparticles
= effective degrees-of-freedom

❖ How to learn about degrees-of-freedom of QGP?

Theory ⇔ HIC experiments

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 a 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 small μ_q)

- 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;
W. 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 (propagators) – in the sense of a two-particle irreducible (2PI) approach:

gluon propagator: $\Delta^{-1} = P^2 - \Pi$ & quark propagator $S_q^{-1} = P^2 - \Sigma_q$

gluon self-energy: $\Pi = M_g^2 - i2\gamma_g\omega$ & quark self-energy: $\Sigma_q = M_q^2 - i2\gamma_q\omega$

(scalar approximation)

- the resummed properties are specified by complex (retarded) self-energies:
- 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)
- Spectral functions : $A_q \sim Im S_q^{ret}, \quad A_g \sim Im\Delta^{ret}$

- Entropy density of interacting bosons and fermions in the quasiparticle limit (2PI) (G. Baym 1998):

QGP

$$s^{dqp} = -d_g \int \frac{d\omega}{2\pi} \frac{d^3p}{(2\pi)^3} \frac{\partial n_B}{\partial T} \left(\mathrm{Im} \ln(-\Delta^{-1}) + \mathrm{Im}\, \Pi \,\mathrm{Re}\, \Delta \right) \quad \text{gluons}$$

$$- d_q \int \frac{d\omega}{2\pi} \frac{d^3p}{(2\pi)^3} \frac{\partial n_F((\omega - \mu_q)/T)}{\partial T} \left(\mathrm{Im} \ln(-S_q^{-1}) + \mathrm{Im}\, \Sigma_q \,\mathrm{Re}\, S_q \right) \quad \text{quarks}$$

$$- d_{\bar{q}} \int \frac{d\omega}{2\pi} \frac{d^3p}{(2\pi)^3} \frac{\partial n_F((\omega + \mu_q)/T)}{\partial T} \left(\mathrm{Im} \ln(-S_{\bar{q}}^{-1}) + \mathrm{Im}\, \Sigma_{\bar{q}} \,\mathrm{Re}\, S_{\bar{q}} \right) \quad \text{antiquarks}$$

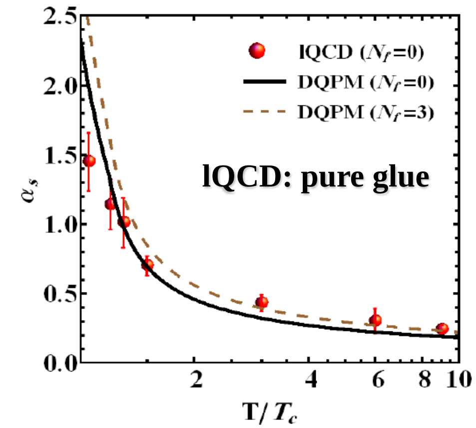
A. Peshier, W. Cassing, PRL 94 (2005) 172301; Cassing, NPA 791 (2007) 365: NPA 793 (2007)

The Dynamical QuasiParticle Model (DQPM)

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

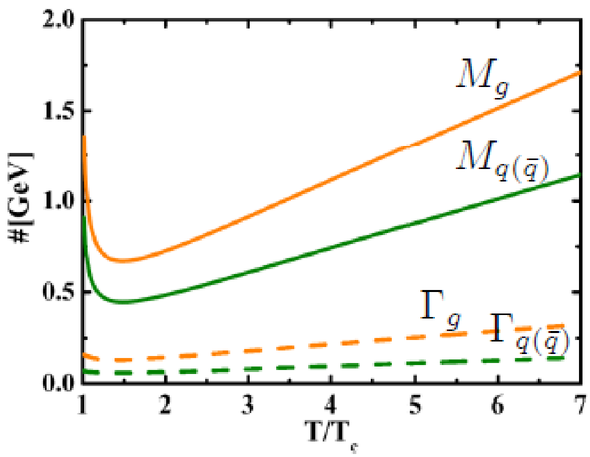
$$\rho_i(\omega,T) = \frac{4\omega\Gamma_i(T)}{\left(\omega^2 - \vec{p}^2 - M_i^2(T)\right)^2 + 4\omega^2\Gamma_i^2(T)} \qquad (i = q, \bar{q}, g)$$

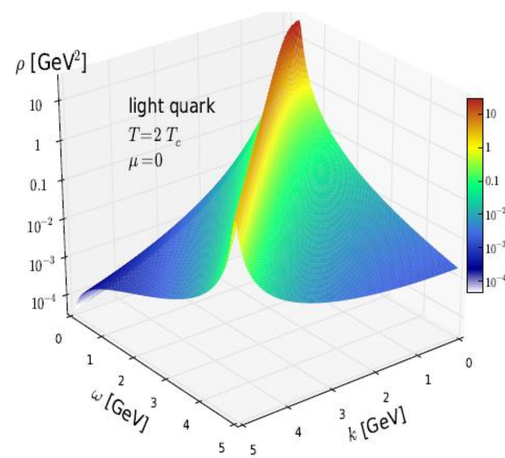
- **Modeling of the quark/gluon masses and widths → HTL limit at high T with 3 model parameters – fited to lattice QCD data**

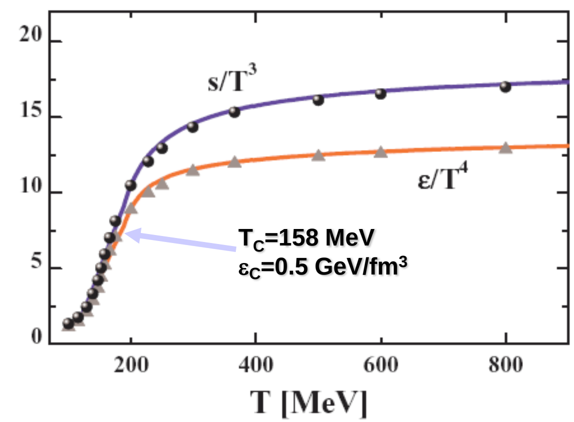


→ Quasi-particle properties:

large width and mass for gluons and quarks



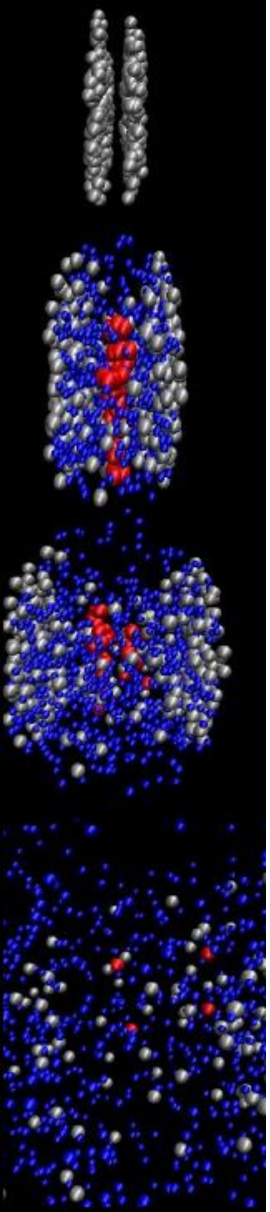




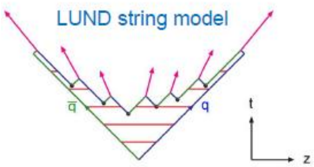
- **DQPM provides mean-fields (1PI) for gluons and quarks as well as effective 2-body interactions (2PI)**
- **DQPM gives transition rates for the formation of hadrons**
  → PHSD

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

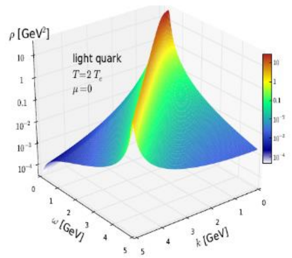
Parton-Hadron-String-Dynamics (PHSD)



- **Initial A+A collisions :**
  N+N → string formation → decay to pre-hadrons



- **Formation of QGP stage** if $\varepsilon > \varepsilon_{critical}$:
  dissolution of pre-hadrons → (DQPM) →
  → massive quarks/gluons + mean-field potential U_q



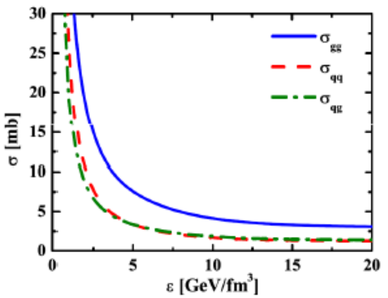
- **Partonic stage – QGP :**
  based on the Dynamical Quasi-Particle Model (DQPM)

  - (quasi-) elastic collisions:

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

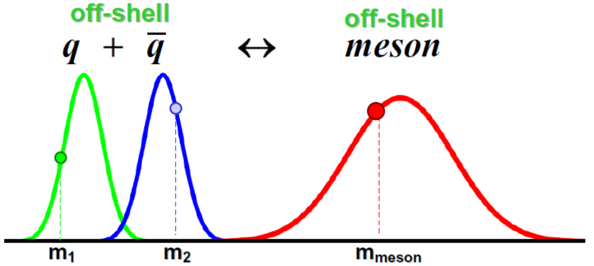
  - inelastic collisions:

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



- **Hadronization (based on DQPM):**

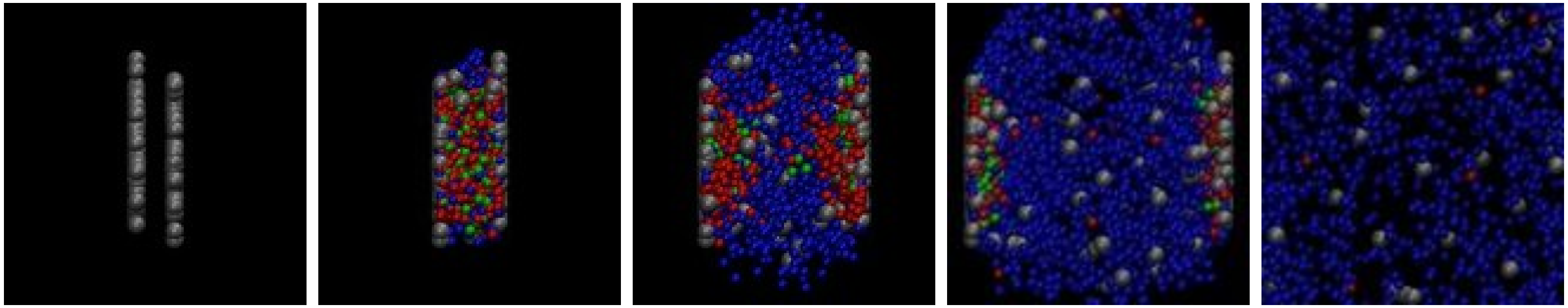
$$g \to q+\bar{q}, \qquad q+\bar{q} \leftrightarrow meson\ \ (or\ 'string\ ')$$
$$q+q+q \leftrightarrow baryon\ \ (or\ 'string\ ')$$



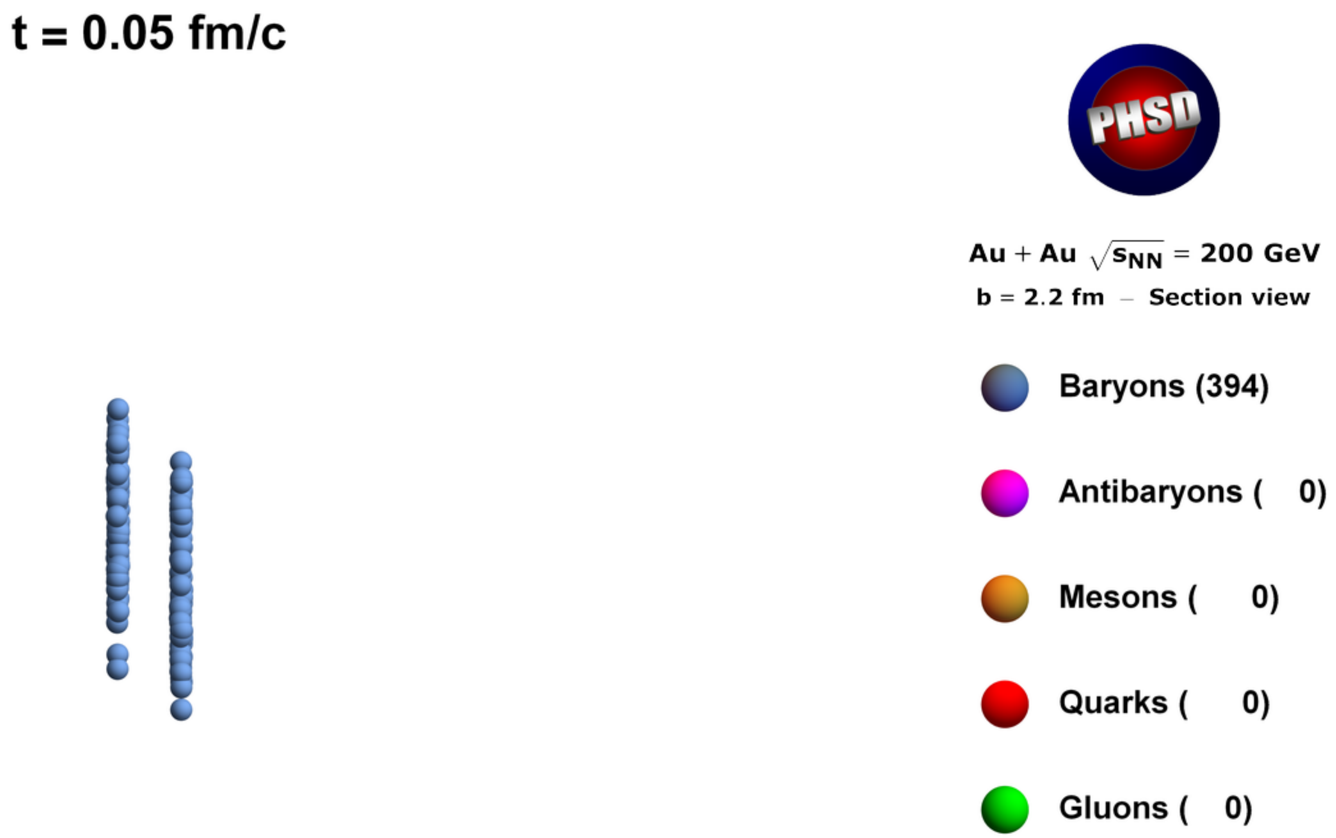
- **Hadronic phase: hadron-hadron interactions – off-shell HSD**

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

Traces of the QGP in observables in high energy heavy-ion collisions

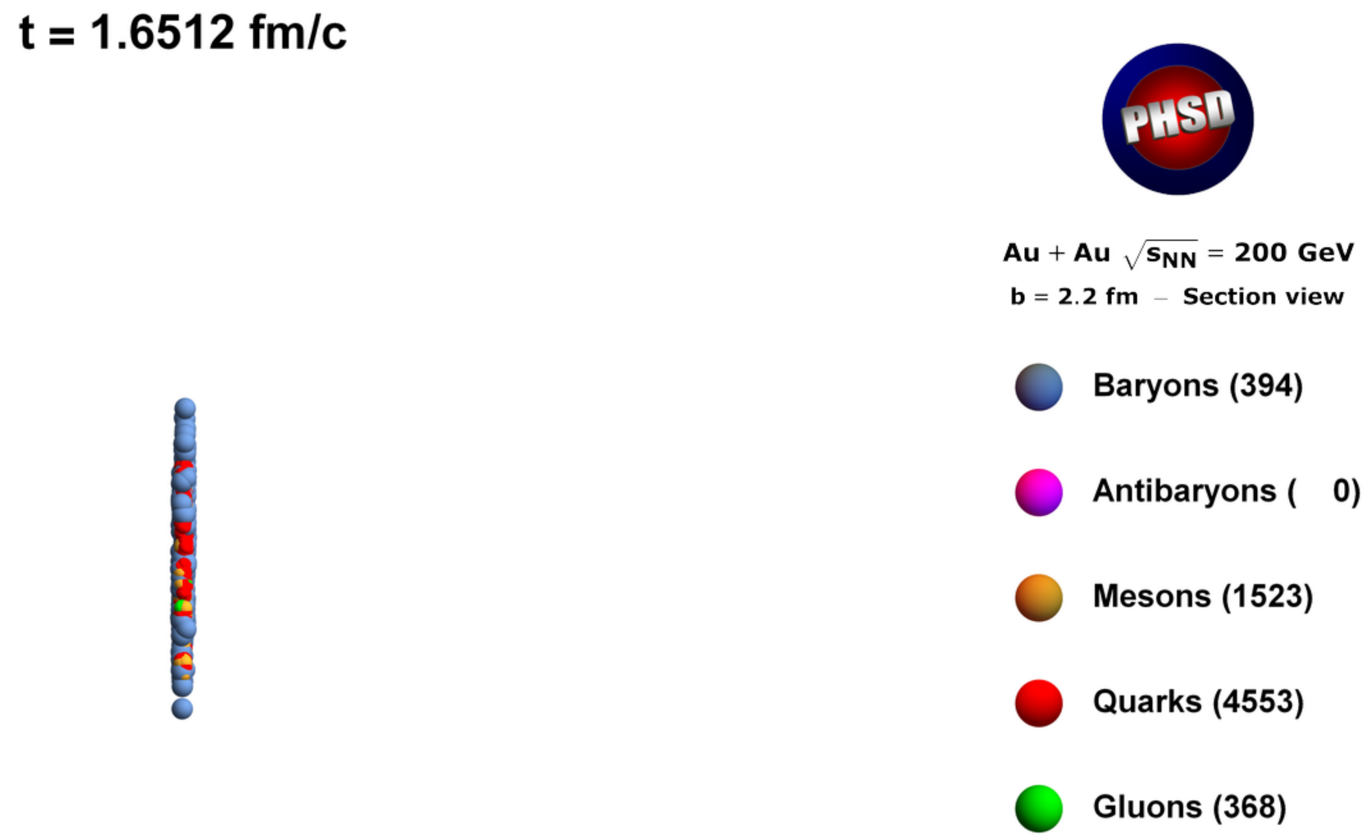


Stages of a collision in PHSD



P.Moreau

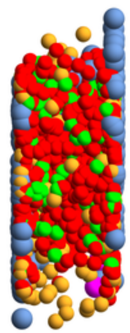
Stages of a collision in PHSD



P.Moreau

Stages of a collision in PHSD

t = 3.91921 fm/c



Au + Au $\sqrt{s_{NN}}$ = 200 GeV

b = 2.2 fm – Section view

Baryons (426)

Antibaryons (29)

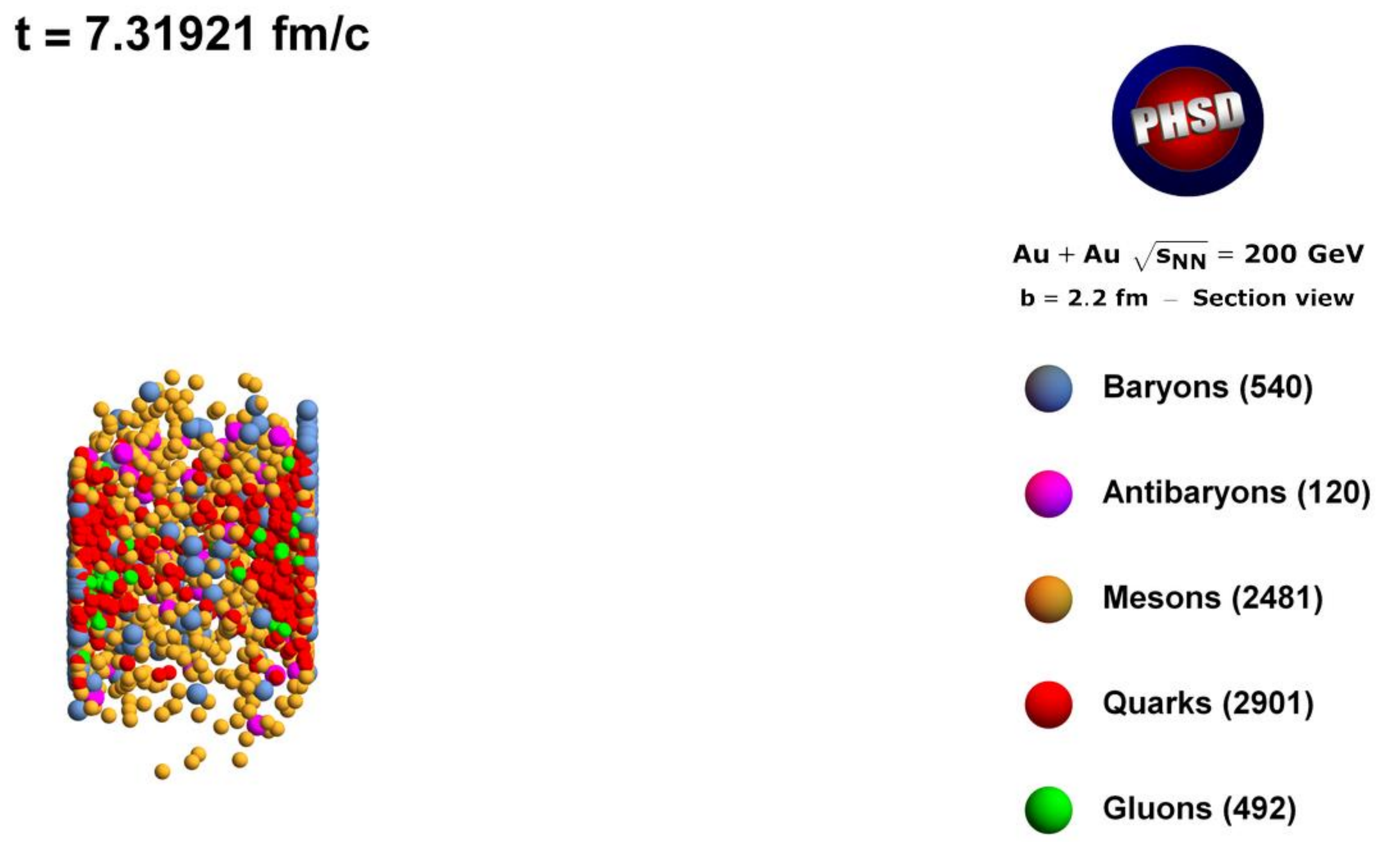
Mesons (1189)

Quarks (4459)

Gluons (783)

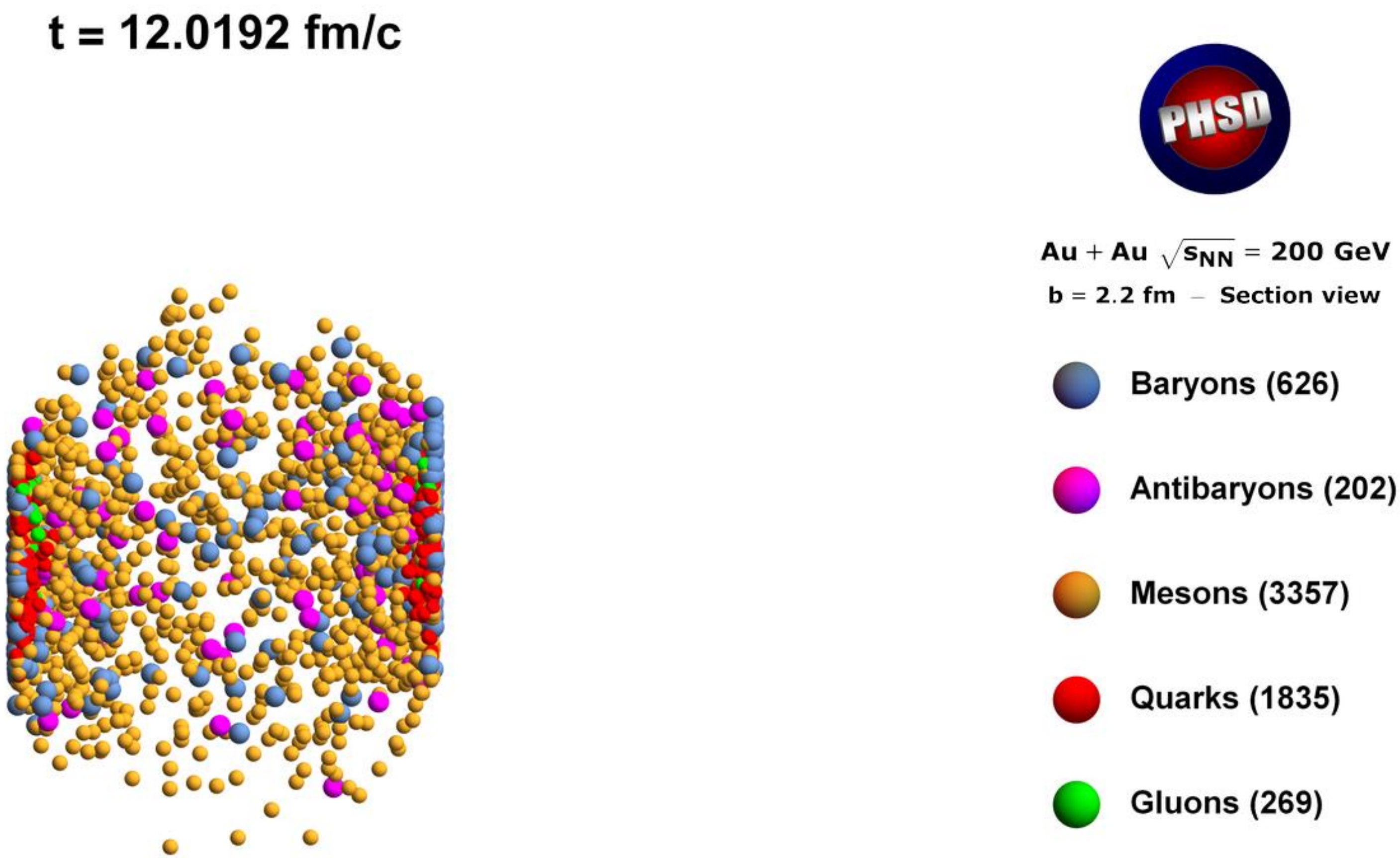
P.Moreau

Stages of a collision in PHSD



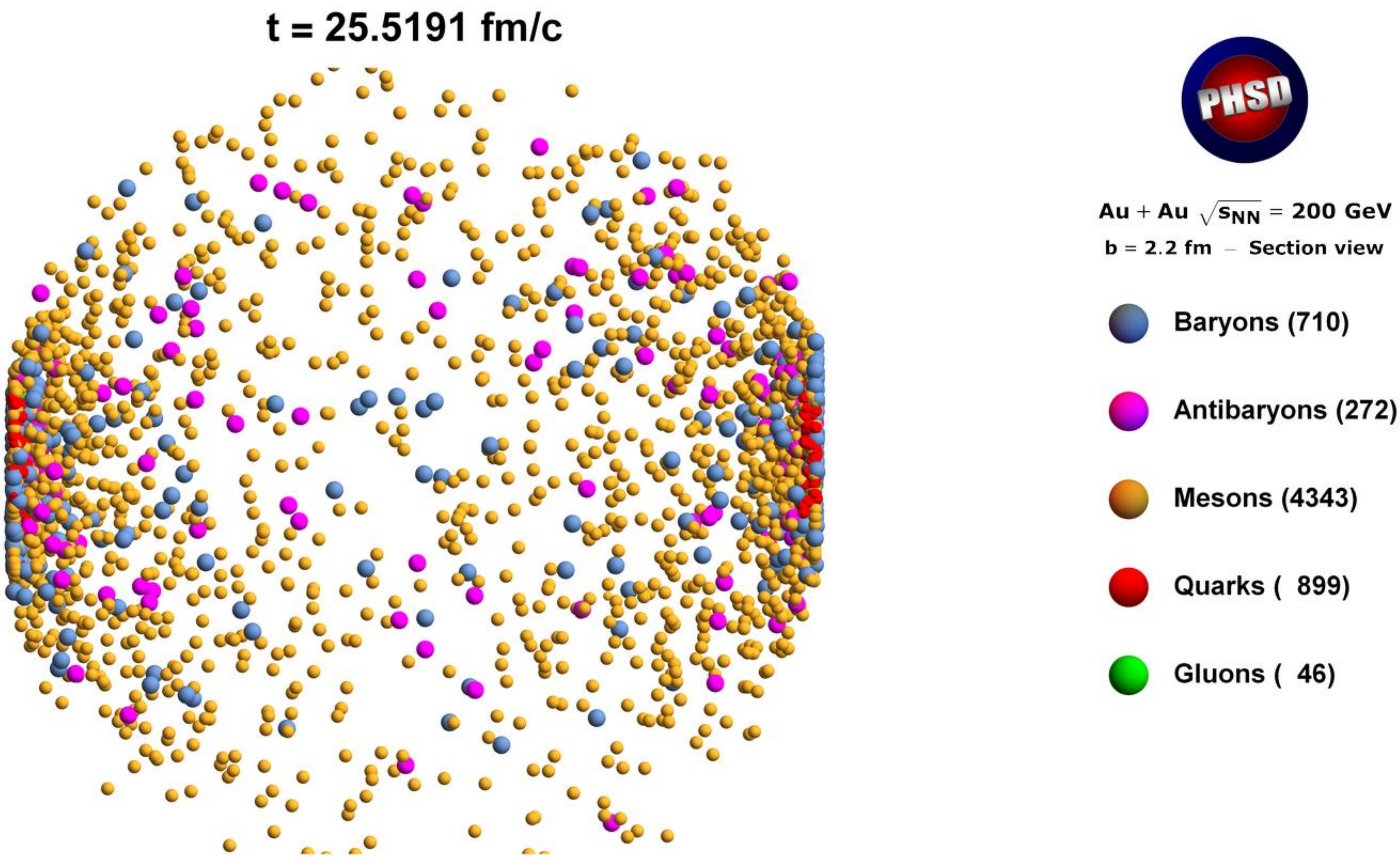
P.Moreau

Stages of a collision in PHSD



P.Moreau

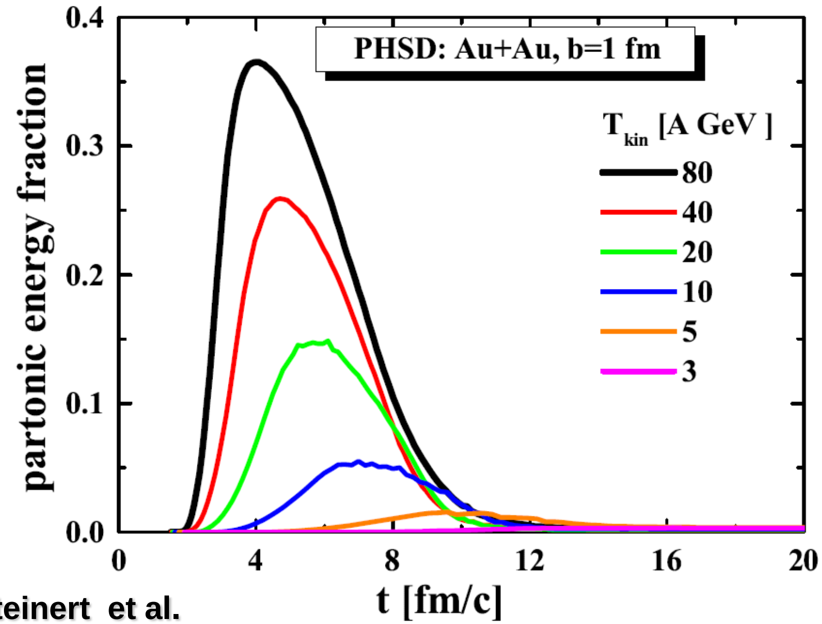
Stages of a collision in PHSD



P.Moreau

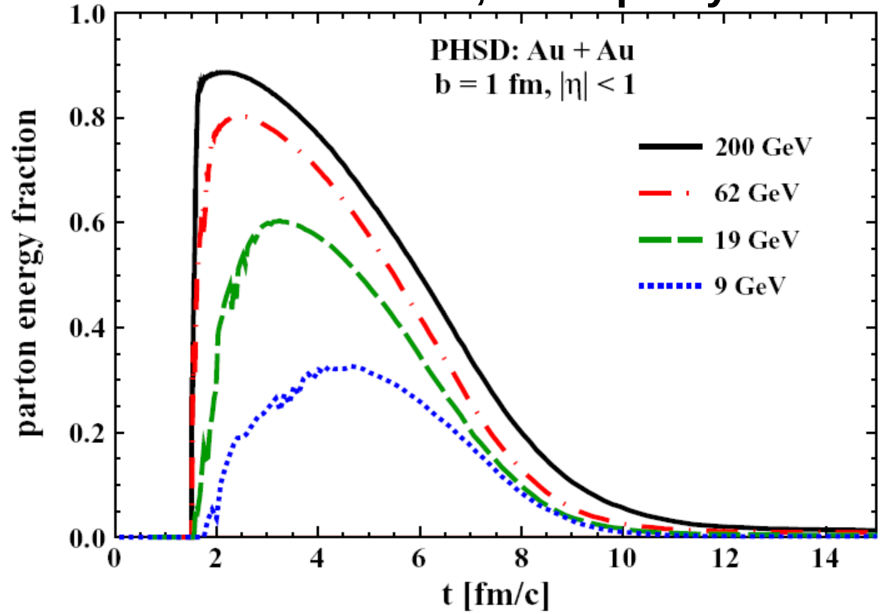
Partonic energy fraction in central A+A

Time evolution of the partonic energy fraction vs energy



T. Steinert et al.

Au+Au, midrapidity

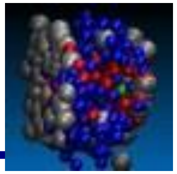


- Strong increase of partonic phase with energy from AGS to RHIC

- 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

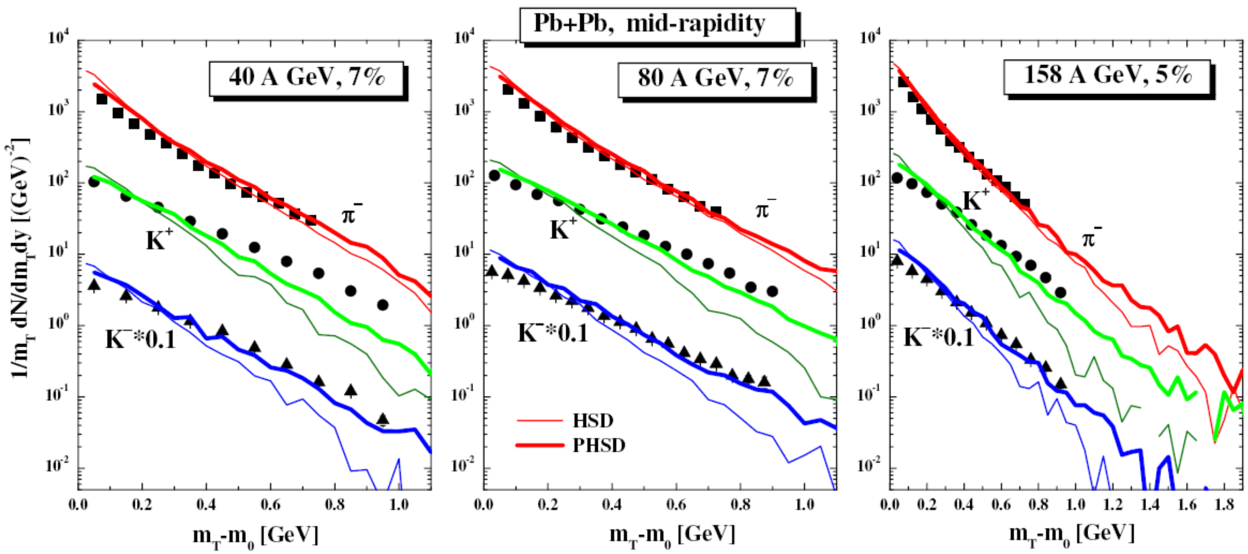
W. Cassing & E. Bratkovskaya, NPA 831 (2009) 215
V. Konchakovski et al., Phys. Rev. C 85 (2012) 011902

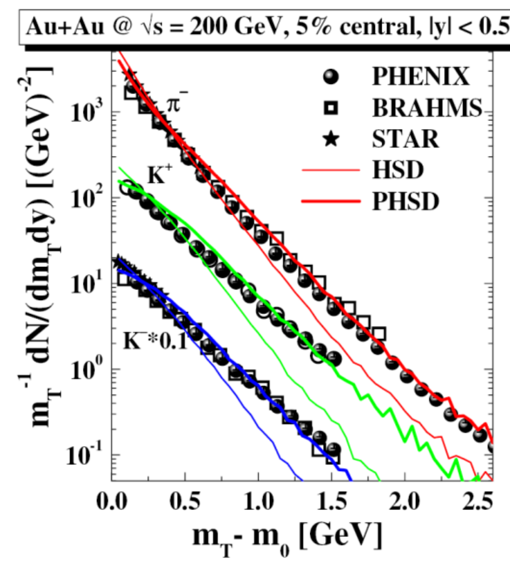
Transverse mass spectra from SPS to RHIC



Central Pb + Pb at SPS energies

Central Au+Au at RHIC

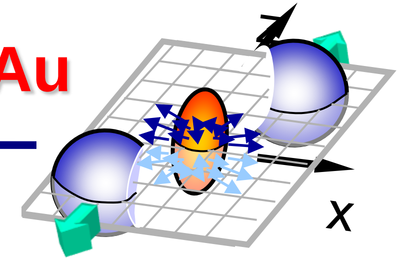




- **PHSD** gives **harder m_T spectra** and works better than HSD (wo QGP) at high energies – RHIC, SPS (and top FAIR, NICA)
- however, at **low SPS** (and low FAIR, NICA) energies the **effect of the partonic phase decreases** due to the decrease of the partonic fraction

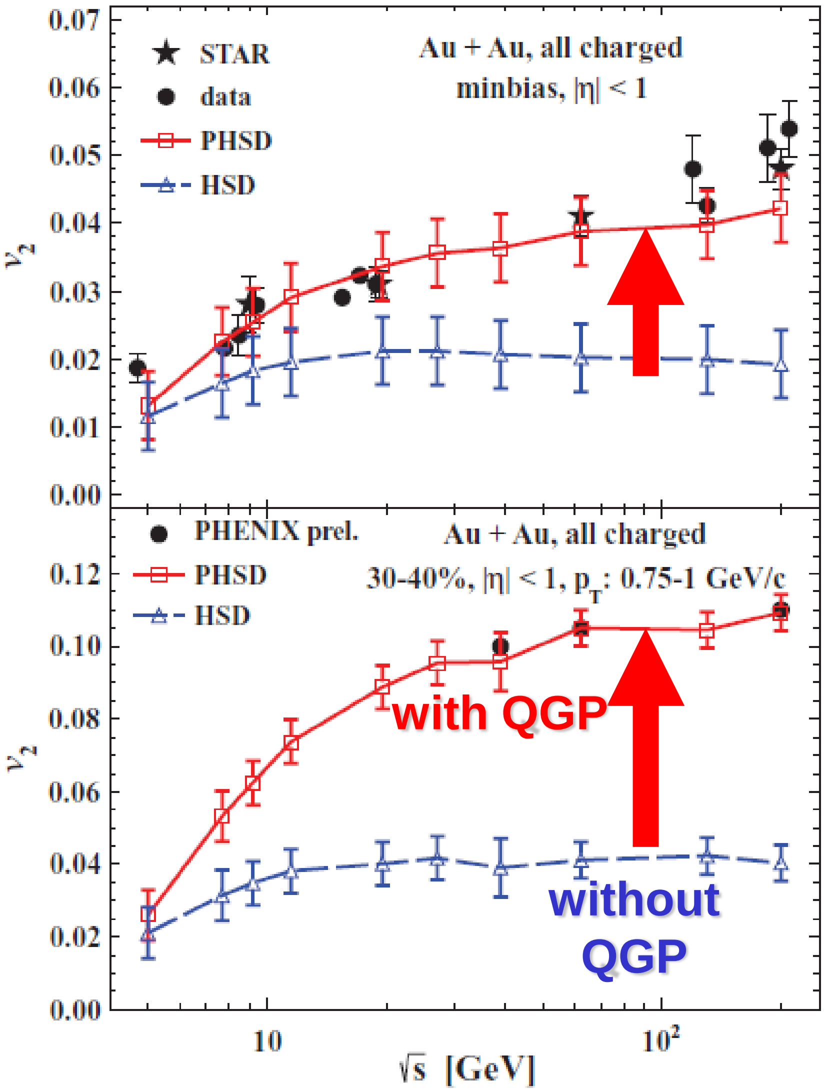
W. Cassing & E. Bratkovskaya, NPA 831 (2009) 215
E. Bratkovskaya, W. Cassing, V. Konchakovski, O. Linnyk, NPA856 (2011) 162

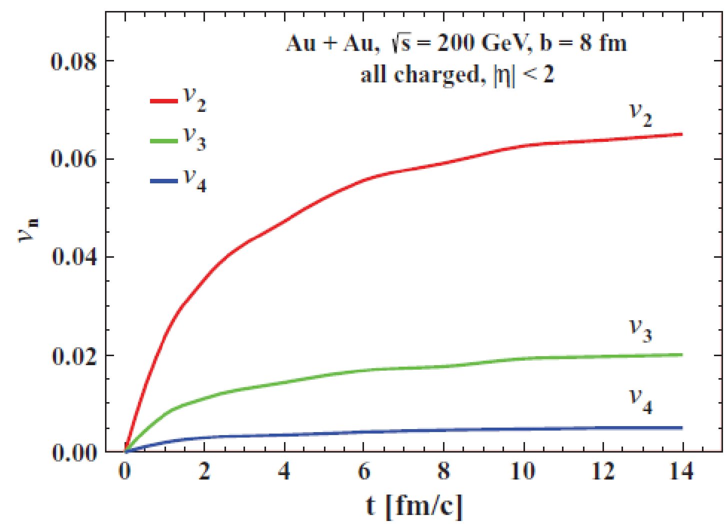
Elliptic flow v_2 vs. collision energy for Au+Au



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

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

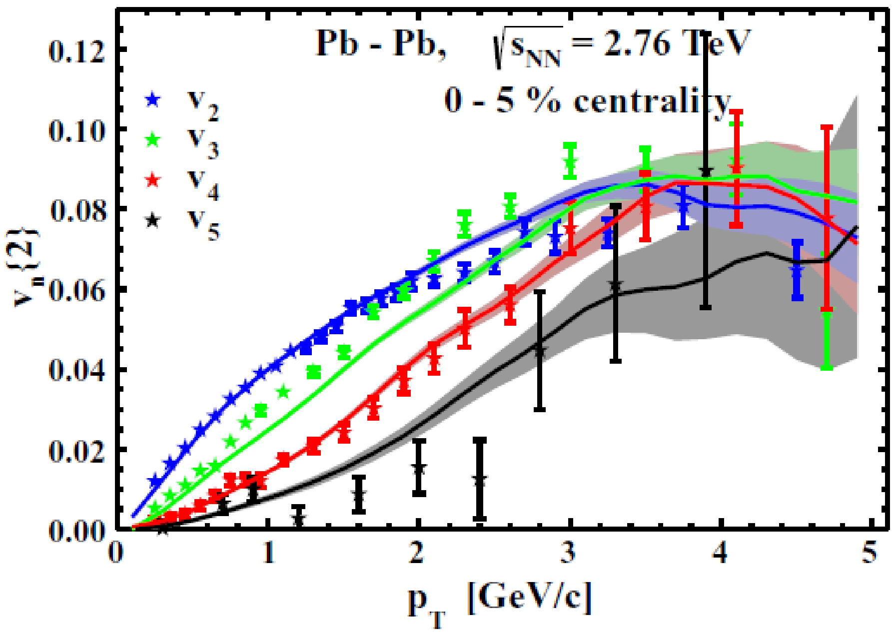


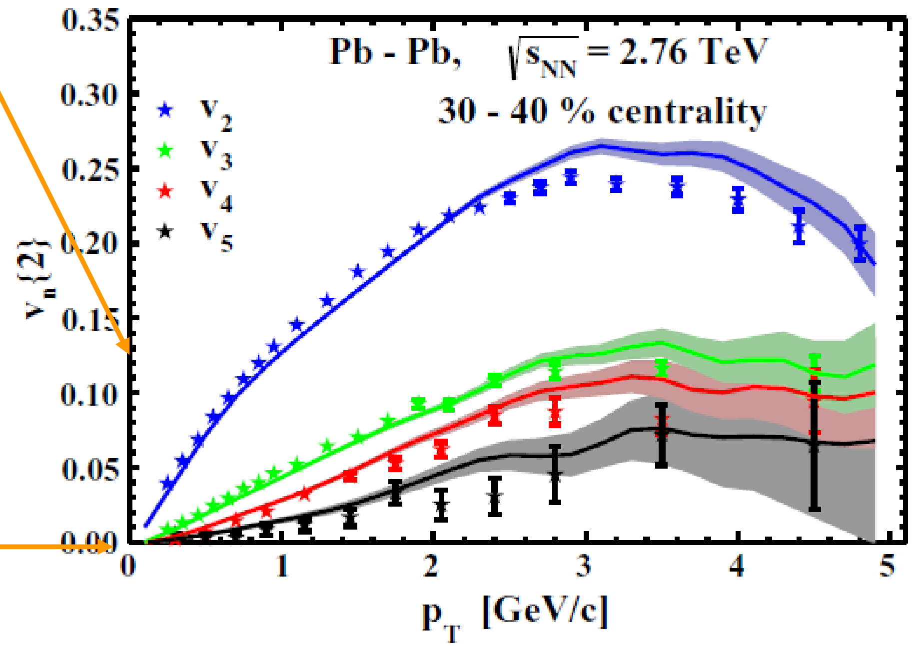


- **v_2 in PHSD is larger than in HSD due to the repulsive scalar mean-field potential $U_s(\rho)$ for partons**
- **v_2 grows with bombarding energy due to the increase of the parton fraction**

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

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





- 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

symbols – ALICE
PRL 107 (2011) 032301
lines – PHSD (e-by-e)

v_n (n=3,4,5) develops by interaction in the QGP and in the final hadronic phase

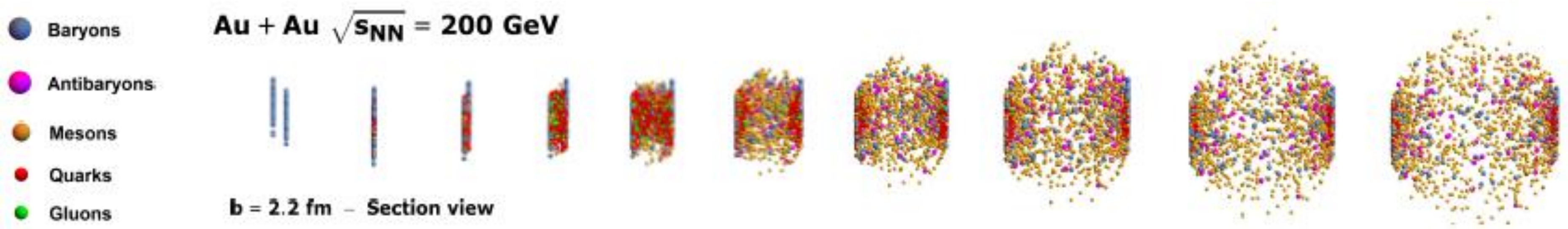
V. Konchakovski, W. Cassing, V. Toneev, J. Phys. G: Nucl. Part. Phys 42 (2015) 055106

Summary

The PHSD is a microscopic off-shell transport approach

- **applicable for the description of strongly-interraction hadronic and partonic matter created in heavy-ion collisions**
- **based on the solution of generalized transport equations derived from Kadanoff-Baym theory**
- **applicable from SIS to LHC energies**

Outlook:
Extention of the PHSD for cluster formation → PHQMD



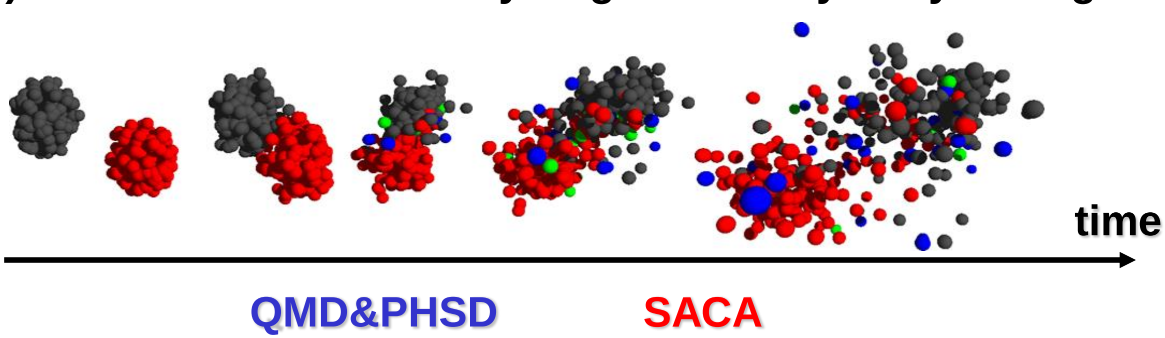
Modeling of clusters and hypernucleus formation

The goal: **Dynamical modeling of cluster formation by a combined model**
PHQMD = (PHSD & QMD) & SACA

Nantes & GU & GSI & JINR collaboration:
J. Aichelin, E. Bratkovskaya, A. Le Fèvre, Y. Leifels, V. Kireyeu, V. Kolesnikov and V. Voronyuk

- **Parton-Hadron-Quantum-Molecular-Dynamics -**
a non-equilibrium microscopic transport model which describes n-body dynamics based on
QMD propagation with collision integrals from PHSD (Parton-Hadron-String Dynamics) and cluster recognition by the SACA model as well as by the Minimum Spanning Tree model (MST). MST can determine clusters at the end of the reaction.

- **Simulated Annealing Clusterization Algorithm – cluster recognition according to the largest binding energy (extension of the SACA model → FRIGA which includes hypernuclei). SACA allows to identity fragments very early during the reaction.**



SACA: R. K. Puri, J. Aichelin, J.Comput.Phys. 162 (2000) 245-266
PHSD: W. Cassing, E. Bratkovskaya, PRC 78 (2008) 034919; NPA831 (2009) 215

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Steffen Bass

Thank you for your attention !

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ECT*

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