GOETHE UNIVERSITÄT FRANKFURT AM MAIN

FIAS Frankfurt Institute for Advanced Studies

HIC for FAIR
Helmholtz International Center

The influence of initial conditions on the final observables for heavy-ion collisions at RHIC energies

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in collaboration with:

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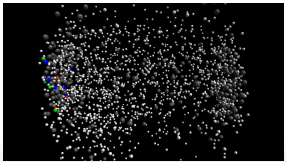
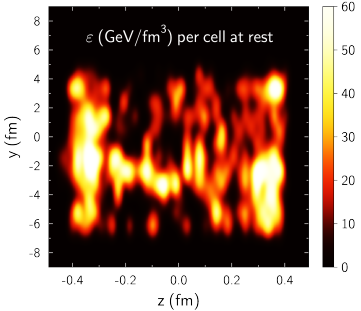
Motivations

We want a **microscopic description** of partonic phase and phase transition (cross over).
→ Transport codes : **PHSD** & **RSP**

With the same **fluctuating initial conditions**, what would be the differences on final observables for two different approaches ?
→ Effective models : **DQPM** & **NJL**





The Parton Hadron String Dynamics

Features:

- Description of heavy-ion collisions,
- Non-equilibrium approach,
- Strings formation and decay to pre-hadrons,
- Pre-hadrons fragmentation into partons,
- Dynamical Quasi-Particle Model (**DQPM**) for describing partons masses and widths,
- **Off-shell** transport of hadrons and partons with mean fields and scattering,
- Dynamical hadronization with cross over.

PRC 78, 034919 (2008)
NPA 831, 215 (2009)
EPJ ST 168, 3 (2009)
NPA 856, 162 (2011)

The Dynamical Quasi-Particle Model

Quasi-partons:

Masses:

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

$$M_{q/\bar{q}}^2(T,\mu_q) = \frac{N_c^2-1}{8N_c}g^2\left(T^2+\sum_q\frac{\mu_q^2}{\pi^2}\right)$$

Widths:

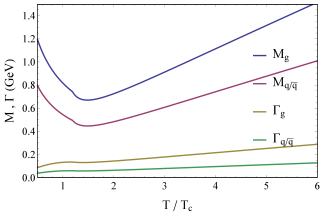
$$\Gamma_g(T) = \frac{1}{3}N_c\frac{g^2T}{8\pi}\ln\left(\frac{2c}{g^2}+1\right),$$

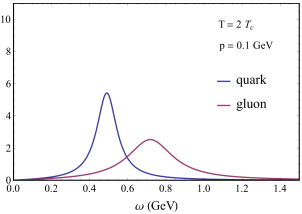
$$\Gamma_{q/\bar{q}}(T) = \frac{1}{3}\frac{N_c^2-1}{2N_c}\frac{g^2T}{8\pi}\ln\left(\frac{2c}{g^2}+1\right).$$

Coupling constant:

$$g^2(T/T_c) = \frac{48\pi^2}{(11N_c-2N_f)\ln[\lambda^2(T/T_c-T_s/T_c)^2]}$$

Based on EPJ ST 168, 3 (2009)





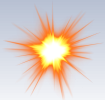
Off-shellness:

Breit-Wigner spectral function:

$$A(\omega,\mathbf{p}) = \frac{\Gamma}{E}\left(\frac{1}{(\omega-E)^2+\Gamma^2}-\frac{1}{(\omega+E)^2+\Gamma^2}\right)$$

with $E^2=\mathbf{p}^2+M^2-\Gamma^2$ and

$$\int_{-\infty}^{\infty}\frac{d\omega}{2\pi}\,\omega A(\omega,\mathbf{p}) = \int_0^{\infty}\frac{d\omega}{2\pi}\,2\omega A(\omega,\mathbf{p}) = 1$$



A new code on the market

Relativistic quantum molecular dynamics for
Strongly interacting matter with
Phase transition or crossover

History:

2008 Born in Subatech, designed for collision methods comparison,

2009 Nambu-Jona-Lasinio (**NJL**) model included with m_i and $\sigma_{2\to2}$ (T, μ),

2010 New relativistic dynamics achieved,

2011 Heavy Ion Collision-like simulations ('pancake' toy model),

2012 Full rewriting of the code for numerical optimization.

Features:

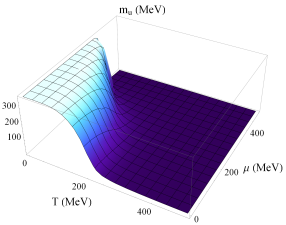
- C++ code, ∼5000 lines (∼1500 lines for cross section/decay channels)
- Fully modular, using 'intuitive' classes for particles, data, ...
- D.o.f.: q and $\bar{q}$ (no gluons) and pseudoscalar mesons (π, K, η),
- Initial conditions: box, HIC, external input (PHSD),
- 'local' mean field (ρ fluctuations).

The Nambu-Jona-Lasinio model

Lagrangian:

$$\mathscr{L}_{NJL} = \bar{\psi}\left(i\partial\!\!\!/ - m_0\right)\psi + G\sum_{a=0}^{8}\left[(\bar{\psi}\lambda^a\psi)^2 + (\bar{\psi}i\gamma_5\lambda^a\psi)^2\right] - K\left[\det\bar{\psi}\left(1-\gamma_5\right)\psi + \det\bar{\psi}\left(1+\gamma_5\right)\psi\right]$$

- Chiral model for $q/\bar{q}$,
- QCD symmetries,
- hadrons construction,
- Finite (T, μ).



Quark mass:

$$m_i = m_{0i} - 4G\langle(\bar{\psi}_i\psi_i)\rangle + 2K\langle(\bar{\psi}_j\psi_j)\rangle\langle(\bar{\psi}_k\psi_k)\rangle$$

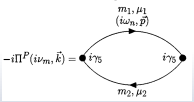
Chiral condensate:

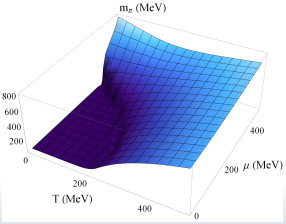
$$\langle(\bar{\psi}_i\psi_i)\rangle = -2N_c\int_0^{\Lambda}\frac{d^3p}{(2\pi)^3}\frac{m_i}{E_{i\mathbf{p}}}[1-f_q-f_{\bar{q}}]$$

Meson mass:

$$\frac{-ig^2_{\pi q\bar{q}}}{k^2-M^2} = \frac{2iG}{1-2G\,\Pi(k)}$$

Polar. loop:

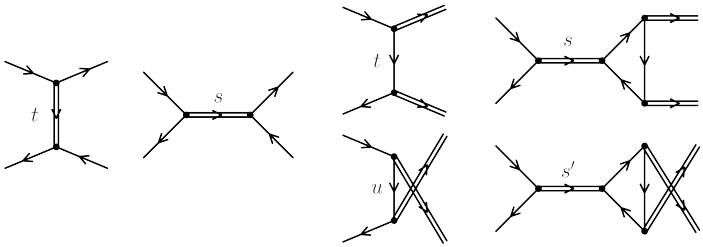




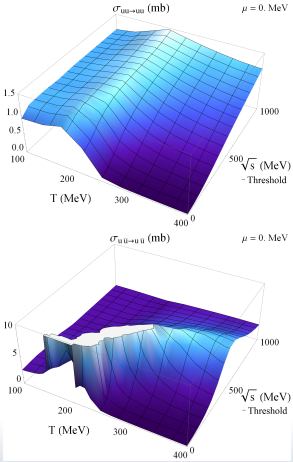
Based on PRC 87, 034912 (2013)

NJL cross sections

Leading order processes (NJL → no gluons !):

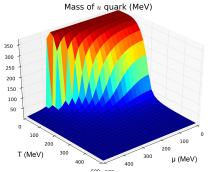


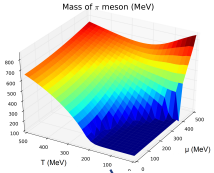
$q\ \bar{q} \to q\ \bar{q}$ $\qquad$ $q\ \bar{q} \to M\ M$

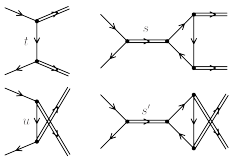


Based on PRD 51, 3728 (1995)

New relativistic dynamics







- $qq(\bar{q}) \leftrightarrow qq(\bar{q})$,
- $q\bar{q} \leftrightarrow MM$,
- $M \rightarrow q\bar{q}$.

$$\frac{\mathrm{d}q_i^\mu}{\mathrm{d}\tau} = \frac{p_i^\mu}{E_i}$$

$$\frac{\mathrm{d}p_i^\mu}{\mathrm{d}\tau} = -\sum_{k=1}^{N} \frac{m_k}{E_k} \frac{\partial m_k}{\partial q_{i\,\mu}} + \langle \text{collisions} \rangle$$

NJL masses and cross sections enter in the propagation equations.
Wigner (Gaussian) distribution in phase-space for particles $f(\vec{q}_i, \vec{p}_i, \tau)$.

(**PRC C87, 034912 (2013)**)

Local mean field

Local densities :

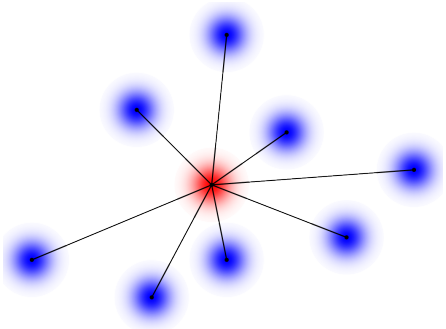
3D-probability that i feels j

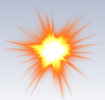
$$R_{ij} = \left(\frac{1}{\sqrt{\pi}L}\right)^3 \exp\left(-\frac{\Delta r_{ij}^2}{L^2}\right)$$

we *define*

$$\rho_{Fi} = \int (f_q + f_{\bar{q}}) d^3p \equiv \sum_{i \neq j} R_{ij}$$

$$\rho_{Bi} = \int (f_q - f_{\bar{q}}) d^3p \equiv \sum_{i \neq j} R_{ij}\ \mathrm{Sign}(j)$$





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Local potentials :

Thermodynamics gives :

$$T_i = (\hbar c)\left(\frac{\pi^2}{g\kappa}\right)^{1/3} {\rho_F}_i^{1/3} \qquad (\text{for } \mu \to 0)$$

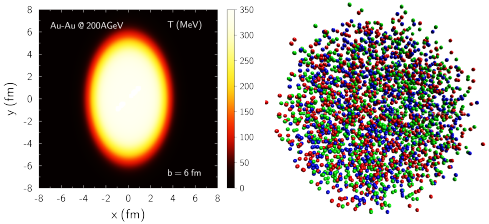
$$\mu_i = (\hbar c)\left(\frac{6\pi^2}{g\kappa}\right)^{1/3} {\rho_B}_i^{1/3} \qquad (\text{for } T \to 0)$$

$\kappa \approx 0.9$ comes from Fermi integral.

In equilibrium (box + large N) $\to$ not sensitive to L anymore !

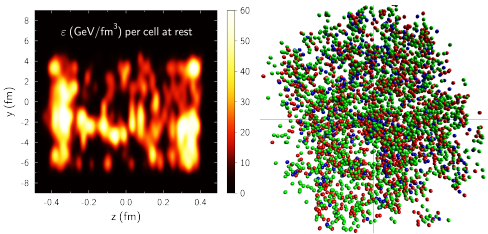
Comparison

Before (RSP + toy model)



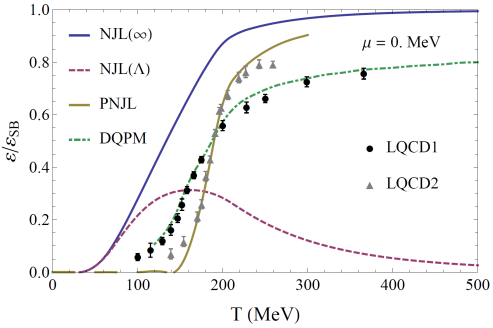
- Pancake shape $\rightarrow$ z-contracted,
- $(A, b) \rightarrow (x, y)$, $\sqrt{s} \rightarrow T_0$,
- $\vec{p}$ for thermal equilibrium.

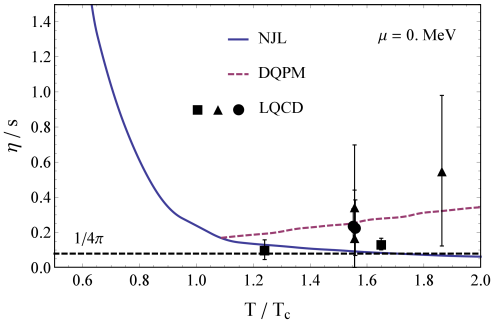
Now (RSP + PHSD)



- energy density per cell from PHSD (+ fluid velocity + flavor mixing),
- conversion to partons using NJL/DQPM **equations of state**.

Equations of state and viscosity



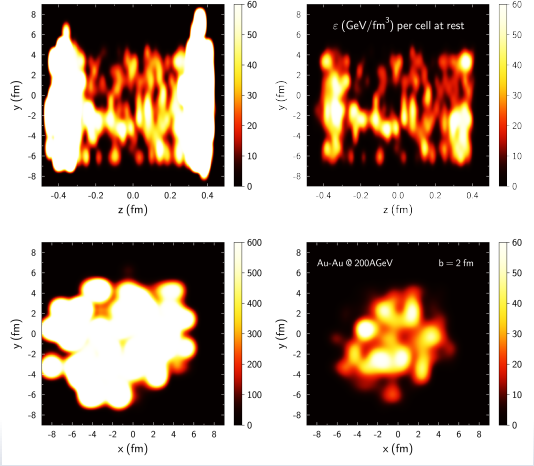


Many models = many equations of state

η/s in NJL is close to lQCD data !

(**arXiv:1305.7180 [hep-ph]**)

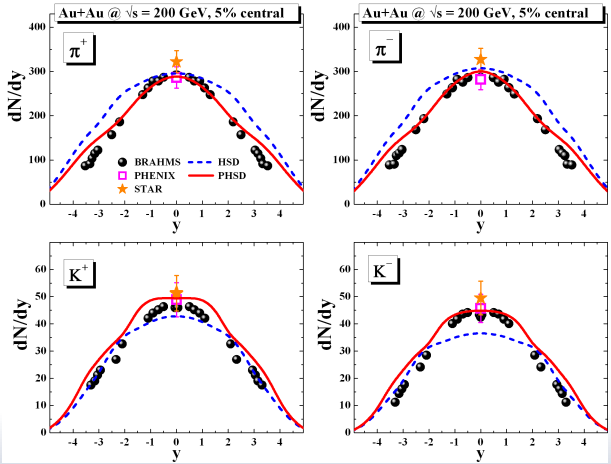
PHSD initial conditions

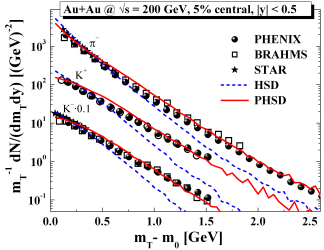


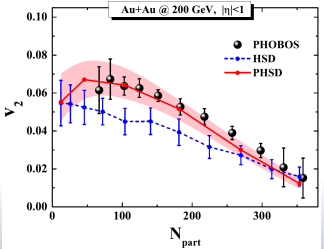
global **at rest**

PHSD results

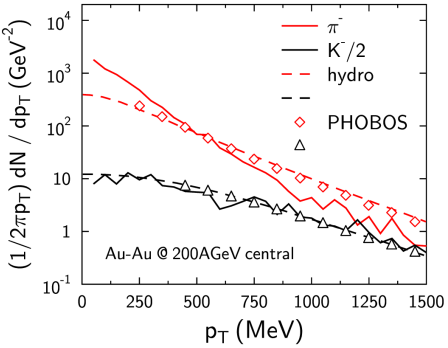
(NPA 856, 162 (2011))

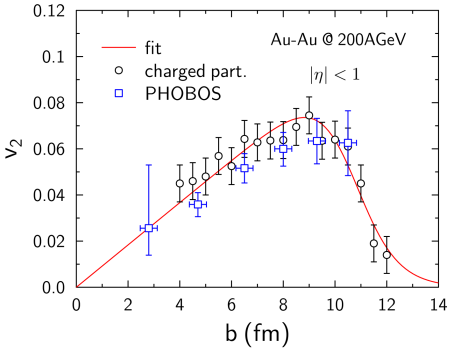






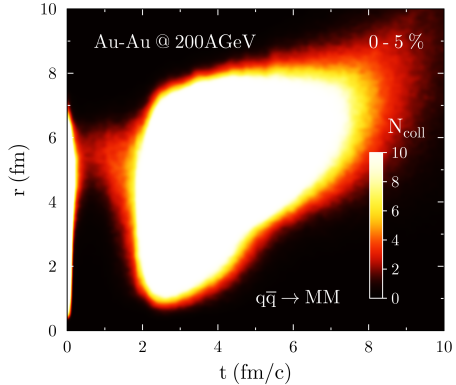
RSP + toy model

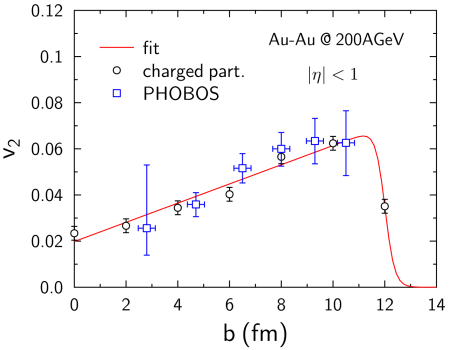




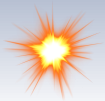
(**PRC C87, 034912 (2013)**)

RSP + PHSD





(**PRC, *in preparation***)



Conclusion

- The NJL model provide a good framework to describe QGP around the critical temperature and allows for a **dynamical description** of the phase transition from a partonic medium to an hadron gaz,
- Using the PHSD initial conditions (knowing that they reproduce RHIC data) give us a good starting point with enough **granularity and fluctuations** in order to test event-by-event simulations,
- The PHSD to RSP conversion is still **under development** (distinguish leading baryons and quark gluon plasma, high baryonic density area).

Then

- First order phase transition for large baryonic densities (FAIR/NICA),
- Polyakov extended NJL model for better equation of state,
- More results ! dN/dp_T, $dN/d\eta$, $v_2(p_T)$, $v_2(\eta)$, v_3, ...
- Work in progress, stay tuned !

PHSD Group:

- Elena Bratkovskaya,
- Wolfgang Cassing,
- Olena Linnyk,
- Volodya Konchakovski,
- Hamza, Berrehrah,
- Daniel Cabrera,
- Taesoo Song.

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- Che-Ming Ko,
- Jorg Aichelin,
- Mark I. Gorenstein,
- Viatcheslav D. Toneev,
- Vadym Voronyuk.

THANK YOU FOR YOUR ATTENTION !