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

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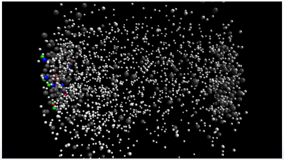
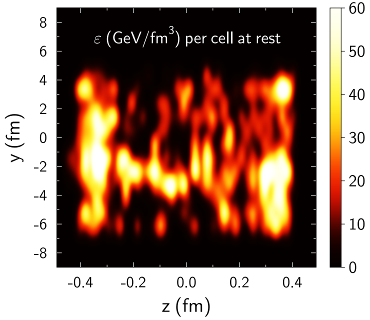
Motivations

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

What is the influence of **initial conditions** using two different approaches on the observables for RHIC energies ?
→ Effective models : **DQPM** & **NJL**





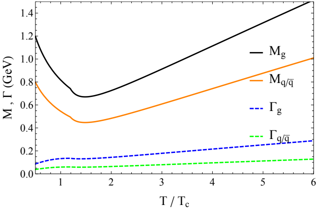
The Parton Hadron String Dynamics

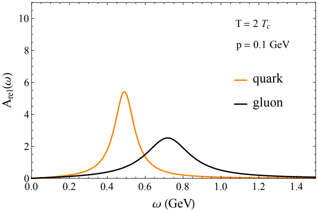
Features:

- 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:

$$M_g^2(T,\mu_q) = \frac{g^2}{6}\left(\left(N_c + \frac{N_f}{2}\right)T^2 + \frac{3}{2}\sum_q \frac{\mu_q^2}{\pi^2}\right)$$

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

Widths:

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

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

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:

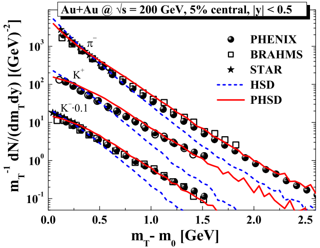
Breit-Wigner spectral function:

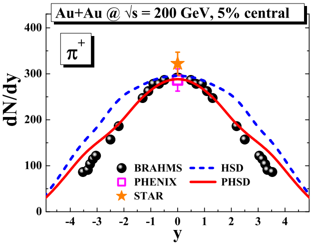
$$A(\omega,\mathbf{p}) = \frac{\Gamma}{E}\left(\frac{1}{(\omega-E)^2+\Gamma^2} - \frac{1}{(\omega+E)^2+\Gamma^2}\right)$$

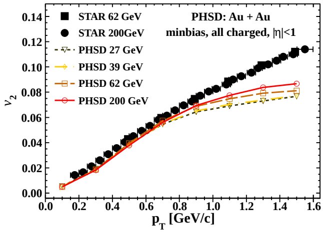
with $E^2 = \mathbf{p}^2 + M^2 - \Gamma^2$ and

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

Some results







(**NPA 856, 162 (2011)**) (**PRC 85, 044922 (2012)**)

A new code on the market

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

Features:

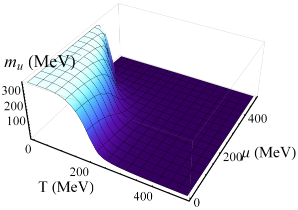
- **C++** code ∼5000 lines (modern and fully parallelizable),
- New relativistic quantum molecular dynamics (which is **causal** and **conserves energy**),
- **(P)NJL model** based dynamics with q and $\bar{q}$ degrees of freedom (no gluons) and pseudoscalar mesons (π, K, η),
- All masses m_i and cross sections $\sigma_{2\to 2}$ at finite (T, μ) for dynamical **cross over** or **phase transition**,
- **Local mean field** and relativistic quantum collisions (for fluctuations),
- Different possible initial conditions: box, toy model for heavy ion collisions, external input (e.g. PHSD).

The Nambu-Jona-Lasinio model

Lagrangian:

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

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



Quark mass:

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

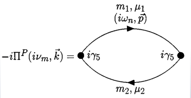
Chiral condensate:

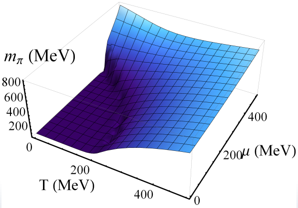
$$\langle\langle\bar{\psi}_i\psi_i\rangle\rangle = -2N_c\int_0^{\Lambda}\frac{d^3p}{(2\pi)^3}\,\frac{m_i}{E_{ip}}\,[1 - f_q - f_{\bar{q}}]$$

Meson mass:

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

Polar. loop:

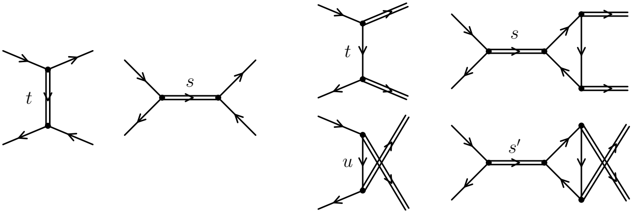




Based on **PRC 87, 034912 (2013)**

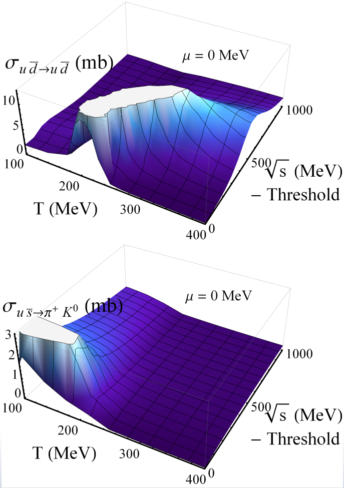
NJL cross sections

Leading order processes (NJL $\rightarrow$ no gluons !):



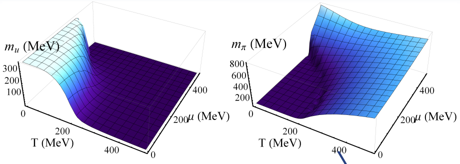
$q\ \bar{q} \rightarrow q\ \bar{q}$

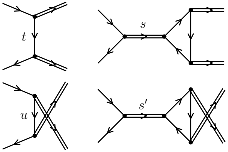
$q\ \bar{q} \rightarrow M\ M$



Based on **PRD 51, 3728 (1995)**

New relativistic dynamics





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

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

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

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 87, 034912 (2013)**)

Local mean field

Local densities :

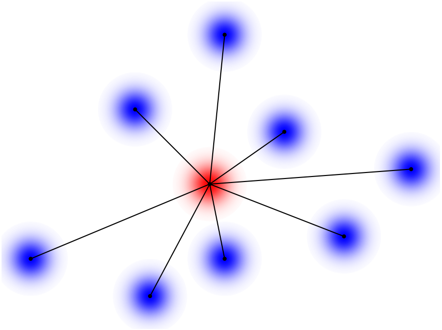
3D-probability that i feels j

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

we *define*

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

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



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Local potentials :

Thermodynamics gives :

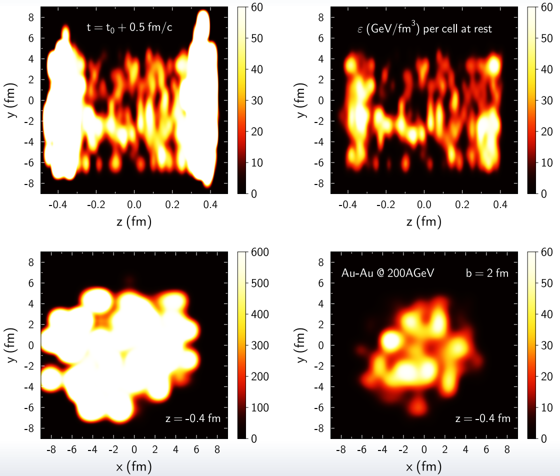
$$T_i = (\hbar c)\left(\frac{\pi^2}{g\kappa}\right)^{1/3} {\rho_F}_i^{1/3} \qquad (\text{for } \mu \to 0)$$

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

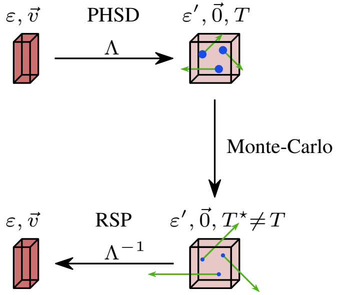
$\kappa \approx 0.9$ comes from Fermi integral.

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

PHSD initial conditions

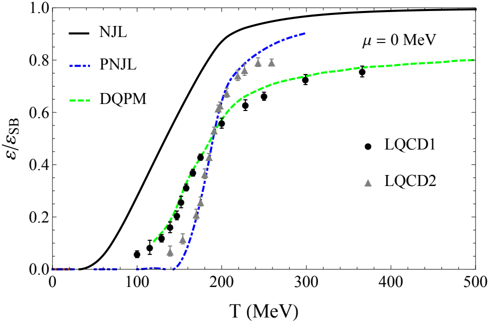


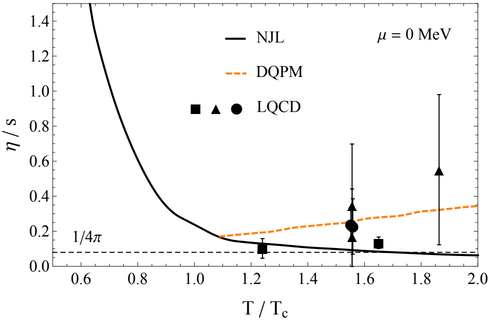
global system **cells at rest**



DQPM partons: heavy
NJL quarks: light

Equations of state and viscosity



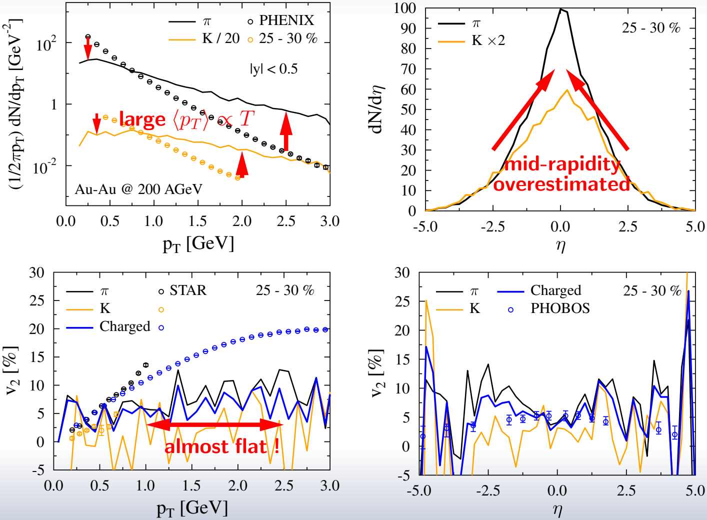


Many models = many equations of state
($T_{c\ NJL} \neq T_{c\ DQPM}$ and $\varepsilon_{SB\ NJL} \neq \varepsilon_{SB\ DQPM}$)

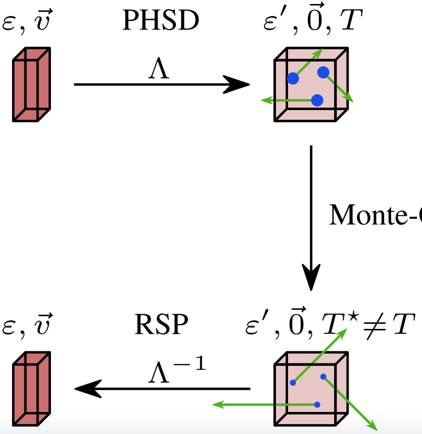
η/s in NJL is close to LQCD data !

(**PRC 88, 045204 (2013)**)

First results



Out of equilibrium conversion



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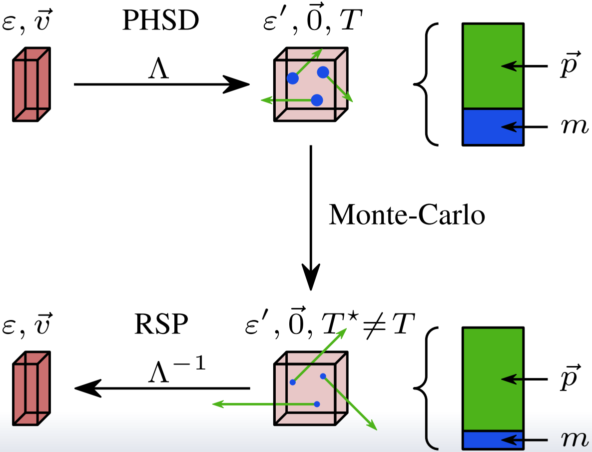

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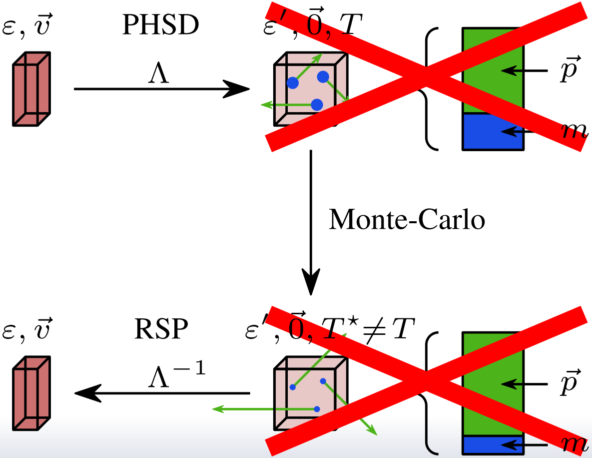

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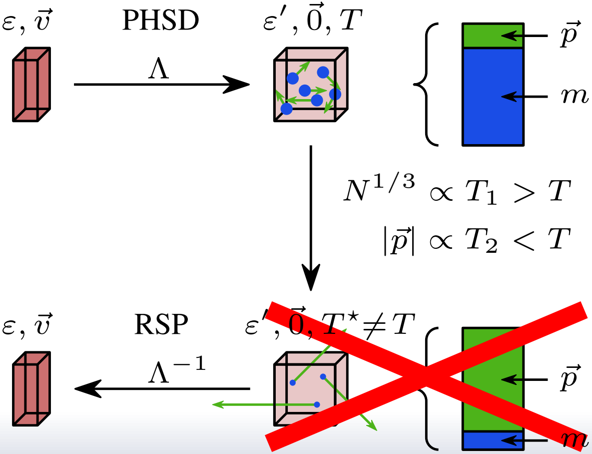
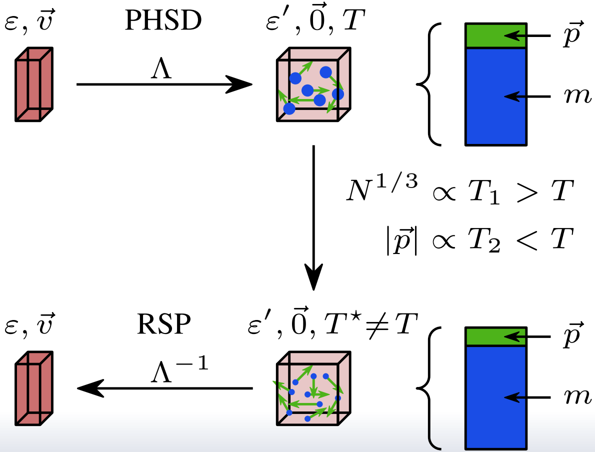
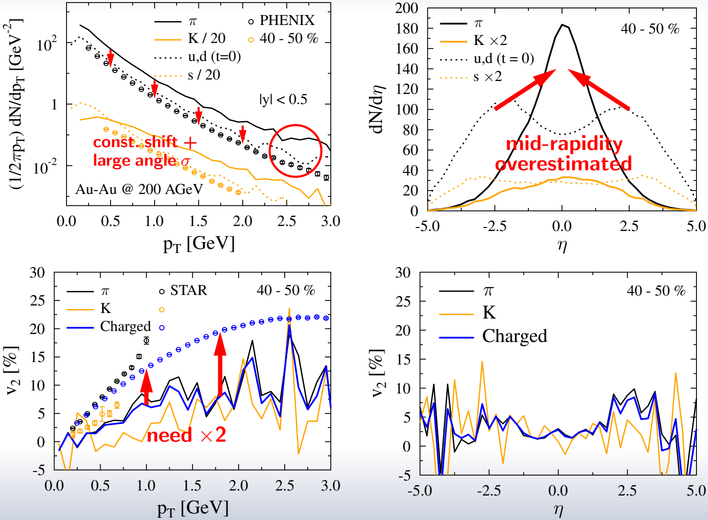


Out of equilibrium conversion

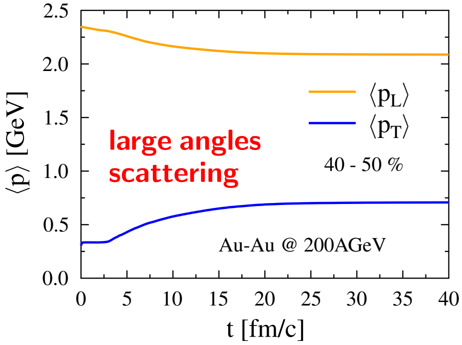


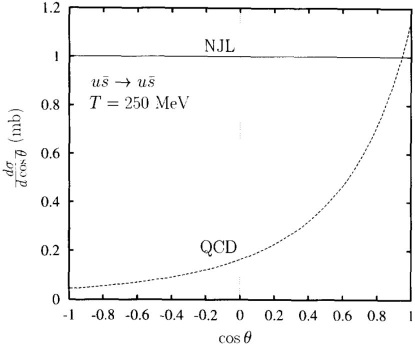
Results


(1/2πp_T) dN/dp_T [GeV^-2]
π
K / 20
u,d (t=0)
s / 20
PHENIX
40 - 50 %
|y| < 0.5
const. shift +
large angle σ
Au-Au @ 200 AGeV
p_T [GeV]
dN/dη
π
K ×2
u,d (t = 0)
s ×2
40 - 50 %
mid-rapidity
overestimated
η
v_2 [%]
π
K
Charged
STAR
40 - 50 %
need ×2
p_T [GeV]
v_2 [%]
π
K
Charged
40 - 50 %
η

Small angles scattering

(NPA 608, 356 (1996))





We need pQCD-like **small angles scattering** !

Conclusion

The main messages:

- The **NJL model** provides 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 a hadron gaz,
- Using the **PHSD initial conditions** (knowing that they reproduce RHIC data) gives us a good starting point with enough **granularity and fluctuations** in order to test event-by-event simulations,
- Out of equilibrium conversion from one model to another is **possible** knowing the equations of state in equilibrium,
- Initial cells at rest are **not in thermal equilibrium** nor in chemical equilibrium ($\langle m\rangle/\langle E\rangle$ ratio, $T(\varepsilon) \neq T^{\star}(\langle|\vec{p}|\rangle)$).

Then ?

- Try first order phase transition for large baryonic densities (FAIR/NICA),
- Use Polyakov extended NJL model for better equation of state,
- ...

PHSD Group:

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- Olena Linnyk,
- Volodya Konchakovski,
- Hamza, Berrehrah,
- Daniel Cabrera,
- Taesoo Song.

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

THANK YOU FOR YOUR ATTENTION !

System evolution