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

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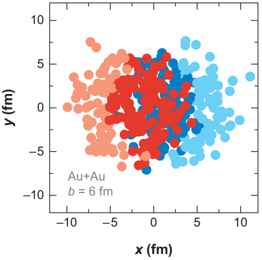
FIAS Frankfurt Institute for Advanced Studies

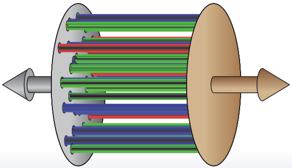
HIC for FAIR
Helmholtz International Center

Motivations

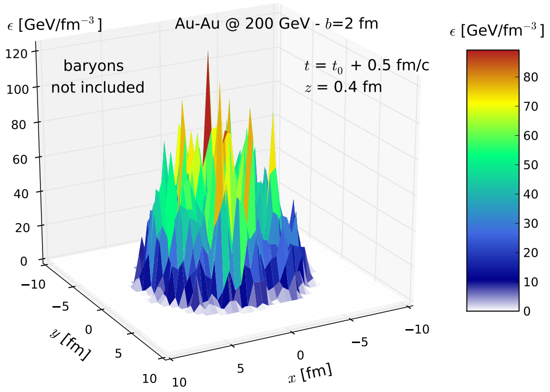
Initial conditions in heavy ion collisions are highly debated topics. The more common description is the **string** picture for the initial distribution. (e.g. Lund strings, PYTHIA, IP-Glasma), but then, what do we do with particles/energy ?

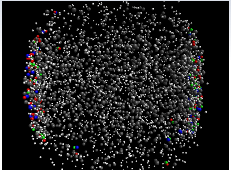
- Can we give some constraints on the particle distribution from these strings ?
- Can all the initial conditions give physical results ?
- Can we apply equilibrium assumptions from initial state ?





Motivations





We have two transport codes : **PHSD** & **RSP** including respectively two models **DQPM** & **NJL** for the **microscopic description** of the partonic phase and the phase transition.

What are the results when one starts with the same initial condition profile ? What can we learn from this ?

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:

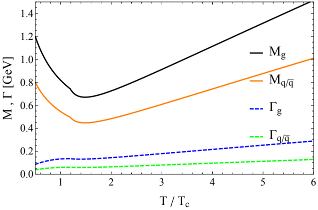
$$\Gamma_g(T) = \frac{1}{3}N_c\frac{g^2T}{8\pi}\ln\left(\frac{2c}{g^2}+1\right),$$

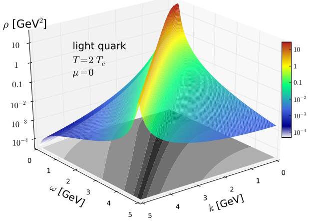
$$\Gamma_{q/\bar{q}}(T) = \frac{1}{3}\frac{N_c^2-1}{2N_c}\frac{g^2T}{8\pi}\ln\left(\frac{2c}{g^2}+1\right),$$

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:

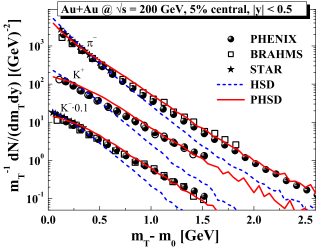
$$\rho(\omega,\mathbf{k}) = \frac{\Gamma}{E}\left(\frac{1}{(\omega-E)^2+\Gamma^2} - \frac{1}{(\omega+E)^2+\Gamma^2}\right)$$

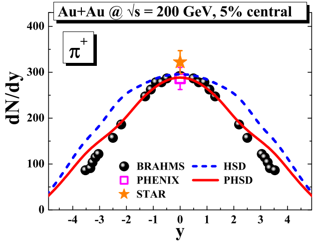
with $E^2 = \mathbf{p}^2 + M^2 - \Gamma^2$ and

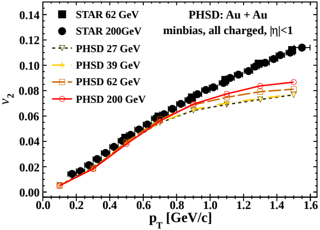
$$\int_{-\infty}^{\infty}\frac{d\omega}{2\pi}\,\omega\rho(\omega,\mathbf{k}) = \int_0^{\infty}\frac{d\omega}{2\pi}\,2\omega\rho(\omega,\mathbf{k}) = 1$$

Some results

PHSD initial conditions + DQPM = good agreement with data







(**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

RSP

Features:

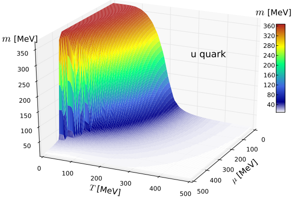
- **C++** code ∼6000 lines,
- New relativistic quantum molecular dynamics (which is **causal** and **conserves energy**),
- **(P)NJL model** based dynamics with q and $\bar{q}$ degrees of freedom (no gluons) and pseudoscalar mesons (π, K, η),
- All masses m_i and cross sections $\sigma_{2\to 2}$ at finite (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:

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

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



Quark mass:

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

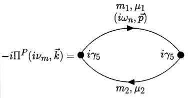
Chiral condensate:

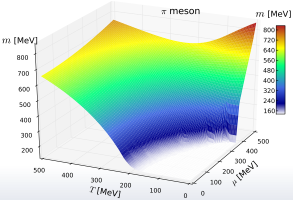
$$\langle\langle\bar{\psi}_i\psi_i\rangle\rangle = -2N_c\int_0^{\Lambda}\frac{d^3p}{(2\pi)^3}\frac{m_i}{E_{ip}}\left[1 - f_q - f_{\bar{q}}\right]$$

Meson mass:

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

Polar. loop:

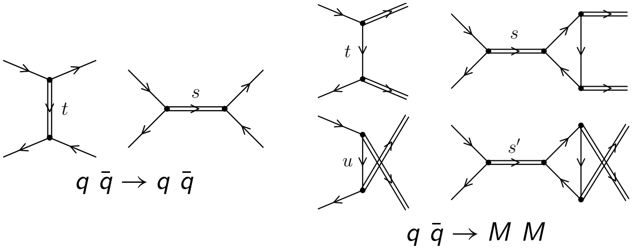


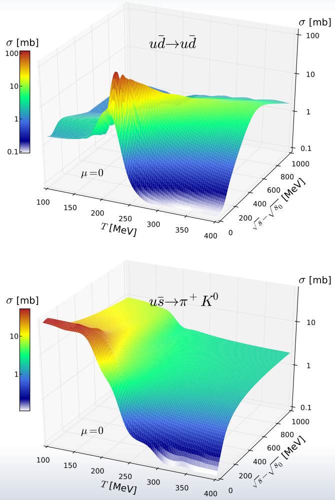


Based on **PRC 87, 034912 (2013)**

NJL cross sections

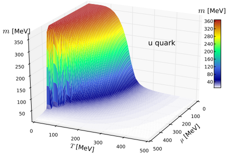
Leading order processes (NJL → no gluons !):

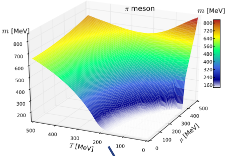


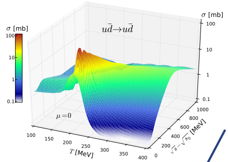


Based on **PRD 51, 3728 (1995)**

New relativistic dynamics







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

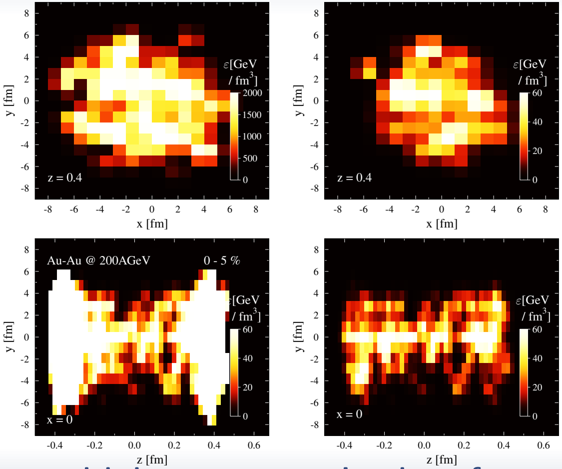
$$\frac{\mathrm{d}q_i^\mu}{\mathrm{d}\tau} = \frac{p_i^\mu}{E_i}$$

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

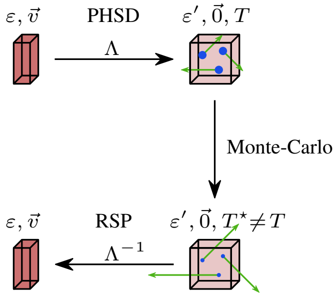
NJL masses and cross sections enter in the propagation equations.
Wigner (Gaussian) distribution in phase-space for particles $f(\vec{q}_i, \vec{p}_i, \tau)$.

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

PHSD initial conditions

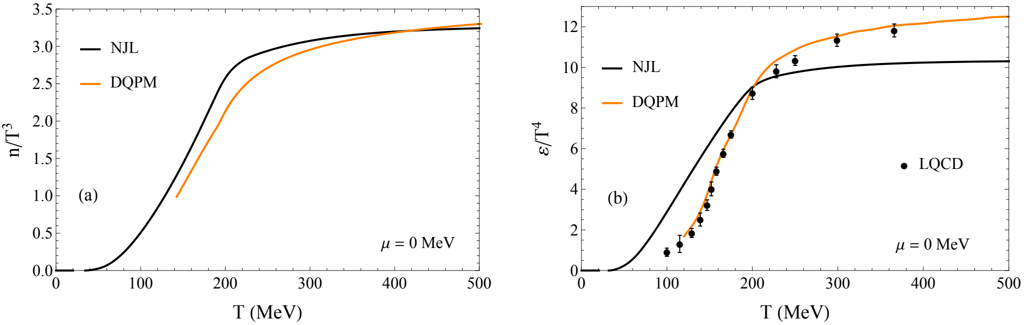


global system — **Local rest frame**



DQPM partons: **heavy**
NJL quarks: **light**

Equations of state

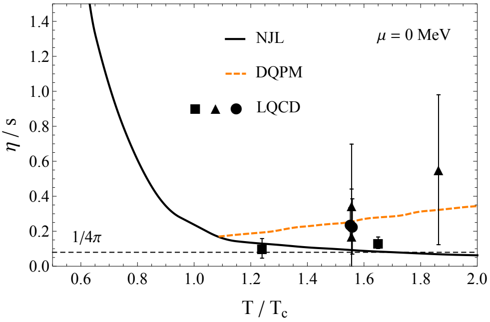


for n, NJL and DQPM are close

large difference in ε: no gluons in NJL

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

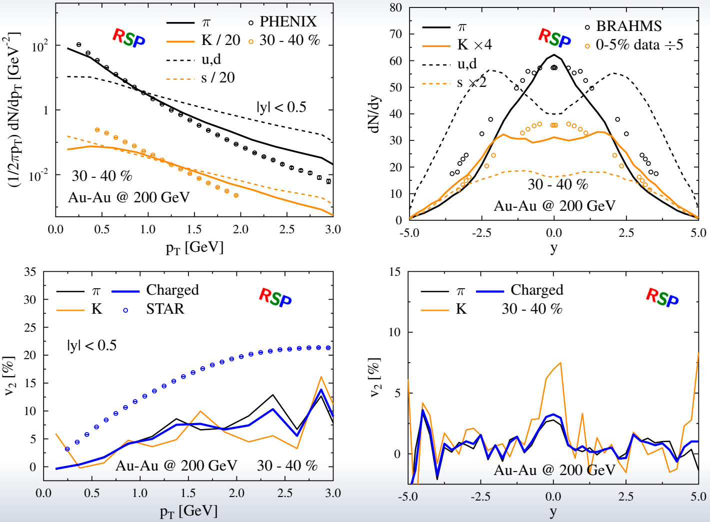
Shear viscosity



η/s in NJL is close to LQCD data around T_c !

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

First results of RSP



Assumptions

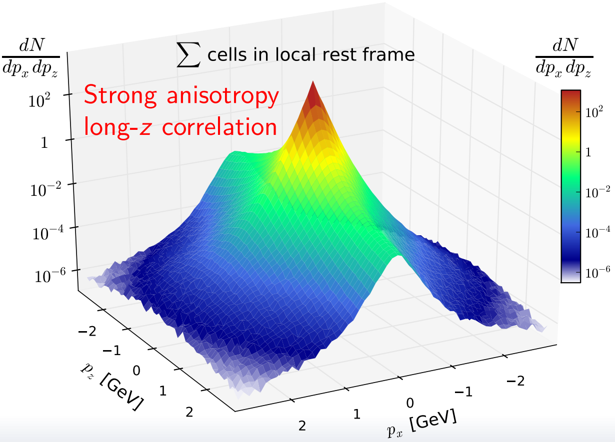
We had hard spectrum for p_T distribution,
and a too small number of final particles.
We suspected a **problem with the conversion**.

We assumed **equilibrium in a cell**, which could mean:

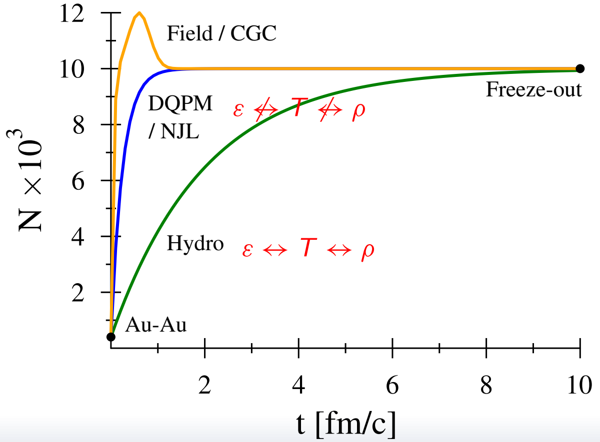
- thermal isotropic momentum distribution: $f(E) = e^{-E/T}$
- chemical balance of species $q, \bar{q}$ (not used, we keeped initial ratio)
- respect equation of state: $\varepsilon \leftrightarrow T \leftrightarrow \rho$

Is that really the case ?

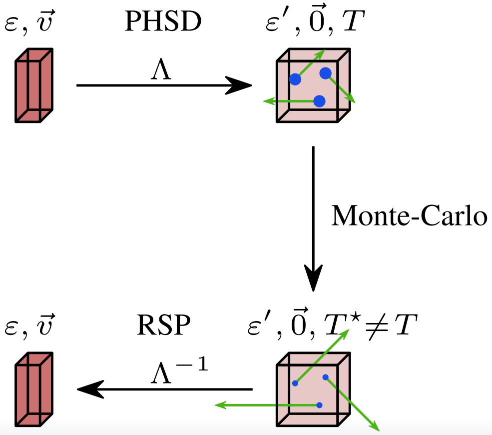
Momentum distribution



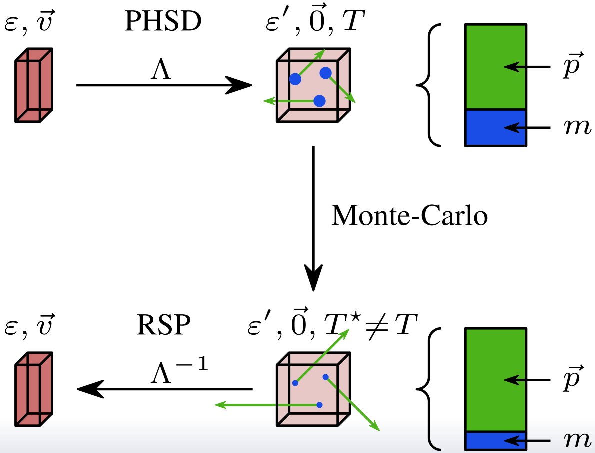
Initial multiplicity



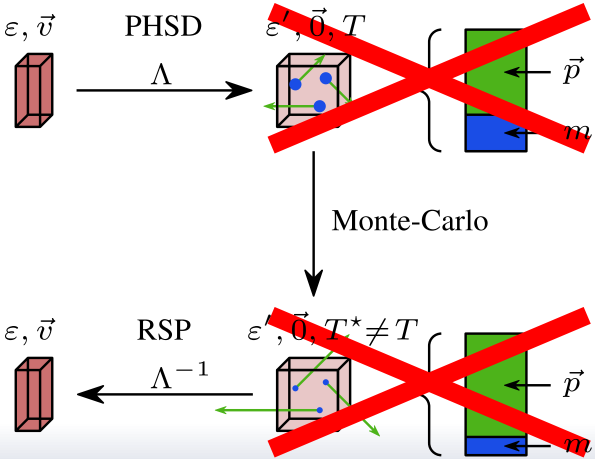
Out of equilibrium conversion



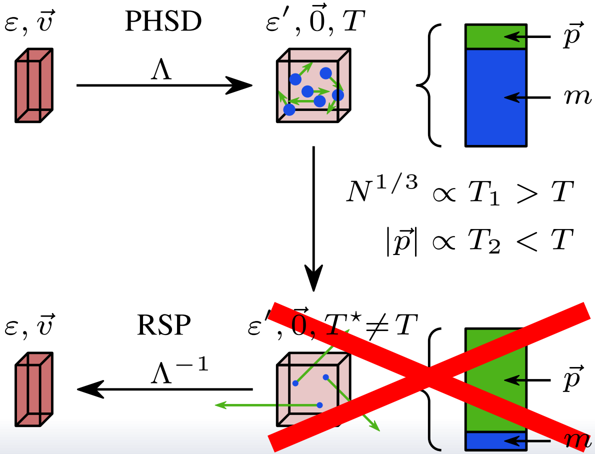
Out of equilibrium conversion



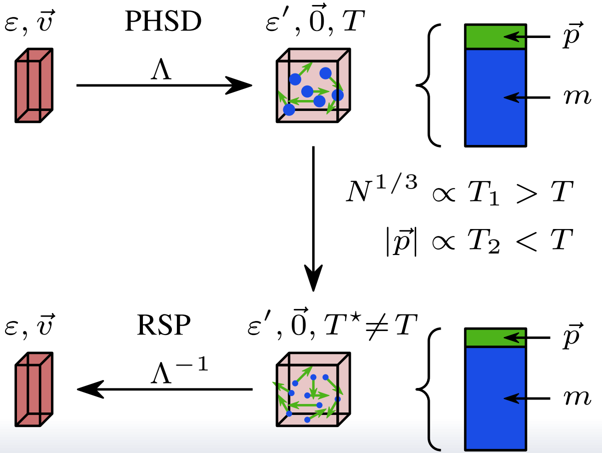
Out of equilibrium conversion



Out of equilibrium conversion



Out of equilibrium conversion



Out of equilibrium conversion

Deviation from equilibrium $f_{eq} \to f'$
From PHSD initial conditions, we see that we have:

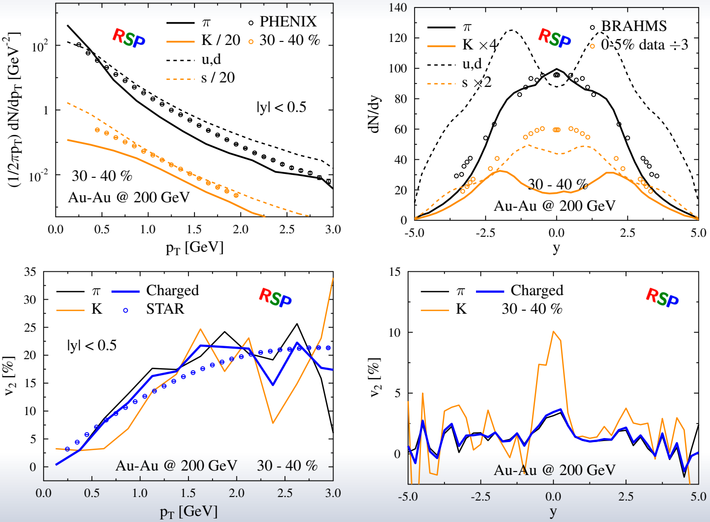
$$n' = \int_0^\infty \alpha f_{eq}(p)\ d^3p = \alpha n,$$

$$\varepsilon' = \int_0^\infty \alpha^{-1} p\ \alpha f_{eq}(p)\ d^3p = \varepsilon.$$

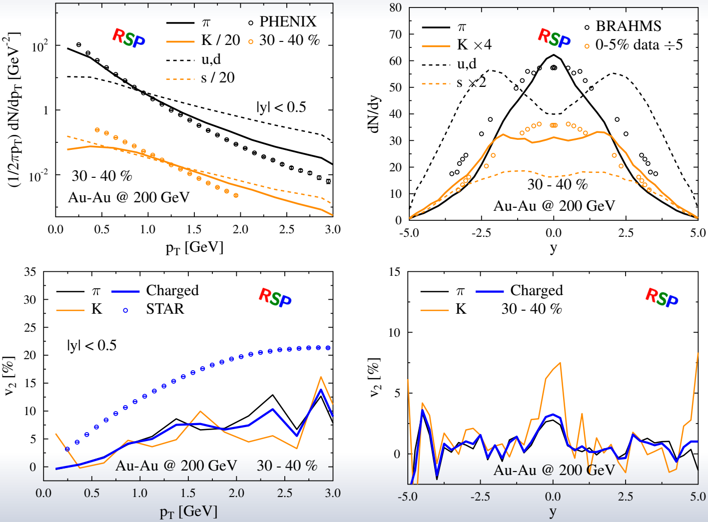
using DQPM EoS: $\varepsilon \to T_1$ and $n \to T_2$, but
we figured out that $T_1 \neq T_2$ because $\alpha \neq 1$!
We can compute the **shift from equilibrium** $\alpha^{1/3} = T_2/T_1$.

Then from NJL equation of state we have $\varepsilon \to T_1^\star$, and
we apply the same strategy for density and momentum Monte-Carlo.

RSP results


RSP
π
K / 20
u,d
s / 20
PHENIX
30 - 40 %
|y| < 0.5
30 - 40 %
Au-Au @ 200 GeV
$(1/2\pi p_T)\, dN/dp_T$ [GeV^{-2}]
p_T [GeV]
RSP
π
K ×4
u,d
s ×2
BRAHMS
0-5% data ÷3
30 - 40 %
Au-Au @ 200 GeV
dN/dy
y
π
K
Charged
STAR
RSP
|y| < 0.5
Au-Au @ 200 GeV
30 - 40 %
v_2 [%]
p_T [GeV]
π
K
Charged
30 - 40 %
RSP
Au-Au @ 200 GeV
v_2 [%]
y

RSP results before



Conclusion

The main messages:

- The **NJL model** provides a framework to describe QGP around T_c and allows for a **dynamical description** of the phase transition from $q, \bar{q}$ to hadrons,
- Using the **PHSD initial conditions** gives us a good starting point with **granularity and fluctuations** including **out-of-equilibrium** plasma,
- From the initial strings melting, the cells are **far from thermal equilibrium** ($T_1(\varepsilon) \neq T_2(n)$, and momentum anisotropy),
- **Out of equilibrium conversion** from one model to another is possible knowing the equations of state in equilibrium.

and then ?

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

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- Daniel Cabrera,
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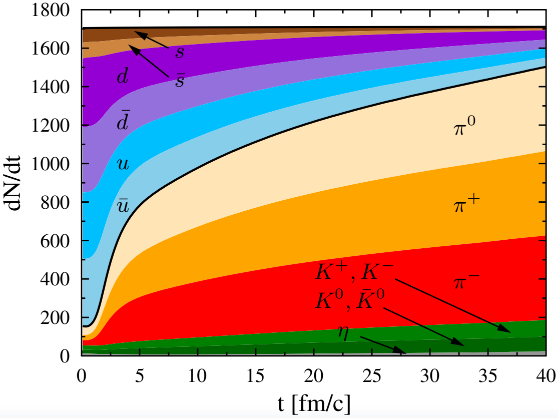
- Mark I. Gorenstein,
- Viatcheslav D. Toneev,
- Vadym Voronyuk.

THANK YOU FOR YOUR ATTENTION !

System evolution



Collisions distribution