Dynamical Thermalization in Heavy-Ion Collisions

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Atelier Physique Théorique des deux infinis

7-8 Jun 2021

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  - Heavy-ion collision Models
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From QCD to QGP:

- At low T_c and low μ_B → Hadronic gas
- At low T_c and high μ_B → gas of neutron
- For $T_c > 175 MeV$ → QGP
- At high T_c and $\mu_B \rightarrow 0$, Big Bang

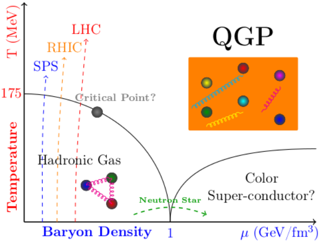


Figure: Phase diagram of nuclear matter [1].

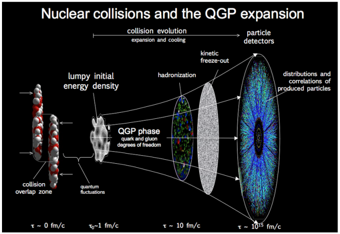


Figure: Space-time evolution of HIC.

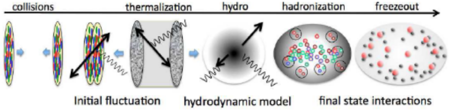
Current Accelerators:

- SPS & LHC, CERN
- RHIC, BNL, New York

Future Accelerators:

- FAIR, Germany
- NICA, Russia

Heavy-Ion Collisions
Bjorken Scenario



EPOS: Energy conserving multiple scattering Partons, parton ladder and strings Off-shell remnantes Saturation [2, 3].

- INITIAL CONDITION: A Gribov-Regge multiple scattering approach is employed (PBGRT).
- CORE-CORONA SEPARATION: based on momentum and density of string segments.
- VISCOUS HYDRODYNAMIC EXPANSION: Using core part and cross-over equation of state (EOS) compatible with lattice QCD.
- STATISTICAL HADRONIZATION: employing Cooper-Frye procedure and equilibrium hadron distribution.
- FINAL STATE HADRONIC CASCADE: applying the UrQMD model.

PHSD: Parton Hadron String Dynamics [4, 5].

- INITIAL A+A COLLISION: leads to formation of strings that decays to pre-hadrons, done by PYTHIA.
- QGP FORMATION: based on local energy-density.
- QGP STAGE: evolution based on off-shell transport eqs. derived by Kadanoff-Baym eqs. with the DQPM defining the parton spectral function i.e. masses and widths.
- HADRONIZATION: massive off-shell partons with broad spectral functions hadronize to off-shell baryons and mesons.
- HADRONIC PHASE: evolution based on the off-shell transport eqs. with hadron-hadron interaction.

Purpose: We endeavor to employ a sophisticated EPOS approach to determine the initial distribution of matter (partons/hadrons) and then use PHSD for the evolution of matter in a non-equilibrium transport approach.

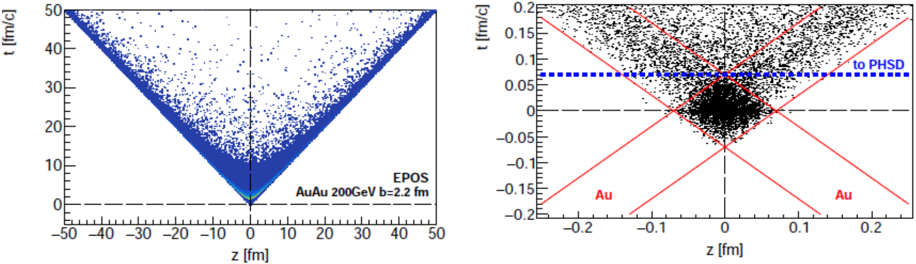
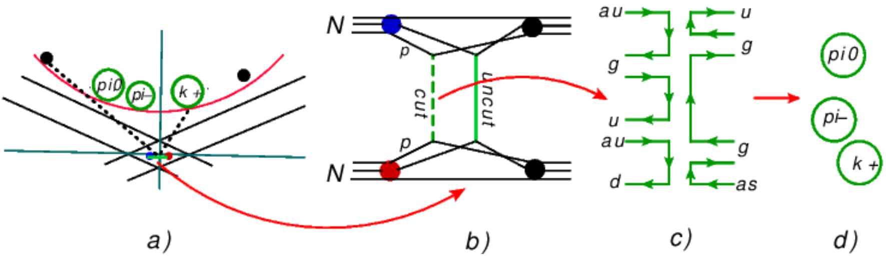


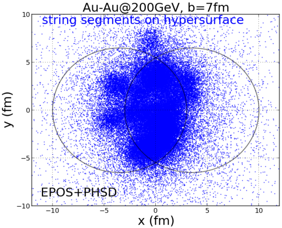
Figure: EPOS particles production hyper-surface initial condition for PHSD model. Zero time corresponds to maximum overlapping.

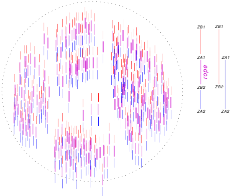
Initial Condition in EPOS:

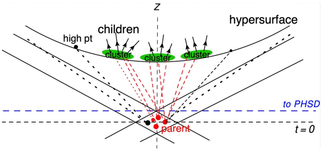
Parton Based Gribov Regge Theory (PBGRT) [6]:

- Hard/Soft processes, Energy conservation by multiple Pomeron exchange
- Calculation of elastic/inelastic Cross-Sections (uncut ladder, soft contribution)
- Particle production [7] (cut ladder, semi-hard/hard contribution)



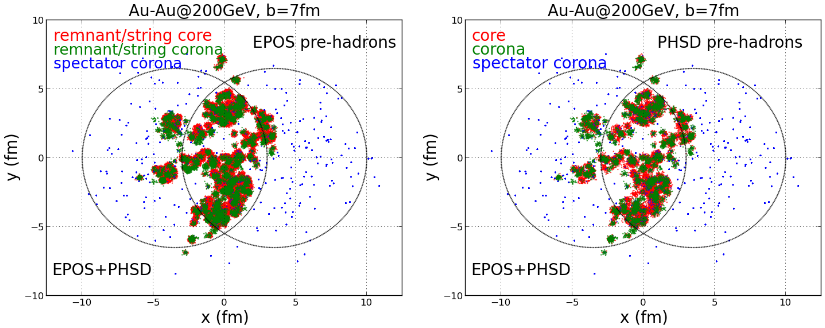






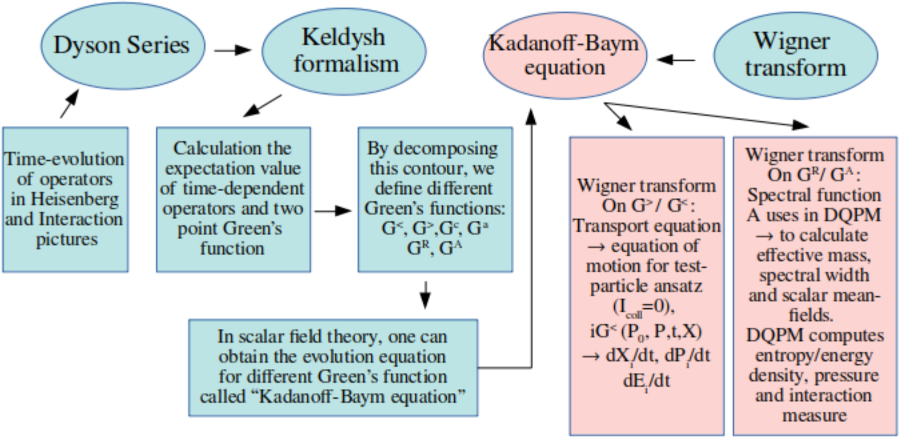
- projectile+target → pomerons → string segments → core/corona part → rope segments → core/corona pre-hadrons
- rope segments: longitudinal color field, consider in 3D, larger string tension and transverse momentum.
- core pre-hadrons : decay of rope segments/clusters based on Microcanonical treatment.
- The principle problem: EPOS uses light-cone dynamics, PHSD uses real-time dynamics.

EPOS+PHSD overview



EPOS pre-hadrons are inserted into PHSD arrays with energy density ($> 0.5 GeV/fm^3$) condition.

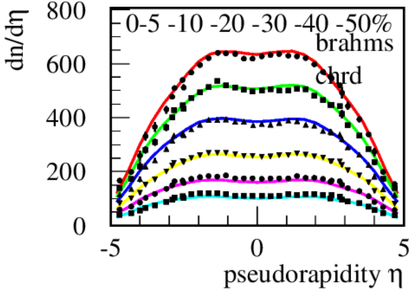
Nonequilibrium Quantum Field Theory in PHSD



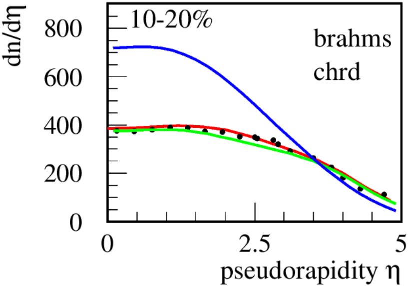
RESULTS

Comparing the
Particle Production, Elliptic Flow (v_2), Transverse Momentum (p_T) and Transverse Mass (m_T) for Au-Au@200GeV
With different simulations:
EPOS+PHSD, EPOS+hydro, EPOS-hydro, pure PHSD

Particle Production:
Au-Au@200GeV



(a) EPOS+PHSD



(b) EPOS+PHSD, EPOS+hydro
EPOS-hydro

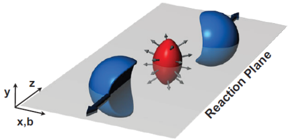
Good agreement to the real DATA ✓

Elliptic Flow v_2:

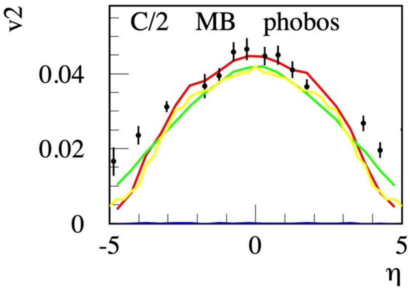
$E\frac{d^3N}{d^3p} = \frac{1}{2\pi}\frac{d^2N}{p_t dp_t dy}(1 + \sum_{n=1}^{\infty} 2v_n cos(n(\phi - \Psi_{RP})))$

$v_n(p_t, y) = < cos(n(\phi - \Psi_{RP})) >$, v_2 = elliptic flow,

Ψ_{RP} =reaction plane angle [8].



Au-Au@200GeV



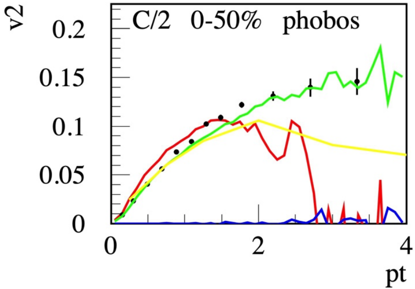


Figure: EPOS+PHSD, EPOS+hydro, EPOS-hydro, pure PHSD

EPOS+PHSD reproduced well the data for low p_T ✓

Transverse Momentum and Transverse Mass: Au-Au@200GeV

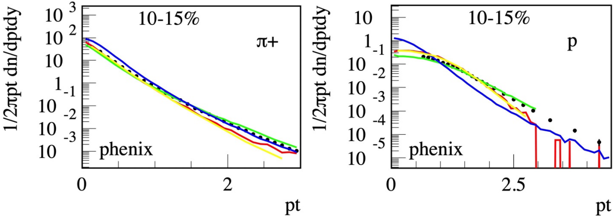


Figure: EPOS+PHSD, EPOS+hydro, EPOS-hydro, pure PHSD

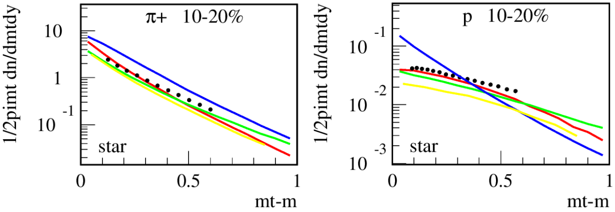


Figure: EPOS+PHSD, EPOS+hydro, EPOS-hydro, pure PHSD

Summary and Conclusion:

- The project done to merge the two models commenting the issue of different framework (Milne coordinates and Minkowski space-time).
- Comparison of space-time evolution by EPOS+PHSD with EPOS+hydro also EPOS-hydro and pure PHSD.
- Considering observables like charged particles production, v_2, p_T, m_T. High p_T has not been improved yet by EPOS+PHSD.

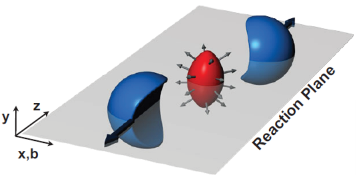
Outlook:

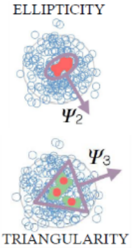
- Comparison EPOS+PHSD with different range energies from RHIC to LHC for various systems like p-p and Au-Au collisions.
- Investigation of other "flow behaviors"; v_n =1; 3; 4; ...
- Investigation of electromagnetic probes, photon and dilepton production.
- Checking heavy flavor particles behavior
- Checking EPOS(+hydo)+PHSD to study the high pt part

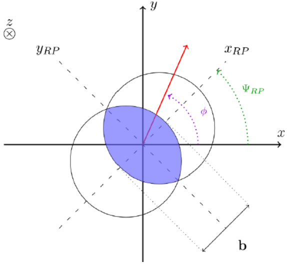

thanks for your time

Appendix

Anistropic radial Flow (Depends on Initial State Fluctuation):
Fourier expansion:
$E\frac{d^3N}{d^3p} = \frac{1}{2\pi}\frac{d^2N}{p_t dp_t dy}(1 + \sum_{n=1}^{\infty} 2v_n cos(n(\phi - \Psi_{RP})))$
$v_n(p_t, y) =< cos(n(\phi - \Psi_{RP})) >$, v_1 =directed flow, v_2 = elliptic flow, v_3 =triangle flow, Ψ_{RP} =reaction plane angle







PHSD group:

Figure: https://theory.gsi.de/ ebratkov/phsd-project/PHSD/index5.html

QGP phase in PHSD

To investigate the dynamics and properties of the medium, one can employ the transport equation and spectral function:

- Using spectral function A in DQPM [9]:
  $A(p) = \frac{2\gamma p_0}{(p^\mu p_\mu - M^2)^2 + 4\gamma^2 p_0^2}, \qquad \tilde{\Gamma} = 2\gamma p_0, \qquad M^2 = m^2 + Re\tilde{\sum}^R$
  To have Masses M^2 and widths γ of partons.
- Entropy density s^{dqp} is a grandcanonical quantity in DQPM which leads to measure the pressure $s = \frac{\partial P}{\partial T}$, energy density $\epsilon = Ts - P$, interaction measure $W(T) = \epsilon(T) - 3P(T)$ and scalar mean-field $U_s(\rho_s) = \frac{dV_p(\rho_s)}{d\rho_s}$

- Generalized transport equation [10]:
  $\frac{1}{2}\bar{A}\bar{\Gamma}[\{\bar{M}, iG^{<}\} - \frac{1}{\bar{\Gamma}}\{\bar{\Gamma}, \bar{M}.iG^{<}\}] = i\bar{\sum}^{<} i\bar{G}^{>} - \bar{\sum}^{>} i\bar{G}^{<}$
  $\bar{A}$ =spectral function, $\bar{\Gamma}$ =Width, $\bar{M}$ = mass function in Wigner-space, $\bar{\sum}$ =self-energy
  Collision term = $i\bar{\sum}^{<} i\bar{G}^{>} - \bar{\sum}^{>} i\bar{G}^{<}$
- Employing the test-particle Ansatz
  $iG^{<}(P_0, P, t, X) \approx \sum_{i=1}^{N} \frac{1}{2P_0} \delta^{(3)}(X - X_i(t))\delta^{(3)}(P - P_i(t))\delta(P_0 - \epsilon_i(t))$
  to transport equation → derive the equation of motion by neglecting the collision term → $dX_i/dt, dP_i/dt, d\epsilon_i/dt$, obtain the coordinates, momentum and energy of particles in time t.
- Hadronization:
  As the system expands and cools down, the energy density drops until hadronization occurs. The colored off-shell partons with broad spectral function are combined into off-shell colorless hadrons.

- Masses and widths of quarks/antiquarks and gluons in DQPM:
$M_g^2(T) = \frac{g^2}{6}[(N_c + \frac{1}{2}N_f)T^2 + \frac{1}{2}\sum_g \frac{\mu_q^2}{\pi^2}], \quad \gamma_g(T) = N_c \frac{g^2 T}{8\pi} ln\frac{2c}{g^2}$
$M_{q/\bar{q}}^2(T) = \frac{N_c^2-1}{8N_c} g^2[T^2 + \frac{\mu_{q/\bar{q}}^2}{\pi^2}], \quad \gamma_{q/\bar{q}}(T) = \frac{N_c^2-1}{2N_c}\frac{g^2 T}{8\pi} ln\frac{2c}{g^2}$
$g^2(T/T_c)$ =running coupling, μ=chemicl potential, N_c, N_f : Number of color and flavor

- Entropy density in DQPM:
$s^{dqp} = -d_g \int \frac{d^4p}{(2\pi)^4}\frac{\partial n_B(p_0/T)}{\partial T}(Imln(-\Delta^-1) + Im\Pi Re\Delta) -$
$d_q \int \frac{d^4p}{(2\pi)^4}\frac{\partial n_F((p_0-\mu_q)/T)}{\partial T}(Imln(-S_q^{-1}) + Im\sum_q ReS_q) -$
$d_{\bar{q}} \int \frac{d^4p}{(2\pi)^4}\frac{\partial n_F((p_0+\mu_q)/T)}{\partial T}(Imln(-S_{\bar{q}}^{-1}) + Im\sum_{\bar{q}} ReS_{\bar{q}})$
Bose distribution function=$n_B(p_0/T) = (exp(p_0/T))^{-1}$
Fermi distribution function=$n_F((p_0 - \mu_q)/T) = (exp((p_0 - \mu_q)/T) + 1)^{-1}$
propagator of gluon: $\Delta^{-1} = p^\mu p_\mu - \Pi$, quasiparticle self-energy for gluon= Π
propagator of quark: $S_q^{-1} = p^\mu p_\mu - \sum_q$, quasiparticle self-energy for quark: $\sum_q$
propagator of antiquark: $S_{\bar{q}} = p^\mu p_\mu - \sum_{\bar{q}}$, quasiparticle self-energy for antiquark: $\sum_{\bar{q}}$

degeneracy: $d_q = d_{\bar{q}} = 2N_c N_f = 18, \quad d_g = 2(N_c^2 - 1) = 16$

- The equation of motion for testparticles in transport equation:

$$\frac{dX_i}{dt} = \frac{1}{1-C_i}\frac{1}{2\epsilon_i}[2P_i + \Delta_{p_i} Re\tilde{\sum}^{R}_{(i)} + \frac{\epsilon_i^2 - P_i^2 - M_0^2 - Re\tilde{\sum}^{R}_{(i)}}{\tilde{\Gamma}_{(i)}}\Delta_{p_i}\tilde{\Gamma}_{(i)}]$$

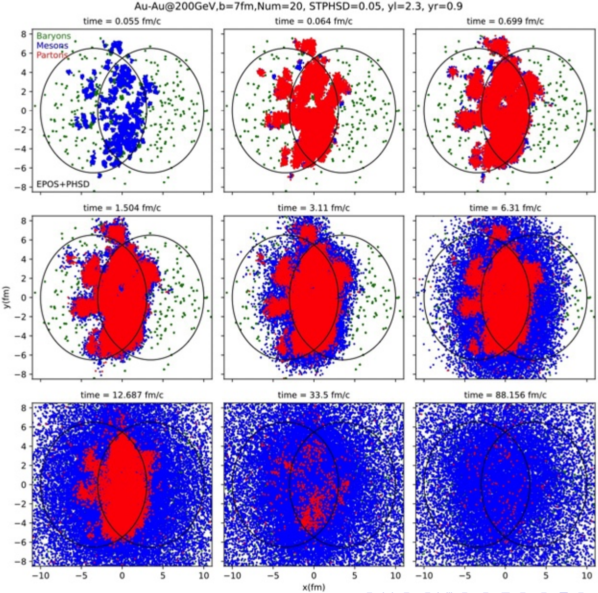
$$\frac{dP_i}{dt} = \frac{1}{1-C_i}\frac{1}{2\epsilon_i}[\Delta_{x_i} Re\tilde{\sum}^{R}_{(i)} + \frac{\epsilon_i^2 - P_i^2 - M_0^2 - Re\tilde{\sum}^{R}_{(i)}}{\tilde{\Gamma}_{(i)}}\Delta_{p_i}\tilde{\Gamma}_{(i)}]$$

$$\frac{d\epsilon_i}{dt} = \frac{1}{1-C_i}\frac{1}{2\epsilon_i}[\frac{\partial Re\tilde{\sum}^{R}_{(i)}}{\partial t} + \frac{\epsilon_i^2 - P_i^2 - M_0^2 - Re\tilde{\sum}^{R}_{(i)}}{\tilde{\Gamma}_{(i)}}\frac{\partial \tilde{\Gamma}_{(i)}}{\partial t}]$$

C_i stands the function of a Lorentz-factor and transforms the system time t to the eigentime of particles i which is given by the energy derivatives:

$$C_{(i)} = \frac{1}{2\epsilon_i}[\frac{\partial Re\tilde{\sum}^{R}_{(i)}}{\partial \epsilon_i} + \frac{\epsilon_i^2 - P_i^2 - M_0^2 - Re\tilde{\sum}^{R}_{(i)}}{\tilde{\Gamma}_{(i)}}\frac{\partial \tilde{\Gamma}_{(i)}}{\partial \epsilon_i}]$$

Time evolution of particles in PHSD space time



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