Dynamical Thermalization in Heavy-Ion Collisions

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From QCD to QGP:

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

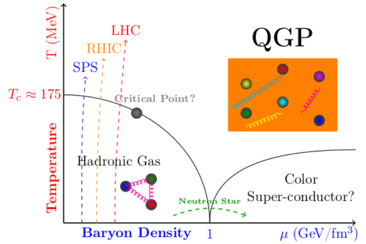


Figure: Phase diagram of nuclear matter [1].

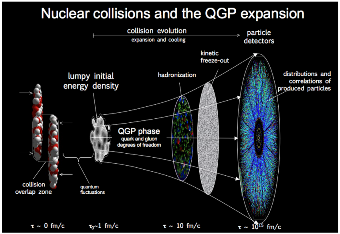


Figure: Space-time evolution of HIC.

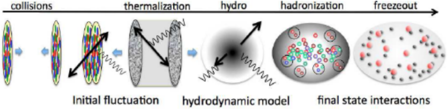
Current Accelerators:

- 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 try 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.

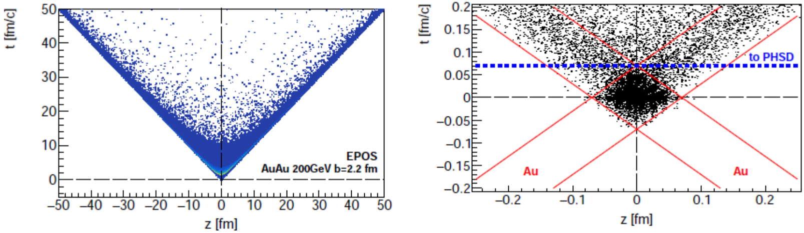
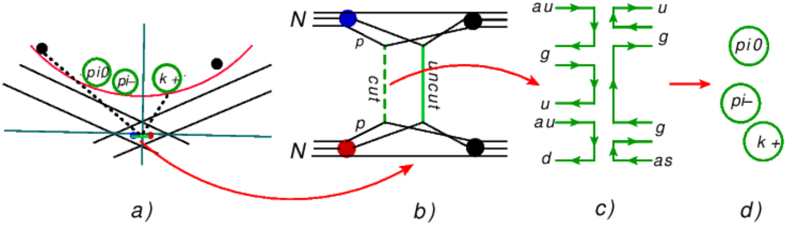


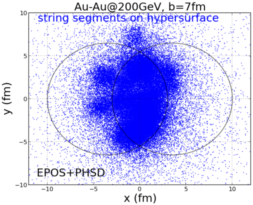
Figure: EPOS particles production hyper-surface initial condition for PHSD model. Zero time corresponds to maximum overlapping.

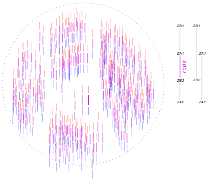
Initial Condition in EPOS:

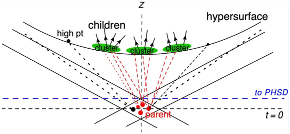
Parton Based Gribov Regge Theory (PBGRT) [6]:

- 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)



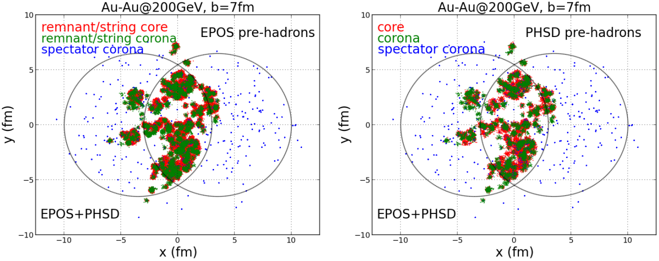






- projectile+target → pomerons → string segments → core/corona part → rope segments → core/corona pre-hadrons
- rope segments: longitudinal color field, consider in 3D, larger string tension and transverse momentum.
- core pre-hadrons : decay of rope segments/clusters based on Microcanonical treatment [8].
- The principle problem: EPOS uses light-cone dynamics, PHSD uses real-time dynamics.

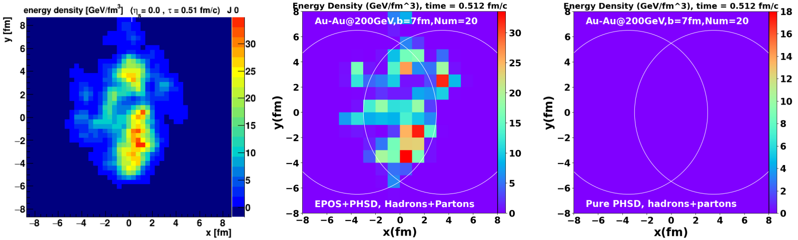
EPOSi+PHSD overview



All EPOS core/corona pre-hadrons are inserted into PHSD arrays and core pre-hadrons melted into QGP with respect to the Energy Density ($> 0.5GeV/fm^3$) condition.

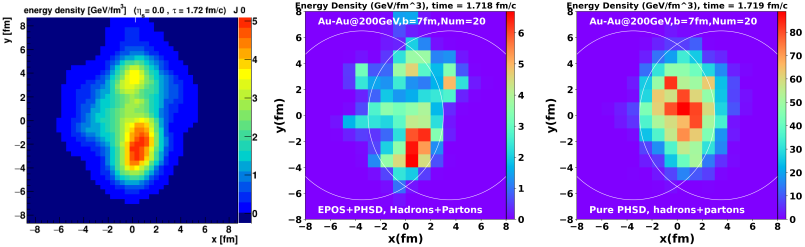
- EPOSi+PHSD and pure PHSD ED: Global computing frame [9]
- EPOS ED: Comoving frame [10]

Energy Density Evolution



(a) EPOS (b) EPOSi+PHSD (c) pure PHSD

Figure: Time evolution of the energy density in the x-y plane (at z=0) for Au-Au collisions at 200A GeV with an impact parameter of 7fm, for three models.



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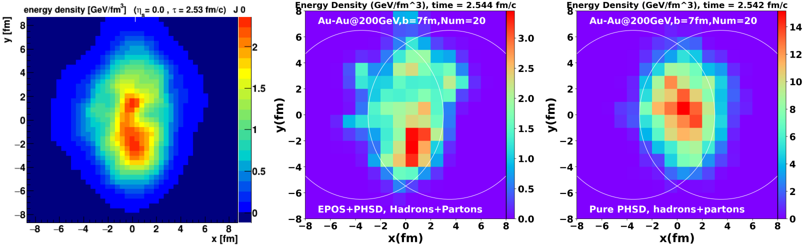

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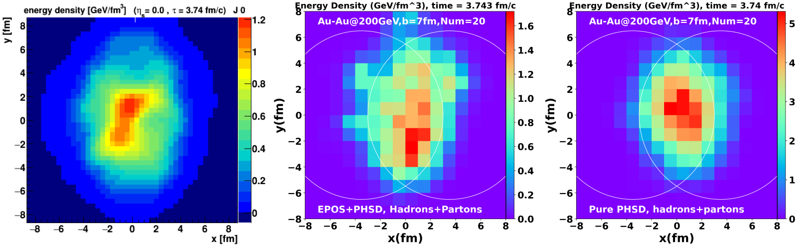
- EPOS: bumpy structure in the longitudinal direction
- EPOSi+PHSD: nearly identical to the EPOS
- PHSD: begins later and has more ED than others



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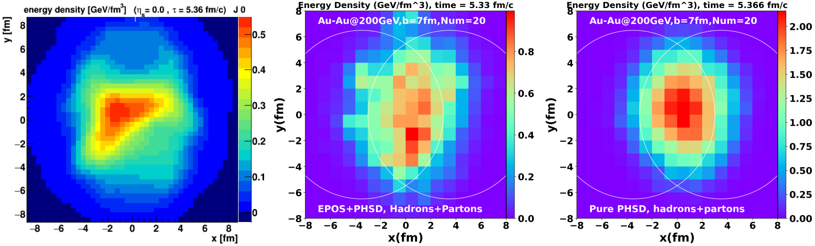

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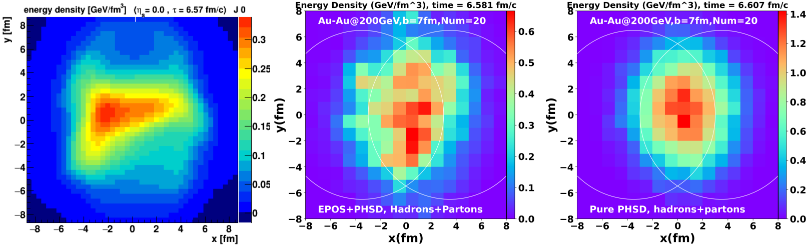

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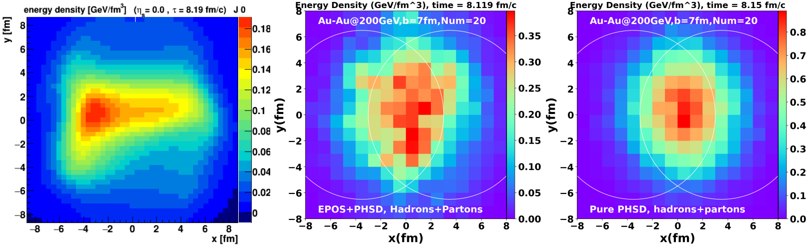

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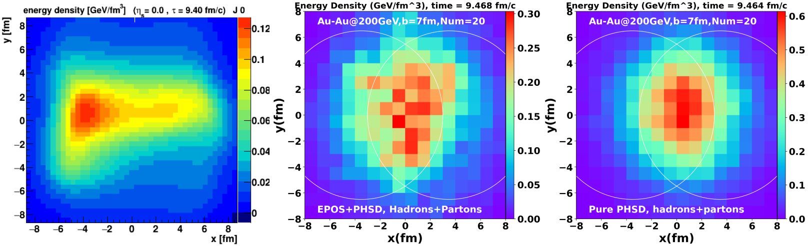

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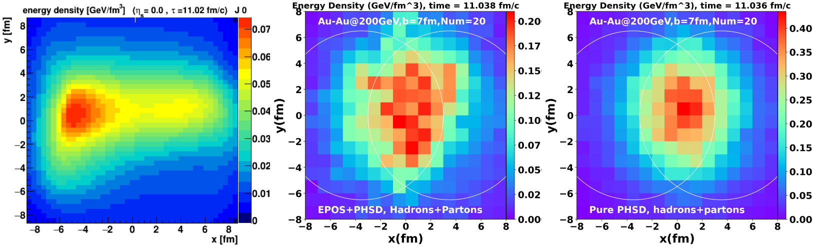

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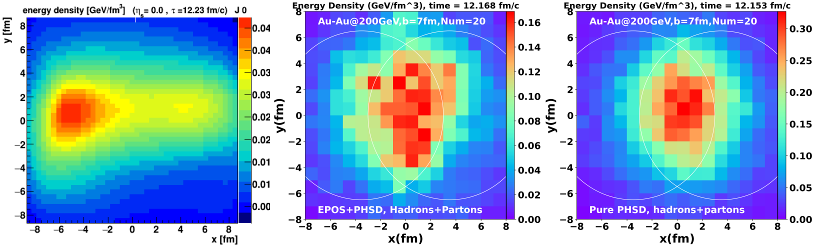

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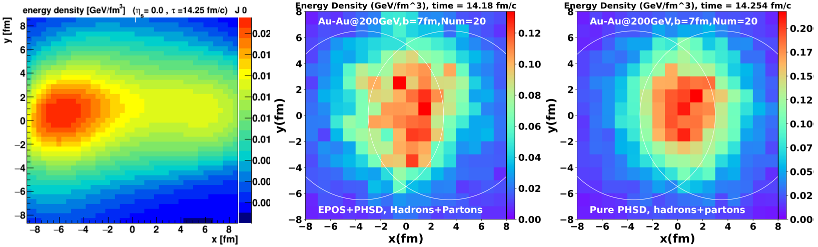

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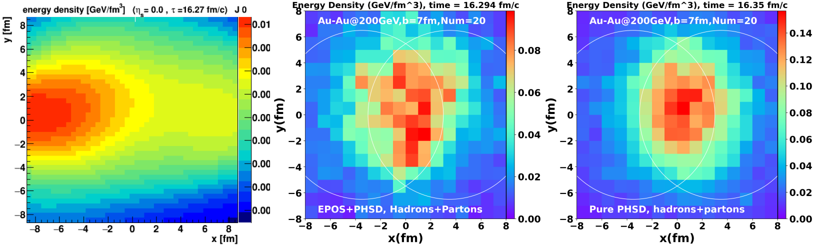
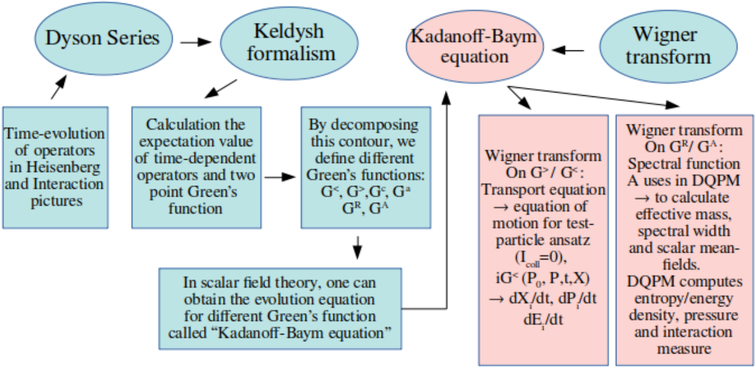


(a) EPOS (b) EPOSi+PHSD (c) pure PHSD

Figure: Time evolution of the energy density in the x-y plane (at z=0) for Au-Au collisions at 200A GeV with an impact parameter of 7fm, for three models.

- EPOS: transverse expansion and transverse flows
- EPOSi+PHSD: less transverse expansion than EPOS, same forms as pure PHSD
- PHSD: more ED than others and expands spherically

Dynamical description of strongly interacting system in PHSD



Dyson Series

Keldysh formalism

Kadanoff-Baym equation

Wigner transform

Time-evolution of operators in Heisenberg and Interaction pictures

Calculation the expectation value of time-dependent operators and two point Green's function

By decomposing this contour, we define different Green's functions: $G^<$, $G^>$, G^c, G^a G^R, G^A

In scalar field theory, one can obtain the evolution equation for different Green's function called "Kadanoff-Baym equation"

Wigner transform On $G^>$ / $G^<$: Transport equation → equation of motion for test-particle ansatz (I_{coll}=0), $iG^<(P_0, P,t,X)$ → dX_i/dt, dP_i/dt dE_i/dt

Wigner transform On G^R/ G^A: Spectral function A uses in DQPM → to calculate effective mass, spectral width and scalar mean-fields. DQPM computes entropy/energy density, pressure and interaction measure

QGP phase in PHSD

To study the properties of the medium → DQPM [11]:

- Using spectral function A in DQPM :
  $A(p) = \frac{2\gamma p_0}{(p^\mu p_\mu - M^2)^2 + 4\gamma^2 p_0^2}$, $\tilde{\Gamma} = 2\gamma p_0$, $M^2 = m^2 + Re\tilde{\sum}^R$
  To have Masses M^2 and widths γ of partons
  $M_g^2(T) = \frac{g^2}{6}[(N_c + \frac{1}{2}N_f)T^2 + \frac{1}{2}\sum_g \frac{\mu_q^2}{\pi^2}]$,
  $\gamma_g(T) = N_c \frac{g^2 T}{8\pi} ln \frac{2c}{g^2}$
  $M_{q/\bar{q}}^2(T) = \frac{N_c^2-1}{8N_c} g^2 [T^2 + \frac{\mu_{q/\bar{q}}^2}{\pi^2}]$, $\gamma_{q/\bar{q}}(T) = \frac{N_c^2-1}{2N_c}\frac{g^2 T}{8\pi} ln \frac{2c}{g^2}$
  $g^2(T/T_c)$ =running coupling, μ=chemicl potential, N_c, N_f : Number of color and flavor
- Entropy density 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 $U_s(\rho_s) = \frac{dV_p(\rho_s)}{d\rho_s}$

To investigate the QGP's dynamics → Generalized transport equation [12]

$$\frac{1}{2}\bar{A}\bar{\Gamma}[\{\bar{M}, iG^{<}\} - \frac{1}{\bar{\Gamma}}\{\bar{\Gamma}, \bar{M}.iG^{<}\}] = i\bar{\sum}^{<} i\bar{G}^{>} - \bar{\sum}^{>} i\bar{G}^{<}$$

$\bar{A}$ =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.

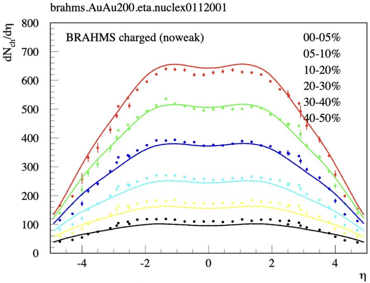
Hadronization:

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.

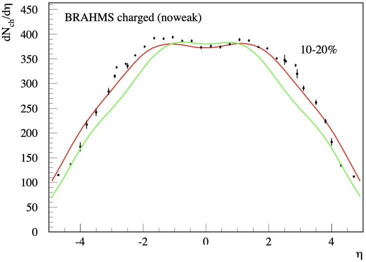
RESULTS

Comparing the
Particle Production, Elliptic Flow (v_2), Triangular Flow (v_3), Quadrangular Flow (v_4), Transverse Momentum (p_T) and Transverse Mass (m_T) for Au-Au@200GeV
With different simulations:
EPOSi+PHSD, EPOS, and pure PHSD

Charged Particle Production: Au-Au@200GeV



(a) EPOSi+PHSD



(b) EPOSi+PHSD, EPOS

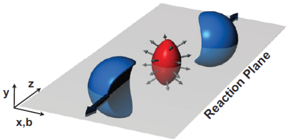
Good agreement to the real DATA ✓

Anisotropic Flow

Fourier series:

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

$v_n(p_t,y) = < cos(n(\phi - \Psi_{RP})) >$, v_2 = elliptic flow, v_3 = triangular flow, v_4 = quadrangular flow, Ψ_{RP} = reaction plane angle [13].



Elliptic Flow v_2: Au-Au@200GeV

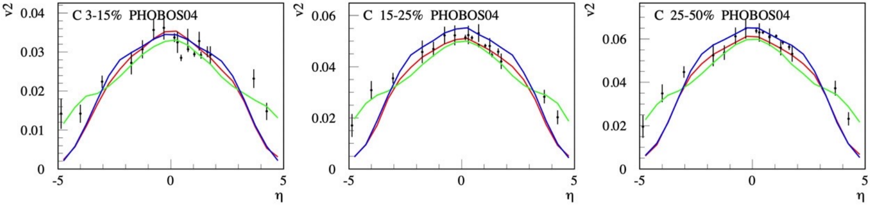


Figure: EPOSi+PHSD, EPOS, Pure PHSD

Elliptic Flow v_2: Au-Au@200GeV

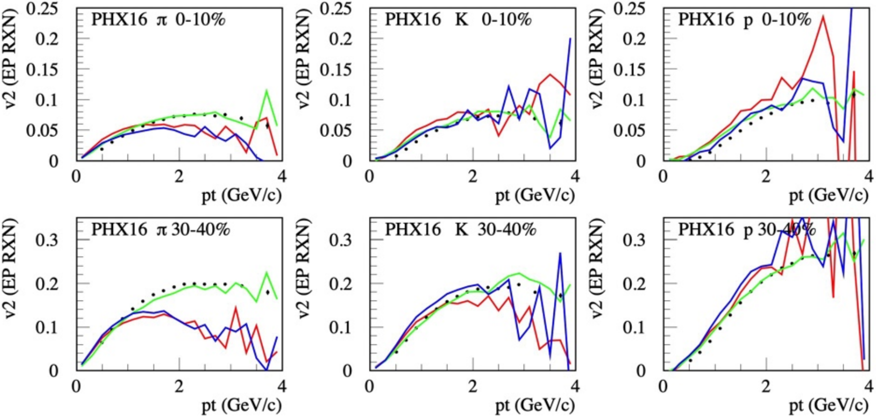


Figure: EPOSi+PHSD, EPOS, Pure PHSD

Triangular Flow v_3: Au-Au@200GeV

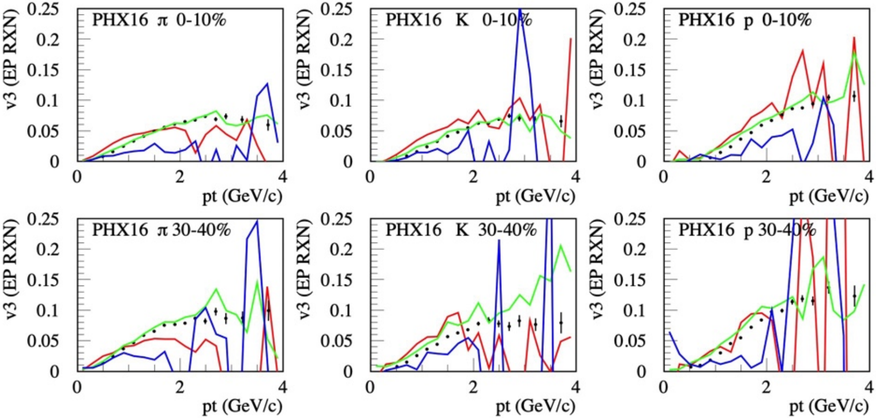


Figure: EPOSi+PHSD, EPOS, pure PHSD

Quadrangular flow v_4: Au-Au@200GeV

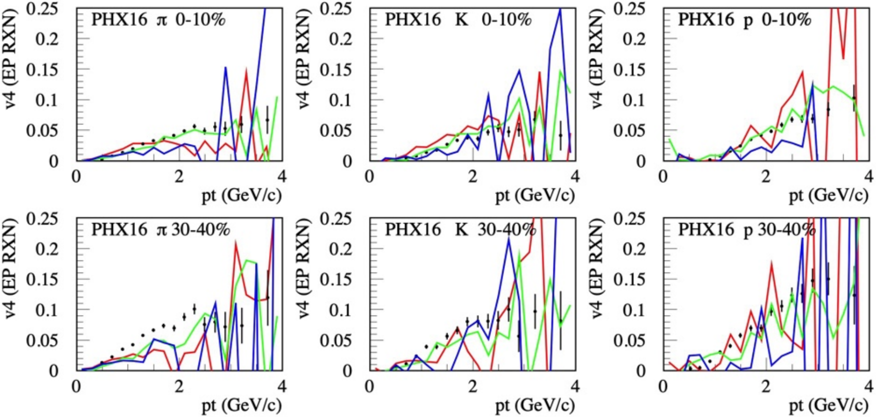
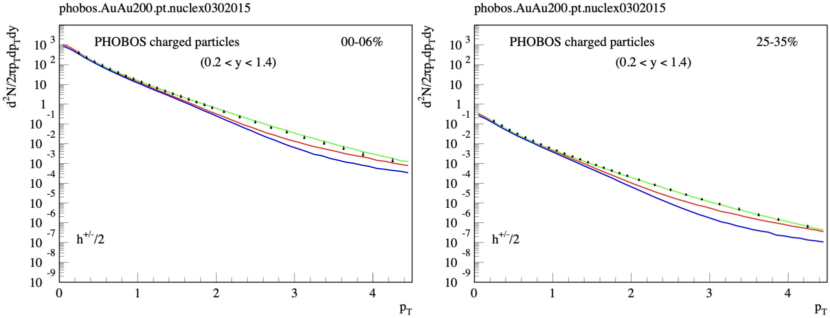


Figure: EPOSi+PHSD, EPOS, pure PHSD

Transverse Momentum: Au-Au@200GeV



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Transverse Mass: Au-Au@200GeV

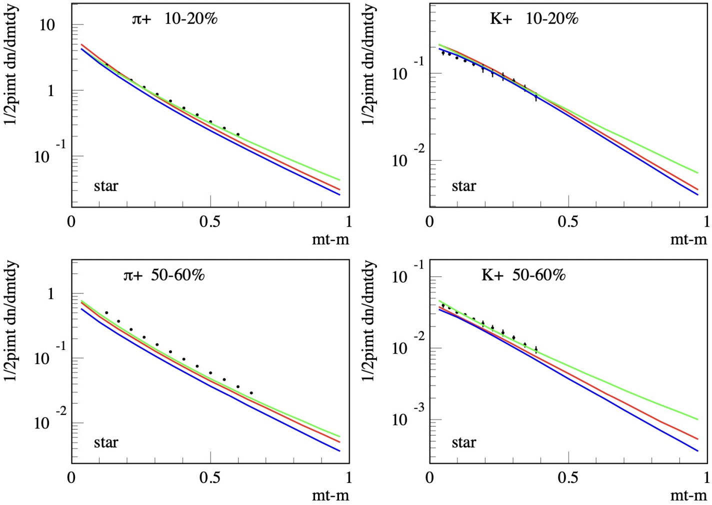


Figure: EPOSi+PHSD, EPOS, pure PHSD

Summary and Conclusion:

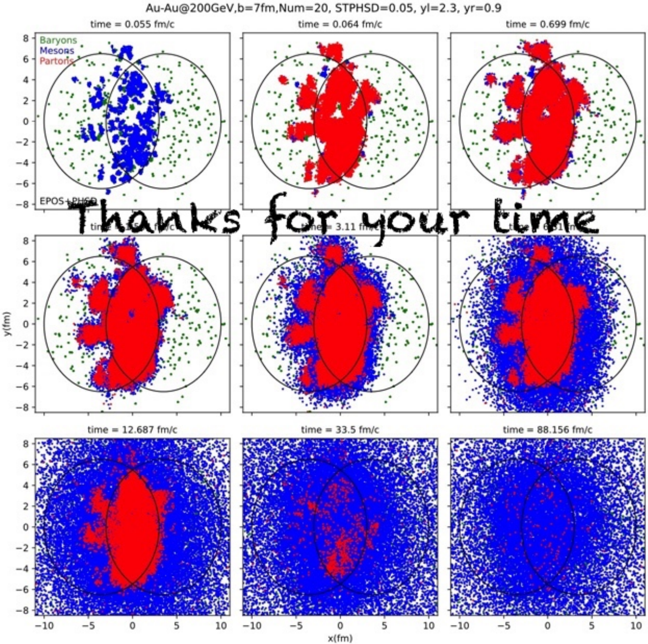
- ✓ Two different HIC models were successfully combined.
- ✓ Comparison of space-time and energy density evolution by EPOSi+PHSD with pure EPOS and pure PHSD.
- ✓ Considering observables like charged particles production, v_2, v_3, v_4, p_T, m_T.
- × High p_T part has not been improved yet by EPOSi+PHSD.

Current work:

- Investigation of electromagnetic probes, photon and dilepton production.

Outlook:

- Checking EPOSh +PHSD to study the high p_T part.
- Comparison EPOSi+PHSD with different range energies from RHIC to LHC for various systems like p-p and Au-Au collisions.
- Checking heavy flavor particles behavior



Thanks for your time

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