Disentangle effects from the initial stage and the evolution stage in heavy ion collions using EPOS and PHSD

Mahbobeh Jafarpour
Subatech, Nantes University, France

PhD supervisor: **Prof. Klaus Werner**

July 13, 2022

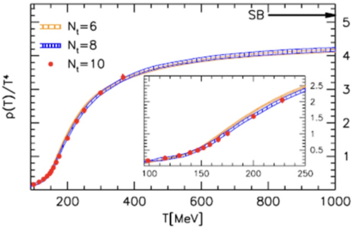
Outline:

- Introduction
  - From QCD to QGP, HIC Models, Purpose of Project
- Initial condition in EPOS
  - PBGRT, Core-Corona picture
- EPOS2PHSD Interface
  - Insertion procedure
- Evolution in EPOSi+PHSDe
  - Space-time evolution, Energy density evolution
- Results
  - Charged particles production, Transverse momentum spectra, Anisotropic flow
- Conclusion and Outlook

From Quantum ChromoDynamics (QCD) to Quark-Gluon Plasma (QGP):

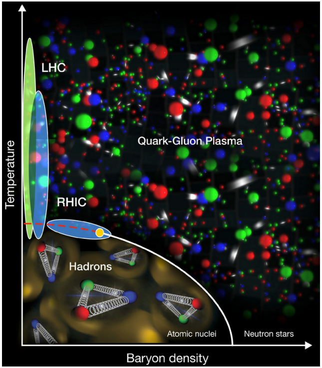
From QCD to QGP:

- QCD: Theory of the strong interaction between quarks and gluons in SM
- At low T and low μ_B $\rightarrow$ Hadronic gas
- For $T > 156$ MeV, and $\mu_B \rightarrow 0 \rightarrow$ QGP



Deconfinement phase transition from lQCD

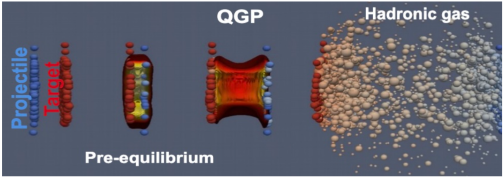
Sz . Borsanyi et al., JHEP 1208 (2012) 053



Phase diagram of nuclear matter

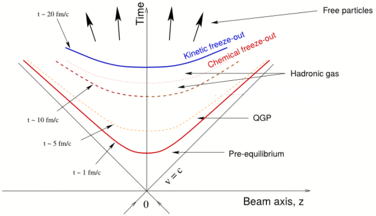
https://www.bnl.gov/newsroom/news.php?a=24281

Heavy-Ion Collisions (HIC)



Space-time evolution of HIC

https://webhome.phy.duke.edu/ jp401/old˙music˙manual/˙images/hic˙petersen˙bernhard.jpg



Space-time evolution of HIC in light-cone dynamics

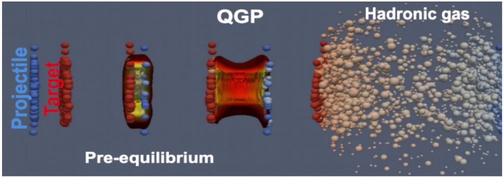
Current Accelerators:

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

Future Accelerators:

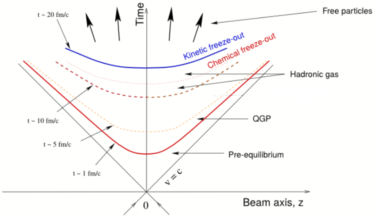
- FAIR, Germany
- NICA, Russia

Heavy-Ion Collisions (HIC)



Space-time evolution of HIC

https://webhome.phy.duke.edu/ jp401/old˙music˙manual/˙images/hic˙petersen˙bernhard.jpg



Space-time evolution of HIC in light-cone dynamics

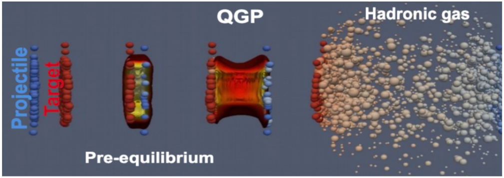
Current Accelerators:

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

Future Accelerators:

- FAIR, Germany
- NICA, Russia

Theoretical models to study HIC:



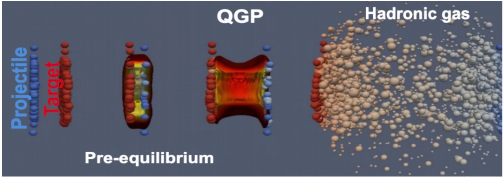
Space-time evolution of HIC

https://webhome.phy.duke.edu/ jp401/old˙music˙manual/˙images/hic˙petersen˙bernhard.jpg

We need models concerning the various stages: initial, evolution, and hadronization.

- EPOS
- PHSD
- AMPT
- UrQMD
- ...

Theoretical models to study HIC:



Space-time evolution of HIC

https://webhome.phy.duke.edu/ jp401/old˙music˙manual/˙images/hic˙petersen˙bernhard.jpg

We need models concerning the various stages: initial, evolution, and hadronization.

- EPOS ✓
- PHSD ✓
- AMPT
- UrQMD
- ...

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

K. Werner et al., Phys. Rev. C 74, 044902 (2006), K. Werner et al., Phys. Rev. C 92, 034906 (2015)

- 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 Microcanonical decay/Cooper-Frye procedure and equilibrium hadron distribution.
- FINAL STATE HADRONIC CASCADE: applying the UrQMD model.

PHSD: Parton Hadron String Dynamics.

W. Cassing and E. Bratkovskaya, Phys. Rev. C 78, 034919 (2008), W. Cassing, E. Bratkovskaya, Nucl. Phys. A 831, 215-242 (2009)

- 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.

Steps \ Models	EPOS	PHSD
Initial Conditions (i)	PBGRT	PYTHIA
Evolutions (e)	Core-Corona Separation Viscous Hydrodynamic Expansion Statistical Hadronization Final State Hadronic Cascade	QGP Formation Non-Equilibrium Parton/Hadron Evolution

EPOSi+PHSDe : Initial distribution of matter (partons/hadrons) from EPOS (EPOSi) + Evolution of matter in PHSD (PHSDe)

Steps \ Models	EPOS	PHSD
Initial Conditions (i)	**PBGRT**	PYTHIA
Evolutions (e)	Core-Corona Separation Viscous Hydrodynamic Expansion Statistical Hadronization Final State Hadronic Cascade	**QGP Formation** **Non-Equilibrium Parton/Hadron Evolution**

EPOSi+PHSDe

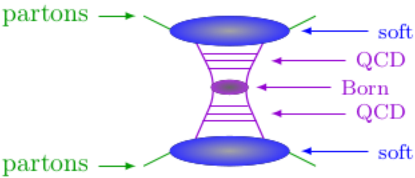
Purpose: Separate "initial" and "evolution" effects

Initial Condition in EPOSi+PHSDe:

Parton Based Gribov Regge Theory (PBGRT):

H. Drescher et al., Phys. Rep. 350, 93-289 (2001)

- Hard (PM)/Soft (GRT) processes, Energy conservation by multiple Pomeron exchange
- Pomeron/Parton ladder : elementary interaction between partons or hadrons

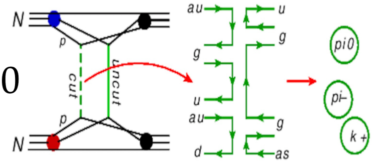


The semi-hard contribution: parton ladder plus "soft ends"

Initial Condition in EPOSi+PHSDe:

- There are two kinds of parton ladders: cut and uncut
- Calculation of elastic/inelastic Cross-Sections (uncut ladder, soft contribution)
- String segments production on the hyperbola (cut ladder, semi-hard/hard contribution, and Color Flow Diagram (CFD))

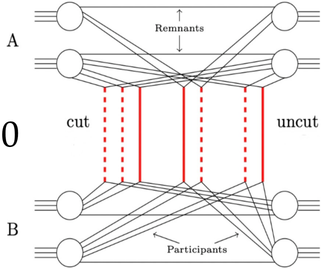
$\tau = 0$

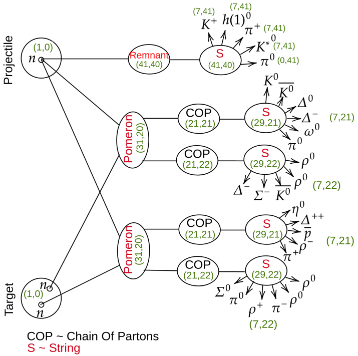


From Pomerons to string segments in pp collision

Initial Condition in EPOSi+PHSDe:

$$\tau = 0$$

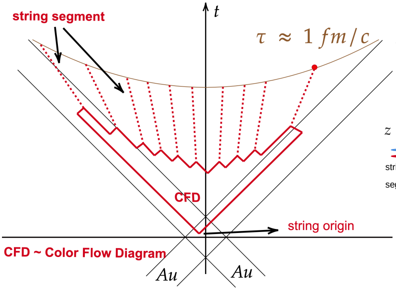


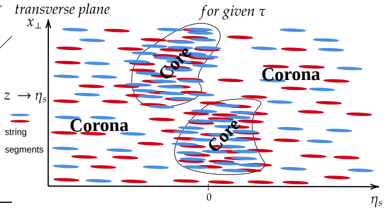


From Pomerons to string segments in AA collision

Initial Condition in EPOSi+PHSDe:

Core-Corona Separation in EPOS:





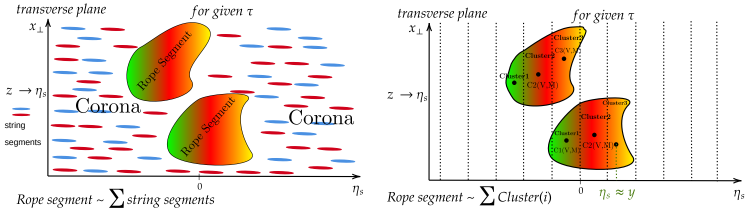
Energy loss of each string segment at given time τ:

$$P_t^{new} = P_t - f_{Eloss} \int_\gamma \rho dL$$

If $P_t^{new} > 0 \rightarrow$ Corona particle
If $P_t^{new} < 0 \rightarrow$ Core particle

Initial Condition in EPOSi+PHSDe:

Core-Corona pre-hadrons in EPOSi+PHSDe:



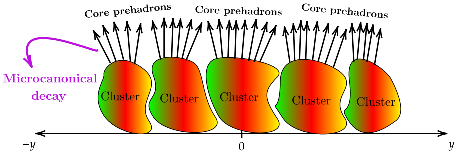
- Rope segments: overlapping of string segments
- Rope segments: longitudinal color field, consider in 3D, larger string tension and transverse momentum
- Clusters: Breaking rope segments into several pieces

Initial Condition in EPOSi+PHSDe:

- Core pre-hadrons: decay of rope segments/clusters based on Microcanonical treatment in their center of mass

  K. Werner, COST THOR Working Group I and II and GDRI Meeting (2018)

- Core pre-hadrons: mostly produced at low momentum and mid-rapidity regions

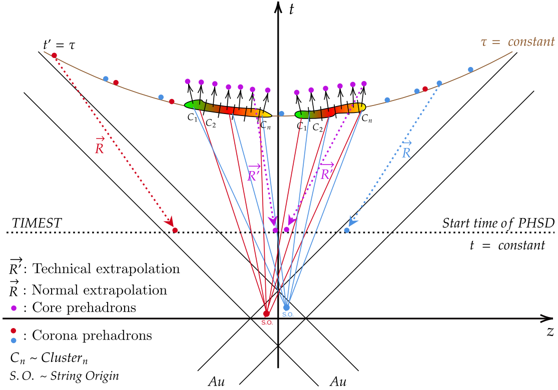


Decaying of clusters into core pre-hahdrons in the rapidity space

- Corona pre-hadrons = Corona particles

EPOS2PHSD

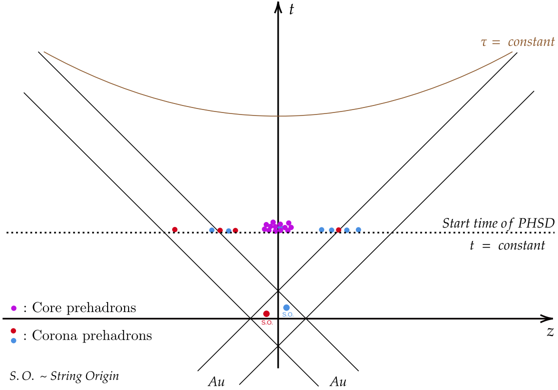
Extrapolation from the EPOS light cone coordinates to the PHSD cartezian coordinates:



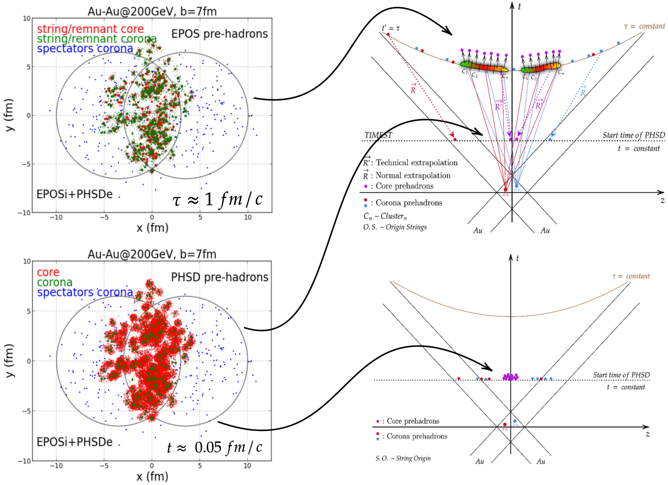
Inserting all pre-hadrons from EPOS into PHSD

EPOS2PHSD

Final positions of core and corona pre-hadrons following extrapolation processes to the PHSD start time:



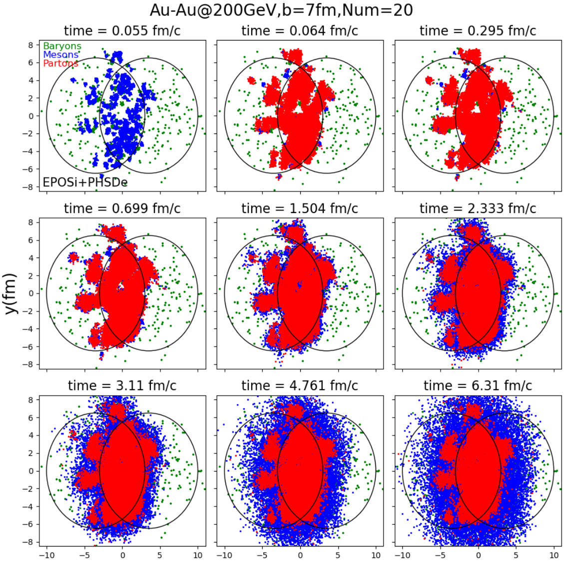
EPOS2PHSD


Au-Au@200GeV, b=7fm
string/remnant core
string/remnant corona
spectators corona
EPOS pre-hadrons
EPOSi+PHSDe
$\tau \approx 1\ fm/c$
x (fm)
y (fm)
Au-Au@200GeV, b=7fm
core
corona
spectators corona
PHSD pre-hadrons
EPOSi+PHSDe
$t \approx 0.05\ fm/c$
x (fm)
y (fm)
$t' = \tau$
τ = constant
TIMEST
Start time of PHSD
t = constant
$\vec{R}'$: Technical extrapolation
$\vec{R}$: Normal extrapolation
: Core prehadrons
: Corona prehadrons
C_n ~ $Cluster_n$
O. S. ~ Origin Strings
Au
Au
z
t
τ = constant
Start time of PHSD
t = constant
: Core prehadrons
: Corona prehadrons
S. O. ~ String Origin
Au
Au
z
t

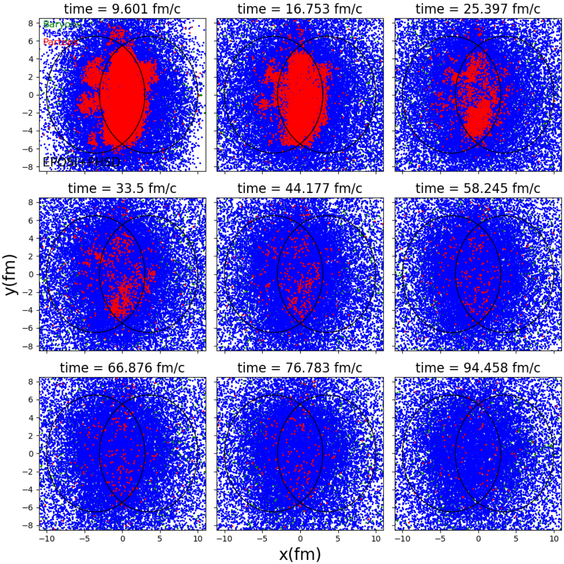
Evolution in EPOSi+PHSDe

- To start the evolution in EPOSi+PHSDe → melting PHSD core pre-hadrons into QGP
- Melting condition : $\varepsilon_p > 0.5 GeV/fm^3$
- Enegy Density is computed in the Comoving frame in the three models: $T^{\mu\nu}(\vec{q}) = \int \frac{d^3p}{E} p^\mu p^\nu f(\vec{q}, \vec{p}), \quad \varepsilon = T^{00}$

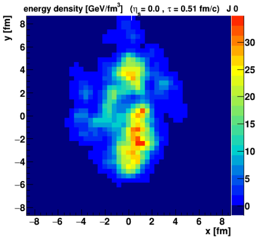
Space-time evolution of HIC in EPOSi+PHSDe



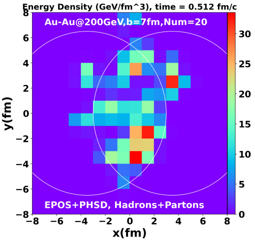
Space-time evolution of HIC in EPOSi+PHSDe



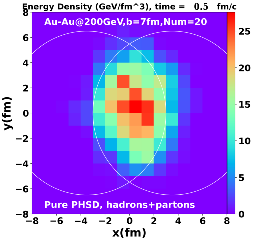
Energy density evolution in the three models



(a) EPOS



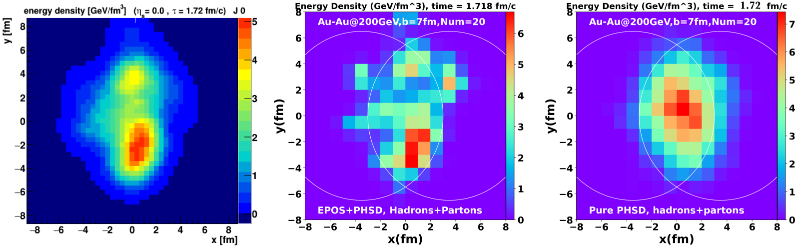
(b) EPOSi+PHSDe



(c) PHSD

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.

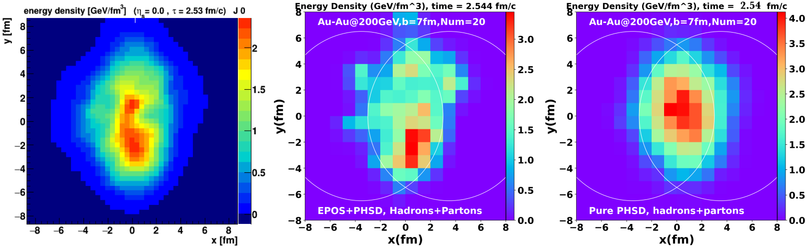
Energy density evolution in the three models



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

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.

Energy density evolution in the three models

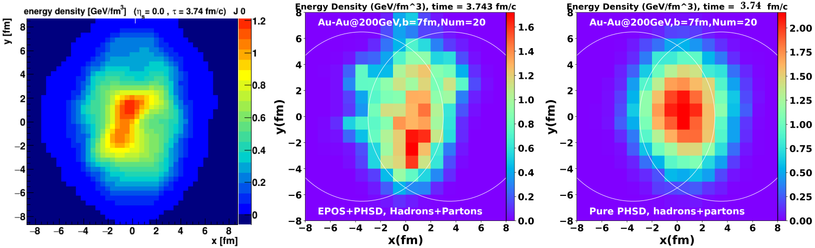


(a) EPOS (b) EPOSi+PHSDe (c) PHSD

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: system expands in the longitudinal direction
- EPOSi+PHSDe: nearly identical to the EPOS
- PHSD: expands homogeneously

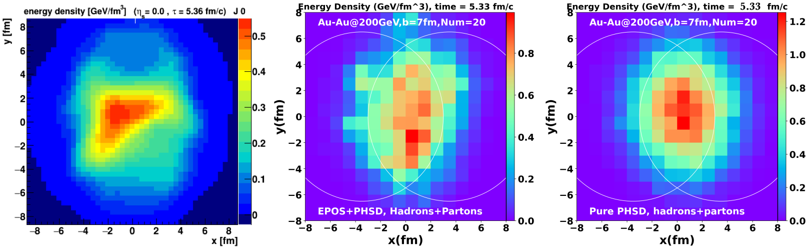
Energy density evolution in the three models



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

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.

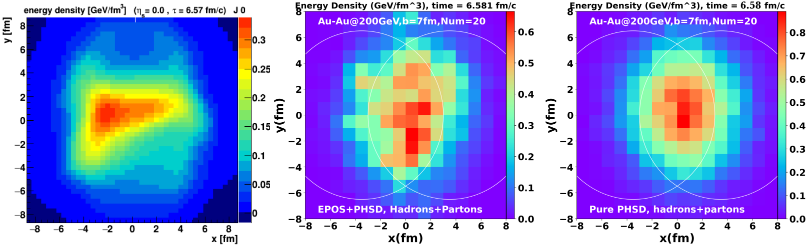
Energy density evolution in the three models



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

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.

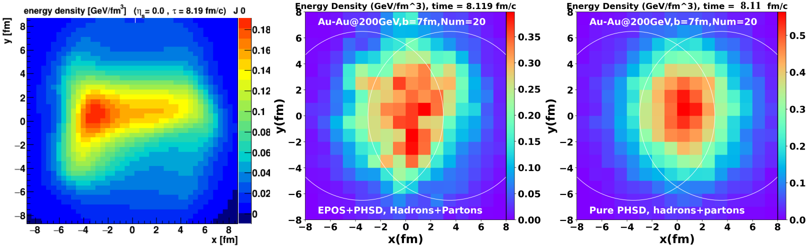
Energy density evolution in the three models



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

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.

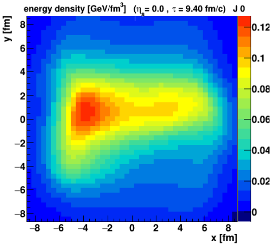
Energy density evolution in the three models



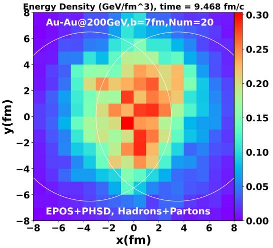
(a) EPOS (b) EPOSi+PHSDe (c) PHSD

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.

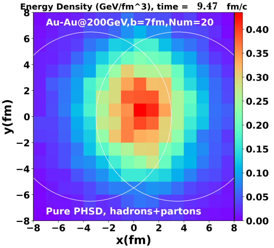
Energy density evolution in the three models



(a) EPOS



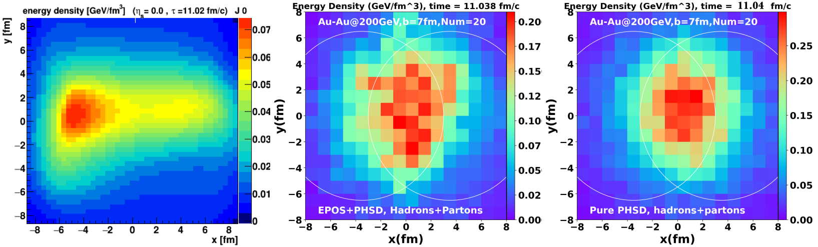
(b) EPOSi+PHSDe



(c) PHSD

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.

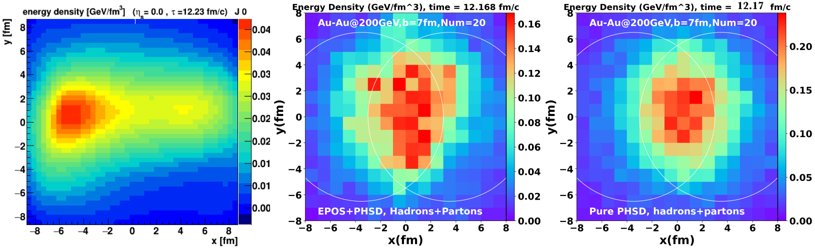
Energy density evolution in the three models



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

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.

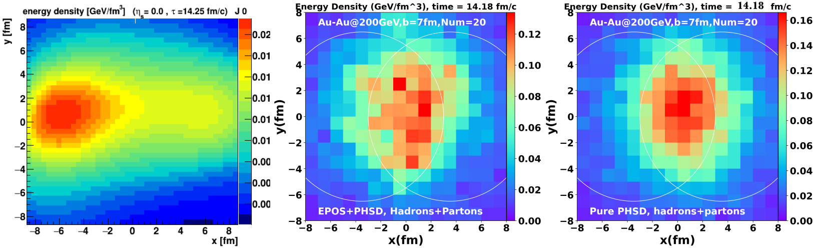
Energy density evolution in the three models



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

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.

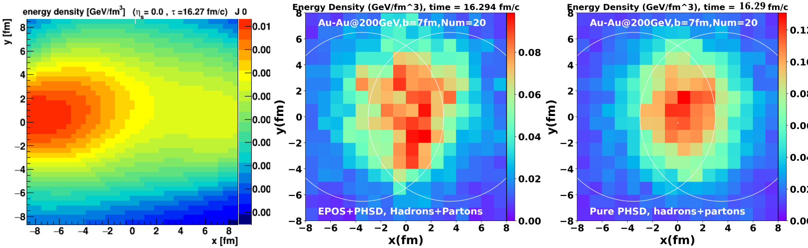
Energy density evolution in the three models



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

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.

Energy density evolution in the three models



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

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: strong transverse expansion leads to more transverse flows
- EPOSi+PHSDe: less transverse expansion than EPOS, same shapes as PHSD

Results

Comparing bulk matter observables for Au-Au@200 GeV/A :

- Charged particles production
  - Rapidity dependence
  - Pseudorapidity dependence
- Transverse momentum spectra
- Anisotropic flow
  - Elliptic flow v_2

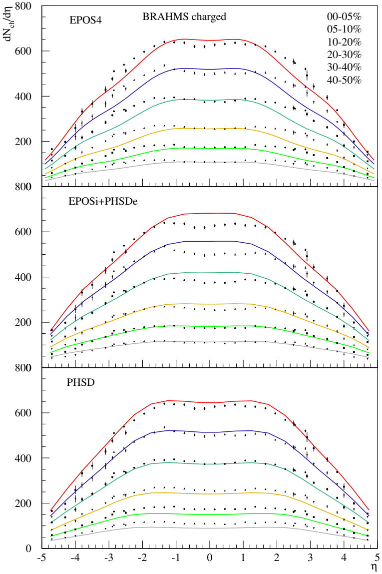
in

EPOS, EPOSi+PHSDe, and PHSD

Charged particles production: pseudorapidity dependence

- EPOS: produces reasonably charged particles
- EPOSi+PHSDe: produces more charged particles at $|\eta| < 1.5$ in $0 - 30\%$
- EPOSi+PHSDe: improves results in $20 - 50\%$ compared to pure PHSD
- PHSD: produces well the real data and the η shapes in $0 - 20\%$

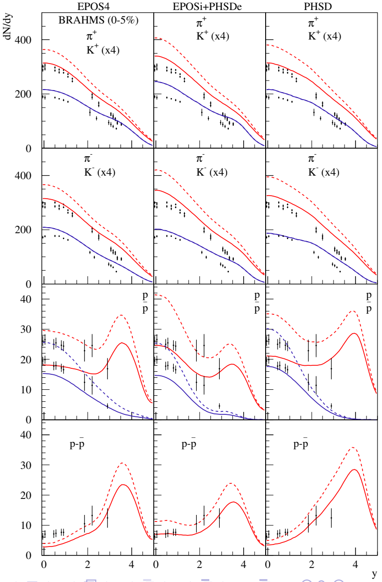
BRAHMS data: PRL 88, 202301 (2002)



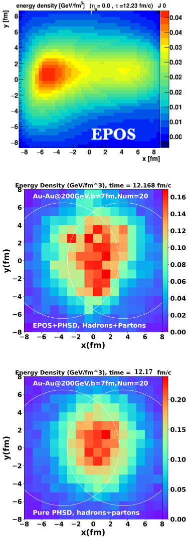
Charged particles production: rapidity dependence

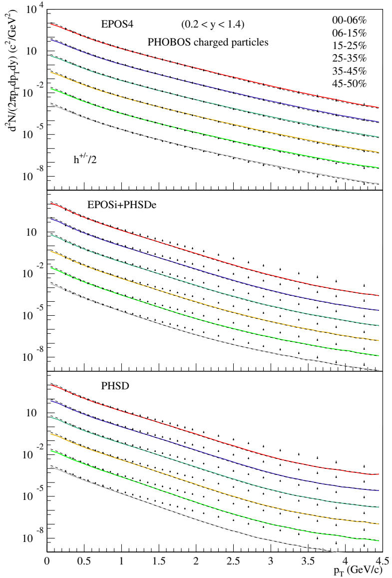
- Considering entire p_T ranges
- Weak decays: dashed lines
- No-Weak decays: full lines
- At mid-rapidity: EPOSi+PHSDe produces more identified particles than others
- At forward-rapidity: PHSD produces more identified particles than others
- Net-proton density: EPOSi+PHSDe: biggest proton stopping PHSD: lowest proton stopping

BRAHMS data: PRL 94, 162301 (2005), PRL 93, 102301 (2004)



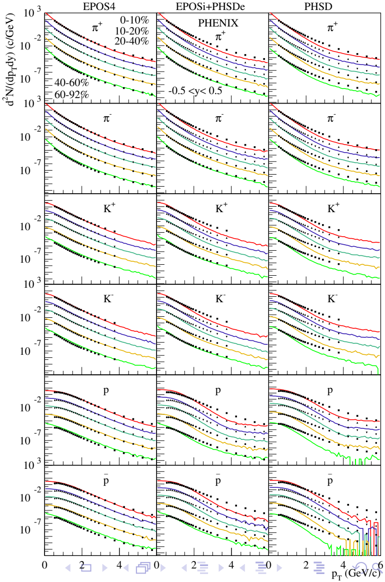
Transverse momentum spectra for all charged particles





Transverse momentum spectra: identified charged hardons

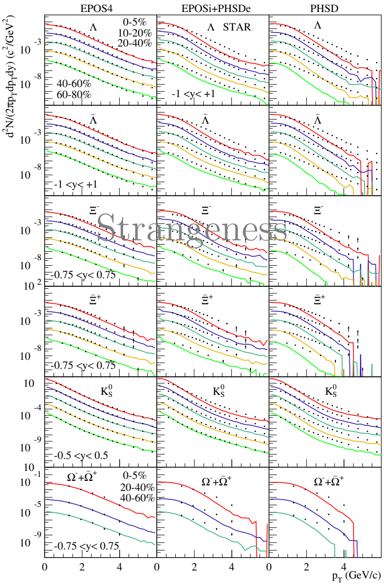
- Weak decays contribute to produce $\pi^{\pm}, K^{\pm}$
- EPOS: good agreement to the real data due to the strong transverse expansion
- EPOSi+PHSDe and PHSD: underestimate the data at intermediate p_T due to missing transverse expansion
- EPOSi+PHSDe a little bit improves results compared to PHSD because of having a bit more flow from rope decays



Transverse momentum spectra: strangeness enhancement

- Weak decays contribute to produce all hyperons not for K_s^0
- Same results as identified charged hadrons

STAR data: PRL 98, 062301 (2007)



Anisotropic Flow

Event Plane method:

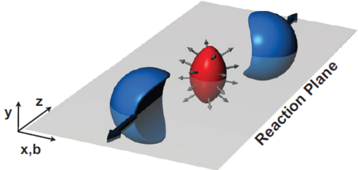
$$E\frac{d^3N}{d^3p} = \frac{1}{2\pi}\frac{d^2N}{p_t dp_t dy}(1 + \sum_{n=1}^{\infty} 2v_n cos(n(\phi - \Psi_{EP})))$$

$$v_n(p_t, y) = < cos(n(\phi - \Psi_{EP})) >$$

v_2 = elliptic flow, v_3 = triangular flow, v_4 = quadrangular flow

Ψ_{EP} = Event Plane angle

PLB 659, 537-541 (2008)

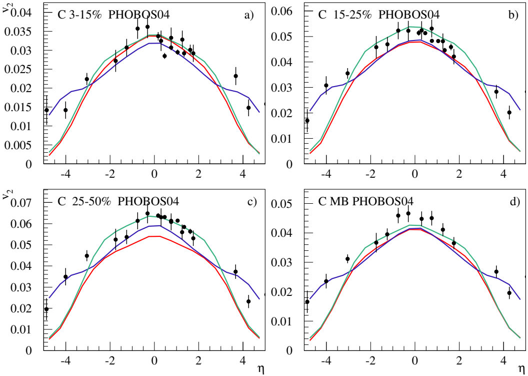


- Collision geometries and fluctuations of the initial state → anisotropic QGP matter in AA
- Initial spatial anisotropy → momentum anisotropy
- Elleptic flow: how the flow is not uniform

Elliptic flow : pseudorapidity dependence

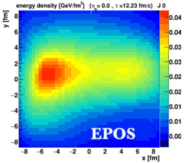
- The flow is smallest at most central collisions
- At mid-pseudorapidity: PHSD has more flow than others
- At large $|\eta|$: EPOS has more flow than others

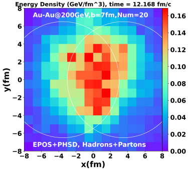
PHOBOS data: PRC 72, 051901 (2005)

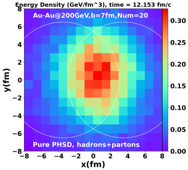


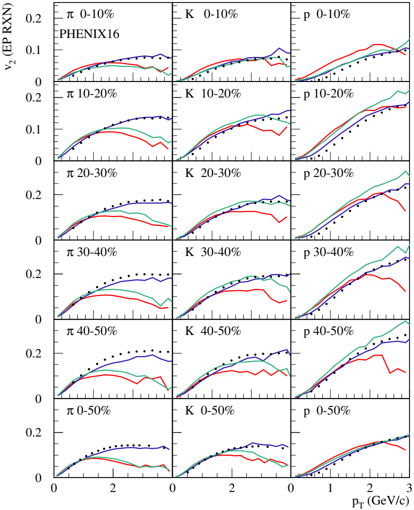
EPOS, EPOSi+PHSDe, PHSD

Elliptic flow : transverse momentum dependence









EPOS, EPOSi+PHSDe, PHSD

Summary and Conclusion

- Combining two separate HIC models successfully
- EPOSi+PHSDe: initial phase state from EPOS + matter evolution from PHSD
- The main distinctions between EPOS and PHSD are related to their "evolutions", while an "initial condition" has a minor role
- Hydrodynamical evolution in EPOS → large system expansion in transverse plane and system evolution in an asymmetric fashion → producing particles and flow at higher p_T
- Parton-Parton scatterings in EPOSi+PHSDe and PHSD → do not create transverse expansion nor evolve system in an asymmetric fashion → missing particle production and flow at higher p_T

Outlook

- Employing the early hydrodynamical evolution from EPOS (EPOSh), then use the PHSD evolution (PHSDe) to study the production of particles in higher p_T.
- Checking the heavy-flavor particle behavior in EPOSi+PHSDe and comparing the results with two other models.
- Comparing EPOSi+PHSDe with different ranges energies from RHIC to LHC for various systems like p-p and Au-Au.
- Studying the inclusive photon yield in EPOSi+PHSDe compared to pure PHSD.


thanks for your time