An Integrated Microscopic+Macroscopic Approach to Heavy Ion Reactions

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H-QM Helmholtz Research School
Quark Matter Studies
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Outline

• Motivation
• Model Description
• Time Evolution
• Multiplicities and Spectra
• $<m_T>$ and Elliptic Flow
  Excitation Function
• Conclusion and Outlook

-> all the information can be found in
Present Approaches

(3+1)dim. Hydrodynamics
with nonequilibrium initial conditions (Nexus) and isothermal freeze-out or continuous emission scenario:

- Results On Transverse Mass Spectra Obtained With Nexspherio

with Glauber or CGC initial conditions and hadronic afterburner:

- Hadronic dissipative effects on elliptic flow in ultrarelativistic heavy-ion collisions.
- 3-D hydro + cascade model at RHIC.
- See also recent work of K. Werner
Introduction

- Fix the initial state and freeze-out
  → learn something about the EoS and the effect of viscous dynamics

1) Non-equilibrium initial conditions via UrQMD

2) Hydrodynamic evolution or Transport calculation

3) Freeze-out via hadronic cascade (UrQMD)
Are differences between hydro and transport as big as expected?

Investigation of differences between

- **UrQMD:**
  - Non-equilibrium (Boltzmann) transport approach
  - Hadron-string and resonance dynamics

- **UrQMD+Hydro:**
  - Non-equilibrium initial conditions
  - Ideal hydrodynamic evolution for the hot and dense phase
  - Freeze-out via hadronic cascade
Initial State I

- Coupling between UrQMD initial state and hydrodynamic evolution at:
  \[ t_{\text{start}} = \frac{2R}{\gamma v} = \frac{2R}{\sqrt{\gamma^2 - 1}} = 2R \sqrt{\frac{2m_N}{E_{\text{lab}}}} \]

- Contracted nuclei have passed through each other
  - Initial NN scatterings have proceeded
  - Energy is deposited
  - Baryon currents have separated

- Energy-, momentum- and baryon number densities are mapped onto the hydro grid

- Hadrons are represented by a Gaussian with finite width

\[ \epsilon_{\text{cf}}(x, y, z) = N \exp \left( -\frac{(x-x_p)^2 + (y-y_p)^2 + (\gamma z(z-z_p))^2}{2\sigma^2} \right) \]

with the proper normalisation

\[ N = \left( \frac{1}{2\pi} \right)^{3/2} \frac{3\gamma^2}{\sigma^2} E_{\text{cf}} \]

Single Event - Initial State

Energy density distribution at $E_{\text{lab}}=40 \text{ AGeV}$,

$t_{\text{hydrostart}} = 2.83 \text{ fm}$

$\varepsilon \text{ [GeV/fm}^3\text{]}$

$\rightarrow$ Event-by-event fluctuations are naturally taken into account
Initial State Comparison

2.83 fm  Energy density distribution, $E_{\text{lab}}=40A$ GeV

Initial conditions from UrQMD are smoother than NeXSPheRIO, but still fluctuate.
Initial Velocity Distribution

Central collisions at different beam energies

In z-direction:
Effect of Lorentz contraction visible
(3+1)d Hydrodynamic Evolution

- Ideal relativistic one fluid hydrodynamics
  \[ \partial_\mu T^{\mu\nu} = 0 \quad \text{and} \quad \partial_\mu (nu^\mu) = 0 \]

- Hadron gas equation of state (EoS)
  - No phase transition included
  - Baseline check
  - All hadrons with masses up to 2.2 GeV are included (consistent with UrQMD)

Freeze-out

- Hydrodynamic evolution until
  - \( \varepsilon < 730 \text{ MeV}/\text{fm}^3 \approx 5 \times \varepsilon_0 \) in all cells
- Isochronous freeze-out is performed via the Cooper-Frye formula

\[
E \frac{dN}{d^3p} = \int_\sigma f(x, p)p^\mu d\sigma_\mu
\]

with boosted Fermi or Bose distributions \( f(x, p) \) including \( \mu_B \) and \( \mu_S \)

- rescatterings and final decays calculated via hadronic cascade (UrQMD)
Freeze-out II

Distribution of the cells at freeze-out at $E_{\text{lab}} = 40$ AGeV

→ Important inhomogeneities are naturally taken into account

Freeze-out conditions

\[ \langle \mu_B \rangle \text{ (MeV)} \]
\[ \langle T \rangle \text{ (MeV)} \]

\[ E_{\text{lab}} \text{ (AGeV)} \]

Graph 1: \( \langle \mu_B \rangle \) as a function of \( E_{\text{lab}} \)
Graph 2: \( \langle T \rangle \) as a function of \( E_{\text{lab}} \)
Freeze-out line


$5\varepsilon_0$

→ Mean values and widths are in line with other calculations
Dependence on Freeze-out

- Variation of the freeze-out criterium does not affect the meson multiplicities and mean transverse masses

Full symbols: 40 AGeV
Open symbols: 11 AGeV
Variation of starting time by a factor 4 changes results only by 10 %

Full symbols: 40 AGeV
Open symbols: 11 AGeV
Time scales
Final State Interactions
Baryon density distribution

Time evolution of the baryon density is smooth

1) in the reaction plane

2) in a central cell
Time Evolution

Central Pb+Pb collisions at 40A GeV:

- Number of particles decreases in the beginning due to resonance creation

- Qualitative behaviour very similar in both calculations

→ UrQMD equilibrates to a rather large degree
Multiplicities

- Both models are purely hadronic without phase transition, **but** different underlying dynamics

→ results for particle multiplicities from AGS to SPS are surprisingly **similar**

→ **strangeness** is enhanced in the hybrid approach due to local equilibration
Rapidity spectra for pions and kaons have a very similar shape in both calculations.
- $m_T$ spectra are very similar at lower energies (11, 40 AGeV)
- $<m_T>$ is higher in hydro calculation at $E_{lab}=160$ AGeV
Excitation Function

- Resonance excitations and non-equilibrium effects in intermediate energy regime lead to a softening of the EoS in pure UrQMD calculation

- hybrid calculation with hadronic EoS just rises as a function of beam energy
Elliptic Flow

• Smaller mean free path in the hot and dense phase leads to higher elliptic flow

• at lower energies: hybrid approach reproduces the pure UrQMD result

• analysis with different EoS including a phase transition is needed

\( v_2/\varepsilon \) Scaling

- \( v_2 \) depends on initial conditions
- Freeze-out procedure is important
Conclusion and Outlook

• First results from the comparison of a transport and a hybrid calculation with the same initial conditions and freeze-out
  – Multiplicities are surprisingly similar
  – Strangeness is enhanced due to local equilibration
  – $<m_T>$ and elliptic flow excitation function is different

• Gradual freeze-out procedure
• Further studies of different EoS with explicit phase transition are needed
Backup
Temperature at Freeze-out
Initial State Baryon Density

Baryon rapidity distribution from hydro initial state
\( t = t_{\text{ini}} \)

\[ E_{\text{Lab}} = \]
- 5 GeV/A
- 40 GeV/A
- 160 GeV/A

Averaged over 10 events