Comparing Initial Conditions
in a (3+1)d Boltzmann + Hydrodynamics Transport Approach

Quantifying the Properties of Hot and Dense QCD Matter,
Seattle, 04.06.10
Hannah Petersen

Thanks to: Jan Steinheimer, Steffen Bass, Marcus Bleicher
Outline

- Motivation
- The Hybrid Approach
- Initial Conditions
  - Energy density distributions
  - Parameter Sensitivity Test
- Bulk Observables to constrain starting time and initial granularity at RHIC
- Fluctuating vs. Averaged, mostly at SPS
  - Initial velocities
  - Eccentricity fluctuations
  - Energy, Impact Parameter and $p_t$ Dependence of elliptic flow
- Conclusions and Outlook
Initial Conditions

- To specify the initial conditions one needs to know
  - Longitudinal Profile
    - Gaussian Parametrization \( \rightarrow \) Dynamic Approach?
  - Transverse Profile
    - Either CGC or Glauber parametrizations are common
  - Max. Value/ Integral
    - Fitted by looking at final yields
  - Initial Velocity Distributions
    - Bjorken Scaling, zero in transverse direction
  - Fluctuations
    - Mostly neglected

\( \rightarrow \) Here: Initial Conditions from UrQMD for a systematic study
Sources of Fluctuations

• Density profiles are not smooth, but there are local peaks in transverse and longitudinal direction
  – Note: NEXspheRIO has almost no longitudinal fluctuations due to flux tube structure

• Impact parameter fluctuations within one specific centrality class, multiplicity fluctuations and differences in initial geometry

• Reaction plane rotation with respect to event-plane in the laboratory
  – Hirano/Nara in Phys.Rev.C79:064904,2009 made use of this fact

→ All these effects are averaged out if assuming a smooth symmetric initial density profile
Viscosity at RHIC

• Extract transport properties of the QGP from elliptic flow measurements
• For quantitative conclusions small differences matter
• Smooth profiles as initial conditions
• Is it reliable?

⇒ Systematic comparison of averaged versus fluctuating initial conditions
NEXSpheRIO Results

NEXUS initial conditions

- Affects high-pt region
- No hadronic afterburner

Andrade et al, PRL101, 112301, 2008
Hybrid Approach

- Use advantages of transport and hydrodynamics and create combined model
- The idea here: Fix the hydro evolution and freeze-out
  → learn something about the influence of different initial conditions

1) Non-equilibrium initial conditions via UrQMD
2) Hydrodynamic evolution
3) Freeze-out via hadronic cascade (UrQMD)


UrQMD-3.3p1 is available at http://urqmd.org

Hannah Petersen Seattle, 4.6.10
Initial State

- Contracted nuclei have passed through each other
  \[ t_{\text{start}} = \frac{2R}{\gamma v} \]
  - Energy is deposited
  - Baryon currents have separated
- Energy-, momentum- and baryon number densities are mapped onto the hydro grid
- **Event-by-event fluctuations** are taken into account
- Spectators are propagated separately in the cascade

(J. Steinheimer et al., PRC 77, 034901, 2008)

\( E_{\text{lab}} = 40 \text{ AGeV} \)
\( b = 0 \text{ fm} \)
(3+1)d Hydrodynamic Evolution

**Ideal** relativistic one fluid dynamics employing:

- **HG:** Hadron **gas** including the same degrees of freedom as in UrQMD (all hadrons with masses up to 2.2 GeV)
- **CH:** Chiral **EoS** from SU(3) hadronic Lagrangian with first order transition and critical endpoint, updated as DE with Polyakov loop and deconfinement transition
- **BM:** Bag Model **EoS** with a strong first order phase transition between QGP and hadronic phase

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**Graphical Representation**

![Graph showing the evolution of energy density with time for different lab energies](image)

- **D. Rischke et al., NPA 595, 346, 1995, NPA 595, 383, 1995**
- **Papazoglou et al., PRC 59, 411, 1999**
- **Steinheimer et al., PRC 81, 044913, 2010, arXiv:0909.4421**
Freeze-out

1) Transition from hydro to transport when 
$\varepsilon < 730 \text{ MeV/fm}^3 (\approx 5 \times \varepsilon_0)$
in all cells of one transverse slice
(Gradual freeze-out, GF)

→ iso-eigentime criterion

• Particle distributions are generated according to 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)
Initial State at RHIC

- Energy-, momentum- and baryon number densities are mapped onto the hydro grid using for each particle

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

- Main parameters are \(\sigma\) and \(t_{\text{start}}\), \(|y|<2\)
- Smooth but still event-by-event in contrast to averaging over many fluctuating initial conditions

\(\sigma = 0.8\ \text{fm}\)
\(\sigma = 1.0\ \text{fm}\)
\(\sigma = 2.0\ \text{fm}\)
Initial Profiles

**Transverse Direction**

\[ b = 0 \text{ fm}; \ |y| < 2; \ t_{\text{start}} = 0.5 \text{ fm} \]

**Longitudinal Direction**

\[ b = 0 \text{ fm}; \ |y| < 2; \ t_{\text{start}} = 0.5 \text{ fm} \]

The integral is the same \( \rightarrow \) magnitude differs
Hybrid @ RHIC vs. Data

Starting time fixed to 0.5 fm to reproduce pion rapidity spectra with $\sigma = 1$ fm

- Higher granularity (lower $\sigma$)
  - Reduced yields
  - Longer lifetime
Parameter Sensitivity Tests

- Sophisticated statistical analysis
- Emulator predicts results of calculations for parameter sets by means of advanced statistics
- Number of pions in the $t_{\text{start}} - \sigma$ plane
  → Determine reasonable combinations of parameters

Thanks to Chris Coleman-Smith, MADAI collaboration
Rapidity Spectra

- Larger starting time leads to double-hump structure in rapidity spectra
  → longitudinal dynamics constrains starting time ∼0.5 fm
Transverse Spectra

- All four cases really produce similar yields
- Transverse spectra are too flat $\rightarrow$ Other EoS?
Elliptic Flow

For smoother profiles starting time is larger than 1 fm
→ Too late to build up enough $v_2$
Lattice EoS

- Particle yields and elliptic flow constant (requires earlier transition)
- $m_T$ spectra better reproduced
Comparison of Initial Conditions at SPS

\[ \text{E}_{\text{lab}} = 160 \text{A GeV, mid-central} \]

Fluctuating (default)

Glauber (\( N_{\text{part}} \))

Averaged (over 100 events)

- UrQMD initial conditions have a different shape than the ones from a Glauber model (parameters taken from Teaney et al. nucl-th/0110037)
Initial State for Non-Central Collisions

Pb+Pb at $E_{lab} = 40$ AGeV with $b = 7$ fm at $t_{\text{start}} = 2.83$ fm

Energy density profile

Weighted velocity profile

Shapes look different event-by-event

(H.P. et al., PRC 79, 054904, 2009)
Initial Transverse Velocity Profile

- The initial velocity is finite in transverse direction

Test influence by setting \( v_x \) and \( v_y \) to zero

Mid-central (b=5-9 fm) Pb+Pb collisions

\[ \langle \beta_T \rangle = 0.09 \]
\[ \langle \beta_T \rangle = 0.05 \]
Initial Eccentricity I

Reaction Plane Eccentricity

\[ \epsilon_{RP} = \frac{\sigma_y^2 - \sigma_x^2}{\sigma_y^2 + \sigma_x^2} \]

with \( \sigma_x^2 = \langle x^2 \rangle - \langle x \rangle^2 \) and \( \sigma_y^2 = \langle y^2 \rangle - \langle y \rangle^2 \).

Participant Eccentricity

\[ \epsilon_{part} = \frac{\sqrt{(\sigma_y^2 - \sigma_x^2)^2 + 4\sigma_{xy}^2}}{\sigma_y^2 + \sigma_x^2} \]

with \( \sigma_{xy} = \langle xy \rangle - \langle x \rangle \langle y \rangle \)

\(<*,*>\) denotes average over all particles in one event

Eccentricity fluctuations increase with decreasing centrality and increasing beam energy

H.P. et al., PRC81:044906,2010
Initial Eccentricity II

\[ \delta \epsilon = \langle \epsilon^2 \rangle - \langle \epsilon \rangle^2 \] is shown as error bars

- Participant eccentricity finite at \( b=0 \) fm as expected
- Smallest difference for mid-central collisions \( b=5-9 \) fm
- All particles that have interacted at least once or that are newly produced
Rapidity spectra for pions and kaons are steeper for averaged initial conditions and independent of the initial transverse velocity profiles.

Central (b<3.4 fm) Pb+Pb/Au+Au collisions
The transverse mass distributions for pions, kaons and protons do not depend on the initial fluctuations (this is a different average than shown before!)

Difference in the dynamics between hydro and transport becomes visible at 160A GeV
Elliptic Flow - Overview

- $v_2$ is largely insensitive to the initial conditions from UrQMD with respect to fluctuations and initial velocity profile.
Impact Parameter Dependence

- No big differences for different EoS
- For mid-central collisions largest values of $v_2$ are reached
- Seems to be largely insensitive to the fluctuations
- Also fixed impact parameter calculation fits in the picture

H.P. et al., PRC81:044906, 2010
Energy Dependence

Integrated $v_2$ is not sensitive to different setups
Hydro washes out initial differences
For pions at high $p_t$ the BM calculation yields larger elliptic flow for fluctuating initial conditions: longer expansion times?
Conclusions and Outlook

- Dynamical approach for initial evolution constrains starting time to be less than 1 fm at RHIC energies
- Smooth event-by-event profiles produces too much entropy
  → it matters how to average
- $v_2$ is largely insensitive to the initial conditions from UrQMD with respect to fluctuations and initial velocity profile

- Constrain initial conditions by other observables like correlations (Ridge) and fluctuations (charge correlations), $v_2$ fluctuations, triangular flow,...
- Look at smaller systems, Cu+Cu?
Charged Particles in Different Hemispheres

From Quan Wang, Presentation at APS Meeting

\[
(A_{ud}^+)^2 = \frac{(N_u^+ - N_d^+)^2}{(N_u^+ + N_d^+)^2}
\]

\[
(A_{ud}^-)^2 = \frac{(N_u^- - N_d^-)^2}{(N_u^- + N_d^-)^2}
\]

\[
A_{ud}^{+/−} = \frac{(N_u^+ - N_d^+)(N_u^- - N_d^-)}{(N_u^+ + N_d^+)(N_u^- + N_d^-)}
\]

→ Finite correlation on the order of $1 \times 10^{-3}$, UD > LR
Charged Particle Asymmetry

- Asymmetries are larger for mid-central collisions
- More granularity of initial state leads to higher correlation

STAR data

Open symbols: central
Filled symbols: mid-central

\[
\begin{align*}
(A_{ud}^+)^2 & \\
(A_{ud}^-)^2 & \\
A_{ud}^{+/ -} & \\
(A_{lr}^+)^2 & \\
(A_{lr}^-)^2 & \\
A_{lr}^{+/ -} & \\
\end{align*}
\]
Backup
Time Evolution of Elliptic Flow

- Elliptic flow develops after $t_{\text{start}}$ in the hadronic transport approach
- Different EoS lead to very different behaviour
Flow from Different Stages

$v_2$ is mostly generated during the hydrodynamic expansion

Afterburner effect might be larger with different transition criterion
Dependence on Transition Criterion

- Smaller **mean free path** in the hot and dense phase leads to higher elliptic flow.
  - Elliptic flow is sensitive to finite viscosity.
- Gradual transition leads to a better description of the data.
  - Transition criterion has to be further studied.

(H.P. et al., PRC 79, 054904, 2009)

Data from E895, E877, NA49, Ceres, Phenix, Phobos, Star
Multiplicities vs. Energy

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

- Results for particle multiplicities from AGS to SPS are similar

- Strangeness is enhanced in the hybrid approach due to local equilibration

Central (b<3.4 fm) Pb+Pb/Au+Au collisions

Data from E895, NA49

(H. P. et al., PRC 78:044901, 2008)