Beam Energy Scan: Observables and the Equation of State

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The QCD Phase Diagram

- Main goals of the beam energy scan program:
  - Questions to be answered:
    - What is the temperature and the density? What are the relevant degrees of freedom?
    - Phase transition, critical point?
    - What are the transport properties? \((\eta/s)(T,\mu_B)\) and \((\zeta/s)(T,\mu_B)\)
  - The chance to learn about QCD thermodynamics that is not (yet) accessible by lattice techniques
  - What is necessary to establish **definitive links** between observables and structures in the QCD phase diagram?
The Remaining Challenge

- Spread of the system in temperature and baryo-chemical potential has consequences on observables

Detailed dynamical modeling is required:
- EoS and transport coefficients in the whole phase diagram
- Non-equilibrium dynamics at the phase transition
Dynamical Description of Heavy Ion Collisions

- Two regimes with well-established approaches
Dynamical Description of Heavy Ion Collisions

• Two regimes with well-established approaches

'Standard model' at high energies ($\sqrt{s_{NN}} = 39 \text{ GeV}-5.5 \text{ TeV}$):

• Non-equilibrium initial evolution
• Viscous hydrodynamics
• Hadronic transport

→ Refinement and Bayesian multi-parameter analysis
Dynamical Description of Heavy Ion Collisions

- Two regimes with well-established approaches

At very low beam energies ($\sqrt{s_{NN}} < 3$ GeV):

- **Hadronic** transport approaches
- Resonance dynamics
- Nuclear potentials

→ High density phase? Multi-particle interactions?
Dynamical Description of Heavy Ion Collisions

- Two regimes with well-established approaches

- How to interpolate between the two? Transport with hydro bubbles? Hydro with transport corona?

- How to model the phase transition/critical point?

'Standard model' at high energies \( (\sqrt{s_{NN}} = 39 \text{ GeV-5.5 TeV+}) \)

Hadron transport at very low beam energies \( (\sqrt{s_{NN}} < 3 \text{ GeV}) \)
Dynamical Description of Heavy Ion Collisions

• Two regimes with well-established approaches

Low beam energies: \( \sqrt{s_{\text{NN}}} = 3-39 \text{ GeV} \):

THIS TALK

• Disclaimer:
  Personally biased selection of observables and results
Challenges at lower beam energies:

- Finite net-baryon density (as conserved current and in EoS)
- Dissipative effects/hadronic interactions gain importance
- Non-equilibrium dynamics with a probably first order phase transition
Hybrid Approach

• Initial State:
  – Initialization of two nuclei
  – Non-equilibrium hadron-string dynamics
  – Initial state fluctuations are included naturally

• 3+1d Hydro + EoS:
  – SHASTA ideal relativistic fluid dynamics
  – Net baryon density is explicitly propagated
  – Equation of state at finite $\mu_B$
  – Karpenko et al: 3+1d viscous hydrodynamics

• Final State:
  – Hypersurface at constant energy density
  – Hadronic rescattering and resonance decays within hadron transport
Elliptic Flow

Second coefficient of the Fourier expansion of the azimuthal particle distribution:

\[ v_2 = \left\langle \frac{p_x^2 - p_y^2}{p_T^2} \right\rangle \]

Coordinate space asymmetry \rightarrow momentum space anisotropy

Relativistic fluid dynamics with very low viscosity describes elliptic flow at RHIC (and LHC)
• Transition from squeeze-out at low energies to in-plane flow at high energies -> hadron transport underestimates flow charged particles, $|y|<0.1$

by Markus Mayer

• Sensitive to equation of state of nuclear matter, here in terms of a mean field between nucleons

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Elliptic flow scaled by the initial eccentricity vs. density in the overlap region allows to compare different centralities and energies

→ Ideal hydro limit reached at highest RHIC energies
Elliptic flow scaled by the initial eccentricity vs. density in the overlap region allows to compare different centralities and energies

→ Ideal hydro limit reached at highest RHIC energies

Qualitative behaviour nicely reproduced in 3+1d transport+hydro approach

→ Uncertainty due to eccentricity calculation
Elliptic Flow

- Flow observables considered as evidence for QGP

- $v_2(p_T)$ almost identical at all beam energies

- Small energy dependence is reproduced by hybrid approach

STAR, PRC 86 (2012) 054908

Interplay of Hydro + Transport

- Initial non-equilibrium evolution compensates for diminished hydrodynamic stage at lower beam energies
- Contribution of late stage hadronic rescattering ~10%

Equation of State and IC Fluctuations

- Symbols: Event-by-event calculations
- Horizontal lines: Averaged results
- Blue: Hadron Gas EoS
- Black: Bag Model EoS with first order phase transition
- NO difference visible in the centrality dependence of elliptic flow

**η/s Energy Dependence**

- Viscous UrQMD hybrid fitted to beam energy scan and SPS data allows to extract **effective** shear viscosity of the hydrodynamic stage

Analysis „by eye“

Bayesian framework

- More insights on transport coefficients especially at **finite** $\mu_B$ from non-perturbative methods are needed

see e.g. holographic approaches: R. Rougemont et al, Phys. Rev. Lett. 115, 202301 and JHEP 04 (2016) 102


Auvinen et al., arXiv:1610.00590
Fluctuations introduce **higher order flow coefficients** that have been observed at the RHIC and LHC experiments.

A chance to disentangle initial state fluctuations from other e-by-e fluctuations related to phase transition?

Measuring Fluctuations

- At high energies:
  - $\nu_3$ is equal to $\sigma_{v2}$
- At lower energies $\nu_3$ vanishes

$\sigma_{v2} = \sqrt{\frac{1}{2}(v_2\{EP\}^2 - v_2\{RP\}^2)}$

- Initial state geometry and fluctuations rather independent of beam energy

Summary: Elliptic and Triangular Flow

- Elliptic flow also builds up in hadronic transport approach
- $v_3$ is more sensitive to the viscosity
- Disappearance of $v_3$ as a signal of the disappearance of the quark-gluon plasma?
Directed Flow

- Collective deflection of particles in reaction plane

- Non-monotonic energy dependence of $v1$ slope
  - First order phase transition?
Directed Flow

- Collective deflection of particles in reaction plane

- Non-monotonic energy dependence of $v_1$ slope
  - First order phase transition?
  - No quantitative theory description so far
Pure Fluid Calculations

- Negative slope is reproduced in fluid dynamic calculation

- Assumptions
  - Cold nuclear matter initialization (no pre-equilibrium transport)
  - Direct integration of momentum in x-direction without hadronic rescattering

$\nu_1$ Slope for Pions and Protons

- Particlization added including hadronic rescattering
- Isochronous versus iso-energy density transition criterion
  - Drastic effect on dip structure

Hybrid approach with different equations of state shows similar results.

Alternative calculations within transport/3-fluid dynamics confirm complexity of this observable.

Additional issues that influence the energy dependence like nucleon potentials, interactions with spectators have to be sorted out by looking at different particle species and the centrality dependence.

**R_0/R_s Ratio**

- **Idea:** Softest point increases the lifetime of the system

- **NA49 and STAR data show a slight peak**

- **Hybrid approach confirms larger ratio for first order transition**

- **Open question:** **Cluster** formation from phase separation?

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Y. Karpenko, WPCF 2014
Higher Moments

- New result from HADES Au+Au collisions: Skewness and kurtosis show **non-trivial** energy dependence

- Experimental results are **scrutinised**

- Can we draw **exclusion plots** on the phase diagram by extracting 2-, 3- and 4-particle correlations?

A. Bzdak, V. Koch and N. Strodthoff, arxiv:1607.07375
Deep Learning Techniques

- First proof-of-principle application of deep learning to heavy ion physics

- Extraction of QCD equation of state seems possible

- Plans: Device new observables and apply to real data

Inspired from Brain/CNN

- As in image recognition, raw \((p_T, \Phi)\) data is classified

  - „DOG“
  - „CAT“
  - Cross-Over „(0,1)“
  - First-Order „(1,0)“
Importance Maps

• By replacing individual pixels, one can extract crucial features

• Helpful to understand sensitivities and device new observables
Summary

- Heavy ion collisions at low beam energies reach the high density region to explore structures in phase diagram
- Hybrid hydrodynamic + transport approaches are extended to finite net baryon density
  - Elliptic flow is sensitive to overall dynamics
  - Vanishing triangular flow is a possible sign for vanishing quark-gluon plasma
  - Directed flow poses a challenge to theory interpretations
- Deep learning techniques might help to identify new sensitive observables
- New results by BNL-BES I and NA61 at SPS and exciting future experimental programs coming up at BNL-BES II, FAIR, NICA and JPARC-HI
Backup
At low energies:
- Nuclear potentials are crucial to explain the magnitude of the $v_1$ slope

NA 49 data:
- Hints for negative slope - antiflow?

Pure hadron transport shows different energy dependence

Directed and Elliptic Flow

**Directed flow** $v_1$

- $v_1 = \frac{\langle p_x \rangle}{\langle p_T \rangle}$
- Bounce-off at low beam energies

**Elliptic flow** $v_2$

- $v_2 = \frac{\langle p_x^2 - p_y^2 \rangle}{\langle p_T^2 \rangle}$
- Lower energies:
  - Out-of-plane flow due to blocking spectators
- Higher energies:
  - In-plane flow due to pressure gradients

References:
- Taken from: S. Soff, Kollaktiver Fluss in Schwerionenkollisionen - Deduktion elementarer Eigenschaften angeregter Kerne, 1995
- Taken from: H. Büssing, Azimutale Photonen-Korrelationen in ultrarelativistischen p+p-, Pb+Pb- und Au+Au-Reaktionen, 2002
Potentials in SMASH

- Skyrme potential: \( U_{Sk} = \alpha (\rho / \rho_0) + \beta (\rho / \rho_0)^\tau \)

- Skyrme potential describes effective interaction between nucleons

- Skyrme potential acts repulsively at high nucleon densities

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<td>( \kappa )</td>
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- Symmetry potential: \( U_{Sym} = \pm 2 S_{Pot} \frac{\rho_13}{\rho_0} \)

- Fermi motion, Pauli blocking
Λ Polarization

- Global hyperon polarization has been measured

- Exciting possibility to constrain final magnetic field and vorticity

STAR collaboration, arXiv:1701.06657
NA49 Data on Elliptic Flow

- Elliptic flow for pions as a function of transverse momentum:
  - 40A GeV:
    - Pure transport and hybrid approach give similar results
  - 160A GeV:
    - Hadron transport underestimates elliptic flow by a factor of 2

Collective Behaviour

- Response of the system to initial spatial anisotropy

**Spatial anisotropy**

$$\epsilon = \frac{\langle y^2 - x^2 \rangle}{\langle y^2 + x^2 \rangle}$$

**Hydrodynamic behaviour**

mean free path $\lambda \to 0$

**Momentum anisotropy**

$$v_2 = \frac{\langle p_x^2 - p_y^2 \rangle}{\langle p_x^2 + p_y^2 \rangle}$$

- No secondary interactions
  mean free path $\lambda \to \infty$

- Mean free path $\lambda \to \infty$

- Mean free path $\lambda \to 0$

- Interactions between particles
RHIC Beam Energy Scan

- Flow observables considered as evidence for QGP formation - does it disappear at lower energies?

- Differential $v_2$ for charged hadrons almost identical for all beam energies

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