Precision Extraction of QGP Properties with Quantified Uncertainties

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arXiv:1605.03954

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Introduction
Ordinary Matter:
• phases determined by (electro-magnetic) interaction
• apply heat & pressure to study phase-diagram
Phases of Matter

**Ordinary Matter:**
- phases determined by (electromagnetic) interaction
- apply heat & pressure to study phase-diagram

**Phases of QCD matter:**
- heat & compress QCD matter:
  - collide heavy atomic nuclei
- numerical simulations:
  - solve partition function (Lattice)
The only way to heat & compress QCD matter under controlled laboratory conditions is by colliding two heavy atomic nuclei!
Heating & Compressing QCD Matter

ALICE experiment @ CERN:

- 1000+ scientists from 105+ institutions
- dimensions: 26m long, 16m high, 16m wide
- weight: 10,000 tons

two more experiments w/ Heavy-Ions:
- CMS, ATLAS
Heating & Compressing QCD Matter

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typical Pb+Pb collision @ LHC:
- 1000s of tracks
- task: reconstruction of final state to characterize matter created in collision
Time Evolution of a Heavy-Ion Collision

- **Initial State:**
  - fluctuates event-by-event
  - classical color-field dynamics

- **Pre-equilibrium:**
  - rapid change-over from glue-field dominated initial state to thermalized QGP
  - time scale: 0.15 to 2 fm/c in duration
  - significant conceptual challenges!

- **QGP and hydrodynamic expansion:**
  - proceeds via 3D viscous RFD
  - EoS from Lattice QCD

- **hadronic phase & freeze-out**
  - interacting hadron gas
  - separation of chemical and kinetic freeze-out
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**Principal Challenges of Probing the QGP with Heavy-Ion Collisions:**

- time-scale of the collision process: $10^{-24}$ seconds! [too short to resolve]
- characteristic length scale: $10^{-15}$ meters! [too small to resolve]
- confinement: quarks & gluons form bound states, experiments don’t observe them directly
  - computational models are need to connect the experiments to QGP properties!
**Modeling of Heavy-Ion Collisions**

**microscopic transport models** based on the Boltzmann Equation:
- transport of a system of microscopic particles
- all interactions are based on binary scattering

\[
\frac{\partial}{\partial t} f_1(\vec{p}, \vec{r}, t) = \sum_{\text{processes}} C(\vec{p}, \vec{r}, t)
\]

**diffusive transport models** based on the Langevin Equation:
- transport of a system of microscopic particles in a thermal medium
- interactions contain a drag term related to the properties of the medium and a noise term representing random collisions

\[
\vec{p}'(t + \Delta t) = \vec{p}(t) - \frac{\kappa}{2T} \vec{v} \cdot \Delta t + \xi(t) \Delta t
\]

**(viscous) relativistic fluid dynamics:**
- transport of macroscopic degrees of freedom
- based on conservation laws:

\[
\partial_\mu T^{\mu\nu} = 0
\]

\[
T_{ik} = \varepsilon u_i u_k + P (\delta_{ik} + u_i u_k) - \eta \left( \nabla_i u_k + \nabla_k u_i - \frac{2}{3} \delta_{ik} \nabla \cdot u \right) + \zeta \delta_{ik} \nabla \cdot u
\]

(plus an additional 9 eqns. for dissipative flows)

**hybrid transport models:**
- combine microscopic & macroscopic degrees of freedom
- current state of the art for RHIC modeling
Modeling of Heavy-Ion Collisions

**microscopic transport models** based on the Boltzmann Equation:
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- all interactions are based on binary scattering
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\left[ \frac{\partial}{\partial t} + \frac{\vec{p}}{E} \times \frac{\partial}{\partial \vec{r}} \right] f_1(\vec{p}, \vec{r}, t) = \sum_{\text{processes}} C(\vec{p}, \vec{r}, t)
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Each transport model relies on roughly a dozen physics parameters to describe the time-evolution of the collision and its final state. These physics parameters act as a representation of the information we wish to extract from RHIC & LHC.
QCD Transport Coefficients: Shear Viscosity
shear and bulk viscosity are defined as the coefficients in the expansion of the stress tensor in terms of the velocity fields:

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assuming matter to be quasi-particulate in nature:

- microscopic kinetic theory:
  \[ \eta \approx \frac{1}{3} n \bar{\rho} \lambda_f = \frac{\bar{\rho}}{3\sigma_{tr}} \]

- unitary limit on cross sections suggests a lower bound for \( \eta \)
  \[ \sigma_{tr} \leq \frac{4\pi}{\bar{\rho}^2} \quad \Rightarrow \quad \eta \geq \frac{\bar{\rho}^3}{12\pi} \]

• viscosity decreases with increasing cross section (forget molasses!)
• for viscous RFD, the microscopic origin of viscosity is not relevant!
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assuming matter to be quasi-particulate in nature:

- Microscopic kinetic theory:
  \( \eta \) is given by the rate of momentum transport:
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The determination of the QCD transport coefficients is one of the key goals of the US relativistic heavy-ion effort!
Collision Geometry: Elliptic Flow

- two nuclei collide rarely head-on, but mostly with an offset:
  - only matter in the overlap area gets compressed and heated up
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**Reaction plane**

- gradients of almond-shape surface will lead to preferential emission in the reaction plane
- asymmetry out- vs. in-plane emission is quantified by 2nd Fourier coefficient of angular distribution: $v_2$

$vRFD$: good agreement with data for very small $\eta/s$
what can ordinary matter, e.g. He or H$_2$O teach us about $\eta/s$?

- $\eta/s$ has minimum & discontinuity at $T_C$
Temperature Dependence of $\eta/s$

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- $\eta/s$ has minimum & discontinuity at $T_C$

- temperature dependence of $\eta/s$ in QCD can be estimated in low- and high-temperature limit:
  - low temperature: chiral pions
  - high temperature: QGP in HTL approximation

The Challenge of a rigorous Model to Data Comparison

Model Parameter:
- eqn. of state
- shear viscosity
- initial state
- pre-equilibrium dynamics
- thermalization time
- quark/hadron chemistry
- particlization/freeze-out

Experimental data:
- π/K/P spectra
- yields vs. centrality & beam
- elliptic flow
- HBT
- charge correlations & BFs
- density correlations
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- large number of interconnected parameters w/ non-factorizable data dependencies
- data have correlated uncertainties
- develop novel optimization techniques: Bayesian Statistics and MCMC methods
- transport models require too much CPU: need new techniques based on emulators
- general problem, not restricted to RHIC Physics

→ collaboration with Statistical Sciences
high precision Planck data on the CMB has allowed for the verification of the standard cosmological model and the most accurate determination of cosmological parameters to date

- Is Heavy-Ion Physics capable of this type of Precision Science?
we are entering the era of precision extraction of QGP properties via comparison of high quality data with comprehensive computational models

 calibrated posterior distribution of $\Lambda$CDM model parameters with Planck data

calibrated posterior distribution of hybrid vRFD+micro model parameters with LHC data