Studying baryon-rich matter in low energy heavy ion collisions

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Strong interaction matter at extreme conditions

Statistical Hadronization Model of particle production

Chemical potential is always related to net density:

\[ \mu = T \ln \left( \frac{\rho}{g} \left( \frac{mT}{2\pi} \right)^{-3/2} \left( \hbar c \right)^3 \right) \]

(formula for ideal classical gas of one-type particles)

Borsanyi et al. [Wuppertal-Budapest Collab.], JHEP 1009 073 (2010)
Isserstedt, Buballa, Fischer, Gunkel, PRD 100 074011 (2019)
Gao, Pawlowski, PLB 820 136584 (2021)
Cuteri, Philipsen, Sciarra, JHEP 11 141 (2021)
McLerran, Pisarski, NPA 796 63 (2007)

NA60, Specht et al., AIP Conf.Proc. 1322 1, 1-10 (2010)
Andronic et al., Nature 561 no.7723 (2018)
What can we learn?

- Microscopic properties of baryon-dominated matter
- Equation-of-State
- First-order phase transition?
- QCD critical point?

- Observables:
  - E-b-e correlations and fluctuations
  - Flavor production
  - Collective effects
  - Dileptons
Azimuthal anisotropy ("flow")
with respect to the reaction plane (RP)

Fourier coefficients of the particle emission:
\[
\frac{dN}{d(\phi - \Psi_{EP})} \propto 1 + 2 \sum_{n=1}^{\infty} \nu_n \cos(n(\phi - \Psi_{EP}))
\]

\(\nu_1\) antisymmetric around \(y = 0\)

Intermediate energy, \(v_2 < 0\)
High energy, \(v_2 > 0\)

Sensitivity to:
- QCD equation of state
  - Nuclear symmetry energy \([v_2(y_{cm})\ for\ protons]\) Y. Wang et al., PLB 802 135249 (2020)
  - Constraints from comparing with predictions from microscopic transport
- Existence of the first-order phase transition

Paech et al., NPA 681 41-48 (2001)
J. Steinheimer et al., PRC 89 054913 (2014)
Constraining the EoS with $v_n$ and transport models

Nuclear potential in transport models

- Usually implemented as a mean-field Skyrme potential:

$$V_{sk} = \alpha \left( \frac{\rho_{int}}{\rho_0} \right) + \beta \left( \frac{\rho_{int}}{\rho_0} \right)^\gamma$$

which can have “harder” or “softer” energy dependence

- Currently, parameters are partly fixed by requiring NM to be stable around $\rho_0$
- Problem with relativistic treatment
- Higher harmonic order – higher discriminating power
- Consistent description of all $v_n$, for different phase-space regions and centrality classes is not yet there (but is necessary!)
Pion anisotropy in Au+Au collisions

- Good statistics to constrain models and equation of state
- There is room for improvement in the models
- Need for a simultaneous description of all $v_n$, for different:
  - particle species (at HADES pions and kaons)
  - phase-space regions
  - centrality classes
  - colliding systems (at HADES Au+Au and Ag+Ag)
Pion yields and distributions

Example for $\pi^-$, the same holds for $\pi^+$

- Different calculations consistently fail to describe experimental data
- Note high net baryon density:
  - Influence of long-range EM interaction with the positively charged fireball
  - Most pions come from decays of baryonic resonances
  - Proper implementation of the in-medium spectral function of resonances is needed

HADES Collaboration, EPJA 56, 259 (2020)
https://www.hepdata.net/record/ins1796710
Shift of the pion energy by the Coulomb potential

- More accurate extrapolation to low $p_t/m_t$
- Extracting the average value of the Coulomb potential energy
  - Improved formalism compared to previous works
- Translating it to the fireball size at the freeze-out → density → $\mu_B$
  - Method independent from SHM fits
  - Result in good agreement

Black data points, SHM fits:
- Nature 561, no.7723, 321-330 (2018), also the black curve
- PLB 764, 241-246 (2017)
- PRC 73, 034905 (2006)
- PRC 78, 044904 (2017)
- PRC 76, 052203 (2007)
- EPJA 52, no.6, 178 (2016)

HADES Collaboration, arXiv:2202.12750
Correlated pion-proton pairs

- The dominant source of particle production at SIS18
- High statistics allows multi-differential analysis
- Understanding of “kinematical” mass shift with S-matrix formalism
- Fix in-medium cross-sections and spectral functions

Analysis of $\pi^+p$ and $\pi^-p$ pairs

HADES Collaboration, PLB 819, 136421 (2021)

Sensitivity to the shape


Adapting to HADES energies: SH et al., PRC 102, 054903 (2020)
Global spin polarization

- First observed at RHIC: "most vortical fluid"
- What is the mechanism of converting $\vec{L}$ to $\vec{S}$?
  - Do we see hydrodynamic fluid with spin?
  - Hydrodynamics description requires (local) thermal equilibrium
- Now: thorough systematics study and support from Ag+Ag data
- Note that $|\vec{L}|$ is substantially lower in Ag+Ag than in Au+Au:
  \[ L_y \approx \frac{1}{2} A b \sqrt{s} \sqrt{1 - \left(2M/\sqrt{s}\right)^2} \]
System with Multi-Particle Correlations?

- Different particles
- Different production mechanisms
- Different thresholds
- Common scaling with participant number
- Quarks are easily reshuffled between hadron states?

Quantum percolation at $\rho \sim 1.8\rho_0$

K. Fukushima, T. Kojo, W. Weise, PRD 102, 096017 (2020)
Long-range correlations

- Study event-by-event distributions of conserved charges (like baryon number) in a selected phase-space window
- Quantified by moments or cumulants well known from statistics
- Will deviate from the Poisson baseline if the matter is in the vicinity of the phase transition/critical point

Direct link to EoS:
\[
\frac{1}{\sqrt{s_{NN}}} k_n = \frac{\partial n_p}{\partial \mu_R}
\]
\[
\hat{\rho} = \frac{\rho}{T}
\]
\[
\hat{\mu} = \frac{\mu}{T}
\]

M. Stephanov, PRL 107 052301 (2011)

\(\alpha \approx n \rightarrow \) signature of multi-particle correlations \((d_{y_{corr}} > 1)\)
Electromagnetic probes

- Photons (virtual and real):
  - Don't undergo strong interaction
  - Probe all the stages of heavy-ion collisions
- Radiation from hot and dense matter is isolated by subtracting:
  - First-chance NN collisions
  - Meson decays at the freeze-out
Electromagnetic spectral function

- In vacuum, it is measured in $e^+e^-$ annihilation experiments:

$$R \propto \frac{\text{Im}\Pi_{em}}{M^2}$$

Low mass region LMR

EM spectral function is saturated by light vector mesons – with $J^P = 1^-$, same as for (virtual) photon, mainly $\rho^0$

Intermediate mass region IMR

Perturbative QCD continuum, quark degrees of freedom
Thermal dileptons at high $\mu_B$

- Thermal dilepton production rates

  L. D. McLerran, T. Toimela, PRD 31 545 (1985)

  $$\frac{dN_{ll}}{d^4q d^4x} = -\frac{\alpha_{em}^2}{\pi^3} \frac{L(M^2)}{M^2} f^B(q_0, T) \text{Im} \Pi_{em}(M, q, T, \mu_B)$$

- Melting of $\rho$ clearly visible
- Collisional broadening is not sufficient to account for that
- $\rho$ melting handled properly by the local thermal equilibrium approach (CG)

- Role of medium effects - coupling of $\rho$ to resonances

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CG FRA: PRC 92 014911 (2015)
CG GSI-Texas A&M: EPJA, 52 5 131 (2016)
CG SMASH: PRC 98 054908 (2018)
HSD: PRC 87 064907 (2013)
Thermal dileptons at high $\mu_B$

- Boltzmann factor dominates the exponential shape of the spectrum if $\text{Im} \Pi_{\text{EM}}/M^2$ does not change much with $M$
- Slope of the invariant mass not affected by the fireball expansion
- True (average) source temperature – not affected by the blue shift

\begin{equation}
\frac{dN_{\text{ll}}}{d^4q d^4x} = -\frac{\alpha_{\text{em}}^2 L(M^2)}{\pi^3} \frac{f^B(q_0,T)\text{Im} \Pi_{\text{EM}}(M,q,T,\mu_B)}{M^2}
\end{equation}
Discovering the QCD “caloric curve”

Temperature vs. energy density (collision energy as a proxy)

Up to now, only published data from HADES and NA60

Phase transition may manifest itself as a plateau

Nuclear liquid-gas phase transition

Pochodzalla et al., PRL 75 1040-1043 (1995)
Lifetime of the fireball

- Thermal radiation is emitted during the whole lifetime of the system.
- The integrated yield in $0.3 < \frac{M_{\text{ee}}}{\text{GeV/c}^2} < 0.7$ is the most sensitive to measure the lifetime.
- At a phase transition “production” of the latent heat would increase the lifetime.

Heinz and Lee, PLB 259, 162 (1991)
Barz, Friman, Knoll, and Schulz, PLB 254, 315 (1991)
Rapp, van Hees, PLB 753 (2016) 586
Summary

- A comprehensive comparison of flow harmonics between experiment and transport models is a great tool to constrain the EoS

- More work must be done to get good agreement of phase-space distributions
  - Coulomb effect
  - Description of resonances

- Interactions in the system:
  - Global hyperon polarization keeps growing with decreasing collision energy
  - Common power-law scaling for all strange particles (in a given collision system)
  - Proton number cumulants consistent with long-range multi-particle correlations

- Electromagnetic probes:
  - Measurement of temperature and lifetime of the fireball
  - Structures in the excitation function will signify a phase transition