Separating Equation-of-State Dynamics from Hadronic Rescattering in Low-Mass Dileptons [arXiv:2608.04598]

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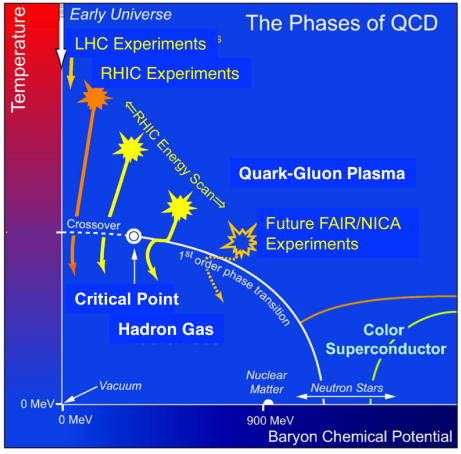
The 7th Sino-Thai Symposium on High Energy Physics, Astrophysics, Materials Science and Beyond
at Bravo Hotel, Guilin, Guangxi, China.

QCD Phase Diagram and the Goal of Heavy-Ion Collisions

- Quantum Chromodynamics (QCD) predicts that strongly interacting matter undergoes phase transition under extreme temperature T and baryon chemical potential μ_B.
  - Hadron gas $\leftrightarrow$ Chiral Symmetry Broken,
  - Quark–Gluon Plasma (QGP) $\leftrightarrow$ Chiral Symmetry Restored,
- HIC and the goal of Beam Energy Scan in:
  - understand the QCD equation of state (EoS),
  - determine the phase structure of QCD,
  - search for:
    - first-order phase transition (FOPT),
    - critical endpoint (CEP).

Challenge: Non-equilibrium and Time-integrated

How do we study and measure them in experiments?



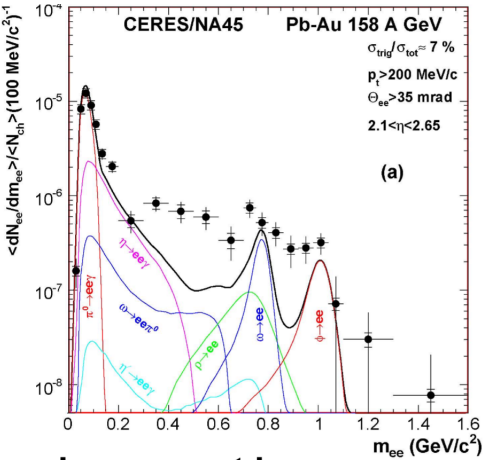
Nayak et al [arXiv:2008.04643]

Dilepton as a probe and its challenge

- Dilepton ($e^+e^-, \mu^+\mu^-$) are clean probe for HIC
- Produced from all stages (complete history of collisions)
  - $q\bar{q} \to \gamma^* \to \ell^+\ell^-$ [Early + QGP]
  - $\pi\pi \to \rho \to \ell^+\ell^-$ [Sensitive Hadronic medium]
- A substantial **dilepton excess** → **in-medium modification** as a signature for FOPT? (see Figure)
- QGP+HRG: McLerran(1985), Rapp(1999) – (Eq)
- Re-scattering: Eletsky(2001) – (Eq)
  - However, the ambiguity is that hadronic rescatterings also contribute to same mass range.

Question: 2 effects in the same range

How can we "Disantangle" these two effects from i) FOPT and ii) hadronic rescattering?



CERES/NA45 [PLB 666(2008) 425]

Strategy: vary the EoS, not the microscopic channels

$$\text{same } \rho, \omega \text{ self-energies} \quad + \quad \begin{cases} \text{FOPT}, \\ \text{COV} \end{cases} \quad \Rightarrow \quad \text{isolated EoS effect}$$

Microscopic radiation

- Describe how ρ and ω propagate and interact with surrouding medium
- ρ and ω self-energies from forward scattering.
- Identical resonance-driven channels for FOPT and COV.
- Differences in dileptons are then traced to the bulk properties.

Macroscopic evolution

- Determine the bulk properties of the medium T, μ_B, e, p, n
- Study trajectories at $\sqrt{s_{NN}} = 2.20 - 6.20$ GeV (low T, high μ_B).
- Phase structure (FOPT or COV) and dynamics are controlled based on chiral symmetry picture.

Non-equilibrium chiral fluid dynamics

- The sigma field $\sigma \sim \langle \bar{q} q \rangle$ represents the chiral condensate responsible for spontaneous chiral symmetry breaking and constituent quark mass generation.
- The chiral order parameter σ is propagated out of equilibrium and coupled to an expanding quark fluid.

$$\mathcal{L} = \bar{q}\left(i\gamma^\mu \partial_\mu - g\sigma\right) q + \frac{1}{2}\partial_\mu \sigma \partial^\mu \sigma - U(\sigma),$$

$$U(\sigma) = \frac{\lambda^2}{4}\left(\sigma^2 - \nu^2\right)^2 - H\sigma, \qquad H = f_\pi m_\pi^2,$$

$$\Omega(T,\mu) = U(\sigma) - 2N_c N_f T \int \frac{d^3p}{(2\pi)^3}\left[\ln\left(1 + e^{-(E-\mu_q)/T}\right) + \ln\left(1 + e^{-(E+\mu_q)/T}\right)\right].$$

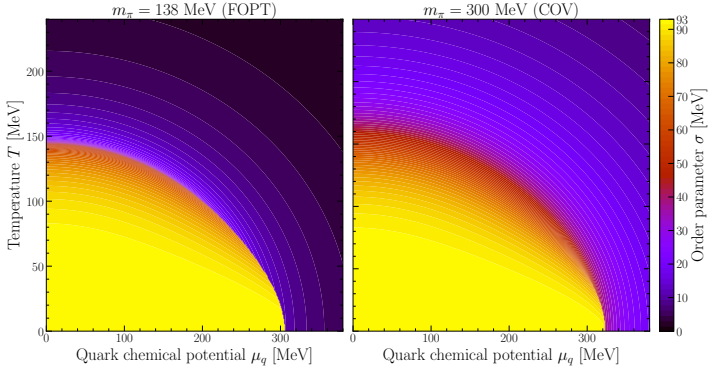
NχFD

$$\ddot{\sigma} + \left(\frac{D}{\tau} + \eta\right)\dot{\sigma} + \frac{\delta\Omega}{\delta\sigma} = \xi, \qquad \dot{e} = -\frac{e+P}{\tau} + \left[\frac{\delta\Omega_{q\bar{q}}}{\delta\sigma} + \left(\frac{D}{\tau} + \eta\right)\dot{\sigma}\right]\dot{\sigma}.$$

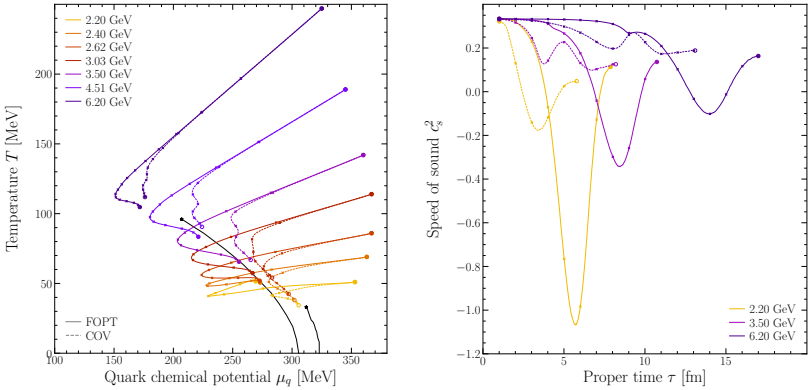
Nahrgang et al [arXiv:1105.1962]

Phase structure

- To acquire FOPT or COV, we modify the chiral broken term $H = f_\pi m_\pi^2$
  - $m_\pi = 138$ MeV: FOPT scenario.
  - $m_\pi = 300$ MeV: (effective) COV scenario.
- The evolution trajectories in phase diagram are mapped from $\sqrt{s_{NN}} = 2.20 - 6.20$ GeV as our initial conditions and stopped with freeze-out critirion.



Dynamical Trajectories and EoS softening



- Low energies, especially $\sqrt{s_{NN}} = 2.20$ GeV, probe the FOPT region most strongly.
- Reheating after supercooling appears as backbending in the (μ_B, T) trajectory.
- FOPT trajectories show stronger reduction of $c_s^2 \equiv \partial P/\partial \epsilon \rightarrow$ EoS softening $\rightarrow$ longer lifetime.

Spectral functions and Dilepton rate

The vector meson is continuously propagating and rescattering inside the medium $V + a \leftrightarrow R$ before eventually converting into a virtual photon γ^* which then gives us dileptons $\gamma^* \to \ell^+\ell^-$.
Dilepton rate in terms of imaginary part of EM correlator:

$$\frac{dN_{ee}}{d^4x\, d^4p} = -\frac{\alpha^2}{3\pi^3 M^2}\, n_B(E;\, T(\tau))\ \mathrm{Im}\,\Pi^R_{\mathrm{em}}(E, \mathbf{p}; \tau), \tag{1}$$

within vector-meson dominance the correlator is expressed through the vector propagators,

$$\mathrm{Im}\,\Pi^R_{\mathrm{em}}(E, \mathbf{p}; \tau) = \sum_{V=\rho,\omega} \left(\frac{m_V^2}{g_V}\right)^2 \mathrm{Im}\, D_V^R(E, \mathbf{p}; \tau). \tag{2}$$

The in-medium retarded propagator,

$$D_V^R(E, \mathbf{p}; \tau) = \frac{1}{E^2 - \mathbf{p}^2 - m_V^2 - \Sigma_V^R(E, \mathbf{p}; \tau)}. \tag{3}$$

Forward-scattering and self-energies

For a vector meson $V = \rho, \omega$ scattering on species $a = \pi, N$ in the medium, the forward amplitude is written as a sum of a resonances (Breit-Wigner)

$$f_{\rm c.m.}^{Va,\rm BW}(s) = \frac{1}{2q_{\rm cm}(s)} \sum_R W_R^{Va} \frac{\Gamma_R \cdot \mathrm{BR}_{R\to Va}}{M_R - \sqrt{s} - \frac{i}{2}\Gamma_R}, \tag{4}$$

Then, retarded self-energy of a vector mesons is obtained from forward amplitude,

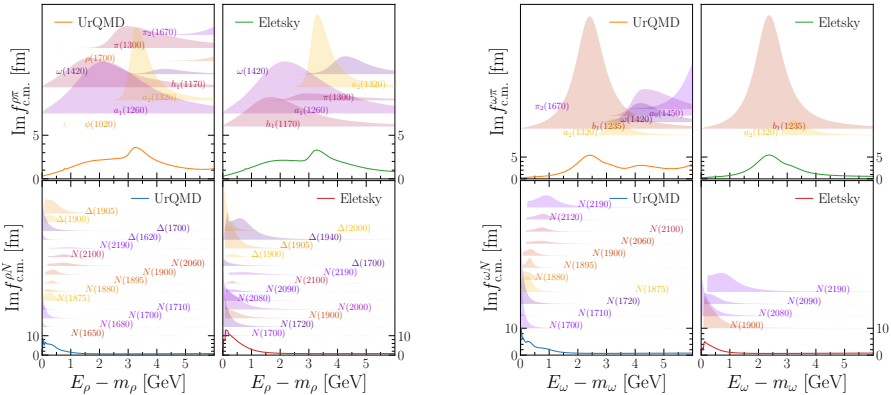
$$\Sigma_V^R(E, \mathbf{p}; \tau) = -\sum_a \int \frac{d^3k}{(2\pi)^3} \frac{n_a(\omega_k; T(\tau), \mu_B(\tau))}{2\omega_k} f_{\rm c.m.}^{Va}(s), \tag{5}$$

Connect this to the macroscopic evolution $T(\tau), \mu_B(\tau)$

- The microscopic rate is unchanged (identical Γ_R and $\mathrm{BR}_{R\to Va}$; FOPT and COV sample it along different thermodynamic histories.

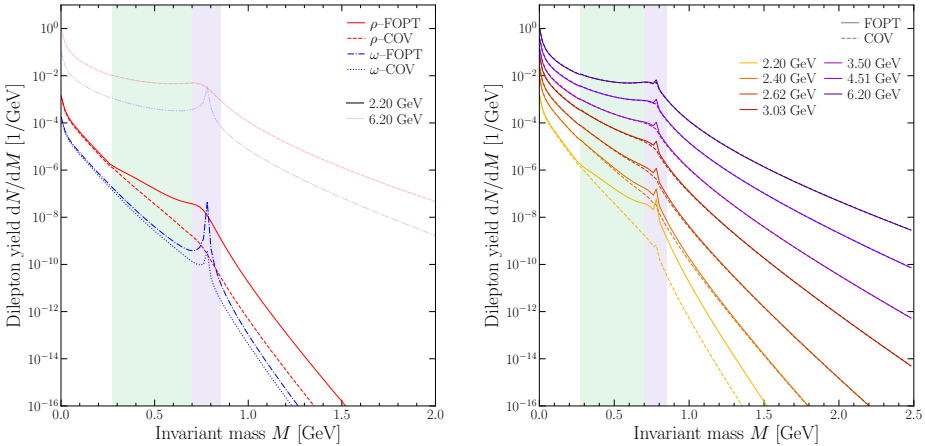
Eletsky et al [arXiv:hep-ph/0104029]

Contributed resonances



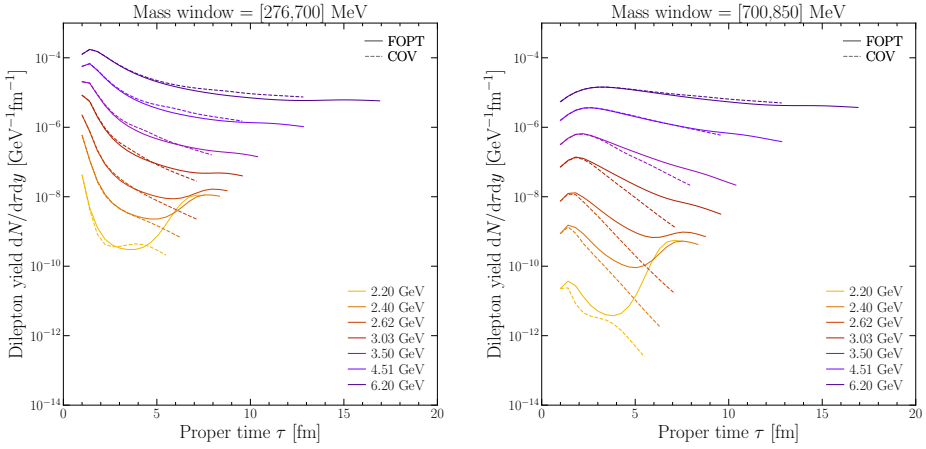
The imaginary part of forward amplitude from (Left) $R \to \rho a$, (Right) $R \to \omega a$

Result I: Invariant-mass spectra (FOPT vs COV)



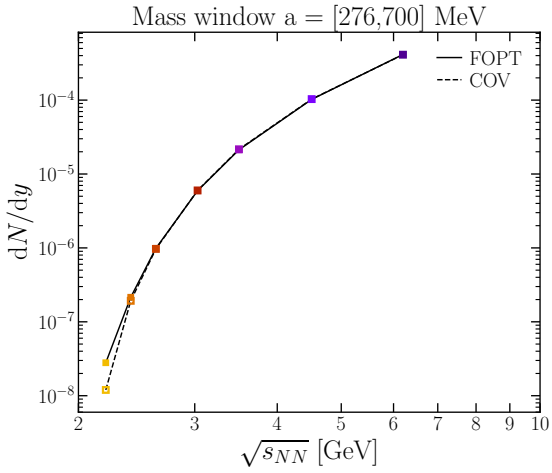
- Both ρ and ω are strongly broadened toward and enhanced is strongest at lowest energy.
- The effects are systematic according to the beam energy. It works! but no interesting physics yet.

Result II: Emission-time profiles in two mass windows

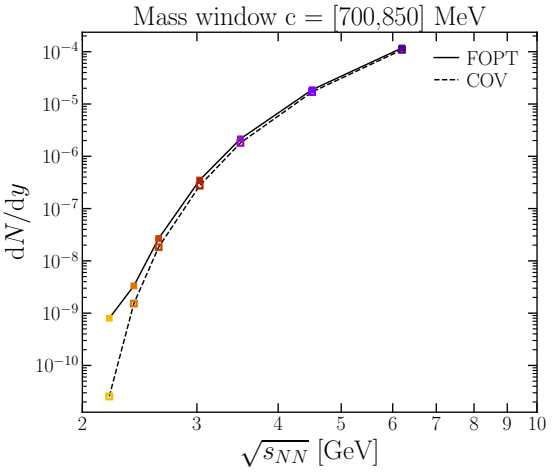


- The low-mass window: Late-time ($\sim$ 5 fm/c) $\rightarrow$ Reheating and accumulation over longer lifetime.
- The pole-mass window: FOPT splits out of COV baseline earlier $\rightarrow$ Onset of EoS softening + Reheating.

Result III: Excitation functions in two mass windows



Low-mass window



Pole-mass window

Physical interpretation

FOPT softening $\rightarrow$ delayed expansion $\rightarrow$ larger emission four-volume

Late-time Broadening

- present from low mass to pole mass,
- generated by lifetime extension and reheating,
- accumulated over a broad part of the evolution.

Early-time Enhancement

- visible mainly in the pole window,
- tied to approaching the phase boundary,
- provides the cleanest chronology handle on FOPT dynamics.

Main statement

The mass spectrum shows enhancement $\rightarrow$ the emission-time profile separates the physical origin of that enhancement $\rightarrow$ The EoS effect is visible in time-integrated

Summary and Conclusion

1. FOPT-COV comparison is investigated with identical ρ, ω rescattering channels.
2. FOPT enhances dileptons through softening, delayed relaxation, reheating, and prolonged lifetime.
3. The pole-mass window contains the clearest early-time FOPT response.
4. The low-mass continuum is mainly an accumulated late-time signal from broadened spectral strength.
5. Combined dilepton and HBT spectroscopy is motivated for future EoS study (time-sensitive observable)

Selected references


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