Enhanced dilepton emission from a phase transition in dense matter

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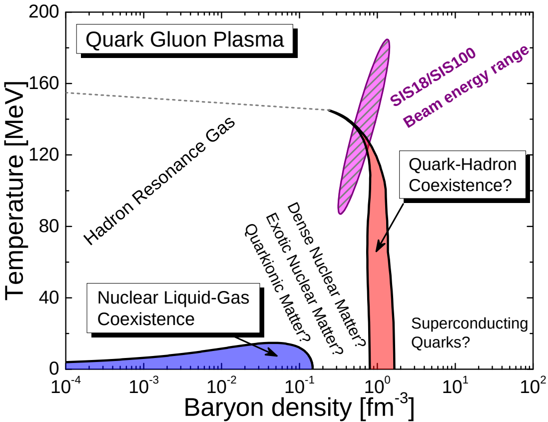
Outline

1. Introduction
2. Dileptons and an equation of state at SIS18/100 energies
    - Coarse Graining
    - Pions‘ fugacity
    - Spectra
    - Dileptons and different EoSs
3. Conclusions

QCD phase diagram



[Anton Motornenko, Jan Steinheimer, Horst Stoecker: arXiv:2105.12475]

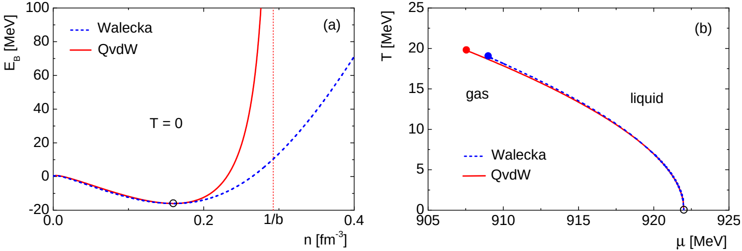
- In the vicinity of the hypothetical phase transition
- Cosmic matter in the laboratory, access to vector and axial interactions important for neutron matter
- Exotic states of matter: phase transition in delta matter, pion interactions

Nuclear matter

Consists of nucleons: **protons and neutrons**. Its **ground state** $(P = 0,\ T = 0)$ parameters estimated from properties of nuclei:

- Normal nuclear **density:** $\boldsymbol{\rho_0 = 0.16}$ $\mathbf{fm}^{-3}$
- Binding energy **E/A = -16 MeV** from extrapolation of energy of finite nuclei

Evidence for nuclear liquid-gas transition found experimentally [ALADIN@GSI (1995)]

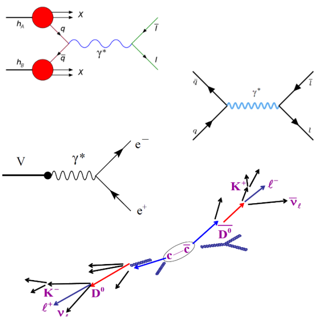


R. V. Poberezhnyuk, V. Vovchenko, D. V. Anchishkin, and M. I. Gorenstein, arXiv:1708.05605 [nucl-th]

Nuclear matter model parameters are commonly constrained to ground state properties. The phase diagram, e.g. the critical point location, are predicted.

Dileptons in heavy ions

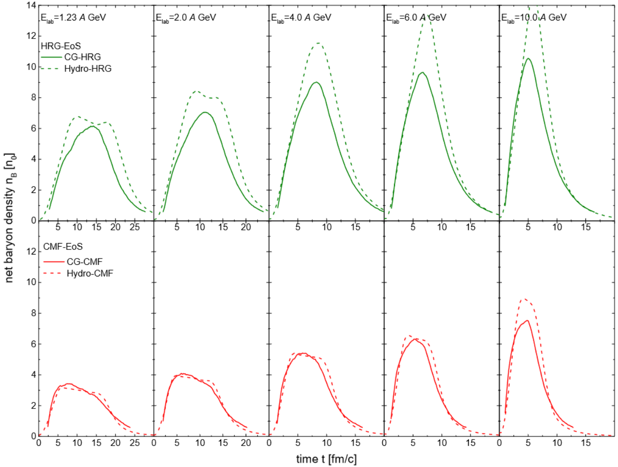
- 'Primordial' $q\bar{q}$ annihilations: $NN \to ee^{+}X$
- Thermal radiation from QGP and hadrons:$q\bar{q} \to ee^{+}$, $\pi^{+}\pi^{-} \to ee^{+}$;
- Short lived states, ρ, chiral symmetry
- Multi-meson reactions "4π"



- $\frac{d^8N}{d^4x d^4k} = -\lambda_\pi^{1.3}\frac{\alpha^2}{\pi^3 M^2} f^{BE}(k^0,T)\frac{1}{3}g^{\mu\nu}\,\mathrm{Im}\left[\Pi^{\mu\nu}_{EM}(M,k,n_B,T)\right]$
- in-medium ρ-, ω- and ϕ meson spectral functions from hadronic many-body theory [Rapp, R., Wambach, J. (2002)]

Ultrarelativistic Quantum Molecular Dynamics

- $\dot{r} = \frac{\partial H}{\partial p}; \dot{p} = -\frac{\partial V(n_B(r))}{\partial n_B(r)} \frac{\partial n_B(r)}{\partial r}$, $n_B(r) = \sum_j \left(\frac{\alpha}{\pi}\right)^{3/2} B_j \exp\left(-\alpha(r-r_j)^2\right)$
- $U(n_B) = \frac{\partial n_B V(n_B)}{\partial n_B}$, $U(n_B) = a\left(\frac{n}{n_0}\right) + b\left(\frac{n}{n_0}\right)^{\gamma}$ or $m^* - m - \mu^* + \mu$

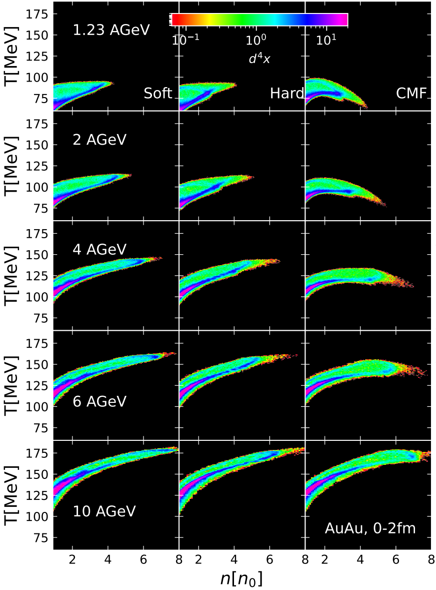


M. O. Kuttan, A. Motornenko, J. Steinheimer, H. Stoecker, Y. Nara, and M. Bleicher, *A chiral mean-field equation-of-state in urqmd: effects on the heavy ion compression stage*, 2022

Coarse Graining

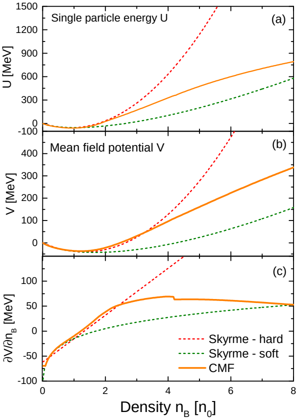
- In order to extract medium properties we apply coarse graining procedure.(see e.g.T. Galatyuk, P. M. Hohler, R. Rapp, F. Seck, and J. Stroth, "Thermal dileptons from coarse-grained transport as fireball probes at SIS energies", The European Physical Journal A **52** (2016), S. Endres, H. van Hees, J. Weil, and M. Bleicher, "Dilepton production and reaction dynamics in heavy-ion collisions at sis energies from coarse-grained transport simulations", Physical Review C **92**, 014911 (2015), S. Endres, H. van Hees, and M. Bleicher, "Photon and dilepton production at the facility for antiproton and ion research and beam-energy scan at the relativistic heavy-ion collider using coarse-grained microscopic transport simulations", Phys. Rev. C **93**, 054901 (2016))
- Space-time is separated into cube's of size $dx^i = .5\text{fm}$.
- For each cube its four velocity is being computed from the $T^{\mu\nu}$ relations in the cube's rest and laboratory frames of reference.
- $T^{\mu\nu} = (e + P)u^\mu u^\nu - Pg^{\mu\nu};$
- $T^{0\nu} = (e_{c.m.}, \vec{p}_{c.m.});$
- $n^\mu_{c.m.} = nu^\mu;$

Coarse Graining



- AuAu collisions at $E_{kin} = 1.23, 2, 4, 6, 10\ AGeV$ considered.
- impact parameter $b = 0 - 2fm$.
- 50000 events generated in each case.

Equations of State



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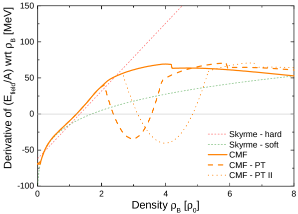
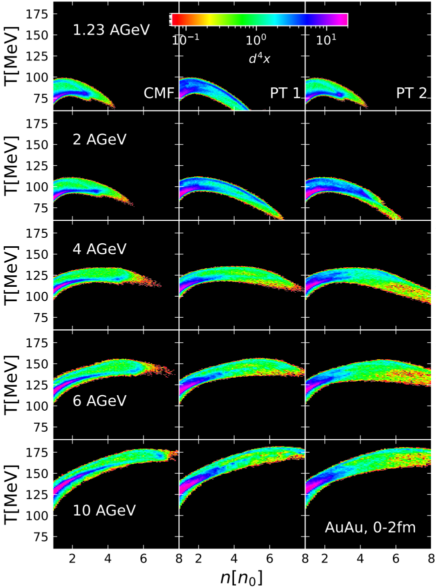


J. Steinheimer, A. Motornenko, A. Sorensen, Y. Nara, V. Koch, and M. Bleicher, *The high-density equation of state in heavy-ion collisions: constraints from proton flow*, 2022

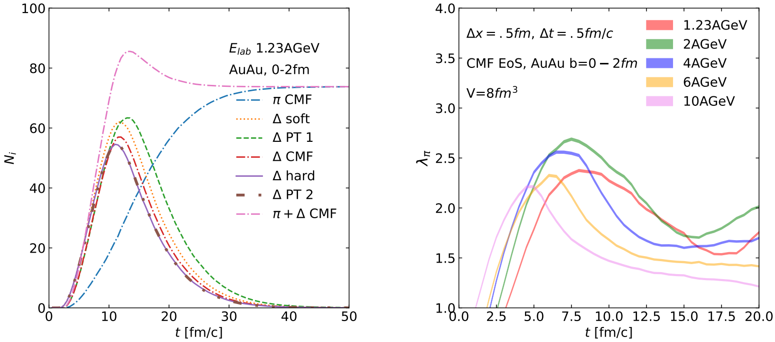
- Hard Skyrme reproduces proton flow data and many other observables however doesnt include phenomenology beyond nuclear saturation density
- CMF includes most of the known QCD phenomenology including high density region. The EoS is expected to soften at higher density.

First Order Phase Transition



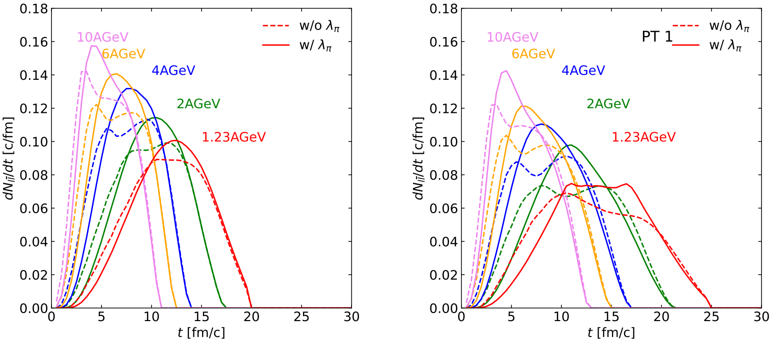
- Phase Transition from Equation of State at T=0
- FOPT at HADES energy (PT 1) and at the energy 2*AGeV* (PT 2)
- Isentropic cooling/reheating
- Softening of the equation of state occurs

Pion excess



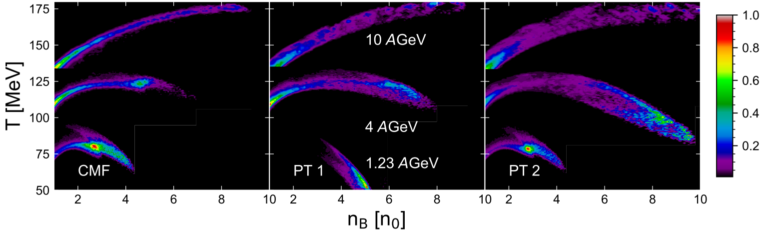
- The number of π's is way above thermal model $n(T)$ predictions
- UrQMD has about 40% more pions than observed in the experiment
- $\mu_\pi \approx T \approx m_\pi$ pion condensation and interaction can be important

Cumulative production of dileptons



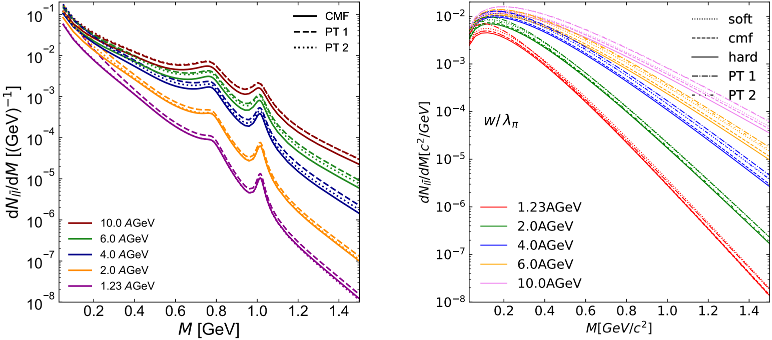
Emission starts around the time of nuclei overlapping and continues for some time. FOPT increases firebals‘ lifetime.

Cumulative production of dileptons



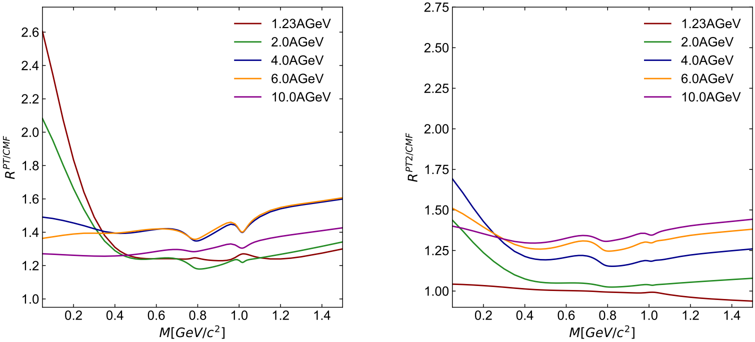
Time-integrated dilepton emission $1/N_{l\bar{l}}^{\max} d^2 N_{l\bar{l}}/dT\,dn_B$, normalized to its maximum value $N_{l\bar{l}}^{\max}$.

Dilepton spectra



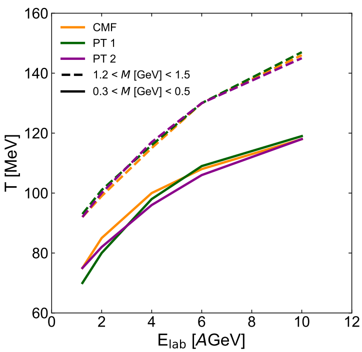
- Fugacity changes dilepton yield by roughly a factor of 2;
- The slope is not sensitive to fugacity factor;

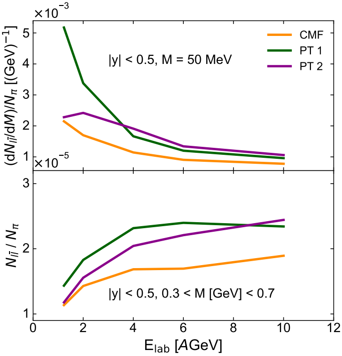
Effects of FOPT



- After the FOPT temperature of the spectra increases $R \approx \exp\left[M(1/T_{CMF} - 1/T_{FOPT})\right]$;
- Low M suggest temperature decreases but fugacity and lifetime increases $R \approx \frac{\left(\tau\lambda_{\pi}^{1.3} V T^{3/2}\right)_{FOPT}}{\left(\tau\lambda_{\pi}^{1.3} V T^{3/2}\right)_{CMF}} \approx \frac{\left(\tau\lambda_{\pi}^{1.3}\right)_{FOPT}}{\left(\tau\lambda_{\pi}^{1.3}\right)_{CMF}}$;

Excitation function from dileptons





The integrated yield of dileptons divided by multiplicity of charged pions in one unit of rapidity

Conclusions

- Dilepton production is sensitive to the hadronic equation of state at large density.
- Dileptons are created relatively early and show denser part of the EoS.
- Enhancement factor of $N_{e\bar{e}}/N_{\pi^{+}+\pi^{-}}$ 2-3 for the emission rate at masses of $M \approx 50$ MeV and 1.4 from the integrated yield.
- Dilepton temperature reduction of about 5 MeV is observed in the low mass.

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Thank you for attention!