Dilepton production from coarse grained UrQMD with a CMF equation of state

Oleh Savchuk

Bogolyubov Institute for Theoretical Physics
GSI Helmholtzzentrum für Schwerionenforschung
Frankfurt Institute For Advanced Studies

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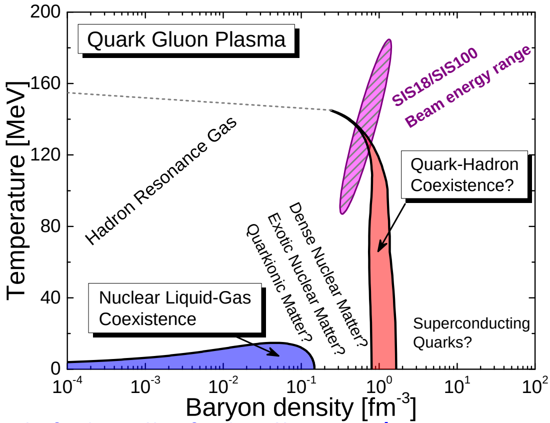
In collaboration with T.Galatyuk, J.Steinheimer, A.Motornenko, M.Gorenstein, H.Stoecker

Outline

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

QCD phase diagram



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

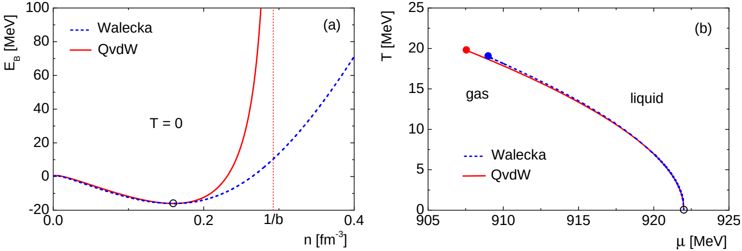
- In the vicinity of the hypothetical phase transition
- Cosmic matter in the laboratory, access to vector and axial interactions important for neutron matter
- Exotic states of matter: phase transition in delta matter, pion interactions

Nuclear matter

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

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

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

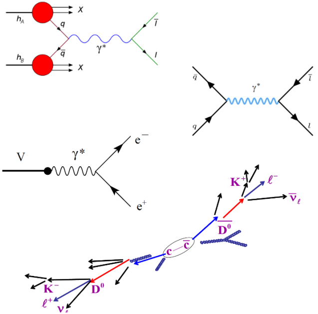


R. V. Poberezhnyuk, V. Vovchenko, D. V. Anchishkin, and M. I. Gorenstein, arXiv:1708.05605 [nucl-th]

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

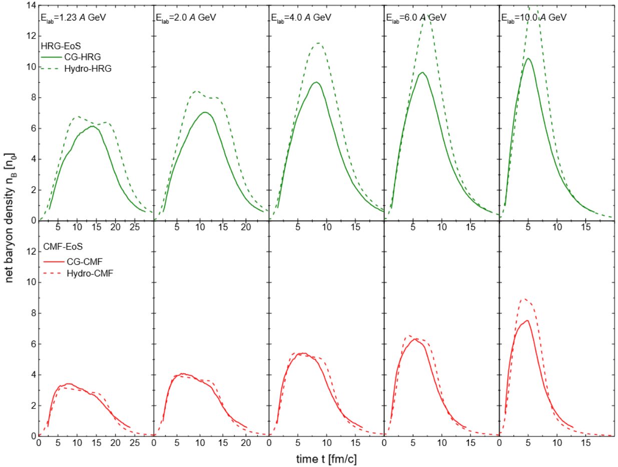
- 'Primordial' $q\bar{q}$ annihilations: $NN \to ee^+X$
- Thermal radiation from QGP and hadrons:$q\bar{q} \to ee^+$, $\pi^+\pi^- \to ee^+$;
- Short lived states, ρ, chiral symmetry
- Multi-meson reactions "4π"



- $\frac{d^8N}{d^4xd^4k} = -\frac{\alpha^2}{\pi^3M^2} f^{BE}(k_0, T)\frac{1}{3}g^{\mu\nu}\mathbf{Im}\Pi^{\mu\nu}_{EM}(M, k, \mu_B, T)$
- $\mathbf{Im}\Pi^{vac}_{EM}(M) = -\frac{M^2}{12\pi}\left[1 + \frac{\alpha_s(M)}{\pi} + \cdots\right] N_c \sum_{q=u,d} e_q^2$

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 $m^* - m - \mu^* + \mu$

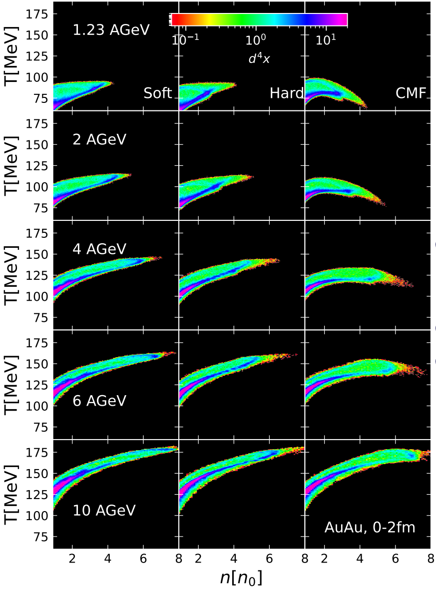


M. O. Kuttan, A. Motornenko, J. Steinheimer, H. Stoecker, Y. Nara, and M. Bleicher, *A chiral mean-field equation-of-state in urqmd: effects on the heavy ion compression stage*, 2022

Coarse Graining

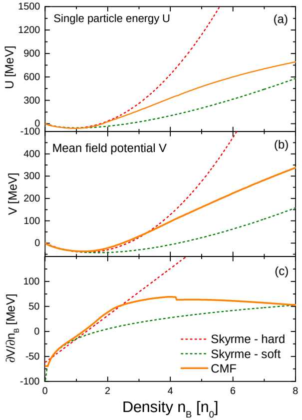
- In order to extract medium properties we apply coarse graining procedure.(see e.g. S. Endres, H. van Hees, J. Weil, and M. Bleicher, "Dilepton production and reaction dynamics in heavy-ion collisions at sis energies from coarse-grained transport simulations", Physical Review C **92**, 014911 (2015), 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 cubes of size $dx^i = .5\text{fm}$.
- For each cube its four velocity is being computed from the $T^{\mu\nu}$ relations in the cubes' rest and laboratory frames of reference.
- $T^{\mu\nu} = (e+P)u^\mu u^\nu - Pg^{\mu\nu}$;
- $T^{0\nu} = (e_{c.m.}, \vec{p}_{c.m.})$;
- $n^\mu_{c.m.} = nu^\mu$;

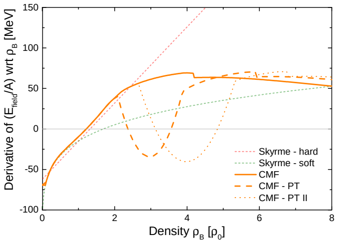
Coarse Graining



- 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





- Three equations of state are being considered
- 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 equations is expected to soften at higher density.

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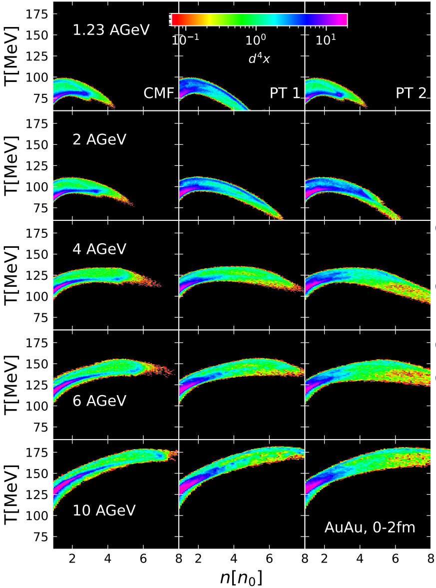
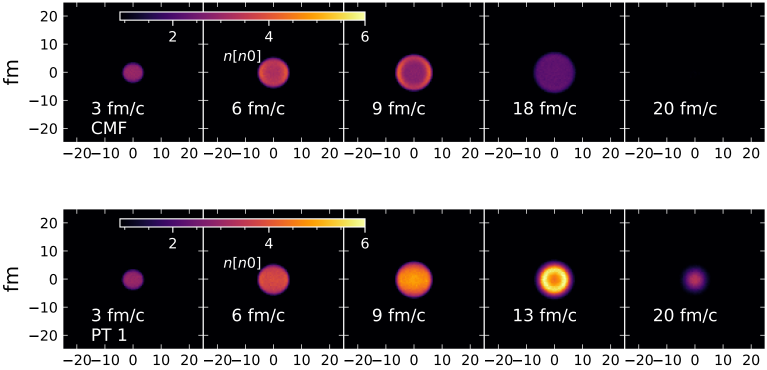
First Order Phase Transition

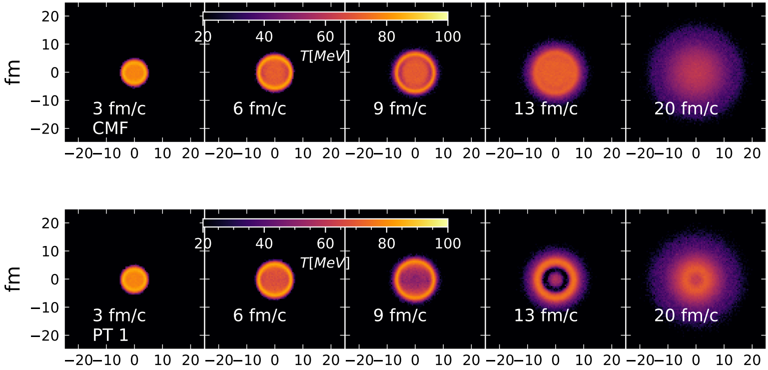


- Phase Transition from Equation of State at T=0
- FOPT at HADES energy (PT 1) and at the energy *2AGeV* (PT 2)
- Isentropic cooling/reheating
- Softening of the equation of state occurs

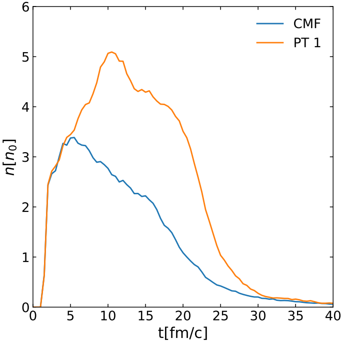
Density in xy plane

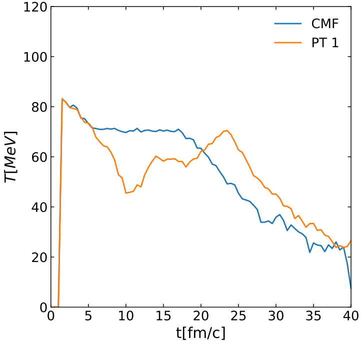


Temperature in the xy plane

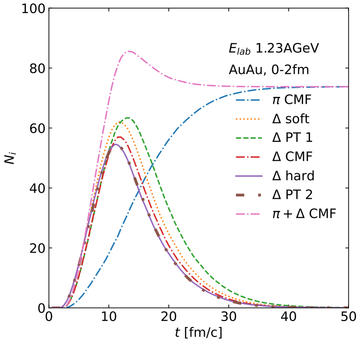


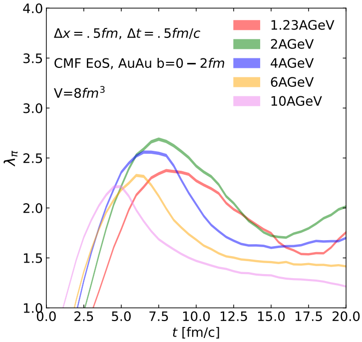
Phase Transition 1.23 AGeV





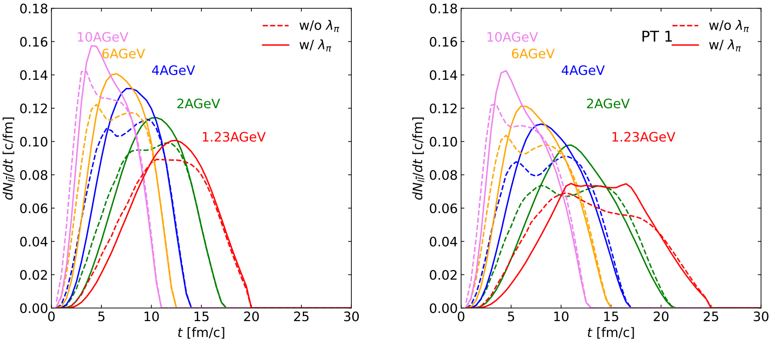
Pion excess





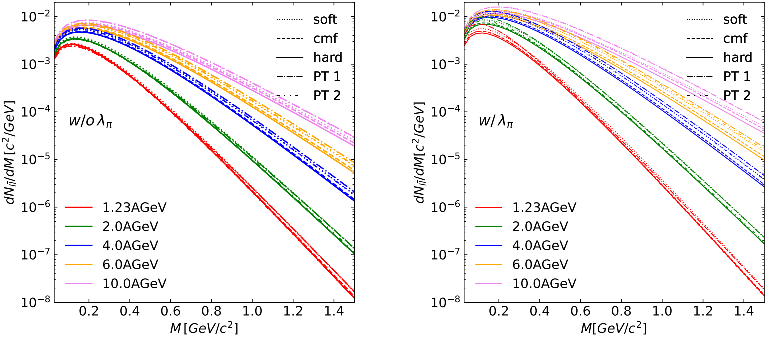
- The number of π's is way above thermal model $n(T)$ predictions
- UrQMD has about 40% more pions than observed in the experiment
- $\mu_\pi \approx T \approx m_\pi$ pion condensation and interaction can be important

Cumulative production of dileptons



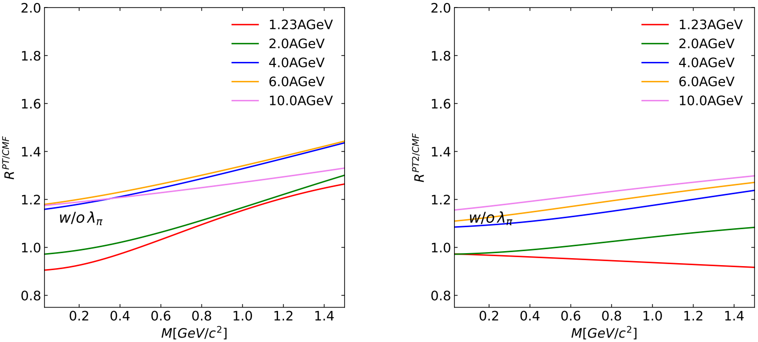
Emission starts around the time of nuclei overlapping and continues for some time. FOPT increases firebals‘ lifetime.

Dilepton spectra



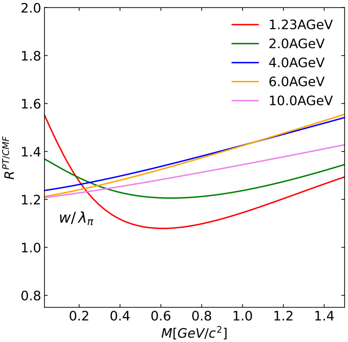
- Fugacity changes dilepton yield by roughly a factor of 2;
- The slope is not sensitive to fugacity factor;

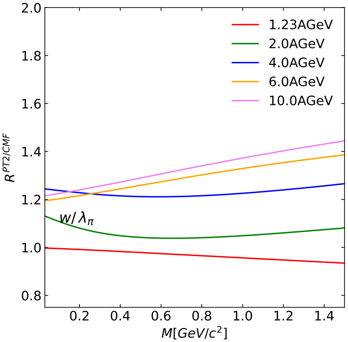
Effects of FOPT



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

Effects of FOPT





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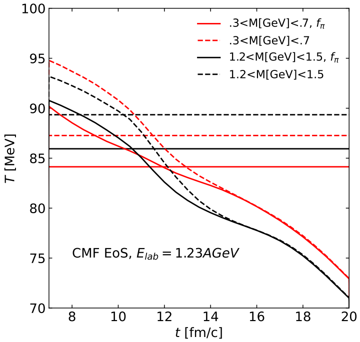
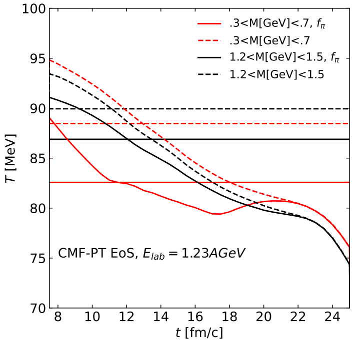
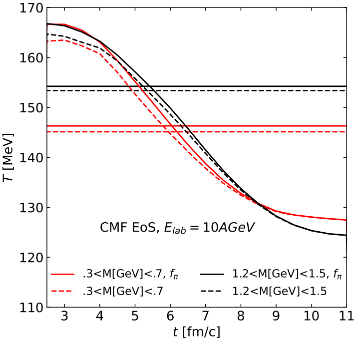
Temperature vs emission time

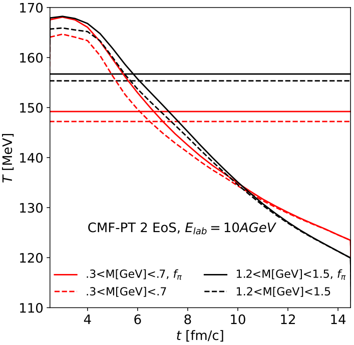




Low M cells temperature falls as system life-time increased and with more contribution from colder cells.

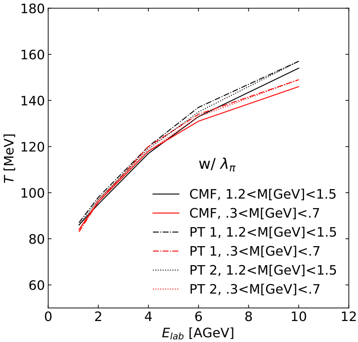
Temperature vs emission time

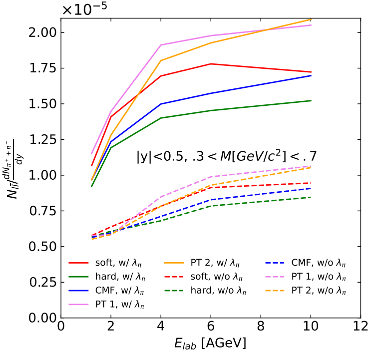




FOPT slightly increases temperature at the high E_{lab}

Excitation function from dileptons





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

Conclusions

- Dileptons are important observables sensetive to the EoS of QCD matter at high density.
- Invatiant mass spectra for different equations of state was obtained.
- UrQMD simulation performed. In order to extract temperature and density coarse graining procedure is being used.

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Thank you for attention!