Signatures of first-order phase transition in heavy-ion collisions

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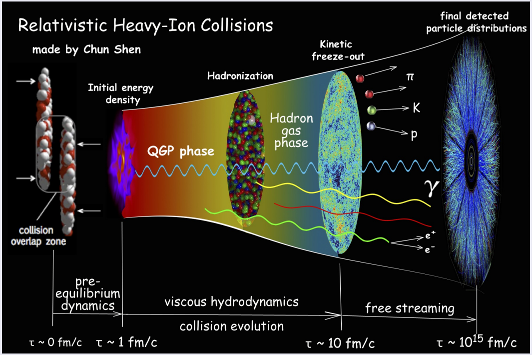
The Background

HIC & QCD

- Stages of evolution of heavy-ion collisions
- HIC's to probe QCD phase structure



Courtesy: Chun Shen, The Ohio State University

- Use of hydrodynamics to track temporal evolution in the equilibrium stage

The Background (contd.)

Ideal Relativistic Hydrodynamics

- Macroscopic description of ideal fluid $\rightarrow$ conserved quantities important in description of system
- Ideal fluid: a continuous system of infinitesimal volume elements, each of which are assumed to be very close to thermodynamic equilibrium
- Conservation laws: $\nabla_\mu T^{\mu\nu}_{(0)} = 0$, $\partial_\mu N^{\mu}_{(0)} = 0$
- Fields: ε , P , n and u^μ - corresponding to 6 degrees-of-freedom
- Equations of motion:

$$\begin{aligned} D\varepsilon + (\varepsilon + P)\theta_\mu u^\mu &= 0 \\ (\varepsilon + P)Du^\alpha + c_s^2\theta^\alpha\varepsilon &= 0 \\ Dn + n\partial_\mu u^\mu &= 0 \end{aligned}$$

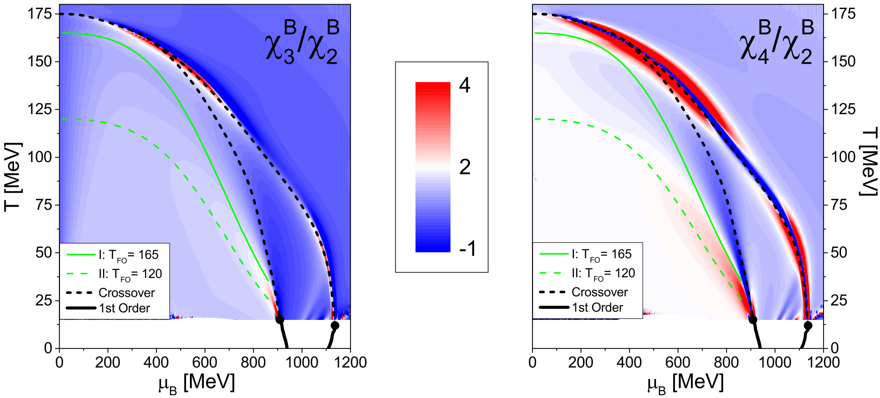
- $c_s(\varepsilon) = \sqrt{\frac{\partial P(\varepsilon)}{\partial \varepsilon}}$; EoS: $P \equiv P(n, \varepsilon)$ from thermodynamic model based on microscopic theory of strong interactions

The Thermodynamic Model I

The Quark-Hadron Chiral Parity-doublet Model (QχP)

- Flavour SU(3) extension of a non-linear representation of the $\sigma - \omega$ model
- $\sigma \rightarrow$ order-parameter for chiral transitions, Polyakov loop $\phi \rightarrow$ order-parameter for deconfinement + excluded-volumes to remove hadrons post deconfinement
- Reproduction of reasonable values of ground-state nuclear properties
- Exploration of the effects of both the nuclear liquid-gas (LG) and the first-order chiral/deconfinement phase transitions on the behaviour of the cumulants of conserved charges, within the same effective model
- Application of the EoS i.e., $P \equiv P(n, \varepsilon)$; produced by this grand-canonical, thermodynamic analysis; to fluid-dynamic (or hydrodynamic) simulations of HIC's
- Application to neutron star matter and extraction of astrophysically viable symmetry energy, slope parameter, max. mass and radius values
- Qualitative agreement with LQCD results

The Thermodynamic Model II: Phase Diagrams

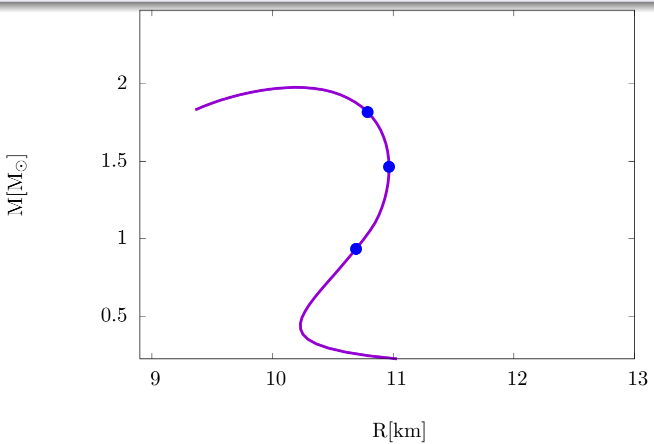


Source: AM, J. Steinheimer & S. Schramm [Phys. Rev. C 96 (2017) no.2, 025205]

The Thermodynamic Model III: Astrophysical Benchmarks

The QχP EoS & the TOV equations

Complete Equation of State used in the Tolman-Oppenheimer-Volkoff (TOV) equations to generate mass-radius diagram for neutron stars



Source: AM, J. Steinheimer, S. Schramm & V. Dexheimer [Astron. Astrophys. 608 (2017) A110]

'Numbers' speak louder than words!

- Ground-state nuclear-matter compressibility $(\kappa) = 267.12$ MeV
- Saturation density $(\rho_0) = 0.142$ fm^{-3}
- Binding energy $(\boldsymbol{E/A})$, *a.k.a*:
  Energy density per baryon $(\varepsilon/\rho_{\mathrm{B}}) = -16$ MeV
- Symmetry energy: $S = \frac{1}{8}\left[\frac{d^2(\varepsilon/\rho_{\mathrm{B}})}{d(I_3/B)^2}\right]_{\rho_{\mathrm{B}}=\rho_0} = 30.02$ MeV
- Slope parameter: $L = 3\rho_0\left[\frac{dS}{d\rho_{\mathrm{B}}}\right]_{\rho_{\mathrm{B}}=\rho_0} = 56.86$ MeV
- Maximum star mass: $M_{\mathrm{max}} = 1.98\ M_{\odot}$
- Maximum star radius: $R_{\mathrm{max}} = 10.25$ km
- Canonical star mass: $M_{\mathrm{c}} = 1.4\ M_{\odot}$
- Canonical star radius: $R_{\mathrm{c}} = 11.10$ km

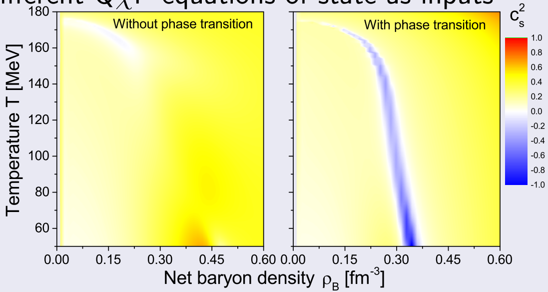
The HADES I

Dileptons

- Dileptons: effective probes for the early evolution of the fireball; on account of electro-weak interactions being unlikely at strong interaction timescales
- Dilepton phase-space distributions $\rightarrow$ T, collectivity, emissivity of QCD medium
- The invariant mass spectrum of the dileptons is obtained from the emissivity $\epsilon = Kf^B(q_0, T)\varrho_{EM}/M^2$
- Invariant mass $M = \sqrt{q_0^2 - q^2}$
- The HADES experiment (GSI/SIS18); with beam-energy scans at 1.23 AGeV using an Au+Au nuclear collision; can measure M
- Hadronic transport model, using UrQMD
- Hydro evolution, without first-order phase transition
- Hydro evolution, with first-order phase transition

Hydro simulations & the equations-of-state

- Using two different QχP equations of state as inputs



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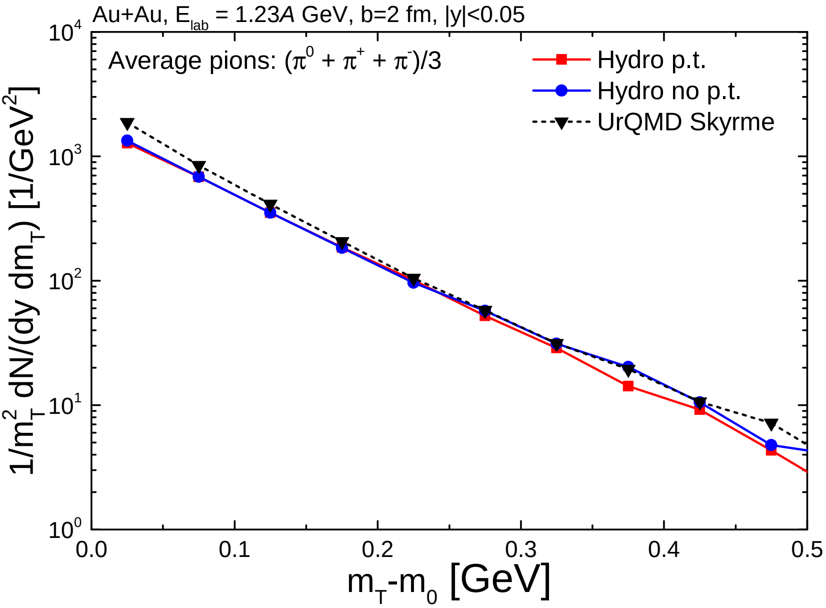
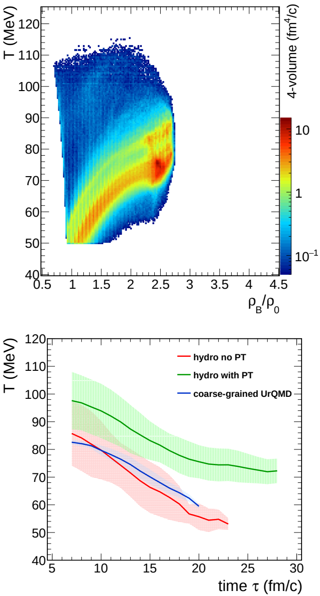
two hydrodynamic simulations are run, for three different impact parameters: 2 fm, 4 fm & 7 fm

- The resulting T and ρ_B, obtained as functions of $\mathbf{x}$ and t, are used to calculate the emissivity and M

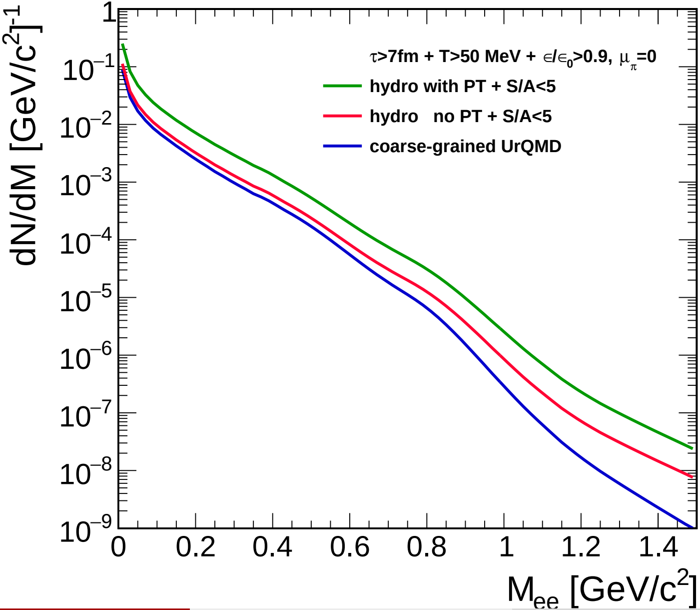
The Outcomes I: Pion m_T Spectrum



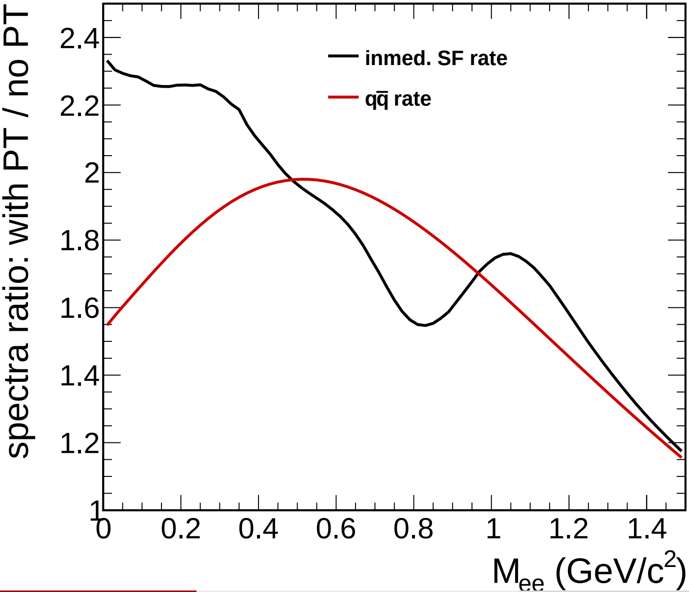
The Outcomes II: T & ρ_B



The Outcomes III: Invariant-mass Spectrum of Dileptons I



The Outcomes III: Invariant-mass Spectrum of Dileptons II



The Summary

Conclusions

- Considerable influence of LG transition on cumulant values
- Phenomenologically acceptable values for nuclear-matter compressibility, saturation density and energy density per baryon, despite inclusion of excluded-volume corrections which stiffen the EoS
- Generation of observationally vindicated values for maximum mass, canonical mass and canonical radius in neutron star family
- First-order phase transition leads to a substantial increase of the low-mass thermal dilepton yield over that from a crossover transition, by about a factor of two, as a consequence of the prolonged lifetime caused by the mixed-phase formation
- The dilepton spectrum from the crossover evolution shows good agreement with the one from coarse-grained transport
- In-medium effects on SF's lead to an additional relative enhancement at masses around 0.2 GeV in the 1^{st}-order scenario, due to higher avg. densities in the more compressible medium with mixed phase

The Outlook

Coming soon... in journals near you

- Further quantitative investigations in comparison to existing HADES data (excitation function measurements at SIS 100 interesting!)
- Extension of the QχP to finite nuclei
- Effects of isospin-symmetry breaking on the model, and in turn on HIC's
- Magnetic field effects on the QCD phase diagram and fluctuations, using the QχP
- Better agreement between QχP and LQCD calculations
- Tidal deformation calculations for NS's, with the QχP EoS
- Further exploration of the properties of ground-state nuclear-matter inside neutron stars, for different charge fractions

The End

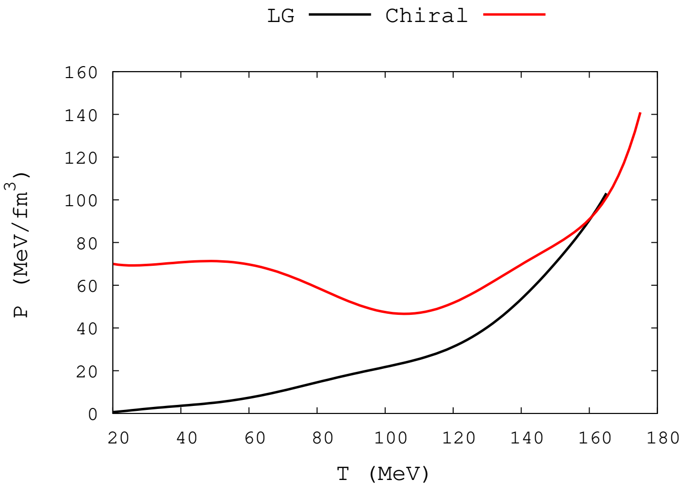
Thank you for your attention!

The Backup

অন্তরে অতৃপ্তি রবে সাঙ্গ করি' মনে হবে
শেষ হয়ে হইল না শেষ।

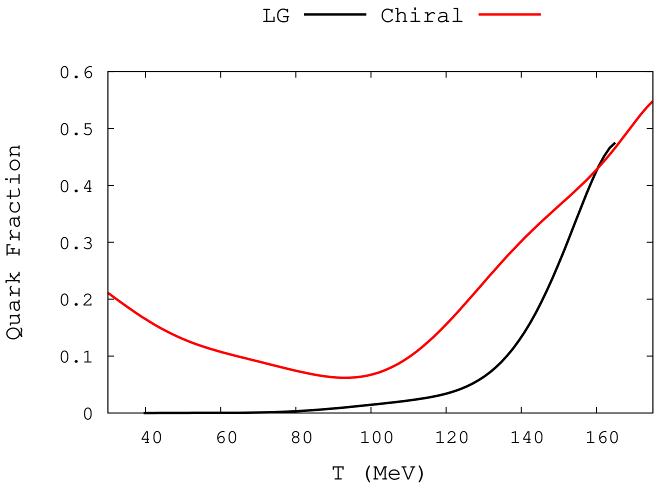
The Backup: Pressure

$P = -\Omega = (T \ln \mathcal{Z})/V$

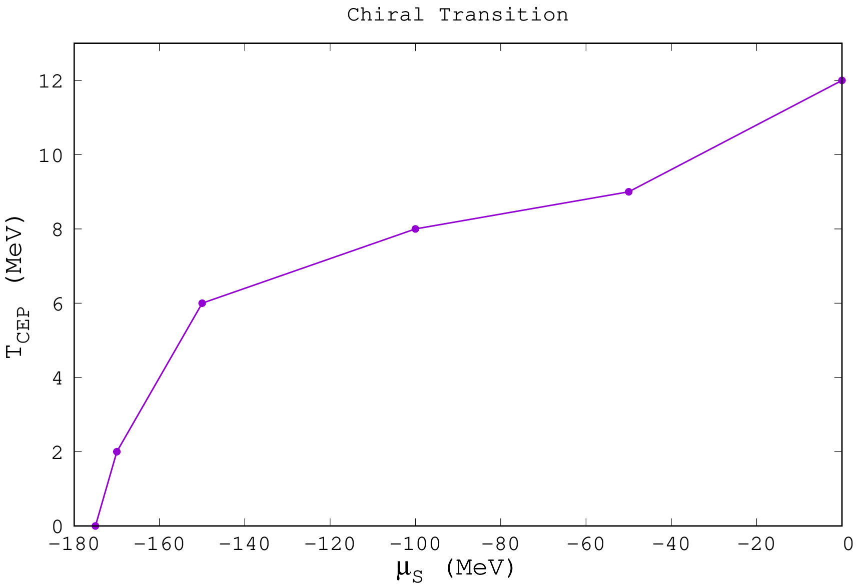


The Backup: Quark fraction

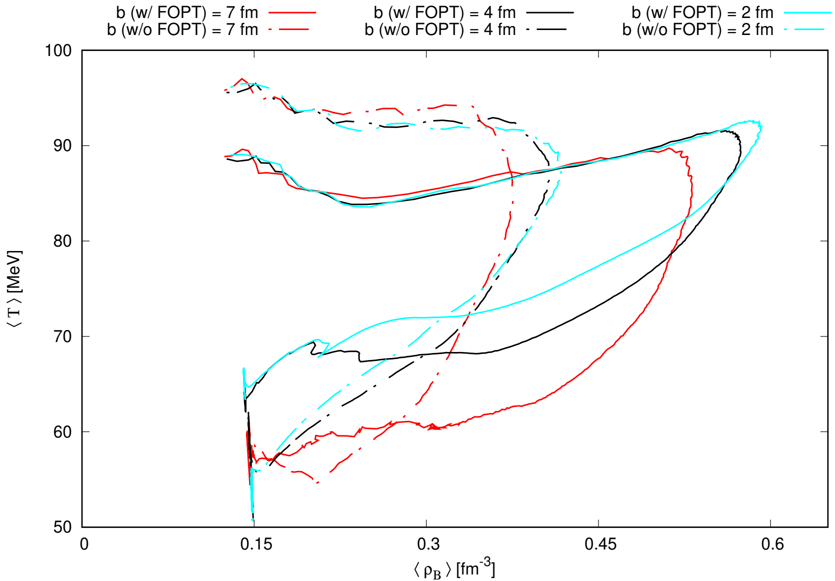
$$q_{\mathrm{f}} = (\varepsilon_{\mathsf{quark}} + \varepsilon_{\mathsf{Polyakov}})/(\varepsilon_{\mathsf{baryon}} + \varepsilon_{\mathsf{meson}} + \varepsilon_{\mathsf{Polyakov}})$$



The Backup: Critical end-point



The Backup: Phase-space



The Model

The Crux

- Lagrangian used:

$$\mathcal{L}_{\mathcal{B}} = \sum_{\mathrm{i}} \left[\bar{B}_{\mathrm{i}} i \partial\!\!\!/ B_{\mathrm{i}} + \bar{B}_{\mathrm{i}} m_{\mathrm{i}}^{*} B_{\mathrm{i}} + \left(\bar{B}_{\mathrm{i}} \gamma_{\mu} (g_{\omega \mathrm{i}} \omega^{\mu} + g_{\rho \mathrm{i}} \rho^{\mu} + g_{\phi \mathrm{i}} \phi^{\mu}) B_{\mathrm{i}} \right) \right]$$

- Effective baryon masses:

$$m_{\mathrm{i}\pm}^{*} = \sqrt{[(g_{\sigma \mathrm{i}} \sigma + g_{\zeta \mathrm{i}} \zeta)^2 + (m_0 + n_{\mathrm{s}} m_{\mathrm{s}})^2]} \pm g_{\sigma \mathrm{i}} \sigma \pm g_{\zeta \mathrm{i}} \zeta$$

  where $\zeta = \langle \bar{s} s \rangle$ & $\sigma = \langle \bar{q} q \rangle$

- Scalar meson interaction potential:

$$V = V_0 + \frac{1}{2} k_0 I_2(\sigma, \zeta) - k_1 I_2^2(\sigma, \zeta) - k_2 I_4(\sigma, \zeta) + k_6 I_6(\sigma, \zeta)$$

The Model (contd.)

Quarks as degrees-of-freedom

- Quarks become the dominant degrees-of-freedom when QCD exhibits a smooth, crossover-like, deconfinement transition from the hadron gas, making a hadronic parity-doublet model an inadequate description of the system
- Polyakov loop Φ, which goes from 0 to 1 during deconfinement, added as order parameter for deconfinement transition to a chiral parity-doublet model:

$$\Phi = \frac{1}{3}\,\mathrm{Tr}\left[\exp\left(i\int d\tau A_4\right)\right]$$

- The thermal contribution, to the grand-canonical potential (Ω), of the quarks-to-Polyakov loop coupling:

$$\Omega_{\mathrm{q\ or\ \overline{q}}} = -T\sum_{\mathrm{i}\in Q}\frac{\gamma_{\mathrm{i}}}{(2\pi)^3}\int d^3k\,\ln\left(1+\Phi\exp\frac{E_{\mathrm{i}}^{*}\pm\mu_{\mathrm{i}}}{T}\right)$$

The Model (contd..)

The Grand Canonical Potential

- All thermodynamic quantities: energy density ε, entropy density s, and densities of the different particle species ρ_{i}, are derived from the grand-canonical potential.
- Effective potential $U(\Phi, \Phi^{*}, T)$:

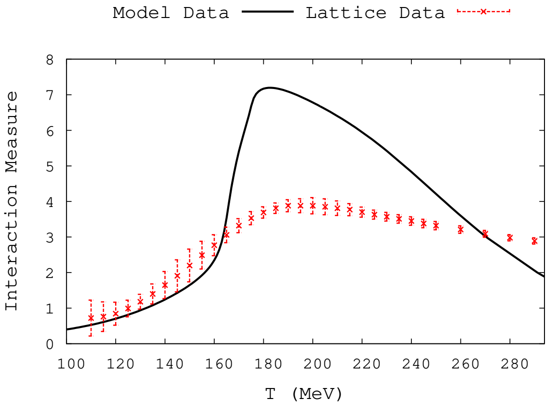
$$U = -\frac{1}{2}a(T)\Phi\Phi^{*} + b(T)\ln\left[16\Phi\Phi^{*} + 4(\Phi^{3}\Phi^{*3}) - 3(\Phi\Phi^{*})^{2}\right] \,,$$

  contained within the grand-canonical potential, controls the dynamics of the Polyakov loop
- Excluded volumes introduced as a way to remove hadrons following the deconfinement of quarks; modifying the effective chemical potential of the hadrons, resulting in their suppression once the quarks and gluons start contributing to the thermodynamic potential of the system

The Results I

Lattice data comparison

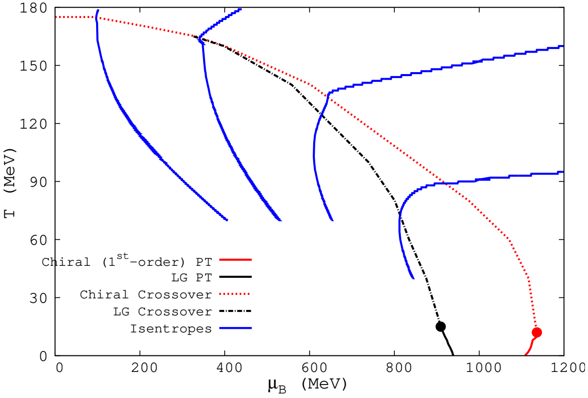
- The model parameters are constrained by actual observables at large ρ_{B} & low T, not by lattice results at $\mu_{\mathrm{B}} = 0$
- Interaction measure, $I = (\varepsilon - 3P)/T^4$, used as means of comparison



The Results I (contd.)

The $T - \mu_{\rm B}$ diagram

- PT lines defined as $(\partial\sigma/\partial\mu_{\rm B})_{\rm max}$, or as $(\partial\rho_{\rm B}/\partial\mu_{\rm B})_{\rm max}$
- A double-Gaussian is fit to the derivatives with each peak assigned to a separate crossover line



The Results I (contd....)

Baryon-number susceptibilities

- Cumulants or susceptibilities (χ_n^B):

$$\frac{\chi_n^B}{T^2} = n!\ c_n^B(T) = \frac{\partial^n (P(T,\mu_B)/T^4)}{\partial(\mu_B/T)^n}$$

- Freeze-out curve, from fit to experimental data:

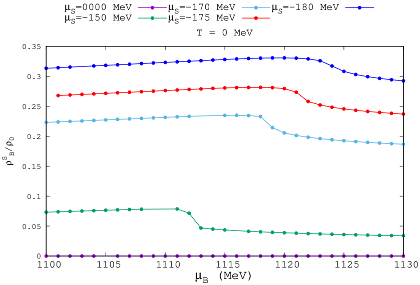
$$T\ (\mathrm{MeV}) = \frac{T_{\mathrm{lim}}}{1 + \exp\left[2.60 - \frac{\ln\left(\sqrt{s_{NN}}\ (\mathrm{GeV})\right)}{0.45}\right]},$$

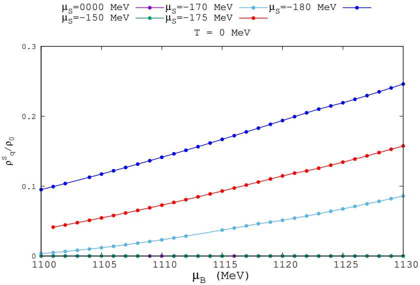
where μ_B and $\sqrt{s_{NN}}$ (the beam energy in GeV) are related as:

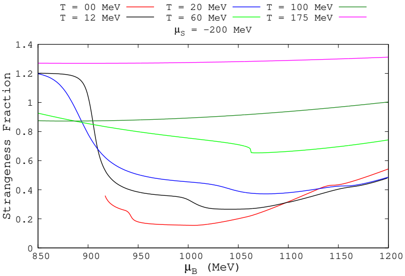
$$\mu_B\ (\mathrm{MeV}) = \frac{1303}{1 + 0.286\sqrt{s_{NN}\ (\mathrm{GeV})}}$$

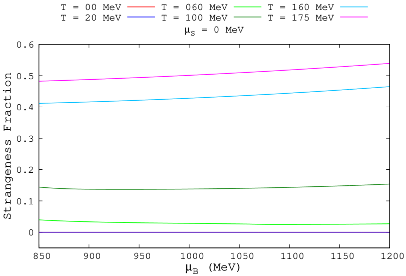
The Results II

The Hyperon Rises





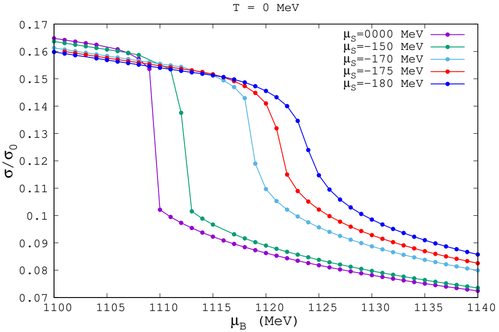




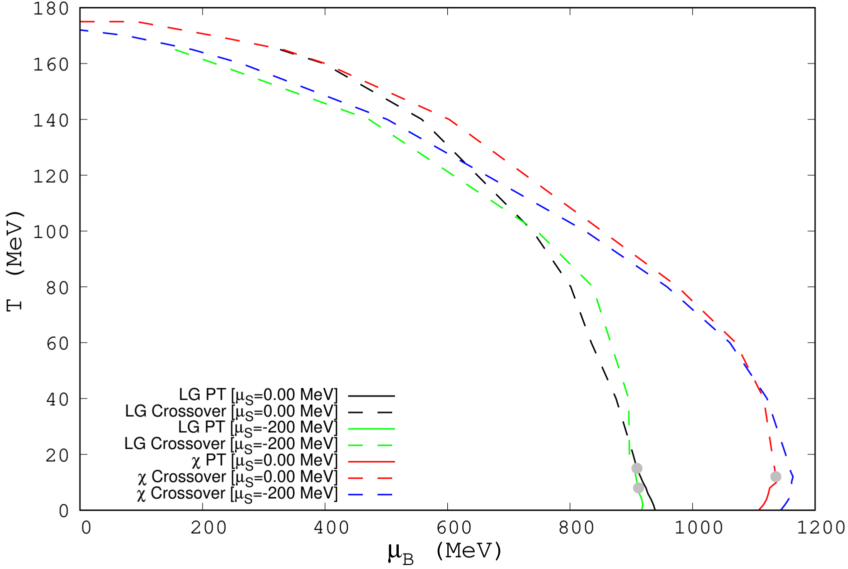
The Digression: Stranger Things

Non-zero net-strangeness chemical potential

- Theoretically, the effects of non-zero net-μ_{S} and net-μ_{I} have been well documented
- Experimentally, from fitting observed particle ratios, μ_{S} has been deduced to have a value of $\sim 25\% - 30\%$ of μ_{B}, while μ_{I} remains small, at around $2\% - 5\%$ of μ_{B}

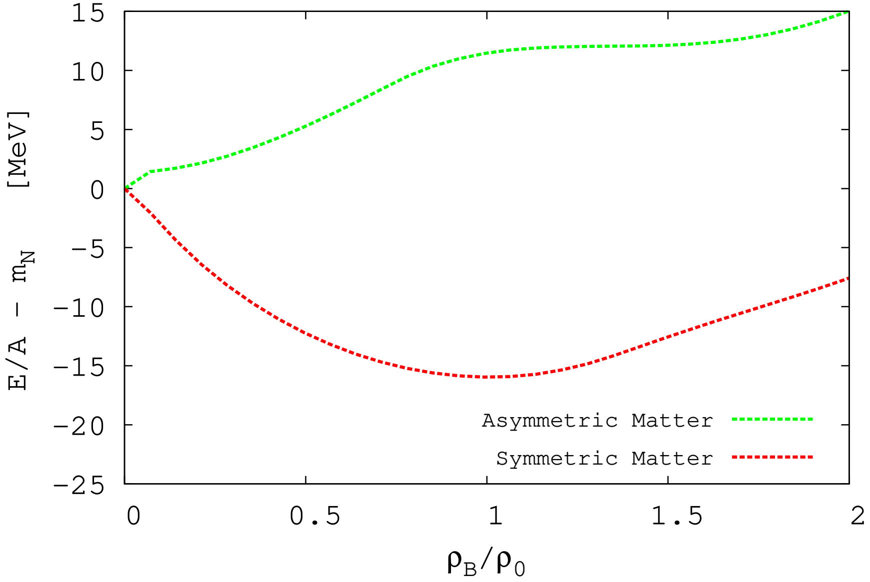


The Outcomes II: The Modified Phase Boundary



Source: AM, A. Bhattacharyya & S. Schramm [arXiv:1807.11319]

The Outcomes I (contd..): Binding & Symmetry Energies



The Outcomes (contd...): Compactness