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

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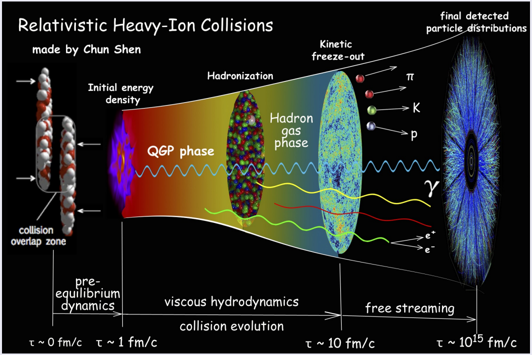
The Background

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:

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

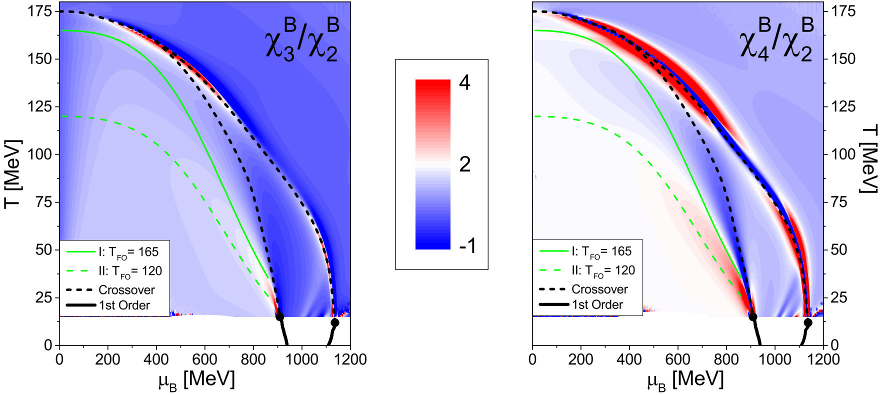
- $c_s(\varepsilon) = \sqrt{\frac{\partial P(\varepsilon)}{\partial \varepsilon}}$; EoS: $P \equiv P(n, \varepsilon)$ from thermodynamic model based on microscopic theory of strong interactions

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

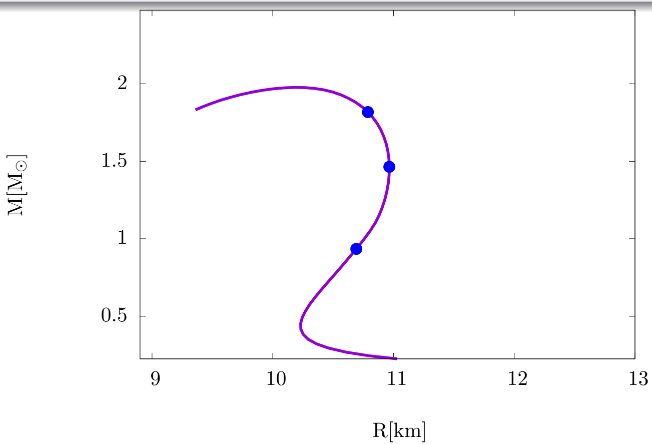


Source: AM, J. Steinheimer & S. Schramm [Phys. Rev. C 96 (2017) no.2, 025205]

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]

The Thermodynamic Model IV

'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

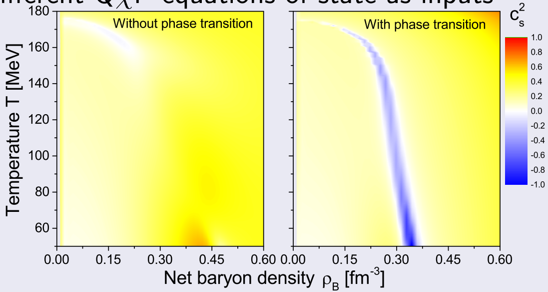
The HADES I

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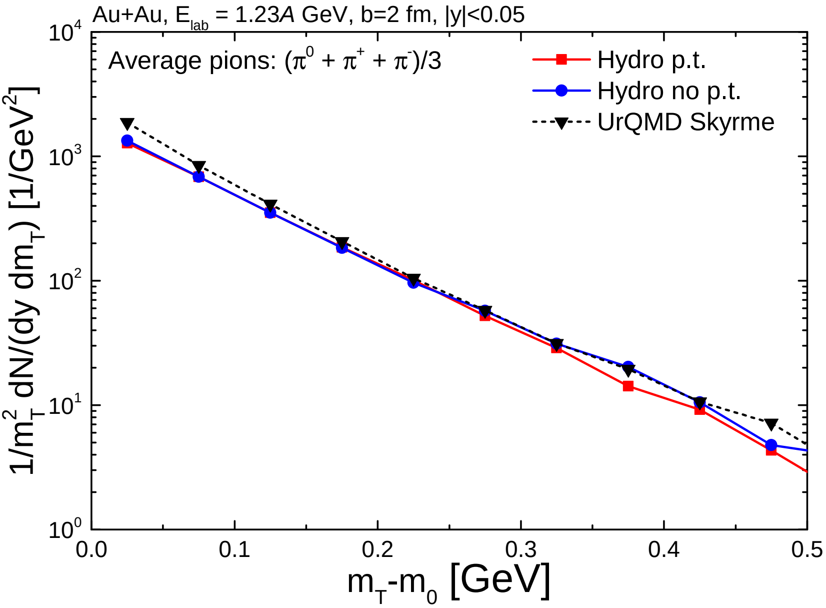
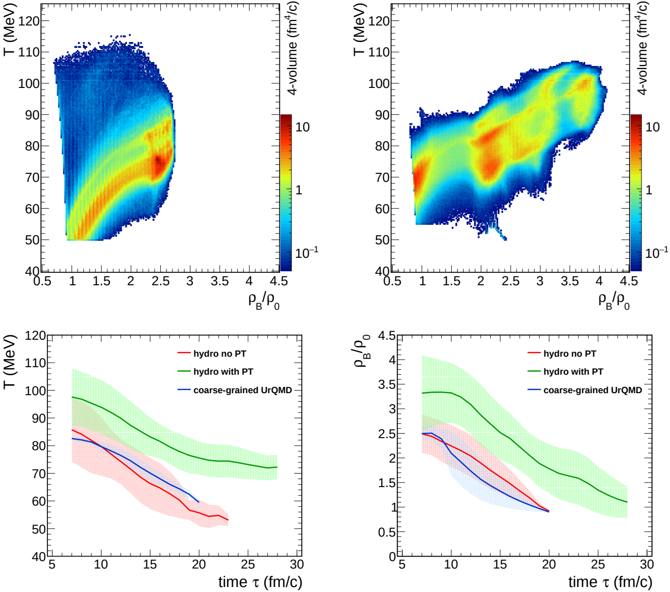
two hydrodynamic simulations are run, for three different impact parameters: 2 fm, 4 fm & 7 fm

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

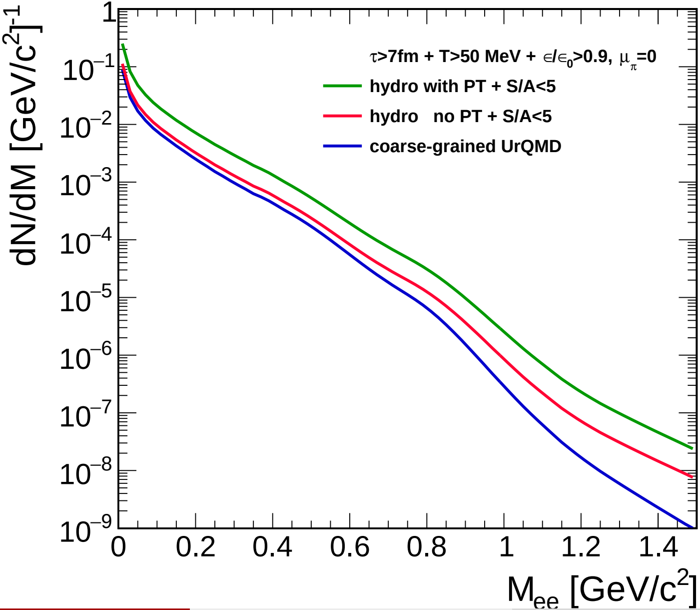
The Outcomes I: Pion m_T Spectrum



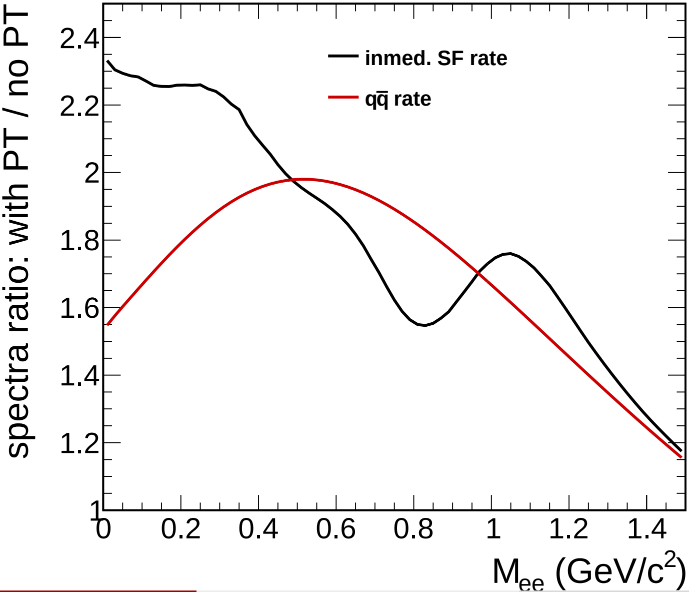
The Outcomes II: T & ρ_B



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$^{\mathrm{st}}$-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!

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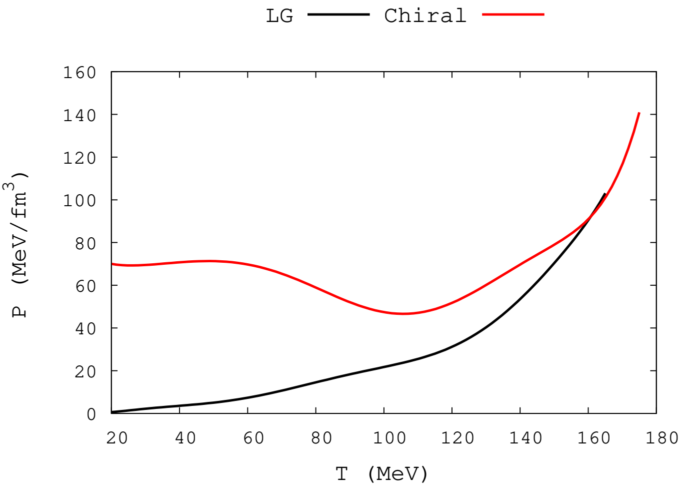
শেষ হয়ে হইল না শেষ।

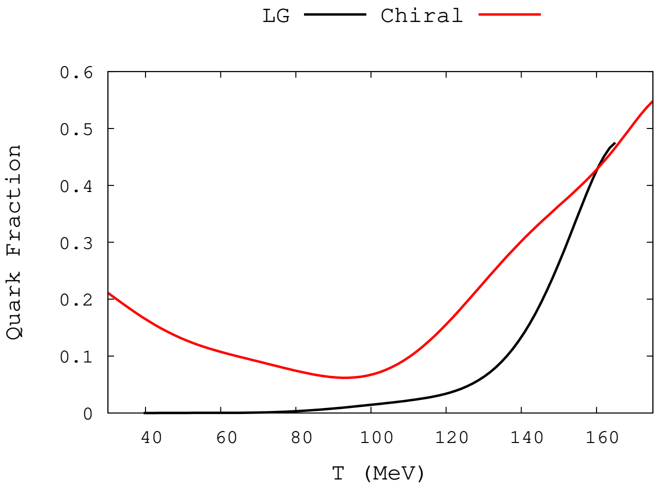
The Backup: Pressure

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

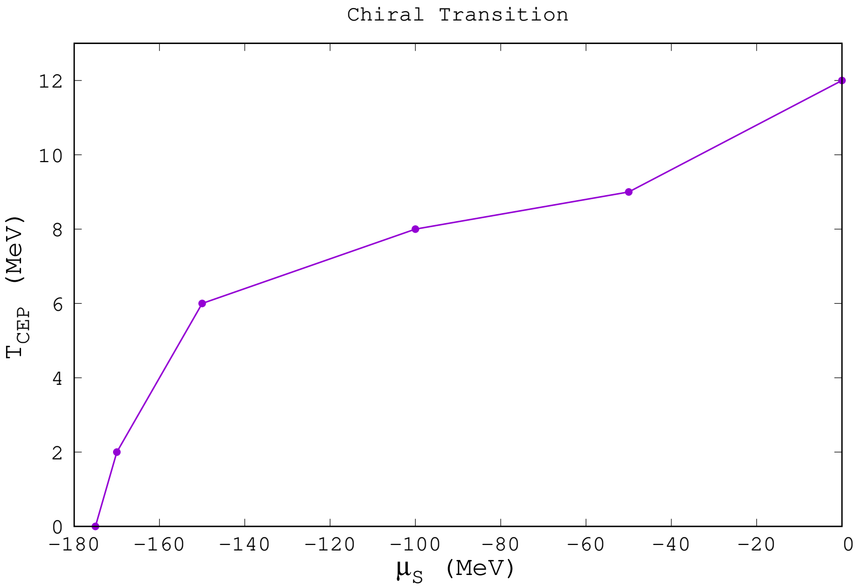


The Backup: Quark fraction

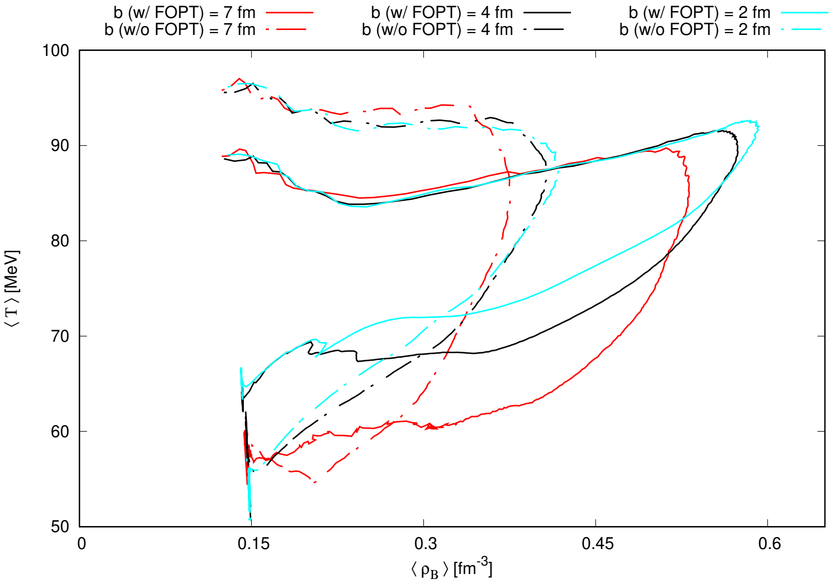
$$q_\mathrm{f} = (\varepsilon_\mathsf{quark} + \varepsilon_\mathsf{Polyakov})/(\varepsilon_\mathsf{baryon} + \varepsilon_\mathsf{meson} + \varepsilon_\mathsf{Polyakov})$$



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 $U(\Phi, \Phi^*, T)$:

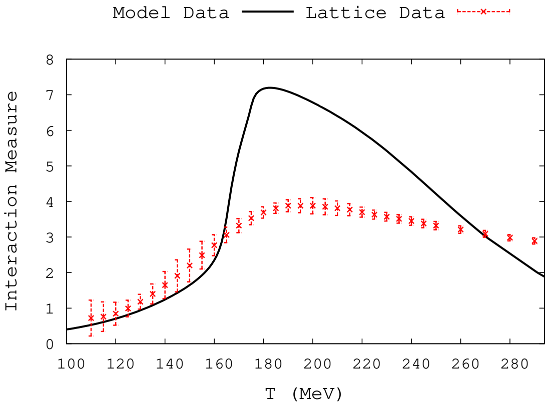
$$U = -\frac{1}{2}a(T)\Phi\Phi^* + b(T)\ln\left[16\Phi\Phi^* + 4(\Phi^3\Phi^{*3}) - 3(\Phi\Phi^*)^2\right] \ ,$$

  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

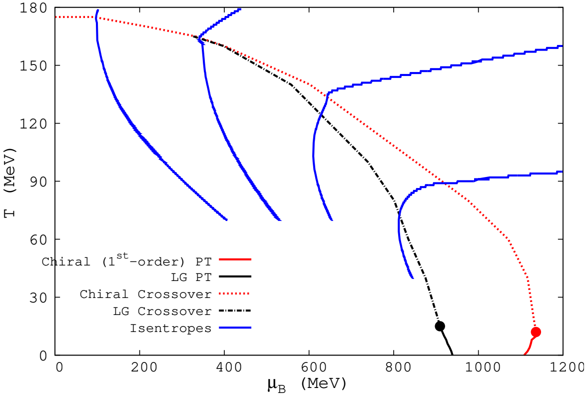
Lattice data comparison

- 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 $T - \mu_B$ diagram

- PT lines defined as $(\partial\sigma/\partial\mu_B)_{\max}$, or as $(\partial\rho_B/\partial\mu_B)_{\max}$
- 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):

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

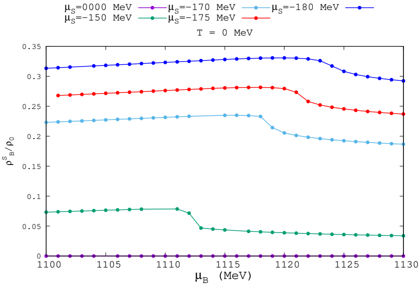
- Freeze-out curve, from fit to experimental data:

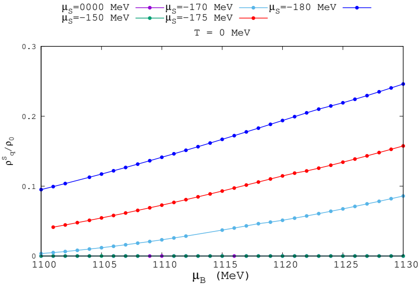
$$T\ (\mathrm{MeV}) = \frac{T_{\mathrm{lim}}}{1 + \exp\left[2.60 - \frac{\ln\left(\sqrt{s_{NN}}\ (\mathrm{GeV})\right)}{0.45}\right]},$$

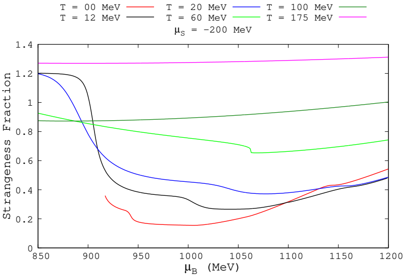
where μ_B and $\sqrt{s_{NN}}$ (the beam energy in GeV) are related as:

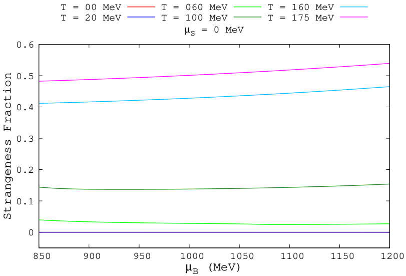
$$\mu_B\ (\mathrm{MeV}) = \frac{1303}{1 + 0.286\sqrt{s_{NN}\ (\mathrm{GeV})}}$$

The Hyperon Rises





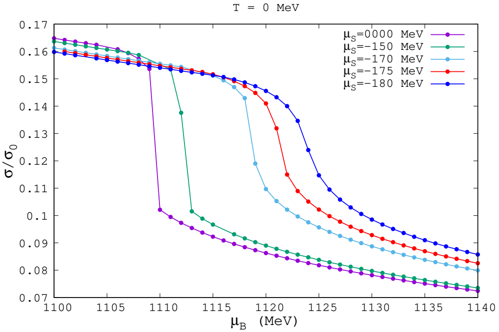




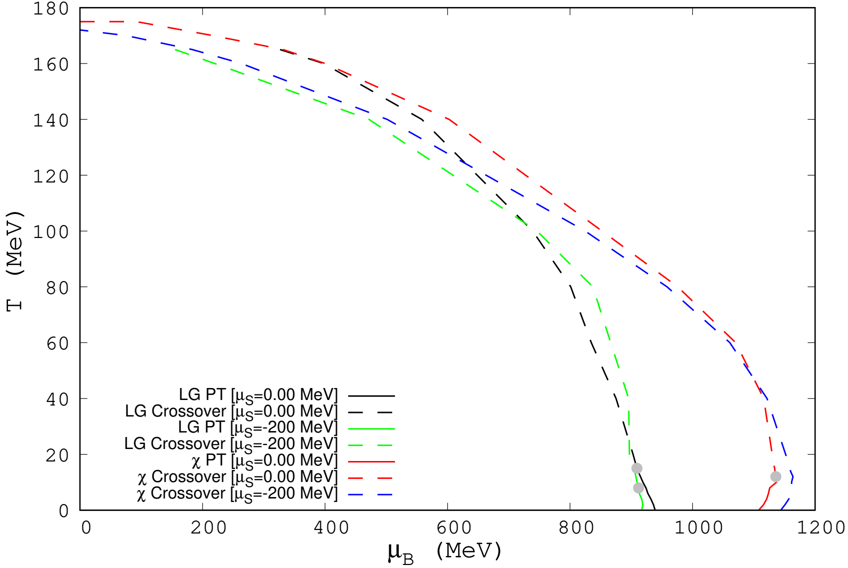
The Digression: Stranger Things

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

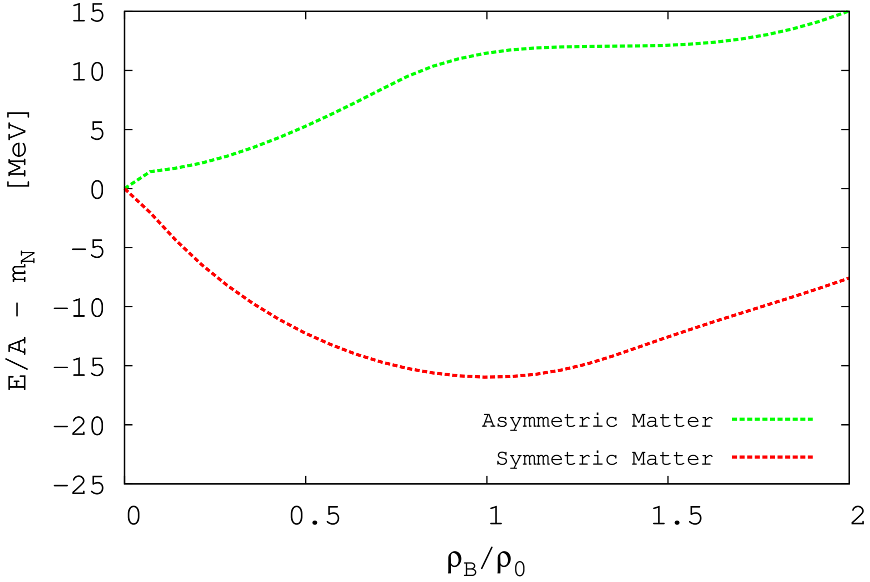


The Outcomes II: The Modified Phase Boundary



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

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



The Outcomes (contd...): Compactness