STRANGENESS NEUTRALITY AND THE QCD PHASE STRUCTURE

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[FR, Fu, Pawlowski, work in progress]

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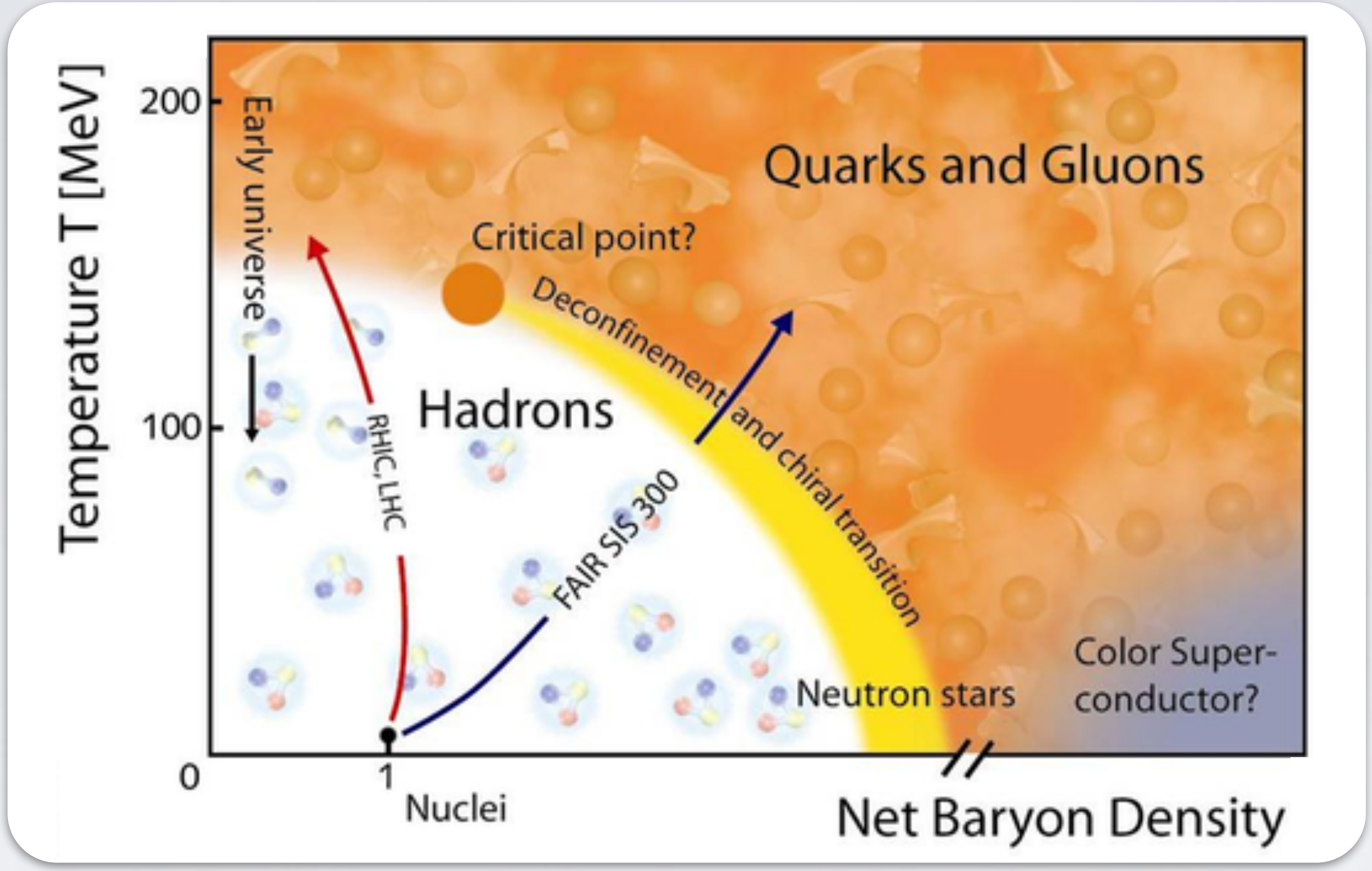
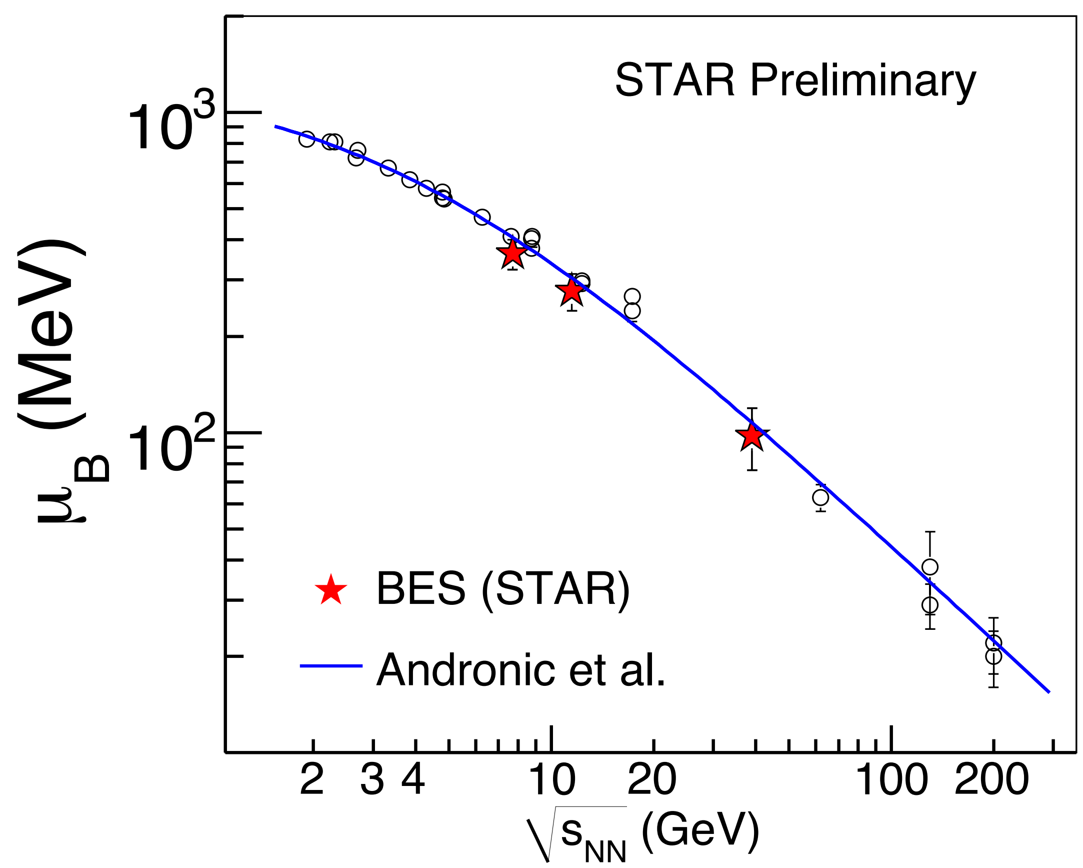
— FROM CORRELATION FUNCTIONS TO QCD PHENOMENOLOGY —

BAD HONNEF, 03/04/2018

QCD PHASE DIAGRAM



PROBING THE PHASE DIAGRAM IN HICS



[L. Kumar (STAR), J.Phys. G38 (2011)]

- increasing baryon chemical potential with decreasing beam energy
- net baryon content determined by incident nuclei
  (quark numbers are conserved under strong interactions)
- net strangeness has to be zero ⟶ strangeness neutrality

NOMENCLATURE

- chemical potentials:

$$q = \begin{pmatrix} u \\ d \\ s \end{pmatrix} \longrightarrow \mu = \begin{pmatrix} \mu_u \\ \mu_d \\ \mu_s \end{pmatrix} = \begin{pmatrix} \frac{1}{3}\mu_B + \frac{1}{2}\mu_I \\ \frac{1}{3}\mu_B - \frac{1}{2}\mu_I \\ \frac{1}{3}\mu_B - \mu_S \end{pmatrix}$$

isospin

baryon

strangeness

- here: $\mu_I = 0$

- cumulants of conserved charges

pressure

$$\chi_{ij}^{BS} = T^{i+j-4} \frac{\partial^{i+j} p(T, \mu_B, \mu_S)}{\partial \mu_B^i \partial \mu_S^j}$$

net baryon number: $B = \langle N_B - N_{\bar{B}} \rangle = \chi_{10}^{BS} V T^3$

net strangeness: $S = \langle N_S - N_{\bar{S}} \rangle = \chi_{01}^{BS} V T^3$

BARYON-STRANGENESS CORRELATION

- B-S correlations:

[Koch, Majumder, Randrupp, nucl-th/0505052]

strangeness neutrality

$$C_{BS} \equiv -3\,\frac{\chi_{11}^{BS}}{\chi_{02}^{BS}} = -3\,\frac{\langle BS\rangle - \langle B\rangle\langle S\rangle}{\langle S^2\rangle - \langle S\rangle^2} = -3\,\frac{\langle BS\rangle}{\langle S^2\rangle}$$

- **diagnostic tool for deconfinement:**

QGP

- all strangeness is carried by $s,\ \bar{s}$
- strict relation beween B and S: $B_s = -S_s/3$
- if all flavors are independent: $\chi_{11}^{BS} = -\chi_{02}^{BS}/3$

$$\longrightarrow \quad C_{BS} = 1$$

hadronic phase

- mesons can carry only strangeness, baryons both

χ_{11}^{BS} : only strange baryons

χ_{02}^{BS} : strange baryons & mesons

$$\longrightarrow \quad C_{BS} \neq 1$$

STRANGENESS NEUTRALITY

- HIC: colliding nuclei have zero strangeness $\longrightarrow$ $S = 0 \ \forall \ T, \mu_B$

- strangeness neutrality implicitly defines $\mu_S(\mu_B)$

$$\chi_{01}^{BS}(\mu_B, \mu_S(\mu_B)) = 0 \ \Rightarrow \ \frac{d\chi_{01}^{BS}}{d\mu_B} = 0 \ \Leftrightarrow \ \boxed{\frac{\partial \mu_S}{\partial \mu_B} = \frac{1}{3} C_{BS}}$$

$\longrightarrow$ **access B-S correlation through strangeness neutrality**

$\longrightarrow$ **effect of strangeness neutrality on thermodynamics / phase structure?**

LOW-ENERGY MODELING OF QCD

PQM MODEL

- Polyakov-loop enhanced Quark-Meson model (in the local potential approximation LPA):

$$\Gamma_k = \int_x \Big\{ \bar{q}\big(\gamma_\nu D_\nu + \gamma_\nu C_\nu\big) q + \bar{q}\, h \cdot \Sigma_5 q + \mathrm{tr}\big(\bar{D}_\nu \Sigma \cdot \bar{D}_\nu \Sigma^\dagger\big) + \tilde{U}_k(\Sigma) + U_{\mathrm{glue}}(\langle L \rangle, \langle \bar{L} \rangle) \Big\}$$

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- scalar and pseudoscalar meson nonets:

$$\Sigma = T^a(\sigma^a + i\pi^a) \ni \begin{matrix} \{\sigma\,, f_0,\, a_0^0,\, a_0^+,\, a_0^-,\, \boxed{\kappa^0,\, \bar{\kappa}^0,\, \kappa^+,\, \kappa^-}\} \\ \{\eta\,, \eta',\, \pi^0,\, \pi^+,\, \pi^-,\, \boxed{K^0,\, \bar{K}^0,\, K^+,\, K^-}\} \end{matrix}$$

open strange mesons: $l\bar{s}\,,\ s\bar{l}$

$$\Sigma_5 = T_a(\sigma_a + i\gamma_5 \pi_a)$$

- quarks (assume light isospin symmetry):

$$q = \begin{pmatrix} l \\ l \\ s \end{pmatrix} \qquad \mu = \begin{pmatrix} \frac{1}{3}\mu_B \\ \frac{1}{3}\mu_B \\ \frac{1}{3}\mu_B - \mu_S \end{pmatrix}$$

PQM MODEL

- Polyakov-loop enhanced Quark-Meson model (in the local potential approximation LPA):

cov. derivative with A_0 background

$$D_\nu = \partial_\nu - ig\delta_{\nu 0} A_0$$

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quarks and mesons:

$$q = \begin{pmatrix} l \\ l \\ s \end{pmatrix} \qquad \begin{aligned} \Sigma &= T^a(\sigma^a + i\pi^a) \\ \Sigma_5 &= T_a(\sigma_a + i\gamma_5 \pi_a) \end{aligned}$$

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vector source / cov. derivative for the chemical potential

$$C_\nu = \delta_{\nu 0}\, \mu \qquad \bar{D}_\nu \Sigma = \partial_\nu \Sigma + [C_\nu, \Sigma]$$

couples μ_S to mesons!

$$\Gamma_k = \int_x \Big\{ \bar{q}\big(\gamma_\nu D_\nu + \gamma_\nu C_\nu\big) q + \bar{q}\, h \cdot \Sigma_5 q + \mathrm{tr}\big(\bar{D}_\nu \Sigma \cdot \bar{D}_\nu \Sigma^\dagger\big) + \tilde{U}_k(\Sigma) + U_{\mathrm{glue}}(\langle L \rangle, \langle \bar{L} \rangle) \Big\}$$

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effective meson potential:

$$\tilde{U}_k = U_k(\rho_1, \tilde{\rho}_2) - j_l \sigma_l - j_s \sigma_s - c_k\, \xi$$

U(3) x U(3) symmetric potential (as a function of two chiral invariants)

$$\rho_i = \mathrm{tr}(\Sigma \cdot \Sigma^\dagger)^i$$

explicit chiral symmetry breaking: finite light & strange current quark masses

anomalous $U(1)_A$ breaking via 't Hooft determinant

$$\xi = \det(\Sigma + \Sigma^\dagger)$$

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Polyakov loop potential: [Lo et. al., hep-lat/1307.5958]

$$L = \frac{1}{N_c}\Big\langle \mathrm{Tr}_f\mathcal{P}\,e^{ig\int_0^\beta d\tau A_0(\tau)}\Big\rangle$$

$$\frac{U_{\mathrm{glue}}(L,\bar{L})}{T^4} = -\frac{1}{2}a(T)\bar{L}L + b(T)\ln\left[M_H(L,\bar{L})\right] + \frac{1}{2}c(T)(L^3+\bar{L}^3) + d(T)(\bar{L}L)^2$$

$$M_H(L,\bar{L}) = 1 - 6\bar{L}L + 4(L^3+\bar{L}^3) - 3(\bar{L}L)^2$$

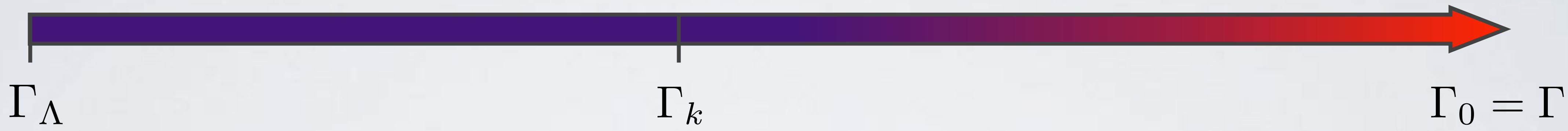
- parameters fitted to reproduce lattice pressure and Polyakov loop susceptibilities
- approximate N_f and μ dependence from QCD and HTL/HDL arguments [Herbst et. al., hep-ph/1008.0081, 1302.1426] [Haas et. al., hep-ph/1302.1993]

FUNCTIONAL RG

non-perturbative quantum fluctuations via FRG

- relevant object: scale dependent effective action Γ_k

successively integrate out fluctuations from UV to IR (Wilson RG)



full quantum effective action (generates 1PI correlators)

⟶ Γ_k is eff. action that incorporates all fluctuations down to scale k

⟶ lowering k: zooming out / coarse graining

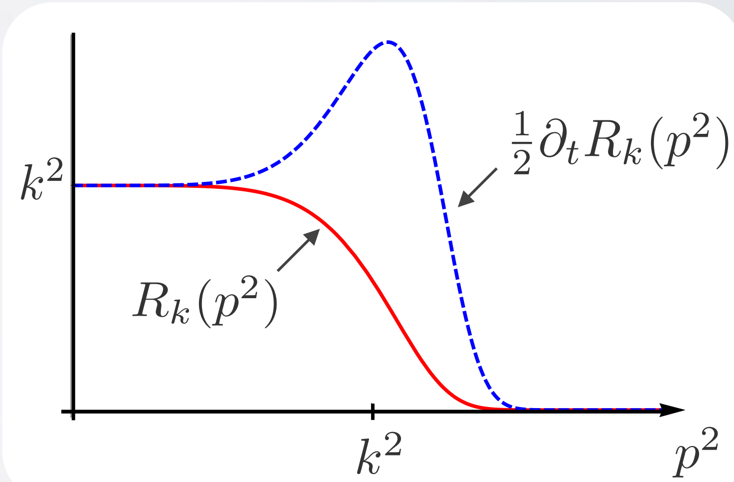
- evolution equation for Γ_k:

mass-like IR regulator

$$\partial_t \Gamma_k = \tfrac{1}{2}\mathrm{STr}\left[\left(\Gamma_k^{(2)} + R_k\right)^{-1}\partial_t R_k\right]$$

$$\partial_t = k\frac{d}{dk}$$

[Wetterich 1993]



PQM + FUNCTIONAL RG

- dynamical chiral symmetry breaking though U_k
- \`statistical´ confinement through A_0 background (U_{glue})
- thermal quark distributions modified through feedback from A_0

$$n_F(E) = \frac{1}{e^{(E-\mu)/T}+1} \quad \xrightarrow{A_0 \neq 0} \quad N_F(E;L,\bar{L}) = \frac{1+2\bar{L}e^{(E-\mu)/T}+Le^{2(E-\mu)/T}}{1+3\bar{L}e^{(E-\mu)/T}+3Le^{2(E-\mu)/T}+e^{3(E-\mu)/T}}$$

$$\longrightarrow \begin{cases} \frac{1}{e^{3(E-\mu)/T}+1}, & L \to 0 \text{ (confinement)} \\ \frac{1}{e^{(E-\mu)/T}+1}, & L \to 1 \text{ (deconfinement)} \end{cases}$$

→ \`interpolation´ between baryon and quark d.o.f.

[Fukushima, hep-ph/0808.3382]
[Fu & Pawlowski, hep-ph/1508.06504]

→ correct \`N_c - scaling´ of particle number fluctuations

[Ejiri et al., hep-ph/0509051]
[Skokov et al., hep-ph/1004.2665]

- thermodynamics from Euclidean (off-shell) formulation

→ simple hierarchy of relevant fluctuations: the lighter the particle, the more relevant it is

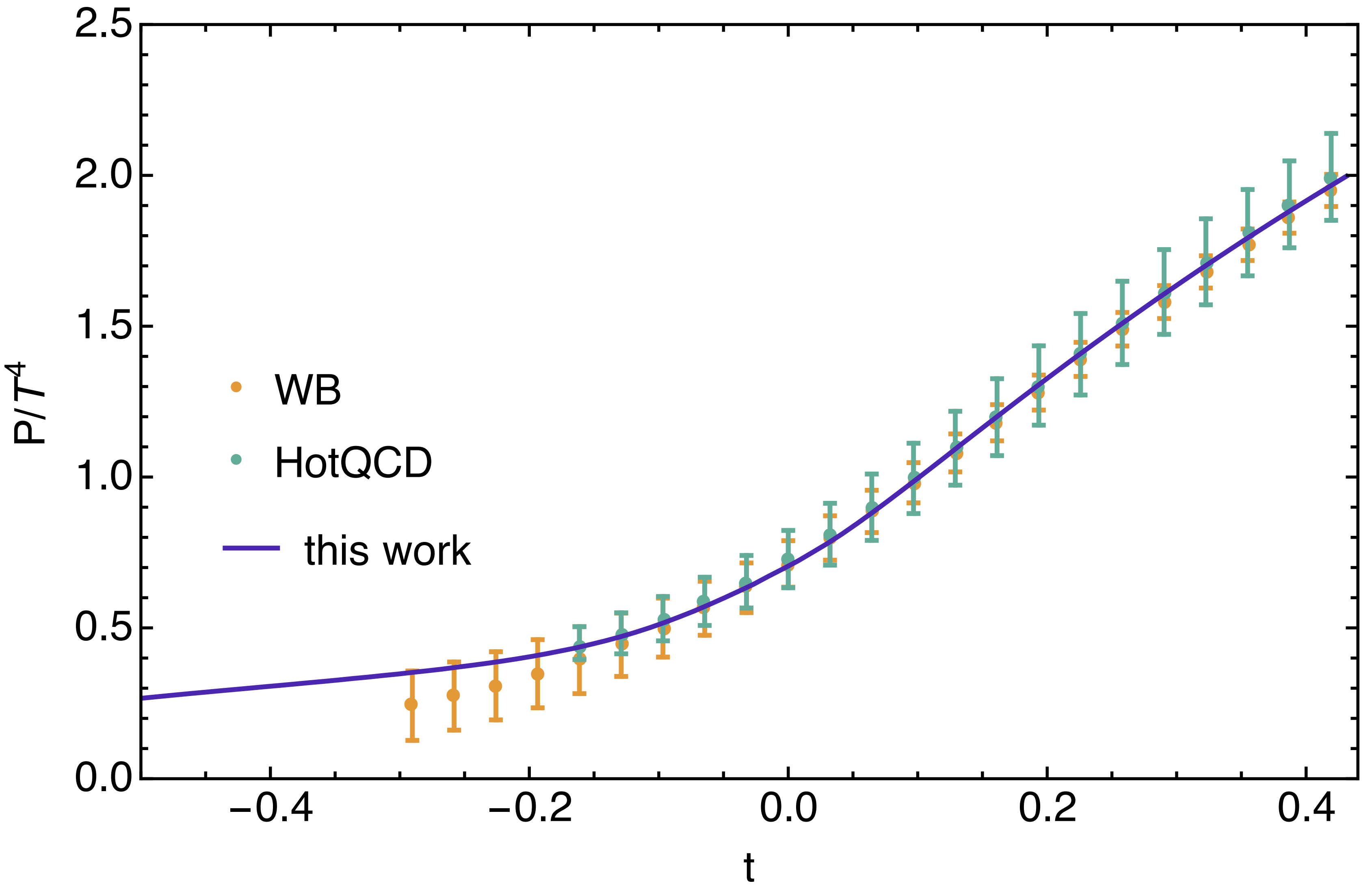
→ fluctuations of kaons and s-quarks (coupled to A_0) already sufficient for qualitative description of the relevant strangeness effects (for moderate μ)

preliminary

RESULTS

MODEL VS LATTICE EOS

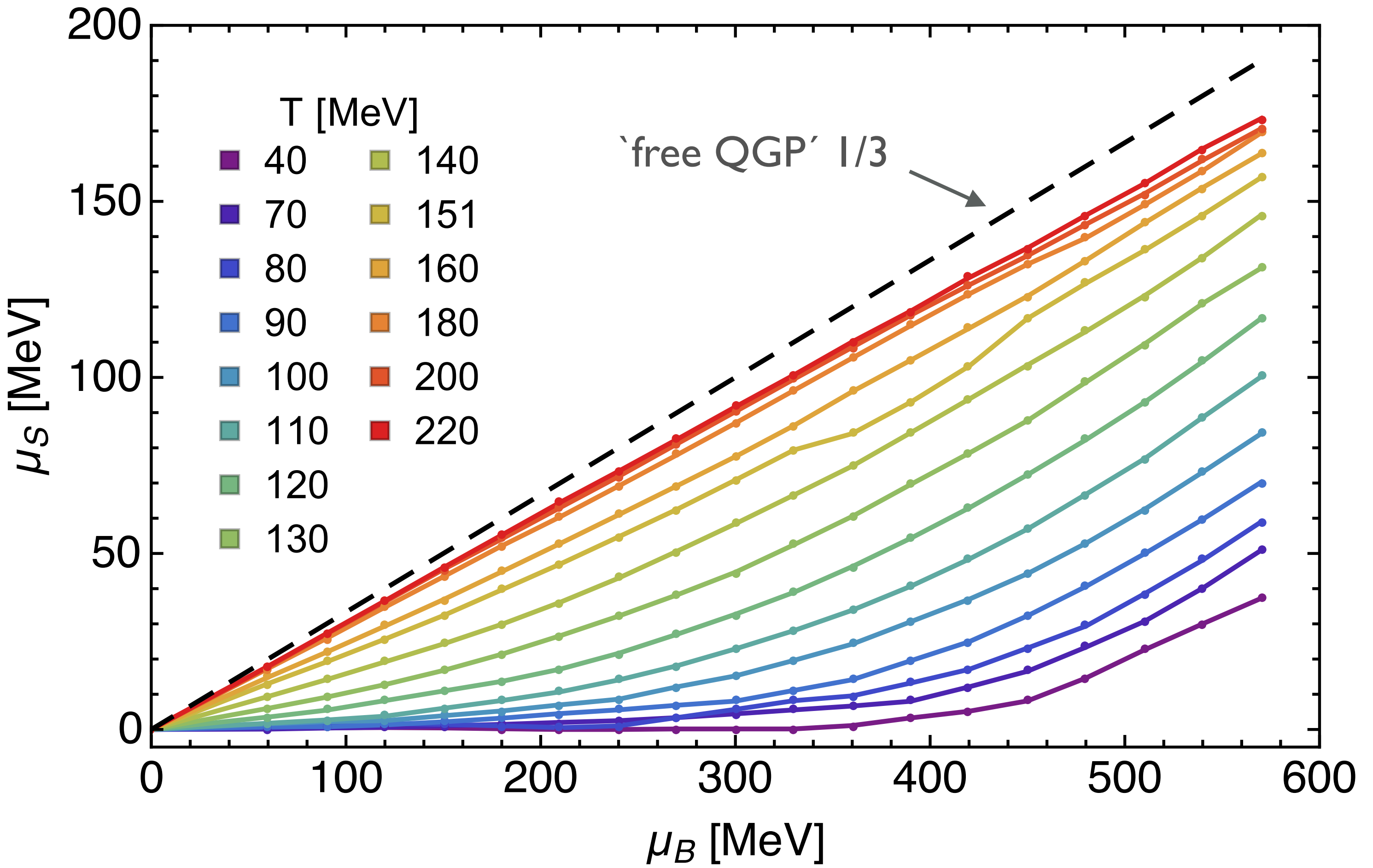
cf. [Herbst et al., hep-ph/1308.3621]



$$t = \frac{T - T_c}{T_c}$$

STRANGENESS NEUTRALITY

$\mu_S(\mu_B)$ at strangeness neutrality



- slope directly related to baryon-strangeness correlations:

$$\frac{\partial \mu_S}{\partial \mu_B} = \frac{1}{3} C_{BS}$$

→ C_{BS} for any T and μ

→ competition between baryonic and mesonic sources of strangeness!

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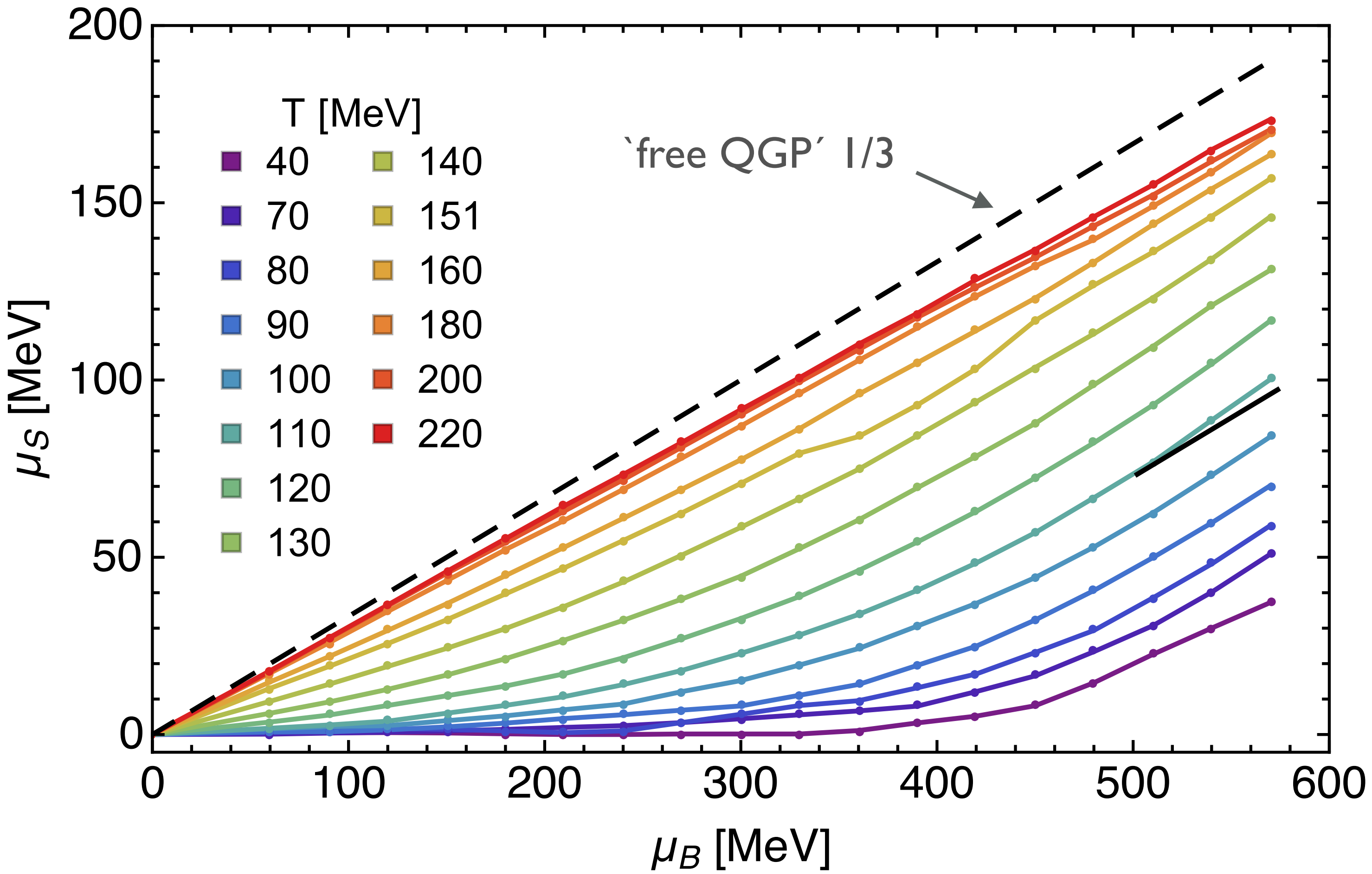

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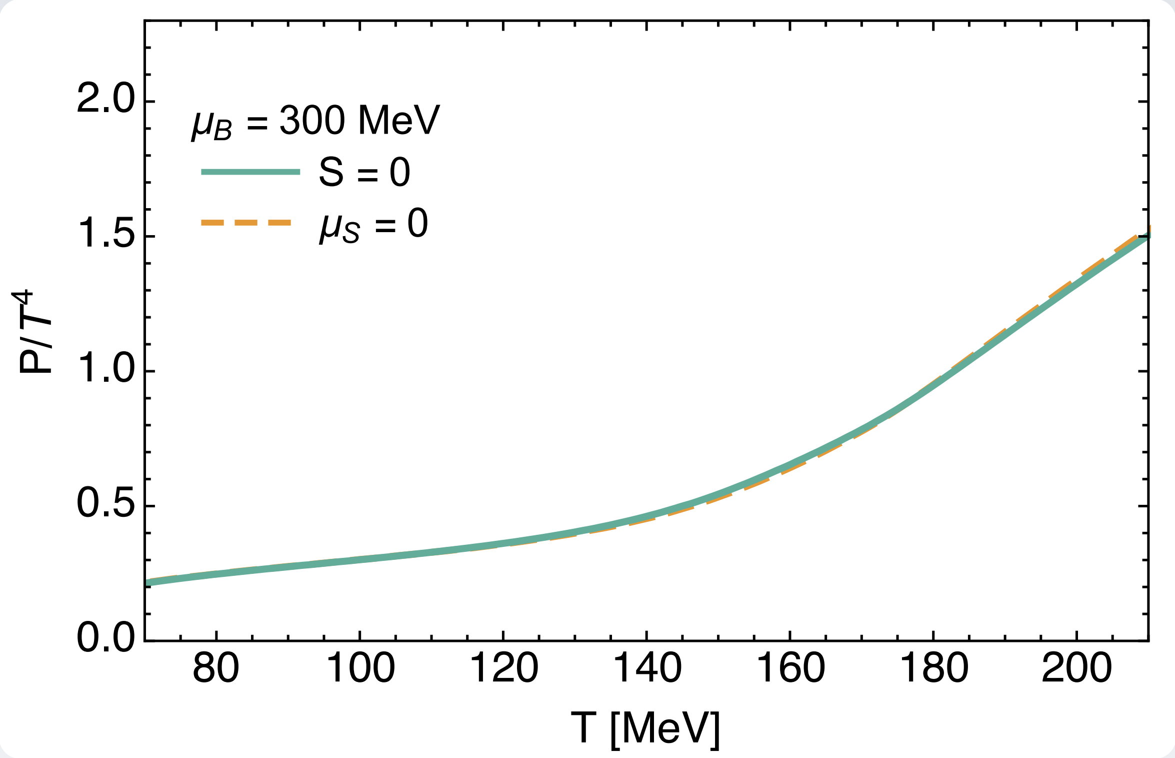
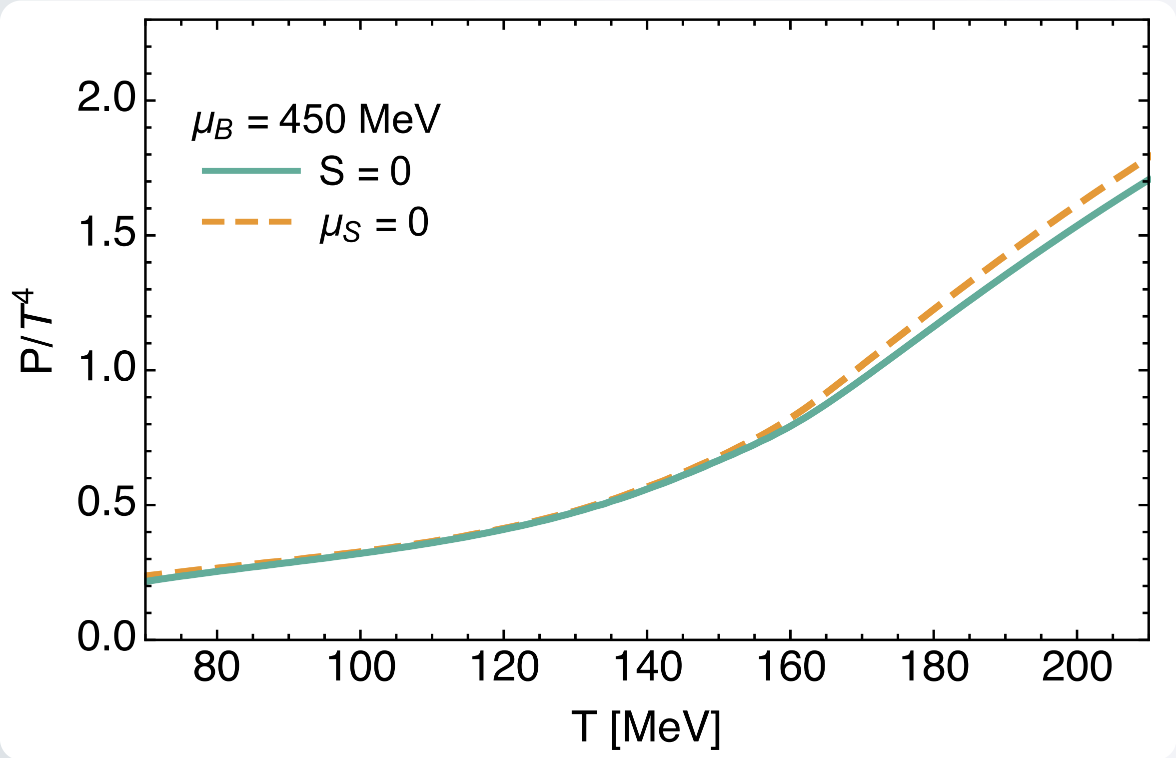
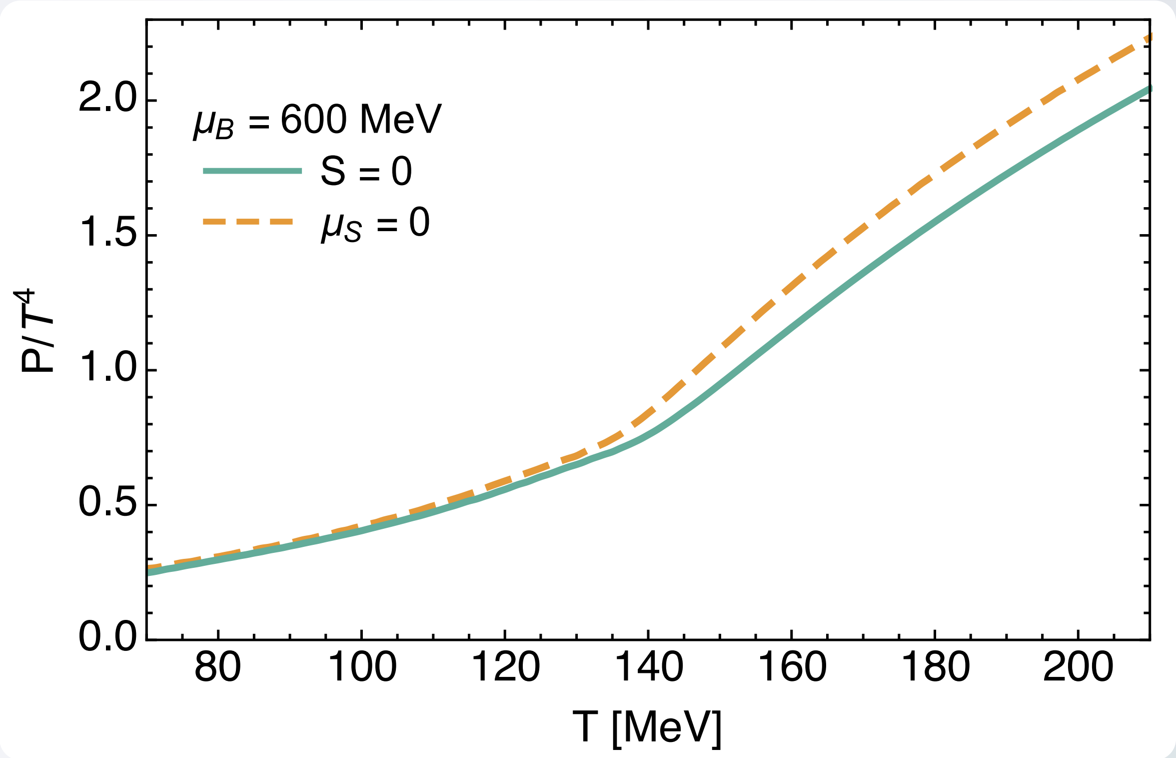
$$3\frac{\partial \mu_S}{\partial \mu_B} = C_{BS} \sim \frac{\langle \text{strange baryons} \rangle}{\langle (\text{strange baryons \& mesons})^2 \rangle} \begin{cases} < 1 & \text{mesons dominate} \\ = 1 & \text{mesons \& baryons (or free flavors)} \\ > 1 & \text{baryons dominate} \end{cases}$$

STRANGENESS NEUTRALITY

EoS at strangeness neutrality

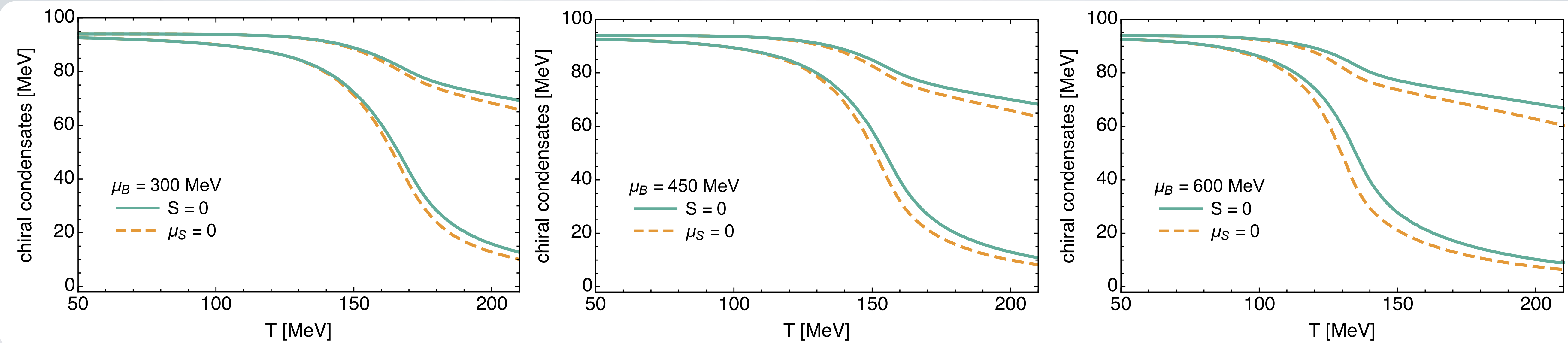


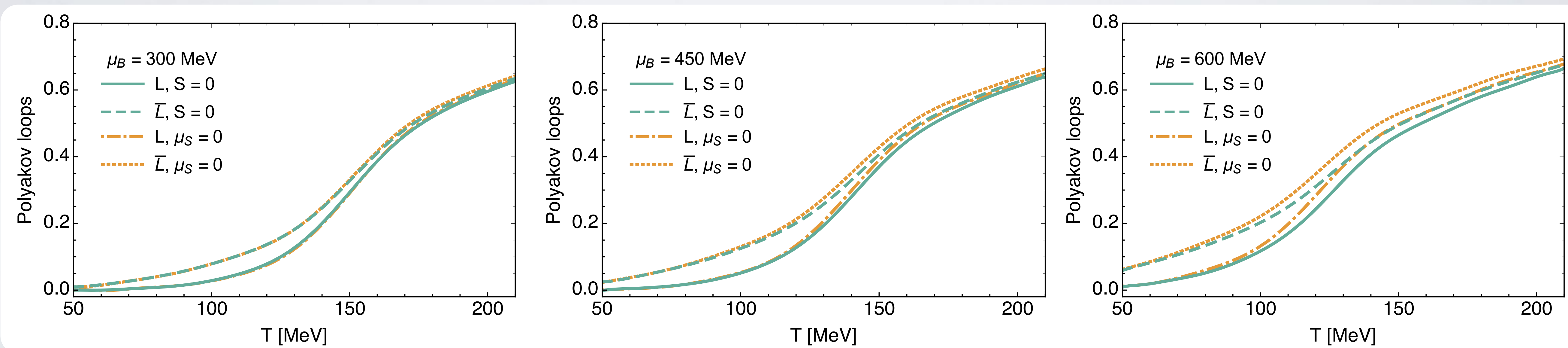




STRANGENESS NEUTRALITY

phase structure at strangeness neutrality





→ **critical temperature starts increasing at moderate μ_B due to strangeness neutrality**

→ **smaller curvature of the phase boundary**

→ **CEP at larger T (?)**

SUMMARY & OUTLOOK

- strangeness neutrality in heavy ion collisions
    - intimate relation to baryon strangeness correlations
    - sensitive to QCD phase transition
- relevant for phase structure and thermodynamics at finite μ_B
    - phase transition at larger T for moderate μ_B
    - likely to affect position of the CEP

In progress:

- study larger μ and the CEP
- eigenvalue potential vs loop potential: minimum vs saddle point
- going beyond LPA
- including gluon fluctuations: dynamical hadronization
- self-consistent computation of the A_0 potential

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thank you