STRANGENESS NEUTRALITY AND THE QCD PHASE STRUCTURE

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[Fu, Pawlowski, FR, hep-ph/1808.00410]
[Fu, Pawlowski, FR, hep-ph/1809.01594]

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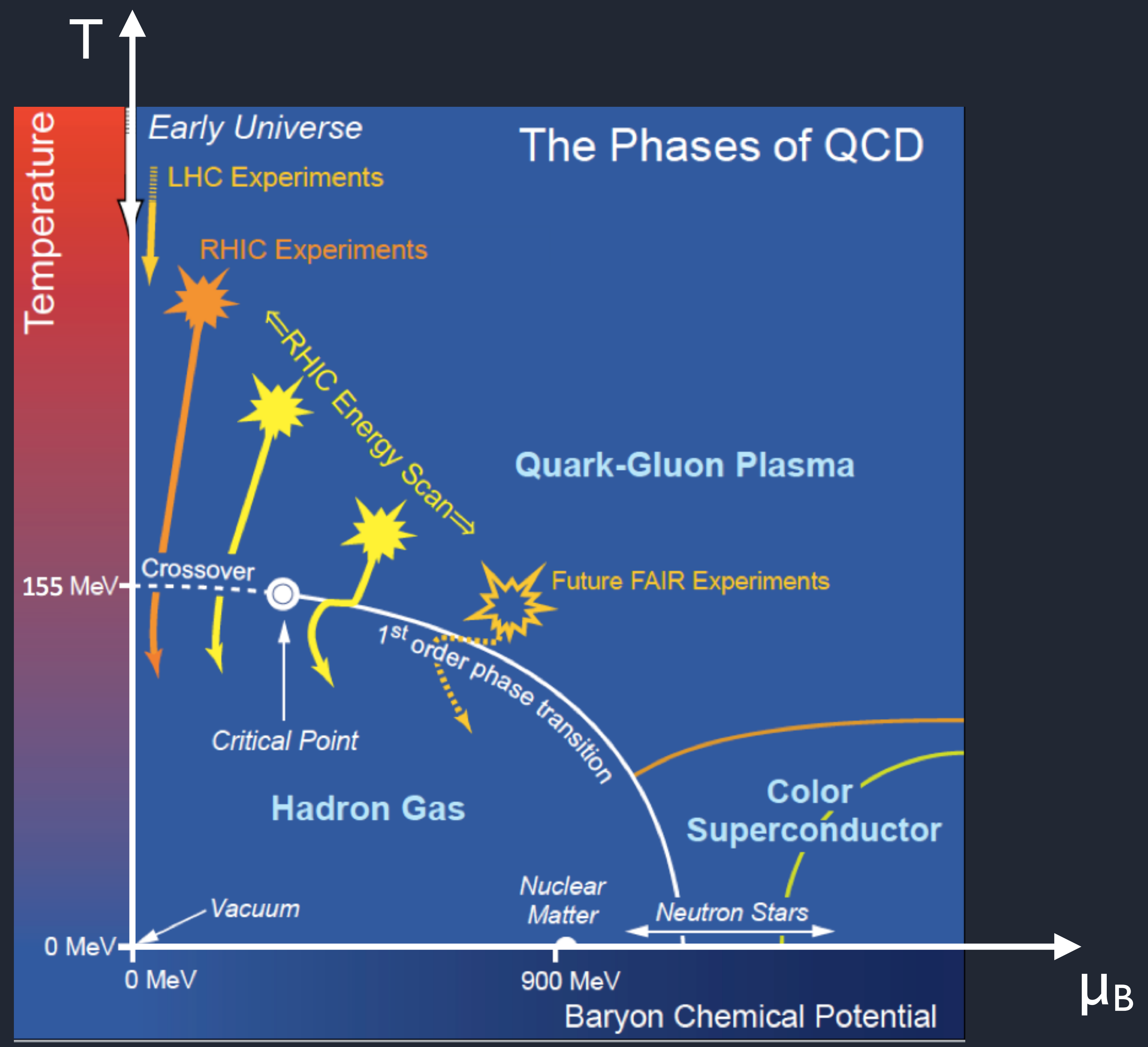
DFG Deutsche Forschungsgemeinschaft

— CRITICAL POINT AND ONSET OF DECONFINEMENT —

CORFU 26/09/2018

QCD PHASE DIAGRAM



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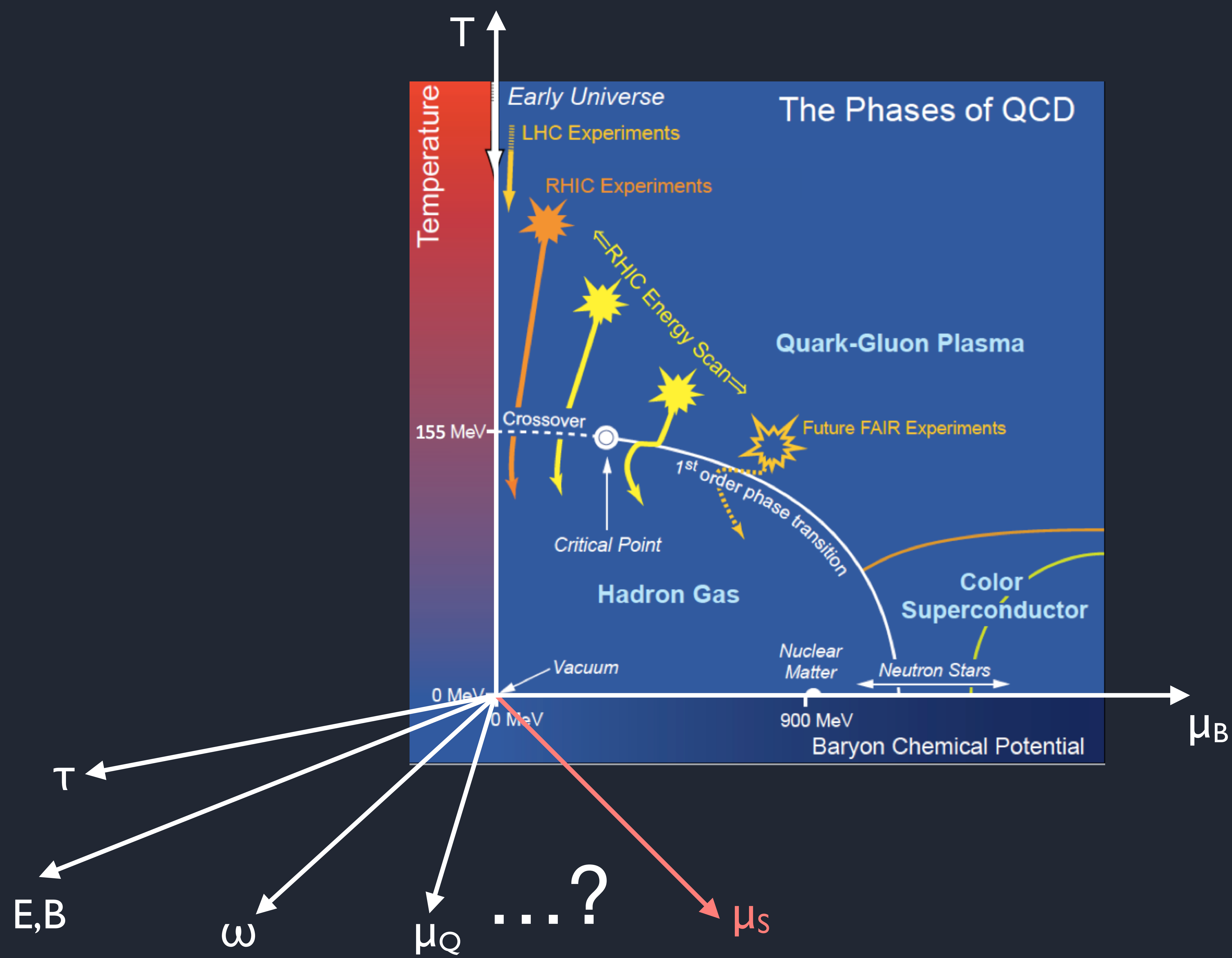
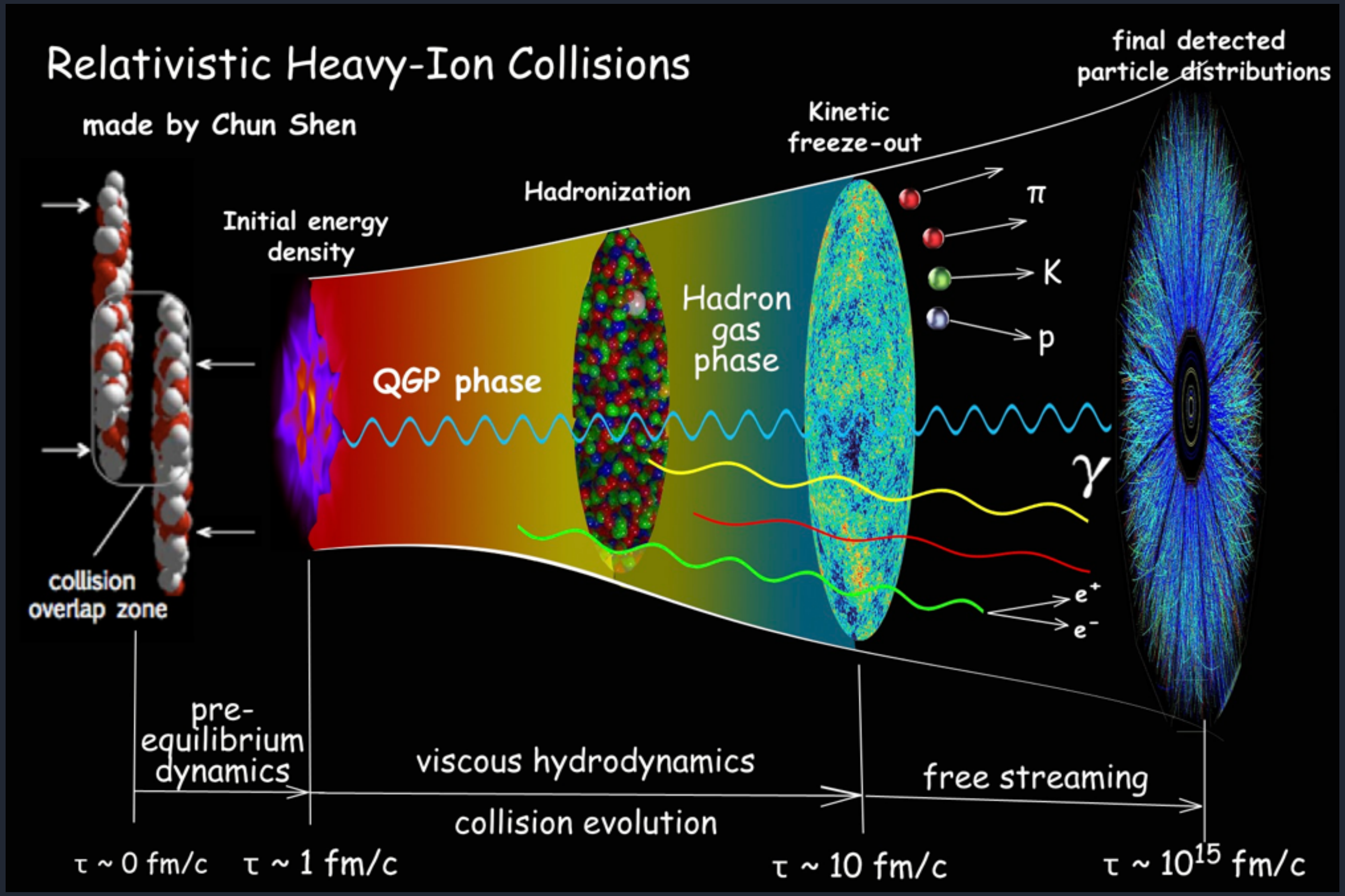


PROBING THE PHASE DIAGRAM



- phase diagram probed at freeze-out; timescale ~10 fm/c
- typical timescales of strong and (flavor-changing) weak decays: ~1 fm/c vs ~10^{13} fm/c

⟶ quark number conservation of the strong interactions at the freeze-out!

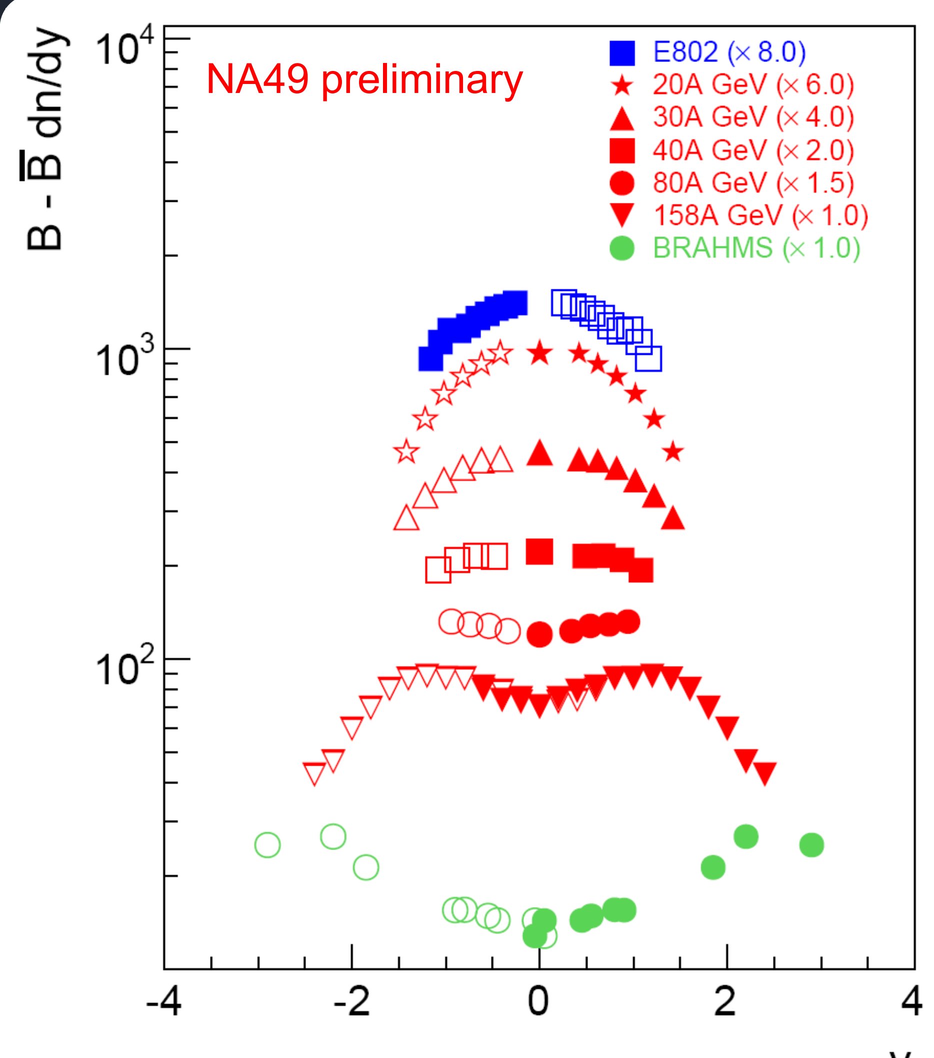
⟶ baryon number, strangeness & charge are conserved

$$\mu = \begin{pmatrix} \mu_u \\ \mu_d \\ \mu_s \end{pmatrix} = \begin{pmatrix} \frac{1}{3}\mu_B + \frac{2}{3}\mu_Q \\ \frac{1}{3}\mu_B - \frac{1}{3}\mu_Q \\ \frac{1}{3}\mu_B - \frac{1}{3}\mu_Q - \mu_S \end{pmatrix}$$

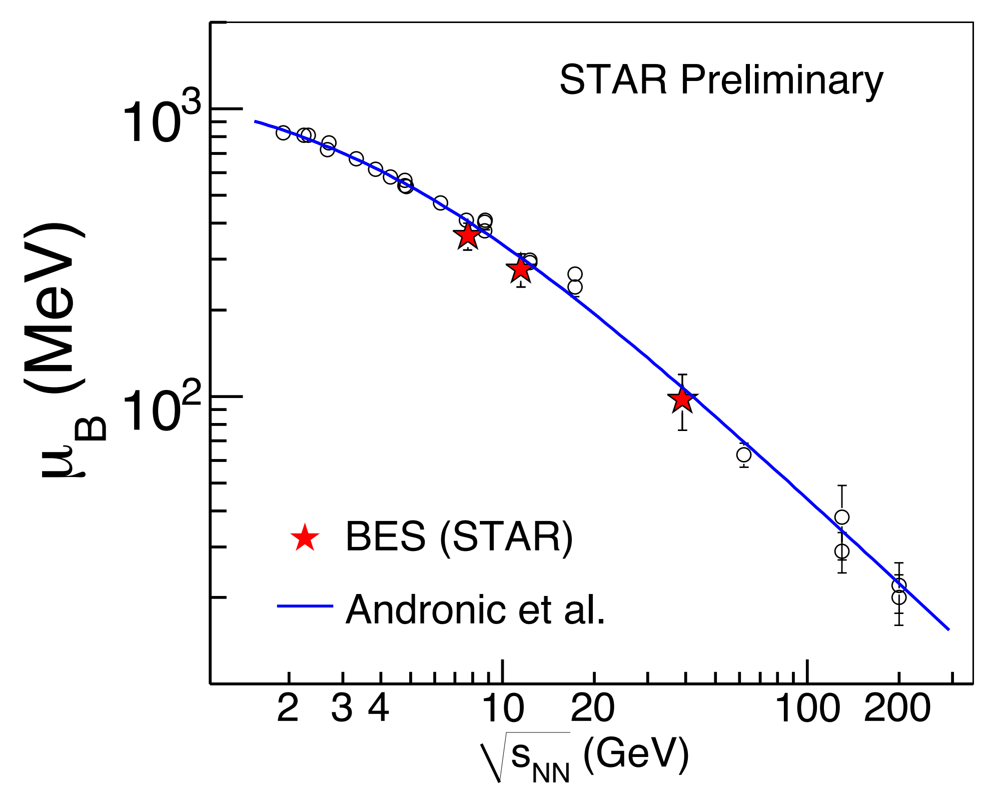
PROBING THE PHASE DIAGRAM

- net quark content determined by incident nuclei
- net strangeness has to be zero ⟶ fixes μ_S : strangeness neutrality
- net charged fixed ⟶ fixes μ_Q here: $\mu_Q = 0$
- increasing baryon chemical potential with decreasing beam energy (at mid-rapidity)

⟶ μ_B is a ´free´ parameter



[NA49, compiled by C. Blume]



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

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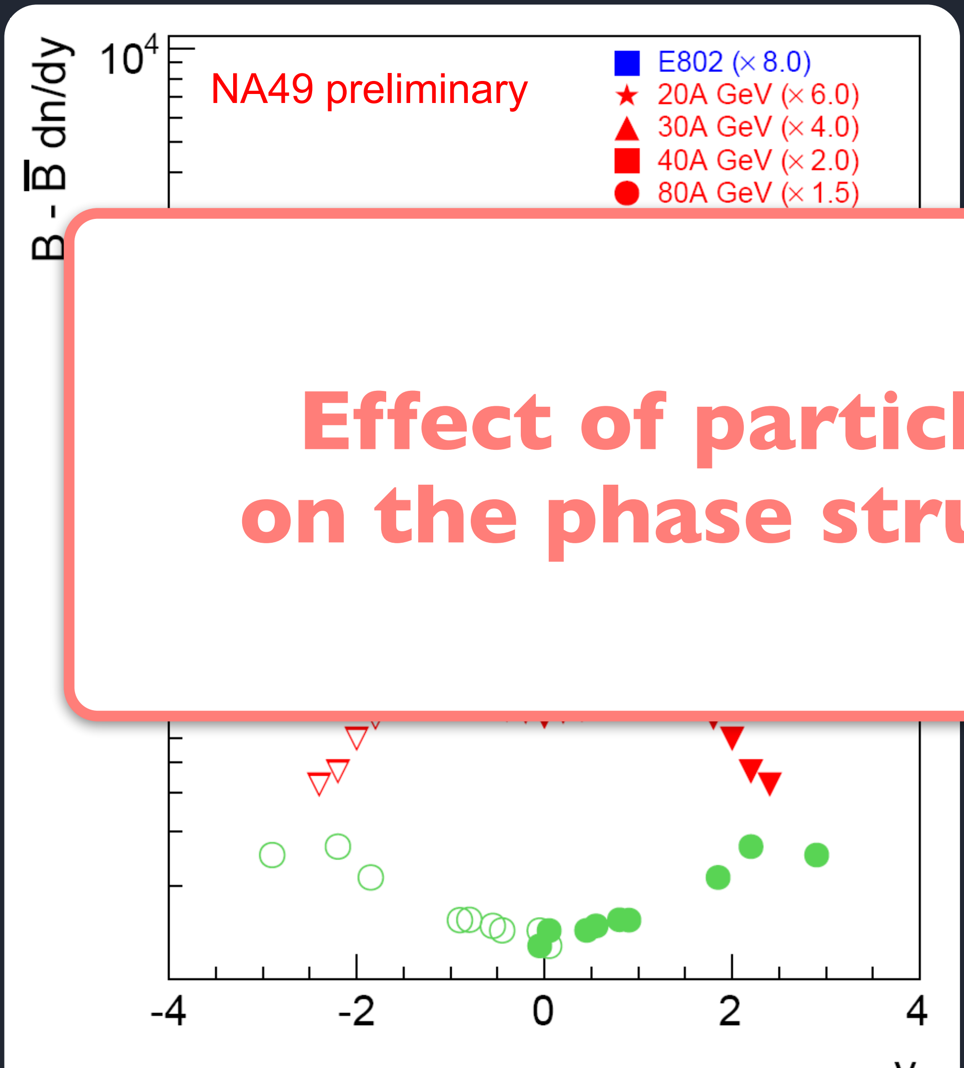

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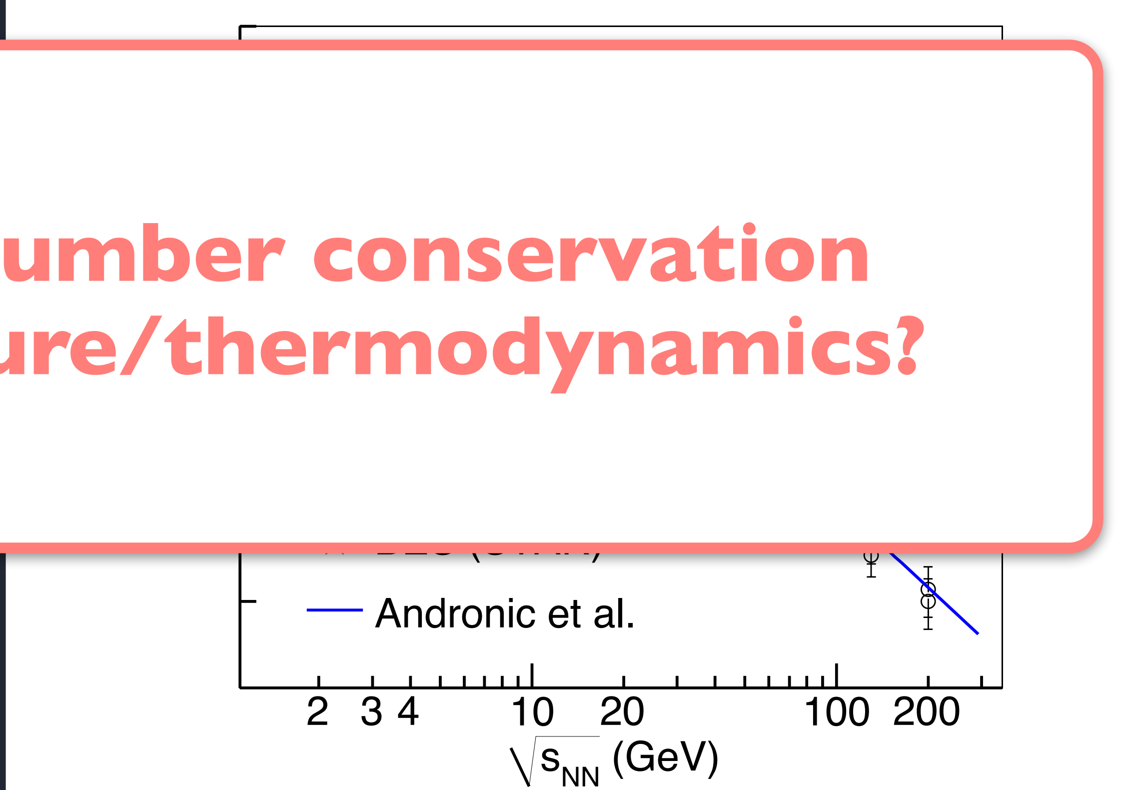

[L. Kumar (STAR), J.Phys. G38 (2011)]

Effect of particle number conservation on the phase structure/thermodynamics?

BARYON-STRANGENESS CORRELATION

- generalized susceptibilities can be measured (more or less)

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

pressure

- baryon-strangeness correlation

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

strangeness neutrality

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

- **C_{BS} as 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: $\chi_{11}^{BS} = -\chi_{02}^{BS}/3$

$\longrightarrow C_{BS} = 1$

hadronic phase

- mesons can carry only strangeness, baryons both

χ_{11}^{BS} : only strange baryons

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

$\longrightarrow C_{BS} \neq 1$

STRANGENESS NEUTRALITY

- net strangeness: $\langle S \rangle = \langle N_{\bar{S}} - N_S \rangle = \chi_{01}^{BS} V T^3$
- HIC: colliding nuclei have zero strangeness $\longrightarrow$ $\langle S \rangle = 0$
- strangeness neutrality implicitly defines $\mu_{S0}(T, \mu_B) = \mu_S(T, \mu_B)\big|_{\langle S \rangle = 0}$

$$\chi_{01}^{BS}(T, \mu_B, \mu_{S0}) = 0 \;\Rightarrow\; \frac{d\chi_{01}^{BS}}{d\mu_B} = 0 \;\Leftrightarrow\; \boxed{\frac{\partial \mu_{S0}}{\partial \mu_B} = \frac{1}{3} C_{BS}}$$

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particle number conservation $\longleftrightarrow$ phases of QCD

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

PQM MODEL

captures relevant dynamics at low energy

$$\Gamma_k = \int_0^{1/T} dx_0 \int d^3x \left\{ \bar{q}\big(\gamma_\nu D_\nu + \gamma_\nu C_\nu\big) q + \bar{q}\, h\cdot\Sigma_5 q + \mathrm{tr}\big(\bar{D}_\nu \Sigma\cdot \bar{D}_\nu \Sigma^\dagger\big) + \tilde{U}_k(\Sigma) + U_{\mathrm{glue}}(L,\bar{L}) \right\}$$

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- scalar and pseudoscalar meson nonets:

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

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): $q = \begin{pmatrix} l \\ l \\ s \end{pmatrix}$

PQM MODEL

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- chemical potential matrix

$$\mu = \begin{pmatrix} \frac{1}{3}\mu_B & 0 & 0 \\ 0 & \frac{1}{3}\mu_B & 0 \\ 0 & 0 & \frac{1}{3}\mu_B - \mu_S \end{pmatrix}$$

- vector source for the chemical potential

$$C_\nu = \delta_{\nu 0}\, \mu$$

- covariant derivative couples chemical potentials to mesons

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

PQM MODEL

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effective meson potential:
meson self-interactions & condensates

→ spontaneous chiral symmetry breaking

PQM MODEL

captures relevant dynamics at low energy

$$\Gamma_k = \int_0^{1/T} dx_0 \int d^3x \left\{ \bar{q}(\gamma_\nu D_\nu + \gamma_\nu C_\nu) q + \bar{q}\, h \cdot \Sigma_5 q + \mathrm{tr}\big(\bar{D}_\nu \Sigma \cdot \bar{D}_\nu \Sigma^\dagger\big) + \tilde{U}_k(\Sigma) + U_{\text{glue}}(L, \bar{L}) \right\}$$

- temporal gluon background field in cov. derivative: $D_\nu = \partial_\nu - ig\delta_{\nu 0} A_0$
- Polyakov loop: $L = \frac{1}{N_c} \left\langle \mathrm{Tr}_f \mathcal{P}\, e^{ig \int_0^\beta d\tau A_0(\tau)} \right\rangle$
- Polyakov loop potential: $U_{\text{glue}}(L, \bar{L})$

  parameters fitted to reproduce lattice pressure and Polyakov loop susceptibilities of the pure gauge theory

  [Lo et. al., hep-lat/1307.5958]

→ `statistical confinement´

thermal quark distribution: $n_F(E) \xrightarrow{A_0} \begin{cases} \frac{1}{e^{3(E-\mu)/T}+1}, & L \to 0 \text{ (confinement)} \\ \frac{1}{e^{(E-\mu)/T}+1}, & L \to 1 \text{ (deconfinement)} \end{cases}$

FUNCTIONAL RG

non-perturbative quantum fluctuations

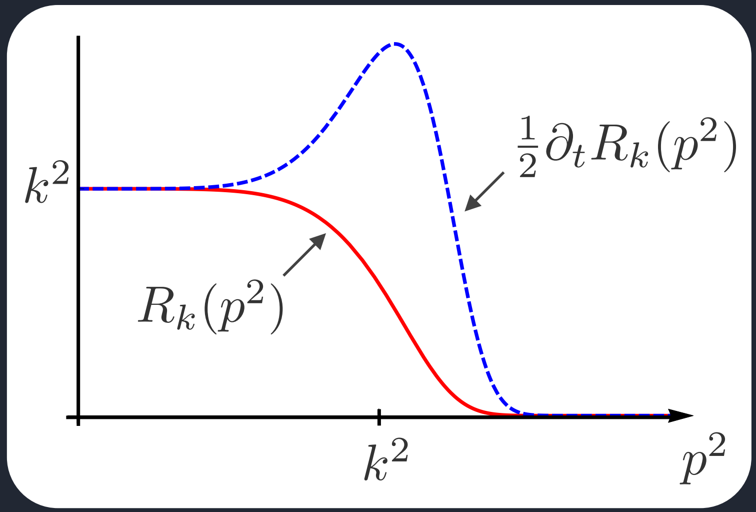
- scale dependent effective action Γ_k

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:

[Wetterich 1993]

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

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

- here: convenient tool for regularization and renormalization of fluctuations ⟶ open strange meson fluctuations

- no sign problem ⟶ direct computations at finite μ possible

THERMODYNAMICS

compare to lattice gauge theory

- thermodynamic potential:

$$\Omega = \left(\widetilde{U}_0 + U_{\text{glue}}\right)\Big|_{\text{EoM}}$$

- thermodynamics:

$$p = -\Omega$$

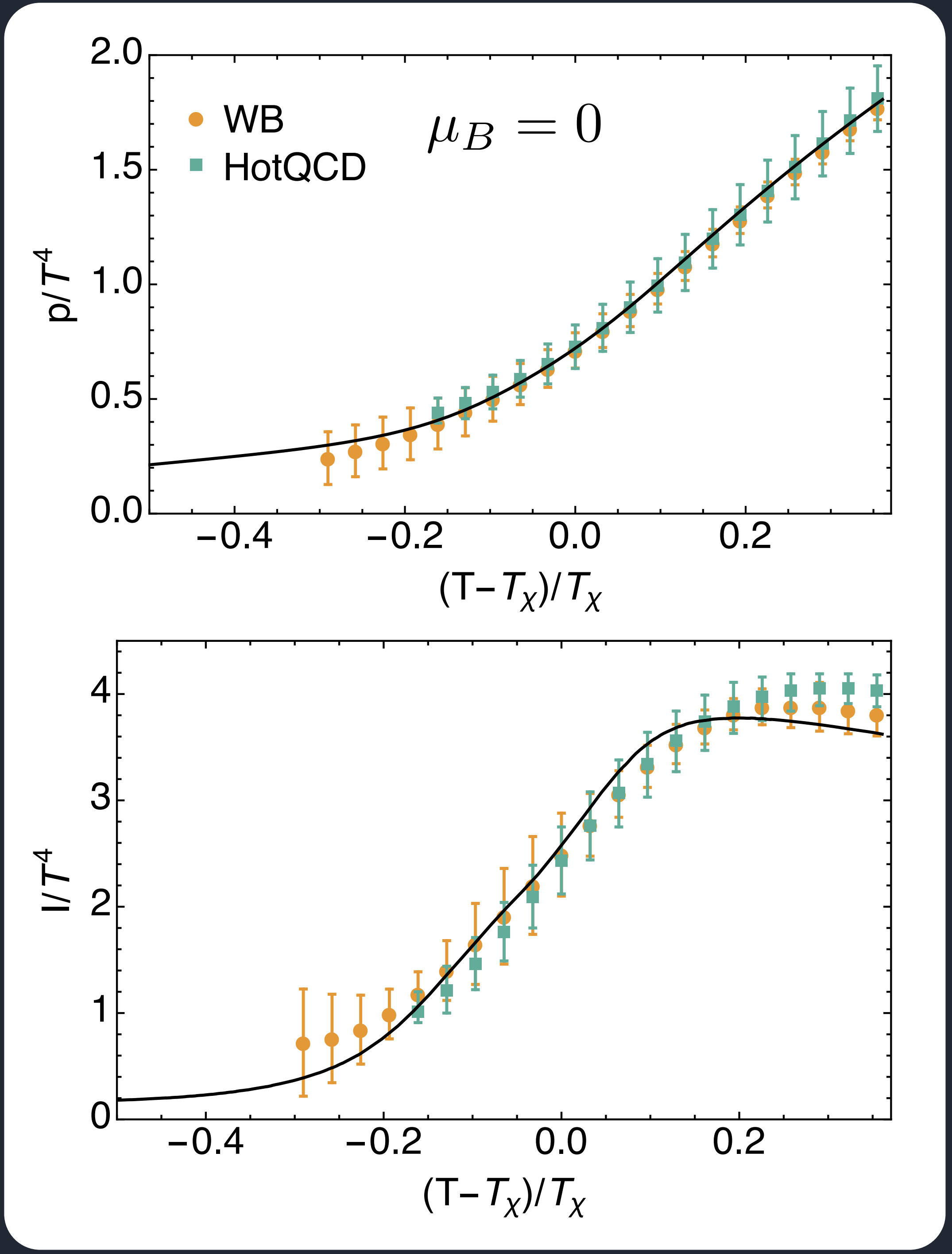
$$s = \frac{\partial p}{\partial T}$$

$$\epsilon = -p + Ts + \mu_B n_B + \mu_S n_S$$

$$I = \epsilon - 3p$$

$$n_B = \chi_{10}^{BS} T^3$$

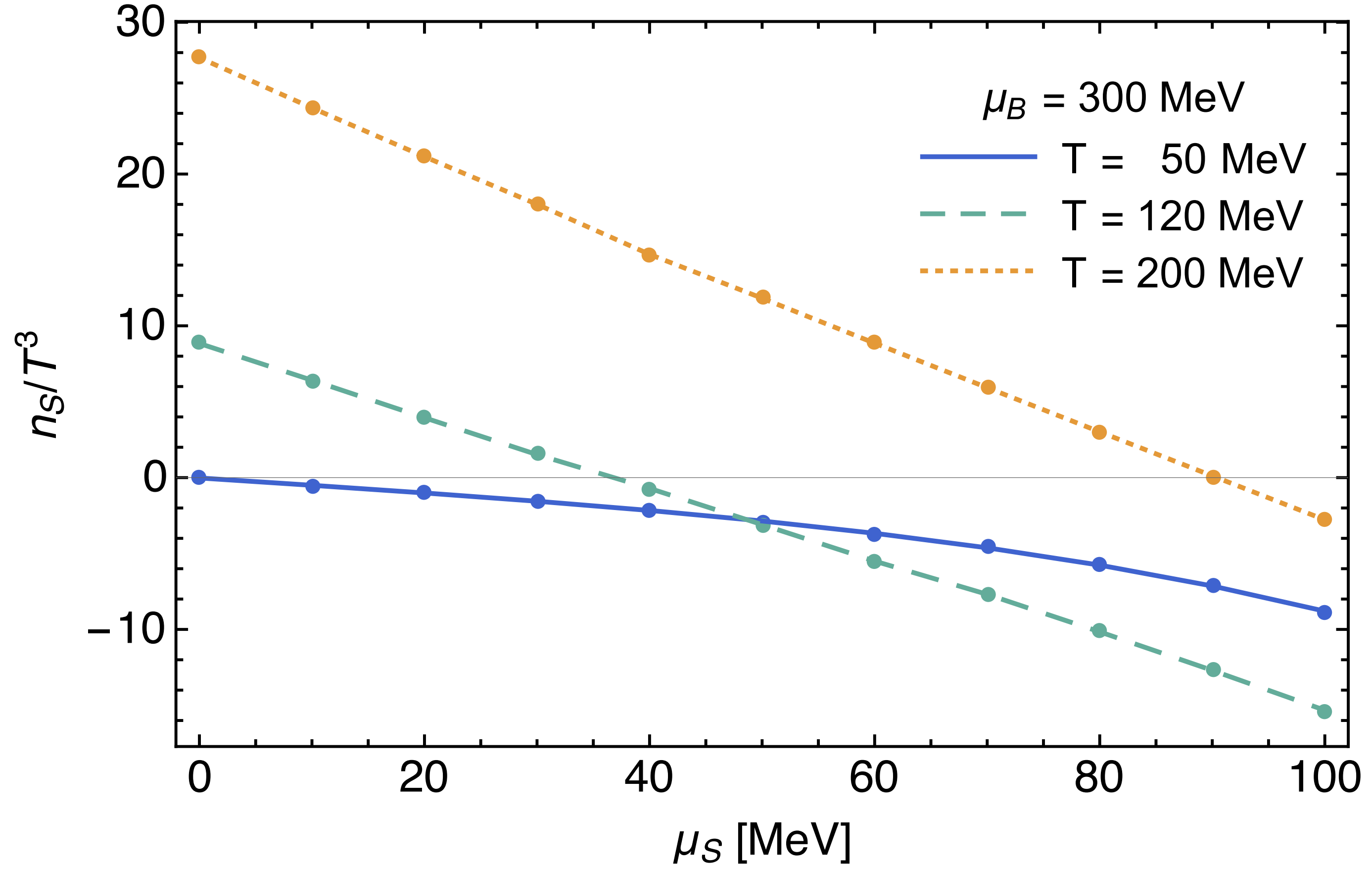
$$n_S = \chi_{01}^{BS} T^3$$



[HotQCD, hep-lat/1407.6387]
[Wuppertal-Budapest, hep-lat/1309.5258]

STRANGENESS DENSITY

as a function of μ_S

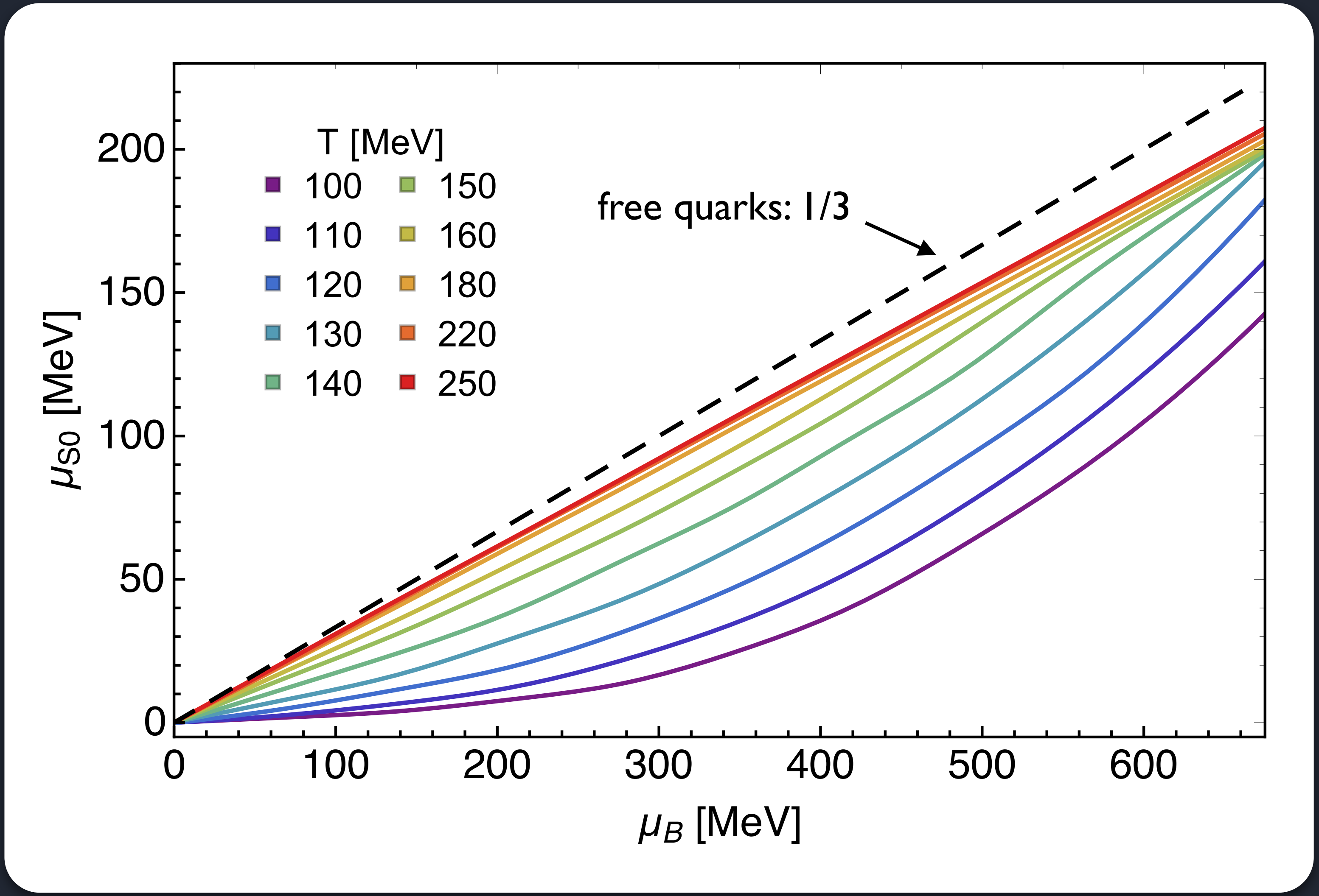


- strangeness number density decreases with increasing μ_S
- strangeness neutrality: zero crossing

$$\mu_{S0} \equiv \mu_S(T, \mu_B)\big|_{n_S=0}$$

STRANGENESS CHEMICAL POTENTIAL

as a function of μ_B at strangeness neutrality



- slope directly related to baryon-strangeness correlations:

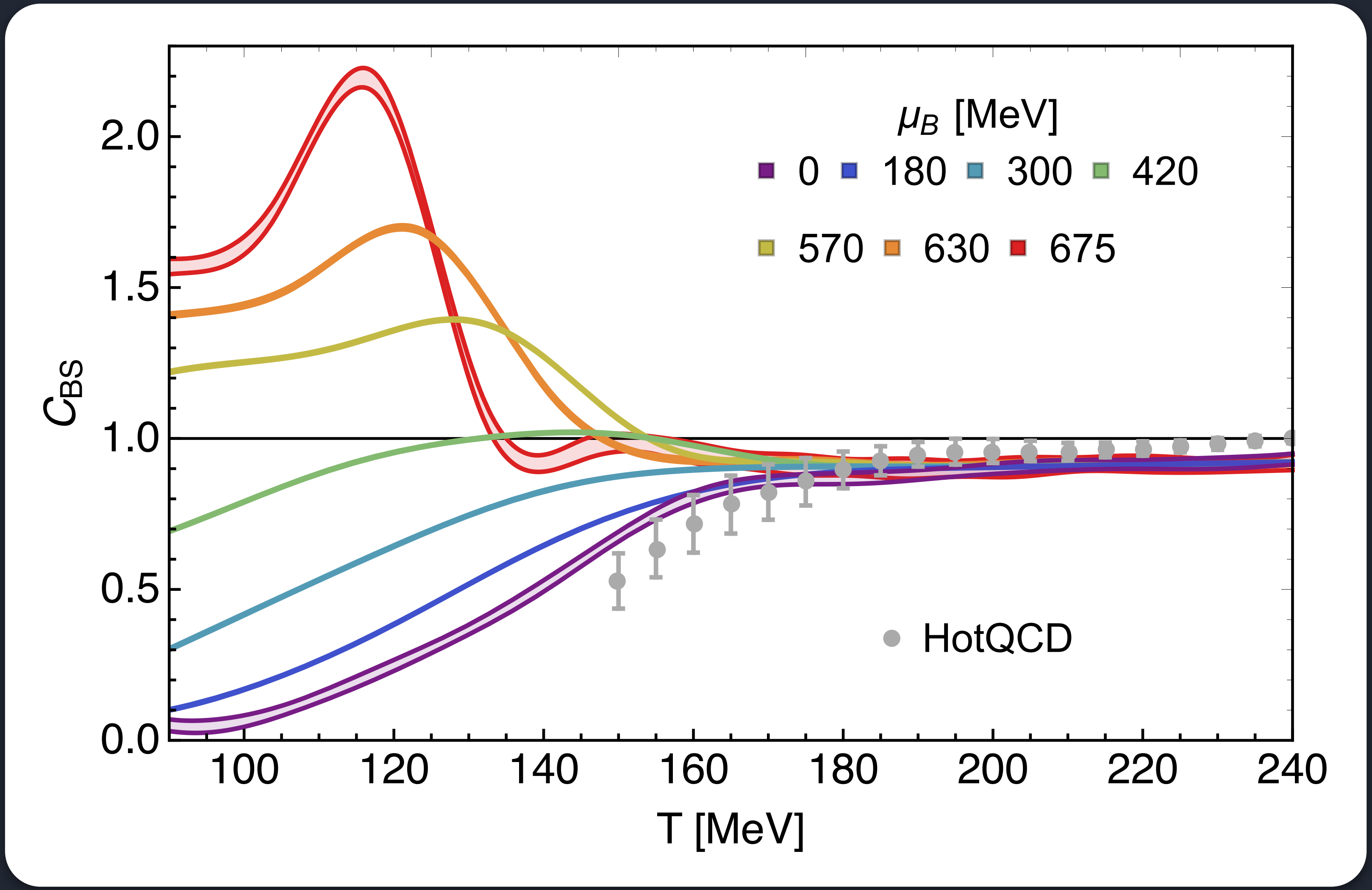
$$\frac{\partial \mu_{S0}}{\partial \mu_B} = \frac{1}{3} C_{BS}$$

⟶ C_{BS} for any T and μ

BARYON-STRANGENESS CORRELATION

at strangeness neutrality

$$3\frac{\partial \mu_{S0}}{\partial \mu_B} = C_{BS} \sim \frac{\langle \text{strange baryons} \rangle}{\langle \text{strange baryons \& mesons} \rangle} \sim \begin{cases} < 1 & \text{mesons dominate} \\ = 1 & \text{mesons \& baryons (or uncorrelated flavor)} \\ > 1 & \text{baryons dominate} \end{cases}$$



lattice results: [HotQCD, hep-lat/1203.0784]

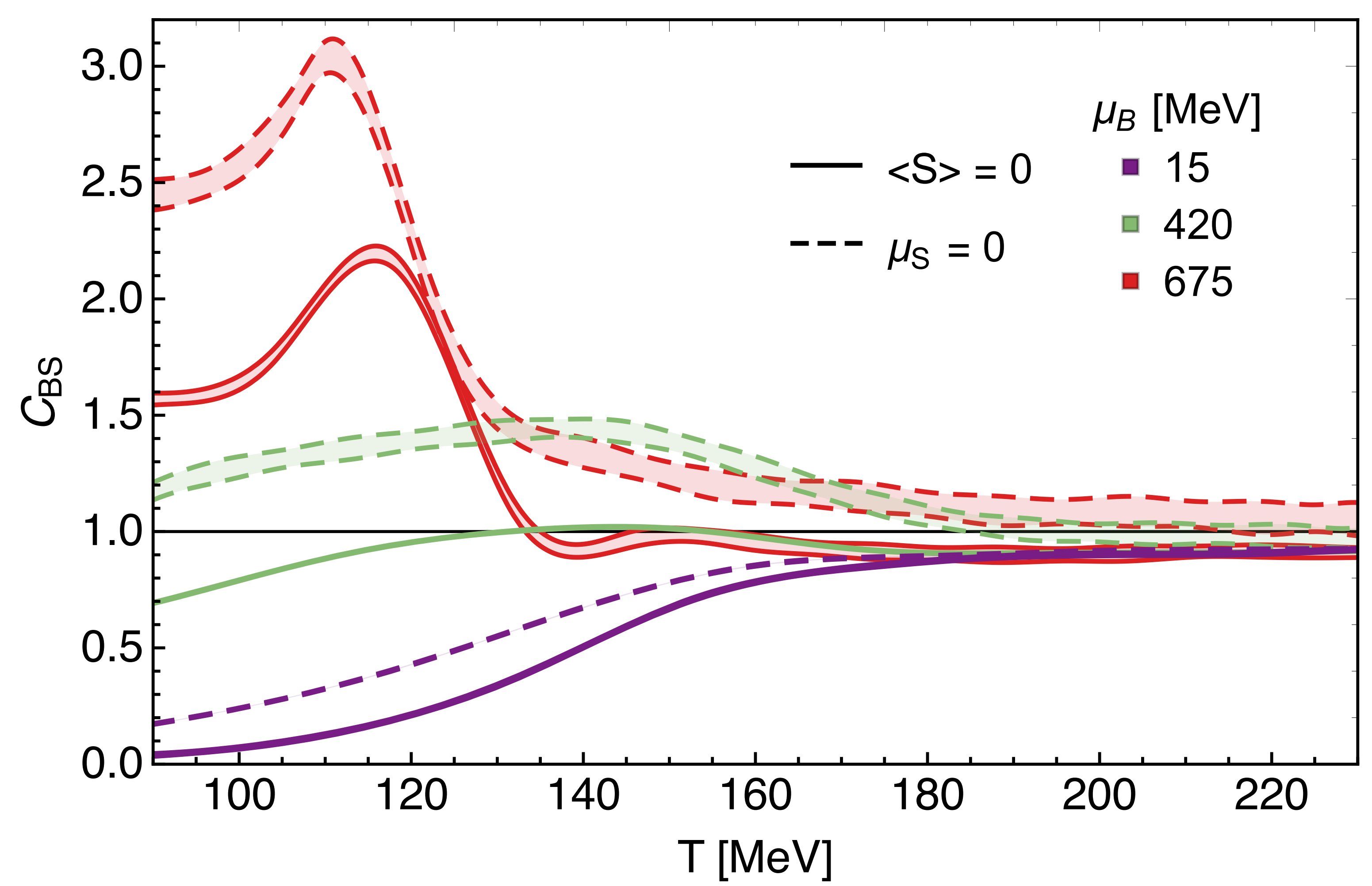
→ competition between baryonic and mesonic sources of strangeness!

maxima at the chiral transition!

→ direct sensitivity to the QCD phase transition

BARYON-STRANGENESS CORRELATION

strangeness conservation vs non-conservation



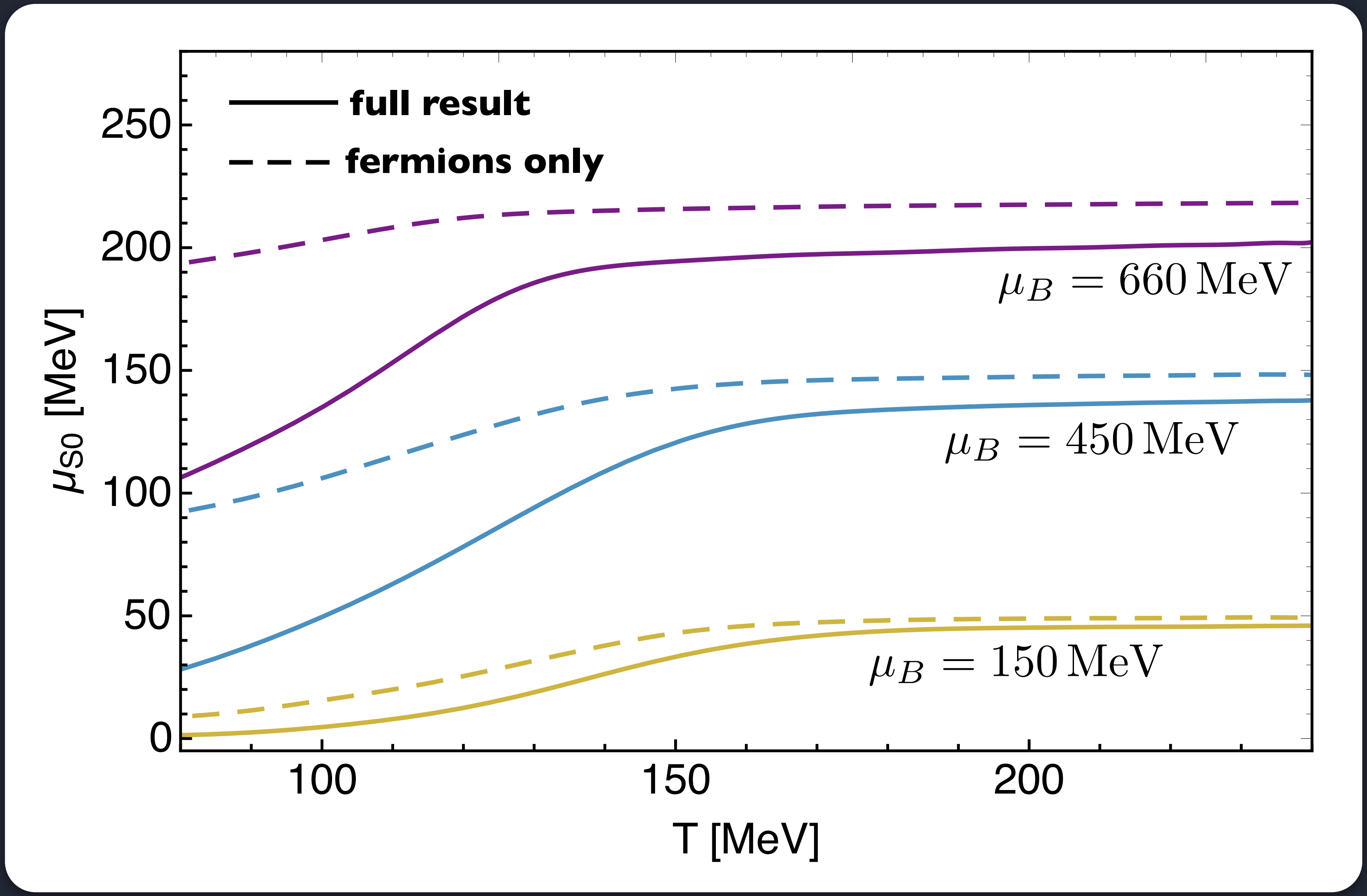
→ sizable suppression from strangeness neutrality!

STRANGENESS CHEMICAL POTENTIAL

role of open strange meson dynamics

- quark/baryon vs meson dynamics?
- equation for μ_{S0} from the fermion part of the RG flow [Fukushima, hep-ph/0901.0783]

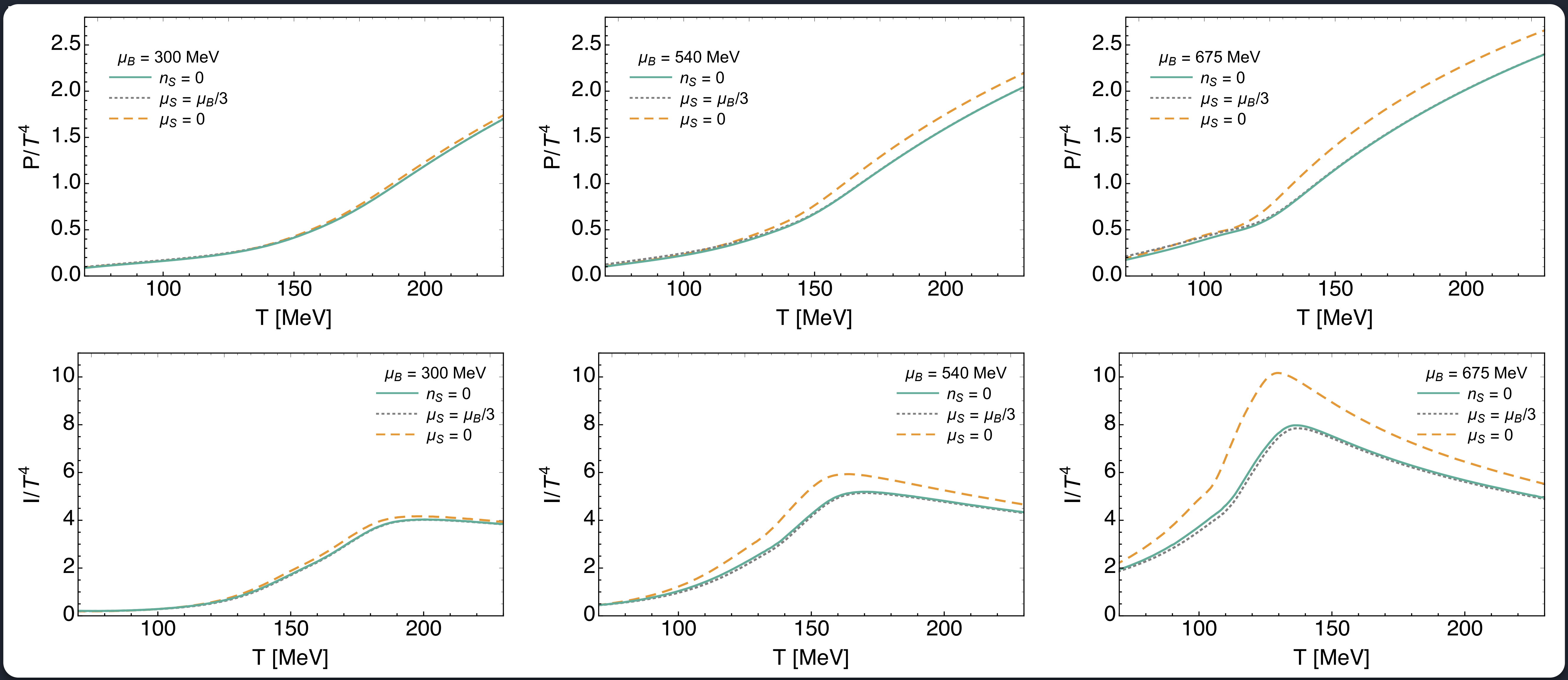
$$\mu_{S0}\big|_{\text{fermions}} = \frac{\mu_B}{3} - \frac{T}{2}\ln\left[\frac{\bar{L}(T,\mu_B)}{L(T,\mu_B)}\right]$$



→ open strange meson fluctuations crucial!

EQUATION OF STATE

strangeness conservation vs non-conservation

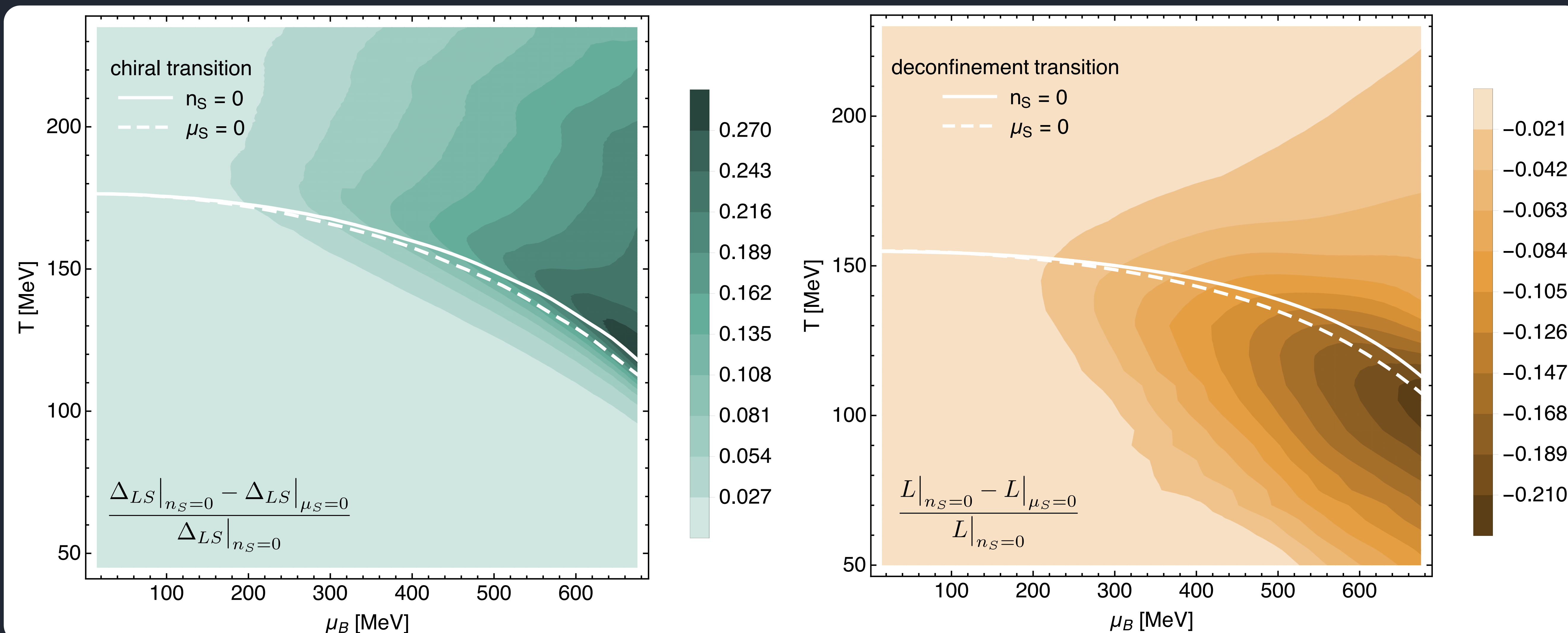


PHASE STRUCTURE

strangeness conservation vs non-conservation

$$\Delta_{LS} = \frac{\left(\sigma_L - \frac{j_L}{j_S}\sigma_S\right)\Big|_T}{\left(\sigma_L - \frac{j_L}{j_S}\sigma_S\right)\Big|_{T=0}} \qquad \begin{array}{l}\sigma_L \sim \langle \bar{l} l\rangle \\ \sigma_S \sim \langle \bar{s} s\rangle\end{array}$$

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



→ transition to QGP at larger T (for fixed μ_B)

→ smaller curvature of the phase boundary

→ CEP at smaller μ_B & larger T (?)

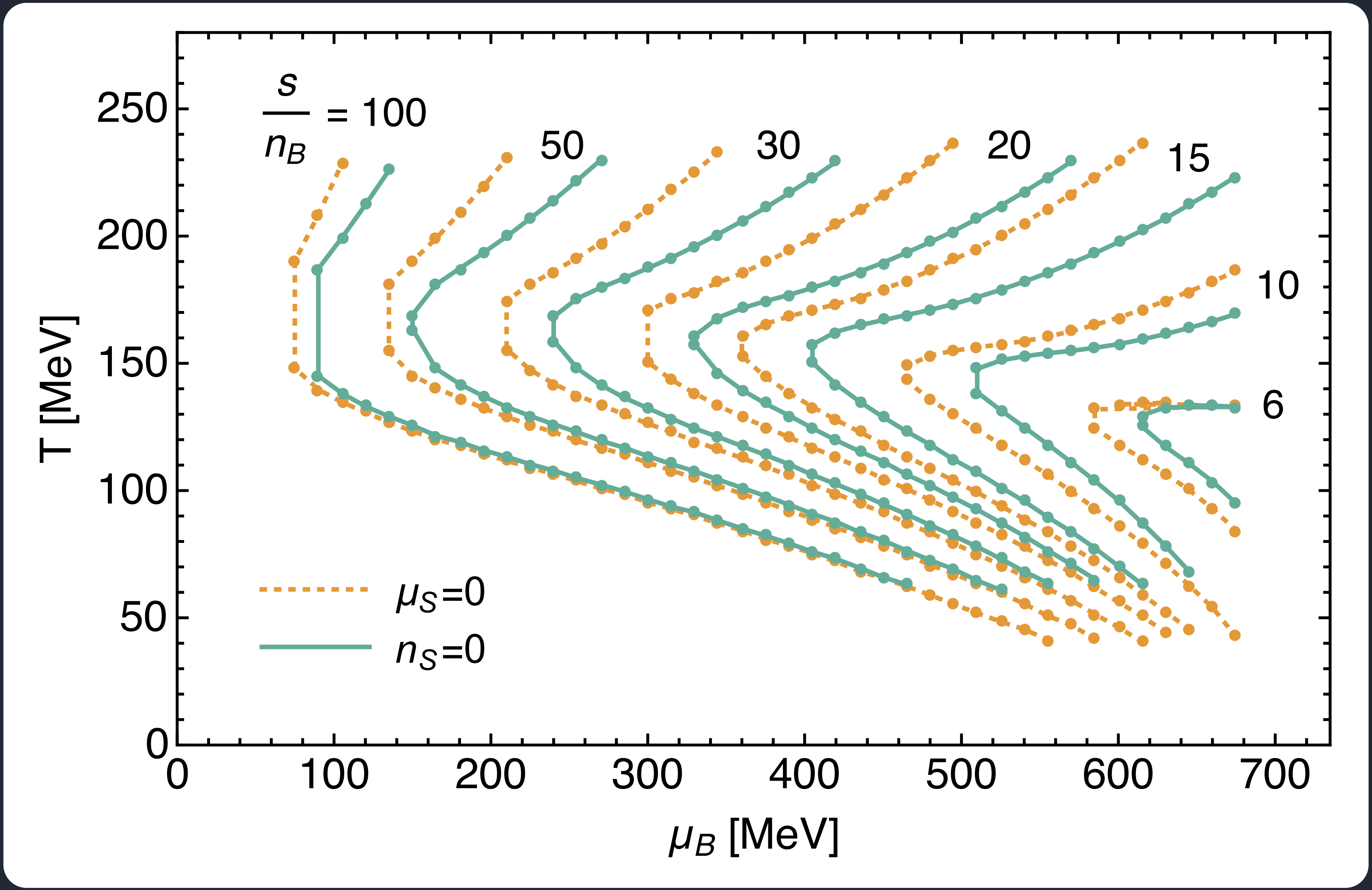
ISENTROPES

strangeness conservation vs non-conservation

- QGP evolves hydrodynamically at late stages
- `almost´ perfect fluid: small viscosity over entropy density

→ QGP evolves close to isentropes in hydro regime

$$s/n_B = \text{const.}$$



SUMMARY & OUTLOOK

- strangeness neutrality in heavy ion collisions
  - intimate relation between strangeness conservation and phases of QCD as probed in heavy-ion collisions
  - baryon-strangeness correlation via strangeness neutrality
  - finite μ_B requires finite μ_S: sensitive to interplay of QCD d.o.f.
- relevant for phase structure and thermodynamics at finite μ_B
  - ~30% effects already at moderate μ_B, C_{BS} is most sensitive
  - \`delayed´ transition to the QGP in the phase diagram

For the (near) future:

- study larger μ and the CEP
- include charge chemical potential
- including gluon fluctuations: dynamical hadronization
- self-consistent computation of the A_0 potential
- computation of off-diagonal cumulants

BACKUP

STRANGENESS AND CHARGE CONSERVATION

- particle number conservation implicitly defines two functions:

$$\mu_{Q0}(T,\mu_B) = \mu_Q(T,\mu_B)\big|_{n_S=0,\, n_Q=rn_B}$$

$$\mu_{S0}(T,\mu_B) = \mu_S(T,\mu_B)\big|_{n_S=0,\, n_Q=rn_B} \qquad r = \frac{Z}{A}$$

- this implies:

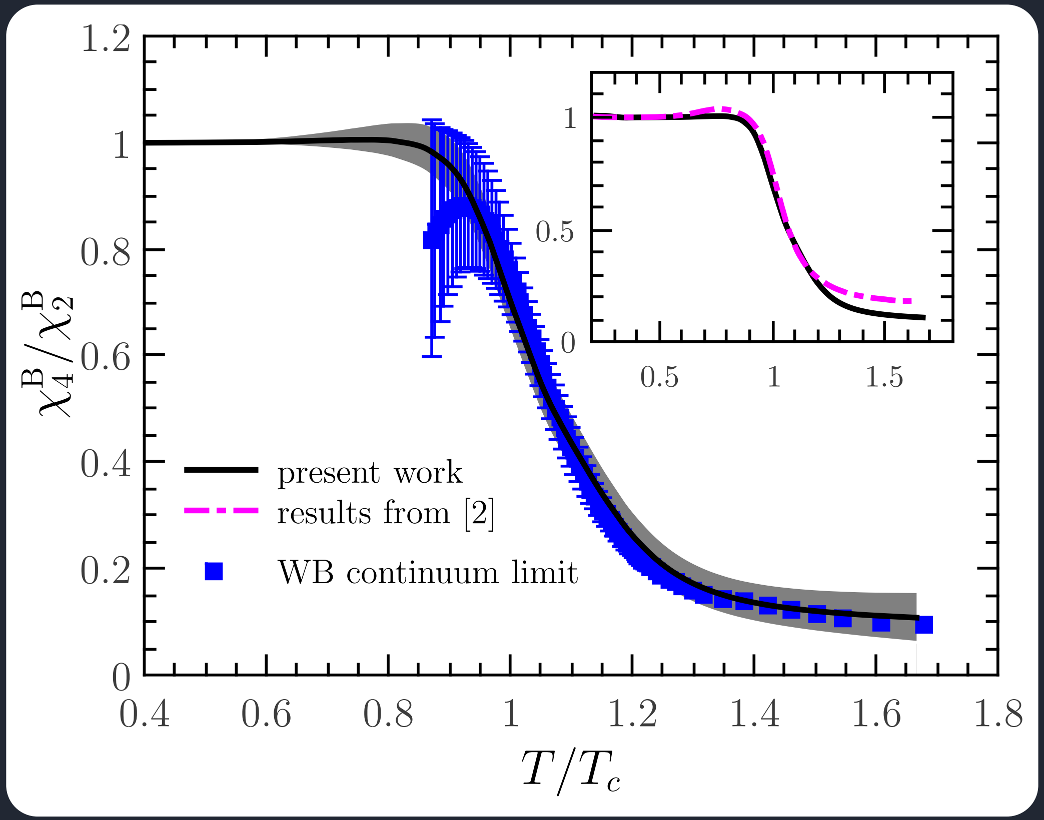
$$\frac{\partial \mu_{S0}}{\partial \mu_B} = \frac{1}{3}C_{BS} - \frac{\chi_{11}^{QS}}{\chi_2^S}\frac{\partial \mu_{Q0}}{\partial \mu_B}$$

$$\frac{\partial \mu_{Q0}}{\partial \mu_B} = \frac{\chi_{11}^{BS}(\chi_{11}^{SQ} - r\chi_{11}^{BS}) - \chi_2^S(\chi_{11}^{BQ} - r\chi_2^B)}{\chi_2^S(\chi_2^Q - r\chi_{11}^{BQ}) - \chi_{11}^{SQ}(\chi_{11}^{SQ} - r\chi_{11}^{BS})}$$

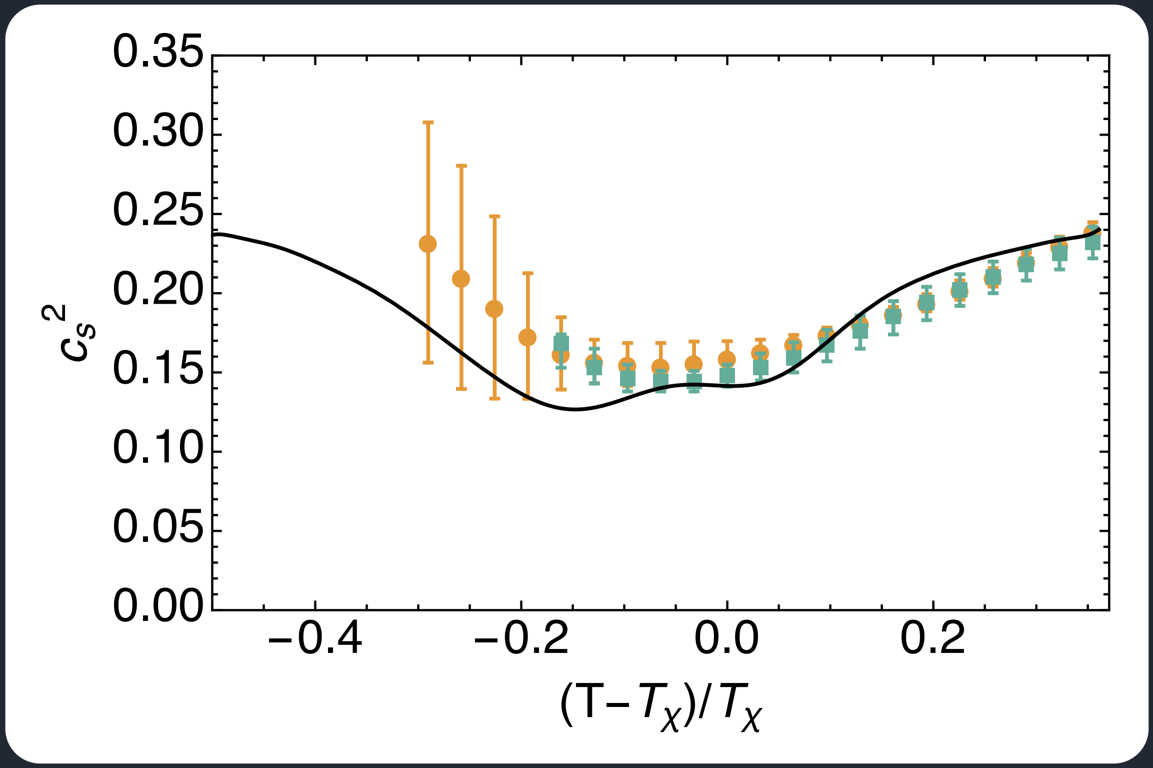
→ generalization of `freeze-out relations´ used on the lattice to any T and μ_B

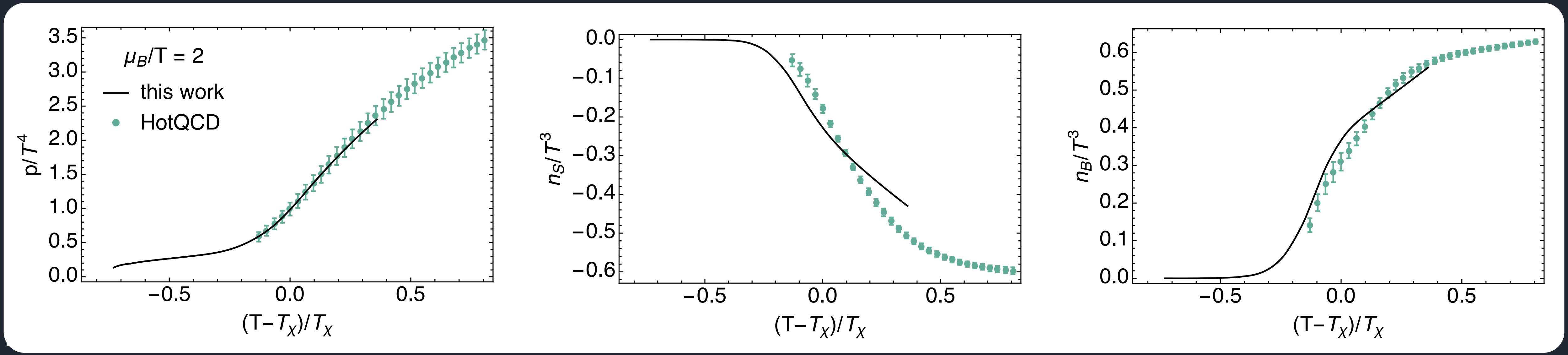
MORE RESULTS

in comparison to lattice gauge theory



[Fu, Pawlowski, FR, Schaefer, hep-ph/1608.04302]



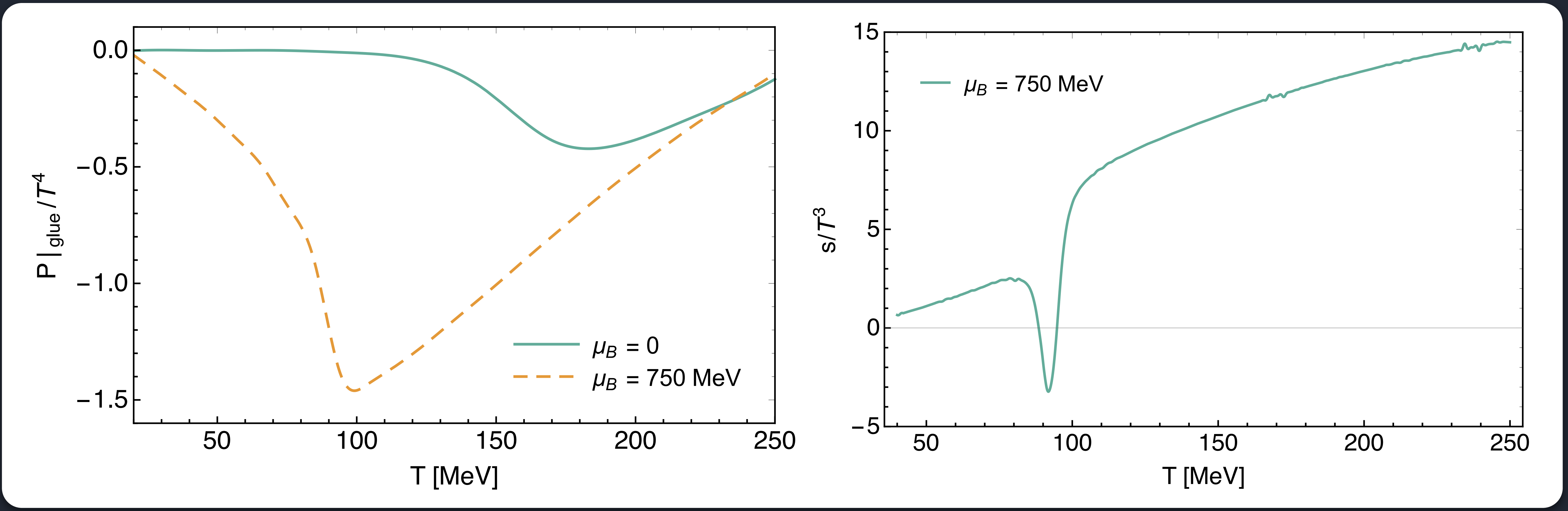


[HotQCD, hep-lat/1701.04325]

2+1 FLAVOR PQM AT LARGE CHEMICAL POTENTIAL

- gluon contribution to the pressure at large chemical potential

$$p\big|_{\text{glue}} = -U_{\text{glue}}(L, \bar{L})$$



→ model becomes unphysical at large μ_B

likely due to missing feedback from the matter to the gauge sector / input potential not accurate at large $\bar{L} - L$