ASPECTS OF THE QCD PHASE DIAGRAM

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DFG Deutsche Forschungsgemeinschaft

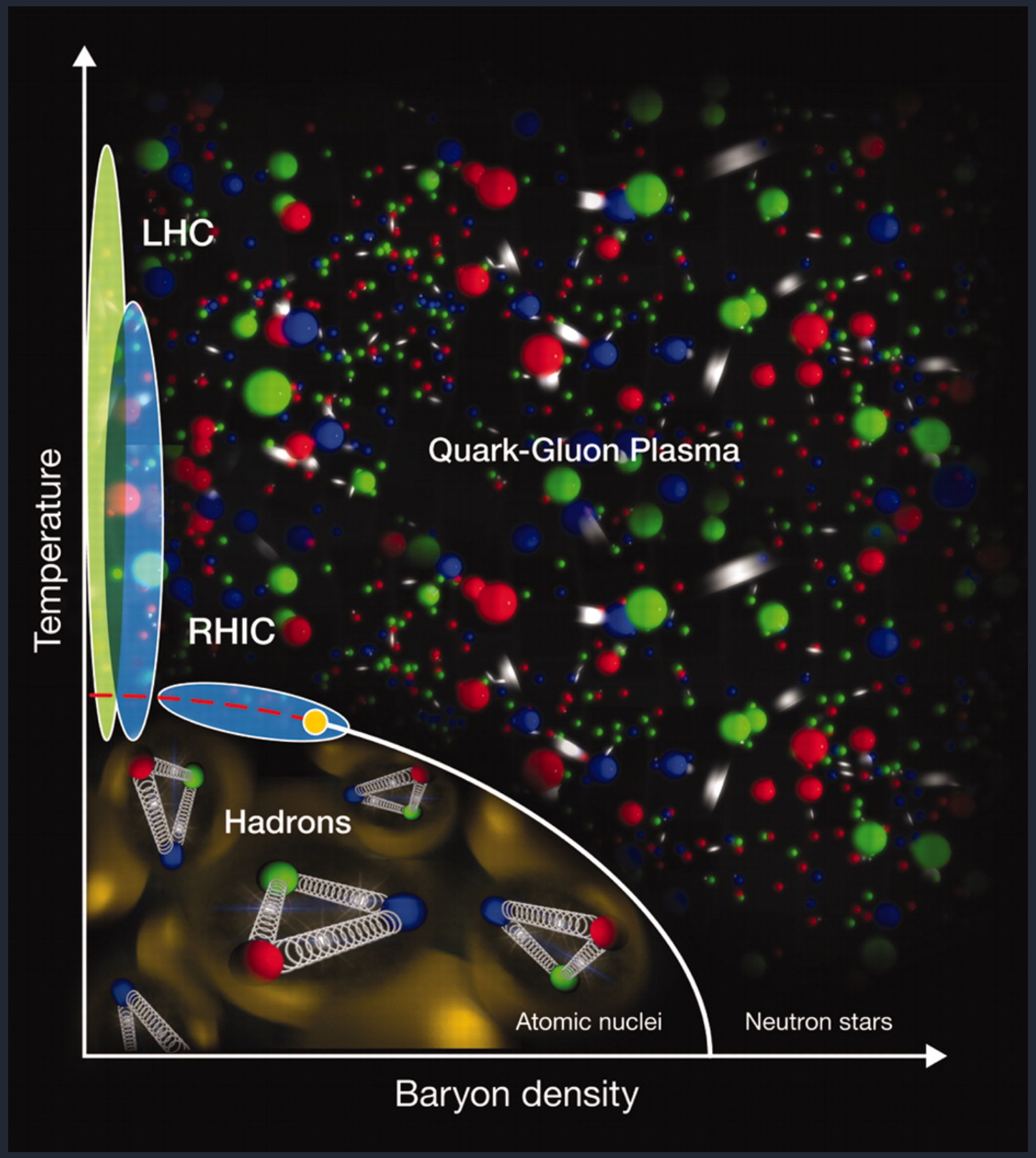
— FUNCTIONAL METHODS IN STRONGLY CORRELATED SYSTEMS —

HIRSCHEGG, AUSTRIA, 01/04/2019

OUTLINE

- The scale evolution of QCD
- FRG with emergent bound states
- The phase diagram of QCD
- Quark mass dependence & the axial anomaly
- HICs, particle number conservation & strangeness

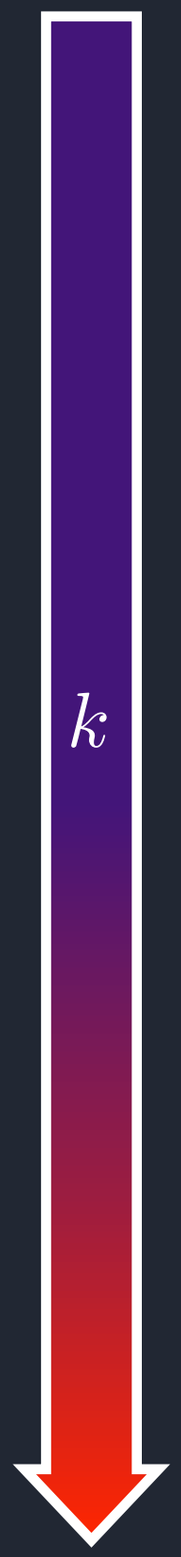
THE QCD PHASE DIAGRAM



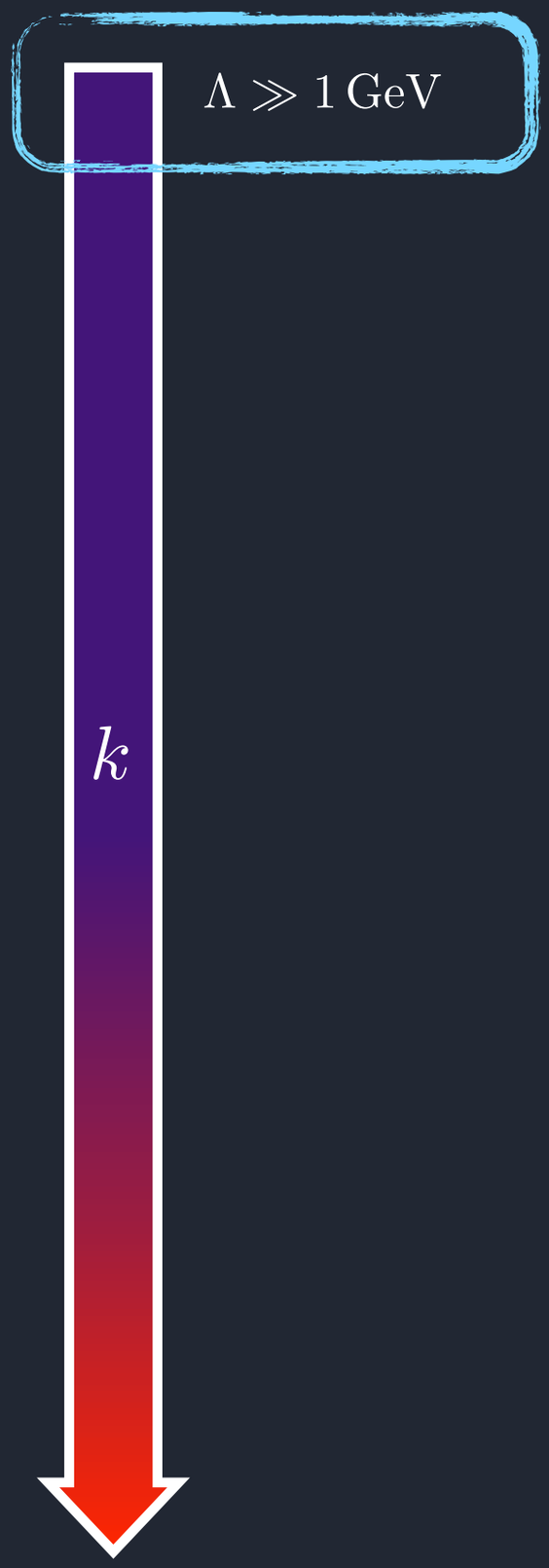
[Jacak, Müller, Science 337 (2012)]

SCALE EVOLUTION OF QCD

integrating out fluctuations from UV to IR



SCALE EVOLUTION OF QCD



- initial action: gauge fixed Euclidean QCD

$$\mathcal{L}_{\mathrm{QCD}} = \bar{q}(\gamma_\mu D_\mu + m_q)q + \frac{1}{4}F^a_{\mu\nu}F^a_{\mu\nu} + \frac{1}{2\xi}(\partial_\mu A^a_\mu)^2 + \bar{c}^a \partial_\mu D^{ab}_\mu c^b$$

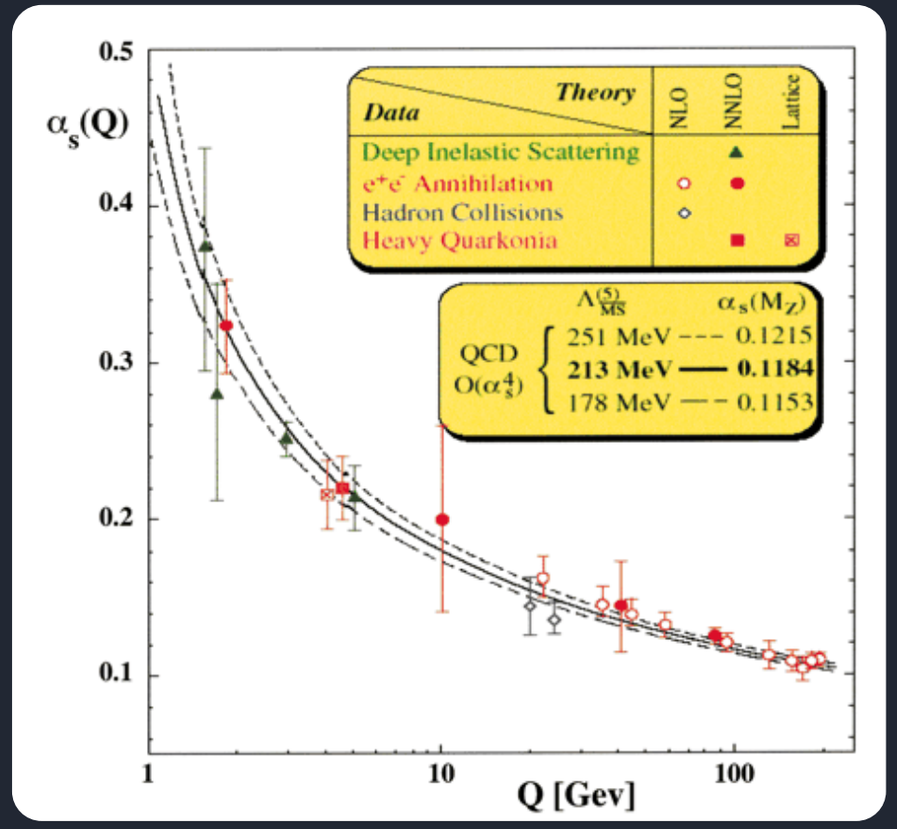
covariant derivative

$$D_\mu = \partial_\mu - igA^a_\mu t^a$$

field strength

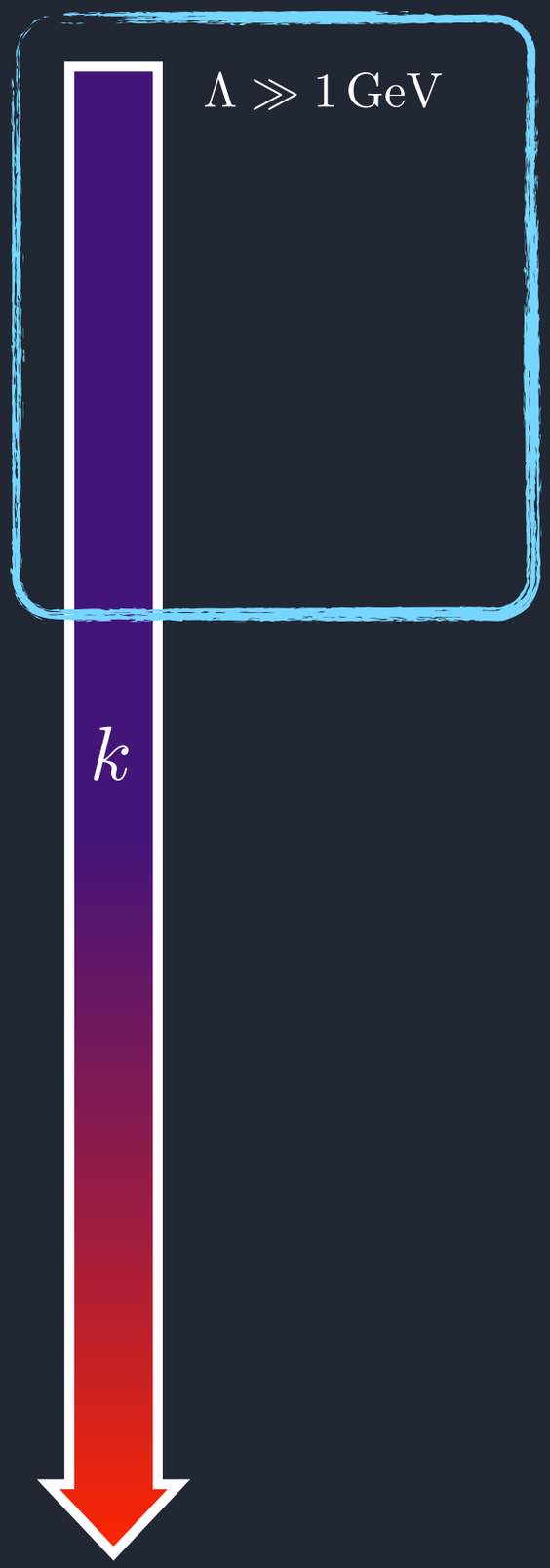
$$F^a_{\mu\nu}t^a = \frac{i}{g}[D_\mu, D_\nu]$$

- asymptotic freedom: fluctuations increase strong coupling

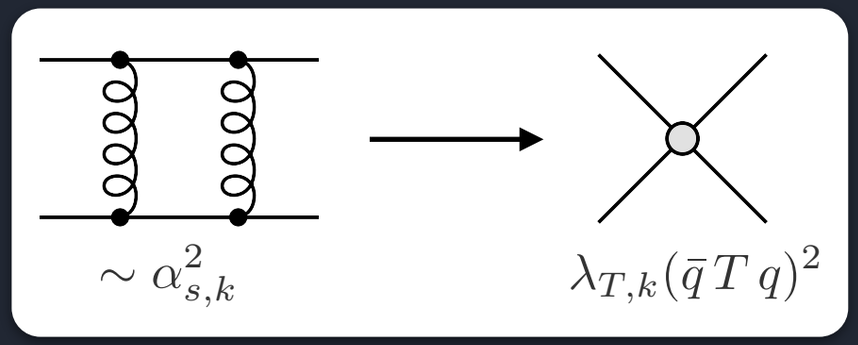


[S. Bethke, hep-ex/0606035]

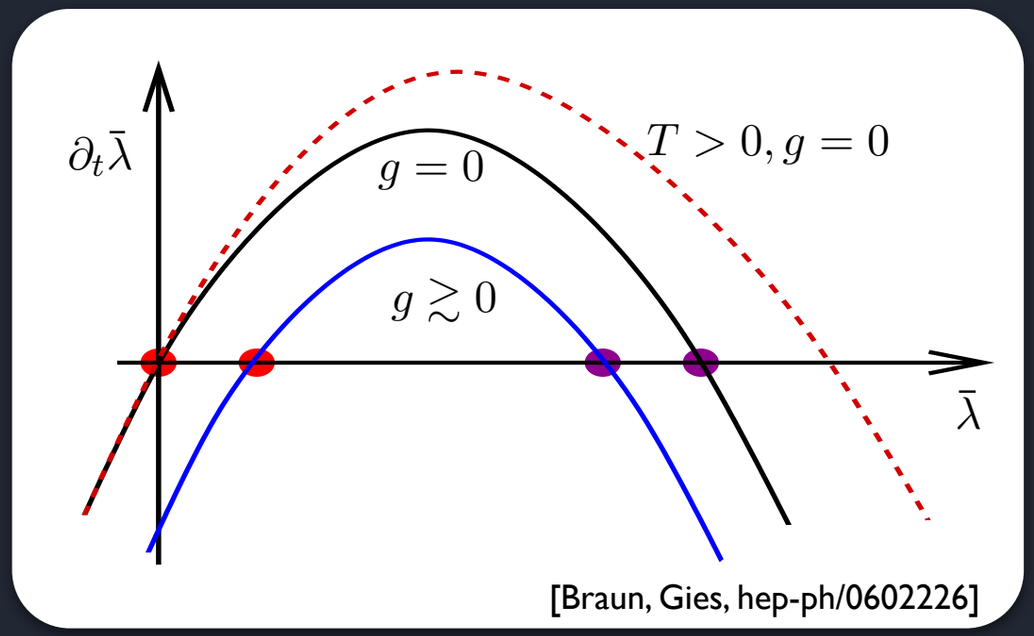
SCALE EVOLUTION OF QCD



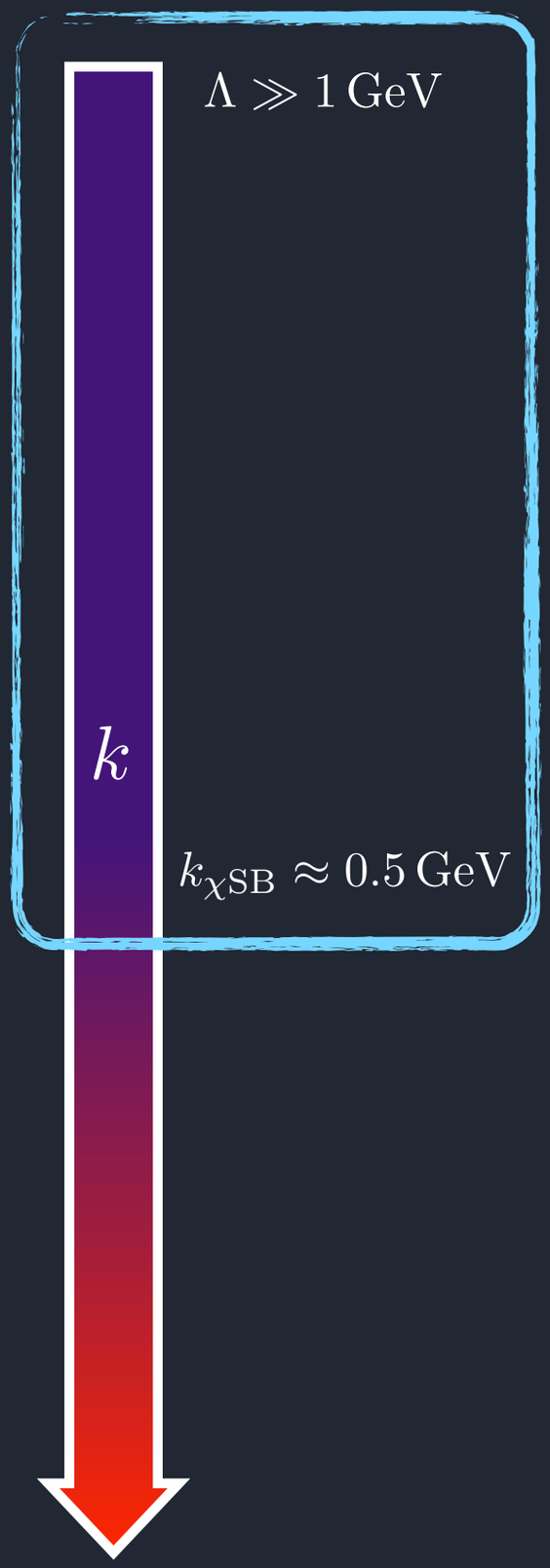
- effective four-quark interactions are generated



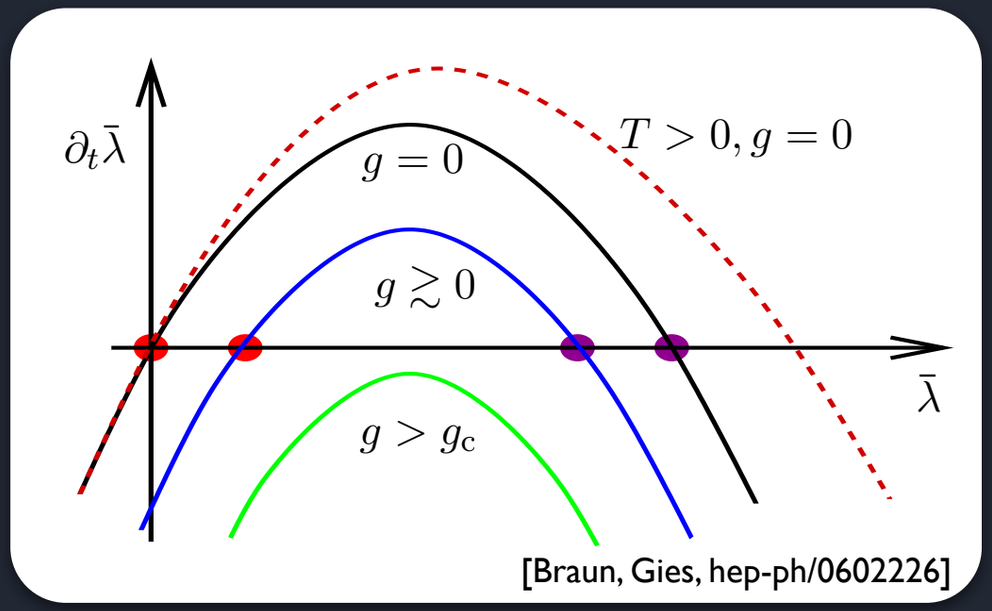
- $\lambda_{T,k}$ grows with decreasing energy scale
- running controlled by IR-attractive fixed point



SCALE EVOLUTION OF QCD



- strong coupling exceeds critical value: $\lambda_{T,k}$ diverges

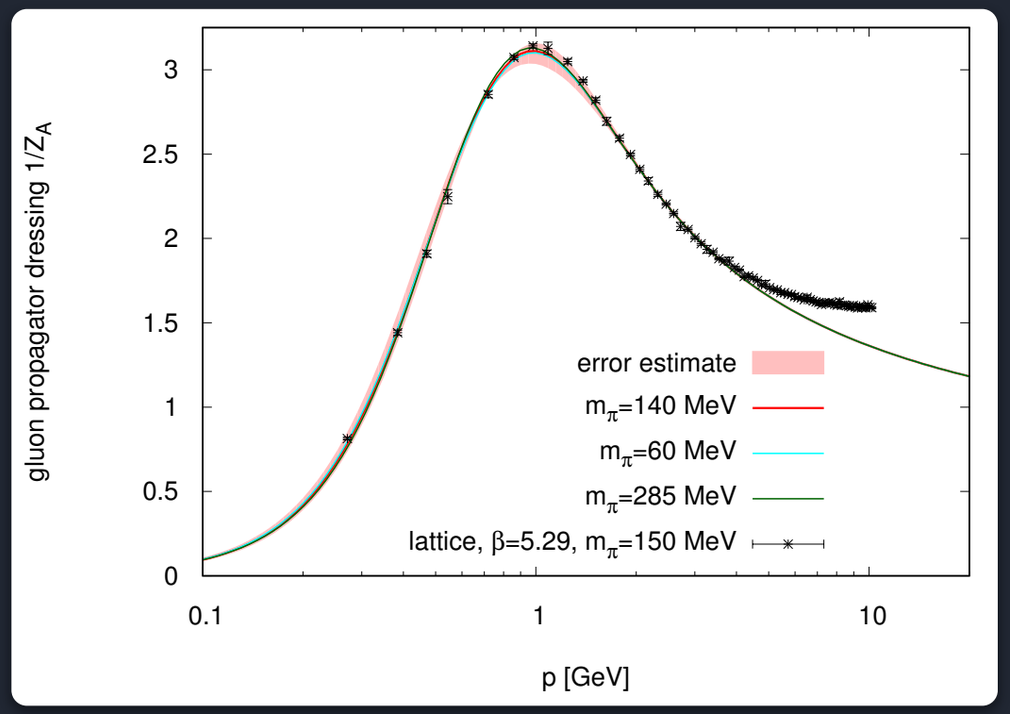


[Braun, Gies, hep-ph/0602226]

- resonance in condensate channel: **chiral symmetry breaking**

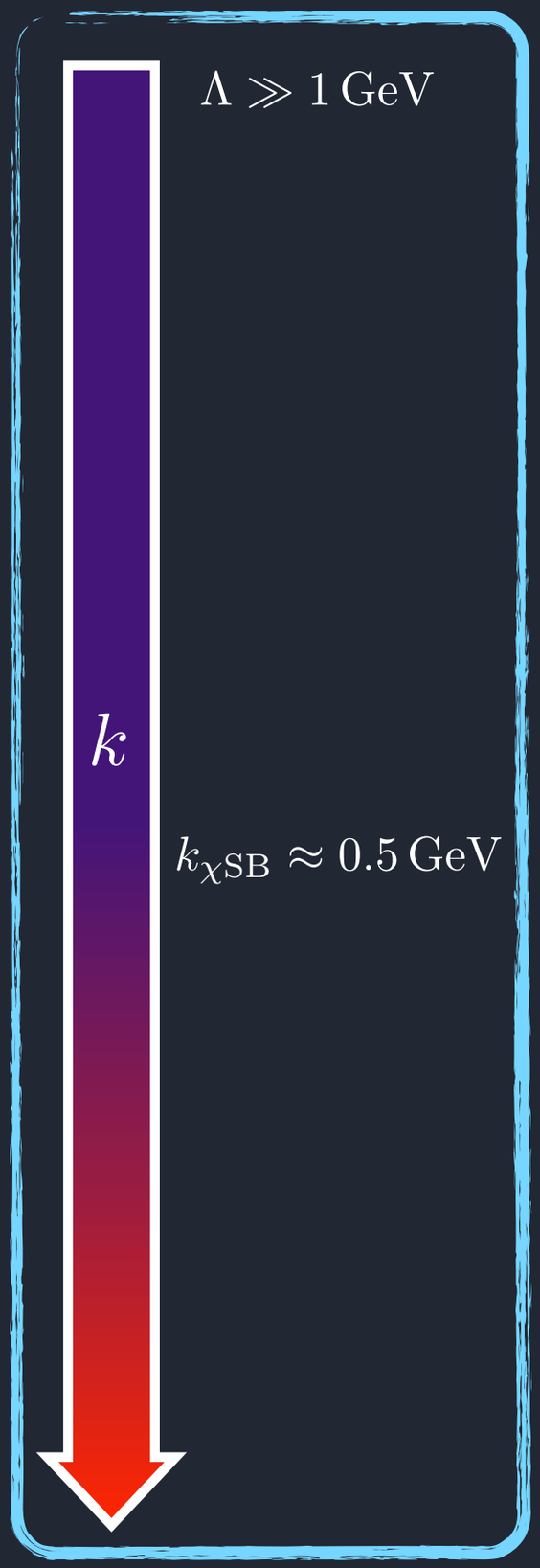
$$\lambda_{S,k}(\bar{q}q)^2 \to \infty \longleftrightarrow \langle \bar{q}q \rangle \neq 0$$

- around the same scale gluon mass-gap develops: **confinement**



[Cyrol, Mitter, Pawlowski, Strodthoff, hep-ph/1706.06326]

SCALE EVOLUTION OF QCD

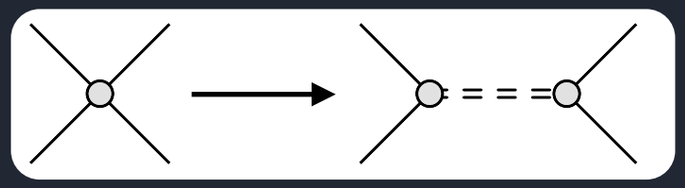


- rewrite resonant 4-quark channels in terms of mesons
  (similar: baryonization from 6-quark interactions)

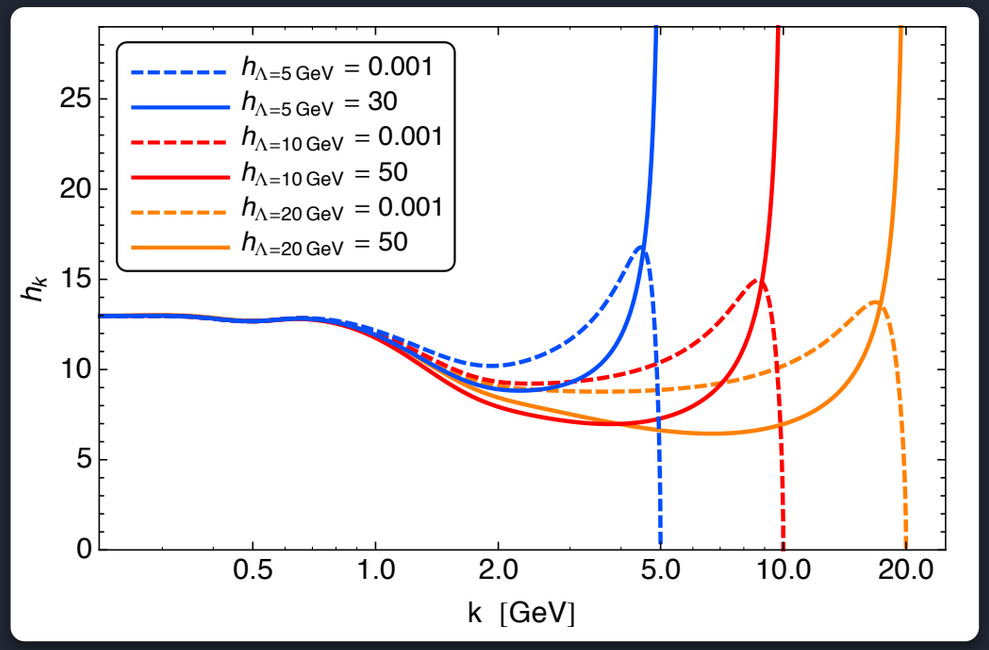
Yukawa coupling

$$\lambda_{T,k} = \frac{h^2_{T,k}}{m^2_{\phi,k}}$$

meson mass parameter



[Braun, Fister, Pawlowski, FR, hep-ph/1412.1045]



- low-energy models **emerge** when gauge sector decouples
- fixed point at small g: low-energy parameters uniquely determined
- different tensor structures of $\lambda_{T,k}$: different bound states

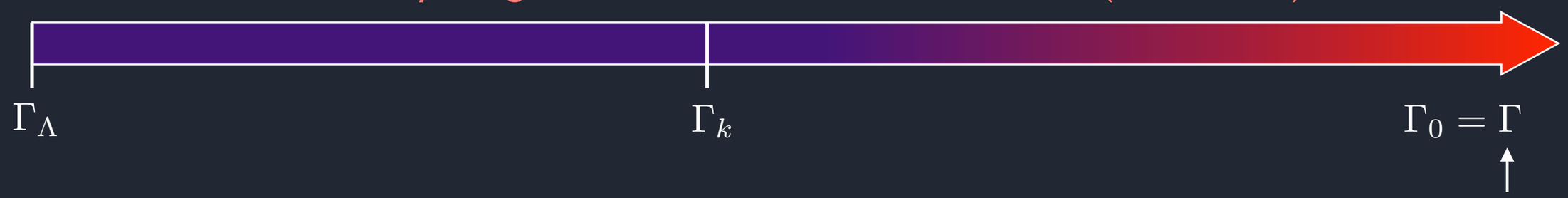
$$(\bar{q}T^a q)^2 + (\bar{q}i\gamma_5 T^a q)^2 \longrightarrow \pi,\ K, \eta,\ \eta',\ a_0,\ \kappa,\ \sigma,\ f_0$$

U(3) generators

FUNCTIONAL RG

- low-energy QCD inherently strongly interacting: non-perturbative method
- capture fundamental and emergent d.o.f.: scale dependent effective action

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]

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

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

DYNAMICAL HADRONIZATION

[Gies, Wetterich, Phys.Rev. D '02, Pawlowski, Ann.Phys. '07, Floerchinger, Wetterich, Phys.Lett. B '09]
[Braun, Fister, Pawlowski, FR, hep-ph/1412.1045]

- need unified description in terms of one scale dep. effective action

  → continuous transition from quarks and gluons to hadrons

- bosonize 4-quark interactions in each RG-step: **scale-dep. meson fields** $\phi \to \phi_k$

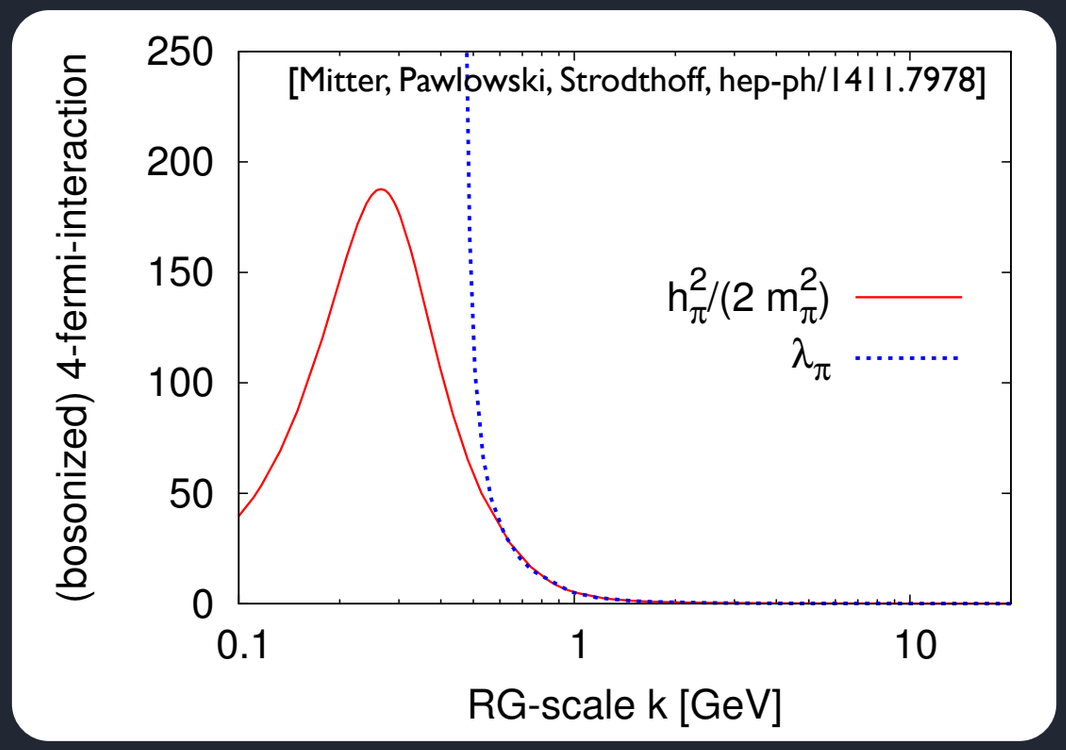
$$\partial_t\big|_\phi \Gamma_k[\Phi] = \frac{1}{2}\left[G_k[\Phi]\cdot\left(\partial_t + \frac{\delta\partial_t\phi_k}{\delta\phi_k}\right)R_k^\Phi\right] - \frac{\delta\Gamma_k}{\delta\phi_k}\cdot\partial_t\phi_k$$

- running mesons reflect bound state nature:

$$\partial_t\phi_k \sim \frac{\partial_t\lambda_{T,k}}{h_{T,k}}\,(\bar{q}\,T\,q)$$

"bookkeeping" of 4-quark interactions

mesons constituents

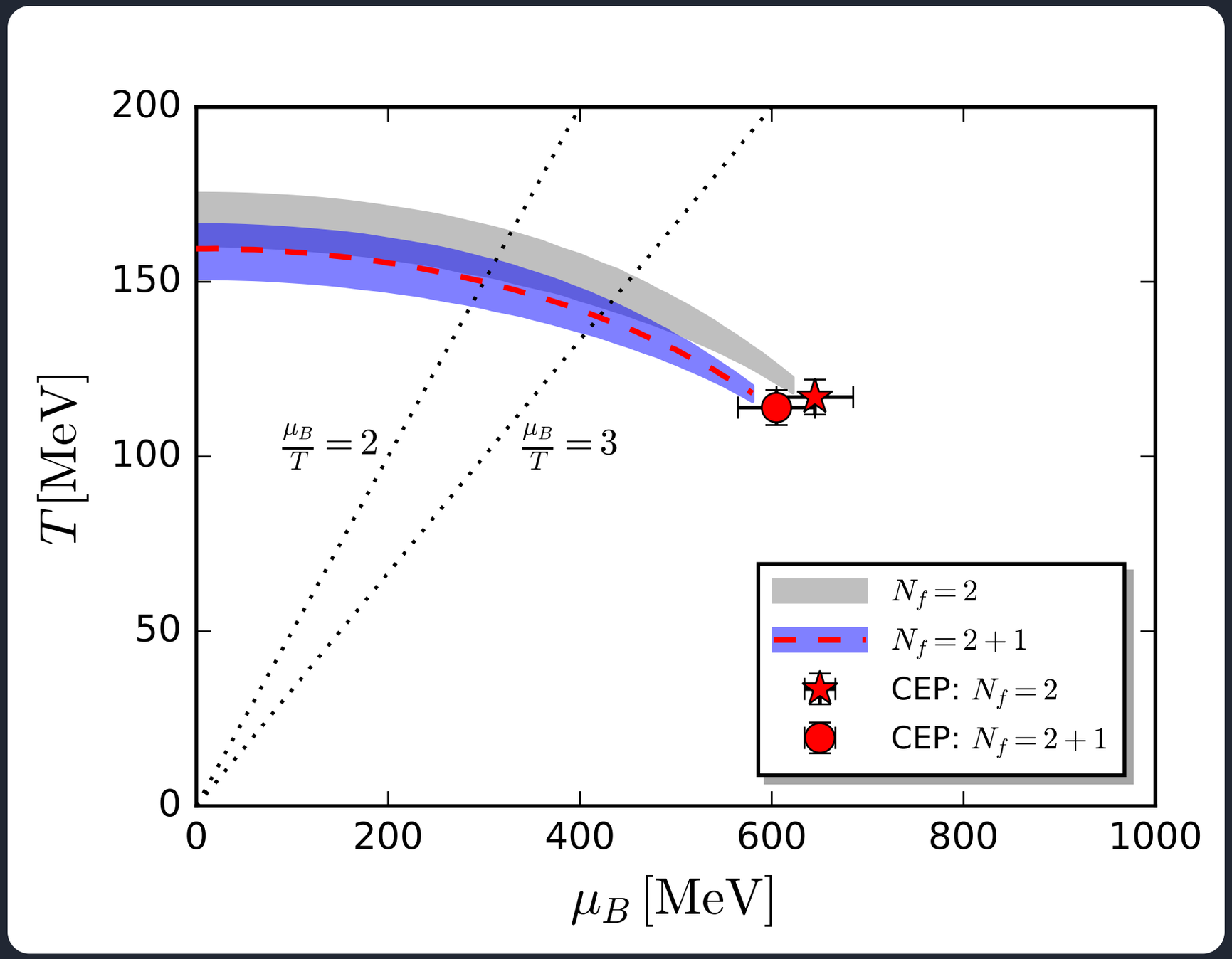


→ 4-quark interaction encoded in Yukawa coupling

→ unified description of quark-gluon and hadronic phase

APPLICATION: PHASE DIAGRAM

[Fu, Pawlowski, FR (in preparation)]



All the details in Wei-jie Fu's talk

APPLICATION: PHASE DIAGRAM

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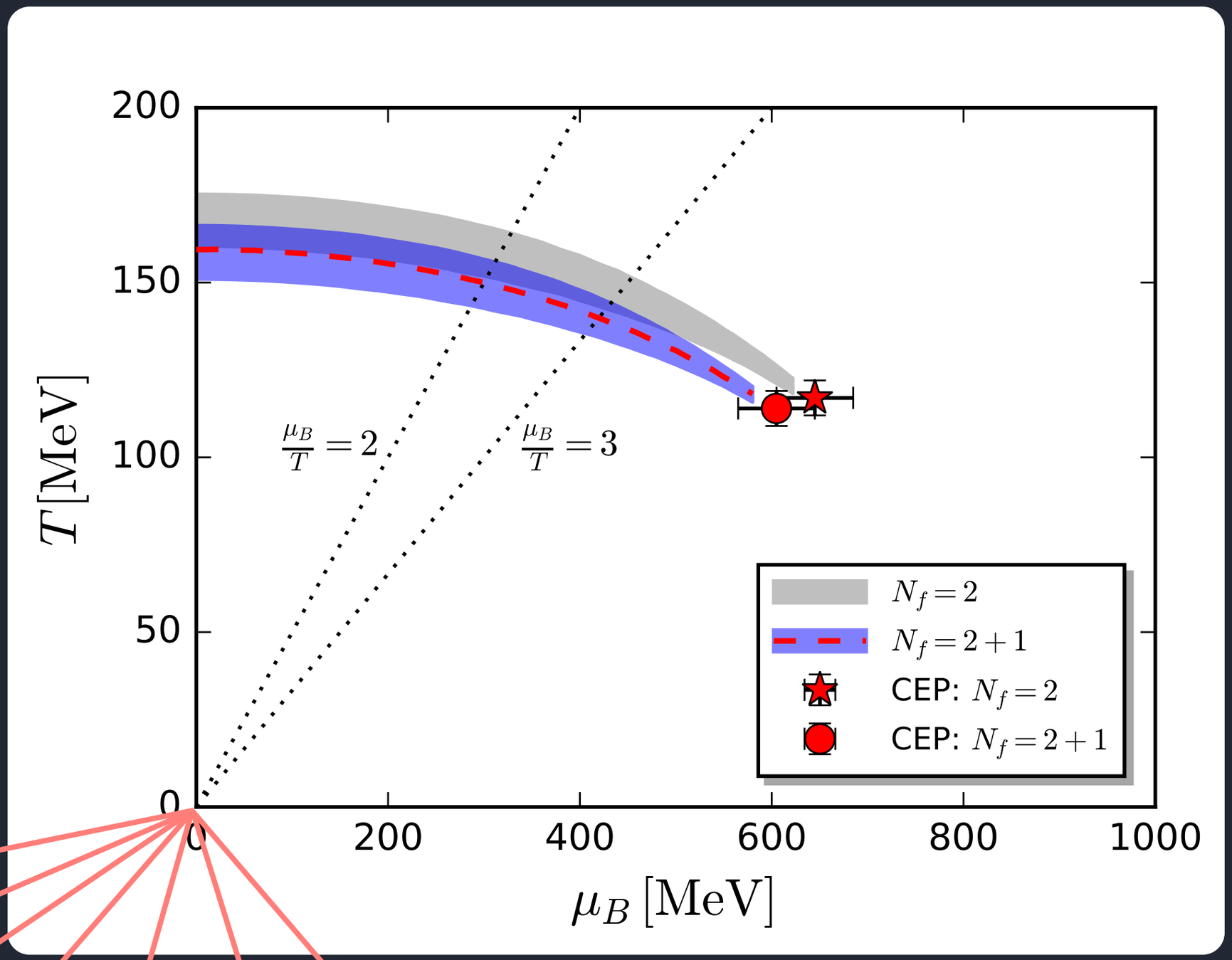

[Skokov (2011)]
[Fukushima, Pawlowski (2012)]
[Kamikado, Kanazawa (2014)]
[Braun, Mian, Rechenberger (2014)]
[Mueller, Pawlowski (2015)]

E, B

ω

m_q

$U(1)_A$

μ_S

$\mu_{Q,I}$

L

[Braun, Klein, Piasecki (2010)]
[Juricic, Schaefer (2016)]
[Almasi, Pisarski, Skokov (2016)]

[Kamikado, Strodthoff, Smekal, Wambach (2012)]

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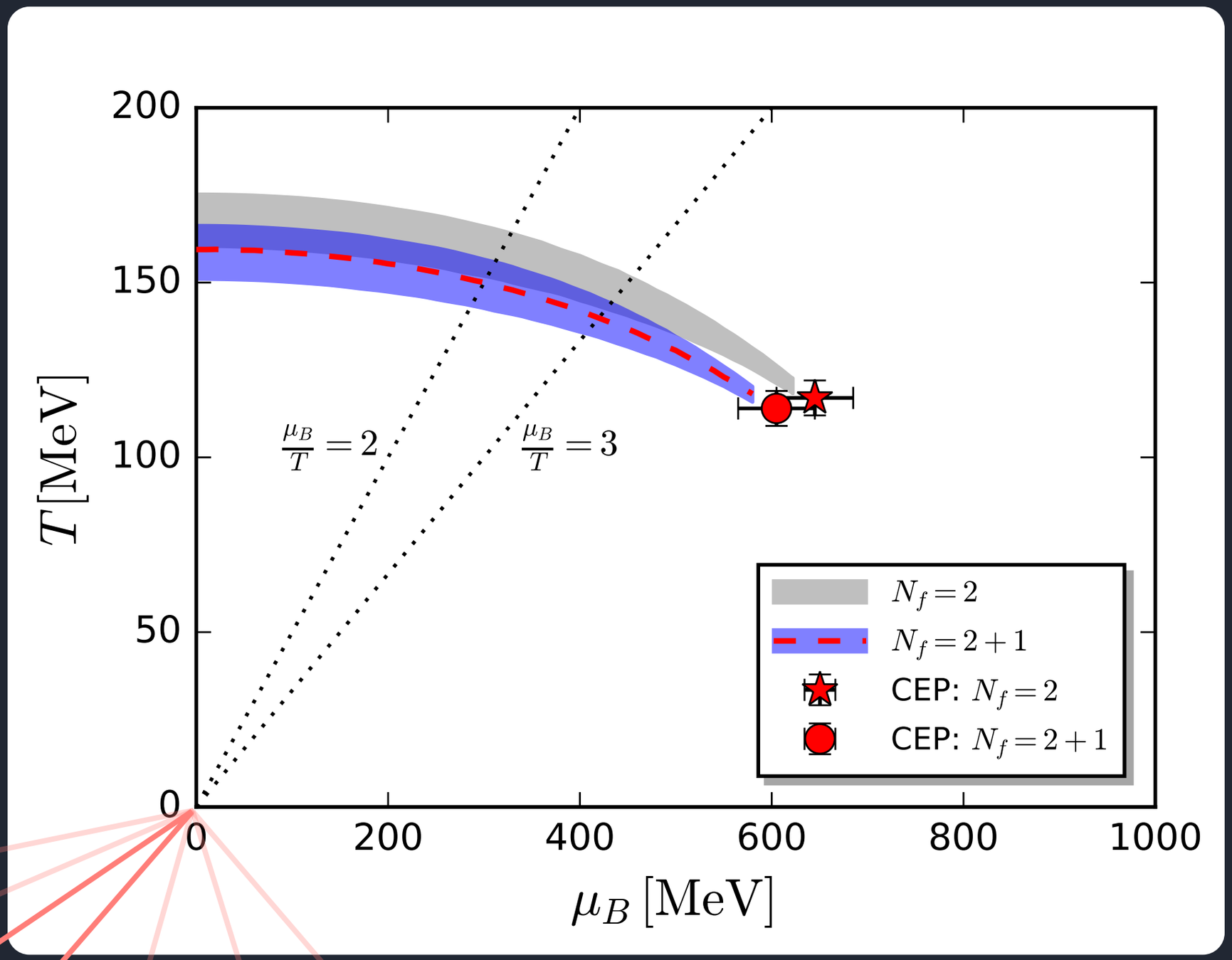
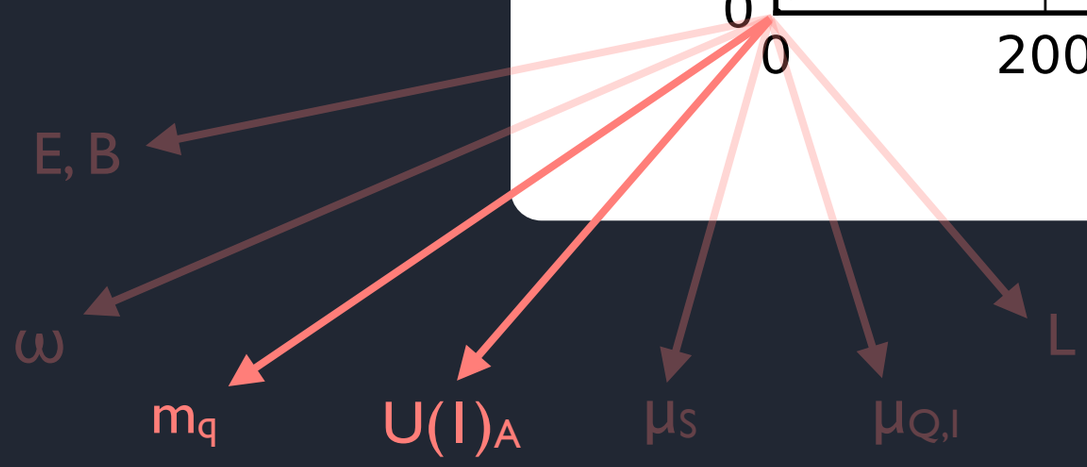
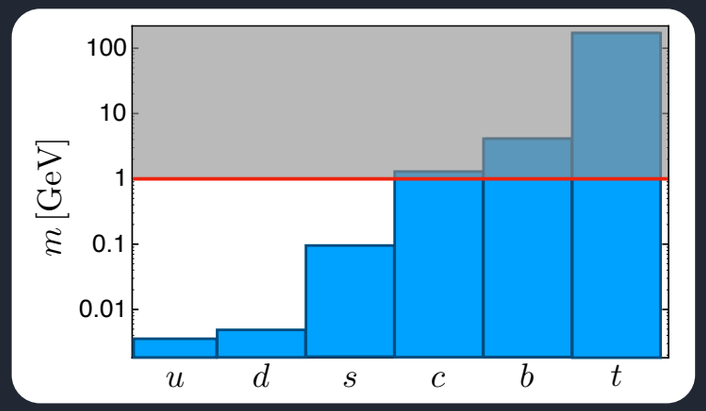




QUARK MASS DEPENDENCE

- distinct mass hierarchy of quarks ($2\pi T_C \approx 1$ GeV)

  → what if u, d were even lighter?



- relevant flavor symmetries:

$$U(3)_L \times U(3)_R \approx SU(3)_V \times SU(3)_A \times U(1)_V \times U(1)_A$$

↓ axial anomaly

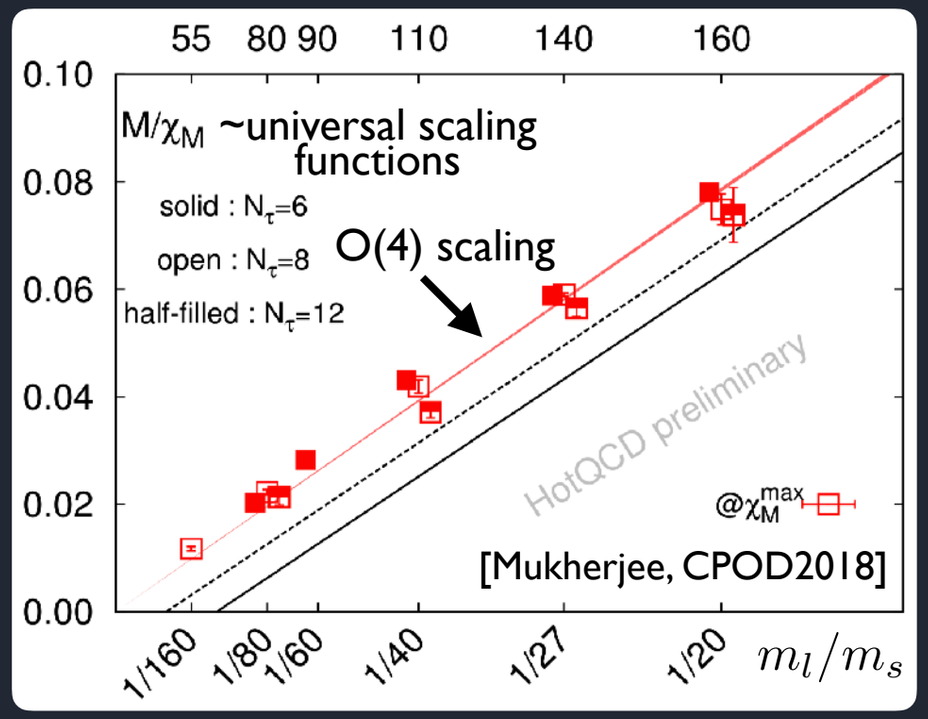
$$SU(3)_V \times SU(3)_A \times U(1)_V \times \mathbb{Z}^A_{N_f}$$

↓ s is chubby

$$\overbrace{SU(2)_V \times SU(2)_A}^{O(4)} \times U(1)_V \times \mathbb{Z}^A_{N_f}$$

- explicit breaking very mild in light quark sector

  → any `remnants´ of the underlying flavor symmetry?



QUARK MASS DEPENDENCE

expectation for the chiral phase transition:

[Pisarski, Wilczek, PRD29 (1983)], based on linear sigma model in LO ε expansion

- $N_f = 3$ chiral quarks: **1st order transition**

- $N_f = 2$ chiral quarks: **depends on the fate of the axial anomaly at T_c**
  ($U(1)_A$ expected to be restored at large T, but how large exactly?)
  [Pisarski, Yaffe, PLB 97 (1980)]

  - $U(1)_A$ still broken: **2nd order with 3D O(4) universality**

  - $U(1)_A$ restored: **1st order transition possible**

still an open problem!

current status on the lattice, e.g. [Sharma, hep-lat/1901.07190]

QUARK MASS DEPENDENCE

expectation for the chiral phase transition:

[Pisarski, Wilczek, PRD29 (1983)], based on linear sigma model in LO ε expansion

- $N_f = 3$ chiral quarks: **1st order transition**

What is the non-perturbative picture?

[S. Resch, FR, B. J. Schaefer (2017)]

- $U(1)_A$ restored: **1st order transition possible**

still an open problem!

current status on the lattice, e.g. [Sharma, hep-lat/1901.07190]

QUARK MASS DEPENDENCE

QM model

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

$$\Sigma = T^a(\sigma^a + i\pi^a)$$

$$\Sigma_5 = T^a(\sigma^a + i\gamma_5\pi^a)$$

$$\rho_n = \mathrm{Tr}\big(\Sigma\Sigma^\dagger\big)^n$$

- $SU(3)_L \times SU(3)_R \times U(1)_A$ symmetric part

$$\Gamma_k^\chi = \int_x \Big\{ \bar{q}\left(\gamma_\nu\partial_\nu + \gamma_0\mu + h\Sigma_5\right)q + \mathrm{Tr}\big(\partial_\nu\Sigma\partial_\nu\Sigma^\dagger\big) + U_k^\chi(\rho_1,\rho_2) \Big\}$$

- explicit symmetry breaking part:

$$\Gamma_k^{\mathrm{SB}} = \int_x \Big\{ -j_l\overset{\langle\bar{l}l\rangle}{\sigma_l} - j_s\overset{\langle\bar{s}s\rangle}{\sigma_s} - c_A\big(\det\Sigma + \det\Sigma^\dagger\big) \Big\}$$

light and strange quark masses
(light isospin symmetry)

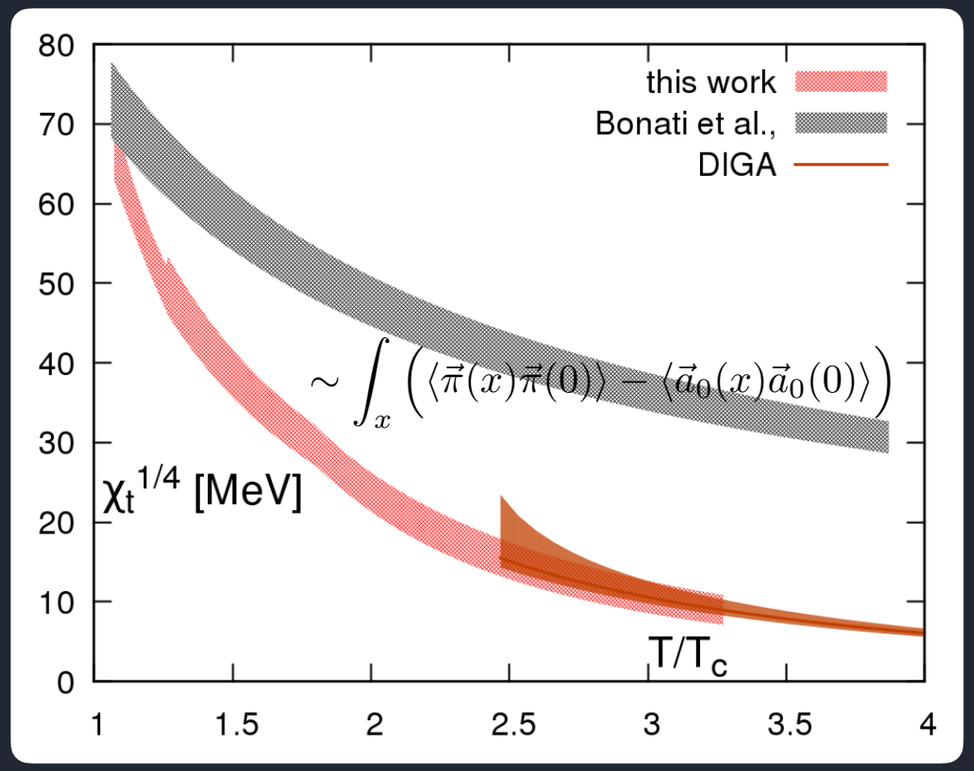
- $U(1)_A$ breaking through `t Hooft determinant: generated by a dilute gas of small instantons with top. charge Q = 1

[`t Hooft, PRL37 & PRD14 (1976)]

- dilute gas of small instantons with charge Q:

$$(\det\Sigma)^{|Q|} + (\det\Sigma^\dagger)^{|Q|}$$

[Pisarski, Rennecke (in preparation)]



[Petreczky, Schadler, Sharma, hep-lat/1606.03145]

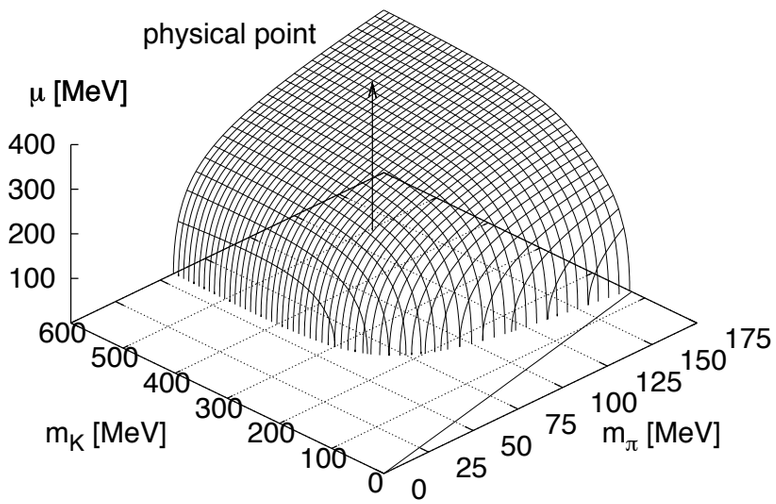
QUARK MASS DEPENDENCE

the order of the phase transition in the plane of the quark masses: the Columbia plot

- the role of fluctuation **with** the axial anomaly

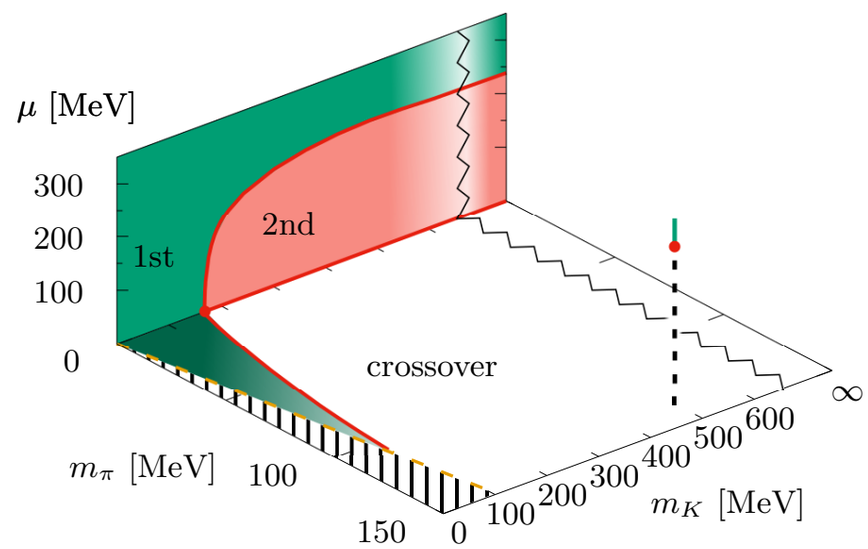
$$c_A = \text{const.} > 0$$

mean-field

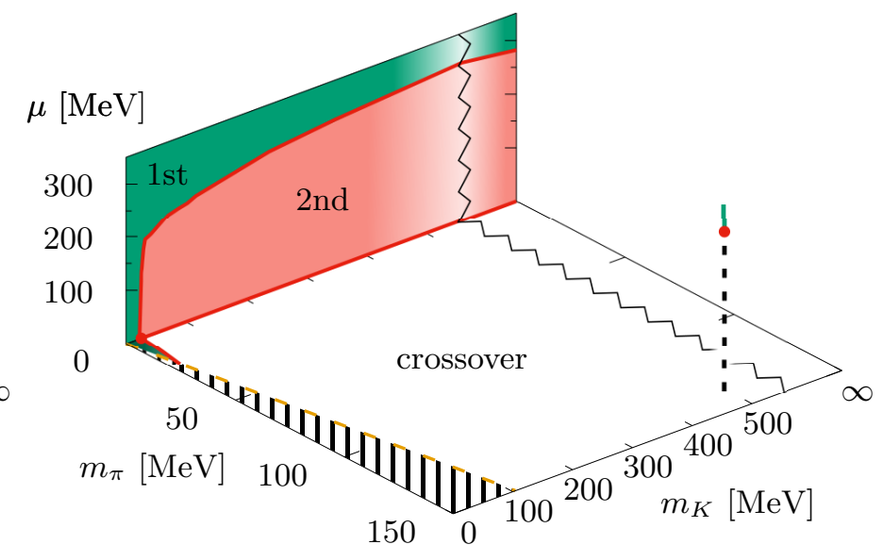


[Schaefer, Wagner, hep-ph/0808.1491]

mean-field + quark vacuum fluctuations



FRG (LPA)



[Resch, FR, Schaefer, hep-ph/1712.07961]

$$m_l \propto f_\pi m_\pi^2$$

$$m_s \propto \sqrt{2} f_K m_K^2 - \frac{1}{\sqrt{2}} f_\pi m_\pi^2$$

→ non-perturbative confirmation of Pisarski-Wilczek

→ fluctuations are crucial

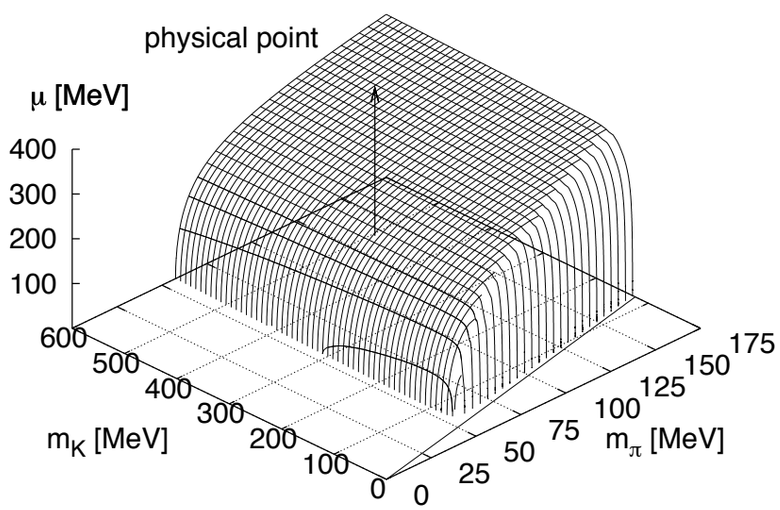
QUARK MASS DEPENDENCE

the order of the phase transition in the plane of the quark masses: the Columbia plot

- the role of fluctuation **without** the axial anomaly

$$c_A = 0$$

mean-field



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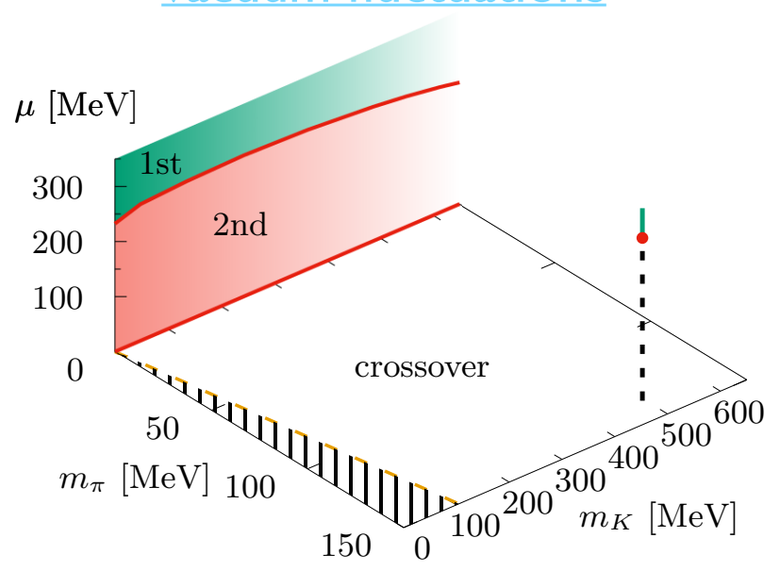

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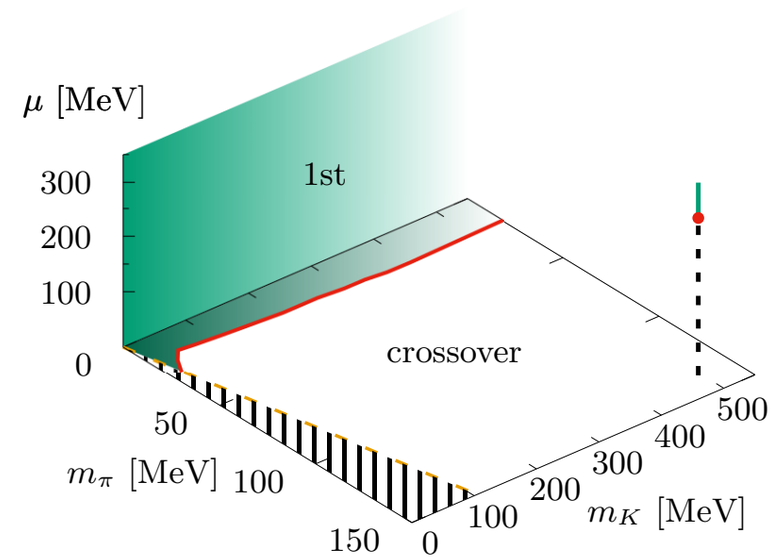


[Resch, FR, Schaefer, hep-ph/1712.07961]

- Note: this is strictly speaking only realized in the large-N_C limit

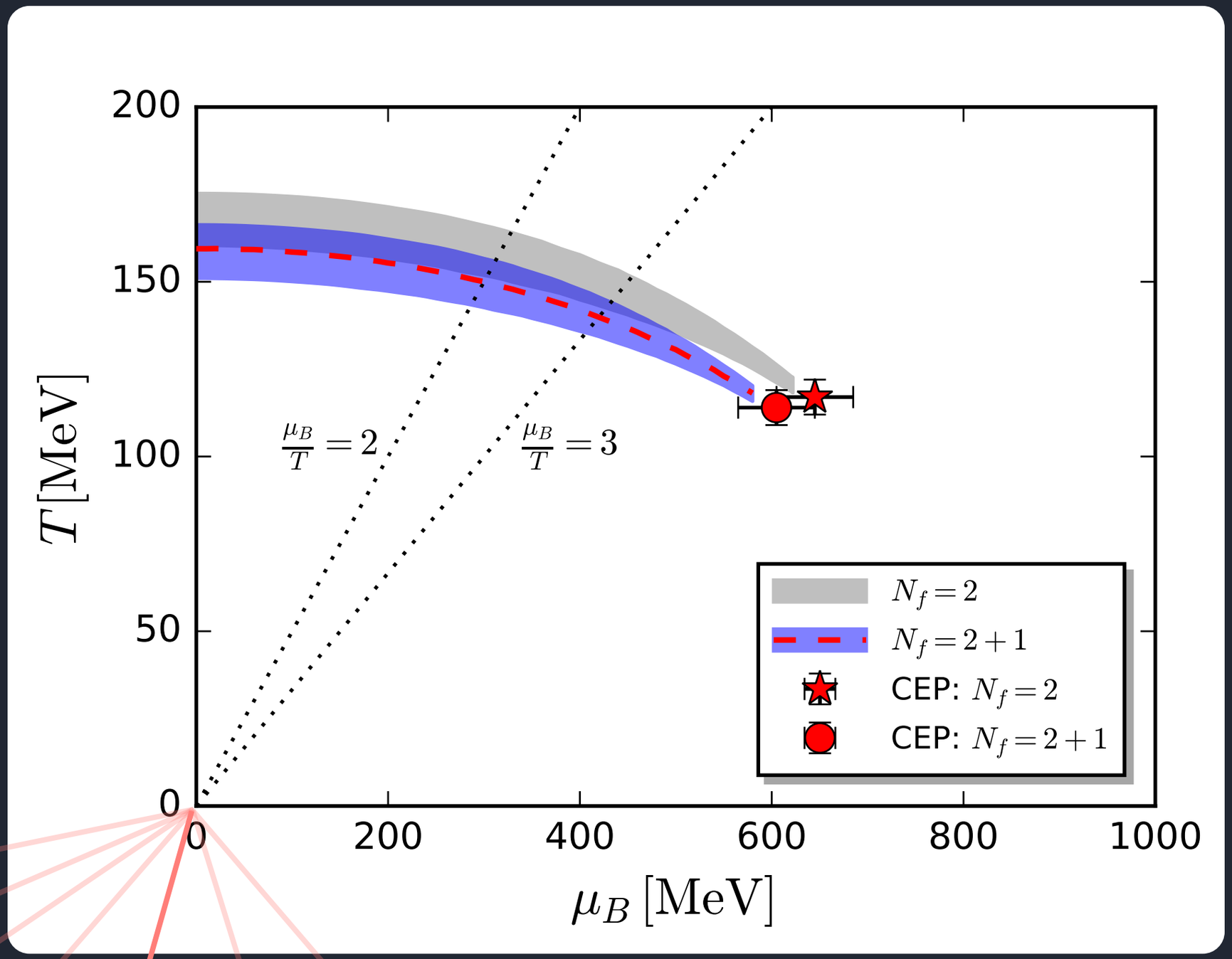
  instanton contribution ≈

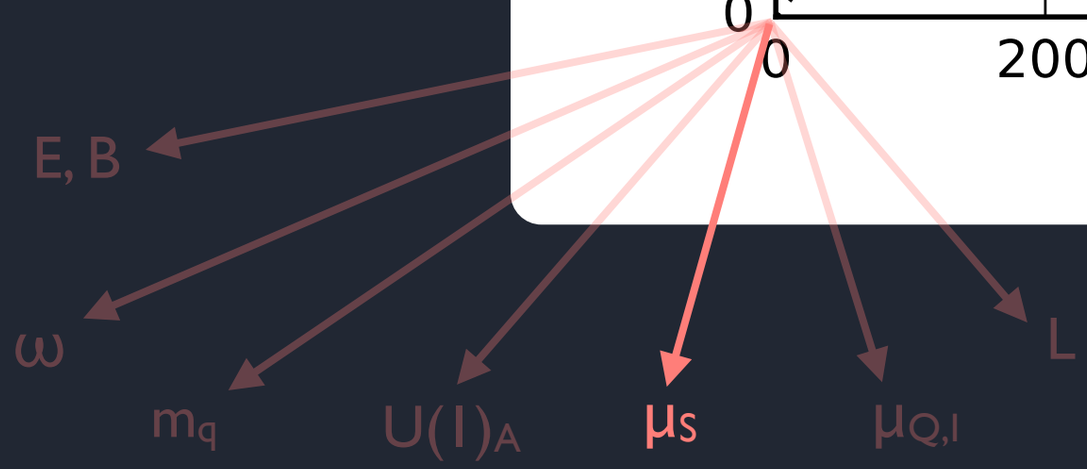
$$e^{-\frac{8\pi^2}{g^2}|Q|} = e^{-\frac{8\pi^2 N_c}{g^2 N_c}|Q|} = e^{-\frac{8\pi^2}{\lambda}|Q|N_c} \xrightarrow{N_c\to\infty} 0$$

→ non-perturbative confirmation of Pisarski-Wilczek

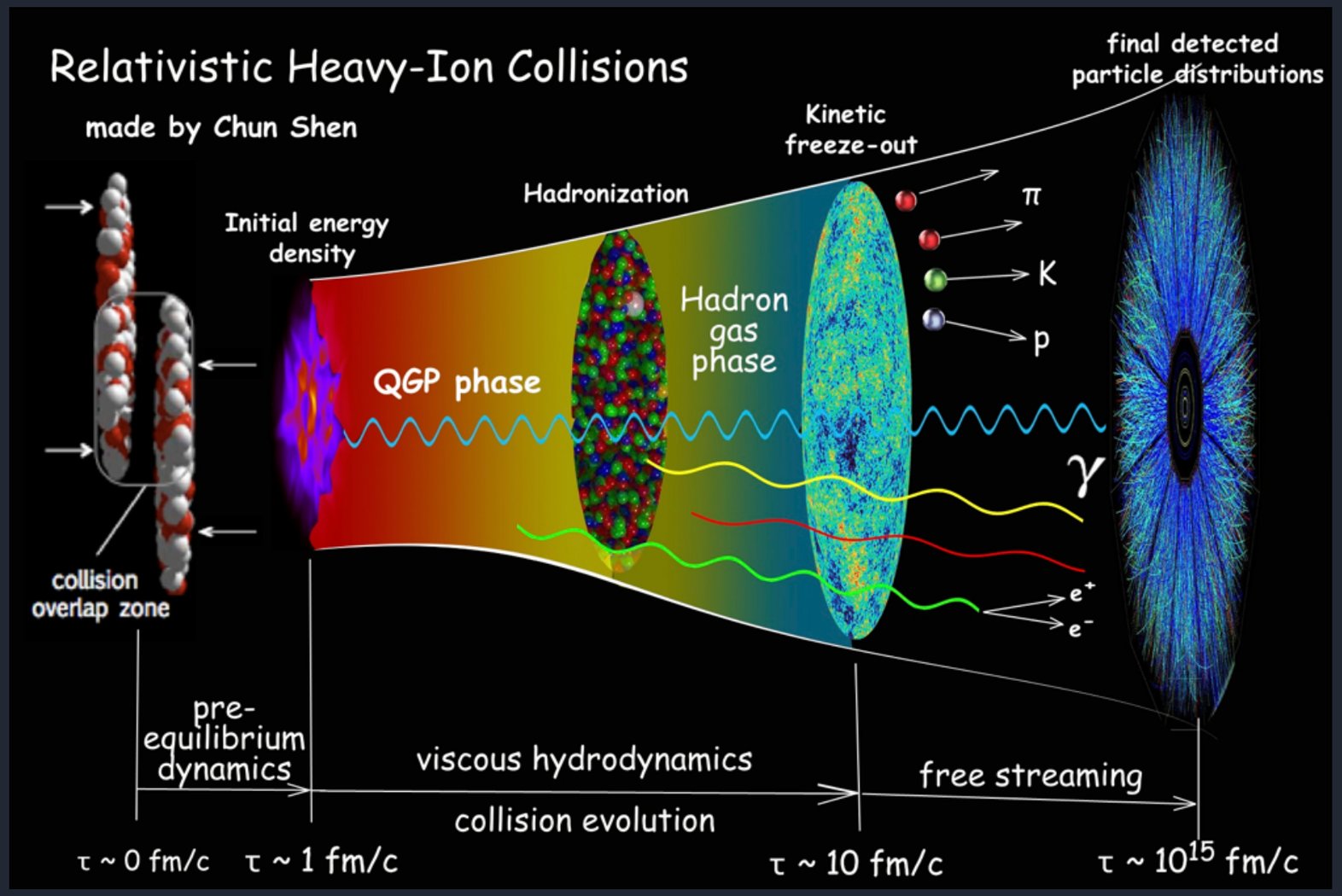
→ fluctuations are crucial

STRANGENESS & HICS





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!

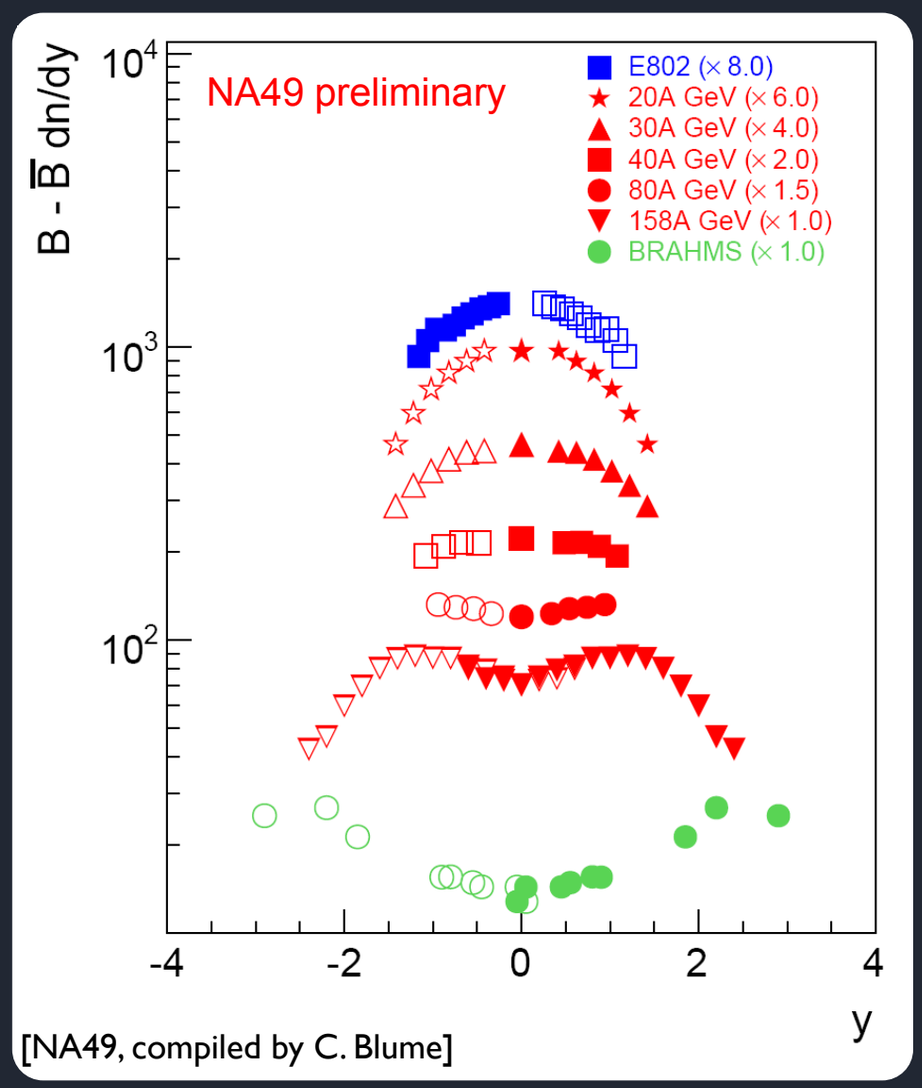
→ baryon number, strangeness & charge are conserved

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

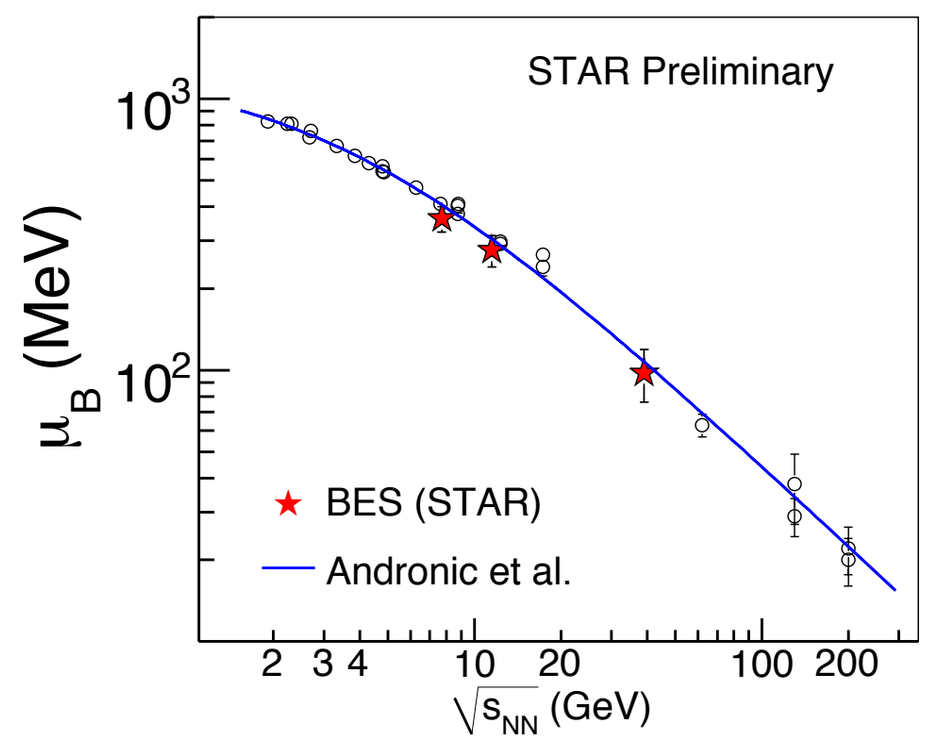
PROBING THE PHASE DIAGRAM

- 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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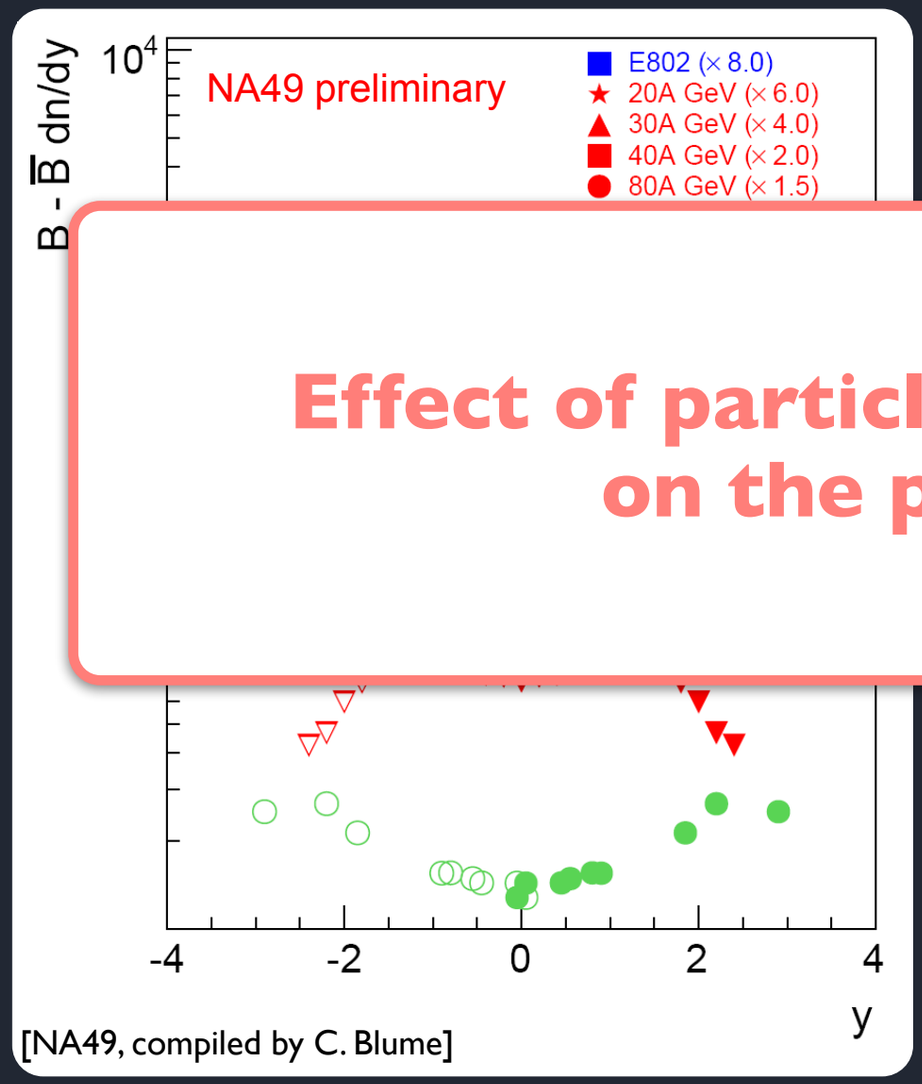
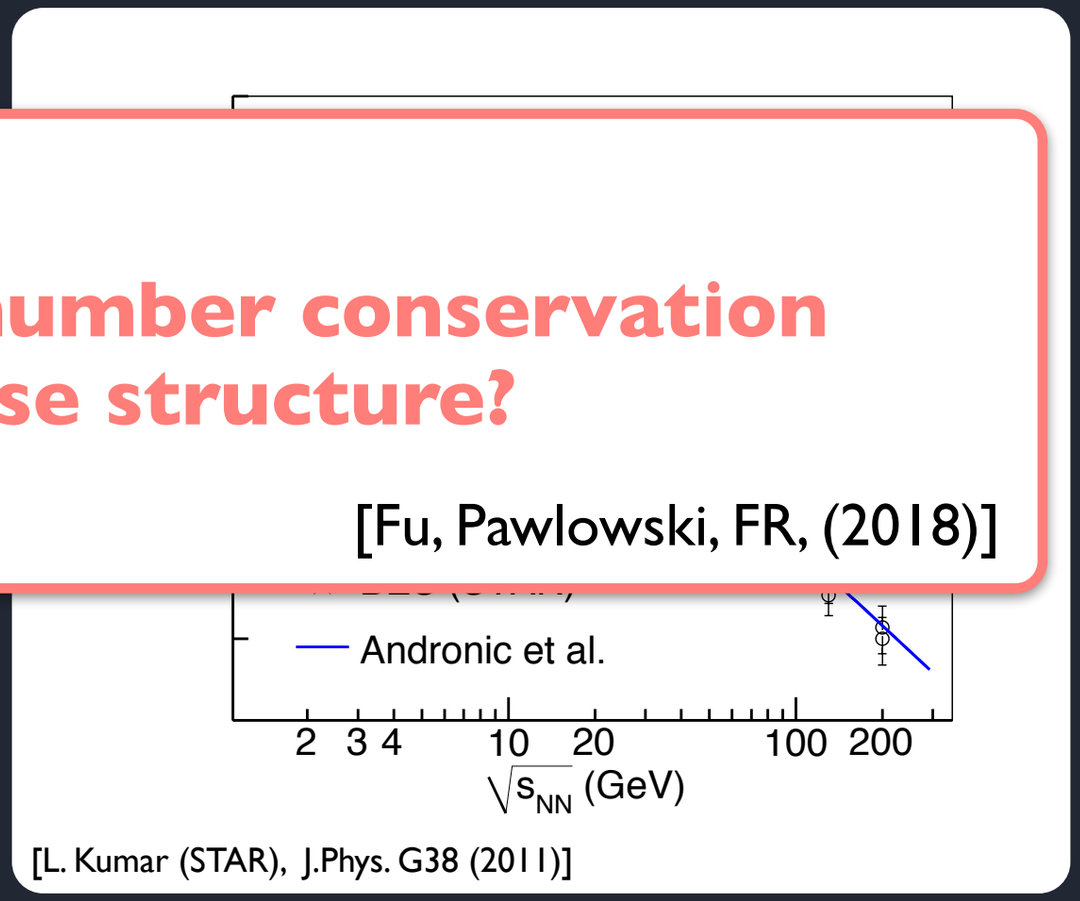
- increasing baryon chemical potential with decreasing beam energy (at mid-rapidity)

→ μ_B is a `free´ parameter



[NA49, compiled by C. Blume]



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

Effect of particle number conservation on the phase structure?

[Fu, Pawlowski, FR, (2018)]

BARYON-STRANGENESS CORRELATION

- order parameters can't be measured, but particle number correlations can

  and they are sensitive to critical fluctuations!

  [Stephanov, Rajagopal, Shuryak, hep-ph/9903292]

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

$$\chi_{n0}^{BS} \sim \langle (B - \langle B \rangle)^n \rangle$$
$$B = N_B - N_{\bar{B}}$$

- baryon-strangeness correlation

strangeness neutrality

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

[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: $\chi_{11}^{BS} = -\chi_{02}^{BS}/3$

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

hadronic phase

- mesons can carry only strangeness, baryons both

χ_{11}^{BS} : strange baryons dominate

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

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

STRANGENESS NEUTRALITY

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

- 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 [Fukushima, hep-ph/0310121]

captures relevant dynamics at low energy [Fu, Pawlowski, FR, hep-ph/1808.00410]

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

chemical potential

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

- vector source: $C_\nu = \delta_{\nu 0}\, \mu$
- coupling to mesons: $\bar{D}_\nu \Sigma = \partial_\nu \Sigma + [C_\nu, \Sigma]$

gluon background field

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

- Polyakov loop: order parameter

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

- effective potential: input $U_{\mathrm{glue}}(L, \bar{L})$

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

baryons

- thermal quark distributions modified through feedback from A_0:

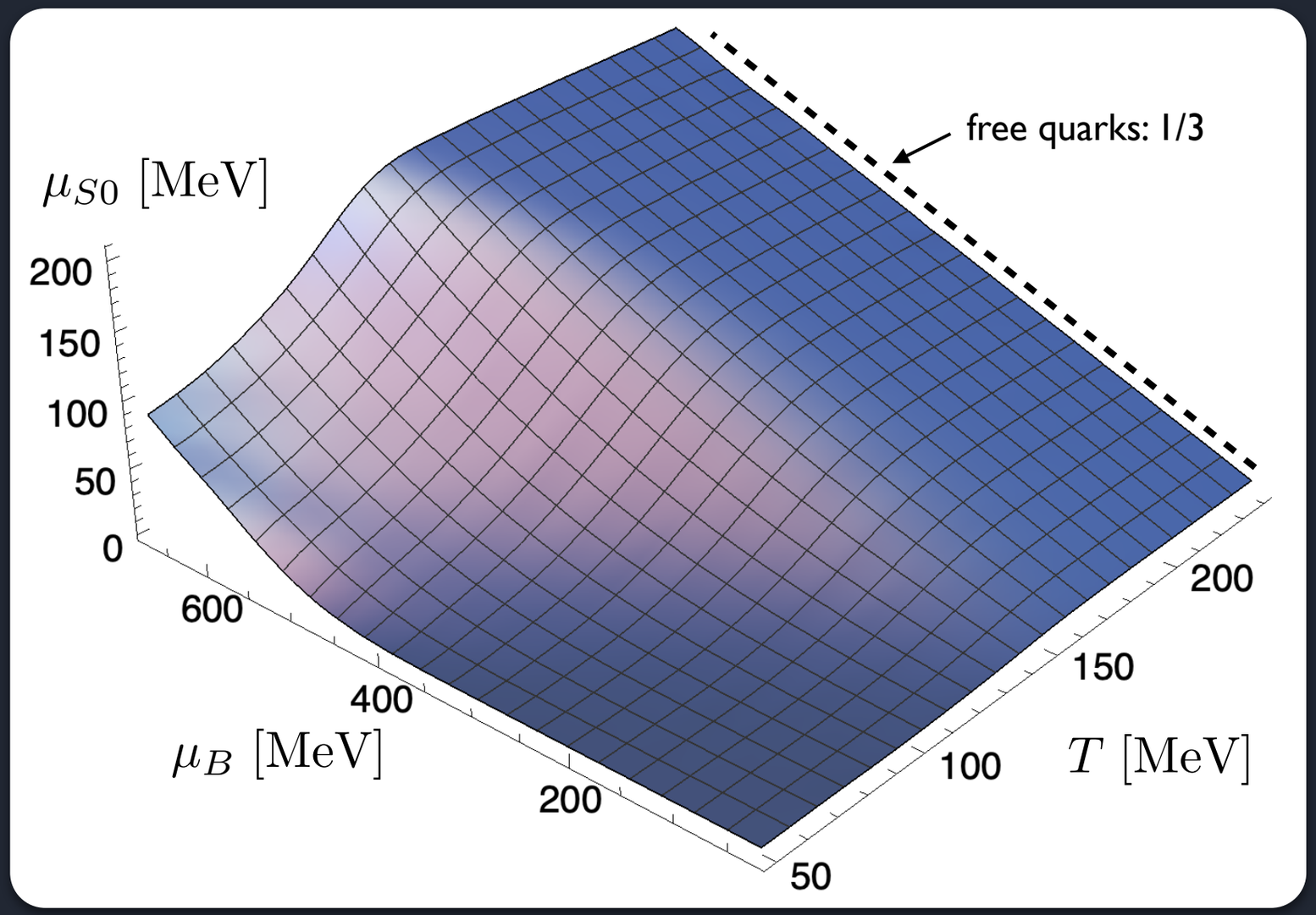
$$n_F(E) \xrightarrow{A_0} \begin{cases} \frac{1}{e^{3(E-\mu)/T}+1}\,, & L \to 0 \text{ (confinement)} \\ \frac{1}{e^{(E-\mu)/T}+1}\,, & L \to 1 \text{ (deconfinement)} \end{cases}$$

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

[Fukushima, hep-ph/0310121]
[Fu & Pawlowski, hep-ph/1508.06504]

STRANGENESS CHEMICAL POTENTIAL

T and μ_B dependent to enforce strangeness neutrality



→ μ_{S0} is nontrivial function

- 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

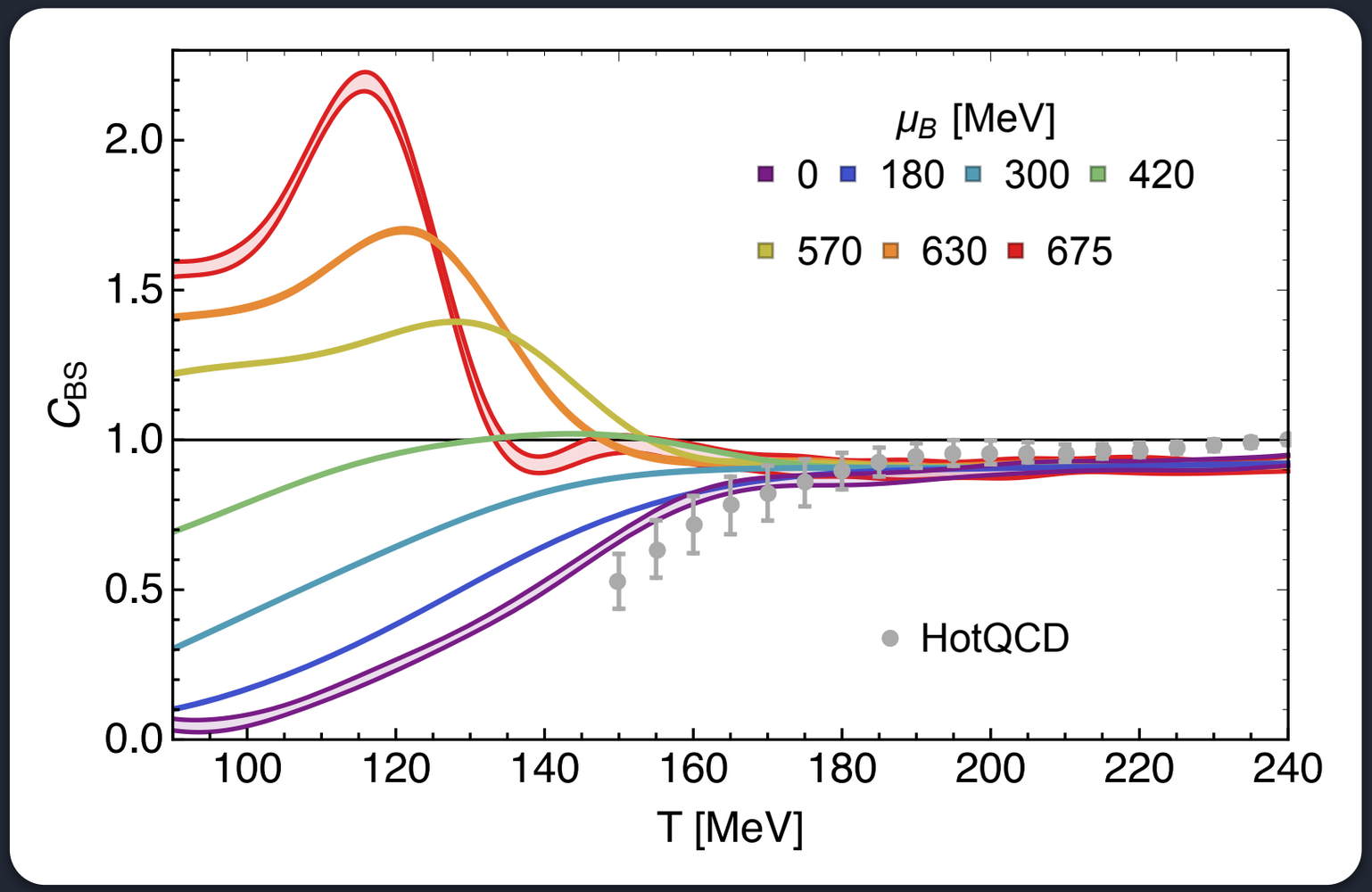
[Fu, Pawlowski, FR, hep-ph/1808.00410]
[Fu, Pawlowski, FR, hep-ph/1809.01594]

BARYON-STRANGENESS CORRELATION

at strangeness neutrality

beyond mean-field!

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



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

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

→ competition between baryonic and mesonic sources of strangeness!

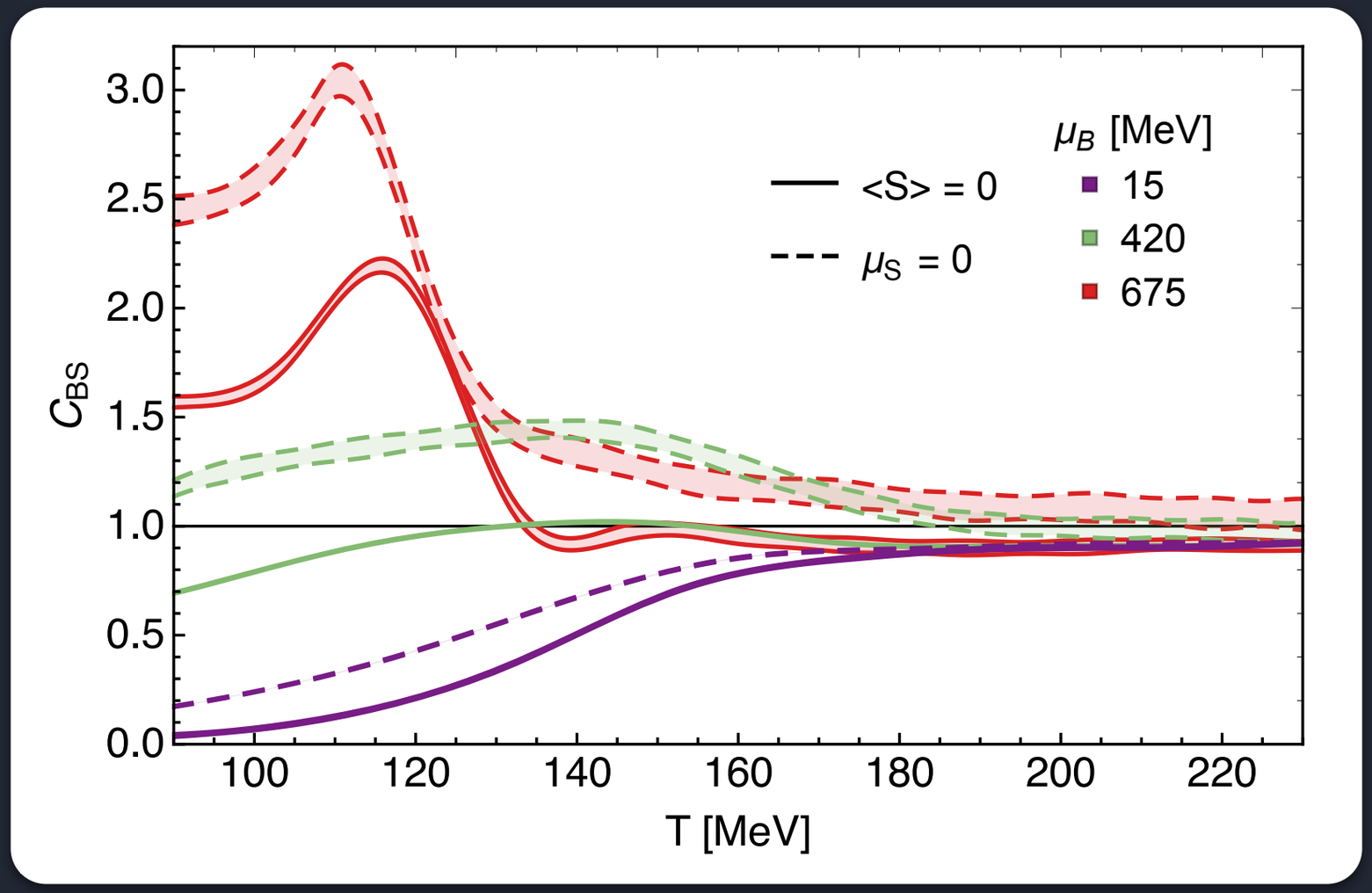
maxima at the chiral transition!

→ direct sensitivity to the QCD phase transition

Note: not necessarily due to growing correlation length; the composition of matter matters here!

BARYON-STRANGENESS CORRELATION

strangeness conservation vs non-conservation



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

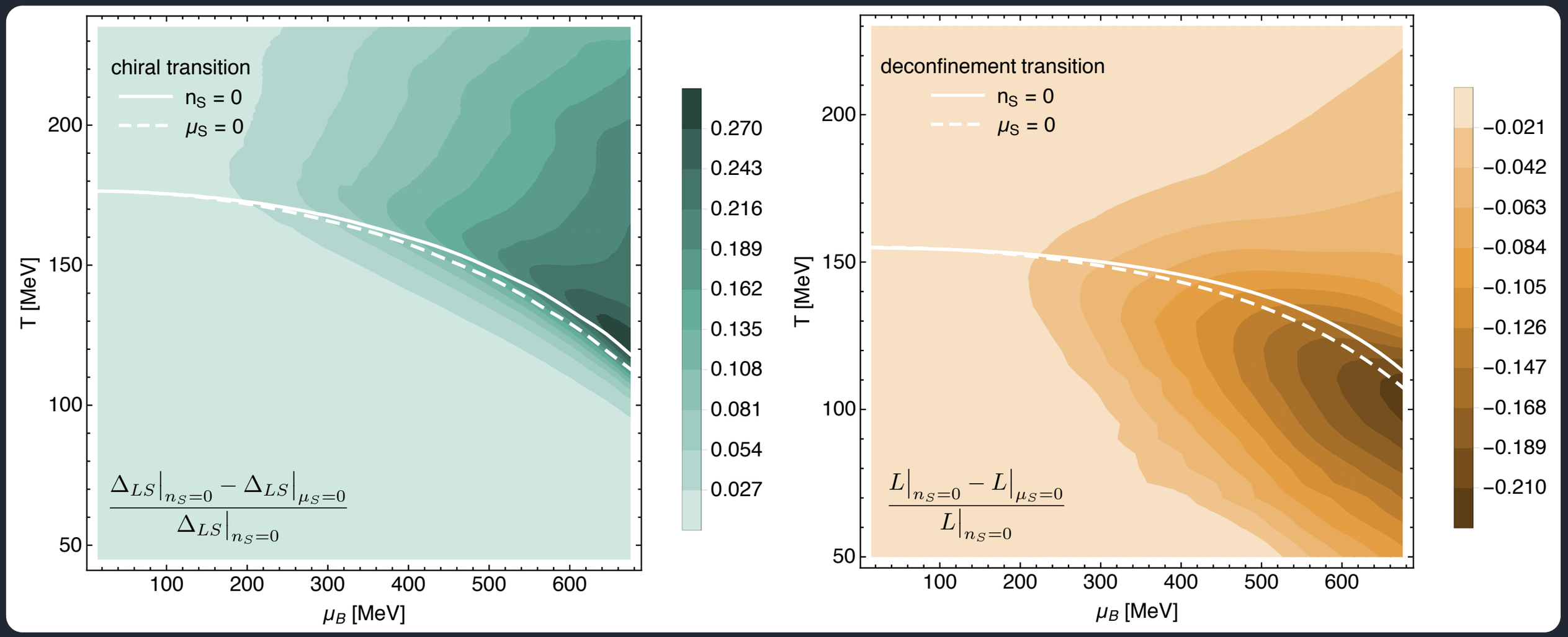
→ sizable suppression from strangeness neutrality!

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 shifted to larger μ_B (for fixed T)

→ smaller curvature of the phase boundary

→ ≥30% effect on location of the CEP?

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

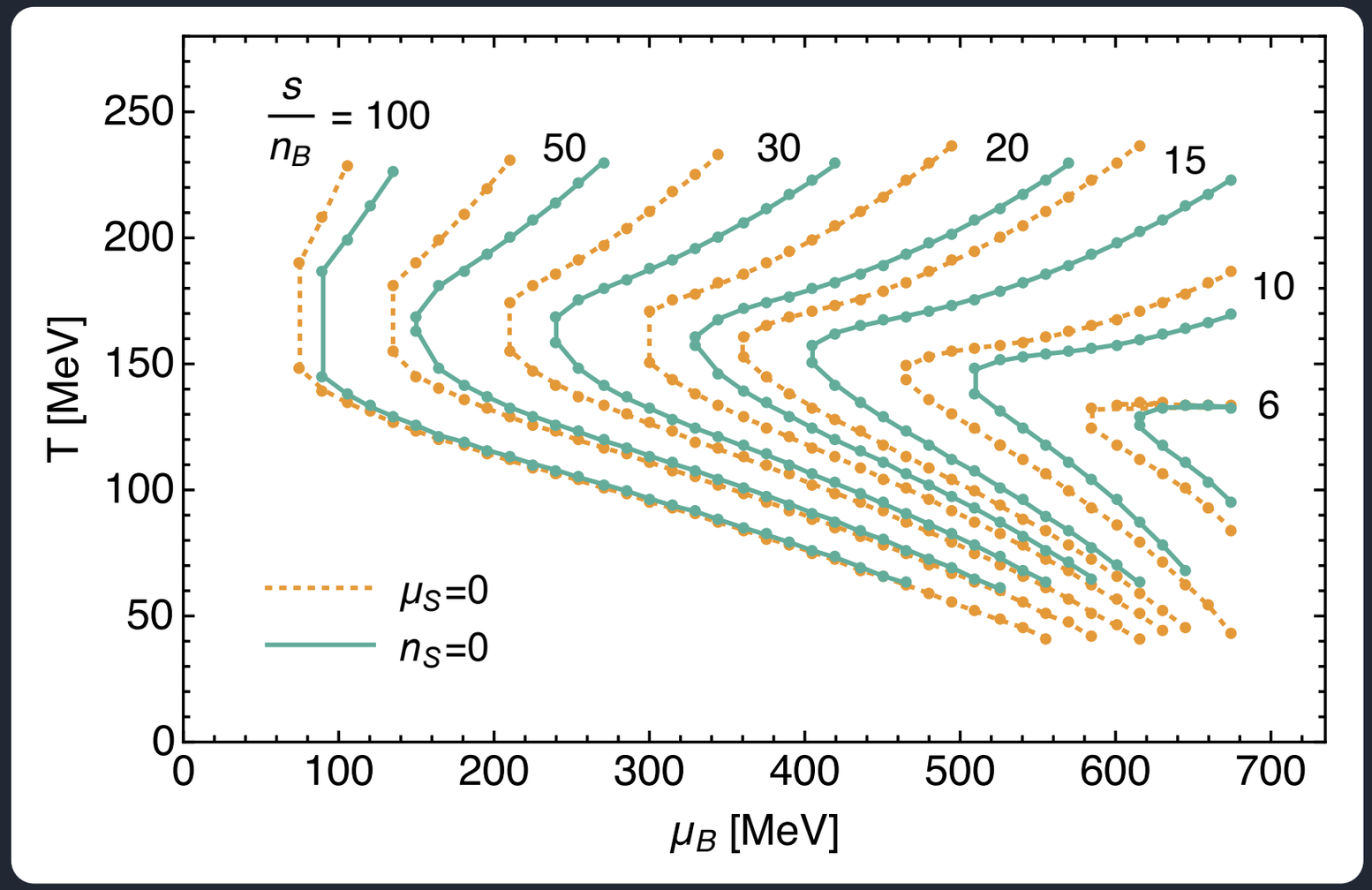
ISENTROPES

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

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



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

cf. mean-field NJL [Fukushima, hep-ph/0901.0783]

SUMMARY

- chiral phase transition driven by strong couplings
  - low energy sector emerges through resonant interactions
  - CEP is a robust feature of the phase diagram
- quark mass dependence: Columbia plot
  - fluctuations are crucial
  - light chiral limit: sensitive to fate of the axial anomaly
- the phase diagram & heavy-ion collisions
  - particle number conservation has to be taken into account
  - intimate relation between strangeness conservation and phases of QCD
  - baryon-strangeness correlations probe the phase transition

the phase diagram has many faces!

BACKUP

STRANGENESS AND CHARGE CONSERVATION

- particle number conservation implicitly defines two functions:

$$\mu_{Q0}(T,\mu_B) = \mu_Q(T,\mu_B)\big|_{n_S=0,\, n_Q=r n_B}$$
$$\mu_{S0}(T,\mu_B) = \mu_S(T,\mu_B)\big|_{n_S=0,\, n_Q=r n_B}$$

$$r = \frac{Z}{A}$$

- 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

THERMODYNAMICS

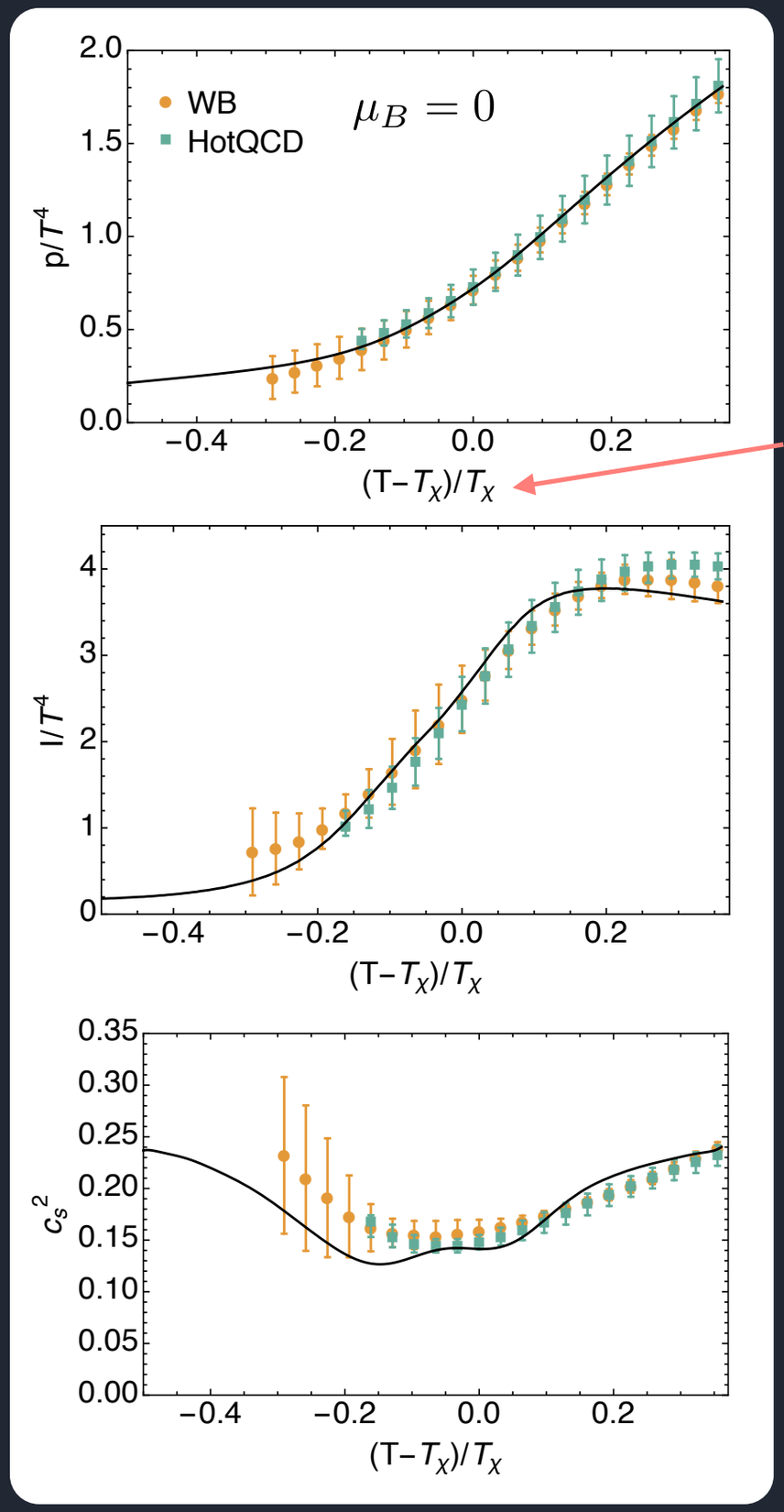
compare to lattice gauge theory

- thermodynamic potential:

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

- thermodynamics:

$$p = -\Omega$$
$$s = \frac{\partial p}{\partial T}$$
$$\epsilon = -p + Ts + \mu_B n_B + \mu_S n_S$$
$$I = \epsilon - 3p$$
$$c_s^2 = \frac{s}{\partial\epsilon/\partial T}$$
$$n_B = \chi_{10}^{BS}\, T^3$$
$$n_S = \chi_{01}^{BS}\, T^3$$



chiral transition temperature

[HotQCD, hep-lat/1407.6387 & 1701.04325]
[Wuppertal-Budapest, hep-lat/1309.5258]

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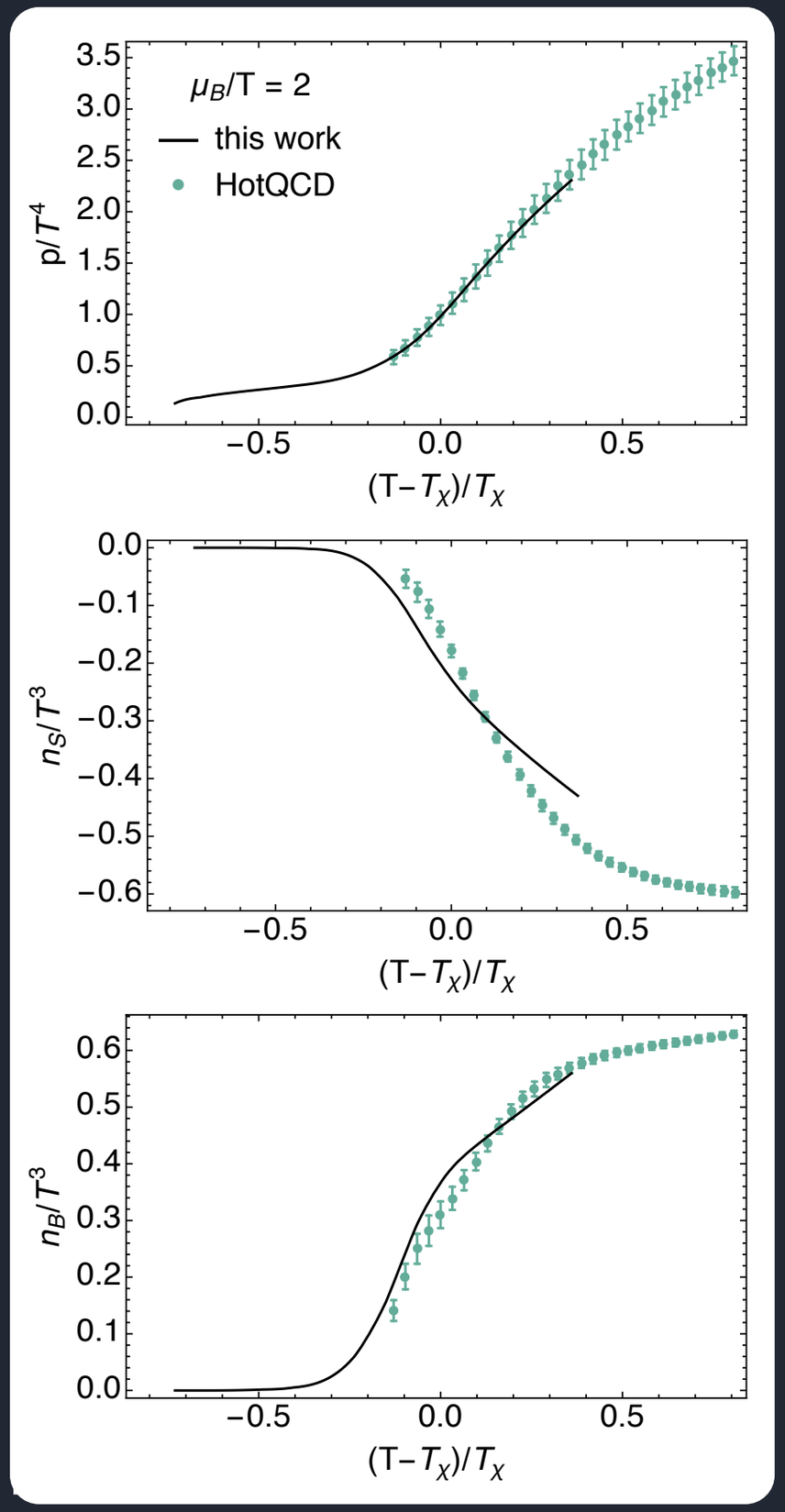

[HotQCD, hep-lat/1407.6387 & 1701.04325]
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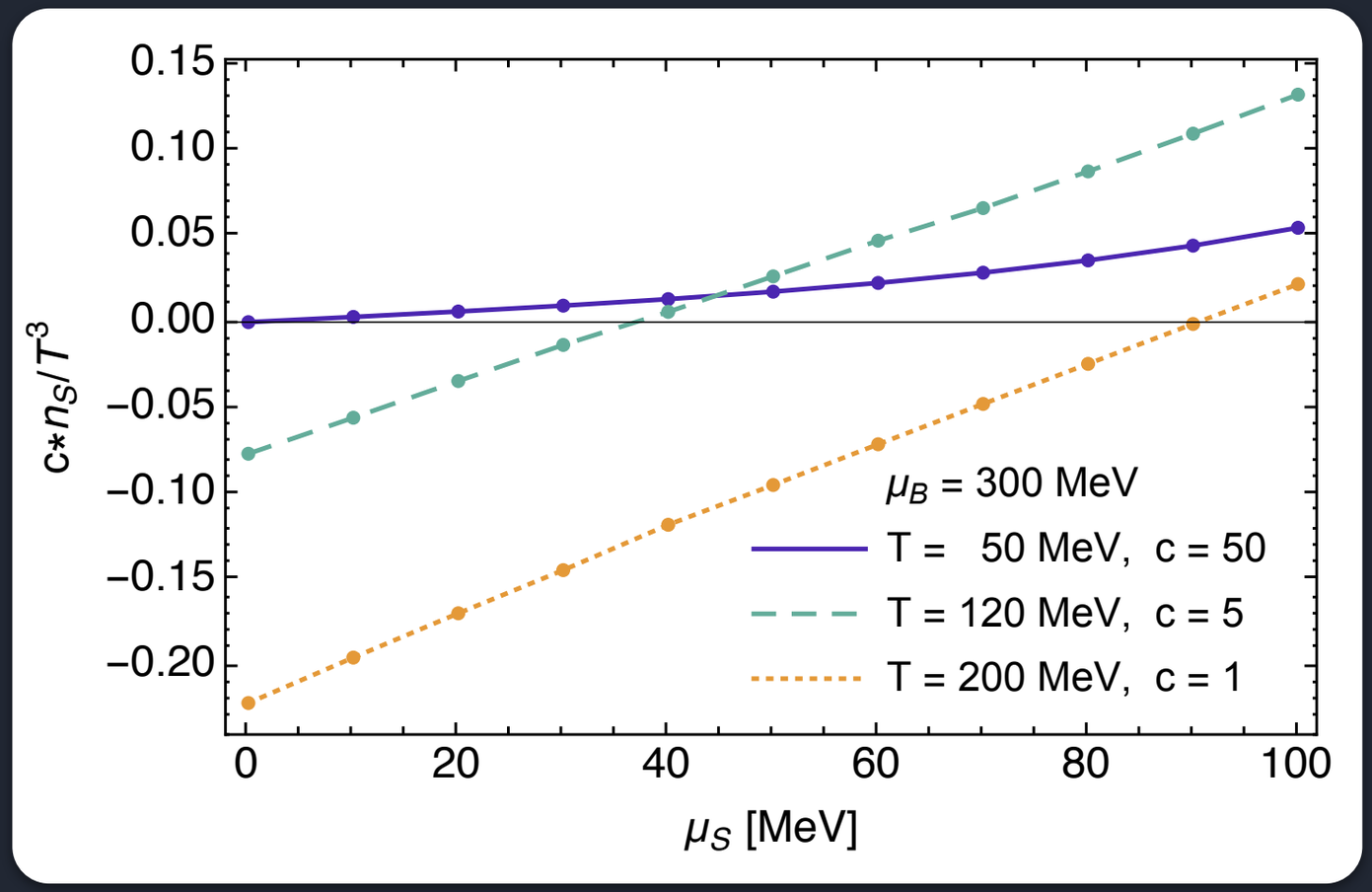
STRANGENESS DENSITY

as a function of μ_S



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

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

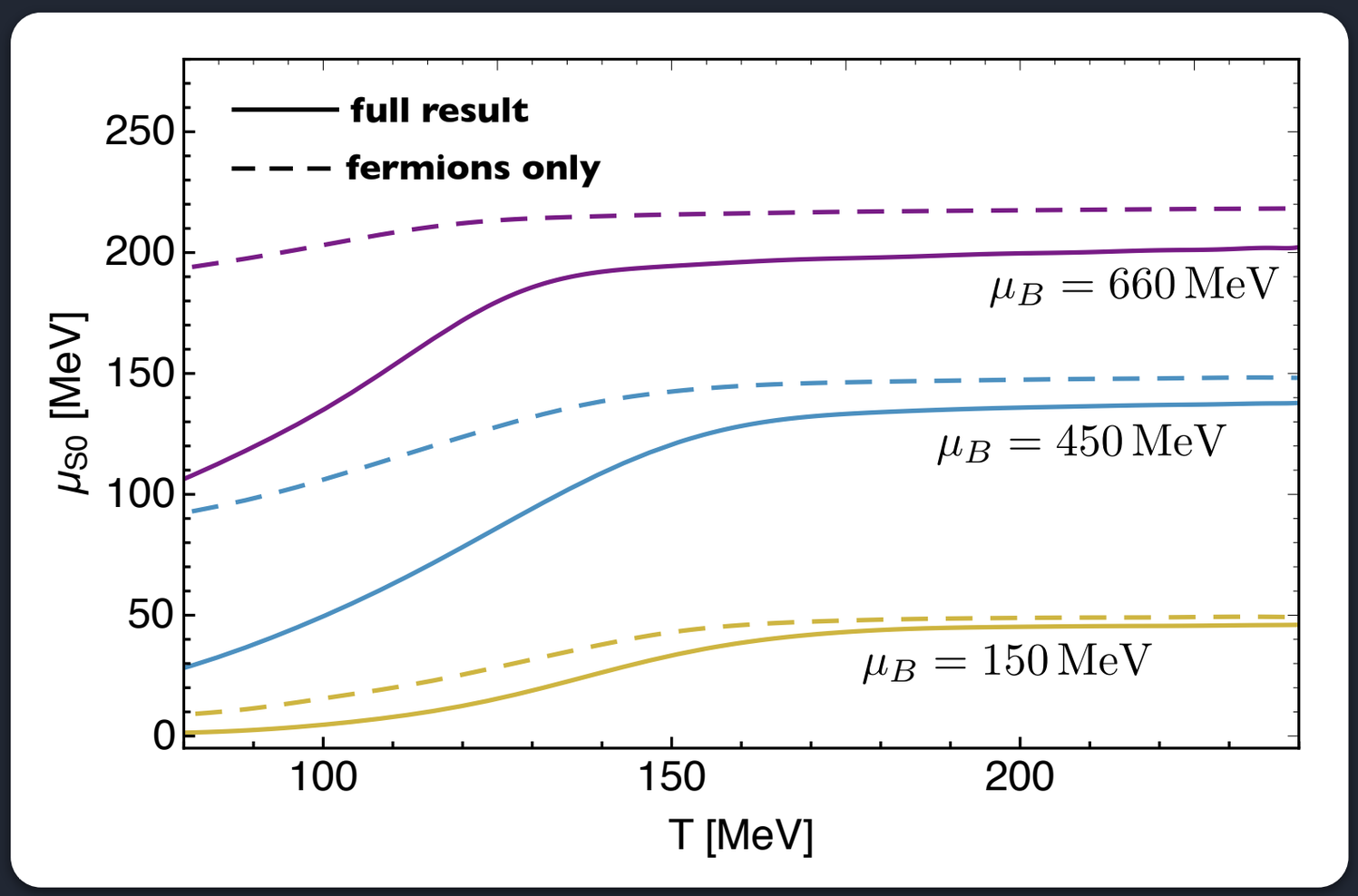
STRANGENESS CHEMICAL POTENTIAL

role of open strange meson dynamics

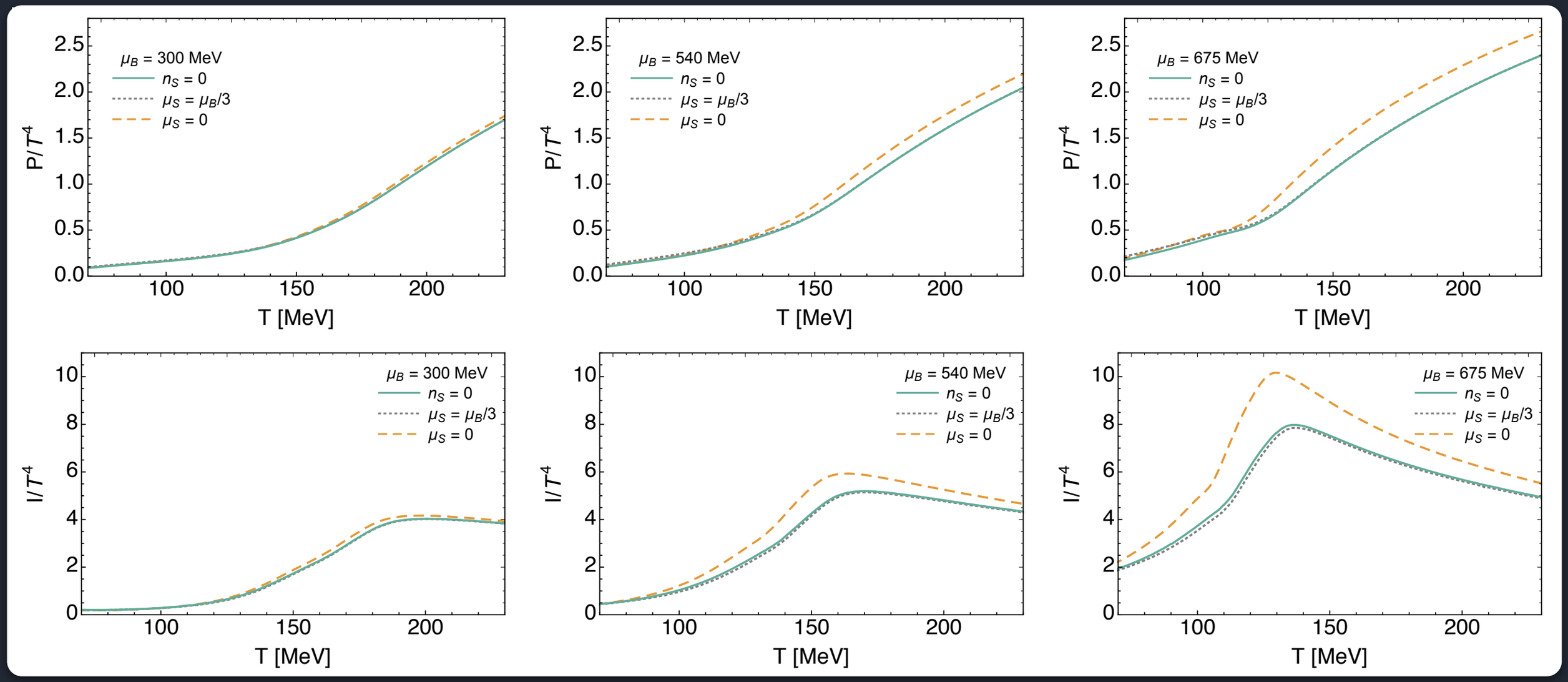
- quark/baryon vs meson dynamics?
- equation for μ_{S0} from the fermion part of the RG flow [Fukushima, hep-ph/0901.0783]

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

(~3% accurate in mean-field)



open strange meson fluctuations crucial!

EQUATION OF STATE

strangeness conservation vs non-conservation