THE CHIRAL PHASE TRANSITION OF QCD

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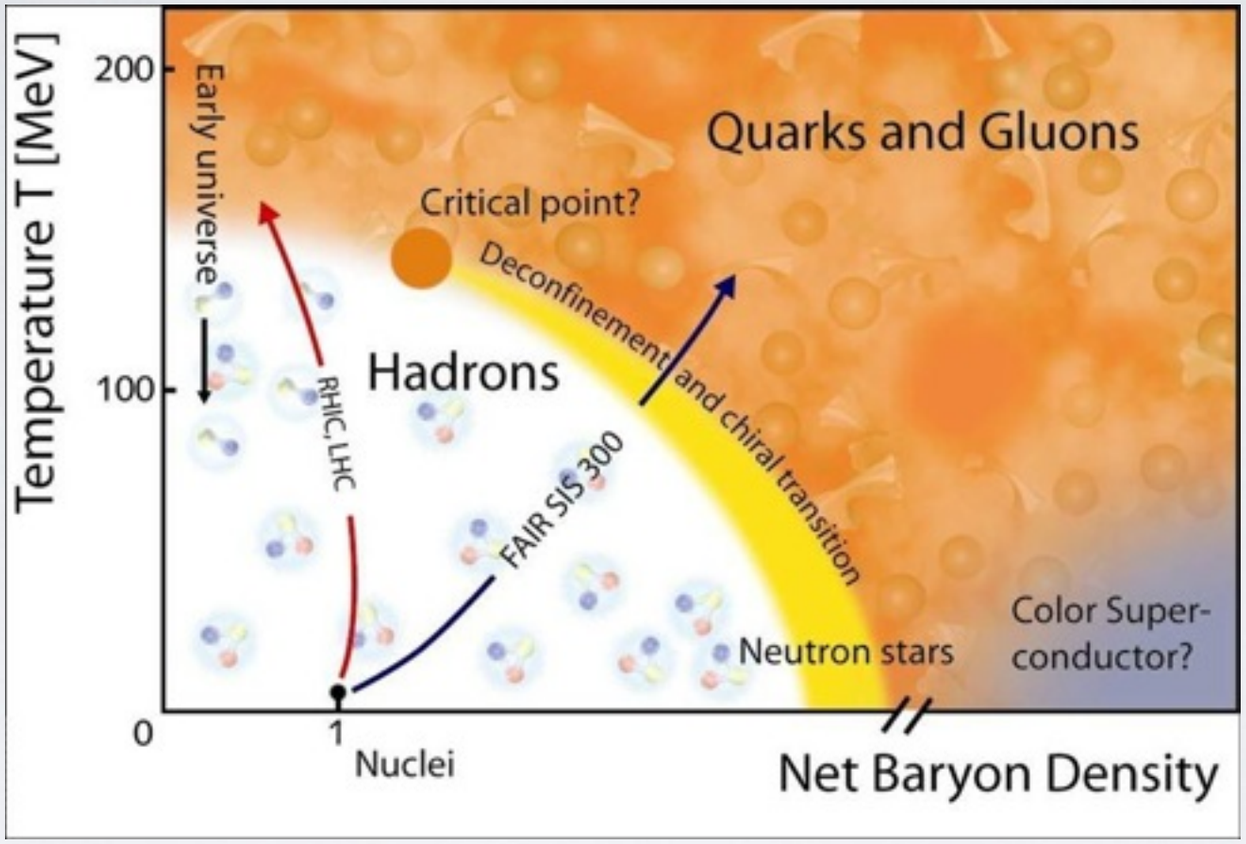
ERG2014, LEFKADA, 22.09.2014

OUTLINE

- Dynamical hadronization
- The chiral transition in QCD

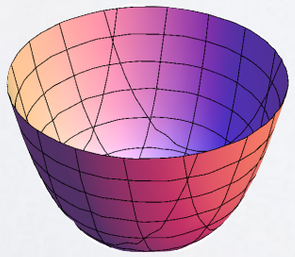
QCD PHASE DIAGRAM



[FAIR, www.gsi.de]

symmetric phase

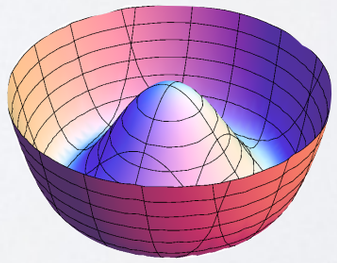
- $\langle \bar{\psi}\psi \rangle = 0$
- d.o.f.: quarks & gluons
- effective meson potential:



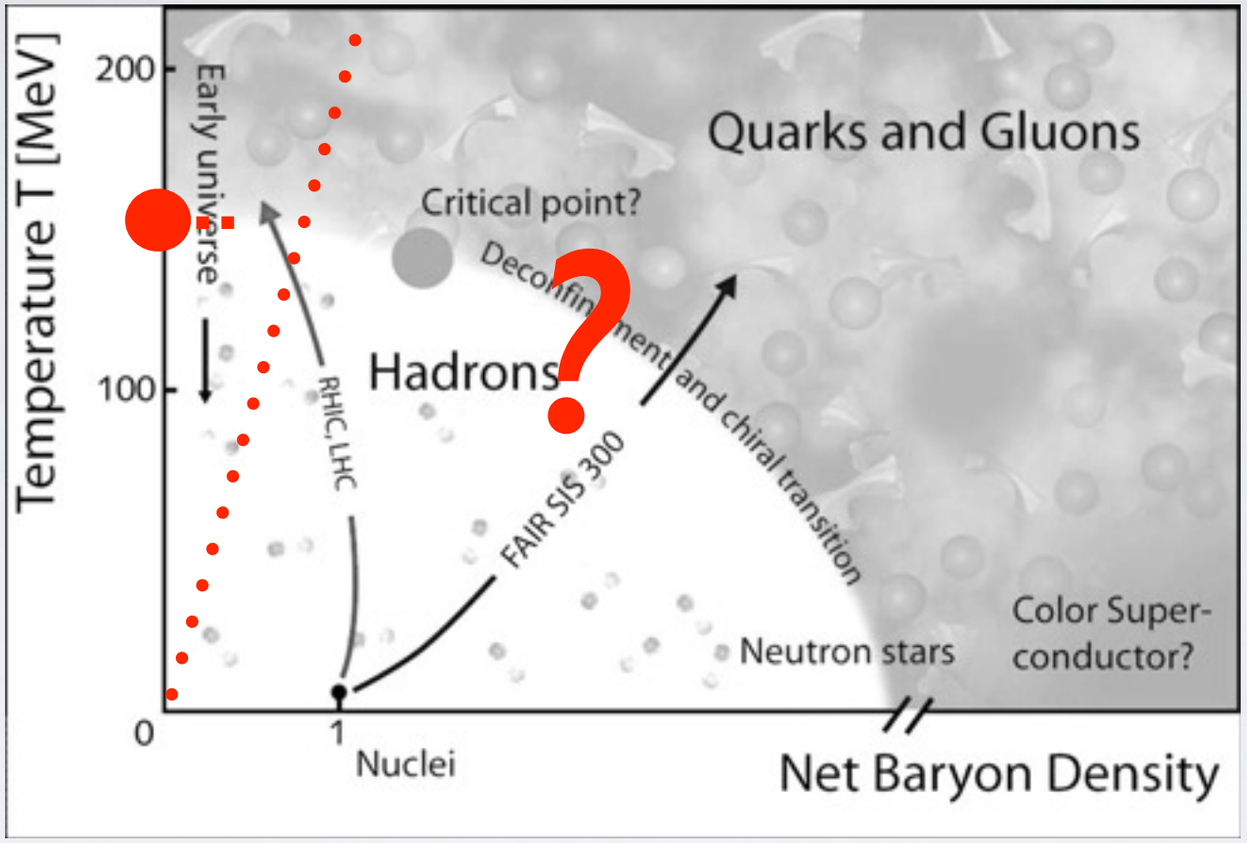
SSB

broken phase

- $\langle \bar{\psi}\psi \rangle \neq 0$
- d.o.f.: hadrons
- effective meson potential:



QCD PHASE DIAGRAM - KNOWN



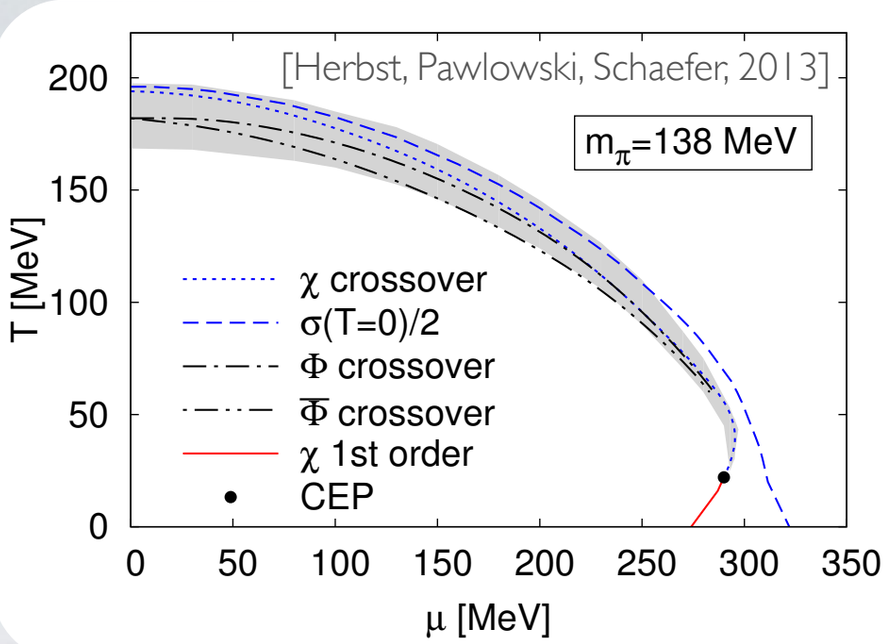
[FAIR, www.gsi.de]

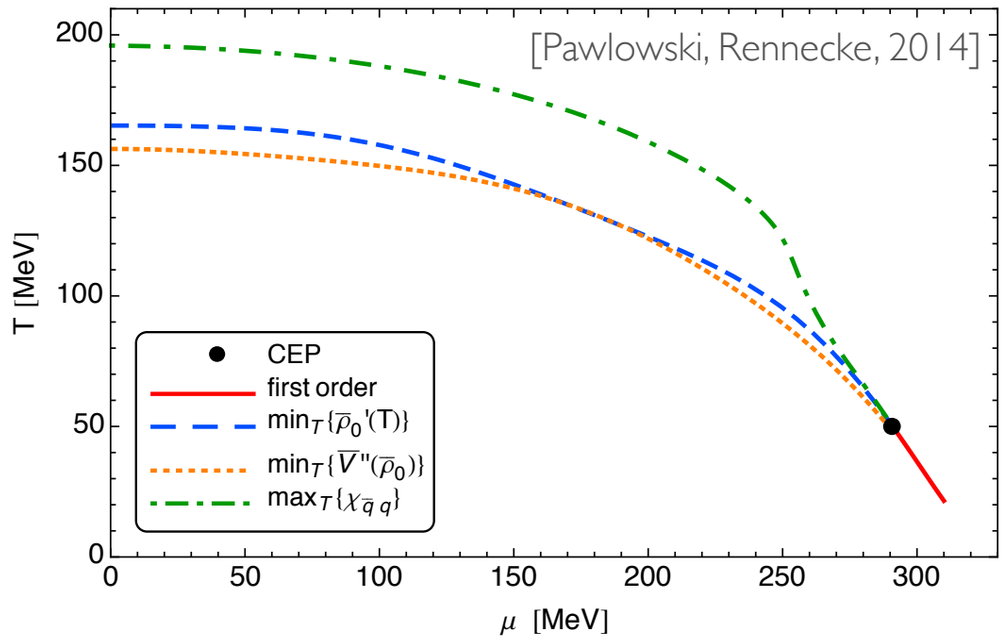
- $T_c \approx 155\,\mathrm{MeV}$ (depends on definition)
- crossover transition at small chemical potential
- no critical point for $T \gtrsim \mu_B/\pi$

→ NOT MUCH

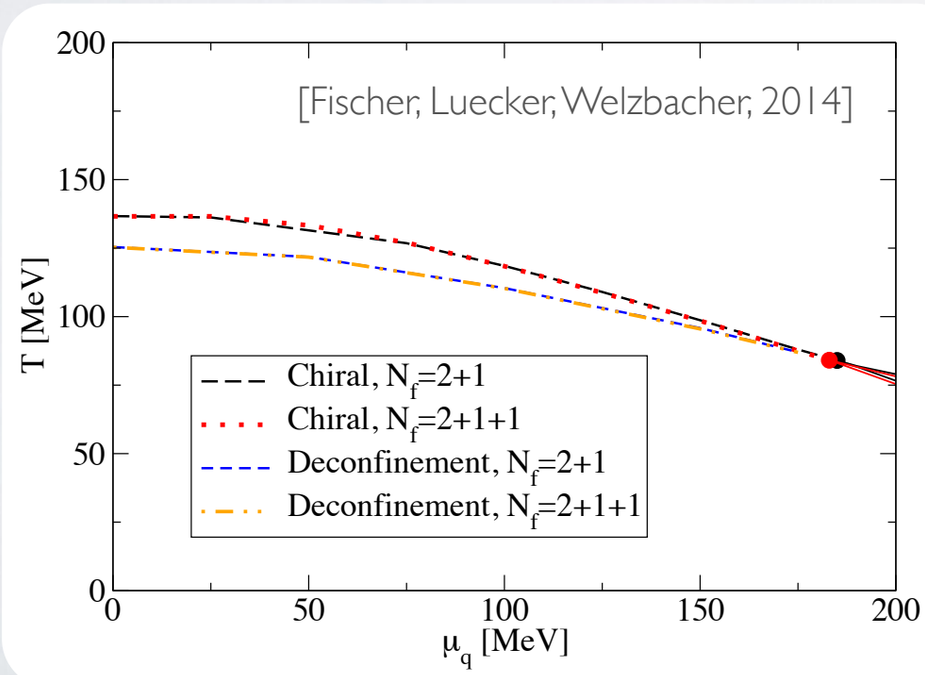
[HotQCD, Phys.Rev. D '12, Herbst, Pawlowski, Schäfer, Phys.Lett. B '11, Fischer, Luecker, Mueller, Phys.Lett. B '11, Wuppertal-Budapest, JHEP '10, Braun, Haas et al. Phys.Rev. D '13 and many more …]

QCD PHASE DIAGRAM - FUNCTIONAL APPROACHES





- low-energy effective models, $\Lambda \approx 1\,\mathrm{GeV}$
- lattice input for Polyakov loop potential



- lattice input for gluon propagator
- vertex construction for quark gluon vertex

FRG FOR VACUUM QCD

- Start at microscopic energy scale $\Lambda \gtrsim 5\,\mathrm{GeV}$

  → only dynamical quarks and gluons

  → strong coupling and current quark masses fixed by perturbation theory

- hadronic degrees of freedom emerge dynamically at smaller (non-perturbative) scales $\Lambda \lesssim 1\,\mathrm{GeV}$

  → dynamical change of d.o.f.

  → hadronic parameters fixed from high-energy QCD flow

DYNAMICAL HADRONIZATION

DYNAMICAL HADRONIZATION

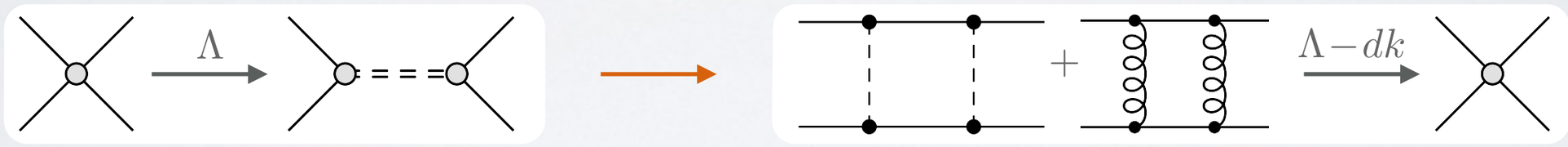
Need unified description in terms of **one** scale dep. effective action!

⟶ continuous translation of UV to IR degrees of freedom

⟶ dynamical hadronization (re-bosonization)

conventional bosonization:

- translate 4-quark interaction into Yukawa coupling at scale $\Lambda \approx 1\,\mathrm{GeV}$
- but: 4-fermi coupling immediately re-generated during RG-flow



- (some) double counting of 4-fermi interaction at lower scales
- **missing 4-fermi interaction at high scales**
- **no continuous change of d.o.f.**

DYNAMICAL HADRONIZATION

[Gies, Wetterich, Phys.Rev. D '02, Pawlowski, Ann.Phys. '07, Floerchinger, Wetterich, Phys.Lett. B '09]

- introduce scale dependent meson fields: $\phi \to \phi_k$

- hadronization field reflects bound state nature of mesons

$$\partial_t \phi_k = A_k \bar{\psi} \tau \psi + B_k \phi_k \qquad \tau = (\gamma_5 \vec{\tau}, i)$$

"store" 4-quark interaction $\partial_t \lambda_{\psi,k}$

e.g. remove/reduce momentum dependence of $h_k(p)$

- modified flow equation for mesons:

$$\partial_t \big|_{\phi_k} \Gamma_k = \frac{1}{2} \left(\partial_t R_{\phi,k} + R_{\phi,k} \frac{\delta \partial_t \phi_k}{\delta \phi_k} \right) \cdot G_{\phi,k} - \frac{\delta \Gamma_k}{\delta \phi_k} \partial_t \phi_k$$

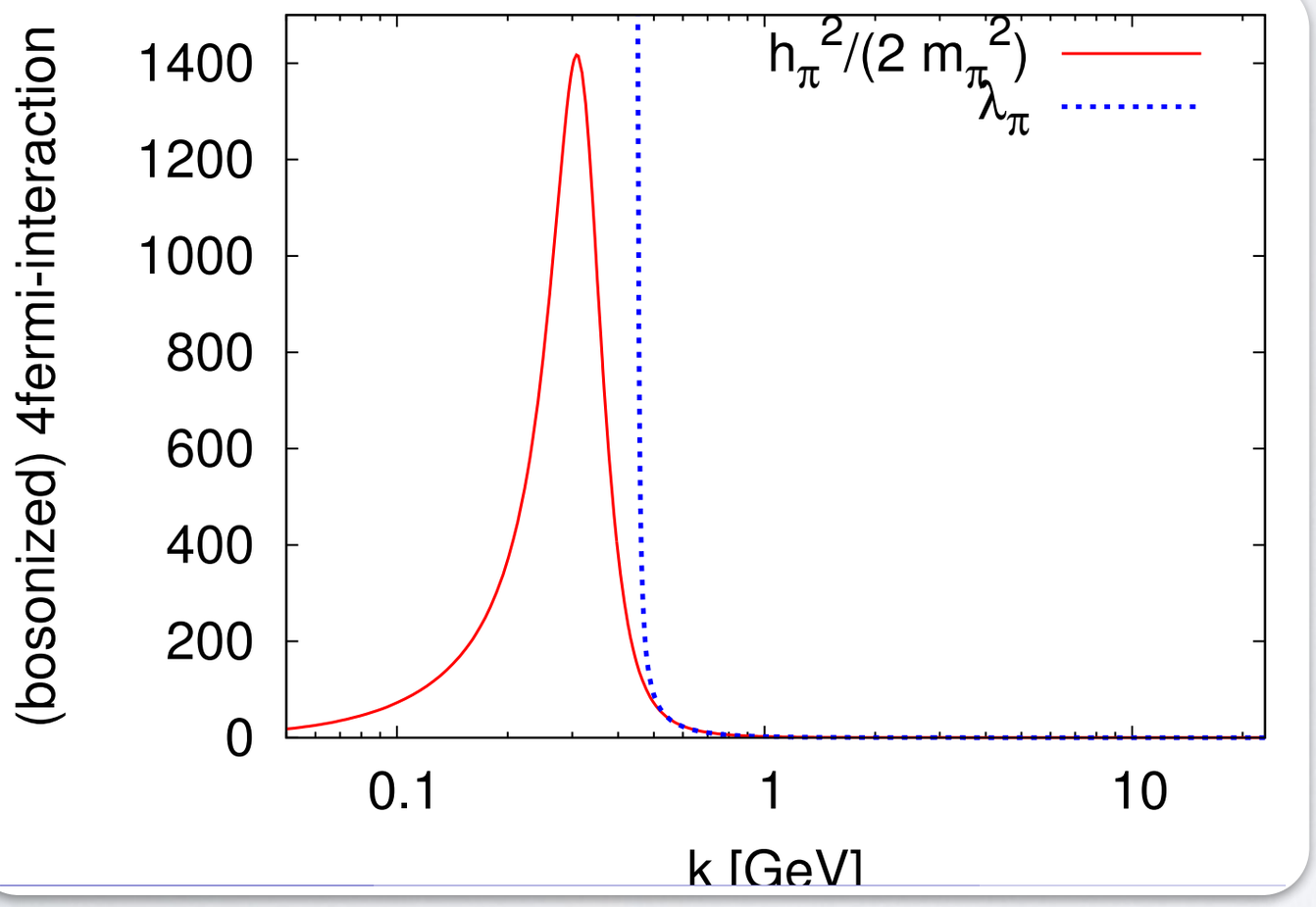
→ 4-quark interaction "absorbed" in hadronization field

→ unified description of both composite and fundamental fields

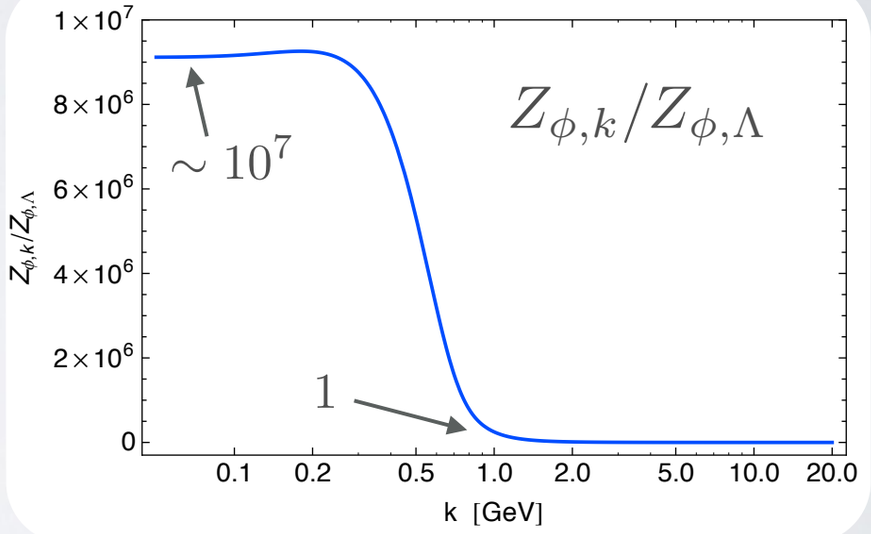
DYNAMICAL HADRONIZATION

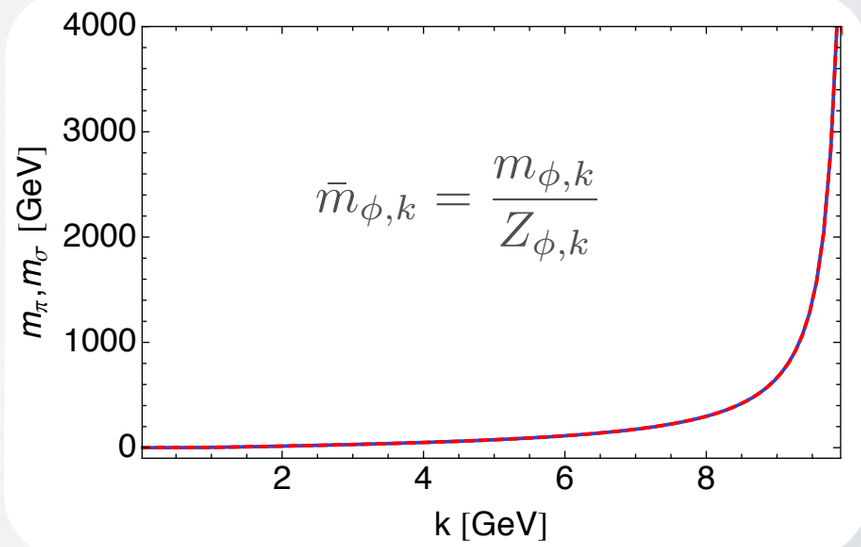
- fix flow of hadronization field

$$\partial_t \lambda_{\psi,k} = \partial_t \lambda_{\psi,k}\big|_{\phi_k} + 2h_k \dot{A}_k \stackrel{!}{=} 0 \quad \longrightarrow \quad \partial_t h_k = \partial_t h_k\big|_{\phi_k} - \frac{m^2_{\pi,k}}{2h_k} \partial_t \lambda_{\psi,k}\big|_{\phi_k}$$



[M. Mitter, J. M. Pawlowski, N. Strodhoff]



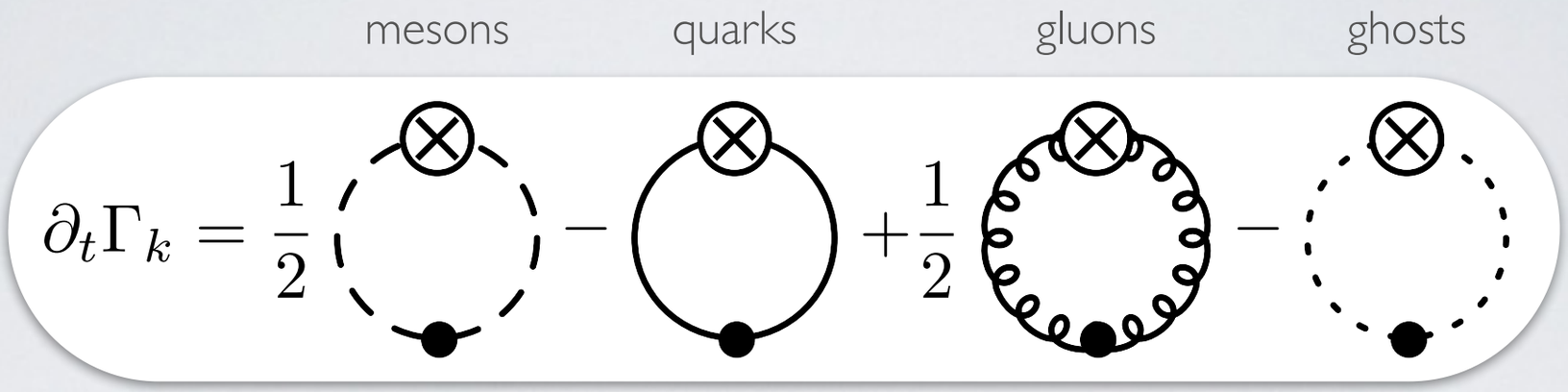


CHIRAL SYMMETRY BREAKING IN QCD

c.f. talk by Mario Mitter

FRG FOR QCD

- QCD flow:



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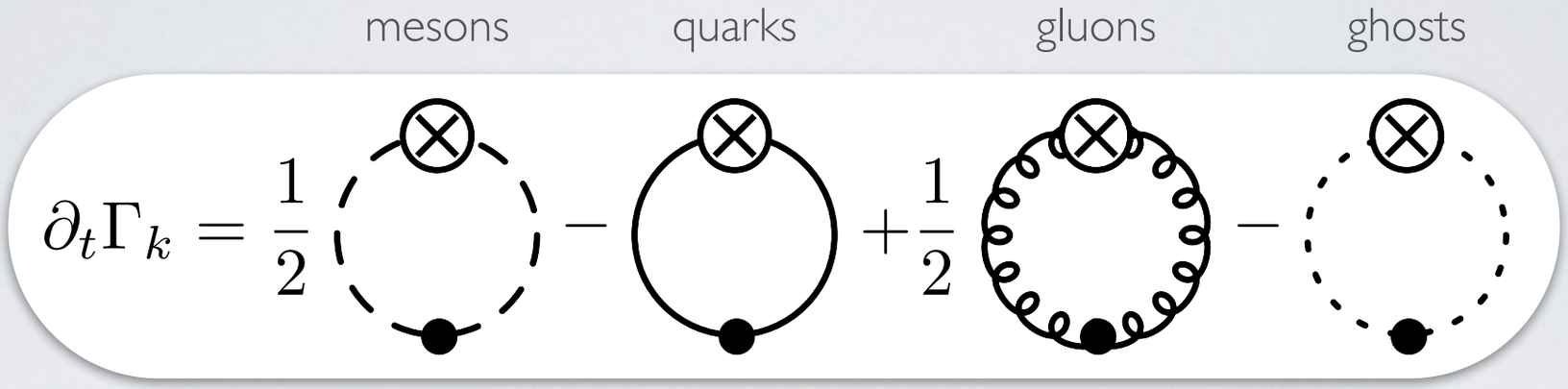
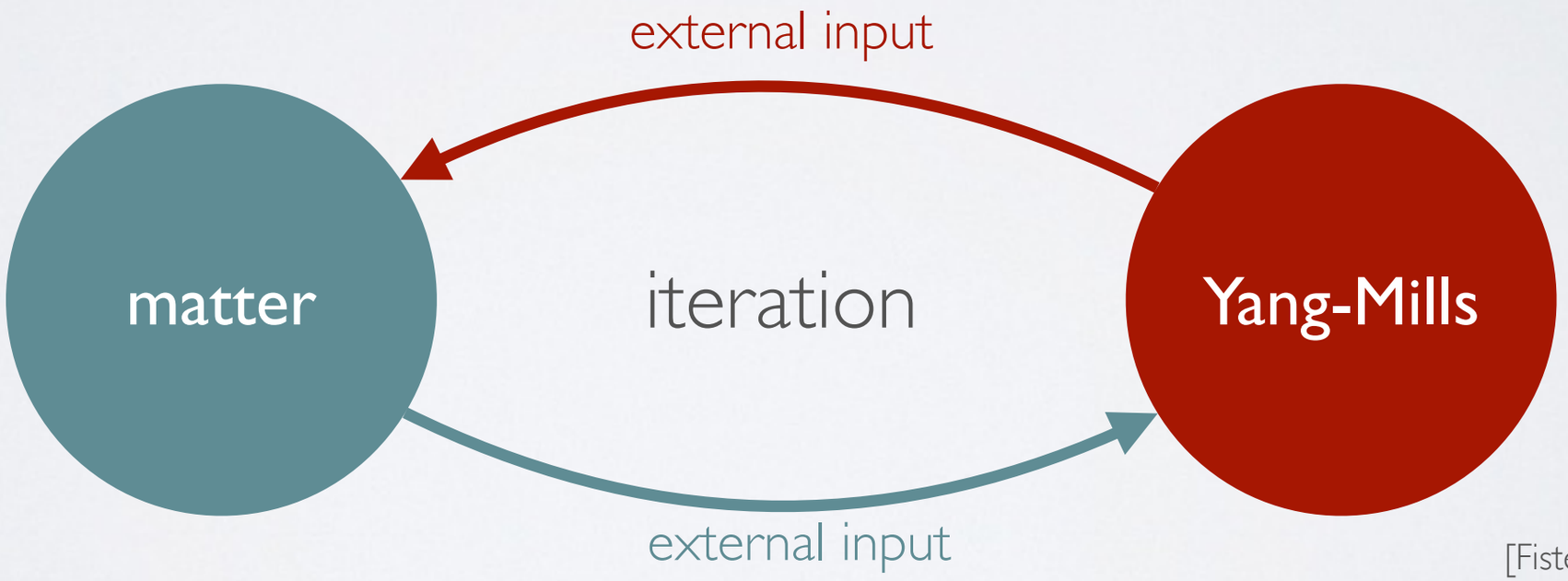


- strategy:



[Fister, Pawlowski]

- aim: start with strong coupling as only free parameter at perturbative scale - predict IR-observables

FRG FOR QCD (ZEROTH ITERATION)

- truncation:

Leo Fister

$$\Gamma_k = \int_x \left\{ \frac{1}{4} F^a_{\mu\nu} F^a_{\mu\nu} + \bar{C}^a \partial_\mu D^{ab}_\mu C^b + \frac{1}{2\xi} (\partial_\mu A^a_\mu)^2 \right\} + \Delta\Gamma_{\text{glue}}$$
$$+ \int_x \left\{ Z_{\psi,k}\, \bar{\psi} \left[i\gamma_\mu (\partial_\mu - i g_k A_\mu) \right] \psi + \frac{\lambda_{\psi,k}}{2} \left[(\bar{\psi}\psi)^2 - (\bar{\psi}\gamma_5 \vec{\tau}\psi)^2 \right] \right.$$
$$\left. + h_k(\phi^2) \left[\bar{\psi} (\gamma_5 \vec{\tau}\vec{\pi} + i\sigma)\psi \right] + \frac{1}{2} Z_{\phi,k} (\partial_\mu \phi)^2 + V_k(\phi^2) - c\sigma \right\}$$

FRG FOR QCD (ZEROTH ITERATION)

- truncation:

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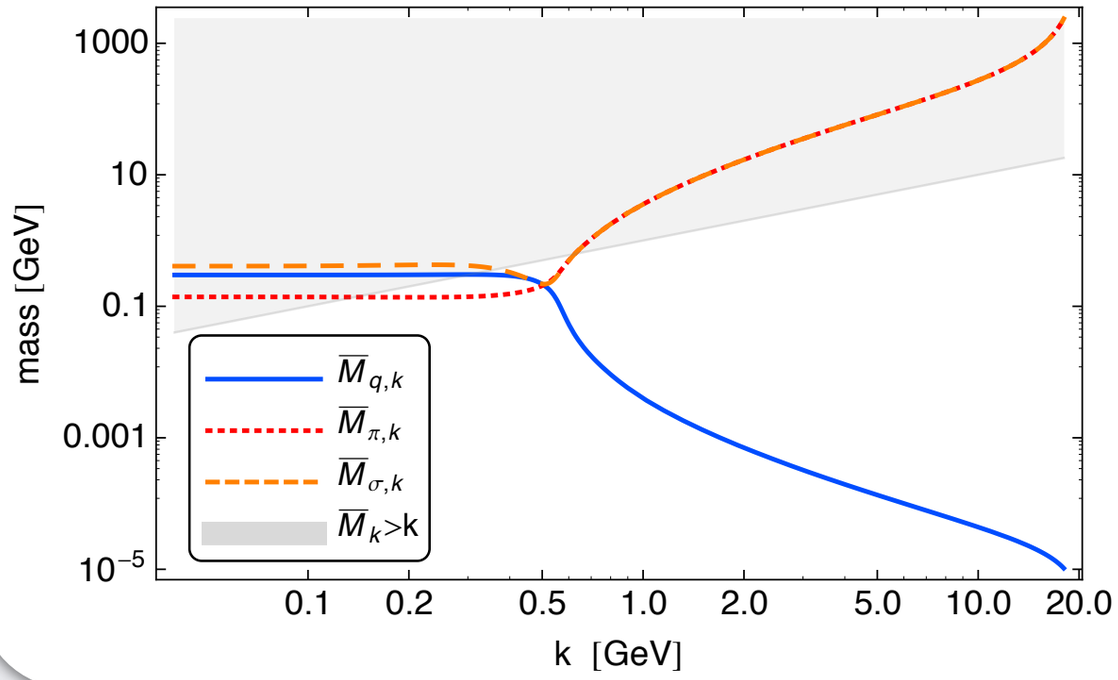
$$\left. + h_k(\phi^2) \left[\bar{\psi} (\gamma_5 \vec{\tau}\vec{\pi} + i\sigma)\psi \right] + \frac{1}{2} Z_{\phi,k} (\partial_\mu \phi)^2 + V_k(\phi^2) - c\sigma \right\}$$

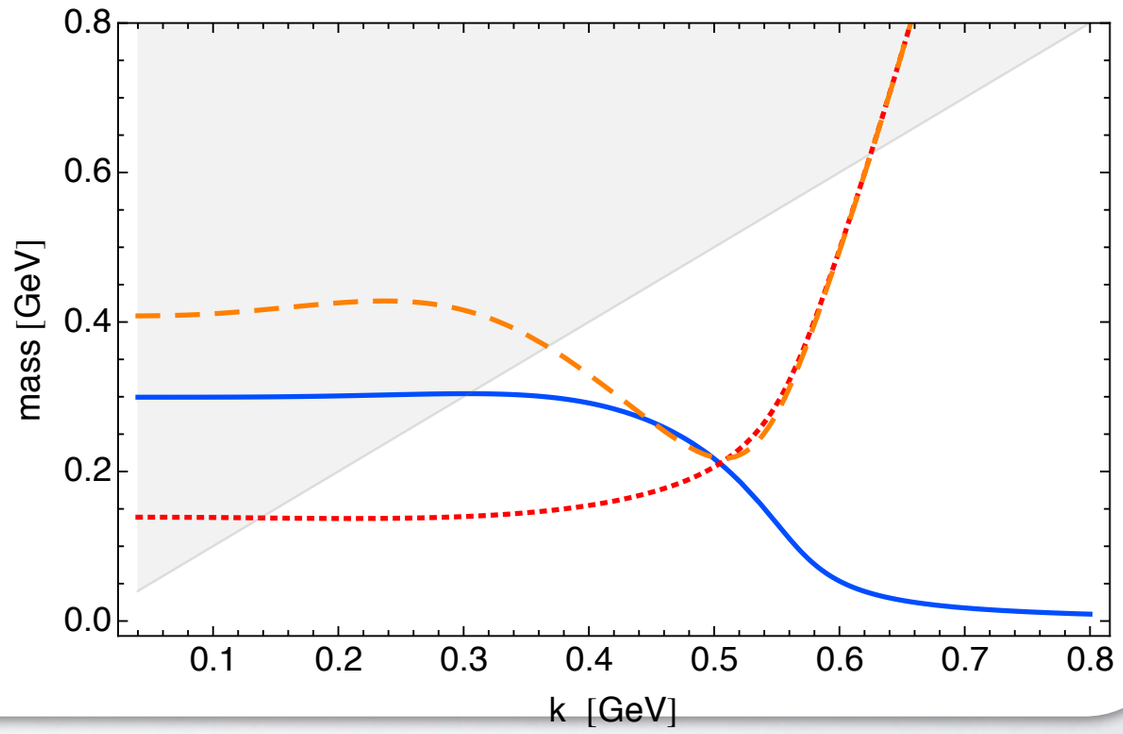
better: Marios talk

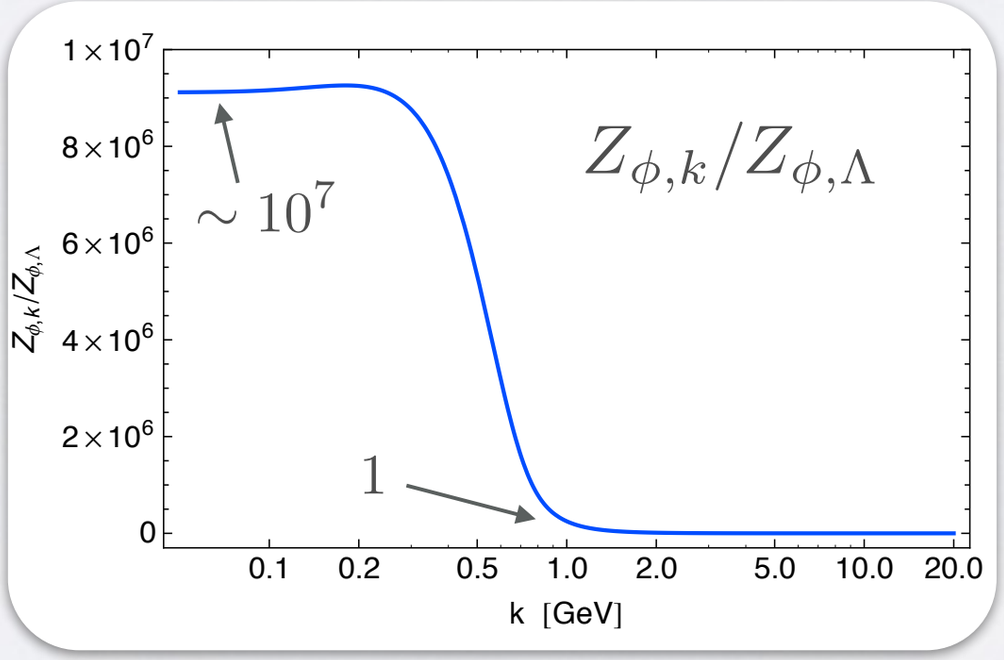
  - 2 quark flavors
  - O(4) approximation with explicit symmetry breaking $c \sim M_{\text{current}}$
  - scalar-pseudoscalar channel: pions and sigma meson $\phi = \begin{pmatrix} \vec{\pi} \\ \sigma \end{pmatrix}$
  - wave function renormalizations
  - field-dependent effective potential and Yukawa coupling
  - vacuum (for now)
  - sharp regulator: $R_k(p^2) \sim \left(k^2 - p^2\right) \Theta(k^2 - p^2)$
  - point-like limit: no explicit momentum dependence of vertices (only k-dep.)

RESULTS

- fix strong coupling and current quark mass at $\Lambda = 20\,\mathrm{GeV}$

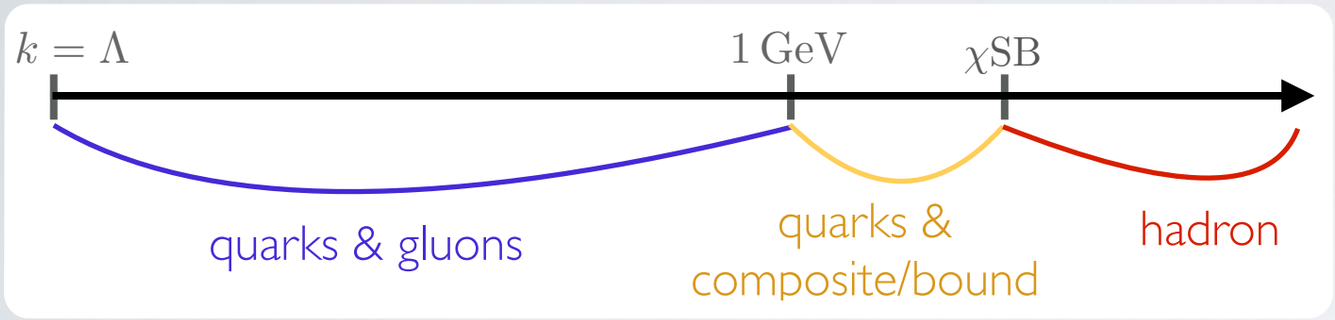




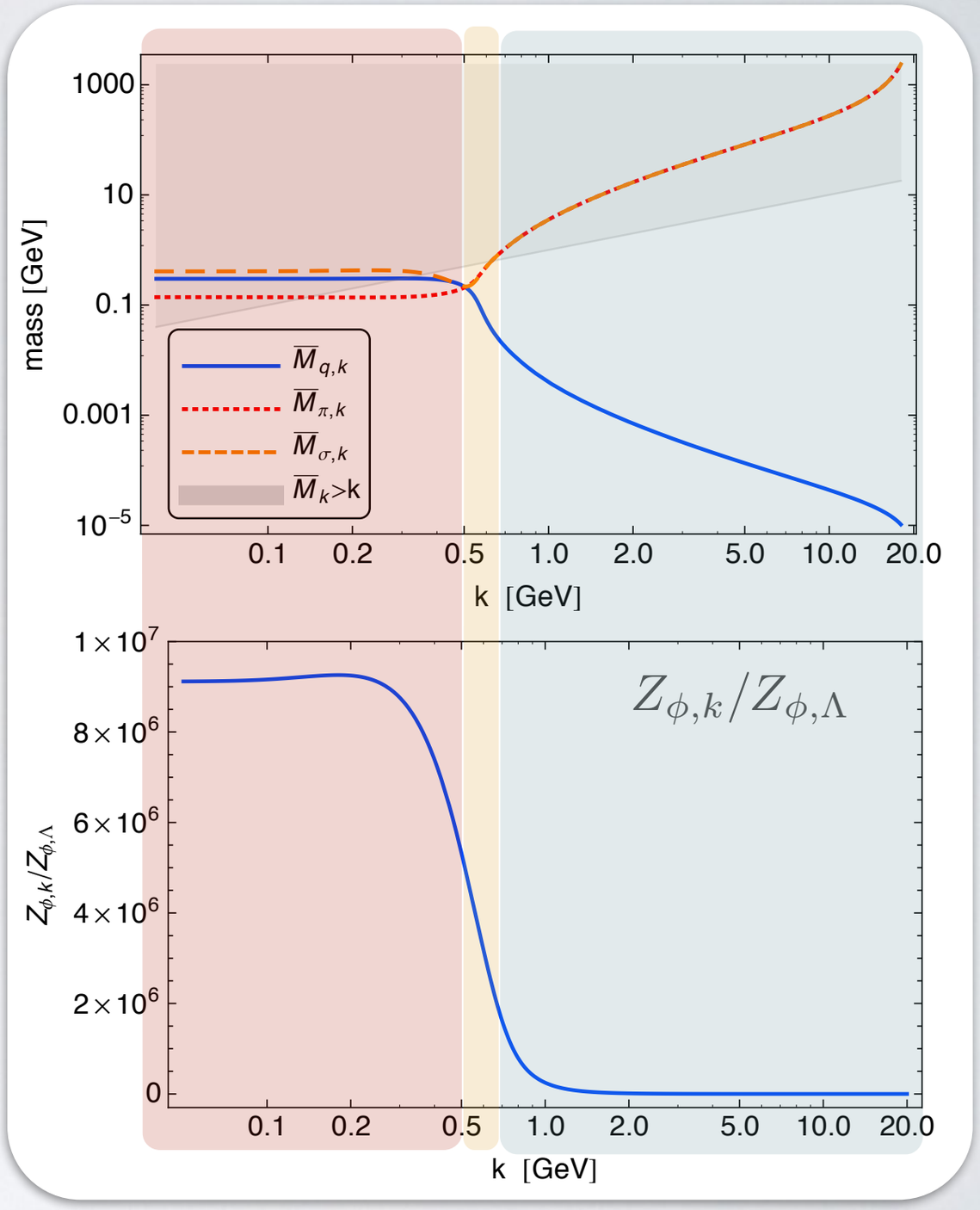


RESULTS

- RG evolution from UV to IR:

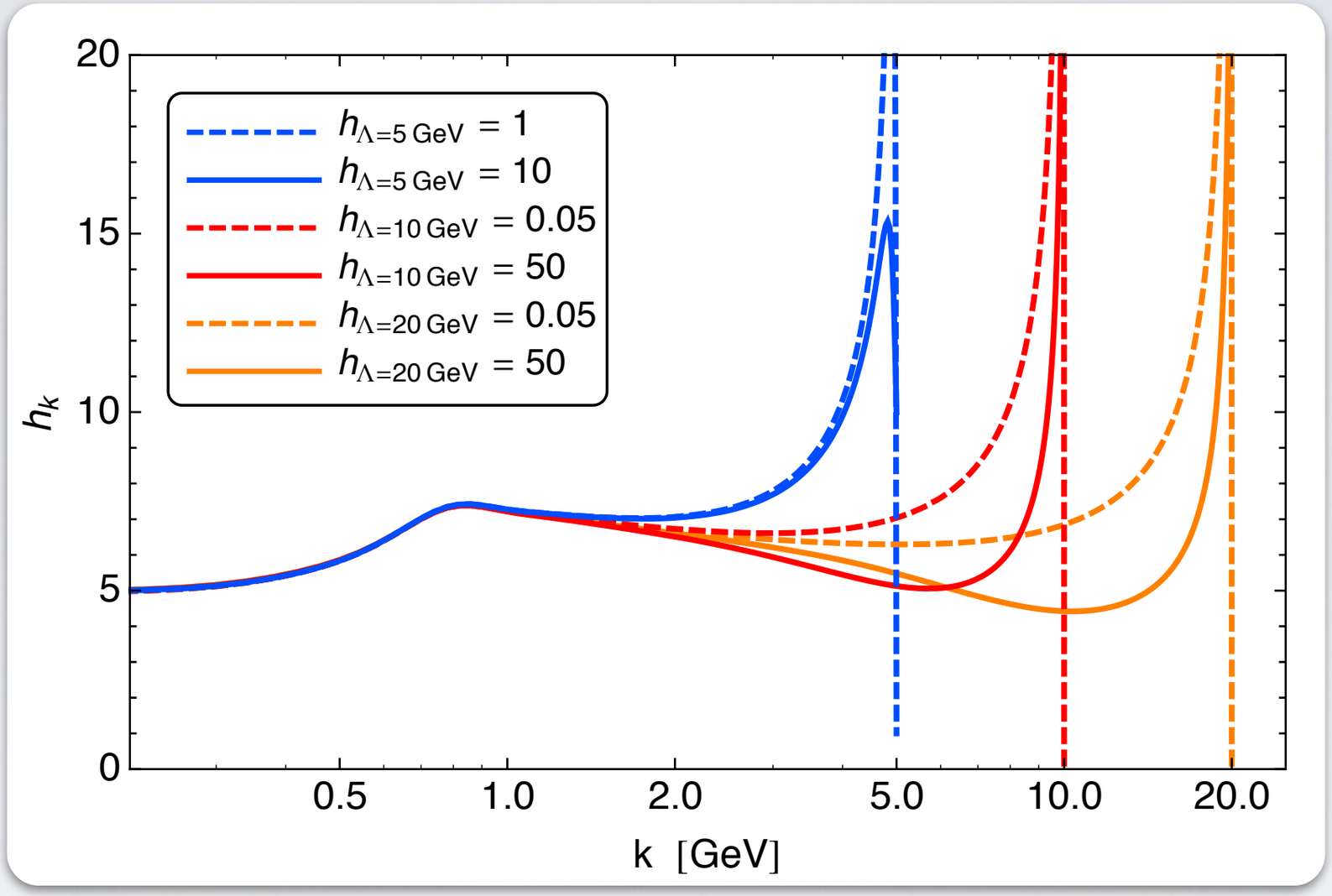


⟶ unified description via ϕ_k



RESULTS

- Low energy models fixed from QCD



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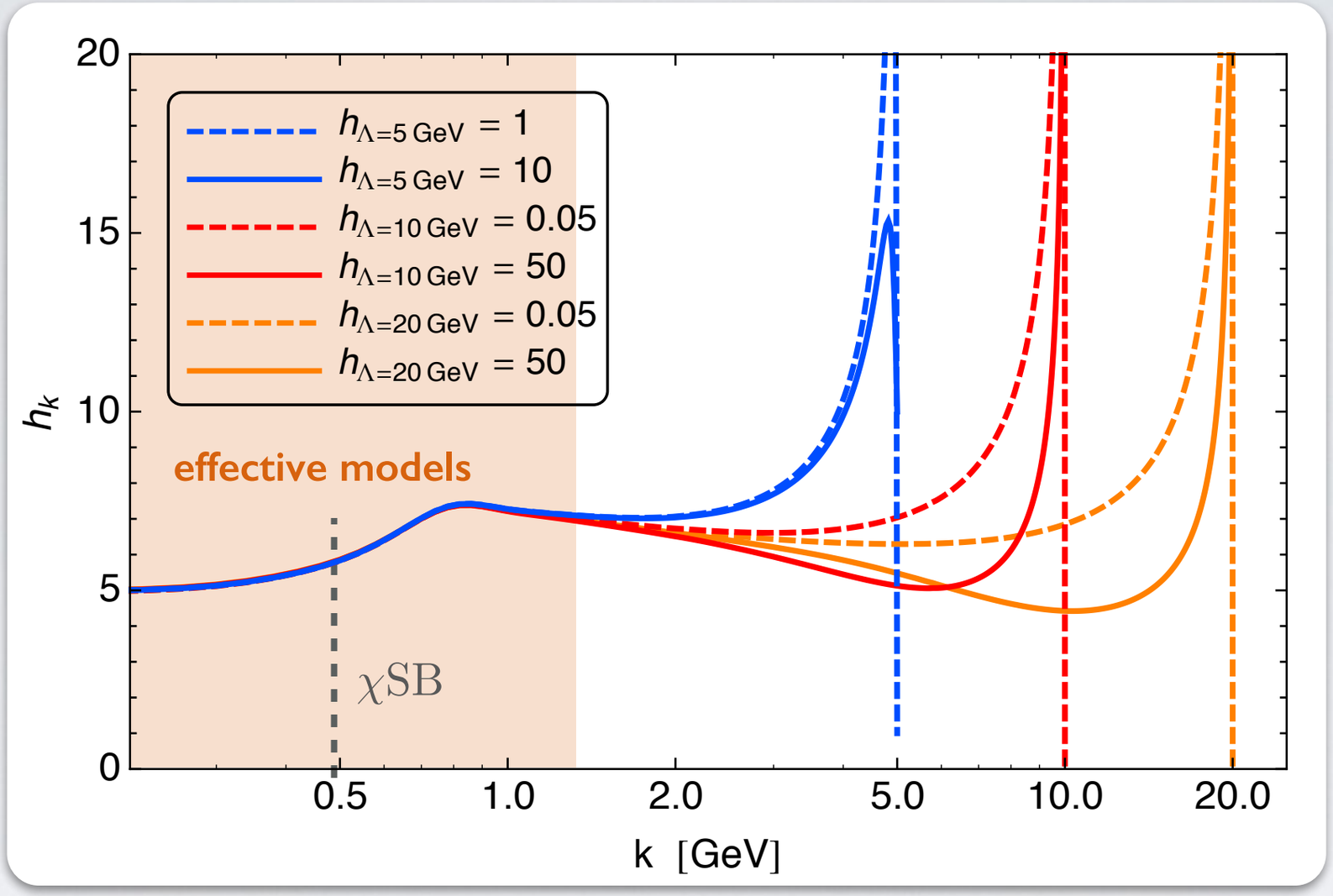


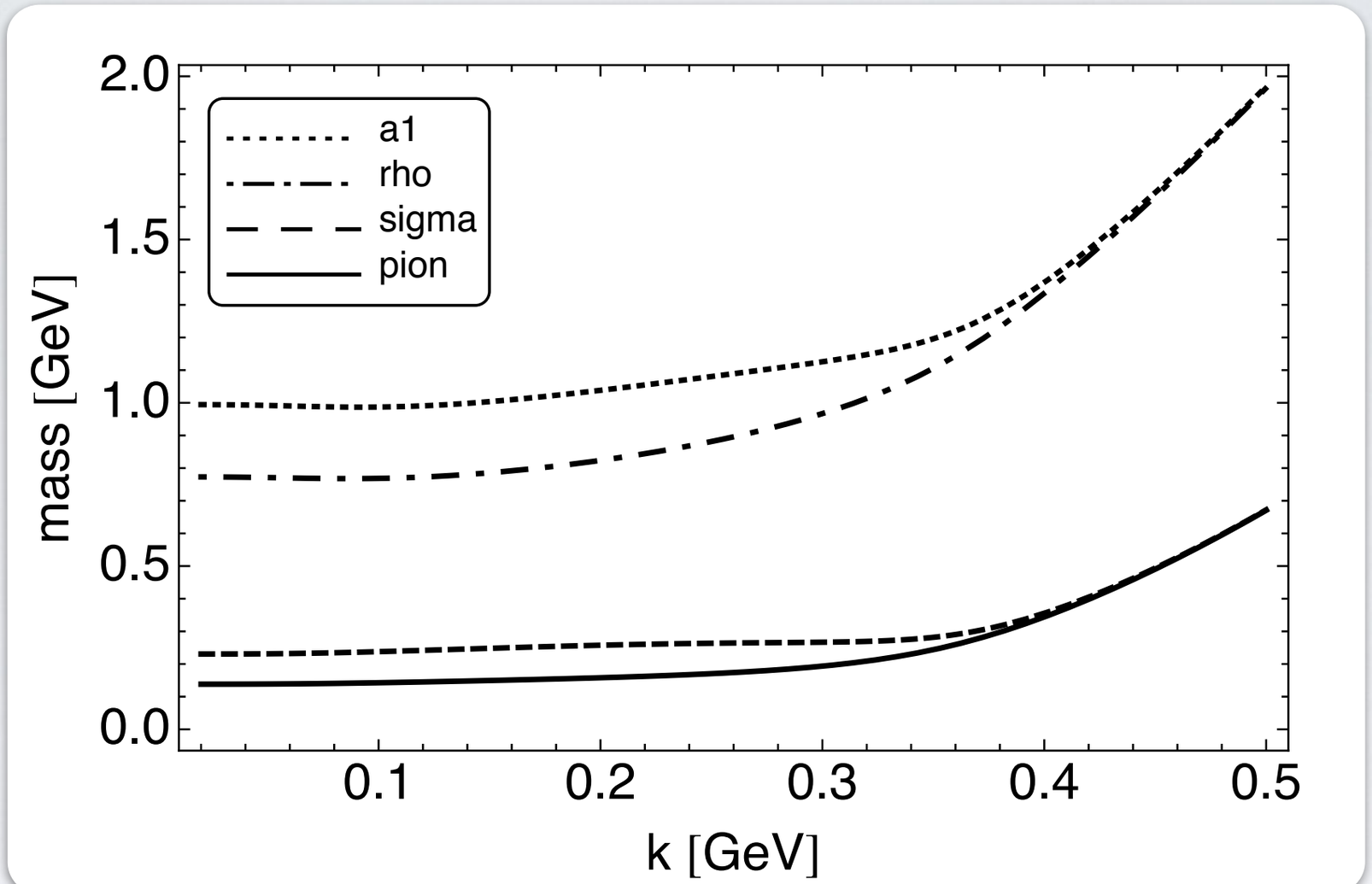
→ system in the UV is driven into stable solution (for not too small UV-cutoff)

→ initial parameters of effective low-energy model fixed from microscopic QCD

OUTLOOK: VECTOR MESONS

with Rob Pisarski

- heavier mesons fixed from pion & sigma dynamics (in vacuum)
- $\pi - a_1$ mixing: scale dependent $a_1 = a_{1,k}$



- behavior of vector mesons close to the chiral transition? (Brown-Rho scaling?, dilepton spectra…)

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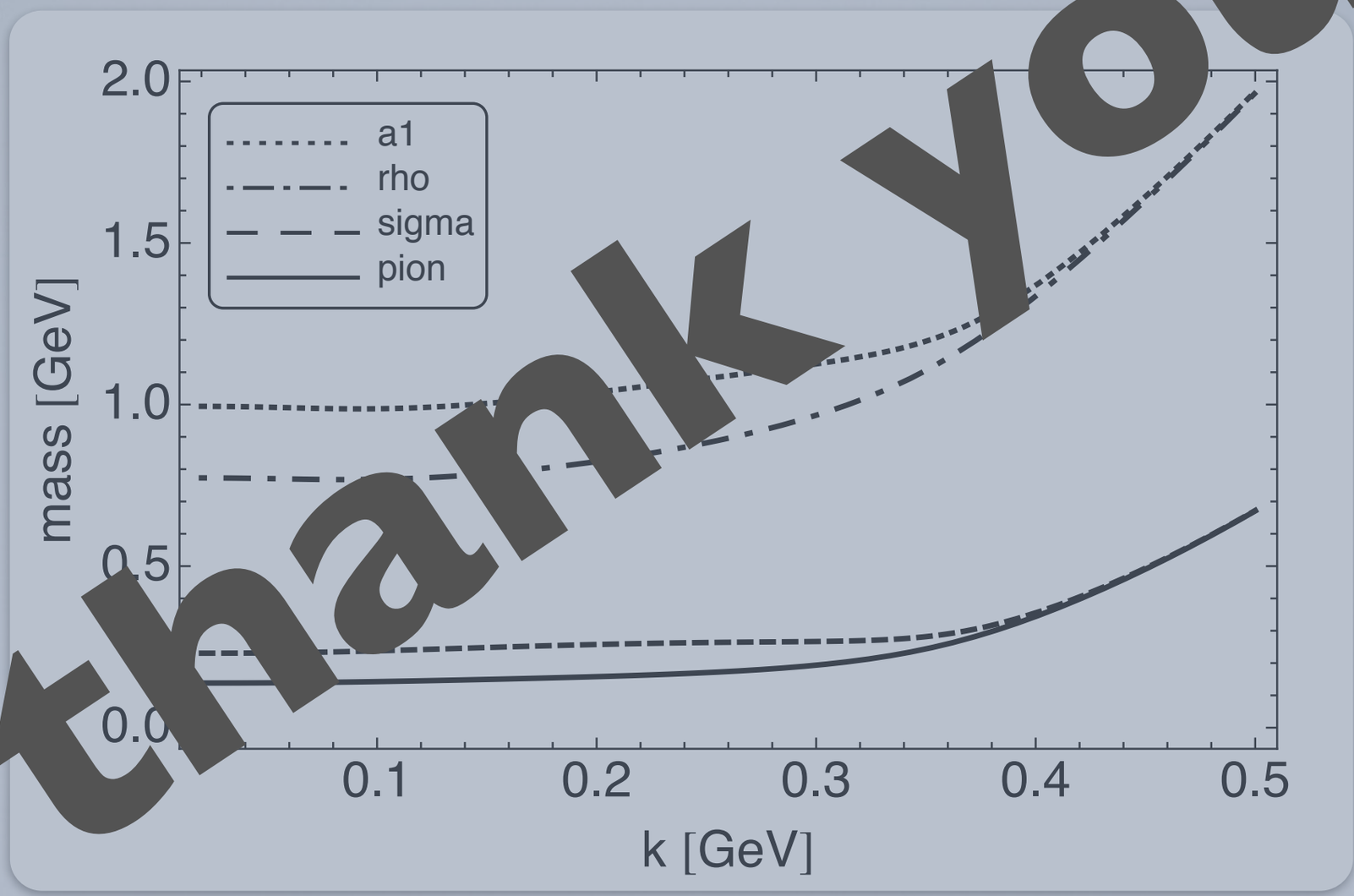

thank you

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