IN-MEDIUM SPECTRAL FUNCTIONS OF VECTOR- AND AXIAL-VECTOR MESONS

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[Jung, FR, Tripolt, von Smekal, Wambach, hep-ph/1610.08754]
[FR, hep-ph/1504.03585]

BROOKHAVEN NATIONAL LABORATORY

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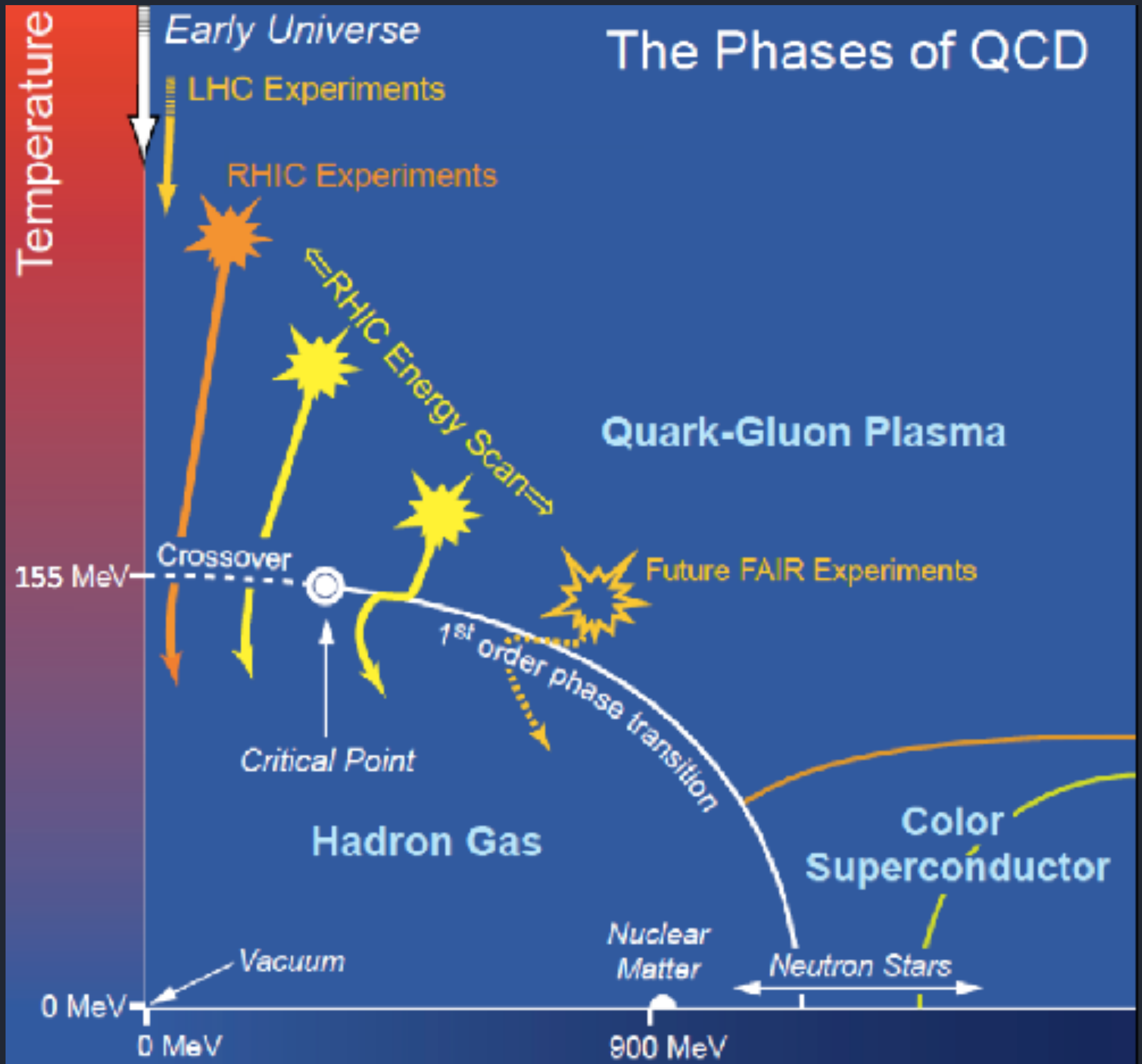
OUTLINE

- Chiral symmetry restoration, dilepton spectra & vector mesons
- Spectral functions from the functional renormalization group
- (Axial) vector meson spectral functions in the medium
- Beyond low-energy modeling: dynamical hadronization

QCD PHASE DIAGRAM



[Hot QCD White Paper (2015)]

<u>Theory</u>

compute order parameters

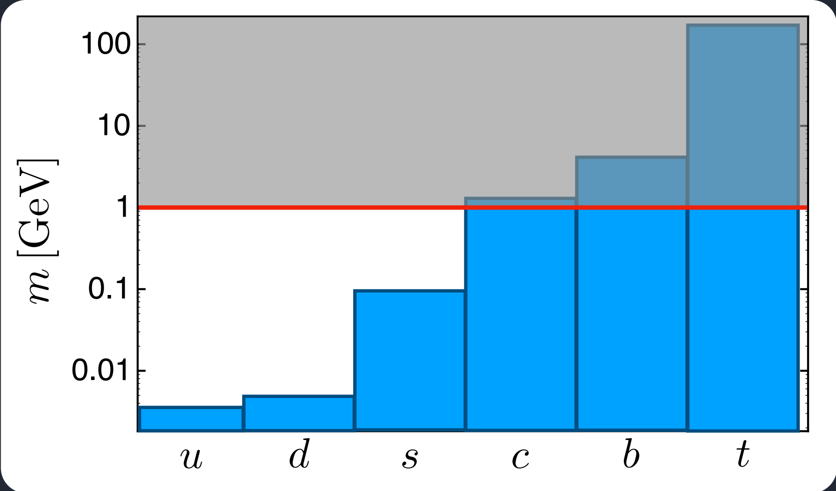
- confinement: $L = \dfrac{1}{N_c}\left\langle \mathrm{Tr}_f \mathcal{P}\, e^{ig\int_0^\beta d\tau A_0(\tau)} \right\rangle$
- χSB: $\langle \bar{q}q \rangle = \langle \bar{q}_L q_R + \bar{q}_R q_L \rangle$

<u>Experiment</u>

measure hadronic final states

⟶ phase transitions difficult to grasp!

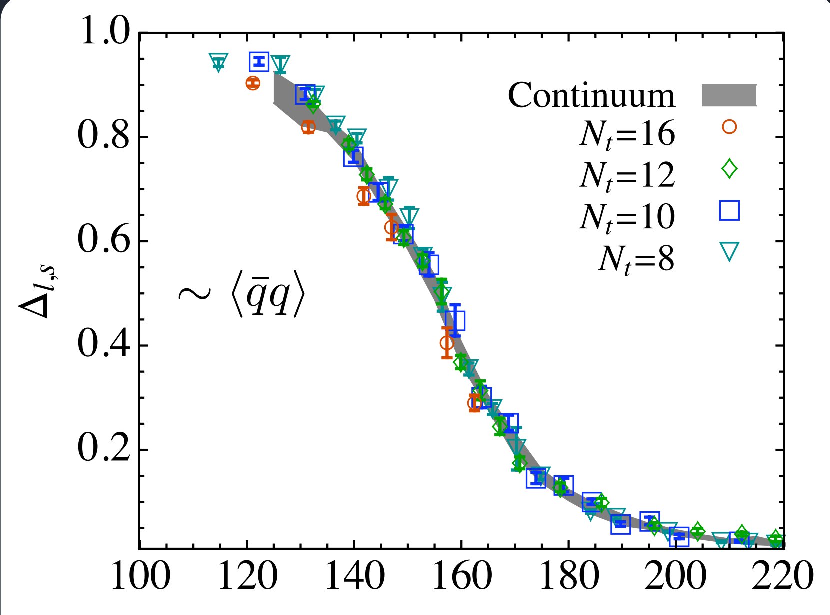
CHIRAL SYMMETRY BREAKING



- 3 (2) (super) light quark flavors

  ⟶ approximate QCD flavor symmetry:

$$SU(3)_L \times SU(3)_R$$



[WB, hep-lat/1005.3508]

- spontaneous symmetry breaking down to $SU(3)_{L+R}$

  ⟶ origin of hadron masses

  - 8 light pseudoscalar mesons π, K, η (pseudo Goldstones)
  - nucleon masses via coupling to chiral condensate
  - mass-splitting of chiral partners …

But: no experimental verification of chiral symmetry restoration in QGP yet!

DILEPTON SPECTRA

How to observe chiral symmetry restoration?

- dileptons escape fireball essentially without interaction

  ⟶ ideal probes for high T/mu regions formed in early stages of collisions

- low- / intermediate-mass regime of dilepton spectra dominated by vector meson decays

$$\frac{dN_{l^+l^-}}{d^4x\, d^4q} \sim \alpha_{\mathrm{EM}}^2\, \rho_{\mathrm{EM}} \overset{\mathrm{VMD}}{\sim} \alpha_{\mathrm{EM}}^2 \left(\rho_\rho + \frac{1}{9}\rho_\omega + \frac{2}{9}\rho_\phi\right)$$

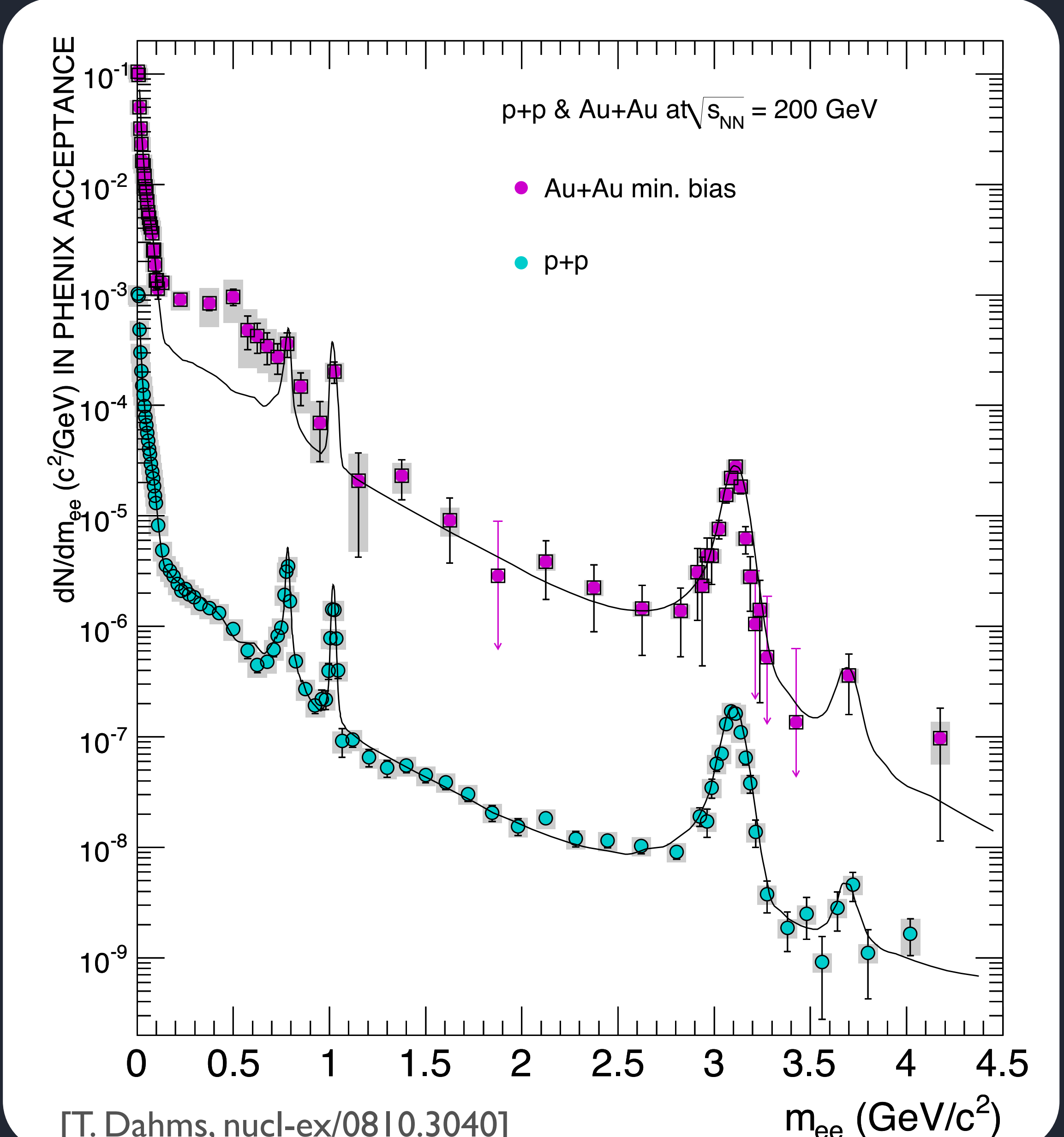
[Feinberg (\`76), McLerran, Toimela (\`85), Weldon (\`90)]
[Sakurai (\`69)]

- in-medium modification of rho-peak

  ⟶ chiral transition?

  (proposed by Pisarski in \`81)

- suggestions:
  - dropping ρ mass at chiral restoration scale [Brown, Rho (\`91)]
  - rising ρ mass [Pisarski (\`95)]
  - melting ρ resonance [Rapp, Wambach (\`99)]



DILEPTON SPECTRA

- melting scenario works well for describing dilepton data!

⟶ connection to χSR?

- Weinberg sum rule:

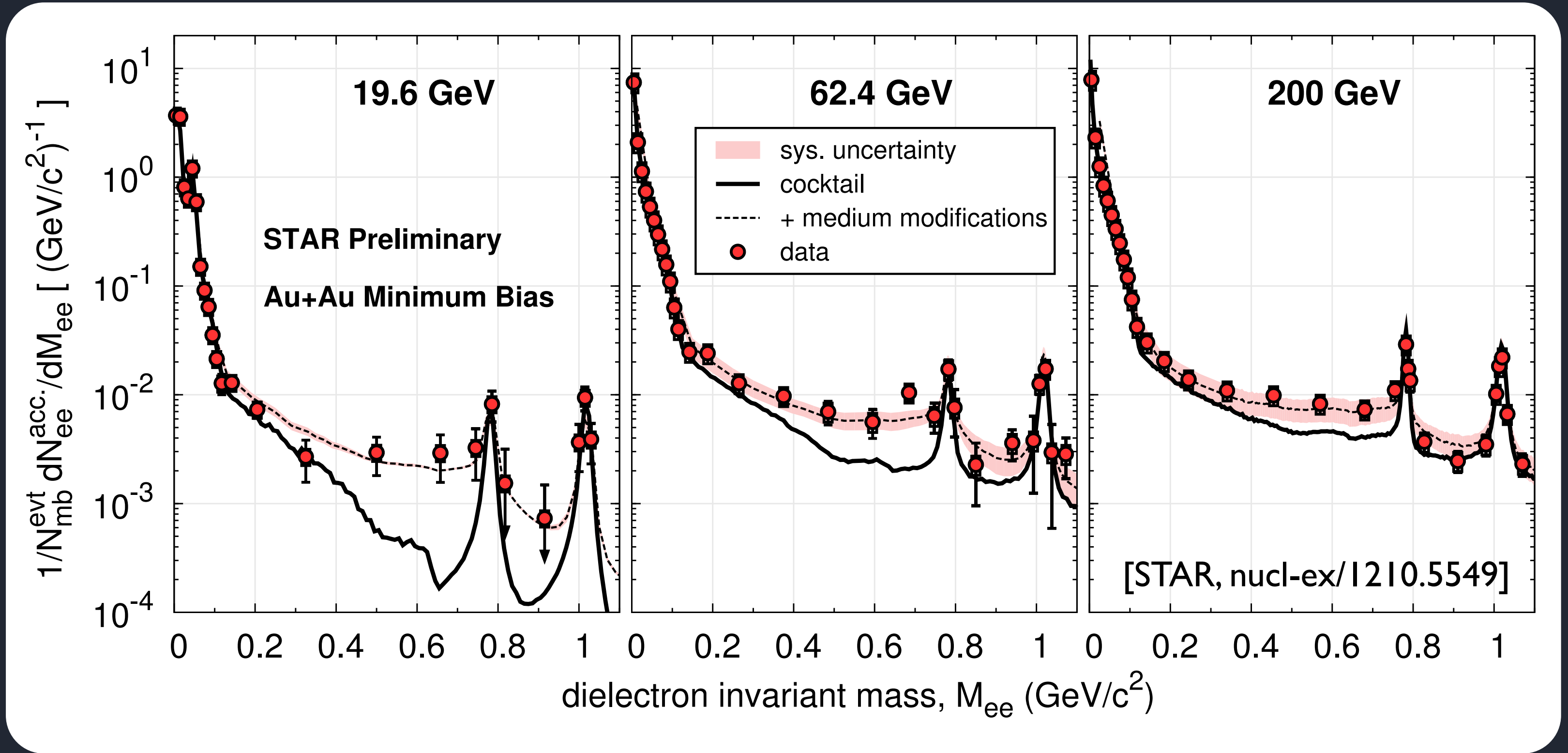
$$\int_0^\infty ds\left[\rho_V(s) - \rho_A(s)\right] = -2m_q\langle\bar{q}q\rangle$$

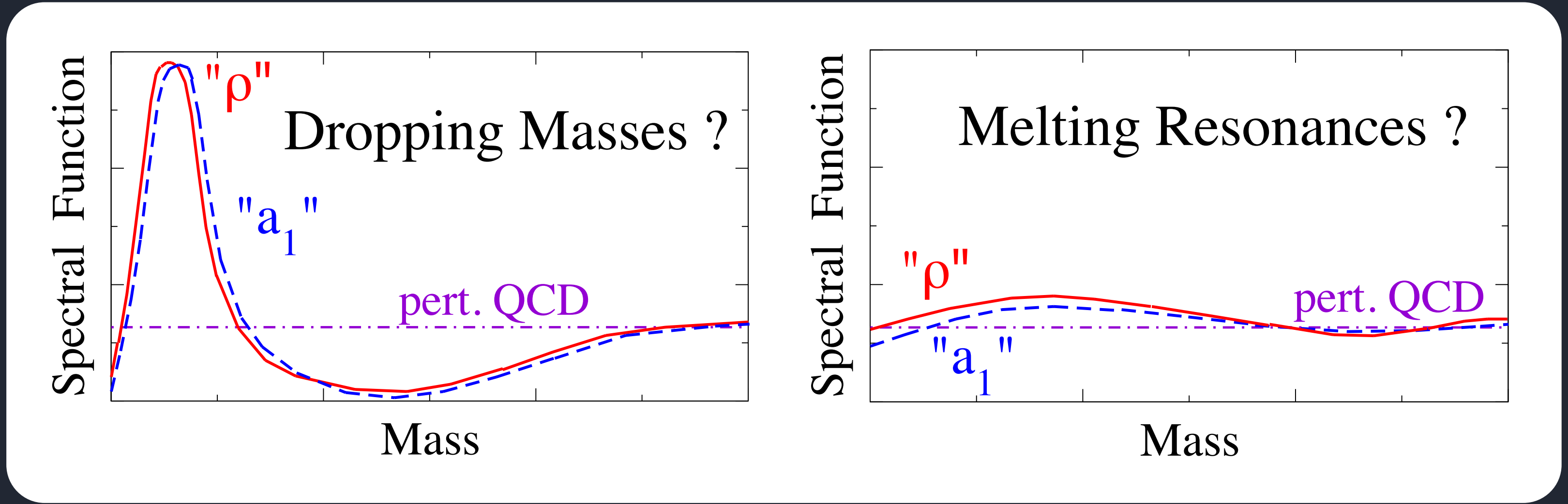
vector & axial-vector spectral functions

chiral condensate

need spectral function of ρ and its chiral partner a_1

⟶ degeneration: χSR!





[Rapp, Wambach, van Hees, hep-ph/0901.3289]

WHAT WE NEED

We need a framework to compute thermodynamic properties / the phase structure and spectral properties on the same footing!

Requirements:

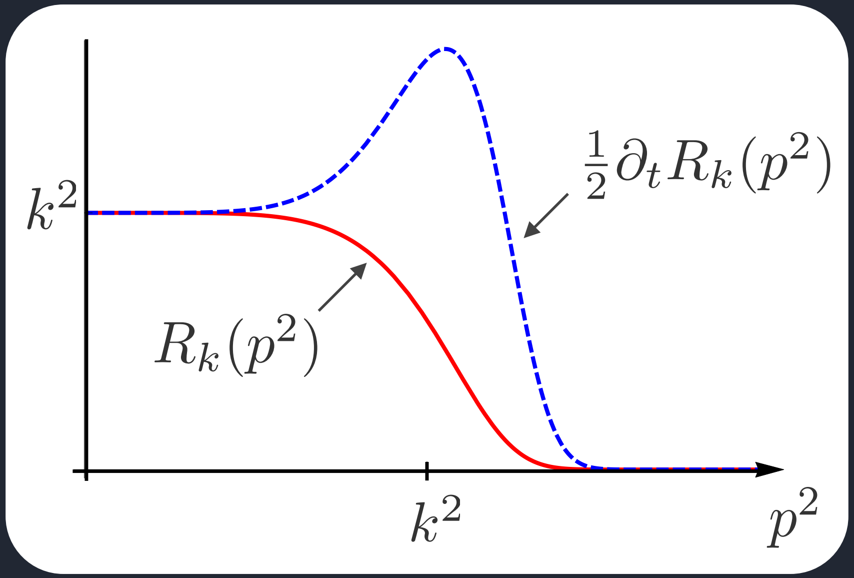
- non-perturbative method to describe QCD at low energies
- capture symmetries and their breaking patterns
- direct access to spectral properties (avoid analytic continuation of numerical data)
- quantum fluctuations (beyond mean-field approximations)
- access to finite μ (no sign problem)

FUNCTIONAL RG

- introduce regulator to partition function to suppress momentum modes below energy scale k (Euclidean space):

$$Z_k[J] = \int \mathcal{D}\varphi \, e^{-S[\varphi]-\Delta S_k[\varphi]+\int_x J\varphi}$$

$$\Delta S_k[\varphi] = \frac{1}{2}\int \frac{d^4q}{(2\pi)^4}\,\varphi(-q)R_k(q)\varphi(q)$$

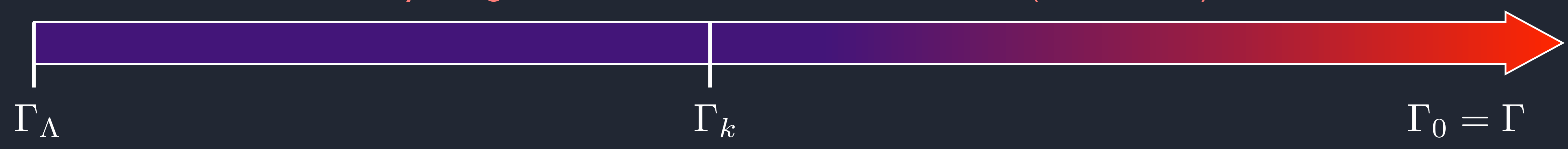


- scale dependent effective action: $\Gamma_k[\phi] = \sup_J \left\{ \int_x J(x)\phi(x) - \ln Z_k[J] \right\} - \Delta S_k[J]$ $\qquad \phi = \langle\varphi\rangle_J$

- evolution equation for Γ_k:
  [Wetterich 1993]

$$\boxed{\partial_t \Gamma_k = \tfrac{1}{2}\mathrm{STr}\left[\left(\Gamma_k^{(2)} + R_k\right)^{-1}\partial_t R_k\right]} \qquad \partial_t = k\frac{d}{dk}$$

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



full quantum effective action (generates 1PI correlators)

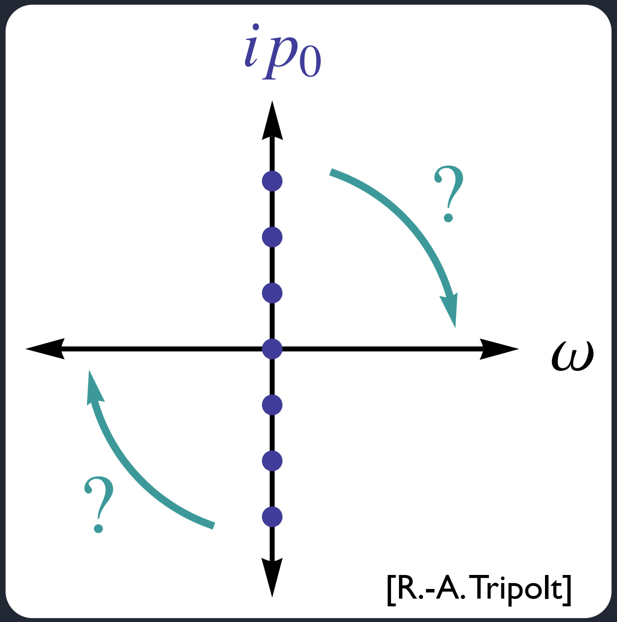
⟶ Γ_k is eff. action that incorporates all fluctuations down to scale k

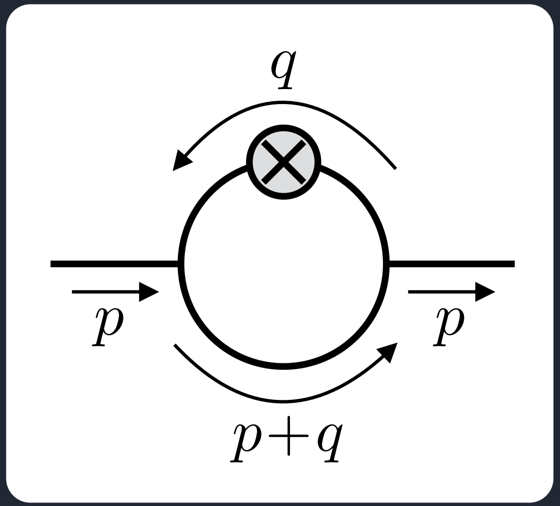
⟶ lowering k: zooming out / coarse graining

ANALYTIC CONTINUATION

- one-loop like structure of the FRG allows for straightforward analytic continuation!

[Floerchinger, hep-ph/1112.4374]
[Tripolt, Strodthoff, von Smekal, J. Wambach, hep-ph/1311.0630]
[Pawlowski, Strodthoff, hep-ph/1508.01160]





1. start from Euclidean spacetime (Matsubara formalism for finite T)

   → Euclidean 2-pt function $\partial_t \Gamma_k^{(2),E}(p_0, \vec{p})$, with $p_0 \sim n \in \mathbb{Z}$

2. exploit the periodicity of the occupation numbers

$$n_{B/F}(E + ip_0) = n_{B/F}(E)$$

3. rotate frequency to the real axis → retarded 2-pt function

$$\partial_t \Gamma_k^{(2),R}(\omega, \vec{p}) = -\lim_{\epsilon \to 0} \partial_t \Gamma_k^{(2),E}\big(p_0 = -i(\omega + i\epsilon), \vec{p}\big)$$

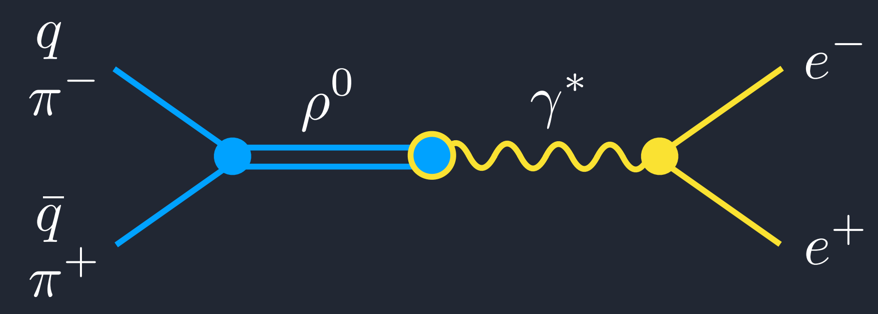
4. spectral function

$$\rho(\omega, \vec{p}) = -\frac{1}{\pi} \mathrm{Im}\, G^R(\omega, \vec{p}) = \frac{1}{\pi} \frac{\mathrm{Im}\, \Gamma^{(2),R}(\omega, \vec{p})}{\left|\Gamma^{(2),R}(\omega, \vec{p})\right|^2}$$

→ direct non-perturbative computation of spectral functions (without sign-problem)

A LOW ENERGY MODEL

- need hadronic electromagnetic current for dilepton spectrum: $\dfrac{dN_{l^+l^-}}{d^4x\, d^4p} \sim \rho_{\rm EM} \sim \langle\, j_{\rm EM}\, j_{\rm EM} \rangle$
- vector meson dominance: $j^\mu_{\rm EM}\Big|_{\rm hadrons} = \dfrac{e}{g}\left(m_\rho^2 \rho^\mu + m_\phi^2 \phi^\mu + m_\omega^2 \omega^\mu\right)$
- VMD can be realized by promoting the flavor symmetry to a gauge symmetry; vector mesons emerge as gauge bosons
  [Sakurai (`60), Kroll, Lee, Zumino (`68), Lee, Nieh (`68)]



- 2 flavor (no Φ) quark-meson model based on VMD (only iso-triplet vector mesons: no ω):

$$\Gamma_k = \int d^4x \Big\{ \bar{q}\big[\gamma_\mu \partial^\mu - \mu\gamma_0 + h_S(\sigma + i\gamma_5 \vec{\tau}\vec{\pi}) + i h_V(\gamma_\mu \vec{\tau}\vec{\rho}^\mu + \gamma_\mu\gamma_5\vec{\tau}\vec{a}_1^\mu)\big] q$$
$$+ U_k(\phi^2) - c\sigma + \frac{1}{2}\big(D_\mu \phi\big)^2 + \frac{1}{8}\mathrm{tr}\, V_{\mu\nu}V^{\mu\nu} + \frac{1}{4} m_V^2\, \mathrm{tr}\, V_\mu V^\mu \Big\} + \Delta\Gamma_{\pi a_1}$$

$$\phi = (\vec{\pi}, \sigma)$$
$$V^\mu = \vec{\rho}^\mu\, \vec{T} + \vec{a}_1^\mu\, \vec{T}^5$$

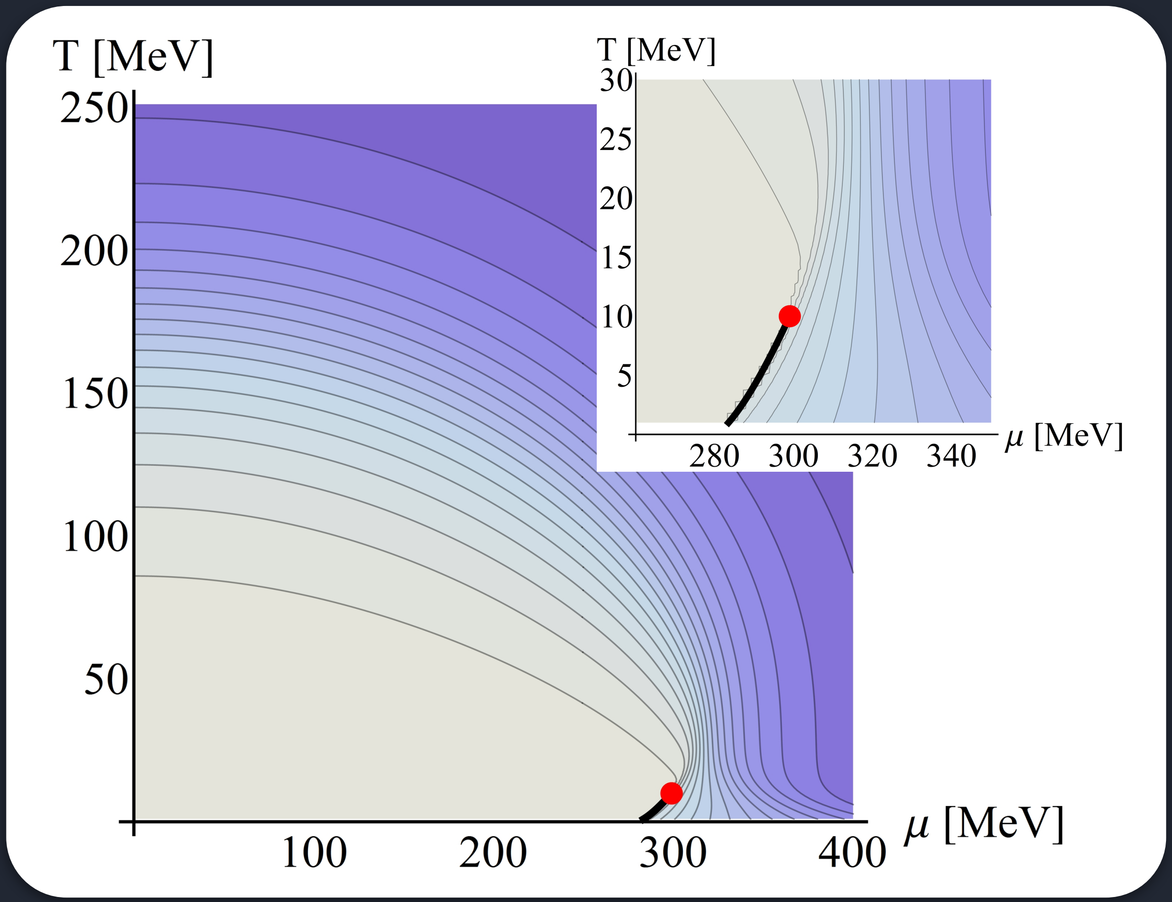
[Jung, FR, Tripolt, von Smekal, Wambach, hep-ph/1610.08754]

- covariant derivative: $\dfrac{1}{2}(D_\mu\phi)^2 = \dfrac{1}{2}(\partial_\mu\phi)^2 - i g_V \partial_\mu \phi \cdot V_\mu \phi - \dfrac{g_V^2}{2}(V_\mu\phi)\cdot(V_\mu\phi)$
- field strength: $\dfrac{1}{8}\mathrm{tr}\, V_{\mu\nu}V_{\mu\nu} = \dfrac{1}{8}\mathrm{tr}\,(\partial_\mu V_\nu - \partial_\nu V_\mu)^2 - \dfrac{i g_V}{2}\mathrm{tr}\, \partial_\mu V_\nu\, [V_\mu, V_\nu] - \dfrac{g_V^2}{8}\mathrm{tr}\, [V_\mu, V_\nu]^2$

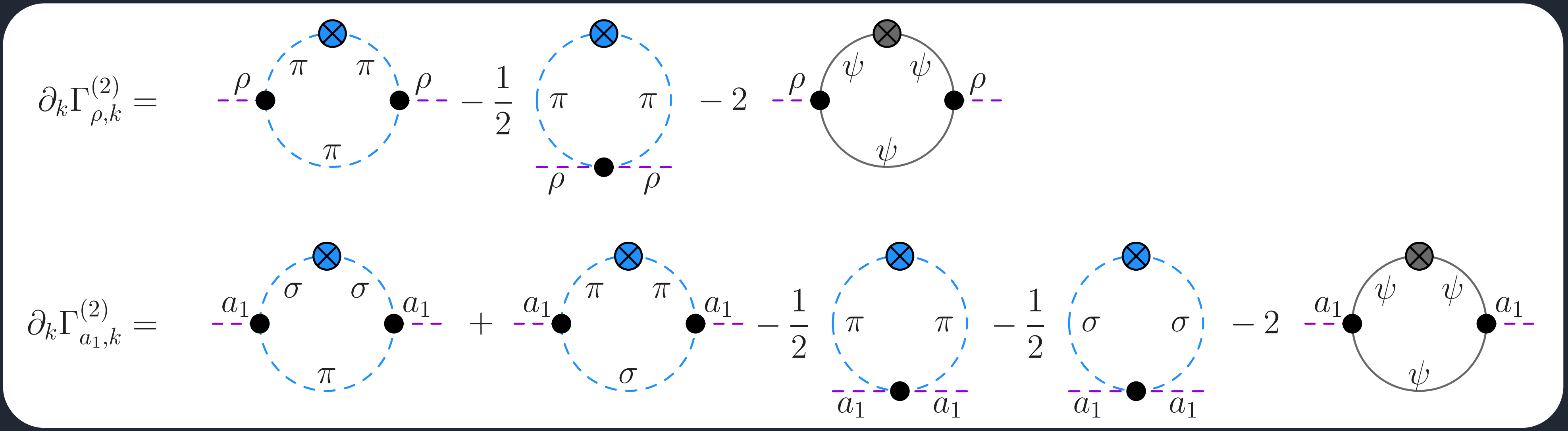
A LOW ENERGY MODEL

[Jung, FR, Tripolt, von Smekal, Wambach, hep-ph/1610.08754]

phase diagram:



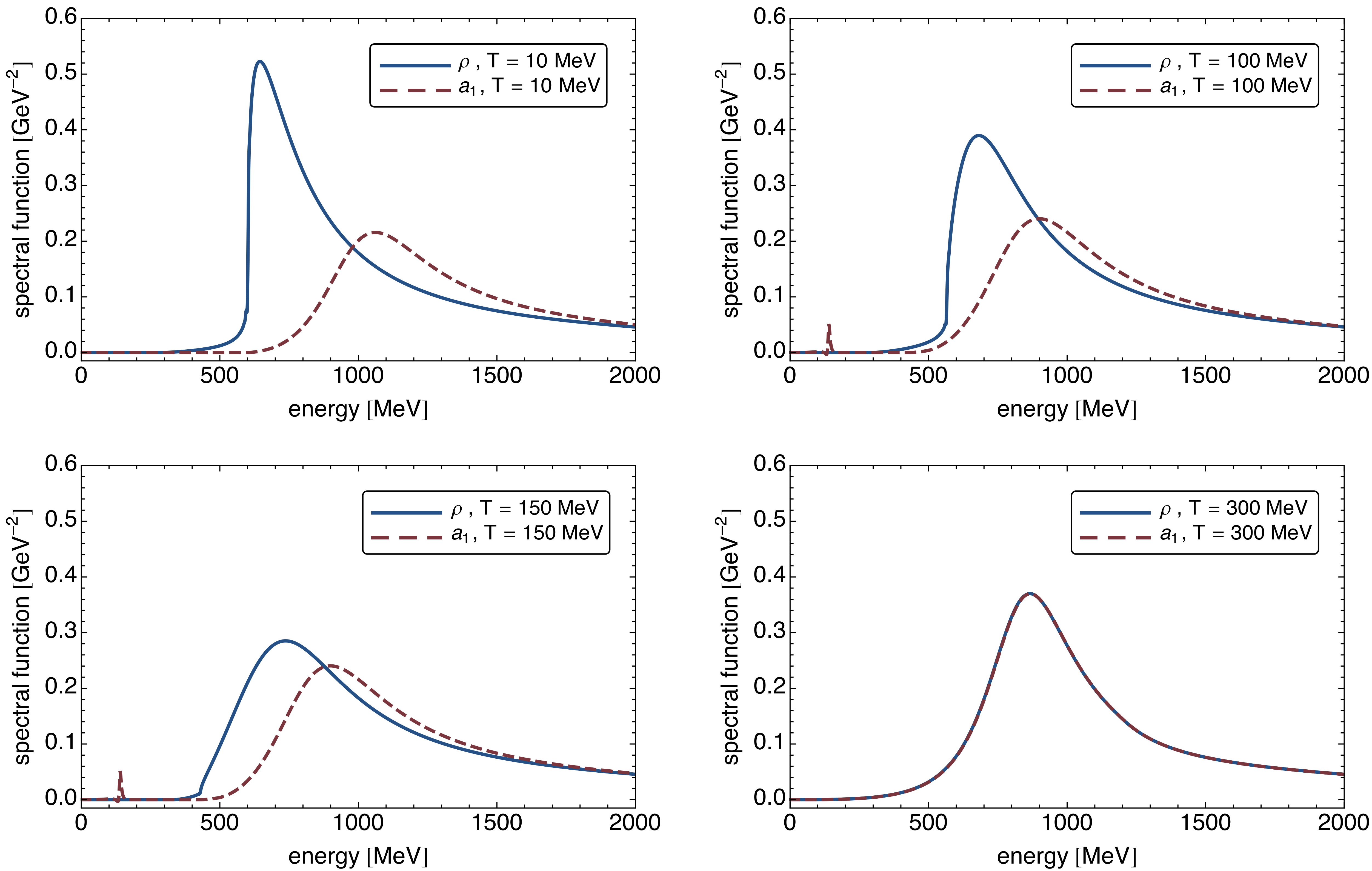
RG flow of the two-point functions:



approx.: no internal vector mesons

SPECTRAL FUNCTIONS

[Jung, FR, Tripolt, von Smekal, Wambach, hep-ph/1610.08754]



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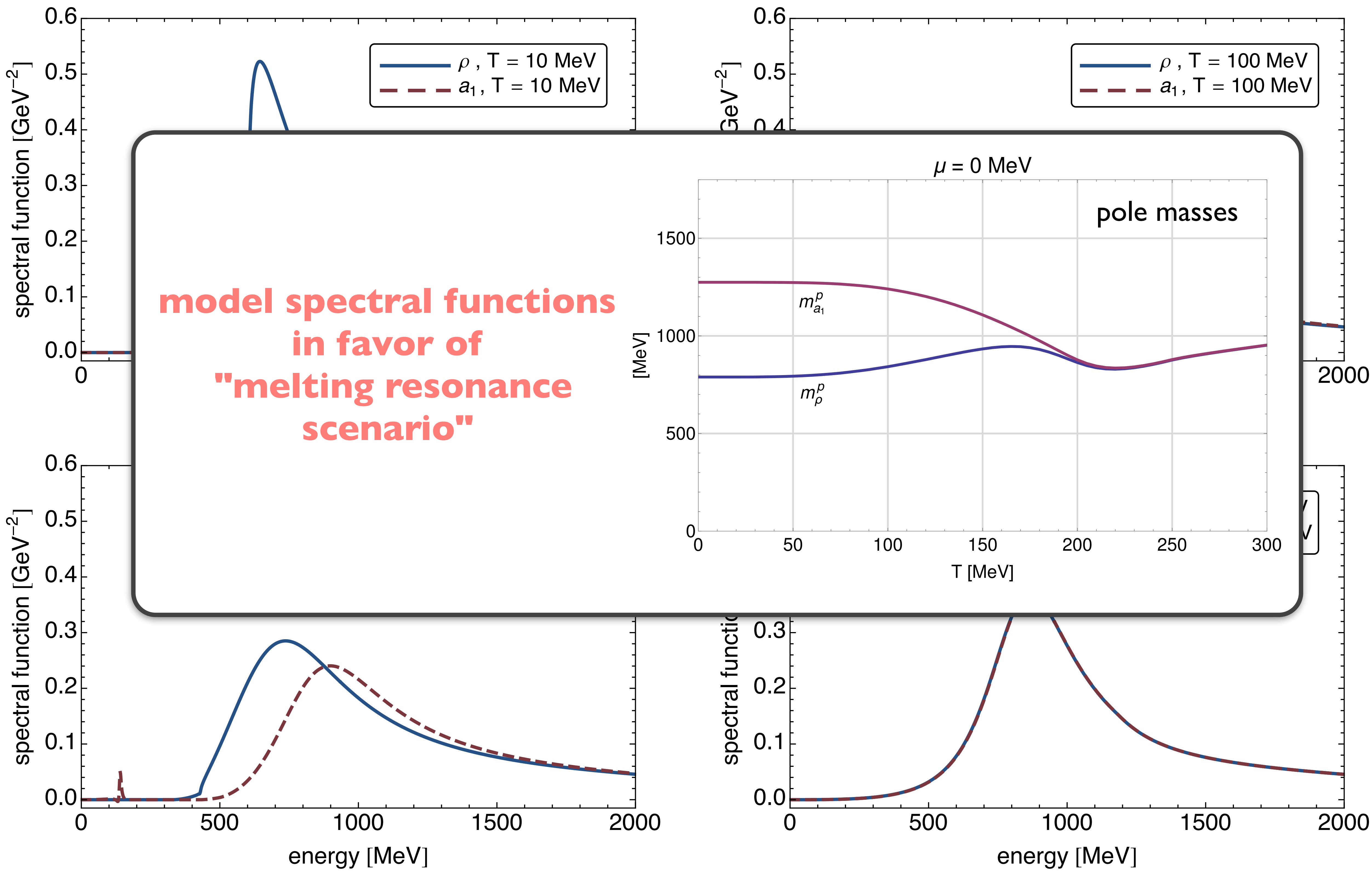
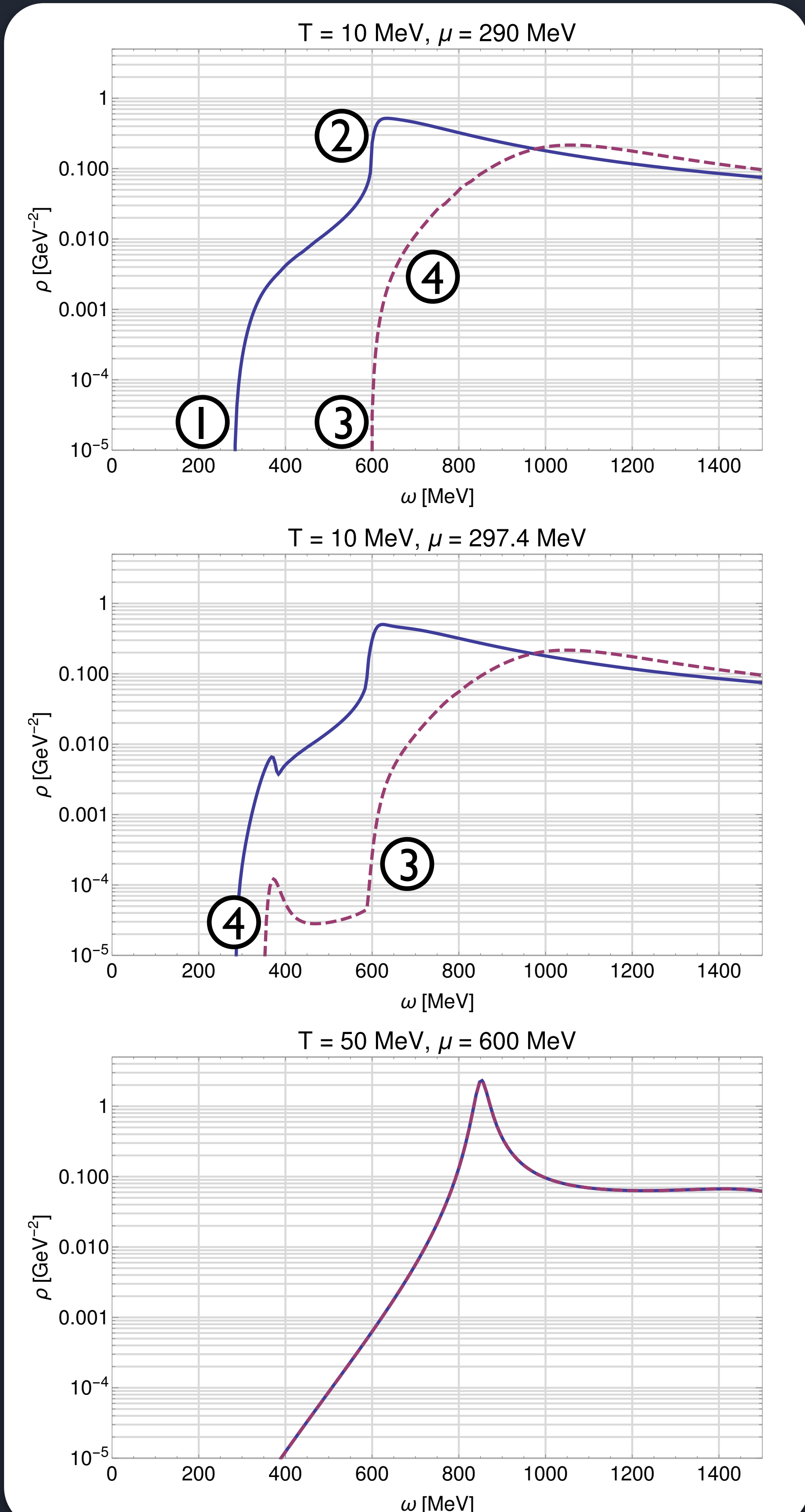


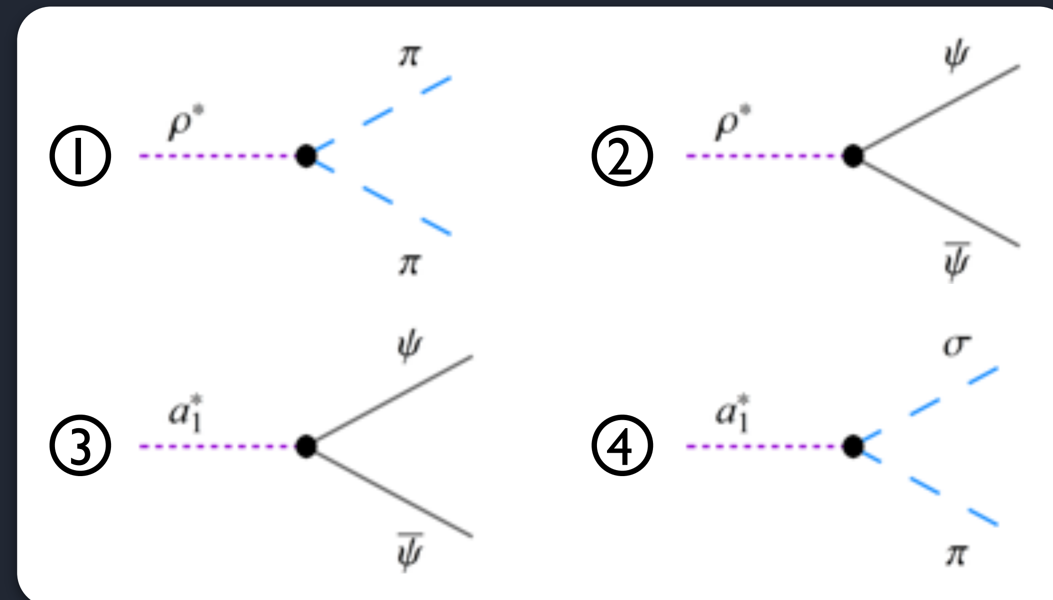
model spectral functions in favor of "melting resonance scenario"

SPECTRAL FUNCTIONS

[Jung, FR, Tripolt, von Smekal, Wambach, hep-ph/1610.08754]

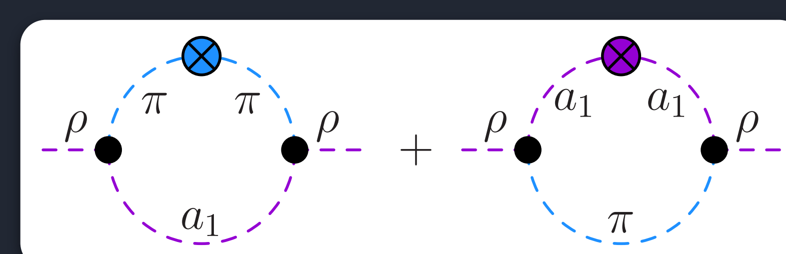


- some decay channels:



- manifestation of CEP in dilepton spectra:
  - a_1 couples to critical mode σ
  - include vector meson fluctuations

    ⟶ feedback on ρ spectral function



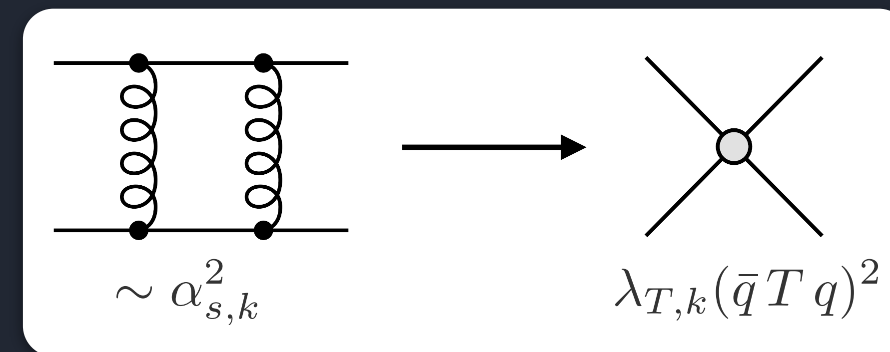
  - similar contribution from π's
  - fine-tuning of T and μ to CEP necessary

DYNAMICAL HADRONIZATION

$\Lambda \gg 1\,\mathrm{GeV}$

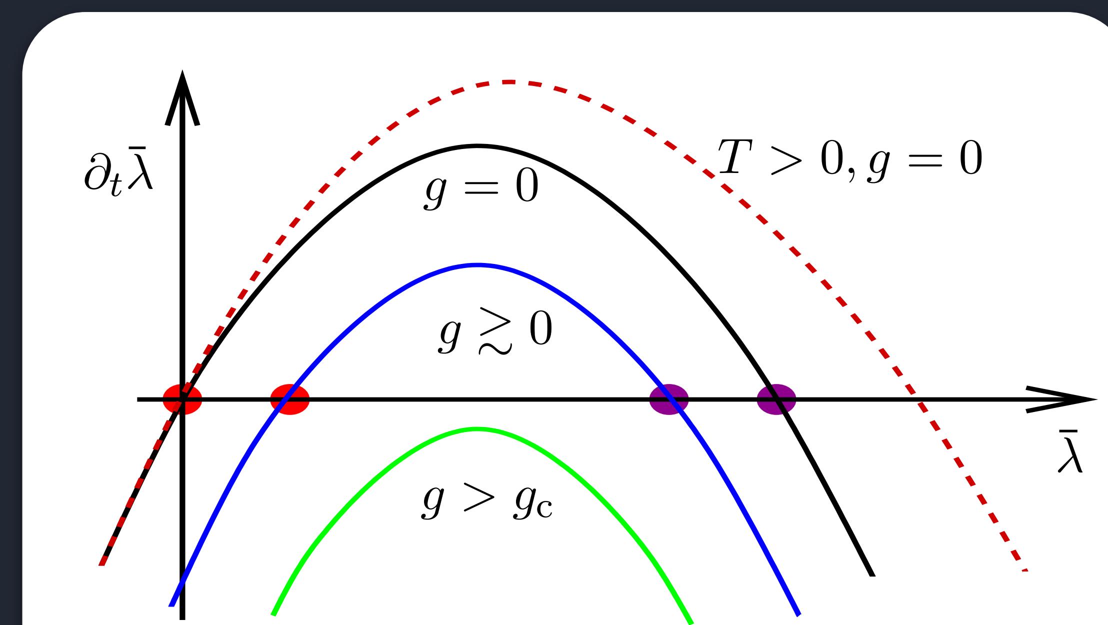
Up to now only low-energy model; what happens if gluon fluctuations are included?

- initial action: gauge fixed QCD
- effective four-quark interaction channels are generated:



- $\lambda_{T,k}$ grows with decreasing scale
- RG-flow controlled by IR-attractive fixed point for small g
- strong coupling exceeds critical value: chiral symmetry breaking

⟶ four-quark interaction diverges



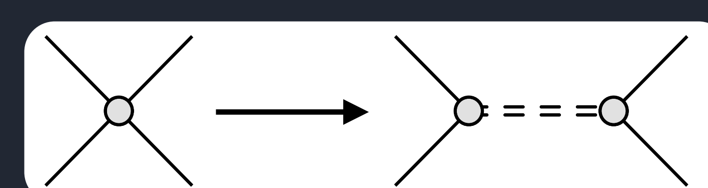
[Gies, Wetterich, hep-th/0209183]

- introduce mesons via bosonization:
  (similar: baryonization from 6-quark interactions)

Yukawa coupling

$$\lambda_{T,k} = \frac{h_{T,k}^2}{m_{\phi,k}^2}$$

meson mass parameter



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]

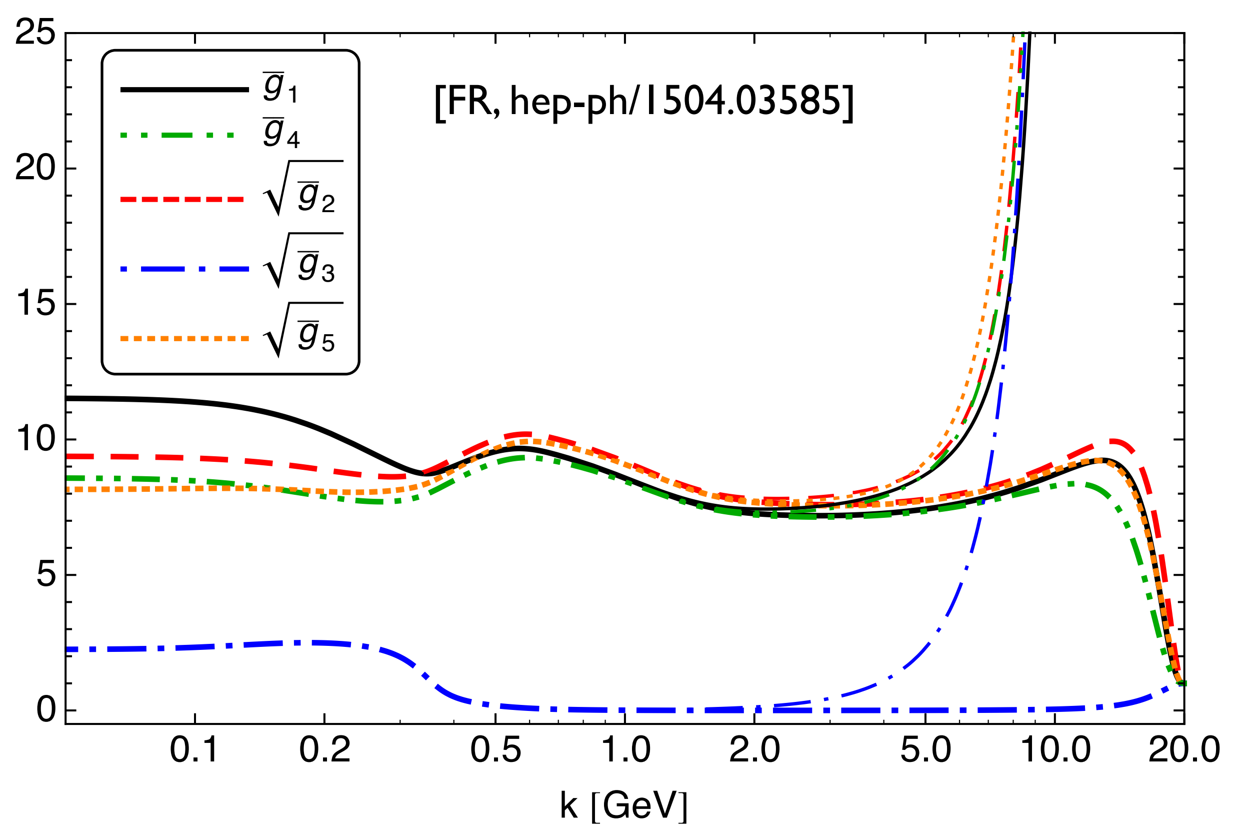
- bosonize 4-quark interaction in each RG step: dynamical hadronization

⟶ \`mesons´ become scale dependent fields

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

e.g. for ρ
$T = \gamma_\mu \vec{\tau}$

⟶ low-energy parameters are predicted; only α_S and quark masses as input
(intermediate fixed point in 4-quark interaction!)



- no VMD assumed here: vector meson couplings different a priori

- VMD would imply

$$g_V = g_1 = \sqrt{g_2} = g_4 = \sqrt{g_5}$$
$$g_3 = 0$$

SUMMARY & OUTLOOK

- in-medium vector- and axial-vector meson spectral functions
    - low-energy model based on VMD
    - direct, non-perturbative computation
    - degeneration of vector and axial-vector spectral functions above the chiral transition
    - consistent with melting resonance scenario
- including gauge fields: dynamical hadronization
    - no model parameter dependence
    - \`test´ of VMD

Outlook / work in progress:

- \`marry´ dynamical hadronization and analytic continuation
- vector meson fluctuations
- baryons & more decay channels
- confinement
- dilepton rates

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thank you

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