In-medium spectral functions of vector and axial-vector mesons from aFRG flow equations

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CRC–TR 211
Strong-interaction matter under extreme conditions

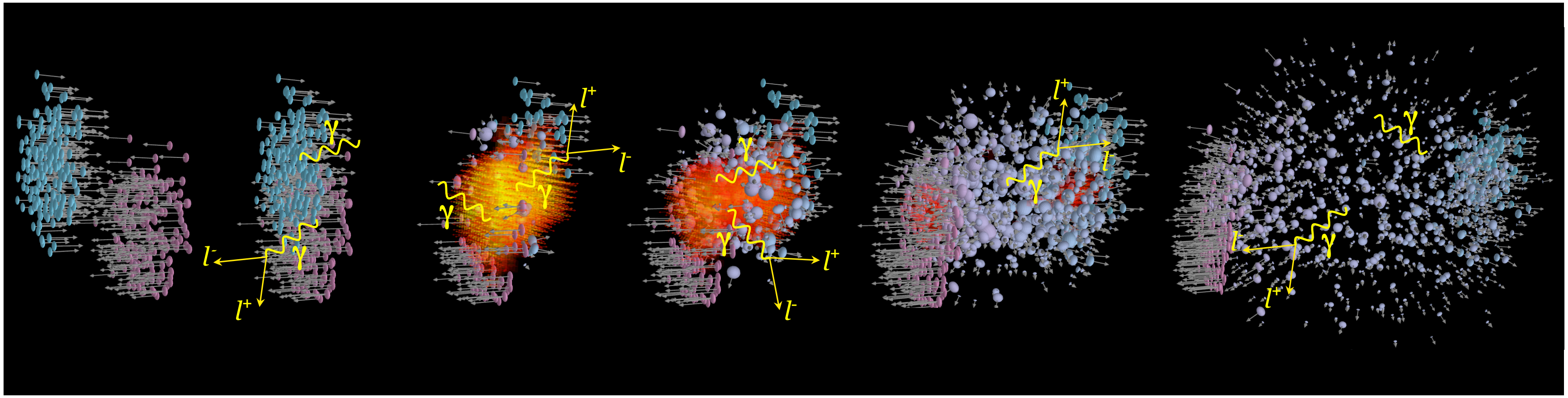
HIC for FAIR
Helmholtz International Center

Bundesministerium für Bildung und Forschung

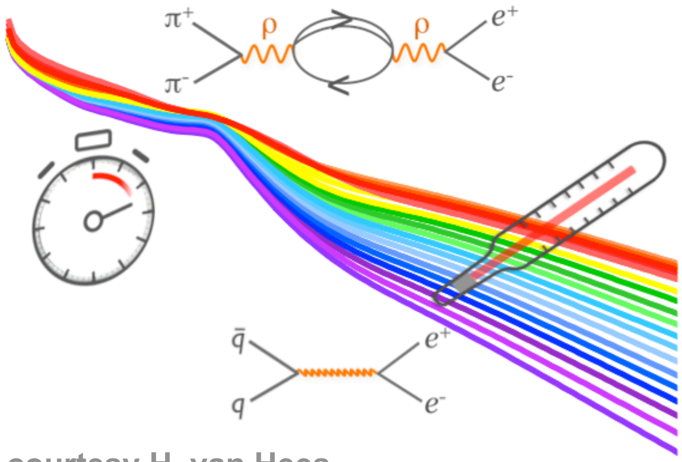
Outline

- Intro / Motivation, Dileptons in HIC
- Spectral functions from analytically continued (aFRG) flows
- Vector and axial-vector spectral functions
- Fluctuating (axial-)vectors
- Summary and Outlook

Photons and Dileptons in HIC



T. Galatyuk et al., Physik Journal 17 (2018) no. 10

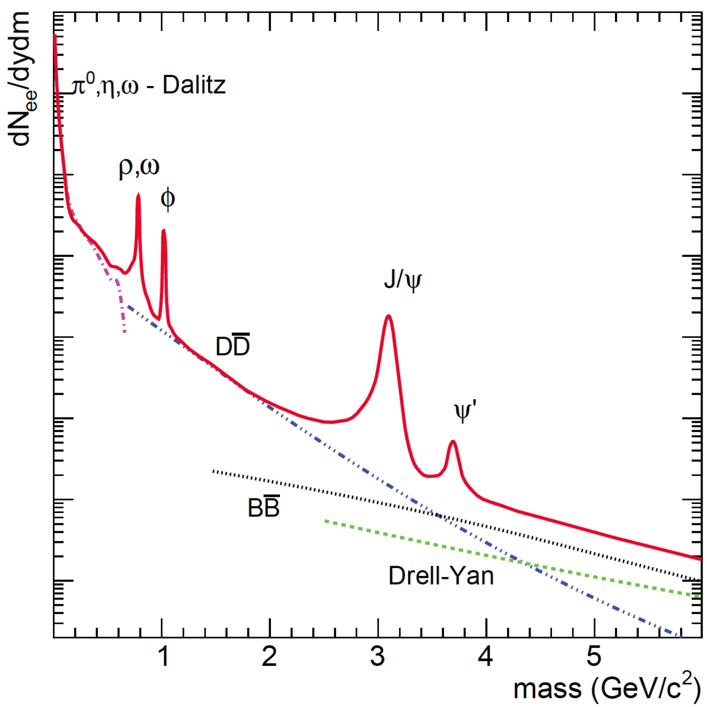


courtesy H. van Hees

- **from all stages of the collision**
- **measure temperature in QGP, lifetime of fireball…**

Dilepton Spectra

A. Drees, NPA 830 (2009) 435



dilepton rate (local thermal equilibrium):

$$\frac{dN_{ll}}{d^4x d^4q} = -\frac{\alpha_{em}^2}{\pi^3 M^2}\,\frac{1}{3} g_{\mu\nu}\,\mathrm{Im}\,\Pi^{\mu\nu}_{em}\big(M,|\vec{q}|;\mu,T\big)$$

electromagnetic correlator:

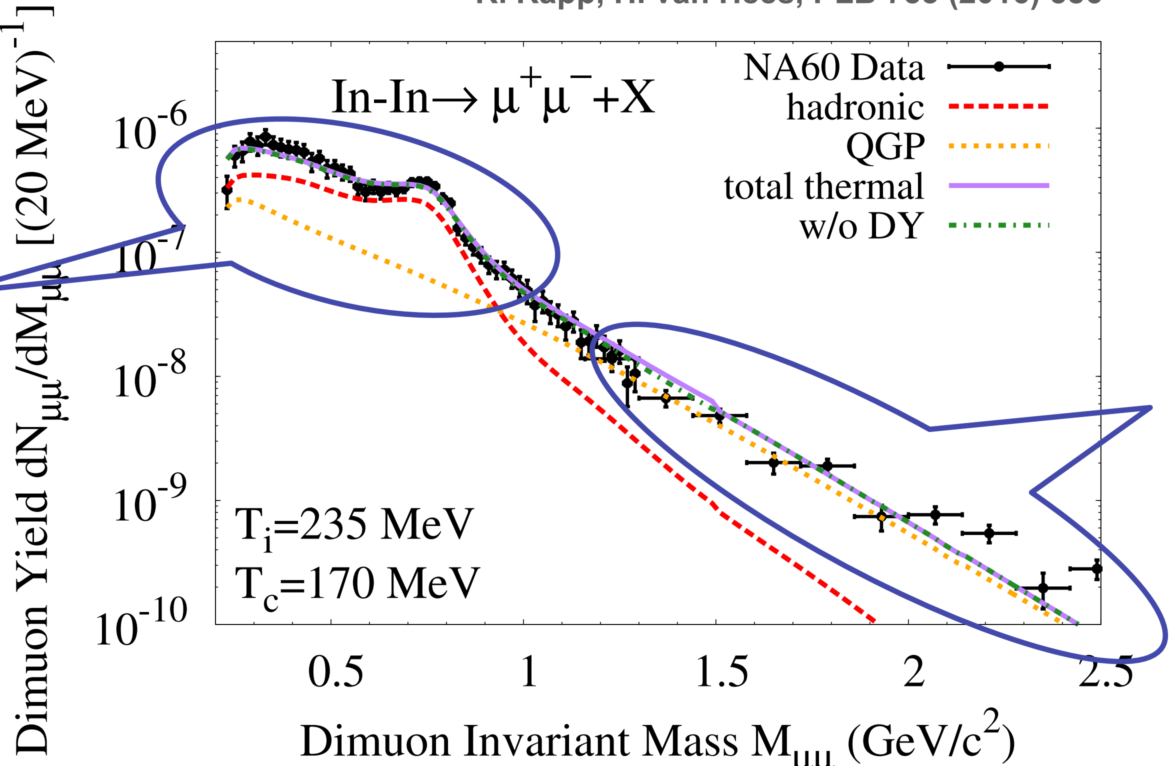
$$\Pi^{\mu\nu}_{em}\big(q;\mu,T\big) = -i\int d^4x\; e^{iqx}\theta(x^0)\,\big\langle [j^\mu_{em}(x), j^\nu_{em}(0)]\big\rangle$$

vector meson dominance & quark counting:

$$\mathrm{Im}\,\Pi^{\mu\nu}_{em}\big(M \le 1\mathrm{GeV}\big) \sim \mathrm{Im}\,D^{\mu\nu}_\rho + \frac{1}{9}\mathrm{Im}\,D^{\mu\nu}_\omega + \frac{2}{9}\mathrm{Im}\,D^{\mu\nu}_\phi$$

In-Medium Modifications

R. Rapp, H. van Hees, PLB 753 (2016) 586



effective **hadronic** models

currently accessible with lattice QCD in **QGP** phase

early probes

deduce medium modifications to the vector spectral function, find signatures of chiral symmetry restoration

Spectral Functions

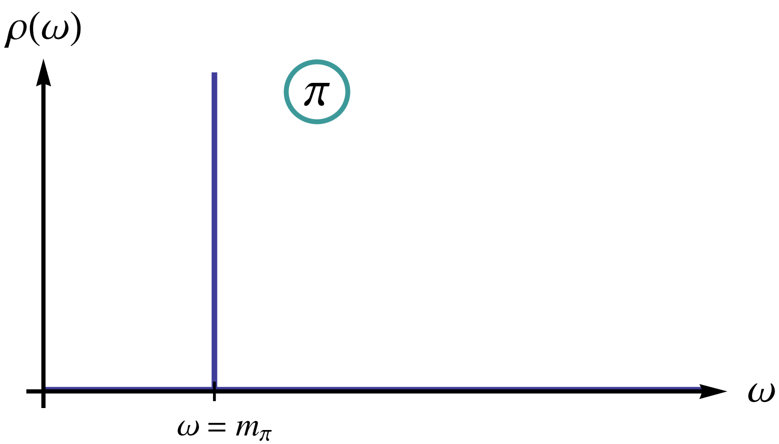
commutator of interacting fields:

free fields

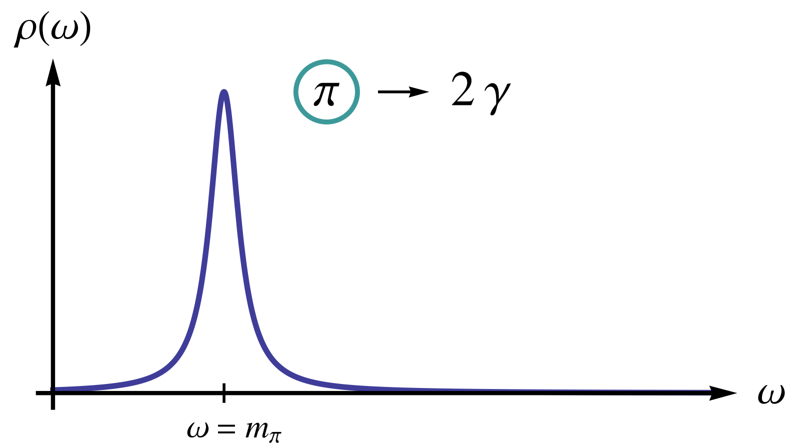
$$\langle [\phi(x), \phi(0)] \rangle = \int_0^\infty dm^2 \; \rho(m^2) \; i\Delta(x; m^2)$$

spectral function: $$\rho(p^2) = (2\pi)^3 \sum_\psi \delta^4(p - q_\psi) \, \big| \langle \Omega | \phi(0) | \psi \rangle \big|^2 \; , \quad p_0 > 0$$

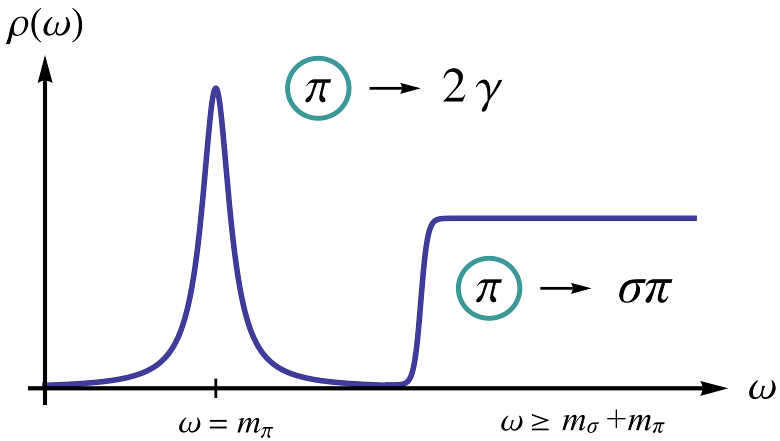
free fields (stable pion):



finite lifetime/width:

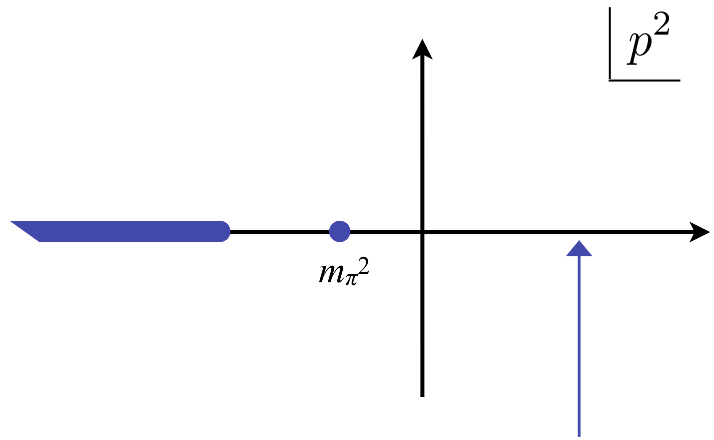


two-particle thresholds:



discontinuity at cut of propagator:

$$D(p) = \int_0^\infty dm^2\, \rho(m^2)\, \frac{1}{p^2 + m^2}$$



retarded, imaginary part: $\rho(p^2) = -\frac{1}{\pi}\,\mathrm{Im}\, D_R(p)$

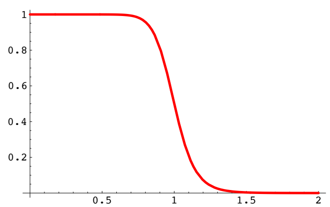
Euclidean space:

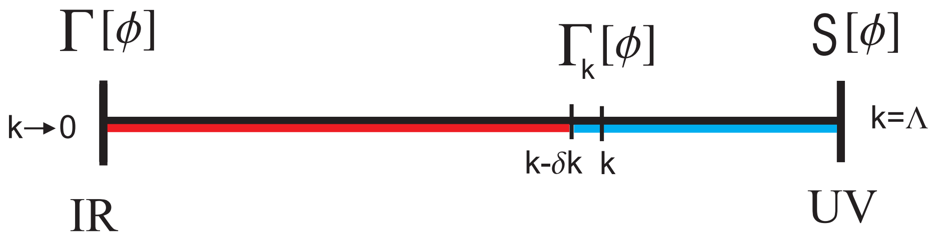
$p^2 > 0$

Euclidean data: $D(t, \vec{p} = 0) = \int_0^\infty dm\, \rho(m^2)\, \exp\{-mt\}$

(inverse Laplace, try e.g. MEM, but ill-posed numerical problem)

Functional RG (Flow) Equations





Effective action: $\Gamma[\phi_j] = (j, \phi_j) - \ln Z[j]$

Legendre transform

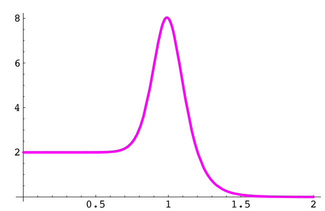
→ **1PI vertex functions**

$\Gamma^{(n)}(x_1, \ldots x_n)$

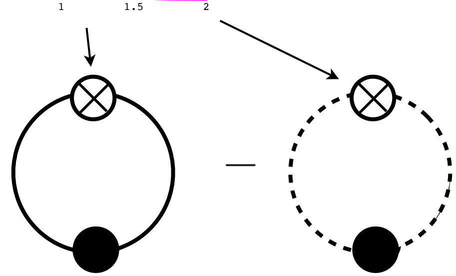
→ **grand potential**

$\Omega(T, \mu)$, at

$$\phi_{\min} = \langle \phi \rangle_{T,\mu}$$



$$k\partial_k \Gamma_k[\phi] = \frac{1}{2}$$



bosons **fermions**

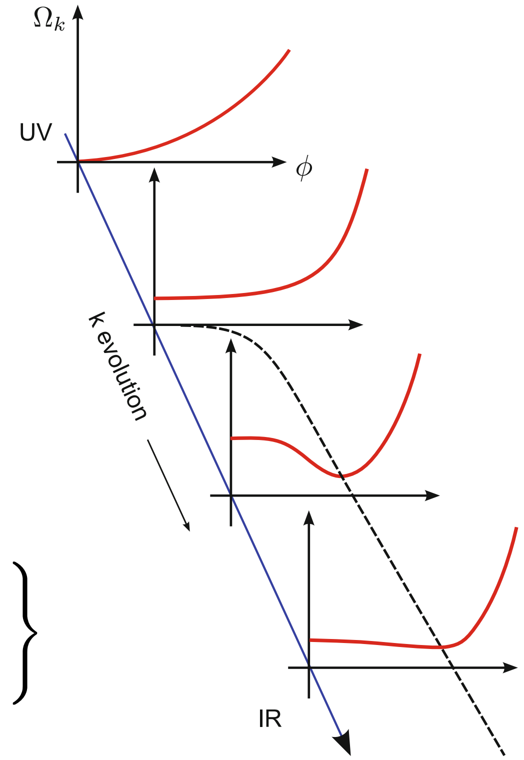
Wetterich, Phys. Lett. B 301 (1993) 90

Flow of Grand Potential

- **e.g. quark-meson model:**

$$\Gamma_k = \int d^4x \left\{ \bar\psi\left(\partial\!\!\!/ + g(\sigma + i\gamma_5\vec\tau\cdot\vec\pi)\right)\psi + \frac{1}{2}(\partial_\mu\vec\phi)^2 + U_k(\phi^2) - c\sigma \right\}, \quad \vec\phi = (\sigma,\vec\pi)$$

(leading order derivative expansion)



- **flow of Landau free energy density:**

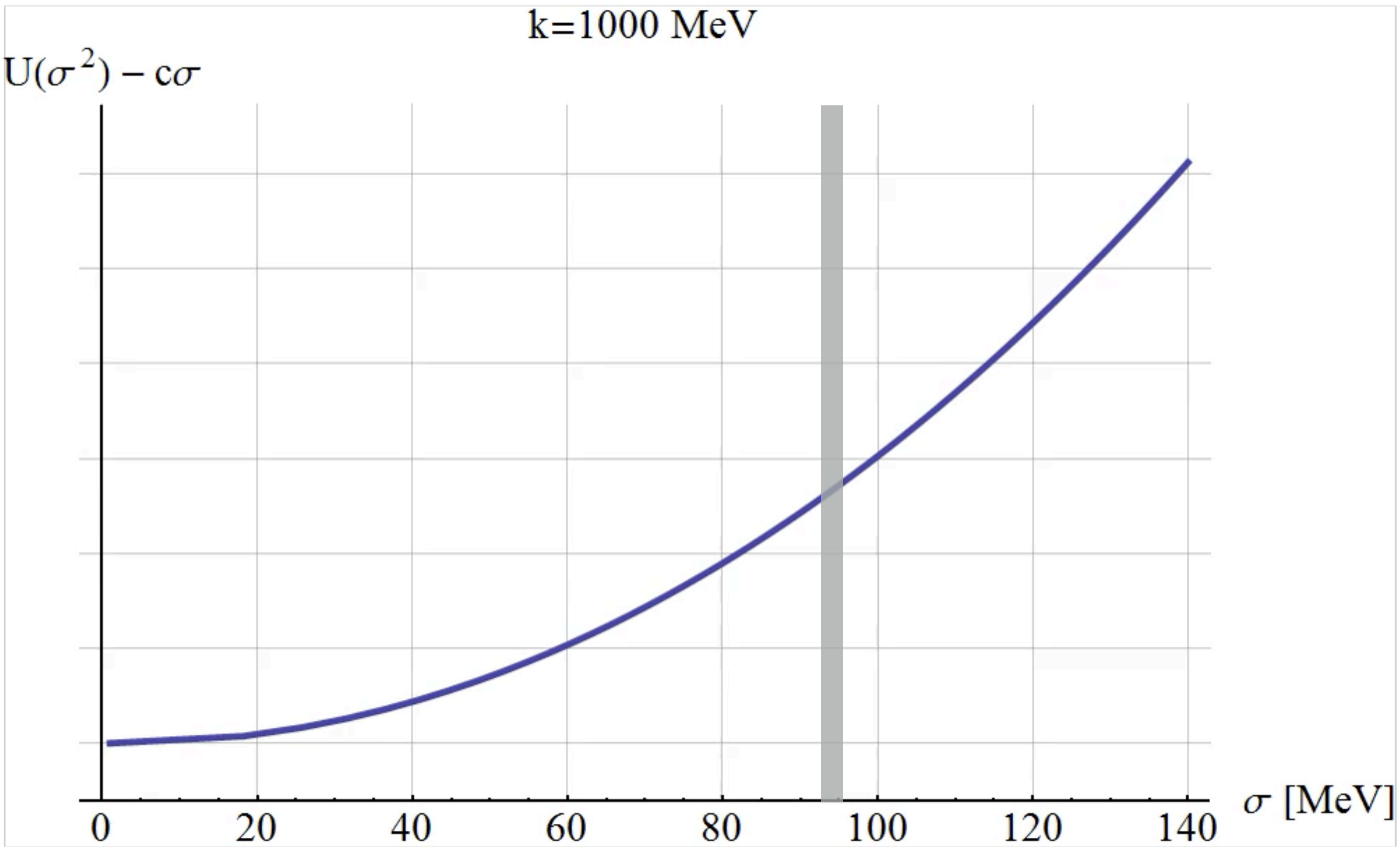
$$\partial_k\Omega_k(T,\mu;\phi^2) =$$

$$\frac{k^4}{12\pi^2}\left\{ \frac{1}{E_k^\sigma}\coth\left(\frac{E_k^\sigma}{2T}\right) + \frac{3}{E_k^\pi}\coth\left(\frac{E_k^\pi}{2T}\right) \right.$$

$$\left. - \frac{2N_cN_f}{E_k^q}\left[\tanh\left(\frac{E_k^q-\mu}{2T}\right) + \tanh\left(\frac{E_k^q+\mu}{2T}\right)\right]\right\}$$

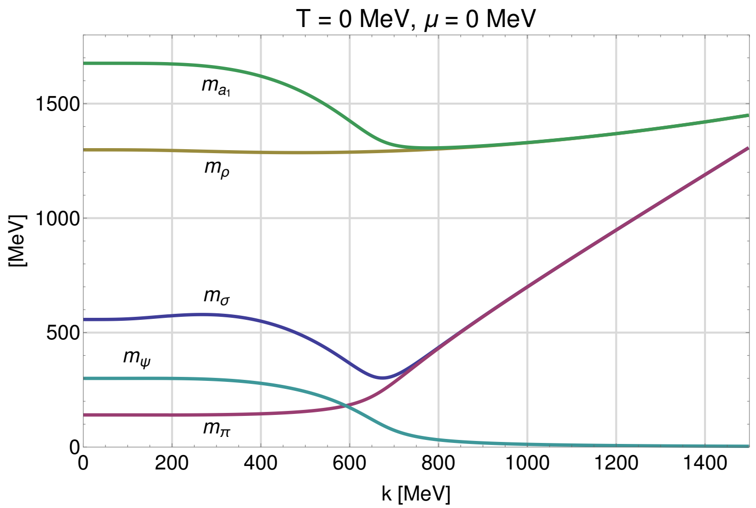
Flow of Effective Potential

- **extract mass parameters & running 3- and 4-point vertices**
  (thermodynamically consistent & symmetry preserving)



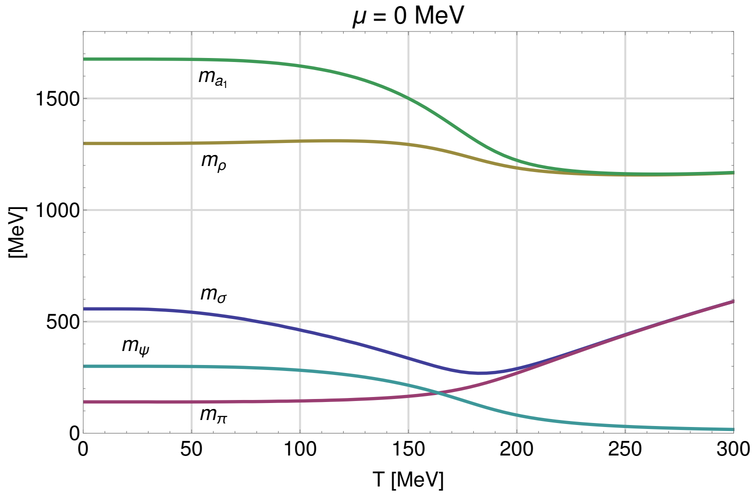
Euclidean Mass Parameters

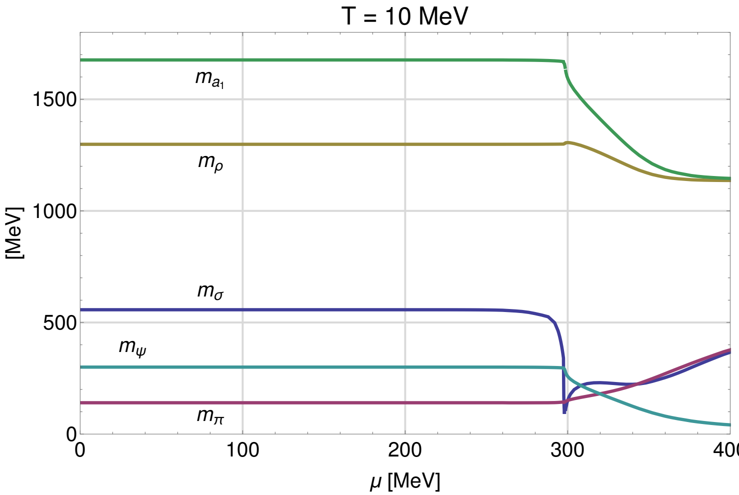
Flow of Euclidean (curvature) masses



including (axial-)vector mesons
Jung *et al.*, PRD95 (2017) 036020

chiral restoration at finite T and μ





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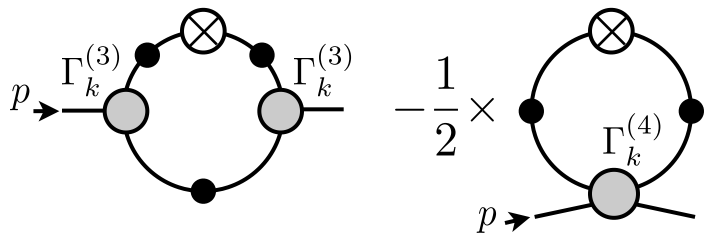
Analytically Continued aFRG Flows

- **e.g. O(4) linear sigma model:**

$$k\partial_k\Gamma_k^{(2)}(p_0,\vec{p}) =$$

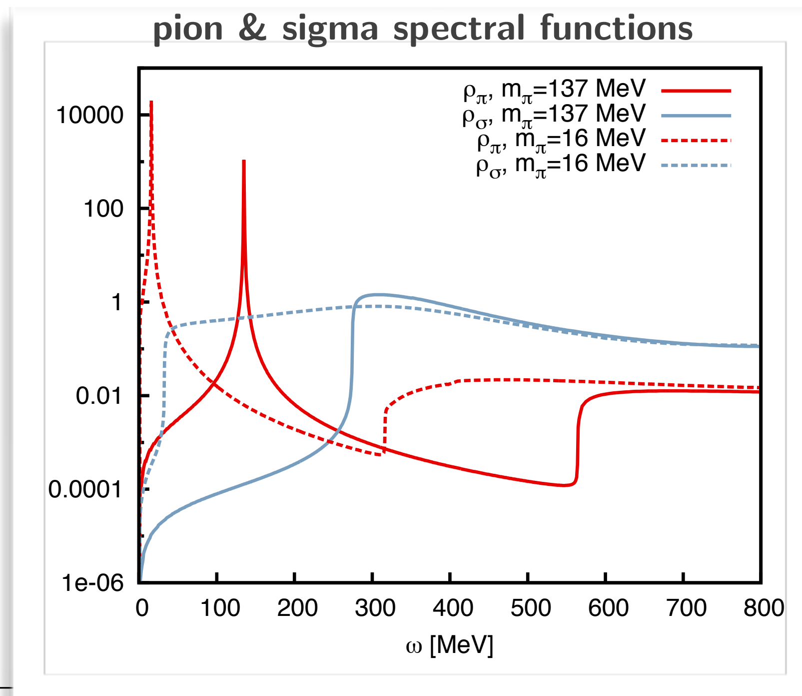


- **continue to real time:**

$$p_0 = -i(\omega + i\varepsilon) \quad \textbf{(retarded)}$$

solve analytically continued flow equation $T = \mu = 0$:

K. Kamikado, N. Strodthoff, L.v.S. & J. Wambach, EPJC 74 (2014) 2806



- **compare:**

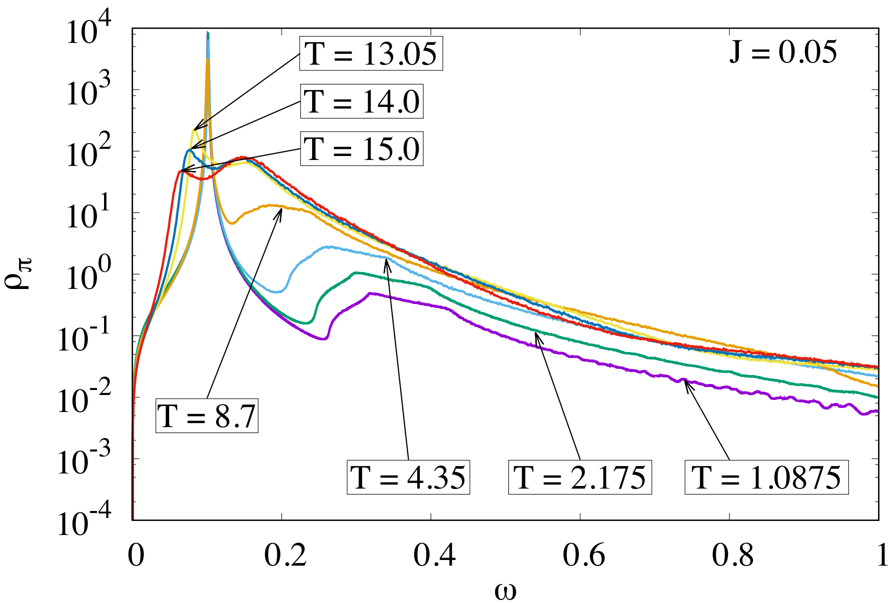
Lattice: J. Engels & O. Vogt, NPB 832 (2010) 538

2-PI: D. Röder, J. Ruppert & D.H. Rischke, NPA 775 (2006) 127

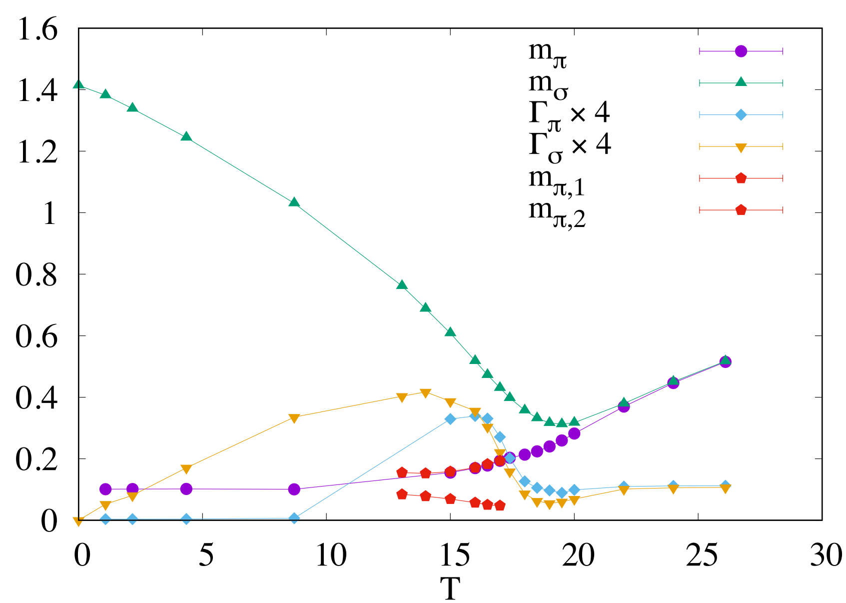
Classical-statistical: S. Schlichting, D. Smith & L.v.S., arXiv:1908.00912

Classical-Statistical Simulations

- **large boson occupancies, universal critical behavior**



Spectral functions: transverse (pion) below T_c in $O(4)$ model

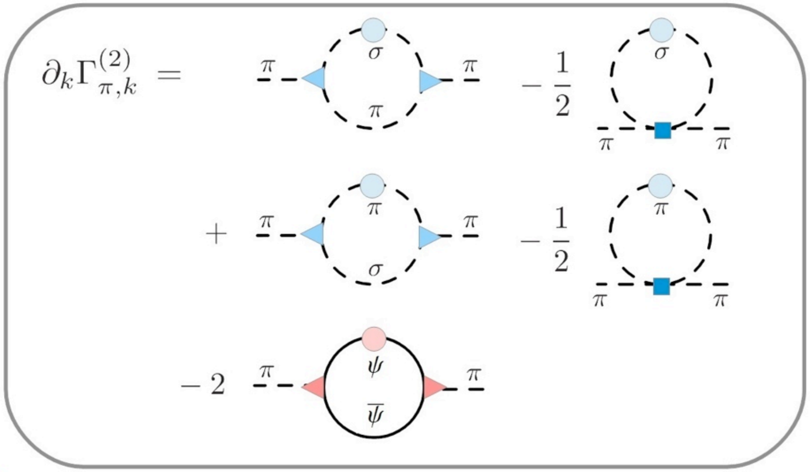


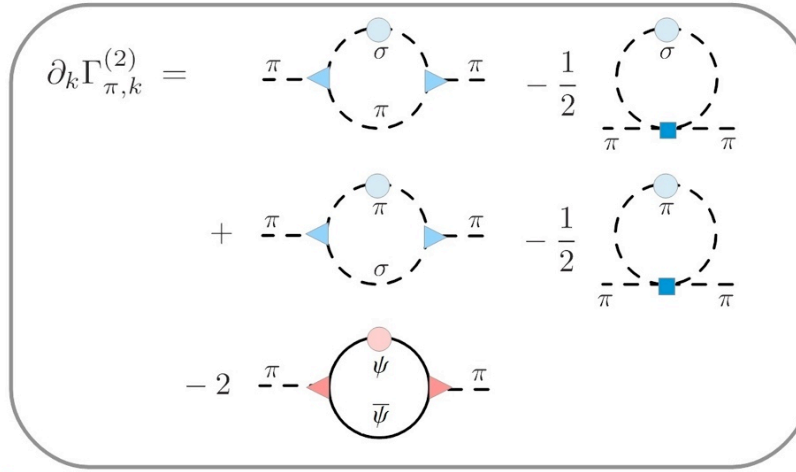
masses/widths: transverse (pion) & longitudinal (sigma) across T_c

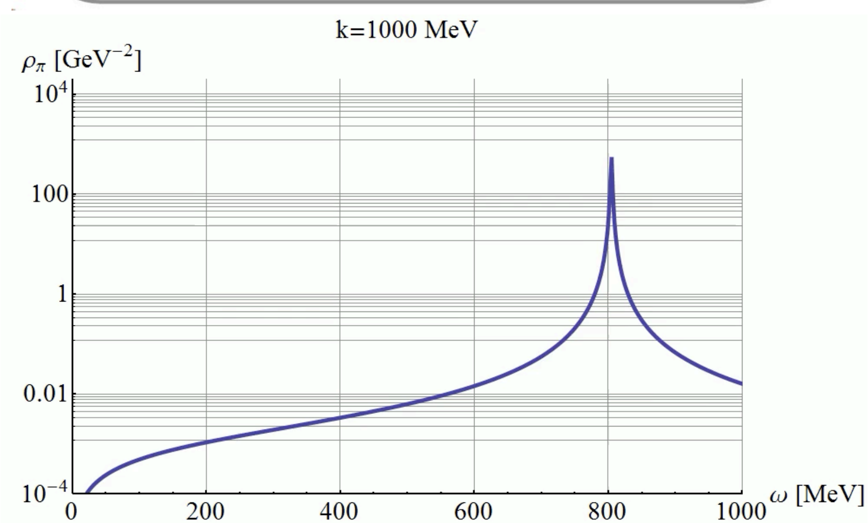
S. Schlichting, D. Smith & L.v.S., arXiv:1908.00912

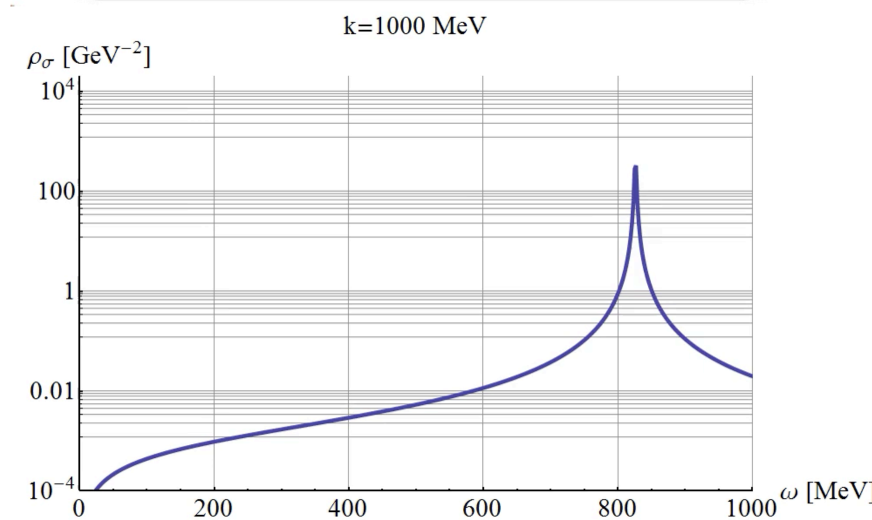
aFRG Flow of Pion and Sigma

- **quark-meson model, $T = \mu = 0$:**







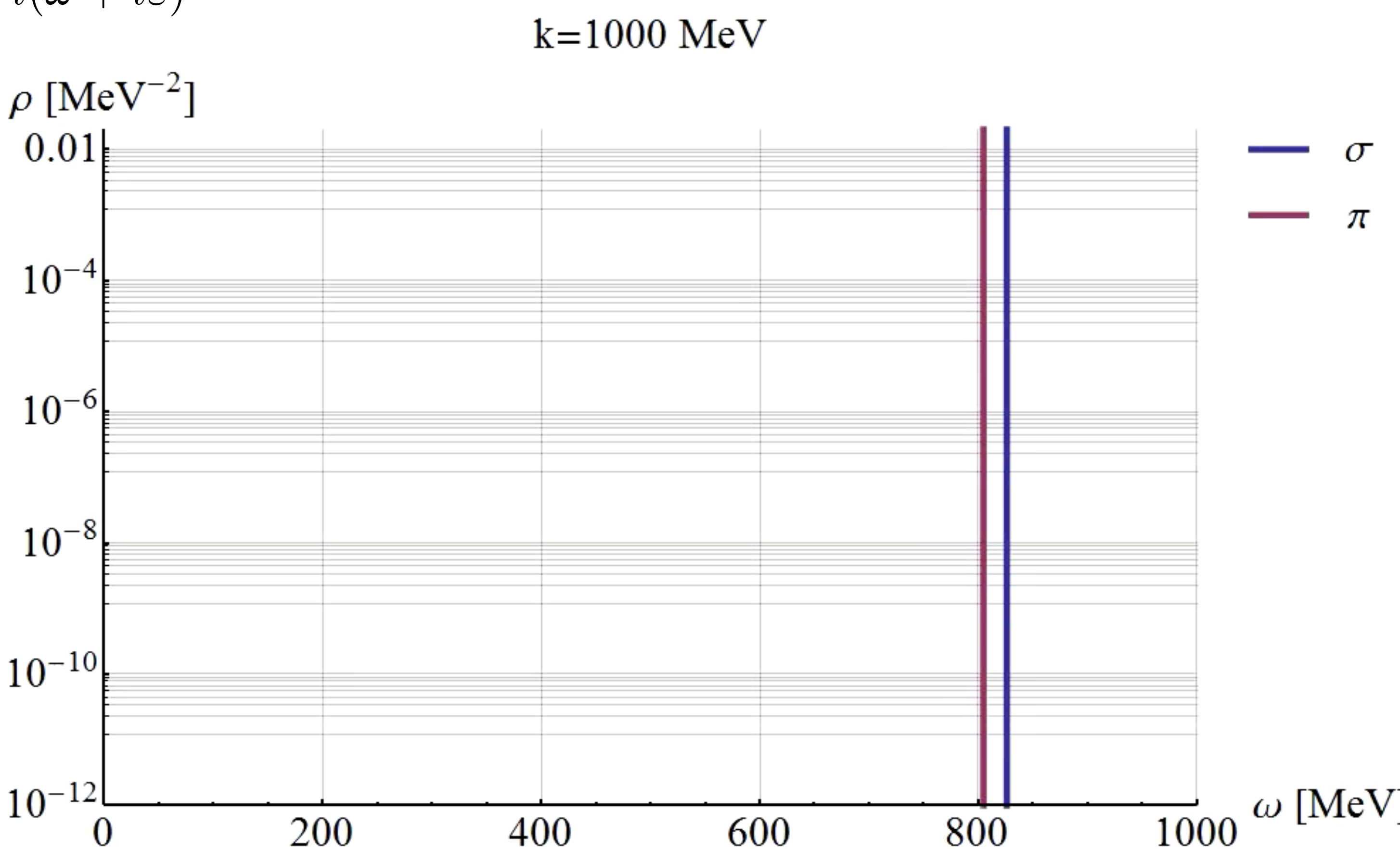


aFRG Flow of Pion and Sigma

- **for $\varepsilon \to 0$:**

$$\rho(\omega, \vec{p}) = -\frac{1}{\pi} \mathrm{Im}\, D^R(\omega, \vec{p})$$

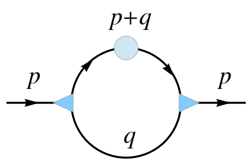
$$p_0 = -i(\omega + i\varepsilon)$$



aFRG Flow at Finite Temperature

- **analytic continuation not unique:**

exploit one-loop structure, 3-dim. regulators

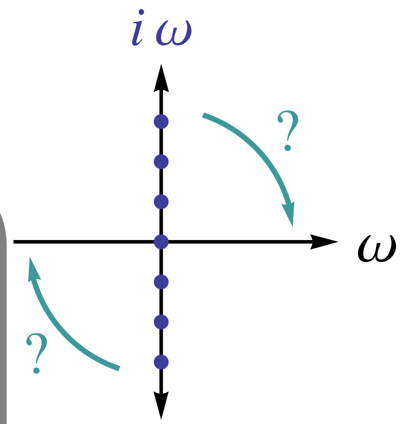


1) Use periodicity in external energy $p_0 = n\,2\pi T$:

$$n_{B,F}(E + ip_0) \to n_{B,F}(E)$$

2) Substitute p_0 by continuous real frequency:

$$\Gamma^{(2),R}(\omega) = -\lim_{\epsilon\to 0} \Gamma^{(2),E}(p_0 = i\omega - \epsilon)$$



- **for $\varepsilon \to 0$:**

$$p_0 = -i(\omega + i\varepsilon)$$

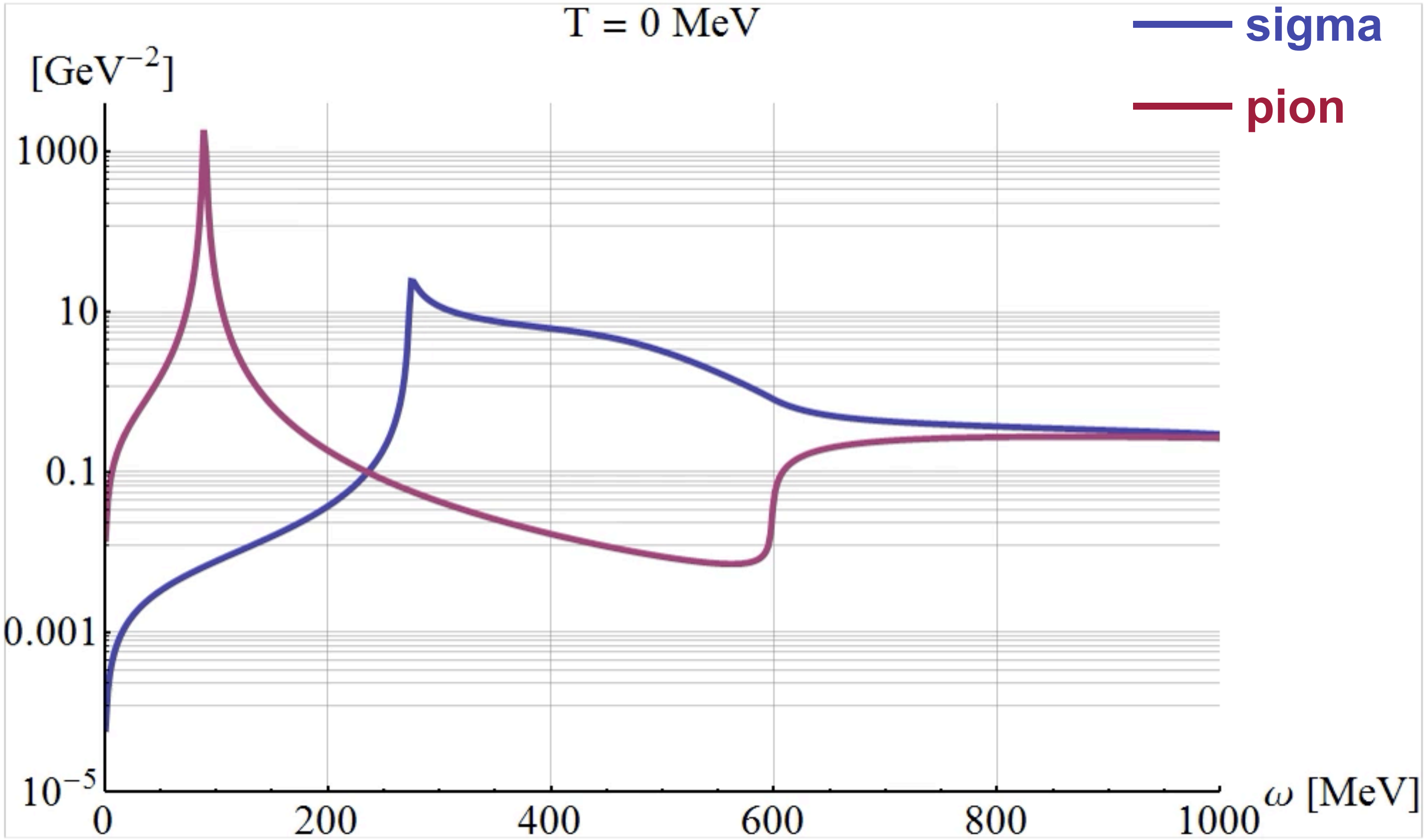
$\rightsquigarrow$ **Baym-Mermin physical b.c.'s satisfied**

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

In-Medium Spectral Functions

- **quark-meson model:**

$\mu = 0$

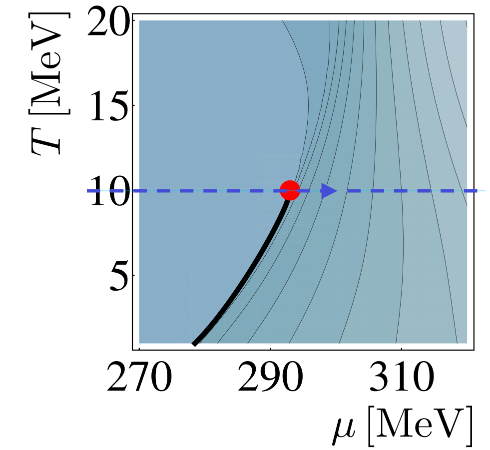


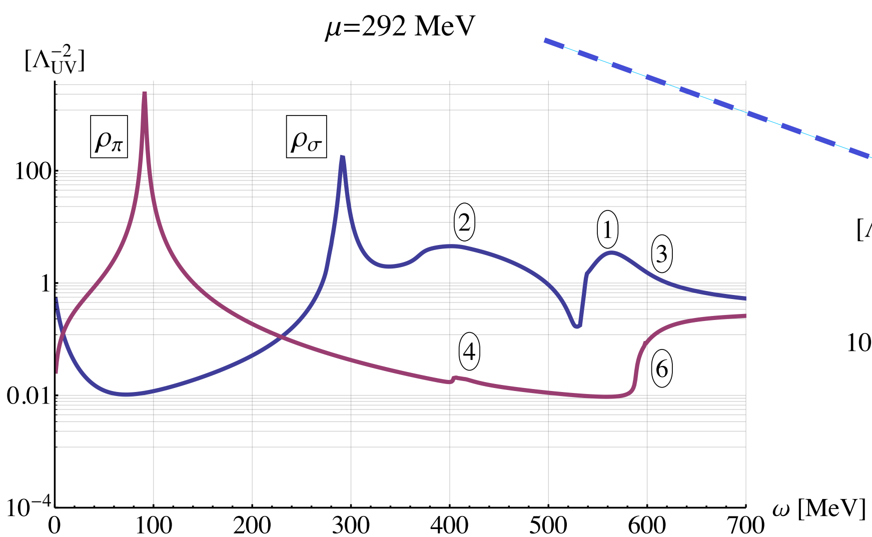
A. Tripolt, N. Strodthoff, L.v.S. & J. Wambach, PRD 89 (2014) 34010

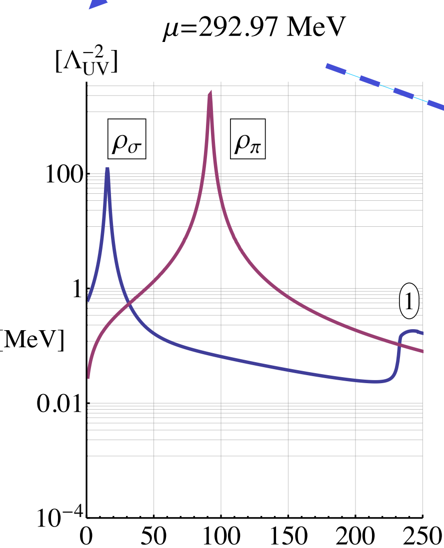
In-Medium Spectral Functions

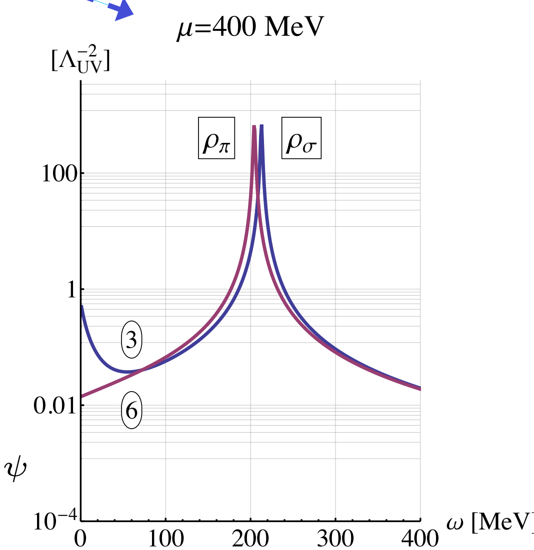
- **quark-meson model:**

  $T = 10\,\mathrm{MeV}$







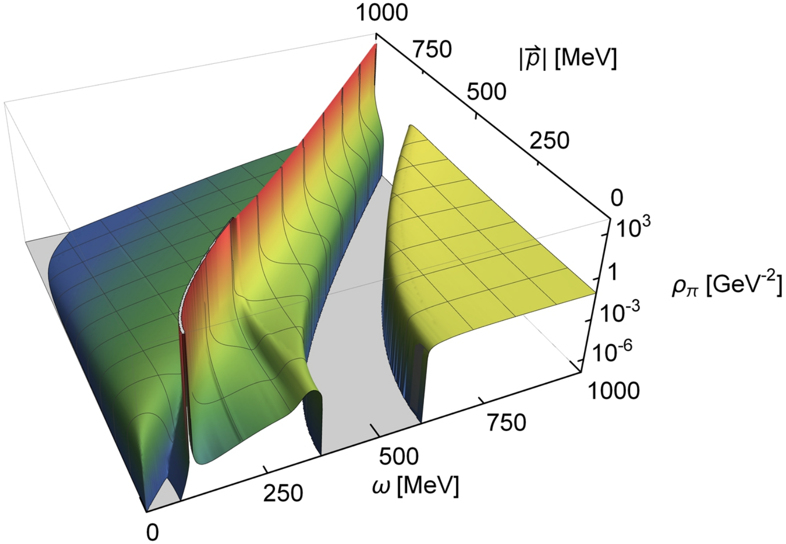


1: $\sigma^* \to \sigma\sigma$, 2: $\sigma^* \to \pi\pi$, 3: $\sigma^* \to \bar{\psi}\psi$, 4: $\pi^* \to \sigma\pi$, 5: $\pi^*\pi \to \sigma$, 6: $\pi^* \to \bar{\psi}\psi$

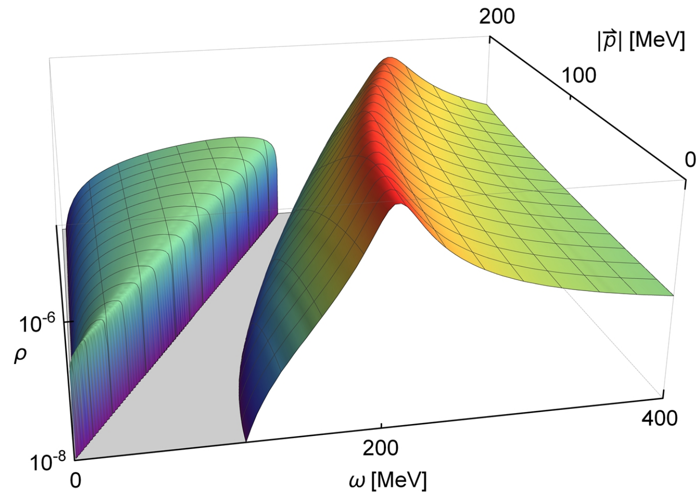
A. Tripolt, N. Strodthoff, L.v.S. & J. Wambach, PRD 89 (2014) 34010

Finite Momenta

pion SF $\rho(\omega, \vec{p})$ below T_c



sigma meson SF $\rho(\omega, \vec{p})$ above T_c



$\rightsquigarrow$ transport coefficients

A. Tripolt, L.v.S. & J. Wambach, PRD 90 (2014) 074031

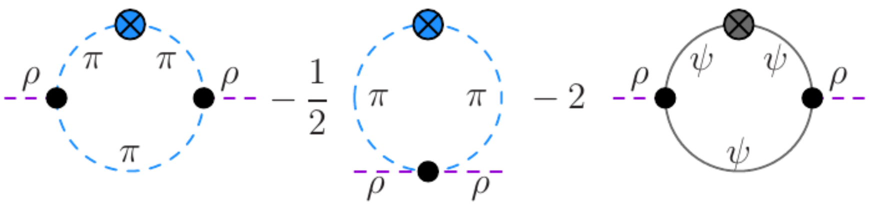
Vector and Axial-Vector SFs

- **gauged linear-sigma model with quarks:**

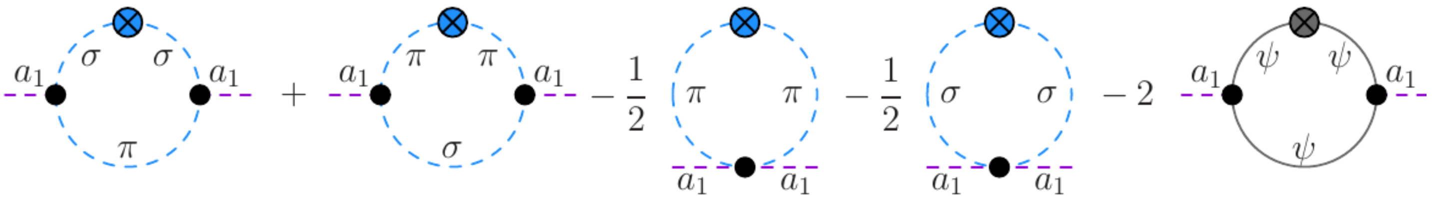
$$\Gamma_k = \int d^4x \Big\{ \bar\psi \left(\partial\!\!\!/ - \mu\gamma_0 + h_S \left(\sigma + i\vec\tau\vec\pi\gamma_5\right) + i h_V \left(\gamma_\mu \vec\tau \vec\rho_\mu + \gamma_\mu\gamma_5 \vec\tau \vec a_{1\mu}\right)\right)\psi + U_k(\phi^2) - c\sigma$$
$$+ \frac{1}{2}\left(D_\mu\phi\right)^\dagger \left(D_\mu\phi\right) + \frac{1}{8}\left(V_{\mu\nu}V_{\mu\nu}\right) + \frac{1}{4} m_{V,k}^2 \left(V_\mu V_\mu\right) + \frac{1}{4}\lambda_k \left(\partial_\mu V_\mu\right)^2 \Big\}$$

- **aFRG flow equations for (axial-)vector mesons from:**

$\partial_k \Gamma^{(2)}_{\rho\rho,k} =$

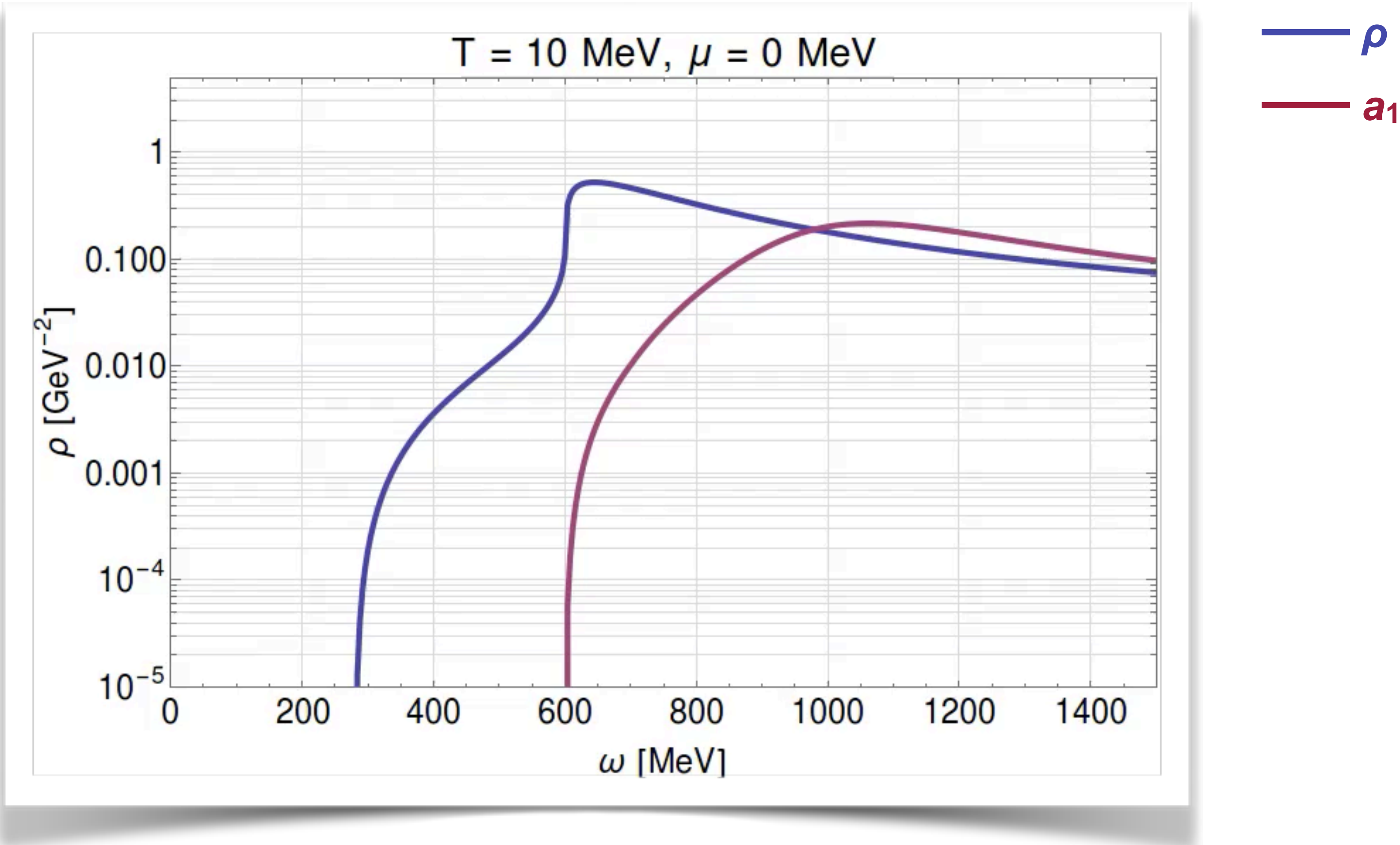


$\partial_k \Gamma^{(2)}_{a_1 a_1,k} =$



Ch. Jung, F. Rennecke, A. Tripolt, L.v.S. & J. Wambach, PRD95 (2017) 036020

Vector and Axial-Vector SFs



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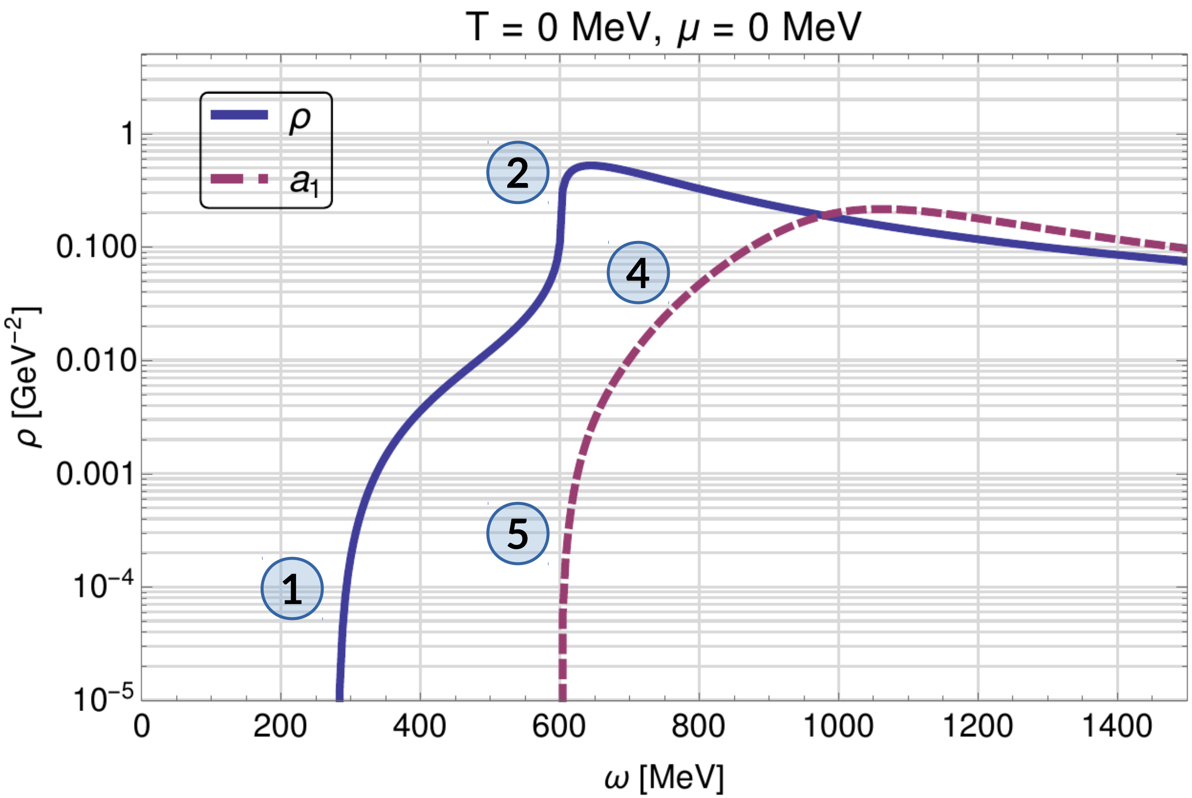
Vector and Axial-Vector SFs

- **chiral restoration with temperature**



1 $\rho^* \to \pi + \pi$

2 $\rho^* \to \bar{\psi} + \psi$

3 $a_1^* + \pi \to \sigma$

4 $a_1^* \to \pi + \sigma$

5 $a_1^* \to \bar{\psi} + \psi$

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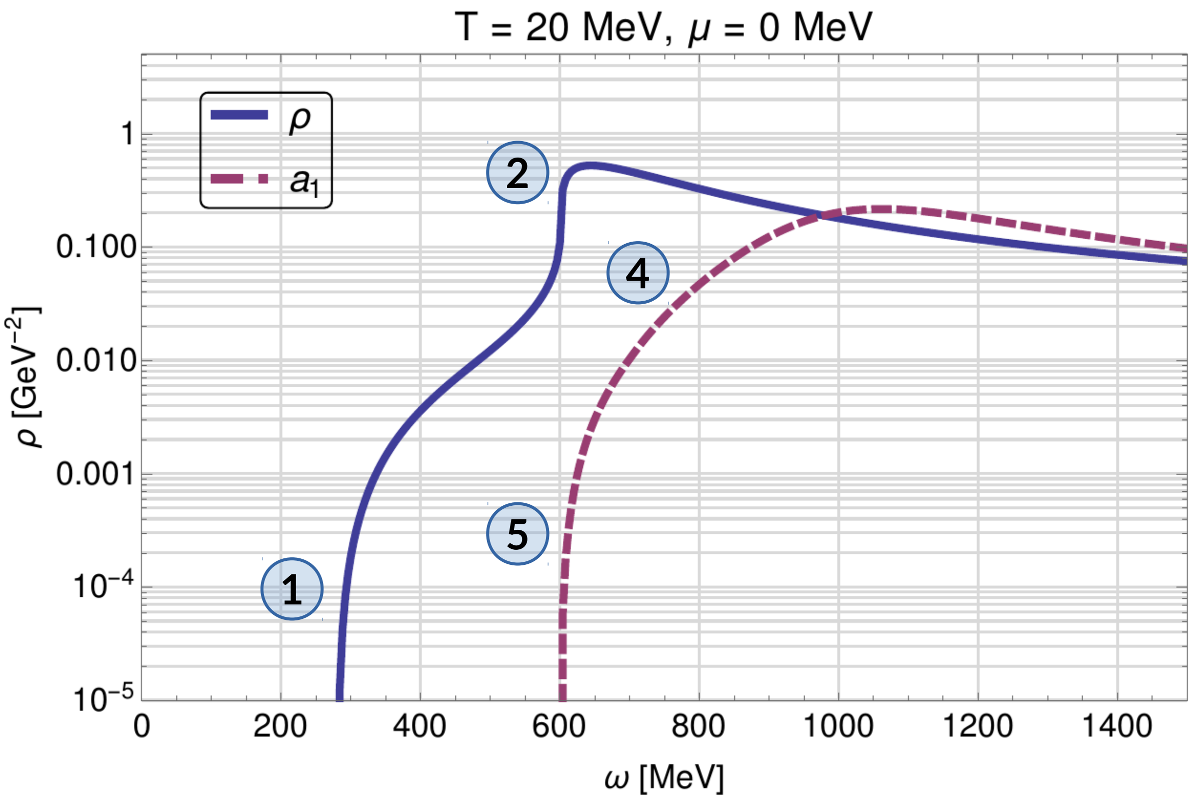

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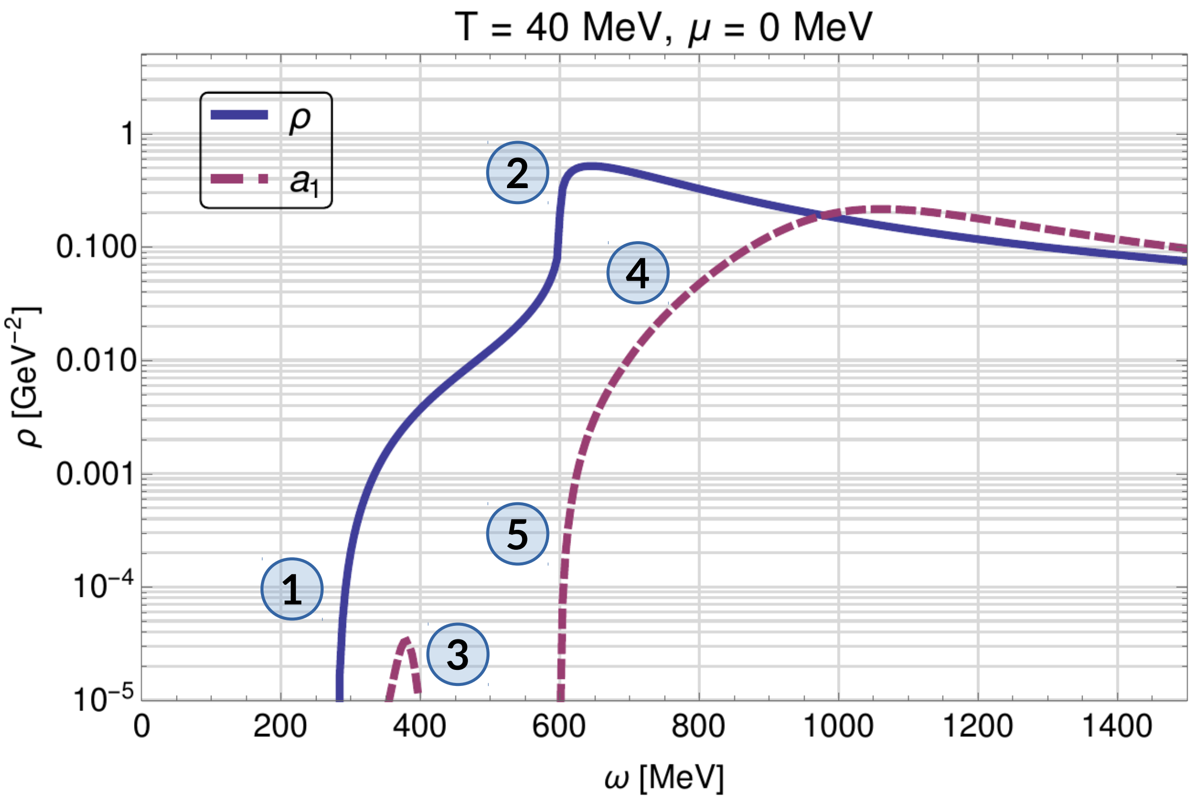

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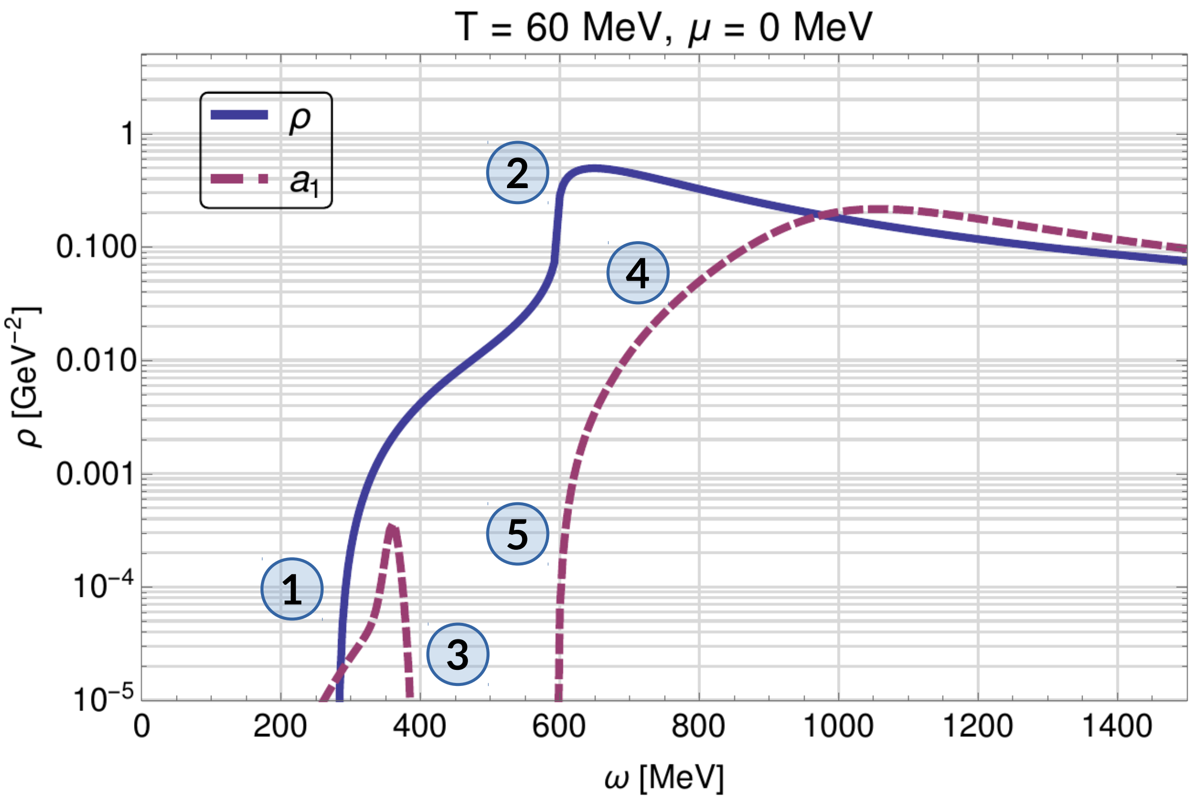

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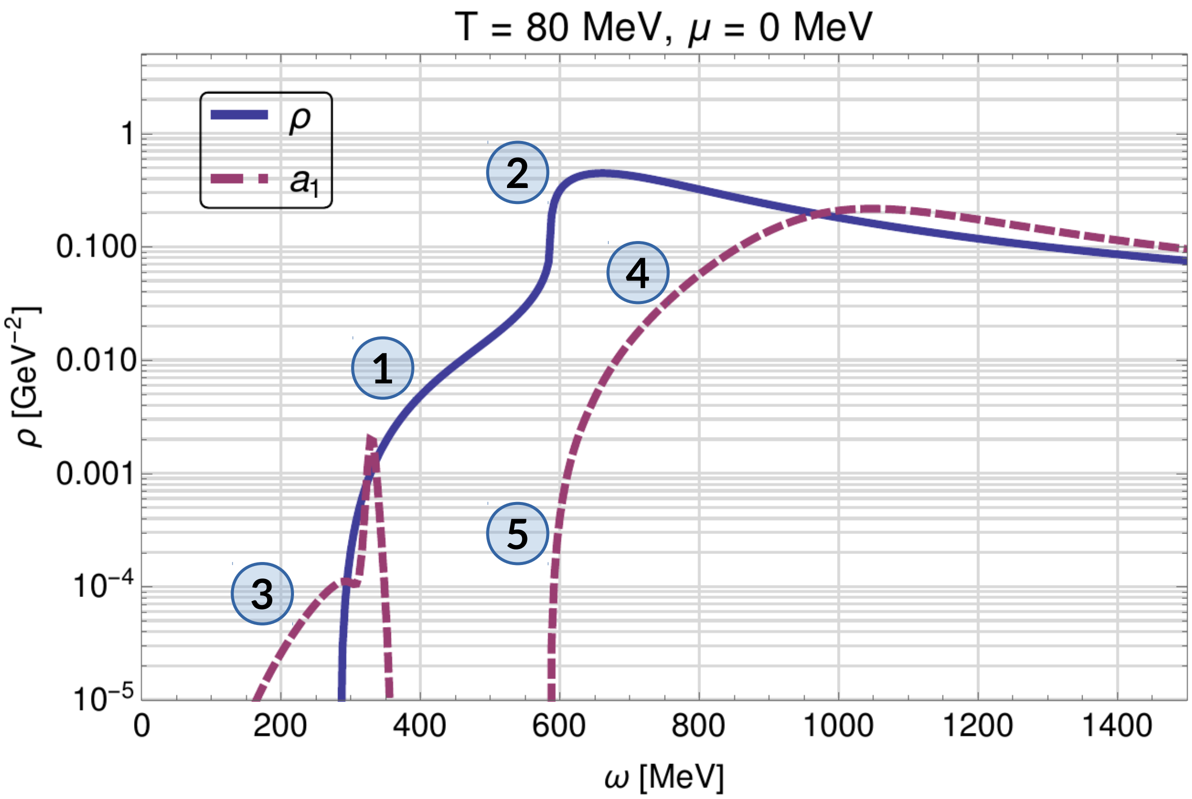

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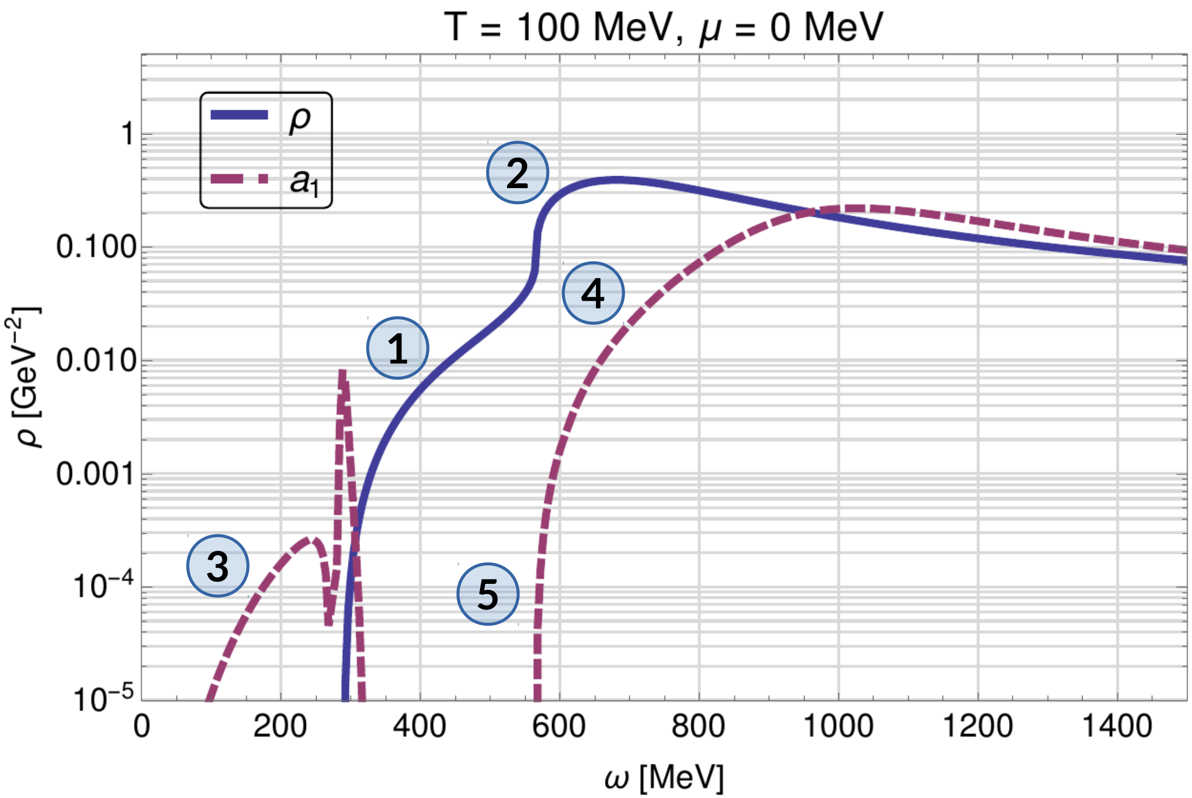
Vector and Axial-Vector SFs

- **chiral restoration with temperature**



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Ch. Jung, F. Rennecke, A. Tripolt, L.v.S. & J. Wambach, PRD95 (2017) 036020

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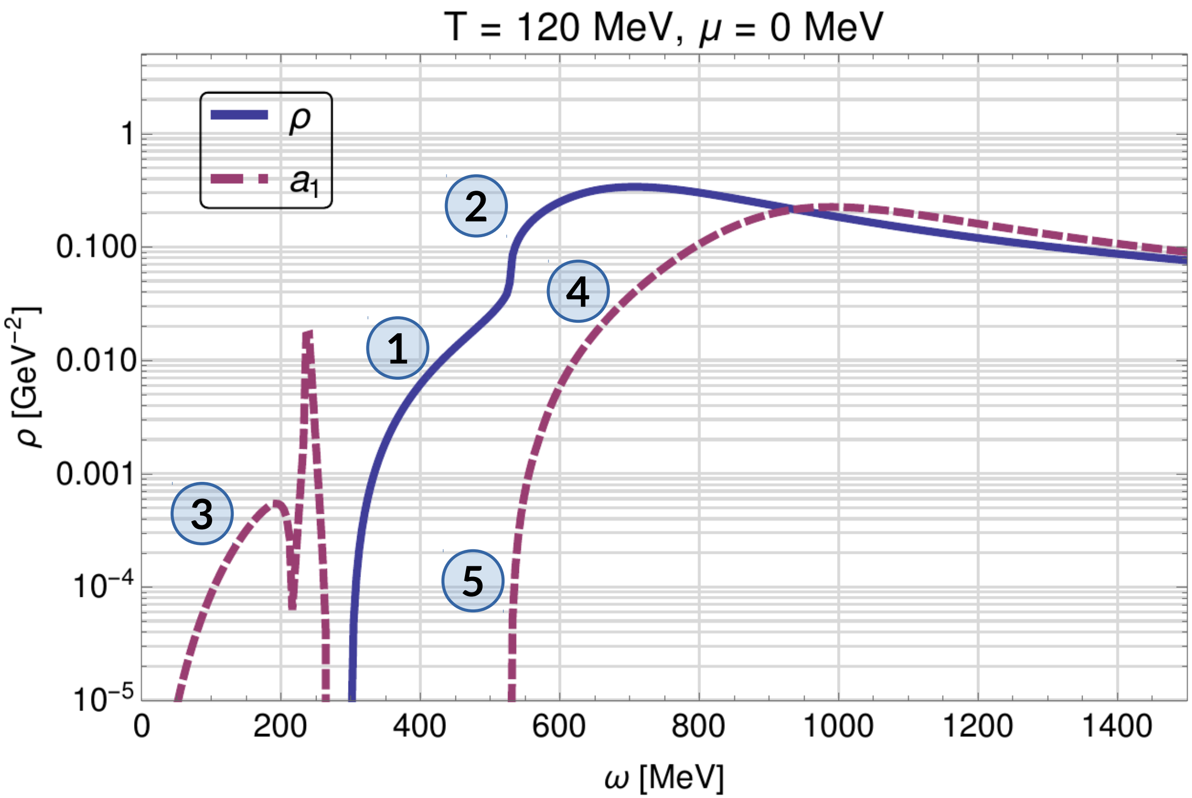

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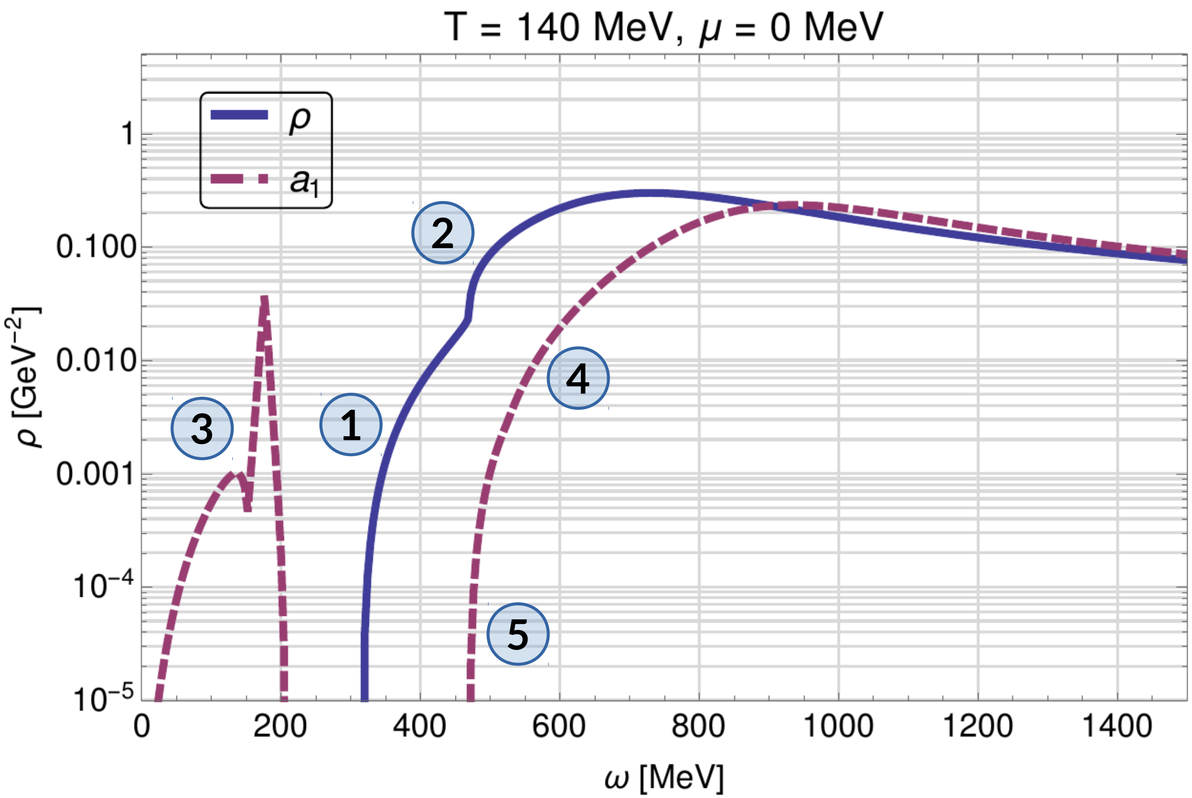

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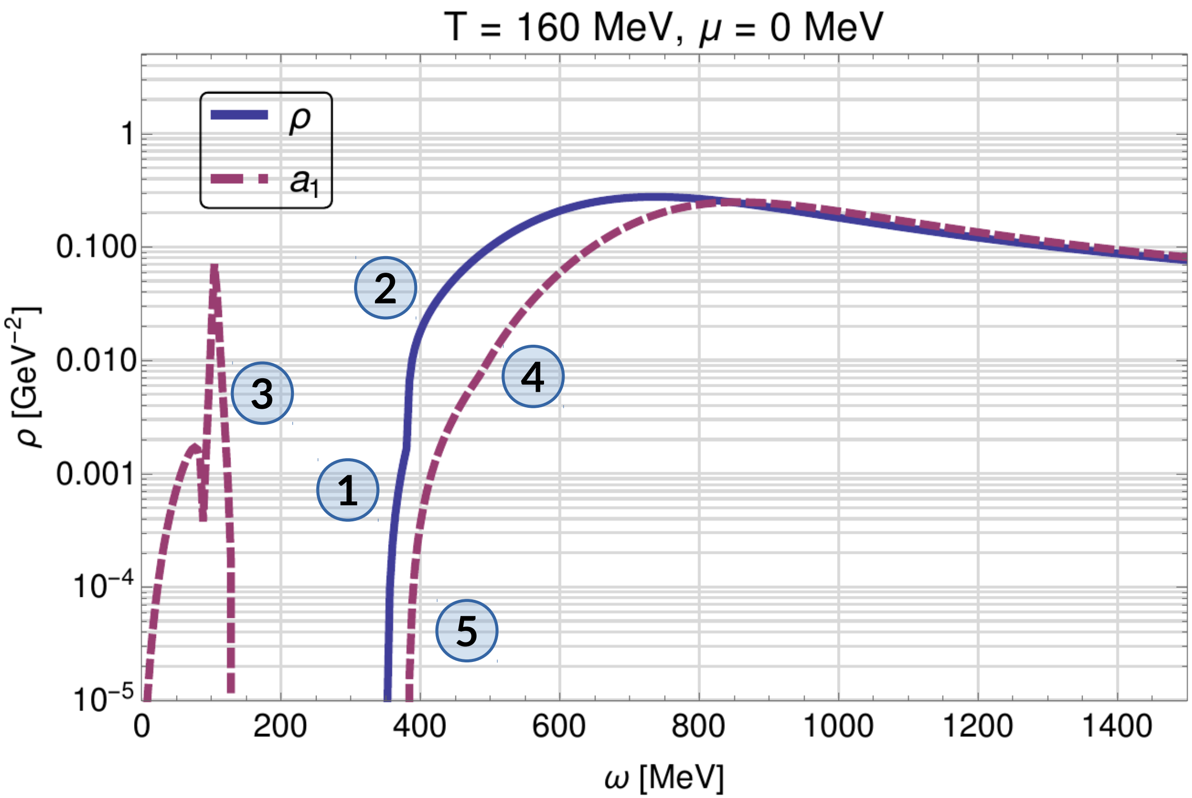

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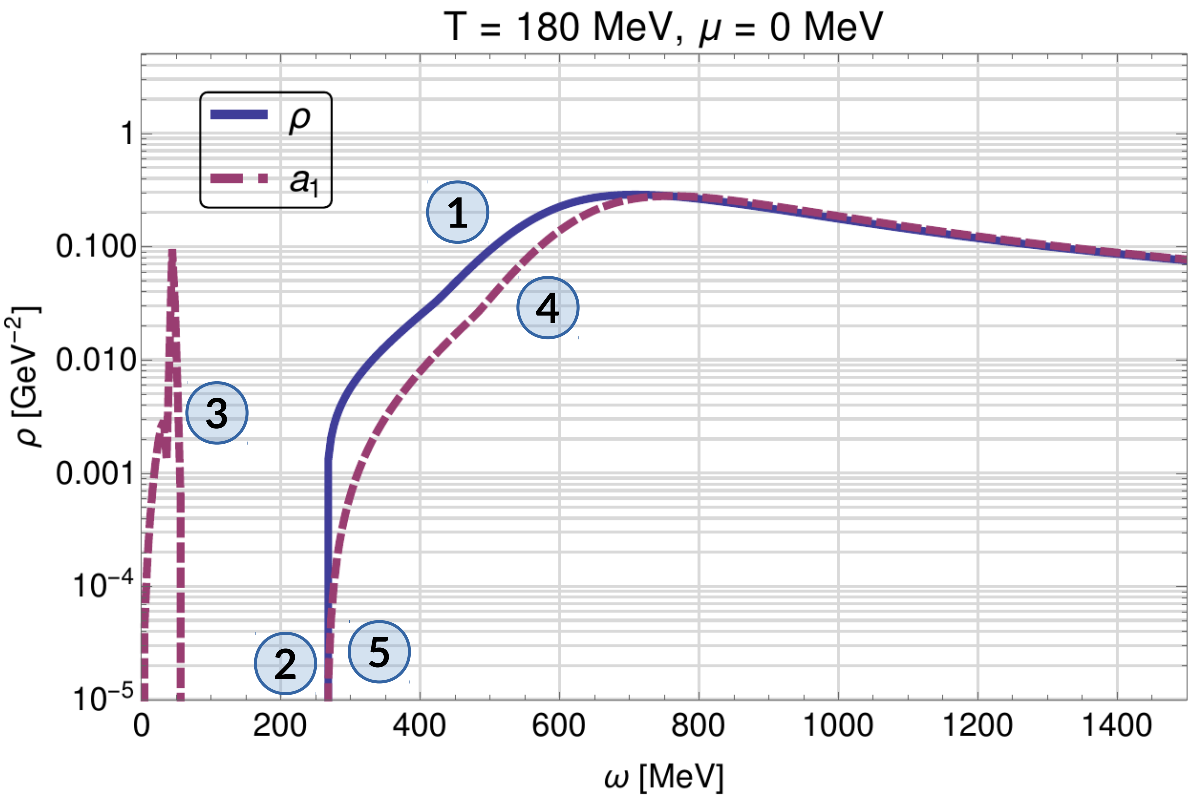

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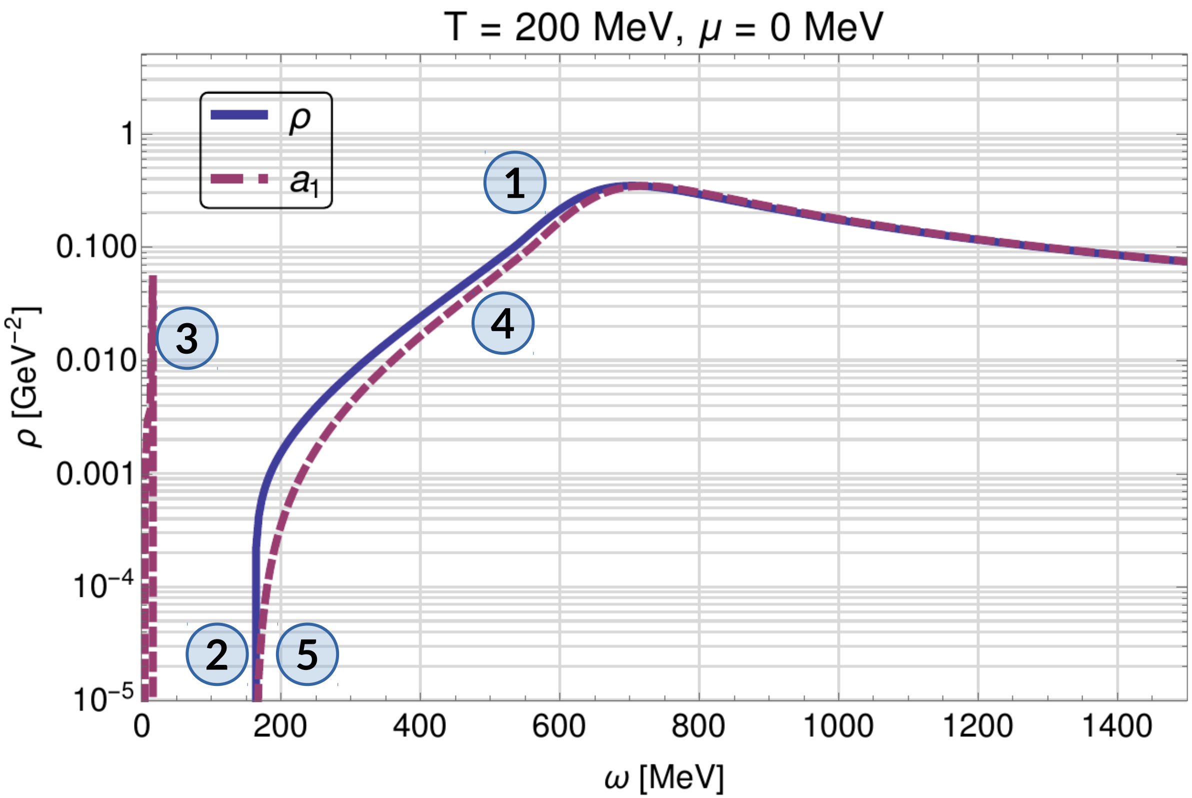

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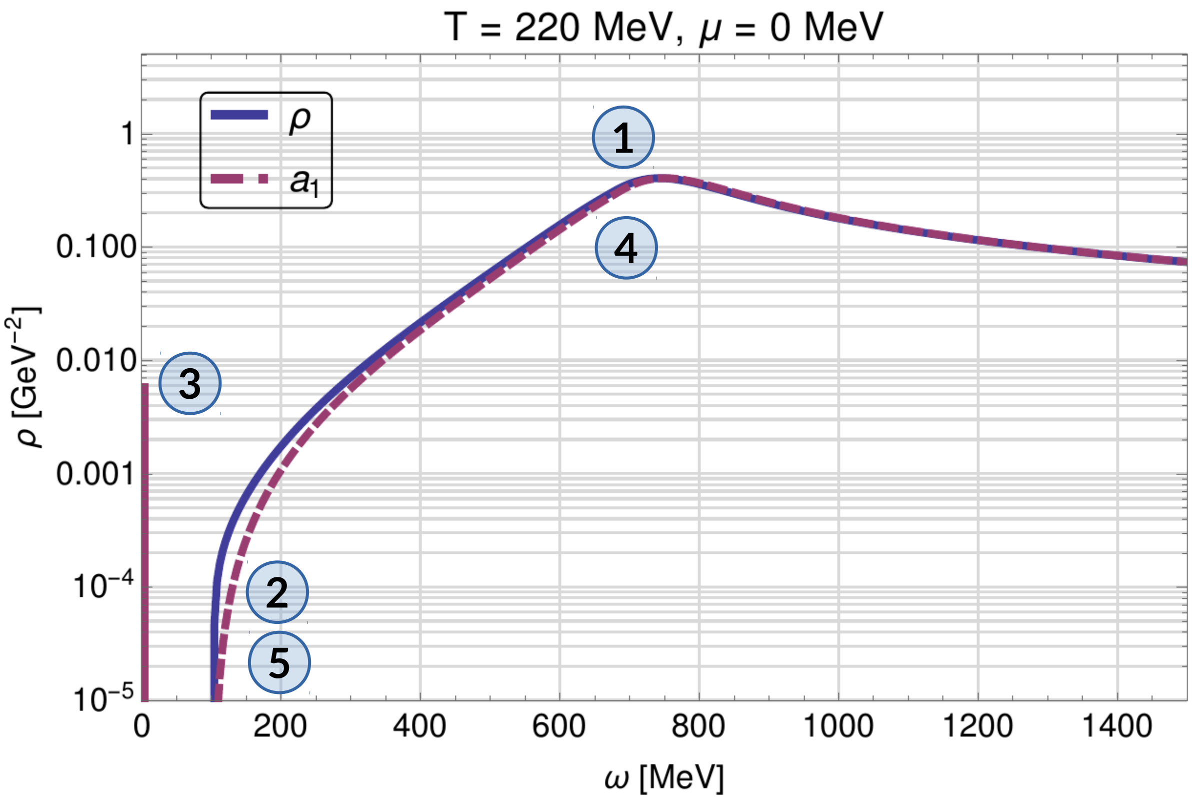

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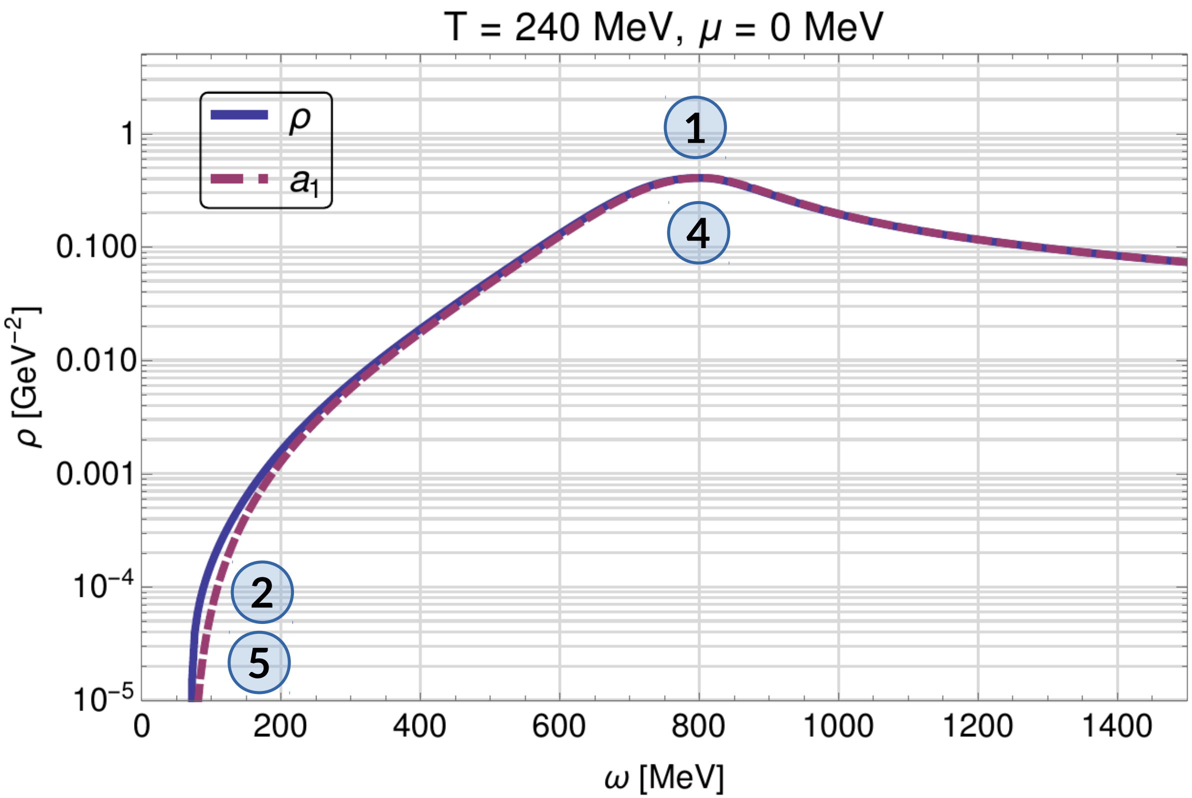

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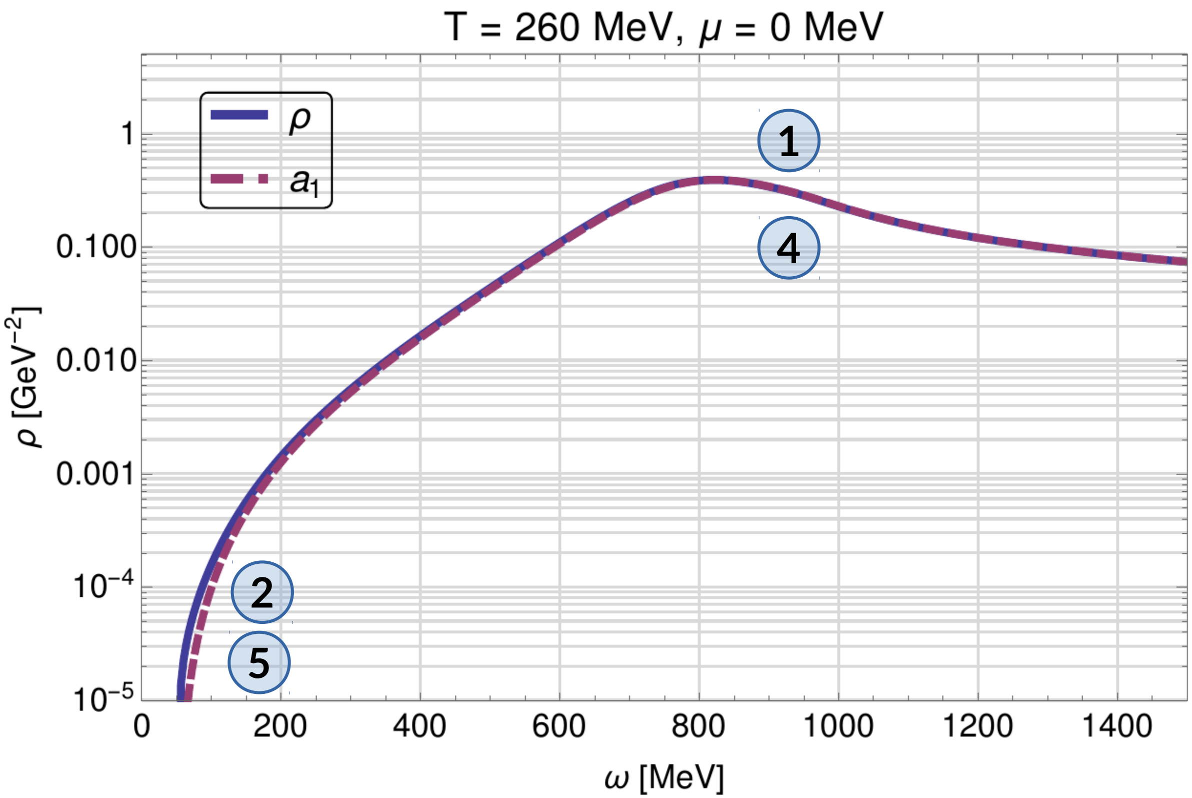

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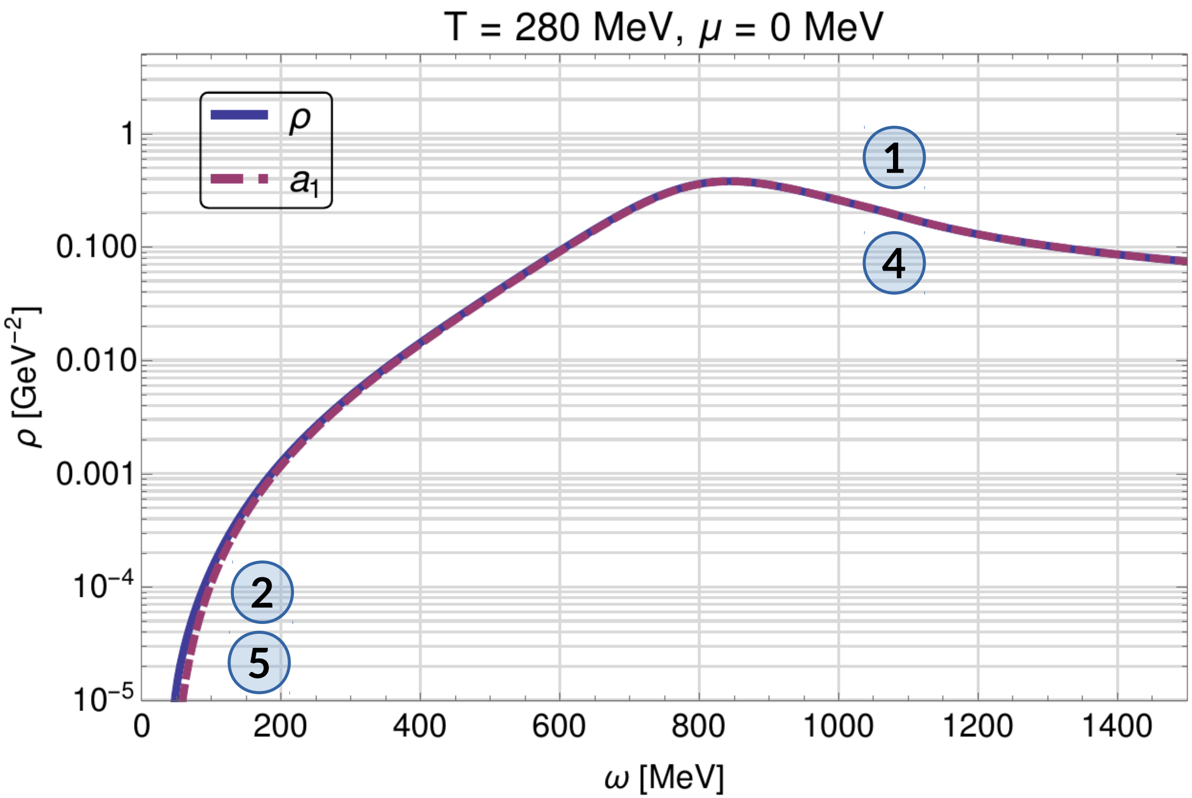

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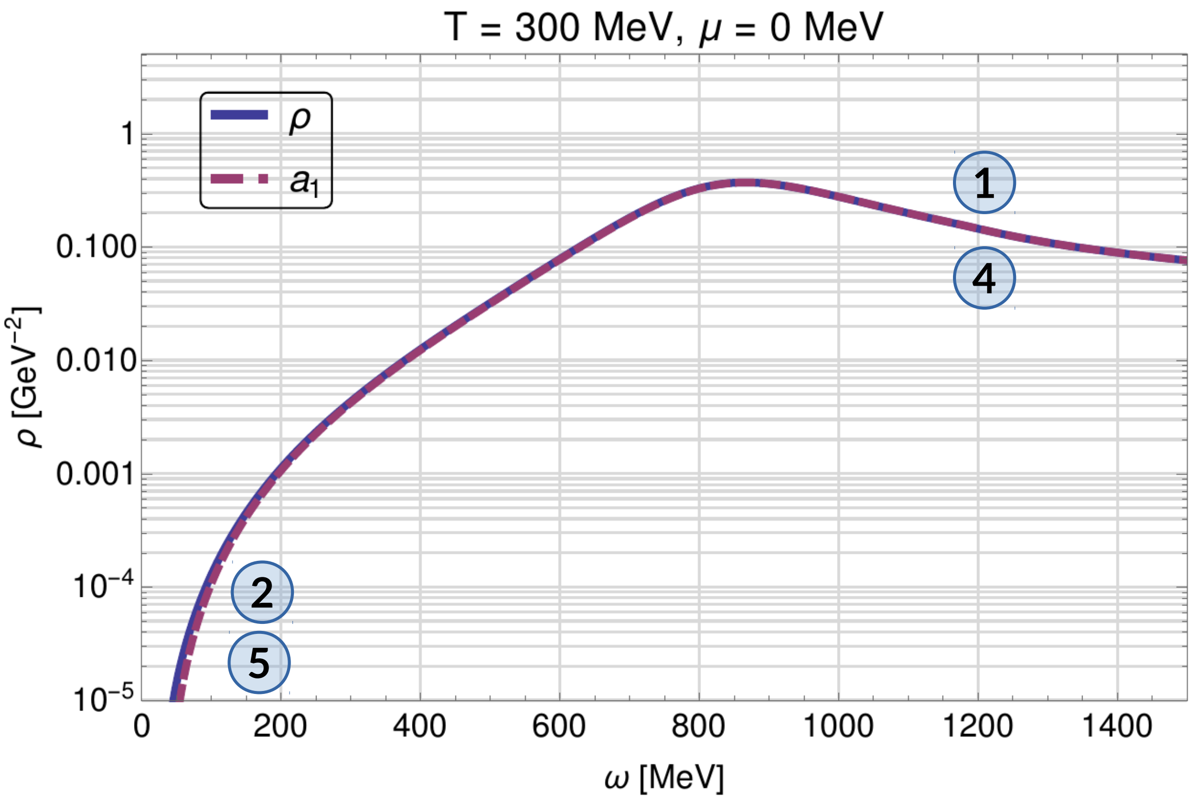

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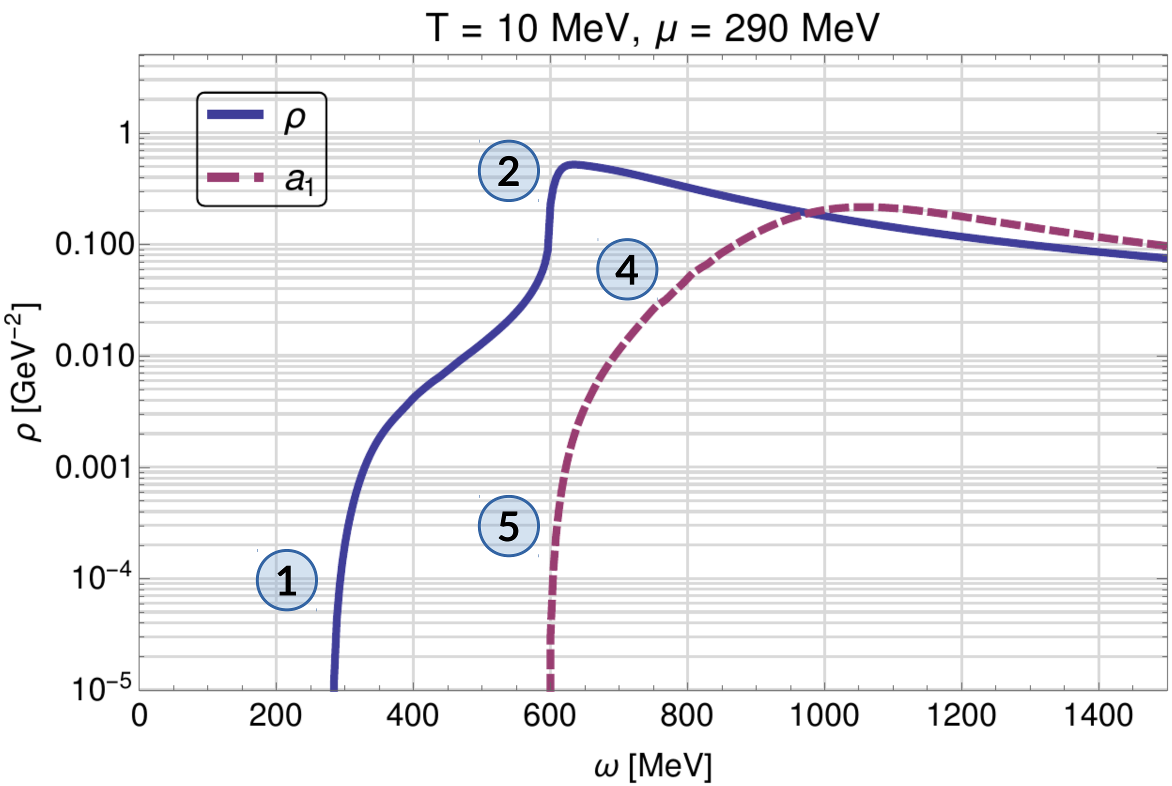
Vector and Axial-Vector SFs

- **finite density, CEP:**

$(\mu_{CEP}, T_{CEP}) = (298, 10)$ MeV



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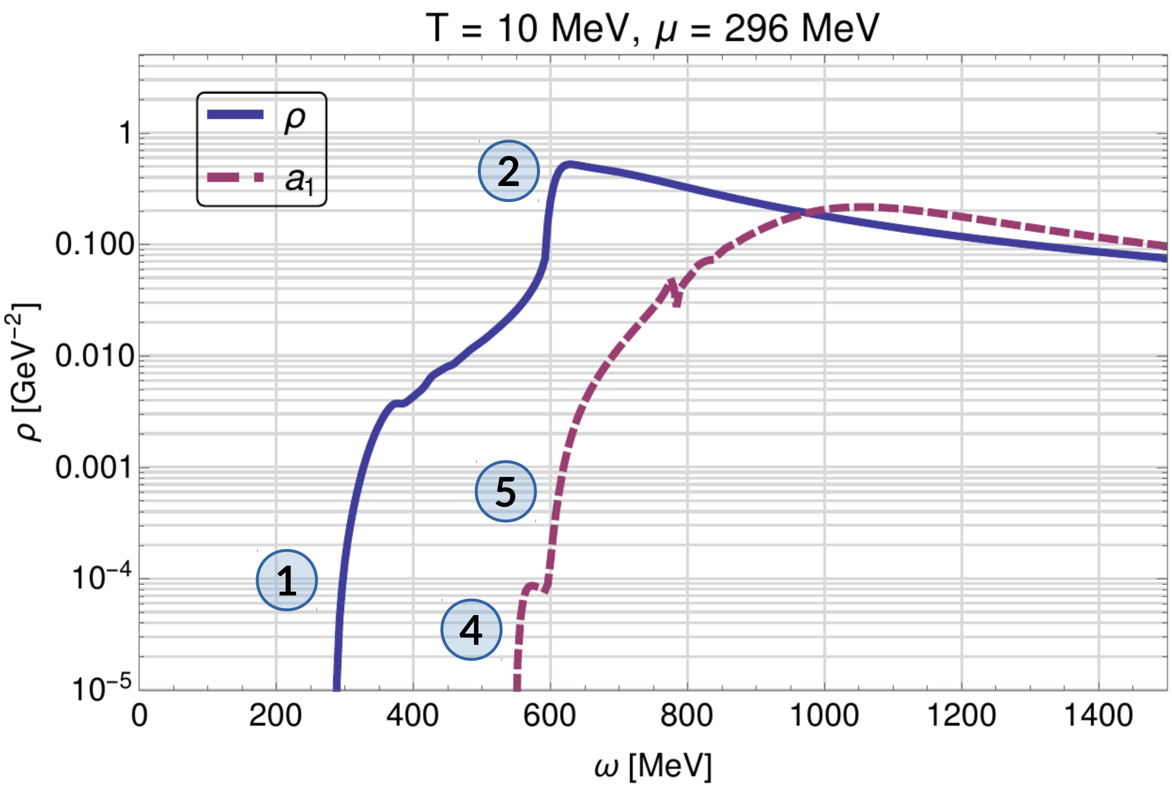

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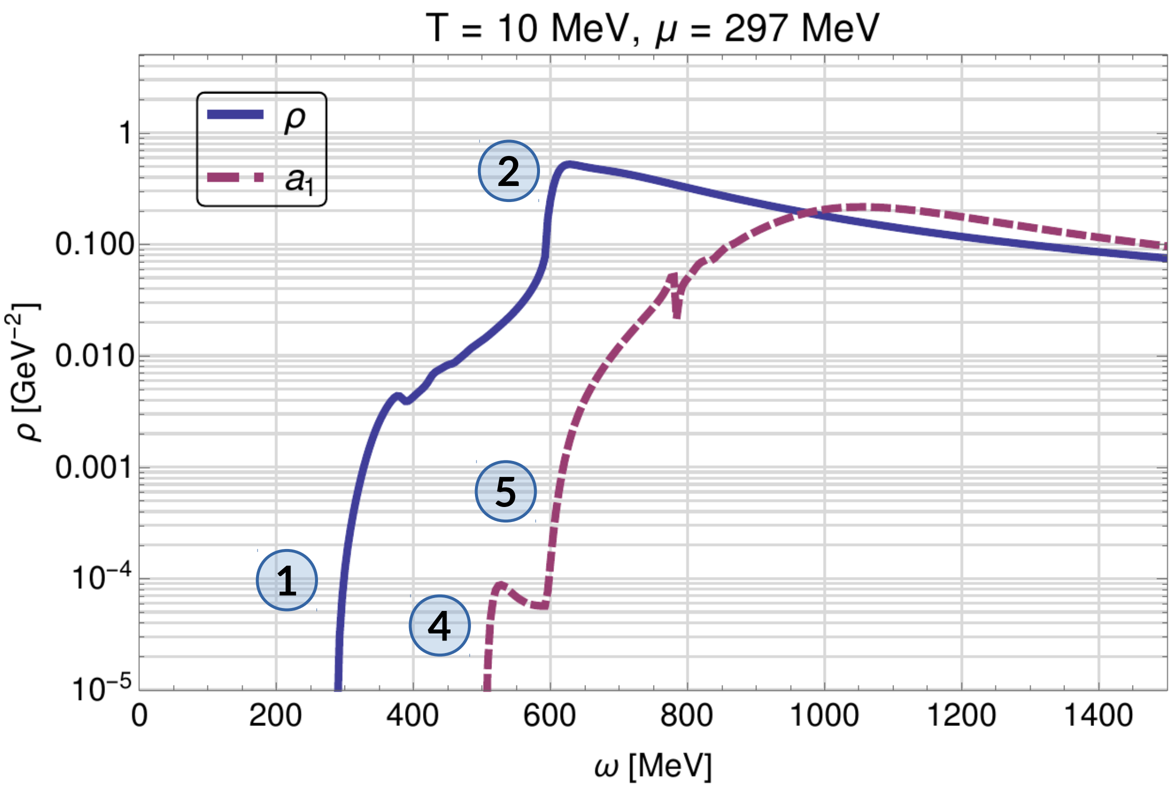

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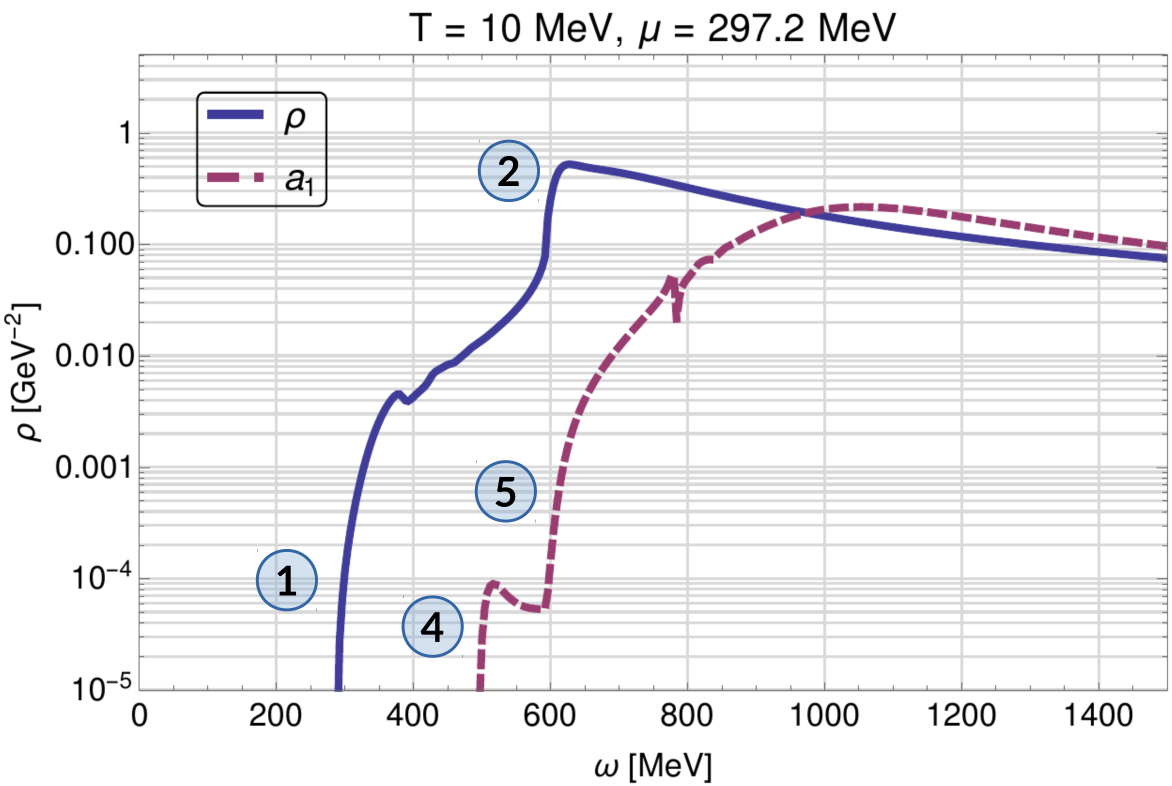

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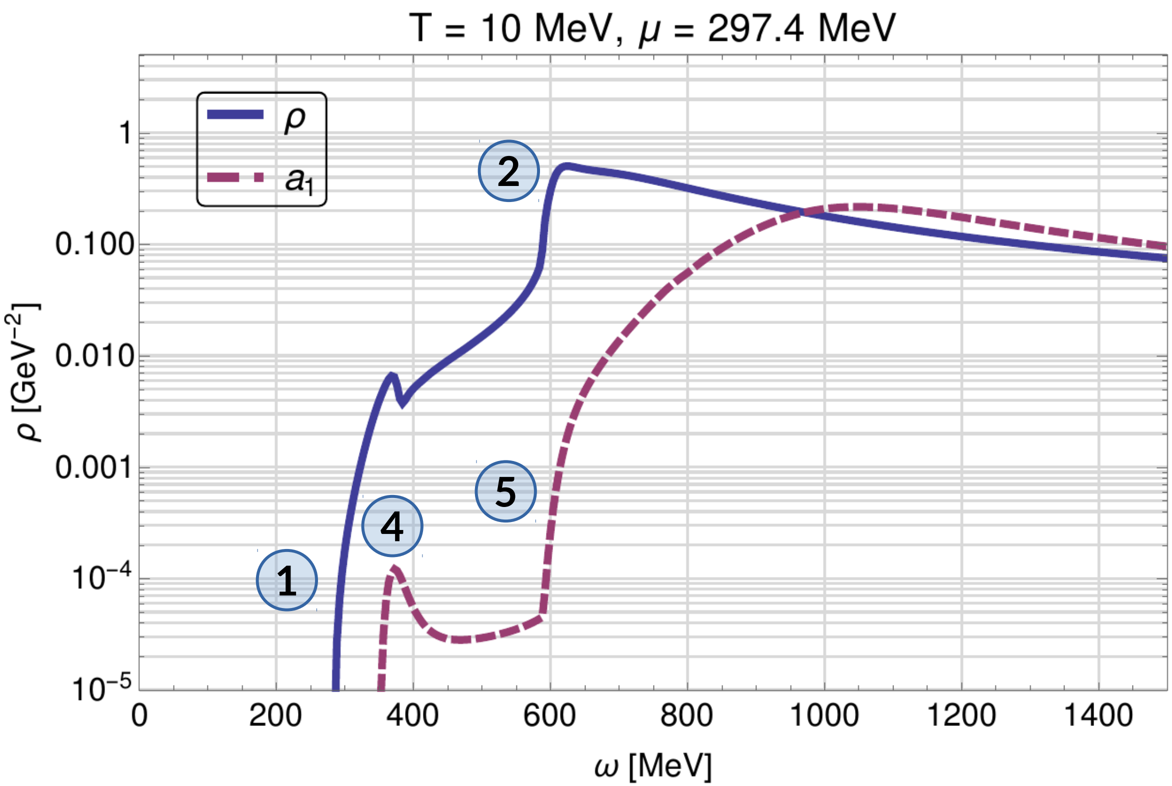

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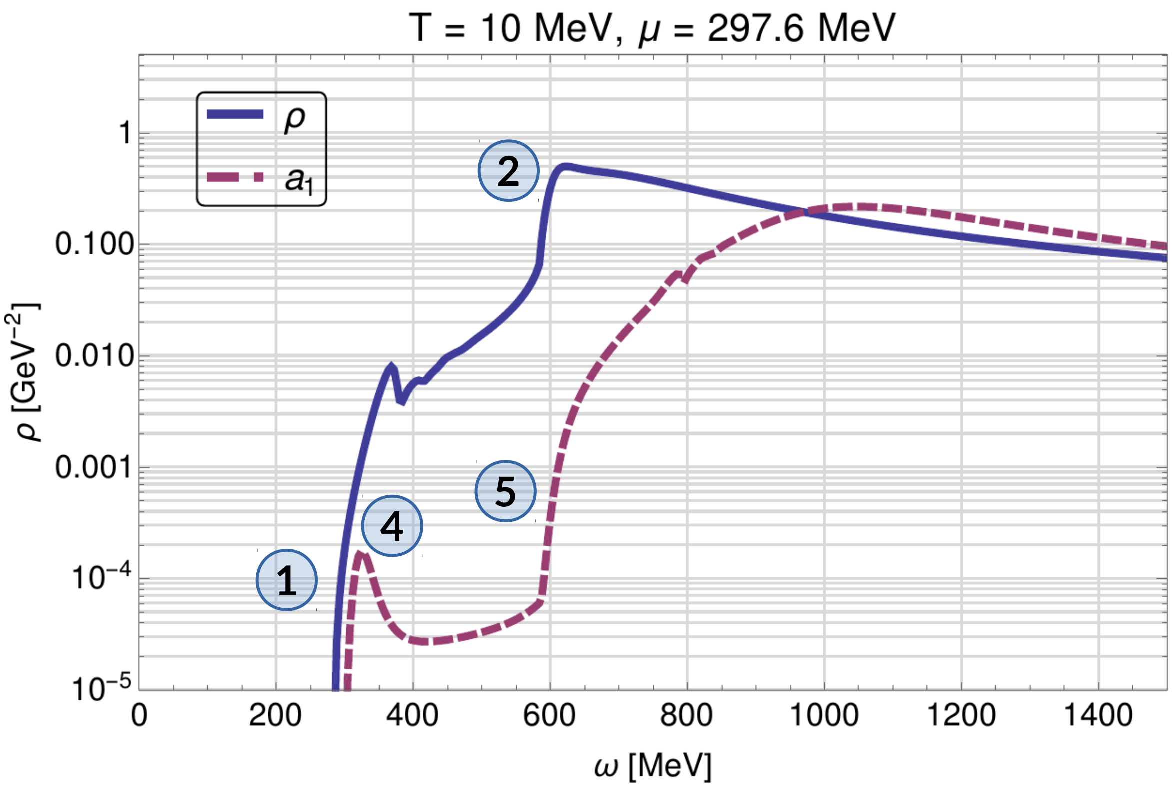

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Vector and Axial-Vector SFs

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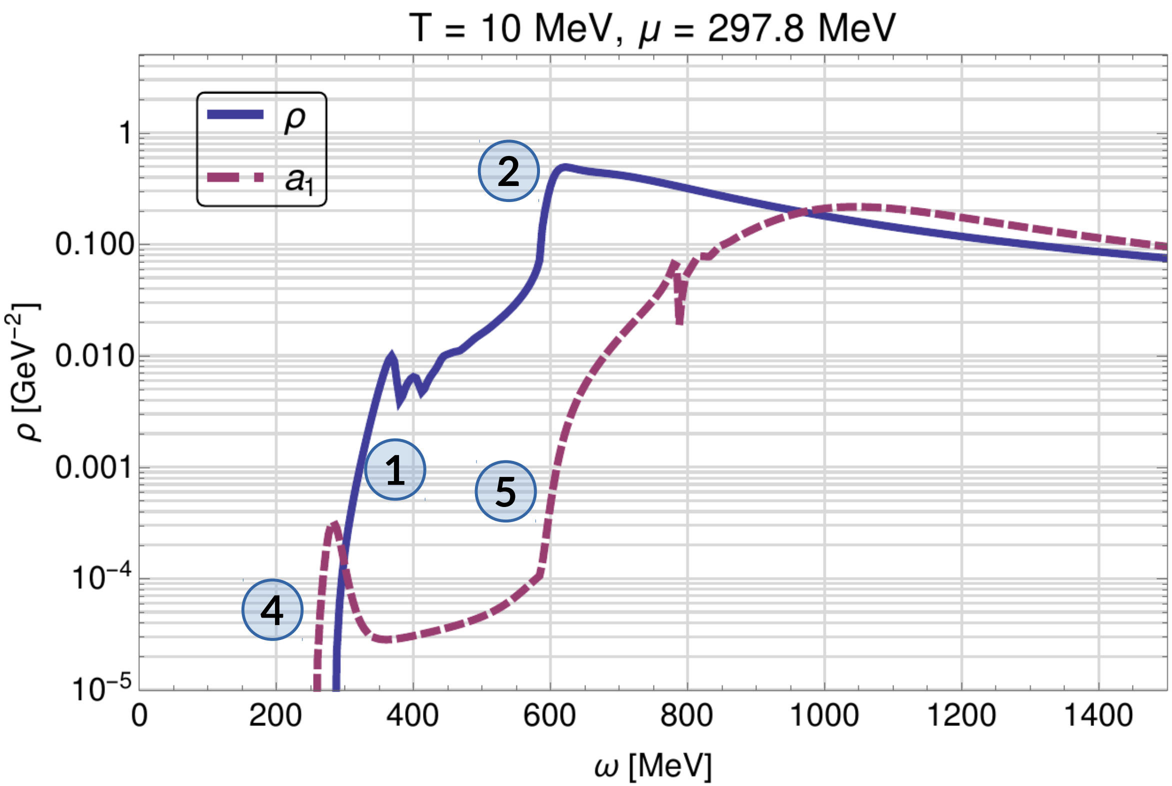

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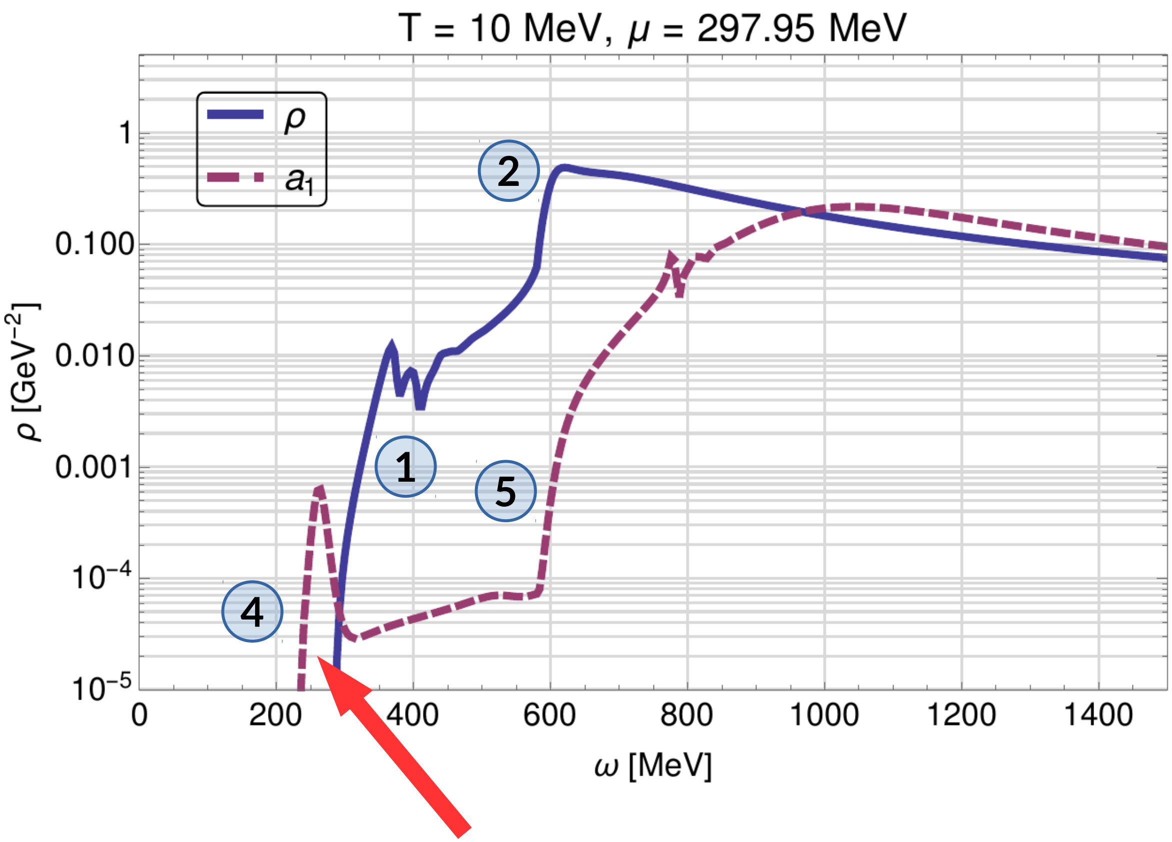

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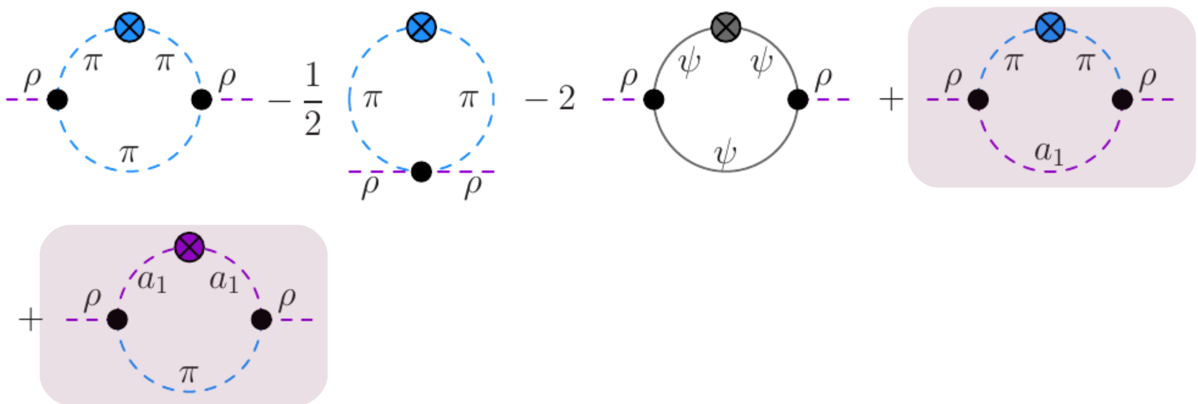
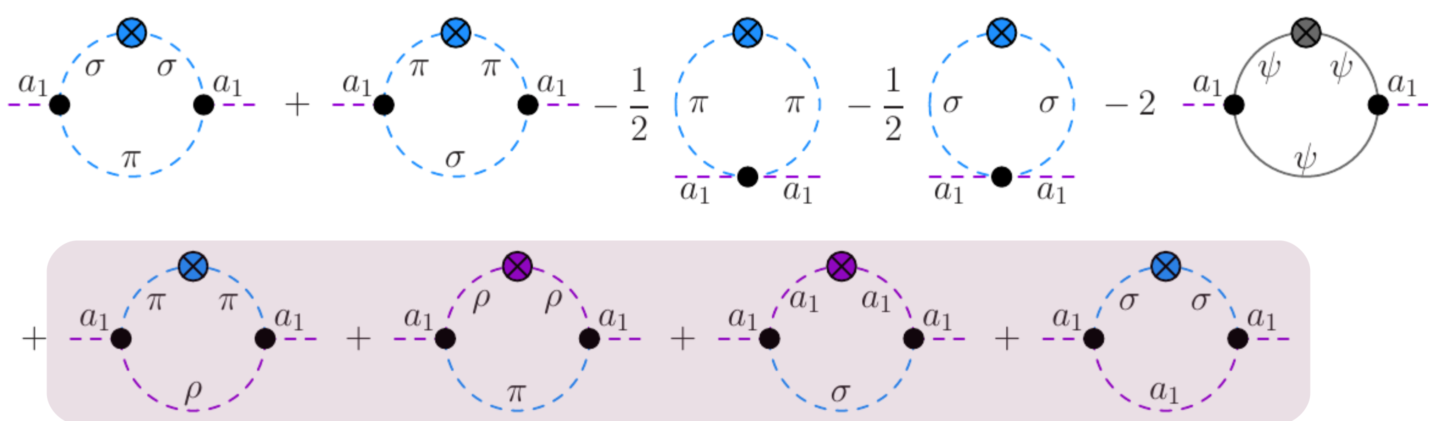
Fluctuating (Axial-) Vectors

$\partial_k \Gamma^{(2)}_{\rho\rho,k} =$



$\partial_k \Gamma^{(2)}_{a_1 a_1,k} =$



Fluctuating (Axial-)Vectors

- **spectral representation of conserved current:**

$$\langle T_{\text{cov}}\, j_\mu(x) j_\nu(0) \rangle = \\ -\,\mathrm{i} \int_0^\infty ds\, \frac{\rho(s)}{s} \int \frac{d^4p}{(2\pi)^4}\, \mathrm{e}^{-\mathrm{i}px}\, \frac{p^2 g_{\mu\nu} - p_\mu p_\nu}{p^2 - s + \mathrm{i}\epsilon}$$

- **current-field identity, transverse vector propagator:**

$$D^{T,V}_{\mu\nu}(p) = -\mathrm{i} \int_0^\infty ds\, \frac{\rho_v(s)}{s} \int \frac{d^4p}{(2\pi)^4}\, \mathrm{e}^{-\mathrm{i}px}\, \frac{p^2 g_{\mu\nu} - p_\mu p_\nu}{p^2 - s + \mathrm{i}\epsilon}$$

$$= -\mathrm{i} \frac{Z}{m_v^2}\, \frac{p^2 g_{\mu\nu} - p_\mu p_\nu}{p^2 - m_v^2 + \mathrm{i}\epsilon} + \dots$$

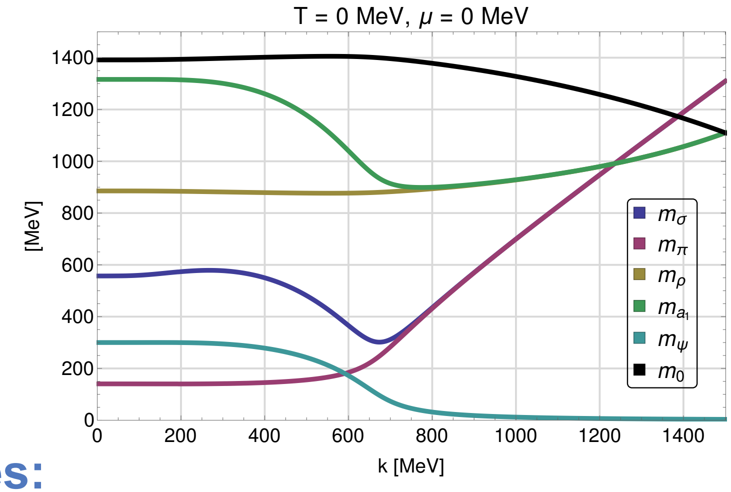
- **Euclidean two-point function, single-particle contribution:**

$$\Gamma^{(2)T}_{\mu\nu}(p) = -\frac{m_0^2}{p^4}\,(p^2 + m_v^2)\,\big(p^2\delta_{\mu\nu} - p_\mu p_\nu\big) \qquad m_{0,k}^2 = m_{v,k}^2 / Z_k$$

Ch. Jung & L.v.S., in preparation

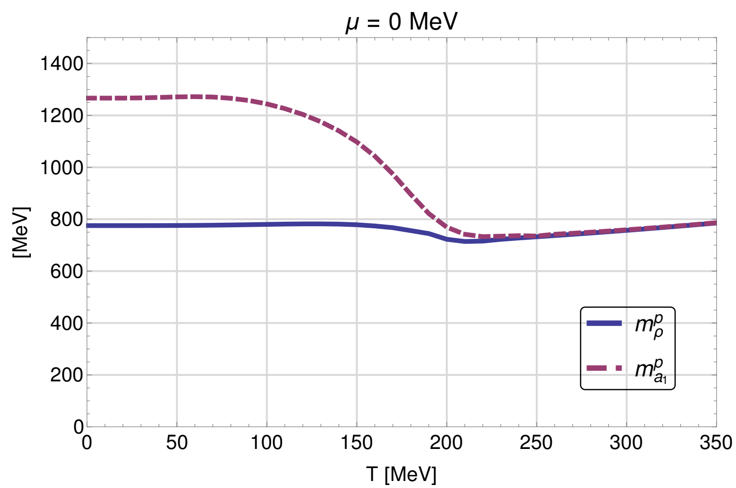
Fluctuating (Axial-)Vectors

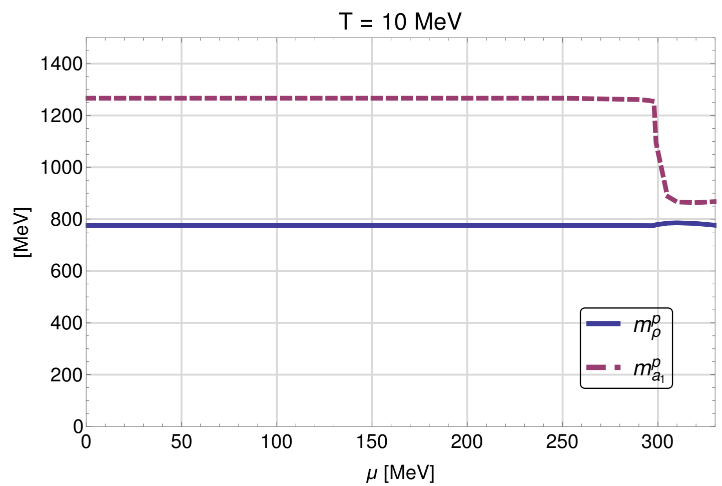
Flow of Euclidean (curvature) masses



- **physical pole masses:**

chiral restoration at finite T and μ





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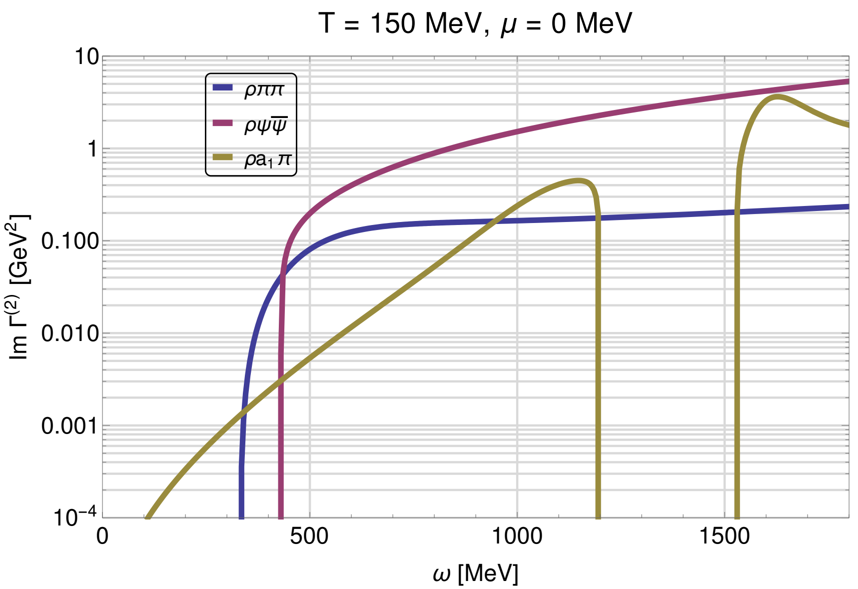
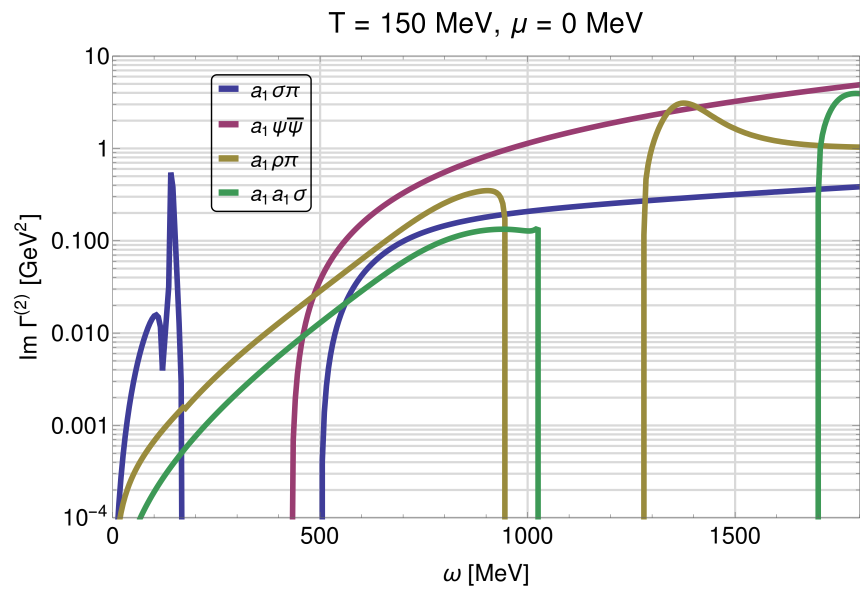
Fluctuating (Axial-)Vectors

- new processes/imaginary parts contribute to SFs:



rho meson



a_1 meson

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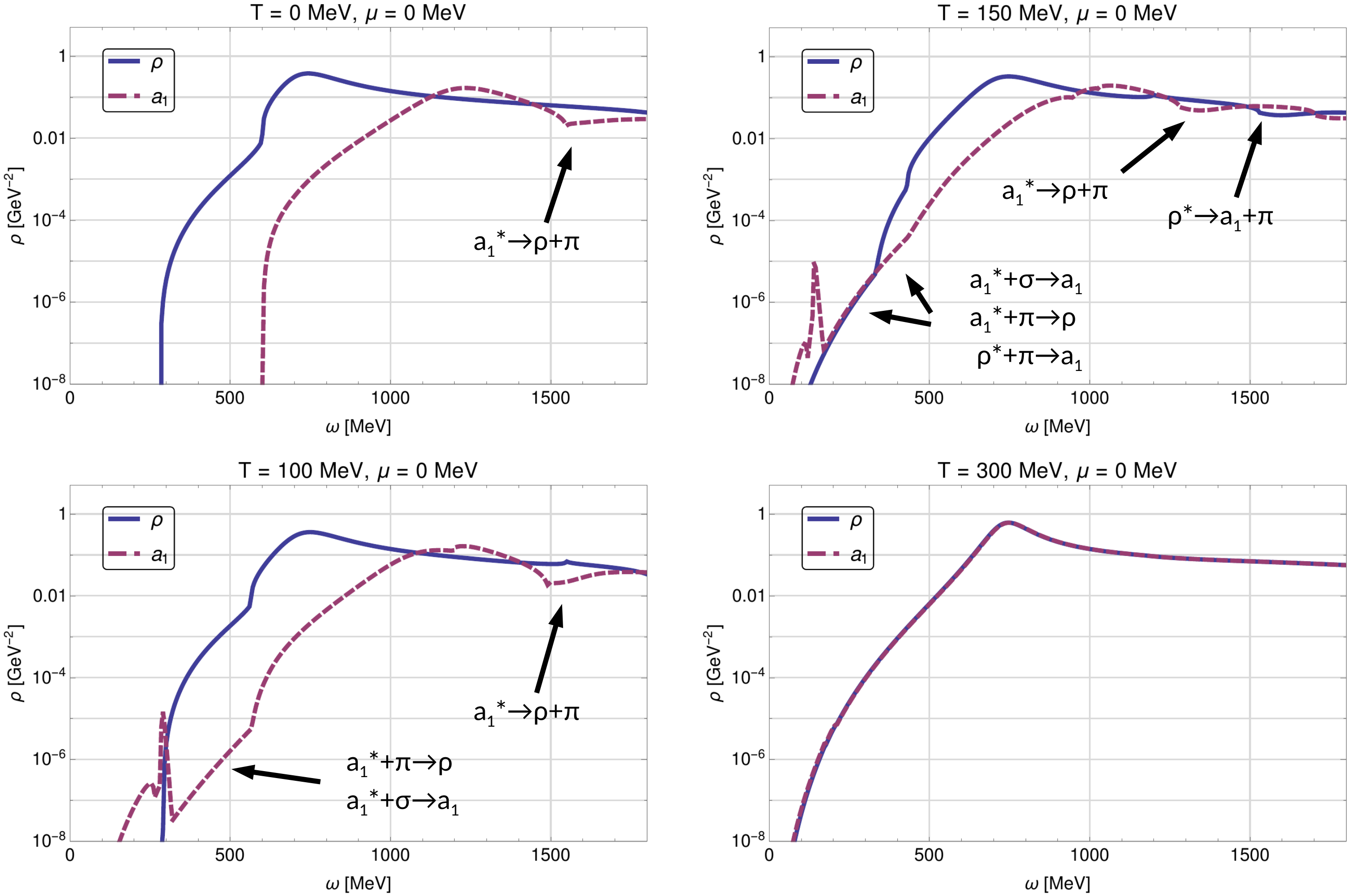

Ch. Jung & L.v.S., in preparation

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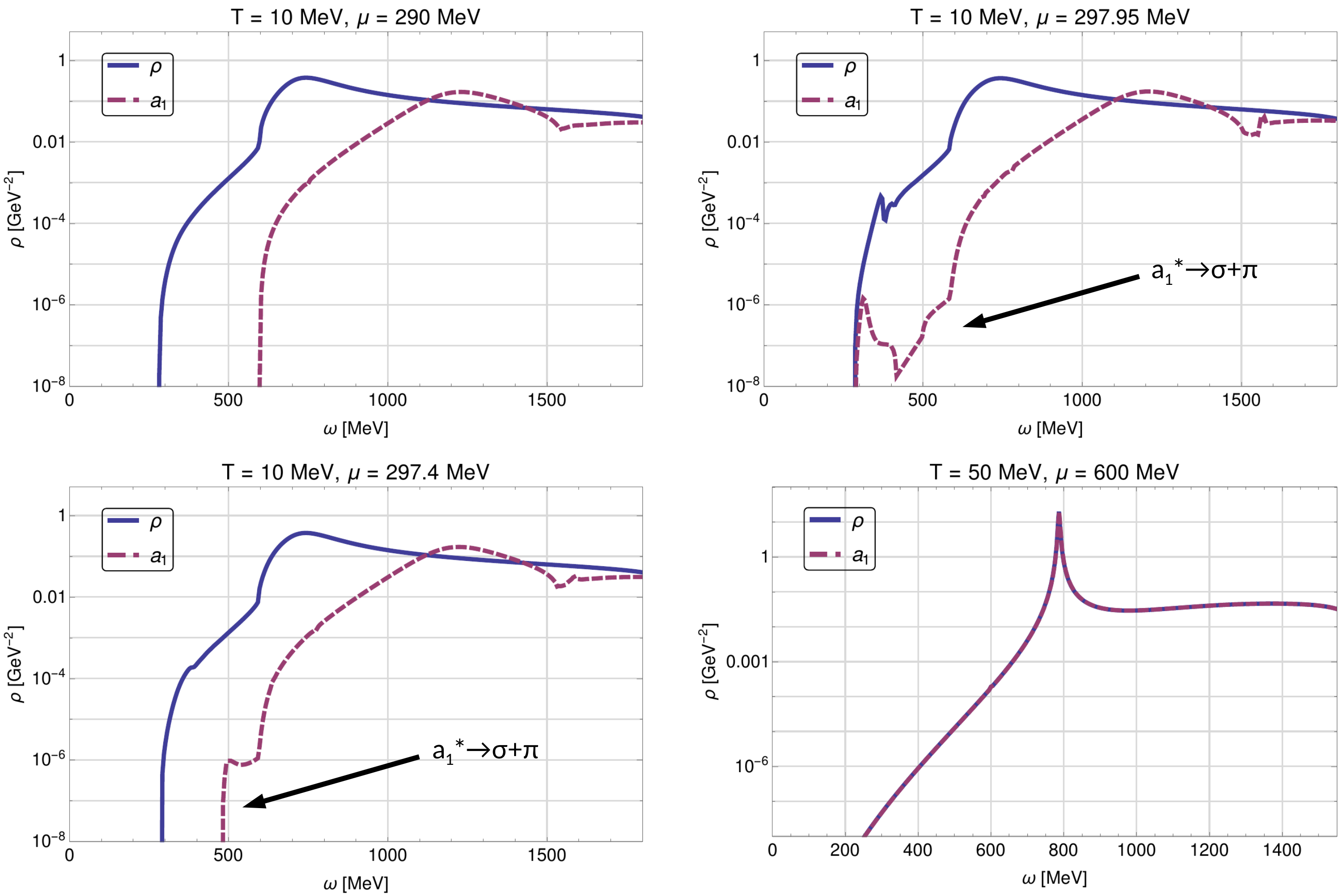


Ch. Jung & L.v.S., in preparation

Summary and Outlook

- **Spectral functions from analytically contd. aFRG flows**

  effective theories (chiral, linear)

- **Vector and axial-vector SFs at finite *T* and *μ***

  melting-rho scenario

- **Fermionic spectral functions**

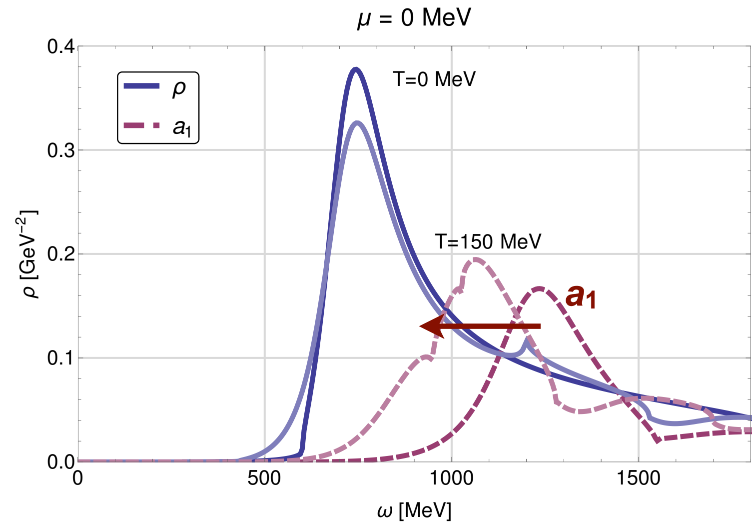
  R.-A. Tripolt, J. Weyrich , L. v. S.
  & J. Wambach, Phys. Rev. D98 (2018) 094002

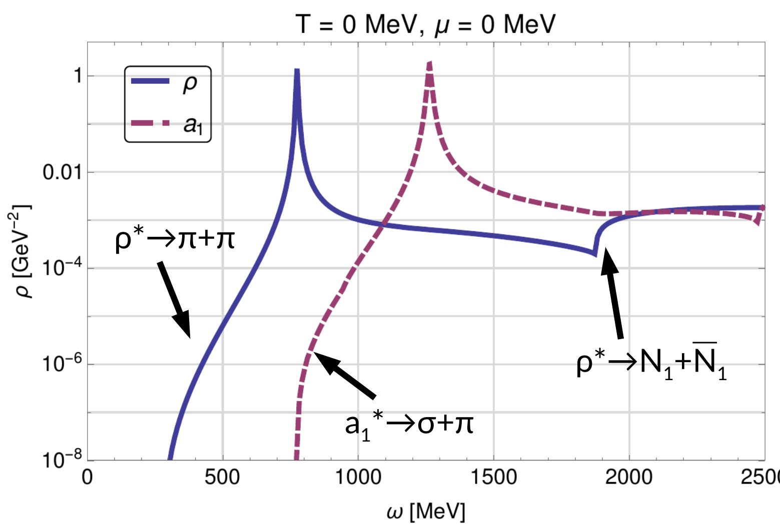
- **Electromagnetic spectral function**

  R.-A. Tripolt, Ch. Jung, N. Tanji, L. v. S.
  & J. Wambach, Nucl. Phys. A982 (2019) 775

- **SFs in nuclear matter, parity doubling**

  Ch. Jung, PhD thesis, JLU 2019





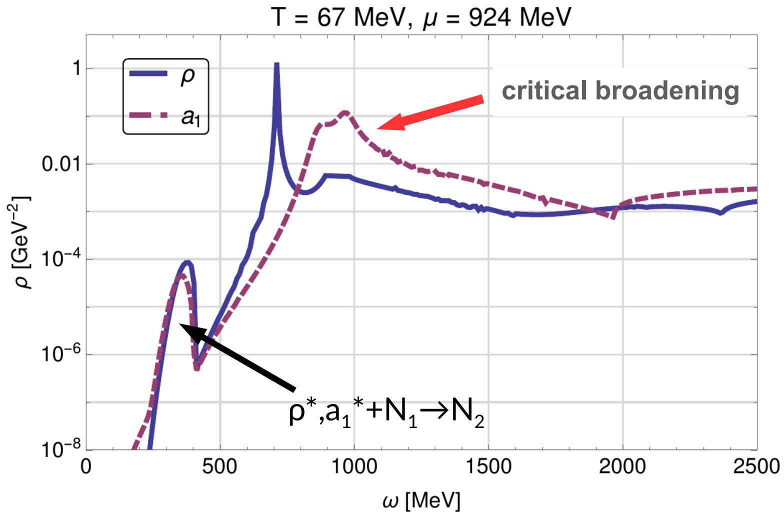
Summary and Outlook

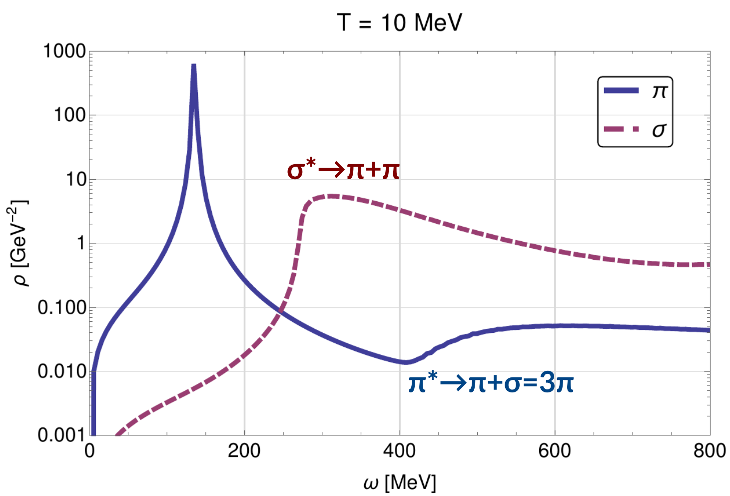
- **SFs in nuclear matter, parity doubling**

  Ch. Jung, PhD thesis, JLU 2019

- **Self-consistent spectral functions**

  O(4)-model, Ch. Jung, N. Wink, J. Pawlowski, & L.v.S., in preparation





Thank you for your attention!