Symmetries and Self–consistency:

Vector mesons at finite Temperature

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Motivation

- Thermodynamics of strongly interacting systems
- Conservation laws, detailed balance, thermodynamical consistency
- Finite width effects (resonance, damping, $\cdots$)

Concepts

- Real time quantum field theory
- The Φ-derivable scheme (example $O(N)$)
- Renormalization
- Restoration of symmetries
- Gauge Symmetries and Vector Mesons

Schwinger-Keldysh Formalism

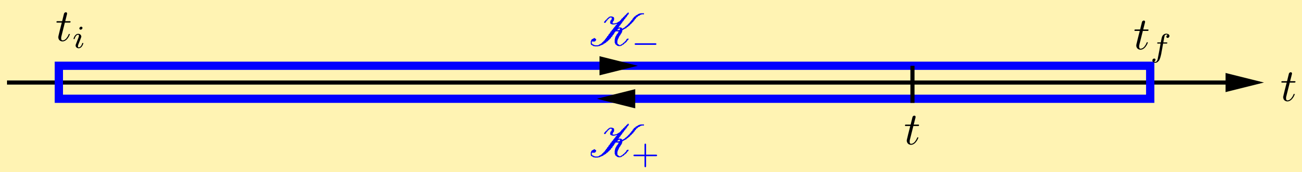
- Initial statistical operator $\boldsymbol{\rho}_i$ at $t = t_i$
- Time evolution

$$\langle O(t)\rangle = \mathrm{Tr}\left[\boldsymbol{\rho}(t_i)\,\underbrace{\mathcal{T}_a\left\{\exp\left[+\mathrm{i}\int_{t_i}^{t}\mathrm{d}t'\mathbf{H}_I(t')\right]\right\}}_{\text{anti time–orderd}}\right.$$

$$\mathbf{O}_I(t)$$

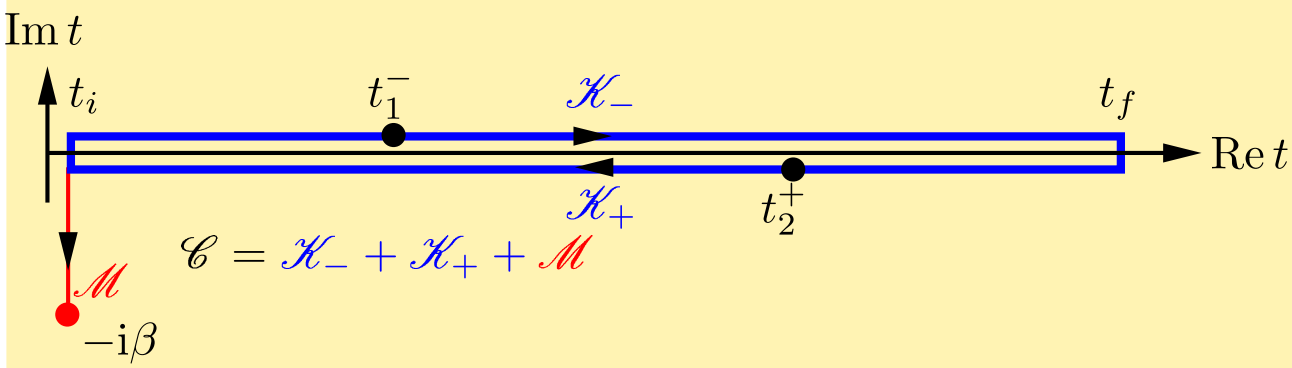
$$\left.\underbrace{\mathcal{T}_c\left\{\exp\left[-\mathrm{i}\int_{t_i}^{t}\mathrm{d}t'\mathbf{H}_I(t')\right]\right\}}_{\text{time–ordered}}\right].$$

- Difference to vacuum: Contour-ordered Green's functions



$\mathscr{C} = \mathscr{K}_- + \mathscr{K}_+$

- In equilibrium: $\boldsymbol{\rho} = \exp(-\beta\mathbf{H})/Z$ with $Z = \mathrm{Tr}\exp(-\beta\mathbf{H})$
- Imaginary part of the time contour



- Correlation functions with real times: $\mathrm{i}G_{\mathscr{C}}(x_1^-, x_2^+)$
- Fields periodic (bosons) or anti-periodic (fermions)
- Feynman rules $\Rightarrow$ time integrals $\rightarrow$ contour integrals

The Φ-Functional

- Introduce local and bilocal auxiliary sources
- Generating functional

$$Z[J,K] = N \int \mathrm{D}\phi \exp\left[\mathrm{i}S[\phi] + \mathrm{i}\,\{J_1\phi_1\}_1 + \left\{\frac{\mathrm{i}}{2}K_{12}\phi_1\phi_2\right\}_{12}\right]$$

- Generating functional for connected diagrams

$$Z[J,K] = \exp(\mathrm{i}W[J,K])$$

- The mean field and the connected Green's function

$$\underbrace{\varphi_1 = \frac{\delta W}{\delta J_1},\ G_{12} = -\frac{\delta^2 W}{\delta J_1 \delta J_2}}_{\text{standard quantum field theory}} \Rightarrow \frac{\delta W}{\delta K_{12}} = \frac{1}{2}[\varphi_1\varphi_2 + \mathrm{i}G_{12}]$$

- Legendre transformation for φ and G:

$$\Gamma[\varphi,G] = W[J,K] - \{\varphi_1 J_1\}_1 - \frac{1}{2}\{(\varphi_1\varphi_2 + \mathrm{i}G_{12})K_{12}\}_{12}$$

- Exact closed form:

$$\Gamma[\varphi,G] = S_0[\varphi] + \frac{\mathrm{i}}{2}\operatorname{Tr}\ln(-\mathrm{i}G^{-1}) + \frac{\mathrm{i}}{2}\left\{D_{12}^{-1}(G_{12} - D_{12})\right\}_{12}$$
$$+ \Phi[\varphi,G] \Leftarrow \text{all closed 2PI interaction diagrams}$$

$$D_{12} = \left(-\Box - m^2\right)^{-1}$$

Equations of Motion

- Physical solution defined by vanishing auxiliary sources:

$$\frac{\delta \mathbb{\Gamma}}{\delta \varphi_1} = -J_1 - \{K_{12}\varphi_2\}_2 \stackrel{!}{=} 0$$

$$\frac{\delta \mathbb{\Gamma}}{\delta G_{12}} = -\frac{\mathrm{i}}{2} K_{12} \stackrel{!}{=} 0$$

- Equation of motion for the mean field φ

$$-\Box\varphi - m^2\varphi := j = -\frac{\delta\Phi}{\delta\varphi}$$

- for the "full" propagator G ⇒ Dyson's equation:

$$-\mathrm{i}(D_{12}^{-1} - G_{12}{}^{-1}) := -\mathrm{i}\Sigma = 2\frac{\delta\Phi}{\delta G_{21}}$$

- Integral form of Dyson's equation:

$$G_{12} = D_{12} + \{D_{11'}\Sigma_{1'2'}G_{2'2}\}_{1'2'}$$

- Closed set of equations of for φ and G

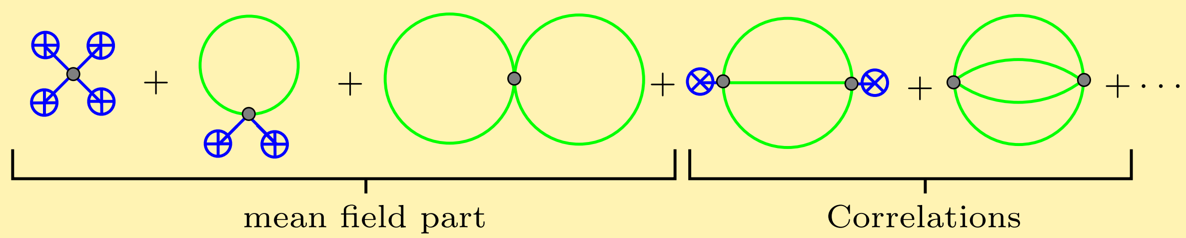
“Diagrammar”

- $O(N)$-theory

$$\mathscr{L} = \frac{1}{2}(\partial_\mu \phi)(\partial^\mu \vec{\phi}) - \frac{m^2}{2}\vec{\phi}^2 - \frac{\lambda}{4!}(\vec{\phi}^2)^2$$

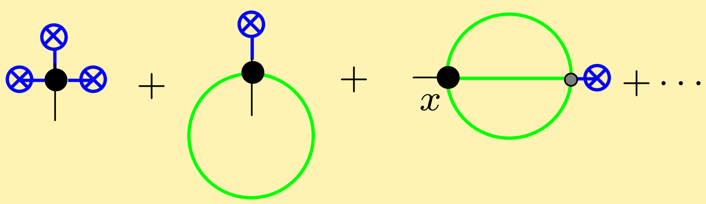
- 2PI Generating Functional

$\mathrm{i}\Phi =$



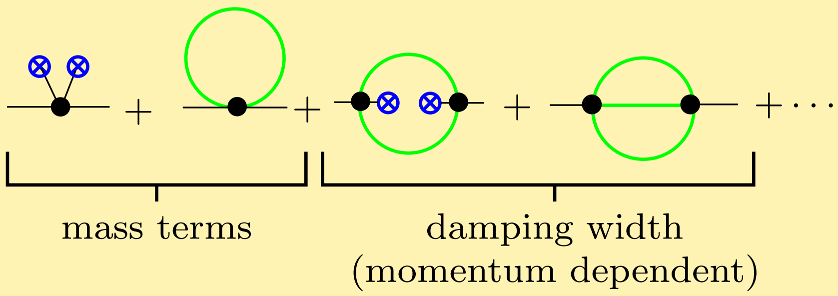
- Mean field equation of motion

$\mathrm{i}(\Box + m^2)\varphi =$



- Self-energy

$-\mathrm{i}\Sigma_{12} =$



Properties of the Φ-derivable Approximations

Why using the Φ-functional?

- Truncation of the Series of diagrams for Φ

☞ Expectation values for currents are conserved
$\Rightarrow$ "Conserving Approximations"

- In equilibrium $\mathrm{i}\Gamma[\varphi, G] = \ln Z(\beta)$
(thermodynamical potential)
- consistent treatment of Dynamical quantities (real time formalism) and thermodynamical bulk properties (imaginary time formalism) like energy, pressure, entropy

- Real- and Imaginary-Time quantities "glued" together by Analytic properties from (anti-)periodicity conditions of the fields (KMS-condition)

- Self-consistent set of equations for self-energies and mean fields

Problem of Renormalization

Why renormalization?

- ☞ Diagrams UV-divergent
- ☞ Control the physical parameters in vacuum
- ☞ Temperature dependence from theory alone

How to renormalize self-consistent diagrams?

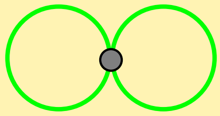
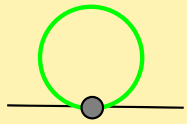
- ☞ In terms of perturbation theory: Resummation of all self-energy insertions in propagators
- ☞ Self-consistent diagrams with explicit nested and overlapping sub-divergences
- ☞ "Hidden" sub-divergences from self-consistency

How to manage it numerically?

- ☞ Power counting (Weinberg) valid for self-consistent diagrams
- ☞ At finite temperatures:
  Self-consistent scheme rendered finite with local counterterms independent of temperature
- ☞ Analytical properties ⇒ subtracted dispersion relations
- ☞ BPHZ-renormalization ⇒ Subtracting the integrands
- ☞ Advantage: Clear scheme how to subtract temperature independent sub-divergences
- ☞ Φ-functional ⇒ consistency of counterterms

Self-Consistent Renormalisation

Example: Tadpole approximation

$\Phi =$  $-\mathrm{i}\Sigma =$ 

- Here: Only time-ordered propagator needed
- The renormalized tadpole $d = 2\omega = 2(2-\epsilon)$:

$$-\mathrm{i}\Sigma = -\frac{\mathrm{i}\lambda}{2}\int \frac{\mathrm{d}^{2\omega}p}{(2\pi)^{2\omega}}\mu^{2\epsilon}\mathrm{i}G(p) + \mathrm{CT}$$

- Self-energy constant in p

☞ temperature dependent effective mass

- Dyson's equation can be resummed:

$$\mathrm{i}G(p) = \frac{\mathrm{i}}{p^2 - M^2 + \mathrm{i}\eta} + 2\pi n(p_0)\delta(p^2 - M^2)$$

$$\text{with } M^2 = m^2 + \Sigma,\ n(p_0) = \frac{1}{\exp(\beta|p_0|) - 1}$$

- Use standard formulae for dimensional regularized Feynman integrals:

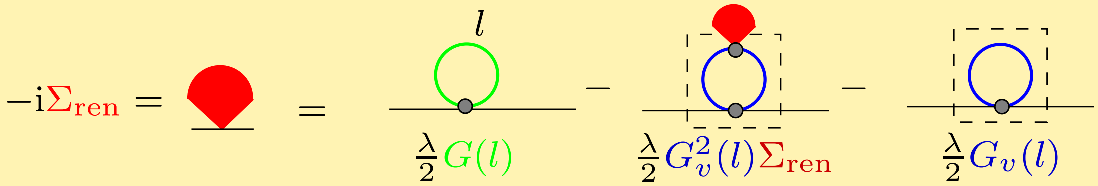
$$\Sigma_{\mathrm{inf}} = -\frac{\lambda}{32\pi^2}M^2\left[\frac{1}{\epsilon} - \gamma + 1 + \ln\left(\frac{4\pi\mu^2}{M^2}\right)\right]$$

- Does one need temperature dependent counter terms ($\propto \lambda M^2/\epsilon$)?

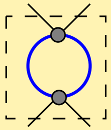
Self-Consistent Renormalisation

How to determine the counterterms?

- Use BPHZ-Renormalization: Subtract the integrands



☞ vertex counterterm

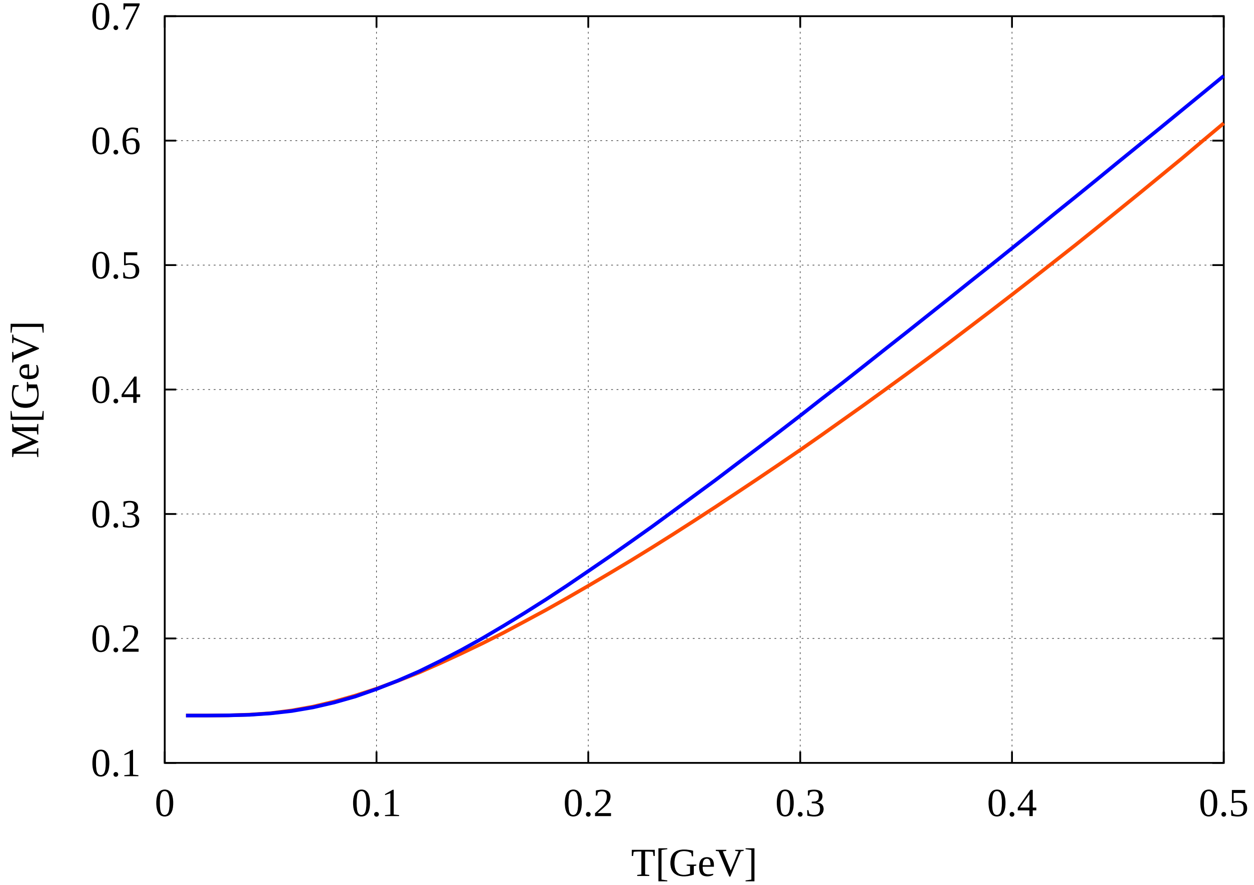

$= \frac{\lambda^2}{2} G_v^2(l)$

Finite Self-consistent equation (gap equation)

$$M^2 = m^2 + \Sigma_{\mathrm{ren}} = m^2 + \frac{\lambda}{32\pi^2}\left(M^2 \ln \frac{M^2}{m^2} - \Sigma_{\mathrm{ren}}\right) + \underbrace{\frac{\lambda}{2}\int \frac{\mathrm{d}^4 p}{(2\pi)^4} 2\pi\delta(p^2 - M^2) n(p_0)}_{\to 0 \text{ for } T \to 0}$$

☞ Renormalisation conditions: $\Sigma_{\mathrm{vac}} = 0$, $\Gamma^{(4)}_{\mathrm{vac}}(p = 0) = \lambda$

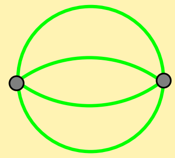
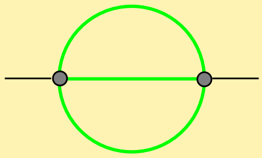
Numerical Results



Numerical solution of the self-consistent tadpole equation compared to the perturbative result for $m = 140\text{MeV}$ and $\lambda = 50$

The Sunset Diagram

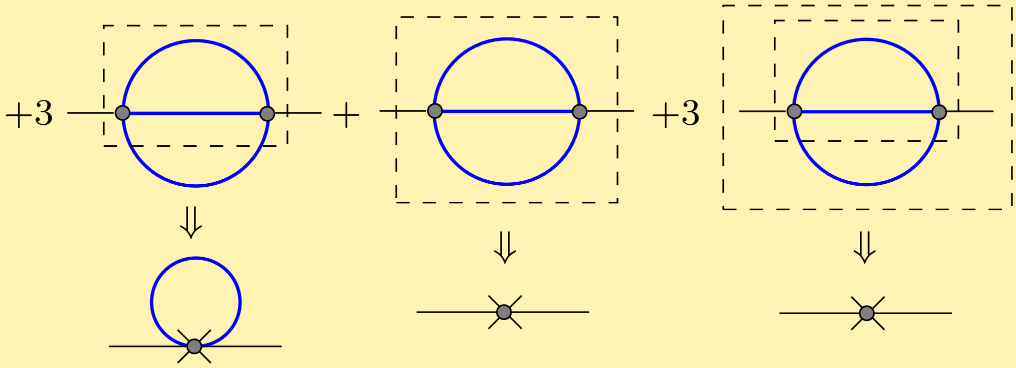
The vacuum part

$\mathrm{i}\Phi =$  $\Leftrightarrow\ -\mathrm{i}\Sigma =$ 

$\frac{1}{2\cdot 4!}$ $\qquad$ $\frac{1}{3!}$

- Overall and sub-divergences to all orders perturbation theory

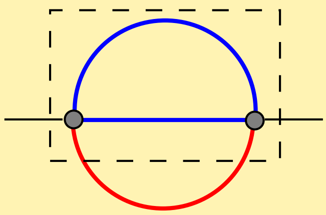
☞ Subtracted dispersion relations for vacuum divergences



At finite temperature

- Split Propagator: $G = G_v + G_T$
- $\delta(G_T) < -4$

☞ Only one sub-divergence:

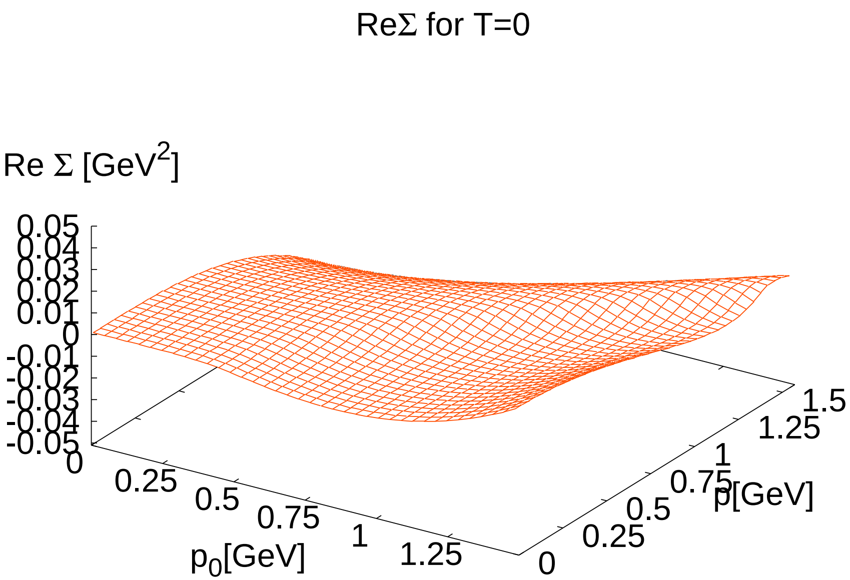


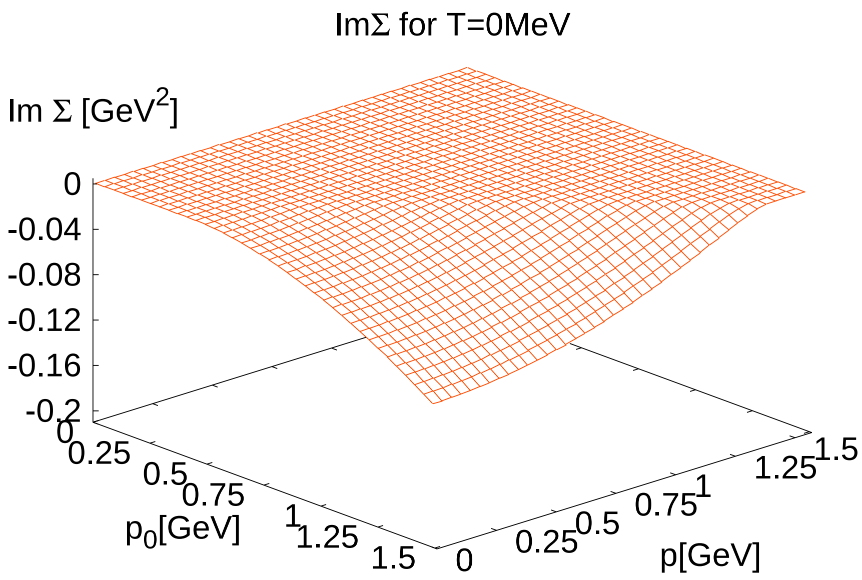
☞ Adding also tadpole $\Rightarrow \delta(G_T) = -4$

☞ Additional complications treatable in the same way!

☞ Coupled Eqs. for $\Sigma^{\mathrm{tad}}_{\mathrm{ren}}$ and $\Sigma^{\mathrm{sunset}}_{\mathrm{ren}}$

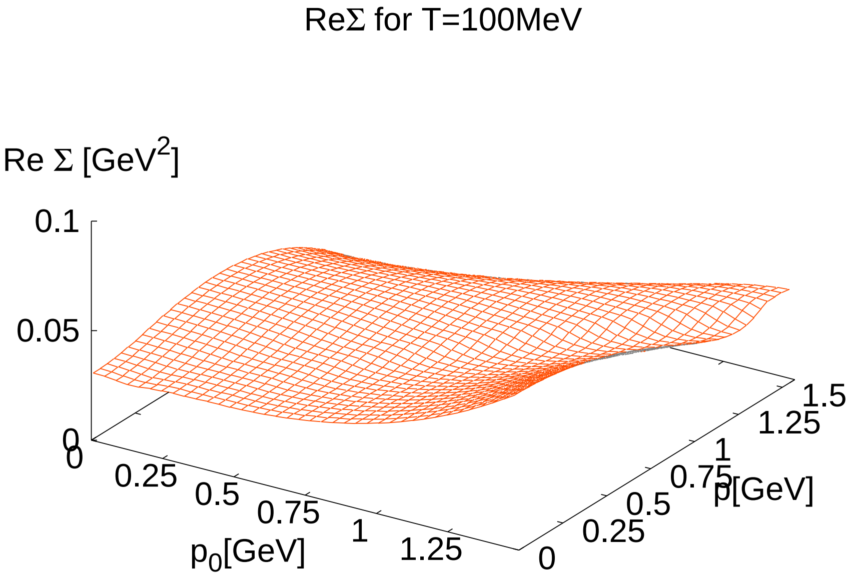
Results for the Vacuum Sunset Diagram

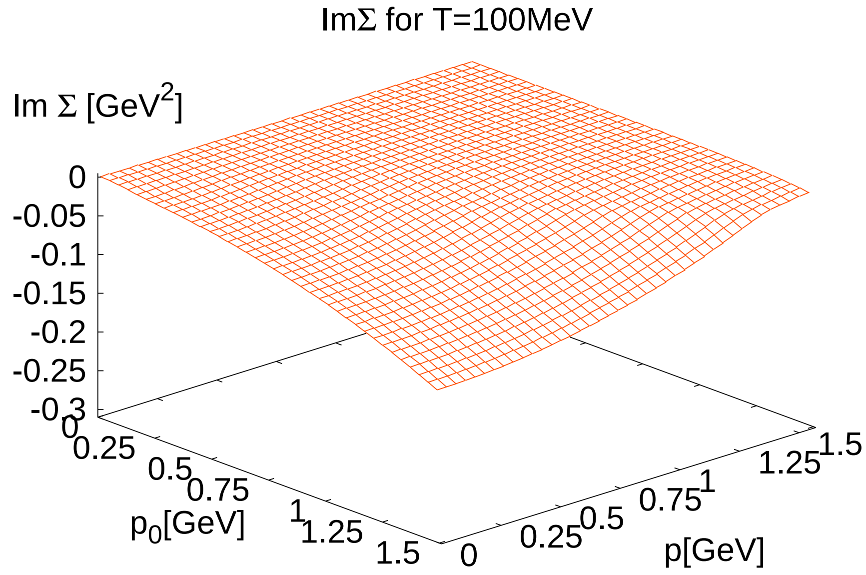




Vacuum: $m = 140\text{MeV}$, $\lambda = 65$

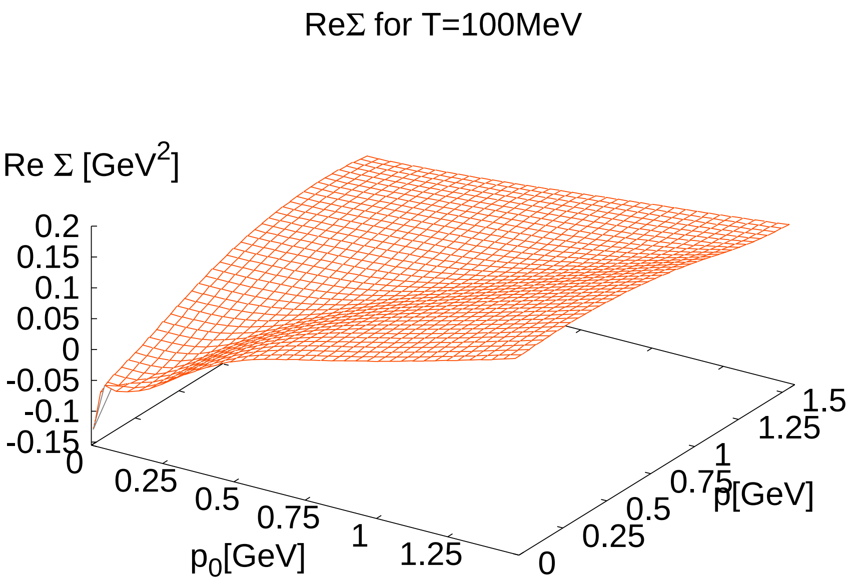
Perturbative Result for "Sunset + Tadpole" at $T > 0$

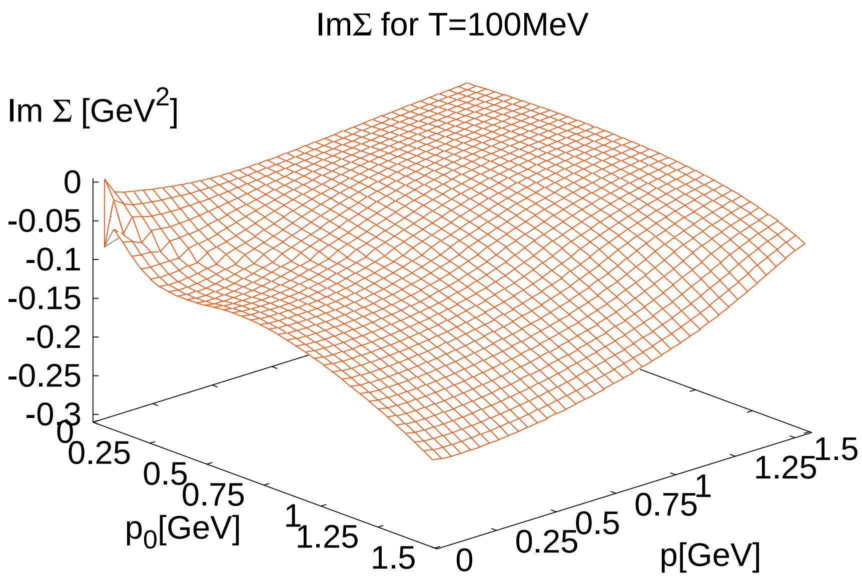




$T = 100\text{MeV}$

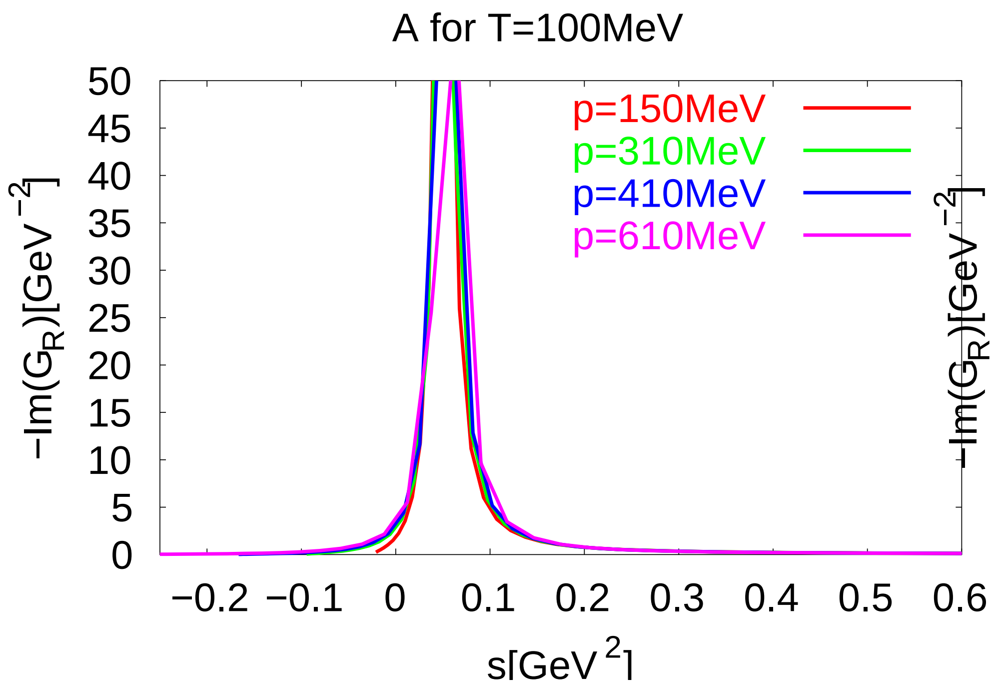
Self-consistent Result for "Sunset + Tadpole" at $T > 0$

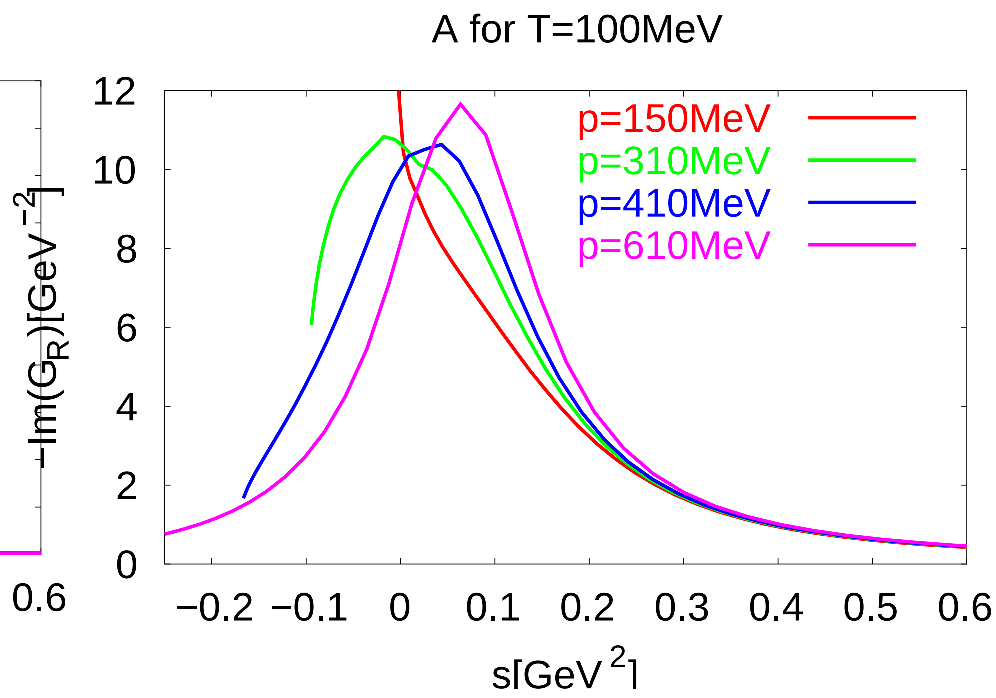




$T = 100\text{MeV}$

Spectral function of the "Meson"





$T = 100$MeV:Perturbative (left) and self-consistent (right) calculation

The Analytic Green's Function

The imaginary part of the contour

- So far real-time formalism
- Entropy, pressure, mean energy,$\cdots$

- Analytic propagator
- Branch of analytic continuation of $G_{\text{Matsubara}}$

$$G_C(p_0, \vec{p}) = \int \frac{\mathrm{d}z'}{2\pi} \frac{A(z', \vec{p})}{z' - p_0} \text{ with}$$
$$\forall z \in \mathbb{R} : \mathbb{R} \ni \ A(z, \vec{p}) = -A(-z, \vec{p}) = -2\,\mathrm{Im}\, G_R(z, \vec{p})$$

- Causality structure of G_R and G_A

$$G_C(p_0 \pm \mathrm{i}0) = -G_{R/A}(p) \text{ for } p_0 \in \mathbb{R}$$

- Matsubara-propagator

$$G_M(\mathrm{i}\omega_n, \vec{p}) = G_C(\mathrm{i}\omega_n, \vec{p}) \text{ with } \omega_n = \frac{2\pi\mathrm{i}}{\beta} n = 2\pi \mathrm{i} n T,\ n \in \mathbb{Z}$$

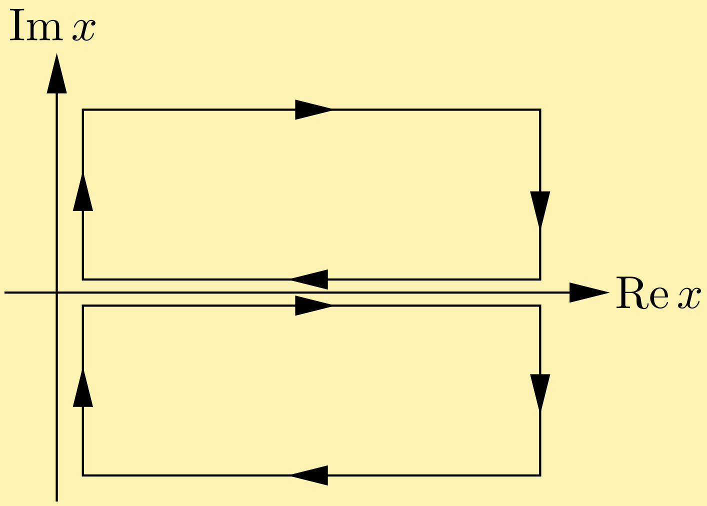
Matsubara Sums

Summing over Matsubara frequencies

- $F(z)$: analytic in an open strip around imaginary axis

$$\frac{1}{\beta}\sum_{n\in\mathbb{Z}} F(\mathrm{i}\omega_n) = \frac{1}{2\pi\mathrm{i}}\int_{-\mathrm{i}\infty+\epsilon}^{\mathrm{i}\infty+\epsilon} \mathrm{d}x[F(x)+F(-x)]\left[\frac{1}{2}+\frac{1}{\exp(\beta x)-1}\right]$$

- F(z): also analytic away from the real axis



$$\frac{1}{\beta}\sum_{n\in\mathbb{Z}} F(\mathrm{i}\omega_n) = \frac{1}{2\pi\mathrm{i}}\int_{-\infty}^{\infty} \mathrm{d}x\frac{1}{2}[F(x-\mathrm{i}\epsilon\sigma(x)) - F(x+\mathrm{i}\epsilon\sigma(x))] +$$

$$+\frac{1}{2\pi\mathrm{i}}\int_{-\infty}^{\infty} \mathrm{d}x n(x)[F(x-\mathrm{i}\epsilon\sigma(x)) - F(x+\mathrm{i}\epsilon\sigma(x))]$$

The Entropy

Thermodynamical properties

- Expectation values from thermal quantum field theory:

$$Z(\beta, V) = \operatorname{Tr} \exp(-\beta \mathbf{H})$$
$$\Rightarrow \varepsilon = \frac{1}{V} \langle \mathbf{H} \rangle = -\frac{1}{V} \partial_\beta \ln Z, \quad \frac{1}{V} \mathrm{d}(\beta \ln Z) = -\varepsilon \mathrm{d}\beta$$

- Define thermodynamical quantities:

$$P = \frac{\ln Z}{\beta V}, \; s = \beta(P + \varepsilon) \Rightarrow \mathrm{d}P = s\mathrm{d}T$$

- Solution of the real time Φ-derived self-consistent equations

$$\ln Z = \mathrm{i}\Gamma \Rightarrow P = \mathrm{i}\Gamma \Rightarrow s = \mathrm{i}\partial_T \Gamma$$

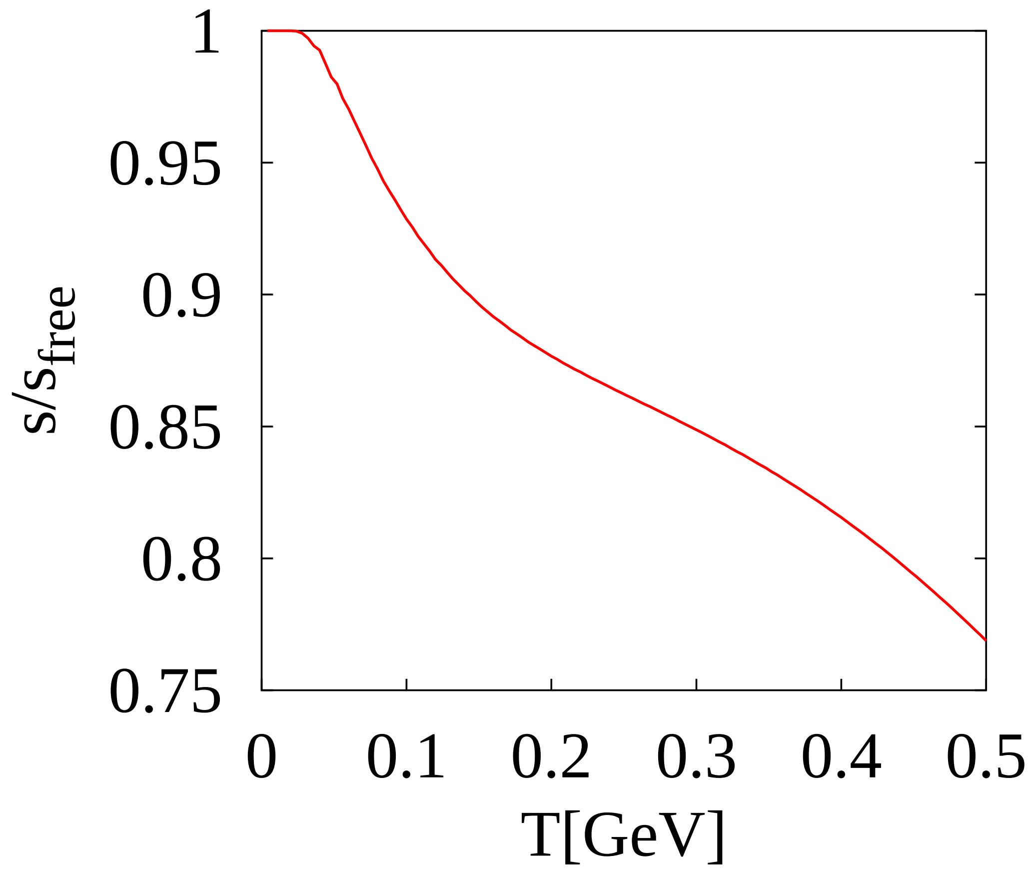
- Stationarity with respect to G_R: Need to derive only with respect to explicit temperature dependency

$$s = -2 \int_{p_0 > 0} \frac{\mathrm{d}^4 p}{(2\pi)^4} \partial_T n(p_0) \left\{ \operatorname{Im} \ln[-G_R^{-1}(p)] + \operatorname{Im}(\Sigma_R G_R) \right\} +$$
$$+ \mathrm{i} \left\{ \frac{\delta \Phi[\varphi, G]}{\delta n} \right\} \bigg|_{G_R, \varphi \text{ fixed}} \partial_T n$$

- Especially for 2-point Φ-functionals

$$s = -2 \int_{p_0 > 0} \frac{\mathrm{d}^4 p}{(2\pi)^4} \partial_T n(p_0) \left\{ \operatorname{Im} \ln[-G_R^{-1}(p)] + (\operatorname{Im} \Sigma_R)(\operatorname{Re} G_R) \right\}$$

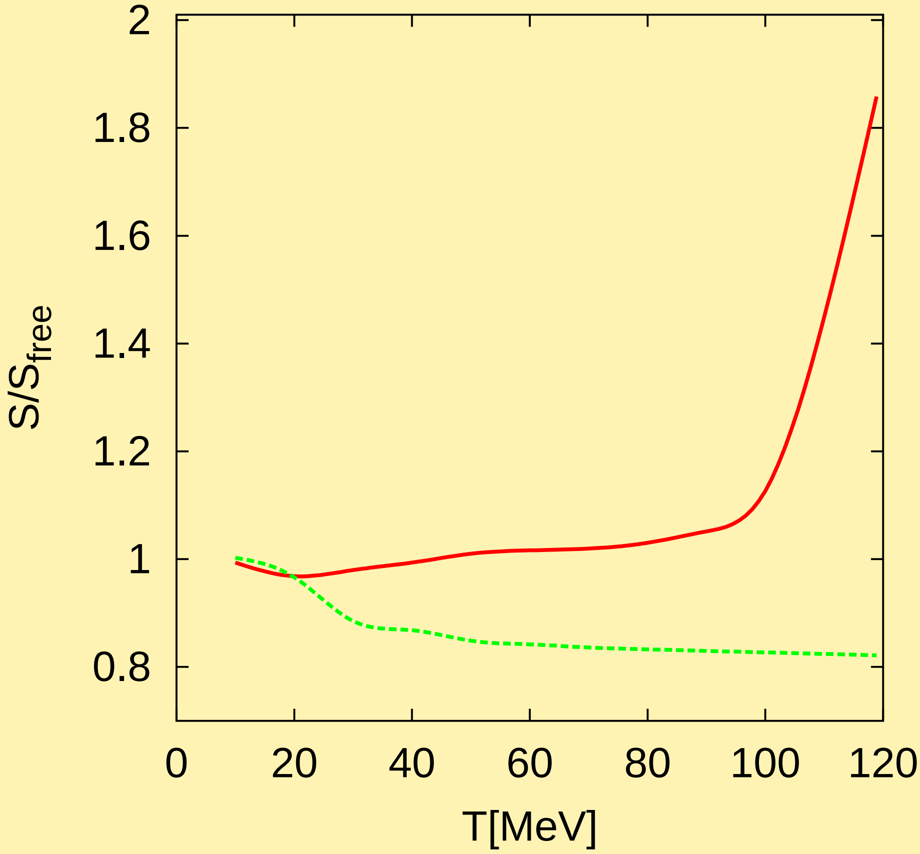
Result for Tadpole Resummation



The entropy density of the selfconsistent tadpole approximation per entropy of the free gas (for $\lambda = 50$).

Result for the sunset approximation

The entropy



Entropy per ideal gas entropy for the perturbative (green) and self–consistent calculation (red)

Symmetries at the correlator level

Symmetry restoration

- Problem with Φ–Functional: Most approximations break symmetry!
- Reason: Only conserving for Expectation values for currents, not for correlation functions
- Dyson's equation as functional of φ:

$$\left.\frac{\delta \mathbb{\Gamma}[\varphi, G]}{\delta G}\right|_{G=G_{\text{eff}}[\varphi]} \equiv 0$$

- Define new effective action functional

$$\Gamma_{\text{eff}}[\varphi] = \mathbb{\Gamma}[\varphi, G_{\text{eff}}[\varphi]]$$

- Symmetry analysis ⇒ $\Gamma_{\text{eff}}[\varphi]$ symmetric functional in φ
- Stationary point

$$\left.\frac{\delta \Gamma_{\text{eff}}}{\delta \phi}\right|_{\varphi=\varphi_0} = 0$$

☞ φ_0 and $G = G_{\text{eff}}[\varphi_0]$: self–consistent Φ–Functional solutions!

☞ Γ_{eff} generates external vertex functions fulfilling Ward–Takahashi identities of symmetries

☞ External Propagator

$$(G_{\text{ext}}^{-1})_{12} = \left.\frac{\delta^2 \Gamma_{\text{eff}}[\varphi]}{\delta \varphi_1 \delta \varphi_2}\right|_{\varphi=\varphi_0}$$

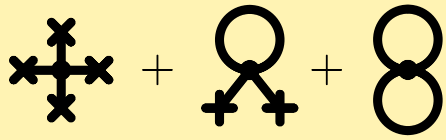
☞ G_{ext} generally not identical with Dyson resummed propagator

Example: Hartree approximation

External self–energy

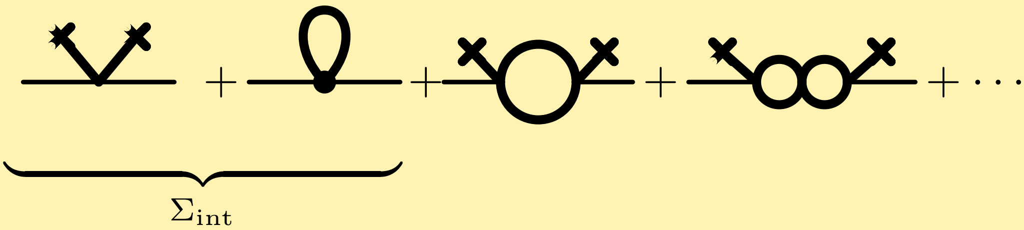
- Hatree approximation:

$i\Phi =$



- External self–energy defined on top of Hartree approximation

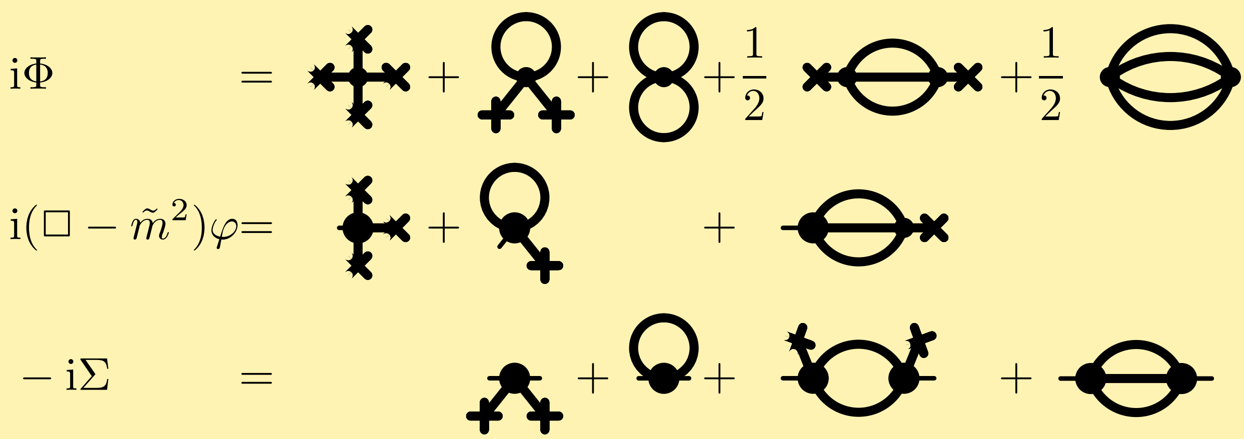
$-i\Sigma_{\text{ext}} =$



☞ RPA–Resummation restores symmetry

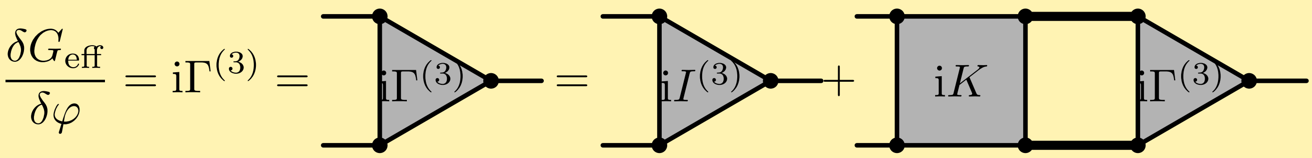
Diagrammar for external vertices I

1st step: define Φ and internal propagator

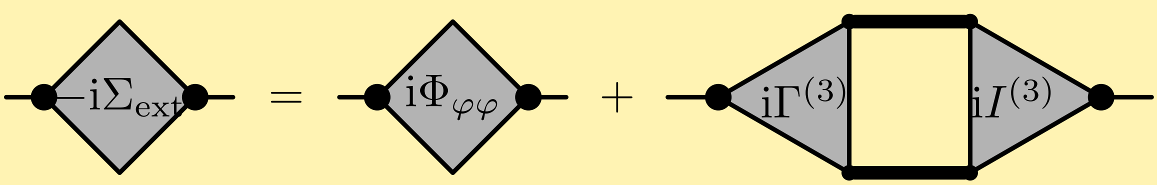


☞ Defines mean field and Dyson resummend internal propagator

2nd step: Derivatives



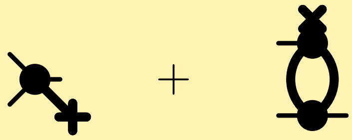
External self–energy

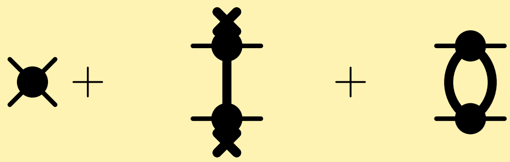


Diagrammar for external vertices II

Definition of Bethe–Salpeter equation elements

$\mathrm{i}\Phi_{\varphi,\varphi} =$ 

$\mathrm{i}I^{(3)} = \mathrm{i}\Phi_{\mathrm{i}G,\varphi} =$ 

$\mathrm{i}K = \mathrm{i}\Phi_{\mathrm{i}G,\mathrm{i}G} =$ 

- Here: Green's function lines and mean fields: fixed from self–consistent Φ–Functional solution

Application to the π–ρ–System

The free vector meson

- Gauge invariant classical Lagrangian:

$$\mathscr{L} = -\frac{1}{4} V_{\mu\nu} V^{\mu\nu} + \frac{1}{2} m^2 V_\mu V^\mu + \frac{1}{2} (\partial^\mu \varphi)(\partial_\mu \varphi) + m \varphi \partial_\mu V^\mu$$

- Gauge invariance:

$$\delta V_\mu(x) = \partial_\mu \chi(x), \; \delta\varphi = m\chi(x)$$

- Quantisation: Gauge fixing and ghosts

$$\begin{aligned}\mathscr{L}_V = & -\frac{1}{4} V_{\mu\nu} V^{\mu\nu} + \frac{m}{2} V_\mu V^\mu - \frac{1}{2\xi} (\partial_\mu V^\mu)^2 + \\ & + \frac{1}{2} (\partial_\mu \varphi)(\partial^\mu \varphi) - \frac{\xi m^2}{2} \varphi^2 + \\ & + (\partial_\mu \eta^*)(\partial_\mu \eta) - \xi m^2 \eta^* \eta.\end{aligned}$$

- Free vacuum propagators

$$\begin{aligned}\Delta_V^{\mu\nu}(p) &= -\frac{g^{\mu\nu}}{p^2 - m^2 + \mathrm{i}\eta} + \frac{(1-\xi) p^\mu p^\nu}{(p^2 - m^2 + \mathrm{i}\eta)(p^2 - \xi m^2 + \mathrm{i}\eta)} \\ \Delta_\varphi(p) &= \frac{1}{p^2 - \xi m^2 + \mathrm{i}\eta} \\ \Delta_\eta(p) &= \frac{1}{p^2 - \xi m^2 + \mathrm{i}\eta}.\end{aligned}$$

☞Usual power counting ⇒ renormalisable

☞Partition sum: Three bosonic degrees of freedom!

Application to the π–ρ–System

Adding $\pi^{\pm}$ and γ

- Gauge–covariant derivative

$$\mathrm{D}_\mu \pi = \partial_\mu \pi + \mathrm{i} g V_\mu \pi + \mathrm{i} e A_\mu$$

☞Quantisation of free photon as usual

- Minimal coupling:

$$\mathscr{L}_{\pi V} = \mathscr{L}_V + (\mathrm{D}_\mu \pi)^* (\mathrm{D}^\mu \pi) - m_\pi^2 \pi^* \pi - \frac{\lambda}{8} (\pi^* \pi)^2 - \frac{e}{2 g_{\rho\gamma}} A_{\mu\nu} V^{\mu\nu}$$

☞Eqs. of motion: Vector meson dominance (Kroll, Lee, Zumino)

- Adding Leptons like in QED:

$$\mathscr{L}_{e\gamma} = \bar{\psi}(\mathrm{i}\not{D} - m_e)\psi$$

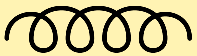
with

$$\mathrm{D}_\mu \psi = \partial_\mu \psi + \mathrm{i} e \psi \tag{1}$$

Application to the π–ρ–System

The Propagators

p

μ  ν $$= -\frac{\mathrm{i}g^{\mu\nu}}{p^2 - m_\rho^2 + \mathrm{i}\eta} + \frac{\mathrm{i}(1-\xi_\rho)p^\mu p^\nu}{(p^2 - m_\rho^2 + \mathrm{i}\eta)(p^2 - \xi m_\rho^2 + \mathrm{i}\eta)}$$

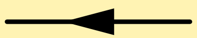
p

μ  ν $$= -\frac{\mathrm{i}g^{\mu\nu}}{p^2 + \mathrm{i}\eta} + \frac{\mathrm{i}(1-\xi_\gamma)p^\mu p^\nu}{(p^2 + \mathrm{i}\eta)^2}$$

p

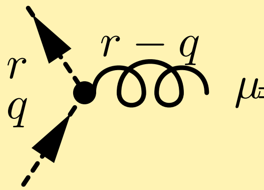
 $$= \frac{\mathrm{i}}{p^2 - m_\pi^2 + \mathrm{i}\eta}$$

p

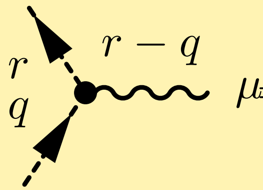
 $$= \frac{\mathrm{i}(\not{p} + m)}{p^2 - m_l^2 + \mathrm{i}\eta}$$

Application to the π–ρ–System

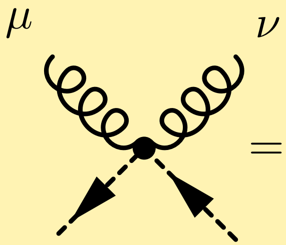
The Vertices



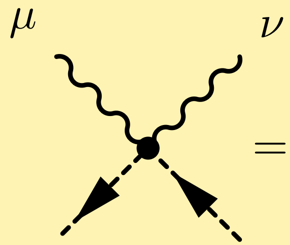
$= -\mathrm{i}g_{\rho\pi}(q^\mu + r^\mu)$



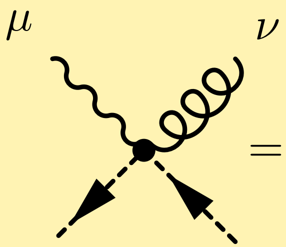
$= -\mathrm{i}e(q^\mu + r^\mu)$



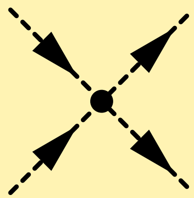
$= \mathrm{i}g_{\rho\pi}^2 g^{\mu\nu}$



$= \mathrm{i}e^2 g^{\mu\nu}$



$= 2\mathrm{i}e g_{\rho\pi} g^{\mu\nu}$



$= -\frac{\mathrm{i}\lambda}{8}$

$= \mathrm{i}\frac{e}{g_{\rho\gamma}} p^2 \Theta^{\mu\nu}(p)$

Application to Vector bosons

- Kroll–Lee–Zumino interaction: Coupling of massive vector bosons to conserved currents ⇒ gauge theory
- Symmetry breaking at correlator level

Problems:

☞ Internal propagators contain spurious degrees of freedom

☞ Negative norm states

☞ Numerically instable due to light cone singularities

- Classical picture (Fokker–Planck–equation):

$$\Pi^{\mu\nu}(\tau, \vec{p} = 0) \propto \langle v^\mu(\tau) v^\nu(0) \rangle$$

- „One–loop" approximation in the classical limit

$$\Pi^{\mu\nu}(\tau, \vec{p} = 0) \propto \exp(-\Gamma\tau)$$

☞ $1/\Gamma$: Relaxation time scale due to scattering

- Exact behaviour:

$$\Pi^{00}(\tau, \vec{p} = 0) \propto \langle 1 \cdot 1 \rangle = \text{const}$$
$$\Pi^{jk}(\tau, \vec{p} = 0) \propto \left\langle v^j v^k \right\rangle \propto \exp(-\Gamma_x \tau)$$

☞ For Π^{jk}: If $\Gamma \approx \Gamma_x \Rightarrow$ 1–loop approximation justified

☞ Classical limit also shows:
Π^{jk} only slightly modified by ladder resummation

- In self–consistent approximations:
Use only $p_j p_k \Pi^{jk}$ and $g_{jk} \Pi^{jk}$

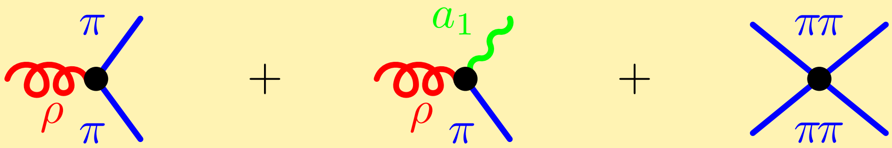
☞ Construct Π_T and Π_L

The interacting π-ρ-a_1 *system*

The self–consistent approximation

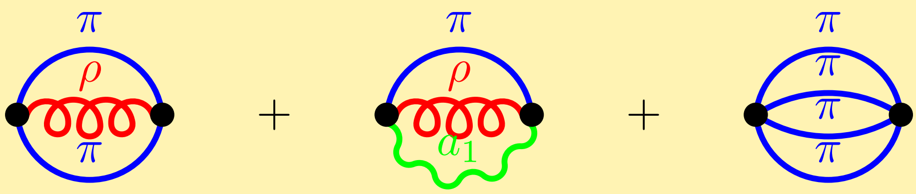
Lagrangian:

$\mathscr{L}_{\text{int}} =$



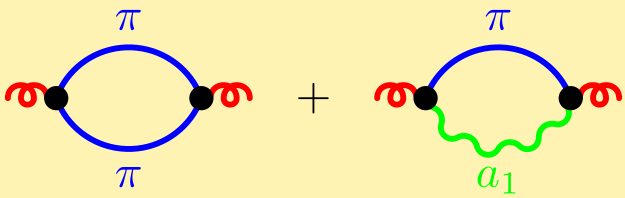
Φ–Funktional:

$\Phi =$

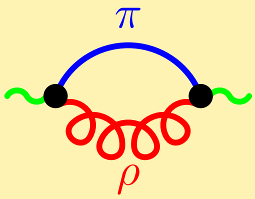


Self–energies:

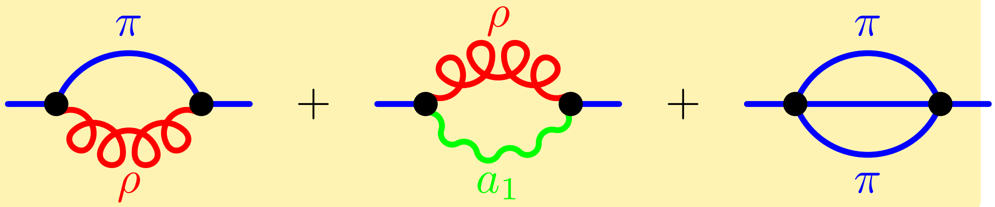
$\Pi_\rho =$



$\Pi_{a_1} =$

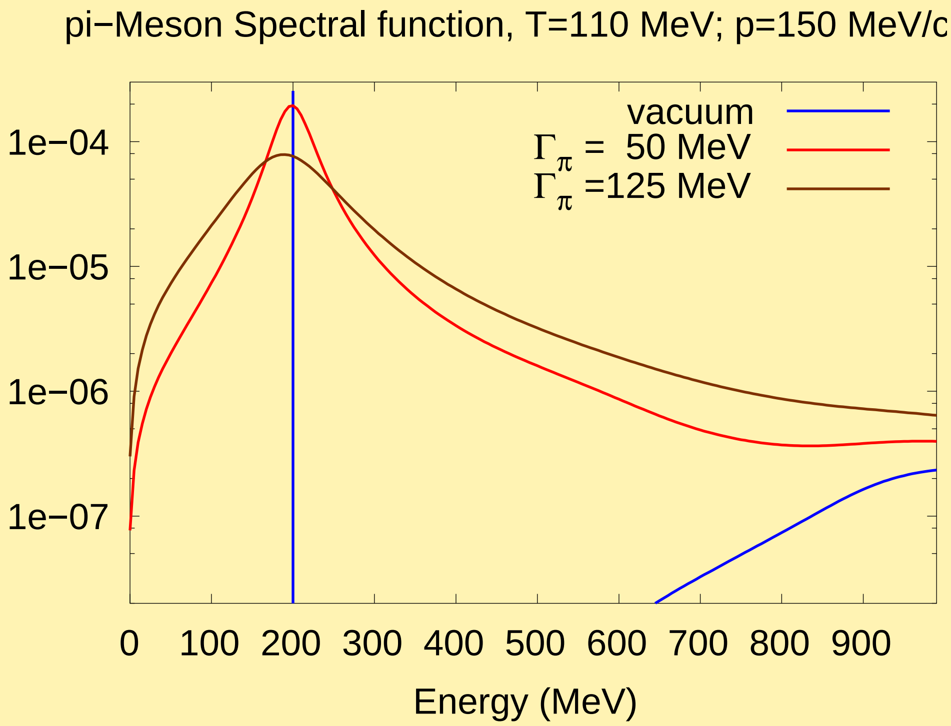


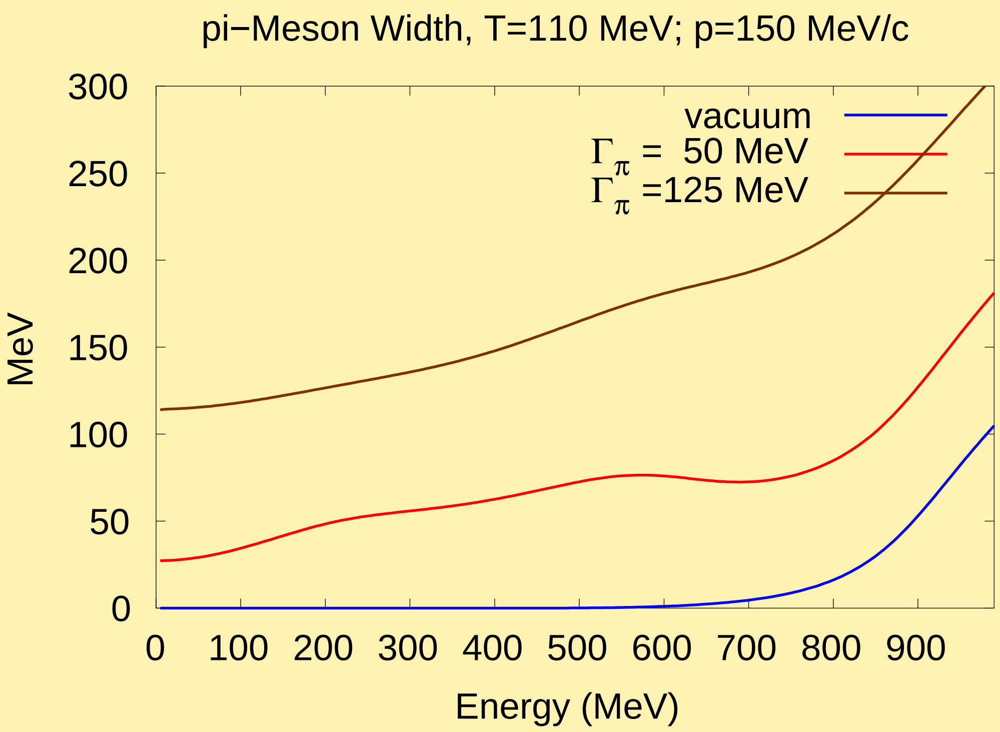
$\Sigma_\pi =$



Results for the $\pi\rho a_1$–System

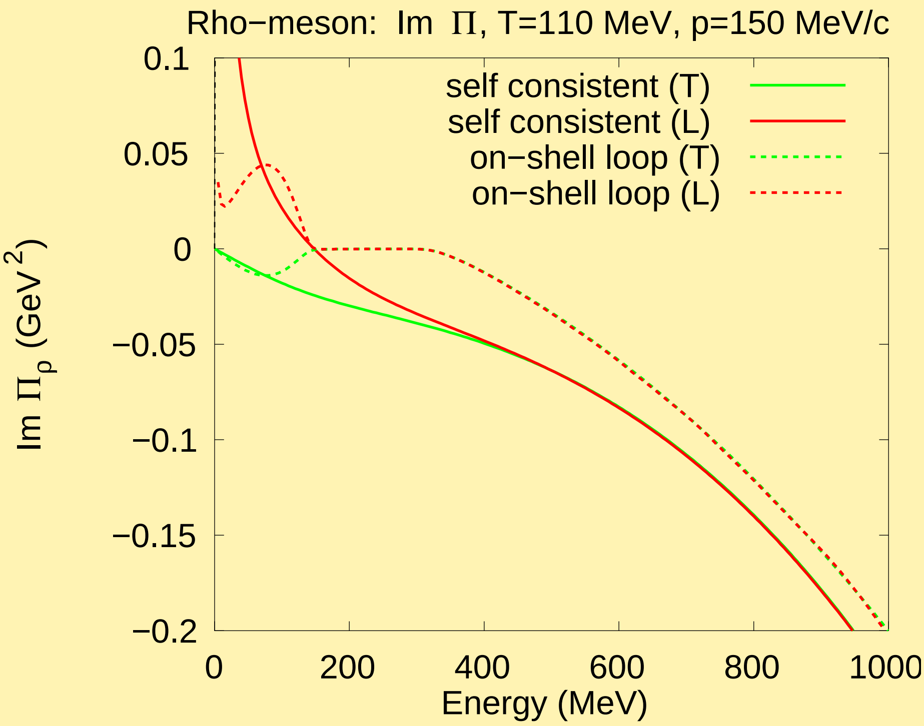
Broad pions in the medium

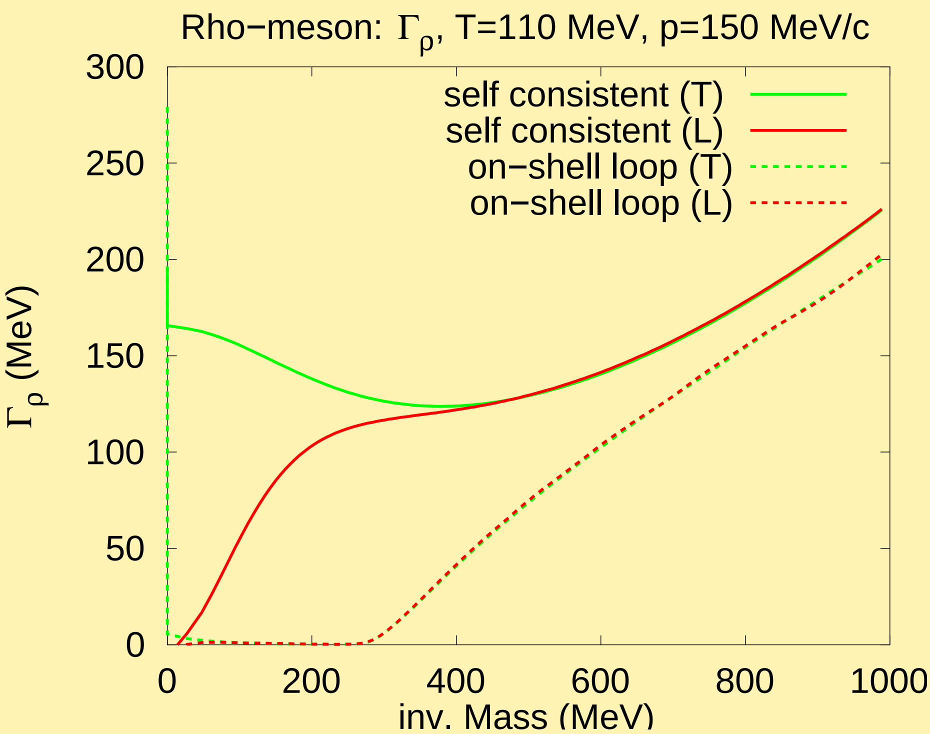




Results for the $\pi\rho a_1$–System

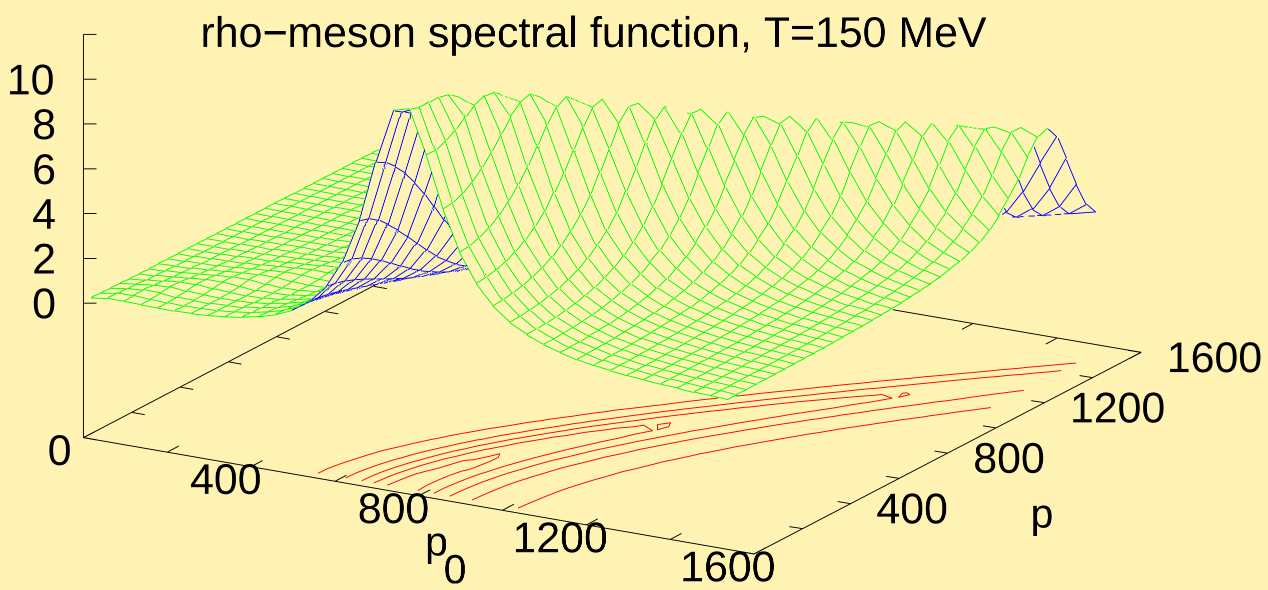
ρ–meson Polarisation tensor

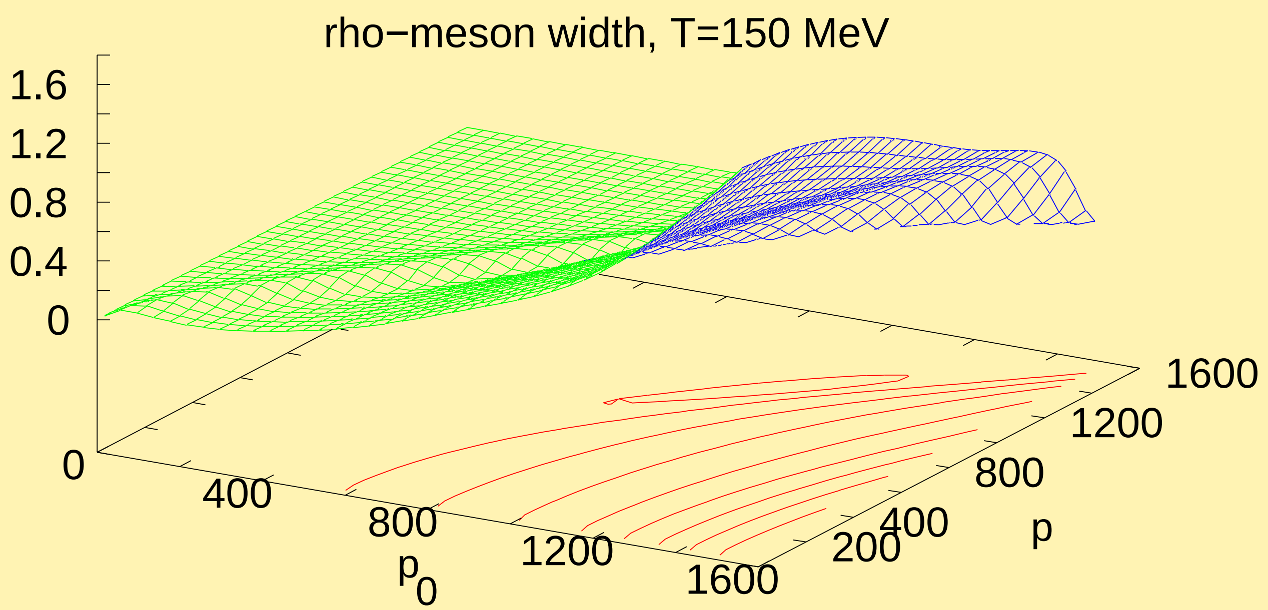




Results for the $\pi\rho a_1$–System

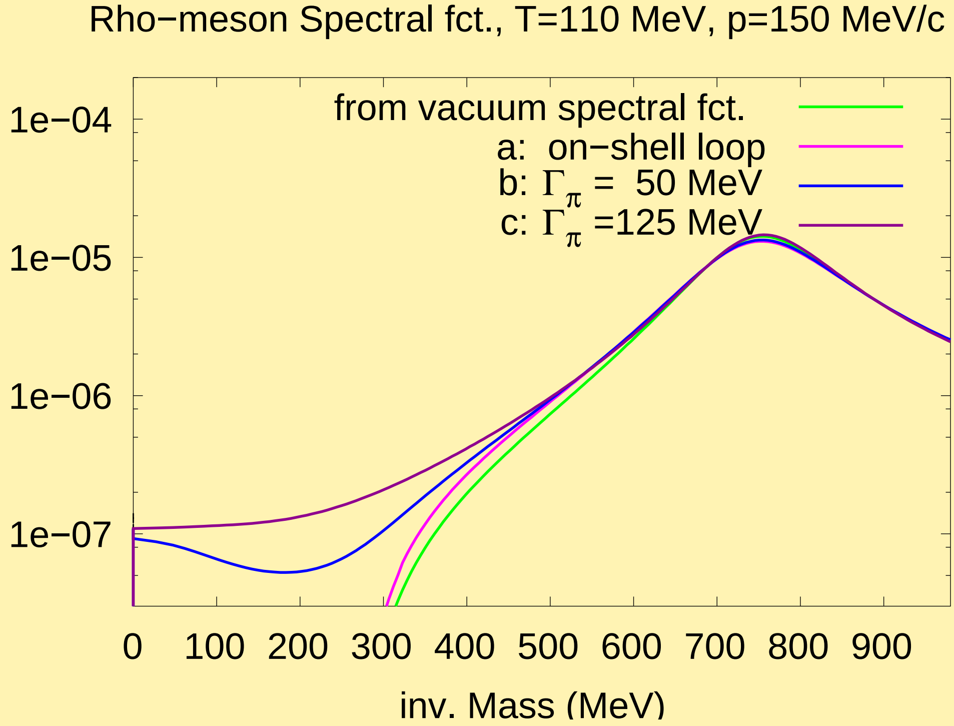
ρ–meson properties I

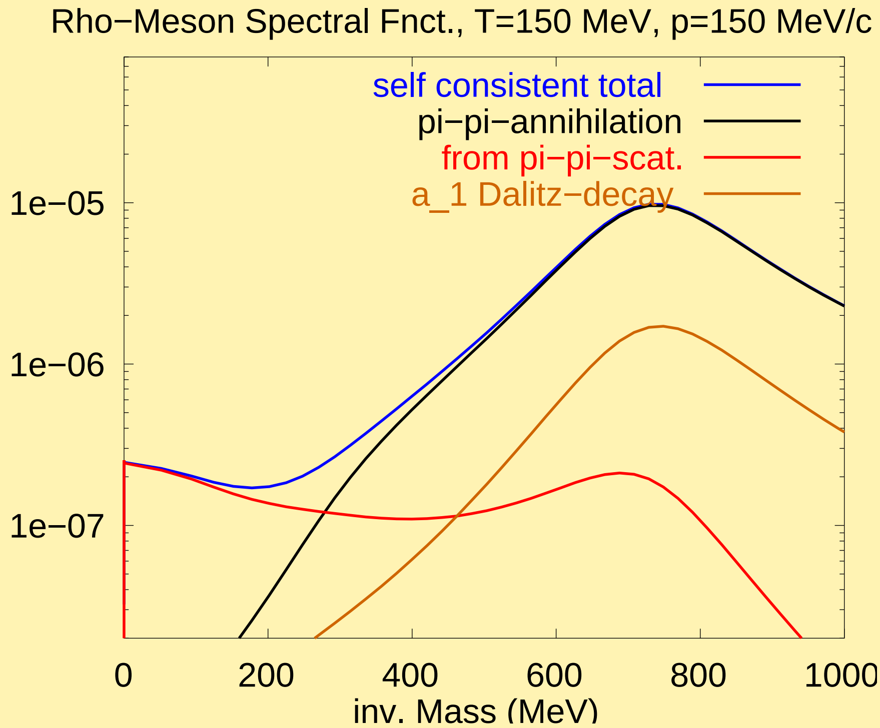




Results for the $\pi\rho a_1$–System

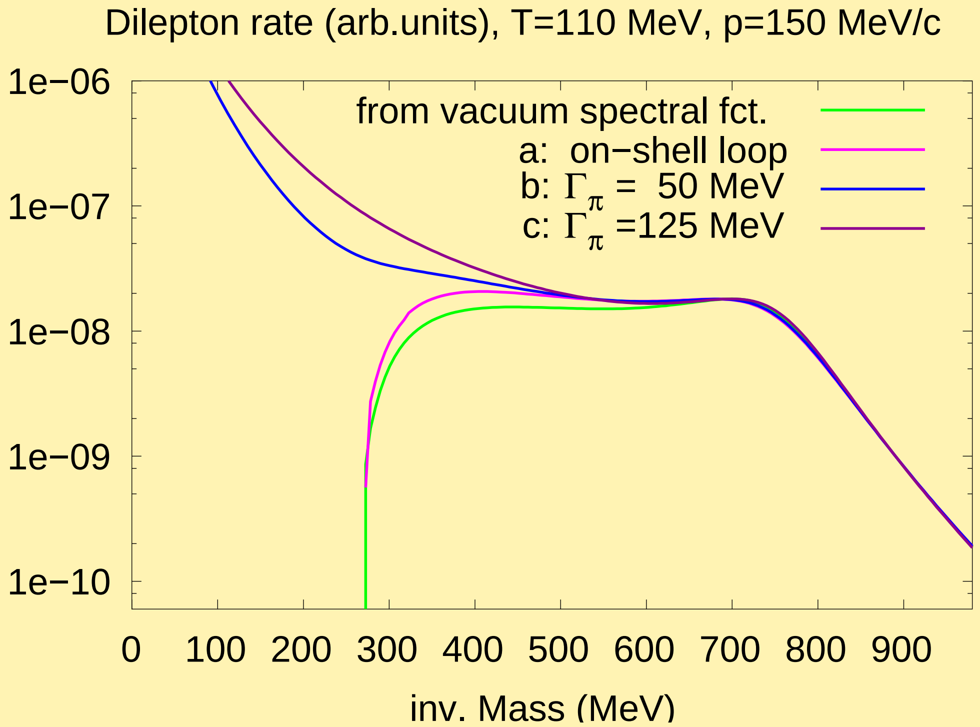
ρ–meson properties II

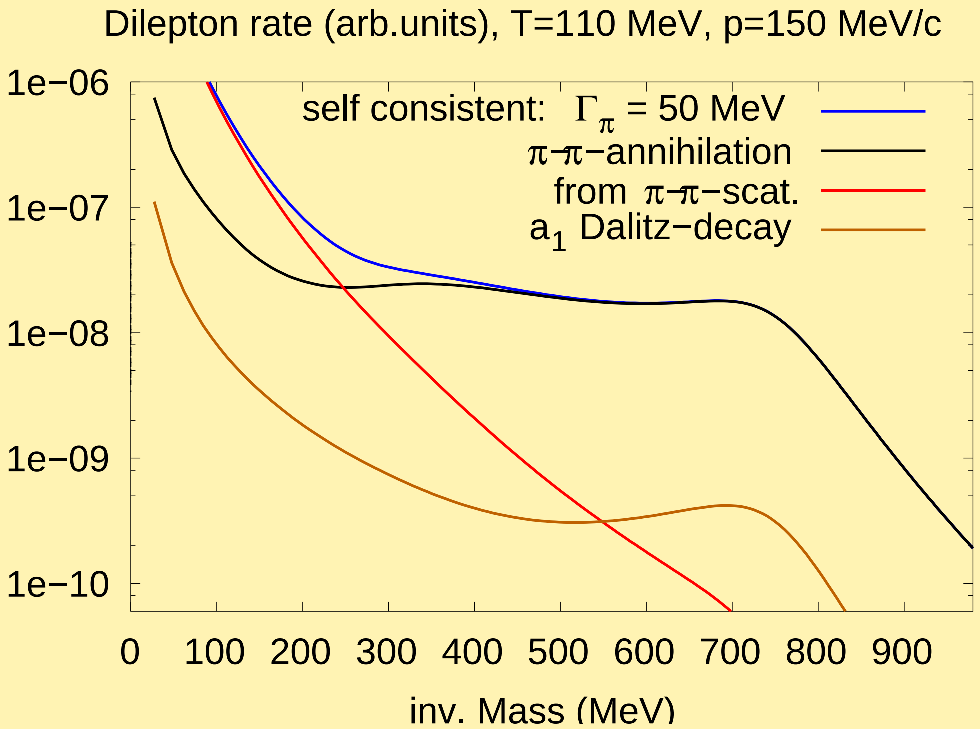




Results for the $\pi\rho a_1$–System

Dilepton rate





Conclusions

Summary

- Self–consistent Φ–derivable schemes
- Renormalization
- Symmetry analysis
- Scheme for vector particles
- Numerical treatment

Outlook

- "Toolbox" for application to realistic models
- Perspectives for self–consistent treatment of gauge theories
- QCD e.g. beyond HTL?
- Transport equations for particles with finite width