The Polarization Tensor of the Massless Mode in Yang-Mills Thermodynamics

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Review of Ralf's talk

- After coarse-graining, nonperturbative YMT ground state described by scalar field $\phi(T)$
  [Herbst,Hofmann '04, Hofmann '05, Giacoa,Hofmann '05]
- Effective action for top. trivial sector

$$S_E[a_\mu] = \int_0^{\frac{1}{T}} \mathrm{d}x_4 \int \mathrm{d}x^3 \mathrm{Tr}\left(\frac{1}{2} G_{\mu\nu} G_{\mu\nu} + D_\mu \phi D_\mu \phi + \Lambda^6 \phi^{-2}\right)$$

- In deconfining phase ($T > \Lambda$): $SU(2) \to U(1)$
- Two tree-level massive modes (TLH) with mass
  $m^2(T) = 4e^2(T)|\phi(T)|^2 = 4e^2\Lambda^3/2\pi T$,
  one tree-level massless mode (TLM)
- Eff. coupling $e(T)$ has plateau value $e_{\text{plateau}} \sim \sqrt{8}\pi \approx 8.8$,
  no PT but loop expansion
- $|\phi|$ yields max. resolution

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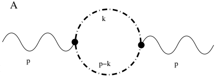
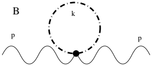
Polarization Tensor, Motivation

- Effect TLH modes on propagation of TLM modes described by polarization tensor $\Sigma^{\mu\nu}$.
- On one-loop level: $\Sigma^{\mu\nu} =$ 

$+$ 

(one-loop sufficient, cmp. talk by Dariush)
- simplest radiative correction
- generic radiative correction
- interesting consequences for physics

Polarization Tensor, Decomposition

$U(1)$ gauge symmetry unbroken, $\Rightarrow \Sigma^{\mu\nu}$ 4D transverse: $p_\mu \Sigma_{\mu\nu} = 0$
Decomposition into spatially transverse and longitudinal part:

$$\Sigma^{\mu\nu} = G(p_4, \mathbf{p}) P_T^{\mu\nu} + F(p_4, \mathbf{p}) P_L^{\mu\nu}$$

with

$$P_L^{\mu\nu} \equiv \delta^{\mu\nu} - \frac{p^\mu p^\nu}{p^2} - P_T^{\mu\nu} \,,$$

projecting also onto $\mathbf{p}$.

Free Propagators

Free propagator for TLH and TLM modes in

- unitary gauge (particle content manifest)
- Coulomb gauge ($\nabla \mathbf{A} = 0$)

$$D^{TLH,0}_{\mu\nu,ab}(k) = -\delta_{ab}\tilde{D}_{\mu\nu}\frac{1}{k^2+m^2}\,, \qquad \{a,b\} \in \{1,2\}$$

$$D^{TLM,0}_{\mu\nu,ab}(p) = -\delta_{a3}\delta_{b3}\left(P^T_{\mu\nu}\frac{1}{p^2} + \frac{u_\mu u_\nu}{\mathbf{p}^2}\right)$$

$u_\mu = \delta_{4\mu}$ four-velocity of head bath.
$\tilde{D}_{\mu\nu}$ projects out the component transverse to k
$P_T^{\mu\nu}$ projects out the component transverse to $\mathbf{p}$.
Gauge fixed completely $\Rightarrow$ no ghost fields needed.

Dressed Propagator

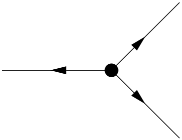
Propagator for interacting TLM mode (imaginary time)

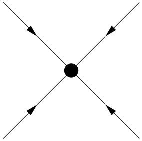
$$D^{TLM}_{\mu\nu,ab}(p) = -\delta_{a3}\delta_{b3}\left(P^T_{\mu\nu}\frac{1}{p^2+G} + \frac{p^2}{\mathbf{p}^2}\frac{u_\mu u_\nu}{p^2+F}\right)$$

$F(p_4,\mathbf{p}) = \left(1 - \frac{p_4^2}{p^2}\right)^{-1}\Sigma^{44}$ describes propagation of longitudinal mode A_4

For $\mathbf{p} \parallel \mathbf{e}_3$, $G(p_4,\mathbf{p}) = \Sigma^{11} = \Sigma^{22}$ describes propagation of transverse mode A_i

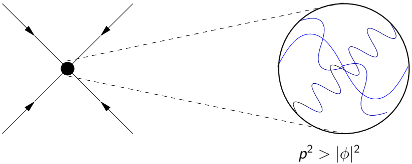
Vertices and Momentum constraints





$\Gamma^{\mu\nu\rho}_{[3]abc}$ $\Gamma^{\mu\nu\rho\sigma}_{[4]abcd}$

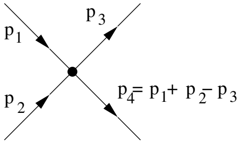
- Momentum conservation at each vertex.
- Effective vertex contains modes with $\left|p^2\right| > |\phi|^2$:



- Exclude these modes in effective theory to avoid "double counting" (already included in $a_\mu^{\text{g.s.}}$; cmp. talk by Ralf)

Momentum constraints

$|\phi|$ yields maximum resolution in effective theory $\Rightarrow$ constraints on momentum transfer in vertex



s-channel: $\left|(p_1 + p_2)^2\right| \leq |\phi|^2$
t-channel: $\left|(p_1 - p_3)^2\right| \leq |\phi|^2$
u-channel: $\left|(p_2 - p_3)^2\right| \leq |\phi|^2$

Recall

Finite temperature QFT defined in imaginary time x_4 with fields being periodic in x_4. Only discrete p_4 momenta allowed (Matsubara sums).

Problem

Momentum constraints formulated in terms of physical, continuous four momenta.

Real time propagators

Solution

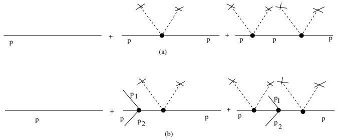
Express Matsubara sums as integrals over continuous real time t. [Kapusta, LeBellac]

Free propagator for TLH and TLM modes in unitary Coulomb gauge and real-time formalism

$$D^{TLM,0}_{\mu\nu,ab}(p) = \delta_{a3}\delta_{b3}\left\{ P^T_{\mu\nu}\left[\frac{-\mathrm{i}}{p^2+\mathrm{i}\epsilon} - 2\pi\delta(p^2)\, n_B(|p_0|/T)\right] + \mathrm{i}\frac{u_\mu u_\nu}{\mathbf{p}^2}\right\}$$

$$D^{TLH,0}_{\mu\nu,ab}(k) = -2\pi\delta_{ab}\tilde{D}_{\mu\nu}\delta(k^2-m^2)\, n_B(|k_0|/T)\,, \quad a,b\in\{1,2\}$$

No vacuum propagator for TLH modes (cmp. talk by Ralf):



Modified dispersion relation of TLM

Dressed propagator of transverse and longitudinal TLM mode (real time)

$$D^{TLM}_{\mu\nu,ab}(p_t) = -\delta_{a3}\delta_{b3}P^T_{\mu\nu}\left[\frac{\mathrm{i}}{p_t^2 - G} + 2\pi\delta(p_t^2 - G)\, n_B(|p_{0,t}|/T)\right]$$

$$D^{TLM}_{\mu\nu,ab}(p_l) = \delta_{a3}\delta_{b3}u_\mu u_\nu\left[\frac{p_l^2}{\mathbf{p}_l^2}\frac{\mathrm{i}}{p_l^2 - F} - 2\pi\delta(p_l^2 - F)\, n_B(|p_{0,l}|/T)\right]$$

Poles yield dispersion relations ($p_0 = \omega + \mathrm{i}\gamma$, assume $\gamma \ll \omega$):

$$\omega_t^2(\mathbf{p}_t) = \mathbf{p}_t^2 + \mathrm{Re}\,G(\omega(\mathbf{p}_t), \mathbf{p}_t) \qquad \omega_l^2(\mathbf{p}_l) = \mathbf{p}_l^2 + \mathrm{Re}\,F(\omega_L(\mathbf{p}_l), \mathbf{p}_l)$$

$$\gamma(\mathbf{p}_t) = -\mathrm{Im}\,G(\omega(\mathbf{p}_t), \mathbf{p}_t)/2\omega \qquad \gamma_l(\mathbf{p}_l) = -\mathrm{Im}\,F(\omega_l(\mathbf{p}_l), \mathbf{p}_l)/2\omega_l$$

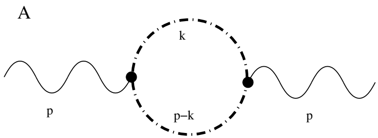
Diagrams for G and F

Chosing $\mathbf{p} \parallel e_3$:

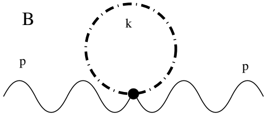
$$G(p_0, \mathbf{p}) = \Sigma^{11} = \Sigma^{22}$$

$$F(p_0, \mathbf{p}) = \left(1 - \frac{p_0^2}{p^2}\right)^{-1} \Sigma^{00}$$

$\Sigma^{\mu\nu}$ sum of two diagrams:



Purely imaginary: $\Rightarrow$ yields γ



Purely real: $\Rightarrow$ yields dispersion relation

One-loop level sufficient (see talk by Dariush)!

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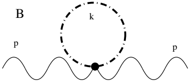
Approximation $p^2 = 0$

Applying Feynman rules to $\mathrm{Re}G = \mathrm{Re}\Sigma^{11} =$ 

yields gap equation:

$$\mathrm{Re}G(p_0, \mathbf{p}) = \Sigma_{\mathrm{B}}^{11}(p) = 8\pi e^2 \int_{|(p+k)^2| \leq |\phi|^2} \left[-\left(3 - \frac{k^2}{m^2}\right) + \frac{k^1 k^1}{m^2} \right] \times n_{\mathrm{B}}\left(|k_0| / T\right) \delta\left(k^2 - m^2\right) \frac{\mathrm{d}^4 k}{(2\pi)^4} \Bigg|_{p^2 = G} \quad (1)$$

4 vertex imposes constraint $\left|(p+k)^2\right| \leq |\phi|^2$

Difficulty

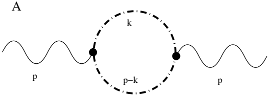
Equation (1) is a transzendental equation for G.

Approximation

Use $p^2 = 0$ in constraint [Schwarz,Giacosa,Hofmann '06].
Valid if $G \ll \mathbf{p}^2$. Check later!

Consequences of $p^2 = 0$

1. For finite Σ^{00}, $F(p_0, \mathbf{p}) = \left(1 - \frac{p_0^2}{p^2}\right)^{-1} \Sigma^{00}$ vanishes.
   Hence, no propagation of longitudinal modes.
2. Diagram A vanishes:

   Momentum conservation at vertex vorbids TLM mode with $p^2 = 0$ to split into two on-shell particles with mass m.
3. Diagram A $= 0$, hence no imaginary part of G, hence $\gamma = 0$ and assumption $\gamma \ll \omega$ satisfied trivially.

Calculation of diagram B, $p^2 = 0$

With $p^2 = 0$:

$$G(|\mathbf{p}|, \mathbf{p}) = 8\pi e^2 \int_{|2pk+k^2|\leq|\phi|^2} \left[g^{11}\left(3 - \frac{k^2}{m^2}\right) + \frac{k^1 k^1}{m^2} \right] \times n_{\mathrm{B}}\left(|k_0|\,/\,T\right) \delta\left(k^2 - m^2\right) \frac{\mathrm{d}^4 k}{(2\pi)^4}$$

Via δ-function, integration over k_0 yields $k_0 \to \pm\sqrt{\mathbf{k}^2 + m^2}$.
Using $p_0 \geq 0$, $p^2 = 0$, $k^2 = m^2 = 4e^2|\phi|^2$, $\theta \equiv \angle(\mathbf{p}, \mathbf{k})$, and $k_0 = \pm\sqrt{\mathbf{k}^2 + m^2}$ constraint reads:

$$\left| 2|\mathbf{p}| \left(\pm\sqrt{\mathbf{k}^2 + 4e^2|\phi|^2} - |\mathbf{k}| \cos\theta \right) + 4e^2|\phi|^2 \right| \leq |\phi|^2$$

Integrand symmetric under $k_0 \to -k_0$, but constraint is not!

Dealing with constraints, + sign

Consider + sign and observe:

$$\left| 2|\mathbf{p}| \left(+\sqrt{\mathbf{k}^2 + 4e^2|\phi|^2} - |\mathbf{k}| \cos\theta \right) + 4e^2|\phi|^2 \right| \leq |\phi|^2$$

1. Term in parentheses always positive.
2. $e \gtrsim \sqrt{8}\pi \sim 8.8$

Hence, constraint never satisfied.

Dealing with constraints, – sign

Using $X \equiv |\mathbf{p}|/T$, $\mathbf{y} \equiv \mathbf{k}/|\phi|$, $|\phi|/T = 2\pi\lambda^{-3/2}$, and $\lambda \equiv 2\pi T/\Lambda$ constraint reads

$$-1 \leq -\lambda^{3/2}\frac{X}{\pi}\left(\sqrt{\mathbf{y}^2 + 4e^2} + y_3\right) + 4e^2 \leq 1$$

Convenient to use polar coordinates $y_1 = \rho\cos\varphi$, $y_2 = \rho\sin\varphi$. Constraint then reads

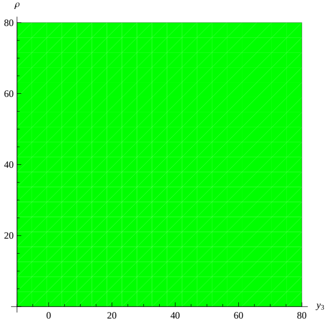
$$\frac{4e^2 - 1}{\lambda^{3/2}}\frac{\pi}{X} \leq \sqrt{\rho^2 + y_3^2 + 4e^2} + y_3 \leq \frac{4e^2 + 1}{\lambda^{3/2}}\frac{\pi}{X}$$

Integration over φ not constraint!

Dealing with constraints, – sign

$$\frac{4e^2 - 1}{\lambda^{3/2}} \frac{\pi}{X} \leq \sqrt{\rho^2 + y_3^2 + 4e^2} + y_3 \leq \frac{4e^2 + 1}{\lambda^{3/2}} \frac{\pi}{X}$$

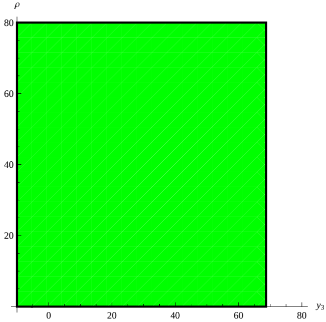
1. y_3, ρ plane



Dealing with constraints, – sign

$$\frac{4e^2 - 1}{\lambda^{3/2}} \frac{\pi}{X} \leq \sqrt{\rho^2 + y_3^2 + 4e^2} + y_3 \leq \frac{4e^2 + 1}{\lambda^{3/2}} \frac{\pi}{X}$$

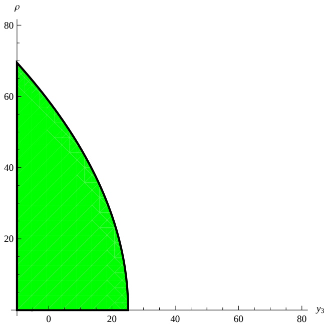
1. y_3, ρ plane
2. $y_3 < y_{\max} \equiv \frac{4e^2+1}{\lambda^{3/2}} \frac{\pi}{X}$



Dealing with constraints, – sign

$$\frac{4e^2-1}{\lambda^{3/2}}\frac{\pi}{X} \le \sqrt{\rho^2+y_3^2+4e^2}+y_3 \le \frac{4e^2+1}{\lambda^{3/2}}\frac{\pi}{X}$$

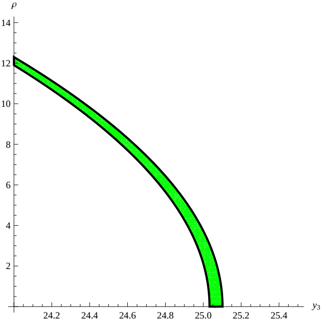
1. y_3, ρ plane
2. $y_3 < y_{\text{max}} \equiv \frac{4e^2+1}{\lambda^{3/2}}\frac{\pi}{X}$
3. $\rho \le \rho_{\text{max}}(y_3) \equiv \sqrt{\left(\frac{\pi}{X}\right)^2 \frac{(4e^2+1)^2}{\lambda^3} - \frac{2\pi}{X}\frac{4e^2+1}{\lambda^{3/2}y_3-4e^2}}$ for $y_3 \le y_3^{\text{M}} \equiv \frac{\pi}{2X}\frac{4e^2+1}{\lambda^{3/2}} - \frac{2\lambda^{3/2}X}{\pi}\frac{e^2}{4e^2+1}$



Dealing with constraints, – sign

$$\frac{4e^2-1}{\lambda^{3/2}}\frac{\pi}{X} \le \sqrt{\rho^2+y_3^2+4e^2}+y_3 \le \frac{4e^2+1}{\lambda^{3/2}}\frac{\pi}{X}$$

1. y_3, ρ plane
2. $y_3 < y_{\max} \equiv \frac{4e^2+1}{\lambda^{3/2}}\frac{\pi}{X}$
3. $\rho \le \rho_{\max}(y_3) \equiv \sqrt{\left(\frac{\pi}{X}\right)^2 \frac{(4e^2+1)^2}{\lambda^3} - \frac{2\pi}{X}\frac{4e^2+1}{\lambda^{3/2}y_3-4e^2}}$ for $y_3 \le y_3^{\mathrm{M}} \equiv \frac{\pi}{2X}\frac{4e^2+1}{\lambda^{3/2}} - \frac{2\lambda^{3/2}X}{\pi}\frac{e^2}{4e^2+1}$
4. $\rho \ge \rho_{\min}(y_3) \equiv \sqrt{\left(\frac{\pi}{X}\right)^2 \frac{(4e^2-1)^2}{\lambda^3} - \frac{2\pi}{X}\frac{4e^2-1}{\lambda^{3/2}y_3-4e^2}}$ for $y_3 \le y_3^{\mathrm{m}} \equiv \frac{\pi}{2X}\frac{4e^2-1}{\lambda^{3/2}} - \frac{2\lambda^{3/2}X}{\pi}\frac{e^2}{4e^2-1}$



Expression for G, $p^2 = 0$

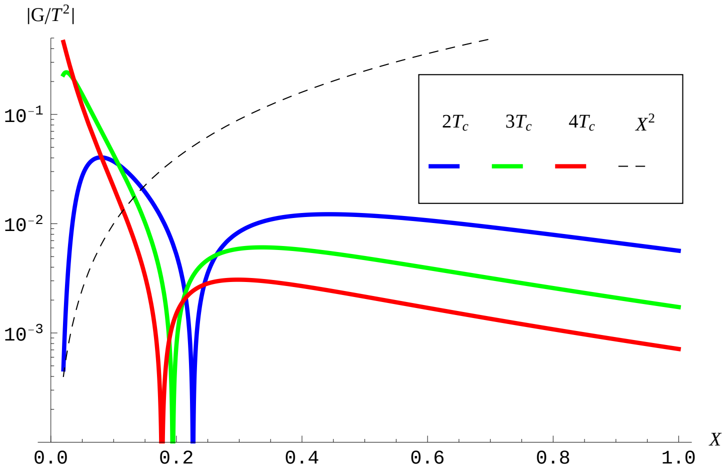
Constraint in terms of boundaries for (y_3, ρ) integration:

$$\frac{G(X,T)}{T^2} = \left[\int_{-\infty}^{y_3^{\mathrm{m}}} \mathrm{d}y_3 \int_{\rho_{\min}}^{\rho_{\max}} \mathrm{d}\rho + \int_{y_3^{\mathrm{m}}}^{y_3^{\mathrm{M}}} \mathrm{d}y_3 \int_0^{\rho_{\max}} \mathrm{d}\rho\right]$$

$$\frac{e^2\rho}{\lambda^3}\left(\frac{\rho^2}{4e^2} - 4\right) \frac{n_{\mathrm{B}}\left(2\pi\lambda^{-3/2}\sqrt{\rho^2 + y_3^2 + 4e^2}\right)}{\sqrt{\rho^2 + y_3^2 + 4e^2}}$$

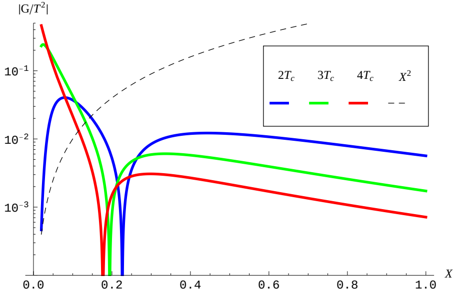
$X = |\mathbf{p}|/T$ momentum of external TLM mode in units of temperature,
$\lambda \equiv 2\pi T/\Lambda$ temperature in units of YM scale Λ.
Integration performed numerically via Gaussian quadrature (unlike Monte-Carlo for 3-loop, comp. talk by Dariush).

Result for G, $p^2 = 0$



Result for G, $p^2 = 0$

All results based on $\left|G/T^2\right| \ll X^2$!



- $X \gtrsim 0.2$: $G < 0$ (anti-screening)
- Dip: $G = 0$
- $X \lesssim 0.2$: $G > 0$ (screening)

- $G \ll \mathbf{p}^2$ for $X \gtrsim 0.2$
- $G = 0$ at $X \sim 0.2$, dispersion relation solved selfconsistently
- $G \geq \mathbf{p}^2$ for $X \lesssim 0.1$, **approximation breaks down**

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Full calculation of G

Gap equation:

$$\mathrm{Re}\, G(p_0, \mathbf{p}) = 8\pi e^2 \int_{|(p+k)^2| \leq |\phi|^2} \left[-\left(3 - \frac{k^2}{m^2}\right) + \frac{k^1 k^1}{m^2} \right] \times n_\mathrm{B}\left(|k_0| / T\right) \delta\left(k^2 - m^2\right) \frac{\mathrm{d}^4 k}{(2\pi)^4} \Bigg|_{p^2 = G} \equiv H(T, \mathbf{p}, G)$$

Via δ-function, integration over k_0 yields $k_0 \to \pm\sqrt{\mathbf{k}^2 + m^2}$.
With $p_0 = \pm\sqrt{\mathbf{p}^2 + G(p_0, \mathbf{p})}$ and $\mathbf{p} \parallel \mathbf{e}_3$ constraint reads

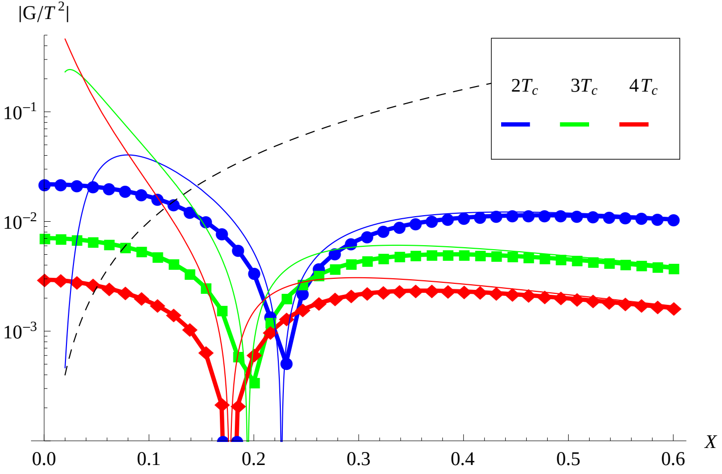
$$\left| G + 2\left(\pm\sqrt{\mathbf{p}^2 + G}\sqrt{\mathbf{k}^2 + m^2} - p k_3\right) + m^2 \right| \leq |\phi|^2$$

Full calculation of G

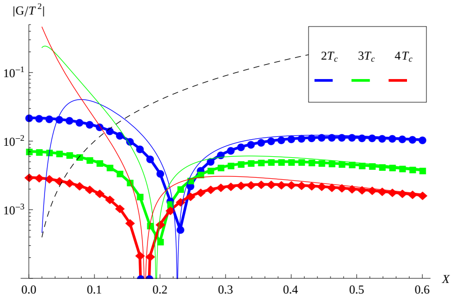
Strategy to solve $\mathrm{Re}G(p_0, \mathbf{p}) = H[T, \mathbf{p}, G(p_0, \mathbf{p})]$ [Ludescher,Hofmann '08]:

1. fix T and $\mathbf{p}$ (integrand in H independent of $p_0 \Rightarrow G = G(\mathbf{p})$)
2. prescribe any value of G_1
3. calculate $H(T, \mathbf{p}, G_1)$ using Monte-Carlo integration
4. repeat steps 2 and 3 to obtain $H(T, \mathbf{p}, G)$
5. solve $G = H(T, \mathbf{p}, G)$ numerically using Newton's method

Selfconsistent result for G, real part



Selfconsistent result for G, real part

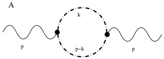


- $X \gtrsim 0.2$: $G < 0$ (anti-screening)
- Dip: $G = 0$
- $X \lesssim 0.2$: $G > 0$ (screening)

Comparison with approximate result:

- Zeros of G agree (must be)
- For $X \gtrsim 0.2$, approximate agrees with selfconsistent result (expected)
- Results different when $G \gtrsim X^2$ (not suprising)

Selfconsistent result for G, imaginary part

Imaginary part: $\mathrm{Im}G \propto$ 

At left vertex: particle with mass $\sqrt{G}$ decaying into two on-shell particles with mass m only possible if

$$\frac{G}{T^2} \geq 4\frac{m^2}{T^2} = 64\pi^2\frac{e^2}{\lambda^3} \quad (2)$$

- $G \leq 0$: condition (2) never satisfied
- $G > 0$:

$$\frac{G(X=0,T)}{T^2} \propto \frac{1}{\lambda^3} \ll 64\pi^2\frac{e^2}{\lambda^3} \sim 5\times 10^4/\lambda^3$$

  condition (2) never satisfied

Diagram A $= 0$, hence no imaginary part of G, hence $\gamma = 0$ and assumption $\gamma \ll \omega$ satisfied trivially.

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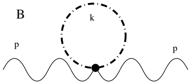
Full Calculation of F

Assume $F \in \mathbb{R}$ (turns out to be selfconsistent)

Apply Feynman rules to $\mathbf{p}^2 = \mathrm{Re}\Sigma^{00} =$ 

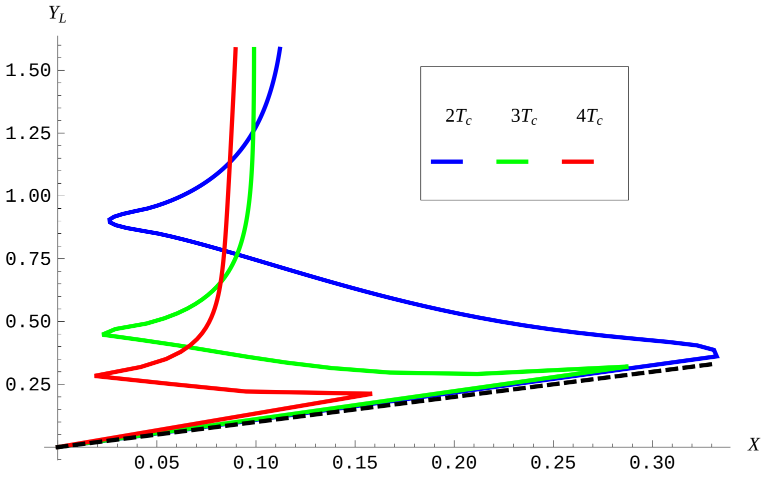
yields gap equation:

$$\mathbf{p}^2 = \Sigma_{\mathrm{B}}^{00}(p) = 8\pi e^2 \int_{|(p+k)^2| \leq |\phi|^2} \left[\left(3 - \frac{k^2}{m^2} \right) + \frac{k^0 k^0}{m^2} \right] \times n_{\mathrm{B}} \left(|k_0| \, / \, T \right) \delta \left(k^2 - m^2 \right) \frac{\mathrm{d}^4 k}{(2\pi)^4} \Bigg|_{p^2 = F} \quad (3)$$

Strategy to find F similar to that of finding G [Falquez,Hofmann,Baumbach '11].

Selfconsitent Result for F

$$Y_l \equiv \frac{\omega_l(\mathbf{p}_l, T)}{T} = \sqrt{\frac{F(p_l^2, T)}{T^2} + \frac{\mathbf{p}_l^2}{T^2}}, \; X \equiv |\mathbf{p}_l|/T$$



Selfconsitent Result for F

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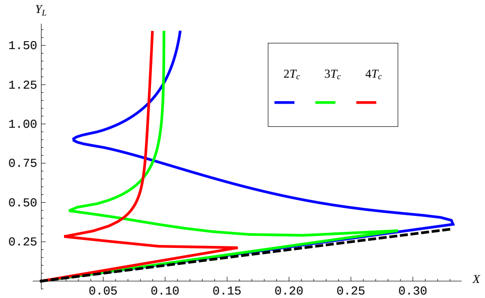
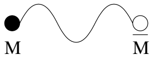


- 3 branches
- Y_L defined only for $X \lesssim 0.34$
- superluminal group velocity

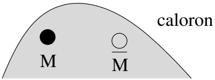
Selfconsistent Result for F, Interpretation

Interpretation in terms of magnetic monopoles [Falquez,Hofmann,Baumbach '11]

- longitudinal modes due to charge density waves
- light like propagation:
  - stable (yet unresolved) monopoles released by large holonomy caloron dissociation [Diakonov et al. '04]
  - density disturbance can only be propagated by radiation field, which propagates at the speed of light



- superluminal propagation:
  - unstable monopoles contained in small holonomy caloron
  - extended calorons provide instantaneous correlation between monopoles, leading to superluminal propagation



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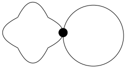
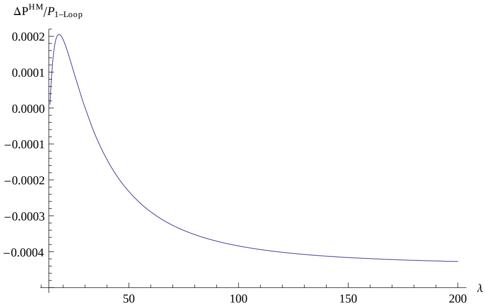
2-Loop Corrections

- "Bubble diagrams" yield pressure (cmp. talk by Dariush)
- For $T \gg T_c$ only relevant diagram: 



- $\Delta P \propto -4 \times 10^{-4} T^4$
- Temperature of TLM gas reduced!

Monopole Properties

Explanation

Energy used to break up calorons, creating monopole anti-monopole pairs [Schwarz,Giacosa,Hofmann '06].

Detailed analysis shows [Ludescher,Keller,Giacosa,Hofmann '08]:

- average monopole-antimonopole distance $\bar{d} < |\phi|^{-1}$
  $\Rightarrow$ monopoles unresolved in effective theory
- screening length l_s due to small-holonomy calorons: $l_s = 3.3\bar{d}$
  $\Rightarrow$ magnetic flux of monopole and antimonopole cancel (no area law for spatial Wilson loop)

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Summary and Outlook

- Coarsegrained YMT ground state described by scalar field $\phi(T)$, $SU(2) \overset{\phi}{\rightarrow} U(1)$
- $|\phi|$ constrains loop momenta
- Calculated polarization tensor $\Sigma^{\mu\nu}$ for TLM mode on 1-loop level
- Approximation $p^2 = 0$ in constraint
  - Constraint solvable analytically
  - Dispersion relation for transverse mode; no propagating longitudinal mode
- Selfconsistent calculation
  - Constraint implemented numerically
  - Dispersion relation for transverse- and longitudinal mode
- In YMT monopoles are unresolvable and screened

Question

Is 1-loop calculation sufficient?

Answer

See talk by Dariush!

Thank you.

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