Vector Manifestation and Chiral Phase Transition
— An Effective Field Theory near Chiral Phase Transition —

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based on

- M. Harada and C. S., Phys. Lett. B 537, 280 (2002)
- M. Harada and C. S., Nucl. Phys. A 736, 300 (2004)

How can we understantd non-perturbative aspects of QCD?

Hadron physics, phase transition

$$\Updownarrow$$

closely related to QCD (underlying theory)

- What is the relevant description of the chiral phase transition?

$$\Downarrow$$

Widely accepted scenario : (π, S)

- A new proposal

  Vector Manifestation (VM)

  Massless vector meson becomes the chiral partner of pion.

M. Harada and K. Yamawaki, PRL 86, 757 (2001).

Anomalous distribution of lepton-pair production [CERN-SPS]

G. Agakishiev *et al.* [CERES Collaboration], PLB **422**, 405 (98)

$\cdots$ Evidence of in-medium modification of ρ meson?

Dropping mass of vector meson $\sim$ Brown-Rho scaling

What is the vector manifestation (VM)?

Wigner Realization of Chiral Symmetry

Chiral representations of low-lying mesons (zero helicity)

- Broken phase
  The eigenstate of the chiral representation under $SU(3)_L \times SU(3)_R$ symmetry does not agree with the mass eigenstate.

$$
\begin{aligned}
|s\rangle &= |(3,3^*) \oplus (3^*,3)\rangle, \\
|\pi\rangle &= |(3,3^*) \oplus (3^*,3)\rangle \sin\psi + |(1,8) \oplus (8,1)\rangle \cos\psi, \\
|V\rangle &= |(1,8) \oplus (8,1)\rangle, \\
|A_1\rangle &= |(3,3^*) \oplus (3^*,3)\rangle \cos\psi - |(1,8) \oplus (8,1)\rangle \sin\psi.
\end{aligned}
$$

mixing angle $\psi \simeq 45^\circ$

F. J. Gilman and H. Harari, PR 165, 1803 (1968);

S. Weinberg, PR 177, 2604 (1969).

- Chiral symmetry restoration
  $\rightarrow$ Representation mixing is dissolved.
  $\rightarrow$ 2 possibilities for pattern of chiral symmetry restoration.

<u>One possibility</u> $(\cos\psi \rightarrow 0)$

$$|\pi\rangle = |(3,3^*)\oplus(3^*,3)\rangle,$$
$$|s\rangle = |(3,3^*)\oplus(3^*,3)\rangle.$$

$\cdots$ Standard scenario (GL)

<u>Another possibility</u> $(\sin\psi \rightarrow 0)$

$$|\pi\rangle = |(1,8)\oplus(8,1)\rangle,$$
$$|V\rangle = |(1,8)\oplus(8,1)\rangle.$$

$\cdots$ Vector Manifestation (VM)

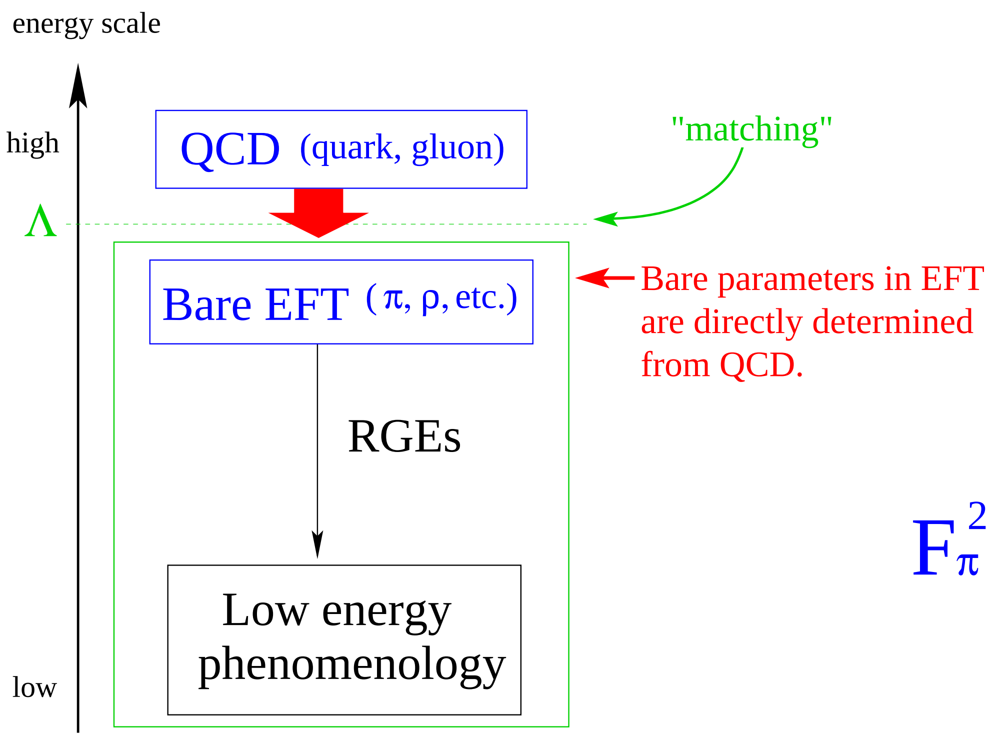
- $\star$ **How to formulate the VM?**
- $\star$ **What does the VM predict?**

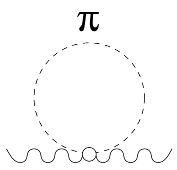
Plan of my talk

1. Introduction
2. Effective Field Theory and Renormalization Group Approach
3. Vector Manifestation in Hot Matter
4. Predictions of Vector Manifestation
5. Summary and Discussions

- Concept of the matching in the Wilsonian sense

The bare Lagrangian of the EFT is defined at a suitable matching scale Λ.



$$F_\pi^2 = F_\pi^2(\Lambda) + $$  $$+ \cdots$$

$$\Downarrow$$

We obtain the bare Lagrangian of the EFT after integrating out the high energy modes.

i.e, the quarks and gluons above Λ

Application to hot and/or dense matter

- Integrating out high energy modes in hot and/or dense matter

$$\Downarrow$$

The bare parameters are in general dependent on temperature and/or density.

"Intrinsic temperature and/or density dependences"

- Integrating out high energy modes in hot and/or dense matter

$$\Downarrow$$

The bare parameters are in general dependent on temperature and/or density.

"Intrinsic temperature and/or density dependences"

$$\Downarrow$$

The signature

that hadron has an internal structure

constructed from quarks and gluons.

- There are 2 kinds of T and/or μ dependences
  - Hadronic T and/or μ dependences

    $\cdots$ generated by the interaction between medium and hadrons.
  - Intrinsic T and/or μ dependences

    $\cdots$ introduced through the matching between EFT and QCD.

- How to get physical (on-shell) quantities?

Physical quantity = Parameter + Hadronic T/μ corrections

Bare parameter + Quantum correction

determined through the matching

included through the RGEs

Vector Manifestation in Hot Matter

M. Harada and C. S., PLB 537, 280 (2002)

- An EFT : Theory based on the hidden local symmetry (HLS)
  dynamical d.o.f. $=\pi$ and ρ mesons
- Leading order Langangian

$$\mathcal{L} = F_\pi^2 \mathrm{tr}\left[\hat{\alpha}_{\perp\mu}\hat{\alpha}_\perp^\mu\right] + F_\sigma^2 \mathrm{tr}\left[\hat{\alpha}_{\|\mu}\hat{\alpha}_\|^\mu\right] - \frac{1}{2}\mathrm{tr}\left[\rho_{\mu\nu}\rho^{\mu\nu}\right],$$

$$\hat{\alpha}^\mu_{\perp,\|} = (D^\mu\xi_R \cdot \xi_R^\dagger \mp D^\mu\xi_L \cdot \xi_L^\dagger)/(2i),$$

$$D_\mu\xi_{L(R)} = \partial_\mu\xi_{L(R)} - ig\rho_\mu\xi_{L(R)} + i\xi_{L(R)}\mathcal{L}_\mu(\mathcal{R}_\mu).$$

3 parameters

- F_π : decay constant of π
- F_σ : decay constant of σ
- g : HLS gauge coupling constant

How to determine these parameters?

Wilsonian matching = matching HLS to OPE

⋆ Assumption

HLS theory
(π, ρ)

OPE
(q, g)

$\Uparrow$

Crossover region

⋆ Chiral perturbation theory with HLS

- Order counting : $g \sim \mathcal{O}(p)$ $[\, m_\rho \sim \mathcal{O}(p)\,]$
- Expansion parameter : p^2/Λ_χ^2 $[\, p^2 \sim m_\pi^2 \sim m_\rho^2\,]$

Wilsonian matching well describes the real world at $T = \mu = 0$.

M. Harada and K. Yamawaki, PRD 64, 014023, (2001);

M. Harada and K. Yamawaki, PRept. 381, 1 (2003)

$\Rightarrow$ Wilsonian matching in hot and/or dense matter

How to realize chiral symmetry restoration?

⋆ For $T \to T_c$, the axial-vector and vector current correlators agree with each other.

$$\boxed{G_A^{(\mathrm{HLS})}(\Lambda;T) - G_V^{(\mathrm{HLS})}(\Lambda;T) \to 0 \quad \text{for } T \to T_c}$$

• Current correlators :

$$G_A^{(\mathrm{HLS})}(\Lambda^2;T_c) = \frac{F_\pi^2(\Lambda;T_c)}{\Lambda^2} - 2z_2(\Lambda;T_c),$$

$$G_V^{(\mathrm{HLS})}(\Lambda^2;T_c) = \frac{F_\sigma^2(\Lambda;T_c)[1-2g^2(\Lambda;T_c)z_3(\Lambda;T_c)]}{{M_\rho}^2(\Lambda;T_c)+\Lambda^2} - 2z_1(\Lambda;T_c).$$

• Bare pion decay constant :

$$\frac{F_\pi^2(\Lambda;T_c)}{\Lambda^2} = \frac{1}{8\pi^2}\left[1+\frac{\alpha_s}{\pi}+\frac{2\pi^2}{3}\frac{\langle\frac{\alpha_s}{\pi}G_{\mu\nu}G^{\mu\nu}\rangle_{T_c}}{\Lambda^4}\right] \neq 0$$

How to realize it in HLS side?

$$\boxed{G_A^{(\mathrm{HLS})}(\Lambda;T) - G_V^{(\mathrm{HLS})}(\Lambda;T) \to 0 \quad \text{for } T \to T_c}$$

$$\boxed{G_A^{(\mathrm{HLS})}(\Lambda;T) - G_V^{(\mathrm{HLS})}(\Lambda;T) \to 0 \quad \text{for } T \to T_c}$$

$$\Downarrow$$

$$\begin{array}{ll} a(\Lambda;T) \to 1 & (F_\sigma = \sqrt{a}\, F_\pi \to F_\pi) \\ g(\Lambda;T) \to 0 & (M_\rho = g\, F_\sigma \to 0) \quad \text{for} \quad T \to T_c \end{array}$$

- realized by the intrinsic T dependence only.
- $(g, a) = (0, 1)$ is the fixed point of RGEs.

$$\Downarrow$$

VM conditions :

$(g, a) \to (0, 1) \quad$ for $T \to T_c$

- Order parameter

$$f_\pi^2(T) = \underline{F_\pi^2(\mu=0;T)} + \underline{\delta_{f_\pi}^{(\mathrm{had})}(T)} \overset{T\to T_c}{\to} 0.$$

[matching + RGE] [hadronic thermal loop]

$$\to \frac{N_f}{24}T_c^2 \qquad \to -\frac{N_f}{24}T_c^2$$

- Vector meson pole mass

$$m_\rho^2(T) = \underline{M_\rho^2(T)}\left[1+\delta_{m_\rho}^{(\mathrm{had})}(T)\right] \overset{T\to T_c}{\to} 0.$$

$\to 0$ [fixed point]

VM is realized for $T \to T_c$.

$(m_\rho,\ f_\rho/f_\pi) \to (0,1)$ for $T \to T_c$: protected as fixed point

M. Harada and C. Sasaki, PLB 537, 280 (2002).

$\star$ **What does it reflect?**

- Scaling property of m_ρ near $T \sim T_c$

Wilsonian matching conditions

$$\Downarrow T \sim T_c$$

$$M_\rho(T) \sim m_\rho(T) \sim \langle \bar{q}q \rangle_T$$

$$\boxed{m_\rho(T)\ \textbf{vanishes as}\ \langle \bar{q}q \rangle_T}$$

$\cdots$ BR-scaling

Anomalous distribution of lepton pair observed at SPS

||

Due to chiral symmetry restoration,

m_ρ becomes lighter.

Predictions of the VM

⋆ Predictions of the VM ($T \to T_c$)

- Axial-vector and vector susceptibilities

M. Harada, Y. Kim, M. Rho and C. S., NPA 727, 437 (2003)

- Large violation of vector meson dominance

M. Harada and C. S., NPA 736, 300 (2004)

- Pion velocity

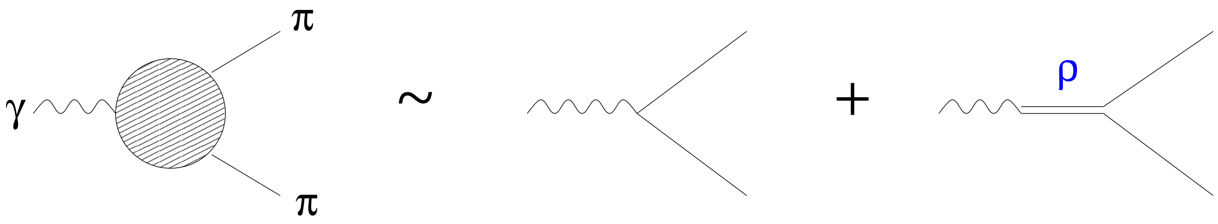
C. S., NPA 739, 151 (2004)

M. Harada, Y. Kim, M. Rho and C. S., NPA 730, 379 (2004)

- Vector meson dominance

M. Harada and C. S., NPA 736, 300 (2004)

Pion EM form factor in HLS theroy



$$\sim e\left(1-\frac{a}{2}\right) \;+\; e\,\frac{a}{2}\frac{m_\rho^2}{m_\rho^2-p^2}$$

$$a \equiv F_\sigma^2/F_\pi^2$$

Vector Dominance (VD) $=$ HLS : $a=2$

$$a(T) = a_{\rm bare} + [\,\text{Quantum correction}\,] + [\,\text{Hadronic } T \text{ corrections}\,]$$

Predictions :

– For $T \sim 0$, $\quad a(T) = 1.3 + [\Lambda^2] + [\mathrm{hadonicT}] \simeq 2$

: VD is satisfied.

– For $T \to T_c$, $\quad a(T) \to 1$ $\quad$: VD is largely violated.

$$\Uparrow$$

$a_{\rm bare}(T_c) = 1$: Fixed point of RGE

Summary and Discussions

- Our premise :
  Bare HLS theory is to be defined through the Wilsonian matching.
- In this framework,
  - Intrinsic T dependence of bare parameter is introduced.
  - Chiral symmetry is restored as the VM :

$$f_\pi \to 0, \quad m_\rho \to 0$$

- Predictions
  - Axial-vector and vecor susceptibilities
  - Large violation of vector meson dominance
  - Pion velocity
- VM is testable by heavy ion collisions

- Extended VM conditions

C. S., NPA 739, 151 (2004)

Current correlators :

$$G^{\mu\nu}_{A,V} = P^{\mu\nu}_L p^2 G^L_{A,V} + P^{\mu\nu}_T p^2 G^T_{A,V} .$$

longitudinal transverse

$$\boxed{G^L_{A,\mathrm{bare}} - G^L_{V,\mathrm{bare}} \stackrel{T\to T_c}{\to} 0 \quad \text{and} \quad G^T_{A,\mathrm{bare}} - G^T_{V,\mathrm{bare}} \stackrel{T\to T_c}{\to} 0}$$

$$\Downarrow$$

$$\boxed{\begin{array}{l} (g^L_{\mathrm{bare}}, g^T_{\mathrm{bare}}) \to (0,0) \\ (a^t_{\mathrm{bare}}, a^s_{\mathrm{bare}}) \to (1,1) \quad \text{for } T \to T_c \end{array}}$$

$$\Downarrow$$

VM conditions (VM fixed point):

$$(g_L, a^t, a^s) \to (0,1,1) \quad \text{for } T \to T_c$$