Hadrons in nuclear matter

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1. Introduction

  - UA(1) effect, Mass in the chiral symmetric vacuum

2. ϕ in medium

3. K1 and K* mesons in medium

4. Summary

S.H. Lee: Symmetry 15 (2023) 799: JSPC 1-2 (2024) 100008.

Symmetries in Quantum Chromodynamics (QCD)

- *Symmetry of Lagrangian when $m \to 0$; $U(3)_R X U(3)_L$*

$q \to \exp[i\theta\,(1\pm\gamma^5)]q$ where $\theta=\theta^a\lambda^a$ including $\lambda^0=1$

- *Anomaly breaks the $U_A(1)$ part $SU(3)_R X SU(3)_L X U(1)$*

broken: $q \to \exp[i\theta\,(\gamma^5)]q$ where $\theta=\theta^0\lambda^0$

- *Spontaneous breaking of Chiral symmetry $SU(3)_R X SU(3)_L \to SU(3)_V$*

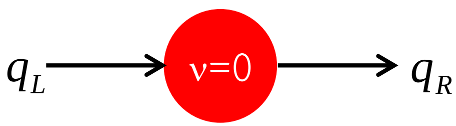
broken $q \to \exp[i\theta\,(\gamma^5)]q$ where $\theta=\theta^a\lambda^a$ including a=1,..8

But we have SU(3) Flavor symmetry (u,d,s quark)

$\mathrm{SU}(N_F)_L \times \mathrm{SU}(N_F)_R \to \mathrm{SU}(N_F)_{L+R=V}$

☞ Topologically trivial

$$Z = Z_{\nu=0} + \ldots..$$



$$\langle \bar{q}q \rangle \propto \int dA e^{-S_{Glue}} \det[\not{D}+m] \left(\frac{1}{\not{D}+m} \right)$$

take the $\lim_{m\to 0} \lim_{V\to\infty}$

Dirac modes $\not{D}\psi_n = i\lambda_n \psi_n$

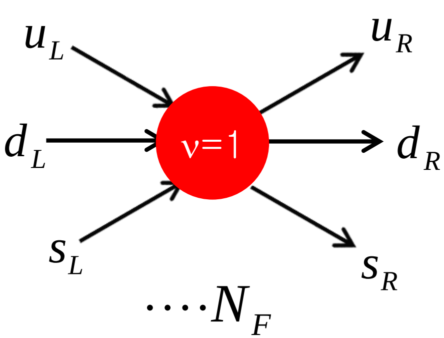
1) For $N_{\lambda<m} \propto V\rho(\lambda=0) \to \langle \bar{q}q \rangle \propto \rho(0)$

2) For $\lambda > m \quad \to \langle \bar{q}q \rangle \propto O(m)$

$U_A(1)$ Breaking

☞ Topologically non-trivial

$$Z = \ldots + Z_{\nu=\pm 1} + \ldots..$$



$$\nu = \frac{\alpha_s}{4\pi} \int d^4x \left(G\tilde{G} \right) = n_R - n_L$$

Its contribution involves exact zero modes $\lambda = 0$

$$\left\langle (\bar{q}\gamma..q)^C \right\rangle_{\nu=\pm 1} \propto \int dA e^{-S_{Glue}} \det[\not{D}+m] \left(\frac{1}{\not{D}+m} \right)^C$$

$$\propto m^{N_F} \frac{1}{m^C}$$

For $N_F = 2$ $\left\langle (\bar{q}\gamma..q)^C \right\rangle_{\nu=\pm 1} \begin{cases} = 0 \text{ for } C = 1 \\ \neq 0 \text{ for } C \geq 2 \end{cases}$

Affected hadron masses

tHooft determinant interaction

$$\det\Phi = (\sigma + i\eta)^2 - (a + i\pi)^2 , \qquad V_{U_A(1)} = -K\left(\det\Phi + \det\Phi^{\dagger}\right)$$

$$V_{U_A(1)} = -K\left(\sigma^2 - \eta^2 - a^2 + \pi^2\right)$$

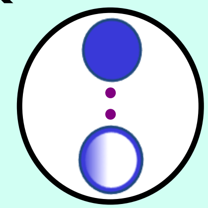
Nucleons and their chiral partners in general also has non-vanishing contributions

So the generalization of Brown-Rho scaling is limited

$$\frac{m_{a_1}^{*2} - m_{\rho}^{*2}}{m_{a_1}^2 - m_{\rho}^2} \sim \frac{m_{K_1}^{*2} - m_{K^*}^{*2}}{m_{K_1}^2 - m_{K^*}^2} \sim \left(\frac{f_\pi^*}{f_\pi}\right)^2 .$$

Chiral symmetry restoration and hadron mass

QCD Vacuum



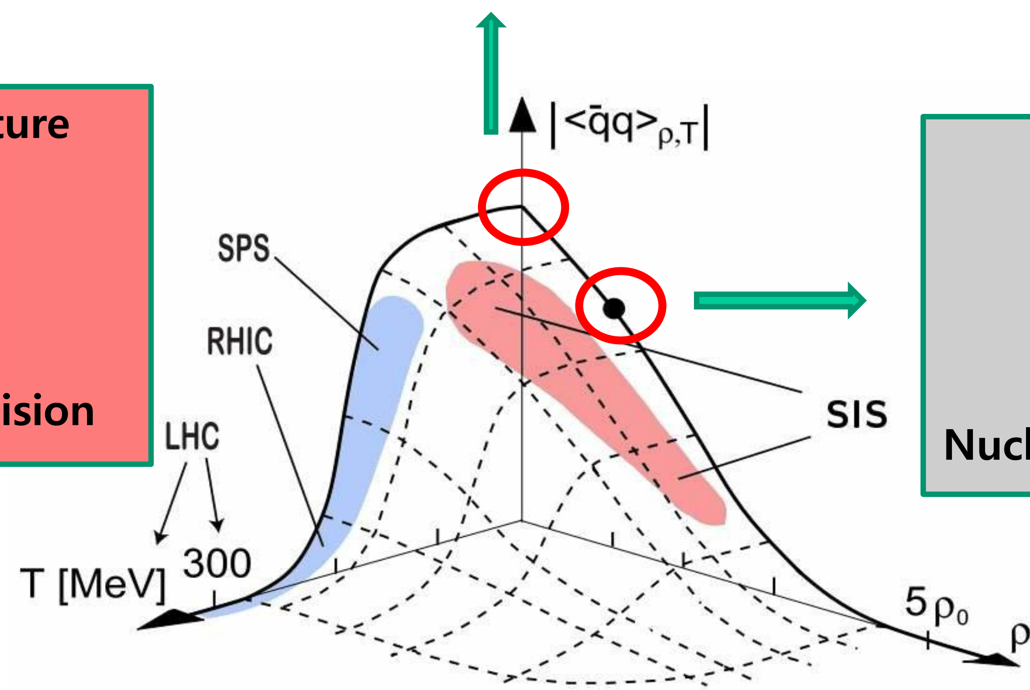
χ-sym is broken

$M_{proton} \gg m_{quark}$

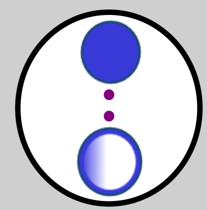
$m_{\rho} \gg m_{a1}$

Finite temperature

Heavy Ion Collision

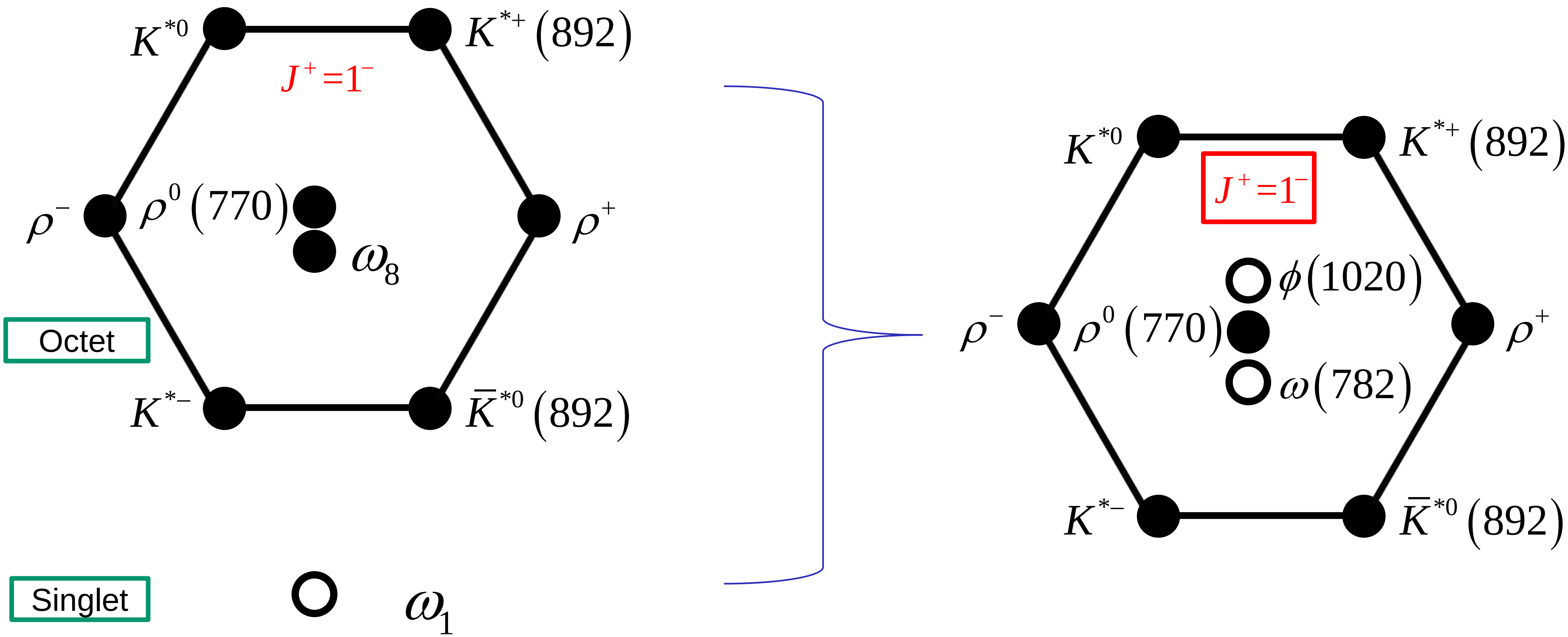


Nuclear Matter



Nuclear Target experiment

Vector meson in Flavor SU(3) symmetry and broken symmetry



$$\omega_1 = \frac{1}{\sqrt{3}}\left(\bar{u}u + \bar{d}d + \bar{s}s\right)$$

$$\omega_8 = \frac{1}{\sqrt{6}}\left(\bar{u}u + \bar{d}d - 2\bar{s}s\right)$$

Mixing due to

$m_s \gg m_d \sim m_u$

$$\phi(1020) = \bar{s}s$$

$$\omega(782) = \frac{1}{\sqrt{2}}\left(\bar{u}u + \bar{d}d\right)$$

Why does meson representation mix for Y=0, I=0 ?

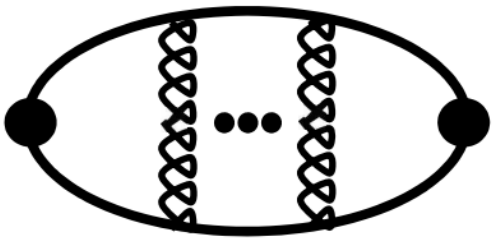
1) Consider correlation function or Mass matrix

Example in SU(2) case with 1 light 1 strange flavor

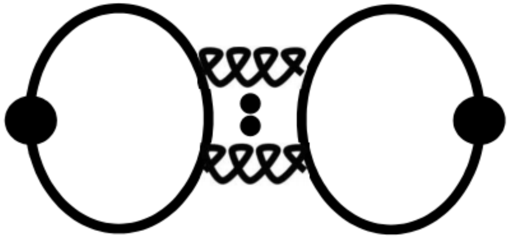
$$\omega_1 = \bar{q}q + \bar{s}s$$
$$\omega_8 = \bar{q}q - \bar{s}s$$

$$\begin{pmatrix} \langle \omega_1 \omega_1 \rangle & \langle \omega_1 \omega_8 \rangle \\ \langle \omega_8 \omega_1 \rangle & \langle \omega_8 \omega_8 \rangle \end{pmatrix} = \begin{pmatrix} a + D & \Delta \\ \Delta & a - D \end{pmatrix}$$

$$\begin{cases} a = \langle (\bar{q}q)(\bar{q}q) + (\bar{s}s)(\bar{s}s) \rangle \\ \Delta = \langle (\bar{q}q)(\bar{q}q) - (\bar{s}s)(\bar{s}s) \rangle \longrightarrow \text{Symmetry breaking} \\ D = \langle 2(\bar{q}q)(\bar{s}s) \rangle \longrightarrow \text{Disconnected contribution} \end{cases}$$



Connected



Disconnected contribution

$$\omega_1 = \bar{q}q + \bar{s}s \qquad \omega_3 = \bar{q}q - \bar{s}s$$

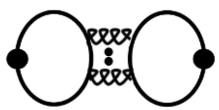
☞ $$\begin{pmatrix} \langle\omega_1\omega_1\rangle & \langle\omega_1\omega_8\rangle \\ \langle\omega_8\omega_1\rangle & \langle\omega_8\omega_8\rangle \end{pmatrix} = \begin{pmatrix} a+D & \Delta \\ \Delta & a-D \end{pmatrix} \quad \begin{cases} a = \langle(\bar{q}q)(\bar{q}q) + (\bar{s}s)(\bar{s}s)\rangle \\ \Delta = \langle(\bar{q}q)(\bar{q}q) - (\bar{s}s)(\bar{s}s)\rangle \\ D = \langle 2(\bar{q}q)(\bar{s}s)\rangle \end{cases}$$

☞ $$E_{\pm} = a \pm \sqrt{D^2 + \Delta^2}$$

- If SU(3) symmetric limit: Δ =0, there is no mixing, and singlet and octet do not mix.

- If SU(3) symmetry is broken

1) Ideal mixing when D=0<< Δ (Vector meson)



$$\begin{pmatrix} a & \Delta \\ \Delta & a \end{pmatrix} \rightarrow \begin{pmatrix} \langle(\bar{q}q)(\bar{q}q)\rangle & 0 \\ 0 & \langle(\bar{s}s)(\bar{s}s)\rangle \end{pmatrix}$$

2) Small mixing when D >> Δ (Pseudo-scalar meson)

$$\begin{pmatrix} a+D & \Delta \\ \Delta & a-D \end{pmatrix} \rightarrow \begin{pmatrix} \langle((\bar{q}q)+(\bar{s}s))^2\rangle & 0 \\ 0 & \langle((\bar{q}q)-(\bar{s}s))^2\rangle \end{pmatrix}$$

Chiral transformation of quark bilinears

- Chiral symmetry $SU(3)_R X SU(3)_L$

$$q_{R,L} \to \exp\left(i\vec{\theta}\left(1 \pm \gamma^5\right)\right) q_{R,L} \quad \text{where} \quad \vec{\theta} = \theta^a \lambda^a$$

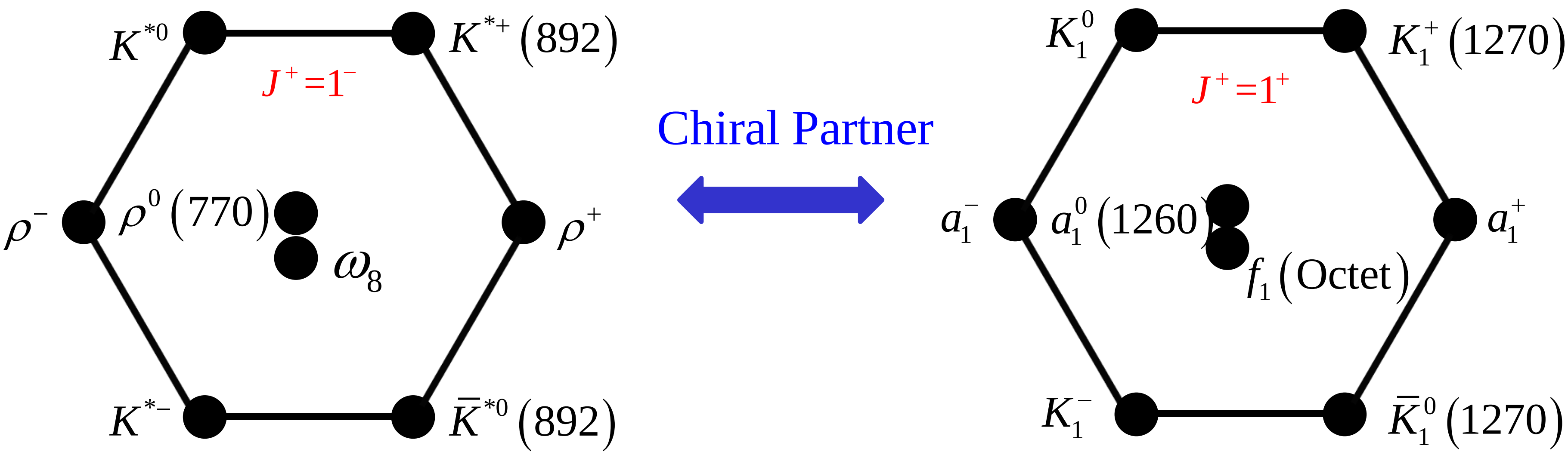
- Spontaneous breaking of Chiral symmetry $SU(3)_R X SU(3)_L \rightarrow SU(3)_V$

☞ Broken part is $q \to \exp\left(i\vec{\theta}\gamma^5\right) q, \quad \bar{q} \to \bar{q}\exp\left(i\vec{\theta}\gamma^5\right)$

- Quark bilinear $\bar{q}\Gamma q \to \bar{q}\left(1 + i\vec{\theta}\gamma^5\right)\Gamma\left(1 + i\vec{\theta}\gamma^5\right) q \to \bar{q}\Gamma q + \bar{q}\left(i\vec{\theta}\gamma^5\Gamma + \Gamma i\vec{\theta}\gamma^5\right) q$

$$\begin{cases} \bar{q}q \to \bar{q}q + 2\bar{q}\left(i\vec{\theta}\gamma^5\right) q \\ \bar{q}\gamma^\mu \tau^a q \to \bar{q}\gamma^\mu \tau^a q + \bar{q} i\gamma^5 \gamma^\mu \left[\vec{\theta}, \tau^a\right] q \\ \bar{q}\gamma^\mu q \to \bar{q}\gamma^\mu q + \bar{q} i\gamma^5 \gamma^\mu \left[\vec{\theta}, 1\right] q = \bar{q}\gamma^\mu q \end{cases}$$

Spin-1 Flavor Octet



Spin-1 Flavor Singlet

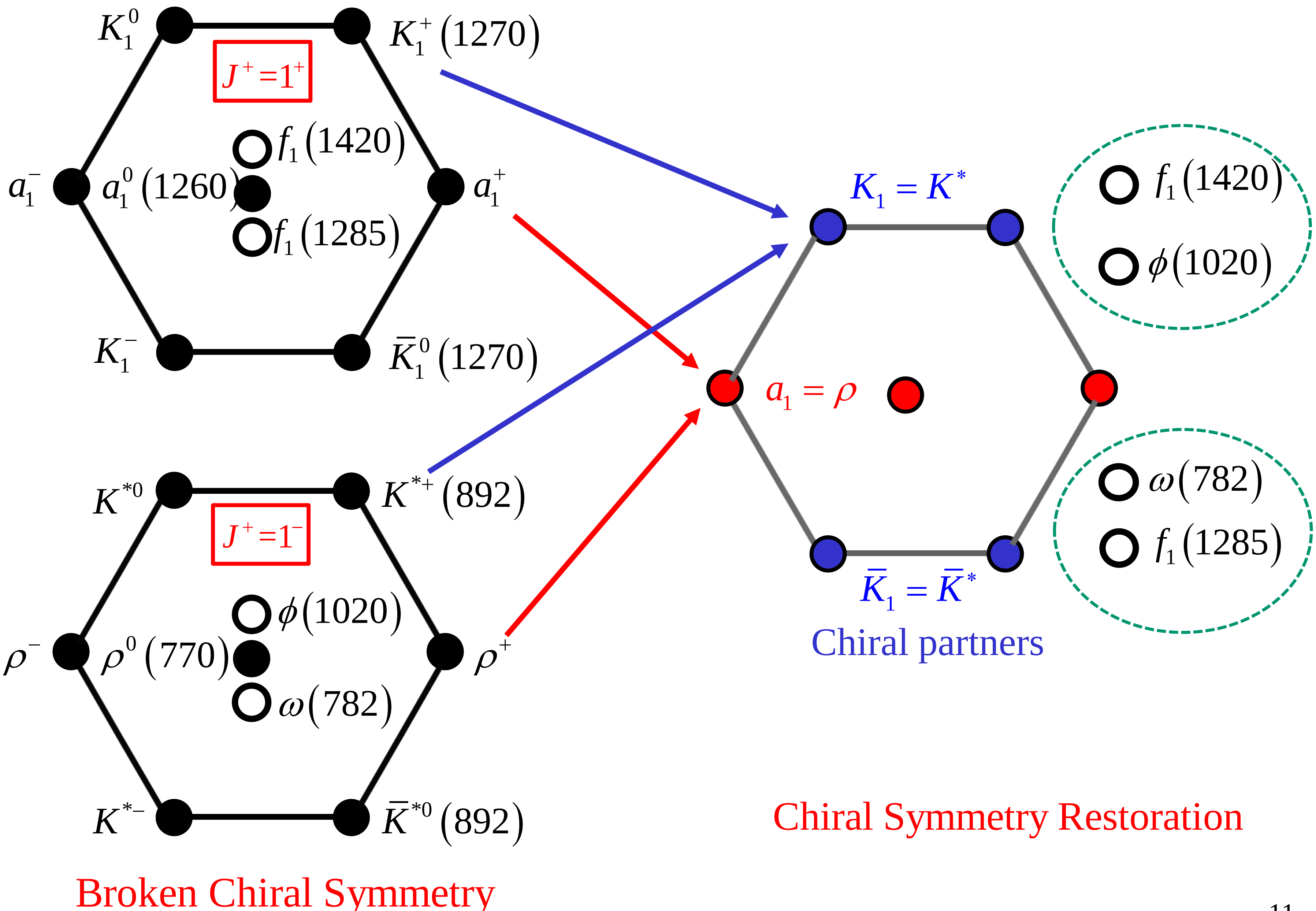
$$\phi(1020) = \bar{s}s$$

$$\omega(782) = \frac{1}{\sqrt{2}}\left(\bar{u}u + \bar{d}d\right)$$

$$m_s \gg m_d \sim m_u$$

$$\omega_1 = \frac{1}{\sqrt{3}}\left(\bar{u}u + \bar{d}d + \bar{s}s\right)$$

$$\omega_8 = \frac{1}{\sqrt{6}}\left(\bar{u}u + \bar{d}d - 2\bar{s}s\right)$$



K_1^0
$K_1^+(1270)$
$J^+=1^+$
$f_1(1420)$
a_1^-
$a_1^0(1260)$
a_1^+
$f_1(1285)$
K_1^-
$\bar{K}_1^0(1270)$
K^{*0}
$K^{*+}(892)$
$J^+=1^-$
$\phi(1020)$
ρ^-
$\rho^0(770)$
ρ^+
$\omega(782)$
K^{*-}
$\bar{K}^{*0}(892)$
Broken Chiral Symmetry
$K_1 = K^*$
$f_1(1420)$
$\phi(1020)$
$a_1 = \rho$
$\omega(782)$
$f_1(1285)$
$\bar{K}_1 = \bar{K}^*$
Chiral partners
Chiral Symmetry Restoration

1. Original QCD sum rule (Hatsuda, Lee PRC46 (1992)r34)

   did not separate the four quark condensate according to chiral symmetric and breaking part

2. By looking at rho and A1 sum rule, one can determine them separately

   (J.Kim, Lee PRD 104 (2021) L051501, PRD 205 (2022) 014014)

☞

$$\Pi^{VV} = ...\frac{1}{Q^6}\left[-2\pi\alpha\left\langle\left(\bar{q}\gamma_\mu\gamma^5\lambda^a\tau^3 q\right)^2\right\rangle - \frac{4\pi\alpha}{9}\left\langle\left(\sum_{ud}\bar{q}\gamma_\mu\lambda^a q\right)\left(\sum_{uds}\bar{q}\gamma_\mu\lambda^a q\right)\right\rangle\right] = ...\frac{1}{Q^6}\left[\frac{14}{9}\langle B\rangle + \langle S\rangle\right]$$

$$\Pi^{AA} = ...\frac{1}{Q^6}\left[-2\pi\alpha\left\langle\left(\bar{q}\gamma_\mu\lambda^a\tau^3 q\right)^2\right\rangle - \frac{4\pi\alpha}{9}\left\langle\left(\sum_{ud}\bar{q}\gamma_\mu\lambda^a q\right)\left(\sum_{uds}\bar{q}\gamma_\mu\lambda^a q\right)\right\rangle\right] = ...\frac{1}{Q^6}\left[-\frac{22}{9}\langle B\rangle + \langle S\rangle\right]$$

$\langle S\rangle$ no contribution from $\rho(\lambda=0)$ $\pm$ $\langle B\rangle \propto \left\langle\left(\rho(\lambda=0)\right)^2\right\rangle \propto \langle\bar{q}q\rangle^2$

$\mathrm{m}_\rho = \mathrm{m}_{a_1} = \mathrm{m}_0$ □ 550 ± 50 MeV in the chiral symmetry restored vacuum

$$\frac{m_{a_1}^{*2} - m_\rho^{*2}}{m_{a_1}^2 - m_\rho^2} \sim \frac{m_{K_1}^{*2} - m_{K^*}^{*2}}{m_{K_1}^2 - m_{K^*}^2} \sim \left(\frac{f_\pi^*}{f_\pi}\right)^2.$$

Chiral symmetry restoration and Baryon meson mass

When chiral symmetry breaking operators are taken to be zero

(J. Kim, S Lee, PRD 205 (2022) 014014)

Particle	$\kappa_6(\sqrt{s_0}(\mathrm{GeV}))$	κ_8	S_6/B_6	S_6/B_8	$\bar{m}_{\mathrm{sym}}(\mathrm{MeV})$
N	0.0425(1.235)	0.16	−0.9575	−0.84	525
Δ	0.26(1.56)	0.4	−0.74	−0.6	600

In general $$m_H^* = m_H^{\mathrm{sym}} + \Delta m_H^{\chi},$$

But there is a subtle issue related to UA(1) breaking effect.

ϕ-N interaction, or ϕ mass shift in medium

First Theory papers: 1992

First positive result: 2007

Final answer: J-PARC E16, E88 (2025+)

Which vector meson should one study in medium

1) Hadrons with small width: ϕ is the best candidate

$J^{PC}=1^{--}$	Mass	Width	$J^{PC}=1^{++}$	Mass	Width
ρ	770 MeV	150 MeV	a_1	1260	250–600
ω	782	8.49	f_1	1285	24.2
ϕ	1020	4.266	f_1	1420	54.9
$K*(1^-)$	892	50.3	$K_1(1^+)$	1270	90

- Decay mode of chiral partners typically has one more pion

2) a_1 is impossible to measure. Even ρ can not be seen well

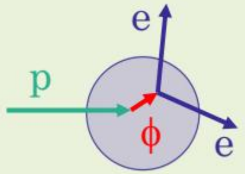
3) Study ϕ that has the sharpest peak: Brilliant idea KEK EE325 J-PARC E16, E88

$$m_\phi - m_{f_1(1420)} \propto \langle \bar{s}s \rangle + \text{other}$$

- *ϕ-in medium: KEK E325 (2007)*

Previous experimental results

KEK
E325



12 GeV
pA-reaction

Pole mass: $$\frac{m_\phi(\rho)}{m_\phi(0)} = 1 - k_1 \frac{\rho}{\rho_0}$$

k_1: 0.034 ± 0.007

Pole width: $$\frac{\Gamma_\phi(\rho)}{\Gamma_\phi(0)} = 1 + k_2 \frac{\rho}{\rho_0}$$

k_2: 2.6 ± 1.5

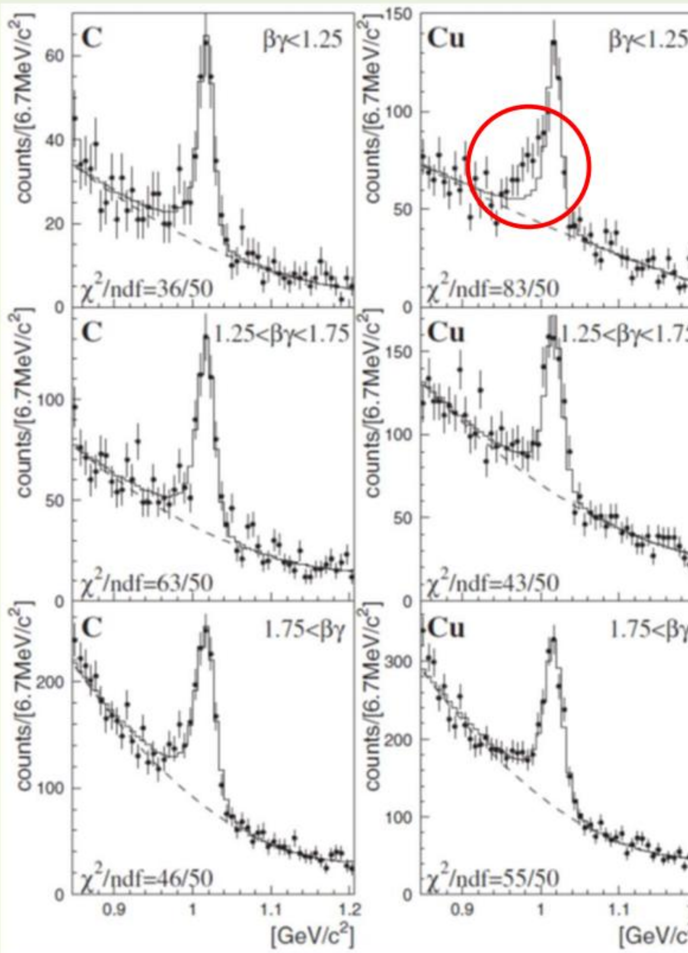
Measurement is being repeated with
~100x increased statistics at the
J-PARC E16 experiment!

slow φs

intermediate
φs

fast φs

$$\beta\gamma = \frac{|\vec{p}|}{m_\phi}$$



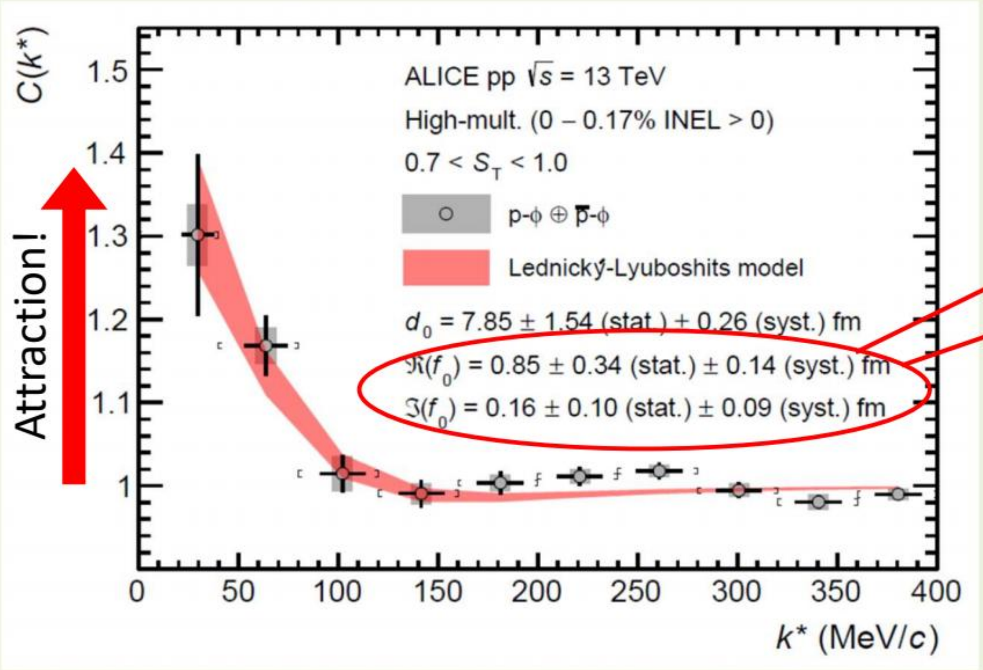
R. Muto et al. (E325 Collaboration), Phys. Rev. Lett. **98**, 042501 (200

Huge statistics at J-PARC, E-16: ϕ→ e+ e- decay ; E-88 : ϕ→ K+ K- decay

- ϕ-N correlation: ALICE

ALICE: pp

φN correlation function



★ Strongly attractive

★ Small absorption

Caution:
Spin averaged value with non-trivial weights (thanks to Kamiya-san!)

S. Acharya et al. (ALICE Coll.), Phys. Rev. Lett. **127**, 172301 (2021).

$$V_\phi(\rho) = -\frac{2\pi}{m_\phi}\rho\left(1+\frac{m_\phi}{m_N}\right)a_0$$
$$\simeq -85\frac{\rho}{\rho_0}\left(\frac{a_0}{\mathrm{fm}}\right)\,\mathrm{MeV}$$

• ϕ-N potential: Lattice

Y. Lyu et al (HAL) PRD106,074507(22)

❑ Long range part: attraction 2-π

$$V\left(r \gg (2m_\pi)^{-1}\right) = -\alpha\,\frac{\exp(-2m_\pi r)}{r^2}, \quad \alpha \approx 91\ \mathrm{MeV}\cdot\mathrm{fm}^2$$

$$\Delta E_{2\pi-N} \approx \rho_{n.m}\int_{r_0} -\alpha\,\frac{\exp(-2m_\pi r)}{r^2}\,d^3x \leq 30\ \mathrm{MeV}$$

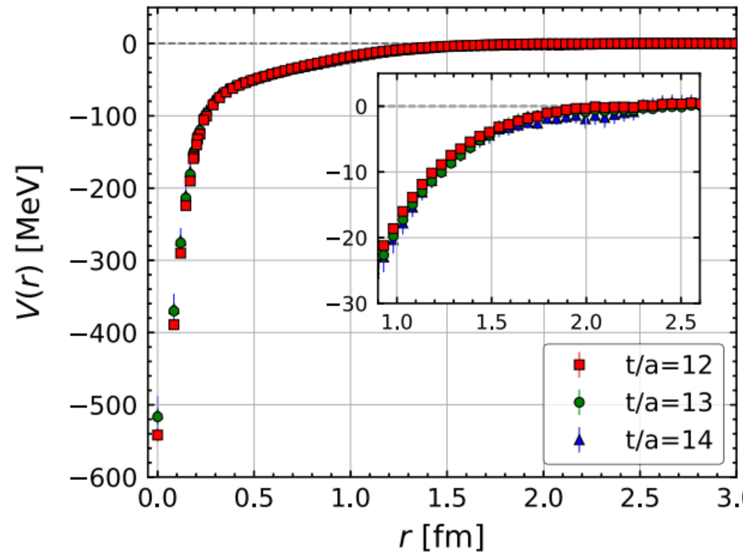
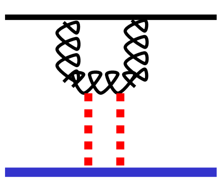
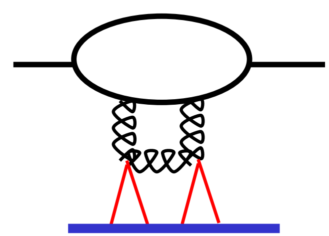


FIG. 1. The N-ϕ potential $V(r)$ in the $^4S_{3/2}$ channel as a function of separation r at Euclidean time $t/a = 12$ (red squares), 13 (green circles), and 14 (blue triangles).

→ Coupling to 2-π



Also present in OPE



ϕ-in medium: JPARC E-16 and E-88

E-16 : $\phi \rightarrow e^+ e^-$ decay

E-88 : $\phi \rightarrow K^+ K^-$ decay

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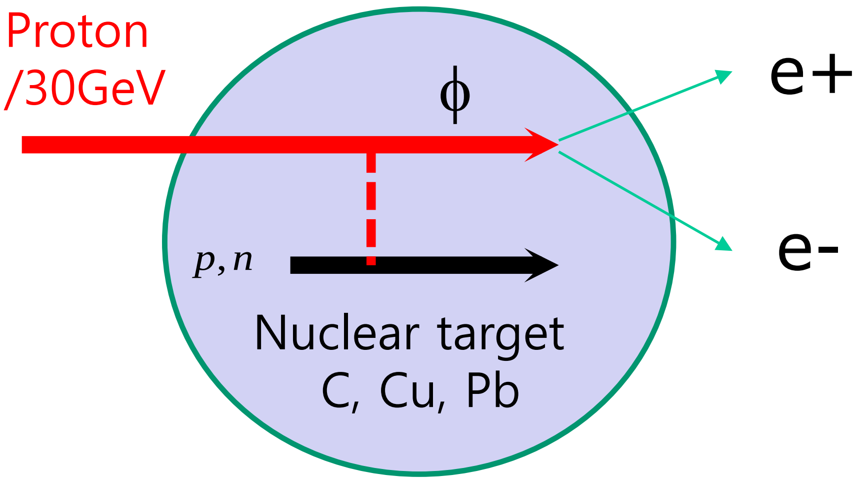
ELSEVIER

Full Length Article

Experimental investigation of vector mesons in medium through dielectron decay at J-PARC

Kazuya Aoki [a,*], Sakiko Ashikaga [b], Wen-Chen Chang [c], Tatsuya Chujo [d], Ren Ejima [e], Hideto En'yo [f], Shinichi Esumi [d], Dairon Rodriguez Garces [g,h], Hideki Hamagaki [i], Johann M. Heuser [h], Ryotaro Honda [a], Masaya Ichikawa [a], Daichi Ishii [j], Shunsuke Kajikawa [k], Jo Kakunaga [l], Koki Kanno [a], Akio Kiyomichi [m], Yusuke Hori [j], Chih-Hsun Lin [c], Yuhei Morino [a], Tomoki N. Murakami [f], Ryotaro Muto [a], Shunnosuke Nagafusa [j], Wataru Nakai [a], Satomi Nakasuga [j], Megumi Naruki [j], Toshihiro Nonaka [d], Hiroyuki Noumi [b], Shuta Ochiai [j], Makoto Ogura [j], Kyoichiro Ozawa [a], Adrian Rodriguez Rodriguez [h], Takao Sakaguchi [n], Hiroyuki Sako [o], Fuminori Sakuma [f], Susumu Sato [o], Shinya Sawada [a], Michiko Sekimoto [a], Kenta Shigaki [e], Kotaro Shirotori [b], Hitoshi Sugimura [a], Tomonori N. Takahashi [b], Tomohiro Taniguchi [j], Maksym Teklishyn [h], Alberica Toia [g,h], Rento Yamada [e], Kanako H. Yamaguchi [j], Yorito L. Yamaguchi [e], Shogo Yanai [j], Satoshi Yokkaichi [f]

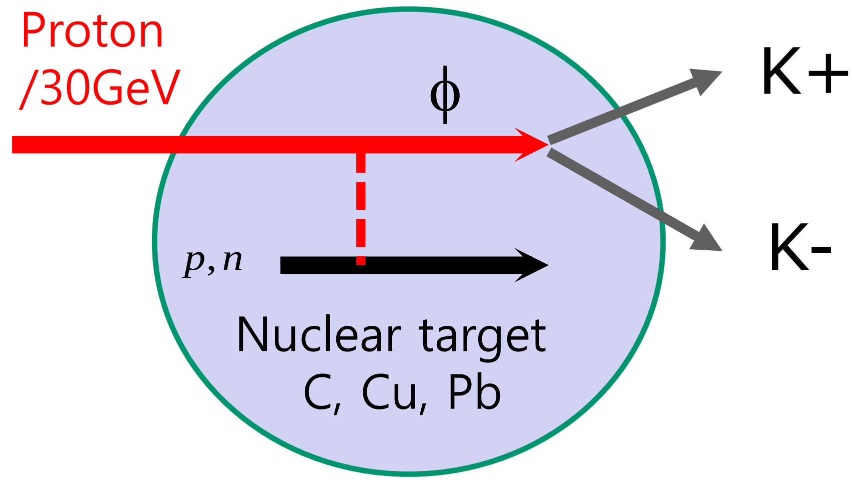
E16



No Final state interaction
Small Rate

→ Currently taking data

E88



Large Final state interaction
Large Rate x 10^3

→ Detector installed

- *Budapest BUU Transport calculation*

Balassa, Aoki, Gluber, Lee, Sako, Wolf (PTEP 2025, 113C01 arXiv:2508.11344)

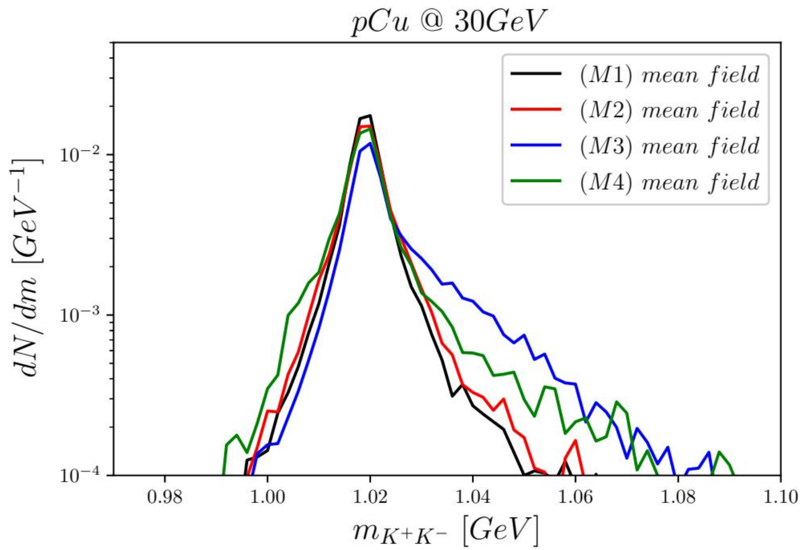
- ❑ Include Kaon mean field+ scattering

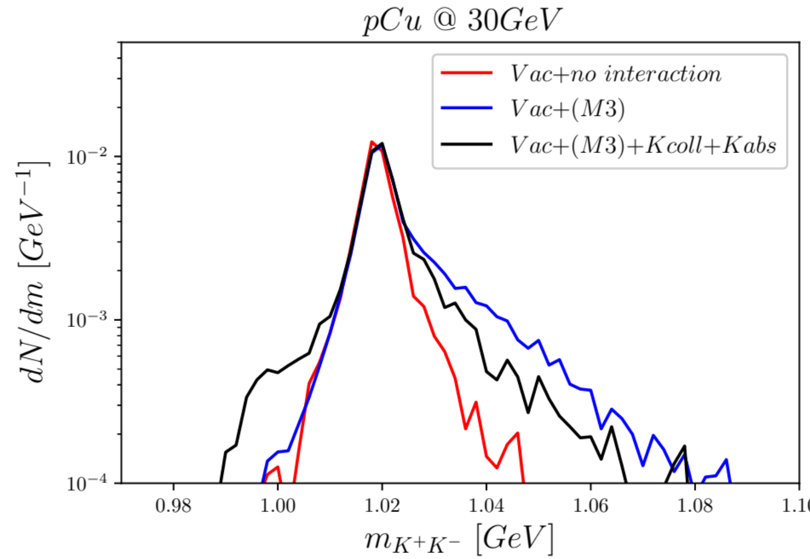
Table 2. Mean field models for K^+ and K^-. To obtain the potentials in [GeV], the kaon momenta p_K should be given in [GeV], while the densities should be given in [fm^{-3}].

Model		Mean field expression	Parameter values
M1	K^+	$U_{K^+} = 0$	…
	K^-	$U_{K^-} = 0$	…
M2	K^+	$U_{K^+} = a_2 \cdot \rho$	$a_2 = 0.167$ [GeV $\cdot$ fm^3]
	K^-	$U_{K^-} = -a_2 \cdot \rho$	
M3	K^+	$U_{K^+} = a_3 \cdot \rho$	$a_3 = 0.167$ [GeV $\cdot$ fm^3]
(W. Cassing et al.)	K^-	$U_{K^-} = -\rho(b_3 + c_3 \cdot e^{-d_3 \cdot p_K})$	$b_3 = 0.341$ [GeV $\cdot$ fm^3], $c_3 = 0.823$ [GeV $\cdot$ fm^3], $d_3 = 2.5$ [GeV^{-1}]
M4 (L. Tolos et al.)	K^+, K^-	Density- and momentum-dependent mean fields extracted from Refs. [38,39]	

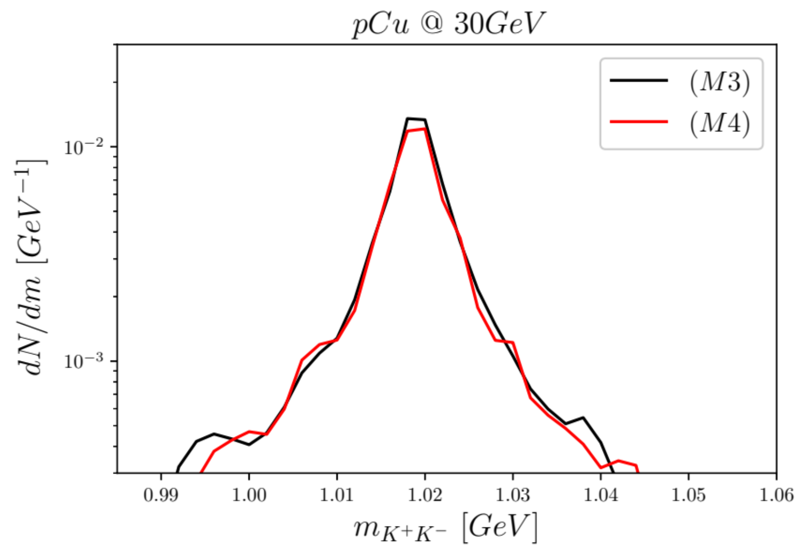
Balassa, Aoki, Gluber, Lee, Sako, Wolf (PTEP 2025, 113C01 arXiv:2508.11344)

- Kaon Mean field will smear out: collision and absorption effects are important





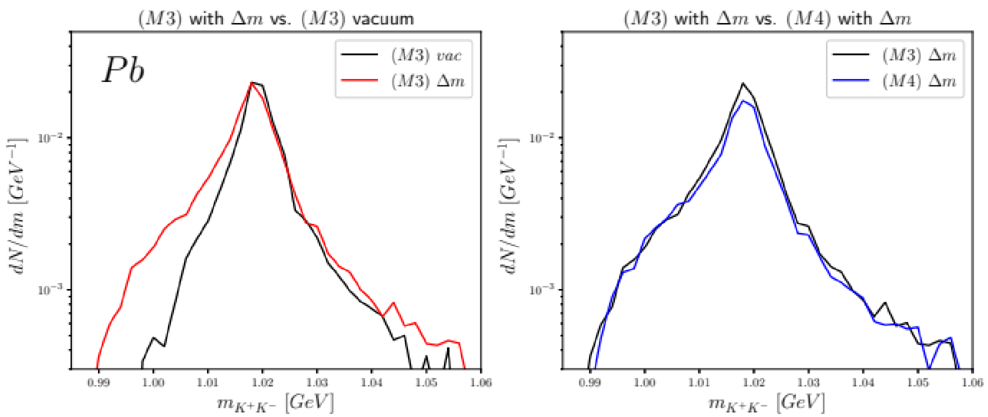
+Kcoll+Kabs



- *Budapest BUU Transport calculation*

Balassa, Aoki, Gluber, Lee, Sako, Wolf (PTEP 2025, 113C01 arXiv:2508.11344)

Effects of mass shift leads to enhancement at low invariant mass



Effects of different mean fields for K : small effect

Fig. 6 Invariant mass spectra of the K meson pairs when $\Delta m(\rho_0) = -34$ MeV mass shift is applied to the ϕ mesons using the (M3) and (M4) mean fields. On the left side, the vacuum (without mean fields, or final state interactions for reference) and the mass shift cases are compared using only the (M3) mean field, while on the right side, the (M3) and (M4) mean field cases are compared using $\Delta m(\rho_0) = -34$ MeV.

Combining two experiment will provide definite answer

E-88 : $\phi \rightarrow K+ K-$

E-16 : $\phi \rightarrow e+ e-$

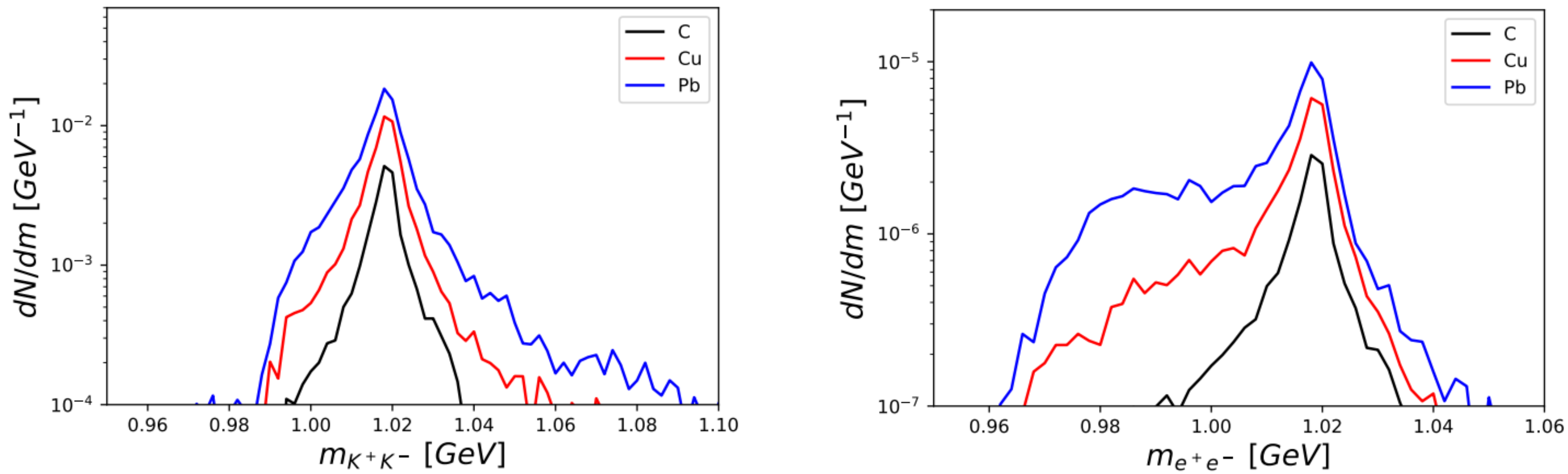


Fig. 7 Invariant mass distribution of kaon pairs (upper), and dileptons (lower) for 30 GeV p+C, p+Cu and p+Pb reactions, with a $m(\rho_0) = -34$ MeV mass shift scenario. In these simulations, the (M3) kaon mean fields were applied.

K* and K1 in medium

Which vector meson should one study in medium

1) Hadrons with small width (Song, Hatsuda, Lee PLB792 (2019)160); Lee JSPC, 1 (2024) 100008

Chiral partners with small widths →

$J^{PC}=1^{--}$	Mass	Width	$J^{PC}=1^{++}$	Mass	Width
ρ	770 MeV	150 MeV	a_1	1260	250−600
ω	782	8.49	f_1	1285	24.2
ϕ	1020	4.266	f_1	1420	54.9
K*(1⁻)	892	50.3	$K_1(1^+)$	1270	90

2) Use condensate based Operator Product Expansion (OPE) methods

- Can identify Chiral symmetry breaking effects

$$\langle \bar{q}q \rangle \qquad q \to \exp(i\gamma_5 \vec{\alpha})\, q$$

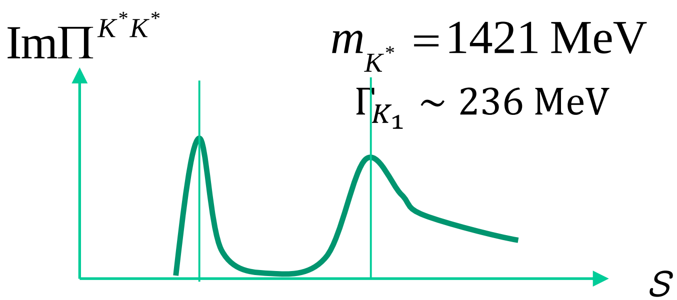
$$\Pi^{K^*K^*} - \Pi^{K_1K_1} = \frac{1}{V}\int d^4x e^{iqx}\Big[\langle \bar{s}\gamma^\mu q(x), \bar{q}\gamma^\mu s(0)\rangle - \langle \bar{s}i\gamma^5\gamma^\mu q(x), \bar{q}i\gamma^5\gamma^\mu s(0)\rangle \Big] = \frac{c_4}{q^4}\langle m_s \bar{q}q\rangle + \frac{c_6}{q^6}\langle \bar{s}s\bar{q}q\rangle .....$$

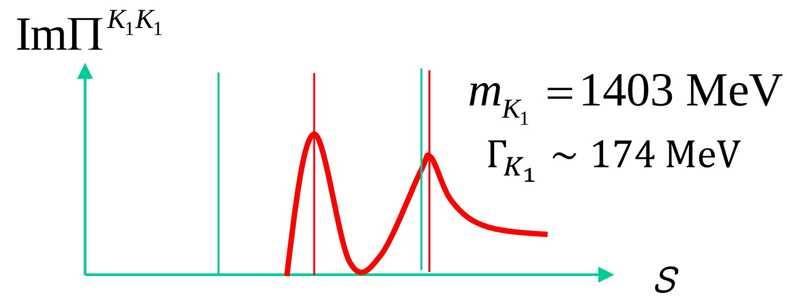
- Can relate them to mass

$$\Pi(q^2) = \frac{1}{\pi}\int ds \frac{\mathrm{Im}\Pi(s)}{s-q^2}.$$

- *Weinberg type sum rules*

☞ $$\Pi^{K^*} - \Pi^{K_1} = \ldots.\frac{1}{Q^6}\left[2\langle B_{su}\rangle\right] + .. = \frac{1}{\pi}\int ds \frac{\mathrm{Im}\left(\Pi^{K^*} - \Pi^{K_1}\right)}{s-q^2}$$





$m_{K^*} = 892$ MeV
$\Gamma_{K^*} \simeq 47$ MeV

$m_{K_1} = 1272$ MeV
$\Gamma_{K_1} \simeq 90$ MeV

☞ $$f_{K^*}^2 m_{K^*}^4 - f_{K_1}^2 m_{K_1}^4 = -2m_s\langle \bar{u}u\rangle \qquad f_{K^*}^2 m_{K^*}^6 - f_{K_1}^2 m_{K_1}^6 = 2\langle B_{su}\rangle = -64\pi\alpha_s\langle \bar{u}u\rangle\langle \bar{s}s\rangle$$

$$\Rightarrow \quad f_{K^*}^2 m_{K^*}^4\left(m_{K_1}^2 - m_{K^*}^2\right) = 2m_s\langle \bar{u}u\rangle m_{K_1}^2 + 64\pi\alpha_s\langle \bar{u}u\rangle\langle \bar{s}s\rangle$$

$$\Rightarrow \quad m_{K_1}^2(T) = m_{K^*}^2 + \frac{\langle \bar{u}u\rangle_T}{\langle \bar{u}u\rangle_0}\left(m_{K_1}^2 - m_{K^*}^2\right)$$

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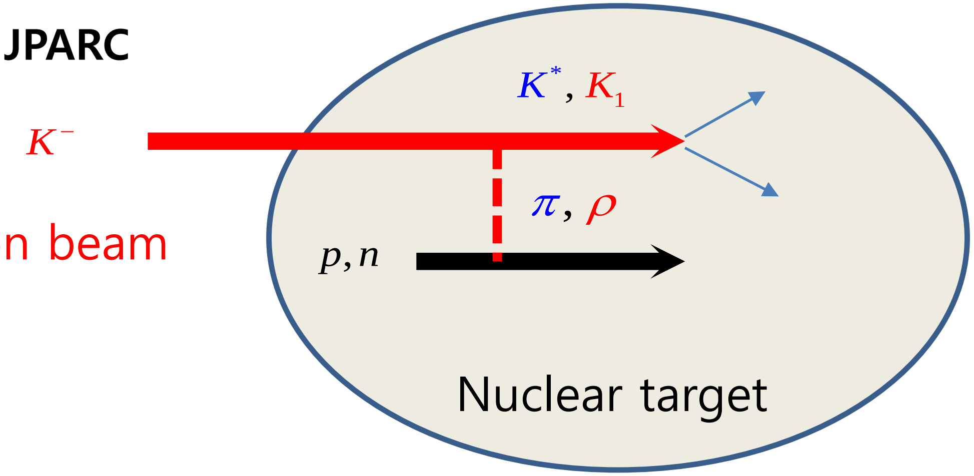
4) K1/K* ratio in heavy ion collsion

- Haesom Sung, et al. PLB 819 (2021) 136388; PRC 109 (2024) 4

5) Seung-Il Nam (PRC114 (26) 014918: Dalitz decay K1→ π+π- K+

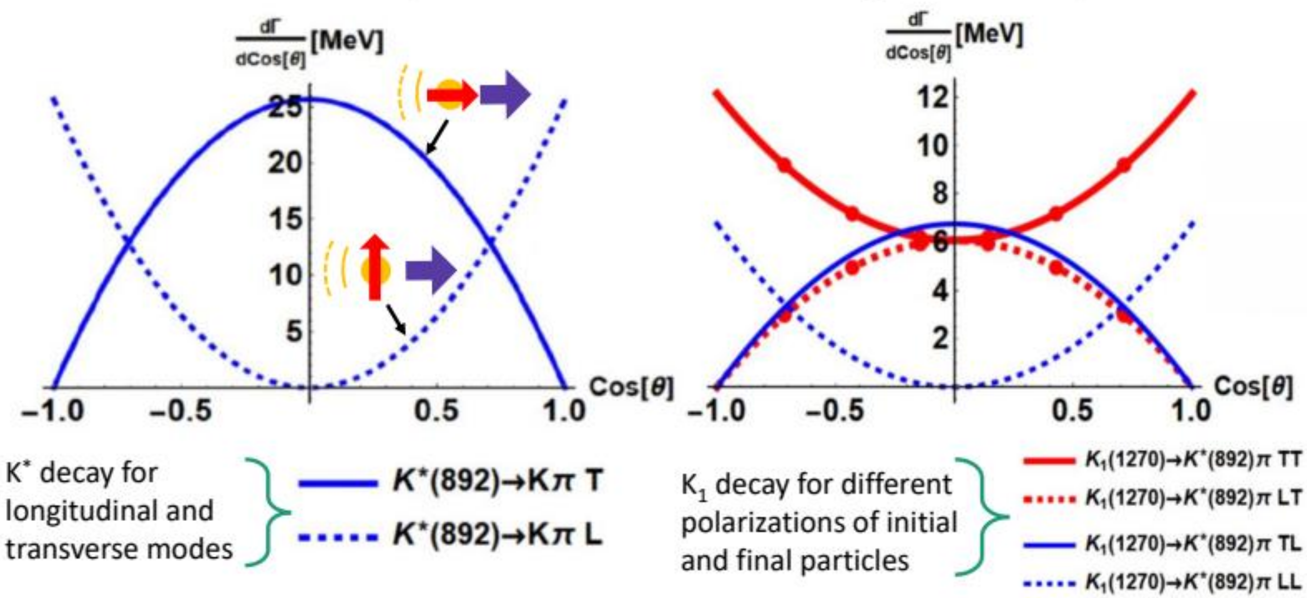
6) K1/K* at JPARC



$$K_1^- \to \left(\begin{matrix} \rho^0 K^- \\ \rho^- \bar{K}^0 \end{matrix} \right. \quad \left(\begin{matrix} \pi^0 K^{*-} \\ \pi^- \bar{K}^{*0} \end{matrix} \right.$$

$$\bar{K}_1^0 \to \left(\begin{matrix} \rho^+ K^- \\ \rho^0 \bar{K}^0 \end{matrix} \right. \quad \left(\begin{matrix} \pi^+ K^{*-} \\ \pi^0 \bar{K}^{*0} \end{matrix} \right.$$

Obtained angular distributions for K* and K_1 meson decays



In Woo Park, H. Sako, K. Aoki, P. Gubler, SHL, PRD109 (2024) 11, 114042

Summary

1) The UA(1) effect above Tc is still not clear !!

   Chiral symmetry breaking is responsible for part of the mass

2) ϕ meson attraction in medium

   - ALICE ϕ –N correlation
   - Lattice calculation of ϕ –N potential
   - QCD sum rules

3) ϕ –in medium experiment: KEK 325 → JPARC E-16 (e+e- decay), E-88 (K+K-decay)

   - First direct measurement of mass shift
   - World class experiment to provide a final say on mass shift

4) In future K1, K* measurement should also be interesting

   - A chiral partner