Chiral symmetry restoration, ϕ, K* and K_1 in nuclear medium

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1. Introduction
2. Chiral partners: K1, K*
3. Vector mesons with small width: ϕ meson
4. K1 and K* in experiment
5. Outlook

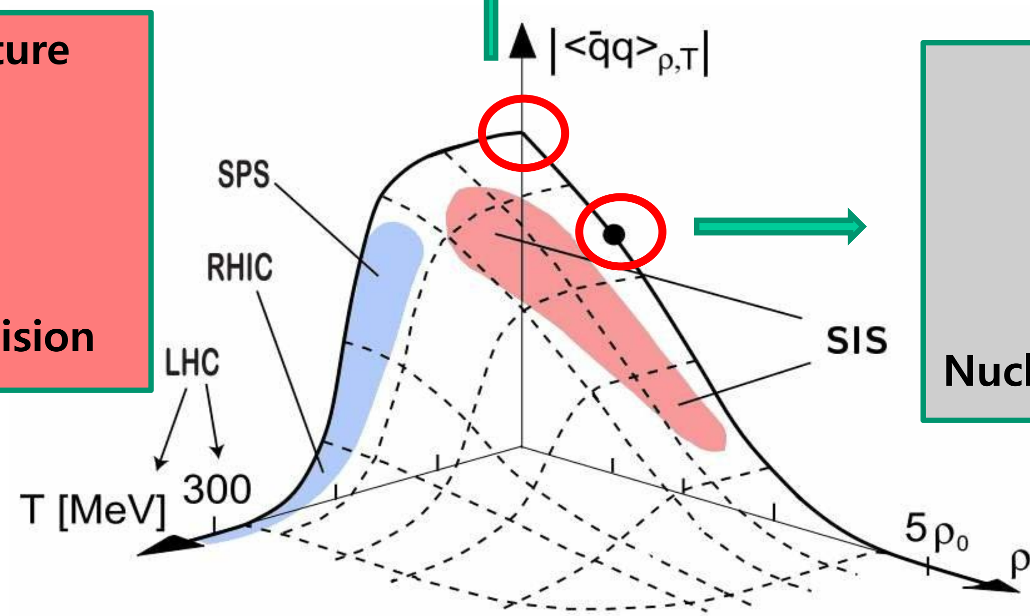
Chiral symmetry restoration and hadron mass

QCD Vacuum

χ-sym is broken

Finite temperature

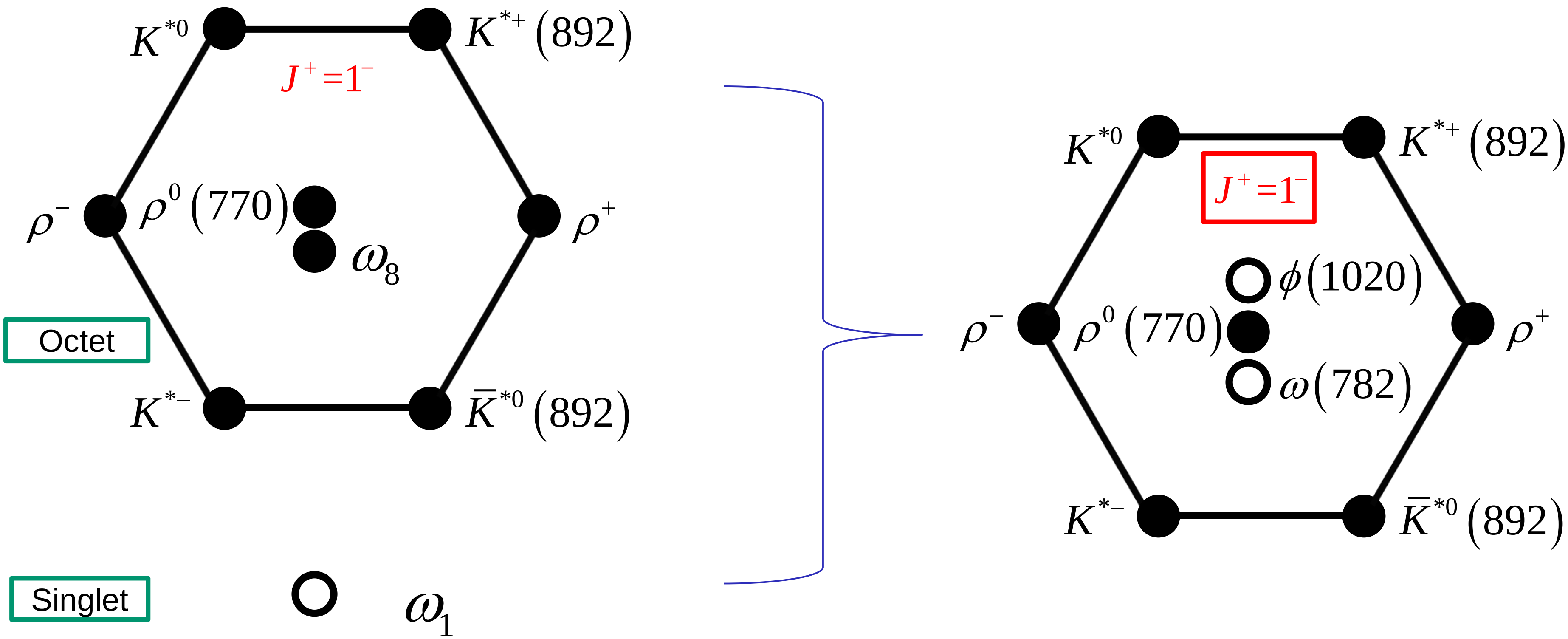
Heavy Ion Collision



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 ?

- Consider correlation function or Mass matrix

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

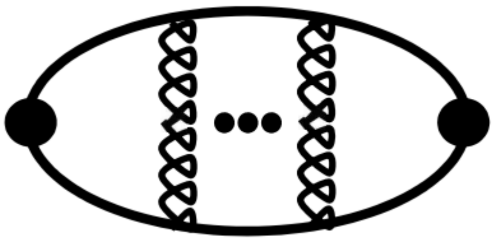
$$\omega_1 = \bar{q}q + \bar{s}s$$
$$\omega_8 = \bar{q}q - \bar{s}s$$

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

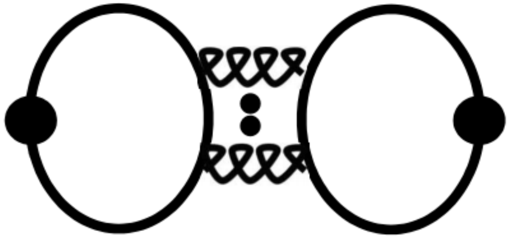
$$\begin{cases} a = \langle (\bar{q}q)(\bar{q}q) + (\bar{s}s)(\bar{s}s) \rangle \\ \Delta = \langle (\bar{q}q)(\bar{q}q) - (\bar{s}s)(\bar{s}s) \rangle \\ D = \langle 2(\bar{q}q)(\bar{s}s) \rangle \end{cases}$$

Δ → Symmetry breaking

D → Disconnected contribution



Connected



Disconnected contribution

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

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

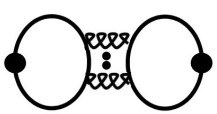
$$\begin{cases} a = \langle (\bar{q}q)(\bar{q}q) + (\bar{s}s)(\bar{s}s) \rangle \\ \Delta = \langle (\bar{q}q)(\bar{q}q) - (\bar{s}s)(\bar{s}s) \rangle \\ D = \langle 2(\bar{q}q)(\bar{s}s) \rangle \end{cases}$$

- Eigenvalues $\quad \mathrm{M}_{\pm} = a \pm \sqrt{D^2 + \Delta^2}$

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

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

- If SU(3) symmetry is broken: Ideal mixing when D=0<< Δ (Vector meson)

If  $\rightarrow D = 0$ $\qquad \mathrm{M}=\begin{pmatrix} a & \Delta \\ \Delta & a \end{pmatrix} \rightarrow \begin{pmatrix} \langle (\bar{q}q)(\bar{q}q) \rangle & 0 \\ 0 & \langle (\bar{s}s)(\bar{s}s) \rangle \end{pmatrix}$

Chiral transformation of quark bilinears

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

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

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

❑ Broken transformation $\quad q \rightarrow \exp\left(i\vec{\theta}\gamma^5\right) q, \quad \bar{q} \rightarrow \bar{q}\exp\left(i\vec{\theta}\gamma^5\right)$

❑ Transformation of Quark bilinear

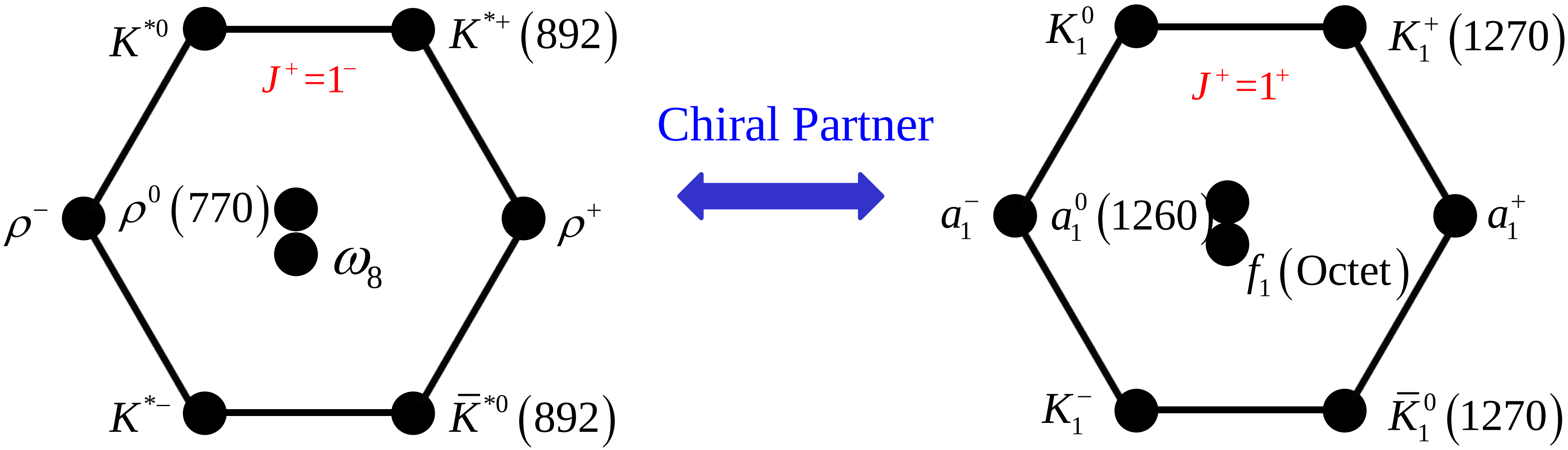
$$\bar{q}\Gamma q \rightarrow \bar{q}\left(1 + i\vec{\theta}\gamma^5\right)\Gamma\left(1 + i\vec{\theta}\gamma^5\right) q \rightarrow \bar{q}\Gamma q + \bar{q}\left(i\vec{\theta}\gamma^5\Gamma + \Gamma i\vec{\theta}\gamma^5\right) q$$

scalar: $\quad \bar{q}q \rightarrow \bar{q}q + 2\bar{q}\left(i\vec{\theta}\gamma^5\right) q$

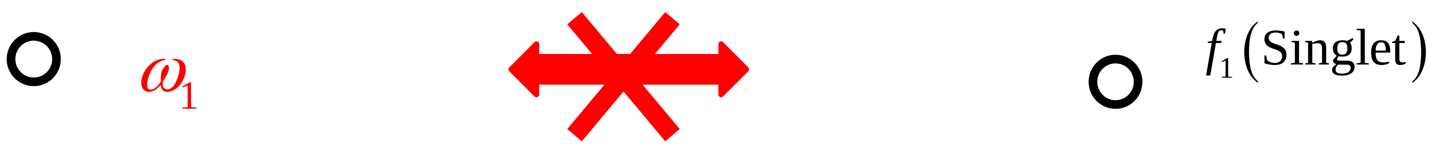
Flavor octet vector meson: $\bar{q}\gamma^\mu \tau^a q \rightarrow \bar{q}\gamma^\mu \tau^a q + \bar{q} i \gamma^5 \gamma^\mu \left[\vec{\theta}, \tau^a\right] q$

Flavor singlet vector meson: $\bar{q}\gamma^\mu q \rightarrow \bar{q}\gamma^\mu q + \bar{q} i \gamma^5 \gamma^\mu \left[\vec{\theta}, 1\right] q = \bar{q}\gamma^\mu q$

Spin-1 Flavor Octet



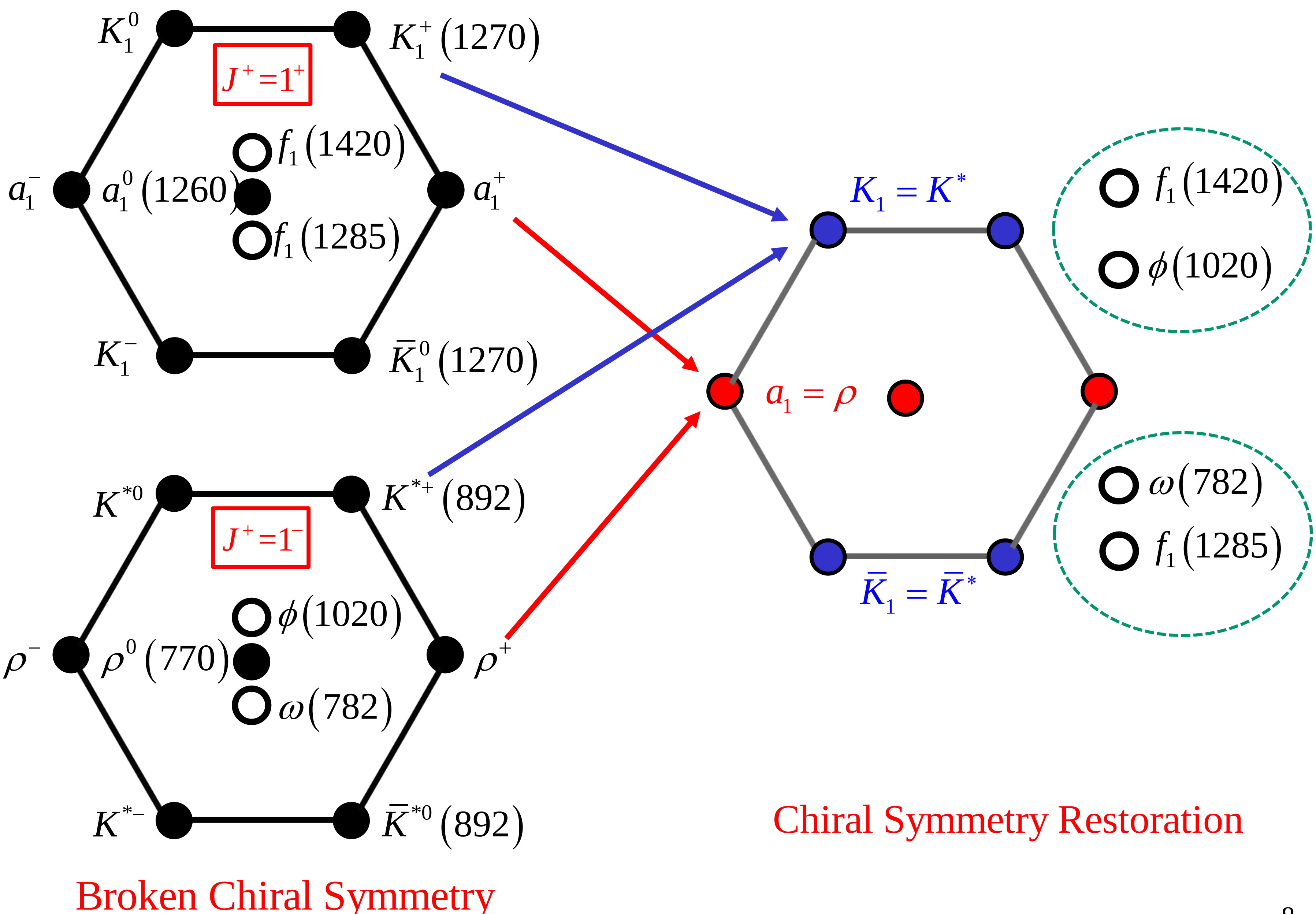
Spin-1 Flavor Singlet



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

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

$$m_s \gg m_d \sim m_u \quad \begin{cases} \phi(1020) = \bar{s}s = \frac{1}{\sqrt{3}}\left(\omega_1 - \sqrt{2}\omega_8\right) \\ \omega(782) = \frac{1}{\sqrt{2}}\left(\bar{u}u + \bar{d}d\right) = \frac{1}{\sqrt{3}}\left(\omega_8 + \sqrt{2}\omega_1\right) \end{cases}$$


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^{*-}
$\bar{K}^{*0}(892)$
$K_1 = K^*$
$a_1 = \rho$
$\bar{K}_1 = \bar{K}^*$
$f_1(1420)$
$\phi(1020)$
$\omega(782)$
$f_1(1285)$
Chiral Symmetry Restoration
Broken Chiral Symmetry

Chiral partners: K*, K1

- *Operator product expansion for K* and K1*

❑ $$\Pi^{K^*K^*} = \left\langle \left(\bar{u}\gamma_\mu s\right)_x \left(\bar{s}\gamma_\mu u\right)_0 \right\rangle = \ldots\ldots - \frac{2\pi\alpha}{Q^6}\left[\left\langle \left(\bar{u}\gamma_\mu\gamma^5\lambda^a s\right)\left(\bar{s}\gamma_\mu\gamma^5\lambda^a u\right)\right\rangle + \frac{1}{9}\left\langle \left(\sum_{su}\bar{q}\gamma_\mu\lambda^a q\right)\left(\sum_{uds}\bar{q}\gamma_\mu\lambda^a q\right)\right\rangle \right]$$

$$\Pi^{K_1K_1} = \left\langle \left(\bar{u}i\gamma_\mu\gamma^5 s\right)_x \left(\bar{s}i\gamma_\mu\gamma^5 u\right)_0 \right\rangle = \ldots - \frac{2\pi\alpha}{Q^6}\left[\left\langle \left(\bar{u}\gamma_\mu\lambda^a s\right)\left(\bar{s}\gamma_\mu\lambda^a u\right)\right\rangle + \frac{1}{9}\left\langle \left(\sum_{ud}\bar{q}\gamma_\mu\lambda^a q\right)\left(\sum_{uds}\bar{q}\gamma_\mu\lambda^a q\right)\right\rangle \right]$$

❑ Only connected diagrams contribute in the difference

$$\Pi^{K^*K^*} - \Pi^{K_1K_1} = \ldots - \frac{2\pi\alpha}{Q^6}\left[\left\langle \left(\bar{u}\gamma_\mu\gamma^5\lambda^a s\right)\left(\bar{s}\gamma_\mu\gamma^5\lambda^a u\right)\right\rangle - \left\langle \left(\bar{u}\gamma_\mu\lambda^a s\right)\left(\bar{s}\gamma_\mu\lambda^a u\right)\right\rangle \right]$$

$$= \ldots + \frac{2\pi\alpha}{Q^6}\left[\left\langle \left(\bar{s}\lambda^a\gamma_\mu\left[S_u(x,0) - i\gamma^5 S_u(x,0) i\gamma^5\right]\lambda^a\gamma_\mu s\right)\right\rangle - \left\langle u \leftrightarrow s\right\rangle \right]$$

Because they are chiral partners, this part is a chiral order parameter

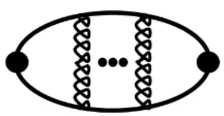
$$\langle \bar{u}u \rangle = -\lim_{x\to 0}\left\langle \frac{1}{2}\left[S_u(x,0) - i\gamma^5 S_u(x,0) i\gamma^5\right]\right\rangle$$

• Operator product expansion for ϕ and $f_1(1420)$

❑ $$\Pi^{\phi\phi}=\left\langle\left(\bar{s}\gamma_\mu s\right)_x\left(\bar{s}\gamma_\mu s\right)_0\right\rangle=\ldots\ldots\ldots-\frac{2\pi\alpha}{Q^6}\left[\left\langle\left(\bar{s}\gamma_\mu\gamma^5\lambda^a s\right)\left(\bar{s}\gamma_\mu\gamma^5\lambda^a s\right)\right\rangle+\frac{2}{9}\left\langle\left(\bar{s}\gamma_\mu\lambda^a s\right)\left(\sum_{uds}\bar{q}\gamma_\mu\lambda^a q\right)\right\rangle\right]$$

$$\Pi^{f_1 f_1}=\left\langle\left(\bar{s}i\gamma_\mu\gamma^5 s\right)_x\left(\bar{s}i\gamma_\mu\gamma^5 s\right)_0\right\rangle=\ldots.-\frac{2\pi\alpha}{Q^6}\left[\left\langle\left(\bar{s}\gamma_\mu\lambda^a s\right)\left(\bar{s}\gamma_\mu\lambda^a s\right)\right\rangle+\frac{2}{9}\left\langle\left(\bar{s}\gamma_\mu\lambda^a s\right)\left(\sum_{uds}\bar{q}\gamma_\mu\lambda^a q\right)\right\rangle\right]$$

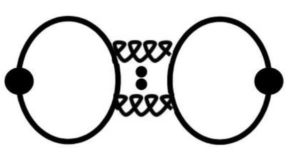
❑ The Difference has contribution from disconnect diagram, and is chiral symmetric



$$\lim_{x\to 0}\left\langle\left[S_s(x,0)-i\gamma^5 S_s(x,0)i\gamma^5\right]\right\rangle=-\left\langle\bar{s}s\right\rangle$$

$$\Pi^{\phi\phi}-\Pi^{f_1 f_1}=\ldots.+\frac{4\pi\alpha}{Q^6}\left[\left\langle\left(\bar{s}\lambda^a\gamma_\mu\left[S_s(x,0)-i\gamma^5 S_s(x,0)i\gamma^5\right]\lambda^a\gamma_\mu s\right)\right\rangle\right]$$

$$-\frac{2\pi\alpha}{Q^6}\left[\left\langle\mathrm{Tr}\left(\lambda^a\gamma_\mu\gamma^5 S_s(x,x)\right)\mathrm{Tr}\left(\lambda^a\gamma_\mu\gamma^5 S_s(0,0)\right)\right\rangle+\left\langle\mathrm{Tr}\left(\lambda^a\gamma_\mu S_s(x,x)\right)\mathrm{Tr}\left(\lambda^a\gamma_\mu S_s(0,0)\right)\right\rangle\right]$$



$$S_s=\frac{1}{2}\left[S_s-i\gamma^5 S_s i\gamma^5\right]+\frac{1}{2}\left[S_s+i\gamma^5 S_s i\gamma^5\right]\not\propto\left\langle\bar{s}s\right\rangle$$

- Disconnect diagram is known to be small in vacuum (ideal mixing)

Which vector meson should one study in medium

- **Hadrons with small width: ϕ is the best candidate**

J-PARC E16, E88 → ϕ

$J^{PC}=1^{--}$	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

- **Chiral partner: K* and K1 is the best candidate**

  - Decay mode of chiral partners typically has one more pion

$$m_{K^*} - m_{K_1} \propto \langle \bar{q}q \rangle$$

$$K^* \to K\pi, \qquad K_1^- \to \begin{cases} \rho(\pi\pi) + K \\ \pi + K^*(K\pi) \end{cases}$$

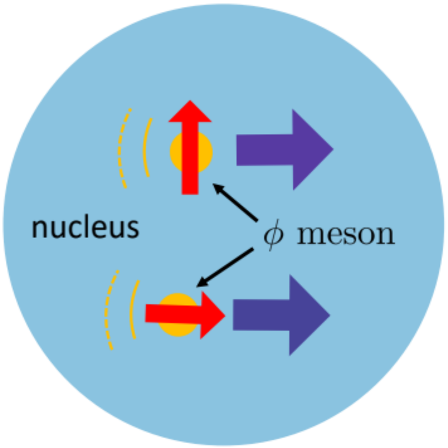
- **Measurement of $f_1(1420)$ is still interesting (parity partner of ϕ)**

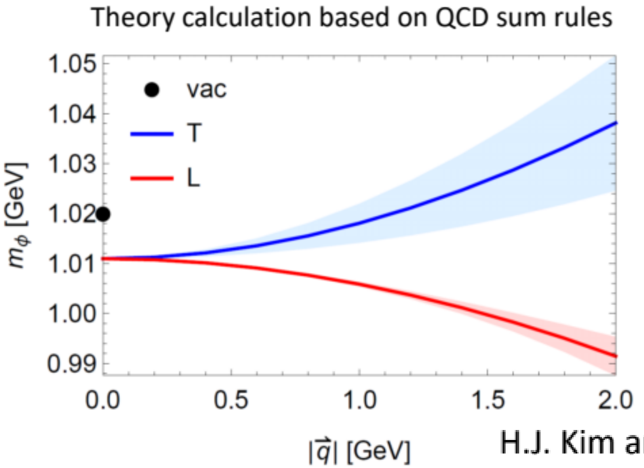
$$m_\phi - m_{f_1(1420)} \propto \langle \bar{s}s \rangle + \text{other}$$

$$\phi \to K + K \qquad f_1(1420) \to K + K^*(K\pi)$$

ϕ meson with small momentum

- Transverse and Longitudinal modes at large momentum





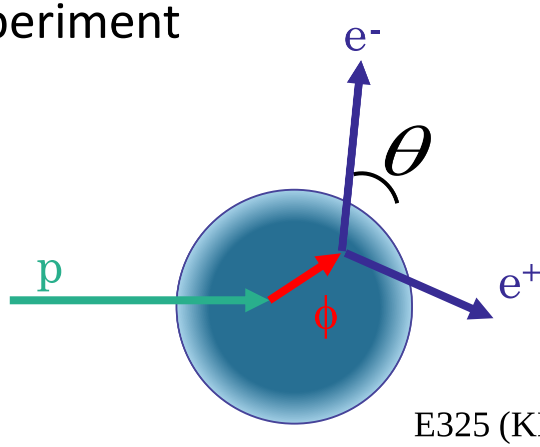
H.J. Kim and P. Gubler, Phys. Lett. B **805**, 135412 (2020).

- This momentum dependence is Chiral symmetric contributions

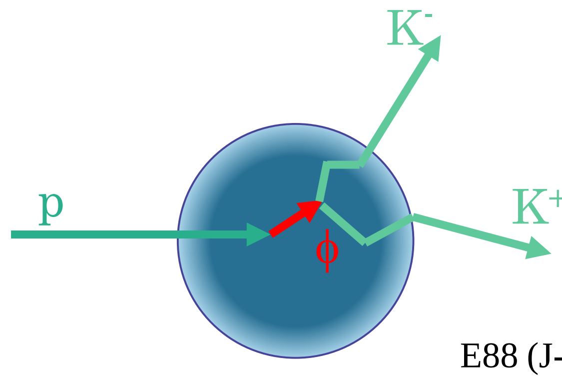
$$\Pi^T(\omega,\vec{q}) - \Pi^L(\omega,\vec{q}) = \frac{m A_2^{u+d} \vec{q}^2}{\omega^6}\rho_n.$$

where $A_2^q \propto \langle N | \bar{q}\gamma_\mu D_\nu q | N \rangle$

❑ Experiment

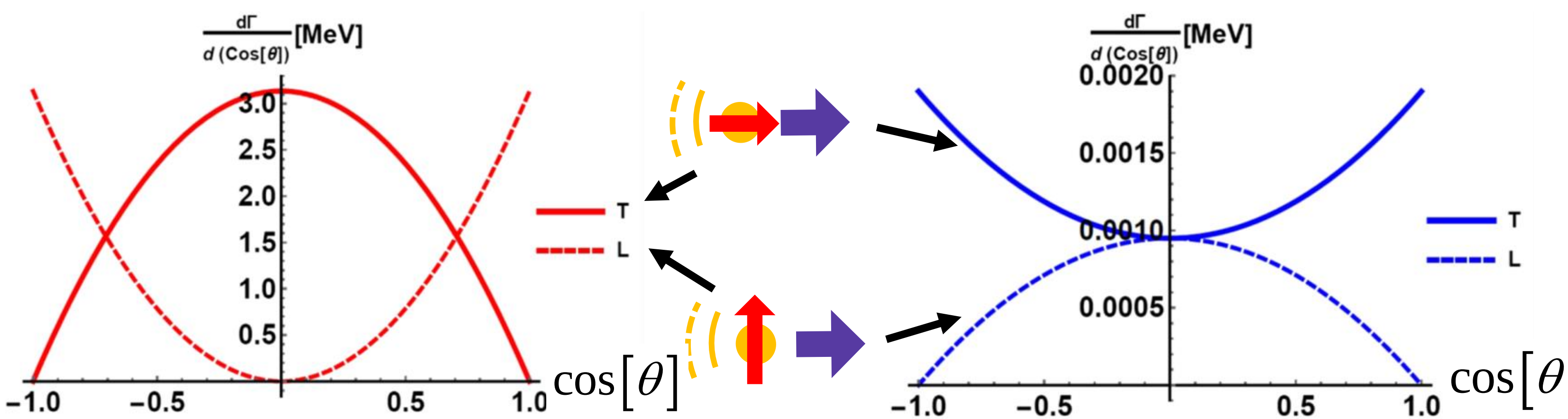


E325 (KEK)
E16 (J-PARC)



E88 (J-PARC)

❑ Angular decay distributions for Transverse and Longitudinal modes



K^+K^- decay

e^+e^- decay

I.W. Park, H. Sako, K. Aoki, P. Gubler and S.H. Lee, Phys. Rev. D **107**, 074033 (2023).

K* and K1 mass in the chiral symmetric vacuum

- *Sum rules in the chiral symmetric vacuum*

☞
$$\Pi^{\rho\rho} = ... - \frac{2\pi\alpha}{Q^6}\left[\frac{28}{9}\langle B_{uu}\rangle + \langle S_{\rho-a_1}\rangle\right] \qquad \Pi^{K^*K^*} = ... - \frac{2\pi\alpha}{Q^6}\left[\langle B_{su}\rangle - \frac{1}{9}\langle B_{uu}\rangle + \langle S_{K^*-K_1}\rangle\right]$$

$$\Pi^{K_1K_1} = ... - \frac{2\pi\alpha}{Q^6}\left[-\frac{44}{9}\langle B_{uu}\rangle + \langle S_{\rho-a_1}\rangle\right] \qquad \Pi^{K_1K_1} = ... - \frac{2\pi\alpha}{Q^6}\left[-\langle B_{su}\rangle - \frac{1}{9}\langle B_{uu}\rangle + \langle S_{K^*-K_1}\rangle\right]$$

From phenomonlogy of ρ, a_1, K^*, K_1 can determine $\langle B_{su}\rangle, \langle B_{uu}\rangle, \langle S_{\rho-a_1}\rangle, \langle S_{K^*-K_1}\rangle$

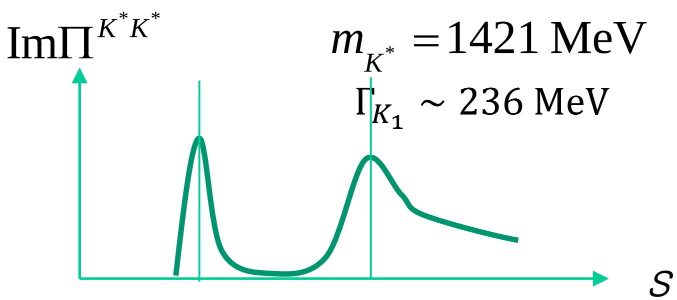
Mass when in the chiral symmetry restored phase can be estimated by

$\langle B_{su}\rangle = \langle B_{uu}\rangle = 0$, but keep vacuuum values for $\langle S_{\rho-a_1}\rangle, \langle S_{K^*-K_1}\rangle$

Particle	m_0	m_B	m_{sym}
ρ	775.26 MeV	610 MeV	572.5 MeV
K^*	895.81 MeV	775 MeV	545 MeV
K_1	1272 MeV	1080 MeV	545 MeV

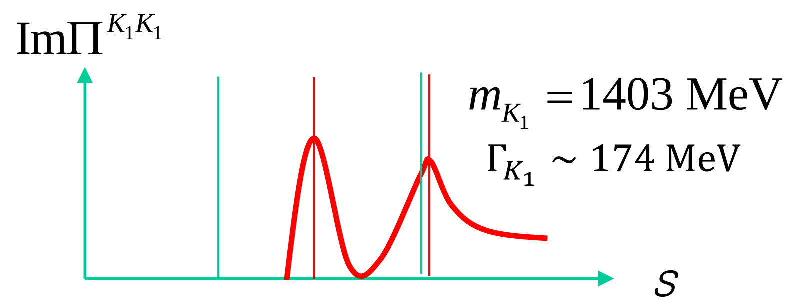
• *Weinberg type sum rules*

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



$m_{K^*} = 892$ MeV

$\Gamma_{K^*} \sim 47$ MeV



$m_{K_1} = 1272$ MeV

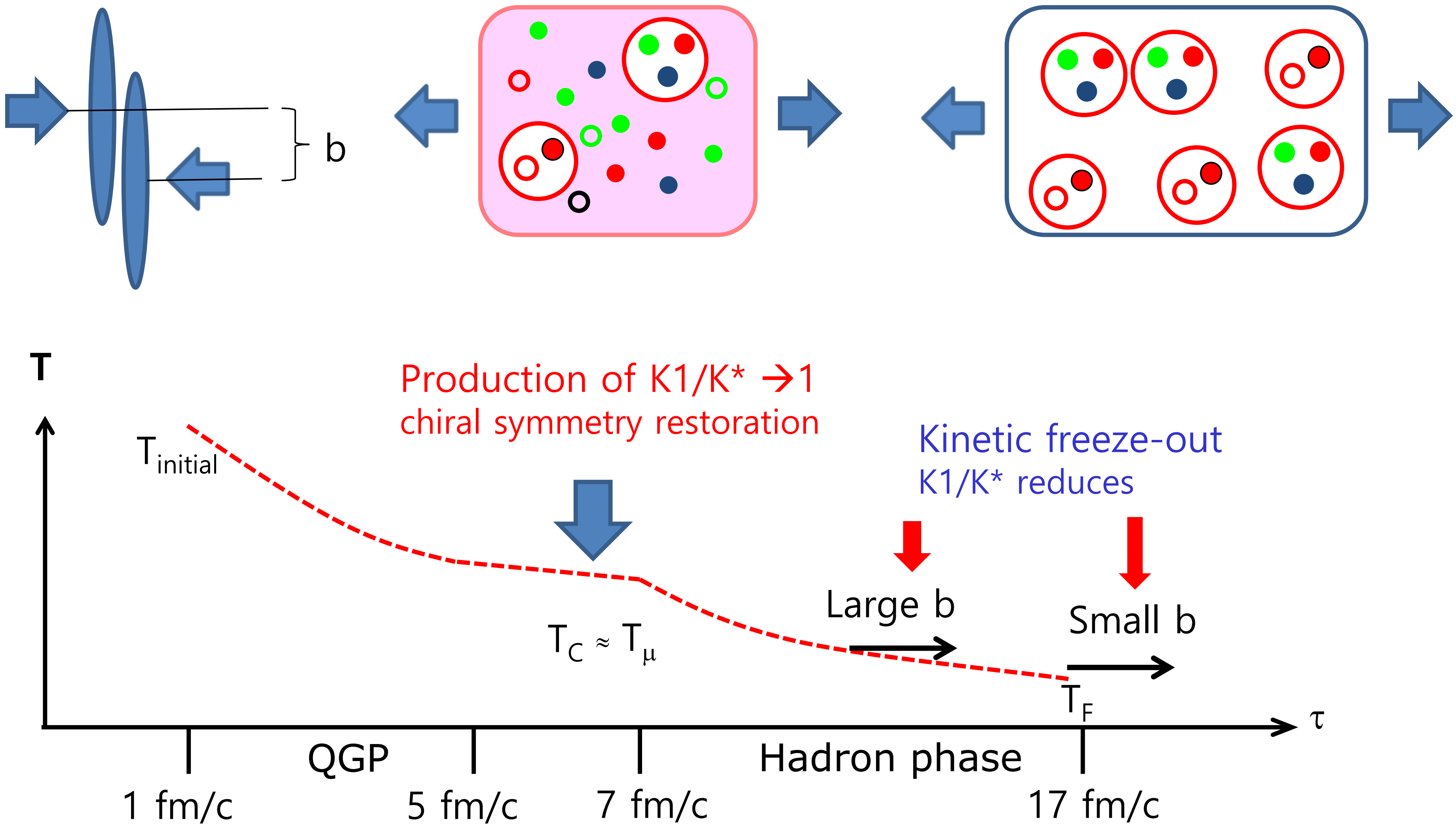
$\Gamma_{K_1} \sim 90$ MeV

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

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

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

K1/K* production in heavy ion collision



- *K1/K* vs centrality*

Haesom Sung, et al. (PLB819(2021) 136388, PRC109 (2024) 4

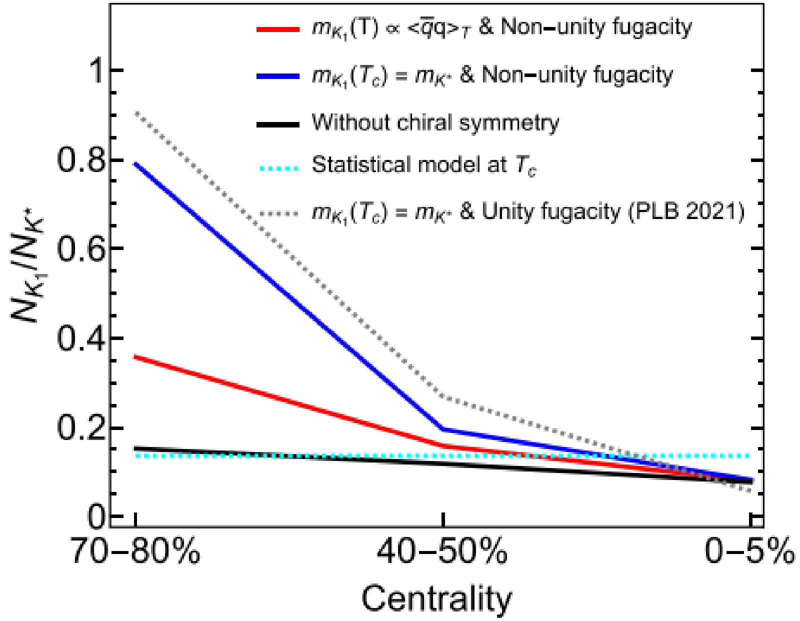


FIG. 5. The yield ratio K_1/K^* in Pb+Pb collisions at $\sqrt{s_{NN}} =$ 5.02 TeV at three centralities of 0–5%, 40–50%, and 70–80% for various scenarios.

K1 measurement in heavy ion collision ?

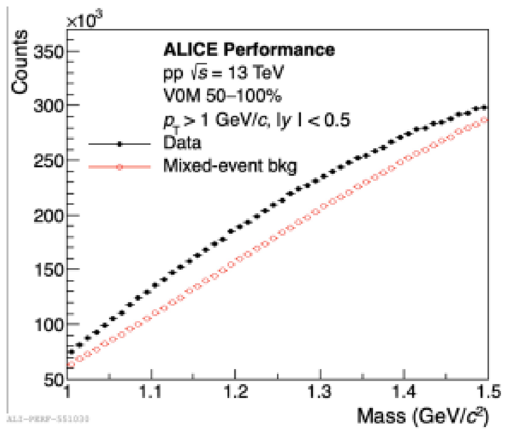
2023

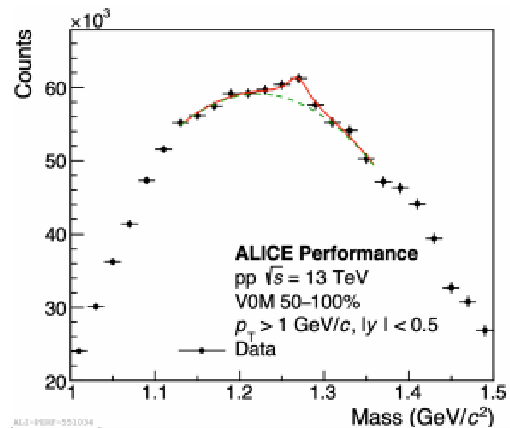
Study of K_1 meson production in pp collisions with ALICE

SU-JEONG JI[1] ON BEHALF OF THE ALICE COLLABORATION | 1) PUSAN NATIONAL UNIVERSITY

ALICE

SIGNAL EXTRACTION





Signal: $\pi^{\pm}\pi^{\mp}K^{\pm}$ pairs

Background:

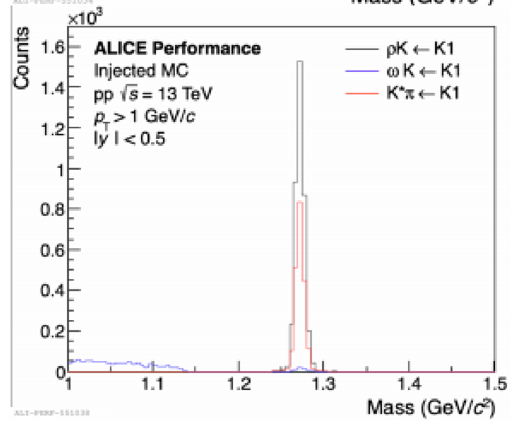
$\pi^{\pm}\pi^{\pm}K^{\mp}$, $\pi^{\pm}\pi^{\pm}K^{\pm}$

pairs from mixed event

(30 events, $\Delta z_{vtx} \leq 2$ cm)

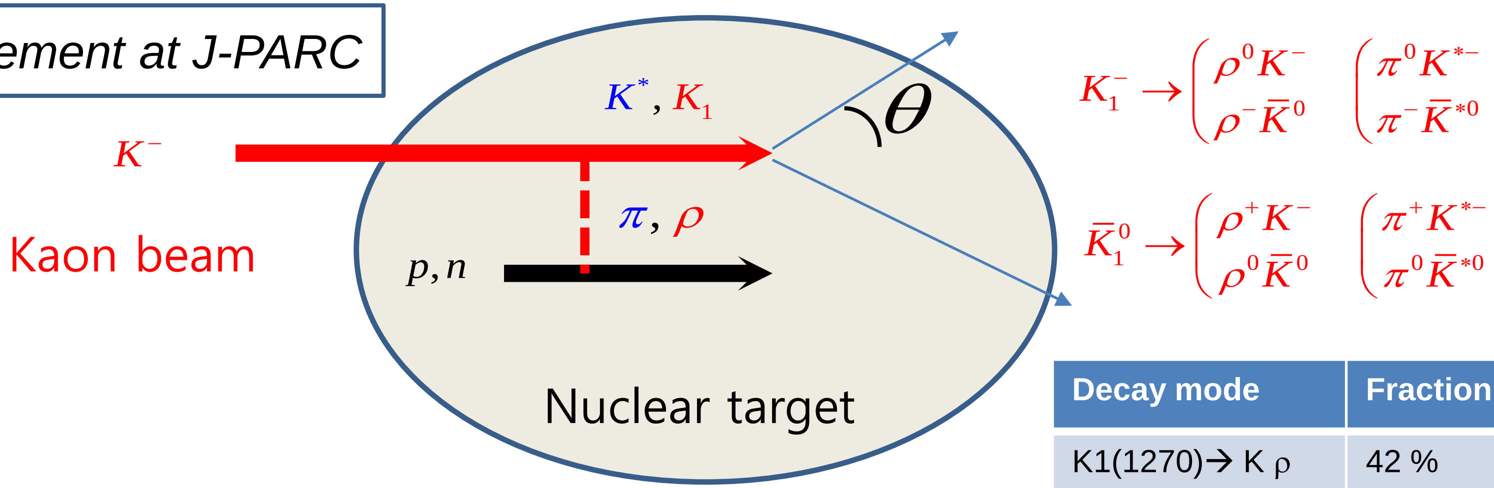
Fit Function: Breit-Wigner

+ quadratic fn.



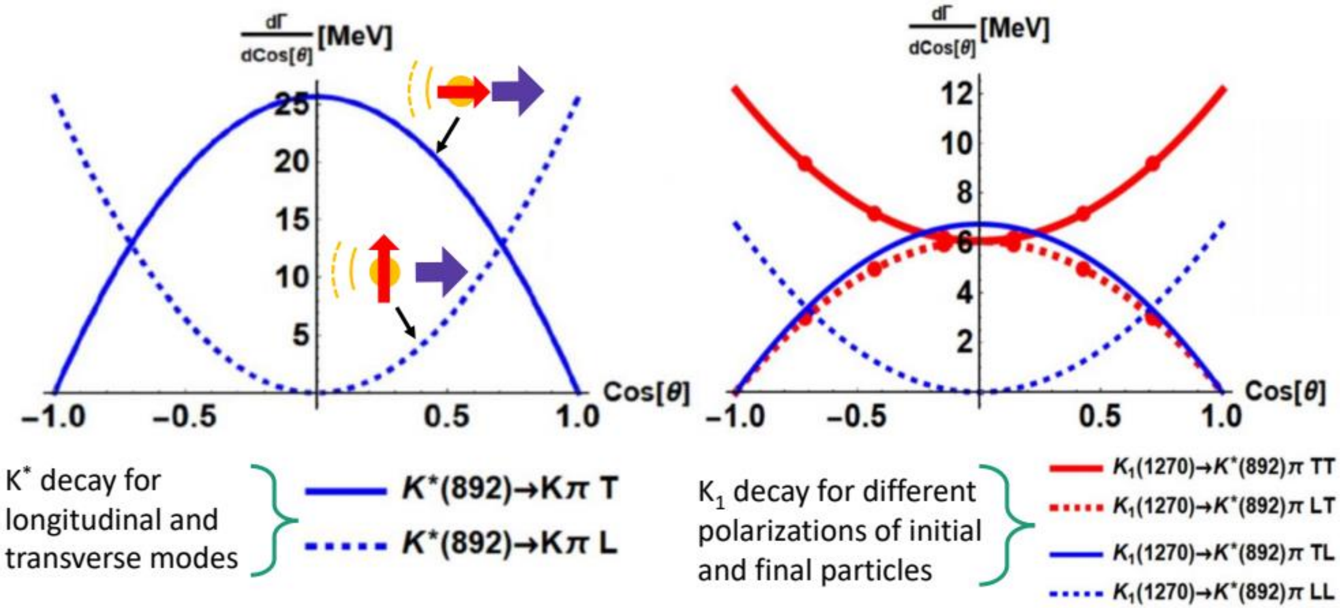
The signal peak is seen at 1270 MeV/c^2 in data.

K1 measurement at J-PARC



Decay mode	Fraction
K1(1270)→ K ρ	42 %
K1(1270)→ K* π	16 %

❑ Transvers and longitudinal modes from angular dependence of decay particles



I.W. Park, H. Sako, K. Aoki, P. Gubler and S.H. Lee, Phys. Rev. D **109**, 114042 (2024).

Summary

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$$m_{K^*} - m_{K_1} \propto \langle \bar{q}q \rangle$$

$$K^* \to K\pi, \qquad K_1^- \to \begin{cases} \rho(\pi\pi) + K \\ \pi + K^*(K\pi) \end{cases}$$

3) If possible measurement of $f_1(1420)$ is also interesting (parity partner of ϕ)

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

$$\phi \to K + K \qquad f_1(1420) \to K + K^*(K\pi)$$

Outlook

1. K1 and K* are Chiral Partners with Γ<100 MeV

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

2. K1/K* production could be measured for different centralities in Heavy Ion Collision

→ Signature of chiral symmetry restoration

3 K1 K* masses can also be measured in J-PARC

Some additions

Which vector meson should one study in medium

1) Hadrons with small width

J-PARC E16, E88 → (arrow to the φ row)

$J^{PC}=1^{--}$	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

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

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

- Can relate them to mass

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

Chiral parters: K* and K1 *(in a chiral symmetry restored vacuum)*

- *Operator product expansion*

Jisu Kim, SHL: arXiv2012.06463 (PRD21)

Jisu Kim, SHL: arXiv2109.12791 (PRD22)

☞ $$\Pi^{K^*K^*} = ... - \frac{2\pi\alpha}{Q^6}\left[\left\langle\left(\bar{u}\gamma_\mu\gamma^5\lambda^a s\right)\left(\bar{s}\gamma_\mu\gamma^5\lambda^a u\right)\right\rangle + \frac{1}{9}\left\langle\left(\sum_{su}\bar{q}\gamma_\mu\lambda^a q\right)\left(\sum_{uds}\bar{q}\gamma_\mu\lambda^a q\right)\right\rangle\right]$$

$$\Pi^{K_1K_1} = ... - \frac{2\pi\alpha}{Q^6}\left[\left\langle\left(\bar{u}\gamma_\mu\lambda^a s\right)\left(\bar{s}\gamma_\mu\lambda^a u\right)\right\rangle + \frac{1}{9}\left\langle\left(\sum_{ud}\bar{q}\gamma_\mu\lambda^a q\right)\left(\sum_{uds}\bar{q}\gamma_\mu\lambda^a q\right)\right\rangle\right]$$

$$\Pi^{K^*K^*} = ... - \frac{2\pi\alpha}{Q^6}\left[\langle B_{su}\rangle - \frac{1}{9}\langle B_{uu}\rangle + \left\langle S_{K^*-K_1}\right\rangle\right]$$

$$\Pi^{K_1K_1} = ... - \frac{2\pi\alpha}{Q^6}\left[-\langle B_{su}\rangle - \frac{1}{9}\langle B_{uu}\rangle + \left\langle S_{K^*-K_1}\right\rangle\right]$$

$$\Pi^{K^*K^*} - \Pi^{K_1K_1} = ... - \frac{2\pi\alpha}{Q^6}\left[2\langle B_{su}\rangle\right]$$

$\langle B_{su}\rangle$ Chiral symmetry breaking operator involving u/s quarks

$\langle S_{uds}\rangle$ Chiral symmetric operator involving $u/d/s$ quarks

Different effects from the medium: Perspectives from OPE

Chiral symmetry breaking operators

1. Changes in Chiral symmetry breaking operators: $\langle \bar{q}q \rangle_{nm} = \langle \bar{q}q \rangle_0 + \rho \langle P | \bar{q}q | P \rangle$

2. 4-quark operator : $\frac{1}{2}\left[\left\langle \left(\bar{q}\gamma_\mu \gamma^5 \lambda^a \tau^3 q \right)^2 - \left(\bar{q}\gamma_\mu \lambda^a \tau^3 q \right)^2 \right\rangle \right] \propto \langle \bar{q}q \rangle_{nm}^2$

$\Rightarrow$ Tends to decrease mass

Chiral symmetric operators

1. Appearance of Tensor operators due to denisty and energy ect. :

$\langle \bar{q}\gamma_0 q \rangle,\ \langle \bar{q}\gamma_\mu D_\nu q \rangle,\ \langle E^2 + B^2 \rangle$ ......

$\Rightarrow$ Tends to increase mass

$\Rightarrow$ when $q \neq 0$, Momentum dependent masses; Transverse and Longitudinal Masses