The identification of (axial) vector meson polarization through its 2-body decay

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Contents.

1. Introduction: Why do we need to know about the vector meson polarization?
2. (Axial) Vector meson 2-body decay
   ① Effective Lagrangian
   ② Disentanglement of transverse and longitudinal mode via polarization tensor
   ③ General angular distribution
   ④ Result: Angular dependent decay distribution + Final vector meson polarization in A→VP
3. Summary

Introduction: Why do we need to know about $J^P = 1^{\pm}$ polarization?

- Chiral symmetry is expected to be partially restored in a nuclear medium.

- The observation of a mass shift is crucial.

- $\phi(1020)$ and chiral partners $\left(K^*(892), K_1(1270)\right)$ have small decay width.

  Γ_ϕ=4.249MeV, Γ_{K^*}=51.4MeV, Γ_{K_1}=90MeV(JPS Conf. Proc. 26, 011012 (2019), Phys. Lett. B 792, 160 (2019))

- Mass shift of a vector meson in a nuclear medium is polarization dependent.(Phys. Lett. B 805, 135412 (2020).)

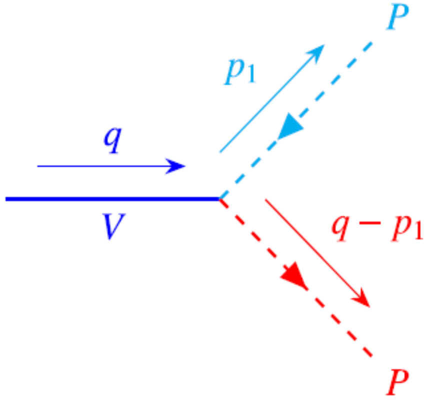
- Vector meson polarization needs to be isolated.

Effective Lagrangian

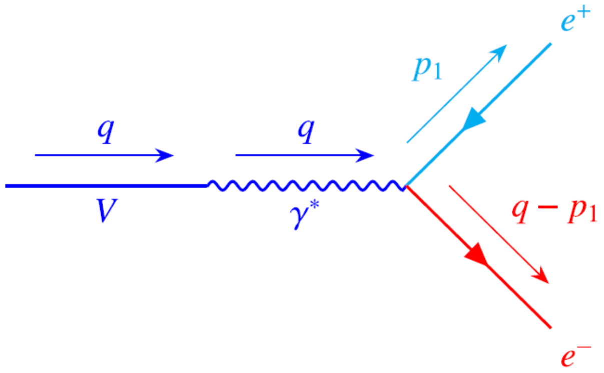
$$\mathcal{L}_{\phi K^+K^-} = g_{\phi K^+K^-}(K^+\partial_\mu K^- - K^-\partial_\mu K^+)\phi^\mu,$$

$$\mathcal{L}_{\rho\pi\pi} = g_{\rho\pi\pi}\left(\pi^+\overleftrightarrow{\partial}_\mu\pi^-\rho_0^\mu + \pi^+\overleftrightarrow{\partial}_\mu\pi^0\rho_-^\mu + \pi^-\overleftrightarrow{\partial}_\mu\pi^0\rho_+^\mu\right),$$

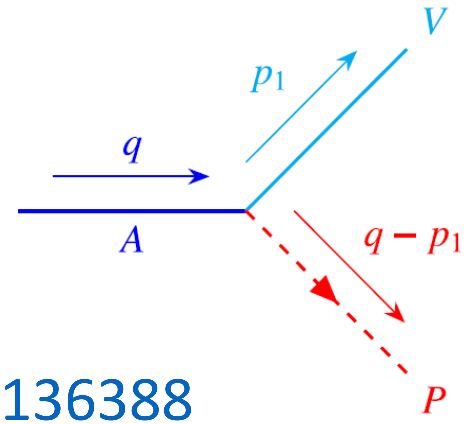
$$\mathcal{L}_{K^*K\pi} = \sqrt{2}g_{K^*K\pi}\left(\bar{K}\vec{\tau}\cdot\partial_\mu\vec{\pi} - \partial_\mu\bar{K}\vec{\tau}\cdot\vec{\pi}\right)K^{*\mu}.$$



$$\mathcal{L}_{\phi\gamma} = -\frac{e}{2g_J}F^{\mu\nu}\phi_{\mu\nu}, \quad \mathcal{L}_{\gamma e^+e^-} = -e\bar{\psi}\gamma^\mu A_\mu\psi$$



$$\mathcal{L}_{K_1VP} = \sqrt{2}m_{K_1}\left(g_{K_1\rho K}\bar{K}\vec{\tau}\cdot\vec{\rho}_\mu - g_{K_1K^*\pi}\bar{K}^*_\mu\vec{\tau}\cdot\vec{\pi}\right)K_1^\mu.$$



Effective lagrangian reference: [10.1016/j.physletb.2021.136388](https://doi.org/10.1016/j.physletb.2021.136388)

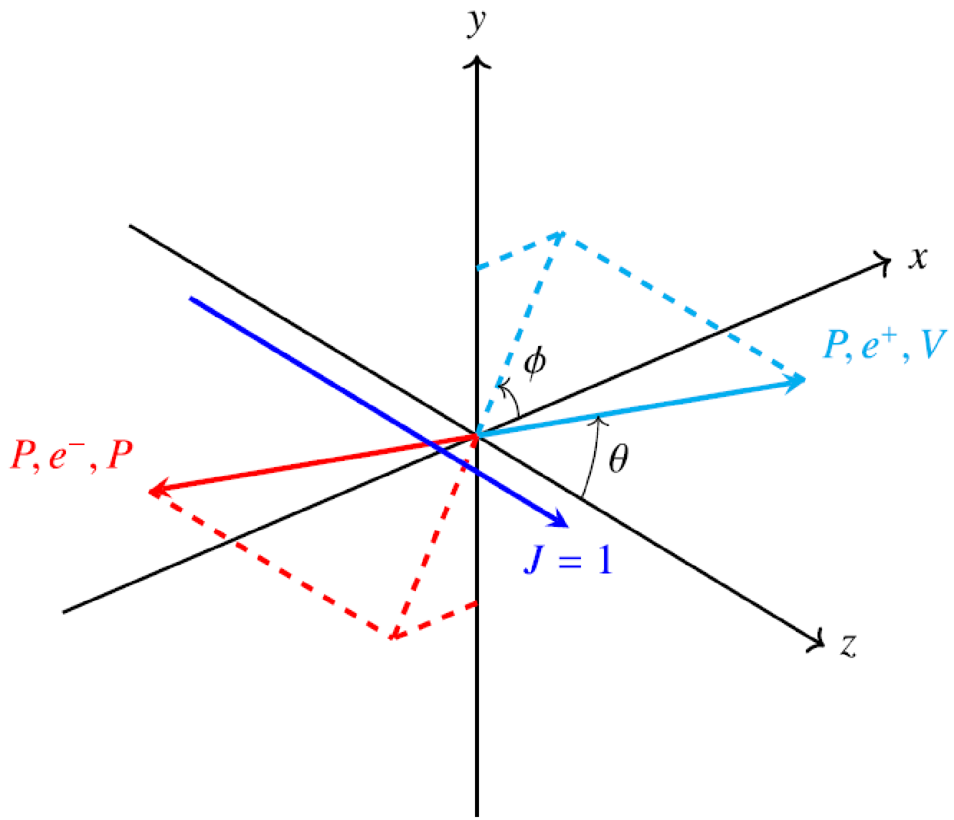
Coupling constant and momentum of produced particle

Table 1

Coupling constants and momenta of the produced particle in the c.m. frame for each decay process. For $\phi \to e^+e^-$, g_{ABC} represents g_J.

Decay	$\phi \to K^+K^-$	$\phi \to e^+e^-$	$\rho \to \pi\pi$	$K^* \to K\pi$	$K_1 \to \rho K$	$K_1 \to K^*\pi$
$\lvert p_1 \rvert$(MeV)	127	510	362	289	27	299
g_{ABC}	4.48	13.4	5.96	3.27	3.26	0.71

$V \longrightarrow PP$ & $V \longrightarrow ll$ & $A \longrightarrow VP$



$$\phi \to K^+ + K^- \quad \begin{cases} |\mathcal{M}|_T^2 = 2g_{\phi K^+ K^-}^2 |p_1|^2 \sin^2\theta, \\ |\mathcal{M}|_L^2 = 4g_{\phi K^+ K^-}^2 |p_1|^2 \cos^2\theta, \end{cases}$$

$$\phi \to e^+ + e^- \quad \begin{cases} |\mathcal{M}|_T^2 = \dfrac{64\pi^2\alpha^2}{g_J^2}\dfrac{1}{4}m_\phi^2\left(1+\sin^2\theta\right), \\ |\mathcal{M}|_L^2 = \dfrac{64\pi^2\alpha^2}{g_J^2}\dfrac{1}{2}m_\phi^2 \sin^2\theta, \end{cases}$$

$$K_1 \to K^* + \pi \quad \begin{cases} |\mathcal{M}|_T^2 = m_{K_1}^2 g_{K_1K^*\pi}^2\left(2+\dfrac{|p_1|^2}{m_{K^*}^2}\sin^2\theta\right), \\ |\mathcal{M}|_L^2 = 2m_{K_1}^2 g_{K_1K^*\pi}^2\left(1+\dfrac{|p_1|^2}{m_{K^*}^2}\cos^2\theta\right) \end{cases}$$

$J^P = 1^\pm$ 2-body decay angular distribution is unified

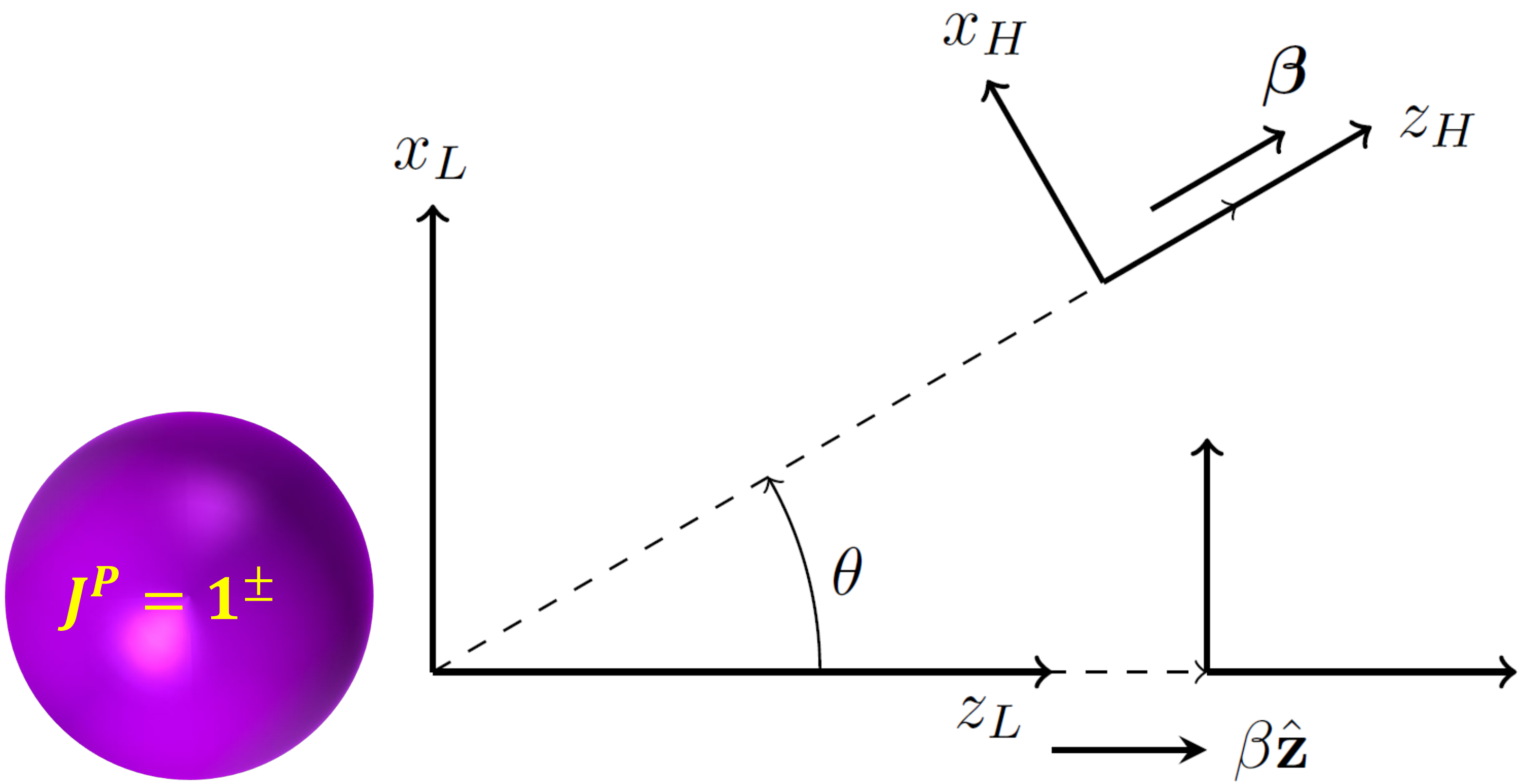
$$\frac{\mathrm{d}\Gamma}{\mathrm{d}\cos\theta} = \frac{1}{16\pi}\frac{|p_1|}{E_{\mathrm{c.m.}}^2}\left((1-\rho_{00})|\mathcal{M}|_T^2 + \rho_{00}|\mathcal{M}|_L^2\right)$$

General angular distribution

① Initial state: $|\mathrm{V/A}\rangle = \mathrm{a}_1|1\rangle + \mathrm{a}_{-1}|-1\rangle + \mathrm{a}_0|0\rangle$

$$\rho_{MM'} = a_M a^*_{M'}$$

② Helicity formalism(Wigner D-matrix)



$$\frac{1}{\Gamma}\frac{\mathrm{d}\Gamma}{\mathrm{d}\Omega} = \frac{3}{8\pi}\left(2\rho_{00}\cos^2\theta + (1-\rho_{00})\sin^2\theta - 2\mathrm{Re}[\rho_{1-1}]\sin^2\theta\cos 2\phi \right.$$
$$+ 2\mathrm{Im}[\rho_{1-1}]\sin^2\theta\sin 2\phi \qquad (5)$$
$$\left. - \sqrt{2}\mathrm{Re}[\rho_{10}-\rho_{-10}]\sin 2\theta\cos\phi + \sqrt{2}\mathrm{Im}[\rho_{10}+\rho_{-10}]\sin 2\theta\sin\phi \right).$$

$$\frac{1}{\Gamma}\frac{\mathrm{d}\Gamma}{\mathrm{d}\Omega} = \frac{3}{16\pi}\left(2(1-\rho_{00})\cos^2\theta + (1+\rho_{00})\sin^2\theta + 2\mathrm{Re}[\rho_{1-1}]\sin^2\theta\cos 2\phi \right.$$
$$- 2\mathrm{Im}[\rho_{1-1}]\sin^2\theta\sin 2\phi \qquad (9)$$
$$\left. + \sqrt{2}\mathrm{Re}[\rho_{10}-\rho_{-10}]\sin 2\theta\cos\phi - \sqrt{2}\mathrm{Im}[\rho_{10}+\rho_{-10}]\sin 2\theta\sin\phi \right).$$

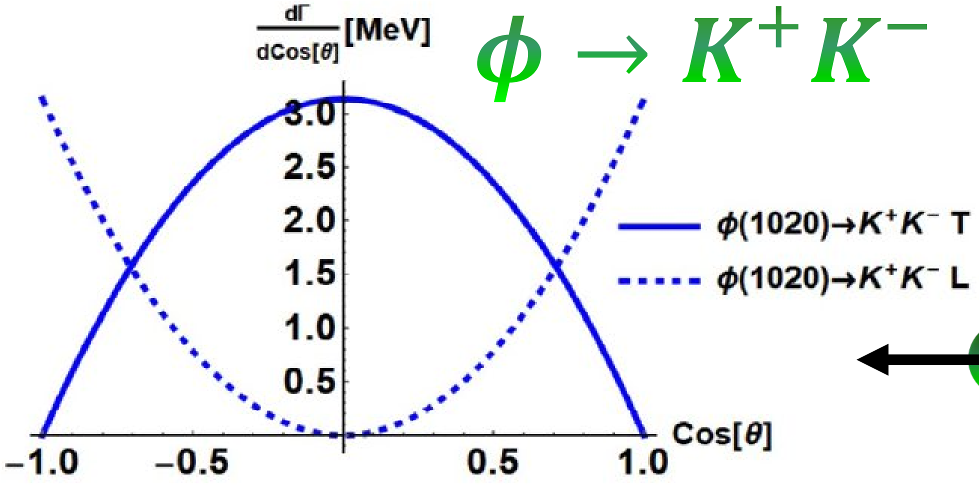
$$\frac{1}{\Gamma}\frac{\mathrm{d}\Gamma}{\mathrm{d}\Omega} = \frac{3}{4\pi\left(3+\frac{|p_1|^2}{m_1^2}\right)}\left(1+\frac{|p_1|^2}{2m_1^2}\left(1-\rho_{00}+(3\rho_{00}-1)\cos^2\theta \right.\right.$$
$$- 2\mathrm{Re}[\rho_{1-1}]\sin^2\theta\cos 2\phi + 2\mathrm{Im}[\rho_{1-1}]\sin^2\theta\sin 2\phi \qquad (13)$$
$$\left.\left. - \sqrt{2}\mathrm{Re}[\rho_{10}-\rho_{-10}]\sin 2\theta\cos\phi + \sqrt{2}\mathrm{Im}[\rho_{10}+\rho_{-10}]\sin 2\theta\sin\phi\right)\right).$$

$\rho_{00} = \frac{1}{3}$: **Unpolarized**

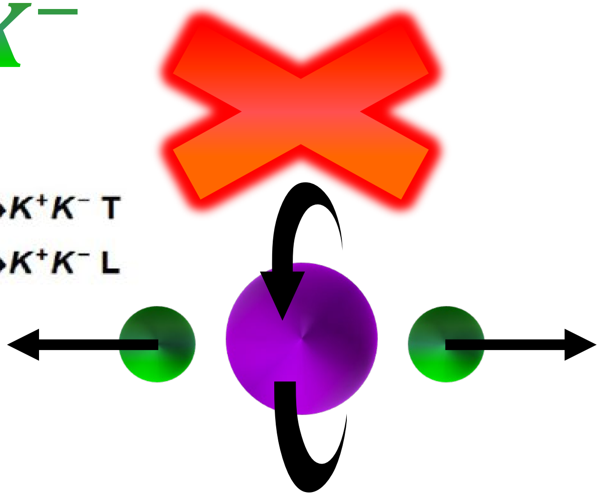
$\rho_{00} = 0$: **Transversely polarized**

$\rho_{00} = 1$: **Longitudinally polarized**

Result 1: Initial particle polarization analysis



(a) $\frac{\mathrm{d}\Gamma}{\mathrm{d}\cos\theta}$ of $\phi \to K^+K^-$ decay in the c.m. frame



Forward / Backward:

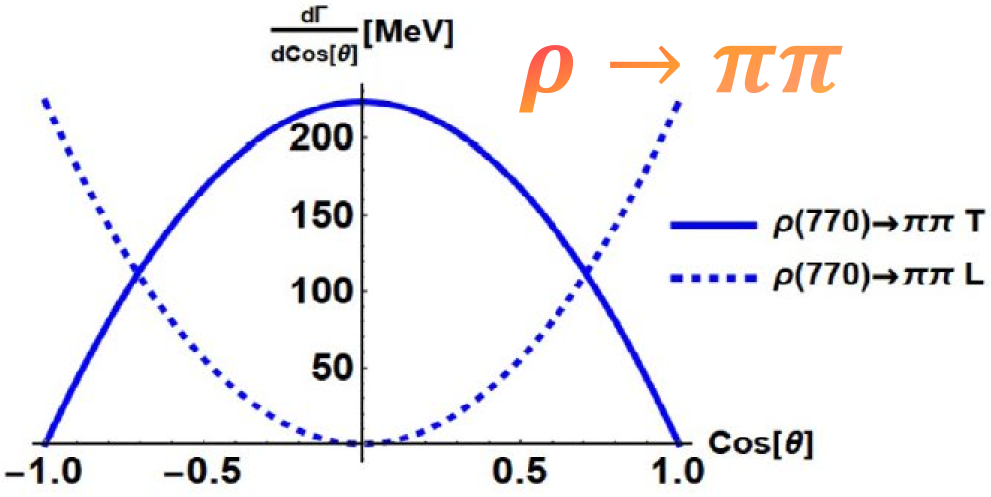
Longitudinal(0)

Transverse(X)

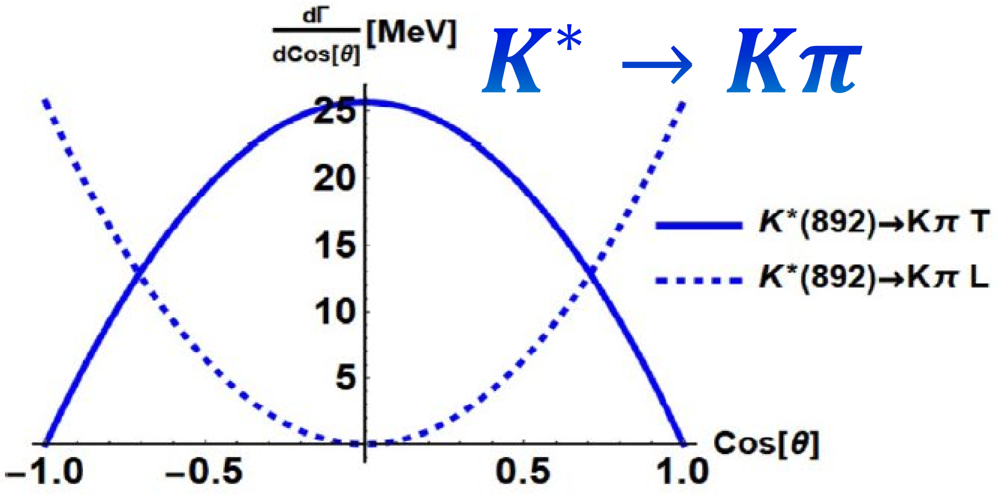
Perpendicular:

Transverse(0)

Longitudinal(X)



(b) $\frac{\mathrm{d}\Gamma}{\mathrm{d}\cos\theta}$ of $\rho \to \pi\pi$ in the c.m. frame



(c) $\frac{\mathrm{d}\Gamma}{\mathrm{d}\cos\theta}$ of $K^* \to K\pi$ in the c.m. frame

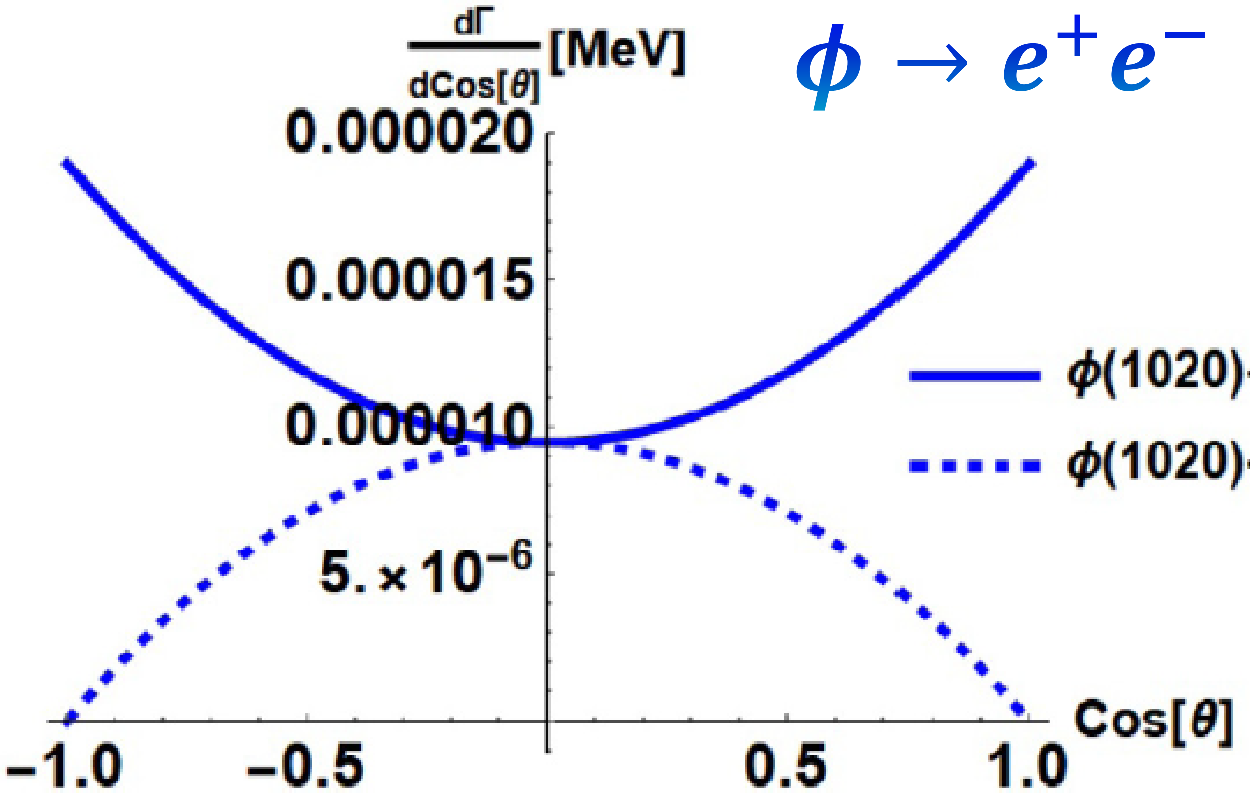
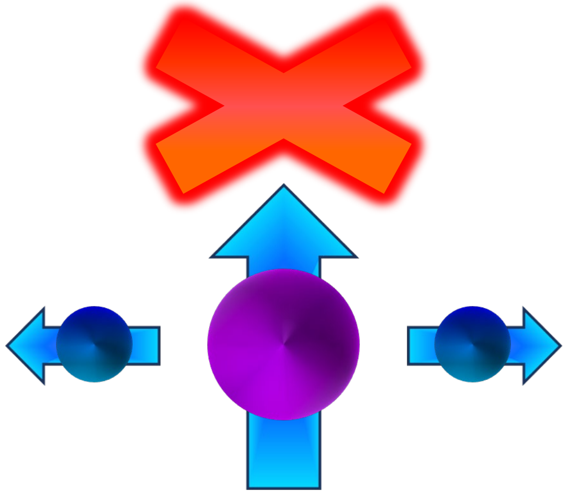


Fig. 4. $\frac{d\Gamma}{d\cos\theta}$ of $\phi \to e^+e^-$ in the c.m. frame.

$\phi \to e^+e^-$



Forward / Backward:

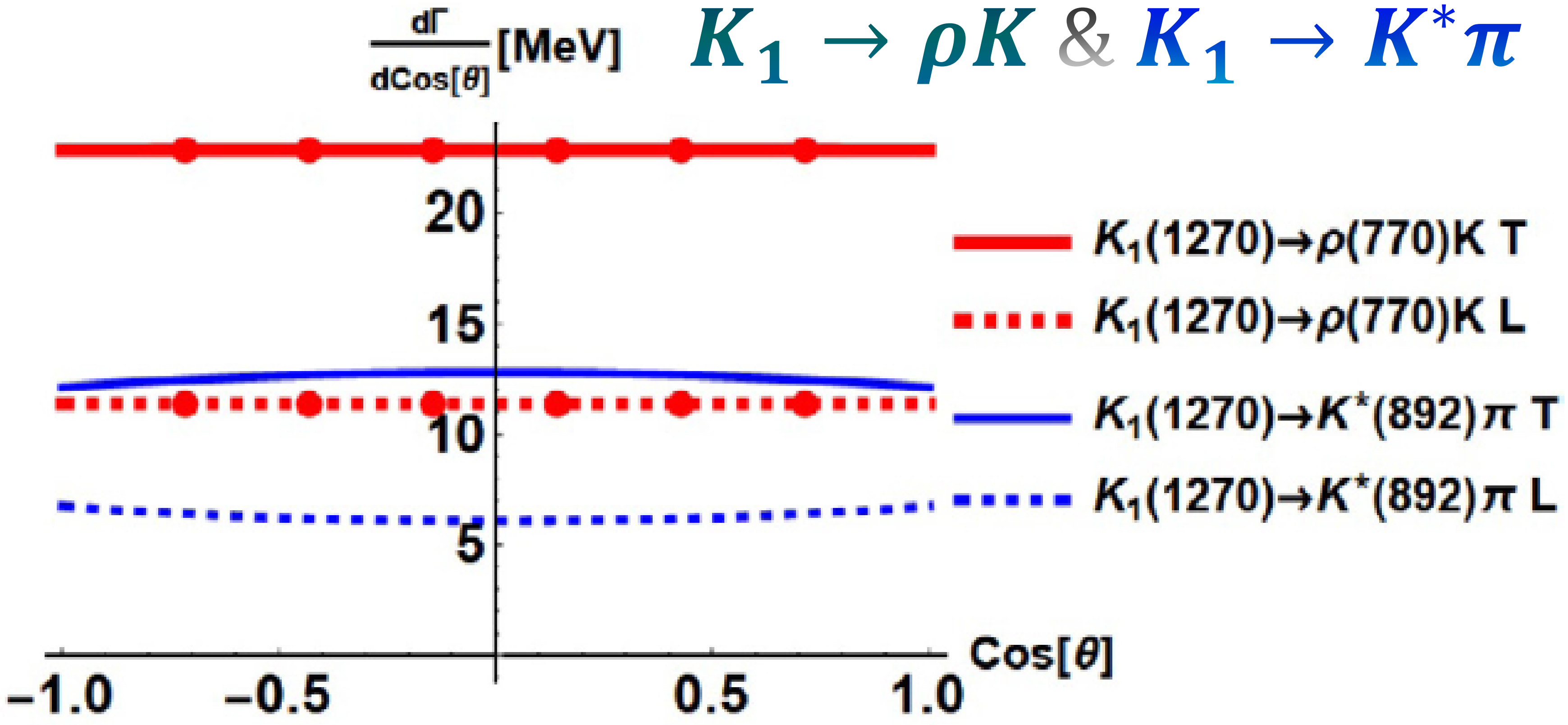
Transverse(O)

Longitudinal(X)

$\theta = 0/\pi$, $e^+\&e^-$ of same helicity does not couple to the longitudinal mode

V→PP and V→ll are complementary!

$K_1 \to \rho K$ & $K_1 \to K^*\pi$



- $\frac{\vec{p}_1^{\,2}}{2m_V^2} = 6 \times 10^{-4}(\rho K), 5.6 \times 10^{-2}(K^*\pi)$
- The angular distribution alone is not sufficient enough to discern the initial K_1 polarization

Result2: Final vector meson polarization in A⟶VP

- Specifying the final vector meson polarization.

(It should be feasible in future J-PARC experiment)

- Initial K_1 polarization is distinguished by observing forward or backward.

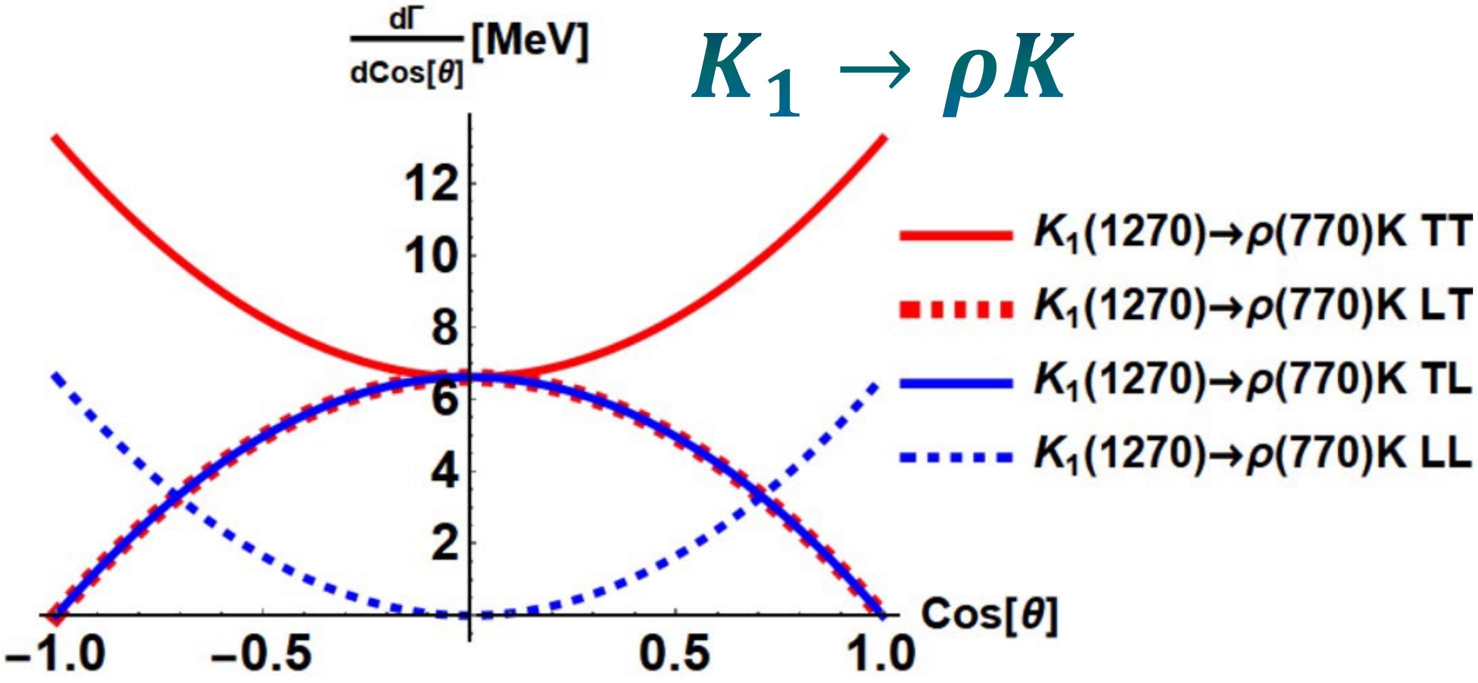
$$|\mathcal{M}_{TT}|^2 = 2m_{K_1}^2 g_{K_1VP}^2 (1+\cos^2\theta),$$

$$|\mathcal{M}_{LT}|^2 = 2m_{K_1}^2 g_{K_1VP}^2 \sin^2\theta,$$

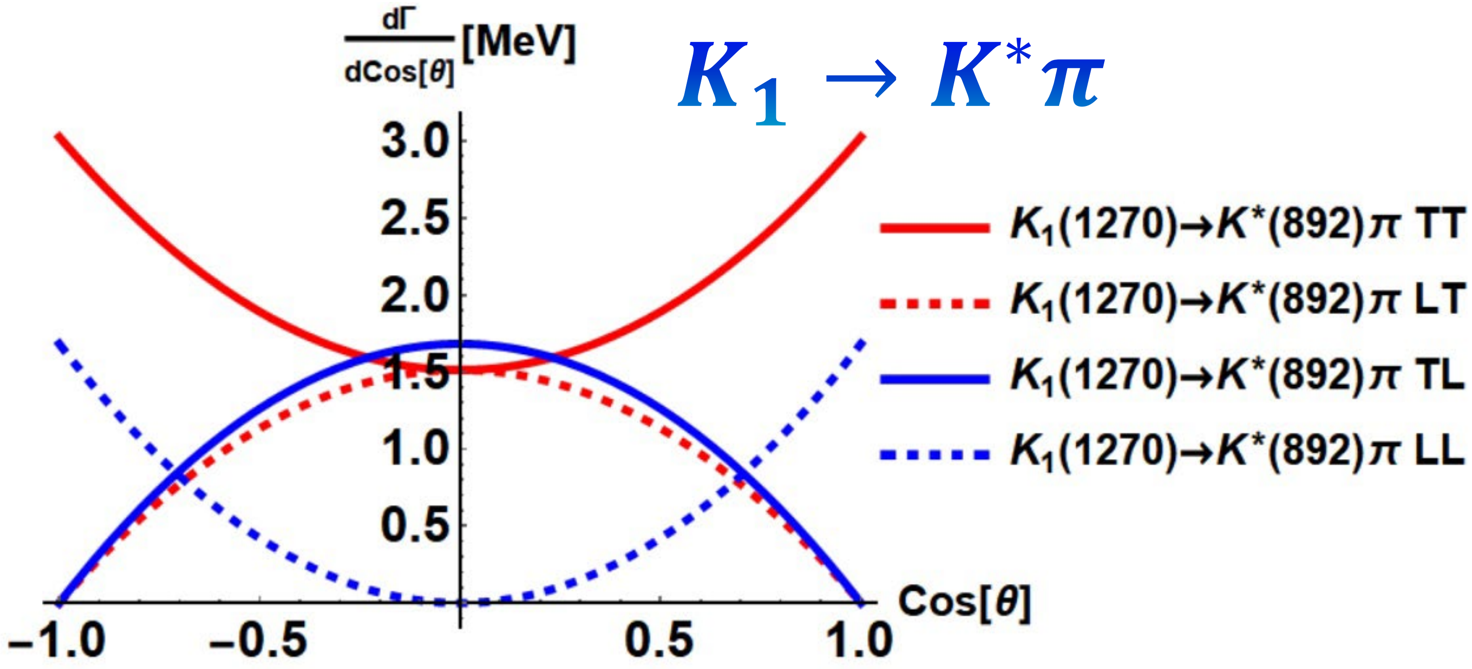
$$|\mathcal{M}_{TL}|^2 = 2m_{K_1}^2 g_{K_1VP}^2 \frac{E_1^2}{m_1^2} \sin^2\theta,$$

$$|\mathcal{M}_{LL}|^2 = 2m_{K_1}^2 g_{K_1VP}^2 \frac{E_1^2}{m_1^2} \cos^2\theta.$$

$K_1 \rightarrow \rho K$



$K_1 \rightarrow K^*\pi$



Summary of today's talk

- Effective Lagrangian and helicity formalism yield the same result.

- In $V \to PP$, forward & backward → Longitudinal vector meson.
- In $V \to ll$, forward & backward → Transverse vector meson.

- In $A \to VP$, final vector meson polarization measure required.

- Discerning (axial) vector meson polarization will help to find more clues about mass shift.