Disentangling polarization of the ϕ meson through hadronic and electronic decay channel

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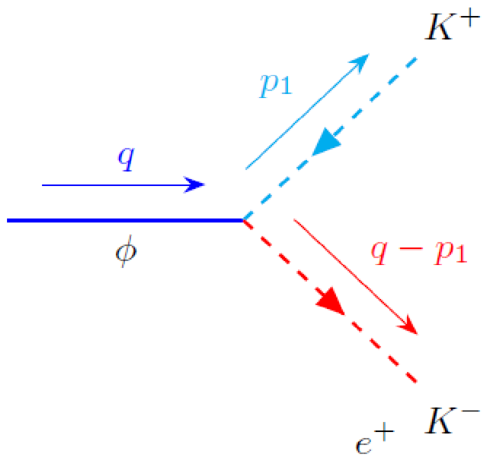
J－PARCシンボルマークとロゴ（2点）

ıs in vacuum & matter"

Why calculate angular distribution of each polarization

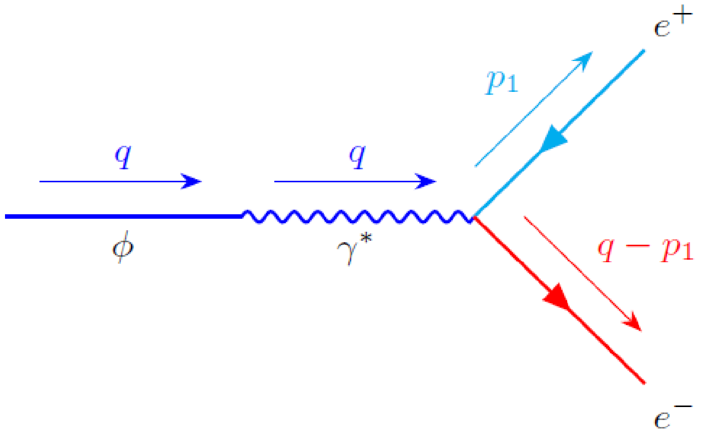
- Mass shift in nuclear matter depends on momentum and polarization mode when three momentum is not zero.

- Current on-going experiment, ϕ meson invariant mass in the nucleus is studied through dilepton channel(ex: J-PARC E16(2020)).

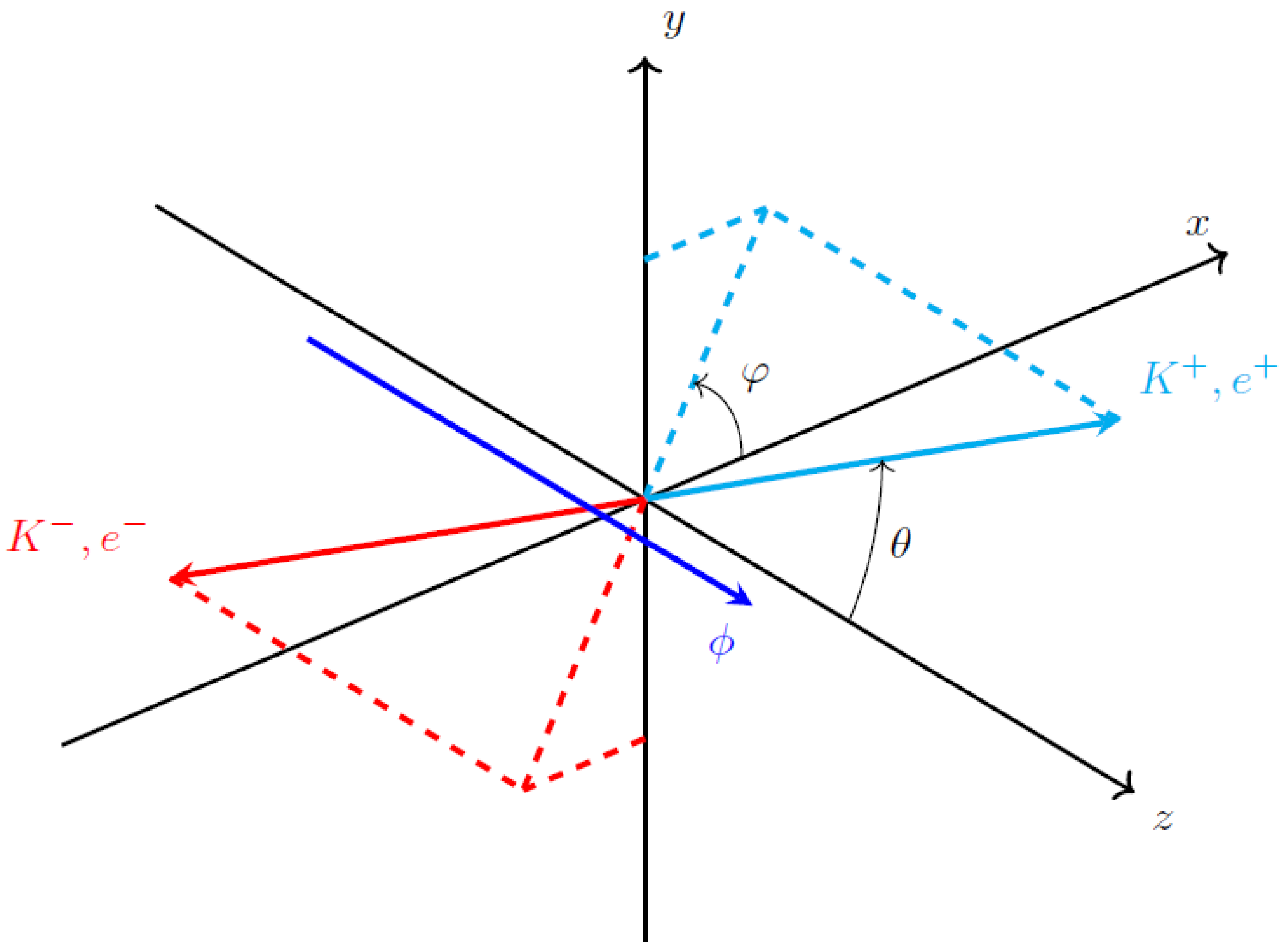


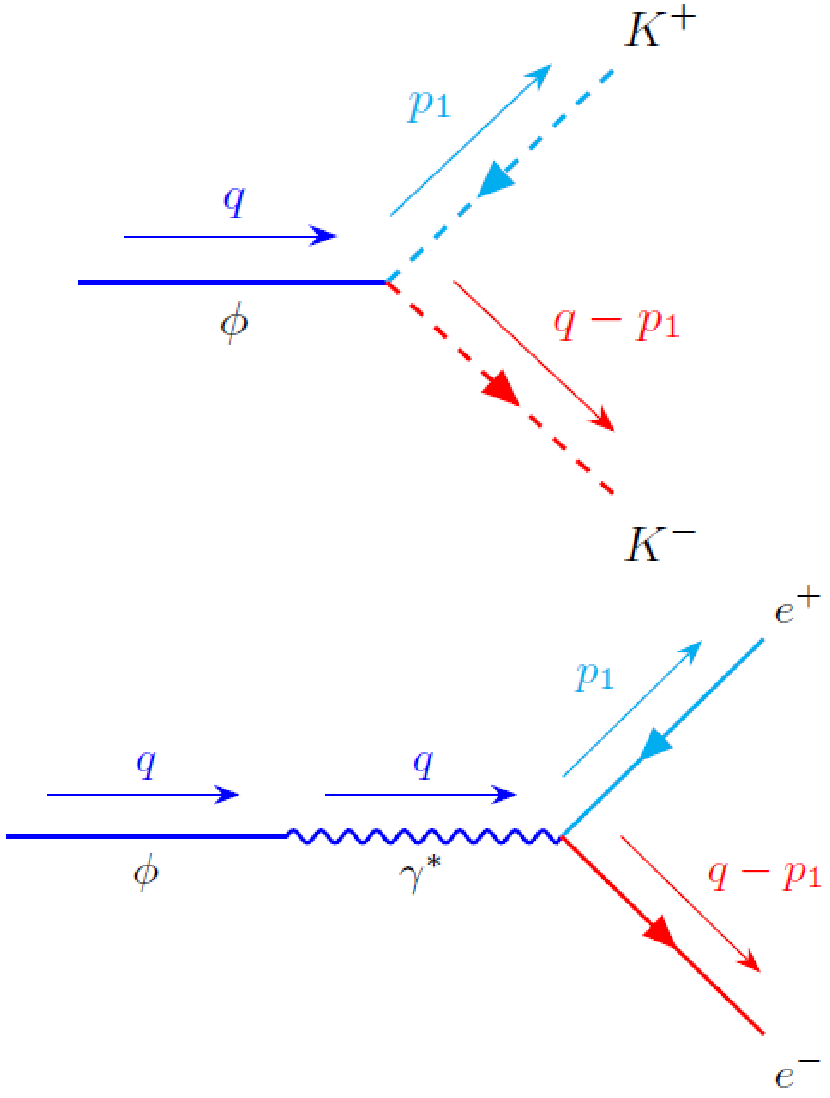
- Recently proposed experiment J-PARC E88: Kaon channel
- $\phi \rightarrow K^+ + K^-$ has a larger branching ratio

- Kaon channel can complement dilepton channel



Basic kinematics of 1→2 decay in the CM frame



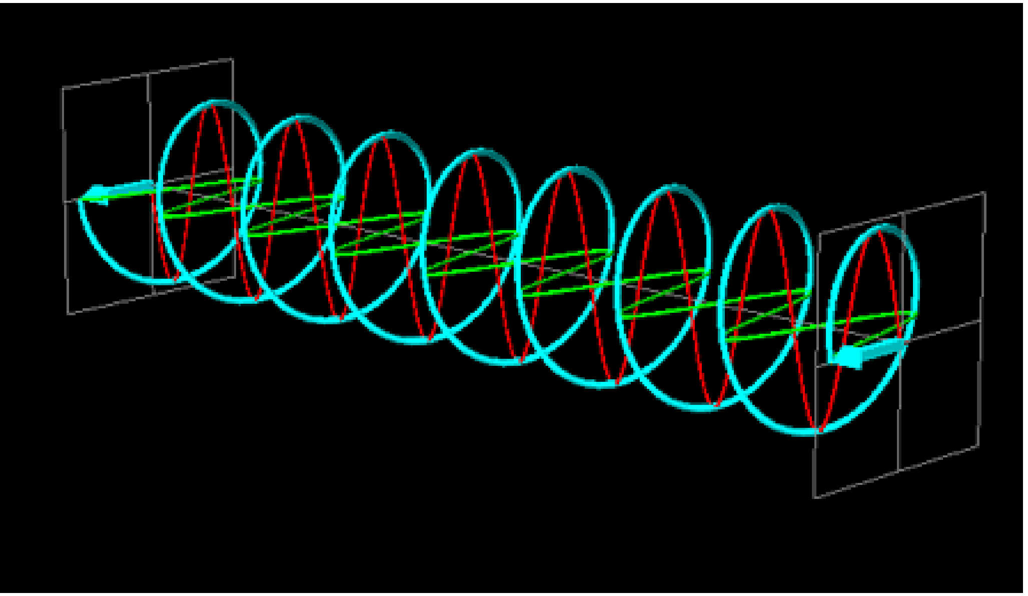


Polarization vector

- Four momentum, circularly polarized basis vectors of the ϕ meson in its rest frame

$$q^{\mu} = \left(m_{\phi}, \vec{0}\right), \varepsilon_{+1}^{\mu} = \left(0, -\frac{1}{\sqrt{2}}, -\frac{i}{\sqrt{2}}, 0\right), \varepsilon_{-1}^{\mu} = \left(0, \frac{1}{\sqrt{2}}, -\frac{i}{\sqrt{2}}, 0\right), \varepsilon_{0}^{\mu} = (0,0,0,1)$$

- Satisfy a constraint $q^{\mu}\varepsilon_{\lambda\mu} = 0(\lambda = \pm 1,0)$



From Applied PhotoPhysics

Effective Lagrangian & Decay width of each process

$$\mathcal{L}_{\phi\to K^+K^-} = g_K\phi_\mu(K^+\partial^\mu K^- - K^-\partial^\mu K^+)$$

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

F. Klingl, N. Kaiser and W. Weise, Z. Phys. A 356, 193-206 (1996)

$$\Gamma = \begin{cases} 4.249 \times 0.492\ \mathrm{MeV}(\phi \to K^+ + K^-) \\ 4.249 \times (2.974 \times 10^{-4})\ \mathrm{MeV}(\phi \to e^+ + e^-) \end{cases}$$

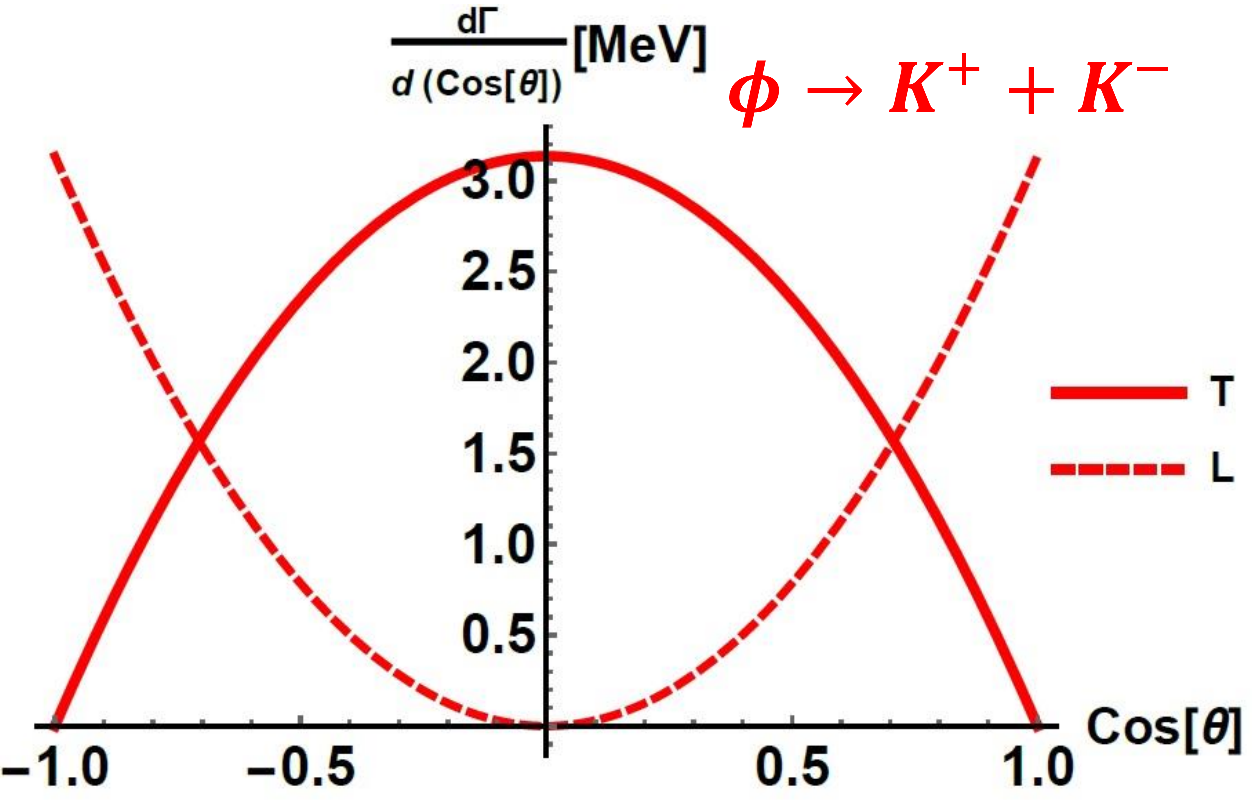
R. L. Workman et al. [Particle Data Group], PTEP 2022, 083C01 (2022)

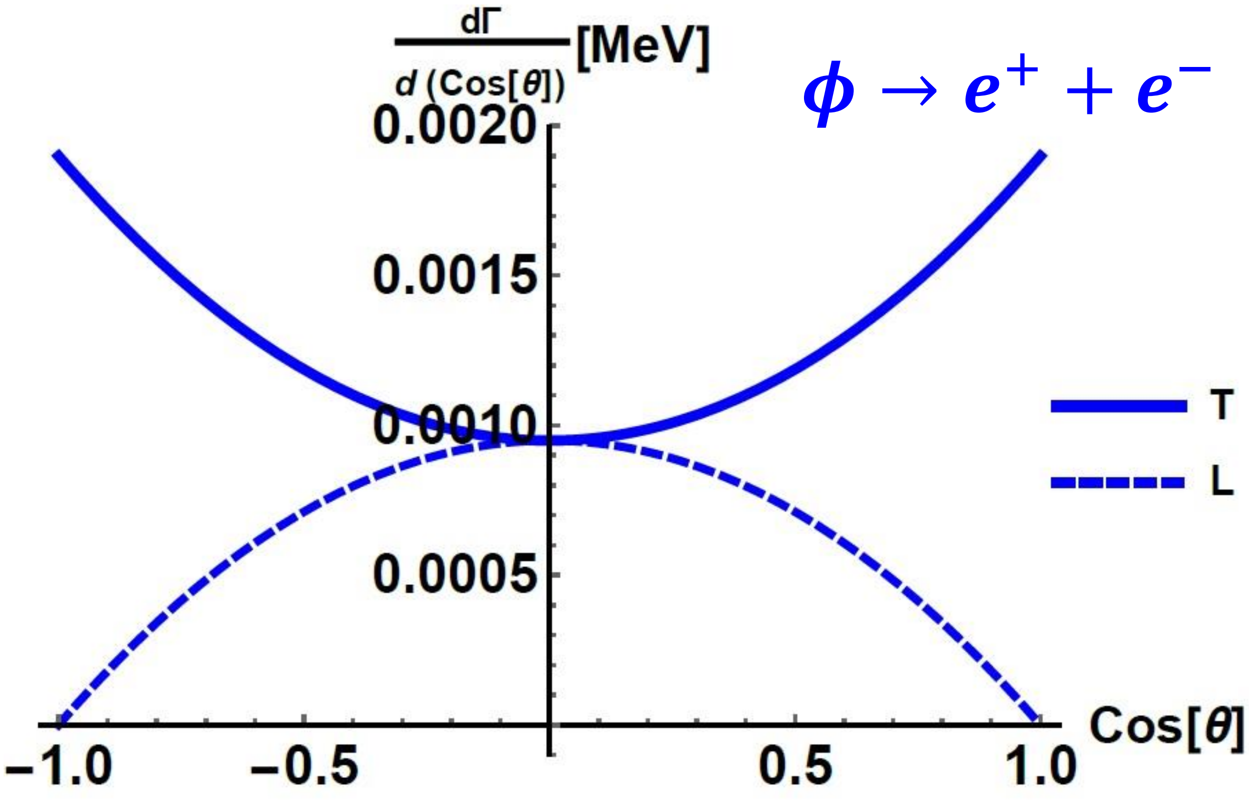
Hadronic tensor & Leptonic tensor

- Kaonic decay
  - $g_K = 4.476$
  - $\mathcal{M}^{\mu\nu}_{Hadronic} = g_K^2 (p_1 - p_2)^\mu (p_1 - p_2)^\nu$
- Electronic decay
  - $g_J = 13.4$
  - $\mathcal{M}^{\mu\nu}_{Leptonic} = \frac{64\pi^2\alpha^2}{g_J^2}\left(p_1^\mu p_2^\nu + p_1^\nu p_2^\mu - \frac{1}{2} m_\phi^2 g^{\mu\nu}\right)$

- Polarization tensor to separate transverse and longitudinal
  - $P_{\mu\nu} = P^T_{\mu\nu} + P^L_{\mu\nu} = \varepsilon^T_\mu \varepsilon^{T*}_\nu + \varepsilon^L_\mu \varepsilon^{L*}_\nu$

$\frac{d\Gamma}{d\cos\theta}$ for each polarization using polarization tensor





T: Transverse, L: Longitudinal

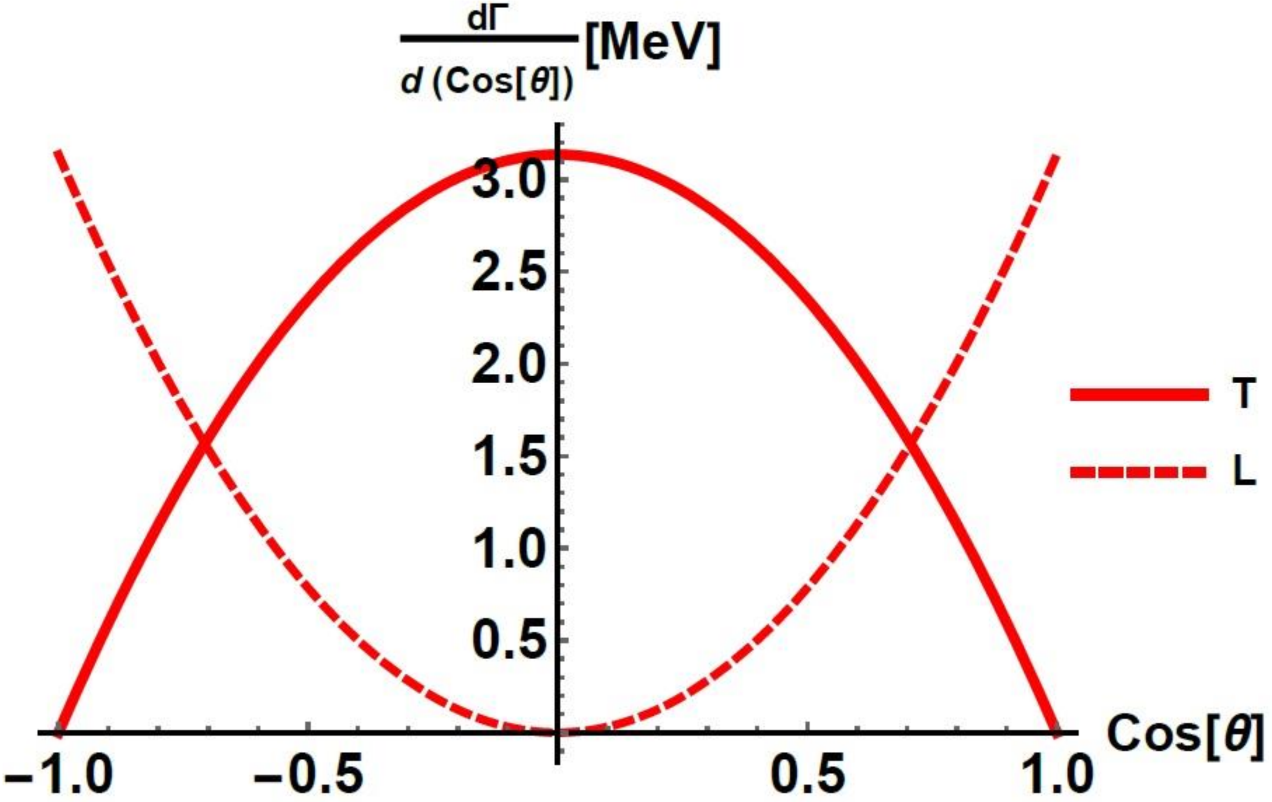
$$|\mathcal{M}|_T^2 = 4g_K^2 p_f'^2 \sin^2\theta$$
$$|\mathcal{M}|_L^2 = 4g_K^2 p_f'^2 \cos^2\theta$$

$$|\mathcal{M}|_T^2 = \frac{64\pi^2\alpha^2}{g_J^2}\left(m_\phi^2 - 2p_f'^2 \sin^2\theta\right)$$
$$|\mathcal{M}|_L^2 = \frac{64\pi^2\alpha^2}{g_J^2}\left(\frac{1}{2}m_\phi^2 - 2p_f'^2 \cos^2\theta\right)$$

What happens at $\theta = 0, \pi$ & $\theta = \frac{\pi}{2}$?

- Hadronic Decay
  ① Forward & backward direction, $\vec{p}_1 - \vec{p}_2 \perp \vec{\varepsilon}_{\pm 1}$(Transverse vanishes)

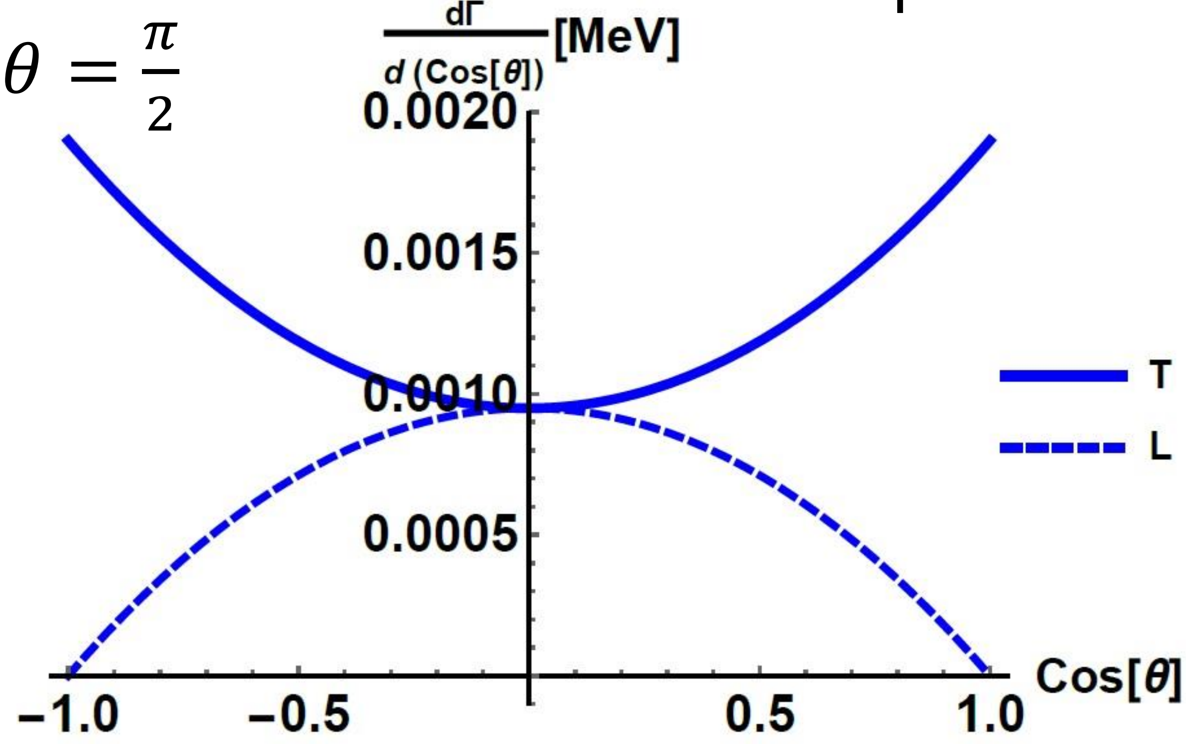
  ② Transverse direction, $\vec{p}_1 - \vec{p}_2 \perp \vec{\varepsilon}_0$(Longitudinal vanishes)



What happens at $\theta = 0, \pi$ & $\theta = \frac{\pi}{2}$?

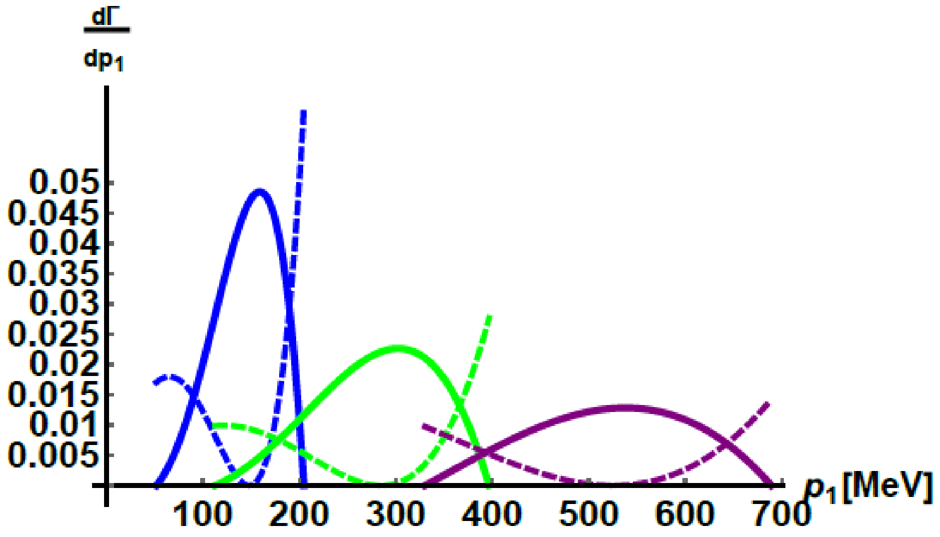
- Electronic Decay
  ① $\mathcal{J}^{\mu} = \bar{u}(p_2)\gamma^{\mu}v(p_1)$ of opposite spin becomes 0 by helicity conservation (Combination of up & down, down & up spin)

  ② Unlike kaonic decay, vector current carries a transverse component so it has a nonvanishing value at $\theta = \frac{\pi}{2}$

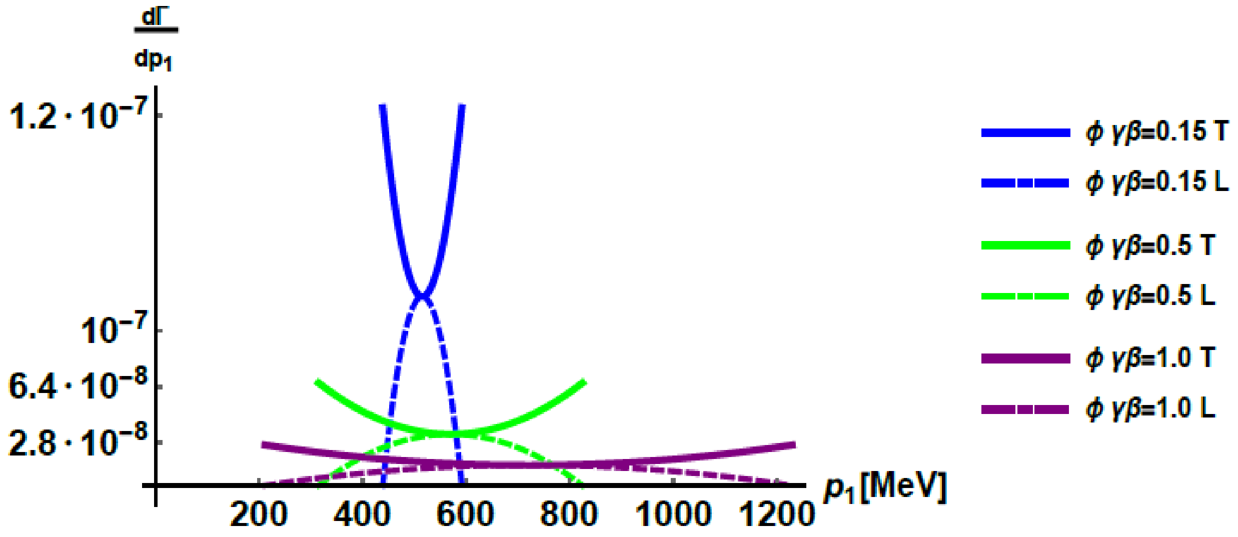


$\frac{d\Gamma}{dp_1}$ in the Lab frame

Decay width Γ decreases as $\gamma\beta$ increases due to time dilation



(a) $\frac{d\Gamma}{dp_1}$ of kaonic decay in the Lab frame



(b) $\frac{d\Gamma}{dp_1}$ of leptonic decay in the Lab frame

$\boldsymbol{\phi \to K^+ + K^-}$

$\boldsymbol{\phi \to e^+ + e^-}$

p_1: Momentum of $K^+(e^+)$ in the Lab frame

Vector meson state

$$|V\rangle = \sum_{\lambda=\pm 1,0} a_\lambda |\lambda\rangle, \rho_{\lambda\lambda'} = a_\lambda a^*_{\lambda'}$$

$\rho_{\lambda\lambda'}$: Spin density matrix of massive spin 1 particle

Normalized general angular distribution in the ϕ meson rest frame

Hadronic decay

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

Z. T. Liang and X. N. Wang, “Spin alignment of vector mesons in non-central A+A collisions,” Phys. Lett. B 629, 20-26 (2005)

Leptonic decay

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

P. Faccioli, C. Lourenco, J. Seixas and H. K. Wohri, “Towards the experimental clarification of quarkonium polarization,” Eur. Phys. J. C 69, 657-673 (2010)

- Integrating over azimuthal angle φ, we obtain distribution of θ

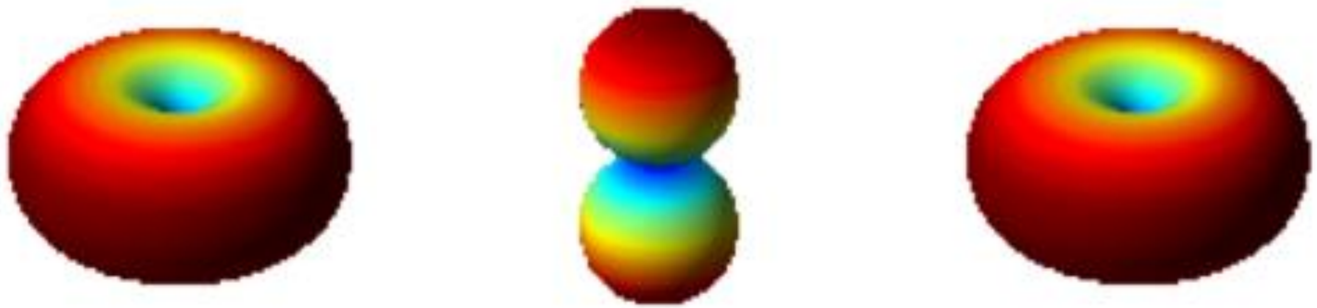
- $\boldsymbol{W_{\phi\to K^+K^-}(\theta) = \frac{3}{4}\left(1 - \rho_{00} + (3\rho_{00} - 1)\cos^2\theta\right)}$

- $\boldsymbol{W_{\phi\to e^+e^-}(\theta) = \frac{3}{8}\left(1 + \rho_{00} + (1 - 3\rho_{00})\cos^2\theta\right)}$
- Unpolarized→ $\boldsymbol{\rho_{00} = \frac{1}{3}}$
- Transversely polarized→ $\boldsymbol{\rho_{00} = 0}$
- Longitudinally polarized→ $\boldsymbol{\rho_{00} = 1}$

$\phi \to K^+ + K^-$ using Wigner D matrix

$$\left(\frac{1}{\Gamma}\frac{d\Gamma}{d\Omega}\right)_{K^+K^-} \propto \sum_{m,m'=\pm 1,0} D^{1\dagger}_{0m}\rho_{mm'}D^{1}_{m'0}$$

- Orbital angular momentum wavefunction (Spherical Harmonics)
- $Y_1^{\pm 1}(\theta,\varphi) \propto \sin\theta\, e^{\pm i\varphi}, Y_1^0(\theta,\varphi) \propto \cos\theta$
- K^+K^-: Zero spin
- Spin is transferred to relative orbital angular momentum



$\phi \rightarrow e^+ + e^-$ using Wigner D matrix

$$\left(\frac{1}{\Gamma}\frac{d\Gamma}{d\Omega}\right)_{e^+e^-} \propto \sum_{\lambda=\pm1} \sum_{m,m'=\pm1,0} D^{1\dagger}_{\lambda m}\rho_{mm'}D^{1}_{m'\lambda}$$

- By helicity conservation, positron and electron with same spin contributes to the summation.
- Only $\lambda = \pm 1$ are permitted

Summary & Future possible work

- Polarization of the ϕ meson can be disentangled by polarization tensor $P^{\mu\nu}$.

- Though general angular distribution is anisotropic, we can make it isotropic by averaging over φ.

- Wigner D matrix can also produce the same result by rotation of axes.

- Applying the same method to Λ&Δ baryon