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The processes $\tau \to (a_1\pi, K_1\pi, K_1K)\nu_\tau$ and $e^+e^- \to (a_1\pi, K_1K)$ in the NJL model

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BLTP, JINR

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- $\tau \to (a_1\pi, K_1\pi, K_1K)\nu_\tau$
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Lagrangian of the NJL model

$$\Delta L_{int} = \bar{q}\left\{\sum_{i=0,\pm}\left[iA_{\pi}\gamma^5\lambda_i^{\pi}\pi^i + iA_K\gamma^5\lambda_i^K K^i + \frac{1}{2}\gamma^{\mu}\lambda_i^{\rho}(A_{\rho}\rho_{\mu}^i + B_{\rho}\rho_{\mu}^{'i})\right.\right.$$

$$+\frac{1}{2}\gamma^{\mu}\lambda_i^K(A_{K^*}K_{\mu}^{*i} + B_{K^*}K_{\mu}^{*'i}) + \frac{A_{K_1}}{2}\gamma^{\mu}\gamma^5\lambda_i^K K_{1\mu}^i + \left.\frac{A_{a_1}}{2}\gamma^{\mu}\gamma^5\lambda_i^{\rho}a_{1\mu}^i\right]$$

$$\left.+\frac{1}{2}\gamma^{\mu}\lambda^{\omega}(A_{\omega}\omega_{\mu} + B_{\omega}\omega_{\mu}^{'}) + \frac{1}{2}\gamma^{\mu}\lambda^{\phi}(A_{\phi}\phi_{\mu} + B_{\phi}\phi_{\mu}^{'})\right\}q$$

Lagrangian of the NJL model

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$$+\frac{1}{2}\gamma^\mu\lambda_i^K(A_{K^*}K_\mu^{*i} + B_{K^*}K_\mu^{*'i}) + \frac{A_{K_1}}{2}\gamma^\mu\gamma^5\lambda_i^K K_{1\mu}^i + \frac{A_{a_1}}{2}\gamma^\mu\gamma^5\lambda_i^\rho a_{1\mu}^i\Big]$$

$$+\frac{1}{2}\gamma^\mu\lambda^\omega(A_\omega\omega_\mu + B_\omega\omega_\mu^{'}) + \frac{1}{2}\gamma^\mu\lambda^\phi(A_\phi\phi_\mu + B_\phi\phi_\mu^{'})\Bigg\}q$$

$$A_M = \frac{1}{\sin(2\theta_M^0)}\left[g_M\sin(\theta_M + \theta_M^0) + g_M^{'}f_M(k_\perp^2)\sin(\theta_M - \theta_M^0)\right],$$

$$B_M = \frac{-1}{\sin(2\theta_M^0)}\left[g_M\cos(\theta_M + \theta_M^0) + g_M^{'}f_M(k_\perp^2)\cos(\theta_M - \theta_M^0)\right]$$

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$$+\frac{1}{2}\gamma^{\mu}\lambda_i^K(A_{K^*}K_{\mu}^{*i} + B_{K^*}{K^*}'^{i}_{\mu}) + \frac{A_{K_1}}{2}\gamma^{\mu}\gamma^5\lambda_i^K K_{1\mu}^i + \left.\frac{A_{a_1}}{2}\gamma^{\mu}\gamma^5\lambda_i^{\rho}a_{1\mu}^i\right]$$
$$\left.+\frac{1}{2}\gamma^{\mu}\lambda^{\omega}(A_{\omega}\omega_{\mu} + B_{\omega}\omega'_{\mu}) + \frac{1}{2}\gamma^{\mu}\lambda^{\phi}(A_{\phi}\phi_{\mu} + B_{\phi}\phi'_{\mu})\right\} q$$

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$$f_M\left(k_{\perp}^2\right) = 1 + d_M {k_{\perp}}^2$$

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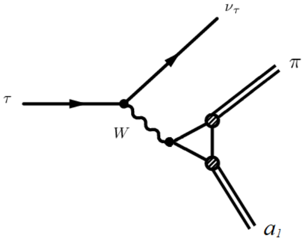
$$\Delta L_{int} = \bar{q}\left\{\sum_{i=0,\pm}\left[iA_\pi\gamma^5\lambda_i^\pi\pi^i + iA_K\gamma^5\lambda_i^K K^i + \frac{1}{2}\gamma^\mu\lambda_i^\rho(A_\rho\rho_\mu^i + B_\rho\rho_\mu^{'i})\right.\right.$$
$$+\frac{1}{2}\gamma^\mu\lambda_i^K(A_{K^*}K_\mu^{*i} + B_{K^*}K_\mu^{*'i}) + \frac{A_{K_1}}{2}\gamma^\mu\gamma^5\lambda_i^K K_{1\mu}^i + \left.\frac{A_{a_1}}{2}\gamma^\mu\gamma^5\lambda_i^\rho a_{1\mu}^i\right]$$
$$\left.+\frac{1}{2}\gamma^\mu\lambda^\omega(A_\omega\omega_\mu + B_\omega\omega_\mu^{'}) + \frac{1}{2}\gamma^\mu\lambda^\phi(A_\phi\phi_\mu + B_\phi\phi_\mu^{'})\right\} q$$

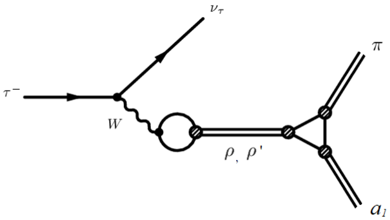
$$A_M = \frac{1}{\sin(2\theta_M^0)}\left[g_M\sin(\theta_M + \theta_M^0) + g_M^{'}f_M(k_\perp^2)\sin(\theta_M - \theta_M^0)\right],$$
$$B_M = \frac{-1}{\sin(2\theta_M^0)}\left[g_M\cos(\theta_M + \theta_M^0) + g_M^{'}f_M(k_\perp^2)\cos(\theta_M - \theta_M^0)\right]$$

$$f_M\left(k_\perp^2\right) = 1 + d_M {k_\perp}^2$$

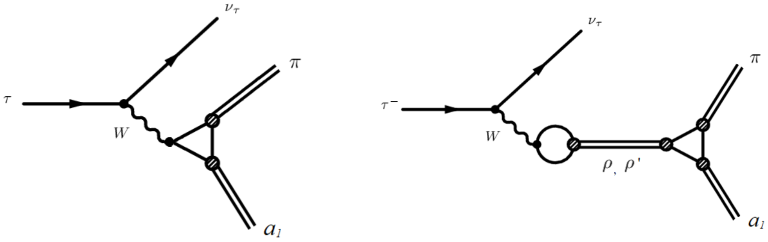
$$I_{n_1 n_2}^{f^m} = -i\frac{N_c}{(2\pi)^4}\int\frac{f^m(k_\perp^2)}{(m_u^2 - k^2)^{n_1}(m_s^2 - k^2)^{n_2}}\Theta(\Lambda^2 - k_\perp^2)\mathrm{d}^4k$$

Decay $\tau \to a_1 \pi \nu_\tau$



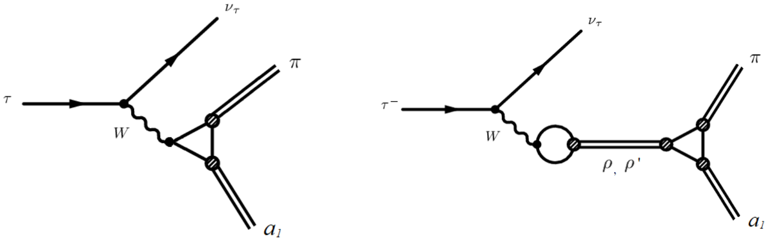


Decay $\tau \to a_1\pi\nu_\tau$



$$\mathcal{M}_{\tau\to a_1\pi\nu_\tau} = -iG_F V_{ud} 4 m_u g_\pi L_\mu^{weak} \left[I_{20}^{a_1} g_{\mu\nu} + I_{20}^{a_1\rho} \frac{C_\rho}{g_\rho} \frac{g_{\mu\nu}s - p_\mu p_\nu}{M_\rho^2 - s - i\sqrt{s}\Gamma_\rho} + I_{20}^{a_1\rho'} \frac{C_{\rho'}}{g_\rho} \frac{g_{\mu\nu}s - p_\mu p_\nu}{M_{\rho'}^2 - s - i\sqrt{s}\Gamma_{\rho'}} \right] \epsilon_\nu^*(p_{a_1})$$

Decay $\tau \to a_1 \pi \nu_\tau$



$$\mathcal{M}_{\tau\to a_1\pi\nu_\tau} = -iG_F V_{ud} 4 m_u g_\pi L_\mu^{weak} \left[I_{20}^{a_1} g_{\mu\nu} + I_{20}^{a_1\rho} \frac{C_\rho}{g_\rho} \frac{g_{\mu\nu}s - p_\mu p_\nu}{M_\rho^2 - s - i\sqrt{s}\Gamma_\rho} \right.$$

$$\left. + I_{20}^{a_1\rho'} \frac{C_{\rho'}}{g_\rho} \frac{g_{\mu\nu}s - p_\mu p_\nu}{M_{\rho'}^2 - s - i\sqrt{s}\Gamma_{\rho'}} \right] \epsilon_\nu^*(p_{a_1})$$

$$C_\rho = \frac{1}{\sin\left(2\theta_\rho^0\right)} \left[\sin\left(\theta_\rho + \theta_\rho^0\right) + R_\rho \sin\left(\theta_\rho - \theta_\rho^0\right)\right],$$

$$C_{\rho'} = \frac{-1}{\sin\left(2\theta_\rho^0\right)} \left[\cos\left(\theta_\rho + \theta_\rho^0\right) + R_\rho \cos\left(\theta_\rho - \theta_\rho^0\right)\right]$$

Decay $\tau \to K_1 \pi \nu_\tau$

$$\begin{aligned} K_1(1270) &= K_{1A} \sin\alpha + K_{1B} \cos\alpha, \\ K_1(1400) &= K_{1A} \cos\alpha - K_{1B} \sin\alpha \end{aligned}$$

Decay $\tau \to K_1 \pi \nu_\tau$

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\end{aligned}
$$

$$
L_B = \frac{g_B}{2} \sum_{j=0,\pm} K_{1B}^{\mu j} \left(\bar{q} \lambda_j^K \gamma^5 \overleftrightarrow{\partial}_\mu \, q \right)
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$$L_B = \frac{g_B}{2} \sum_{j=0,\pm} K_{1B}^{\mu j} \left(\bar{q} \lambda_j^K \gamma^5 \overleftrightarrow{\partial}_\mu \; q \right)$$

$$\mathcal{M}_{\tau^- \to K_1(1270)^- \pi^0 \nu_\tau} = -G_F V_{us} g_\pi L_\mu^{weak} [i T_{K_{1A}} + T_{K_{1B}}]^{\mu\nu} \epsilon_\nu^*(p_{K_1})$$

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$$\begin{aligned} T_{K_{1A}}^{\mu\nu} &= 2m_s\sin\alpha\left[I_{11}^{K_1}g^{\mu\nu} + I_{11}^{K_1K^*}\frac{C_{K^*}}{g_{K^*}}\frac{g^{\mu\nu}s - p^\mu p^\nu}{M_{K^*}^2 - s - i\sqrt{s}\Gamma_{K^*}}\right. \\ &\left. + I_{11}^{K_1K^{*\prime}}\frac{C_{K^{*\prime}}}{g_{K^*}}\frac{g^{\mu\nu}s - p^\mu p^\nu}{M_{K^{*\prime}}^2 - s - i\sqrt{s}\Gamma_{K^{*\prime}}}\right] \end{aligned}$$

$$\begin{aligned} T_{K_{1B}}^{\mu\nu} &= g_B\cos\alpha\left[\left(I_{10}^{K_1} - m_s^2 I_{11}^{K_1}\right)g^{\mu\nu} + \left(I_{10}^{K_1K^*} - m_s^2 I_{11}^{K_1K^*}\right)\frac{C_{K^*}}{g_{K^*}}\frac{g^{\mu\nu}s - p^\mu p^\nu}{M_{K^*}^2 - s - i\sqrt{s}\Gamma_{K^*}}\right. \\ &\left. + \left(I_{10}^{K_1K^{*\prime}} - m_s^2 I_{11}^{K_1K^{*\prime}}\right)\frac{C_{K^{*\prime}}}{g_{K^*}}\frac{g^{\mu\nu}s - p^\mu p^\nu}{M_{K^{*\prime}}^2 - s - i\sqrt{s}\Gamma_{K^{*\prime}}}\right] \end{aligned}$$

Numerical estimations

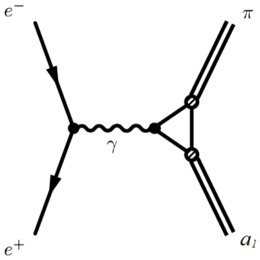
Decay mode	[1]	[2]	NJL[3]	
$\tau \to a_1(1260)^- \pi^0 \nu_\tau$	6.9 ± 6.3		0.14 ± 0.02	$\times 10^{-3}$
	6.1 ± 5.9			$\times 10^{-3}$
$\tau \to a_1(1260)^0 \pi^- \nu_\tau$	6.8 ± 6.1	1.3	0.13 ± 0.02	$\times 10^{-3}$
	5.9 ± 5.7			$\times 10^{-3}$
$\tau \to K_1(1270)^- \pi^0 \nu_\tau$	0.8 ± 0.2		3.59 ± 0.61	$\times 10^{-6}$
$\tau \to K_1(1270)^0 \pi^- \nu_\tau$	1.4 ± 0.5	21	6.84 ± 1.16	$\times 10^{-6}$
$\tau \to K_1(1400)^- \pi^0 \nu_\tau$	1.1 ± 0.1		0.27 ± 0.04	$\times 10^{-6}$
$\tau \to K_1(1400)^0 \pi^- \nu_\tau$	2.1 ± 0.2	4.1	0.49 ± 0.08	$\times 10^{-6}$
$\tau \to K_1(1270)^- K^0 \nu_\tau$	2.8 ± 1.9		4.25 ± 0.72	$\times 10^{-9}$
$\tau \to K_1(1270)^0 K^- \nu_\tau$	13 ± 8.9		6.79 ± 1.15	$\times 10^{-9}$

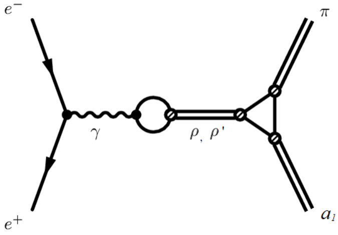
[1] *G. Calderon, J. H. Munoz and C. E. Vera, Phys. Rev. D **87** (2013) no.11, 114011*

[2] *L. R. Dai, L. Roca and E. Oset, Phys. Rev. D **99** (2019) no.9, 096003*

[3] *M. K. Volkov, A. A. Pivovarov and K. Nurlan, arXiv:2205.02810 [hep-ph] —* принято к публикации в Modern Phisics Letters A

Process $e^+e^- \to a_1\pi$





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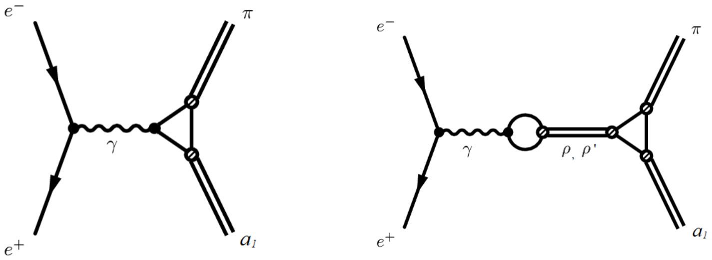
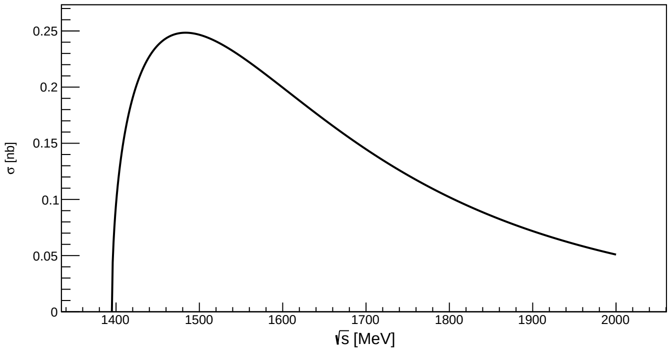


$$\mathcal{M}_{e^+e^-\to a_1\pi} = \frac{16\pi\alpha_{em}}{s} L_\mu^{em}\left[g^{\mu\nu} I_{20}^{a_1} + \frac{C_\rho}{g_\rho}\frac{g_{\mu\nu}s - p_\mu p_\nu}{M_\rho^2 - s - i\sqrt{s}\Gamma_\rho} I_{20}^{\rho a_1} + \frac{C_{\rho'}}{g_\rho}\frac{g_{\mu\nu}s - p_\mu p_\nu}{M_{\rho'}^2 - s - i\sqrt{s}\Gamma_{\rho'}} I_{20}^{\rho' a_1}\right] e_\nu^*(a_1)$$

Cross section of the process $e^+e^- \to a_1\pi$



Process $e^+e^- \to K_1 K$

$$\mathcal{M}_{e^+e^-\to K_1(1270)K} = \frac{8\pi\alpha_{em}}{s} L_\mu^{em} \left[T_\gamma + T_{\rho+\rho'} + T_{\omega+\omega'} + e^{i\pi} T_{\phi+\phi'} \right]^{\mu\nu} e_\nu^*(p_{K_1})$$

Process $e^+e^- \to K_1 K$

$$\mathcal{M}_{e^+e^-\to K_1(1270)K} = \frac{8\pi\alpha_{em}}{s} L_\mu^{em} \left[T_\gamma + T_{\rho+\rho'} + T_{\omega+\omega'} + e^{i\pi} T_{\phi+\phi'} \right]^{\mu\nu} e_\nu^*(p_{K_1})$$

$$T_{(\gamma)\mu\nu} = i(m_s + m_u) I_{11}^{K_1 K} \sin\alpha g_{\mu\nu} + g_B g_K \cos\alpha \left[\frac{2}{3} F(u,s) + \frac{1}{3} F(s,u) \right] g_{\mu\nu}$$

$$T_{(V+V')\mu\nu} = r_V \left[\frac{C_V}{g_V} \frac{g_{\mu\nu} s - p_\mu p_\nu}{M_V^2 - s - i\sqrt{s}\Gamma_V} \left(i \sin\alpha G_{VK_{1A}K} + \cos\alpha G_{VK_{1B}K} \right) + \frac{C_{V'}}{g_V} \frac{g_{\mu\nu} s - p_\mu p_\nu}{M_{V'}^2 - s - i\sqrt{s}\Gamma_{V'}} \left(i \sin\alpha G_{V'K_{1A}K} + \cos\alpha G_{V'K_{1B}K} \right) \right]$$

Process $e^+e^- \to K_1 K$

$$\mathcal{M}_{e^+e^-\to K_1(1270)K} = \frac{8\pi\alpha_{em}}{s} L_\mu^{em}\left[T_\gamma + T_{\rho+\rho'} + T_{\omega+\omega'} + e^{i\pi}\, T_{\phi+\phi'}\right]^{\mu\nu} e_\nu^*(p_{K_1})$$

$$T_{(\gamma)\mu\nu} = i(m_s+m_u)I_{11}^{K_1K}\sin\alpha g_{\mu\nu} + g_B g_K \cos\alpha\left[\frac{2}{3}F(u,s)+\frac{1}{3}F(s,u)\right] g_{\mu\nu}$$

$$T_{(V+V')\mu\nu} = r_V\left[\frac{C_V}{g_V}\frac{g_{\mu\nu}s - p_\mu p_\nu}{M_V^2 - s - i\sqrt{s}\Gamma_V}\left(i\sin\alpha G_{VK_{1A}K} + \cos\alpha G_{VK_{1B}K}\right)\right.$$
$$\left. + \frac{C_{V'}}{g_V}\frac{g_{\mu\nu}s - p_\mu p_\nu}{M_{V'}^2 - s - i\sqrt{s}\Gamma_{V'}}\left(i\sin\alpha G_{V'K_{1A}K} + \cos\alpha G_{V'K_{1B}K}\right)\right]$$

$$F(u,s) = I_{10} - \left((m_s-m_u)^2 + m_u^2\right) I_{11} - 2m_u^2(m_s-m_u)I_{21}$$

$$G_{VK_{1A}K} = (m_s+m_u)I_{11}^{VK_1K}$$

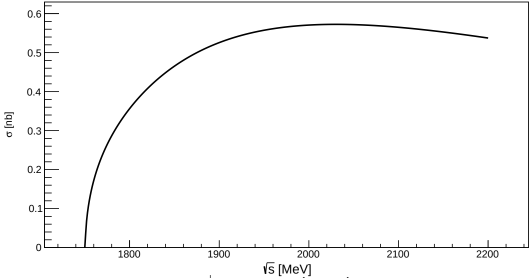
$$G_{V'K_{1A}K} = (m_s+m_u)I_{11}^{V'K_1K}$$

$$G_{\rho K_{1B}K} = g_B\left[I_{10}^{\rho K} - \left((m_s-m_u)^2+m_u^2\right) I_{11}^{\rho K} - 2m_u^2(m_s-m_u)I_{21}^{\rho K}\right]$$

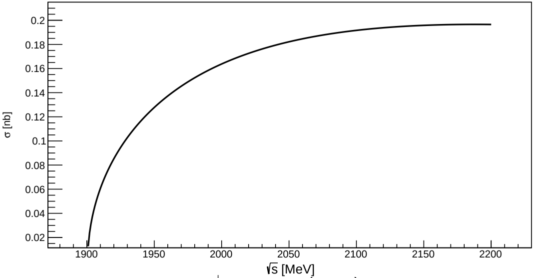
$$G_{\rho' K_{1B}K} = g_B\left[I_{10}^{\rho' K} - \left((m_s-m_u)^2+m_u^2\right) I_{11}^{\rho' K} - 2m_u^2(m_s-m_u)I_{21}^{\rho' K}\right]$$

$$r_\rho = 1/2 \quad r_\omega = 1/6 \quad r_\phi = 1/3$$

Cross section of $e^+e^- \to (K_1(1270), K_1(1400))K$



$e^+e^- \to K_1(1270)K$



$e^+e^- \to K_1(1400)K$

Summary

- The processes $\tau \to (a_1\pi, K_1\pi, K_1K)\nu_\tau$ were calculated in the framework of the NJL model
- The comparison of the obtained results with the results of other theoretical works was carried out
- The processes $e^+e^- \to (a_1\pi, K_1K)$ were calculated in the framework of the NJL model
- The mixing of the states $K_1(1270)$ and $K_1(1400)$ was taken into account