Pion charge asymmetries in $e^+e^- \longrightarrow \pi^+\pi^-\gamma$ below 1 GeV

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- KLOE Collaboration published experimental data about the asymmetry [PLB634 148 (2006)]

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with the kinematics variables
$Q = p_1 + p_2, q = p_+ + p_-, l = p_+ - p_-$ and the Lorentz scalars

$$s \equiv Q^2 = 2p_1 \cdot p_2,$$
$$t_1 \equiv (p_1 - k)^2 = -2p_1 \cdot k,$$
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$$\tau_1^{\mu\nu} = k^\mu Q^\nu - g^{\mu\nu} k \cdot Q,$$
$$\tau_2^{\mu\nu} = k \cdot l \, (l^\mu Q^\nu - g^{\mu\nu} k \cdot l) + l^\nu \left(k^\mu k \cdot l - l^\mu k \cdot Q\right),$$
$$\tau_3^{\mu\nu} = Q^2 \left(g^{\mu\nu} k \cdot l - k^\mu l^\nu\right) + Q^\mu \left(l^\nu k \cdot Q - Q^\nu k \cdot l\right).$$

The scalar structure functions $f_i \equiv f_i\left(Q^2, k \cdot Q, k \cdot l\right)$ are even $\left(f_{1,2}\right)$ or odd $\left(f_3\right)$ under sign change of the argument $k \cdot l$. These functions depend of FSR model.

Asymmetry

The pions produced in this process differs under charge conjugation, it depends if the foton comes from FSR (odd) or ISR (even), then the interference term has odd charge conjugation and therefore we have charge asymmetry. This asymmetry is defined as:

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where θ_{π^+} is the positive pion polar angle.

Bremsstrahlung

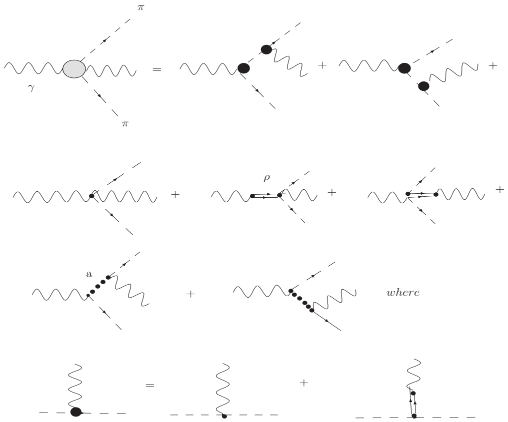

Figure: Feynman diagrams for Bremsstrahlung

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$$f_i = f_i^{sQED} + \Delta f_i^{RPT}$$

$$f_1^{sQED} = \frac{2k \cdot q F_\pi\left(Q^2\right)}{(k \cdot Q)^2 - (k \cdot l)^2}$$

$$f_2^{sQED} = \frac{-2F_\pi\left(Q^2\right)}{(k \cdot Q)^2 - (k \cdot l)^2}$$

$$f_3^{sQED} = 0$$

$$\Delta f_1^{RPT} = \frac{F_V^2 - 2F_V G_V}{f_\pi^2}\left(\frac{1}{m_\rho^2} + \frac{1}{m_\rho^2 - s - i m_\rho \Gamma_\rho(s)}\right)$$

$$- \frac{F_A^2}{f_\pi^2 m_a^2}\left(2 + \frac{(k\cdot l)^2}{D(l)\,D(-l)} + \frac{(s + k\cdot Q)\left[4m_a^2 - \left(s + l^2 + 2k\cdot Q\right.\right.}{8D(l)\,D(-l)}\right.$$

$$\Delta f_2^{RPT} = -\frac{F_A^2}{f_\pi^2 m_a^2}\frac{\left[4m_a^2 - \left(s + l^2 + 2k\cdot Q\right)\right]}{8D(l)\,D(-l)}$$

$$\Delta f_3^{RPT} = \frac{F_A^2}{f_\pi^2 m_a^2}\frac{k\cdot l}{D(l)\,D(-l)}$$

$$D(l) = m_a^2 - \frac{s + l^2 + 2k\cdot q + 4k\cdot l}{4}$$

The pion form factor

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$$F_\pi\left(q^2\right) = 1 + \frac{F_V G_V}{f_\pi^2} B_\rho\left(q^2\right)\left(1 - \frac{\Pi_{\rho\omega}}{3q^2} B_\omega\left(q^2\right)\right)$$

$$B_r\left(q^2\right) = \frac{q^2}{m_r^2 - q^2 - i m_r \Gamma_r\left(q^2\right)}$$

$$\Gamma_r\left(q^2\right) = \Gamma_\rho \sqrt{\frac{m_r^2}{q^2}} \left(\frac{q^2 - 4m_\pi^2}{m_\rho^2 - 4m_\pi^2}\right)^{3/2} \Theta\left(q^2 - 4m_\pi^2\right)$$

Double resonance

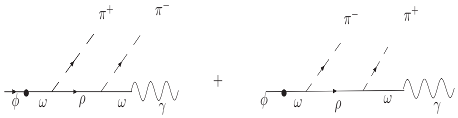

Figure: Feynman diagrams for double resonance

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The double resonance contribution corresponds to the decay of ϕ to ρ and π and this ρ in pion and foton, this contribution has been calculated in [JHEP 0605:049 (2006)]

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$$f_1^{JHEP} = -\frac{1}{4\pi\alpha}\left(\left[-1+\frac{3}{2}x+\sigma\right]\left[g\left(x_1\right)+g\left(x_2\right)\right]\right.$$
$$\left.+\frac{1}{4}\left(x_1-x_2\right)\left[g\left(x_1\right)+g\left(x_2\right)\right]\right)$$
$$f_2^{JHEP} = -\frac{1}{4\pi\alpha s^2}\left(g\left(x_1\right)+g\left(x_2\right)\right)$$
$$f_3^{JHEP} = -\frac{1}{8\pi\alpha s^2}\left(g\left(x_1\right)-g\left(x_2\right)\right)$$

where

$$g(x) = \frac{e g^{\phi}_{\rho\pi} g^{\rho}_{\pi\gamma}}{4F_{\phi}} \frac{m_{\phi}^{2} e^{i\beta_{\rho}} e^{i\beta_{\omega\phi}}}{s - m_{\phi}^{2} + i m_{\phi}\Gamma_{\phi}} \frac{s^{2}\Pi_{\rho}^{VMD}}{(1-x)s - m_{\rho}^{2} + i m_{\rho}\Gamma_{\rho}((1-x)s)}$$

$$x_{1,2} = \frac{2p_{+,-}\cdot(p_1+p_2)}{s}, x = 2 - x_1 - x_2.$$

We find another double resonance formulation in [NPA 729 743 (2003)]

$$
\begin{aligned}
f_1^{NPA} &= \alpha \left[D_\rho \left(P_\rho \right) \left(l^2 + Q \cdot k - 2k \cdot l \right) + D_\rho \left(P'_\rho \right) \left(l^2 + Q \cdot k + 2k \cdot l \right) \right] \\
f_2^{NPA} &= -\alpha \left[D_\rho \left(P_\rho \right) + D_\rho \left(P'_\rho \right) \right] \\
f_3^{NPA} &= -\alpha \left[D_\rho \left(P_\rho \right) - D_\rho \left(P'_\rho \right) \right] \\
\alpha &= -C\tilde{\epsilon} \frac{M_V^2}{9} \frac{f^2 G^2}{M_\omega^2} D_\phi \left(Q^2 \right), P_\rho = \frac{(Q - l + k)}{2}, P'_\rho = \frac{(Q + l + k)}{2}
\end{aligned}
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$$f_1 = \frac{g_s g_\phi}{f_\phi} \frac{g_f}{2\pi^2 m_{K^+}^2} \widetilde{I}_P^{ab} F_\phi(s) P_f\left(q^2\right) e^{i\delta_B},$$

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where

$$F_\phi(s) = \frac{m_\phi^2}{s - m_\phi^2 + i\sqrt{s}\Gamma_\phi}, \qquad P_f\left(q^2\right) = \frac{1}{q^2 - m_f^2 + i m_f \Gamma_f},$$

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The angle δ_B is the elastic background phase and it must be included with the kaon loop [PRD56 4084 (1997)]. This phase is very relevant in the interference term. In this case $\delta_B = b\sqrt{q^2 - 4m_\pi^2}$ with $b = 75^\circ/\text{GeV}$.

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The kaon loop function is given by

$$\widetilde{I}_P^{ab} = \frac{1}{2(a-b)} - \frac{2}{(a-b)^2}\left[f\left(\frac{1}{b}\right) - f\left(\frac{1}{a}\right)\right] + \frac{a}{(a-b)^2}\left[g\left(\frac{1}{b}\right) - g\left(\frac{1}{a}\right)\right],$$

$$f(z) = \begin{cases} -\left[\arcsin\left(\frac{1}{2\sqrt{z}}\right)\right]^2 & z > \frac{1}{4} \\ \frac{1}{4}\left[\ln\left(\frac{n_+}{n_-}\right) - i\pi\right]^2 & z < \frac{1}{4} \end{cases}$$

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$$g(z) = \begin{cases} \sqrt{4z-1}\arcsin\left(\frac{1}{2\sqrt{z}}\right) & z > \frac{1}{4} \\ \frac{1}{2}\sqrt{1-4z}\left(\ln\left|\frac{n_+}{n_-}\right| - i\pi\right) & z < \frac{1}{4} \end{cases}$$

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$$a = \frac{Q^2}{m_K^2}, \quad b = \frac{q^2}{m_K^2}, \quad n_\pm = \frac{1}{2}\left[1 \pm \sqrt{1-4z}\right].$$

Linear sigma model

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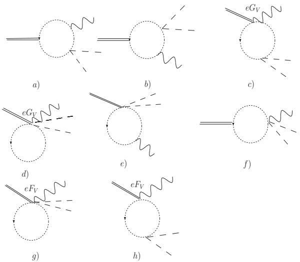
$$\begin{aligned}\mathcal{A}\left(K^+K^- \rightarrow \pi^0\pi^0\right)_{L\sigma M} = & \frac{m_\pi^2 - q^2/2}{2f_\pi f_K} \\ & + \frac{q^2 - m_\pi^2}{2f_\pi f_K}\left[\frac{m_K^2 - m_\sigma^2}{D_\sigma\left(q^2\right)} c\phi_S\left(c\phi_S - \sqrt{2}s\phi_S\right)\right. \\ & \left. + \frac{m_K^2 - m_{f_0}^2}{D_{f_0}\left(q^2\right)} s\phi_S\left(s\phi_S + \sqrt{2}c\phi_S\right)\right]\end{aligned}$$

UχPT

The ϕ decayment under UχPT model is calculated with the Feynman diagrams[PRD76 074012 (2007)]



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$$\left. - \left(G_V - \frac{F_V}{2}\right)\frac{m_K^2}{4} g_K(q^2) g_{\mu\nu} k_\alpha\right]\eta^{\alpha\nu}\epsilon^\mu$$

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and the structure functions are

$$f_1 = \frac{-1}{\sqrt{3}}\frac{F_V}{3f^2}\frac{1}{Q^2 - M_\phi^2 + i\Gamma_\phi M_\phi}\frac{t^0_{K\pi}}{\pi^2\sqrt{3}}\times \left(\frac{Q^2}{m_K^2}G_V\widetilde{I}^{ab}_P - \frac{1}{4}\left(G_V - \frac{F_V}{2}\right)g_K(q^2)\right),$$

$$f_2 = 0, f_3 = 0.$$

Numeric calculation

We developed a fortran program based on montecarlo including the experimental restrictions reported by KLOE to obtain the asymmetry: $45^\circ < \theta_\pi < 135^\circ$, $45^\circ < \theta_\gamma < 135^\circ$ and an energy cut for the foton of 10 MeV.

Bremsstrahlung and double resonance

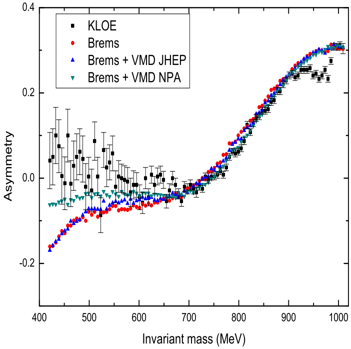

Figure: Asymmetry without ϕ decayment

KL

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Parameter	Value
m_f (MeV)	980
Γ_f (MeV)	70
g_s^2 (GeV^2)	3.61
g_ϕ^2	19.56
g_f^2 (GeV^2)	7.78
f_ϕ^2	179.14
g_ρ^2	35.95
f_ρ^2	24.66

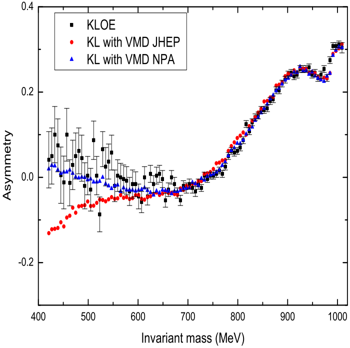

Figure: Asymmetry using KL model

LSM

For the linear sigma model we use for the f_0 $m_f = 980$ MeV, $\Gamma_f = 70$ MeV and for the sigma [PRD69, 074033 (2004)] $m_\sigma = 528$ MeV y $\Gamma_\sigma = 414$ MeV, the best results are obtained with a scalar angle $\phi_S = -5°$.

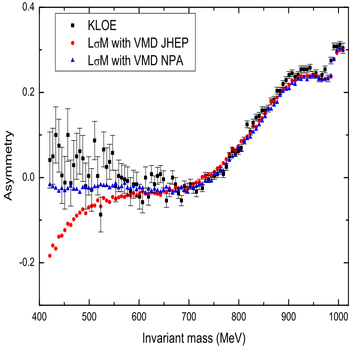

Figure: Asymmetry with LσM

UχPT

For the UχPT case we use the results for VMD limit i.e.
$G_V - \frac{F_V}{2} = 0$

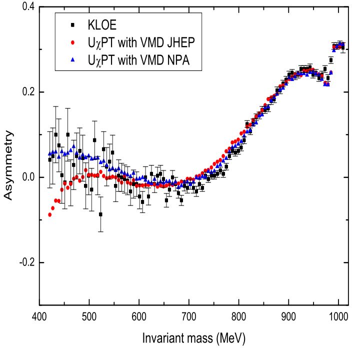

Figure: Asymmetry with UχPT

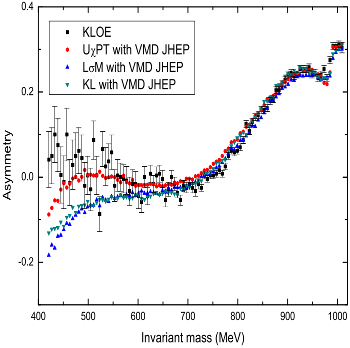

Figure: Asymmetry with the three models using JHEP formulation for double resonance

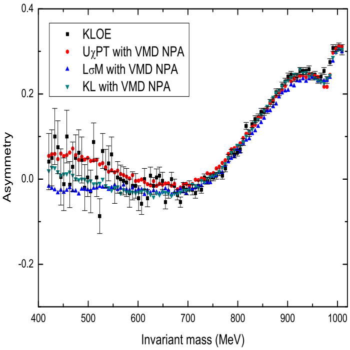

Figure: Asymmetry with the three models using NPA formulation for double resonance

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- In general UχPT describes better the low energy region of the asymmetry.

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- Different FSR models can be included by mean of structure functions.
- The Bremmstrahlung is the dominant contribution.
- We use trhee different models to describe the ϕ decayment (KL,LSM y UχPT).
- In general UχPT describes better the low energy region of the asymmetry.
- Relative phases are relevant to describe the asymetry

Thank you!!!