$B(\tau^- \to \eta\pi^-\nu_\tau)$, the $a_0(980)$, and New Weak Interactions

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Outline

- Motivation
- Estimate of $B(\tau^- \to \eta\pi^-\nu_\tau)$:
  - Vector contribution
  - Scalar contribution
- Sensitivity to new interactions
- Implications of various $B(\tau^- \to \eta\pi^-\nu_\tau)$ values

Motivation

- $\tau^- \to \eta\pi^-\nu_\tau$ is sensitive to new-physics
- CLEO limit on $B(\tau^- \to \eta\pi^-\nu_\tau) < 1.4 \times 10^{-4}$ (90% CL)
- Chiral perturbation theory: $B(\tau^- \to \eta\pi^-\nu_\tau) \approx 1.3 \times 10^{-5}$
  - Pich, PLB 196, 561 (1987); Tisserant and Truong, PLB 115, 264 (1982); Neufeld, and Rupertsberger, Z. Phys. C 68, 91 (1995).
  - Assumes $a_0^-(980) \to \eta\pi^-$ contribution dominates, and that $a_0(980)$ is a $q\bar{q}$ state
  - However, $a_0(980)$ is probably a 4-quark, $u\bar{d}s\bar{s}$ state
- At this level, $\rho^-(770) \to \eta\pi^-$ could also lead to a vector contribution

- Therefore, we…
  - calculate the ρ contribution to $\tau^- \to \eta\pi^-\nu_\tau$
  - perform an alternative calculation of the a_0 contribution
  - comment on sensitivity of $B(\tau^- \to \eta\pi^-\nu_\tau)$ to new weak interactions

Vector contribution

- Note: $B(\tau^- \to \pi^- \pi^0 \nu_\tau)$ is large (25.5%) and completely dominated by ρ^- contribution
- So expect ρ^- to also dominate the vector contribution to $\tau^- \to \eta \pi^- \nu_\tau$, with branching fraction

1 power from phase space,
2 from vector amplitude

$$B_{L=1}\left(\tau^- \to \eta \pi^- \nu\right) = \left(\frac{g_{\rho\eta\pi}}{g_{\rho\pi\pi}}\right)^2 \left(\frac{p_{\rho\to\eta\pi}}{p_{\rho\to\pi\pi}}\right)^3 B\left(\tau^- \to \rho^- \nu\right)$$

Obtaining $g_{\rho\eta\pi}$ Coupling

- $\rho^- \to \eta\pi^-$ has not been observed, but we can obtain $g_{\rho\eta\pi}$ from the Dalitz-plot distribution of $\eta \to \pi^+\pi^-\pi^0$
  - Method used by Ametller & Bramon, PRD 24, 1325 (1981)
  - Now more precise data, access to more terms in Dalitz-plot distribution
- Assume the decay has 3 contributions: scalar, ρ^+ and ρ^-:
  - (ρ^0 is forbidden due to C conservation)

$$M_{\eta\to\pi^+\pi^-\pi^0} \equiv M_{+-0} = M_S + M_{\rho^+} + M_{\rho^-}$$

- Scalar part has flat distribution in the $\pi^+\pi^-\pi^0$ Dalitz plot, and is also the only contribution to $\eta \to 3\pi^0$

$$|\mathcal{M}_S|^2 = 8(2\pi)^3 m_\eta \Gamma_\eta \mathcal{B}(\eta \to \pi^0\pi^0\pi^0) \frac{6\sqrt{3}}{Q^2 S_1} \frac{3!}{9}$$
$$= 0.065,$$

$$Q \equiv m_\eta - 3m_\pi$$

$$S_1 \equiv \int dX\, dY = 2.75 = \text{area of Dalitz plot}$$

Dalitz plot variables $X = \frac{\sqrt{3}\left(T_{\pi^+} - T_{\pi^-}\right)}{Q}, \quad Y = \frac{3\left(T_{\pi^0} - 1\right)}{Q}$

Write vector part as: $M_{\rho^\mp} = -g_{\rho\eta\pi} g_{\rho\pi\pi} \frac{\left(P_\eta + P_{\pi^\pm}\right)\cdot\left(P_{\pi^\mp} - P_{\pi^0}\right)}{\left(P_{\pi^\mp} + P_{\pi^0}\right)^2 - m_\rho^2 + i\Gamma_\rho m_\rho}$

The coupling we are after

- Expand squared amplitude to 3rd order in

$$r = \frac{m_\eta Q}{m_\rho^2 - m_\eta^2/3 - m_\pi^2 - i\Gamma_\rho m_\rho} = 0.14 - 0.03i$$

- Obtain total rate relative to scalar part:

$$\left|M_{+-0}\right|^2 \propto 1 + \alpha Y + \beta Y^2 + \gamma X^2 + \delta\left(Y^3 + YX^2\right)$$

- Where

$$\alpha = -4 g_{\eta\rho\pi} g_{\rho\pi\pi} \Re\{\mathcal{M}_S^* r\} \frac{1}{|\mathcal{M}_S|^2}$$

$$\beta = \left[-\frac{4}{3} g_{\eta\rho\pi} g_{\rho\pi\pi} \Re\{\mathcal{M}_S^* r^2\} + 4(g_{\eta\rho\pi} g_{\rho\pi\pi})^2 |r|^2\right] \frac{1}{|\mathcal{M}_S|^2}$$

$$\gamma = \frac{4}{3} g_{\eta\rho\pi} g_{\rho\pi\pi} \Re\{\mathcal{M}_S^* r^2\} \frac{1}{|\mathcal{M}_S|^2}$$

$$\delta = \left[\frac{4}{9} g_{\eta\rho\pi} g_{\rho\pi\pi} \Re\{\mathcal{M}_S^* r^3\} + \frac{8}{3} (g_{\eta\rho\pi} g_{\rho\pi\pi})^2 \Re\{r (r^2)^*\}\right] \frac{1}{|\mathcal{M}_S|^2}$$

- Dalitz-plot parameters measured by KLOE (arXiv:0707.2355):

$$|M_{+-0}|^2 \propto 1 - 1.09Y + 0.124Y^2 + 0.057X^2 + 0.14Y^3 + ?YX^2$$

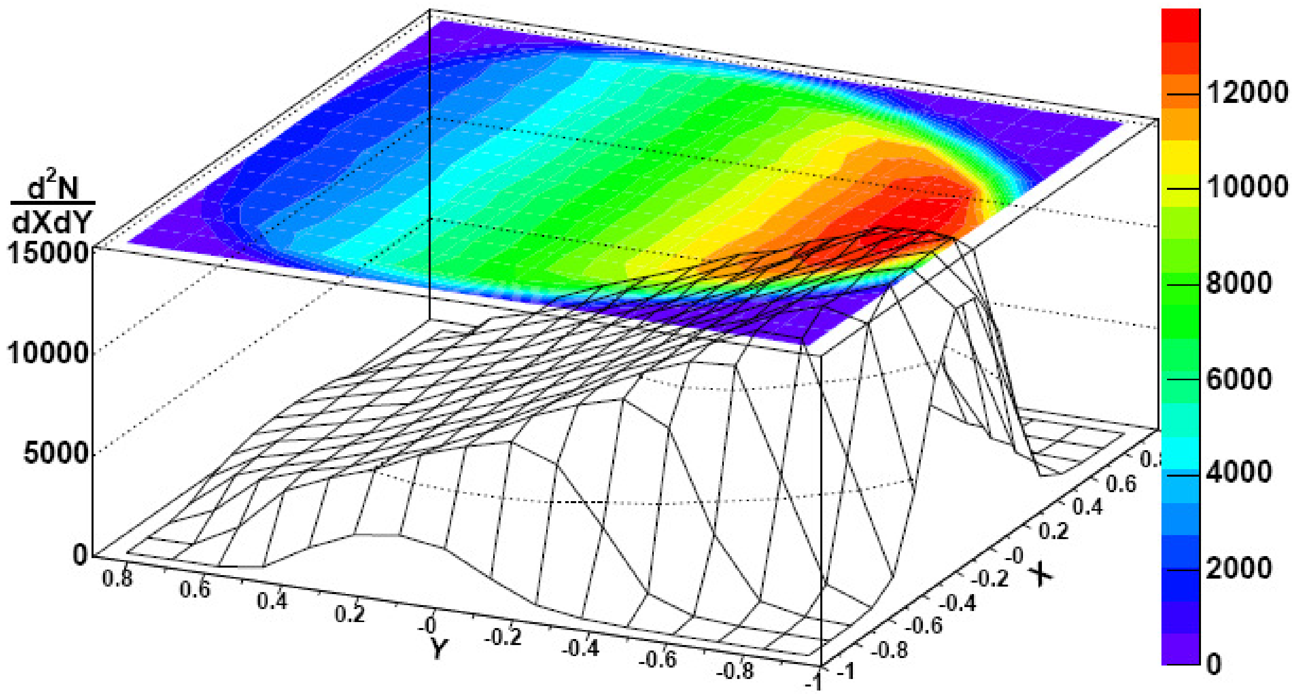

Fig. 2. Dalitz-plot distribution for the whole data sample. The plot contains 1.34 millions of events in 256 bins.

- Comparing the Y coefficients, get:

Taken to be real

$$g_{\eta\rho\pi} g_{\rho\pi\pi} = \frac{1.09}{4} \frac{\mathcal{M}_S}{\Re(r)} = 0.51$$

- Extract $g_{\rho\pi\pi}$ from $\rho \to \pi\pi$ width:

$$g_{\rho\pi\pi} = \sqrt{\frac{6\pi m_\rho^2 \Gamma_\rho}{p^3_{\rho\to\pi\pi}}} = 6.0.$$

$$g_{\eta\rho\pi} \approx 0.085$$

Consistent w. Ametller & Bramon

- So the vector contribution to $B(\tau \to \eta\pi\nu)$ is

$$B_{L=1} = \left(\frac{g_{\rho\eta\pi}}{g_{\rho\pi\pi}}\right)^2 \left(\frac{p_{\rho\to\eta\pi}}{p_{\rho\to\pi\pi}}\right)^3 B\left(\tau^- \to \rho^- \nu\right) \approx 3.6\times 10^{-6}$$

Cross-checks

- The other coefficients are a test of the model:

$$\left|M_{+-0}\right|^2 \propto 1 - 1.09Y + 0.27Y^2 + 0.05X^2 + 0.03\left(Y^3 - YX^2\right)$$

- Compare with KLOE measurement:

$$\left|M_{+-0}\right|^2 \propto 1 - 1.09Y + 0.124Y^2 + 0.057X^2 + 0.14Y^3$$

- Floating arg(M_S) = 15° improves agreement only slightly
- Also check ratio of BR's::

$$\frac{B(\eta \to \pi^+\pi^-\pi^0)}{B(\eta \to 3\pi^0)} = \begin{cases} 0.7 & \text{, measured} \\ 0.71 & \text{, model + KLEO parameters} \\ 0.76 & \text{, model + our parameters} \end{cases}$$

Scalar Contribution to B($\tau^- \rightarrow \eta\pi^-\nu_\tau$)

- Chiral perturbation theory calculates assumed $a_0(980)$ is a $q\bar{q}$ state and are complicated
- We conduct a simpler estimate and arrive at a similar result:
- Vector current is conserved up to $m_d - m_u$:

$$\nabla^\mu \bar{u}(x)\gamma_\mu d(x) = (m_d - m_u)\bar{u}(x)d(x) \quad + \text{EM term}$$

- We estimate the scalar matrix element by relating the P-wave states $a_0(980)$ & $a_1(1260)$:

$$\frac{B_{L=0}\left(\tau^- \rightarrow a_0^-(980)\nu\right)}{B\left(\tau^- \rightarrow a_1^-(1260)\nu\right)} \sim 1.3 \left|\frac{\langle 0|S|a_0(980)\rangle}{\langle 0|A|a_1(1260)\rangle}\right|^2 \left(\frac{m_d - m_u}{m_{a_1(1260)}}\right)^2$$

Phase space

~1, since fixed by quark-model wave functions

$$B_{\text{L=0}} \sim 10^{-5}$$

Limits on New Physics

- $B(\tau^- \to \eta\pi^-\nu)$ can be used to put bounds on new scalar interactions up to the SM expectation $B(\tau^- \to \eta\pi^-\nu) \sim 10^{-5}$
- A limit $B(\tau^- \to \eta\pi^-\nu) < 3 \times 10^{-5}$ implies

$$\frac{M_{Scalar}}{M_W} > \left(3 \times 10^{-5}\right)^{-\frac{1}{4}} \sim 13$$

for the same couplings as in the SM.

- Competitive with limits from angular distributions in nuclear β decay, ~4 (expected to improve to ~7 and then to ~15)
- The two limits are complementary:
  - β-decay: 1^{st}-generation couplings
  - $\tau^- \to \eta\pi^-\nu$: 3^{rd}-generation couplings

Conclusions

- Our estimates
  - $B_{L=0}(\tau^- \to \eta\pi^-\nu) \sim 10^{-5}$
  - $B_{L=1}(\tau^- \to \eta\pi^-\nu) \approx 3 \times 10^{-6}$

  imply the following for the measured value of $B_{L=0}(\tau^- \to \eta\pi^-\nu)$:
- $\approx 3 \times 10^{-6}$, especially with a $\rho^-(770)$ peak $\Rightarrow$
  - No surprises
- $\approx 10 \times 10^{-6}$, especially with a $a_0^-(980)$ peak $\Rightarrow$
  - $a_0^-(980)$ is a $q\bar{q}$ state after all
- $> \sim 30 \times 10^{-6}$, especially with scalar dominance $\Rightarrow$
  - Possibly new scalar interactions, $M_S \sim 13\ M_W$ for weak coupling
- Note that BaBar has limit $B\,(\tau^- \to \eta'\pi^-\nu) < 7.2 \times 10^{-6}$
  - Contributions from additional intermediate resonances

Backup Slides

Arguments for 4-quark $a_0(980)$

- $\Gamma(a_0(980)) \sim 50$ MeV, compare with $\Gamma(\rho(770)) \sim 150$ MeV
- $B(a_0(980) \rightarrow K\bar{K}) / B(a_0(980) \rightarrow \eta\pi) = 18\%$
  despite highly limited phase space in KK final state
- $a_0(980)$ production much suppressed wrt. $q\bar{q}$ states.
  - This suppression might be smaller in heavy ion collisions due to high quark multiplicity, especially s quarks

- 2^{nd}-class currents: Weinberg, Phys. Rev. 112, 1375 (1958):
  - 1^{st}-class currents: $GJ_1G^{-1} = -\xi J_1$, JPG = 0^{++}, 0^{--}, 1^{+-}, 1^{-+}
  - 2^{nd}-class currents: $GJ_2G^{-1} = +\xi J_2$, JPG = 0^{+-}, 0^{-+}, 1^{++}, 1^{--}
  - where $\xi = 1(-1)$ for S, A, P (V, T) and $G = Ce^{i\pi I_2}$:

- Full expression for $\eta\to3\pi^0$:

$$|\mathcal{M}_S|^2 = 8(2\pi)^3 m_\eta \Gamma_\eta \mathcal{B}(\eta \to \pi^0\pi^0\pi^0)\frac{6\sqrt{3}}{Q^2 S_1}\frac{3!}{9}$$
$$= 0.065,$$

- Rho decay amplitude:

$$\Gamma(\rho \to \pi\pi) = \frac{p_{\rho\to\pi\pi}}{32\pi^2 m_\rho^2}\int \left|M_\rho\right|^2 d\Omega$$

$$M_\rho = g_{\eta\rho\pi}\varepsilon_\mu \left(P_{\pi^+} - P_{\pi^-}\right)^\mu$$