Predictions on the second-class current decays \( \tau^- \to \pi^- \eta(0) \nu_\tau \)

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Objectives
1. We readdress the \( \tau^- \to \pi^- \eta(0) \nu_\tau \) decays, unseen in Nature so far.
2. To motivate near future B-factories e.g. Belle-II, their discovery.

Introduction
\( \tau^- \to \pi^- \eta(0) \nu_\tau \) decays belong to the so-called second-class current processes: parity conservation implies that these decays must proceed through the vector current, which has opposed \( c \)-parity to the \( \pi^- \eta(0) \) system.

- Isospin is however an approximate symmetry, slightly broken both by m_u \( \neq m_d \) (in QCD) and \( q_\pi \neq q_\eta \) (in QED), which results in a sizable suppression of these decays.

Decay width
- Amplitude of the process
\[ \mathcal{M} = \frac{G_F}{\sqrt{2}} \text{Im} \langle 0|J_{\mu}(1 - \gamma_5)|\pi^- \eta(0)|\bar{\nu}_\tau(0) \rangle. \]
- Hadronic matrix element in terms of form factors
\[ \langle \pi^- \eta(0)|\bar{\nu}_\tau(0) \rangle = \left( m_{\nu\tau} - m_{\pi} \right) + \frac{\Delta_{\pi} - \Delta_{\eta}}{\Delta_{\pi} + \Delta_{\eta}} \right) + \frac{\Delta_{QCD}}{\Delta_{\pi} + \Delta_{\eta}}. \]
- The finiteness of the matrix element at the origin imposes
\[ \mathcal{F}(\pi^- \eta(0)|0) = \frac{s_{\pi-\eta}(0)}{c_{\pi-\eta}(0)}, \Delta_{\pi} = m_{\eta} - m_{\pi}. \] (1)
- Differential decay width as a function of the invariant mass
\[ d \Gamma(\tau^- \to \pi^- \eta(0) \nu_\tau) = \frac{e^2 q_{\nu\tau}^2}{24 \pi^3} \text{E}_{\text{EW}} \left( \text{E}_{\text{EW}} \right)^2 \left( 1 - \frac{s}{M_{\pi}^2} \right)^2 \left\{ 1 - \frac{2s}{M_{\pi}^2} \right\} + \left( \frac{3\Delta^2}{4s} \right) \left( \frac{2\Delta_{\pi}}{M_{\pi}^2} \right)^2, \]
where \( q_{\nu\tau}(0) = \sqrt{s - 2(s + m_{\pi}^2) + \Delta_{\pi} s} \), and where \( q_{\nu\tau}(s) = \frac{q_{\nu\tau}(0)}{s - s_{\nu\tau}(0)} \), are the two form factors normalised to unity at the origin.

Form factors parameterizations
- Vector Form Factor
\[ F^\pi_{\nu\tau}(s) = \frac{m_{\pi}^2}{4M_{\pi}^2} \left( 1 + \frac{m_{\pi}^2}{M_{\pi}^2 - s} \right) \]
where \( \epsilon_{\nu\tau} \) and \( \epsilon_{\nu\tau}^\eta \) accounts for the \( \pi^- \eta(0) \) mixing.
- Scalar Form Factor
\[ F^\pi_{\nu\tau}(s) = \frac{m_{\pi}^2}{4M_{\pi}^2} \left( 1 + \frac{m_{\pi}^2}{M_{\pi}^2 - s} \right) \]
From Eqs. (1,2,3) we find
\[ \epsilon_{\nu\tau} = 0.5 \pm 0.3 \times 10^{-4} \]
\[ \epsilon_{\nu\tau}^\eta = 2.5 \pm 1.5 \times 10^{-4} \]
- Dispersion Relations
  - Elastic unitarity: Omnès equation
\[ F^\pi_{\nu\tau}(s) = r(s) \exp \left\{ \frac{u - s}{\sqrt{u}} \right\} \left( \int_v^{\infty} \frac{d \xi}{\sqrt{\xi}} \delta_{\pi,0}(\xi) \right) \]
where \( \delta_{\pi,0}(\xi) = \arctan \left( \frac{\hbar_{\pi,0}(\xi)}{m_{\pi}^2} \right) \) with \( \hbar_{\pi,0}(\xi) \) from Ref. [2].
  - Inelastic cuts: \( \pi^- \eta \) coupled to \( \pi^- \eta' \) and/or \( K^- K^0 \) and vice versa [1].

Results: Branching ratio predictions
- \( \tau^- \to \pi^- \eta(0) \nu_\tau \)

<table>
<thead>
<tr>
<th>Form Factor</th>
<th>Contribution (10^{-5})</th>
<th>Total (10^{-5})</th>
</tr>
</thead>
<tbody>
<tr>
<td>ChPT (1 resonance)</td>
<td>0.72 \pm 0.06</td>
<td>0.98 (51)</td>
</tr>
<tr>
<td>ChPT (2 resonances)</td>
<td>0.48 \pm 0.06</td>
<td>0.74 (32)</td>
</tr>
<tr>
<td>Elastic approximation</td>
<td>0.10 \pm 0.03</td>
<td>0.36 (4)</td>
</tr>
<tr>
<td>( \pi^- \eta ) coupled to ( \pi^- \eta' )</td>
<td>0.15 (9)</td>
<td>0.41 (9)</td>
</tr>
<tr>
<td>( \pi^- \eta ) coupled to ( K^- K^0 )</td>
<td>1.86 (11)</td>
<td>2.12 (11)</td>
</tr>
<tr>
<td>( \pi^- \eta ) coupled to ( \eta' ) and ( K^- K^0 )</td>
<td>1.41 (9)</td>
<td>1.67 (9)</td>
</tr>
</tbody>
</table>

Table 1: Total branching ratio includes the vector, \( 2.0 \times 10^{-3} \), and the scalar contributions.

Results: Invariant mass distribution
- \( \tau^- \to \pi^- \eta(0) \nu_\tau \)

![Figure 1: \( \tau^- \to \pi^- \eta(0) \nu_\tau \) distribution showing the vector contribution (red-dashed curve) and the full distribution as obtained by employing the scalar form factor in its elastic version (black solid curve), the three coupled-channels analysis (green dot-dashed curve) and ChPT with two resonances (blue dotted curve).](image)

Conclusions
- We focus on the Standard Model prediction of \( \tau^- \to \pi^- \eta(0) \nu_\tau \) decays.
- We have addressed the description of the participator vector and scalar form factors based on Chiral Perturbation Theory with resonances supplemented by dispersion relations.
- According to our results, the discovery of second-class currents might be possible at Belle-II thanks to the increased luminosity with respect to its predecessors.

References

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