Measurement of the branching ratio of a rare decay $\eta \rightarrow \pi^0 \gamma \gamma$ with WASA-at-COSY

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Outline

- Physics Motivation
- WASA-at-COSY setup
- Simulation
- Data Analysis
- Results
- Summary and outlook
Two peculiar properties of QCD

**Asymptotic Freedom**: At high momentum transfers (short distances)
Coupling small quark inside hadron behaves as a free particle.
Perturbative QCD explains experimental observations well.

**Confinement**: At small momentum transfers (large distances)
Coupling large confinement of quarks and gluons inside hadrons.
Perturbative QCD fails Effective field theory
Most successful Effective field Theory ➔ Chiral Perturbation Theory

Lagrangian in terms of increasing powers of momentum in $\chi$PT
- $O(p^2)$ is absent, because no direct coupling of photon with $\pi^0$ and $\eta$.
- $O(p^4)$ very small, because hadronic loops are suppressed.
- $O(p^6)$ first sizable contribution.

The reaction $\eta \rightarrow \pi^0\gamma\gamma$ is a gold plated test of higher order $\chi$PT.

<table>
<thead>
<tr>
<th>Theory</th>
<th>$\Gamma(\eta \rightarrow \pi^0\gamma\gamma)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\chi$PT, $O(p^2)$</td>
<td>0</td>
</tr>
<tr>
<td>$\chi$PT, $\ldots+ O(p^4)$</td>
<td>0.004</td>
</tr>
<tr>
<td>$\chi$PT, $\ldots+ O(p^6)$</td>
<td>$0.42 \pm 0.20$</td>
</tr>
<tr>
<td>$\chi$PT, $\ldots+ O(p^6)$</td>
<td>0.47</td>
</tr>
<tr>
<td>$\chi$PT, ENJL $\ldots+ O(p^6)$</td>
<td>$0.58 \pm 0.30$</td>
</tr>
<tr>
<td>VMD</td>
<td>$0.30 \pm 0.15$</td>
</tr>
<tr>
<td>Q box</td>
<td>0.70</td>
</tr>
<tr>
<td>$\chi$PT, $\ldots+ O(p^6)$</td>
<td>$0.44 \pm 0.09$</td>
</tr>
<tr>
<td>Unitarized $\chi$PT</td>
<td>$0.47 \pm 0.10$</td>
</tr>
</tbody>
</table>

Theoretical predictions for $\eta \rightarrow \pi^0\gamma\gamma$

Another stringent test of the theory would be the shape of the invariant mass of two photons not forming a pion.

Earlier studies have been hampered by the lack of statistics.

We have $3 \times 10^7$ total eta produced in 2008 and 2009.

The existing experimental results of $\text{BR}(\eta \rightarrow \pi^0 \gamma \gamma)$ and theoretical calculations for $\Gamma(\eta \rightarrow \pi^0 \gamma \gamma)$ vary a lot.

Motivated us to measure the branching ratio of $\eta \rightarrow \pi^0 \gamma \gamma$ with WASA-at-COSY.

<table>
<thead>
<tr>
<th>Experiments</th>
<th>$\text{BR}(\eta \rightarrow \pi^0 \gamma \gamma)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>GAMS</td>
<td>$(7.1 \pm 1.4) \times 10^{-4}$ [3]</td>
</tr>
<tr>
<td>Crystal Ball</td>
<td>$(2.21 \pm 0.24_{\text{stat}} \pm 0.38_{\text{sys}}) \times 10^{-4}$ [1]</td>
</tr>
<tr>
<td>KLOE</td>
<td>$(8.4 \pm 2.7_{\text{stat}} \pm 1.4_{\text{sys}}) \times 10^{-5}$ [2]</td>
</tr>
</tbody>
</table>

COSY (Cooler SYnchrotron)

Operated at the Institute For Nuclear Physics (IKP), Forschunszentrum, Juelich in Germany.

Salient features:
- Circumferences : 184 cm
- Delivers polarized and unpolarized proton and deuteron beams in the momentum range 0.3 to 3.7 GeV/c
WASA-at-COSY setup

WASA (Wide Angle Shower Apparatus)

Reaction: \( p + d \rightarrow ^3\text{He} \eta \rightarrow ^3\text{He} \pi^0\gamma\gamma \)

Salient features of WASA
- 4\(\pi\) setup.
- Pellet target (35\(\mu\)m)
- Good mass resolution in FD
- High Granularity \(\rightarrow\) Less probability of merging cluster in CD

Invariant mass of \(\eta\)

Missing mass of \(^3\text{He}\)

Sum of the decay products of \(\eta\) meson (\(\pi^0, \gamma, \gamma\))

\[
M_{\text{missing}}^2 = E_{\text{missing}}^2 - p_{\text{missing}}^2 \\
= \left(E_{\text{beam}} - E_{^3\text{He}}\right)^2 - \left(P_{\text{beam}} - P_{^3\text{He}}\right)^2
\]
@ beam kinetic energy 1.0 GeV

- $pd \rightarrow ^3\text{He} \ \eta$
- $pd \rightarrow ^3\text{He} \ \eta \rightarrow ^3\text{He} \ \pi^0\gamma\gamma$
- $pd \rightarrow ^3\text{He} \ \eta \rightarrow ^3\text{He} \ 3\pi^0$
Analysis of $pd \rightarrow ^3\text{He} \eta$


**Identification of $^3\text{He}$**

Measured: $8.014 \times 10^6 \eta$ events from missing mass of $^3\text{He}$ analysis

Reconstruction efficiency: 77%

$\Rightarrow$ Total eta produced: $1.03 \times 10^7$
As the branching ratio of the channel is very small ($\sim 10^{-4}$), detailed simulations are required.

On the basis of simulations the following channels contribute as the background:

<table>
<thead>
<tr>
<th>Background Channel</th>
<th>Cross section</th>
</tr>
</thead>
<tbody>
<tr>
<td>$pd \rightarrow ^3\text{He} \ 2\pi^0$</td>
<td>Four photons in the final state</td>
</tr>
<tr>
<td>$pd \rightarrow ^3\text{He} \ 3\pi^0$</td>
<td>Overlapping of two photon cluster or missing of two photons</td>
</tr>
<tr>
<td>$\eta \rightarrow 3\pi^0$</td>
<td></td>
</tr>
</tbody>
</table>

$\eta$ Production cross section : 0.4 $\mu$b
Event Selection Criteria

Basic Conditions

- One charged track in the Forward Detector
- Four neutral clusters in the Central Detector with $E_{\text{dep}} > 20$ MeV
- No charged track in the Mini Drift Chamber (MDC)
Missing mass of $^3$He for signal and contributing channels

$3 \times 10^6$ events generated using event generator PLUTO @ $T_{beam} 1.0$ GeV.

- $\eta \rightarrow \pi^0 \gamma \gamma$
- $2\pi^0$
- $\eta \rightarrow 3\pi^0$
- $3\pi^0$
Further Selection Criteria

Simulations $\eta \rightarrow 3\pi^0$, $pd \rightarrow ^3He 3\pi^0$

$-0.1 < \text{Missing energy of full event} < 0.1$ GeV

- Energy deficit in the final state because of the two photon missing in the forward direction
Kinematic fitting

- Four photons in the final state \( \eta \rightarrow \pi^0 \gamma \gamma \)

- Two hypothesis have been simultaneously confirmed for each event

\[ pd \rightarrow {}^3\text{He} \; \pi^0 \pi^0 \]
\[ pd \rightarrow {}^3\text{He} \; \pi^0 \gamma \gamma \]

- Selecting \( 2\pi^0 \) confidence level less than 0.01\%, throws away most of the \( 2\pi^0 \) background.

- Selecting \( \pi^0 \; \gamma \gamma \) confidence level greater than 0.1, accepts good \( \pi^0 \gamma \gamma \) events.
Discarding all events for which $m_{\text{max}}(\pi^0\gamma)$ lies above the line

$$m_{\text{max}}(\pi^0\gamma) = 4.062 \times m(\pi^0\gamma) - 1.627$$
Further Selection Criteria

Simulations

Scattering angle ($\theta_{\pi^0\gamma\gamma}$) < 70°

- $\eta \rightarrow \pi^0\gamma\gamma$
- $\eta \rightarrow 3\pi^0$
- $2\pi^0$
- $3\pi^0$
## Event Selection Criteria

### Reconstruction Efficiency (%)

<table>
<thead>
<tr>
<th>Condition</th>
<th>$\varepsilon(\eta\rightarrow\pi^0\gamma\gamma)$</th>
<th>$\varepsilon(\eta\rightarrow3\pi^0)$</th>
<th>$\varepsilon(2\pi^0)$</th>
<th>$\varepsilon(3\pi^0)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Preliminary cuts</td>
<td>42.5</td>
<td>4.97</td>
<td>3.88</td>
<td>1.61</td>
</tr>
<tr>
<td>-0.1 &lt; MEsys &lt; 0.1, IM$_\eta$ &gt; 0.529 GeV/c$^2$</td>
<td>26.36</td>
<td>0.81</td>
<td>2.37</td>
<td>0.23</td>
</tr>
<tr>
<td>CL($2\pi^0$) &lt; 0.01%</td>
<td>18.48</td>
<td>0.71</td>
<td>0.043</td>
<td>0.202</td>
</tr>
<tr>
<td>Cut on 2d (m$_{\max}(\pi^0\gamma)$, m($\pi^0\gamma\gamma$))</td>
<td>18.3</td>
<td>0.71</td>
<td>0.023</td>
<td>0.102</td>
</tr>
<tr>
<td>CL($\pi^0\gamma\gamma$) &gt; 0.1</td>
<td>13.90</td>
<td>0.304</td>
<td>0.0023</td>
<td>0.085</td>
</tr>
<tr>
<td>$\theta_{\eta}$ &lt; 70°</td>
<td>13.84</td>
<td>0.30</td>
<td>0.001</td>
<td>0.083</td>
</tr>
<tr>
<td>IM$_{2\gamma}$ &gt; 0.179</td>
<td>12.28</td>
<td>0.20</td>
<td>0.0006</td>
<td>0.080</td>
</tr>
<tr>
<td>35$^0$ &lt; Opening angle($^3$He and $\pi^0\gamma\gamma$) &lt; 70$^0$</td>
<td>9.04</td>
<td>0.10</td>
<td>0.0003</td>
<td>0.053</td>
</tr>
</tbody>
</table>
Analysis of $pd \rightarrow ^3He \eta \rightarrow \pi^0\gamma\gamma$...

**Results**

**Missing mass of $^3He$**

- **Entries 271329**
  - $\eta \rightarrow \pi^0\gamma\gamma$
  - simulation

- **Entries 3269**
  - $\eta \rightarrow 3\pi^0$
  - simulation

- **Entries 1616**
  - $3\pi^0$
  - simulation

**Preliminary**

- $\eta \rightarrow \pi^0\gamma\gamma$
- $\eta \rightarrow 3\pi^0$
- $3\pi^0$
- $2\pi^0$
- Sum MC
- Data points
To find out $\eta \rightarrow 3\pi^0$ events in the same data set
Missing mass of $^3\text{He}$

Analysis of $\eta \rightarrow 3\pi^0 \rightarrow 6\gamma$ as signal

Results

15 possible combinations

$\chi^2 = \sum_{i=1,3} \frac{(IM_{\gamma_i} - m_{\pi^0})^2}{\sigma_{\text{det}}^2}$

Total $\eta \rightarrow 3\pi^0$ produced $2.9 \times 10^6$
Reconstruction efficiency of $\eta \rightarrow \pi^0 \gamma \gamma$ is 9.04% and the reconstruction efficiency of $\eta \rightarrow 3\pi^0$ is 0.10% as background.

After subtracting remaining contributions of background, we have measured 300$\pm$54 $\eta \rightarrow \pi^0 \gamma \gamma$ events.

Statistical error on the branching ratio of $\eta \rightarrow \pi^0 \gamma \gamma = 0.7 \times 10^{-4}$
Monte Carlo describes the experimental data.

Measured $300\pm54 \eta \rightarrow \pi^0 \gamma \gamma$ events and statistical error on branching ratio of $\eta \rightarrow \pi^0 \gamma \gamma : 0.7 \times 10^{-4}$

Can investigate whether additional condition of $z$ vertex would increase the signal to background ratio.

Understand $\eta \rightarrow 3\pi^0$ background and estimate other systematical errors.

Extract the spectrum of invariant mass of $2\gamma$ with more statistics in 2009.
WASA-at-COSY collaboration

Thanks
Invariant mass of $\eta \rightarrow \pi^0\gamma\gamma$ for signal and contributing channels

Simulations
To improve S/B ratio

Implemented z vertex fitting

\[ \eta \rightarrow \pi^0 \gamma \gamma \]

Z of the cluster is changed from -15 to 15mm in step of 1mm

\[ \eta \rightarrow 3\pi^0 \] (background)
Analysis of pd→ $^3$He $\eta(\rightarrow \pi^0\gamma\gamma)$…

Simulations

$35^0 < \text{Opening angle (}^3\text{He, }\pi^0\gamma\gamma) < 70^0$
Calculation of the branching ratio of $\eta \rightarrow \pi^0\gamma\gamma$

\[ BR(\eta \rightarrow \pi^0\gamma\gamma) = B_1 \times (BR(\eta \rightarrow 3\pi^0)) \]

\[ B_1 = \frac{n(\eta \rightarrow \pi^0\gamma\gamma)}{n(\eta \rightarrow 3\pi^0)} \]

\[ n = N / \epsilon \]

Here $N(\eta \rightarrow \pi^0\gamma\gamma) = 289$ \\
\[ \epsilon = 9.04\% \]
\[ N(\eta \rightarrow 3\pi^0) = 7.84 \times 10^5 \]
\[ \epsilon = 27\% \]

$BR(\eta \rightarrow 3\pi^0) = 32\%$ (PDG value)

\[ BR(\eta \rightarrow \pi^0\gamma\gamma) = (3.48 \pm 0.67_{\text{stat}}) \times 10^{-4} \]
Analysis of $p d \to ^3\text{He} \eta(\to \pi^0 \gamma \gamma)$.

Count 289 $\eta \to \pi^0 \gamma \gamma$ events in 3σ range of eta peak.
We have measured 300 $\eta \rightarrow \pi^0\gamma\gamma$ events.

Reconstruction efficiency from Monte Carlo is 9.04% and the reconstruction efficiency of $\eta \rightarrow 3\pi^0$ 0.10% as background.

Statistical error on the branching ratio of $\eta \rightarrow \pi^0\gamma\gamma = 0.7 \times 10^{-4}$

After subtracting $\eta \rightarrow 3\pi^0$ background