Physics and Outlook for Rare Eta Decays to All-Neutral Final States

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Rome, Italy
Oct 2, 2013
some physics motivation
Beyond SM
C and P Symmetries (assuming CPT)

<table>
<thead>
<tr>
<th>P</th>
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</thead>
<tbody>
<tr>
<td><strong>C</strong></td>
<td><strong>C</strong></td>
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<tr>
<td><strong>C, P, CP</strong></td>
<td><strong>C, P, CP</strong></td>
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<tr>
<td>Strong, EM</td>
<td>Weak (loop-level)</td>
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<tr>
<td>Big SM “background” in any search for new forces</td>
<td>Small SM “background”. New sources of P, CP constrained by EDM searches</td>
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<table>
<thead>
<tr>
<th><strong>ε</strong></th>
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<td>Small SM “background”. New sources of P, CP less constrained by EDM searches</td>
<td>Big SM “background” in any search for new forces</td>
</tr>
<tr>
<td>New sources of PV also constrained by amplitude-sensitive PV asymmetry measurements</td>
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</tbody>
</table>
The charge conjugation operator $C$ reverses all generalized charges, effectively replacing a particle by its anti-particle.

$C$ violation is known only in

1. Weak interactions at tree level which violate $P$ (hence conserving $CP$)
2. Weak interactions at loop level which violate $CP$

Both $C$- and $CP$-violation are among the Sakharov criteria for baryogensis.

Everybody knows strong and EM forces conserve $C$ .... but direct bounds on $C$ violation in these amplitudes are only $\sim 0.5\%$. How to improve this?

It is surprisingly hard:

i. Only a few neutral particles are states of good $C$ and thus suitable for tests ($\gamma, \pi^0, \eta, J/\psi$, or a self-conjugate system like $e^+e^-$).

ii. Most of the particles of good $C$ appropriate for initial states aren't easy to make in large quantities (and with sufficiently low backgrounds).
η Decays Testing C Violation

Why η's?
• The η full width is only 1.3 keV. It cannot decay by the isospin conserving strong interaction. This means that achievable BR's of $10^{-6}$ to $10^{-7}$ probe the weak scale.
• η decays are flavor-conserving, a sector less thoroughly studied than $\Delta S = 1$, etc.
• Theory calculations predict large mass enhancements, hence relatively crude η decay BR upper limits place tighter constraints than more precise $\pi^0$ decay BR upper limits.
• The η has a significant s-sbar content, unlike the $\pi^0$ or nucleon.

<table>
<thead>
<tr>
<th>Final State</th>
<th>Branching Ratio (upper limit)</th>
<th>Gammas in Final State</th>
</tr>
</thead>
<tbody>
<tr>
<td>3γ</td>
<td>&lt; 1.6 $\cdot 10^{-5}$</td>
<td></td>
</tr>
<tr>
<td>“$\pi^0γ$”</td>
<td>&lt; 9 $\cdot 10^{-5}$</td>
<td>3</td>
</tr>
<tr>
<td>2$\pi^0γ$</td>
<td>&lt; 5 $\cdot 10^{-4}$</td>
<td></td>
</tr>
<tr>
<td>3γ$\pi^0$</td>
<td>Nothing published</td>
<td>5</td>
</tr>
<tr>
<td>3$\pi^0γ$</td>
<td>&lt; 6 $\cdot 10^{-5}$</td>
<td></td>
</tr>
<tr>
<td>3γ2$\pi^0$</td>
<td>Nothing published</td>
<td>7</td>
</tr>
</tbody>
</table>

Considerations of acceptance and phase space have focused us on $\eta \rightarrow 3\gamma$ and $\eta \rightarrow 2\pi^0\gamma$.

Most C test channels are **all-neutral** except for $\eta \rightarrow \pi^0\gamma^* \rightarrow \pi^0 l^+ l^-$. 

1/20/2014
Placing the tightest direct limits on C violation sounds interesting to experimentalists, but what about theorists?

• Little literature on C violation with P conservation.
  (appropriate models for this would be non-renormalizable - Herczeg)

• Some literature on T violation with P conservation
  (under CPT, equivalent to C violation with P conservation).

• By contrast, tremendous literature on CP violation and EDM’s.

• C violation without P violation is apparently not on the radar of those working with SUSY, leptoquarks.

• C violation does arise in discussions of violation of Lorentz invariance, but the predicted C violating $\eta$ decay BR’s are effectively zero for any experiment, ever.

We'd like theorists studying T violation with P conservation to know that $\eta$ decays can place tight limits in an isospin-violating sector.
some physics motivation
$O(p^6)$ in ChPTh
Allowed Rare Decay $\eta \rightarrow \pi^0 \gamma \gamma$

A measurement of $O(p^6)$ contribution in $\chi$PTh.

- Tree level amplitudes $O(p^2)$ and $O(p^4)$ vanish
- $O(p^4)$ kaon loops suppressed by large kaon mass
- $O(p^4)$ pion loops suppressed by $G$ parity

First sizable contribution at $O(p^6)$.

The two $O(p^6)$ constants are undetermined.

The BR and differential decay $d\Gamma/dm_{\gamma \gamma}^2$ can constrain these two constants (as well as the relative sign).

Provides theory with nature's only window on $O(p^6)$ to test their models.

In rare kaon decays, when first significant contribution is $O(p^4)$, BSM interpretation of precision $CP$ violation may require $O(p^6)$ calculations.
The Rare Decay $\eta \rightarrow \pi^0 2\gamma$ and SM Tests: $K_L$ sector

The golden search channel for new CP violating physics with flavor change is $K \rightarrow \pi \nu \bar{\nu}$ (90% short-distance physics). The easier to measure channels $K_L \rightarrow \pi^0 l^+l^-$ are also important (40% short-distance physics) but require correction for SM long-distance, CP conserving backgrounds.

$K_L \rightarrow \pi^0 2\gamma$ has been used to estimate the CP conserving $2\gamma$ contributions. Theoretical uncertainties in the predicted BR’s for $K_L \rightarrow \pi^0 l^+l^-$ are a factor of 2.

Sehgal in PRD 38 (1988) 808-813 showed how to relate

$$A_{2\gamma}(K_L \rightarrow \pi^0 e^+e^-) \rightarrow A_{2\gamma}(\eta \rightarrow \pi^0 e^+e^-) \rightarrow A_{2\gamma}(\eta \rightarrow \pi^0 2\gamma)$$

Precise $\eta \rightarrow \pi^0 2\gamma$ data may provide a cross-check on some contributions in $K_L \rightarrow \pi^0 l^+l^-$. 
Previous Measurements of $\eta \rightarrow \pi^0 2\gamma$

- Although $O(p^6)$, the BR is accessible near $2.7 \times 10^{-4}$
- Still, a long history of factor of $\sim 2$ discrepancies between experiments
- Backgrounds from $\eta \rightarrow 3\pi^0 \rightarrow 6\gamma$ have been fierce
Theory Talking Points for Doubly Radiative $\eta$ Decay

• Accessing the only window to check $O(p^6)$ models in ChPT sounds interesting.

• 25 years after the Sehgal publication, consistent $K_L \rightarrow \pi^0 2\gamma$ data exist. Would precise $\eta \rightarrow \pi^0 2\gamma$ data still help reduce uncertainties in the interpretation of $K_L \rightarrow \pi^0 2\gamma$?
short overview of issues with all-neutral $\eta$ decays
The Most Common \( \eta \) Decay Modes

<table>
<thead>
<tr>
<th>Final State</th>
<th>Branching Ratio (decreasing order)</th>
<th>Physics Interest</th>
</tr>
</thead>
<tbody>
<tr>
<td>2( \gamma )</td>
<td>0.39</td>
<td>( \eta, \eta', \pi^0 ) mixing</td>
</tr>
<tr>
<td>3( \pi^0 )</td>
<td>0.33</td>
<td>( m_u - m_d, \pi\pi ) scattering length</td>
</tr>
<tr>
<td>( \pi^+\pi^-\pi^0 )</td>
<td>0.23</td>
<td></td>
</tr>
<tr>
<td>( \pi^+\pi^-\gamma )</td>
<td>0.046</td>
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</table>

The light blue sliver represents BR = 0.7%. All other \( \eta \) rare decays would be invisible on this pie chart.

The 3\( \pi^0 \) reactions can be a big background for all-neutral decays \( \eta \rightarrow \) lotsa photons.
### Channels Obscured by $\eta \rightarrow 3\pi^0$

<table>
<thead>
<tr>
<th>Neutral Channels</th>
<th>Charged Channels</th>
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<tbody>
<tr>
<td>$\eta \rightarrow 2\gamma$ (39%)</td>
<td>$\eta \rightarrow \pi^+\pi^-\pi^0$ (23%)</td>
</tr>
<tr>
<td>$\eta \rightarrow 3\pi^0 \rightarrow 6\gamma$ (33%)</td>
<td>$\eta \rightarrow \pi^+\pi^-\gamma$ (5%)</td>
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<tr>
<td></td>
<td>$\eta \rightarrow \gamma l^+l^-$</td>
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<tr>
<td></td>
<td>$\eta \rightarrow \pi^+\pi^-\gamma$</td>
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<tr>
<td>(obscured by loss or merging of photons from $\eta \rightarrow 3\pi^0$)</td>
<td></td>
</tr>
<tr>
<td>$\eta \rightarrow \pi^02\gamma$</td>
<td>$\eta \rightarrow \pi^02\gamma2\gamma$</td>
</tr>
<tr>
<td>$\eta \rightarrow 2\pi^02\gamma$</td>
<td>$\eta \rightarrow 2\pi^02\gamma$2\gamma</td>
</tr>
<tr>
<td>(C: $\eta \rightarrow 2\pi^0\gamma, 3\gamma$)</td>
<td>(CP: $\eta \rightarrow 2\pi^0$)</td>
</tr>
</tbody>
</table>

Backgrounds from the splitting of photons from $\eta \rightarrow 2\gamma$
(e.g., in an: $\eta \rightarrow 3\gamma$ search)
are probably easily removed.
Figure of Merit for Anomalous Decays

Understanding the appropriate figure of merit is critical.

Since the background fluctuations are \( \approx \sqrt{N} \), a useful estimate for the branching ratio upper limit at 90% CL is

\[
BR \approx 2 \sqrt{\frac{N_{bkg}}{N_{\eta} \epsilon}} = 2 \sqrt{\frac{f_{bkg} N_{\eta} \epsilon}{N_{\eta} \epsilon}} = 2 \sqrt{f_{bkg}}
\]

\( N_{\eta} \) = number of \( \eta \)'s produced
\( \epsilon \) = efficiency for detecting \( \eta \) decay products (includes acceptance, cuts, etc)
\( f_{bkg} \) = background fraction normalized to \( N_{\eta} \epsilon \)

The smaller the BR upper limit, the better. The FOM is therefore \( \frac{N_{\eta} \epsilon}{f_{bkg}} \).

Lessons Learned:

• Rare decays with non-negligible backgrounds are a very tough game.
  (One must increase the FOM 100x to reduce the BR by 10x.)
• Experiments often highlight \( N_{\eta} \) but \( N_{\eta} \epsilon \) is more relevant.
• It is as important to decrease \( f_{bkg} \) as it is to increase \( N_{\eta} \epsilon \).
1. Produce a competitive $N_{\eta} \varepsilon$ of $O(10^7)$ in one year.

Note European facilities like KLOE and WASA@COSY have already acquired $\eta$ decay data-sets at that level. KLOE-II will extend this!

We cannot do better on most charged channels.

2. For all-neutral channels which have historically suffered enormous backgrounds from $\eta \rightarrow 3\pi^0 \rightarrow 6\gamma$, we can lower these backgrounds up to 2 orders of magnitude by

i. Fine grained, high resolution calorimeter of PbWO$_4$

ii. Beam of boosted, exclusively produced $\eta$'s

(Our biggest improvement in FOM comes from reducing background.)

Under these circumstances, the JLab Eta Factory in a 1 year run could lower existing BR upper limits for many rare $\eta$ decays to all-neutral final states by 1-1.5 orders of magnitude.
apparatus and bkg reduction
Proposed Experiment in Hall D

**η** produced on LH$_2$ target with **9-11.7 GeV tagged photon beam**:

$\gamma + p \rightarrow \eta + p$

- Reduce non-coplanar backgrounds by detecting recoil p's with GlueX detector

- Upgraded Forward Calorimeter with **High resolution, high granularity** PbWO$_4$ (FCAL-II) to detect multi-photons from the $\eta$ decays
New Equipment: FCAL-II

118x118 cm² in Size (3445 PWO crystal modules) with a 12x12 cm² central hole.

Similar as the inner part PrimEx HyCal with a minor modification for magnetic shielding.

Using the same techniques as the current FCAL-I for magnetic shielding: Annealed iron, 0.5 mm μ-metal, and ~2 cm long light guide.

Energy and position resolutions are factor of two better than current FCAL-I, with one order of magnitude improvement in radiation-resistance.

Estimated total cost is ~$3-4 M.
Why Boosted Etas Reduces Bkg from Missing Photons

Quick explanation:

Average energy of photons in $\eta \rightarrow 3\pi^0 \rightarrow 6\gamma$ when $\eta$ produced at rest: $\sim 90$ MeV.

When produced by a 10 GeV photon: $\sim 1650$ MeV.

In the first case, it's much more likely to lose a photon below a 10-20 MeV threshold.
Filter Background with $\eta$ Energy Boost

Jlab: high energy $\eta$ production
($E_\gamma = 9\text{-}11.9 \text{ GeV}$)

Example: low energy $\eta$ production

Signal: $\eta \rightarrow \pi^0 \gamma \gamma$

Note:
- Statistics is normalized to 1 beam day.
- BG will be further reduced by requiring only one pair of $\gamma$'s to have the $\pi^0$ invariant mass.

Projected JEF Measurement on $\eta \rightarrow \pi^0 2\gamma$
Jlab’s Projected Sensitivity for $\eta \rightarrow 3\gamma$

This is a graphical presentation of the relationship between the BR upper limit and two key experimental parameter: $N_{\eta\varepsilon}$ and $f_{bkg}$. It allows us to compare experiments and understand how to do better.

Main reason for improvement will be $bkg$ reduction.

Our $3\gamma$ bkg estimates were hand-wavy though. Should be improved for next year.

Ref: JEF proposal 2012
Other facilities have an equal or larger number of η’s.

In the JEF proposal, our focus was all-neutral final states which have large backgrounds due to the quirk of nature that $\eta \rightarrow 3\pi^0 \rightarrow 6\gamma$.

JEF calorimetry may also be useful for decays containing $e^+$, in that it should provide good $\pi/e$ discrimination via the measurement of $E_{\text{cal}}/P_{\text{tracking}}$.

Muon channels are a possibility since the pion polarizability collaboration is planning to build a muon filter. (e.g., $\eta \rightarrow \pi^0 \mu^+ \mu^-$ is potentially interesting in a light, CP odd Higgs search.)
Potential JEF Charged BR Measurements

\[ \eta \rightarrow \pi^0 e^+ e^- : \text{ For this C violating channel, JEF might be able to improve on the existing BR upper limit by one order of magnitude. One would like to understand the complementarity of this channel with other, all neutral C-violaters like } \eta \rightarrow 2\pi^0 \gamma \text{ and } \eta \rightarrow 3\gamma. \]

\[ \eta \rightarrow e^+ e^- : \text{ The di-electron decay is helicity-suppressed, and this may be the best way to constrain the } PS(e) \text{ and } PS(e) \times PS(e) \text{ couplings. But HADES dropped the upper limit by a factor of 6 in a 2012 publication (details are vague), and a WASA conference proceeding indicated they will publish something similar. The low-hanging fruit has been picked.} \]

Other channels for which new calorimeter might be helpful:

- \[ \eta \rightarrow \pi^+ \pi^- \pi^0 \gamma \text{ (box anomaly?)} \]
- \[ \eta \rightarrow \gamma \gamma^* \text{ (hadronic corrections to } g-2?) \]
- \[ \eta \rightarrow \pi^+ \pi^- \nu \text{ (test of } 2^{\text{nd}} \text{ class currents - there are no published limits with } \eta \text{'s!)} \]
- \[ K_s \rightarrow 2\gamma \text{ which has large bkg from } K_s \rightarrow 2\pi^0 \text{ (kaon ff's needed for BSM studies)} \]
Summary

• The $\eta$ meson provides a unique laboratory to search for new sources of C and CP violation.

• $\eta$ rare decays to all-neutral final states suffer from a unique large background from $\eta \rightarrow 3\pi^0 \rightarrow 6\gamma$ which *never been adequately addressed*. A new Lead Tungstate calorimeter, the $\sim 10$ GeV tagged photon beam in Hall D, along with recoil proton detection, would dramatically reduce background.

Symmetries tests

Charge conjugation violation: $\eta \rightarrow 3\gamma, 2\pi^0\gamma, (\pi^0\gamma^*)$

ChPTh

Measurement of $O(p^6)$ terms in ChPTh: $\eta \rightarrow \pi^0 2\gamma$

Other channels for which new calorimeter might be helpful:

We have a few ideas, but suggestions are welcome.

We plan to hold a workshop with theorists in Spring 2014
Collaboration

(\textit{GlueX Collaboration and Other Participants, 33 institutes})

Extras
Charged Channels Summary

I have reviewed JEF prospects for $\eta$ decays to charged final states.

Trade-offs between BR’s and asymmetries were discussed. They both potentially contain important information, but which is superior depends on the details of backgrounds, branching ratios, and relative phases.

Several interesting decay branches for which 1) we could make major improvements, 2) which would help motivate FCAL-II, but 3) which are probably not fashionable, are:

- BR in $\eta \rightarrow \pi^0 e^+ e^-$ ($\mathcal{C}$ observable)
- Asymmetry in $\eta \rightarrow \pi^+ \pi^- \gamma$ ($\mathcal{C}$ observable): (KLOE could eat our lunch though)
- BR in $\eta \rightarrow \pi^+ e^- \nu_x$ or $\rightarrow \pi^- \pi^0 e^- \nu_x$ (constrains scalar or especially 2$^{nd}$ class currents): no published BR upper limits!

Several interesting branches where 1) we could possibly make major improvements, but 2) which do not need FCAL-II, and 3) which require more muon ID than the base JEF proposal are:

- $\eta \rightarrow \pi^0 \mu^+ \mu^-$: ($\mathcal{C}$ observable, but also constrains light CP-odd Higgs so PAC might like)
- $\eta \rightarrow \pi^+ \mu^+ \nu_x$ or $\rightarrow \pi^- \pi^0 \mu^+ \nu_x$ (similar to above reactions with $l = e$): no published BR upper limits!
Even More Discussion of Potential JEF Branching Ratio Measurements

Speaking of decays *requiring additional muon ID*:

Maybe a comparison of

\[ \eta \rightarrow \gamma + e^+e^- \]

with

\[ \eta \rightarrow \gamma + \mu^+\mu^- \]

to constrain new lepton universality-violating isoscalar forces to which the two \( \pi \rightarrow l\nu \) reactions are not sensitive???

This could be done at about the 1% level in the total BR. The errors on the form factor would be larger, but family-dependence might be larger in some parts of the phase space.

Note that if the proton radius discrepancy does not go away, there will be increasing interest in comparing e-q and e-\( \mu \) interactions.
More Discussion of Potential JEF Branching Ratio Measurements

$\eta \rightarrow \pi^+ e^+ \nu_x$, $\eta \rightarrow \pi^- \pi^0 e^+ \nu_x$ (inclusive limit on charged current decays): Due to the violation of $G$ parity, $\eta$ decays may be the cleanest way to constrain 2nd class currents. In other approaches, the 2nd class currents are buried in a big SM background. Also provides a constraint on scalar currents though seemingly not competitive with $\beta$ decay. There are no published limits, and the photon conversion bkg isn’t as important as you might think. The main bkg is probably from misidentifying a $\pi^-$ for an $e^-$, so HCAL-II will help. Due to the undetected neutrino, wide missing energy and invariant mass cuts have to be used. But even a BR upper limit of 1E-3 would be great.

Decays requiring additional muon ID:

$\eta \rightarrow \pi^0 \mu^+ \mu^-$: $C$ violating branch that could perhaps be improved a factor of several. This is also a (non $C$ violating?) search channel for a light CP-odd Higgs. Because the Higgs couples to mass, the muon channel is much more sensitive than the electron channel. It’s possible the b factories haven’t closed all the phase space at our low energies.

$\eta \rightarrow \mu e$: Lepton flavor violating branch that could perhaps be improved a factor of several.

$\eta \rightarrow \mu^+ \mu^-$: This branch was already seen decades ago, so further improvements in $PS(q) \times PS(\mu)$ constraints require careful theoretical analysis of the SM background.

$\eta \rightarrow \pi^+ \mu^+ \nu_x$, $\eta \rightarrow \pi^- \pi^0 \mu^+ \nu_x$ (inclusive limit on charged current decays): Same comments apply as for the case with electrons in the final state.
### Potential JEF Branching Ratio Measurements

<table>
<thead>
<tr>
<th>Channel</th>
<th>Physics Interest</th>
<th>SM Background</th>
<th>Status</th>
<th>JEF Outlook</th>
</tr>
</thead>
<tbody>
<tr>
<td>Symmetry Violation</td>
<td>( \eta \rightarrow \pi^+\pi^- )</td>
<td>( G ) of variety ((C, P))</td>
<td>( \sim 0 )</td>
<td>BR &lt; 1.3( \times 10^{-5} ) Probably can't beat KLOE.</td>
</tr>
<tr>
<td></td>
<td>( \eta \rightarrow \pi^0\eta^\prime )</td>
<td>( \epsilon )</td>
<td>10-9???</td>
<td>( \eta \rightarrow \pi^0e^+e^- ) BR &lt; 4( \times 10^{-5} ) FCAL-II helps with ( \pi^\pm \pi^0 ) bkg. need muon ID</td>
</tr>
<tr>
<td></td>
<td>( \eta \rightarrow \mu e )</td>
<td>LF</td>
<td>( \sim 0 )</td>
<td>BR &lt; 6( \times 10^{-6} ) FCAL-II helps for ( e ) but need muon ID.</td>
</tr>
<tr>
<td></td>
<td>( \eta \rightarrow \pi^+\pi^-e^+\nu ) ( \eta \rightarrow \pi^+\pi^0e^+\nu )</td>
<td>constraints on scalar or 2(^{nd} ) class currents</td>
<td>( \eta \rightarrow \pi^0m^+m^- ) BR &lt; 5( \times 10^{-6} )</td>
<td>FCAL-II is essential for ( e ) vs ( \pi ) discrimination. Need muon ID</td>
</tr>
<tr>
<td>Rare Processes</td>
<td>( \eta \rightarrow e^+e^- )</td>
<td>new particles with pseudo-scalar couplings to quarks and electrons</td>
<td>( \eta \rightarrow 2\gamma \rightarrow e^+e^- ) (helicity suppressed) 10-9???</td>
<td>BR &lt; 2.7( \times 10^{-5} ) FCAL-II helps with invariant mass discrimination against photon conversion bkg. Need muon ID, and theory for SM bkg</td>
</tr>
</tbody>
</table>
Determination of $O(p^6)$ Low Energy Constants

The total amplitude for the decay $\eta(P) \to \pi^0(p) + \gamma(q_1) + \gamma(q_1)$ is

$$M = \sum_{i=2,6,2} (a_i^{\text{tree}} + a_i^{\pi} + a_i^k) A(\varepsilon_1, q_1, \varepsilon_2, q_2) + \sum_{i=2,6,2} (b_i^{\text{tree}} + b_i^{\pi} + b_i^k) B(\varepsilon_1, q_1, \varepsilon_2, q_2)$$

where $A, B$ are two kinematically different amplitudes, and the $a, b$ are the coefficients for tree level, $\pi$ loops, and $k$ loops contributions.

Expanding as $O(p^2) + O(p^4) + O(p^6)$ ... many terms vanish or are very small:

$$M = (a_4^{\pi} + a_4^k)A + a_6^{\text{tree}} A + b_6^{\text{tree}} B + \text{suppressed } O(p^6) \text{ loops} + \text{HOT}$$

The dominant coefficients $a_6^{\text{tree}}$ and $b_6^{\text{tree}}$ depend on two low energy constants $d_1, d_2$:

$$a_6^{\text{tree}} = \frac{4\sqrt{2}}{3\sqrt{3}f^2} [4m_\eta^2d_1 - (4d_1 + d_2) P \cdot (q_1 + q_2)] \\
 b_6^{\text{tree}} = \frac{8\sqrt{2}}{3\sqrt{3}f^2} d_2$$

Hence a precise $\eta \to \pi^0 2\gamma$ measurement provides a unique window into $O(p^6)$ of XPT, determining the low energy constants $d_1, d_2$ model independently.
The Rare Decay $\eta \rightarrow \pi^0 2\gamma$ and SM Tests: $\eta$ sector

The rare decay $\eta \rightarrow \pi^0 2\gamma$ (BR~3x10^{-4}) is a “doorway” to decays of the type $\eta \rightarrow \pi^0 + \gamma$'s or $e^+e^-'$'s or $\mu^+\mu^-$'s. For example,

$$\eta \rightarrow \pi^0 l^+ l^-$$

is the SM background to the potential $C$- and $CP$-violating single virtual photon process suggested by Bernstein, Feinberg, and Lee PR 139 B1650 (1965) →

$\text{BR} \sim 10^{-9} \text{ (theory)}$


So the observation of $\eta \rightarrow \pi^0 l^+ l^-$ with a significantly larger BR than $10^{-9}$ would imply a new source of $C$- and $CP$-violation. Current limits are:

$$\text{BR}(\eta \rightarrow \pi^0 e^+e^-) < 4 \times 10^{-5} \quad \text{BR}(\eta \rightarrow \pi^0 \mu^+\mu^-) < 5 \times 10^{-6}$$

As these limits are reduced, one would like to reduce the factor of $\sim 3$ uncertainty in the SM background which requires improved $\eta \rightarrow \pi^0 2\gamma$ data.

(See Pawal Moskal, doctoral dissertation, http://arxiv.org/abs/1301.0098, for recent WASA at COSY $\eta \rightarrow \pi^0 e^+e^-$.)

1/20/2014
Event Selection

- Elasticity is $E_{\text{L}} = \frac{\sum E_\gamma}{E_{\text{tagged-\gamma}}}$
- Energy conservation for $\gamma + p \rightarrow \eta + p$ reaction:
  $\Delta E = E(\eta) + E(p) - E(\text{beam}) - M(p)$
- Co-planarity $\Delta \phi = \phi(\eta) - \phi(p)$

Note:
- Statistics is normalized to 1 beam day.
- BG will be further reduced by requiring that only one pair of $\gamma$'s have the $\pi^0$ invariant mass.
Detection of Recoil Proton with GlueX
(needed for cut establishing $\eta$-proton coplanarity)

Recoil proton kinematics

- Polar angle $\sim 55^\circ-80^\circ$
- Momentum $\sim 200$-$1200$ MeV/c
### C-violating η Decays to π's and γ's

**Gamma Column implicitly includes γ*→e^+e^-**

<table>
<thead>
<tr>
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<th>η→X</th>
<th>0π</th>
<th>1π</th>
<th>2π</th>
<th>3π</th>
<th>4π</th>
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<tbody>
<tr>
<td>L = 0</td>
<td>0γ</td>
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<td></td>
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<td>☹</td>
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<tr>
<td>L = 1</td>
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<td>2γ</td>
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<td>3γ</td>
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<td></td>
<td>4γ</td>
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</tr>
</tbody>
</table>

**Key:**

- ☹: C and P allowed, observed
- ☹: C and P allowed, upper limits only
- ☹, CP: C violating, CP conserving, etc.
- ☹: Forbidden by energy and momentum conservation.

**Most of the explicitly C violating channels could be CP-violating or -conserving. If observed, one would have to extract L from the angular distribution to determine whether P is conserved or not.**
I survey physics opportunities in the charged η decay channels, and examine the trade-offs between the measurement of BR’s (or decay widths) vs asymmetries. No large improvements in asymmetry measurements can be made, so we will continue to concentrate on BR’s. As expected, the base JEF design is not competitive for charged channels that have low backgrounds, however HCAL-II should make it competitive for high background channels containing e⁺e⁻. One interesting channel to complement our C violation search program is $\eta \rightarrow \pi^0 e^+ e^-$. In addition, the difficult reactions $\eta \rightarrow \pi^+ e^+ \nu_x$ or $\eta \rightarrow \pi^0 \pi^+ e^+ \nu_x$, for which there are no published limits, might provide the tightest constraints on 2nd class currents. With muon ID, these studies could be greatly extended. In particular, the larger lepton mass enables the reaction $\eta \rightarrow \pi^0 \mu^+ \mu^-$ to constrain the existence of a CP-odd light Higgs.
Why Are η Meson Decays Unique and Interesting?

• The most massive member of the pseudoscalar meson octet (547.9 MeV/c^2)

• Significant strange quark content (but no net strangeness)

\[(u^* u \bar{u} + d^* d \bar{d} - s^* s \bar{s})/\sqrt{3}\]

• Since the η, π^0, and γ are states of good C, decays of the η to all-neutral final states permit interesting C and CP tests.

Given the mass of the η, one would naively expect it to quickly decay to multiple pions and have a decay width \(O(100)\) MeV. But due to inhibitions by chiral symmetry and selection rules, the η decay width is only \(\Gamma_\eta = 1.3\) KeV. (The \(\rho\) meson width by contrast is \(\Gamma_\rho = 149\) MeV.)

Because the isospin conserving strong interaction does not participate in η decays, potential exotic phenomena in the isospin violating strong interaction could be enhanced by 5 orders of magnitude in an η decay compared to a ρ decay for example.

η decays provide a unique, flavor-conserving laboratory to search for new sources of C, P, and CP violation between the strong and weak scales.
# Interesting All-Neutral Final States

<table>
<thead>
<tr>
<th>Mode</th>
<th>Branching Ratio (PDG)</th>
<th>Physics Highlight</th>
<th>Role in Proposal</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\pi^0 2\gamma$</td>
<td>$(2.7 \pm 0.5) \times 10^{-4}$</td>
<td>$\chi_{\text{PTh}}, O(p^6)$</td>
<td>priority</td>
</tr>
<tr>
<td>$2\pi^0$</td>
<td>$&lt;3.5 \times 10^{-4}$</td>
<td>CP, P</td>
<td>priority</td>
</tr>
<tr>
<td>$3\gamma$</td>
<td>$&lt;1.6 \times 10^{-5}$</td>
<td>C</td>
<td>priority</td>
</tr>
<tr>
<td>$\pi^0 \gamma$</td>
<td>$&lt;9 \times 10^{-5}$</td>
<td>C, L, gauge inv.</td>
<td>(control)</td>
</tr>
<tr>
<td>$4\gamma$</td>
<td>$&lt;2.8 \times 10^{-4}$</td>
<td>Suppressed ($&lt;10^{-11}$)</td>
<td>ancillary</td>
</tr>
<tr>
<td>$\pi^0 \pi^0 \gamma$</td>
<td>$&lt;5 \times 10^{-4}$</td>
<td>C</td>
<td>ancillary</td>
</tr>
<tr>
<td>$\pi^0 \pi^0 \pi^0$</td>
<td>$&lt;6 \times 10^{-5}$</td>
<td>C</td>
<td>ancillary</td>
</tr>
<tr>
<td>$4\pi^0$</td>
<td>$&lt;6.9 \times 10^{-7}$</td>
<td>CP, P</td>
<td>ancillary</td>
</tr>
</tbody>
</table>
Selection Rules for $\eta \rightarrow M\gamma$

$\eta$: $I^G (J^{PC}) = 0^+ (0^{--})$
$\gamma$: $I (J^{PC}) = 0, 1 (1^{--})$

$M_\eta = 547.9$ MeV/$c^2$
$M_\gamma = 0$ MeV/$c^2$

What is observed? The $\eta$ decays into $2\gamma$ about 39% of time due to the electromagnetic interaction.

$C$ parity conservation blocks the EM decays into $3\gamma$.

Implicitly includes $\gamma^* \rightarrow e^+ e^-$ by internal conversion.
Selection Rules for $\eta \to N\pi$

$\eta$: $I^G(J^{PC}) = 0^+ (0^{-+})$
$\pi^0$: $I^G(J^{PC}) = 1^- (0^{-+})$

$M_\eta = 547.9$ MeV/c$^2$
$M_{\pi^0} = 135.0$ MeV/c$^2$

Momentum/Energy
Only $N = 2,3,4$ allowed

$G$ parity
$G_\eta = G_{N\pi}$
$+1 = (-1)^N$

hence $N = 2,4$. Possible decays are $\eta \to 2\pi$, $4\pi$

Parity:
$P_\eta = P_{N\pi}$
$-1 = (-1)^N (-1)^L$

$(J = 0$ in initial and final states demands $L=0$)

hence $N = 3$. Possible decay is $\eta \to 3\pi$

$C$ parity:
$C_\eta = C_{N\pi}$
$+1 = (+1)^N$
No constraints from $C$ parity

What is observed? The $\eta$ decays into $3\pi$ about 56% of the time due to isospin violating strong interactions. Parity conservation blocks the otherwise $G$ parity-allowed strong decay to $2\pi^0$.

The hypothetical $P$ violating decay $\eta \to 2\pi^0$ would imply $CP$ violation since $C$ is conserved.
Selection Rules for $\eta \to N\pi + M\gamma$
(for $N,M \geq 1$ not covered in previous slides)

$\eta$: $I^G(J^{PC}) = 0^+(0^+)$
$\pi^0$: $I^G(J^{PC}) = 1^-(0^+)$
$\gamma$: $I(J^{PC}) = 0,1(1^-)$

$M_\eta = 547.9$ MeV/$c^2$
$M_{\pi 0} = 135.0$ MeV/$c^2$
$M_\gamma = 0$ MeV/$c^2$

Momentum/Energy
$N = 1,2,3,4; M = 1,\ldots,\infty; N+M \geq 2$ allowed

$G$ parity
not meaningful with photons

Parity:
$P_\eta = P_{N\pi + M\gamma}$
$-1 = (-1)^N(-1)^M(-1)^L$

(The final state can usually select a value of $L$ that conserves parity.
The case of a single $\gamma$ is unique since only $L=1$ is allowed.)
No constraints from parity.

$C$ parity:
$C_\eta = C_{N\pi + M\gamma}$
$+1 = (+1)^N(-1)^M$ (note: only the number of photons matters)
hence $M = \text{even}$. Possible decays are $\eta \to N\pi^0\gamma, N\pi^04\gamma$, etc.

What is observed? The $\eta$ decays to $\pi^0\gamma$ about 0.03% of the time. $C$ parity blocks the otherwise parity-allowed decays like $\pi^0\gamma, \pi^03\gamma$, etc.

Note that the $\eta$ decays to $\pi^+\pi^-\gamma$ with a 4.6% branching ratio. $C$ is evaded by $\pi^+$!
Unobserved C Violating $\eta$ Decay Modes

<table>
<thead>
<tr>
<th>Final State</th>
<th>Branching Ratio (upper limit)</th>
<th>Gammas in Final State</th>
</tr>
</thead>
<tbody>
<tr>
<td>$3 \gamma$</td>
<td>$&lt; 2 \cdot 10^{-5}$</td>
<td>3</td>
</tr>
<tr>
<td>&quot;$\pi^0\gamma$&quot;</td>
<td>$&lt; 9 \cdot 10^{-5}$</td>
<td>3</td>
</tr>
<tr>
<td>$\pi^0 e^+ e^-$</td>
<td>$&lt; 4 \cdot 10^{-5}$</td>
<td>$2 +e^+ e^-$</td>
</tr>
<tr>
<td>$\pi^0 \mu^+ \mu^-$</td>
<td>$&lt; 5 \cdot 10^{-6}$</td>
<td>$2 +\mu^+ \mu^-$</td>
</tr>
<tr>
<td>$2 \pi^0 \gamma$</td>
<td>$&lt; 5 \cdot 10^{-4}$</td>
<td>5</td>
</tr>
<tr>
<td>$3 \pi^0 \gamma$</td>
<td>$&lt; 6 \cdot 10^{-5}$</td>
<td>7</td>
</tr>
</tbody>
</table>

We will examine all these channels, but considerations of acceptance, phase space, backgrounds, and powers of alpha suggest the most interesting channels are $\eta \rightarrow 3 \gamma$ and $\eta \rightarrow 2 \pi^0 \gamma$. 

PDG 2011
# FCAL-II Projected Cost (118x118cm²)

<table>
<thead>
<tr>
<th>Item</th>
<th>Channels</th>
<th>Cost/Channel</th>
<th>Cost</th>
</tr>
</thead>
<tbody>
<tr>
<td>Crystal</td>
<td>3445</td>
<td>$250</td>
<td>$0.86M</td>
</tr>
<tr>
<td>PMT/base</td>
<td>3445</td>
<td>$400</td>
<td>$1.38M</td>
</tr>
<tr>
<td>Flash ADC</td>
<td>3445</td>
<td>$378</td>
<td>$1.30M</td>
</tr>
<tr>
<td>HV</td>
<td>3445</td>
<td>$300</td>
<td>$1.03M</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td></td>
<td></td>
<td><strong>$4.57M</strong></td>
</tr>
</tbody>
</table>

Possible cost offsets from loans:

<table>
<thead>
<tr>
<th>Item</th>
<th>Channels</th>
<th>Cost/Channel</th>
<th>Cost</th>
</tr>
</thead>
<tbody>
<tr>
<td>PrimEx</td>
<td>1200</td>
<td>$650</td>
<td>$-0.78M</td>
</tr>
<tr>
<td>(xtal+pmt/base)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>FCAL-I</td>
<td>2800</td>
<td>$378</td>
<td>$-1.06M</td>
</tr>
<tr>
<td>(Flash ADC)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Revised Total</strong></td>
<td></td>
<td></td>
<td><strong>$2.73M-$4.57M</strong></td>
</tr>
</tbody>
</table>

For the 118x118 cm² FCAL-II, the total cost is $2.7M to $4.6M.

This is within the $4M range of an NSF MRI assuming a small equipment loan or foreign funds or Physics Division support for ADCs or HV.
Discussion of Potential JEF Asymmetry Measurements

It's clearer now why asymmetries have been measured mainly for $\eta \rightarrow \pi^+\pi^-\pi^0$ and $\eta \rightarrow \pi^+\pi^-\gamma$, though surprisingly an asymmetry measurement for $\eta \rightarrow \pi^+\pi^-e^+e^-$ exists.

Basically:
1. In many channels, an asymmetry simply cannot be defined due to a combination in the final state of: too-few particles, identical particles, pions (no spin), or real photons (no longitudinal polarization).
2. The BR's for these two channels are not too small.

Note the all-neutral final states for which JEF is optimized simply don’t appear to have definable asymmetries (e.g.: $\gamma\gamma$, $3\pi^0$, or $\pi^02\gamma$).

For $\eta \rightarrow \pi^+\pi^-\pi^0$, we cannot improve much on the KLOE result.

For $\eta \rightarrow \pi^+\pi^-\gamma$, we could significantly improve the published result. However, I would worry that KLOE already has competitive data in their silo and could scoop us simply by assigning a student to the analysis. Presumably, $\eta \rightarrow \pi^+\pi^-\pi^0$ asymmetries provide tighter constraints on C violation in the strong amplitude, while $\eta \rightarrow \pi^+\pi^-\gamma$ provides tighter constraints on C violation in the EM amplitude.

For $\eta \rightarrow \pi^+\pi^-e^+e^-$ we get the virtual photon transverse polarization for free. This can be used to define a CP asymmetry, but we cannot improve much on the KLOE result.
## Potential JEF Asymmetry Measurements

<table>
<thead>
<tr>
<th>$\eta \rightarrow ?$</th>
<th>BR</th>
<th>Can an Asymmetry be Defined?</th>
<th>Closely Related To</th>
<th>PDG Limits</th>
<th>JEF Uncertainty $\Delta M_{\text{new}}/\Delta M_{\text{sm}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\gamma\gamma$</td>
<td>39.3%</td>
<td>No</td>
<td></td>
<td>---</td>
<td></td>
</tr>
<tr>
<td>$3\pi^0$</td>
<td>32.6%</td>
<td>No</td>
<td></td>
<td>---</td>
<td></td>
</tr>
<tr>
<td>$\pi^+\pi^-\pi^0$</td>
<td>22.7%</td>
<td>Charge (several)</td>
<td>$\eta \rightarrow 2\pi^0\gamma$</td>
<td>$\sim 0.1%$ (KLOE)</td>
<td>$\sim 0.07%$</td>
</tr>
<tr>
<td>$\pi^+\pi^-\gamma$</td>
<td>4.60%</td>
<td>Charge</td>
<td></td>
<td>$\sim 0.6%$</td>
<td>$0.15%$</td>
</tr>
<tr>
<td>$e^+e^-\gamma$</td>
<td>0.69%</td>
<td>$P_{\text{long}}$?</td>
<td></td>
<td>Not measured</td>
<td></td>
</tr>
<tr>
<td>$\mu^+\mu^-\gamma$</td>
<td>$3.1 \times 10^{-4}$</td>
<td>$P_{\text{long}}$?</td>
<td></td>
<td>Not measured</td>
<td></td>
</tr>
<tr>
<td>$\pi^+\pi^-e^+e^-$</td>
<td>$2.7 \times 10^{-4}$</td>
<td>$CP$</td>
<td>$\eta \rightarrow 2\pi^0\gamma$</td>
<td>2.5% (KLOE)</td>
<td>$\sim 1.9%$</td>
</tr>
<tr>
<td>$\pi^02\gamma$</td>
<td>$2.7 \times 10^{-4}$</td>
<td>No</td>
<td></td>
<td>---</td>
<td></td>
</tr>
<tr>
<td>$\mu^+\mu^-$</td>
<td>$5.8 \times 10^{-6}$</td>
<td>$P_{\text{long}}$</td>
<td>$K_L \rightarrow \mu^+\mu^-$ (theory interest, but impossible)</td>
<td>Not measured</td>
<td></td>
</tr>
</tbody>
</table>
C Violation in the SM: Theory

Some calculations exist for the $C$ violating decay $\pi^0 \to 3\gamma$ which we will cautiously use as an analog of $\eta \to 3\gamma$.

A weak interaction model of $C$ violation in $\pi^0 \to 3\gamma$ by Dicus (1975) assuming CP conservation (hence $P$ violation) found the highly suppressed value

$$\text{BR}(\pi^0 \to 3\gamma)/\text{BR}(\pi^0 \to 2\gamma) = 10^{-31\pm 6}$$

The form of the amplitude is highly constrained by both Bose statistics and the requirement for parity violation. Equation 17 in that paper suggests the corresponding $\eta$ decay would be larger by $(m_\eta/m_\pi)^{12}$

$$\text{BR}(\eta \to 3\gamma)/\text{BR}(\eta \to 2\gamma) \sim 10^{-24}$$

Although an enormous enhancement is expected due to the larger mass of the $\eta$, the SM background remains negligible.
Are we doing the right thing by pursuing BR (i.e., Yield) measurements? I.e., aren't asymmetries the smart way to determine small, new physics effects? In general,

\[ M \equiv M_{SM} + M_{NEW} \]

\[ M^2 = M_{SM}^2 + 2 \text{Re} M_{SM}^* M_{NEW} + M_{NEW}^2 \]

There are two interesting cases:

1. For a highly forbidden SM process, the upper limit on the decay width for channel I is interpreted as constraining

\[ \Gamma_i \propto M_{NEW}^2 \]

Expressing this as a BR by normalizing to \( \Gamma(\eta \to \text{all}) \) this becomes

\[ \text{BR}_i \propto \frac{M_{NEW}^2 (i)}{M_{SM}^2 (\text{all})} \]

Hence a new physics amplitude of 0.1% of the SM would produce a BR \( \sim 1 \times 10^{-6} \).

2. For an allowed SM process (which may contain new physics effects in the form of interferences) we can in principle first bin the data in theta, polarization, charge, etc., then form an asymmetry

\[ A \equiv \frac{Y(\theta > 90^\circ) - Y(\theta < 90^\circ)}{Y(\theta > 90^\circ) + Y(\theta < 90^\circ)} = \frac{2 \text{Re} M_{SM}^* M_{NEW}}{M_{SM}^2} \propto \frac{M_{NEW}}{M_{SM}} \]

Loosely speaking, a new physics amplitude of 0.1% of the SM produces an asymmetry of up to 0.1%.
Simplified Error Analysis of BR vs Asymmetry

The uncertainty of a BR measurement for decay channel \( i \) in the no-signal limit is

\[
\Delta BR_i \approx \frac{\sqrt{N_{BKG}}}{N_\eta \varepsilon_i}
\]

where \( N_\eta \) is the number of \( \eta \)'s produced, \( \varepsilon_i \) is the acceptance for decay channel \( i \), and \( N_{BKG} \) is the number of background events. Using typical JEF values for a 100 day run (\( N_\eta = 3 \times 10^7 \), \( \varepsilon \sim 0.25 \)),

\[
\Delta BR_i \approx 1.33 \times 10^{-7} \sqrt{N_{BKG}}
\]

For an asymmetry measured in the allowed decay branch \( i \), the uncertainty is

\[
\Delta A_i \geq \frac{1}{\sqrt{N_\eta BR_i \varepsilon_i \text{PhaseFactor}}} \frac{1}{\text{PhaseFactor}} = 3.65 \times 10^{-4} \frac{1}{\sqrt{BR_i \text{PhaseFactor}}}
\]

Note it goes like \( 1/N_\eta \).

(Also, the BR technique loses FOM if bkg is high.)

Note it goes like \( 1/\sqrt{N_\eta} \).

(Also, the asymmetry technique loses FOM if \( BR_i \) is small. Furthermore, the asymmetry technique may have no FOM at all if the PhaseFactor is unlucky.)
### Uncertainties Summary: BR vs Asymmetry

<table>
<thead>
<tr>
<th>Observable</th>
<th>Uncertainty $dM_{\text{NEW}}/dM_{\text{SM}}$ for JEF Proposal</th>
</tr>
</thead>
<tbody>
<tr>
<td>BR</td>
<td>$= \frac{(N_{\text{BKG}})^{1/4}}{\sqrt{N_{\eta} \varepsilon_i}} \approx 3.65 \times 10^{-4} (N_{\text{BKG}})^{1/4}$</td>
</tr>
<tr>
<td>Asymmetry</td>
<td>$= \frac{1}{\sqrt{N_{\eta} BR_i \varepsilon}} \frac{1}{\text{PhaseFactor}} = 3.65 \times 10^{-4} \frac{1}{\sqrt{BR_i}} \frac{1}{\text{PhaseFactor}}$</td>
</tr>
</tbody>
</table>

In general, both BR and the asymmetry are potentially valuable.

With respect to meson decays: branching ratios and asymmetries may offer a similar capability to constrain new physics at the amplitude level. In both cases, the amplitude uncertainties in both are proportional to $1/\sqrt{(N_{\eta} \varepsilon)}$. After that, the devil is in the details:

- Amplitude uncertainties obtained from BR upper limits for SM (effectively) forbidden branches increase slowly as $N_{\text{BKG}}^{1/4}$.
- Amplitude uncertainties obtained from asymmetry measurements for a SM allowed branch $i$ increase as $1/\sqrt{BR_i}$.
- For the asymmetry measurements, an unfortunate relative phase between the SM and new physics amplitudes can greatly increase the uncertainty.
CP Violation

- In the Standard Model, the weak interaction violates P but usually respects CP.

- CP violation occurs via the weak interaction through a complex phase in the CKM matrix describing quark mixing. It’s a 2nd order process (loop level) so effects are generally small.

- This Standard Model source of CP violation fails by several orders of magnitude to explain the observed matter-antimatter asymmetry of the Universe. Many extensions of SM imply additional sources of CP violation. Indeed, it is a mystery why the strong interaction appears to conserve CP so well.

- CP violation has been intensively investigated in K, B, and D meson decays, and no positive new source of CP violation has been discovered.

- The flavor-conserving regime remains much less explored.
Jlab’s Projected Sensitivity for $\eta \rightarrow 2\pi^0$

This is a graphical presentation of the relationship between the BR upper limit and two key experimental parameters: $N_{\eta}\varepsilon$ and $f_{bkg}$. It allows us to compare experiments and understand how to do better.

Improvement will come from $bkg$ reduction and a larger number of accepted $\eta$'s.

(Apparently, modern experiments with large $\eta$ datasets haven’t even tried.)
Rate Estimates

• The $\eta$ production rate:
  LH2 target length $L=30\text{cm}$, $\rho = 0.0708 \text{ g/cm}^3$

  \[ N_p = \frac{\rho L}{A} \]
  \[ N_A = \frac{0.0708 \times 30}{1} \times 6.022 \times 10^{23} = 1.28 \times 10^{24} \text{ p/cm}^2 \]

  The $\gamma+p \rightarrow \eta+p$ cross section $\sim 70 \text{ nb}$ ($\theta_\eta = 1-6^\circ$)

  Photon beam intensity $N_\gamma \sim 4 \times 10^7 \text{ Hz}$ (for $E_\gamma \sim 9-11.7 \text{ GeV}$)

  \[ N_\eta = N_\gamma N_p \sigma = 4 \times 10^7 \times 1.28 \times 10^{24} \times 70 \times 10^{-33} \]
  \[ = 3.6 \text{ Hz} \]
  \[ \approx 3.1 \times 10^5 \text{ (}\eta\text{'s/day)} \]

  $\eta$ factory!

• The $\eta \rightarrow \pi^0 \gamma \gamma$ detection rate:
  
  - $\text{BR}(\eta \rightarrow \pi^0 \gamma \gamma) \sim 2.7 \times 10^{-4}$
  - Average geometrical acceptance is $\sim 20\%$ ($118 \times 118 \text{ cm}^2$ FCAL-II)
  - Event selection efficiency $\sim 60\%$

  \[ N_{\eta \rightarrow \pi^0 \gamma \gamma} \approx 3.1 \times 10^5 \times 2.7 \times 10^{-4} \times 0.2 \times 0.60 \approx 10 \text{ events/day} \]
Optimizing the Tgt-to-Calorimeter Distance

Too far: lose signal.
Too close: peaking background from shower merging.

$$FOM = \frac{N_S}{\sqrt{N_B}}$$

The proposed 118cmx118cm calorimeter is roughly optimized at about 6m distance.

We’re excited by the possibility of the larger calorimeter (150cmx150cm) with 50% larger acceptance.

- Background window is $3\sigma$
- Signal is $\eta \rightarrow \pi^0 \gamma \gamma$
- Background is $\eta \rightarrow 3\pi^0$
- Signal window is $\pm 3\sigma$
Lessons From RadPhi

JEF bears a more-than-superficial resemblance to the RadPhi experiment that ran in Hall B. RadPhi also used a tagged photon beam, forward calorimeter, proton recoil detection, and boost.

The pioneering RadPhi measurement encountered severe pile-up by apparent neutrals: e.g., about half their \( \pi^0 \rightarrow 2\gamma \) events ended up classified as “3\( \gamma \)” events. They were able to extract a \( \Phi \rightarrow \eta \gamma \) signal (BR \( \sim \) 1.3%), but no truly rare decays. An insightful NIM article resulted but no other publications. (NIM A 570 (2007) 384-398)

JEF advantages that address accidentals and/or pile-up relative to RadPhi:

- TDC on every channel of calorimeter improves time resolution by \( \times 100 \).
- Trigger based on low rate of > 8 GeV energy sum in forward calorimeter.
- Luminosity lower by a factor of \( \times 2.8 \)
- No backgrounds from photon beam interactions in helium or air.
- LH2 target instead of Be (reducing any potential neutron background)
- 5x better energy resolution, 10x better invariant mass resolution.
  (RadPhi’s lead glass energy resolution was 10.8% at 1 GeV, and was located only 1m from the target.)

other JEF offline cuts that improve Signal/Bkg

- JEF sensitivity projections only take credit for \( \eta \)’s produced at small angles in the exclusive \( \gamma + p \rightarrow \eta + p \) reaction.
  - Recoil proton detection with co-planarity cut helps suppress multi-step continuum backgrounds like \( \gamma + p \rightarrow \pi^0 + \Delta^+ \rightarrow 2\pi^0 + p \).
  - Missing energy cut helps suppress feed-down from \( \gamma + p \rightarrow X + p \) where \( M_X > M_\eta \) and \( X \) decays with photons lost out of the acceptance.
### Selection Rule Summary Table: \( \eta \) Decay to \( \pi \)'s and \( \gamma \)'s

<table>
<thead>
<tr>
<th>( \eta \rightarrow X )</th>
<th>0( \pi )</th>
<th>1( \pi )</th>
<th>2( \pi )</th>
<th>3( \pi )</th>
<th>4( \pi )</th>
</tr>
</thead>
<tbody>
<tr>
<td>L = 0</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0( \gamma )</td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>L = 1</td>
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<tr>
<td>1( \gamma )</td>
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<tr>
<td>L = even or odd (no parity constraint)</td>
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<tr>
<td>2( \gamma )</td>
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<tr>
<td>3( \gamma )</td>
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<tr>
<td>4( \gamma )</td>
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</tbody>
</table>

**Key:**

- \( C \) and \( P \) allowed, observed
- \( C \) and \( P \) allowed, upper limits only
- \( C \) violating, \( CP \) conserving, etc.
- Forbidden by energy and momentum conservation.

\( \eta \rightarrow \pi^+ \pi^- \) \( \gamma \) \( \gamma \)

Here I've marked up all-neutral final states yielding up to 8 photons.

1/20/2014
EDM Indirect Constraints on New TV, PC Interactions  
(equivalent to CV, PC under CPT)

EDMs should be produced by new TVPC interactions plus the SM weak interaction, potentially indirectly constraining the existence of new TVPC forces. 

An Effective Field Theory evaluation finds the constraints depends on the scenario:

<table>
<thead>
<tr>
<th>Scenario A:</th>
<th>Scenario B:</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\Lambda_{TVPC}$</td>
<td>$\Lambda_{TVPC}$ (parity symmetry restored)</td>
</tr>
<tr>
<td>$\Lambda_{PV}$ (parity symmetry restored)</td>
<td>$\Lambda_{PV}$ (parity symmetry restored)</td>
</tr>
</tbody>
</table>

**EDM expression in Effective Field Theory**

(Unknown short distance physics is in $C_i$'s. $\beta$'s are calculable.)

**In A, EDMs would tightly constrain new TVPC interactions at loop level in the $C_7$ coefficient.**

**In B, it’s ambiguous. EDMs arise from a combination of potential TVPV and TVPC operators. Loop corrections could be as large as tree level.**

$n$ rare decays will provide **unambiguous, direct constraints on new TVPC interactions**.
Rate Estimates

• The $\eta$ production rate:
  LH2 target length $L=30\text{cm}$, $\rho=0.0708\text{ g/cm}^3$

$$N_p = \frac{\rho L}{A} \quad N_A = \frac{0.0708 \times 30}{1} \times 6.022 \times 10^{23} = 1.28 \times 10^{24} \text{ p/cm}^2$$

The $\gamma+p \to \eta+p$ cross section $\sim 70\text{ nb}$ ($\theta_\eta=1-6^\circ$)

Photon beam intensity $N_\gamma \sim 4 \times 10^7 \text{ Hz}$ (for $E_\gamma \sim 9-11.7 \text{ GeV}$)

$$N_\eta = N_\gamma N_p \sigma = 4 \times 10^7 \times 1.28 \times 10^{24} \times 70 \times 10^{-33}$$

$$= 3.6 \text{ Hz}$$

$$\approx 3.1 \times 10^5 \text{ (}\eta\text{'s/day) } \eta \text{ factory!}$$

• The $\eta \to \pi^0 \gamma \gamma$ detection rate:
  - BR($\eta \to \pi^0 \gamma \gamma$)$\sim 2.7 \times 10^{-4}$
  - Average geometrical acceptance is $\sim 20\%$ (118x118 cm$^2$ FCAL-II)
  - Event selection efficiency $\sim 60\%$

$$N_{\eta \to \pi^0 \gamma \gamma} \approx 3.1 \times 10^5 \times 2.7 \times 10^{-4} \times 0.2 \times 0.60 \approx 10 \text{ events/day}$$
T-Violating, P-Conserving References

Recent References for: EDM Indirect Constraints on New TV, PC Interactions

Constraints on T-odd, P-even interactions from electric dipole moments, reexamined, Kurylov, McLaughlin, and Ramsey-Musolf, PRD 63, 076007.


Recent TVPC experimental references:


Test of Time-Reversal Invariance in Proton-Deuteron Scattering at COSY, Exp. No. 215, Eversheim, Lorentz, and Valdau.

Proposed search for T-odd, P-even interactions in spectra of chaotic atoms, Morrison and Derevianko, PRA 86 (2012) 022115.
**S/B Ratio vs. Calorimeter Types**

**signal:** \( \eta \rightarrow \pi^0 \gamma \gamma \)

**background:** \( \eta \rightarrow 3\pi^0 \)

**PWO**

**S/B=10:1**

**Pb Glass FCAL**

**@Z= 9m**

**Event selection cuts:**
1. Elasticity
2. Invariant mass.

**PWO provides major improvements**
1. Granularity
2. Energy and position resolutions.

**Invariant Mass of 4\( \gamma \) (GeV)**

**S/N=0.5:1**