

The Early Eta Physics Program with JLab's GlueX/Hall D



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The Mother Ship: the GlueX Hybrid Program

Expected Decay Modes

$$\begin{aligned} \pi_1 &\rightarrow \pi\rho, \pi b_1, \pi f_1, \pi\eta', \eta a_1 \\ \eta_1 &\rightarrow \eta f_2, a_2\pi, \eta f_1, \eta\eta', \pi(1300)\pi, a_1\pi, \\ \eta_1' &\rightarrow K^*K, K_1(1270)K, K_1(1270)K, \eta\eta' \end{aligned}$$

$$\begin{aligned} b_2 &\rightarrow \omega\pi, a_2\pi, \rho\eta, f_1\rho, a_1\pi, h_1\pi, b_1\eta \\ h_2 &\rightarrow \rho\pi, b_1\pi, \omega\eta, f_1\omega \\ h_2' &\rightarrow K_1(1270)K, K_1(1270)K, K_2^*K, \phi\eta, f_1\phi \end{aligned}$$

$$\begin{aligned} b_0 &\rightarrow \pi(1300)\pi, h_1\pi, f_1\rho, b_1\eta \\ h_0 &\rightarrow b_1\pi, h_1\eta \\ h_0' &\rightarrow K_1(1270)K, K(1460)K, h_1\eta \end{aligned}$$

Early Reach With Statistics Hard

List from C. Meyer,
Future Directions in Spectroscopy Analysis

- Hall D/GlueX 's priority program is a search for heavy ($\sim 1.5-2.5 \text{ GeV}/c^2$) gluon-quark hybrid mesons.

These are broad states which must be identified by partial wave analyses. The linearly polarized photon beam is a big advantage.

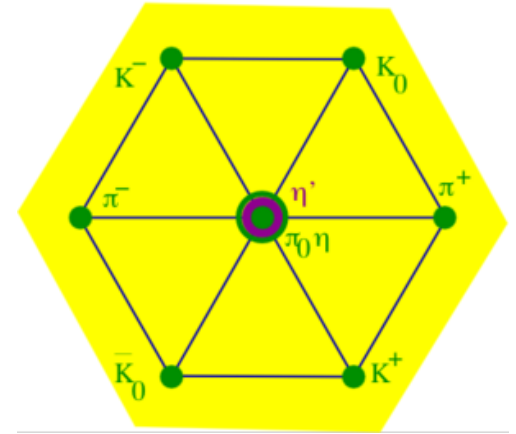
Hall D/GlueX is the flagship of the Jlab 12 GeV upgrade.

- The eta working groups deal with a well-known, light, narrow state.

However the requirement for high precision in relatively familiar territory makes these measurements as challenging as the main GlueX program.

Overview of η 's in GlueX

Why η Decays?



- The $\eta(548)$ has $I = 0$ and cannot decay by the isospin-conserving strong interaction.

- It is straightforward to produce η 's in quantity in Hall D ("20%" of π^0 rate).

(Hence measurements with statistical precision better than 0.1% are possible.)

- The η full width is only 1.3 keV, so clean isolation of the signal is possible.

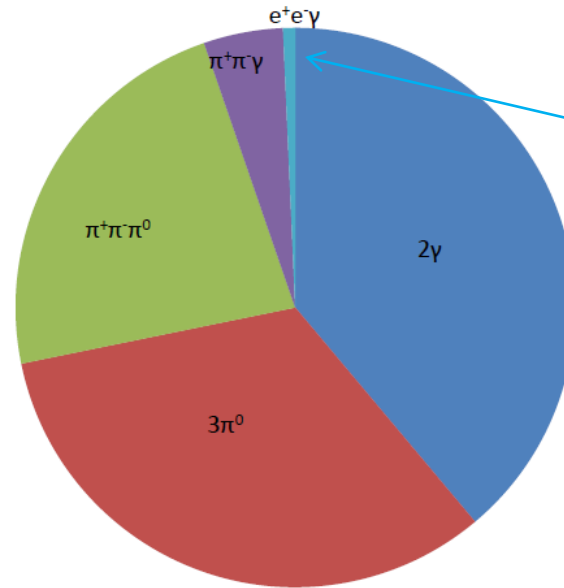
(Its lifetime is 4 orders of magnitude longer than the $\omega(770)$ for example, so it appears as a resolution-limited peak above background.)

These features make the η a natural laboratory for precision studies of isospin violation.

The Most Common η Decay Modes

PDG 2011

Major Observed η Decay Branching Ratios



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

Final State	Branching Ratio (decreasing order)	Physics Interest
2γ	0.39	η, η', π^0 mixing, normalization for $m_u - m_d$
$3\pi^0$	0.33	$m_u - m_d$
$\pi^+\pi^-\pi^0$	0.23	$m_u - m_d$
$\pi^+\pi^-\gamma$	0.046	

This talk.



The Light Quark Masses

The masses of the up, down, and strange quarks are basic input parameters of the Standard Model/QCD.

Since some precision measurements such as V_{us} in $Kl3$ decays require corrections for isospin violation, it is useful to know $m_u - m_d$.

$\eta \rightarrow 3\pi$ proceeds through isospin violation with minimal EM contributions, so the amplitude is cleanly proportional to quark mass difference $m_u - m_d$.

$$A = (m_u - m_d) A_1 + \alpha_{em} A_2$$

The following theory slides are based heavily on

E. Passemar, <http://www.physics.umass.edu/acfi/seminars-and-workshops/hadronic-probes-of-fundamental-symmetries>

The Quark Mass Ratio

In practice, one works with the quantity

$$Q^2 \equiv \frac{m_s^2 - \hat{m}^2}{m_d^2 - m_u^2}$$

so that an $O(m_q)$ correction can be cancelled. For example, in earlier studies based on pion and kaon mass differences:

$$Q^2 \equiv \frac{m_s^2 - \hat{m}^2}{m_d^2 - m_u^2} = \frac{M_K^2}{M_\pi^2} \frac{M_K^2 - M_\pi^2}{(M_{K^0}^2 - M_{K^+}^2)_{QCD}} \left[1 + O(m_q^2, e^2) \right]$$

However, the determination of Q^2 based on mass differences has significant EM corrections of scale $e^2 m_s$.

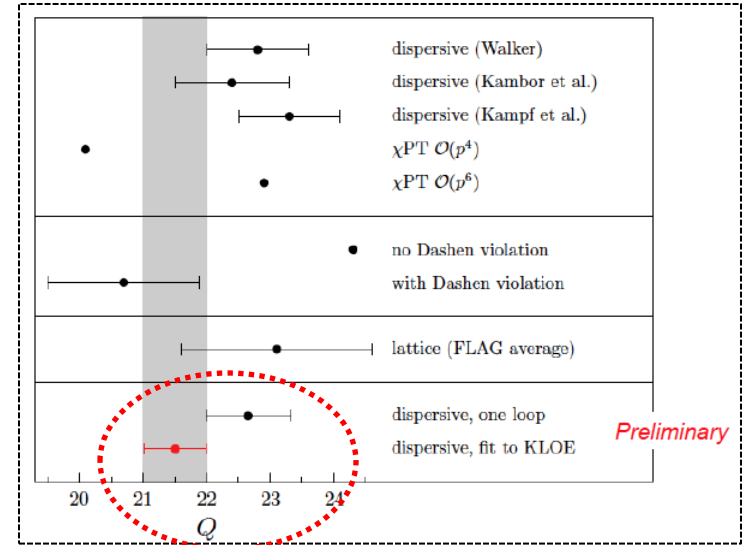
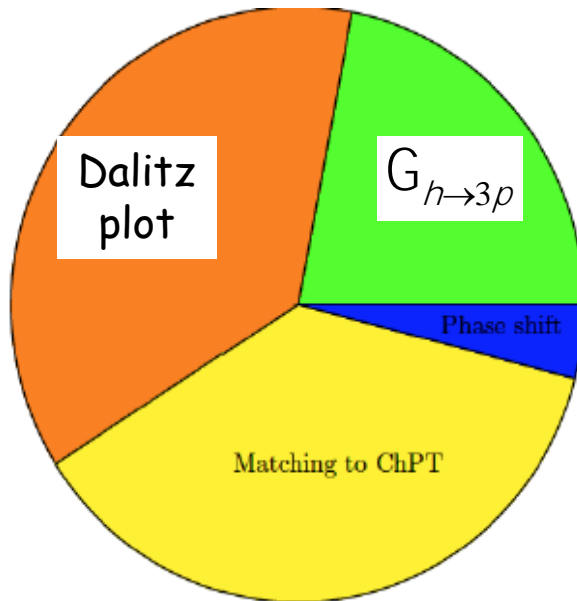
Dispersion Analysis of $\eta \rightarrow 3\pi$

Writing the amplitude in terms of Q^2 :

$$A(s, t, u) = -\frac{1}{Q^2} \frac{M_K^2}{M_\pi^2} \frac{M_K^2 - M_\pi^2}{3\sqrt{3}F_\pi^2} M(s, t, u)$$

$$\Gamma_{\eta \rightarrow 3\pi} \propto \int |A(s, t, u)|^2 \propto Q^{-4}$$

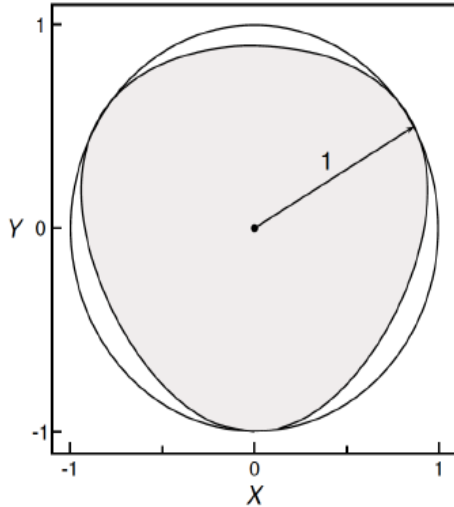
Error pie chart for dispersion analysis:



The fit to KLOE-I data reduced the error on Q and shifted the central value more than the error bar.

We will improve the precision of the Dalitz distribution.
Also, improved $\eta \rightarrow 2\gamma$ measurements will improve normalization of $\eta \rightarrow 3\pi$ absolute decay width.

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

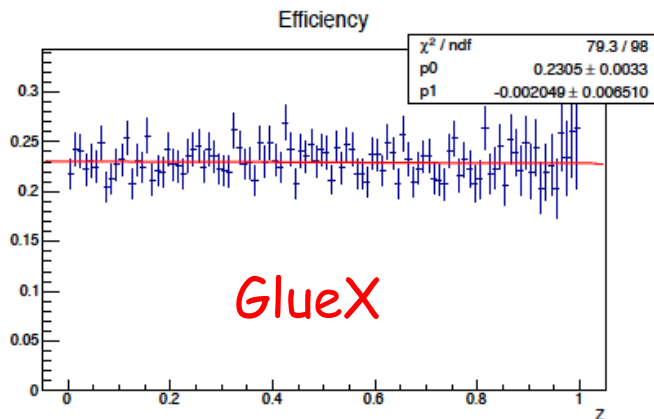
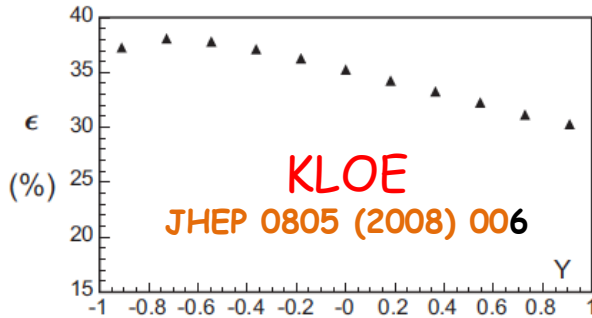


$$X = \frac{\sqrt{3}}{2M_\eta Q_c} (u - t)$$

$$Y = \frac{3}{2M_\eta Q_c} \left((M_\eta - M_{\pi^0})^2 - s \right) - 1$$

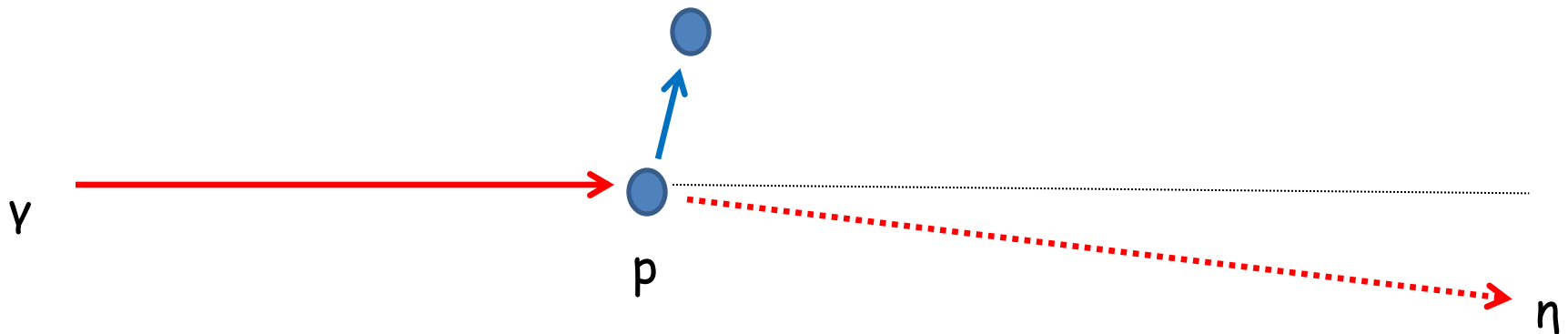
$$Z = X^2 + Y^2$$

$$Q_c \equiv M_\eta - 2M_{\pi^+} - M_{\pi^0}$$



- JEF will provide an increase in statistics and hopefully reduced systematic errors.
- We are less sensitive to detection threshold than other experiments, and our acceptance is quite flat.
- (But I'm sure we'll have new systematics to worry about.)

Forward η Photo-production



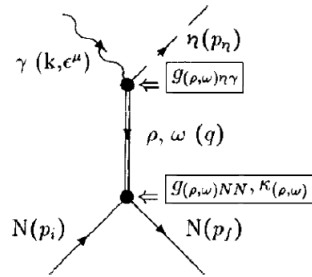
Hall D, a facility designed to efficiently produce LQCD-anticipated heavy mesons by t -channel exchange, is also a factory for light mesons produced in the forward direction.

While the detector acceptance was not optimized for light mesons, it is respectable for most $\eta(540)$ decay branches.

(The $\eta'(980)$ and $\phi(1020)$ decay product acceptances in general also look interesting but need further study.)

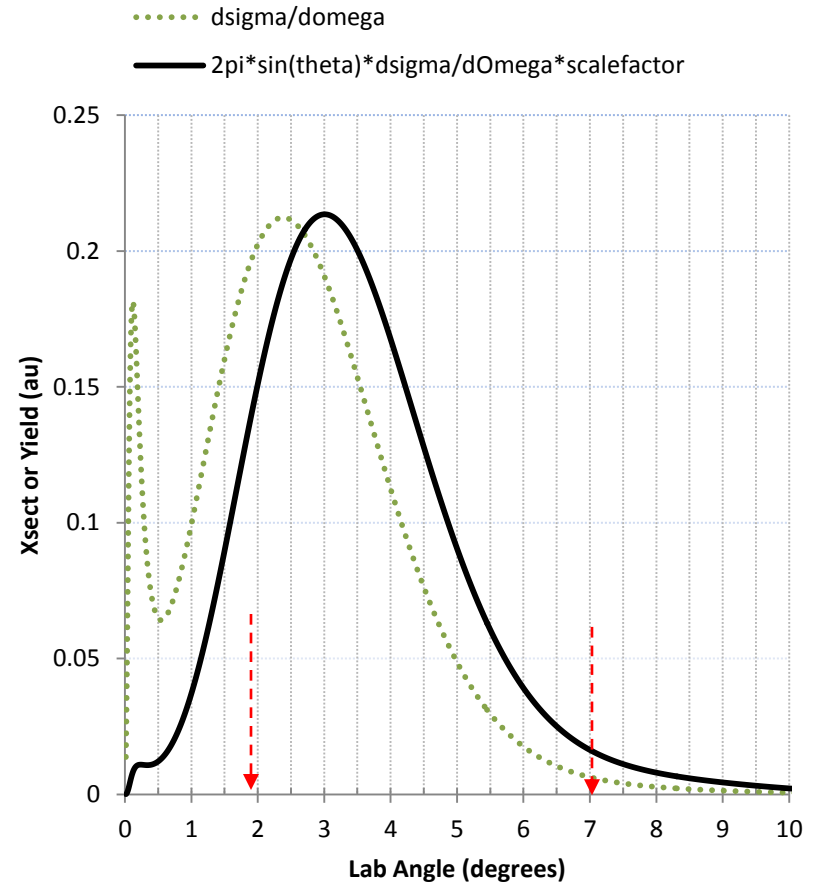
Yield vs $-t$ or θ_{LAB}

S. Taylor.
Modeling Eta and Eta' Cross Sections,
Feb 10, 2014, JEF tech note.



- Primakov production is only $O(1)\%$ of the integral forward production.
- The yield peaks at $-t \sim 0.3$ (or 3 degrees). (Beam hole is 1 degree radius.)
- The yield has a long tail, but the majority of forward production is below $-t \sim 1 \text{ GeV}^2$ (or 7 degrees).

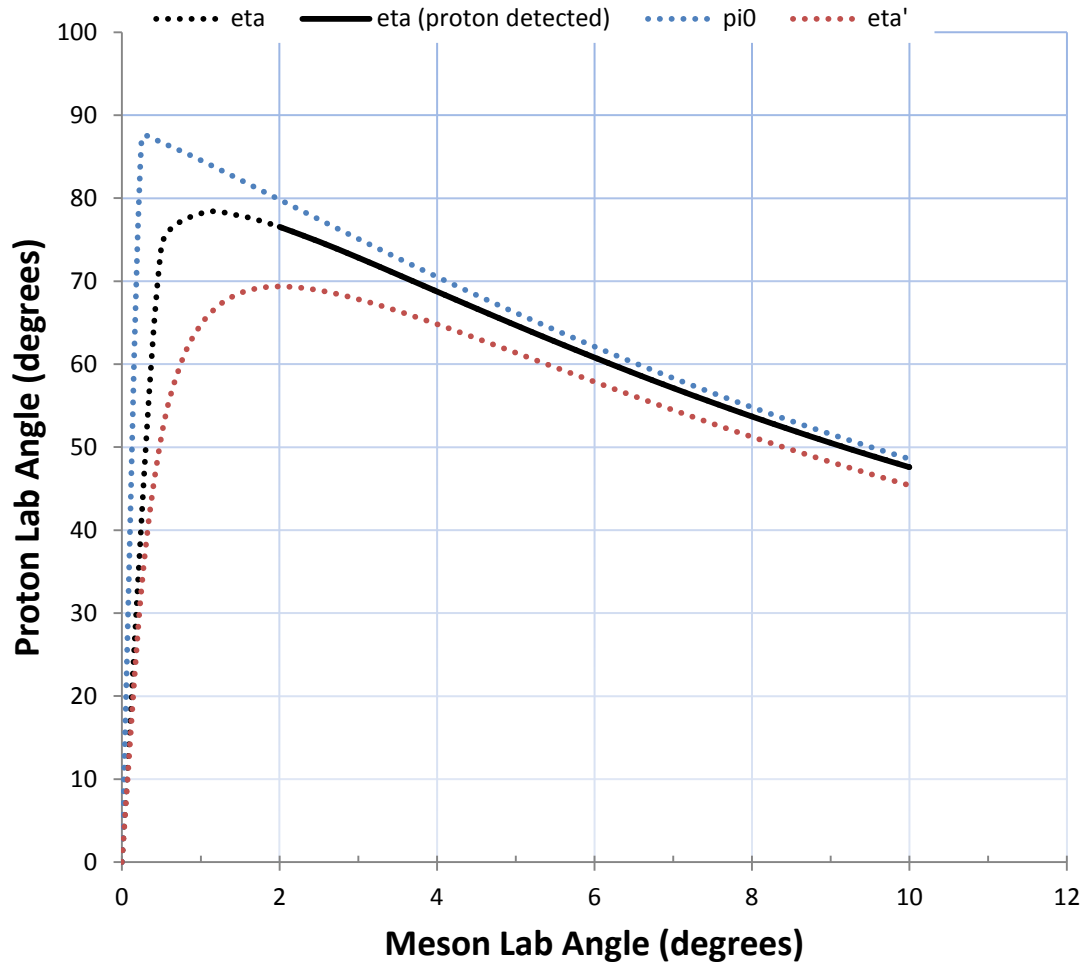
Xsect or Yield vs ThetaLab
 $E_\gamma = 8.5 \text{ GeV}$



Angle Correlation in Forward Direction

Proton Lab Angle vs Meson Lab Angle

$E_\gamma = 8.5 \text{ GeV}$



Recoil proton detection is important to exclude backgrounds.

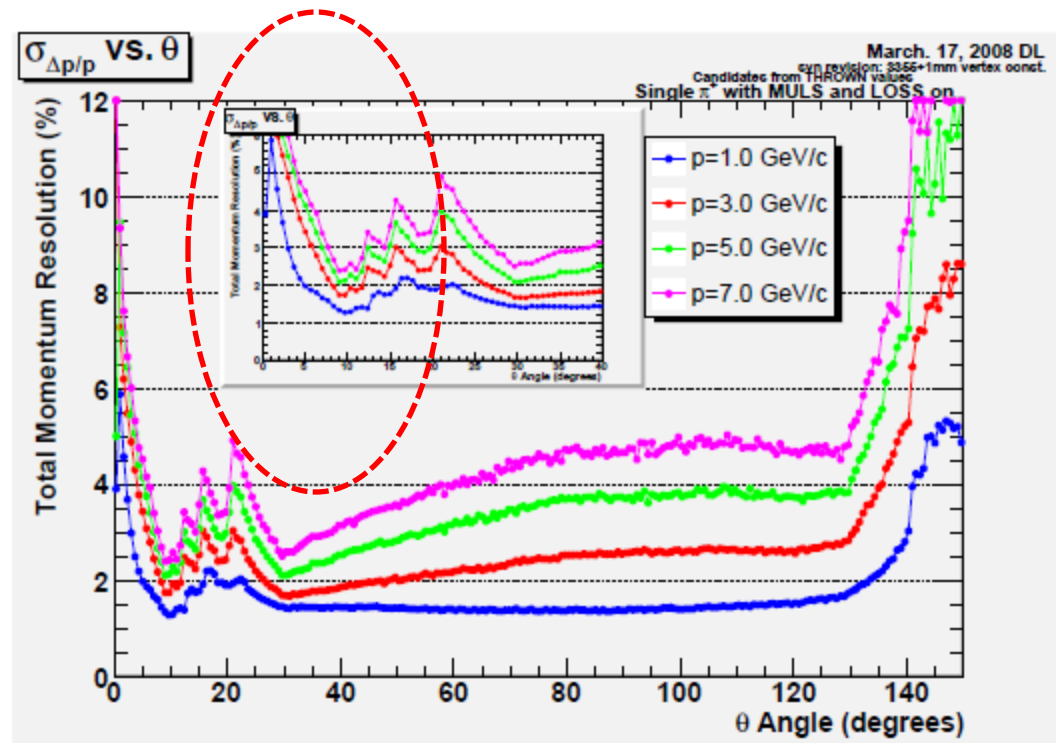
Efficiency is ~75% to get a proton of interest out of the target and tracked in CDC.

The most useful proton angles are 58-78 degrees.

Light Meson Program Facts of Life

A light meson program with GlueX base equipment has the advantage of narrow peaks each containing $O(0.1)\%$ to $O(1)\%$ of the total hadronic xsect.

However, the decay products are boosted to small angles and high energies where solenoid momentum resolutions are modest.



Note that 1% of 10 GeV is almost enough energy to make a pion.

Good calibrations, recoil proton detection, and kinematic fitting are essential.

Forward η Photo-production Rate Estimates

For an LH2 target length 30 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 $\sim 70 \text{ nb}$ ($\theta_\eta = 1-6^\circ$).

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

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

$$= 3.6 \text{ Hz}$$

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

KLOE-I η production was about 1 Hz.

Hall D is an η factory!

(The η ' rates are only a factor of 2 smaller.)

GlueX Commissioning

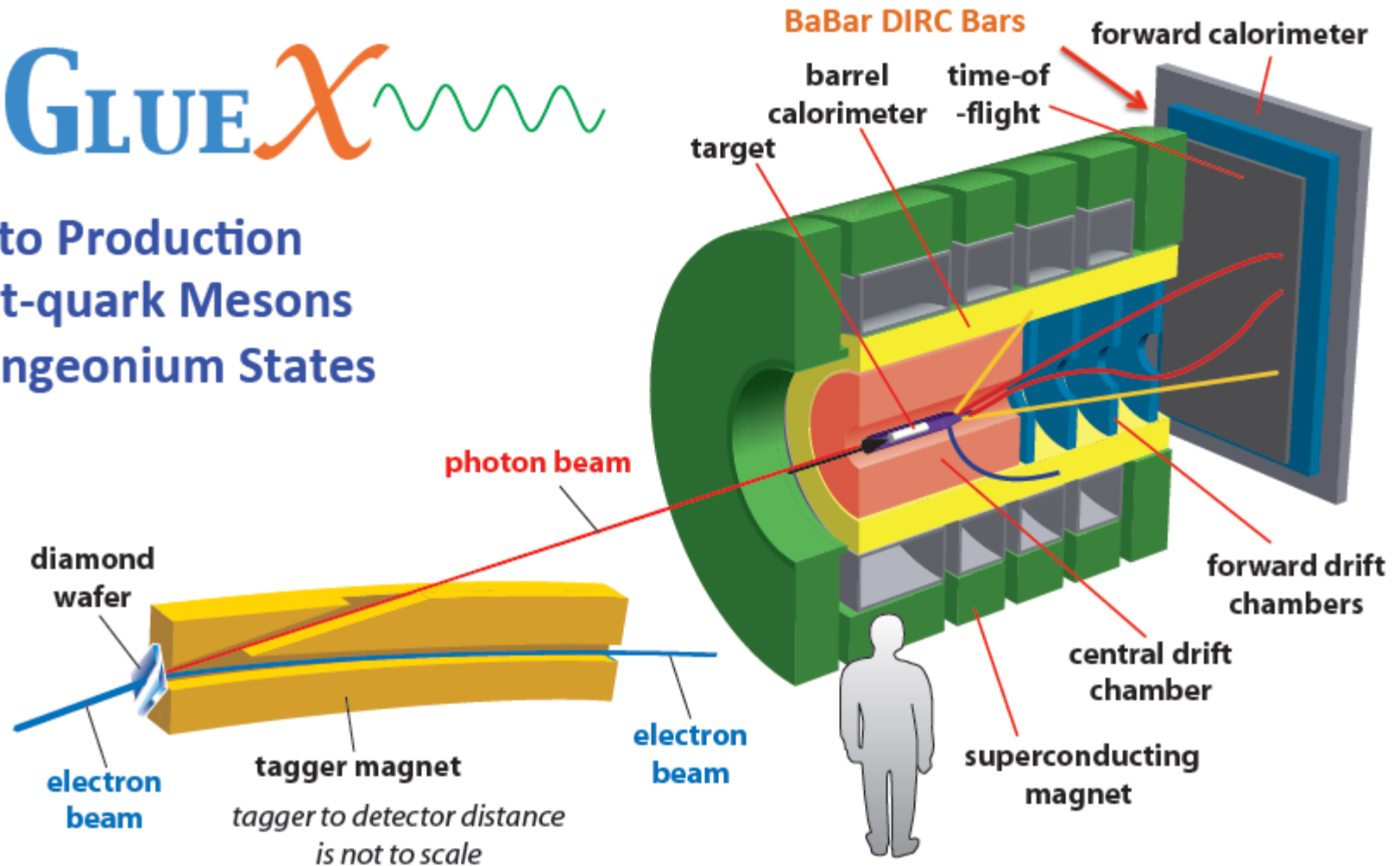
My apologies to any theorists who didn't appreciate that
"early physics program"
is a euphemism for
"getting things to work".

The GlueX Experiment at Jefferson Lab



GLUEX

Photo Production
Light-quark Mesons
Strangeonium States



Slide from C. Meyer, Future Directions in Spectroscopy Analysis

GlueX Running

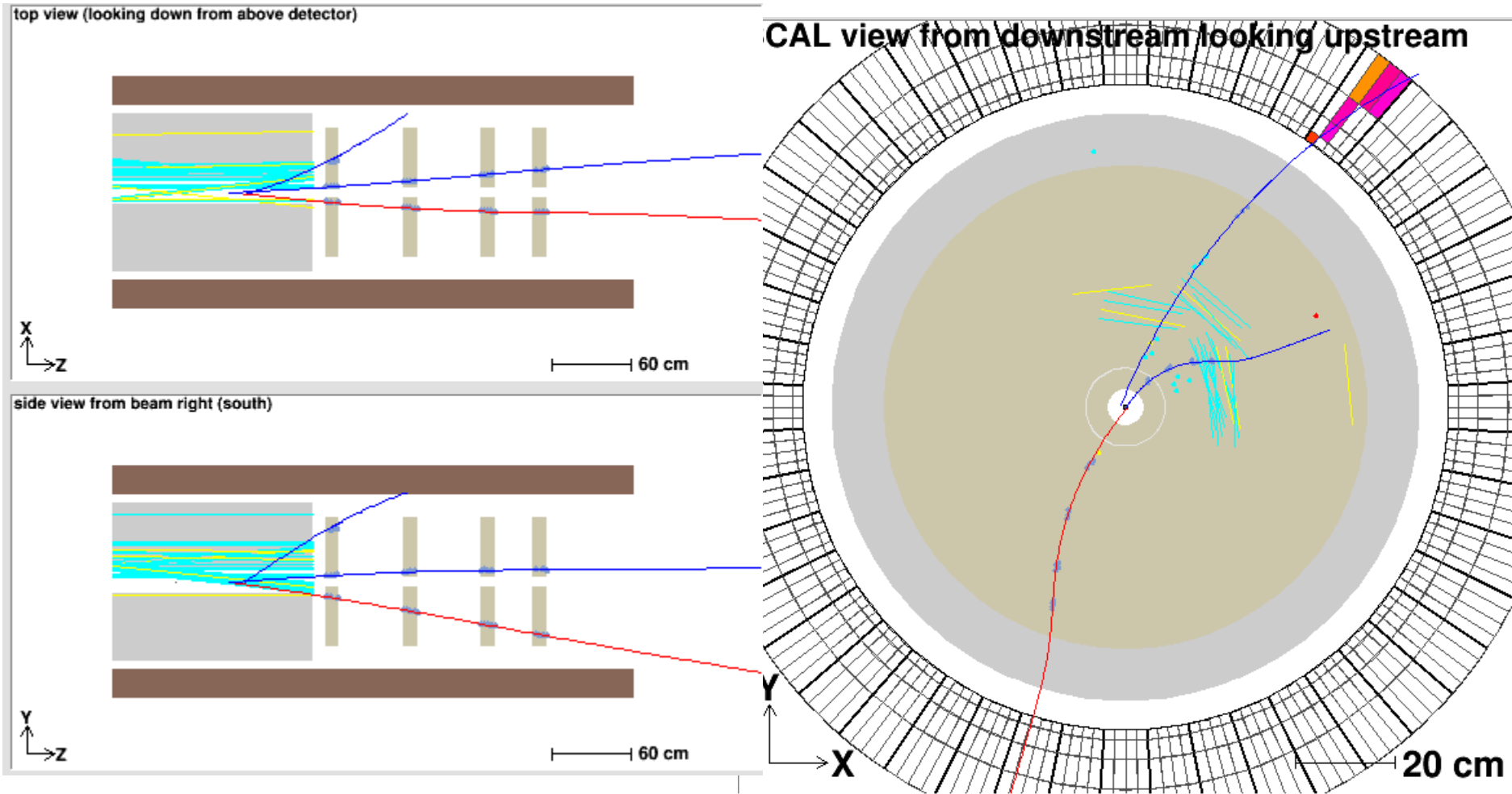


- GlueX is taking commissioning data now (Phase I). **Done!**
- There is an engineering/physics run in Spring of 2015 (Phase II).
 - Beam energy is below 12-GeV.
 - Some linear polarization.
 - Hydrogen target.
- Low-intensity physics running in late 2015.
 - 12-GeV electron beam.
 - Linearly polarized photons.
 - Software trigger tests.
- High-intensity physics running starting in 2016.
- Forward kaon identification in 2017.

Phased Running:

Phase	Event Rates			Data Volume		Yearly Data Storage			
	Rate γ/s	Year	E_e GeV	Raw kHz	DST kHz	Raw MB/s	DST MB/s	Raw PB	DST PB
I	10^6	2014	10	2	0.1	30	1.5	0.1	0.1
II	10^7	2015	11	20	1	300	15	0.8	0.2
III	10^7	2015	12	20	2	300	30	1.6	0.2
IV	$5 \cdot 10^7$	2016	12	20	10	300	150	1.6	1.0

GlueX Detector and Tagged Photon Beamline

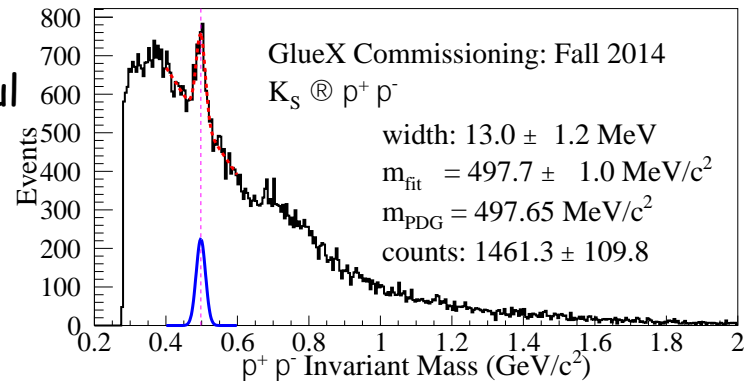


Fall 2014 Commissioning

CH2 target/ 10 GeV

- 1st priority: commission, calibrate, understand the apparatus

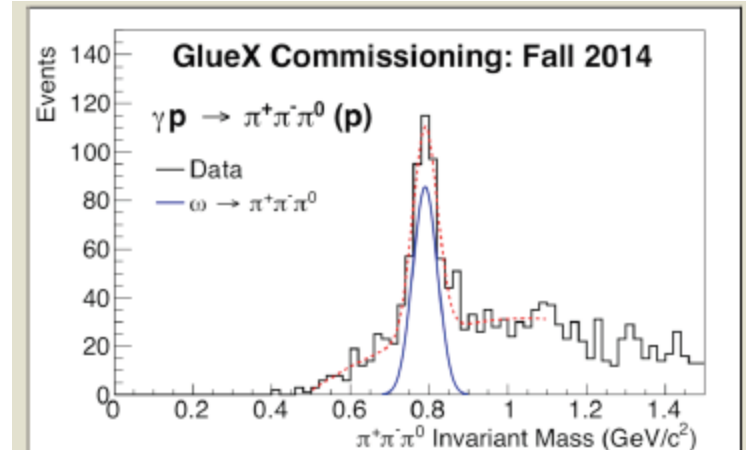
Exclusive $\gamma + "p" \rightarrow "p" + \rho \rightarrow "p" + \pi^+ \pi^-$ and inclusive $K_S \rightarrow \pi^+ \pi^-$ (on right top) are proving useful for checking charged particle reconstruction.



Inclusive $\pi^0 \rightarrow 2\gamma$ is used for photon calibrations.

$\omega \rightarrow \pi^+ \pi^- \pi^0$ (on right bottom) combines charged particle and photon reconstruction. (This was an inclusive analysis since few recoil protons escaped the 1cm thick CH2 target.)

All calibrations very preliminary. Still have to calibrate the 1000's of EM calorimeter channels needed for photon detection in FCAL and BCAL.



$\omega \rightarrow \pi^+ \pi^- \pi^0$

Upcoming Spring 2015 Commissioning

LH2 Target/ 11 GeV/ \rightarrow 1300Amps

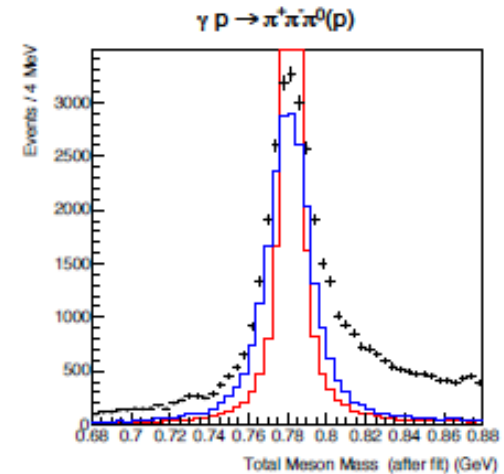
no proton used in reconstruction.

Figures by R. Mitchell

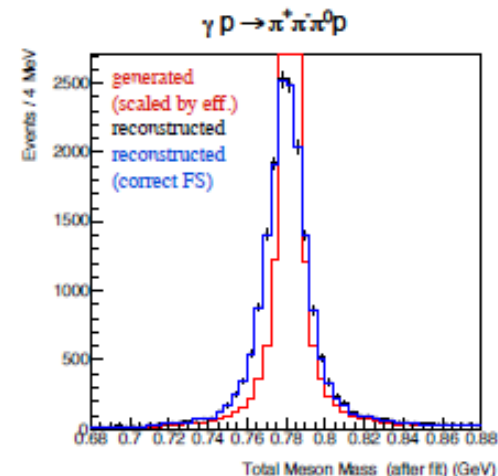
A clean w is a necessary condition
for a clean η .

Simulations for w reconstruction
with LH2 target suggest recoil
proton detection will dramatically
reduce background.

(Mostly due to an extra π^0 or
charged 2π pair).



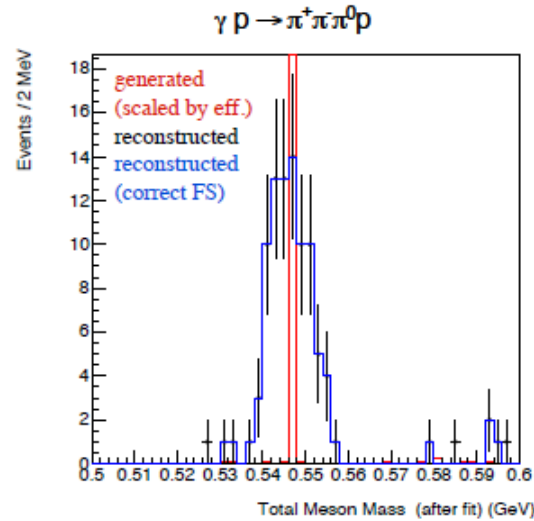
proton used in reconstruction.



Expected Quality of $\eta \rightarrow \pi^+\pi^-\pi^0$ Reconstruction

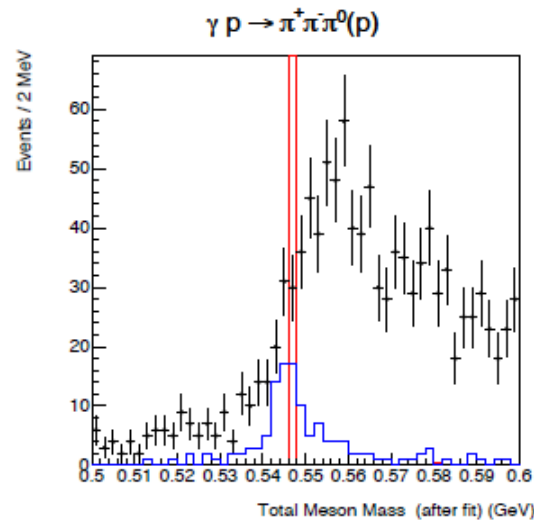
Figures by R. Mitchell

reconstructed proton



A clean η signal is expected with proton detection.

missing proton



Without proton detection, there would be large backgrounds.

High Statistics $\eta \rightarrow \pi^+\pi^-\pi^0$ Datasets

Experiment	Number of Events
KLOE (published)	1.3×10^6
KLOE (under analysis [130])	4.5×10^6
Hall D projection (JEF proposal)	16.5×10^6

JHEP 0805:006,2008
<http://arxiv.org/abs/0801.2642>

[130] A. Kupsc, "Decays and transition form factors of π^0 , η' and η' meso Fundamental Symmetries" <http://www.physics.umass.edu/acfi/>.

<https://cnidlamp.jlab.org/RareEtaDecay/JDocDB/node/40>

- Data will be taken during GlueX running as an approved analysis.
(It will be a few years however before we can become competitive.)

This reaction was extensively reviewed at the Fall 2014 MesonNet conference by Li Paula Caldeira Balkestahl (Uppsala University) and others

<https://agenda.infn.it/conferenceOtherViews.py?view=standard&confId=8209>

C and P Symmetries (assuming CPT)

	P	\bar{P}
C	<p>C, P, CP Strong, EM</p> <p>Big SM background (one does a "bump hunt")</p>	<p>$C, \bar{P}, C\bar{P}$ Weak (loop-level)</p> <p>Small SM background (one does an EDM search)</p>
\bar{C}	<p>C, P, CP Weak (loop-level)</p> <p>Small SM background. (less constrained by EDM Searches)</p>	<p>$\bar{C}, \bar{P}, C\bar{P}$ Weak</p> <p>Big SM background (one does a "precision EW test")</p>

Dalitz Distribution for $\eta \rightarrow \pi^+ \pi^- \pi^0$

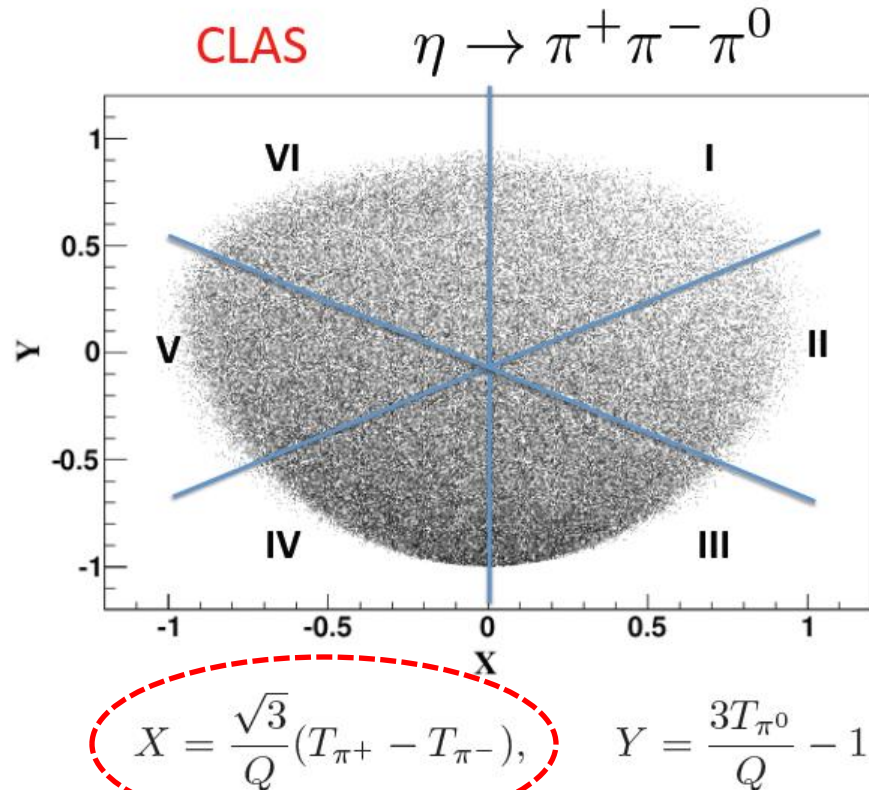


Figure from M. Amaryan, Future Directions in Spectroscopy Analysis

After acceptance and phase space corrections, the data can be expanded about $(X, Y) = 0, 0$ in a polynomial series.

If the physics were symmetric wrt exchange of $\pi^+ \rightarrow \pi^-$, the coefficients for terms containing X^1, X^3 , etc. would vanish.

Evidence for C violation is contained in odd powers in X .

For formalism linking potential C violating amplitudes in $\eta \rightarrow \pi^+ \pi^- \pi^0$ and $\eta \rightarrow \pi^0 \gamma^*$ see

B. Barrett et al,
Phys. Rev. 141, p1342 (1966).

$\eta \rightarrow \pi^+\pi^-\pi^0$ Test of C Violation

Figure from M. Zielinski, thesis
<http://arxiv.org/abs/1301.0098>

From the Dalitz distribution, one can define various C violating asymmetries.

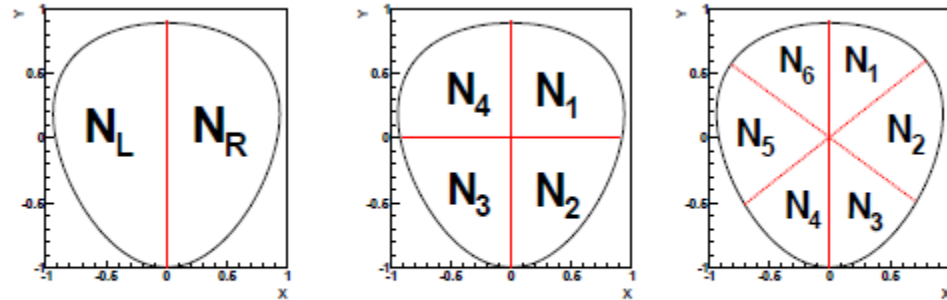


Figure 2.2: The partition of the Dalitz plot into sectors in order to define the asymmetries: (left) left-right (A_{LR}), (middle) quadrant (A_Q), (right) sextant (A_S).

The most precise published results are from KLOE using 1.3×10^6 events and consistent with zero.

JHEP 0805:006,2008
<http://arxiv.org/abs/0801.2642>

Asymmetry	Result +- Stat. Error (%)	Systematic Error (%)
$A_{\text{LeftRight}}$ $\Delta I = \text{ambiguous}$	$+0.09 \pm 0.10$	$+0.09-0.14$
A_{quadrant} $\Delta I = 2$	-0.05 ± 0.10	$+0.03-0.05$
A_{sextant} $\Delta I = 1$	$+0.08 \pm 0.10$	$+0.08-0.13$

To be competitive, one needs at least 10^6 events while controlling systematic errors appropriately.

Summary and Outlook

- GlueX/Hall D is commissioning. This is an exceptional opportunity for training young physicists. Local universities looking for graduate students include Old Dominion University, William and Mary, and Catholic University.

- The η program has a handful of base-equipment GlueX projects (no upgrades needed):

$\eta \rightarrow 3\pi$ (JEF: quark mass ratio, C violation)

$\eta \rightarrow 2\gamma$ (Primakov: preparations)

along with two involving the η' :

$\eta' \rightarrow \pi^+ \pi^- \pi^0 + \gamma$ (JEF: constrain leptophobic dark B boson between 0.5-1 GeV/c²)

$\eta' \rightarrow \pi^+ \pi^- \eta$ (unapproved analysis: source of tagged etas for $\eta \rightarrow \gamma + \text{invisible}$)

- Later phases of both the dark matter and C violation programs require the detection of forbidden or rare all-neutral decays. But neutral eta decays suffer from a unique large background from $\eta \rightarrow 3\pi^0 \rightarrow 6\gamma$. This "missing photon" problem has *never been adequately addressed*.
- A new Lead Tungstate calorimeter, the ~10 GeV tagged photon beam in Hall D, and recoil proton detection, would dramatically reduce backgrounds for all-neutral final states.

The GlueX Experiment



Oct. 2014



Slide from C. Meyer, Future Directions in Spectroscopy Analysis

Collaboration

(GlueX Collaboration and Other Participants, 33 institutes)

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A. Sitnikov,^{26,*} V. Vishnyakov,^{26,*} S. Gevorkyan,^{27,*} L. Roca,^{28,*} S. Fang,^{29,*} H. Lui,^{29,*}
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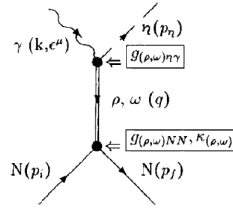
³²Lanzhou university, Lanzhou, P.R.China

³³National Research Nuclear University MEPhI, Moscow, Russia

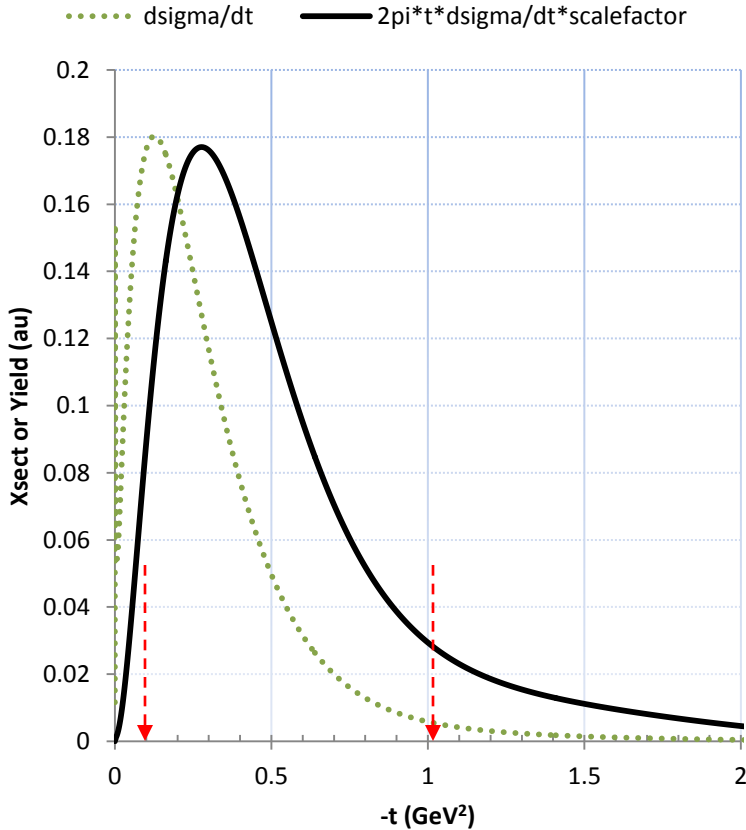
Extras

Yield vs $-t$ or θ_{LAB}

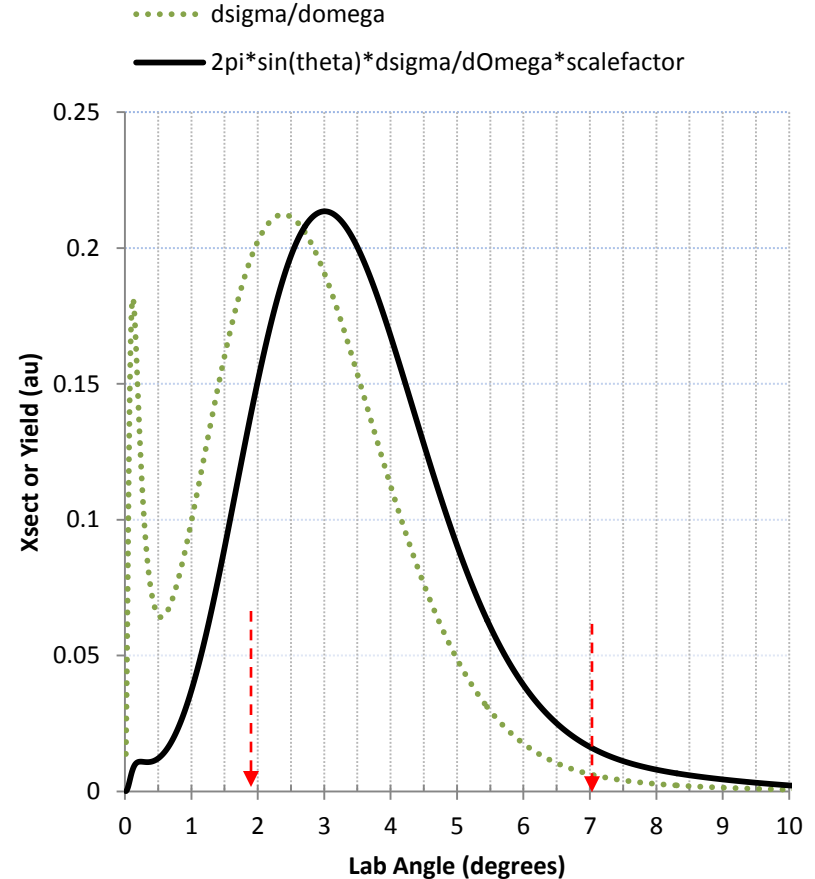
S. Taylor.
Modeling Eta and Eta' Cross Sections,
Feb 10, 2014, JEF tech note.



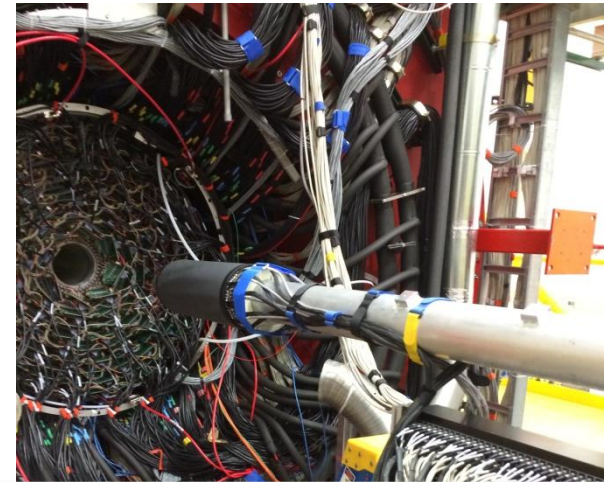
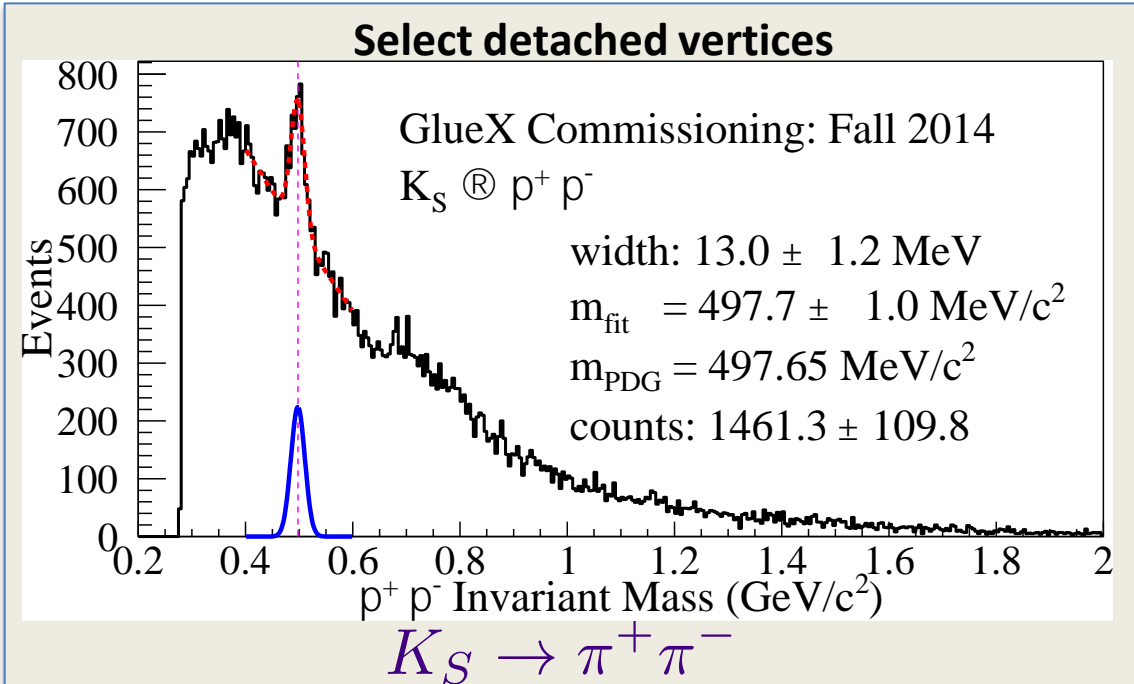
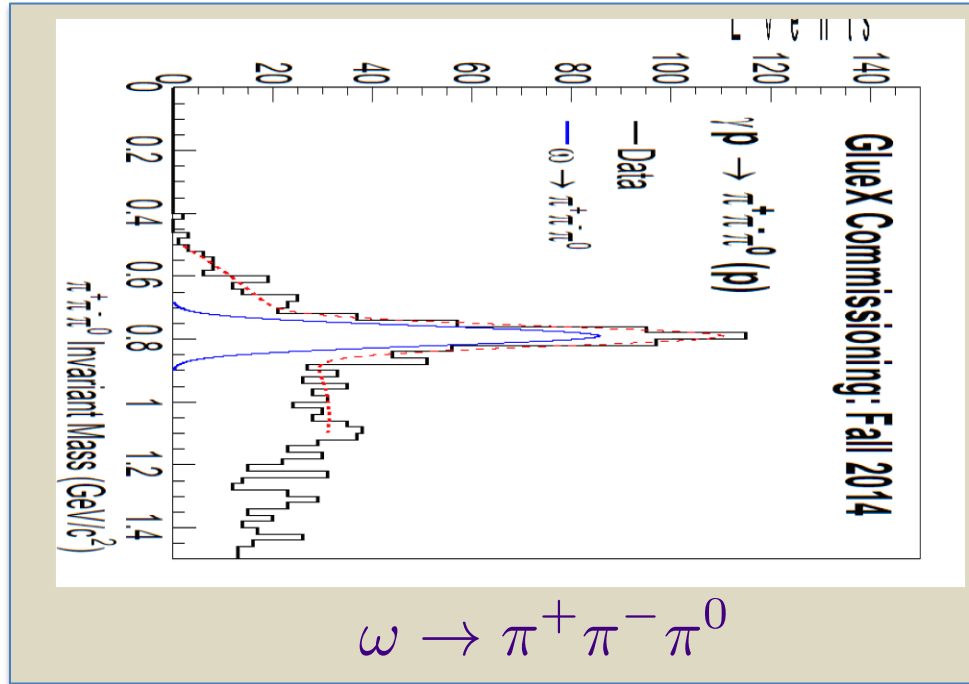
Xsect or Yield vs $-t$
 $E_\gamma = 8.5 \text{ GeV}$



Xsect or Yield vs ThetaLab
 $E_\gamma = 8.5 \text{ GeV}$




- Primakov production is only $O(1)\%$ of the integral forward production.
- The yield peaks at $-t \sim 0.3$ (or 3 degrees). (Beam hole is 1 degree radius.)
- The yield has a long tail, but the majority of forward production is below $-t \sim 1 \text{ GeV}^2$ (or 7 degrees).



Start Counter mounted to LH2 target prior to installation in GlueX, February 2014

Ultimate Goal

- Use Q to determine m_u and m_d from lattice determinations of m_s and \hat{m}

 $m_u = \hat{m} - \frac{m_s^2 - \hat{m}^2}{4\hat{m}Q^2}$ and $m_d = \hat{m} + \frac{m_s^2 - \hat{m}^2}{4\hat{m}Q^2}$

3pi Statistics Projections

TABLE II: Event sizes of recent, large 3 π datasets, both published and preliminary. Our projection for these non-rare channels is based on 100 days of JEF running plus 200 days of already approved GlueX-IV running. (See Table VII for details.)

Channel	Experiment	Number of Events
$\eta \rightarrow \pi^0 \pi^+ \pi^-$	KLOE [98]	1.3×10^6
	KLOE prelim. [130]	4.5×10^6
	WASA prelim. [130]	0.15×10^6
		World Total = 6×10^6
		(Our Projection: 16.5×10^6)
$\eta \rightarrow 3\pi^0$	Crystal Ball at MAMI [100]	3×10^6
	Crystal Ball at MAMI [101]	1.8×10^6
	Crystal Ball at BNL [99]	1×10^6
	KLOE [103]	0.6×10^6 ^a
	WASA [102]	0.12×10^6
		World Total = 6.5×10^6
	(Our Projection: 16.9×10^6)	

^amedium purity

The "Missing Photon" Problem in All-Neutral Rare Decays of the Eta

The eta has a big decay branch to $\eta \rightarrow 3\pi^0 \rightarrow 6\gamma$.

Photons can become "missing" due to

- going down the beam-pipe, thus becoming truly lost,

or only apparently becoming lost due to

- falling below energy threshold, or
- the merging of showers in the EM calorimeter.

Rare all-neutral decays of the eta to 4-5 photons are usually severely impacted by this.

(Eta $\rightarrow 3\gamma$ is probably affected more by "4 γ " sources like continuum $\gamma+p \rightarrow 2\pi^0+p \rightarrow 4\gamma$.)

All Neutral Channels Obscured by $\eta \rightarrow 3\pi^0 \rightarrow 6\gamma$

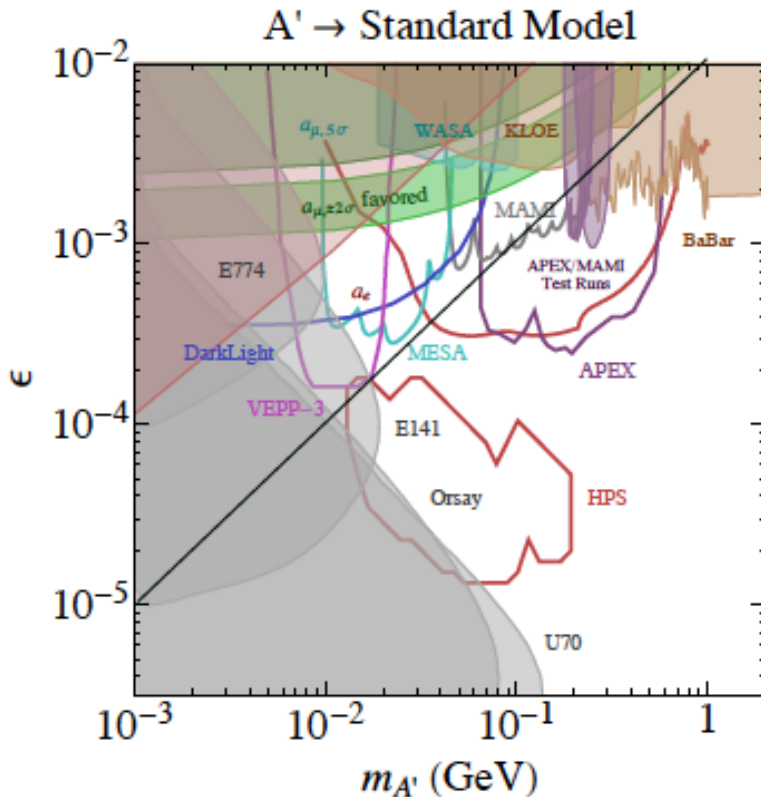
Neutral Channels		Charged Channels
$\eta \rightarrow 2\gamma$ (39%)	$\eta \rightarrow 3\pi^0 \rightarrow 6\gamma$ (33%)	$\eta \rightarrow \pi^+\pi^-\pi^0$ (23%)
	<div style="border: 2px solid red; padding: 10px; text-align: center;"> obscured by loss or merging of photons from $\eta \rightarrow 3\pi^0$ </div>	$\eta \rightarrow \pi^+\pi^-\gamma$ (5%)
		$\eta \rightarrow \gamma l^+l^-$
		$\eta \rightarrow \pi^+\pi^-\pi^0\gamma$
	$\eta \rightarrow \pi^0 2\gamma$ $\eta \rightarrow 2\pi^0 2\gamma$	
	(CP: $\eta \rightarrow 2\pi^0\gamma, 3\gamma$) (CP: $\eta \rightarrow 2\pi^0$)	

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

"Vector Portal" to Dark Sector

1. Dark photon A'

$$-\frac{1}{2}eF^{mn}F'_{mn} \text{ Kinetic mixing and } U(1)'$$



Most A' searches are through its decay to l^+l^- relying on the leptonic coupling of new force

2. Dark lepto-phobic B-boson (dark ω , γ_B , or Z'): $\frac{1}{3}g_B\bar{q}g^mqB_m$

Gauged baryon symmetry $U(1)_B$

Early studies by Lee and Yang, Phys.Rev.,98 (1955) 1501; Okun, Yad.Fiz., 10 (1969) 358,

Features theorists appreciate:

- A potential explanation for the stability of dark matter
- a unified genesis of baryonic and dark matter
- a natural framework for "Strong CP problem" in QCD

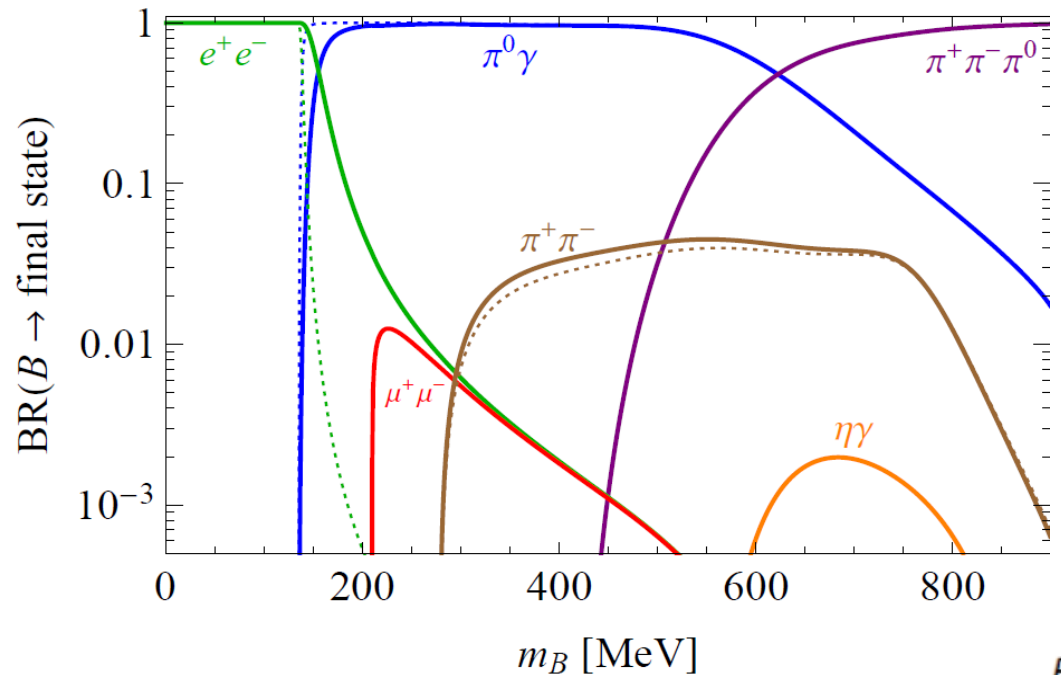
Experimentally,

- the $m_B < m_\pi$ region is strongly constrained by long-range forces searches.
- the $m_B > 50 \text{ GeV}$ region is constrained by collider experiments.
- which leaves the GeV-scale domain less explored.

Striking signature for B-boson in η decay

Early work: A.E. Nelson, N. Tetradis, Phys. Lett., B221, 80 (1989)

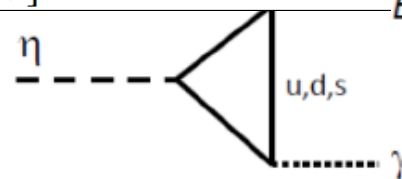
Recent work: Sean Tulin, Phys.Rev., D89, 14008 (2014)



Early workers thought that decay of the B would be swamped by $\rho \rightarrow \pi\pi$.

Sean realized that the 2π decay of the B is blocked by G parity (isospin conservation).

$\eta \rightarrow B\gamma$ decay ($m_B < m_\eta$)

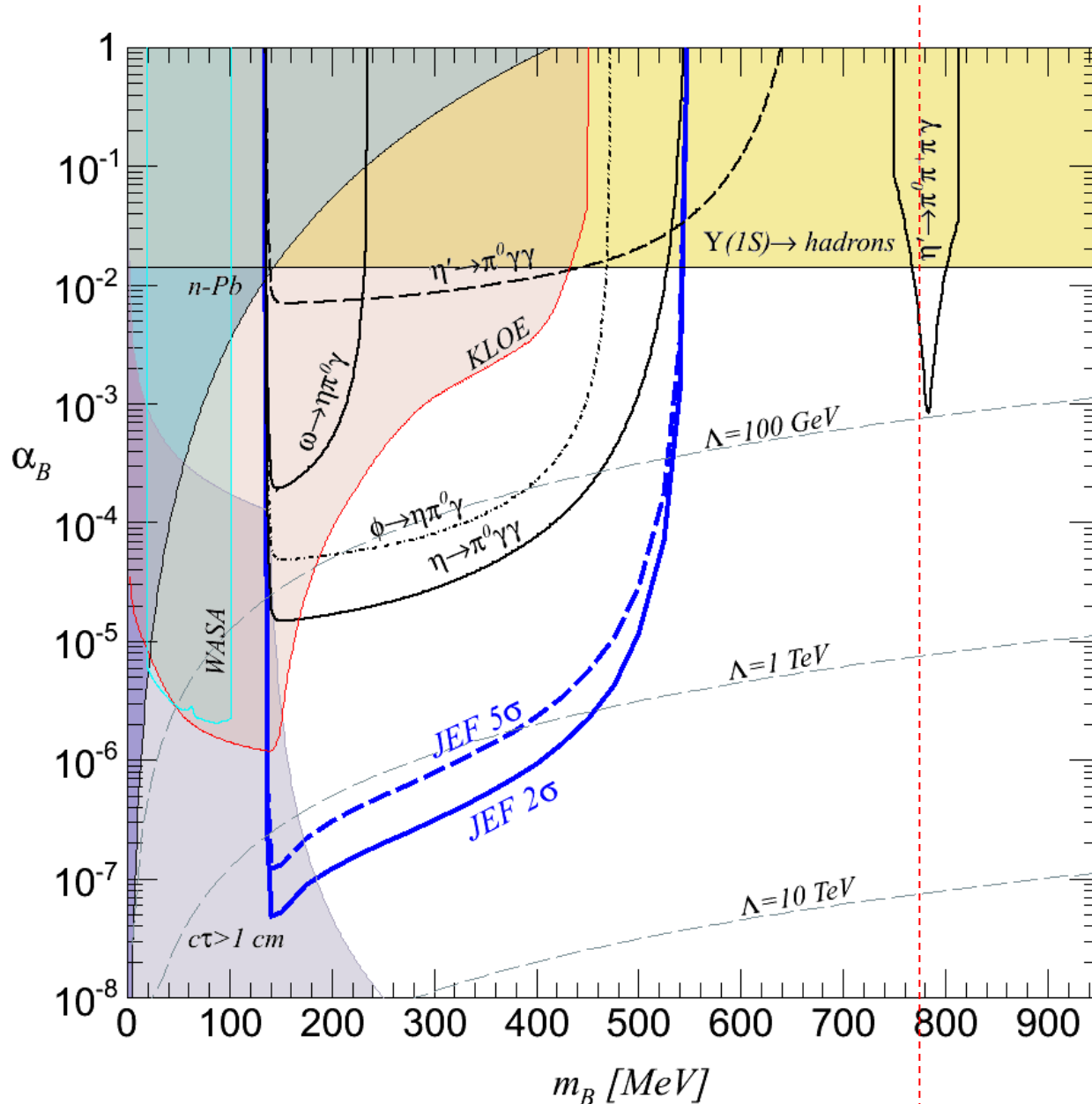


Triangle diagram

$B \rightarrow \pi^0 \gamma$ for 140-600 MeV range

$B \rightarrow \pi^+ \pi^- \pi^0$ for 600-900 MeV range.

Possibilities for $\eta' \rightarrow B \gamma \rightarrow (\pi^+ \pi^- \pi^0) \gamma$



Hall D will be one of the world's best η' factories.

(Same quantum numbers at the η , but we are generally less interested because strong decays are allowed.)

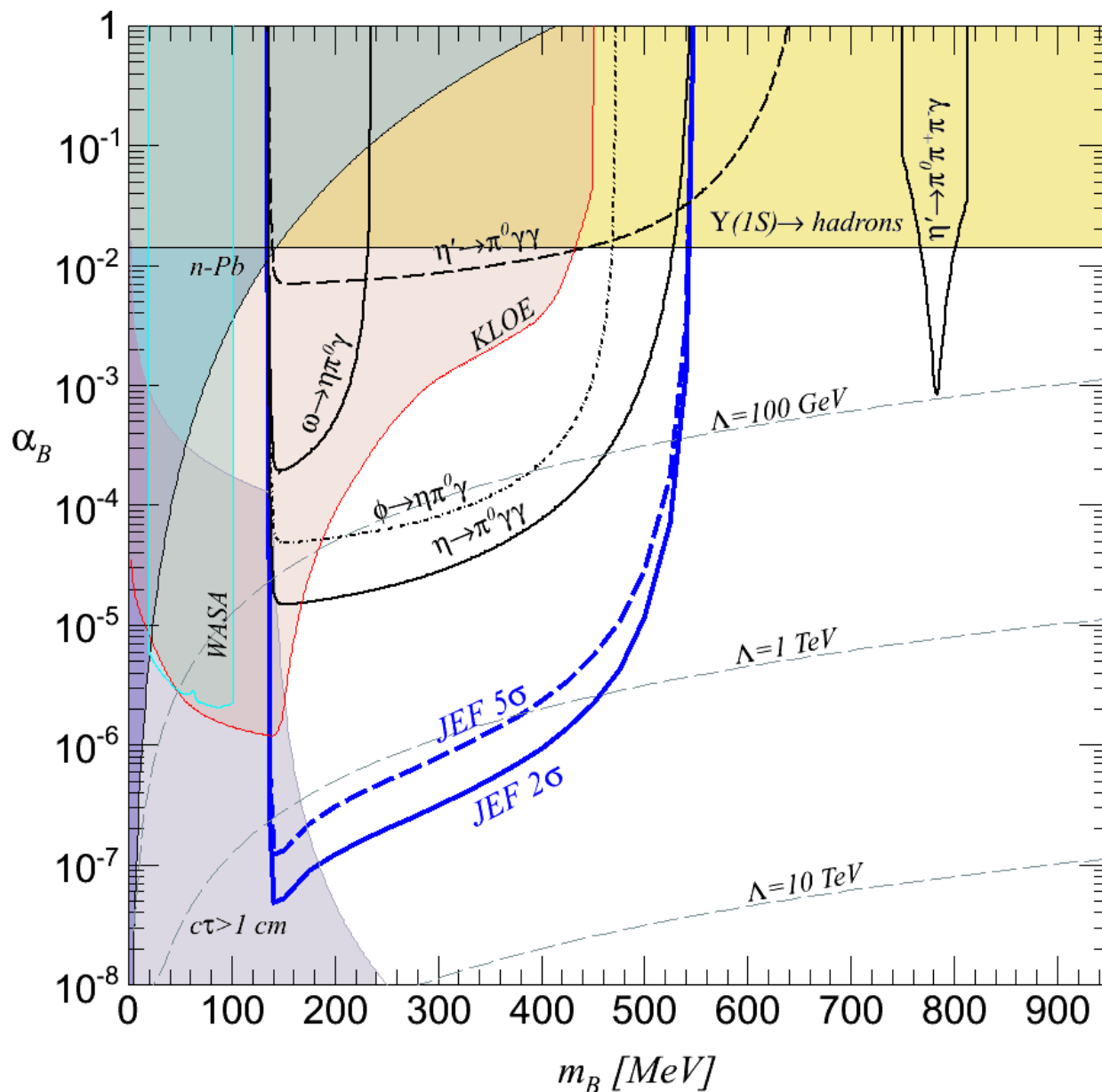
HOWEVER, without any upgrades, the η' allows improved constraints up to 1 GeV using $\eta' \rightarrow \gamma + B$

(In this case it's useful to remember another name for the B is the "dark w".)

We will look for a coherent enhancement in the tails of the w resonance.

Possible serious competition in BES-III.

JEF Projected Constraints from $\eta \rightarrow B\gamma \rightarrow (\pi^0\gamma)\gamma$



With the calorimeter upgrade:

- The SM background is very small in the $\eta \rightarrow \pi^0 2\gamma$ channel ($\Gamma \sim 0.3\text{eV}$).

(bump hunt in Dalitz plot)

- η decay would allow a stringent constraint in the 140-550 MeV range.
- Indirectly sensitive to TeV-scale physics: a positive signal would imply a new fermion with a mass up to a few TeV due to electro-weak anomaly cancellation.

Partially Visible Eta Decays: $\eta \rightarrow \gamma + \Upsilon$

If recoil proton detection does not provide a sufficiently clean η tag, we might employ an η' decay cascade.

Signal:

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

$$\eta' \rightarrow \pi^+ \pi^- \eta \quad (43.4\%)$$

$$\eta \rightarrow \gamma + \Upsilon$$

$$\text{Net: } \gamma + p \rightarrow p \pi^+ \pi^- \gamma \Upsilon$$

Under the hypothesis that the detected γ is from $\eta \rightarrow \gamma + \Upsilon$, we must search for the second γ . (The relevant part of the calorimeter must be $\sim 100\%$ efficient.)

Background 1:

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

$$\eta' \rightarrow \pi^+ \pi^- \gamma \quad (29.3\%)$$

$$\text{Net: } \gamma + p \rightarrow p \pi^+ \pi^- \gamma$$

This background is excluded by the lack of missing energy/momentum.

Background 2:

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

$$\eta' \rightarrow \pi^+ \pi^- \gamma + \gamma_{\text{rad}} \quad (29.3\% \times \alpha)$$

$$\text{Net: } \gamma + p \rightarrow p \pi^+ \pi^- \gamma \gamma_{\text{rad}}$$

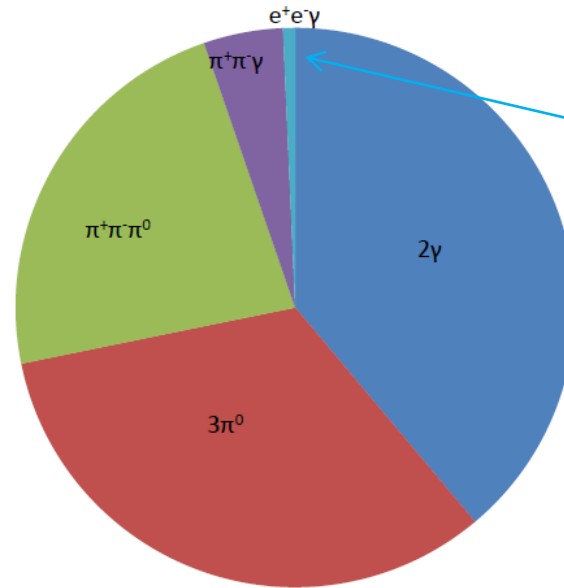
This background will have to be suppressed by rejecting events with two detected photons, or with one photon which is soft or co-linear with the pions, or events with too high a probability of meeting the $\eta' \rightarrow \pi^+ \pi^- \gamma$ hypothesis.

This is the one that needs study! 40

The Most Common η Decay Modes

PDG 2011

Major Observed η Decay Branching Ratios



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

All-neutral final states in yellow.

Final State	Branching Ratio (decreasing order)	Physics Interest
2γ	0.39	η, η', π^0 mixing
$3\pi^0$	0.33	$m_u - m_d$, $\pi\pi$ scattering length
$\pi^+\pi^-\pi^0$	0.23	
$\pi^+\pi^-\gamma$	0.046	

The $3\pi^0$ reactions can be a big background for all-neutral decays $\eta \rightarrow$ lotsa photons.

Neutral η Decays Testing C Violation

Gammas in Final State	Channel	Branching Ratio upper limit
3	3γ	$< 1.6 \cdot 10^{-5}$
	" $\pi^0\gamma$ "	$< 9 \cdot 10^{-5}$
5	$2\pi^0\gamma$	$< 5 \cdot 10^{-4}$
	$3\gamma\pi^0$	Nothing published
7	$3\pi^0\gamma$	$< 6 \cdot 10^{-5}$
	$3\gamma 2\pi^0$	Nothing published

PDG 2012

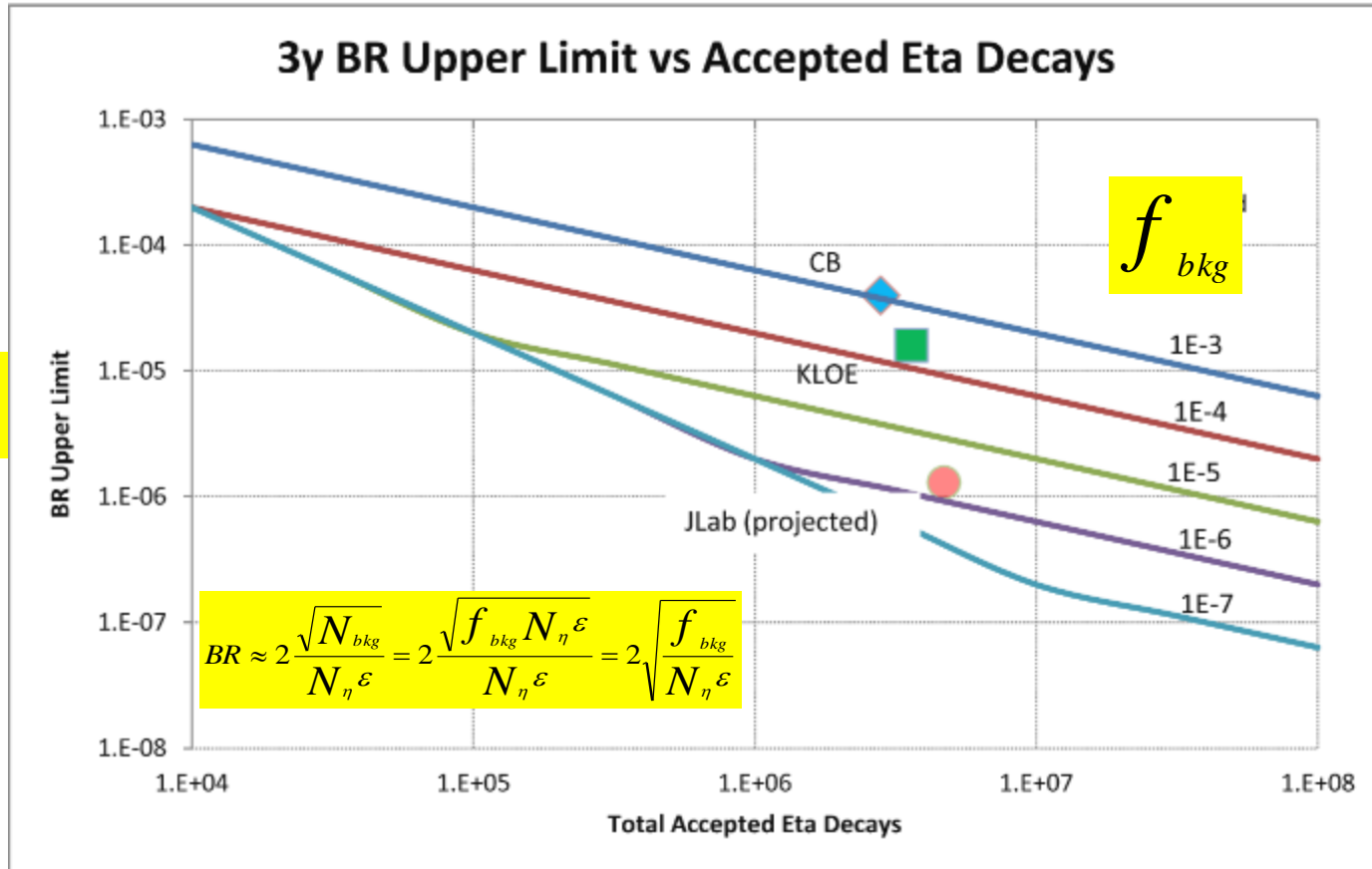
We expect to make the biggest improvements in $\eta \rightarrow 3\gamma$, $2\pi^0\gamma$, and $3\gamma\pi^0$

($\eta \rightarrow \pi^0\gamma$ violates angular momentum conservation so we consider it a control.)

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 parameters: $N_\eta \epsilon$ and f_{bkg} . It allows us to compare experiments and understand how to do better.

BR

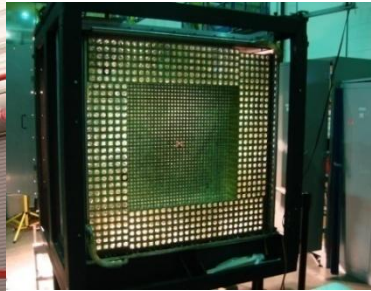
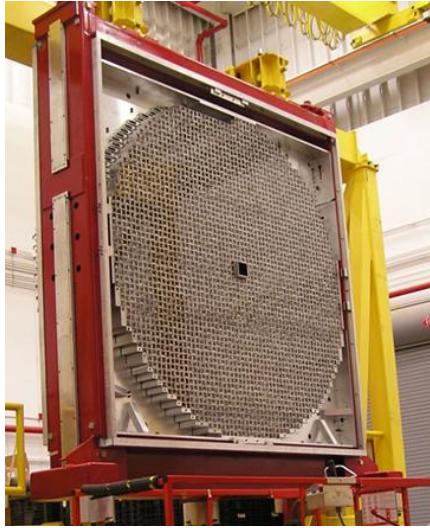


Main reason for improvement will be bkg reduction.

$N_\eta \epsilon$

Ref: JEF proposal 2012

New Equipment: FCAL-II



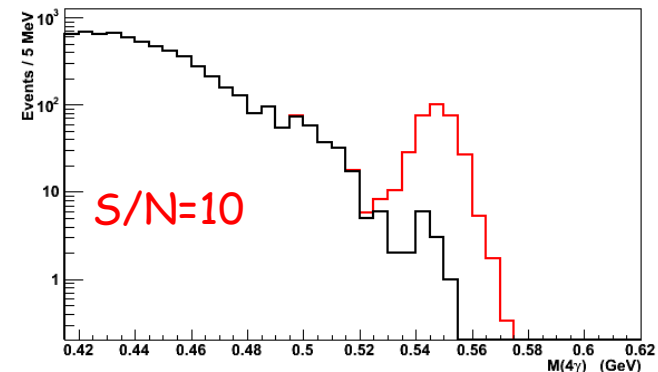
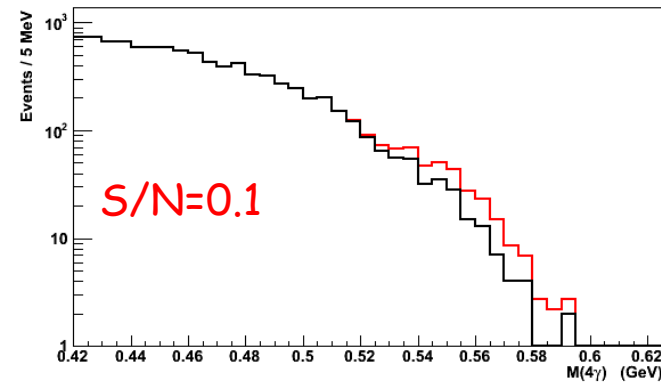
FCAL with PWO insertion:
 118x118 cm² in Size (3445 PbWO₄)
 2cm x 2cm x 18cm per module

S/N Ratio vs. Calorimeter Types

signal: $\eta \rightarrow \pi^0 \gamma \gamma$, background: $\eta \rightarrow 3\pi^0$

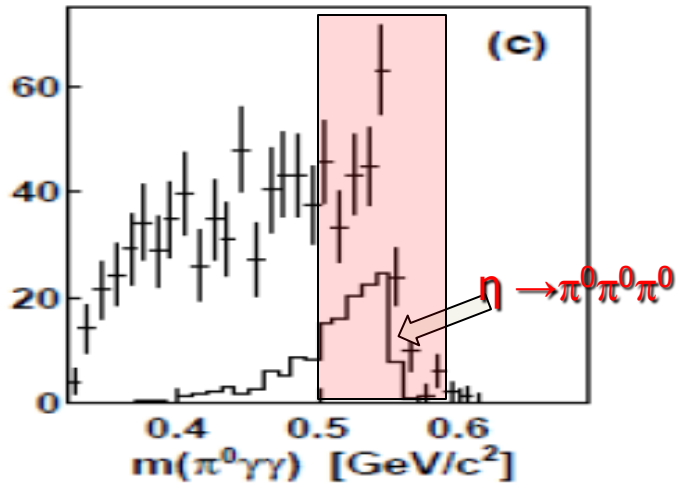
FCAL-II (PbWO₄) vs. FCAL (Pb glass)

Property	Improvement factor
Energy σ	2
Position σ	2
Granularity	4
Radiation-resistance	10

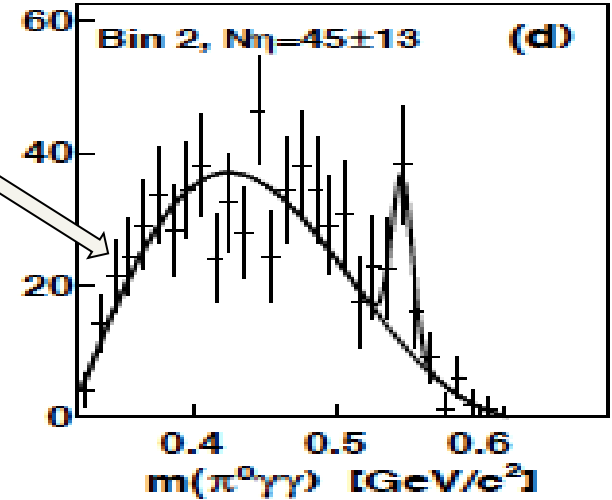


Reducing Background in $\eta \rightarrow \pi^0 2\gamma$

A2 at MAMI (arXiv:1405.4904, 2014): $\gamma p \rightarrow \eta p$ ($E_\gamma = 1.5$ GeV)

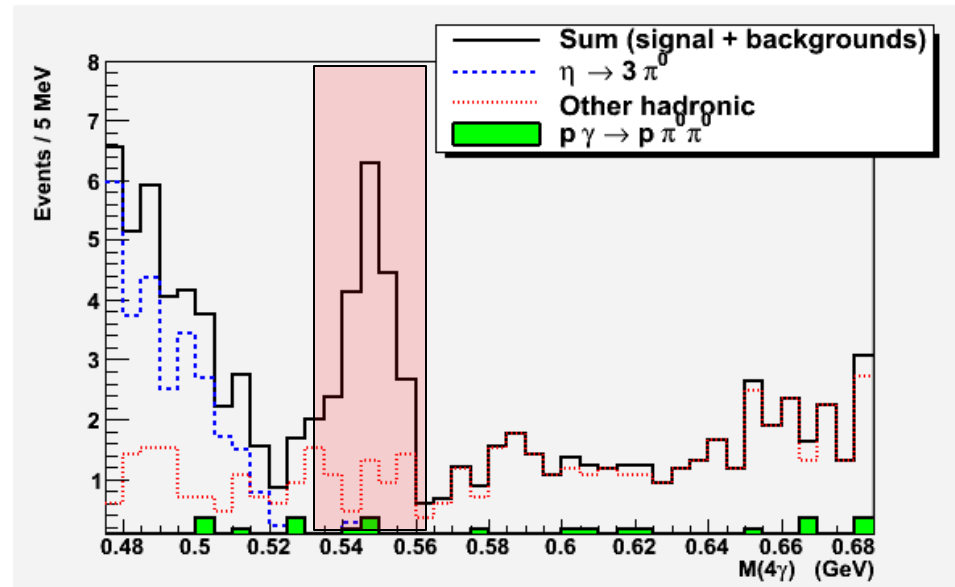


$\gamma p \rightarrow \pi^0 \pi^0 + p$



Jlab:

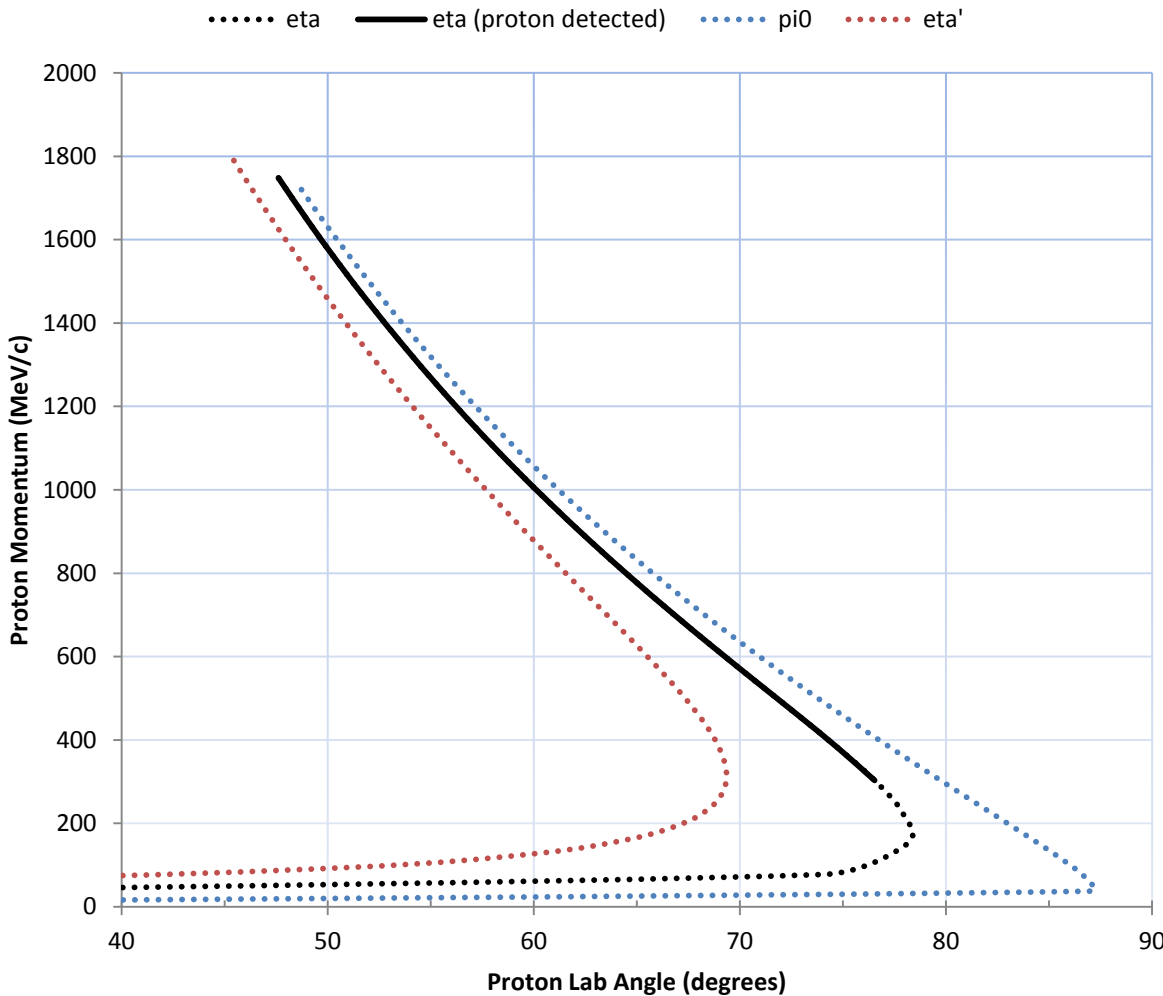
$\gamma p \rightarrow \eta p$ ($E_\gamma = 9-11.7$ GeV)



Proton Momentum vs Angle

Proton Momentum vs Lab Angle

$E_\gamma = 8.5 \text{ GeV}$



All detectable recoil protons are at fairly large angles, 48-77 degrees here.

Requiring the recoil proton reduces the eta rate by 25%, but is

- essential for a rare decay program

- Useful for precision measurements,

However, see comment below about Primakov.

Dark Matter Outlook for GlueX/Hall D

The η and η' provide a means to search for lepto-phobic dark matter over a wide mass range. This possibility is increasingly interesting given improving constraints on $A' \rightarrow l^+l^-$.

Starting now -

- Commission/calibrate the GlueX detectors including FCAL.
- Begin 1st generation GlueX analysis of $\eta' \rightarrow \gamma + B \rightarrow \pi^+\pi^-\pi^0 + \gamma$.

(the non-rare control channel and background is $\eta' \rightarrow \omega\gamma \rightarrow \pi^+\pi^-\pi^0 + \gamma$).

- Study backgrounds for $\eta \rightarrow \gamma + B \rightarrow \gamma + \pi^0\gamma$.

Note: placing the best constraints on a lepto-phobic dark matter in the η mass range also leads to the best dataset to constrain axial meson contributions in the rare decay $\eta \rightarrow \pi^0\gamma$.

- Update JEF proposal which justifies calorimeter upgrade: FCAL (lead glass) \rightarrow FCAL-II (PbWO_4)

Future (same as on previous slide) -

- Following JEF proposal approval, prepare NSF MRI proposal for new PbWO_4 calorimeter.
- Build and install new calorimeter.
- Commission and begin forbidden decay program on $\eta \rightarrow \gamma + B$. (FCAL-II is ESSENTIAL for this.)

C Violation Outlook for GlueX/Hall D

The η provides a unique laboratory to directly constrain new sources of C and CP violation. GlueX/Hall D can make significant advances with its high η and η' production and/or potentially lower backgrounds (the latter requires hardware upgrades).

Starting now -

- Commission/calibrate the GlueX detectors including FCAL.
- Begin 1st generation GlueX analysis of the non-rare decay $\eta \rightarrow \pi^+ \pi^- \pi^0$.

Note: placing the best direct constraints on a C violating asymmetry will also best determine the quark mass ratio.

- Study backgrounds for C forbidden decays $\eta \rightarrow 3\gamma$, $\eta \rightarrow 2\pi^0\gamma$.
(... and backgrounds for C forbidden decays $\eta \rightarrow \pi^0 \gamma^*$, $\eta' \rightarrow \eta \gamma^*$, $\eta' \rightarrow \pi^0 \gamma^*$.)
- Update JEF proposal which justifies calorimeter upgrade: FCAL (lead glass) \rightarrow FCAL-II (PbWO_4)

Future -

- Following JEF proposal approval, prepare NSF MRI proposal for new PbWO_4 calorimeter.
- Build and install new calorimeter.
- Commission and begin forbidden decay program on $\eta \rightarrow 3\gamma$, $\eta \rightarrow 2\pi^0\gamma$. (FCAL-II is ESSENTIAL.)

(Reactions like $\eta \rightarrow \pi^0 \gamma^*$ will also benefit from DIRC and muon filter upgrades.)

PAC42 Results

“In particular, the PAC sees the determination (iv) of Q from the $\eta \rightarrow 3\pi$ decay ratio and the Dalitz distribution as the most compelling physics result and recommends to perform this measurement as a run group with GlueX and experiment PR12-10-011 (which is approved to measure the $\eta \rightarrow 2\gamma$ decay width via the Primakoff effect). This part of the proposal can be performed with the existing calorimeter (FCAL) used by GlueX.”

Probable action on our part:

- i. Proceed with $\eta \rightarrow 3\pi$ program.
- ii. Drop this topic from next proposal except for 1 page on the C violating asymmetry in $\eta \rightarrow \pi^+\pi^-\pi^0$.

“Of course, the impact of a discovery in the proposed [leptophobic dark boson and CVPC] channels would be enormous; so as not to prevent these studies from running in the near future, we therefore ask that FCAL-II and the associated JEF physics program be fully incorporated to run in parallel with GlueX. We have thus given the experiment a C2 rating: approval of the physics case with the condition that JEF return to a later PAC with a convincing demonstration of their capabilities for running concurrently with GlueX. We ask that the experimenters include all approved phases of GlueX in their simulations, including JEF compatibility with the newly approved DIRC detector. ...

... We approve these parts of the proposal under the conditions that (i) it is demonstrated that they can run simultaneously with the approved GlueX program (this should in particular include an estimate of the background due to the higher coincidence rate) even when the expected DIRC bars will be installed, and (ii) that the theory motivation is sharpened further.”

Probable action on our part:

- i. Study impact of random coincidences on the rare decay program (tagger, Compton gammas, etc.)
- ii. Incorporate hybrid FCAL-II into simulation.
- iii. Estimate sensitivity of rare decay program during all phases of GlueX running.
- iv. Continue to sharpen the theory motivation for CVPC (and ChPTh in doubly radiative decay?)

“The PAC would also like to see more details on the envisioned program on η' decays.”

Probable action on our part:

- i. Focus on improving dark leptophobic boson limits in the omega mass range via $\eta' \rightarrow \gamma + B \rightarrow \gamma + \pi^+\pi^-\pi^0$.

Estimated Cost for FCAL-II*

(hybrid PbWO₄-Lead Glass version replacing FCAL-I, as of April 2013)

Item	Channels	Cost/Channel	Cost	Nominal Responsibility
Crystal	3445	\$250	\$0.86M	China
PMT+base+ magshield	3445	\$450*	\$1.55M	U.S.
Flash ADC	3445 - 861** = 2584	\$378	\$0.98M	
HV	3445	\$300	\$1.03M	

Total			\$4.4M	
<p>*Increase per channel of \$50 wrt April 2012 estiate reflects recent Hamamatsu quote of \$350/pmt.</p> <p>** 861 is the approximate number of 4cmx4cm lead glass modules displaced by the new 2cmx2cm PbWO₄ modules at small angles.</p>				

Neglects infrastructure costs like the support structure (\$250K), cables and patch panels (\$345K assuming \$100/channel).

C-violating η Decays to π 's and γ 's

Gamma Column
implicitly
includes
 $\gamma^* \rightarrow e^+e^-$

L = 0

L = 1

L = even or
odd (no parity
constraint)

⋮
⋮
⋮
⋮

$\eta \rightarrow X$	0π	1π	2π	3π	4π
0γ	Forbidden	Forbidden	P, CP	Observed	P, CP
1γ	Forbidden	€	€	€	€
2γ	Observed	Observed	Allowed	Allowed	Allowed
3γ	€	€	€	€	€
4γ	Allowed	Allowed	Allowed	Allowed	Allowed

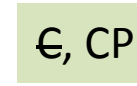
Key:



C and P
allowed,
observed



C and P
allowed,
upper limits
only



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.

Highlight of η decays in the proposal

Main physics goals:

Mode	Branching Ratio	Physics Highlight	Photons
priority:			
$\pi^0 2\gamma$	$(2.7 \pm 0.5) \times 10^{-4}$	χ PTh at $\mathcal{O}(p^6)$	4
$\gamma + B$	beyond SM	leptophobic dark boson	4
$3\pi^0$	$(32.6 \pm 0.2)\%$	$m_u - m_d$	6
$\pi^+ \pi^- \pi^0$	$(22.7 \pm 0.3)\%$	$m_u - m_d, CV$	2
3γ	$< 1.6 \times 10^{-5}$	CV, CPV	3
ancillary:			
4γ	$< 2.8 \times 10^{-4}$	$< 10^{-11}$ [112]	4
$2\pi^0$	$< 3.5 \times 10^{-4}$	CPV, PV	4
$2\pi^0 \gamma$	$< 5 \times 10^{-4}$	CV, CPV	5
$3\pi^0 \gamma$	$< 6 \times 10^{-5}$	CV, CPV	6
$4\pi^0$	$< 6.9 \times 10^{-7}$	CPV, PV	8
$\pi^0 \gamma$	$< 9 \times 10^{-5}$	CV, Ang. Mom. viol.	3
normalization:			
2γ	$(39.3 \pm 0.2)\%$	anomaly, η - η' mixing PR12-10-011	2

1. Search for a leptophobic dark boson (B).

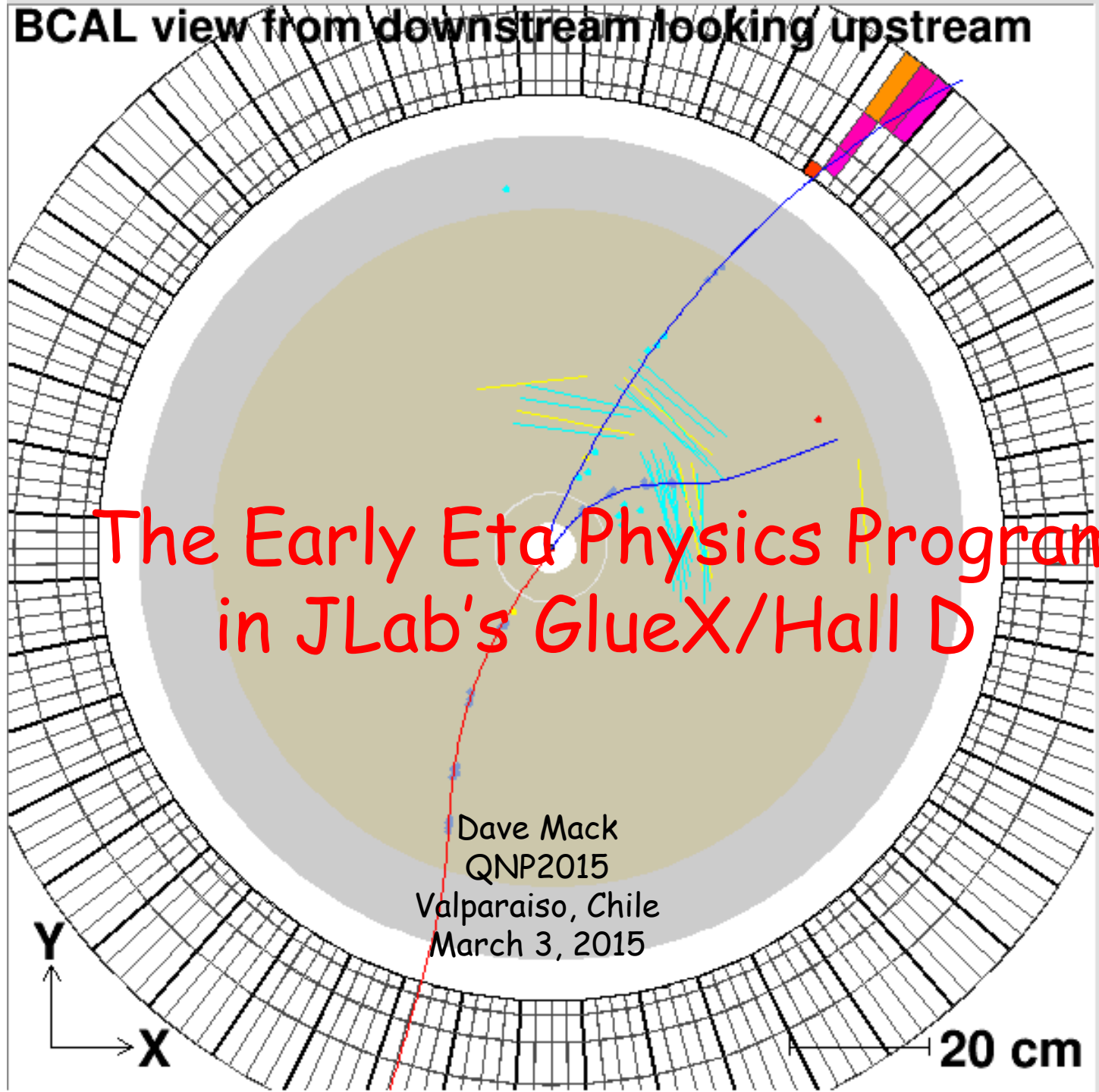
2. Directly constrain CVPC new physics

3. Probe interplay of VMD & scalar resonances in ChPT to calculate $\mathcal{O}(p^6)$ LEC's in the chiral Lagrangian.

4. Constrain the light quark mass ratio

Note: FCAL-II is required for the rare decays

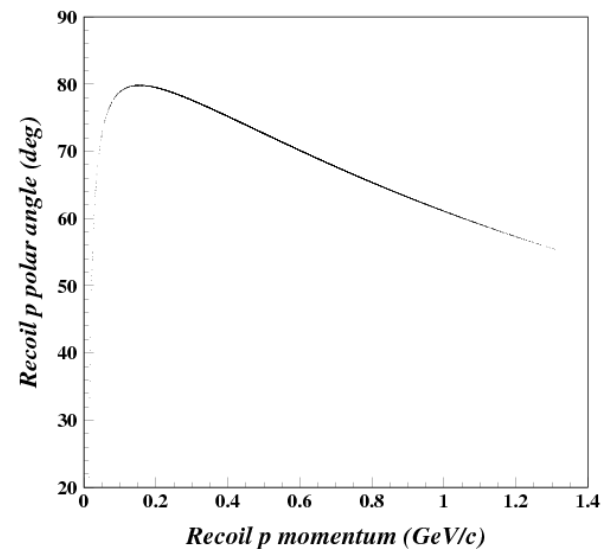
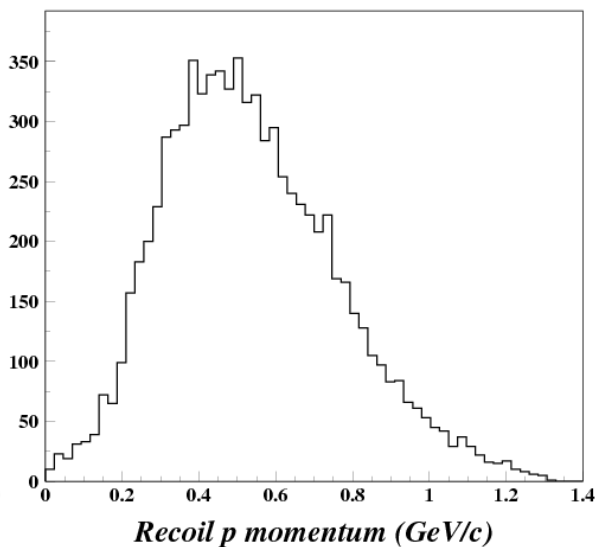
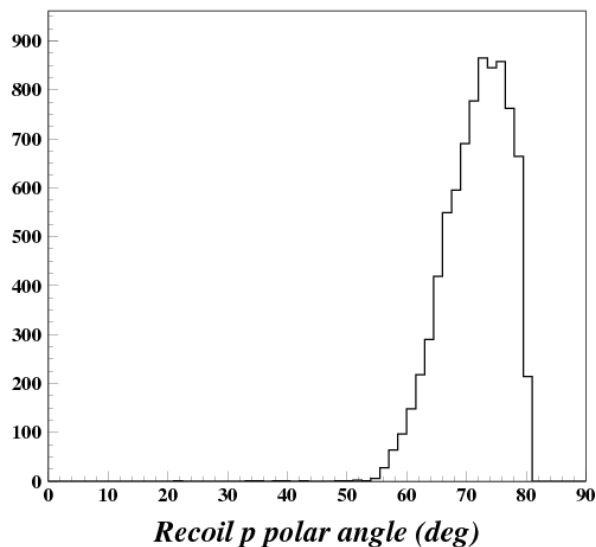
BCAL view from downstream looking upstream



The Early Eta Physics Program in JLab's GlueX/Hall D

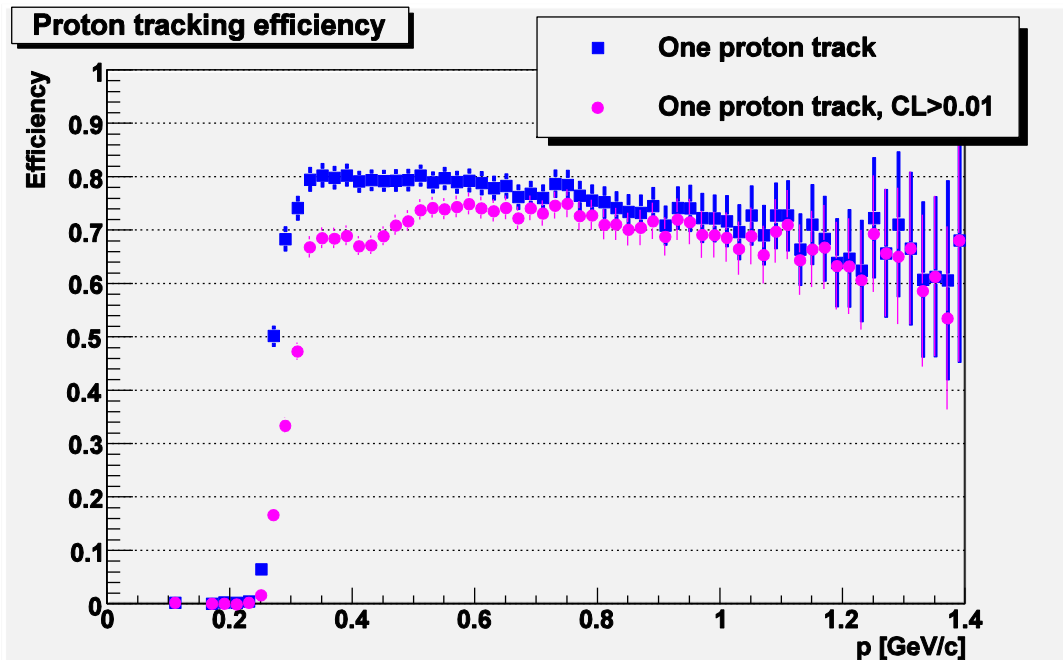
Dave Mack
QNP2015
Valparaiso, Chile
March 3, 2015

Detection of Recoil Proton with GlueX (needed for cut establishing η -proton coplanarity)



Recoil proton kinematics

- Polar angle $\sim 55^\circ$ - 80°
- Momentum ~ 200 - 1200 MeV/c



Selection Rules for $\eta \rightarrow N\pi$

$$\eta: I^G(J^{PC}) = 0^+(0^{-+})$$
$$M_\eta = 547.9 \text{ MeV}/c^2$$

$$\pi^0: I^G(J^{PC}) = 1^-(0^{-+})$$
$$M_{\pi^0} = 135.0 \text{ MeV}/c^2$$

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 $\eta \rightarrow 2\pi, 4\pi$

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 $\eta \rightarrow 3\pi$

C parity:

$$C_\eta = C_{N\pi}$$
$$+1 = (+1)^N$$

No constraints from C parity

What is observed? The η decays into 3π 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 $\eta \rightarrow 2\pi^0$ would imply CP violation since C is conserved.