The JLab Eta Factory (JEF) Experiment

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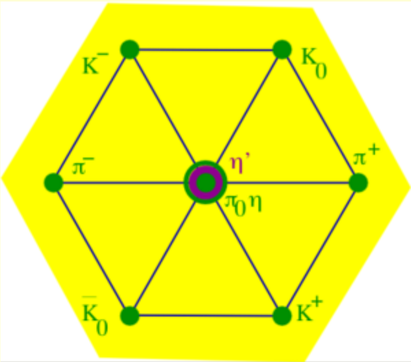
Outline

- Introduction and Motivation
- JEF experiment with GlueX
- Status of JEF project
- Summary

Why η is a unique probe for QCD and BSM physics?



- A Goldstone boson due to spontaneous breaking of QCD chiral symmetry
  ➡ η is one of key mesons bridging our understanding of low-energy hadron dynamics and underlying QCD

- η decay width Γ_η =1.3KeV is narrow (relative to Γ_ω=8.5 MeV)
  ➡ The lowest orders of η decays are filtered out, enhancing the contributions from higher orders (by a factor of ~7000 compared to ω decays).

- Eigenstate of P, C, CP, and G: $I^G J^{PC} = 0^+ 0^{-+}$
  ➡ Study violations of discrete symmetries

- The η decays are flavor-conserving reactions effectively free of SM backgrounds for new physics search.

Overview of JEF project

Mode	Branching Ratio	Physics Highlight	Photons
priority:			
$\pi^0 2\gamma$	$(2.7 \pm 0.5) \times 10^{-4}$	χPTh 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

Main physics goals:

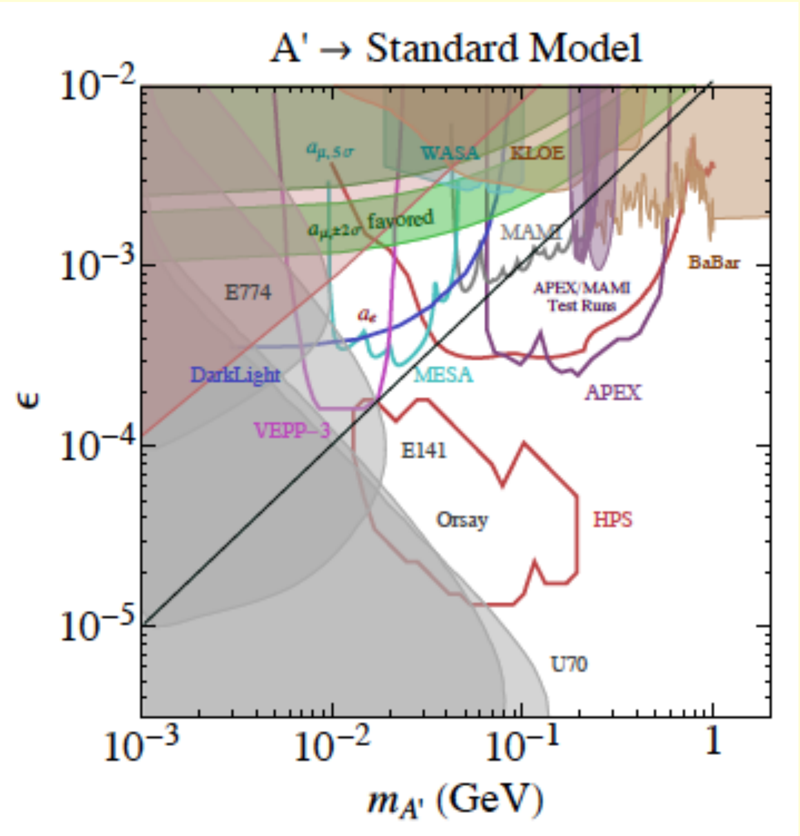
1. Search for a leptophobic dark boson (B).
2. Directly constrain CVPC new physics
3. Probe interplay of VMD & scalar resonances in ChPT to calculate $O(p^6)$ LEC's in the chiral Lagrangian.
4. Constrain the light quark mass ratio

FCAL-II is required for the rare decays

"Vector Portal" to Dark Sector

1. Dark photon A'

$-\frac{1}{2}\varepsilon F^{\mu\nu}F'_{\mu\nu}$ Kinetic mixing and U(1)'



Most A' searches rely on the leptonic coupling of new force

2. Dark leptophobic B-boson (dark ω, γ_B, or Z'): $\frac{1}{3}g_B\bar{q}\gamma^{\mu}qB_{\mu}$

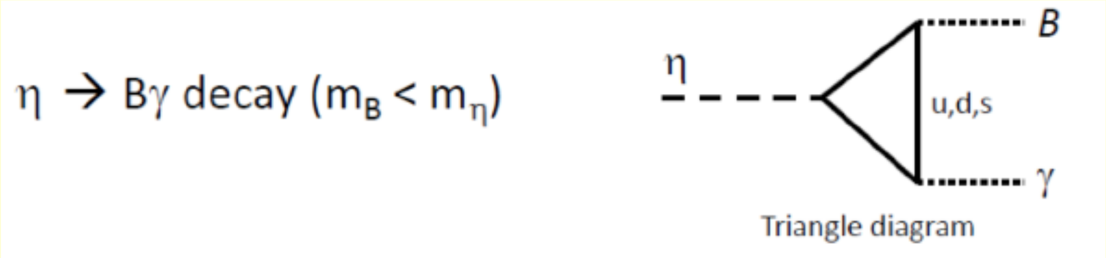
Gauged baryon symmetry $U(1)_B$

P. Langacker, Rev.Mod.Phys. 81, 1199 (2009), 0801.1345; M. Williams, C. Burgess, A. Maharana, and F. Quevedo, JHEP 1108, 106 (2011),

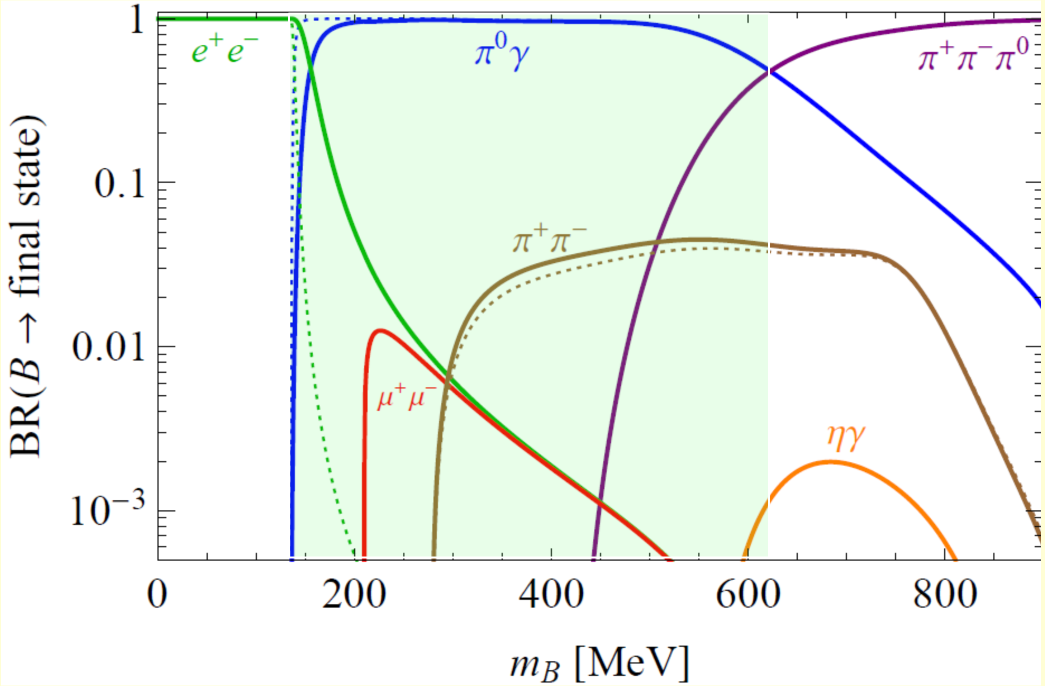
- the stability of baryonic and dark matter
- a unified genesis of baryonic and dark matter M.Graesser, I. Shoemaker and L. Vecchi, arXiv:1107.2666
- a natural framework for resolving "Strong CP problem" in QCD
- the $m_B < m_\pi$ region is strongly constrained by long-range forces search and nuclear scattering exp. ; the $m_B > 50GeV$ has been investigated by the collider exp.
- GeV-scale domain is nearly untouched, → a discovery opportunity!

Striking signature for B-boson in $\eta \to \pi^0\gamma\gamma$

- B production: A.E. Nelson, N. Tetradis, Phys. Lett., B221, 80 (1989)



- B decays: $B \to \pi^0\gamma$ in 140-620 MeV mass range



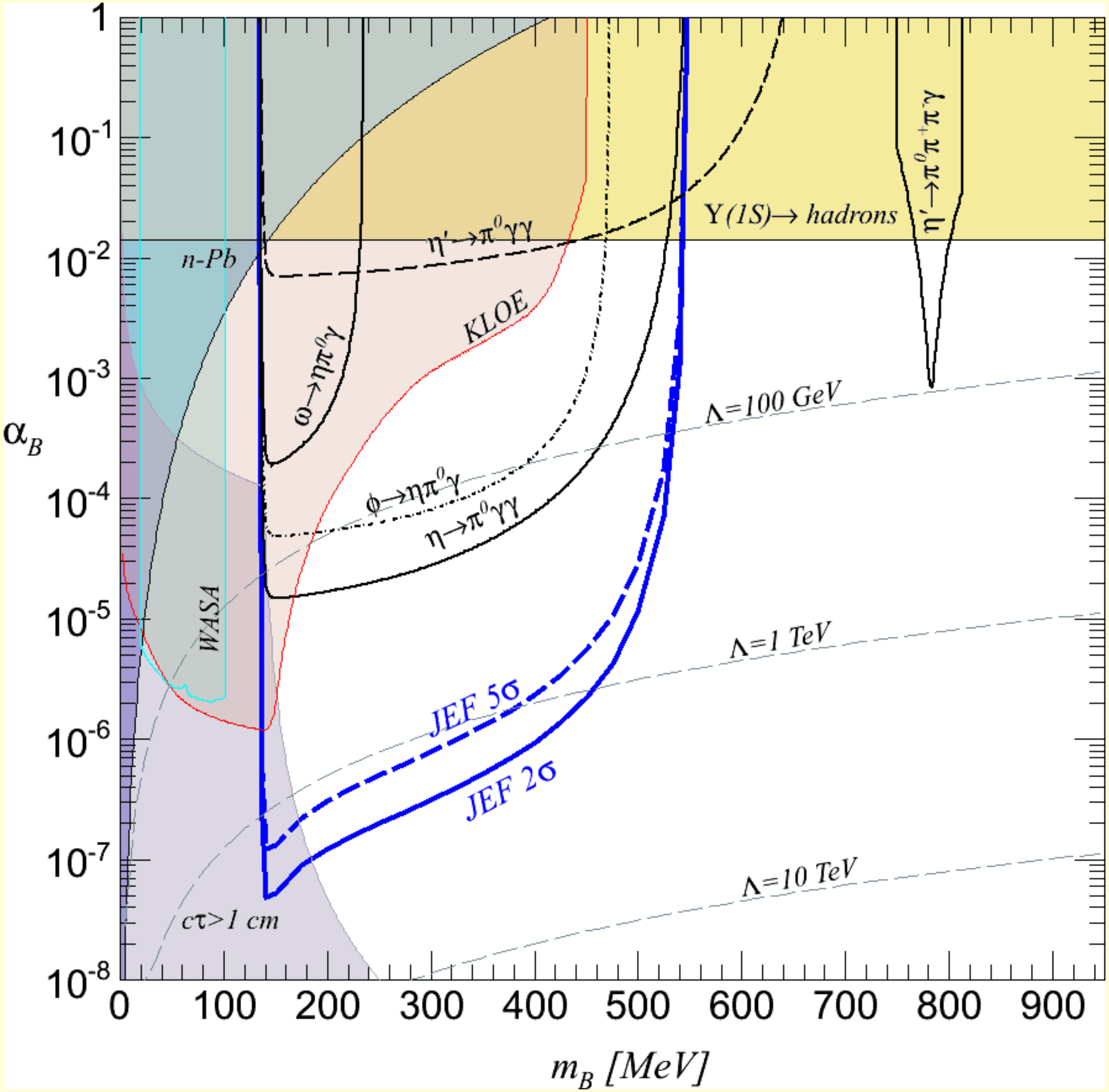
$\eta \to \gamma B \to \gamma + \pi^0\gamma$

Search for a resonance peak of $\pi^0\gamma$ for m_B ~140-550 MeV

S. Tulin, Phys.Rev., D89, 14008 (2014)

- $\Gamma(\eta \to \pi^0\gamma\gamma) \sim 0.3eV$ ➡ highly suppressed SM background

JEF Experimental Reach ($\eta \to B\gamma \to \pi^0\gamma\gamma$)



- A stringent constraint on the leptophobic B-boson in 140-550 MeV range.
- A positive signal of B in JEF will **imply a new fermion with a mass up to a few TeV due to electro-weak anomaly cancellation.**
- Future η' experiment will extend the experimental reach up to 1 GeV

Constraints from A' search (KLOE and WASA) assumed:

$$\varepsilon \sim 0.1 \times e g_B / (4\pi)^2$$

C Invariance

- Maximally violated in the weak force and is well tested.
- Assumed in SM for electromagnetic and strong forces, but **it is not experimentally well tested (The current constraint: $\Lambda \geq 1$ GeV)**
- EDMs place no constraint on CVPC in the presence of a conspiracy or new symmetry; **only the direct searches are unambiguous**.

(M. Ramsey-Musolf, phys. Rev., D63, 076007 (2001); talk at the AFCI workshop)

C Violating η neutral decays

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

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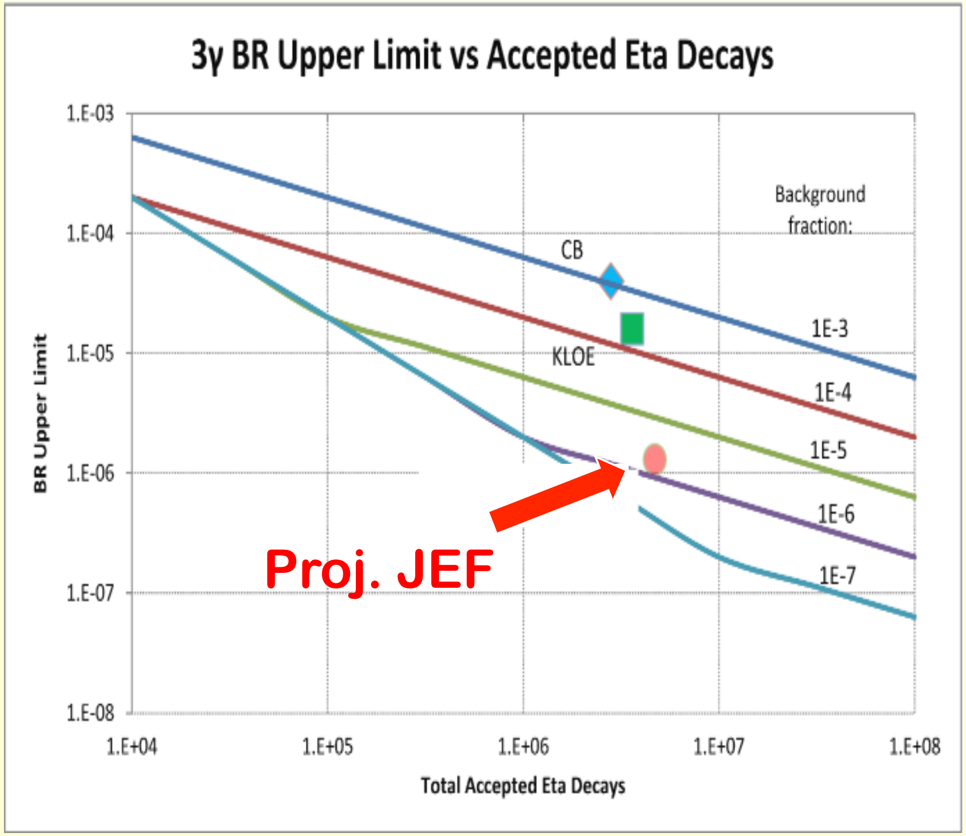
Experimental Improvementon η→3γ

- SM contribution: BR(η→3γ) <10^{-19} via P-violating weak interaction.
- A new C- and T-violating, and P-conserving interaction was proposed by Bernstein, Feinberg and Lee   Phys. Rev.,139, B1965 (1965)
- A calculation due to such new physics by Tarasov suggests: BR(η→3γ)< 10^{-2} Sov.J.Nucl.Phys.,5,445 (1967)
- A new investigation by M. Ramsey-Musolf and two Ph.D. students is in progress



Improve BR upper limit by one order of magnitude to directly tighten the constraint on CVPC new physics

What is the expected impact of the SM allowed $\eta \to \pi^0 \gamma\gamma$ measurement on ChPT?

➡ A rare window to probe interplay of VMD & scalar resonances in ChPT to calculate $O(p^6)$ LEC's in the chiral Lagrangian

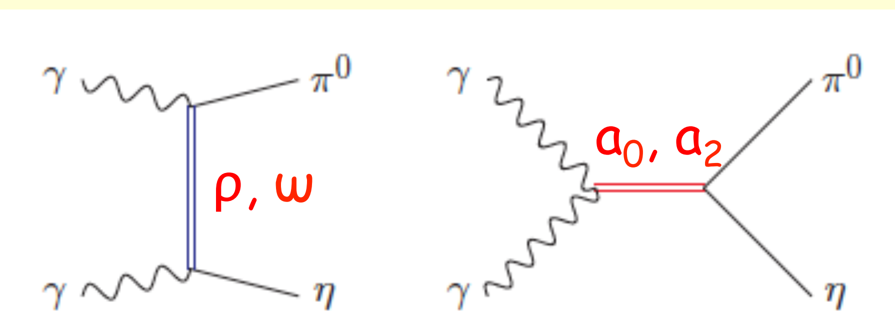
◆ The major contributions to $\eta \to \pi^0 \gamma\gamma$ are two $O(p^6)$ counter-terms in the chiral Lagrangian ➡ an unique probe for the high order ChPT.

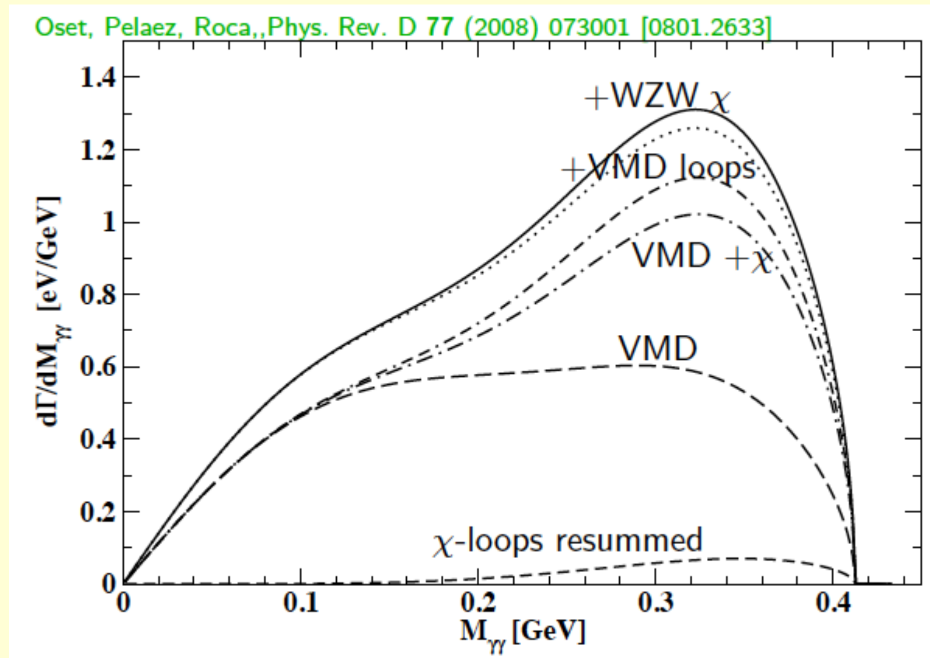
L. Ametller, J, Bijnens, and F. Cornet, Phys. Lett., B276, 185 (1992)

◆ Shape of Dalitz distribution is sensitive to the role of scalar resonances.

LEC's are dominated by meson resonances

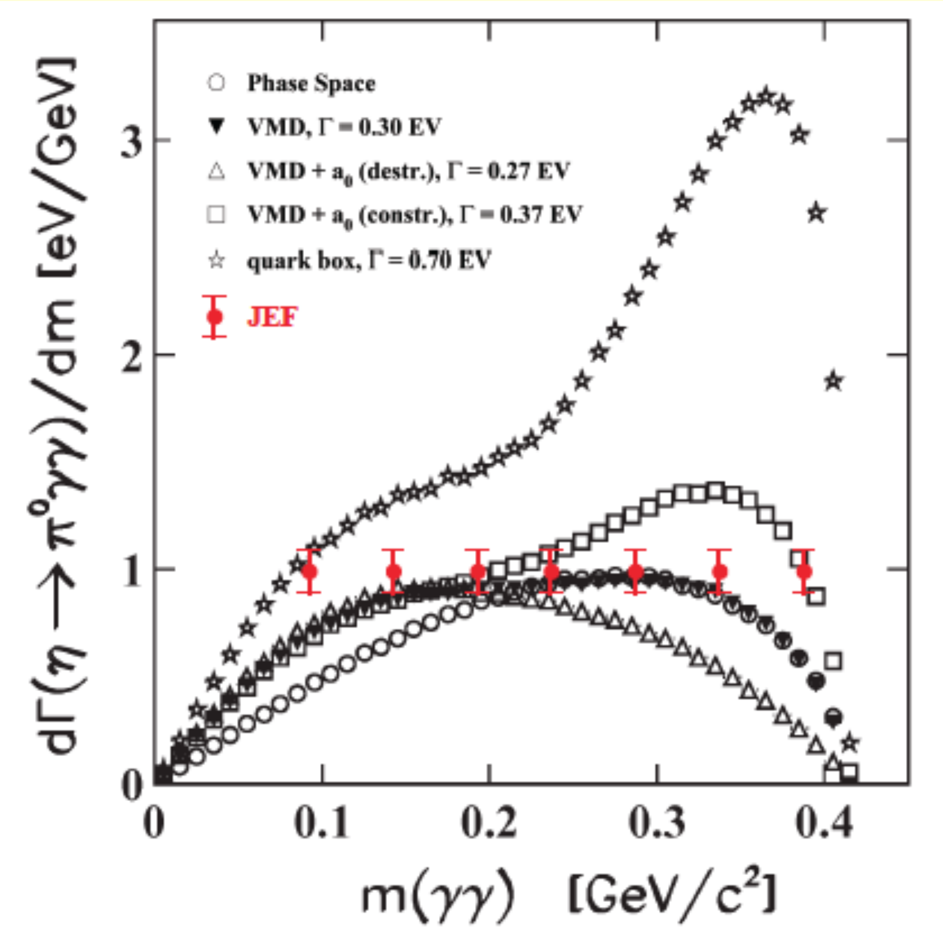
Gasser, Leutwyler 84; Ecler, Gasser, Pich, de Rafael 1989; Donoghue, Ramirez, Valencia 1989

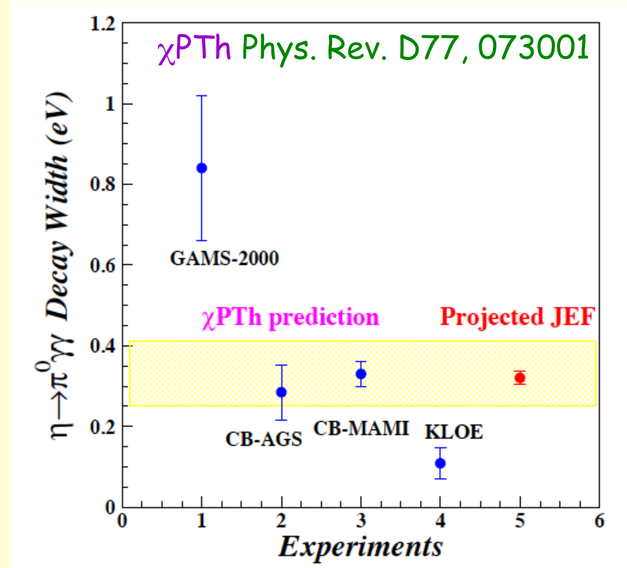


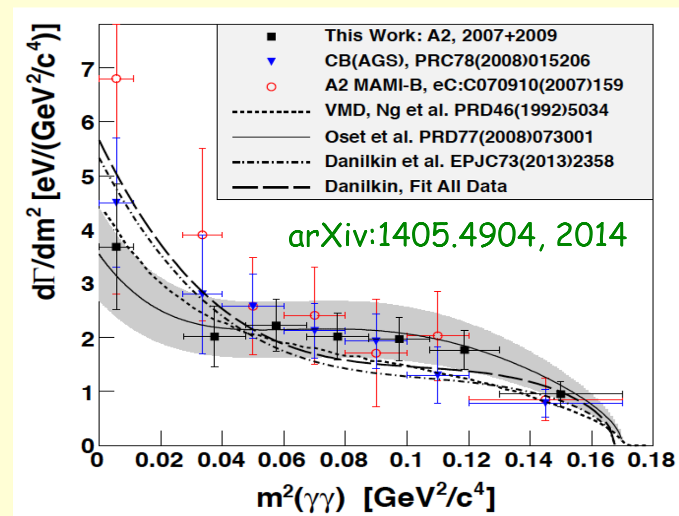


Projected JEF results on $\eta \to \pi^0 \gamma\gamma$

J.N. Ng and D.J. Peters, Phys. Rev. D47, 4939







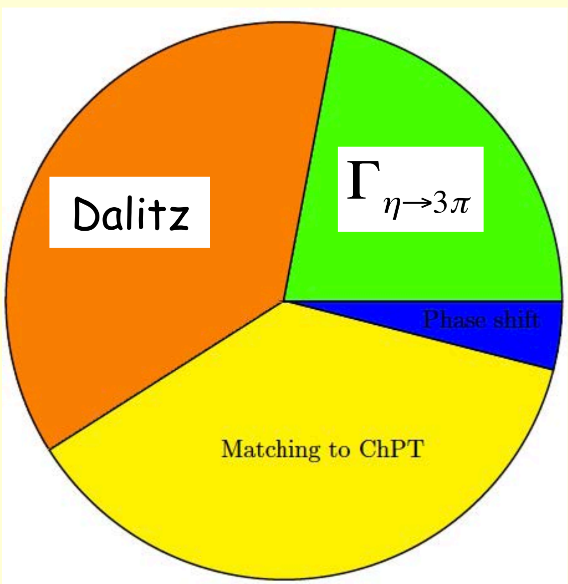
We measure both BR and Dalitz distribution

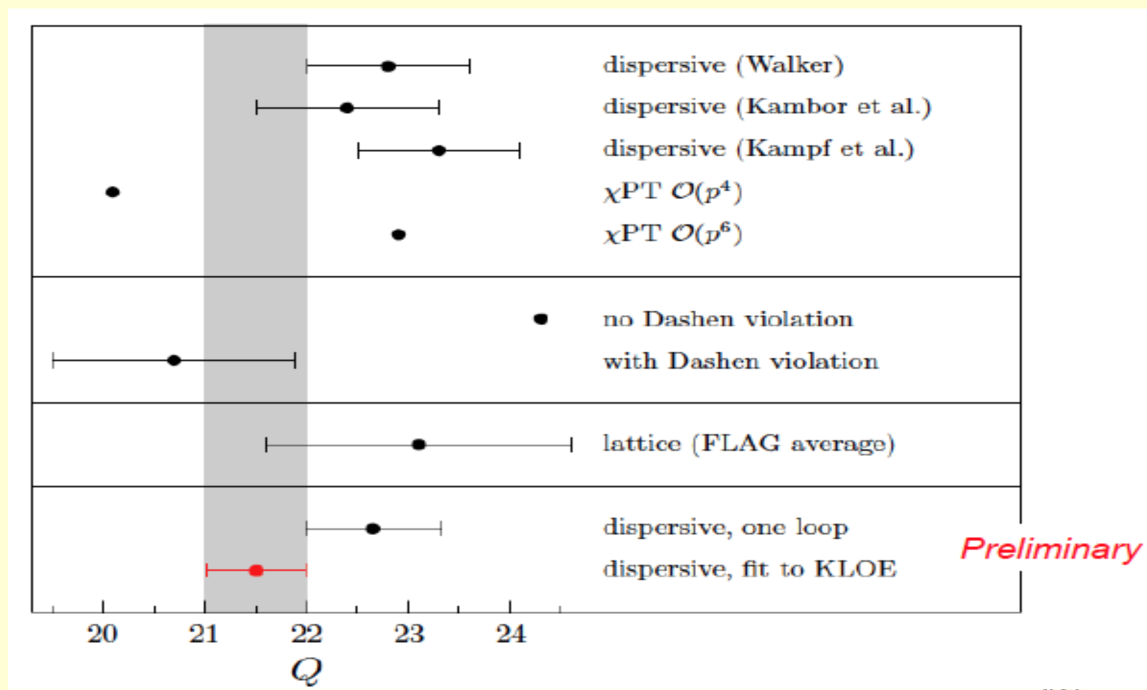
- model-independent determination of two LEC's of the $O(p^6)$ counter- terms
- probe the role of scalar resonances to calculate other unknown $O(p^6)$ LEC's

J. Bijnens, talk at AFCI workshop

What is the physics impact $\eta\to 3\pi$ measurement?

- **A clean probe for quark mass ratio:** $Q^2 = \frac{m_s^2 - \hat{m}^2}{m_d^2 - m_u^2}$ $\hat{m} = \frac{m_u + m_d}{2}$
  - decays through isospin violation: $A = (m_u - m_d)A_1 + \alpha_{em}A_2$
  - α_{em} is small
  - Amplitude: $A(s,t,u) = \frac{1}{Q^2}\frac{m_K^2}{m_\pi^2}(m_\pi^2 - m_K^2)\frac{\mathcal{M}(s,t,u)}{3\sqrt{3}F_\pi^2}$,
- Uncertainties in quark mass ratio (E. Passemar, talk at AFCI workshop)





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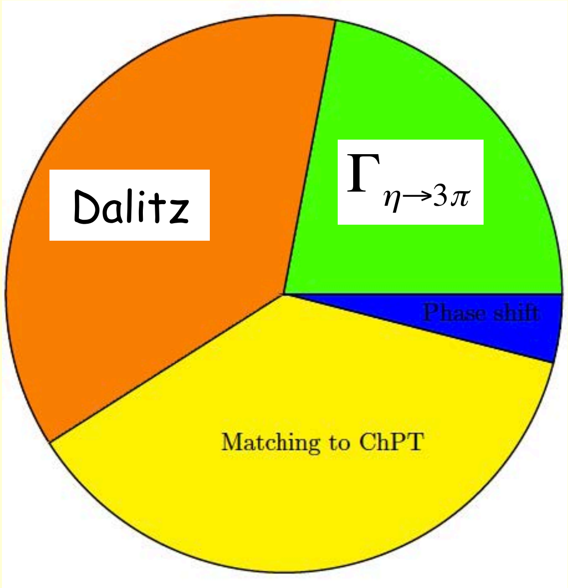
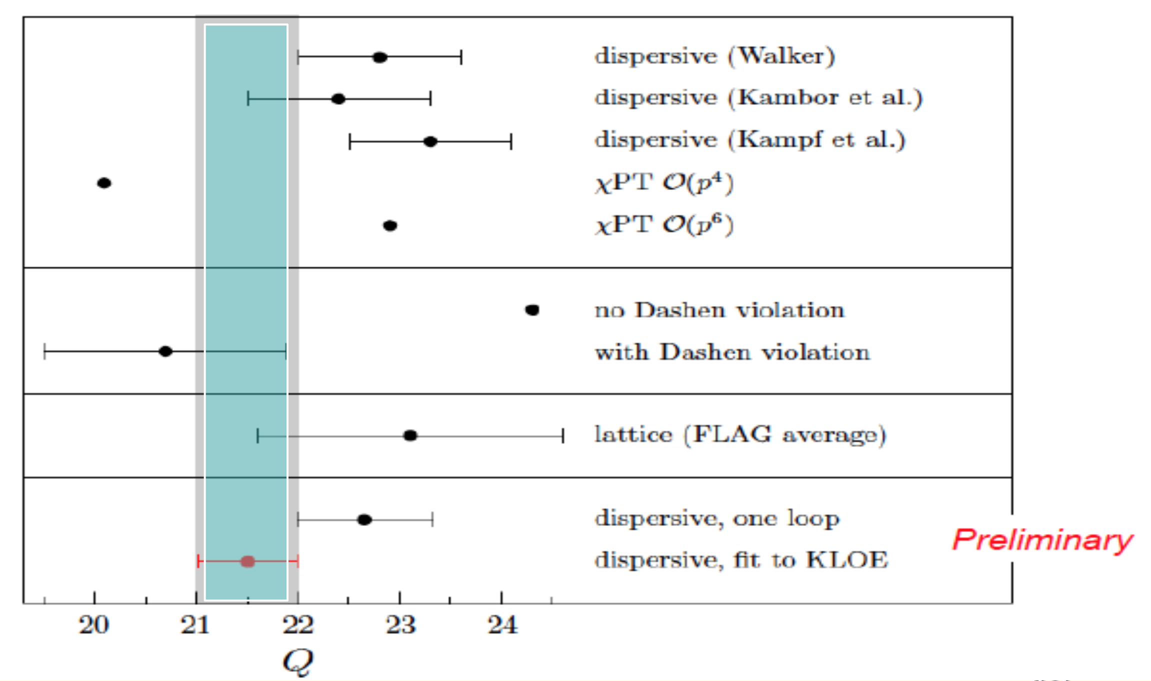
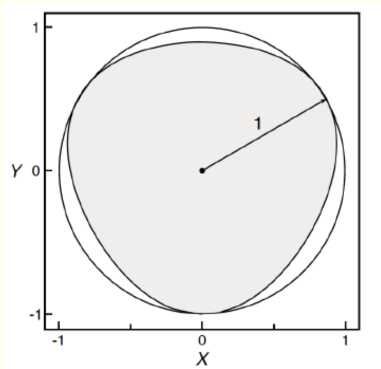




Experimental Measurements of $\eta \to 3\pi$



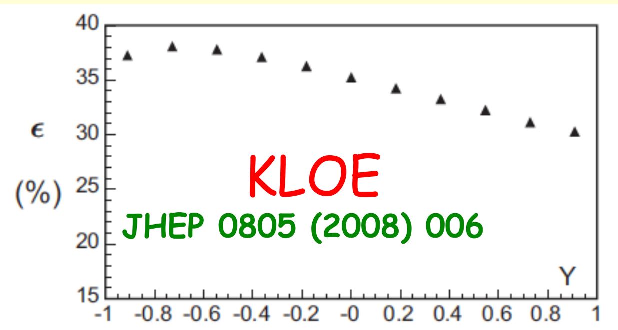
$$X = \frac{\sqrt{3}}{2 M_\eta Q_c}(u - t)$$

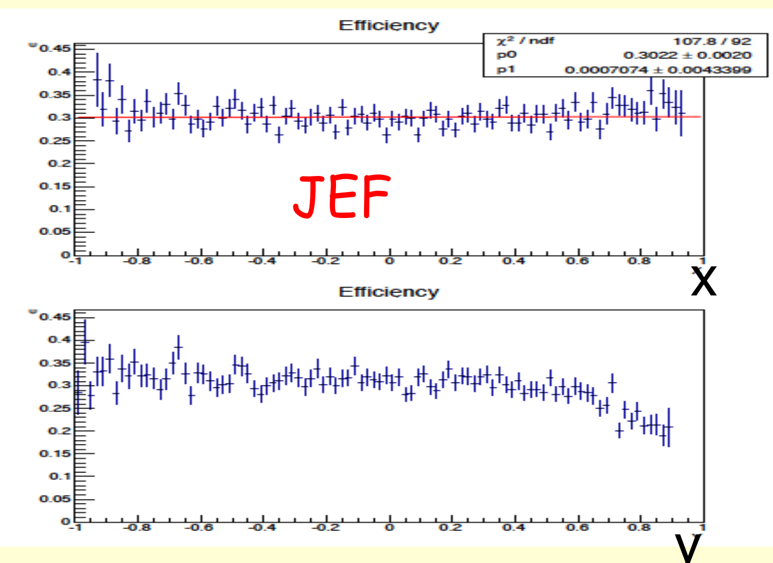
$$Y = \frac{3}{2 M_\eta Q_c}\left(\left(M_\eta - M_{\pi^0}\right)^2 - s\right) - 1$$

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

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

Exp.	$3\pi^0$ Events (10^6)	$\pi^+ \pi^- \pi^0$ Events (10^6)
Total world data (include prel. WASA and prel. KLOE)	6.5	6.0
GlueX+PrimEx-η +JEF	20	19.6





- Existing data from the low energy facilities are sensitive to the detection threshold effects
- JEF at high energy has uniform detection efficiency over Dalitz phase space
- JEF will offer large statistics and improved systematics

World competition in η decays

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e^+e^- Collider

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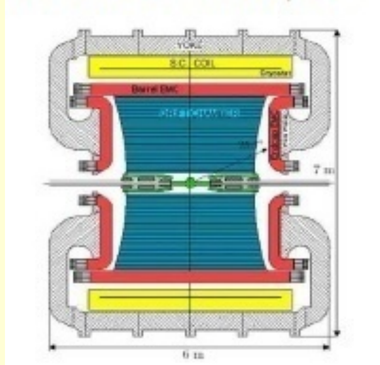
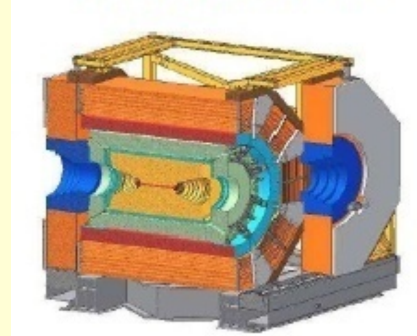
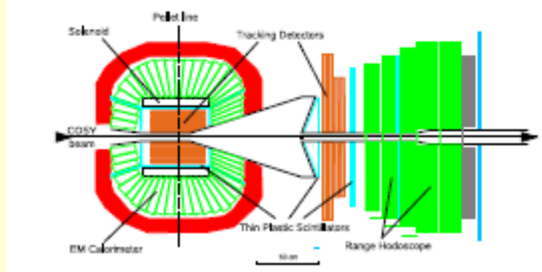


KLOE-2 at DAΦNE



BESIII at BEPCII

Fixed-target



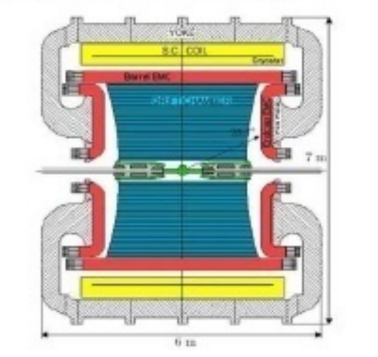
WASA at COSY

hadroproduction

World competition in η decays

e⁺e⁻
Collider

KLOE-2 at DAΦNE



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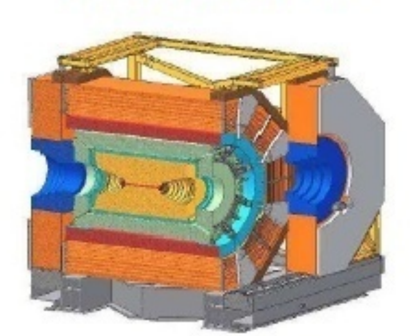

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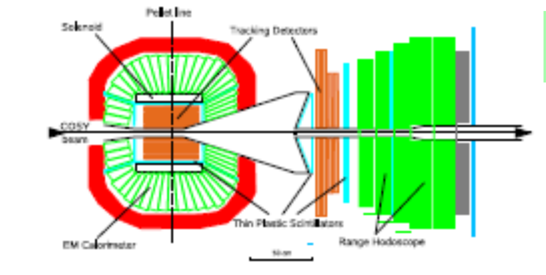
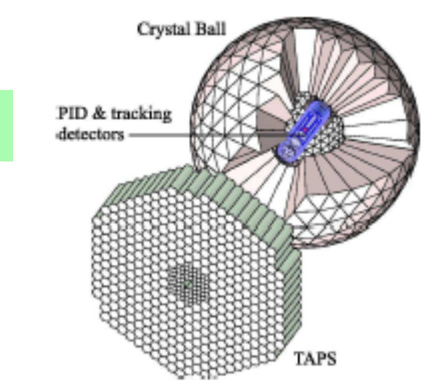


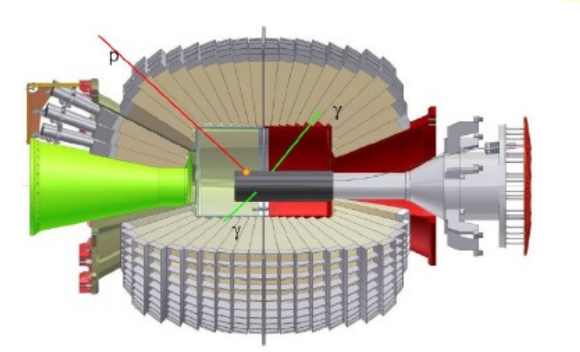
hadroproduction

photoproduction

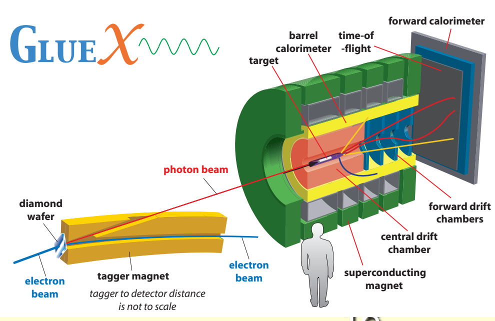
Crystall Ball at MAMI



CBELSA/TAPS at ELSA



JEF at Jlab



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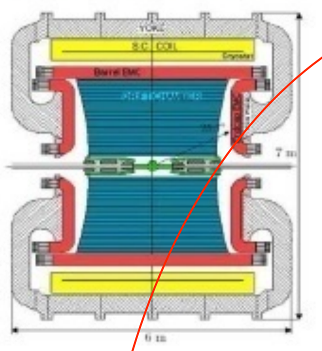

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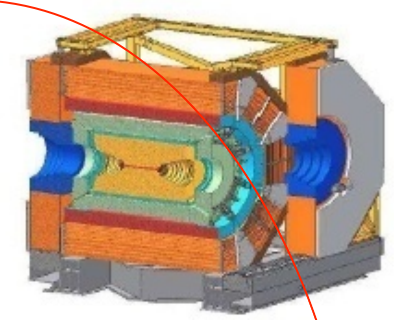
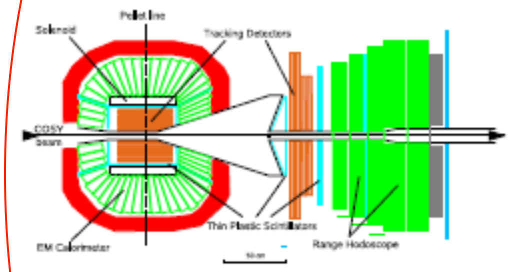


Low energy η-facilities

Fixed-target

WASA at COSY



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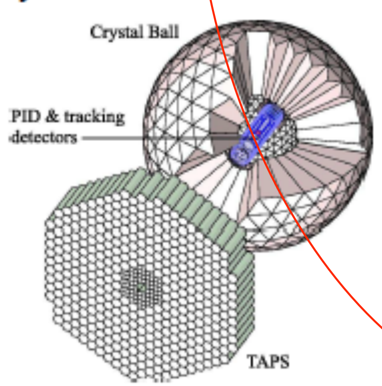

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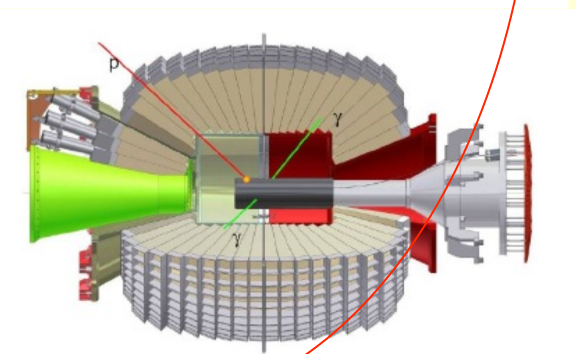

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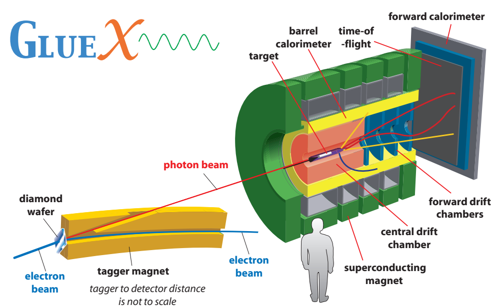

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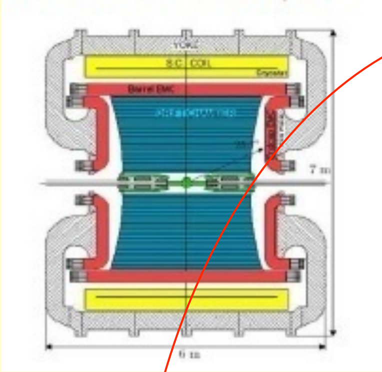

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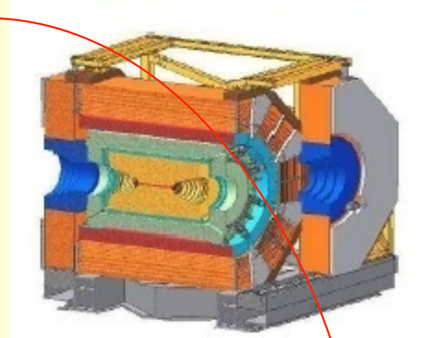

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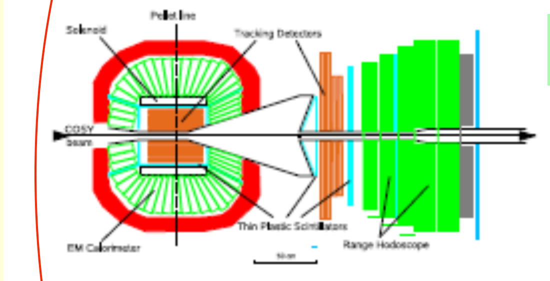

hadroproduction

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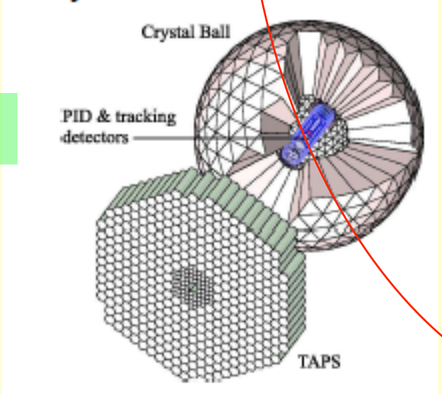

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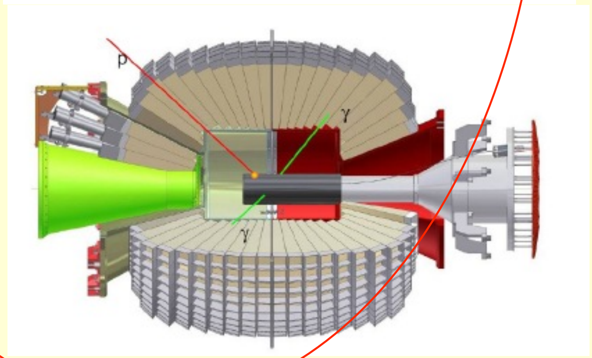
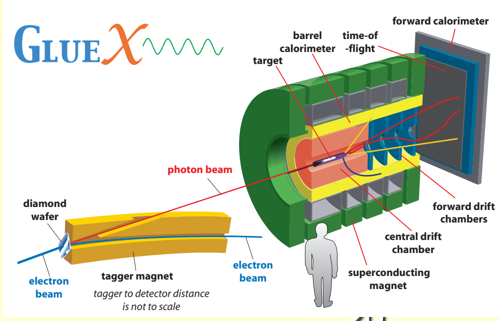
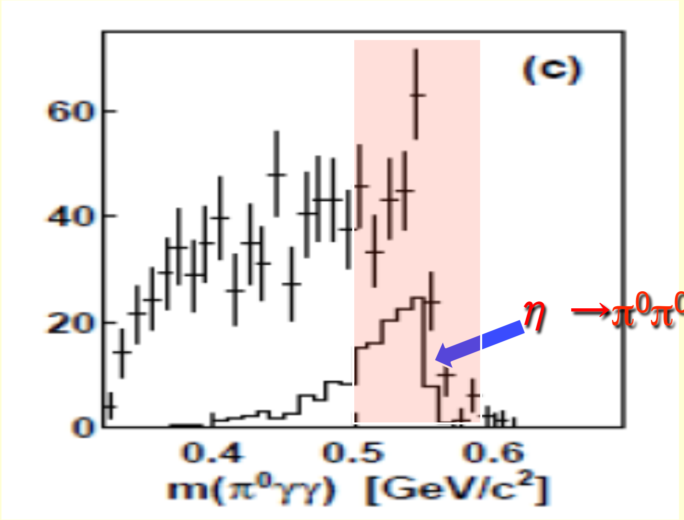


JEF at Jlab

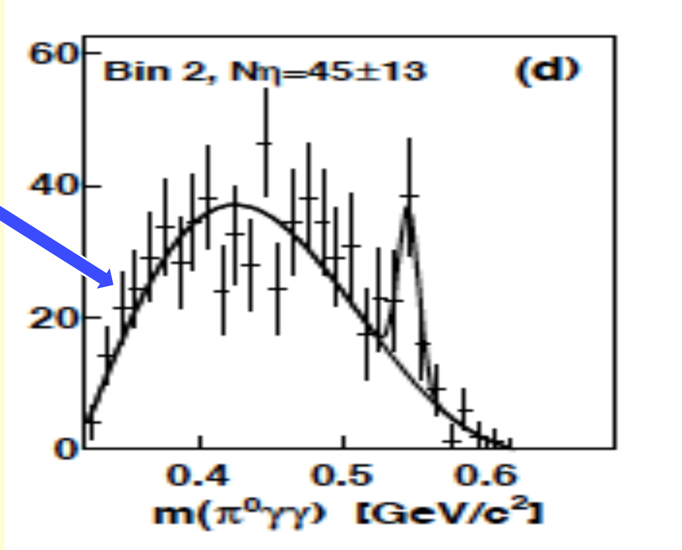


Filter Background with η Energy Boost ($\eta \to \pi^0\gamma\gamma$)

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



γp→ π⁰π⁰ + p



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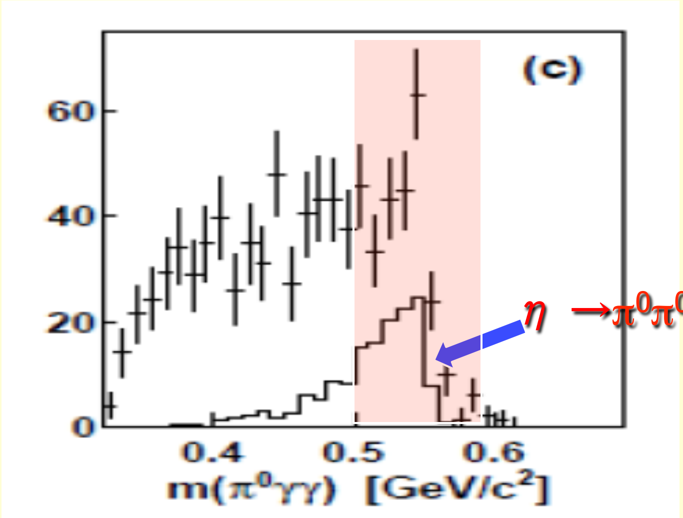
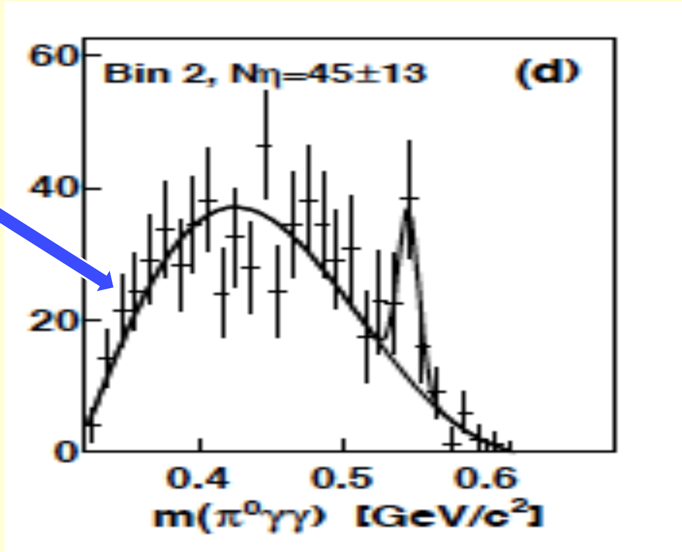
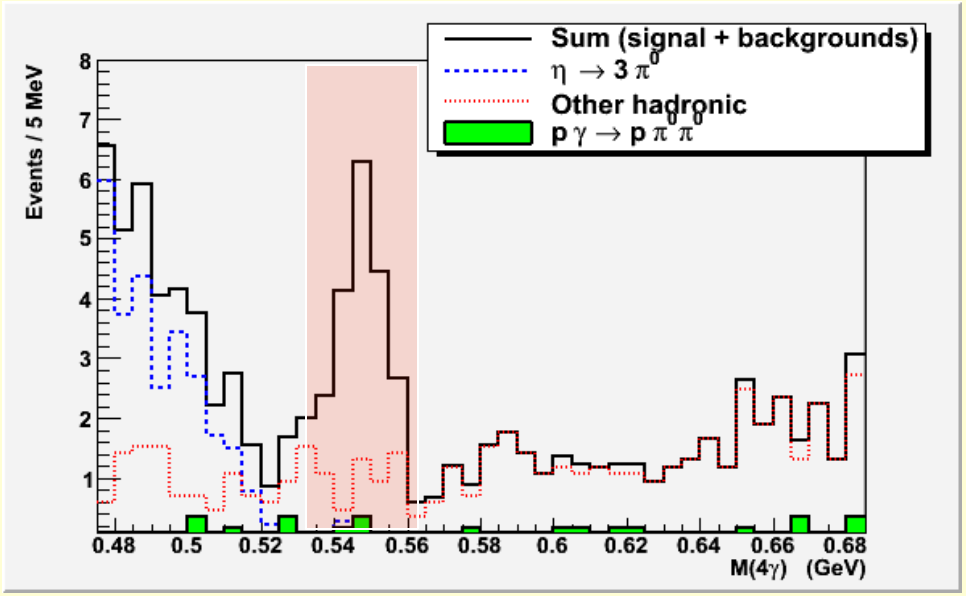


$\gamma p \to \pi^0\pi^0 + p$

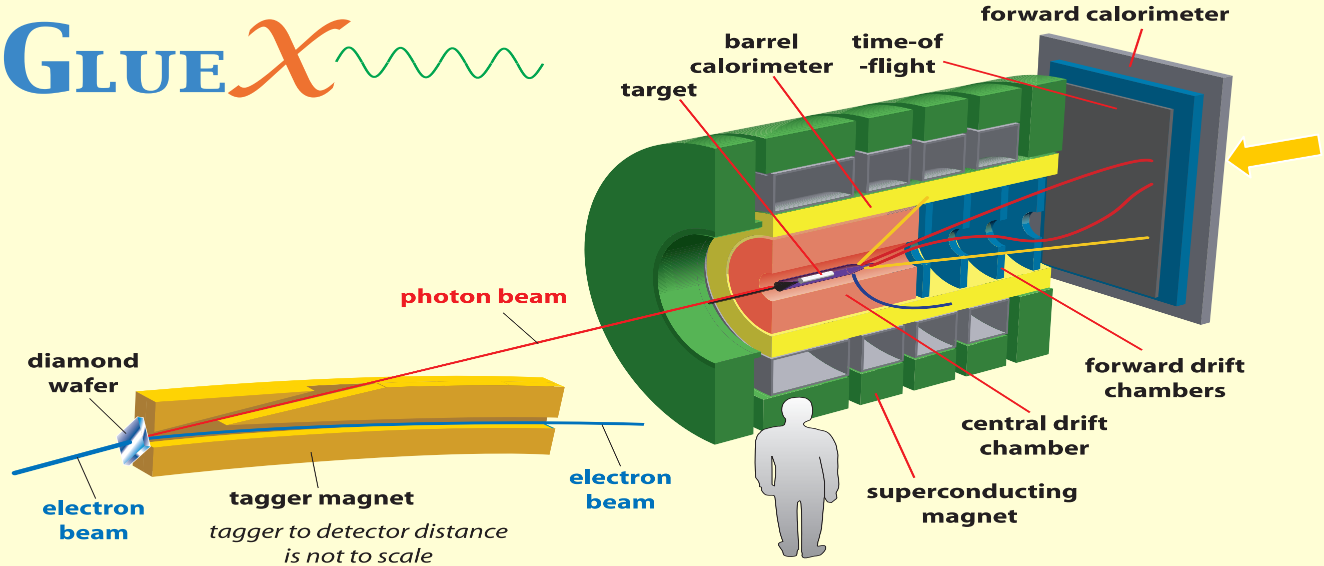


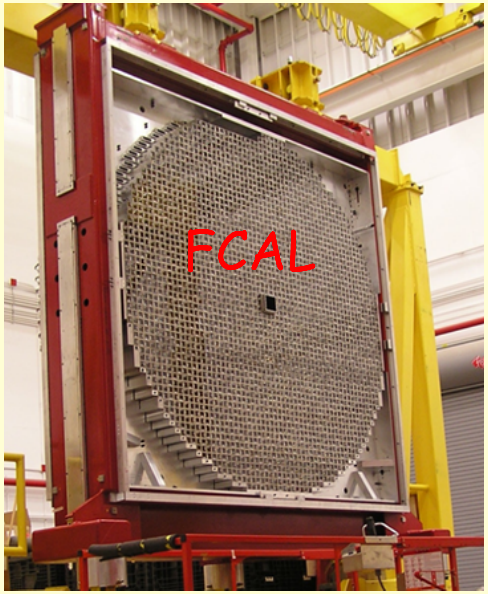
Jlab:

$\gamma p \to \eta p$ ($E\gamma$ = 9-11.7 GeV)



Proposed JEF run





Simultaneously measure η neutral decays: $\eta\to\pi^0\gamma\gamma$, $\eta\to3\gamma$, and …

- η produced on LH_2 target with **9-11.7 GeV tagged photon beam:**

  $\gamma+p \to \eta+p$

- Reduce non-coplanar backgrounds by **detecting recoil p's** with GlueX detector (ε~75%)

- Upgraded Forward Calorimeter with **High resolution, high granularity** **$PbWO_4$** insertion (**FCAL-II**) to detect multi-photons from the η decays

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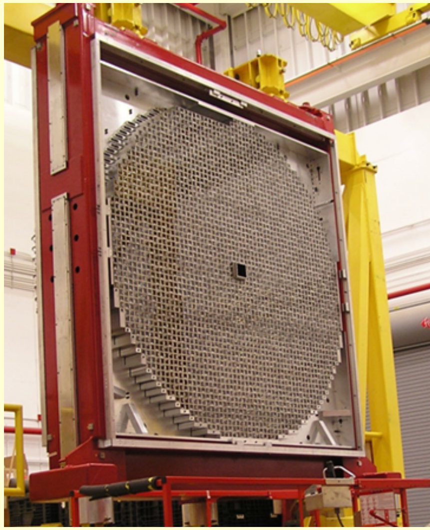
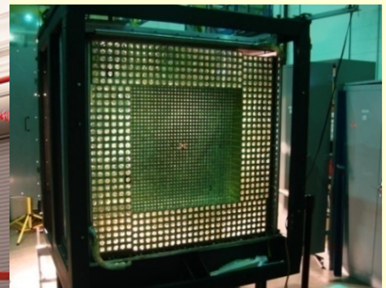
New Equipment: FCAL-II



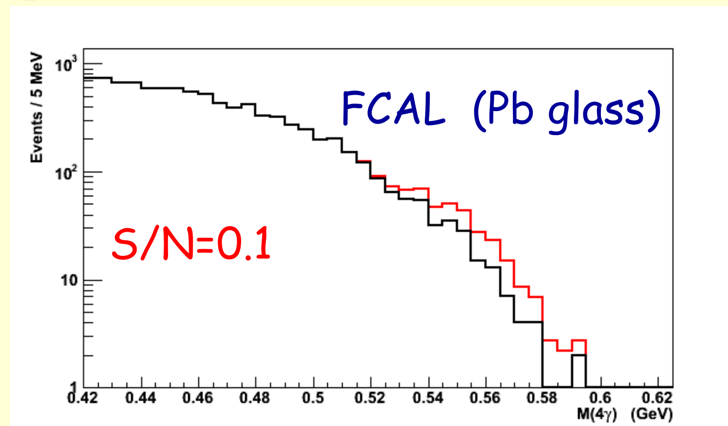
HyCal

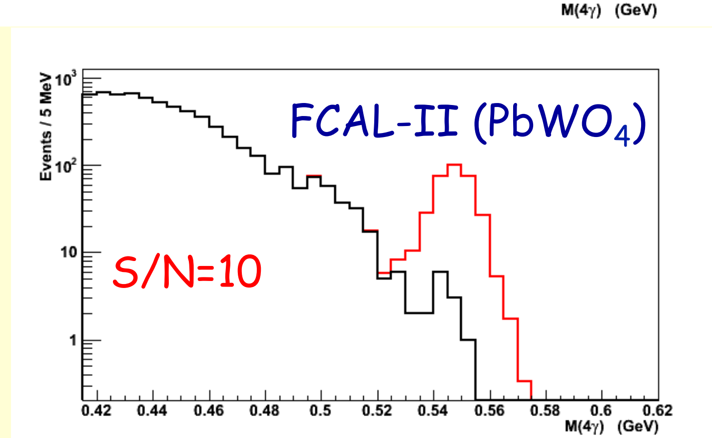


FCAL with PWO insertion:
$118 \times 118\ cm^2$ in Size (3445 $PbWO_4$)
2cm x 2cm x 18cm per module

S/N Ratio vs. Calorimeter Types

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





FCAL-II ($PbWO_4$) vs. FCAL (Pb glass)

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

Status Of JEF Project

- Proposed experiment was submitted to Jlab PAC42

- Non-rare $\eta \rightarrow 3\pi$ decays can run in parallel to approved GlueX using **standard GlueX setup**. Jlab PAC42 considers it to be "the most compelling physics result and recommends to perform this measurement as a run group with GlueX and experiment PR12-10-011".

- The rare η decays require upgraded FCAL-II. PAC42 recognizes "the impact of a discovery in the proposed channels would be enormous". PAC conditionally approved the rare decay part of physics with the condition that JEF can be running concurrently with the GlueX program.

Summary

- 12 GeV tagged photon beam with GlueX setup offers a unique opportunity for discovering weakly-coupled new forces in neutral mode. It provides two orders of magnitude in background reduction in the neutral rare η decays compared to other facilities in the world.

- Perform a simultaneous measurement of η decays:
  1. **Probe a leptophobic dark B-boson in 140-550 MeV range via $\eta \to B\gamma \to \pi^0\gamma\gamma$ (complementary to ongoing A' search)**
  2. **Directly constrain CVPC new physics via $\eta \to 3\gamma$ and other C-violating channels**
  3. **Test the role of scalar dynamics in ChPT through $\eta \to \pi^0\gamma\gamma$**
  4. **A clean determination of the light quark mass ratio via $\eta \to 3\pi$**

- Future extension to η' decays

This project is supported by the U.S. National Science Foundation grant PHY-1206043.

Thank you

Kinetic Mixing

C, D. Carone and H. Murayama, Phys. ReV., D52, 484, (1995)
A. Aranda, C.D. Carone, Phys. Let., B443, 352 (1998)

kinetic mixing term is generated only through radiative corrections, so that $c(\Lambda) = 0$ but $c(\mu) \neq 0$ for $\mu < \Lambda$. We will show that if 200 GeV $\lesssim \Lambda \lesssim$ 1.3 TeV, $c(\mu)$ never becomes large enough in the low-energy theory to conflict with precision electroweak measurements, even when α_B is as large as 0.1. We then present a model that satisfies this boundary condition. In addition, we show that

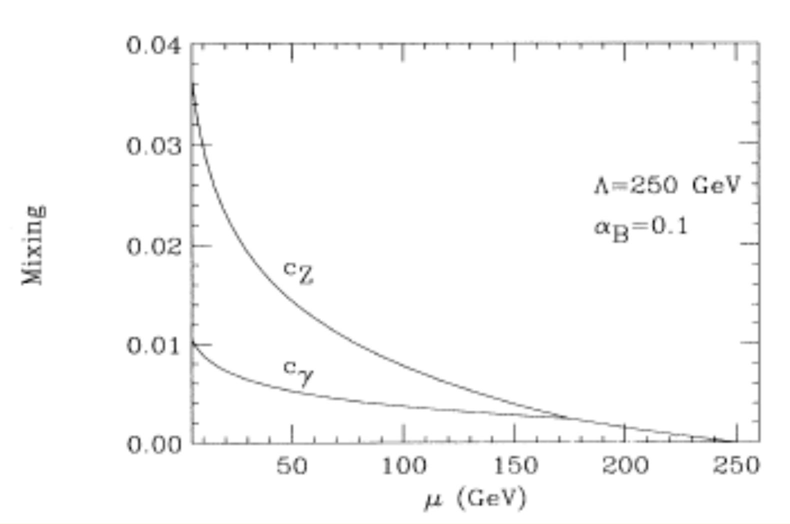
A. A model

The gauge structure of the model is

$$SU(3)_C \times SU(2)_L \times U(1)_Y \times SU(4)_H,$$

where $SU(4)_H$ is a horizontal symmetry. In addition to the ordinary three families of the standard model, f^i $(i = 1, 2, 3)$, we assume there is a fourth family F; the horizontal symmetry acts only on the quarks in the four families, which together transform as a **4** under the $SU(4)_H$. The $U(1)_B$ gauge group is embedded into $SU(4)_H$ as

$$B = \begin{pmatrix} 1/3 & & & \\ & 1/3 & & \\ & & 1/3 & \\ & & & -1 \end{pmatrix}. \qquad (3.2)$$



Typical

Anomaly Cancellation

There a variety of constructions exist in the literature for anomy free UV completions of a local $U(1)_B$ symmetry

B. Batell, M. Pospelov, et. al., arXiv:1405.7049
M. William, C.P. Burgess, et., al., JHEP 08, 106 (2011)

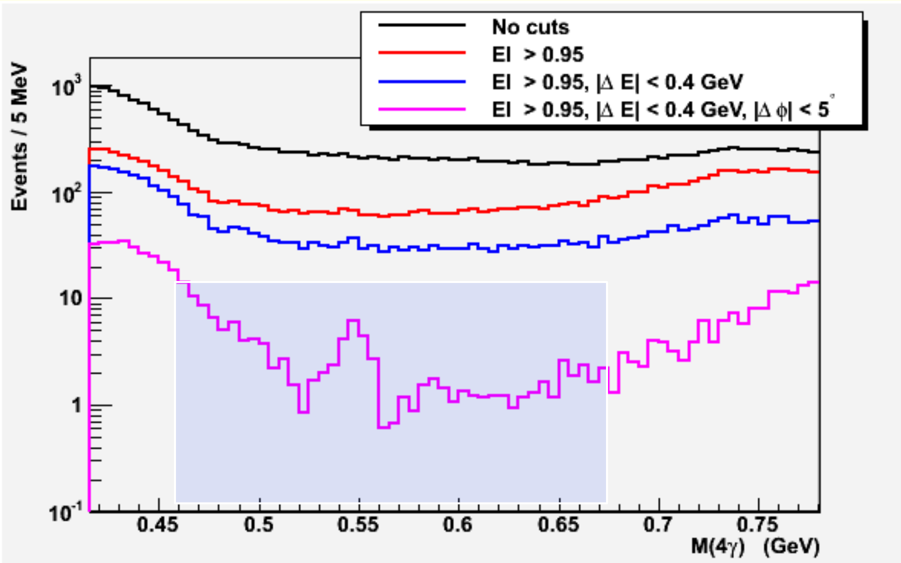
The simplest model is a 4th generation of fermions that is vector-like under the SM gauge symmetries and chiral under $U(1)_B$.

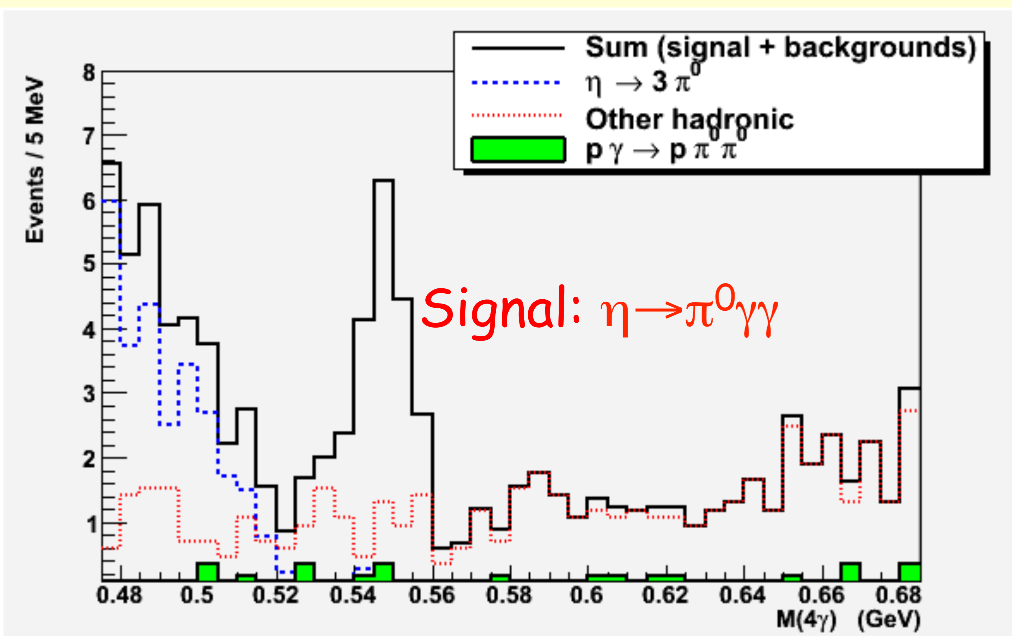
M. Duerr and P. F. Perez, Phys.Lett. B732 (2014) 101-104
P. F.Perez and M.B. Wise, Phys.Rev. D82 (2010) 011901

Having the extra states heavy enough to evade direct constraints does imply a additional bound on B-boson from the collider data $m_B/\Lambda \gtrsim g_B/(4\pi)$

B.A. Dobrescu and C. Frugiuele, arXiv:1404.3947
S. Tulin, Phys.Rev. D89 (2014) 114008

Hadronic Backgrounds Reduction in 4γ States



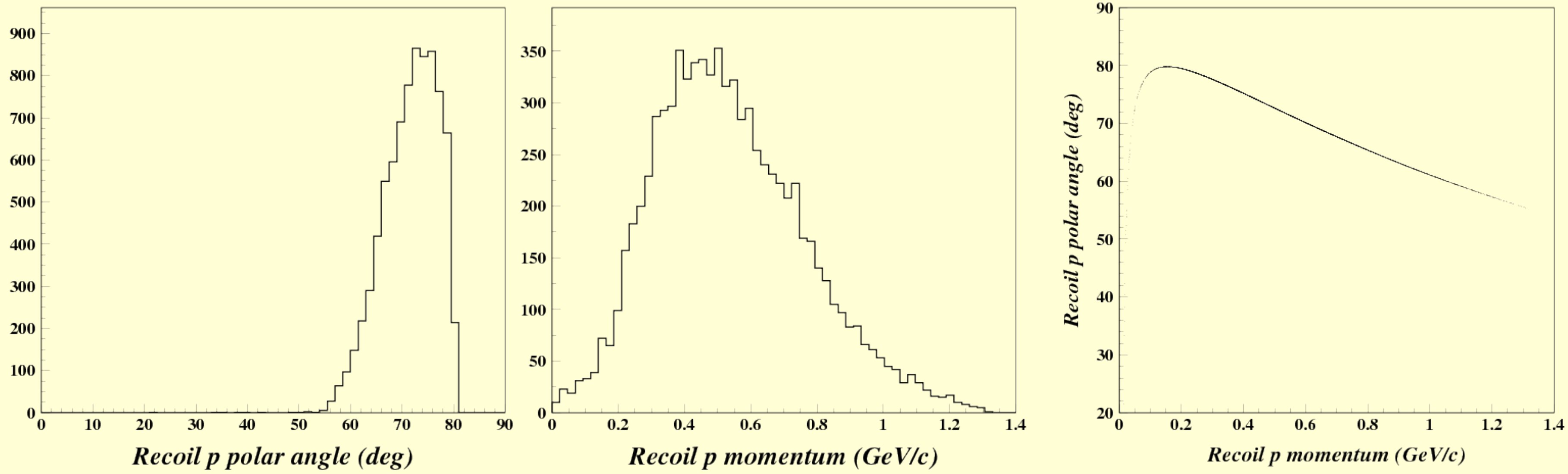


Event Selection

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

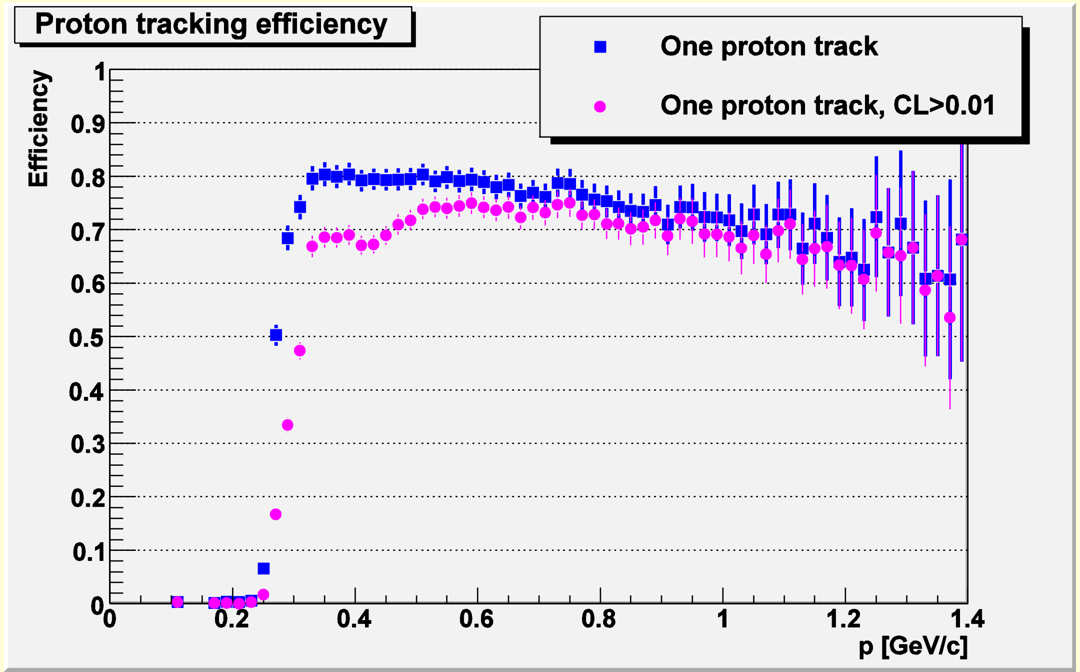
Note:
- Statistics is normalized to 1 beam day.
- BG will be further reduced by requiring that only one pair of γ's have the π^0 invariant mass.

Detection of Recoil Proton with GlueX



Recoil proton kinematics

- Polar angle ~55°-80°
- Momentum ~200-1200 MeV/c



η Production Rate Estimation

LH2 target length L=30cm, ρ=0.0708 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 $\gamma + p \to \eta + p$ cross section ~70 nb (J.M. Laget , Phys.Rev. , C72, 022202 (2005) and A. Sibirtsev et al. Eur.Phys.J., A44, 169 (2010))

Photon beam intensity **N_γ ~5x10^7 Hz** (for E_γ ~9-11.7 GeV)

$$N_\eta = N_\gamma N_p \sigma = 5 \times 10^7 \times 1.28 \times 10^{24} \times 70 \times 10^{-33}$$

$$= 4.5 \text{ Hz}$$

$$\approx 3.9 \times 10^5 \ (\eta\text{'s/day})$$

Jlab Eta Factory (JEF)