Update to the JLab Eta Factory (JEF) Proposal (C12-14-004)

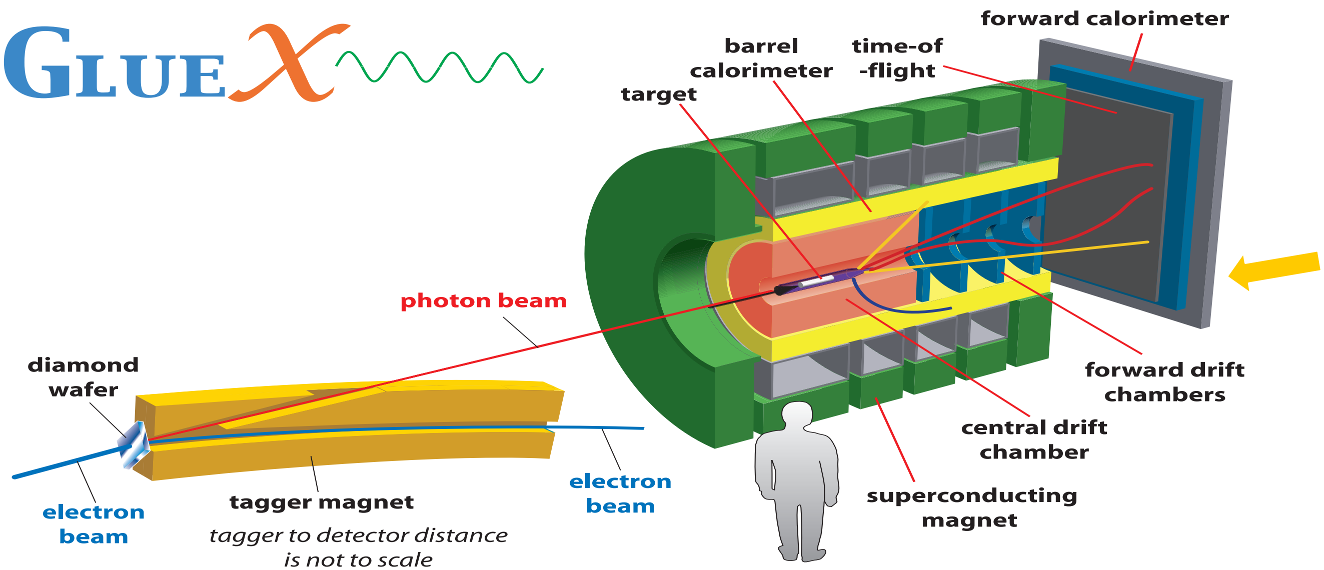
Liping Gan
University of North Carolina Wilmington
(for the GlueX Collaboration and Other Participants)

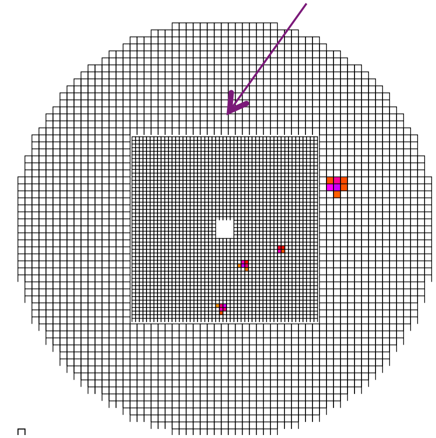
Outline

- Introduction
- Physics Highlight
- Response to PAC42 comments
- Beam request
- Summary

Proposed JEF experiment

GLUEX





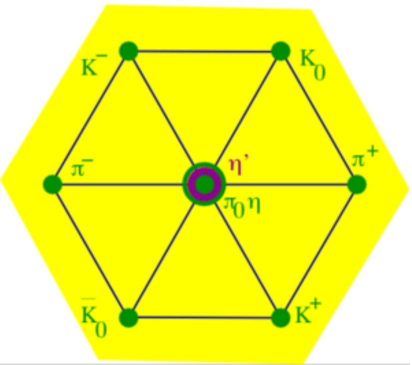
FCAL-II

Simultaneously measure η decays: $\eta\to\pi^0\gamma\gamma$, $\eta\to 3\gamma$, and …

- η produced on LH_2 target with 8.4-11.7 GeV tagged photon beam:
  $\gamma+p \to \eta+p$
- Reduce non-coplanar backgrounds by detecting recoil protons with GlueX detector
- Upgraded Forward Calorimeter with High resolution, high granularity PWO insertion (FCAL-II) to detect multi-photons from the η decays

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



- All its possible strong and EM decays are forbidden in the lowest order so that η has narrow decay width (Γ_η =1.3KeV compared to Γ_ω=8.5 MeV)
  → Enhance the higher order contributions (by a factor of ~7000 compared to ω decays). Sensitive to weakly interacting forces.

- Eigenstate of P, C, CP, and G: $I^G J^{PC} = 0^+ 0^{-+}$
  → tests for C, CP

- All its additive quantum numbers are zero and its decays are flavor-conserving
  → effectively free of SM backgrounds for new physics search.

Overview of JEF Physics

Mode	Branching Ratio	Physics Highlight	Photons
priority:			
$\gamma + B'$	beyond SM	leptophobic vector boson	4
$\pi^0 + \phi'$	beyond SM	electrophobic scalar boson	4
$\pi^0 2\gamma$	$(2.7 \pm 0.5) \times 10^{-4}$	χPTh at $\mathcal{O}(p^6)$	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	$< 2.8 \times 10^{-4}$	$< 10^{-11}$[4]	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 E12-10-011	2

Main physics goals:

i. Search for sub-GeV gauge bosons: leptophobic vector B′ and electrophobic scalar Φ′

ii. Directly constrain CVPC new physics

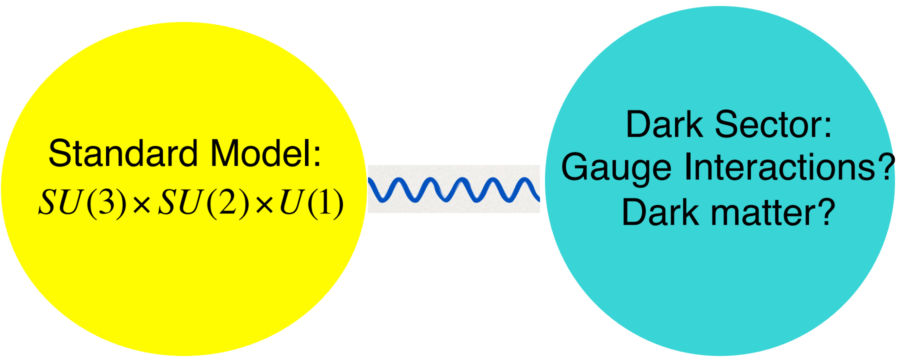
iii. Probe interplay of VMD & scalar resonances in ChPT to calculate LEC's in the chiral Lagrangian

iv. Improve the quark mass ratio via $\eta \rightarrow 3\pi$

FCAL-II is required

Key Channel: $\eta \rightarrow \pi^0 \gamma\gamma$

1. New physics:



Portal: $(n = 4)$

vector	$\kappa B^{\mu\nu} V_{\mu\nu}$
scalar	$H^+ H(\varepsilon S + \lambda S^2)$
fermion	ξLHN

- **Search for sub-GeV gauge bosons**
  - A leptophobic vector B′:
    $\eta \rightarrow \gamma B'$, $B' \rightarrow \pi^0 \gamma$ **PR,D89,114008**
  - An electrophobic scalar Φ′:
    $\eta \rightarrow \pi^0 \Phi'$, $\Phi' \rightarrow \gamma\gamma$

→ A 100 keV-100 MeV electrophobic scalar can solve proton radius and $(g-2)_\mu$ puzzles.

PRL 117,101801 (2016); PL B740,61(2015)

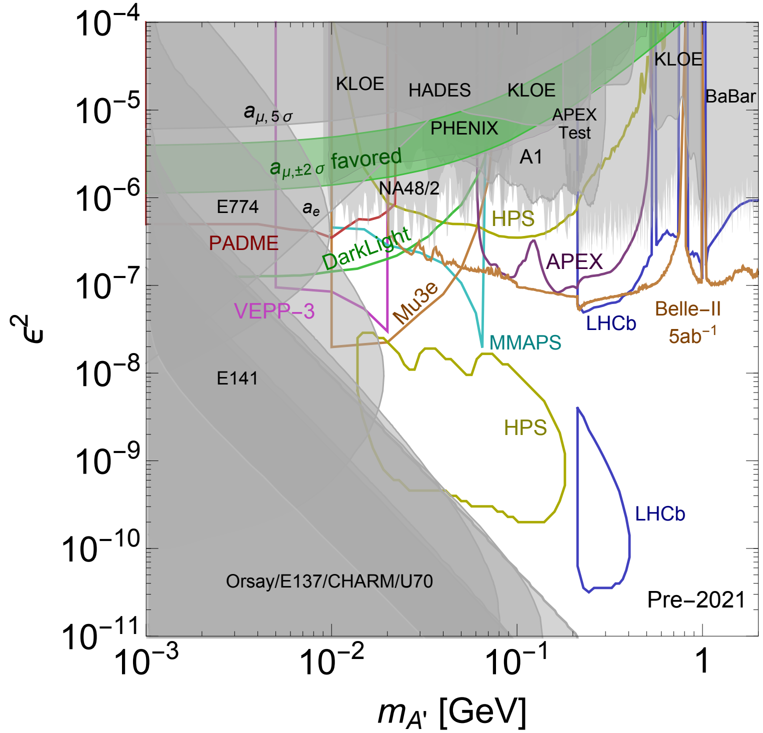
2. Confinement QCD:

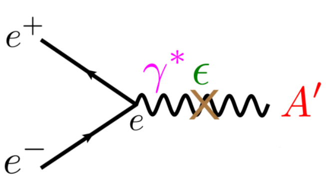
- **A rare window to probe interplay of VMD & scalar resonance in ChPT**

"Vector Portal" to Dark Sector

1. Dark photon A′

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





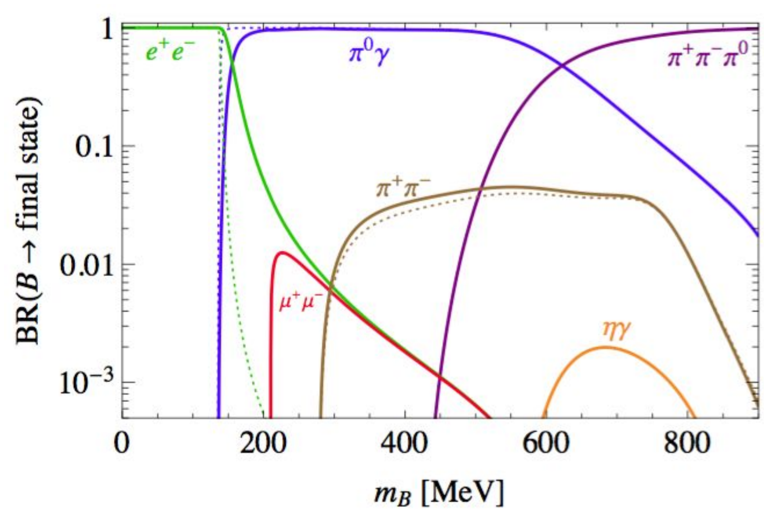
Most A′ searches look for $A' \rightarrow l^+l^-$, relying on the leptonic coupling of new force

2. Leptophobic B′ (dark ω, γ_B , or Z′): $\frac{1}{3}g_B\bar{q}\gamma^\mu qB_\mu$

Gauged baryon symmetry $U(1)_B$

T.D. Lee and C.N. Yang, Phys.Rev.,98, 1501 (1955)

- $m_B < m_\pi$ is strongly constrained by long-range forces searches; the $m_B > 50$ GeV has been investigated by the collider experiments.
- GeV-scale domain is nearly untouched, a discovery opportunity!



PR,D89,114008

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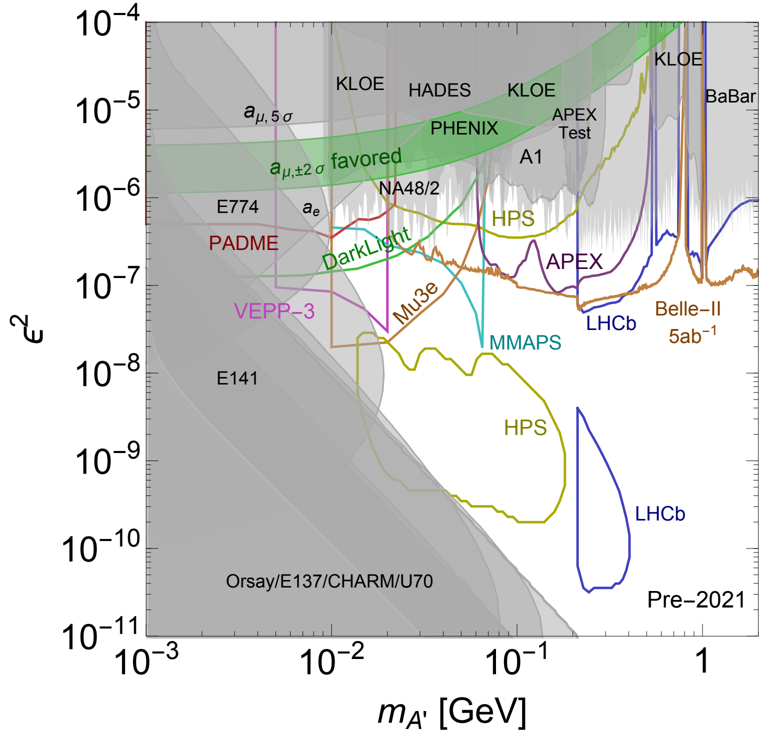

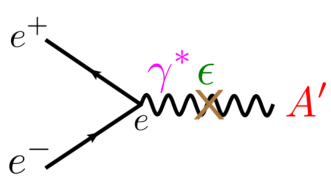

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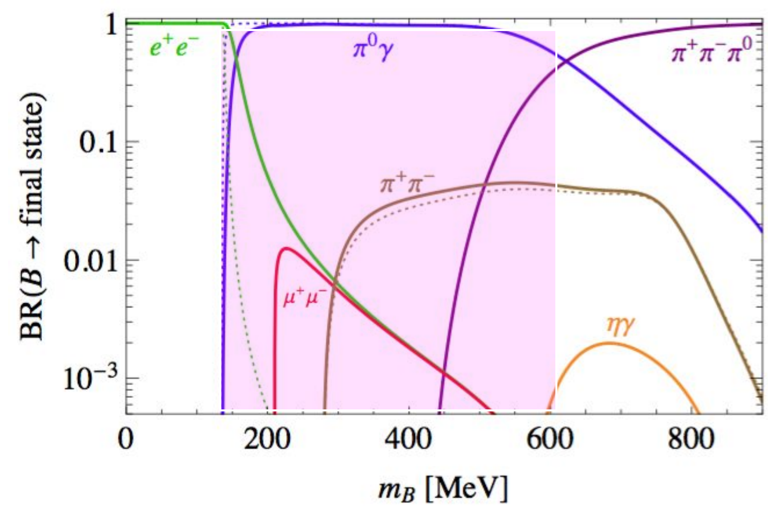
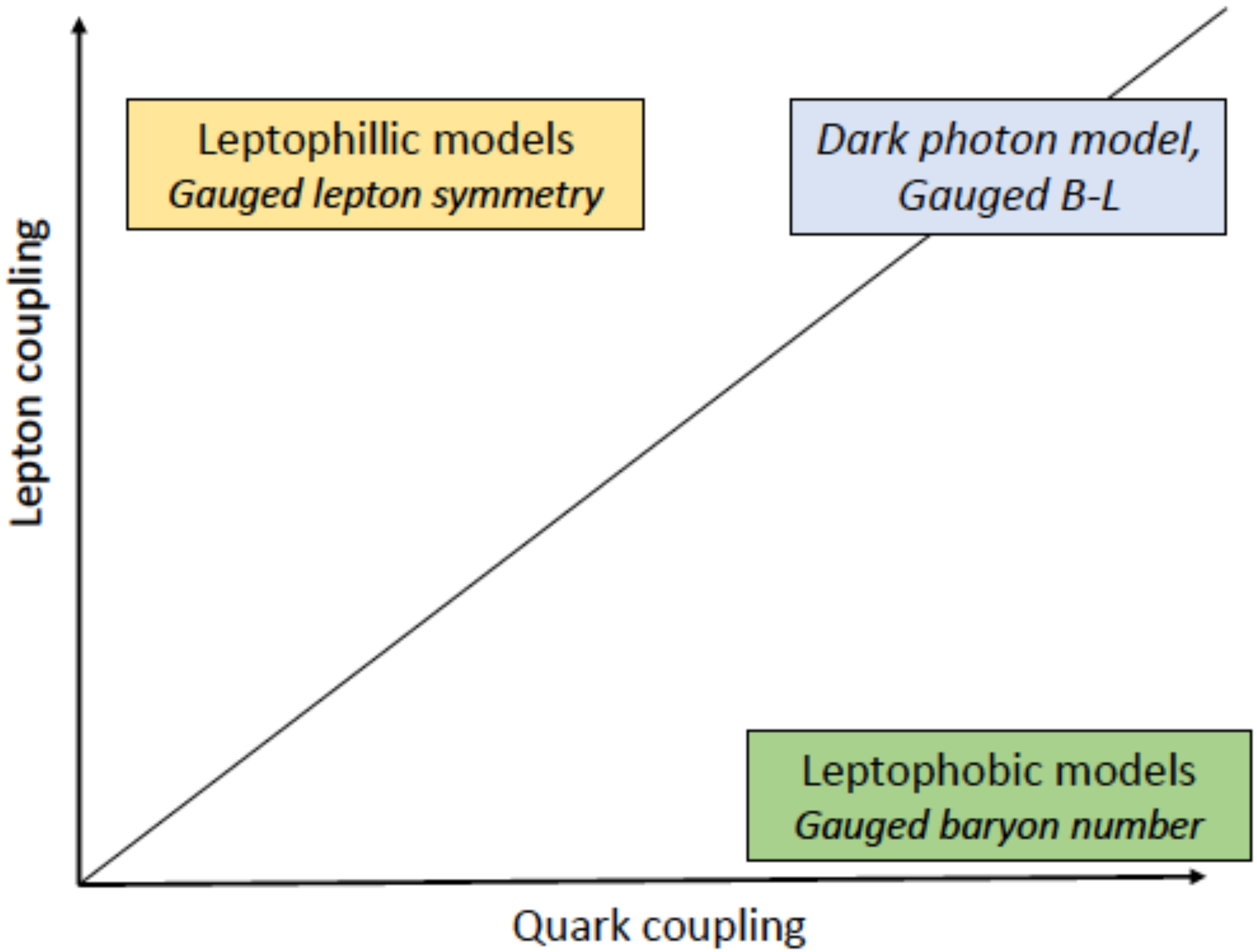


PR,D89,114008

Landscape of New GeV-Scale Forces



Also a third axis: decays to invisible states (neutrinos, light dark matter)

Davoudiasl et al (2012), Batell et al (2009), deNiverville et al (2011,2012)

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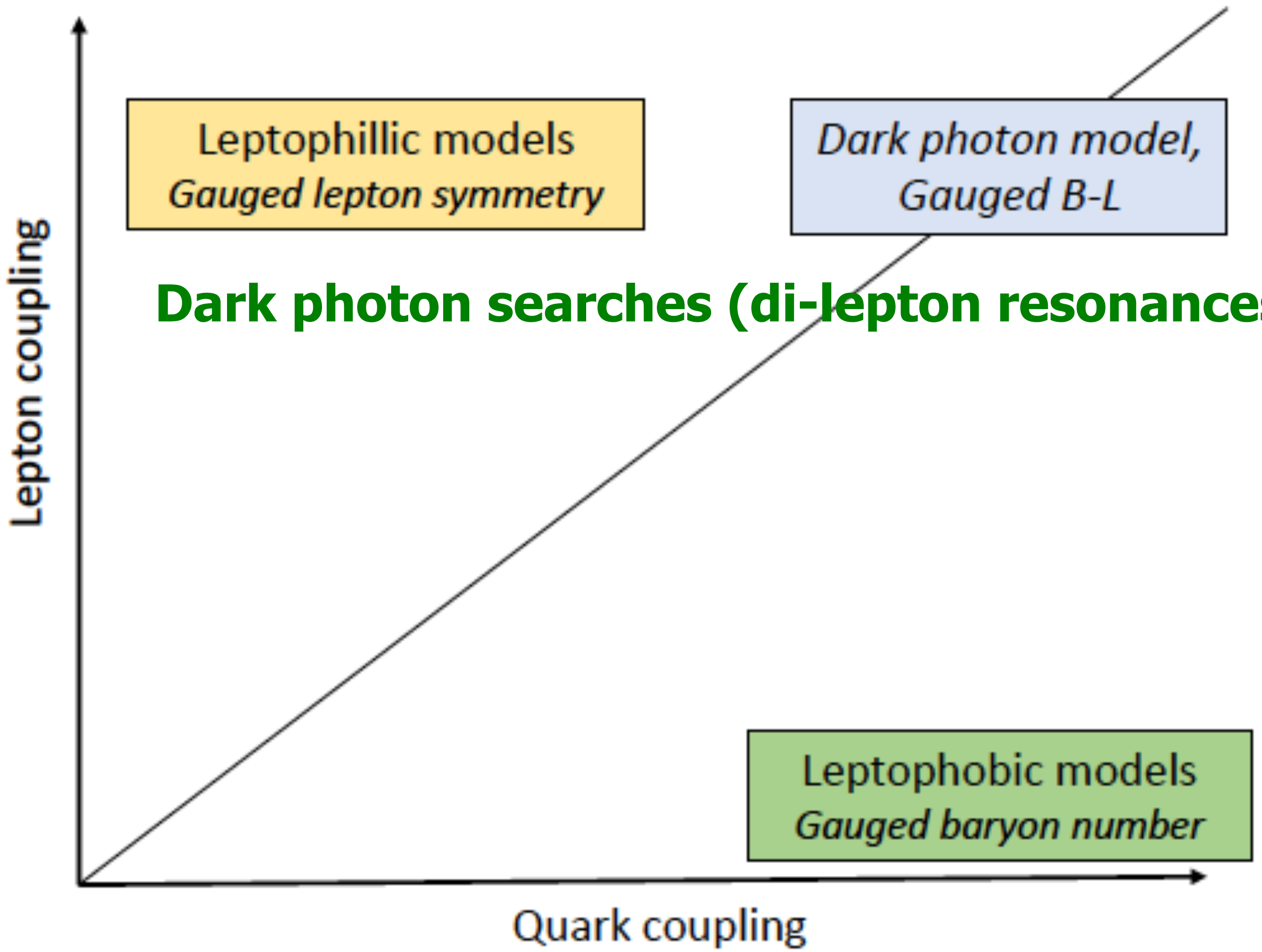

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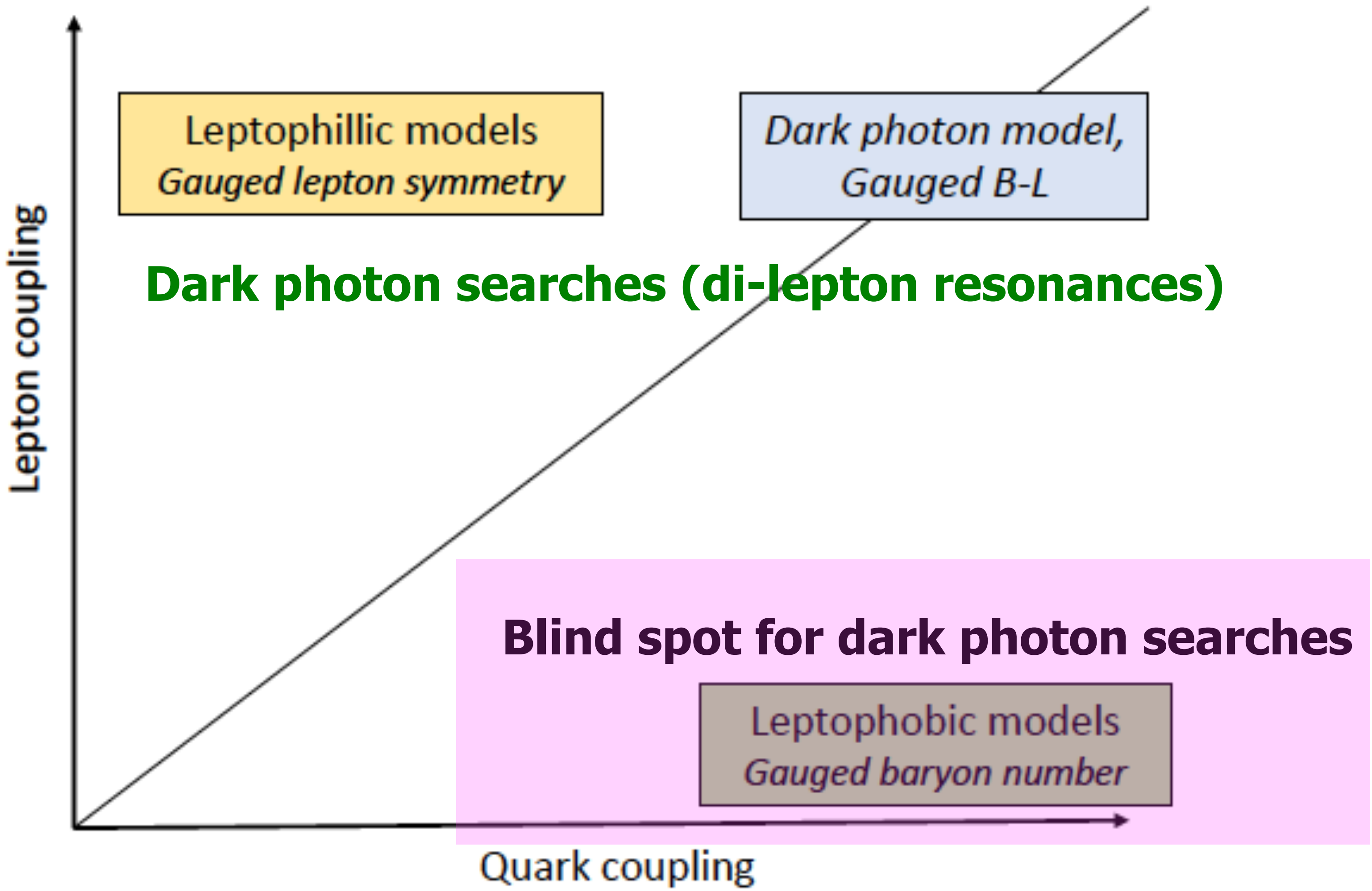

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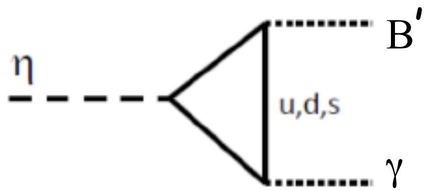
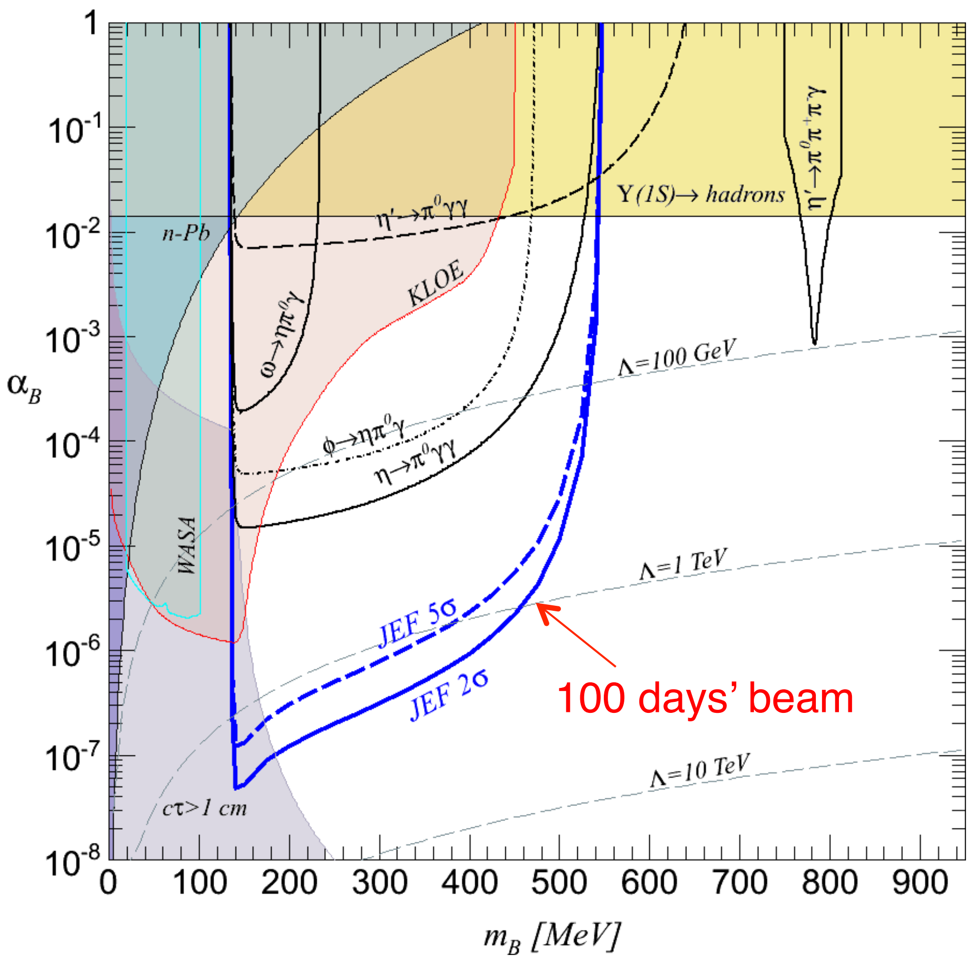
JEF Experimental Reach for B′

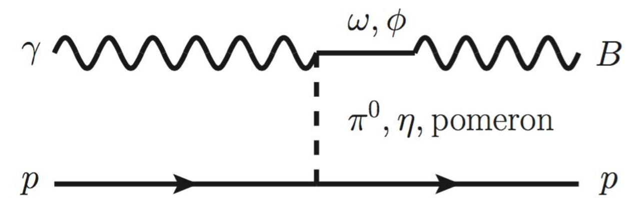
1. Meson decay $\eta \to B'\gamma \to \pi^0\gamma\gamma$

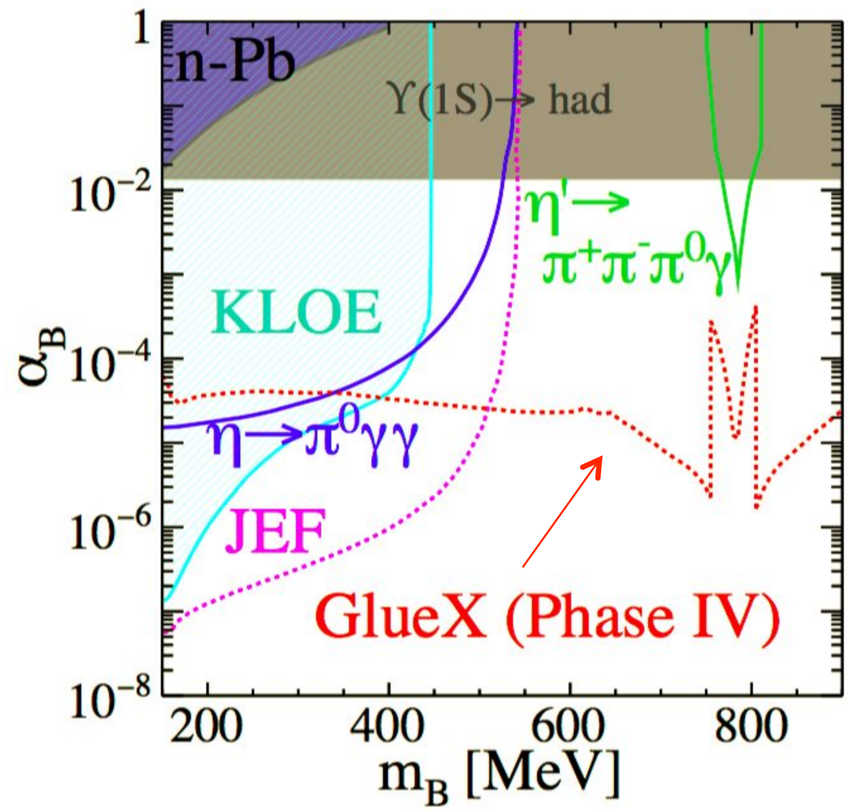


PL, B221, 80 (1989)
PR,D89,114008



2. Photoproduction $\gamma p \to B'p$





arXiv:1605.07161

Impact of the SM allowed $\eta\to\pi^0\gamma\gamma$ measurement

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

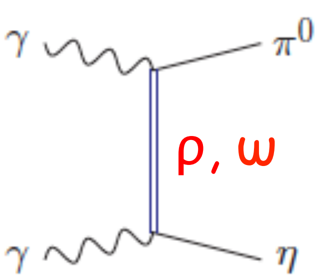
- The major contributions to $\eta\to\pi^0\gamma\gamma$ are two $O(p^6)$ counter-terms in the chiral Lagrangian ➡ an unique probe for the high order ChPT.

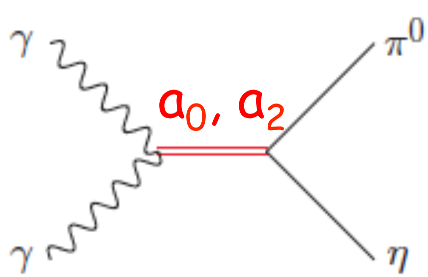
  L. Ametller, J, Bijnens, and F. Cornet, Phys. Lett., B276, 185 (1992)

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

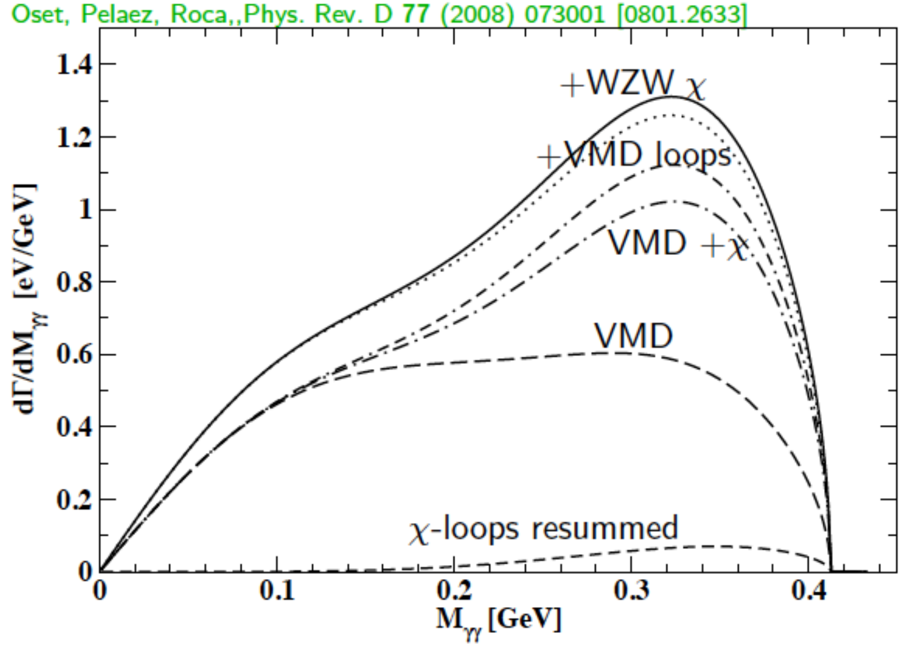
LEC's are dominated by resonances

Gasser, Leutwyler 84; Ecler, Gasser, Pich, de Rafael1989
Donoghue, Ramirez, Valencia 1989



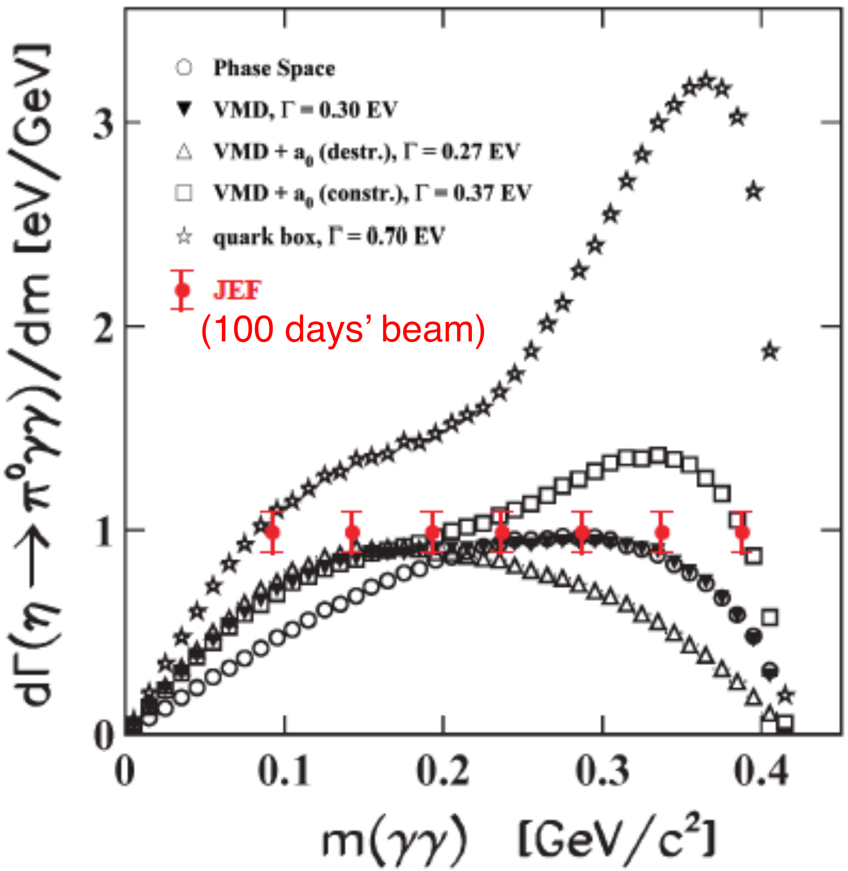


Oset, Pelaez, Roca,,Phys. Rev. D 77 (2008) 073001 [0801.2633]

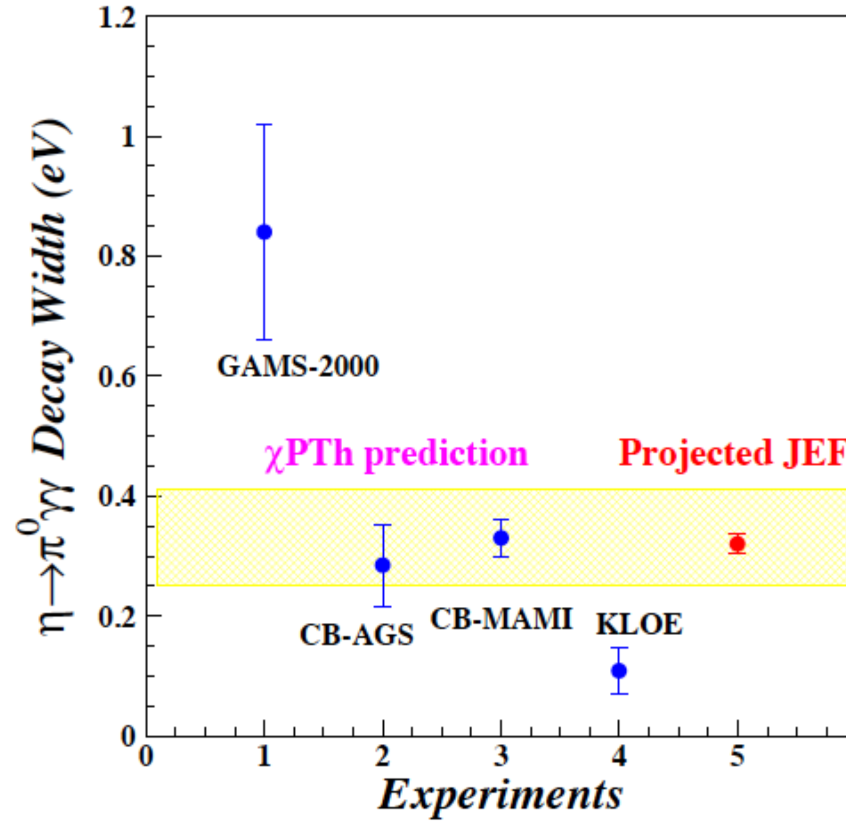


Projected JEF on SM Allowed $\eta\rightarrow\pi^0\gamma\gamma$

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



χPTh by Oset et al., Phys. Rev. D77, 073001



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

Charge Conjugation 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
  (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

Mode	Branching Ratio (upper limit)	No. γ's
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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$3\gamma 2\pi^0$	Nothing published	

Experimental Improvement on $\eta \to 3\gamma$

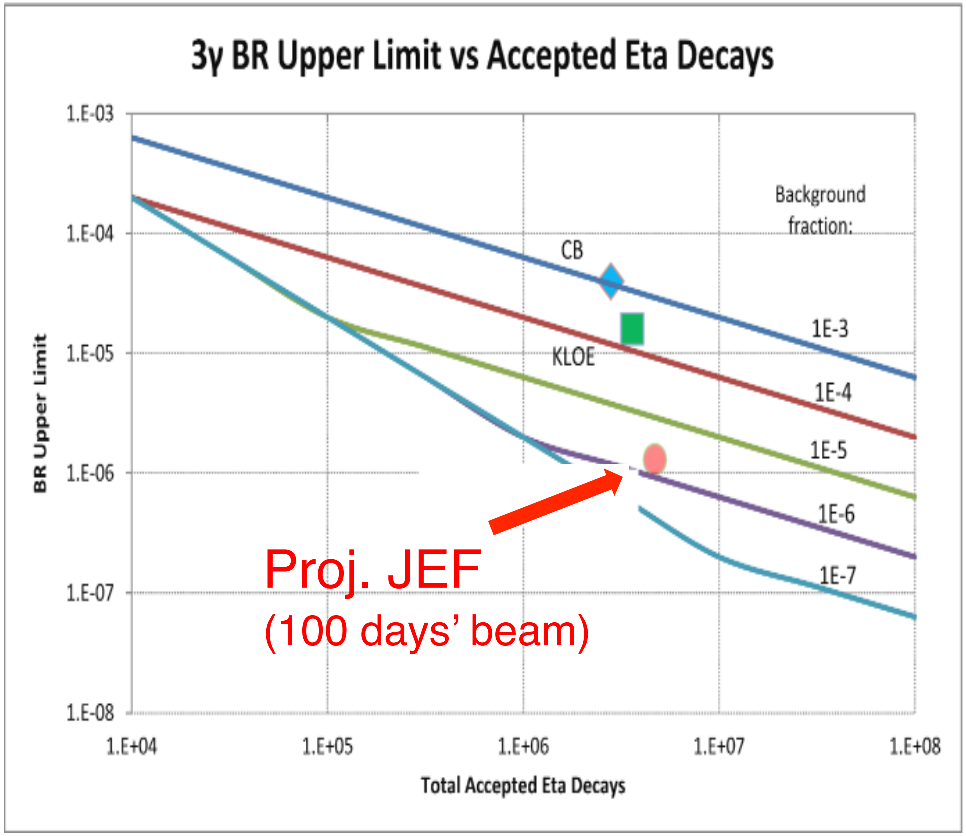
- SM contribution:
  BR($\eta \to 3\gamma$) $< 10^{-19}$ via P-violating weak interaction.

- A new C- and T-violating, and P-conserving interaction was proposed by Bernstein, Feinberg and Lee

  Phys. Rev.,139, B1650 (1965)

- A calculation due to such new physics by Tarasov suggests:
  BR($\eta \to 3\gamma$)$< 10^{-2}$

  Sov.J.Nucl.Phys.,5,445 (1967)



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

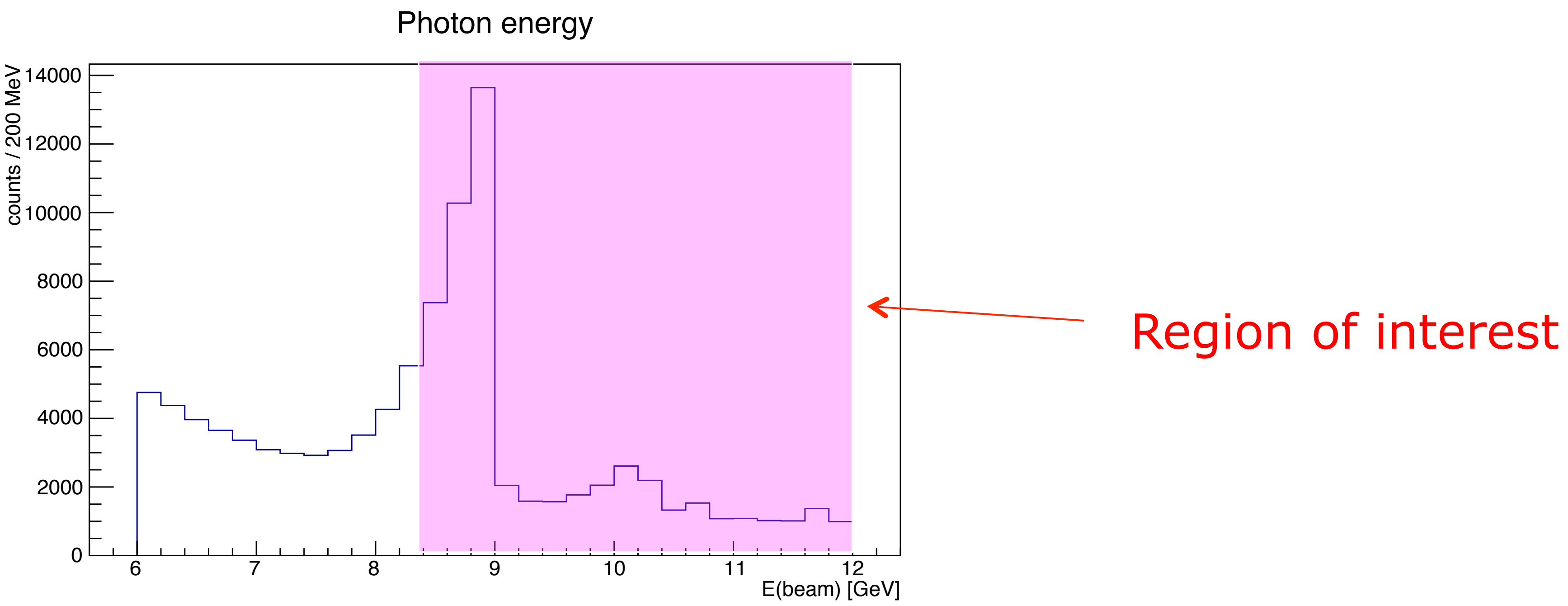
PAC42 Recommendation

- "The proposed measurements appear to be feasible and the experiment is well suited for the tagged Hall D photon beam."
- "The PAC understands the very strong scientific interest of performing new measurements of rare η decays with improved sensitivity to test the SM."
- "the PAC sees the determination (iv) of Q (quark mass ratio) 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" ⟶ in progress
- "The other three physics goals (i)-(iii) will need the FCAL-II, … 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." ⟶ Phase II

Address PAC42 Recommendation

- GlueX-IV running conditions
- Material of DIRC detector
- Upgraded FCAL-II

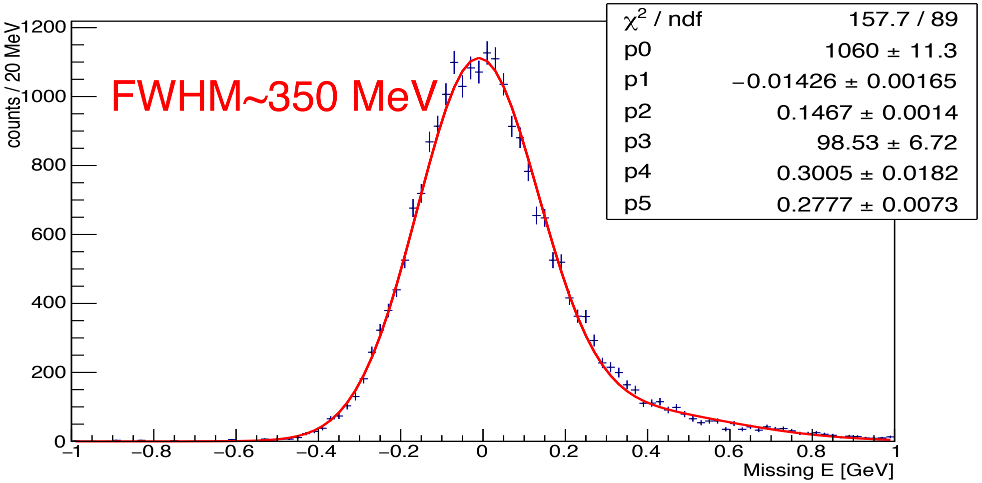
- Tagger accidental fraction
- Production rate of η and η'
- Full simulation:
  key signal $\eta \to \pi^0 \gamma\gamma$ with backgrounds



Tagger Accidental Fraction

E_γ (GeV)	γ's on tagger (Hz)	γ's on target (Hz)	Collimator acceptance (%)	Accidental fraction (%)
8.4-9.0	$1.3x10^8$	$5.1x10^7$	41	17
9.0-11.7	$2.7x10^8$	$4.3x10^7$	16	7.3

The accidental fraction is defined as the ratio of the multi-hit events over the single-hit events, P(N>1)/P(N=1), per beam bunch (4ns) per 350 MeV in the tagger.



- Accidental fractions are manageable
- Photon flux on the target is doubled from the original proposal

Tagged η and η' Production Rate

JEF for 100 days of beam:

	η	η'
Tagged mesons	6.5×10^7	4.9×10^7

Previous Experiments:

Experiment	Total η	Total η'
CB at AGS	10^7	-
CB MAMI-B	2×10^7	-
CB MAMI-C	6×10^7	-
WASA-COSY	$\sim10^9$	-
KLOE	10^8	5×10^5
BESIII	10^6	6×10^6

JEF offers a competitive η/η' factory

Tagged η and η' Production Rate

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KLOE	10^8	$5\text{x}10^5$
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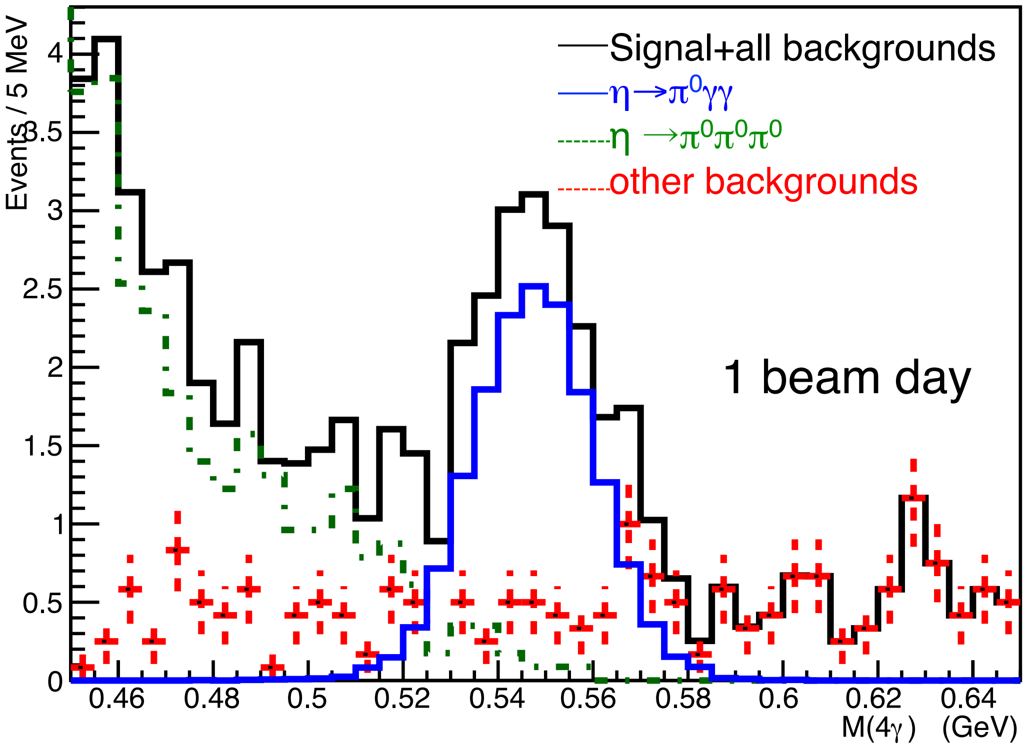
JEF offers a competitive η/η' factory

Some interesting η' decays:

Decays	B.R.	Physics highlight
$\pi^0\gamma\gamma$	$<8\times10^{-4}$	leptophobic B′, electrophobic Φ′
$2\pi^0$	$<5\times10^{-4}$	PV, CPV
3γ	$<1.1\times10^{-4}$	CV, CPV
$\pi^0 e^+e^-$	$<1.4\times10^{-3}$	CV, CPV
ηe^+e^-	$<2.4\times10^{-3}$	CV, CPV
γe^+e^-	$(4.73 \pm 0.30) \times 10^{-4}$	ChPT, dark A′

Ratio of Signal to Background

N (PWO) > 2



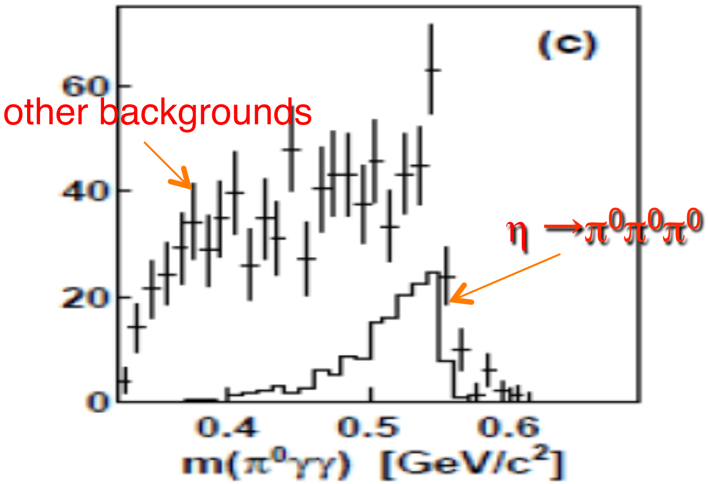
	GlueX IV	JEF PAC42
E_γ (GeV)	8.4-11.7	9-11.7
PWO insert (m^2)	1x1	1.2x1.2
S/N	2.3	3
Reconstruction Efficiency (%)	9	18
Flux (10^7 Hz)	9.4	5

JEF has full capabilities for running concurrently with GlueX and any experiments with LH2 target in Hall D

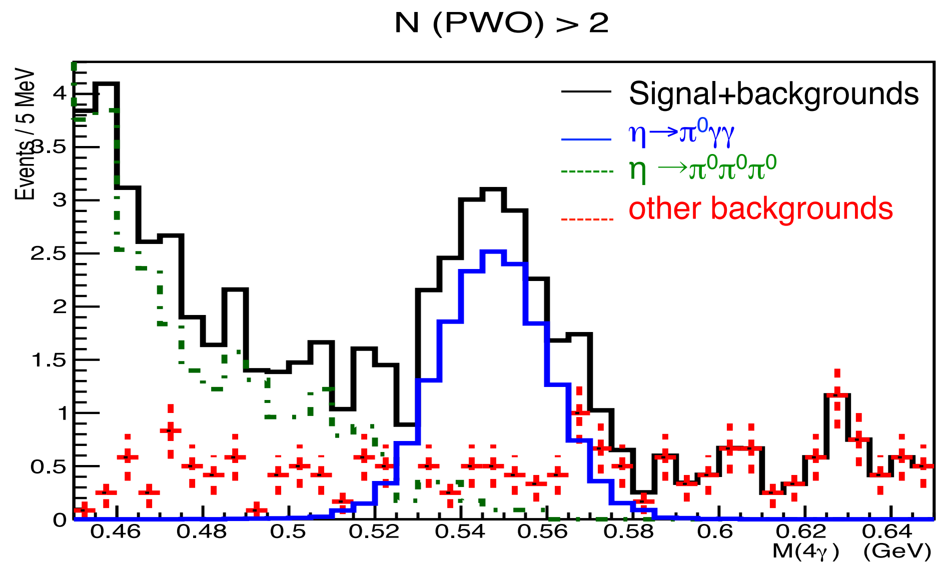
Unique of JEF Experiment

1. Highly suppressed background with:
   a) η/η' energy boost; b) FCAL-II; c) exclusive detections

A2 at MAMI: $\gamma p \rightarrow \eta p$ (E_γ=1.5 GeV)
(P.R. C90, 025206)



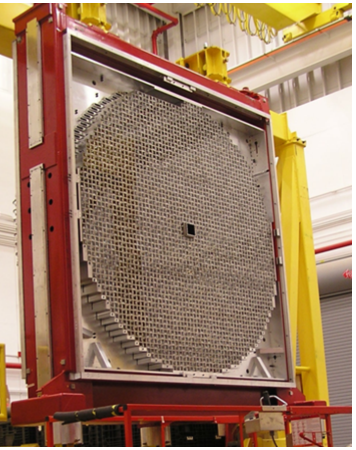
JEF: $\gamma p \rightarrow \eta p$ (E_γ=8.4-11.7 GeV)



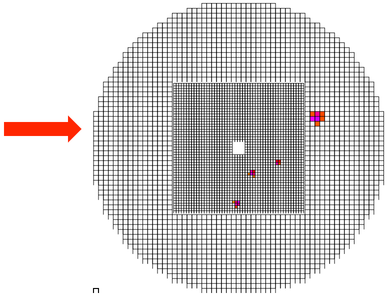
2. Simultaneously produce η and η' with similar rates

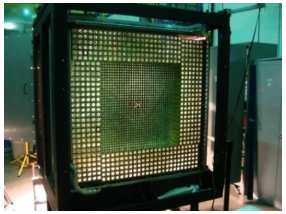
3. Capability of running in parallel with GlueX and other experiments in Hall D → potential for high statistics

New Equipment: FCAL-II



FCAL





HyCal

PWO vs. lead glass

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

- 1x1 m^2 PWO insert (2464 PWO crystal modules) with 12x12 cm^2 beam hole
- Similar as the inner part PrimEx HyCal with a minor modification for magnetic shielding
- Using the same techniques as the current FCAL for magnetic shielding: Annealed iron, 0.2 mm μ-metal, and ~2 cm long light guide.

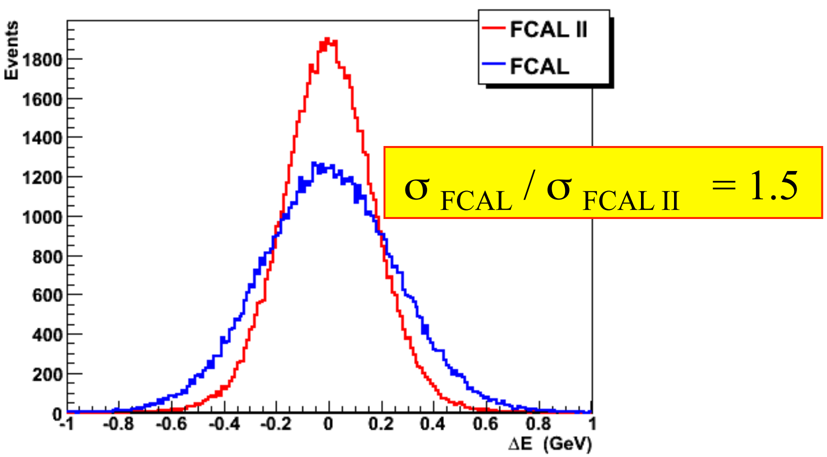
  → test shows that the PMT pulse amplitude dropped <5% when the external B field up to 76 G
- Estimated total cost is ~\$4.5 M for detector and ~\$1 M for infrastructure
- ~4-5 years for all crystal modules to be constructed, ~1 year for installation

Benefits of FCAL-II to Hall D Physics Program

- Impact on GlueX spectroscopy program:
  - Better neutral particle identification for PWA.
  - More radiation-resistant calorimeter for high intensity runs

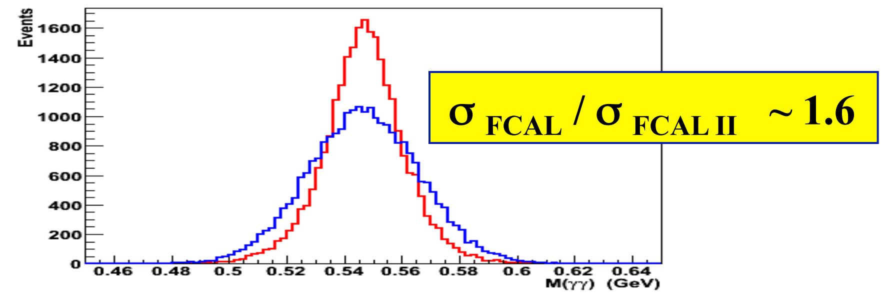
$p + \gamma \rightarrow p + X(1400)$

$X(1400) \rightarrow \eta \pi^0$

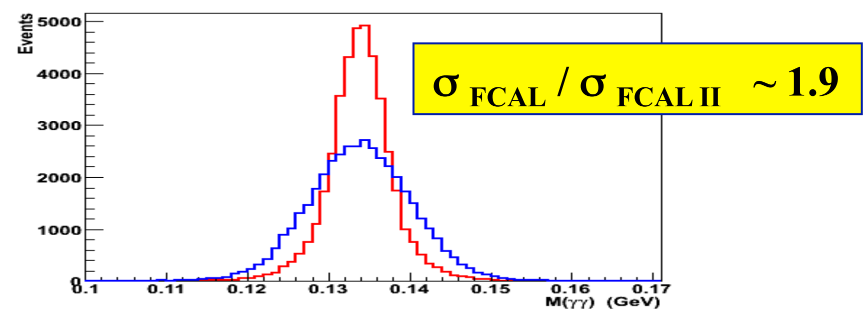


$$\Delta E = E_{\eta\pi} + E_p - m_p - E_{beam}$$

Invariant Mass: $\eta \rightarrow \gamma\gamma$



Invariant Mass: $\pi^0 \rightarrow \gamma\gamma$



- Reduce the uncertainty for the Primakoff experiment on $\Gamma(\eta \rightarrow \gamma\gamma)$ from 3% to 2%

Beam Time Request

Run type	Beam Time (days)
LH_2 Production	100
Empty target and target out	7
Tagger efficiency, TAC runs	3
FCAL-II commissioning	12
Luminosity optimization	8
Total	130

We also consider to run in parallel with GlueX. If GlueX is extended after FCAL-II upgrade (~2023), there could be overlap in the beam time.

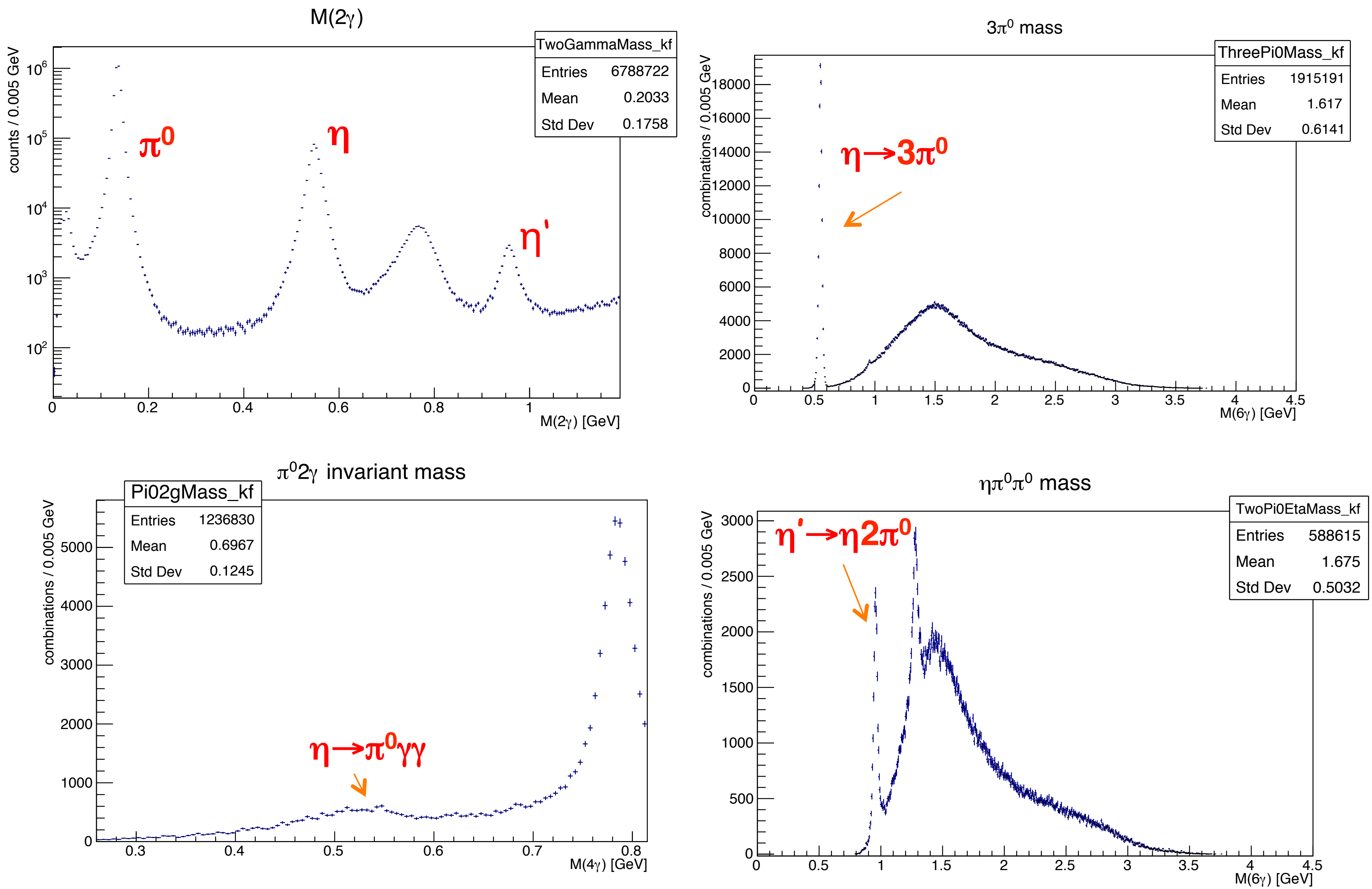
Summary

- 12 GeV tagged photon beam with GlueX setup offers a unique η/η' factory to test SM and search for new BSM physics, with two orders of magnitude in background reduction in the neutral rare decay modes compared to other facilities in the world.
- JEF has full capabilities to run concurrently with GlueX
- Simultaneously measure η/η' decays with main physics goals:
  - **Probe a sub-GeV leptophobic vector B' and an electrophobic scalar Φ' through $\eta/\eta' \to \pi^0\gamma\gamma$**
  - **Directly constrain CVPC new physics via $\eta \to 3\gamma$ and other C-violating η/η' decays**
  - **Test the role of scalar dynamics in ChPT through $\eta \to \pi^0\gamma\gamma$**
  - **Improve the light quark mass ratio via $\eta \to 3\pi$ (which has been taking data in parallel to GlueX)**
- Upgraded FCAL-II with PWO insertion will have significant positive impact on other experiments in Hall D: GlueX and PrimEx-η

The End

Thank you!

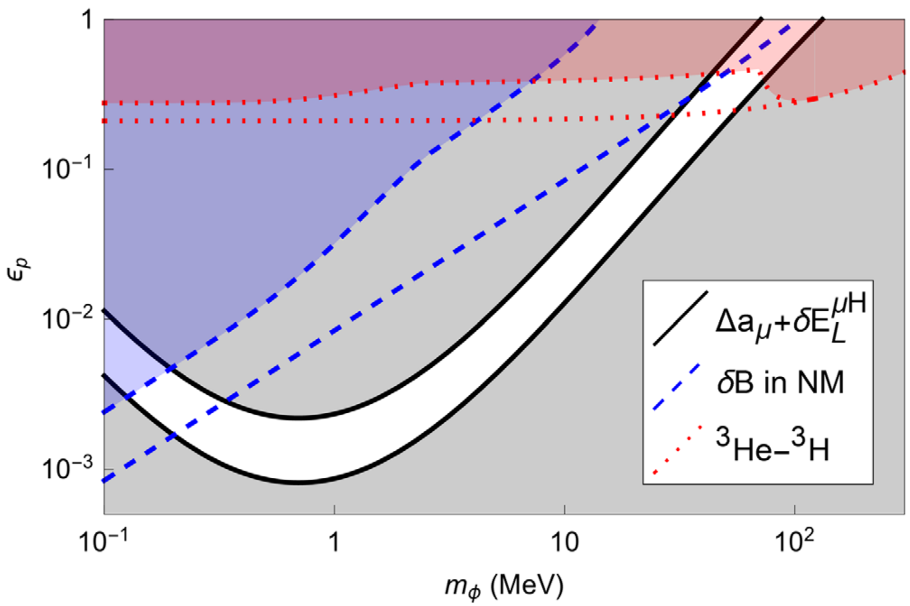
Analysis Results from GlueX Data

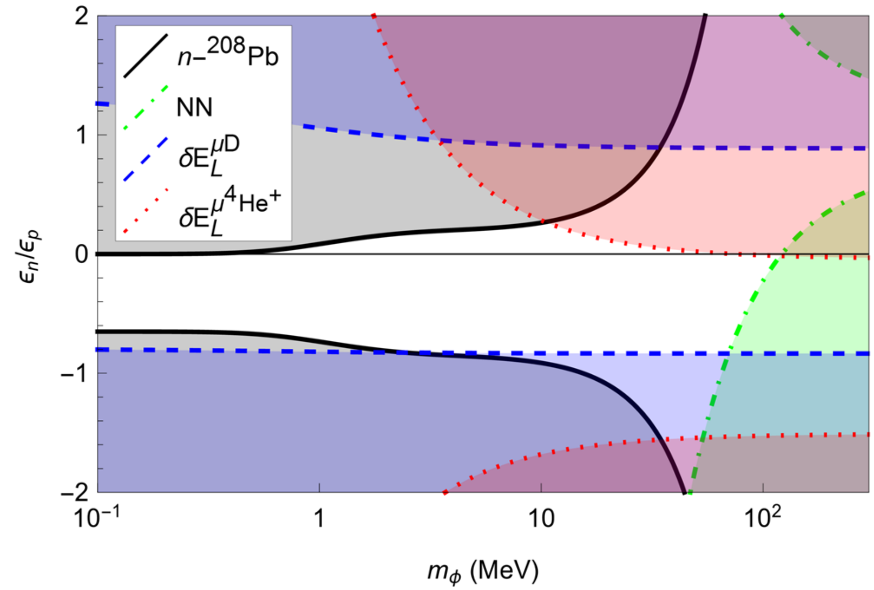


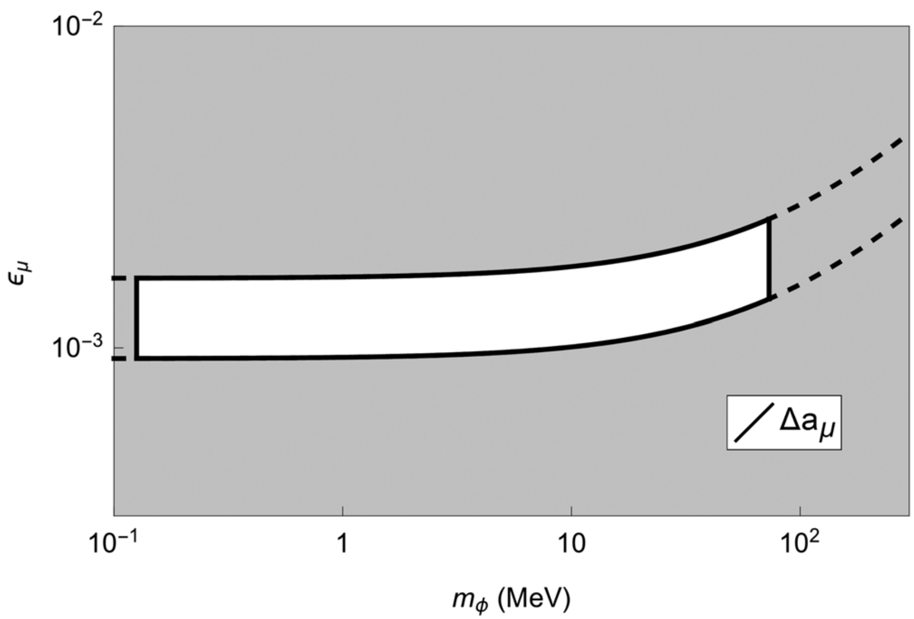
Efficiency and Yield

Mode	BR	Reconstruction efficiency	Event per 100 days
$\eta \to \gamma\gamma$	0.3941	0.38	$1.5\text{x}10^{7}$
$\eta \to \pi^0\gamma\gamma$	$2.56\text{x}10^{-4}$	0.28 (0.09)	6900 (2200)
$\eta \to 3\pi^0$	0.3268	0.20	$6.3\text{x}10^{6}$
$\eta \to 3\gamma$	$<1.6\text{x}10^{-5}$	0.34	-
$\eta' \to \pi^0\gamma\gamma$	$<8\text{x}10^{-4}$	0.26	-
$\eta' \to 3\gamma$	$<1.1\text{x}10^{-4}$	0.32	-

Exclusion plots for Electrophobic Scalar Φ′

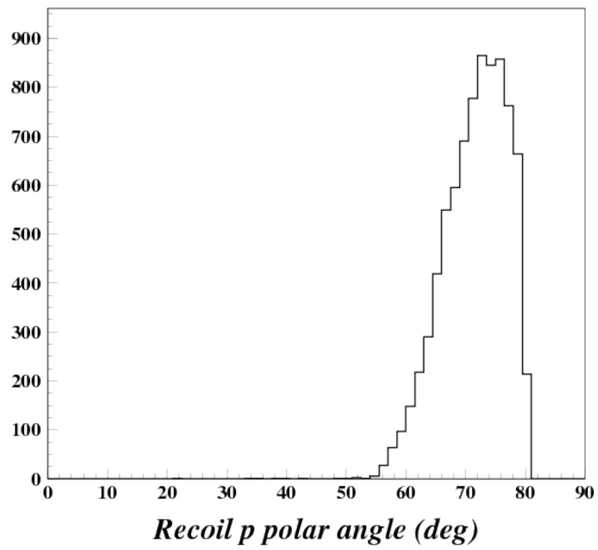


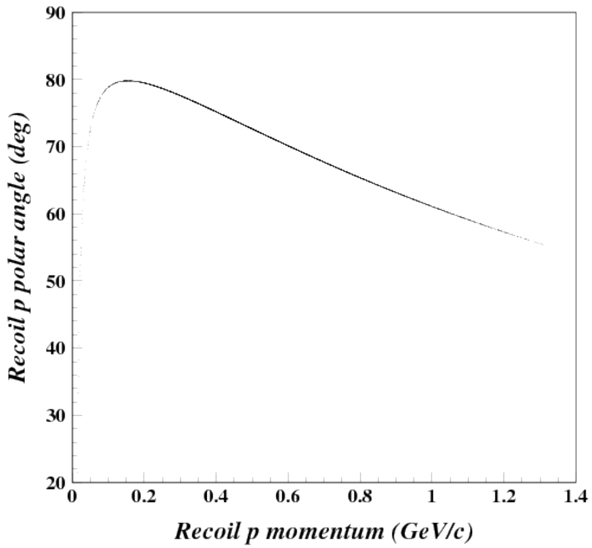




PRL 117,101801 (2016)

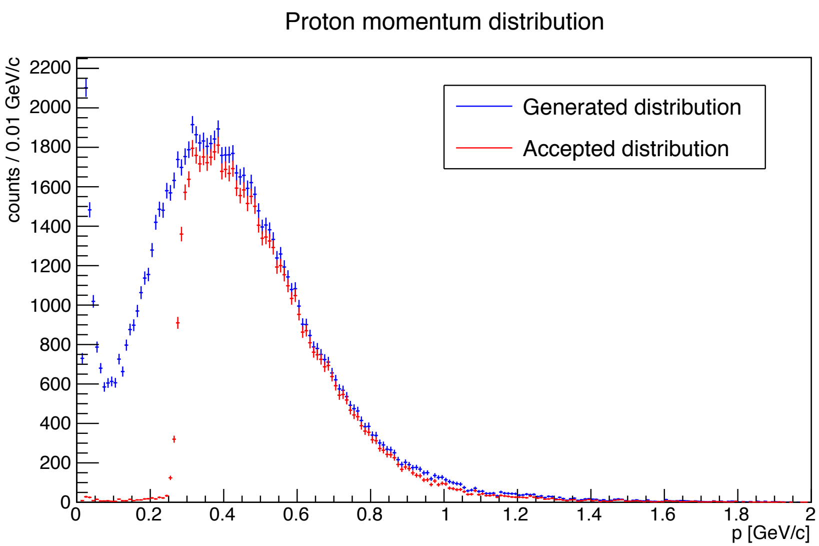
Detection of Recoil Proton with GlueX

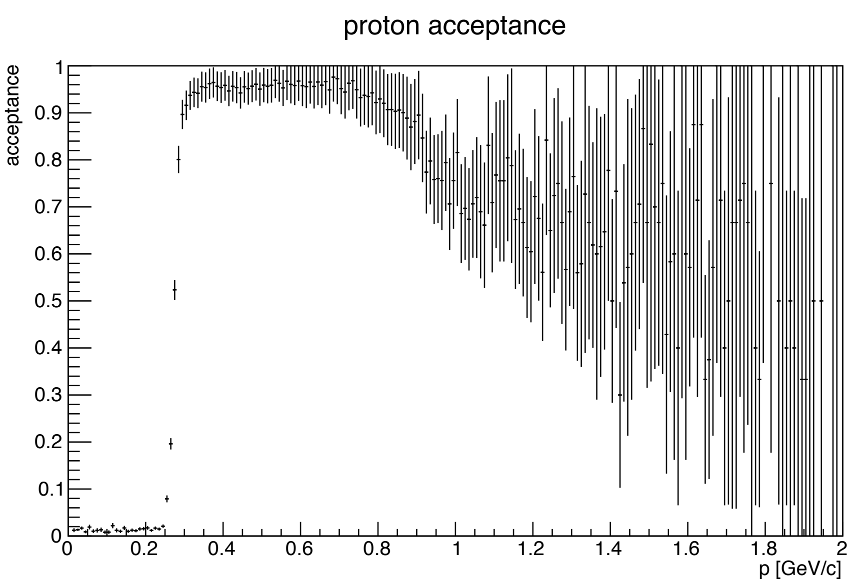




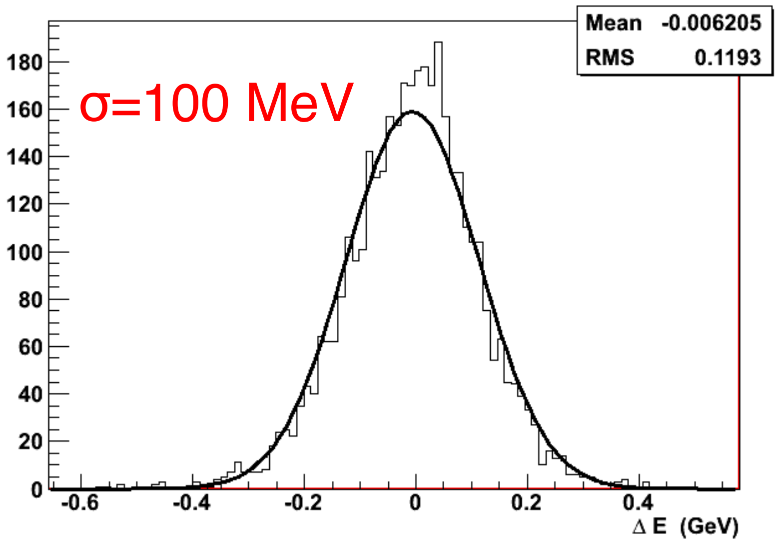
Recoil proton kinematics

- Polar angle ~55°-80°
- Momentum ~100-1200 MeV/c



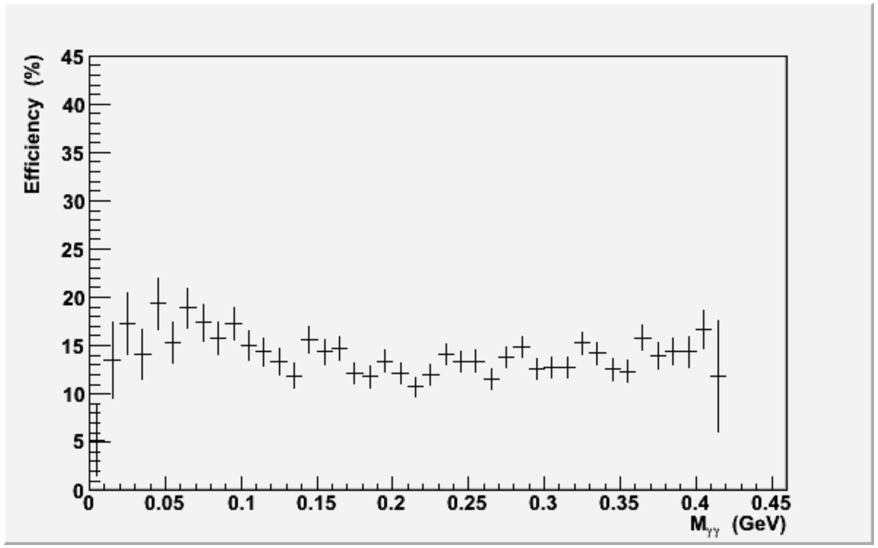


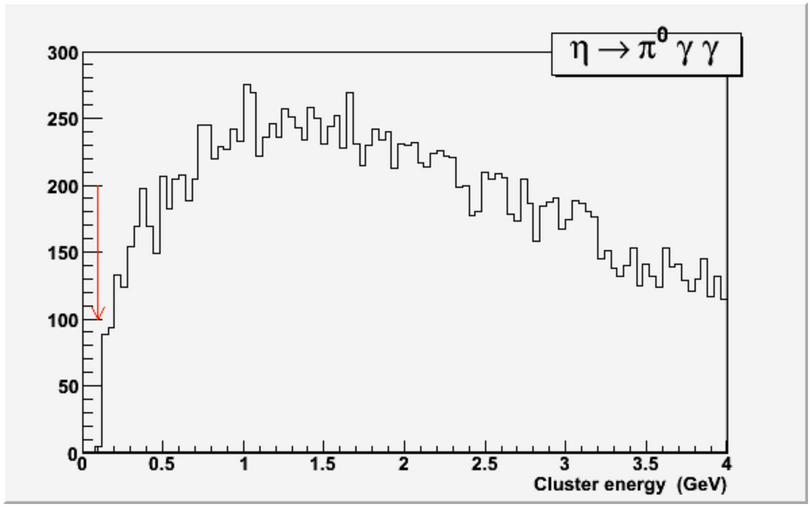
More about $\eta \to \pi^0 \gamma\gamma$



σ=100 MeV

$\Delta E/E_\gamma = 0.01$

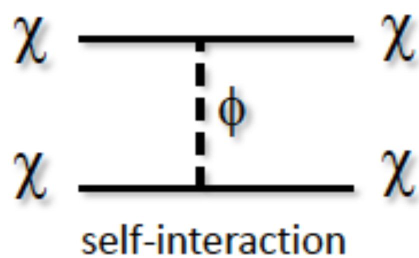


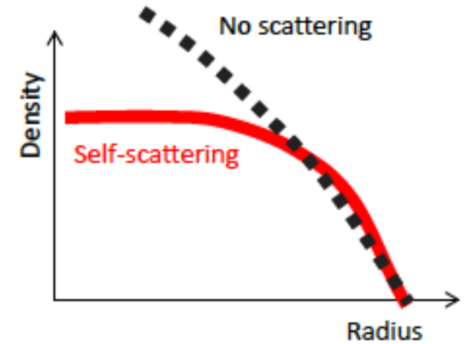


A Prime Target: Sub-GeV Mediator

arXiv:1608.08632

Puzzles in CCDM:
- Core-vs-cusp
- Too-big-to-fail
- Missing satellite

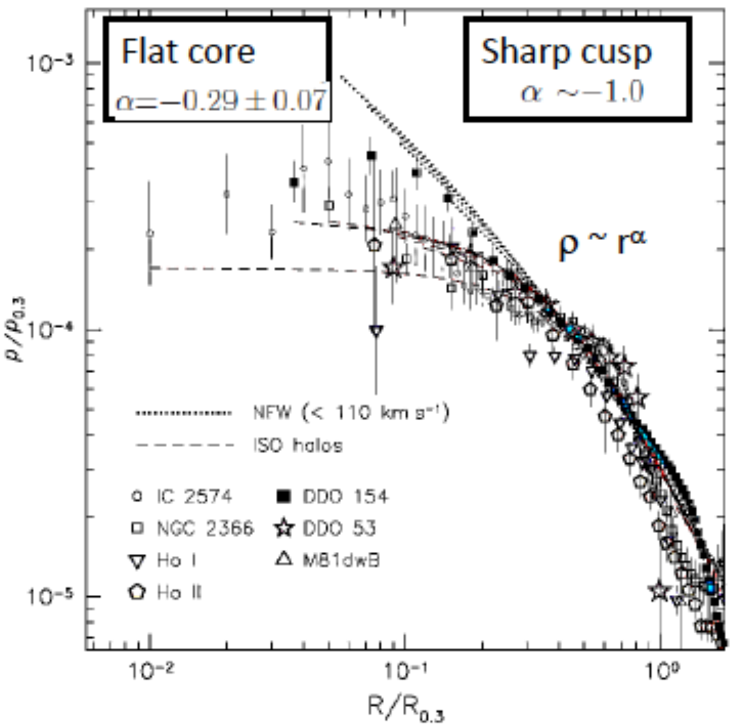


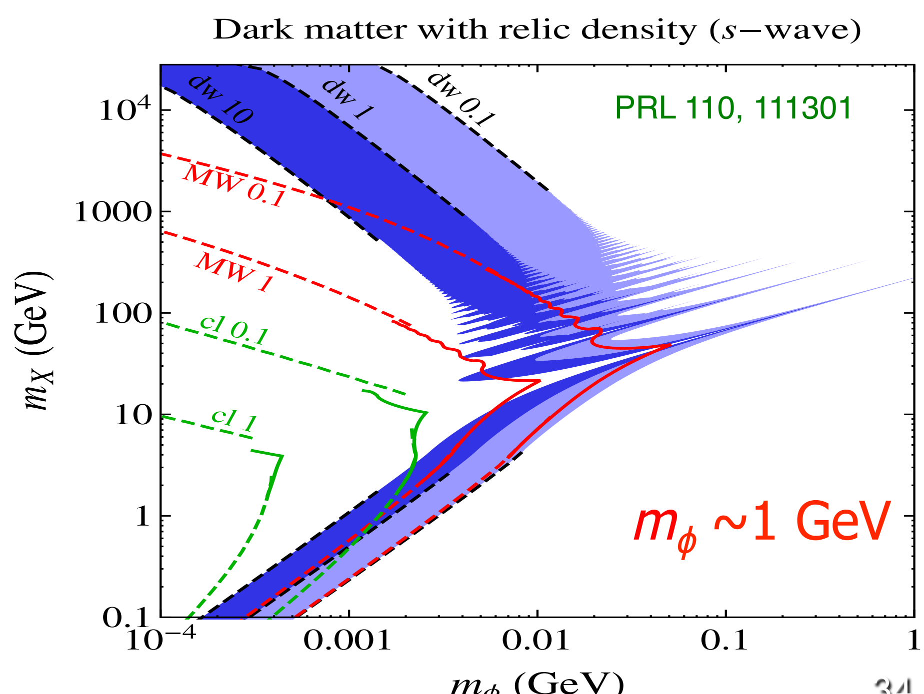


..f-interactions solve core-vs-cusp

Particles get scattered out of dense halo centers

THINGS (dwarf galaxy survey) - Oh et al. (2011)

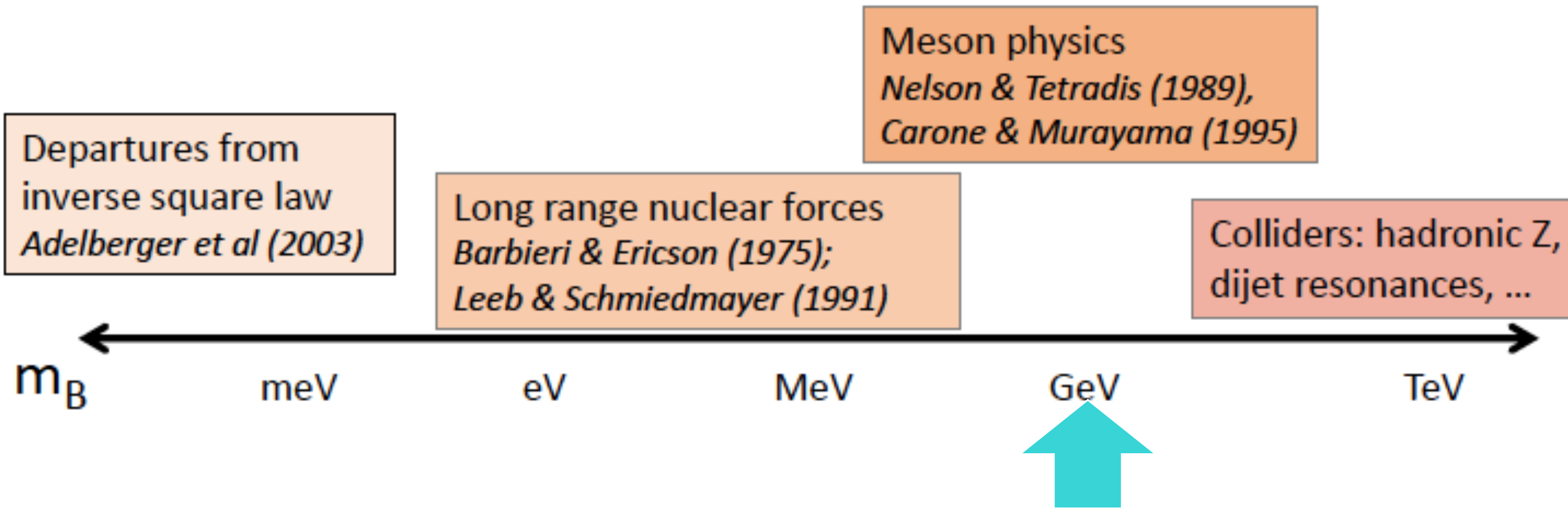




Experimental probes for B′-boson

Discovery signals depend on the B mass:

- the $m_B < m_\pi$ region is strongly constrained by long-range forces search and nuclear scattering experiments.
- the $m_B > 50 GeV$ region has been investigated by the collider experiments.
- GeV-scale domain is nearly untouched.



a discovery opportunity hiding in nonperturbative QCD regime!

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**
  Current constraint: Λ≥ 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; talk at the AFCI workshop

CHARGE CONJUGATION (*C*) INVARIANCE

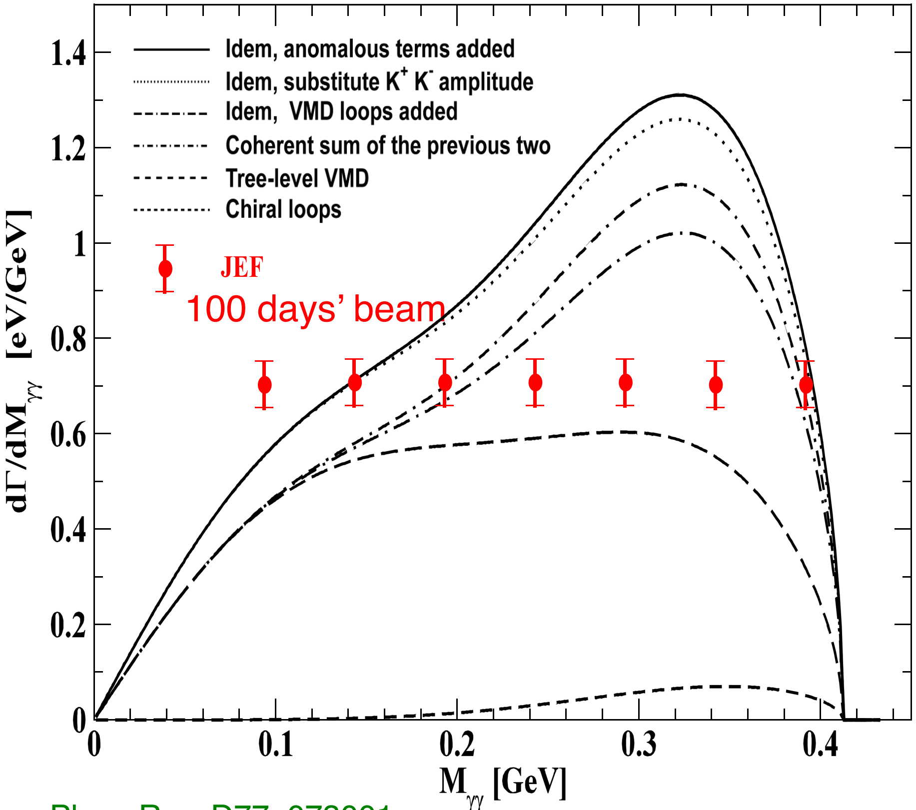
$\Gamma(\pi^0 \to 3\gamma)/\Gamma_{total}$		$<3.1 \times 10^{-8}$, CL = 90%
η *C*-nonconserving decay parameters		
$\pi^+\pi^-\pi^0$ left-right asymmetry		$(0.09^{+0.11}_{-0.12}) \times 10^{-2}$
$\pi^+\pi^-\pi^0$ sextant asymmetry		$(0.12^{+0.10}_{-0.11}) \times 10^{-2}$
$\pi^+\pi^-\pi^0$ quadrant asymmetry		$(-0.09 \pm 0.09) \times 10^{-2}$
$\pi^+\pi^-\gamma$ left-right asymmetry		$(0.9 \pm 0.4) \times 10^{-2}$
$\pi^+\pi^-\gamma$ parameter β (*D*-wave)		-0.02 ± 0.07 (S = 1.3)
$\Gamma(\eta \to \pi^0\gamma)/\Gamma_{total}$		$<9 \times 10^{-5}$, CL = 90%
$\Gamma(\eta \to 2\pi^0\gamma)/\Gamma_{total}$		$<5 \times 10^{-4}$, CL = 90%
$\Gamma(\eta \to 3\pi^0\gamma)/\Gamma_{total}$		$<6 \times 10^{-5}$, CL = 90%
$\Gamma(\eta \to 3\gamma)/\Gamma_{total}$		$<1.6 \times 10^{-5}$, CL = 90%
$\Gamma(\eta \to \pi^0 e^+ e^-)/\Gamma_{total}$	[a]	$<4 \times 10^{-5}$, CL = 90%
$\Gamma(\eta \to \pi^0 \mu^+ \mu^-)/\Gamma_{total}$	[a]	$<5 \times 10^{-6}$, CL = 90%
$\Gamma(\omega(782) \to \eta\pi^0)/\Gamma_{total}$		$<2.1 \times 10^{-4}$, CL = 90%
$\Gamma(\omega(782) \to 2\pi^0)/\Gamma_{total}$		$<2.1 \times 10^{-4}$, CL = 90%
$\Gamma(\omega(782) \to 3\pi^0)/\Gamma_{total}$		$<2.3 \times 10^{-4}$, CL = 90%
asymmetry parameter for $\eta'(958) \to \pi^+\pi^-\gamma$ decay		-0.03 ± 0.04
$\Gamma(\eta'(958) \to \pi^0 e^+ e^-)/\Gamma_{total}$	[a]	$<1.4 \times 10^{-3}$, CL = 90%
$\Gamma(\eta'(958) \to \eta e^+ e^-)/\Gamma_{total}$	[a]	$<2.4 \times 10^{-3}$, CL = 90%
$\Gamma(\eta'(958) \to 3\gamma)/\Gamma_{total}$		$<1.0 \times 10^{-4}$, CL = 90%
$\Gamma(\eta'(958) \to \mu^+\mu^-\pi^0)/\Gamma_{total}$	[a]	$<6.0 \times 10^{-5}$, CL = 90%
$\Gamma(\eta'(958) \to \mu^+\mu^-\eta)/\Gamma_{total}$	[a]	$<1.5 \times 10^{-5}$, CL = 90%
$\Gamma(J/\psi(1S) \to \gamma\gamma)/\Gamma_{total}$		$<2.7 \times 10^{-7}$, CL = 90%
$\Gamma(J/\psi(1S) \to \gamma\phi)/\Gamma_{total}$		$<1.4 \times 10^{-6}$, CL = 90%

η decays

η' decays

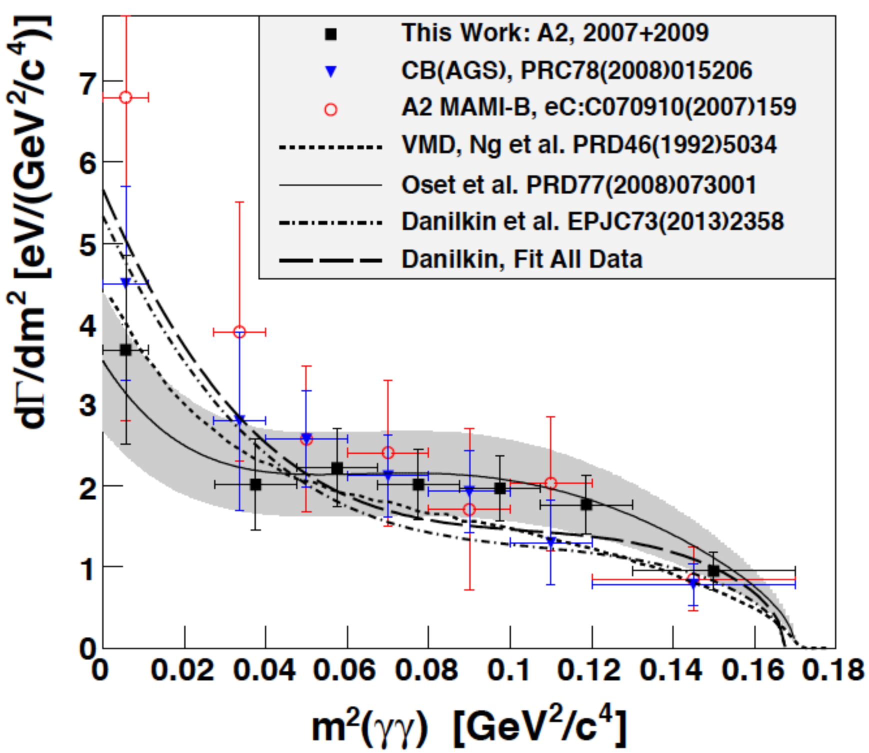
PDG 2017

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

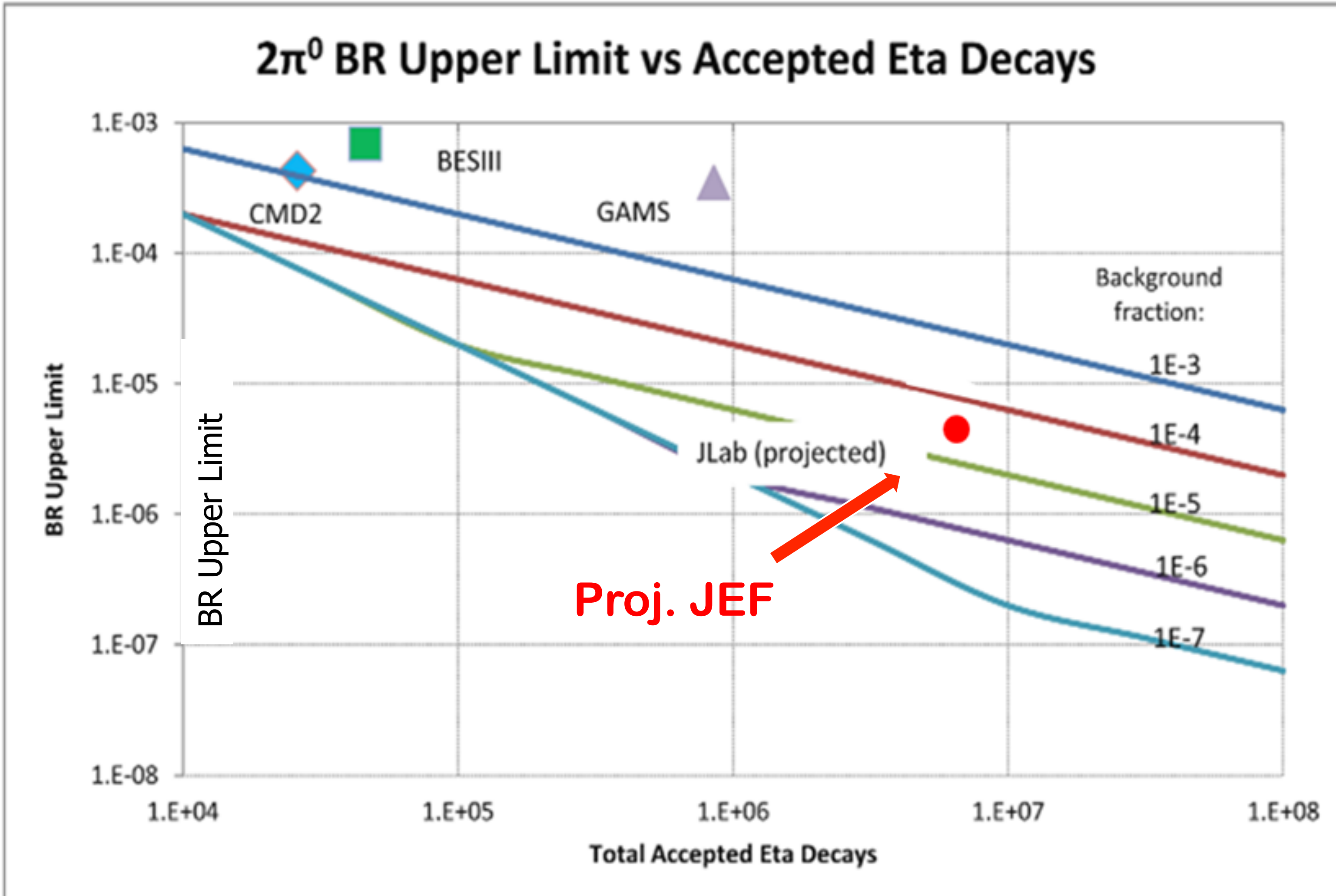


Phys. Rev. D77, 073001

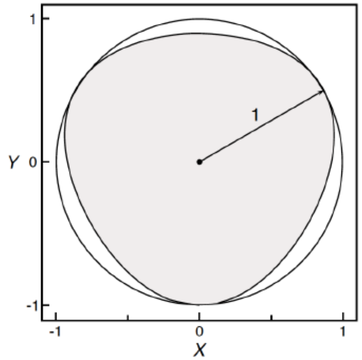
A2 at MAMI P.R. C90, 025206



Projected JEF Result



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



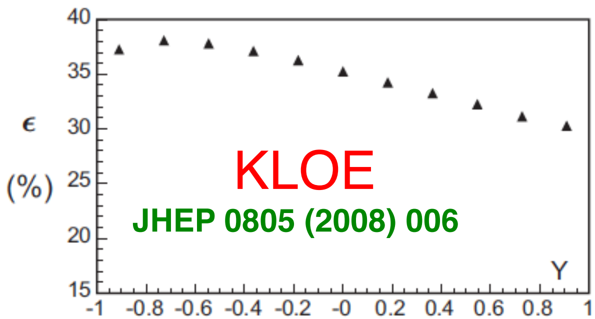
$$X = \frac{\sqrt{3}}{2M_\eta Q_c}(u-t)$$

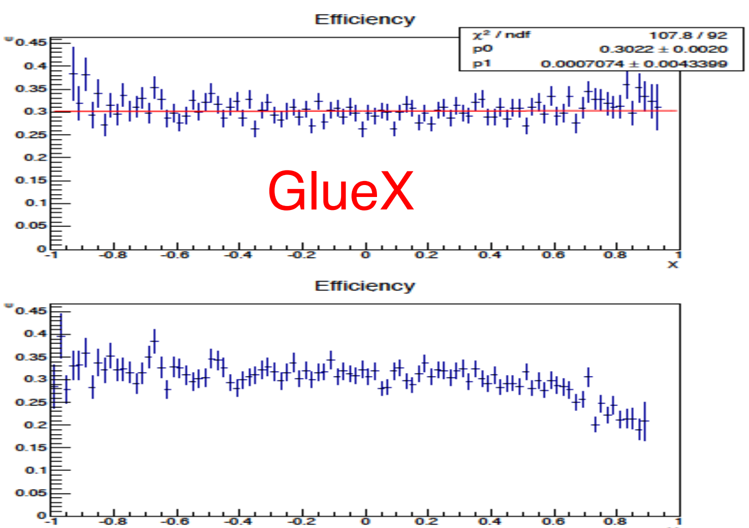
$$Y = \frac{3}{2M_\eta Q_c}\left((M_\eta - M_{\pi^0})^2 - s\right) - 1$$

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

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

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

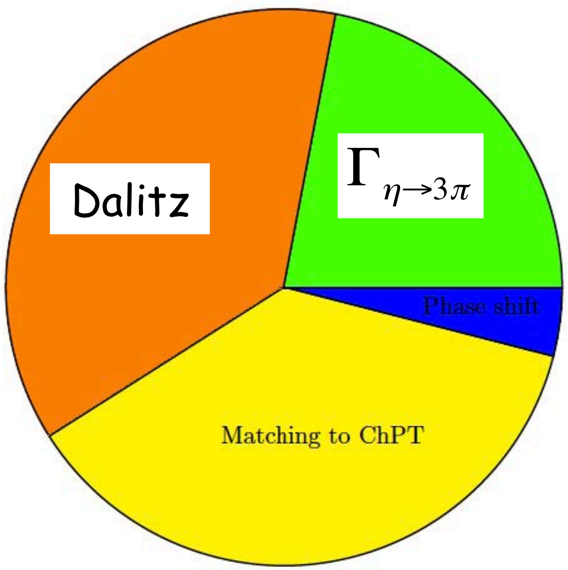


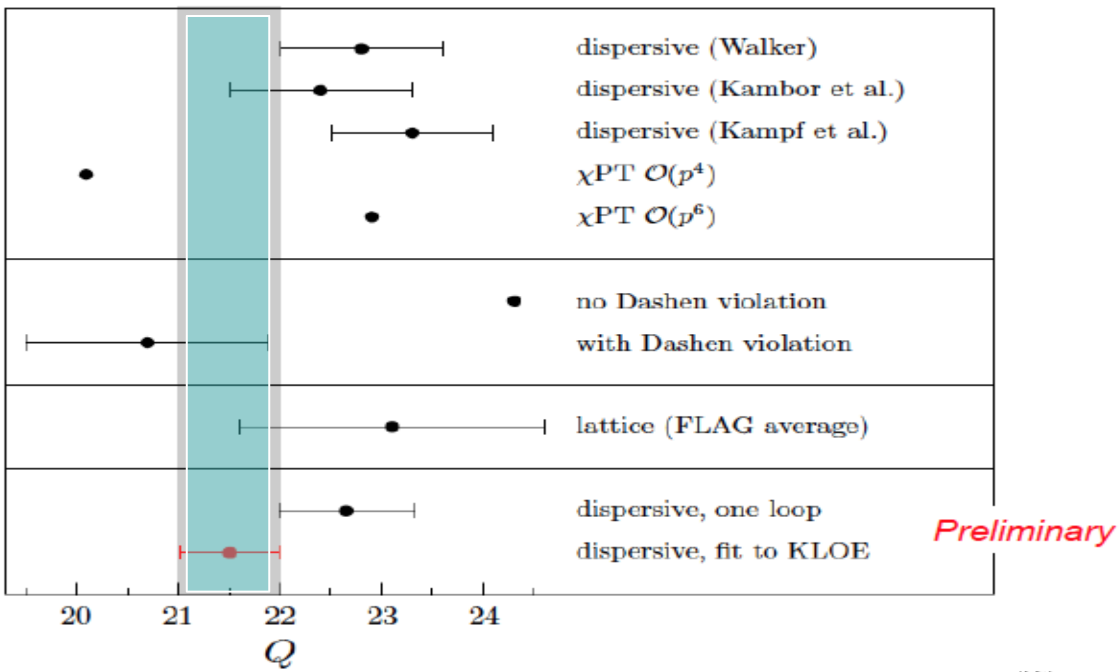


- Existing data from the low energy facilities are sensitive to the detection threshold effect
- JEF at high energy has uniform detection efficiency over Dalitz phase space
- JEF will offer large statistics and improved systematics

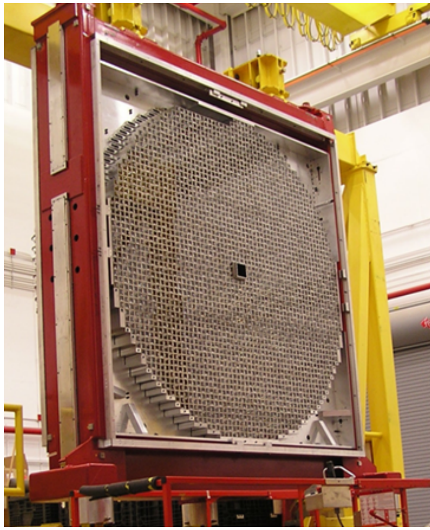
Physics Impact $\eta \to 3\pi$ Measurement

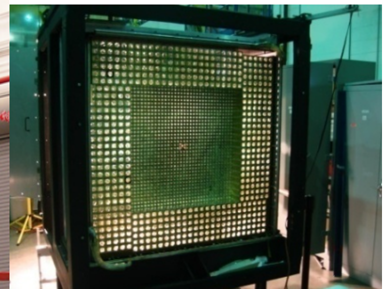
- **A clean probe for quark mass ratio:** $Q^2 = \frac{m_s^2 - \hat{m}^2}{m_d^2 - m_u^2}$ $\hat{m} = \frac{m_u + m_d}{2}$
  - decays through isospin violation: $A = (m_u - m_d)A_1 + \alpha_{em} A_2$
  - α_{em} is small
  - Amplitude: $A(s,t,u) = \frac{1}{Q^2}\frac{m_K^2}{m_\pi^2}(m_\pi^2 - m_K^2)\frac{\mathcal{M}(s,t,u)}{3\sqrt{3}F_\pi^2}$,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





FCAL vs. FCAL-II



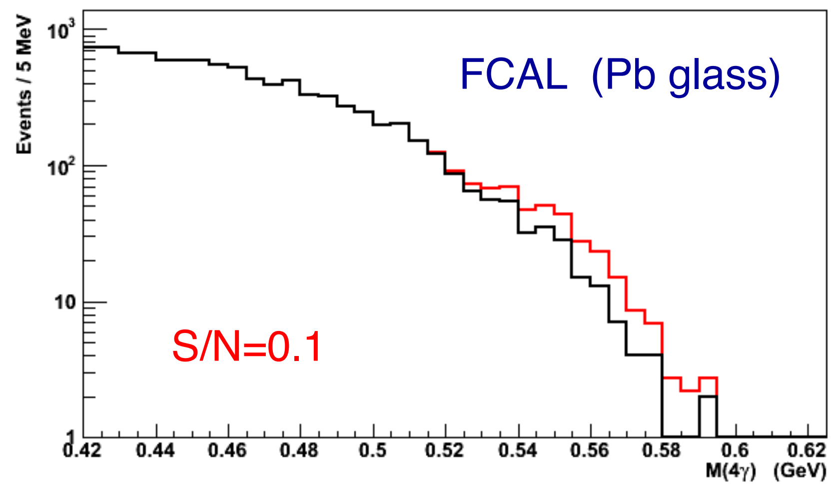


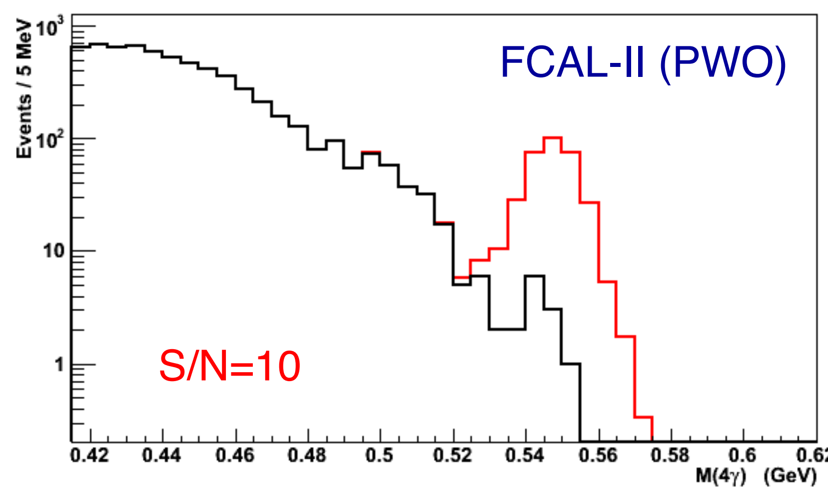
FCAL-II (PWO) vs. FCAL (Pb glass)

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

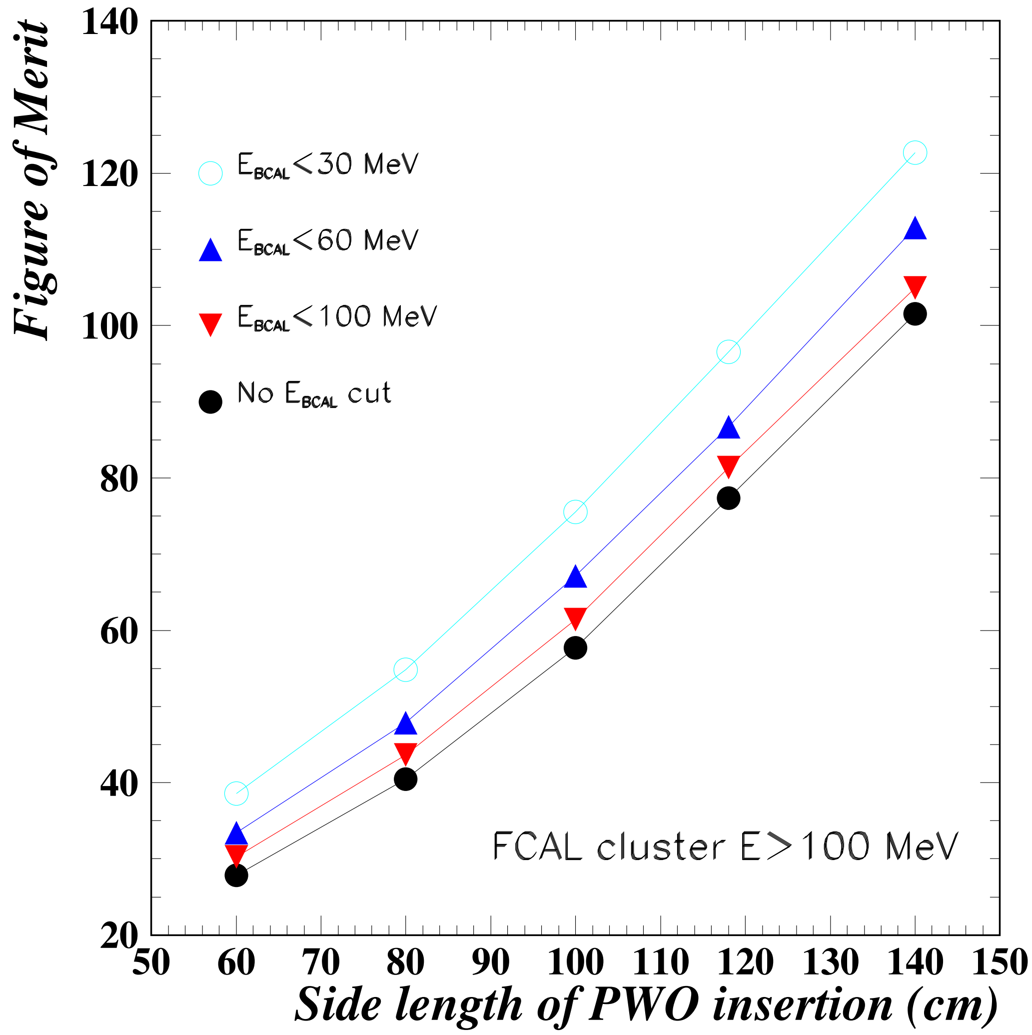
S/N Ratio vs. Calorimeter Types

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





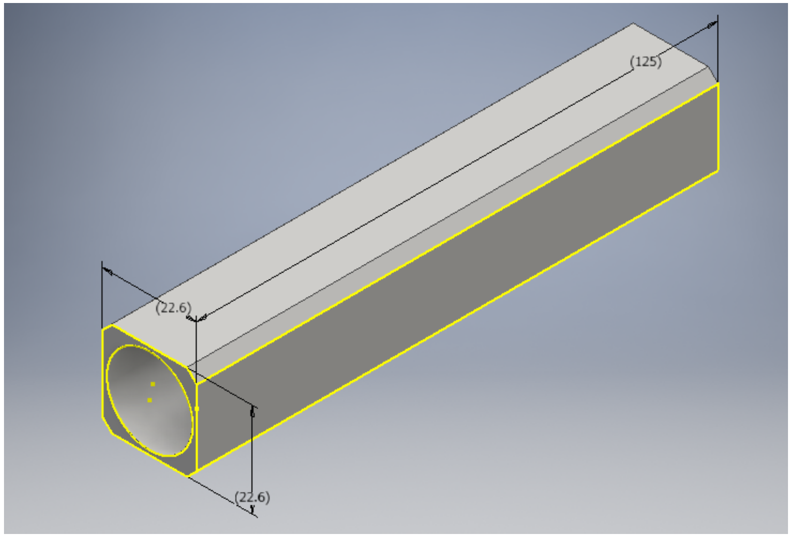
Optimization of PWO Insert Size

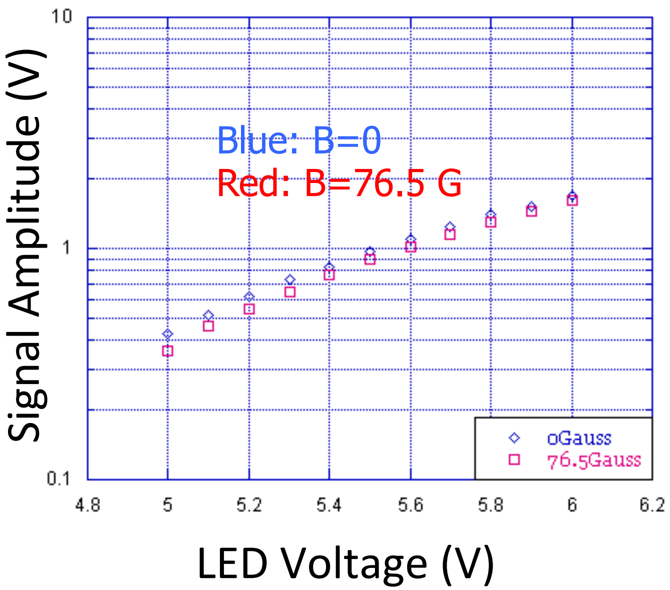


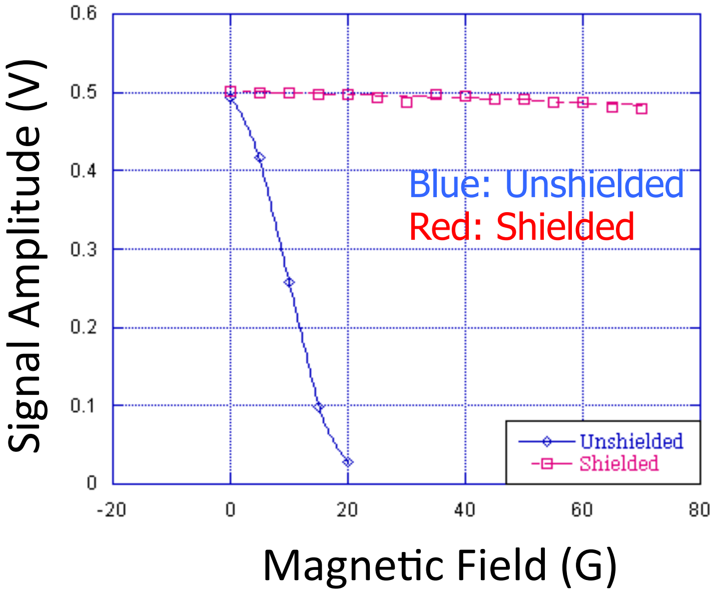
$$FOM = \frac{N(\eta \to \pi^0\gamma\gamma)}{\sqrt{N_b(\eta \to 3\pi^0)}}$$

Magnetic Shield Test Result

- A Hamamatsu R4125HA PMT wrapped with two layers of 0.1mm thick μ-metal
- Helmholtz coils to produce B field along the axis of PMT up to 76.5 G
- PMT was placed inside of the inner hole (Φ=20.5 mm) of a rectangular soft iron and was ~16 mm receding from the entrance of the hole.







Magnetic Shield Continue

- Our recent test result looks encouraging.
- A full calorimeter assembly with a soft iron array will further improve the effect on the magnetic field shielding.
- Double-layer shield (the outer soft iron and the inner μ-Metal) was used for the Lead glass counter (4x4x45 cm^3) in the current FCAL. It was proving to work for magnetic field up to 200 G.
- The same technique is planned for future PWO counter (2x2x18 cm^3): annealed soft iron, μ-metal, and ~2 cm long light guide between PMT and crystal. It should provide sufficient shielding for PMTs under the environment of the maximum field of GlueX solenoid magnet.

Estimated Cost for FCAL-II

Item	**Channels**	**Unit Cost**	**Cost**
PWO crystal	2464	$790	$1.95M
PMT+base+house	2464	$450	$1.11M
Flash ADC	2464-616=1848	$378	$0.70M
HV	2464	$300	$0.74M
Total			$4.50M

Estimated Cost for FCAL-II Infrastructure

Items	Cost ($)
Frame	300k
7 VXS crates with server	300K
1848 signal & HV cables	300K
FCAL platform modification	100k
Total	1M

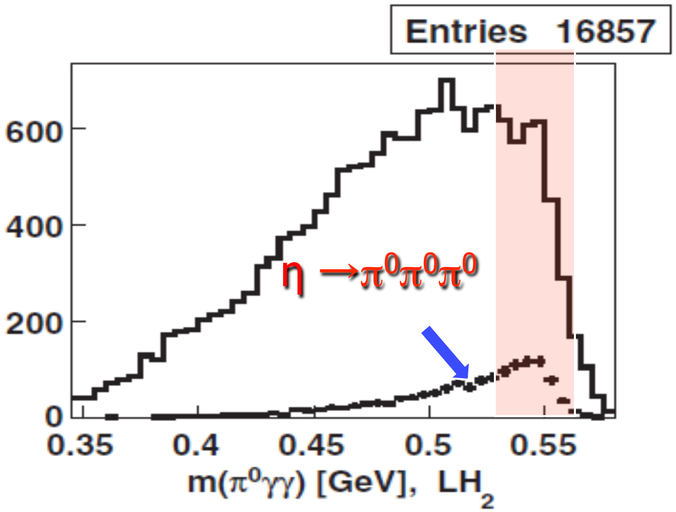
Estimated Schedule for FCAL-II Installation

Activities	**time (month)**
Disconnect cables, disassemble FCAL and inspect lead glass counters	2
Install additional 2000 channels of cable and electronics	1
Stack FCAL-II counters, refurbish some bad lead glass counters	6
Connect cables, monitoring system, cooling system	1
Final check-out	2
Total	12

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

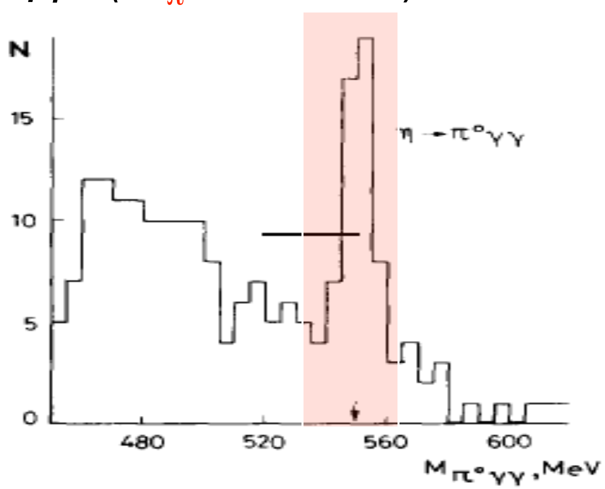
CB-AGS Experiment

$\pi^- p \to \eta\, p$ (E_π=730 MeV)

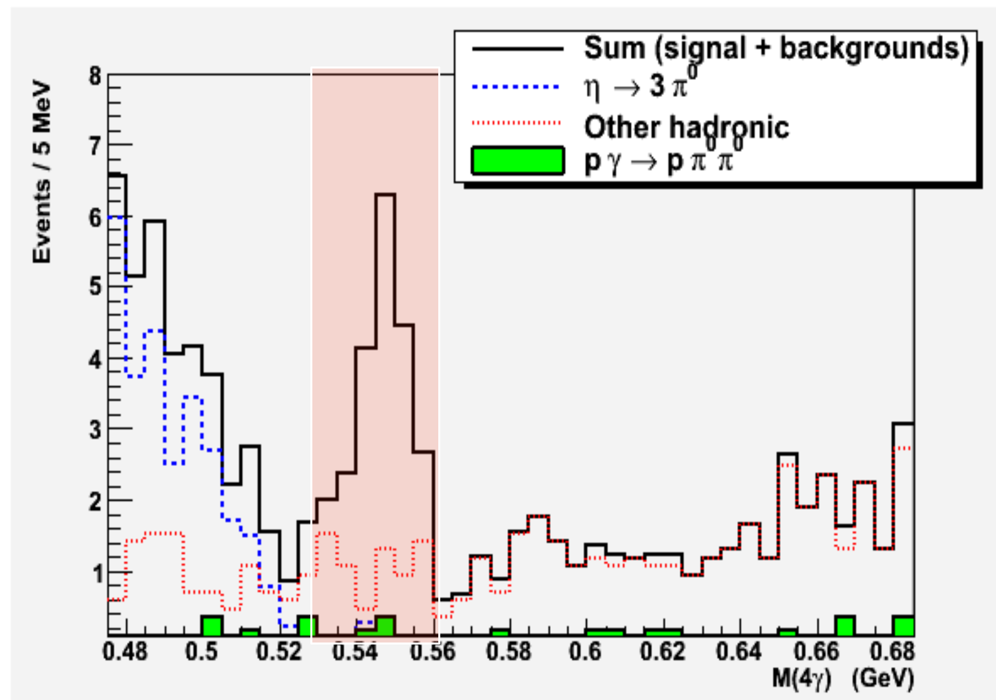


GAMS Experiment

$\pi^- p \to \eta\, p$ (E_π= 30 GeV)



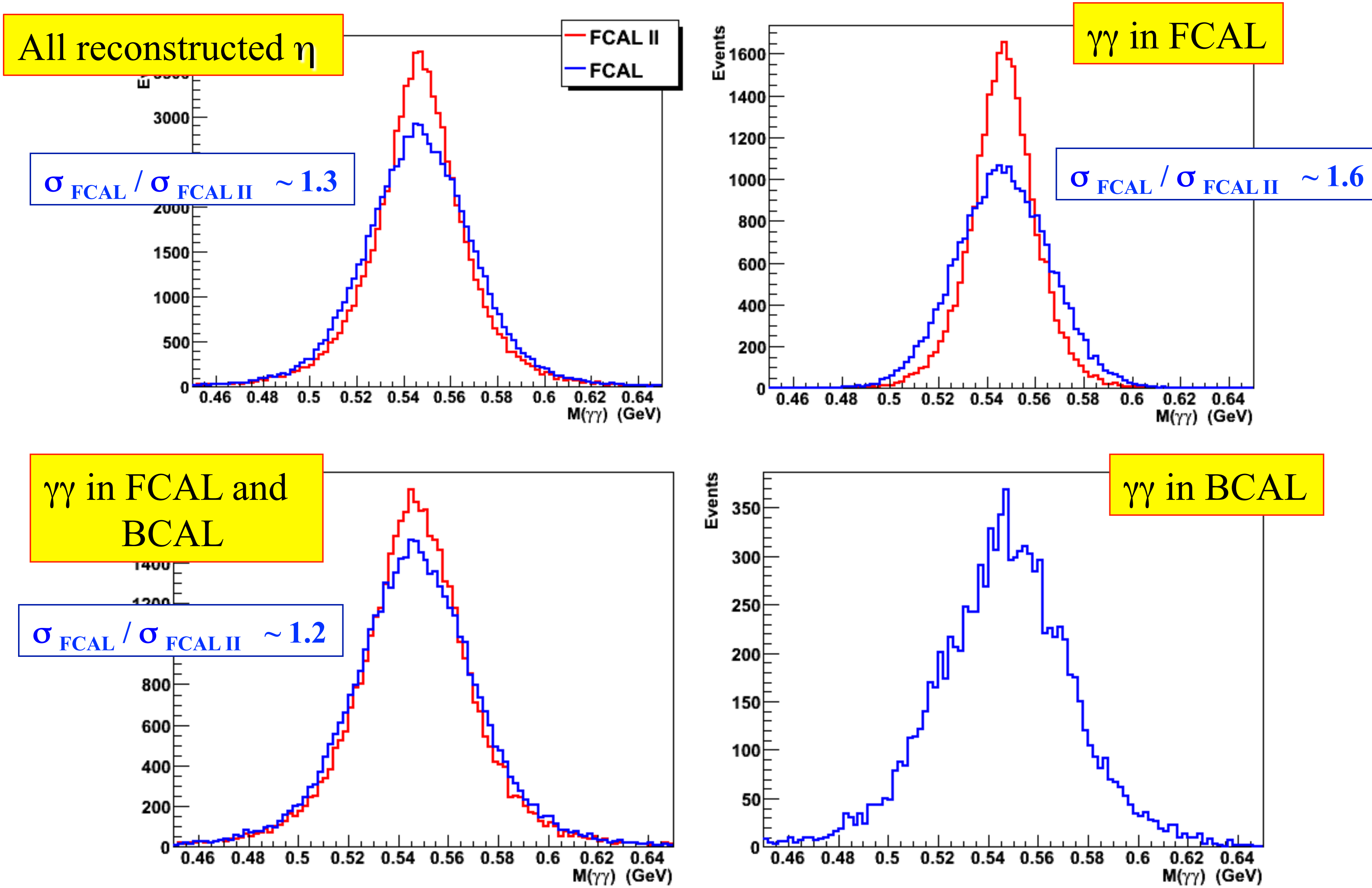
Jlab: $\gamma p \to \eta p$ (E_γ = 9-11.7 GeV)



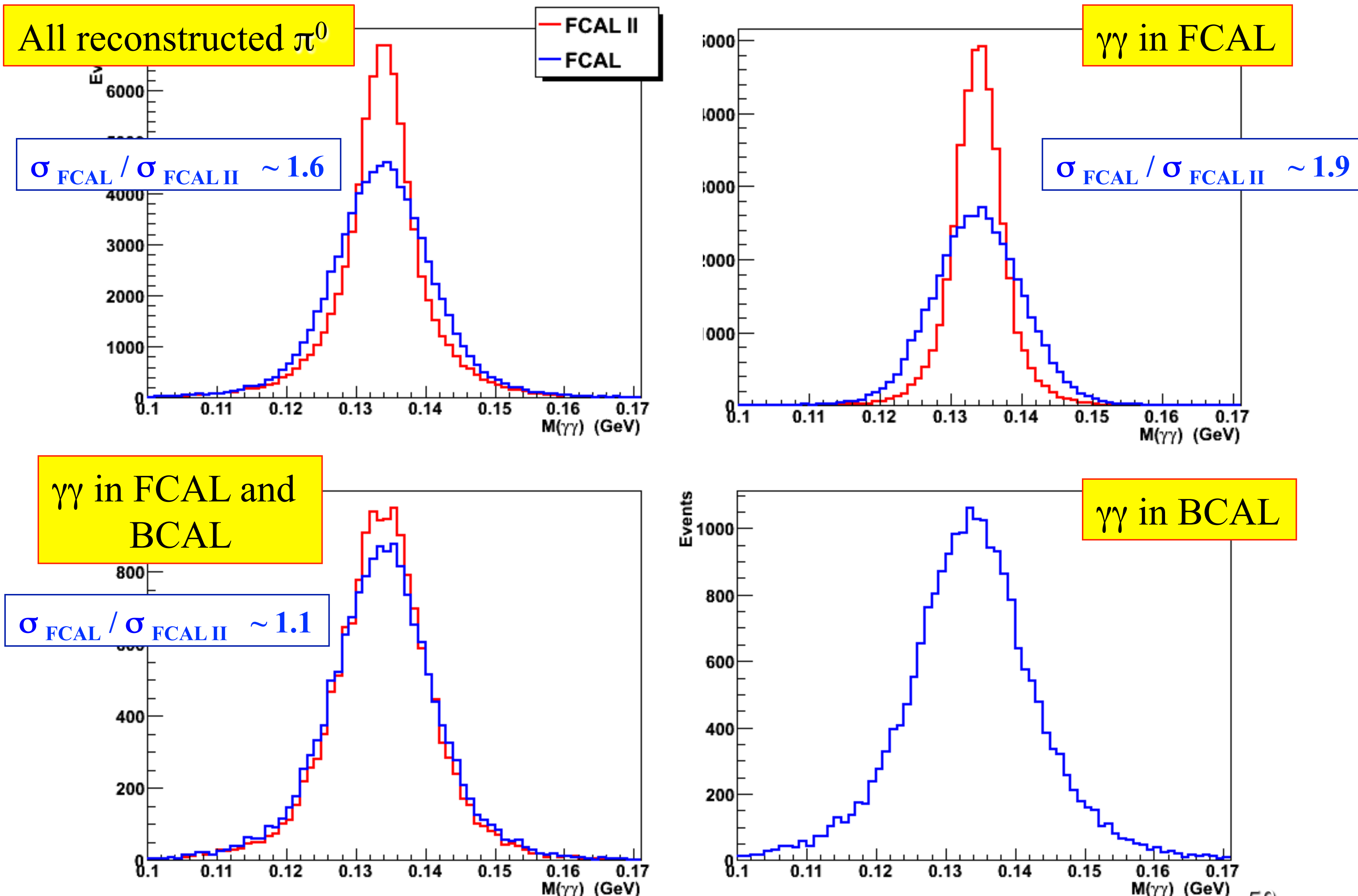
Major Background

- $\eta \to \pi^0\pi^0\pi^0 \to 6\gamma$
- $\pi^- p \to \pi^0\pi^0$ + neutron

Invariant Mass: $\eta \rightarrow \gamma\gamma$



Invariant Mass: $\pi^0 \rightarrow \gamma\ \gamma$



$p + \gamma \rightarrow p + X(1400),\ X(1400) \rightarrow \eta\ \pi^0$

	π^0		η	
	FCAL	FCAL II	FCAL	FCAL II
Overall $\gamma\gamma$ mass resolution, MeV	6.6	4.1	22.3	17

Both photons in Forward Calorimeter

Fraction of events	52 %		32 %	
$\gamma\gamma$ mass resolution, MeV	6.2	3.2	19	12

One photon in Forward Calorimeter and one in BCAL

Fraction of events	19.8 %		55 %	
$\gamma\gamma$ mass resolution, MeV	7.0	6.2	22.9	19.5