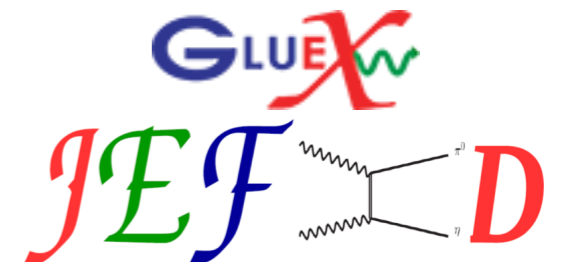# Rare η/η' Neutral Modes and Beyond-Standard-Model Physics

Z. Papandreou for JEF/GlueX

Hadron 2021

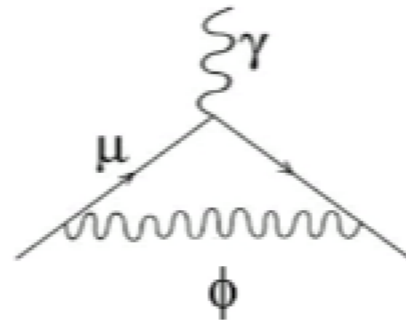*July 28, 2021*

Outline

- ## SM and BSM Searches

  - Physics goals and sensitivities

- ## Jefferson Lab Eta Factory

  - Features and capabilities

- ## Status Quo
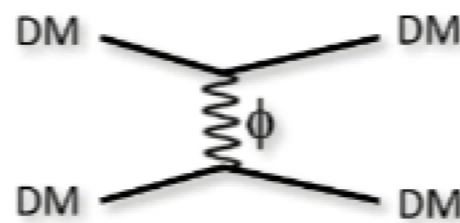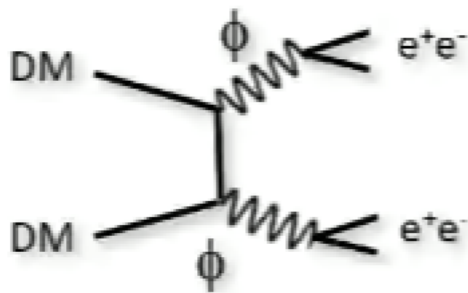
  - Hardware and preparations

Sub-GeV New Physics

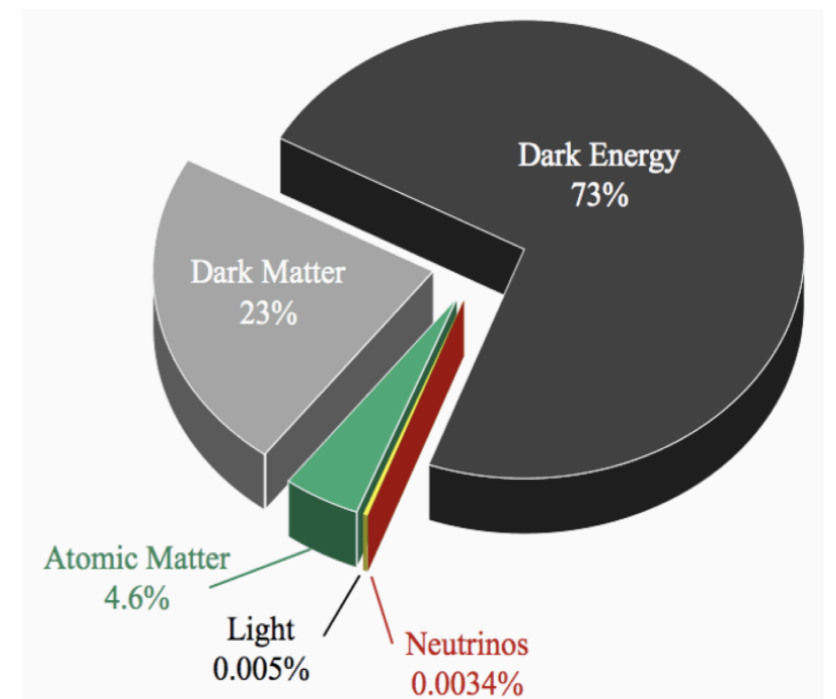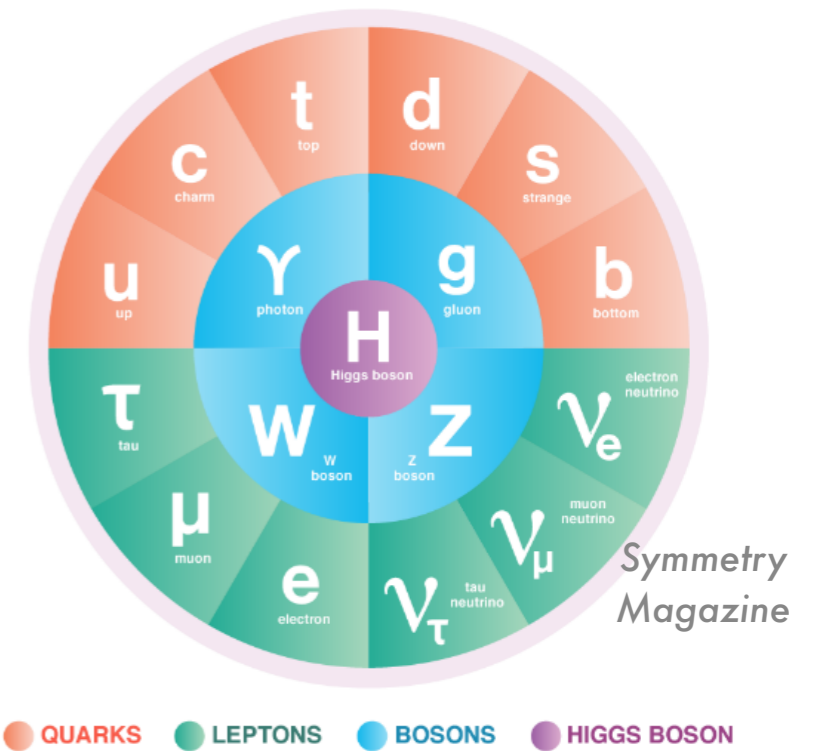- New gauge forces or scalar bosons beyond the minimal standard model

- Anomalies: $(g-2)_\mu$, $^8\text{Be}/^4\text{He}$

- Dark Matter physics

- DM candidates produced in meson decays and direct photo production

Symmetry Magazine

QUARKS   LEPTONS   BOSONS   HIGGS BOSON

JEF Overview

- Model space for sub-GeV dark matter continues to be refined and expanded

- JEF will search for a variety of dark gauge boson candidates

- DM search strategy: resolve narrow structures in invariant mass spectra in many decays

- Additional thrusts: search for C-violating η decays, ChPT…

- Requirement: high-resolution and high-granularity calorimeter

Parameter Landscape
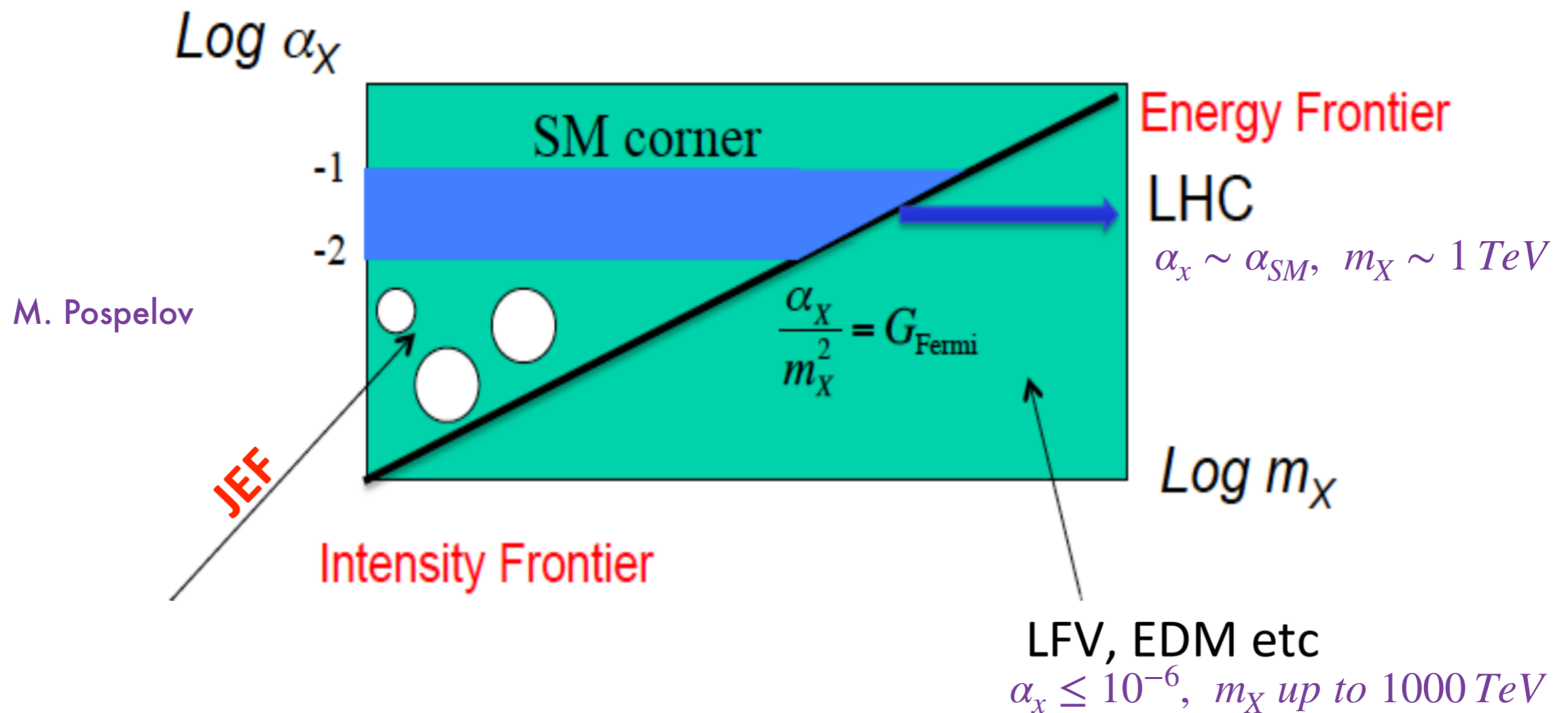
η/η' decays offer **unique sensitivity** for new physics that are flavor-conserving, light quark-coupling, C-violating—P-conserving processes; **complementary** to other experiments

Physics Coverage - 1

1. Search for sub-GeV, hidden bosons

mass ranges ↓

- **vector**:

  - Leptophobic vector B′ $\eta^{(\prime)} \to B'\gamma \to \pi^0\gamma\gamma \ (0.14 - 0.54 \ GeV)$

    $\eta' \to B'\gamma \to \pi^+\pi^-\pi^0\gamma \ (0.62 - 1.00 \ GeV)$

  - Hidden or dark photon $\eta^{(\prime)} \to A'\gamma \to e^+e^-\gamma$

- **scalar**: $\eta \to \pi^0 S \to \pi^0\gamma\gamma, \pi^0 e^+e^- \ (10 \ MeV < m_S < 2m_\pi)$

  $\eta^{(\prime)} \to \pi^0 S \to 3\pi, \eta' \to \eta S \to \eta\pi\pi \ (m_S > 2m_\pi)$

- **Axion-Like Particles (ALP)**: $\eta^{(\prime)} \to \pi\pi a \to \pi\pi\gamma\gamma, \pi\pi e^+e^-$

Physics Coverage - 2

2. Directly constrain CVPC new physics:

$$\eta^{(')} \to 3\gamma, \, 2\pi^0\gamma, \, \pi^+\pi^-\pi^0$$

3. Precision tests of low-energy QCD:

- Interplay of VMD & scalar dynamics in ChPT: $\eta^{(')} \to \pi^0\gamma\gamma$

- Transition Form Factors of η(') : $\eta^{(')} \to e^+e^-\gamma$

4. Improve the quark mass ratio via $\eta^{(')} \to 3\pi^0, \, \pi^+\pi^-\pi^0$

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Rich physics program at η, η′ factories

Standard Model highlights
- Theory input for light-by-light scattering for $(g-2)_\mu$
- Extraction of light quark masses
- QCD scalar dynamics

Fundamental symmetry tests
- P,CP violation
- C,CP violation

[Kobzarev & Okun (1964), Prentki & Veltman (1965), Lee (1965), Lee & Wolfenstein (1965), Bernstein et al (1965)]

Dark sectors (MeV—GeV)
- Vector bosons (dark photon, B boson, X boson)
- Scalars
- Pseudoscalars (ALPs)

(Plus other channels that have not been searched for to date)

Channel	Expt. branching ratio	Discussion
$\eta \to 2\gamma$	39.41(20)%	chiral anomaly, η–η' mixing
$\eta \to 3\pi^0$	32.68(23)%	$m_u - m_d$
$\eta \to \pi^0\gamma\gamma$	$2.56(22) \times 10^{-4}$	χPT at $O(p^6)$, leptophobic B boson, light Higgs scalars
$\eta \to \pi^0\pi^0\gamma\gamma$	$< 1.2 \times 10^{-3}$	χPT, axion-like particles (ALPs)
$\eta \to 4\gamma$	$< 2.8 \times 10^{-4}$	$< 10^{-11}$[52]
$\eta \to \pi^+\pi^-\pi^0$	22.92(28)%	$m_u - m_d$, C/CP violation, light Higgs scalars
$\eta \to \pi^+\pi^-\gamma$	4.22(8)%	chiral anomaly, theory input for singly-virtual TFF and $(g-2)_\mu$, P/CP violation
$\eta \to \pi^+\pi^-\gamma\gamma$	$< 2.1 \times 10^{-3}$	χPT, ALPs
$\eta \to e^+e^-\gamma$	$6.9(4) \times 10^{-3}$	theory input for $(g-2)_\mu$, dark photon, protophobic X boson
$\eta \to \mu^+\mu^-\gamma$	$3.1(4) \times 10^{-4}$	theory input for $(g-2)_\mu$, dark photon
$\eta \to e^+e^-$	$< 7 \times 10^{-7}$	theory input for $(g-2)_\mu$, BSM weak decays
$\eta \to \mu^+\mu^-$	$5.8(8) \times 10^{-6}$	theory input for $(g-2)_\mu$, BSM weak decays, P/CP violation
$\eta \to \pi^0\pi^0\ell^+\ell^-$		C/CP violation, ALPs
$\eta \to \pi^+\pi^-e^+e^-$	$2.68(11) \times 10^{-4}$	theory input for doubly-virtual TFF and $(g-2)_\mu$, P/CP violation, ALPs
$\eta \to \pi^+\pi^-\mu^+\mu^-$	$< 3.6 \times 10^{-4}$	theory input for doubly-virtual TFF and $(g-2)_\mu$, P/CP violation, ALPs
$\eta \to e^+e^-e^+e^-$	$2.40(22) \times 10^{-5}$	theory input for $(g-2)_\mu$
$\eta \to e^+e^-\mu^+\mu^-$	$< 1.6 \times 10^{-4}$	theory input for $(g-2)_\mu$
$\eta \to \mu^+\mu^-\mu^+\mu^-$	$< 3.6 \times 10^{-4}$	theory input for $(g-2)_\mu$
$\eta \to \pi^+\pi^-\pi^0\gamma$	$< 5 \times 10^{-4}$	direct emission only
$\eta \to \pi^\pm e^\mp \nu_e$	$< 1.7 \times 10^{-4}$	second-class current
$\eta \to \pi^+\pi^-$	$< 4.4 \times 10^{-6}$ [53]	P/CP violation
$\eta \to 2\pi^0$	$< 3.5 \times 10^{-4}$	P/CP violation
$\eta \to 4\pi^0$	$< 6.9 \times 10^{-7}$	P/CP violation

Gan, Kubis, Passemar, ST [arxiv:2007.00664]

PDG - η

$$\boxed{\eta} \qquad {}^{I}{}^{G}(J^{PC}) = 0^{+}(0^{-+})$$

Mass $m = 547.862 \pm 0.018$ MeV

Full width $\Gamma = 1.31 \pm 0.05$ keV

$$\eta \approx \frac{1}{\sqrt{6}}(u\bar{u} + d\bar{d} - 2s\bar{s})$$

η DECAY MODES	Fraction (Γ_i/Γ)		Scale factor/ Confidence level	p (MeV/c)
Neutral modes				
neutral modes	(72.12 ± 0.34) %		S=1.2	–
2γ	(39.41 ± 0.20) %		S=1.1	274
$3\pi^0$	(32.68 ± 0.23) %		S=1.1	179
$\pi^0 2\gamma$	$(2.7 \pm 0.5) \times 10^{-4}$		S−1.1	257
$2\pi^0 2\gamma$	< 1.2	$\times 10^{-3}$	CL=90%	238
4γ	< 2.8	$\times 10^{-4}$	CL=90%	274
invisible	< 1.0	$\times 10^{-4}$	CL=90%	–
Charged modes				
charged modes	(28.10 ± 0.34) %		S=1.2	–
$\pi^+ \pi^- \pi^0$	(22.92 ± 0.28) %		S=1.2	174
$\pi^+ \pi^- \gamma$	(4.22 ± 0.08) %		S=1.1	236
$e^+ e^- \gamma$	$(6.9 \pm 0.4) \times 10^{-3}$		S=1.3	274
Charge conjugation (C) or Lepton Family number (LF) violating modes				
3γ	C	< 3.1	$\times 10^{-8}$ CL=90%	67

PDG - η′

$\eta'(958)$ $I^G(J^{PC}) = 0^+(0^{-+})$

$\eta' \approx \dfrac{1}{\sqrt{3}}(u\bar{u} + d\bar{d} + s\bar{s})$

Mass $m = 957.78 \pm 0.06$ MeV
Full width $\Gamma = 0.198 \pm 0.009$ MeV

$\eta'(958)$ DECAY MODES	Fraction (Γ_i/Γ)		Confidence level	p (MeV/c)
$\pi^+\pi^-\eta$	(42.9 ± 0.7) %			232
$\rho^0\gamma$ (including non-resonant $\pi^+\pi^-\gamma$)	(29.1 ± 0.5) %			165
$\pi^0\pi^0\eta$	(22.2 ± 0.8) %			239
$\pi^0\gamma\gamma$	< 8	$\times 10^{-4}$	90%	469
$\gamma\gamma$	(2.20 ± 0.08) %			479
$3\pi^0$	$(2.14 \pm 0.20) \times 10^{-3}$			430

w/o BESIII

Charge conjugation (C), Parity (P), Lepton family number (LF) violating modes

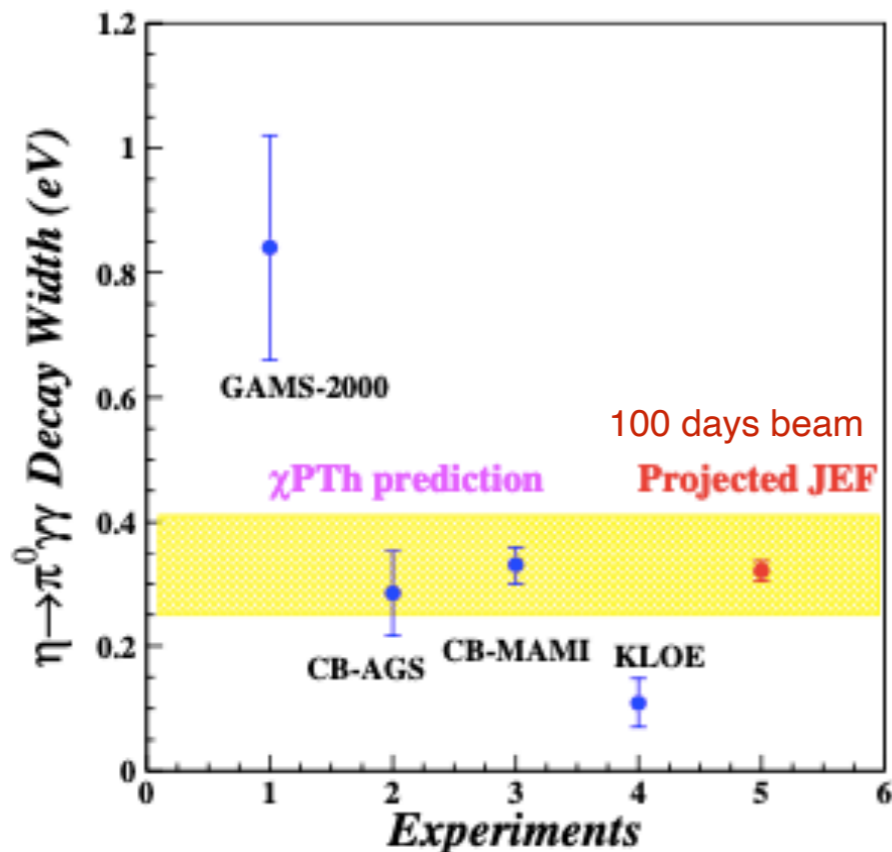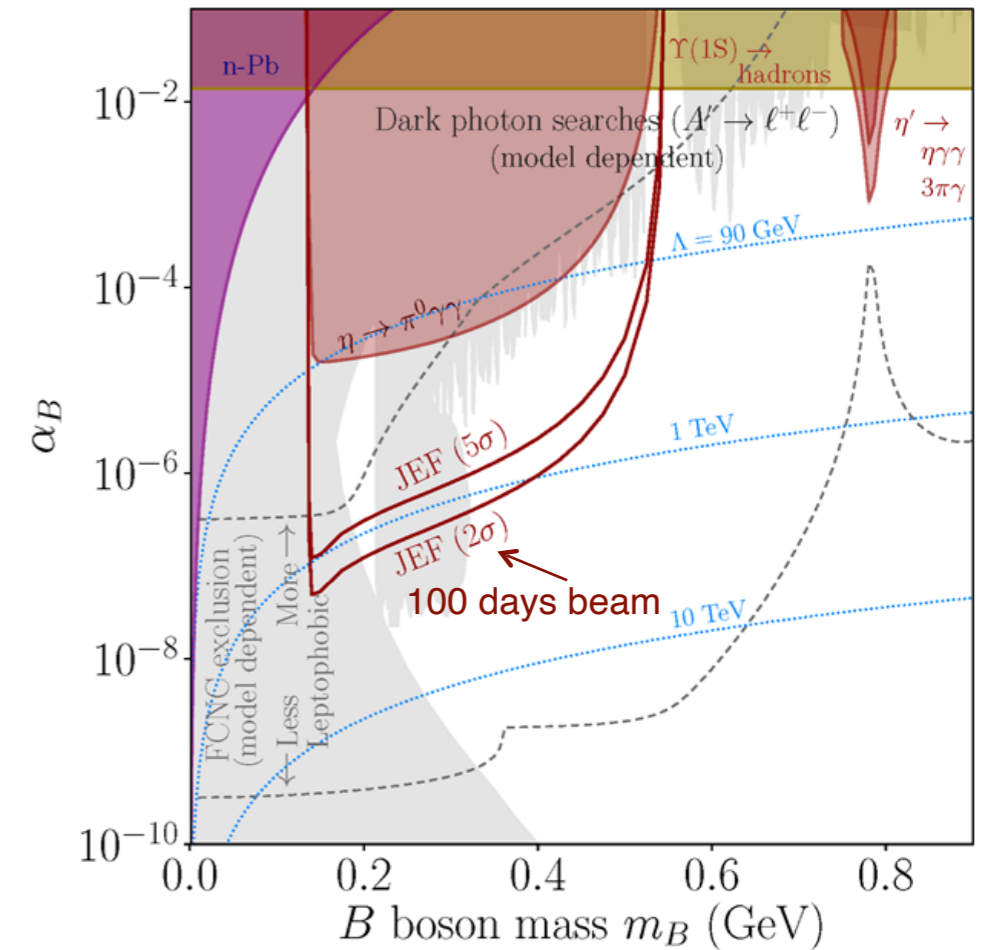|					Confidence level	p (MeV/c)
$\pi^+\pi^-$	P,CP		< 6	$\times 10^{-5}$	90%	458
$\pi^0\pi^0$	P,CP		< 4	$\times 10^{-4}$	90%	459
$\pi^0 e^+ e^-$	C	$[f]$	< 1.4	$\times 10^{-3}$	90%	469
$\eta e^+ e^-$	C	$[f]$	< 2.4	$\times 10^{-3}$	90%	322
3γ	C		< 1.0	$\times 10^{-4}$	90%	479

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

- **Search for sub-GeV gauge bosons:**

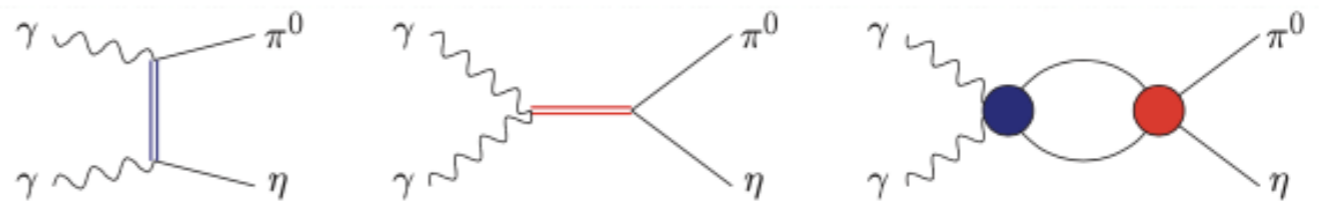 - **leptophobic vector B′** coupling to baryon no.

    $$\eta \to B'\gamma \to \pi^0\gamma\gamma \quad \text{Nelson PLB 221, 80 // Tulin PRD 89,114008}$$

  - **scalar S**: a electrophobic scalar can help solve proton radius and (g-2)$_\mu$ puzzles.

    $$\eta \to \pi^0 S \to \pi^0\gamma\gamma \quad \text{Batell, PRD 100,095020 / Liu Nucl.Phy.B,114638}$$

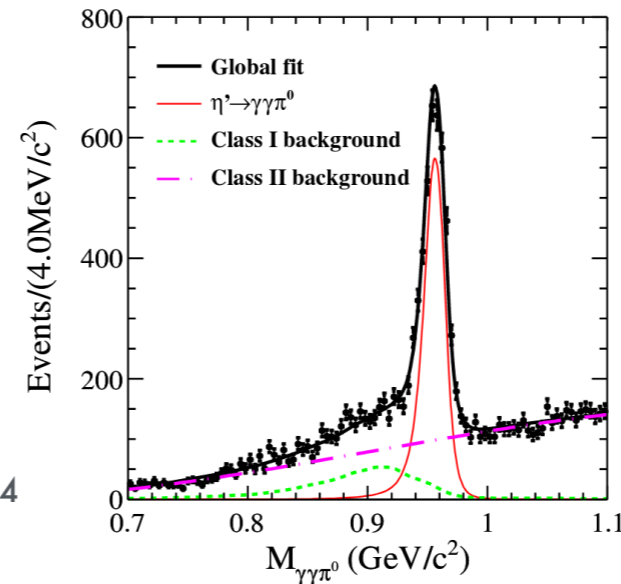- A rare window to probe interplay of VMD & scalar resonance in ChPT Prakhov PRC 78,015206

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Key Channel: $\eta' \to \pi^0\gamma\gamma$

Recent BES-III measurement on η':

- doubly-radiative decay measured for first time

- BR(inclusive) = 3.20±0.07(stat)±0.23(sys))×10⁻³

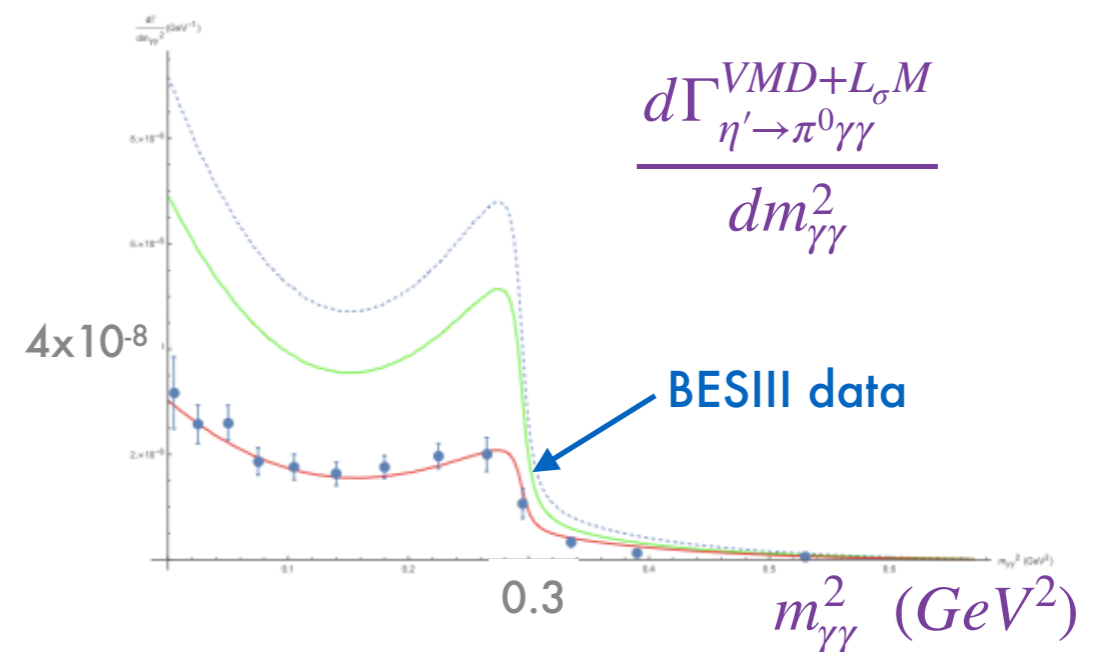- BR(η'→γω) = 23.7±1.4(stat)±1.8(sys))×10⁻⁴

- BR(non-resonant) = (6.16±0.64(stat)±0.67(sys))×10⁻⁴

Ablikim, Phys. Rev. D 96, 012005
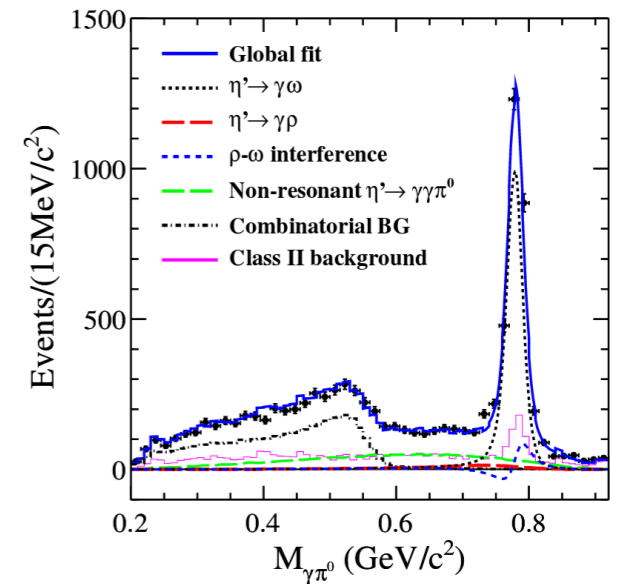
Recent theory developments: Balytzkyi, arXiv:1811.01402

VMD + (Chiral Perturbation theory or Linear sigma model) (highly suppressed)

- Result Γ(η'→π⁰γγ)=1.6-3.0 keV disagrees with BESIII result Γ(η'→π⁰γγ)≈0.64 keV

- Dark photon? Increase mass range for B search?

Key Channel: $\eta \to 3\pi^0$

- A clean probe for **quark mass ratio**:

  - decays through isospin violation:
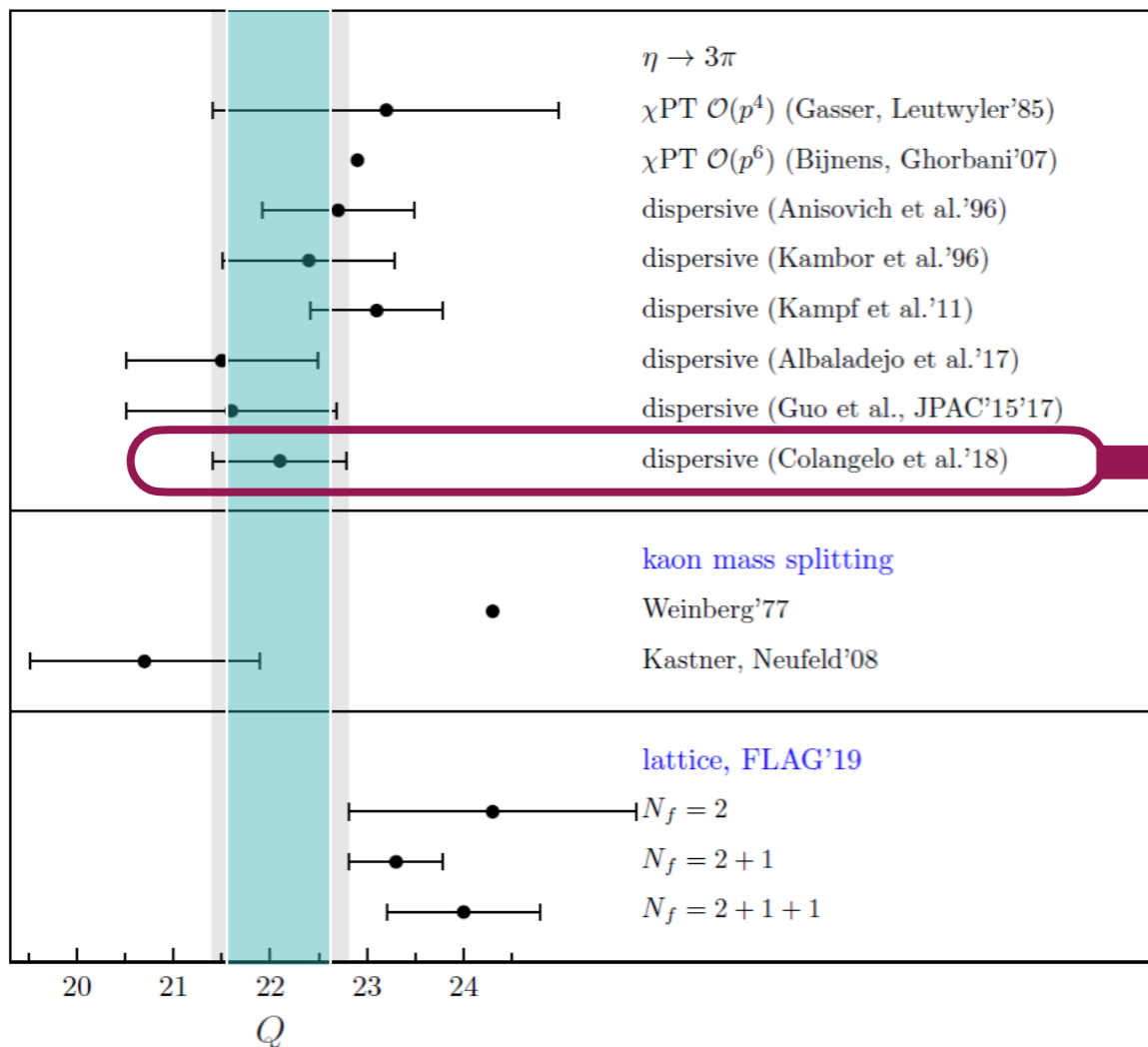
$$Q^2 = \frac{m_s^2 - \hat{m}^2}{m_d^2 - m_u^2}, \quad \hat{m} = \frac{m_u + m_d}{2}$$
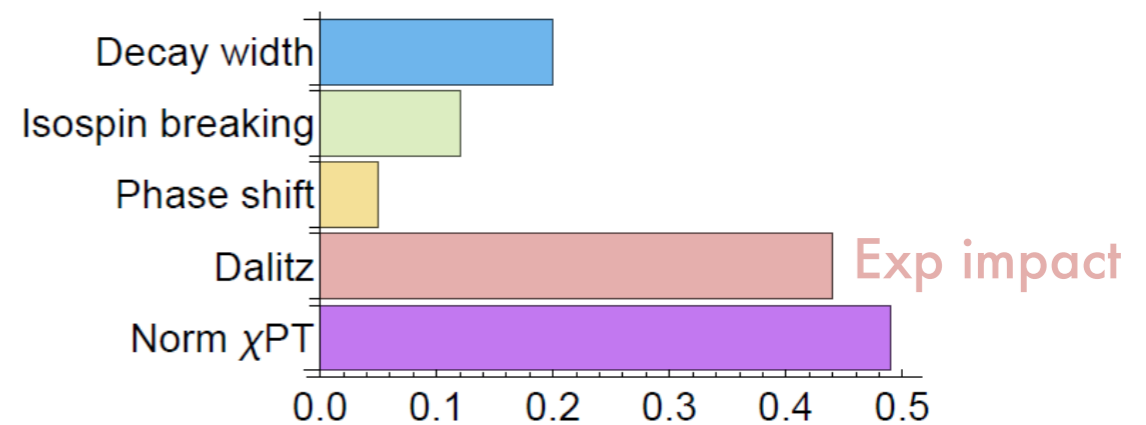
$$A = (m_u - m_d)A_1 + \alpha_{em}A_2, \quad \alpha_{em} \sim small$$

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


$\eta \to 3\pi$
χPT $\mathcal{O}(p^4)$ (Gasser, Leutwyler'85)
χPT $\mathcal{O}(p^6)$ (Bijnens, Ghorbani'07)
dispersive (Anisovich et al.'96)
dispersive (Kambor et al.'96)
dispersive (Kampf et al.'11)
dispersive (Albaladejo et al.'17)
dispersive (Guo et al., JPAC'15'17)
dispersive (Colangelo et al.'18)

kaon mass splitting
Weinberg'77
Kastner, Neufeld'08

lattice, FLAG'19
$N_f = 2$
$N_f = 2+1$
$N_f = 2+1+1$

- Uncertainties in quark mass ratio:

Decay width
Isospin breaking
Phase shift
Dalitz — Exp impact
Norm χPT

e-Print: 2007.00664

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Key Channel: $\eta \to 3\gamma$

- **SM contribution:**

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

- **Theoretical push?**

  - A new C- and T-violating, and P-conserving interaction was proposed by Bernstein, Feinberg and Lee. Phys. Rev.,139, B1650 (1965)

  - A calculation by Tarasov suggests: BR($\eta \to 3\gamma$)$< 10^{-2}$
    Sov.J.Nucl.Phys.,5,445 (1967)

3γ BR Upper Limit vs Accepted Eta Decays

Proj. JEF
(100 days' beam)
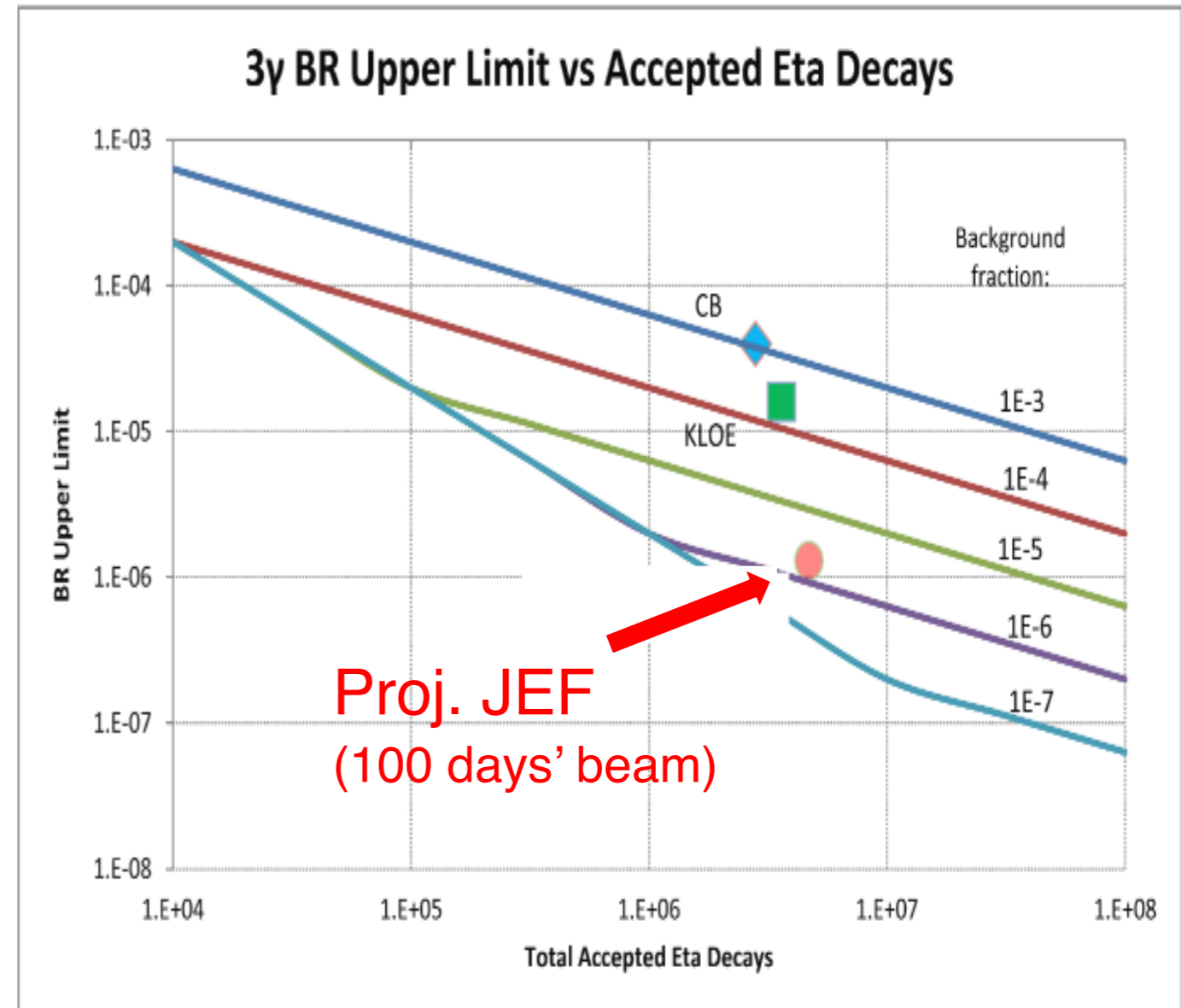
Improve BR upper limit by one order of magnitude to directly tighten the constraint on CVPC new physics

- Sensitivity of photon-beam experiments to axionlike particles (ALPs):

  - QCD-scale masses; dominant coupling to SM is either to photons or gluons.

- Data-driven method

  - eliminates the need for knowledge of nuclear form factors or the photon-beam flux

- GlueX/PrimEx-type calorimeter
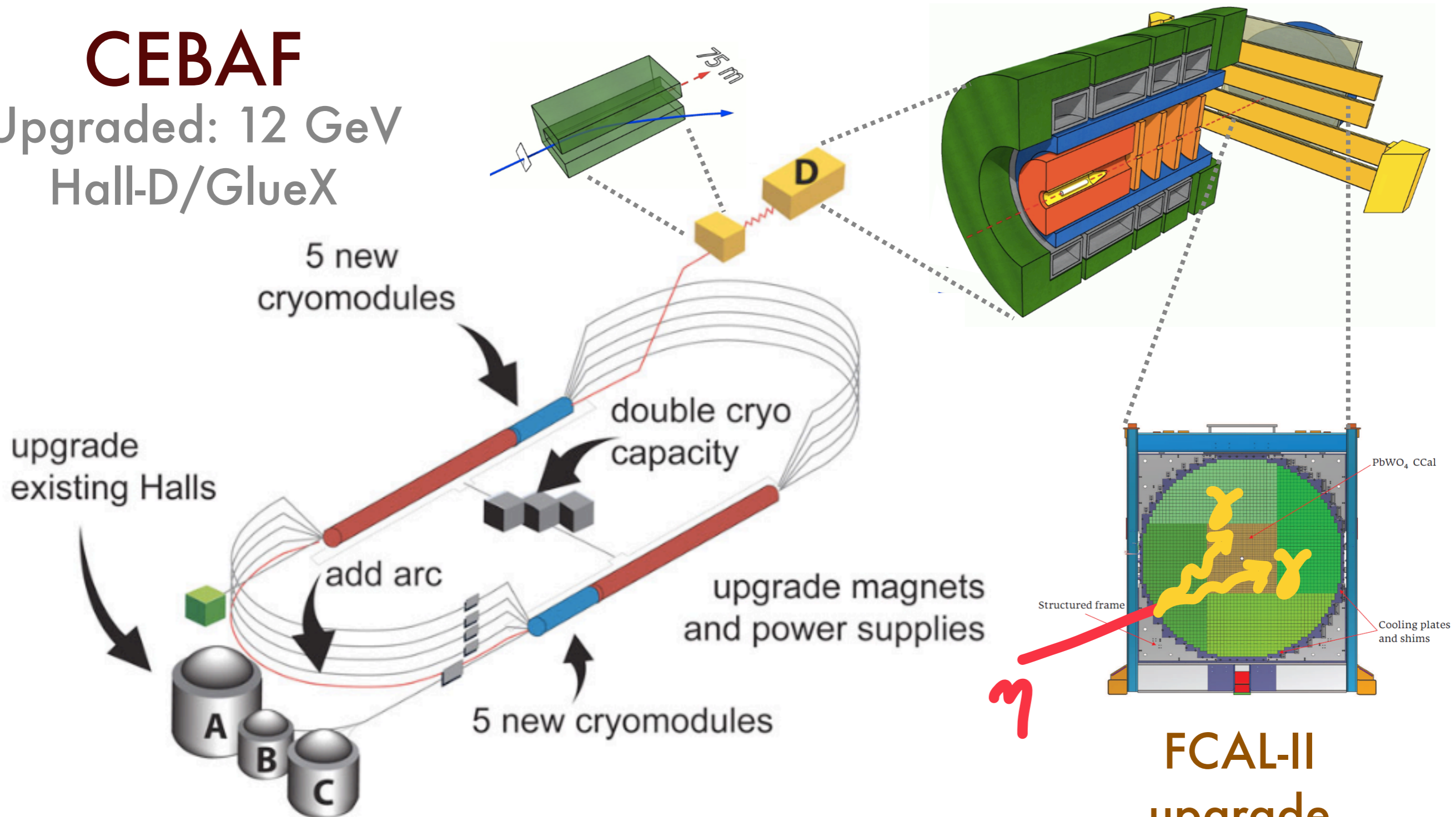
  - $0.15 < m_\alpha < 0.46$ GeV region
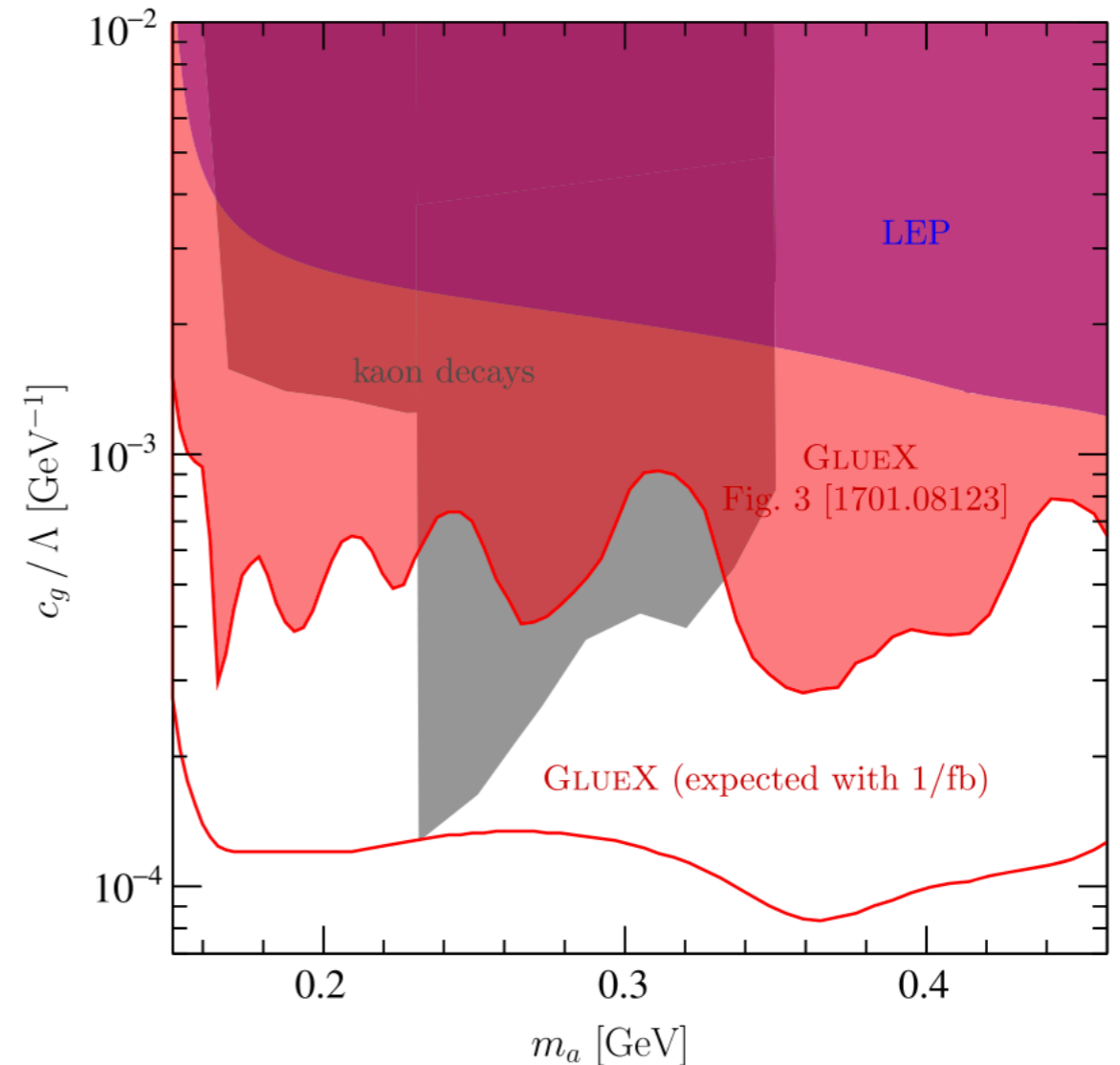
New limit is set using the published $m_{\gamma\gamma}$ spectrum from ≈1/pb of GLUEX data

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Jefferson Lab/GlueX/JEF

CEBAF
Upgraded: 12 GeV
Hall-D/GlueX

75m

D

5 new
cryomodules

double cryo
capacity

upgrade
existing Halls

add arc

upgrade magnets
and power supplies

5 new cryomodules

A B C

PbWO$_4$ CCal

Structured frame

Cooling plates
and shims

η

FCAL-II
upgrade

GlueX goal: look for exotic hybrids

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Production Rates

JEF (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	10^6
WASA-COSY	$\sim 3 \times 10^7$ (p+d), $\sim 5 \times 10^8$ (p+p)	-
KLOE-II	3×10^8	5×10^5
BESIII	$\sim 10^7$	$\sim 5 \times 10^7$

JEF offers a competitive η/η′ factory
(proposed REDTOP $10^{13}/10^{11}$ per year)

Key Features of JEF
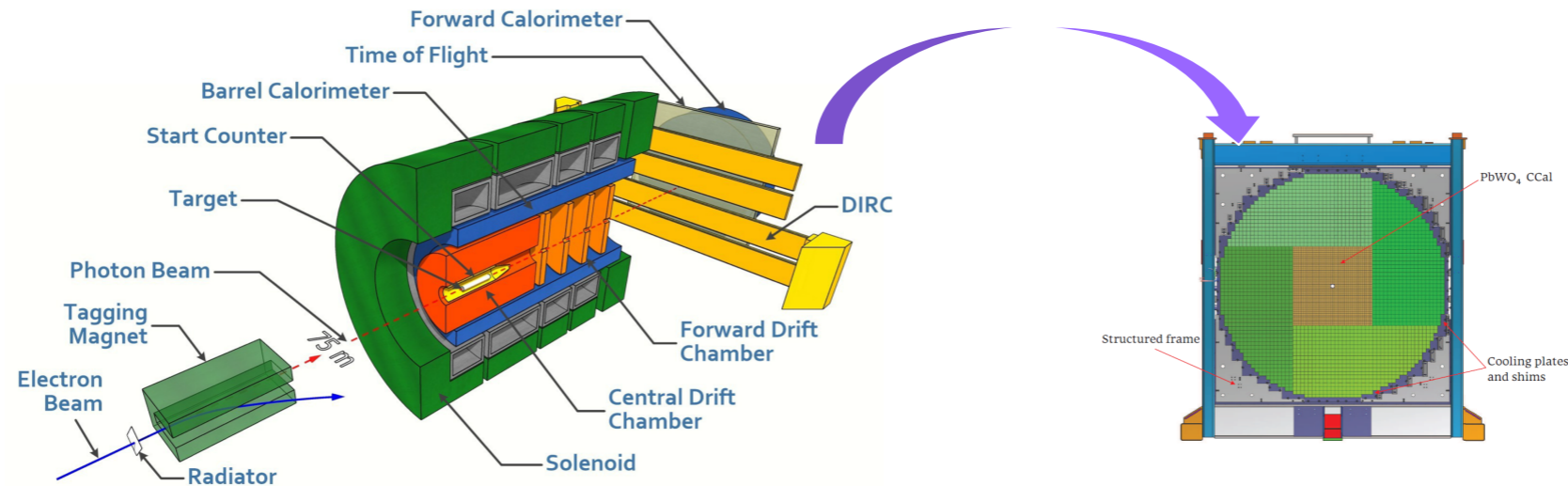
- η/η' production: 8.4-11.7 GeV tagged γ beam; η, η' energy boost

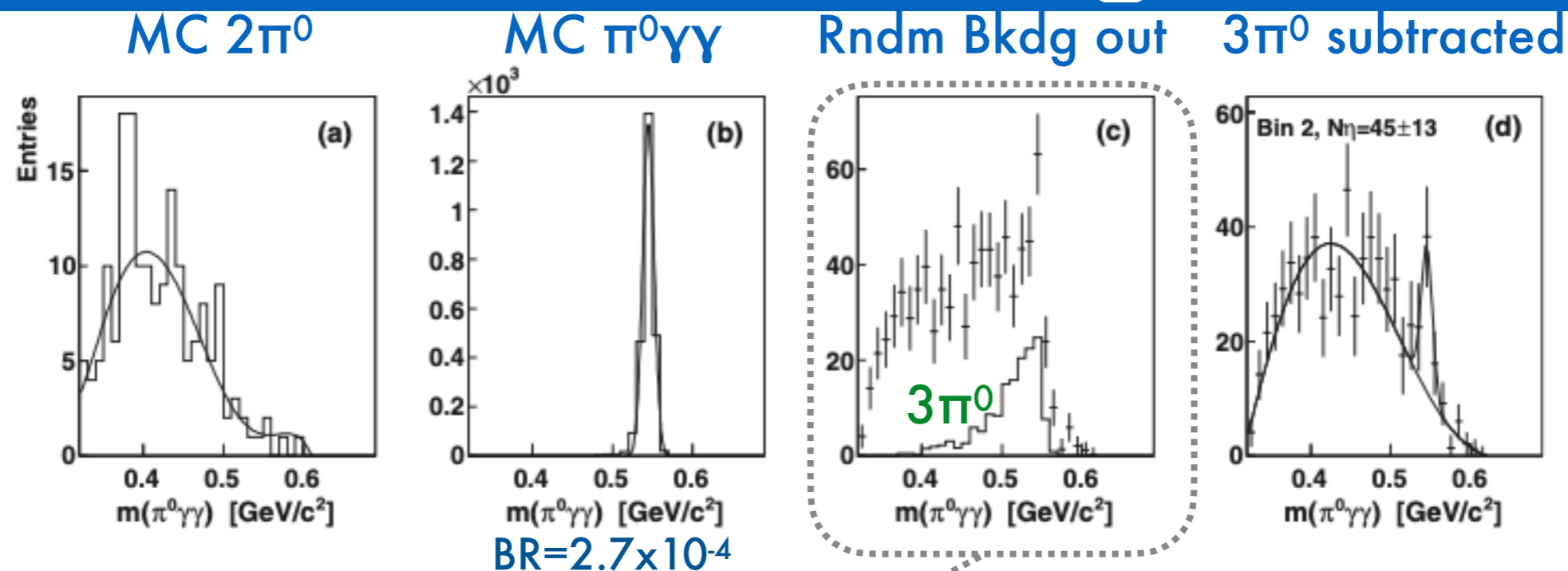- produce & detect η/η' simultaneously; exclusive channels

$$\gamma p \rightarrow p(\eta/\eta') \text{ and } \eta/\eta' \rightarrow \gamma\gamma, \pi^0\gamma\gamma \ldots$$

- Reduce non-coplanar backgrounds by detecting recoil protons with the GlueX detector.

- Upgraded FCAL-II with 40x40 crystal (80x80cm^2) lead tungstate (PbWO$_4$) insert for improved resolution and superior granularity.

Neutral Channels: $n \times \gamma$

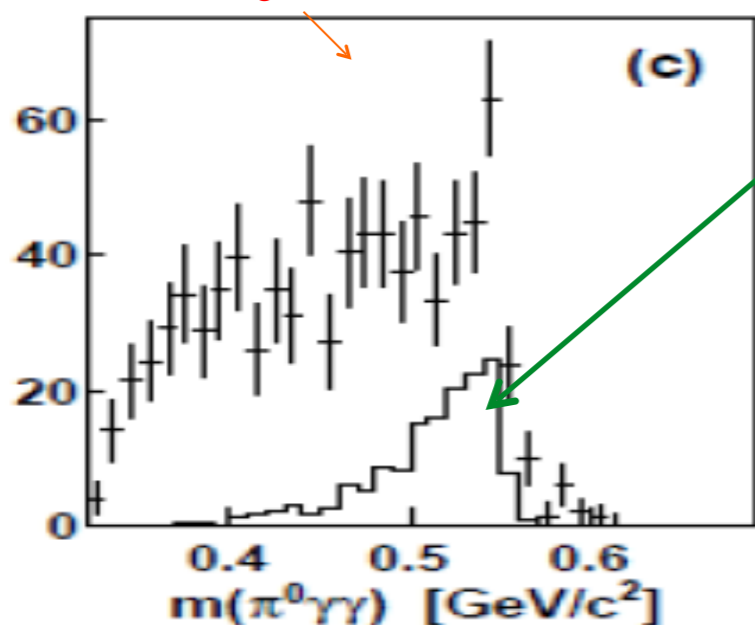| Mode	Branching Ratio	Physics Highlight	Photons
priority:			
$\gamma + B'$	beyond SM	leptophobic dark vector boson	4
$\pi^0 + \phi'$	beyond SM	electrophobic dark scalar boson	4
$\pi^0 2\gamma$	$(2.7 \pm 0.5) \times 10^{-4}$	χPTh at $\mathcal{O}(p^6)$	4
$3\pi^0$	$(32.7 \pm 0.2)\%$	$m_u - m_d$	6
$\pi^+\pi^-\pi^0$	$(22.9 \pm 0.3)\%$	$m_u - m_d$, CV	2
3γ	$< 1.6 \times 10^{-5}$	CV, CPV	3
ancillary:			
4γ	$< 2.8 \times 10^{-4}$	$< 10^{-11}$ [23]	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	7
$4\pi^0$	$< 6.9 \times 10^{-7}$	CPV, PV	8
$\pi^0\gamma$	$< 9 \times 10^{-5}$	CV, Ang. Mom. viol.	3
normalization:			
2γ	$(39.4 \pm 0.2)\%$	anomaly, η-η' mixing E12-10-011	2

Boost & Background

MC 2π⁰   MC π⁰γγ   Rndm Bkdg out   3π⁰ subtracted

Nefkens, PRC90, 025206

BR=2.7×10⁻⁴

A2 at MAMI: γp→ηp (E_γ=1.5 GeV)

(P.R. C90, 025206)

backgrounds

η → 3π⁰

JEF: γp→ηp (E_γ=8.4-11.7 GeV)

N (PWO) > 2   simulation

2π⁰ not included

Signal+backgrounds
η→π⁰γγ signal
η →π⁰π⁰π⁰ background
Pythia hadronic bkgd

1 day's running
(50x50 insert)

20
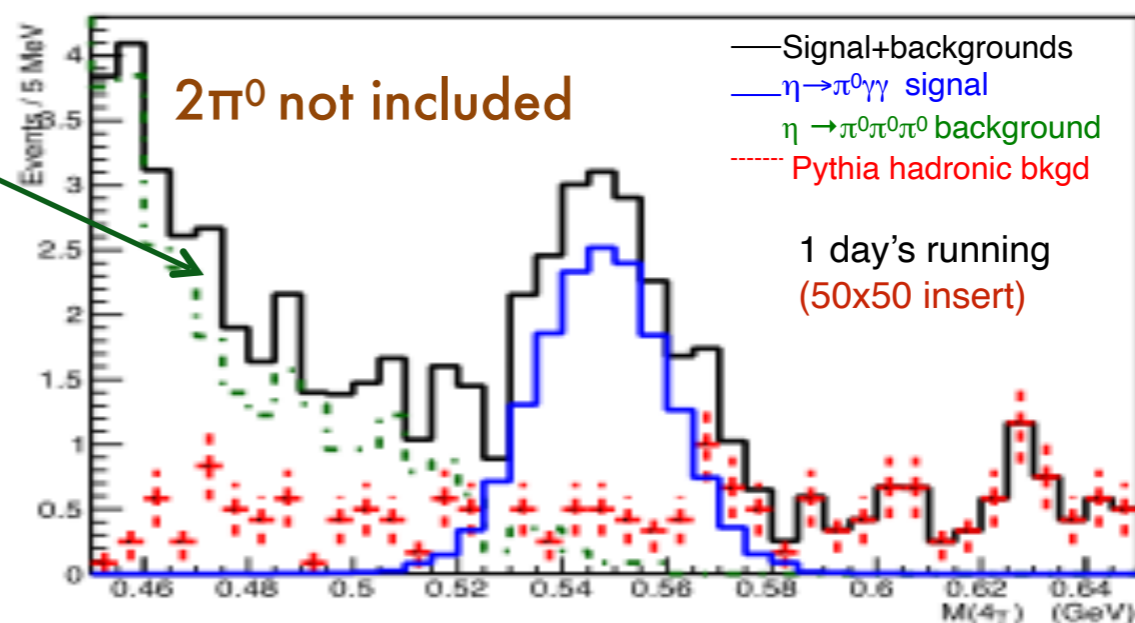
GlueX Data & MC

Reconstructed GlueX data from 2016 and 2017, original FCAL

- Significant source of background: $\eta \to 3\pi^0$ with missing/merged photons

Simulation for 1 day running with upgraded FCAL-II

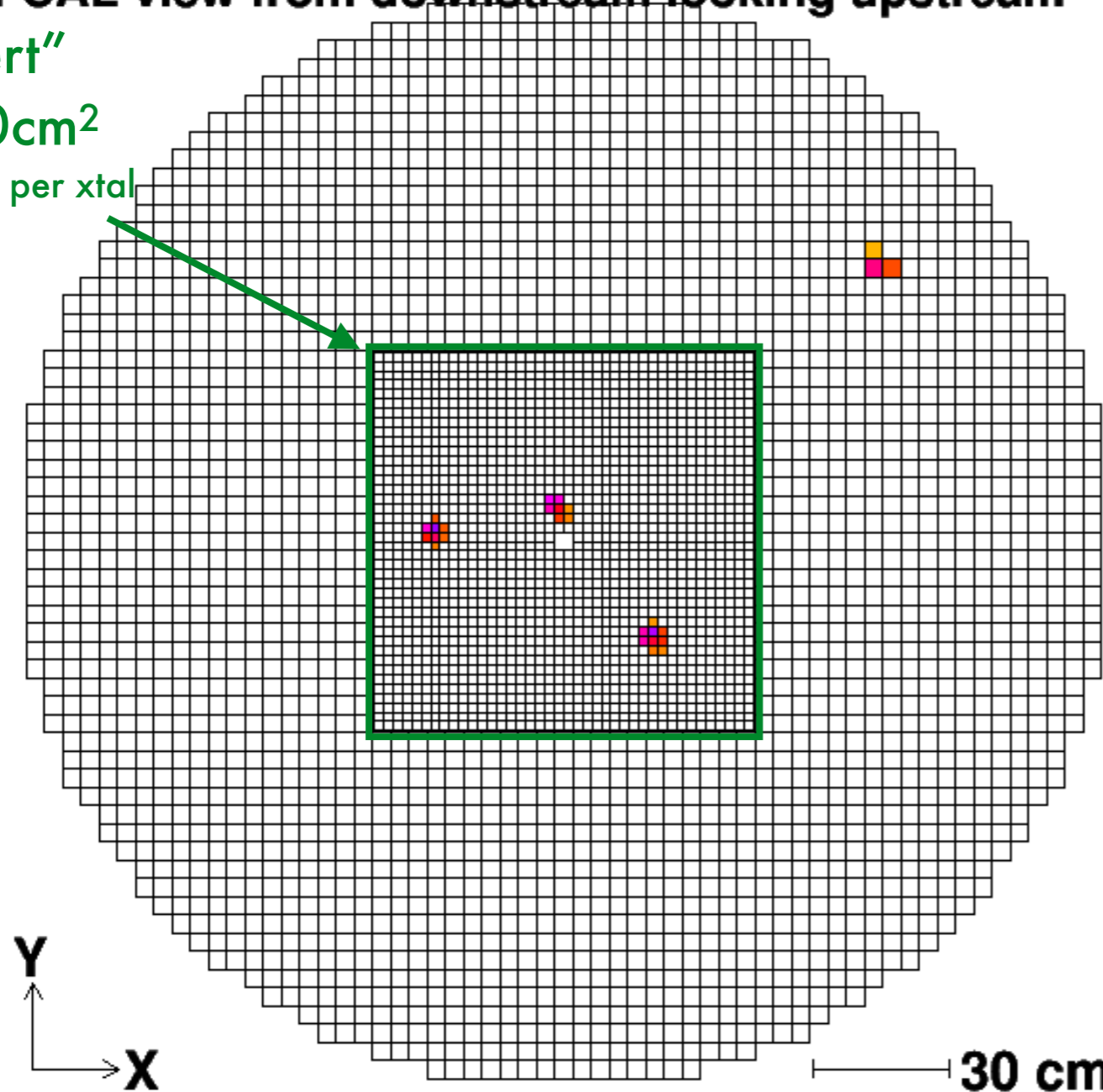- Beam energy range: 8.4-11.7 GeV Intensity $N_\gamma \sim 1\times10^8$/s

data

$\pi^0 2\gamma$ invariant mass

← η mass

simulation

N (PWO) > 2

- Sum (signal + BGs)
- $\eta \to 3\pi^0$
- Other hadronic
- Signal

S/B~2.3
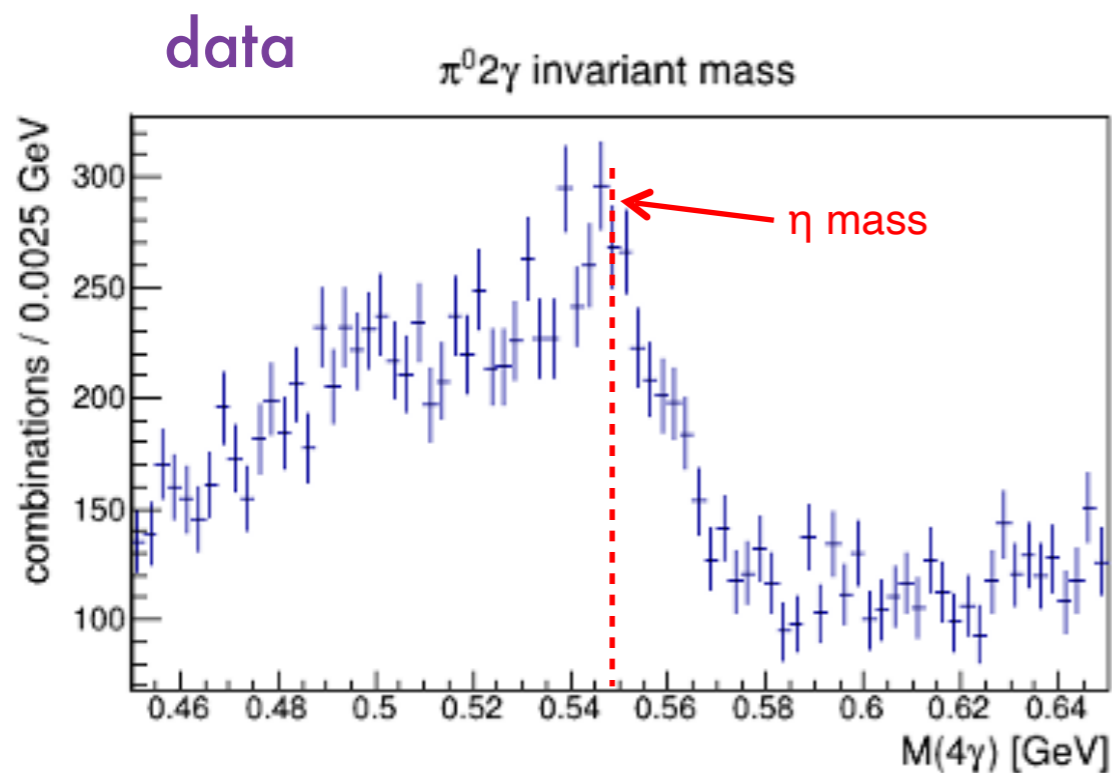
GlueX Phase-I data under analysis
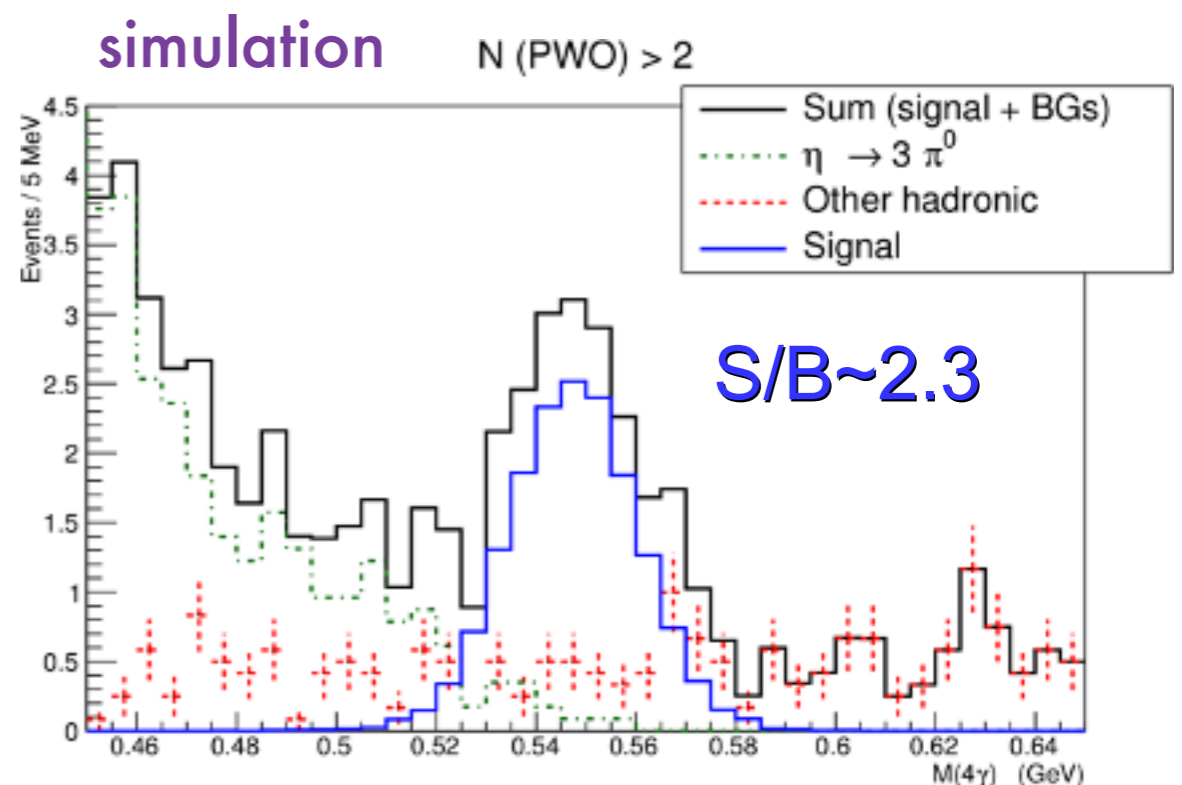
FCAL-II PbWO$_4$ Insert

S. Taylor

Simulated $\eta \to \pi^0\gamma\gamma$ event

FCAL view from downstream looking upstream

"insert"
80x80cm^2

2x2x18cm^3 per xtal

Y

X

30 cm

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

algorithms: Standard/Island and Machine Learning
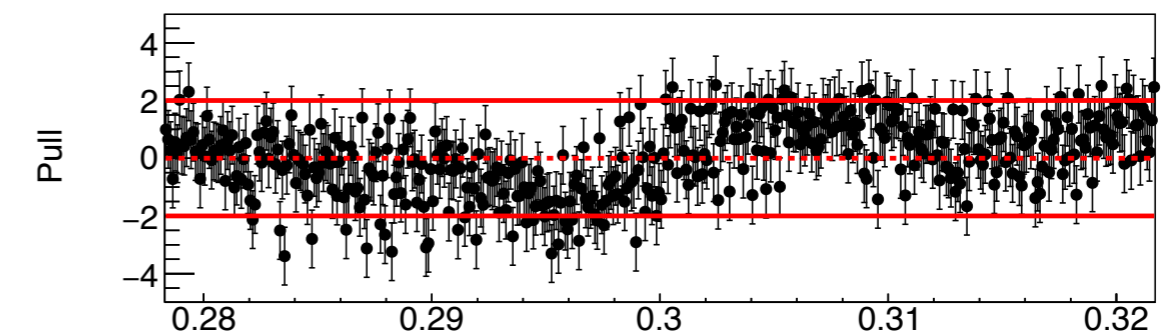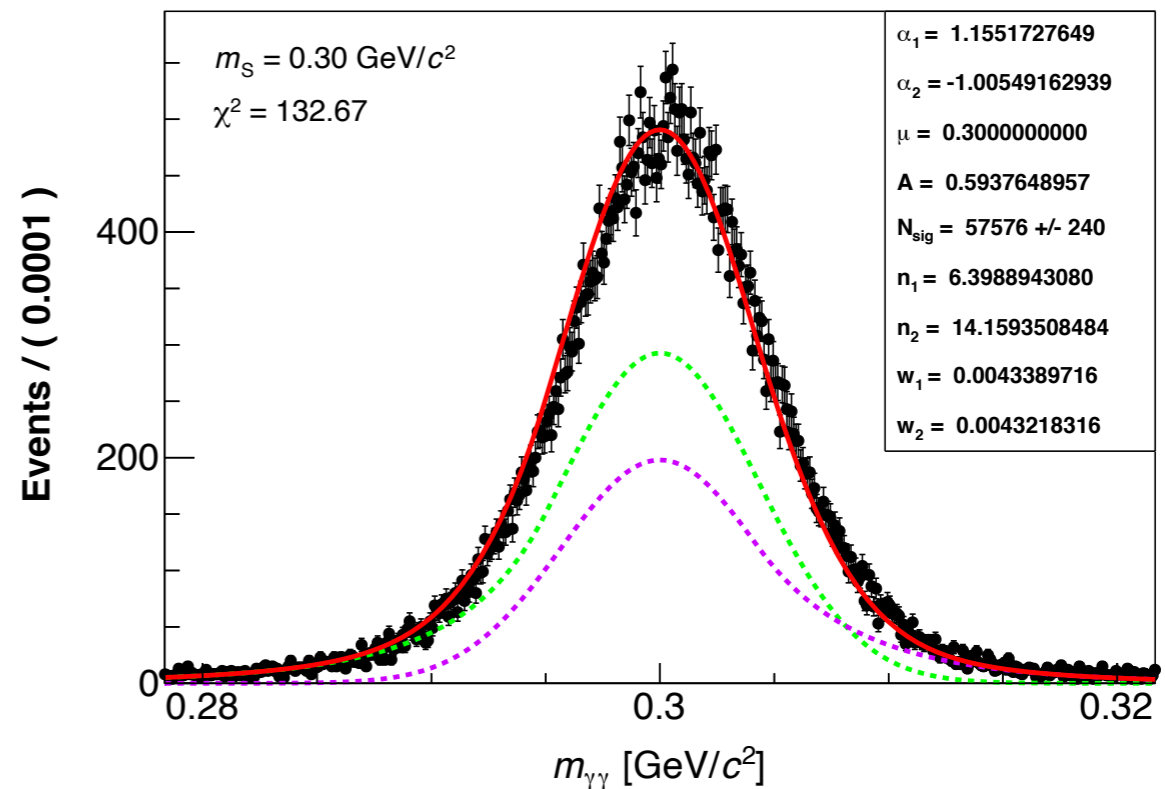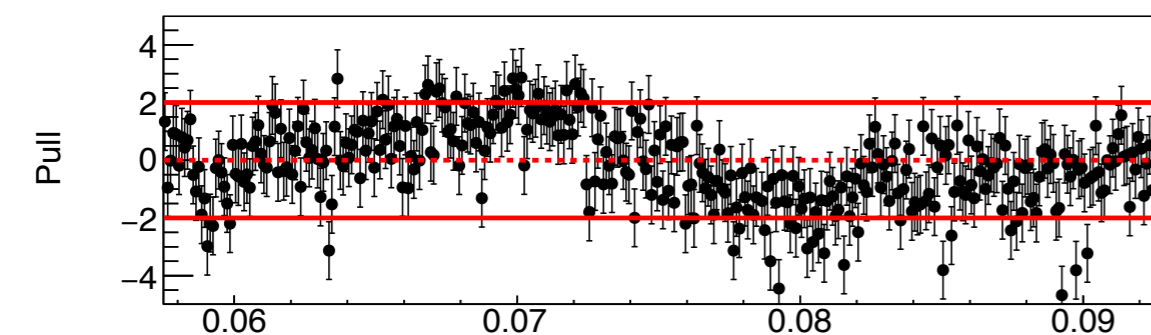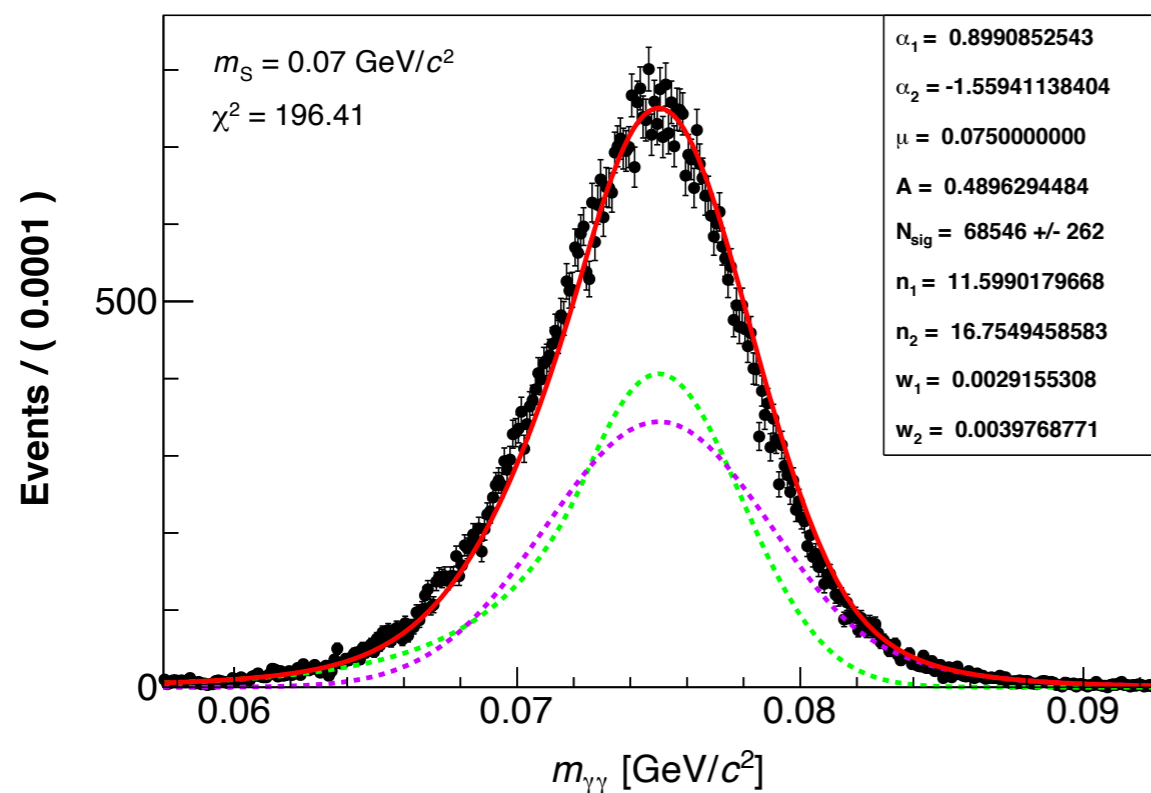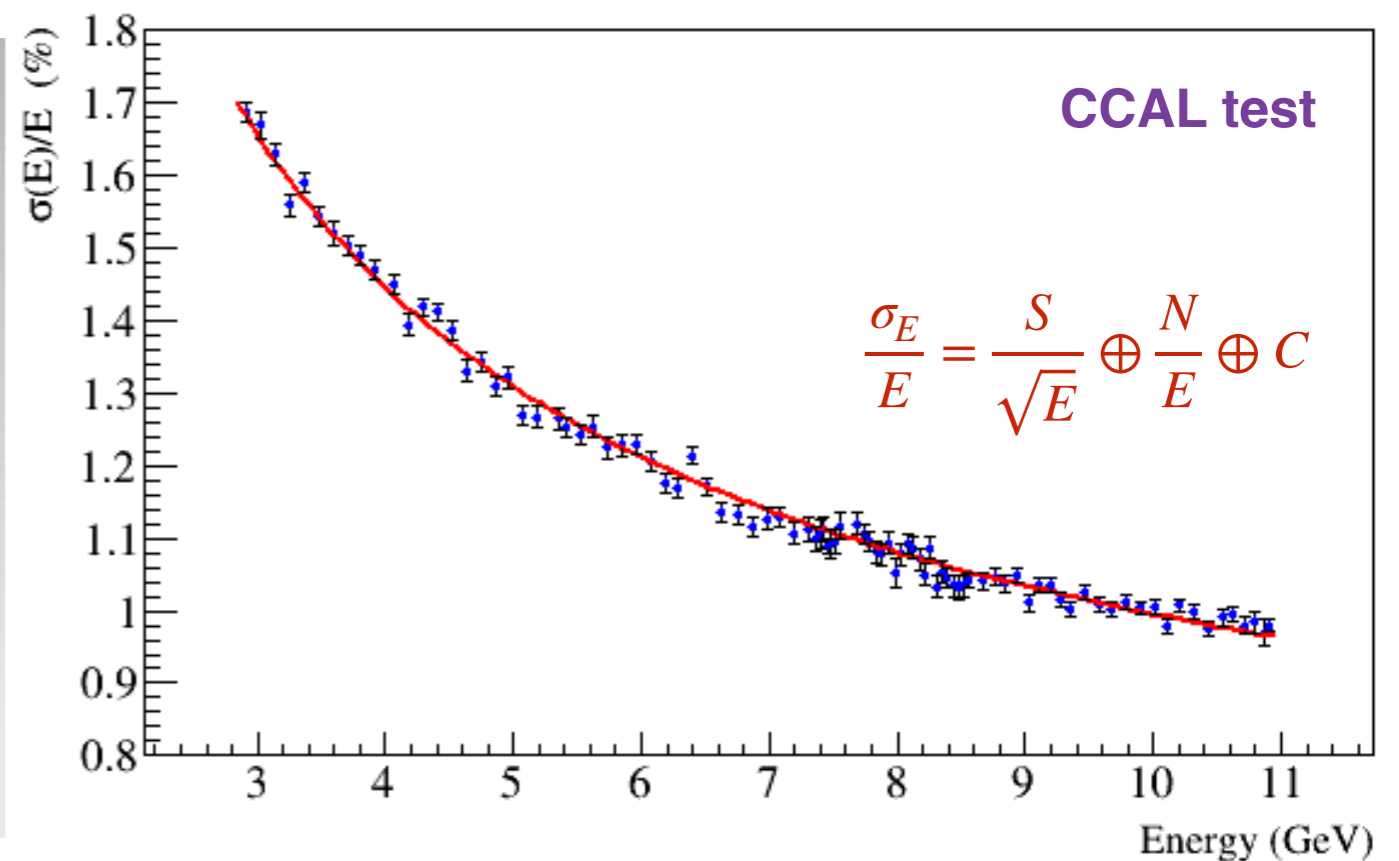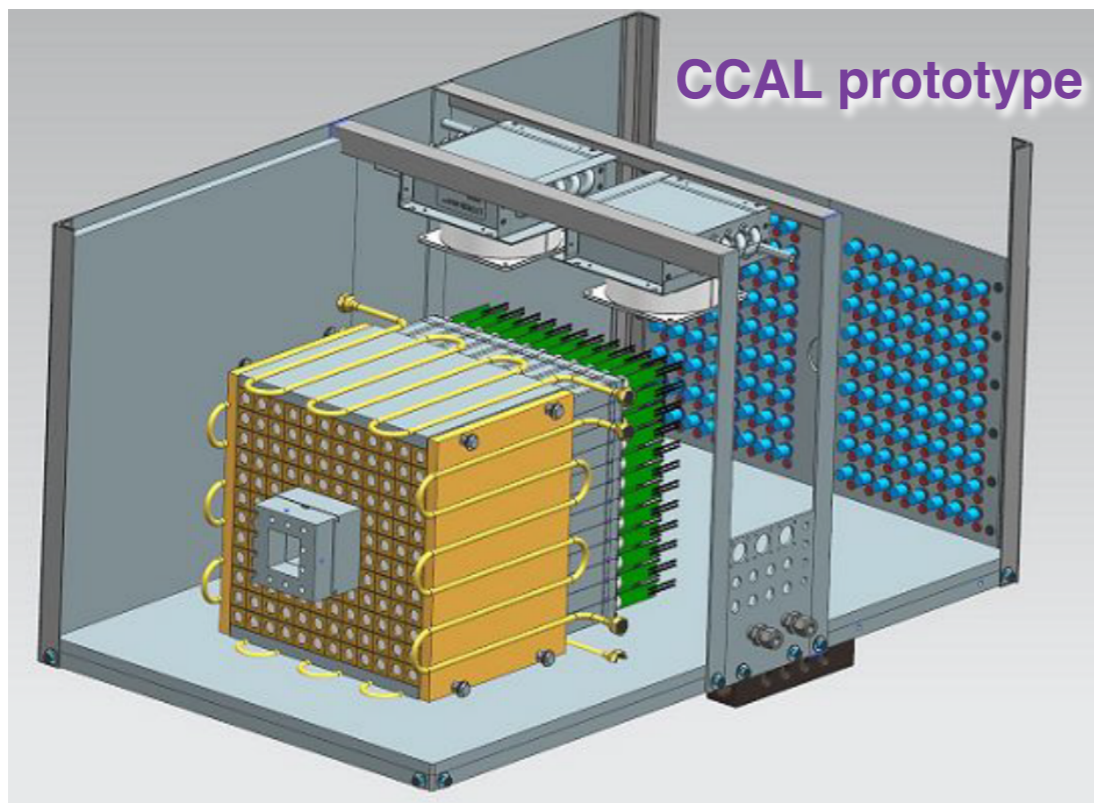

hadron

hadron

photon
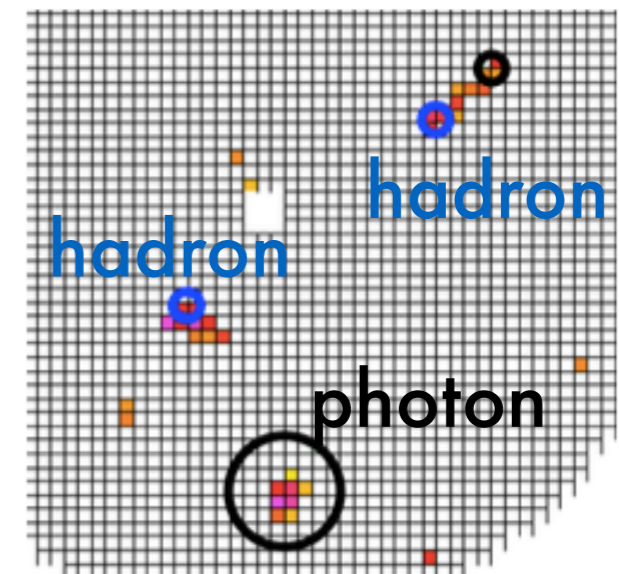
Dark Scalar Simulations

J. Richards
and I. Jaegle

$$\gamma p \to \eta p, \ \eta \to S\pi^0, \ S \to \gamma\gamma$$

Calorimeter Prototype

CCAL Prototype: 12x12 PbWO$_4$ array successfully tested and used for the PrimEx-η experiment in 2019 and in fall 2021.

CCAL prototype

CCAL test

$$\frac{\sigma_E}{E} = \frac{S}{\sqrt{E}} \oplus \frac{N}{E} \oplus C$$

NIM article accepted:
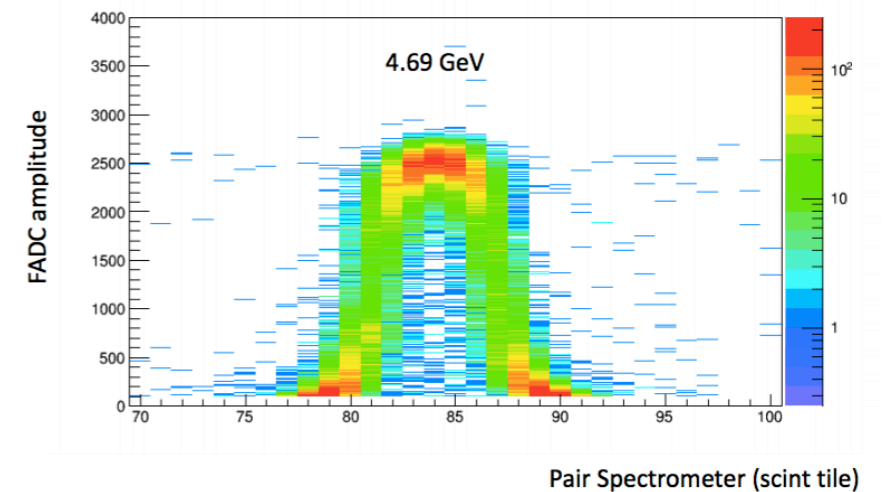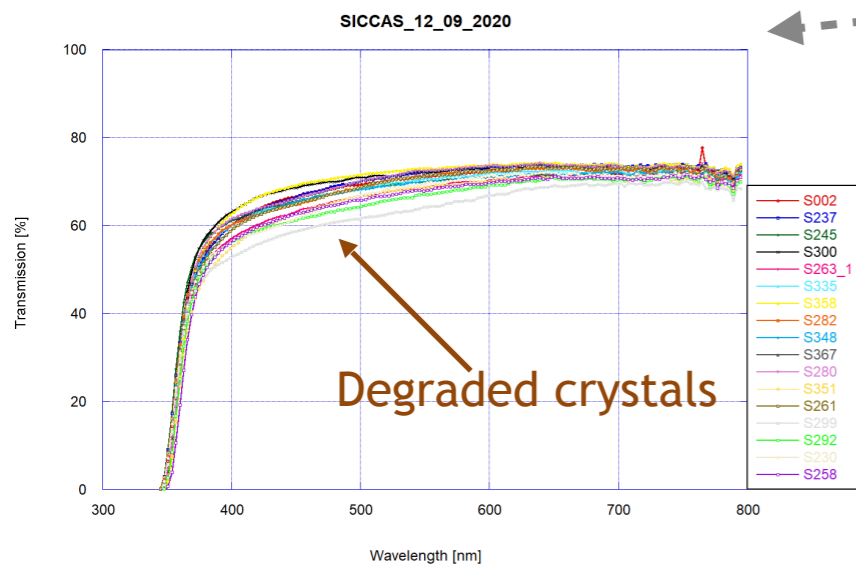
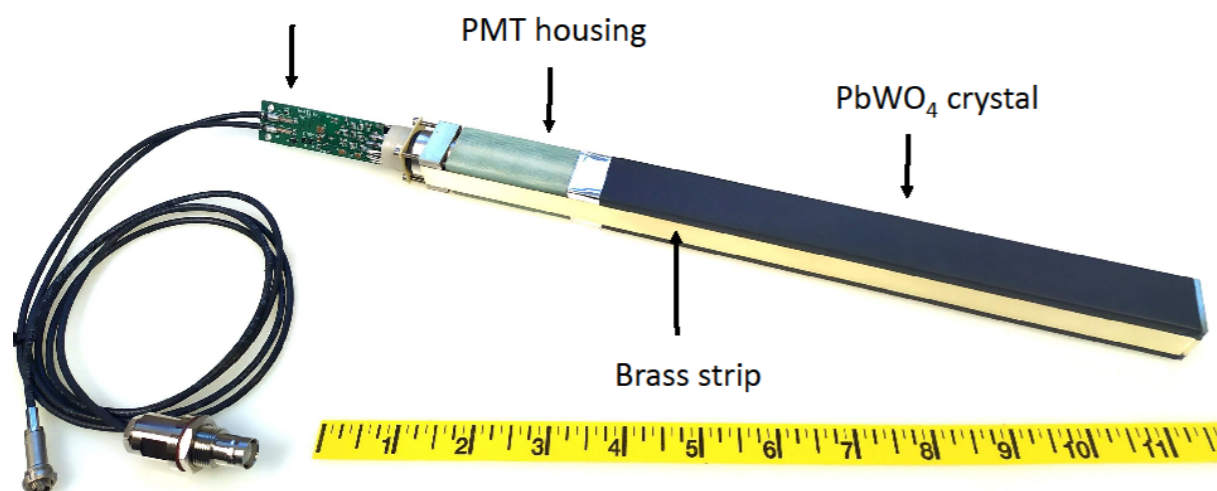Electromagnetic calorimeters based on scintillating lead tungstate crystals for experiments at Jefferson Lab ☆

Hardware Status

- PbWO$_4$ crystal Quality Assurance.

 - surface, clarity, color, dimensions, light transmission & yield

SICCAS_12_09_2020

Degraded crystals

S002
S237
S245
S300
S263_1
S335
S358
S282
S348
S367
S280
S351
S261
S299
S292
S230
S258

Transmission [%] vs Wavelength [nm]

4.69 GeV

FADC amplitude vs Pair Spectrometer (scint tile)

- ## Module assembly

PMT divider & amplifier

PMT housing

PbWO$_4$ crystal

Brass strip

- ## Fabrication and Installation

  - Finalizing engineering design for **frame**
  - Modules ready for installation in 2023
  - Planned installation duration: 6 months
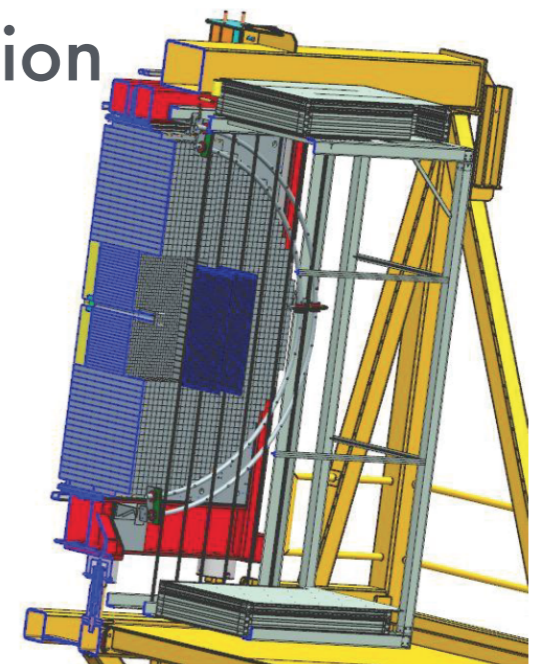
Summary & Outlook

▶ GlueX + 12 GeV tagged photon beam yields a **unique η/η′ factory**

  ▶ $\mathcal{O}(2)$ **background reduction** in neutral rare decay modes vs other facilities.

▶ **Simultaneously measure η/η′ decays** with main physics goals of:

  ▶ Test SM and search for new BSM physics; constrain CVPC new physics;
  precision tests of low-energy QCD, improve the light quark mass ratio, a.o.

▶ Require upgraded FCAL-II with a PWO insert currently under construction.
 Data taking expected in 2024.

gluex.org/thanks