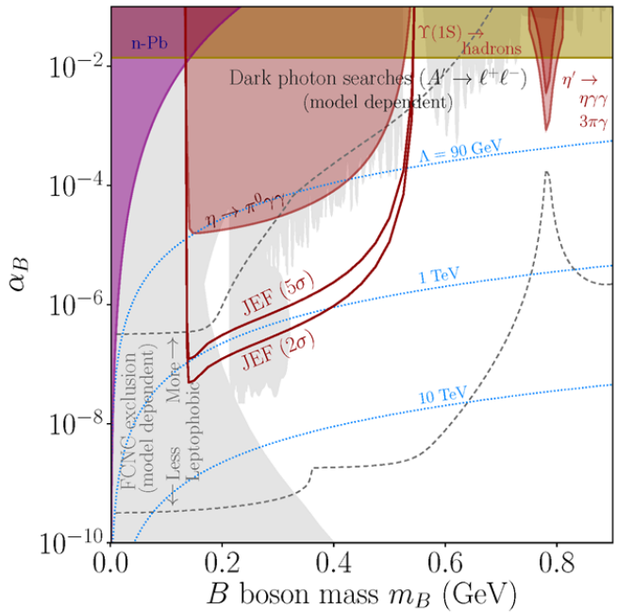
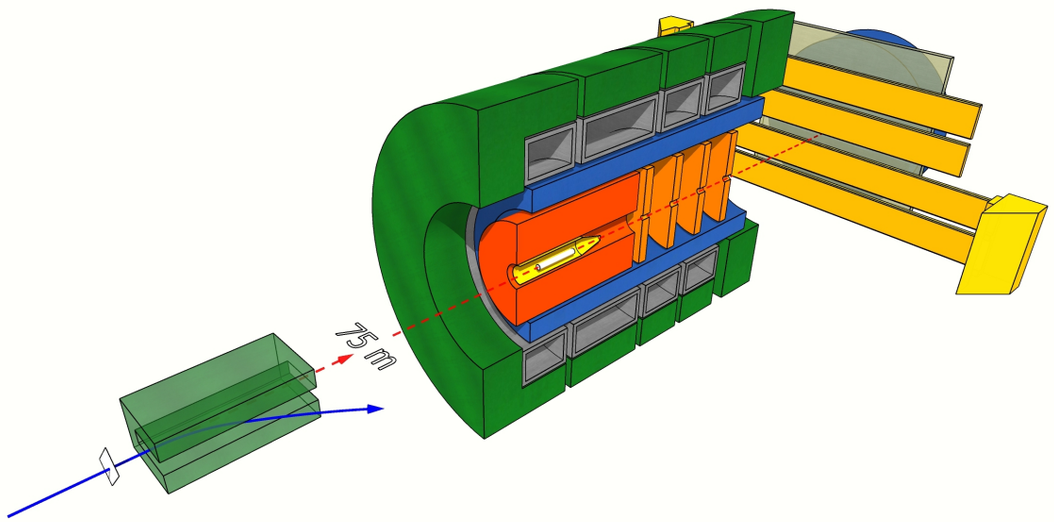
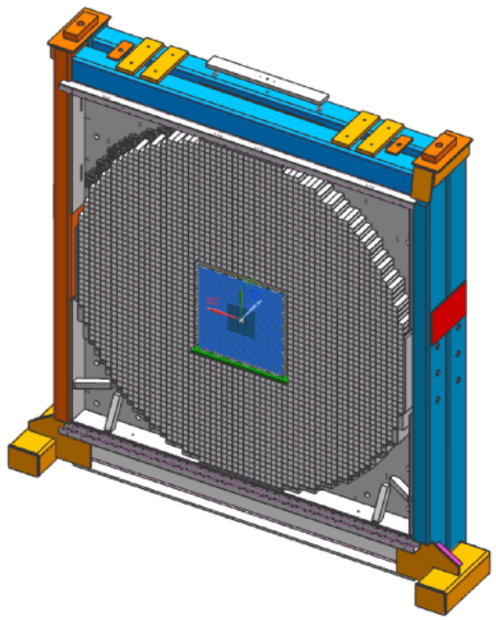






Rare η/η′ Neutral Modes and BSM Physics

L. Gan, A. Somov, S. Taylor, Z. Papandreou, JEF/GlueX

Workshop on New Light Physics & Photon-beam Experiment

March 9, 2021

Outline

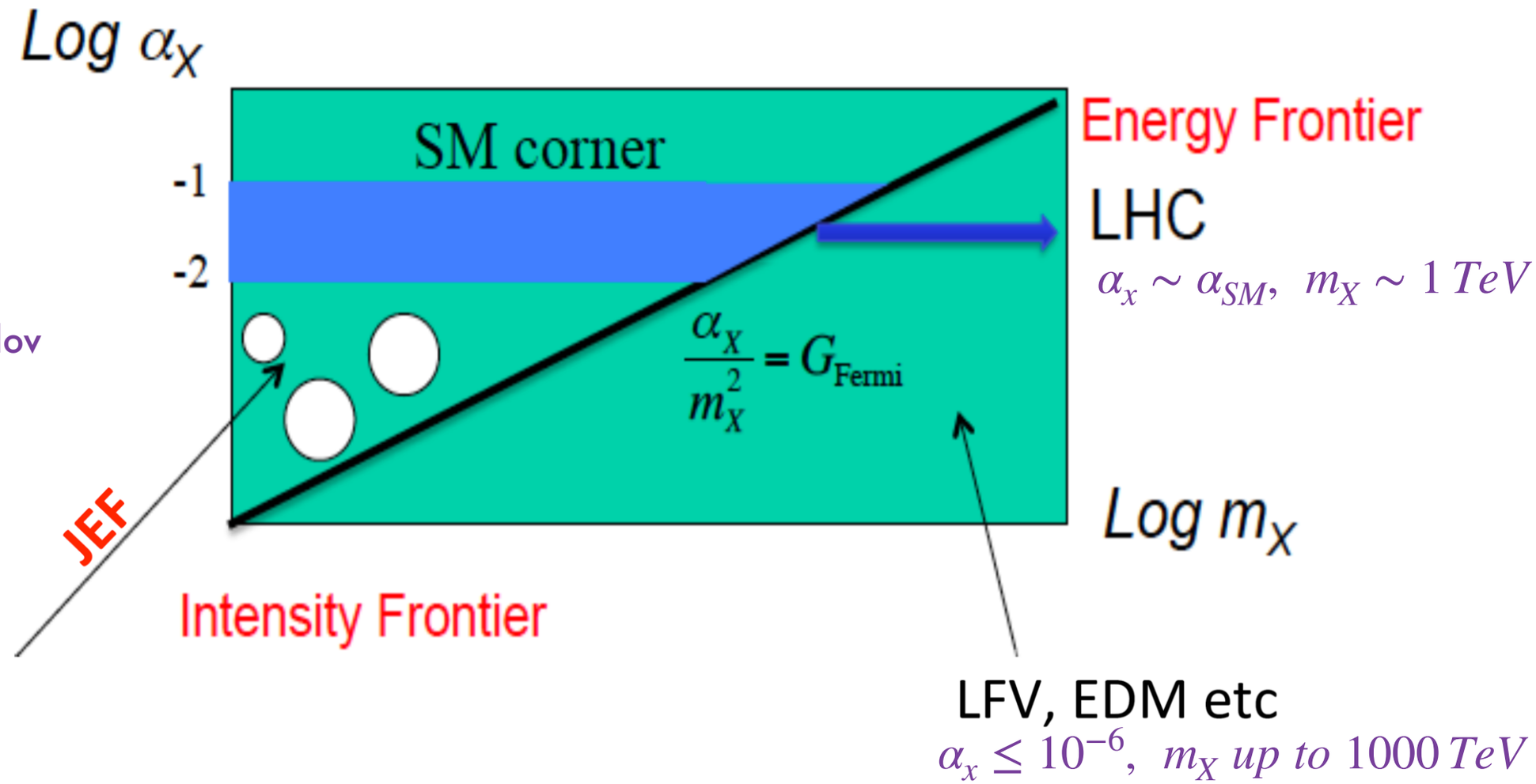
- Searches
  - Physics goals and sensitivities
- Experiment
  - Design and hardware status
- Status Quo

Searches

JEF Overview

- Model space for sub-GeV dark continues to be refined and expanded – JEF will search for a variety of dark matter candidates:
  - leptophobic dark vector boson
  - dark photons or leptophilic vector bosons
  - hadrophilic scalar particles
  - axion-like light pseudoscalars
- DM search strategy: resolve narrow structures in invariant mass spectra in the decays
  - $\eta \to \pi^0\gamma\gamma$, $e^+e^-\gamma$, $\pi^0e^+e^-$, 3π, $\pi\pi\gamma\gamma$, $\pi\pi e^+e^-$
  - $\eta' \to \pi^0\gamma\gamma$, $\pi^+\pi^-\pi^0\gamma$, $e^+e^-\gamma$, 3π, $\eta\pi\pi$, $\pi\pi\gamma\gamma$, $\pi\pi e^+e^-$
- Additional thrust: search for C-violating η decays, ChPT…
- Requirement: high-resolution and high-granularity calorimeter

Parameter Landscape



M. Pospelov

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:

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

3. Precision tests of low-energy QCD:

- Interplay of VMD & scalar dynamics in ChPT: $\eta^{(\prime)} \to \pi^0\gamma\gamma$
- Transition Form Factors of η(') : $\eta^{(\prime)} \to e^+e^-\gamma$

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

arXiv: 20070064

L. Gan, B. Kubis, E. Passemar, S. Tulin

Precision tests of fundamental physics with η and η′ mesons

Decays

Channel	Expt. branching ratio	Discussion	Sect.
$\eta \to 2\gamma$	39.41(20)%	chiral anomaly, η–η' mixing	6.1
$\eta \to 3\pi^0$	32.68(23)%	$m_u - m_d$	5.1
$\eta \to \pi^0\gamma\gamma$	$2.56(22) \times 10^{-4}$	χPT at $O(p^6)$, leptophobic B boson, light Higgs scalars	7, 10.1, 10.2
$\eta \to \pi^0\pi^0\gamma\gamma$	$< 1.2 \times 10^{-3}$	χPT, axion-like particles (ALPs)	10.3
$\eta \to 4\gamma$	$< 2.8 \times 10^{-4}$	$< 10^{-11}$ [52]	
$\eta \to \pi^+\pi^-\pi^0$	22.92(28)%	$m_u - m_d$, C/CP violation, light Higgs scalars	5.1, 9.2, 10.2
$\eta \to \pi^+\pi^-\gamma$	4.22(8)%	chiral anomaly, theory input for singly-virtual TFF and $(g-2)_\mu$, P/CP violation	6.3, 9.1
$\eta \to \pi^+\pi^-\gamma\gamma$	$< 2.1 \times 10^{-3}$	χPT, ALPs	10.3
$\eta \to e^+e^-\gamma$	$6.9(4) \times 10^{-3}$	theory input for $(g-2)_\mu$, dark photon, protophobic X boson	6.4, 10.1
$\eta \to \mu^+\mu^-\gamma$	$3.1(4) \times 10^{-4}$	theory input for $(g-2)_\mu$, dark photon	6.4, 10.1
$\eta \to e^+e^-$	$< 7 \times 10^{-7}$	theory input for $(g-2)_\mu$, BSM weak decays	6.9, 8
$\eta \to \mu^+\mu^-$	$5.8(8) \times 10^{-6}$	theory input for $(g-2)_\mu$, BSM weak decays, P/CP violation	6.9, 8, 9.1
$\eta \to \pi^0\pi^0\ell^+\ell^-$		C/CP violation, ALPs	9.2, 10.3
$\eta \to \pi^+\pi^-e^+e^-$	$2.68(11) \times 10^{-4}$	theory input for doubly-virtual TFF and $(g-2)_\mu$, P/CP violation, ALPs	6.6, 9.1, 10.3
$\eta \to \pi^+\pi^-\mu^+\mu^-$	$< 3.6 \times 10^{-4}$	theory input for doubly-virtual TFF and $(g-2)_\mu$, P/CP violation, ALPs	6.6, 9.1, 10.3
$\eta \to e^+e^-e^+e^-$	$2.40(22) \times 10^{-5}$	theory input for $(g-2)_\mu$	6.7
$\eta \to e^+e^-\mu^+\mu^-$	$< 1.6 \times 10^{-4}$	theory input for $(g-2)_\mu$	6.7
$\eta \to \mu^+\mu^-\mu^+\mu^-$	$< 3.6 \times 10^{-4}$	theory input for $(g-2)_\mu$	6.7
$\eta \to \pi^+\pi^-\pi^0\gamma$	$< 5 \times 10^{-4}$	direct emission only	6.8
$\eta \to \pi^\pm e^\mp \nu_e$	$< 1.7 \times 10^{-4}$	second-class current	8
$\eta \to \pi^+\pi^-$	$< 4.4 \times 10^{-6}$ [53]	P/CP violation	9.1
$\eta \to 2\pi^0$	$< 3.5 \times 10^{-4}$	P/CP violation	9.1
$\eta \to 4\pi^0$	$< 6.9 \times 10^{-7}$	P/CP violation	6.5, 9.1

Table 1: Summary of η meson decays. Experimental information on the branching ratios is taken from the Particle Data Group (PDG) review [54] unless otherwise indicated. The total η width is $\Gamma_\eta = 1.31(5)$ keV [54].

Channel	Expt. branching ratio	Discussion	Sect.
$\eta' \to \eta\pi^+\pi^-$	42.6(7)%	large-N_c χPT, light Higgs scalars	5.2, 10.2
$\eta' \to \pi^+\pi^-\gamma$	28.9(5)%	chiral anomaly, theory input for singly-virtual TFF and $(g-2)_\mu$, P/CP violation	6.3, 9.1
$\eta' \to \eta\pi^0\pi^0$	22.8(8)%	large-N_c χPT	5.2
$\eta' \to \omega\gamma$	2.489(76)% [55]	theory input for singly-virtual TFF and $(g-2)_\mu$	6.8
$\eta' \to \omega e^+e^-$	$2.0(4) \times 10^{-4}$	theory input for doubly-virtual TFF and $(g-2)_\mu$	6.8
$\eta' \to 2\gamma$	2.331(37)% [55]	chiral anomaly, η–η' mixing	6.1
$\eta' \to 3\pi^0$	2.54(18)% $^{(\star)}$	$m_u - m_d$	5.3
$\eta' \to \mu^+\mu^-\gamma$	$1.09(27) \times 10^{-4}$	theory input for $(g-2)_\mu$, dark photon	6.4, 10.1
$\eta' \to e^+e^-\gamma$	$4.73(30) \times 10^{-4}$	theory input for $(g-2)_\mu$, dark photon	6.4, 10.1
$\eta' \to \pi^+\pi^-\mu^+\mu^-$	$< 2.9 \times 10^{-5}$	theory input for doubly-virtual TFF and $(g-2)_\mu$, P/CP violation, dark photon, ALPs	6.6, 9.1, 10.1, 10.3
$\eta' \to \pi^+\pi^-e^+e^-$	$2.4(^{+1.3}_{-1.0}) \times 10^{-3}$	theory input for doubly-virtual TFF and $(g-2)_\mu$, P/CP violation, dark photon, ALPs	6.6, 9.1, 10.1, 10.3
$\eta' \to \pi^0\pi^0\ell^+\ell^-$		C/CP violation, ALPs	9.2, 10.3
$\eta' \to \pi^+\pi^-\pi^0$	$3.61(17) \times 10^{-3}$	$m_u - m_d$, C/CP violation, light Higgs scalars	5.3, 9.2, 10.2
$\eta' \to 2(\pi^+\pi^-)$	$8.4(9) \times 10^{-5}$	theory input for doubly-virtual TFF and $(g-2)_\mu$	6.5
$\eta' \to \pi^+\pi^-2\pi^0$	$1.8(4) \times 10^{-4}$		6.5
$\eta' \to 2(\pi^+\pi^-)\pi^0$	$< 1.8 \times 10^{-3}$	ALPs	10.3
$\eta' \to K^\pm\pi^\mp$	$< 4 \times 10^{-5}$	weak interactions	8
$\eta' \to \pi^\pm e^\mp \nu_e$	$< 2.1 \times 10^{-4}$	second-class current	8
$\eta' \to \pi^0\gamma\gamma$	$3.20(24) \times 10^{-3}$	vector and scalar dynamics, B boson, light Higgs scalars	7.4, 10.1, 10.2
$\eta' \to \eta\gamma\gamma$	$8.3(3.5) \times 10^{-5}$ [56]	vector and scalar dynamics, B boson, light Higgs scalars	7.4, 10.1, 10.2
$\eta' \to 4\pi^0$	$< 4.94 \times 10^{-5}$ [57]	(S-wave) P/CP violation	6.5
$\eta' \to e^+e^-$	$< 5.6 \times 10^{-9}$	theory input for $(g-2)_\mu$, BSM weak decays	6.9, 8
$\eta' \to \mu^+\mu^-$		theory input for $(g-2)_\mu$, BSM weak decays	6.9, 8
$\eta' \to \ell^+\ell^-\ell^+\ell^-$		theory input for $(g-2)_\mu$	6.7
$\eta' \to \pi^+\pi^-\pi^0\gamma$		B boson	10.1
$\eta' \to \pi^+\pi^-$	$< 1.8 \times 10^{-5}$	P/CP violation	9.1
$\eta' \to 2\pi^0$	$< 4 \times 10^{-4}$	P/CP violation	9.1

Table 2: Summary of η' meson decays. Experimental information on the branching ratios is taken from the PDG review [54] unless otherwise indicated. We remark that for $\mathcal{B}(\eta' \to 3\pi^0)$ marked with $^{(\star)}$ above, there is significant tension between the PDG *fit* and *average*; see the discussion in Sect. 5.3. Also, in this review, we take the PDG *fit* value for the total η' width $\Gamma_{\eta'} = 196(9)$ MeV, which differs somewhat from the PDG *average* that is dominated by the COSY measurement $\Gamma_{\eta'} = 226(17)(14)$ keV [58].

arXiv: 20070064

PDG - η

η

$I^G(J^{PC}) = 0^+(0^{-+})$

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

Mass $m = 547.862 \pm 0.018$ MeV
Full width $\Gamma = 1.31 \pm 0.05$ keV

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 ±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 ±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′

η′(958)

$I^G(J^{PC}) = 0^+(0^{-+})$

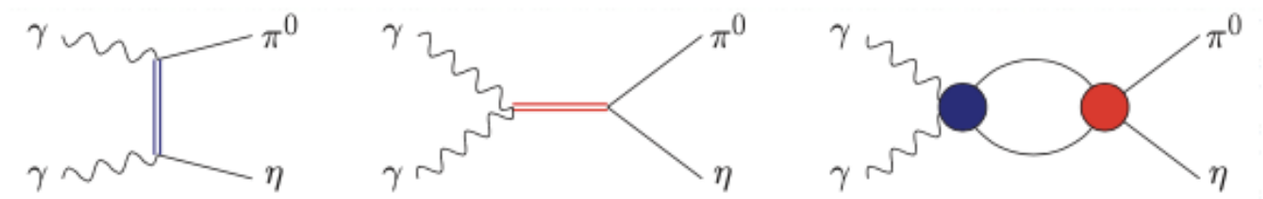
$$\eta' \approx \frac{1}{\sqrt{3}}(u\bar{u} + d\bar{d} + s\bar{s})$$

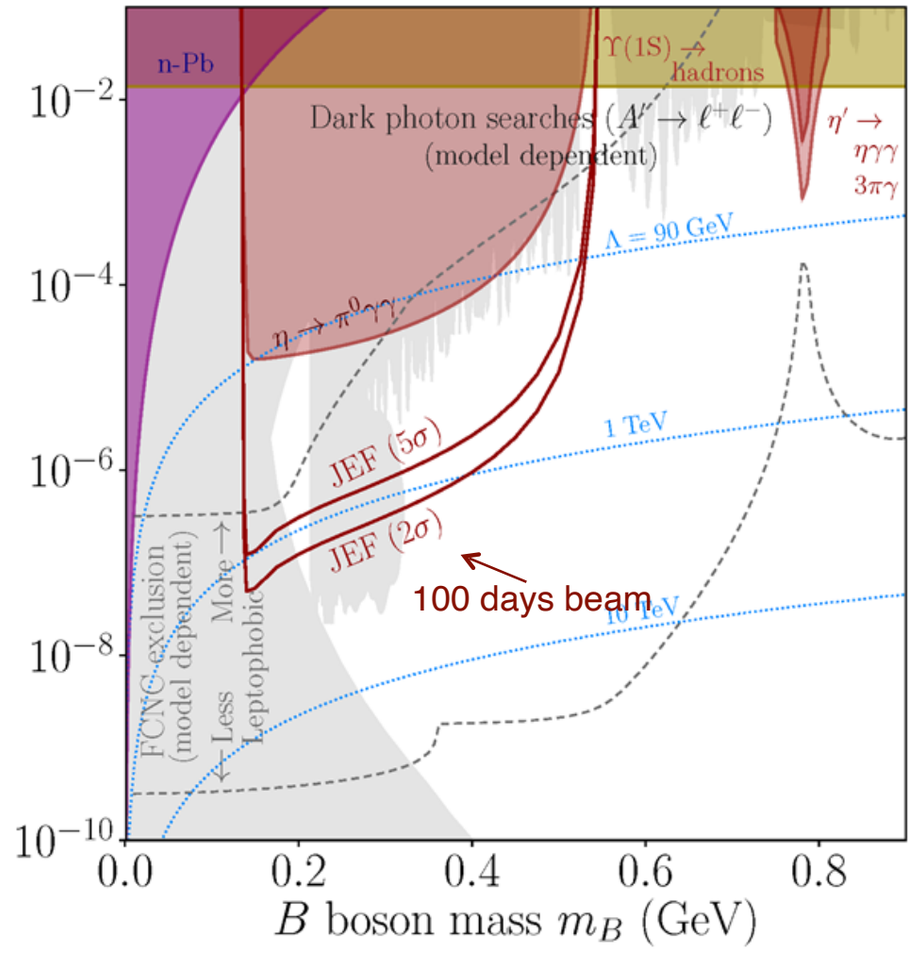
Mass $m = 957.78 \pm 0.06$ MeV
Full width $\Gamma = 0.198 \pm 0.009$ MeV

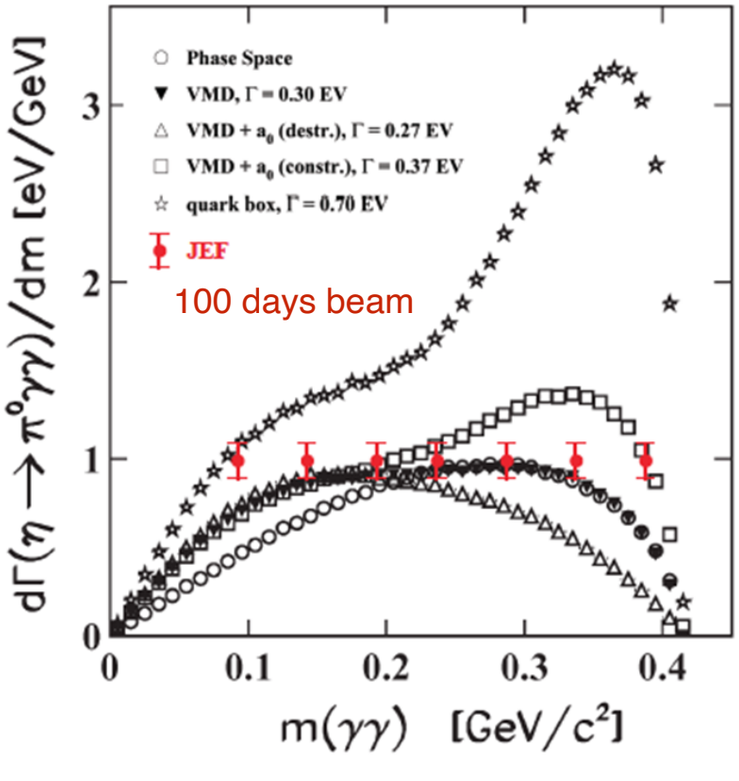
η′(958) DECAY MODES	Fraction (Γ_i/Γ)	Confidence level	p (MeV/c)
$\pi^+\pi^-\eta$	(42.9 ±0.7) %		232
$\rho^0\gamma$(including non-resonant $\pi^+\pi^-\gamma$)	(29.1 ±0.5) %		165
$\pi^0\pi^0\eta$	(22.2 ±0.8) %		239
$\pi^0\gamma\gamma$	$< 8 \times 10^{-4}$	90%	469
$\gamma\gamma$	(2.20±0.08) %		479
$3\pi^0$	(2.14±0.20) $\times 10^{-3}$		430
Charge conjugation (C), Parity (P), Lepton family number (LF) violating modes			
$\pi^+\pi^-$	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

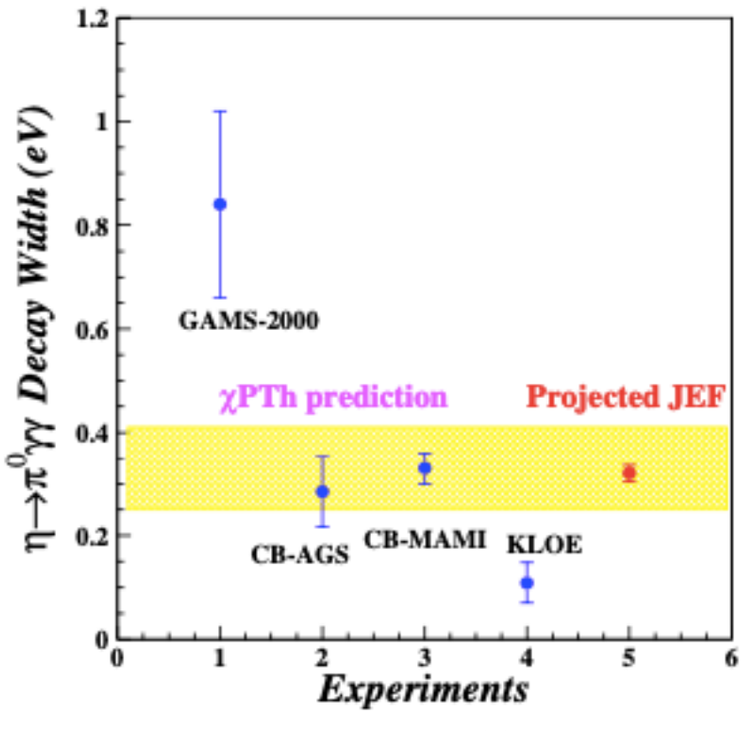
Key Channel: $\eta \to \pi^0\gamma\gamma$

- Search for sub-GeV gauge bosons:
  - leptophobic vector B′ coupling to baryon no.
    $\eta \to B'\gamma \to \pi^0\gamma\gamma$ Nelson PLB 221, 80 // Tulin PRD 89,114008
  - scalar S: a 100 keV-100 MeV electrophobic scalar can help solve proton radius and $(g\text{-}2)_\mu$ puzzles.
    $\eta \to \pi^0 S \to \pi^0\gamma\gamma$ Batell, PRD 100,095020 / Liu Nucl.Phy.B,114638









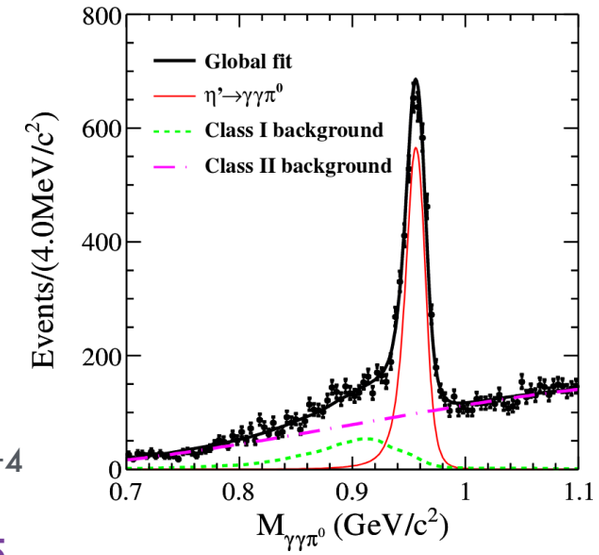
- A rare window to probe interplay of VMD & scalar resonance in ChPT Prakhov PRC 78,015206

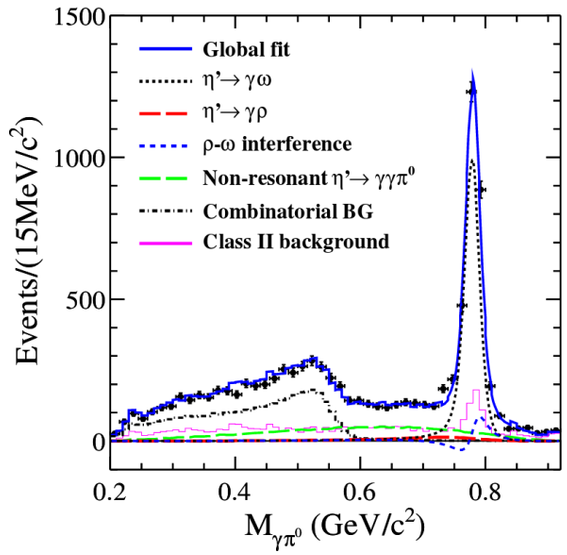
Key Channel: $\eta' \to \pi^0\gamma\gamma$

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

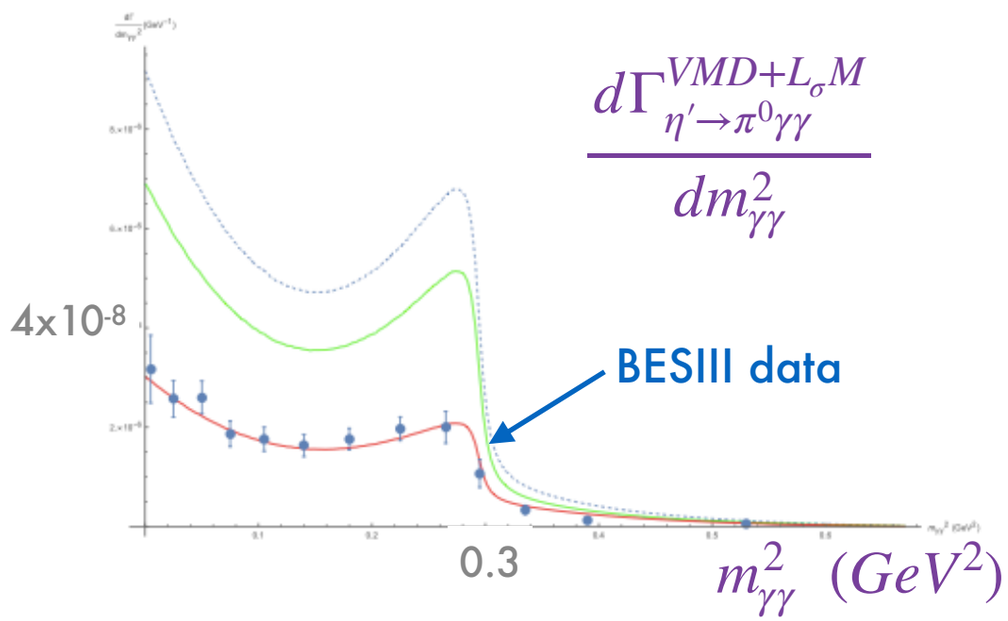




Recent theory developments: Balytzkyi, arXiv:1811.01402

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: $\eta \to 3\pi$

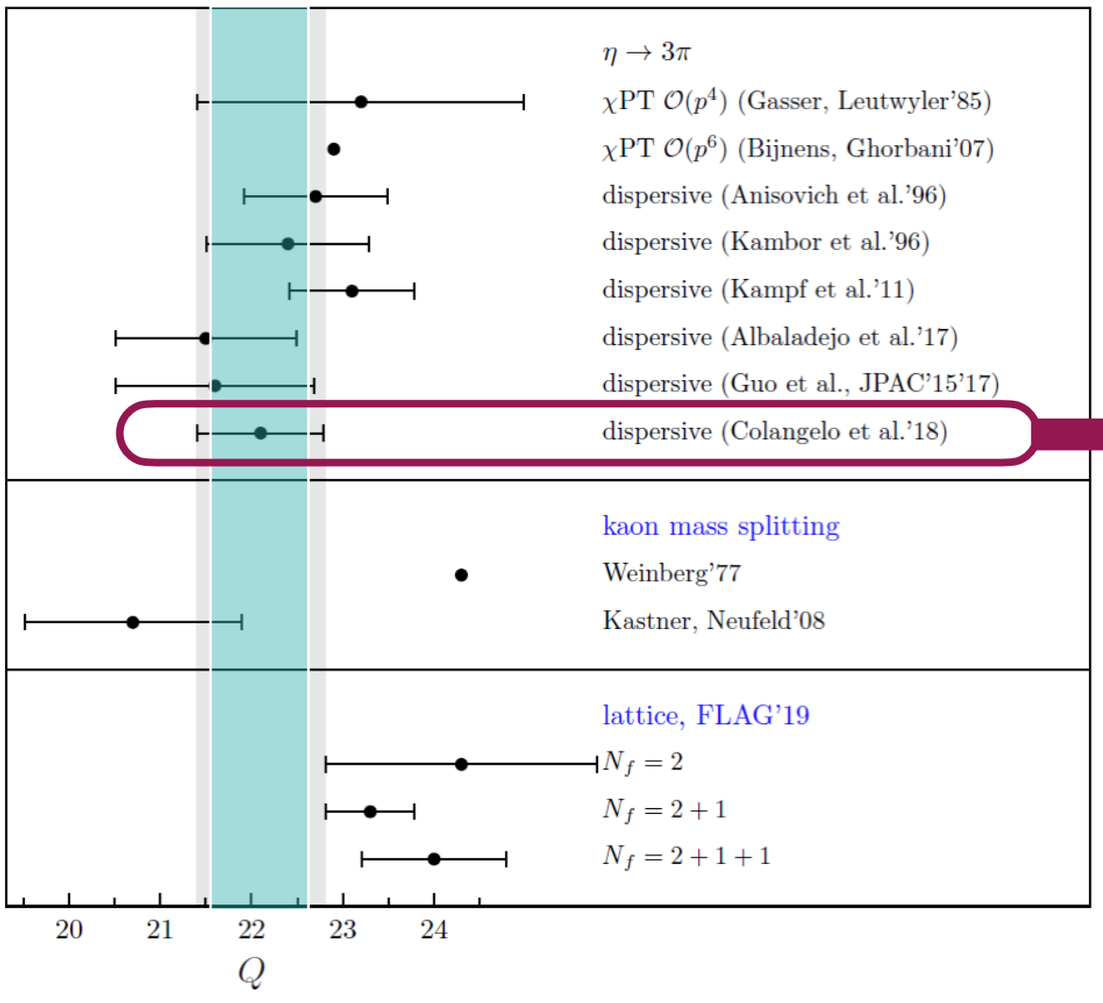
- A clean probe for **quark mass ratio**:

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

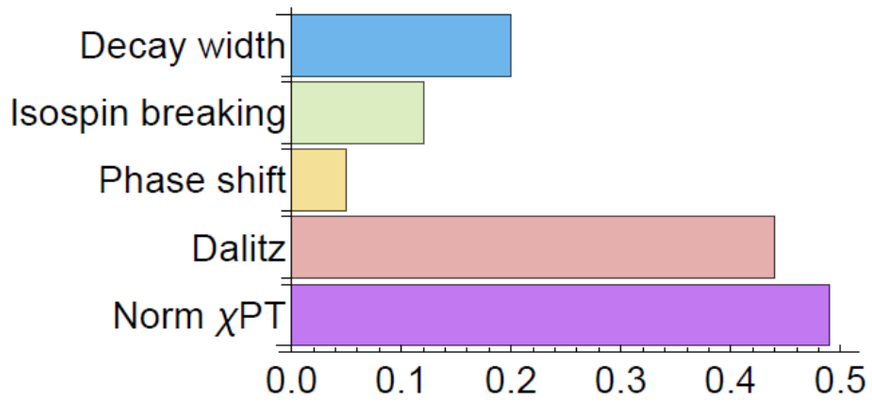
  - decays through isospin violation:

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

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



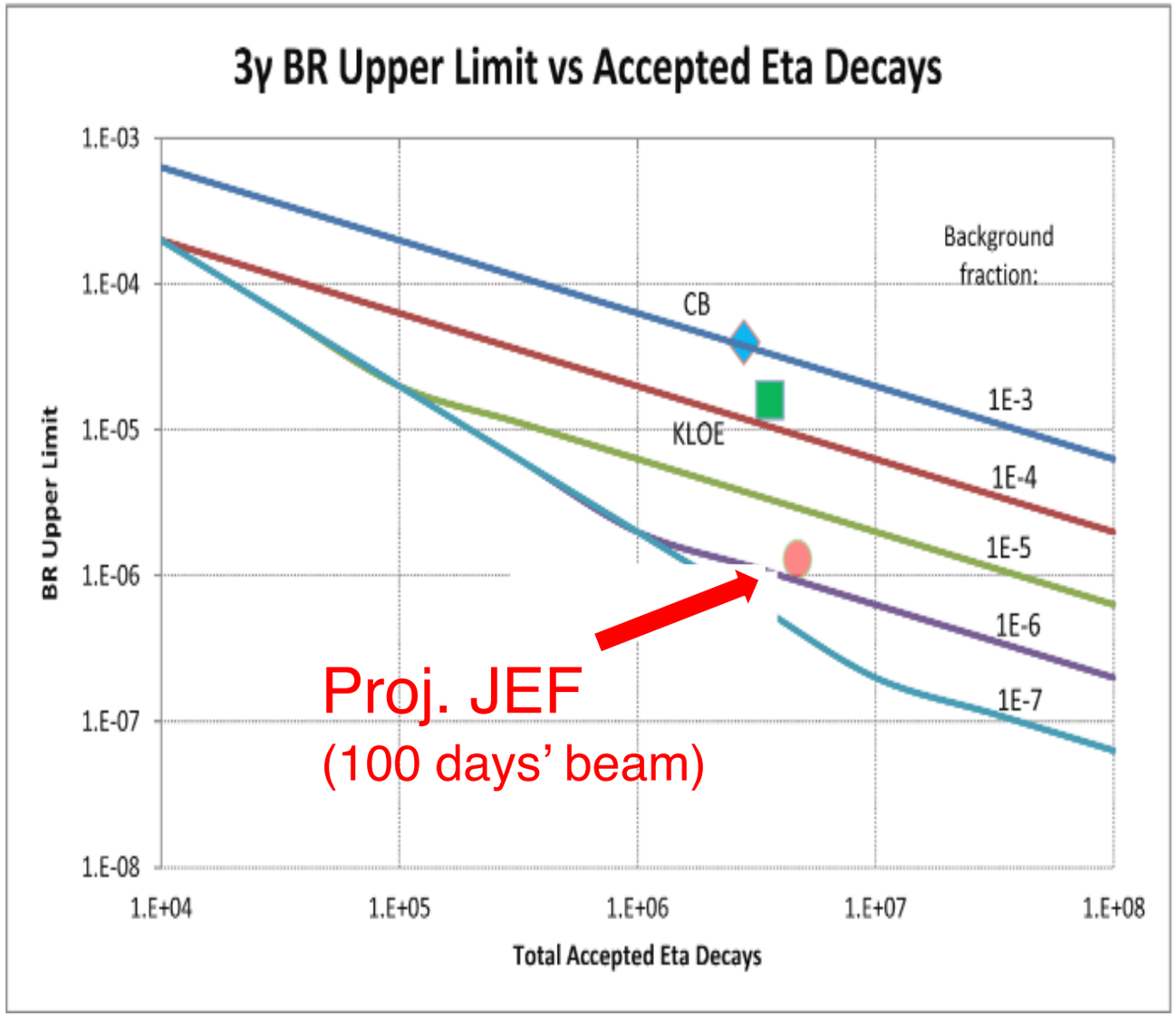
- Uncertainties in quark mass ratio:



e-Print: 2007.00664

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

- SM contribution:
  - BR($\eta \rightarrow 3\gamma$) $<10^{-19}$ 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 by Tarasov suggests: BR($\eta \rightarrow 3\gamma$)$< 10^{-2}$
  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

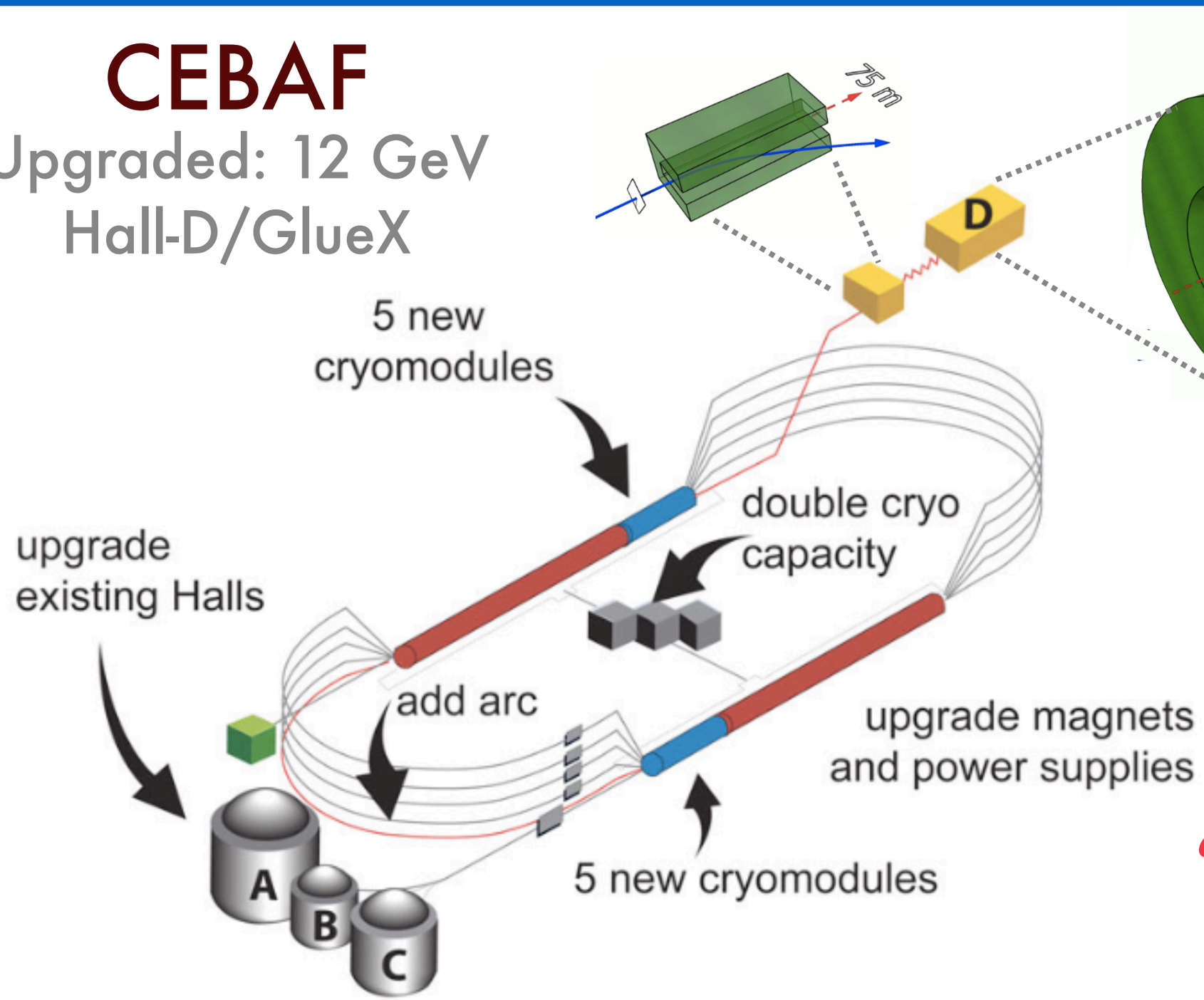
Experiment

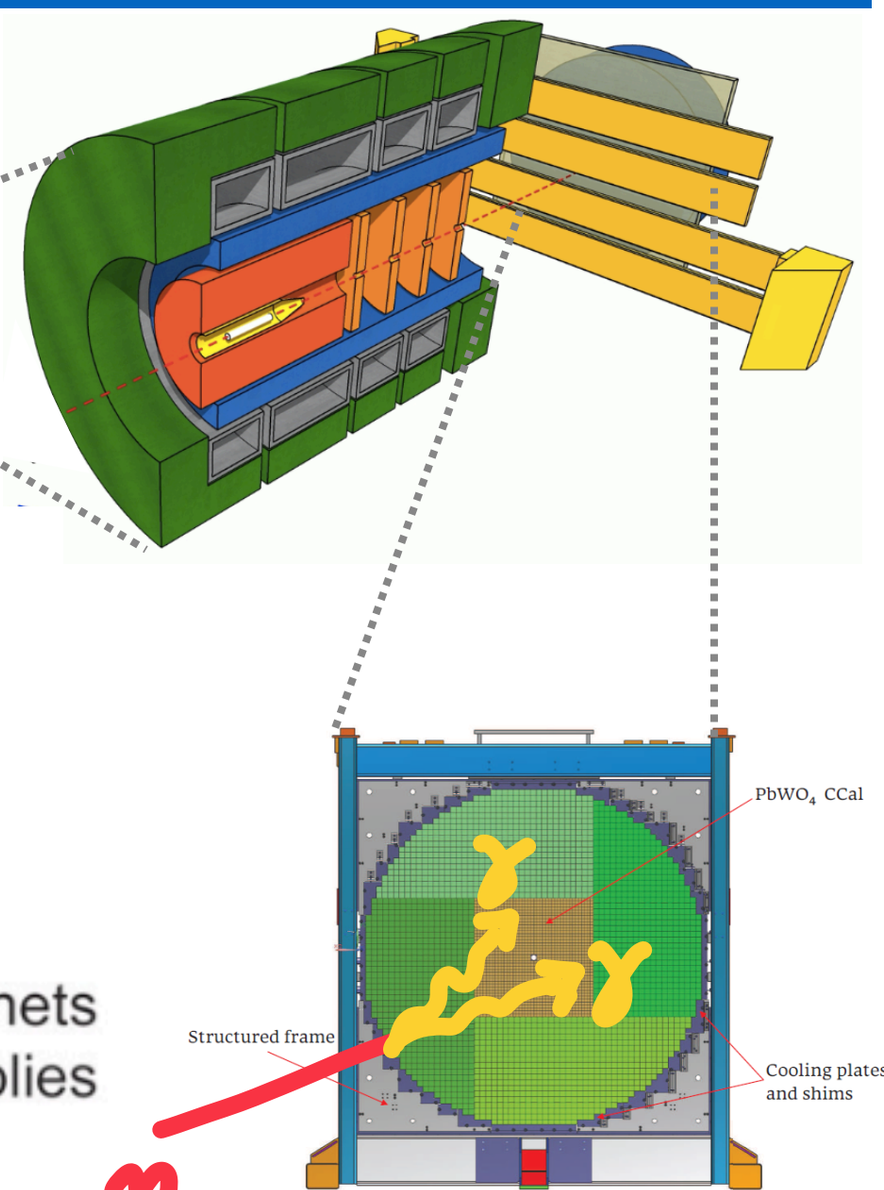
Jefferson Lab/GlueX/JEF

CEBAF

Upgraded: 12 GeV

Hall-D/GlueX

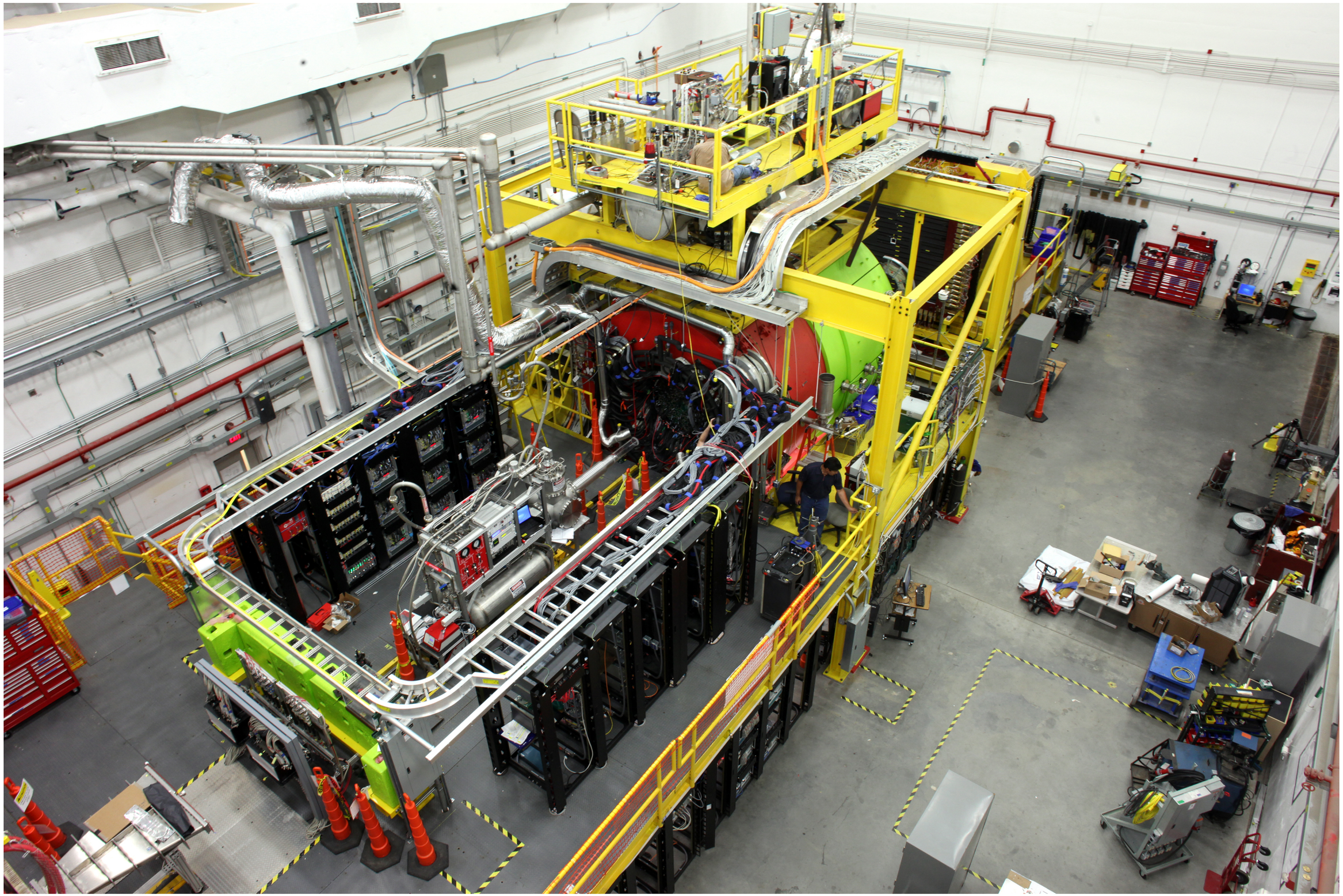




FCAL-II upgrade

GlueX goal: look for exotic hybrids

The GlueX Detector



Production Rates

JEF (100 days of beam)

	η	η′
Tagged mesons	6.5×10^7	4.9×10^7

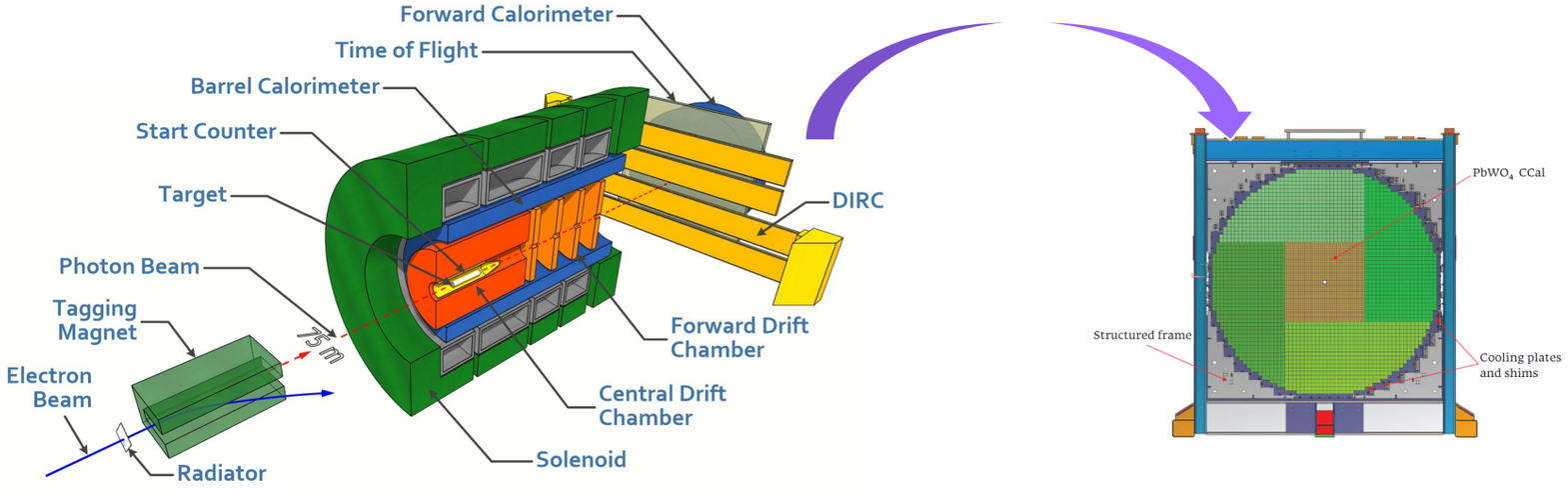
Previous Experiments

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



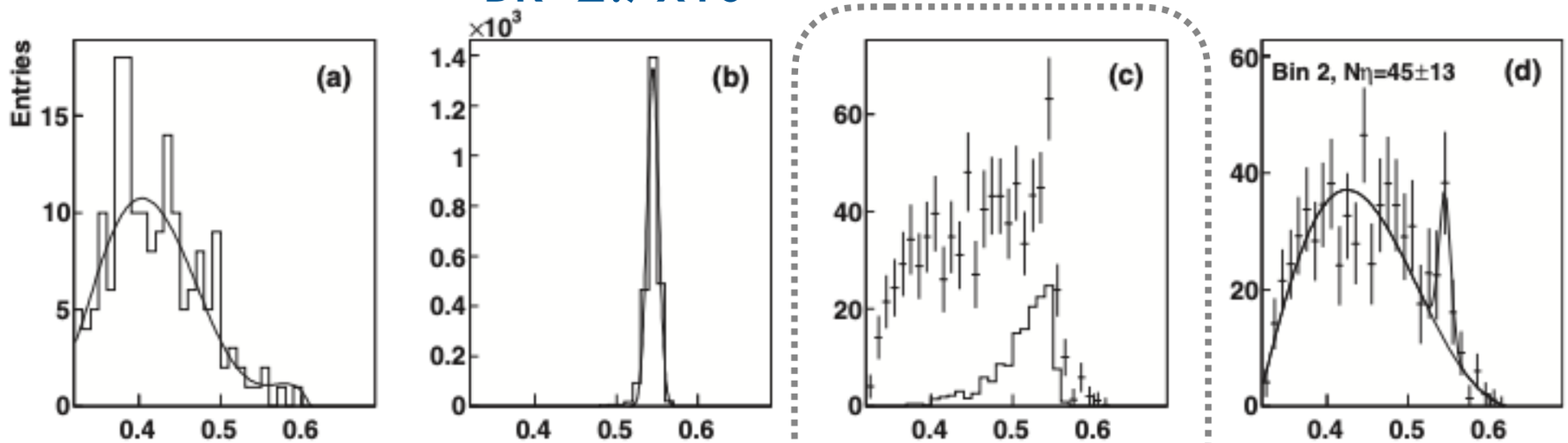
- η/η′ production: 8.4-11.7 GeV tagged γ beam; η, η′ energy boost
- produce & detect η/η′ simultaneously; exclusive channels

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

- Reduce non-coplanar backgrounds by detecting recoil protons with the GlueX detector.
- Upgraded FCAL-II with $PbWO_4$ crystal insert for improved resolution, and superior granularity.

Boost & Background

BR=2.7x10^{-4}

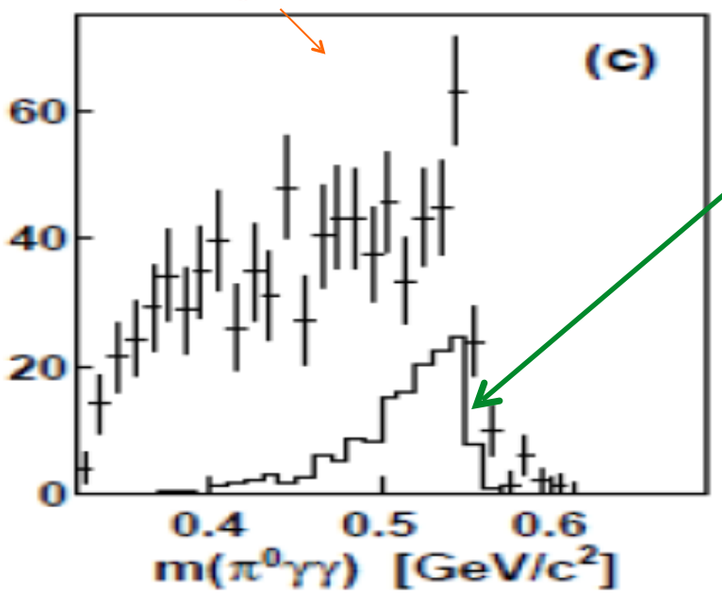


Nefkens, PRC90, 025206

A2 at MAMI: γp→ηp (E_γ=1.5 GeV)

(P.R. C90, 025206)

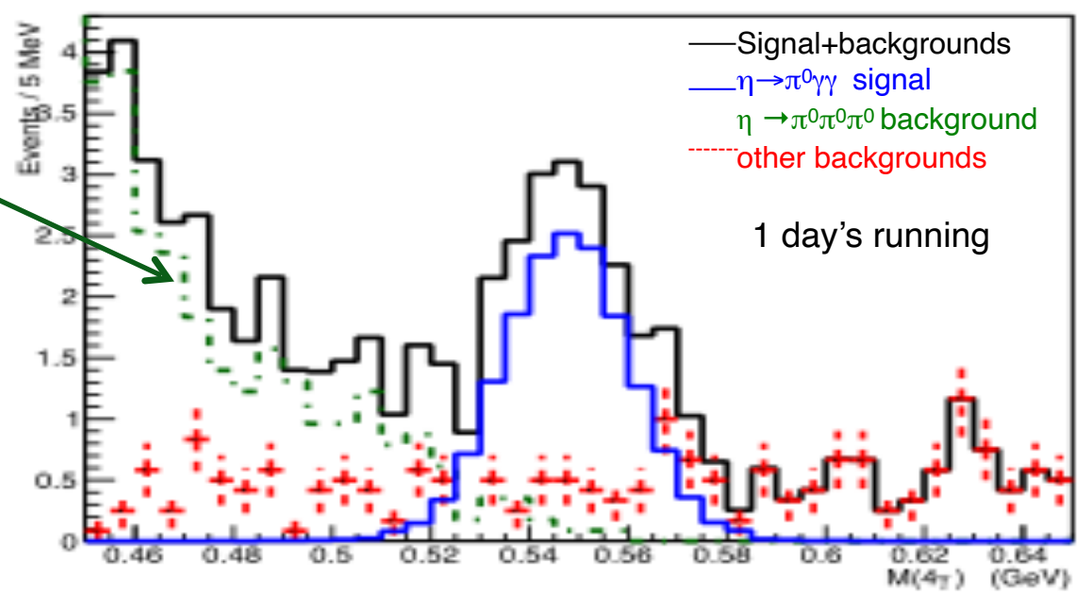
backgrounds



$\eta \rightarrow 3\pi^0$

JEF: γp→ηp (E_γ=8.4-11.7 GeV)

simulation



FCAL-II $PbWO_4$ Insert

Reconstructed GlueX data from 2016 and 2017, original FCAL

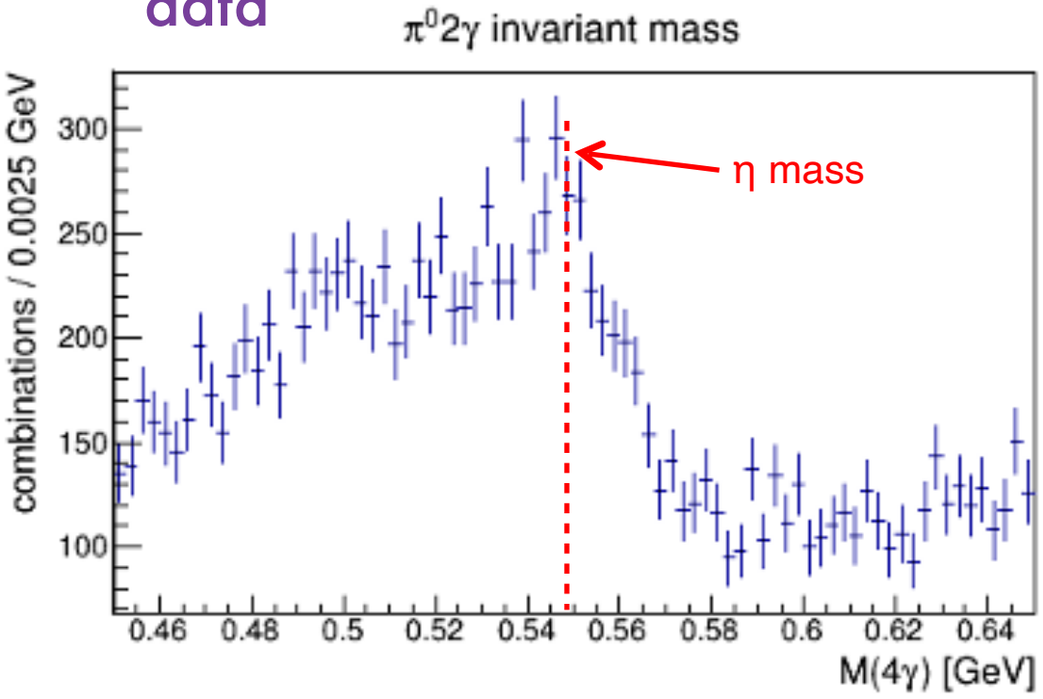
- Significant source of background: $\eta \rightarrow 3\pi^0$ with missing/merged photons

Simulation for 1 day running with upgraded FCAL-II

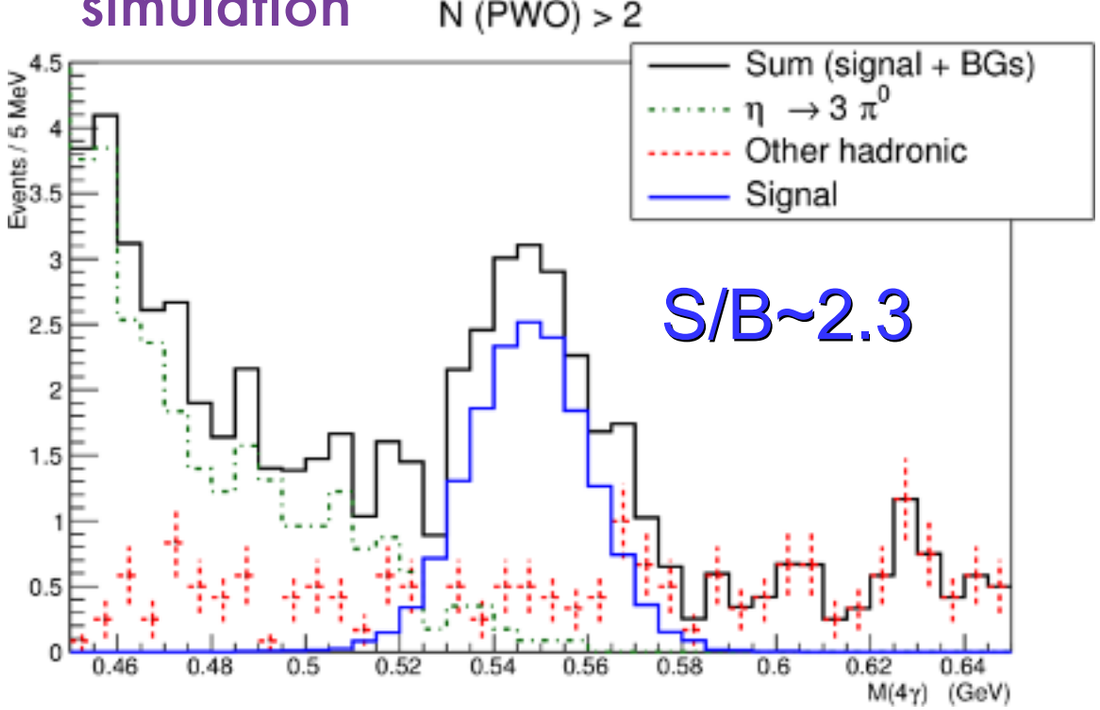
- Beam energy range: 8.4-11.7 GeV

Intensity $N_\gamma \sim 1 \times 10^8$/s

data



simulation



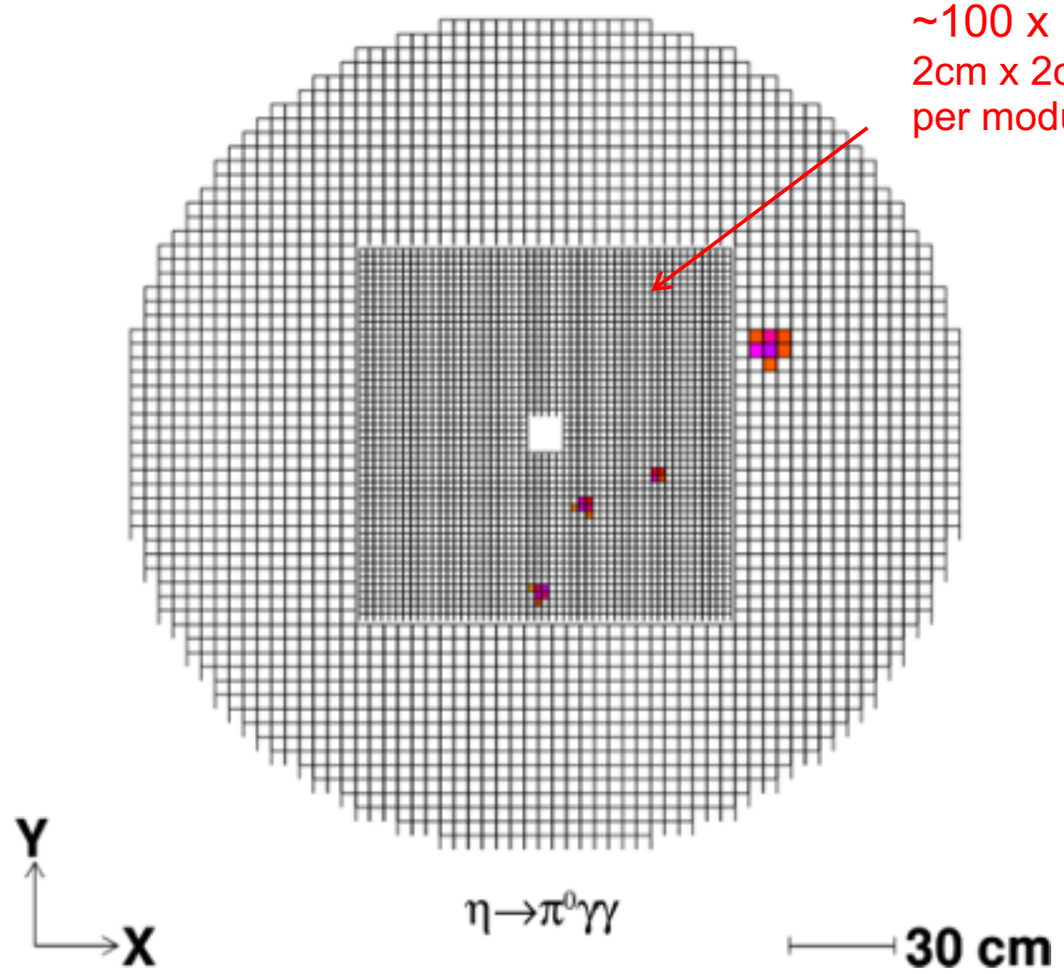
Neutral Channels: $n \times \gamma$

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

FCAL-II $PbWO_4$ Insert

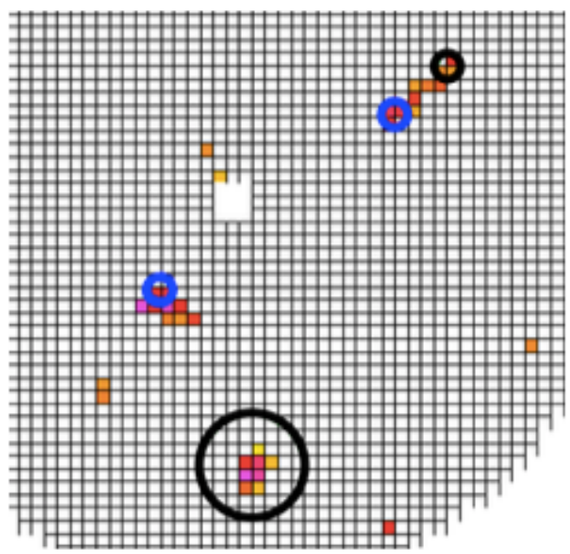
S. Taylor

FCAL view from downstream looking upstream



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

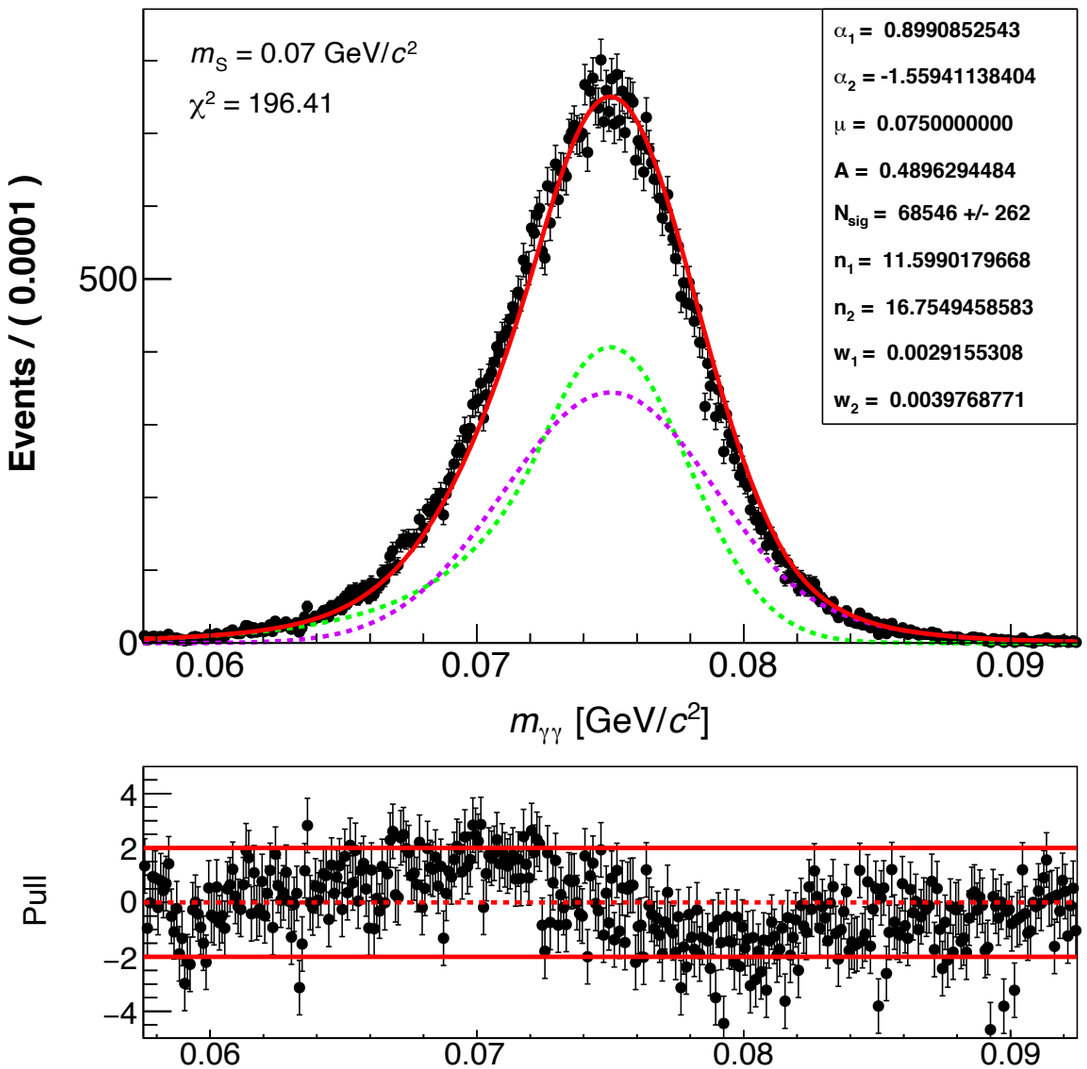
algorithms (Island, ML)

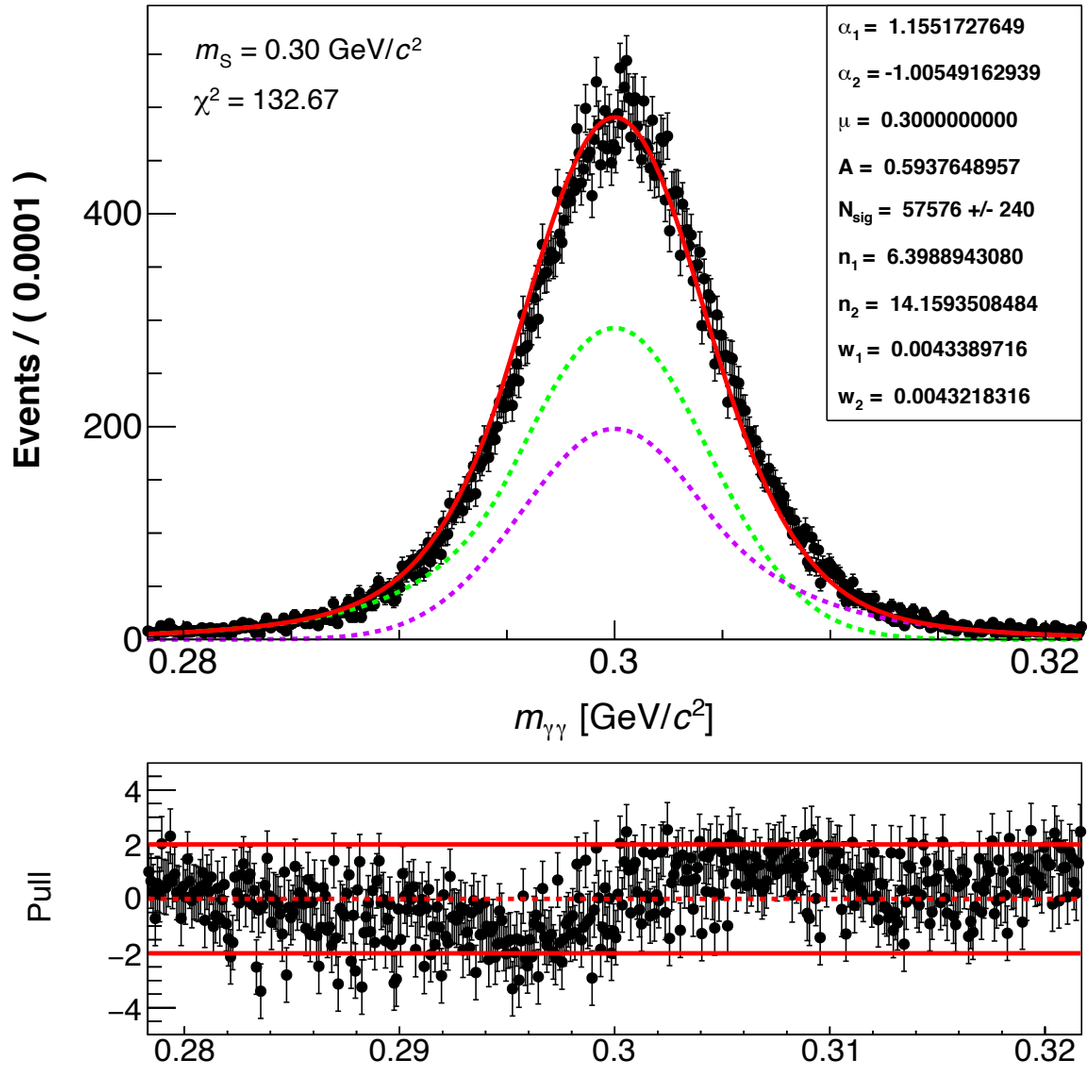


Dark Scalar Simulations

J. Richards
and I. Jaegle

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





Status Quo

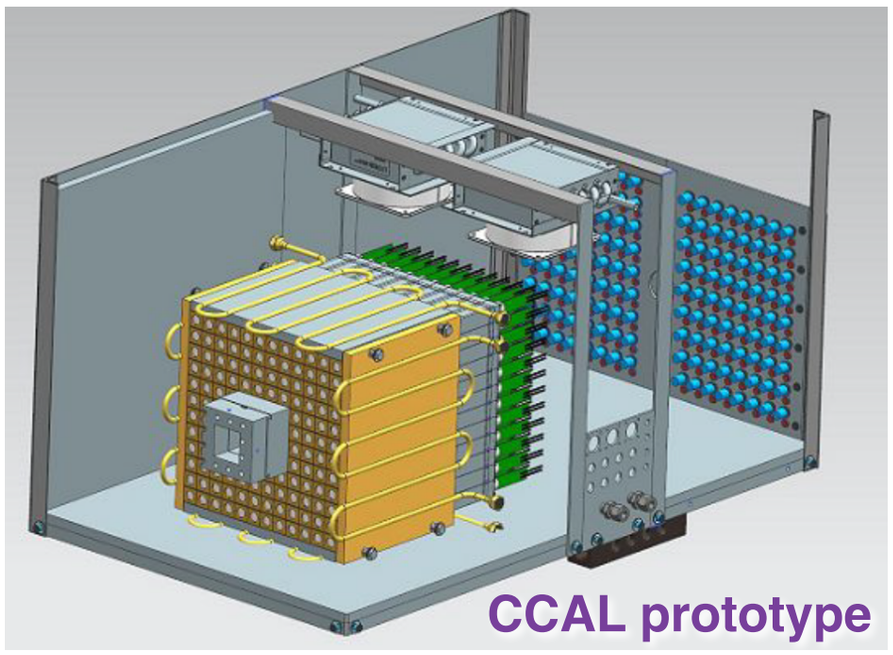
R&D

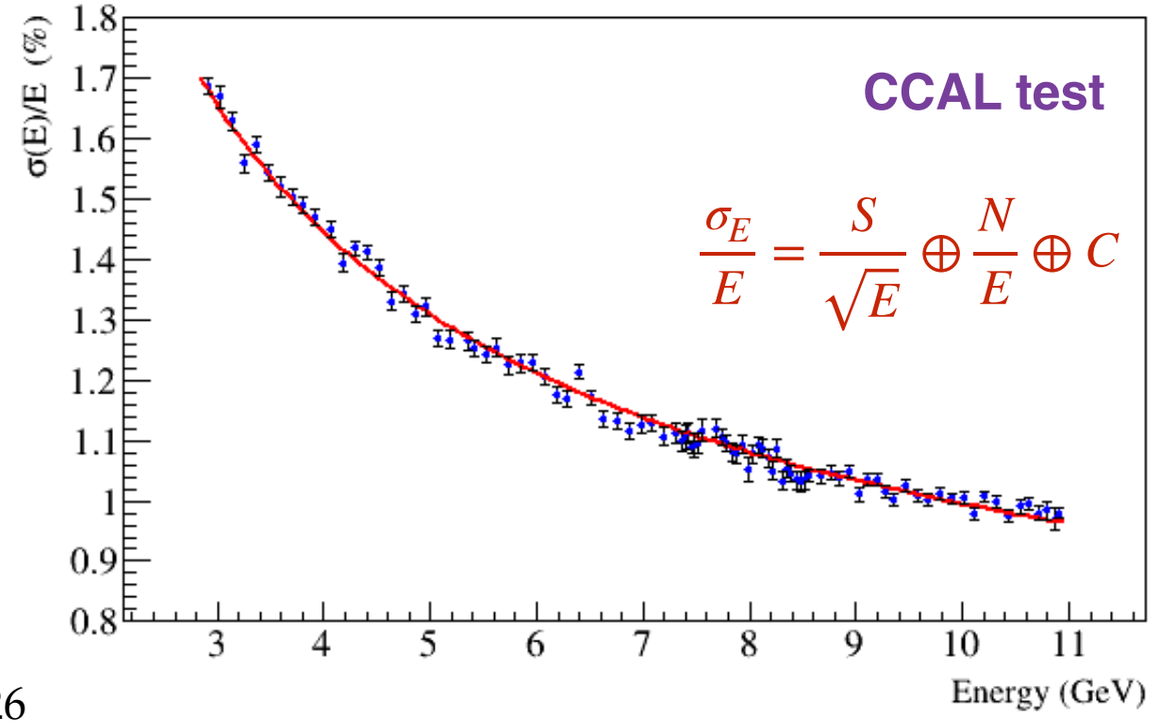
1. JEF was approved by PAC in 2017 to run concurrently with GlueX-II; passed PAC jeopardy review on Sept 25, 2020.

2. FCAL-II: a 50x50 array of PWO insert (~1m^2) is underway.

3. HyCal, CCAL, BCAL, FCALs: extensive experience.

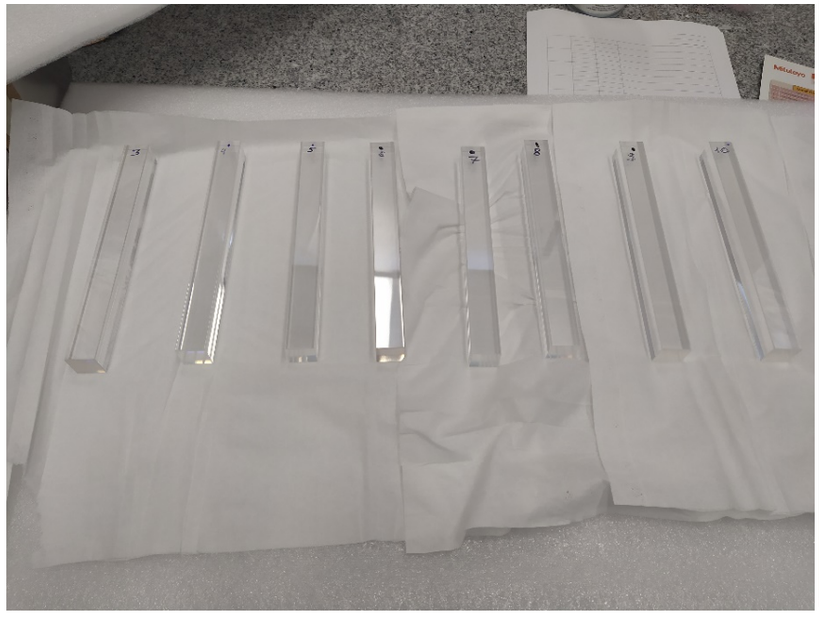
4. CCAL Prototype: 12x12 PWO array successfully tested and used for the PrimEx-η experiment in 2019.



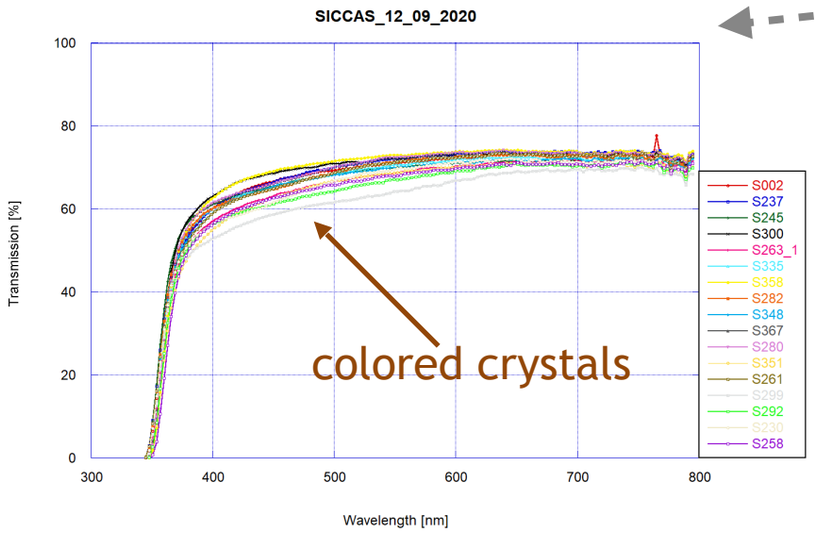


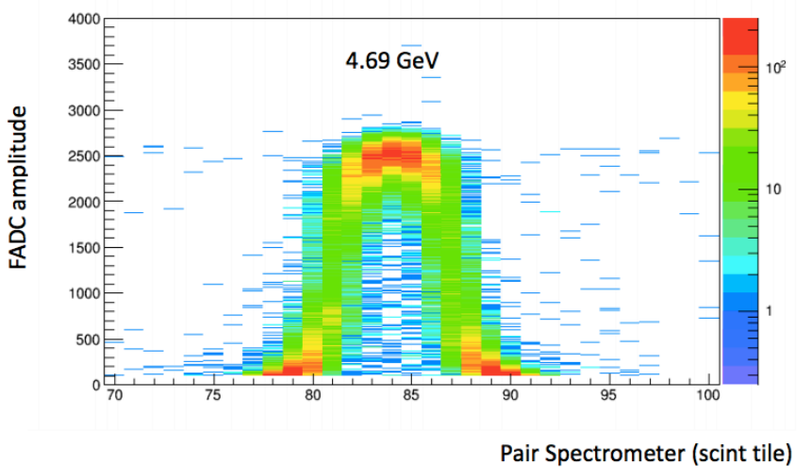
PWO Crystals

- Supplier: SICCAS.
- 356 PbWO4 crystals on hand and tested. Clean room shown. More on their way.



- $PbWO_4$ crystal Quality Assurance.
  - surface, clarity, color, dimensions, light transmission & yield

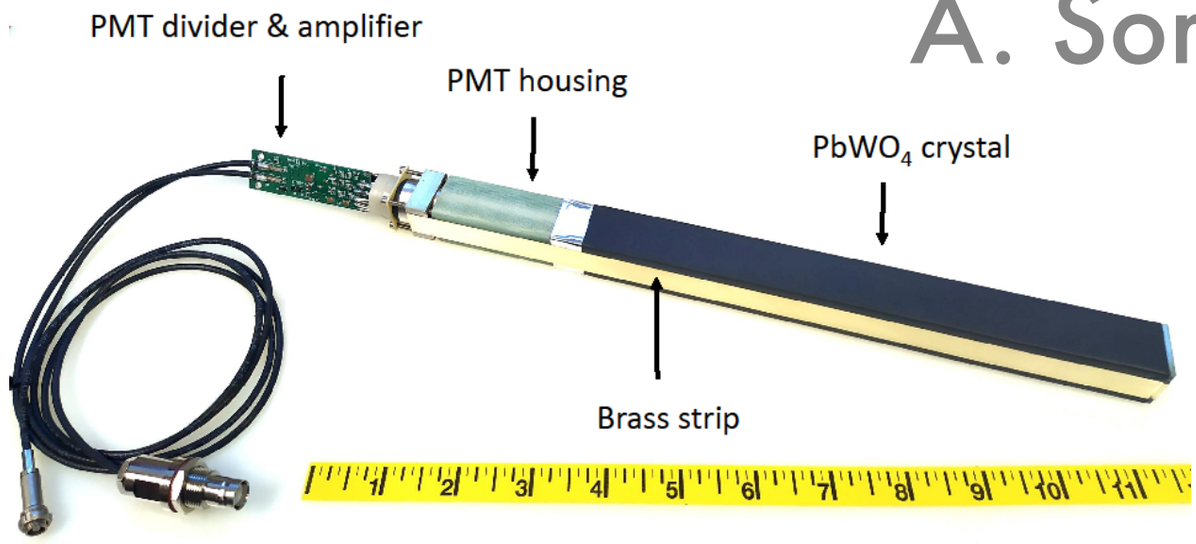




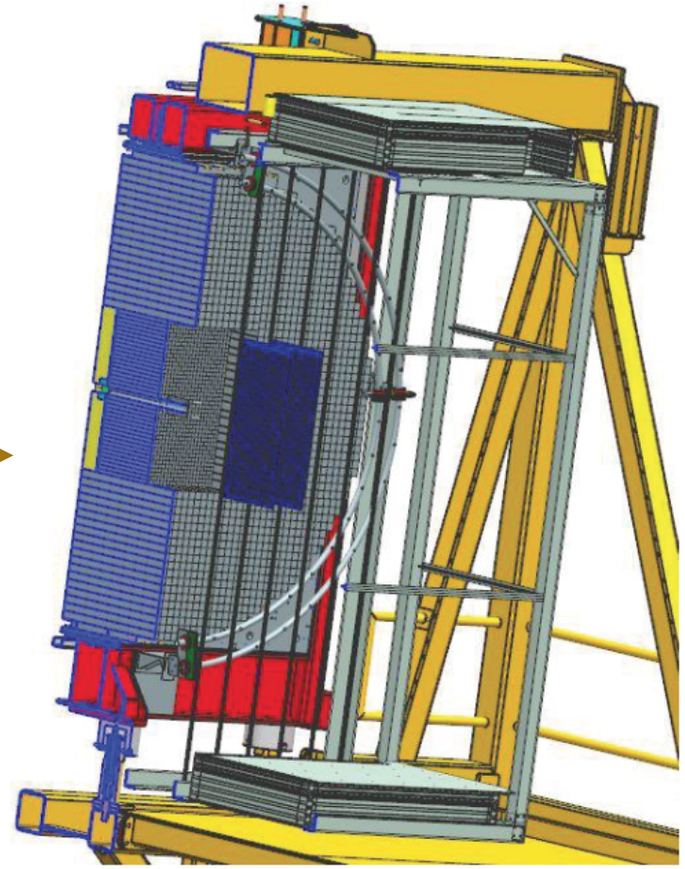
Hardware Status

A. Somov

- Module assembly
  - Hamamatsu R4125 PMT, iron PMT housing, μ-metal, light guides, Si-cookie, divider-amplifier, …



- Fabrication and Installation
  - All mechanical parts are in hand.
  - Mass production of modules expected to begin soon
    - module mechanical design is complete
    - finalizing PMT base design
  - Finalizing engineering design for frame
    - stacking procedure and alignment
    - cable management and dark room
    - water cooling system
    - beam hole support
  - Modules will be 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; search for sub-GeV hidden bosons: vector, scalar, and ALP
  - Directly constrain CVPC new physics
  - Precision tests of low-energy QCD: the role of scalar dynamics in ChPT; transition form factors of η/η′ for (g-2)μ
  - Improve the light quark mass ratio via η→3π, η'→3π
- Require upgraded FCAL-II with a PWO insert; currently under construction. Data taking expected in 2024.

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NSERC CRSNG

GlueX JEF D

Backup Slides

GlueX Run Group

The Proposals

- **GlueX-II**: a extension of the GlueX spectroscopy program at high intensity (E12-13-003) and with enhanced particle identification (E12-12-002)
- **JEF**: a focus on rare and forbidden decays of $\eta^{(\prime)}$ mesons that is enabled by a high-resolution upgrade to the forward calorimeter
- PAC approved JEF to run concurrently with GlueX-II

		Commissioning		Production	
Topic	Proposal Number	Approved	Completed	Approved	Completed
GlueX II with DIRC	E12-12-002	20	14	200	38
GlueX II	E12-13-003	0	0	200	38
JEF	E12-12-002A	0	0	100	0
Total Unique	-	20	14	200	38

PAC Recommendation

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

PAC Recommendation

Text from PAC45 report

Measurement and Feasibility: The JEF program will use the existing beam line and detector array of the current GlueX experiment with a modification to the forward calorimeter (FCAL). This proposal addressed issues raised by the PAC42 "that FCAL-II and the associated JEF physics program be fully incorporated to run in parallel with GlueX". A detailed simulation of the key signal channel $\eta \rightarrow \pi^0\gamma\gamma$ is performed along with various background channels. The results suggest that the JEF experiment has full capability to take data concurrently with GlueX or any other experiments using a LH_2 target in Hall D.

Summary: The PAC endorses the physics of the JEF program. The simulation of the key channel suggests that the proposed measurements are feasible. The PAC recommends approval of this proposal, as a run group addition to approved GlueX running with the DIRC. The PAC encourages the collaboration to further develop and optimize the technical design of the FCAL-II utilizing existing resources, and to make a credible plan to build a sufficient FCAL-II to carry out the measurements. No new beam time will be allocated, so the PAC encourages the collaboration to develop a concurrent run plan.

Hardware Status

From A. Somov

Item	Availability	Comments
PMT housing	168	Produced at CMU, Annealed at Jlab
350 um mu-metal schileding cylinder	1000	Ordered for 1600 modules
50 um mu-metal foil	1600 modules	
Light Guides	140	
ESR	1600 modules	
Flanges	500	Ordered for 500 modules
Brass strips	1600 modules	
PMT tension plate (G10)	1600 modules	
Kapton, Tedlar, Screws, Tape	Available	

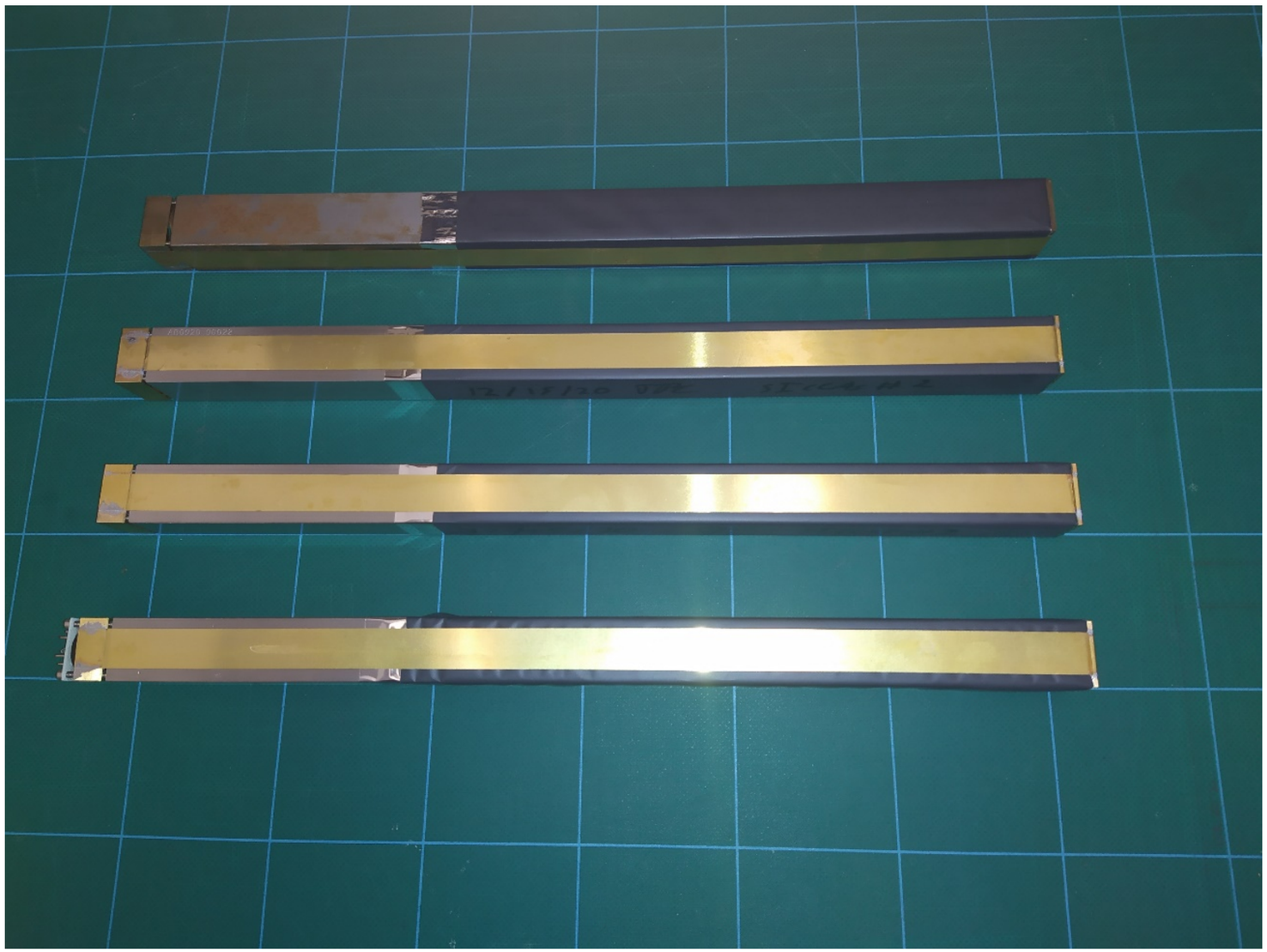
- All components (except crystals and PMTs) for 1600 modules are expected to be in the lab during summer
- Fabrication tools are ready (ESR pre-shaping, brazing, LG gluing, etc)
- Most fabrication procedures are finalized (used during CCAL fabrication) https://halldweb.jlab.org/wiki-private/index.php/CompCal_Construction
- OSP for module fabrication (GlueX-doc-4379)

Hardware Status

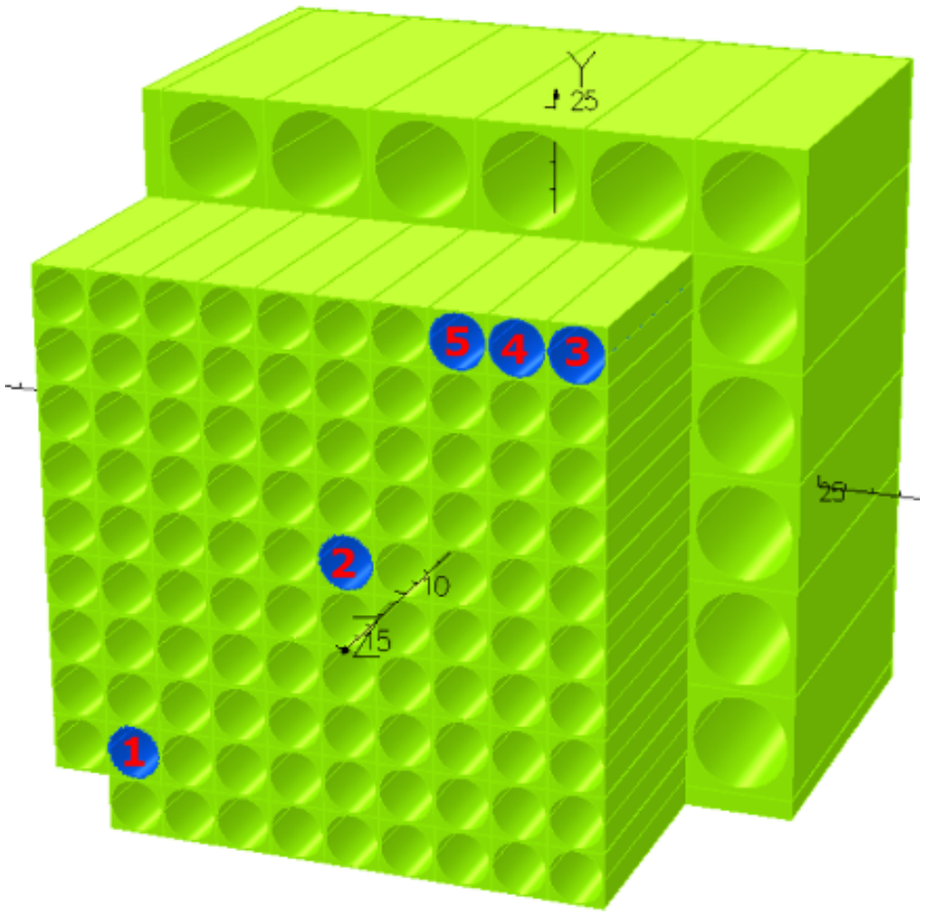
From A. Somov

TEDF clean room

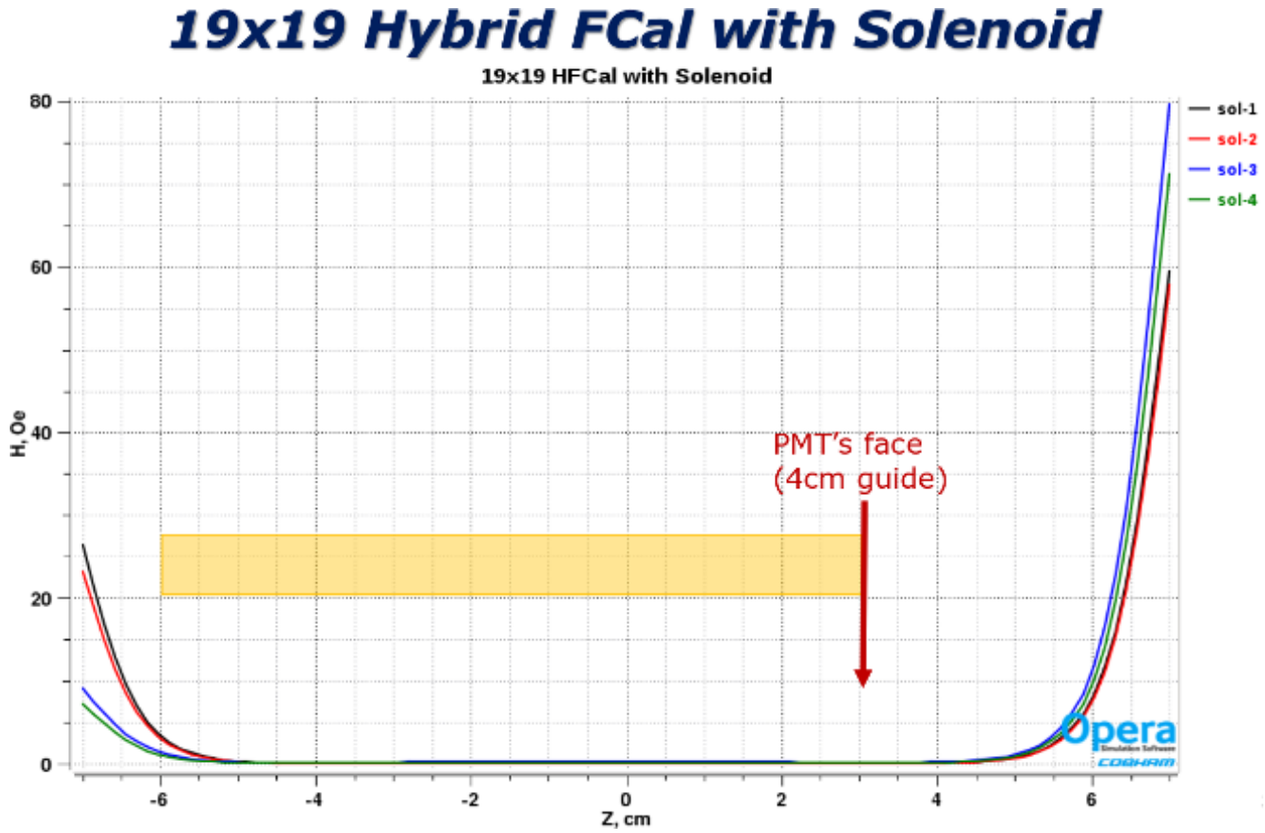
- modules assembled
- brazing tests
- fabrication



Hardware Status



Magnetic field ~100 G at TOF,
~50 G at back of FCAL;
need magnetic shielding:
iron tube + μ-metal shield

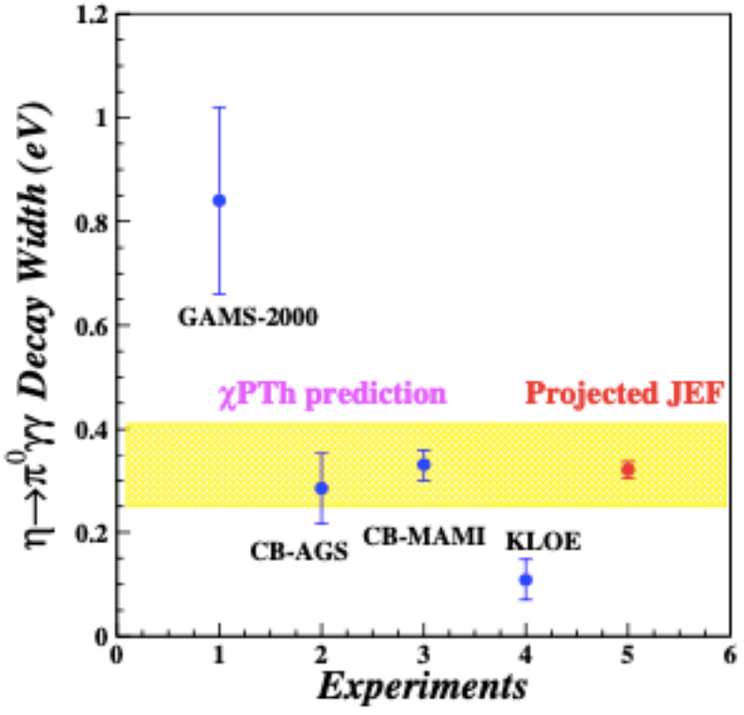


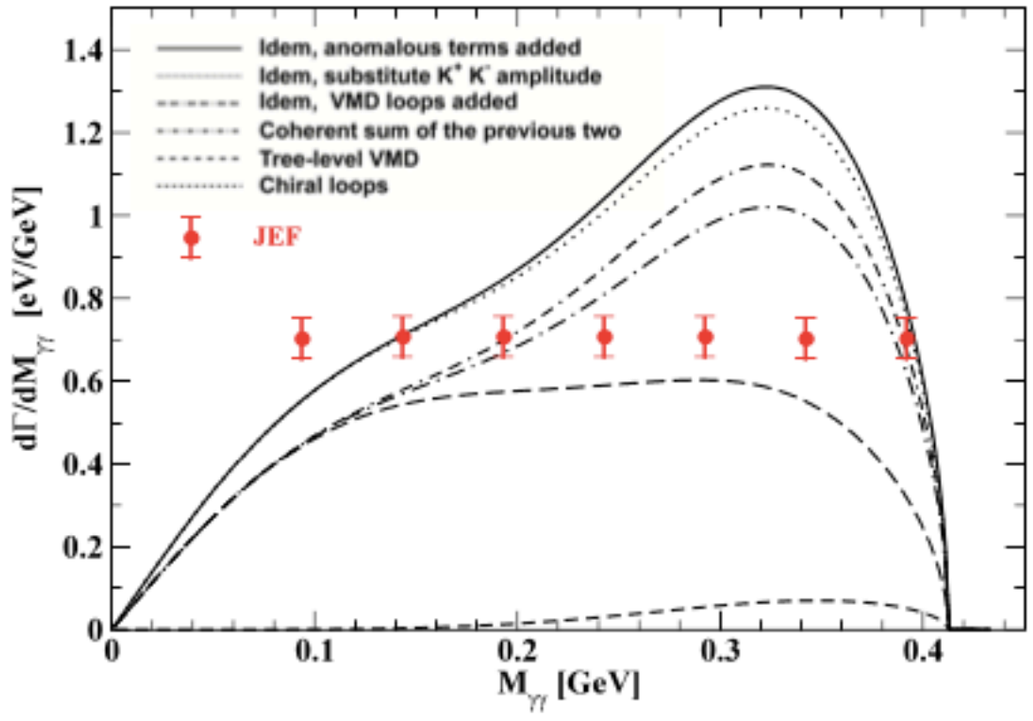
Need ~4 cm long light guide…

$$B = \mu H, \mu \approx 1 \quad (air)$$

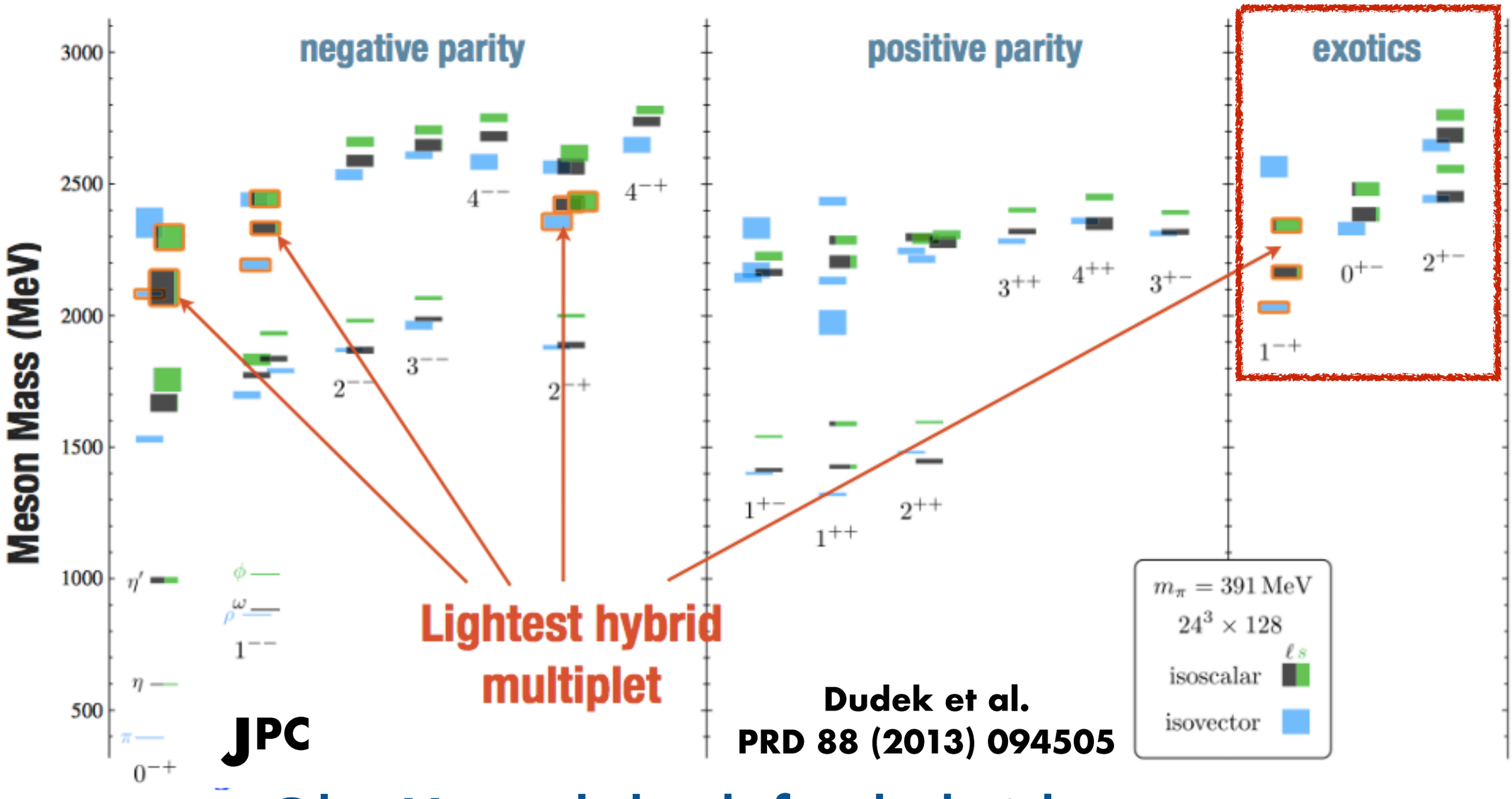
- Earth 25-65 μT (0.25-0.65 G)

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





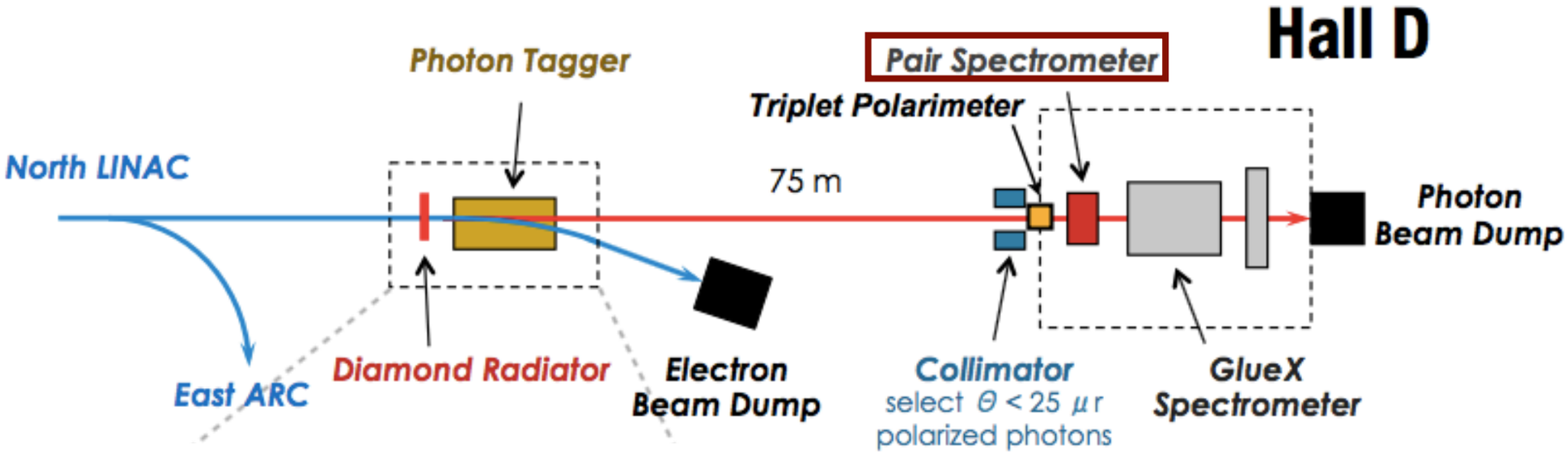
LQCD Full Spectrum



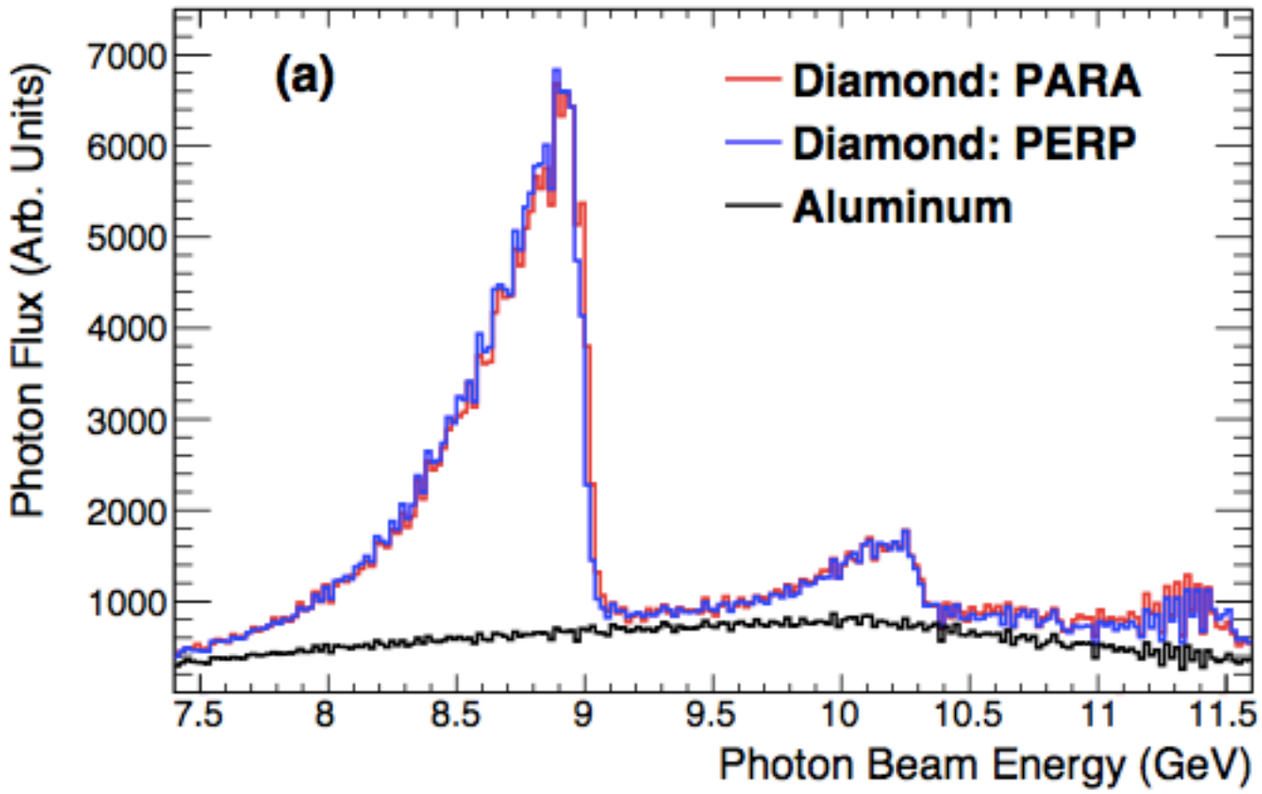
Dudek et al.
PRD 88 (2013) 094505

GlueX goal: look for hybrid patterns

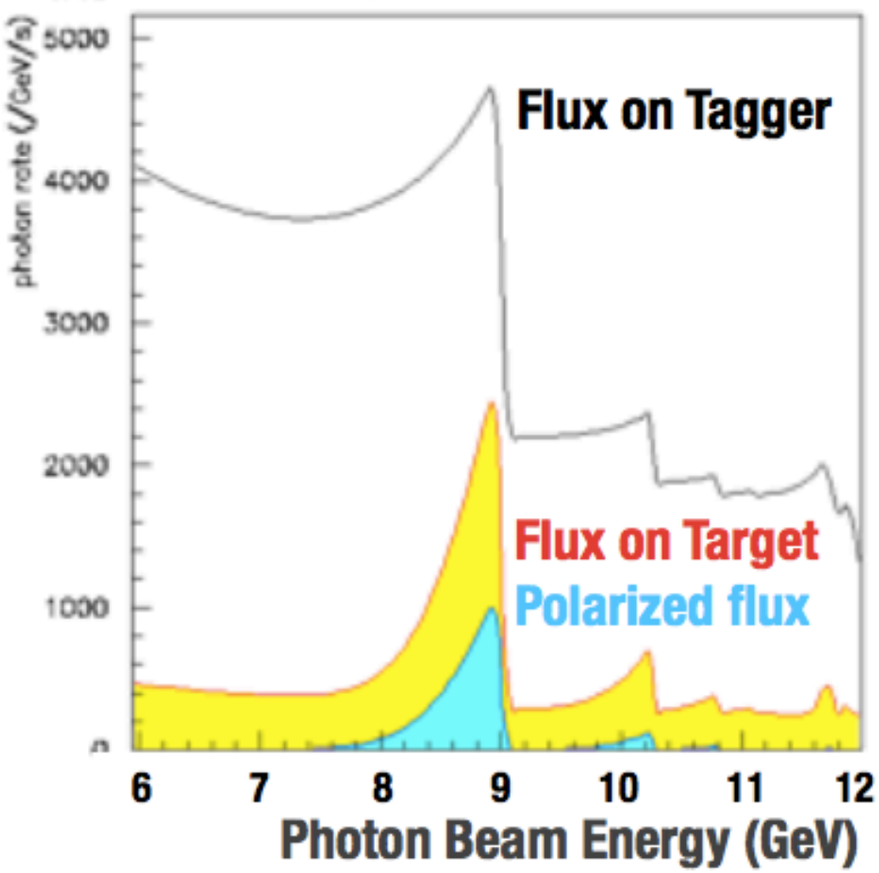
The Beam Line



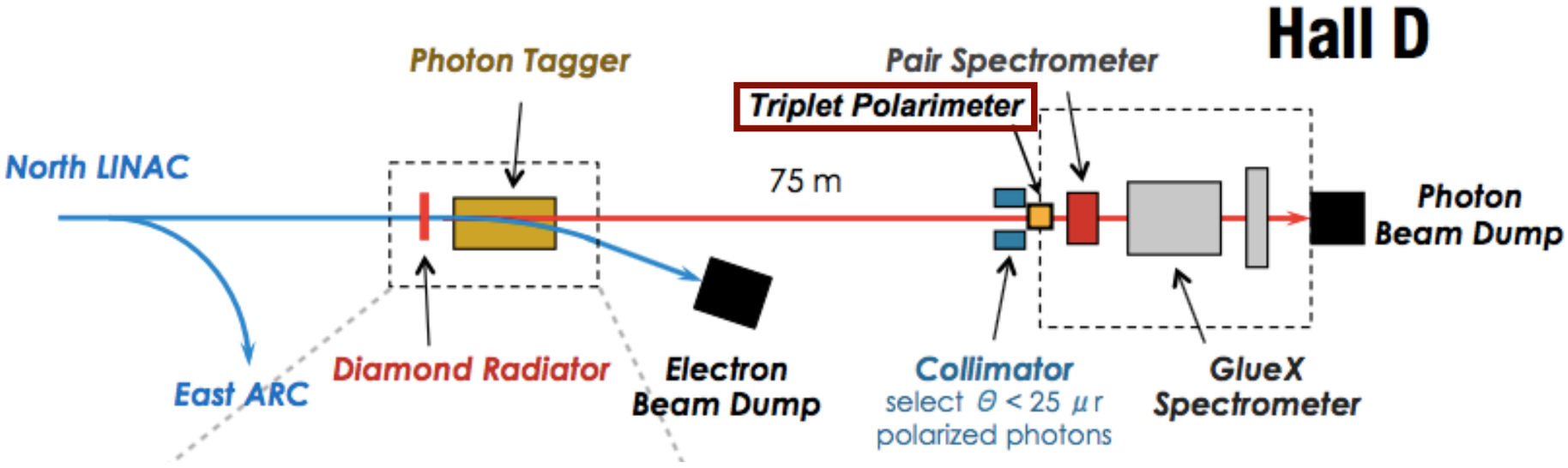
Measured Flux



Expected Flux



The Beam Line



- **Triplet production**

$$\gamma e^- \rightarrow e^- e^+ e^-$$

  - Known analyzing power

$$d\sigma \sim 1 \pm P\Sigma cos(2\phi_{e^-})$$

  - Measure beam polarization independent of spectrometer

arXiv:1703.07875