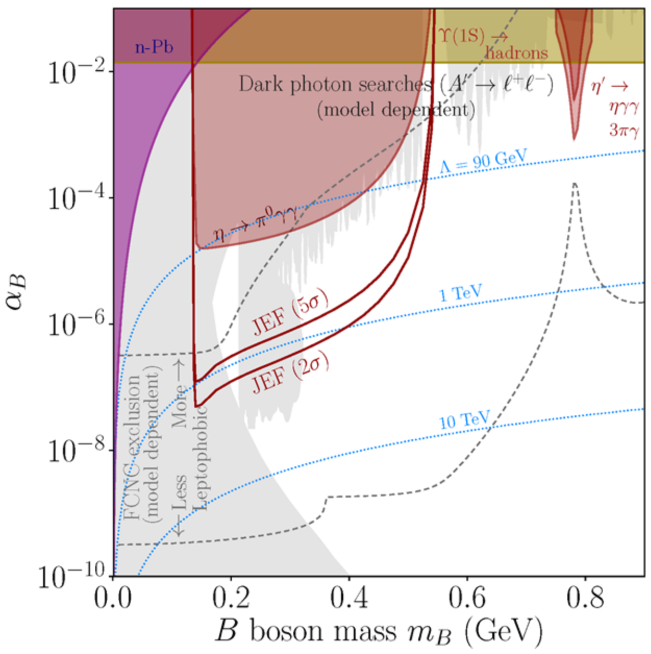
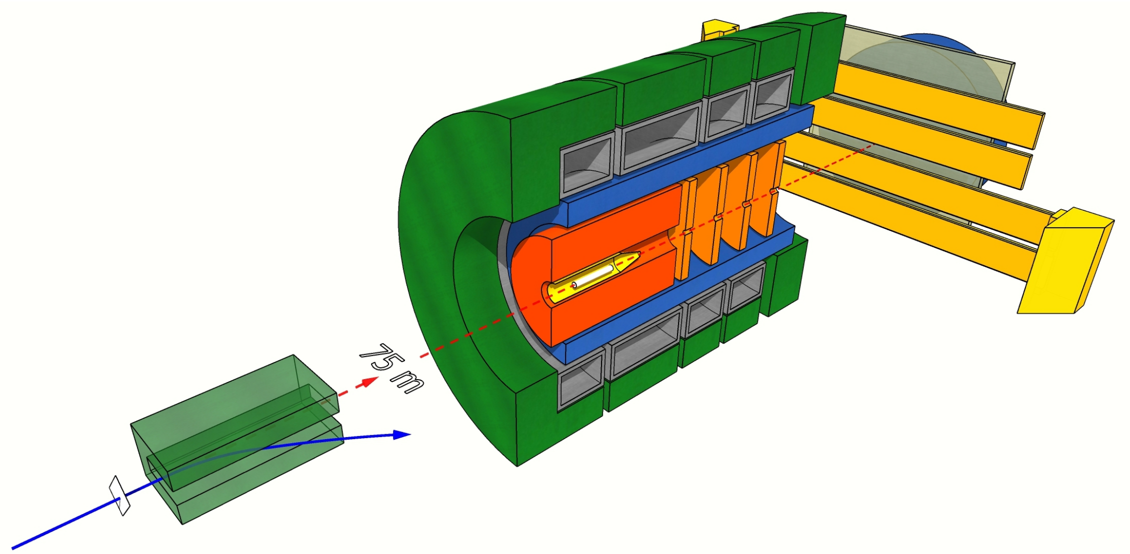
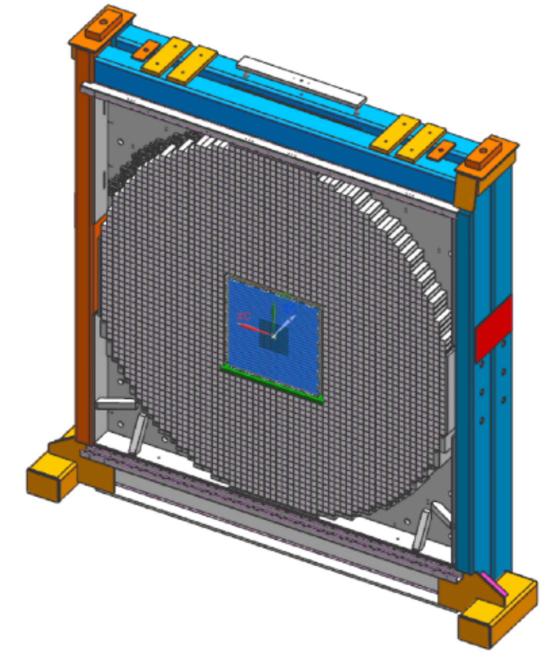






Beyond-Standard-Model Physics using Rare Eta and Eta-prime Neutral Decays

Z. Papandreou for JEF/GlueX

CAP Congress 2022

June 9, 2022

University of Regina | Faculty of Science

NSERC CRSNG

GlueX

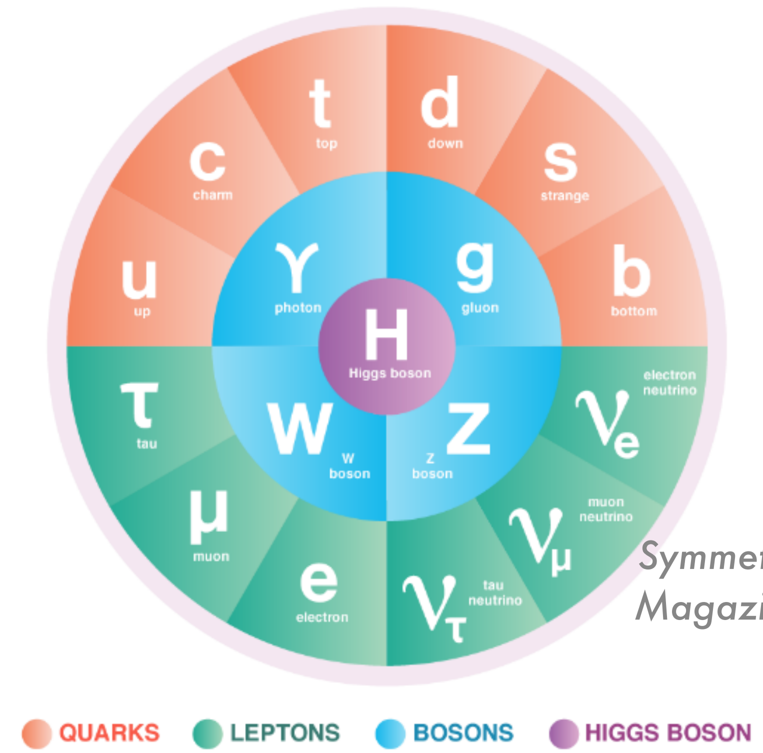
JEF

Outline

- SM and BSM Searches
  - Physics goals and sensitivities
- Jefferson Lab Eta Factory
  - Features and capabilities
- Status Quo
  - Hardware and preparations

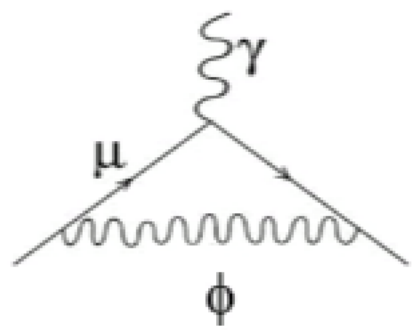
Sub-GeV New Physics

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

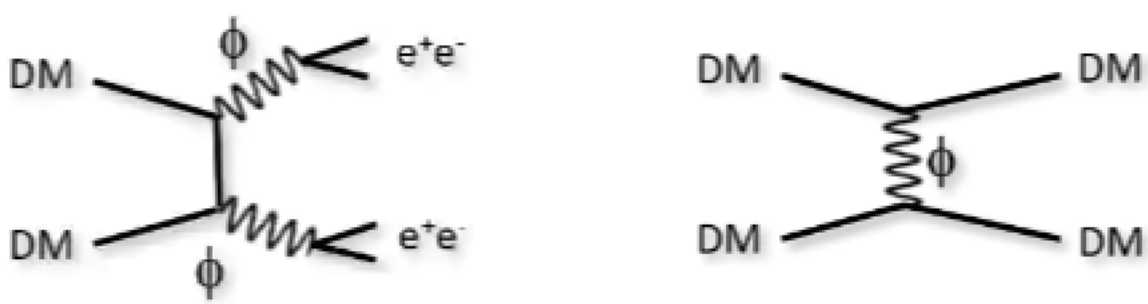


Symmetry Magazine

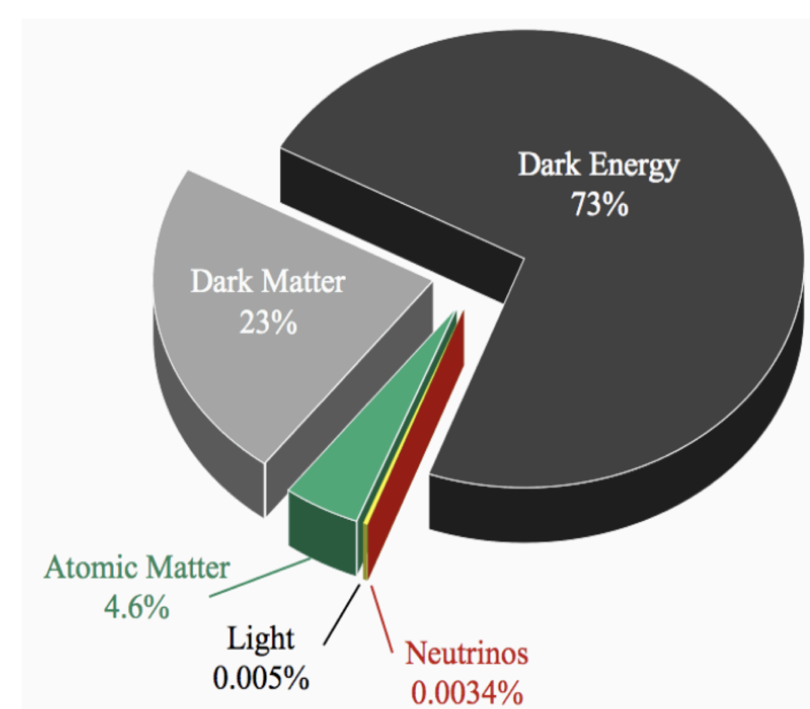
- Anomalies: $(g\text{-}2)_\mu$, $^8Be/^4He$



- Dark Matter physics



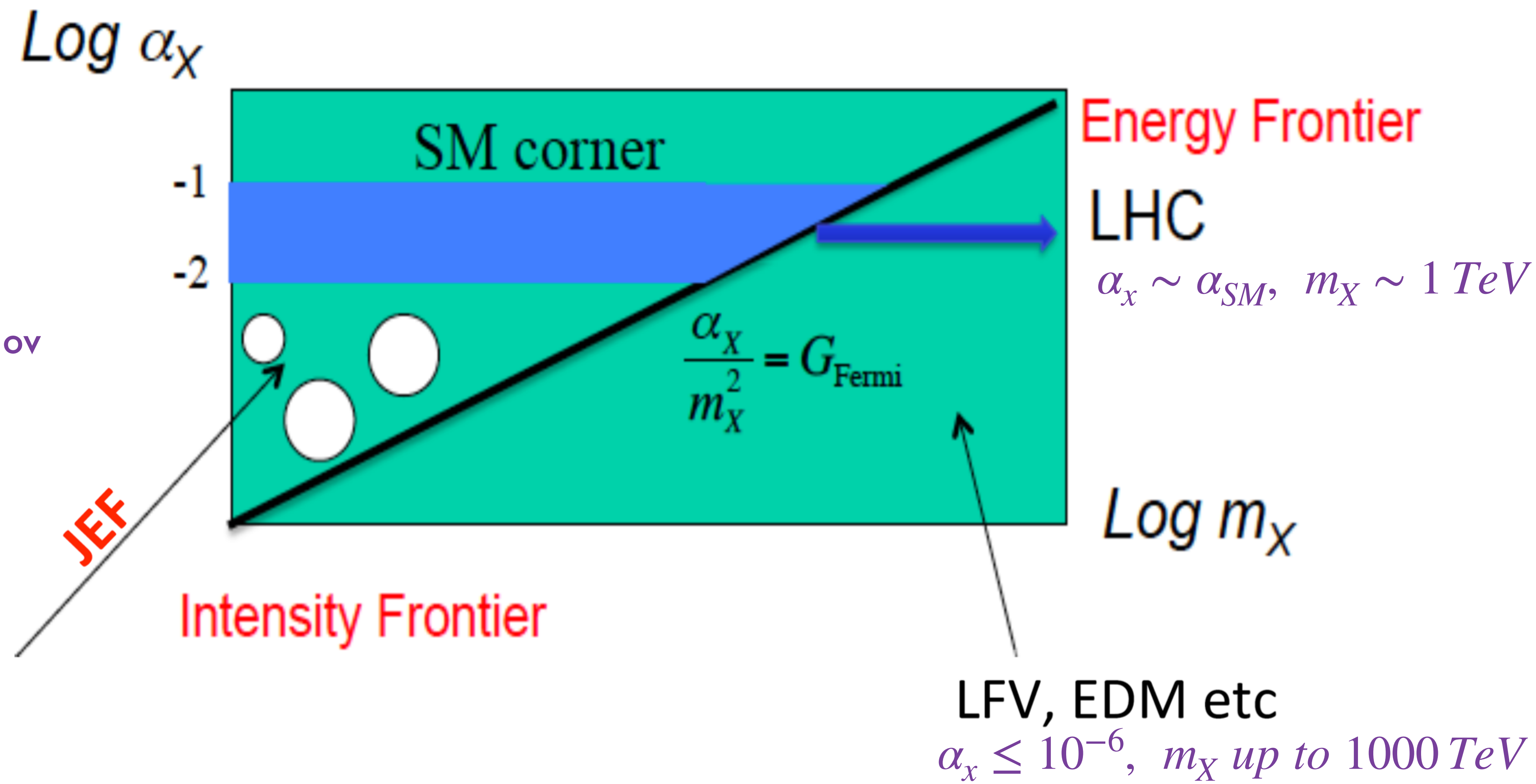
- DM candidates produced in meson decays and direct photo production



JEF Overview

- **"Dark Things"**
  - Model space for sub-GeV dark matter continues to be refined and expanded
  - JEF will search for a number of dark gauge boson candidates
  - DM search strategy: resolve narrow structures in invariant mass spectra in many decays
- **Other Physics**: search for CVPC, quark mass ratio, ChPT...
- **Detector**: 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

JEF Physics - 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)**: $\eta^{(\prime)} \to \pi\pi a \to \pi\pi\gamma\gamma, \pi\pi e^+e^-$

JEF Physics - 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 $\eta^{(\prime)}$: $\eta^{(\prime)} \to e^+e^-\gamma$

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

Physics Reports 945 (2022) 1–105

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

Precision tests of fundamental physics with η and η' mesons

Rich physics program at η,η' factories

Standard Model highlights
- Theory input for light-by-light scattering for $(g\text{-}2)_\mu$
- 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

Courtesy S. Tulin

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

this talk

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'

$\eta'(958)$

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

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

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

this talk

$\eta'(958)$ 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

$\pi^+\pi^-$	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

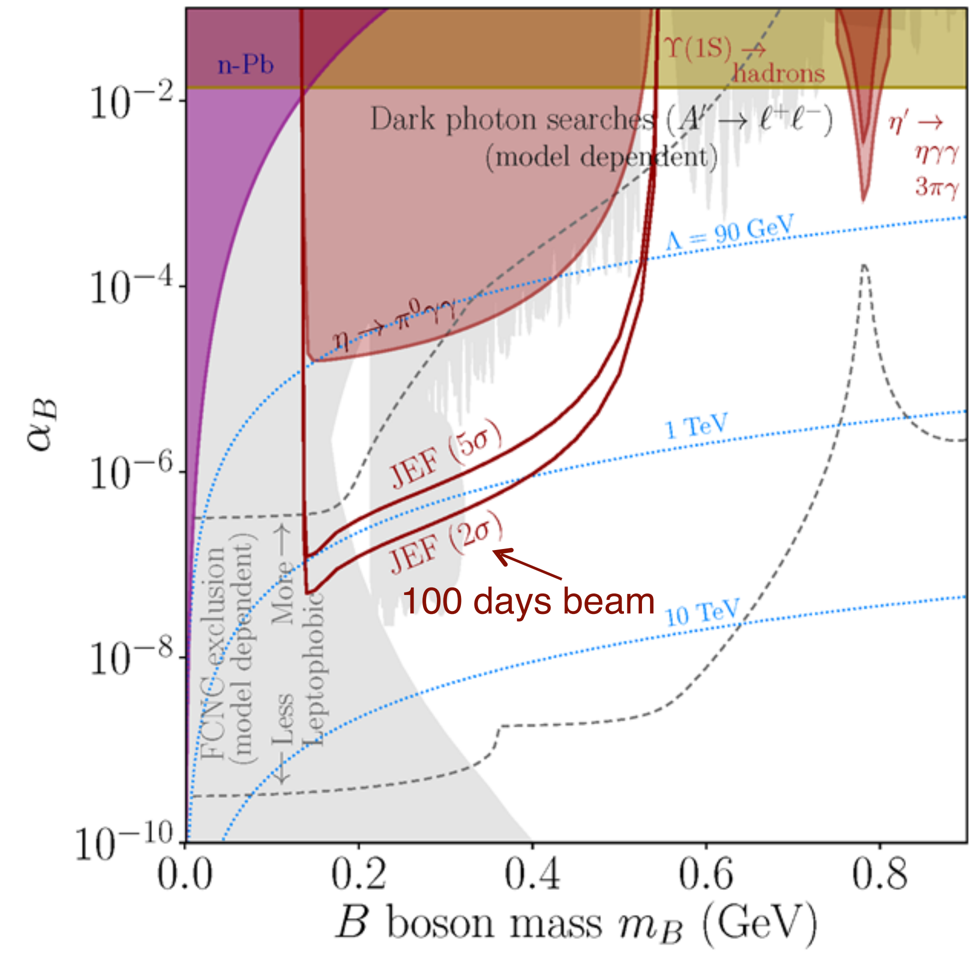
Key Channel: $\eta \to \pi^0\gamma\gamma$

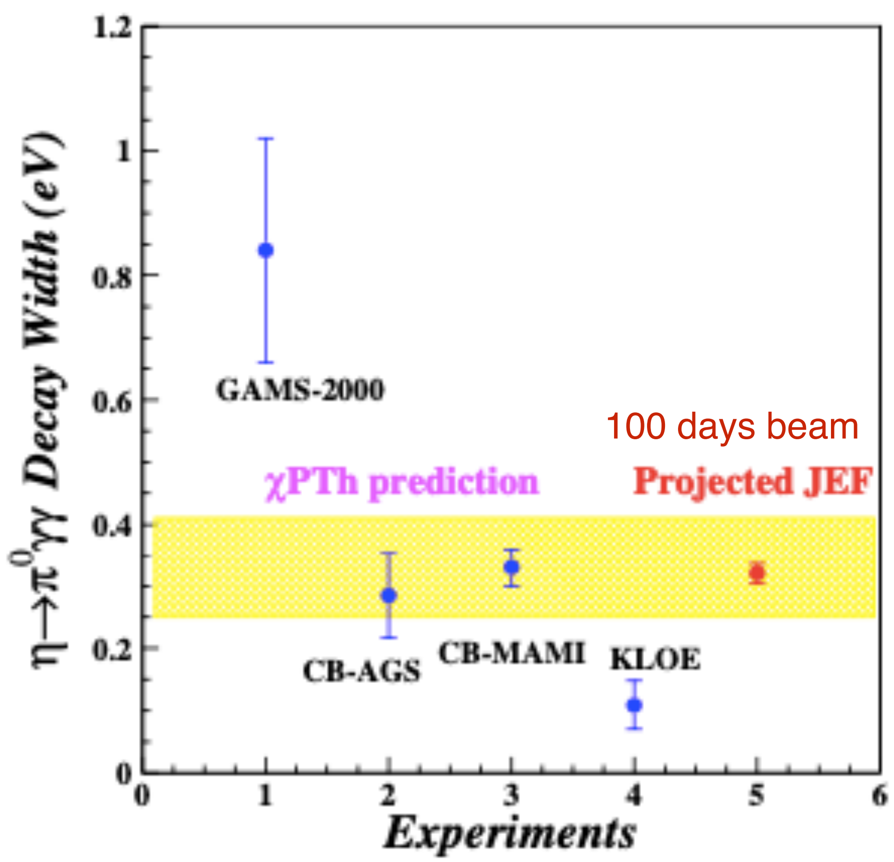
- Search for sub-GeV gauge bosons:
  - **leptophobic vector B′** coupling to baryon no.

$\eta \to B'\gamma \to (\pi^0\gamma)\gamma$ Nelson PLB 221, 80 // Tulin PRD 89,114008

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

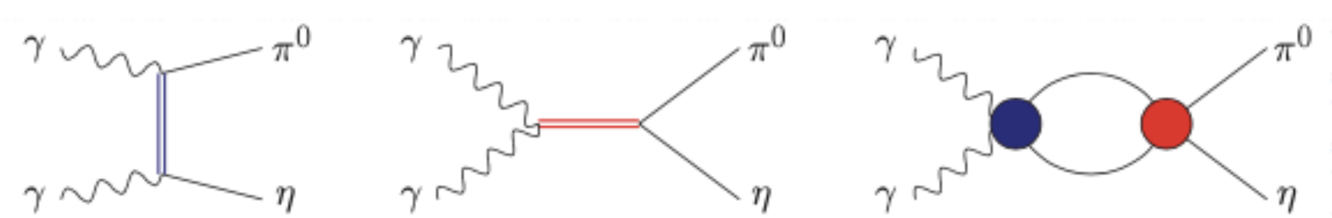
$\eta \to \pi^0 S \to \pi^0(\gamma\gamma)$ Batell, PRD 100,095020 / Liu Nucl.Phy.B,114638





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

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

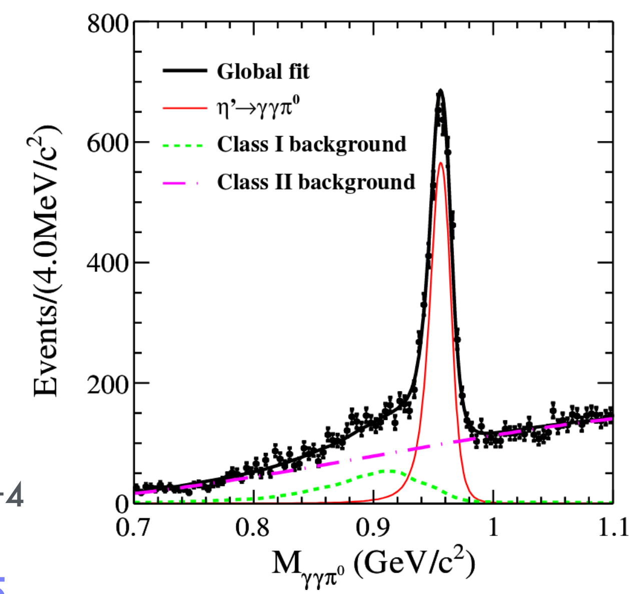


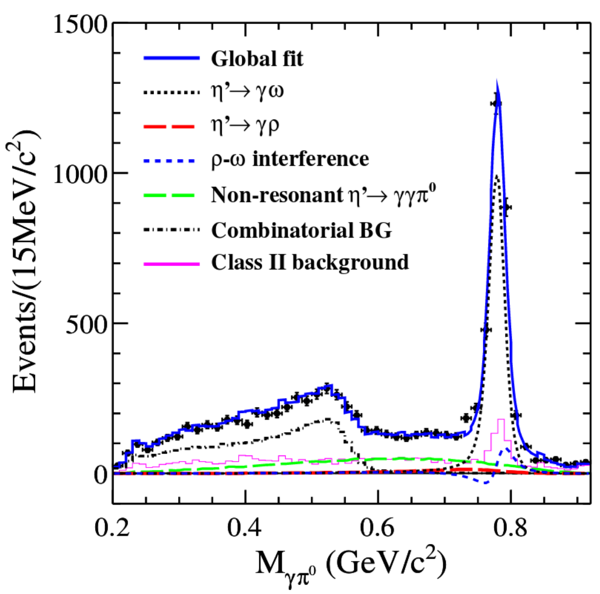
Key Channel: $\eta' \to \pi^0\gamma\gamma$

Recent BES-III measurement on η′:

- doubly-radiative decay measured for first time
- BR(inclusive) = $3.20\pm0.07(stat)\pm0.23(sys))\times10^{-3}$
- BR($\eta'\to\gamma\omega$) = $23.7\pm1.4(stat)\pm1.8(sys))\times10^{-4}$
- BR(non-resonant) = $(6.16\pm0.64(stat)\pm0.67(sys))\times10^{-4}$

Ablikim, Phys. Rev. D 96, 012005





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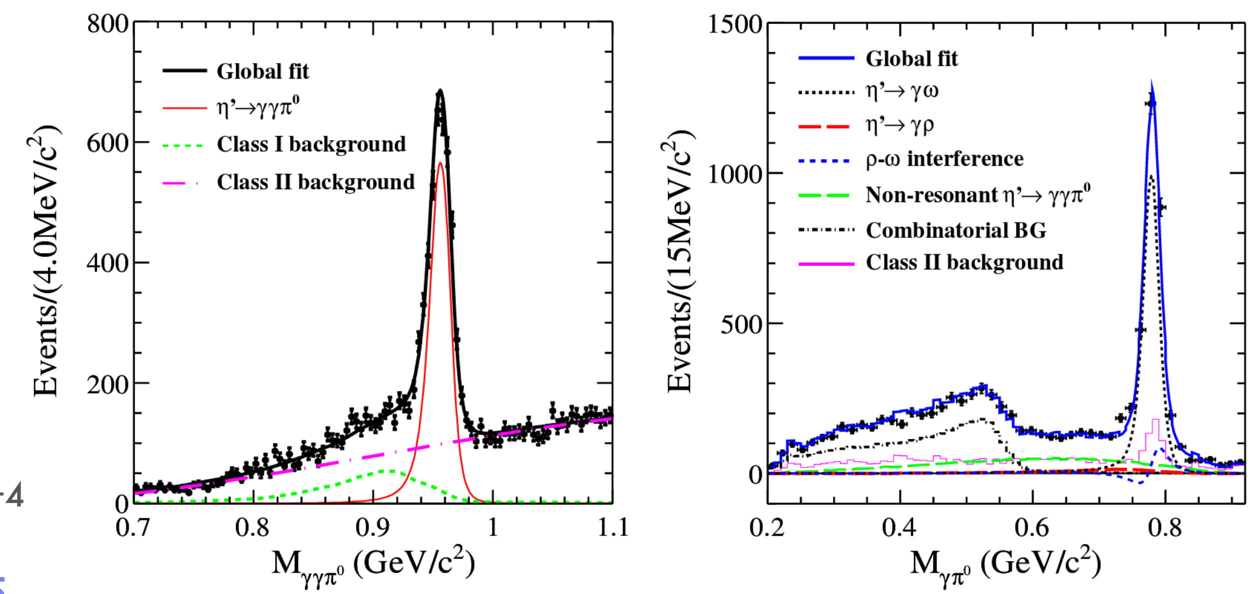
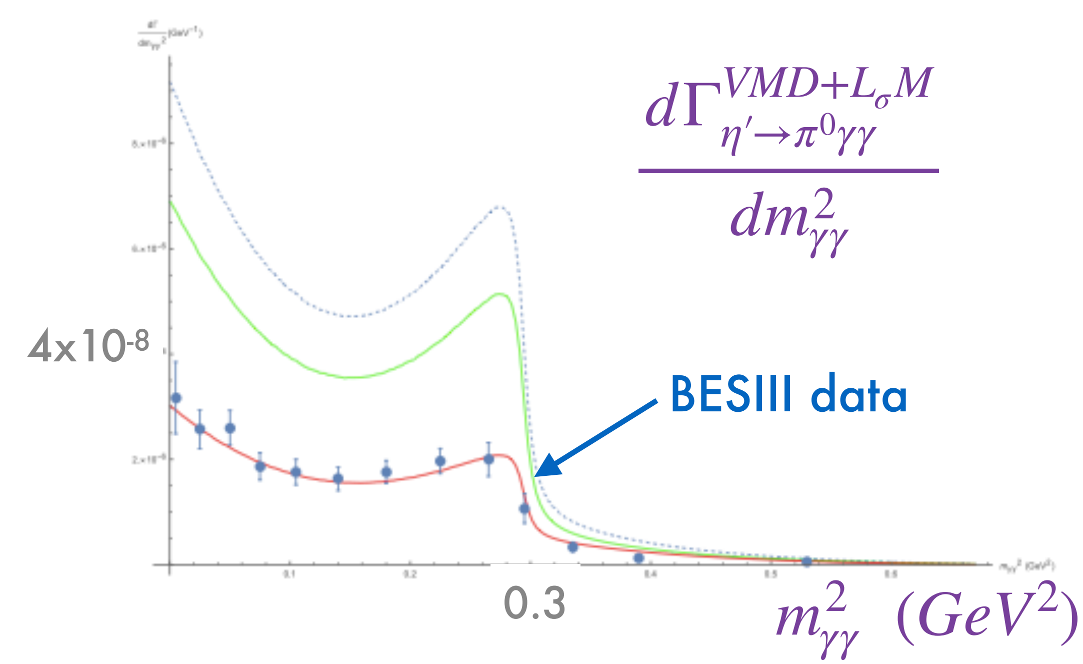


Tension with theory: Balytzkyi, arXiv:1811.01402

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

- Result $\Gamma(\eta'\to\pi^0\gamma\gamma)$=1.6-3.0 keV disagrees with BESIII result $\Gamma(\eta'\to\pi^0\gamma\gamma)\approx$0.64 keV
- Dark photon? Increase mass range for B search?



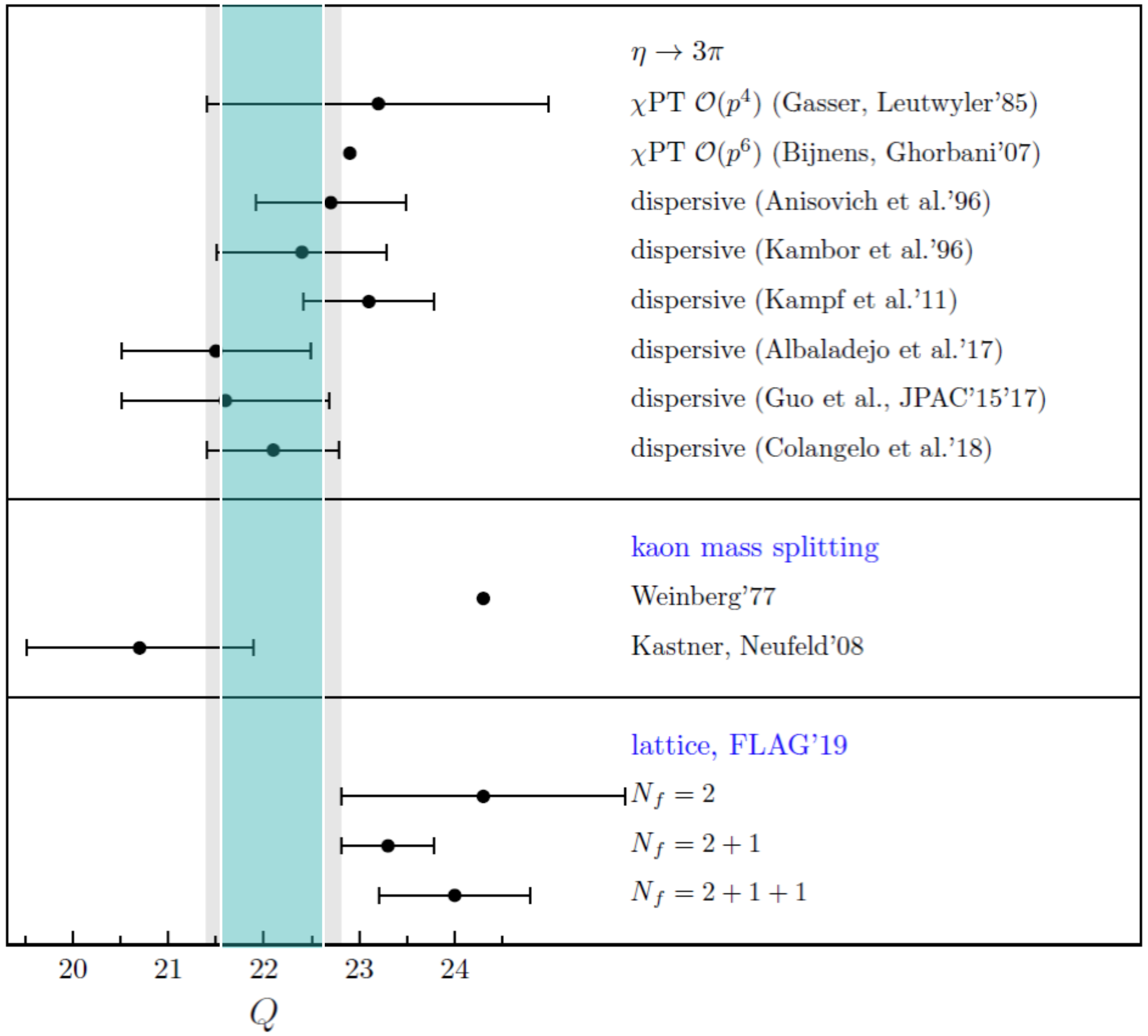
Key Channel: $\eta \to 3\pi^0$

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

- A clean probe for **quark mass ratio**:
  - decays through isospin violation:

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

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



e-Print: 2007.00664

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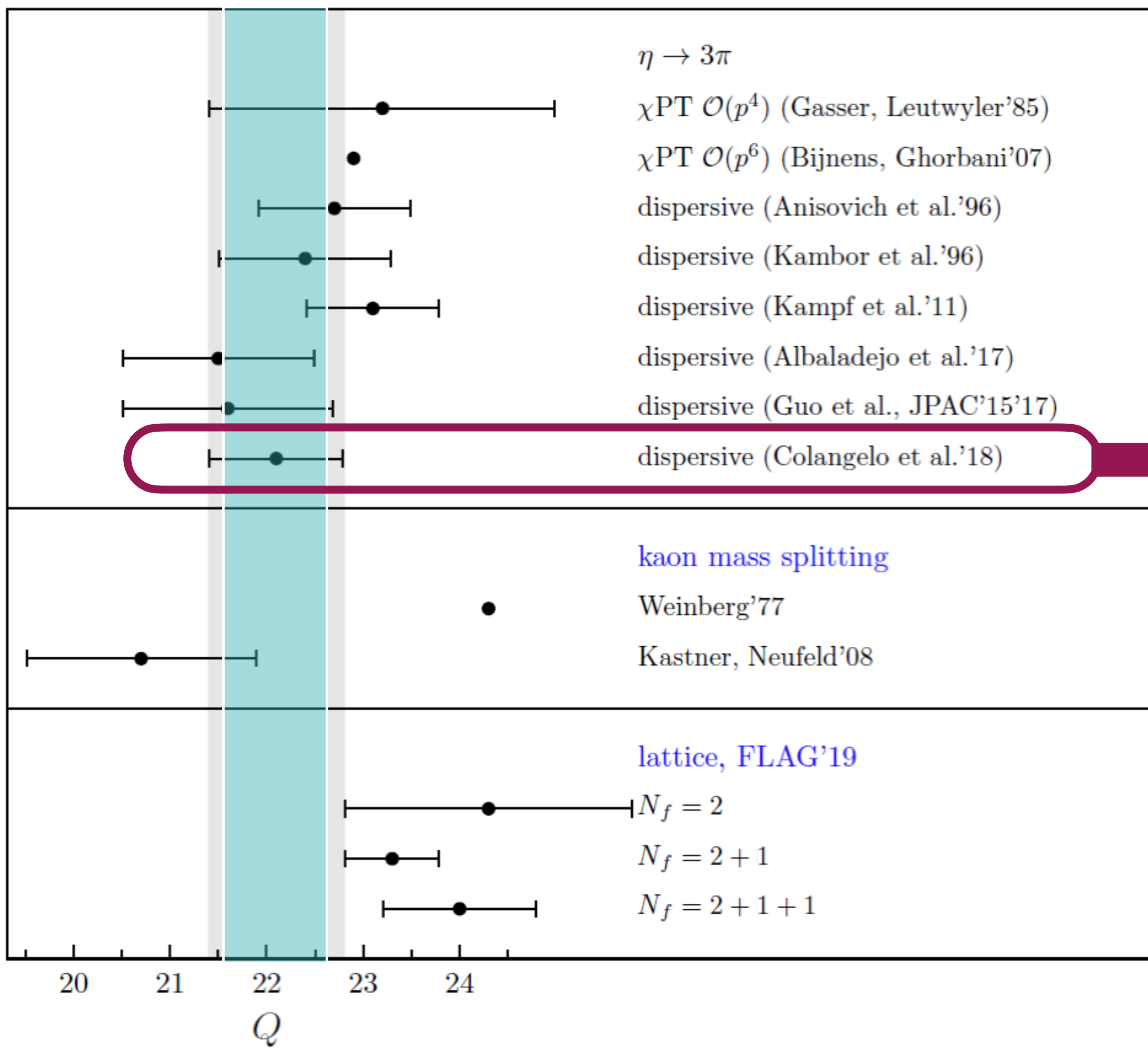
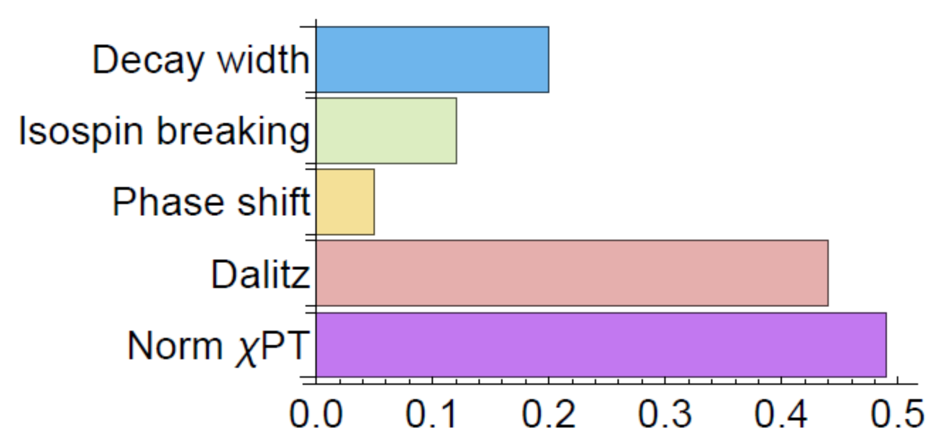


- Uncertainties in quark mass ratio:



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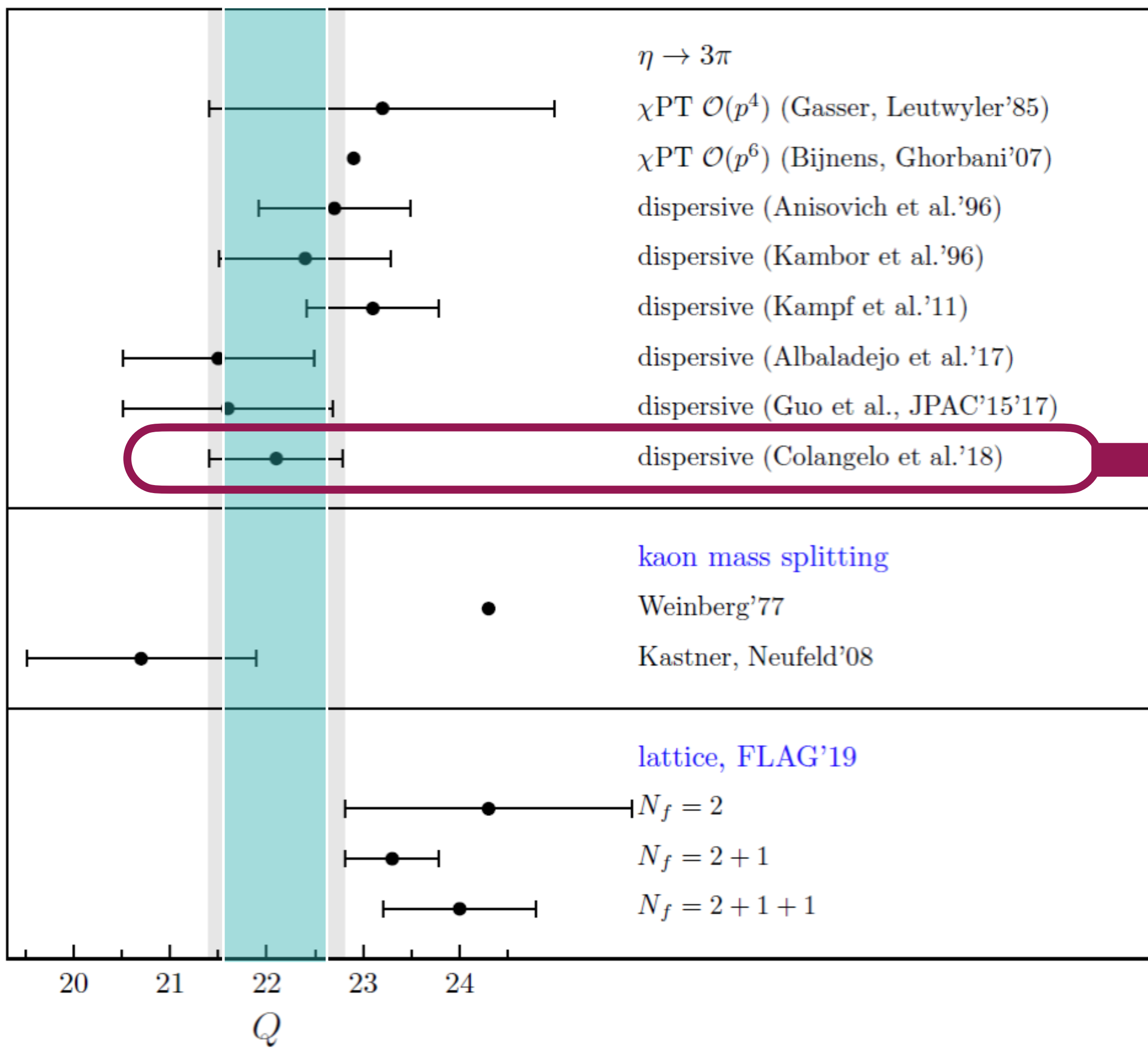

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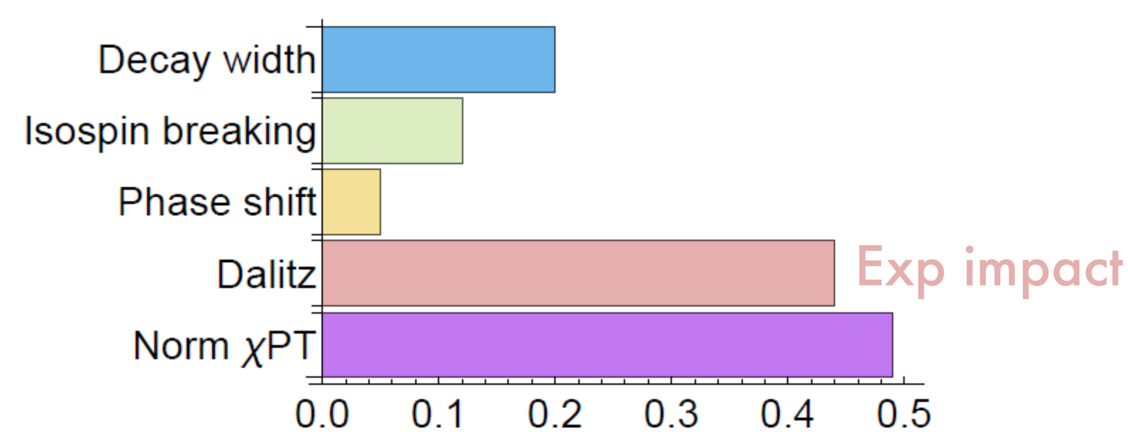

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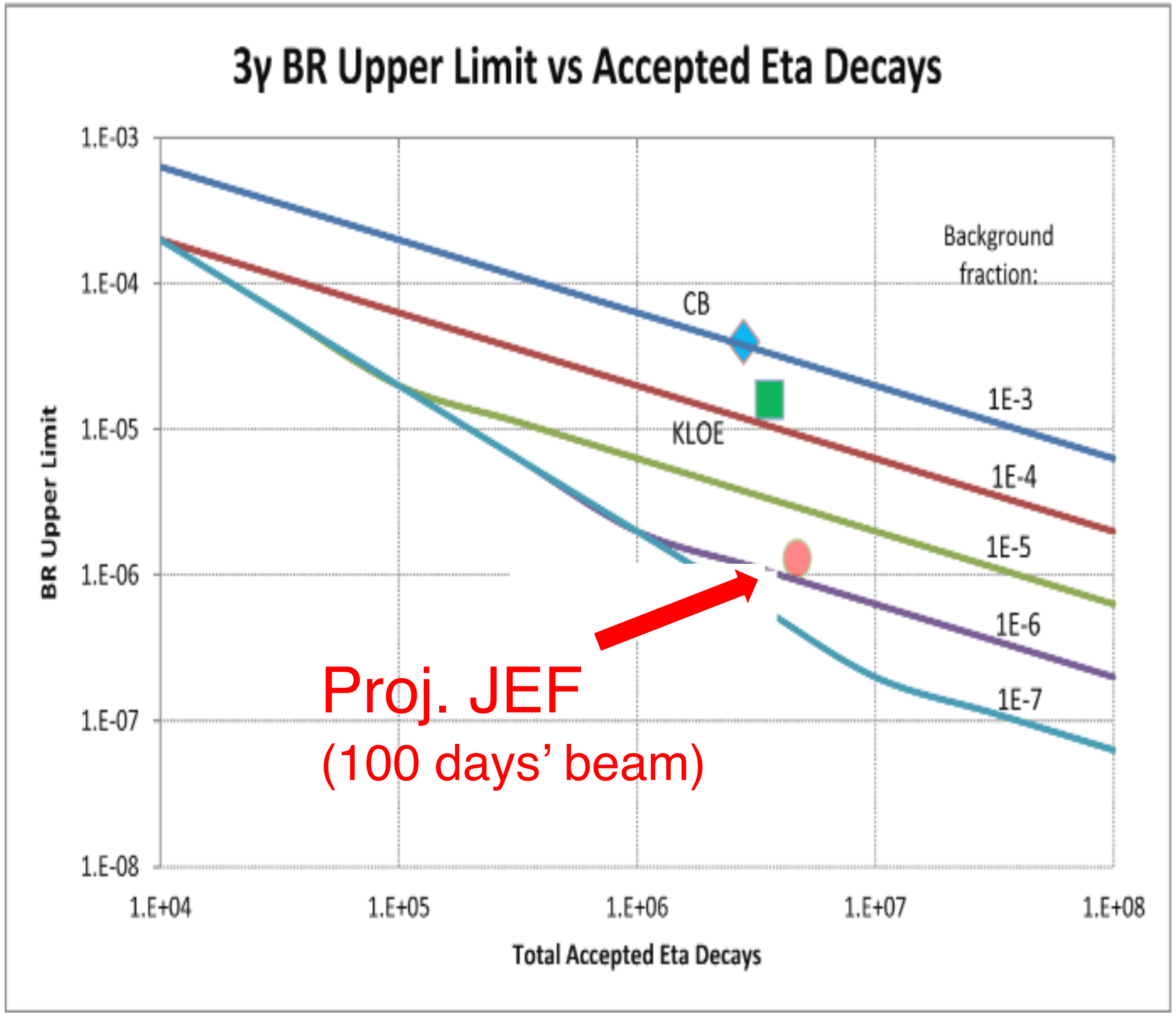
Key Channel: $\eta \to 3\gamma$

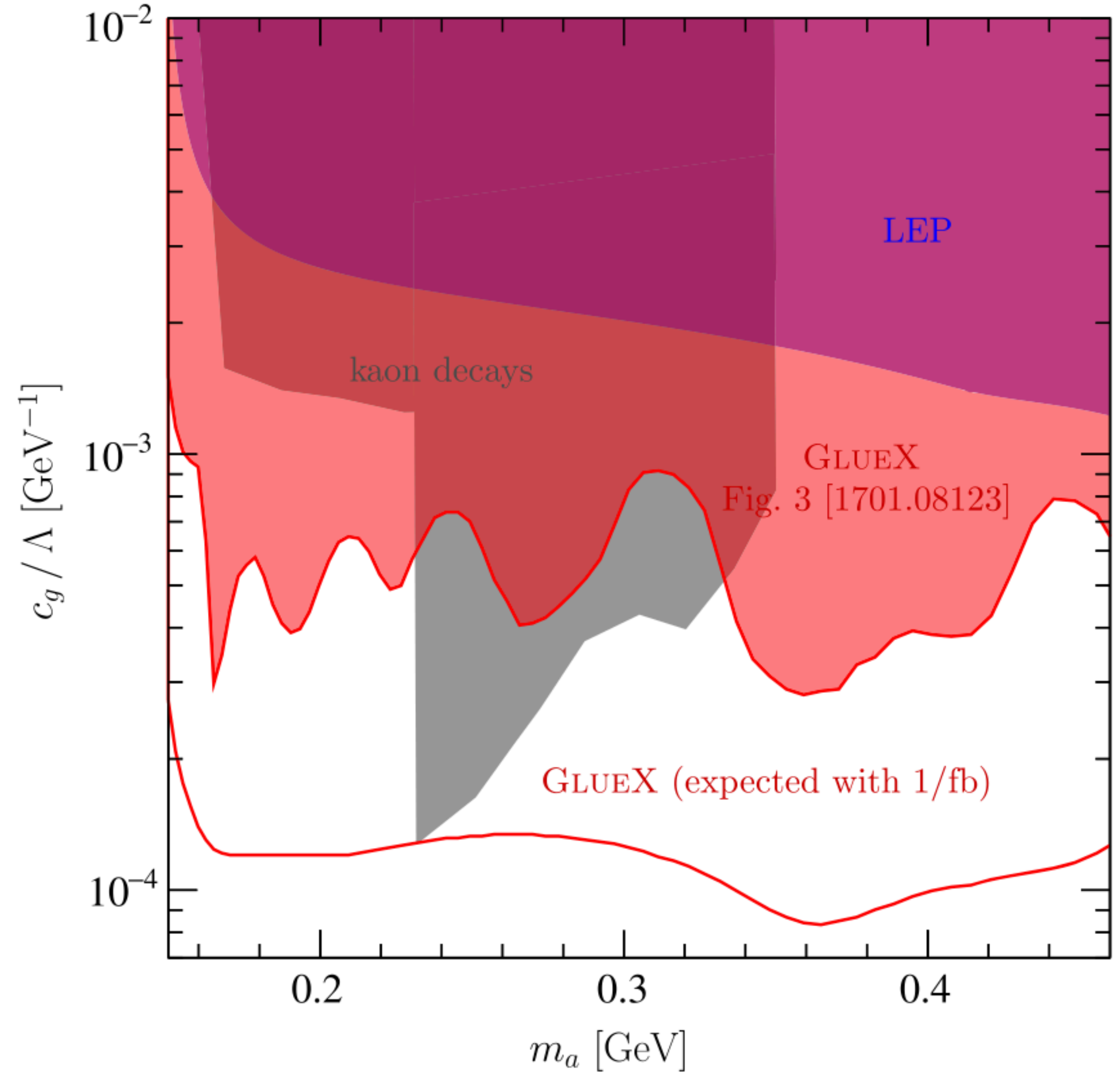
- SM contribution:
  - BR($\eta\to3\gamma$) <10^{-19} via P-violating weak interaction.
- Theoretical push?
  - A C- and T-violating, and P-conserving interaction was proposed by Bernstein, Feinberg and Lee. Phys. Rev.,139, B1650 (1965)
  - A calculation by Tarasov suggests: BR($\eta\to3\gamma$)< 10^{-2} 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

Key Channel: $\eta^{(\prime)} \to \pi\pi a$

- 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
  - $0.15 < m_a < 0.46$ GeV region



New limit is set using the published $m_{\gamma\gamma}$ spectrum from ≈1/pb of GLUEX data

PHYSICAL REVIEW LETTERS 123, 071801 (2019)

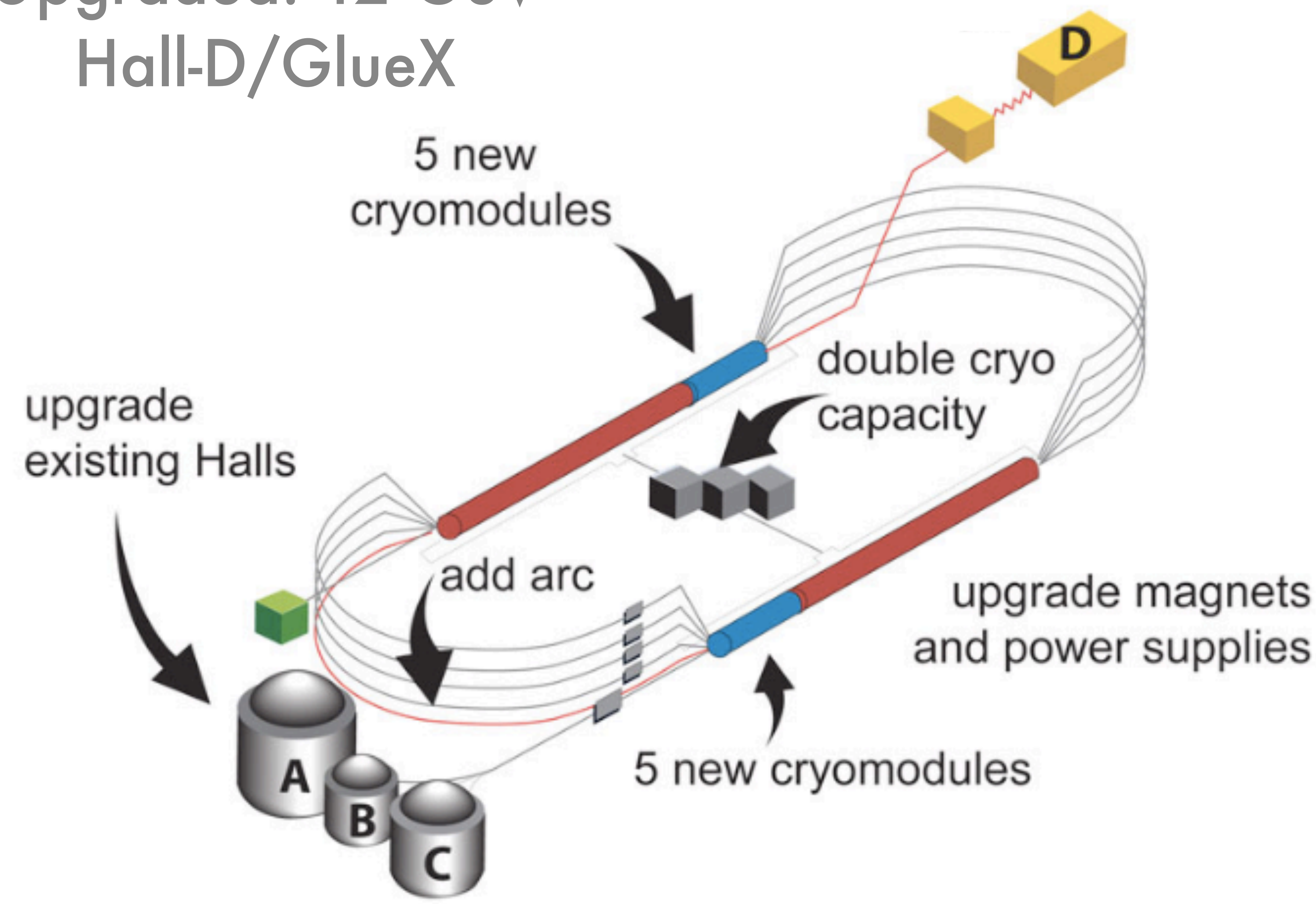
Jefferson Lab/GlueX/JEF

CEBAF

Upgraded: 12 GeV

Hall-D/GlueX

GlueX: exotic hybrids
& BSM,a.o.



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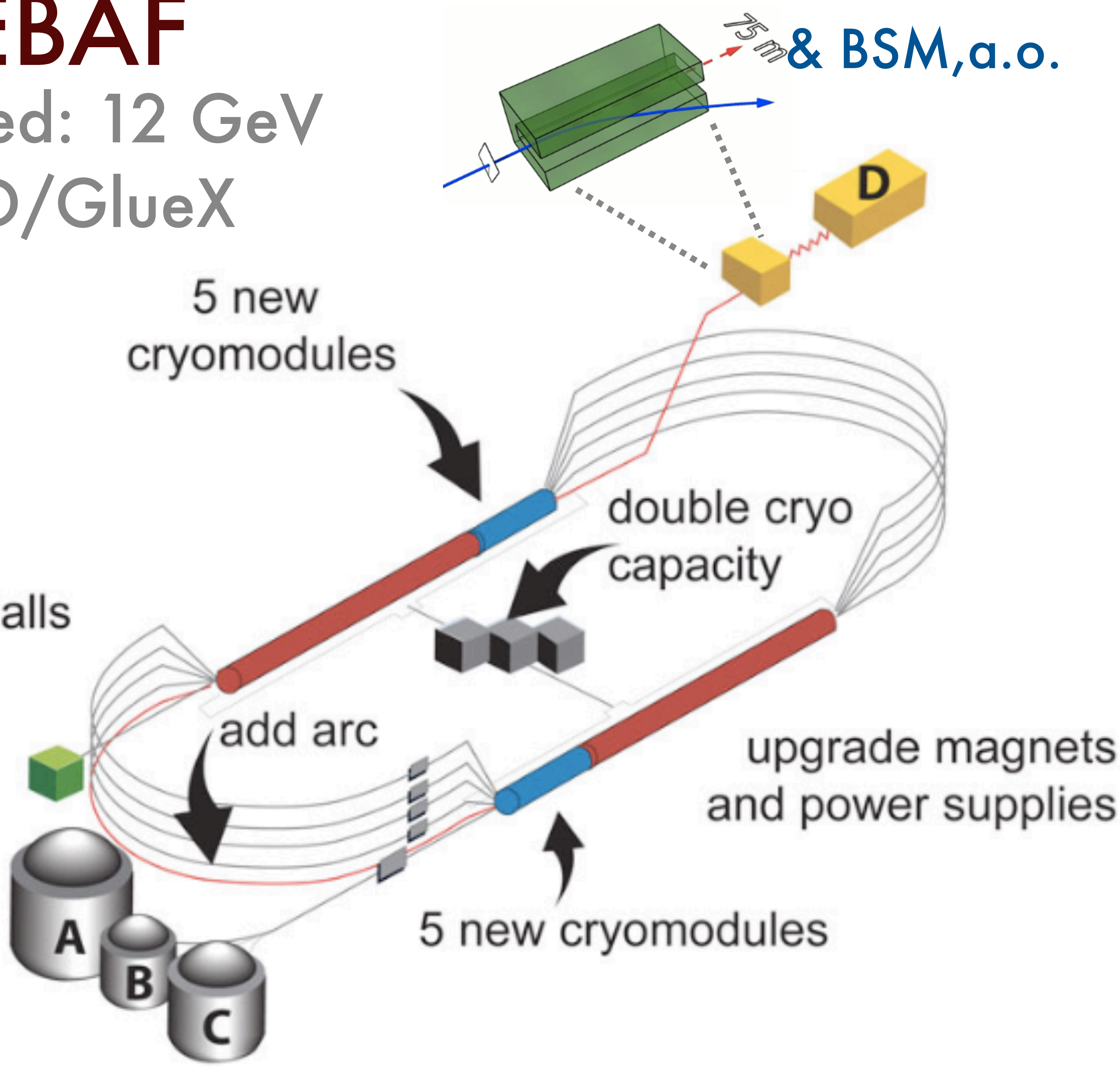

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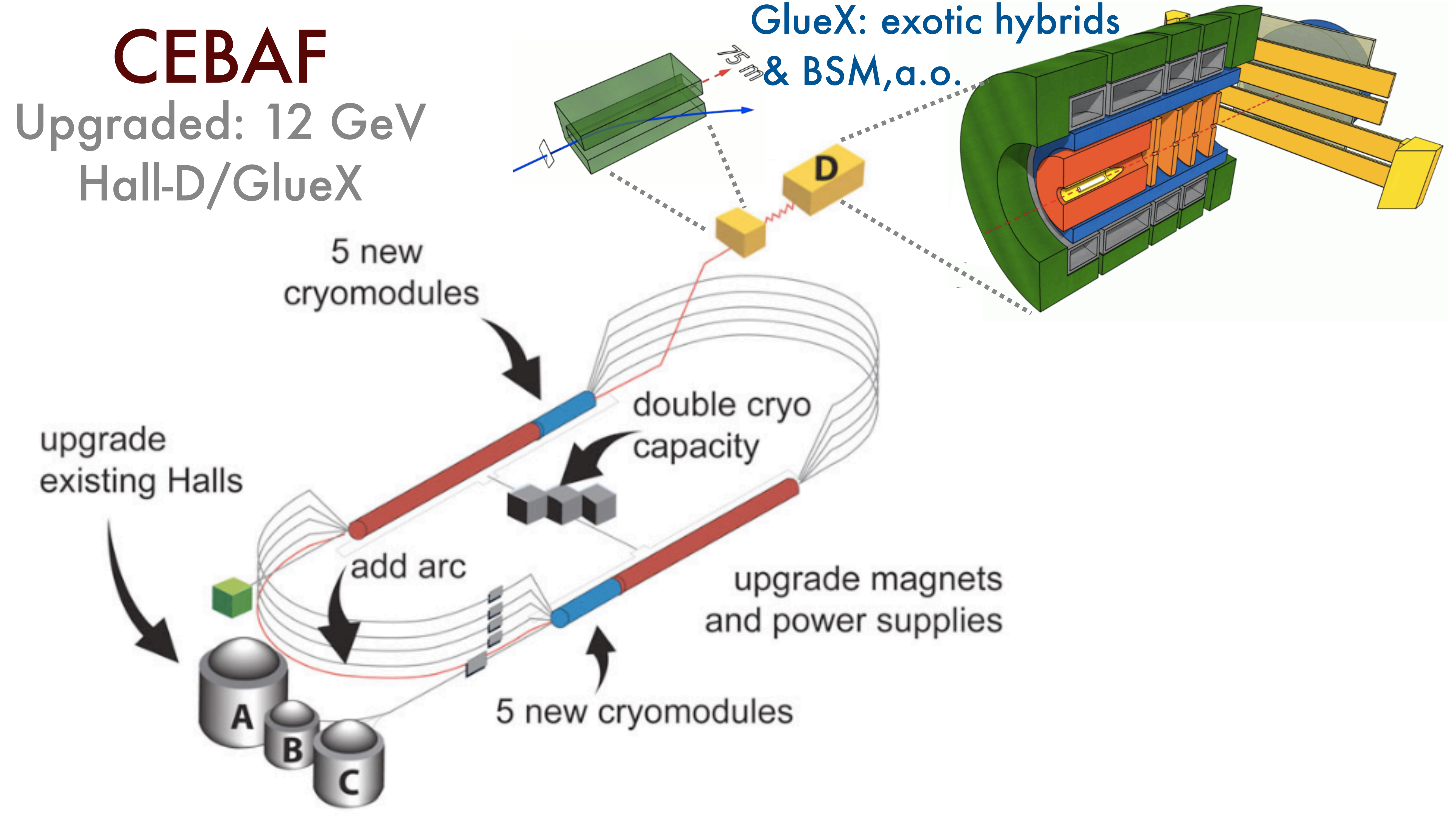

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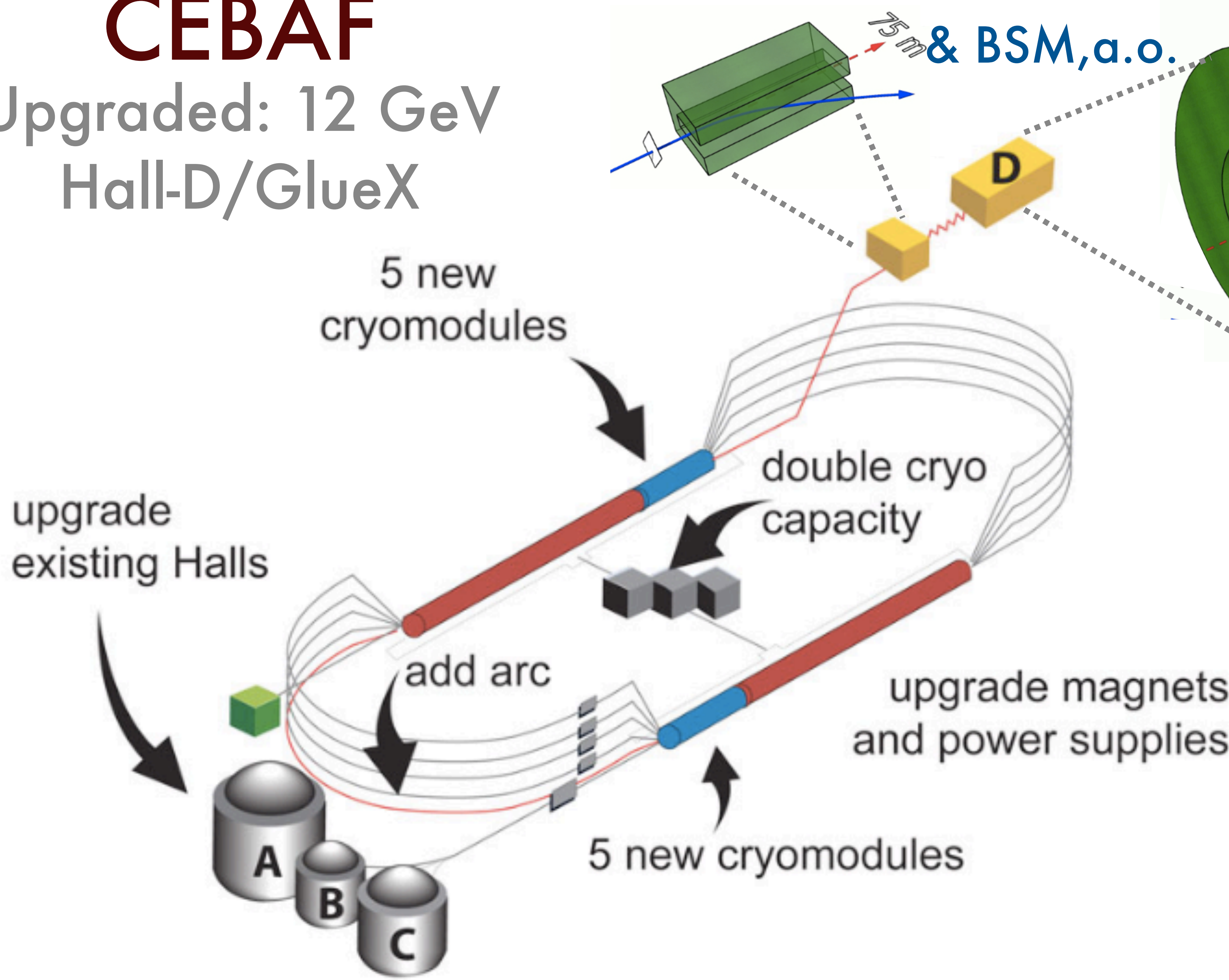
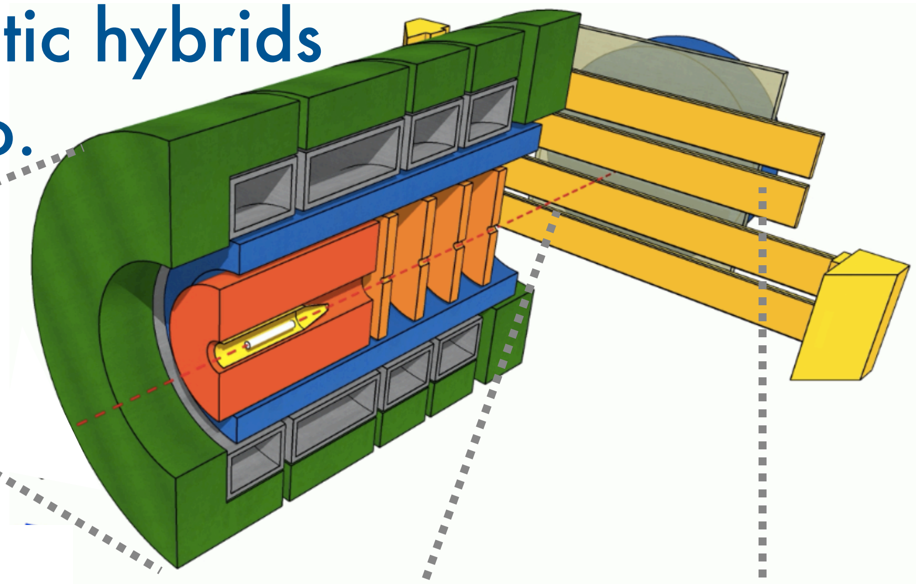
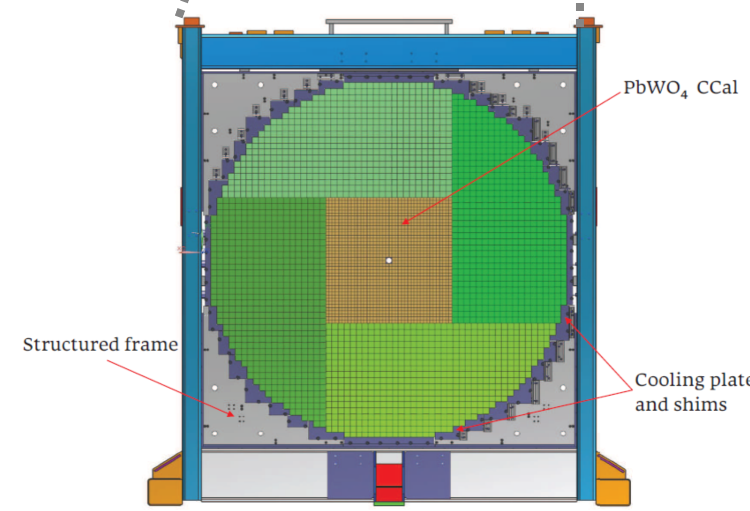
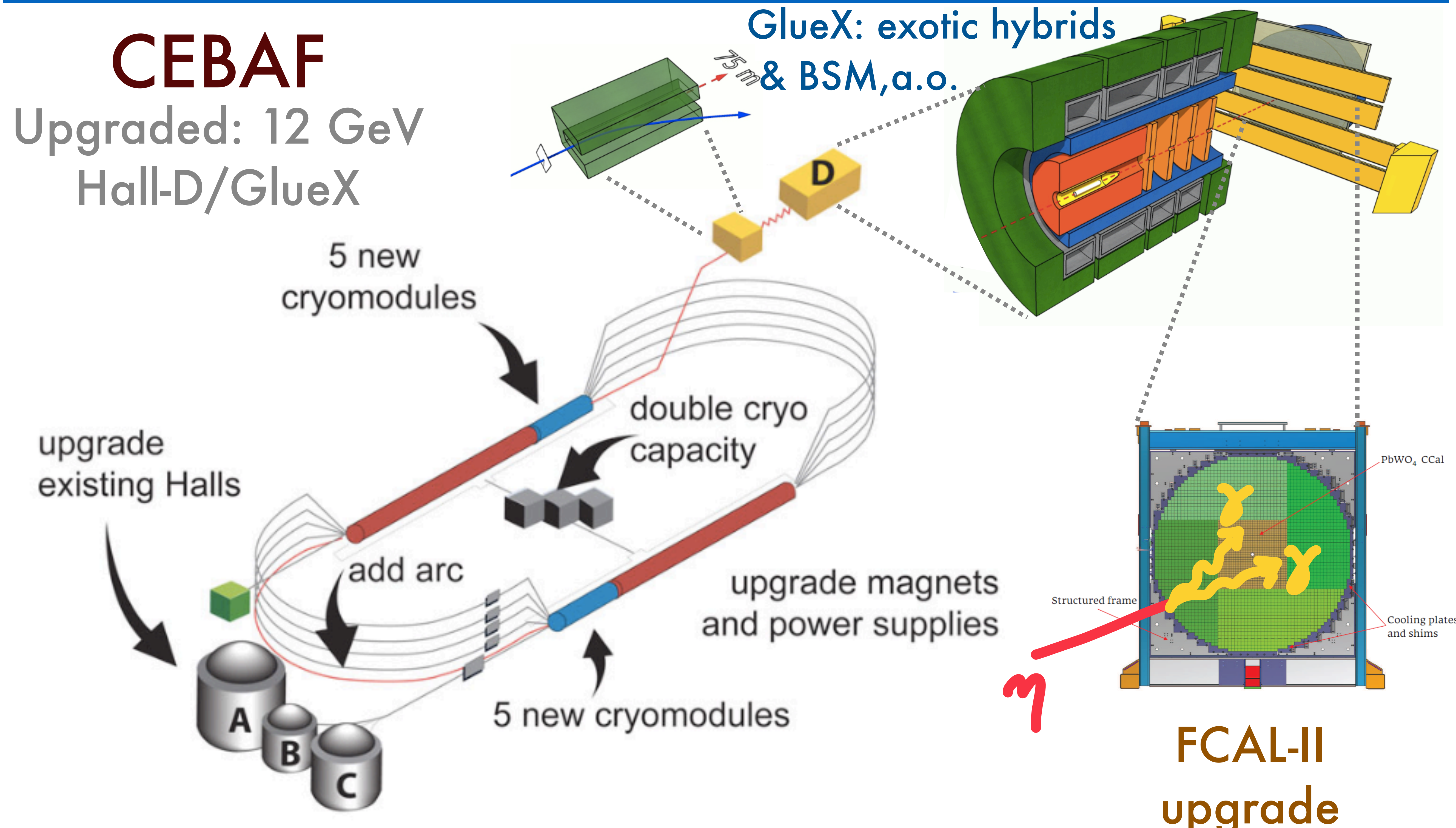






FCAL-II upgrade

Jefferson Lab/GlueX/JEF



Production Rates

JEF (100 days of beam)

	η	η'
Tagged mesons	6.5×10^7	4.9×10^7

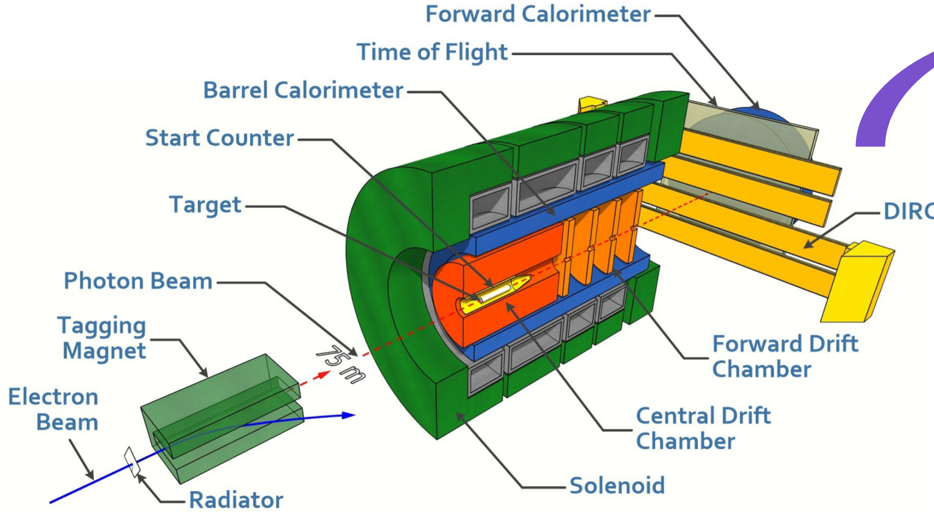
Previous Experiments

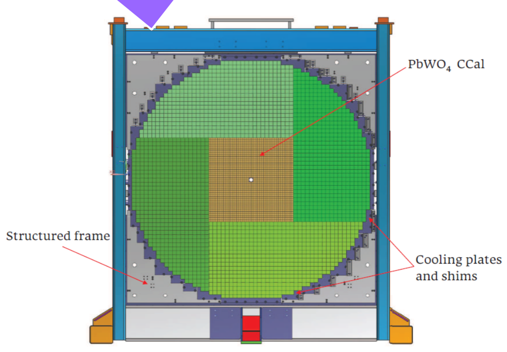
Experiment	**Total** η	**Total** η'
CB at AGS	10^7	-
CB MAMI-B	2×10^7	-
CB MAMI-C	6×10^7	10^6
WASA-COSY	$\sim3\times10^7$ (p+d), $\sim5\times10^8$ (p+p)	-
KLOE-II	3×10^8	5×10^5
BESIII	$\sim10^7$	$\sim5\times10^7$

JEF offers a competitive η/η' factory

(proposed REDTOP $10^{13}/10^{11}$ per year)

Key Features of JEF





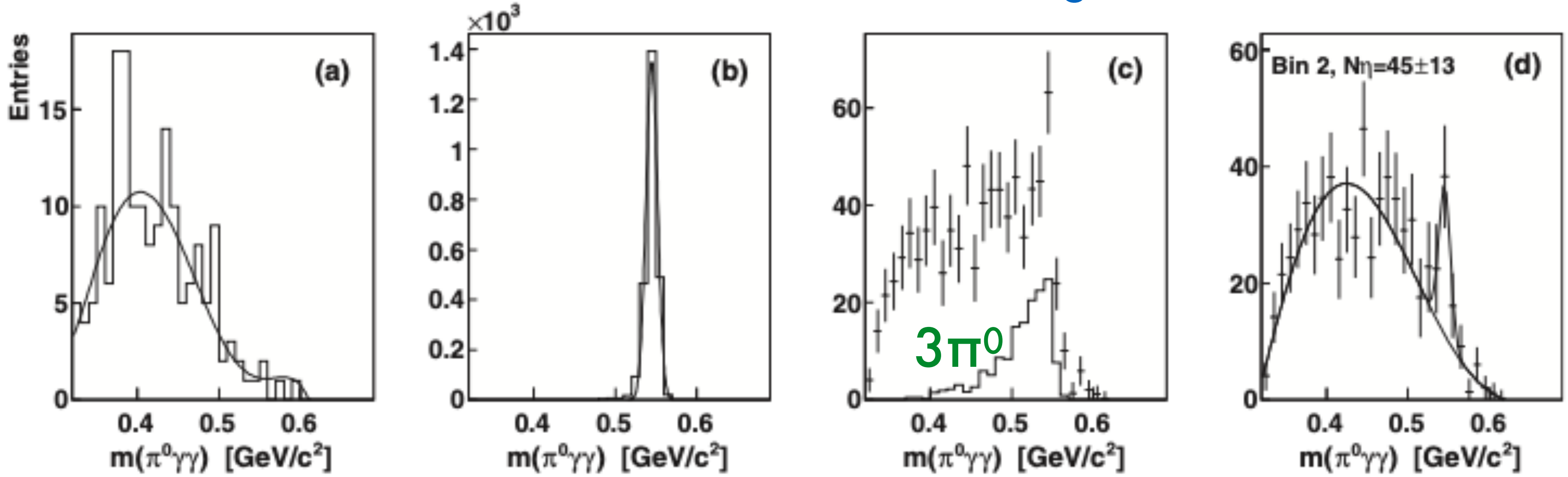
- η/η′ production: 8.4-11.7 GeV tagged γ beam; η, η′ energy boost
- produce & detect η/η′ simultaneously; exclusive channels

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

- Reduce non-coplanar backgrounds by detecting recoil protons with the GlueX detector.
- Upgraded FCAL-II with 40x40 crystal (80x80cm^2) lead tungstate ($PbWO_4$) insert for improved resolution and superior granularity.

Boost & Background

MC $2\pi^0$ | MC $\pi^0\gamma\gamma$ | Rndm Bkdg out | $3\pi^0$ subtracted

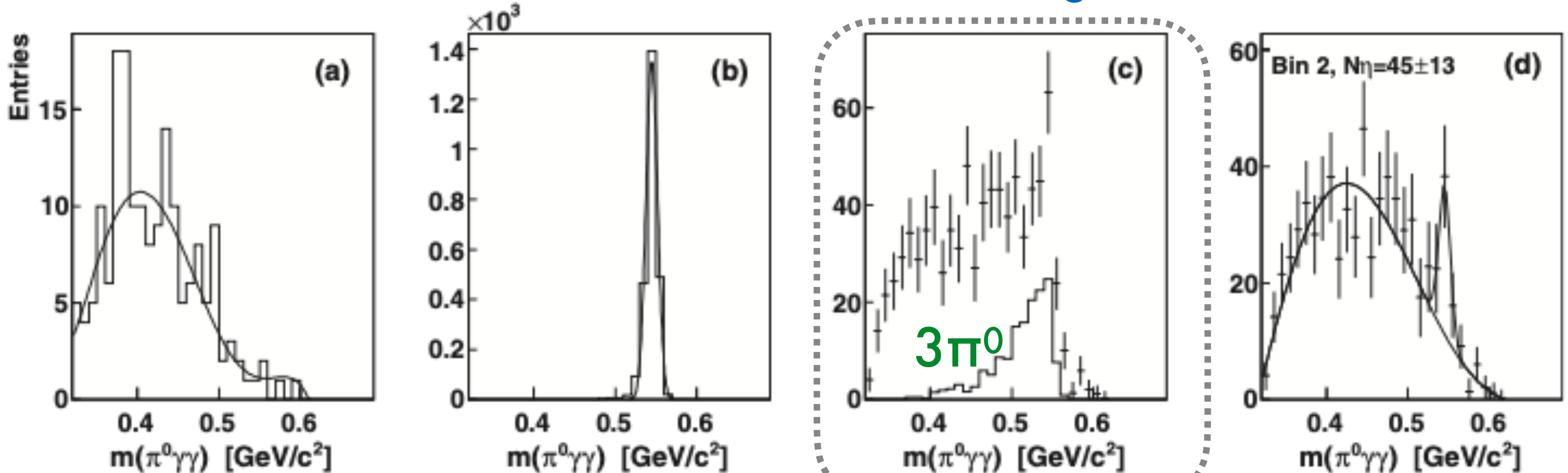


BR=2.7×10^{-4}

Nefkens, PRC90, 025206

Boost & Background

MC $2\pi^0$ | MC $\pi^0\gamma\gamma$ | Rndm Bkdg out | $3\pi^0$ subtracted



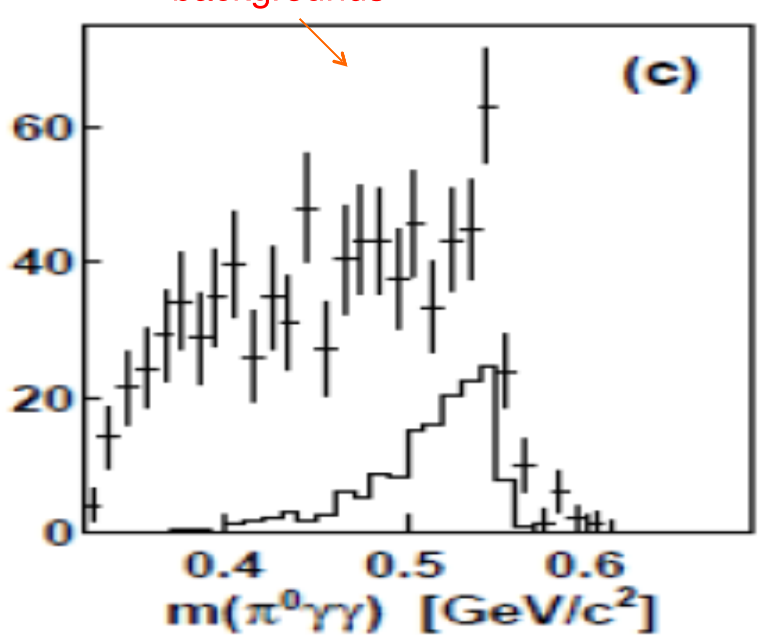
BR=2.7×10^{-4}

Nefkens, PRC90, 025206

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

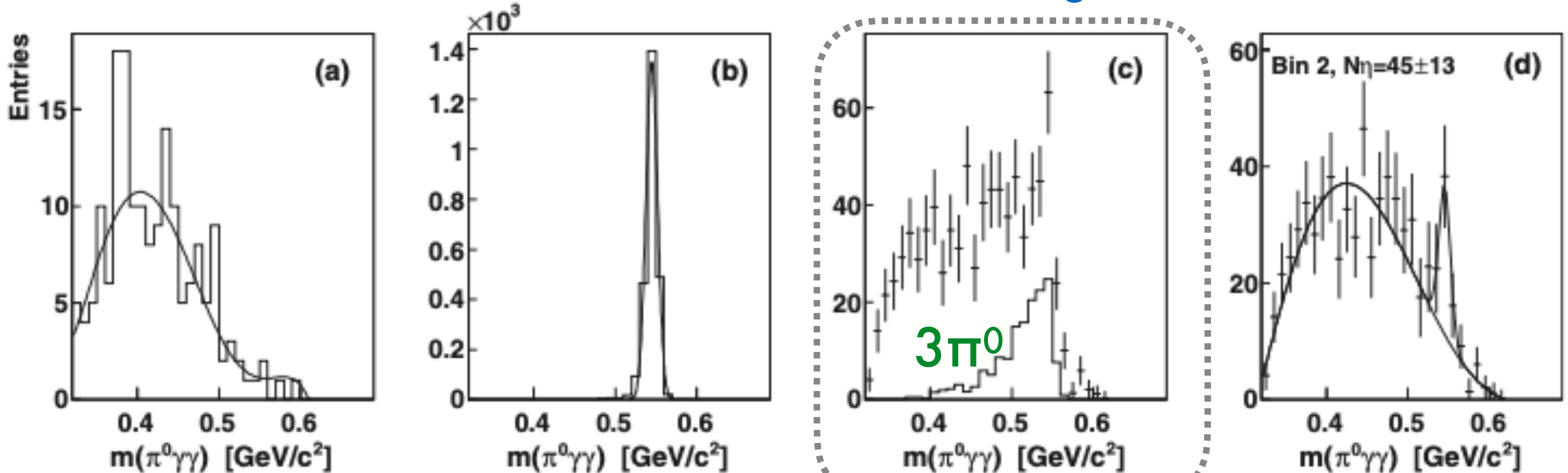
(P.R. C90, 025206)

backgrounds



Boost & Background

MC $2\pi^0$ | MC $\pi^0\gamma\gamma$ | Rndm Bkdg out | $3\pi^0$ subtracted



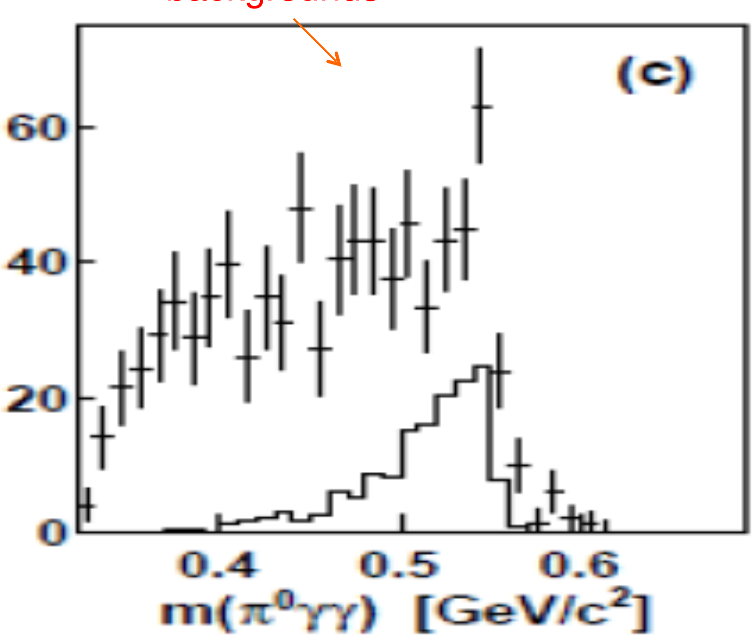
BR=2.7x10^{-4}

Nefkens, PRC90, 025206

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

(P.R. C90, 025206)

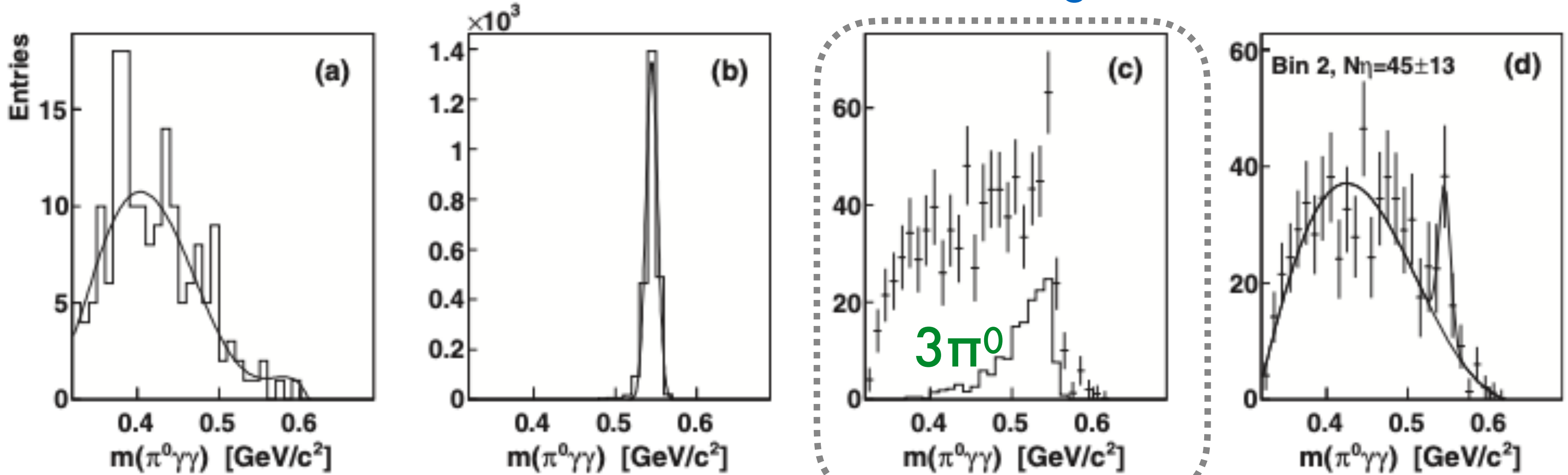
backgrounds



simulation

Boost & Background

MC $2\pi^0$ | MC $\pi^0\gamma\gamma$ | Rndm Bkdg out | $3\pi^0$ subtracted

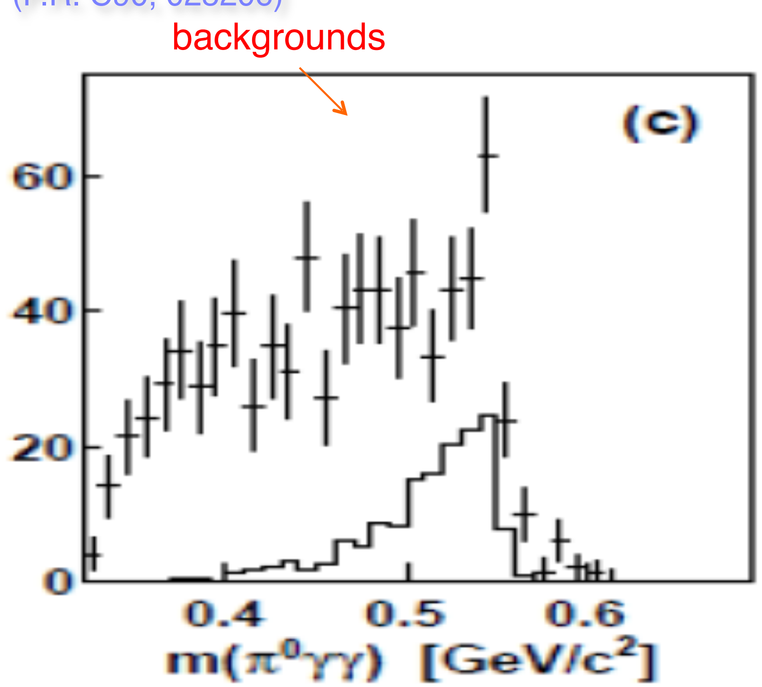


BR=2.7x10^{-4}

Nefkens, PRC90, 025206

A2 at MAMI: $\gamma p \rightarrow \eta p$ (E_γ=1.5 GeV)

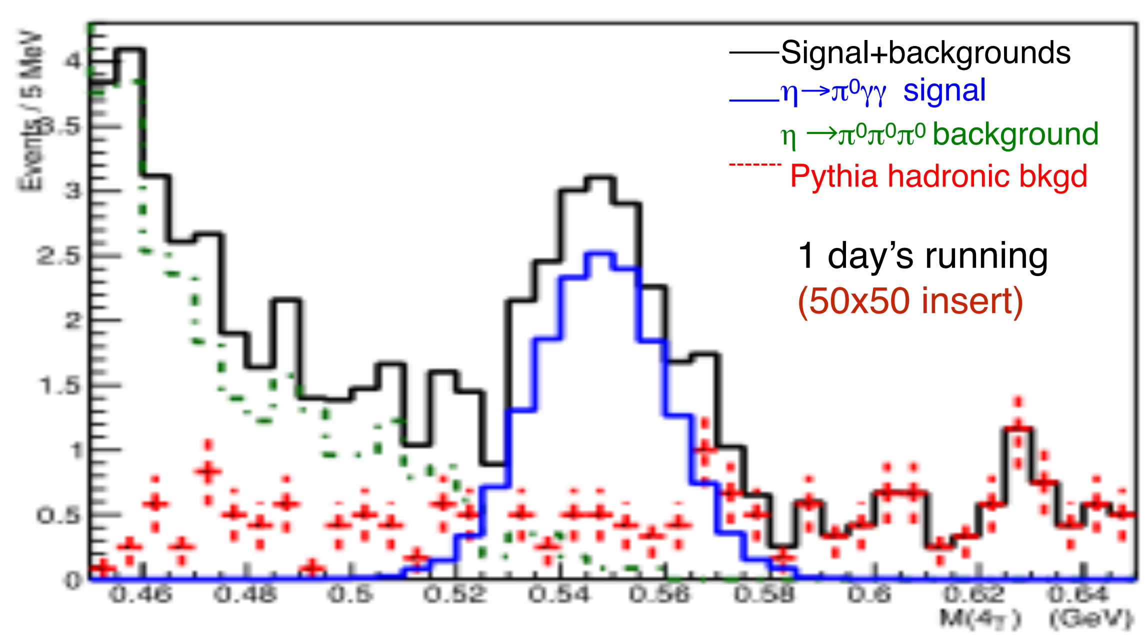
(P.R. C90, 025206)



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

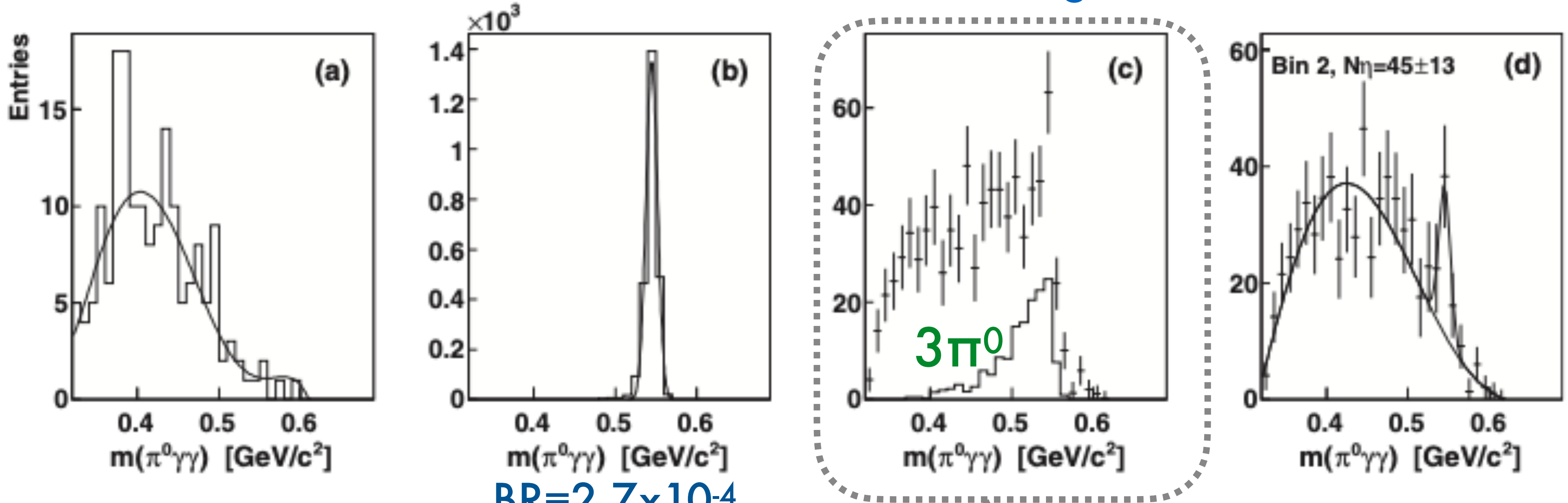
N (PWO) > 2

simulation



Boost & Background

MC $2\pi^0$ | MC $\pi^0\gamma\gamma$ | Rndm Bkdg out | $3\pi^0$ subtracted



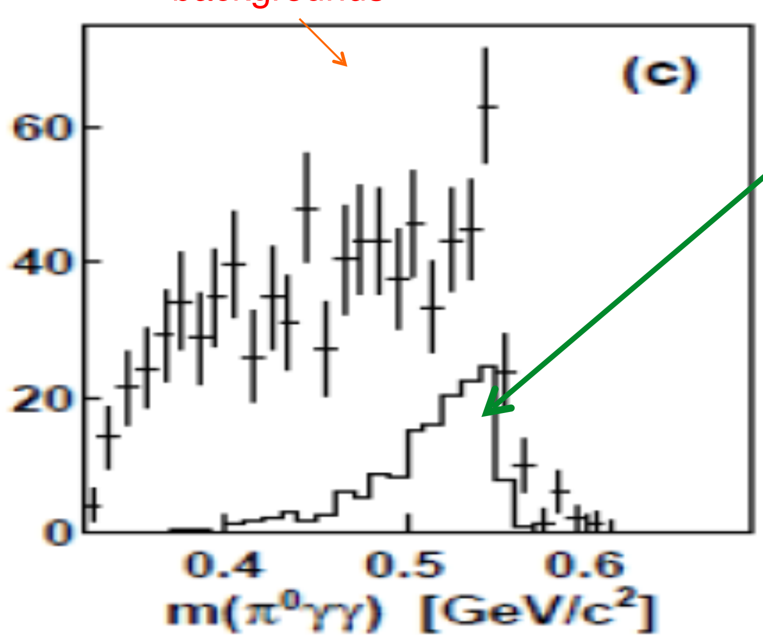
BR=2.7x10-4

Nefkens, PRC90, 025206

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

(P.R. C90, 025206)

backgrounds

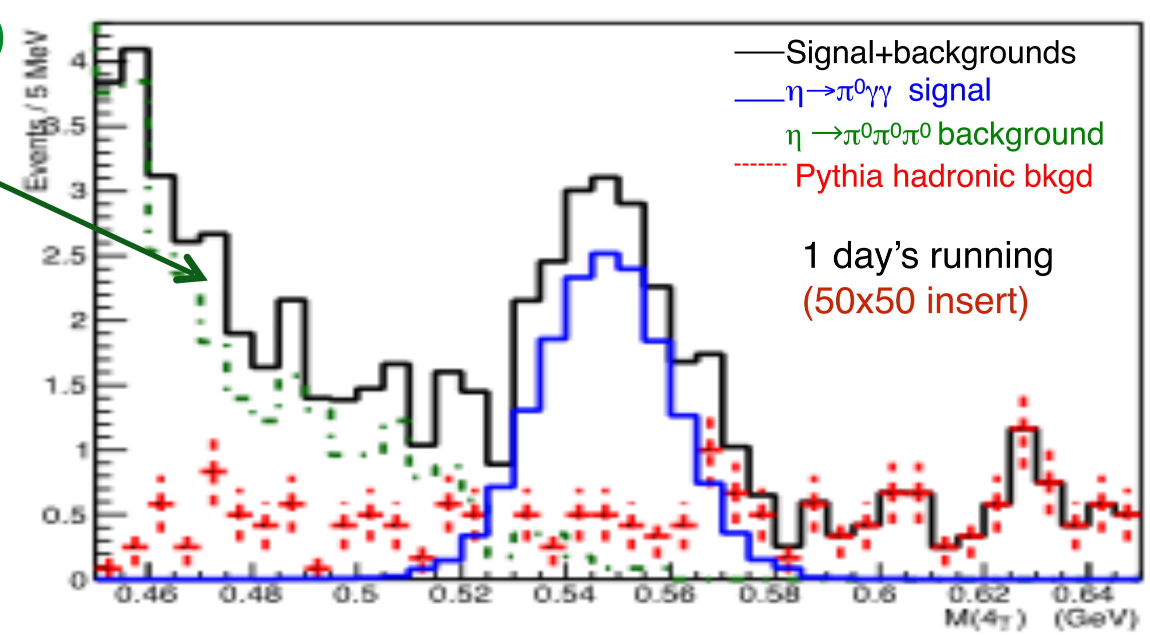


$\eta \to 3\pi^0$

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

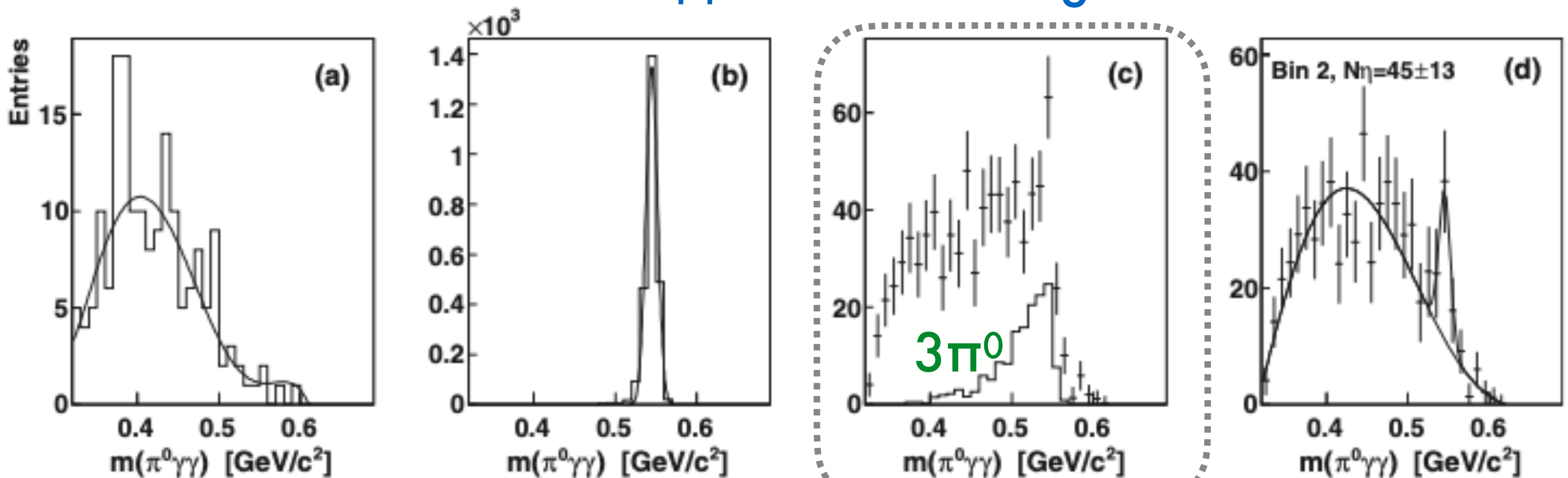
N (PWO) > 2

simulation



Boost & Background

MC $2\pi^0$ | MC $\pi^0\gamma\gamma$ | Rndm Bkdg out | $3\pi^0$ subtracted



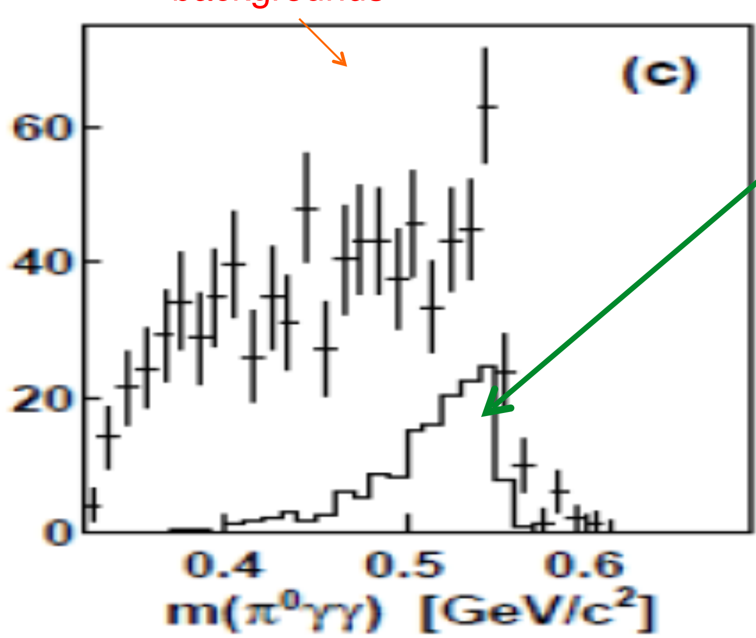
Nefkens, PRC90, 025206

BR=2.7x10^{-4}

A2 at MAMI: $\gamma p \rightarrow \eta p$ (E_γ=1.5 GeV)

(P.R. C90, 025206)

backgrounds

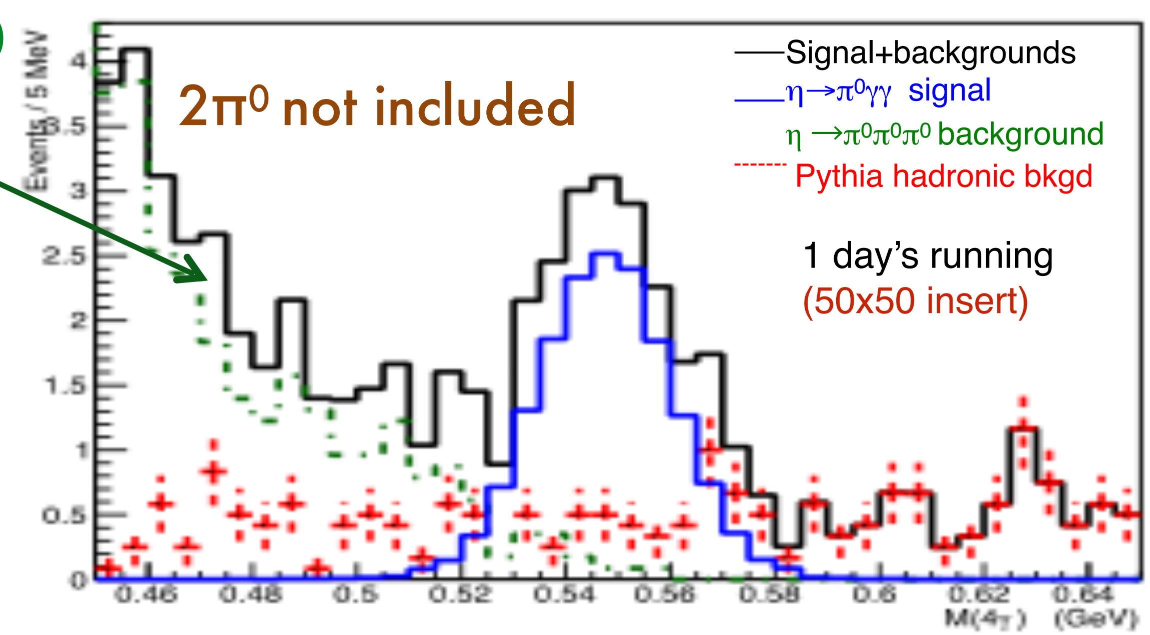


$\eta \rightarrow 3\pi^0$

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

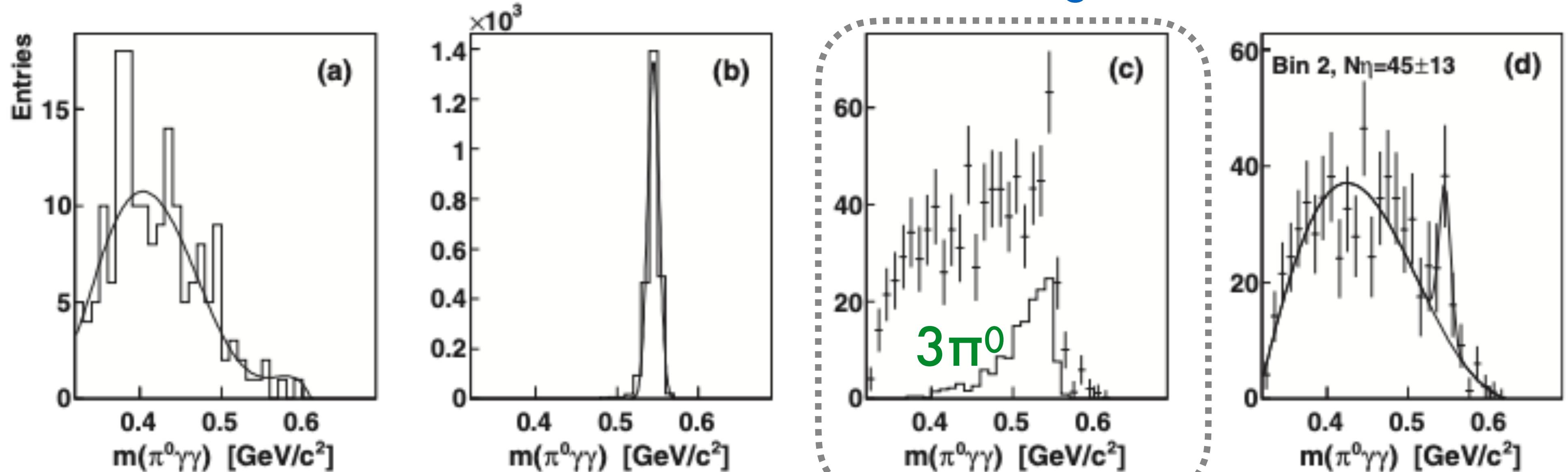
N (PWO) > 2

simulation



Boost & Background

MC $2\pi^0$ | MC $\pi^0\gamma\gamma$ | Rndm Bkdg out | $3\pi^0$ subtracted

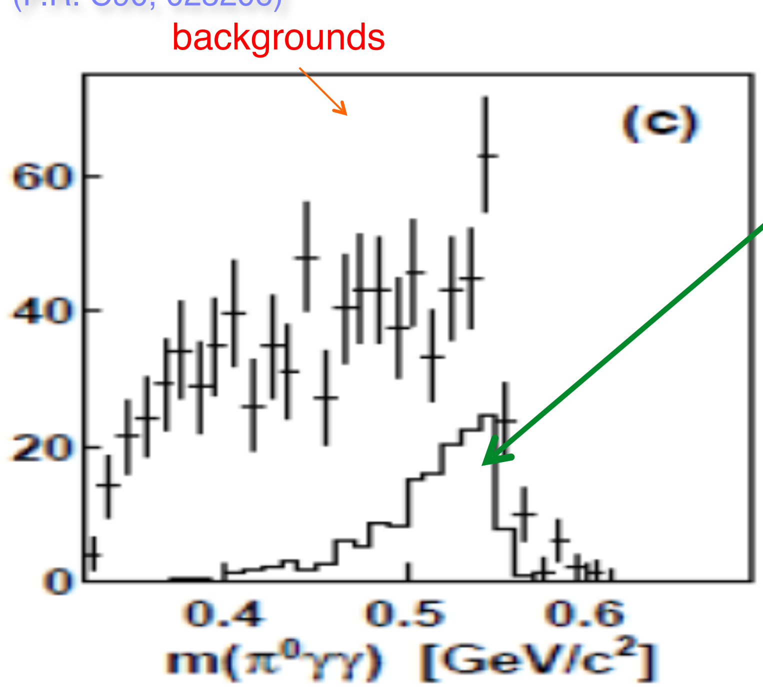


Nefkens, PRC90, 025206

BR=2.7×10^{-4}

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

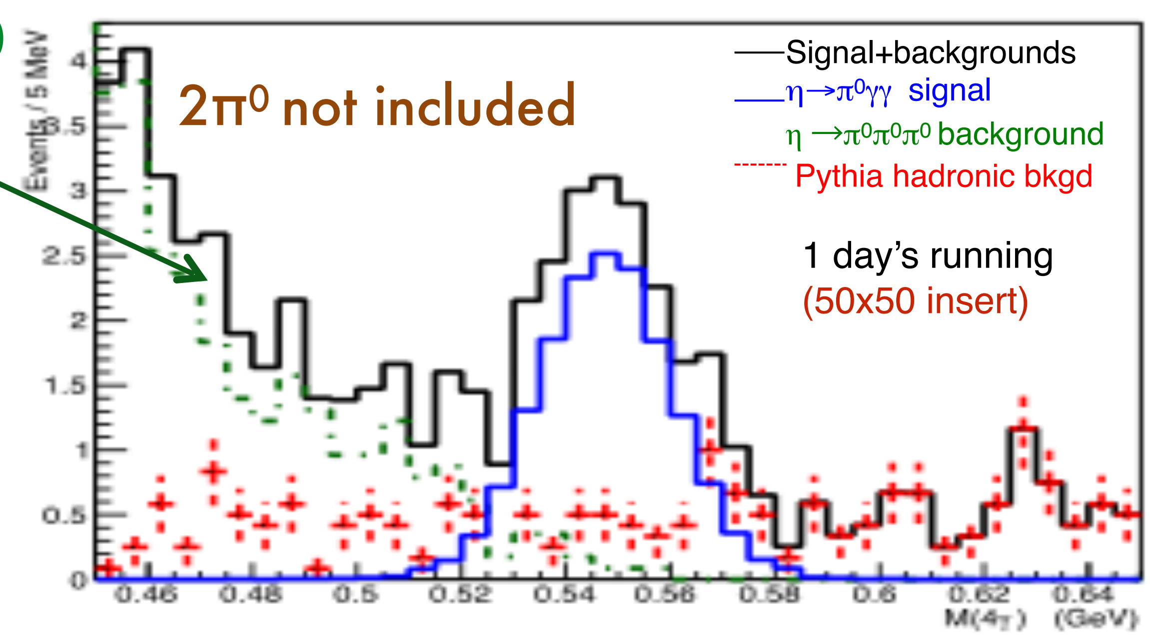
(P.R. C90, 025206)



$\eta \to 3\pi^0$

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

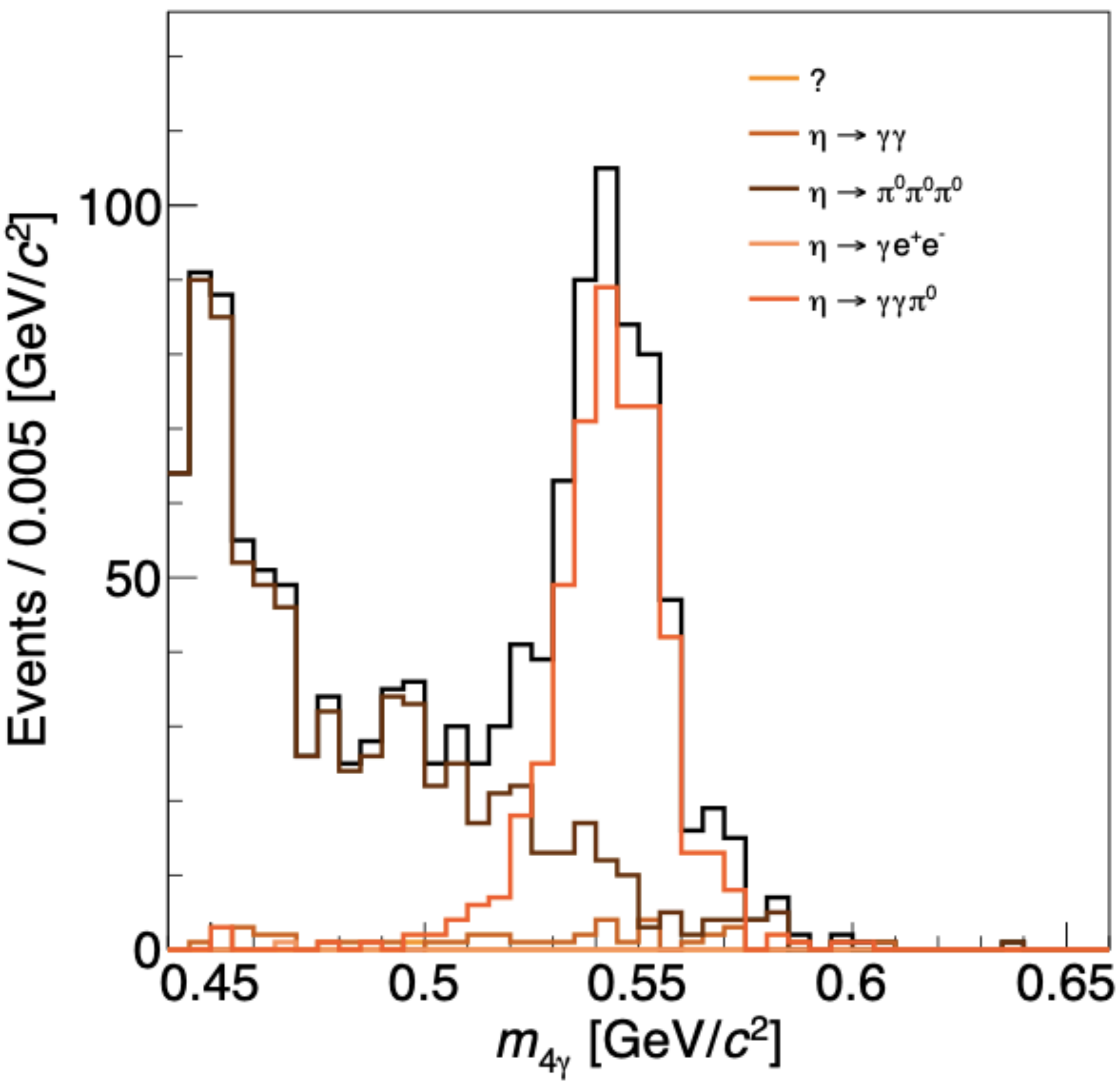
simulation



ca. 2020

Simulations

40x40 insert



Non-peaking $\eta \to \gamma\gamma$ and $\eta \to \pi^0\pi^0\pi^0$ backgrounds

I.Jaegle, T. Beattie

Selection Criteria

- Default ReactionFilter selection criteria applied +
- 4 neutrals and 1 track in sync. with RF
- Track originates from within the target
- 1 photon pair with invariant mass corresponding to π^0
- Other pair of bachelor photons with invariant mass outside π^0-window
- Masking $\pi^0\pi^0$, $\pi^0\eta$, $\eta\eta$ events
- 4 neutrals in FCAL and 1 in insert
- $d_\gamma^{\pi^0} \geq 100$ cm

May 2022

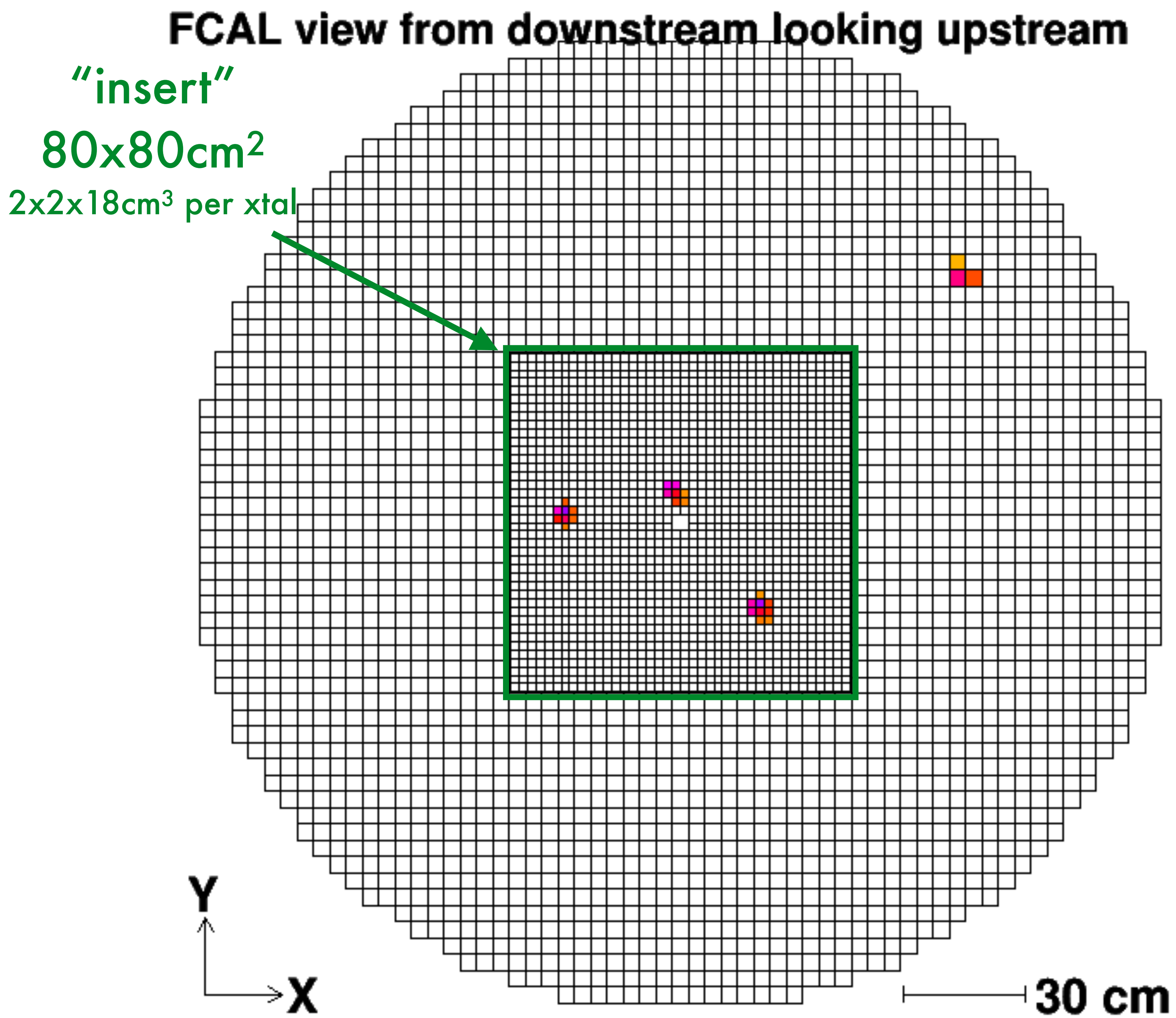
Many photons

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

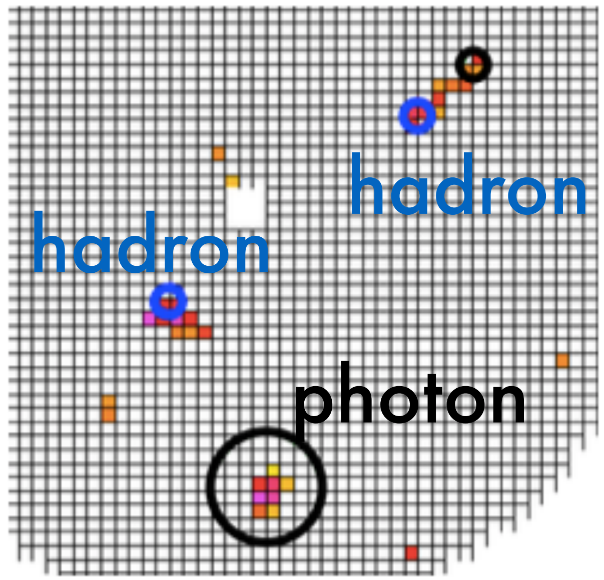
Simulated $\eta \rightarrow \pi^0\gamma\gamma$ event

S. Taylor

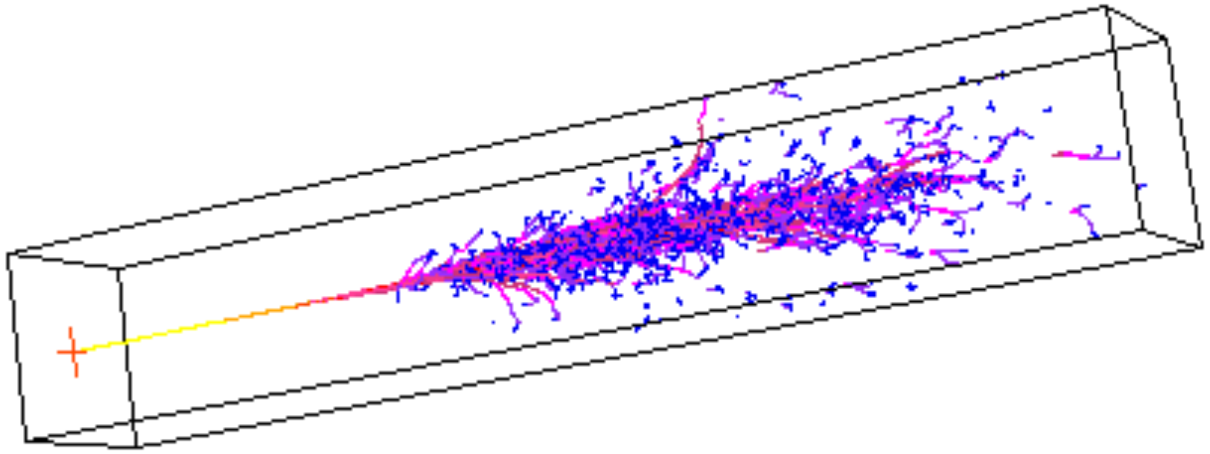


Property	Improvement factor
Energy σ	2
Position σ	2
Granularity	4
Radiation-resistance	10

algorithms: Default/Island and Machine Learning



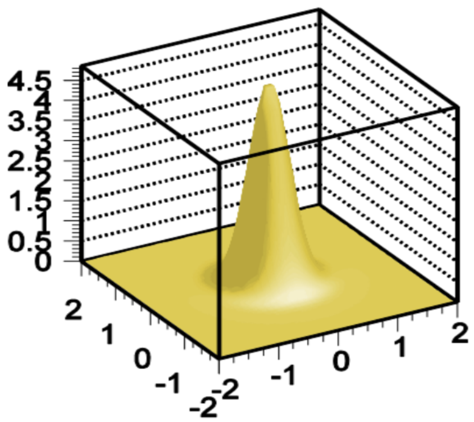
Distinguishing Reconstructed Photon Showers



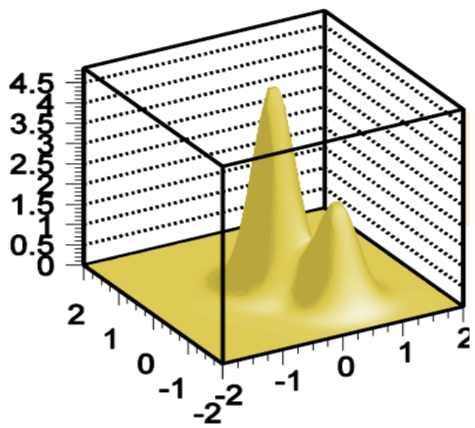
Single volume shower

E-M Shower Simulator, mpp.mpg.de

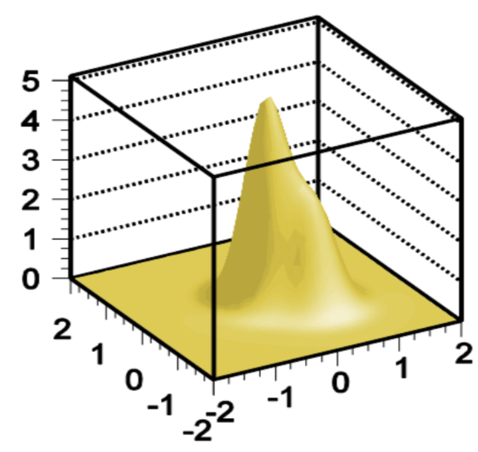
- Showers fire multiple FCAL blocks: clusters
- Photons with small angular separation can look like a single photon on the FCAL
- FCAL-II has improved granularity
- Study limits of separation in FCAL-II



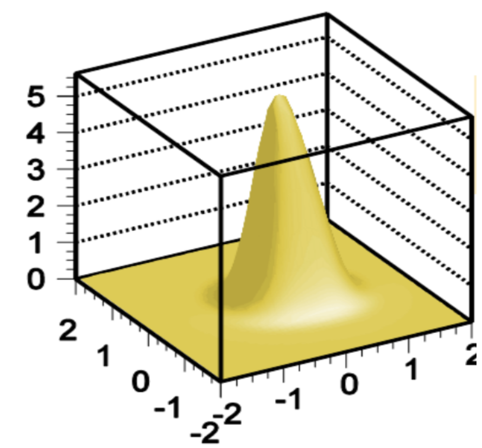
Single cluster



Two clusters produce two maxima



Two clusters that do not produce two maxima but can be distinguished



Two Indistinguishable clusters

I. Larin, JLab

Photon Separation

Clusterizer & Reconstruction:

- GlueX Default Reconstruction Algorithm adapted from RADPHI
- Island Algorithm adapted from GAMS

Performance of the RADPHI detector and trigger in a high rate tagged photon beam

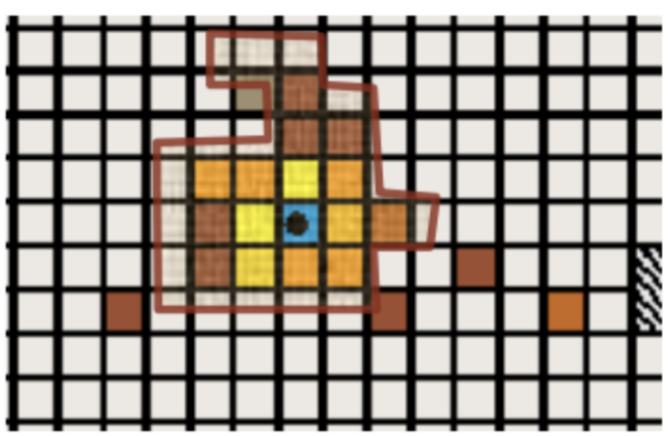
R.T. Jones[a,1], T. Bogue[a,2], B.E. Evans[a], M. Kornicer[a], A.R. Dzierba[b], R. Gardner[b,3], J.L. Gunter[b,4], D. Krop[b], R. Lindenbusch[b], D.R. Rust[b], E. Scott[b], P. Smith[b], C. Steffen[b,5], S. Teige[b,*], D.S. Armstrong[c], J.H.D. Clark[c,6], L.J. Kaufman[c,7], D.J. Steiner[c], E. Frlez[d], D. Pocanic[d], J.J. Kolata[e], L.O. Lamm[e], G. Rogachev[e], C. Campbell[f], E. Collins[f], L. McGlinchey[f], P. Rubin[f,8,9], E. Walker[f], G.S. Adams[g], J. Napolitano[g], H. Crannell[h], D.I. Sober[h], R.R. Mammei[i,10], E.S. Smith[i]

NIM A 570 (2007) 384-398

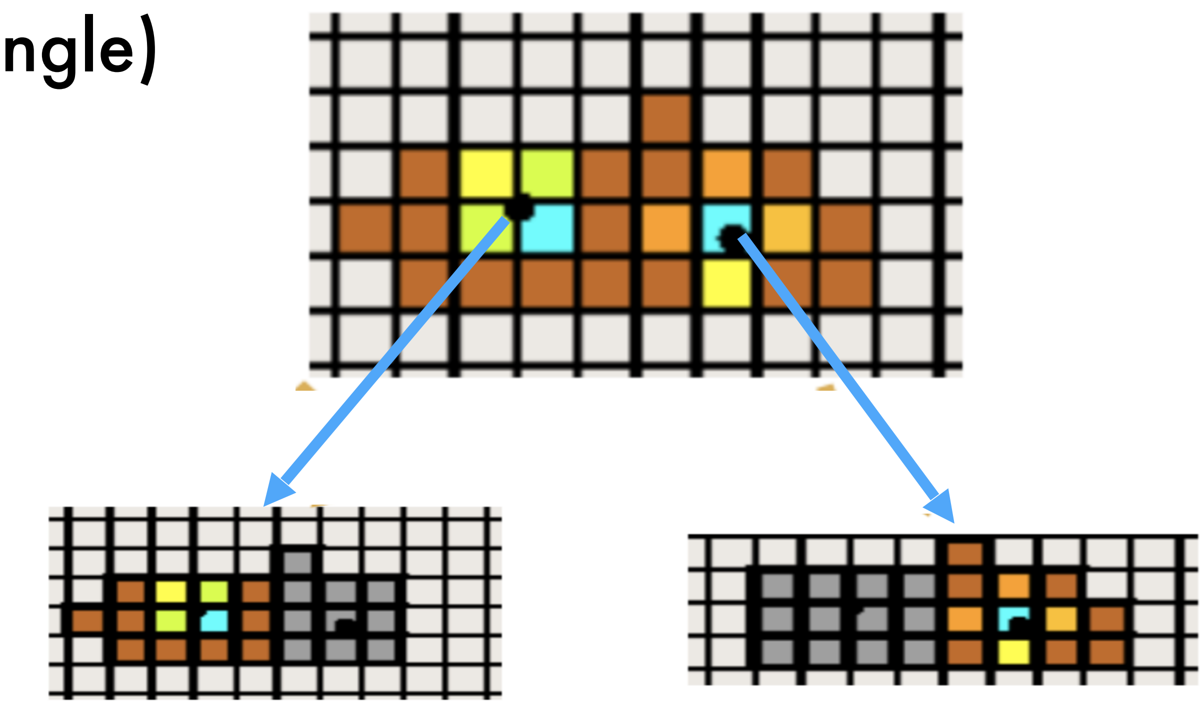
A. A. Lednev, IHEP preprint 93-153
Bland, et al., Instruments and Experimental Techniques 51(2008) 342-350.

Tasks:

- COG-weighted vs LOG-weighted
- evaluate as f(energy, photon opening angle)
- deploy Machine Learning (ML)



Single photon candidate



Two photon candidate

I. Larin, JLab

ML: Photon Vs Background Classification

Type 0 : True photon showers

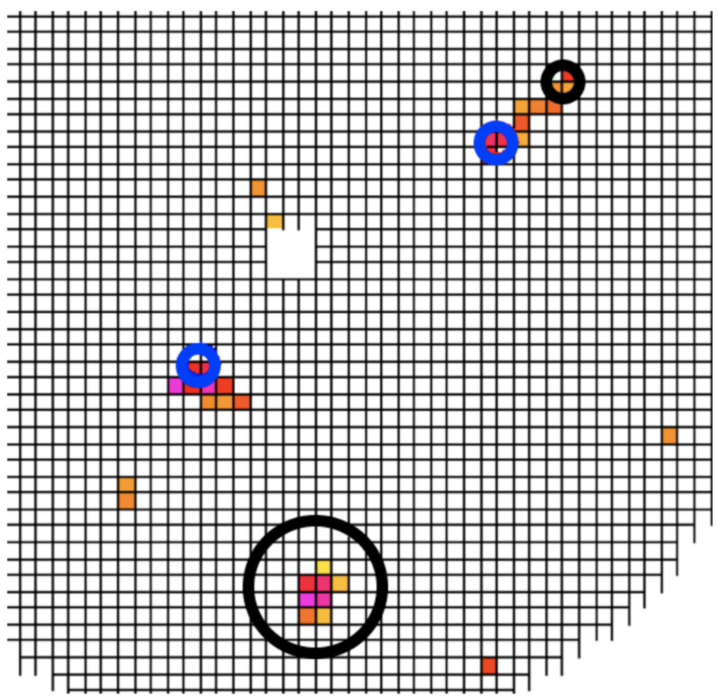
Type 1: Showers from charged particles

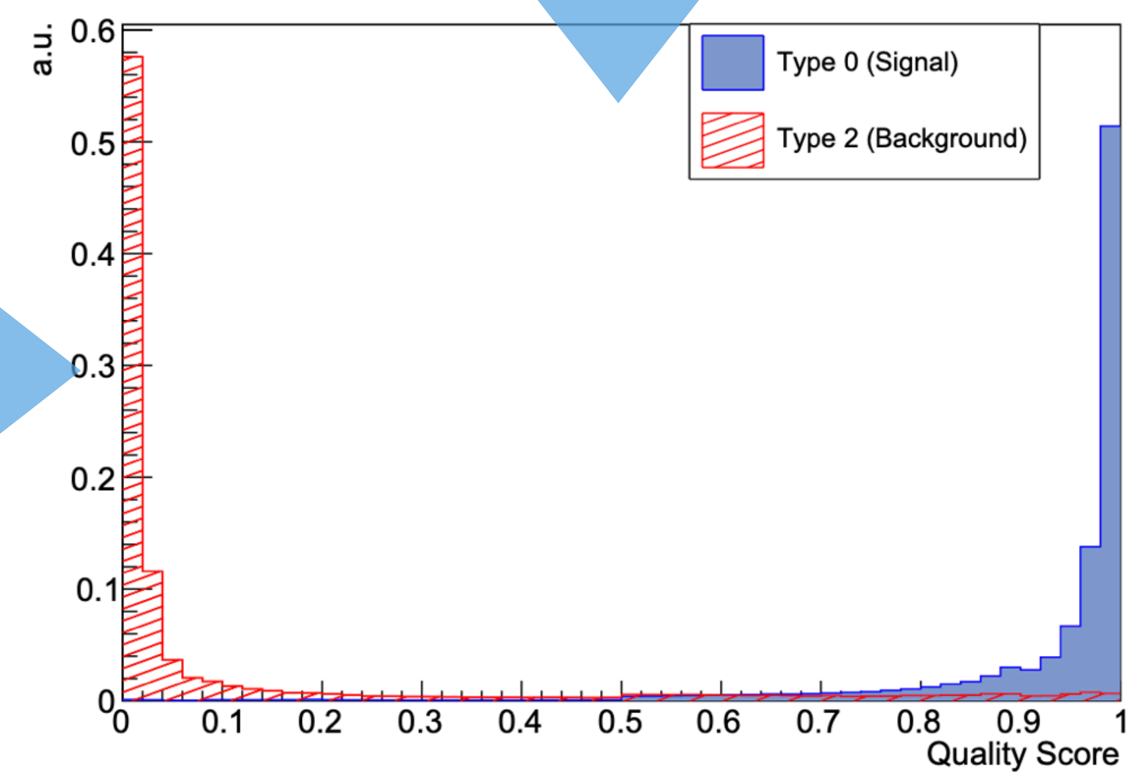
Type 2: All others: split-offs from Type 1, bkdg, …

Use Machine Learning

Photon Candidate

Charged Hadron Candidate





Using machine learning to separate hadronic and electromagnetic interactions in the GlueX forward calorimeter

R. Barsotti[1] and M.R. Shepherd[1]

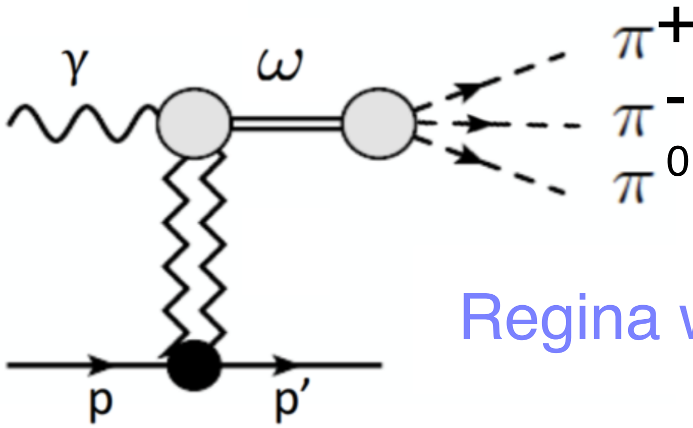
Published 27 May 2020 • © 2020 IOP Publishing Ltd and Sissa Medialab
Journal of Instrumentation, Volume 15, May 2020

JINST 15 P05021

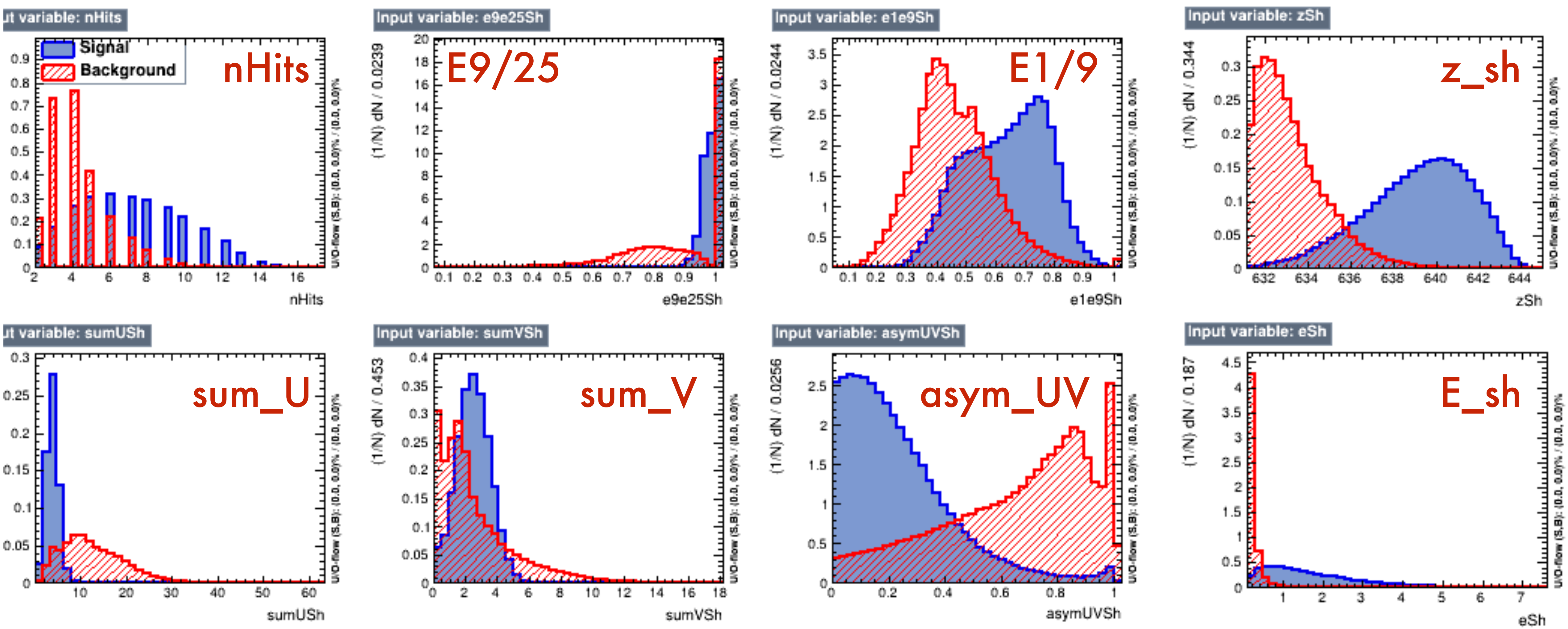
ML: Photon Vs Background Classification

- Machine Learning: binary classification
- Multivariate analysis: combined discriminating power from all key variables

Omega decays

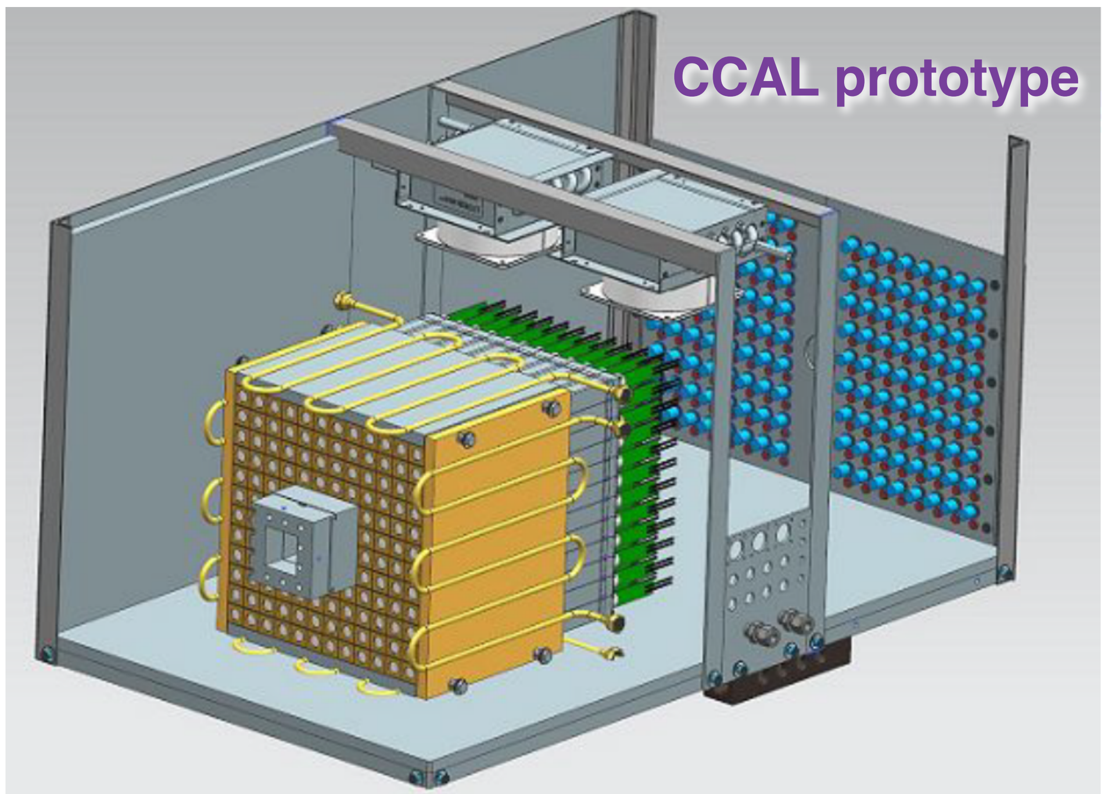


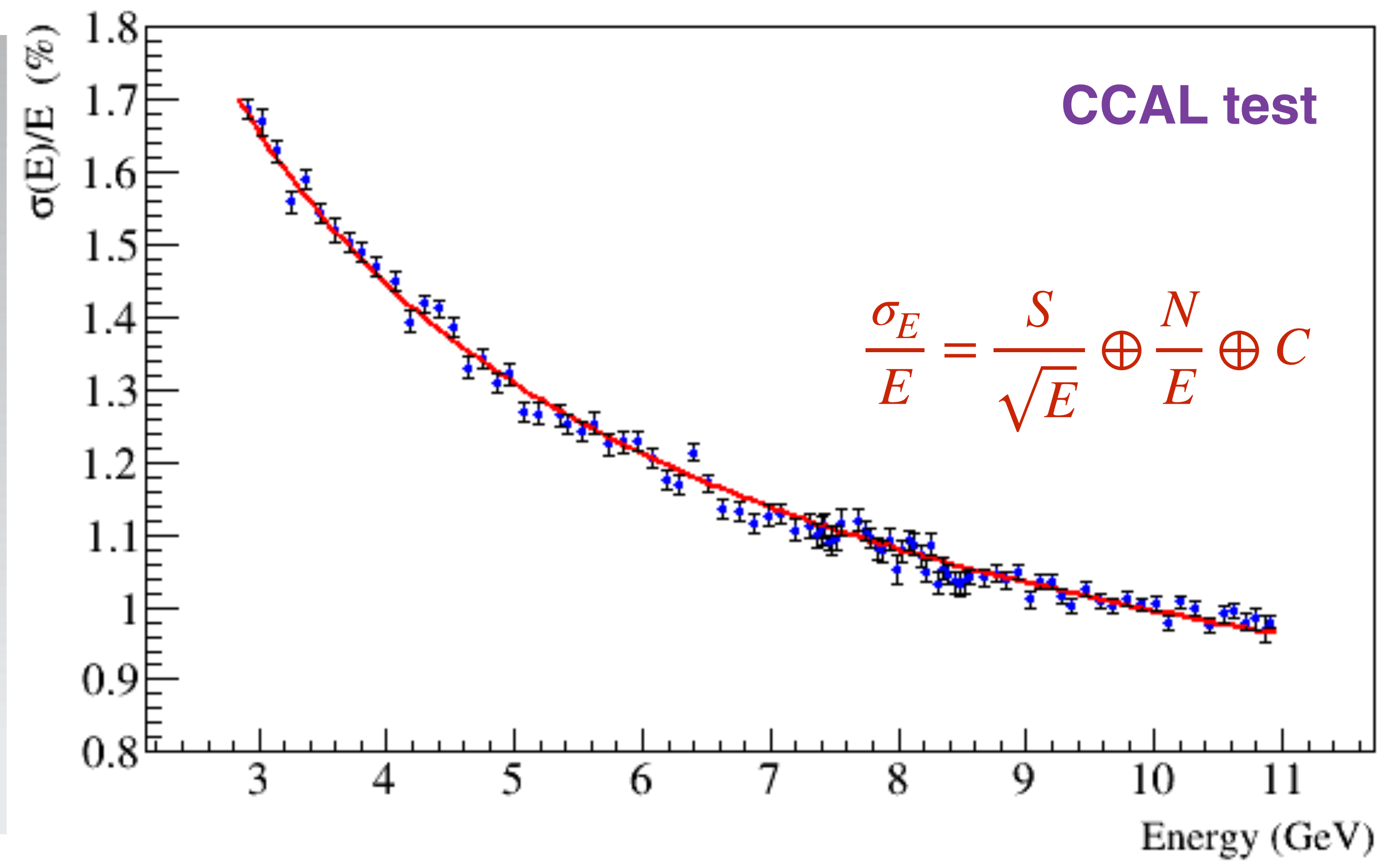
Regina work

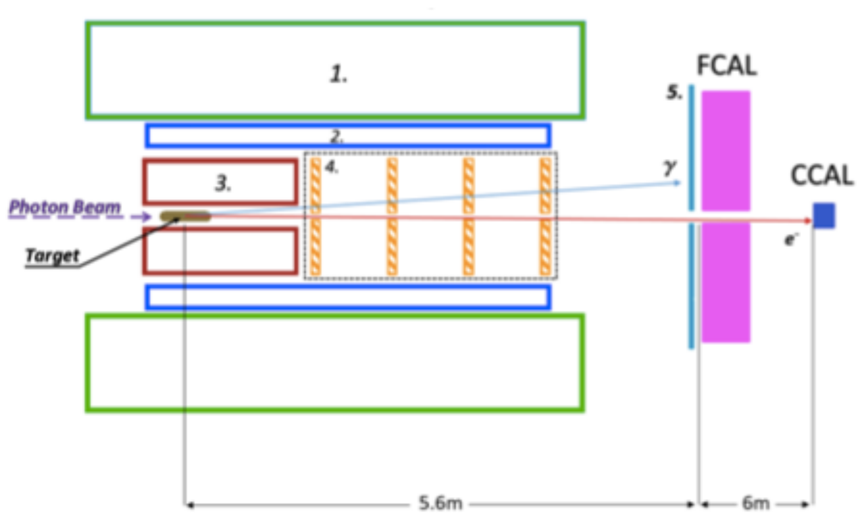


Calorimeter Prototyping

CCAL Prototype: 12x12 $PbWO_4$ array successfully tested and used for the PrimEx-η experiment in 2019 and in fall 2021.







ELSEVIER

Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment

Volume 1013, 11 October 2021, 165683

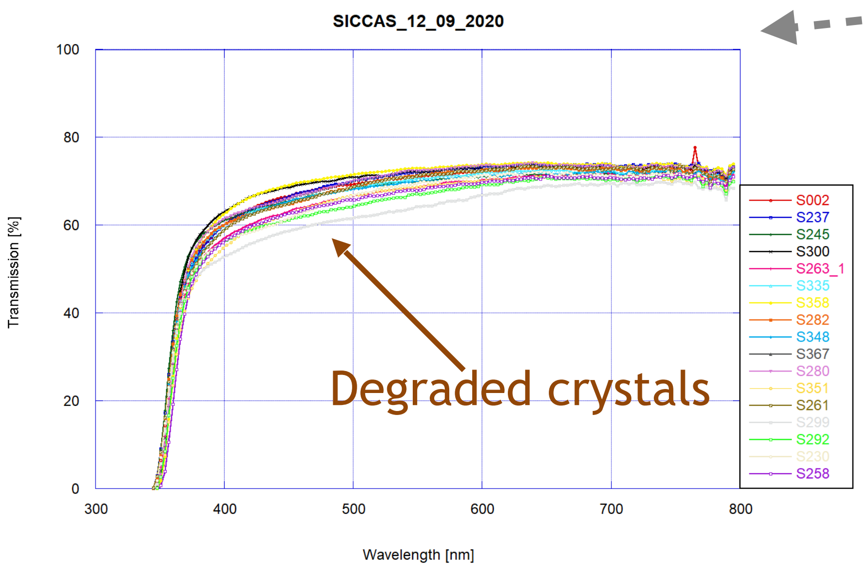
Halls C+D

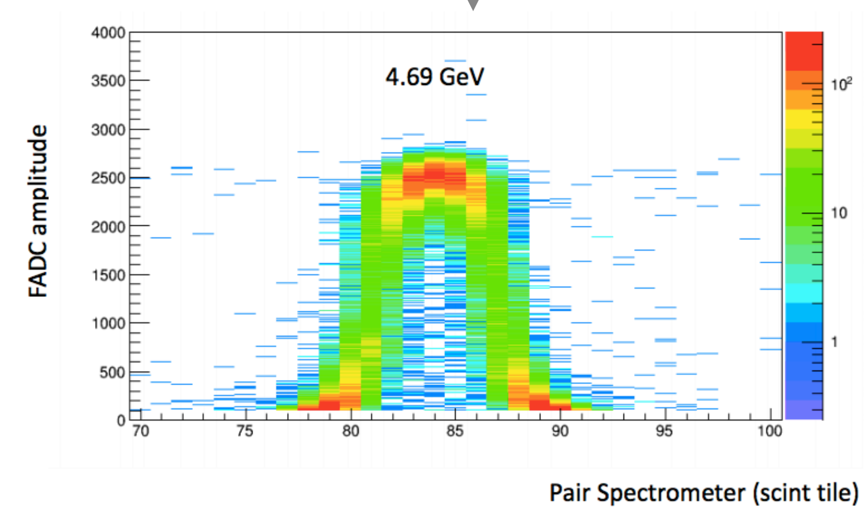
Electromagnetic calorimeters based on scintillating lead tungstate crystals for experiments at Jefferson Lab ☆

https://doi.org/10.1016/j.nima.2021.165683

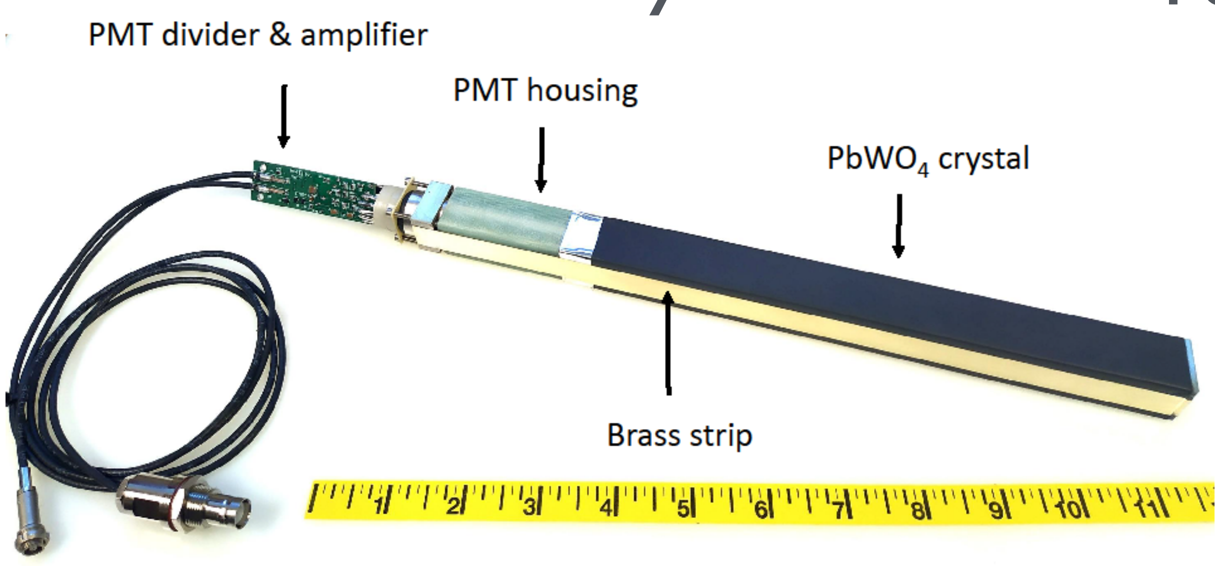
Hardware Status

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

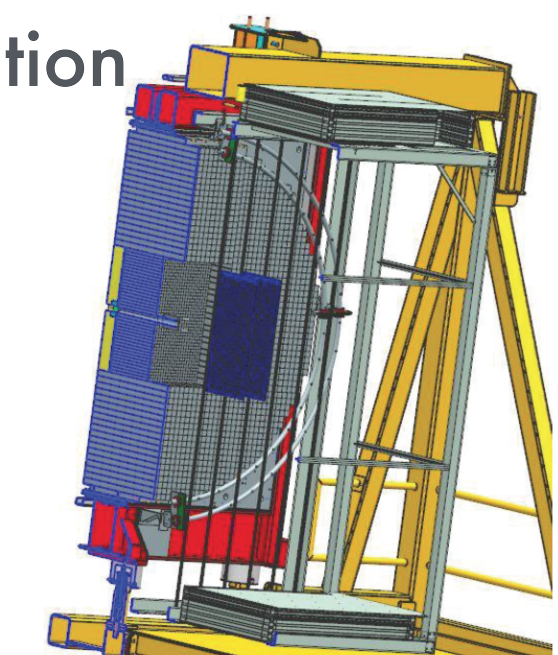




- Module assembly



- Fabrication and Installation
  - Finalizing engineering design for frame
  - Modules ready for installation in 2023
  - Planned installation duration: ~ 6 months

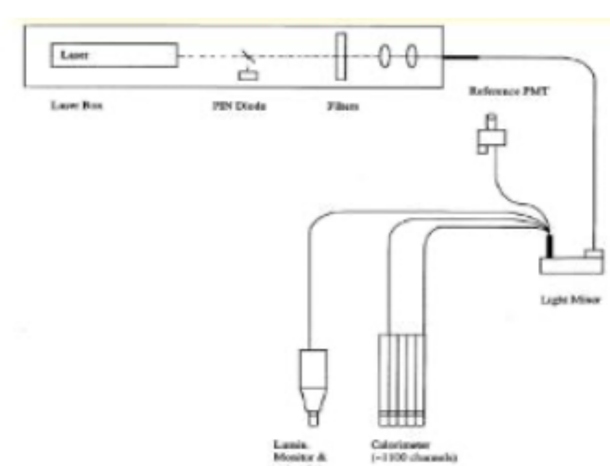


Module Assembly

- **Assembly Line:** crew (techs, summer students, pdfs), 459/1600 modules done

- **Light Monitoring System:** transmittance variation

Example of damaged block from radiation (DVCS experiment)



PrimeX laser based LMS

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.
- Conventional cuts look very promising, e.g. for the key channel of $\eta \rightarrow \pi^0\gamma\gamma$
- Algorithm work ongoing; Machine Learning will applied this summer.
- Upgraded FCAL-II with a PWO insert is under construction. Data in 2024.

gluex.org/thanks

University of Regina | Faculty of Science

NSERC CRSNG

GlueX JEF

Backup Slides

Decays

η

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].

η'

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)% $^{(*)}$	$m_u - m_d$	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 $^{(*)}$ 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

GlueX Data & MC

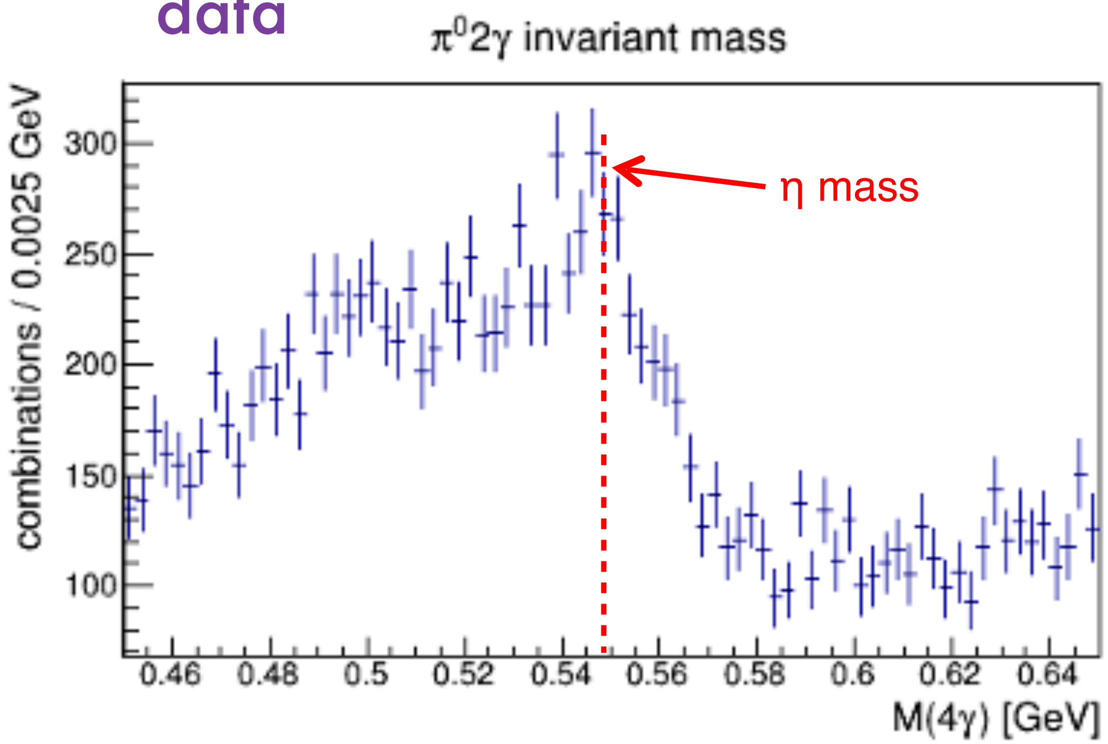
Reconstructed GlueX data from 2016 and 2017, **original FCAL**

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

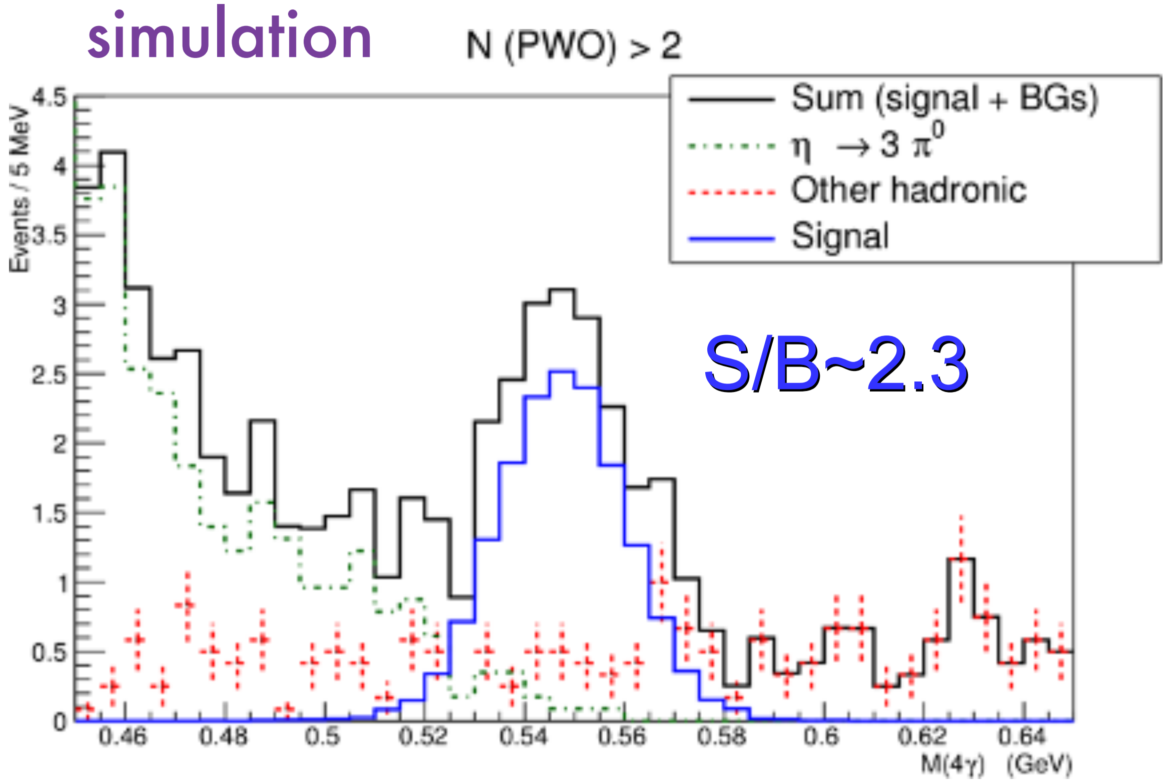
Simulation for 1 day running with **upgraded FCAL-II**

- Beam energy range: 8.4-11.7 GeV Intensity $N_\gamma \sim 1\text{x}10^8/\text{s}$

data



simulation

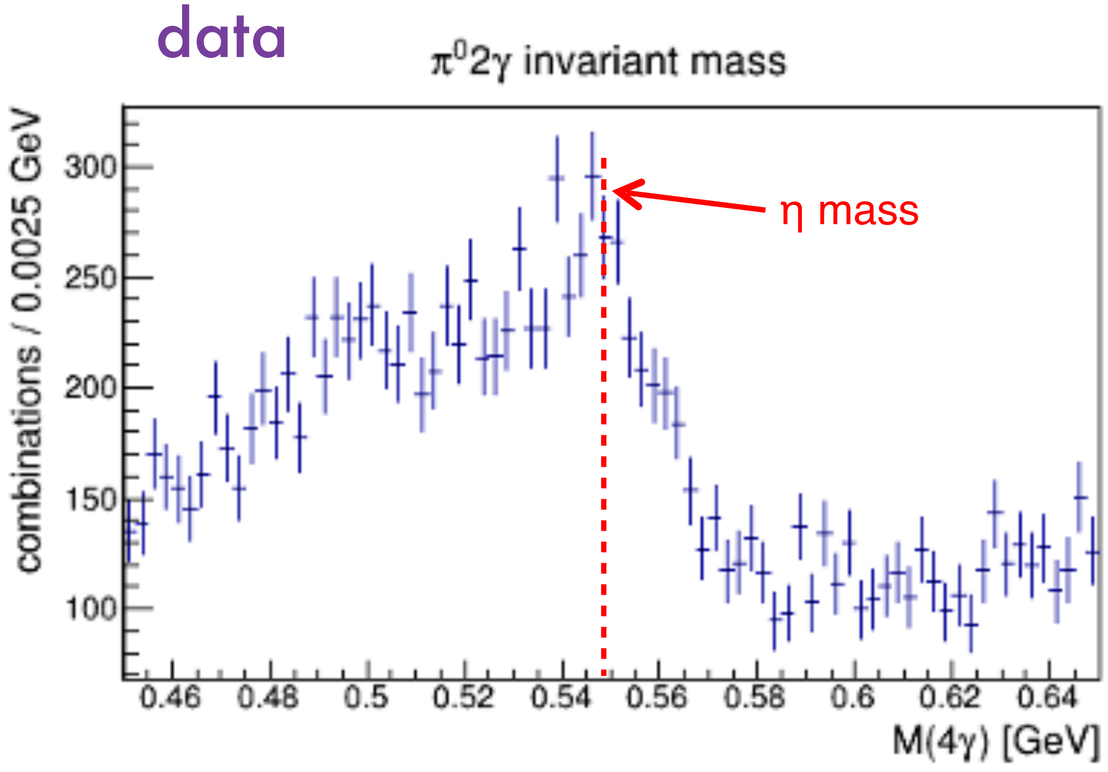


GlueX Data & MC

Reconstructed GlueX data from 2016 and 2017, original FCAL

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

data

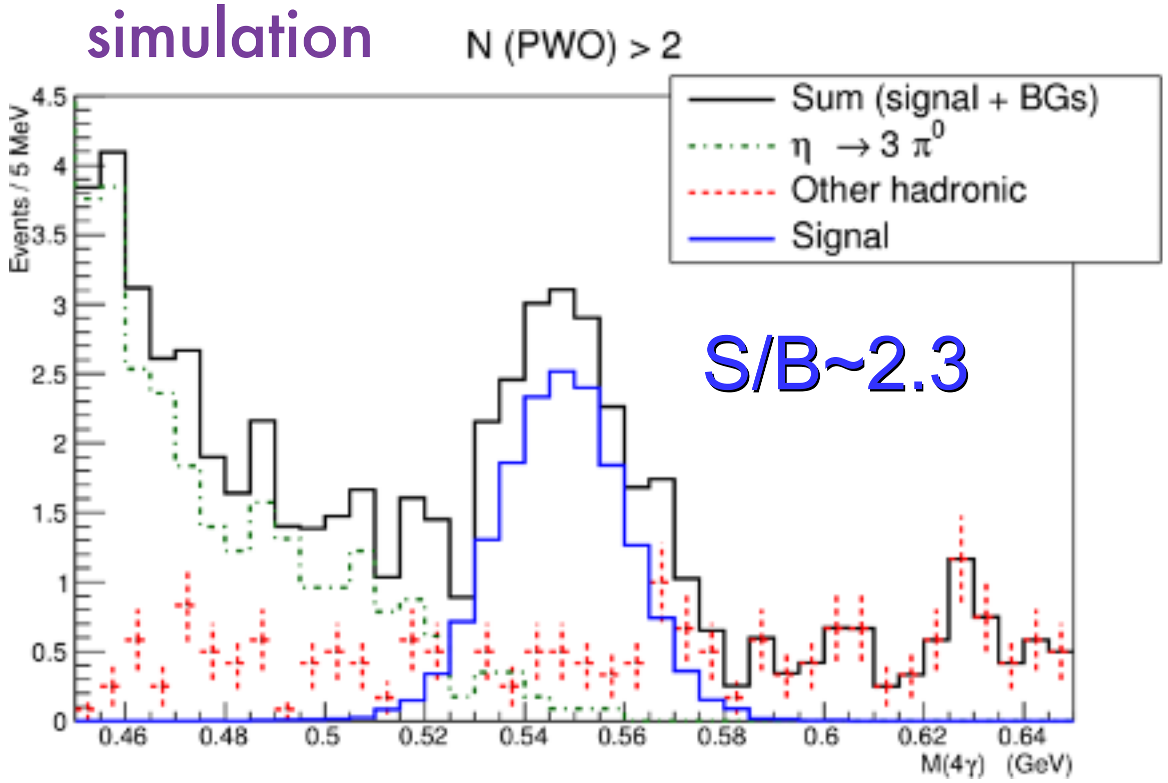


GlueX Phase-I data under analysis

Simulation for 1 day running with upgraded FCAL-II

- Beam energy range: 8.4-11.7 GeV Intensity $N_\gamma \sim 1\text{x}10^8$/s

simulation



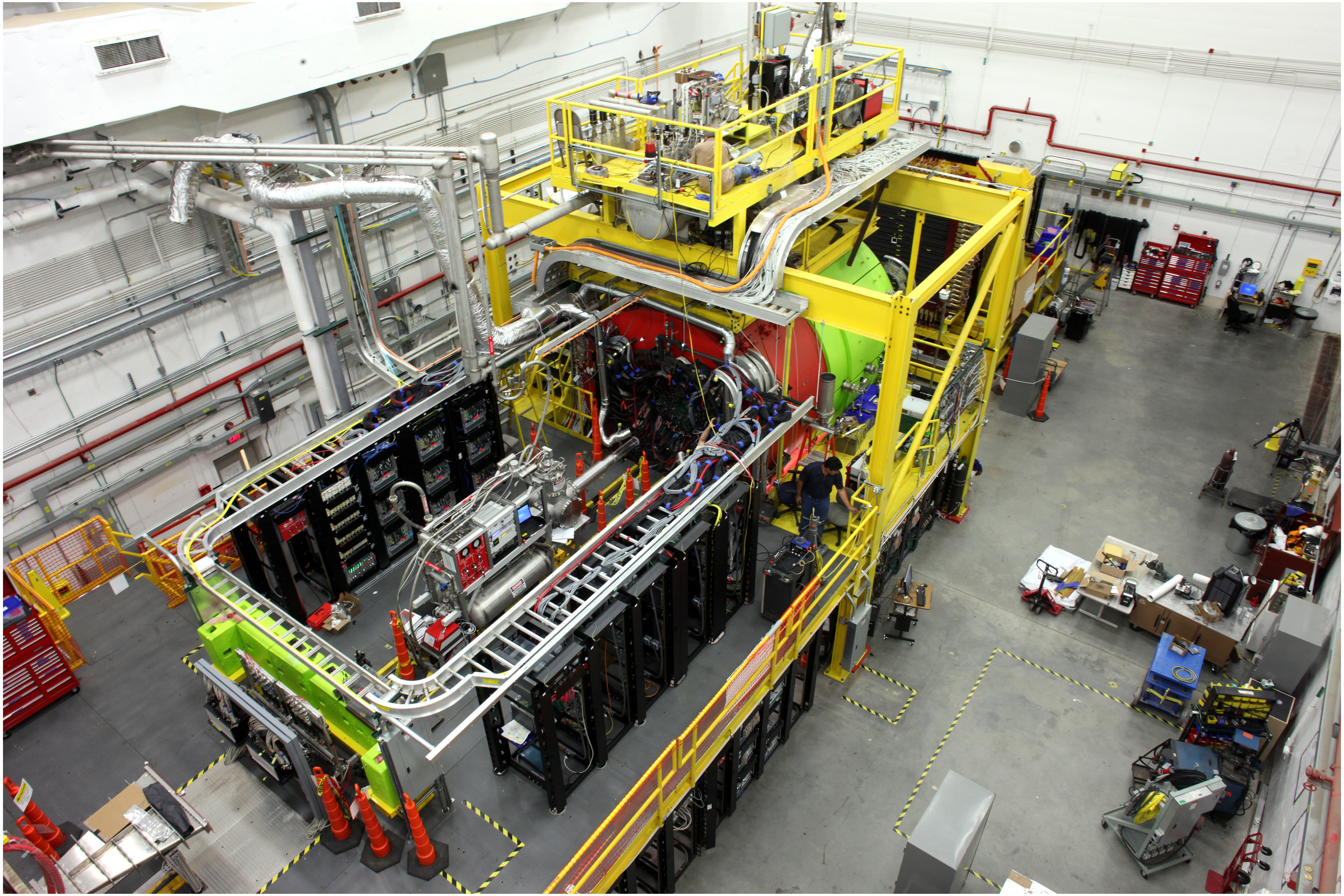
GlueX Run Group

The Proposals

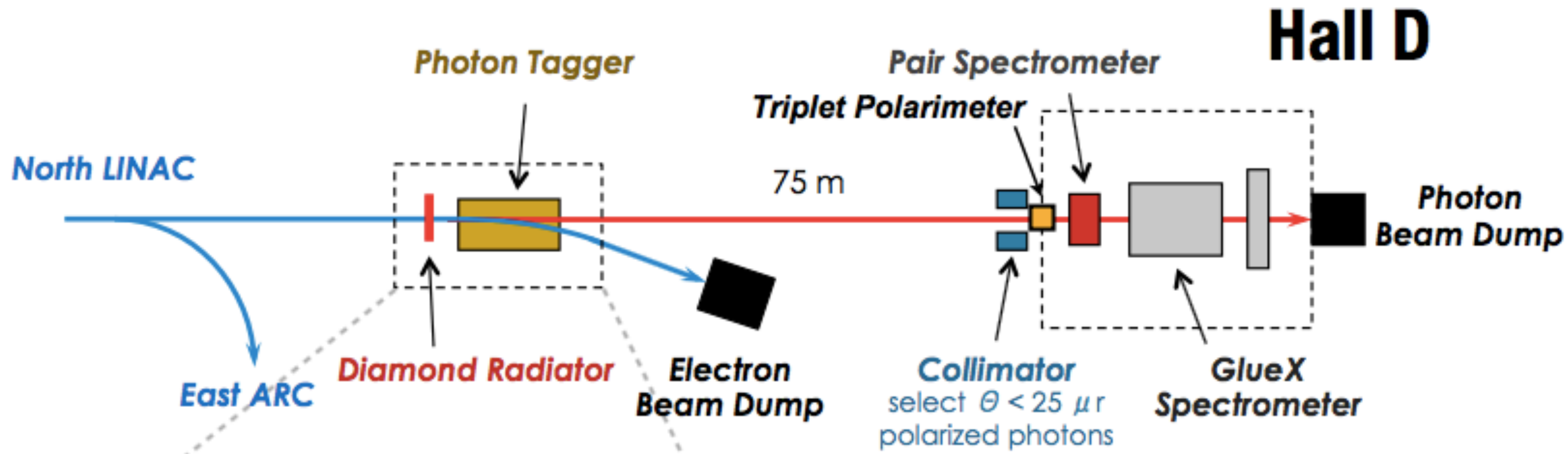
- **GlueX-II**: a extension of the GlueX spectroscopy program at high intensity (E12-13-003) and with enhanced particle identification (E12-12-002)
- **JEF**: a focus on rare and forbidden decays of $\eta^{(\prime)}$ mesons that is enabled by a high-resolution upgrade to the forward calorimeter
- PAC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

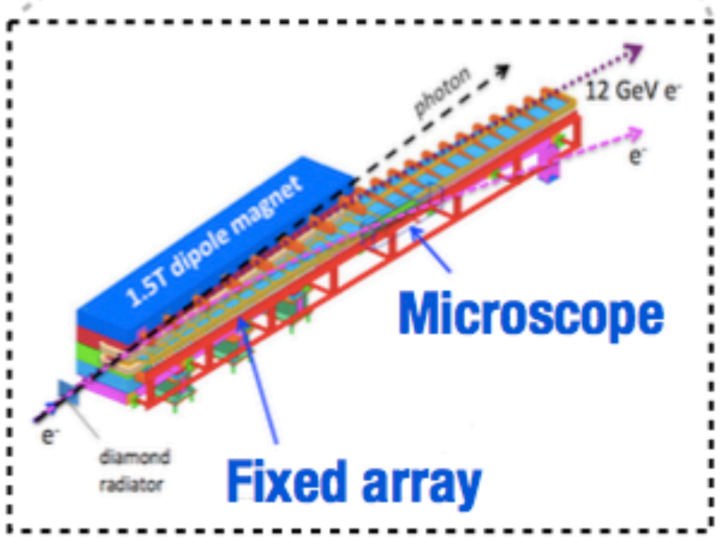
		Commissioning		Production	
Topic	Proposal Number	Approved	Completed	Approved	Completed
GlueX II with DIRC	E12-12-002	20	14	200	38
GlueX II	E12-13-003	0	0	200	38
JEF	E12-12-002A	0	0	100	0
Total Unique	-	20	14	200	38

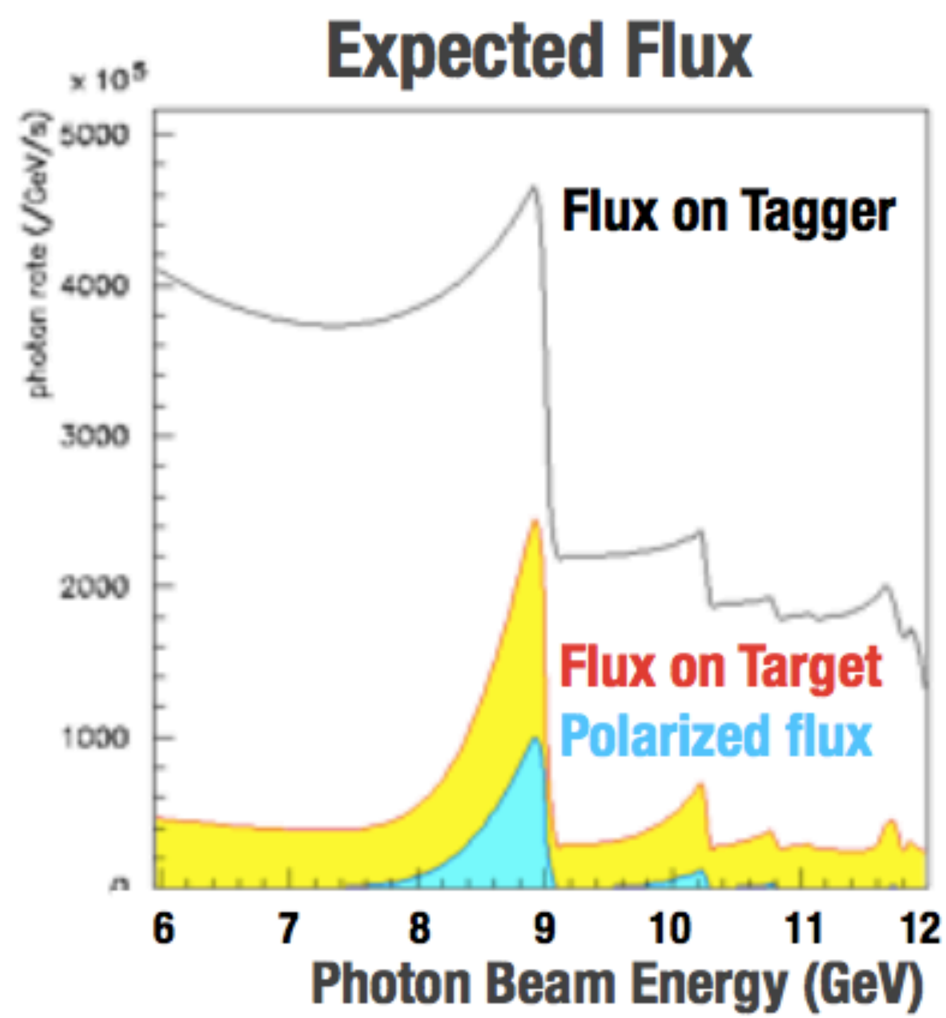
The GlueX Detector



The Beam Line

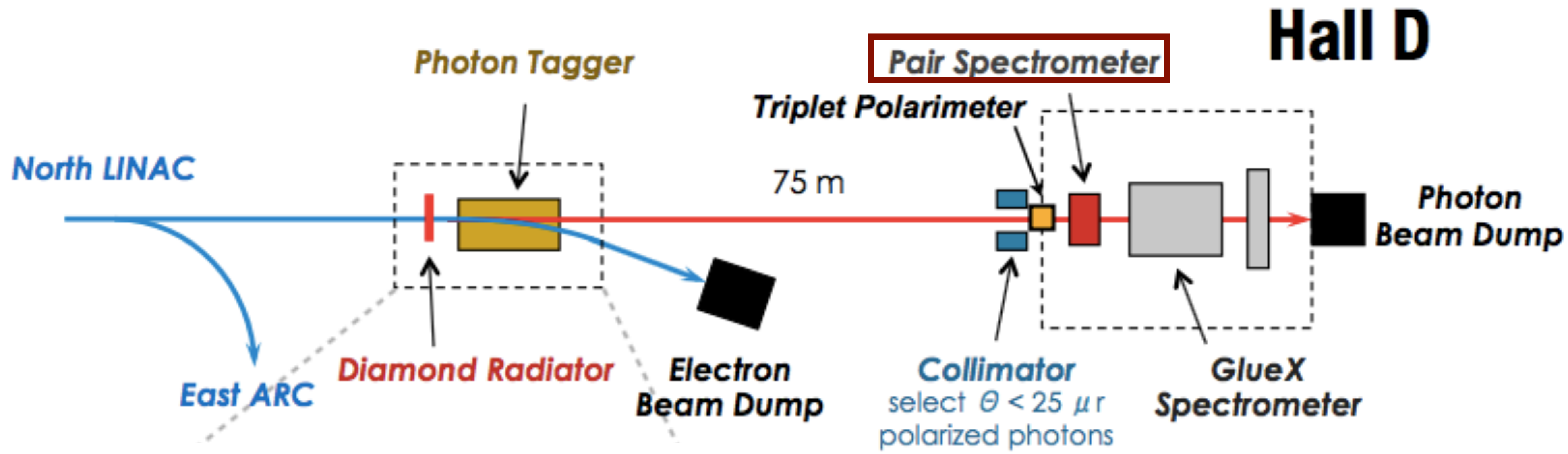




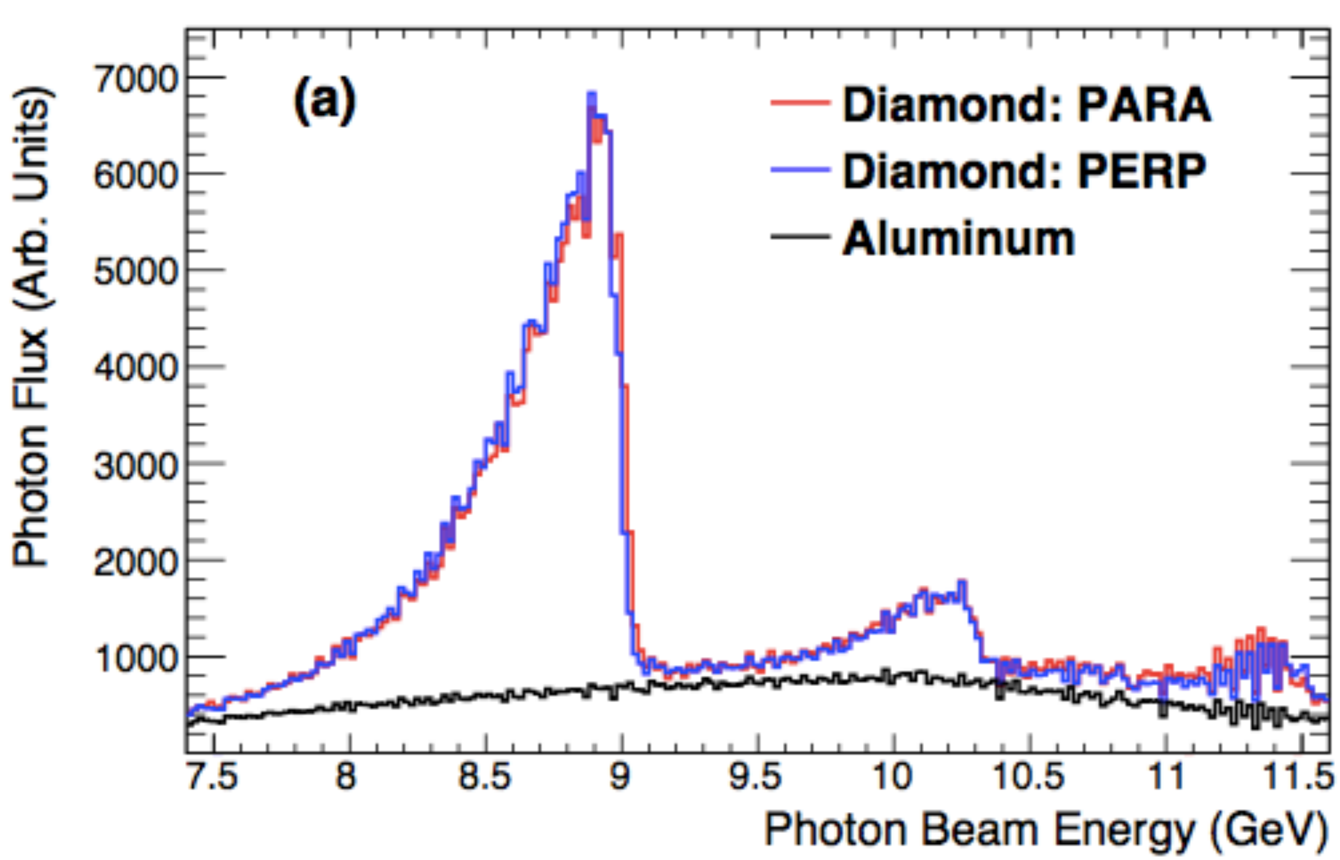


- Linearly polarized photons via coherent bremsstrahlung from diamond radiator
- Design intensity of 10^8 γ/s in coherent peak between E_γ = 8.4 and 9 GeV

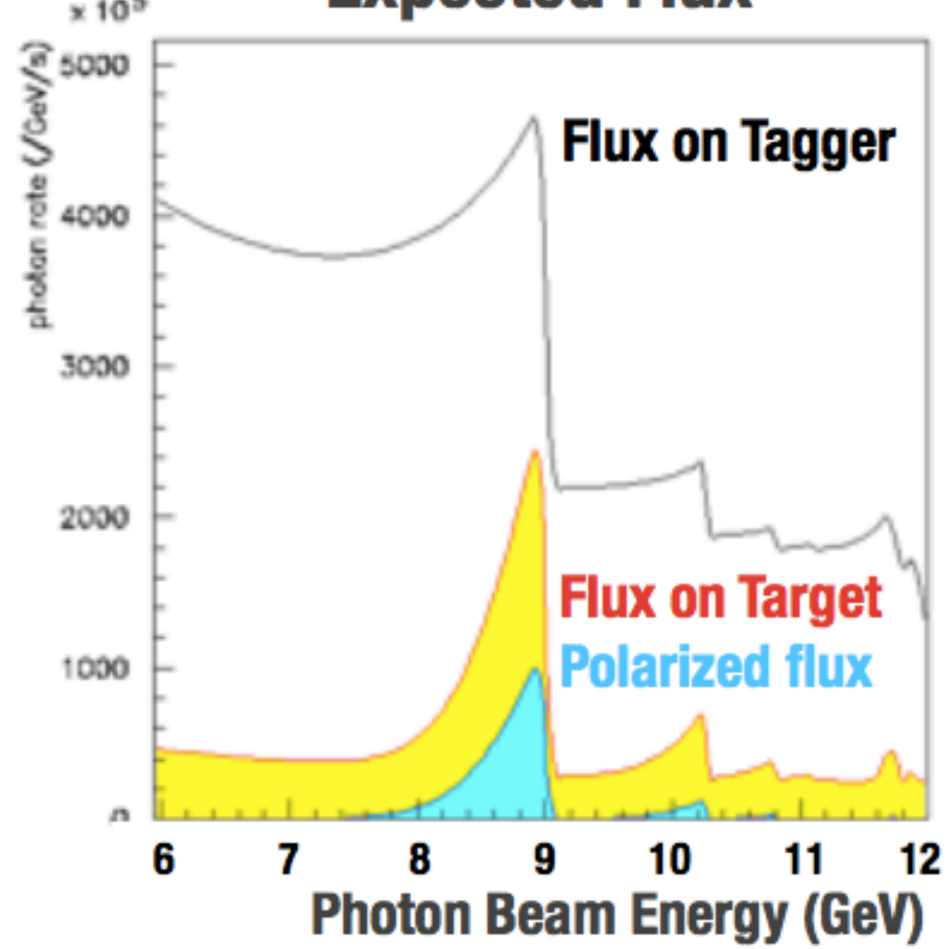
The Beam Line



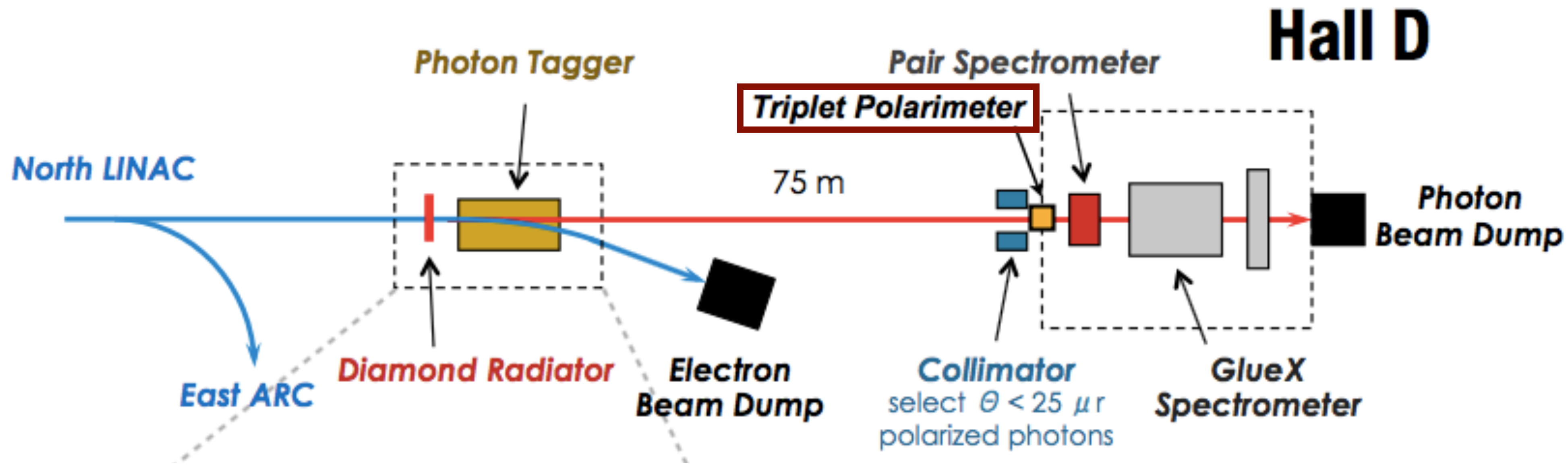
Measured Flux



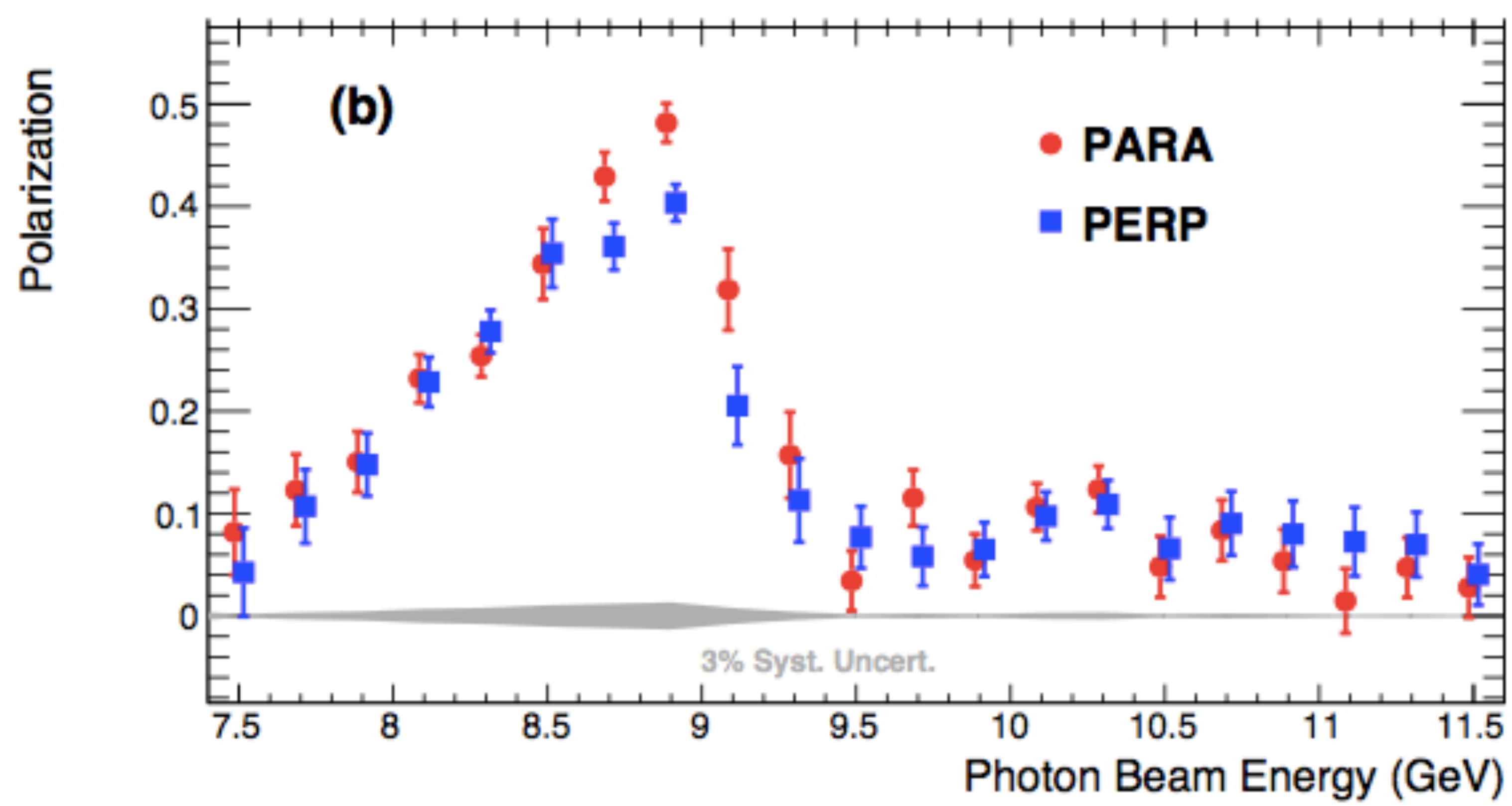
Expected Flux



The Beam Line



Measured Polarization



- **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