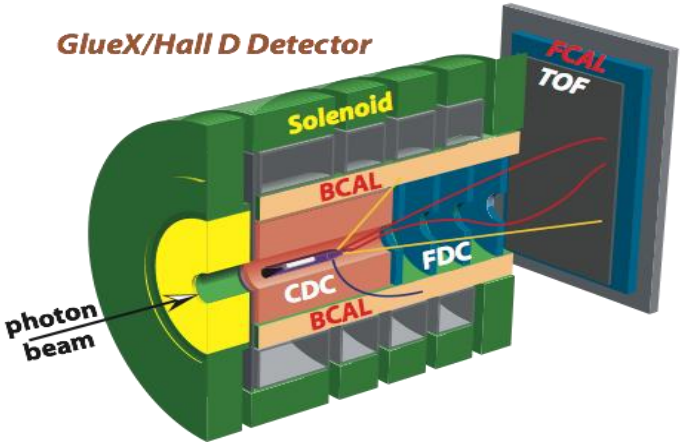


JLAB η Factory Experiment in Hall D

A. Somov, Jefferson Lab

for the GlueX Collaboration

The 10th International Workshop on Chiral Dynamics 2021
Beijing, China, November 16, 2021

Outline

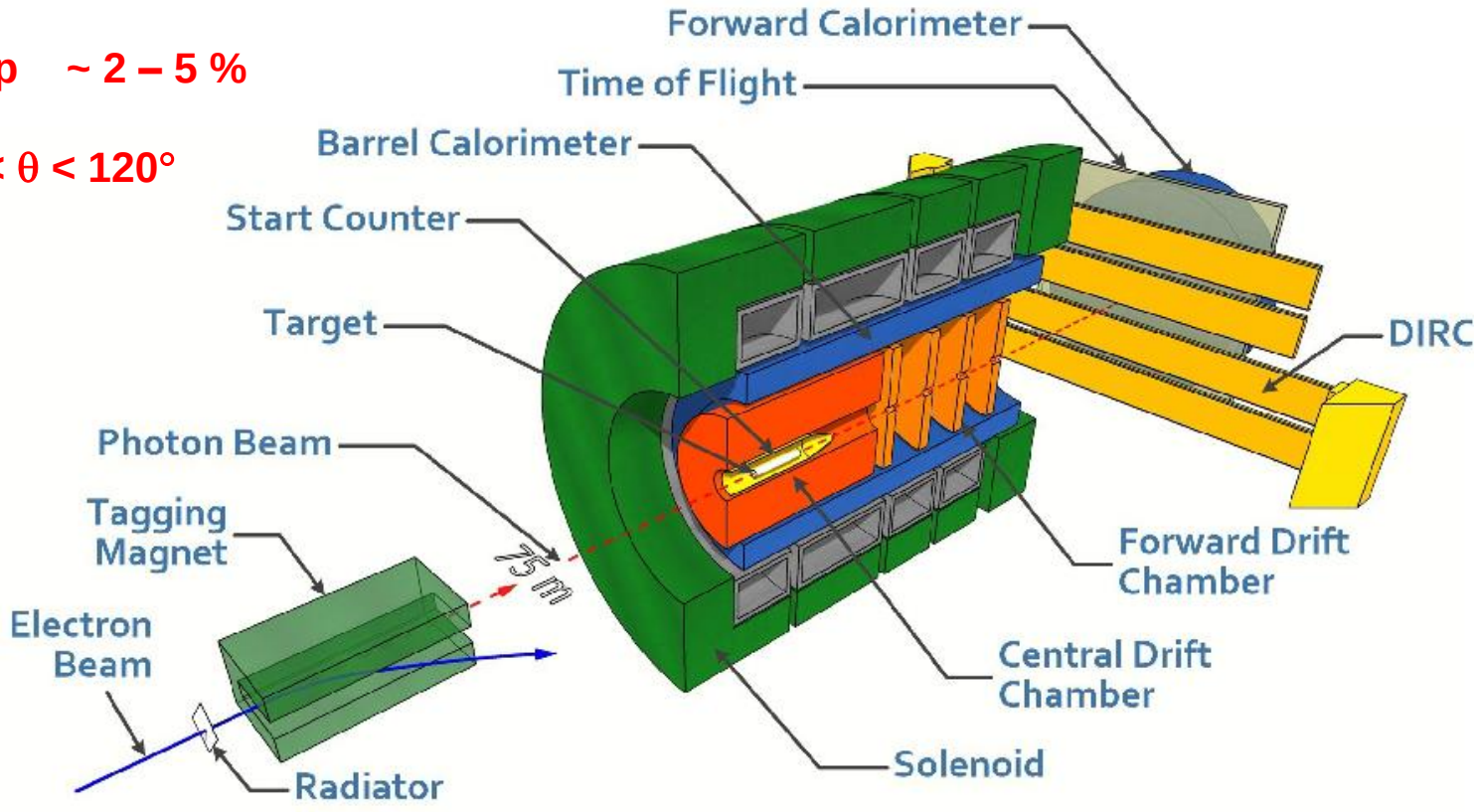
- GlueX detector in Hall D
- Jefferson Lab η Factory (JEF) experiment with the GlueX detector
- Physics Program
- Upgrade of the GlueX Forward Calorimeter

GlueX Detector in Hall D

Photons: $\sigma_E / E \sim 6\,\% / \sqrt{E} \oplus 2.0\,\%$

Tracks: $\sigma_p / p \sim 2 - 5\,\%$

Acceptance: $1^\circ < \theta < 120^\circ$



- Beam of photons (linear polarization)
- Optimized to detect multi-particle final states

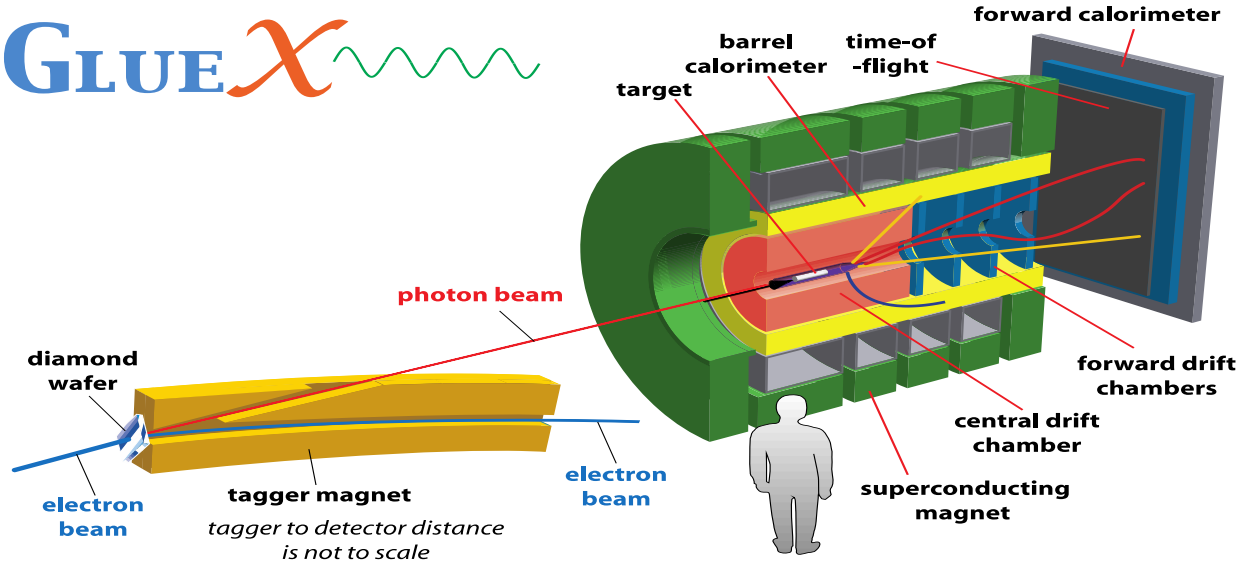
Experiments with the GlueX detector

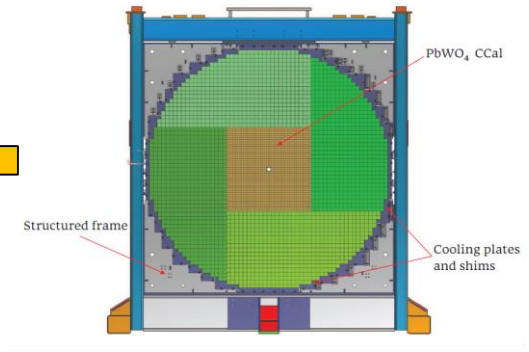
GlueX experiment: search for mesons with exotic quantum numbers; a study of meson and baryon decays to strange final states		2016 – present collected ~30% of data
A precision measurement of the η radiative decay width via the Primakoff effect *(see talk by I. Jaegle)*	**Calorimeter prototype**	Spring 2019, Fall 2021 (~50 % of data)
Measuring the charged pion polarizability *(see talk by R. Miskimen)*		Scheduled for 2022
Studying short range correlations with real photon beams at GlueX		Taking data

Upgrade Forward Calorimeter

Eta decays with emphasis on rare neutral modes: The JLab Eta Factory experiment (JEF)	2023 Run in parallel with GlueX

JEF Experiment using GlueX Detector





FCAL 2

- Upgrade the inner part of the lead glass Forward Calorimeter with high-granularity high-resolution **$PbWO_4$** crystals to improve reconstruction of multi-photon final states
- Produce η / η' using a beam of tagged photons with the energy between 8.4 - 11.7 GeV
- Reconstruct η / η' in exclusive reactions:

$$\gamma + p \rightarrow \eta/\eta' + p \qquad \eta/\eta' \rightarrow \gamma\gamma,\ \pi^0\gamma\gamma,\ \ldots$$

- Run in parallel with other GlueX experiments: collect large data set of η / η' mesons

Expected Rate of η/η′

Previous Experiments:

Experiment	Total η	Total η′
CB at AGS	10^7	-
CB MAMI-B	$2x10^7$	-
CB MAMI-C	$6x10^7$	10^6
WASA-COSY	~$3x10^7$ (p+d), ~$5x10^8$ (p+p)	-
KLOE-II	$3x10^8$	$5x10^5$
BESIII	~10^7	~$5x10^7$

JEF for 100 days of beam:

	η	η′
Tagged mesons	$6.5x10^7$	$4.9x10^7$

JEF will produce a competitive sample of η/η′ events

(see also proposed experiment REDTOP, talk by Corrado Gatto)

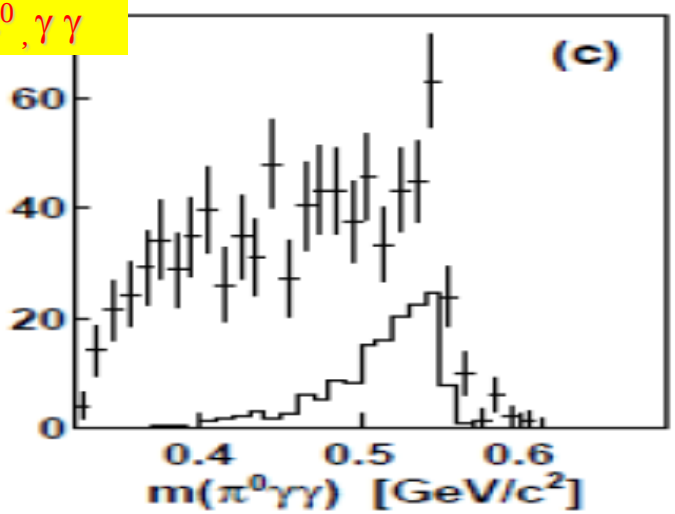
Unique Capabilities of JEF

- High production rate of η / η′ mesons
  - about 5×10^7 tagged η per 100 days of beam time
  - large data sample compared to existing η(′) experiments, such as A2-MAMI, WASA-at-COSY, KLOE-II, BES-III
- Produce η / η′ with high boost. Good reconstruction of photons in the upgraded lead tungstate Forward Calorimeter
  - significantly smaller background compared to other low-energy experiments

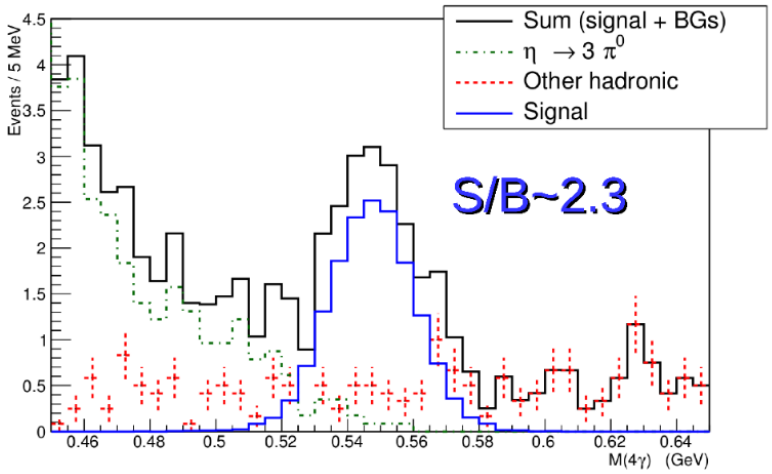
A2 at MAMI **(E_γ = 1.5 GeV)**

Phys.Rev. C90, 025206,2014

$\eta \rightarrow \pi^0, \gamma\gamma$



JEF **(E_γ = 9-11.7 GeV)** simulation



JEF Physics Program

Mode	Branching Ratio	Physics Highlight	Photons
priority:			
$\pi^0 2\gamma$			4
$\gamma + B$	beyond SM	leptophobic dark boson	4
$3\pi^0$	$(32.6 \pm 0.2)\%$	$m_u - m_d$	6
$\pi^+\pi^-\pi^0$	$(22.7 \pm 0.3)\%$	$m_u - m_d$, CV	2
3γ	$< 1.6 \times 10^{-5}$	CV, CPV	3
ancillary:			
4γ	$< 2.8 \times 10^{-4}$	$< 10^{-11}$ [112]	4
$2\pi^0$	$< 3.5 \times 10^{-4}$	CPV, PV	4
$2\pi^0\gamma$	$< 5 \times 10^{-4}$	CV, CPV	5
$3\pi^0\gamma$	$< 6 \times 10^{-5}$	CV, CPV	6
$4\pi^0$	$< 6.9 \times 10^{-7}$	CPV, PV	8
$\pi^0\gamma$	$< 9 \times 10^{-5}$	CV, Ang. Mom. viol.	3
normalization:			
2γ	$(39.3 \pm 0.2)\%$	anomaly, η-η' mixing PR12-10-011	2

Upgrade the Forward Calorimeter

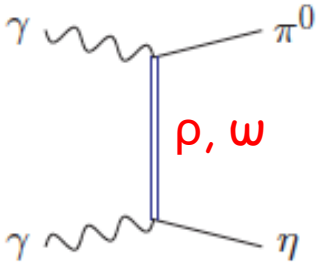
Main physics topics:

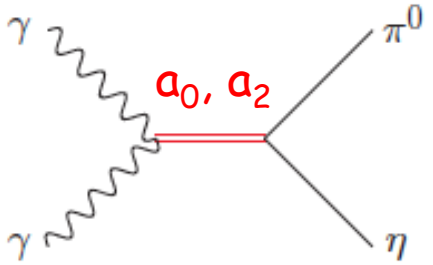
1. Test of low-energy QCD
2. Search for dark matter
3. Directly constrain CVPC new physics
4. Constrain the light quark mass ratio

Impact of $\eta \to \pi^0\gamma\gamma$ measurements on Chiral Perturbation Theory

- Unique probe for the high order ChPT: L. Ametller, et.al, Phys. Lett., B276, 185 (1992)
  - contribution from two $O(p^6)$ counter-terms in the chiral Lagrangian
- Study contribution of scalar resonances in calculation of $O(p^6)$ low-energy constants (LEC) in the chiral Lagrangian
- Shape of Dalitz distribution is sensitive to the role of scalar resonances

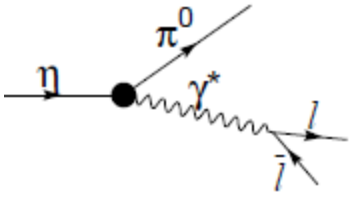
Higher order LEC's are dominated by resonances
Gasser, Leutwyler 84; Ecler, Gasser, Pich, de Rafael 1989; Donoghue, Ramirez, Valencia 1989



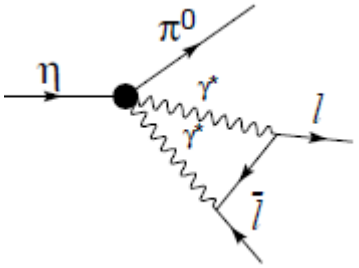


- A cross-check of LEC's with different processes

C and CP violating



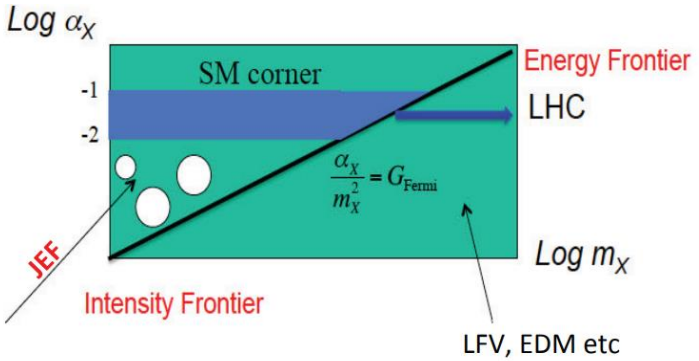
C and CP conserving background



J.N. Ng, et al., Phys. Rev., D46, 5034 (1992)

Dark Matter Search in η Decays

Search for dark matter in sub-GeV range:



Vector

leptophobic vector boson B.

$\eta, \eta' \to \gamma B$ $\quad B \to \pi^0 \gamma$ $\quad (0.14 < m_B < 0.62$ GeV$)$

$B \to \pi^+ \pi^- \pi^0$ $\quad (0.62 < m_B < 1.0$ GeV$)$

dark photon:

$\eta, \eta' \to A' \gamma \to e^+ e^- \gamma$

Scalar

$\eta \to \pi^0 S$ $\quad S \to \gamma\gamma,\ e^+ e^-$ $\quad (m_S < 2 m_\pi)$

$\eta, \eta' \to \pi^0 S$ $\quad S \to \pi^+\pi^-$ $\quad (m_S > 2 m_\pi)$

$\eta' \to \eta S$

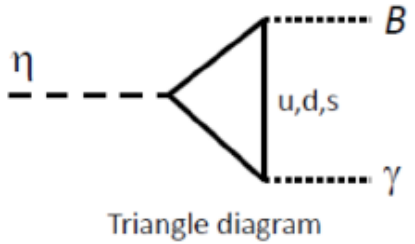
Light pseudoscalar (axion-like particle)

$\eta, \eta' \to \pi\pi\gamma\gamma,\ \pi\pi e^+ e^-$

Search for B-boson in η decay

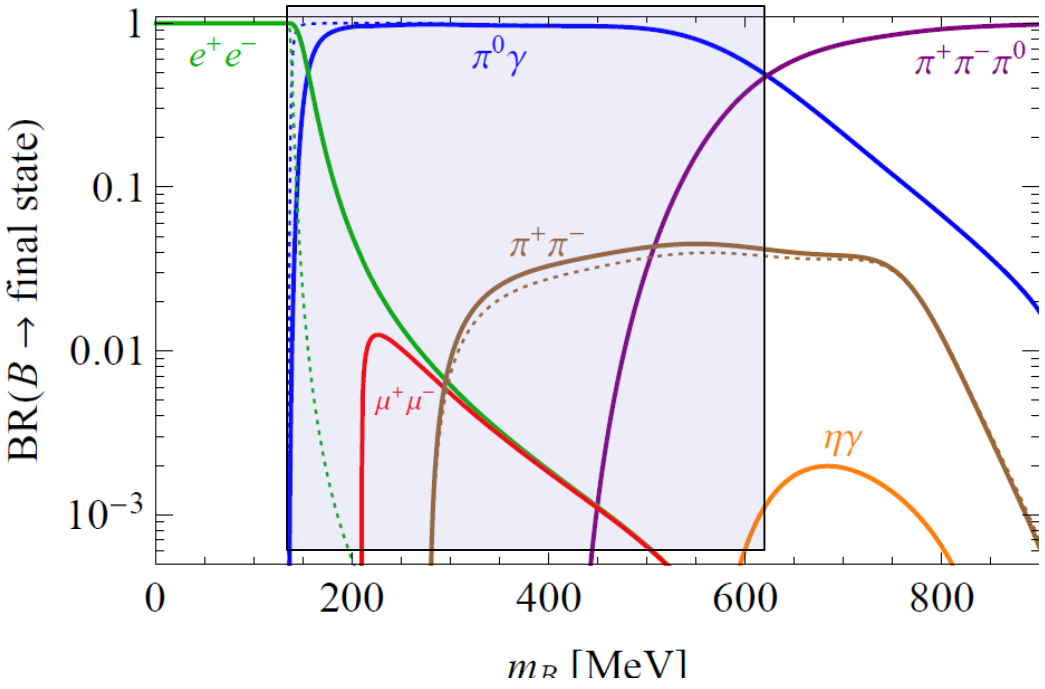
B production: A.E. Nelson, N. Tetradis, Phys. Lett., B221, 80 (1989)

$\eta \rightarrow B\gamma$ decay ($m_B < m_\eta$)



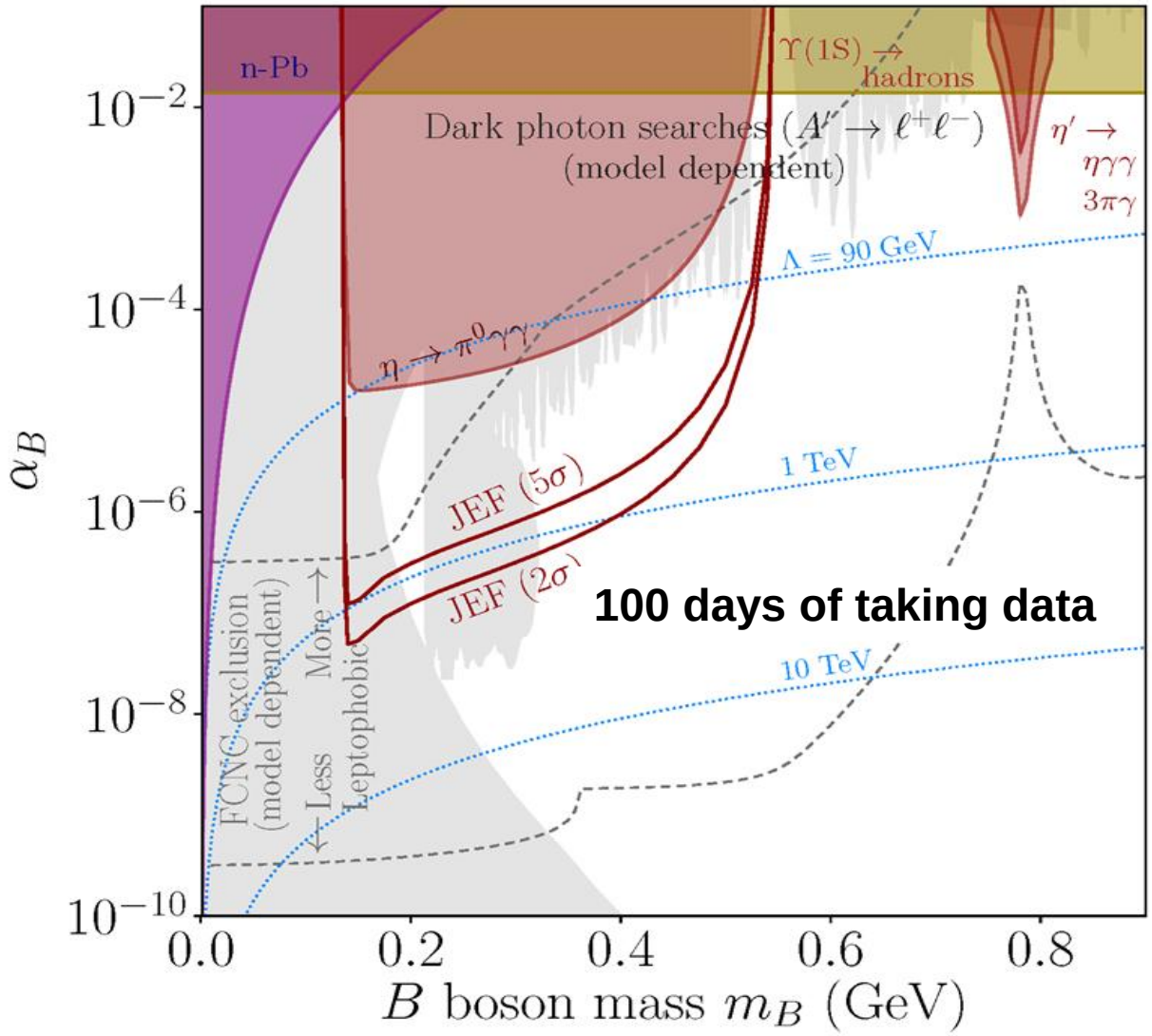
Triangle diagram

B decay: $B \rightarrow \pi^0\gamma$ in 140-600 MeV mass range



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

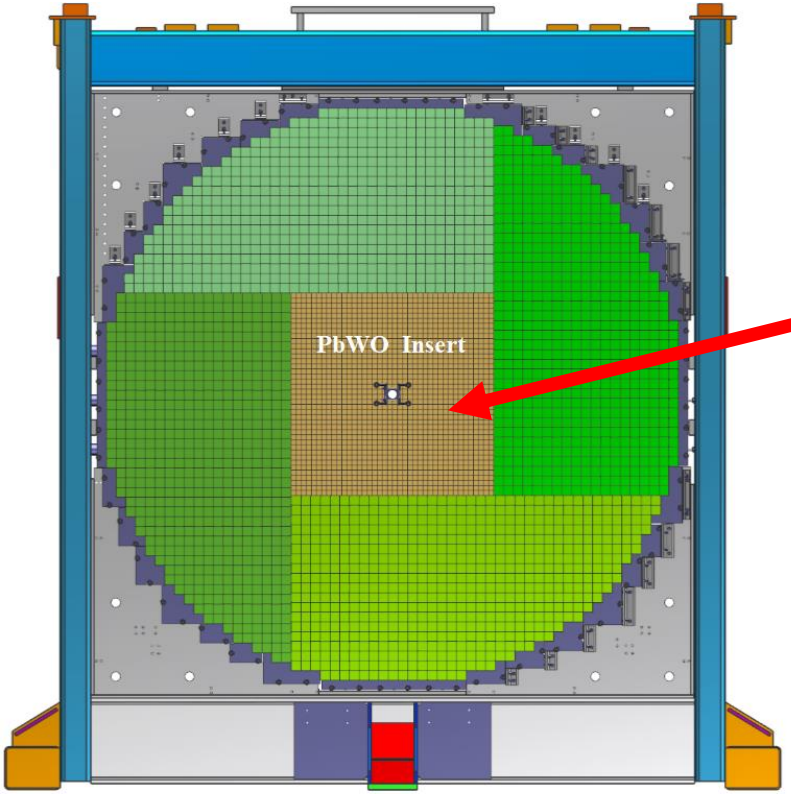
JEF Experimental Reach ($\eta \rightarrow B\gamma \rightarrow \pi^0\gamma\gamma$)



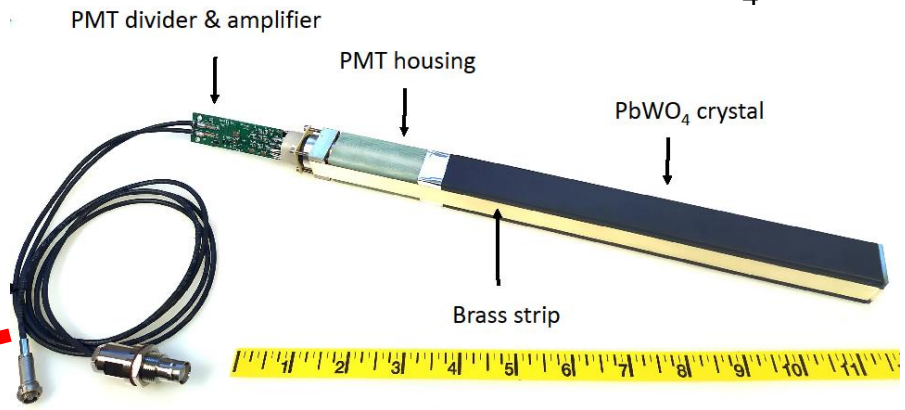
A stringent constraint on the leptophobic B-boson in 140 - 550 MeV range

Calorimeter Upgrade

Forward Calorimeter



$PbWO_4$ module



- Install an array of 40 x 40 $PbWO_4$ modules in the inner part of the FCAL
  (replace lead glass modules)

  - 2 cm x 2 cm x 20 cm $PbWO_4$
  - 4 cm x 4 cm x 45 cm lead glass

- A factor of 4 better detector granularity
  - significantly improve shower separation

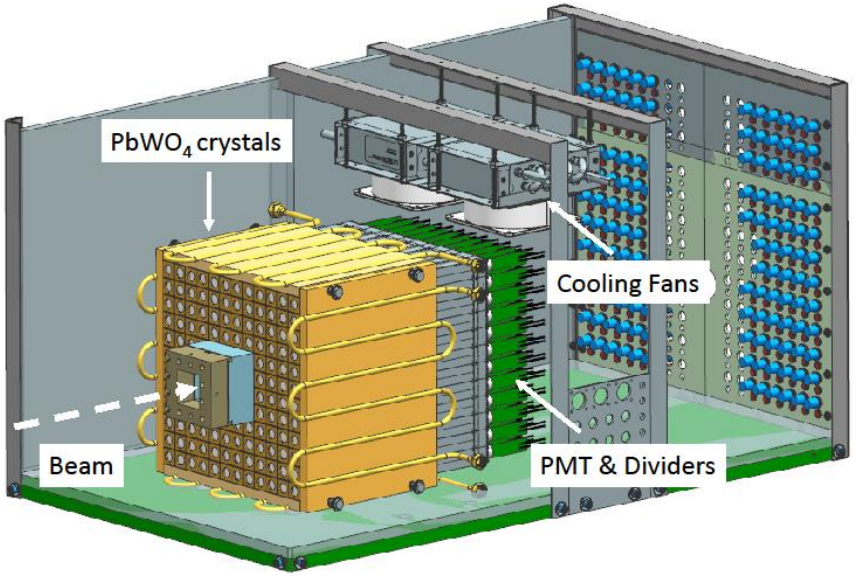
- Improves the energy and position resolution by about a factor of 2

Calorimeter Prototype

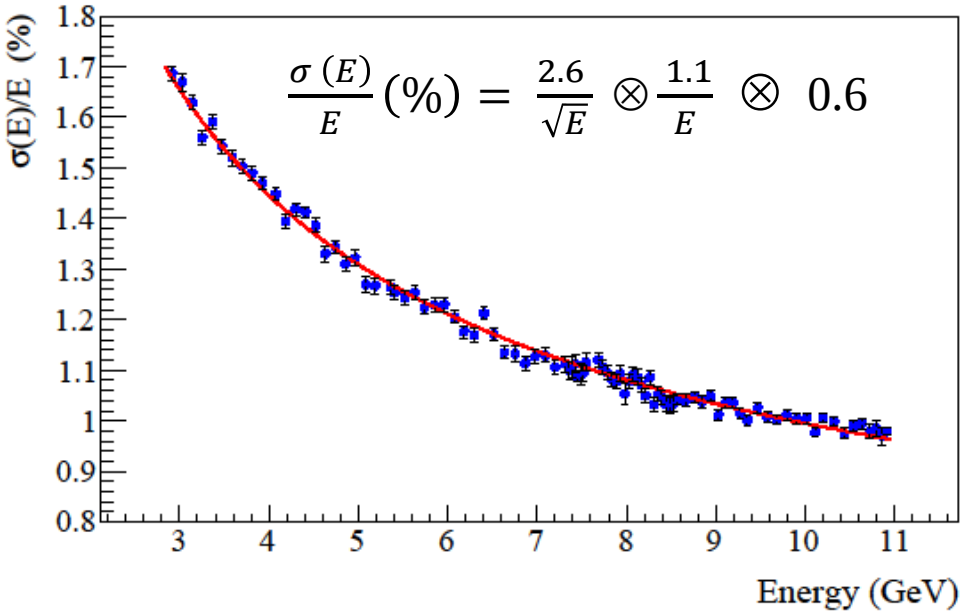
- Beam test of calorimeter prototype

  -12 x 12 modules

  - used as a Compton calorimeter in the PrimEx experiment in 2019 / 2021



Energy resolution



NIM, A 1013 (2021)


Nuclear Inst. and Methods in Physics Research, A 1013 (2021) 165683

Contents lists available at ScienceDirect

Nuclear Inst. and Methods in Physics Research, A

journal homepage: www.elsevier.com/locate/nima

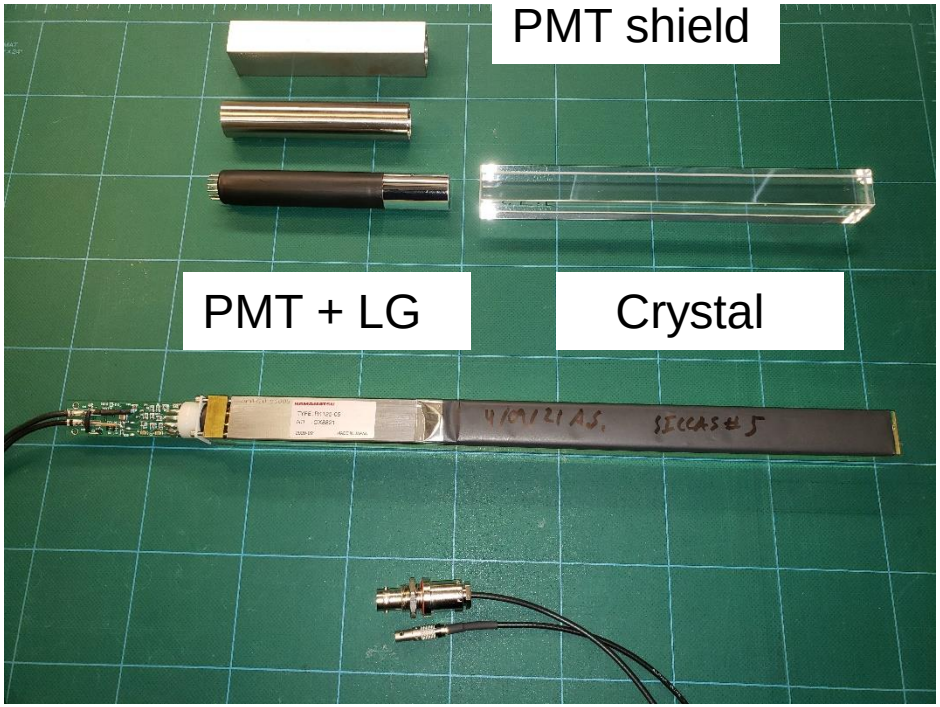
Electromagnetic calorimeters based on scintillating lead tungstate crystals for experiments at Jefferson Lab☆

A. Asaturyan[a], F. Barbosa[c], V. Berdnikov[b], E. Chudakov[c], J. Crafts[b,c], H. Egiyan[c], L. Gan[f], A. Gasparian[g], K. Harding[c], T. Horn[b], V. Kakoyan[a], H. Mkrtchyan[a], Z. Papandreou[e], V. Popov[c], N. Sandoval[c], A. Somov[c,*], S. Somov[d], A. Smith[h], C. Stanislav[c], S. Taylor[c], H. Voskanyan[a], T. Whitlatch[c], S. Worthington[c]

Finalizing Module Design

- Magnetic shielding studies

  - use soft iron and mu-metal PMT housing
  - use light-guides



- Optimize geometry of light guides (light collection studies)

- Optimize design of PMT divider (active base)

- Study properties of PbWO crystals, perform quality checks: *NIM A 956 (2020) 163375*

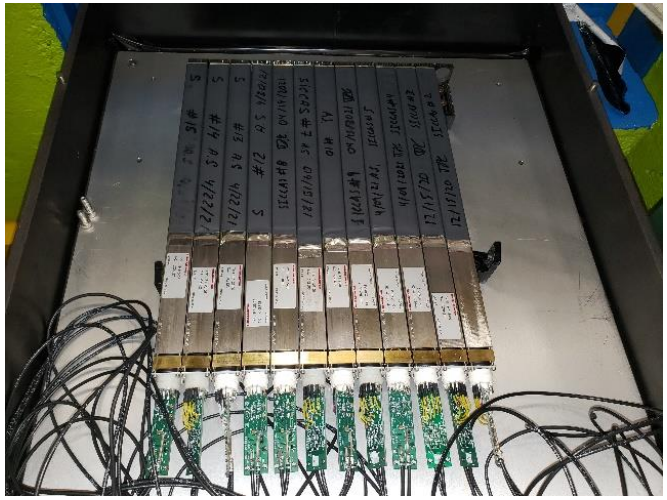
  - procure from two vendors: SICCAS (China) and CRYTUR (Czech Republic)

  - measure dimensions, light transmittance and yield

Beam Tests of Fabricated PbWO Modules

- Test fabricated modules using electrons/positrons with known energies provided by the GlueX Pair Spectrometer *NIM A 956 (2020) 163375, NIM A 795 (2015)*
- Perform tests in parallel with GlueX data taking

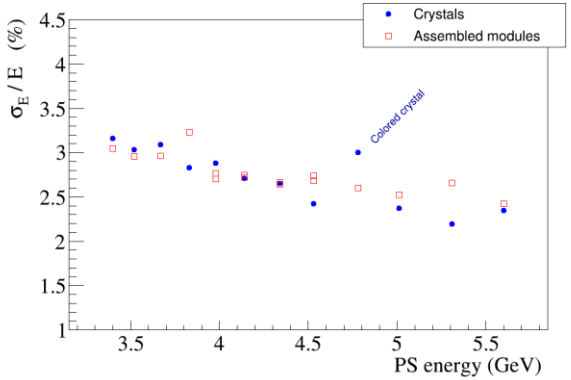
Test up to 12 PbWO modules



Pair Spectrometer setup in Hall D

- **Fabrication of FCAL2 modules in progress**
- **Installation in Hall D: 2023**

Energy resolution of a single module



Summary

- The new JEF experiment in Hall D will extend the physics potential of the GlueX detector. The JEF physics program spans from the study of rare decays of η mesons to the dark matter searches in the sub-GeV mass region.

- The experiment requires upgrade of the lead glass GlueX forward calorimeter with high-granularity, high-resolution $PbWO_4$ crystals

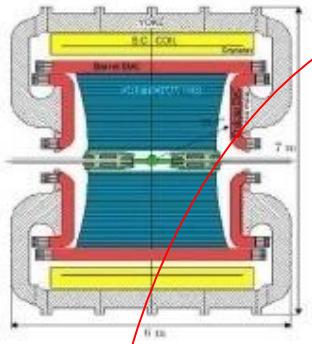
- The new calorimeter will be installed in Hall D in 2023

Backup Slides

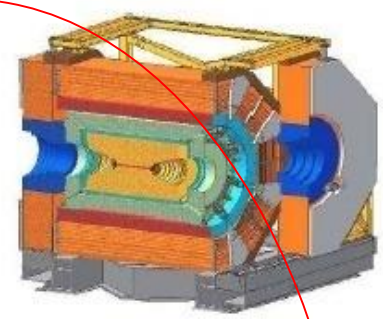
World competition in η decays

e^+e^- Collider

KLOE-2 at DAϕNE



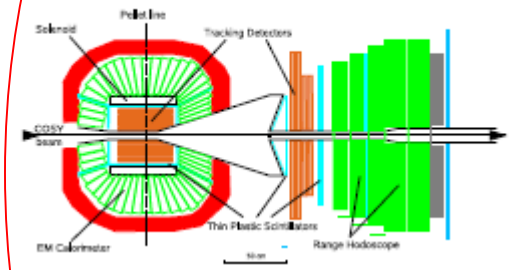
BESIII at BEPCII



Low energy η-facilities

Fixed-target

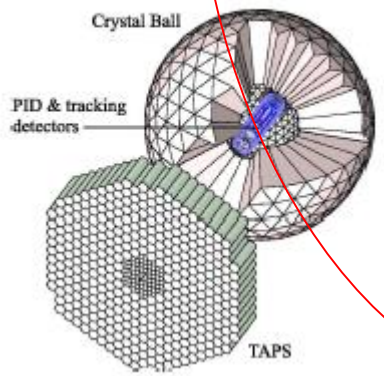
WASA at COSY



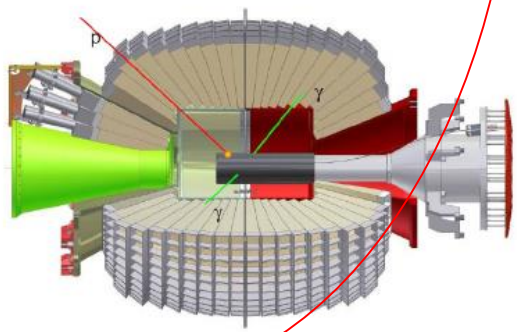
hadroproduction

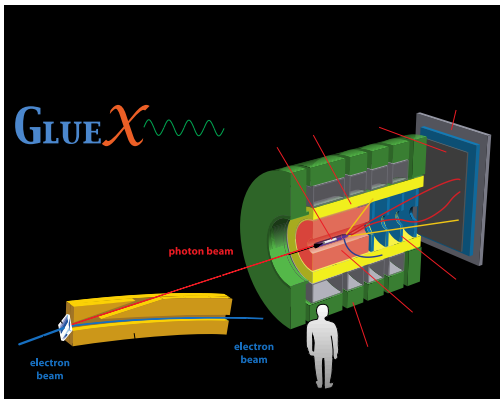
High energy η-facility

Crystall Ball at MAMI



photoproduction





Search for B boson

- Dark leptophobic B-boson

$$L = \frac{1}{3} g_B \bar{q} \gamma^\mu q B_\mu + \ldots$$

- Arises from a new gauge baryon symmetry $U(1)_B$

Early studies by Lee and Yang, Phys.Rev.,98 (1955) 1501; Okun, Yad.Fiz., 10 (1969) 358,

- Unified genesis of baryonic and dark matter

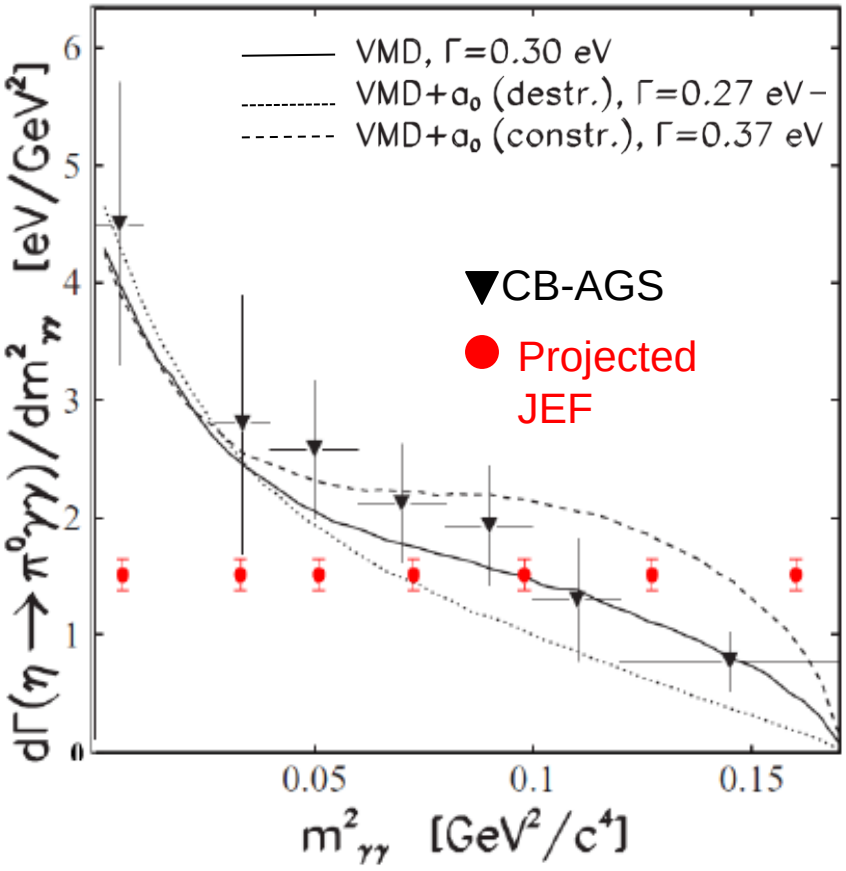
- the $m_B < m_p$ region is strongly constrained by long-range forces search exp. ; the $m_B > 50 GeV$ has been investigated by the collider experiments

- GeV-scale domain is poorly constrained

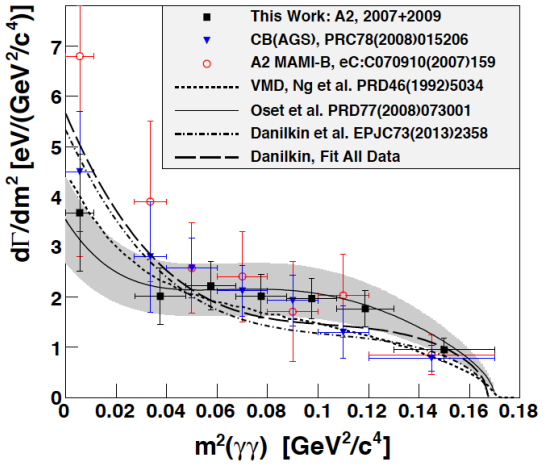
discovery opportunity!

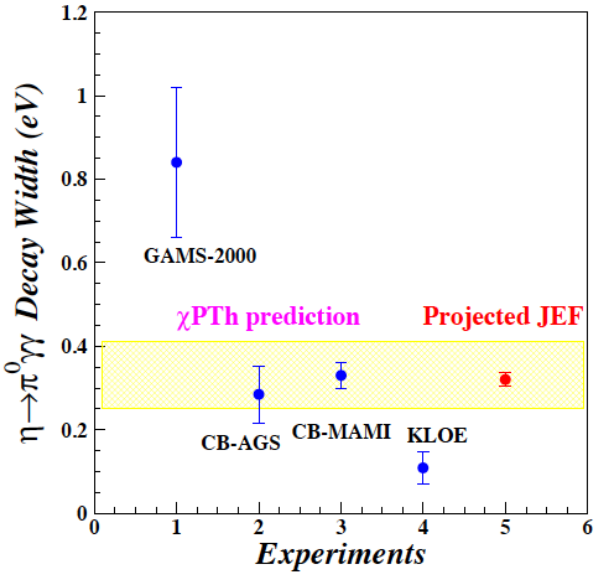
Projections for $\eta \to \pi^0\gamma\gamma$ Decay

Prakhov et al., Phys. Rev. C78, 015206 (2008)



A2 at MAMI arXiv:1405.4904, 2014





Constrain contribution of scalar resonances in the calculation of $O(p^6)$ low-energy constants

C Invariance

- Maximally violated in the weak force and is well tested
- SM prediction:
  BR(η→3γ) <10^{-19} via P-violating weak interaction.
- Study constraints on CVPC from EDM
  - no constraints in the presence of a conspiracy or new symmetry; only the direct searches are unambiguous

M. Ramsey-Musolf, phys. Rev., D63 (2001);
talk at the AFCI workshop,
studies are in progress

C Violating η neutral decays

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