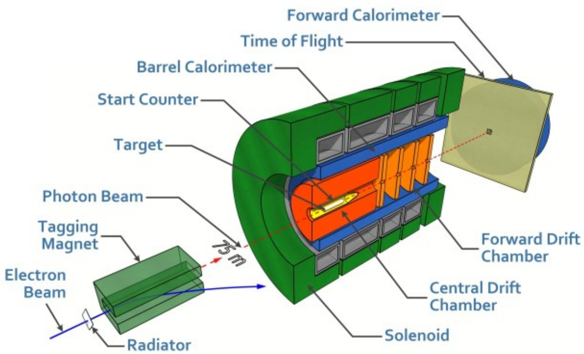


The Jefferson Lab Eta Factory Experiment and Applications of $PbWO_4$ Calorimeters in Future Experimental Facilities

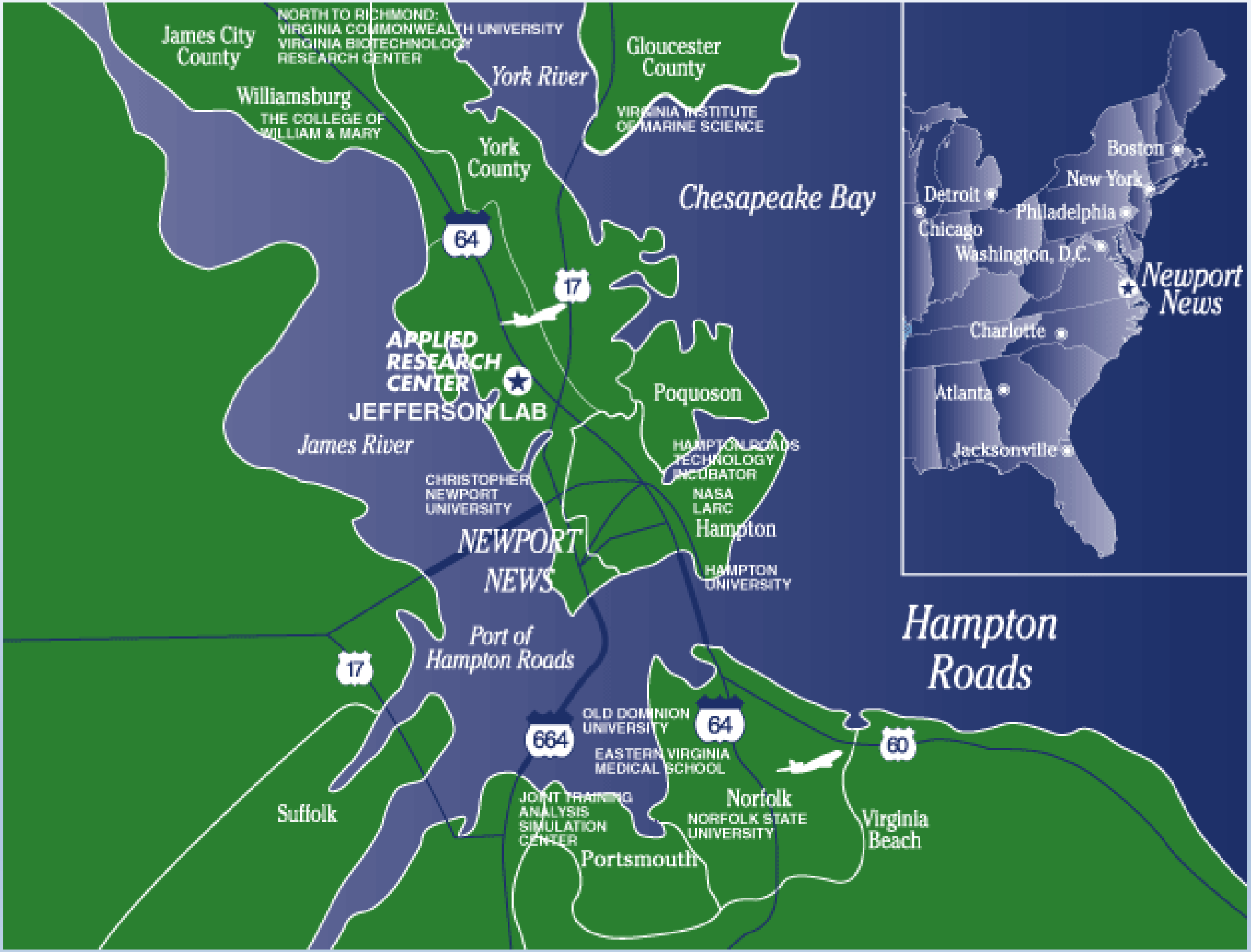
A. Somov   Jefferson Lab

Workshop on Beyond Standard Model Physics at η / η′ - Factories
Lund University, Sweden
May 13 - 16, 2025

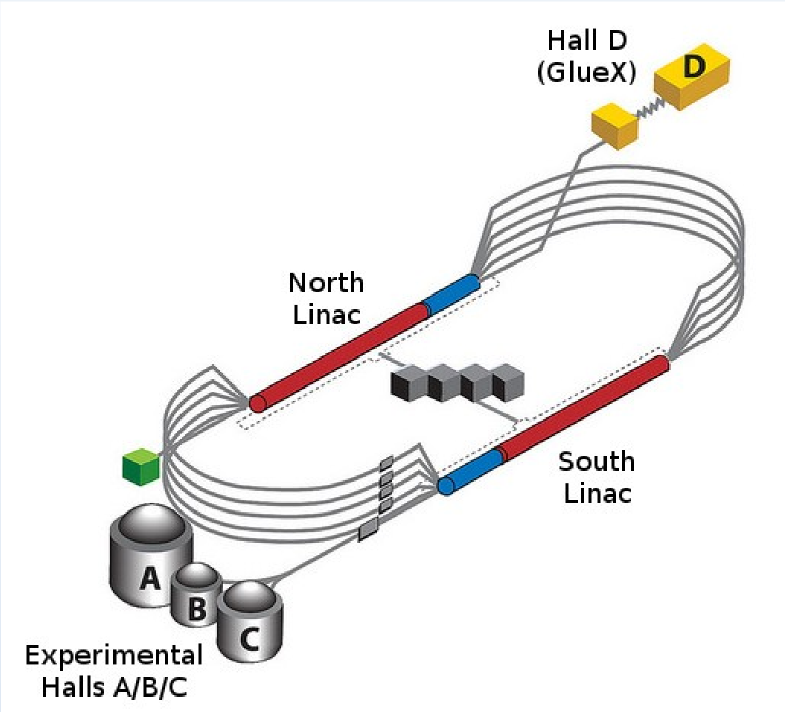
Outline

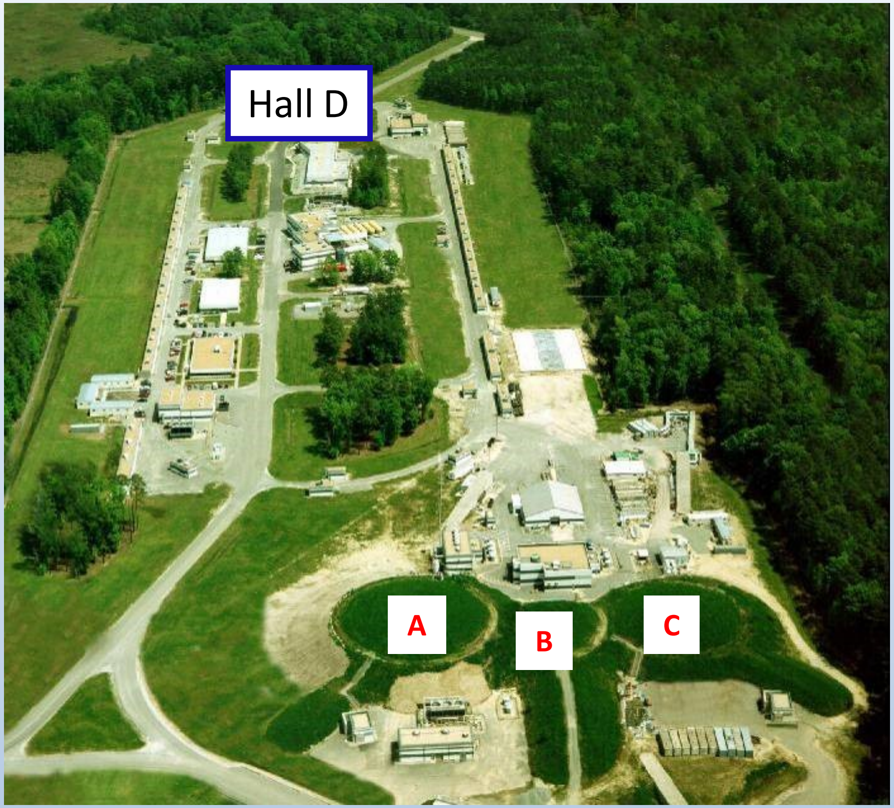
- The GlueX detector in Hall D at Jeffferson Lab
- The Jefferson lab Eta Factory (JEF) experiment
- Applications of $PbWO_4$ calorimeters
- Upgrade of the GlueX electromagnetic calorimeter
- Future plans

Jefferson Lab



Jefferson Lab





- CEBAF energy upgrade from 6 GeV to 12 GeV
- Four experimental halls: A, B, C, and D
- Hall D constructed in 2016
  - beam of linearly polarized photons

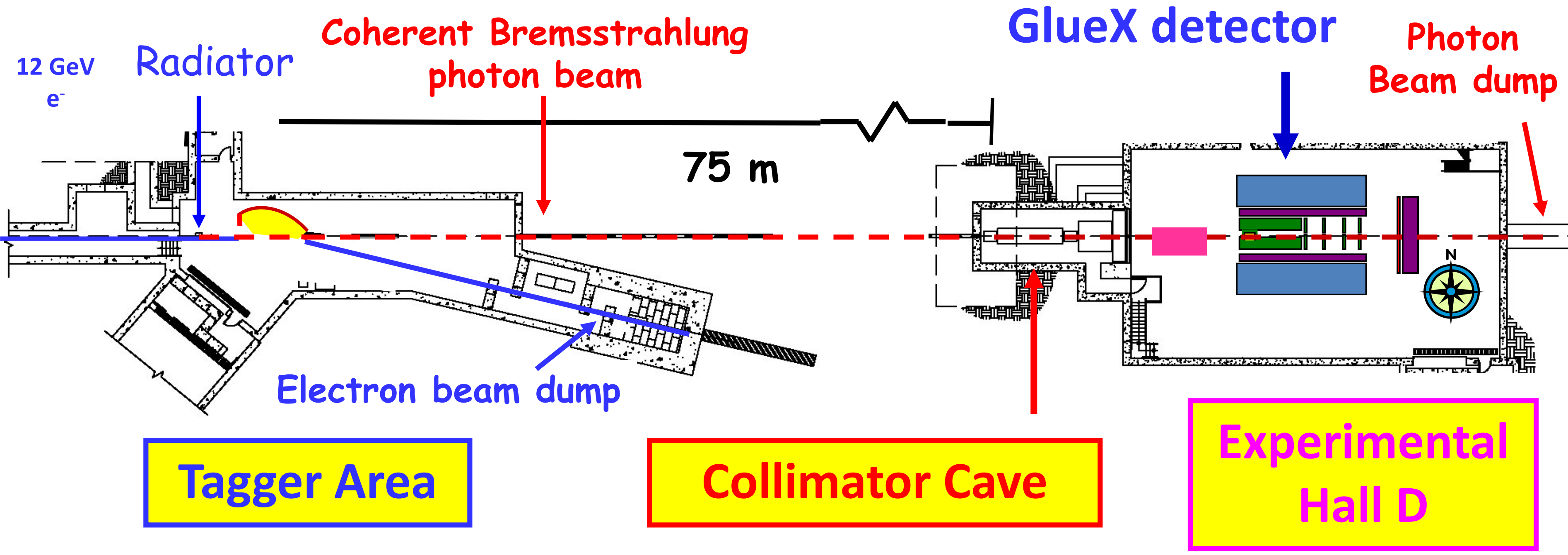
Physics Program in Hall D (Recent Experiments)

Experiment	Name	PAC Days	Target
GlueX I	Mapping the spectrum of light quark mesons and gluonic excitations with Linearly polarized photons	120	LH_2
PrimEx - η	A precision measurement of the η radiative decay width via the Primakoff effect	79	LHe_4, Be
CPP/NPP	Measuring the pion polarizability in the $\gamma\gamma \to \pi\pi$ reaction	25	Pb
SRC/CT	Studying short-range correlations with real photon beams at GlueX	15	LH_2 LHe_4 ^{12}C
GlueX II	A study of meson and barion decays to strange final states with GlueX in Hall D	220	LH_2
JEF	Eta decays with emphasis on rare neural modes: The JLab Eta Factory (JEF) experiment	100*	LH_2

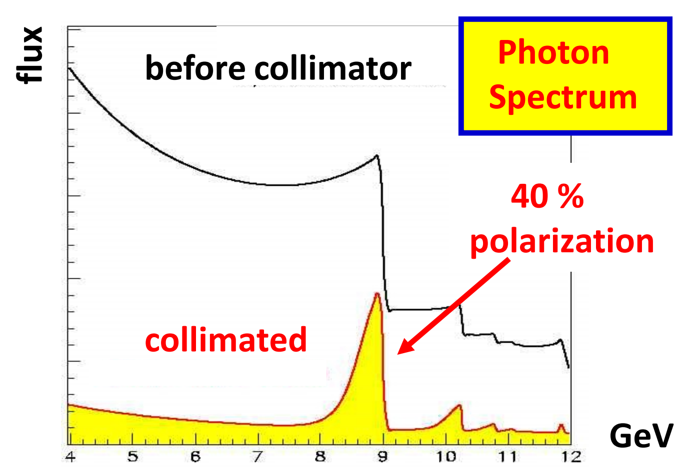
- The PrimEx-η experiment required the installation a new calorimeter
- The JEF experiment required an upgrade of the forward calorimeter in the GlueX detector

* the JEF will run in parallel with the GlueX II

Polarized Photon Beam



- Beam photons are produced by 12 GeV electrons on a thin diamond crystal (thickness: 20 – 80 μm)
- Photon energy: detect bremsstrahlung electrons
  $\Delta E / E \sim 10^{-3}$
- Pass beam photons through the collimator
  - increase the fraction of linearly polarized photons
  - current beam intensity:
    $5 \cdot 10^7$ γ/sec for $8.4 < E_\gamma < 9.1$ GeV



The GlueX Detector in Hall D

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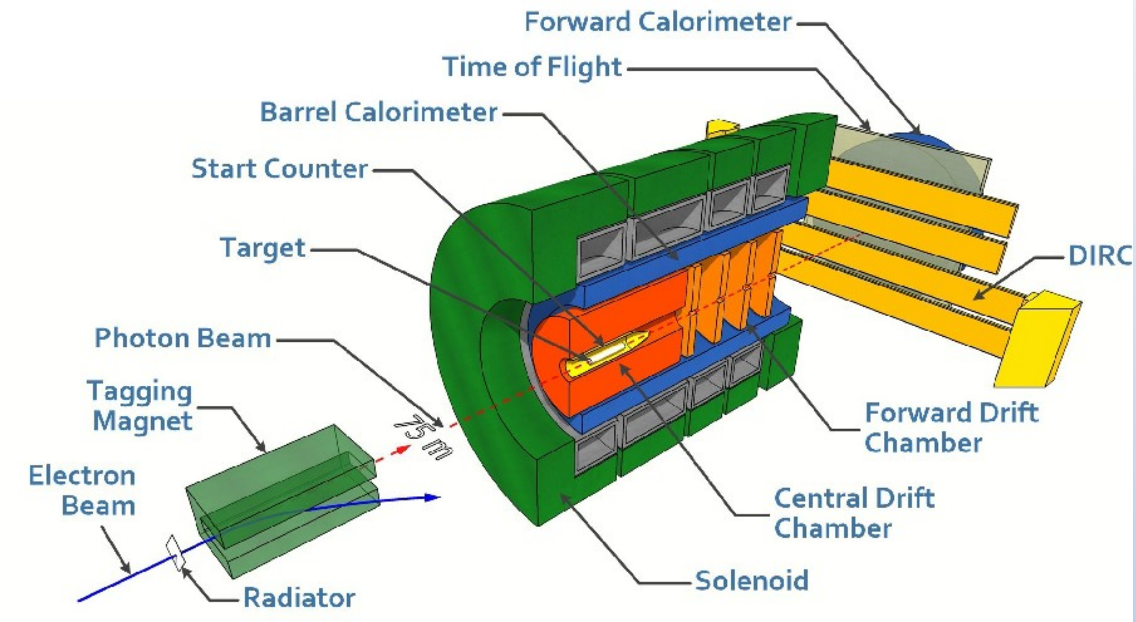

- A beam of tagged photons with energies up to 12 GeV is directed onto a fixed target
- The forward spectrometer is optimized for detecting multi-particle final states
- Nearly uniform acceptance for both neutral and charged particles
- The detector was commissioned in 2016. Several experiments have been carried out since then

The GlueX Detector

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Tracking:

- Central Drift Chamber
- Forward Drift Chamber

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

$\sigma_p / p \sim 2 - 5\ \%$

Calorimetry:

- Barrel Calorimeter

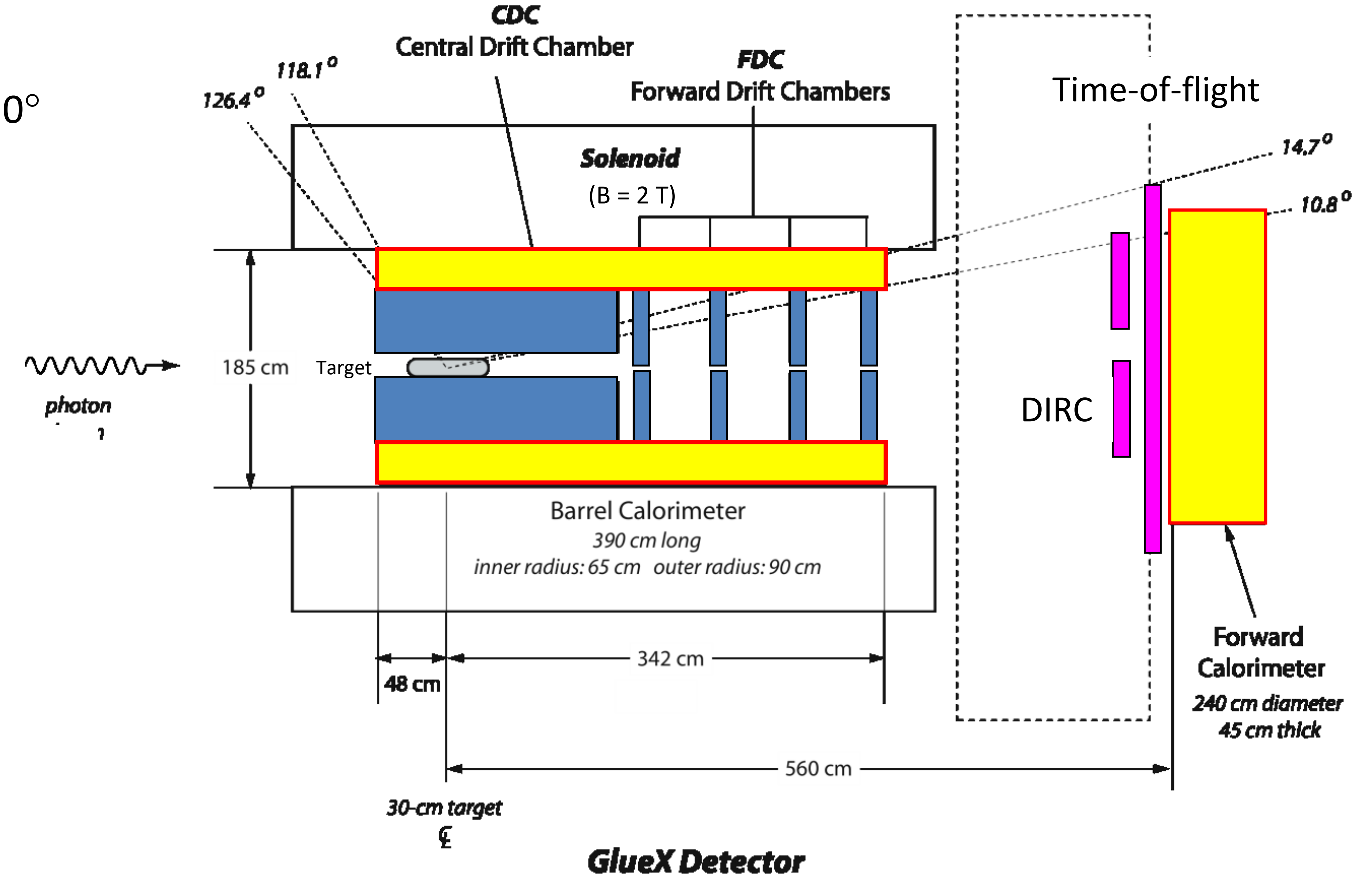
$$\frac{\sigma(E)}{E}(\%) = \frac{5.2}{\sqrt{E}} \oplus 3.6$$

- Forward Calorimeter

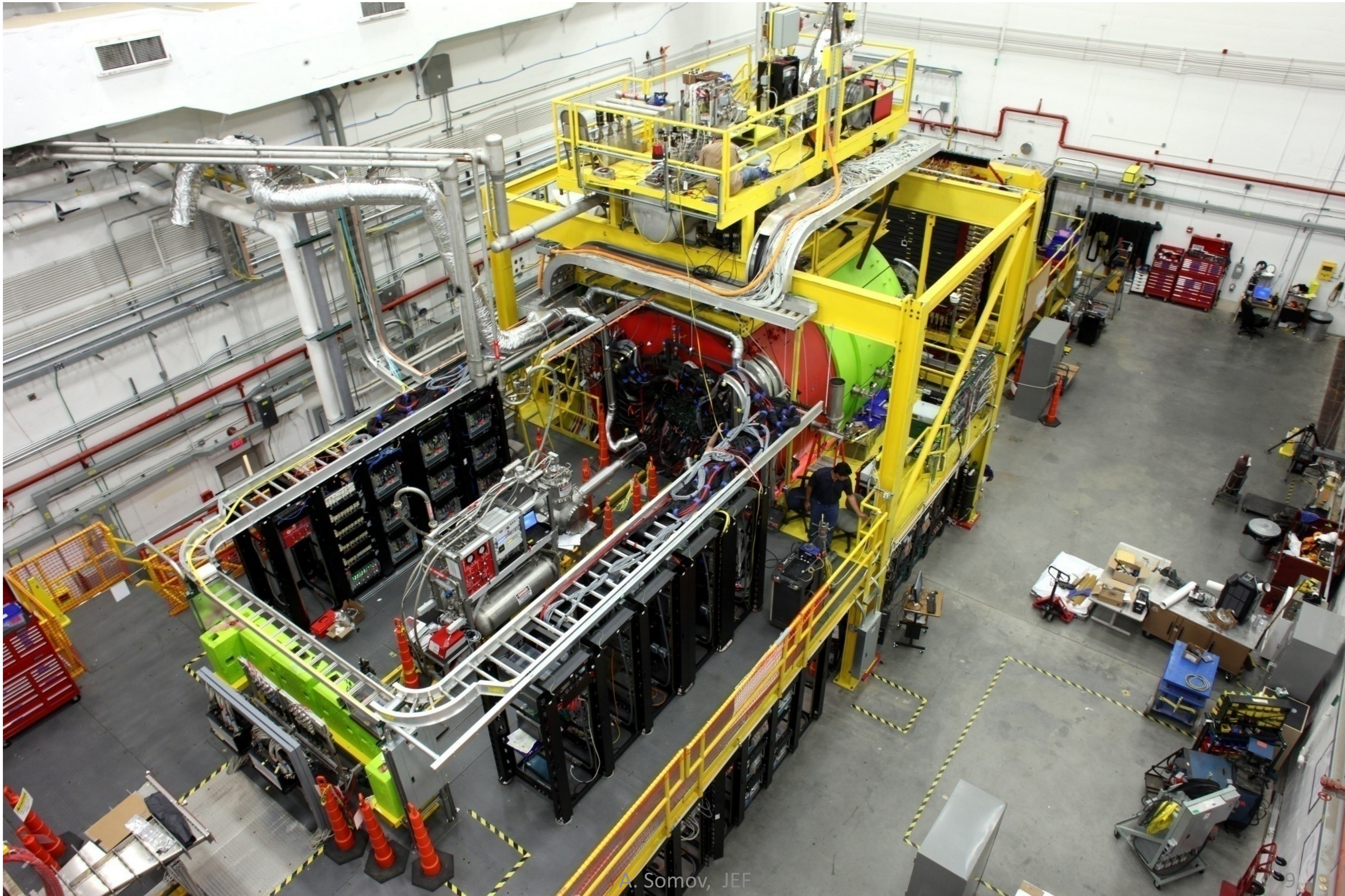
$$\frac{\sigma(E)}{E}(\%) = \frac{6.2}{\sqrt{E}} \oplus 4.7$$

PID:

- Time of Flight wall
- Start Counter
- DIRC detector



The GlueX Detector



Physics Program of the Jefferson Lab Eta Factory (JEF) Experiment

see talk by L. Gan

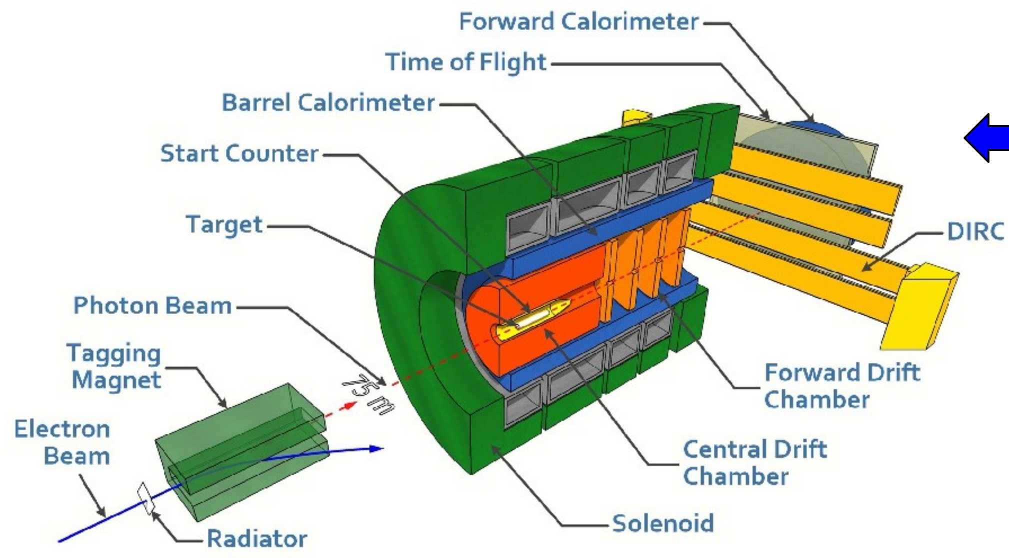
Upgrade the Forward Calorimeter

Mode	Branching Ratio	Physics Highlight	Photons
priority:			
$\pi^0 2\gamma$	$(2.7 \pm 0.5) \times 10^{-4}$	χPTh at $\mathcal{O}(p^6)$	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

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

JEF Experiment with the GlueX Detector



Upgrade Forward Calorimeter

- 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

Calorimeter Requirements for High-Intensity Experiments

- **High Energy Resolution**

- **High Granularity:**
  - important for integration into dense detector environments
  - ability to perform at high rates
  - enables good shower reconstruction

- **Radiation Hardness**:
  - withstand prolonged exposure to high radiation levels without performance degradation

- **Fast Response Time**:
  - performance at high rates

- **Thermal Stability and Light Yield**:
  - consistent performance across varying temperatures and sustained high light output

Properties of Scintillator Materials

	NaI(Tl)	CsI(Tl)	CsI	BaF_2	CeF_3	BGO	$PbWO_4$	LSO	SciGlas
Density (g/cm3)	3.7	4.5	4.5	4.9	6.2	7.1	8.3	7.4	4-5
Radiation Length (cm)	2.6	1.9	1.9	2	1.7	1.1	0.9	1.1	2.2-2.8
Moliere Radius (cm)	4.1	3.6	3.6	3.1	2.4	2.2	2.0	2.07	2-3
Light yield (γ / MeV)	41 k	60 k	1.3 k	16k	2.8	8k	240	35	1-2 k
Luminescence peak (nm)	410	560	310 (420)	310 (420)	300 (340)	480	425	420	440 (460)
Decay time (ns)	245	1220	6(30)	0.9(650)	30	300	10(30)	40	20 (450)
Radiation Hardness (krad)	2	1	> 20	1	>50	>1000	>1000	>1000	>1000

NaI (Tl), CsI (Tl) - small detector granularity, very large light yield, long decay time, low radiation hardness

BaF_2 - small detector granularity, contribution to decay time from slow scintillation component

BGO - high-granularity, slow scintillator

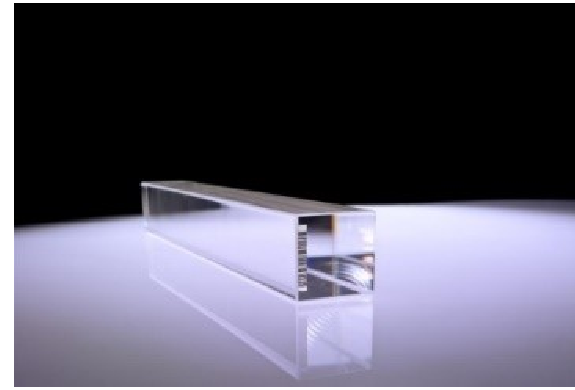
PbWO4 - high-granularity, fast response, radiation hard (ideal for high-intensity experiments)

First Crystal Calorimeters

	Crystal Ball	CLEO II	L3	Crystal Barrel	KTeV	BaBar	Belle	CB/TAPS	ALICE	CMS	HyCal
Facility	SPEAR	CESR	LEP	LEAR	FNAL	SLAC	KEK	ELSA	LHC	LHC	CEBAF
Date	1972	Late 1980s			1996	1999		2001	2005		2004
Beam	$e^+ e^-$	$e^+ e^-$	$e^+ e^-$	anti-p	kaon	$e^+ e^-$	$e^+ e^-$	photon	Ion ion	pp	photon
Energy (GeV)	4	6	100	0.1 - 2	20-220	9 + 3.1	8 + 3.5	3.5		$7\cdot 10^3$	6
Crystal	NaI(Tl)	CsI(Tl)	BGO	CsI(Tl)	CsI	CsI(Tl)	CsI(Tl)	BaF_2	$PbWO_4$	$PbWO_4$	$PbWO_4$
Modules	700	7800	11400	1380	3100	6800	8800	528	36000	76000	1152
Length (R.L.)	16	16	21.5	16.1	27	16	16	12	22	25	20

- NaI(Tl) was the first scintillator used in large-scale calorimeters; was followed by CsI(Tl)
- Increasing size of experiment, necessity to have good granularity - era of BGO (relatively slow scintillator)
- R&D for high-luminosity experiments at LHC – development of $PbWO_4$ crystals

Main Properties of $PbWO_4$ crystals



Light yield

- The typical light yield in experiments is:

  8 – 12 p.e. / MeV ($PbWO_4$ Type I)
  15 – 20 p.e. / MeV ($PbWO_4$ Type II)

- Depends on the geometry and photo sensor type

- The light yield temperature coefficient at T = 20° C:

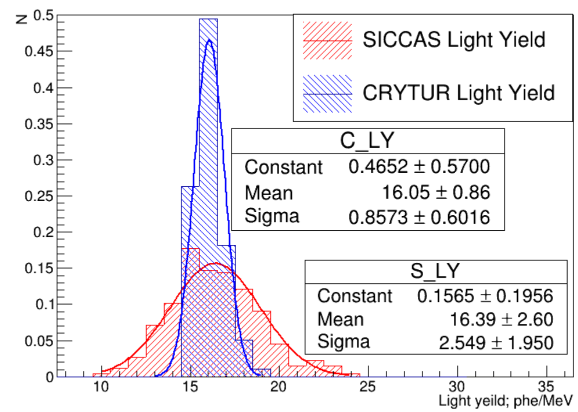
  -2 % / °C (Type I)
  -3 % / °C (Type II)

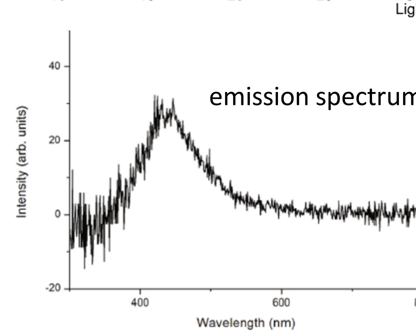
- Emission spectrum: maximum at 420 nm

- Luminescence decay time: 10 ns (80 %) 30 ns (20 %)

NIM A 956 (2020) 163375

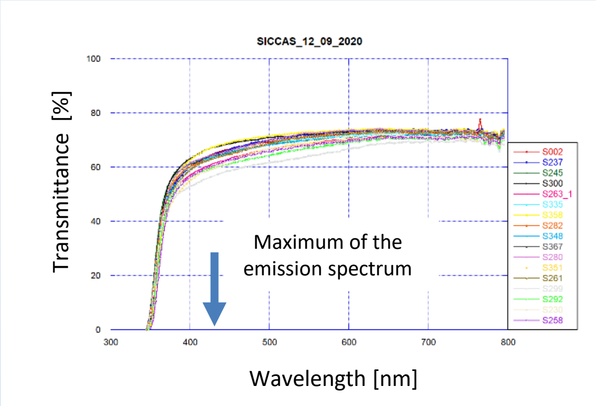
Light yield measured for crystals used at JLab





Main Properties of $PbWO_4$ Crystals

Light transmittance measured for crystals used at Jefferson Lan (for NPS and ECAL)



Optical Transmittance

- Important property of lead tungstate modules. Measured as a function of the wavelength.
- Transmittances of crystal (20 x 20 x 200 mm^3) recently used at JLab:

  360 nm: 29 % (SICCAS) 45 % (CRYTUR)
  420 nm: 64 % (SICCAS) 69 % (CRYTUR)

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Radiation Damage

- Radiation induced absorption caused by formation of color centers (related to the concentration of pre-existing defects and impurities in the crystal)
  - effects the light output, attenuation length
- Radiation induced phosphorescence (afterglow); cause increased readout noise
- Part of the damage can be recovered by optical curing (blue light)

Can be quantified by the change of transmittance

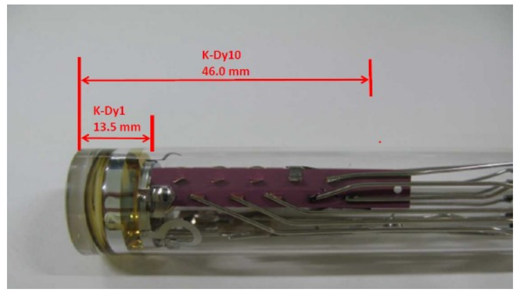
$$\delta K = \frac{\ln(\frac{T_0}{T_{RAD}})}{Crystal\ length}$$

Photodetectors for $PbWO_4$

- Several types of photo sensors have been used for the instrumentation of large-scale $PbWO_4$ calorimeters:

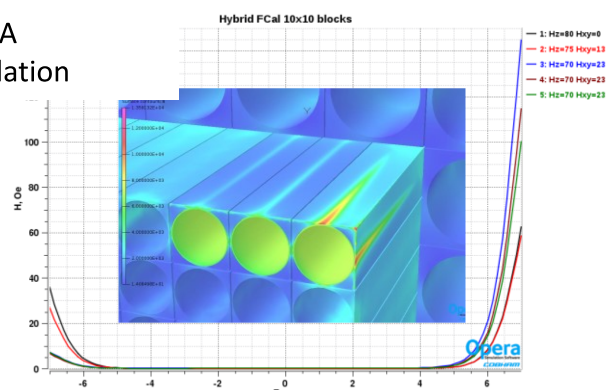
Hamamatsu R4125
Photo Multiplier (PMT)

HyCal, CCAL, NPS, ECAL calorimeters

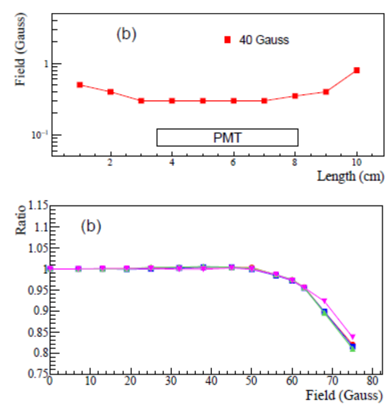


- Large and adjustable gain in a wide range
- Small noise
- Good linearity
- Radiation resistant

TOSCA Simulation



Prototype positioned inside Helmholz coils



- Cannot operate in large magnetic fields
  - optimize PMT shielding using TOSCA simulation
  - measure field using prototypes

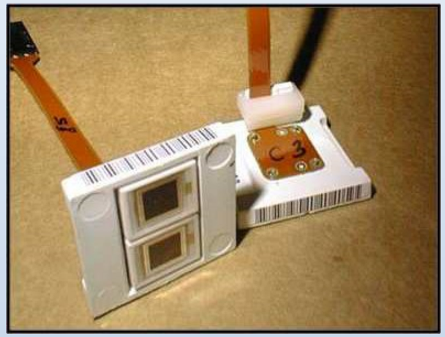
- Anode current limitations:
  - limitations at high rate (charge of 80 C results in the gain degradation of about 15 %)
  - reduce HV, use amplifier

Photodetectors for $PbWO_4$

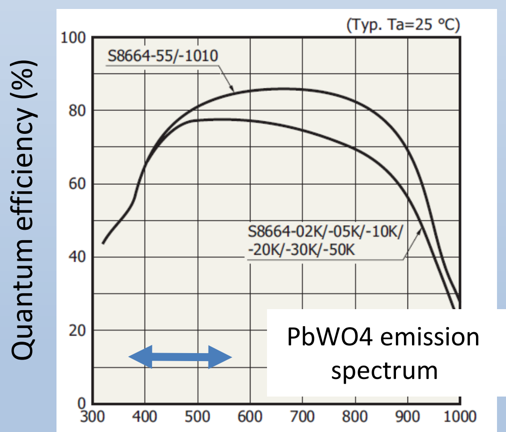
Avalanche Photo Detectors (APD)

CMS barrel calorimeter, PANDA, Forward Tagger

Two 5 x 5 mm^2 sensors used by CMS
1 cm x 1 cm APDs used for FT

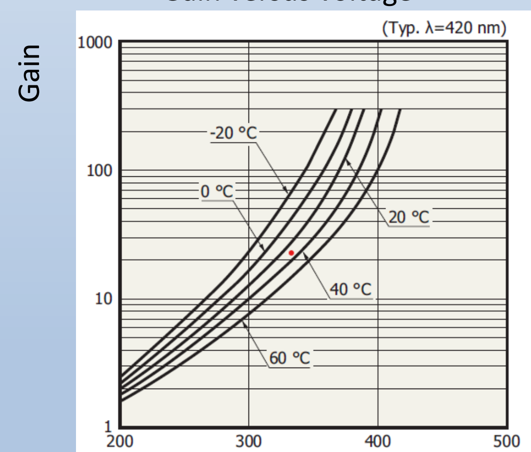


S8664-1010 LAAPD
Quantum efficiency versus wavelength



Wavelength (nm)

Gain versus voltage



Reverse voltage (v)

- Can operate in large magnetic fields
- Large quantum efficiency

- Small intrinsic gain: 50 – 200
- Amplifier with a large gain is needed
- Gain depends on temperature (temperature compensation / stabilization)
- Noise level is larger than in conventional PMTs, has to be considered
- Increase of dark current and noise due to radiation damage

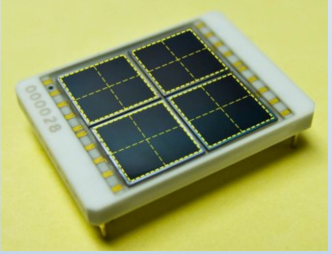
(CMS and Panda used Vacuum Photo Triodes and Tedrodes for the end-cap calorimeters)

Photodetectors for $PbWO_4$

Silicon Photo Multipliers (SiPM)

- SiPMs were used for the instrumentation of large scale calorimeters

- Barrel Calorimeter in Hall D at JLab
  - 4x4 array of 3 x 3 mm^2 sensors, Hamamatsu S12045
  - composed of 3600 50×50 μm^2 pixels
  - 3840 arrays installed on the calorimeter



- SiPMs have been chosen for the EIC backward ECAL

  -require large dynamic range and good linearity for large signals: use pixel size of 10 (15) μm

  - use a 2x2 array of 6 x 6 mm^2 Hamamatsu S1460-6010PS sensors (1.4 M pixels in total)

- Can operate in large magnetic fields
- Large intrinsic gain: $2\text{-}4 \cdot 10^5$

- Limited ability to adjust gain using bias voltage
- Gain depends on temperature (use bias voltage temperature compensation)
- Dark current rate, several Mcps per sensor, reduced when cooled down
- Dark current and noise depend on the radiation damage

Photo Detectors for $PbWO_4$

	PMT (4125)	APD	SiPM
Operation in magnetic field	Limited to small fields, shielding required	✓	✓
Gain	$10^4 – 10^6$	50 - 200	$2 \cdot 10^5$
Gain adjustability	Large range	limited	Limited
Peak sensitivity (nm)	400	600	460
Photon detection efficiency at λpeak (%)	27	70	18
Amplifier	may be required (reduce anode current)	needed (large gain)	needed (small gain)
Gain dependence on temperature	small	significant	significant
Linearity	good	good	depends on the pixel size (10 μm)
Noise	Small (kHz)	Large	Large (Mcps)
Sensitivity to radiation	Small	Moderate	Moderate

$PbWO_4$ Calorimeters

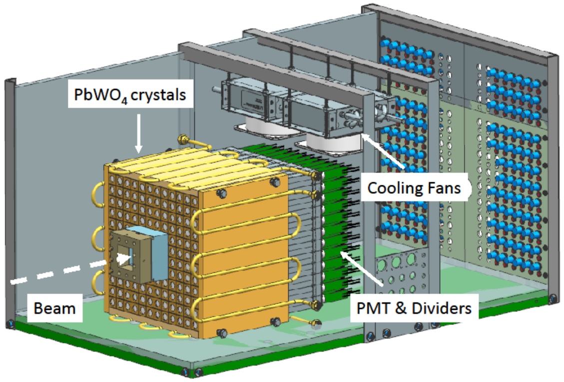
	Facility	Date	# crystals	Type	Vendor	Photo sensor
CMS	CERN	2005	75848	1	BTCP, SICCAS	APD, VTP
ALICE	CERN	2005	12544	1	BTCP	APD
PANDA	RAIR	under constr.	16000	2	BTCP	APD, VTTP
HyCal	JLab, Hall B	2004	1152 576 Pb-glass	1	SICCAS	PMT (H4125)
CLAS IC	JLab, Hall B		424	1	BTCP	APD
HPS	Jlab, Hall B	2015	442	1	BTCP	APD
Forward Tagger	JLab, Hall B	2017	332	2	SICCAS	APD
Compton Calorimeter	JLab, Hall D	2018	140	2	SICCAS	PMT (H4125)
NPS	JLab, Hall C	2022	1080	2	CRYTUR	PMT (H4125)
ECAL	JLab, Hall D	2024	1596 2360 Pb-glass	2	SICCAS, CRYTUR	PMT (H4125)
Electron Endcap	EIC, BNL	2030	3256	2	CRYTUR	SiPM

$\left.\begin{array}{l}\text{HyCal}\\ \vdots \\ \text{ECAL}\end{array}\right\}$ Jefferson Lab

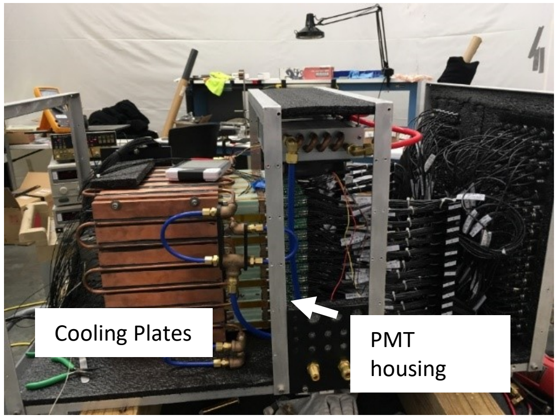
- ECAL (for JEF) is the largest $PbW0_4$ calorimeter at JLab

JEF Calorimeter Prototype

Nucl. Inst. Meth. A 1013 (2021) 165683

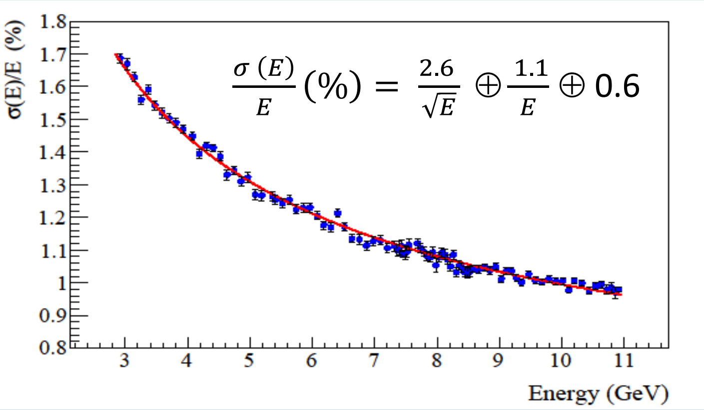


- Consists of an array of 12 x 12 modules made of SICCAS crystals
  - beam hole: 2 x 2 modules
- Used in PrimEx η experiment in Hall D in 2019, 2021, 2022 to reconstruct Compton scattering events
- Positioned on a movable platform
  - each module was inserted into the photon beam for energy calibration
- Temperature stabilization ($17^\circ \pm 0.2^\circ$ during run)
- Beam tests were used to optimize design of the PMT active base
- Instrumented with a light monitoring system, prototype of the ECAL

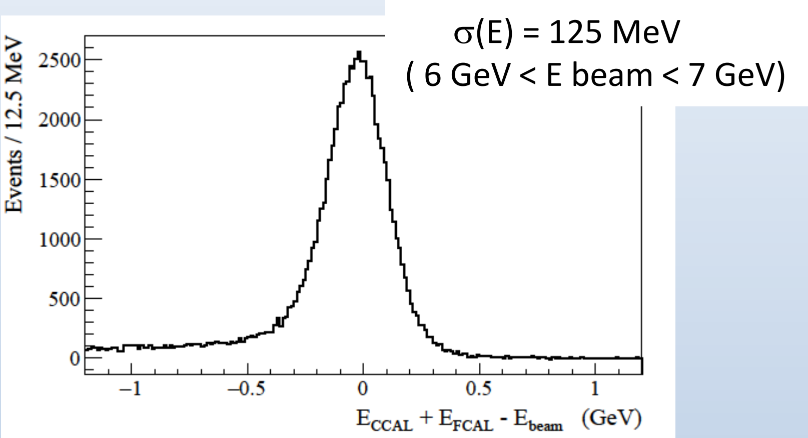


Performance during PrimEx η Experiment

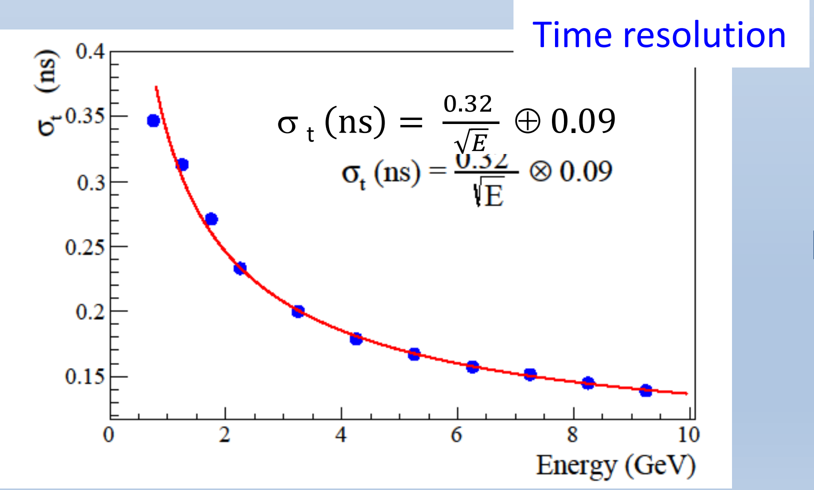
Energy resolution



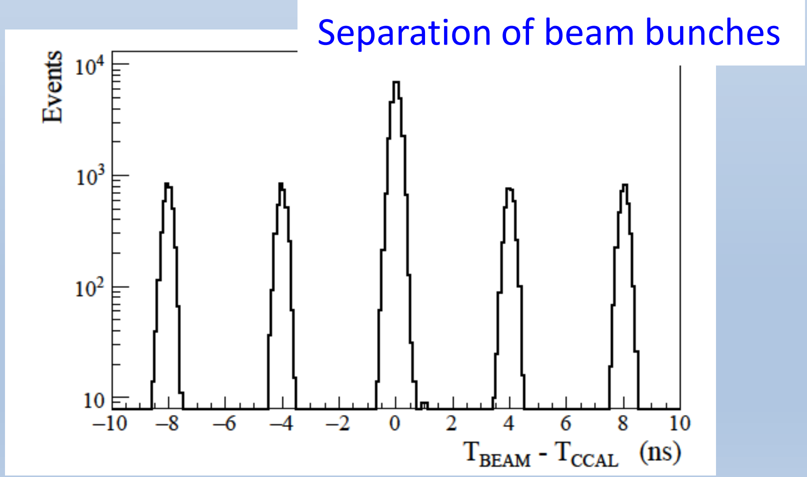
Elasticity distribution (Compton candidates)



Time resolution



Separation of beam bunches



JEF Experiment: Upgrade of the Forward Calorimeter

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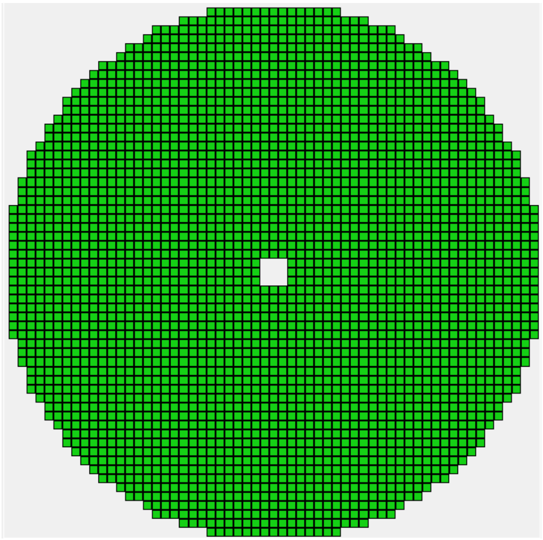
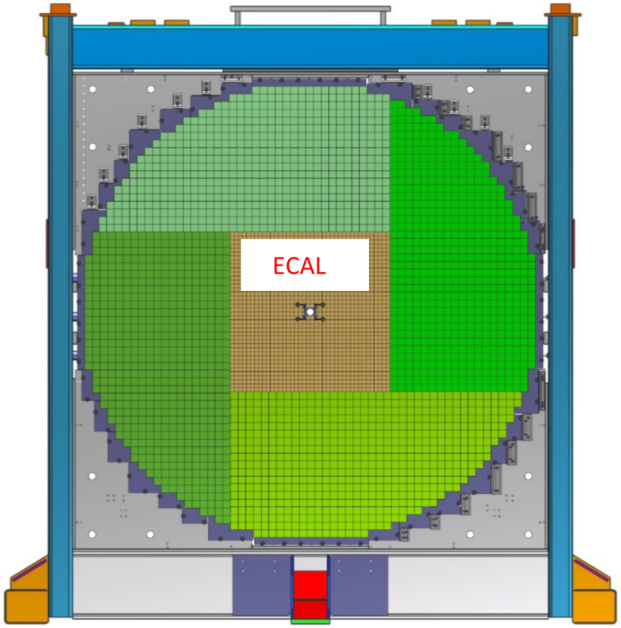


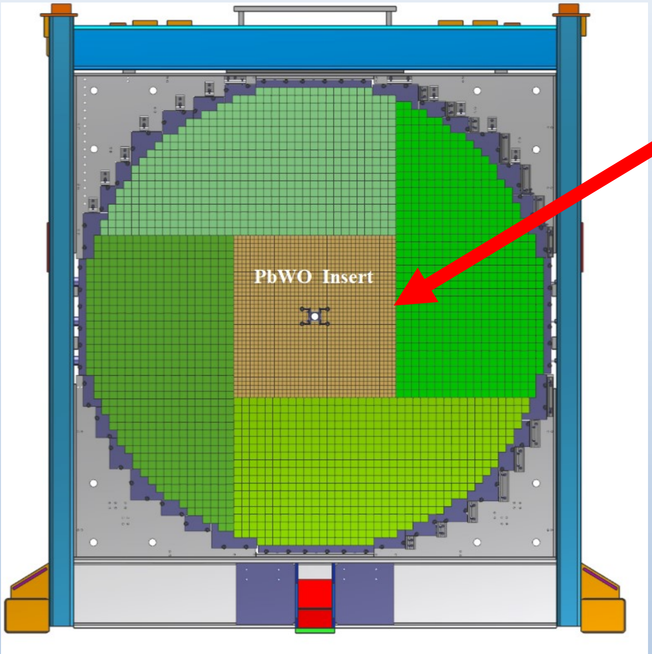


- 2800 lead glass modules
  - lead glass block size: 4 cm x 4 cm x 45 cm
  - taken from E852 experiment at BNL
- Photodetectors: FEU 84-3 PMTs with Cockroft-Walton bases
- The energy resolution: $\frac{\sigma(E)}{E}(\%) = \frac{6.2}{\sqrt{E}} \oplus 4.7$

- Replace lead glass modules in the inner part of the detector with high-granularity high-resolution lead tungstate scintillating crystals

Eta Calorimeter (ECAL)

Lead Tungstate Eta Calorimeter (ECAL)



- ECAL consists of an array of 40 x 40 $PbWO_4$ (1596) modules
  - 2 cm x 2 cm x 20 cm $PbWO_4$ crystal
  - 4 cm x 4 cm x 45 cm   lead glass block

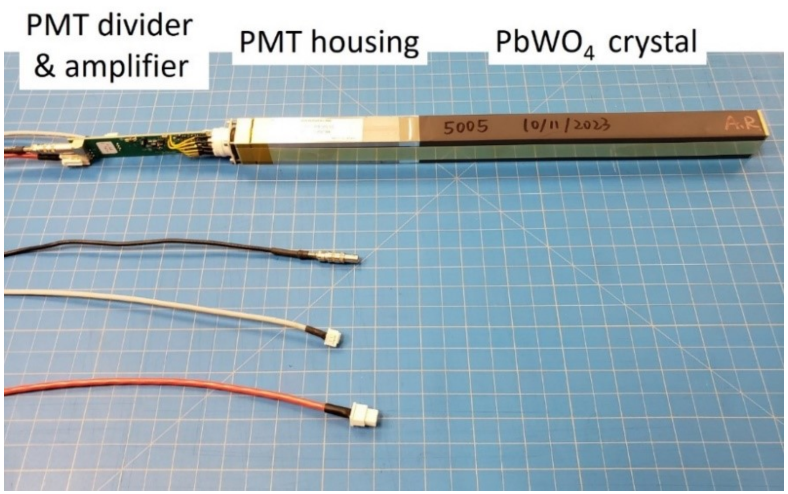
Lead Glass & $PbWO_4$ modules

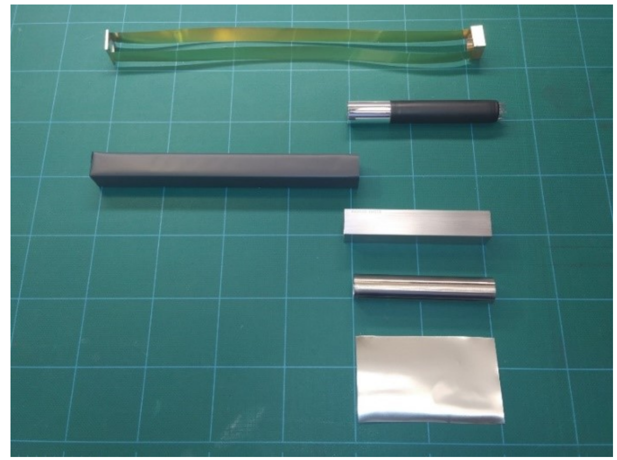
- A factor of 4 better detector granularity
  - significantly improve shower separation
- Improves the energy and position resolutions by about a factor of 2

<u>ECAL installation required:</u>

- removing all lead glass blocks
- modifying the detector mounting frame, installing cooling blocks
- installing lead glass and lead tungstate modules
- the construction of the ECAL has started in 2022, the installation was completed in July 2024

ECAL Module Design





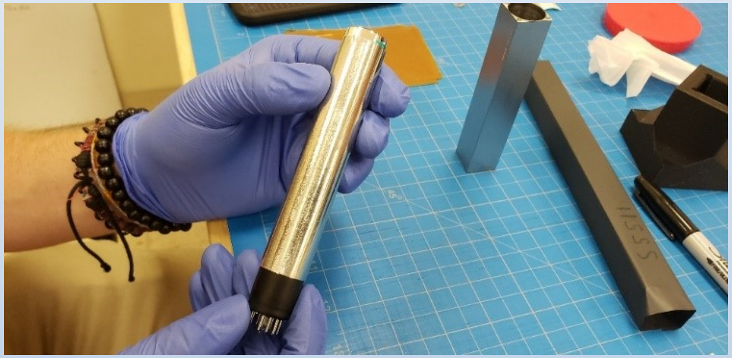
- $PbWO_4$ crystal wrapped with the 65 μm thick ESR reflective foil and light-tight Tedlar
- Hamamatsu R4125 PMT placed inside the 350 μm and 50 μm mu-metal cylinders and soft iron housing
- 3.5 cm long light guide (18.5 mm diameter) is glued to the PMT and coupled to the crystal using a silicon cookie
- PMT divider attached to the socket

Fabrication of ECAL Modules at Jefferson Lab

- A total of 1,620 calorimeter modules were fabricated at Jefferson Lab with the project began in 2022

Wrapping modules with the ESR and Tedlar

Installation of PMT

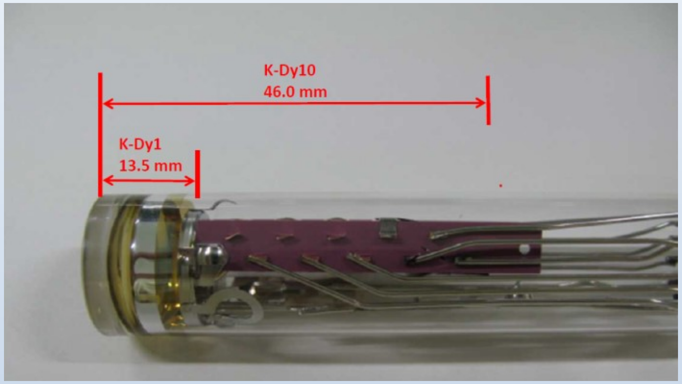


Module fabrication

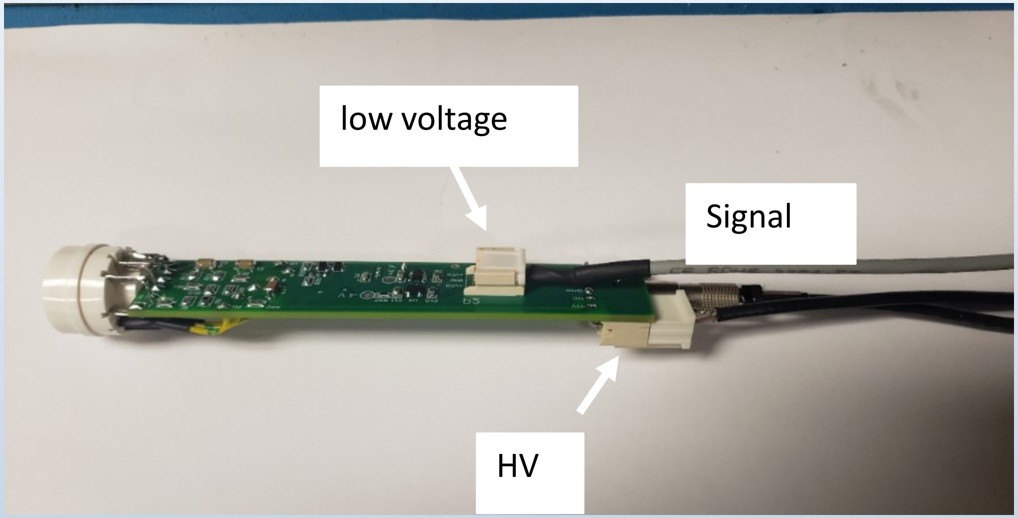
Final quality check

Active Base for Hamamatsu 4125 PMT

Hamamatsu R4125 PMT



Active Base for PMT

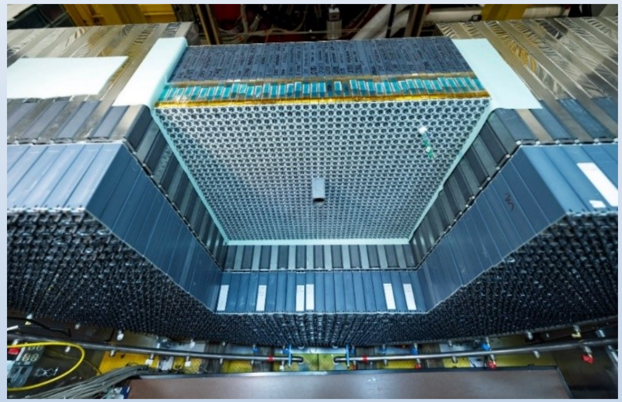


- Designed at JLab
- Modified the original Hamamatsu voltage divider by adding two bipolar transistor to the last two dynodes
  - gain stabilization at high rate
- Added an amplifier positioned on the same PCB with the divider
  - lower the PMT operating voltage and reduce the anode current. Prolongs the PMT's life
  - requires to supply $\pm$ 5 V
- Switches on the PCB allow to by-pass the amplifier
  - enable amplifier on layers around the beam
- Three cables are connected to each divider: signal, LV, and HV

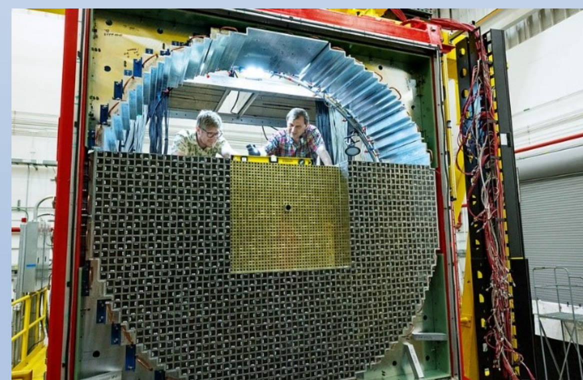
Detector Installation in Hall D

Detector installation: July 12 – Oct 6, 2023 (3 months)

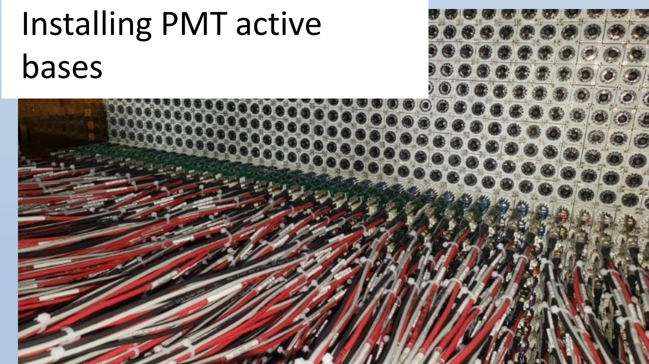
First module installed



Installing $PbWO_4$ modules

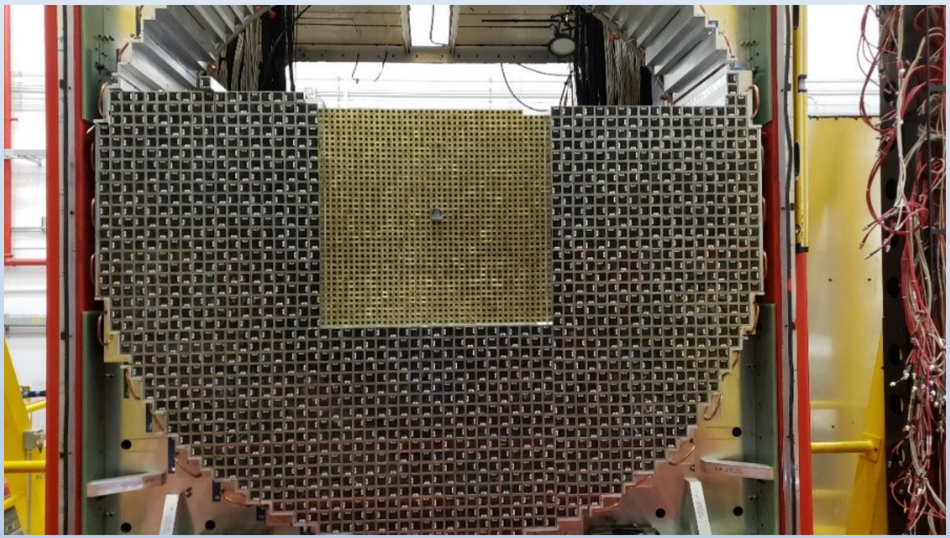


Installing PMT active bases

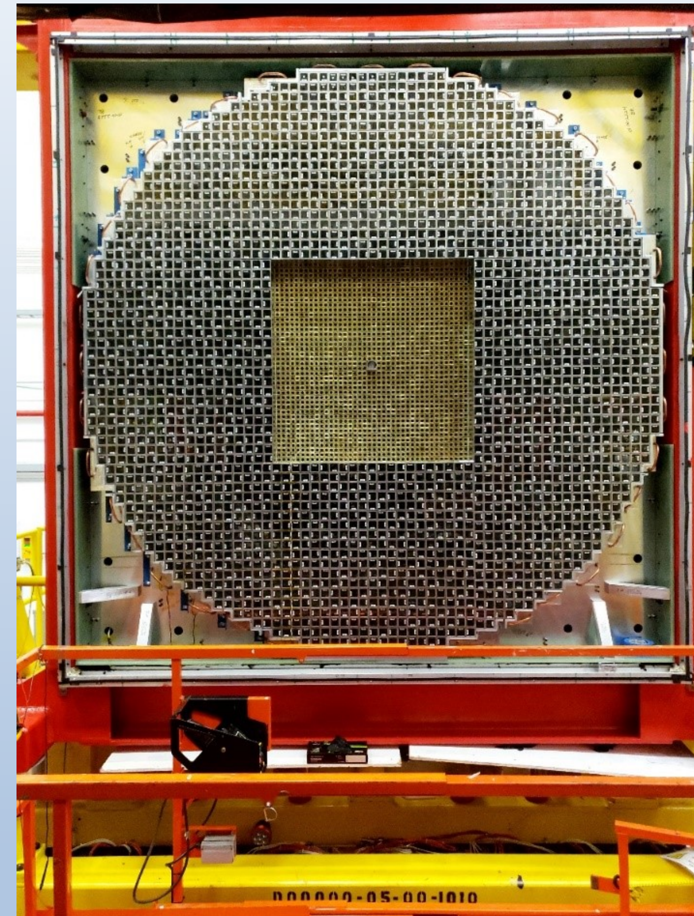


Detector Installation

September 20, 2023



October 6, 2023

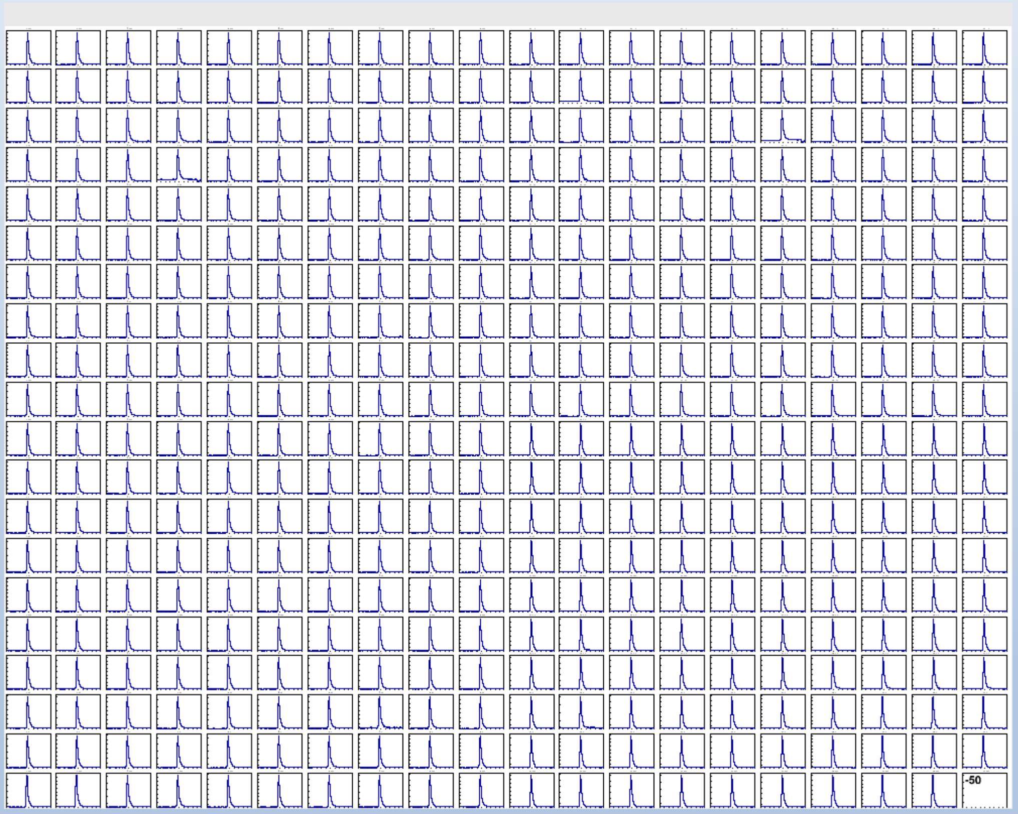


- Completed installation of the whole detector by October 6, 2024

EPJ Web Conf. 320 (2025) 00058

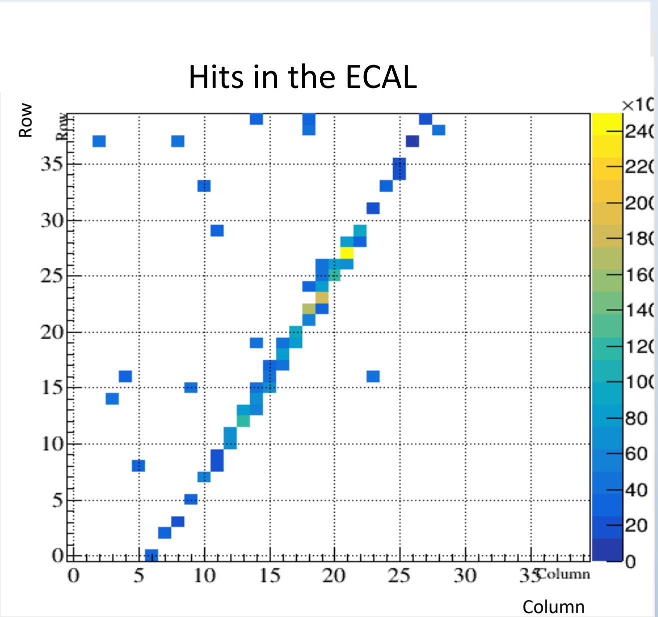
ECAL Commissioning Without Beam

- Test using light monitoring system
- Read out digitized signal waveforms

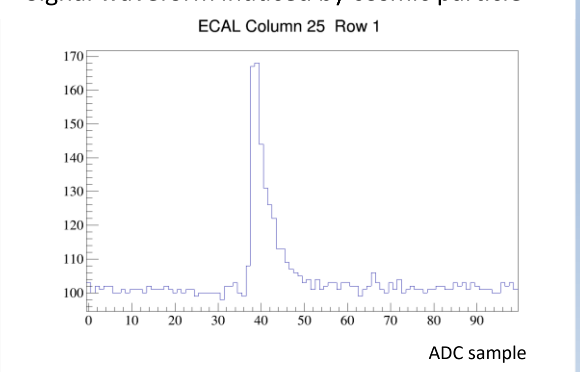


One quadrant of the ECAL, corresponding to 25% of the total modules

- Use cosmic rays to check the ECAL and perform initial gain calibration



Signal waveform induced by cosmic particle



Setting ECAL Voltages Using Compton Scattering Events

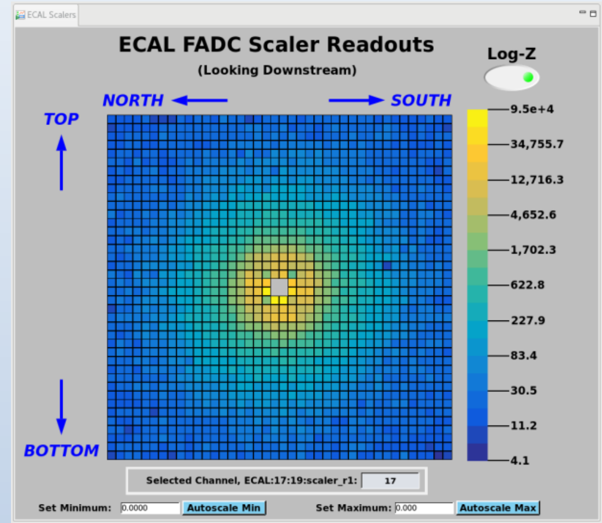
Set high voltages on the ECAL to equalize PMT gains

Step I

- Use Compton scattering data to determine a global scaling factor for high voltages. Refine individual HV settings in the inner part of the detector

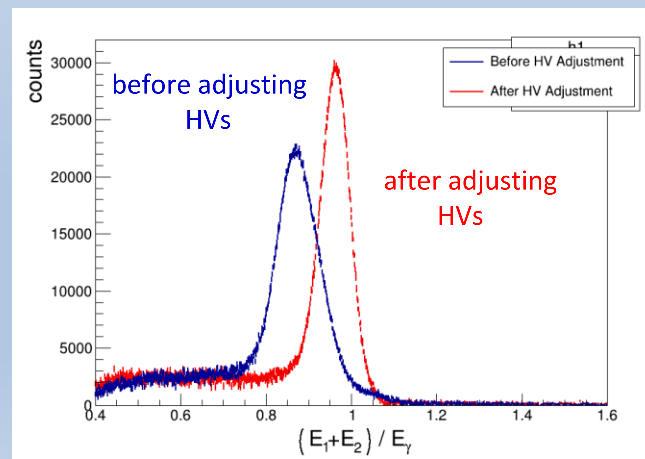
Step II

- Refine voltages and calibrate gains using π^0

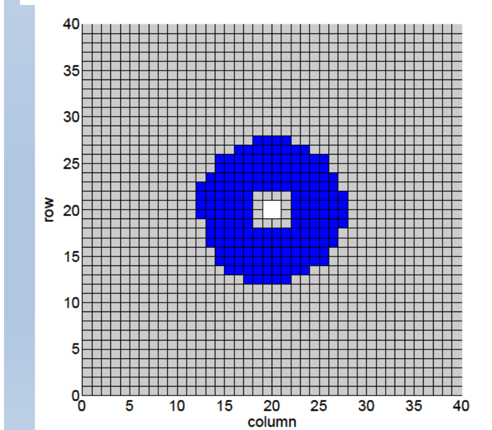


Compton Scattering

- Two body final state
- Constrain reconstructed energy to the beam energy



ECAL coverage for Compton events



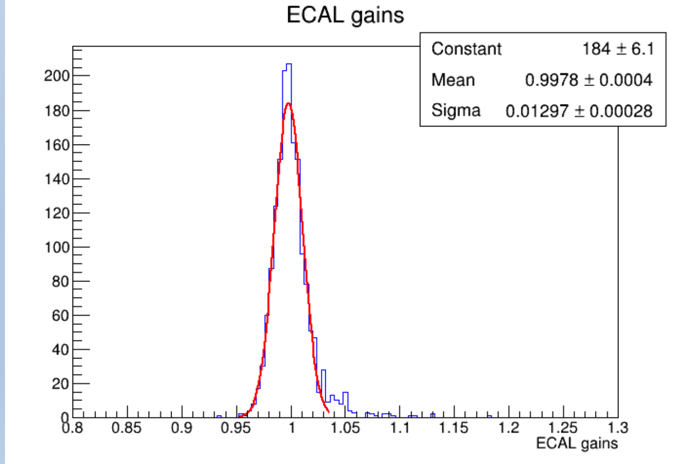
Setting ECAL Voltages Using π^0

- High voltages were subsequently adjusted using the π^0 peak as a reference

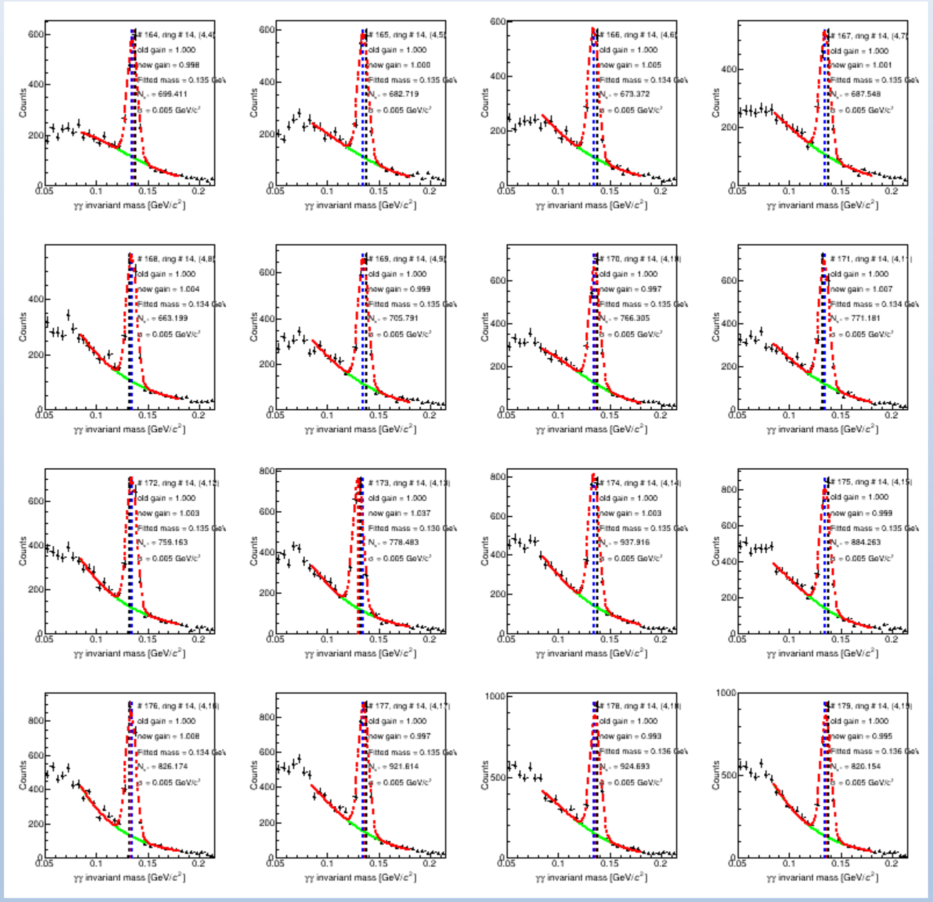
  - PMT gains for individual modules were calculated to align the reconstructed π^0 mass with its nominal value

- Clear π^0 peaks observed in all ECAL modules

- After the final HV iteration, the spread of the gain distribution is approximately 1.3%



An example of π^0 peaks seen in the ECAL modules

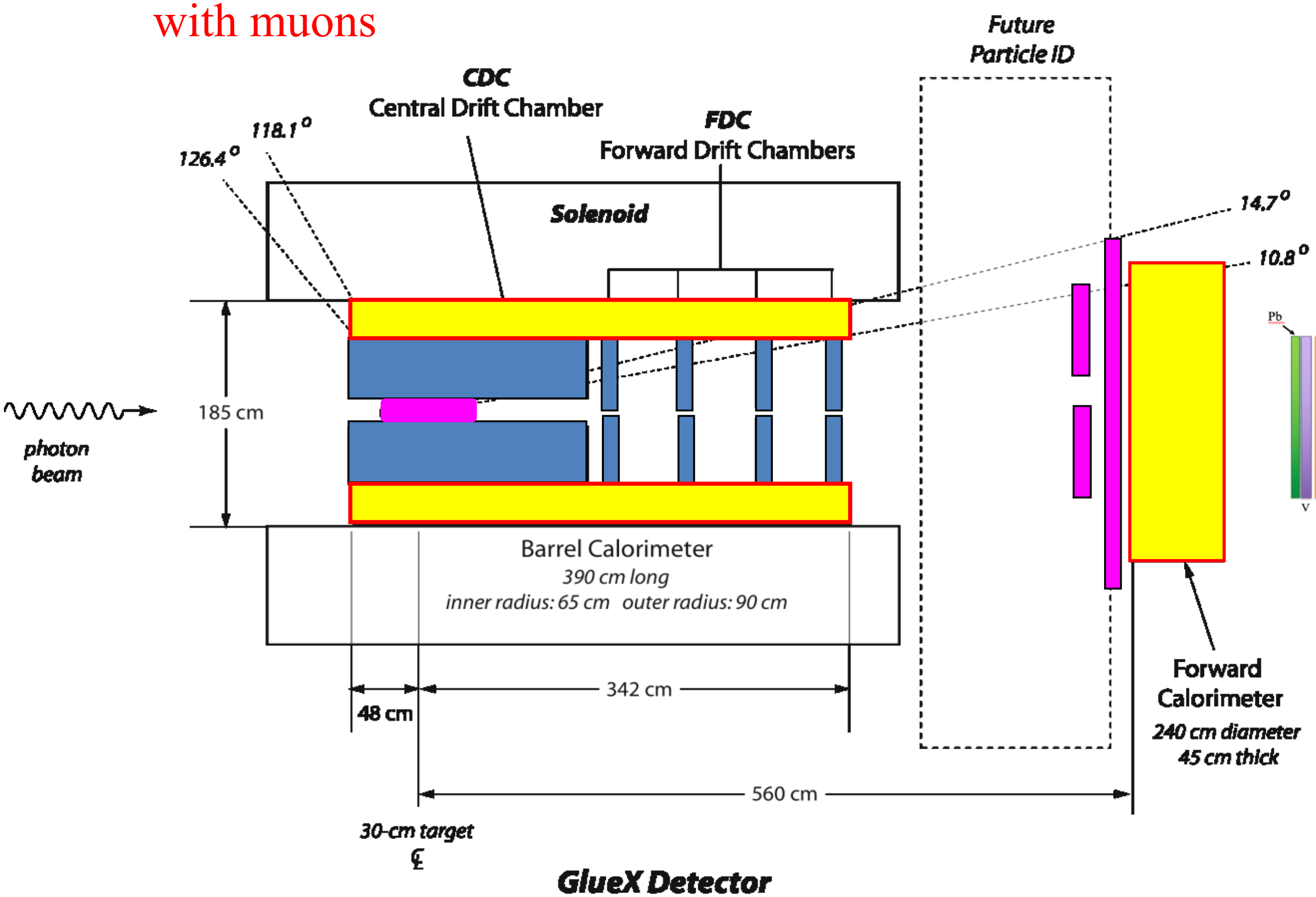


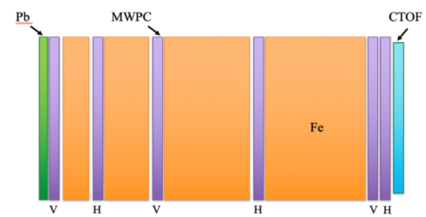
m ($\gamma\gamma$) GeV

Future Plans

GlueX Upgrade with Muon Detector

- Study feasibility of extending the JEF physics program by reconstructing final states with muons



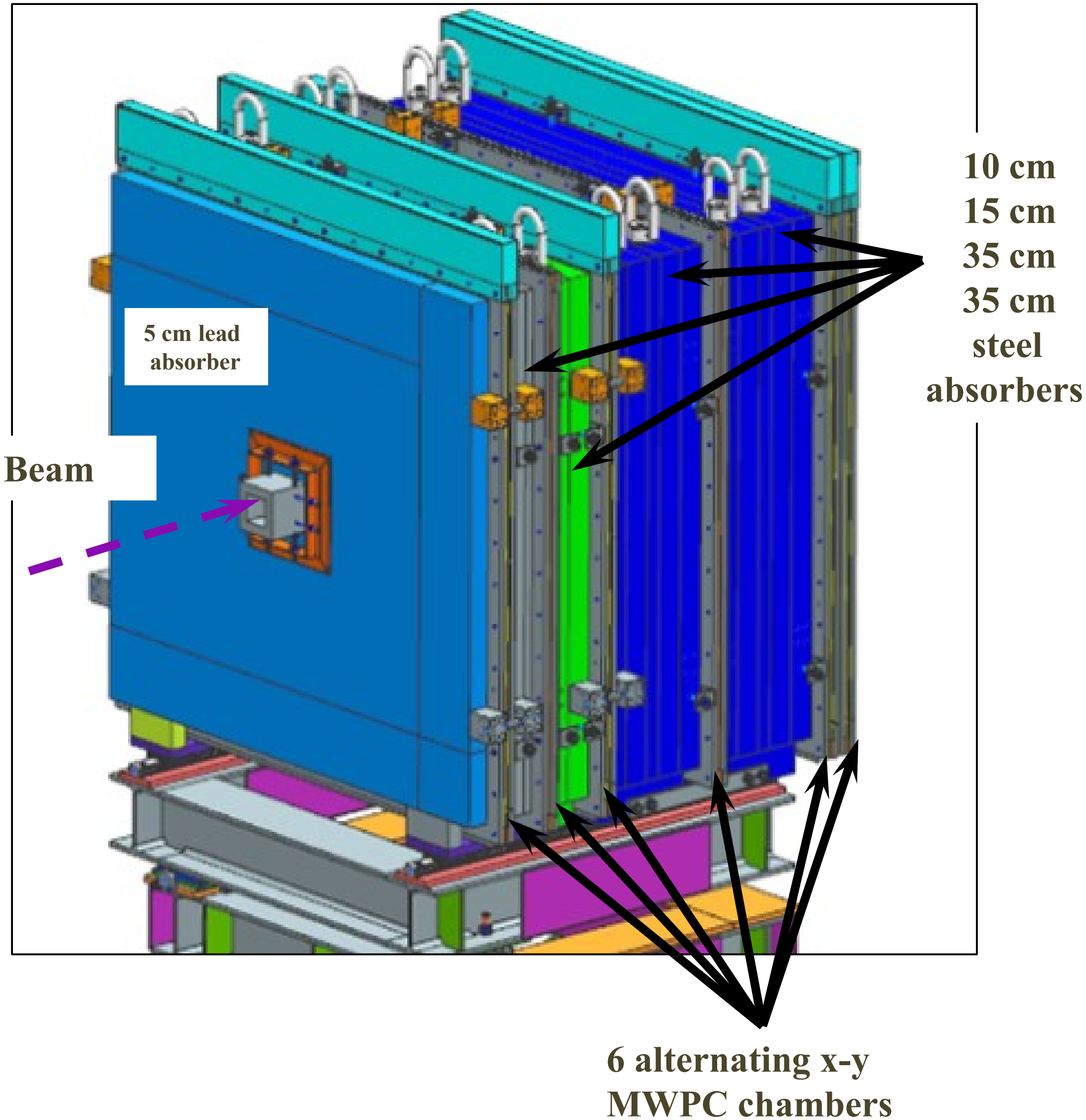


Muon detector
for π / μ separation

Effective size:
150 cm x 150 cm

- The muon detector was build by the UMass group
- It was used during the CPP / NPP experiment in 2022

Muon Detector



- 6 MWPC planes installed between of iron walls
- 144 channels in each plane
  - sense wires read out via flash ADC
- operated at ~1780 V
- 90 % Ar + 10 % CO_2 gas mixture
- the detector exists, readout electronics is needed (~$200 k)
  - may use flash ADCs designed by Julich group for PANDA
  - use open VPX crate

Summary

- The goal of the JEF experiment in Hall D is to perform precision measurements of various η and η' decays, with a primary focus on rare neutral decay modes
- The experiment required upgrading the forward calorimeter of the GlueX detector
- The unique properties of lead tungstate ($PbWO_4$) crystals make them the material of choice for calorimeter instrumentation in many high-intensity experiments, including GlueX
- Construction of the new lead tungstate calorimeter began in 2022. A total of 1,596 modules have been fabricated and successfully installed on the GlueX detector
- The JEF experiment will run in parallel with GlueX-II and began taking data in April 2025
  - the new calorimeter is currently being successfully commissioned.
- We are exploring the feasibility of extending the JEF physics program by installing a muon detector, which may enable or improve the reconstruction of $\eta^{(\prime)}$ decays to final states involving muons.
- We expect to collect a large data set in the coming months. Join us if you're interested!

Backup Slides

Future Experiments in Hall D

Experiment	Name	PAC Days	Target
KLF	Strange hardon spectroscopy with secondary KL beam In Hall D	200	LH_2
REGGE	Measurement of the high-energy contribution to the Gerasimov-Drell-Hearn sum rule	33	
GlueX III	Photoproduction of charmonia at high luminosity	200	LH_2

- The experiments have been approved but are not yet scheduled

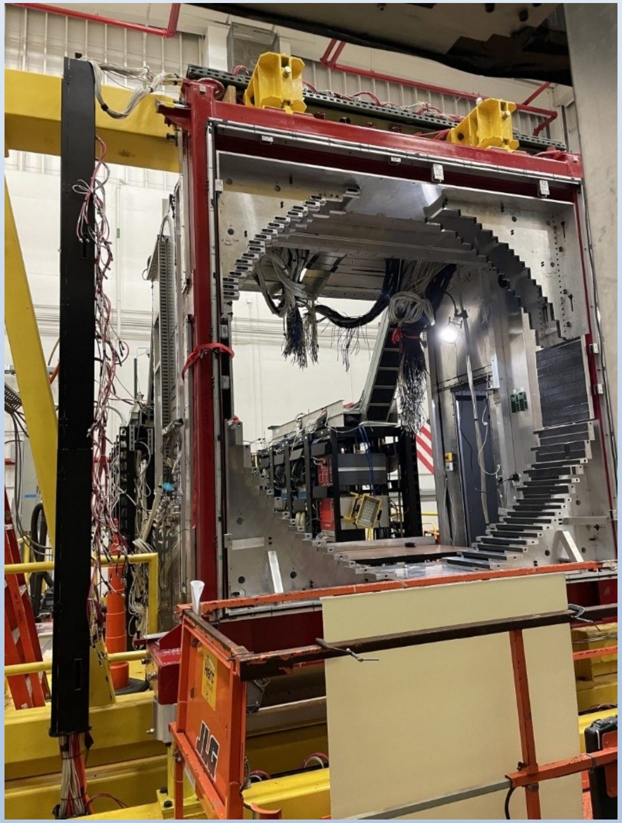
Crystal Quality Specifications

Parameter	CMS	HYCAL	NPS	ECAL	PANDA	EIC
Crystal vendor	BTCP/SICCAS	SICCAS	CRYTUR	SICCAS/CRYTUR	BTCP/CRYTUR	CRYTUR
Light Yield p.e./Mev	>8	>8	>15	>12	>16	>15
Decay time LY(100ns)/LY(μs) (%)	>90	>90	>90	>90	>90	>90
Longitudinal transmission						
360 nm (%)	>25	>25	>35	>25	>35	>35
420 nm (%)	>55	>55	>60	>55	>60	>60
620 nm (%)	>65	>65	>70	>65	>70	>70
Transverse transmission $\delta\lambda$ (nm) at T = 50%	<3	<5	<5	<5	<3	<5
Induced radiation absorption δK for integral dose > 100 Gy	<1.6	<1.5	<1.1	<1.5	<1.1	<1.1
Tolerances for sides (μm)	<±50	<±50	<±50	<±50	<±50	<±50
Tolerances for length (μm)	<±100	<±100	<±150	<±100	<±50	<±150
Tolerances in rectangularity (degree)	<0.12	<0.1	<0.1	<0.1	<0.1	<0.1
Surface polishing, roughness (μm)	<0.02	<0.02	<0.02	<0.02		<0.02

Disassembling Lead Glass Calorimeter

Removing lead glass modules

All modules removed

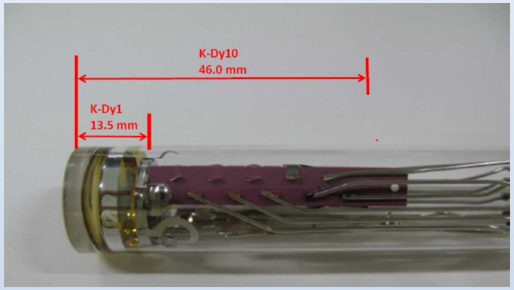


Magnetic Shielding for Hamamatsu R4125 PMT

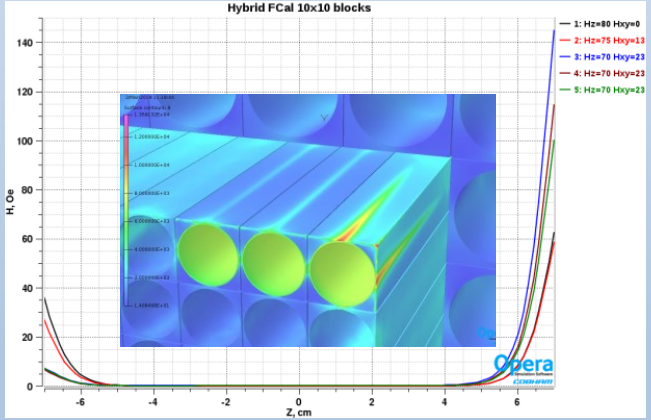
- Fringe field of the GlueX solenoid magnet
  maximum B_z ~ 50 Gauss, B_r < 10 Gauss

  - optimize PMT shielding using TOSCA simulation

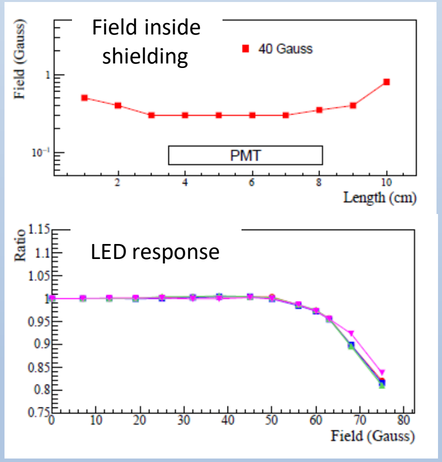
  - study shielding using prototypes positioned into Helmholz coils.
    Check performance in the field using LED



TOSCA Simulation



Prototype positioned inside Helmholz coils



- Extend PMT shielding above the face of the photo cathode
  - 3.5 cm long acrylic light guide with a diameter of 18.5 mm

- PMT is placed inside the soft iron housing (AISI 1020 steel)

- Two layers of mu-metal cylinders with the thickness of 350 μm and 50 μm

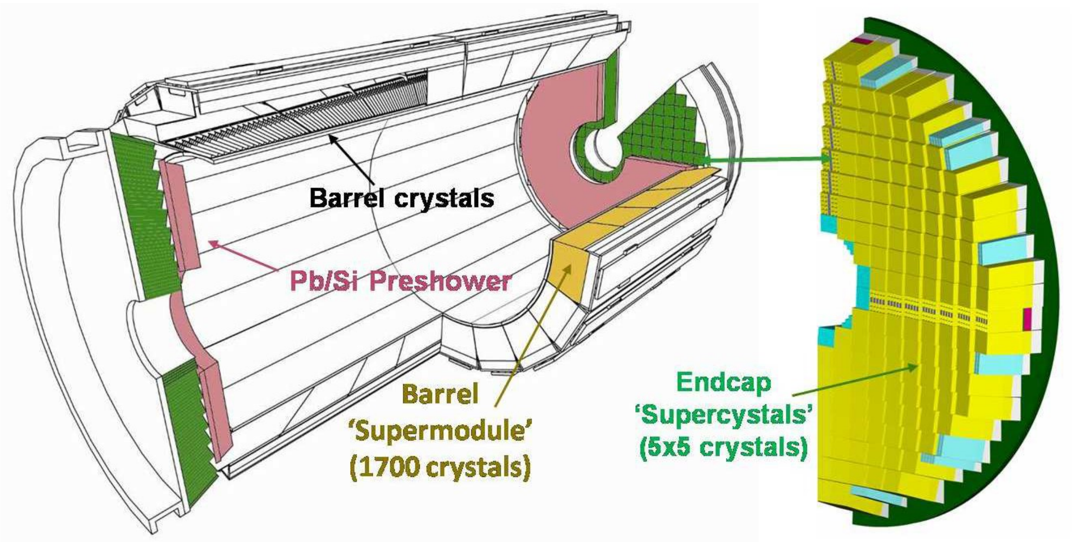
CMS Electromagnetic Calorimeter

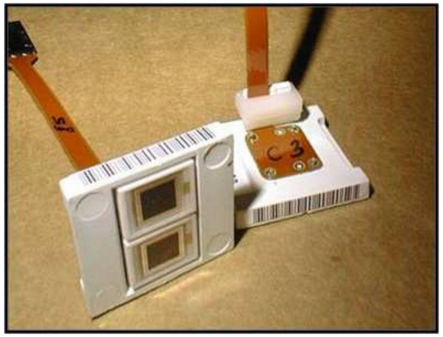
Barrel: 61200 crystals
tapered 22 mm face 26 mm rear face,
23 cm long 26 R.L.

Endcap: 14648 crystals
28.6 mm front, 30 mm rear face,
22 cm long 25 R.L.

$PbWO_4$ crystals type 1, light yield ~10 p.e./MeV

Crystals produced by BTCP and SICCAS





Barrel:

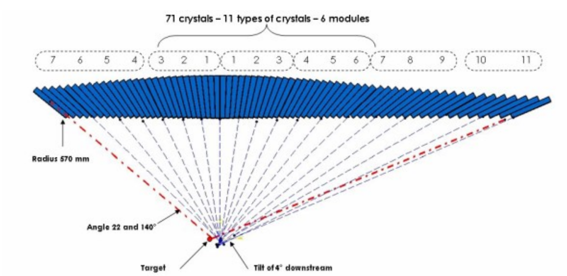
Two APDs, 5 mm x 5 mm, gain 50 (at 18° C), bias voltage 340 – 400 V
Quantum efficiency 75 % at 430 nm, gain dependence: 3.1 % / V, -2.4 % /C

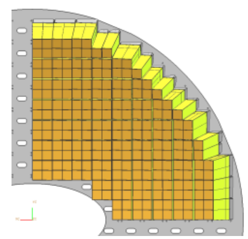
Endcap:

Vacuum Photo Triodes (VTP), Q.E. 22 % at 430 ns

PANDA Experiment

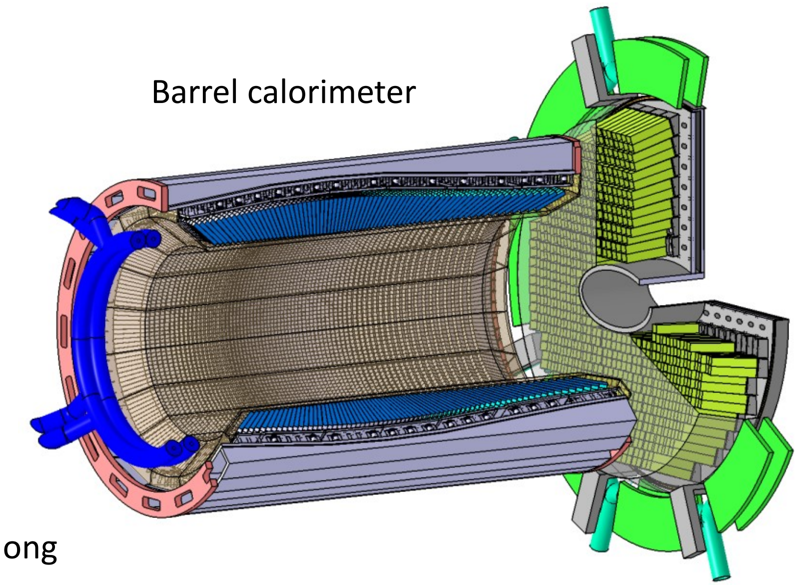
Barrel: 11360 crystals
tapered, several groups, average dimensions
21 mm face 27 mm rear face, 22 cm long 22 R.L.





Forward endcap

Barrel calorimeter



Endcaps: 3856 crystals in forward endcap
tapered, 24.3 mm and 26 mm front and rear faces, 26 cm long
586 crystals in backward endcap (straight)

- About half of the crystal produced by BTCP (switch to CRYTUR)
- Photo sensors:
  - 2 Hamamatsu LAAPD (S11048) per module
  - Hamamatsu Vacuum Photo Tetrodes (R11375-MOD) for the inner part of endcap

- PANDA calorimeter motivates R&D for the PbWO4 Type II crystals
- The calorimeter will be operated at -25° C (about a factor of 4 larger photon yield)

Hybrid Calarimeter (HyCal)

- Constructed for the PrimEx experiment in Hall B
  to measure decay width of $\pi^0 \rightarrow \gamma\gamma$

- First physics run in 2004

- Hybrid Pb-glass $PbWO_4$ calorimeter:
  - array of 34x34 PbWO4 modules (2.05 x 2.05 x 18 cm^3)
    1152 modules in total
  - surrounded by 576 Pb-glass (3.82 x 3.82 x 45 cm3) modules

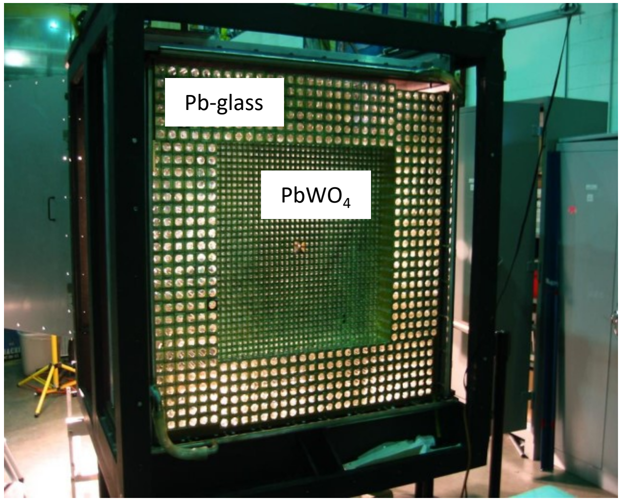
- No magnetic field

- Photo detectors :
  - R4125 photomultipliers ($PbWO_4$)
  - FEU-84-3
  - boosted dividers (supply additional voltage to last dynodes) to improve performance at high rate

- Temperature stabilization at 17° C (± 0.2°C)

- Subsequently used in the Proton Radius Experiment in Hall B at JLab (2016)

HyCal Detector



Energy resolutions:

$$\frac{\sigma(E)}{E}(\%) = \frac{2.5}{\sqrt{E}} \oplus \frac{1}{E} \oplus 0.9 \qquad PbWO_4$$

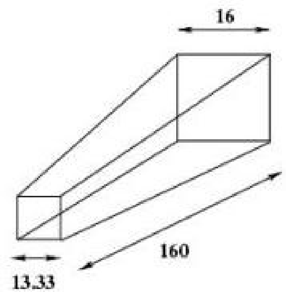
$$\frac{\sigma(E)}{E}(\%) = \frac{5.4}{\sqrt{E}} \oplus \frac{2.3}{E} \qquad \text{Pb-glass}$$

CLAS Inner Calorimeter

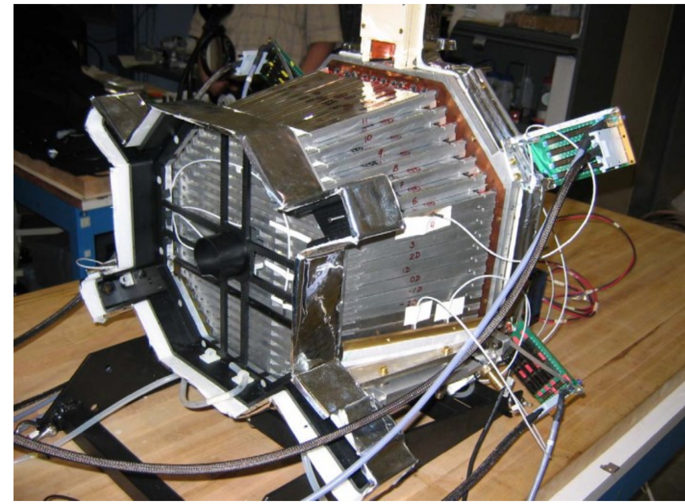
- DVCS experiment in Hall B (2005)

photon detection at small angle (4° - 15 °)

- 424 $PbWO_4$ crystals
  - tapered: 13.3 mm face,
    16 mm rear face, 16 mm long
  - taken from CERN,
  - produced by BTCP
- Light readout via APDs 1 cm x 1 cm
- Operating temperature 17° ± 0.1 °



$PbWO_4$ Crystal



- Light monitoring system:

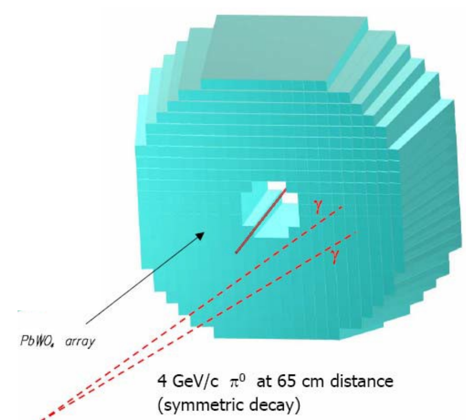
  laser light, individual distribution to each module
  using optical fibers

- Energy resolution

$$\frac{\sigma(E)}{E}(\%) = \frac{2.4}{\sqrt{E}} \oplus \frac{2.9}{E} \oplus 2.1$$

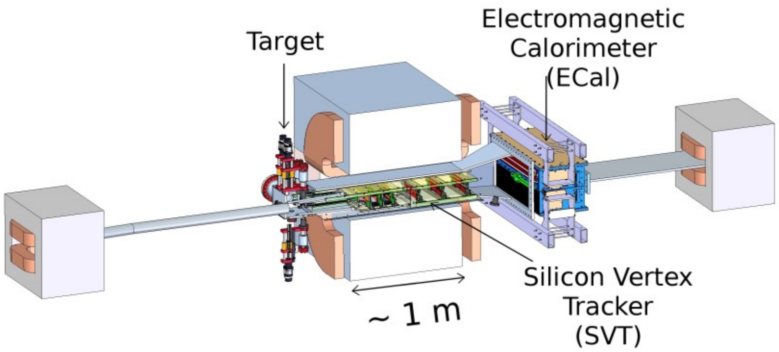
- Position resolution

$$\sigma(x)\ (\text{mm}) = \frac{1.1}{\sqrt{E}} \oplus 0.9$$



Electromagnetic Calorimeter of the HPS Experiment

NIM A 854, 89-99, 2017



- Heavy photon search experiment in Hall B in 2015-2016

- 442 PbWO4 crystals taken from the CLAS inner calorimeter

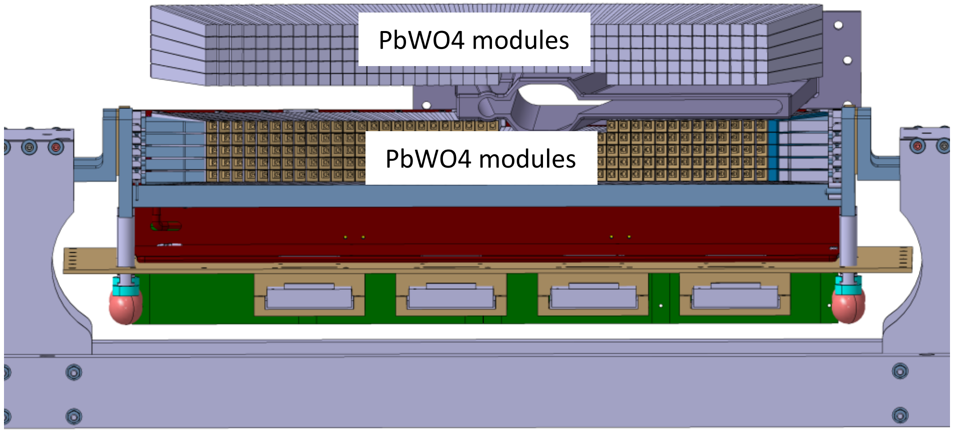
  - tapered $PbWO_4$ crystals with a front (rear) face of 13.3 x 13.3 mm^2 (16 x 16) 160 mm long (18 R.L.)

- Temperature stabilization at $17^\circ \pm 0.3^\circ$

- Read out by 10 x 10 mm^2 Hamamatsu APD

  - APD bias voltage between 385 V and 405 V average gain of 150

  - coupled to a custom amplifier



Electromagnetic Calorimeter of the HPS Experiment

NIM A 854, 89-99, 2017

- Light monitoring system:

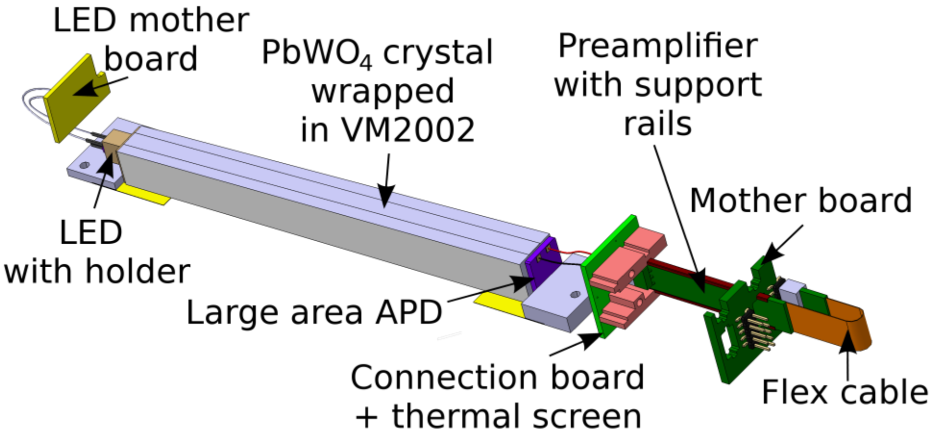
  -red/blue LEDs attached to the face of each crystal

- Energy resolution:

$$\frac{\sigma(E)}{E}(\%) = \frac{2.87}{\sqrt{E}} \oplus \frac{1.62}{E} \oplus 2.5$$

- Time resolution:

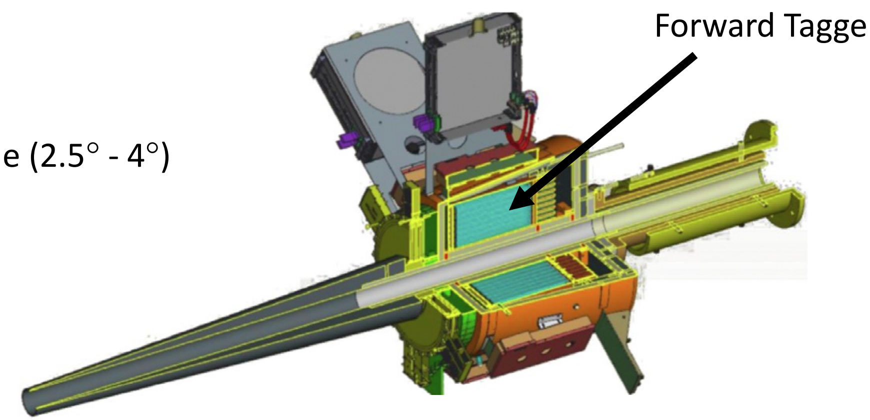
$$\sigma(\mathrm{ns}) = \frac{2.87}{\sqrt{E}} \oplus \frac{1.62}{E} \oplus 2.5$$



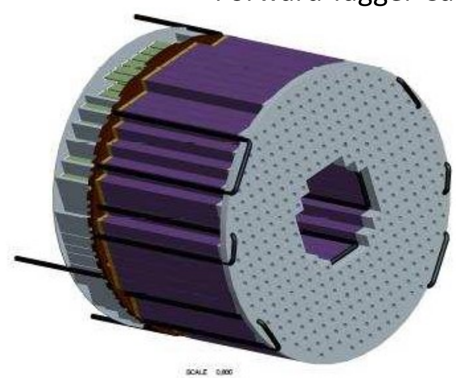
CLAS12 Forward Tagger

NIM A 959, (2020) 163475

- Upgrade of the CLAS detector in Hall B to 12 GeV
- The calorimeter was installed in 2017
  - required for detection of scattered electrons at small angle (2.5° - 4°)
- 332 $PbWO_4$ crystals (Type II)
  - 15 x 15 x 200 mm^3 , 22 R. L.
  - produced by SICCAS
  - operated at 0°
- Light detected using 10 x 10 mm^2 Hamamatsu LAAPD
  - operating gain ~150
  - transimpedance amplifier
- Light monitoring: individual LED attached to the face of each crystal
- Relative energy resolution: 3% at 2 GeV (slightly worse than in a prototype)

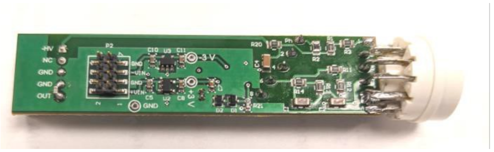


Forward Tagger Calorimeter



Neutral Particle Spectrometer (NPS)

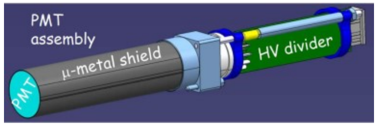
- The calorimeter was build and installed in Hall C in the fall of the 2022
  - will be used in several experiments using high-intensity 12 GeV beam
- An array of 30 x 36 PbWO4 crystals (1080 crystals)
  - crystal size 2.05 x 2.05 x 200 mm^3 (22 R.L.)
  - all crystals were produced by CRYTUR
- The detector is installed inside the temperature controlled frame. Operating temperature 17° C
- Photodetectors: Hamamatsu 4125 PMTs
- PMT divider and on-board amplifier (gain 22) designed at JLab



- some issues with the radiation damage of LV regulators in the beginning of the run. All bases have been recently fixed

- LED system for curing and gain monitoring
- Preliminary energy resolution: 2.3 GeV at 7 GeV (calibration is in process)

Crystals installed into a grid of carbon fibers
A PMT assembly is attached

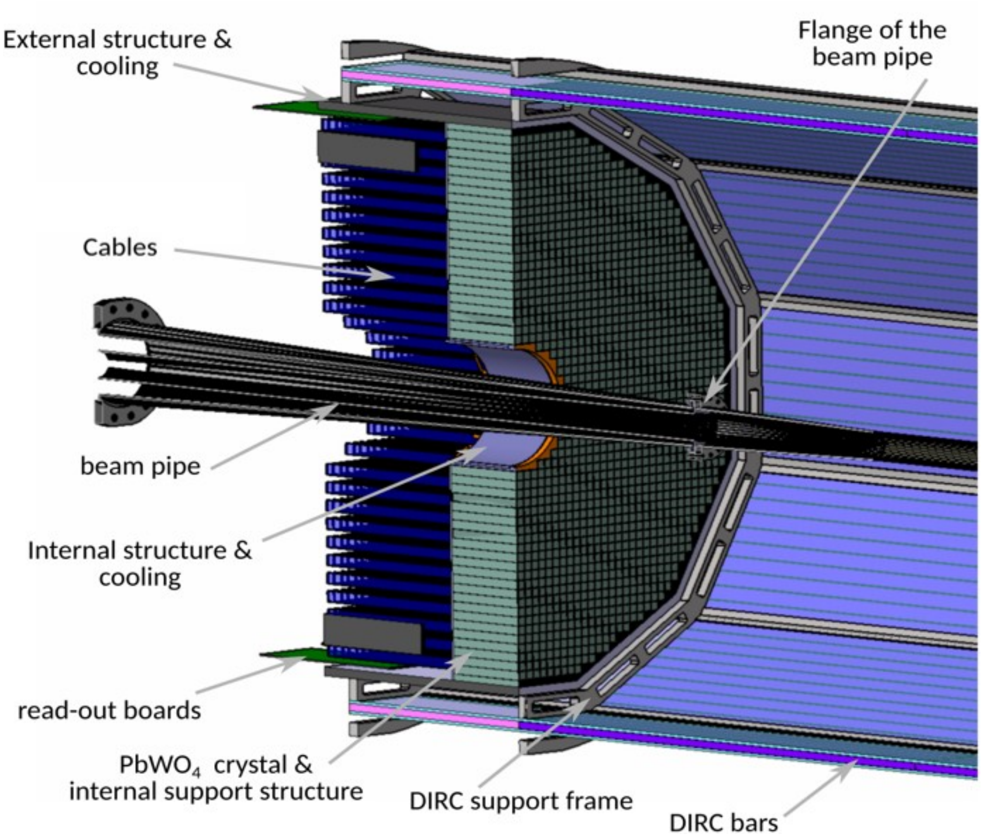


Electron Endcap EM Calorimeter for EIC

- Requirements:
  - energy resolution: 2-3% / $\sqrt{E} \oplus (1-2)\%$
  - minimum detection energy: 100 MeV
  - pion separation, factor of 10^4 together with PID

- 3256 $PbWO_4$ modules:
  - $20.5 \times 20.5 \times 200$ mm^3 , CRYTUR, Type II
    the same size as for the CCAL, NPS, ECAL

- Photodetectors:
  - large magnetic field
  - array of 2x2 6 mm x 6 mm SiPMs
  - pixel size of 10 (15) μm to provide good linearity (on the level of 2%) for large amplitudes
  - consider to use Hamamatsu S14160-6010

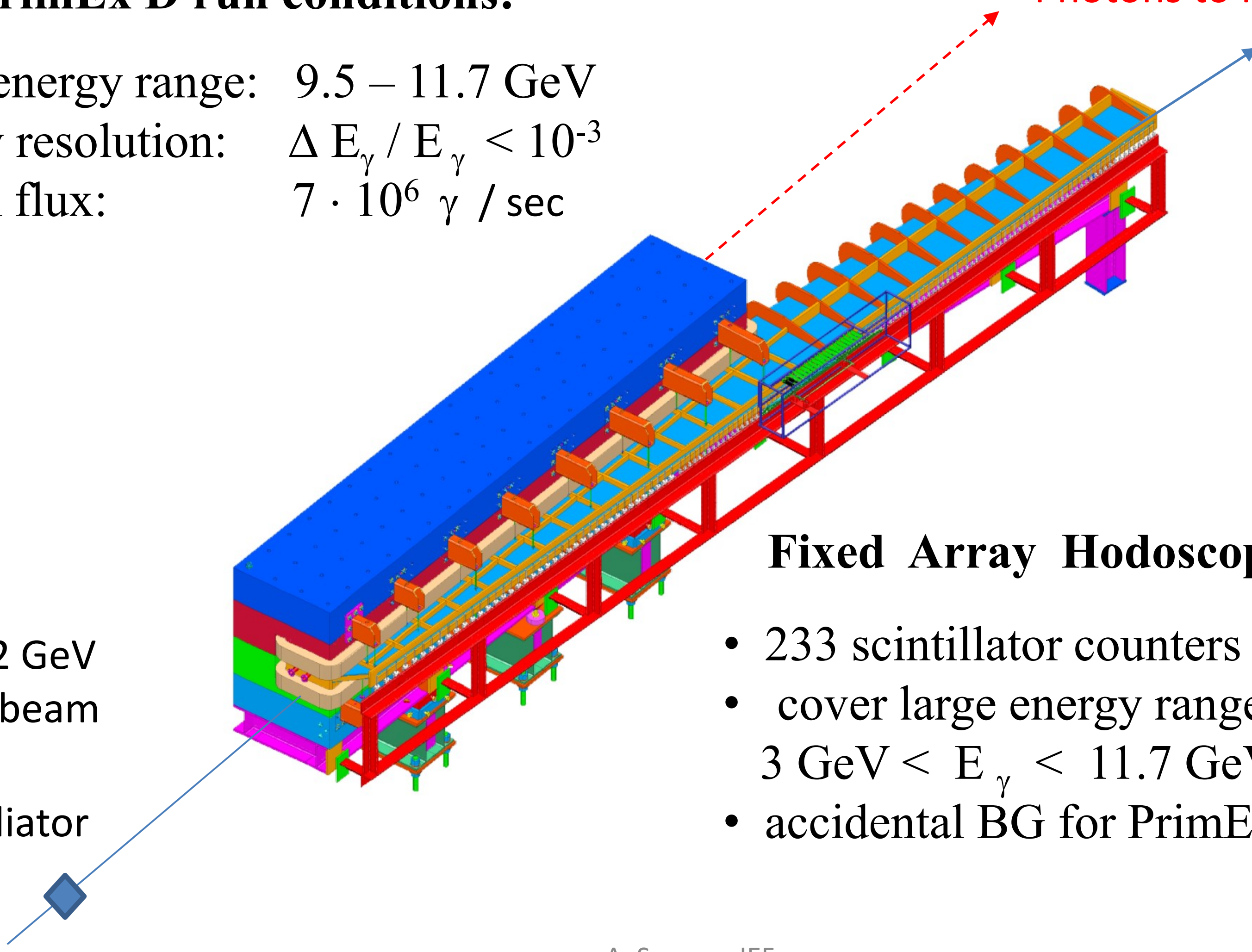


Tagged Photon Beam

Measure energy of each beam photon by detecting a bremsstrahlung electron

PrimEx D run conditions:

Beam energy range: 9.5 – 11.7 GeV
Energy resolution: $\Delta E_\gamma / E_\gamma < 10^{-3}$
Photon flux: $7 \cdot 10^6\ \gamma$ / sec

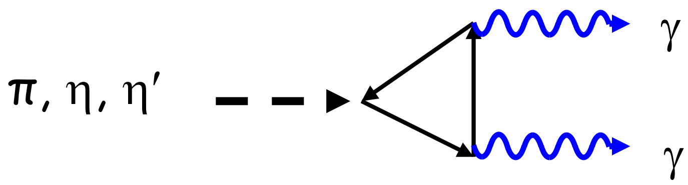


Fixed Array Hodoscope

- 233 scintillator counters
- cover large energy range
  $3\ \text{GeV} < E_\gamma < 11.7\ \text{GeV}$
- accidental BG for PrimEx D < 4 %

Symmetries in QCD and Light Pseudoscalar Mesons

- $\pi^0 \rightarrow \gamma\gamma$, $\eta \rightarrow \gamma\gamma$, and $\eta' \rightarrow \gamma\gamma$ decays are associated with the Chiral anomaly



- Decay widths can be computed precisely in higher orders

- SU(3) and isospin breaking by the unequal quark masses induce mixing among π^0, η, and η'

π^0, η, η' mesons provides a rich laboratory to study the symmetry structure of QCD

Decay Width of η Mesons : Physics Motivation

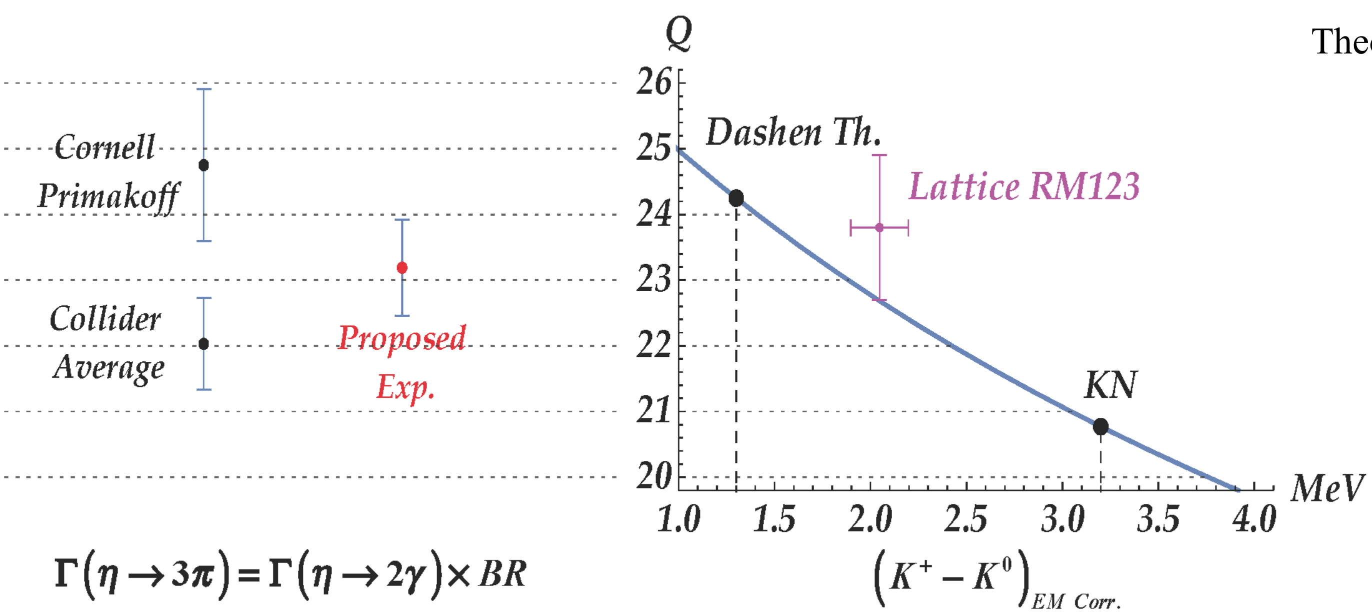
- **Light quark mass ratio:**

$\eta \to 3\pi$ forbidden by isospin symmetry:

$$\Gamma(\eta\to3\pi) \sim |A|^2 \sim Q^{-4} \qquad Q^2 = \frac{m_s^2 - \hat{m}^2}{m_d^2 - m_u^2}, \qquad \text{where } \hat{m} = \frac{1}{2}(m_u + m_d)$$

$\Gamma(\eta\to3\pi)=\Gamma(\eta\to\gamma\gamma) \cdot BR(3\pi) / BR(\gamma\gamma)$

Phys. Rept. 945 (2022) 1-105



$$\Gamma(\eta\to3\pi) = \Gamma(\eta\to2\gamma)\times BR$$

Theoretical calculations:

$$Q^2 \sim \frac{M_K^2}{M_\pi^2}\frac{M_K^2 - M_\pi^2}{(M_{K^0}^2 - M_{K^+}^2)_{QCD}}$$

Uncertainties in EM contributions to $M_{K^0}^2 - M_{K^+}^2$

Physics Motivation

- **(η - η') mixing angle**

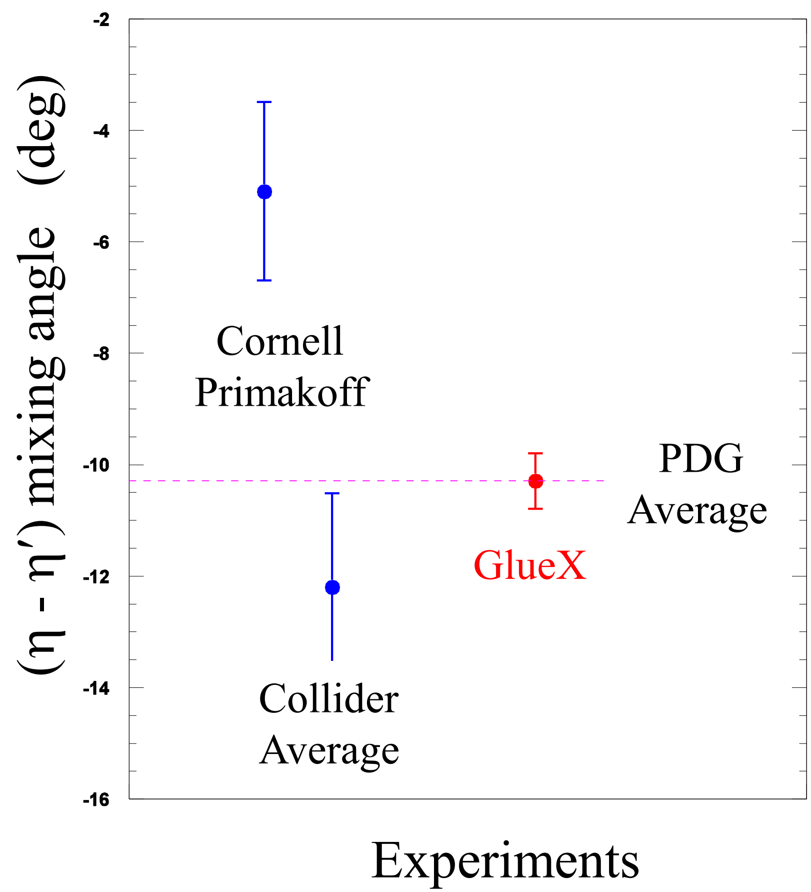
  - *SU(3)* symmetry breaking induces mixing between the *SU(3)* states

$$\begin{pmatrix} \eta \\ \eta' \end{pmatrix} = \begin{pmatrix} \cos\theta & -\sin\theta \\ \sin\theta & \cos\theta \end{pmatrix} \cdot \begin{pmatrix} \eta_8 \\ \eta_0 \end{pmatrix}$$

  - The mixing angle θ can be determined using measured decay widths $\Gamma(\eta^{(\prime)} \to \gamma\gamma)$ and NLO corrections to decay constant

  - Important to analyze together decays $\eta^{(\prime)} \to \gamma\gamma$ and $\eta \to \gamma\gamma$

L. Goity and al. PRD 66 (2002) 076014



- **Significantly improve all η decay widths in PDG**

$$\Gamma(\eta\to X) = \Gamma(\eta\to\gamma\gamma) \cdot BR(X) / BR(\gamma\gamma)$$

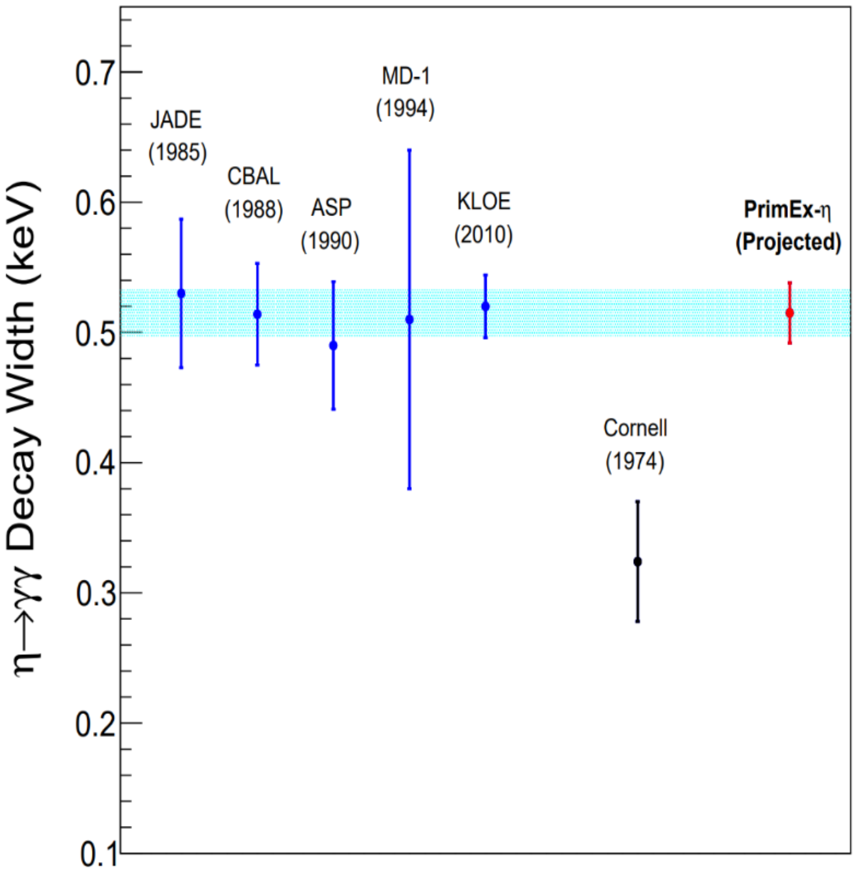
Measurements of $\Gamma(\eta\to\gamma\gamma)$

- The partial width $\Gamma(\eta\to\gamma\gamma)$ was derived from measurements

  - collider experiments in the reaction
    $e^+ e^- \to e^+ e^- \eta$

  - Primakoff production of η mesons

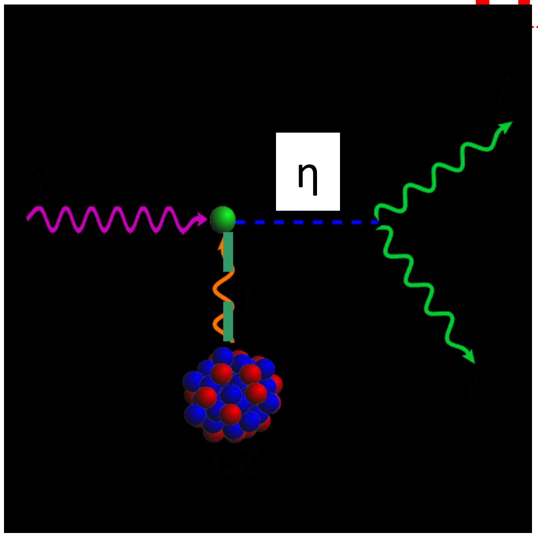
- Some disagreements between collider and Primakoff results



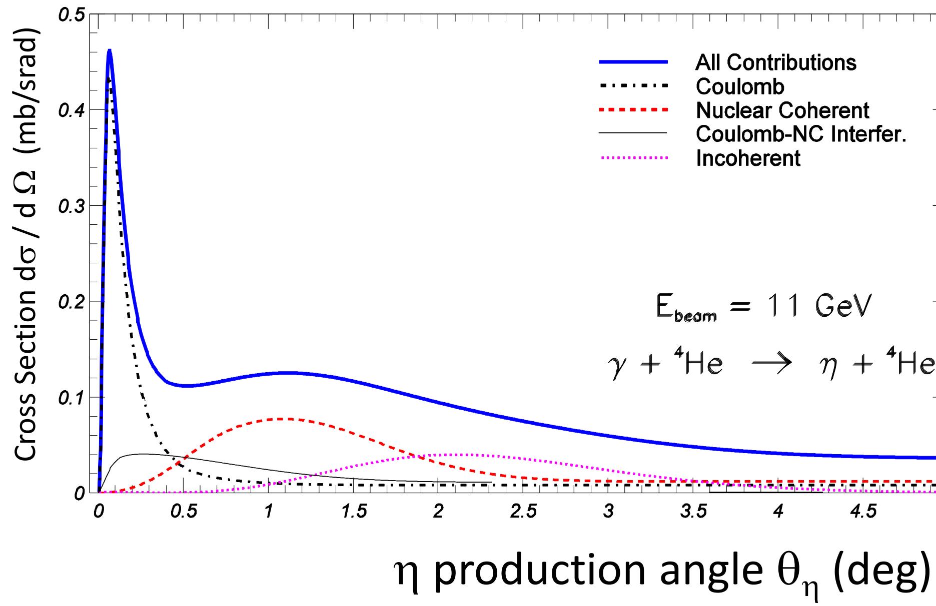
New measurement of the decay width using Primakoff process PrimEx - η experiment at Jefferson Lab

Initial goal for uncertainties 3.2 %, more likely be 6 – 9 %

The Primakoff Method

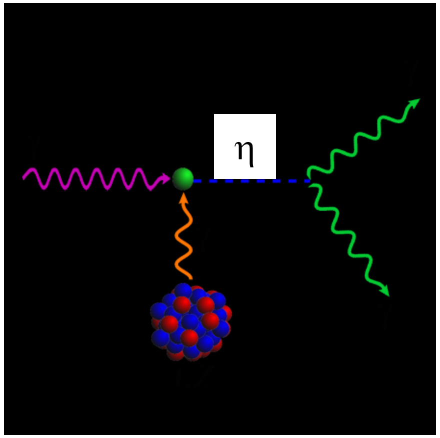


$$\frac{d\sigma_{\Pr}}{d\Omega} = \boxed{\Gamma_{\gamma\gamma}} \frac{8\alpha Z^2}{m_\eta^3} \frac{\beta^3 E^4}{Q^4} |F_{e.m.}(Q)|^2 \sin^2\theta_\eta$$



- Measure differential cross section dσ/dΩ
- Contributions from:
  - signal Coulomb
  - nuclear coherent (incoherent)
  - interference between signal and coherent
  - other hadronic background
- Distribution shapes are computed or measured
- Free parameters in the fit:
  - normalizations, interference phase

Pimakoff Program at Jefferson Lab



I) Determination of two photon decay widths:

$\Gamma(\pi^0 \rightarrow \gamma\gamma)$ PrimEx I, II experiment in Hall B at 6 GeV

$\Gamma(\eta \rightarrow \gamma\gamma)$ PrimeEx-η experiment in Hall D at 12 GeV

$\Gamma(\eta' \rightarrow \gamma\gamma)$

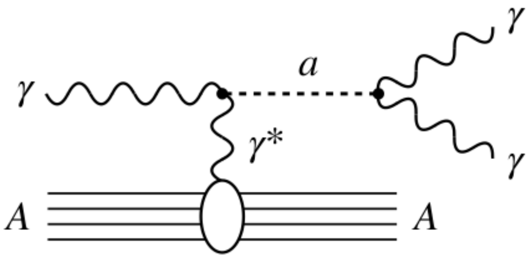
- test Chiral symmetry and anomaly, extract light quark mass ratio, determine η - η′ mixing angle

II) Measuring the charged and neutral pion polarizability

- Primakoff production of $\pi^+ \pi^-$ and $\pi^0 \pi^0$ (see talk by R. Miskimen)
- Hall D, polarized photon beam (collected data in 2022)

III)   Search for axion-like particles through nuclear Primakoff production

- APL predominantly couple to photons, with an effective ALP-photon interaction $\mathcal{L}_{\rm eff} \supset \frac{1}{4\Lambda} a F^{\mu\nu} \tilde{F}_{\mu\nu}$
- portal to probe beyond-SM physics (dark sector)
- Search for ALP in Hall D *Phys.Lett.B 855 (2024) 138790*

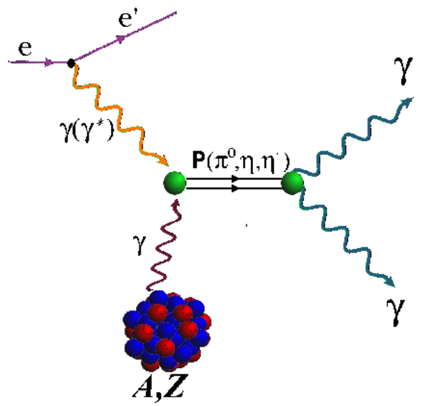


Pimakoff Program at Jefferson Lab

(see talk by L. Gan)

IV) Measure transition form factors at low Q^2 (0.001 – 0.5 GeV^2/c^2) with an electron beam

$F(\gamma\gamma^* \to \pi^0)$, $F(\gamma\gamma^* \to \eta)$, $F(\gamma\gamma^* \to \eta')$



- new experiment in Hall B (in preparation)
- π^0 electromagnetic transition radius, input for hadronic calculations in muon (g-2)

V) Extension of the Primakoff program for the Jefferson's Lab energy upgrade to 22 GeV

- Primakoff production off π^0 of an electron (detect recoil electron)
- Improve measurements of η / η'

PrimEx – η Experiment

- Three sets of data collected at different beam energies

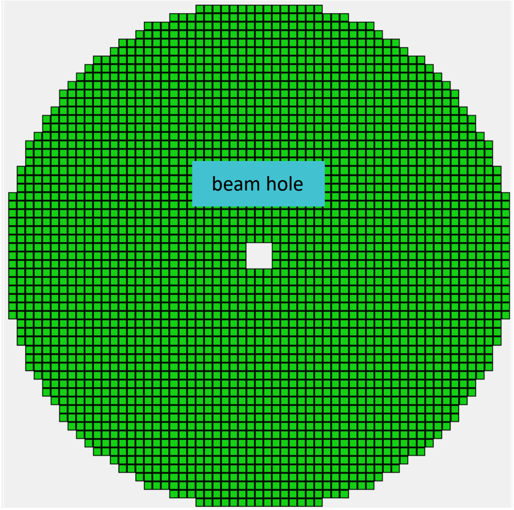
	Phase I	Phase II	Phase III
Year	2019	2021	2022
E_{beam}	11.2	10.0	11.6
Luminosity	6 pb^{-1}	2 pb^{-1}	~ 15 pb^{-1}
Magnetic field	OFF	OFF (most runs)	ON

~ 5 months of data taking in total

- $\eta \to \gamma\gamma$ decays are reconstructed in the forward calorimeter

- 2800 lead glass modules (taken from E852 experiment at BNL)
  - lead glass block size: 4 cm x 4 cm x 45 cm
- The energy resolution: $\frac{\sigma(E)}{E}(\%) = \frac{6.2}{\sqrt{E}} \oplus 4.7$
- Acceptance: $0.6° < \theta < 11°$
- Beam hole in the middle of the detector: 12 cm x 12 cm
  - place Compton calorimeter downstream the beam to improve coverage in the forward direction

Forward Calorimeter



Compton Scattering

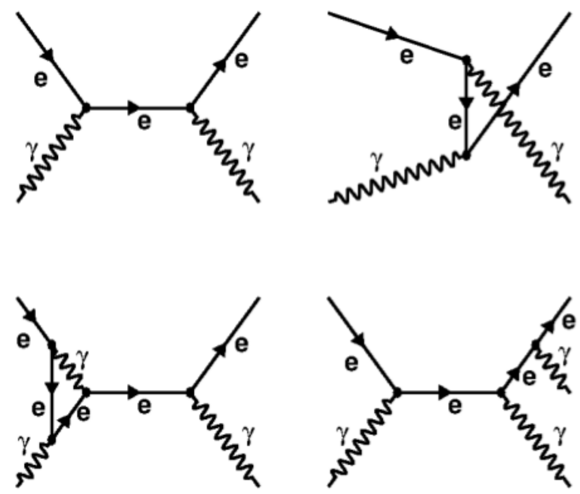
A. Smith

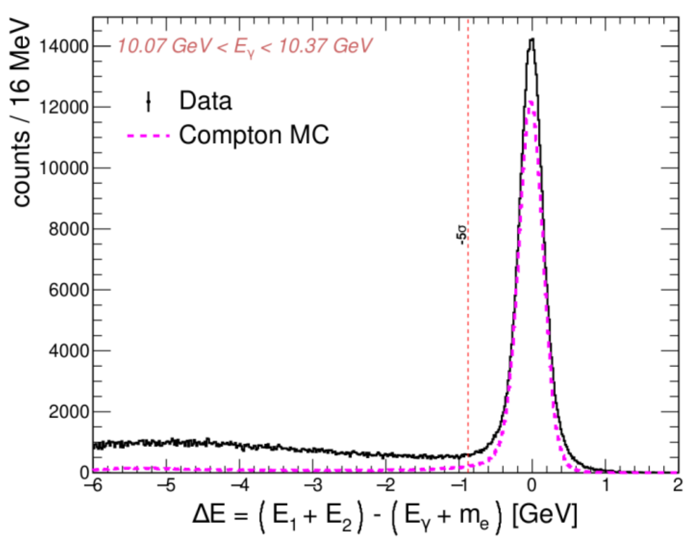
- Differential cross section at leading order (Klein-Nishina)

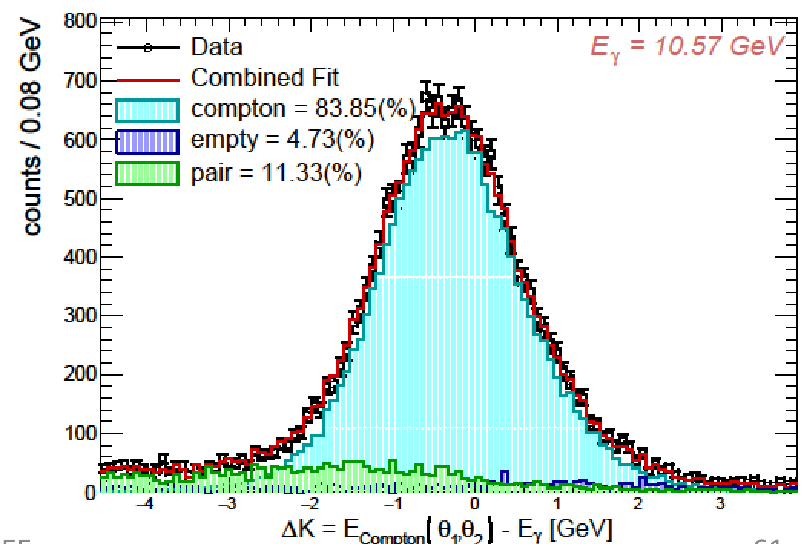
$$\frac{d\sigma_{KN}}{d\Omega_\gamma} = \frac{r_e^2}{2}\frac{1}{[1+E_0(1-\cos\theta_\gamma)^2]}\left[1+\cos^2\theta_\gamma + \frac{E_0^2(1-\cos\theta_\gamma)^2}{1+E_0(1-\cos\theta_\gamma)}\right]$$

- Two-body kinematics
- Main background from $e^{\pm}$ pairs

leading order (top)





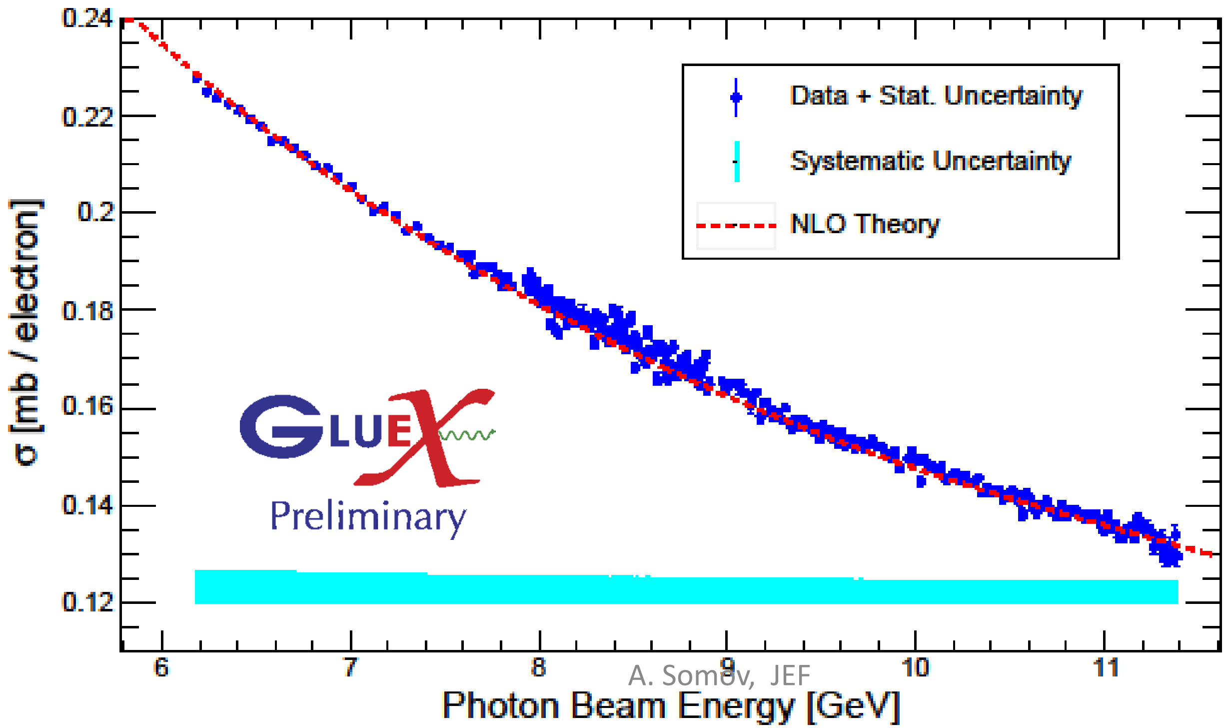


Compton Cross Section

A. Smith

- First cross section measurement in the range between 6 GeV and 11.5 GeV
  - previously measured for beam energies 4.4-5.3 GeV *Phys.Lett.B 797 (2019)*
- Journal paper under preparation
- Measurement are dominated by systematic uncertainties (3.6 %)
- "Good" agreement with NLO calculations *Phys.Rev.Lett. 126 (2021) 21, 211801*

Cross section measured on Be target (preliminary)

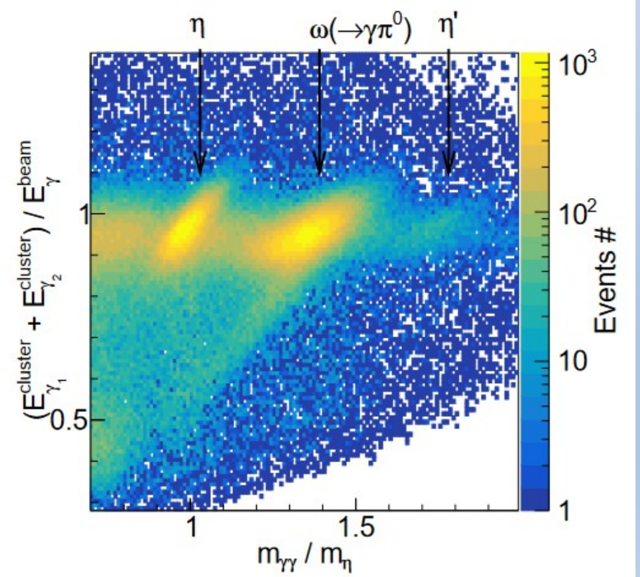


Status of the $\eta \to \gamma\gamma$ Analysis

A. Smith & I. Jaegle

Event selection:

- Two photons in the forward calorimeter originating from the same beam bunch
- Use time-of-flight detector to veto charged tracks
- Use barrel calorimeter to veto on hadronic background
- Elasticity requirement, $E^1_\gamma + E^2_\gamma$ - E_{BEAM} < 1 GeV

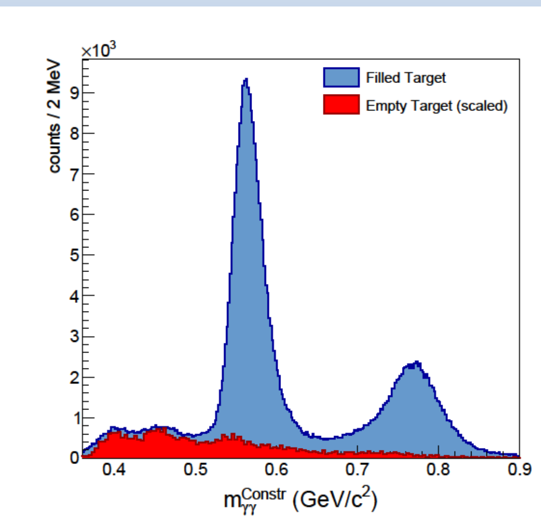


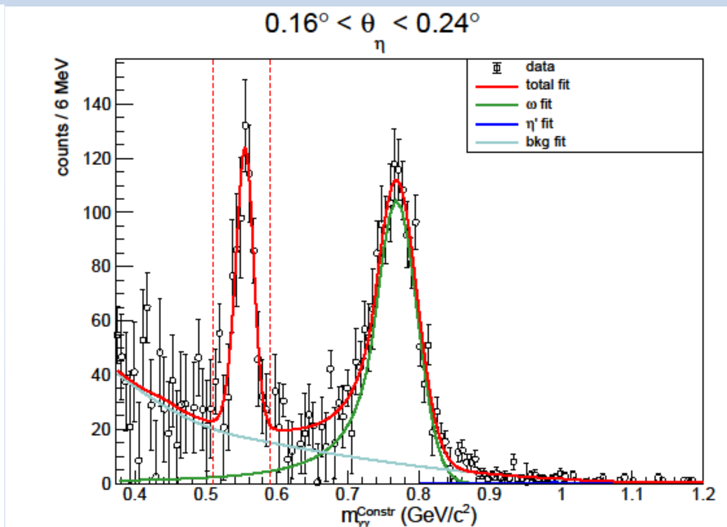
Clear selection of η candidates
(large background)

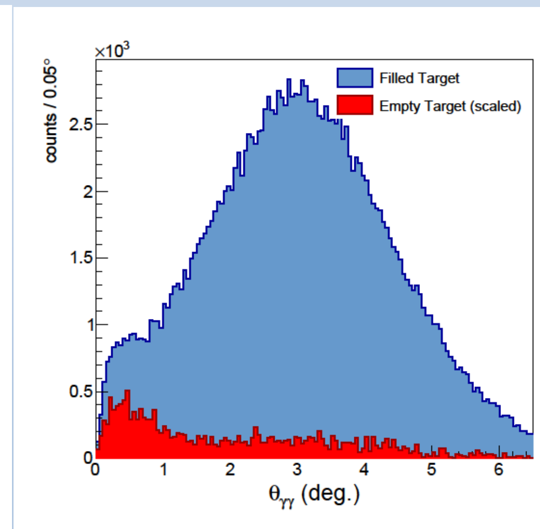
Status of the $\eta \to \gamma\gamma$ Analysis

- Beamline background from electromagnetic pair production downstream the target
  - peaking at small angles
  - collected large empty-target data sample to subtract

- Bin in the production angle, determine yield of η candidates for each bin from the lineshape distribution







Future Plans

Extension of the Primakoff Program with the GlueX Detector

- Upgrade of the GlueX forward calorimeter
- Optimization of the detector beam line for Primakoff measurements
- Study feasibility of using heavier nuclear targets. Measurement of the decay width of η'
- Prospects of Primakoff measurements after Jefferson Lab energy upgrade to 22 GeV

Feasibility of Using Heavy Targets for Measurement of $\eta \to \gamma\gamma$ Decay Width

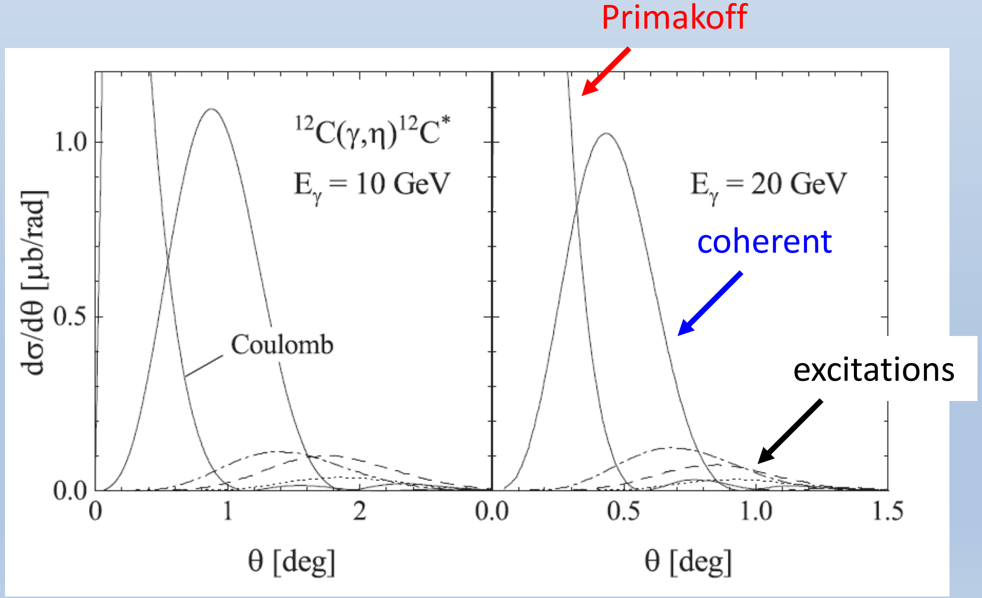
- Primakoff cross section $\sim Z^2$. Relatively large momentum transfer, have to consider nuclear excitations (coherency of the reaction)

- Calculations by A. Fix for coherent and incoherent photoproduction of

$$\gamma + {}^{12}C \to \eta + {}^{12}C^*$$

with various excitation levels

Phys. Rev. C 108, 044607 (2023)



Primakoff Program at 22 GeV

- Primakoff cross sections increases with energy

$$\sigma(E = 20\text{ GeV}) \;/\; \sigma(E = 10\text{ GeV}) \sim 1.5$$

- Better separation of Primakoff from hadronic processes:

$$\langle \theta_{\mathrm{Pr}} \rangle_{peak} \propto \frac{m^2}{2 \cdot E^2} \qquad \theta_{NC} \propto \frac{2}{E \cdot A^{1/3}}$$

- Better energy, mass, and angular resolution of reconstructed η mesons at large energies

- Smaller momentum transfer (t) at larger energies

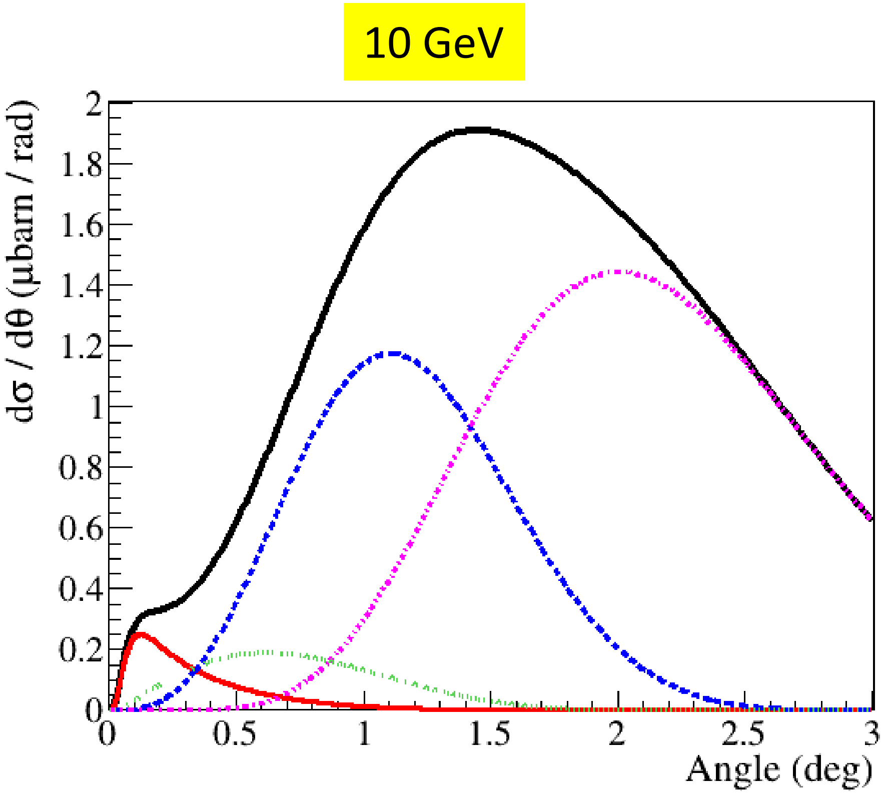
$$q_L \sim (m^2 / 2E),$$
$$q_T \sim 4 E E_\eta \sin^2(\theta/2)$$

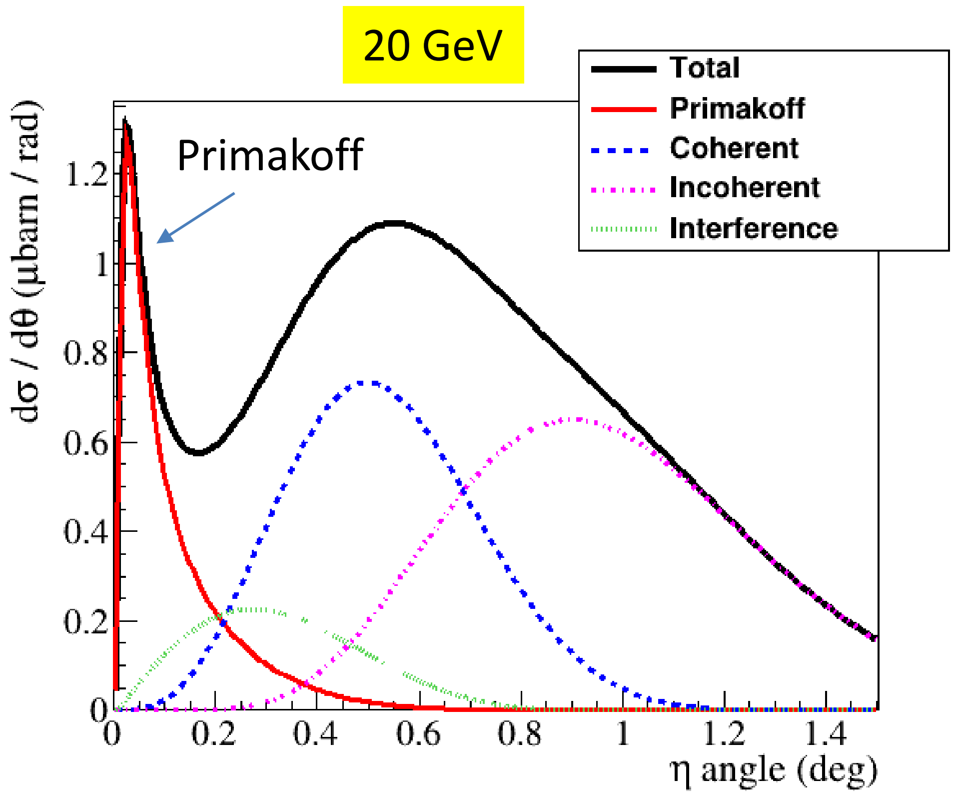
  - consider to use heavier targets (feedback from theorist)
  - smaller contribution from hadronic background

Primakoff η Production at 10 GeV and 20 GeV

Differential cross sections

He4 target





Significantly larger Primakoff peak at 20 GeV

- larger Primakoff cross section and better separation of the signal and backgrounds

Simulation performed in the framework provided by S. Gevorgyan

Measurements of $\eta' \to \gamma\gamma$ Decay Width

- η' width was measured in several collider experiments using reaction

$$e^+ e^- \to e^+ e^- \eta'$$

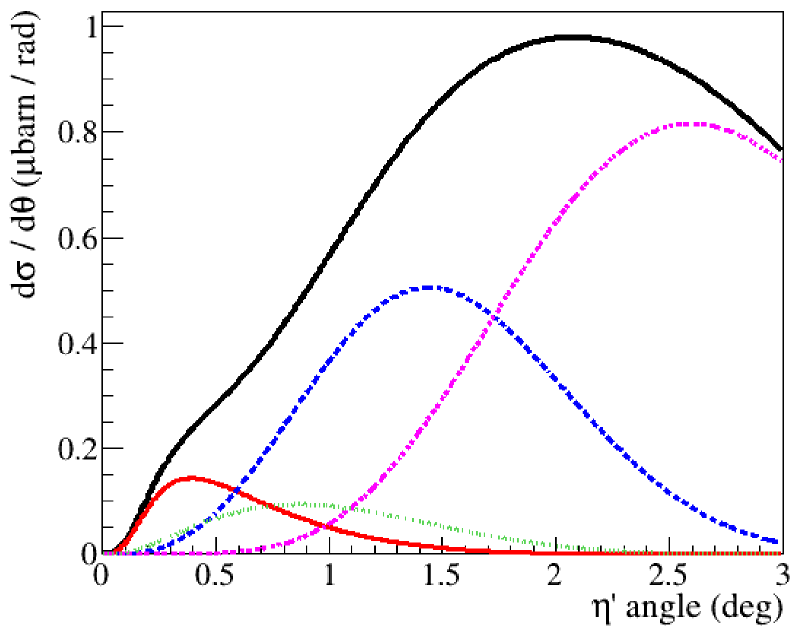
  - no background associated with a nuclear target
  - relatively large uncertainties on luminosity

$\Gamma(\gamma\gamma)$	Exp	Mode
$4.17 \pm 0.1 \pm 0.27$	L3	$\pi^+\pi^-\gamma$
$4.53 \pm 0.29 \pm 0.27$	CBAL	$\eta\pi^0\pi^0$
$3.61 \pm 0.13 \pm 0.48$	CELL	$\rho^0\gamma$, $\eta\pi^+\pi^-$
$4.6 \pm 1.1 \pm 0.6$	MD1	$\pi^+\pi^-\gamma$
$4.57 \pm 0.25 \pm 0.44$	MRK2	$\rho^0\gamma$, $\eta\pi^+\pi^-$
$5.08 \pm 0.24 \pm 0.71$	ASP	$\gamma\gamma$
$3.8 \pm 0.7 \pm 0.6$	TPC	$\eta\pi^+\pi^-$
$1.00 \pm 0.08 \pm 0.10$	CBAL	$\gamma\gamma$

- No Primakoff measurement of the $\eta' \to \gamma\gamma$ decay width has been performed so far

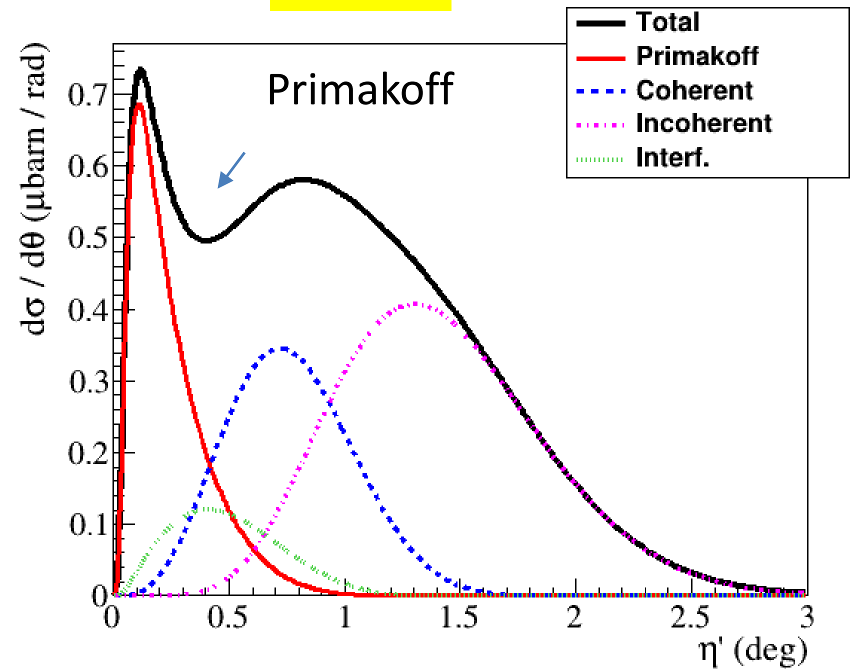
Primakoff η′ Production at 10 GeV and 20 GeV

10 GeV



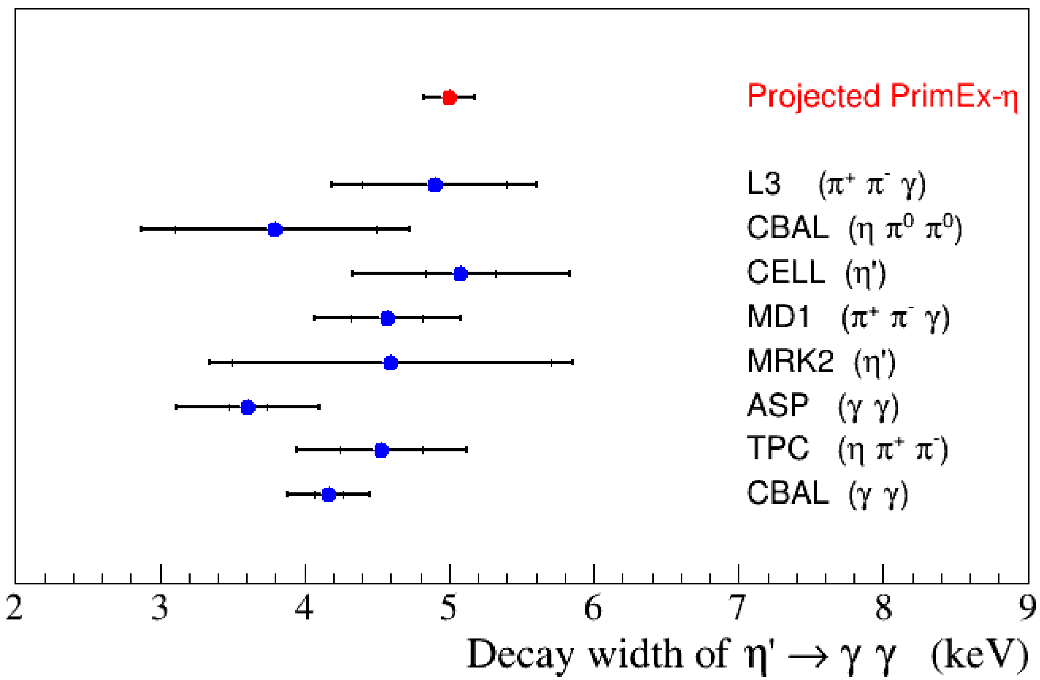
20 GeV

He4 target



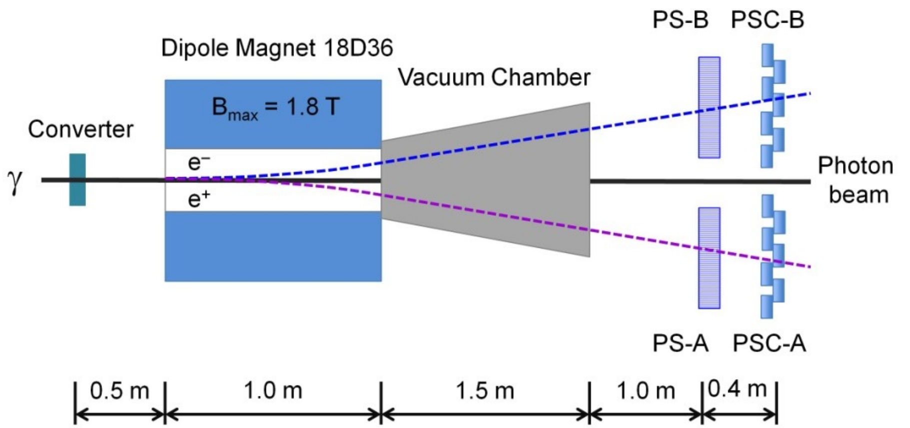
- Difficult to extract Primakoff η′ signal on He target at 10 GeV
- More ‘prominent’ Primakoff peak at 20 GeV
- Currently study feasibility to use ^{12}C target
  - Primakoff cross section ~ Z^2
  - have to consider nuclear excitations

Expected Uncertainties on the $\eta' \to \gamma\gamma$ Decay Width

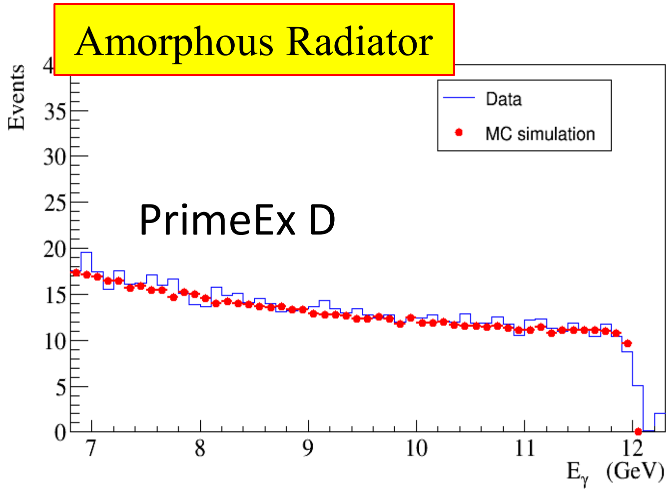


- Run conditions: photon flux in the beam energy range 19 –21 GeV: $2\text{x}10^7$ γ / sec, 6 % R.L. C target
- Stat error on the Primakoff yield for $\eta' \to \pi\pi\eta\ (\gamma\gamma)$ is about 3.5% for 20 days of data taking

Photon Flux Measurements with Pair Spectrometer



- Reconstruct the energy of a beam photon by detecting $e^{\pm}$ pairs ($6 < E_{\gamma} < 12$ GeV)



Two layers of scintillator detectors:

Monitor the photon flux with the precision < 1 %

Expected Rates

JEF (100 days of beam)

Experiment	Total η	Total η'
CB at AGS	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)