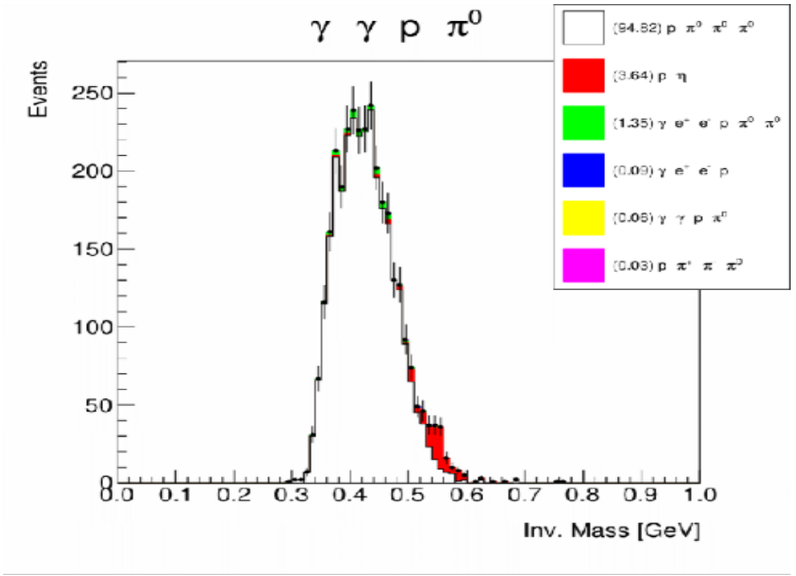
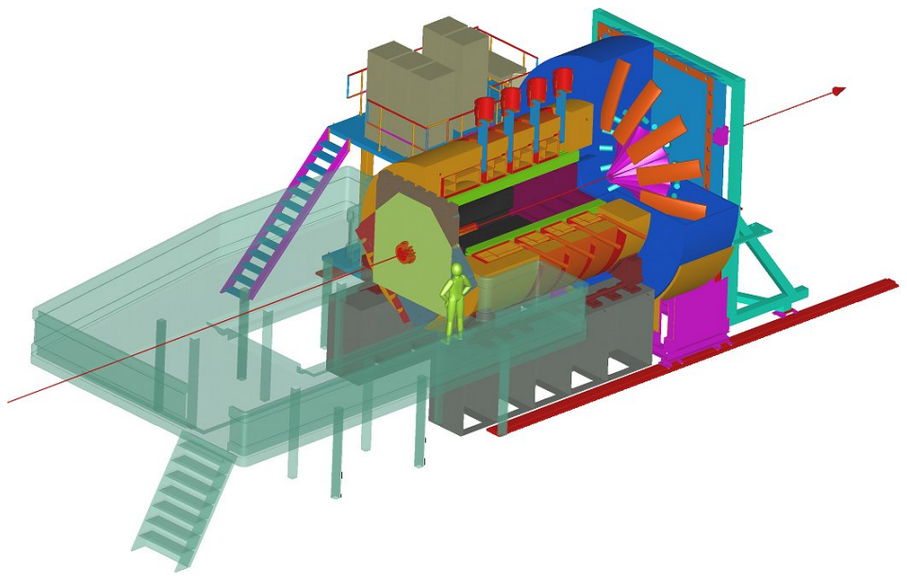
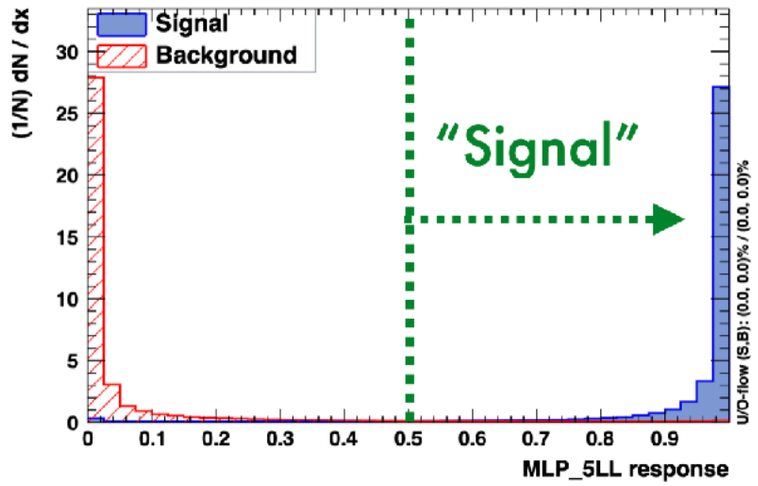






Rare Eta and Eta-prime Decays at Hall D/Jefferson Lab

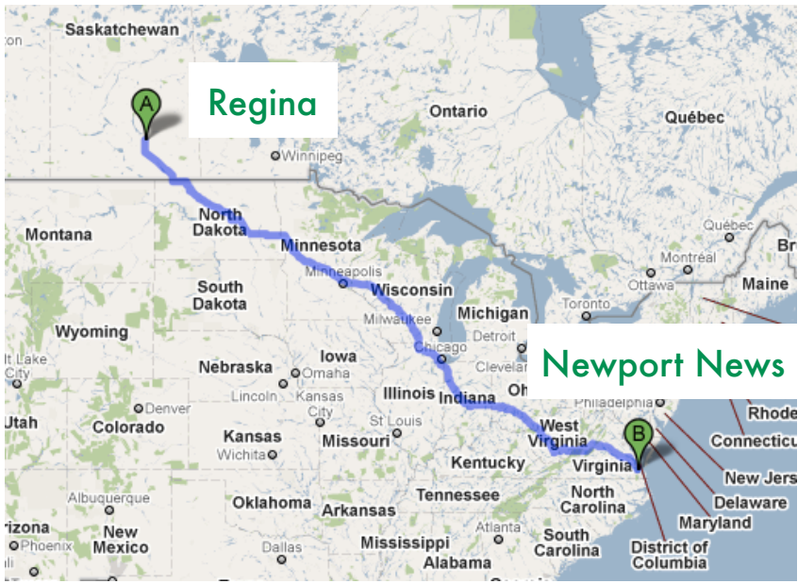
Dr. Zisis Papandreou

CAP Congress 2024

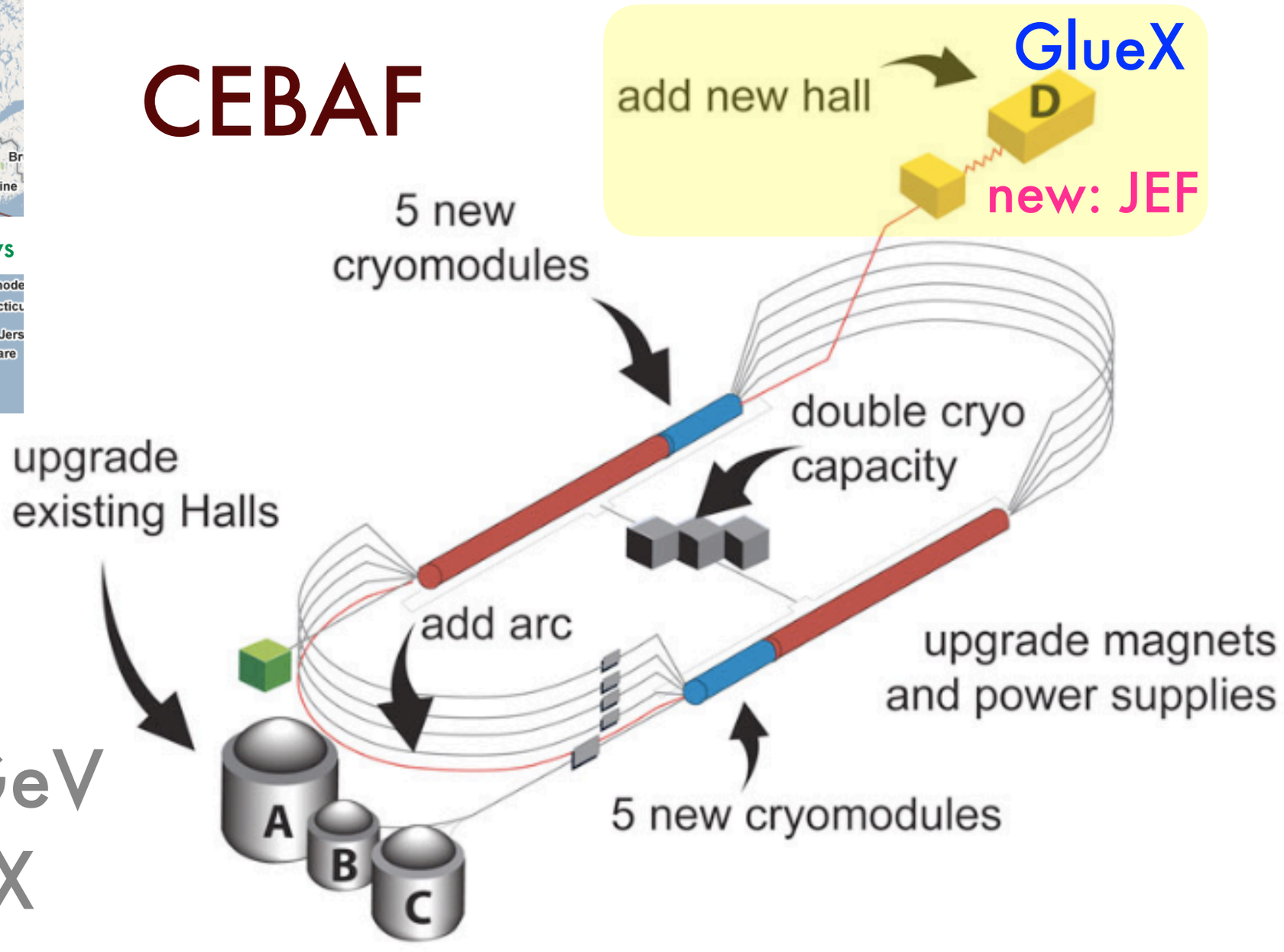
May 28, 2024


GlueX Collaboration
~130 scientists, 32 Institutions
New program: JEF Program Rare Decays
(Main goal: QCD Exotic Hybrid Mesons)

Jefferson Lab



CEBAF

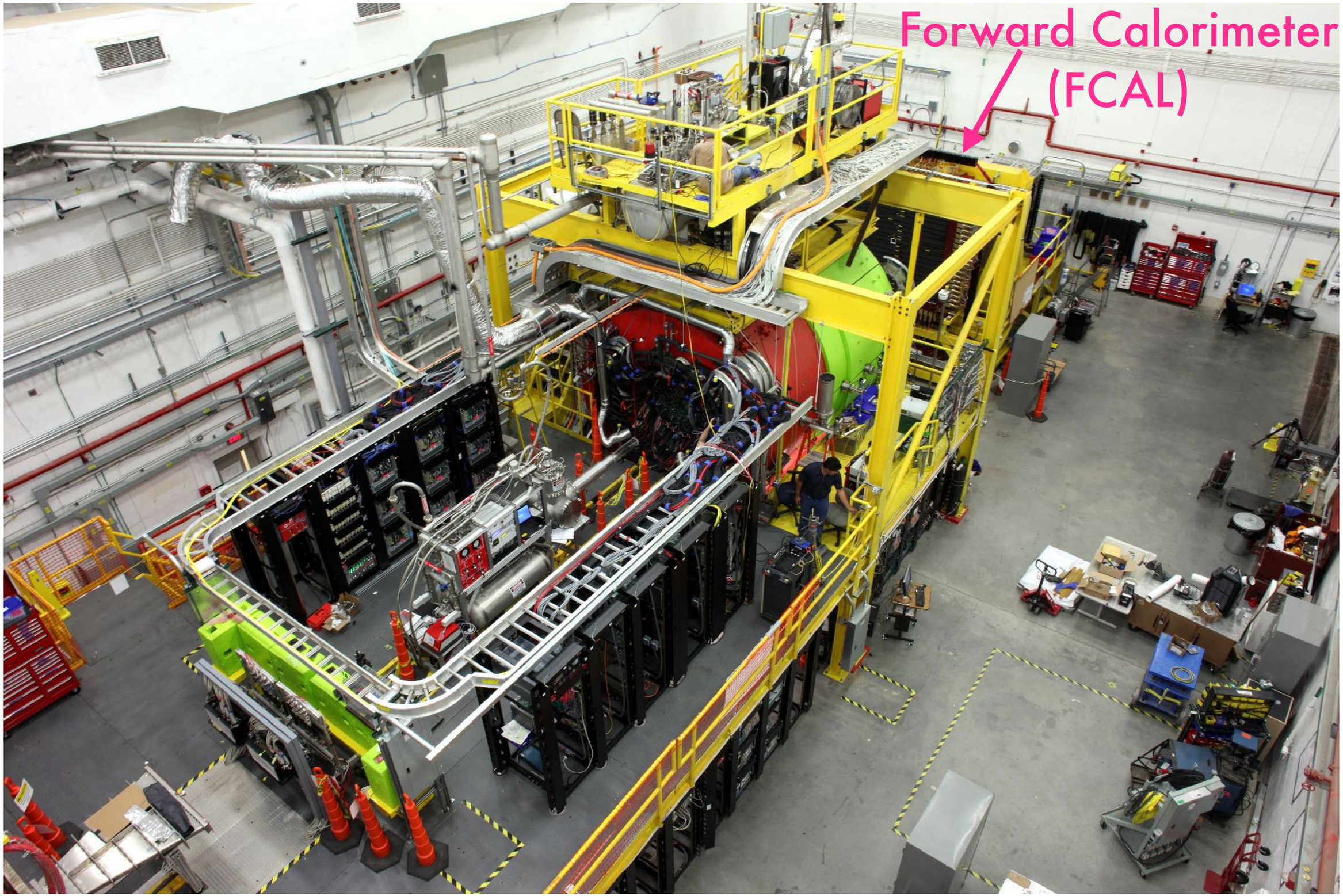


Upgraded: 12 GeV

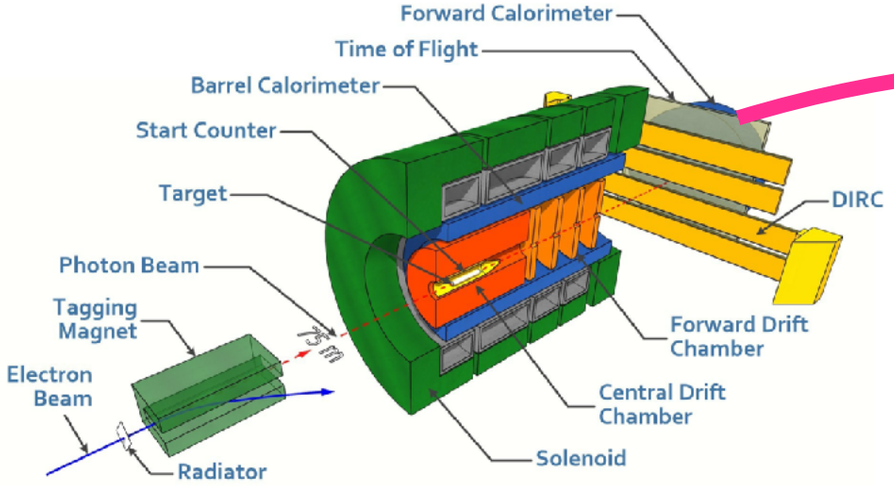
4th Hall: GlueX

Cost > $310M

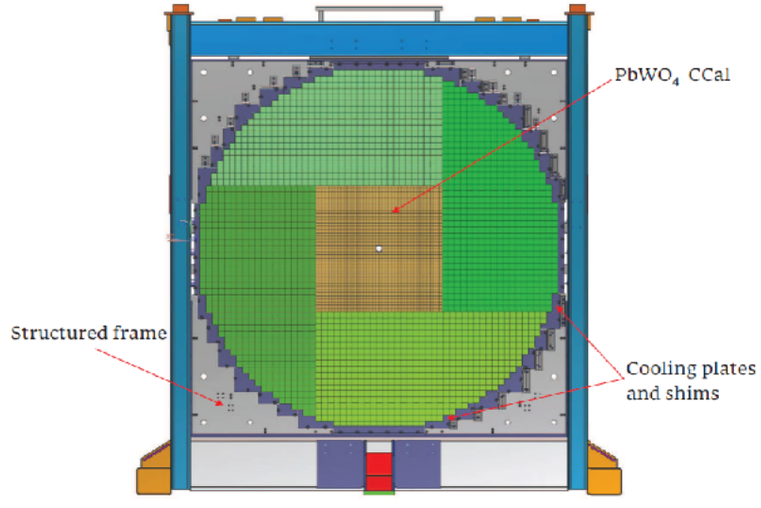
The GlueX Detector



Key Features of JEF



enhance FCAL



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

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

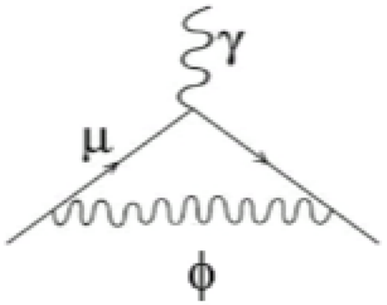
- Reduce non-coplanar backgrounds by detecting recoil protons
- Upgrad FCAL with 40x40 crystal (80x80cm^2) lead tungstate ($PbWO_4$) insert for improved resolution and superior granularity

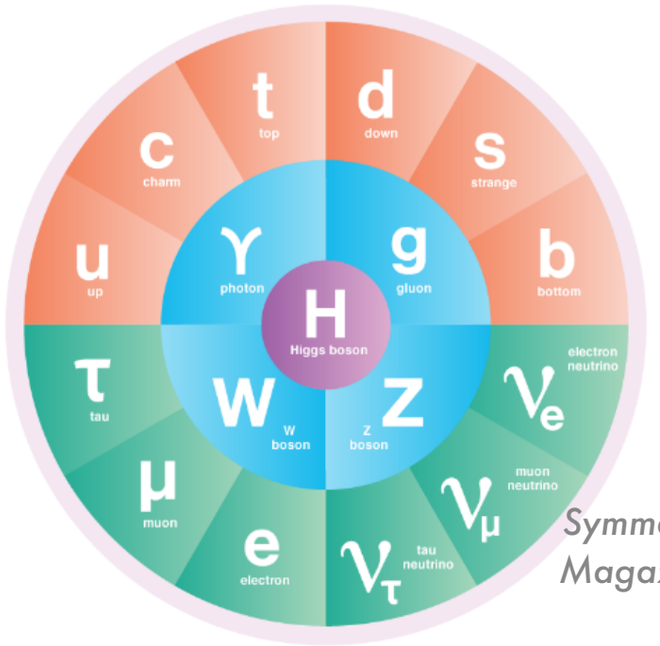
Upgrade cost: US$5M

JEF: New Physics

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

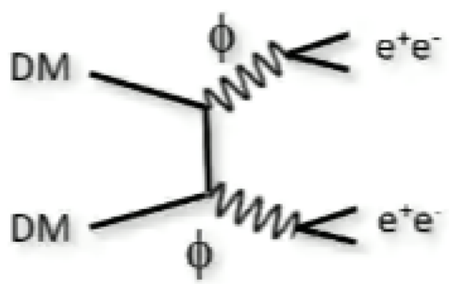
- Anomalies: $(g\text{-}2)_\mu$, $^8Be/^4He$

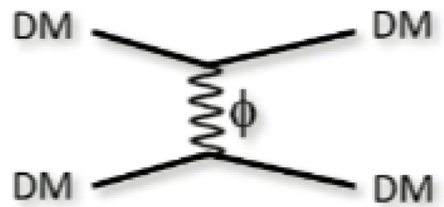




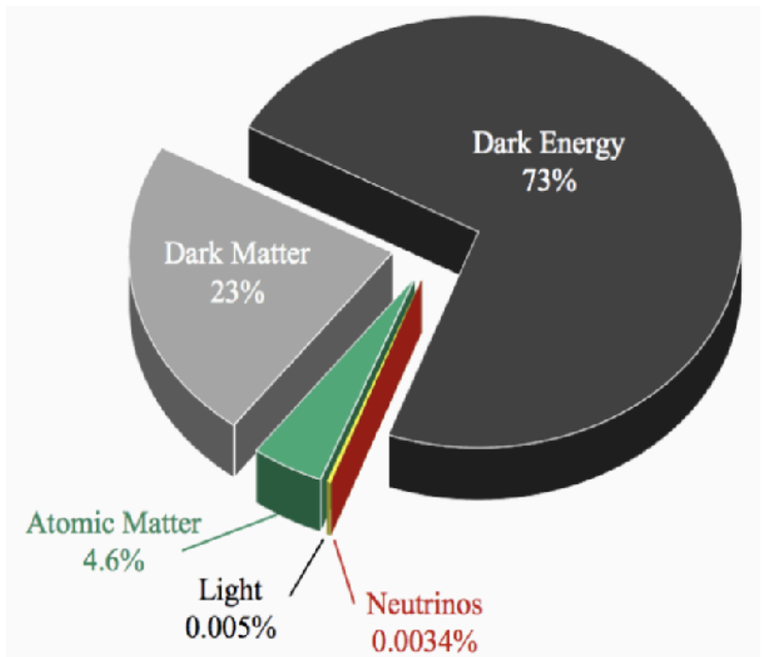
Symmetry Magazine

- Dark Matter: portals SM to DM portal





- **DM candidates produced in meson decays and direct photo production**



JEF - sub-GeV

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 - tests/symmetries

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:

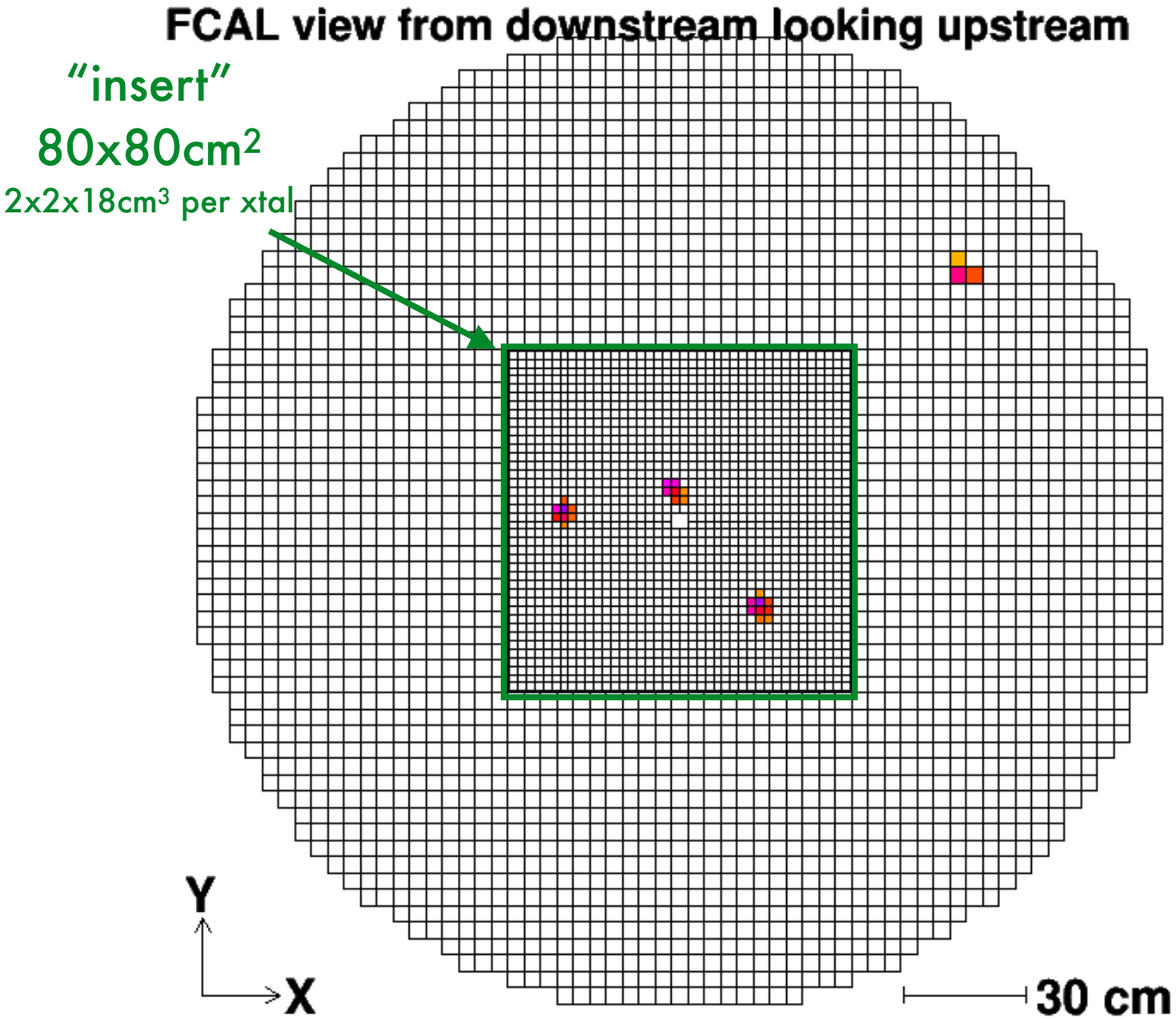
- Interplay of VMD & scalar dynamics in ChPT: $\eta^{(\prime)} \to \pi^0\gamma\gamma$
- Transition Form Factors of $\eta^{(\prime)}$: $\eta^{(\prime)} \to e^+e^-\gamma$

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

FCAL-II Upgrade

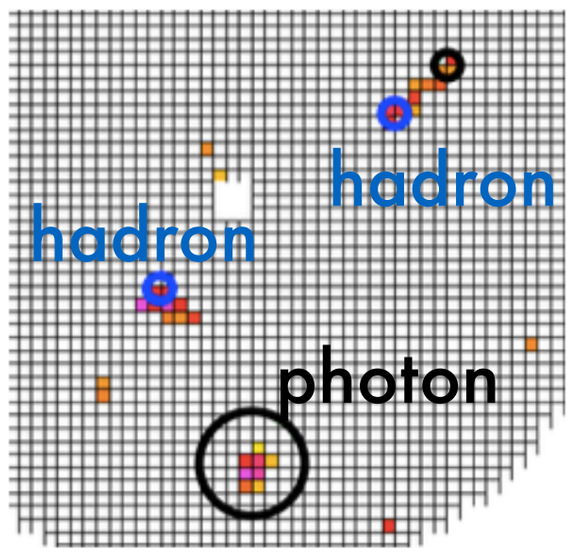
Simulated $\eta \to \pi^0\gamma\gamma$ event



S. Taylor

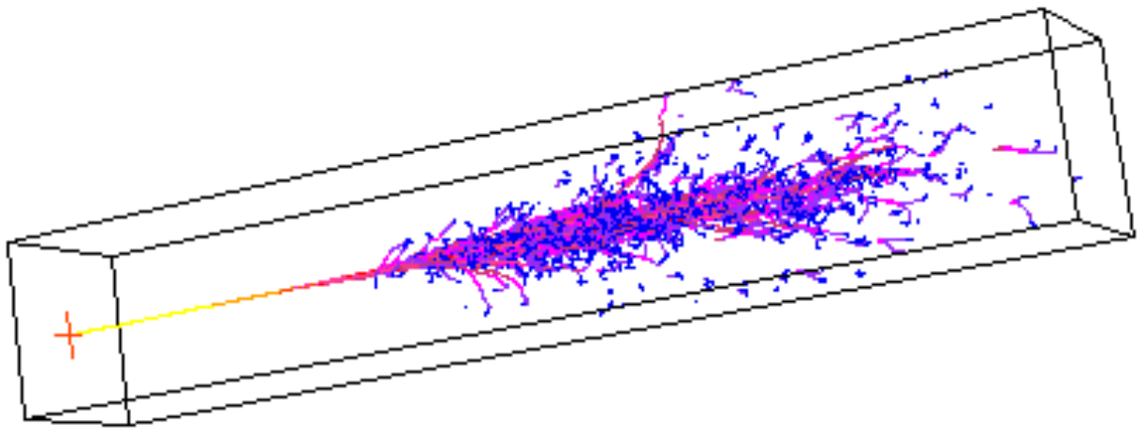
Property	Improvement factor
Energy σ	2
Position σ	2
Granularity	4
Radiation-resistance	10

photon: or not?



Reconstructed Photon Showers

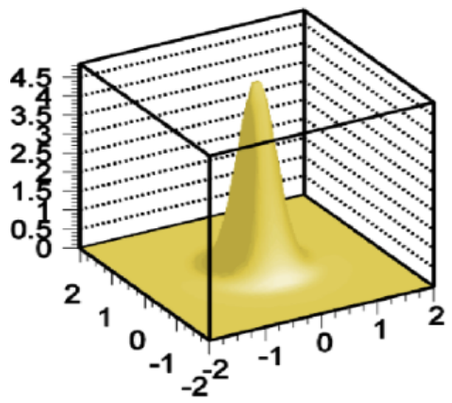
A. Mahmoud



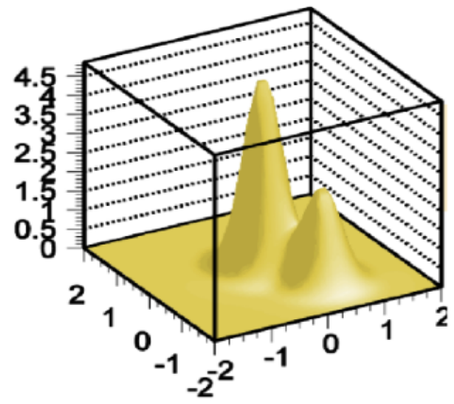
Single volume shower

E-M Shower Simulator, mpp.mpg.de

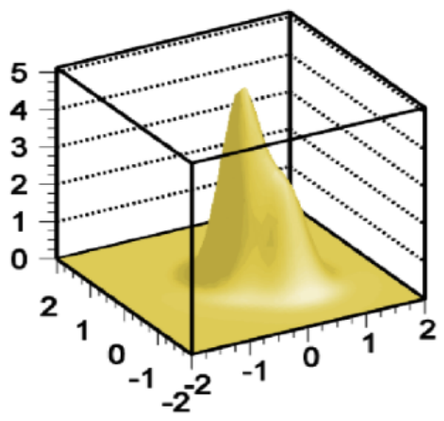
- Photons fire multiple FCAL blocks: clusters
- Two photons with small angular separation can look like a single photon on the FCAL
- Study limits of separation



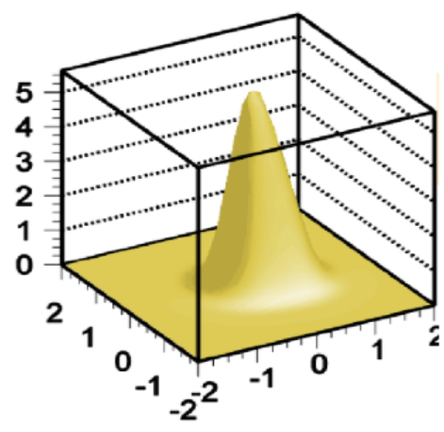
Single cluster



Two clusters produce two maxima



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



Two Indistinguishable clusters

Photon Separation

Clusterizer & Reconstruction:

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

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

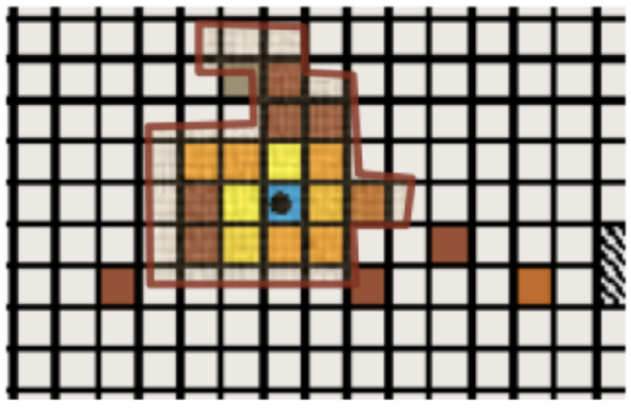
R.T. Jones[a,1], T. Bogue[a,2], B.E. Evans[a], M. Kornicer[a], A.R. Dzierba[b], R. Gardner[b,3], J.L. Gunter[b,4], D. Krop[b], R. Lindenbusch[b], D.R. Rust[b], E. Scott[b], P. Smith[b], C. Steffen[b,5], S. Teige[b,*], D.S. Armstrong[c], J.H.D. Clark[c,6], L.J. Kaufman[c,7], D.J. Steiner[c], E. Frlez[d], 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

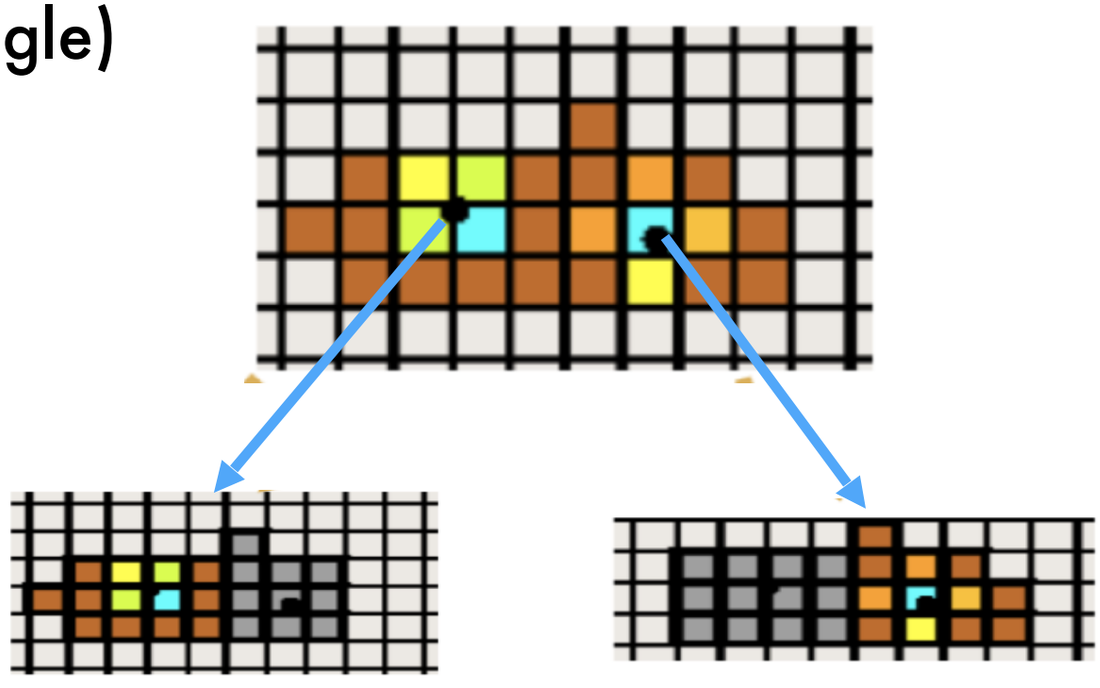
A. A. Lednev, IHEP preprint 93-153
Bland, et al., Instruments and Experimental Techniques 51(2008) 342-350.

Tasks:

- COG-weighted vs LOG-weighted
- evaluate as f(energy, photon opening angle)



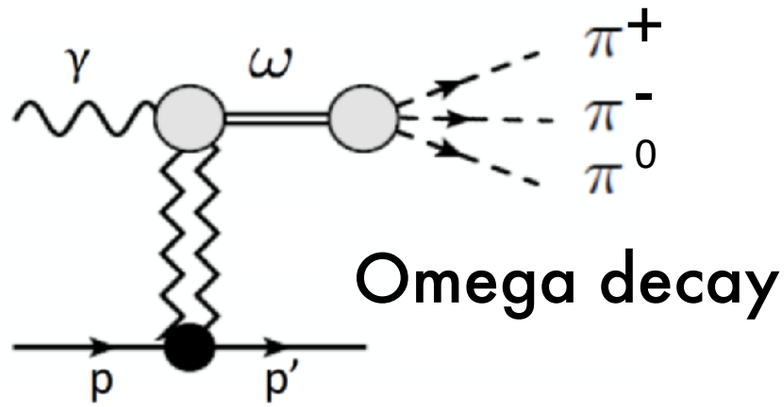
Single photon candidate

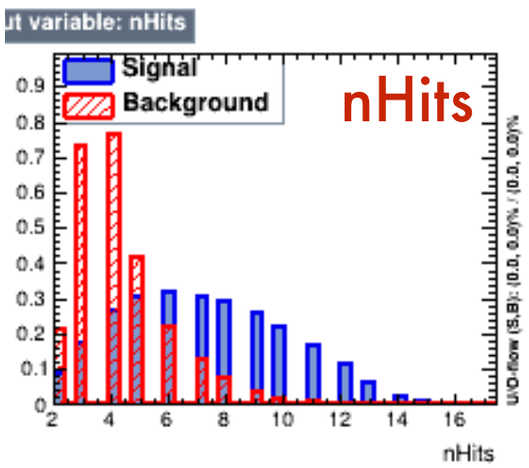


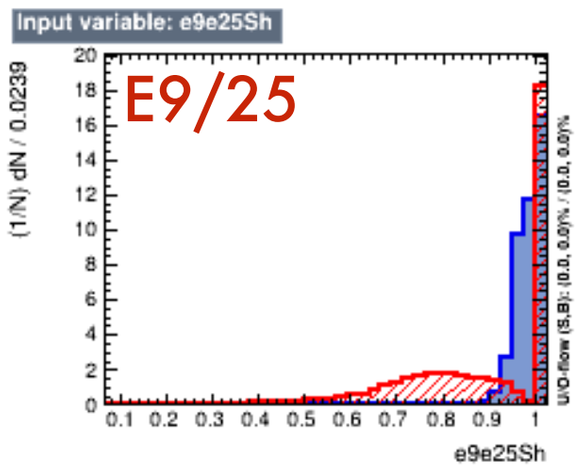
Two photon candidate

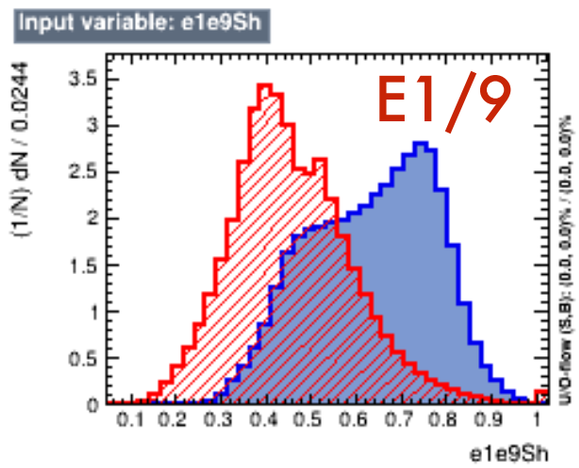
ML: Photon vs Hadron Classification

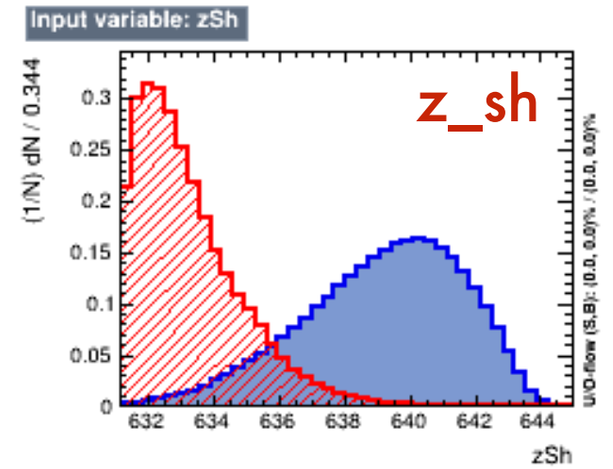
- Machine Learning: binary classification
- Multivariate analysis: combined discriminating power from all key variables: Photon Quality Factor

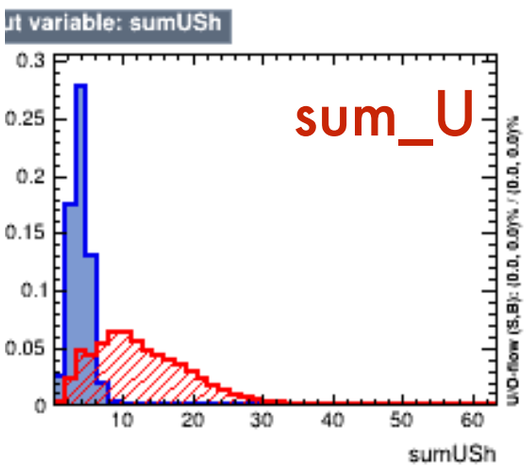


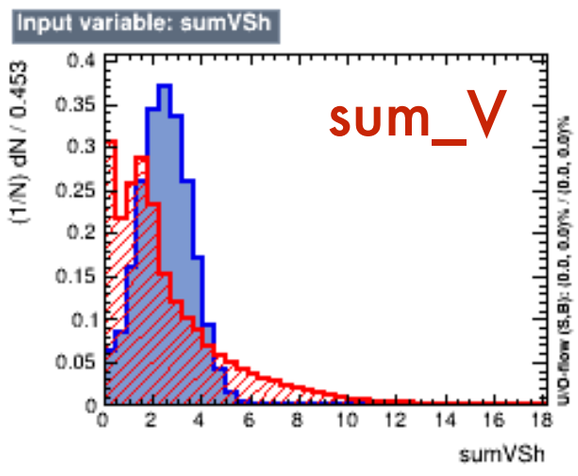


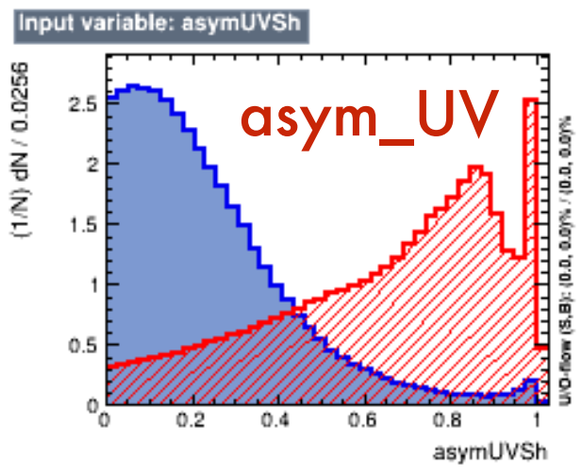


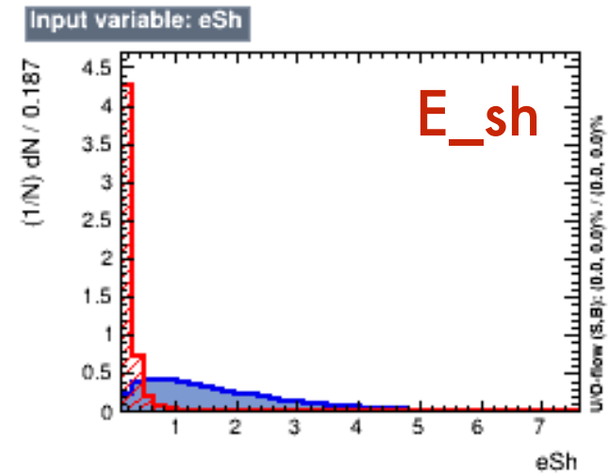




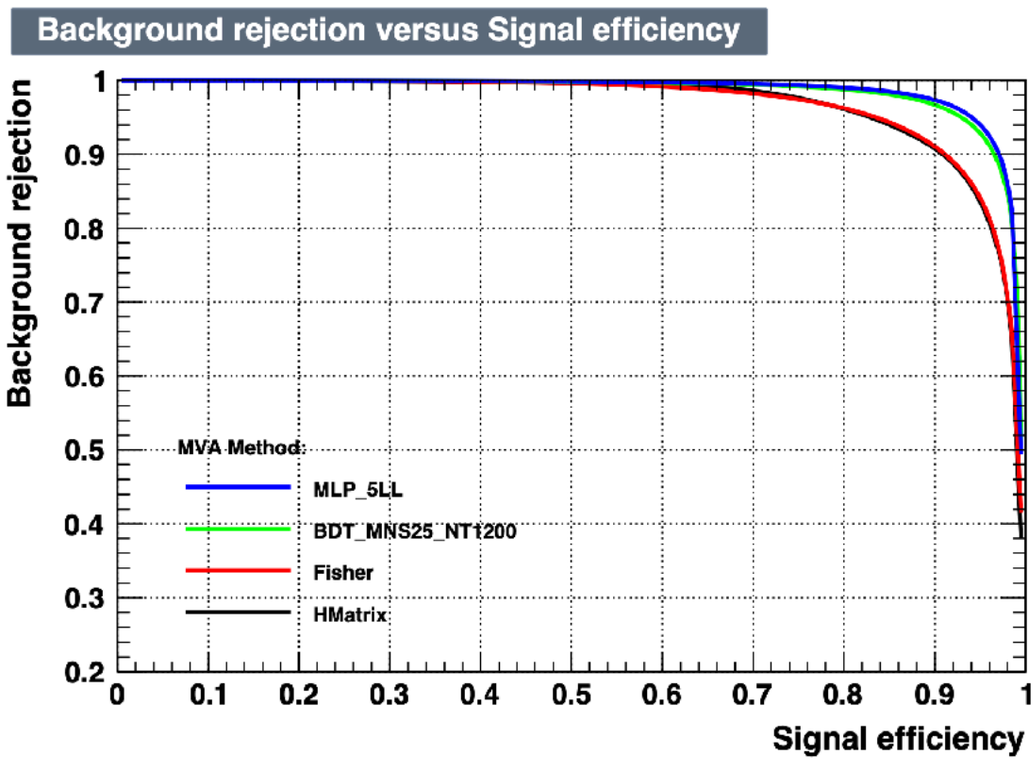


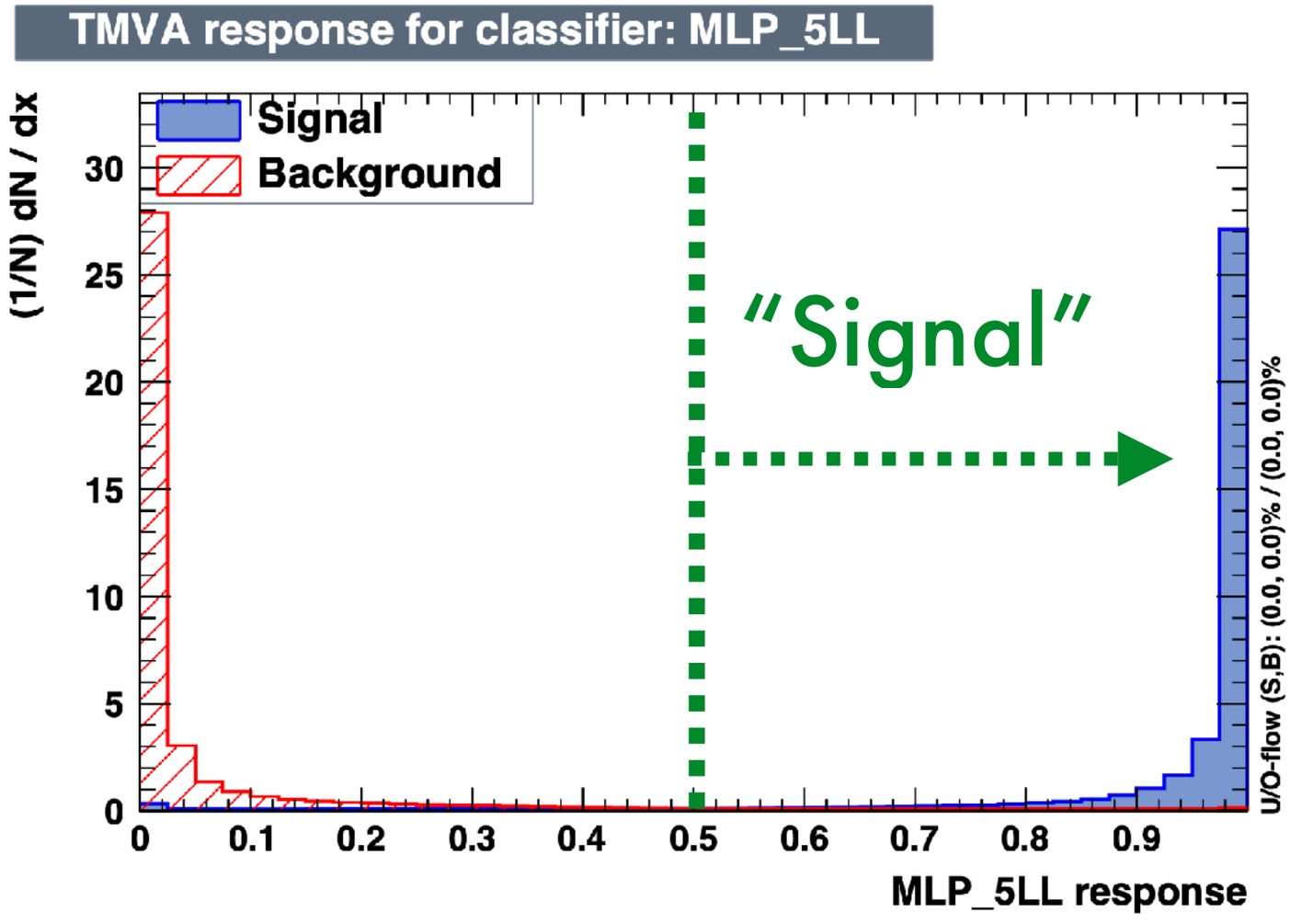






ML: Photon Vs Background Classification





A. Mahmoud: MSc Defense scheduled on June 7

Simulating Events

S. Orešić

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)]

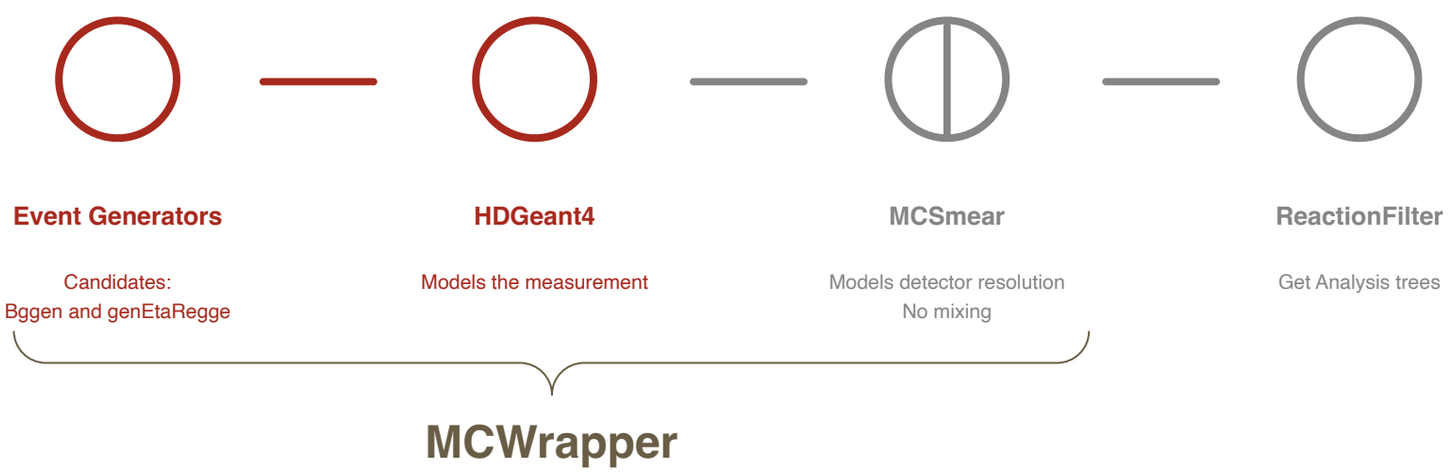
Dark sectors (MeV—GeV)
- Vector bosons (dark photon, B boson, X boson)
- Scalars
- Pseudoscalars (ALPs)

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

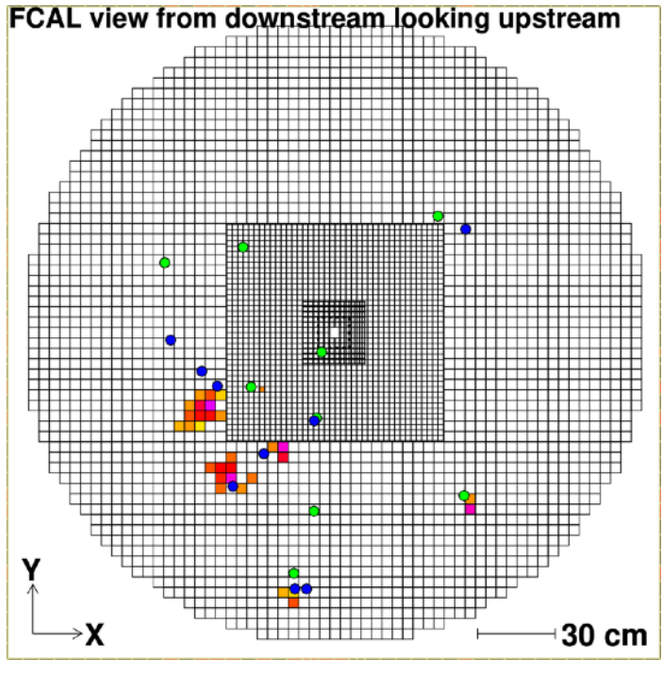
Channel	Expt. branching ratio	Discussion
$\eta \to 2\gamma$	39.41(20)%	chiral anomaly, η–η' mixing
$\eta \to 3\pi^0$	32.68(23)%	$m_u - m_d$
$\eta \to \pi^0\gamma\gamma$	$2.56(22) \times 10^{-4}$	χPT at $O(p^6)$, leptophobic B boson, light Higgs scalars
$\eta \to \pi^0\pi^0\gamma\gamma$	$< 1.2 \times 10^{-3}$	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
$\eta \to \pi^+e^+\nu_e$	$< 1.7 \times 10^{-4}$	second-class current
$\eta \to \pi^+\pi^-$	$< 4.4 \times 10^{-6}$ [53]	P/CP violation
$\eta \to 2\pi^0$	$< 3.5 \times 10^{-4}$	P/CP violation
$\eta \to 4\pi^0$	$< 6.9 \times 10^{-7}$	P/CP violation

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

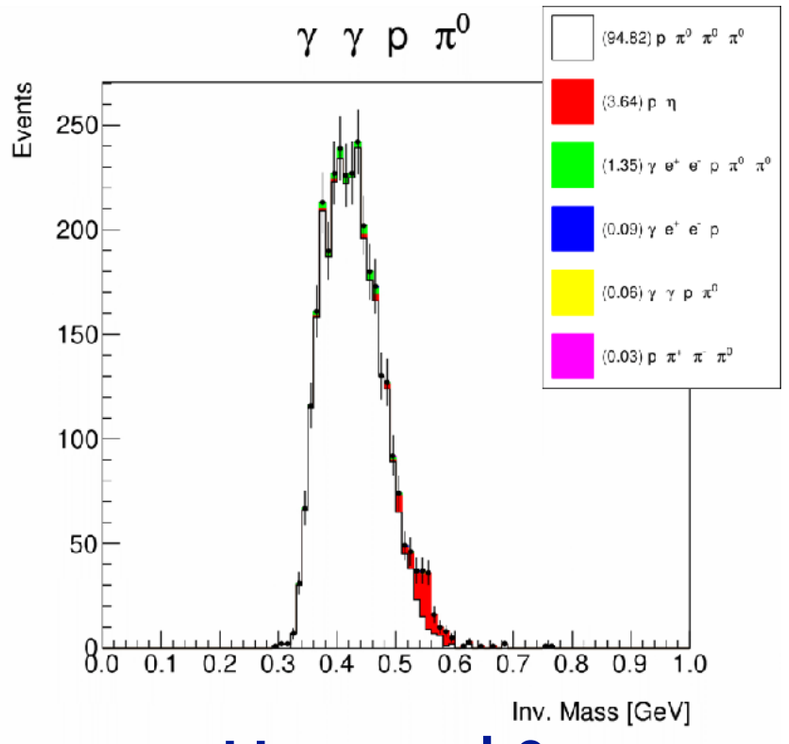
Simulating Events



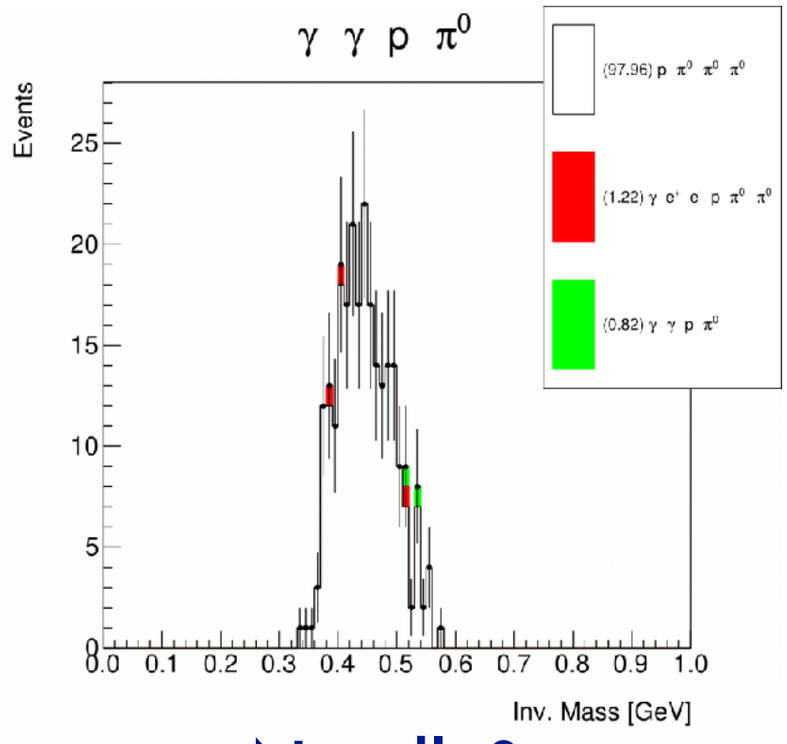
- Simulating data for decay channels of interest
- **Primary channel** $\eta \rightarrow \gamma + \gamma + \pi^0$
- Background → none for starters
- Analysis → FSRoot



Impact pattern



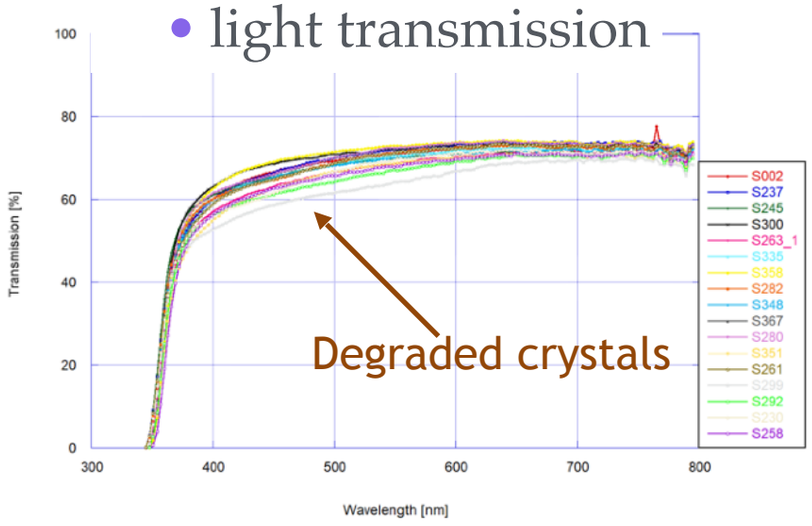
Haystack?



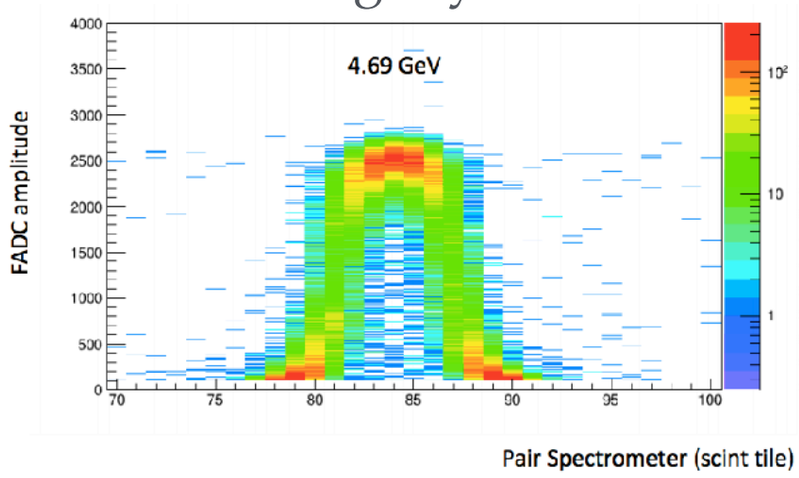
Needle?

Hardware Status

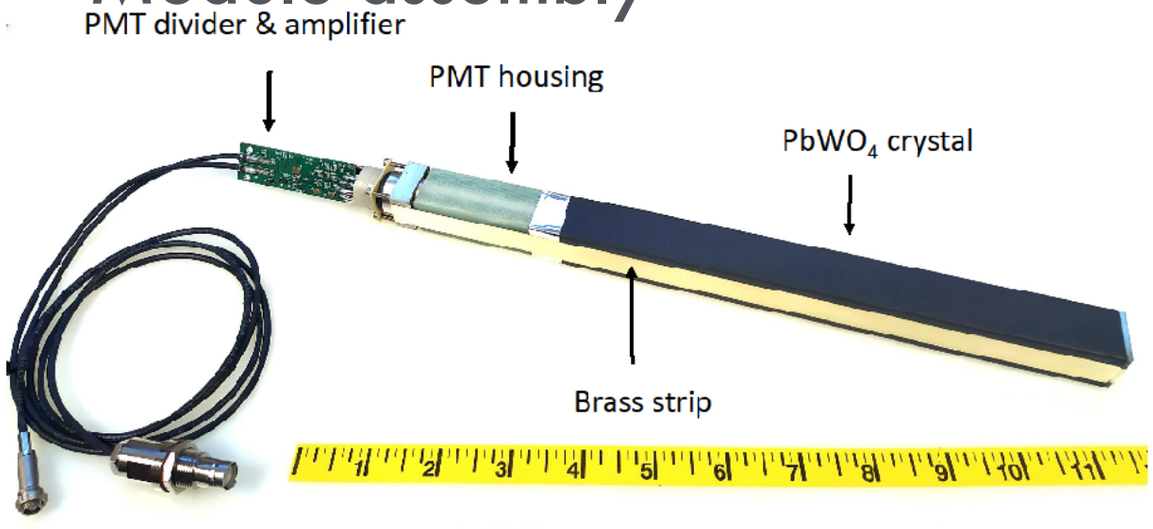
- **$PbWO_4$ crystal QA:** surface, clarity, color, dimensions, etc.
  - light transmission



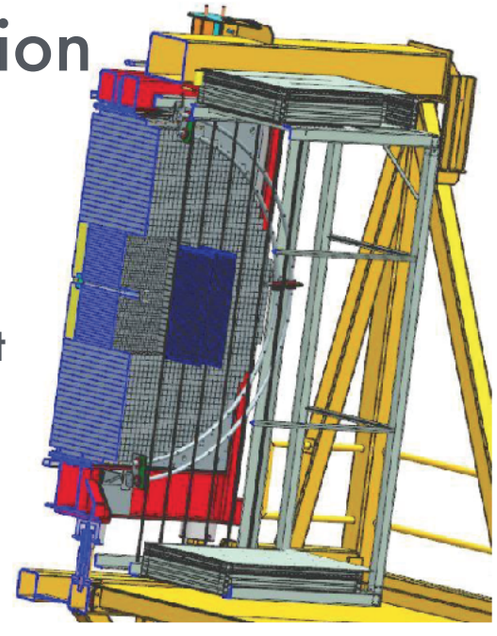
  - light yield



- Module assembly



- Fabrication and Installation
  - Frame redesigned
  - Electronics racks
  - Modules installed July-Oct 2023
  - Cabling underway
  - Cooling & Dark room

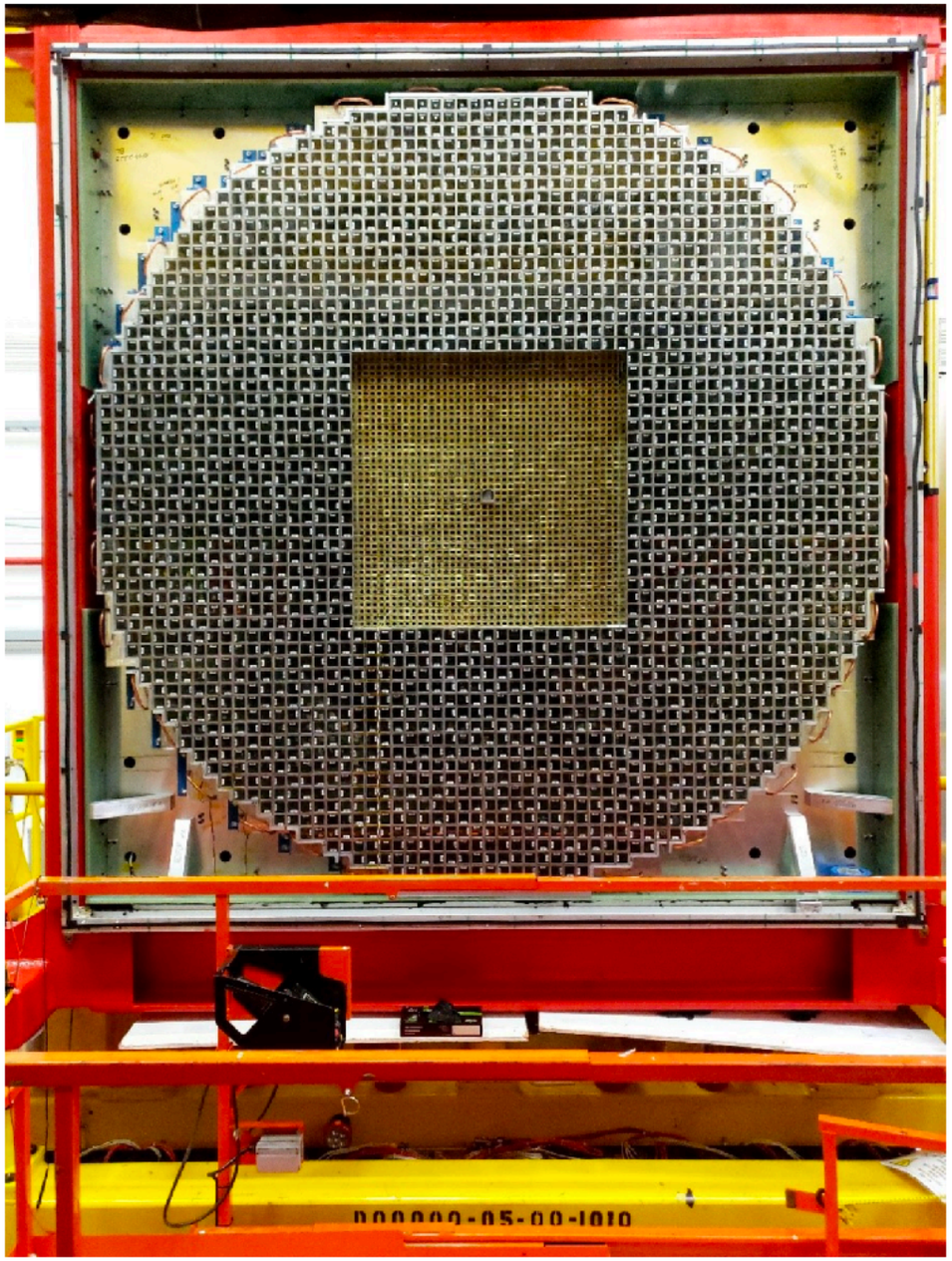


Unstack…

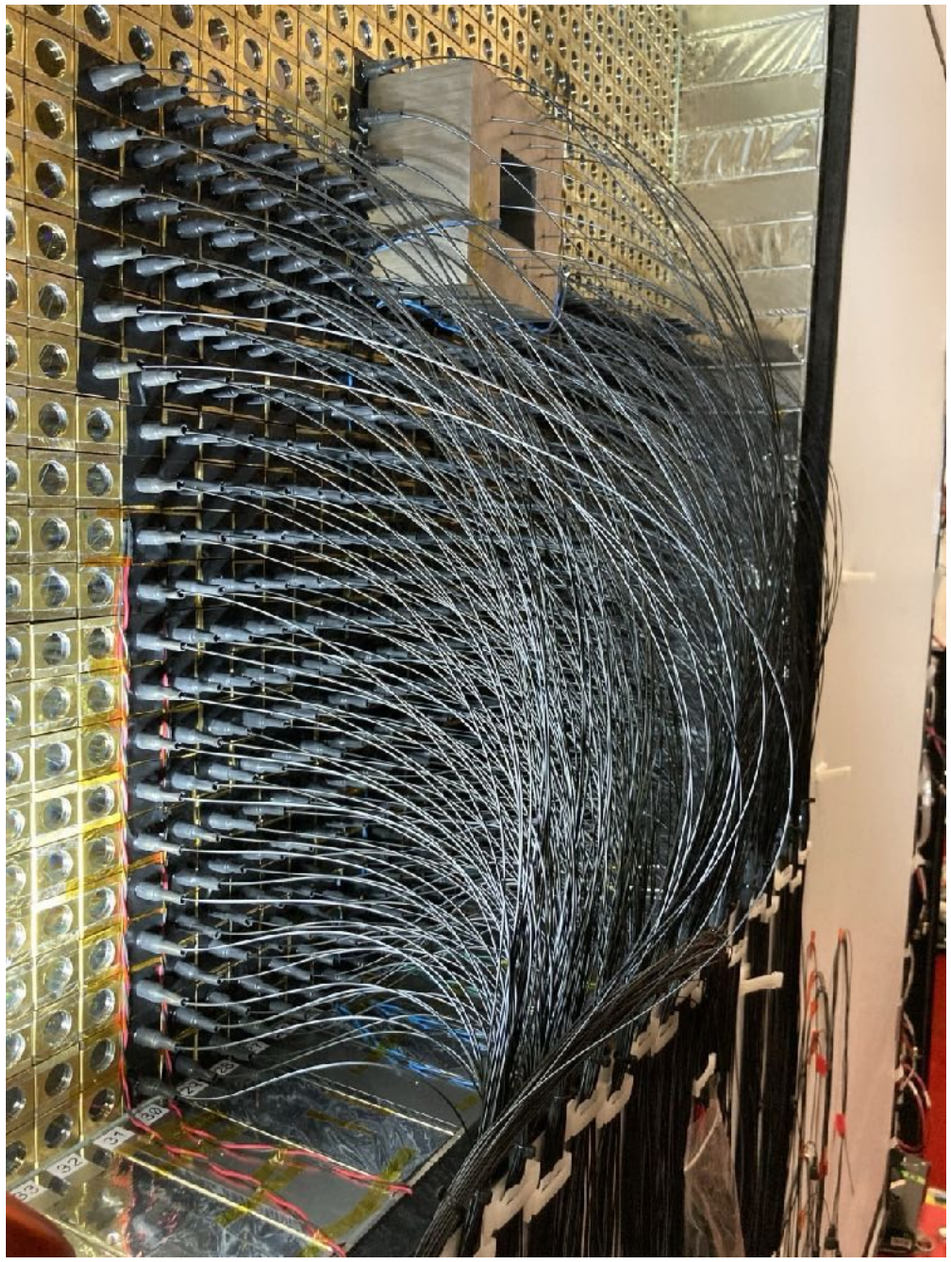
April 2023

May 2023

…restack and install LMS fibers

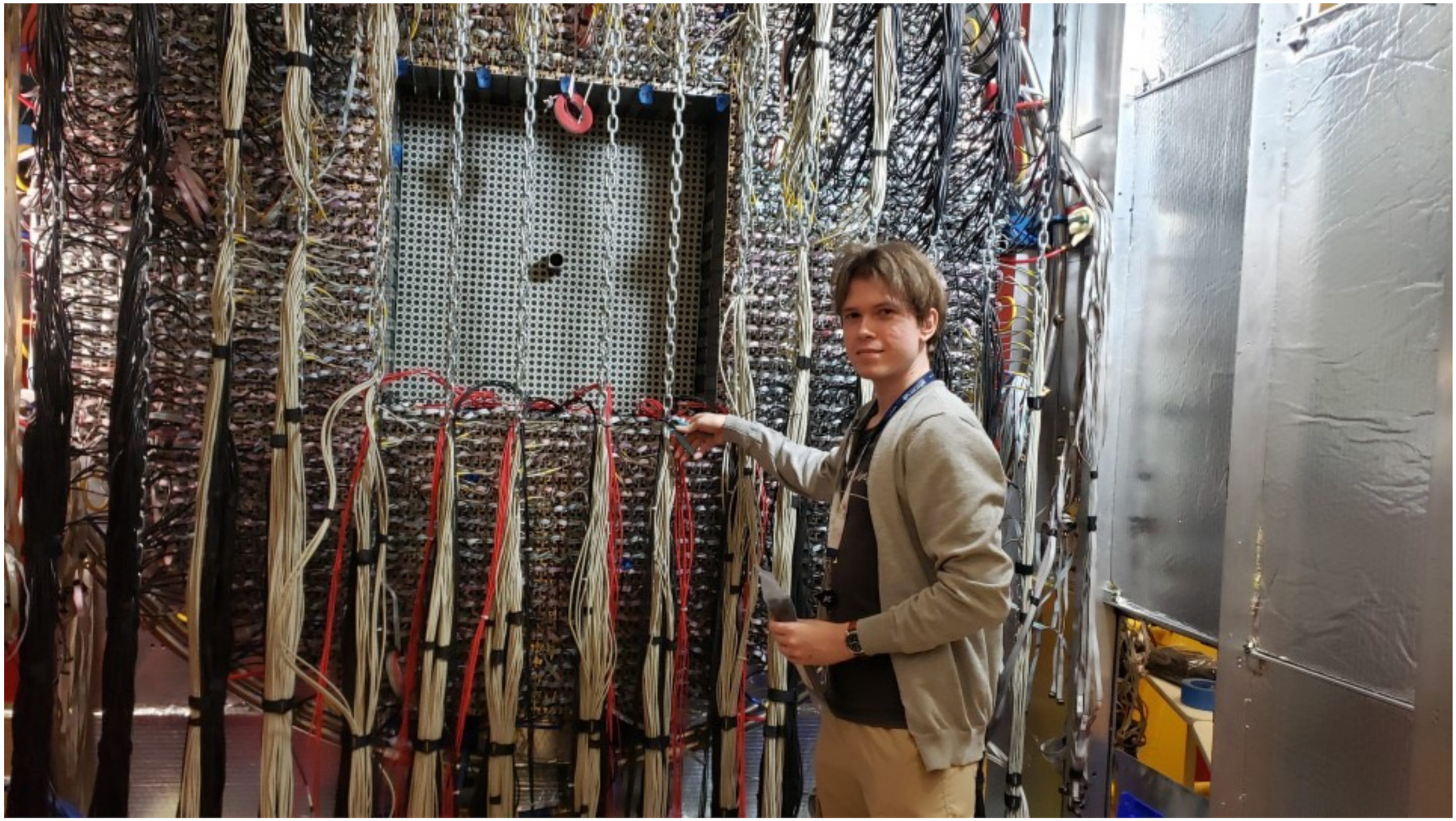


October 2023



February 2024

Cables, cables and more cables…



January 2024

Summary & Outlook

- **JEF:**
  - 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 goals of:
    - SM/BSM physics; CVPC; precision tests of low-energy QCD, quark mass ratio
    - Cluster identification using conventional and Machine Learning algorithms
    - 200 days of running approved ++ more will be requested
- Upgraded FCAL-II will take data starting Nov 2024

Thank you / Merci