Update of the Jefferson Lab Eta Factory and the Search for BSM Physics

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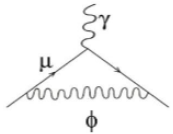
University of Regina | Faculty of Science

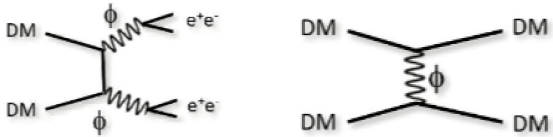
Sub-GeV New Physics

- New gauge forces or scalar bosons beyond the minimal standard model. Dark Sector model space for sub-GeV dark matter continues to be refined and expanded.

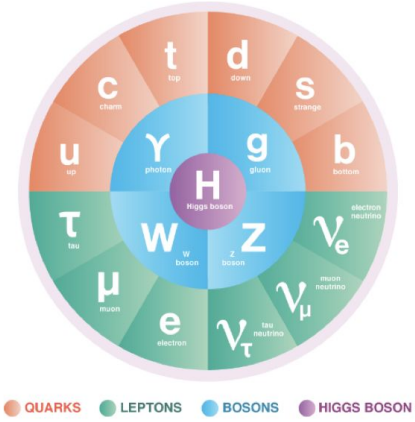
- Anomalies: muon (g-2)μ, and anomalous e^+e^- resonance in $^8Be/^4He$

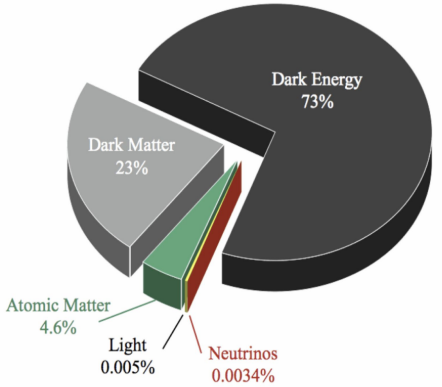


- Dark Matter physics:



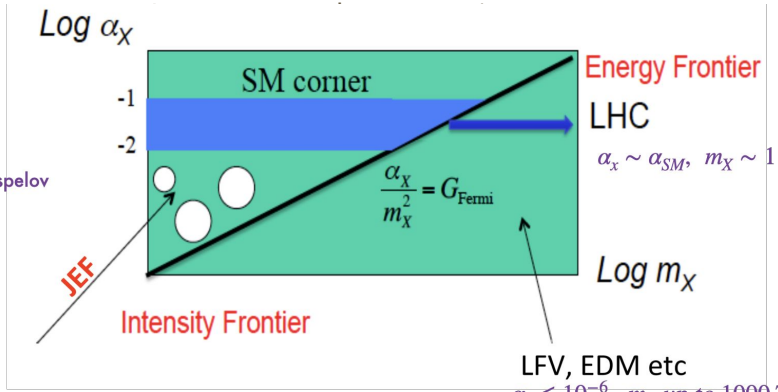
- DM candidates produced in meson decays and direct photo production. Strategy: resolve narrow structures in invariant mass spectra in many decays.





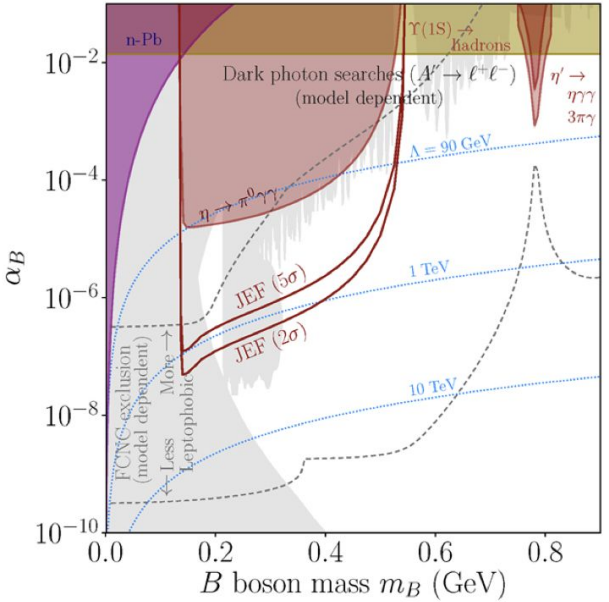
Jefferson Lab Eta Factory (JEF)

- Search for sub-GeV, hidden bosons (vector, scalar, axion-like particles); complementary look at parameter landscape.
- Other physics:
  - Constrain C-violating Parity Conserving new physics
  - Precision test of low-energy QCD (ChPT)



M. Pospelov

L. Gan, B. Kubis, E. Passemar, S. Tulin, Physics Reports 945 (2022) 1–105, or arXiv: 20070064

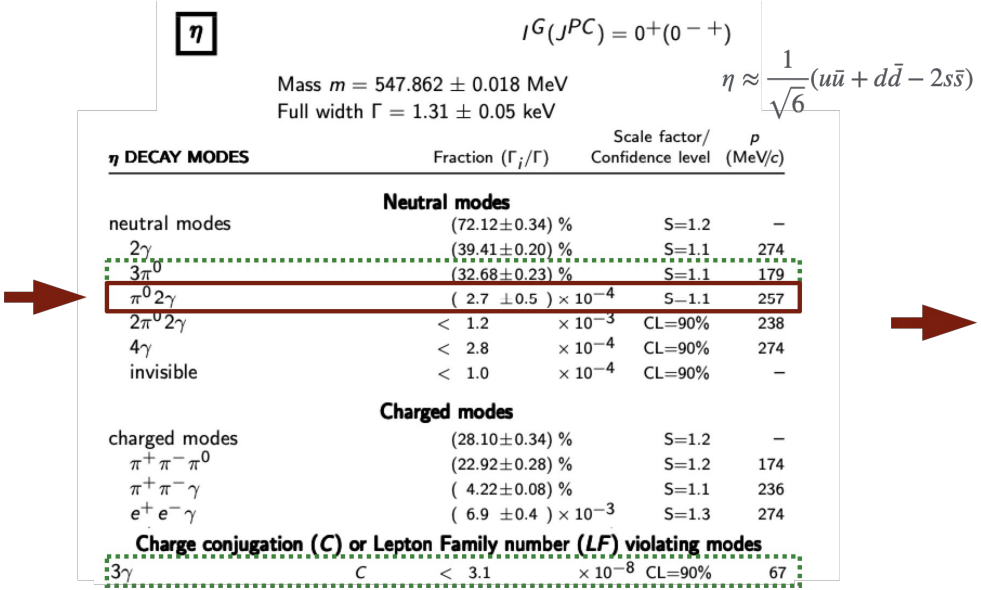


Leptophobic vector B′ coupling to baryon number

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

Nelson PLB 221, 80 // Tulin PRD 89, 114008

Eta and Eta-prime mesons



η $I^G(J^{PC}) = 0^+(0^{-+})$

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

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

η DECAY MODES	Fraction (Γ_i/Γ)	Scale factor/ Confidence level	p (MeV/c)
Neutral modes			
neutral modes	(72.12±0.34) %	S=1.2	–
2γ	(39.41±0.20) %	S=1.1	274
$3\pi^0$	(32.68±0.23) %	S=1.1	179
$\pi^0 2\gamma$	(2.7 ±0.5) × 10^{-4}	S=1.1	257
$2\pi^0 2\gamma$	< 1.2 × 10^{-3}	CL=90%	238
4γ	< 2.8 × 10^{-4}	CL=90%	274
invisible	< 1.0 × 10^{-4}	CL=90%	–
Charged modes			
charged modes	(28.10±0.34) %	S=1.2	–
$\pi^+\pi^-\pi^0$	(22.92±0.28) %	S=1.2	174
$\pi^+\pi^-\gamma$	(4.22±0.08) %	S=1.1	236
$e^+e^-\gamma$	(6.9 ±0.4) × 10^{-3}	S=1.3	274
Charge conjugation (C) or Lepton Family number (LF) violating modes			
3γ	C < 3.1 × 10^{-8}	CL=90%	67

η′(958) $I^G(J^{PC}) = 0^+(0^{-+})$

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

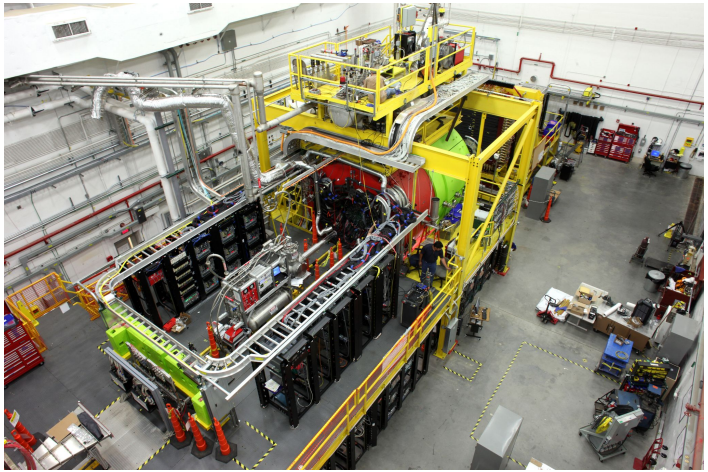
$$\eta' \approx \frac{1}{\sqrt{3}}(u\bar{u} + d\bar{d} + s\bar{s})$$

η′(958) DECAY MODES	Fraction (Γ_i/Γ)	Confidence level	p (MeV/c)
$\pi^+\pi^-\eta$	(42.9 ±0.7) %		232
$\rho^0\gamma$(including non-resonant $\pi^+\pi^-\gamma$)	(29.1 ±0.5) %		165
$\pi^0\pi^0\eta$	(22.2 ±0.8) %		239
$\pi^0\gamma\gamma$	< 8 × 10^{-4}	90%	469
$\gamma\gamma$	(2.20±0.08) %		479
$3\pi^0$	(2.14±0.20) × 10^{-3}		430
Charge conjugation (C), Parity (P), Lepton family number (LF) violating modes			
$\pi^+\pi^-$	P,CP < 6 × 10^{-5}	90%	458
$\pi^0\pi^0$	P,CP < 4 × 10^{-4}	90%	459
$\pi^0 e^+e^-$	C [f] < 1.4 × 10^{-3}	90%	469
ηe^+e^-	C [f] < 2.4 × 10^{-3}	90%	322
3γ	C < 1.0 × 10^{-4}	90%	479

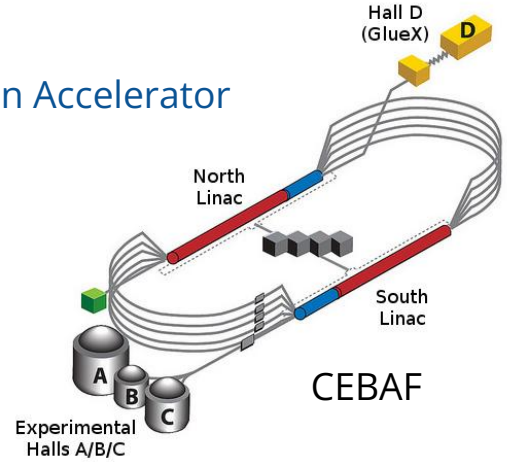
Key Channel : $\eta/\eta' \rightarrow \pi^0\ \gamma\ \gamma$ (identify 4 photons cleanly)

Hall D at Jefferson Lab

Home to the **GlueX** experiment which aims to look for exotic hybrid mesons

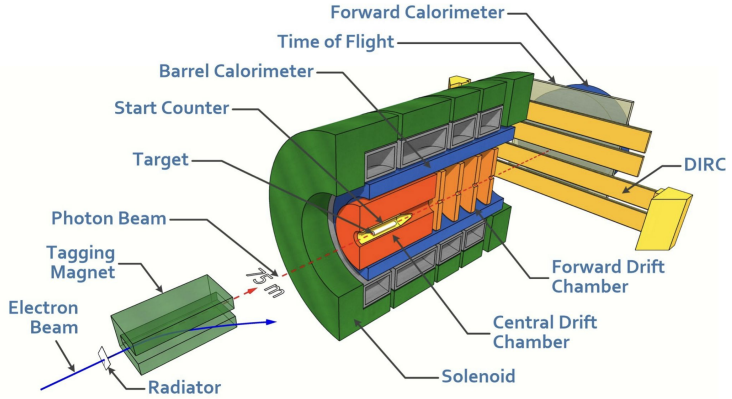


Electron Accelerator



Producing Photon Beam

Designed to study photoproduction reactions with 8-9-GeV linearly polarized photon beam.

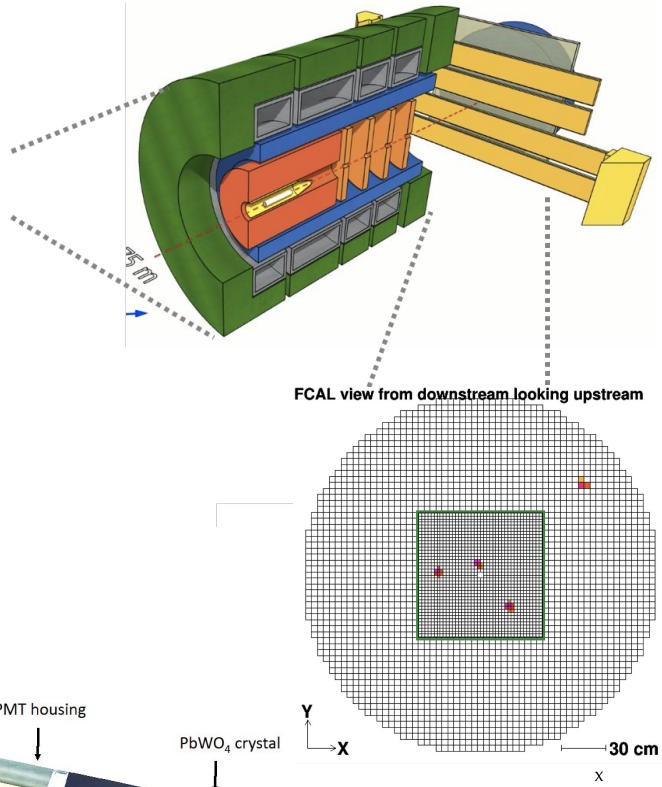


Upgrade of the FCAL-II for JEF

JEF is an extension of the GlueX experiment with focus on performing precision measurements of various η/η’ decays

The inner region (80 x 80 cm^2) of the FCAL is upgraded to higher granularity $PbWO_4$ crystals.

Currently undergoing quality assurance for surface, clarity, color, dimensions, light transmission & yield, assembly.



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

Distinguishing Reconstructed Photon Showers

Ongoing software considerations to improve photons reconstruction

Photons with small angular separation can present as a single photon on the FCAL and need to be further separated

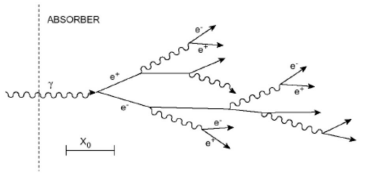
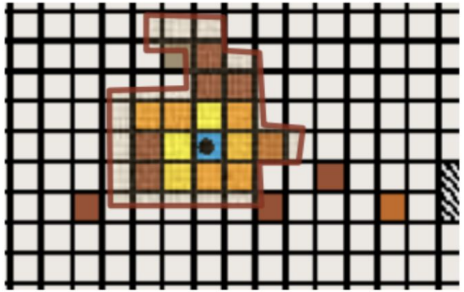
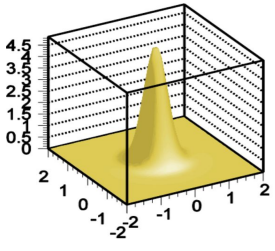


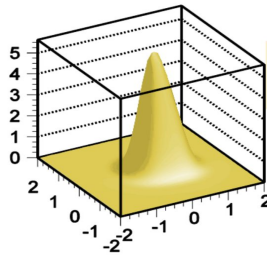
Figure 5: Schematic development of an electromagnetic shower.

T.S.Virdee, Proc. of the 1998 European School of High-Energy Physics, CERN 99-04

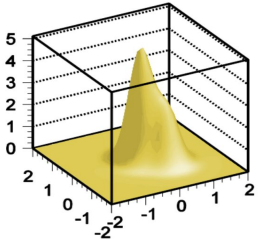




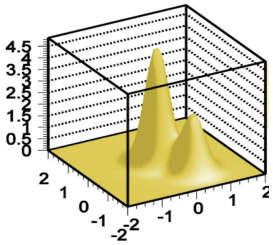
Single Cluster



Two Indistinguishable Clusters



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



Two Clusters Produce Two Maxima

I. Larin, Jefferson Lab

Photon Shower Separation cont'd

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]

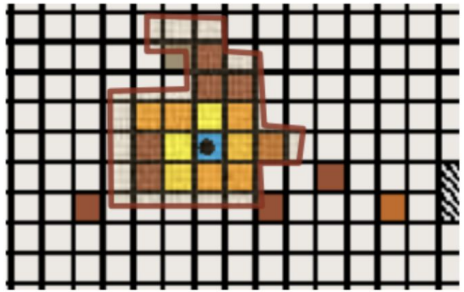
NIM A 570 (2007) 384–398

Reconstruction algorithms :

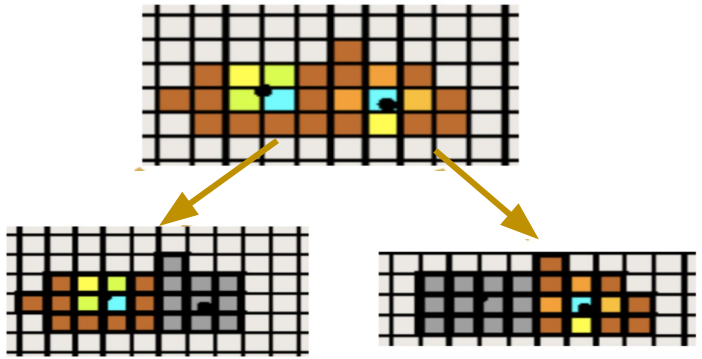
- Current GlueX Default Reconstruction Algorithm adapted from RADPHI
- Island Algorithm adapted from GAMS experiment

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

Goal: Compare Island to Standard GlueX Clusterizer & Reconstruction code



One Photon



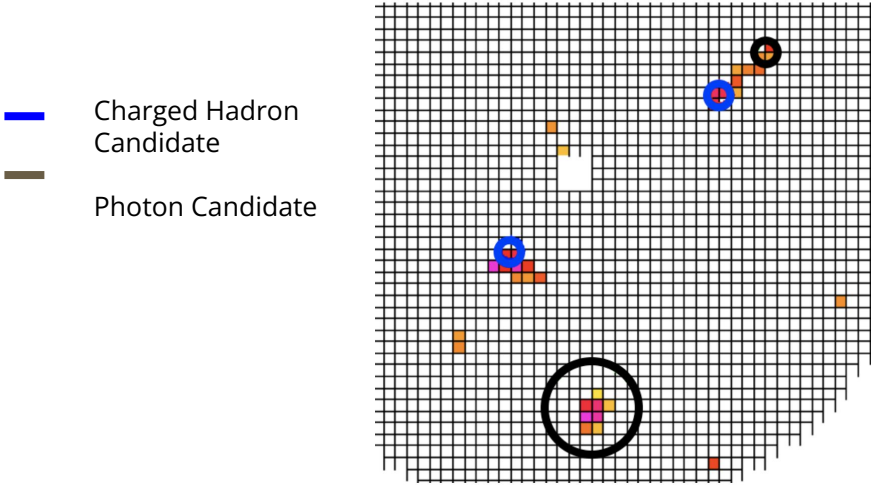
Two Photon Candidate

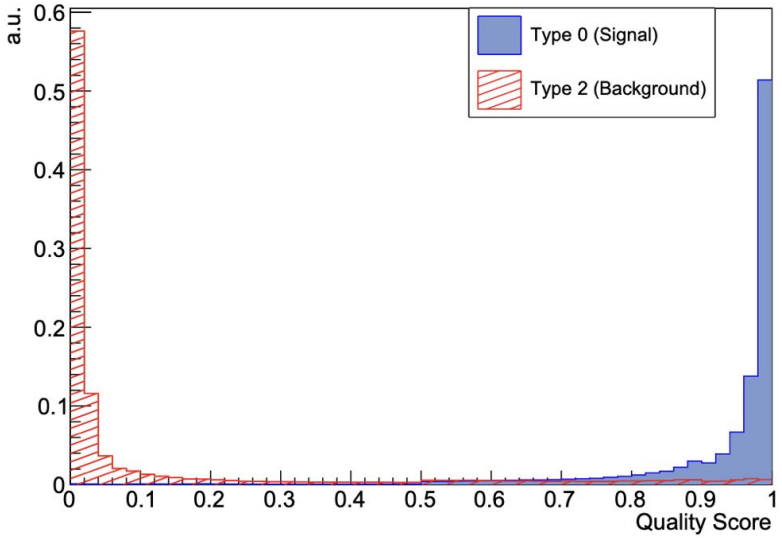
Photon / Background Classification in FCAL

Type 0 : True photon showers

Type 1: Showers from charged particles

Type 2: All other showers, mostly split-offs from type 1 showers, and background





Shower Quality Score, FCAL

Barsotti, Shepherd, IU

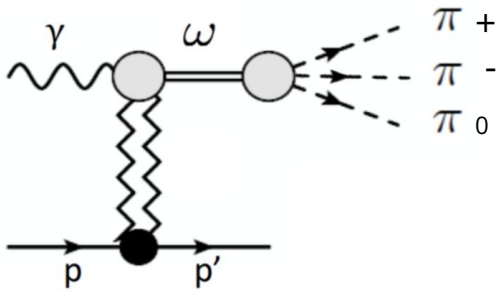
JINST, Vol 15, May 2020

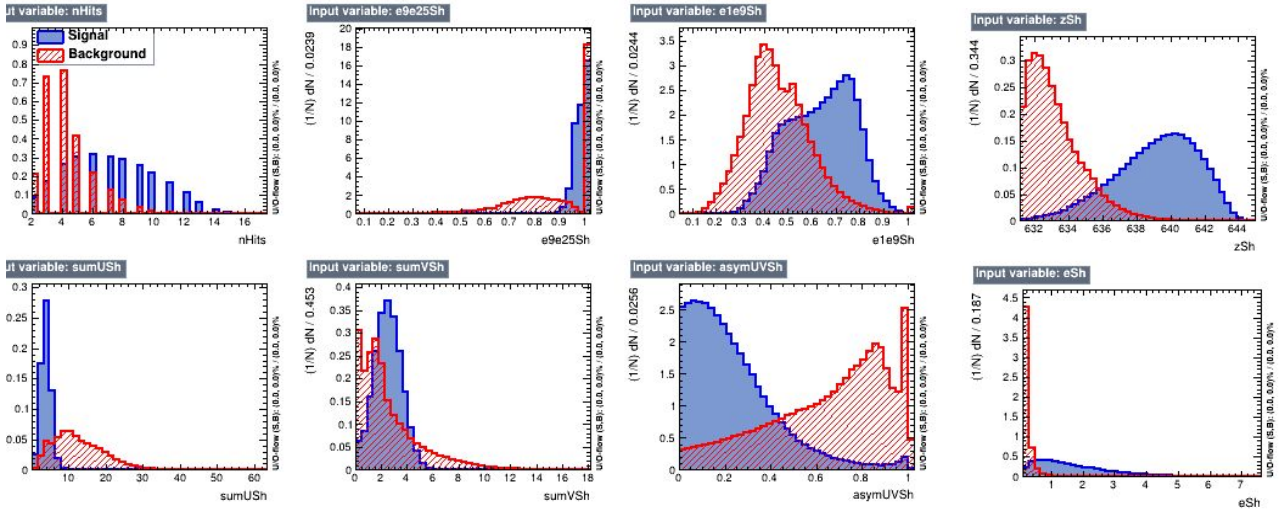
Separating Photons from Background

Omega decays produce photons and charged hadrons as source of background showers

Opportunity for Machine Learning for Classification

Use multivariate analysis (MVAs) for this binary classification problem





Summary

GlueX + 12 GeV tagged photon beam yields a unique η/η'factory: background reduction in neutral rare decay modes vs other facilities.

Simultaneously measure η/η’ decays with main physics goals of:

- Test SM and search for new BSM physics; constrain CVPC new physics; precision tests of low-energy QCD, improve light quark mass ratio, a.o.

Upgraded FCAL-II insert currently under construction data taking expected in 2024.

Ongoing Machine learning to further improve background separation

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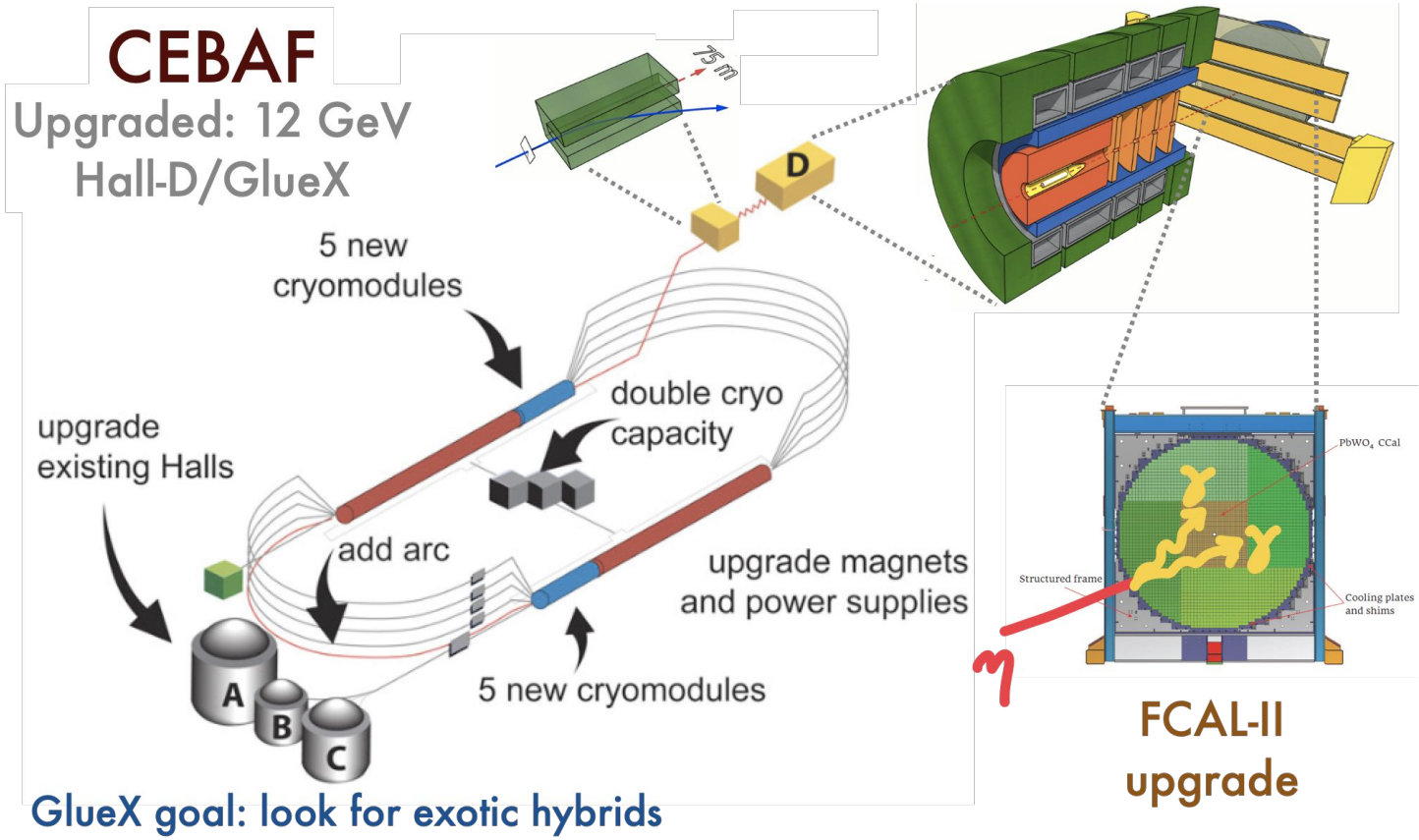
NSERC CRSNG

GlueX JEF D

gluex.org/thanks

Backup Slides

Hall-D Jefferson Lab (GlueX/JEF Experiments)



Reaction Channels - I

1. Search for sub-GeV, hidden bosons

mass ranges

- **vector**:
  - Leptophobic vector B′ $\eta^{(\prime)} \to B'\gamma \to \pi^0\gamma\gamma \quad (0.14 - 0.54\ GeV)$
    $\eta' \to B'\gamma \to \pi^+\pi^-\pi^0\gamma \quad (0.62 - 1.00\ GeV)$
  - Hidden or dark photon $\eta^{(\prime)} \to A'\gamma \to e^+e^-\gamma$
- **scalar**: $\eta \to \pi^0 S \to \pi^0\gamma\gamma, \pi^0 e^+e^- \quad (10\ MeV < m_S < 2m_\pi)$
  $\eta^{(\prime)} \to \pi^0 S \to 3\pi, \eta' \to \eta S \to \eta\pi\pi \quad (m_S > 2m_\pi)$
- **Axion-Like Particles (ALP)**: $\eta^{(\prime)} \to \pi\pi a \to \pi\pi\gamma\gamma, \pi\pi e^+e^-$

Reaction Channels - II

2. Directly constrain CVPC new physics:

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

3. Precision tests of low-energy QCD:

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

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

arXiv: 20070064
L. Gan, B. Kubis, E. Passemar, S. Tulin
Precision tests of fundamental physics with η and η′ mesons

ElectroMagnetic Shower vs Hadronic Shower

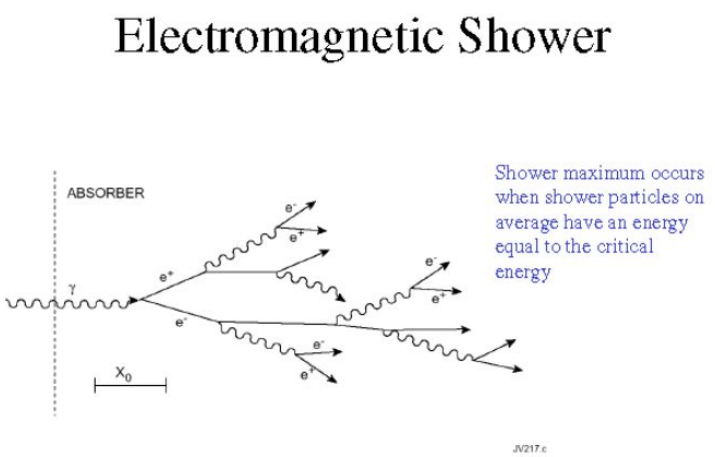


Figure 5: Schematic development of an electromagnetic shower.

T.S.Virdee, Proc. of the 1998 European School of High-Energy Physics, CERN 99-04

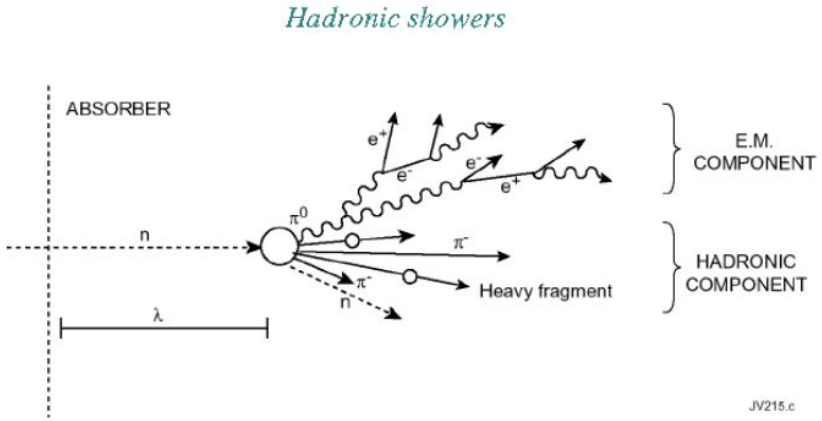


Figure 12: Schematic of development of hadronic showers.

T.S.Virdee, Proc. of the 1998 European School of High-Energy Physics, CERN 99-04

Lead Tungstate Crystals vs Lead Glass

Technology	Experiment	Depth	Energy resolution	Readout
$PbWO_4$	CMS	$25X_0$	$3\%/\sqrt{E} + 0.5\% + 0.2/E$	APD
$PbWO_4$	Primex		$1.75\%/\sqrt{E} + 1.15\%$	PMT
$PbWO_4$	PANDA		$<2\%/\sqrt{E} + <1\%$ (req.)	LAAPD
$PbWO_4$	NPS		$<2\%/\sqrt{E} + <1\%$ (req.)	PMT
Lead glass	OPAL	$20.5X_0$	$5\%/\sqrt{E}$	