Hall D/GlueX Calorimeter Review

Overview and Physics Motivation

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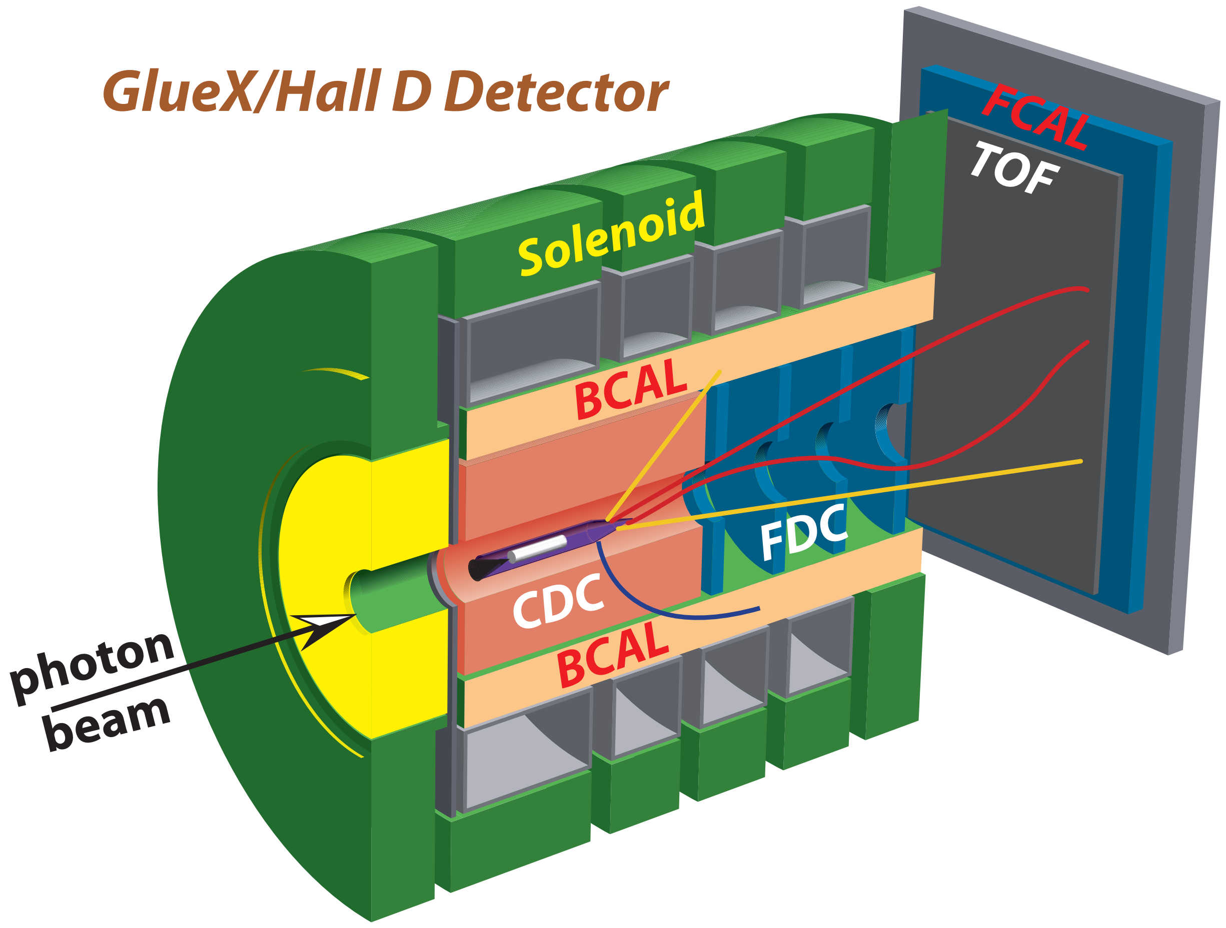


BCAL - barrel calorimeter
FCAL- forward calorimeter

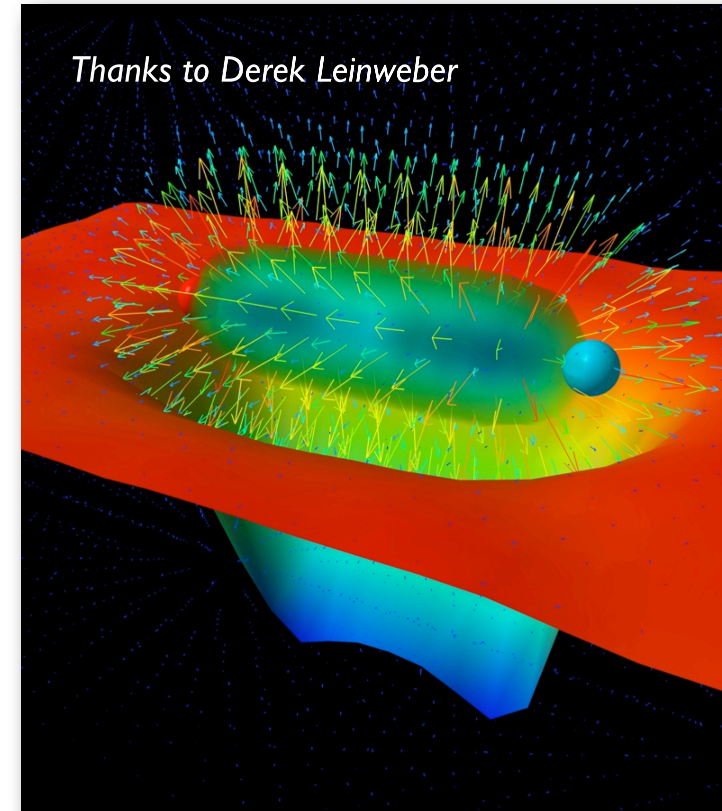
CDC - central drift chamber
FDC - forward drift chambers

TOF - time-of-flight

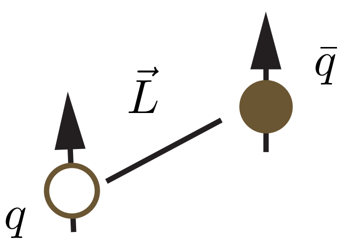
1. ***Brief review of the physics: search for exotic hybrid mesons***
2. ***Importance of neutral particle detection***
3. ***Role of calorimetry and performance metrics***

The Physics of GlueX

Mapping the Spectrum of Exotic Hybrids



The goal of the GlueX experiment is to map out the spectrum of exotic hybrid mesons in the light quark sector. Lattice QCD suggests that the gluonic field between quarks in a meson is confined to a flux-tube and the excitations of the flux-tube are manifested as hybrid mesons, some of which can carry exotic quantum numbers. Their spectroscopy provides important information for the theory of quarks and gluons.



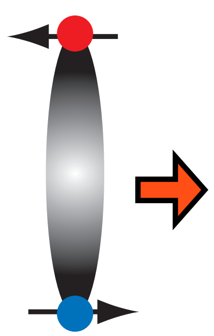
$$\vec{J} = \vec{L} + \vec{S}$$
$$P = (-1)^{L+1}$$
$$C = (-1)^{L+S}$$

these exotic combinations not allowed:

$$J^{PC} = 0^{--}, 0^{+-}, 1^{-+}, 2^{+-}$$

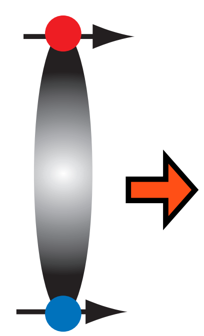
Conventional mesons: gluonic field, in ground state, does not contribute to degrees of freedom.

Including the quantum numbers of the excited gluonic field, can lead to mesons with exotic quantum numbers:



$$J^{PC} = 1^{--} \ or \ 1^{++}$$

$\vec{L} = 0, \ \vec{S} = 0$



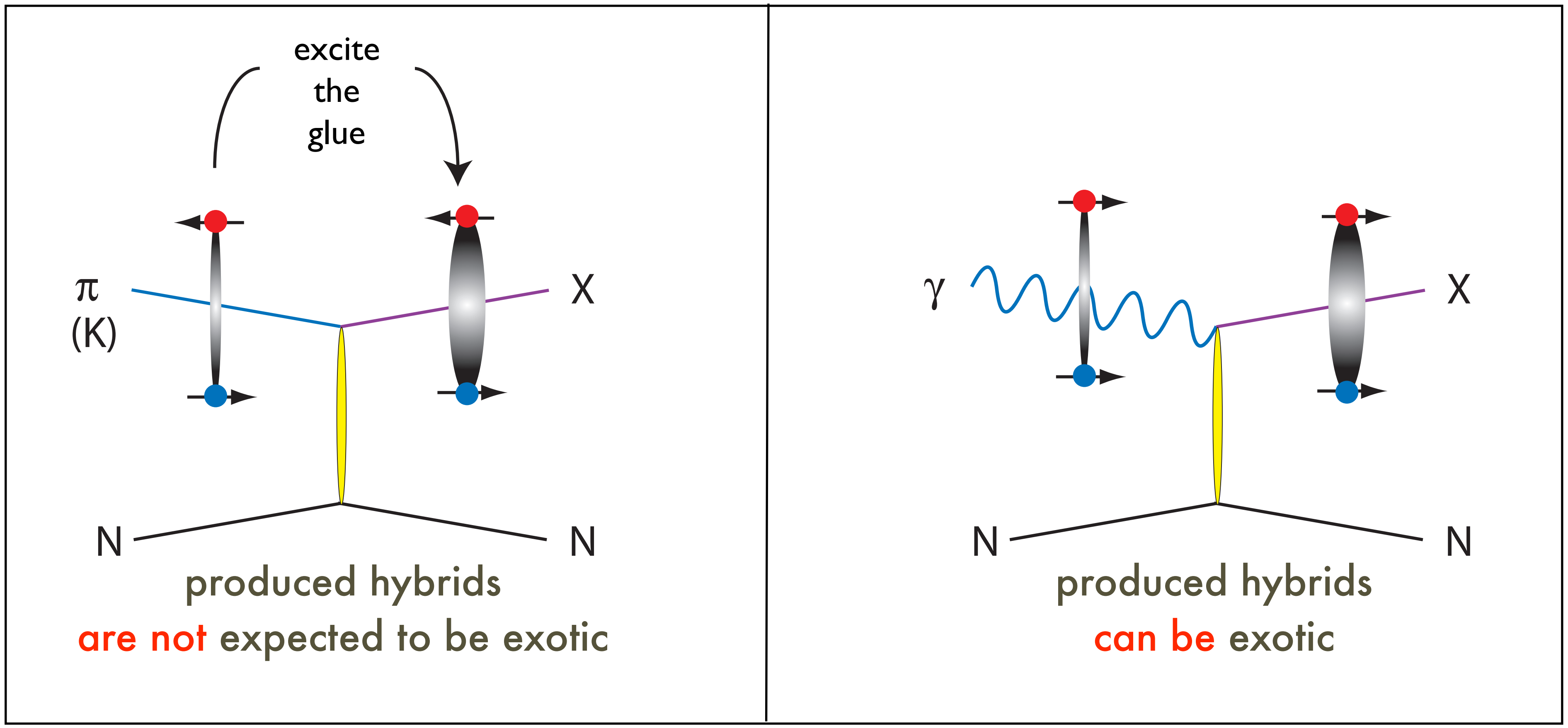
$$J^{PC} = 0^{-+}, 1^{+-}, 2^{-+}$$
$$J^{PC} = 0^{+-}, 1^{-+}, 2^{+-}$$

exotic

$\vec{L} = 0, \ \vec{S} = 1$

Photoproduction of Exotic Mesons

An Effective Method for Producing Exotics?



GlueX will:

- ***use linearly polarized 9 GeV photons produced via coherent bremsstrahlung from 12 GeV electrons;***
- ***use a detector optimized to collect high-quality data from multi-particle exclusive reactions; and***
- ***apply an amplitude analysis to identify the quantum numbers, masses and decay modes of mesons.***

Exotic Meson Decays: Favored and/or Observed Decay Modes

Many include final state mesons that decay into photons

Favored decay modes:

Exotic Meson	J^{PC}	I	G	Possible Modes
b_0	0^{+-}	1	$+$	
h_0	0^{+-}	0	$-$	$b_1\pi$
π_1	1^{-+}	1	$-$	$\rho\pi$, $b_1\pi$
η_1	1^{-+}	0	$+$	$a_2\pi$
b_2	2^{+-}	1	$+$	$a_2\pi$
h_2	2^{+-}	0	$-$	$\rho\pi$, $b_1\pi$

Reported exotics:

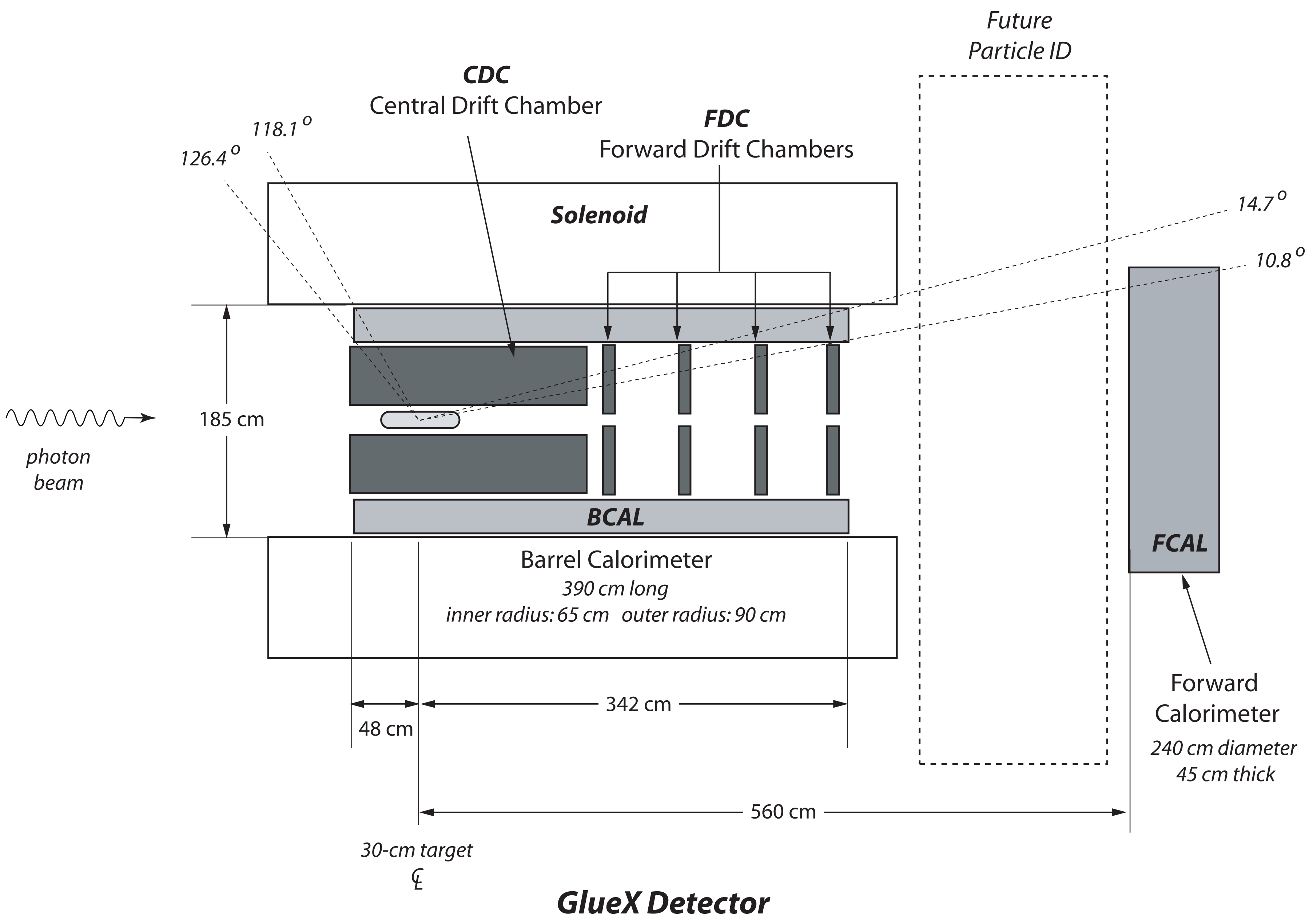
Exotic Meson Candidate	Decay Mode
$\pi_1(1400)$	$\pi^-\eta$
	$\pi^0\eta$
$\pi_1(1600)$	$\rho^0\pi^-$
	$\eta'\pi^-$
$\pi_1(1600/2000)$	$b_1\pi$
	$f_1\pi$

Relevant intermediate mesons:

Meson Decay Mode	Branching Fraction (%)
$\pi^0 \to 2\gamma$	99
$\eta \to 2\gamma$	39
$\eta \to 3\pi^0$	33
$\eta \to \pi^+\pi^-\pi^0$	23
$\omega \to \pi^+\pi^-\pi^0$	89
$\omega \to \pi^0\gamma$	9
$\eta' \to \pi^+\pi^-\eta$	45
$\eta' \to \pi^0\pi^0\eta$	21
$\eta' \to 2\gamma$	2
$b_1(1235) \to \omega\pi$	dominant
$f_1(1285) \to \pi^0\pi^0\pi^+\pi^-$	22
$f_1(1285) \to \eta\pi\pi$	52
$a_2(1320) \to 3\pi$	70
$a_2(1320) \to \eta\pi$	15

The GlueX/Hall D Detector

A Fixed-Target Experiment with a 9 GeV Photon Beam

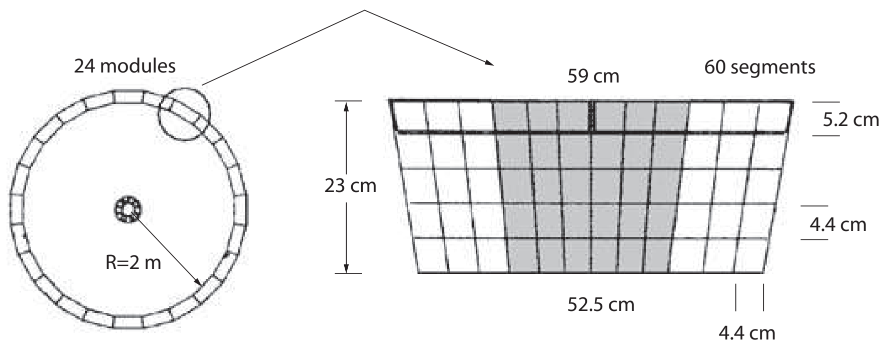


BCAL design builds on the experience with the KLOE calorimeter

FCAL design builds on the experience with the lead glass calorimeters used in BNL E852 and RADPHI at JLab

KLOE Pc/SciFi Calorimetry

Used at the ϕ factory at Frascati



KLOE calorimeter - readout segmentation (one end)

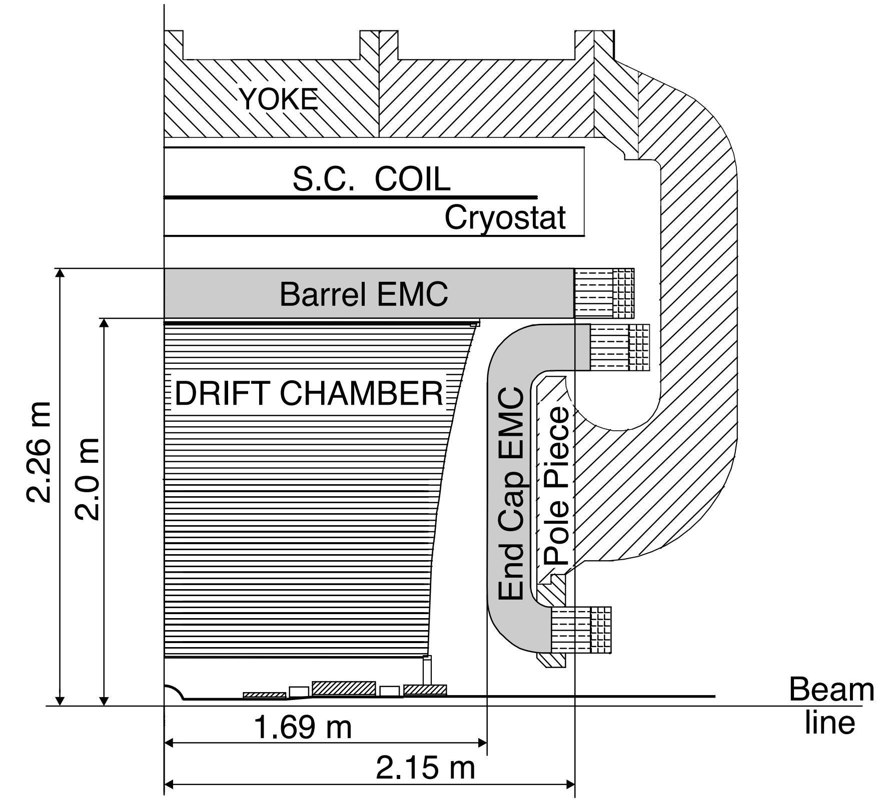
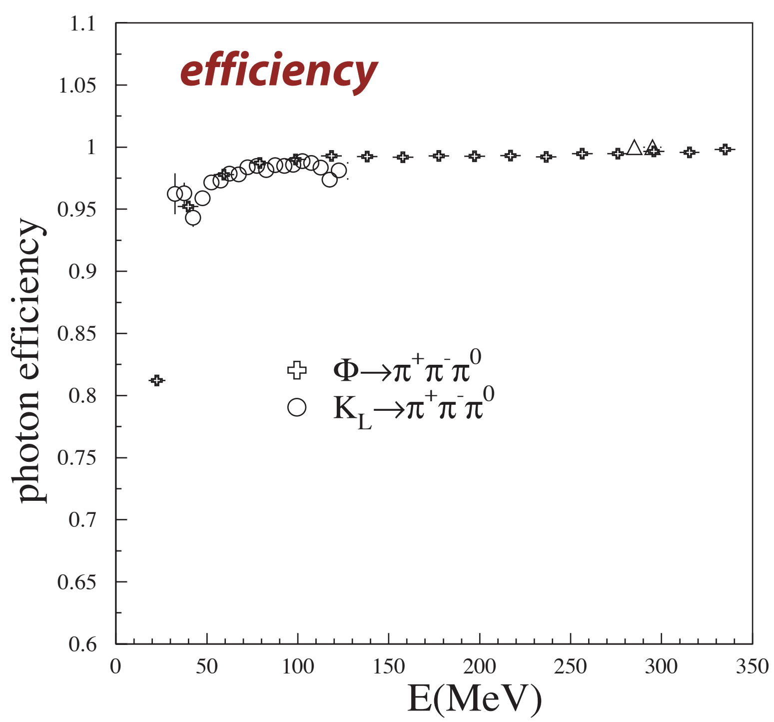
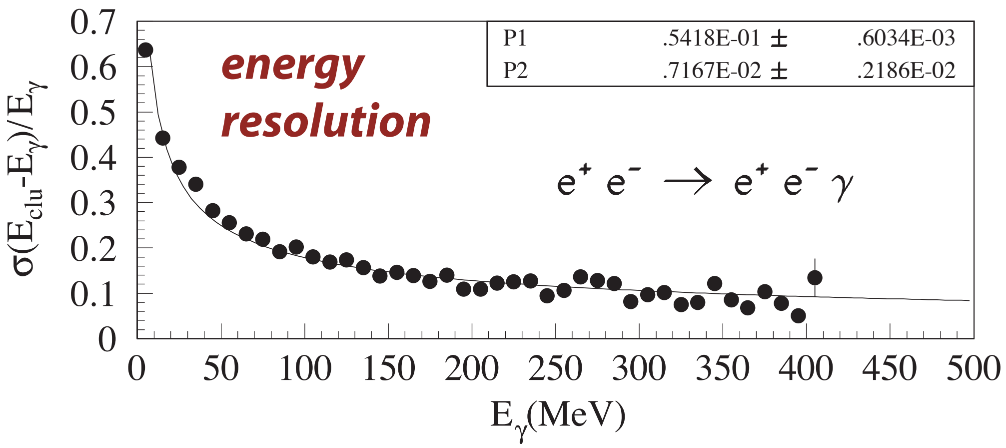


Fig. 1. Vertical cross-section of the KLOE detector.

KLOE Calorimeter Performance





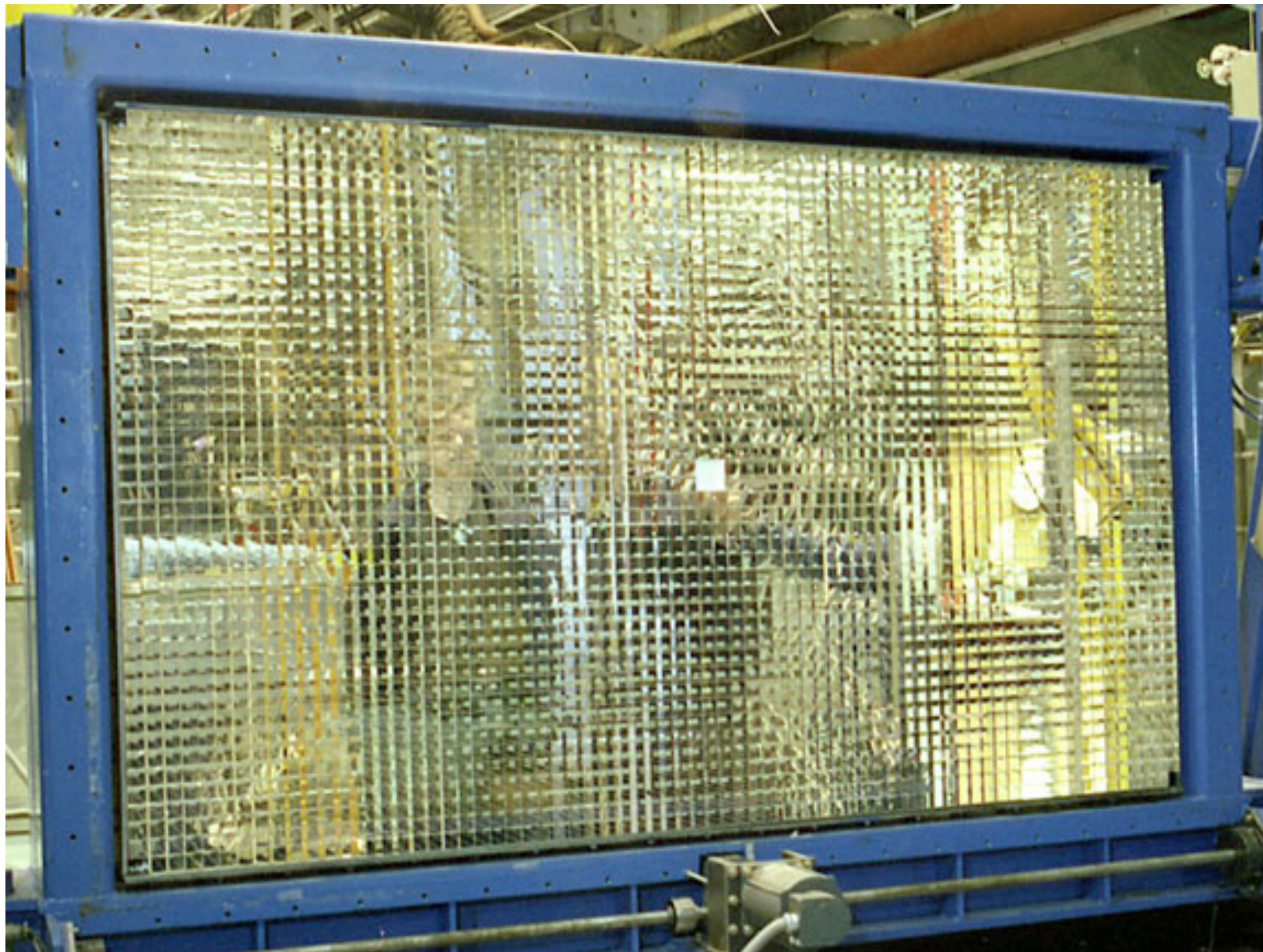
Energy resolution: $\frac{\sigma(E)}{E} = \frac{5.4\%}{\sqrt{E(GeV)}}$

Mean time resolution: $\sigma_t = \frac{56ps}{\sqrt{E(GeV)}} \oplus 50$ ps

Source: M. Adinolfi et al Nucl. Intr. Meth. A494(2002) 326

E852 Lead Glass Calorimeter at BNL

3045 Lead Glass Blocks



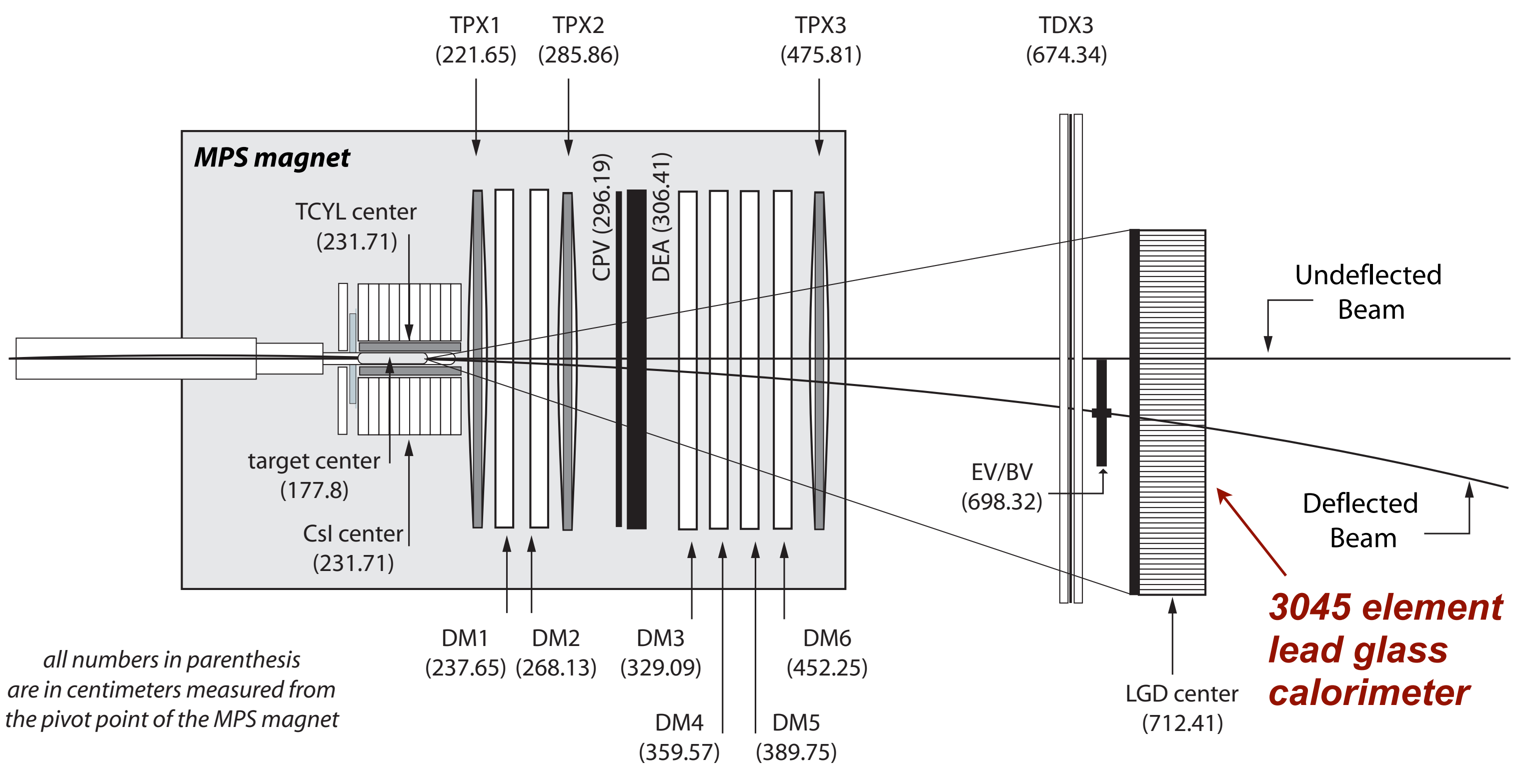
NUCLEAR INSTRUMENTS & METHODS IN PHYSICS RESEARCH

A332 (1993) 419

A387 (1997) 377

Use of Lead Glass Calorimetry in E852

Pion-proton interactions at 18 GeV/c

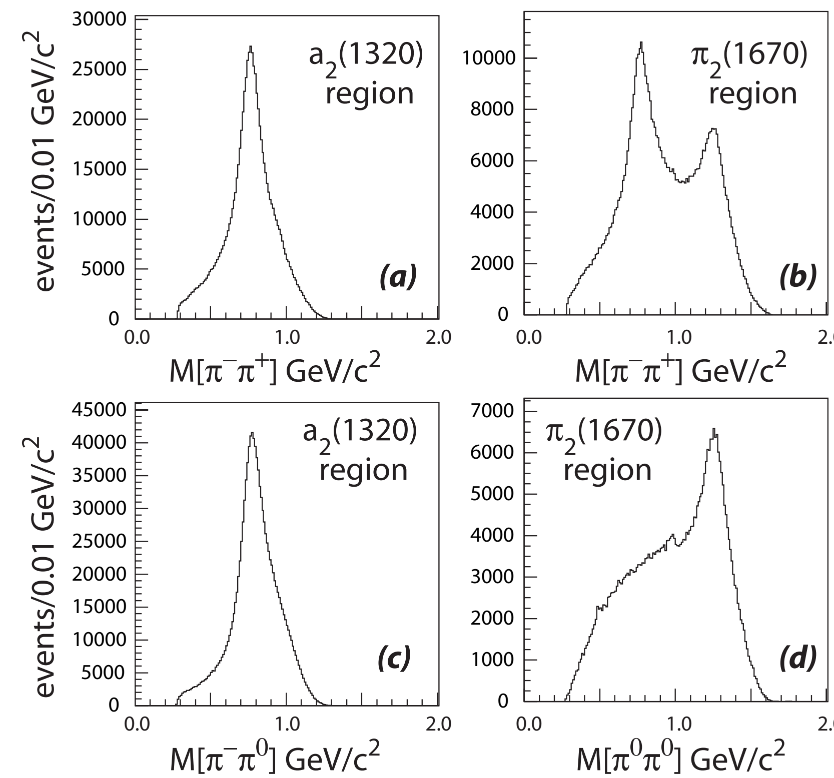


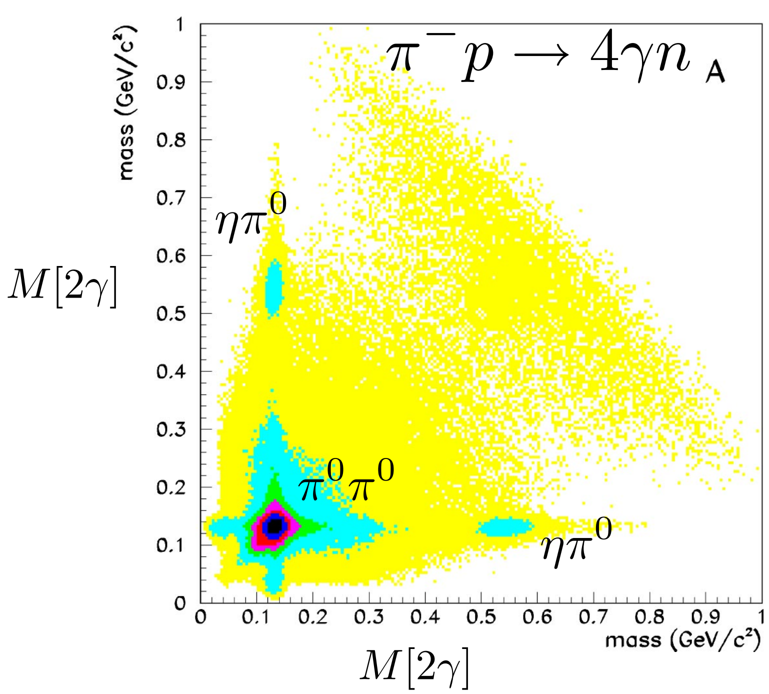
DM1-DM6 are drift chambers

3045 element lead glass calorimeter

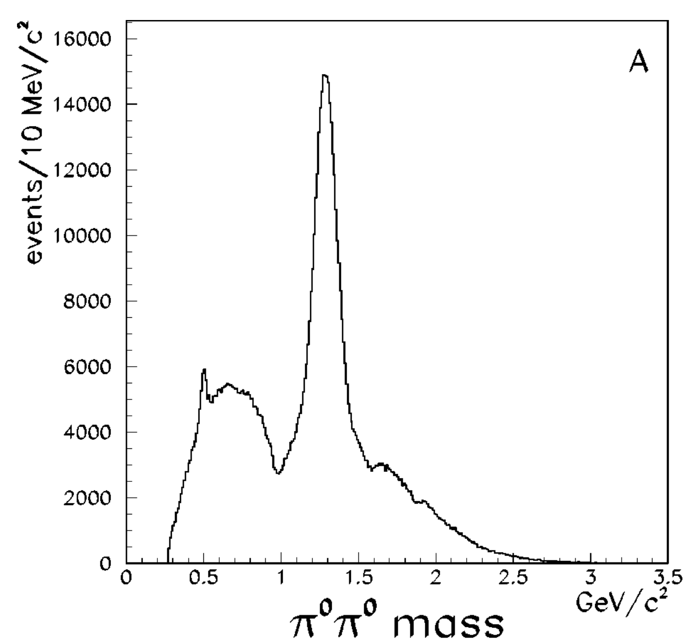
$$\pi^- p \rightarrow \pi^- \pi^- \pi^+ p$$

$$\pi^- p \rightarrow \pi^- \pi^0 \pi^0 p$$

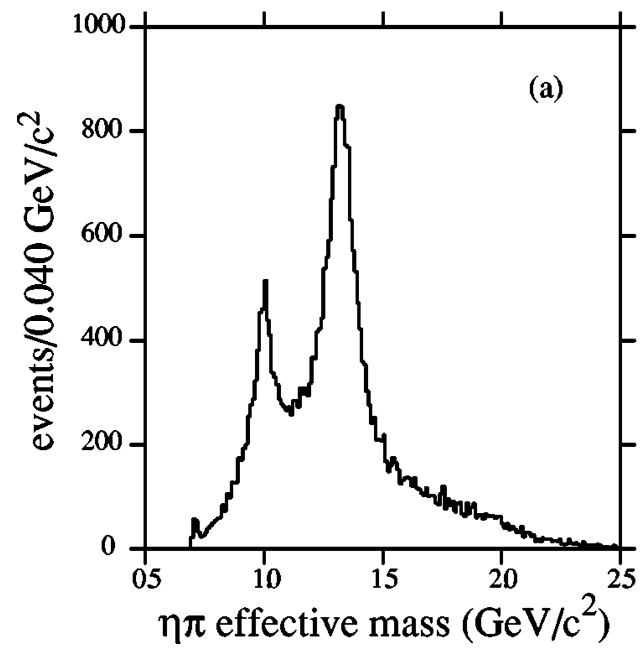




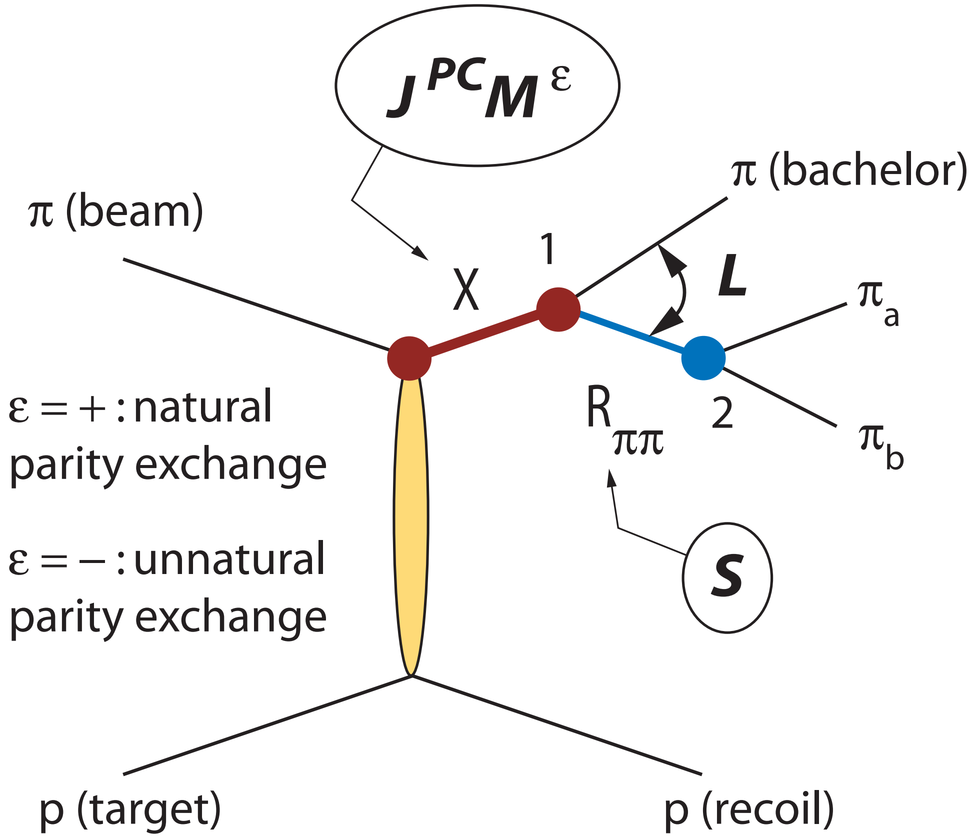
$$\pi^- p \rightarrow \pi^0 \pi^0 n$$

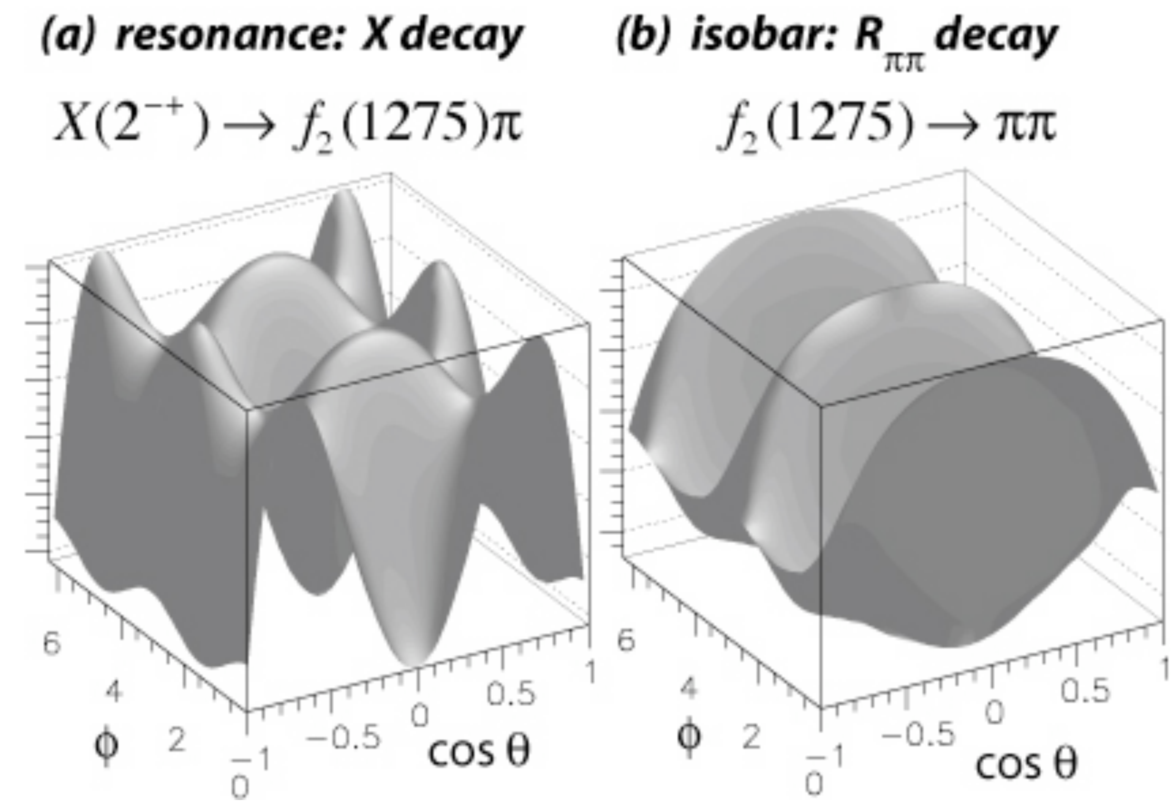


$$\pi^- p \rightarrow \pi^0 \eta n$$



Amplitude Analysis of the 3π System - A Primer





The analysis is based on the ***isobar model*** *that assumes an intermediate 2π resonance*

$$I(m_{3\pi}, t, \tau) = \eta(\tau) \sum_{\varepsilon} \left| \sum_{b} a_b^{\varepsilon}(m_{3\pi}, t) A_b^{\varepsilon}(\tau) \right|^2$$

observed intensity — $I(m_{3\pi}, t, \tau)$

acceptance — $\eta(\tau)$

production — $a_b^{\varepsilon}(m_{3\pi}, t)$

decay — $A_b^{\varepsilon}(\tau)$

spin variables: J, M, S

kinematic variables $\tau = \{\theta_{GJ}, \phi_{GJ}, \theta_H, \phi_H, m_{\pi\pi}\}$

Amplitude Analyses

Can extract signals with small cross sections

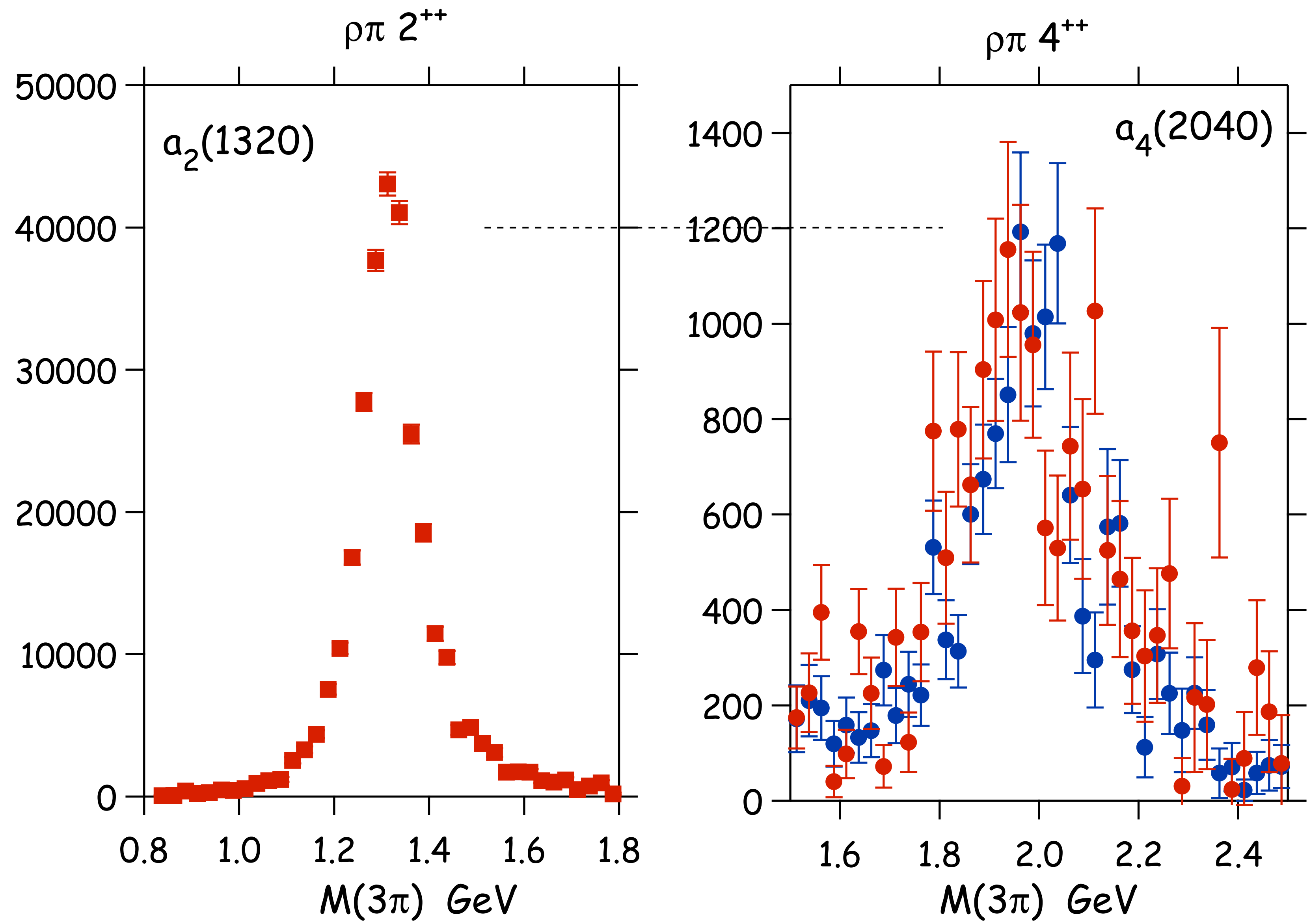
Amplitude Analyses are critical for GlueX and depend on good acceptance and resolution

E852 Analysis of: $\pi^-\pi^0\pi^0$

$\pi^-\pi^-\pi^+$

The PWA of the 3π system shows that E852 can identify well established states - in this case:

$$\frac{a_4(2040)}{a_2(1320)} \approx 3\%$$



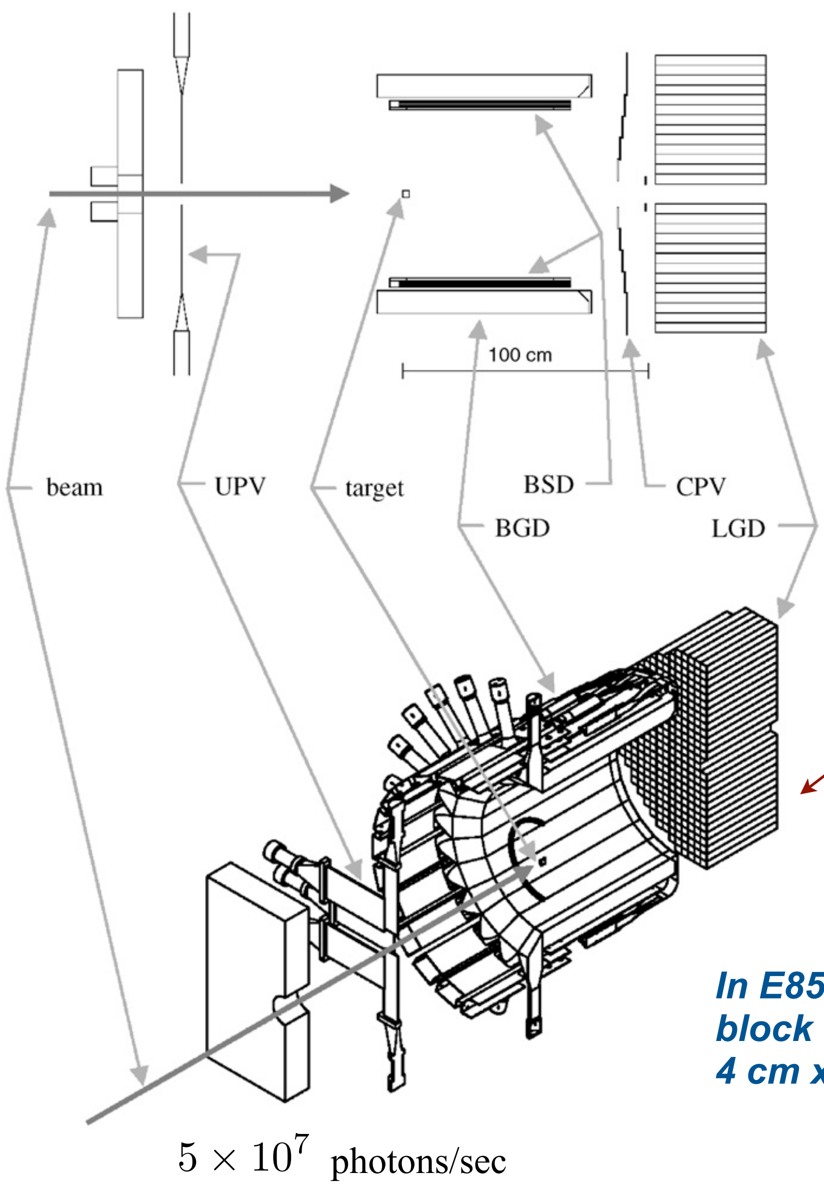
The GlueX detector coverage, charged particle resolution and photon resolution will be better than in E852 so the PWA will be at least as sensitive using the GlueX detector

Use of Lead Glass Calorimetry in RADPHI

Tagged photons between 4.4 and 5.5 GeV

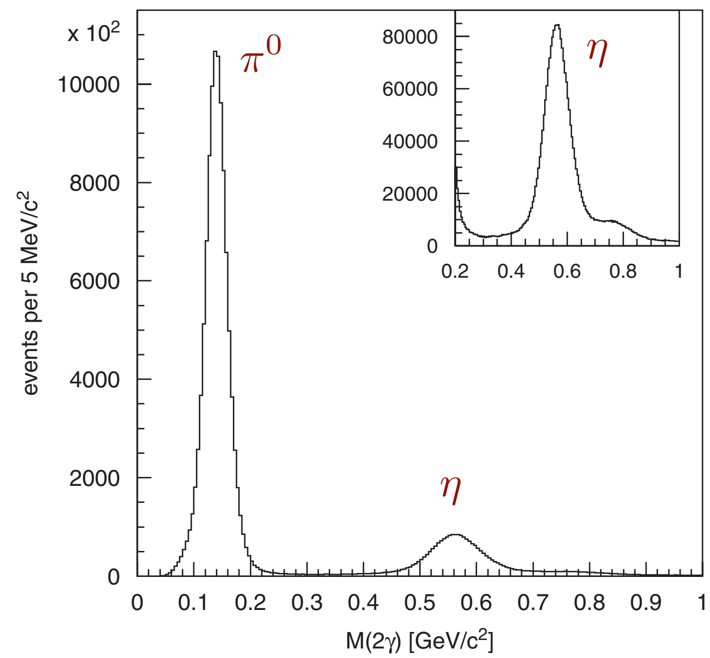
A556 (2006) 366

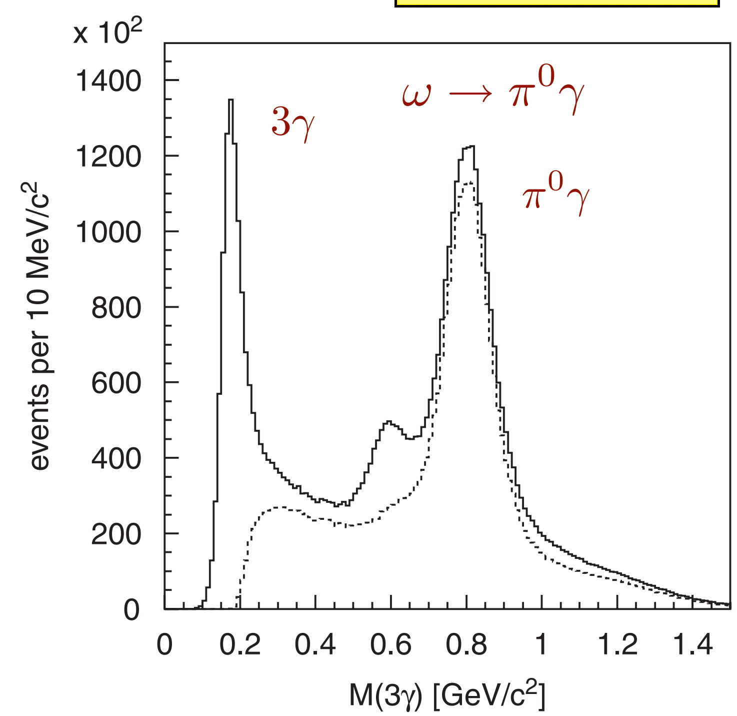
A570 (2007) 384



620 element lead glass calorimeter

In E852 and RADPHI block dimensions: 4 cm x 4 cm x 45 cm





Energy and space resolution:

$$\frac{\sigma_E}{E} = \frac{7.3\%}{\sqrt{E}} + 3.5\%$$

$$\sigma_x = \frac{0.64\,\mathrm{cm}}{\sqrt{E}}$$

E in GeV

Guidance from Existing Data

Information on photoproduction in the GlueX regime is sparse

Most of the information comes from bubble chamber experiments at SLAC with linearly polarized photons in the 7-10 GeV energy range.

There is <u>little</u> detailed information on final states with multi-neutrals.

Bubble chamber data - photoproduction at 9 GeV:

Topology	σ (μb)	% of σ with neutrals
1-prong	8.5 ± 1.1	100
3-prong	64.1 ± 1.5	76 ± 3
5-prong	34.2 ± 0.9	86 ± 4
7-prong	6.8 ± 0.3	86 ± 6
9-prong	0.61 ± 0.08	87 ± 21
With visible strange decay	9.8 ± 0.4	-
Total	124.0 ± 2.5	82 ± 4

Discovery potential high in final states with multi-neutrals

Use a 'tuned' version of Pythia to provide information on final states with photons

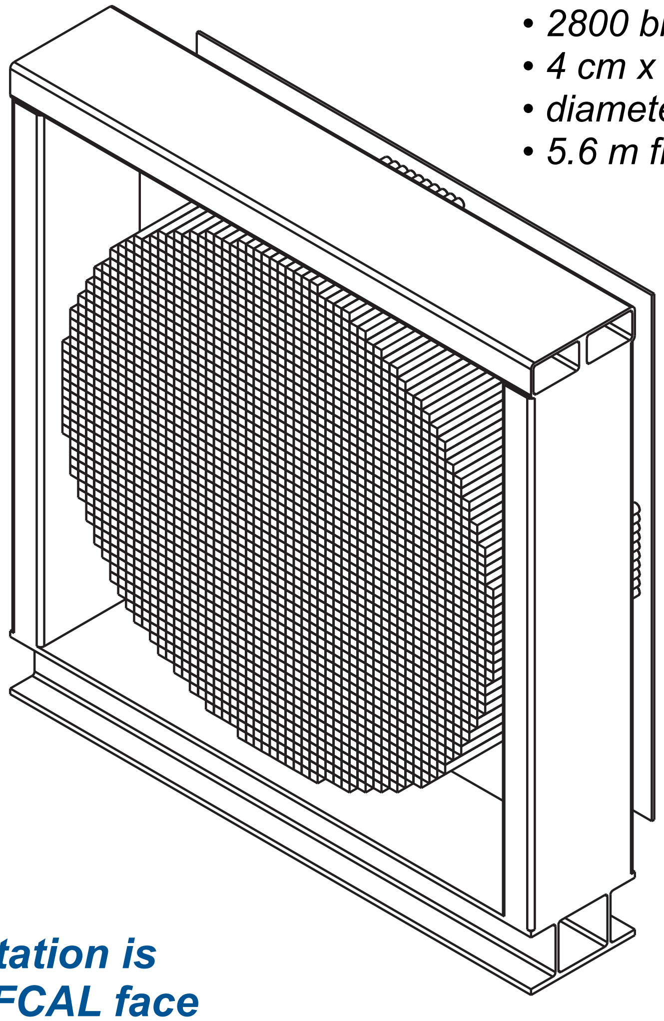
Topology	Pythia Estimates (μb)	Data (μb)
1-prong	8.8 ± 0.02	8.5 ± 1.1
3-prong	63.5 ± 0.09	64.1 ± 1.5
5-prong	42.7 ± 0.2	34.2 ± 0.9
7-prong	7.3 ± 0.1	6.8 ± 0.3
9-prong	0.3 ± 0.1	0.61 ± 0.08

Reaction	Pythia Estimates (μb)	Data (μb)
	$\gamma p \to 3$ prongs	
$\gamma p \to p\pi^+\pi^-$	13.6 ± 0.13	14.7 ± 0.6
$\gamma p \to pK^+K^-$	0.41 ± 0.02	0.58 ± 0.05
$\gamma p \to p\bar{p}p$	0.04 ± 0.01	0.09 ± 0.02
$\gamma p \to p\pi^+\pi^-\pi^0$	5.8 ± 0.1	7.5 ± 0.8
$\gamma p \to n2\pi^+\pi^-$	1.4 ± 0.04	3.2 ± 0.7
With multi-neutrals	42.3 ± 0.3	38.0 ± 1.9
	$\gamma p \to 5$ prongs	
$\gamma p \to p2\pi^+2\pi^-$	2.9 ± 0.06	4.1 ± 0.2
$\gamma p \to pK^+K^-\pi^+\pi^-$	0.51 ± 0.03	0.46 ± 0.08
$\gamma p \to p2\pi^+2\pi^-\pi^0$	8.12 ± 0.1	6.7 ± 1.0
$\gamma p \to n3\pi^+2\pi^-$	$0.8 \pm .3$	1.8 ± 1.9
With multi-neutrals	30.4 ± 0.2	21.1 ± 1.7

Performance Metrics

Start with E852/RADPHI for FCAL

A program of improvements underway



- *2800 blocks*
- *4 cm x 4 cm x 45 cm*
- *diameter: 240 cm*
- *5.6 m from target*

Energy and space resolution:

$$\frac{\sigma_E}{E} = \frac{7.3\%}{\sqrt{E}} + 3.5\%$$

$$\sigma_x = \frac{0.64\,\text{cm}}{\sqrt{E}}$$

E in GeV

spatial segmentation is
4 cm x 4 cm in FCAL face

Threshold Energy = 120 MeV

More to follow from Beni Zihlmann

Performance Metrics

Start with KLOE for BCAL

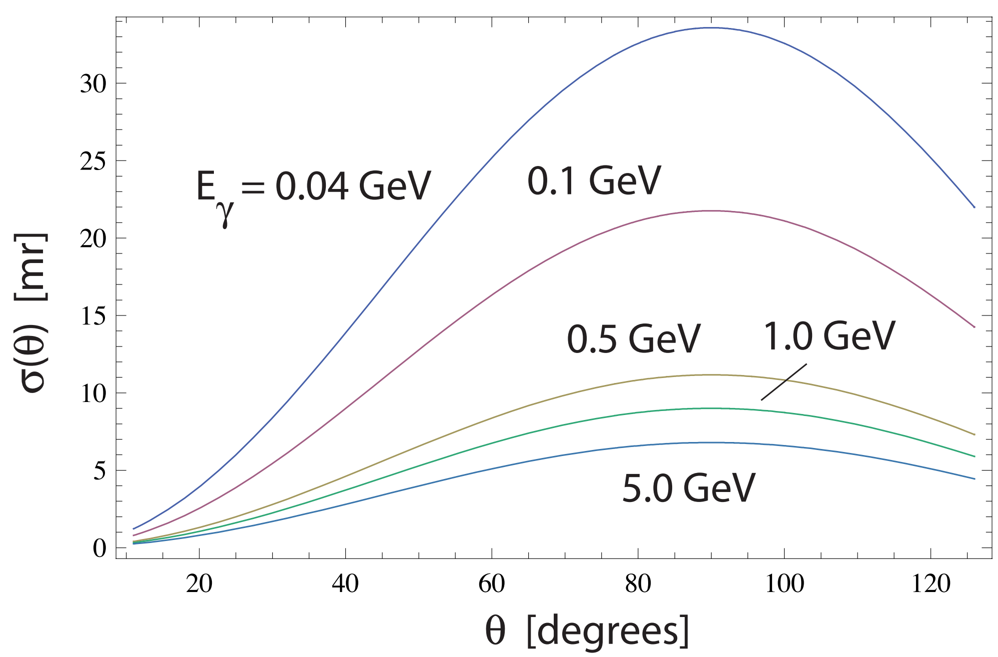
Energy and timing resolutions for BCAL verified in beam test and simulations.
And we are making improvements.

$$\frac{\sigma_E}{E} = \frac{5.4\%}{\sqrt{E(GeV)}}$$

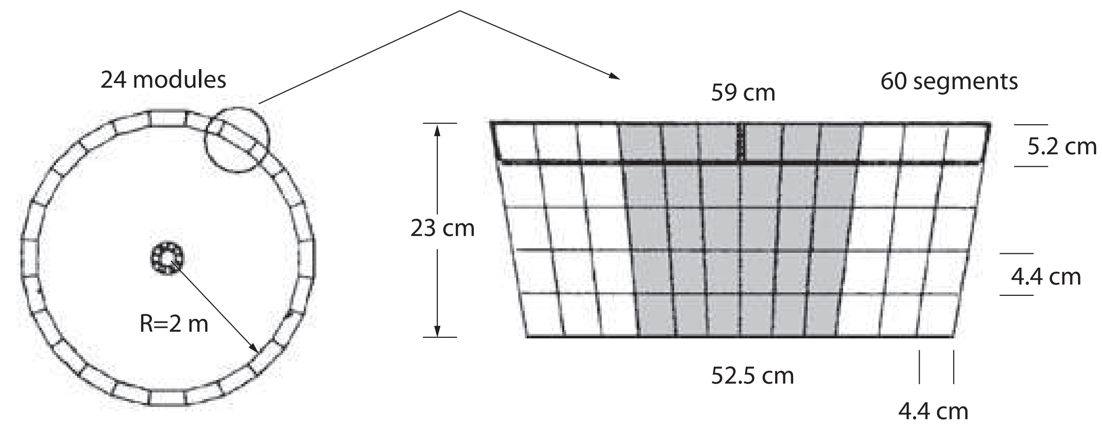
Threshold Energy = 20 MeV (KLOE) and 40 MeV (BCAL)

$$\sigma_{\Delta t} = \frac{56 \text{ ps}}{\sqrt{E(GEV)}} \oplus 50 \text{ ps} \qquad dz = \frac{\sigma_{\Delta t} \cdot 0.53c}{2}$$

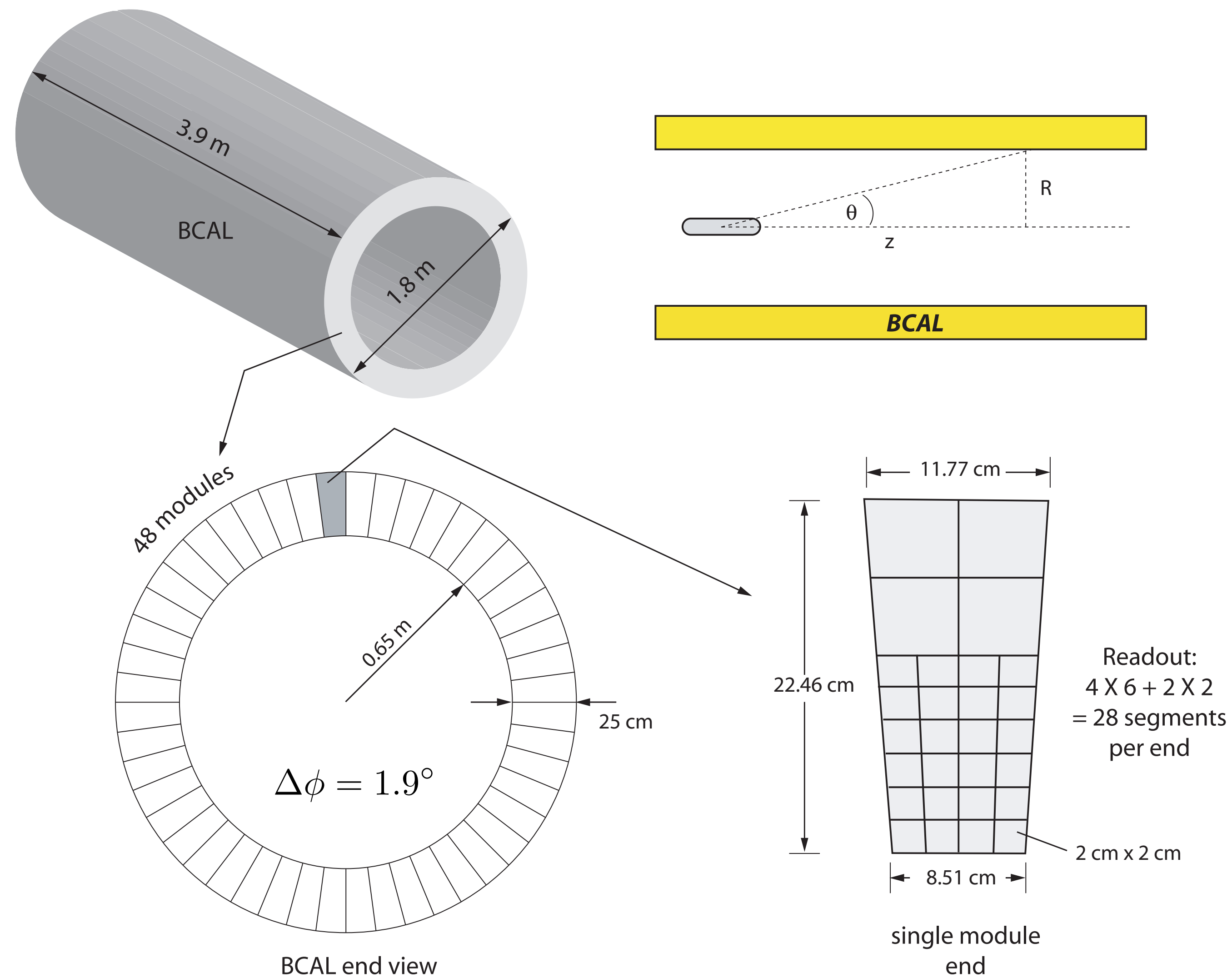
$$\sigma_\theta = \frac{R}{R^2 + z^2} dz \qquad \sigma_\phi = \frac{8 \text{ mr}}{\sqrt{E(GeV)}}$$



KLOE calorimeter is 4.3 m long



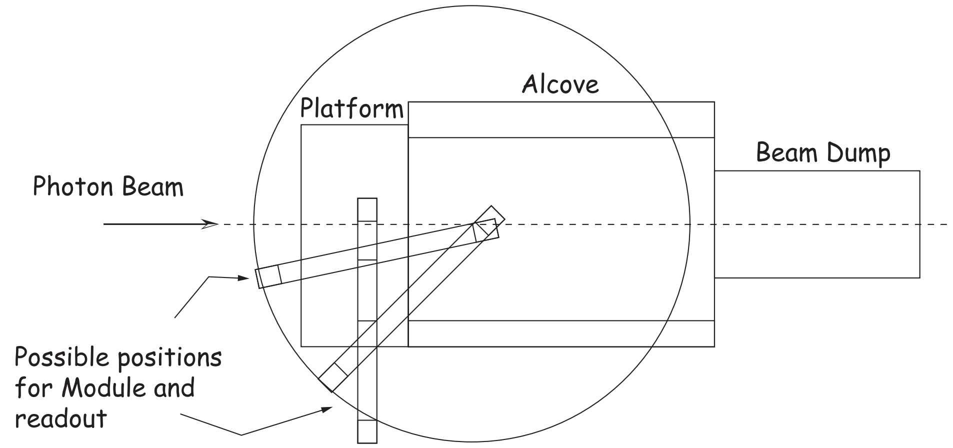
KLOE calorimeter - readout segmentation (one end)



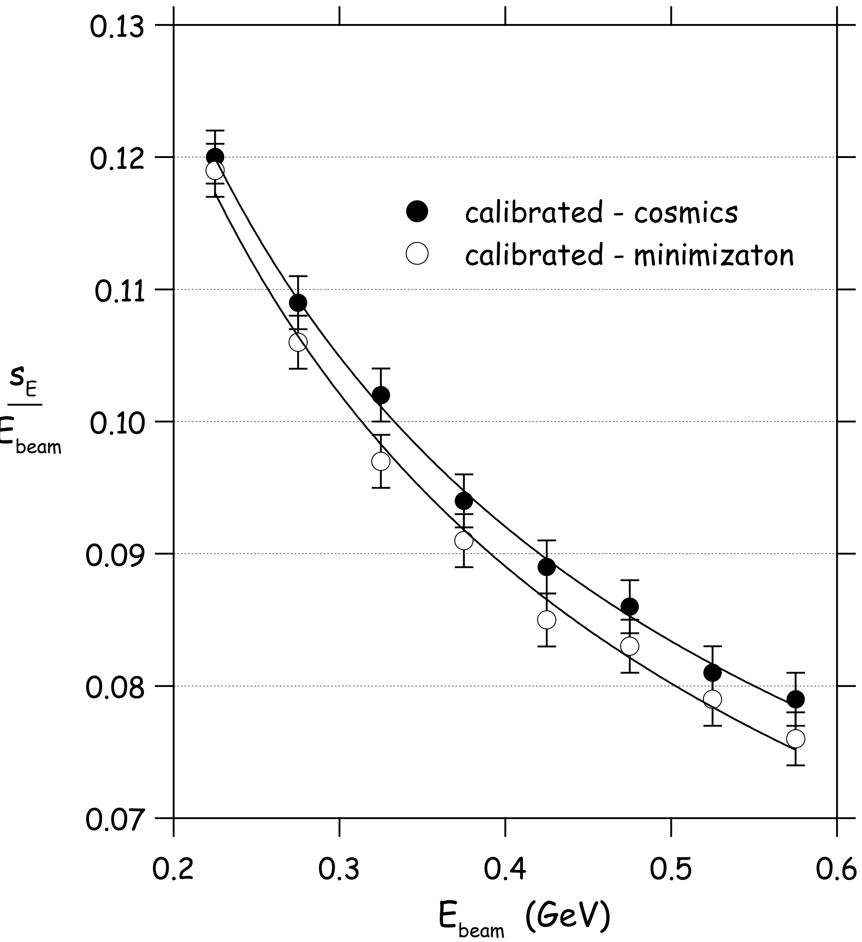
Performance Metrics

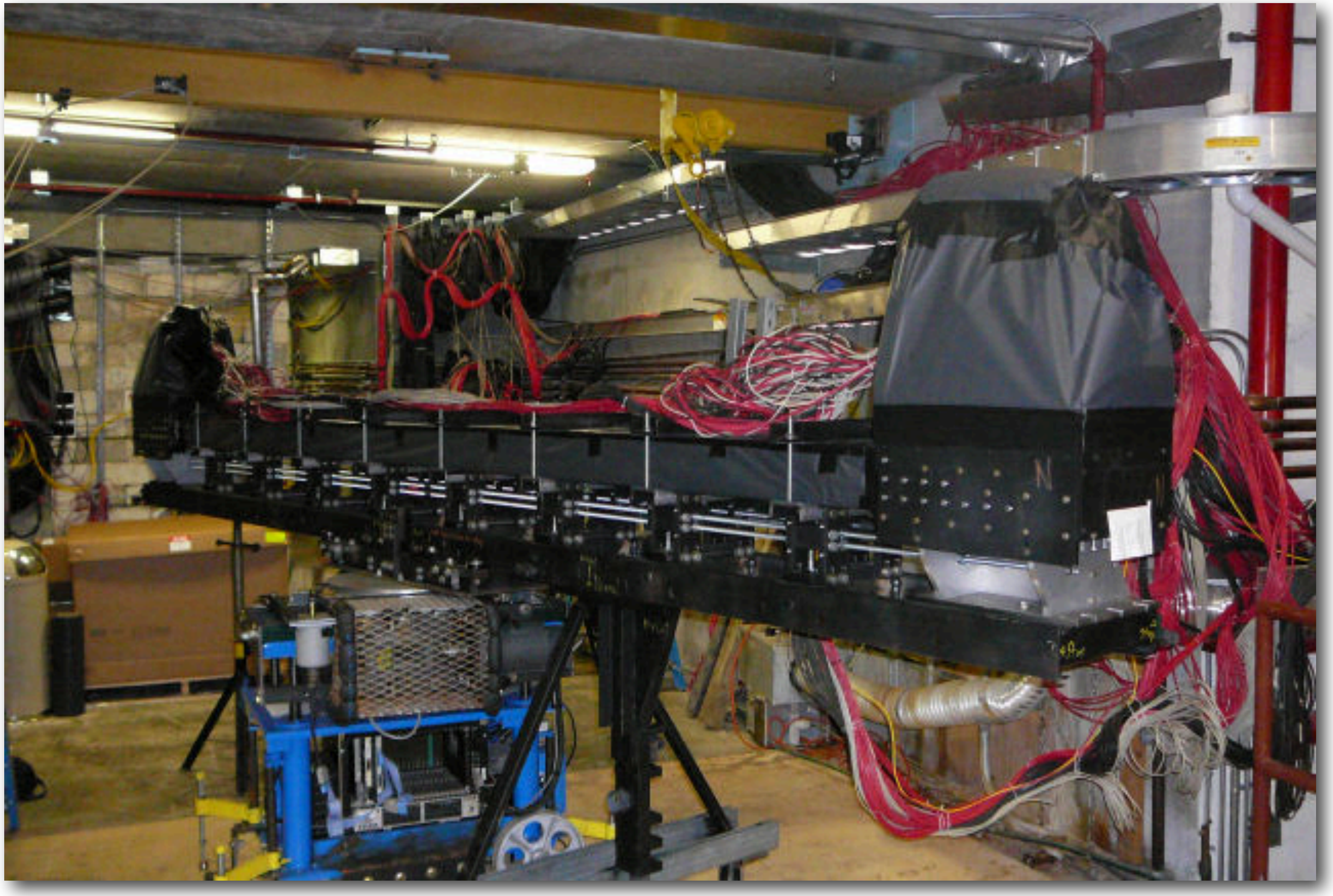
Start with KLOE for BCAL

BCAL prototypes in beam tests at:
(1) TRIUMF and (2) Hall B - JLab



BCAL Module 1 in the Hall B Alcove





More to follow from George Lolos

Performance Metrics

And impact on physics

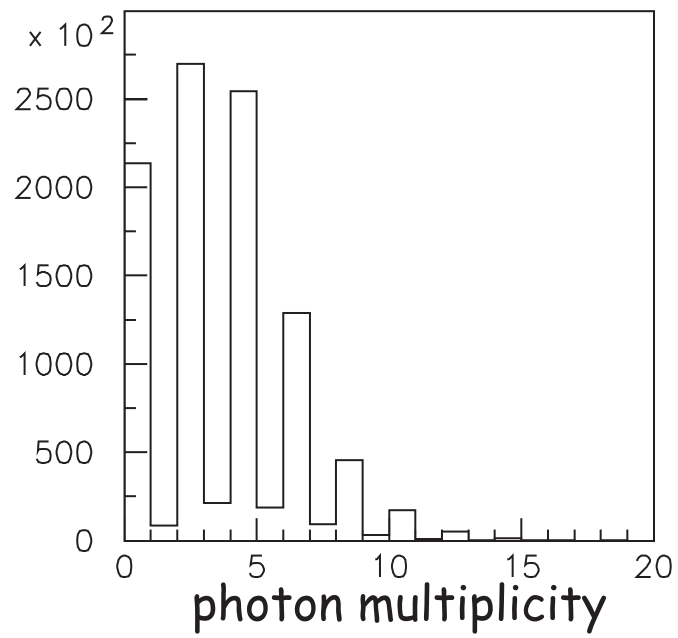
Starting with BCAL/FCAL performance parameters based on KLOE/E852/RADPHI experience we will look at physics impact looking at:

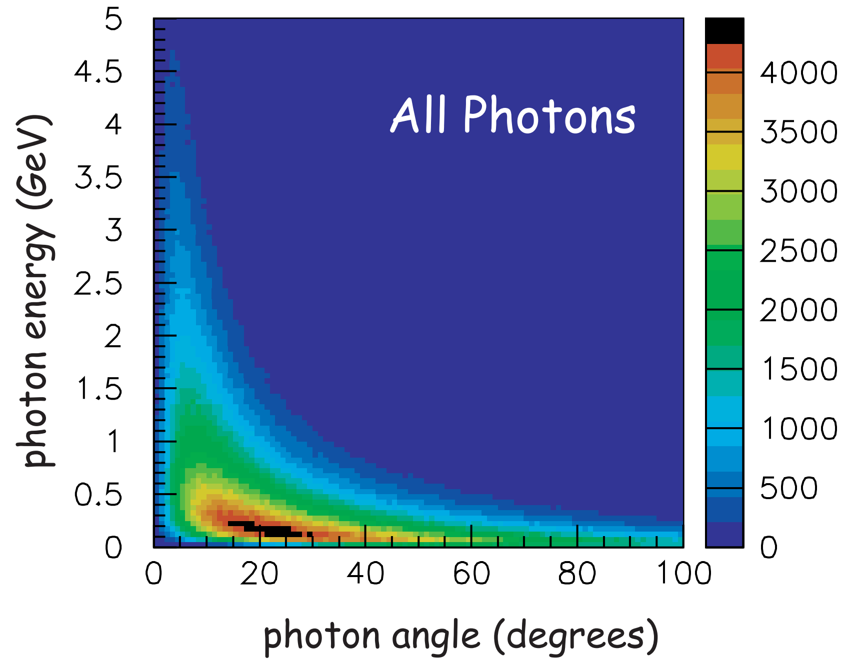
- ***occupancy (segmentation)***
- ***acceptance and spin analysis***
- ***resolution (mass resolutions) and signal/noise***
- ***energy threshold***
- ***time-of-flight***

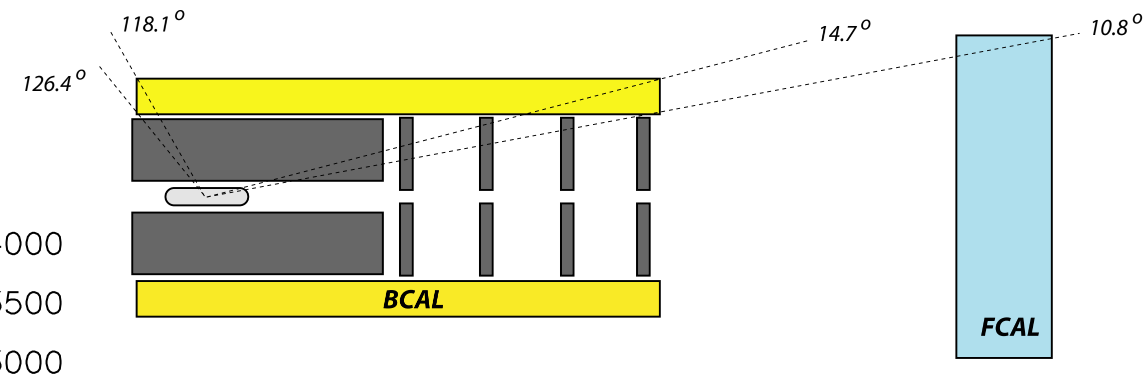
This based on a parametric Monte Carlo
More to follow from Matt Shepherd
using full GEANT simulation - reconstruction - amplitude analysis

How Photons Populate BCAL and FCAL

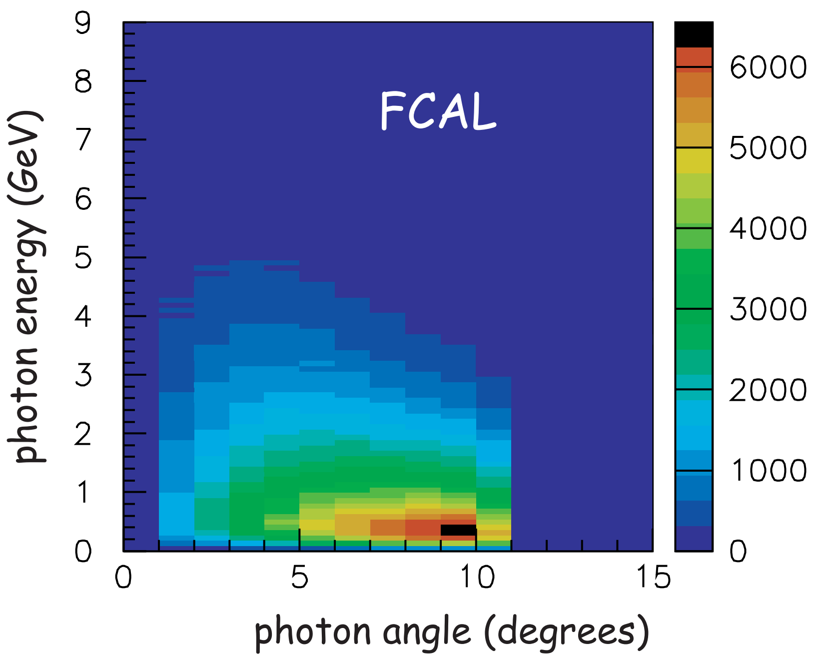
Using information from Pythia

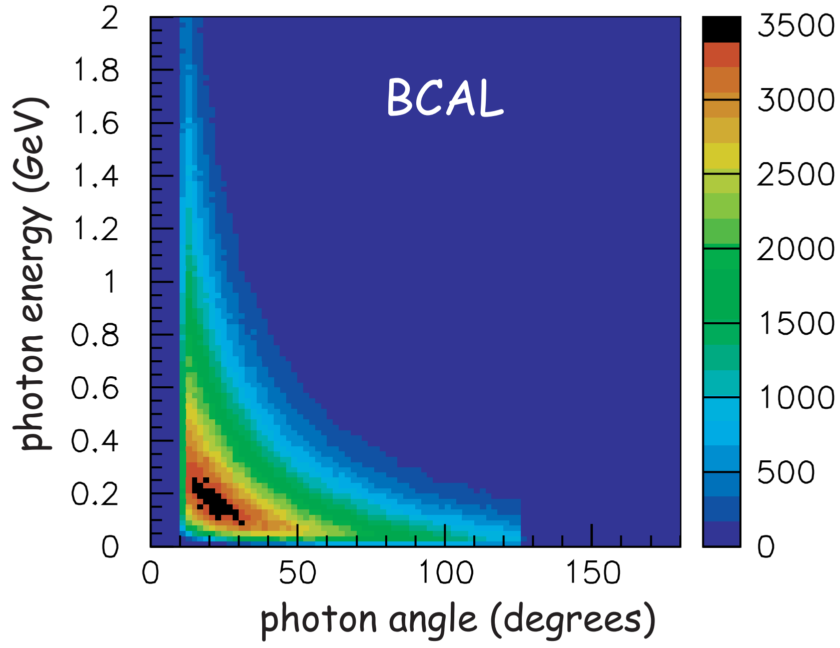


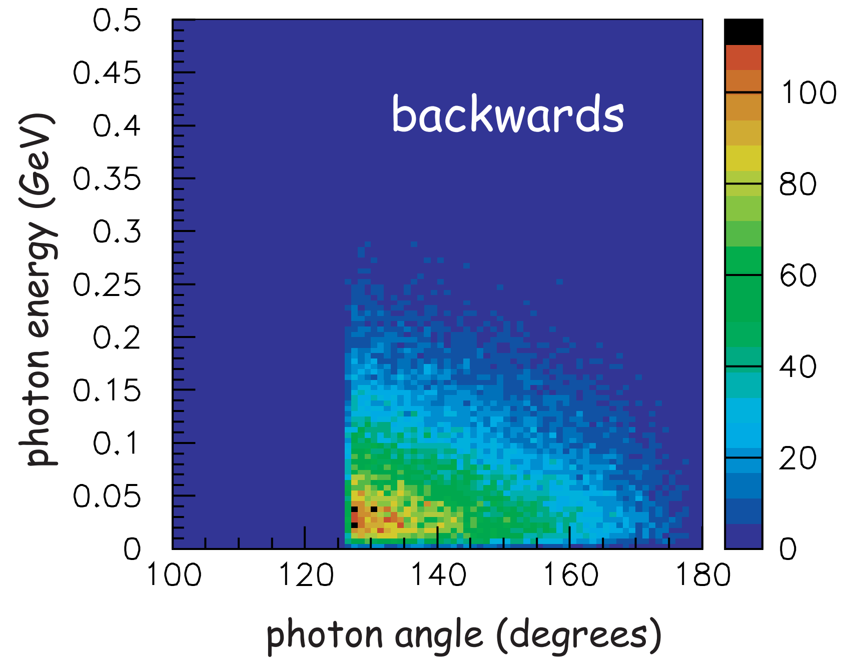




Element	Percent of all photons Pythia Events
Angles > 126°	1.7
BCAL	70.5
FCAL	27.3
Hole in FCAL	0.5



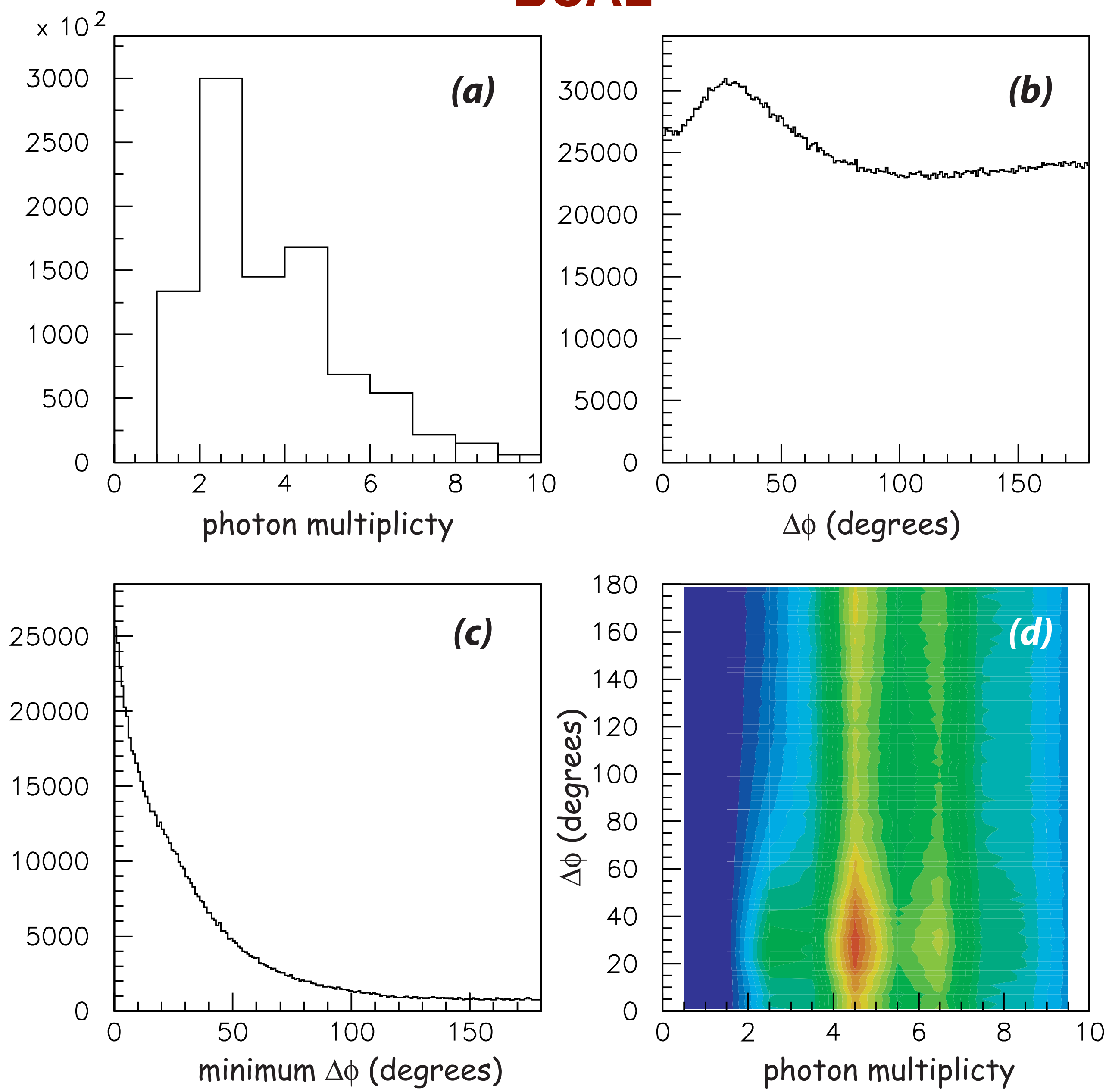




How Photons Populate BCAL and FCAL

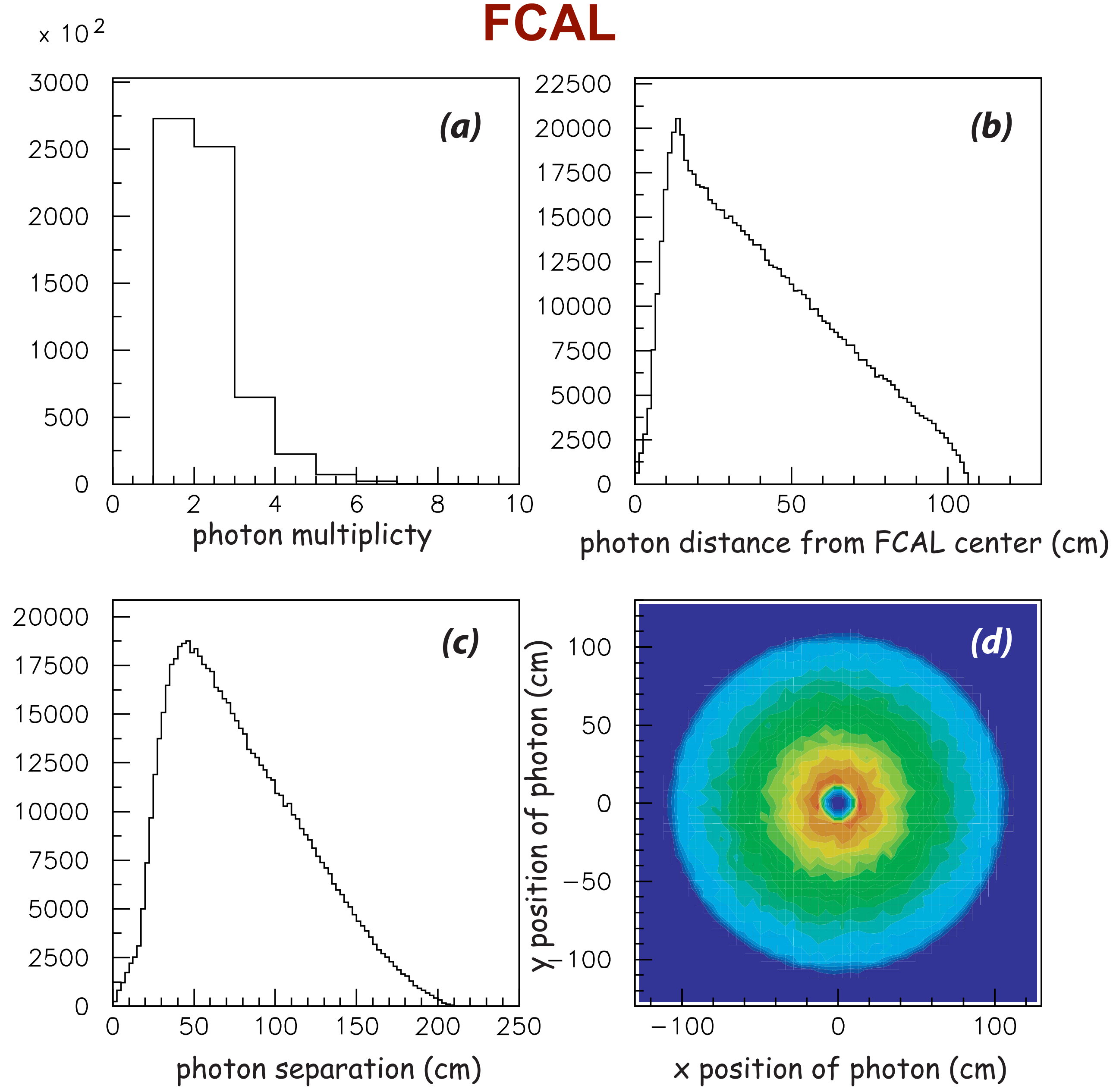
Using information from Pythia

BCAL



6% of events with two or more photons in BCAL have a minimum separation of less than 2 degrees

FCAL



0.7% of events with two or more photons in FCAL have two photons separated by < 8 cm

Photons From a Signature Reaction

Where exotic signals have been reported

BCAL photon population:

A signature reaction: $\gamma p \to \eta \pi^0 p$

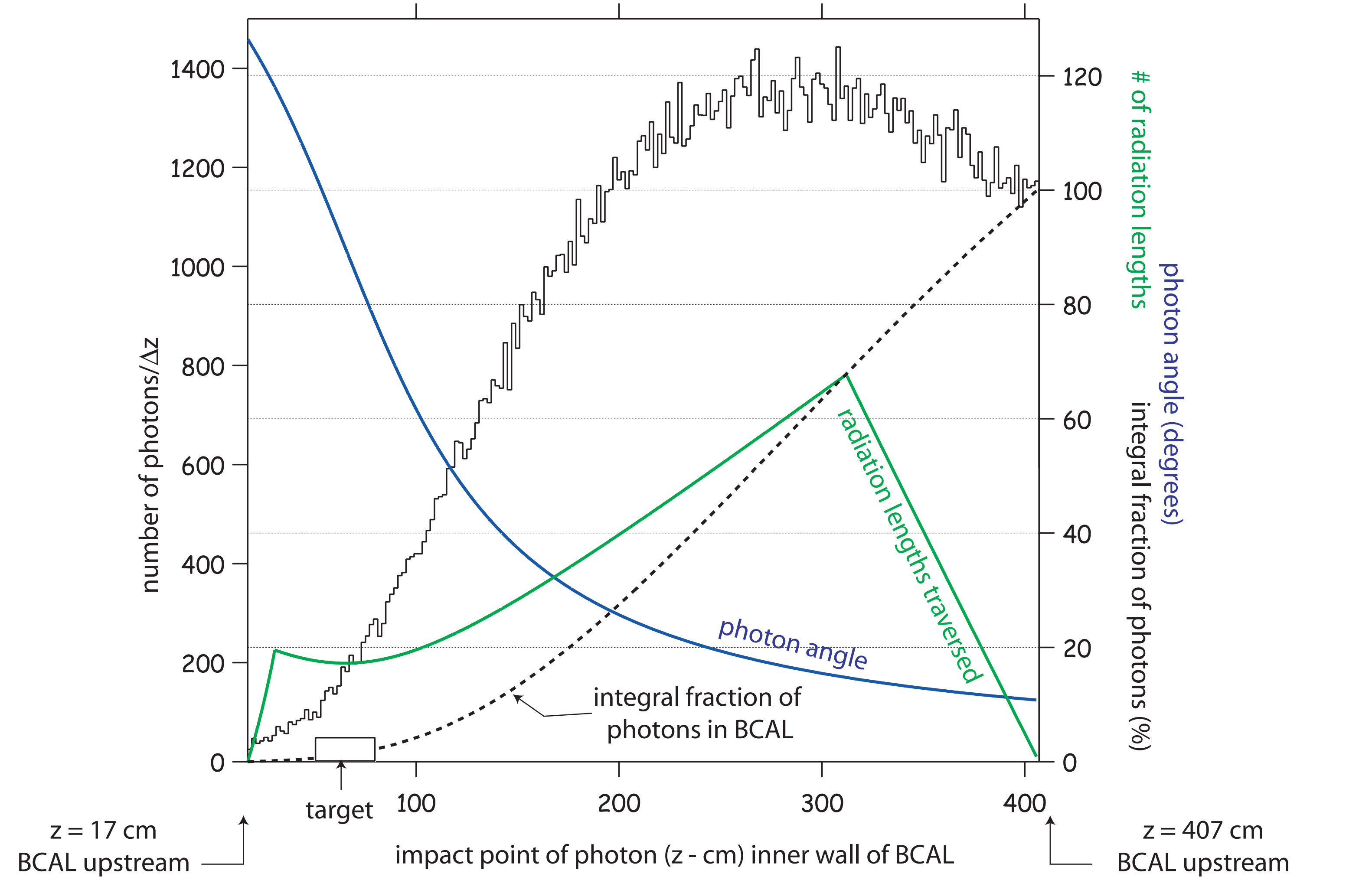
$$\gamma p \to X p$$

$$1.0 < M_X < 2.5\ GeV$$

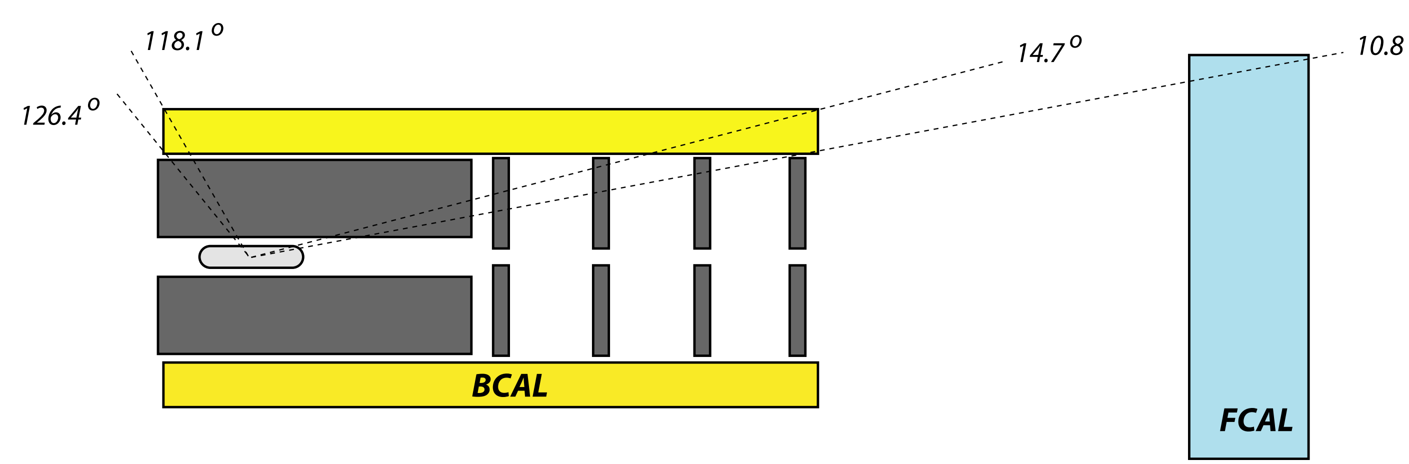
$$X \to \eta \pi^0 \to 4\gamma$$

$$\frac{dN}{d|t|} \propto e^{-5 \cdot |t|}$$

isotropic in decay angles



Element	η	π^0
Both photons in FCAL	27%	46%
Both photons in BCAL	20%	35%
Photons in FCAL and BCAL	53%	19%



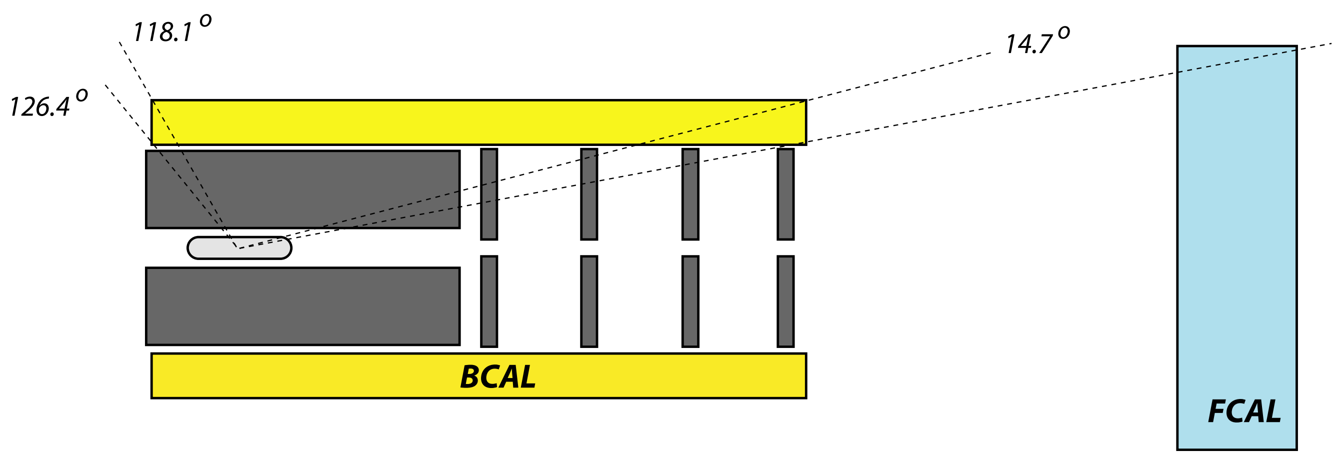
Photons From a Signature Reaction

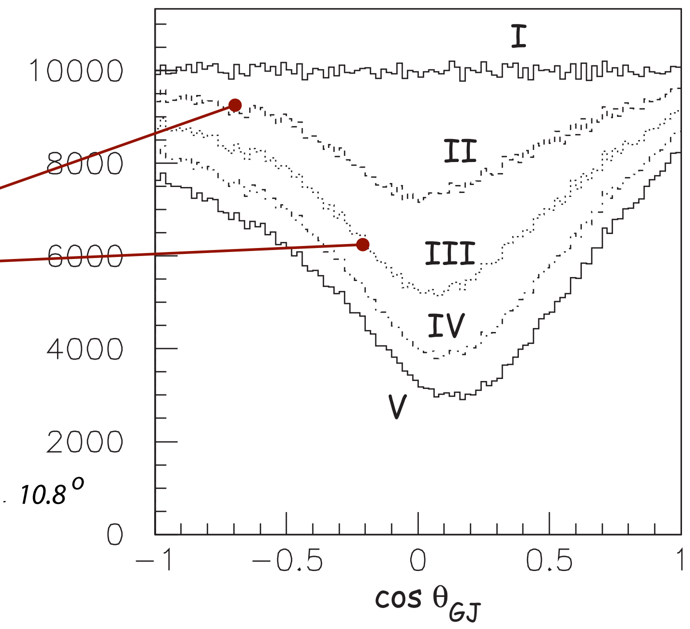
Where exotic signals have been reported

A signature reaction: $\gamma p \rightarrow \eta \pi^0 p$

Acceptance in decay angles:

II: Remove event if any photon lies between 10.8 to 11.8 degrees
III: 10.8 to 12.8 degrees
IV: 10.8 to 13.8
V: 10.8 to 14.7





Case	Acceptance (%)	(F-B)/(F+B)
I	100	0.0
II	85	-0.01
III	73	-0.03
IV	63	-0.06
V	55	-0.08

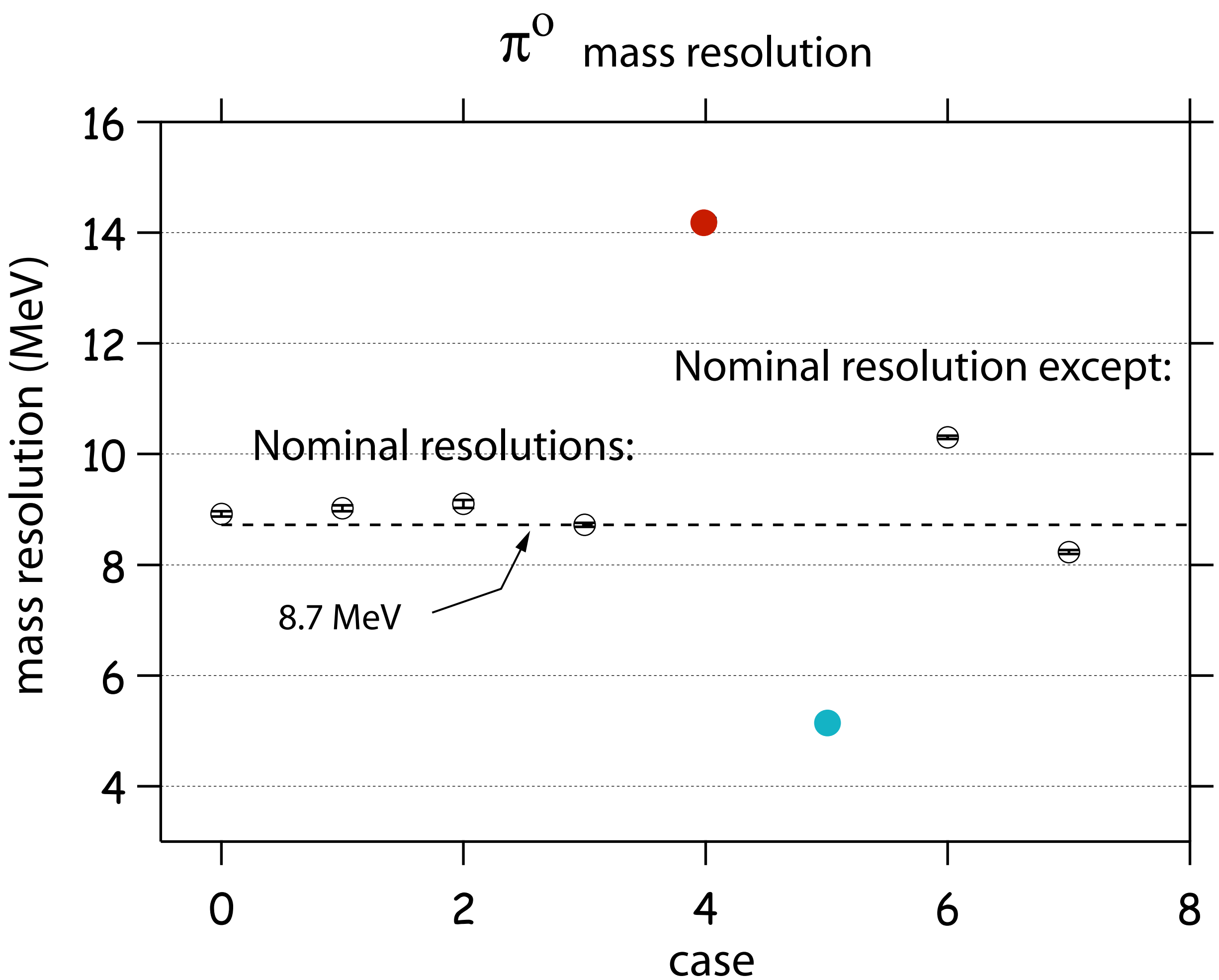
Acceptance in the LAB angular range from 11 to 15 degrees has a strong impact on the decay angular distribution crucial in extracting spin and other quantum numbers. We are considering options for additional instrumentation for all or part of this region.

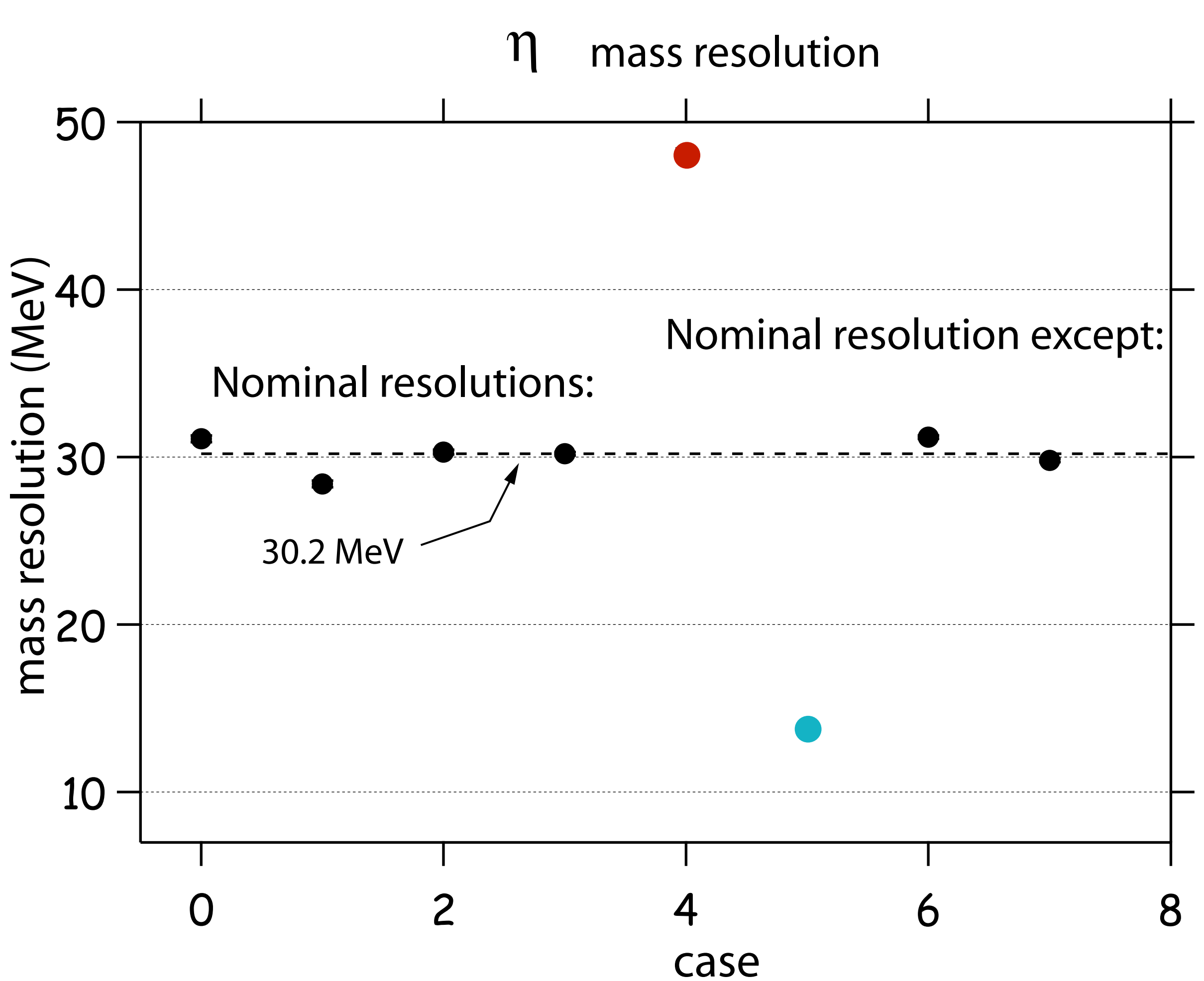
Ordinary mesons decaying into $\eta\pi^0$ correspond to even L (angular momentum). The presence of an asymmetry in the above angular distribution would point to the presence of even L - odd L interference and odd L implies exotic quantum numbers.

Mass Resolutions

Varying calorimeter resolutions

A signature reaction: $\gamma p \rightarrow \eta \pi^0 p$





Nominal resolutions:

- Case 0: Both photons in FCAL
- Case 1: Both photons in BCAL
- Case 2: One in FCAL & one in BCAL
- Case 3: Any combination

Nominal resolution except:

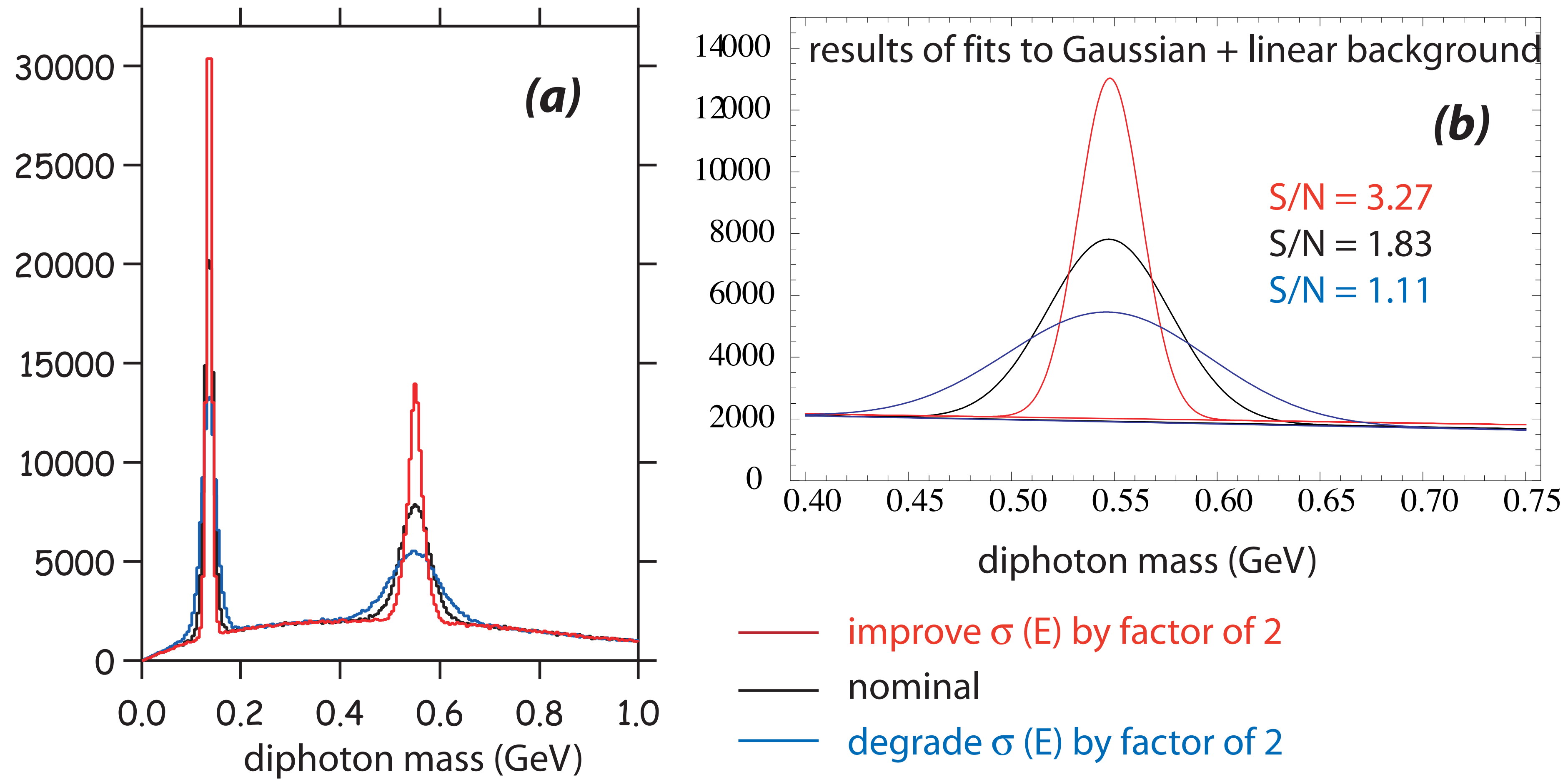
- Case 4: Multiply A by 2.0
- Case 5: Multiply A by 0.5
- Case 6: Double the error in position
- Case 7: Set position error to zero

$$\frac{\sigma_E}{E} = \frac{A}{\sqrt{E}} \oplus B$$

Mass Resolutions

Varying calorimeter resolutions

A signature reaction: $\gamma p \rightarrow \eta\pi^0 p$



$$\frac{\sigma_E}{E} = \frac{A}{\sqrt{E}} \oplus B$$

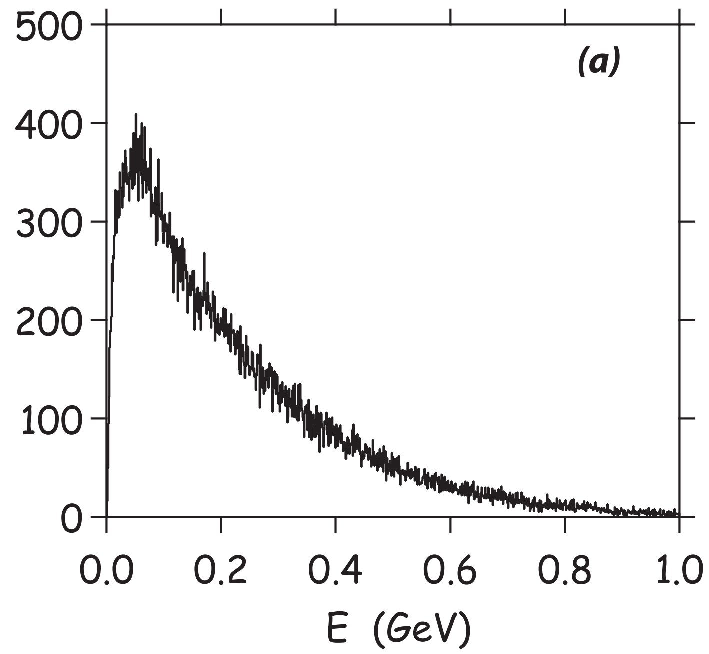
Photons From Another Signature Reaction

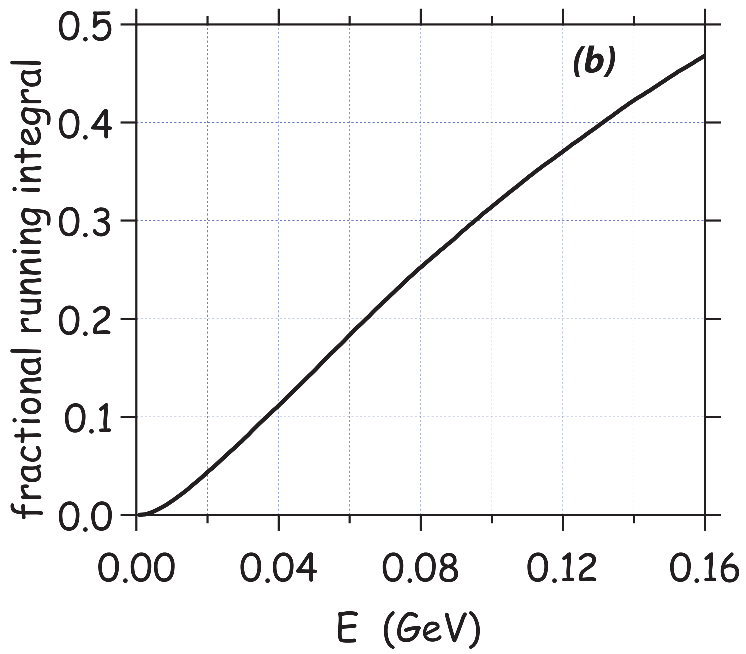
Where exotic signals have been reported

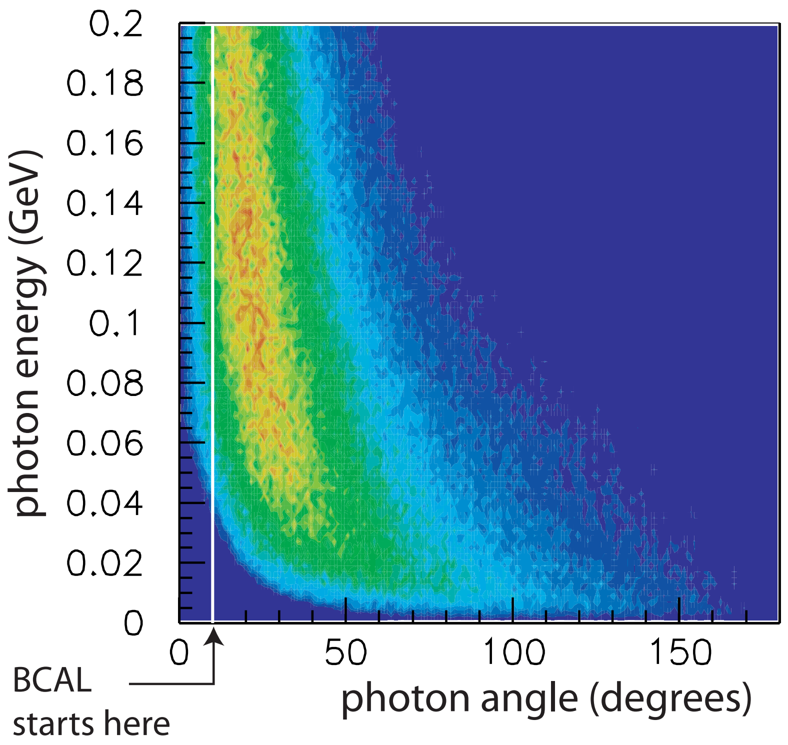
$$\gamma p \to X^0(2000) \to b_1^+(1235)\pi^0 n$$

$$b_1^+\pi^0 \to \omega\pi^+\pi^0 \to \pi^+\pi^-\pi^0\pi^+\pi^0$$
$$\to \pi^+\pi^-\pi^+4\gamma$$

Lowest energy photon in event







Lowest energy photon in Pythia events and threshold energy in BCAL & FCAL:

Energy Threshold E_{thr} (MeV)	BCAL: % with $E_{min} < E_{thr}$	FCAL: % with $E_{min} < E_{thr}$
20	2	0
40	5	0.1
50	8	0.2
100	17	1.9
150	25	4.8

Photon and Charged Particle Resolutions

And decays of long-live mesons

$$\gamma p \to \phi(1020) p$$

$$\phi(1020) \to \pi^+ \pi^- \pi^0$$

Observed width for the ϕ, generated with a width of 4 MeV/c^2, after four-vector smearing.

Condition	Nominal errors for $\pi^\pm$	Nominal errors/2 for $\pi^\pm$
Photon smearing only	14.8 ± 0.1 MeV/c^2	14.8 ± 0.1 MeV/c^2
Charged particle smearing only	16.7 ± 0.1 MeV/c^2	11.1 ± 0.1 MeV/c^2
Both smeared	22.2 ± 0.2 MeV/c^2	17.6 ± 0.1 MeV/c^2

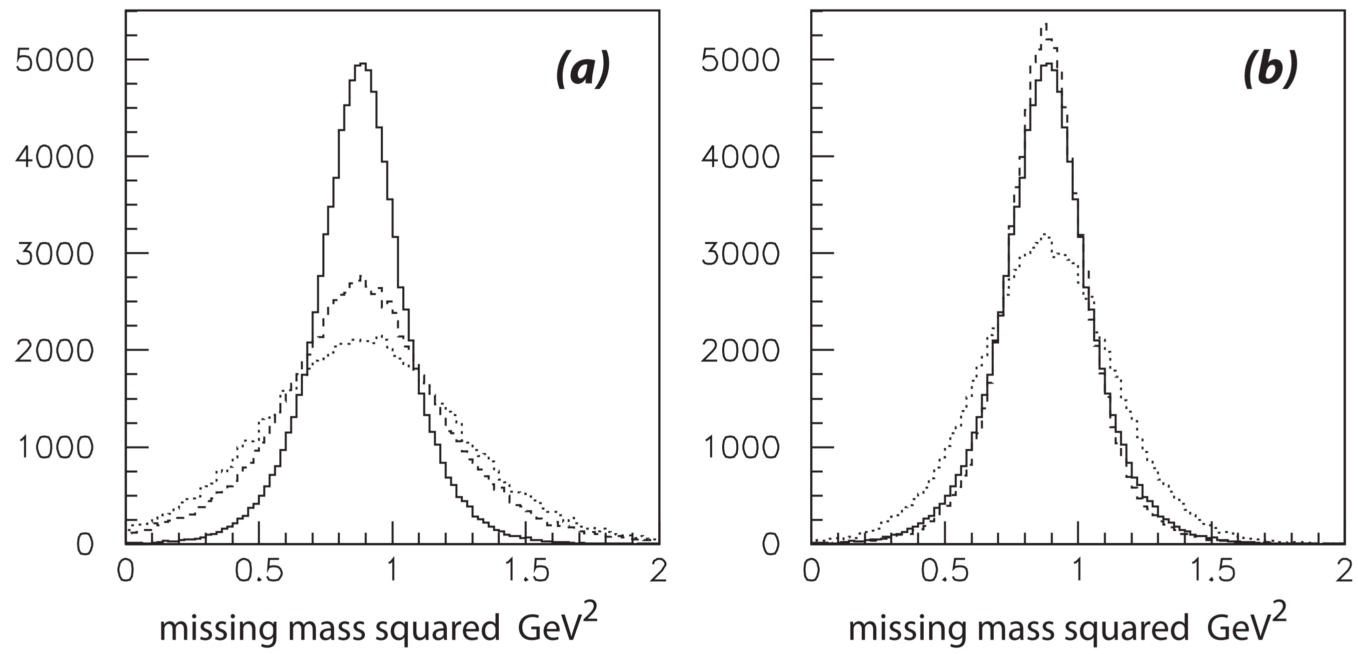


Figure 12: Missing mass squared recoiling off the ϕ for the reaction $\gamma p \to \phi p$ with photon smearing only (solid histogram), charged particle smearing only (dashed) and both (light dashed) for nominal charged particle smearing (a) and smearing reduced by a factor of two (b).

Time-of-Flight Information from BCAL

Useful for pion/proton separation

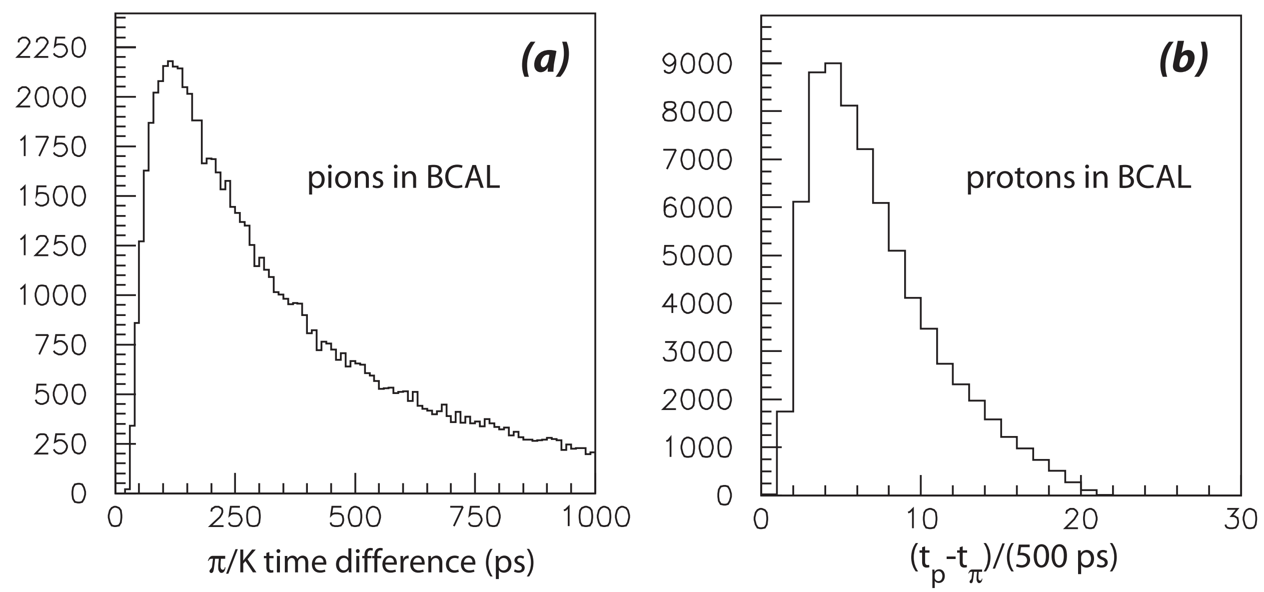


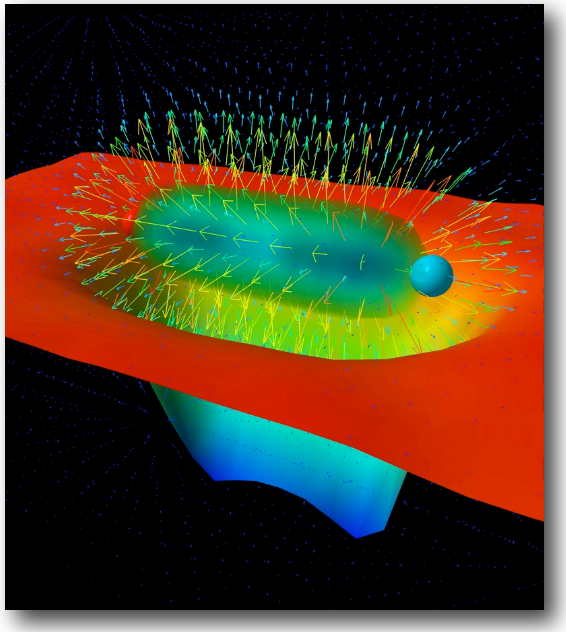
Figure 13: (a) The distribution in π/K time difference for $\pi^{\pm}$ reaching BCAL from the reaction $\gamma p \rightarrow \pi^+\pi^+\pi^- p$; (b) For protons reaching BCAL, the proton/pion time difference divided by 500 ps, the assumed mean time resolution for BCAL for minimum ionizing particles.

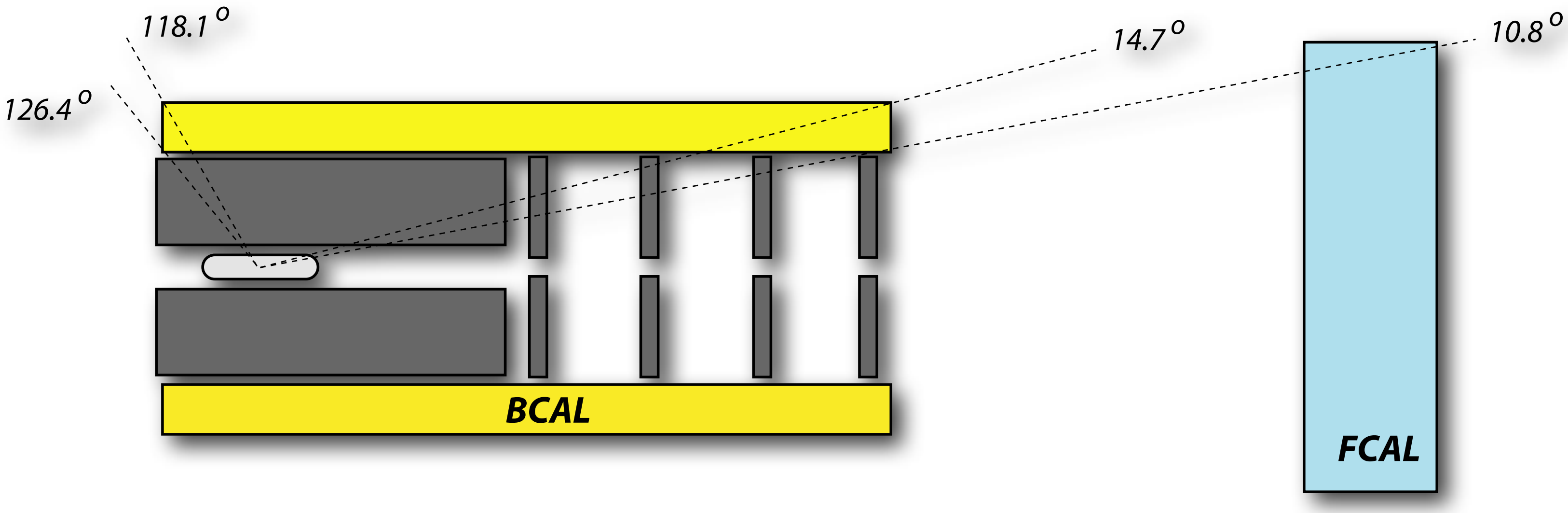
Upcoming Talks

Describing detector realization

BCAL	***George Lolos***
SiPM	***Carl Zorn***
FCAL	***Beni Zihlmann***
Simulations	***Matt Shepherd***
Electronics	***Fernando Barbosa***
Mechanical	***Tim Whitlatch***

Conclusions





GlueX will map the spectrum of gluonic excitations, including exotic mesons.

Neutral particle detection is essential for this discovery physics.

GlueX calorimetry starts with a design used successfully in earlier experiments

Performance metrics required by the physics will be met with BCAL and FCAL