CLAS12 Forward Detector Element
PCAL

Status of the PCAL R&D

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Collaborating Institutions:

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JLab, JMU, OU, NSU, Orsay-IPN

CLAS12 Workshop, JLAB, May 14, 2007

Design Requirement Review

- Comparable geometric coverage for PCAL with respect to the EC,
- Good resolution/calorimetry up to 10 GeV photons and electrons
- Improved particle identification ability to enhance final state reconstruction,
- Information on the longitudinal shower development (5, 5, 8)
- Fast calorimeter response for use the Level 1 trigger (100 ns),
- Reasonable Timing (1 ns)
- Sufficient position information to resolve
- Event reconstruction derived from component properties and the readout information,
- Compatibility with the present EC and other CLAS components.
- Mechanical engineering considerations: support, compatibility, structures (D. Kashy),
- Constructability (reasonable facilities, manpower and resources to assemble detectors)
- Reasonable options for testing components to establish PCAL operational parameters,

EC Achieved

Position Resolution	2-3 cm
Energy Resolution	(10-12)%/√E
PE Yield	3.4 pe/MeV
Time Resolution	< 0.5 ns

DESIGN GOALS →

- e/γ energy resolution $\sigma/E \leq 0.1/\sqrt{E(GeV)}$.
- Position resolution $\delta r \approx 2$ cm @ 1 GeV.
- π/e rejection greater than 99% at $E \geq$1 GeV.
- Fast ($<$ 100 nsec) total energy sum for the event trigger.
- Mass resolution for 2-photon decays $\delta m/m \leq 0.15$
- Neutron detection efficiency $>$ 50% for $\mathrm{E}_n > 0.5\ GeV$
- Time-of-flight resolution $\approx$ 1 nsec

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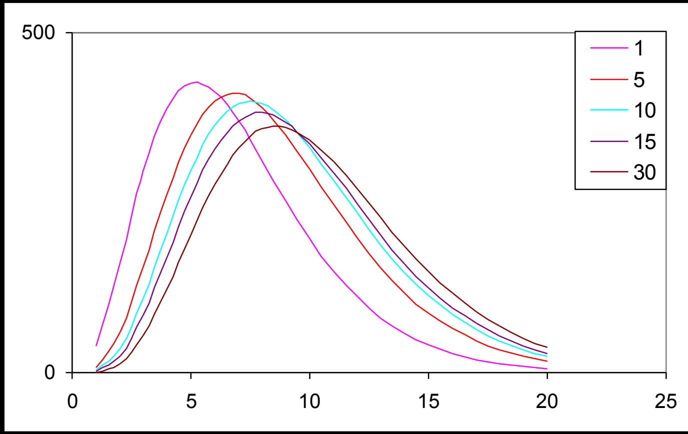
PCAL / EC
Maintain And Improve Performance

	layers	RL	cm
1 layer	1	0.42	1.22
Module	3	1.25	1.52
PCAL	15	6.25	18.30
EC fwd	15	6.25	18.30
EC bkwd	24	9.99	29.28
EC	39	16.24	47.58
total	54	22.49	65.88



Energy GeV	1	5	7	11
Shower Max tmax (RL)	6.8	9.1	9.6	10.2
Distance (cm)	19.9	26.7	28.1	30.0
Distance (layers)	16.3	21.9	23.0	24.6
Containment 2.5 tmax (cm)	49.7	66.7	70.2	75.0
2.5 tmax (fraction)	0.75	1.01	1.07	1.14

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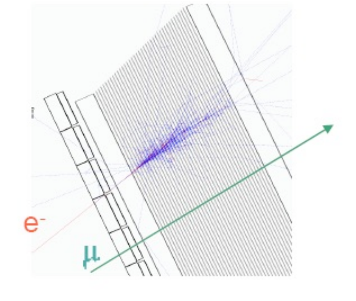
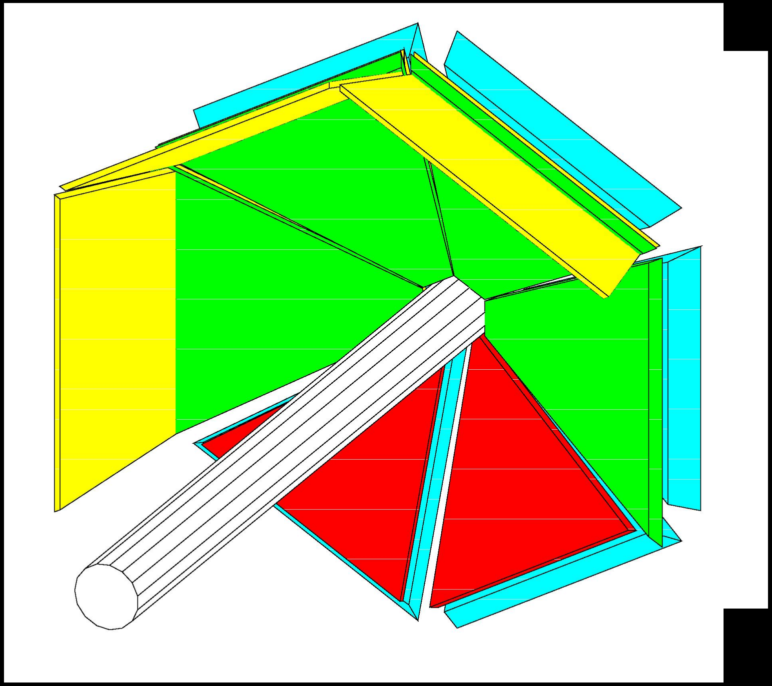
PCAL Design



- Alternating Pb (2.2mm)/Scintillator (10 mm)
- Scintillator Width
  - 4.5 cm
  - 9cm [double width readout]
- U,V,W Readout
- Cover the EC ~4m Sides
- WLS Light Readout
  - 3 fibers



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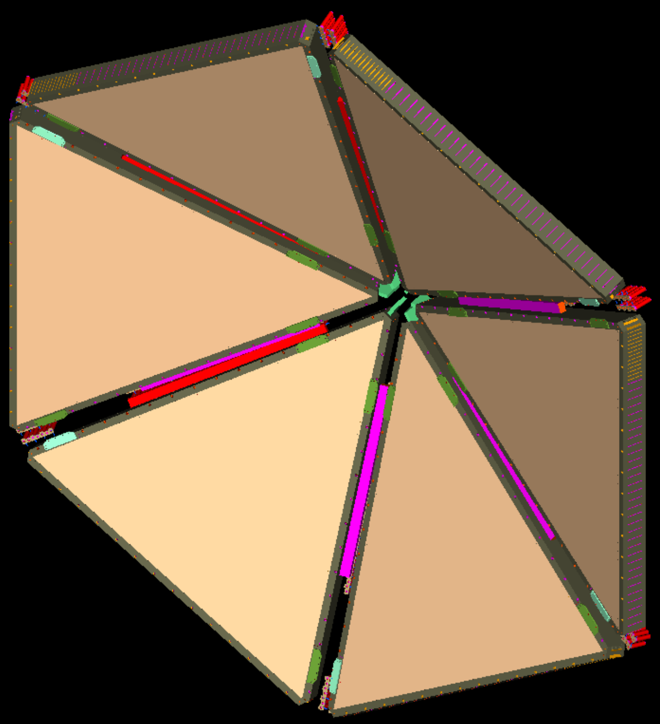
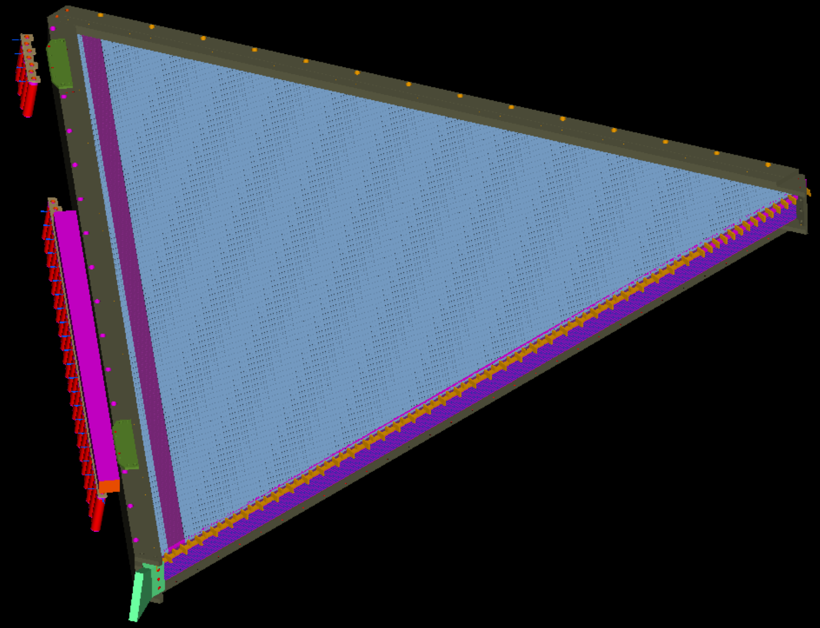
PCAL Components
Maximize Light Yield/ Minimize Cost





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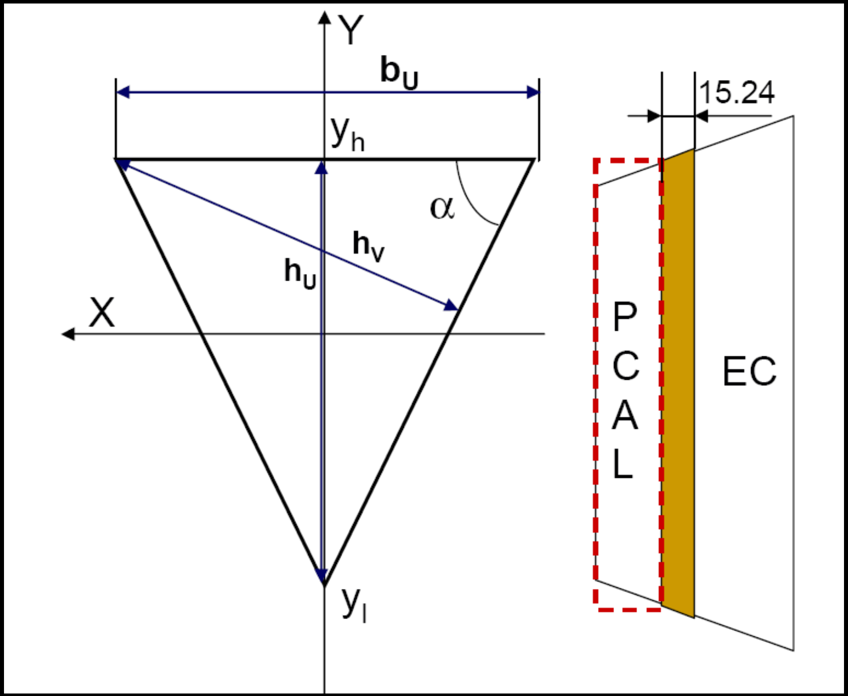
PCAL: Dimensions & Location



The first layer of scintillators of EC will have: h_U=372.93, b_U=381.86

The last layer of PCAL scintillators projected from the EC will be:

h_U=360.3, b_U=368.97
Height for V/W h_V=328.43

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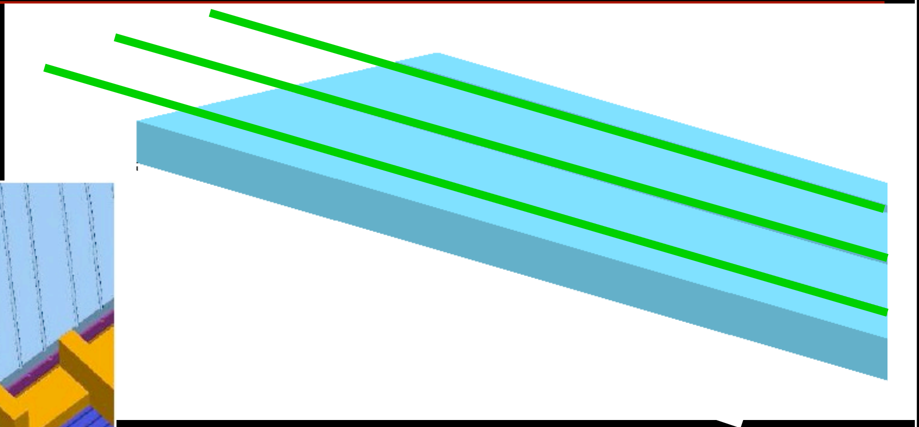
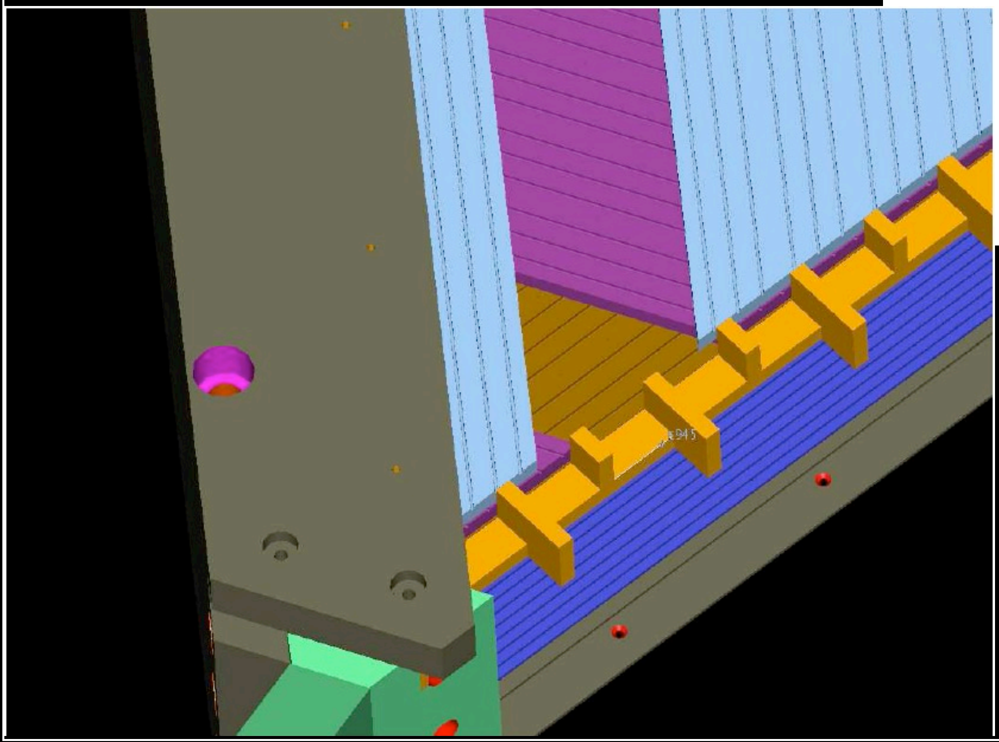
PCAL Components
Maximize Light Yield/ Minimize Cost





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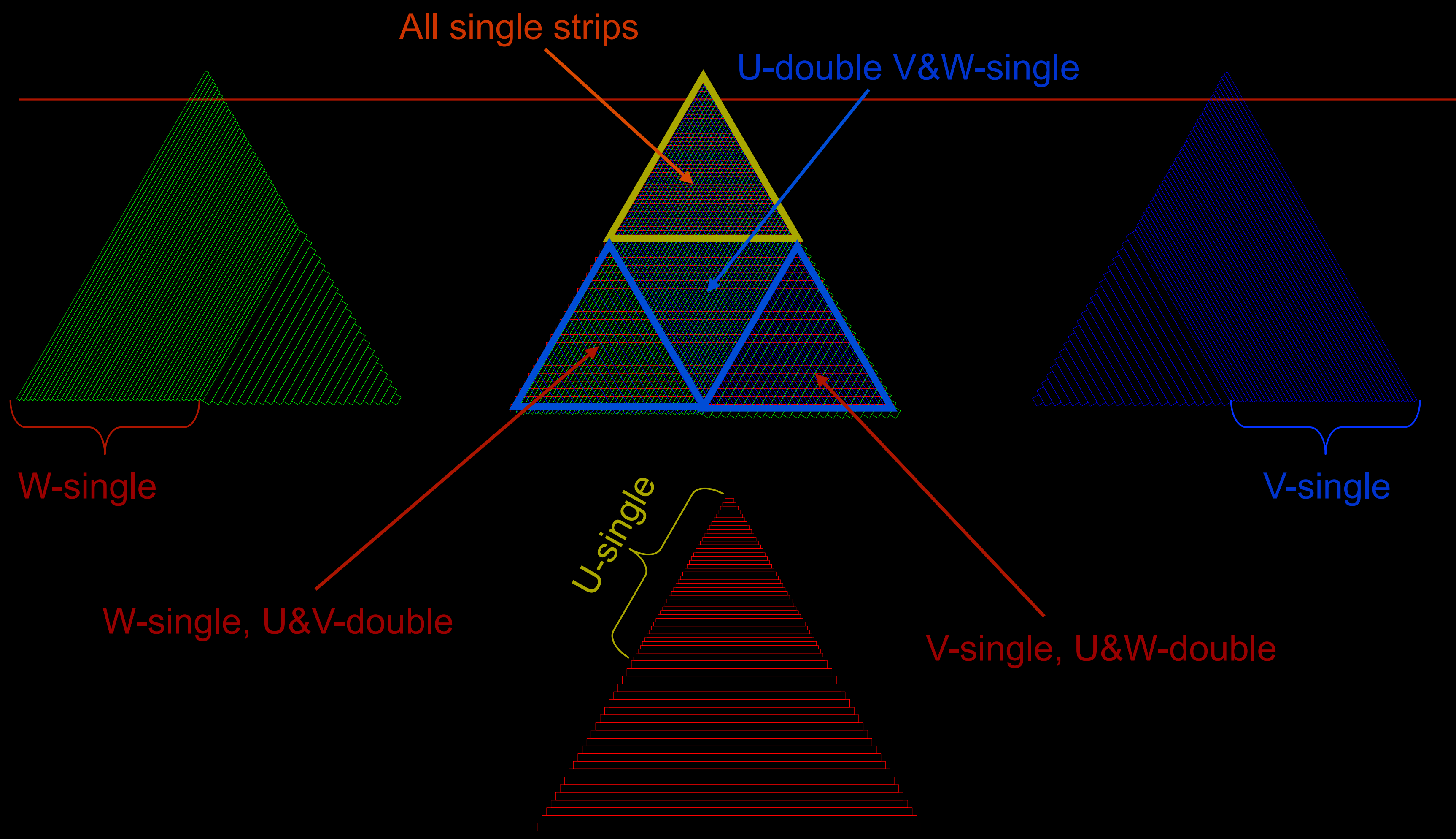

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Components Tested

- Photomultiplier Tubes
- Type Of WLS Fiber
- Number Of Fibers/ Scint.
- Type Of Scintillator

PMT	Type	Quantity	Divider
HAMAMATSU	R7899 R1450 R6095	4 19mm 28mm	R7899 10 11
Electron Tubes	9124B	2	C637A
PHOTONIS	XP1912 XP2802	1 1	DV108 DV1A8
Fibers	**Type**	**Diameter**	**Length**
Kuraray	Y-11 Y-11 Y-11	2mm 1.5mm 1mm	2,5m 2.5m 2.5m
Bicron	BC-91A BC-92	1mm 1mm	2.5m 2.5m
Scintillator			
ELJEN Technology	4F. 0F.	3x1cm2 3x1cm2	2 m 2m
Kharkov	1F. 2F 3F	4x1cm2 2.63x1.06c 2.63x1.06c	1m 2m 2m
Fermi Lab	1F.	4x1cm2	1m
ITEP	1F.	4x1cm2	1m

Test Setup (In The EEL)

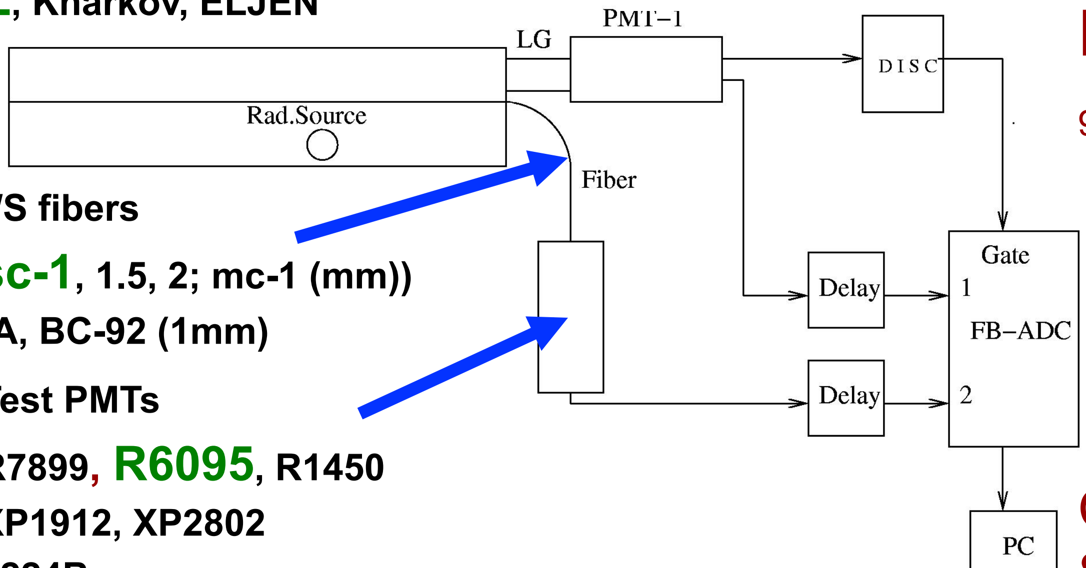
4 m long dark box with moving cart and support fixtures (Hall B engineering)

Simple DAQ (CODA) – FASTBUS with LeCroy ADC

Test Scintillator with Groove(s)

FNAL, Kharkov, ELJEN

Trigger PMT XP2262



Test WS fibers

Y11(sc-1, 1.5, 2; mc-1 (mm))

BC-91A, BC-92 (1mm)

Test PMTs

R7899, R6095, R1450

XP1912, XP2802

9224B

Rad.Sources:

^{90}Sr and ^{207}Bi

$$^{90}Sr \rightarrow 0.546 MeV(\beta^-)$$
$$+^{90}Y \rightarrow 2.28 MeV(\beta^-)$$

Cosmic muons

Second Trigger PMT

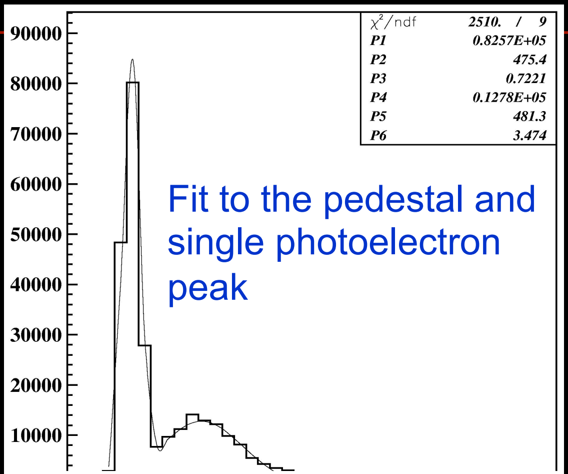
Fits To ADC Distributions

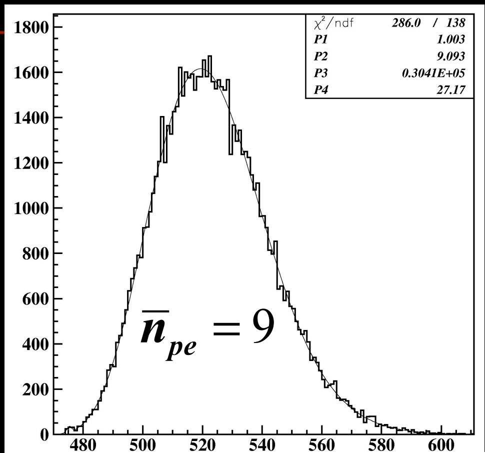
$\Delta E \approx 2 MeV$

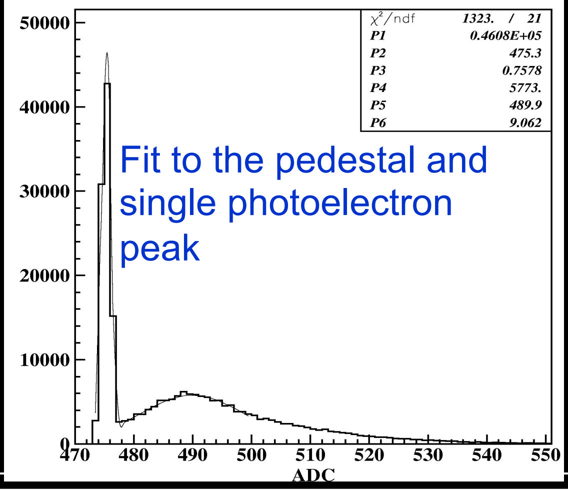
Hamamatsu R7899EG, Green Sensitive Photocathode

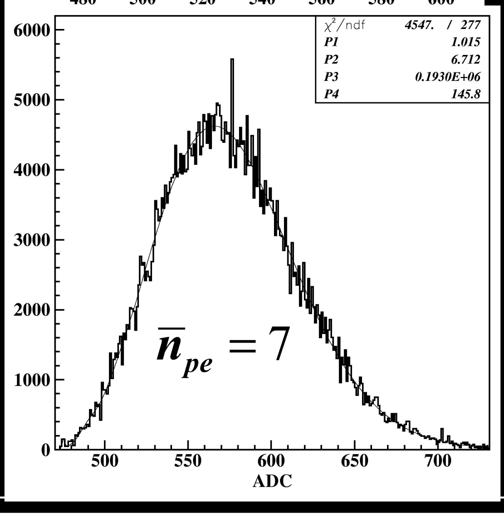
FNAL Scintillator With One Grove, Kuraray Y-11 Single Clad Fiber

Hamamatsu R6095, 15% QE at 500nm



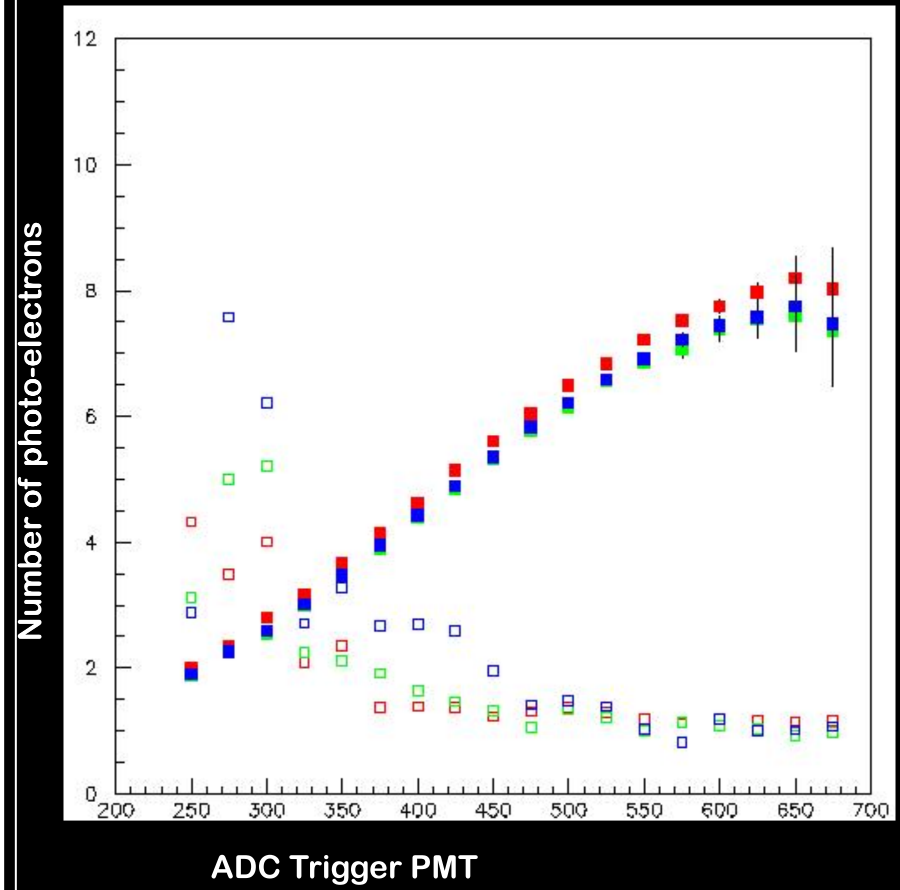






Fit To The ADC Distributions From ^{90}sr For R6095 PMT Of Different HV

Fit to Slices of Trigger PMT ADC Distribution



FNAL Scintillator with 1 Groove

Kuraray 1mm, Single-clad WSF

PMT Hamamatsu R6095

- 800 V
- 850 V
- 900 V

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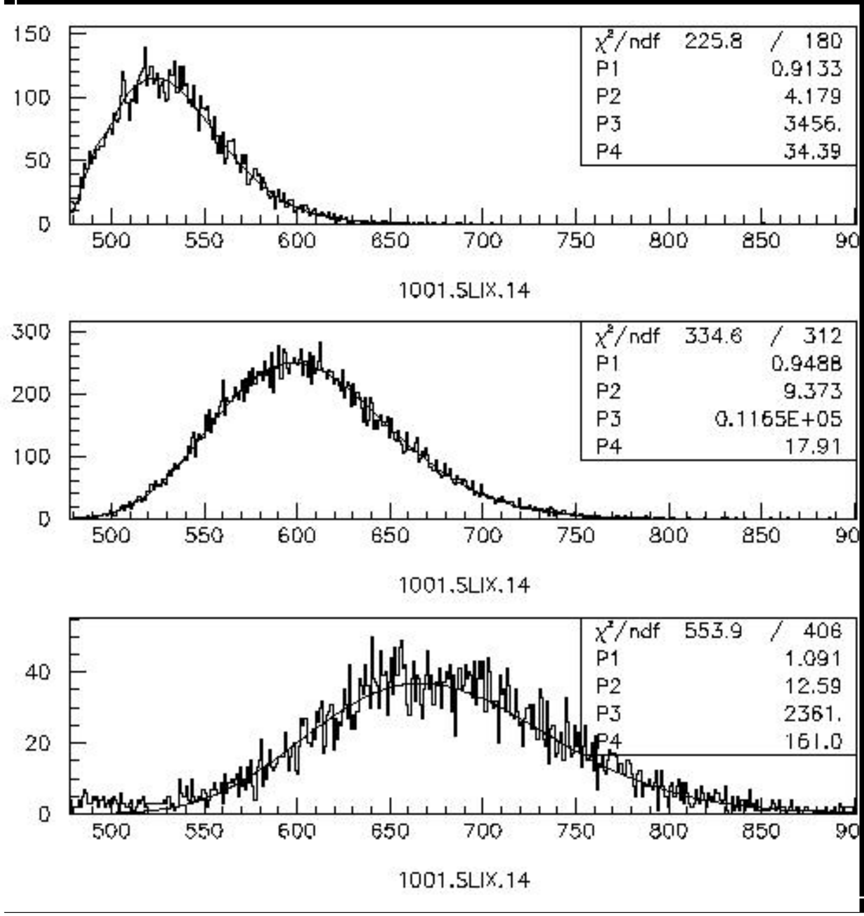
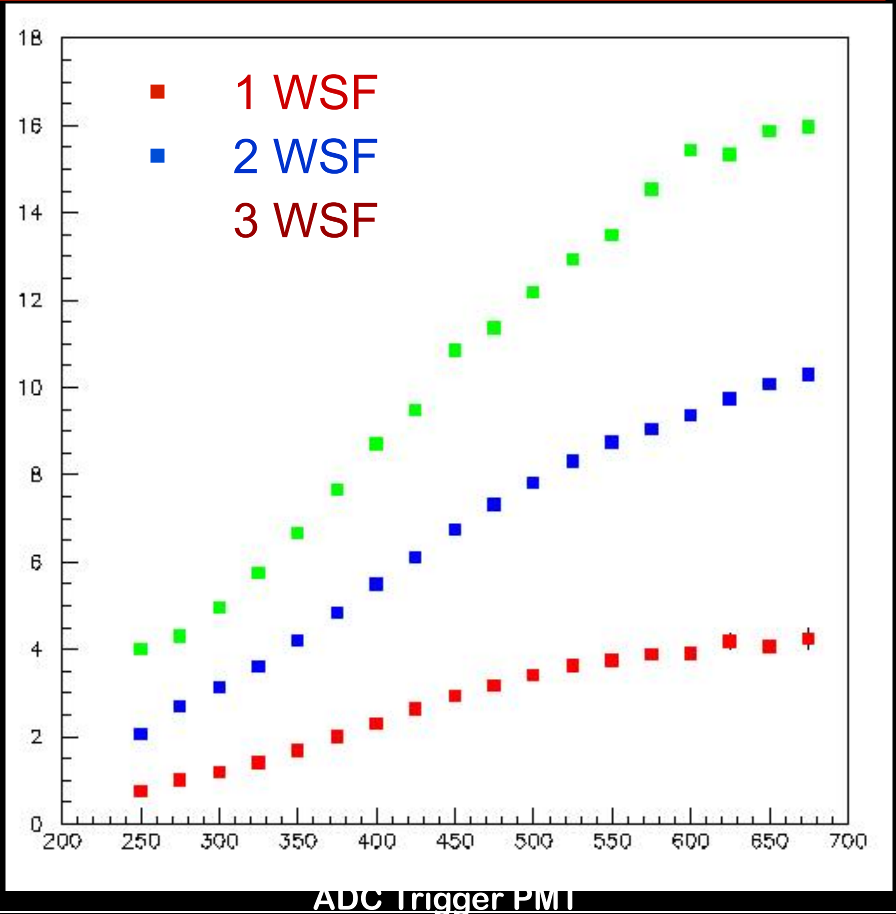
Fit To The ADC Distributions From ^{90}sr

Scintillator Strips With 3-grooves, Kharkov. ADC Distributions Of R6095 For One, Two, And Three Fiber Readout





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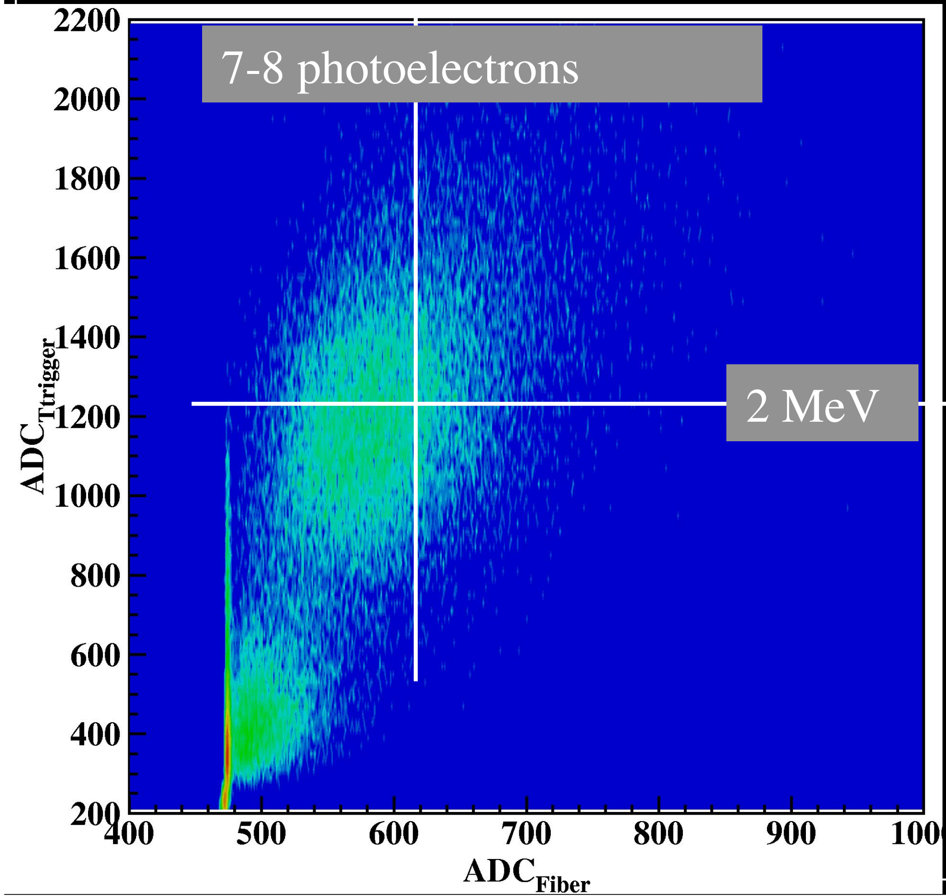
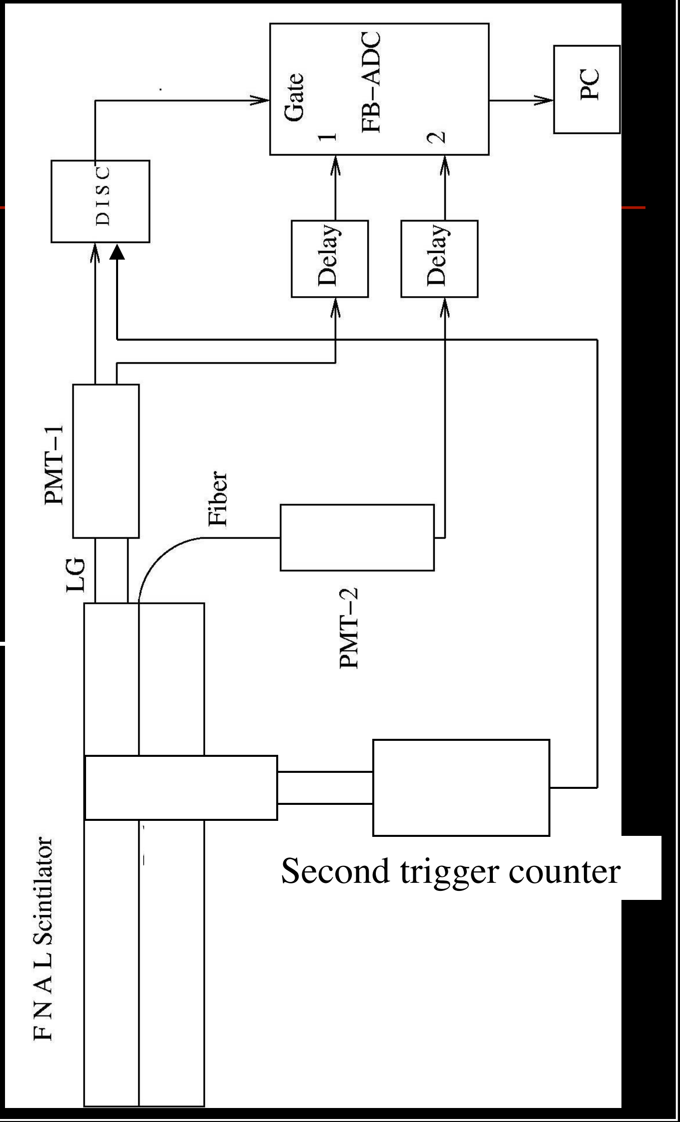
Absolute Light Yield With Cosmic Muons

FNAL scintillator, 1 cm thick, with 1mm WS fiber,
Kuraray Y-11 s.c., PMT Hamamatsu R6095





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Summary of test measurements

- Best PMT is the HAMAMATSU R7899EG, $280/each.
- HAMAMATSU R6095 [selected with QE>16% at 500nm]
  - Photoelectron yield 25% lower.
  - R6095 is $160 ($180 gain spec).
- Other PMTs did not perform better and are expensive, >$250
- Multi-clad fiber
  - 20% more light vs single-clad fiber
  - 30% more expensive
- FNAL extruded scintillator with Y-11 fiber has the best light yield,
  - price, $20-$25/meter.
- Kharkov are close, need R&D to match the FNAL performance.

Component Recommendation

The best combination by the light yield and price is:

FNAL scintillator

Kuraray Y11 single clad

HAMAMATSU R6095.

Light yield ~11p.e./MeV (3 fibers)

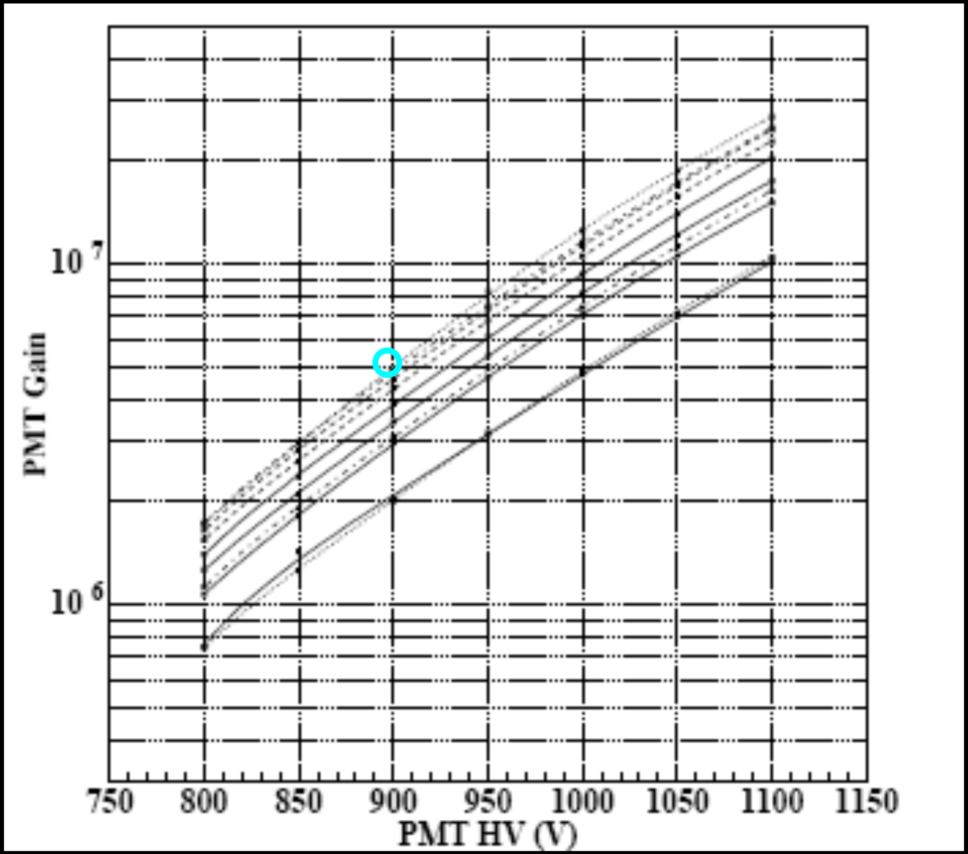
Additional tests

- Gain [900 V] , “Nominal” PMT
  - Input set at one electron
  - Output =[charge/ADC channel] x [peak]
    - 50 fC/channel Lecroy 1881 QDC
    - SPE channel – Pedestal = 15.5 channels
      - Nominal PMT gain at 900 V = 4.8×10^6

Additional tests

- Gain vs Voltage
  - Find SPE peak and measure Gain
  - Examine gain at voltages 800-1100 V

Gains G vs HV



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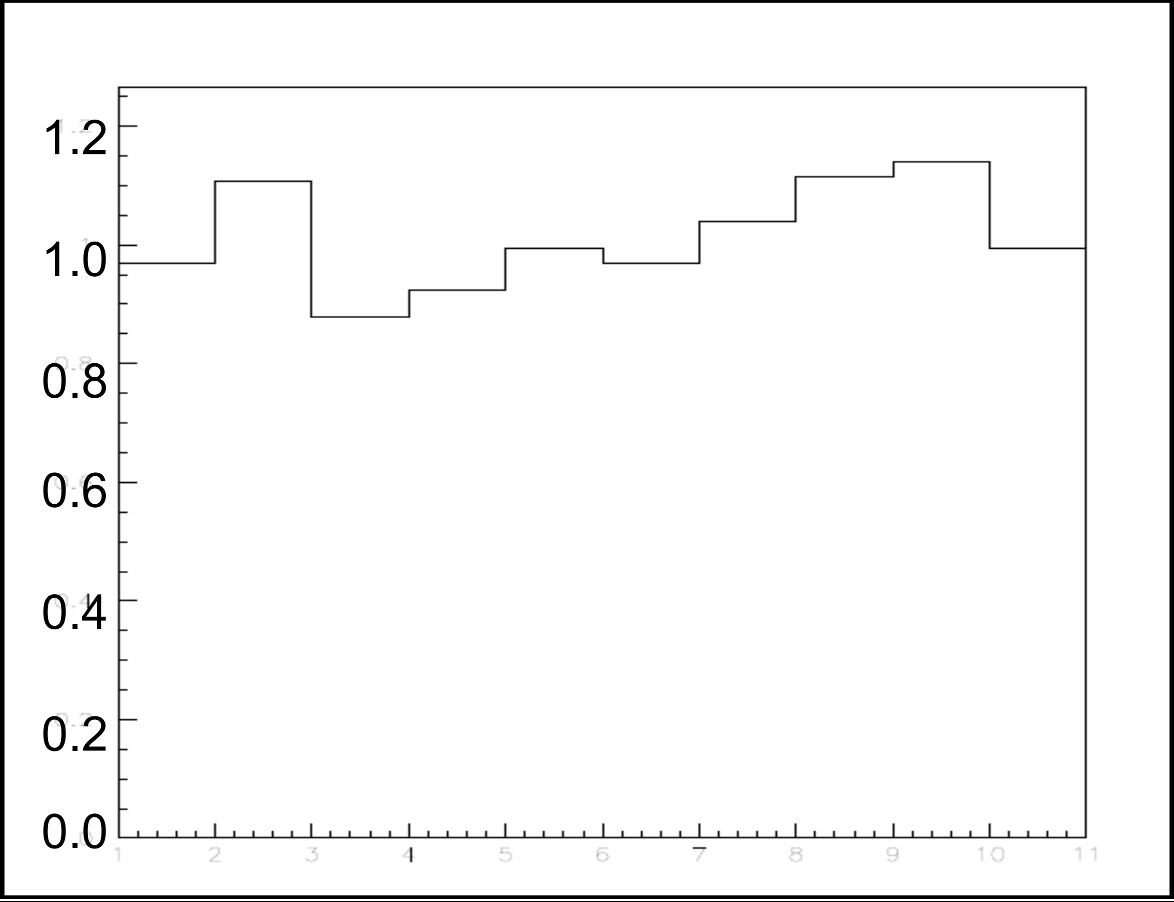
Relative QE α

$$N_\gamma \otimes QE = N_{pe}$$

$$\frac{\left[N_{pe}\right]_1}{\left[N_{pe}\right]_o} = \frac{N_\gamma \, QE_1}{N_\gamma \, QE_o} = \frac{QE_1}{QE_o}$$

$$\alpha = \left(\frac{QE_1}{QE_0}\right) = \frac{\left[N_{pe}\right]_1}{\left[N_{pe}\right]_o}$$

Relative Quantum Efficiency



Attenuation Lengths

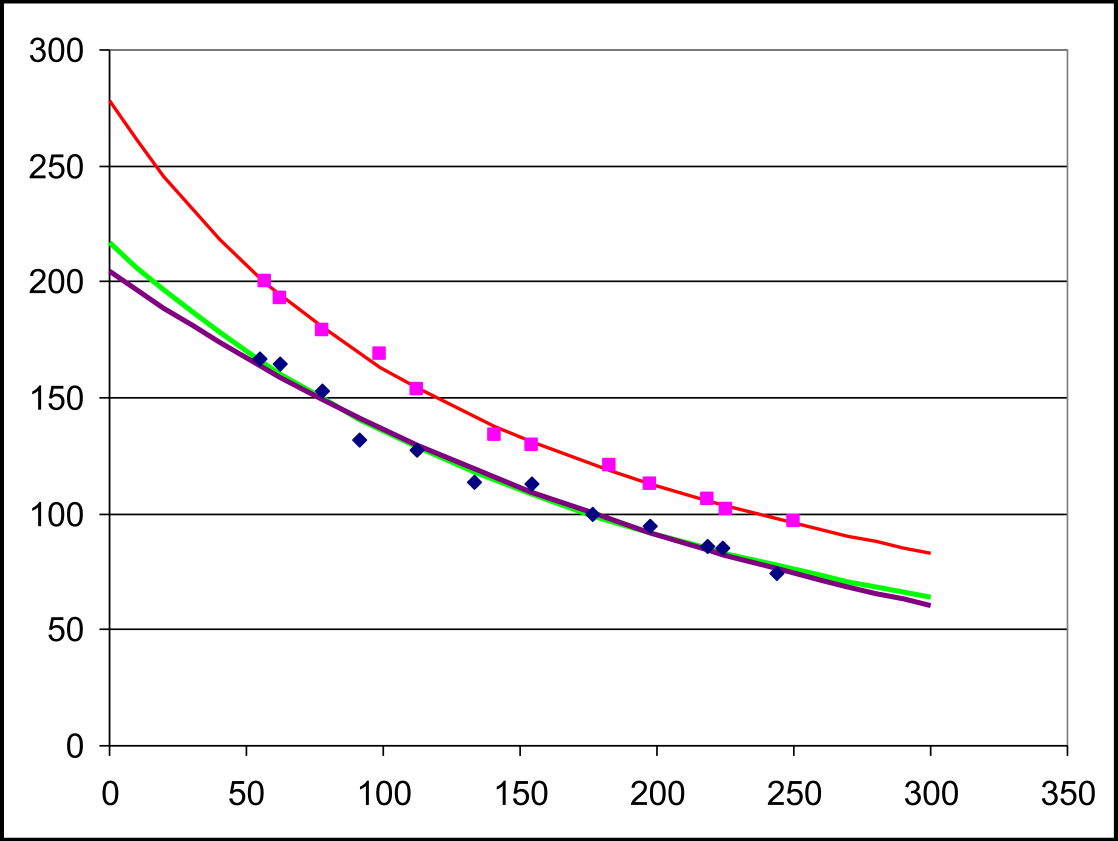
$$A1 \bullet e^{-\frac{x}{L1}} + A2 \bullet e^{-\frac{x}{L2}}$$

- Measure light produced by cosmics as a function of the distance along the scintillator.

	MC	SC	minos	A2=0	
A1	103	91			
L1	75	117	70	260	cm
A2	175	125		0	
L2	391	380	390		cm

Attenuation lengths

	SC	MC
short =	126 cm,	75 cm
long =	380 cm,	391 cm
Equal mix		[Single atten=260]



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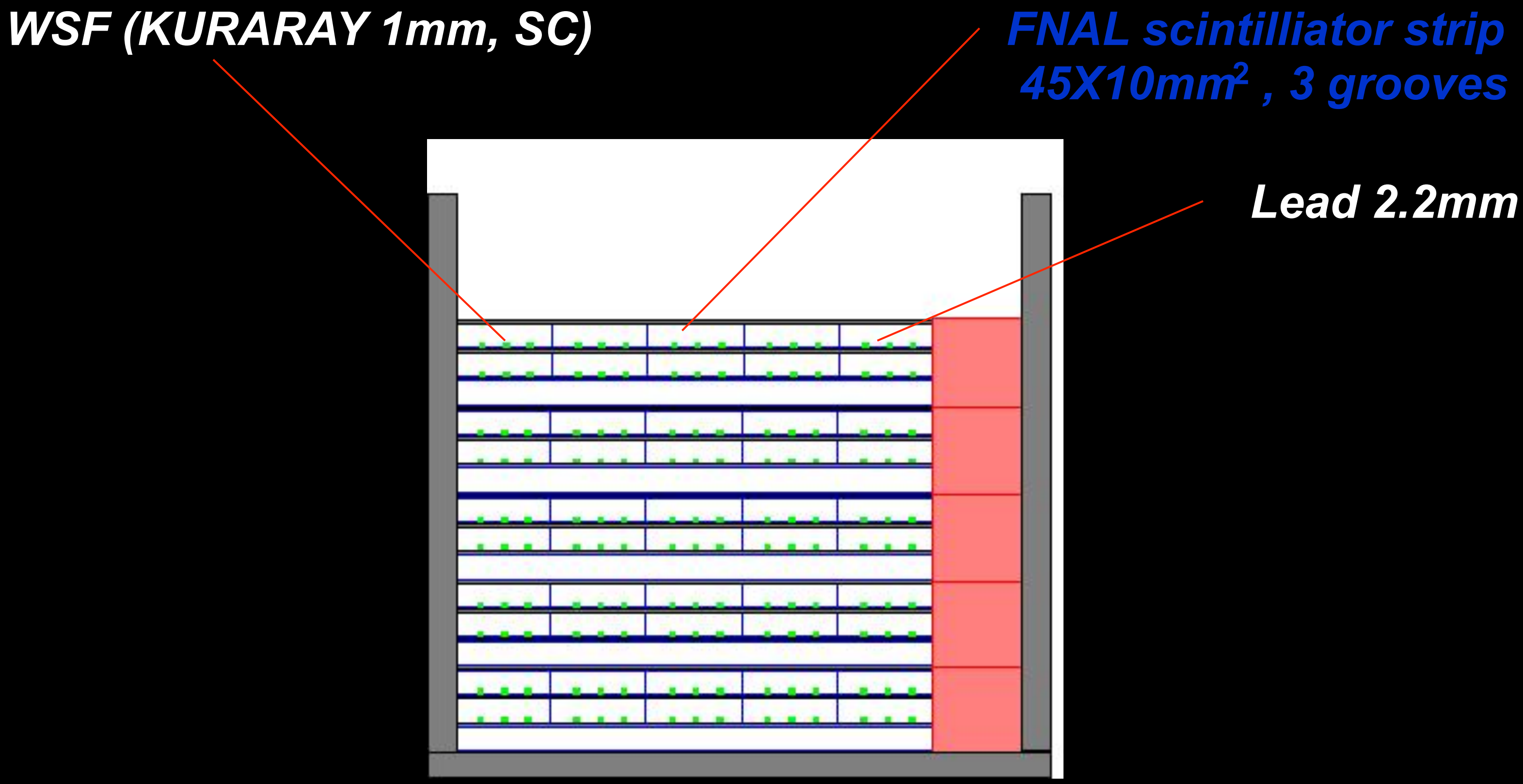
Prototype: Box-Prototype

- Small dimensions = on order of 30 cm
- Full longitudinal structure (5 modules)
- Mimic UVW readout
- Beam tests
- Shower characterization
- Complete component combined response
- Explore fiber routing & PMT mounting

Pre-shower Prototype (Side View)



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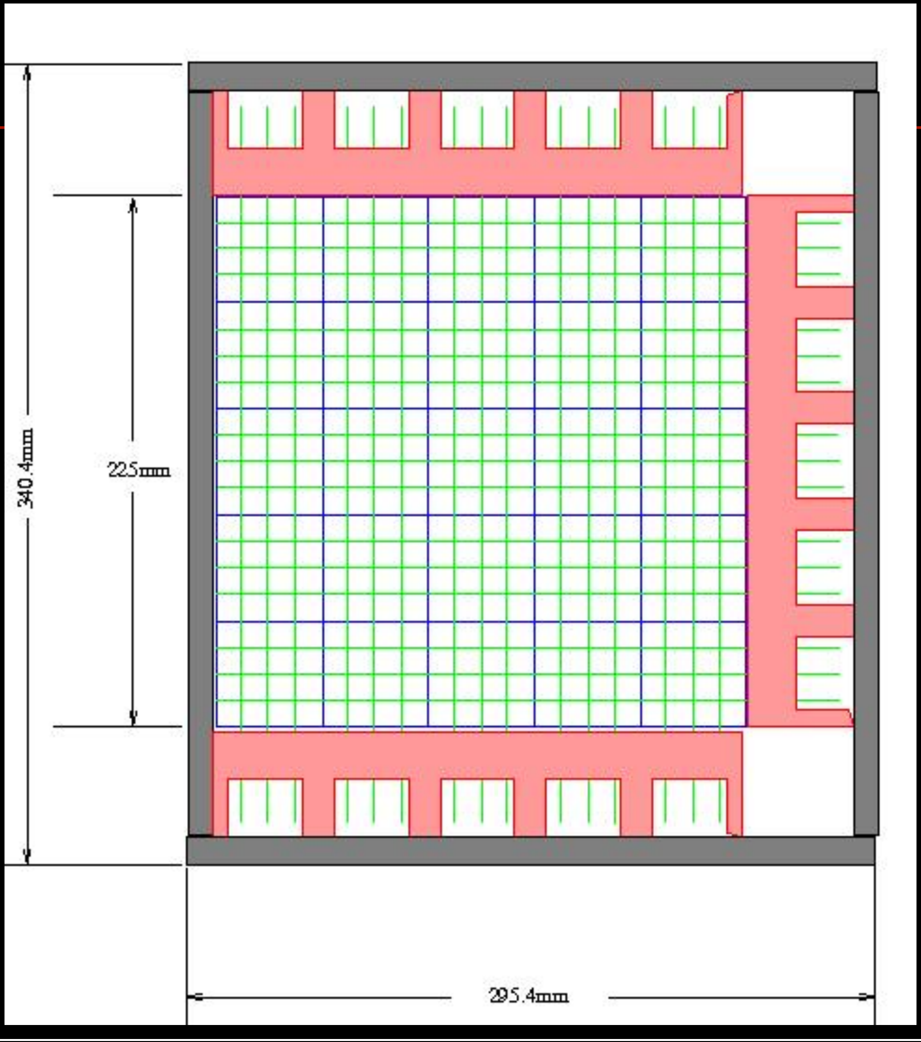
Pre-shower Prototype (Top View)



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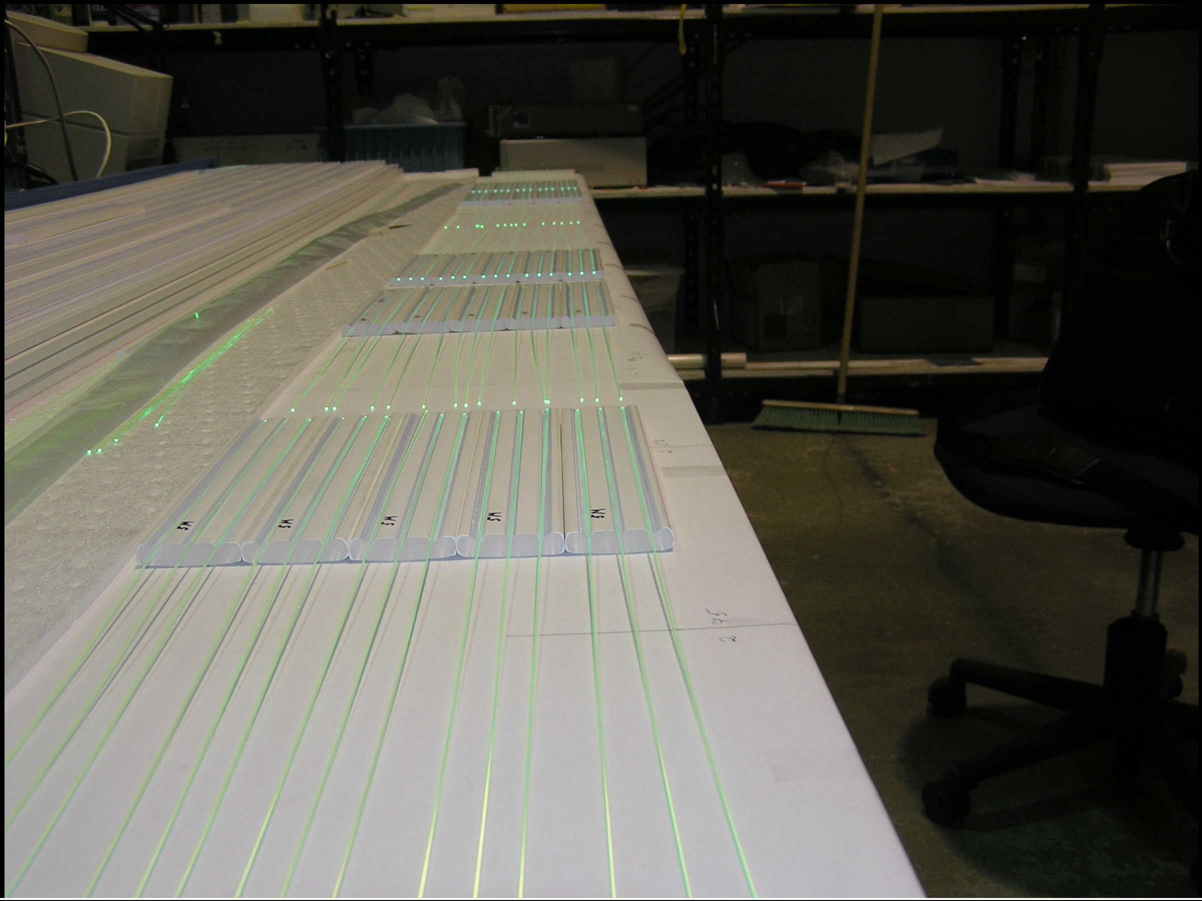
Box-Prototype: WLS Fiber/ Scintillator

Prototype Assembly

Fibers are glued in the grooves of FNAL scintillator. This will be the active medium for the sampling calorimeter.



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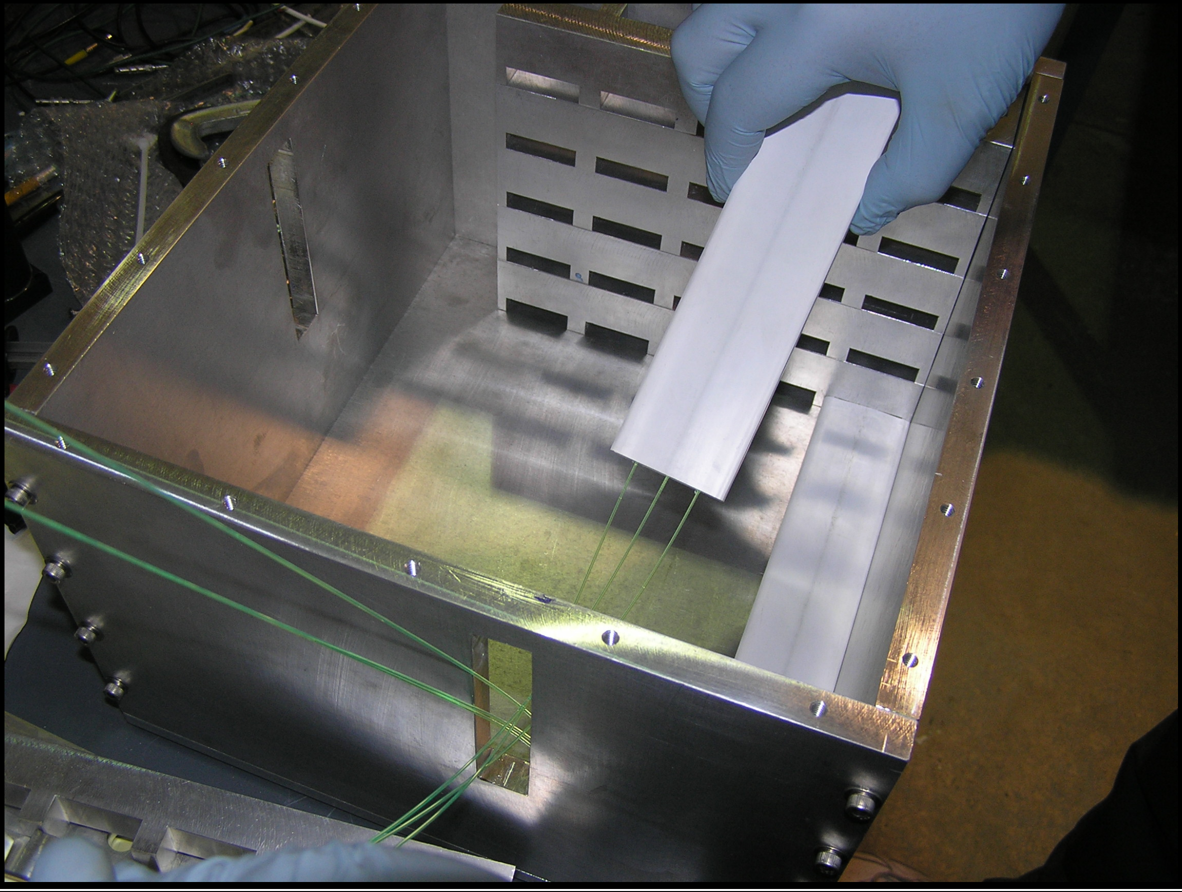
Box-Prototype: Aligning Scintillator

Prototype Assembly

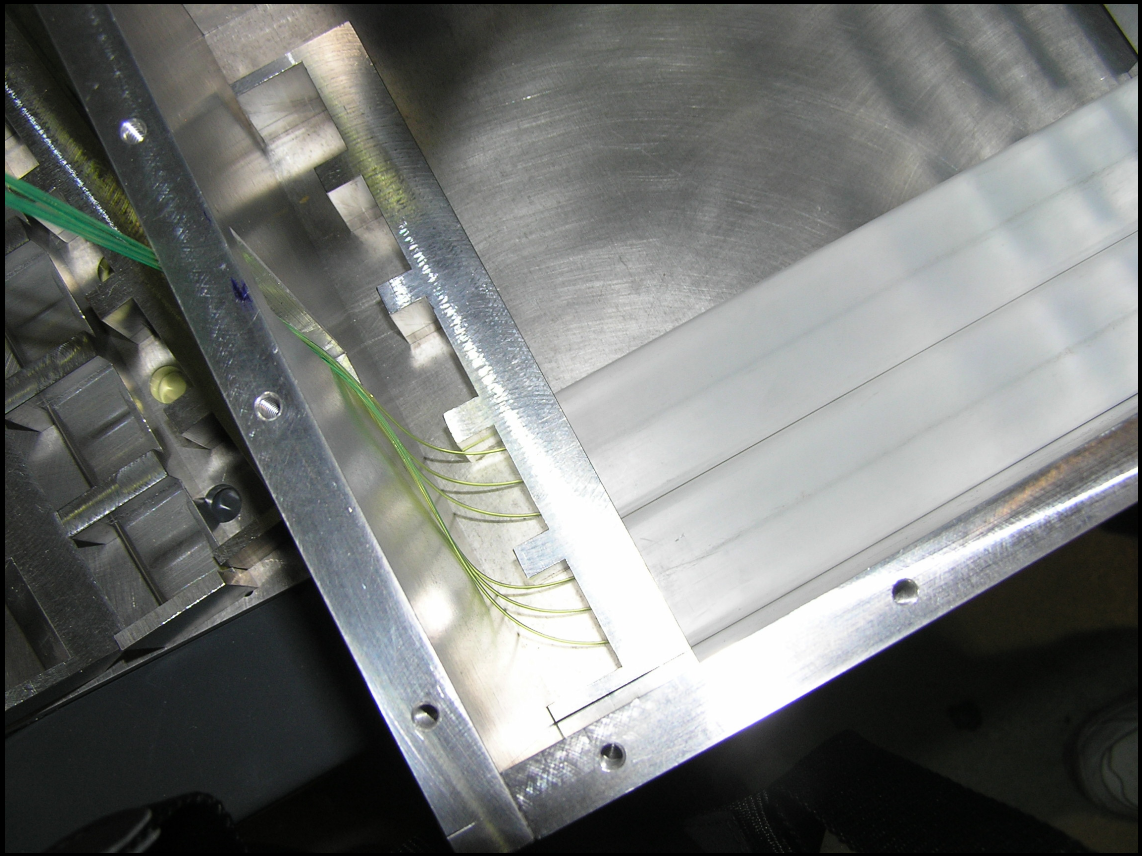
The scintillators are then placed in a supporting structure which holds the scintillator in place while allowing the fiber to be routed to the exterior.



Box-Prototype: Fiber Routing

Prototype Assembly

The photomultipliers will be mounted along the sides. Each of three sides will have fiber channels to the exterior in order to obtain a three view readout.



Prototype: Full Scale

- Match Final Dimensions Of PCAL
- Explore Construction Methods
  - Assembly
  - Component: Storage, Delivery, Alignment
  - Mechanical Support
  - Fiber: Handling, Gluing & Routing
- Develop Quality Control Measures
- Refine Component Testing Methods
  - Large Dimension Attenuation Lengths

Prototype: Full Scale

The large number of photomultipliers, scintillator strips, the significant length of fiber and the length of the longest pieces create challenges that can be best addressed by building at least partially a full scale prototype.

PCAL Review

Closeout Report

on the

Project Design and Safety Review

of the

Hall B Calorimeter and Cerenkov Counter

April 23-24, 2007

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PCAL Review: Response

The requirements for the detectors as provided to the Committee are indeed appropriate for the physics objectives…

The PCAL design as described appears very likely to achieve the stated performance specifications. Conservative design approaches and the planned R&D and prototyping efforts will, we believe, lead to a fully functional detector on time and on cost…

PCAL is already well cost-optimized.

These R&D efforts are surely appropriate and well-directed,.. We support the plans for a full-scale PCAL prototype and consider it to be an important part of this detector's development.

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PCAL Review: Comments

Clarify The e/pi discrimination requirements.

The labor and fiscal requirements reasonable.

PCAL and the HTCC require significant storage, assembly, and testing space … Committee recommends that an explicit commitment for the refurbishment and availability of the cleanroom, as well as the other required workspaces, be obtained from the appropriate JLab organizational unit.

development of the flash ADC and the F1-TDC systems is on track to provide the PCAL and HTCC with the digitization, trigger, and readout services they will need. .. Detailed requirements should be specified …When testing detector prototypes, the use of electronics which closely resembles the final system will be an advantage.

PCAL Review: Recommendations

the Committee felt that an additional study should be made with more layers (up to 18) to be certain that the optimum efficiency level has been reached. In addition, it would also be extremely useful to show the final π0 mass resolution, and not just the reconstruction efficiency, of the combined PCAL and EC calorimeter system over the full energy range.

A complete design of the full scale prototype should be developed, along with a cost estimate and identification of a funding source.

complete plan was required for assembly, quality control and testing of its various components.

- An adequate, clean work area for the gluing of the wavelength shifting fibers into the scintillator plates, including any necessary tooling, fixturing
- A quality check of each scintillator-wavelength shifter element as it is completed.
- A detailed design ..photomultiplier tubes mounting & fibers routing.

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Conclusion

- Components That Meet Design Criteria
- Small Prototype Under Construction
- Significant Advantages Associated With Large Prototype Development

END

EXTRA Slides follow

$$\alpha = \frac{QE_1}{QE_{nominal}} \sim 1$$

$$\frac{\alpha G_1}{G_{nominal}} = \frac{ADC_1 - PED}{ADC_{nominal} - PED}$$

Measurements technique

- For each PMT, a single photo-electron peak position and the width, at given HV, was determined using two Gaussian fit to the ADC distributions of attenuated light
- For each combination, the average number of photo-electrons was extracted as a function trigger PMT ADC value, the fit function:

$$ADC_T = c_1 \sum_i P_i(n_{pe}) \times C_i(n_{ch}) + c_2 e^{-\frac{\left(x - x_p^0\right)^2}{2\sigma_p^2}}$$

$$P_i(n_{pe}) = \frac{(n_{pe})^i e^{-n_{pe}}}{i!}$$

$$C_i(n_{ch}) = \frac{1}{\sigma_1 \sqrt{i}} e^{-\left(\frac{n_{ch} - c_3 a_1}{\sigma_1 \sqrt{2i}}\right)^2}$$

Fit parameters:
c_1, c_2, c_3, and n_{pe}

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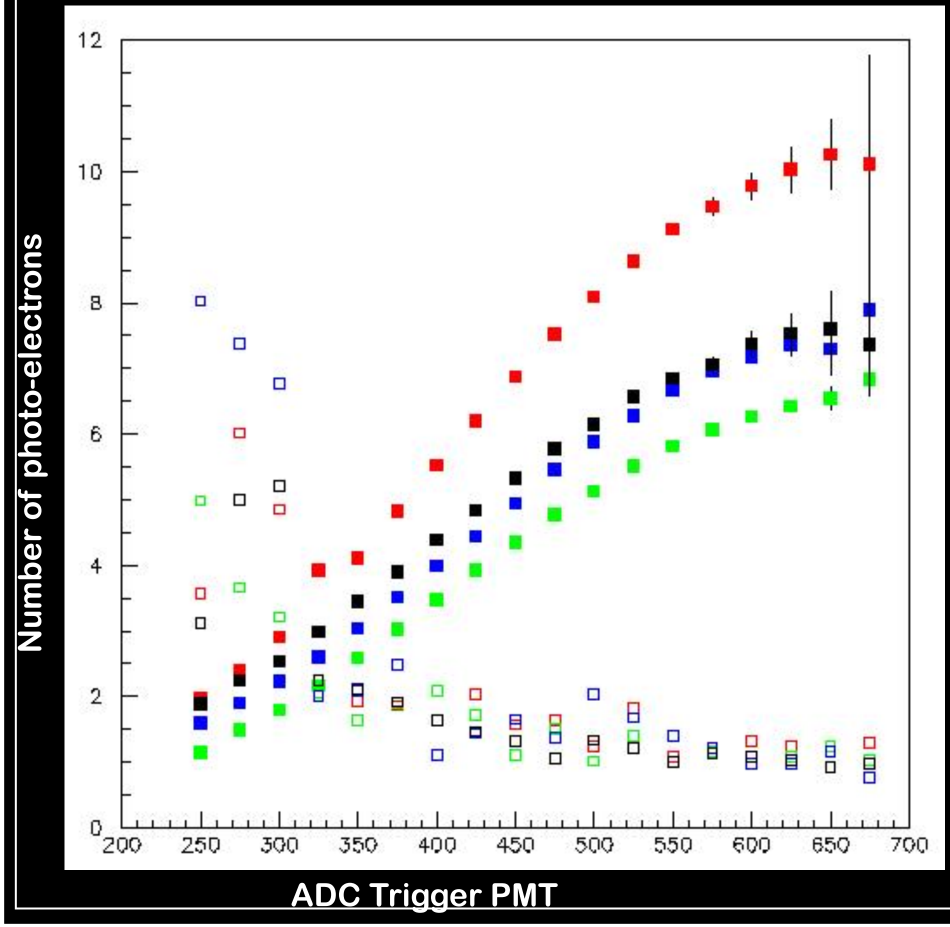
Fit to the ADC distributions from ^{90}Sr for different PMT

Fit to slices of trigger PMT ADC distribution



■	R7899	9.1 pe
■	R6095	6.9 pe
■	XP2802	6.7 pe
■	R1450	5.8 pe

FNAL scintillator with 1 groove

Kuraray 1mm, single-clad WSF

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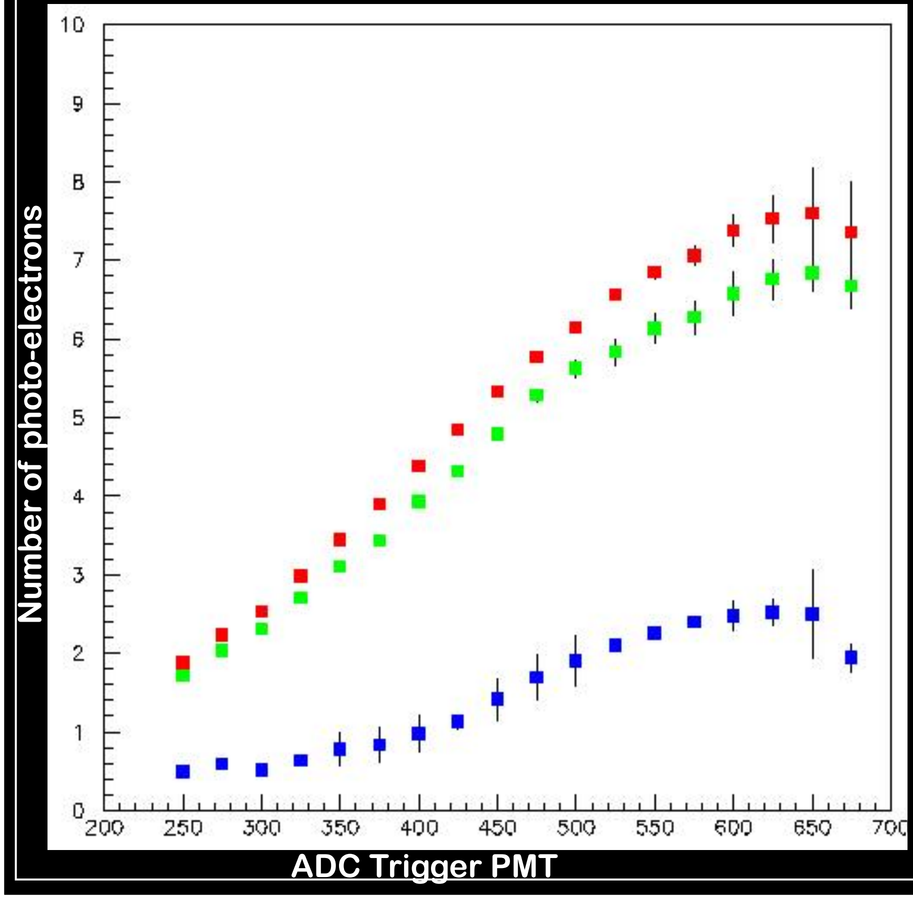
Fit to the ADC distributions from ^{90}Sr for R6095 PMT at different scintillators

Fit to slices of trigger PMT ADC distribution



ELJEN 2.2 pe

FNAL 6.9 pe

Kharkov 6.1 pe

Kuraray 1mm, single-clad WSF

PMT Hamamatsu R6095

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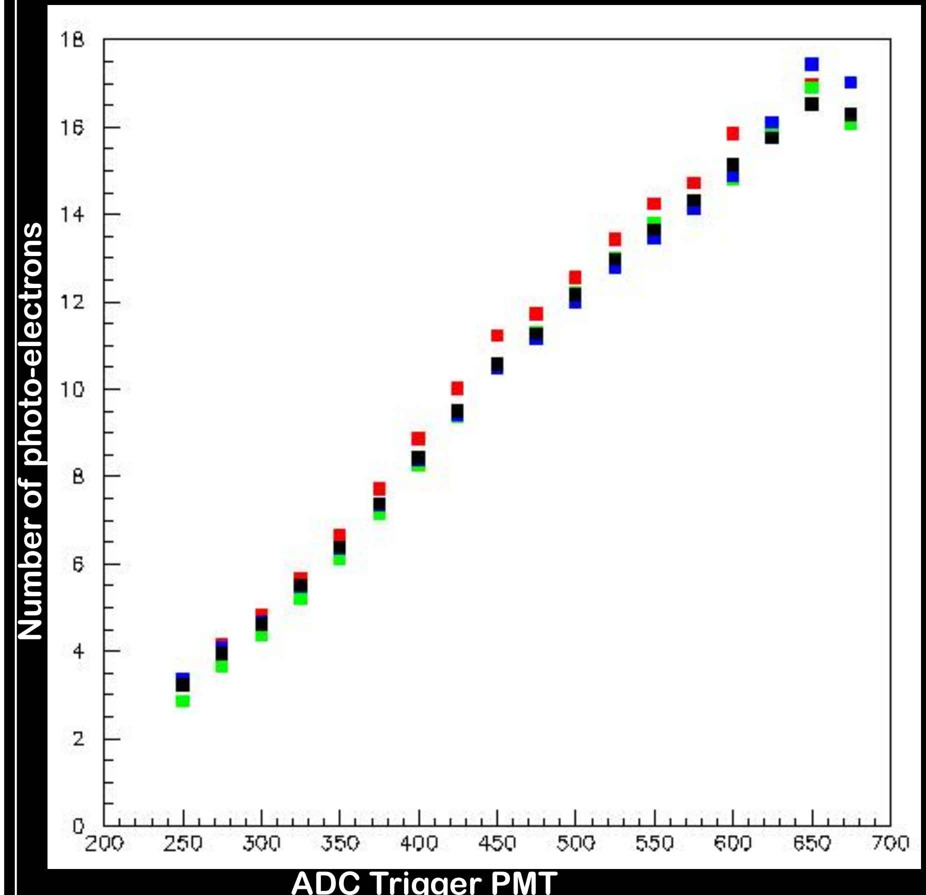
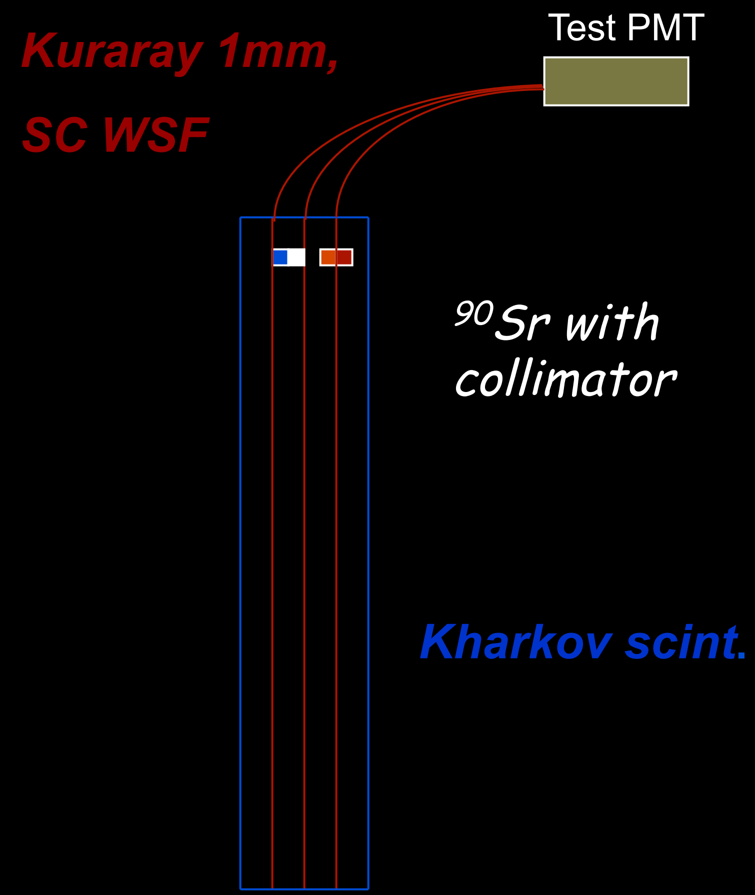
Fit to the ADC distributions from ^{90}Sr for R6095 PMT of different positions source

Fit to slices of trigger PMT ADC distribution





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Possible Configurations

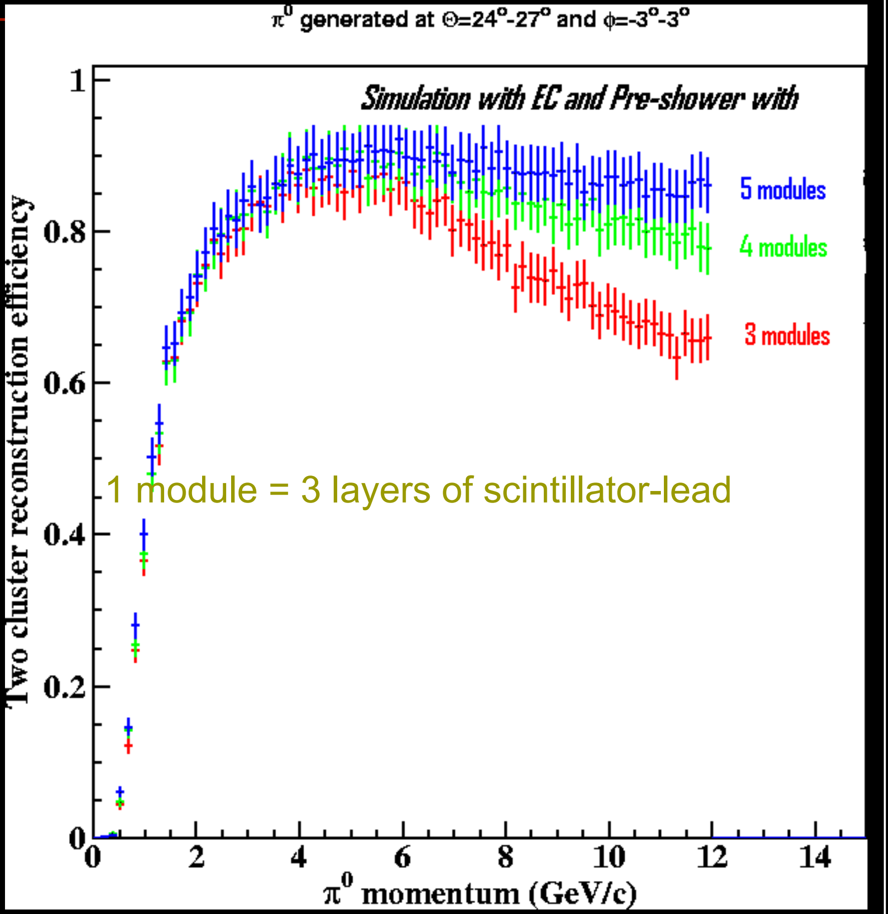
Number of photomultiplier tubes is determined by the segmentation which is is based on the spatial resolution. Improvements in PMT performance do not result in a reduction of the number of photomultiplier tubes.

Improvements in the fiber performance could potentially reduce the number of fibers required. This would reduce redundancy (broken fiber) and most likely uniformity.

Number of layers was examined in Monte Carlo simulations and the results summarizing these results suggest 15 layers (5 modules) is the best choice.

Configurations with 9, 12, and 15 layers

- p[0] reconstruction efficiency decreases at high energies for 12 and 9 layer modules
  - not enough radiator thickness and some of high energy photons do not convert
- 12 layers configuration with first 3 layers of lead with double thickness had comparable efficiency but ~10% worse energy resolution



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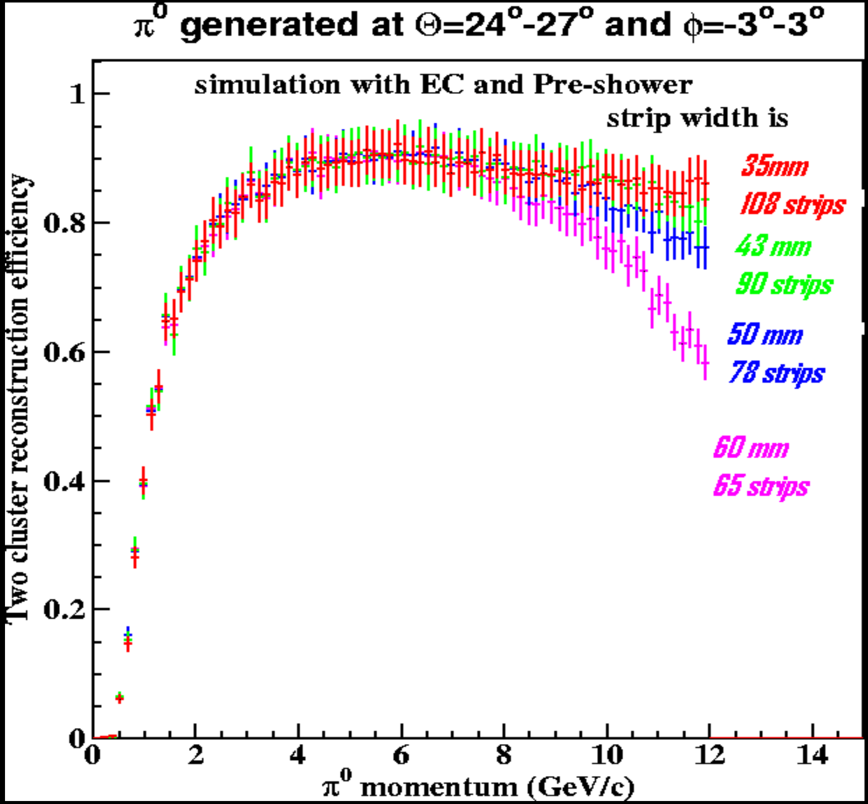
Different Readout Segmentations

Simulations with 15 layers of scintillators and 14 layer of lead

- Efficiency of reconstruction of two clusters from p^0’ gg decay decreases for small number of readout segments
- For p^0 energies up to 10 GeV efficiency of two cluster separation is reasonably high for 4.5 cm wide segmentation



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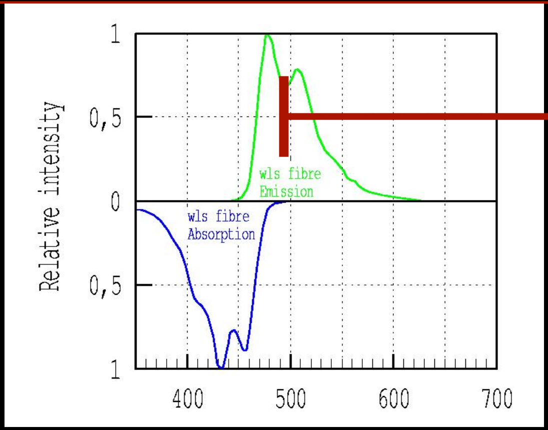
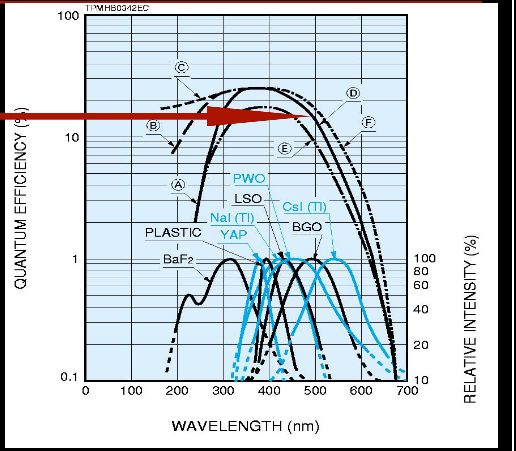
Selection Of The PCAL Components

Scintillator-WLSF-PMT combination with reasonably high photo-electron statistics at low cost





Choice for the scintillator, WLS fiber, and PMT is :

Fermi Lab extruded scintillators, 4.5x1 cm^2 with 3 grooves
Kuraray, 1mm diameter Y11 single clad
HAMAMATSU R6095 selected with Q.E.>16% @ 500 nm

Expected photo-electron yield ~11p.e./MeV for 3 fibers (yield for EC readout from the test measurements was ~8.4p.e./MeV)

CLAS12 workshop, JLAB, May 14, 2007

Table 7.1: CLAS^{++} Forward detector - Expected properties

Particle type	polar angle(°)	phi range (°)	$\delta p/p$	δT(ps)
Electron	8 - 40	0 - 270	$\sqrt{(0.1\%p)^2 + (0.2\%/\beta)^2}$	60
Hadrons (inbend.)	8 - 40	0 - 270	same	60
(outbend.)	5 - 35	0 - 270	same	60
Photons	5 - 40	360	$9\%/\sqrt{E(GeV}$	150
Neutrons	5 - 40	0 - 270	-	300

Table 7.3: CLAS^{++} Luminosity and Particle identification

Operating Luminosity	H_2	$10^{35} cm^{-2} s^{-1}$
	^3He	$1.5 \times 10^{35} cm^{-2} s^{-1}$
	^2H, ^4He, ^{12}C, ^{16}O	$2 \times 10^{35} cm^{-2} s^{-1}$
	polarized NH_3, ND_3	$2 \times 10^{35} cm^{-2} s^{-1}$
pion rejection factor	$>> 1000$	$p < 2.7 GeV/c$
	≈ 1000	$p > 3 GeV/c$
	≈ 100	$p > 5 GeV/c$
π/K separation	Forward detector	$p < 3 GeV/c$
	Central detector	$p < 0.6 GeV/c$
K/p separation	Forward detector	$p < 4.5 GeV/c$
	Central detector	$p < 1.2 GeV/c$

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Measurements technique

- For each PMT, a single photoelectron peak position and the width, at given HV, was determined using two Gaussian fit to the ADC distributions of attenuated light
- For each combination, the average number of photo-electrons was extracted as a function trigger PMT ADC value, the fit function:

Fit parameters: c_1, c_2, c_3, and n_{pe}

Pre-shower components for test

PMT	Type	Quantity	Divider	Quantity	Socket	Quantity	Total price
Electron Tubes	9124B	2	C637A	1	B14B	1	**906**
PHOTONIS	XP1912	1	DV108	1			**697**
	XP2802	1	DV1A8	1			
Fibers	**Type**	**Diameter**	**Length**	**Quantity**	**Total**		
Kuraray	Y-11	2mm	2,5m	14	35m		**1575**
	Y-11	1.5mm	2.5m	14	35m		
	Y-11	1mm	2.5m	14	35m		
Scintillator							
ELJEN Technology	4F.	3x1cm2	2 m	2	4m		**1974**
	0F.	3x1cm2	2m	2	4m		
Kharkov	1F.	4x1cm2	1m	1	1m		**0**
Fermi Lab	1F.	4x1cm2	1m	5	5m		**0**
ITEP	1F.	4x1cm2	1m	1	1m		**0**

CLAS12 workshop, JLAB, May 14, 2007

CLAS forward electromagnetic calorimeter (EC)

Lead-scintillator sandwich, 16 radiation lengths

39 scintillator and 38 lead layers

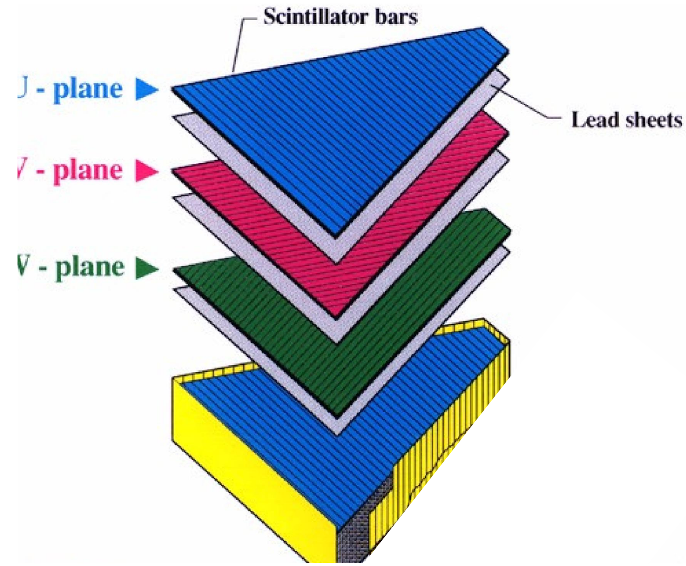
Each layer is almost an equilateral triangle, with 8 m^2 coverage

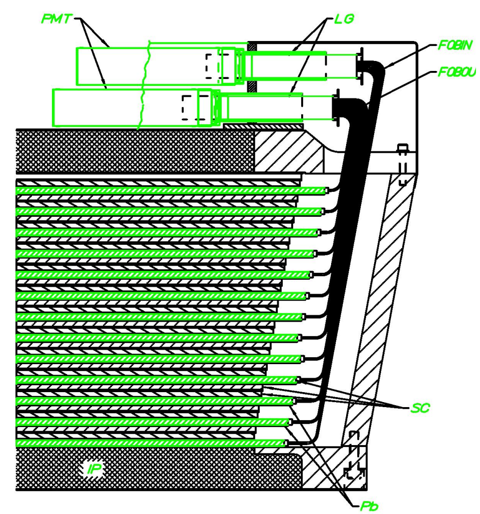
Scintillator layers are 10 mm thick, lead layers 2.2 mm

Three stereo readout planes (13 layers per view), each following scintillator layer have strips rotated to 120 degree relative to the orientation of the previous layer

Readout strip width ~10 cm, 36 scintillators per layer

In the direction of the shower, readout is segmented into 2 parts (5 and 8 layer per view)





CLAS12 pre-shower project [WBS 1.4.2.2.2.3]

- R&D (FY06-FY07):
  - full GEANT simulation and reconstruction
  - test of the pre-shower components (scintillators, WLS fibers, and PMTs)
  - construction and test of prototypes
  - determination of the light yield, light attenuation, and the time characteristics of the pre-shower

(see also K. Giovanetti's presentation)

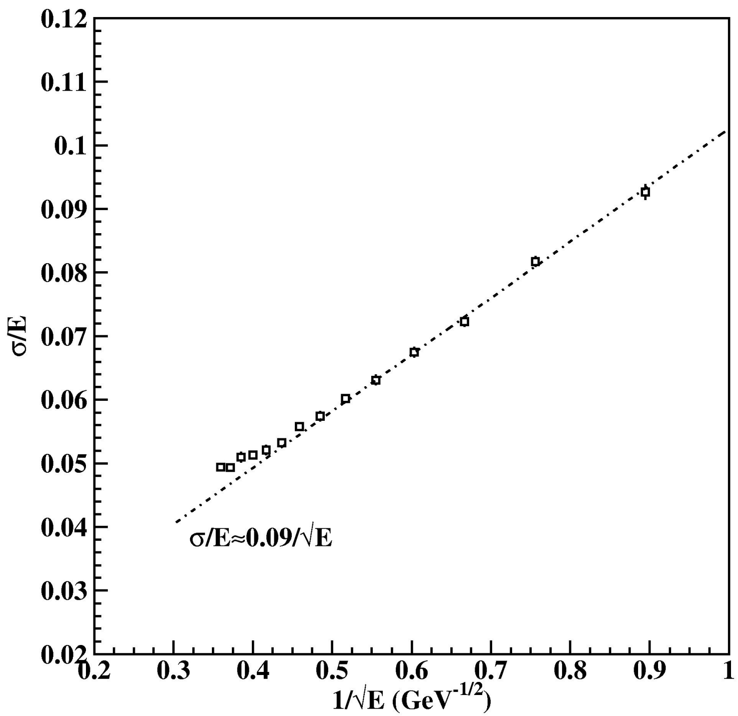
- PED (FY07-FY08):
  - design of the pre-shower module
  - design of the mounting fixtures
  - design of prototypes

(see also D. Kashy's presentation)

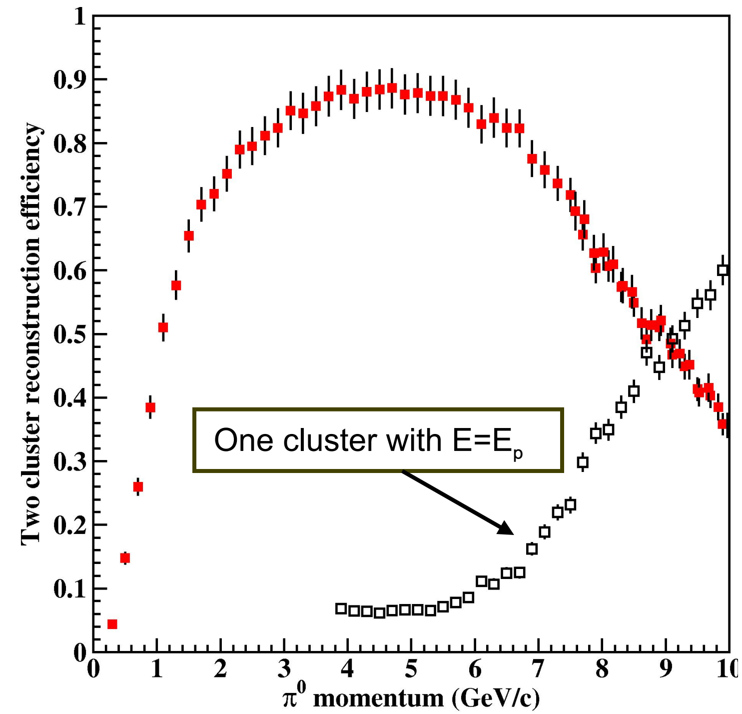
CLAS EC at high energies

Two problems will arise at high energies

Diminishing energy resolution due to leakage from the back



Separation of clusters from high energy p^0’ gg decay



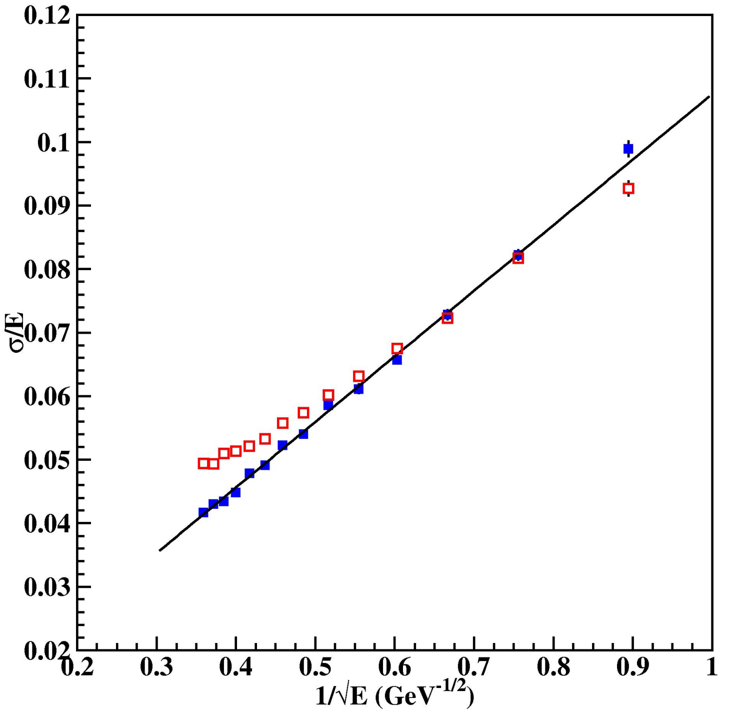
Both are important for successful execution of the CLAS12 physics program

S. Stepanyan, CLAS12 Detector workshop, February 2-3, 2007, JLAB

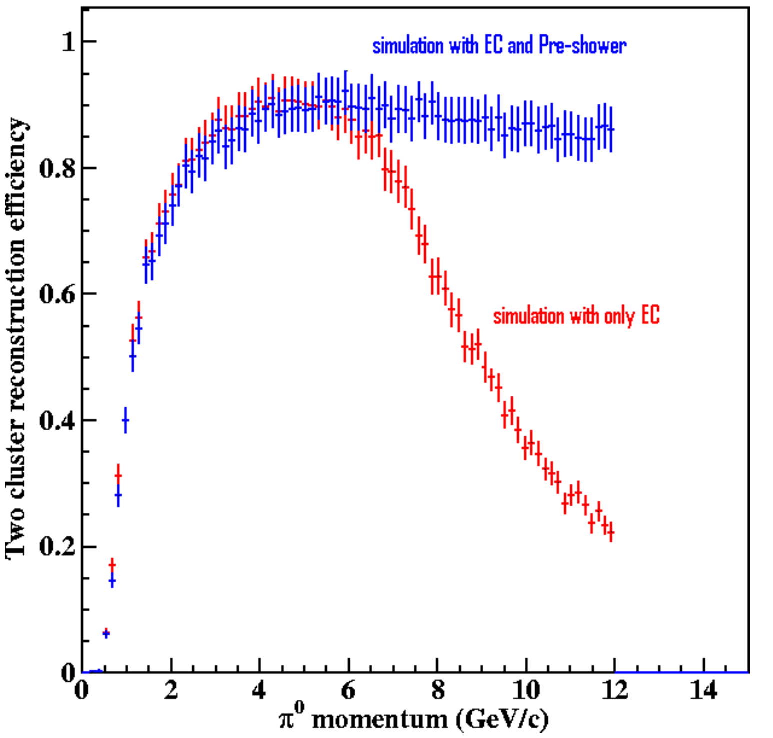
PCAL+EC simulations (15 layers and 108 strips)

Energy resolution for electrons thrown in the center of the of the calorimeter

$$\frac{\sigma_E}{E} \approx \frac{0.1}{\sqrt{E}}$$

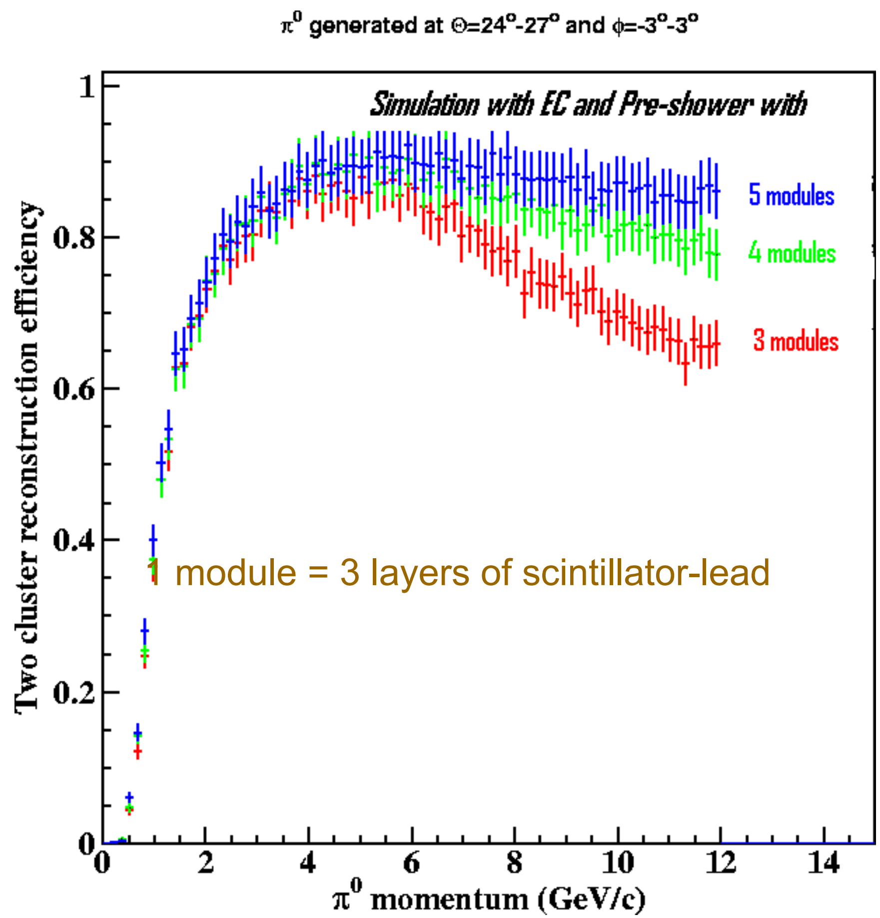


Efficiency of two photon cluster reconstruction from high energy p0' gg decays

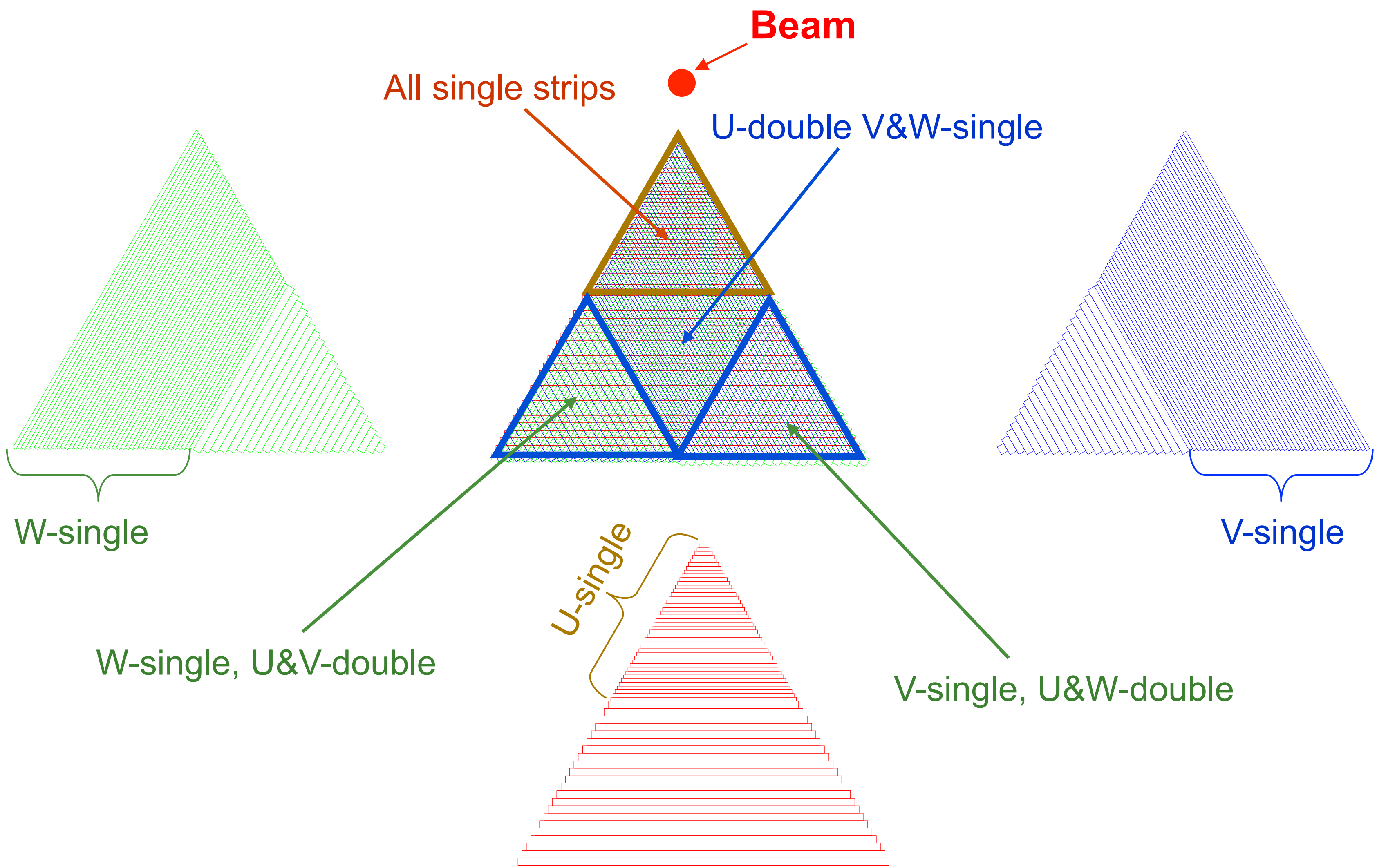


Configurations with 9, 12, and 15 layers

- p^{0} reconstruction efficiency decreases at high energies for 12 and 9 layer modules
  - not enough radiator thickness and some of high energy photons do not convert
- 12 layers configuration with first 3 layers of lead with double thickness had comparable efficiency but ~10% worse energy resolution



Readout with variable segmentation



Configurations with 9, 12, and 15 layers

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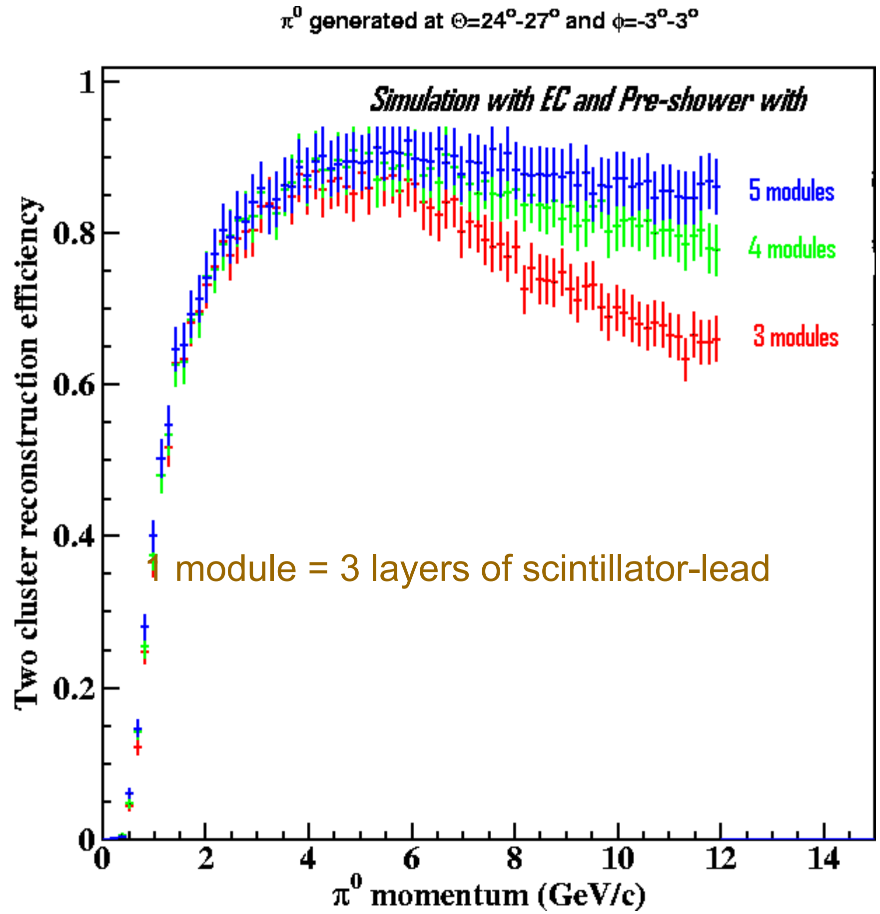
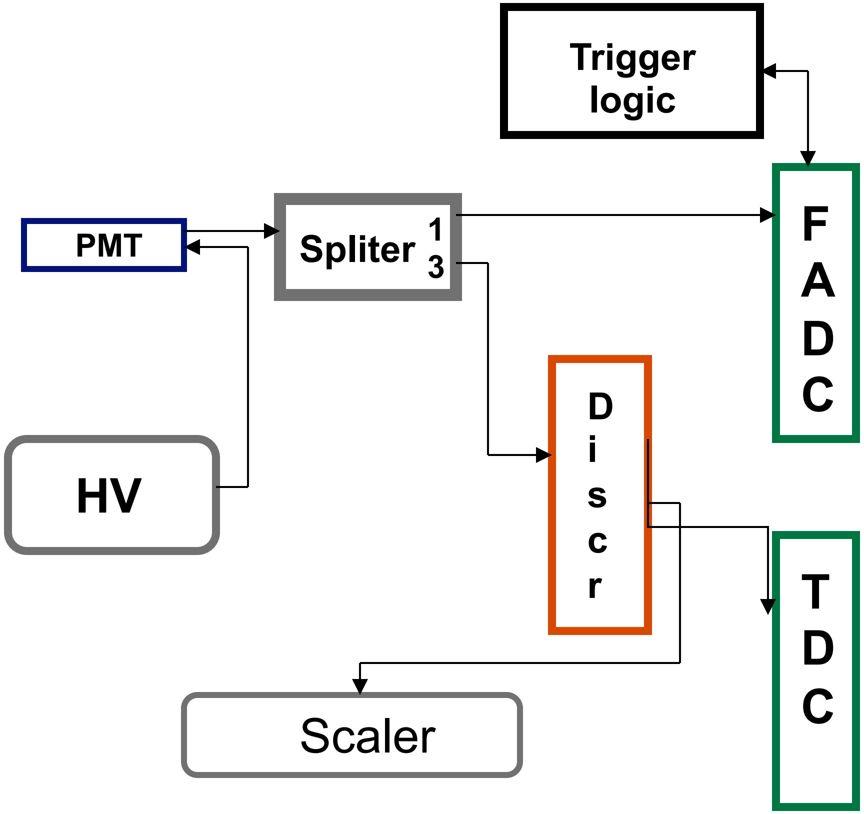


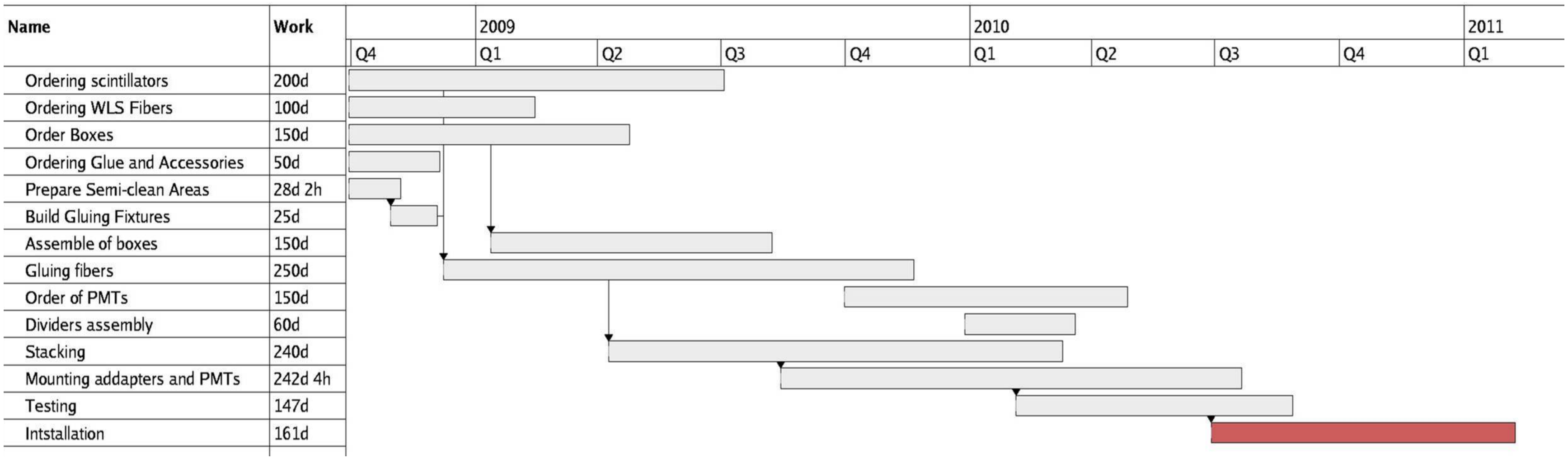
Signal readout and electronics

- Each PMT will be furnished with HV power supply, ADC, TDC, and scaler channel
- Anode signal of the PMT will be split with 1:3 split
- PCAL response will be measured in FADC (25% of the signal)
- Time of the signal will be measure in multi-hit TDC
- Fast readout of FADC will be used in the trigger logic - FPGA programming in the mainframe controller



Details will be discussed in C. Cuevas's presentation

Construction Schedule



Requires three, air conditioned, semi-clean stations (rooms): fiber gluing, stacking, and assembly of PMTs

Air conditioned area is needed for the final tests

PCAL Construction: cost and manpower

Pre-shower		Procurement	Labor (man-weeks)									
			Technicians		Engineers		Designers		Scientists			
Sub-tasks	Amount	Costs (k$)	MT	ET	ME	EE	MD	ED	VU	S	US	Comm.
Box and accessories	6	300	2		2		2			2		CLAS
Scintilaltor strips	14000m	135					2			2		FNAL
WLS fibers	45000m	86								1		KURARAY
PMTs	1152	185								1		HAMAMATSU
PMT housing	1152	35			2		2			2		Ameri.Plast
μ-metal mag. shield	1152	18								1		AD-VANCE MAG
Fiber-PMT adapters	1152	6								1		YerPhI
Dividers with connectors	1152	24.8	2	15		1		1		1	4	JLAB
Lead sheets	90	50	4									CLAS
Accessories	1	30								1		
HV cables	1152	45		1								Catalog
Signal cables	1152	30										Catalog
Spliters	1152	27										UVA
Cables for electronics	1152	42										Catalog
Gluing of fibers	42000m		4		1				54	4	54	3 days/layer
Assembly of boxes	6		12		2		1			1		2 weeks/box
Stacking scintillators	90		36		4				36	4	36	2 days/layer
Mounting PMTs	1152		12		1		2		36	6	36	2 weeks/side
Total		1013.8	72	16	12	1	9	1	126	27	130	