Fast Timing via Cerenkov Radiation

Earle Wilson,
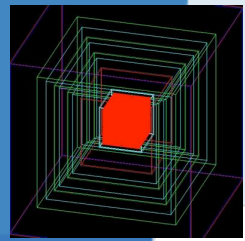
Advisor: Hans Wenzel

Fermilab

August 5, 2009

Project Report

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Why do we need fast timing?
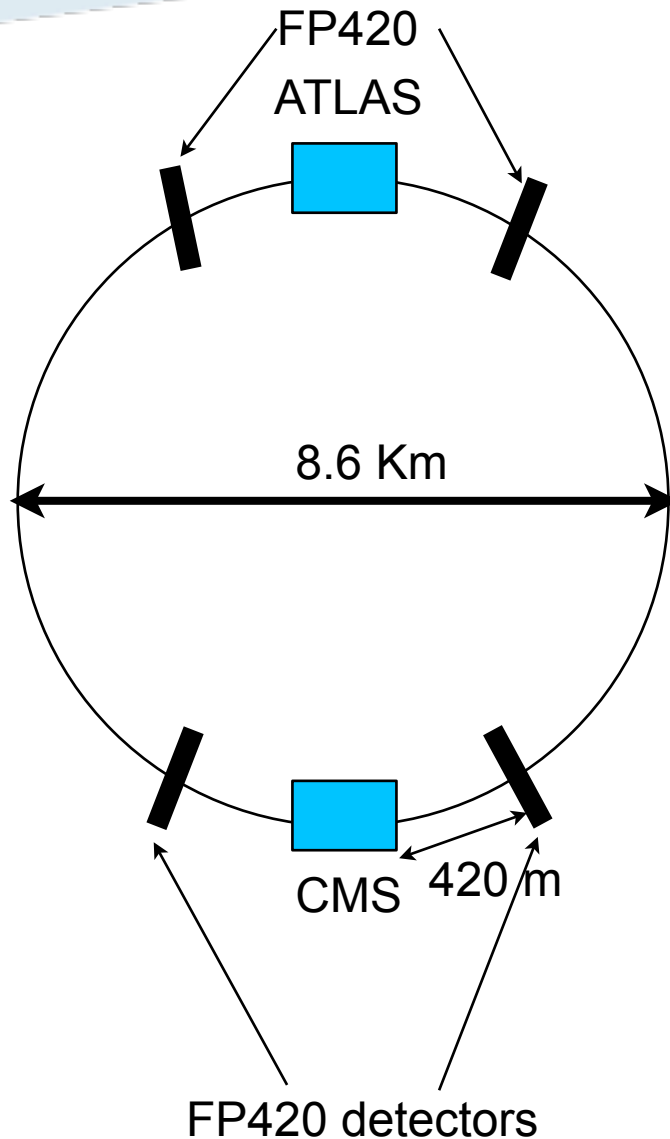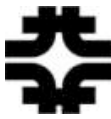
Fig. 1: Simple Layout of the LHC and proposed FP420 detectors

FP420
ATLAS
8.6 Km
420 m
CMS
FP420 detectors

To associate scattered protons with their point of interaction, **timing resolution on the order of picoseconds will be needed.**
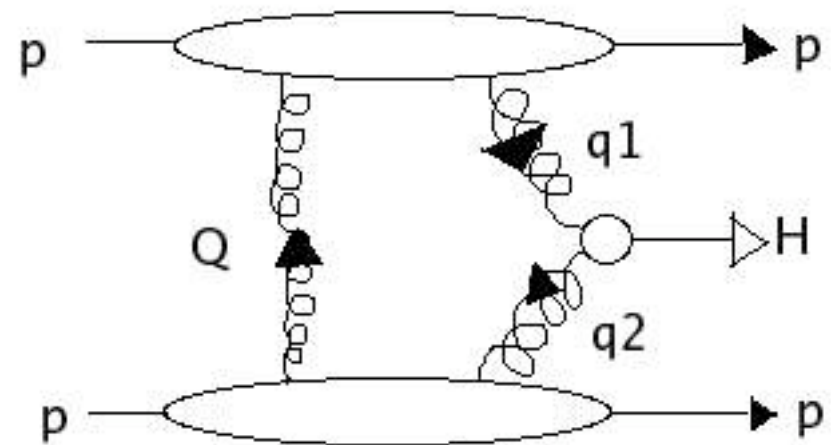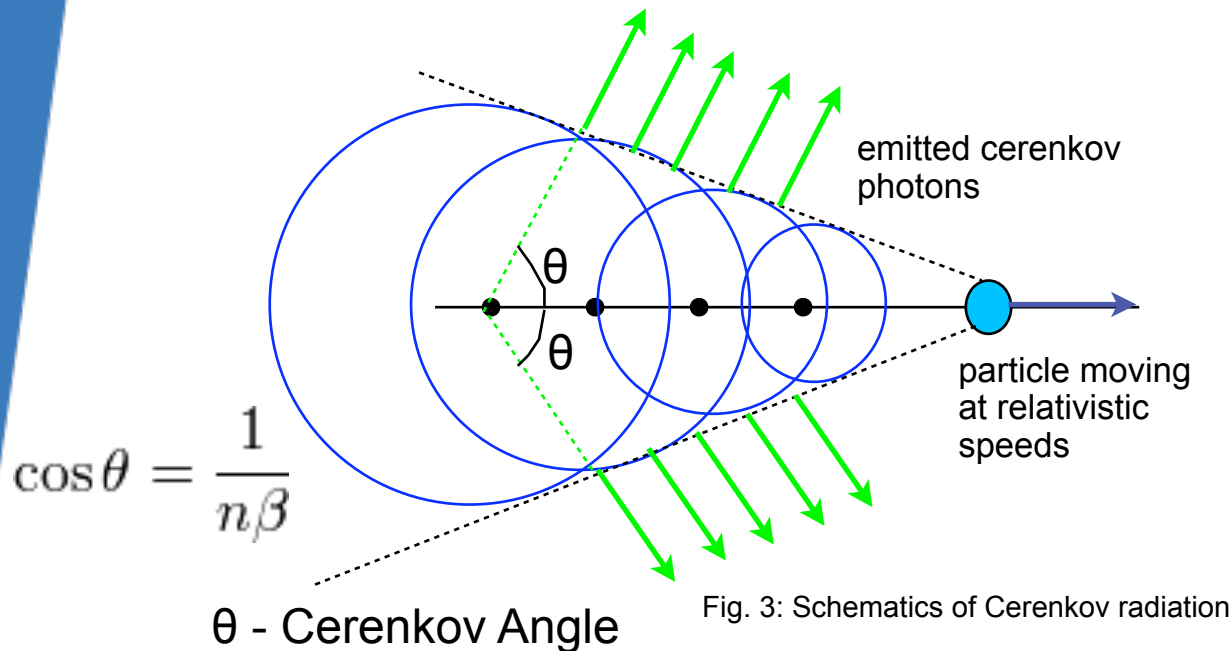

Fig. 2: Central Exclusive Production (CEP): $pp \rightarrow p + H + p$.

- The **FP420 R&D** promises to rich program of studies of the Higgs Boson, quantum chromodynamics, electroweak and beyond the Standard Model physics.

Why Cerenkov Radiation?

- Cerenkov radiation occurs when a charged particle traverses a dielectric medium at a speed greater than the **speed of light in that medium.**

Cerenkov radiation emits mostly blue light in the visible spectrum

emitted cerenkov photons

$$\cos\theta = \frac{1}{n\beta}$$

particle moving at relativistic speeds

θ - Cerenkov Angle

Fig. 3: Schematics of Cerenkov radiation
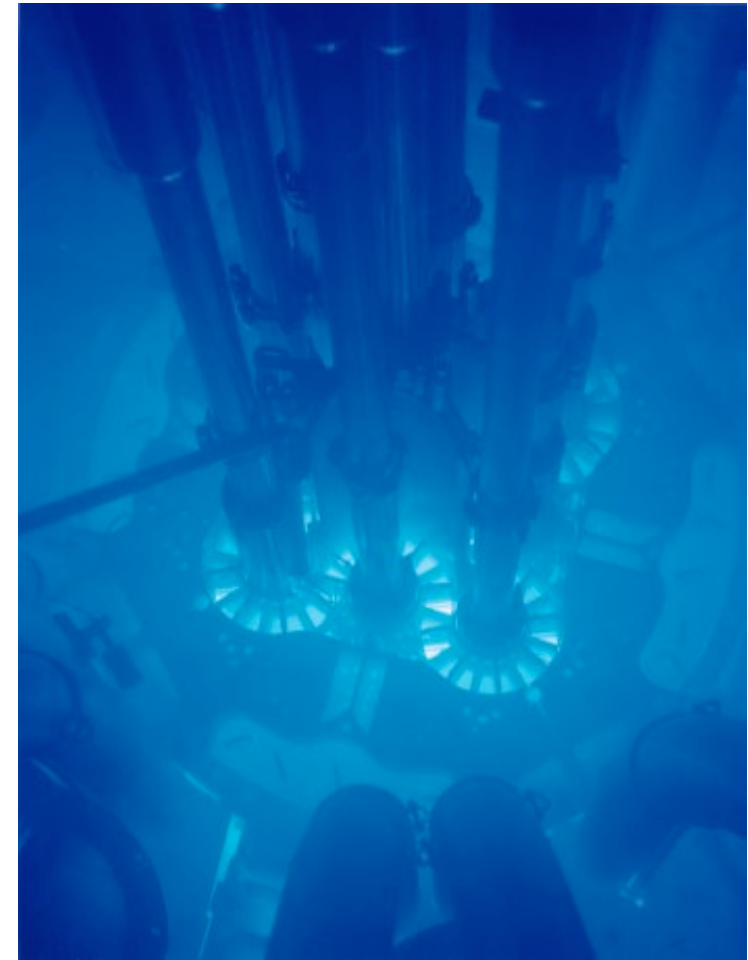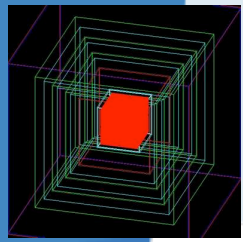

Fig. 4: Blue Cerenkov light seen at a nuclear reactor.

Picture courtesy of Wikipedia: http://en.wikipedia.org/wiki/Cherenkov_radiation

Important properties of cerenkov radiation:
- Cerenkov Light is **prompt.**
- Cerenkov light is emitted at a given angle for given refractive index.

Project Objective: Conduct simulation studies to explore the possibility of using quartz and aerogel to make detectors capable of picosecond timing.

Toolbox

- Geant4: A C++ based Monte Carlo simulation software that simulates the passage of particles through matter. Simulates processes inside radiator, i.e. Quartz bar and Aerogel. Includes:
  - Electro-magnetic physics
  - Cerenkov radiation
  - Rayleigh Scattering (only for Aerogel)
  - Absorption
  - Dispersion (only for Quartz)
  - Reflection, refraction etc...
    - Outputs ROOT file for analysis
- ROOT: A C++ based analysis software. Simulates detector response:
  - Quantum Efficiency
  - Light Collection Efficiency
  - Time transit spread
    - Outputs ROOT file for analysis.

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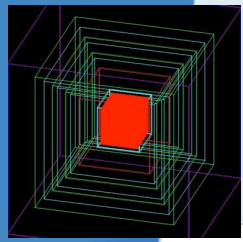
Quartz Bar Geometry and Set-up

Fig. 5: Layout of quart bar simulation
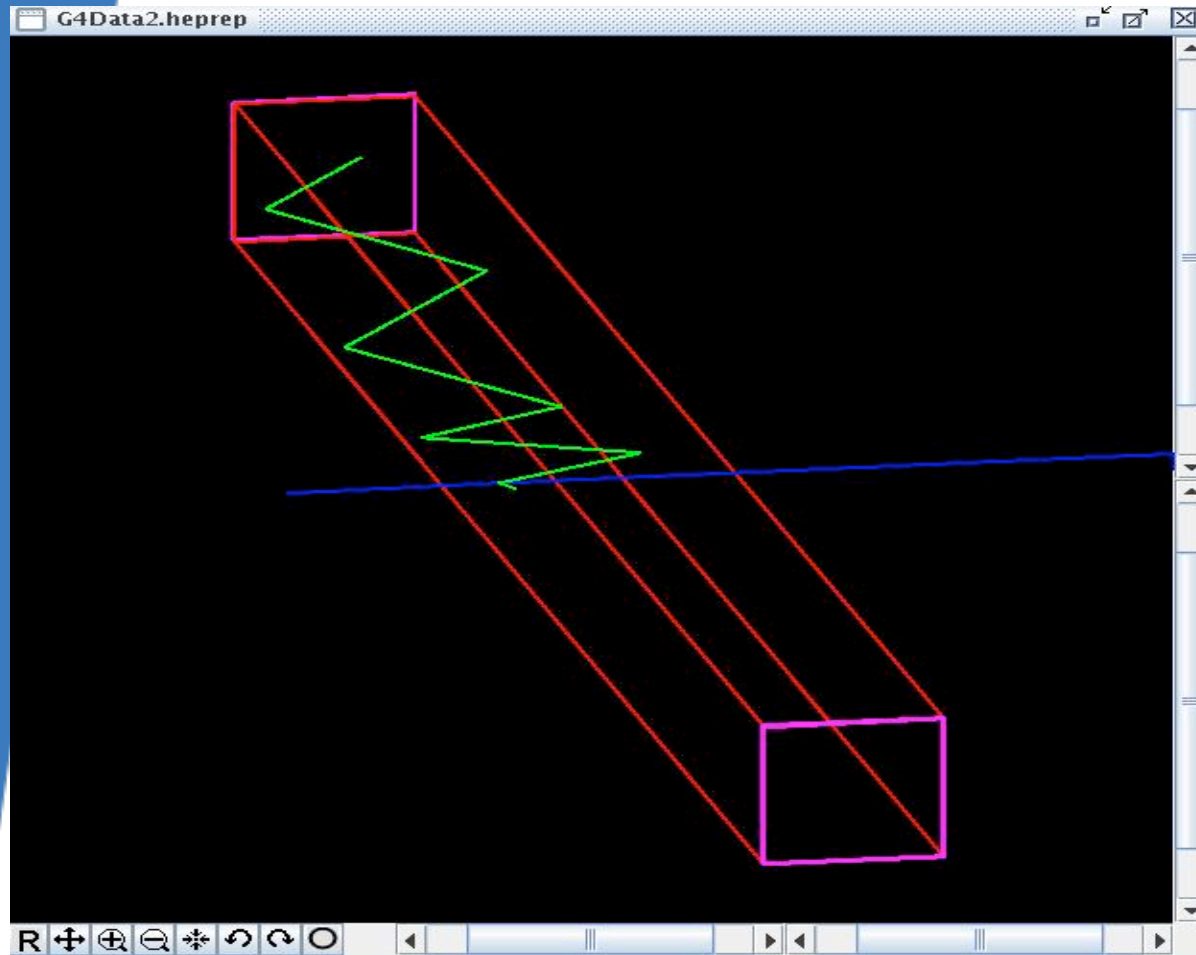
-Quartz bar:
6x6 mm x 9cm.

-6X6 mm sensitive detectors on each end.
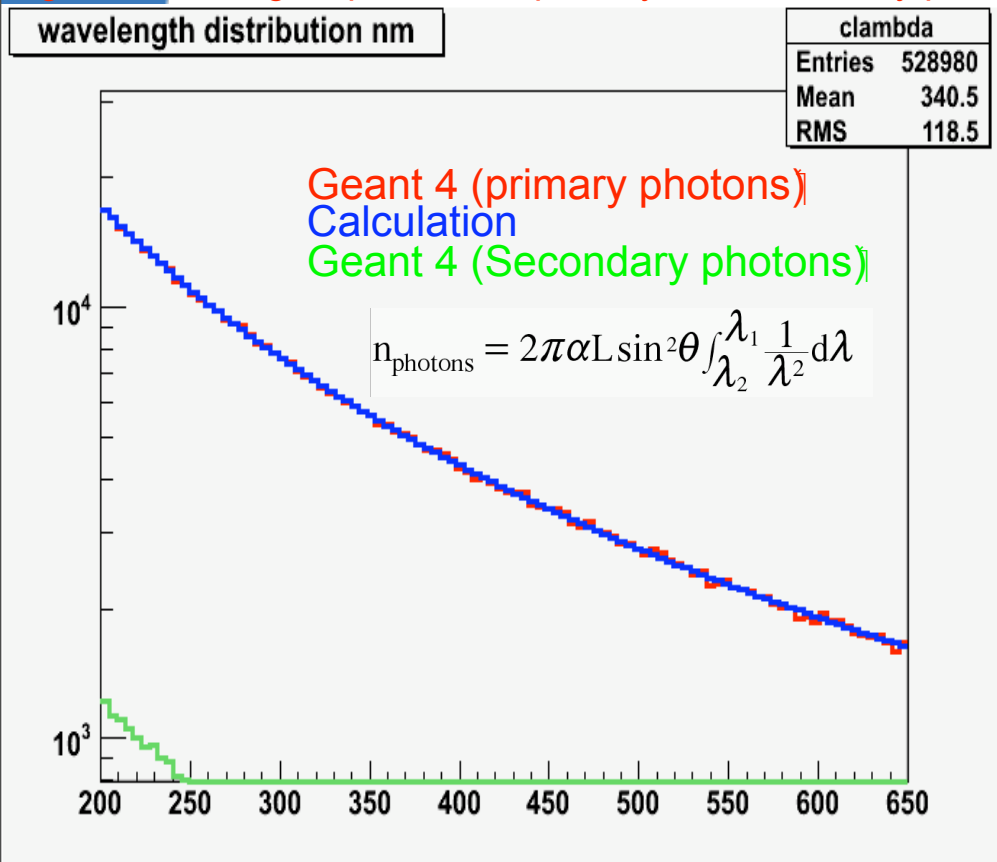
-Incident beam of 7TeV protons perpendicular to bar.

-Only Cerenkov radiation. Scintillation, and rayleigh scattering were not added. Dispersion was not added initially.
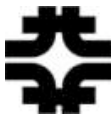
Photon Spectrum/Statistics

Fig. 6: Wavelength spectrum of primary and secondary photons.

wavelength distribution nm

clambda	
Entries	528980
Mean	340.5
RMS	118.5

Geant 4 (primary photons)
Calculation
Geant 4 (Secondary photons)

$$n_{photons} = 2\pi\alpha L \sin^2\theta \int_{\lambda_2}^{\lambda_1} \frac{1}{\lambda^2} d\lambda$$

· **Primary Photon**: Cerenkov photon that originates directly from incident particle (proton).

· **Secondary Photon**: Cerenkov photon that originates from delta electrons.

· Secondary photons can potentially skew timing results by arriving at the detector before the primary photons.
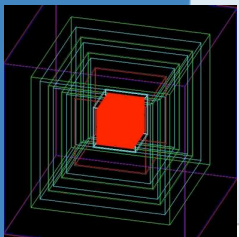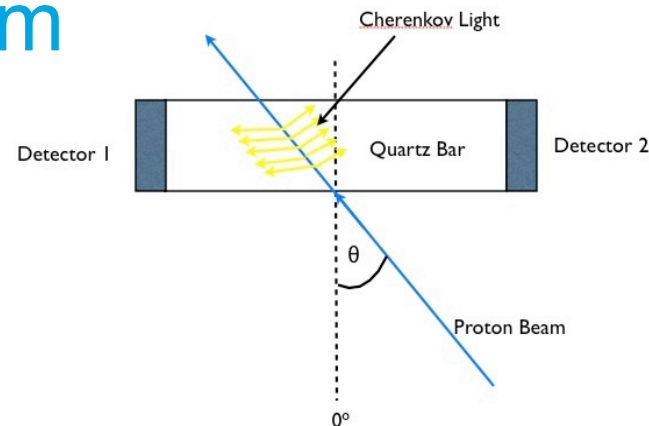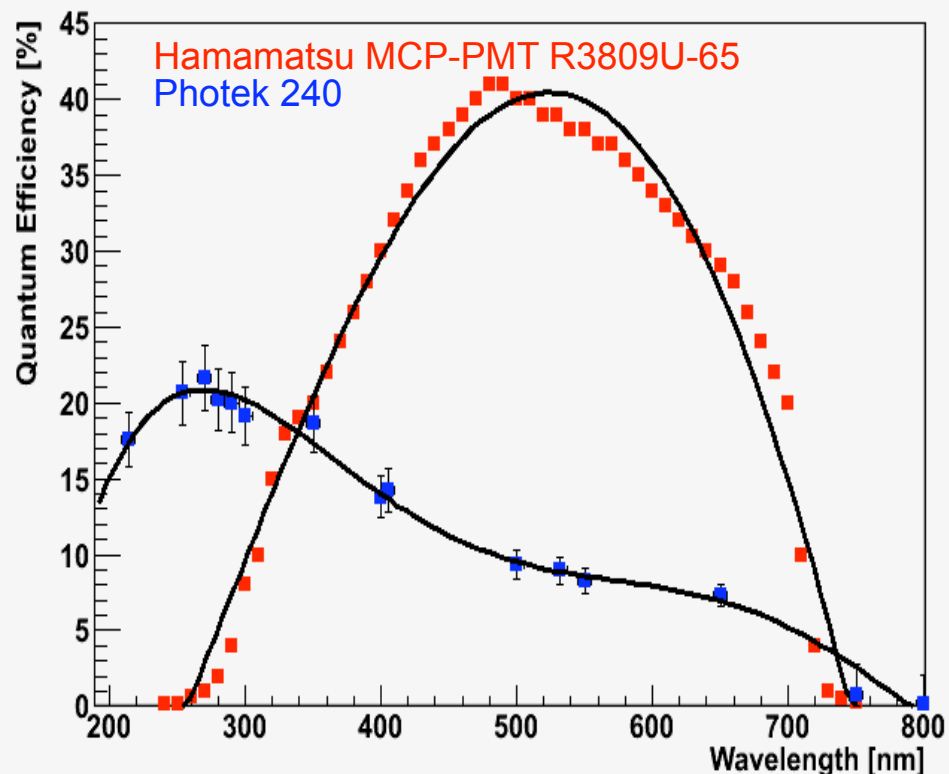
6

Photon Spectrum/Statistics

Fig. 6: Wavelength spectrum of primary and secondary photons. Fig. 7: Number of primary and secondary photons per event.

clambda	
Entries	528980
Mean	340.5
RMS	118.5

Geant 4 (primary photons)
Calculation
Geant 4 (Secondary photons)

$$n_{photons} = 2\pi\alpha L \sin^2\theta \int_{\lambda_2}^{\lambda_1} \frac{1}{\lambda^2} d\lambda$$

Nr_of_sphotons	
Entries	1000
Mean	66.84
RMS	197.3

Nr of secondary Cherenkov Phtons per event

Primary Photons
Secondary Photons

- **Primary Photon**: Cerenkov photon that originates directly from incident particle (proton).

- **Secondary Photon**: Cerenkov photon that originates from delta electrons.

- Secondary photons can potentially skew timing results by arriving at the detector before the primary photons.

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fig. 8: Quantum Efficiency of Photek and Hamamatsu vs. wavelength

A graph Showing Quantum Eff vs. Wavelength

Hamamatsu MCP-PMT R3809U-65
Photek 240

Cherenkov Light

Detector 1   Quartz Bar   Detector 2

θ

Proton Beam

0°

-Time transit spread: 30 psec
-Gain: 100
-Cerenkov angle: 48.2

fig. 8: Quantum Efficiency of Photek and Hamamatsu vs. wavelength

A graph Showing Quantum Eff vs. Wavelength

Hamamatsu MCP-PMT R3809U-65
Photek 240

Cherenkov Light
Detector 1   Quartz Bar   Detector 2
θ
Proton Beam
0°

Fig. 10: Number of photoelectrons vs. incident angle

A graph Showing Average Number of photoelectrons vs. Incident angle
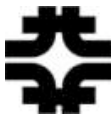
Photoelectrons: Photek 240
Photoelectrons: Hamamatsu MCP-PMT R3809U-65

Cerenkov Angle: ~48°

-Time transit spread: 30 psec
-Gain: 100
-Cerenkov angle: 48.2

7
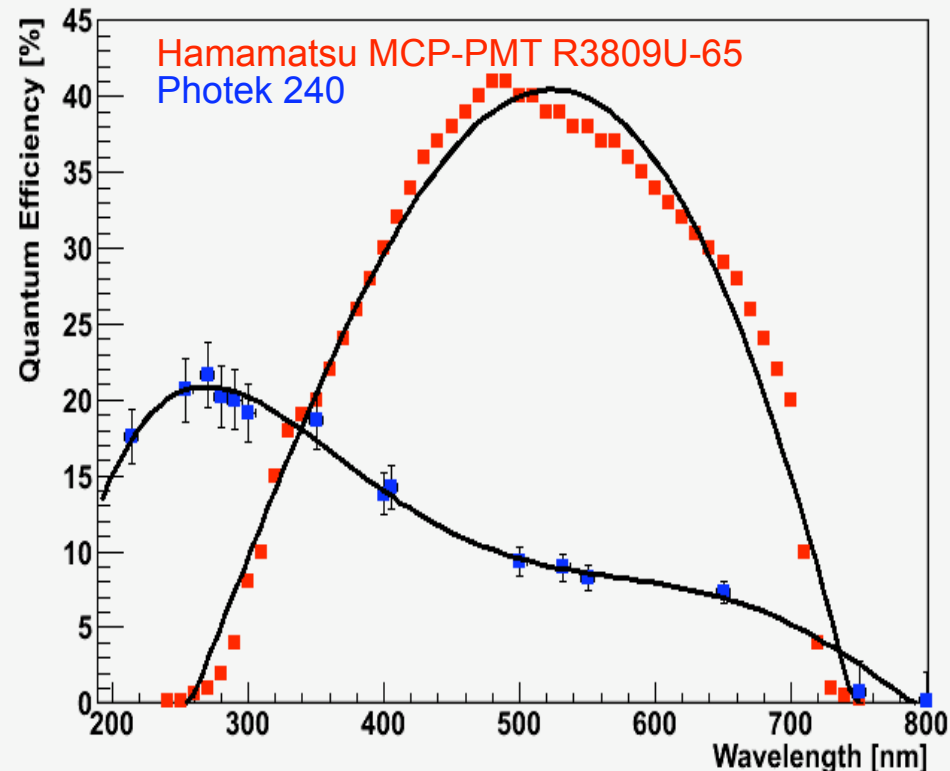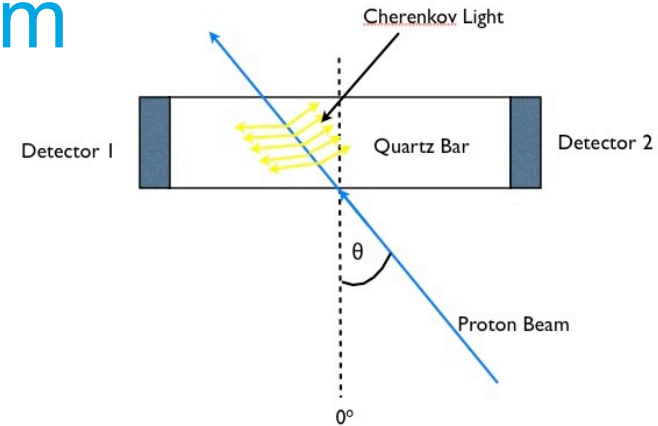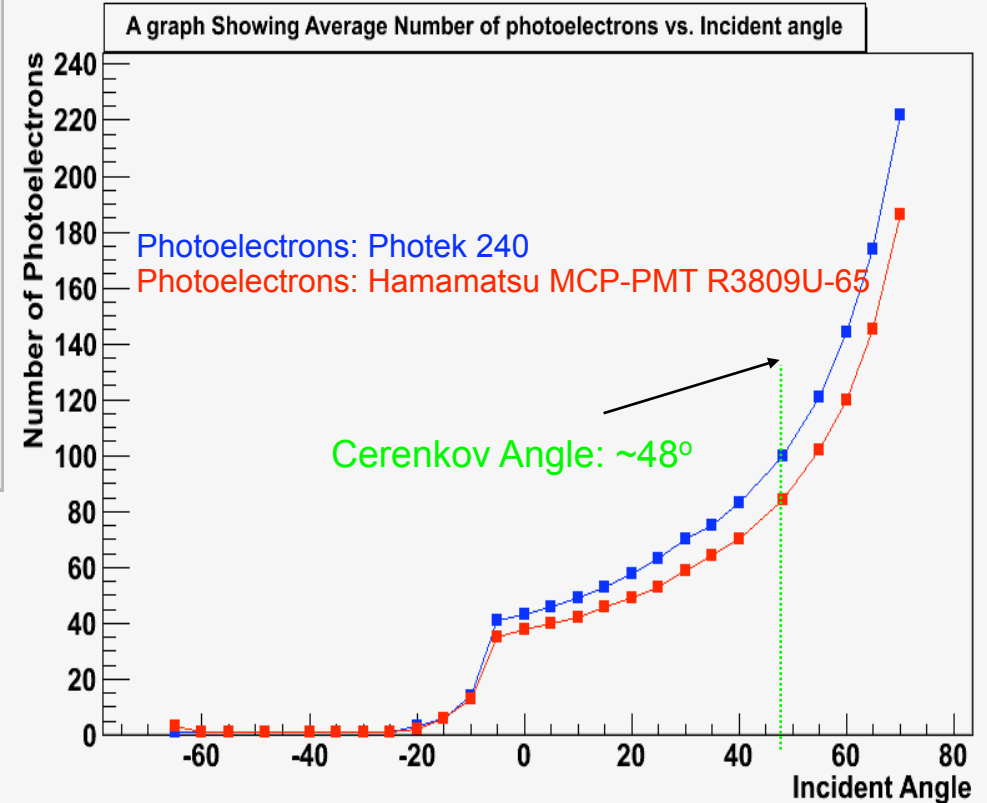
The Differentiated Center of Gravity Method (DCOG)

Fig. 11: Arrival time of electrons
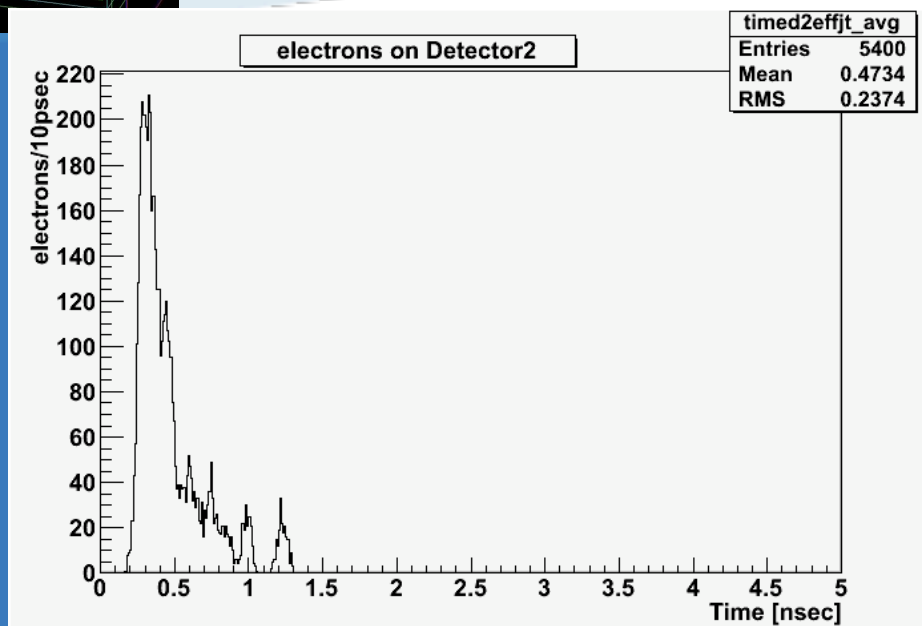
Fig: 12: Arrival Pulse Differentiated
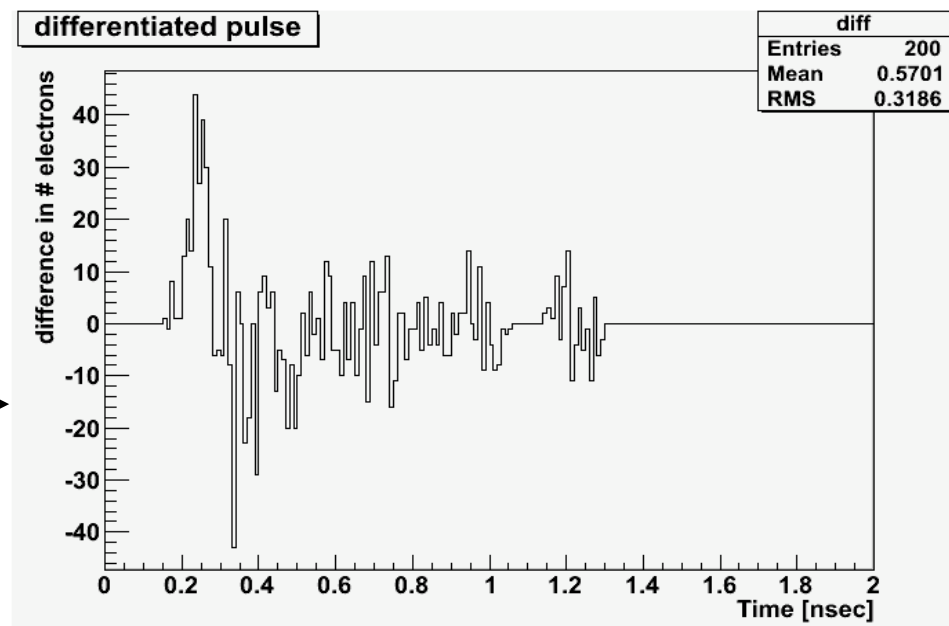
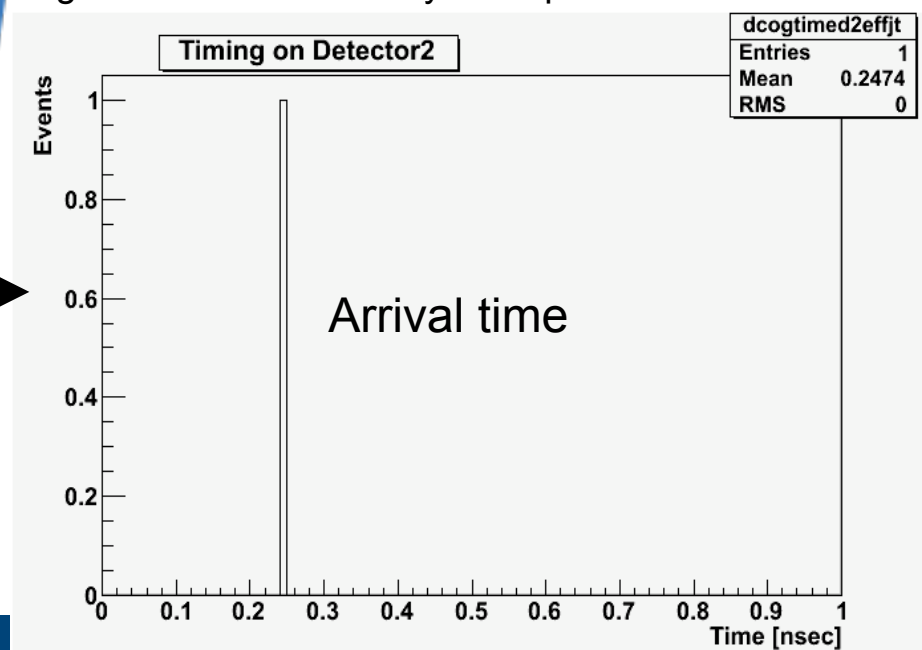Fig. 13: Center of Gravity of 1st peak in Diff. Arrival Pulse
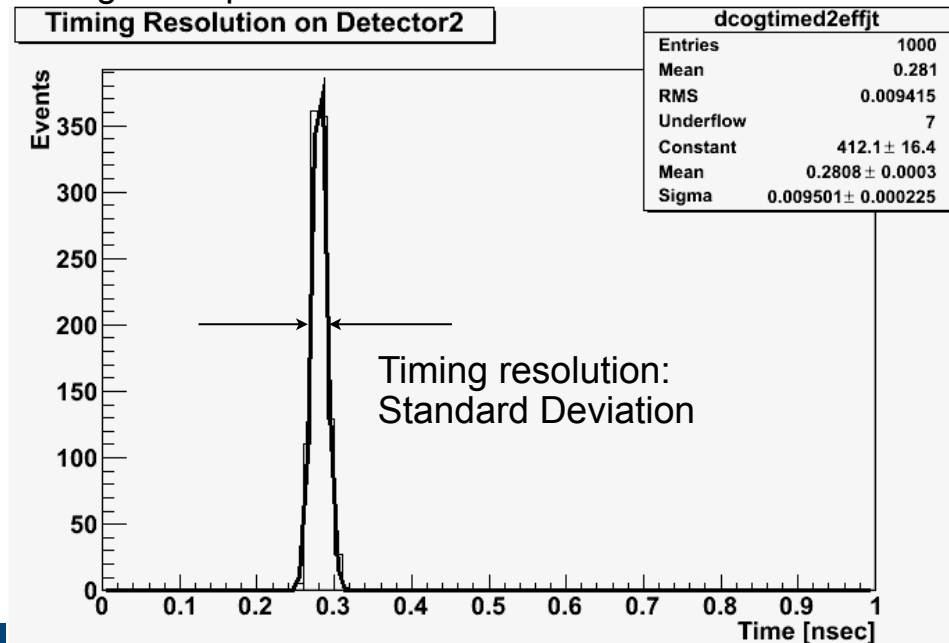

Fig. 14: Spread of arrival time for a 1000 events

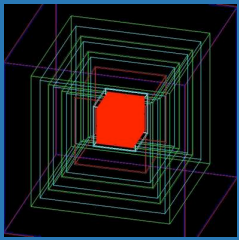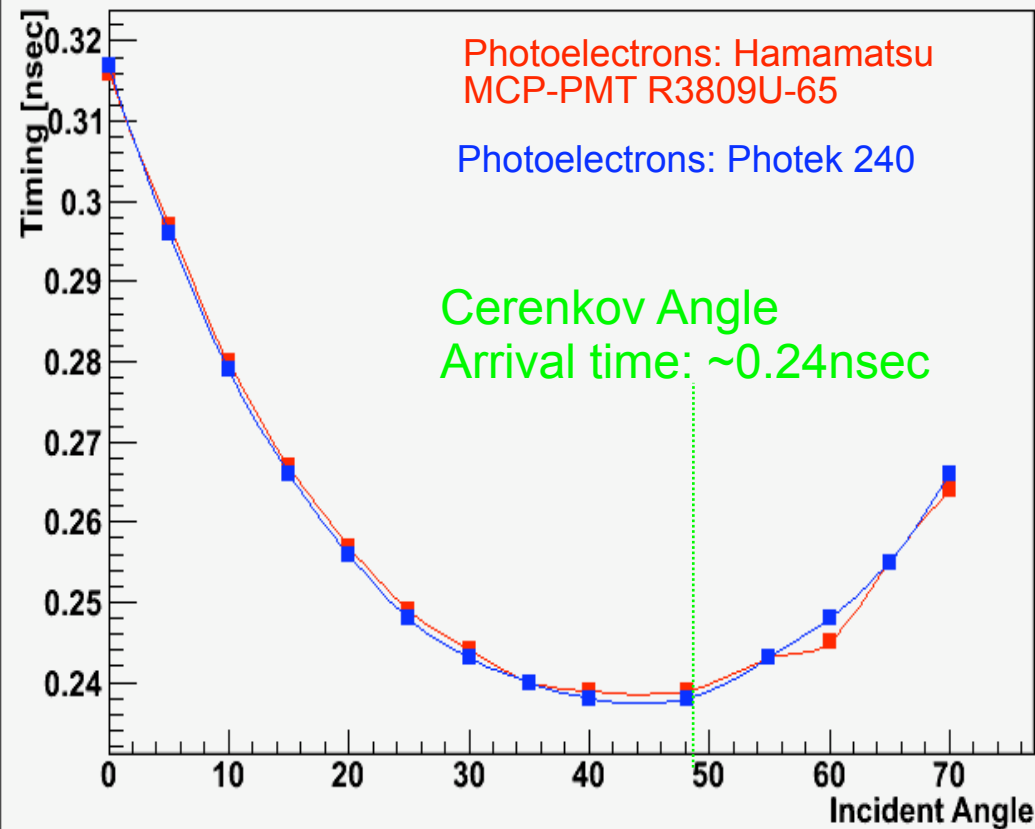# Arrival Time and Timing-Resolution vs. Angle Incident Beam

Fig. 15: Arrival Time vs. incident angle
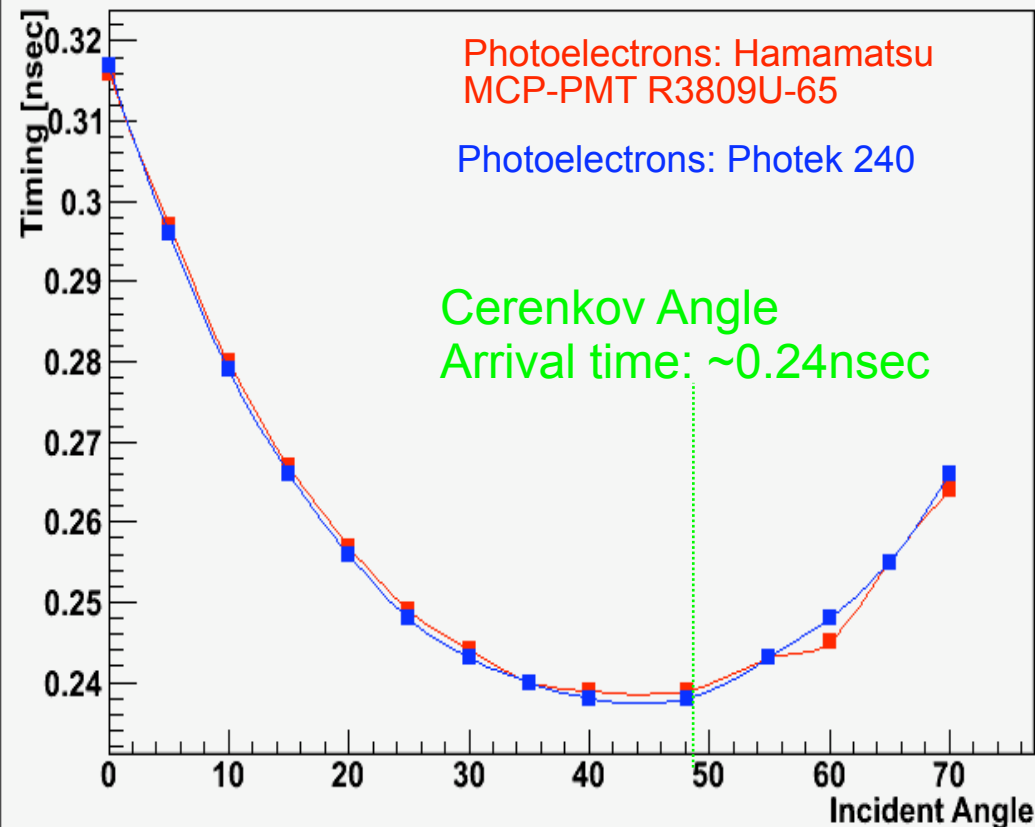

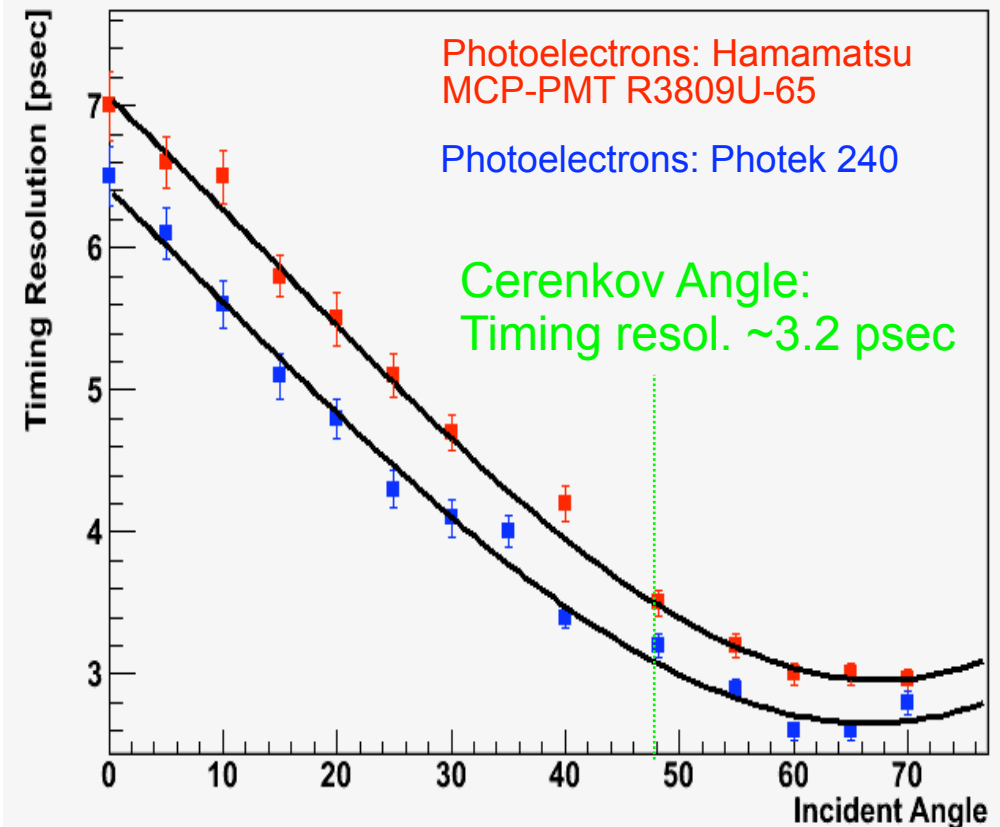A graph Showing Average Timing vs. Incident angle

Photoelectrons: Hamamatsu MCP-PMT R3809U-65

Photoelectrons: Photek 240

Cerenkov Angle
Arrival time: ~0.24nsec

-Timing and timing resolution obtained using DCOG Method
-Cerenkov Angle: 48.2
-Time Transition Spread: 30 psec, Gain: 100
-Each data point is taken over 1000 events.
-**Best timing resolution of ~2.8 psec at 65 degrees.**

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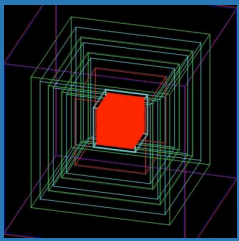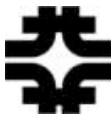# Arrival Time and Timing-Resolution vs. Angle Incident Beam

Fig. 15: Arrival Time vs. incident angle
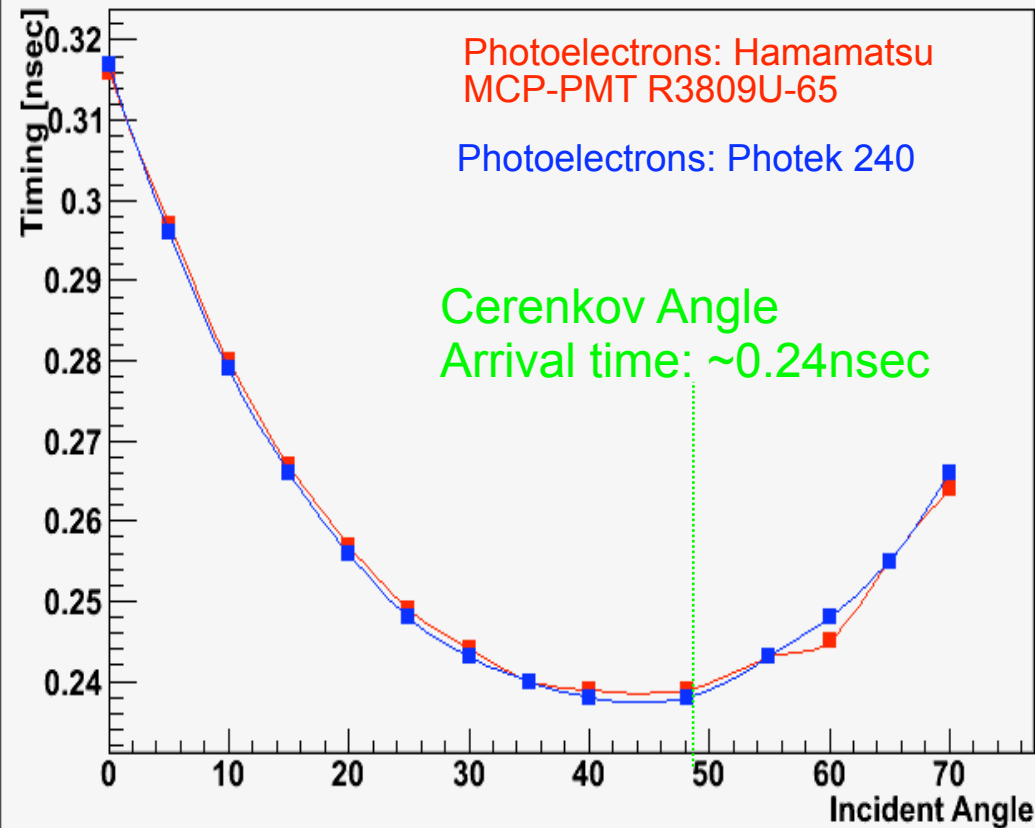
Fig. 16:Timing resolution versus incident angle

A graph Showing Average Timing vs. Incident angle

Photoelectrons: Hamamatsu MCP-PMT R3809U-65

Photoelectrons: Photek 240

Cerenkov Angle
Arrival time: ~0.24nsec

A graph Showing Average Timing Resolution vs. Incident angle

Photoelectrons: Hamamatsu MCP-PMT R3809U-65

Photoelectrons: Photek 240

Cerenkov Angle:
Timing resol. ~3.2 psec

-Timing and timing resolution obtained using DCOG Method
-Cerenkov Angle: 48.2
-Time Transition Spread: 30 psec, Gain: 100
-Each data point is taken over 1000 events.
-**Best timing resolution of ~2.8 psec at 65 degrees.**

9

Fig. 15: Arrival Time vs. incident angle

Fig. 16:Timing resolution versus incident angle

A graph Showing Average Timing vs. Incident angle

Photoelectrons: Hamamatsu MCP-PMT R3809U-65

Photoelectrons: Photek 240

Cerenkov Angle
Arrival time: ~0.24nsec

A graph Showing Average Timing Resolution vs. Incident angle

Photoelectrons: Hamamatsu MCP-PMT R3809U-65

Photoelectrons: Photek 240

Cerenkov Angle:
Timing resol. ~3.2 psec

-Timing and timing resolution obtained using DCOG Method
-Cerenkov Angle: 48.2
-Time Transition Spread: 30 psec, Gain: 100
-Each data point is taken over 1000 events.
-**Best timing resolution of ~2.8 psec at 65 degrees.**

n = 1.5
NO DISPERSION!
100% Light Collection efficiency!
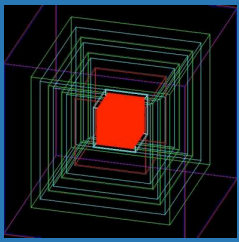
9
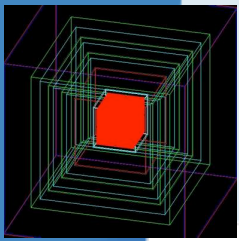
Timing Resolution (Revised)

Fig. 17: Timing resolution Without Dispersion and 100% LCE

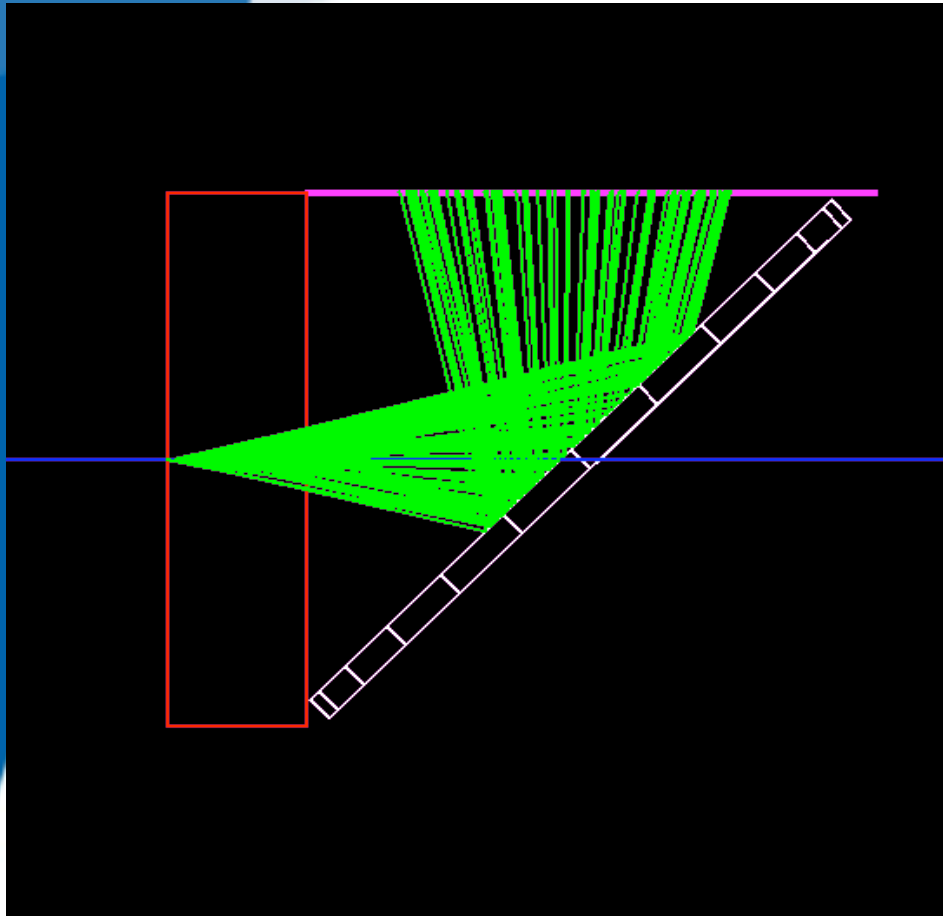Fig. 18: Timing Res. With Dispersion and 60% LCE
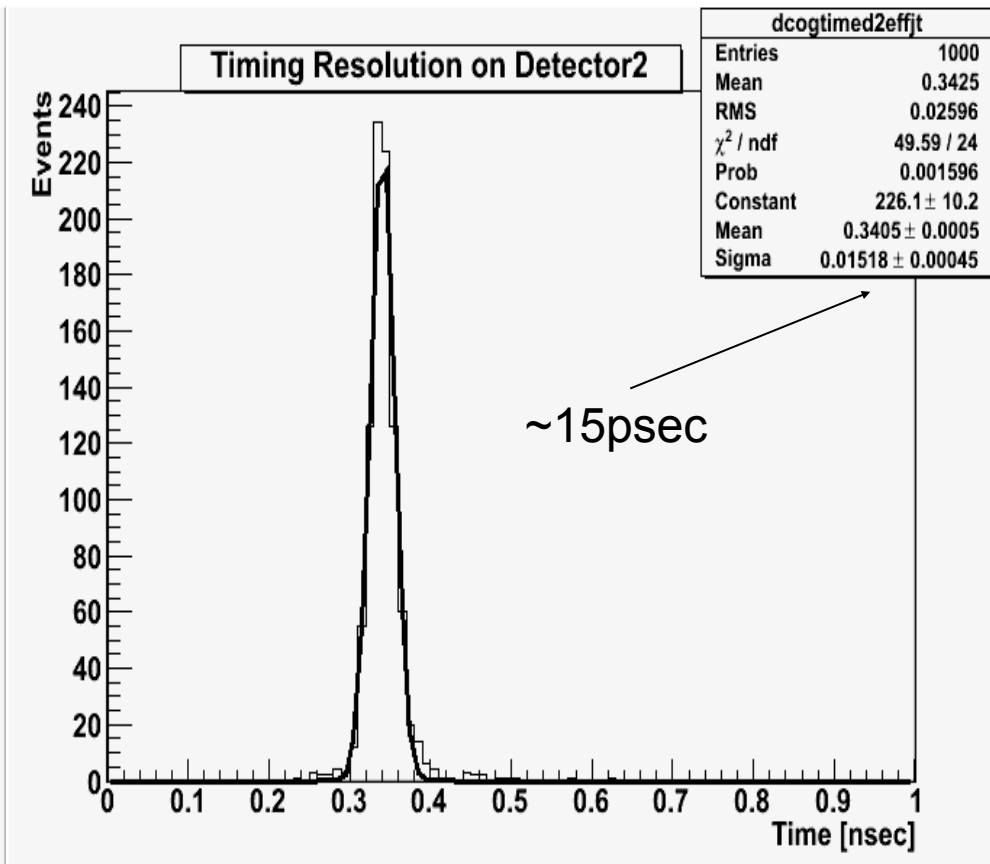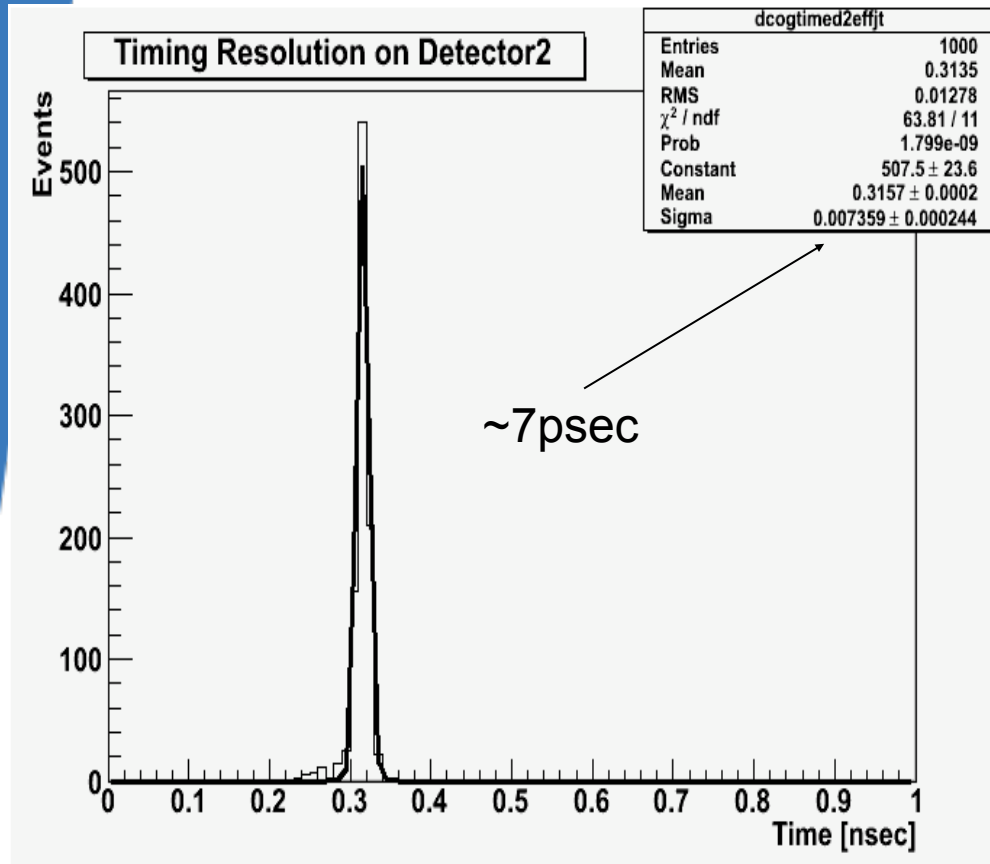
- LCE: Light Collection Efficiency
- Timing and timing resolution obtained using DCOG Method
- Cerenkov Angle: 48.2
- Time Transition Spread: 30 psec, Gain: 100
- Each data point is taken over 1000 events.

Simulation of the Aerogel Counter

Fig. 20: Aerogel Simulation Set-up

Refractive Index: 1.0306

Aerogel (SiO_2)Dimensions:
4cm X 4cm X 1.1cm

Detector Dimensions (Photek):
dia. 4.1cm

Plane Elliptic Mirror:
radx: 3.8cm
rady: 5.3cm

Mirror Tilt: 45 degrees

Optical path length from aerogel surface to detector: 4.0 cm

Incident protons @ 200GeV

Material Properties of Aerogel
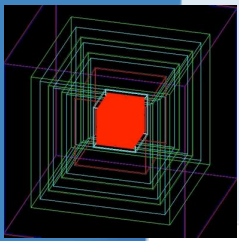
Fig. 21: Scatter length (cm) vs. Wavelength for Aerogel
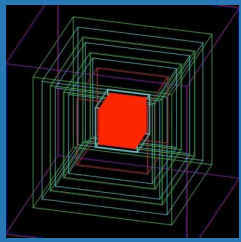
photo of Aerogel block

Scatterlength (cm) vs Wavelength
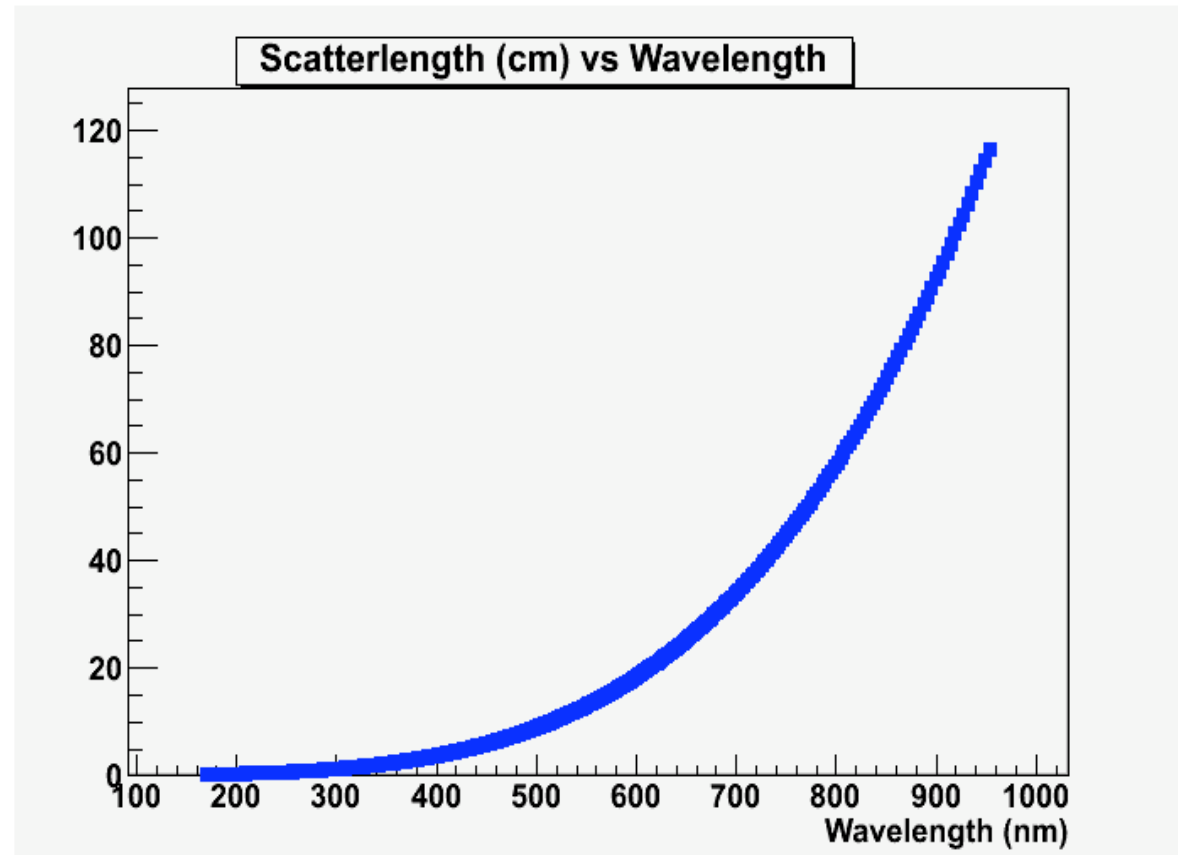
Refractive Index: 1.0306 (Lowest of any known solid)
Density: ~0.2 g/cm^3
Negligible dispersion.
Absorption length: ~62 cm

Values obtained from a Geant4 example for
Rich Detector simulation for LHCb: http://www-geant4.kek.jp/lxr/source/examples/advanced/Rich/

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Photon Hits at Detector

Fig. 22: Photon Hits at Detector
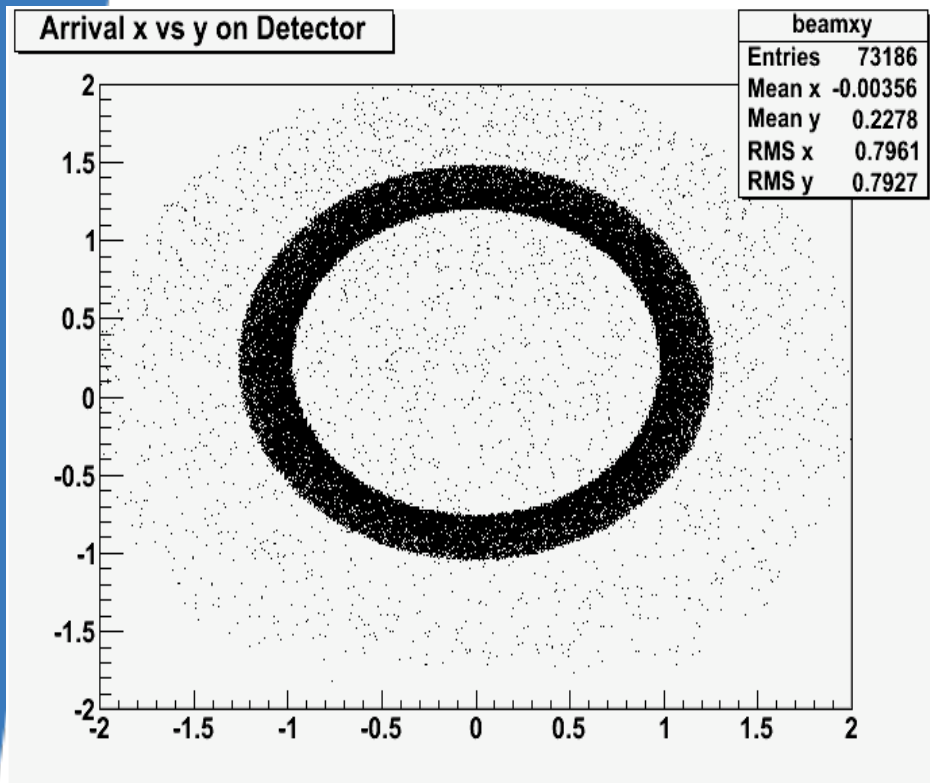
Fig. 23: Timing resolution for a 1.1cm Aerogel Tile
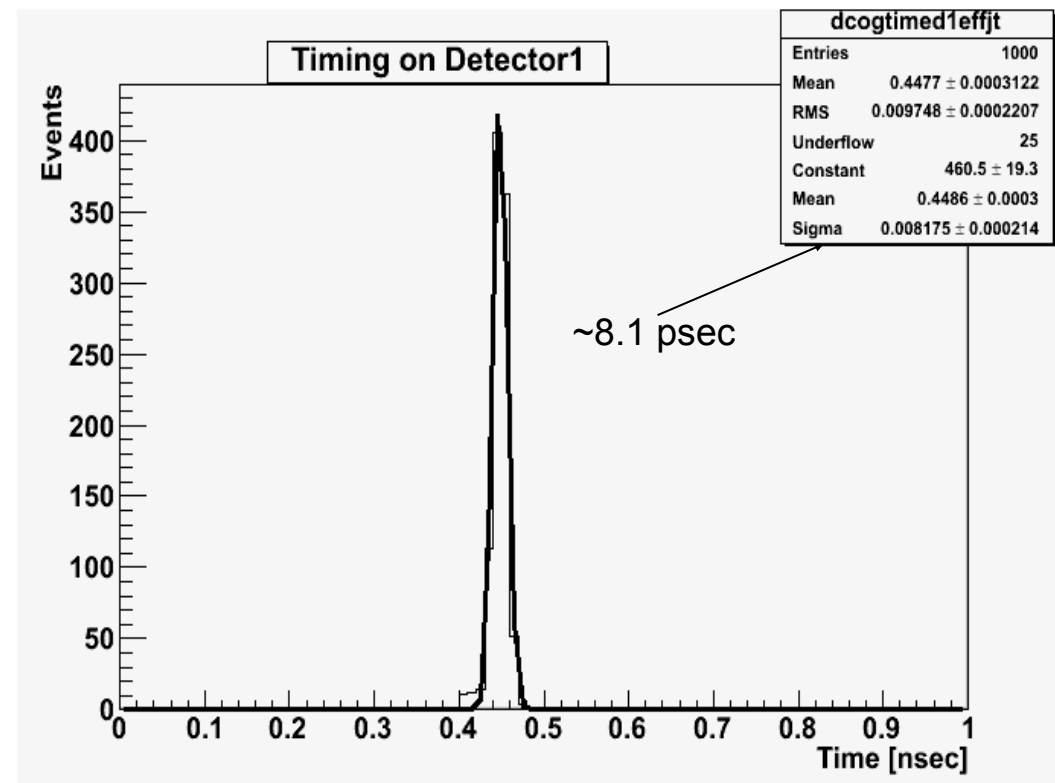
-1000 Events with Rayleigh Scattering
-1.1 cm Aeorgel Tile
-LCE 60%
-Timing res. obtained using DCOG method
-Timing res.: ~ 8.1 psec

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Increasing the number of 1.1cm Tiles
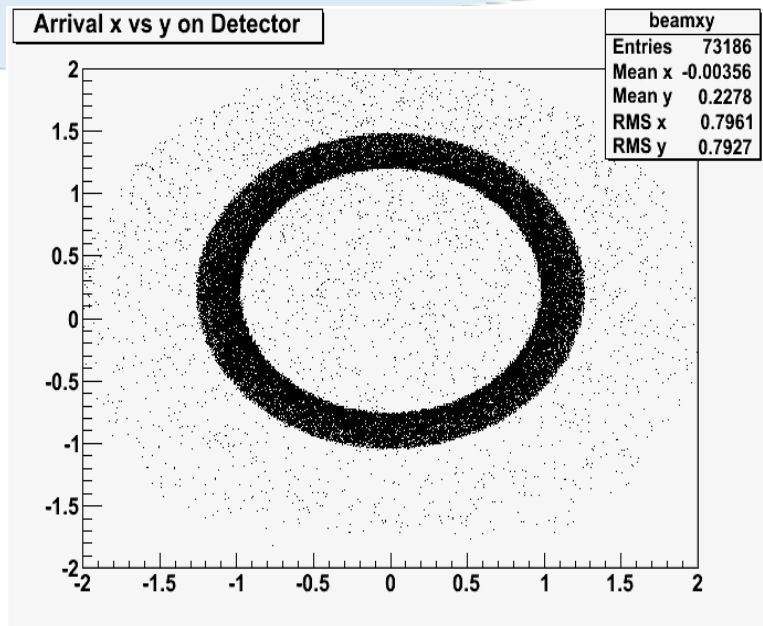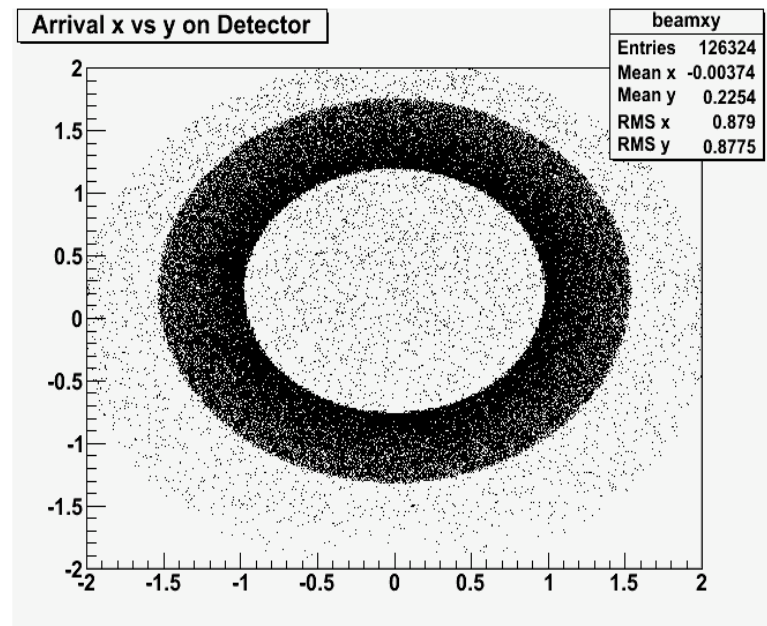
Fig. 24: Photon hits for 1 x 1.1cm Tile

Fig: 25: Photon hits 2 x 1.1cm Tile

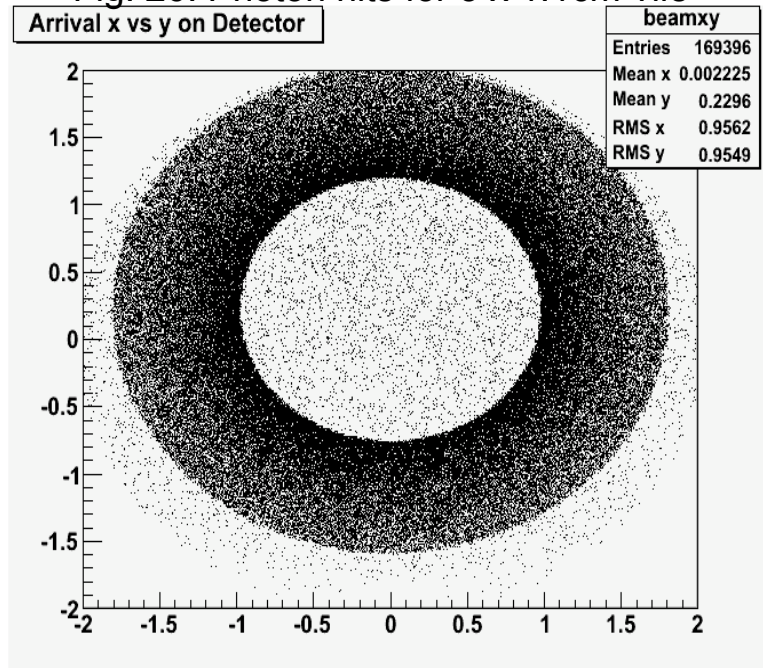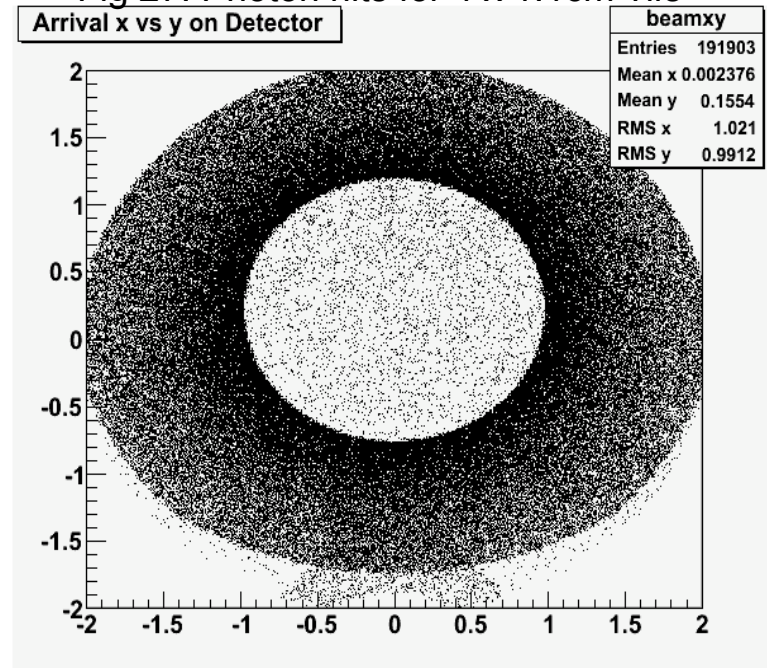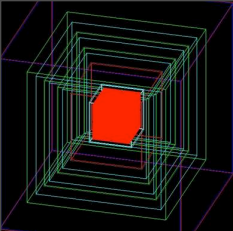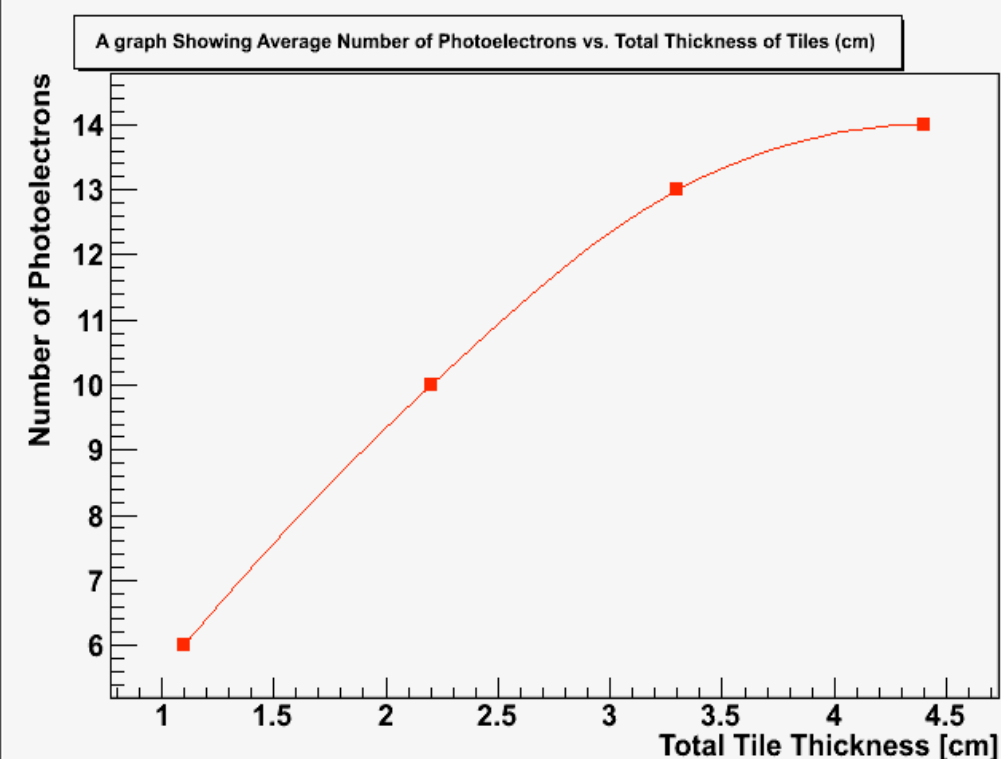Fig. 26: Photon hits for 3 x 1.1cm Tile

Fig 27: Photon hits for 4 x 1.1cm Tile

Varying the Number of 1.1 cm Tiles

Fig. 28: Number of Photoelectrons vs. Total Tile Thickness

Fig. 29: Timing Resolution vs. Total Tile Thickness

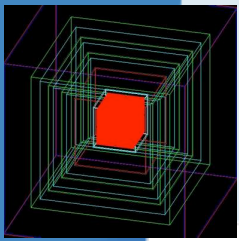
1000 Events with Rayleigh Scattering
Time Transition Spread: 30 psec
Gain: 100
Light Collection Efficiency (Photek): 60%
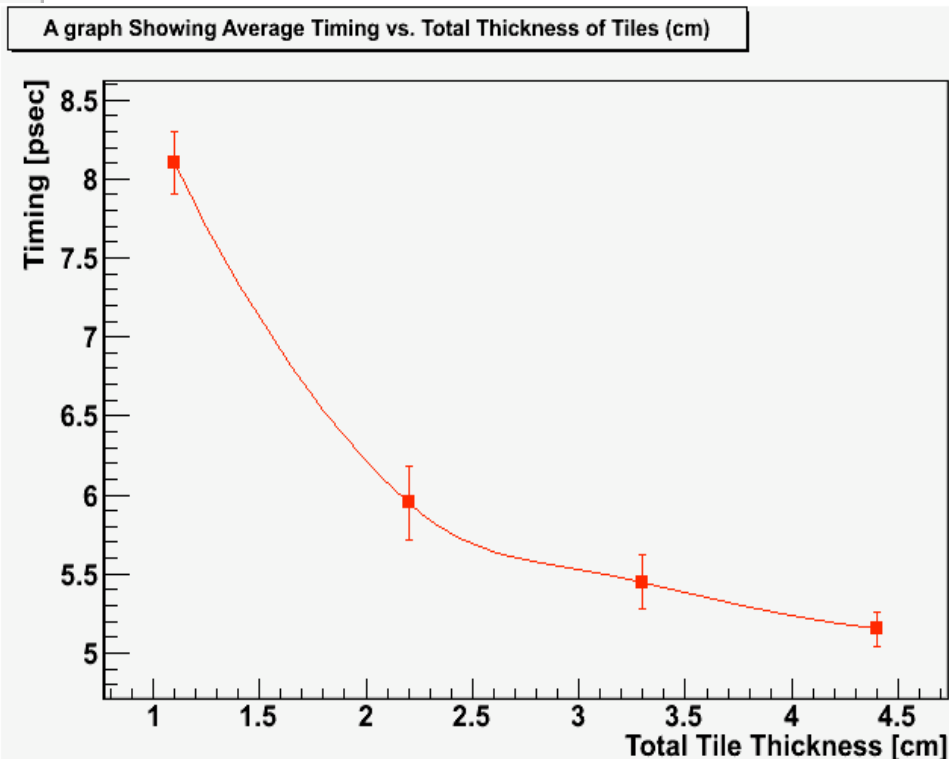
·Timing Resolution levels off
with increase in total tile
thickness.

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Effect of Rayleigh Scattering
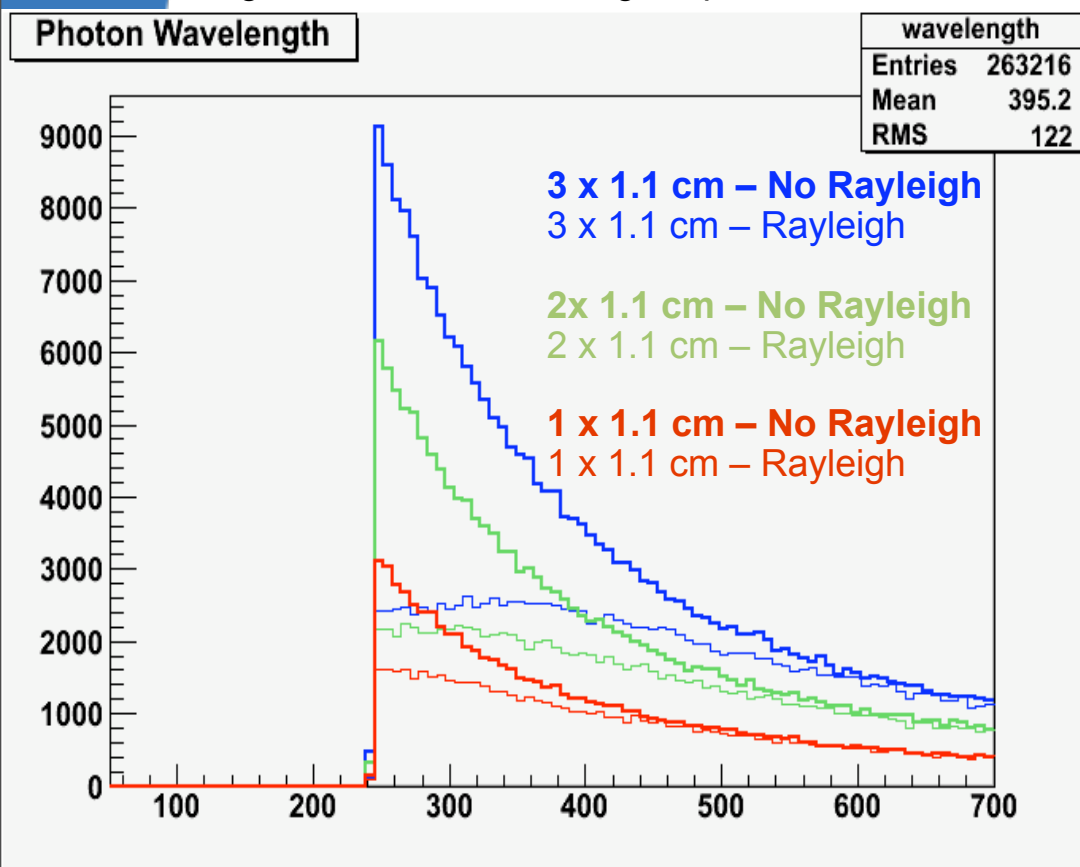
Fig. 30: Photon Wavelength Spectrum at Detector

Fig. 31: Efficiency Spectrum

Photon Wavelength

wavelength	
Entries	263216
Mean	395.2
RMS	122

3 x 1.1 cm – No Rayleigh
3 x 1.1 cm – Rayleigh

2x 1.1 cm – No Rayleigh
2 x 1.1 cm – Rayleigh

1 x 1.1 cm – No Rayleigh
1 x 1.1 cm – Rayleigh

Efficiency

wavelength		
Entries	169396	
Mean	508 ±	16.92
RMS	121.5 ±	11.96

1 x 1.1 cm
2 x 1.1 cm
3 x 1.1 cm

Fig. 17 compares wavelength spectrum of photons arriving at the detector for the cases of one, two and three 1.1 cm Aerogel tiles. The bold lines represent the simulated wavelength spectrum in the case of no Rayleigh Scattering and the thin lines represent the spectrum with Rayleigh Scattering.
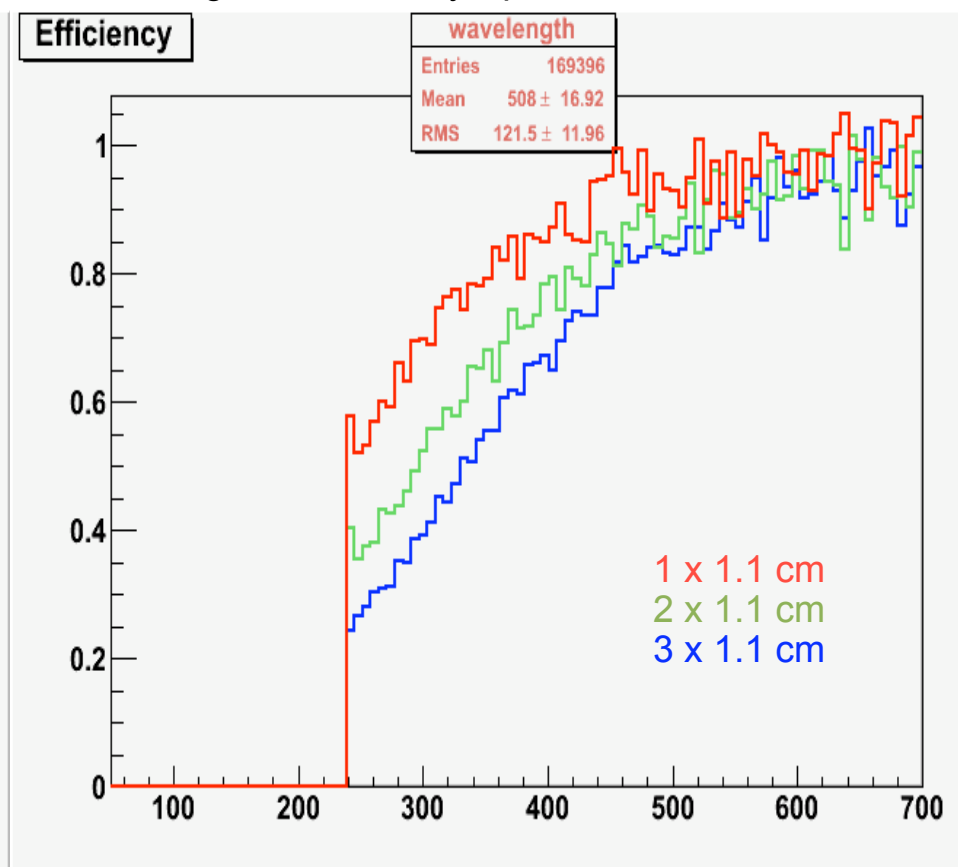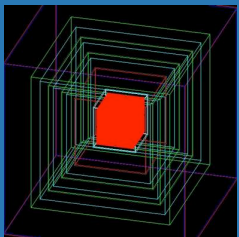
Fig. 18 represents the wavelength spectrum of the proportion of photons that reaches the detector after Rayleigh Scattering.

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Future Work

- Compare DCOG with other methods of obtaining timing resolution.
- Add blue filter in quartz bar simulation.
- Investigate systematic errors in Aerogel experiment. Explore ways to optimize experiment.
- Explore ways to 'focus' the cerenkov light leaving the aerogel radiator onto a detector farther away.
- Find ways to add electronic effects to the detector response simulations.
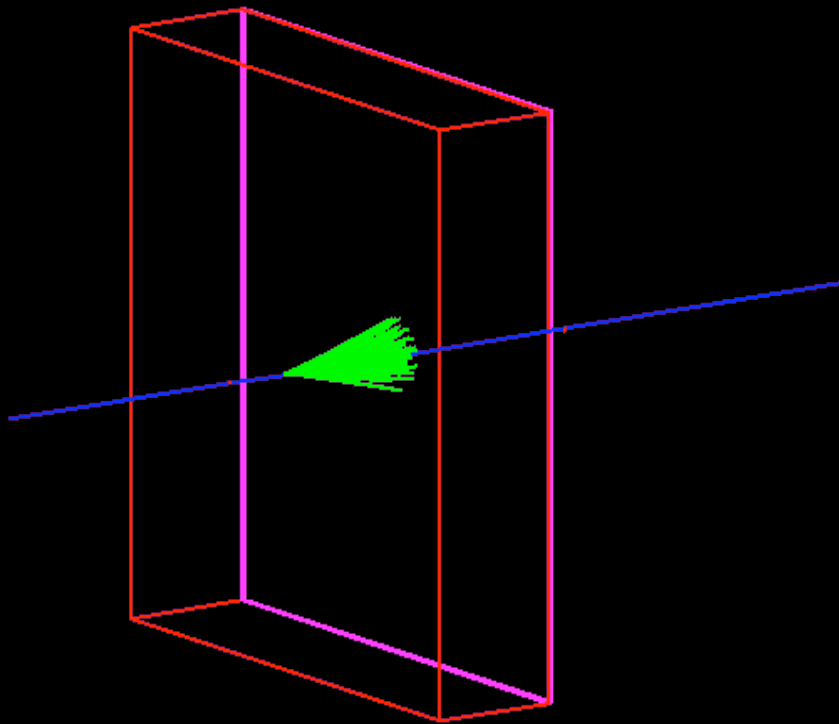- ...much much more.
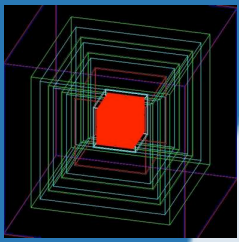
Acknowledgments

- Hans Wenzel (advisor)

- Mike Albrow and Sasha Pranko

- Dual readout calorimetry group

- SIST Program coordinators:

  - Dianne Engram

  - Jamieson Olsen

  - Linda Diepholz

  - ... and others.

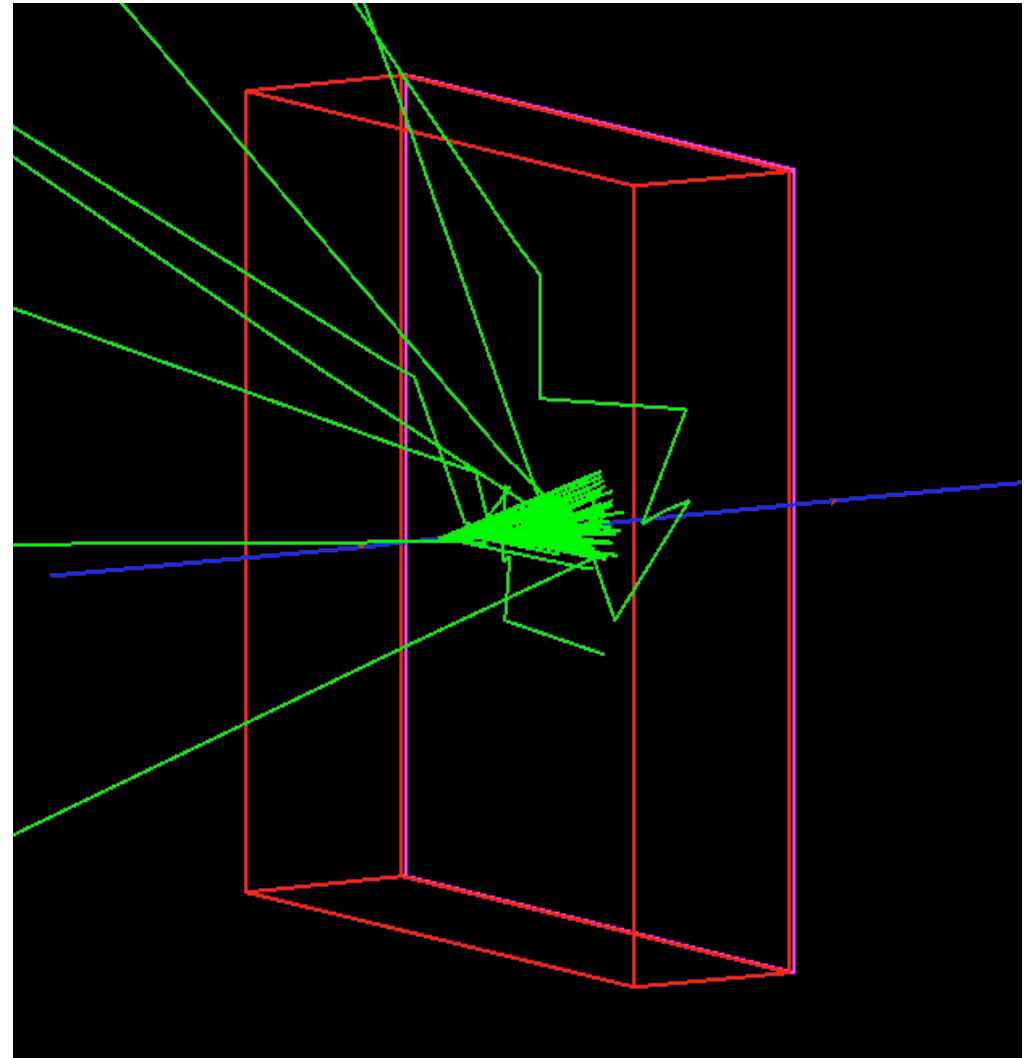The following are some additional slides that might help in explaining a few questions.
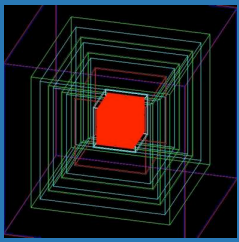
Simulation of Aerogel Radiator

Refractive Index: 1.0306

Without Rayleigh Scattering

With Rayleigh Scattering

~10% loss of Photons

Why Cerenkov Radiation?

We can use the properties of cerenkov light for particle ID, time of flight (TOF) measurements and fast timing.
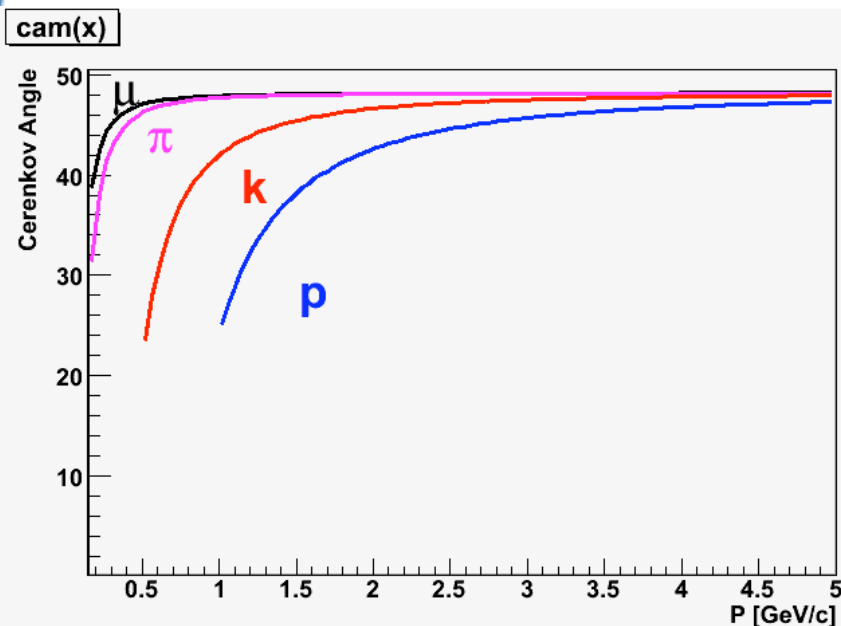
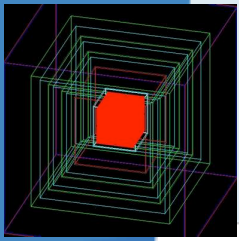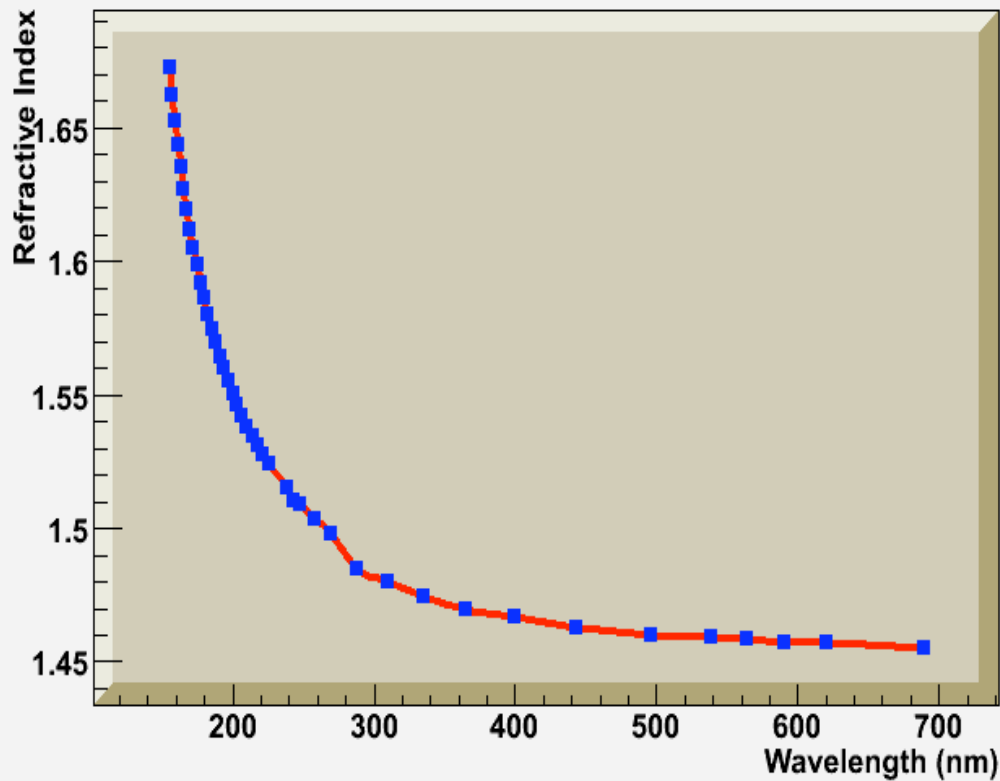Fig. 5: Cerenkov Angle versus particle momentum through a medium of refractive index 1.5
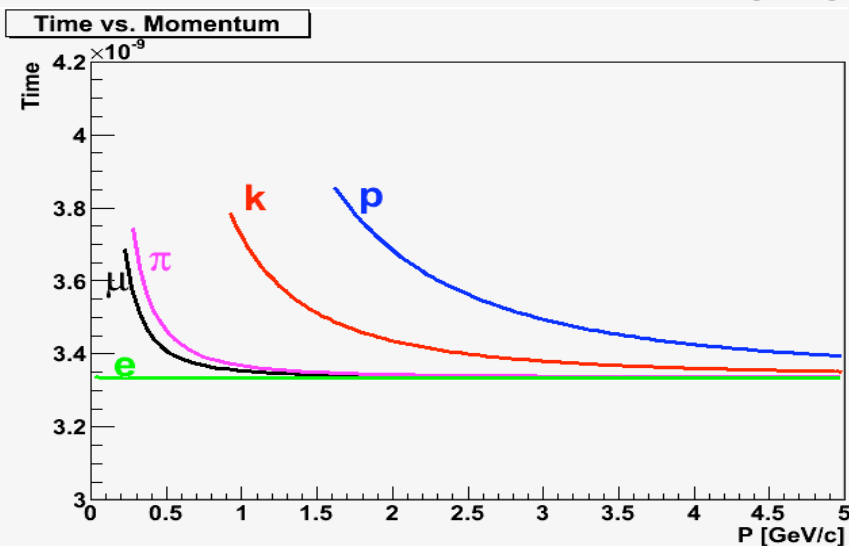
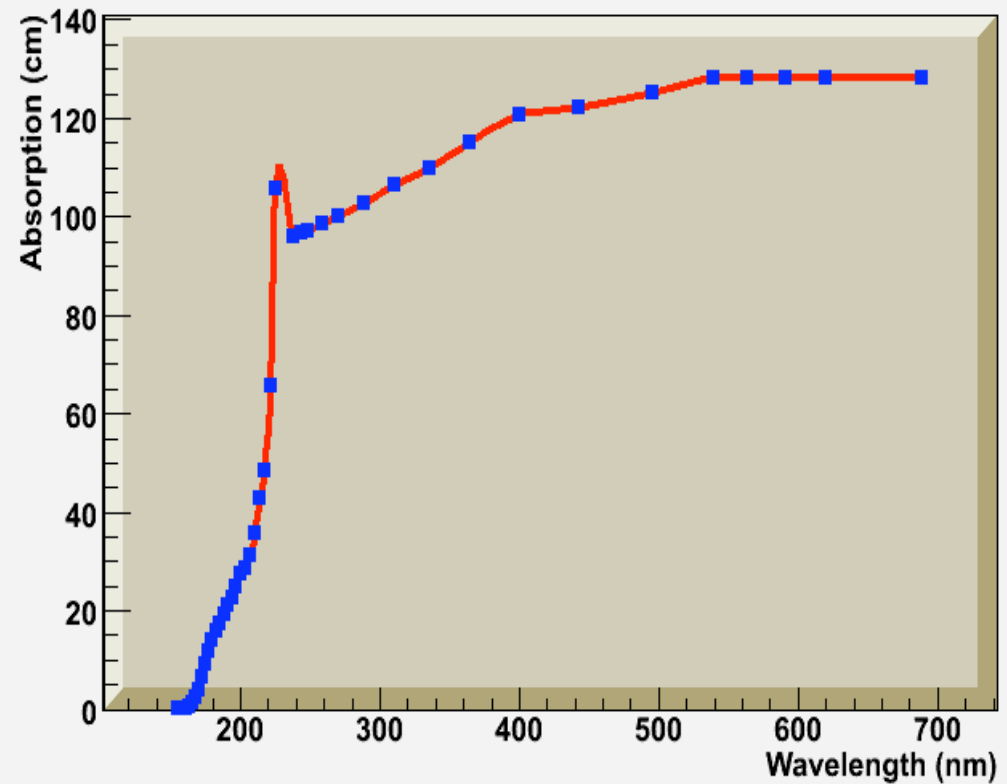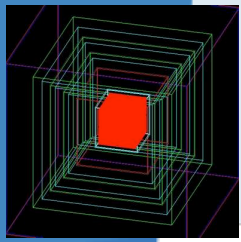Fig. 6: Time taken for a proton,kaon, muon, pion and an electron to travel 1 meter versus momentum.

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Quartz Bar Properties

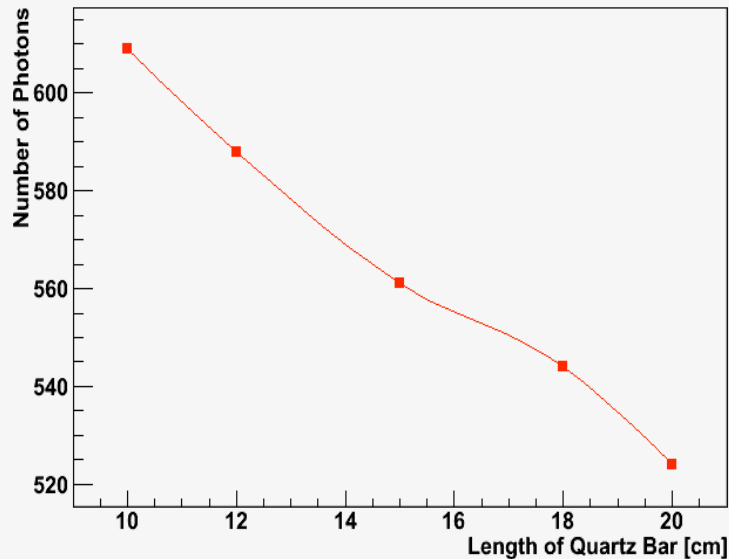Refractive Index vs. Wavelength

Absorption vs. Wavelength

Wednesday, August 5, 2009

Varying Length of Quartz bar

Number of Photons arriving at detector vs. Length of Quartzbar.
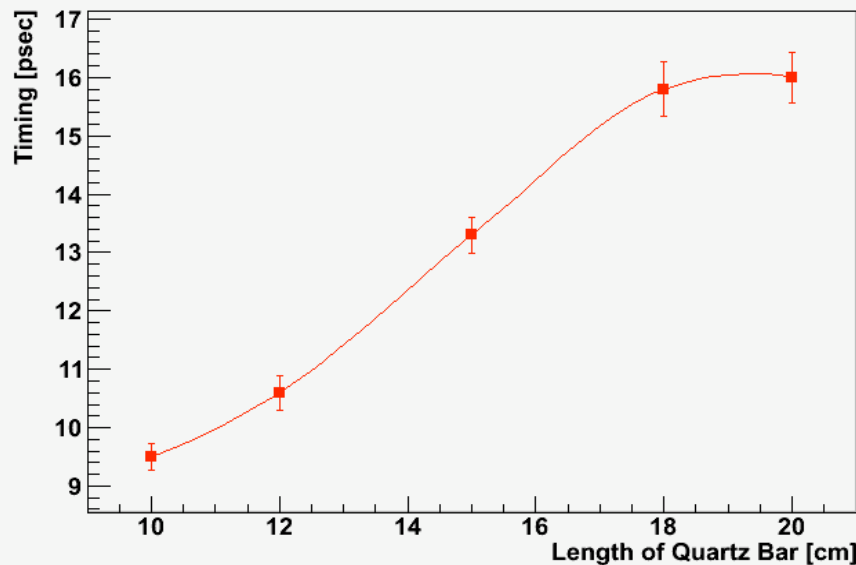

Number of Photoelectrons vs. Length of Quartz bar.
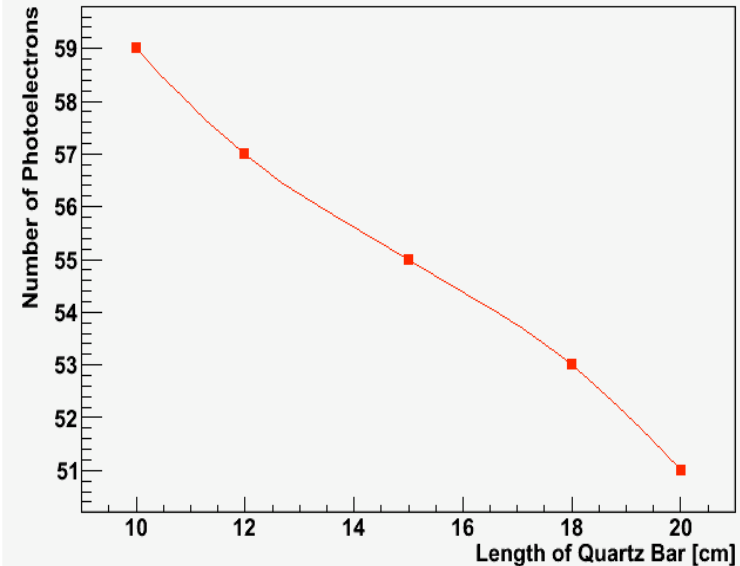
Timing Resolution vs. Length of Quartz bar.

-1000 Events with Rayleigh Scattering and dispersion
-Time Transition Spread: 30 psec
- Gain: 100
- Light Collection Efficiency (Photek): 60%
-Incident beam angle: 48.2 degrees
-Quartz bar thickness: 6mm
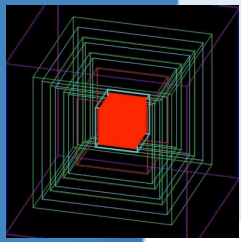
Varying Thickness of Quartz bar

Number of Photons arriving at detector vs. Thickness of Quartzbar.

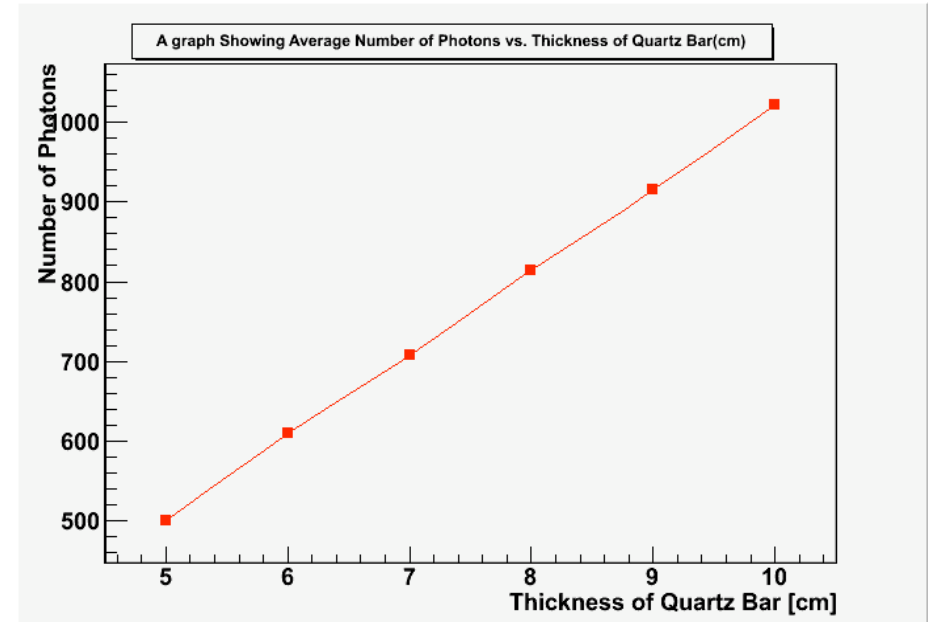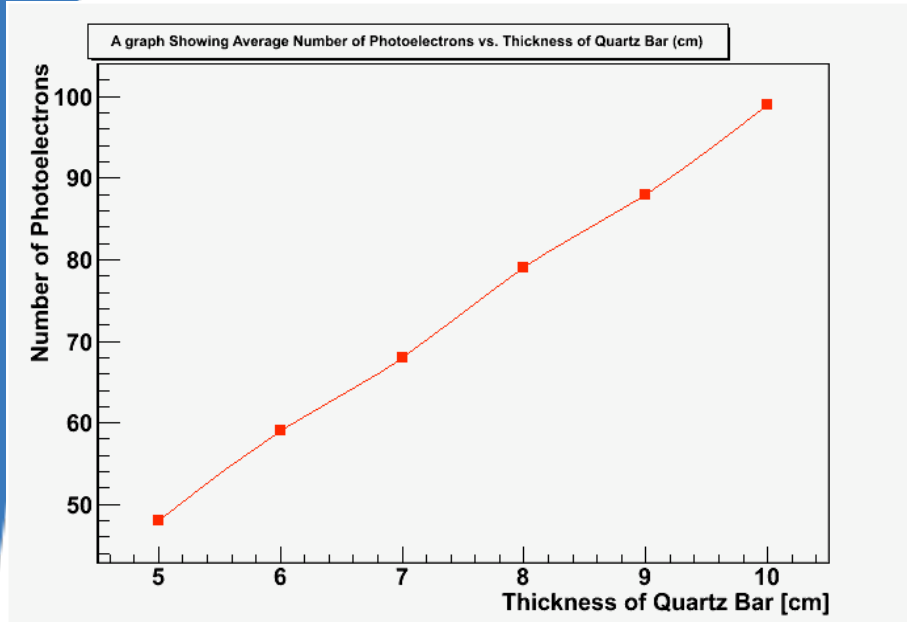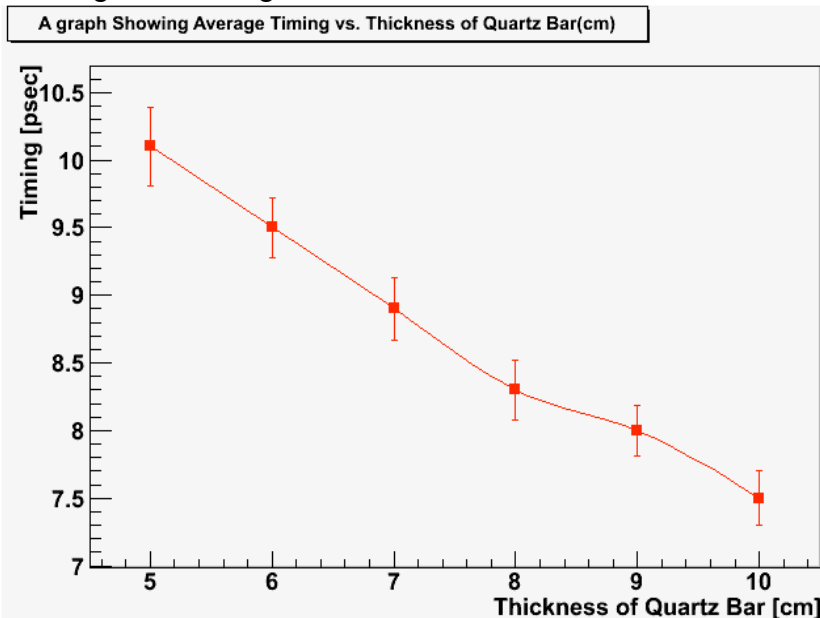Number of Photoelectrons vs. Thickness of Quartz bar.

Fig. 26: Timing Resolution vs. Thickness of Quartz bar.

-1000 Events with Rayleigh Scattering and dispersion
-Time Transition Spread: 30 psec
- Gain: 100
- Light Collection Efficiency (Photek): 60%
-Incident beam angle: 48.2 degrees
-Quartz bar Length: 10 cm