Measurement of Compton scattering cross section at few GeV energies

Li Ye
Mississippi State University
for the PrimEx-II collaboration

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Outline

- *Introduction*
- *Experimental Setup*
- *Monte Carlo Simulations*
- *Cross Section Extraction*
- *Summary*

Physics Motivation

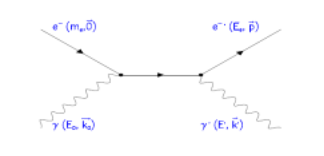
Electron Compton scattering is one of the most fundamental and the best theoretically known reaction in QED.

1. Leading order :

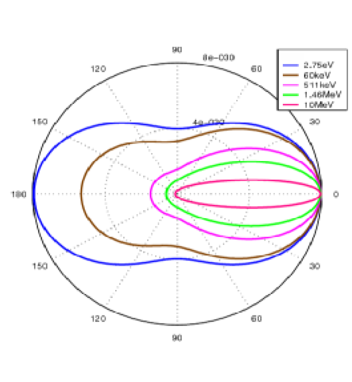
The lowest order Compton scattering diagrams were first calculated by Klein and Nishina in 1929.

The Klein-Nishina formula :

$$\frac{d\sigma}{d\Omega} = \frac{r_e^2}{2} \left(\frac{E'}{E_0}\right)^2 \left[\frac{E'}{E_0} + \frac{E_0}{E'} - \sin^2\theta_\gamma\right]$$



Lowest order Feynman diagram

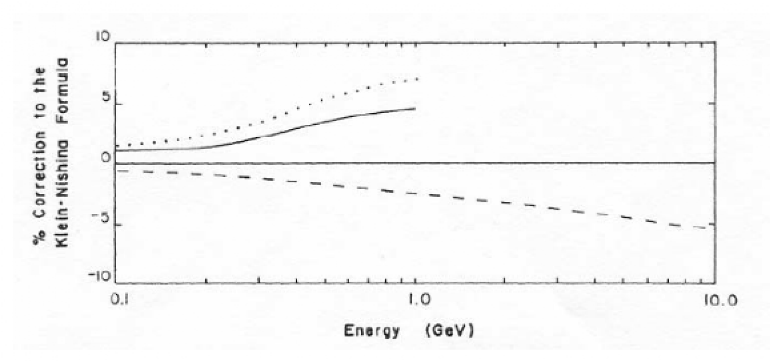


Klein–Nishina distribution of scattering-angle cross sections over a range of commonly encountered energies.

Physics Motivation

2.Higher order corrections (Figure2 and 3) :

Include radiative corrections and double Compton scattering.
[L. M. Brown and R. P. Feynman, Phys. Rev. 85,231 (1952).]



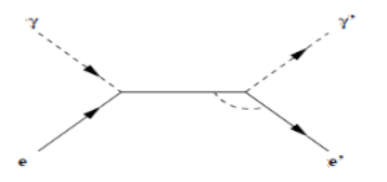


Figure 2: radiative correction

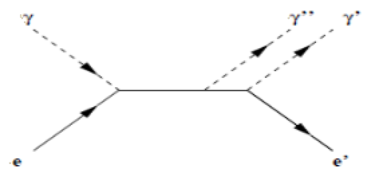


Figure 3: double Compton scattering contributions

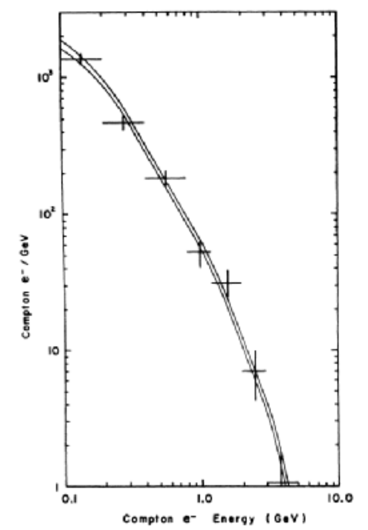
Physics Motivation

Compton scattering in a few GeV energy has not been measured experimentally with high enough precision to verify the higher order corrections.

Previous measurement

[A. T. Goshaw, T. Glanzman, "Compton electron scattering in the 0.1 to 5.0 GeV energy range," Phys. Rev. D, vol. 18, Sep 1978, pp. 1351–1358.]

Right plot from this paper shows the comparison of the measured Compton electron spectrum to that predicted from QED theory. The uncertainty of this measurement for E > 1 GeV was too large to verify higher order corrections



Physics Motivation

- ✓ Precision measurement of Compton scattering in a few GeV electron energy.

to verify the higher order corrections to the Compton scattering cross section

- ✓ Validate systematic error for π^0 lifetime measurement (PrimEx-II) .

the main goal of PrimEx-II experiment is to measure the two photon decay width of the neutral pion with high precision (less than 2%), the Compton scattering measurement which had the same experimental setup was designed to help validate the systematic errors of the PrimEx-II experiment.

Setup for the PrimEx-II Experiment

Includes :

1. Hall B Photon Tagger

2. Targets :

Carbon-I (5% r.l.)

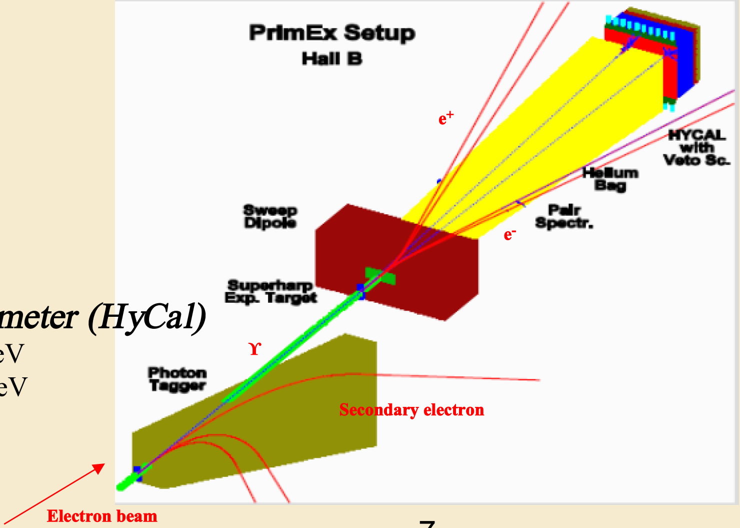
Carbon-II (8% r.l.)

Silicon (10% r.l.)

3. Pair spectrometer

4. Hybrid electro-magnetic calorimeter (HyCal)

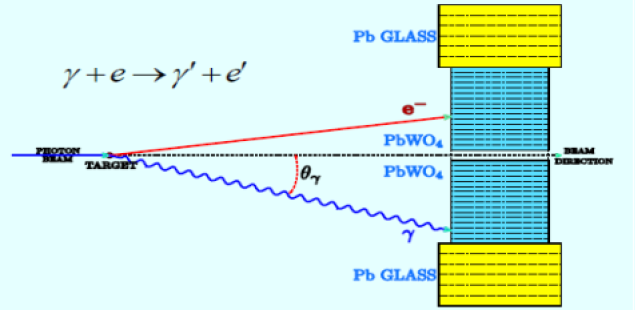
- ✓ Energy resolution : ~ 2.5% at 1GeV
- ✓ Position resolution : ~ 2 mm at 1GeV

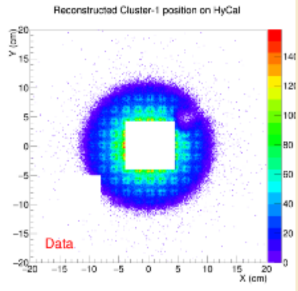


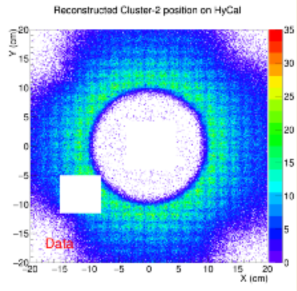
Setup for the Compton Measurement

<u>Measured :</u>

1. Tagged photon beam energy (with photon tagger)
2. Cluster's energies (in HyCal)
3. Cluster's positions (in HyCal)





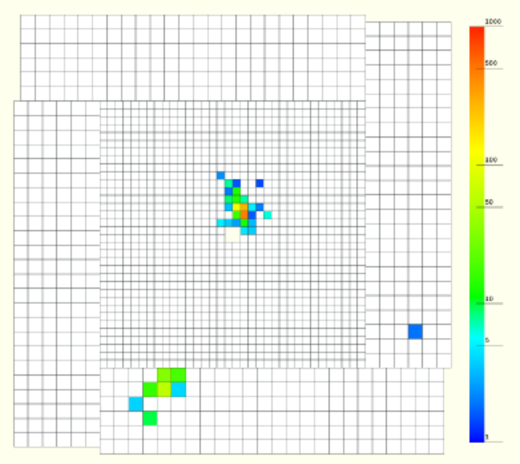


- ❑ Only inner part of HyCal was used.
- ❑ Cluster1 has higher energies.
- ❑ Corner shape due to the Lead-glass cut off.

Cluster Algorithm

1.<u>Find clusters :</u>

The so called 'island' method was used to connect modules in different sectors that fire during an event.
a) Step 1 is to search for a maxima in the energy deposited in the modules of the HyCal and form all possible clusters around the maxima.
b) Step 2 is to test if a single hit can be split into two close by hits.
c) Those hits that satisfy the test are merged together.
d) The probability of step 2 is controlled using a cut on the ADC values.



Cluster Algorithm

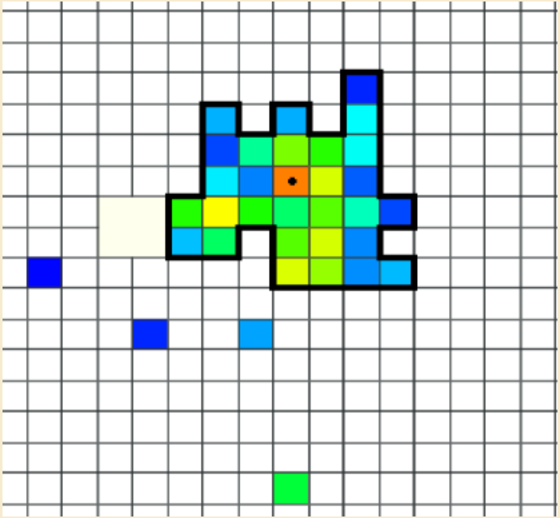
After clustering

2.<u>Energy reconstruction :</u>

Sum of the energy depositions in cluster.

3.<u>Position reconstruction :</u>

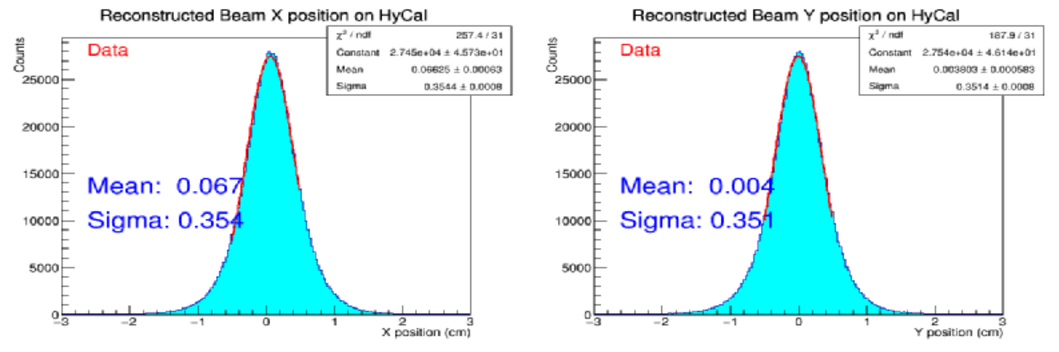
Center of gravity of an cluster



Data Validation

The reconstructed reaction vertex X, Y positions are used to validate the centering of the HyCal coordinate system and the reconstruction algorithm.

✓ *Target center and HyCal center survey was performed by JLab survey group before the experiment.*



Data Validation

- R_{min} Cluster Separation (cm)

  $R_{min} = \sqrt{(x1 - x2)^2 + (y1 - y2)^2}$

  x1(2),y1(2) are cluster positions for cluster 1 (2)

- $\Delta\phi$ Azimuthal Angle Difference (degree)

  $\Delta\phi = | \phi1 - \phi2 |$

- ΔE Elasticity (GeV)

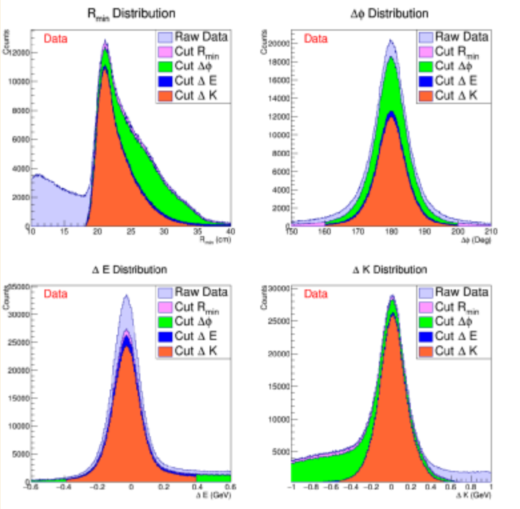
  the difference between photon beam energy (E_0) and the sum of the cluster's energy (E_1 and E_2) deposited in HyCal.

  $\Delta E = E_0 - (E_1 + E_2)$

- ΔK Kinematic Energy Difference (GeV)

  the difference between the sum of the calculated cluster energy and photon beam energy

  $\Delta K = (E_\gamma^{cal} + E_e^{cal}) - E_0$



The cuts applied to select the good Compton events will be described later.

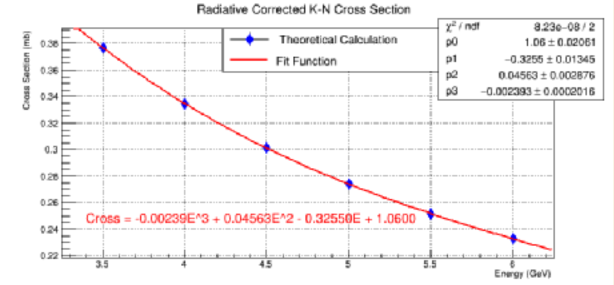
The Compton Scattering Simulation

The Event Generator includes:

1. Born level cross section from Brown and Feynman, Pys. ReV, 85, 231 (1952)
2. Virtual photon radiative corrections developed by M. Konchatnyi (PrimEx note 37)
3. Double Compton scattering correction implemented by A. Tkabladze et al. (PrimEx note 42).

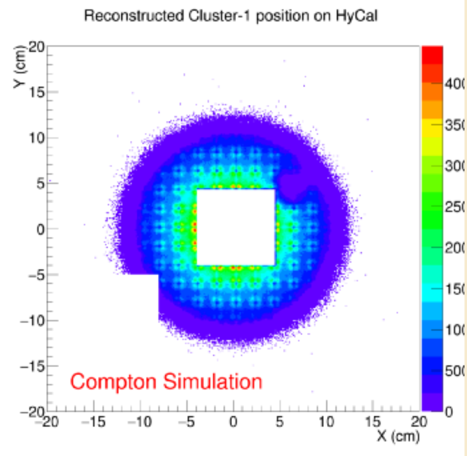
$$\frac{d\sigma}{d\Omega} = \frac{r_e^2}{2}\frac{1}{[1+\gamma(1-\cos\theta_\gamma)]^2}\left[1+\cos^2\theta_\gamma+\frac{\gamma^2(1-\cos\theta_\gamma)^2}{1+\gamma(1-\cos\theta_\gamma)}\right]$$

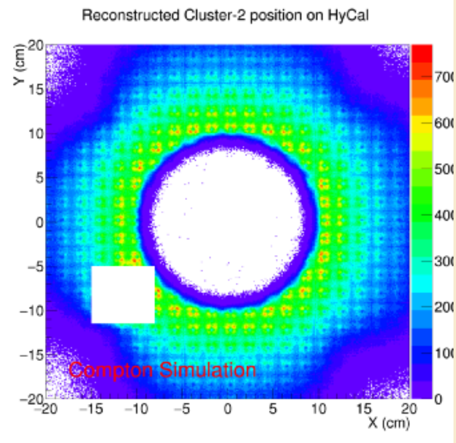
$$d\sigma = d\sigma_0(1+\delta_{SV}+\delta_{dh})$$



The Compton Scattering Simulation

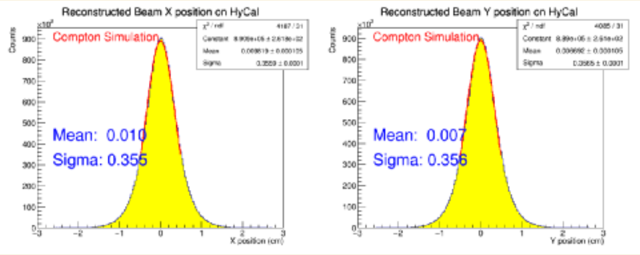
Compton Scattering Event Generation and Validation

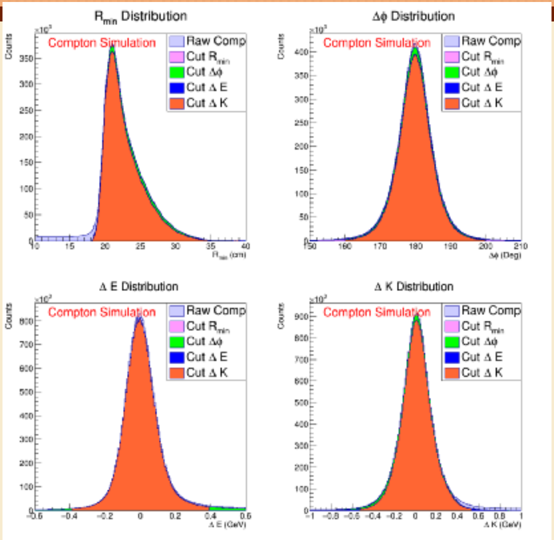




The Compton Scattering Simulation

The definitions of the 4 distributions was mentioned earlier. The mean of the Gaussian fit to the X and Y positions are 0.010 cm and 0.007 cm respectively, which is within the position resolution (0.355 cm) of HyCal relative to the expected value (0,0).





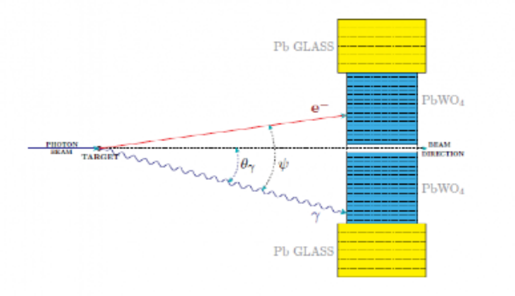
The Electron-Positron Pair Production Simulation

<u>Electron-positron pair production :</u>

When a photon hit the target, an electron-positron pair was created

$$\Upsilon + A = e^{+} + e^{-} + A'$$

where A could be the nucleus or the atomic electron



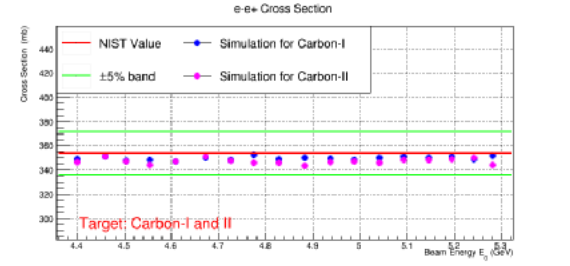
Pair production have large cross section (350 mb for Carbon) compare with Compton scattering (0.28 mb) but very small opening angle. Most of them pass through the central hole of HyCal, but still some of them get into HyCal acceptance due to the mutiple scattering with beamline elements, and HyCal can not identify electrons from photons so these events become our background events.

The Electron-Positron Pair Production Simulation

Cross section Model for the Simulation of Electron-positron pair production :

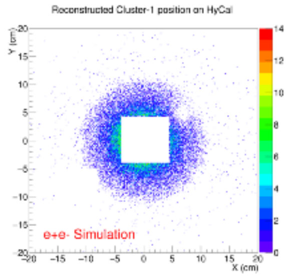
1. Bethe-Heitler mechanism of pair production on the nucleus (coherent process)
2. Pair production on atomic electrons with excitation of all atomic states
3. Quantum Electro-dynamical (QED) radiative corrections
4. Nuclear incoherent contribution quasi-elastic, or quasi-free process on the proton
5. Nuclear coherent contribution, or virtual Compton Scattering (CS) two-step mechanism

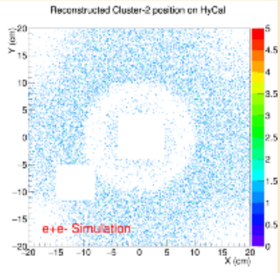
Mechanism	Contribution (%)
Nuclear Bethe-Heitler	82.789
Atomic electrons	17.185
Nuclear incoherent (quasielastic)	0.026
Nuclear coherent (virtual CS)	$\sim 10^{-5}$
Total	100.000

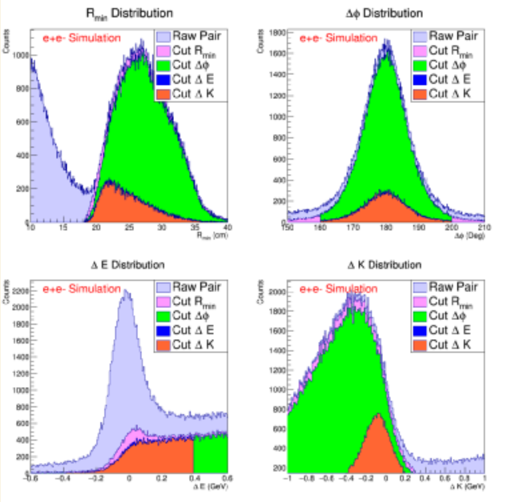


The Electron-Positron Pair Production Simulation

The X, Y position of the pair production background is more uniformly distributed compared to the Compton simulation, because this background only makes it into the HyCal acceptance via multiple scattering and hence does not have the same kinematic distribution as the Compton events.







Data Analysis

Data analysis steps :

1. Event selection
2. Yield extraction
3. Cross section calculation
4. Determining systematic uncertainty

Event Selection

The following cuts are then applied to select Compton events :

1.HyCal fiducial Cut : XY position cut, remove the central hole and dead modules.

2.ΔT Time Difference (ns) : $|\Delta T| < 6.5$

3.Δϕ Azimuthal Angle Difference (Degree) : $|\Delta\phi - 180| < 5\sigma\phi$

the width of the distribution of the azimuthal angle σϕ for each target given by: $\sigma_\phi(C\text{-}I) = 3.99$, $\sigma_\phi(C\text{-}II) = 4.37$, $\sigma_\phi(Si) = 4.70$

4. R_{min} Cluster Separation (cm) : $R(E) < R_{min}$

where R(E) is a function of beam energy defined as : $R(E) = 19.00 + 1.95 \times (4.85 - E_0)$.

5. ΔE Elasticity (GeV) : $|\Delta E| < 5\sigma_E$

the width of the distribution of elasticiry σ_E *for each target given by:* $\sigma_E(C\text{-}I) = 0.078$, $\sigma_E(C\text{-}II) = 0.078$, $\sigma_E(Si) = 0.080$

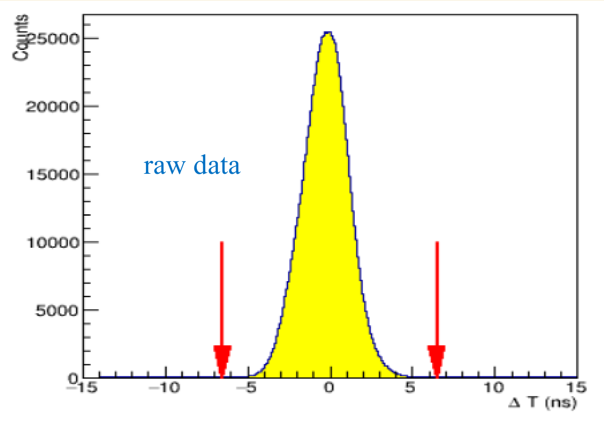
6. ΔK Kinematic Energy Difference (GeV) : $|\Delta K| < 4\sigma_K$

the width of the distribution of kinematic energ difference σ_K *for each target given by:* $\sigma_K(C\text{-}I) = 0.127$, $\sigma_K(C\text{-}II) = 0.136$, $\sigma_K(Si) = 0.172$

Event Selection

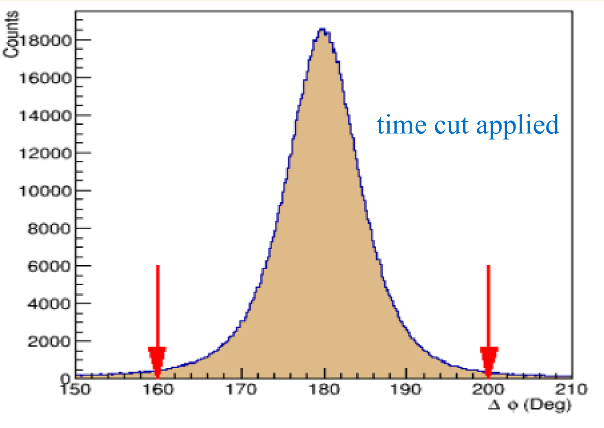
<u>Time Difference (±6.5ns) :</u>

6.5 ns is about 5.5σ of the ΔT distribution



<u>Azimuthal Angle Difference (±20deg) :</u>

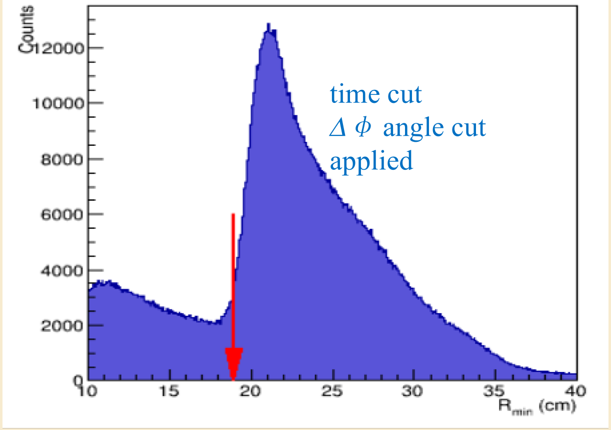
20 deg is about 5σ of the Δϕ distribution



Event Selection

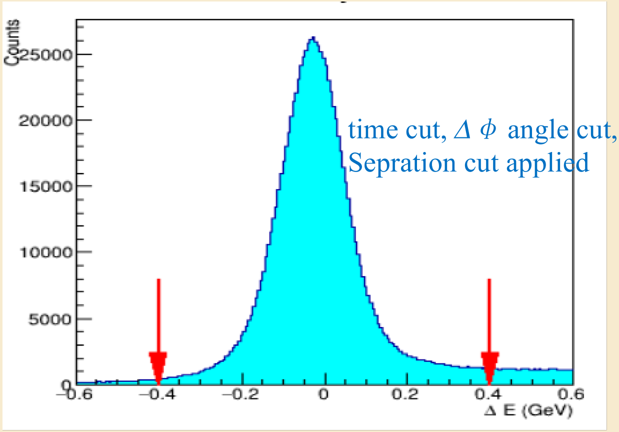
Cluster Separation (19cm) :

Rmin cut is energy dependent, it set to be 19cm because it has the best signal/background ratio



Elasticity (-0.4 ~ 0.4 GeV) :

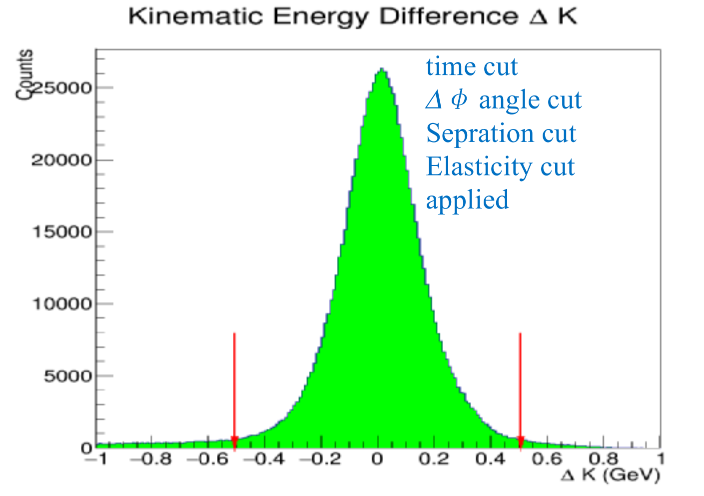
0.4 GeV is about 5σ of the ΔE distribution



Event Selection

Kinematic Energy Difference (-0.5 ~ 0.5 GeV) :

0.5 GeV is about 4σ of the ΔK distribution, and is designed to limit the pair production background, this is the most sensitive distribution that can separate the background from the Compton events.

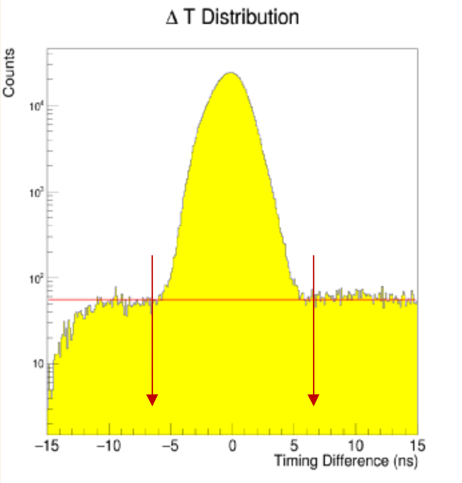


Accidentals

By using events in the tails of the time difference distribution, one can estimate the percentage of accidental coincidence events in the data. The percentage of accidental coincidences is given by :

$$C_i^{acci} = \frac{p_i^{fit} N_i^{bins}}{M_i^{data}}$$

where, i is the energy bin number from 1 to 18, C^{acci} is percentage of accidentals, p^{fit} is the fitting parameter for a given ΔT cut, N^{bins} is the number of bins in the ΔT cut range M^{data} is the total number of events in the ΔT cut range.



Yield Extraction

Fit result
= e+e- + accidentals + Compton simulation fit to data
Carbon-I : Carbon(5% r.l.)

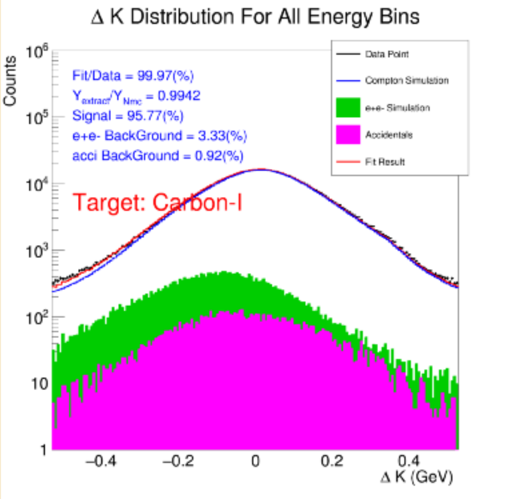
Fitting the simulated distributions to the data gives us 3 parameters p0, p1 and p2, we have

$$Y_{fit} = Y_c + Y_{acc} + Y_p$$

Where Yc is the simulated Compton yield ($p_0 Y_{data}$), Yacc is the yields from accidentals ($p_1 Y_{data}$) and Yp is the yield from the pair production simulation ($p_2 Y_{data}$)

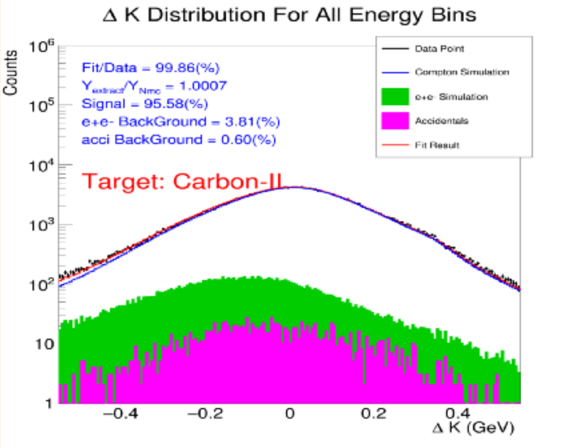
Due to the small difference between data the fit result, we use following fomular to calculate the final Compton yield :

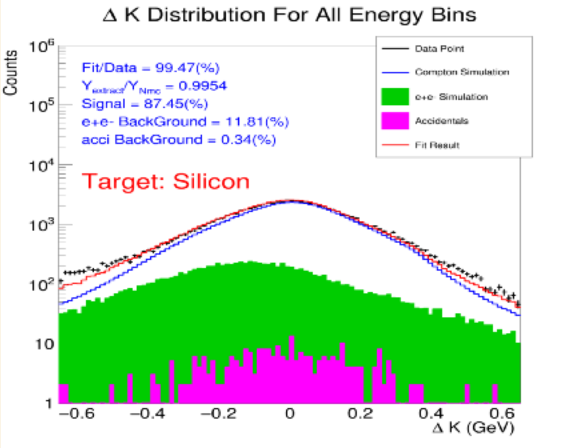
$$Y_{Compton} = Y_{data}(1 - p_1 - p_2)$$



Yield Extraction

Yield from Carbon-II(8% r.l.) and Silicon using the same method as in previous slides





Cross Section Calculation

The integrated cross section for each energy bin is calculated by following expression :

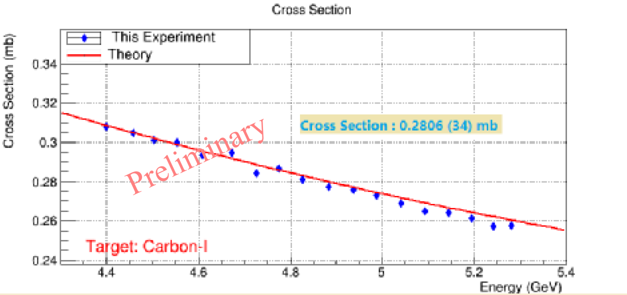
$$\sigma_i = \frac{1}{n_e \Gamma_Y} \frac{Y^{Compton}}{A_i C_{HRF}}$$

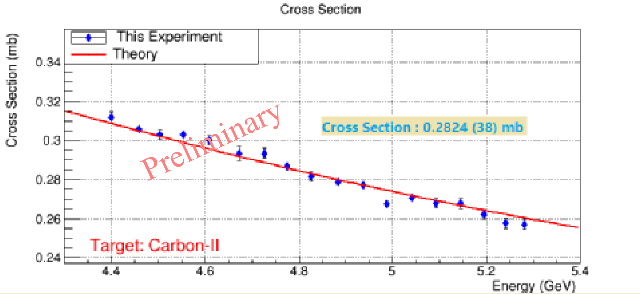
Where,

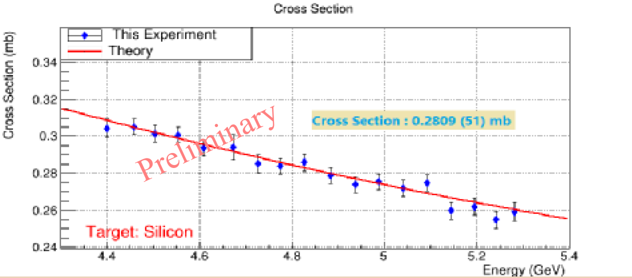
- i is the energy bin number
- n_e is the the number of electrons per cm^2
- Γ_Y is the experimental photon flux which is obtained from Tagger and PS

  (A blind number was added in the flux during the analysis, only unblinded after got the final results)
- $Y^{Compton}$ is experimental yield
- A_i is the simulated acceptance
- C_{HRF} is the HyCal response function correction

Cross Sections as Function of Energies

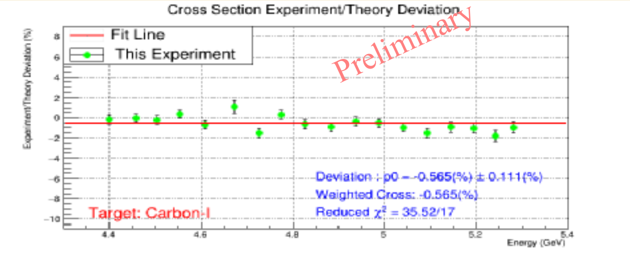






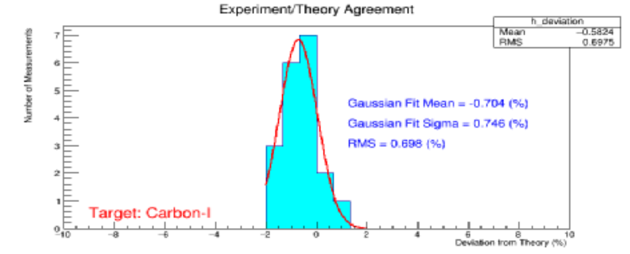
- Statistical uncertainty only

Experiment/Theory Deviation

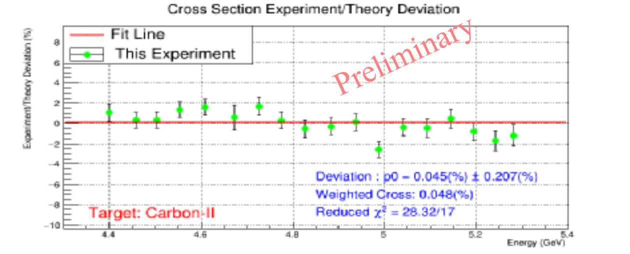


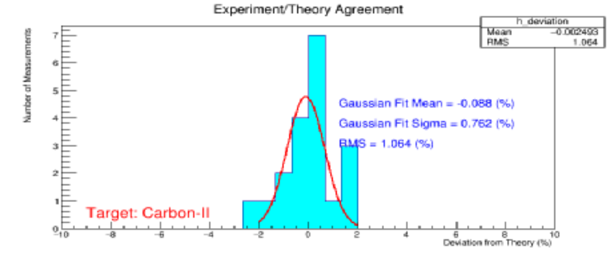
Deviation = Experiment/Theory - 1

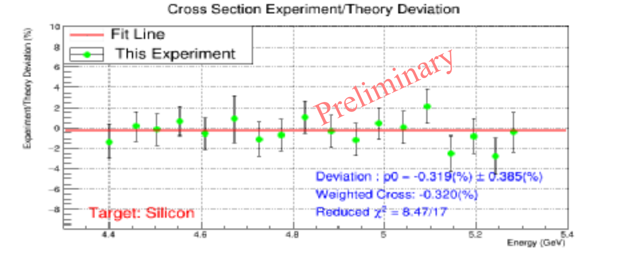
- Statistical uncertainty only

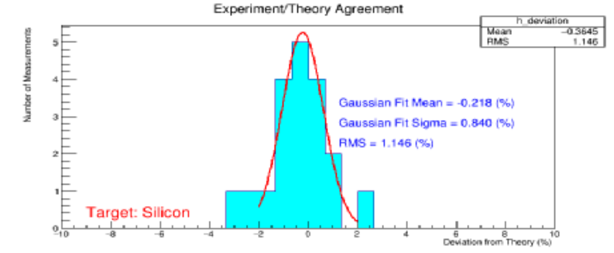


Experiment/Theory Deviation









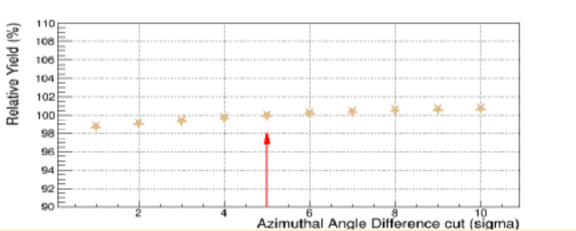
Systematic Studies

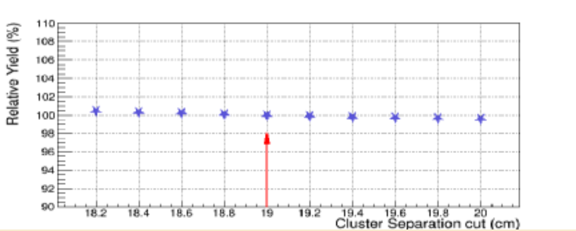
A number of factors were studied to determine the systematic uncertainty, these include :

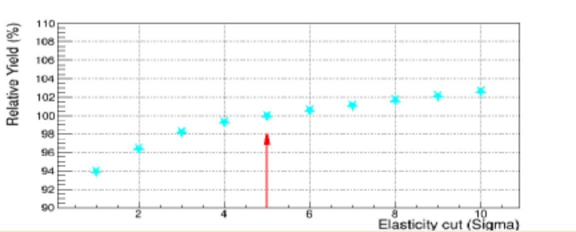
1. Cut stability (Event selection) : *varying the range of the event selection cuts, other studies see thesis for details.*
2. Acceptance : *varying the geometries in the simulation package*
3. Photon flux : *estimated from tagging ratio (by Ilia)*
4. Target density : *using Archimedes principle (by M.R.)*
5. HyCal response function : *studying difference between the calibration data and the calibration simulation. (by Ilia)*

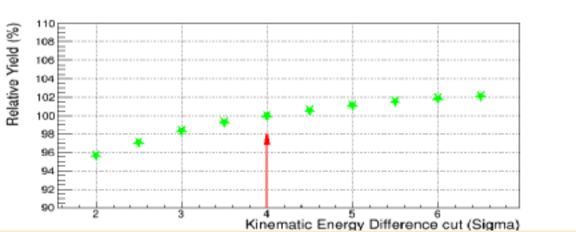
Systematic Study of Cuts Stability

All differences in yield relative to the final result









Photon beam flux

Flux error was estimated from tagging ratio errors, TAC module is 15×15×35 cm lead glass

Table 5.1

Photon flux and associated uncertainty for each energy bin

Energy Bin	^{12}C-*I* Target Flux (*Billion*)	^{12}C-*II* Target Flux (*Billion*)	^{28}Si Target Flux (*Billion*)
E01	1.3485	0.2438	0.1187
E02	1.5863	0.2830	0.1374
E03	1.6705	0.2984	0.1456
E04	1.5935	0.2829	0.1370
E05	1.6871	0.3035	0.1475
E06	1.8276	0.3280	0.1593
E07	1.9705	0.3533	0.1719
E08	1.8133	0.3261	0.1586
E09	1.8274	0.3258	0.1587
E10	1.7065	0.3062	0.1490
E11	1.8903	0.3355	0.1626
E12	1.5150	0.2720	0.1320
E13	0.7827	0.1392	0.0675
E14	1.8114	0.3237	0.1573
E15	1.9283	0.3448	0.1677
E16	1.7338	0.3100	0.1499
E17	1.9689	0.3541	0.1723
E18	1.4775	0.2617	0.1274
ALL	30.1391	5.3918	2.6201

Table 3: Stability of absolute tagging ratio and errors

T-counter	RMS❶	TR change if TAC −5cm	TR change if include beam trips	TR change if ADC cut	Error sum❷ [%]
1	0.0049	−0.0030	−0.0008	−0.0015	0.60
2	0.0038	+0.0018	−0.0003	−0.0014	0.47
3	0.0031	−0.0033	−0.0002	−0.0015	0.38
4	0.0039	+0.0014	−0.0003	−0.0016	0.44
5	0.0033	+0.0009	+0.0002	−0.0014	0.39
6	0.0032	−0.0053	−0.0002	−0.0014	0.37
7	0.0030	−0.0009	−0.0001	−0.0014	0.37
8	0.0039	−0.0032	−0.0003	−0.0016	0.44
9	0.0031	−0.0001	−0.0001	−0.0014	0.37
10	0.0032	−0.0005	+0.0001	−0.0014	0.35
11	0.0030	+0.0012	−0.0001	−0.0015	0.36
12	0.0030	−0.0032	−0.0002	−0.0016	0.38
13	0.0022	+0.0022	+0.0002	−0.0016	0.31
14	0.0029	+0.0029	−0.0001	−0.0014	0.34
15	0.0026	−0.0011	+0.0002	−0.0014	0.32
16	0.0027	−0.0028	−0.0002	−0.0013	0.36
17	0.0023	0.0000	+0.0001	−0.0015	0.30
18	0.0028	+0.0012	−0.0001	−0.0015	0.34
19	0.0032	−0.0003	+0.0001	−0.0015	0.37
<1...19>	0.0031	-0.0006	−0.0001	−0.0015	0.37

Target Density

[29] M. R. and M. P., "Analysis of PrimEx targets," https://www.jlab.org/primex/, no.28, Nov. 2004.
Using Archimedes principle (measure the weight in air and water)

Table 2.1

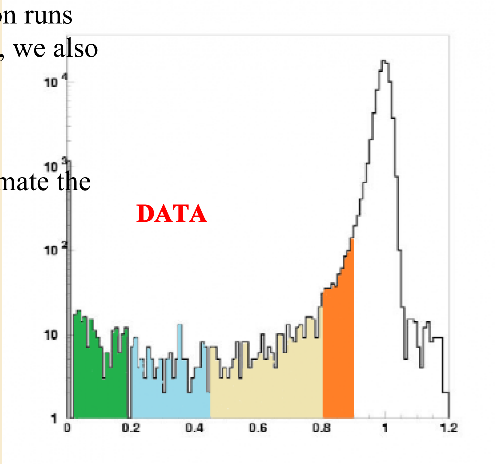
Targets thickness and density

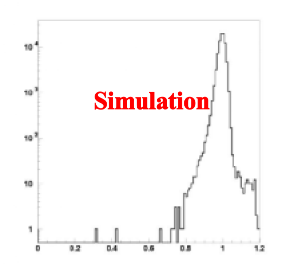
	Target ^{12}C-I	Target ^{12}C-II Block #1	Target ^{12}C-II Block #2	Target ^{28}Si
Density, ρ, (g/cm^3)	2.1979 ± 0.0003	1.4938 ± 0.0006	2.1979 ± 0.0003	2.316 ± 0.008
Central Thickness, T, (cm)	0.9662 ± 0.0001	0.9417 ± 0.0001	0.9662 ± 0.0001	1.0015 ± 0.0003
ρT (g/cm^2)	2.1236 ± 0.0004	1.4068 ± 0.0006	2.1236 ± 0.0004	2.3195 ± 0.008
Fraction Uncertainty in ρT	0.02%	0.04%	0.02%	0.35%

HyCal Response Function Correction

The response function of HyCal was studied during the calibration runs The ratio E_{HyCal}/E_{Tagger} also known as the elasticity (see Figure), we also call this distribution the HyCal response function.

By studying the difference between the calibration run data and the simulation in different ratio regions, we can estimate the overall leakage of HyCal module is about 0.45% and estimate systematic uncertainty is 0.50%





Systematic Uncertainties

All values are in %

	Carbon-I	*Carbon-II*	*Silicon*
Event selection	*0.68*	*0.88*	*0.54*
Signal/Background separation	*0.17*	*0.19*	*0.87*
Acceptance	*0.25*	*0.25*	*0.25*
Photon beam flux	*0.82*	*0.82*	*0.82*
Target density	*0.02*	*0.04*	*0.35*
HyCal Res.Func.	*0.50*	*0.50*	*0.50*
Total Syst.	*1.22*	*1.34*	*1.79*

Preliminary

Cross Sections

Target	Energy (GeV)	Cross Section (mb)	Theory (mb)	Deviation (%)	Syst. Error (%)	Stat. Error (%)	Total Error (%)
Carbon-I	4.84	0.2806	0.2822	-0.57	+/- 1.22	+/- 0.11	+/- 1.22
Carbon-II	4.84	0.2824	0.2822	0.19	+/- 1.34	+/- 0.21	+/- 1.36
Silicon	4.84	0.2809	0.2822	-0.46	+/- 1.79	+/- 0.39	+/- 1.83

Preliminary

Summary

- Compton scattering is one of the fundamental reactions in QED.
- For the first time, the Compton cross sections in the energy range of 4.4 - 5.3 GeV were measured with the accuracy better than 2%.
- The Compton results validated that the systematic uncertainties of the PrimEx-II experiment for the pi0 lifetime measurement were controlled at level of 2%.
- Extracted cross sections agree to the theory predictions with the higher order corrections.
- Publication with these results are in preparation.

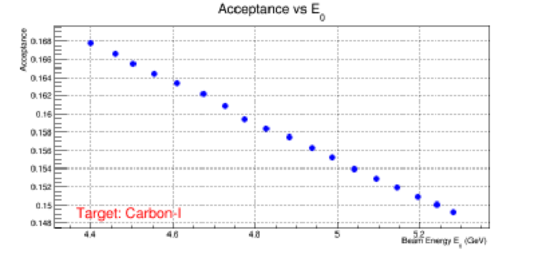
Thank you !

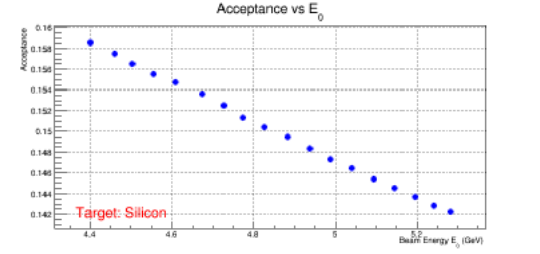
Acceptance

Compton simulation data were used to calculate the acceptance as :

$$A = \frac{N_{simulation}}{N_0^{generate}}$$

where $N_{simulation}$ is the number of events reconstructed or accepted on HyCal, $N^{generate}$ is the number of generated events.





Photon beam flux

The formulas to calculate the flux are given by : (Ilya Larin)

$$\text{Flux}_{tid} = \frac{T \times lt \times N_{tid}}{N_5 \times t_{OOT}}$$

$$T = \frac{N_{ungated}}{v_{gen}}$$

$$lt = \frac{N_{gated}}{N_{ungated}}$$

where, T is the time if interval between two scaler events (10 sec), lt is the DAQ livetime (dimensionless), N_{tid} is the number of hits seen in a selected time window, N_5 is the number of clock triggers recorder in that same interval, t_{OOT} is the size of the time window (2 usec), $N_{(un)gated}$ is the (un)gated scaler counts during the interval and v_{gen} is the generator frequency used for the scaler.