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Polarimetry for Linearly Polarised Photons Using Coherent Pion Production at MAMI

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Erice Nuclear Physics Summer School

September 2018

Outline

- A2
- Coherent Bremsstrahlung
- Calculating the Degree of Linear polarisation
- Tagging Efficiency & Linear Polarisation
- Use of Carbon as a Polarimeter
- Current Work

Observable	Transversity representation	Experiment (B/T/R)	Type
σ_0	$\|b_1\|^2 + \|b_2\|^2 + \|b_3\|^2 + \|b_4\|^2$	-/-/-	Single
Σ	$\|b_1\|^2 + \|b_2\|^2 - \|b_3\|^2 - \|b_4\|^2$	P_L/-/-	
T	$\|b_1\|^2 - \|b_2\|^2 - \|b_3\|^2 + \|b_4\|^2$	-/P^y/-	
P	$\|b_1\|^2 - \|b_2\|^2 + \|b_3\|^2 - \|b_4\|^2$	-/-/y	
G	$2Im(b_1 b_3^* + b_2 b_4^*)$	P_L/P^z/-	Beam-Target
H	$-2Re(b_1 b_3^* - b_2 b_4^*)$	P_L/P^x/-	
E	$-2Re(b_1 b_3^* + b_2 b_4^*)$	P_{circ}/P^z/-	
F	$2Im(b_1 b_3^* - b_2 b_4^*)$	P_{circ}/P^x/-	
O_x	$-2Re(b_1 b_4^* - b_2 b_3^*)$	P_L/-/x'	Beam-Recoil
O_z	$-2Im(b_1 b_4^* + b_2 b_3^*)$	P_L/-/z'	
C_x	$2Im(b_1 b_4^* - b_2 b_3^*)$	P_{circ}/-/x'	
C_z	$-2Re(b_1 b_4^* + b_2 b_3^*)$	P_{circ}/-/z'	
T_x	$2Re(b_1 b_2^* - b_3 b_4^*)$	-/x/x'	Target-Recoil
T_z	$2Im(b_1 b_2^* - b_3 b_4^*)$	-/x/z'	
L_x	$2Im(b_1 b_2^* + b_3 b_4^*)$	-/z/x'	
L_z	$2Re(b_1 b_2^* + b_3 b_4^*)$	-/z/z'	

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Overview of Facility- A2 in Mainz

- Beam supplied to A2 hall from MAMI (**MA**inz **Mi**crotron)
- MAMI is a continuous wave accelerator.
- The amount of accumulated experimental data is distributed equally.
- On entering the A2 hall, the electron beam undergoes Bremstrahlung radiation to produce photons.
- A2 hall is comprised of:

  -Goniometer

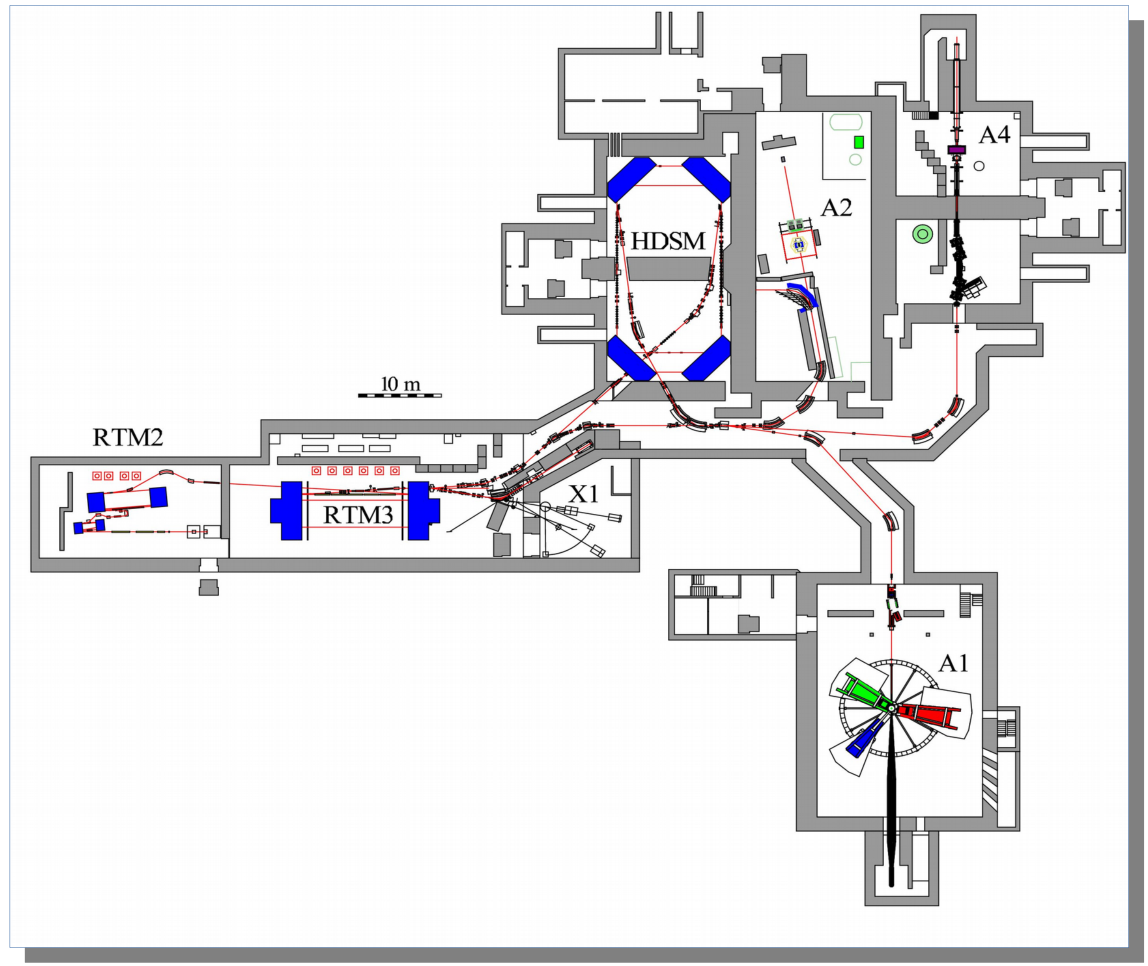
  -Glasgow Tagger

  -Crystal Ball (CB)

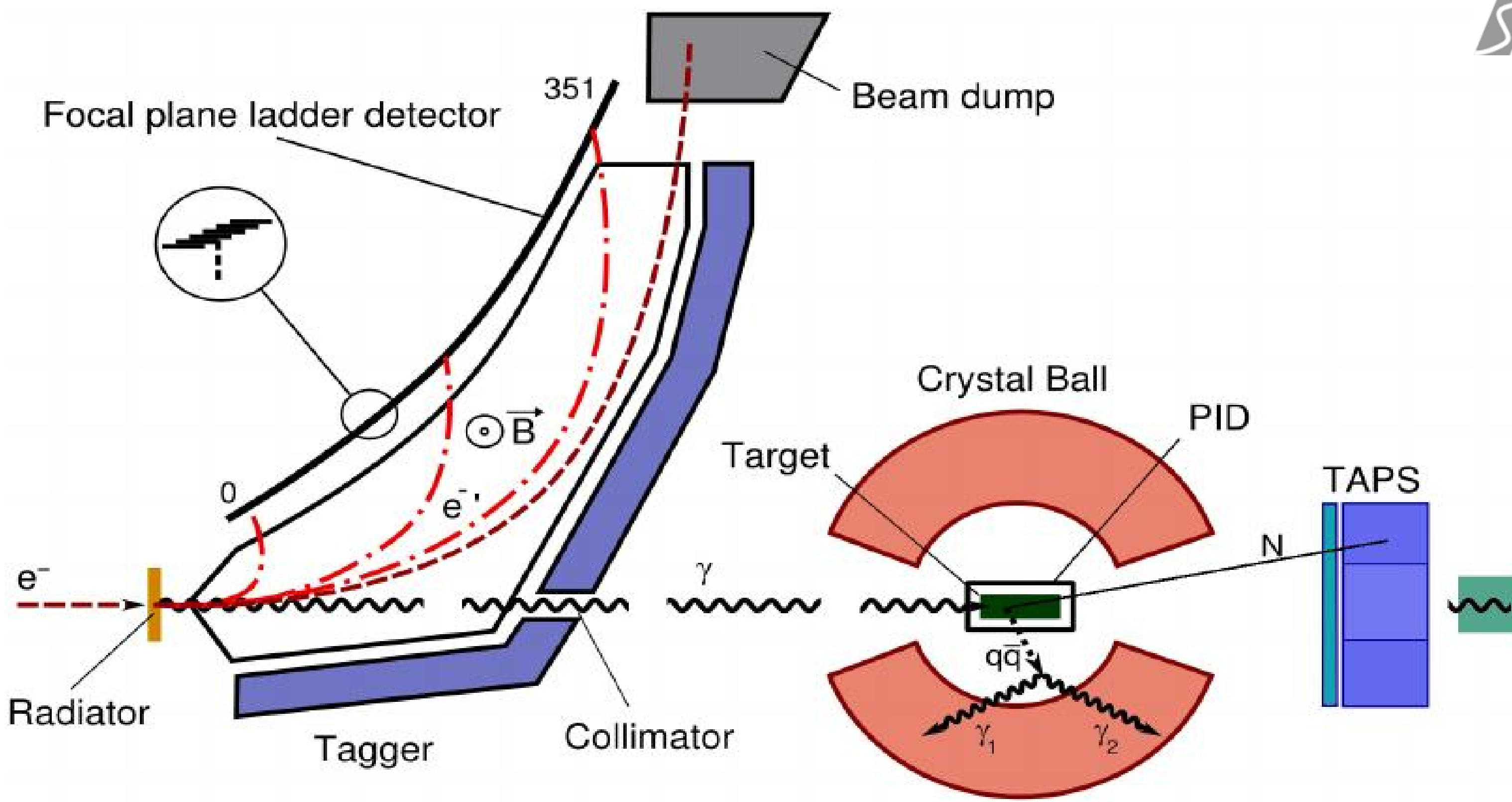
  -PID & MWPC

  -Pizza

  -TAPS

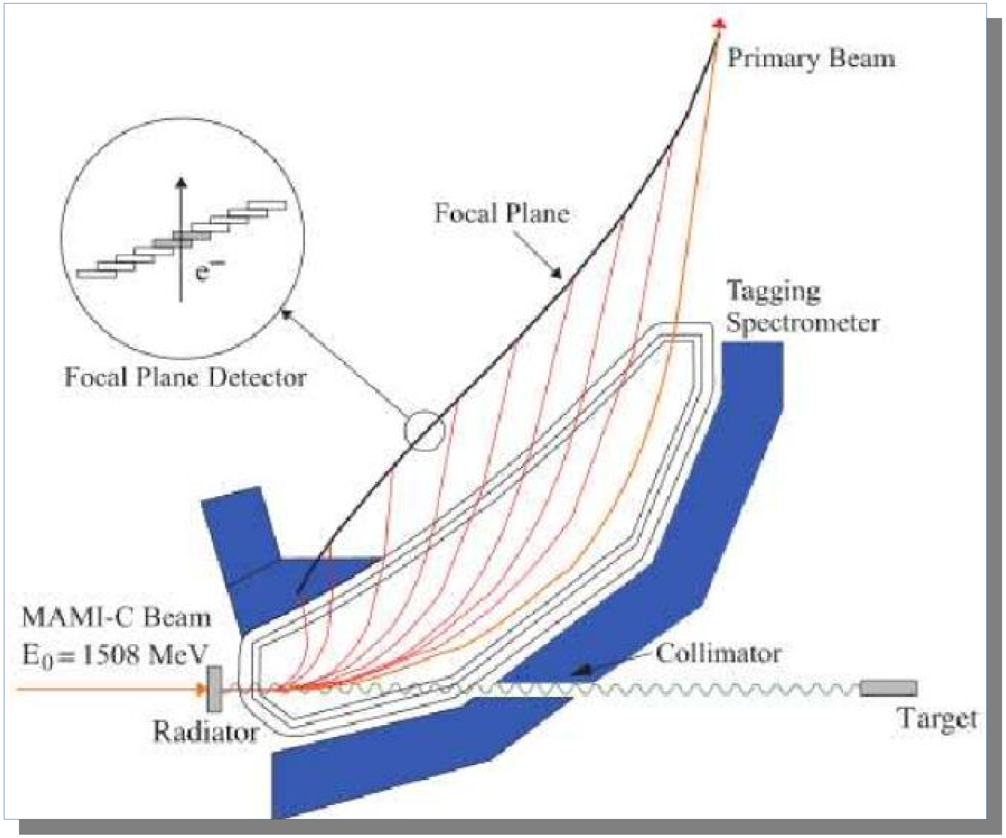


Overview of Facility- A2 in Mainz



Overview of Facility- A2 in Mainz- Glasgow Tagger

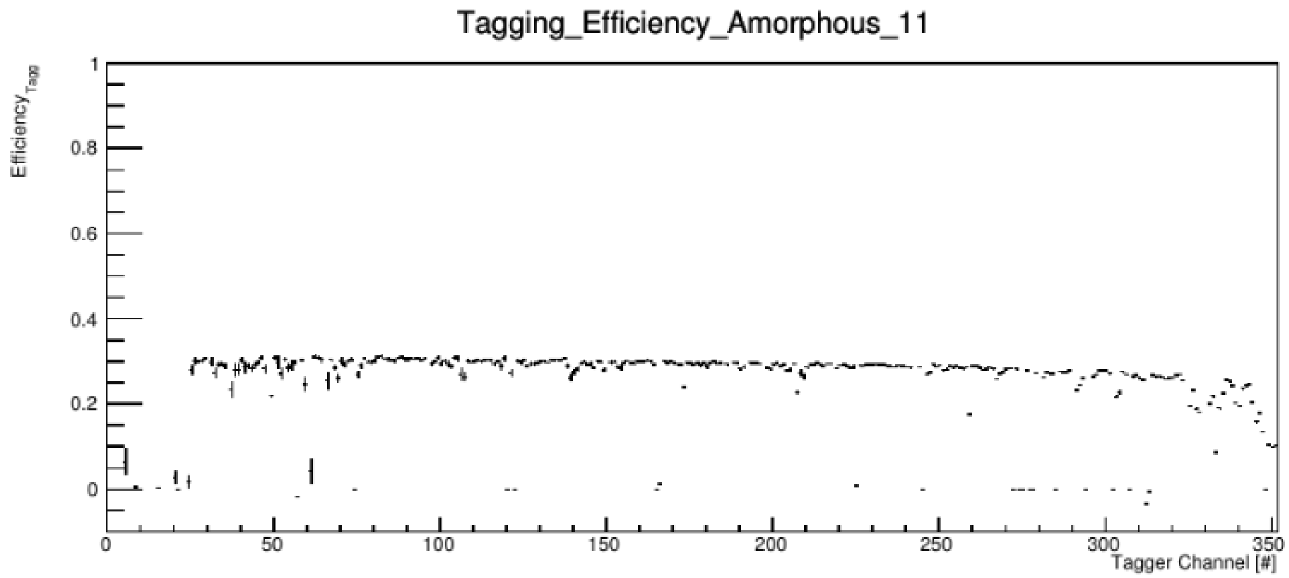
- Electrons bent into focal plane detector (FPD) of 352 channels using 2T magnet
- Photons passed through variable size collimator
- Tagging efficiency- ratio between electrons in FPD and photons passing collimation
- From the energy of the electrons in the FPD, photon energy can be deduced
- A 1/e relationship between the photon and electron energies arises



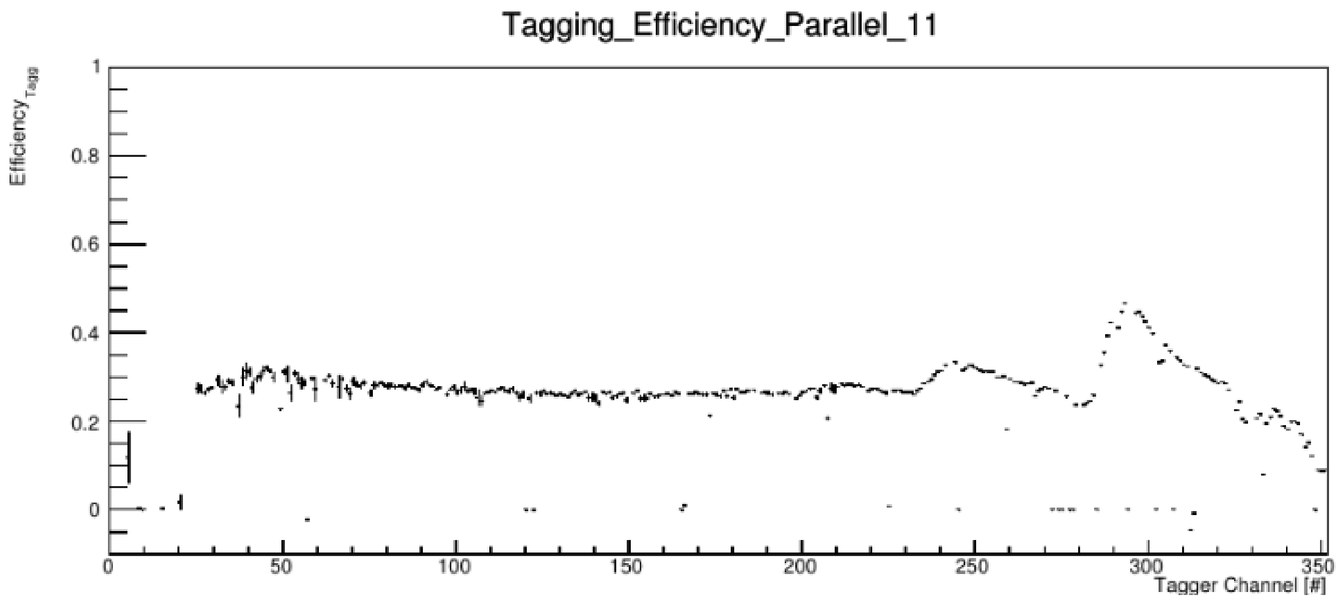
Calculating the Degree of Linear Polarisation

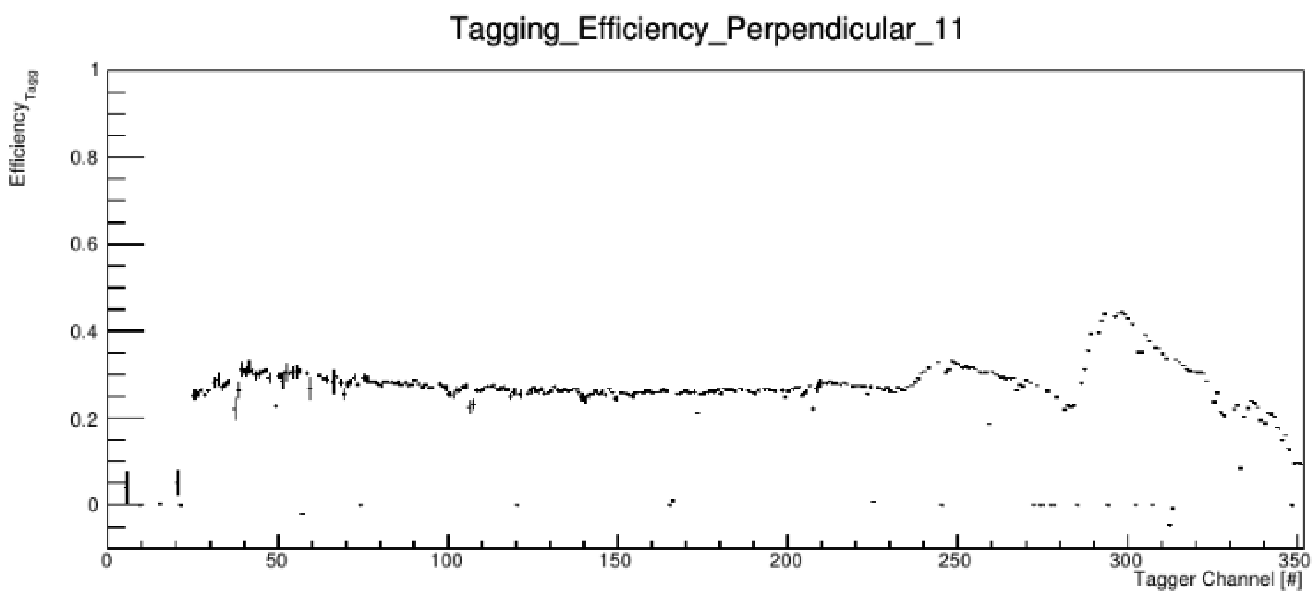
Tagging Efficiency

- Tagging efficiency- ratio between photons passing collimation and total electrons in FPD



Calculating the Degree of Linear Polarisation





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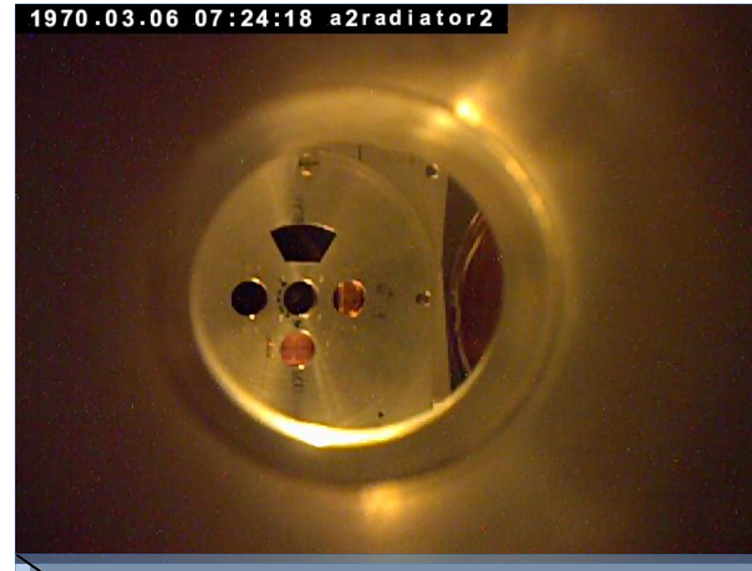
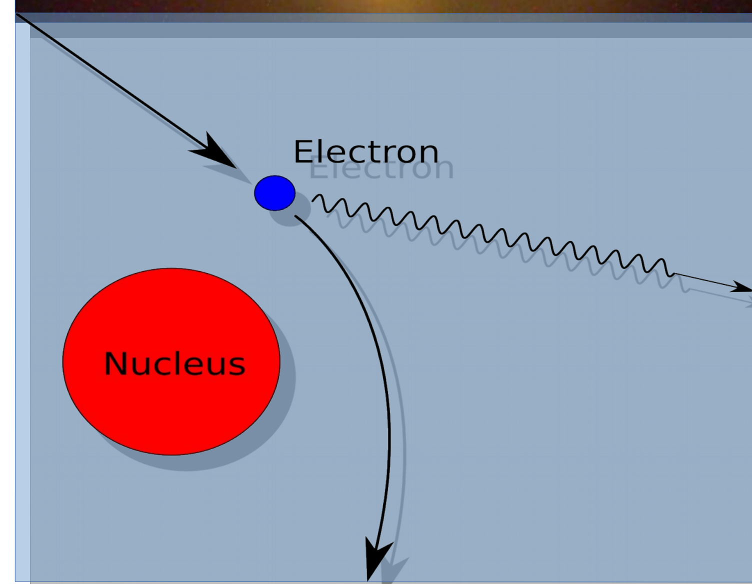
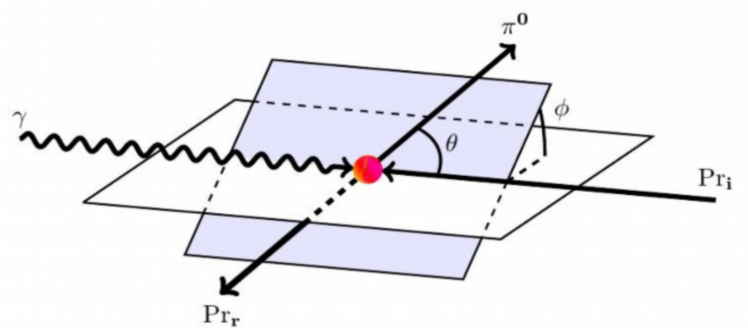
Overview of Facility- A2 in Mainz- Goniometer

- Contains the radiator(s) the electron beam impinges upon.
- Can be set to an amorphous, diamond or blank radiator.
- Diamond radiator used in linear polarisation
  -Diamond is aligned along lattice planes providing preferential planes for momentum transfer
- High Debye-Waller Factor- low thermal fluctuation
  -This will be in one of two orientations of $\pm 45^{o}$
  - A coherent polarised photon beam is produced





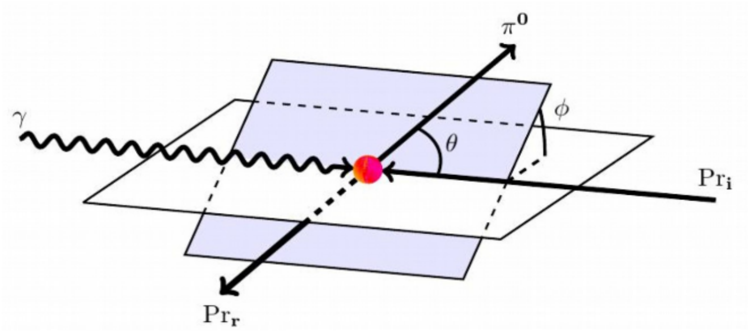
Coherent Bremsstrahlung

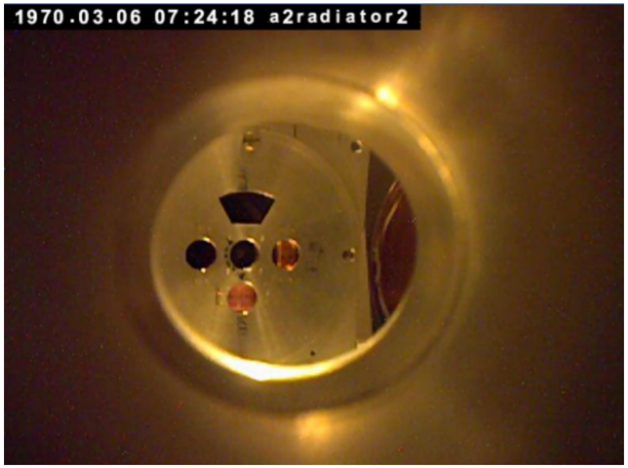


- Analagous to Bragg Scattering
- Scattering from lattice produces coherent peaks; polarisation in primary peak can be high

Coherent Bremsstrahlung

- Analagous to Bragg Scattering
- Scattering from lattice produces coherent peaks; polarisation in primary peak can be high
- Orientation of the plane (para/perp) is about phi
- The polarisation of the peaks is adjusted by changing the angle of the crystal between the lattice and the beamline





Calculating the Degree of Linear Polarisation

- An incoherent contribution is still present from during the coherent process.
- Collective excitations arising from the periodic structure of the crystal- phonons- cause this, giving the crystal cross-section as:

$$\sigma^{crystal} = \sigma^{coh.} + \sigma^{incoh.}$$

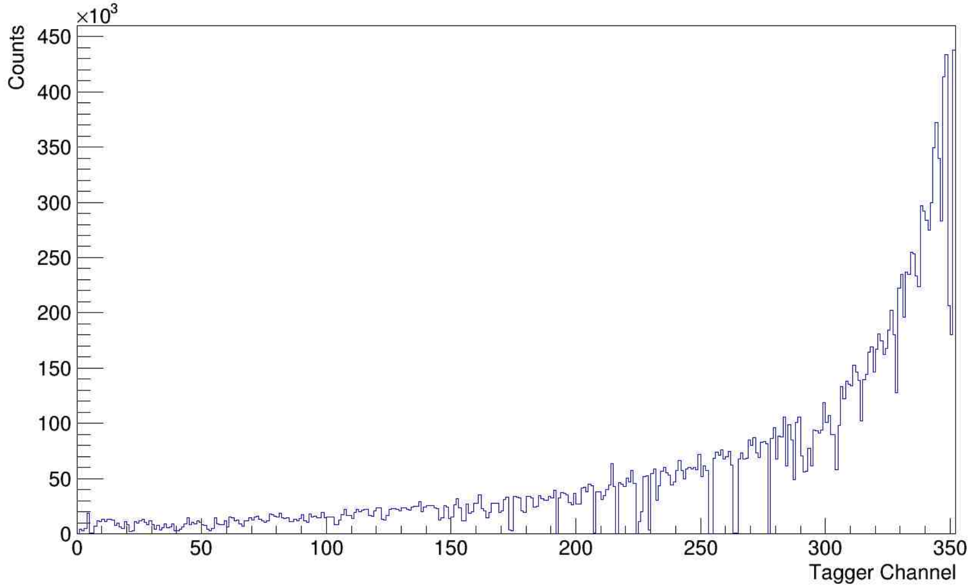
- To remove the incoherent contribution we use an enhancement, dividing by an incoherent spectrum produced using a separate radiator given as:

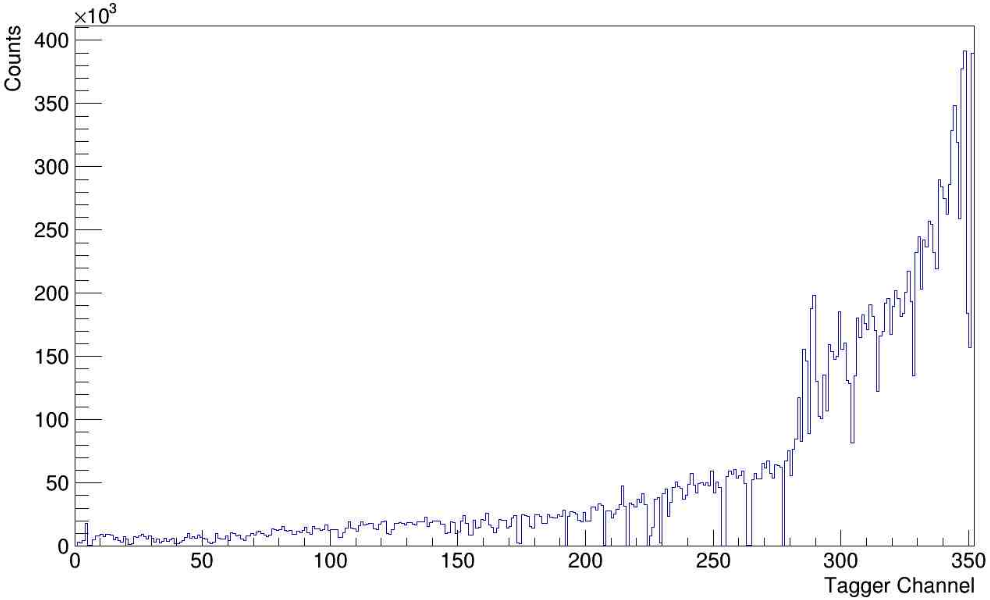
$$R = \frac{\sigma^{crystal}}{\sigma^{in}}$$

Coherent Bremsstrahlung

Calculating the Degree of Linear Polarisation

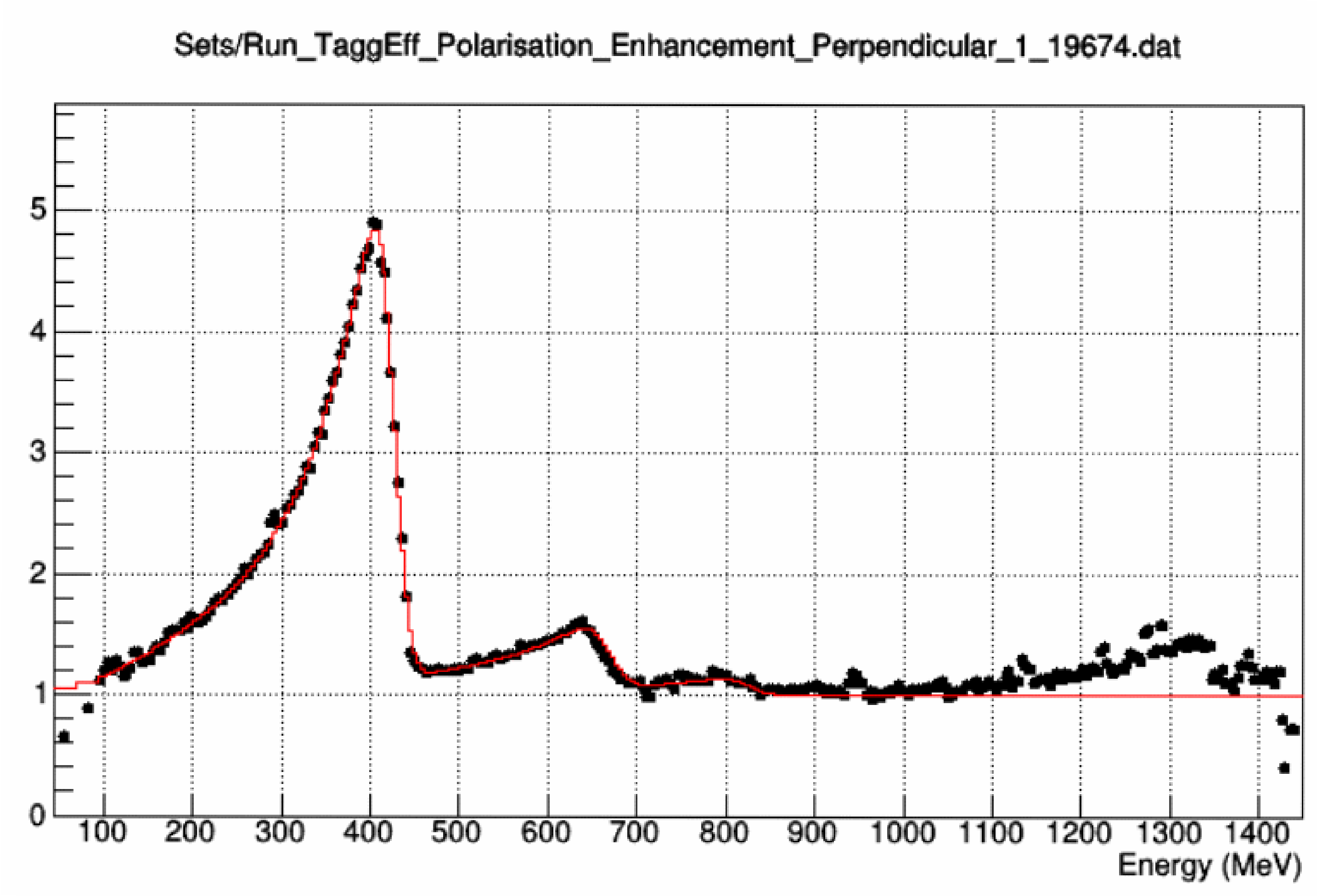
$$R = \frac{\sigma^{crystal}}{\sigma^{in}}$$





Calculating the Degree of Linear Polarisation

$$R = \frac{\sigma^{crystal}}{\sigma^{in}}$$



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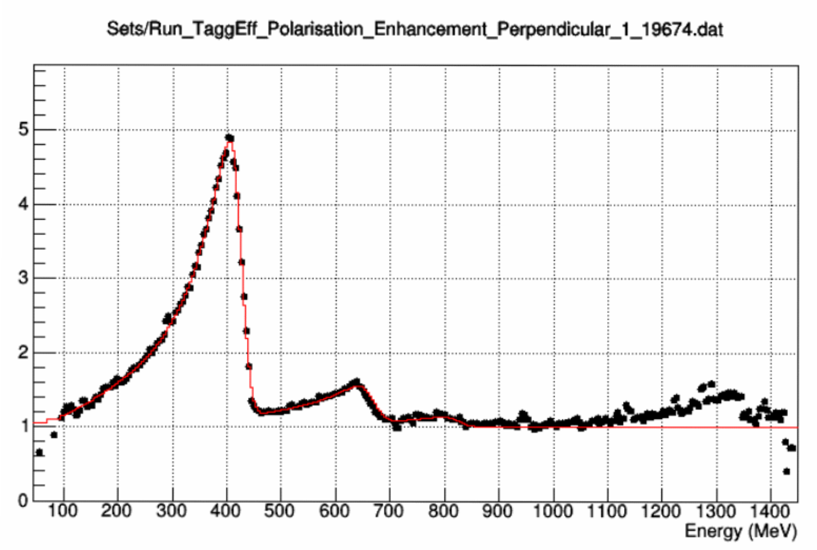
Coherent Bremsstrahlung

- Sharp drops of photon energies associated with discontinuity points, x_d are seen at the coherent edge.

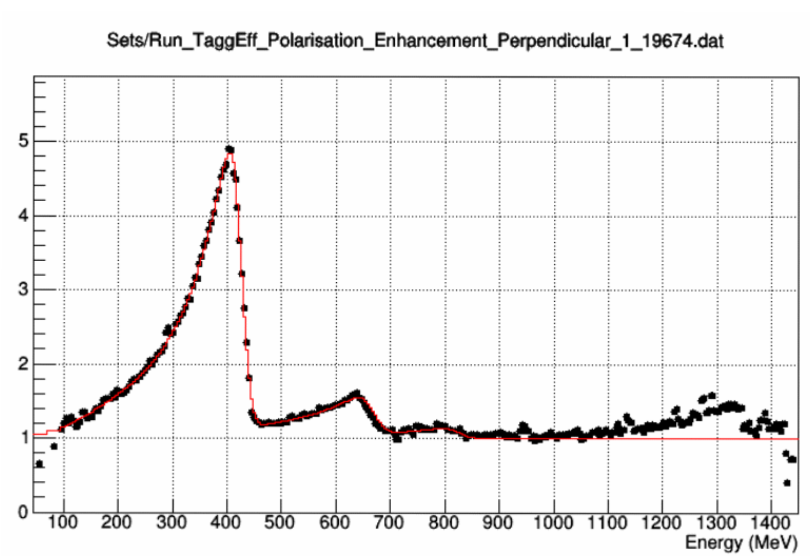


Coherent Bremsstrahlung

$$R = \frac{\sigma^{crystal}}{\sigma^{in}}$$

- Sharp drops of photon energies associated with discontinuity points, x_d are seen at the coherent edge.
- The peaks that can be seen in the enhancement spectra arise from the reciprocal lattice vectors giving allowed momentum transfers.
- Coherent component of $\sigma^{crystal}$ is given as:

$$\sigma^{coh} = \sigma^{perp} + \sigma^{para}$$



Calculating the Degree of Linear Polarisation

Linear Polarisation

- The parallel and perpendicular enhancement files are separated by polarisation- para/perp

Calculating the Degree of Linear Polarisation

Linear Polarisation

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- A fitting function is applied to the enhancement information

Calculating the Degree of Linear Polarisation

Linear Polarisation

- The parallel and perpendicular enhancement files are separated by polarisation- para/ perp
- A fitting function is applied to the enhancement information
- It is a secondary function which then calculates the degree of polarisation, used to generate the polarisation tables detailing the degree of polarisation for given coherent edge positions, beam energies and photon energies.

Calculating the Degree of Linear Polarisation

Enhancement fitting function

$$\xi^s_{tot}(x,G,\theta,\sigma) = \frac{\int_{\theta-3\sigma}^{\theta+3\sigma}\left\{e^{\frac{(\theta'-\theta)^2}{2\sigma^2}}\left[1+\frac{\sum_{g=2,4,..}^{G} I_g^0 \times C(x,g,\theta')\times\chi_g(x,g,\theta')}{I_{amo}(x)}\right]\right\}\mathrm{d}\theta'}{\int_{\theta-3\sigma}^{\theta+3\sigma}\left\{e^{\frac{(\theta'-\theta)^2}{2\sigma^2}}\right\}\mathrm{d}\theta'}$$

Function for degree of polarisation

$$P^s_{tot}(x,G,\theta,\sigma) = \frac{-\int_{\theta-3\sigma}^{\theta+3\sigma}\left\{e^{\frac{(\theta'-\theta)^2}{2\sigma^2}} \times \phi_{tot}(x,G,\theta') \times I_{coh}(x,G,\theta')\right\}\mathrm{d}\theta'}{\int_{\theta-3\sigma}^{\theta+3\sigma}\left\{I_{total}(x,G,\theta') \times e^{\frac{(\theta'-\theta)^2}{2\sigma^2}}\right\}\mathrm{d}\theta'}$$

- θ - Angle between the beam and crystal planes defined by the 022 direction
- σ - Gaussian smearing of θ to accounting for beam divergence, multiple scattering etc
- θ_r- Relative angle of collimation as defined in Timm[1] eqn 24 in units of characteristic angle
- σ_r- Smearing factor for collimation around θ_r via cummulative dist functions $C_g(x,g,\theta)$
- $I^0_2, I^0_4, ..., I^0_G$ - Amplitudes of the discrete coherent peaks

K.Livingston, *Polarisation from Coherent Bremsstrahlung Enhancement, 2011.*

Calculating the Degree of Linear Polarisation

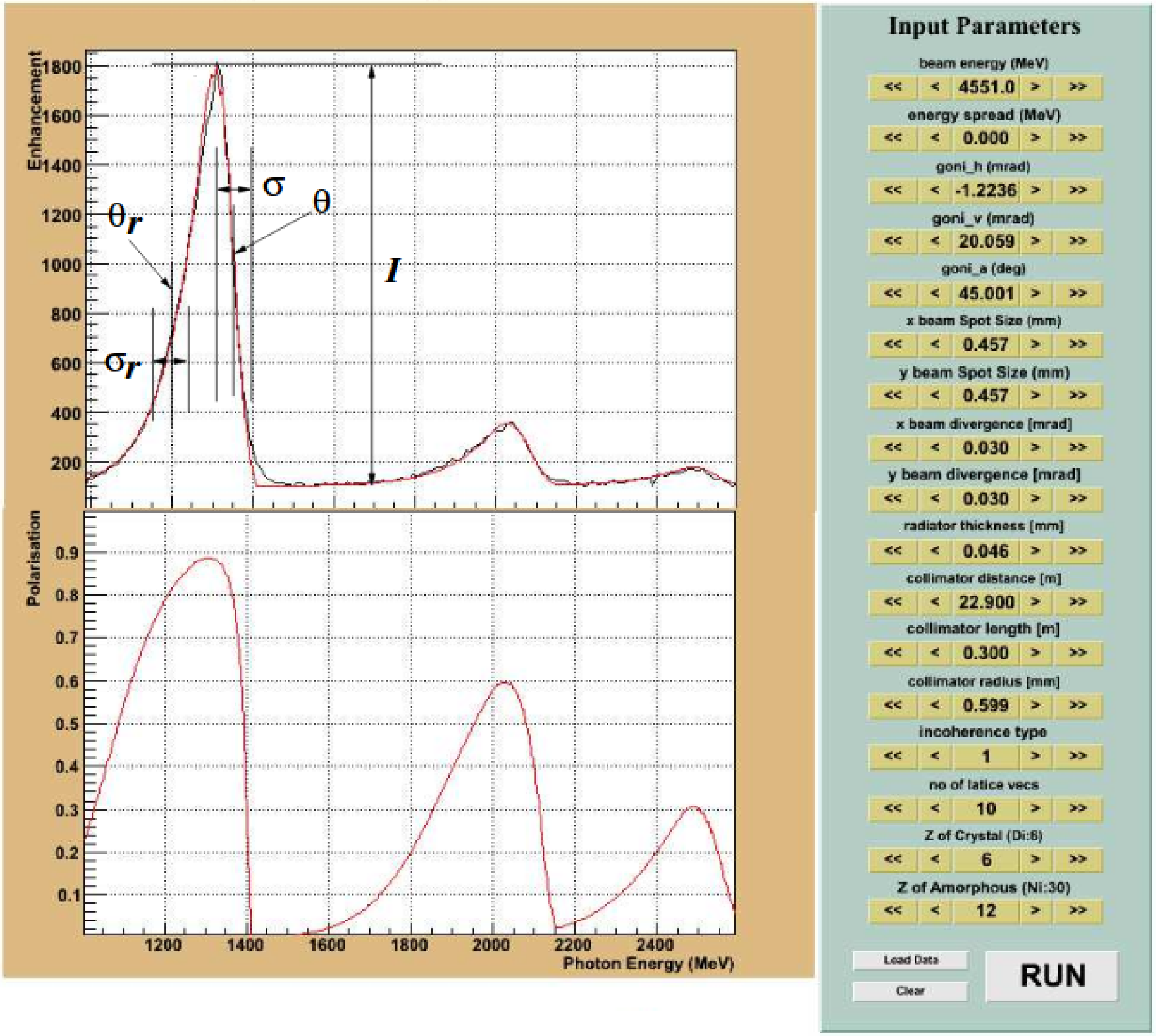
E_0 - Electron beam energy (MeV): This is normally known accurately from the experimental conditions
E_2 - Energy of the discontinuity for the 022 vector (MeV): This can be determined approximately by examining the enhancements spectrum, or by fitting the edge with a polynomial.
C_{dia} - Diameter of the collimator (mm): This is known from the experimental conditions, or can be measured.
C_{dist} - Distance from the radiator to the collimator (m): This is known from the experimental conditions, or can be measured.
n_g - number of vectors to be used from the sequence 022,044,066,088...

...where the above parameters are used to make first guesses at the values of the fit parameters.

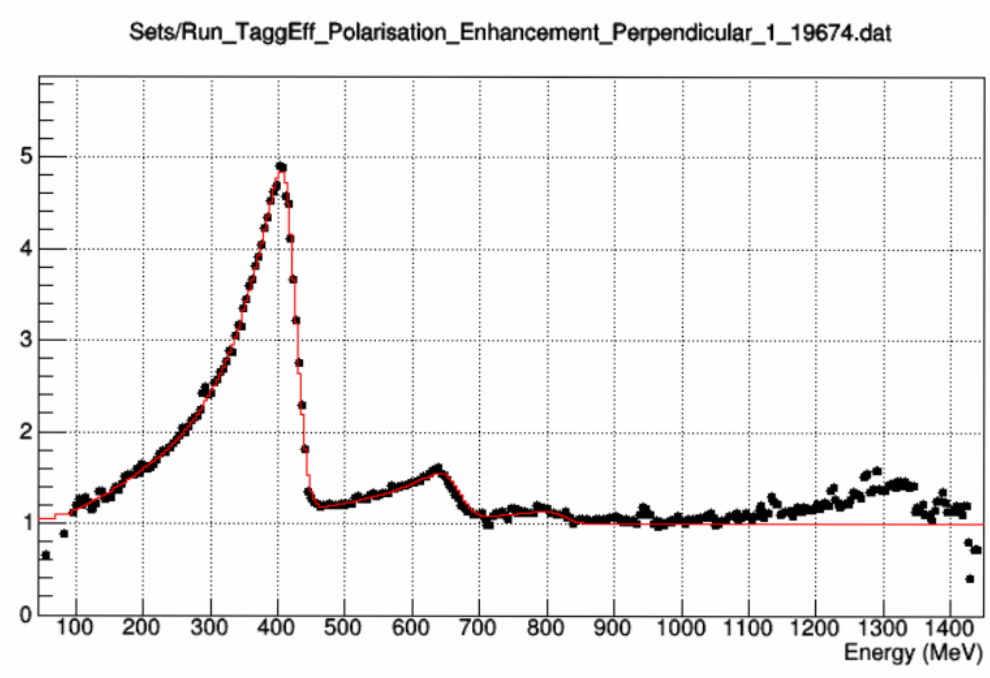
K.Livingston, *Polarisation from Coherent Bremsstrahlung Enhancement, 2011.*

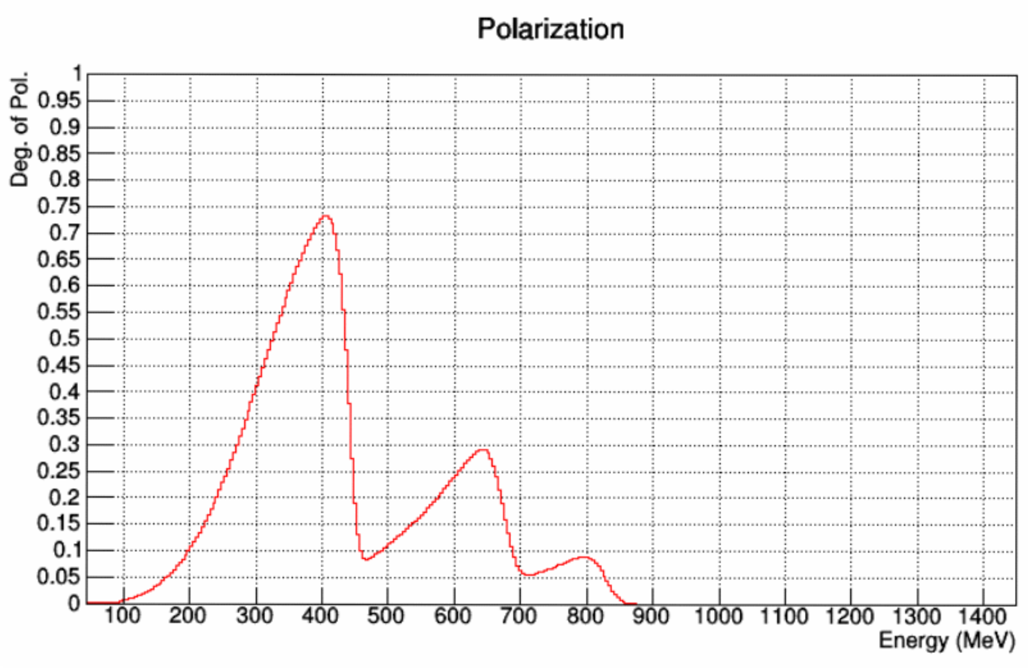
Calculating the Degree of Linear Polarisation

Edge in range 1330-1360 MeV, PARA

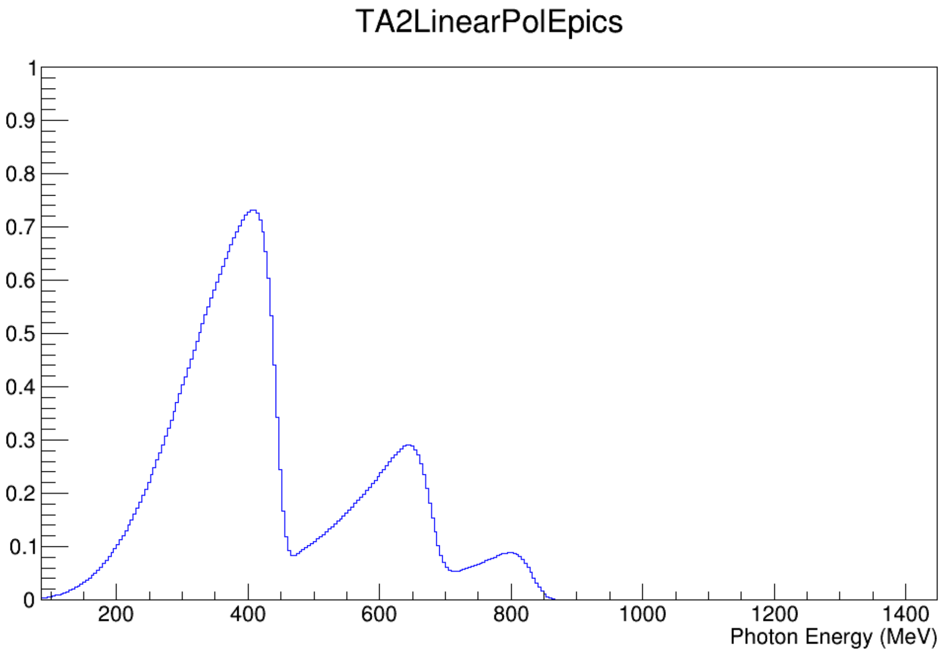


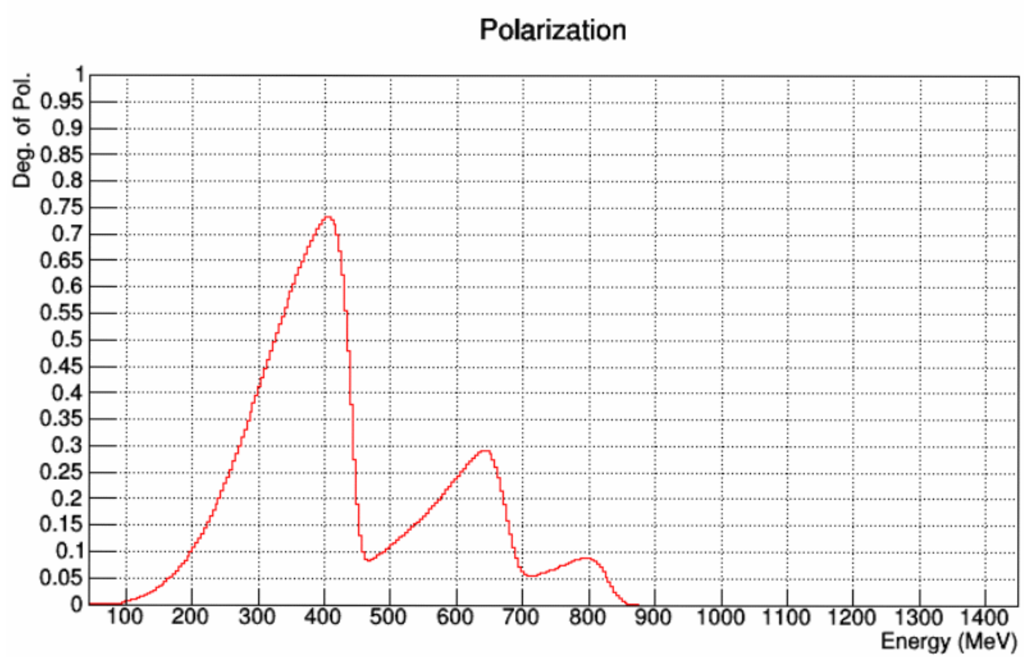
Polarisation Enhancement and Degree of Polarisation



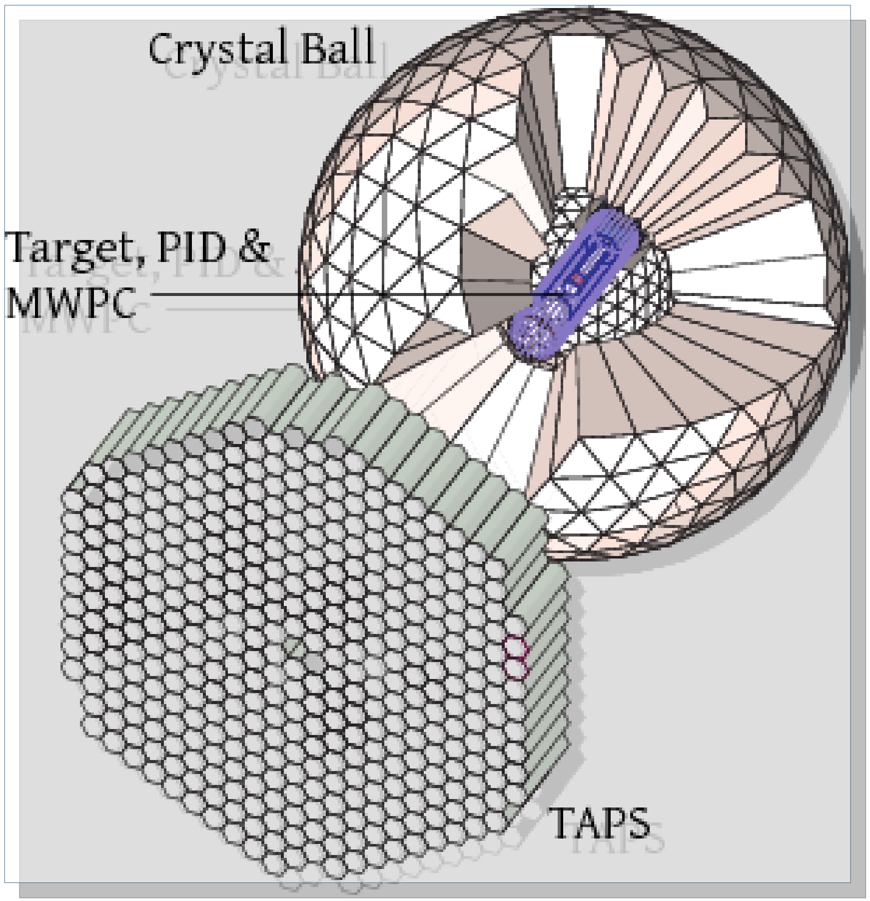


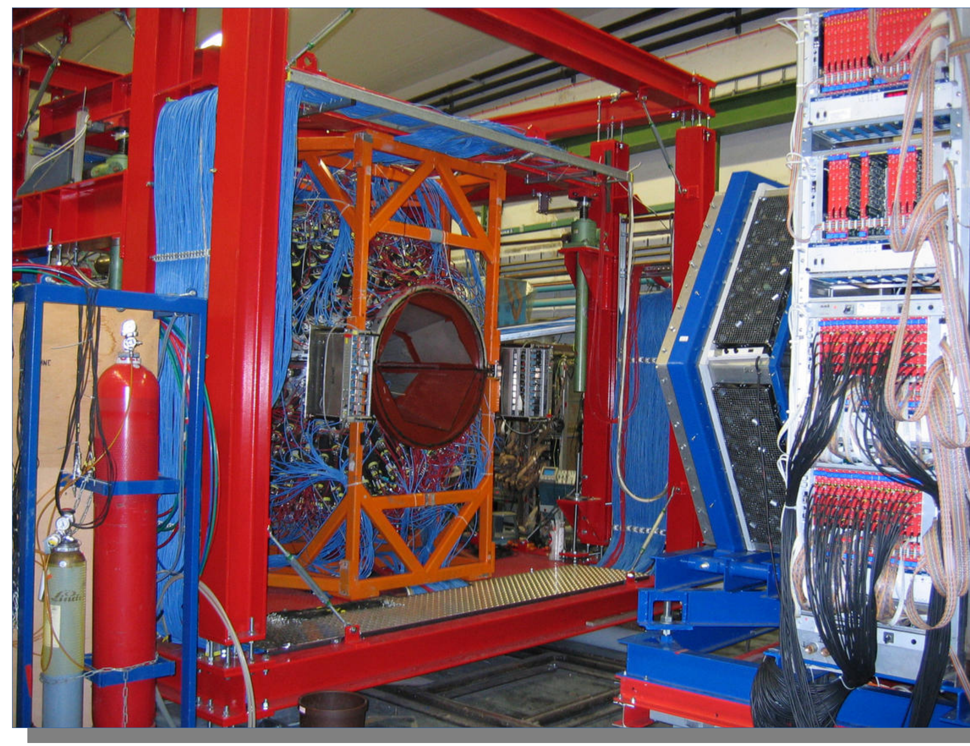
Linear Polarisation From Production Data



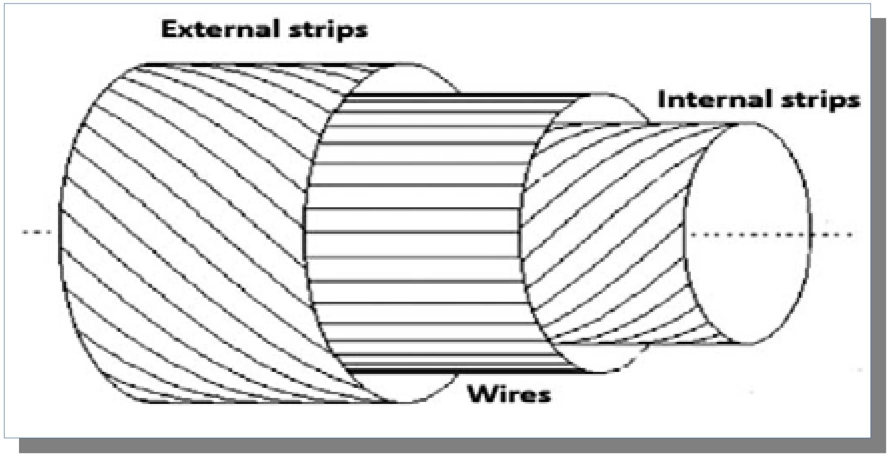


Overview of Facility- A2 in Mainz- Crystal Ball, PID & MWPC





Overview of Facility- A2 in Mainz- Crystal Ball, PID & MWPC

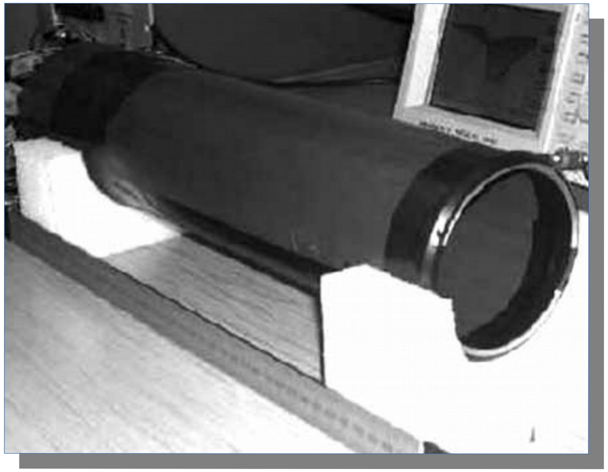


Crystal Ball

- 672 Thalium doped Sodium Iodide (NaI) crystals
- 96% 4π solid angle coverage

PID and MWPC

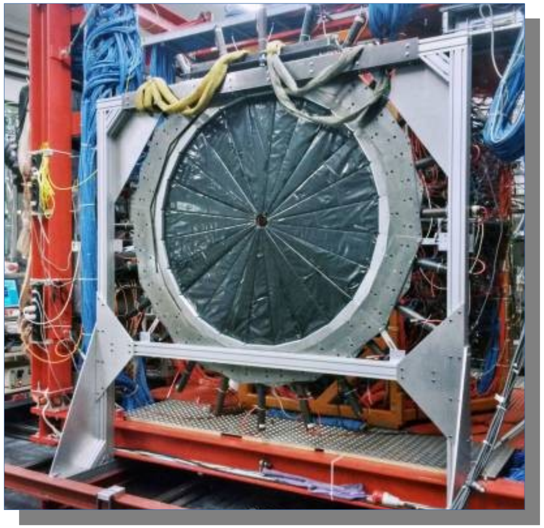
- **MWPC**- Multiwire proportional chambers
  - charged particle tracking detector
  - Two wire chambers
- **PID**- Particle Identification Detector
  - -24 plastic scintillators
  - -Identifies charged particles via energy losses and variation of the azimuthal angle



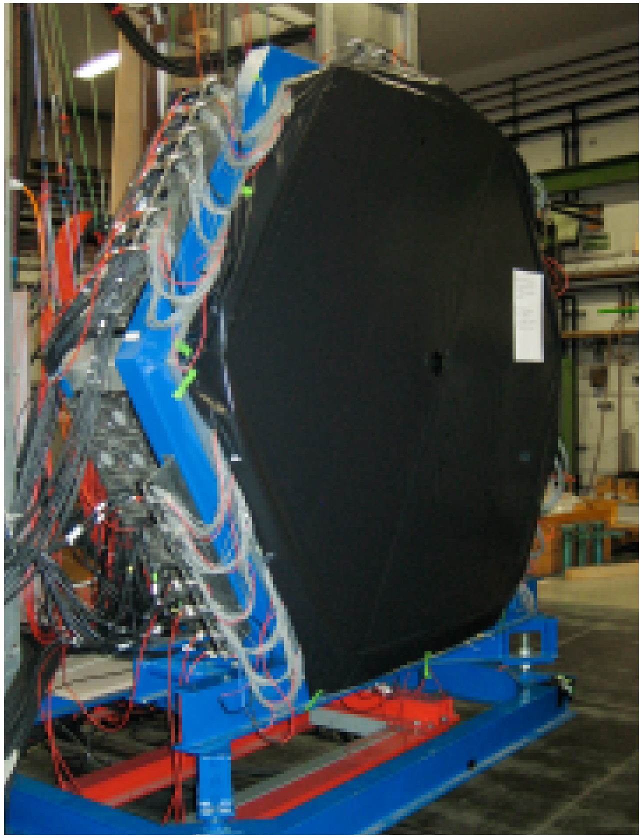
Overview of Facility- A2 in Mainz- TAPS and Pizza detector

Pizza

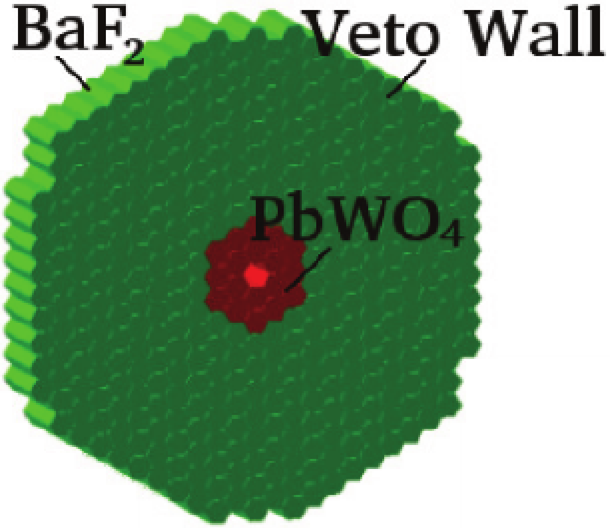
- Holds carbon polarimeter in center
- 24 scintillators/ pizza slices
- Enables high resolution dE/E for TAPS
- High efficiency for proton and pions



TAPS



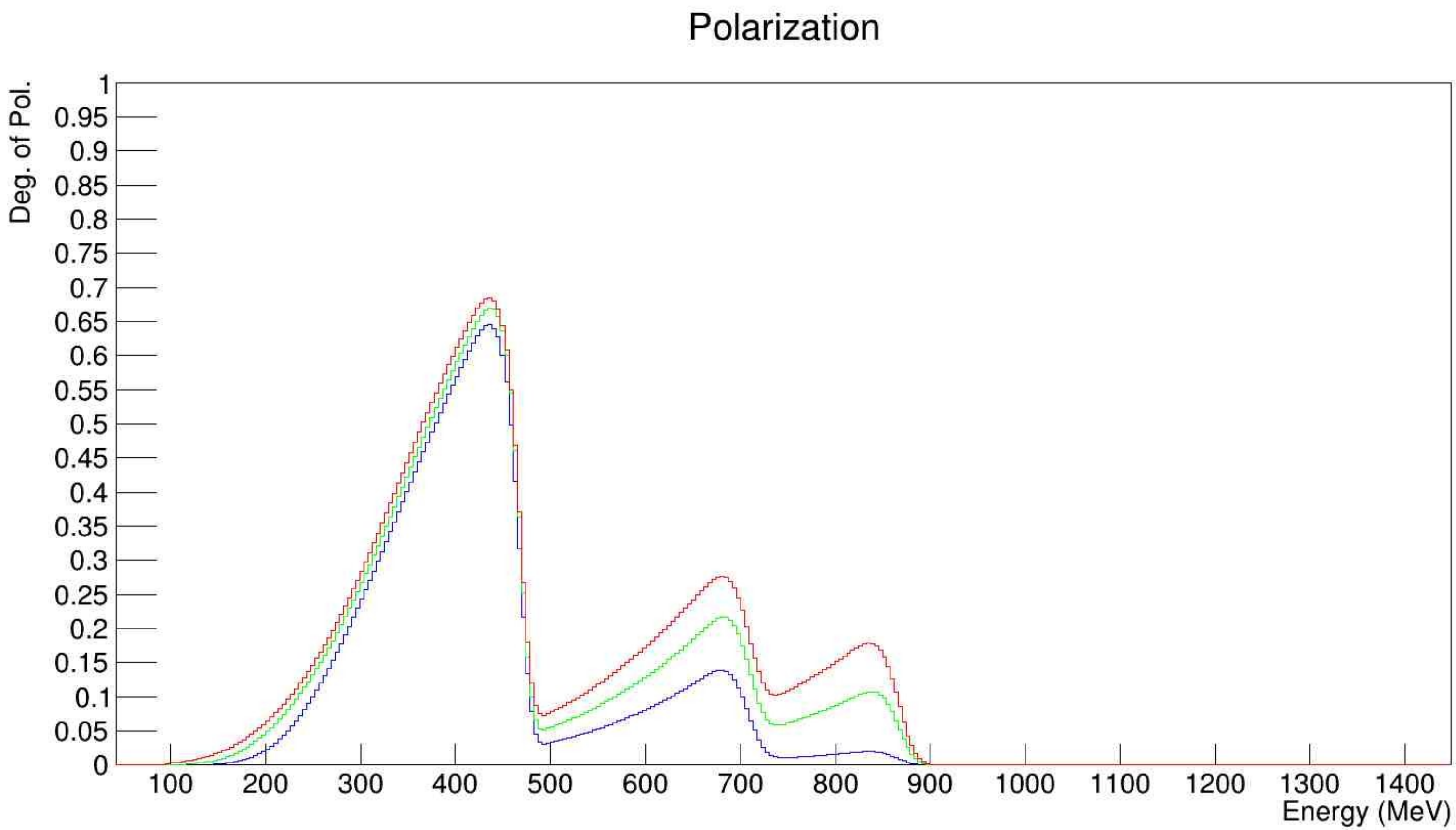
- Two Arm Photon Spectrometer
- Covers forward angles for $0^{o} < \Theta < 20^{o}$
- Plastic Scintillator Veto Wall
- 366 hexagonal BaF_2 crystals on vito
- 72 Pwo4 Crystals
- $0.037/E\gamma 0^{0.25}$ (GeV) ~



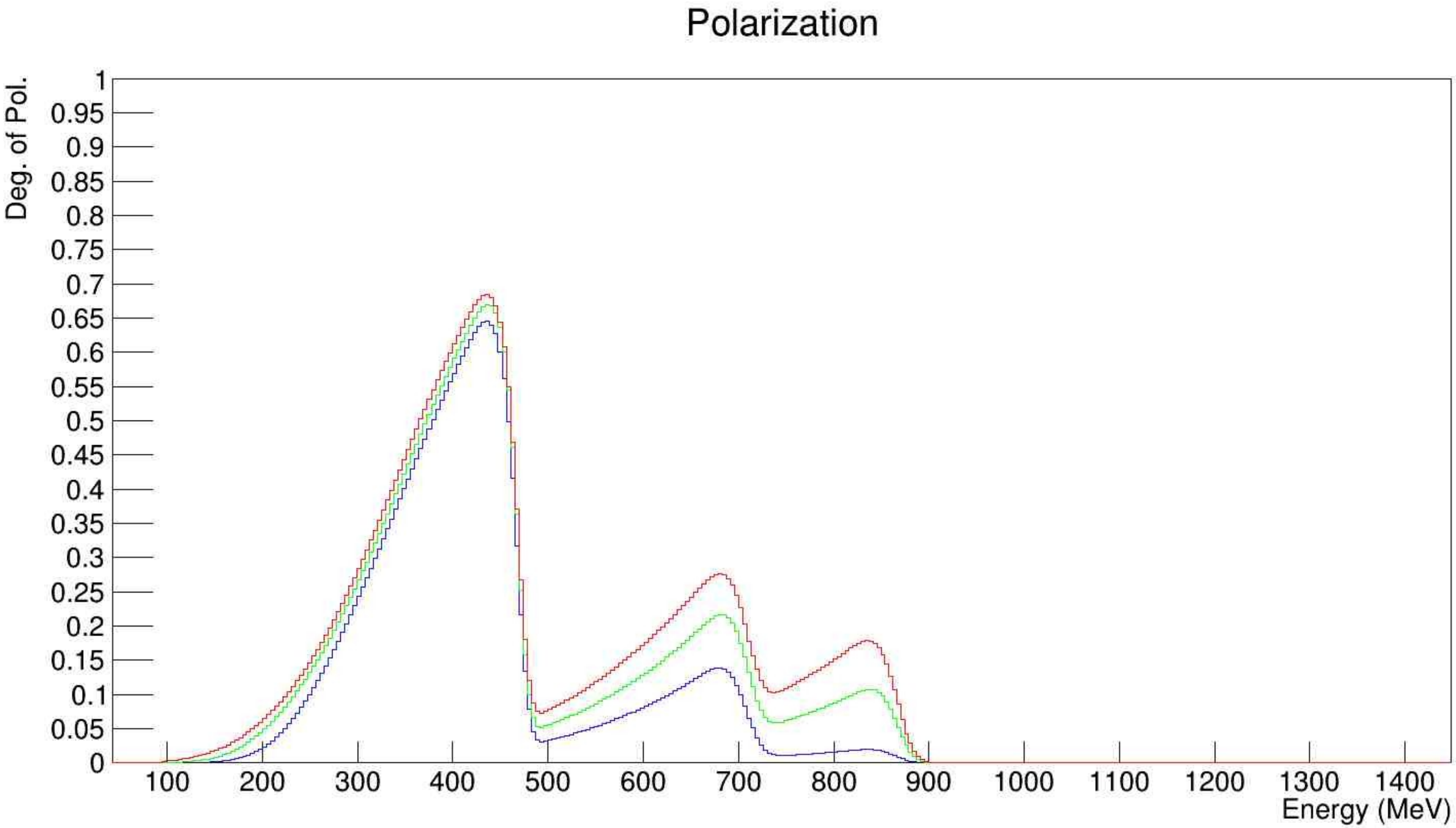
If we can already measure the degree of linear polarisation,

why are you looking at alternative methods?

Linear Polarisation- Systematics



Linear Polarisation- Systematics



-Systematic shift due to the choice of baseline when at 450 MeV.

-By looking at the peak polarisation between the blue and green points, where green was the experimentally used baseline, we can see a change in degree of polarisation of about 3 MeV.

-This gives a percentage change in polarisation between the green and blue of 68/65 = 1.046 (1.05), Representing a 5% uncertainty in the linear polarisation due to the choice of baseline.

Experiment

- **Use a calibration reaction-**

- Coherent pion production:

$$\gamma + {}^{12}C \rightarrow {}^{12}C + \pi^0$$

Well defined beam asymmetry of 1

- Photon asymmetry for coherent pion production on a spin zero nucleus is 1

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Use of Carbon as a Polarimeter

Experiment

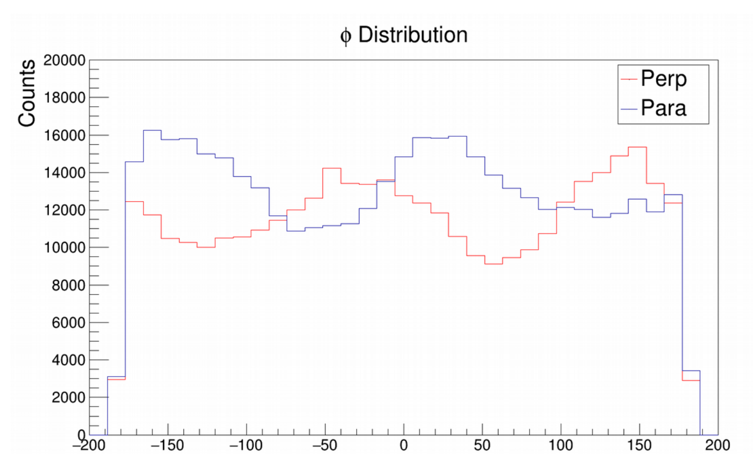
- Flux in each polarised plane:

$$N_{\|}(\phi) = a(\phi)N_{\|}(1 + P_{\|}(\Sigma\cos(2\phi + \phi_0)$$

$$N_{\perp}(\phi) = a(\phi)N_{\perp}(1 - P_{\perp}(\Sigma\cos(2\phi + \phi_0)$$

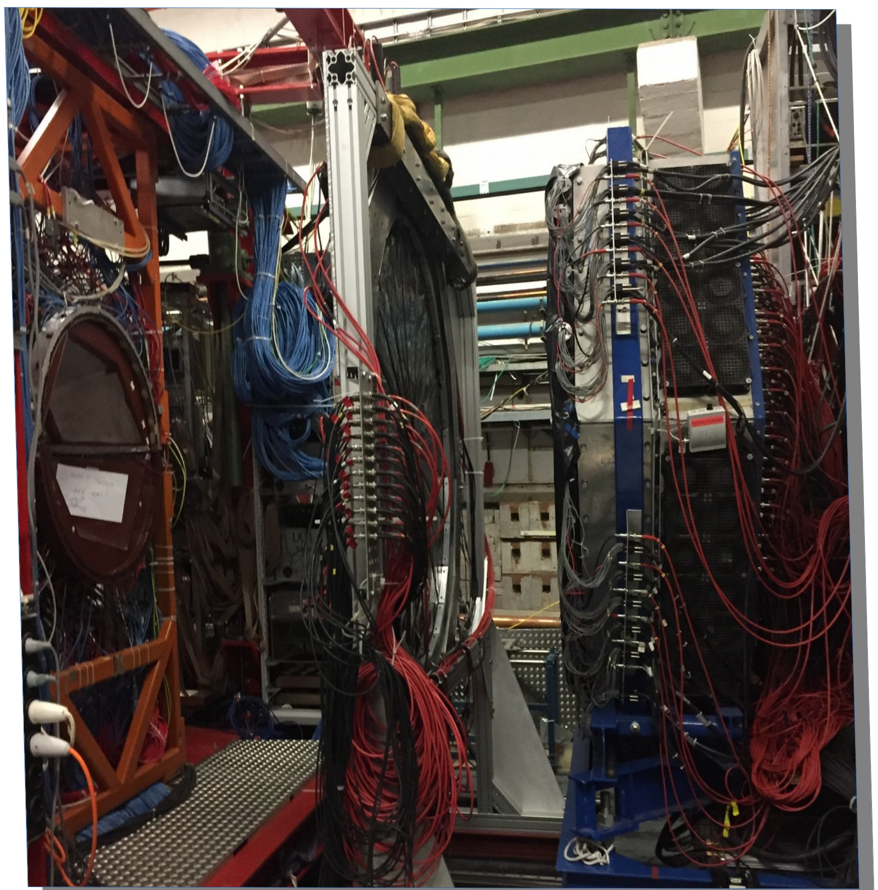
- Relationship between asymmetries and known variables used to find degree of polarisation
- Detector acceptance affects cancelled by taking asymmetry
- Photon asymmetry measured as

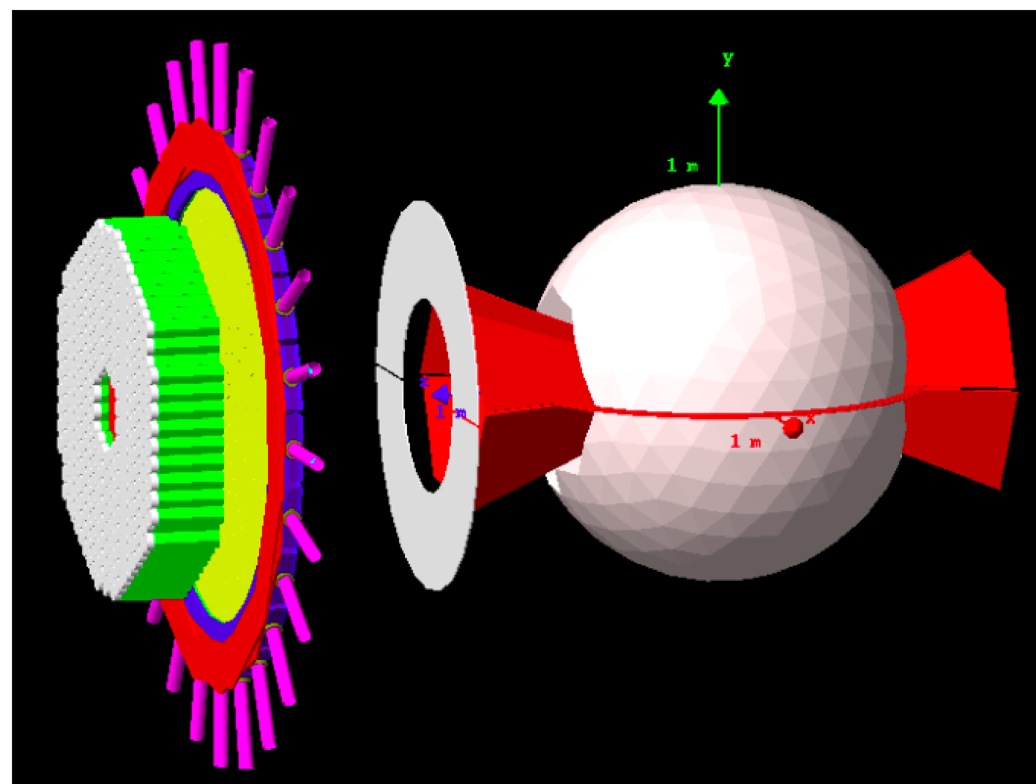
$$\frac{N_{\|}(\phi) - N_{\perp}(\phi)}{N_{\|}(\phi) + N_{\perp}(\phi)}$$



Experiment

- Experiments performed in January, May and June '17 on He and LH2 targets.
- 5mm ^{12}C Polarimeter held in centre of pizza detector.





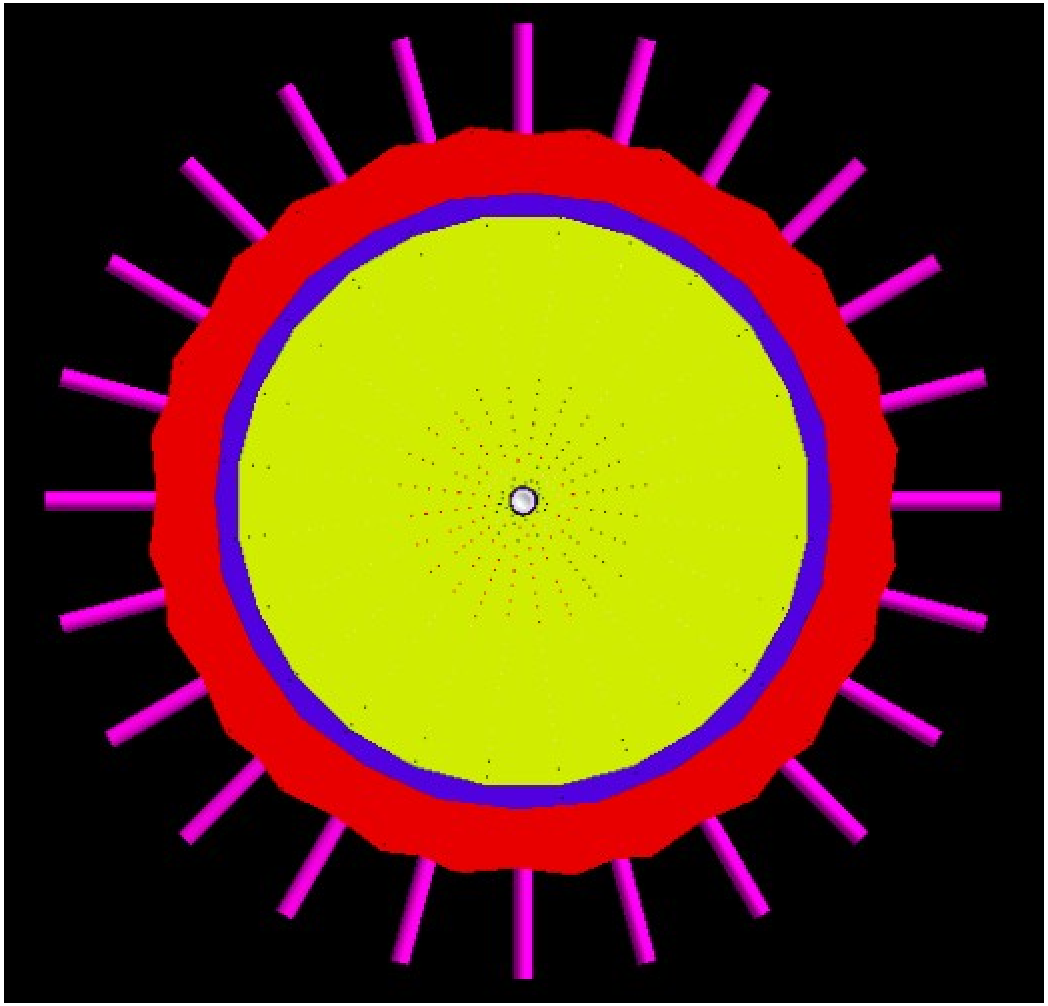
- **Experiment – Primary Concerns**

- Background from events in the CB (vertex placement) and 2 background channels:
  -Incoherent reactions off the carbon
  - Pi0 photoproduction off the proton

- Statistics

- Incoherent and coherent separation

Use of Carbon as a Polarimeter



'Pizza Carbonara'

Experiment

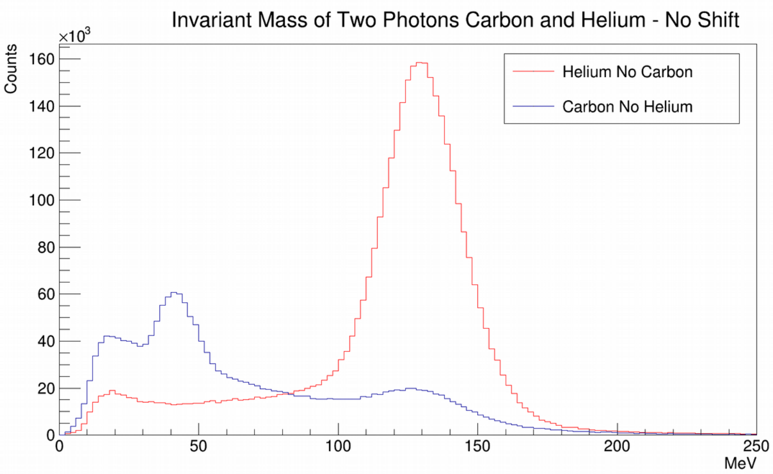
- Due to the placement of the carbon target, background will be present from the primary target
- Veto is in place to remove charged particle noise, reduce signal and erroneus photons
- Ejects the entire detector set prior to TAPS
- Nicknamed ‘Detector ejection Veto’ - De Vito

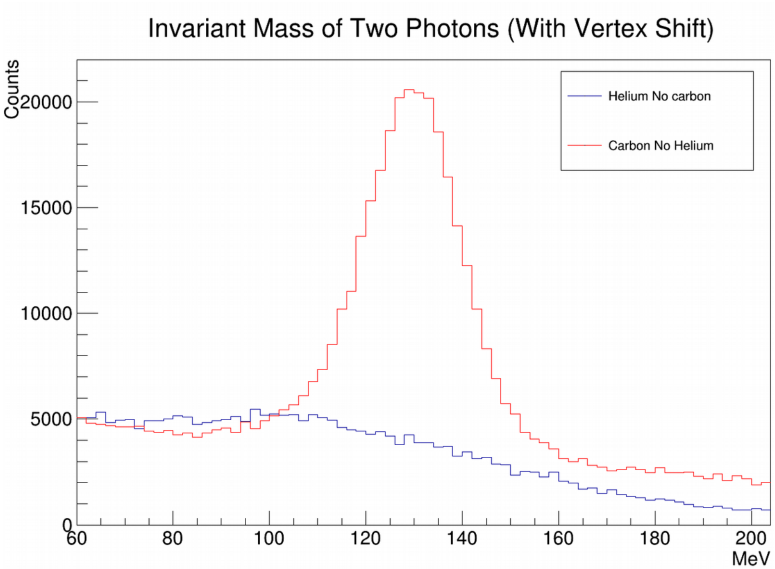
- Veto reduces number of events from $\simeq 4\text{x}10^6 \rightarrow 4\text{x}10^5$
- In final pion peak of interest, events are cut to $\simeq$ 40,000

Experiment

Vertex

- Vertex position needs to be moved from the CB to the carbon target
- Will get pions from vertex in either target
- We should see pions produced from both vertex positions
- We see ≃ 5% of pions after the vertex shift are from the carbon, after shifting the vertex- about 5000 counts at the peak





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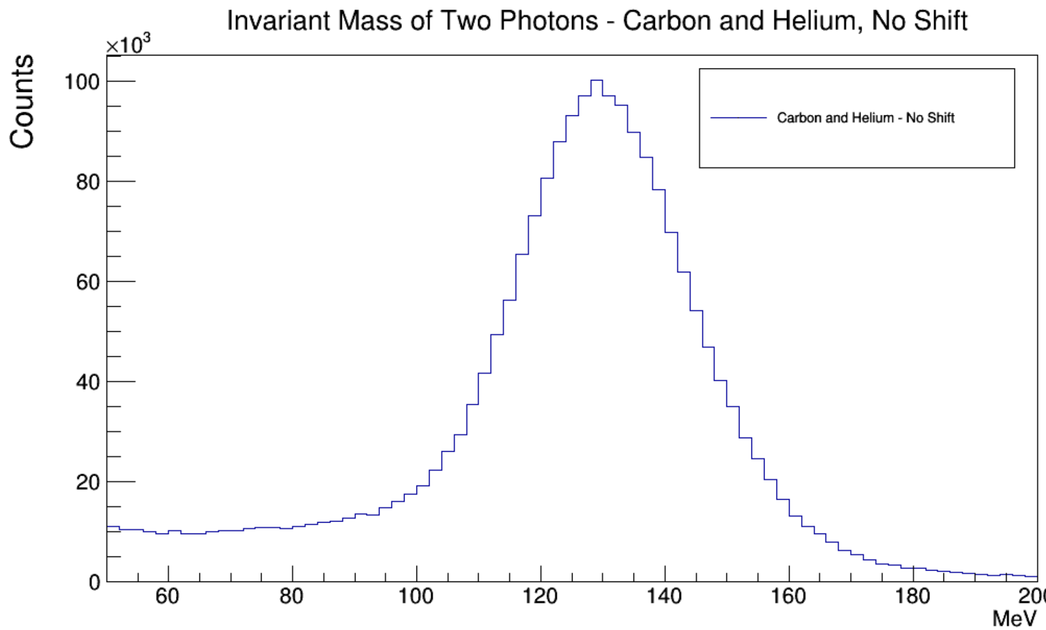
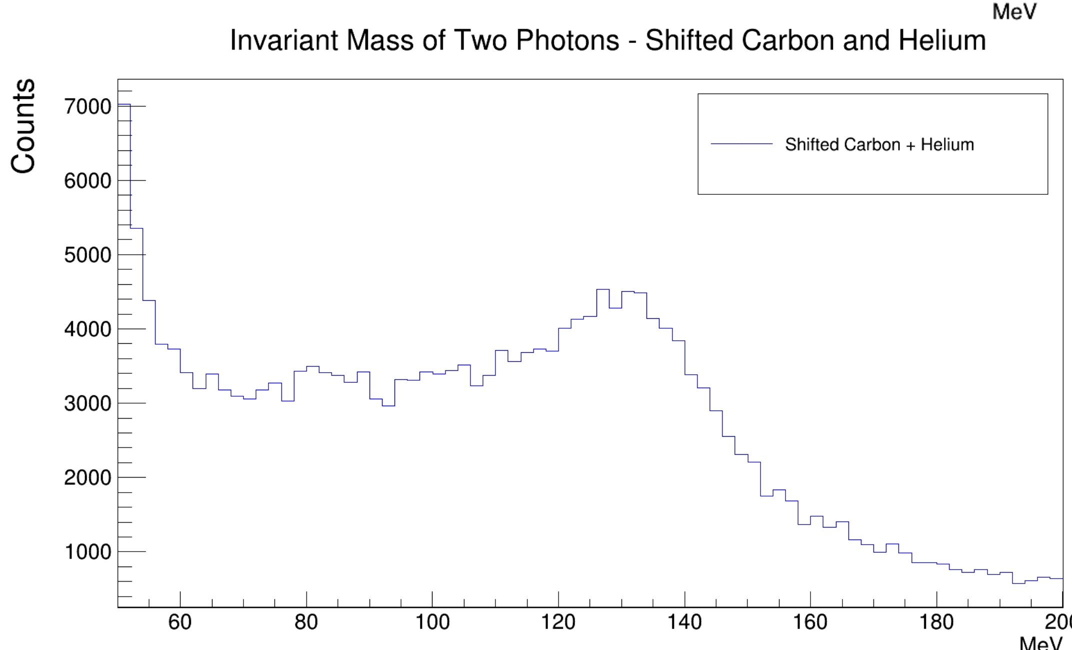
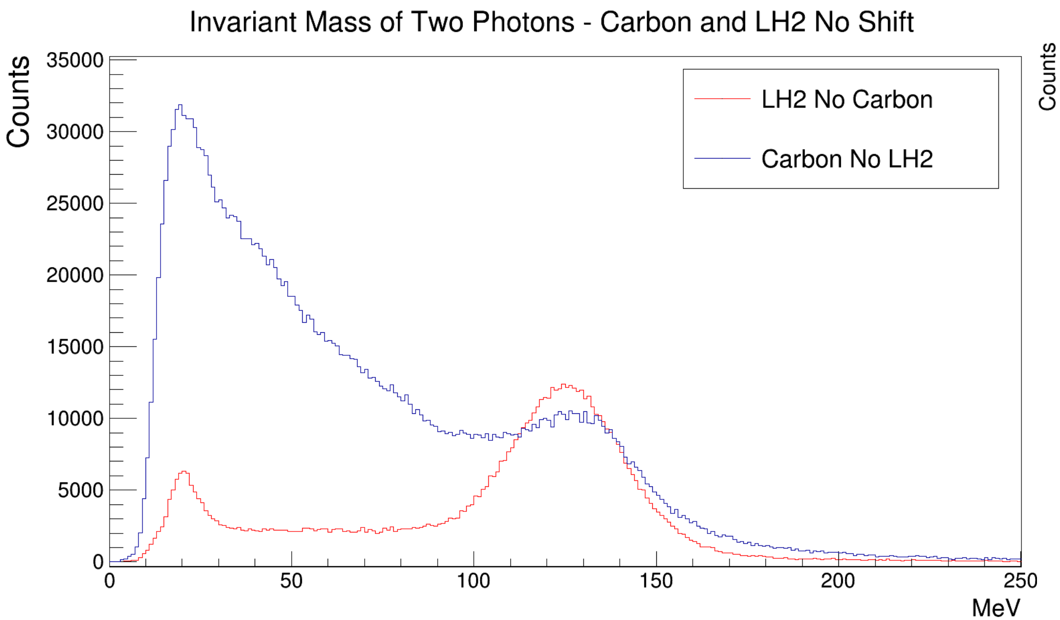
Analysis

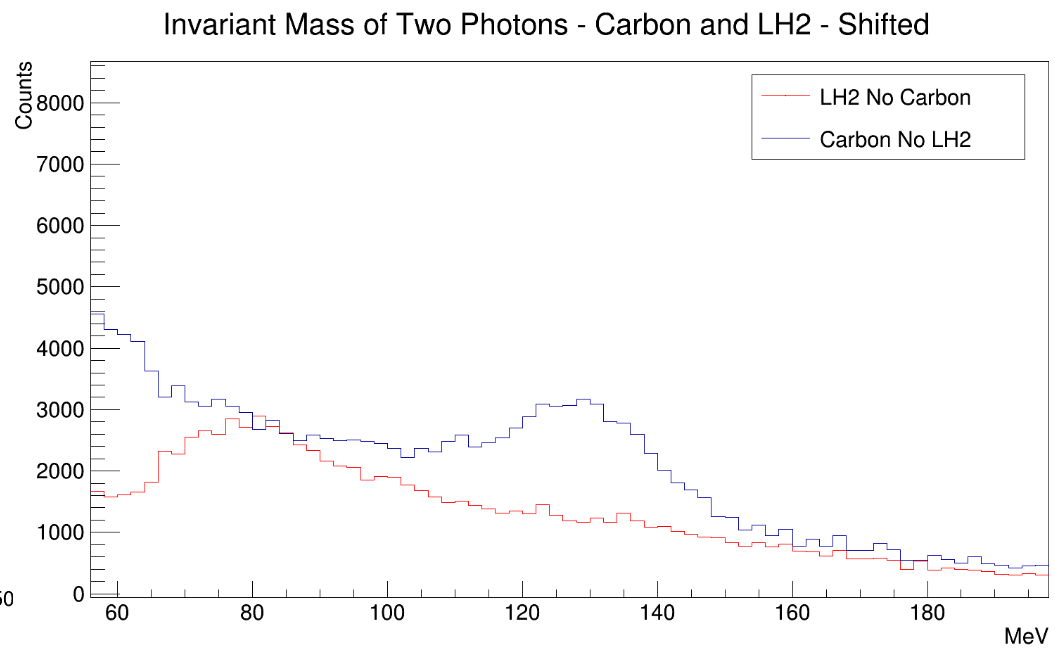




Analysis



Invariant Mass of Two Photons - Carbon and LH2 No Shift
Counts
MeV
LH2 No Carbon
Carbon No LH2



Invariant Mass of Two Photons - Carbon and LH2 - Shifted
Counts
MeV
LH2 No Carbon
Carbon No LH2

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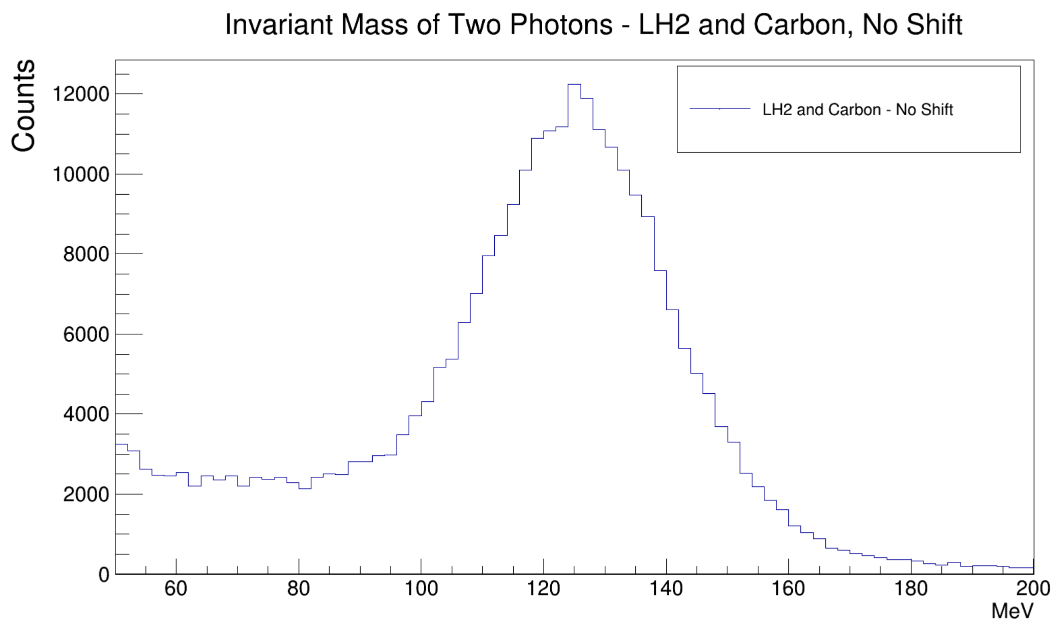
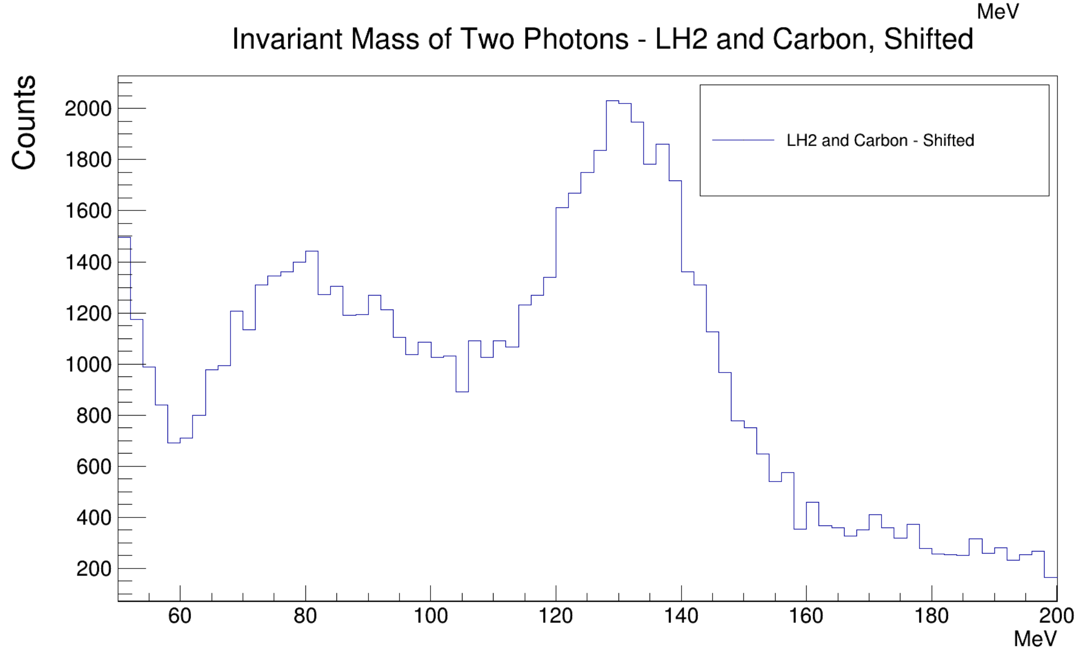
Analysis





Simulation

Experiment

- Reconstruction of 2 photon invarient mass in TAPS alone using simulations (Geant 4)

1. Where the vertex is assumed to be in the target. The pi0 from the 4He target are clear, with a low background from the 12C events.

Simulation

Experiment

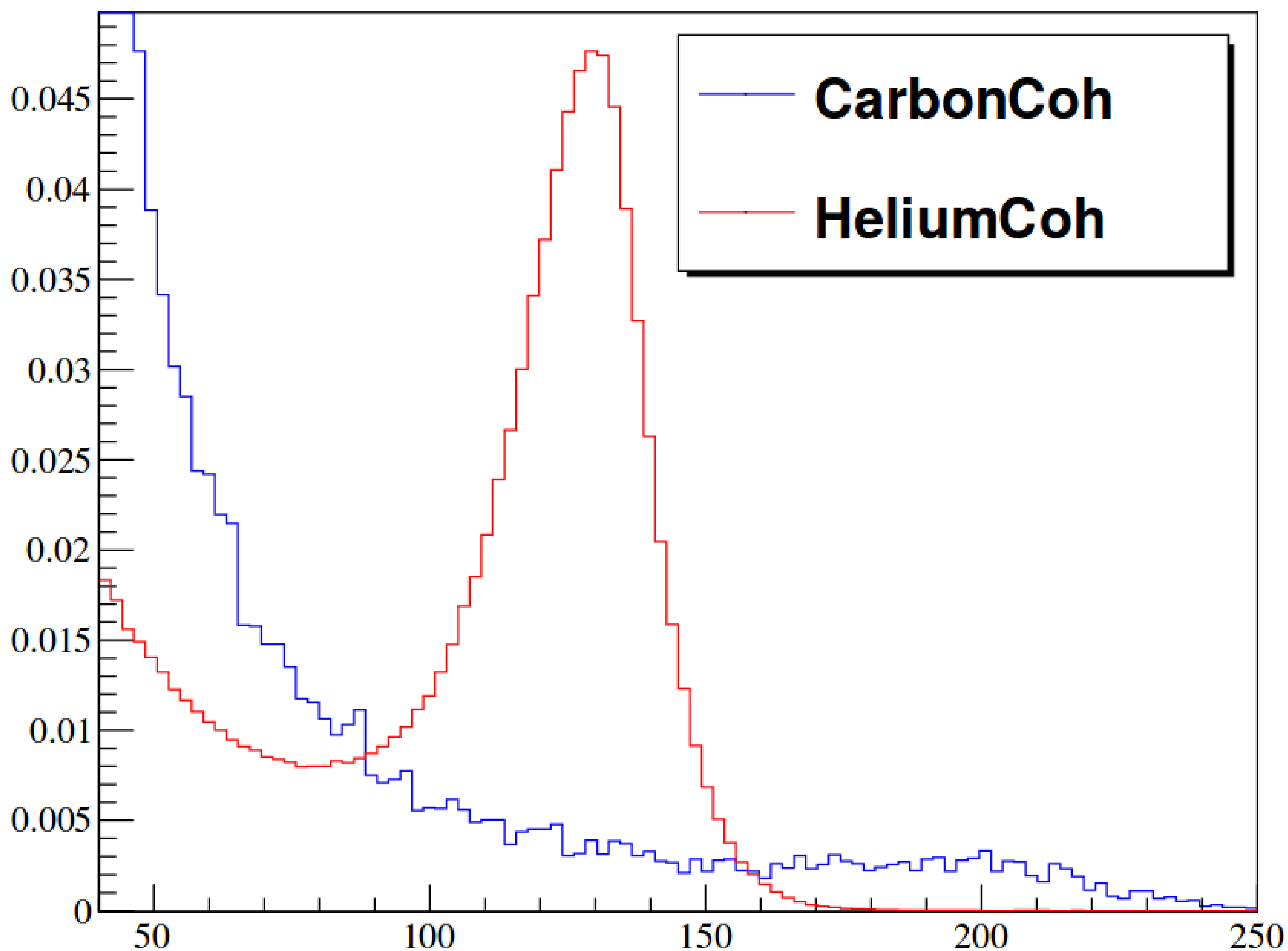
- Reconstruction of 2 photon invarient mass in TAPS alone using simulations (Geant 4)

1. Where the vertex is assumed to be in the target. The pi0 from the 4He target are clear, with a low background from the 12C events.

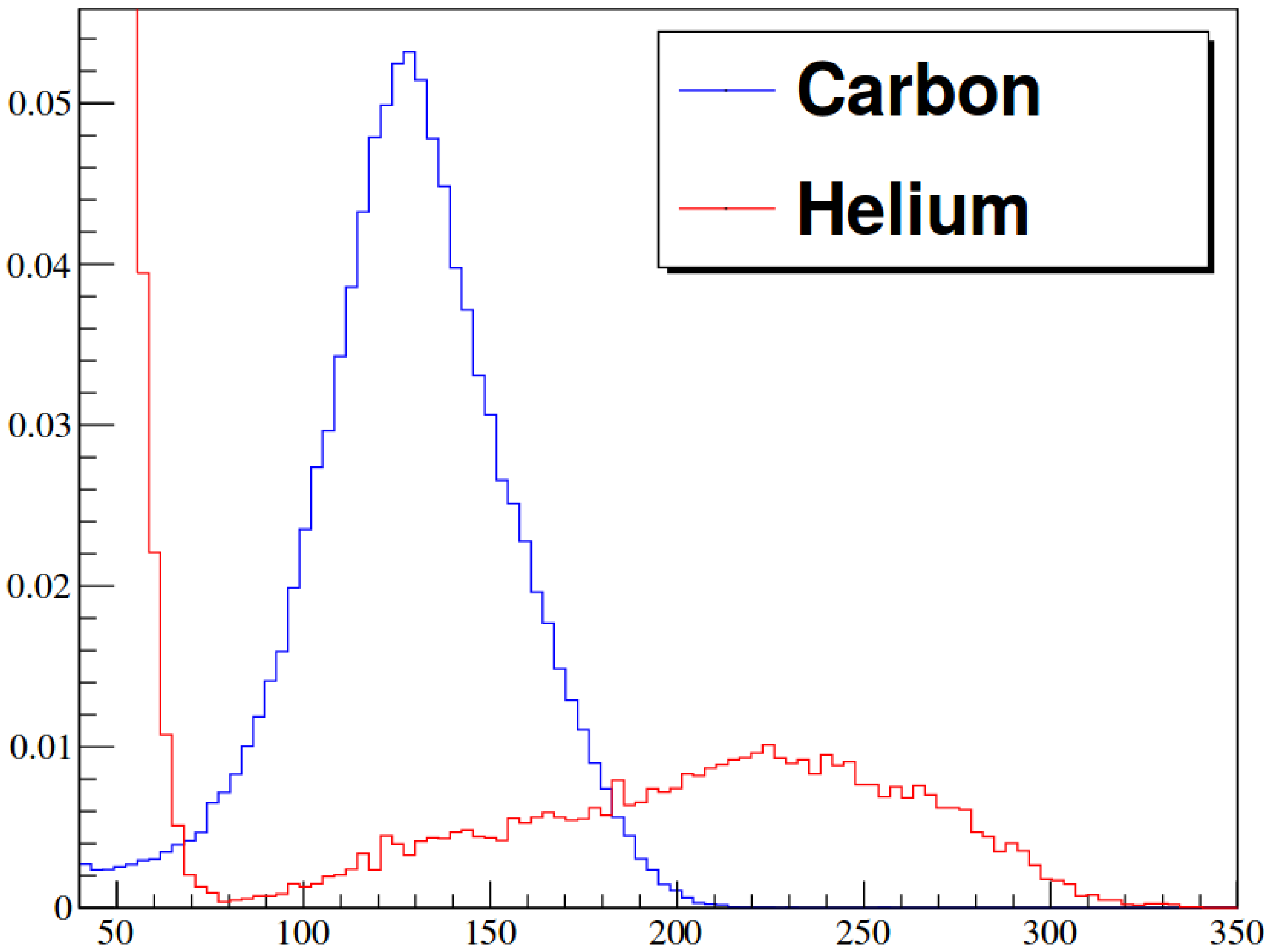
2.Where the vertex is assumed to be in the 12C target. This shows the pi0 from the 12C target are clear, with a low background from the 4He events.

Simulation

1.



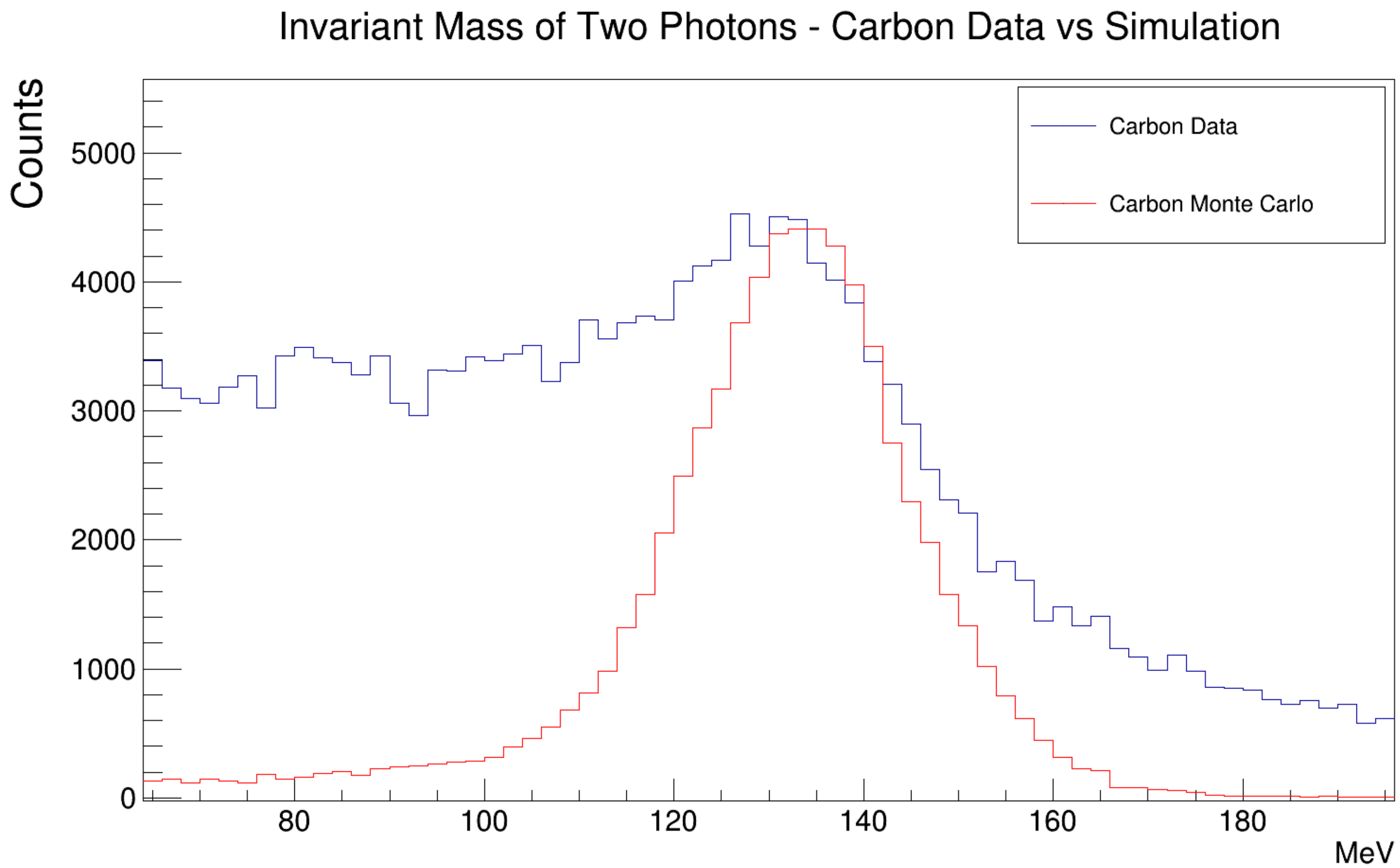
2.



Simulation

Experiment

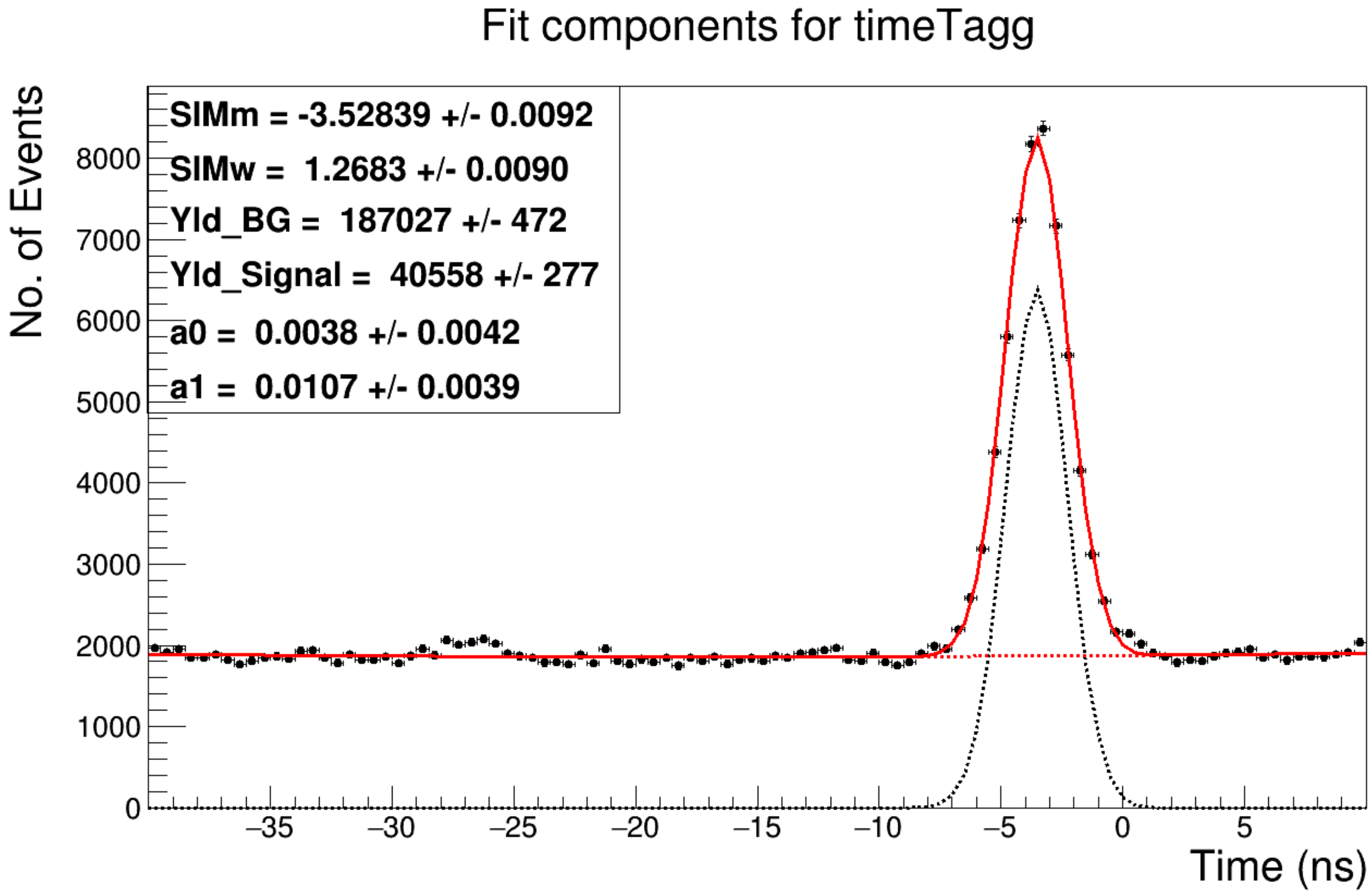
- MC carbon peak has been fitted to vertex shifted and vetoed carbon pion peak



sPlots

- The sPlot technique is used to separate signal from background events.
- This provides event-by-event weights known as ‘sWeights’ which can be used to disentangle different event species such as actual and random tagged photons.
- For this analysis sequential fits were performed to separate tagger random events from prompt signal events before being used again to separate nuclear background events.
- The initial separation was done using the sWeights obtained from a fit to the Tagger-CB coincidence time spectra.

sPlots


Fit components for timeTagg
SIMm = -3.52839 +/- 0.0092
SIMw = 1.2683 +/- 0.0090
Yld_BG = 187027 +/- 472
Yld_Signal = 40558 +/- 277
a0 = 0.0038 +/- 0.0042
a1 = 0.0107 +/- 0.0039
No. of Events
Time (ns)
8000
7000
6000
5000
4000
3000
2000
1000
0
−35
−30
−25
−20
−15
−10
−5
0
5

sPlots

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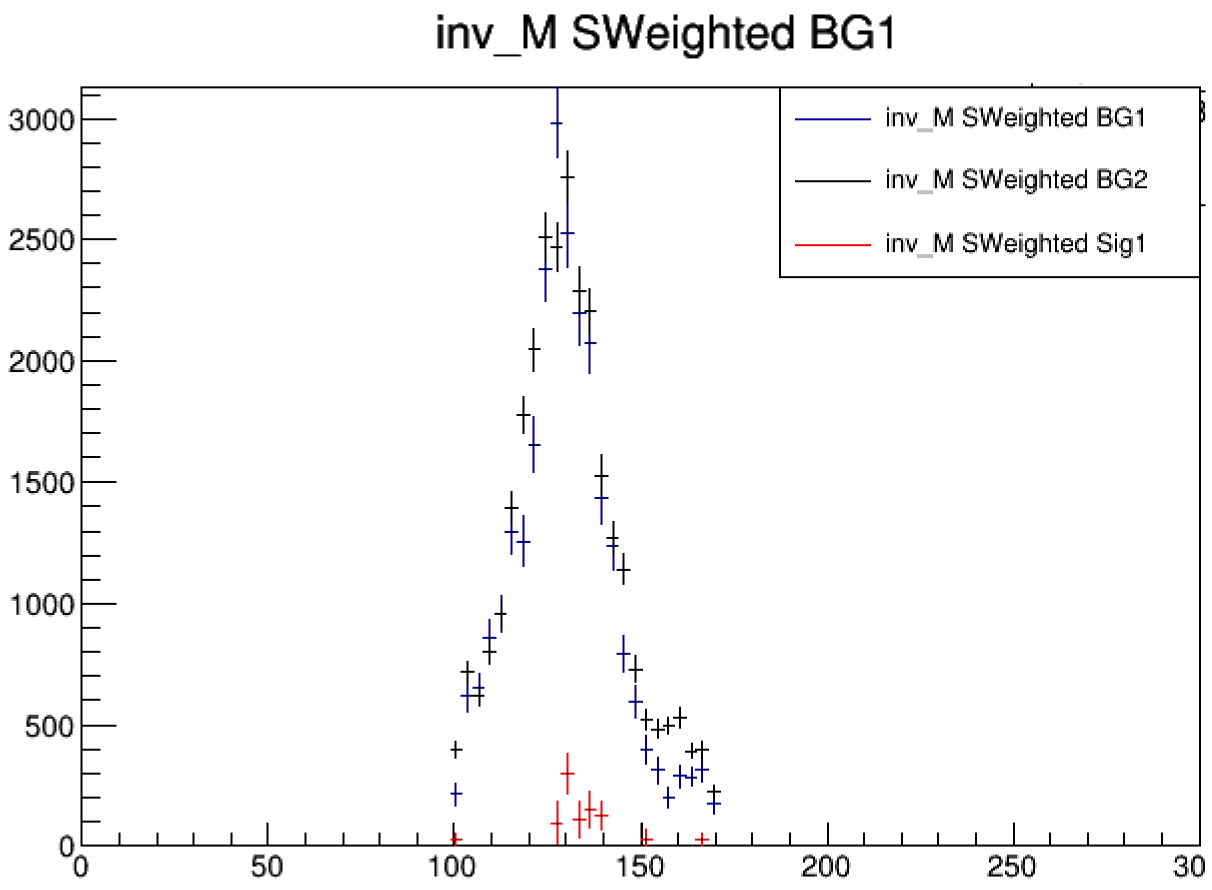
- It is important to note that the control and discriminatory variables should be uncorrelated when performing the extended maximum likelihood fit using a log-likelihood

sPlots

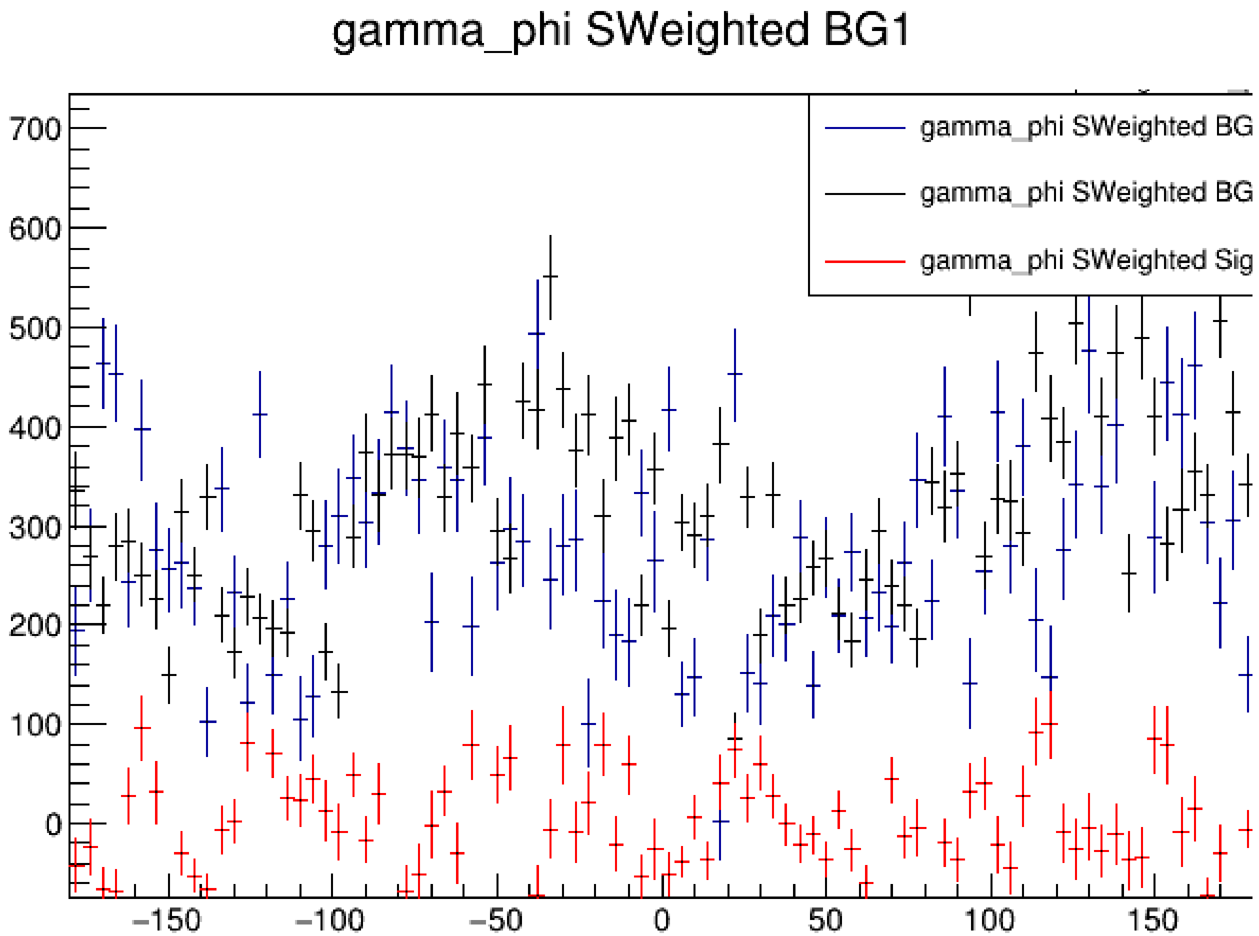
$$\mathcal{L} = \sum_{e=1}^{N} ln\left\{ \sum_{i=1}^{N_s} \mathrm{N}_i \mathrm{f}_i(\mathrm{y}_e) \right\} - \sum_{i=1}^{N_s} \mathrm{N}_i$$

- N = total number of events
- Ns = number of different types of events in the data (species)
- Ni = number of events in the ith species
- Y = the set of discriminating variables
- fi(ye) = PDF value of the ith species for variable y and event e
- By maximizing the equation it is possible to determine the value of the yields of the different species of events in the data while using a full list of discriminating PDFs
- The only free parameters in the fit are the species yields N

sPlots


inv_M SWeighted BG1
inv_M SWeighted BG1
inv_M SWeighted BG2
inv_M SWeighted Sig1
3000
2500
2000
1500
1000
500
0
0
50
100
150
200
250
30

sPlots


gamma_phi SWeighted BG1
gamma_phi SWeighted BG
gamma_phi SWeighted BG
gamma_phi SWeighted Sig
700
600
500
400
300
200
100
0
−150
−100
−50
0
50
100
150

Incoherent vs Coherent Channels

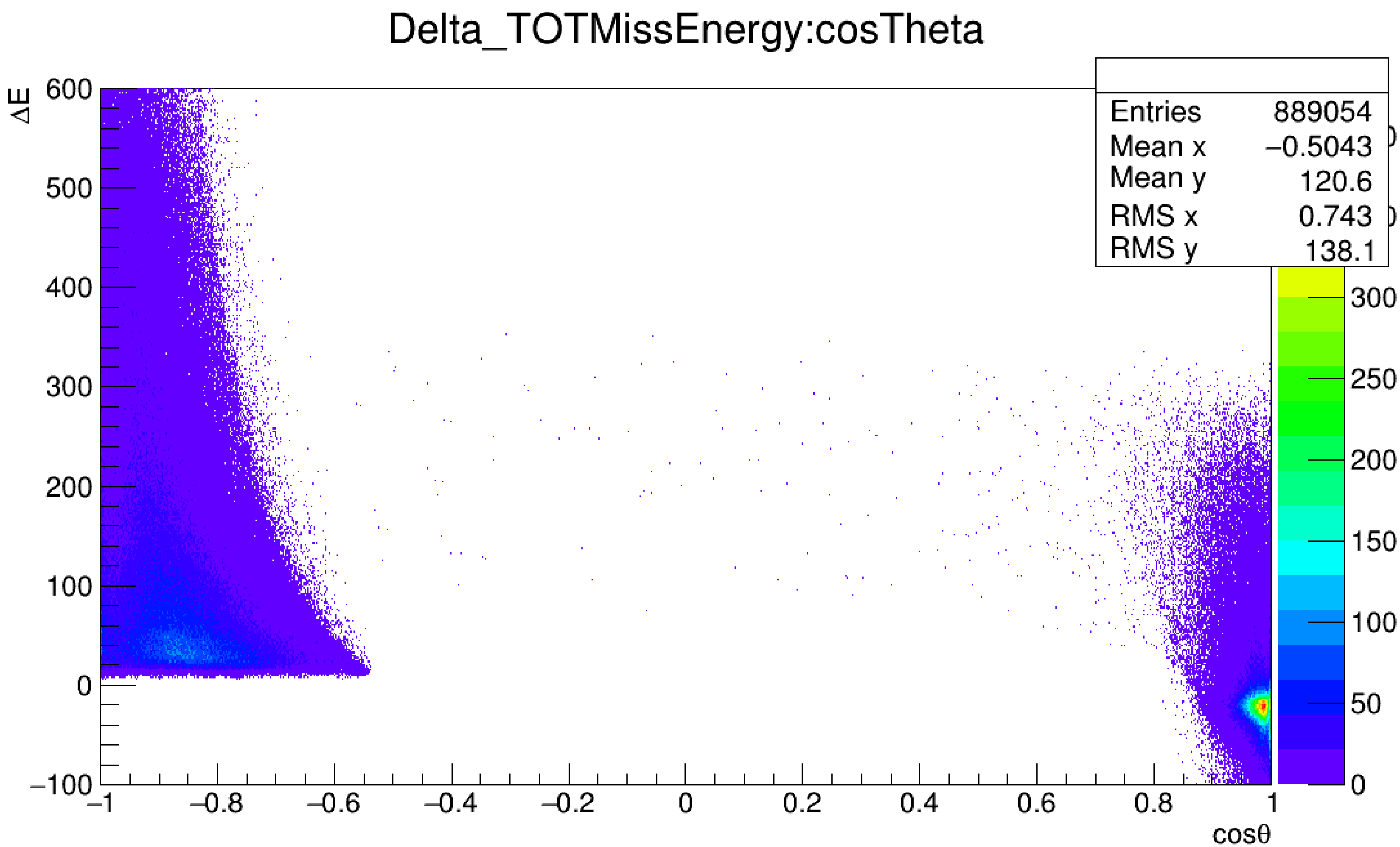
- Using a carbon target, the energy discrepancy between coherent and incoherent events is only 4.44MeV (1^{st} excited state of carbon)

- Coherent - greater forward-bias than Incoherent

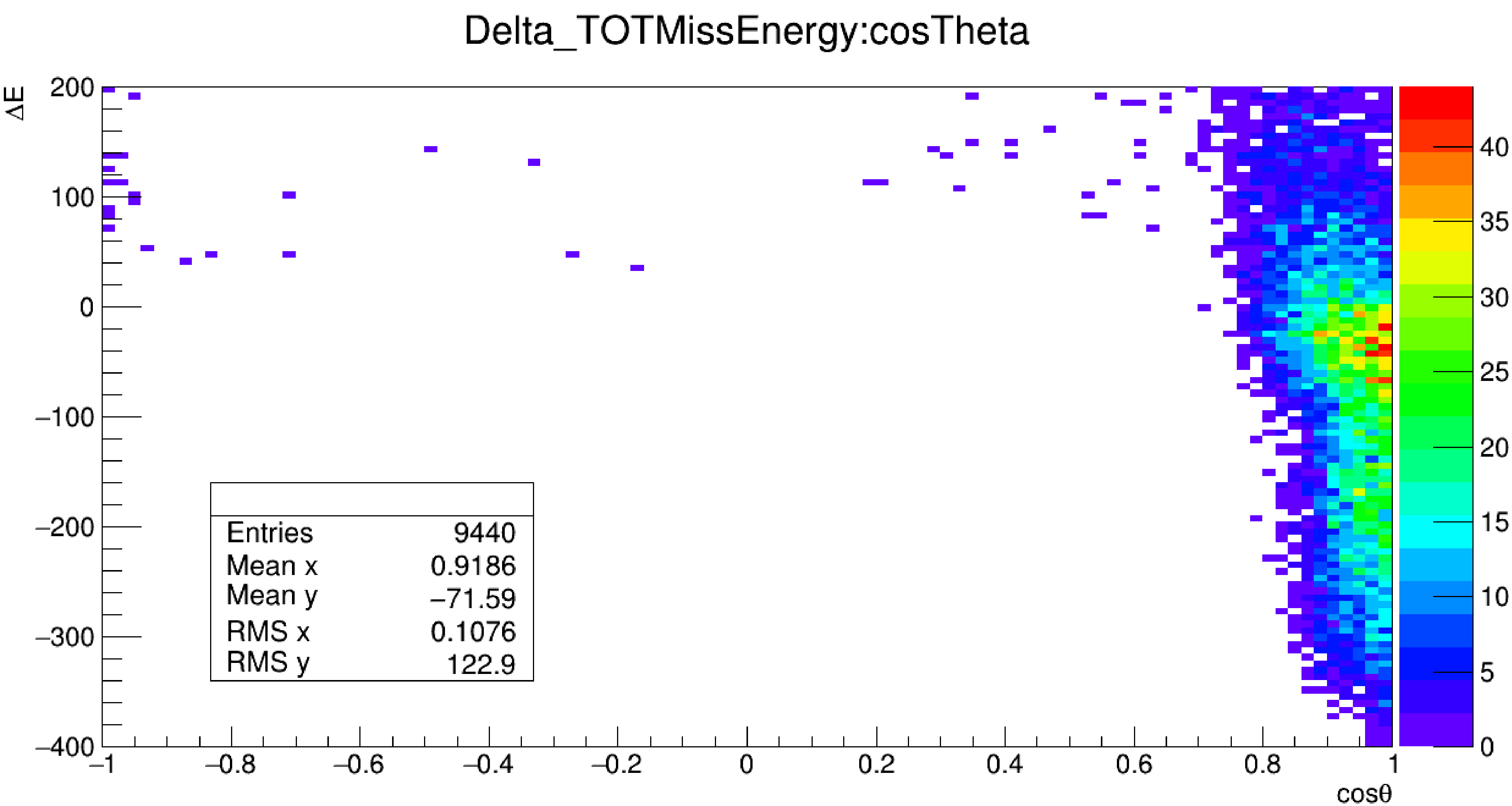
- Using only TAPS, limited angular range but improved resolution (~ +/- 75^o , 0.7^o) compared to CB (, -~93% of 4π, covering the full 2π azimuthal range and polar angles $20 < \theta < 160$)

- Similar energy resolution- CB: 0.02GeV TAPS: 0.018GeV

Incoherent vs Coherent Channels

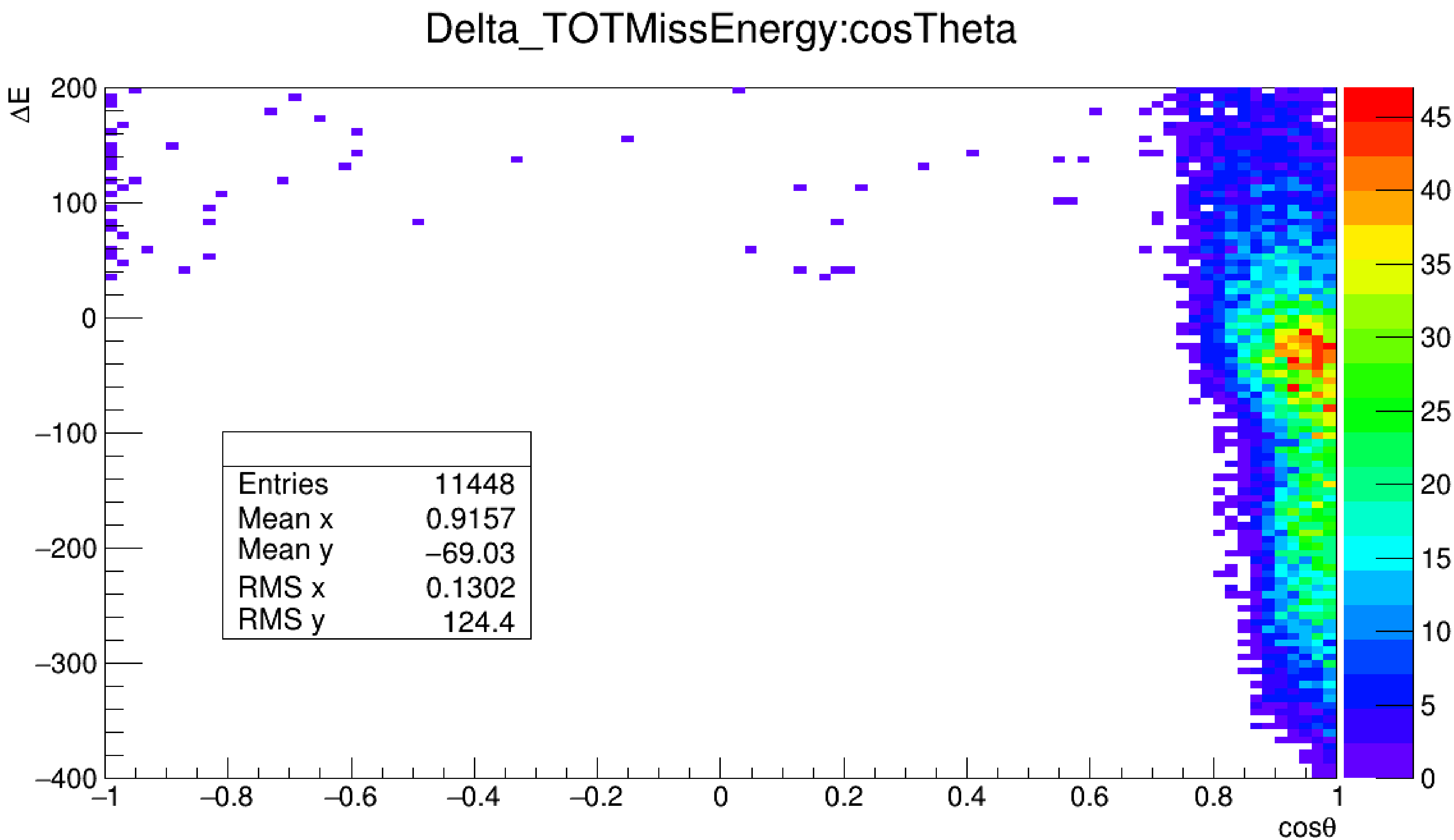


Incoherent vs Coherent Channels



Coherent

Incoherent vs Coherent Channels



Incoherent

Pion Missing Energy

$$\Delta E_\pi = E_\pi^{cm}(E_\gamma) - E_\pi^{cm}(\gamma_1\gamma_2)$$

$$E_\pi^{cm}(E_\gamma) = \frac{s + m_\pi^2 - M^2}{2\sqrt{s}}$$

$$E_\pi = \sqrt{\frac{2m_\pi^2}{(1-X^2)(1-cos\psi)}}$$

$$X = \frac{E_1 - E_2}{E_1 + E_2}$$

E_γ = the incident photon energy.

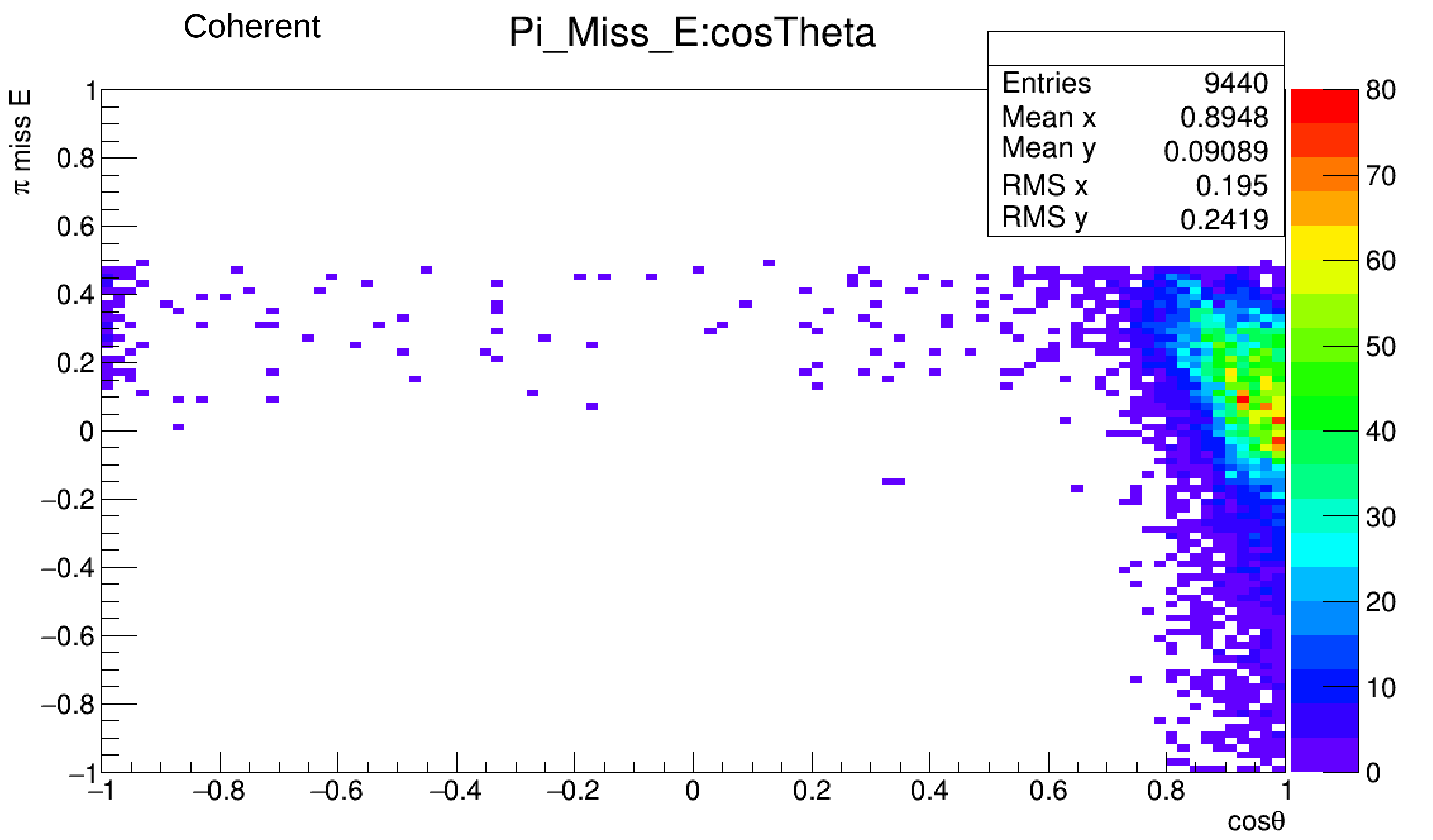
s = the invariant mass of the photon-nucleus pair.

m_π = the pion mass.

M = the mass of the relevant nucleus.

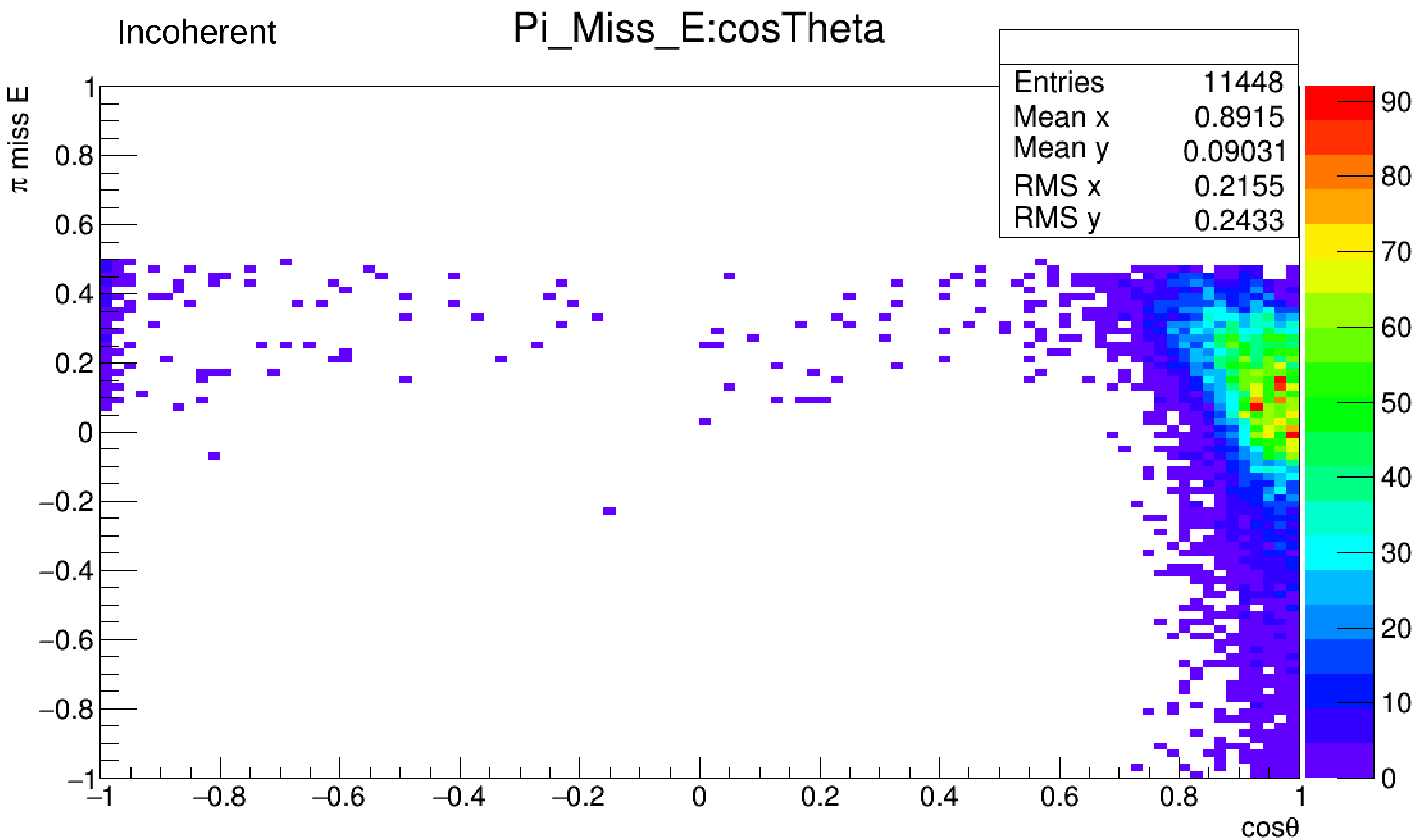
ψ = opening angle between the two π^0 photons

Incoherent vs Coherent Channels



Incoherent vs Coherent Channels

Incoherent



Current Work

Overview

- Alternative method of calculating the degree of linear polarisation of the beam is presented
- Viable statistics for secondary target method
- Results show high background from expected sources
- Differentiation of Coherent and Incoherent channels challenging- major limiting factor

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