Photoproduction of $b_1(1235)$ meson in GlueX

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Overview

* GlueX Experiment

* Motivation

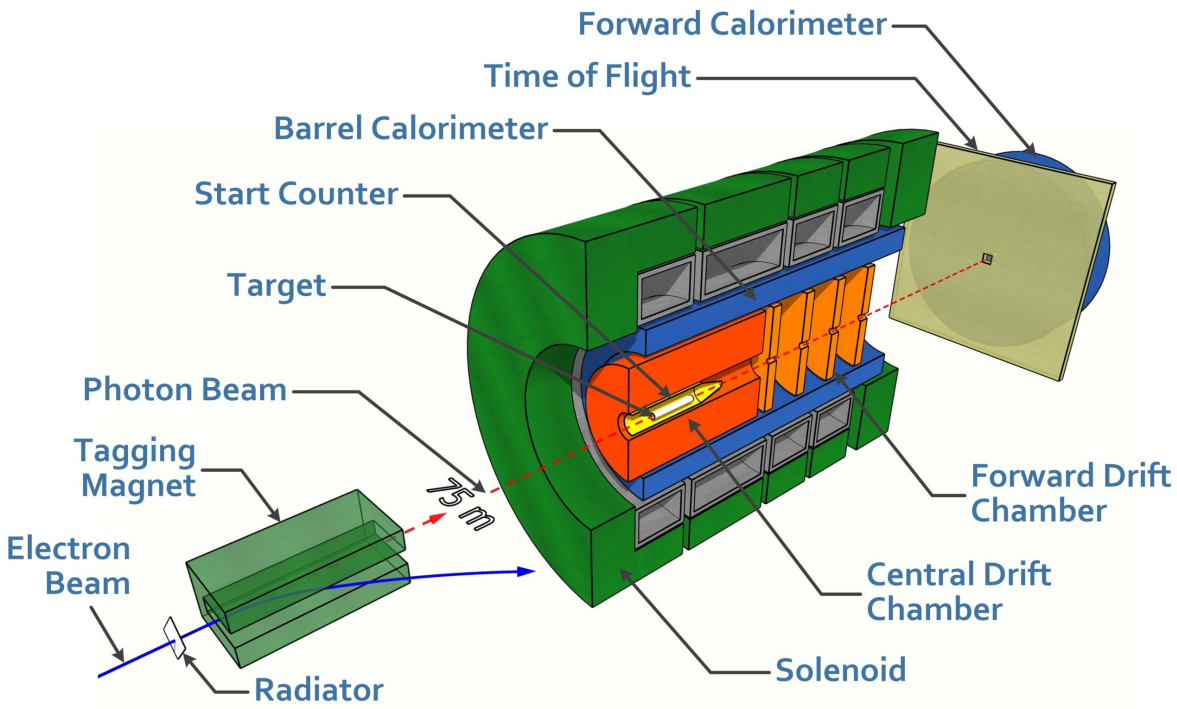
* b_1 Event Selection in GlueX

* b_1 PWA Model

– Angular distribution of the b_1 meson

* Next steps

GlueX Experiment in JLab



GlueX Experimental Setup at Hall-D Jefferson Lab

Main Goal

- Search for hybrid mesons
- Map light meson spectrum

Photoproduction

- Linearly polarised photons in 4 orientations
- LH_2 target

Detector systems offers nearly 4π coverage

Motivation

Motivation

Exotics $\pi_1(1600)$[a] [b], $\pi_1(2015)$[c], $h_0(2400)$ and $b_2(2500)$ could possibly decay to $b_1\pi$ where b_1 decays into $\omega\pi$. In order to precisely measure the exotics, we need to understand the precisely the decay of $b_1(1235)$

GlueX searches for hybrid meson spectrum in the mid-high energy regime (6 - 12 GeV) could measure the complete kinematics of the mentioned exotics.

[a] Reported by E852, VES, COMPASS, and CBAR
[b] Decays of an exotic 1^{-+} hybrid meson resonance in QCD [1]
[c] Reported by E852

$b_1(1235)$

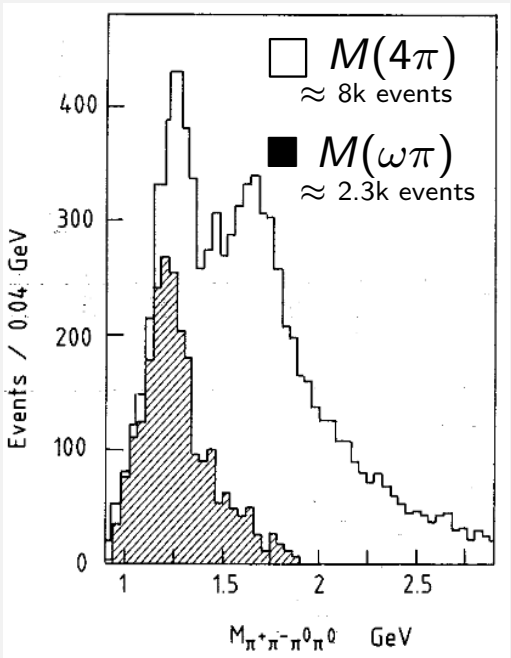
Flavourless meson: 'b' a meson of spin zero ($S = 0$) and odd orbital momentum ($L = 1$). Subscript is total angular momentum of the $q\bar{q}$ system

b1(1235)	$I^G J^{PC}$ $1^+(1^{+-})$
Mass	1229.5 ± 3.2 MeV (S = 1.6)
Width	142 ± 9 MeV (S = 1.2)

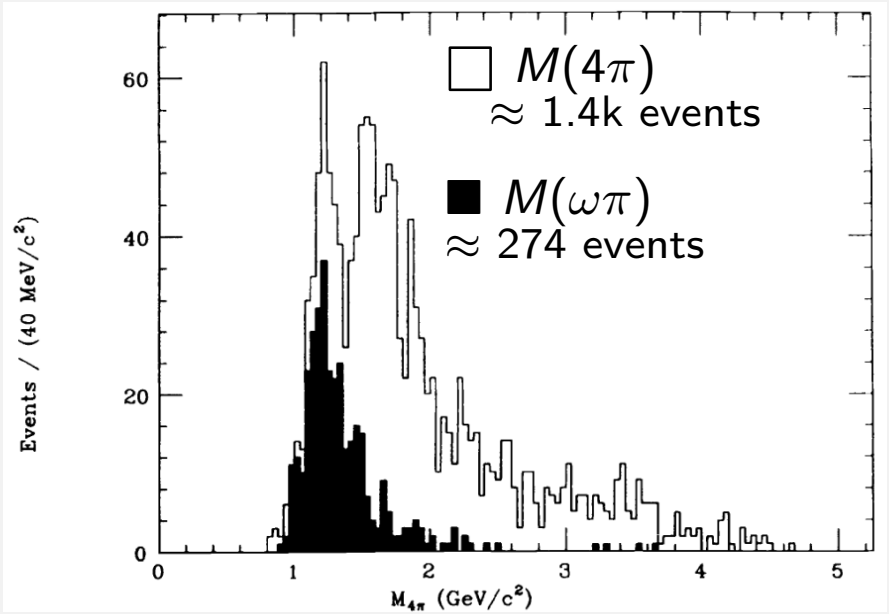
Motivation & History (cont.)

History of the $b_1(1235)$ Photo production (in the 1980s)

Omega-Photon Collaboration



SLAC-S.H.F.P Collaboration



$\omega\pi^0$ mass distributions from Omega-Photon Collaboration [2] (Left) and SLAC-H [3] (right) experiments : modest statistics

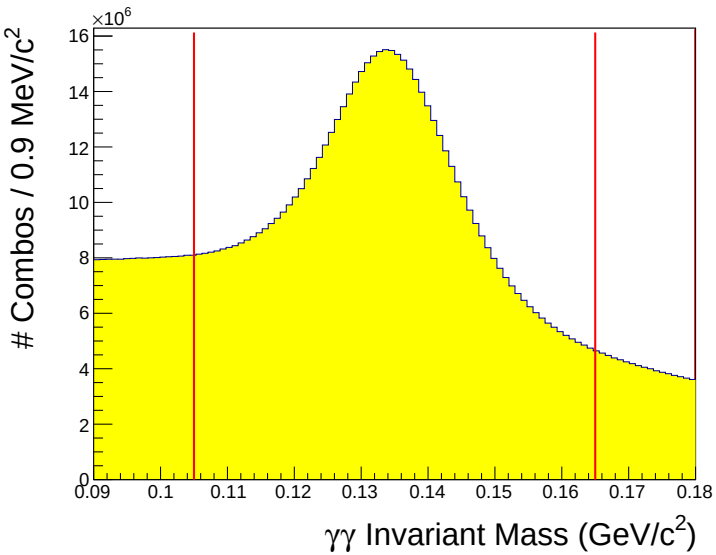
b_1 Event Selection in GlueX

b_1 Photo production reaction

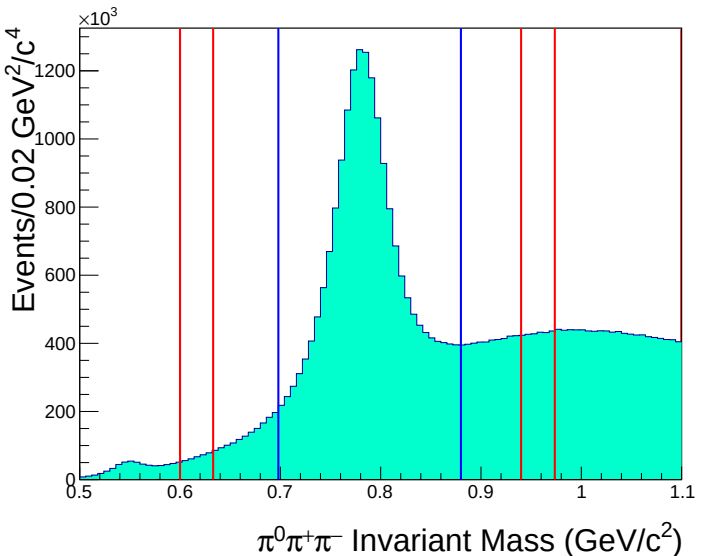
$$\gamma p \rightarrow p b_1(1235) \rightarrow p\omega\pi^0 \rightarrow p\pi^+\pi^-\pi^0\pi^0 \quad (1)$$

All final state particles are detected in the experiment
The analysis is done on 20% of GlueX Phase-1 data

Event Selection Cuts



(a) $1.05 < M(\gamma\gamma) < 1.65\ GeV/c^2$



(b) 3π cuts & Side band cuts

These distributions are before applying accidental subtractions

b1 Event Selection in GlueX (cont.)

Previous Experiments

Omega-Photon Colab = 2300 Events
SLAC-S.H.F.P Colab = 274 Events

Invariant mass of ω events

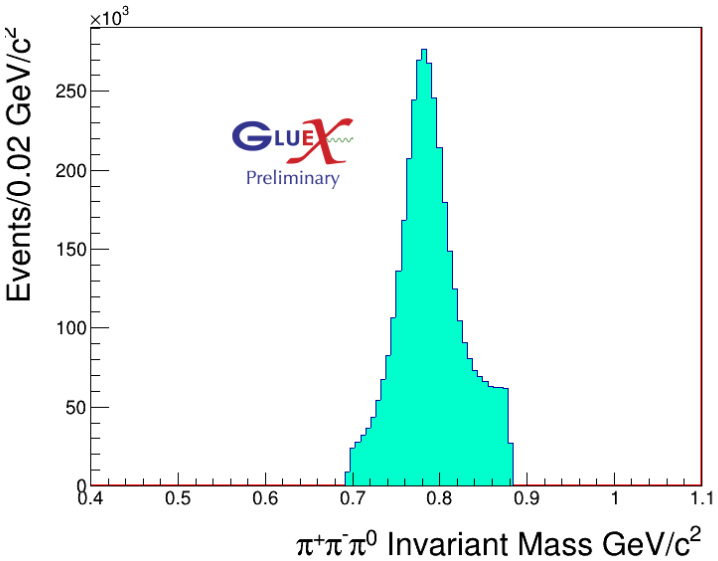


Figure 3: Invariant mass of ω events after accidental + side band subtractions.

Invariant Mass of $\omega\pi$ events

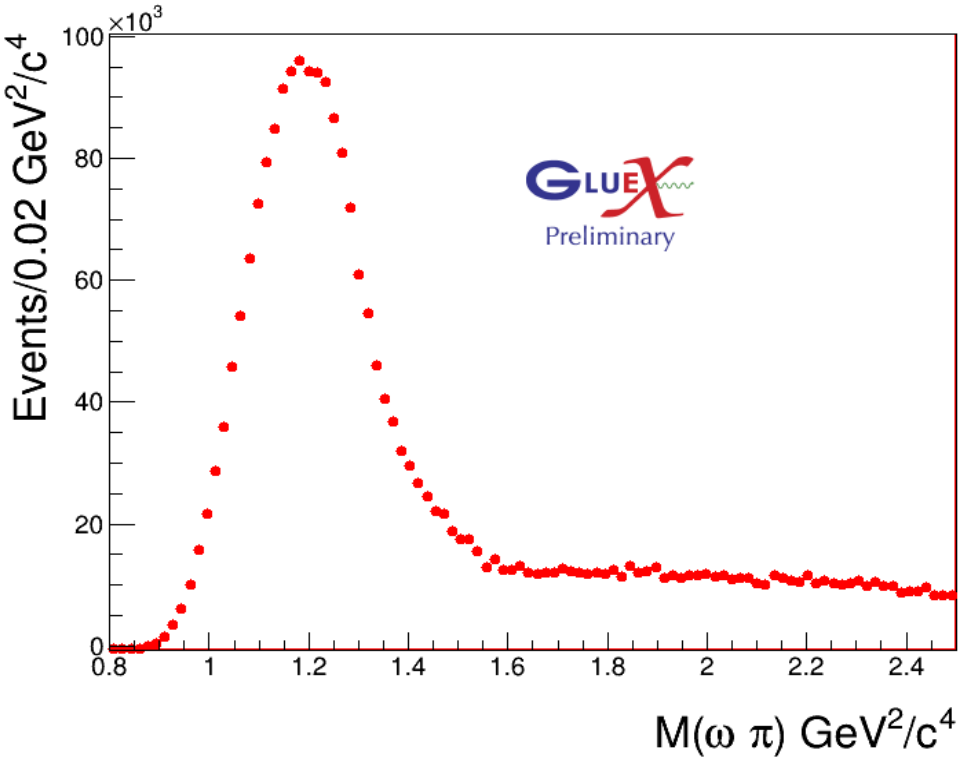
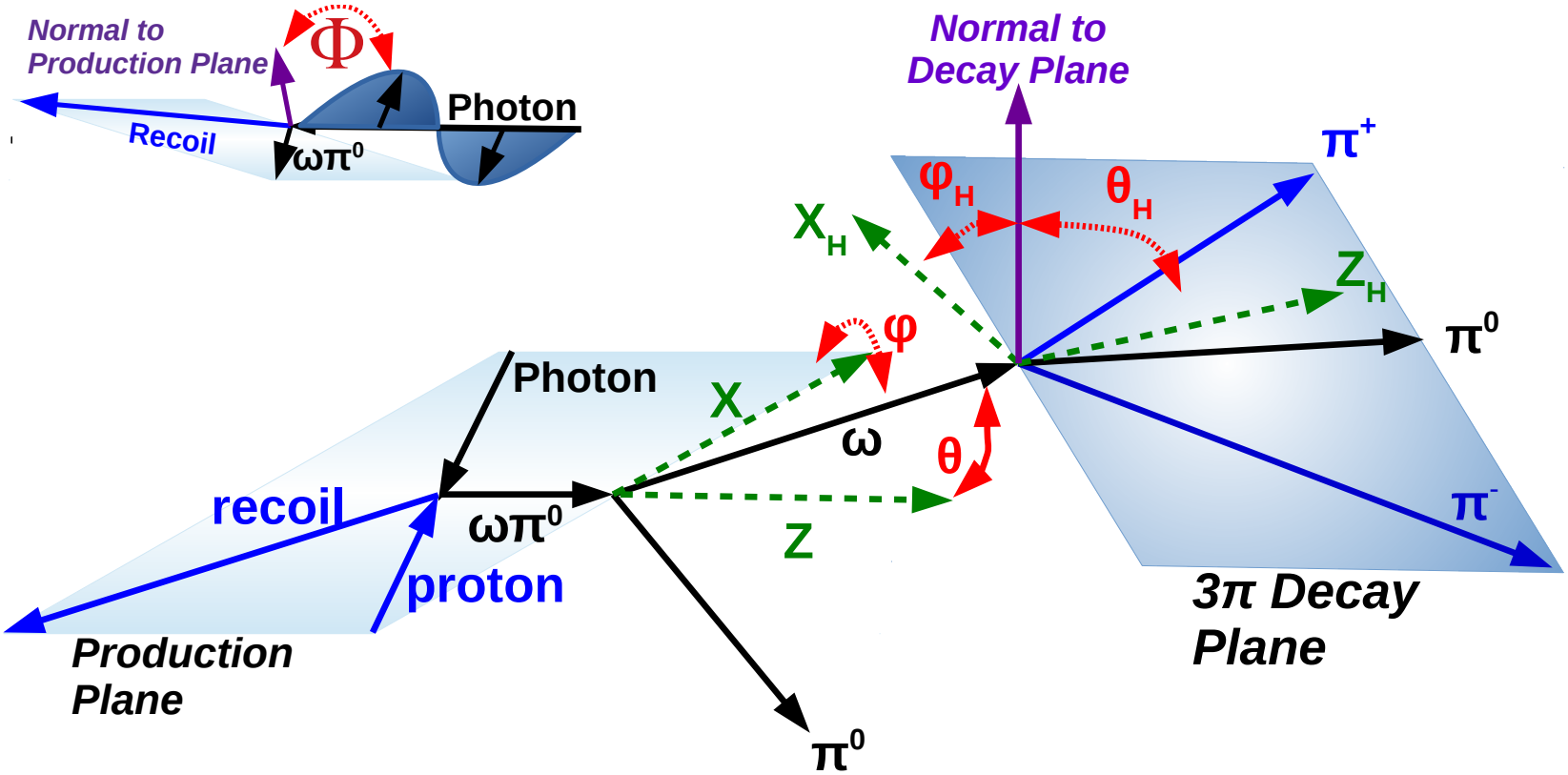
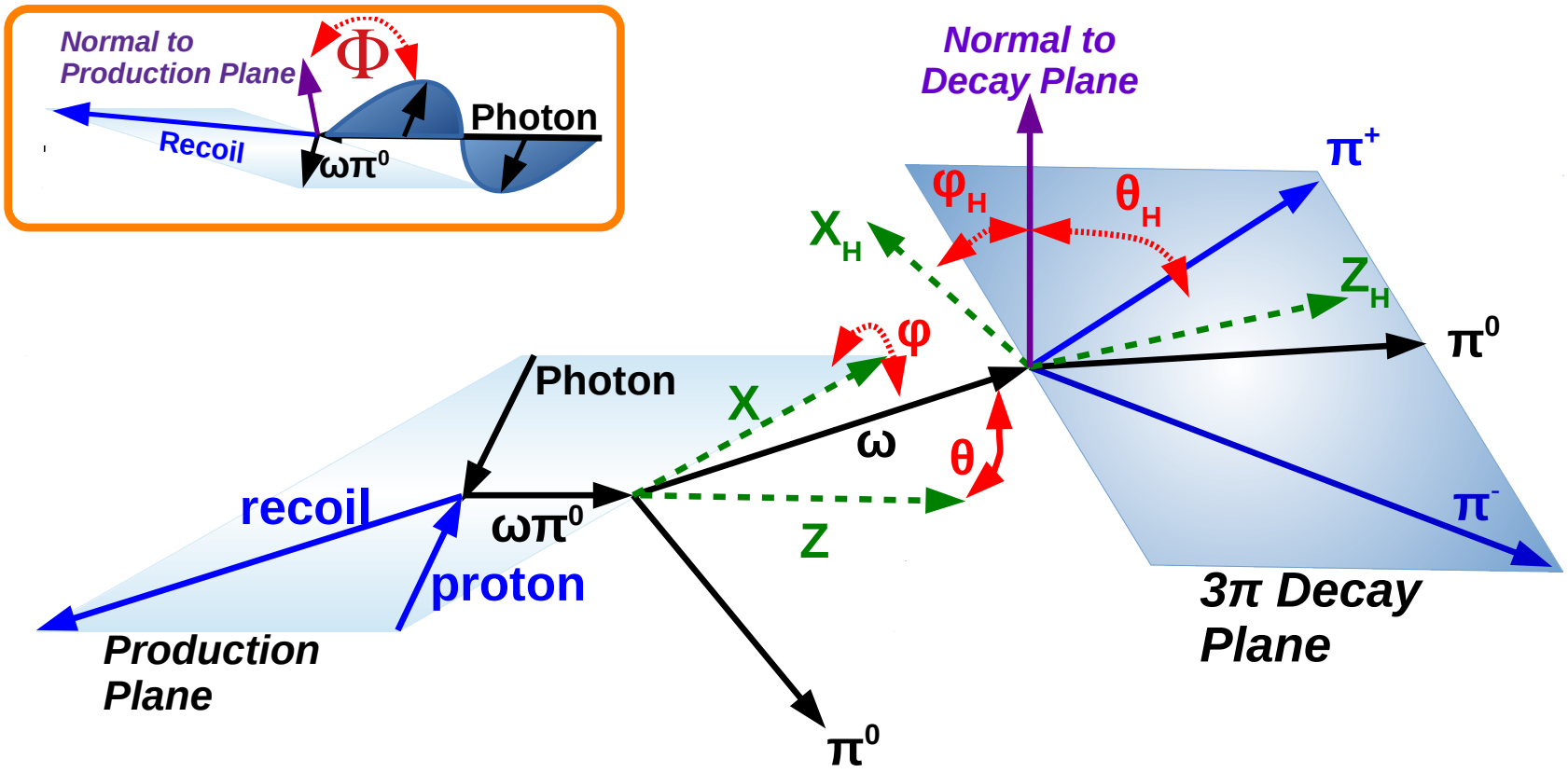


Figure 4: Reconstructed $\omega\pi$ events. The M($\omega\pi$) events are not acceptance corrected. Vertical errors bars are contained in the points. A high statistics channel

$\omega\pi$ Helicity Frame



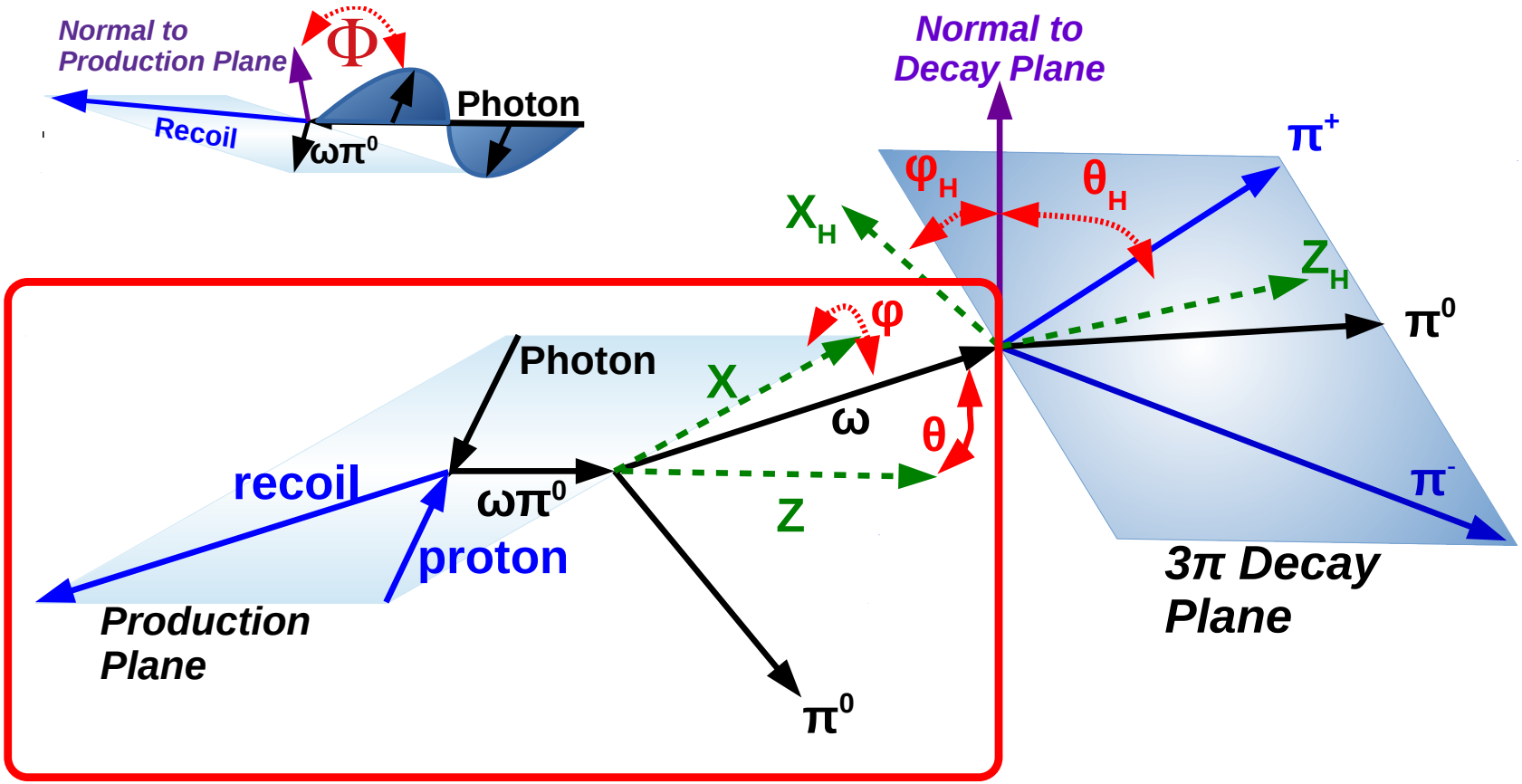
$\omega\pi$ Helicity Frame (cont.)



Production angle (Φ)

Production angle (Φ) is defined as the angle between the photon polarisation plane and normal ($\hat{n}_{prod}$) to the production plane.

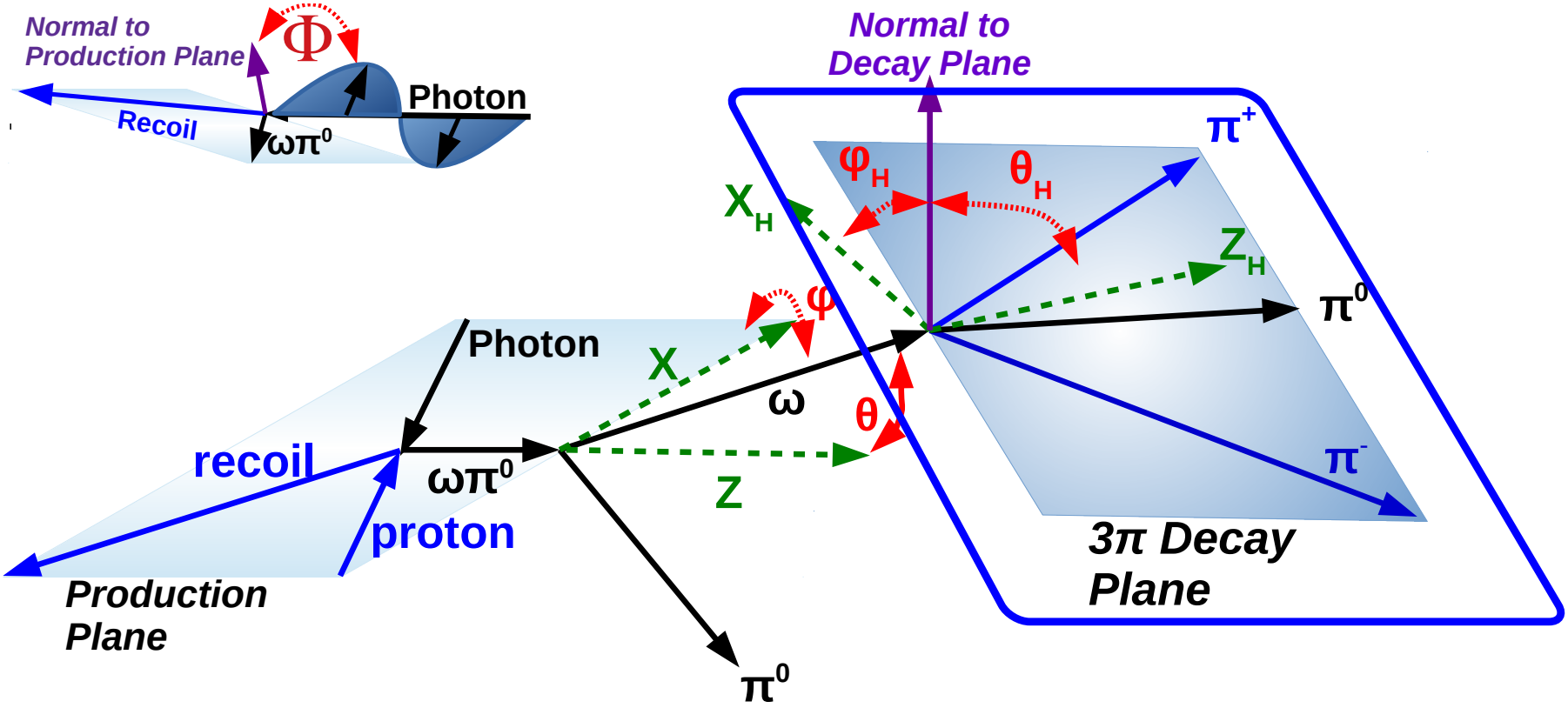
$\omega\pi$ Helicity Frame (cont.)



$\omega\pi$ decay plane

θ and ϕ describe the decay kinematics of ω in the $\omega\pi$ helicity frame.

$\omega\pi$ Helicity Frame (cont.)



3π decay plane

θ_H and ϕ_H describe the decay kinematics of normal ($\hat{n}$) to three-pion (ω) decay plane in its helicity frame

Amplitude Analysis Model

Intensity I is given by

$$I = \frac{1}{2}(1 - P_\gamma)|e^{i\Phi}A_+ + e^{-i\Phi}A_-|^2 + \frac{1}{2}(1 + P_\gamma)|e^{i\Phi}A_+ - e^{-i\Phi}A_-|^2 \quad (2)$$

Amplitude Analysis Model (cont.)

Polarisation fraction

Production angle

$$I = \frac{1}{2}(1 - P_\gamma)|e^{i\Phi}A_+ + e^{-i\Phi}A_-|^2 + \frac{1}{2}(1 + P_\gamma)|e^{i\Phi}A_+ - e^{-i\Phi}A_-|^2$$

Where $A_\pm$ can be expressed as

$$A_{\lambda_\gamma} = \sum_{J_i=0,1,2}^{\omega\pi Spin} \sum_{\eta_i=-1,1}^{\omega\pi Parity} \sum_{\Lambda=-J_i,..,J_i}^{\omega\pi SpinProj} V_{\lambda_\gamma,\Lambda} \sum_{\lambda=-1,0,1}^{\omega Helicity} D^{J_i}_{\Lambda,\lambda}(\Omega) F^i_\lambda D^1_{\Lambda,0}(\Omega_H) G$$

Amplitude Analysis Model (cont.)

Where $A_{\pm}$ can be expressed as

$$A_{\lambda_\gamma} = \sum_{J_i=0,1,2}^{\omega\pi Spin} \sum_{\eta_i=-1,1}^{\omega\pi Parity} \sum_{\Lambda=-J_i,..,J_i}^{\omega\pi SpinProj} V_{\lambda_\gamma,\Lambda} \sum_{\lambda=-1,0,1}^{\omega Helicity} D^{J_i}_{\Lambda,\lambda}(\Omega) F^i_\lambda D^1_{\Lambda,0}(\Omega_H) G$$

$V_{\lambda_\gamma,\Lambda}$

Vertices

$D^{J_i}_{\Lambda,\lambda}(\Omega \text{ or } \Omega_H)$

Wigner function with $\Omega(\theta,\phi)$ and $\Omega_H(\theta_H,\phi_H)$ being decay angles in Helicity frame

F^i_λ Helicity amplitudes

$$F^i_\lambda = \sum_{l=0,1,2}^{PartialWaves} \langle J_i\lambda | l0, 1\lambda\rangle \, C^i_l$$

Amplitude Analysis Model (cont.)

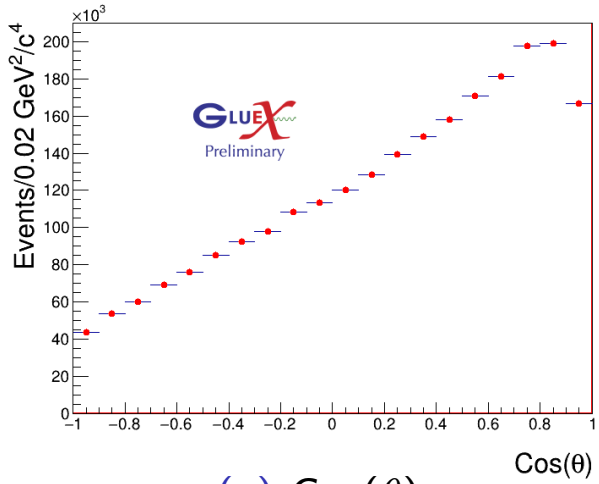
J^{PC} states of 0^-, $1^\pm$, $2^\pm$ and the partial waves $l = 0, 1, 2$ could potentially reproduce the angular distibution of the $\omega\pi$. The total fit parameters corresponding to these are

- 17 Vertices ($V^i_{\lambda_\gamma,\Lambda}$) which depends on Mandelstam t, beam energy and $M(\omega\pi)$. The vertex describes the production mechanisms and naturality of the exchange particles in the reaction.
- 6 partial wave amplitudes C^i_l that depend only on $M(\omega\pi)$. This yields the D/S ratio which has been previously measured by the experiments [2]. Recently, the ratio is theoretically computed using Lattice QCD calculations [4].
- 4 Dalitz parameters α, β, γ, δ

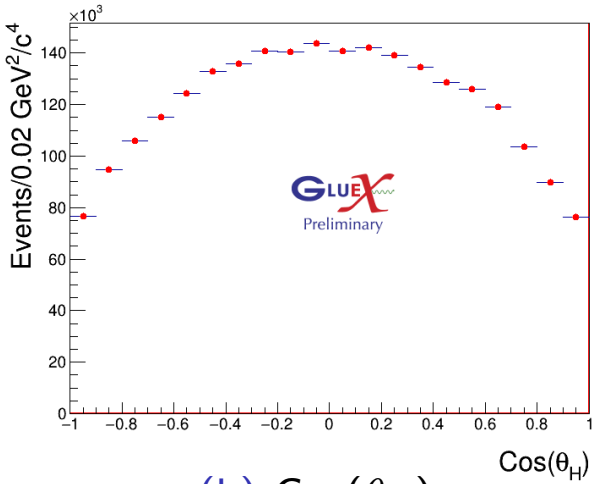
Angular distribution of the b_1 meson

$0.83 < M(\omega\pi) < 1.6\ GeV/c^2$

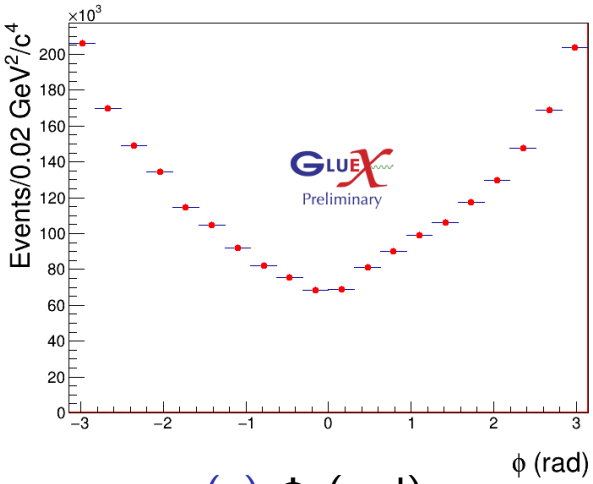
The distributions are not corrected for acceptance



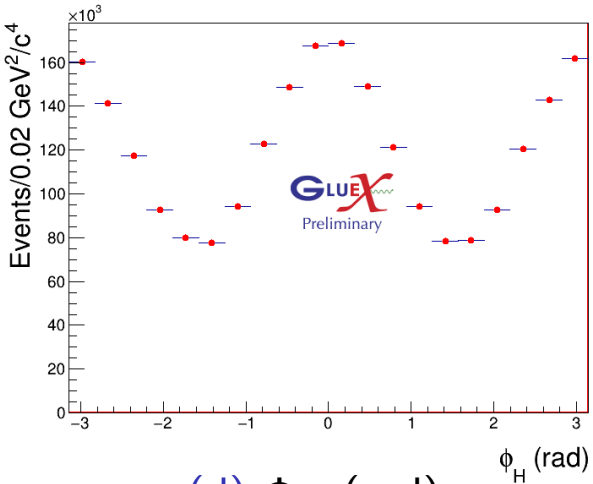
(a) Cos(θ)



(b) Cos(θ_H)



(c) Φ (rad)



(d) Φ_H (rad)

Figure 5: Distribution of M($\omega\pi$) in various decay angles (Ω, Ω_H)

Summary and Next Steps

Summary

- GlueX maps the meson spectrum and search for exotics. The b_1 meson is important part of measuring the lightest hybrid multiplet, because hybrids decay into $b_1\pi$
- Preliminary angular distribution of the b_1 meson is produced using 20% of GlueX Phase-1 data.

Current Analysis

- A preliminary generator to generate Monte Carlo events to model angular distribution has been developed and is being rigorously tested.
- Working on to include the detector response in calculating the angular distribution of $\omega\pi$ events shown before (Fig:5).
- Working closely with JPAC[a] to fully develop and test the amplitude model and implementing in the GlueX framework

[a] A. Sczepaniak et. al Joint Physics Analysis Center (JPAC)

Bibliography

[1] A. J. Woss, J. J. Dudek, R. G. Edwards, C. E. Thomas, and D. J. Wilson, *Decays of an exotic* 1^{-+} *hybrid meson resonance in qcd*, 2020. arXiv: 2009.10034 [hep-lat].

[2] M. Atkinson *et al.*, "Diffractive Photoproduction of a $b_1\pi$ System," *Z. Phys. C*, vol. 34, p. 157, 1987.

[3] S. H. F. P. Collaboration, "Production and decay properties of the $\omega\pi^0$ state at 1250 mev/c^2 produced by 20-gev polarized photons on hydrogen," *Phys. Rev. D*, vol. 37, pp. 2379–2390, 9 May 1988. DOI: 10.1103/PhysRevD.37.2379. [Online]. Available: https://link.aps.org/doi/10.1103/PhysRevD.37.2379.

[4] A. J. Woss, C. E. Thomas, J. J. Dudek, R. G. Edwards, and D. J. Wilson, "b_1 resonance in coupled $\pi\omega$, $\pi\phi$ scattering from lattice qcd," *Phys. Rev. D*, vol. 100, p. 054 506, 5 Sep. 2019. DOI: 10.1103/PhysRevD.100.054506. [Online]. Available: https://link.aps.org/doi/10.1103/PhysRevD.100.054506.

Backups

Event Selection List

- Kin. Fit Confidence level $> 10^{-5}$.
- Missing Mass Squared $< 0.05\ GeV^2/c^4$
- PID ΔT Cuts (FCAL, BCAL, ST and TOF)
- Four momentum Kinematic fit for neutral particles
- $P_{recoil} > 350$ MeV
- Standard $(\frac{dE}{dX})_{proton}$ curve cut
- Target vertex cuts: 52cm $<$ Z $<$ 78cm, R $<$ 1cm
- $E_{beam} > 6.5$ GeV
- Four-momentum + vertex kinematic fit for charged particles

Backups (cont.)

Accidental and Background Subtractions

- Accidental Subtraction: 3 accidental peaks on either side of the coincidence peak ($\frac{coincidence}{accidentals} = \frac{1}{6}$)
- 6 σ wide ω and 2 side-bands on either side of the 1-σ wide ($\frac{peak}{side-band}\ \frac{6}{2} = 3$)

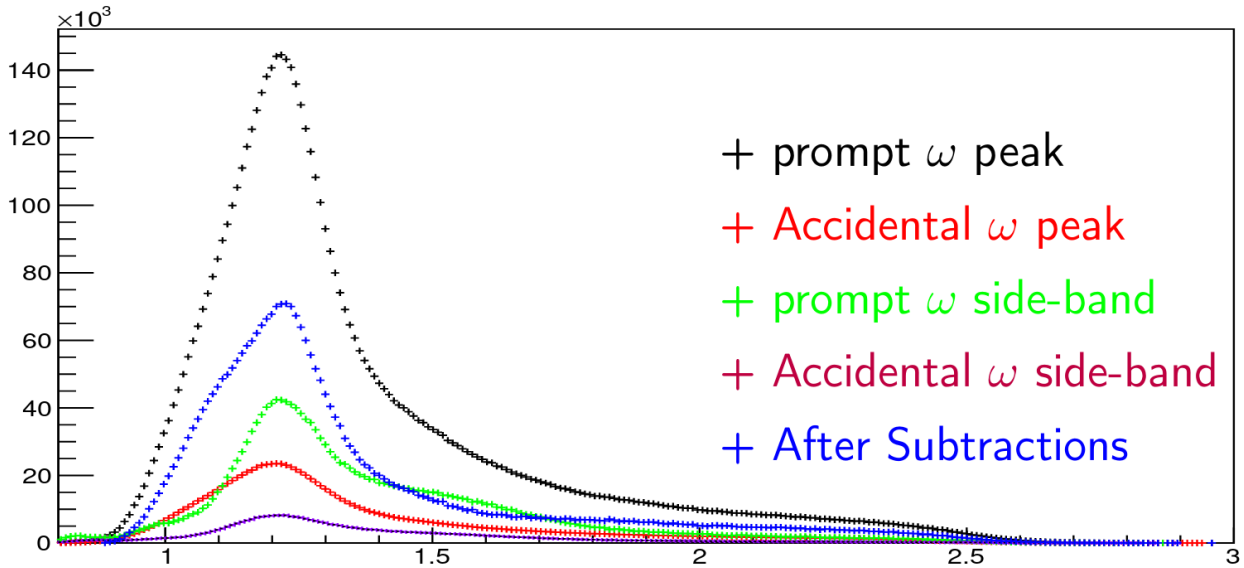


Figure 6: M($\omega\pi$) distribution at every stage of subtraction

Backups (cont.)

Accidental and Background Subtractions

- Accidental Subtraction: 3 accidental peaks on either side of the coincidence peak ($\frac{coincidence}{accidentals} = \frac{1}{6}$)
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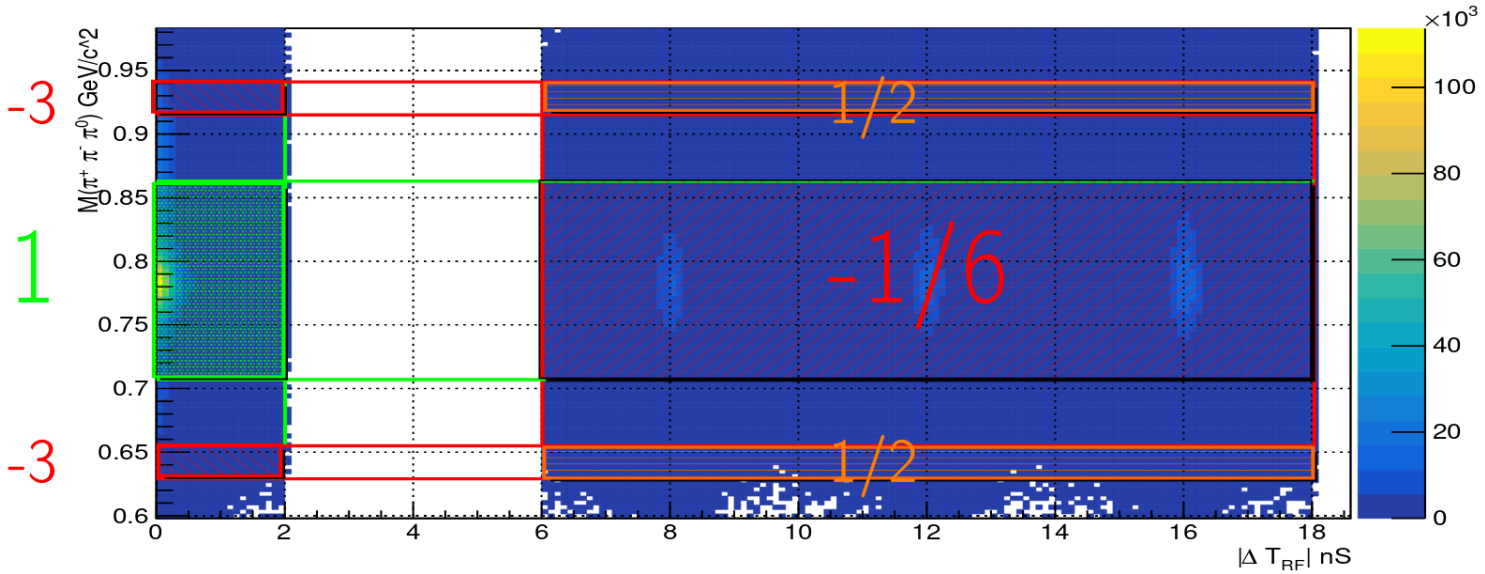


Figure 7: Weighting the events based on their occurrence in the plot for accidental and background subtraction

Dalitz Function

The Dalitz function can be written as

$$G(Z,\theta) = \sqrt{1 + 2\alpha Z + 2\beta Z^{3/2} Sin(3\theta) + 2\gamma Z^2 + 2\delta Z^{5/2} Sin(3\theta)}$$

where Z, θ are defined as

$$Z = \sqrt{x^2 + y^2} \ , \ \theta = \frac{y}{Z}$$

and the Mandelstam variables of the ω decay are defined as

$$s = (p_\omega - p_{\pi^0})^2 \ , \ t = (p_\omega - p_{\pi^-})^2 \ , \ u = (p_\omega - p_{\pi^+})^2$$

where x, y are defined as

$$x = \frac{\sqrt{3}(t-u)}{2M(M-3m_\pi)} \ , \ y = \frac{3(s_c - s)}{2M(M-3m_\pi)}$$

Backups

With the J^{PC} of $0^{\pm}$, $1^{\pm}$, $2^{\pm}$ for the $\omega\pi$ and partial wave l = 0, 1, 2; one can reproduce the complete $\omega\pi$ spectrum.
The fit parameters corresponding to the states and partial waves are:

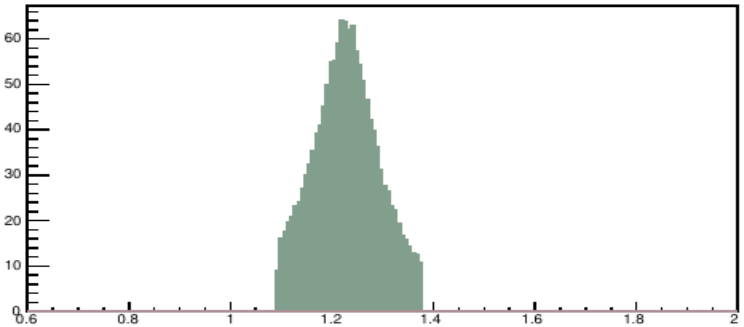
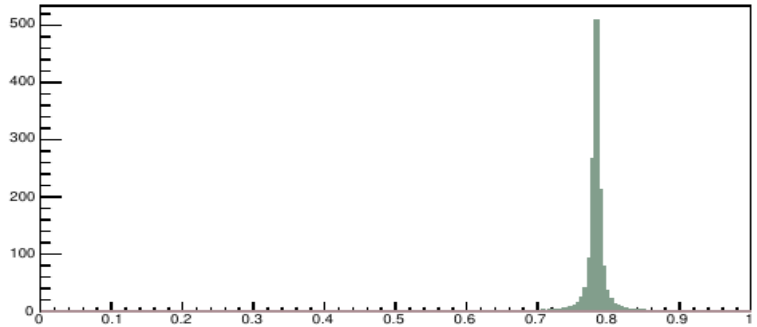
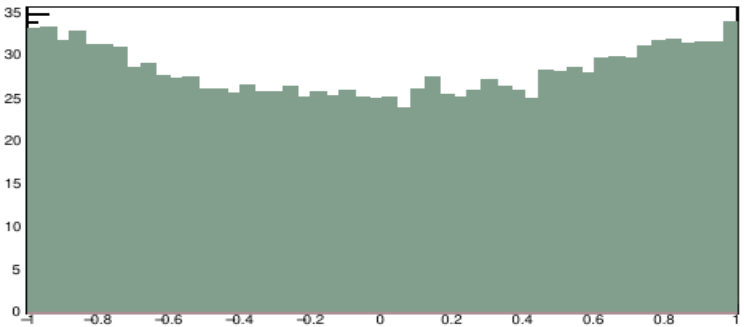
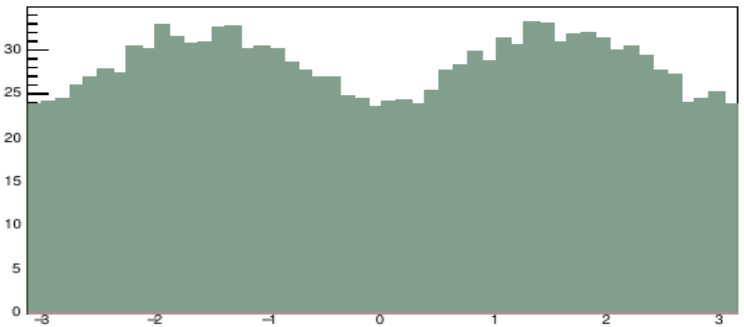
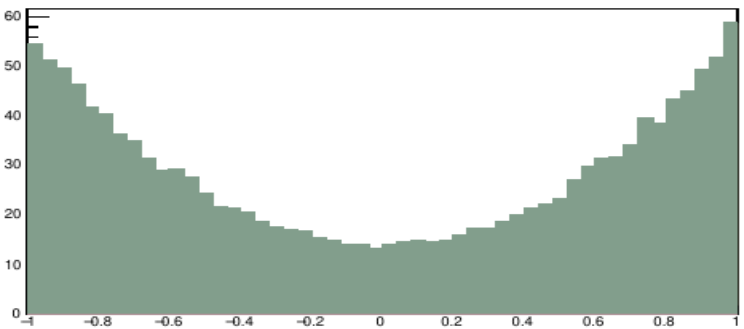
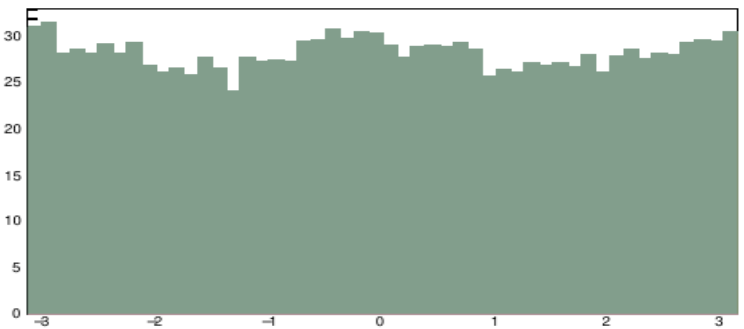
- 12 Vertices $V^{i}_{\lambda_\gamma,\Lambda}$
  - $0^- \rightarrow V^{0^-}_{+1,0}$
  - $1^+ \rightarrow V^{1^+}_{+1,-1}, V^{1^+}_{+1,0}, V^{1^+}_{+1,+1}$
  - $1^- \rightarrow V^{1^-}_{+1,-1}, V^{1^-}_{+1,0}, V^{1^-}_{+1,+1}$
  - $2^+ \rightarrow V^{2^+}_{+1,-2}, V^{2^+}_{+1,-1}, V^{2^+}_{+1,0}, V^{2^+}_{+1,+1}, V^{2^+}_{+1,+2}$
  - $2^- \rightarrow V^{2^-}_{+1,-2}, V^{2^-}_{+1,-1}, V^{2^-}_{+1,0}, V^{2^-}_{+1,+1}, V^{2^-}_{+1,+2}$

Backups (cont.)

- 6 real partial wave amplitudes C_l^i
  - $0^- \rightarrow C_1^{0-}$
  - $1^\pm \rightarrow C_1^{1-}, C_0^{1+}, C_2^{1+}$
  - $2^\pm \rightarrow C_1^{2-}, C_2^{2+}$
- Four Dalitz parameters α, β, γ and δ.

Backups (cont.)

D Wave Fit (Without Signal) (Not for DNP 2020)

Backups (cont.)

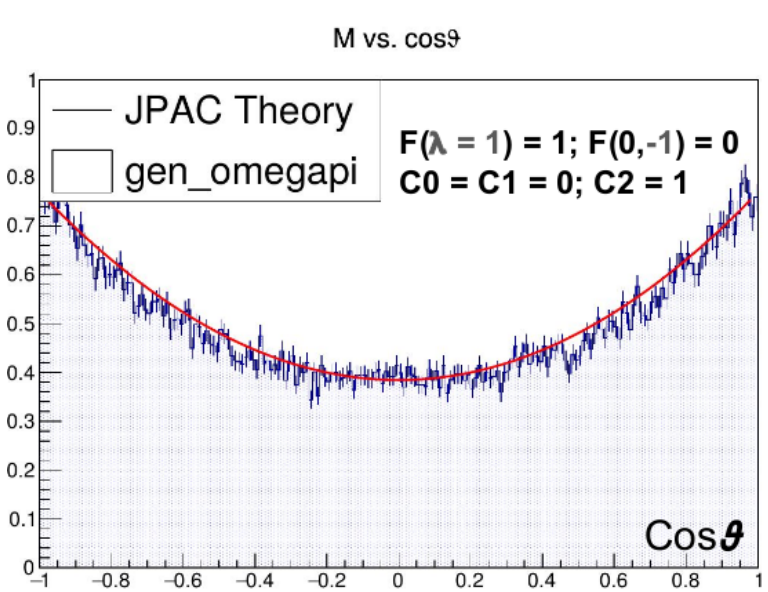
Testing the generator against JPAC Theory predictions.

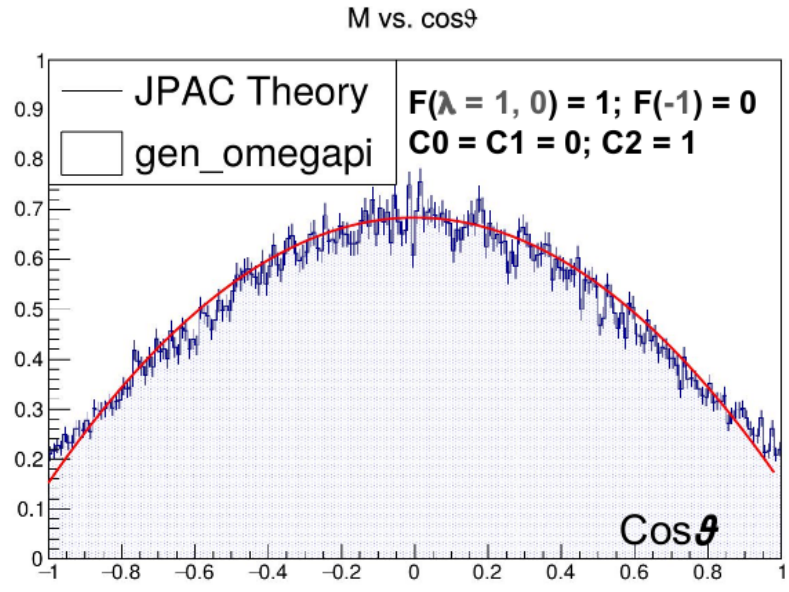
$$A_{\lambda_\gamma} = \sum_{J_i=0,1,2}^{\omega\pi Spin} \sum_{\eta_i=-1,1}^{\omega\pi Parity} \sum_{\Lambda=-J_i,..,J_i}^{\omega\pi SpinProj} V_{\lambda_\gamma,\Lambda} \sum_{\lambda=-1,0,1}^{\omega Helicity} D^{J_i}_{\Lambda,\lambda}(\Omega) F^i_\lambda D^1_{\Lambda,0}(\Omega_H) G$$

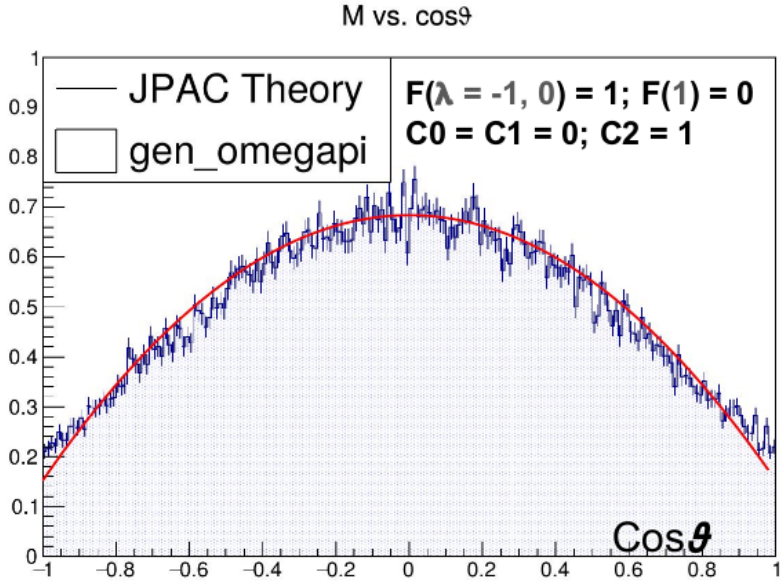
Below are the parameters that are kept constant for the study

- Spin (J) = 1
- $\omega\pi$ Parity (η) = +1
- Spin Projection (J_z or Λ) = +1, 0, 1
- Helicity (λ) = +1, 0, 1
- All the vertices are turned off except V(+1, 0) and V(-1, 0) are set to constant
- C^i_l = (0, 0, 1)
- We can now turn on or off the differential partial waves (turn on **F** for each λ) in the formula for F. F has three parts $F(\lambda = -1)$, $F(\lambda = 0)$, $F(\lambda = 1)$

Backups (cont.)







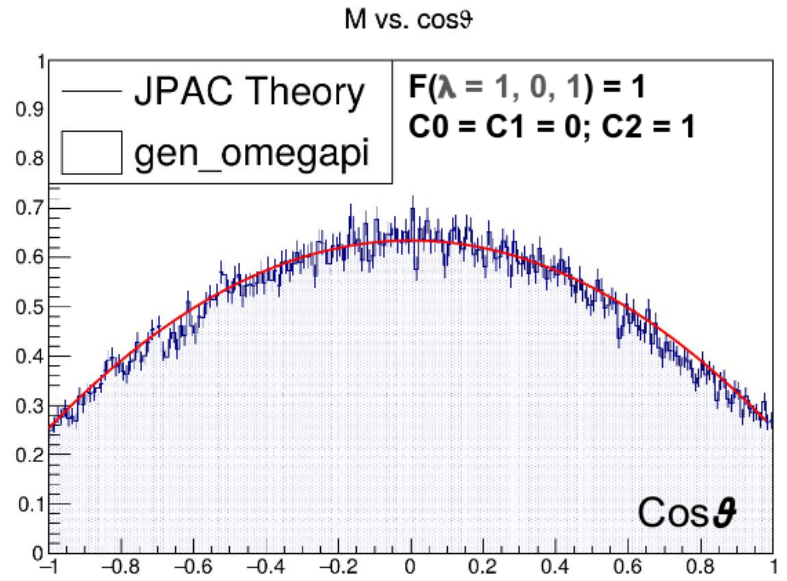


Figure 8: Testing the generator and JPAC predictions

Backups (cont.)

Testing the generator against JPAC Theory predictions.

$$A_{\lambda_\gamma} = \sum_{J_i=0,1,2}^{\omega\pi Spin} \sum_{\eta_i=-1,1}^{\omega\pi Parity} \sum_{\Lambda=-J_i,..,J_i}^{\omega\pi SpinProj} V_{\lambda_\gamma,\Lambda} \sum_{\lambda=-1,0,1}^{\omega Helicity} D^{J_i}_{\Lambda,\lambda}(\Omega) F^i_\lambda D^1_{\Lambda,0}(\Omega_H) G$$

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- Spin (J) = 1
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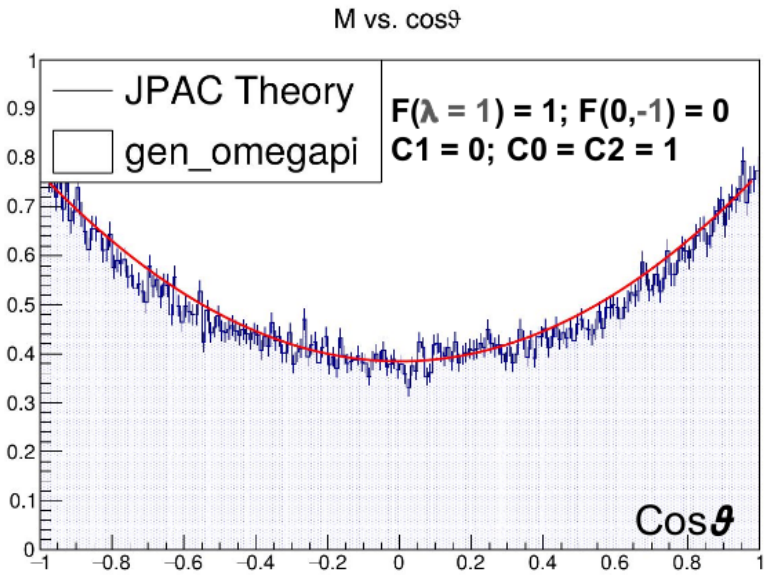
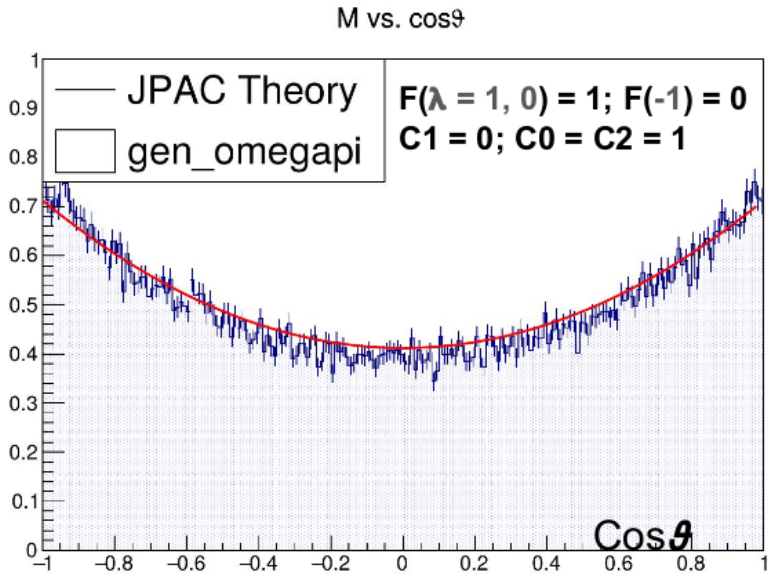
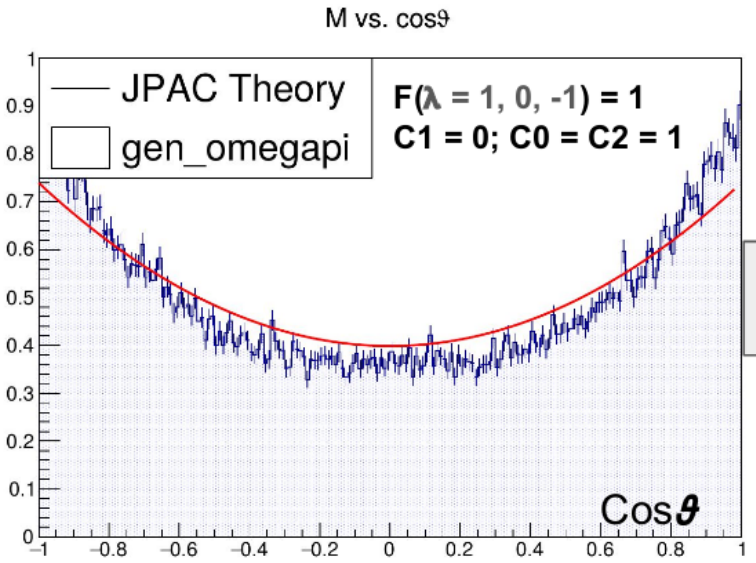
- C^i_l = (1, 0, 1)
- We can now turn on or off the differential partial waves (turn on **F** for each C^i_l).

Backups (cont.)







Switching on C1 doesnt affect the 1^+ state

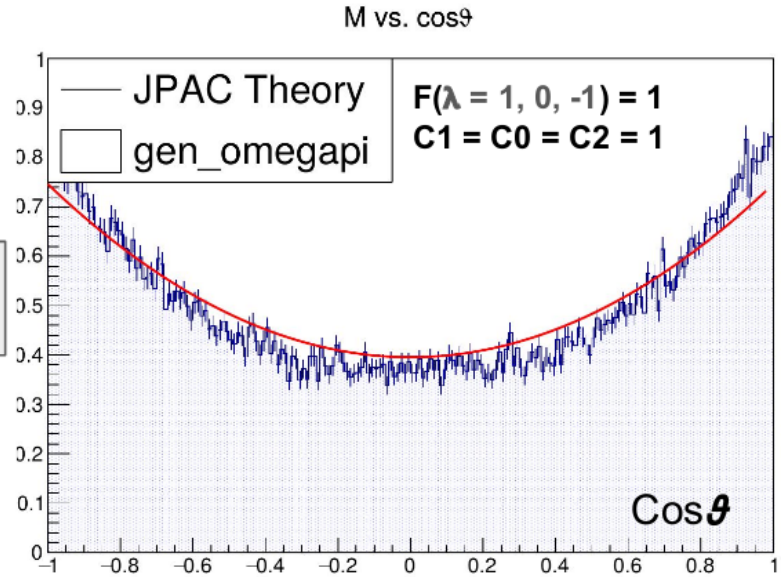


Figure 9: Testing the generator and JPAC predictions