Partial wave analysis studies with simulated $\eta^{(\prime)}\pi^0$ events in GlueX

Florida International University 2020

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Outline

1. Introduction

- Evidence for π_1 (1600) exotic meson with π beam
- Search for exotic π_1 (1600) via $\gamma p \rightarrow p\eta'\pi^0$ in GlueX via Partial Wave Analysis (PWA)
- Newly developed model of intensity for $\eta\pi$ photoproduction
- The GlueX experiment

2. Developing and testing methods for PWA using AMPTOOLs package

- Calculating moments of angular distribution using fitted partial waves
  - Compare moments from different methods

3. Summary

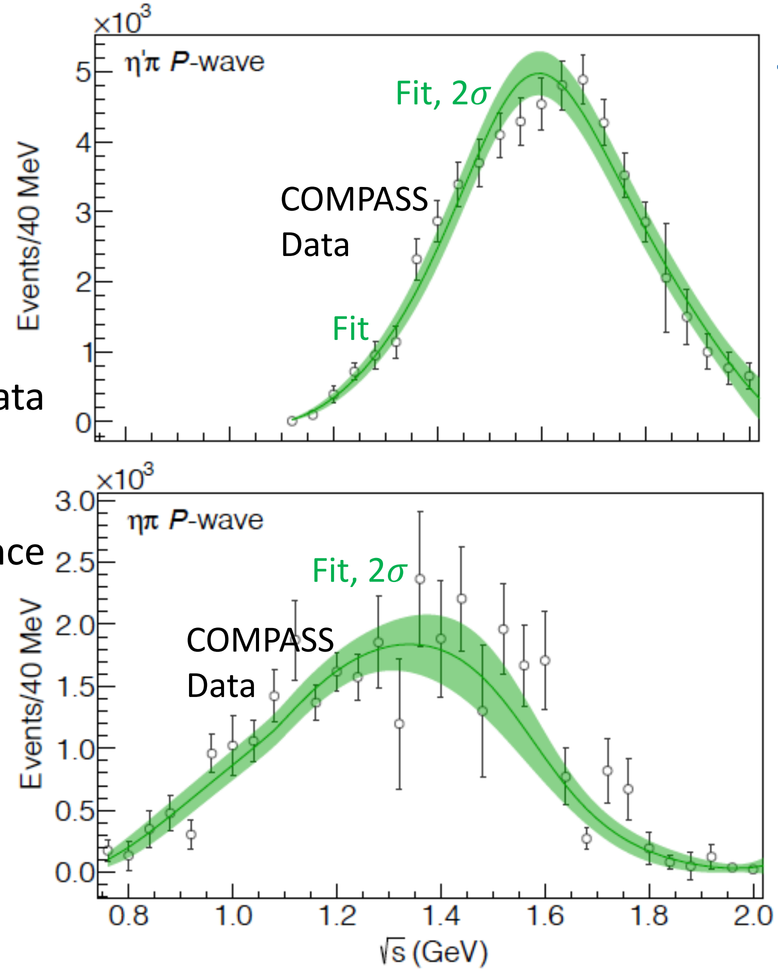
π_1 (1600) results from studies of $\eta'\pi$ system with π beam incident on a p target

Evidence for exotic $I^G J^{PC} = 1^- 1^{-+}$ state π_1 (1600)
$G = C \cdot (-1)^I$, C operator followed by a rotation in isospin (I)

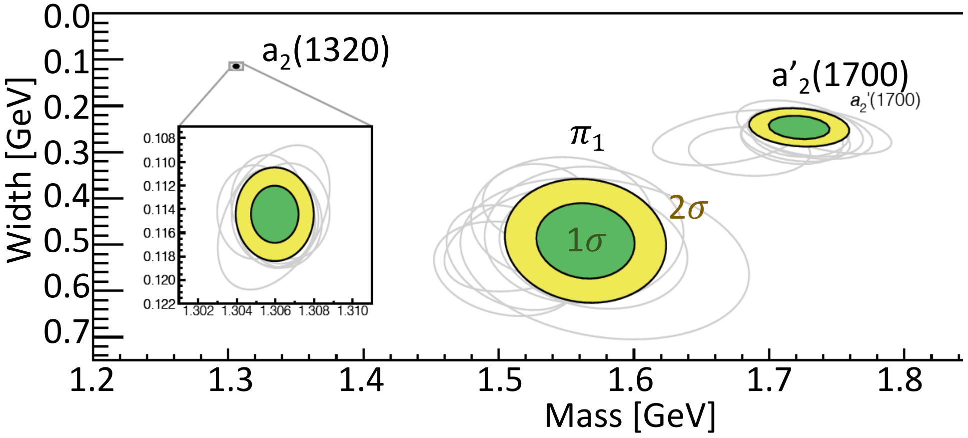
Several experiments suggest existence of π_1:

- **VES,** $E_\pi = 37$ GeV/c (D. V. Amelin et al., Phys. Atom. Nucl. 68, 359 (2005))
- **E852,** $E_\pi = 18$ GeV/c (E. I. Ivanov et al. [E852 Collaboration], Phys. Rev. Lett. 86, 3977 (2001))
- **COMPASS,** $E_\pi = 191$ GeV/c (C. Adolph, et al. [COMPASS Collaboration], Phys. Lett. B740, 303 (2015))

- Fit COMPASS data with amplitude model
- Extract resonance poles



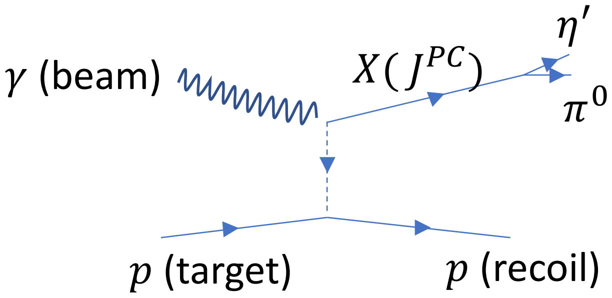
Joint Physics Analysis Center (JPAC)



A. Rodas et al. [Joint Physics Analysis Center], PRL 122, 042002 (2019)

Search for π_1 via $\gamma p \to p\eta'\pi^0$ at GLUEX

t – channel exchange



Decay mode

$$\gamma p \to pX$$
$$\downarrow$$
$$\eta'\pi^0$$

$$\eta' \to \pi^+\pi^-\eta \qquad \pi^0 \to \gamma\gamma$$
$$\eta \to \gamma\gamma$$

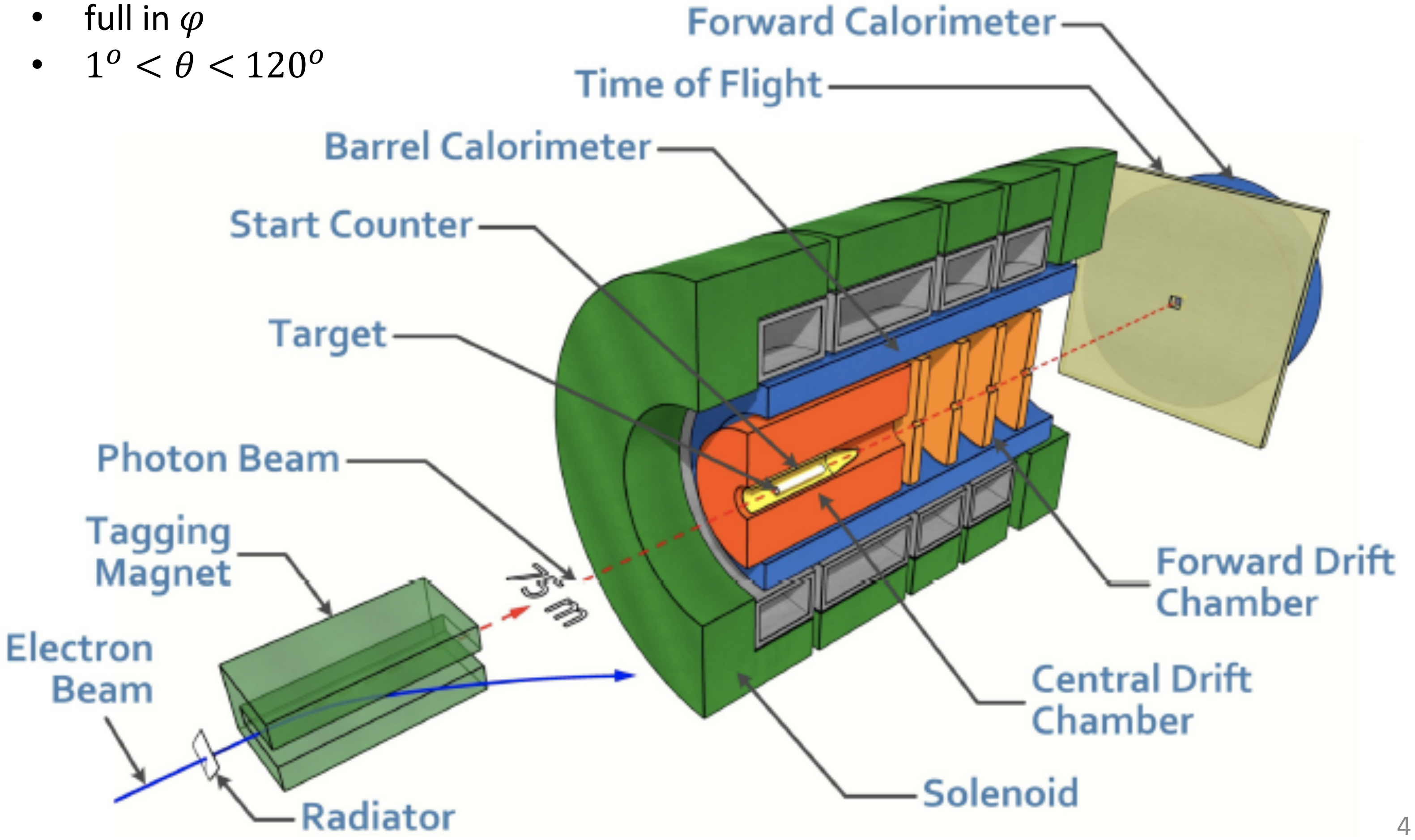
The GlueX experiment

Beam:

- Linearly polarized photon beam
- $E_\gamma \sim 9$ GeV

Angular coverage:

- full in φ
- $1^o < \theta < 120^o$



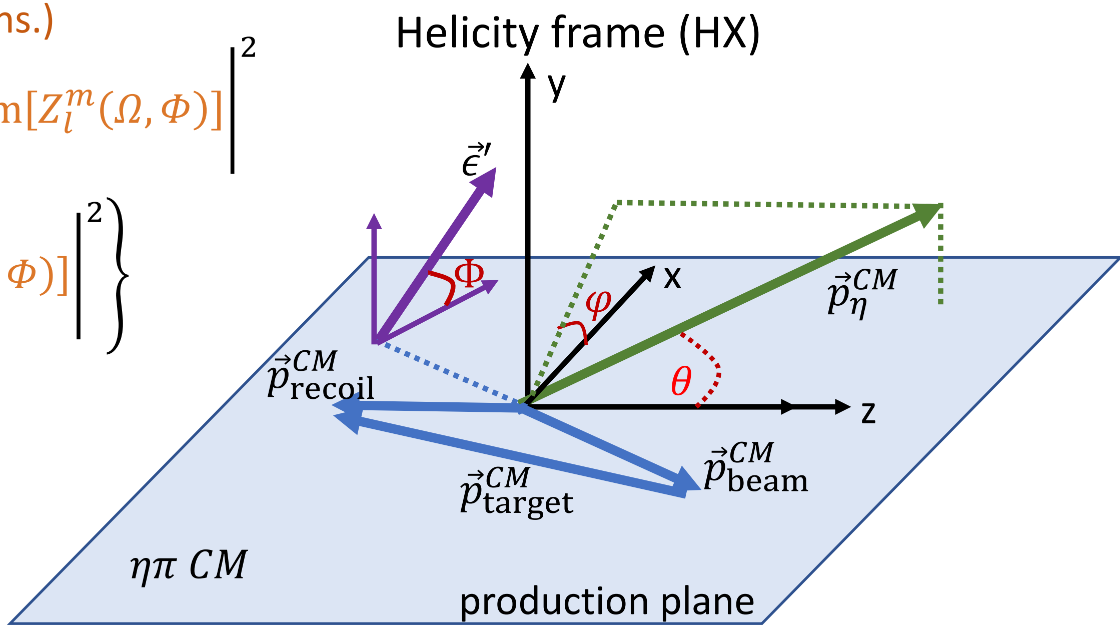
New model of Intensity for $\eta^{(')}\pi^0$ photoproduction at GlueX with polarized beam

- Write intensity I in terms of partial wave amplitudes
- Introduce reflectivity basis to trade helicity λ for the reflectivity index $\epsilon=\pm1$

Partial wave amplitudes (production of the wave)

Decay into two pseudo-scalars (parity constraints, L cons.)

$$I(\Omega,\Phi) = 2\kappa\sum_k\Bigg\{(1-P_\gamma)\left|\sum_{l,m}[l]^{(-)}_{m;k}\mathrm{Re}[Z_l^m(\Omega,\Phi)]\right|^2 + (1-P_\gamma)\left|\sum_{l,m}[l]^{(+)}_{m;k}\mathrm{Im}[Z_l^m(\Omega,\Phi)]\right|^2$$
$$+ (1+P_\gamma)\left|\sum_{l,m}[l]^{(+)}_{m;k}\mathrm{Re}[Z_l^m(\Omega,\Phi)]\right|^2 + (1+P_\gamma)\left|\sum_{l,m}[l]^{(-)}_{m;k}\mathrm{Im}[Z_l^m(\Omega,\Phi)]\right|^2\Bigg\}$$



$\Omega=(\theta,\varphi)$
l, m- spin, its projection
$\vec{\epsilon}'$ - γ polarization vector
P_γ - degree of polarization
$Z_l^m(\Omega,\Phi)\equiv Y_l^m(\Omega)e^{-i\Phi}$
κ- kinematical factors
Nucleon spin flip k=1, non-flip k=0

PWA

- Bin data in small bins of $m_{\eta\pi}$, t and E_γ with constant $[l]^{(-)}_{m;k}$, $[l]^{(+)}_{m;k}$
- Fit data using extended unbinned (in (θ,φ)) maximum likelihood method using AmpTools package (https://github.com/mashephe/AmpTools)

$$\ln L(l) = \sum_{i=1}^{N}\ln I(l,\theta,\varphi) - \int I(V,\theta,\varphi)\eta(\theta,\varphi)\,d\Omega$$

$\eta(\theta,\varphi)$ -acceptance

- Minimize –lnL using MINUIT, to find $[l]^{(-)}_{m;k}$, $[l]^{(+)}_{m;k}$

V. Mathieu et al. Phys. Rev. D 100, 054017 (2019)

Analysis strategy

Generate 2*10⁶ $(p\eta\pi^0)$ events with AmpTools with the wave set $[l]^{(\epsilon)}_{m;k} = \left\{S^{(+)}_0, P^{(+)}_{0,1}, D^{(+)}_{0,1,2}\right\}_{k=0}$ and M>= 0

Generated resonances are

P_γ =0.3

- a_0(980 MeV)
- π_1(1600 MeV) (exotic)
- a2 (1320 MeV)
- a2' (1700 MeV)

1. Fit intensity with generated wave set to find partial waves using AmpTools.

2. Implement and test calculation of moments of angular distribution in terms of $[l]^{(\epsilon)}_{m;k}$ using the following expressions in terms of the $\eta'\pi^0$ SDMEs ${}^{(\epsilon)}\rho^{\alpha,ll'}_{mm'}$:

$$H^0(LM) = \sum_{\substack{ll' \\ mm'}} \left(\frac{2l'+1}{2l+1}\right)^{1/2} C^{l0}_{l'0L0} C^{lm}_{l'm'LM}\, \rho^{0,ll'}_{mm'}$$

$$\rho^{0,ll'}_{mm'} = \sum_{\epsilon} \kappa \sum_{k} \left(|l|^{(\epsilon)}_{m;k} |l'|^{(\epsilon)*}_{m';k} + (-1)^{m-m'} |l|^{(\epsilon)}_{-m;k} |l'|^{(\epsilon)*}_{-m';k} \right)$$

• • •

$$\boldsymbol{H}(LM) = -\sum_{\substack{ll' \\ mm'}} \left(\frac{2l'+1}{2l+1}\right)^{1/2} C^{l0}_{l'0L0} C^{lm}_{l'm'LM}\, \boldsymbol{\rho}^{ll'}_{mm'}$$

where $C^{l0}_{l'0L0}$ and $C^{lm}_{l'm'LM}$ denote the Clebsch-Gordan coeficients, 0≤ $L \leq 4$ and 0≤ $M \leq L$.

Non-zero odd L moments ↔ presence of exotic wave. If M=0, H^2 and H^3 are 0.

3. Compare to moment distributions obtained by Monte Carlo integration:

$$H^0(LM) = \frac{P_\gamma}{2} \int_o I(\Omega,\Phi) d^L_{M0}(\theta) cosM\phi,$$

$$H^1(LM) = \int_o I(\Omega,\Phi) d^L_{M0}(\theta) cosM\phi\, cos2\Phi$$

• • •

with $\int_o = (1/\pi P_\gamma) \int_0^\pi sin\theta d\theta \int_0^{2\pi} d\phi \int_0^{2\pi} d\Phi$ and $d^L_{M0}(\theta)$ is Wigner d-function.

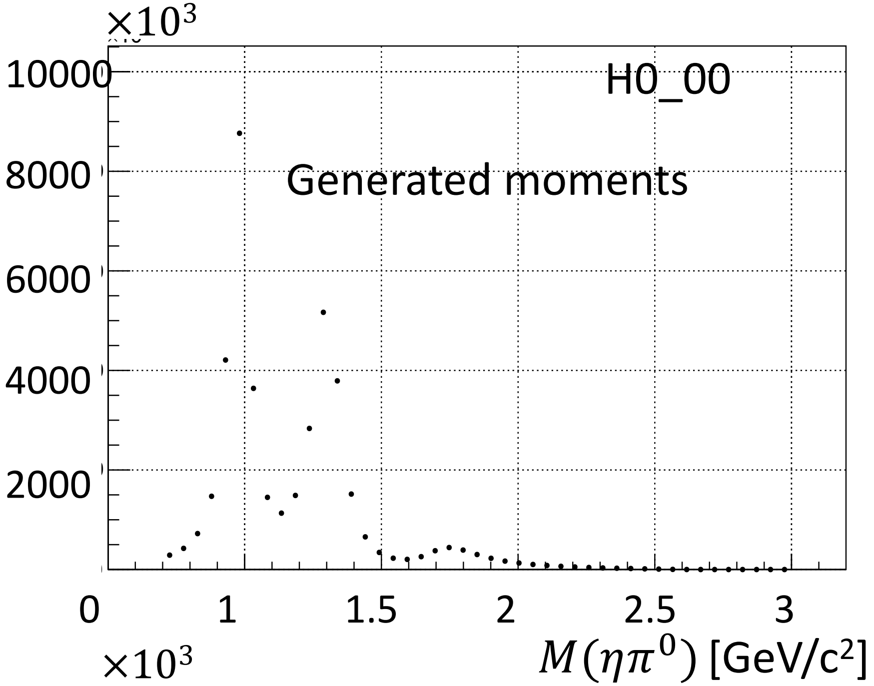
Mathieu et al. Phys. Rev. D 100, 054017 (2019)

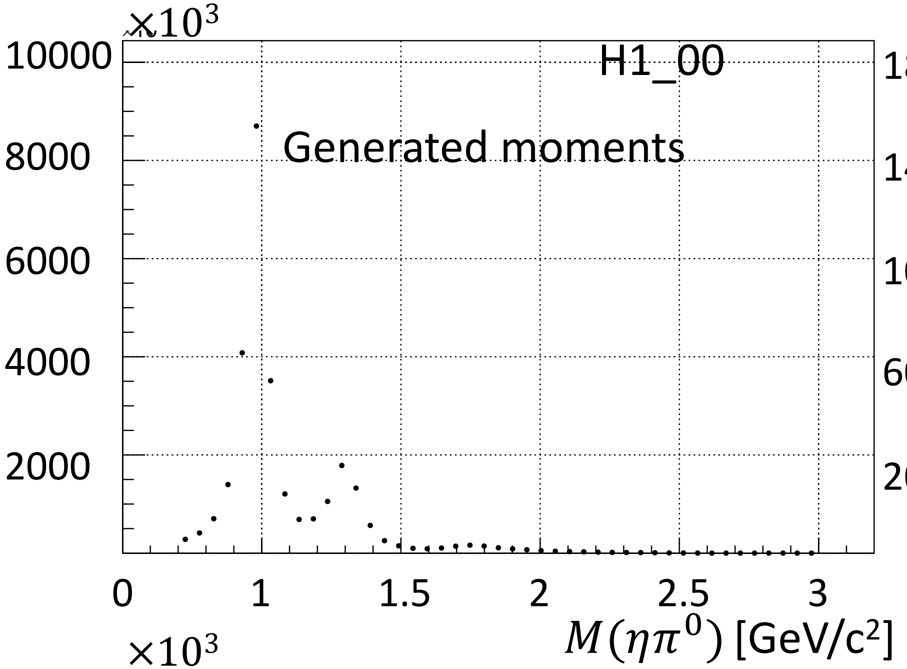
Polarized moments calculated with partial waves agree with those obtained by Monte Carlo integration

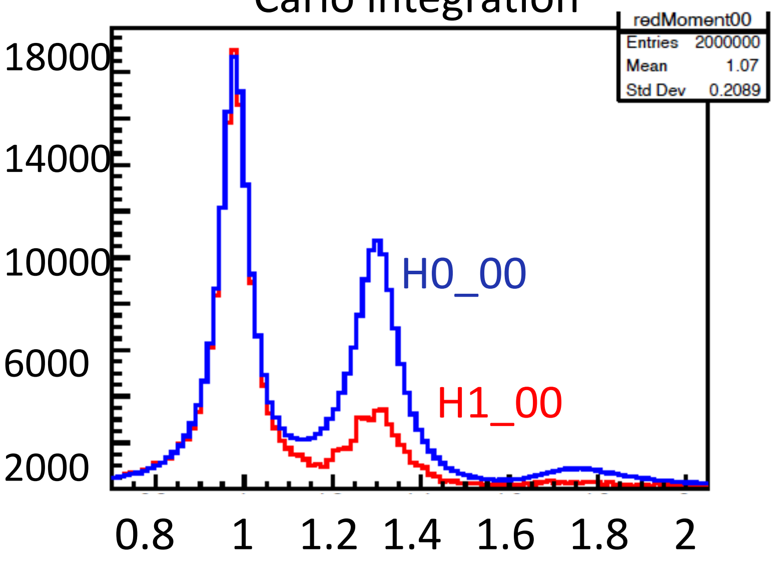
0<t<0.3 (GeV/c)²

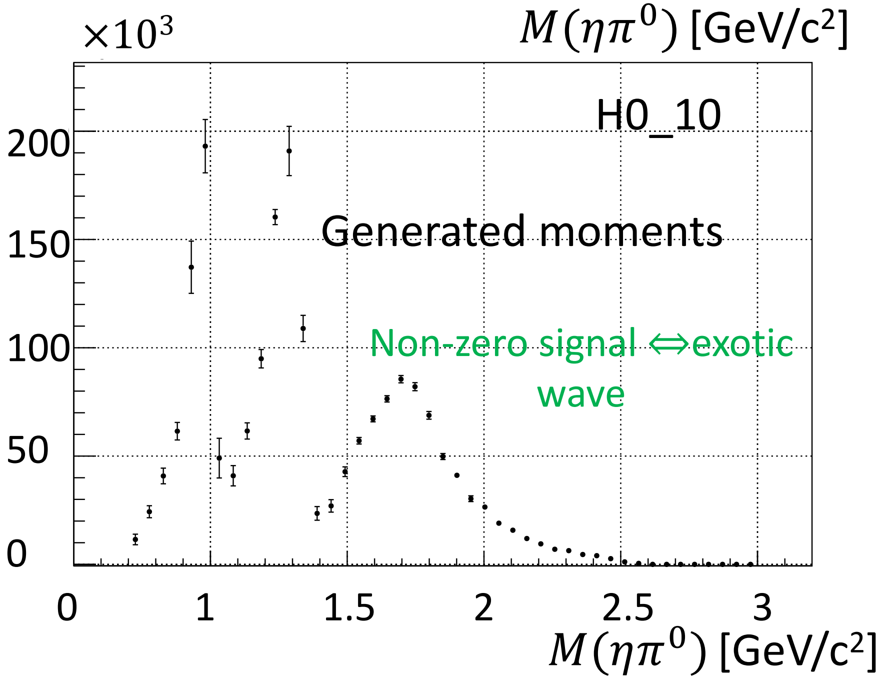
With uncertainties from bootstrapping

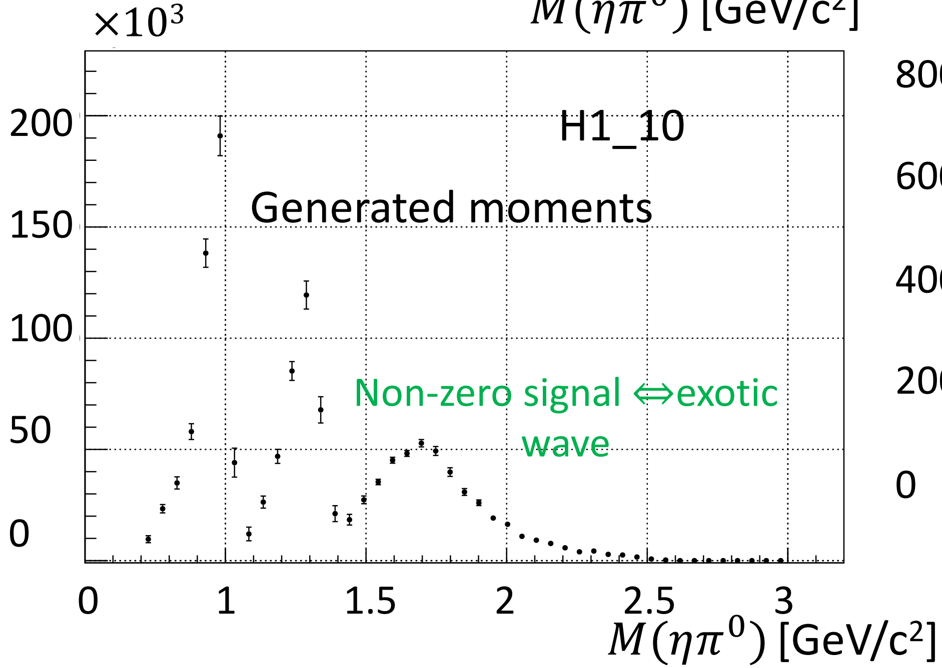
Unnormalized moments from Monte Carlo integration

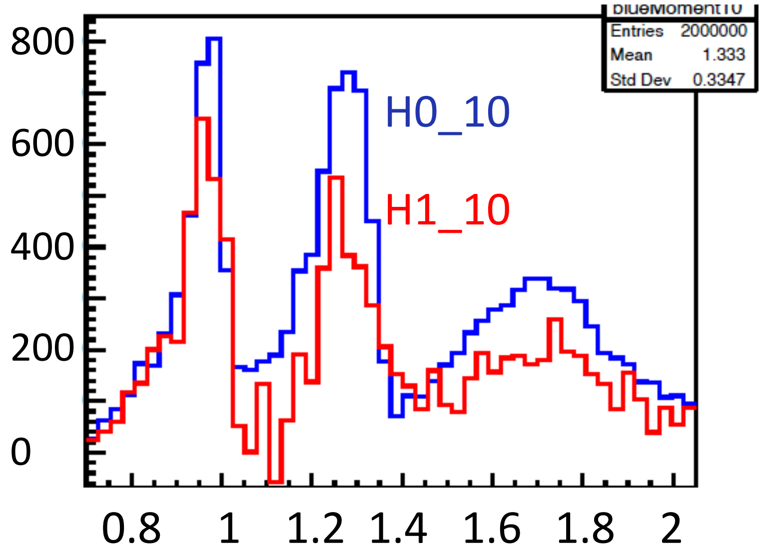








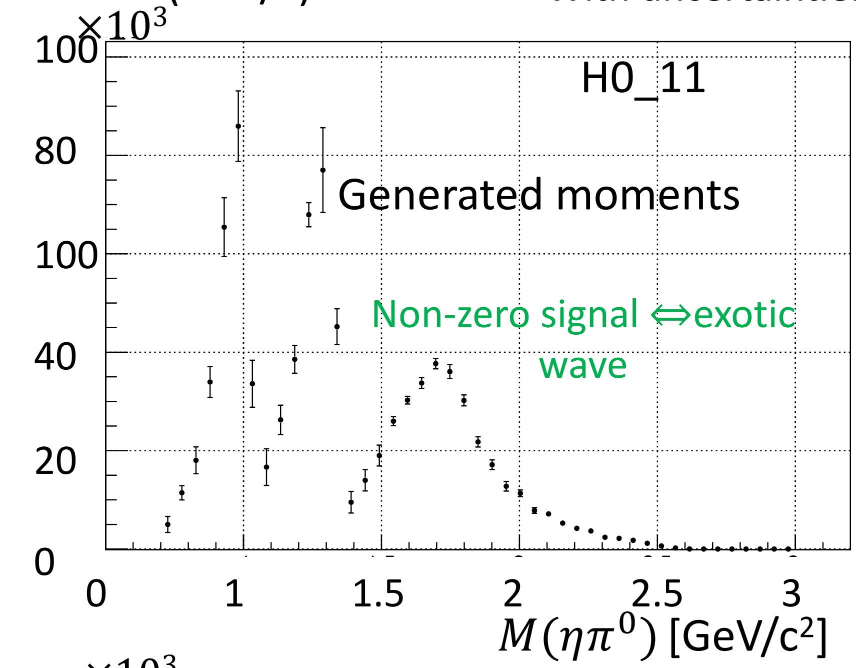


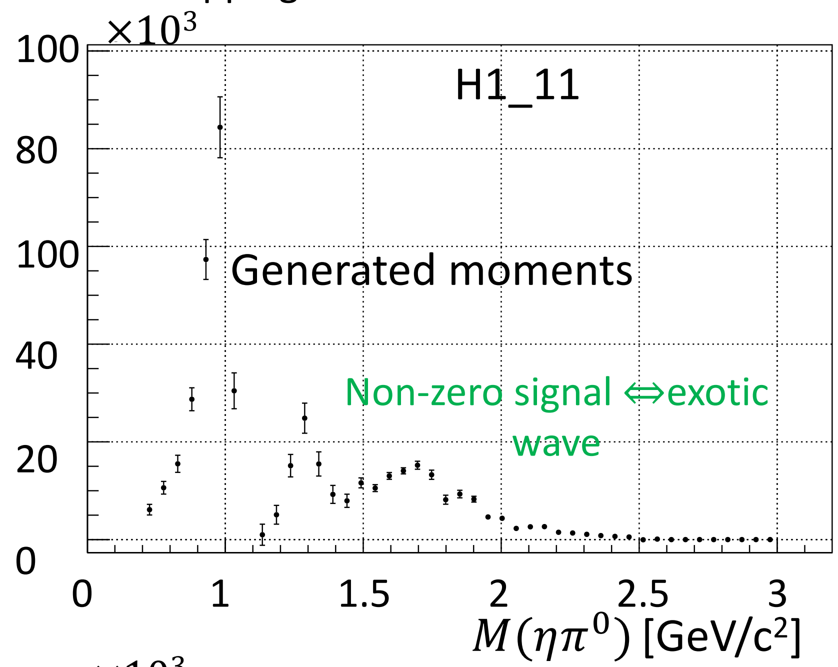


Polarized moments calculated with partial waves agree with those obtained by Monte Carlo integration

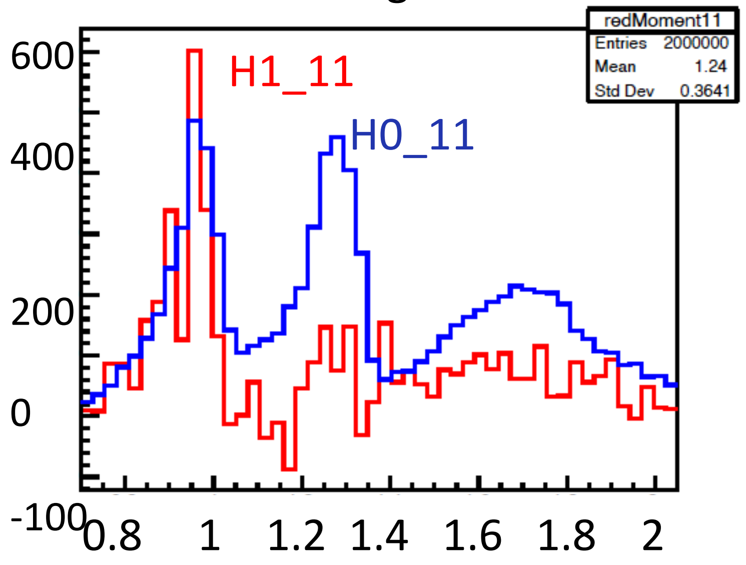
0<t<0.3 (GeV/c)²

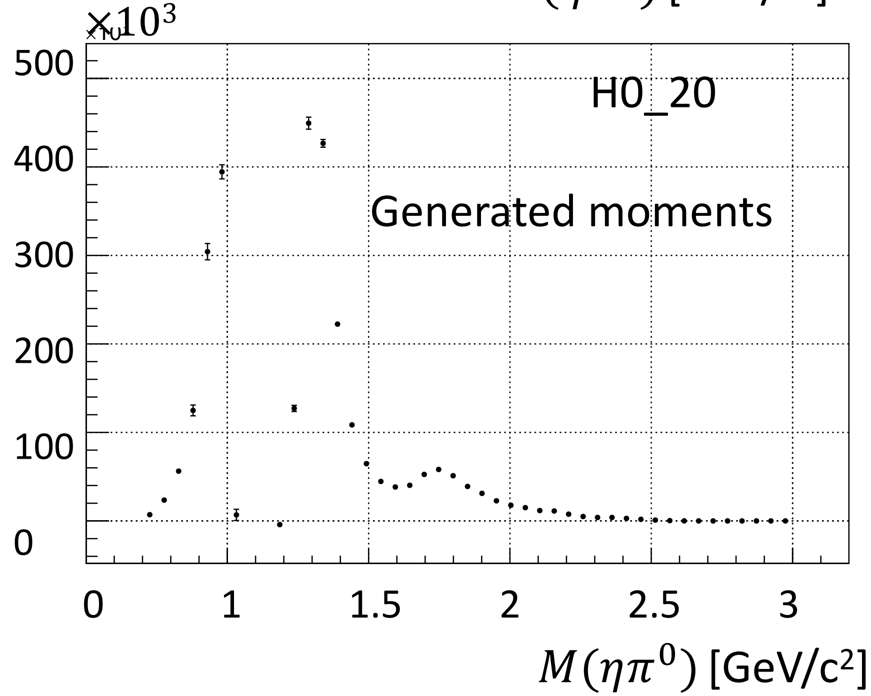
With uncertainties from bootstrapping

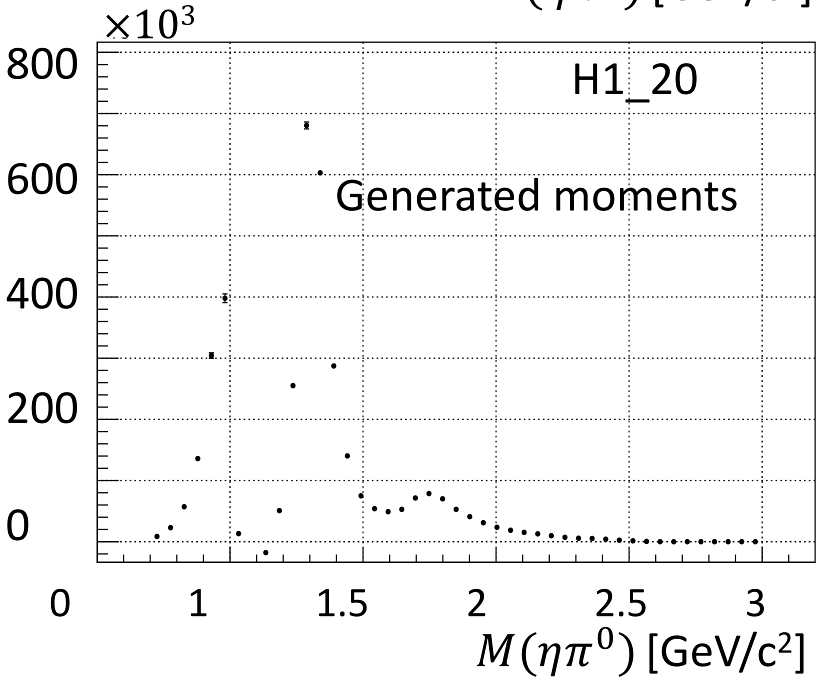


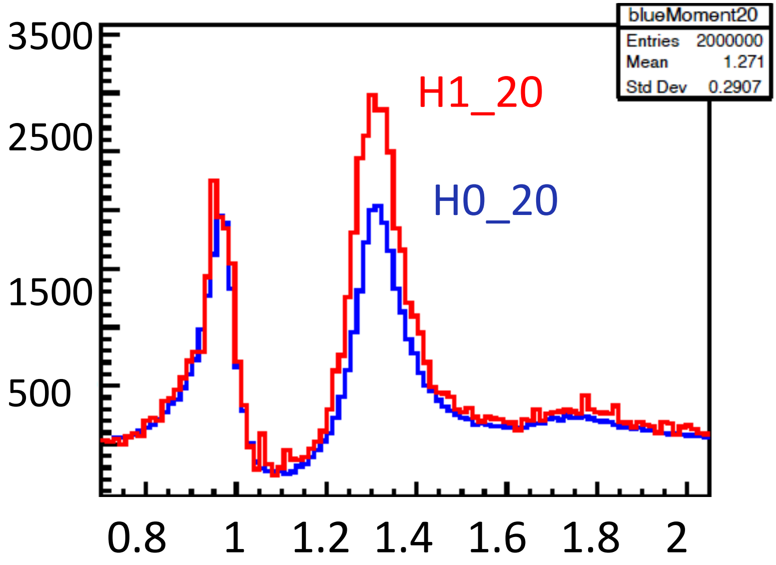


Unnormalized moments from Monte Carlo integration







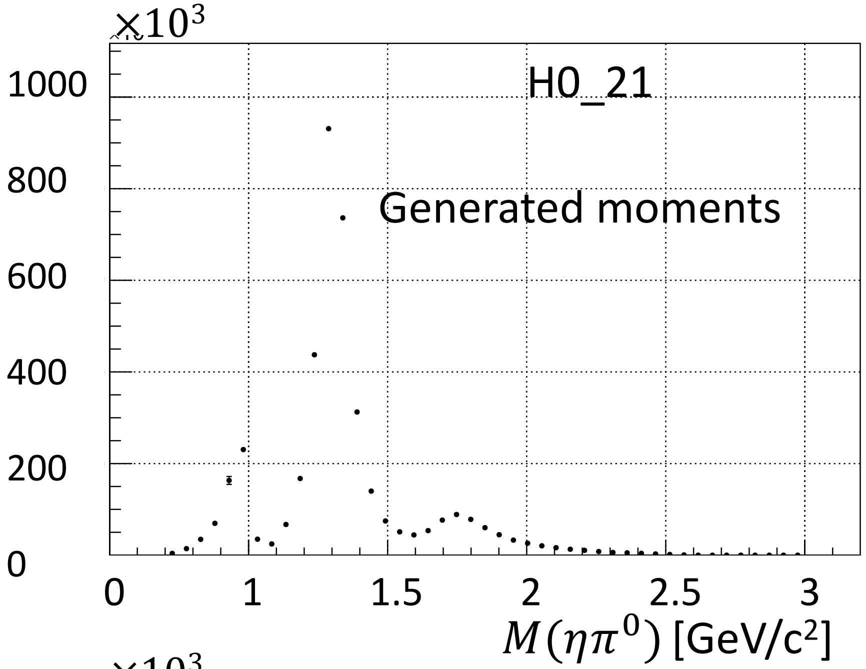


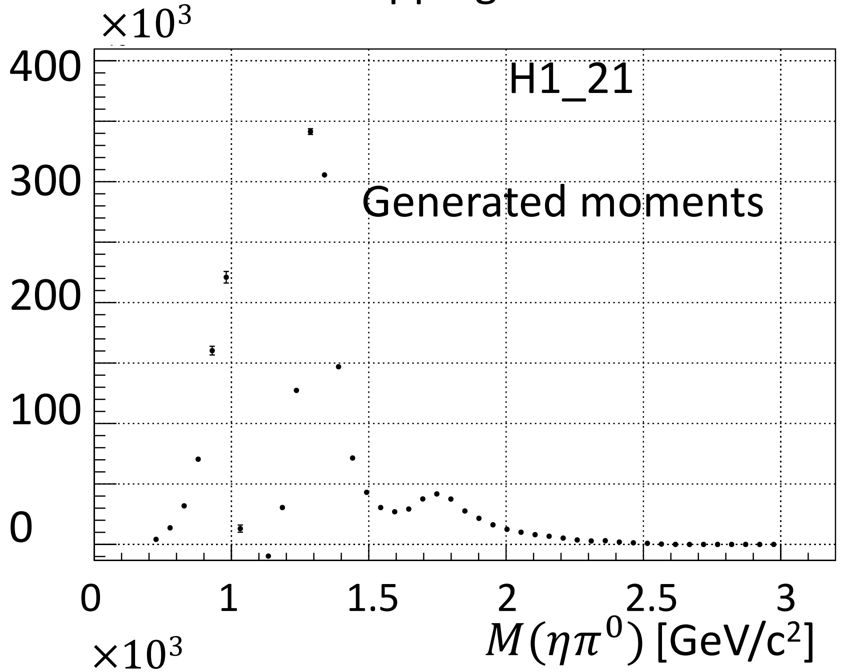
Polarized moments calculated with partial waves agree with those obtained by Monte Carlo integration

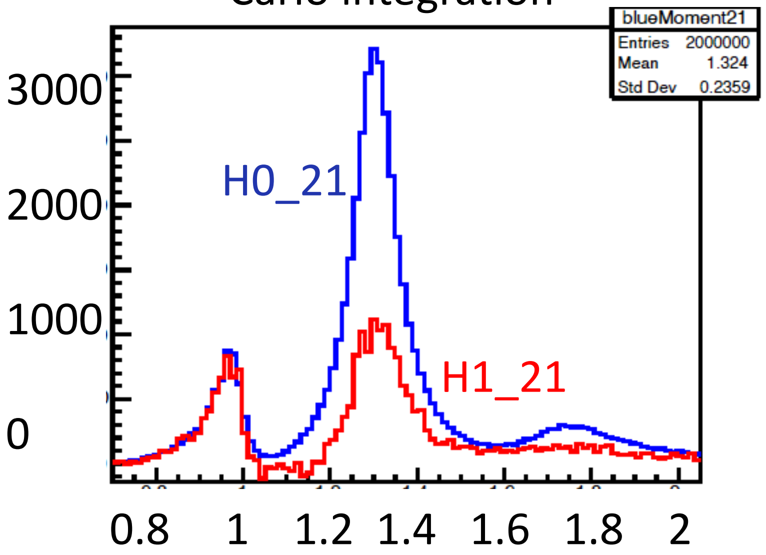
0<t<0.3 $(GeV/c)^2$

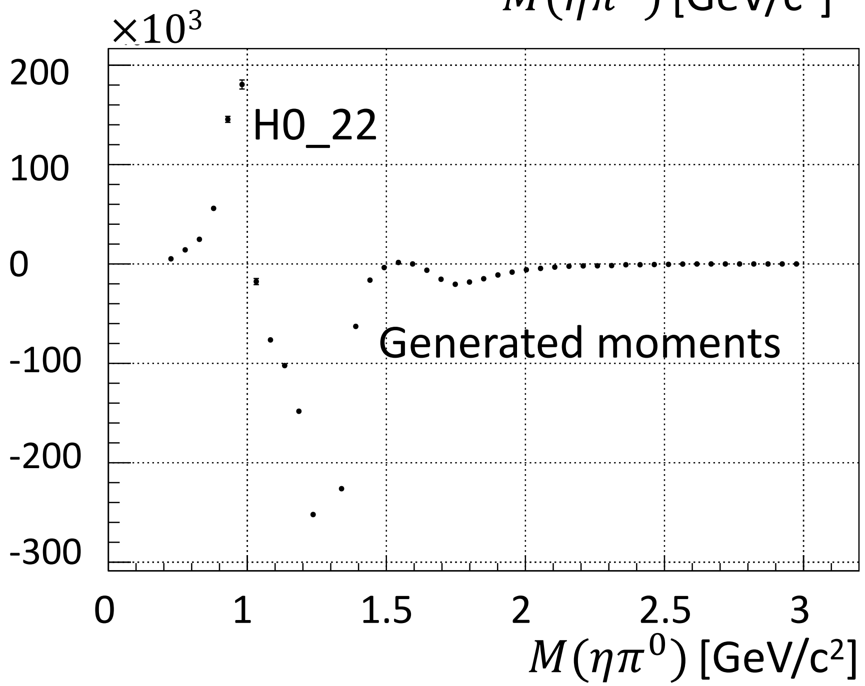
With uncertainties from bootstrapping

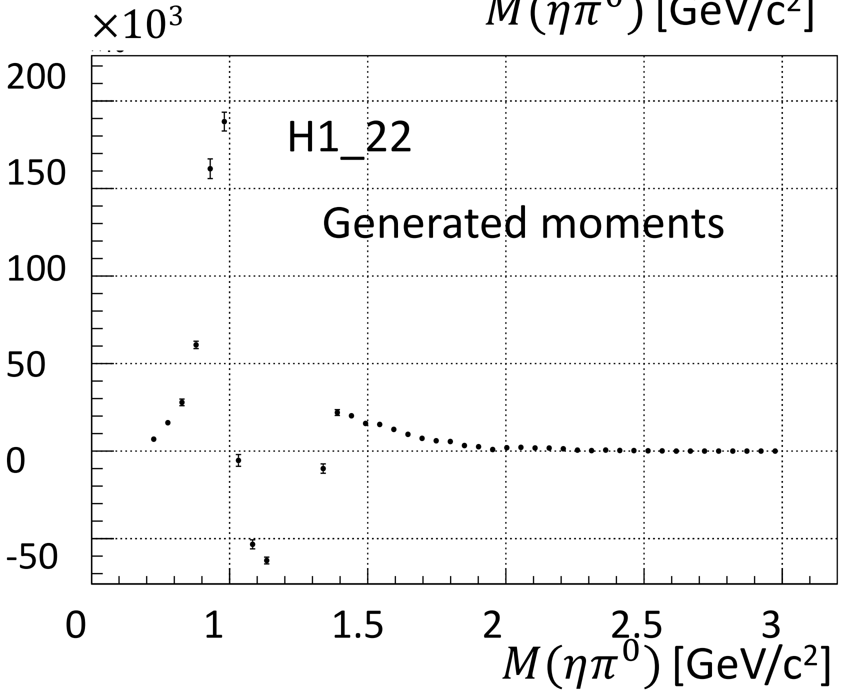
Unnormalized moments from Monte Carlo integration

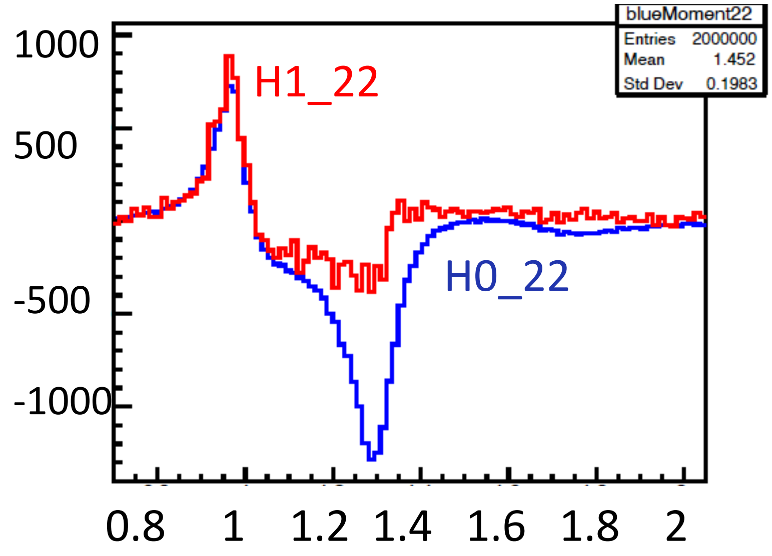












Summary

1. First studies of polarized moments in $\eta\pi^0$ photoproduction at GlueX using generated data sample

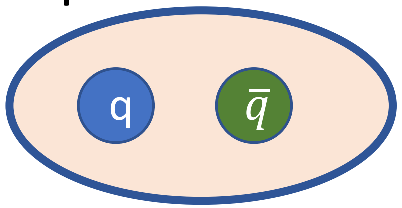
2. Have implemented and tested calculation of moments in terms of fitted partial waves
   - Results agree with moments from Monte Carlo integration.

3. Future plans:
   - Implement fitting of intensity to extract moments in AMPTOOLS.
   - Search for exotic π_1 via amplitude analysis of GLUEX $\gamma p \to p\eta'\pi^0$ data.

Backup slides

Mesons

Mesons in standard quark model



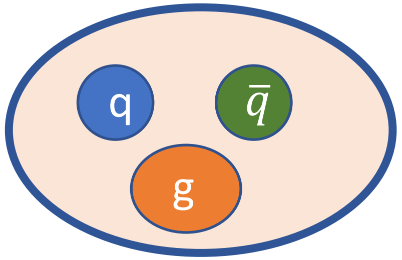
Classified as J^{PC} multilets:

$\vec{J} = \vec{L} + \vec{S}$,
$P = (-1)^{L+1} \rightarrow$ Spherical harmonics $(-1)^{l}$
$\times$ Product of individual parites of $q, \bar{q}$ (-1)
$C = (-1)^{L+S} \rightarrow$ Orbital angular momentum $(-1)^{l}$
$\times$ Flip of spin wavefunctions $(-1)^{S+1}$
$\times$ interchanging q and $\bar{q}$ (-1)

J- total angular momentum
S- total quark spin
L- orbital angular momentum between $q\bar{q}$ pair
P- parity
C- charge conjugation

J^{PC}=$\mathbf{0}^{--}$, $\mathbf{odd}^{-+}$ and $\mathbf{even}^{+-}$ **"exotic"** quantum numbers are not available.

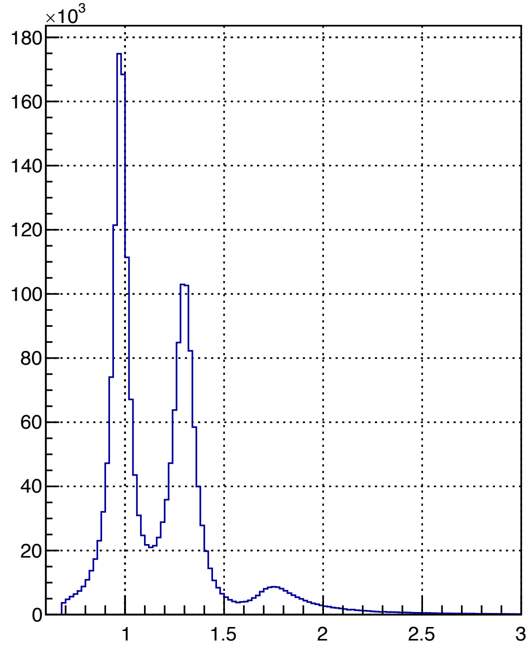
Hybrid mesons



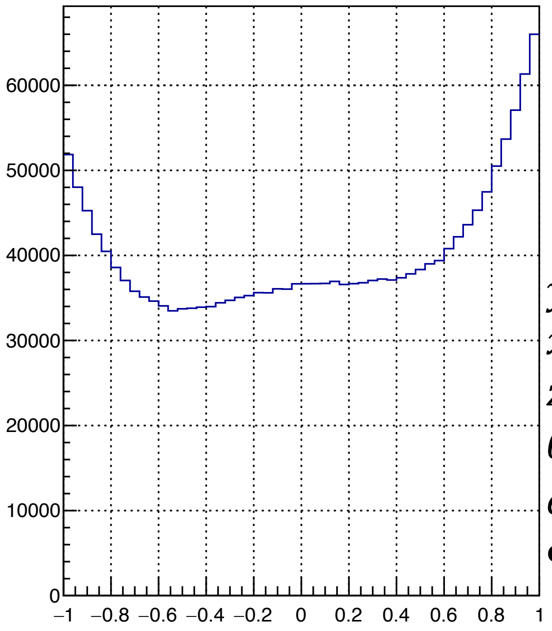
Quark anti-quark pair coupled to valence gluon.
"Exotic" J^{PC} are also available.
Predicted by lattice QCD (quantum chromodynamics) calculations (Phys. Rev. D 88, 094505 (2013)).

Primary motivation of the GLUEX is the search for light hybrid mesons.

Generated $2*10^6$ $(p\eta'\pi^0)$ events with AmpTools

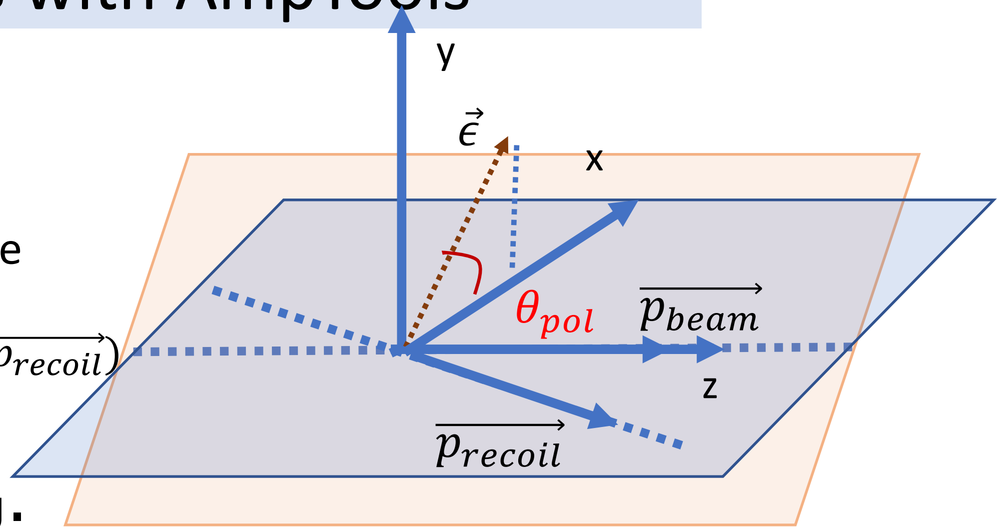


$M(\eta'\pi^0)$ [GeV/c²]



$\cos\theta_{GJ}$

Lab frame



$\vec{y} = \overrightarrow{p_{beam}} \times (-\overrightarrow{p_{recoil}})$

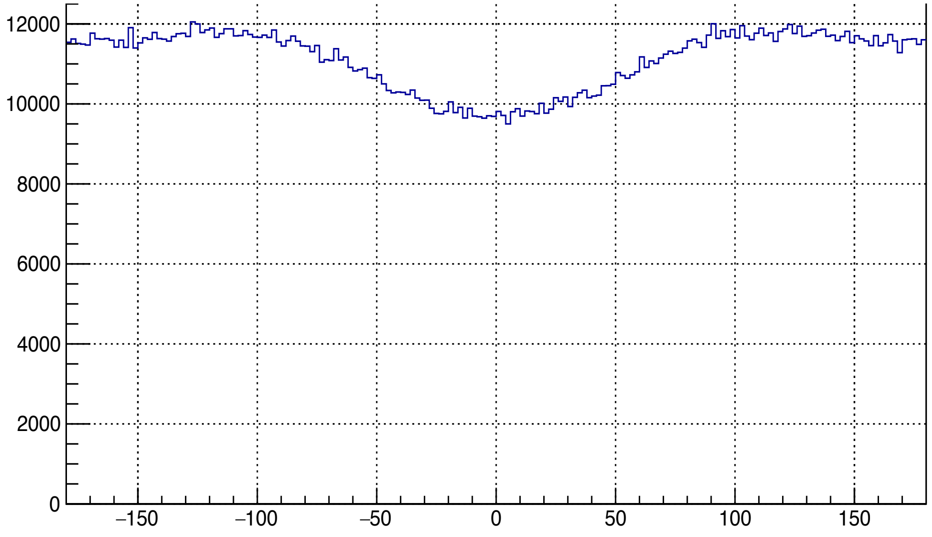
$\vec{x} = \vec{y} \times \overrightarrow{p_{beam}}$

$\vec{z} = \vec{x} \times \vec{y}$

θ_{pol}=1.7 Deg.

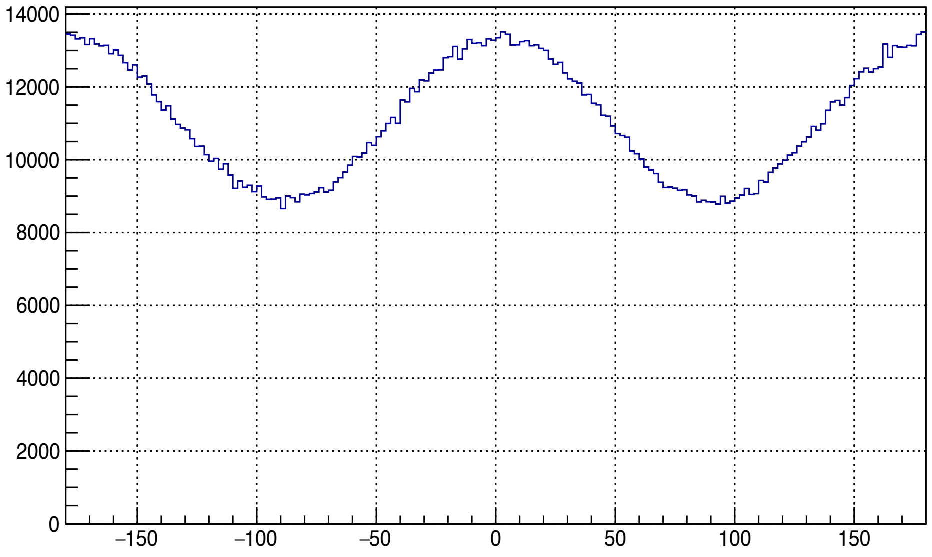
$\vec{\epsilon} = (\cos(\theta_{pol}),\ \sin(\theta_{pol}),\ 0)$

$\Phi\ =\ \mathrm{arctg}(\vec{y}\cdot\vec{\epsilon},\ \overrightarrow{p_{beam}}\cdot(\vec{\epsilon}\times\vec{y}))$



φ

Lab frame



Φ

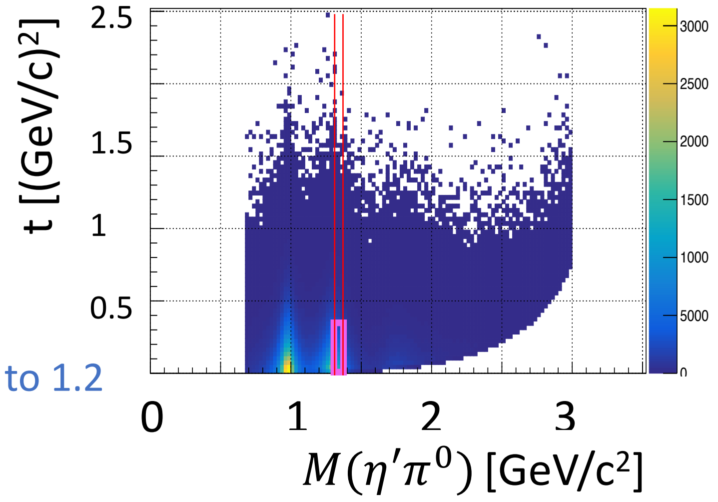
Results for bin M=1.37 and t<0.3

Amplitudes used in fitting are S0+, P0+, P1+, D0+, D1+, D2+. Good starting values for fit parameters

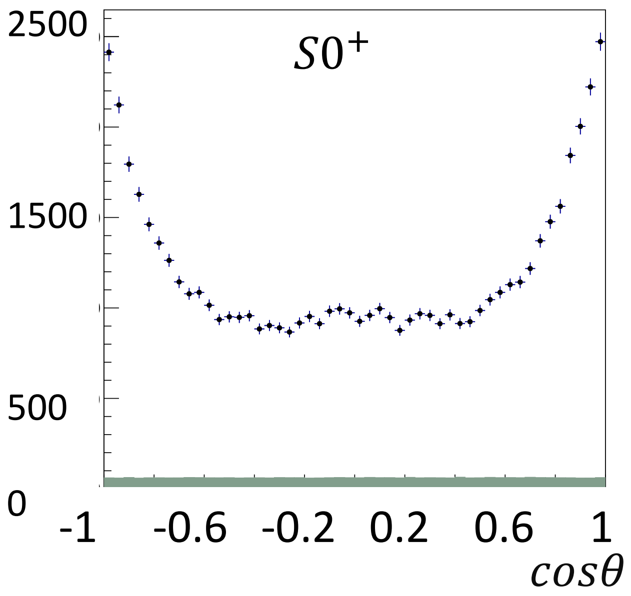
Bin M , t

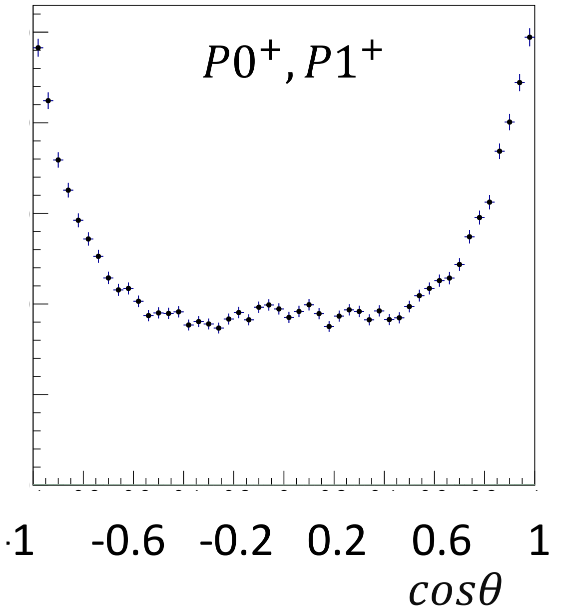
$M(\eta\pi^0)$ range from 0.7 to 3
N bins=45
Bin width≈ 0.051 GeV/c^2

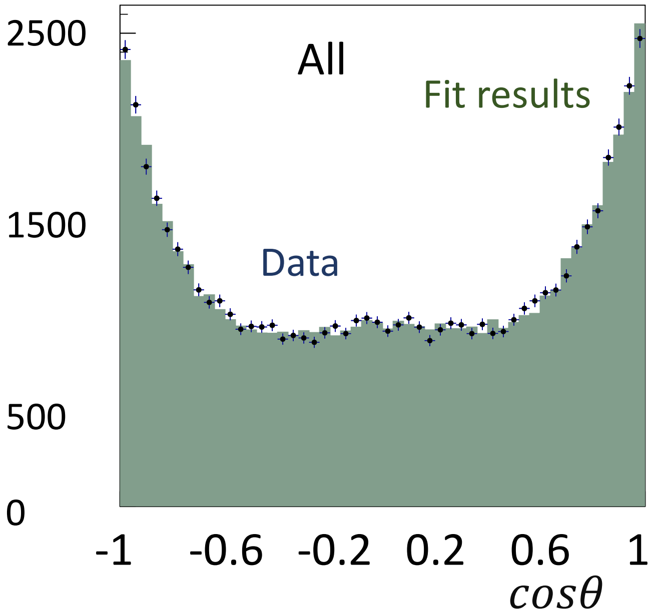
t range from 0 to 1.2
N bins=4
Bin width≈
0.3 (GeV/c)2

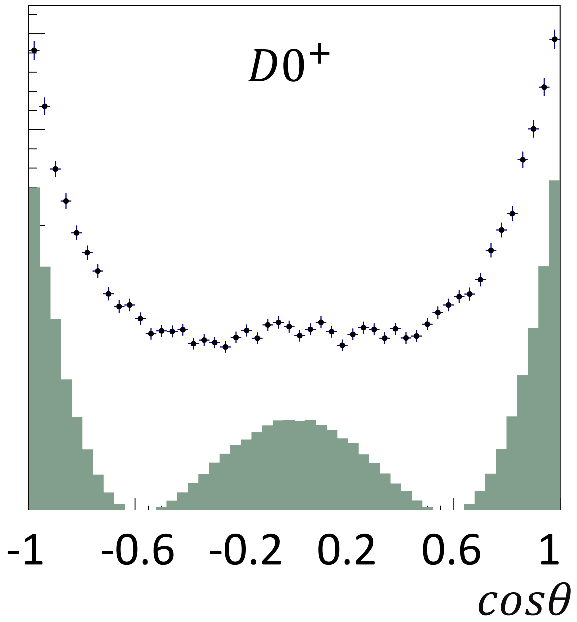


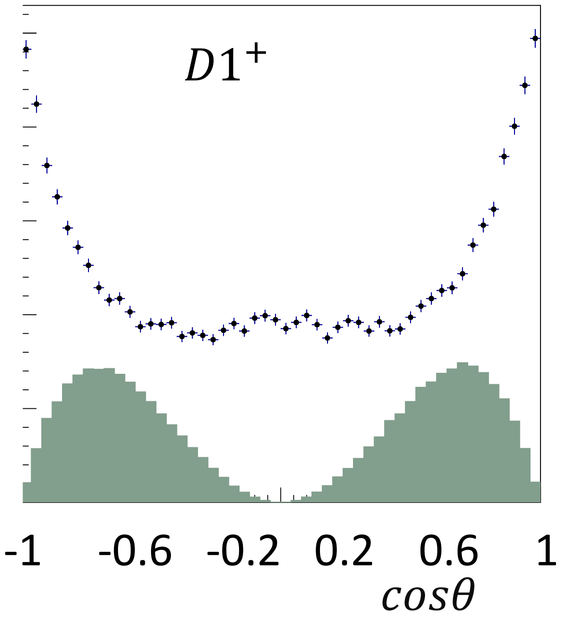
Fit results

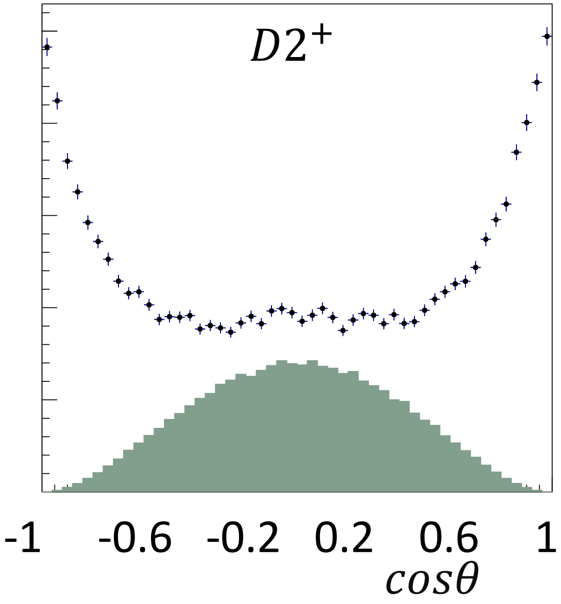












Fit 1 results (fitting in M and t bins)

Amplitudes used in fitting are amplitudes $S_0^{(+)}, P_0^{(+)}, P_1^{(+)}, D_0^{(+)}, D_1^{(+)}, D_2^{(+)}$. Good starting values for fit parameters