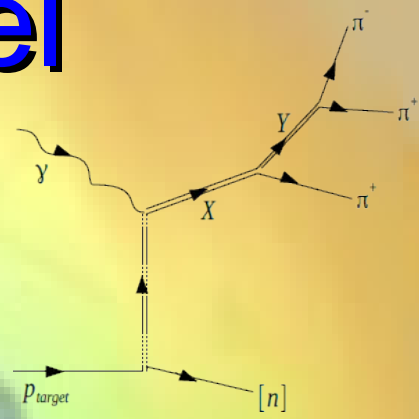
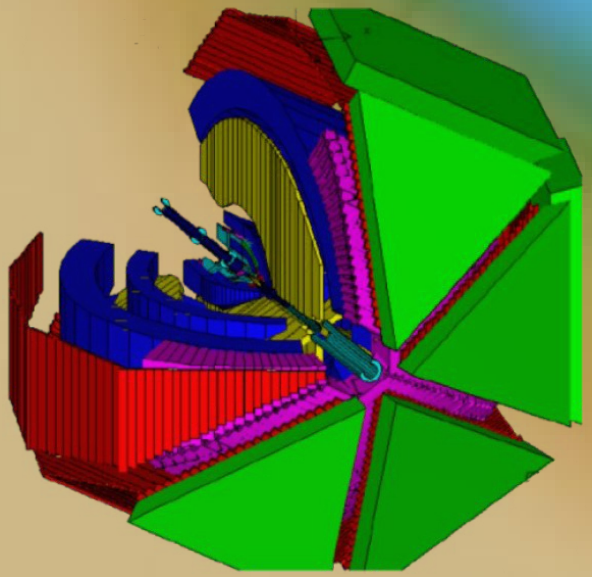
Alexander Ostrovidov
(Florida State University)

Meson Spectroscopy of the 3π decay channel in g12 run of CLAS





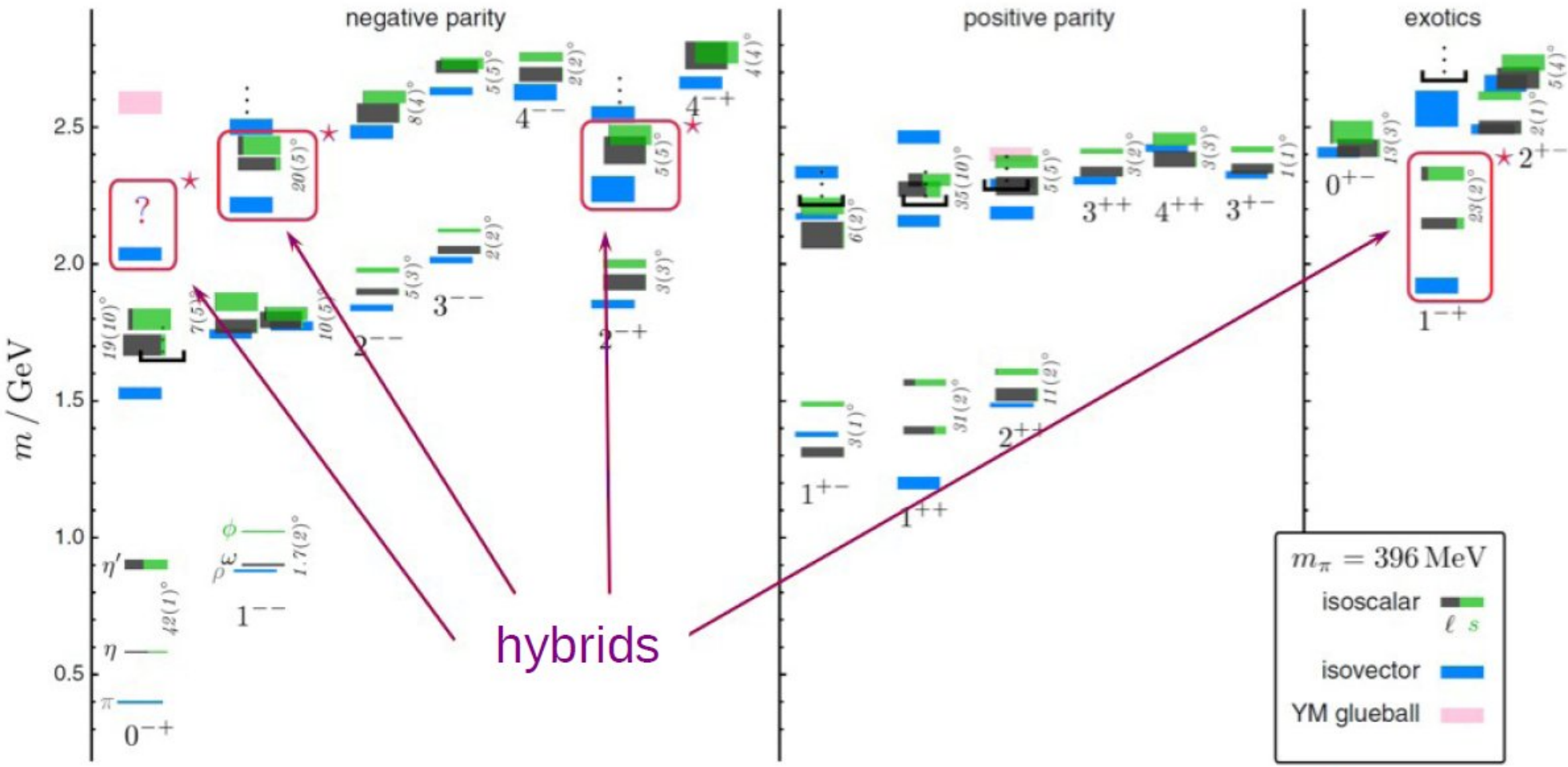
The analysis by

former FSU graduate student

Aristeidis Tsaris

Baryons 2016 Conference | Tallahassee, FL | May 19, 2016

Lattice QCD Meson Spectrum



Jefferson Lab

J. Dudek PRD 84, 074023 (2011)

The discovery of $\pi_1(1600)$ $\pi\, p \rightarrow \pi^+ \pi^- \pi^- p$

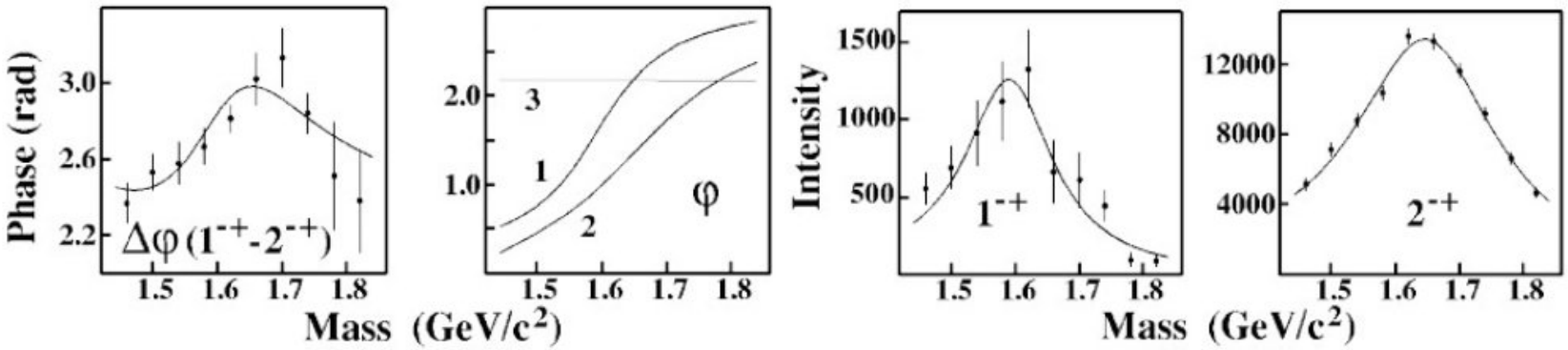


Figure: S.U. Chung *et al* [E852], Phys. Rev. **D65** 072001

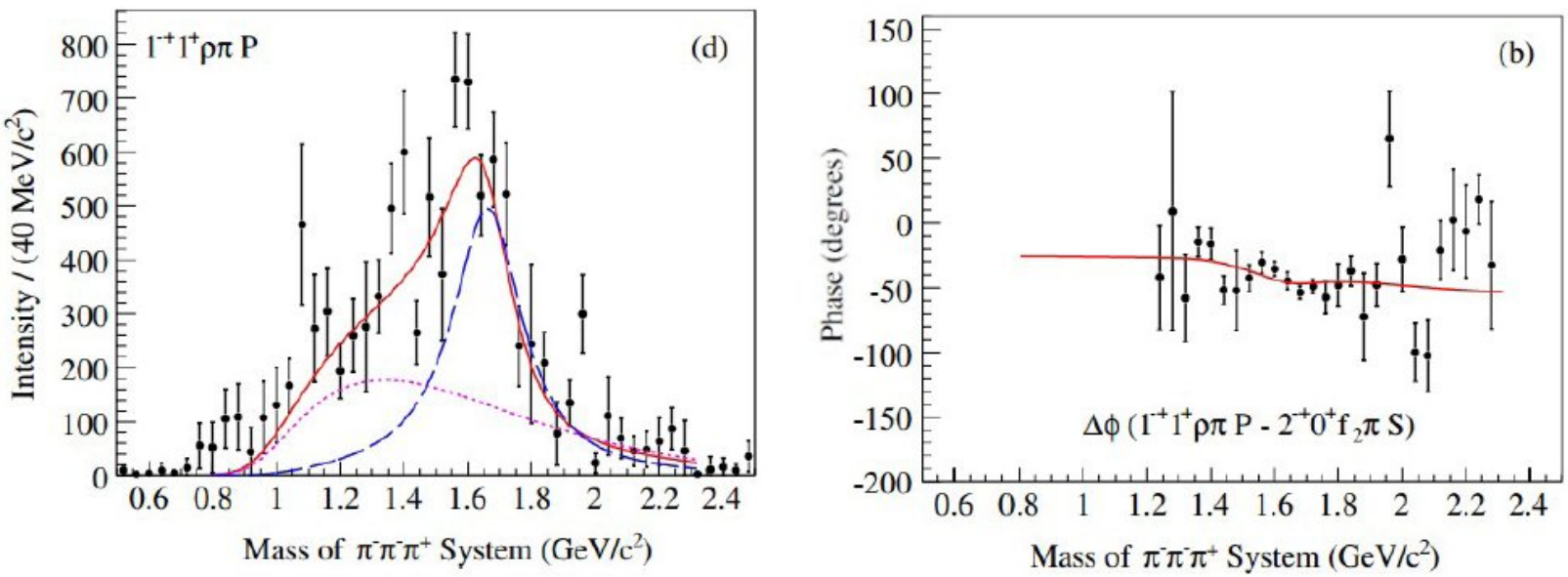
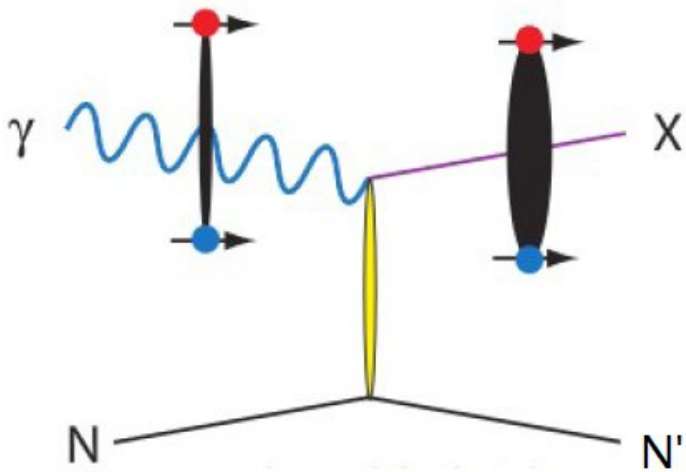


Figure: M. Alekseev *et al.* [COMPASS] Phys. Rev. Lett. **104**, 241803 (2010)

Neutral Exchange Mechanism

Photoproduction Experiments



- **Theoretical work suggests enhance hybrid production with photon beams**
- **Very little photoproduction data exists!**

Current Analysis with CLAS detector using unpolarized photon beam ~5.1 GeV

$$\gamma\, p \rightarrow n\, \pi^+ \pi^+ \pi^-$$
$$\gamma\, p \rightarrow \Delta^{++} \pi^+ \pi^- \pi^-$$

Future Analysis with GlueX detector using polarized photon beam ~9.0 GeV

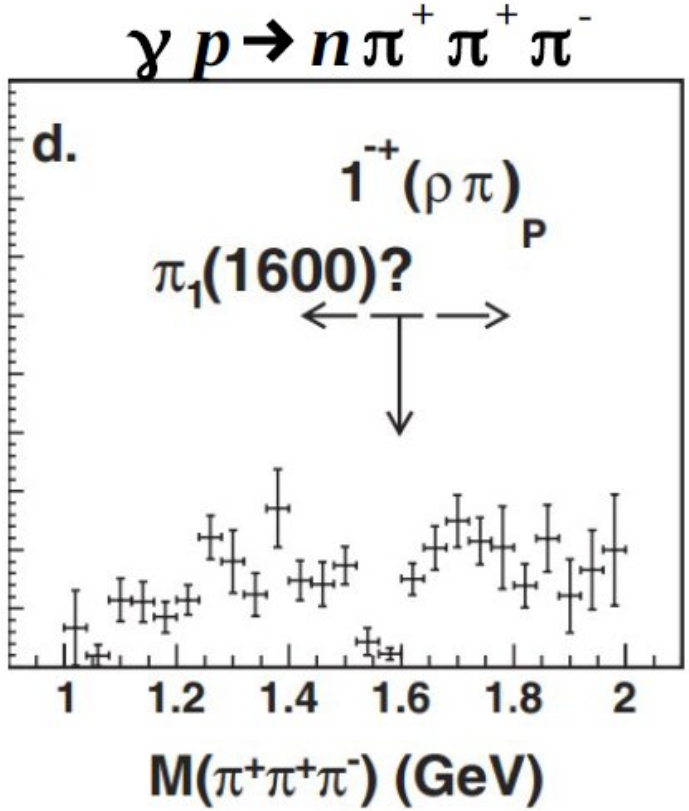
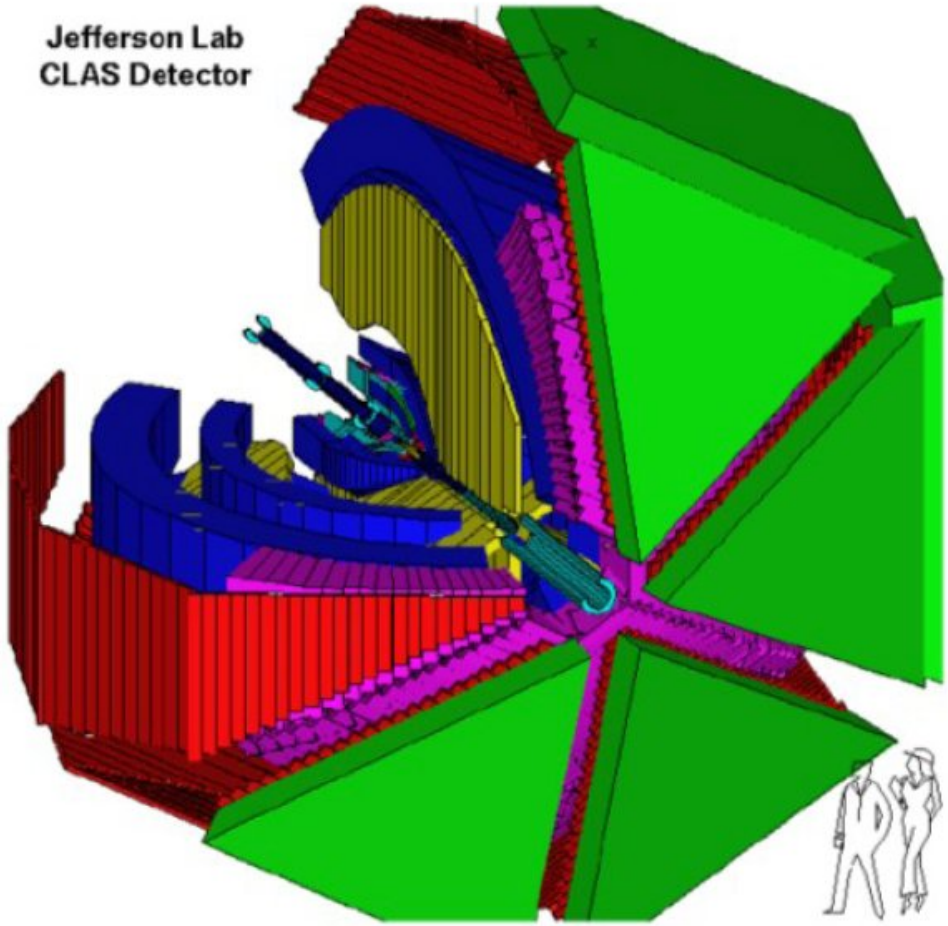


Figure: M. Nozar et al. [CLAS-g6c] Phys. Rev. Lett. **102**:102002, (2009)

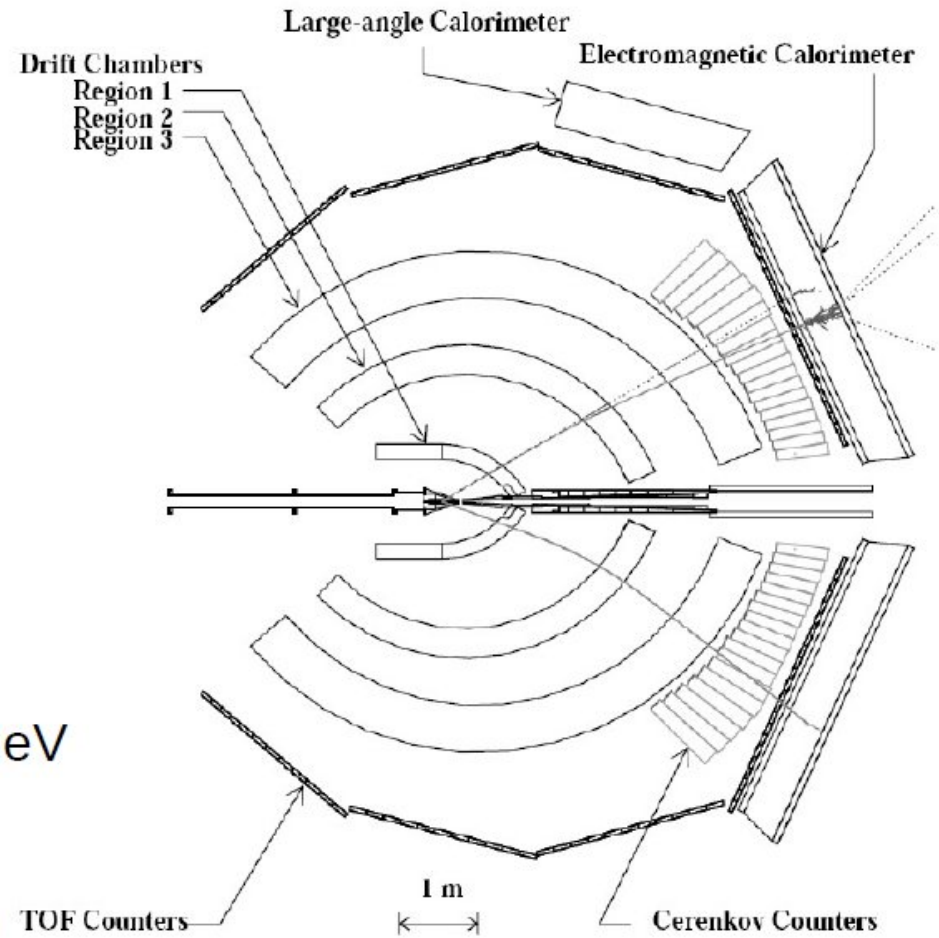
Jefferson Lab and the CLAS Detector



CLAS spectrometer

CLAS: CEBAF Large Acceptance Spectrometer

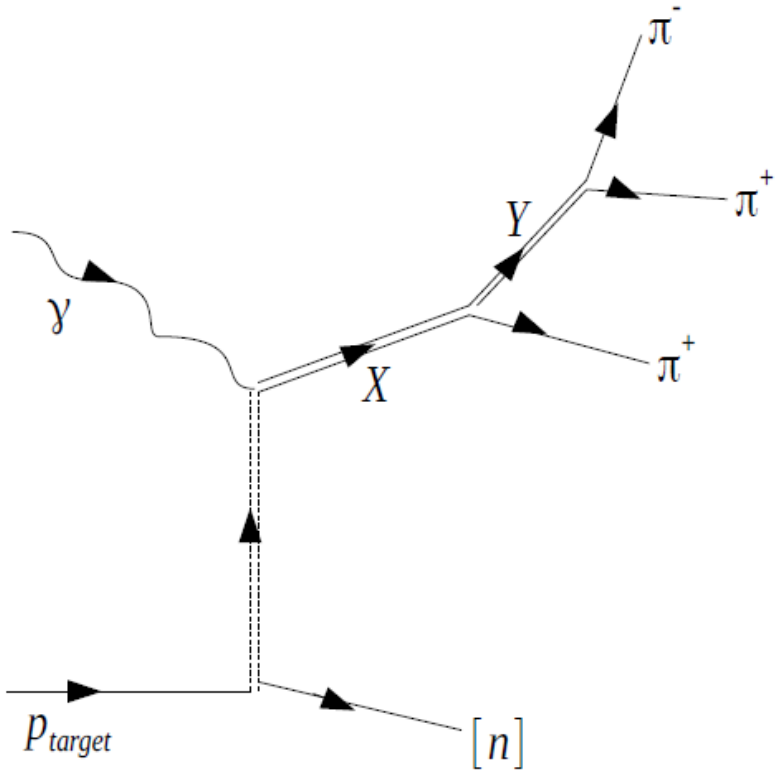
- Six sectors
- lH_2 target
- Start Counter (scintillator)
- Magnets (toroidal)
- Drift chambers (3x per sector)
- Cerenkov Detectors
- Time of Flight Detectors
- Electromagnetic calorimeters

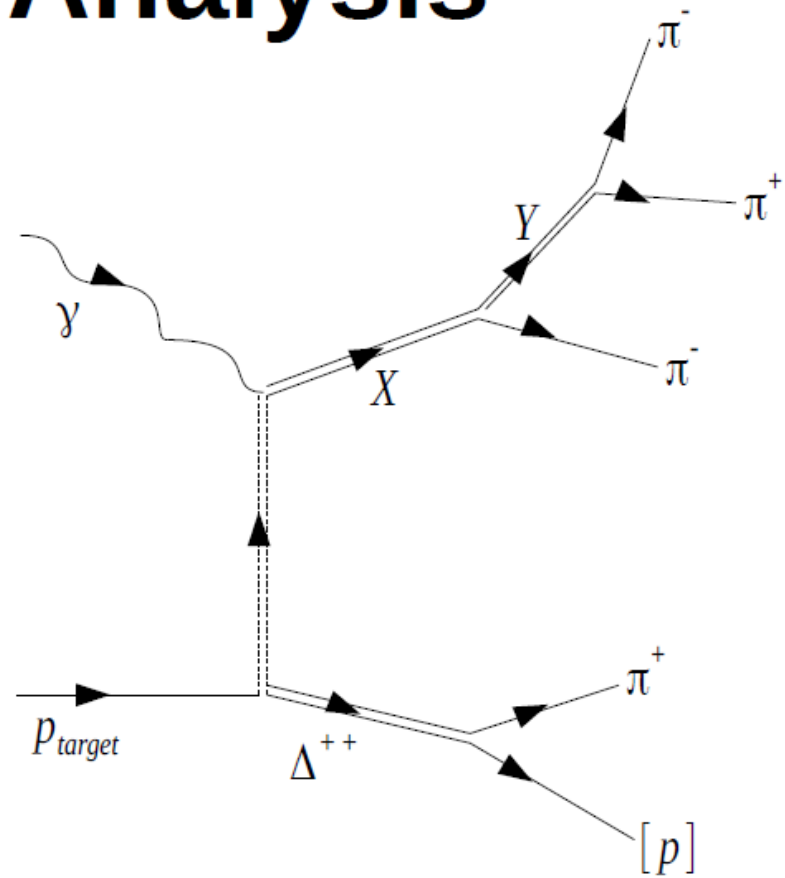


G12 Run Conditions

- 5.7 GeV unpolarized electrons → ≈ 5.1 GeV unpolarized photons
- April – June 2008: 44.2 days active DAQ
- Beam Current 56 nA (DAQ rate ~8 kHz)
- 26.2 billion events → 126 TB of raw data → 250 TB reconstructed data

CLAS-g12 Analysis





$$\gamma\, p \rightarrow n\, \pi^{+} \pi^{+} \pi^{-}$$

Form CLAS-g12 dataset (~25B events):

- **Three** charged pions selected
- **Neutron** is identified by energy and momentum conservation

$$\gamma\, p \rightarrow \Delta^{++} \pi^{+} \pi^{-} \pi^{-}$$

Form CLAS-g12 dataset (~25B events):

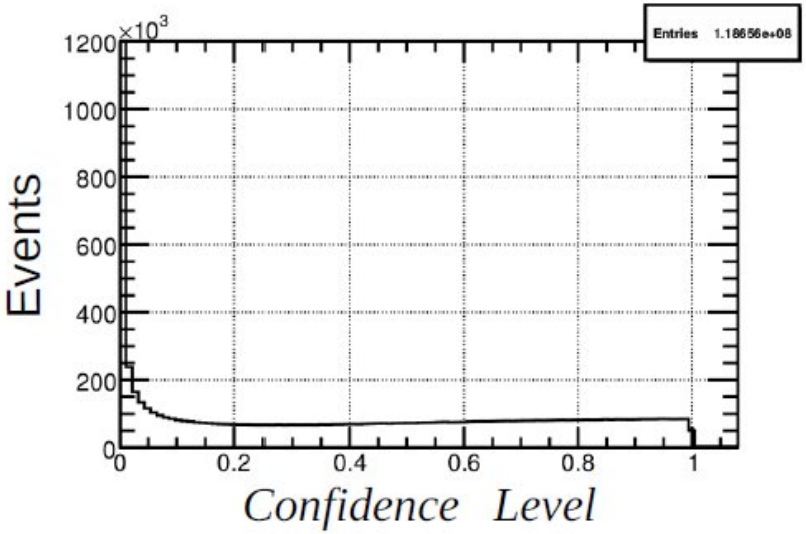
- **Four** charged pions selected
- **Proton** is identified by energy and momentum conservation

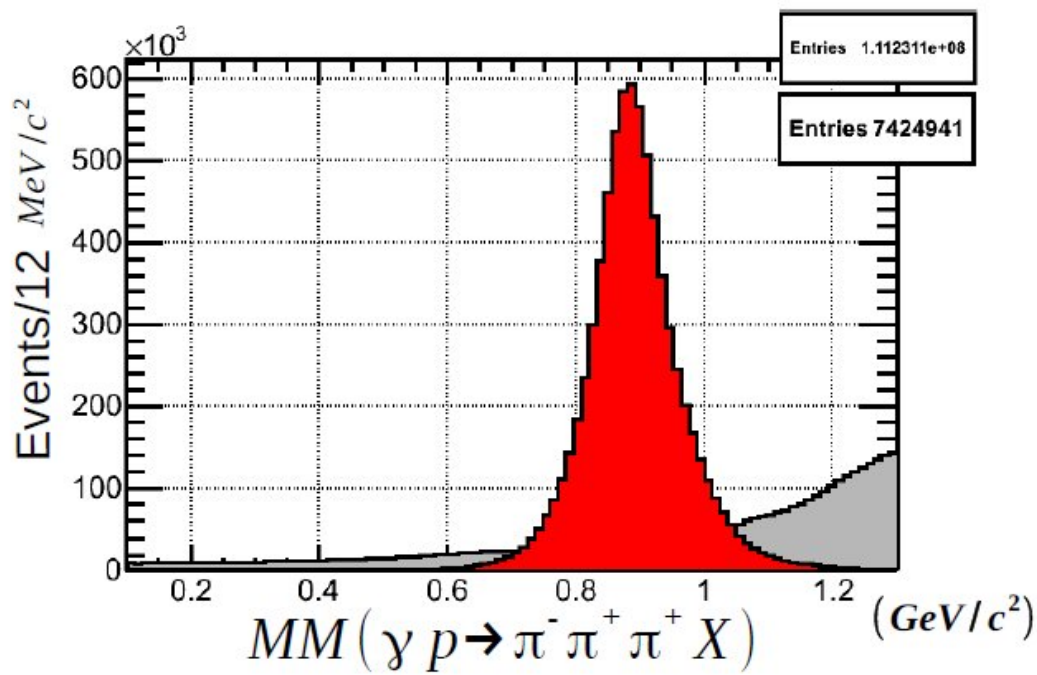
Partial Wave Analysis in the 3π sample

Selection Criteria

$\gamma\, p \rightarrow n\, \pi^+ \pi^+ \pi^-$

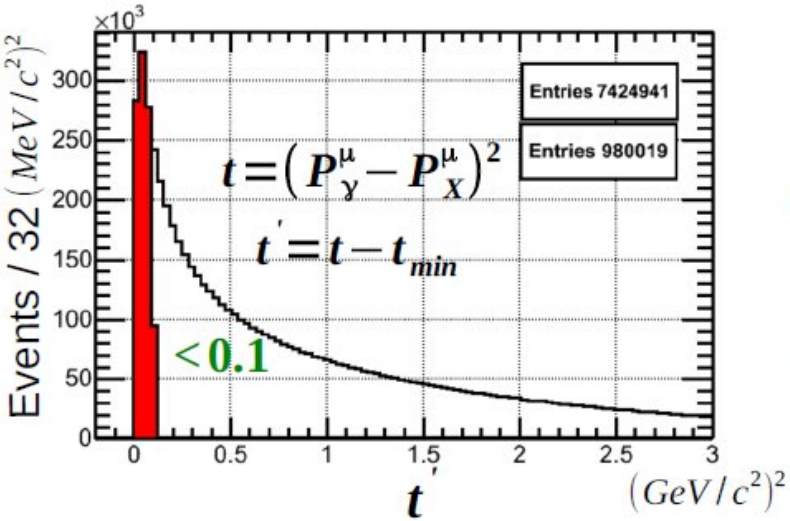
Description	Interval	Events In	Events Selected
Vertex within z-extent of target	$-110 < z < -70$ cm	707,329,219	658,403,589
Vertex within target radius	$r < 10.0$ cm	658,403,589	587,508,335
Event vertex timing cut	$\lvert t_{vtx}(TAG) - t_{vtx}(ST)\rvert < 1.002$ ns	587,508,335	421,091,544
Beta selection for particle tracks	$\lvert \beta_{TOF} - \beta_{p/m}\rvert < 0.03$	421,091,544	382,907,980
Photon Energy	$E_\gamma \geq 4.4 GeV$	382,907,980	118,656,025
Confidence level cut	$FOMkinFit > 1\%$	118,656,025	7,424,941

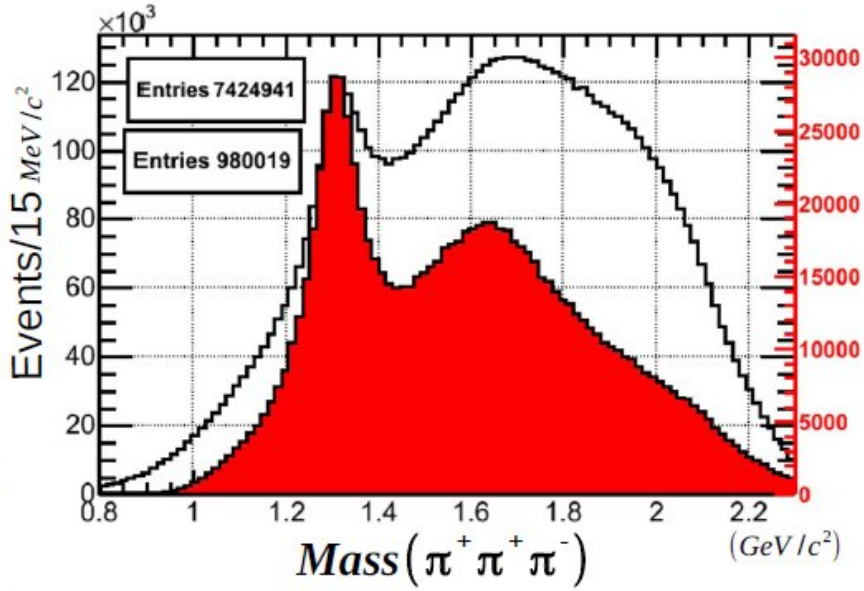


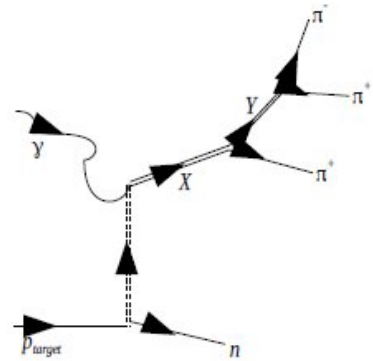


Enhance Peripheral Production

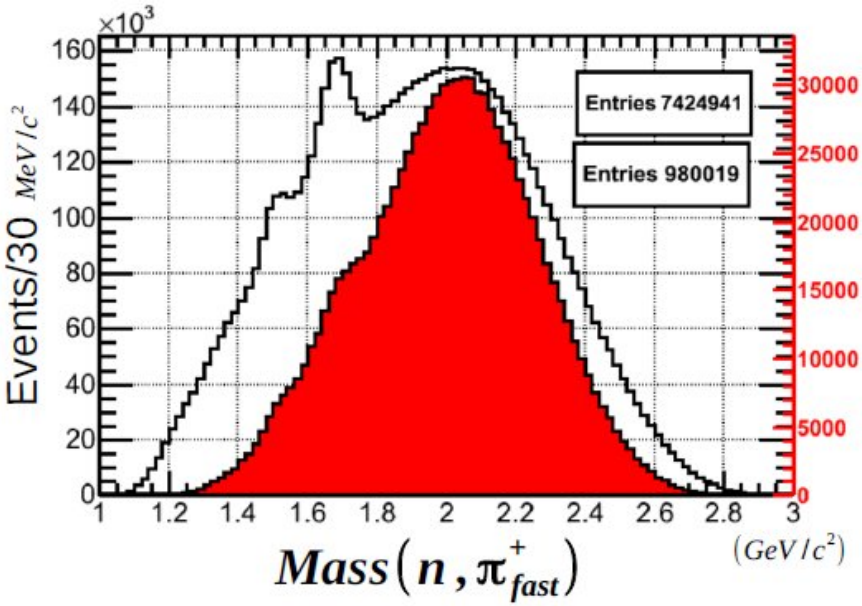
$\gamma\, p \rightarrow n\, \pi^+ \pi^+ \pi^-$

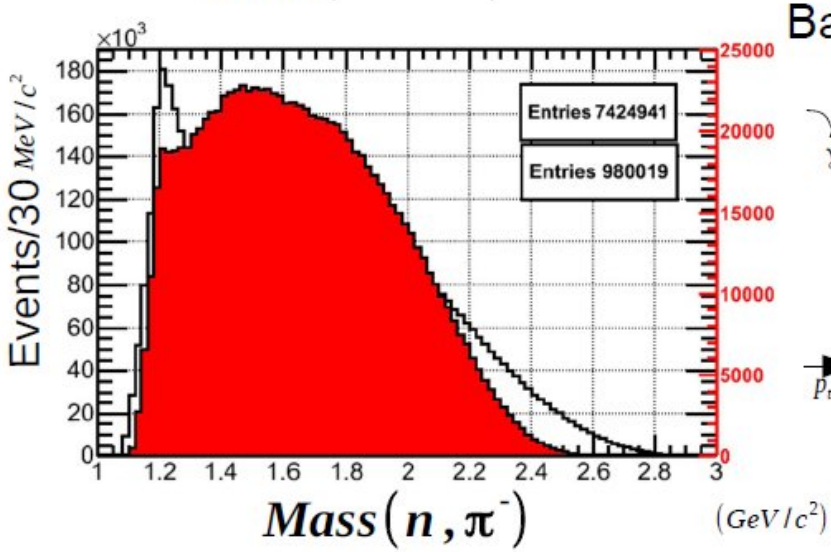


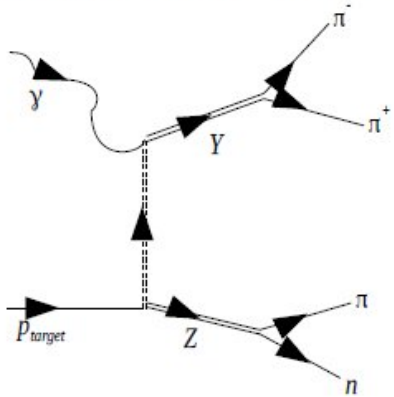




Background sources



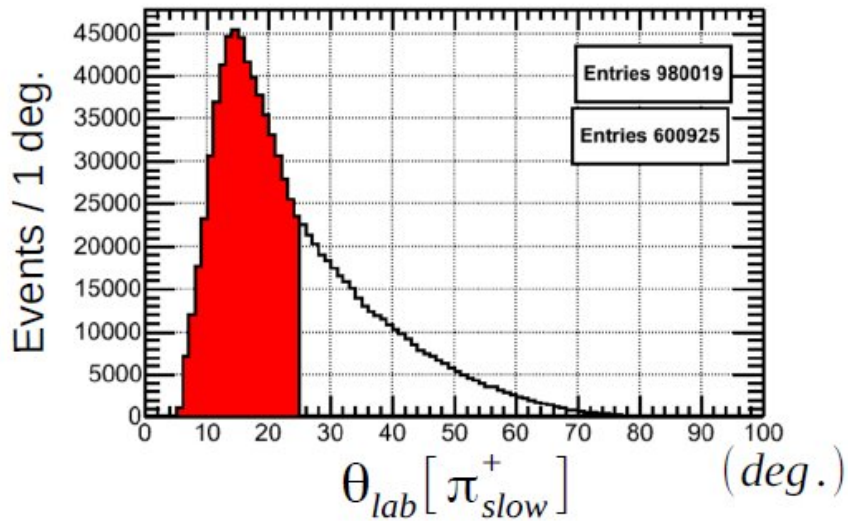


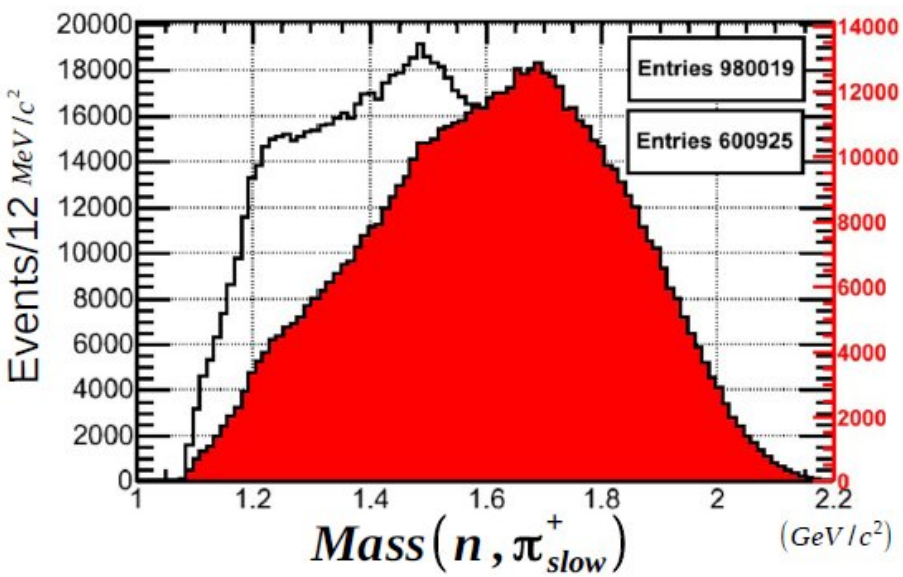


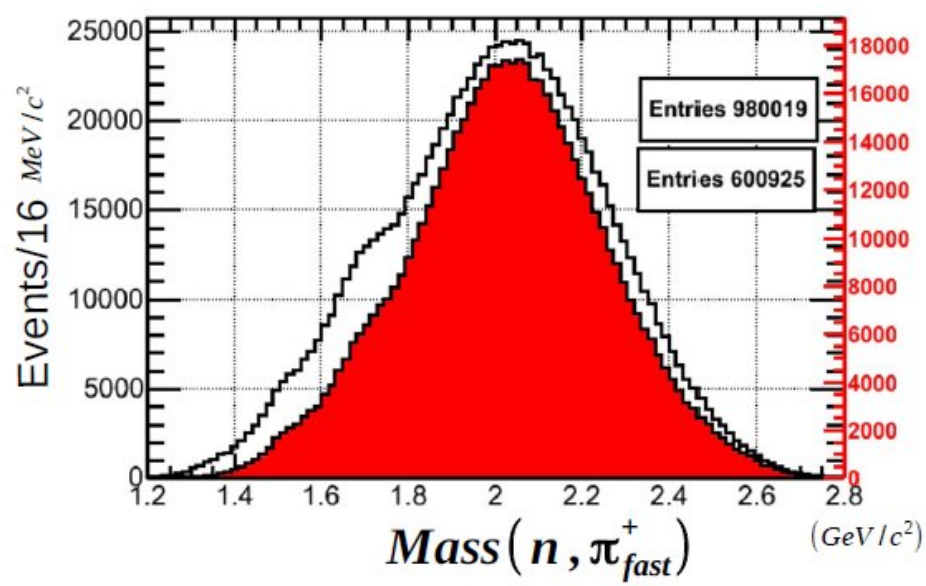
Further Reducing the Baryon Background

$\gamma\, p \rightarrow n\, \pi^+ \pi^+ \pi^-$

$\theta_{lab}[\pi^+_{slow}] < 25^o$

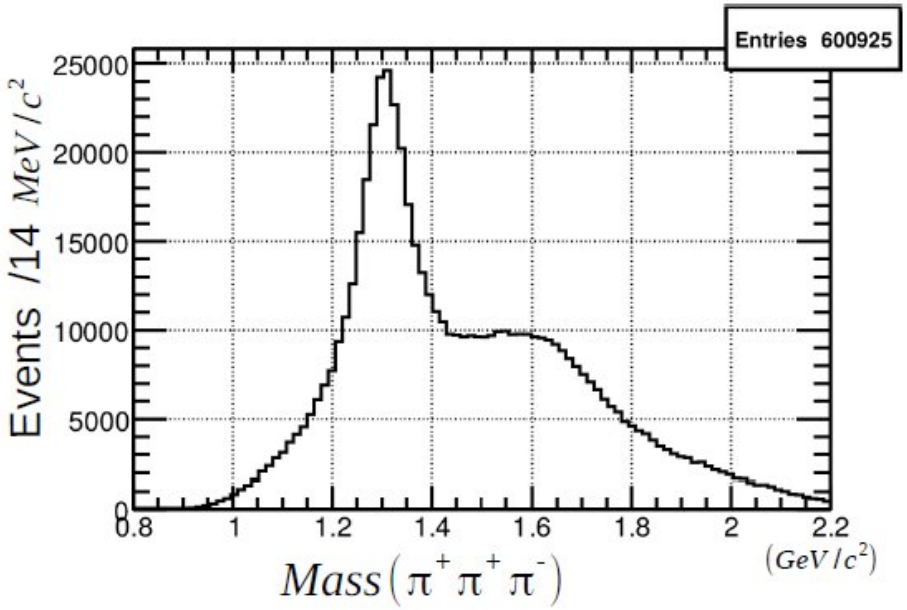


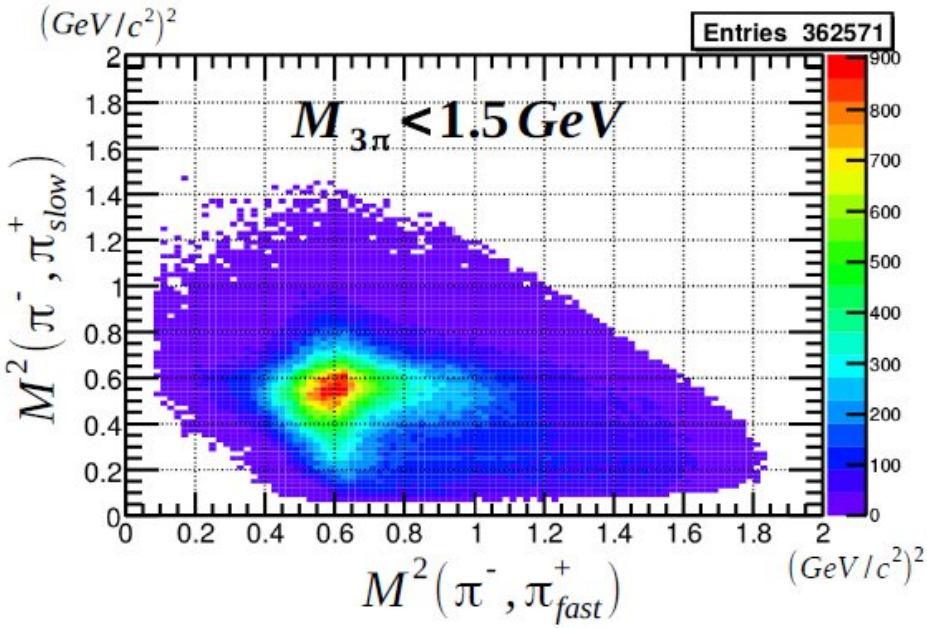


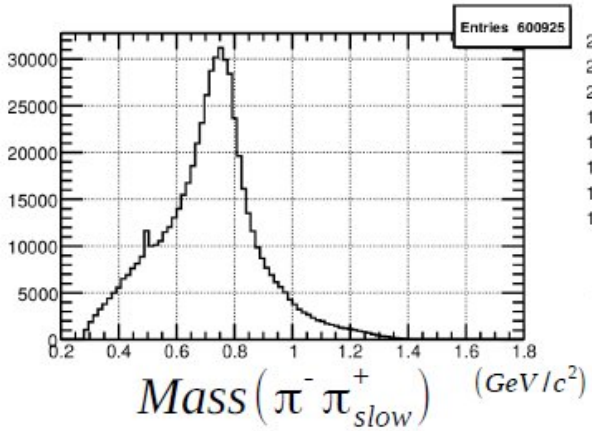


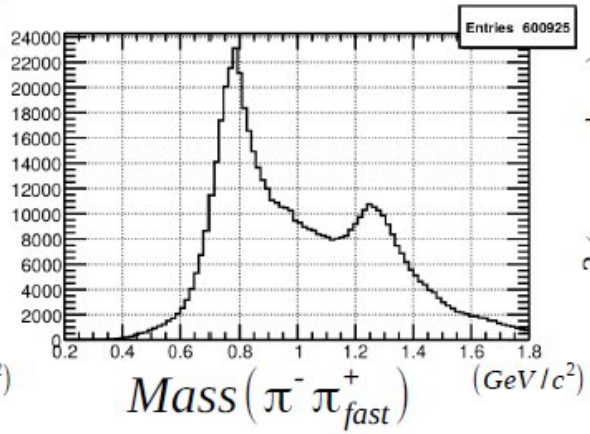
Features of the 3π sample

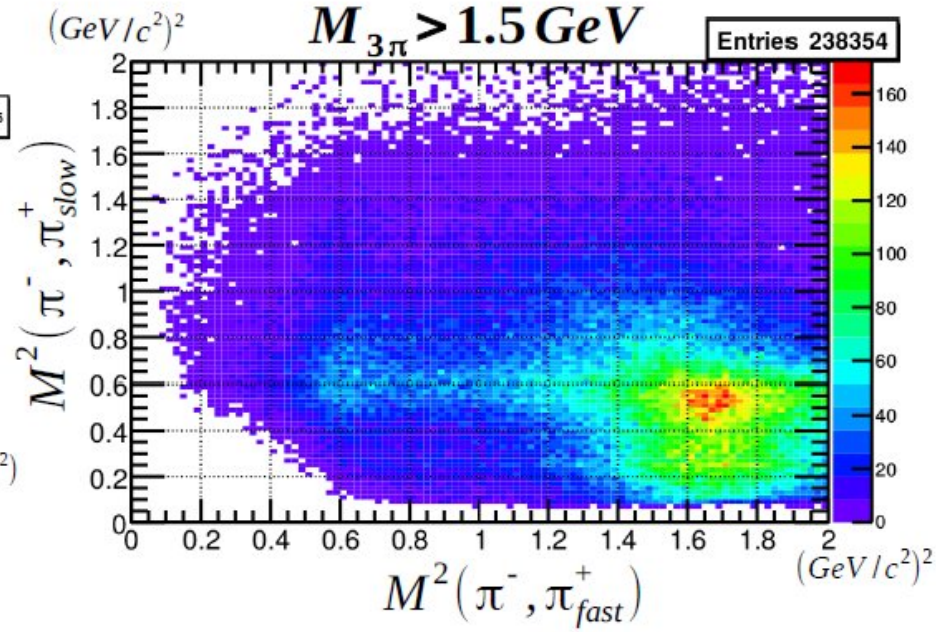
$\gamma p \rightarrow n \pi^+ \pi^+ \pi^-$







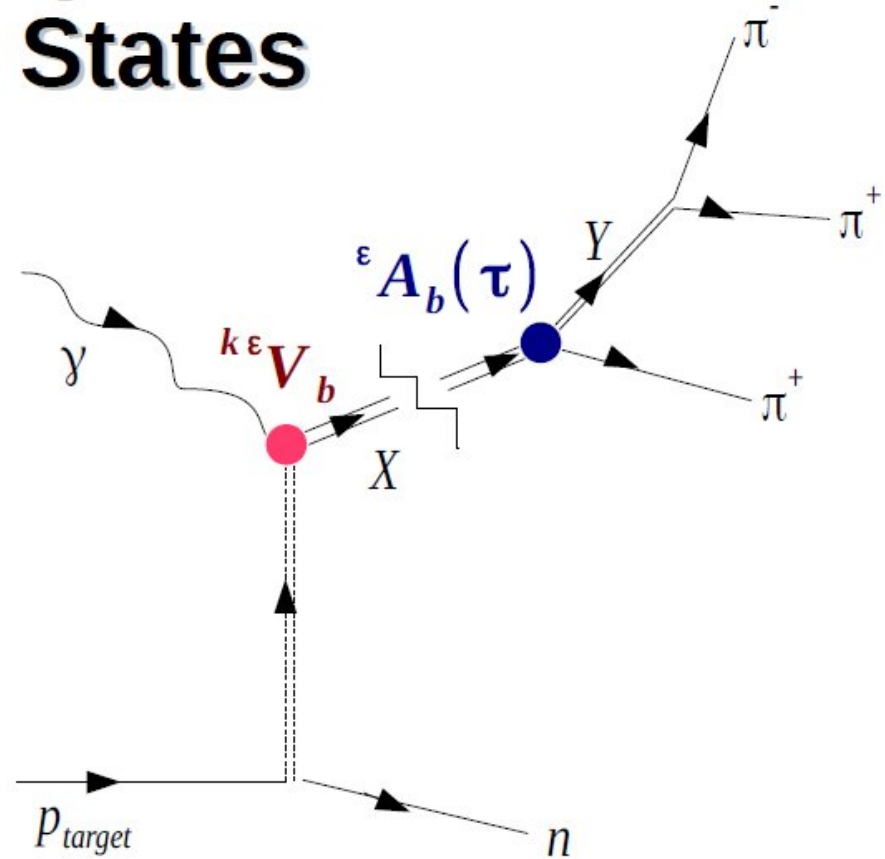




Partial Wave Analysis
Identifying Meson States

For unpolarized beam & target:

$$I(\tau)=\sum_{k\epsilon}\left|\sum_{b}{}^{k\epsilon}V_b\,{}^{\epsilon}A_b(\tau)\right|^2$$



Helicity Decay Amplitudes

$$A_b(\tau) = E_m^{J\ell s\,*}(\Omega,\Omega_h)\; Q^v_{\ell s}(w)$$

$$Q^v_{\ell s}(w) = F_\ell(p)F_s(q)\Delta_v(w)$$

In the Reflectivity Basis

$${}^{\epsilon}E_m^{J\ell s\,*}(\Omega,\Omega_h) = \tilde{\ell}\tilde{s}\sum_{\lambda}{}^{\epsilon}D^{JP\,*}_{m\lambda}(\Phi,\Theta,\phi)\; d^s_{\lambda 0}(\theta)\;(\ell 0 s\lambda|J\lambda)$$

$${}^{\epsilon}D^{JP\,*}_{m\lambda}(\Phi,\Theta,\phi) = \theta(m)\left[D^{J\,*}_{m\lambda}(\Phi,\Theta,\phi) - \epsilon P(-1)^{J-m}D^{J\,*}_{-m\lambda}(\Phi,\Theta,\phi)\right]$$

$$\theta(m) = \frac{1}{\sqrt{2}}, \qquad m>0$$
$$= \frac{1}{2}, \qquad m=0$$
$$= 0, \qquad m<0$$

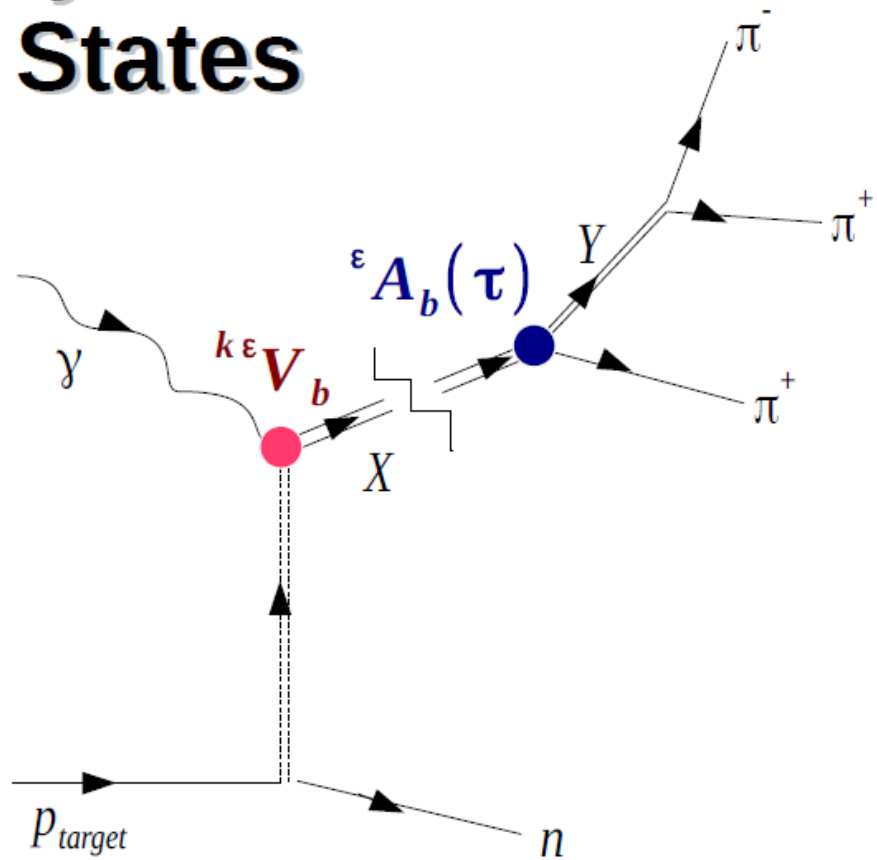
Partial Wave Analysis
Identifying Meson States

For unpolarized beam & target:

$$I(\tau)=\sum_{k\epsilon}\left|\sum_{b}{}^{k\epsilon}V_b{}^{\epsilon}A_b(\tau)\right|^2$$

Unknown

Complex parameters varied in the PWA to fit the data



$$\ln L=\sum_{i}^{n}\ln\Big[\sum_{k\epsilon bb'}{}^{\epsilon}A_b(\tau_i)\,{}^{\epsilon k}V_b\,{}^{\epsilon k}V^*_{b'}\,{}^{\epsilon}A^*_{b'}(\tau_i)\Big]-\eta_x\Big[\sum_{k\epsilon bb'}{}^{\epsilon k}V_b\,{}^{\epsilon k}V^*_{b'}\,{}^{\epsilon}\Psi^x_{bb'}\Big]$$

$$N=\sum_{k\epsilon bb'}{}^{\epsilon k}V_b\,{}^{\epsilon k}V^*_{b'}\,{}^{\epsilon}\Psi_{bb'}$$

$$\Delta\varphi=\arctan\left(\frac{\Im(V_1V_2^*)}{\Re V_1V_2^*}\right)$$

$${}^{\epsilon}\Psi^x_{bb'}=\frac{1}{M_x}\sum_{i}^{M_x}{}^{\epsilon}A_b(\tau_i)\,{}^{\epsilon}A^*_{b'}(\tau_i)$$

Minimum List of Waves Required for the $\gamma p \rightarrow n \pi^+ \pi^+ \pi^-$

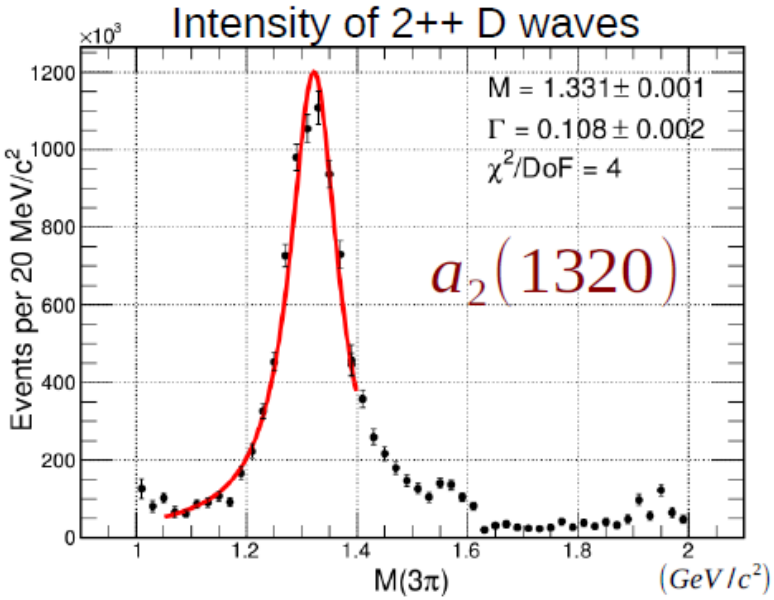
$M_{3\pi} < 1.4\,GeV$

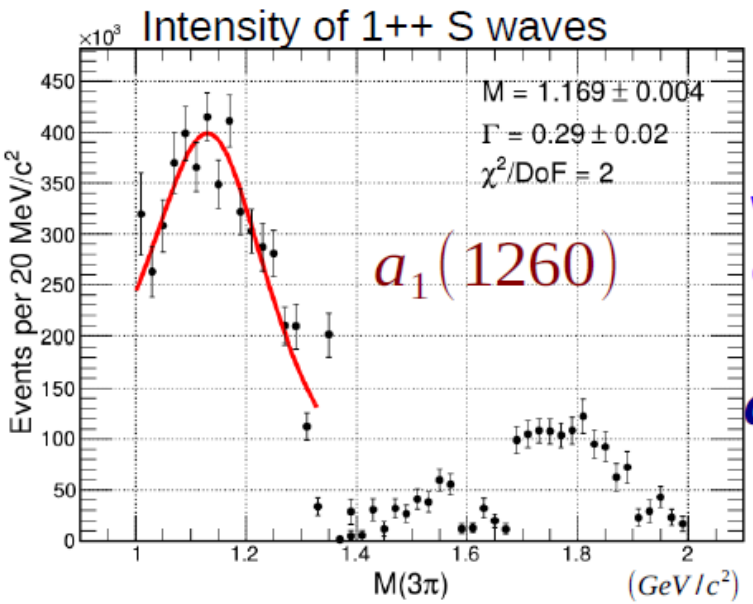
J^{PC}	M^{ϵ}	L	Y	Number of waves
1^{++}	$1^{-/+}$	S, P, D	$\rho(770), \sigma$	6
1^{-+}	$1^{-/+}$	P	$\rho(770)$	2
2^{++}	$1^{-/+}$	D	$\rho(770)$	2
2^{-+}	$1^{-/+}$	P	$\rho(770)$	2
Isotropic background wave				

$M_{3\pi} > 1.38\,GeV$

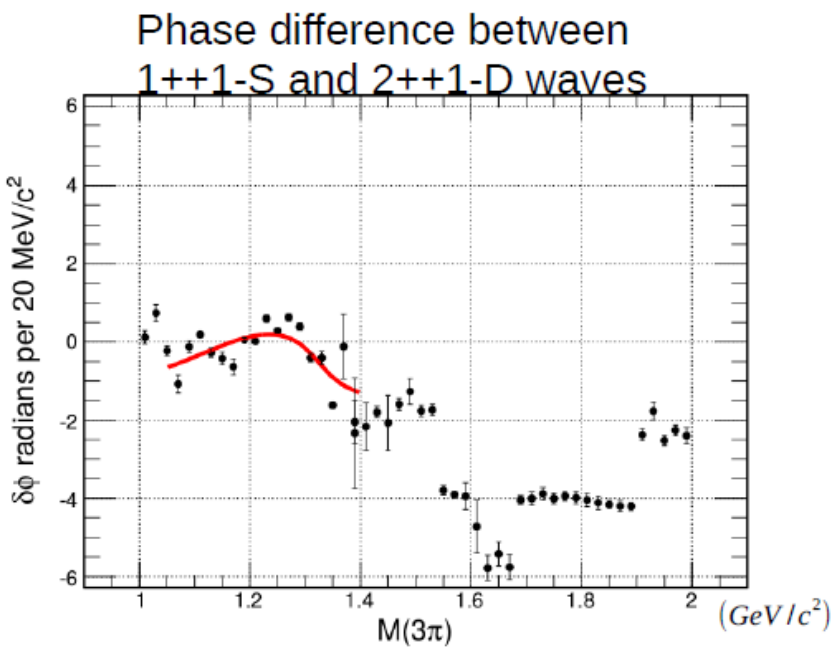
J^{PC}	M^{ϵ}	L	Y	Number of waves
1^{++}	$1^{-/+}$	S, P, D	$\rho(770), \sigma$	6
1^{-+}	$1^{-/+}$	P	$\rho(770)$	2
2^{++}	$1^{-/+}$	D	$\rho(770)$	2
2^{-+}	$1^{-/+}$	S, P, D	$\rho(770), f_2(1270)$	6
Isotropic background wave				

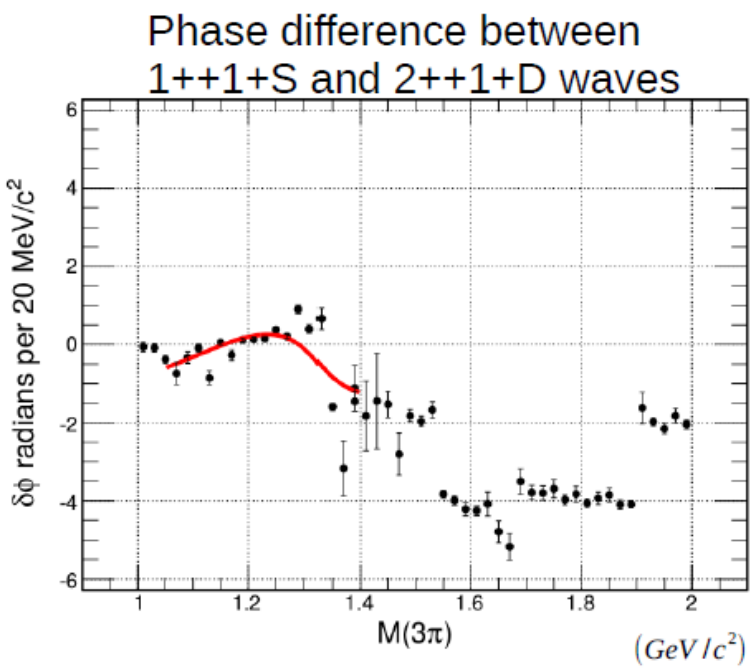
Features of the partial waves of the 3π System for the $\gamma\, p \rightarrow n\, \pi^+ \pi^+ \pi^-$



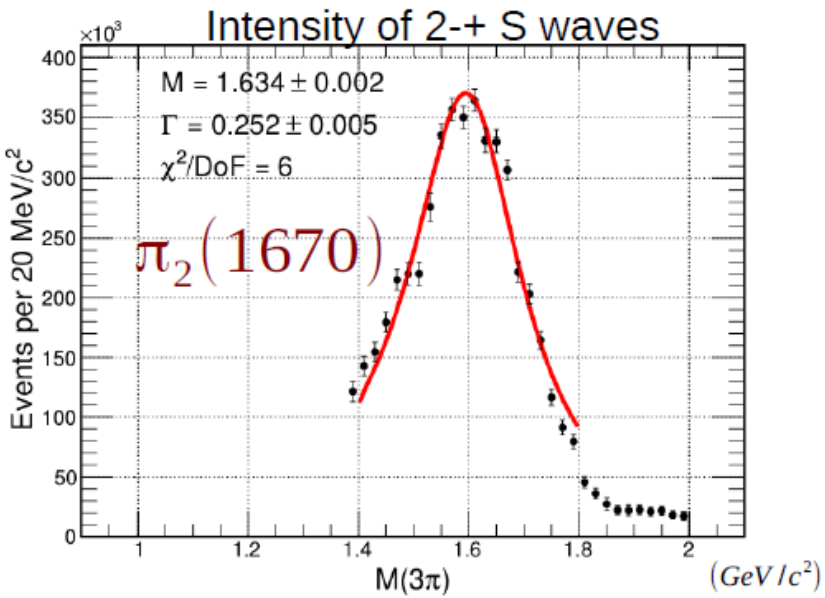


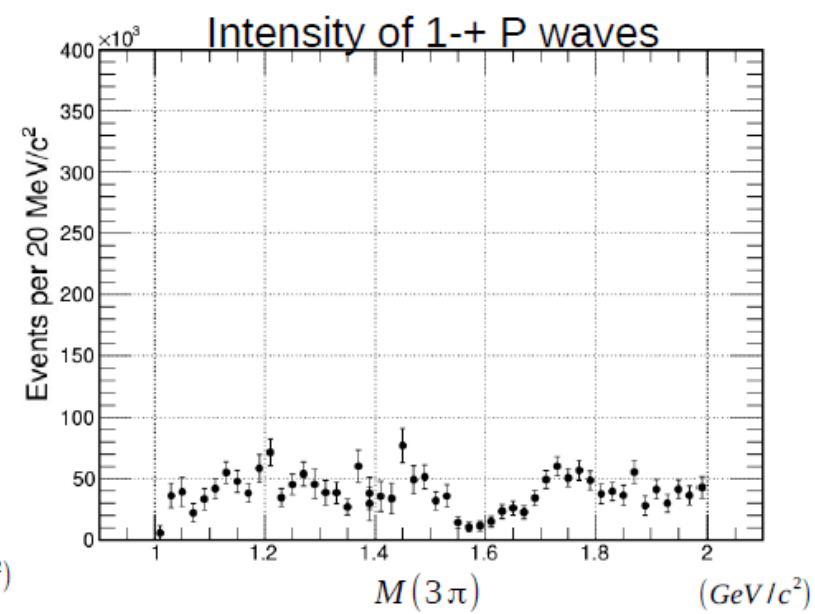
For the first time we report observation of a photoproduced $a_1(1260)$ meson.

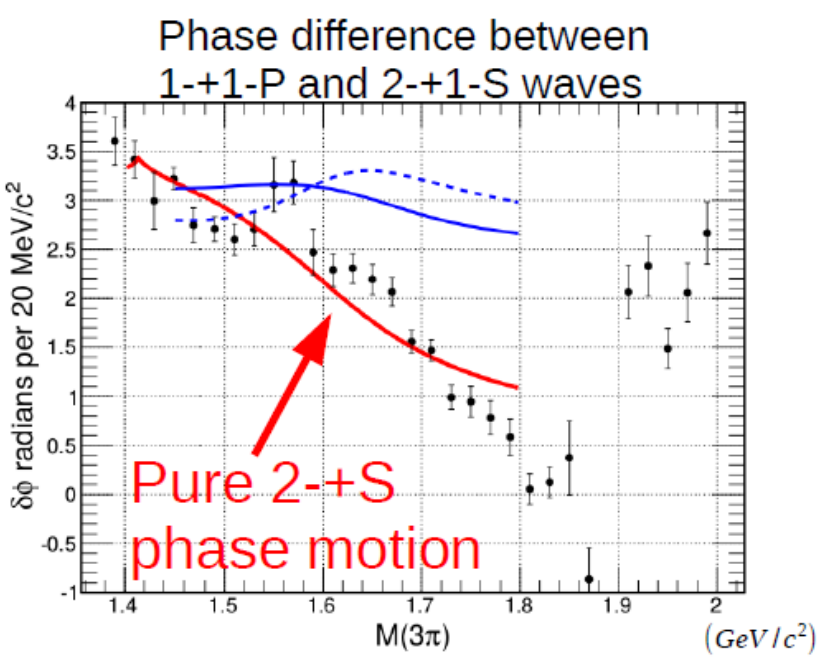


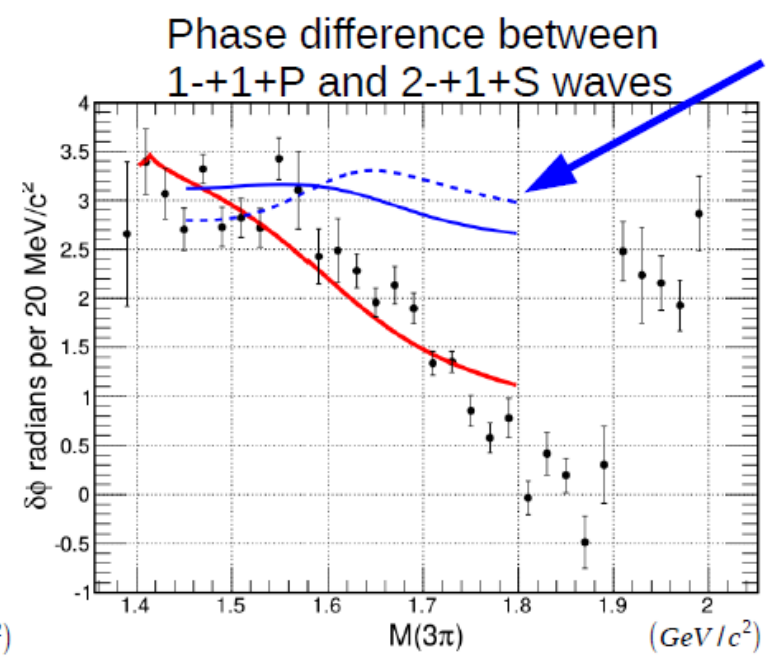


Features of the partial waves of the 3π System for the $\gamma\, p \rightarrow n\, \pi^+ \pi^+ \pi^-$







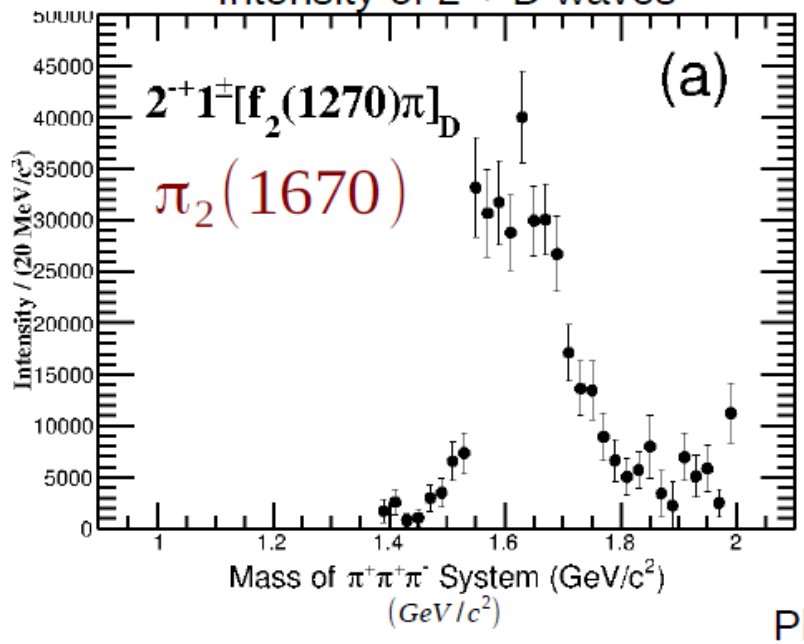


phase difference between 2-+S and a resonating 1-+P

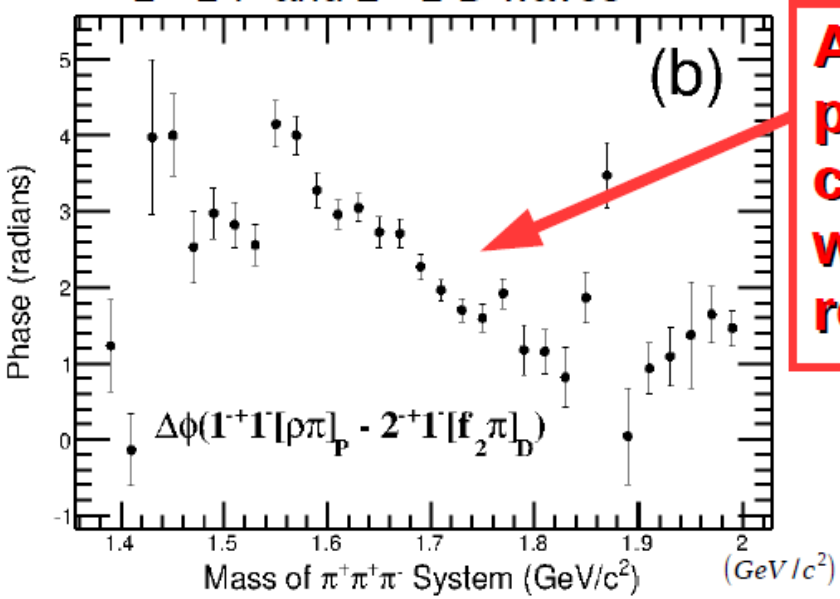
The exotic 1-+ partial wave does not show resonant behavior

Features of the partial waves of the 3π System for the $\gamma\, p \rightarrow n\, \pi^+ \pi^+ \pi^-$

Intensity of 2-+ D waves

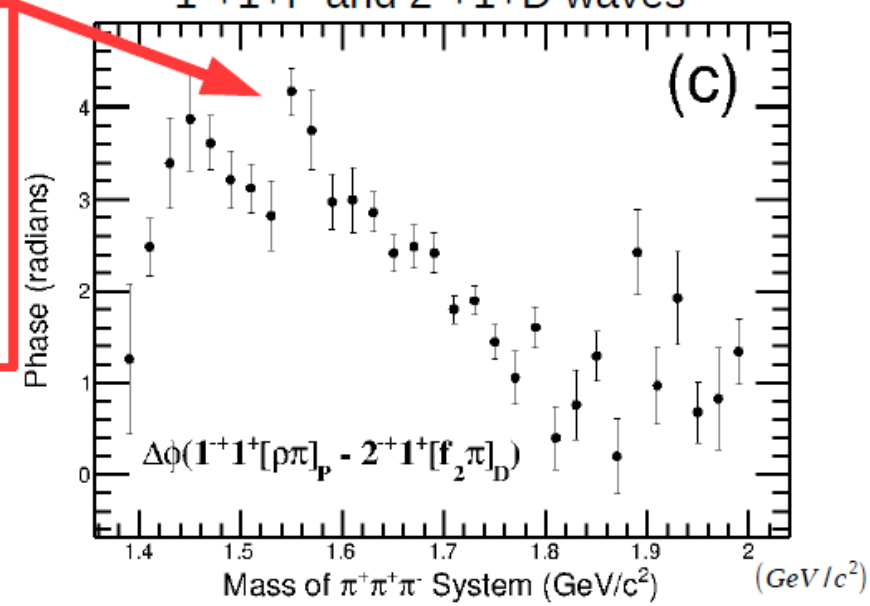


Phase difference between 1-+1-P and 2-+1-D waves



Also a falling phase motion consistent with a non-resonant 1-+

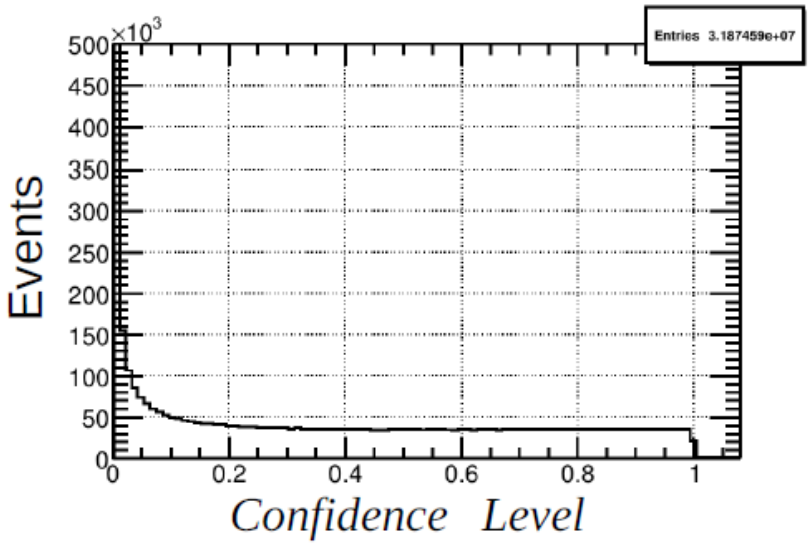
Phase difference between 1-+1+P and 2-+1+D waves

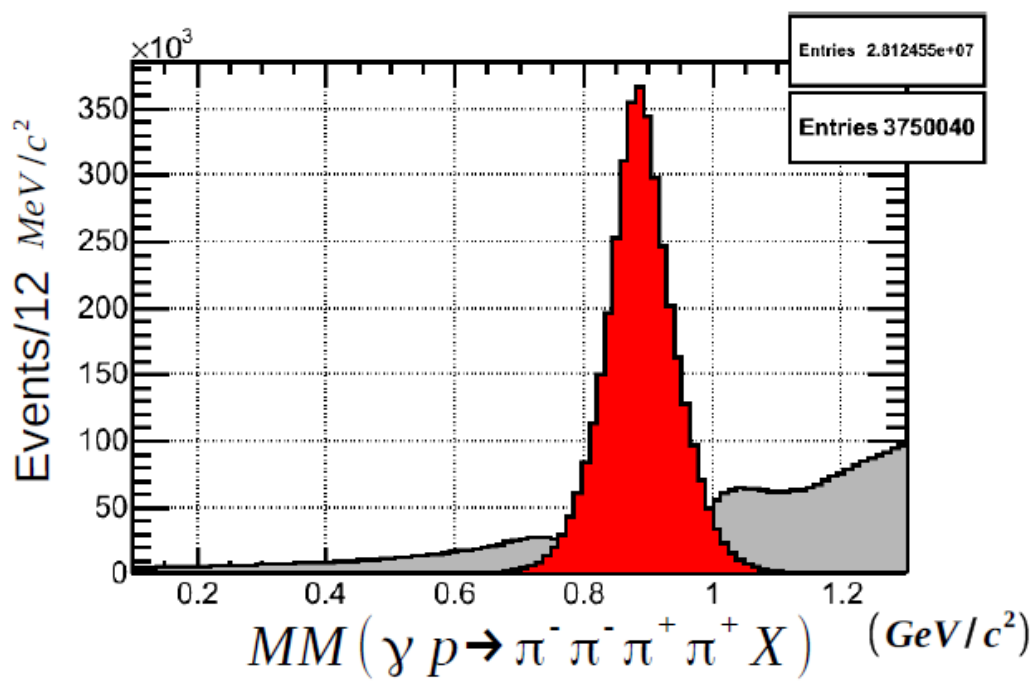


Event Selections and Corrections

$$\gamma\, p \rightarrow \Delta^{++} \pi^{+} \pi^{-} \pi^{-}$$

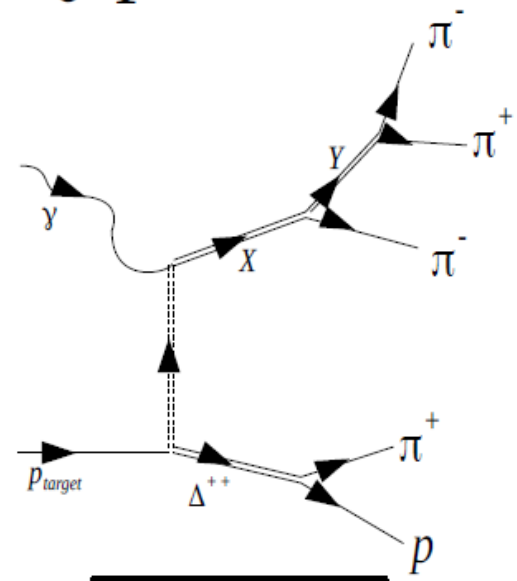
Description	Interval	Events In	Events Selected
Vertex within z-extent of target	$-110 < z < -70$ cm	105,863,100	100,840,300
Vertex within target radius	$r < 10.0$ cm	100,840,300	93,575,180
Event vertex timing cut	$\lvert t_{vtx}(TAG) - t_{vtx}(ST)\rvert < 1.002$ ns	93,575,180	79,764,370
Beta selection for particle tracks	$\lvert\beta_{TOF} - \beta_{p/m}\rvert < 0.03$	79,764,370	75,917,040
Photon Energy	$Beam - Photon \geq 4.4GeV$	75,917,040	31,874,591
Confidence level cut	$FOM - kinFit > 1\%$	31,874,591	3,750,040



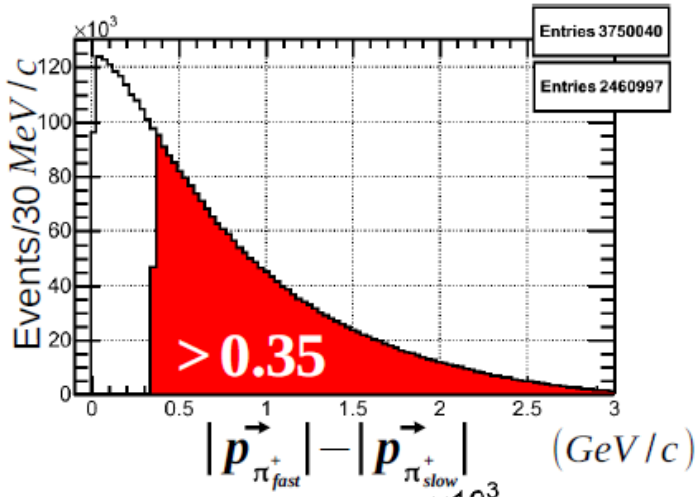


Kinematic Separation of the Δ^{++}

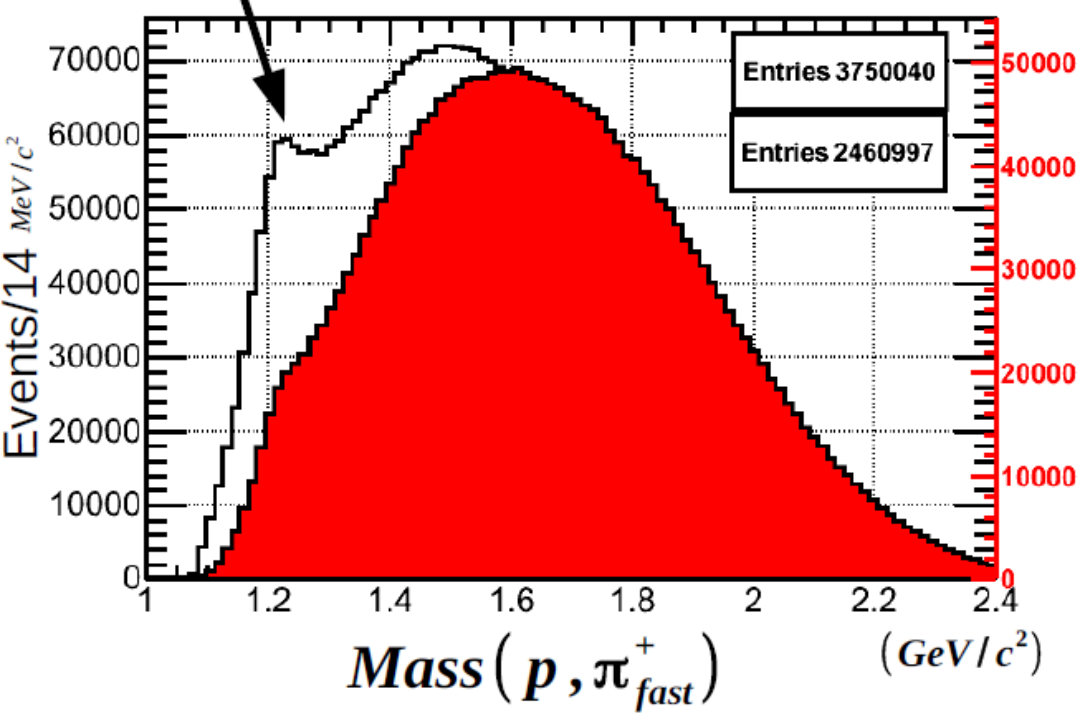
$\gamma\, p \rightarrow \Delta^{++} \pi^{+} \pi^{-} \pi^{-}$



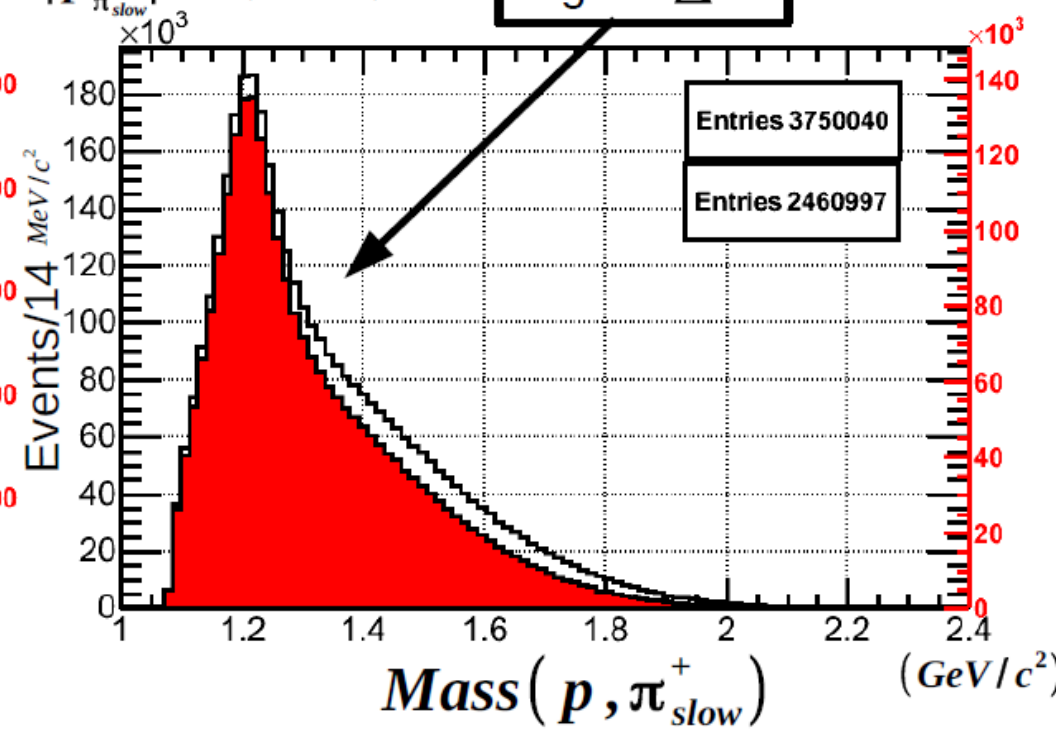
Momentum Difference between fast and slow π^+



Background Δ^{++}

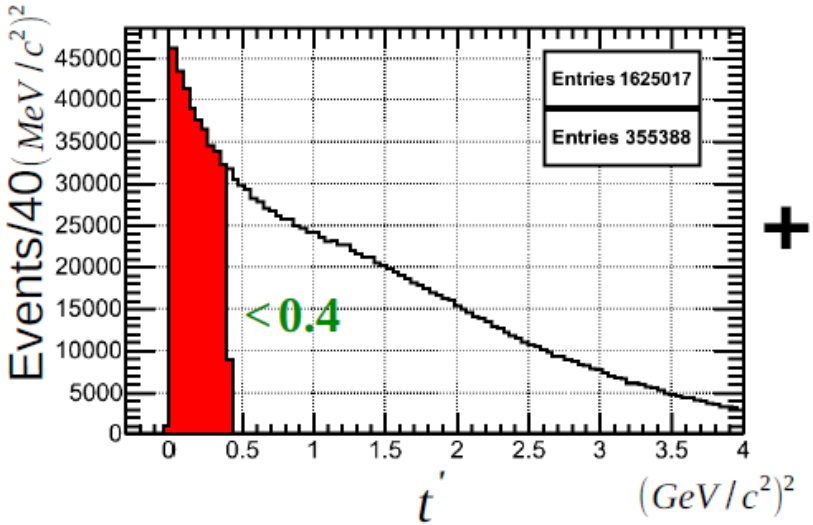


Signal Δ^{++}

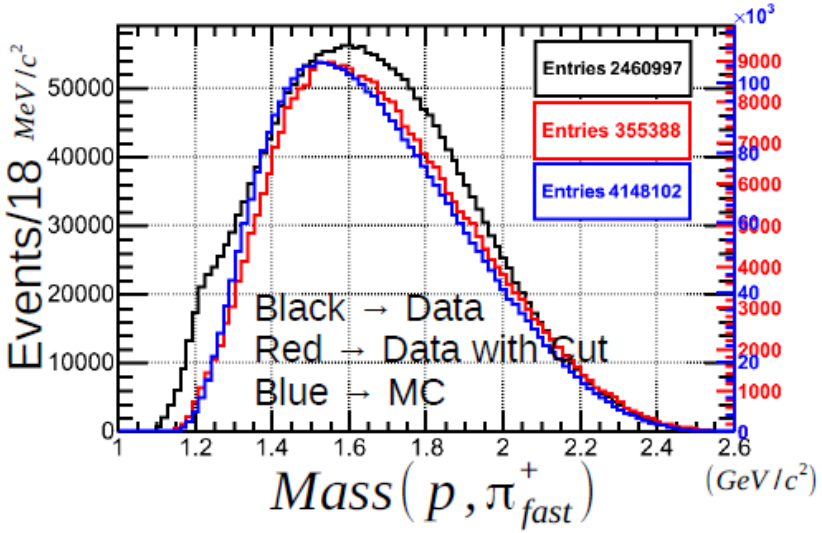


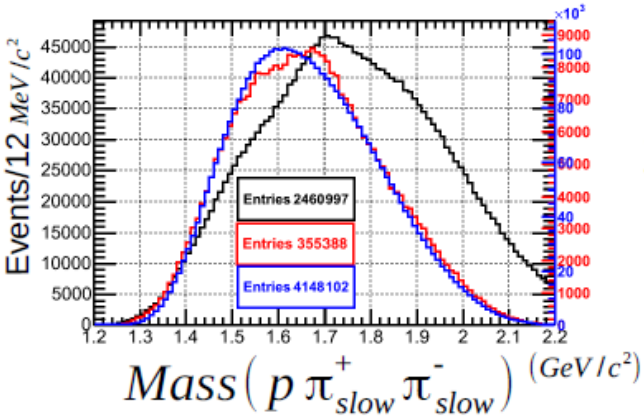
Data Selection and Background Reduction

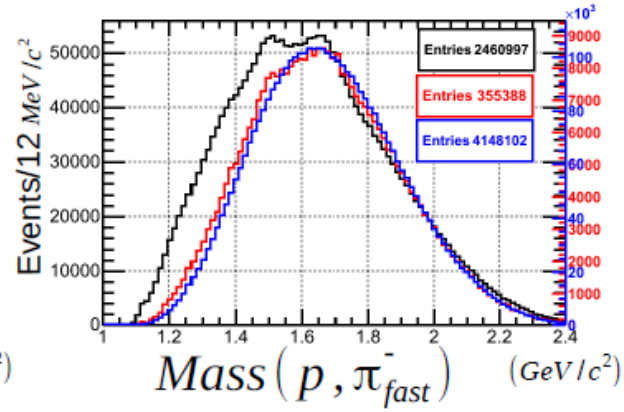
$$\gamma\, p \rightarrow \Delta^{++}\pi^{+}\pi^{-}\pi^{-}$$

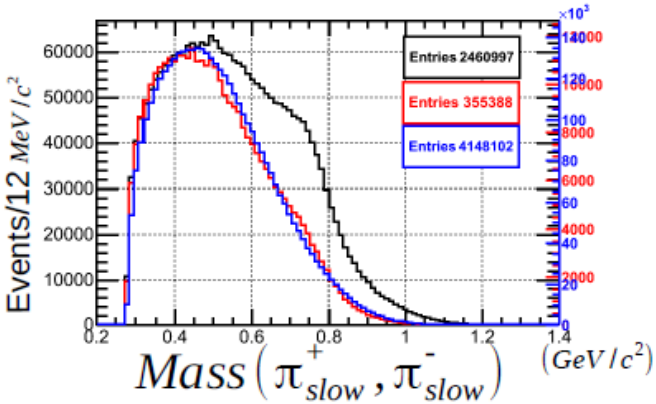


$+ M_{p\pi^+_{slow}} < 1.35$







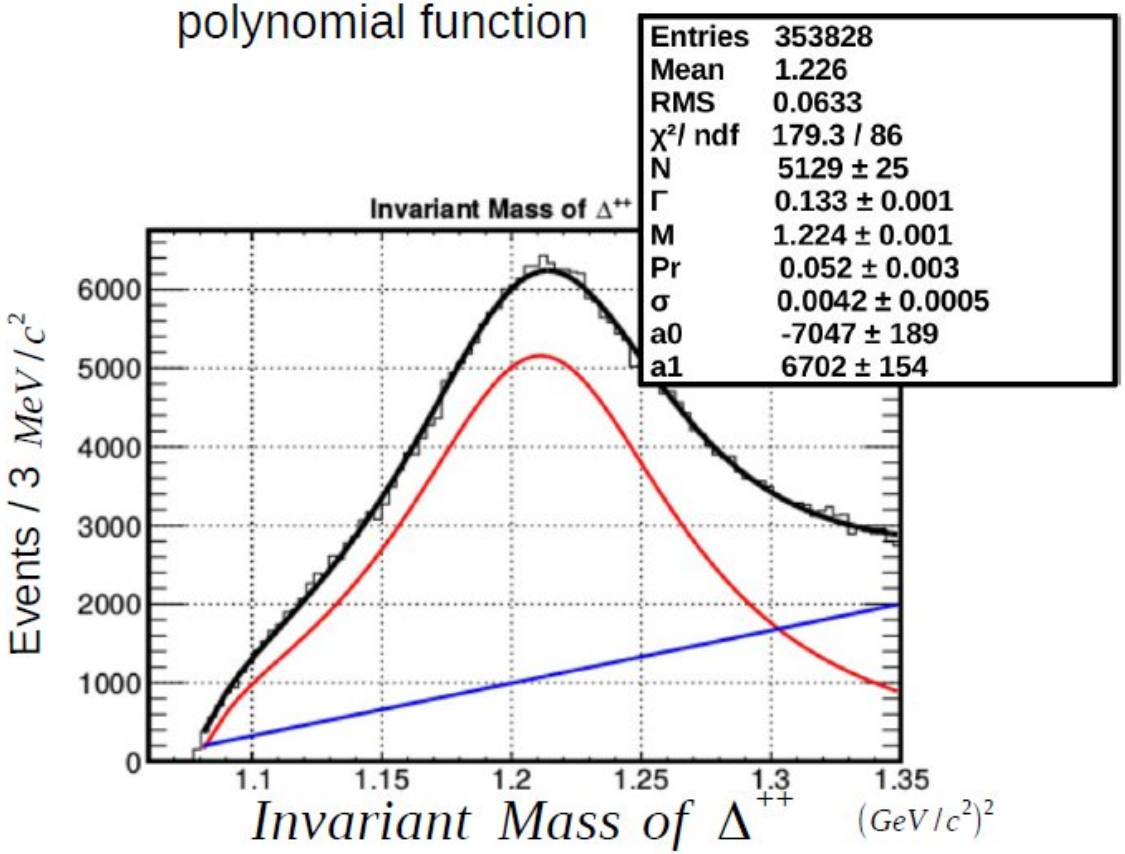


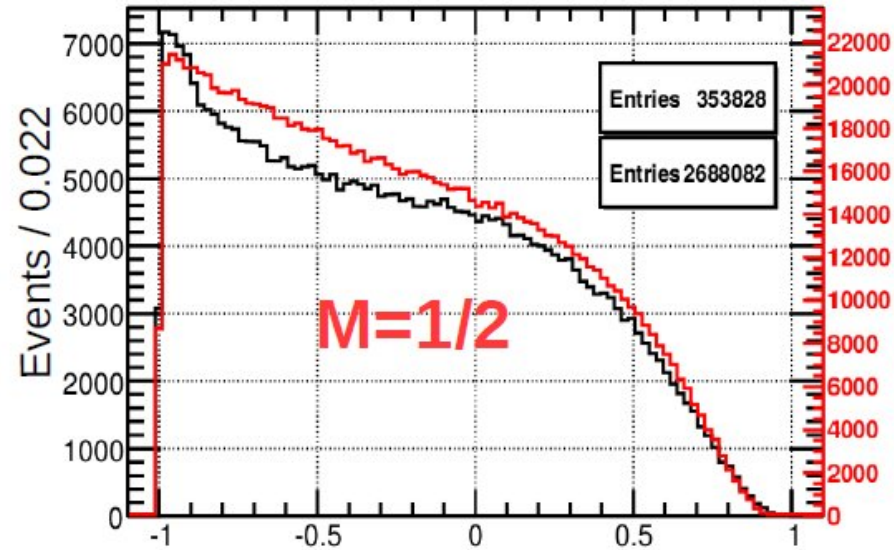
Black → Data
Red → Data with Cuts
Blue → MC with Cuts

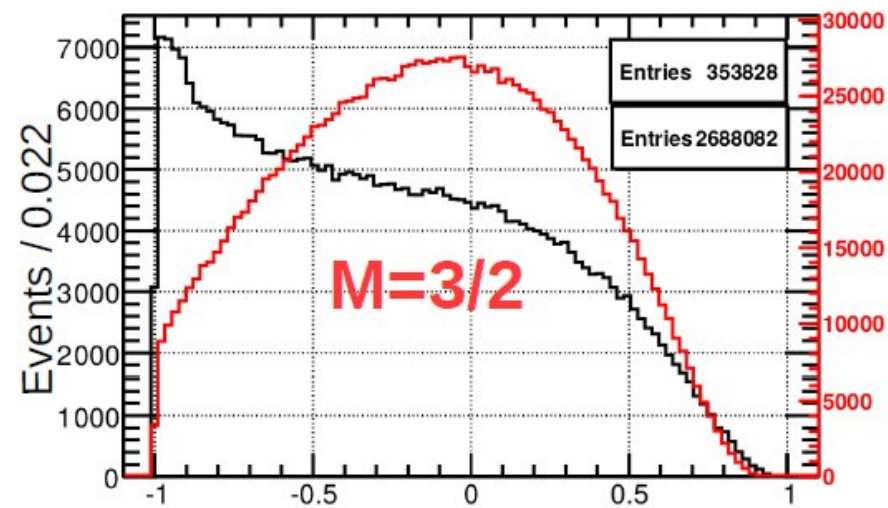
The Δ^{++} Recoil Baryon

$\gamma p \rightarrow \Delta^{++} \pi^{+} \pi^{-} \pi^{-}$

Fitted with a mass dependent Breit-Wigner function convoluted with a Gaussian along with a first degree polynomial function



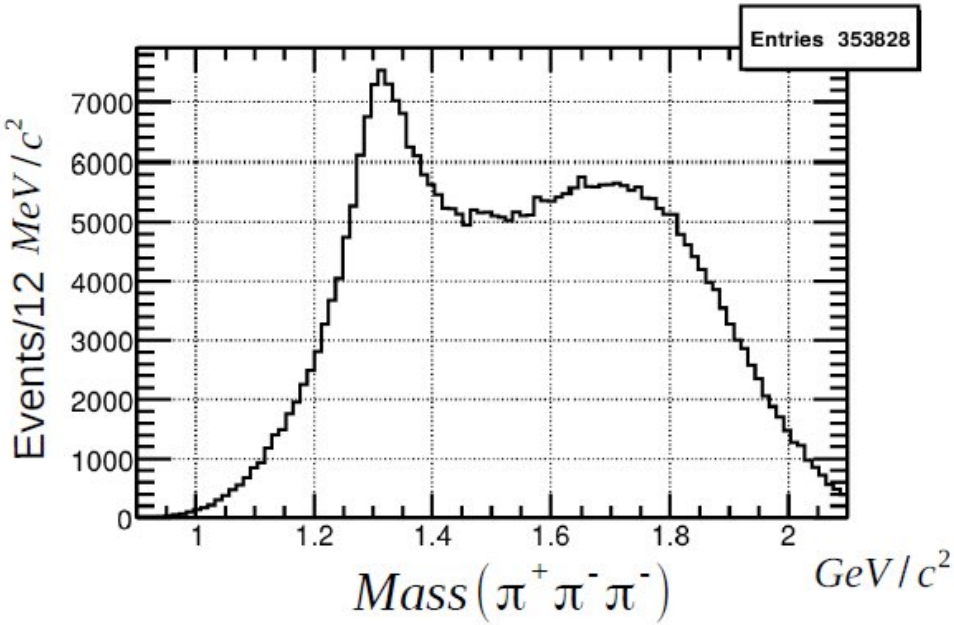


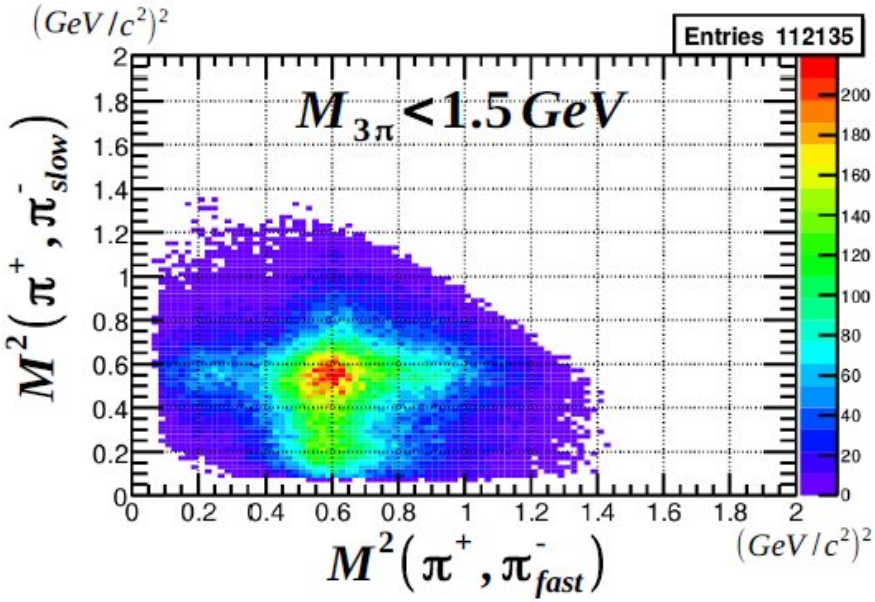


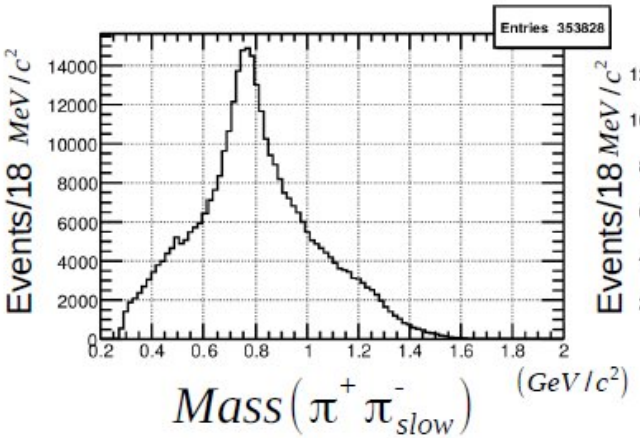
$\cos\theta$ in the Δ^{++} rest frame for data and accepted MC weighted by Δ^{++} amplitudes

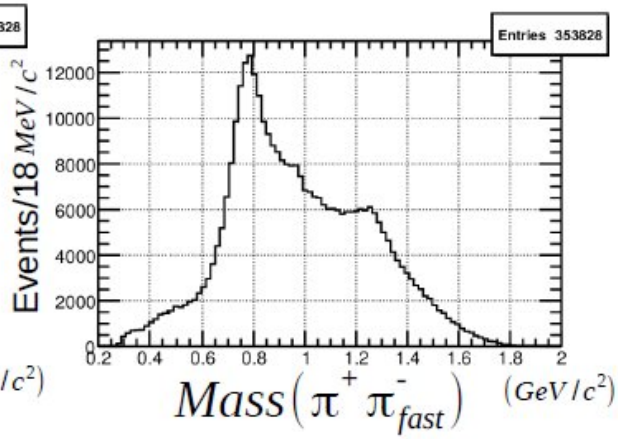
Features of the 3π sample

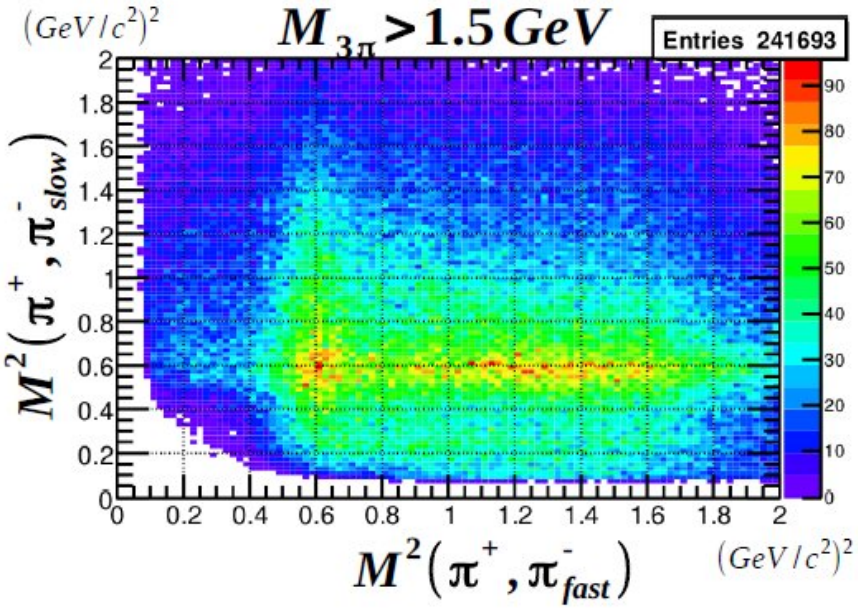
$$\gamma p \rightarrow \Delta^{++}\pi^{+}\pi^{-}\pi^{-}$$











Minimum List of Waves Required for the $\gamma\, p \rightarrow \Delta^{++}\pi^{+}\pi^{-}\pi^{-}$

$M_{3\pi} < 1.4\, GeV$

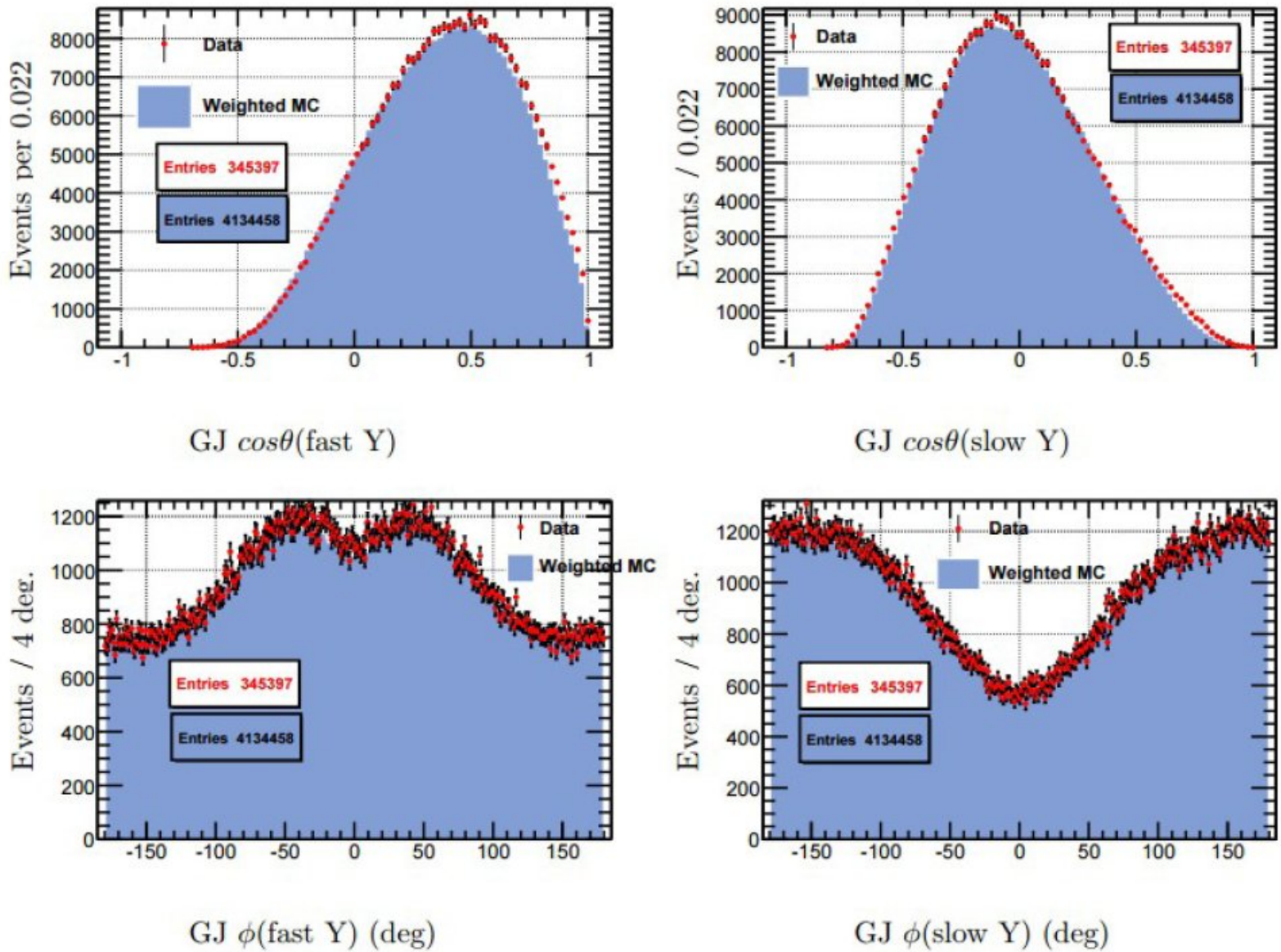
J^{PC}	M^{ϵ}	L	Y	Number of waves
1^{++}	$1^{-/+}$	S, D	$\rho(770)$	4
2^{++}	$1^{-/+}$	D	$\rho(770)$	2
2^{-+}	$1^{-/+}$	P	$\rho(770)$	2
Isotropic Background Wave				

$M_{3\pi} > 1.375\, GeV$

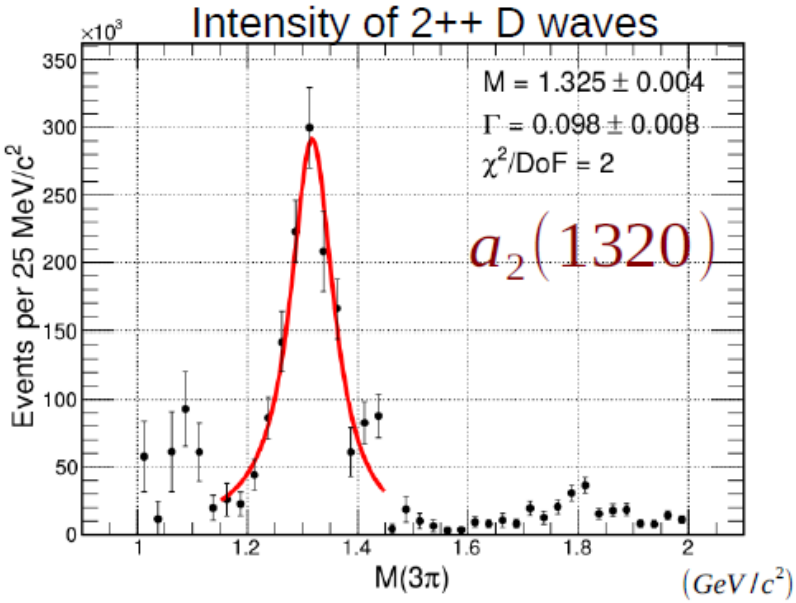
J^{PC}	M^{ϵ}	L	Y	Number of waves
1^{++}	$1^{-/+}$	S, D	$\rho(770)$	4
2^{++}	$1^{-/+}$	D	$\rho(770)$	2
2^{-+}	$1^{-/+}$	S, P, D	$\rho(770), f_2(1270)$	6
Isotropic Background Wave				

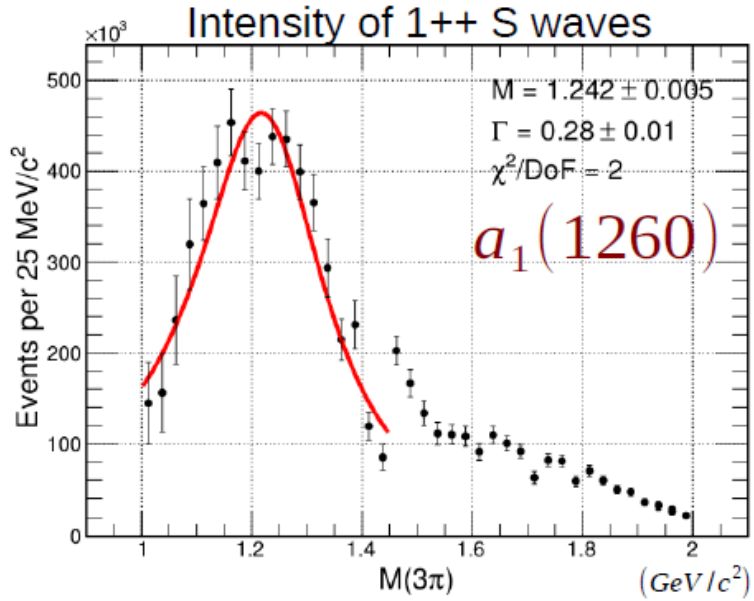
PWA Predicted Distributions

$\gamma p \rightarrow \Delta^{++} \pi^{+} \pi^{-} \pi^{-}$

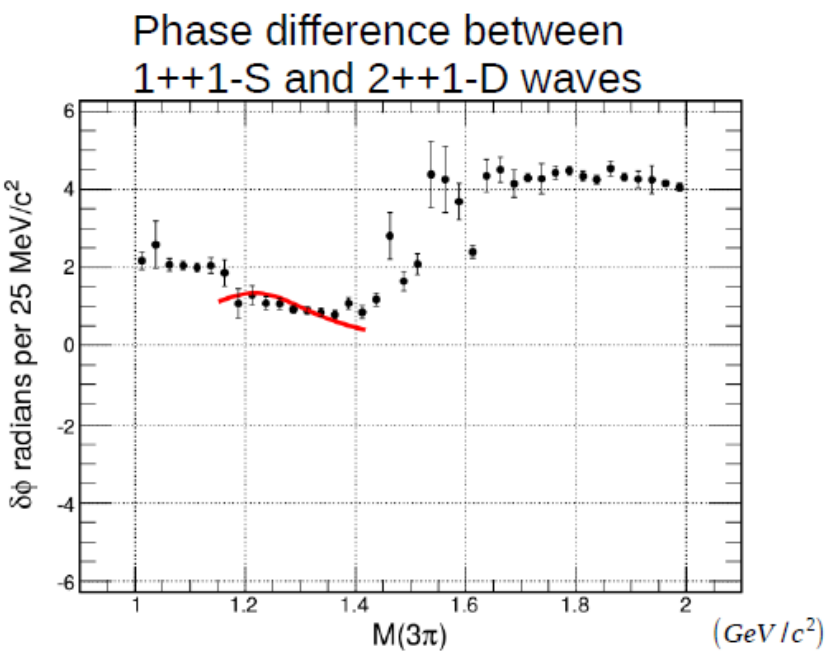


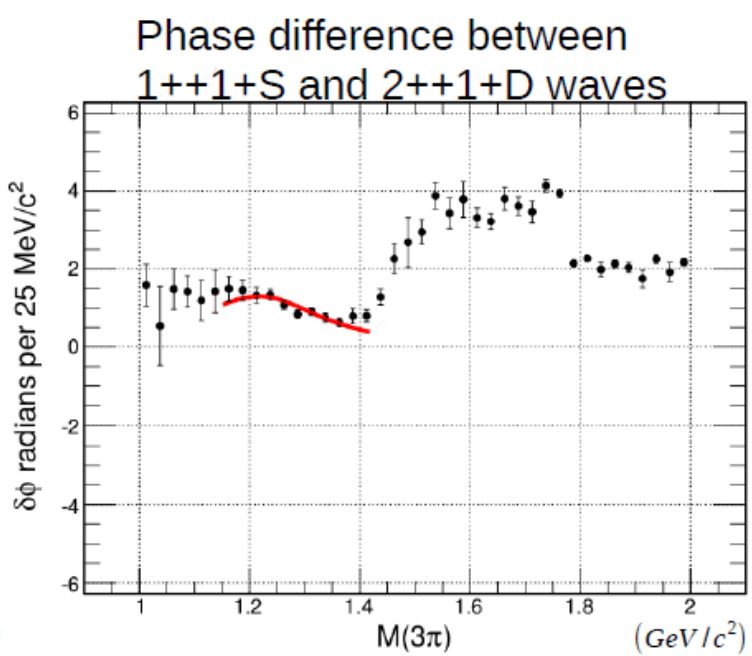
Features of the partial waves of the 3π System for the $\gamma p \rightarrow \Delta^{++}\pi^{+}\pi^{-}\pi^{-}$



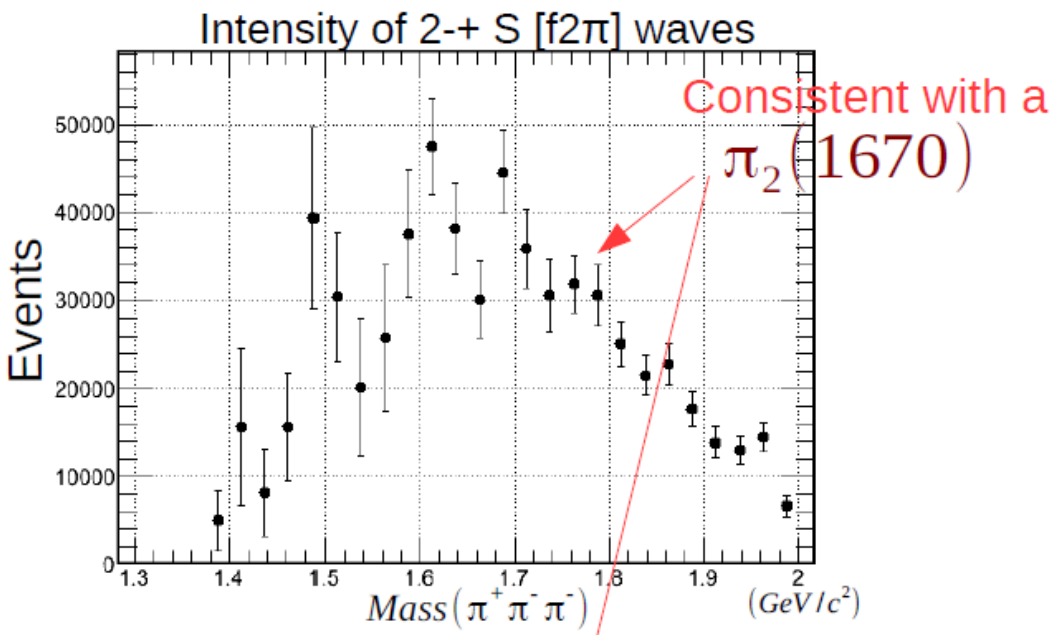


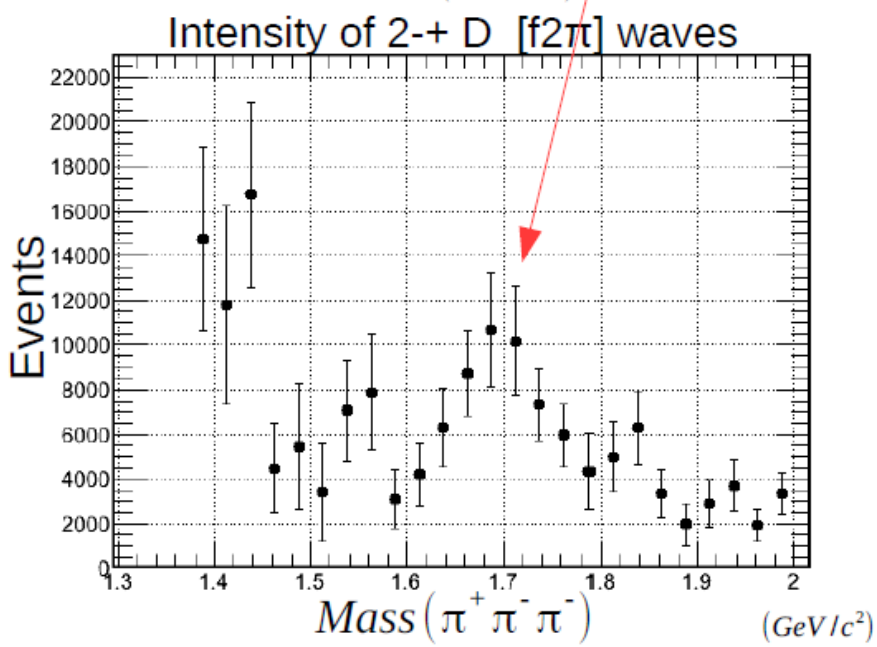
Observation of the $a_1(1260)$ confirms the results first reported in $\gamma p \rightarrow n\pi^{+}\pi^{+}\pi^{-}$



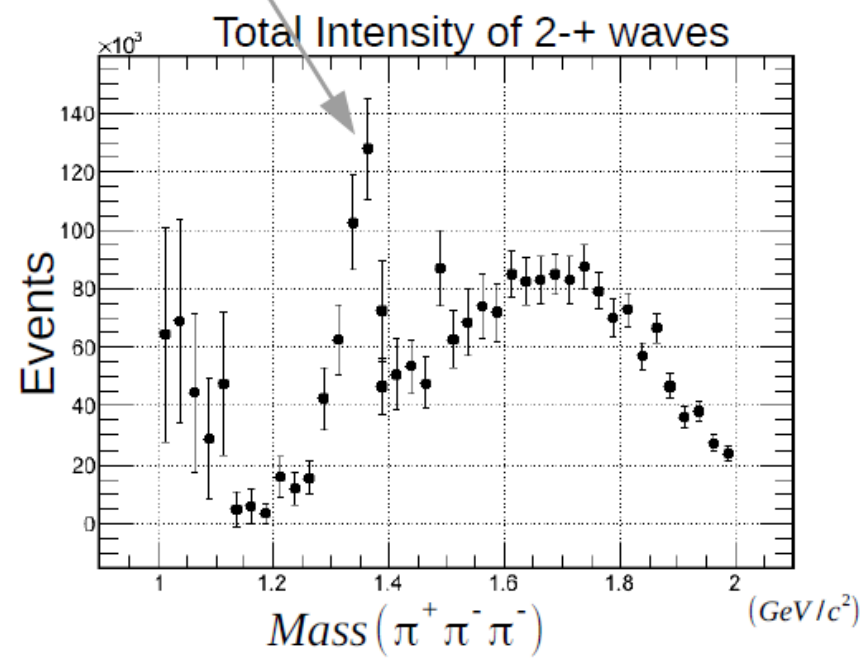


Features of the partial waves of the 3π System for the $\gamma\, p \rightarrow \Delta^{++} \pi^{+} \pi^{-} \pi^{-}$





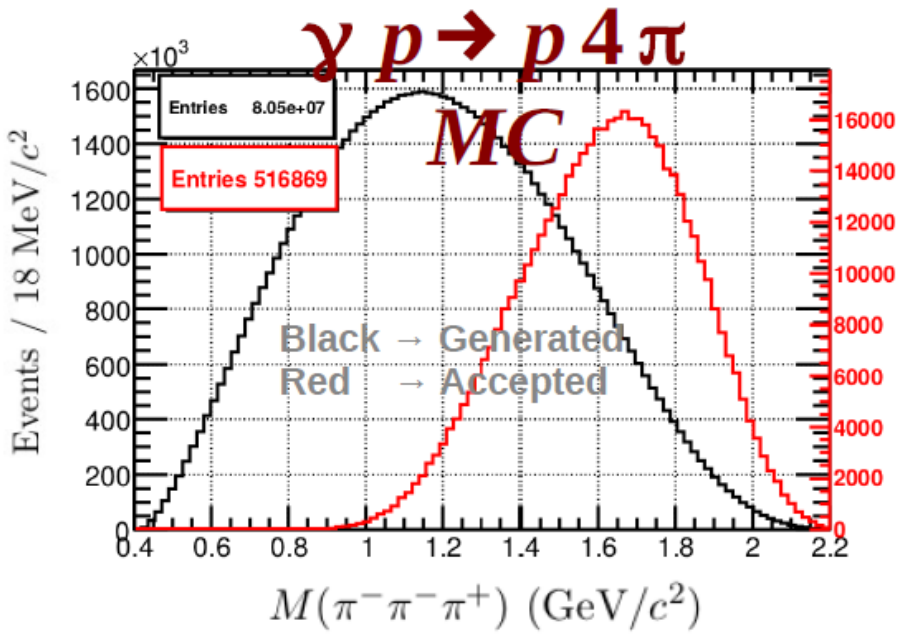
leakage of $a_2(1320)$ into the P-wave

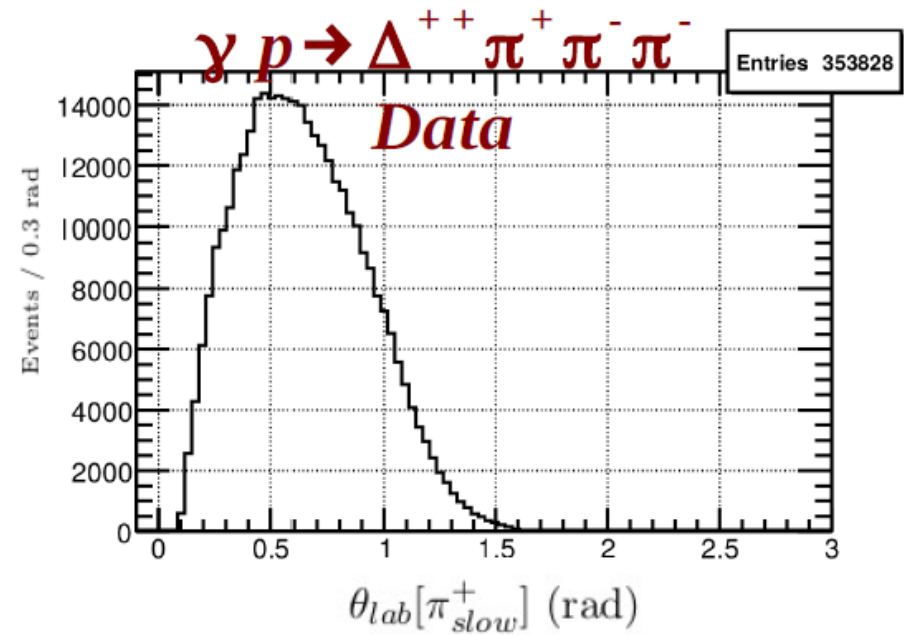


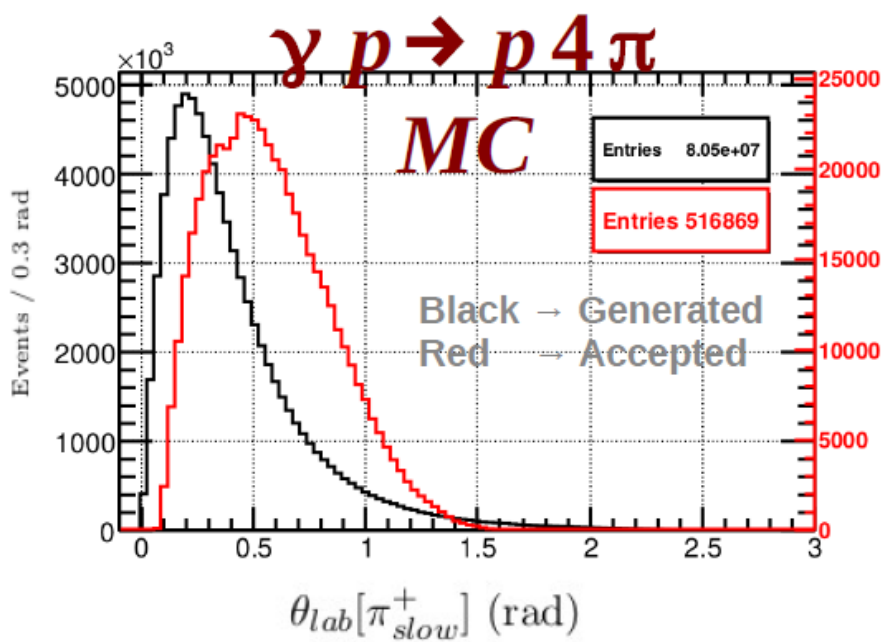
PWA in the high mass region:

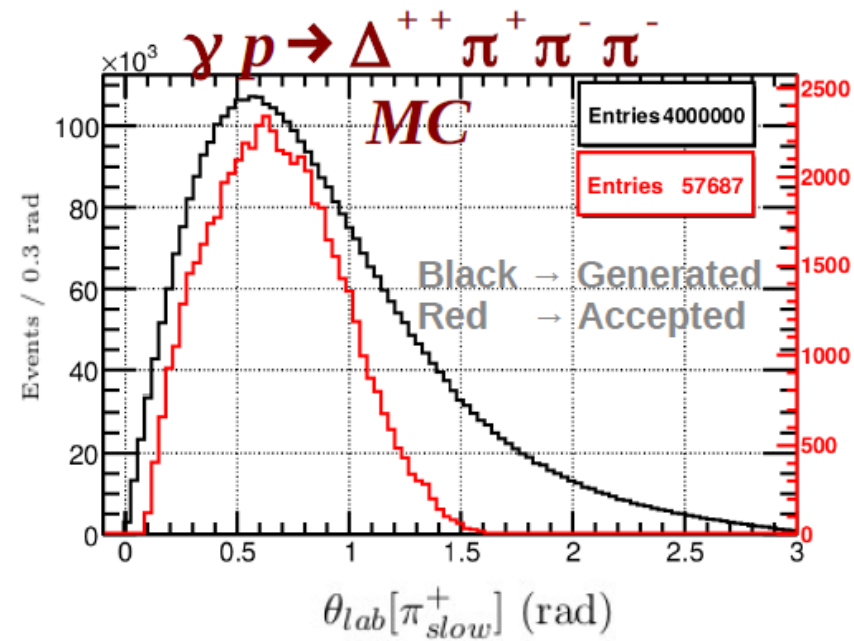
- was more challenging.
- results were less stable here.
- further investigation in this region showed that this channel is suffering from background.

Investigating the high 3π mass of the $\gamma p \rightarrow \Delta^{++}\pi^{+}\pi^{-}\pi^{-}$ reaction for the source of background.









Summary of the Analysis

- $\gamma p \rightarrow n \pi^+ \pi^+ \pi^-$:
  - The $a_2(1320)$ and the $a_1(1260)$ are observed
  - The $\pi_2(1670)$ is observed
  - The $J^{PC} = 1^{-+}$ does not show resonant behavior and it is strongly consistent with a non-resonant non-interfering wave relative to a resonant $\pi_2(1670)$
- $\gamma p \rightarrow \Delta^{++} \pi^+ \pi^- \pi^-$:
  - A first time PWA of the $\Delta^{++} 3\pi$ system
  - The $a_2(1320)$ and the $a_1(1260)$ are observed
  - The $\pi_2(1670)$ is observed