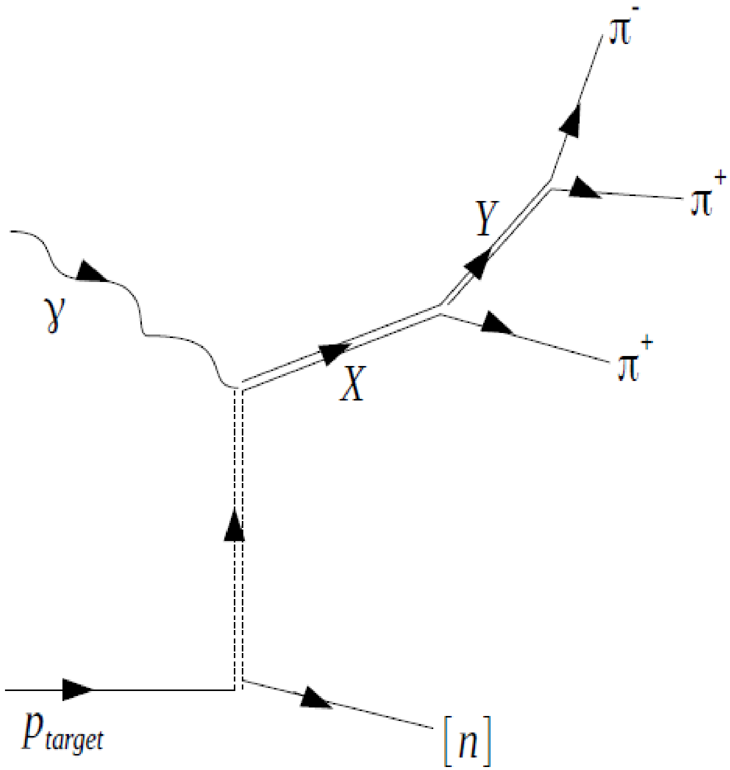
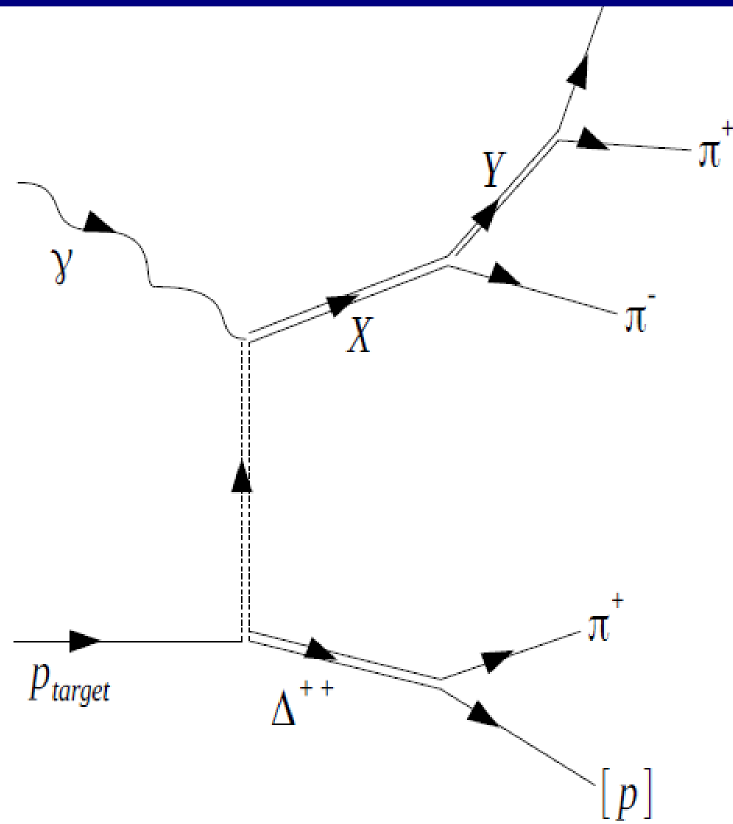
Photoproduction of 3π with CLAS

P. Eugenio
Florida State University

CLAS Collaboration Meeting Hadron Spectroscopy
15 June 2017

CLAS g12 Analysis





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

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

Form CLAS-g12 dataset (~25B events):
- **Three** charged pions selected
- **Neutron** is identified by energy and momentum conservation

Form CLAS-g12 dataset (~25B events):
- **Four** charged pions selected
- **Proton** is identified by energy and momentum conservation

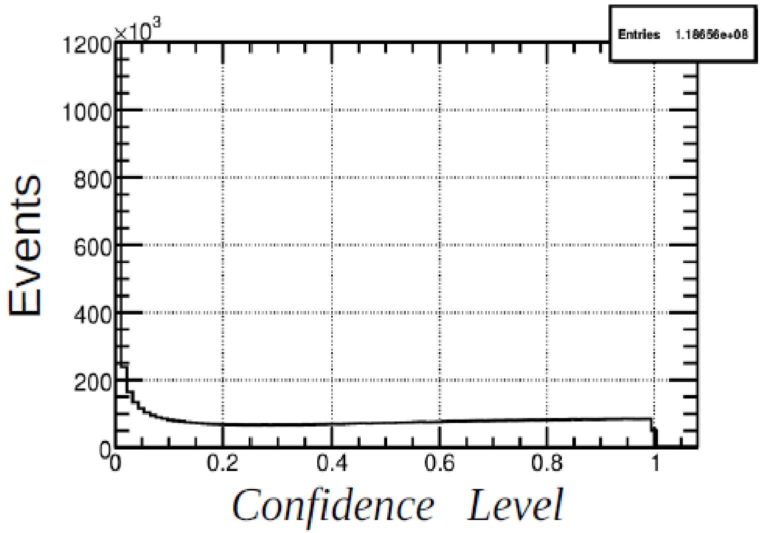
Partial Wave Analysis in the 3π sample

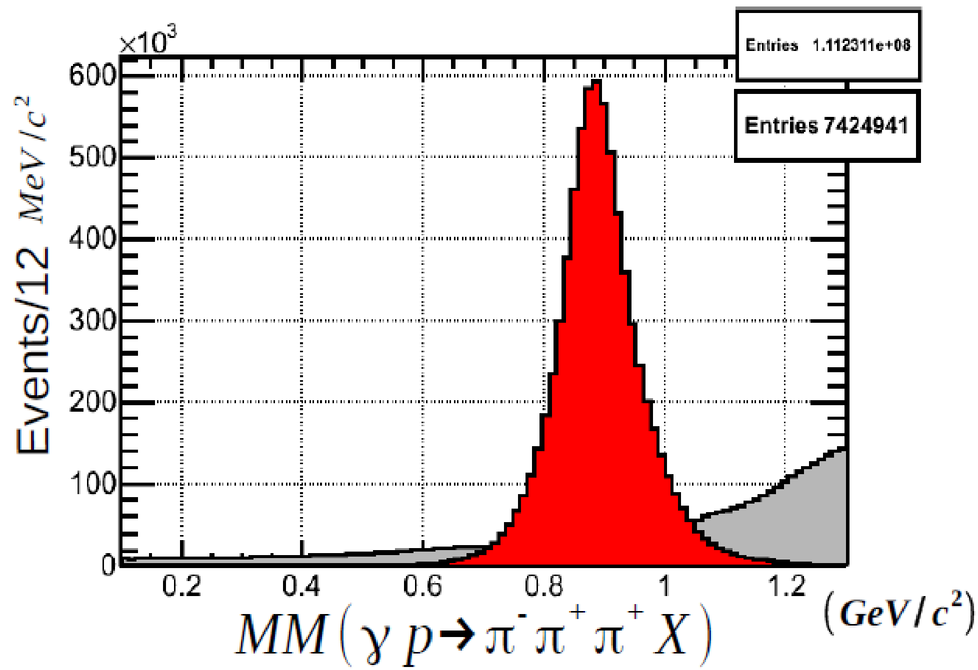
A. Tsaris (2016 FSU Dissertation)

Selection Criteria

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

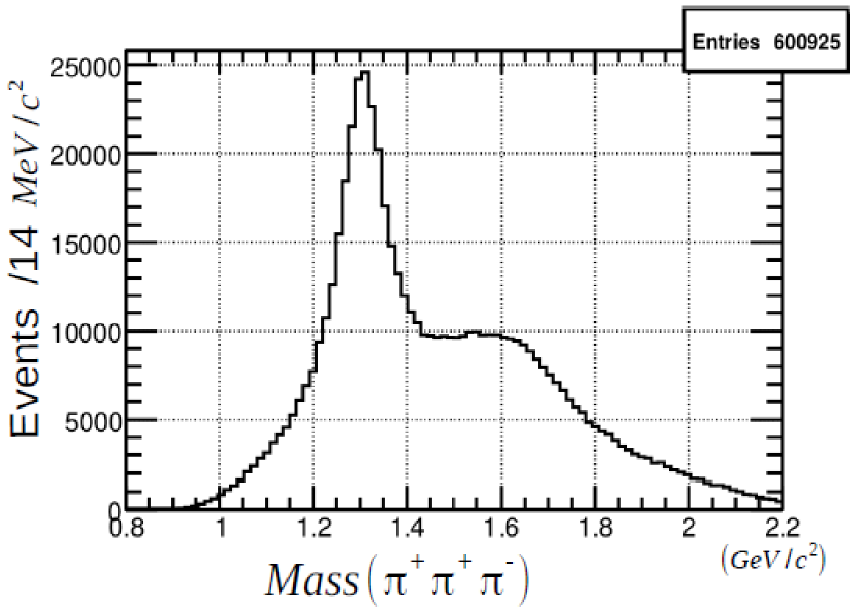
Description	Interval	Events In	Events Selected
Vertex within z-extent of target	$-110 < z < -70$ cm	707,329,219	658,403,589
Vertex within target radius	$r < 10.0$ cm	658,403,589	587,508,335
Event vertex timing cut	$\lvert t_{vtx}(TAG) - t_{vtx}(ST) \rvert < 1.002$ ns	587,508,335	421,091,544
Beta selection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

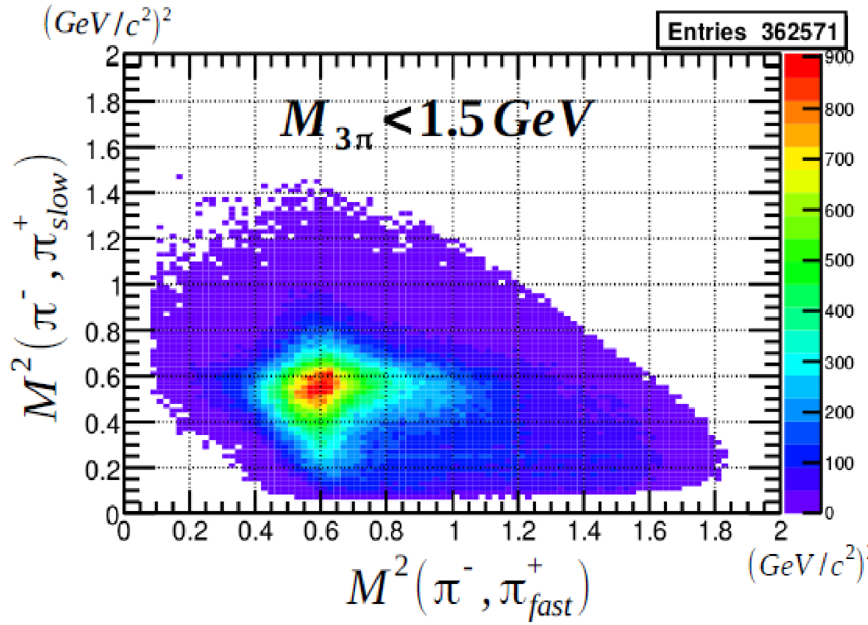


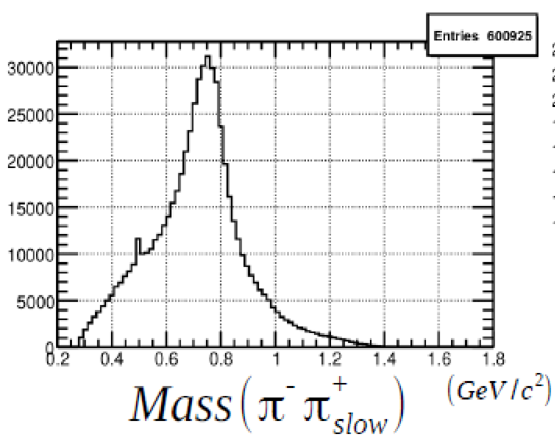


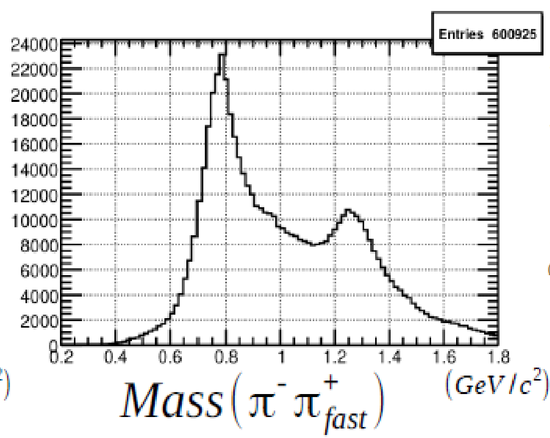
Features of the Data

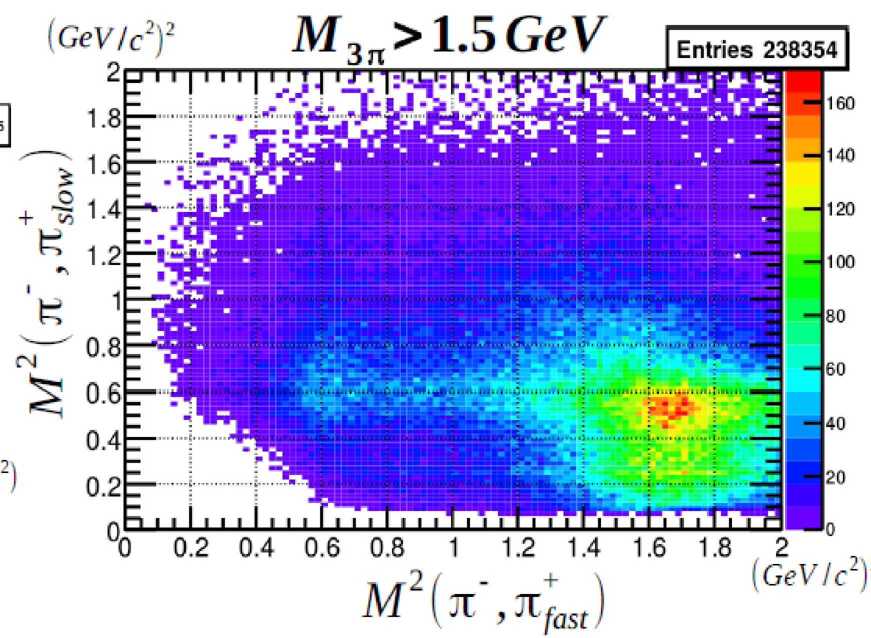
$\gamma p \rightarrow n \pi^+ \pi^+ \pi^-$







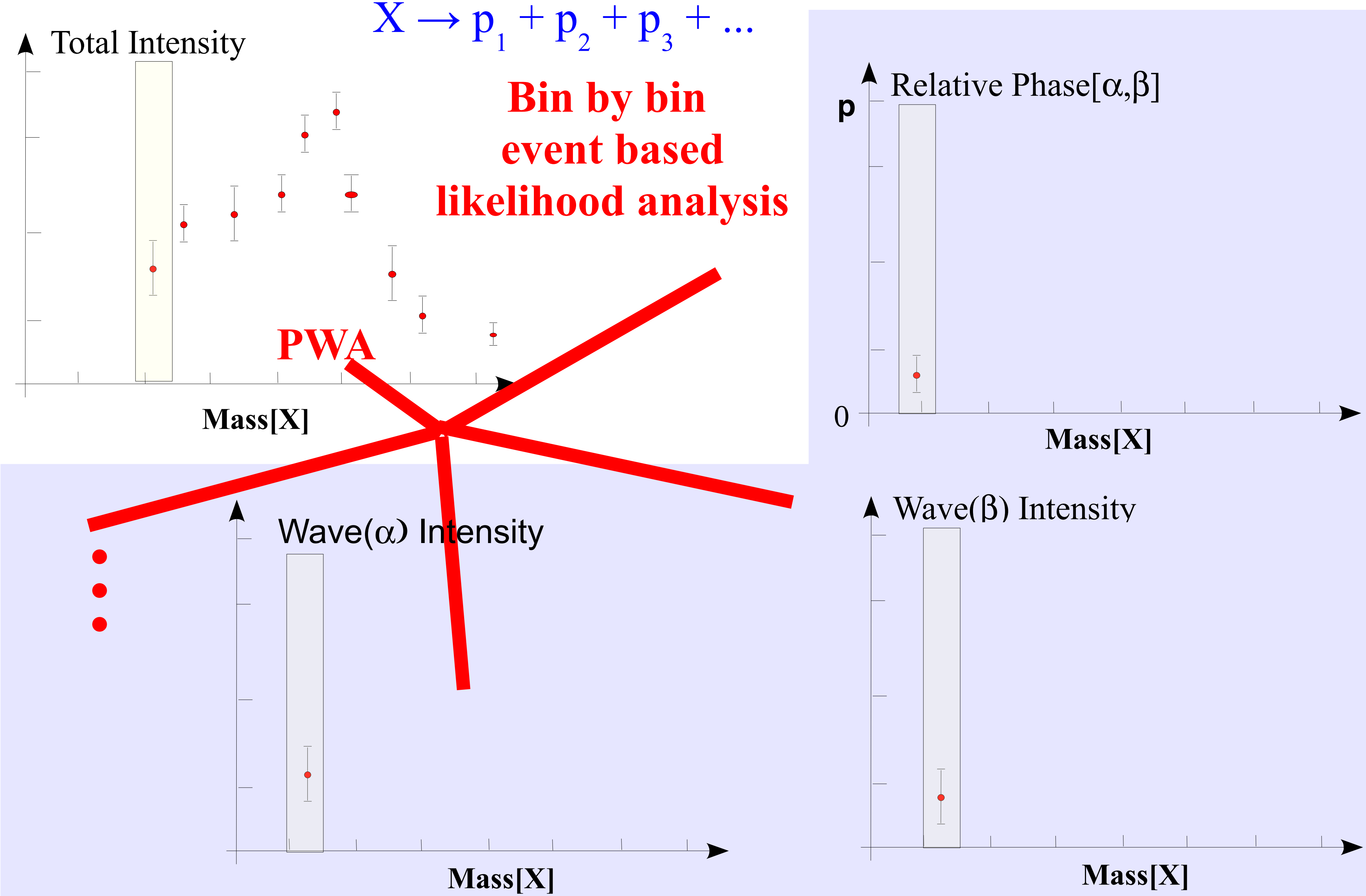




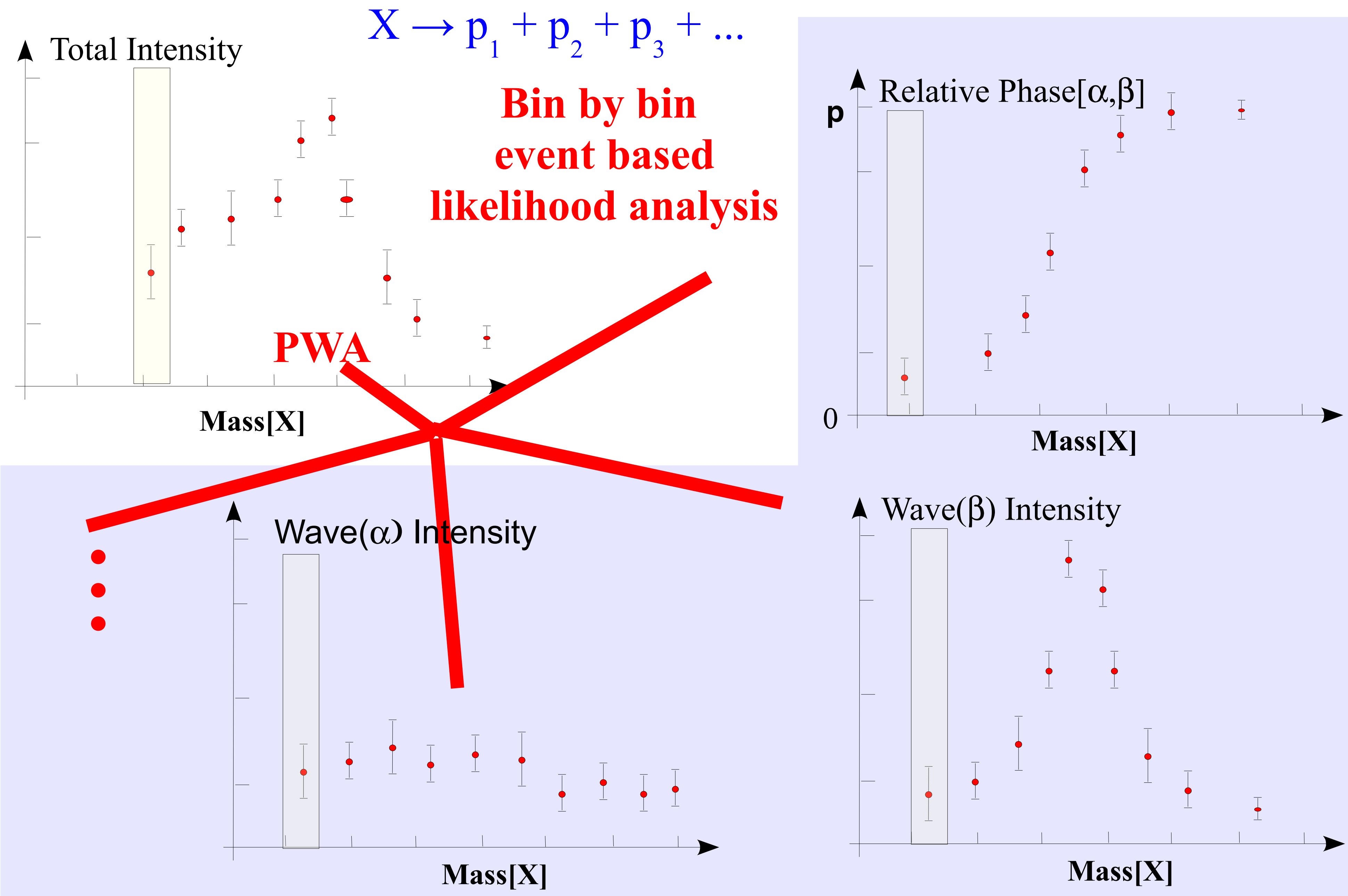
Partial Wave Analysis
Step 1: Decompose to Partial Waves

$X \rightarrow p_1 + p_2 + p_3 + \ldots$

Bin by bin event based likelihood analysis

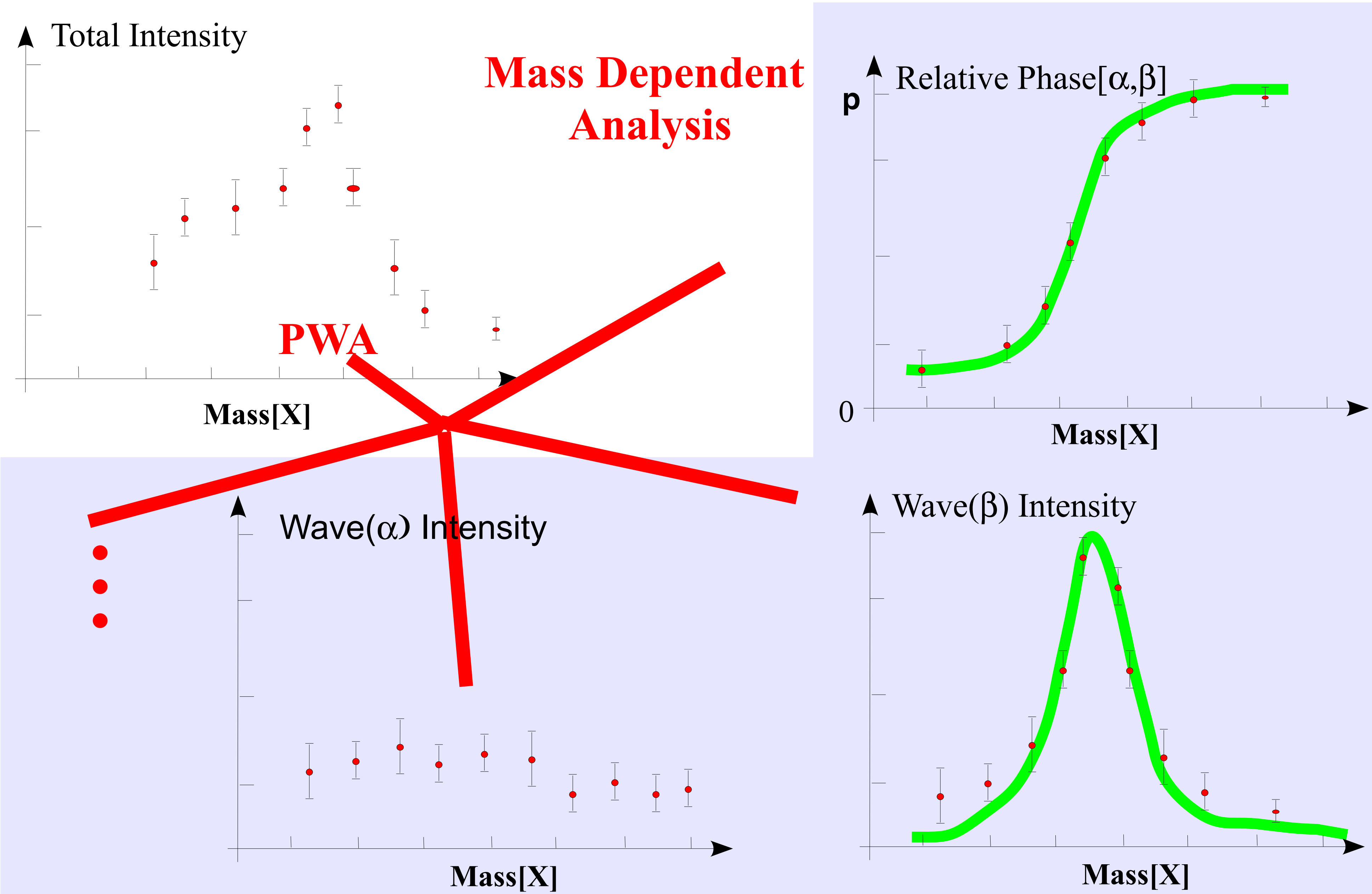


Partial Wave Analysis
Step 1: Decompose to Partial Waves

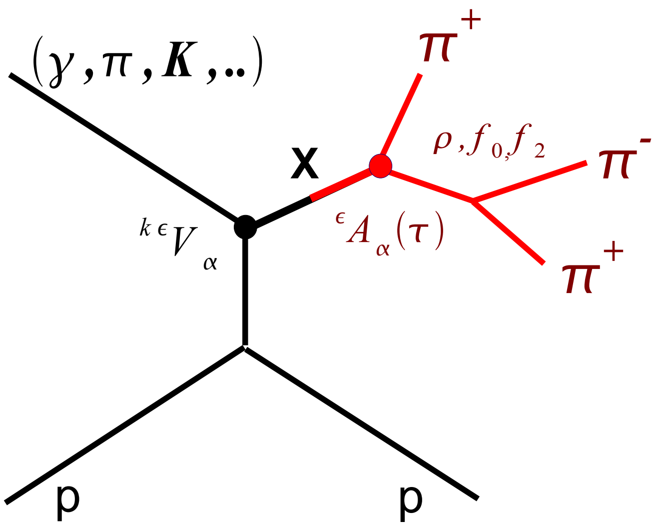


Partial Wave Analysis

Step 2: Extract Resonance Parameters



Using PWA to Identify J^{PC} States



$$I(\tau)=\sum_{k\epsilon\epsilon'} \epsilon\epsilon' \rho_{\epsilon\epsilon'}(\tau) \sum_{\alpha\alpha'} {}^{k\epsilon'}V^*_{\alpha'}\, {}^{\epsilon'}A^*_{\alpha'}(\tau)\, {}^{k\epsilon}V_\alpha\, {}^{\epsilon}A_\alpha(\tau)$$

For unpolarized beam & target:

$$I(\tau)=\frac{1}{2}\sum_{k\epsilon}\left|\sum_\alpha {}^{k\epsilon}V_\alpha\, {}^{\epsilon}A_\alpha(\tau)\right|^2$$

unknown

Complex parameters varied in the PWA to fit the data

Helicity Decay Amplitudes

$$A_{\alpha,M}(\tau)=A_X^{\lambda_1\lambda_2;M} * A_{iso}^{\nu_1\nu_2;\lambda_1}\cdots$$

$$A_X^{\lambda_1\lambda_2;M}=D^J_{\lambda M}(\theta,\phi)\frac{\tilde{L}}{\tilde{J}}(L\,0;S\,\lambda|J\,\lambda)(S_1\lambda_1;S_2-\lambda_2|S\,\lambda)K$$

Wigner D-functions

Clebsch-Gordan Coefficients

Mass Dynamic Factor (like Breit-Wigner, K-matrix, ...)

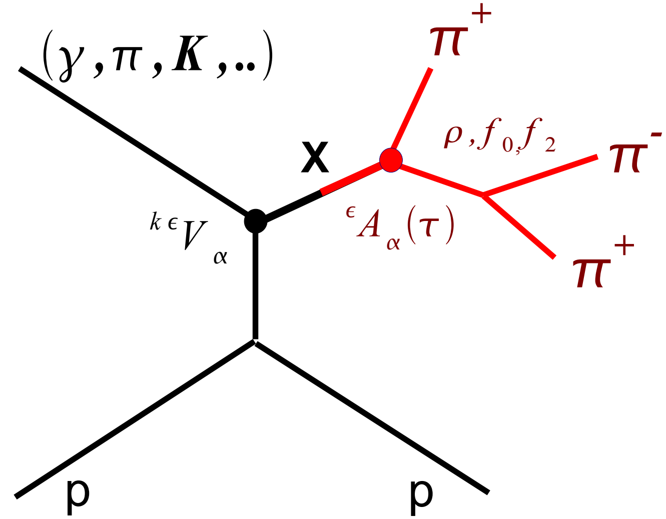
$\tilde{J}=\sqrt{J(J+1)}$

Helicity Decay Amplitudes in the Reflectivity Basis

For unpolarized beam & target:

$$I(\tau)=\frac{1}{2}\sum_{k\epsilon}\left|\sum_{\alpha} {}^{k\epsilon}V_{\alpha}\, {}^{\epsilon}A_{\alpha}(\tau)\right|^2$$

$$\tau = \{\theta, \phi, m_{iso}, \theta', \phi', \ldots\}$$



Helicity amplitudes are not eigenstates of Parity

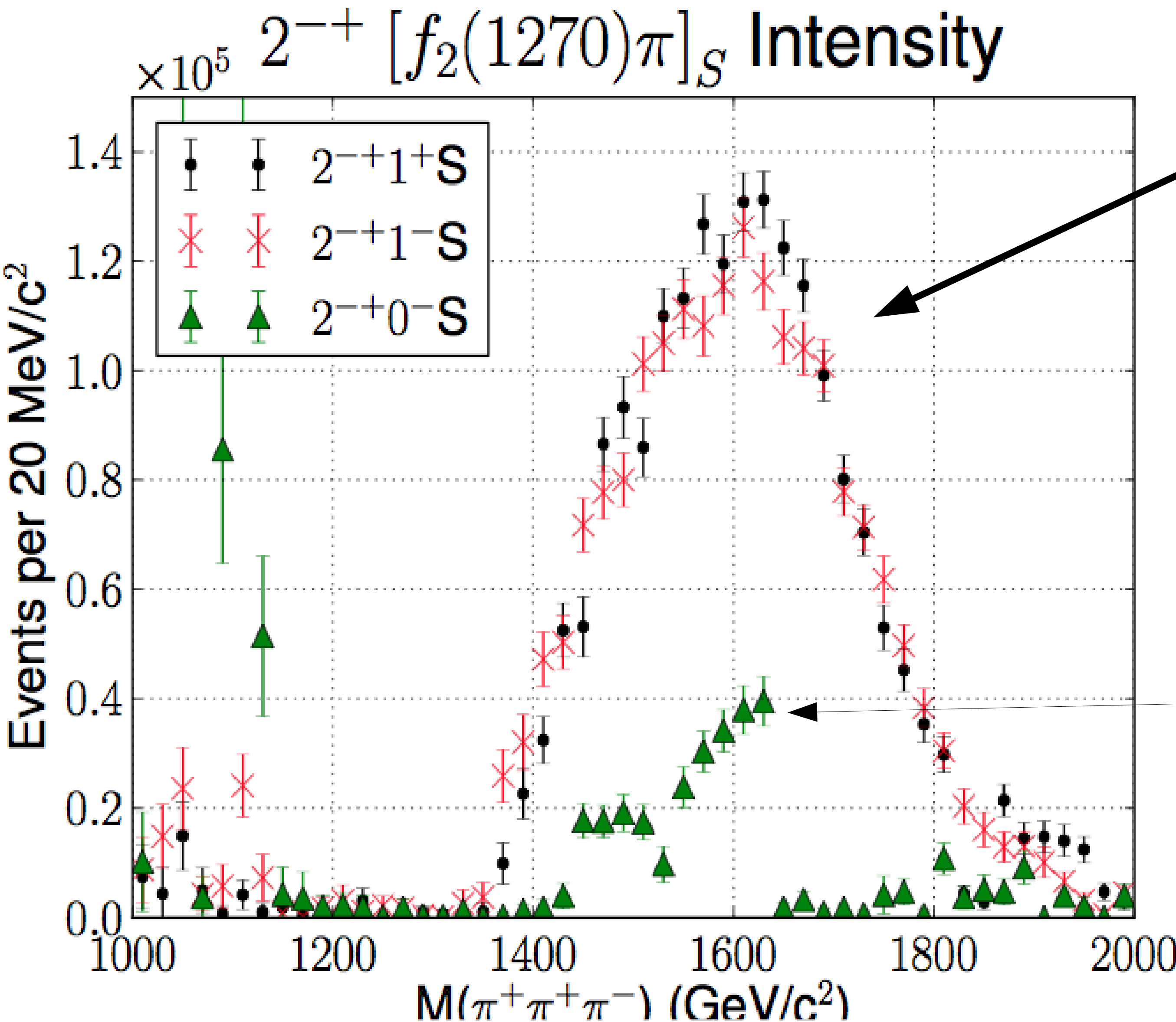
<u>Reflectivity basis takes Parity into account</u>

$$A^{*}_{\alpha\ {}^{\epsilon}M}(\tau) = \Delta(m)\left[A^{*}_{\alpha,m}(\tau) - \epsilon P(-1)^{J-m} A^{*}_{\alpha,-m}(\tau)\right]$$

$$\Delta(m) = \begin{cases} 1/\sqrt{2} & m>0 \\ 1/2 & m=0 \\ 0 & m<0 \end{cases}$$

- Unpolarized photon beam results in equal mixture of $M^{\epsilon} = 1^{+}$ & 1^{-}
- π exchange photoproduction forbids M=0

Earlier FSU Results*



$\pi_2(1670)$

Equal yields for $M^{\epsilon} = 1^+ \& 1^-$

- Large signal in M=0 wave

Did not expect M=0 waves to contribute

*C. Bookwalter (FSU Dissertation)

Minimum List of Partial Waves

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

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				

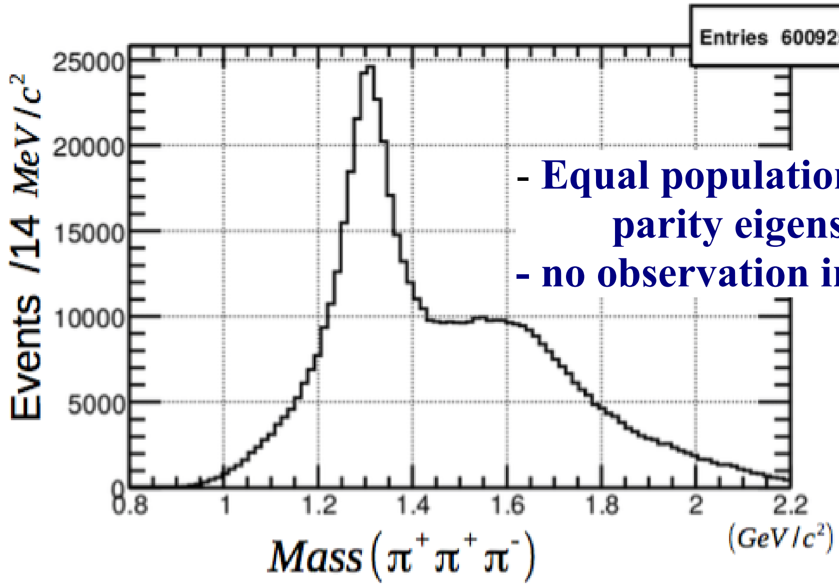
$M_{3\pi} > 1.38\,GeV$

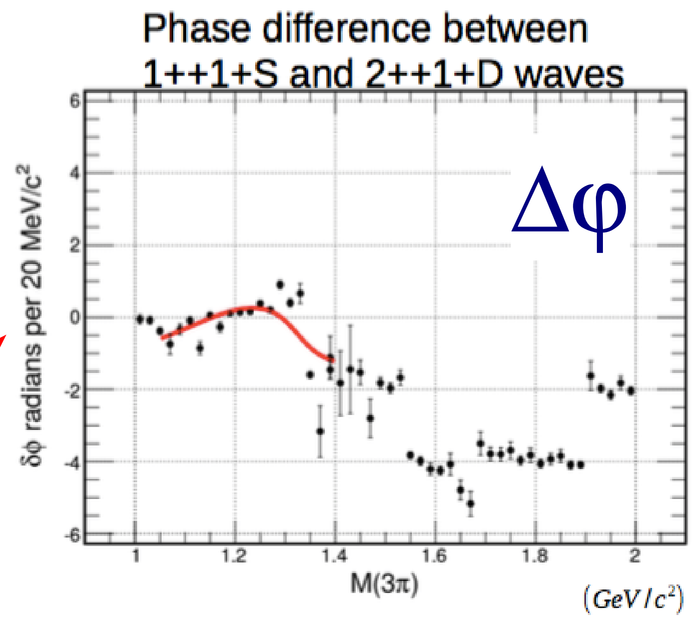
J^{PC}	M^{ϵ}	L	Y	Number of waves
1^{++}	$1^{-/+}$	S, P, D	$\rho(770), \sigma$	6
1^{-+}	$1^{-/+}$	P	$\rho(770)$	2
2^{++}	$1^{-/+}$	D	$\rho(770)$	2
2^{-+}	$1^{-/+}$	S, P, D	$\rho(770), f_2(1270)$	6
Isotropic background wave				

PWA Results: $n\pi^+\pi^+\pi^-$

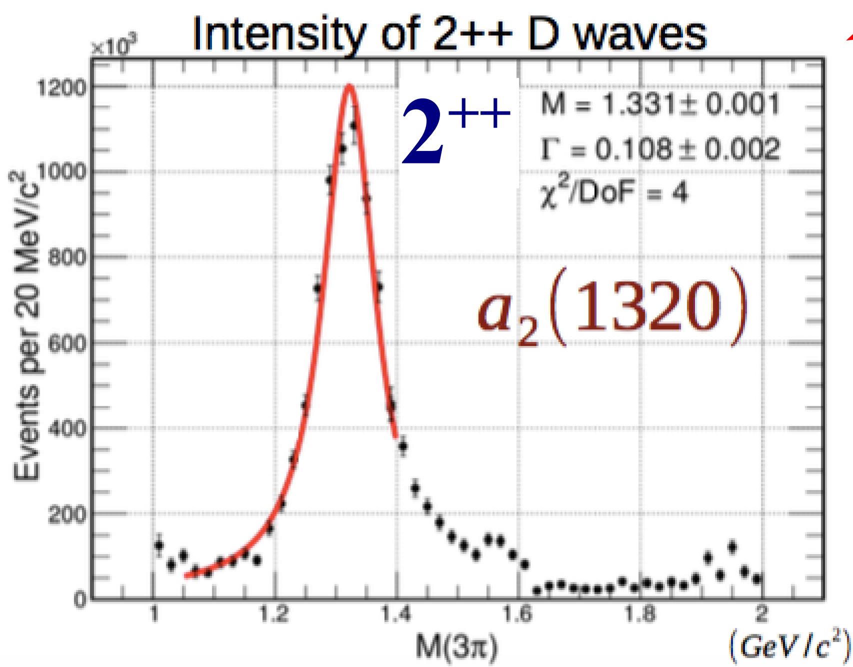
CLAS g12

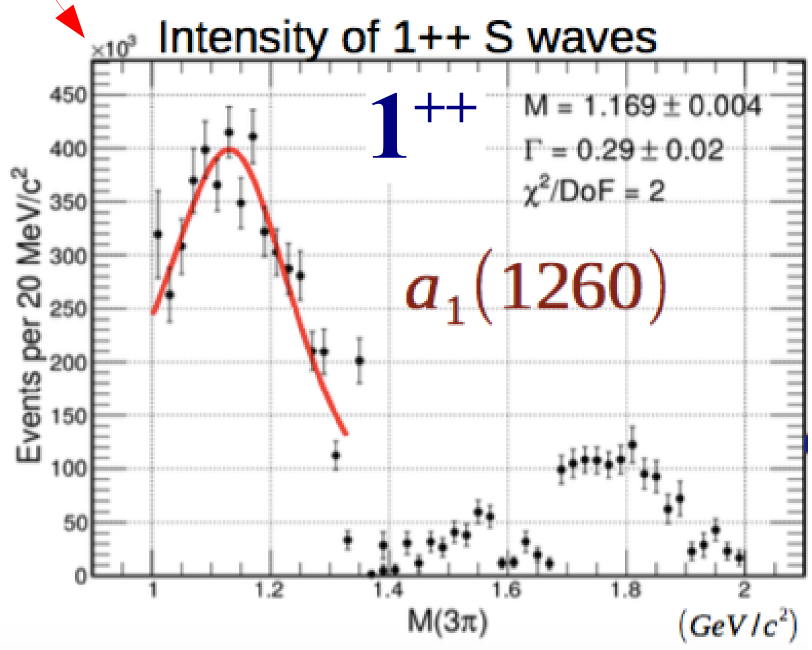
First observation of the $a_1(1260)$ in photoproduction





PWA



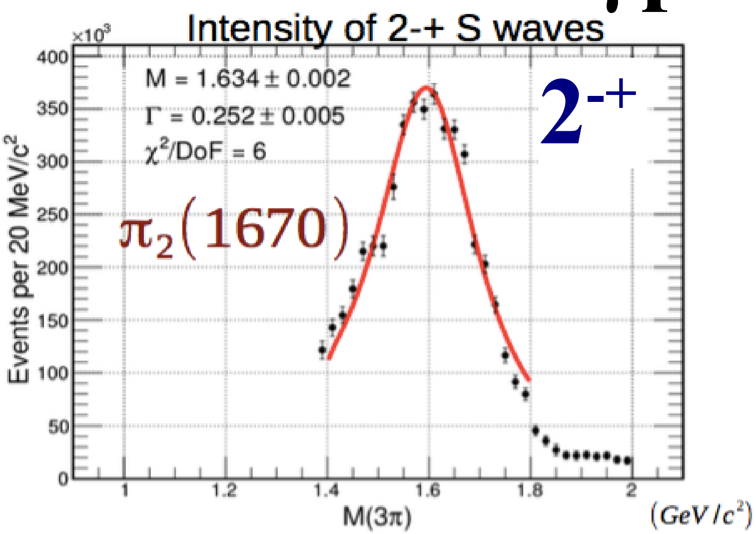


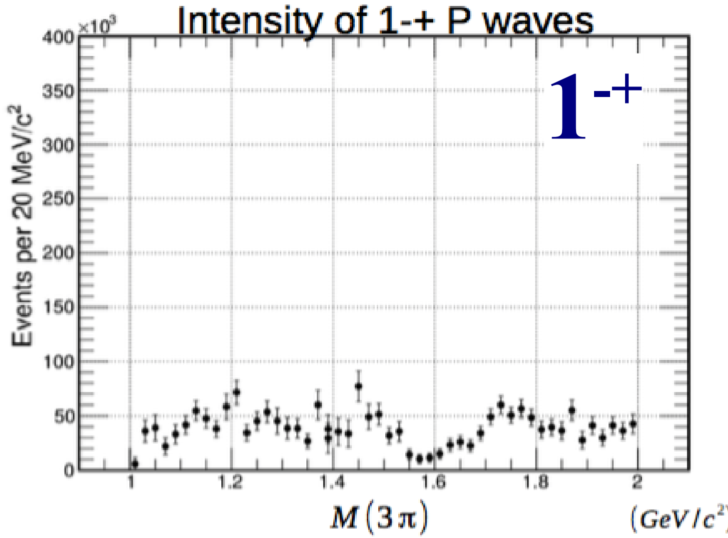
A. Tsaris (2016 FSU Dissertation)

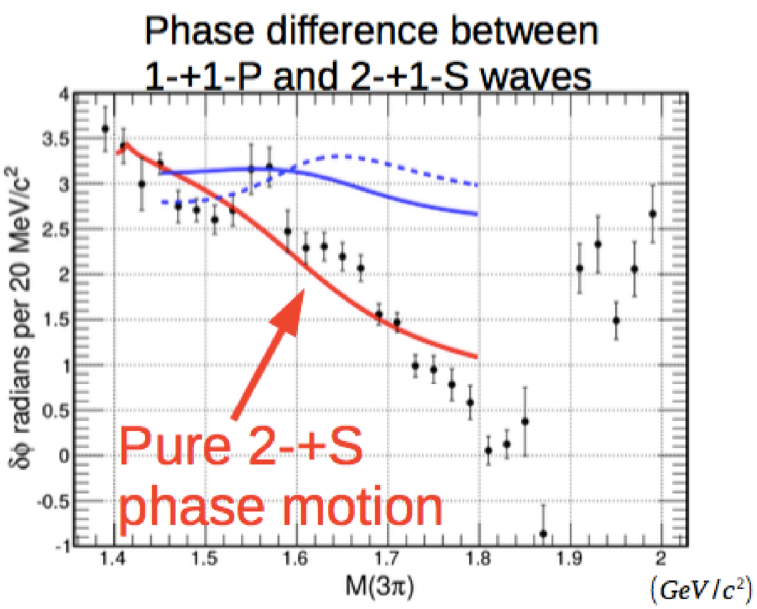
$\pi_2(1670)$ & Non-resonant 1^{-+} wave

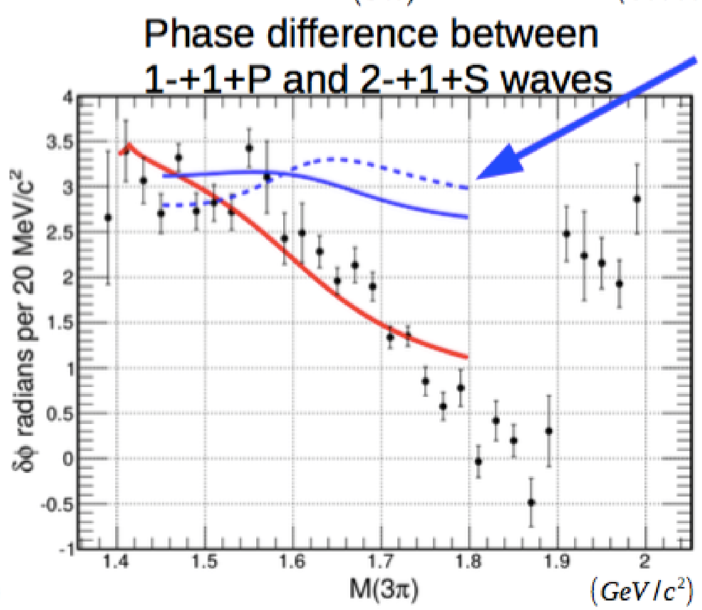
$\gamma p \rightarrow n\ \pi^+ \pi^+ \pi^-$

CLAS g12









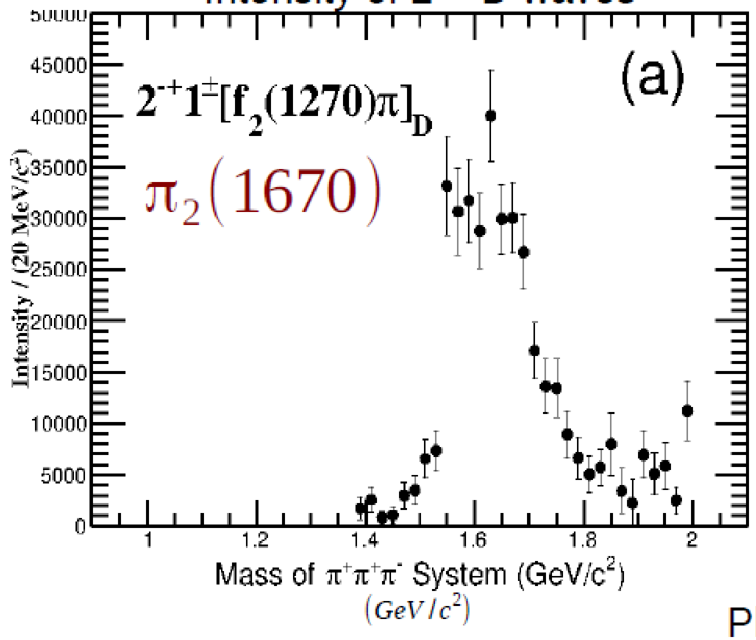
phase difference between 2-+S and a resonating 1-+P

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

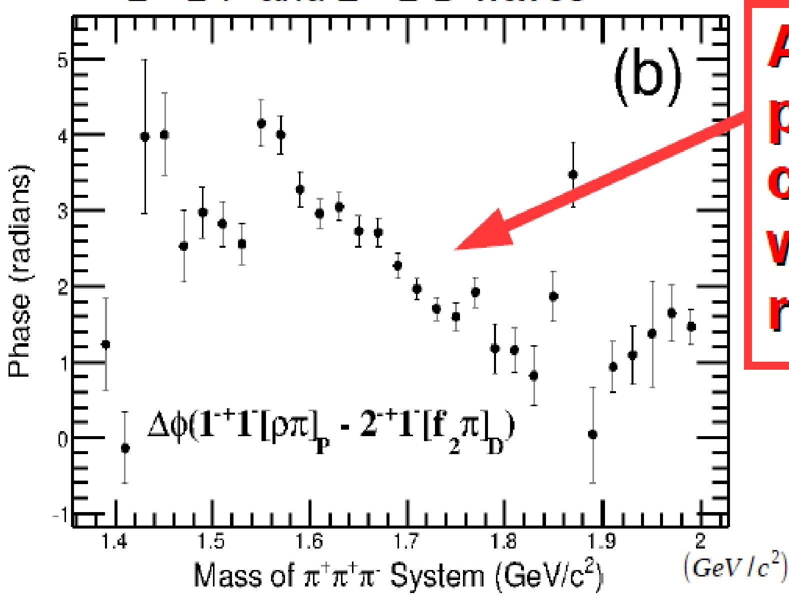
$\pi_2(1670)$ D-wave decay

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

Intensity of 2-+ D waves

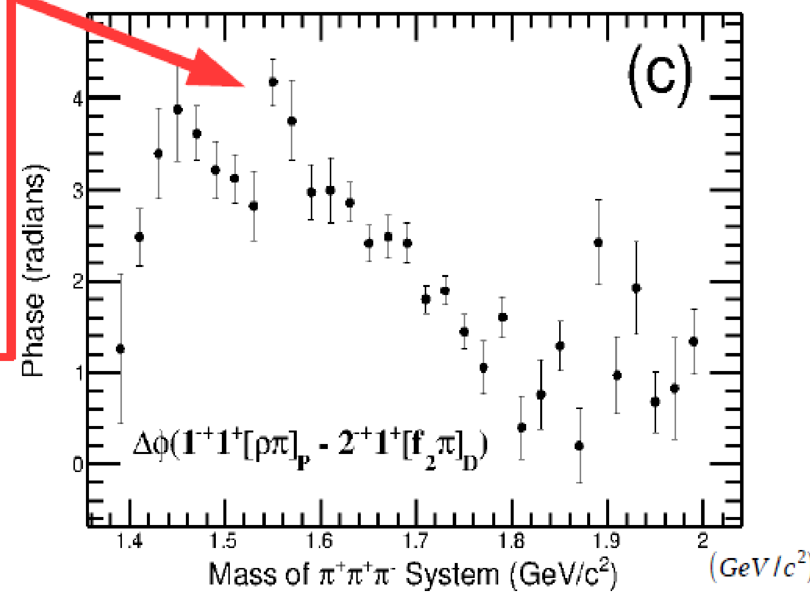


Phase difference between
1-+1-P and 2-+1-D waves



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

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

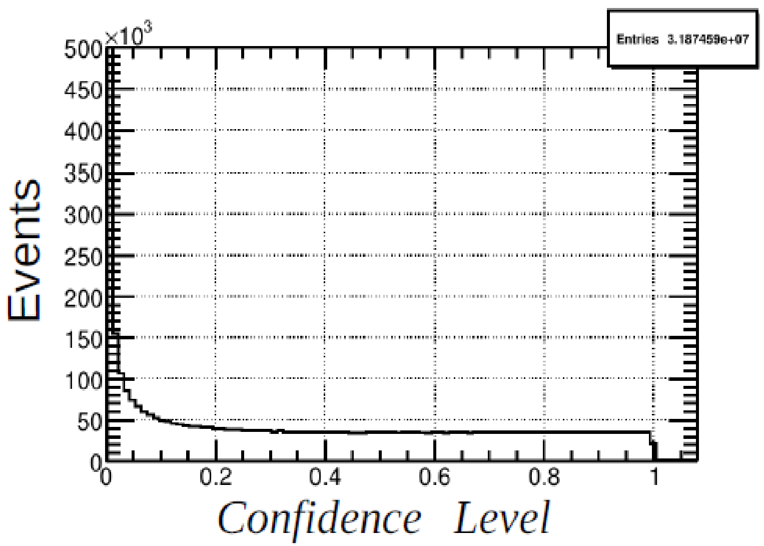


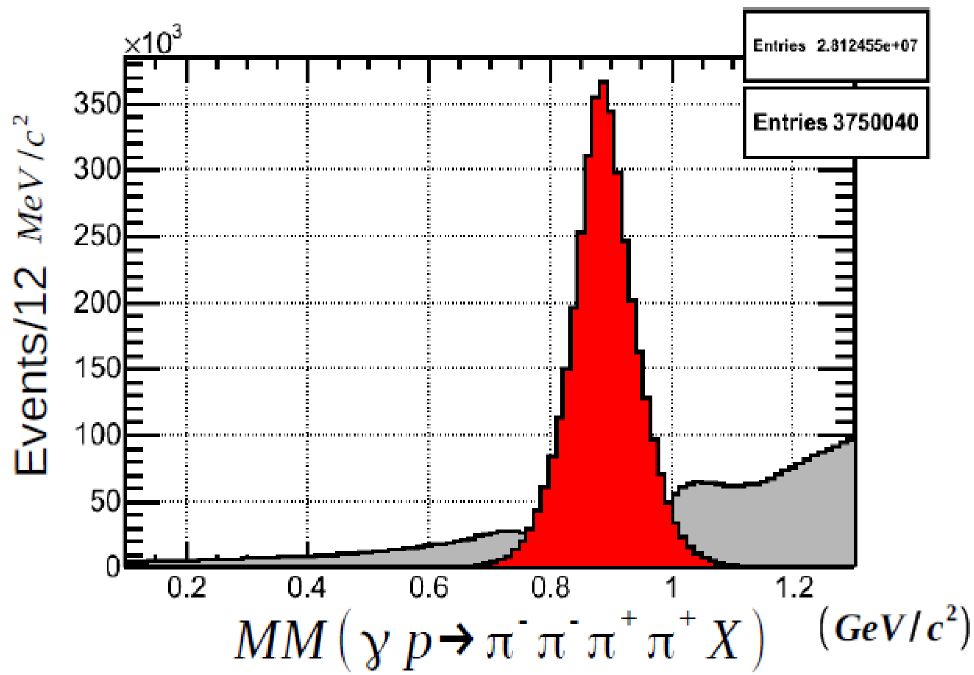
* phase motion was not stable in earlier FSU results

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

Event Selection

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	$\|t_{vtx}(TAG) - t_{vtx}(ST)\| < 1.002$ ns	93,575,180	79,764,370
Beta selection for particle tracks	$\|\beta_{TOF} - \beta_{p/m}\| < 0.03$	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

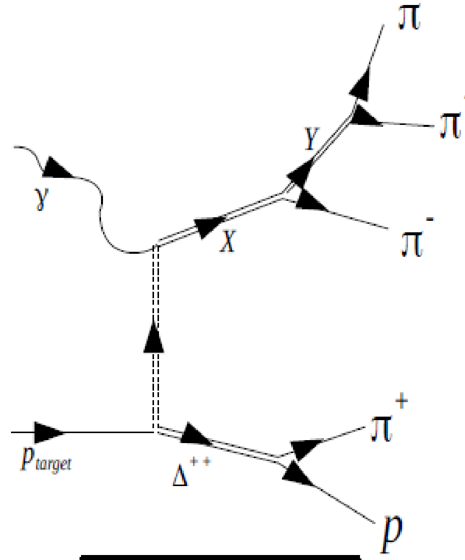




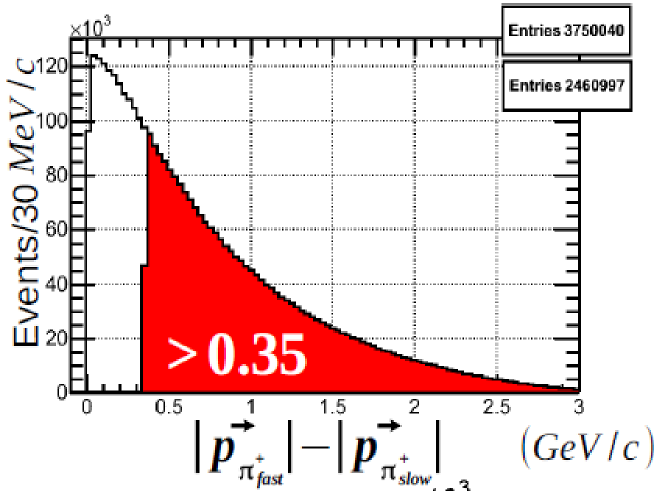
A. Tsaris (2016 FSU Dissertation)

Kinematic Separation of the Δ^{++}

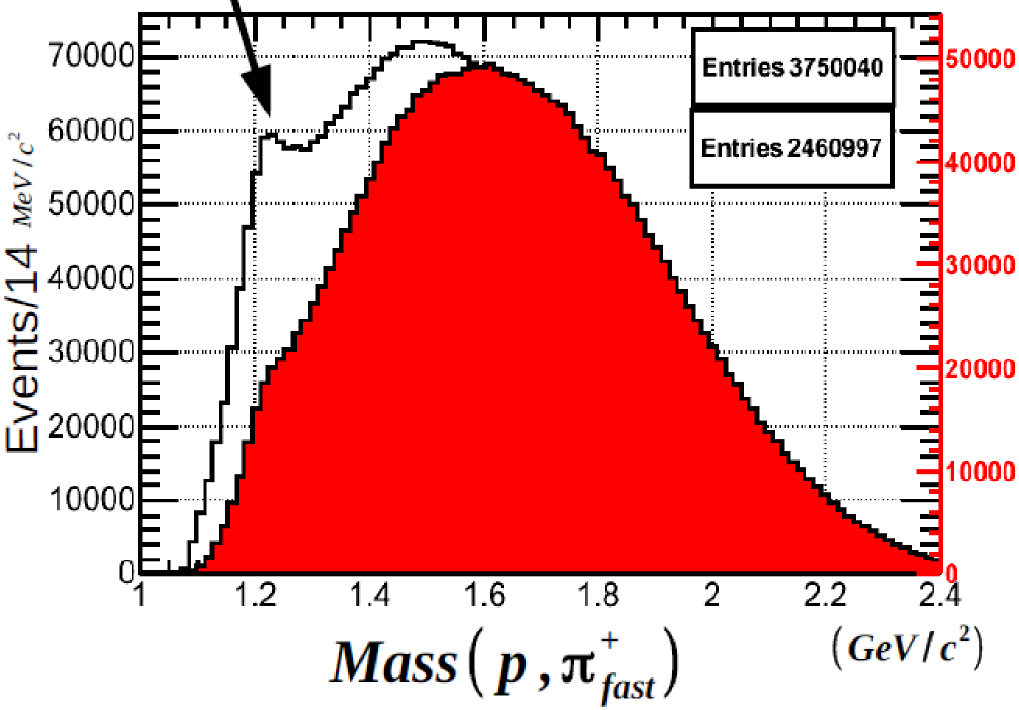
$$\gamma\, p \rightarrow \Delta^{++} \pi^{+} \pi^{-} \pi^{-}$$



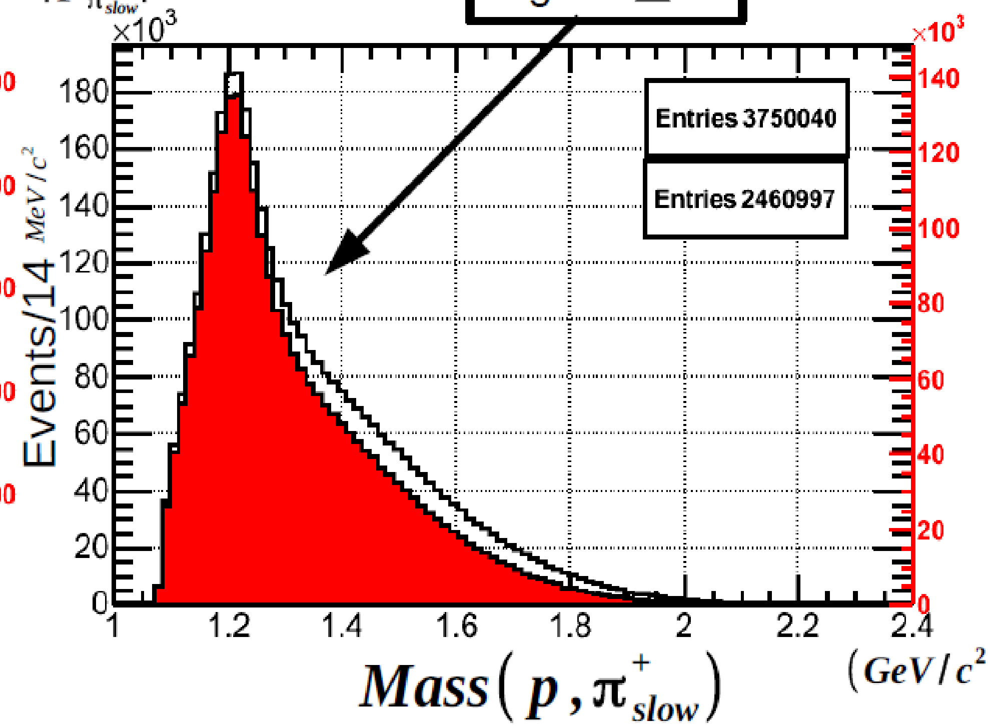
Momentum Difference between fast and slow π^+



Background Δ^{++}

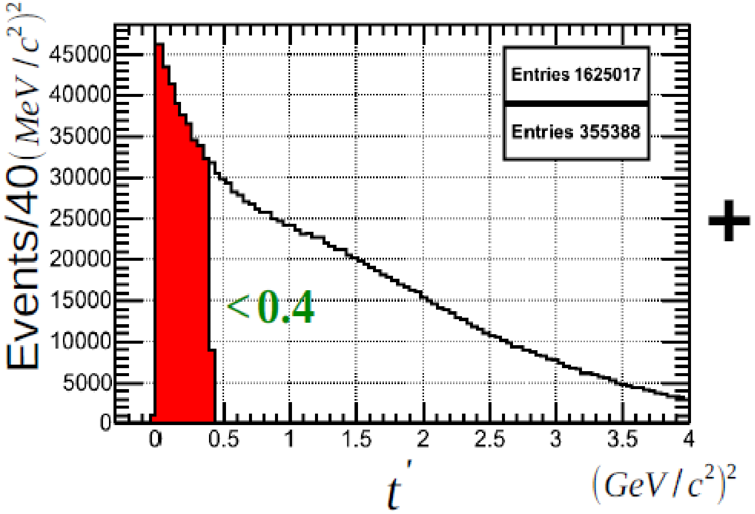


Signal Δ^{++}

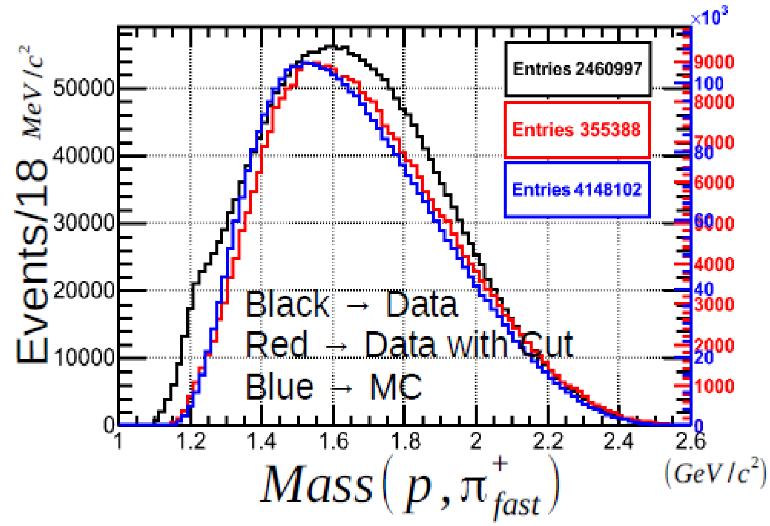


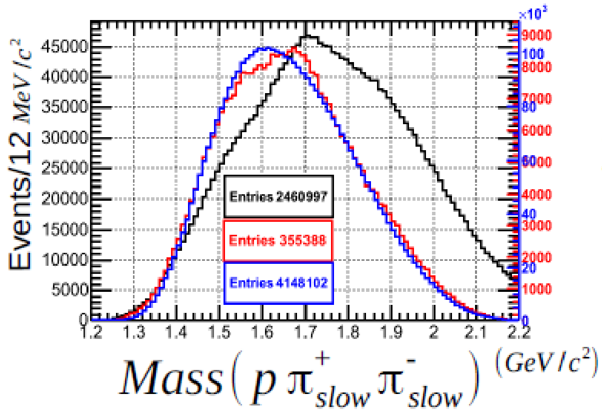
Data Selection & Background Reduction

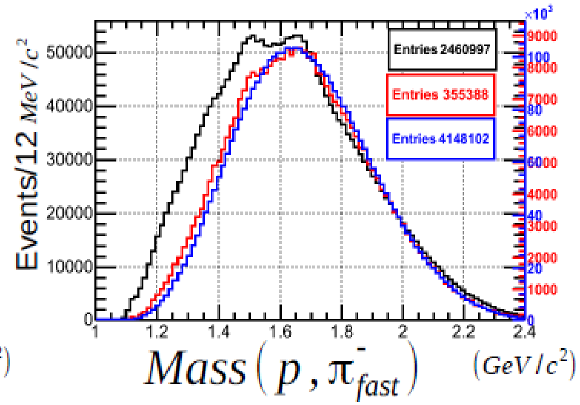
$$\gamma\, p \rightarrow \Delta^{++} \pi^{+} \pi^{-} \pi^{-}$$

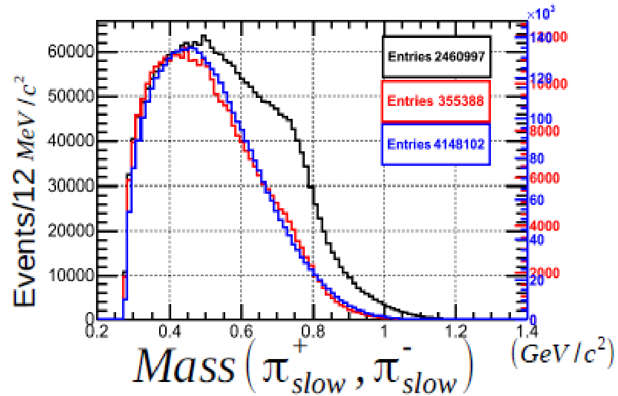


$$+ M_{p\pi^{+}_{slow}} < 1.35$$







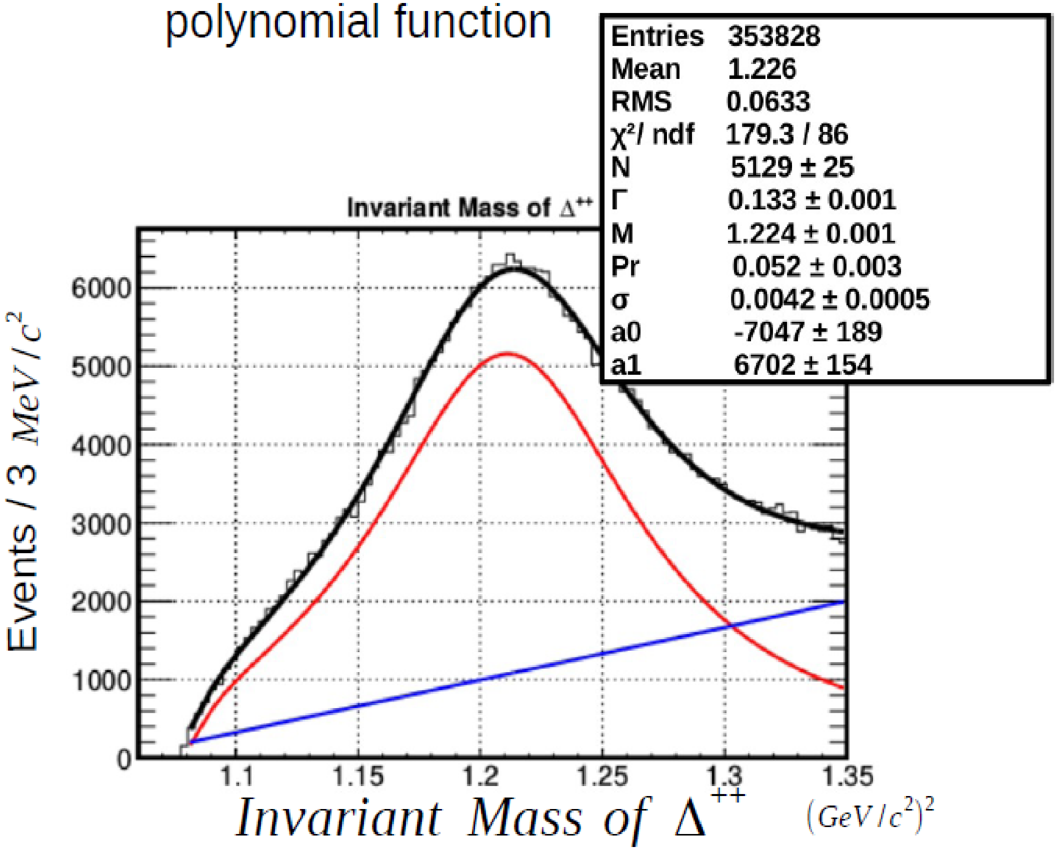


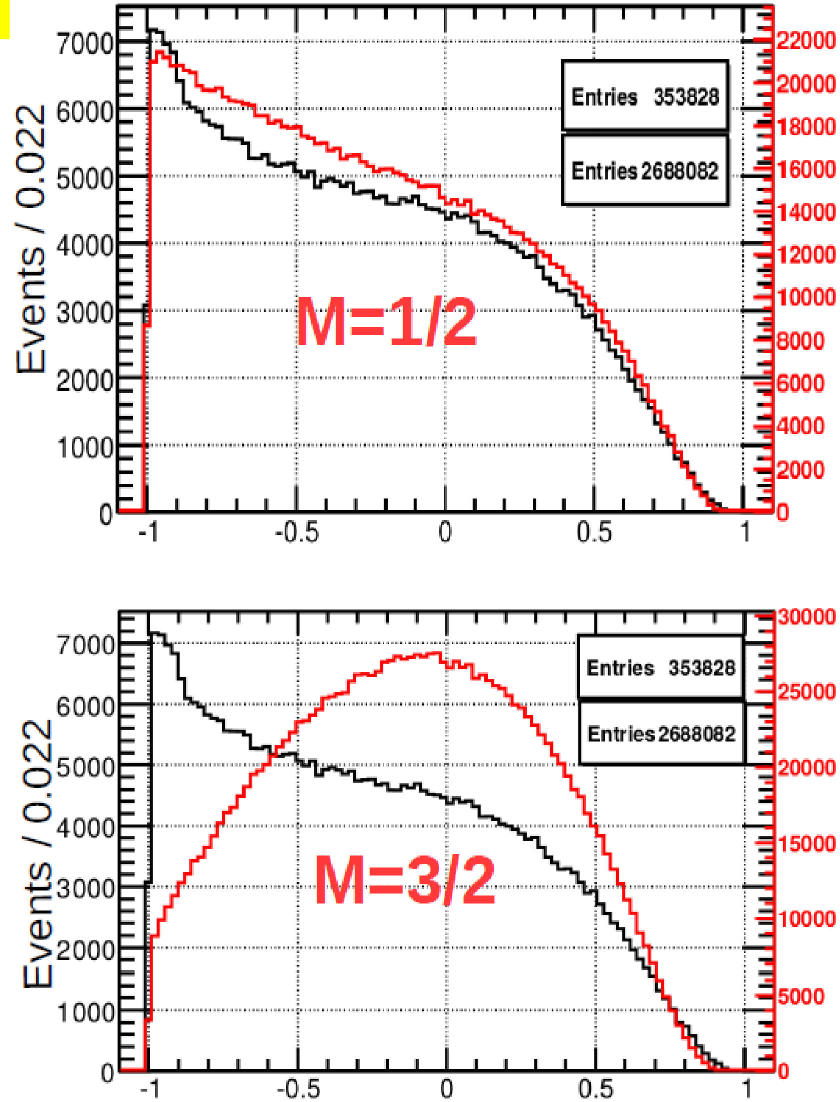
Black → Data
Red → Data with Cuts
Blue → MC with Cuts

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

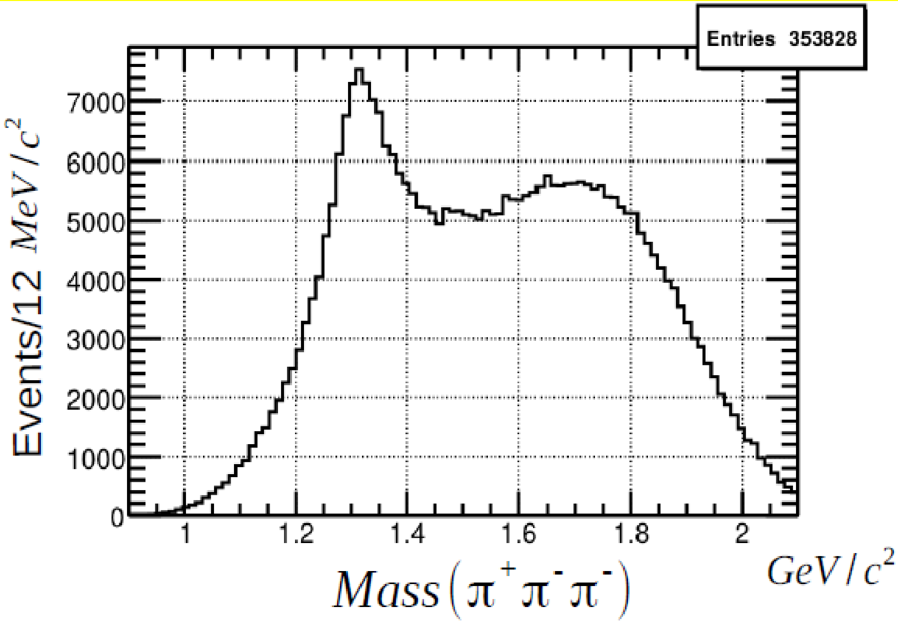


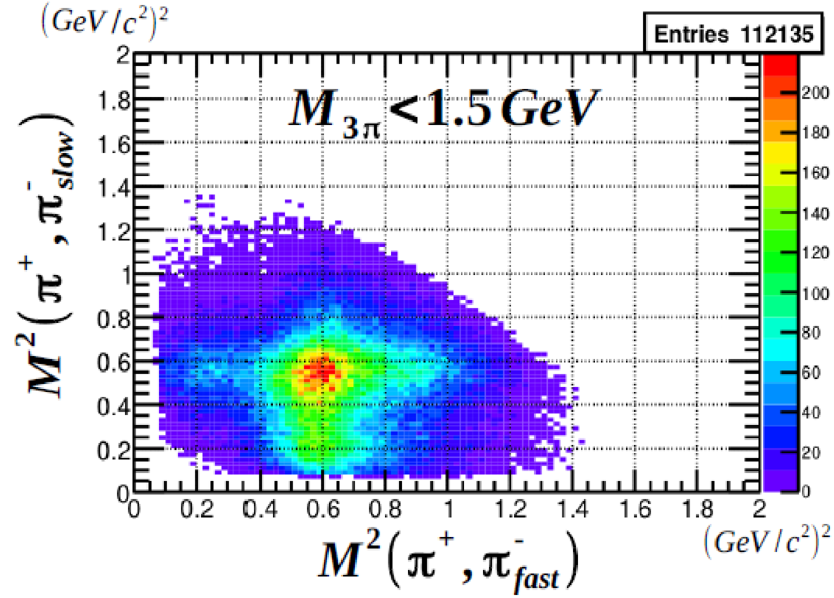


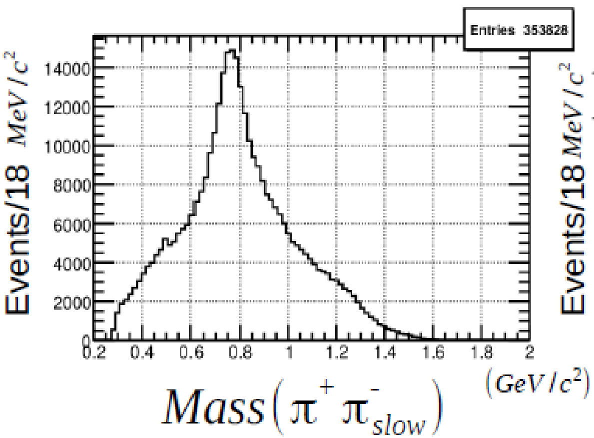
cos θ in the Δ++ rest frame for data and accepted MC weighted by Δ++ amplitudes

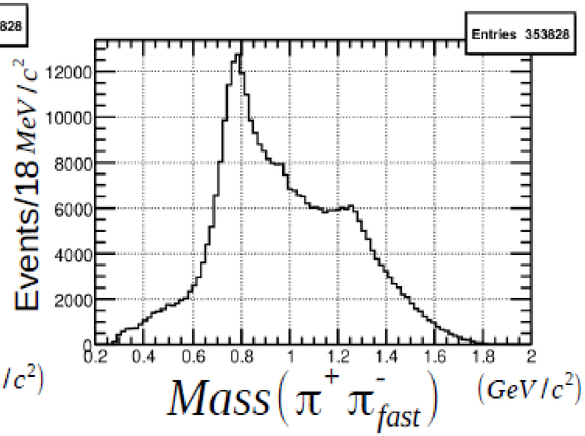
Features of the 3π sample

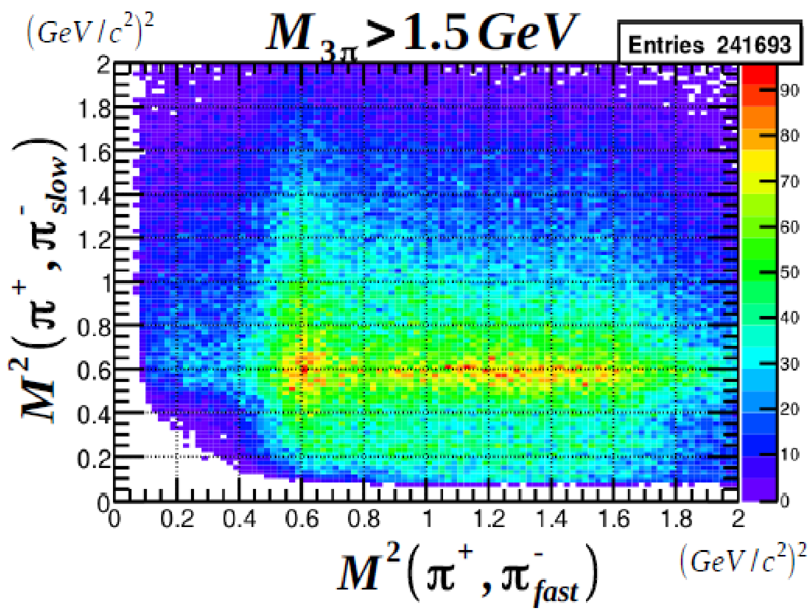
$\gamma\, p \rightarrow \Delta^{++} \pi^{+} \pi^{-} \pi^{-}$





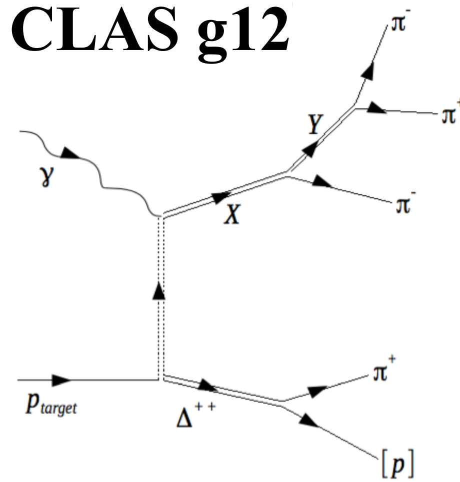


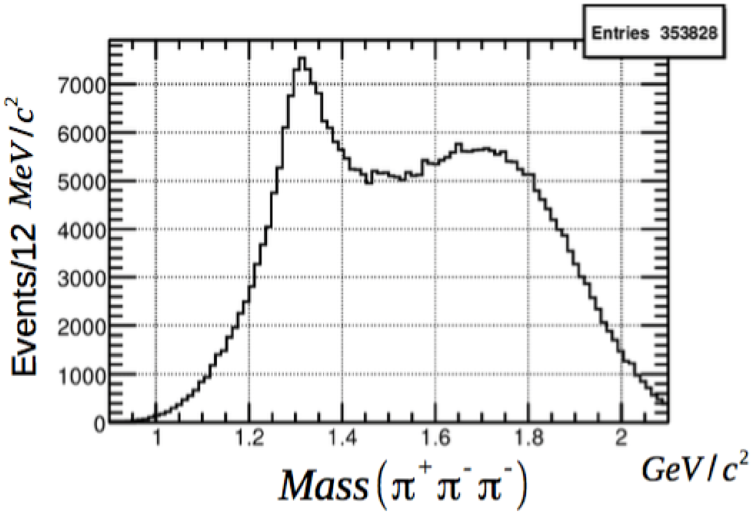


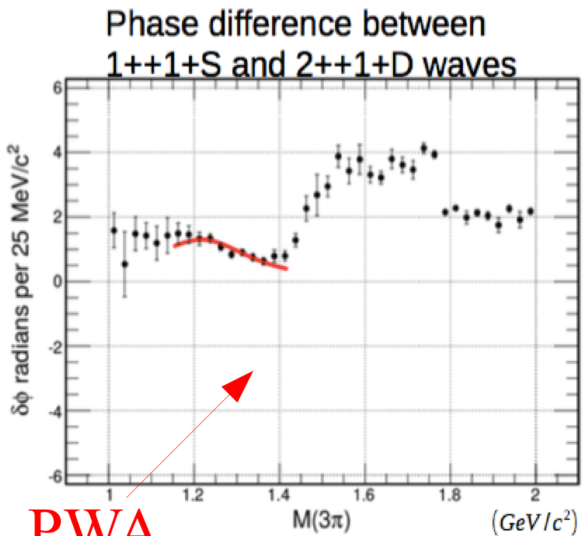


PWA Results: $\Delta^{++}\ \pi^+\pi^-\pi^-$

CLAS g12



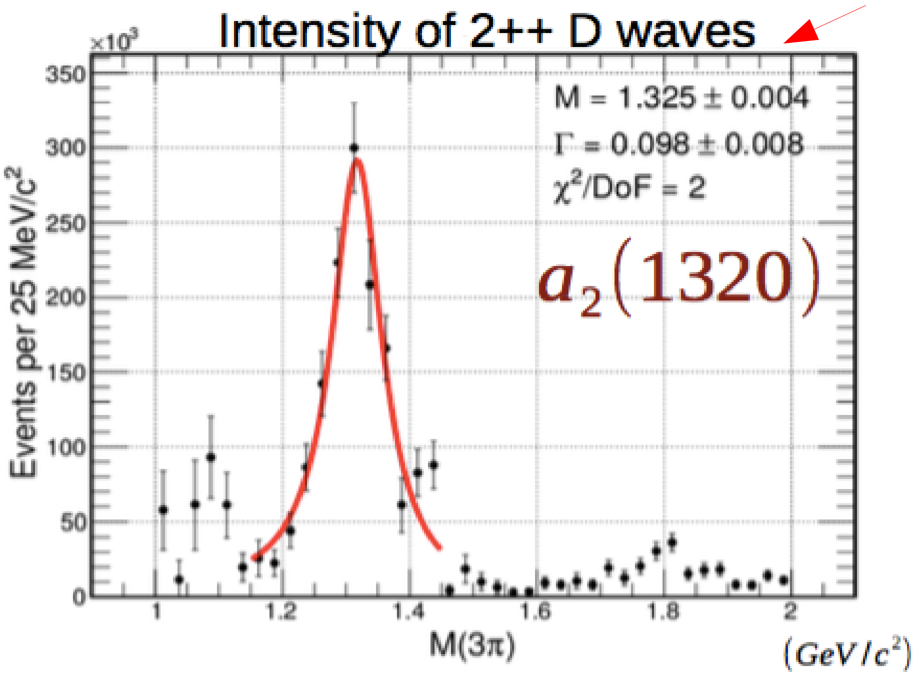


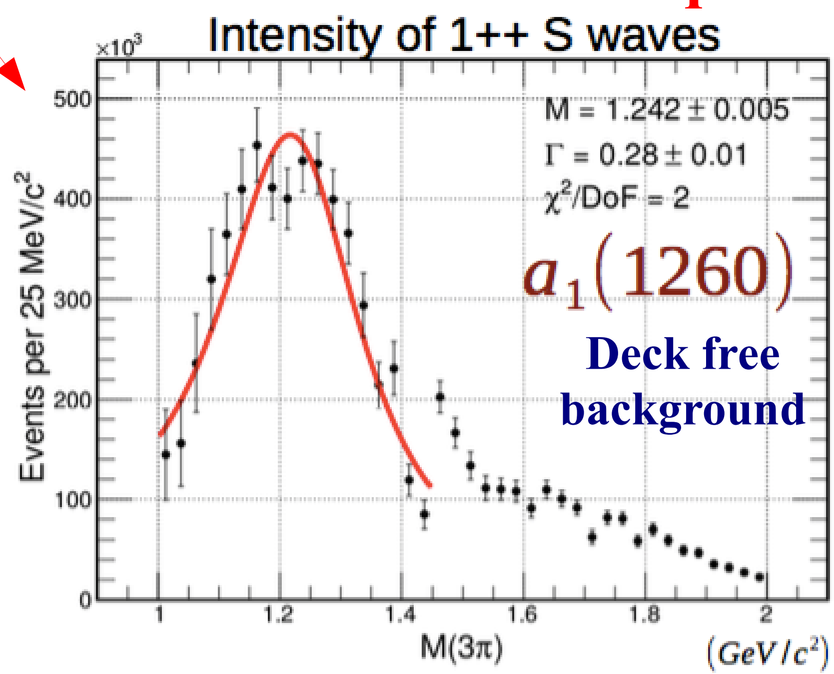


Confirmation of the $a_1(1260)$ in photoproduction

PWA

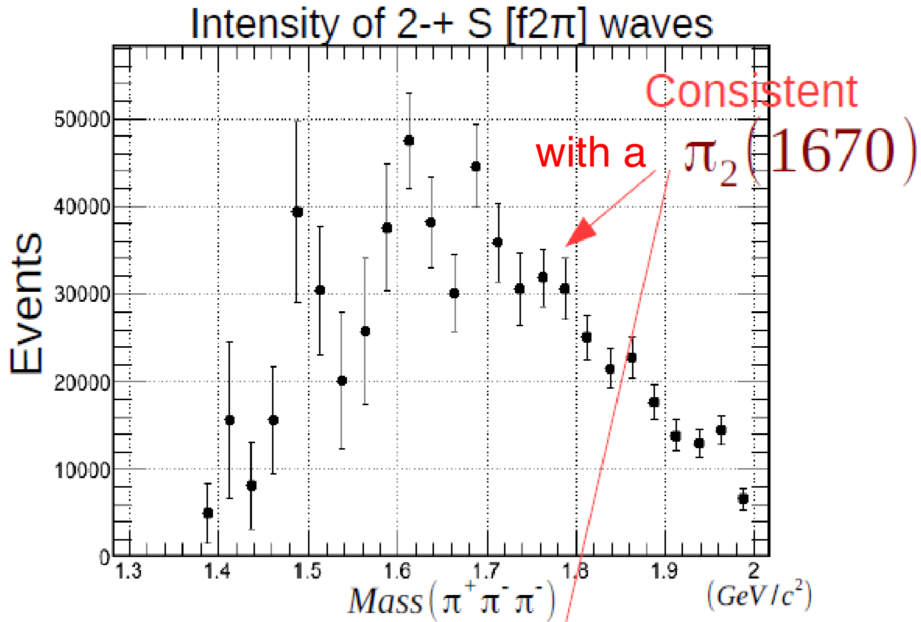
1^{-+} exotic wave was not required





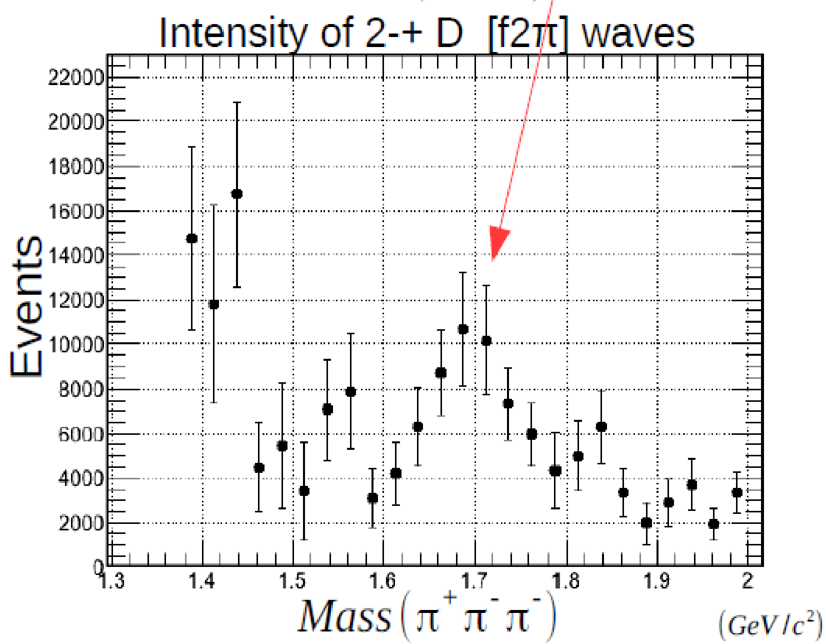
Features of the PWA

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

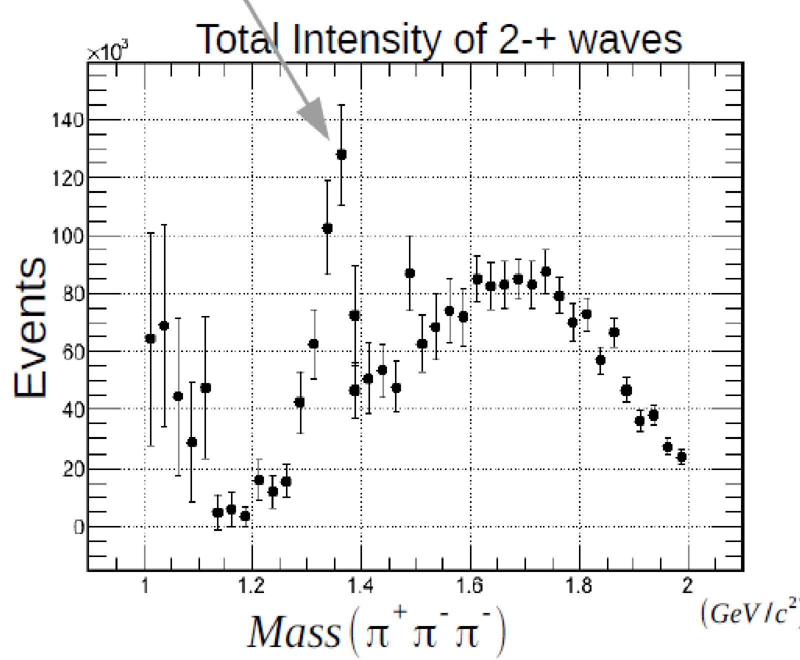


PWA in the high mass region:

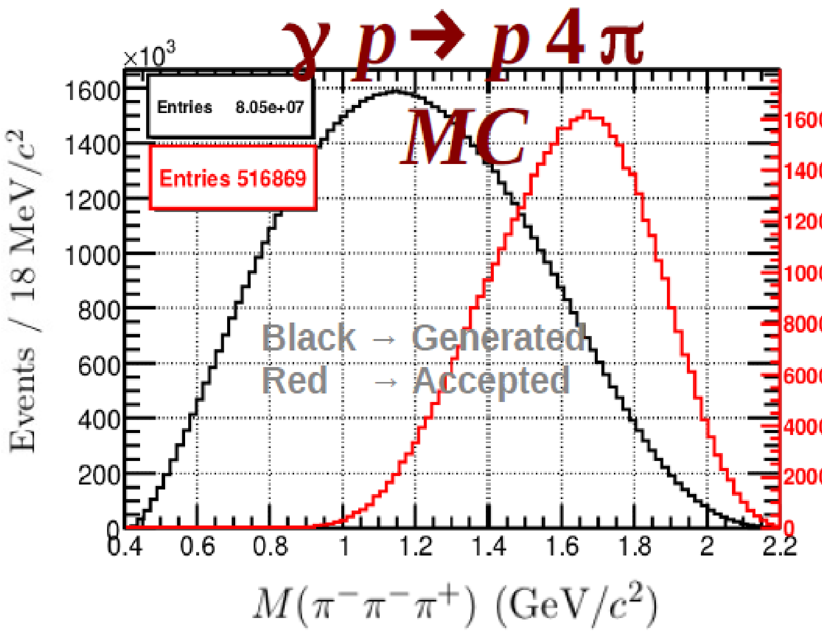
- ➔ was more challenging
- ➔ results were less stable here
- ➔ further investigation in this region shows that this channel suffers from background

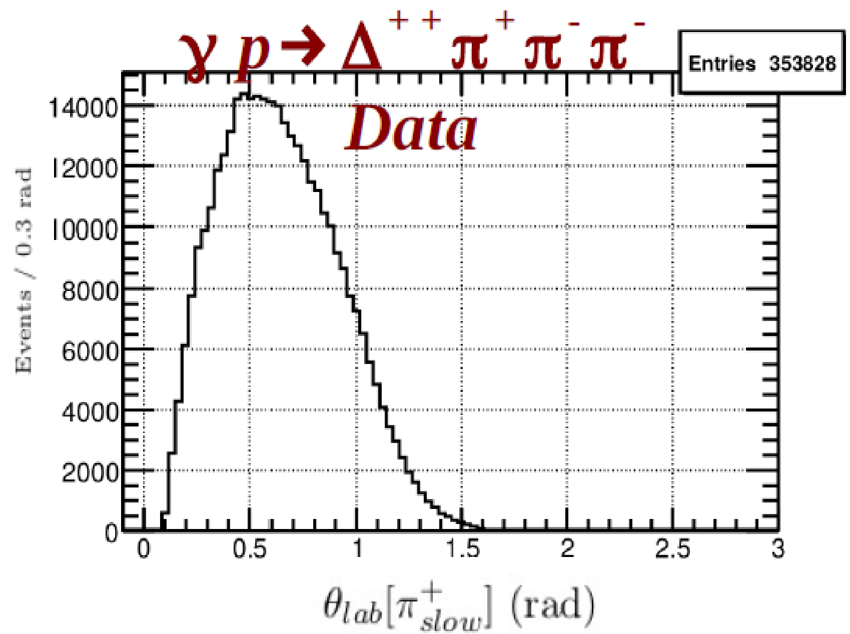


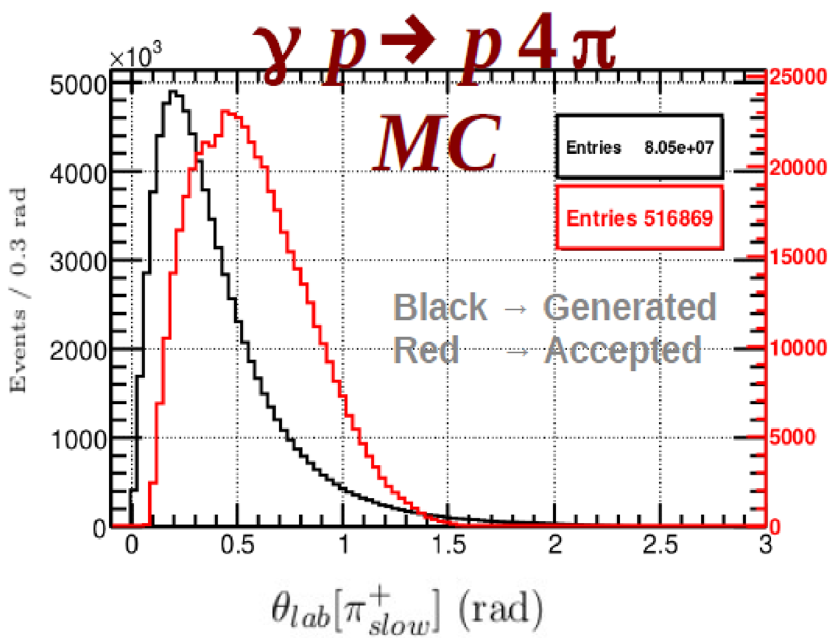
leakage of $a_2(1320)$ into the P-wave

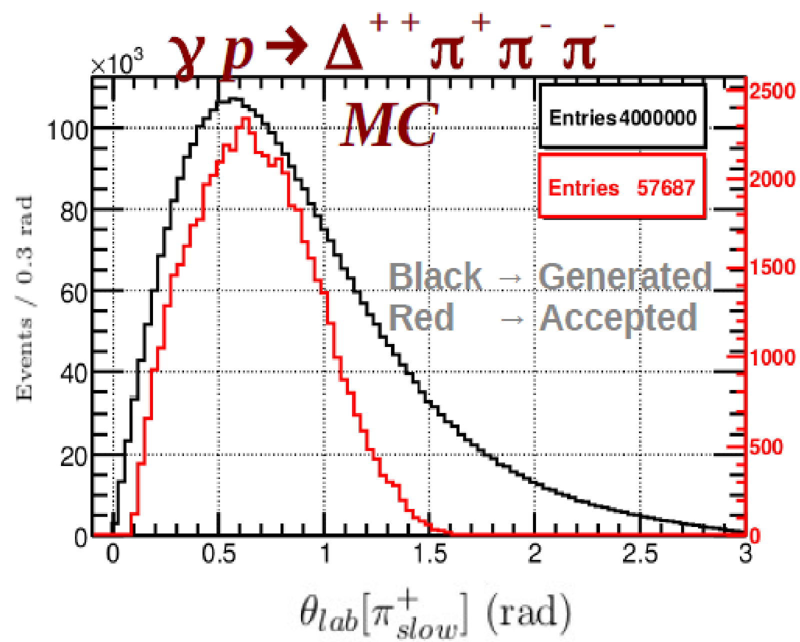


Investigating the high 3π mass region







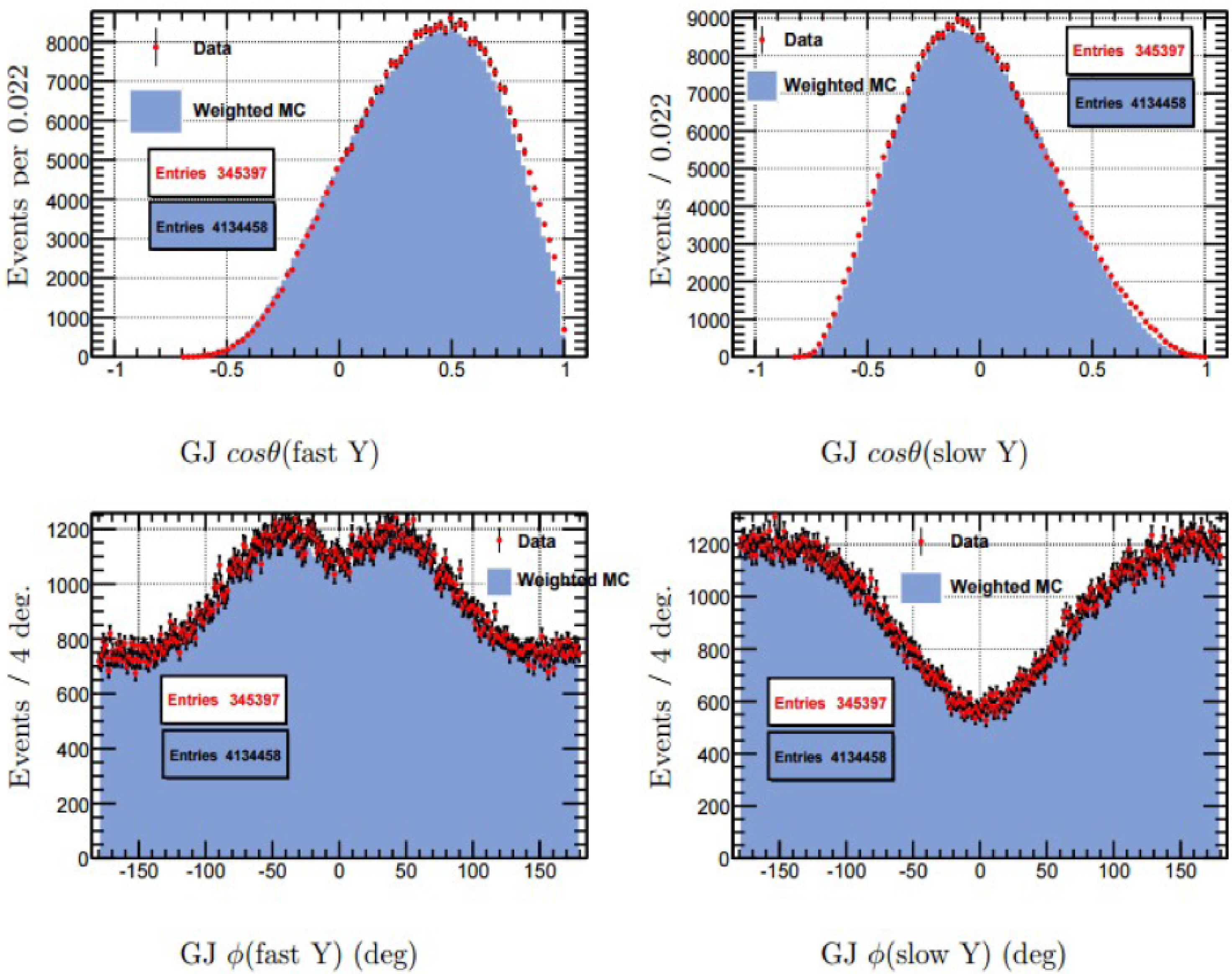


Summary & Plans

- $\gamma p \rightarrow n\pi^+\pi^+\pi^-$:
  - 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
- Analysis Review is underway :
  - written draft PRL for n3π
  - writing longer paper to include details of n3p and $\Delta^{++}3\pi$

PWA Predicted Distributions

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



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

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

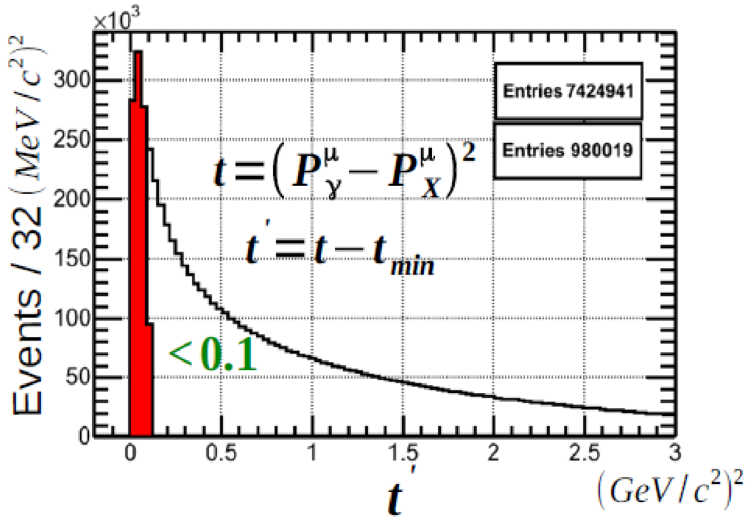
J^{PC}	M^{ϵ}	L	Y	Number of waves
1^{++}	$1^{-/+}$	S, D	$\rho(770)$	4
2^{++}	$1^{-/+}$	D	$\rho(770)$	2
2^{-+}	$1^{-/+}$	P	$\rho(770)$	2
Isotropic Background Wave				

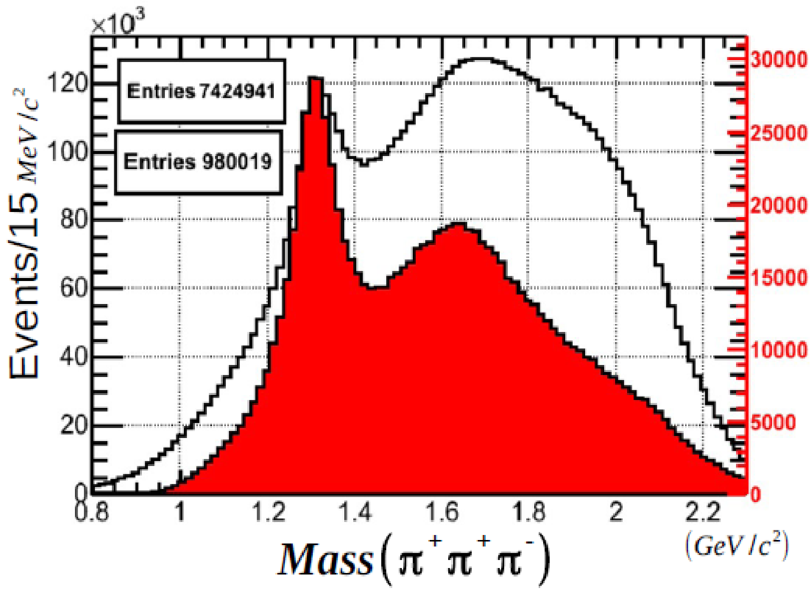
$M_{3\pi} > 1.375\, GeV$

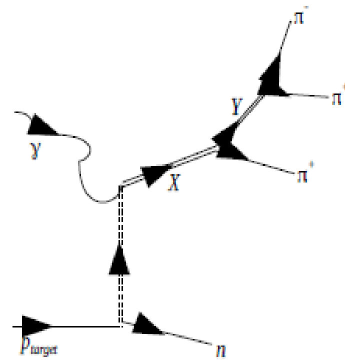
J^{PC}	M^{ϵ}	L	Y	Number of waves
1^{++}	$1^{-/+}$	S, D	$\rho(770)$	4
2^{++}	$1^{-/+}$	D	$\rho(770)$	2
2^{-+}	$1^{-/+}$	S, P, D	$\rho(770), f_2(1270)$	6
Isotropic Background Wave				

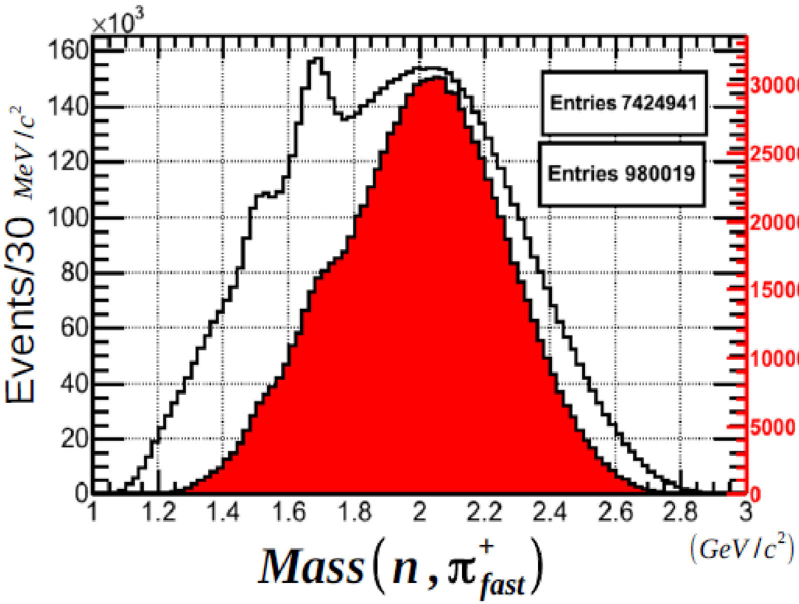
Enhance Peripheral Production

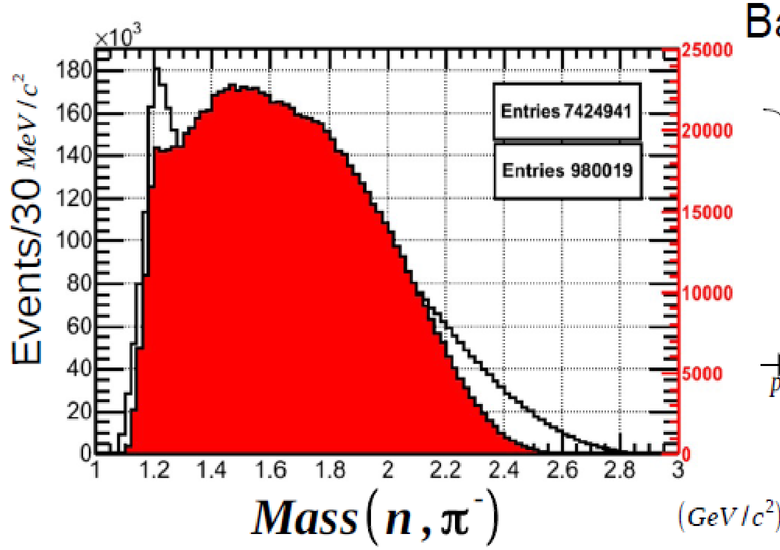
$\gamma p \rightarrow n \pi^{+} \pi^{+} \pi^{-}$



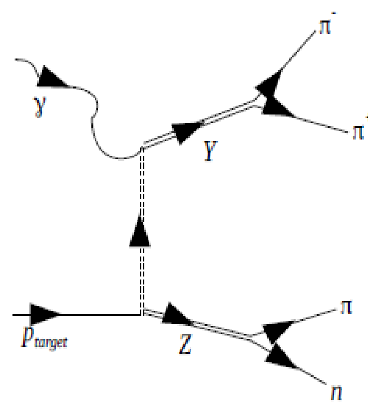








Background sources



Further Reducing the Baryon Background

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

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