# The Search for Exotic Mesons in Photoproduction

Diane Schott

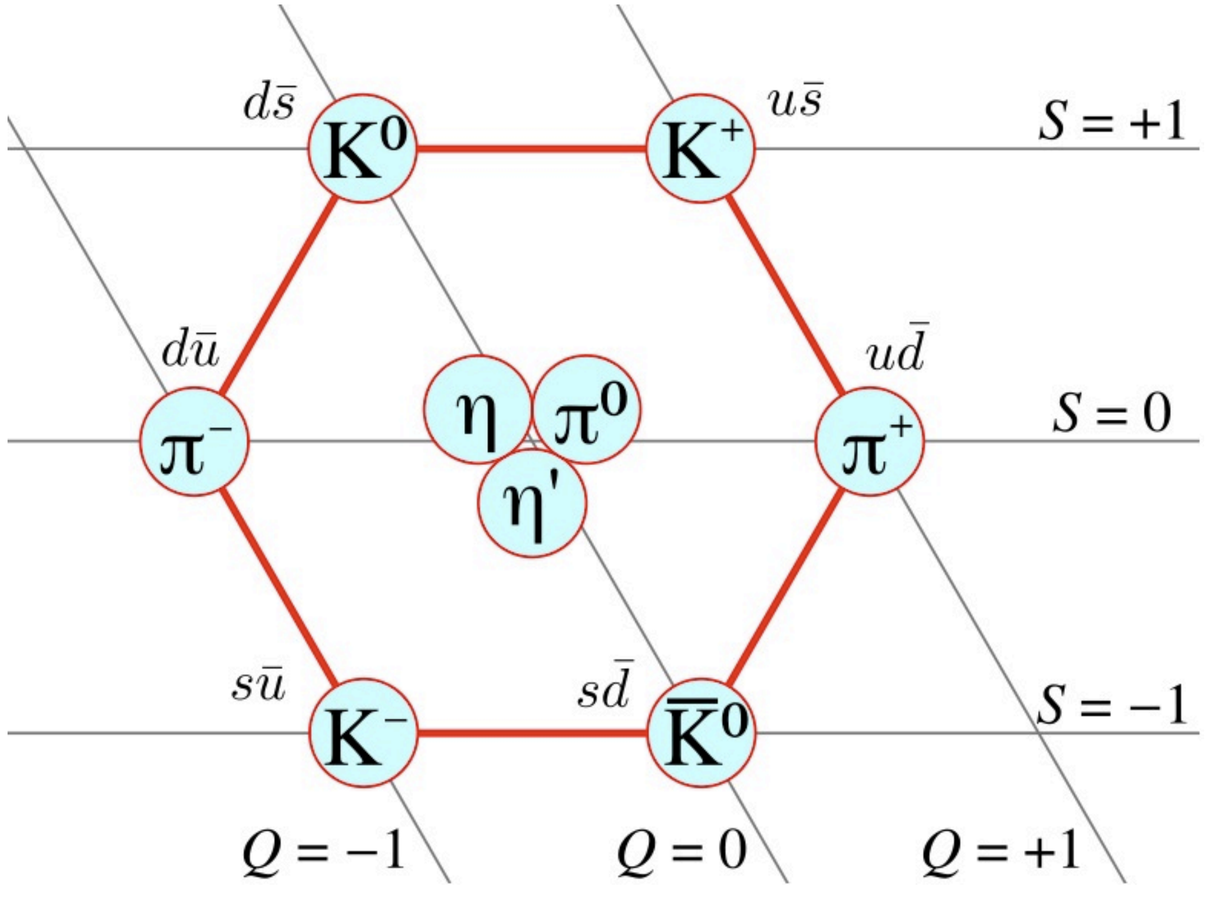

# Purpose

- The constituent quark model gives initial set of mesons formed by qq̄ pairs.

- It is described by simplest QCD bound state.

- QCD allows for additional states known as exotics: qq̄g, qq̄qq̄, ggg, ...

- Production of exotics is fundamental to low-energy QCD.



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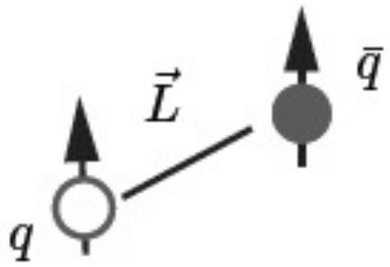



$$\vec{J} = \vec{L} + \vec{S}$$
$$P = (-1)^{L+1}$$
$$C = (-1)^{L+S}$$

- Constituent Quark Model accounts for $q\bar{q}$ pairs.
- Allowed states: $J^{PC} = 0^{++}, 0^{-+}, 1^{++}, 1^{+-}, 2^{++}, 2^{-+}$ ...
- Forbidden states: $J^{PC} = 0^{--}, 0^{+-}, 1^{-+}, 1^{--}, 2^{+-}, ...$


Normal baryon


Normal meson


Pentaquark


Tetraquark


Glueball


Hybrid meson

# Partial Wave Analysis

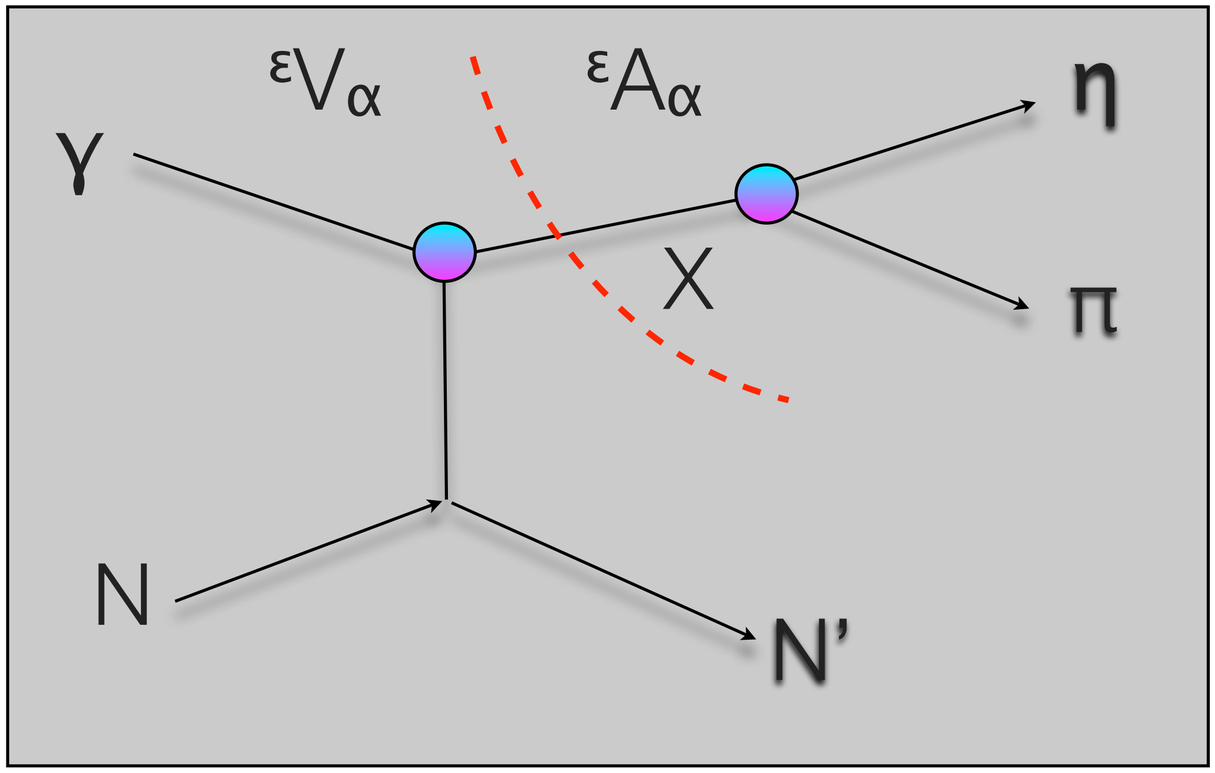
- Maximum Likelihood fit of the intensity:

- $$I(\tau) = \sum_{\epsilon} \sum_{\alpha,\alpha'} \rho_{\gamma}\ {}^{\epsilon}V_{\alpha}\ {}^{\epsilon}A_{\alpha}\ {}^{\epsilon}V_{\alpha'}\ {}^{\epsilon}A_{\alpha'}$$

- α is the set {J, P, |M|, L, I, λ, S} used to describe the resonance X.

- ε is the reflectivity is + or - and is related to the sign of M, where M is the projection of J in z direction.

$${}^{\epsilon}A_{\alpha} = \Theta(M)(A_{\alpha}^{M} - \epsilon P(-1)^{J-M} A_{\alpha}^{-M})$$

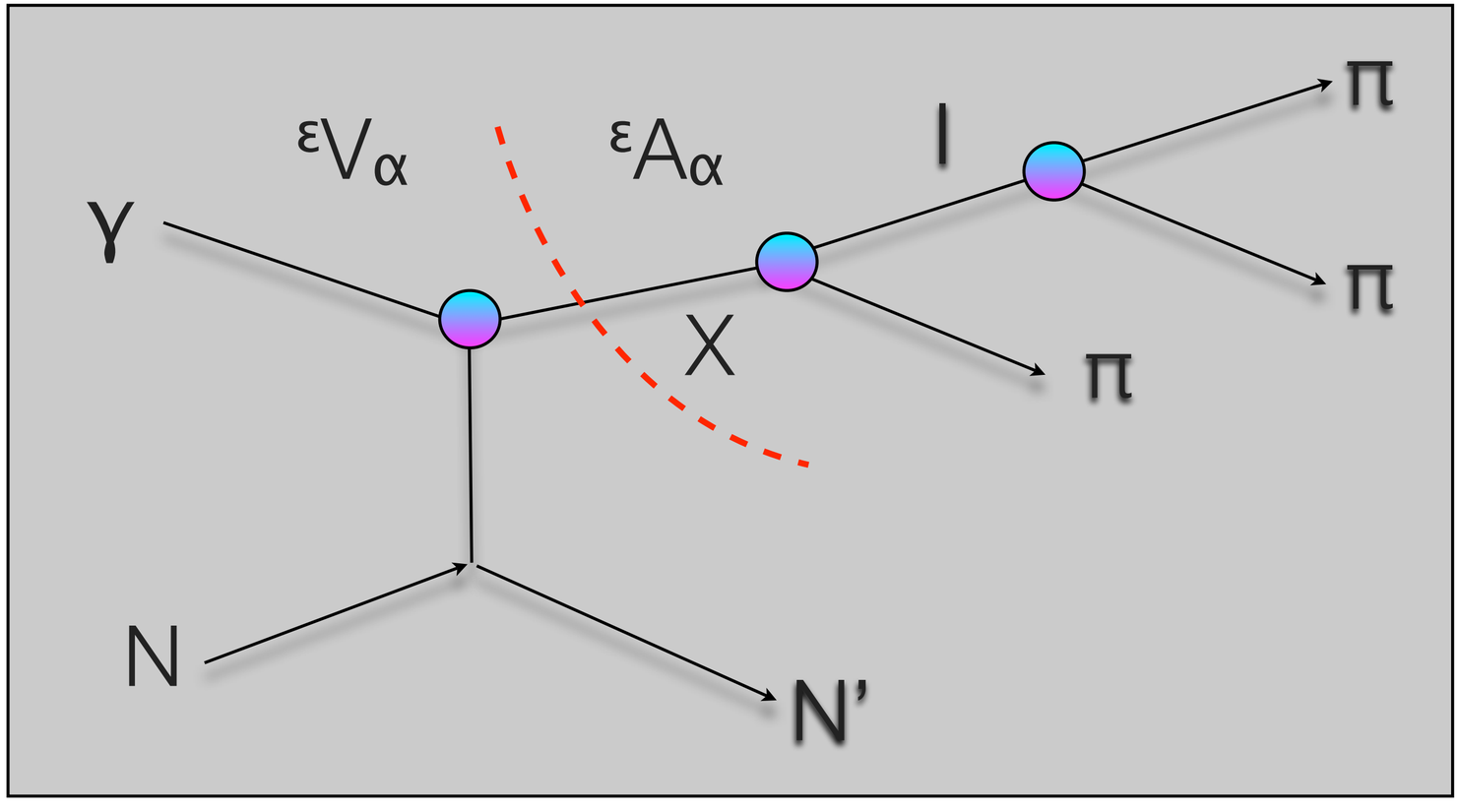


# Partial Wave Analysis

- The reaction is a series of 2 body reactions with no re-scattering.

- Decays resulting in more than 2 final states are expressed as a series of 2 body decays

  - $^{\varepsilon}A_{\alpha} = {}^{\varepsilon}A_{\alpha}(X \rightarrow I\pi)\, {}^{\varepsilon}A_{\alpha}(I \rightarrow \pi\pi)$



# PWA: Quantities of Interest

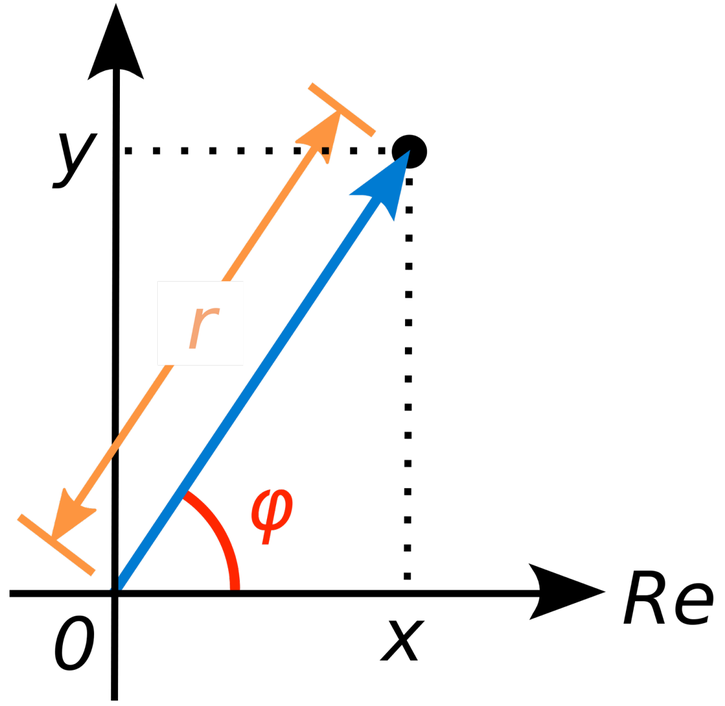
- From the PWA we get a set of complex $^{\epsilon}V_{\alpha}$ and have the normalization integral.

  - From this the yield (N) can be calculated for a given wave or wave set.

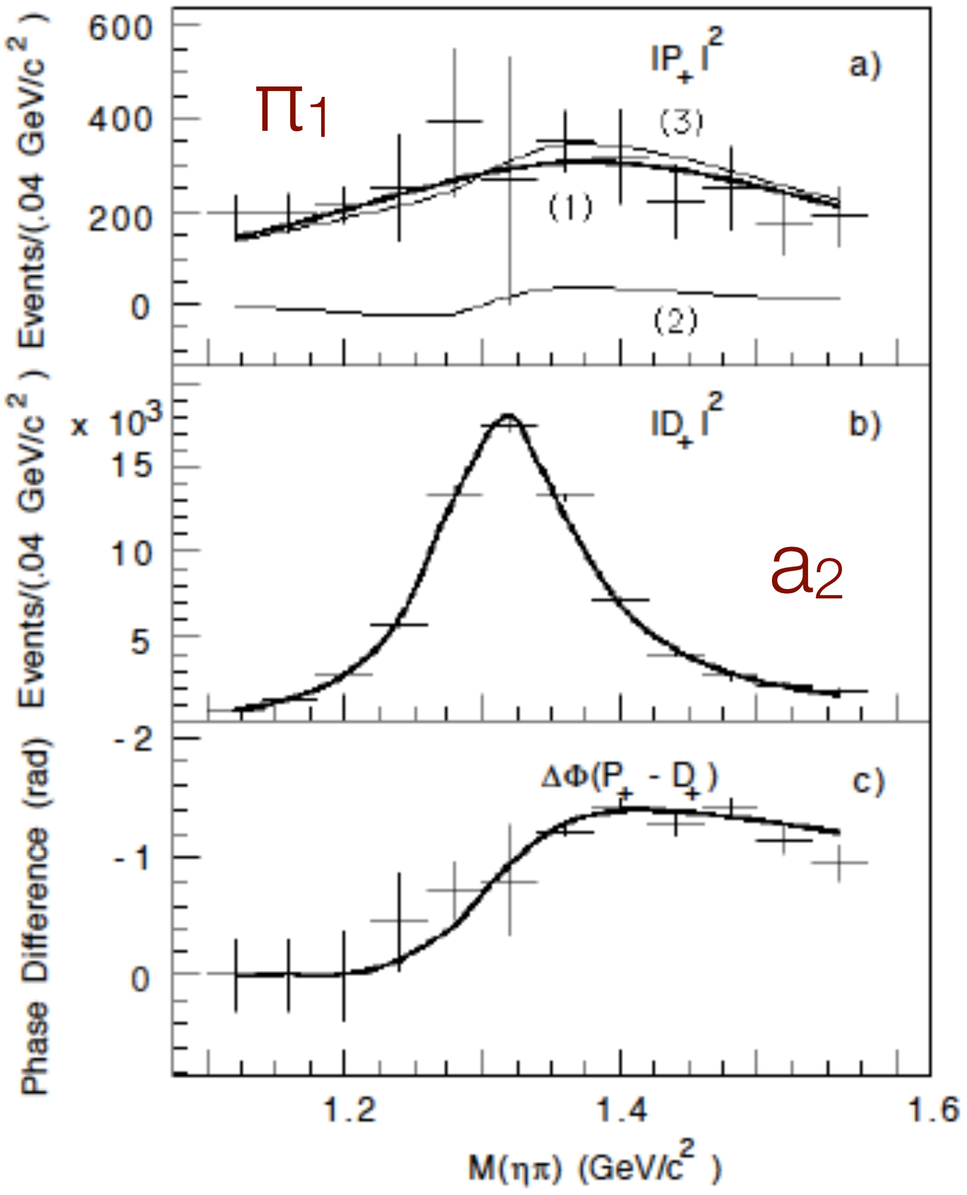
    - Phase differences will show interferences between 2 waves with no dependence on the strength of the waves.

$$N = N_0 \frac{N_r}{N_\eta} \sum_{\epsilon,\alpha,\alpha'} {}^{\epsilon}V_{\alpha}\ {}^{\epsilon}V^{*}_{\alpha'}\ {}^{\epsilon}\Phi^{\eta}_{\alpha\alpha'}$$

$$\tan(\Delta\Phi) = \frac{Im(\ {}^{\epsilon}V_{\alpha}\ {}^{\epsilon}V^{*}_{\alpha'})}{Re(\ {}^{\epsilon}V_{\alpha}\ {}^{\epsilon}V^{*}_{\alpha'})}$$



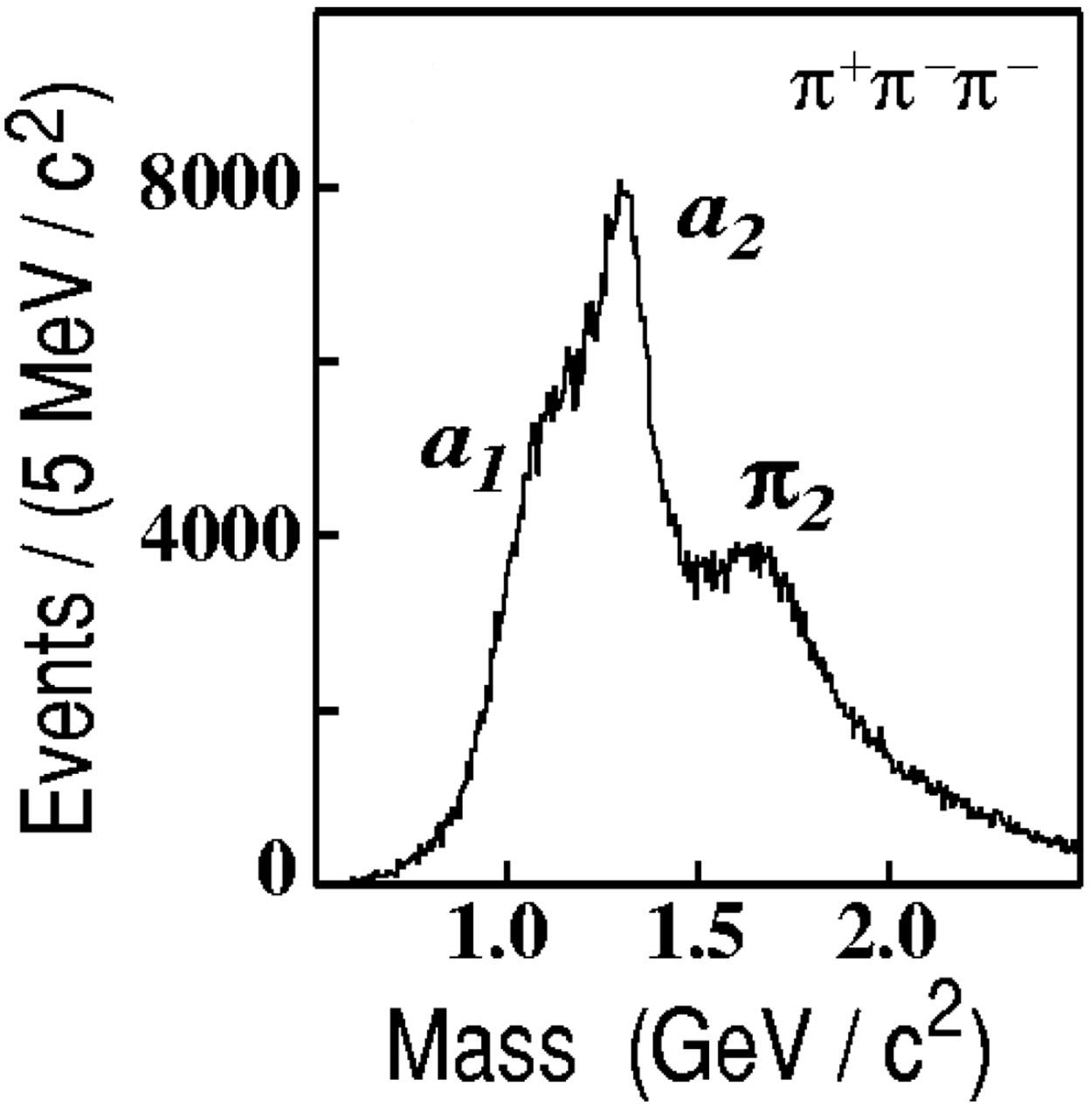
# Previous Results: $\pi_1(1400)$




- At Brookhaven, E852 collaboration:
  - $\pi^- p \rightarrow \pi^- \eta p$ (18.3 GeV)
  - M = 1370 ±16 MeV
  - Γ = 385 ± 40 MeV
- Published a mass and width of the $\pi_1(1400)$.
- This was followed by the $\eta\pi^0$ analysis but no consistent set of amplitude parameters were found.

# Previous Results: $\pi_1(1600)$

- At Brookhaven, E852 collaboration:
  - $\pi^- p \rightarrow \rho \pi^- p$ (18.3 GeV)
  - M = 1593 ±8 MeV
  - $\Gamma$ = 168 ± 20 MeV
- Published a mass and width of the $\pi_1(1600)$.



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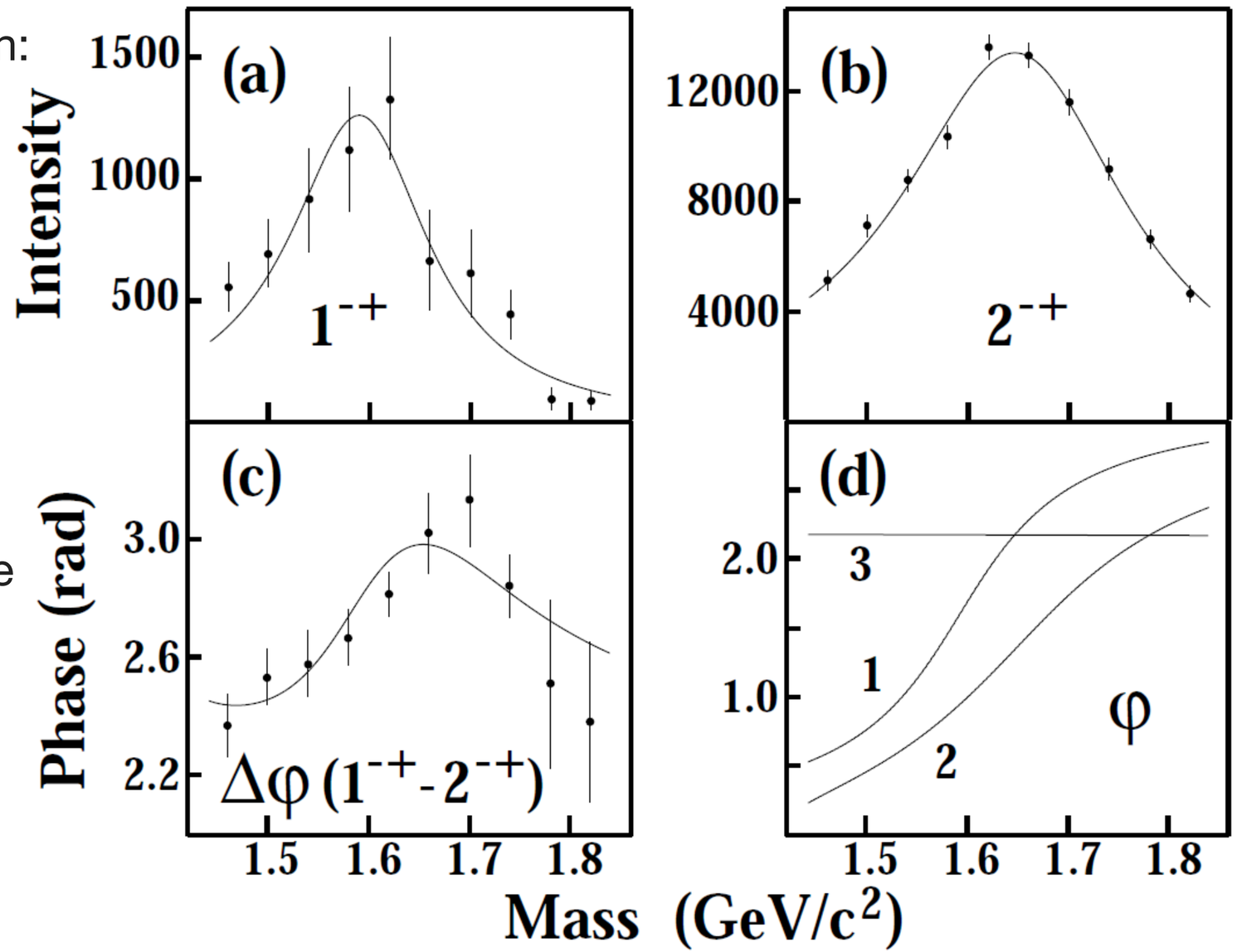


# Previous Results: Summary

| State | Reaction | Mass (MeV) | Width (MeV) |
|---|---|---|---|
| $\pi_1(1400)$ | $\pi^- p \to \eta\pi^- p$ | $1370 \pm 16^{+50}_{-30}$ | $385 \pm 40^{+65}_{-105}$ |
| | $\pi^- p \to \eta\pi^0 n$ | $1406 \pm 20$ | $180 \pm 20$ |
| | $\bar{p}n \to \eta\pi^0\pi^-$ | $1400 \pm 28$, | $310^{+71}_{-58}$ |
| | $\bar{p}p \to \eta\pi^0\pi^0$ | $1360 \pm 25$, | $220 \pm 90$ |
| $\pi_1(1600)$ | $\pi^- p \to \rho^0\pi^- p$ | $1593 \pm 8^{+29}_{-47}$ | $168 \pm 20^{+150}_{-12}$ |
| | $\pi^- p \to \rho^0\pi^- p$ | $1620 \pm 20$ | $240 \pm 50$ |
| | $\pi^- p \to \eta'\pi^- p$ | $1597 \pm 10^{+45}_{-10}$ | $340 \pm 40 \pm 50$ |
| | $\pi^- p \to [b_1(1235), \eta', \rho]\pi^- p$ | $1560 \pm 60$ | $340 \pm 50$ |

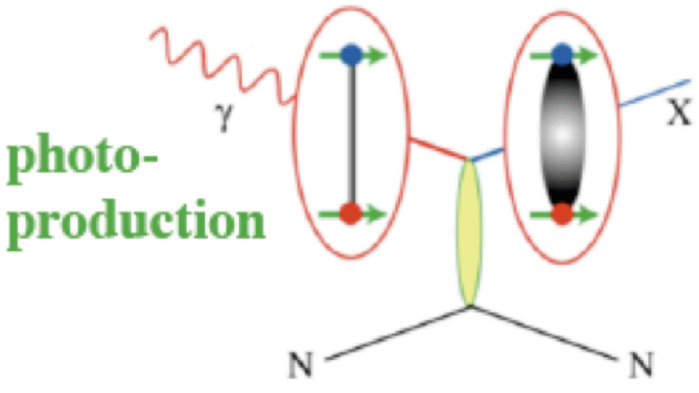
- Other states
  - $\pi_1(2000)$ seen in $b_1\pi$, $f_1\pi$

* C. Amsler. Mesons beyond the naive quark model. Physics Reports, 387:61–117, (2004).

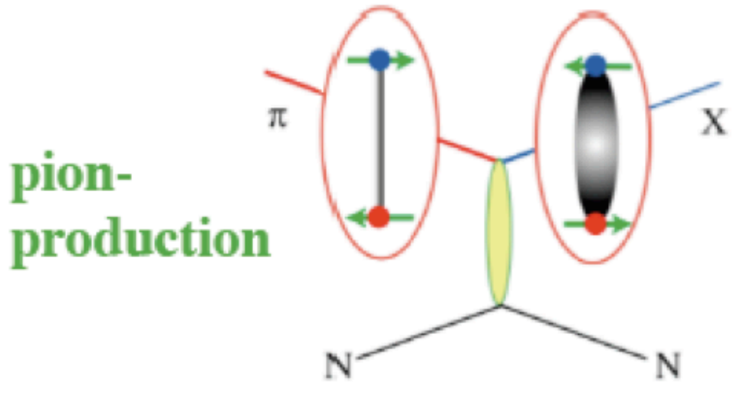
# Photoproduction

- Beams of photons may be a more natural way to create hybrid mesons.
- Simple QN counting leads to the exotic mesons

$$_{quarks}J^{PC} \otimes \ _{gluonic flux}J^{PC} = 0^{-+}, 1^{-+}, 2^{+-}, ...$$

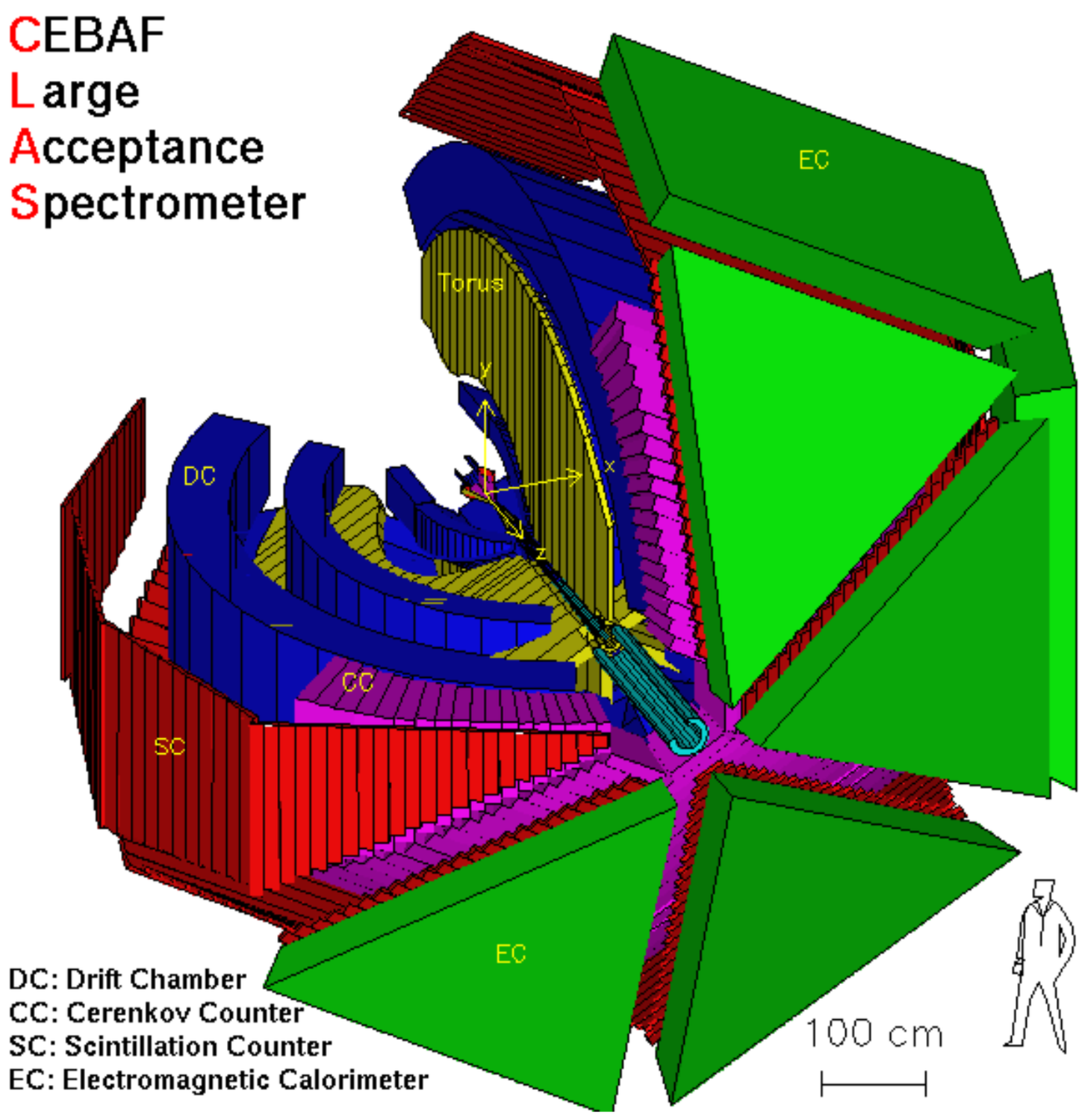



$$_{quarks}J^{PC} \otimes \ _{gluonic flux}J^{PC} = 1^{--}, 1^{++}$$



# g12

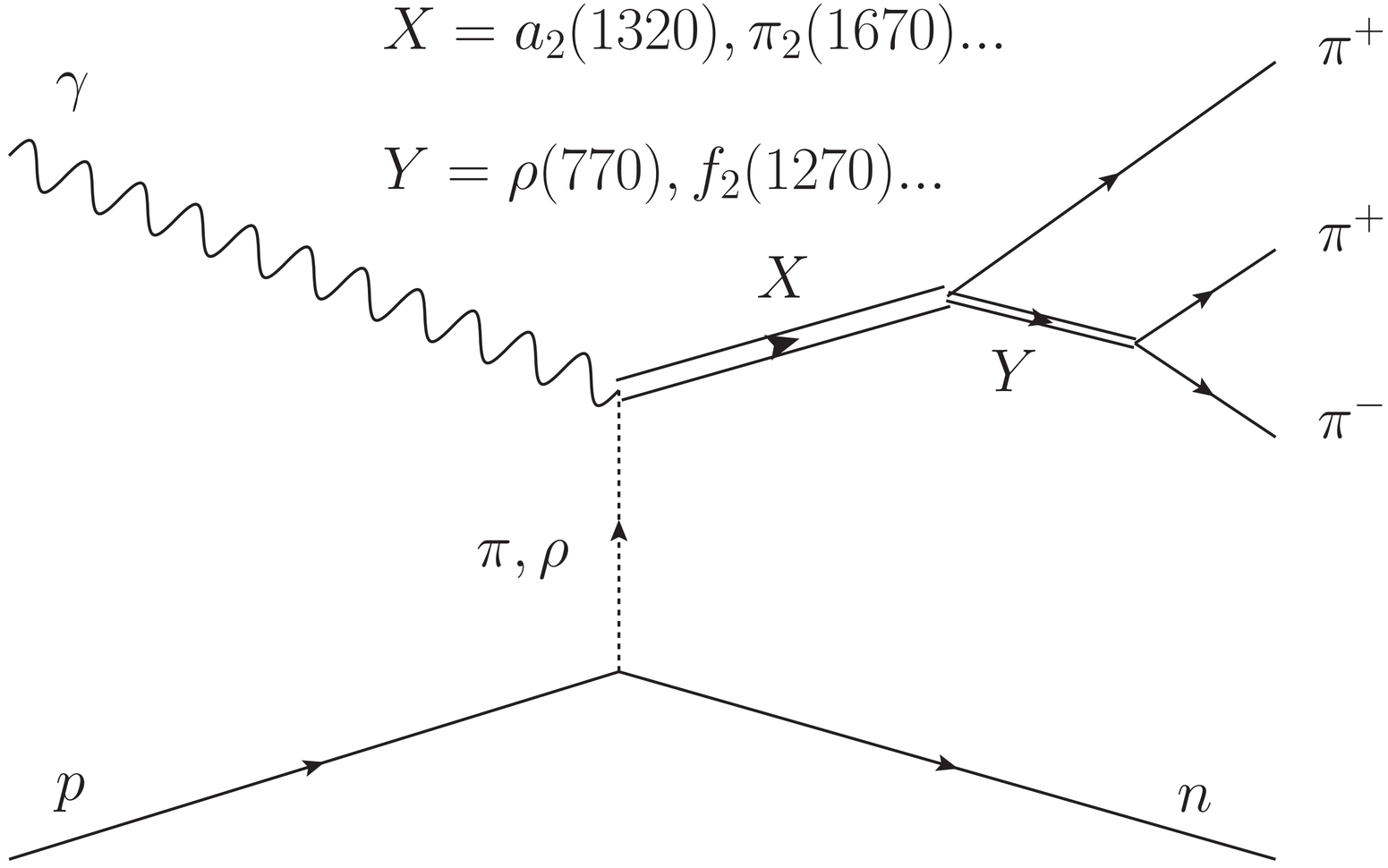
- Is a photoproduction experiment
- Ran in 2008 for 3 months
- A 5.7 GeV $e^-$ beam was used to get a maximum of 5.45 GeV photons.
- Triggers: 26 billion (68 $pb^{-1}$)



# PWA in G12

- Finished:
  - $\pi^+ \pi^+ \pi^-$ (by Craig Bookwalter)
  - $\eta\pi^-$ (by Diane Schott)
- Pending analysis:
  - $\pi^0 \pi^+ \pi^-$(by FSU)
  - $K^+K^-$ (by FSU and CNU)

# g12 - $\pi^+ \pi^+ \pi^-$

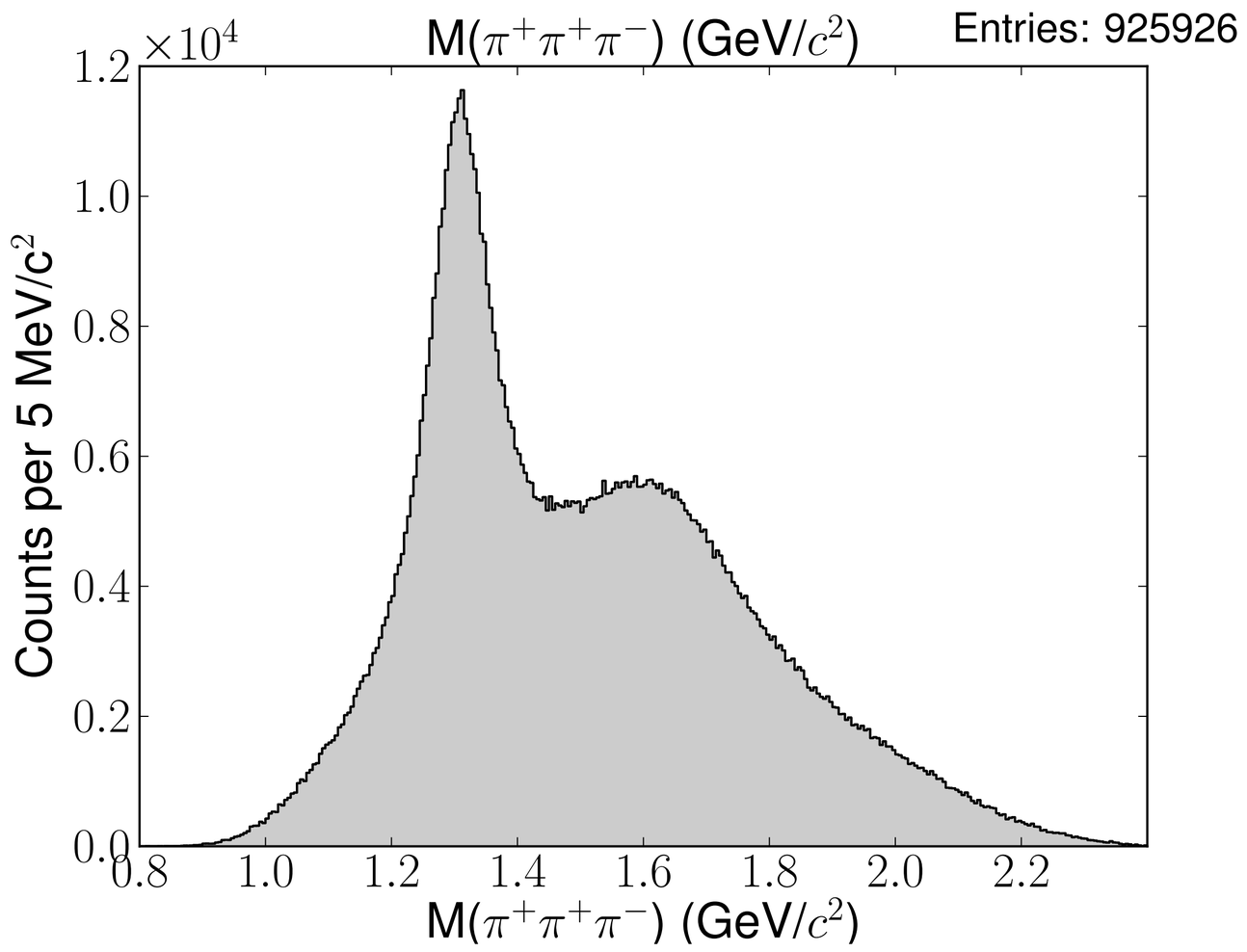


# PWA: Mass Independent Fit

- The allowed wave set is

**Major waves**

| $J^{PC}$ | $M^{\epsilon}$ | $L$ | $Y$ | # waves |
|---|---|---|---|---|
| $1^{++}$ | $1^{\pm}$ | $S$ | $\rho(770)$ | 2 |
| $1^{++}$ | $1^{\pm}, 0^{+}$ | $D$ | $\rho(770)$ | 3 |
| $1^{-+}$ | $0^{-}, 1^{\pm}$ | $P$ | $\rho(770)$ | 3 |
| $2^{++}$ | $1^{\pm}$ | $D$ | $\rho(770)$ | 2 |
| $2^{-+}$ | $0^{-}, 1^{\pm}$ | $S, P, D$ | $f_2(1270)$, $\rho(770)$ | 9 |



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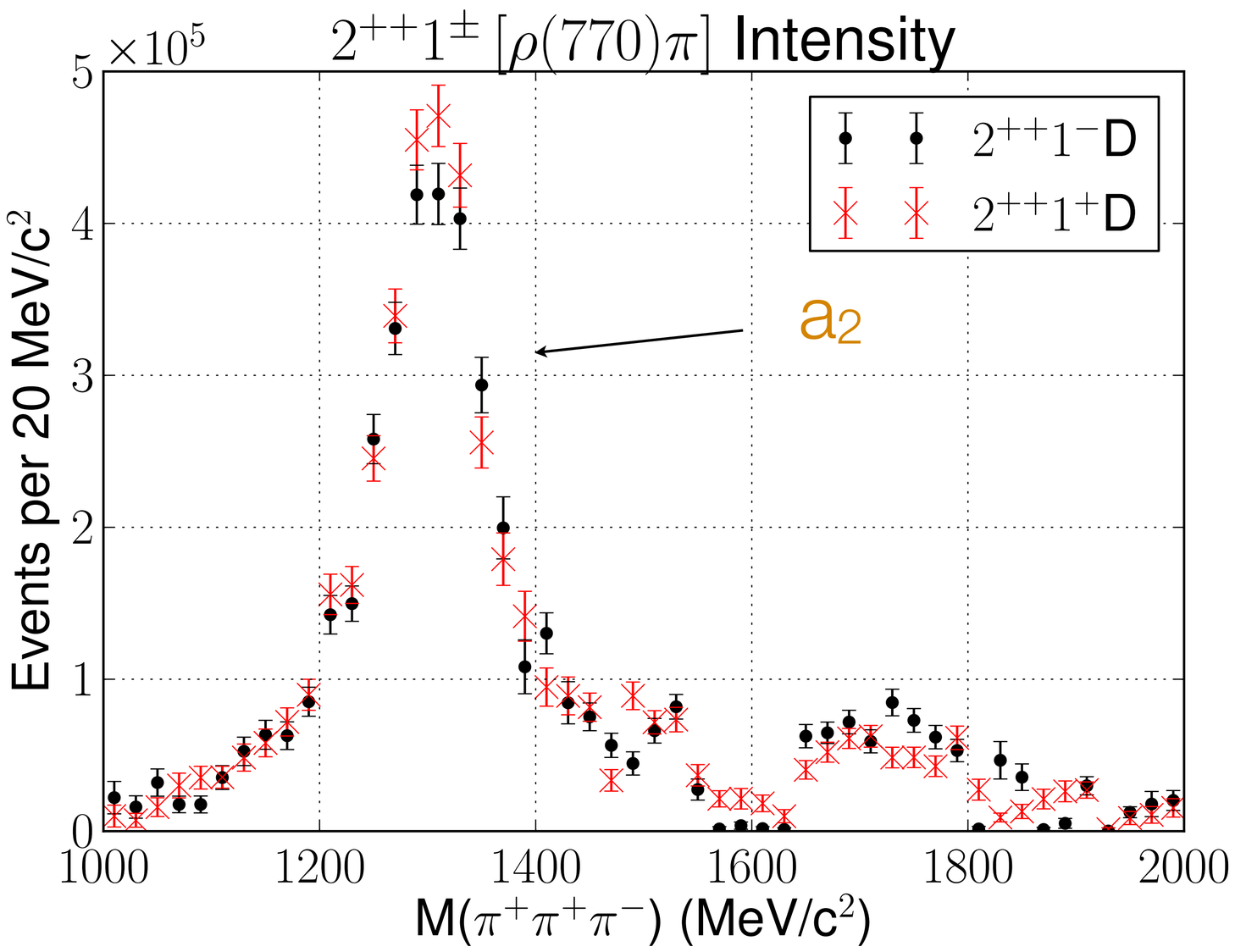

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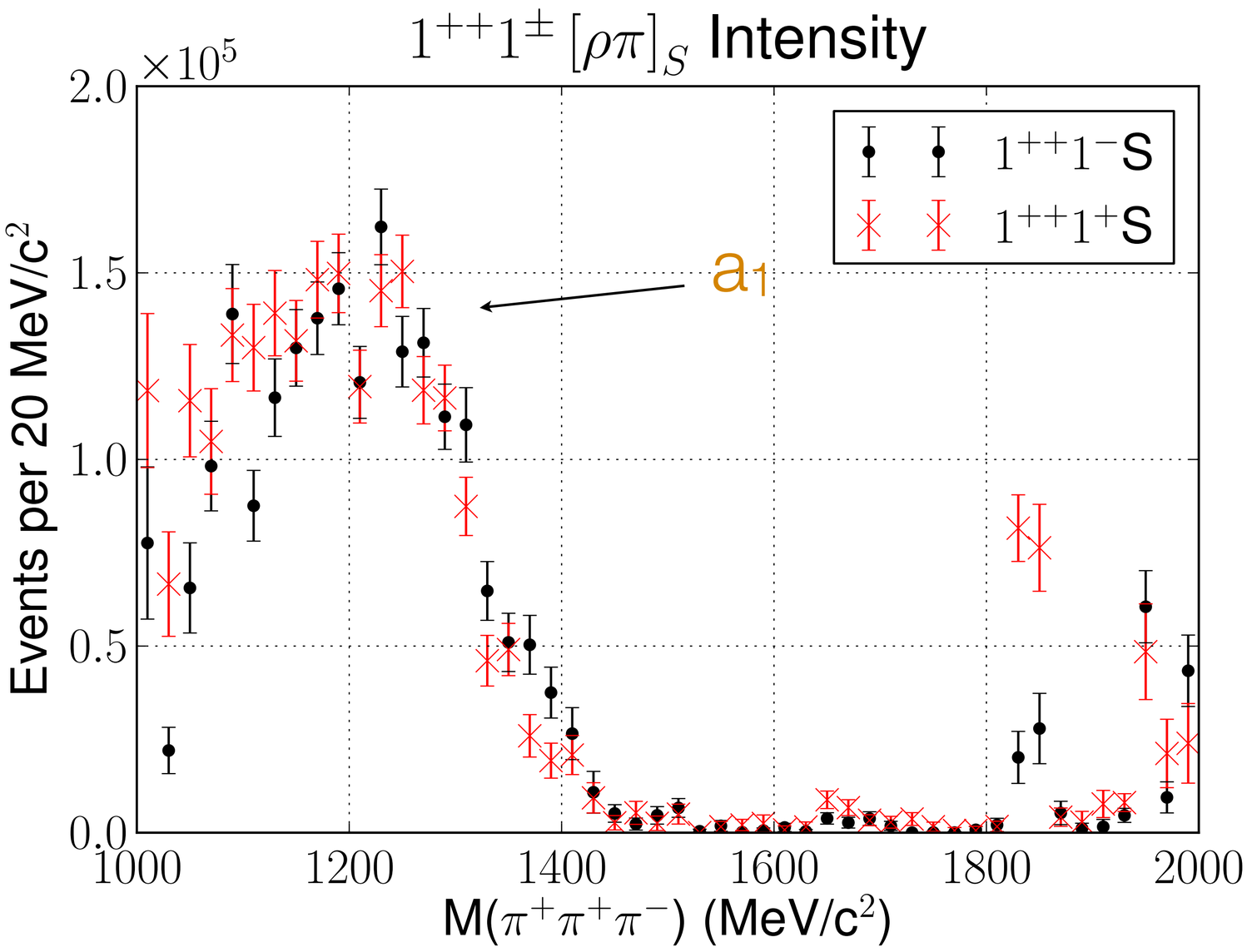
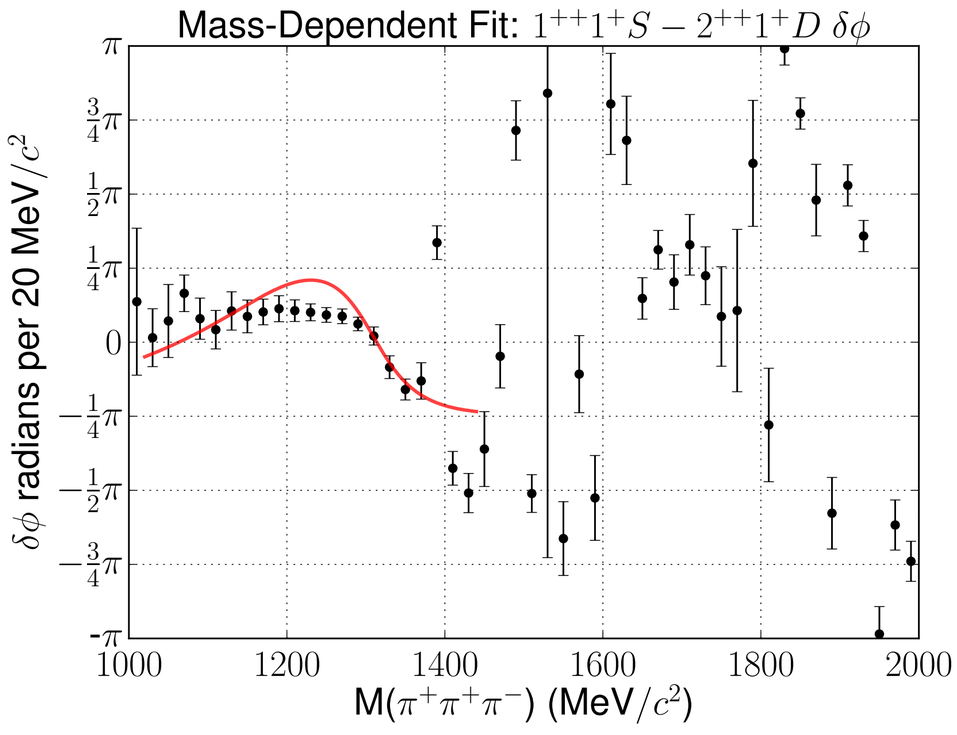
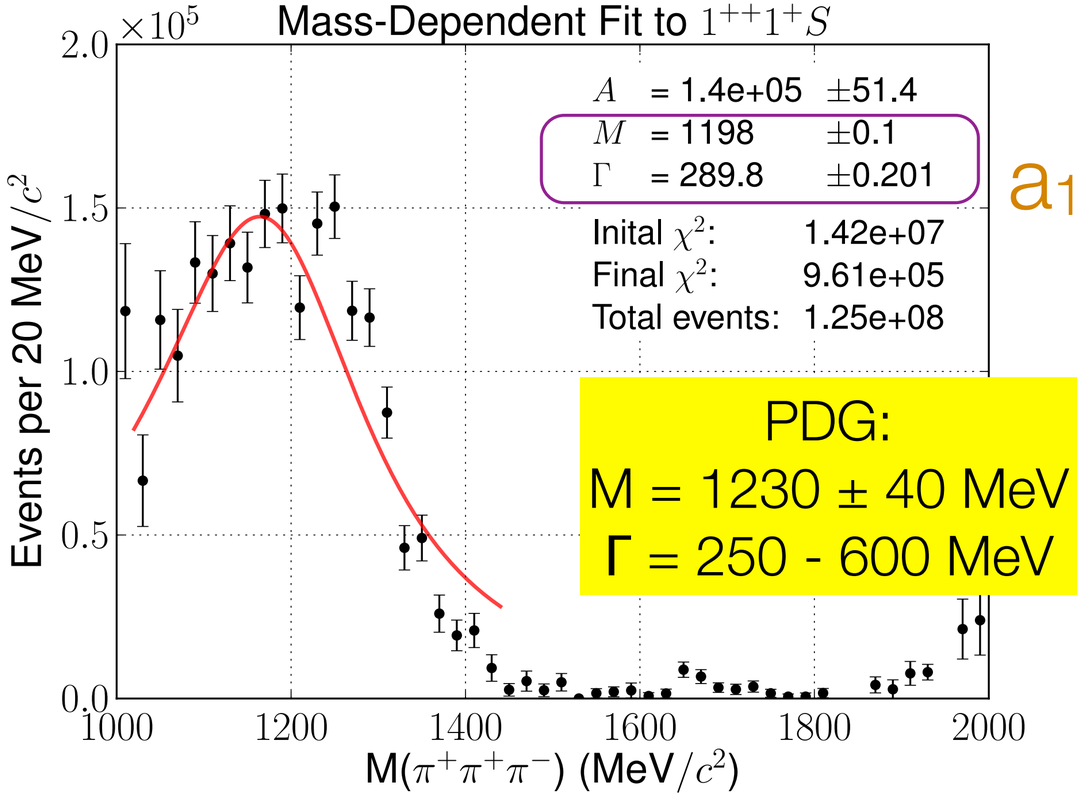


# PWA: Mass Dependent Fit

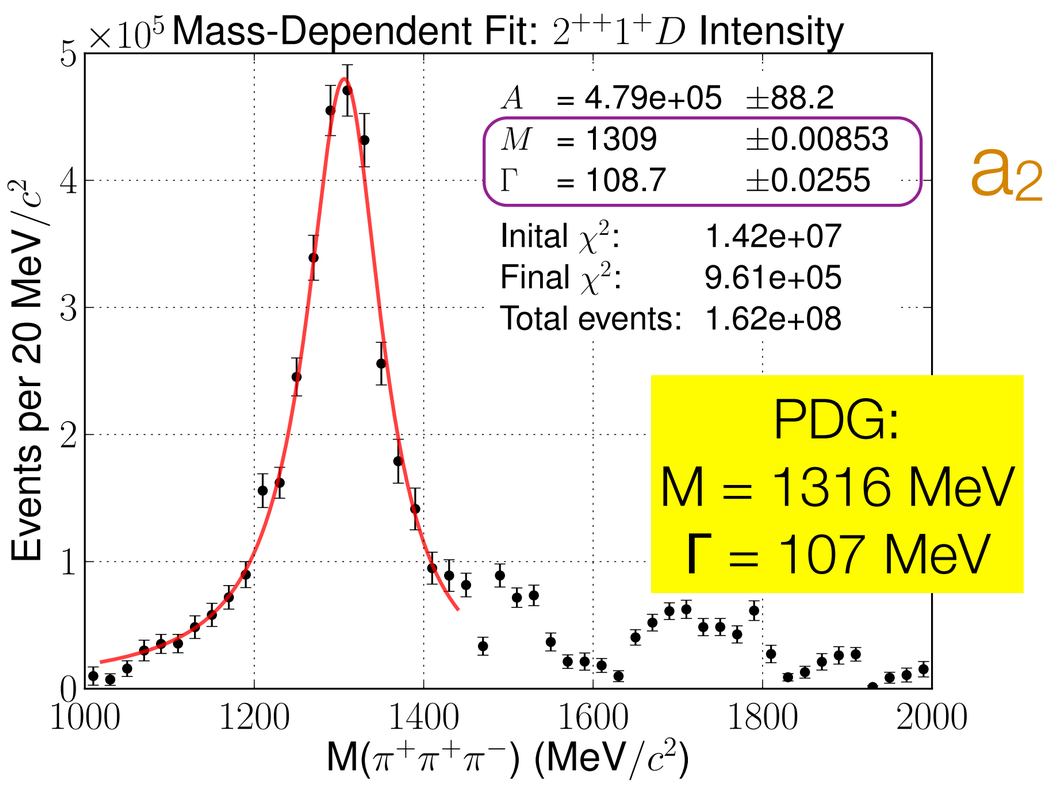
$\pi^+ \pi^+ \pi^-$




$a_1$

PDG:
M = 1230 ± 40 MeV
Γ = 250 - 600 MeV

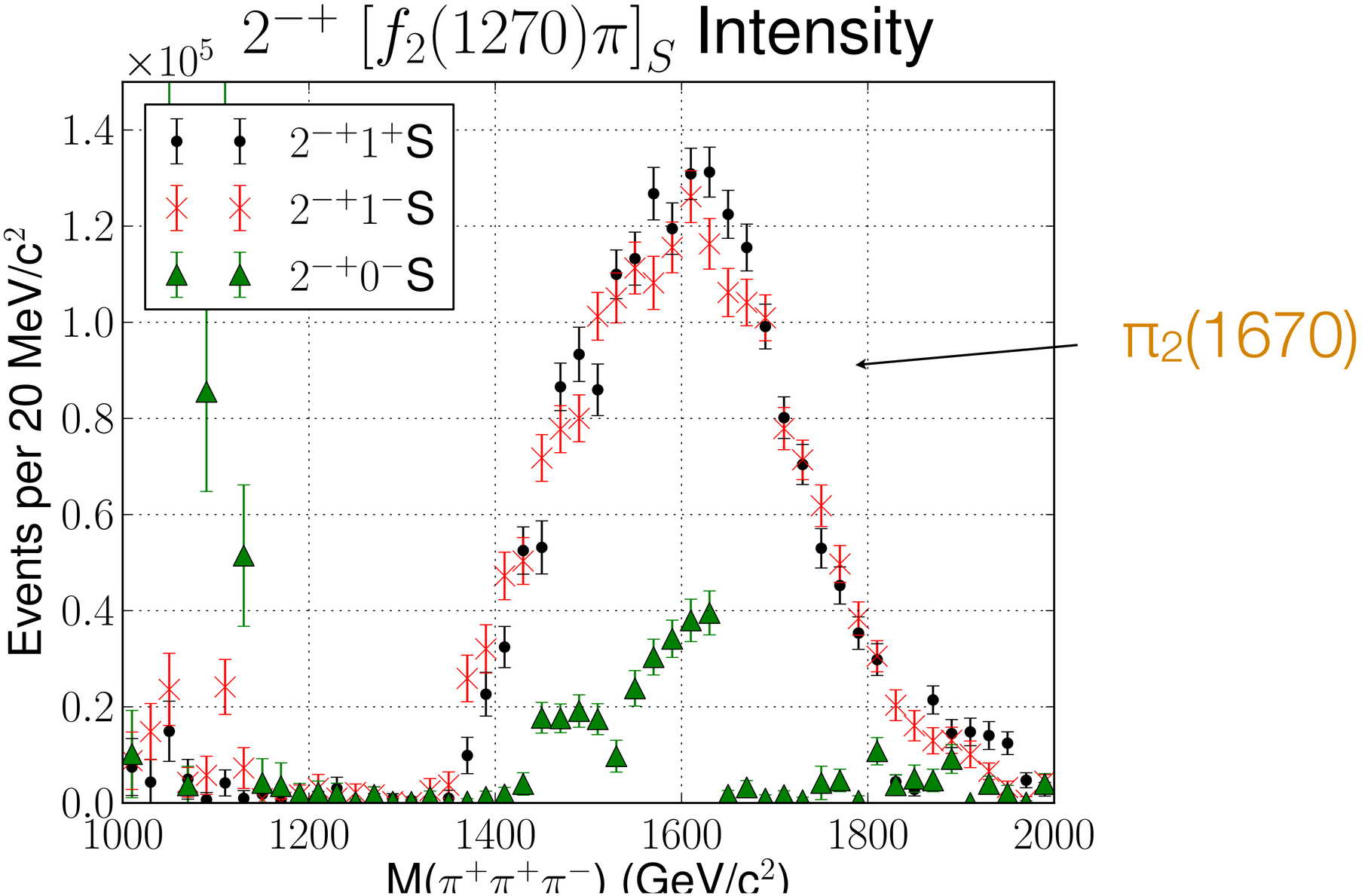



$a_2$

PDG:
M = 1316 MeV
Γ = 107 MeV

$\pi^+ \pi^+ \pi^-$

# PWA: Mass Independent Fit



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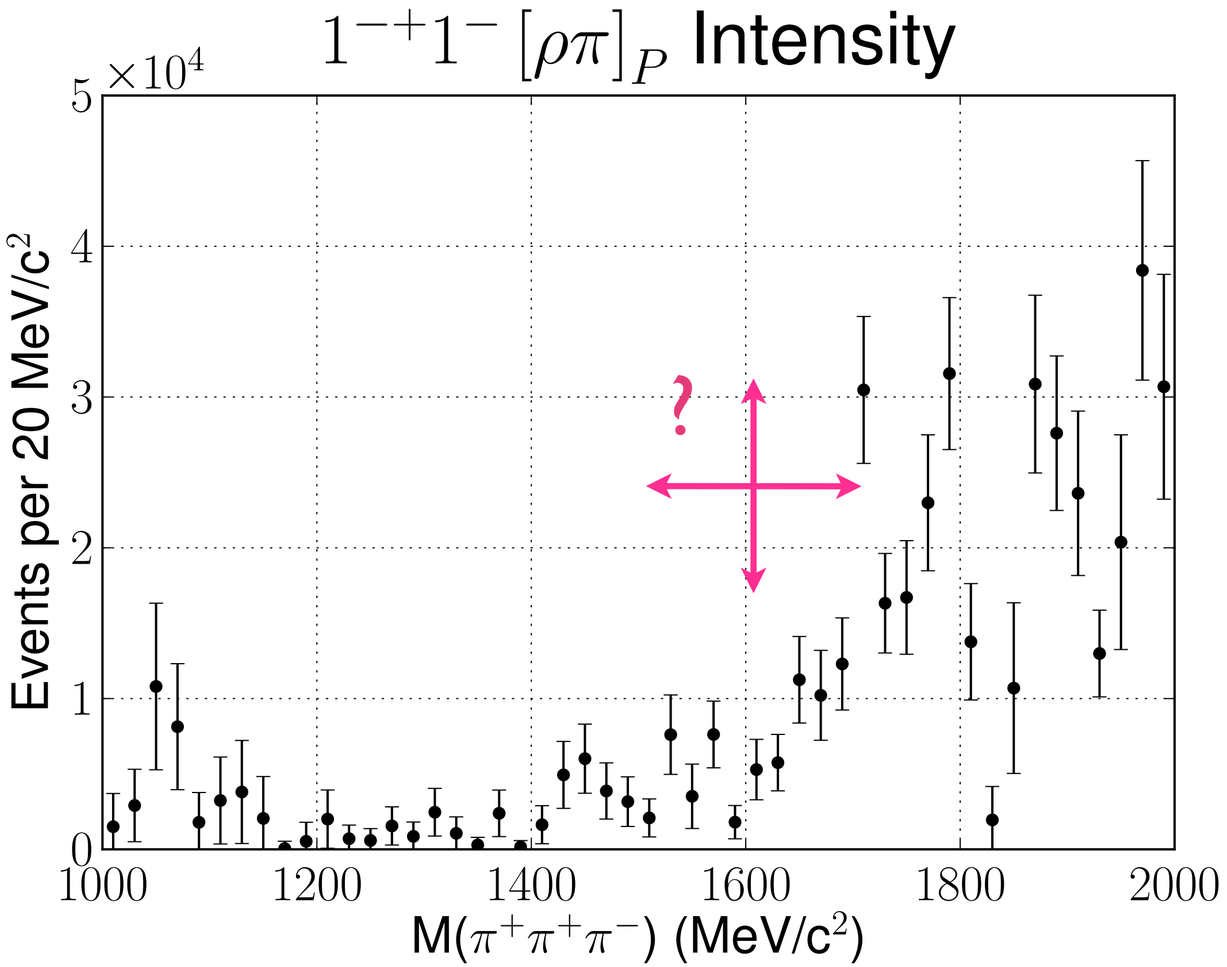
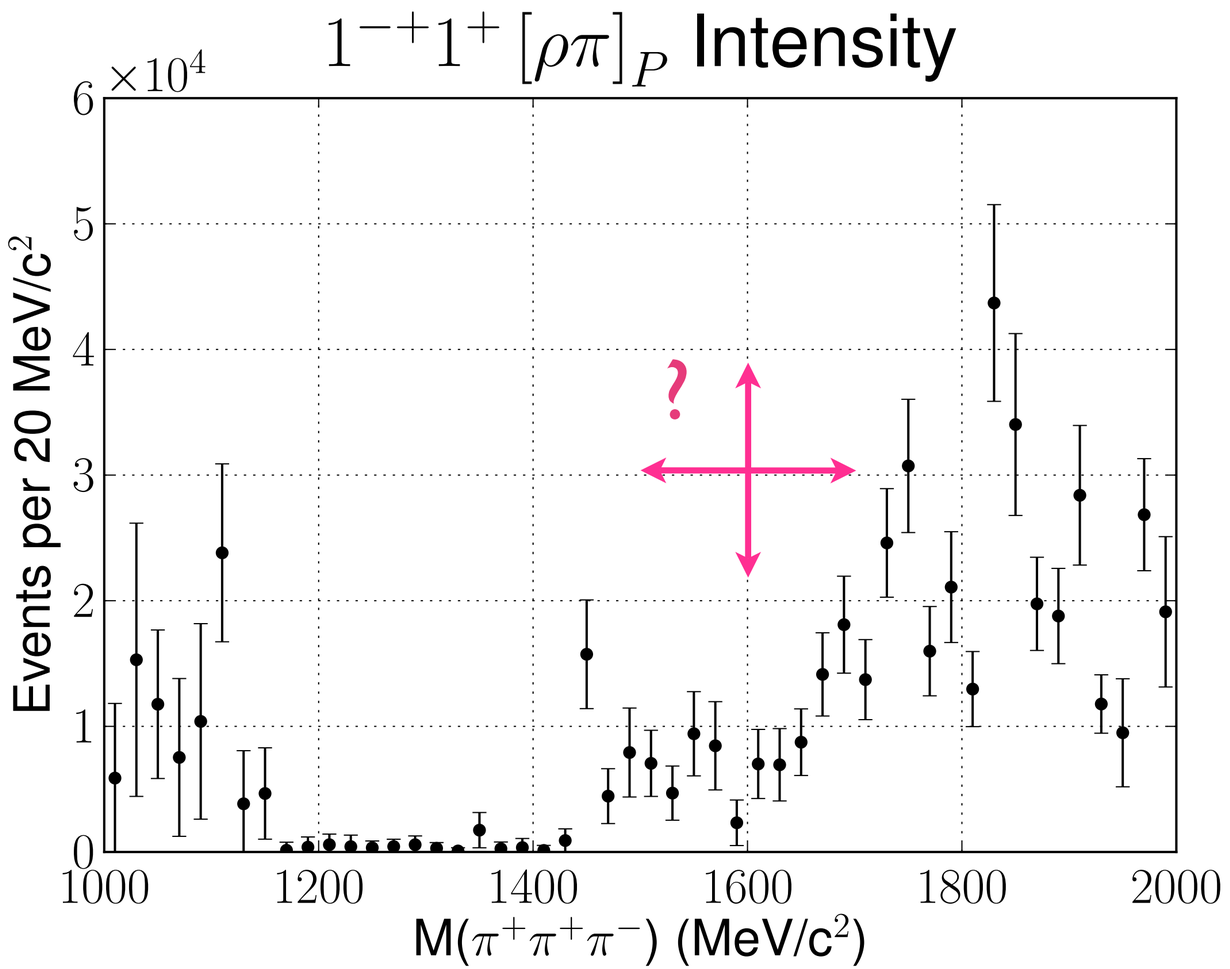


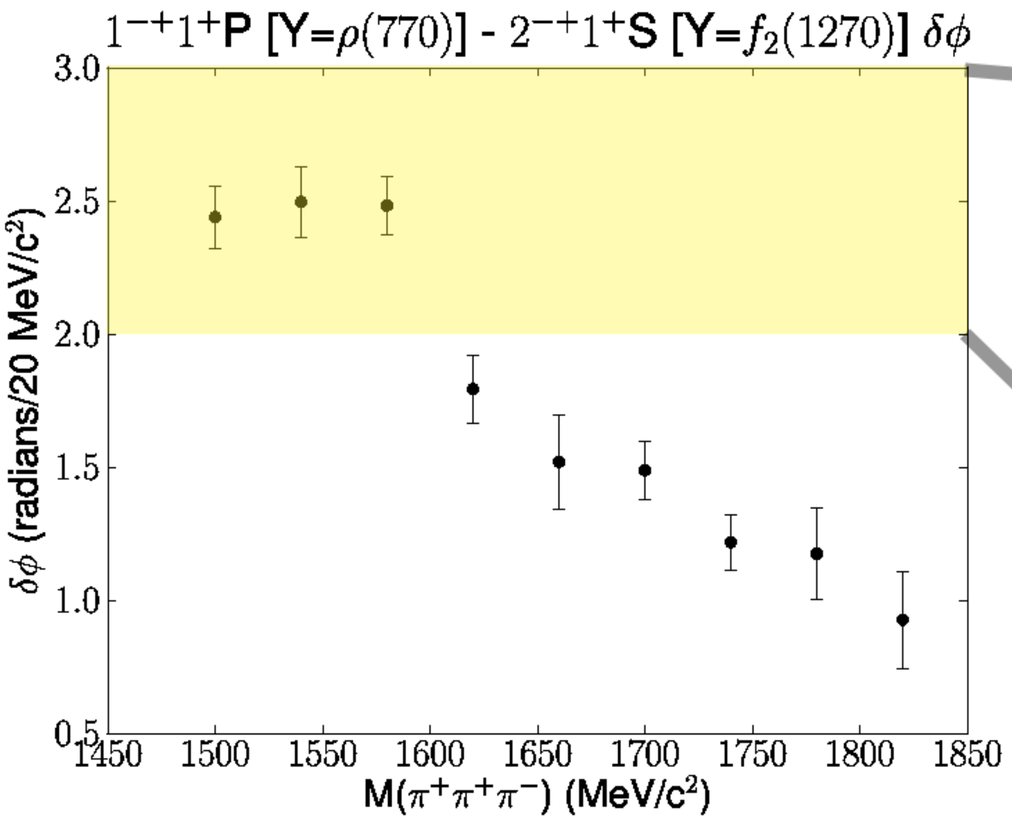



# PWA: Mass Independent Fit

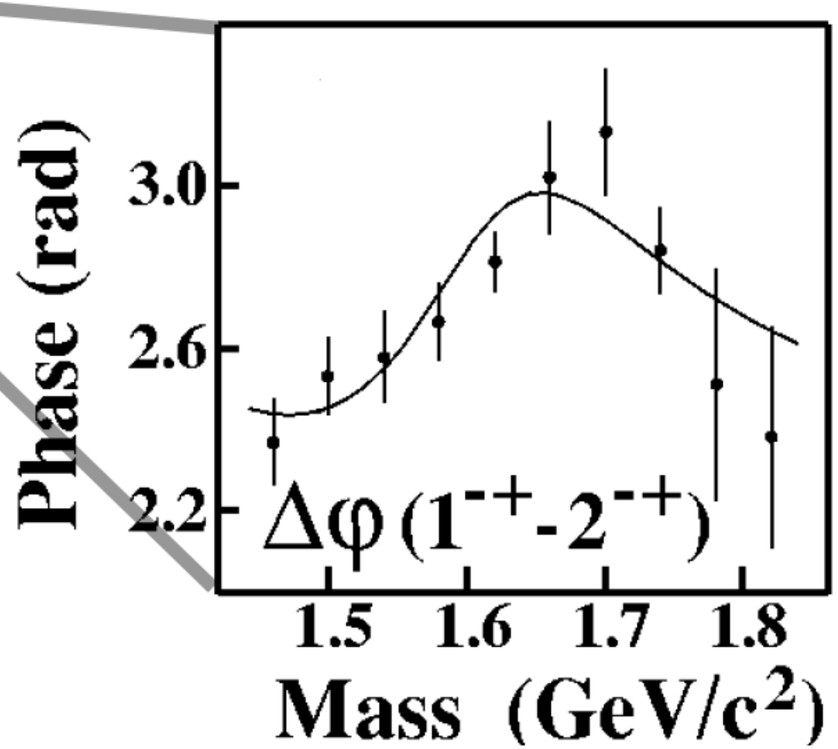
No evidence for exotic $1^{-+}$ phase motion

Phase motion consistent with resonating $2^{-+}$

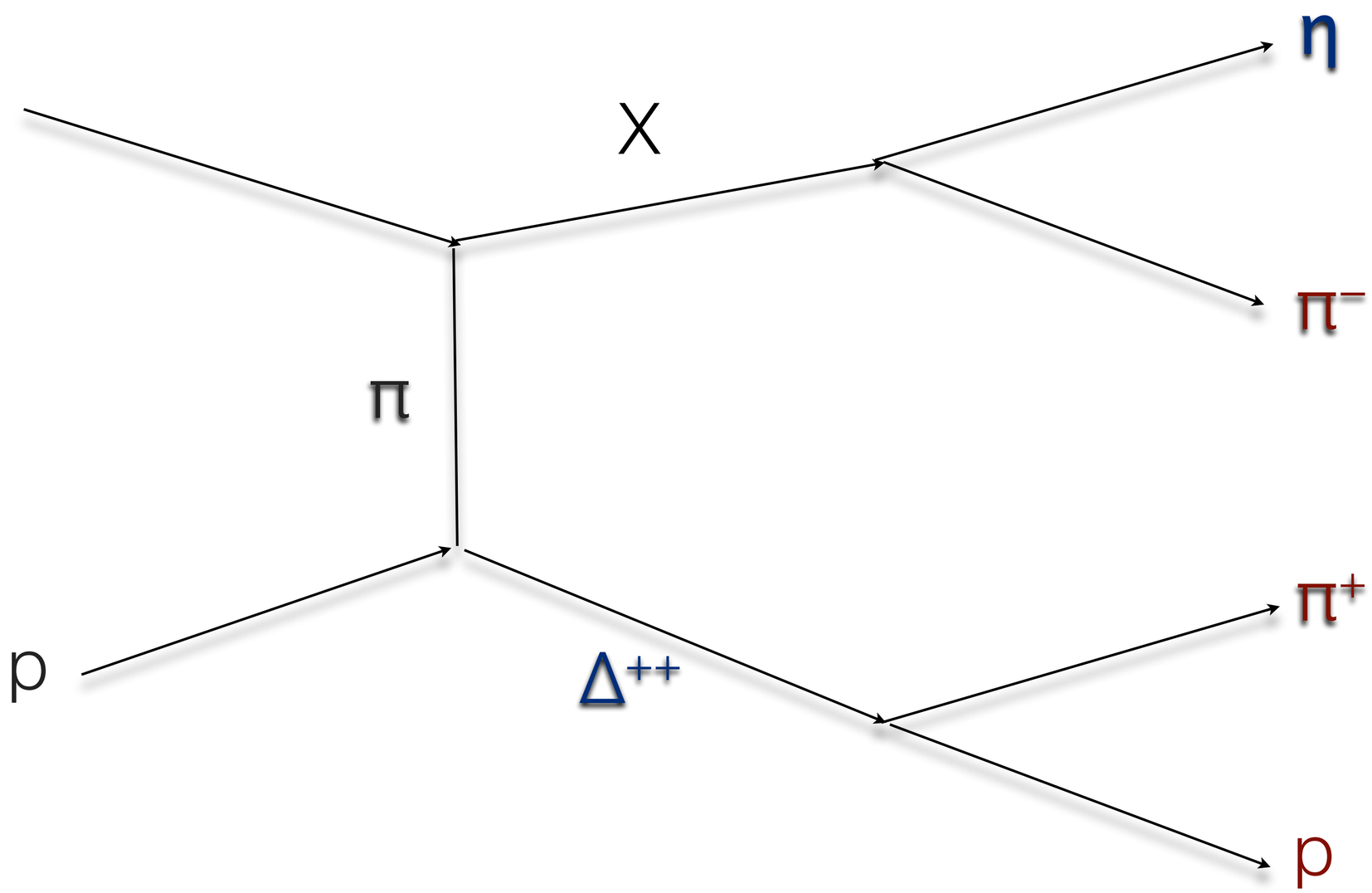
CLAS g12




BNL-E852



# g12 - ηπ-



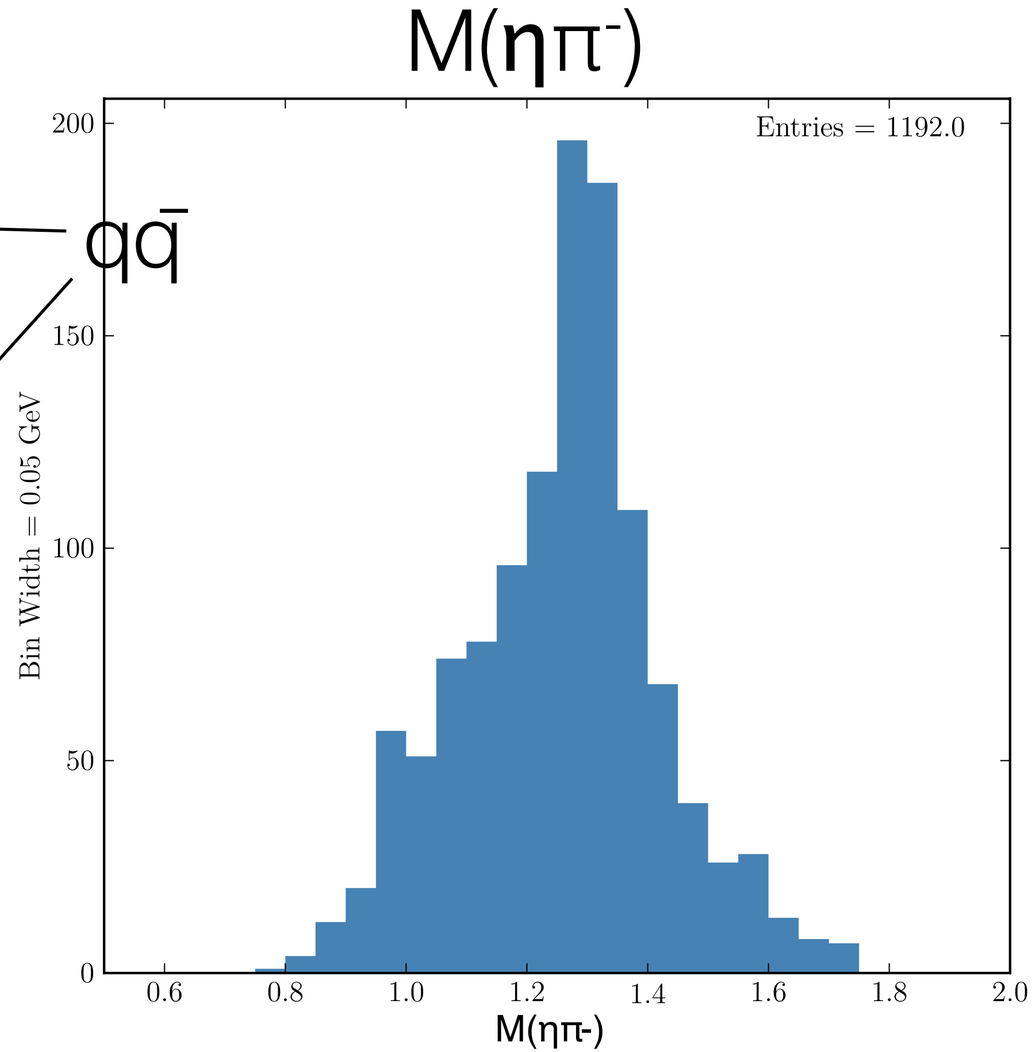
# PWA: Mass Independent Fit

- The allowed wave set is

qq̄g

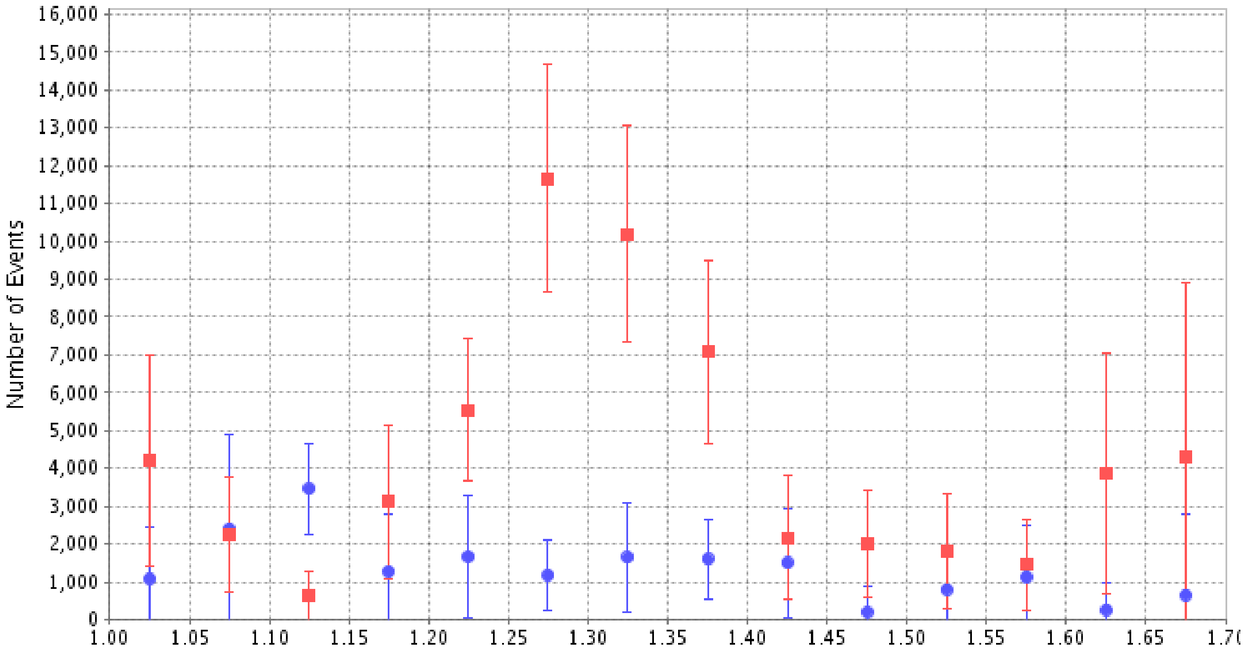
| wave | $J^P M\epsilon$ | corresponding particle |
|---|---|---|
| S | $0^+0^-$ | $a_0(980)$ |
| P | $1^-1(^\pm)$ | $\pi_1(1400)$<br>$\pi_1(1600)$ |
| D | $2^+1(^\pm)$ | $a_2(1320)$ |

qq̄



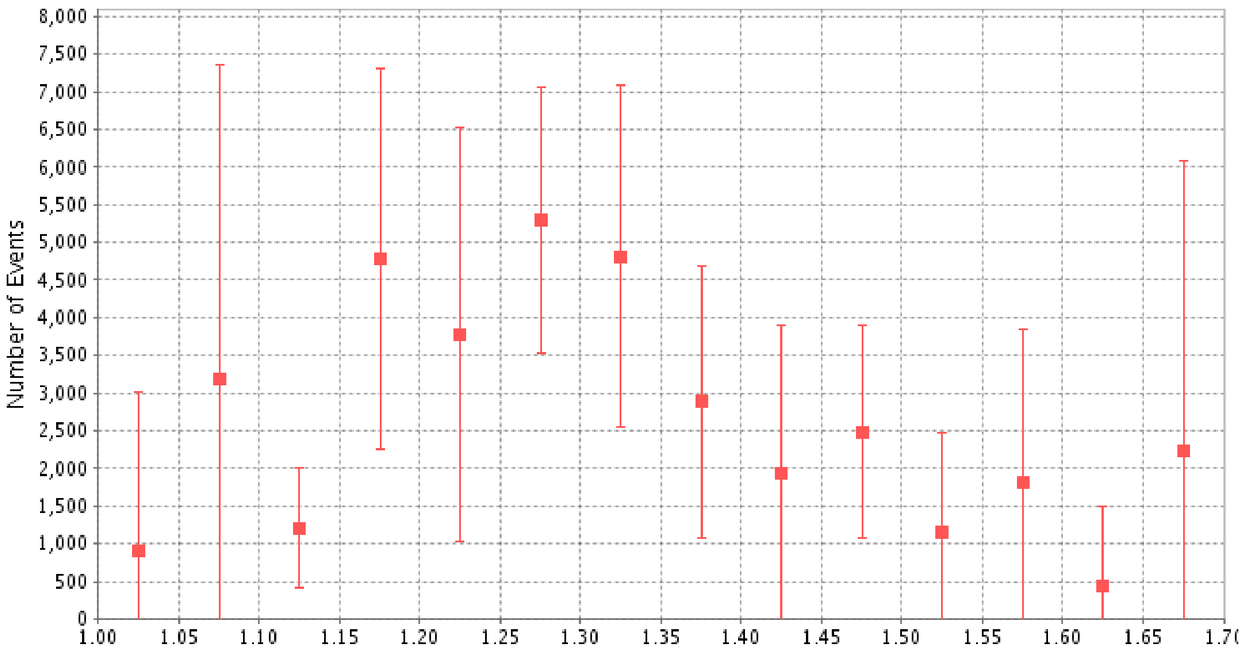
# PWA: Mass Independent Fit

## $J^{PC}m = 1^{-+}1, 2^{++}1$




- The strongest contribution is from the D wave.
- The P waves shows no bump and is roughly 1/5 of the D wave.

## $J^{PC}m = 0^{++}0$




- The S wave shows a broad background with 1/2 the intensity of the D wave.

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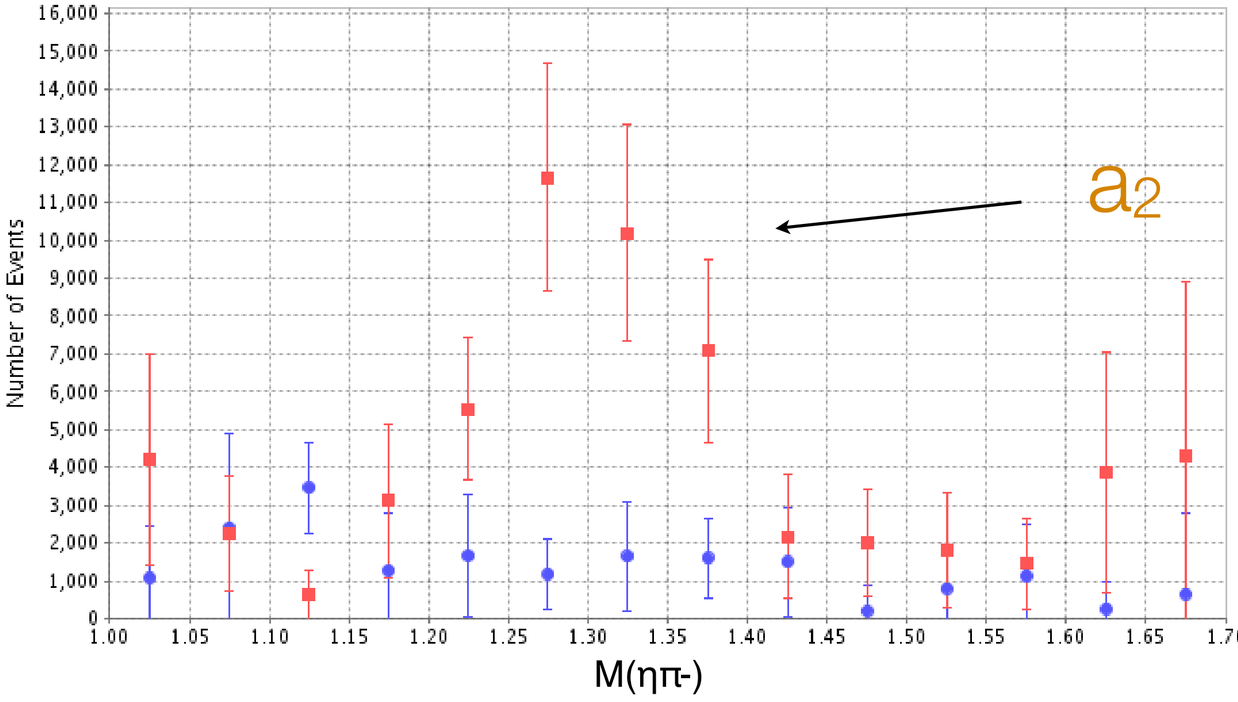


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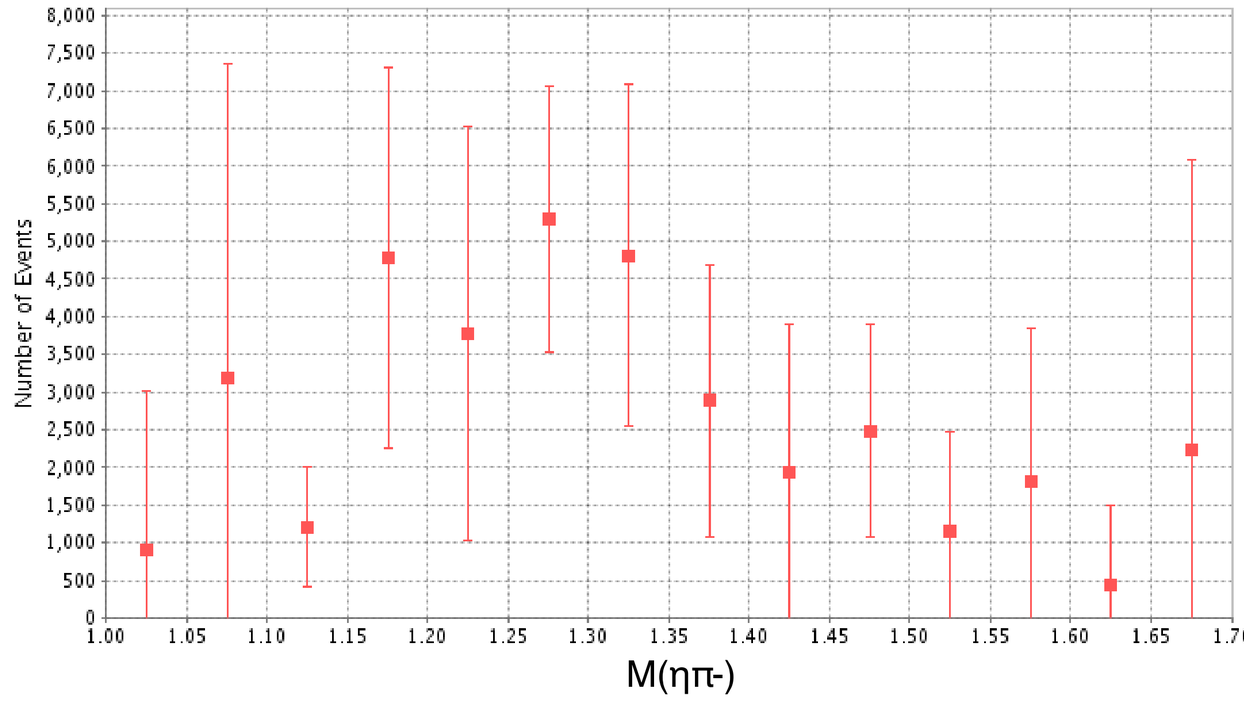



- The S wave shows a broad background with 1/2 the intensity of the D wave.

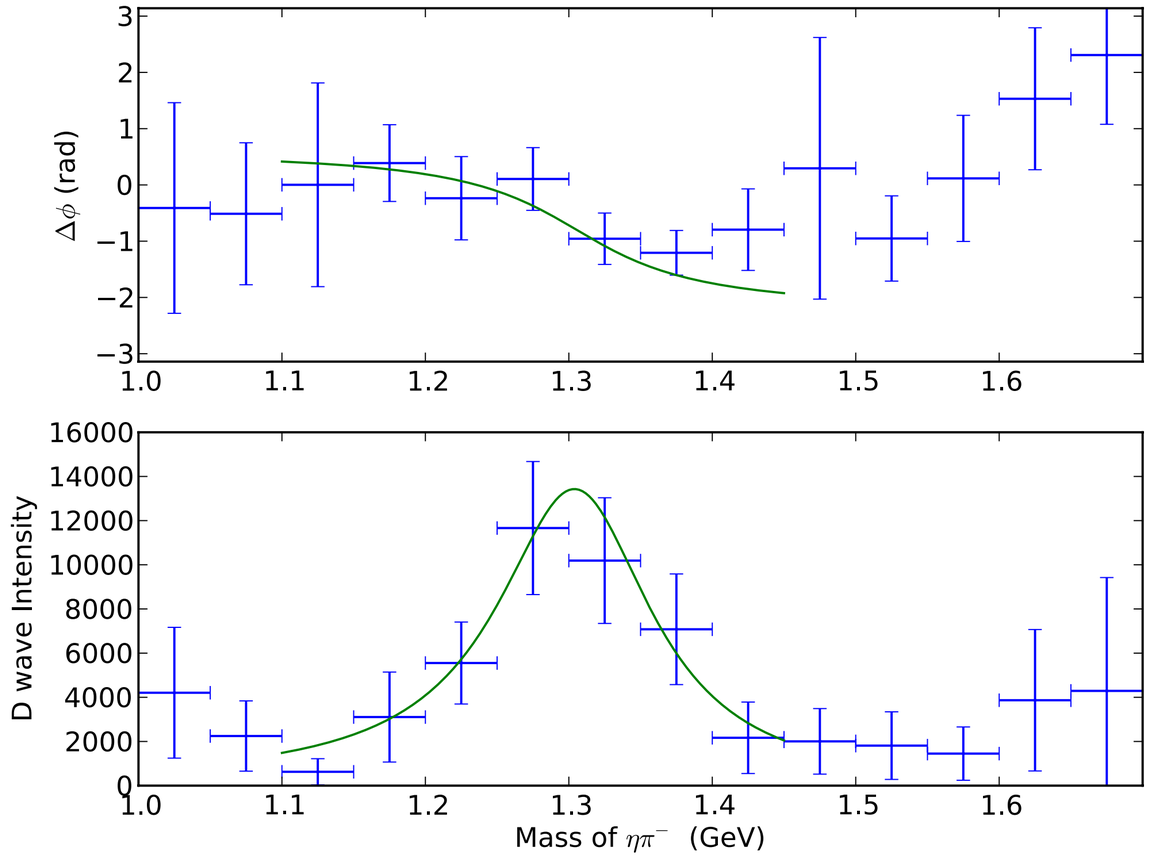
# Mass Dependent Fit

- Used relativistic BW amplitudes to fit the partial wave intensity and phase together using a $\chi^2$ fit.
  - Includes error matrix calculated from PWA.

- mass: 1.32 ± 0.01 GeV
- width: 0.14 ± 0.01 GeV

$a_2$

- PDG values:
  - mass: 1.318 ± 0.0006 GeV
  - width: 0.107 ± 0.005 GeV



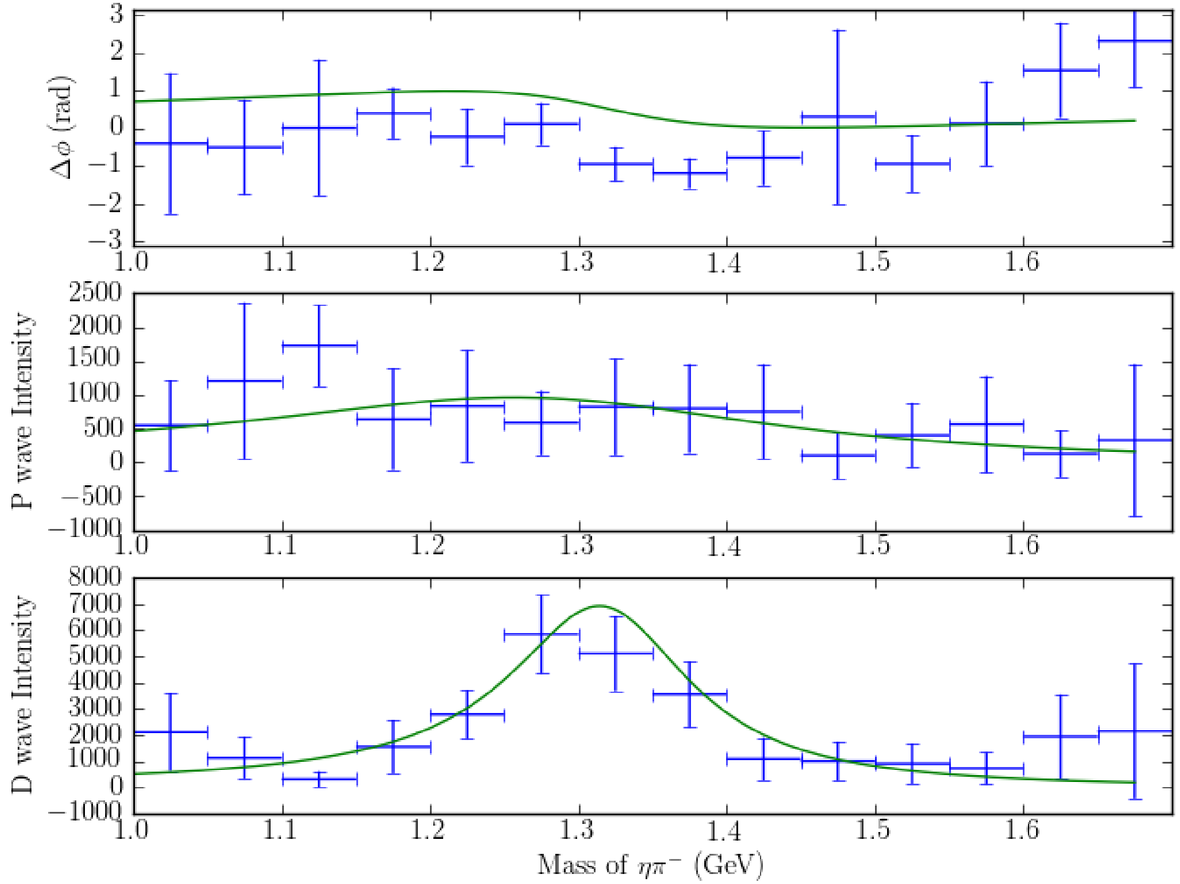
# Mass Dependent Fit

- Included $\pi_1$ with $a_2$

- $a_2$ mass: 1.343 ± 0.003 GeV
- $a_2$ width: 0.174 ± 0.003 GeV

$a_2$

- $\pi_1$ mass: 1.39 ± 0.23 GeV
- $\pi_1$ width: 0.58 ± 0.05 GeV



# Mass Dependent Fit

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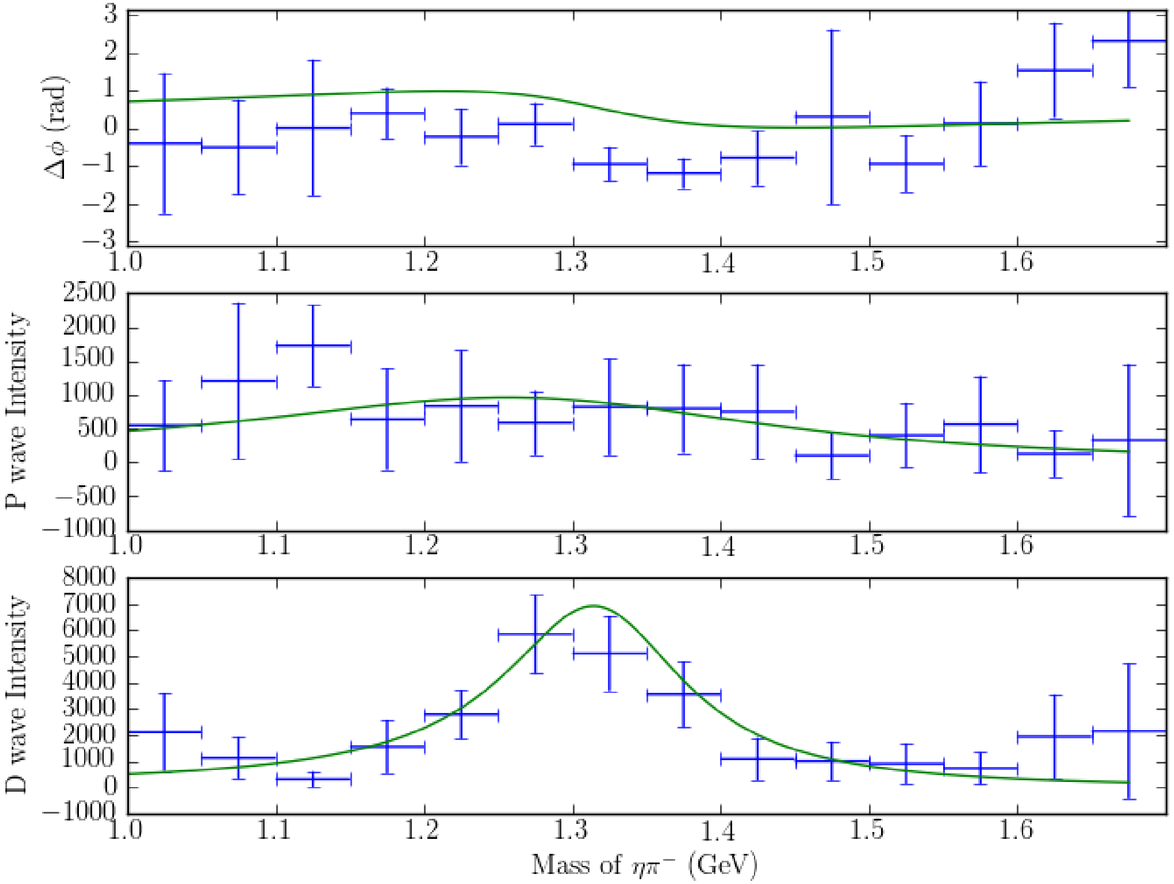
  - $a_2$ width: 0.174 ± 0.003 GeV
  - $\pi_1$ mass: 1.39 ± 0.23 GeV
  - $\pi_1$ width: 0.58 ± 0.05 GeV
- Results of the fit varied greatly. The best fit for the $\pi_1$ resulted in large errors for the mass and a width broader than the pion production value.



# Ratio of $\pi_1$ to $a_2$

- From yields using E852 mass and width:
  - $N_{a2}$: 55240
  - $N_{\pi 1}$: 19340 (fit + 2 sigma)
  - $\frac{\sigma(\gamma p \to \Delta^{++}\pi_1^-)}{\sigma(\gamma p \to \Delta^{++}a_2^-)}$ = 0.35 (CL of 95.4 %)

- From the sum of the partial wave intensity, over the mass range:
  - $N_{a2}$: 49,518 ±7090 ±2652
  - $N_{\pi 1}$: 14,686 ±4674 ±9008
  - Where first is the statistical uncertainty is calculated by the sum of the squares of the error bars of the yields and second is the systematic uncertainty is calculated from the results of multiple PWA results
  - $\frac{\sigma(\gamma p \to \Delta^{++}\pi_1^-)}{\sigma(\gamma p \to \Delta^{++}a_2^-)}$ = 0.30 (±0.21)

# Summary

- Theory has predicted photoproduction of $\pi_1$ to be comparable to the $a_2$.
- The PWA of the M($\eta\pi^-$) resulted in:
  - The wave set to be dominated by the $2^{++}$ partial wave coinciding with the $a_2$
  - The $1^{-+}$ partial wave intensity shows no structure
  - The phase difference between $1^{-+}$ and $2^{++}$ shows a shift
- The fits of the PWA intensity and phase difference resulted in the fit of the $a_2$ but not of the $\pi_1$.

# Conclusion

- CLAS-g12 acquired photoproduction data for 3π and ηπ
  - Performed mass independent PWA from 1.0 - 2.0 GeV/$c^2$
  - Fit PWA yields and phases for resonance masses.
    - Cleanly observe $1^{++}$, $2^{++}$, and $2^{-+}$ well known resonance features.
    - $\pi_1(1400)$ and $\pi_1(1600)$ exotic signal is not observed in charged exchanged photoproduction.
- Currently analyzing neutral exchange channel.
- Future meson spectroscopy experiment with greater luminosity and beam energy is a planned with GlueX.