Partial Wave Analysis of the $\pi^+\pi^+\pi^-$ system in $\gamma p \longrightarrow X^+ n$ @ 4.8-5.4 GeV from the CLAS g6c experiment

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- Introduction: Motivation, previous results
- The experiment: G6c setup, data selection, distributions
- PWA: The technique and results
- Conclusions

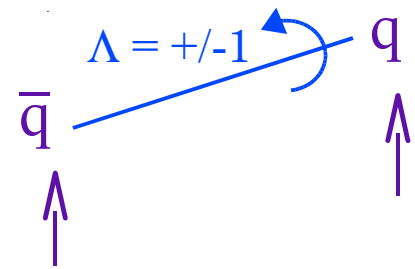
Why study the 3π system in photo-production?

Arguments favoring photo-production of lowest lying exotic meson with $J^{PC} = 1^{-+}$:

Gluon in T.E. excitation mode, $J_g^{pc} = 1^{+-}$ with $\Lambda = +/-1$

The qq pair in the qqg ground state have spins aligned, S = +1 ==> Photon beam

$$J^{pc}_{qqg} = J^{pc}_{qq} \times J^{pc}_{g} \Rightarrow 1^{-+} = 1^{--} \times 1^{+-}$$



Typical partial widths for the lowest lying exotic $I^G J^{PC} = 1^- 1^{-+}$ state:

$f_1(1285)\,\pi : b_1(1235)\,\pi : \rho(770)\,\pi = 170 : 60 : 10$ MeV

Simplicity - $f_1(1285)\,\pi$ and $b_1(1235)\,\pi$ decay modes involve production of 5-7 final state particles.

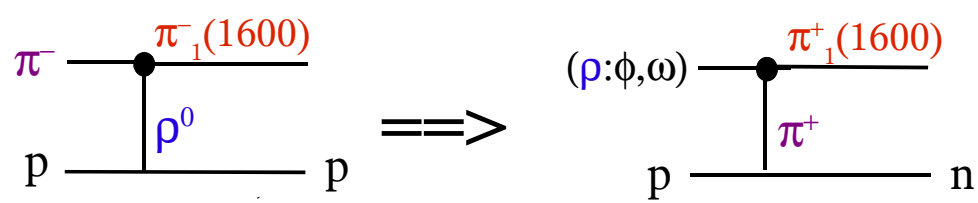
Numerous combinations of isobar/unpaired pion or isobar/isobar involved in the analysis.

Need large statistics and good acceptance coverage.

Constraints - CLAS acceptance on the order of 4% for 3 charged particle identification.

Previous observation of the $\pi_1(1600)$ state in 3π final state with π beam:

E852 @ BNL - Production through natural parity exchange (most likely a ρ).



Existing photo-production data:

Sparse... From SLAC

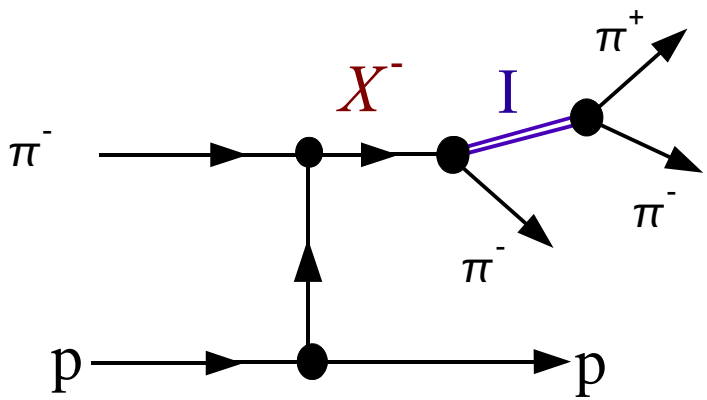
BNL E852: $\pi^- p \to \pi^+ \pi^- \pi^- (p) @ 18\, GeV/c$

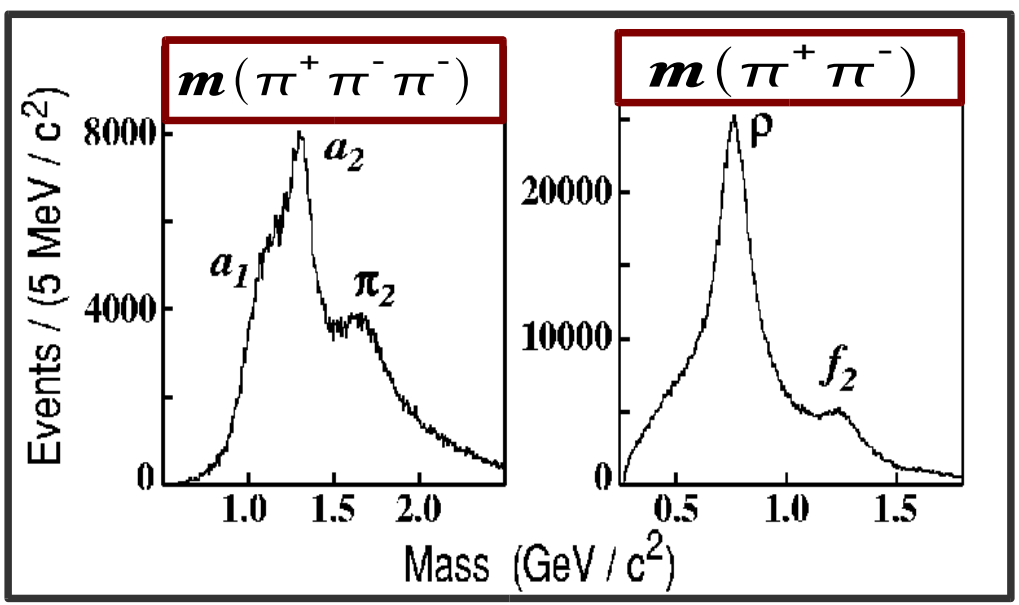
Neutral exchange reaction

250K $\pi^+\pi\,\pi$ events in the PWA

Isobar choices, I: ρ, $f_2(1270)$, $f_0(980)$, σ

Phys. Rev. **D65**, 072001 (2002)



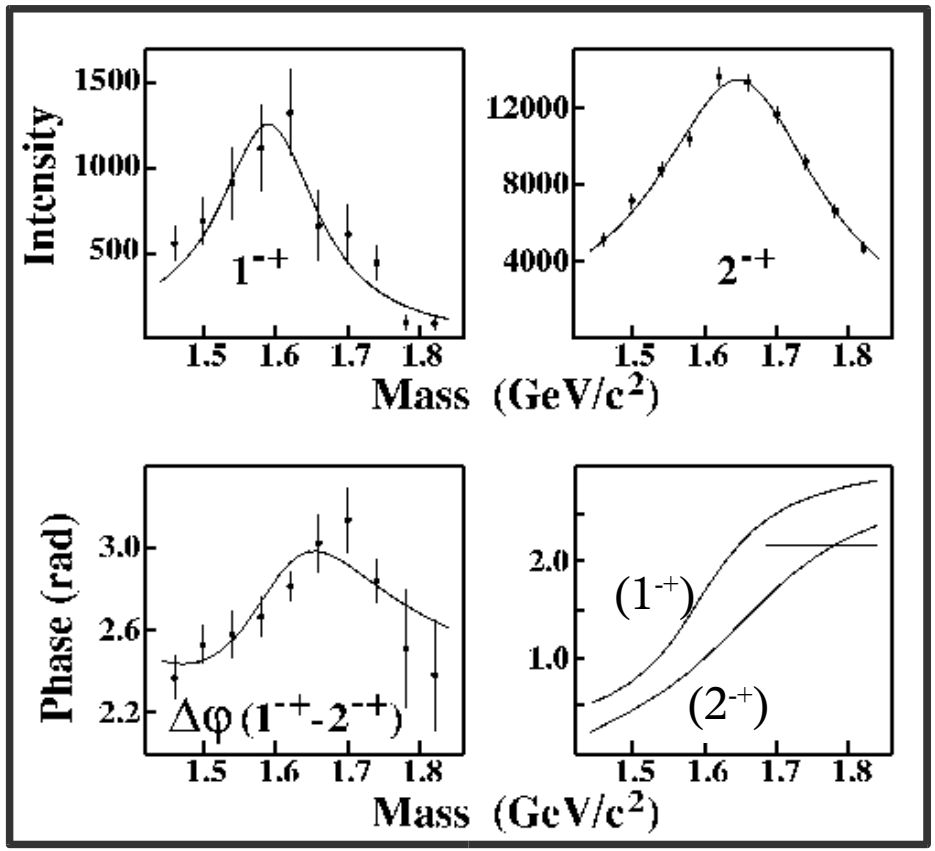


Mass dependent fit results: $\pi_1(1600)/\pi_2(1670)$

$\pi_1(1600)$:

m = 1593 +/- 8 (+29/-47) MeV $\frac{\chi^2}{DOF} = \frac{25.8}{22} = 1.17$

Γ = 168 +/- 20 (+150/-12) MeV



Previous Photo-induced reactions:

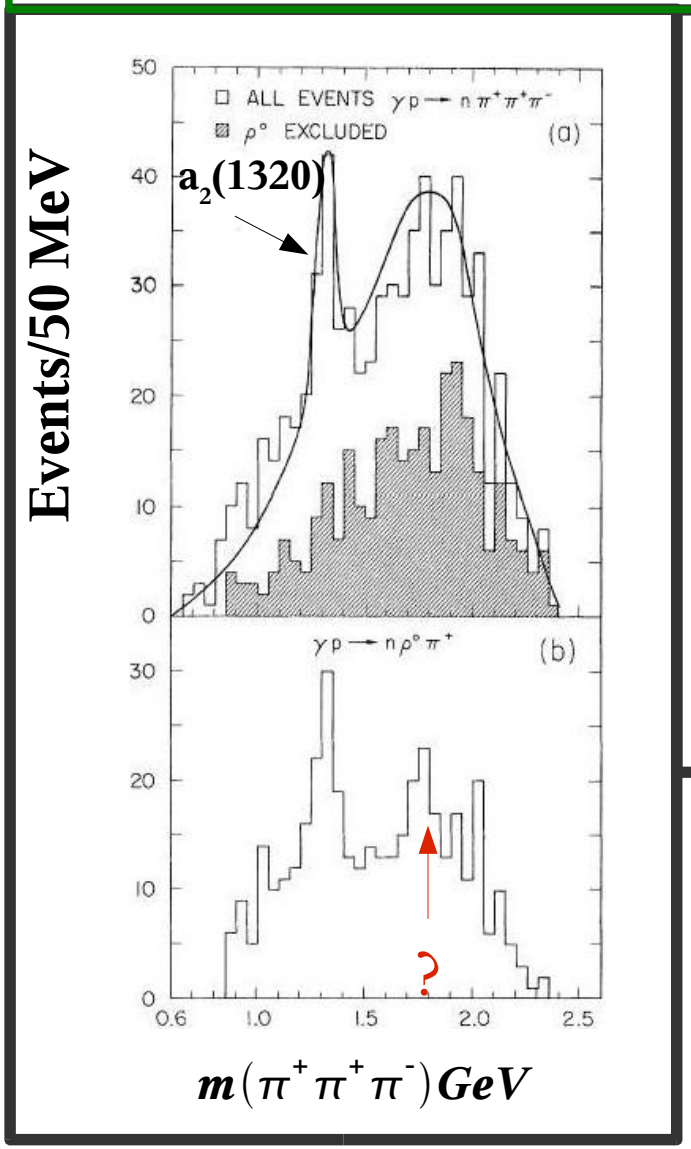
SLAC: $\gamma\, p \rightarrow \pi^+ \pi^+ \pi^- n$

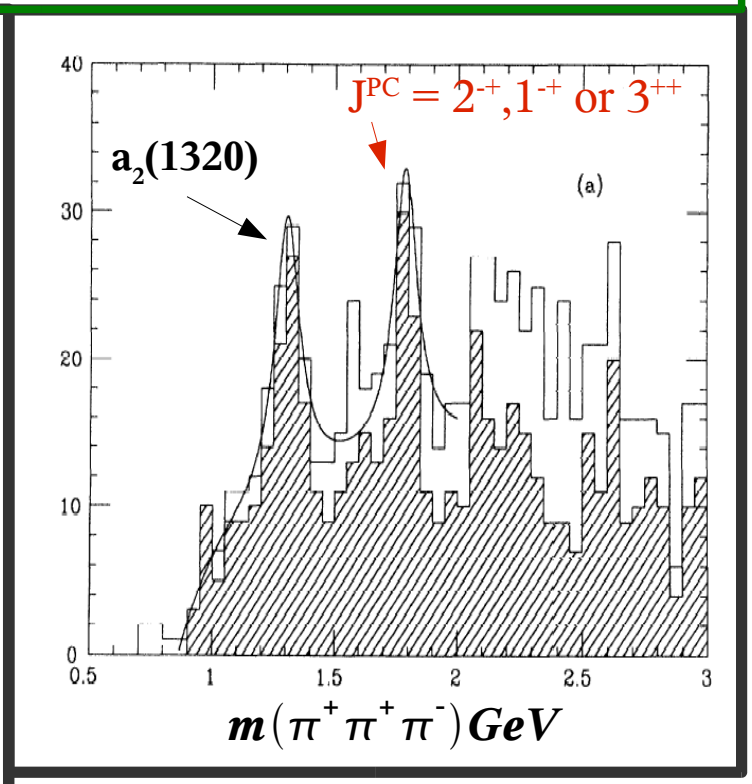
@ 5.4 and 4.3 GeV

Eisenberg et al., PRL 23, 1322 (1969)

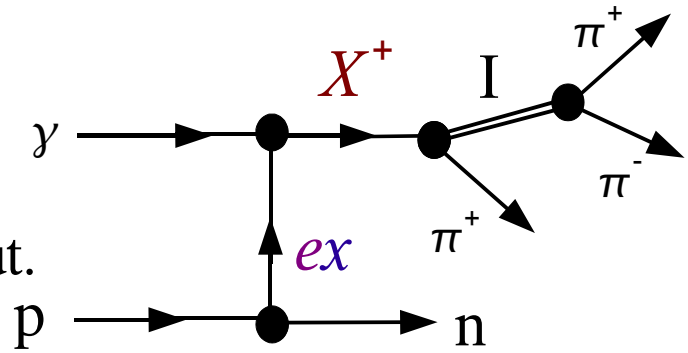
@ ~19 GeV, Γ = 1.7 GeV

Condo et al., PRD 43, 2787 (1991)





CLAS g6c: $\gamma p \rightarrow \pi^+\pi^+\pi^-(n)@4.8-5.4\,GeV$



t-channel charge exchange process

pomeron, ω, and other isoscalar exchanges ruled out.

Using vmd and conservation rules:

For γ == ρ, possible *ex*: π, a_1, a_2 Np : $p = (-1)^J$

ω, ρ, b_1 Up : $p = (-1)^{J+1}$

But $\gamma \longrightarrow \omega$ relative to $\gamma \longrightarrow \rho$ is suppressed from

$\gamma \longrightarrow (\rho:\phi:\omega) = (9:2:1)$

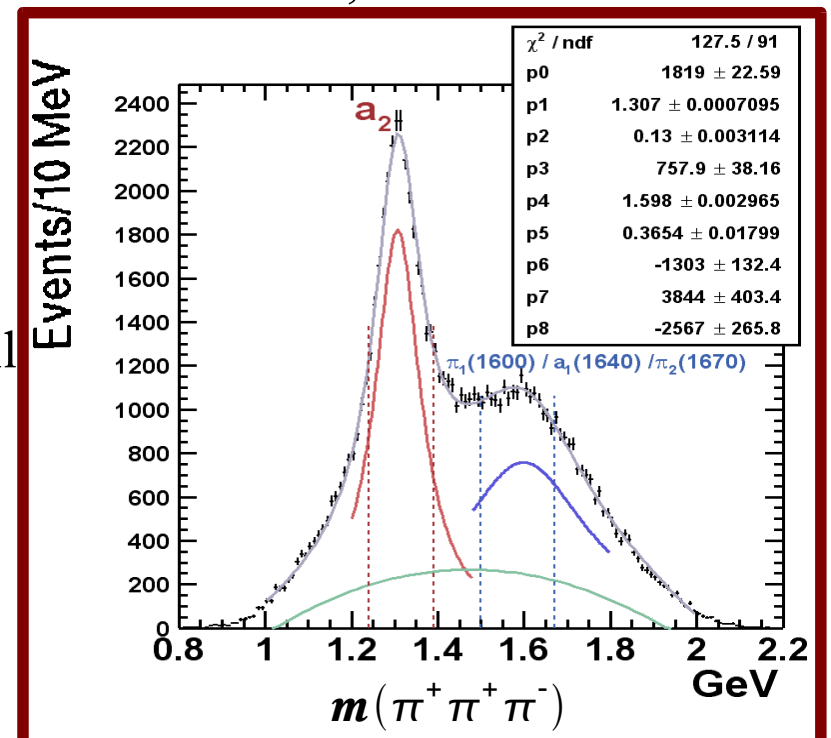
And pρn coupling compared to pπn coupling is small

==> π dominant exchange at low t.

3 pion charged final state:

Only states with $I^G = 1^-$ possible. ***X***: $I^G J^{pc} = 1^- J^p$

83K events, ~400x statistics



$m_{a_2(1320)} = 1307 \pm 0.7\ MeV$

$\Gamma_{a_2(1320)} = 130 \pm 3\ MeV$ $m_X = 1598 \pm 3\ MeV$

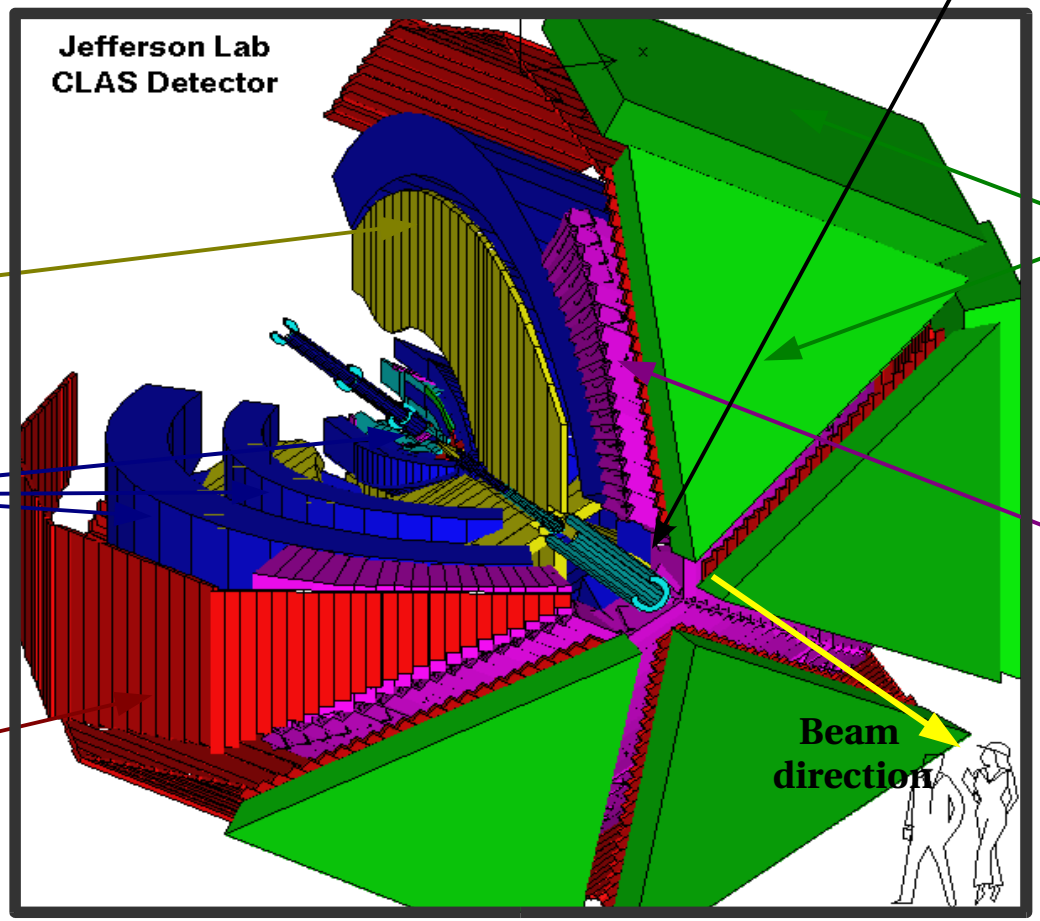
$\Gamma_X = 365 \pm 18\ MeV$

CLAS g6c: Light Meson Spectroscopy in photo-production

Aug. 17th – Sep. 11th of 2001
$E_e = 5.7$ GeV
4.8-5.4 GeV tagged γ beam on LH_2 target
Sensitivity: ~ 2.7 events/pb

$$\gamma\, p \rightarrow \pi^+ \pi^- (p)$$
$$\gamma\, p \rightarrow K^+ K^- \pi^+ (n)$$
$$\gamma\, p \rightarrow \pi^+ \pi^- p (\pi^o)$$
$$\boxed{\gamma\, p \rightarrow \pi^+ \pi^+ \pi^- (n)}$$

No coverage
at very low t



Superconducting Torus Magnet
6 Superconducting coils
$\int Bdl = 1.7\, T-m$

Drift Chambers
Ar-CO_2
6500 wires/sector
$\sigma_R = 350\, \mu m$

Time-of-Flight Hodoscope
48 Scintillators/sector
$\sigma_t = 145\, ps$

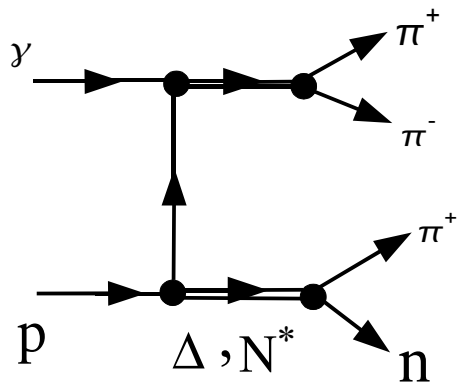
Electromagnetic Calorimeter
Lead-Scintillator
1700+ channels
$\sigma / E = 10\,\% / \sqrt{(E)}$

Gas Cherenkov Counter
e/π separation
36 channels/sector

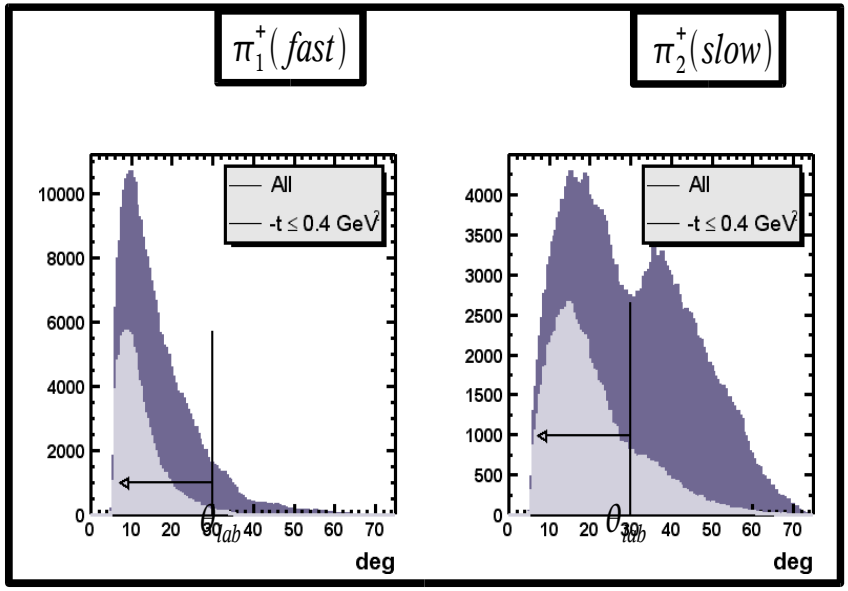
CLAS g6c: $\gamma\, p \rightarrow \pi^+ \pi^+ \pi^- (n)$

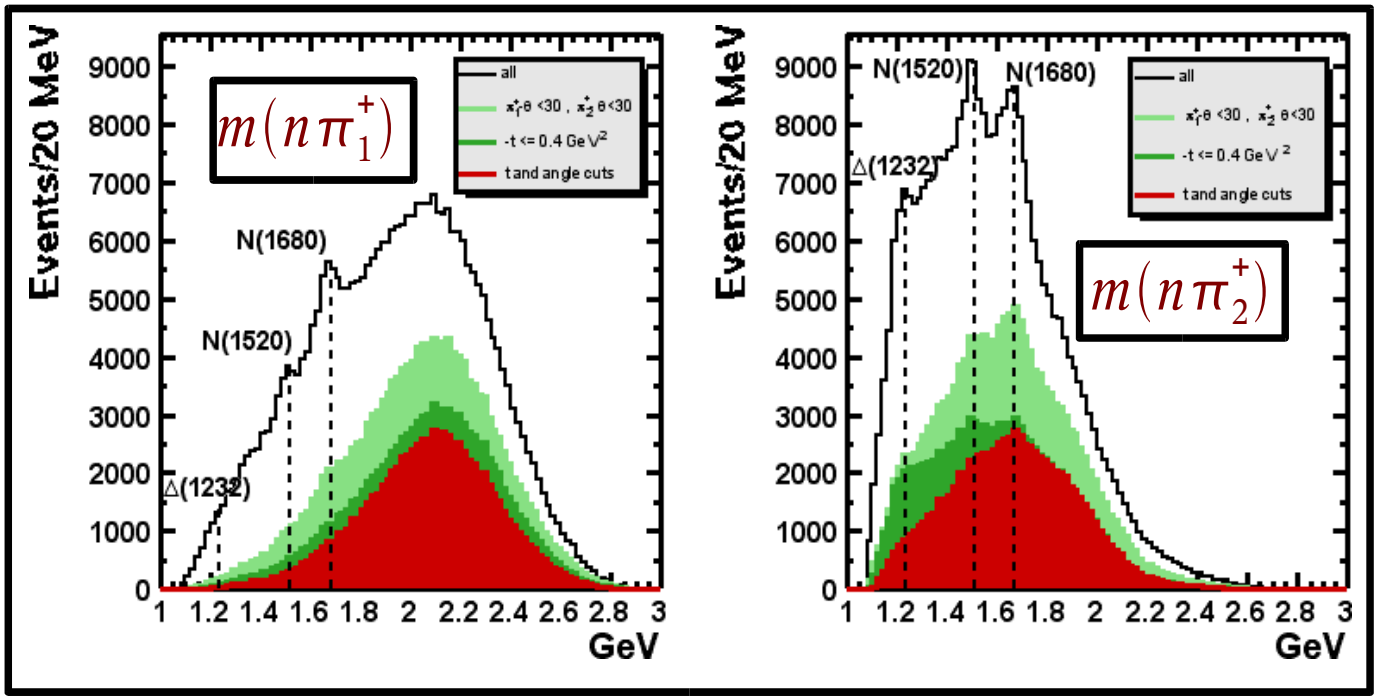
Major source of background with 4.8-5.4 GeV photon beam:

Baryon Resonance production



Lab Angles





(1232)

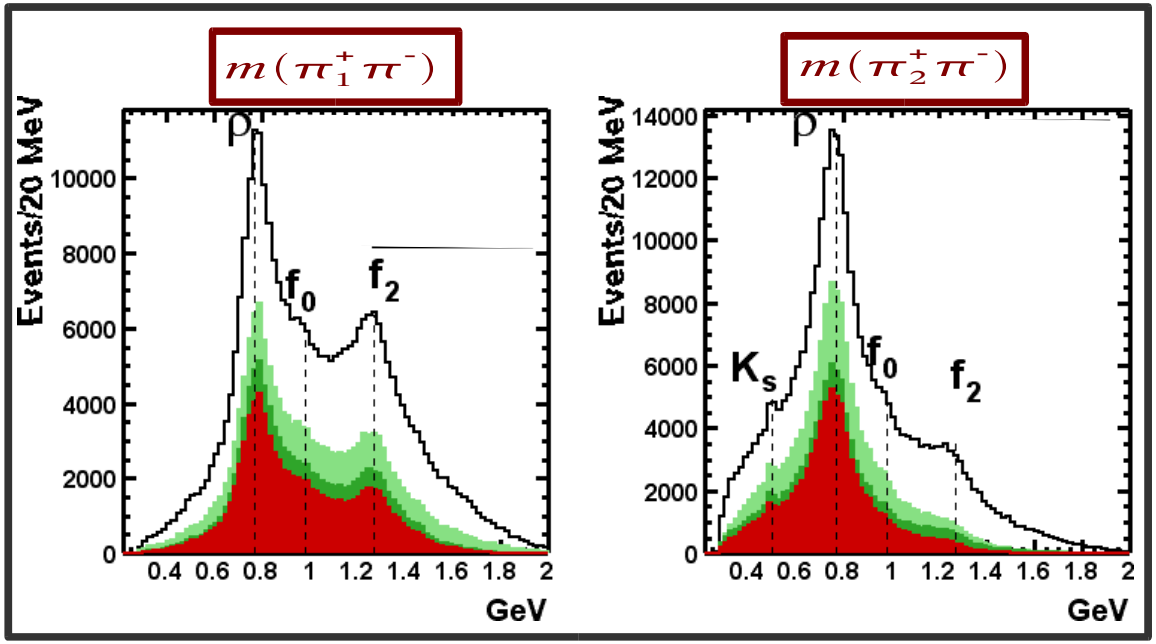
N*(1520)
N*(1535)

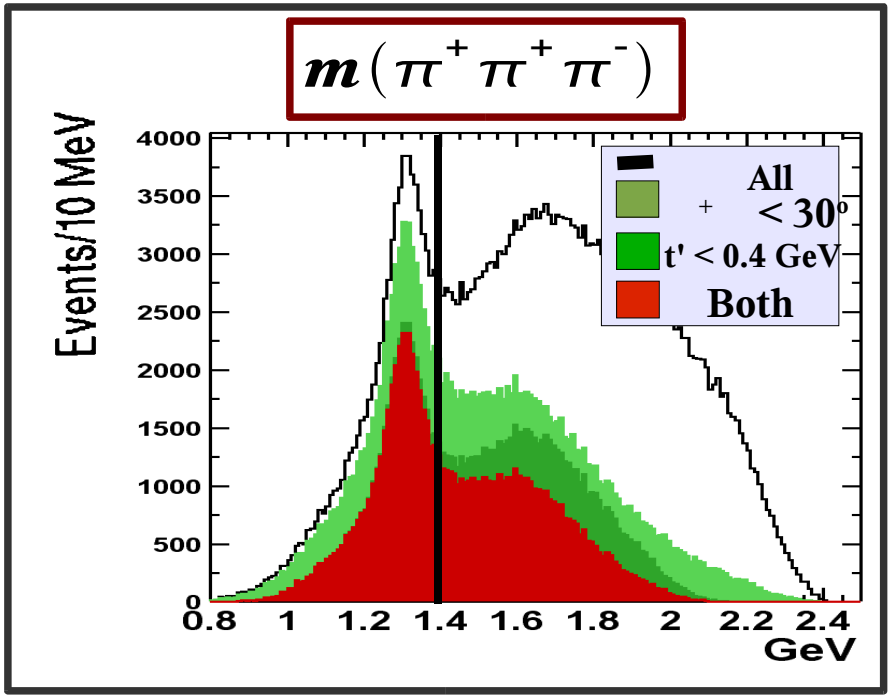
N*(1650)
N*(1675)
N*(1680)

(1600)
(1620)

CLAS g6c: $\gamma\, p \rightarrow \pi^+\pi^+\pi^-(n)$

3π and ππ
Invariant mass distributions

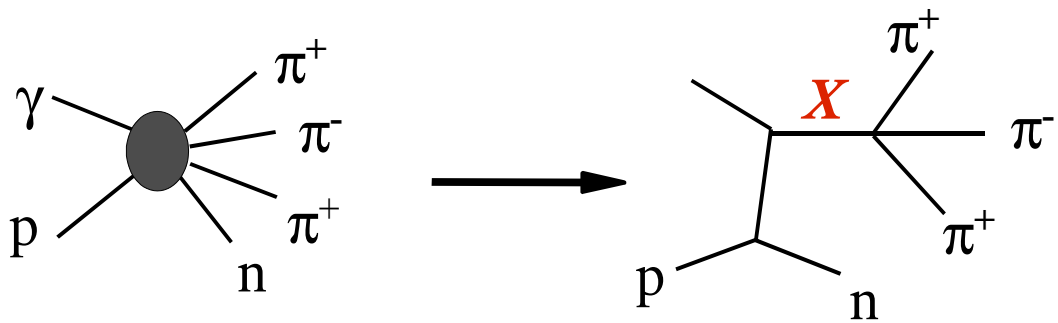




Partial Wave Analysis Technique: The "bare" minimum basics!

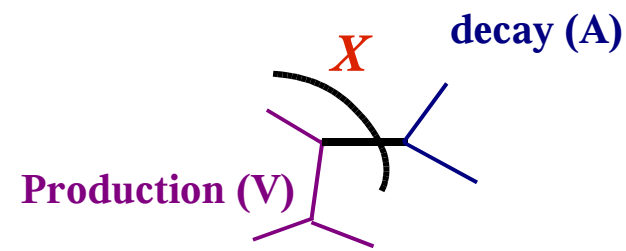
Pick an appropriate production mechanism for the 3π system:

In our case, t-channel 3π production is dominant, both u- and s-channel processes suppressed.



Separate the interaction into production and decay:

$$I(\tau)=\sum_{k}\sum_{\epsilon}\left|\sum_{X}{}^{\epsilon}V_{k\ x}\ {}^{\epsilon}A_{x}(\tau)\right|^{2}$$



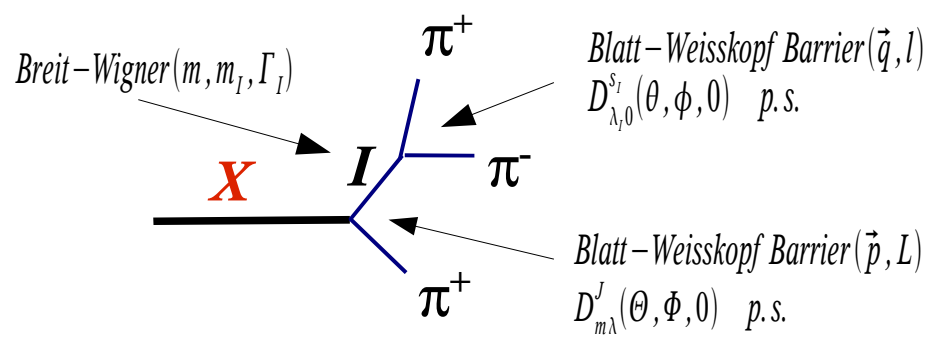
Calculate decay amplitudes, A(τ)

τ: A set of 5 independent kinematical variables describing 3-body final state:

For τ, we choose Ω_{GJ} : $(X \longrightarrow I\ \pi)_{(\Theta,\Phi)}$

M_I

Ω_h : $(I \longrightarrow \pi\ \pi)_{(\theta,\phi)}$



Fit, using the Maximum likelihood:

Given a hypothesis (set of states, *X*), varry A(τ), find V (parameters in the fit).

The fitting process:

CPU intensive,
lots of book keeping,
somewhat tedious!

Fits 0-5: Bug fixes, code development, finding a "reasonable" set of input waves, tracking tests, addition of the capability to do fits with "random" initial parameters in the fit, separation of input waves for the fits low and high 3π mass region, ...

Fit 6: Inclusive, Rank I - First "good" results.

Fit 7: Inclusion of 'High' spin, J>3 states.

Fit 8: 'Limited' Rank II, only 2^{++} waves in two ranks.

Fit 9: 'Full' Rank II.

Fit 10: 'Minimal' set of input waves, Rank II.

Fit 11: 'Same as fit10, without the 1^{-+} waves.

Wave set for fit9

Low mass region: 1 – 1.36 **GeV**

J^{PC}	m^{ϵ}	L	Isobar	# Waves
0^{-+}	0^{+}	0	$f_0(980)$	1
1^{++}	$1^{\pm}$	0,2	$\rho(770)$	4
1^{++}	$1^{\pm}$	1	$f_0(980)$	2
2^{++}	$1^{\pm}$,$2^{\pm}$	2	$\rho(770)$	4
1^{-+}	$1^{\pm}$	1	$\rho(770)$	2
2^{-+}	$1^{\pm}$	1	$\rho(770)$	2
2^{-+}	$1^{\pm}$	2	$f_0(980)$	2
Flat bg				1

Total of 18 waves

With 2 set to real and a rank II fit ⇒ 68 parameters

High mass region: 1.36 – 2.0 **GeV**

J^{PC}	m^{ϵ}	L	Isobar	# Waves
0^{-+}	0^{+}	0	$f_0(980)$	1
1^{++}	$1^{\pm}$	0,2	$\rho(770)$	4
1^{++}	$1^{\pm}$	1	$f_0(980)$	2
1^{++}	$1^{\pm}$	1	$f_2(1270)$	2
2^{++}	$1^{\pm}$,$2^{\pm}$	2	$\rho(770)$	4
1^{-+}	$1^{\pm}$	1	$\rho(770)$	2
2^{-+}	$1^{\pm}$	2	$f_0(980)$	2
2^{-+}	$1^{\pm}$, $2^{\pm}$	1	$\rho(770)$	4
2^{-+}	$1^{\pm}$	3	$\rho(770)$	2
2^{-+}	$1^{\pm}$, $2^{\pm}$	0	$f_2(1270)$	4
2^{-+}	$1^{\pm}$	2	$f_2(1270)$	2
3^{++}	$1^{\pm}$	2	$\rho(770)$	2
3^{++}	$1^{\pm}$	0	$\rho_3(1690)$	2
3^{++}	$1^{\pm}$	1	$f_2(1270)$	2
Flat bg				1

Total of 36 waves

With 2 set to real and a rank II fit ⇒ 140 parameters

CLAS g6c: $\gamma\, p \rightarrow \pi^+ \pi^+ \pi^- (n)$

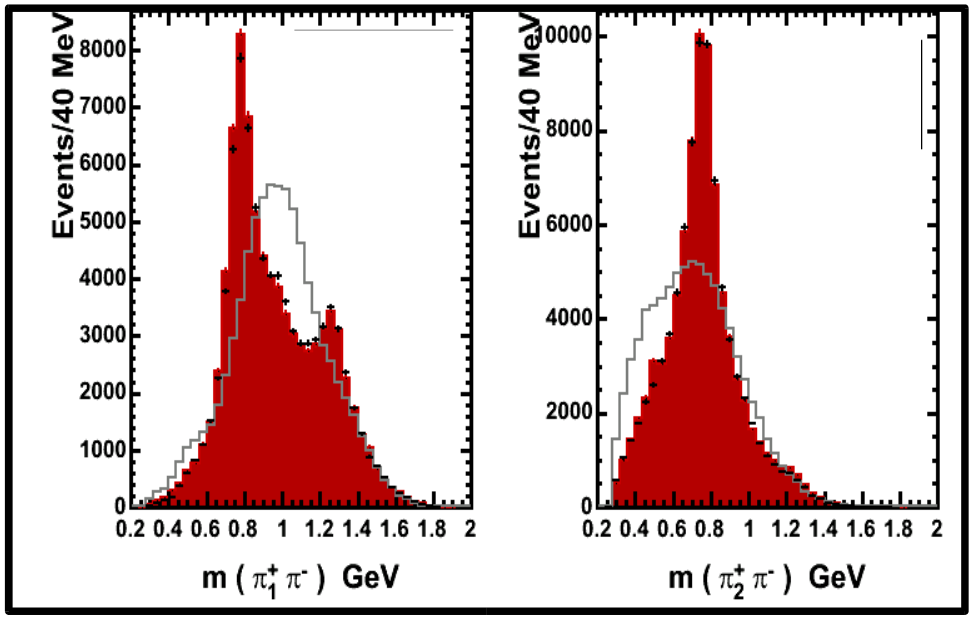
Check of fit9 quality:

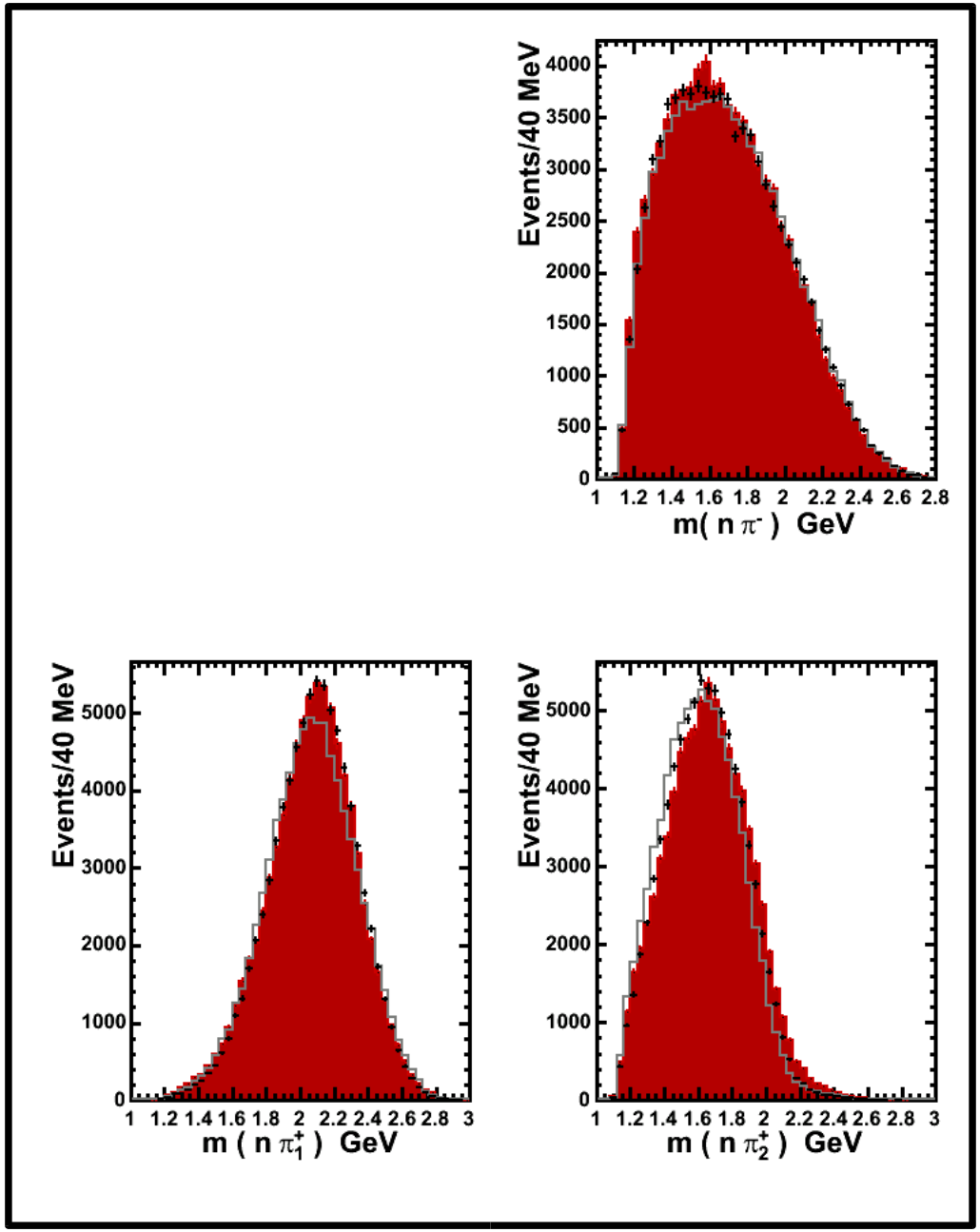
nπ and ππ invariant mass distributions

---- Data

\+ Predicted Data

--- Phase Space

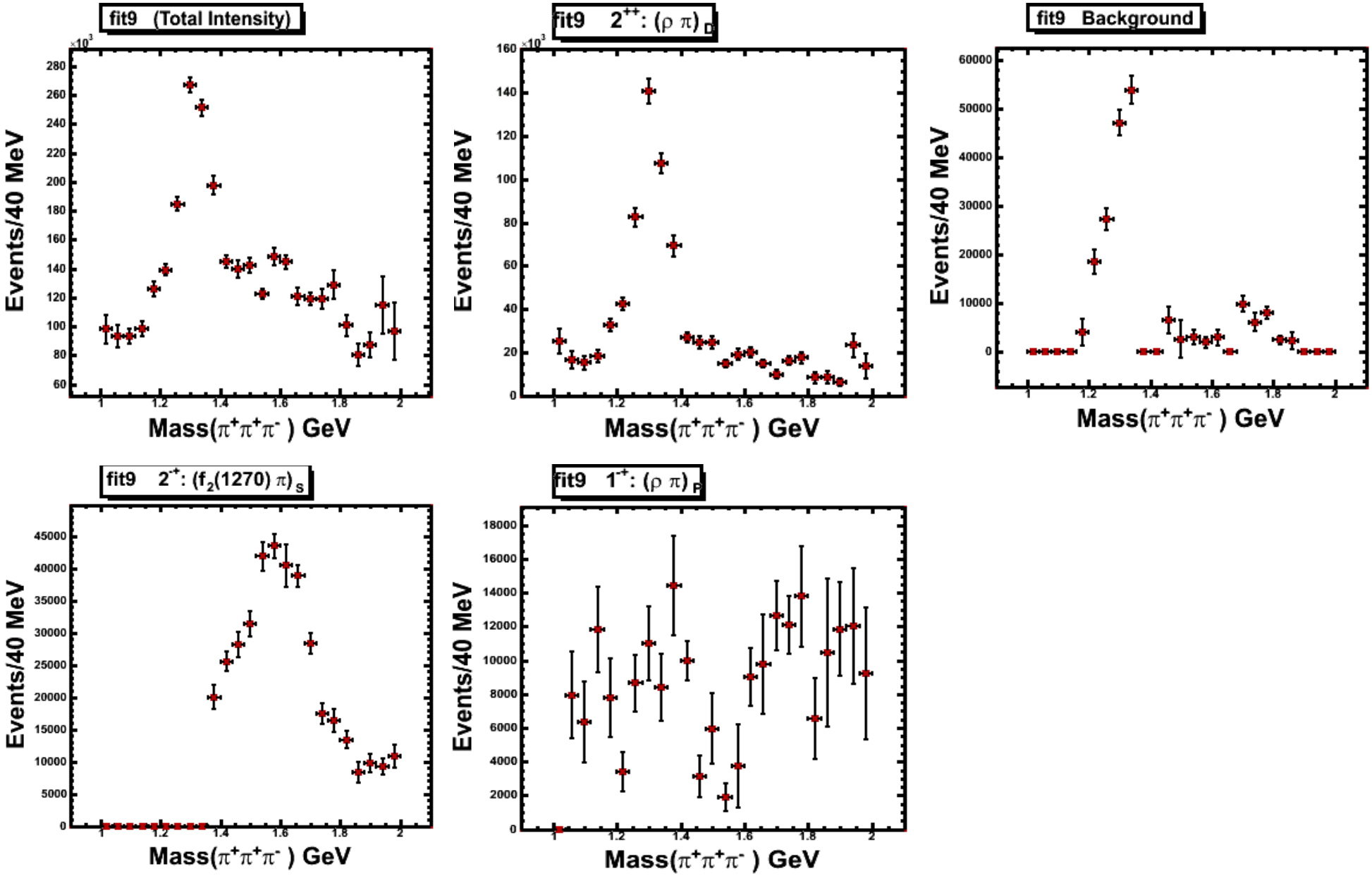




PWA fit9 results:

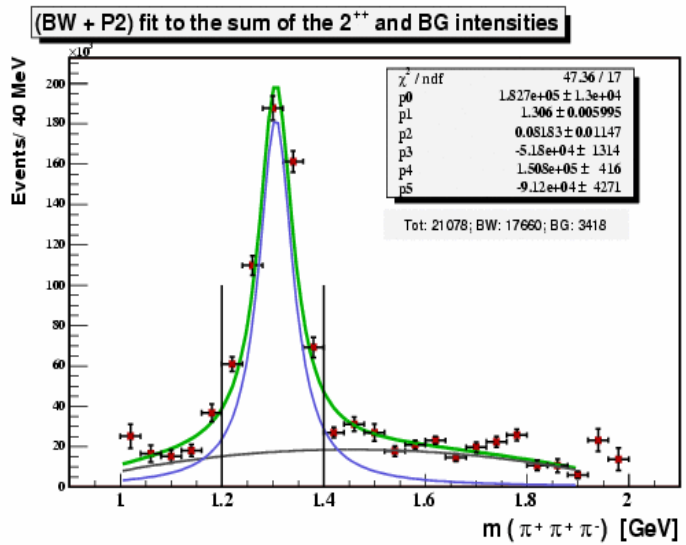
CLAS g6c: $\gamma\, p \rightarrow \pi^+\pi^+\pi^-(n)$

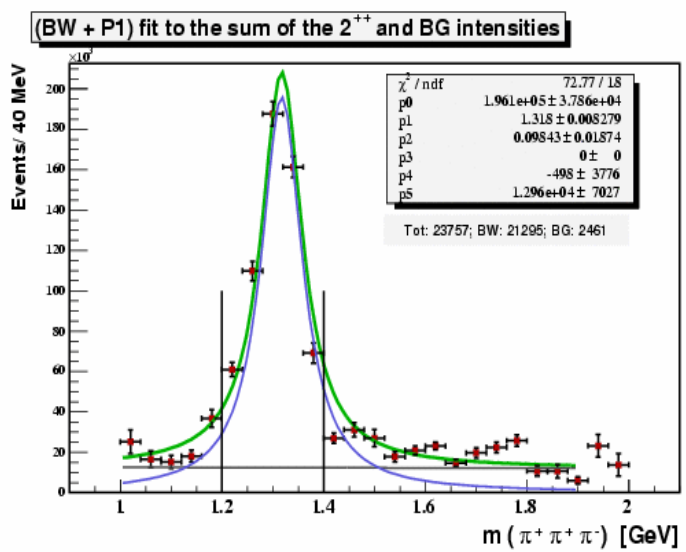
Acceptance corrected intensities



PWA fit9 results:

Preliminary $a_2(1320)$ cross section estimate:





a_2 yield: 534 K

Obtained from the average of three PWA fit results, and two descritptions of the background.

Number of photons: 3.58 x 10^{12} (2.7 pb^{-1})

Correcting for branching ratio, accounting for photon flux overestimation and a start counter timing resolution,

We get:

σ = 0.81 +/- 0.25 μb @ 4.8-5.4 GeV

Ballam et *al.* PL30B, 421, 1961:

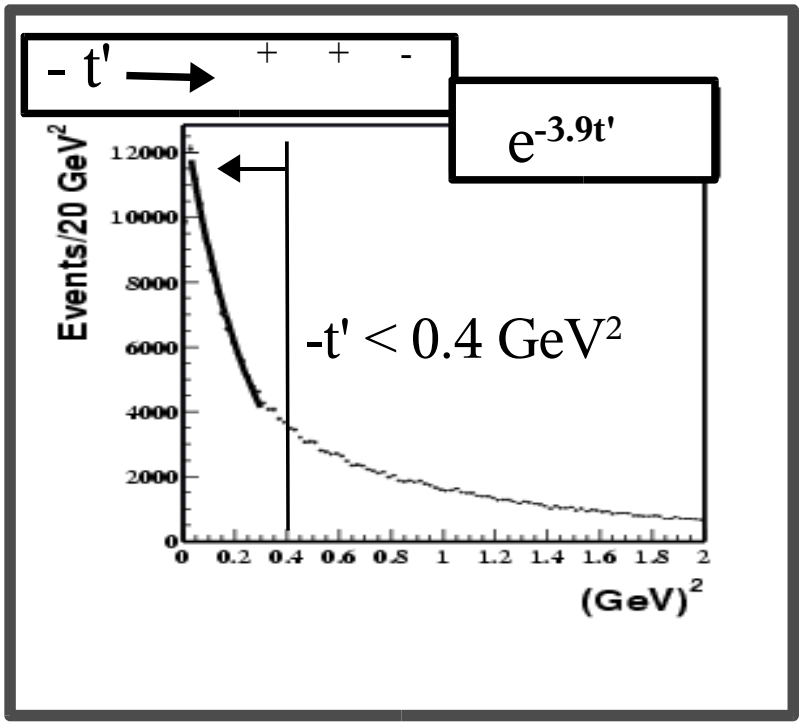
σ = 1.14 +/- 0.34 @ 5.25 GeV

Summary Of Observations

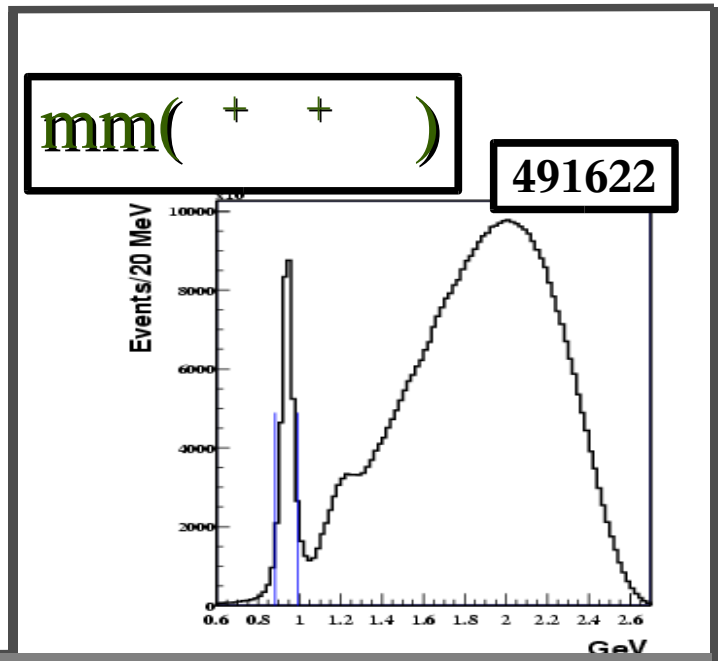
- We have performed numerous PWA fits on the first high statistic $\pi^+\pi^+\pi^-$ sample in photo-production from the Jlab CLAS g6c data. PWA formalism based on Isobar model description of the decays seems to be working.
- . The strongest/cleanest state observed is the $a_2(1320)$, at the expected mass and a width consistent with previously measurements. Our preliminary estimate of the a_2 cross section is 0.81 +/- 0.25 μb.
- Leakage from the background wave into the 2^{-+}, suggests that the rank of the density matrix in $\gamma p \rightarrow \pi^+\pi^+\pi^- n$ is > 2.
- The second strongest signal is the $\pi_2(1670)$, seen mostly in its $f_2\pi$ decay mode. In the $\rho\pi$ channel, the π_2 signal looks clean in the $(\rho\pi)_f$ decay mode but somewhat broad and "distorted" in the $(\rho\pi)_p$ channel. The same observation was reported by the BNL E852.
- We see no evidence of the $a_1(1260)$ and $\pi(1800)$, or the $\pi_1(1600)$ production. No phase motion observed B/N the 1^{-+} $(\rho\pi)_p$ and the 2^{-+} $(f_2\pi)_s$ waves.
- All fit results show production of major states, a_2 and π_2 in equal strengths in the m $= 1^+$ and m $=1^-$ projections. This is a significant confirmation that the method is working since the unpolarized photon beam should equally populate the m $= 1^+$ and m $=1^-$ states.

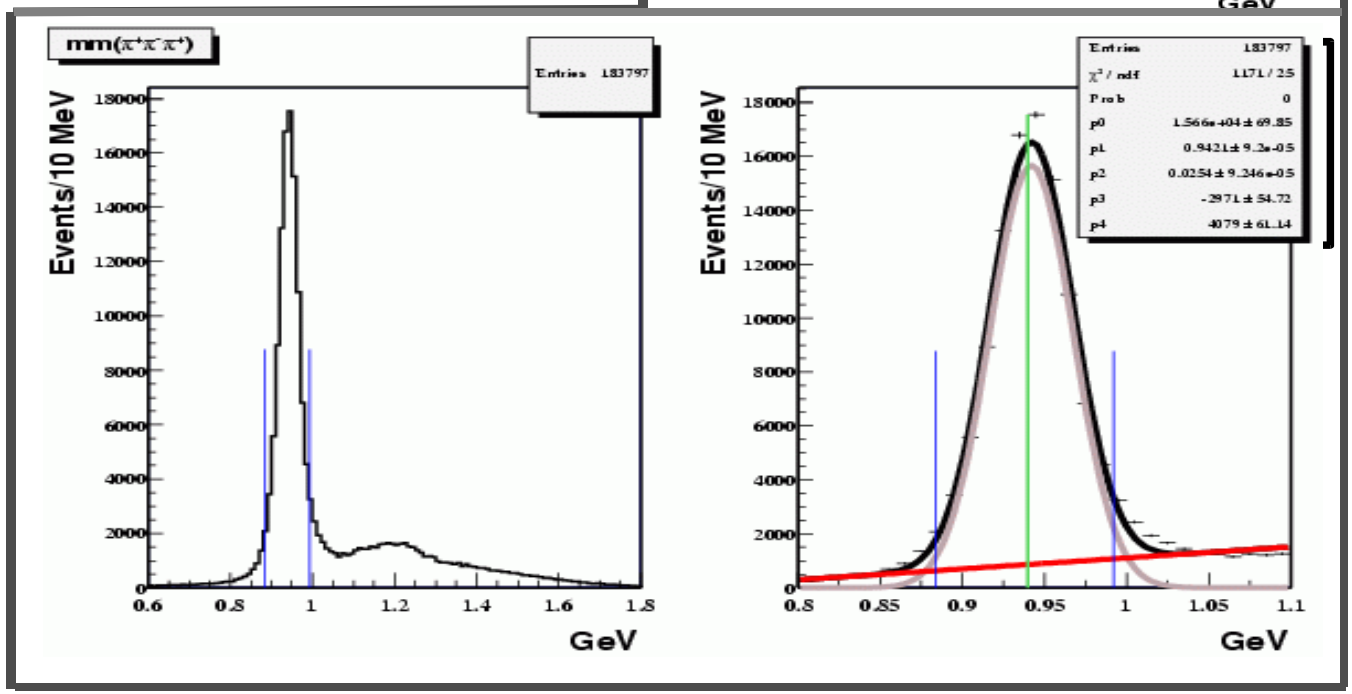
EXTRA SLIDES

CLAS g6c: $\gamma\, p \rightarrow \pi^+ \pi^+ \pi^- (n)$



All t'

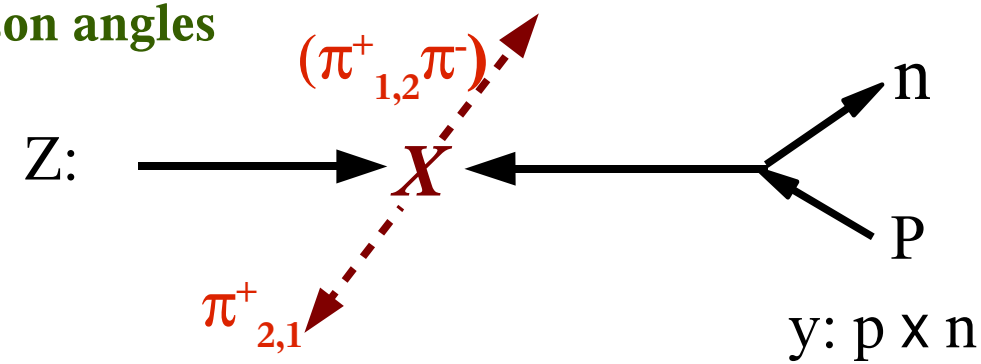




Check of fit9 quality:

Gotfried Jackson angles

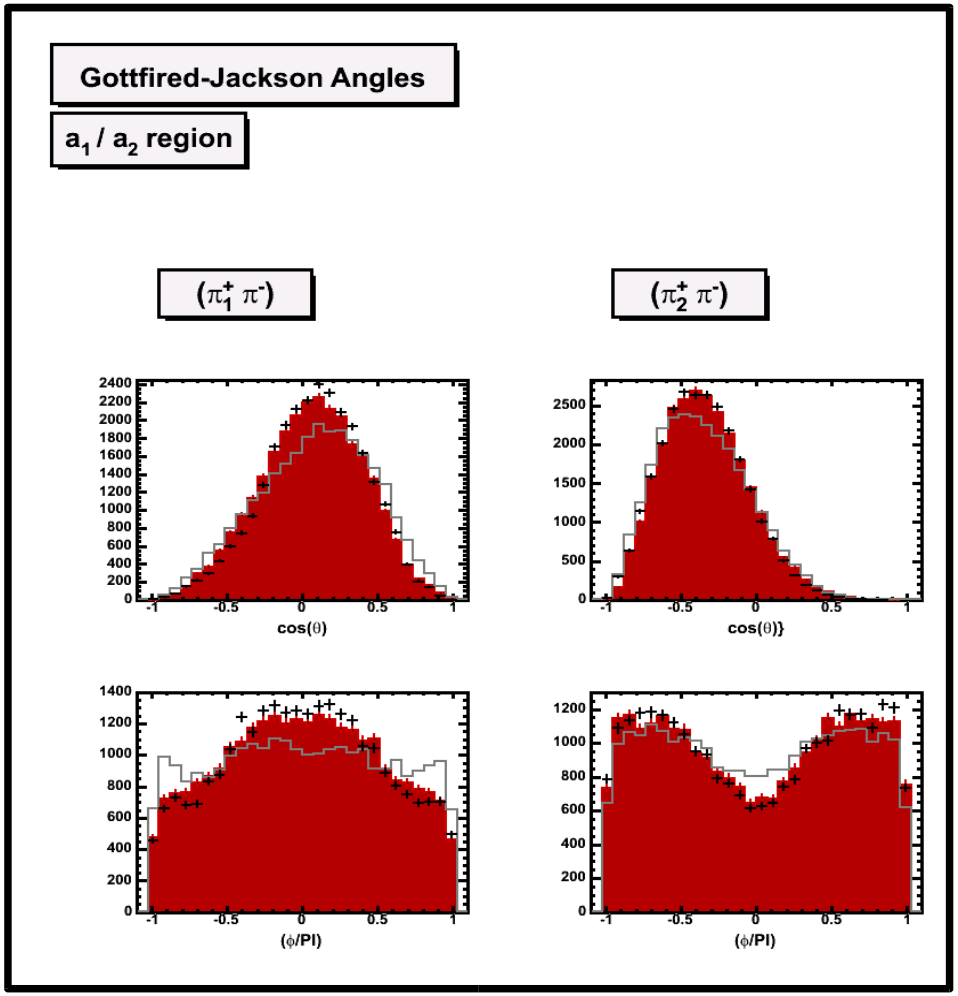
CLAS g6c: $\gamma\, p \rightarrow \pi^+ \pi^+ \pi^- (n)$

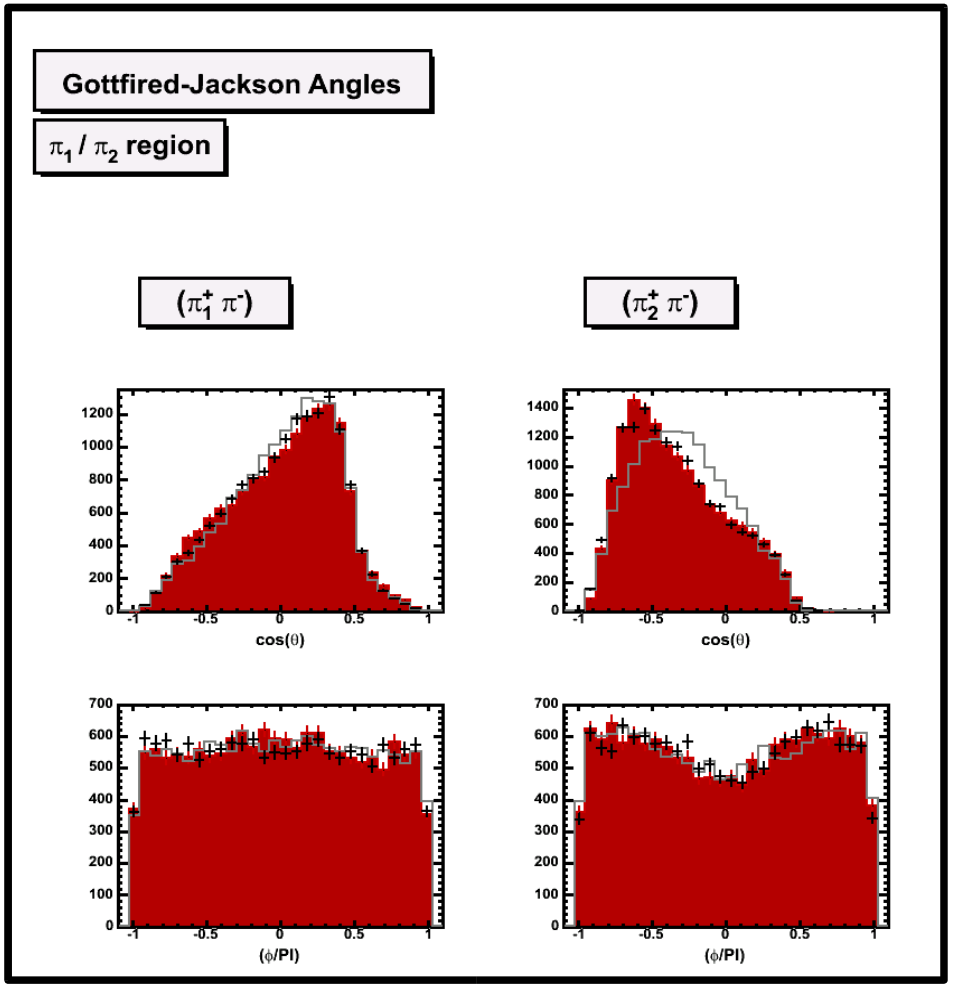


---- Data

\+ Predicted Data

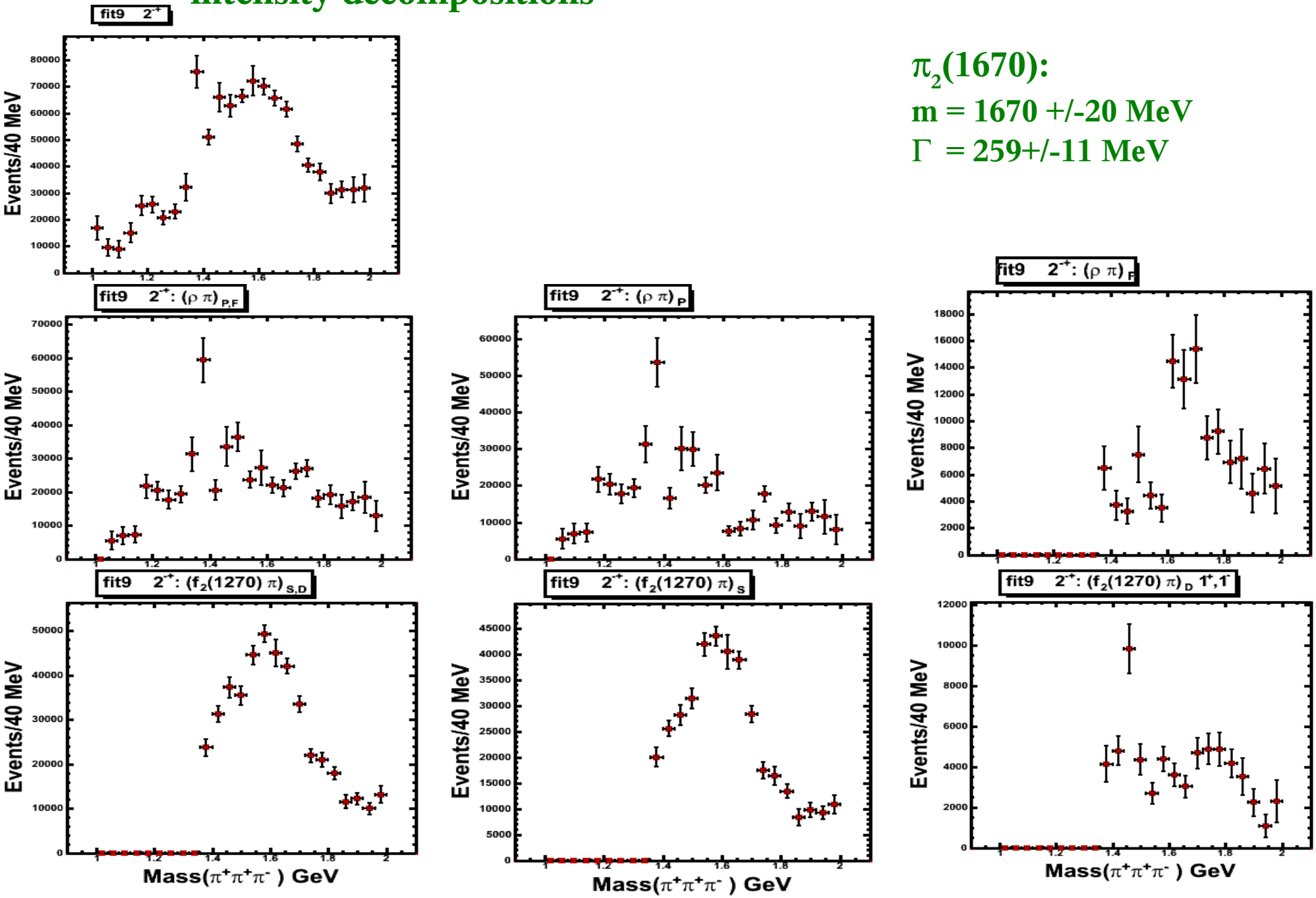
--- Phase Space





PWA fit9 results: 2^{-+} Total intensity and intensity decompositions

CLAS g6c: $\gamma p \rightarrow \pi^+\pi^+\pi^-(n)$



$\pi_2(1670)$:

m = 1670 +/-20 MeV

Γ = 259+/-11 MeV

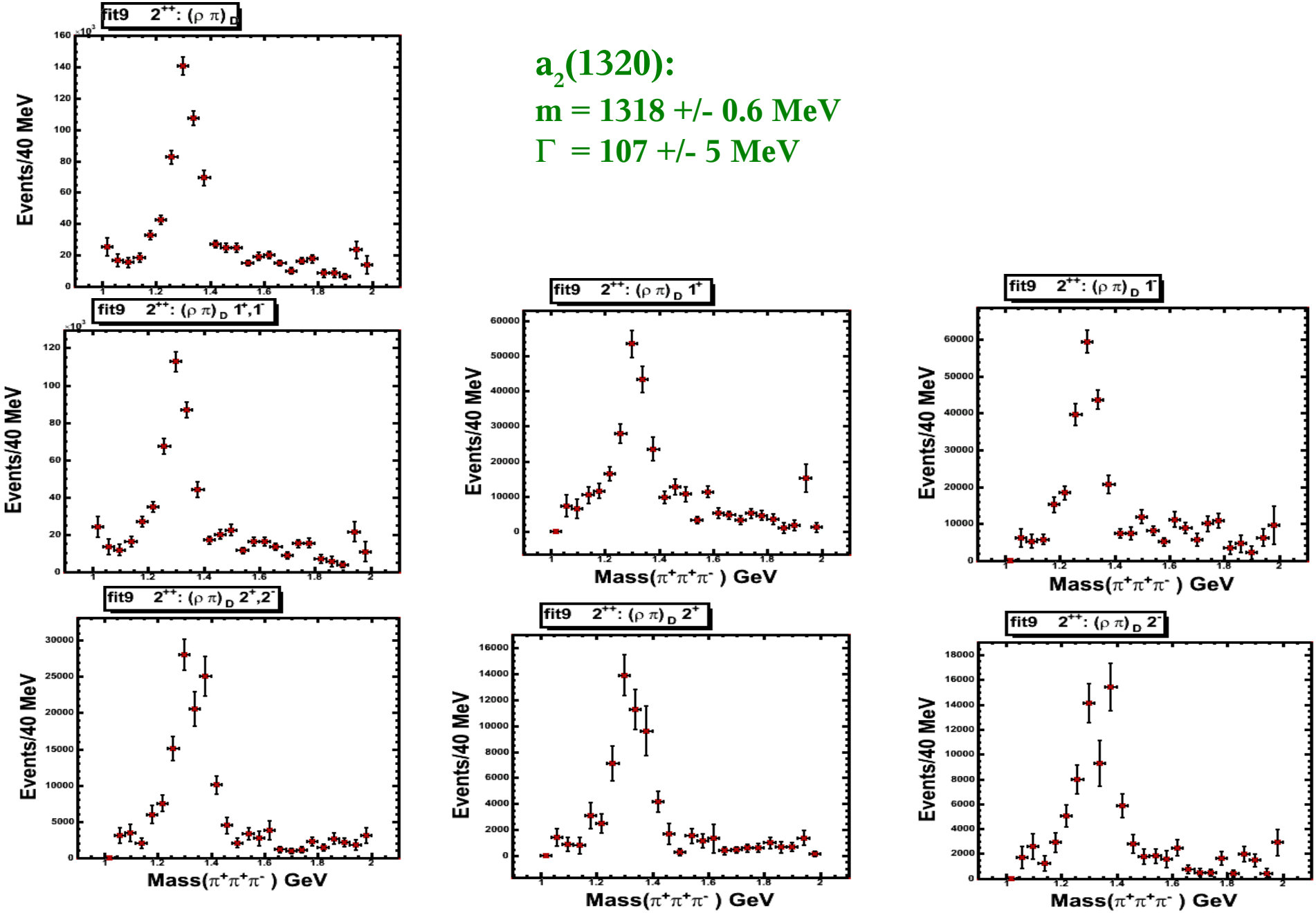
PWA fit9 results: 2^{++} Intensities

CLAS g6c: $\gamma\, p \rightarrow \pi^+\pi^+\pi^-(n)$

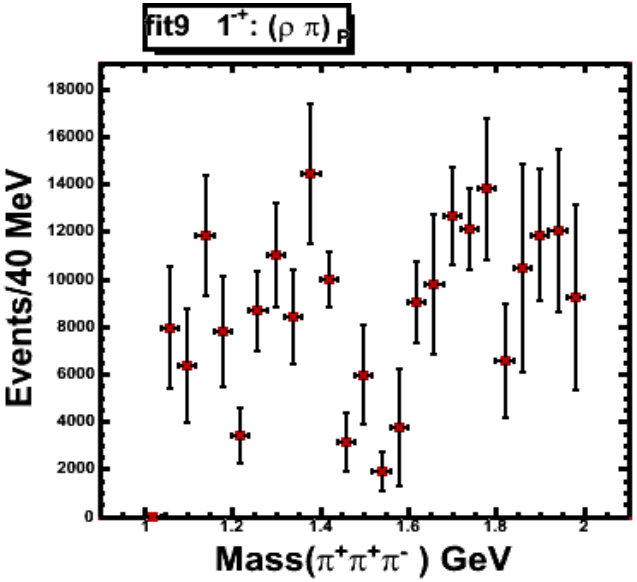
$a_2(1320)$:

m = 1318 +/- 0.6 MeV

Γ = 107 +/- 5 MeV



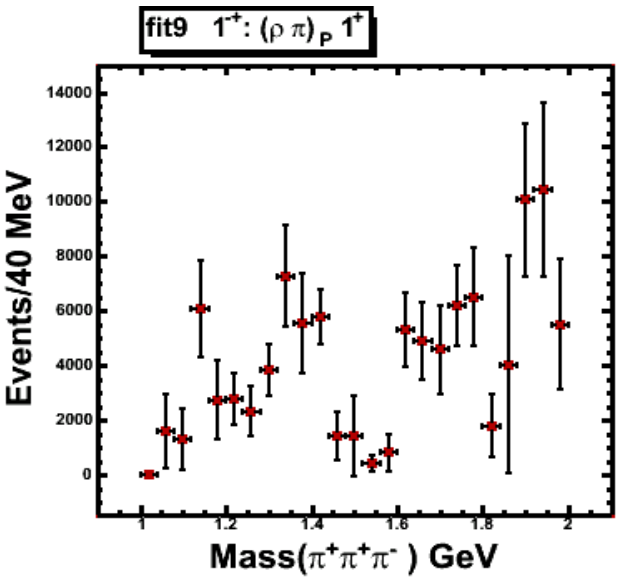
PWA fit9 results: 1^{-+} Intensities

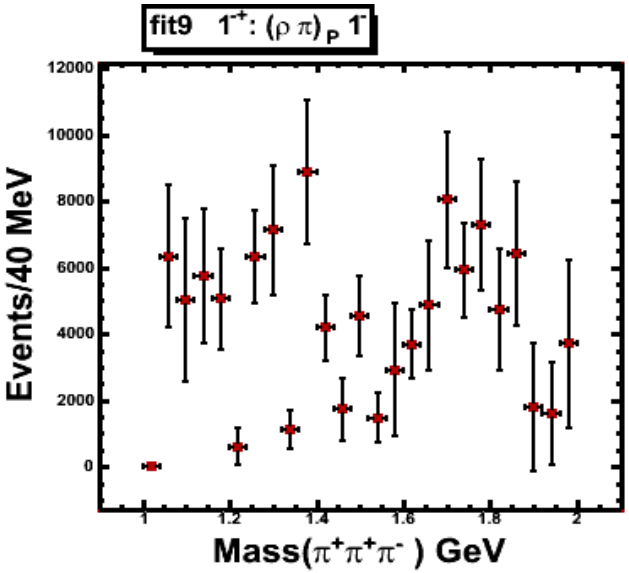


$\pi_1(1600)$:

m = 1593 +/- 8 MeV

Γ = 168 +/-20 MeV





Detector efficiency in PWA

Event Generation: 3 phase space in 20 MeV wide 3 mass bins, the same shape as that of the data distribution but with 15x the acceptance corrected number of events in each bin.
The acceptance is on the order of 4%.

CLAS simulator: gsim
Drift chamber Doca smearing, wire efficiency and TOF TDC smearing: gpp
Event reconstruction: a_1
Analysis: Cuts as applied to data

Decay amplitude calculation: As in the data for the partial waves included in a fit, both for the raw mc, M_r and accepted mc, M_a events.

Computation of the normalization integrals, raw N.I. and accepted N.I.

Accepted Normalization Integrals:
Used during the fitting procedure to take into account the finite acceptance of the detector on a partial wave by partial wave basis.

$$^{\epsilon}\Psi^{a}_{xx'} = \frac{1}{M_a}\sum_{i}^{M_a} {}^{\epsilon}A_x(\tau_i)\,{}^{\epsilon}A^{*}_{x'}(\tau_i)$$

Raw Normalization Integrals:
used after the fittingfor obtainingacceptance corrected number of events in a given 3p mass bin.)

$$^{\epsilon}\Psi^{r}_{xx'} = \frac{1}{M_r}\sum_{i}^{M_r} {}^{\epsilon}A_x(\tau_i)\,{}^{\epsilon}A^{*}_{x'}(\tau_i)$$

Typical tasks involved when during/after PWA fitting procedure:

1) Varying input wave/isobar sets in a fit. Check significance of an input wave by adding/subtracting waves, making note of the change in the likelihood value.

2) Selection of of wave sets for different "low" and "high" 3 mass regions in the fit.

3) Use of the "tracking" method in the fits where the output parameter from the results of a given fit in a mass bin are used as starting input parameter values for the fit in the adjacent bin.

4) Introducction of higher "rank" fits.

5) Checking the "stability" of the fits. Perform many fits for the same input wave set, but with randomly varying initial parameters. Choose the fit for with the "best" likelihood value.

6) Checking the "goodness" of the fit. Weight monte carlo evens by the "predicted" number of events as obtained from the PWA. Compare various distributions between the "data" and the "fit predicted data" sets.

7) Checks for "leakage", where intensities from one state may show up in another, due to "incomplete" knowledge of the detector acceptance/resolution.

8) Extract resonance parameters by performing "mass-dependent" fits.