Testing CLAS12 for Partial Wave Analysis

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Amplitude Analysis in Hadron Spectroscopy
January 24-28th , ECT*, Trento

Meson Spectroscopy with CLAS12

JLAB electron beam upgraded to 12 GeV
Complementary upgrade for highly successful CLAS spectrometer

New proposal (see talk of Marco Battaglieri) :
“Meson Spectroscopy with low Q^2 electron scattering with CLAS12”
M. Battaglieri, R. De Vita, S. Stepanyan, D. Weygand, D. Glazier, C. Salgado,
Approved by PAC January 2011

GOAL : Establish the nature of light quark bound states

THROUGH:
-comprehensive study of meson spectrum
-precise determination of resonance masses and properties

INCLUDING:
-Searching for exotic hybrid mesons
  Access to gluonic degrees of freedom
-Studying the production of scalar mesons
  Sensitive to quark and gluon configurations (glueballs, molecules)
-Measurement of the strangeonia spectrum ($s\bar{s}$)

Exotic mesons

Standard mesons come from $q\bar{q}$ (Quark model)
Quantum numbers : $P=(-1)^{L+1}$ and $C=(-1)^{L+S}$
$J=L+S$, $S=0$ or 1, $L=0,1,2,\ldots$
gives allowed states $J^{PC} = 0^{-+},0^{++},1^{++},1^{--},1^{+-},2^{-+}\ldots$

Additional configurations not prohibited by QCD,

e.g. hybrid mesons with gluonic constituents
- contribute $J^{PC} = 1^{--}$

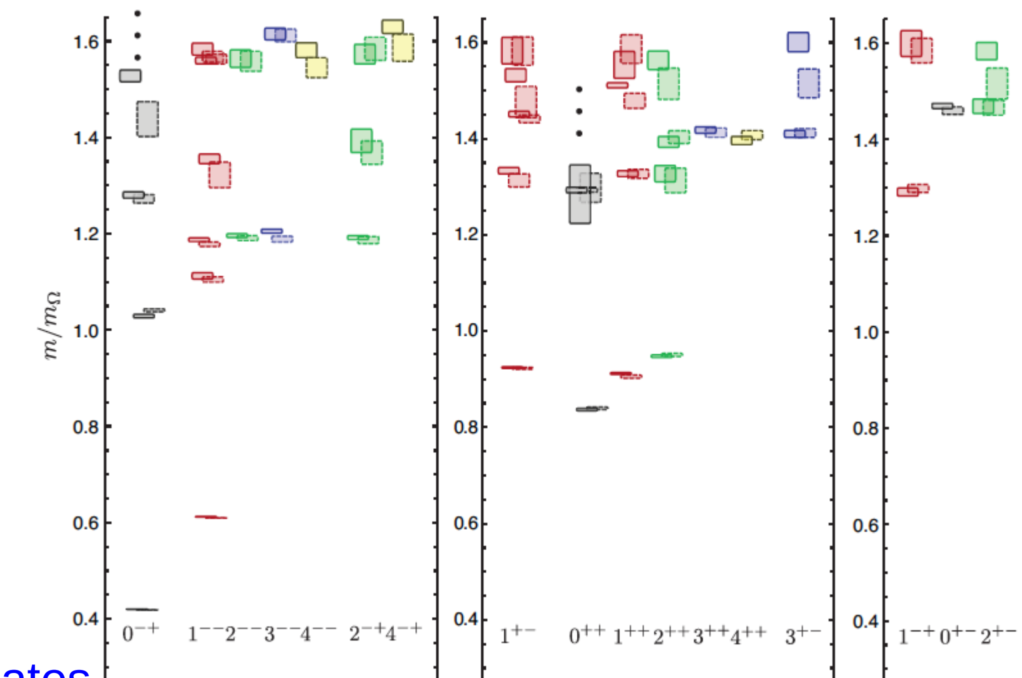
Gives allowed hybrid states :
0^{-+}, 0^{+-}, 0^{++}, 1^{++}, 1^{--}, 1^{-+}...

Now have additional exotic J^{PC} states

-Predicted by lattice QCD
-lowest mass 1^{-+} around 1.5-2 GeV/c^2

Establishing the existence of (exotic) hybrid states will provide a great test of lattice QCD framework

Exotics



Lattice predictions of meson masses
Dudek PRD 82 034508 (2010)

Meson decay to 3π

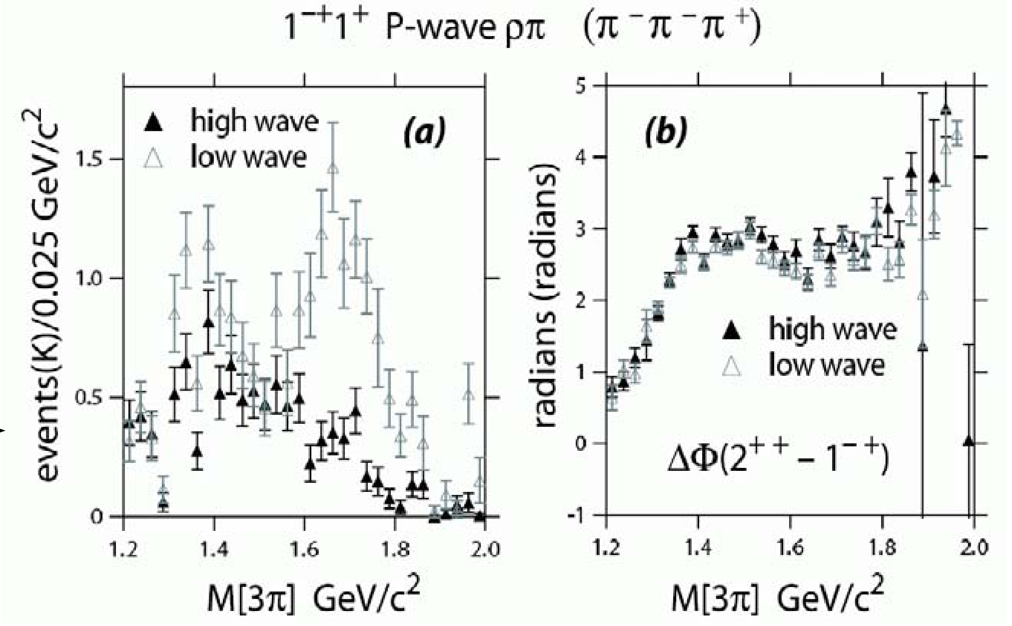
A good guide for CLAS12 spectroscopy potential
Already much experimental and theoretical work on this final state
- Photo and Pion production

One of the main goals is to establish if exotic channel exists

For 3 charged π I=1 G=-1.-1.-1=-1 and so C=+1 (from $G=C(-1)^I$)
For intermediate $\rho\pi^+$ $P=-1.-1.(-1)^L$, so for L=1 P=-1
So a J=1 resonance decaying to $\rho\pi^+$ in the P wave , belongs to exotic 1^{-+} multiplet

In π-p → 3π p
E842 claimed signal, Adams, PRL 81, (1998)
→ $\pi_1(1600)$ 1^{-+}

Reanalysis with larger number of waves in PWA
And higher statistics (5.7M events)
→ no signal, Dzierba, PRD 73, (2006)

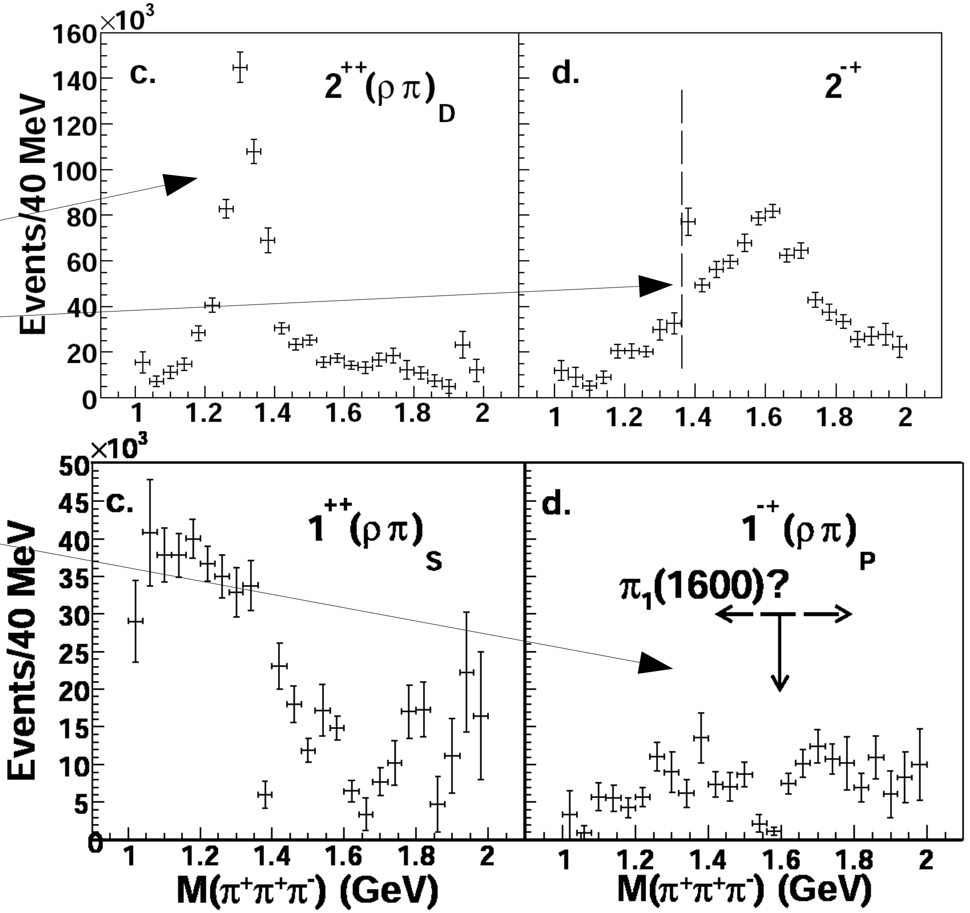


$\gamma p \rightarrow \pi^+\pi^+\pi^- n$

Benefits compared to pion production

No spin flip required from S=1 beam ($q\bar{q}$ spins aligned)
- Higher cross sections, comparable to normal mesons
While pion beams a factor 5-10 lower
Szczepaniak,Swat PLB 516 72(2001)

First results from CLAS collaboration
Novar PRL 102 102002 (2009)
83,000 events
4.8<Eγ<5.4 GeV
Prominent a2(1320) and π2(1670)
<u>Little π1 signal,</u>
<2% a2 strength

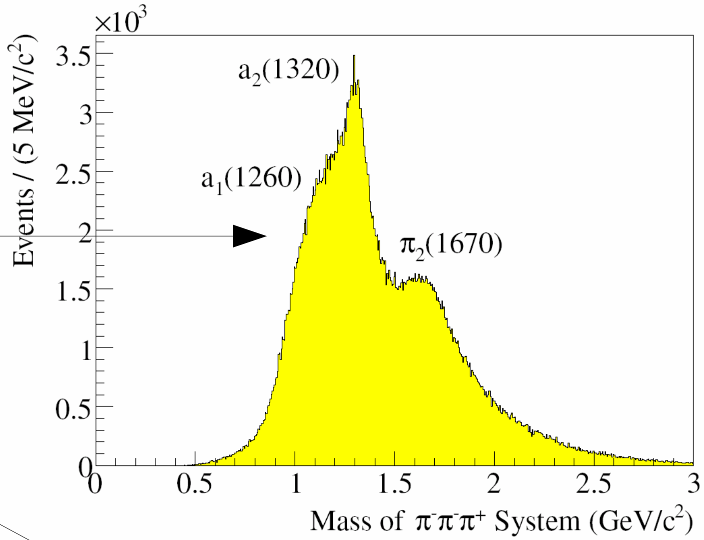


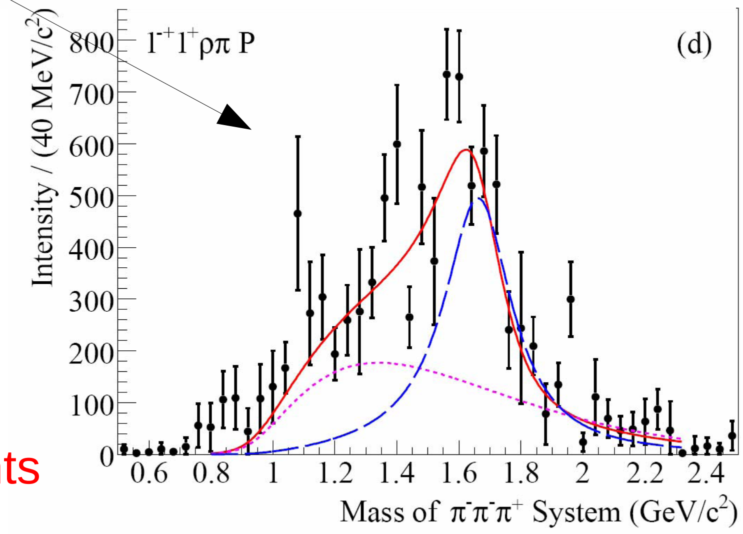
Higher statistics CLAS dataset taken and under analysis

Both are lower beam energy compared to Proposed CLAS12 experiment
7<Eγ<10.5 GeV

COMPASS π-π-π+ decay

Diffractive dissociation of π^- on lead target
PRL 104, 241803 (2010)
420,000 events
Reconstruct well known mesons a_1, a_2, π_2
+signal in exotic wave $\pi_1(1600)$?
~2% of overall yield





Other experiments :
+signals for $\pi_1(1600)$ in several other final states; $\eta'\pi$, $f_1\pi$, $b_1\pi$

Great need for high statistics photoproduction experiments (JLAB - CLAS, GLUEX, CLAS12)

CLAS12 with 11 GeV e^- beam

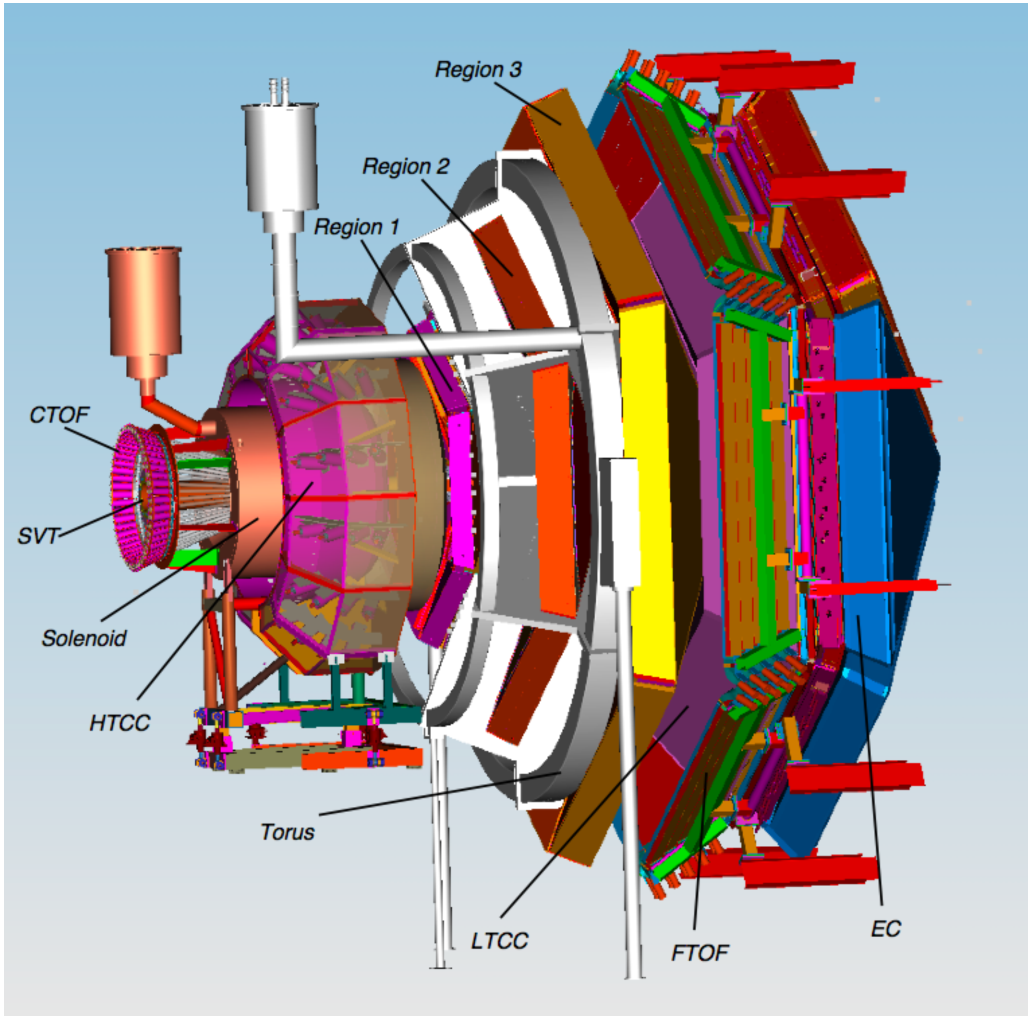
- Large angle acceptance for charged and neutral particles
- Excellent momentum resolution for charged particles → Requirements for PWA
- Excellent particle ID, particularly π/K

Forward Detector

- TORUS Magnet
- Forward silicon vertex tracker
- HThresh Cerenkov Counter
- LThresh Cerenkov Counter
- Forward TOF System
- Preshower calorimeter
- E.M. Calorimeter

Central Detector

- SOLENOID magnet
- Barrel silicon tracker
- Central TOF
- Neutron detector



Proposed additional detector system

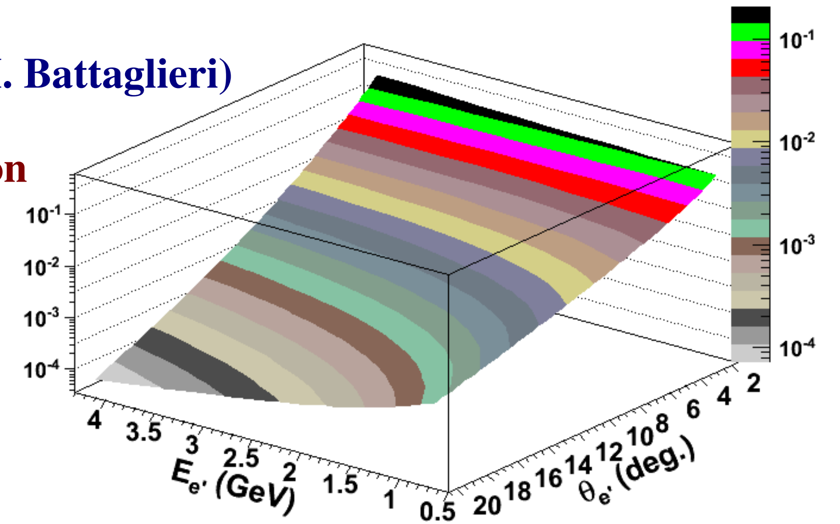
- Forward Tagger for quasi-real photoproduction

Quasi-real Photoproduction

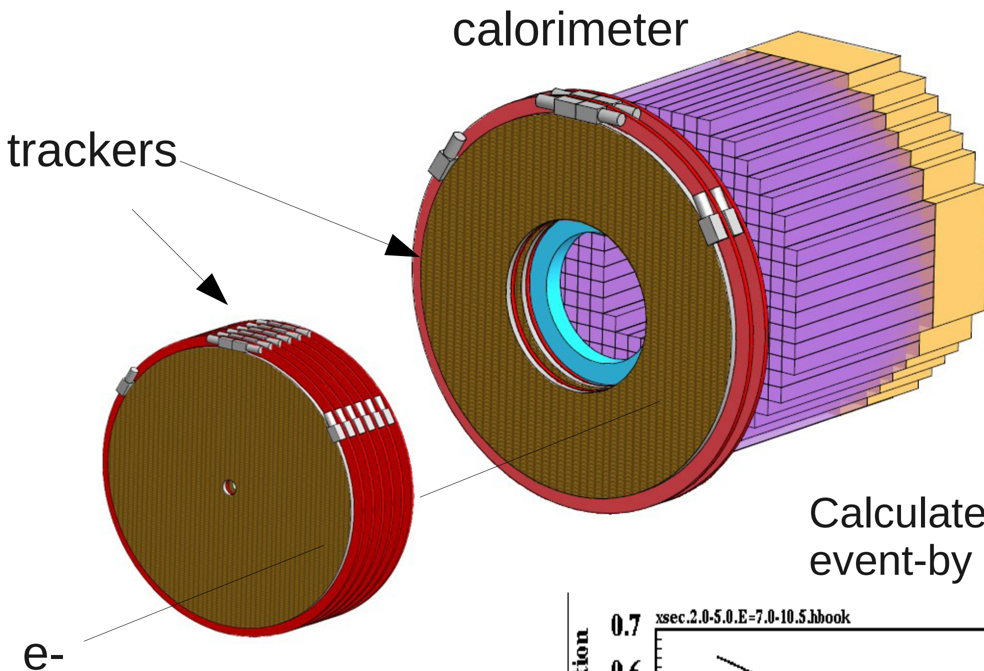
- **Small angle e^- scattering (<5°), tagged by E.M. Calorimeter (M. Battaglieri)**

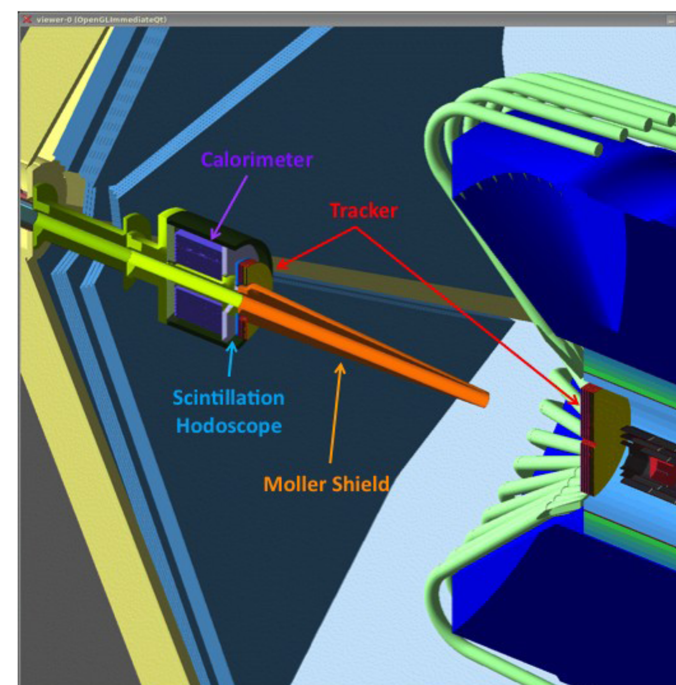
  ⇨ **$Q^2 < 0.1 (GeV/c)^2$ virtual photon ⇔ (almost)real photon**

  -high virtual photon flux ⇨ high production rates



Hadronic production rate at full luminosity
2-5°=8.6kHz
5-20°=3.8kHz



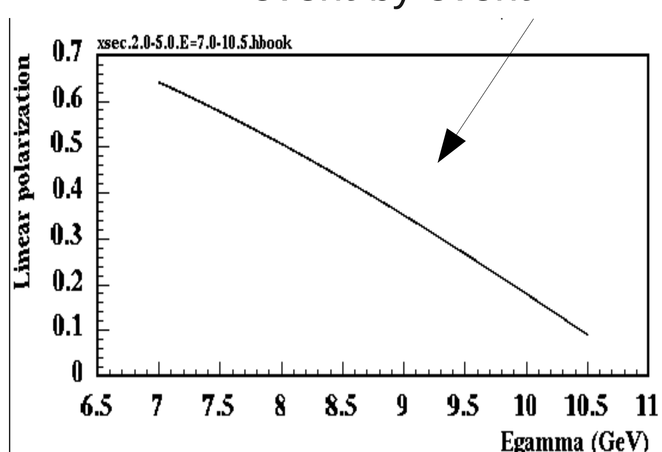


- **Electron $0.5<E_{e'}<4$ GeV ⇔**

  Photon $7<E_\gamma<10.5$ GeV

  Quasi-real photons are linearly polarised wrt scattering plane

Calculate polarisation event-by event



$ep \rightarrow e'\pi^+\pi^+\pi^- n$ with CLAS12

11 GeV e- scattering in 5cm lH_2 target

Luminosity ~ $10^{35} cm^{-2} s^{-1}$

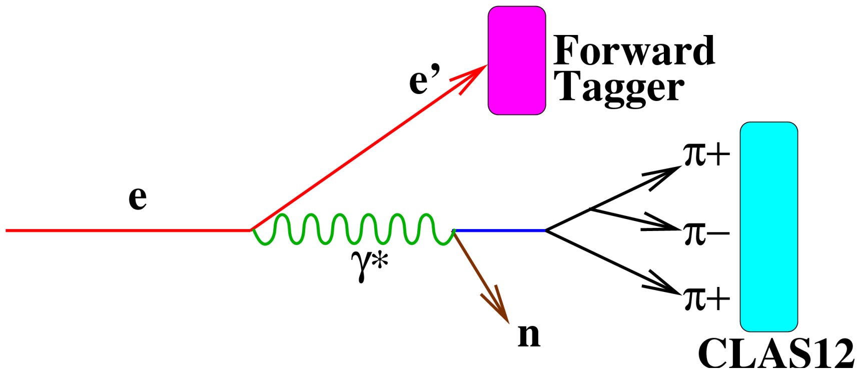
e' detected in forward tagger

$\rightarrow$ γ energy (7-10.5 GeV) and polarisation

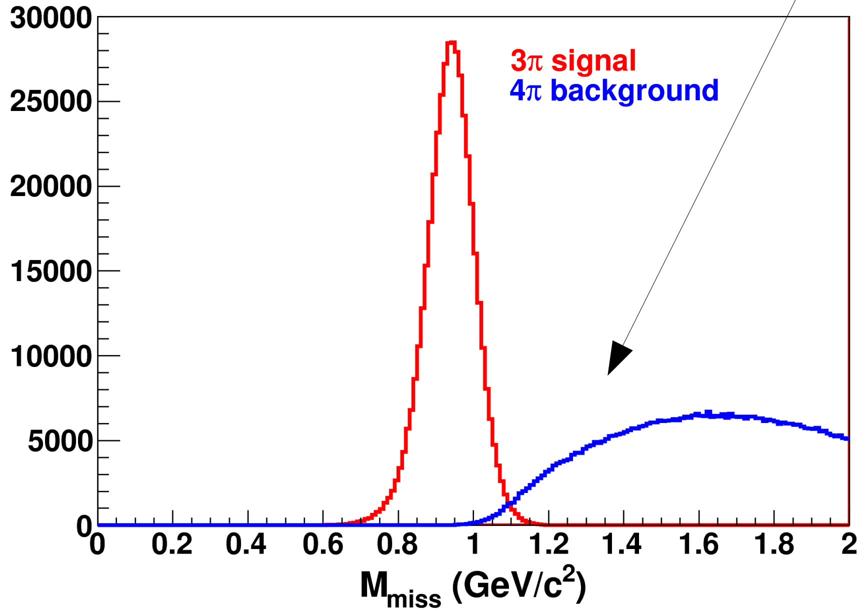
- σ_E = 0.02-0.07 GeV

3π detected in CLAS12

- σ_p=0.5 %, σ_θ=1 mrad , σ_φ=3 mrad

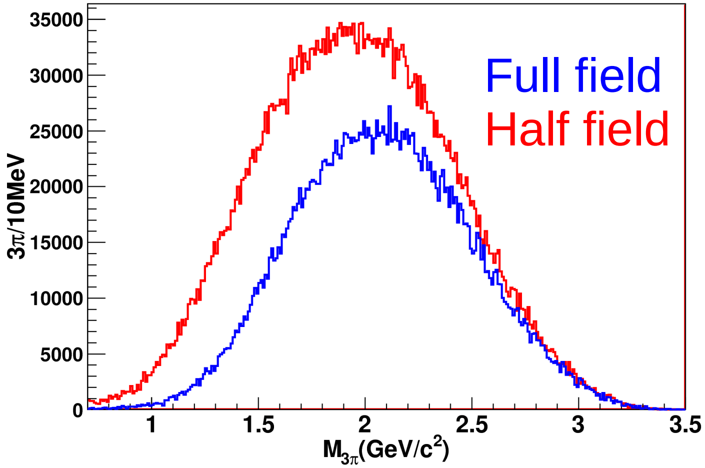


Resolution allows good discrimination from other final states (simulation)



Neutron reconstructed by missing mass

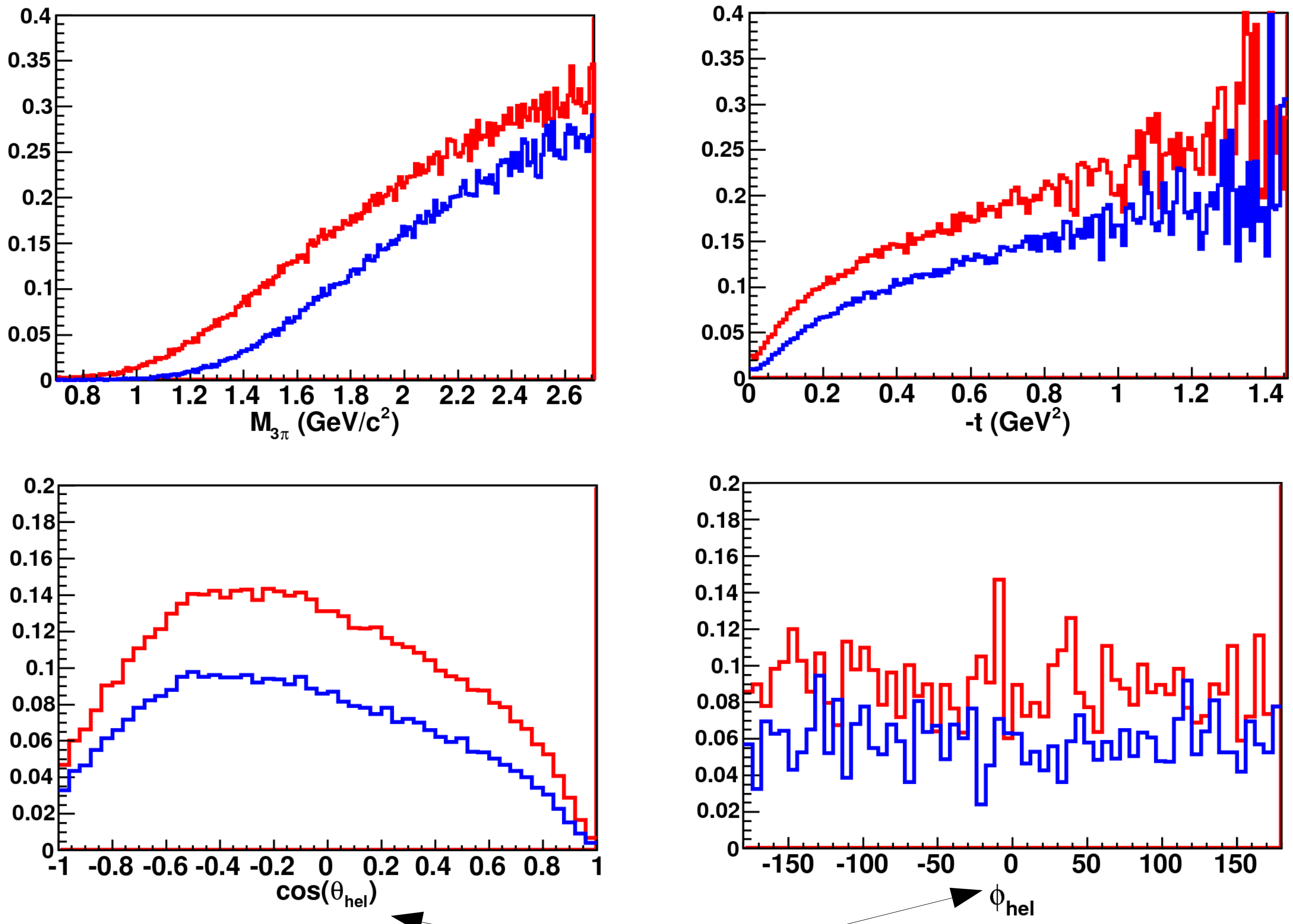
Expected number of reconstructed events from initial low luminosity data (20 days)



80 day experiment with full luminosity

80 X more events or 10^6/10MeV

Kinematic acceptances



Angles used for decay ampitudes

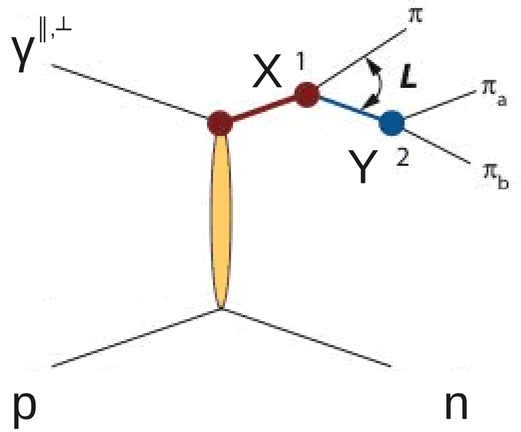
Red line – half CLAS toroidal field, blue line – full CLAS12 toroidal field

IUAmpTools

Developed at Indiana University by H. Matevoysan, R. Mitchell and M. Shepherd
General Amplitude Analysis Tools for event generation, fitting, plotting...
GPU enabled – up to 100 times faster than CPU processing

User:
Requires interface with 4-vector files
function to calculate amplitude

See Matt Shepherd's presentation (next)



Linear polarisation=incoherent sum over $\parallel,\perp$ states

Constructs intensities as

$$I(a_k) = \sum_{p=\parallel,\perp} \omega_p \left| \sum_i^{N_X} V_i A_i^p(a_k) \right|^2$$

$$\textbf{with } a_k = \{M_X, \theta_X, \phi_X, M_Y, \theta_Y, \phi_Y, k, q\} \textbf{ and } \omega_p = \frac{1 \pm P}{2}$$

Can then be used for event generation/fitting

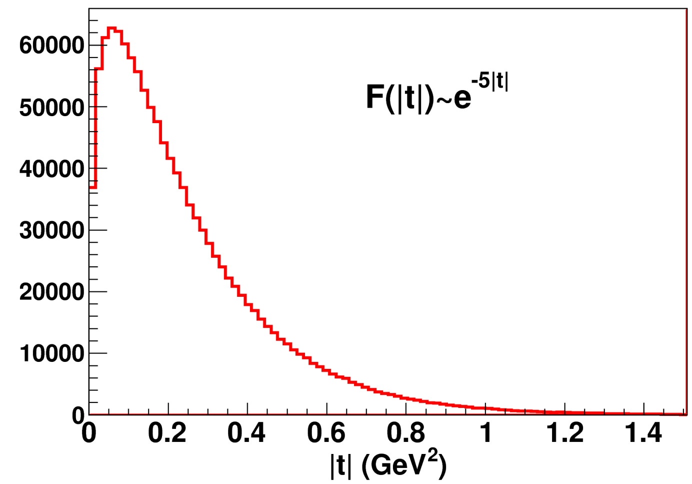
N_X=# of resonance channels
X=resonance
Y=isobar in decay
k=X momenta
q=Y momenta
P=fractional γ polarisation
V_i= production amplitudes
= fit parameters

PWA tests with CLAS12 Simulation

Not attempting rigorous theoretical description of process!

Show CLAS12 can reproduce input model

(Isobar) Model (with Szczepaniak, Shepherd (Indiana))



Assumptions

Factorise production from decay
= fit parameters from amp calculation

Production Eγ dependence is flat
- scattered electron distribution from virtual photon flux

Dominated by one pion exchange
-use e^{-5t} factor (t=momentum transfer)
-single unnatural parity exchange

Helicity conservation in the s-channel
- Sum amplitudes for resonance spins ±1
- Decay angular distributions are defined in the resonance helicity system
Z axis along -ve neutron momentum in the resonance rest frame
Y axis normal to production plane

Neglect photon longitudinal polarisation components
- Linear polarised amplitudes (‖,⊥) related to helicity amplitudes :

$$|\|\rangle = \frac{1}{\sqrt{2}}e^{-i\alpha}\,|\lambda_\gamma = +1\rangle + \frac{1}{\sqrt{2}}e^{i\alpha}\,|\lambda_\gamma = -1\rangle$$

-α is the angle between e scattering plane and production plane

Constructing Isobar Amplitudes

Amps in linear pol basis

Breit-Wigner parameterisation

Sum over identical pions

$$A_X^{\parallel,\perp} = \sum_{perm} B_X\left(M_X,k\right) B_Y\left(M_Y,q\right) F_X^{\parallel,\perp}\left(\theta_X,\phi_X,\theta_Y,\phi_Y,k,q\right)$$

Resonance decay distribution

Isobar decay distribution

Upper vertex contribution

$$F_X^{\lambda_\gamma} = \sum_{m_x=-L_X}^{L_X} \sum_{\lambda_I=-J_I}^{J_I} Y_{L_x}^{m_X}\left(\theta_X,\phi_X\right) Y_{J_I}^{\lambda_I}\left(\theta_Y,\phi_Y\right) V_{\lambda_\gamma\lambda_X}^{u}$$

$$\times \langle ang.mom.CJ\rangle \langle isobar.iso.CJ\rangle \langle res.iso.CJ\rangle$$

Phase space factor

$$\times k^{L_X} q^{J_I}$$

Naturality of produced resonance With P_x its parity

Assuming helicity conservation $\lambda_x=\lambda_\gamma$ and

$V_{11}^u = 1$ **and** $V_{-1-1}^u = -\eta_X\epsilon$ **where** $\eta_X = P_X(-1)^{J_X}$

With ε, the naturality of the exchange

and in linear polarisation basis,

$$F_X^{\parallel} = \frac{1}{\sqrt{2}}\left(e^{-i\alpha}F_X^{\lambda_\gamma=+1} + e^{i\alpha}F_X^{\lambda_\gamma=-1}\right) \textbf{ and } F_X^{\perp} = \frac{i}{\sqrt{2}}\left(e^{-i\alpha}F_X^{\lambda_\gamma=+1} - e^{i\alpha}F_X^{\lambda_\gamma=-1}\right)$$

Resonance channels

$I^G J^{PC}$	Resonance (X)	Decay (Yπ)	L
$1^- 2^{++}$	$a_2(1318)$	$\rho\pi$	2
$1^- 1^{++}$	$a_1(1230)$	$\rho\pi$	0
$1^- 1^{++}$	$a_1(1230)$	$\rho\pi$	2
$1^- 2^{-+}$	$\pi_2(1670)$	$\rho\pi$	1
$1^- 2^{-+}$	$\pi_2(1670)$	$\rho\pi$	3
$1^- 2^{-+}$	$\pi_2(1670)$	$f_2\pi$	0
$1^- 2^{-+}$	$\pi_2(1670)$	$f_2\pi$	2
$1^- 1^{-+}$	$\pi_1(1600)$	$\rho\pi$	1

For tests exotic wave contributes 2% to total

Algorithm flow chart/Testing CLAS12

Initial Production amplitudes → V_i

1M model Events "real"

5M phase Space events

Detector simulation (parametrized)

Split into $M_{3\pi}$ bins

Minimise

$$-2\ln\mathcal{L} = -2\sum_{data}\ln\left(I\left(a_k\right)\right) + 2\sum_{MC} I\left(a_k\right)$$

Amplitude Calculations Without X BW

V_i^{fit} ← Fit Production amplitudes

Intensity Calc

Compare $I(V_i)$ and $I(V_i^{fit})$

Can CLAS12/FT reconstruct events for PWA?

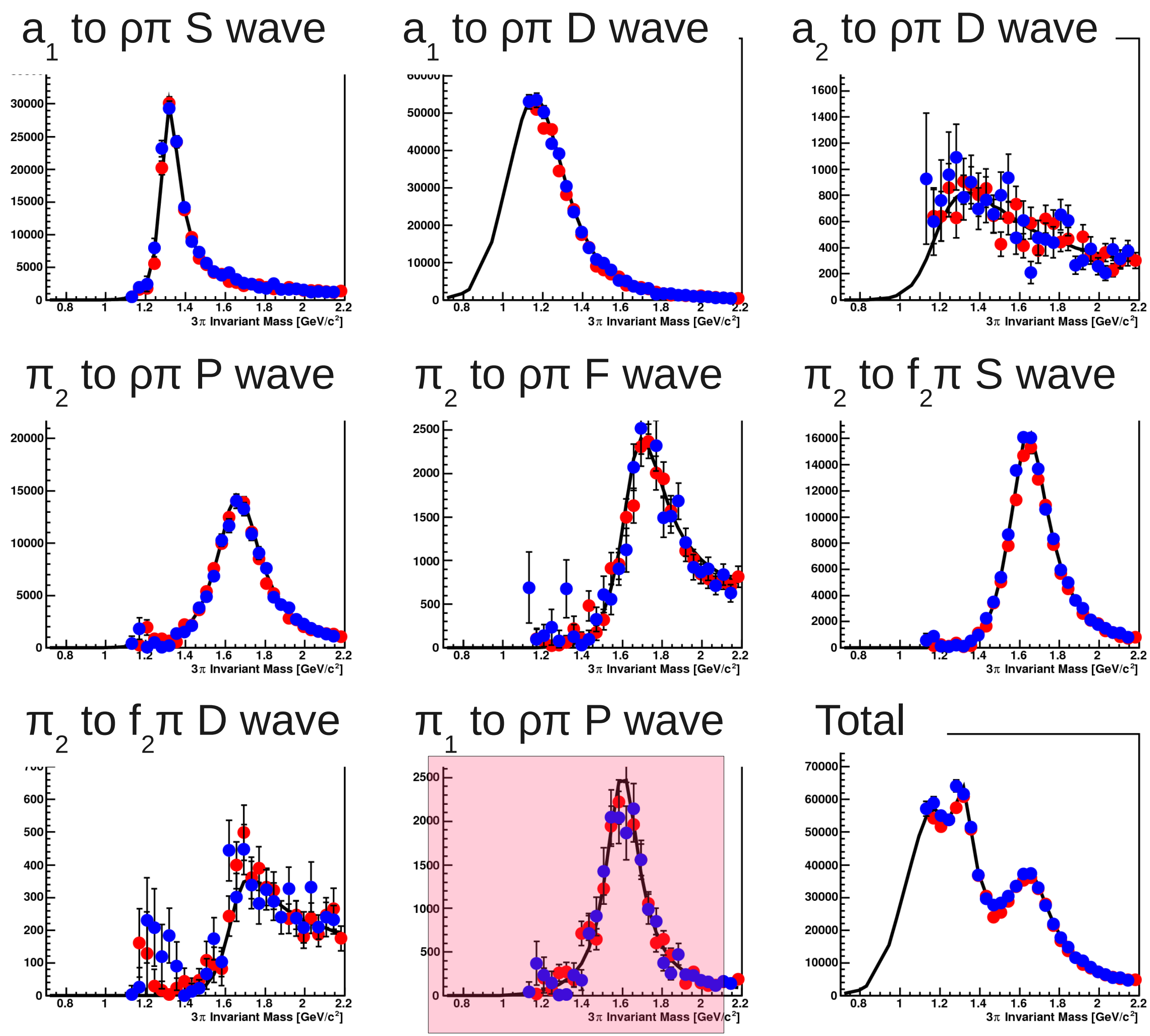
Test 2 t bins.

Generated waves

$|t|=0.2\ \mathrm{GeV}^2$

$|t|=0.5\ \mathrm{GeV}^2$

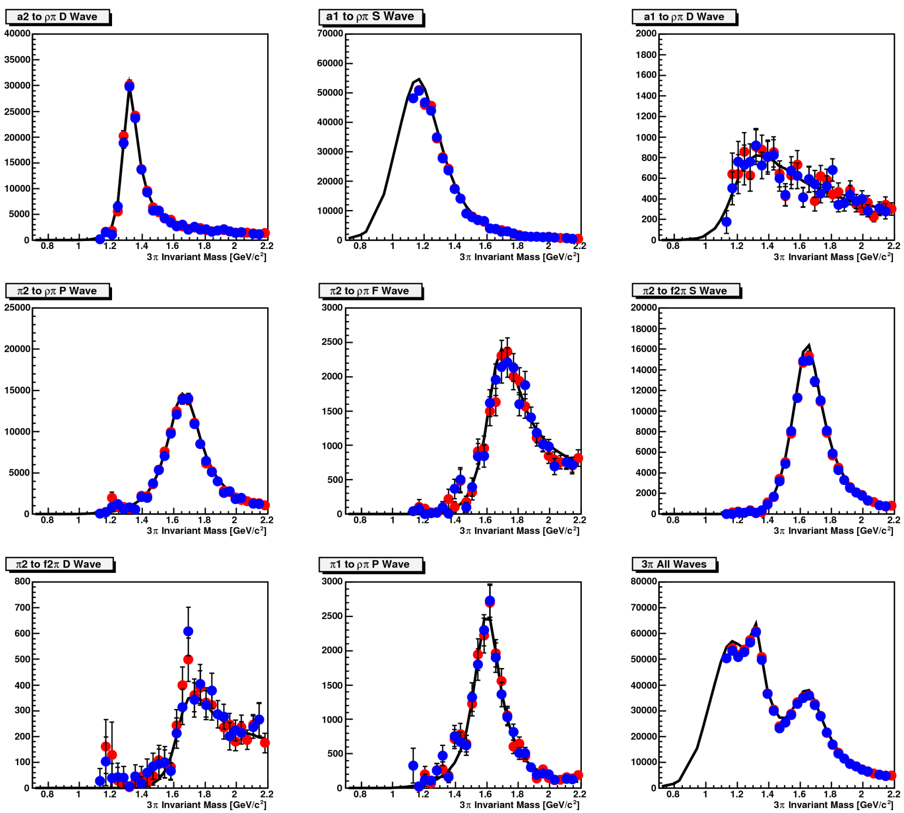
Function of $M_{3\pi}$



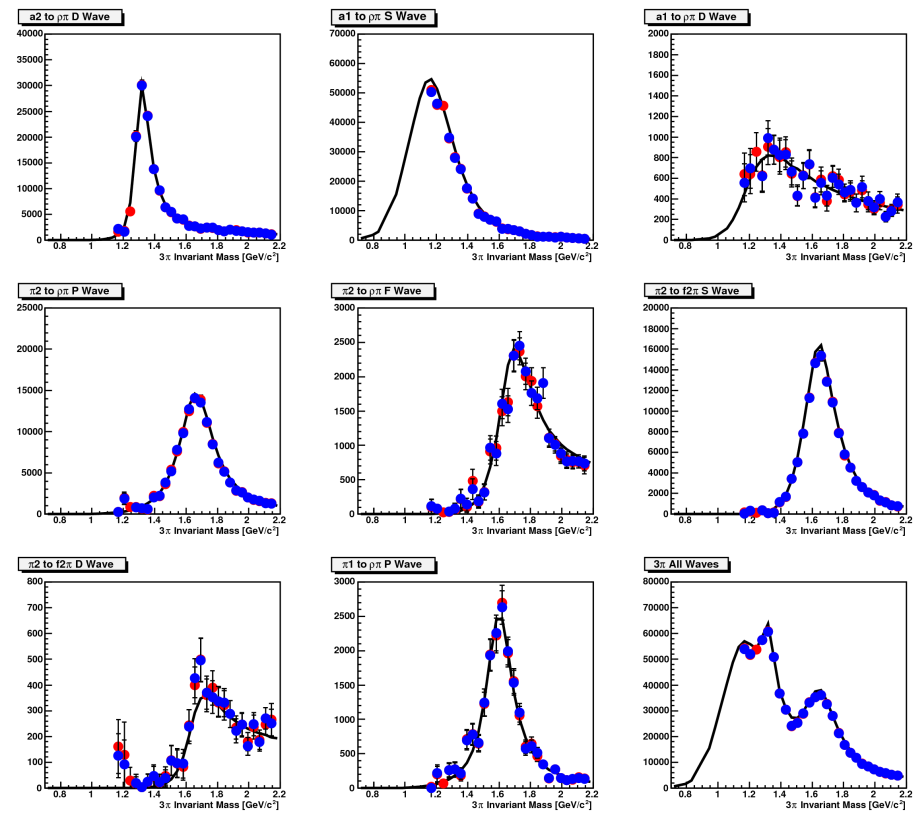
<u>The CLAS12 detector system is intrinsically capable of meson spectroscopy measurements (above 1.4 GeV/c^2)</u>

Is CLAS12 sensitive to poorly understood acceptance?

Mismatch “real” and sim field strength by 2%



Mismatch “real” and sim resolutions by 20%

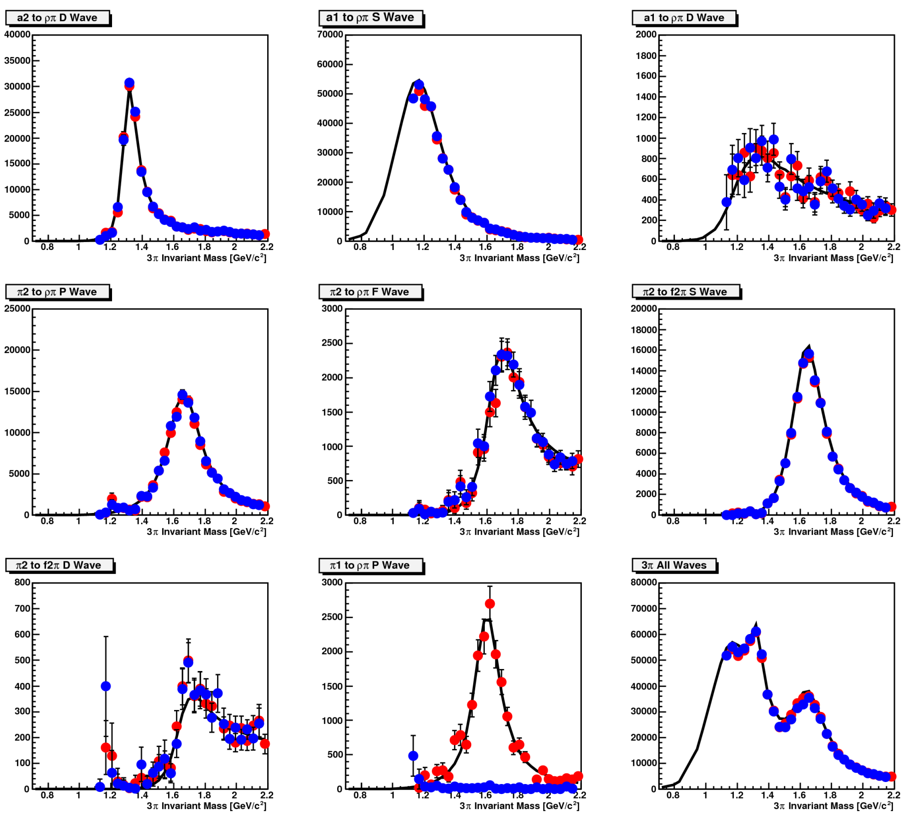


Red – standard fit, Blue – mismatch, Black - generated

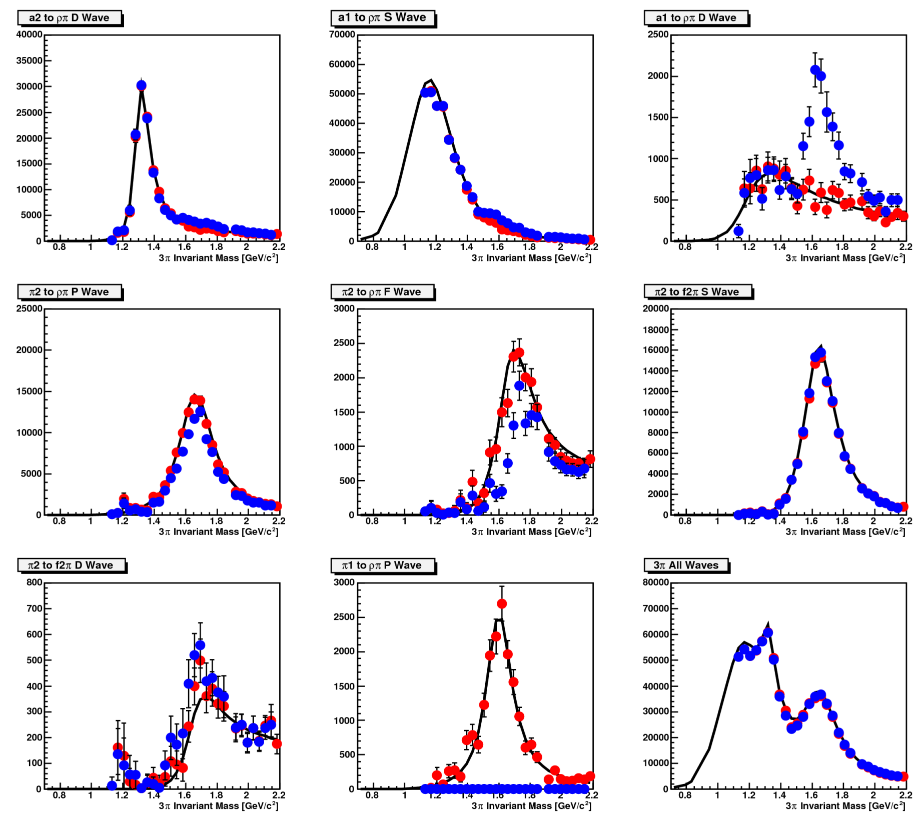
Fit results stable with reasonable mismatches

Tests with incomplete wave-sets

Do not generate π_1



Generate π_1, but not included in fit



Red – standard fit, Blue - mismatch

<u>No exotic signal induced by CLAS12 acceptance</u>

<u>Crucial to include sufficient waves in the fit</u>

Tests with linear polarisation

Linear polarisation sensitive to naturality of produced and exchanged particle

- Negative helicity upper vertex ~$\eta_X \varepsilon$
- Contributions from both exchanges add inchoherently to intensity

(i) For dominant exchange, linear pol + naturality can seperate overlapping states

(ii) For a given state they can seperate different production mechanisms
e.g π or ρ exchange

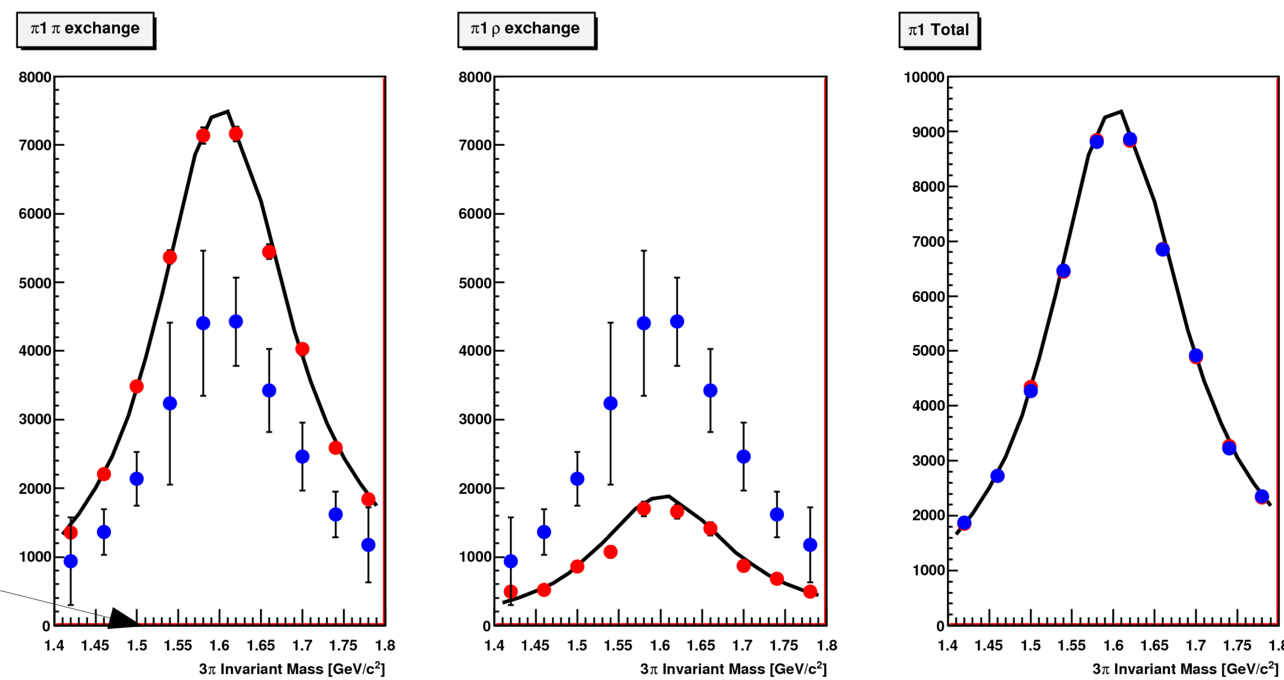
Generate π1
With both exchanges
3:1 π:ρ amps

Unatural pion
exchange

Natural ρ
exchange

total

$M_{3\pi}$



Red- virtual γ polarisation
Blue – zero polarisation
Black - generated

<u>Virtual photon polarisation with CLAS12 can help seperate naturality of the exchange</u>

Test with different decay systems

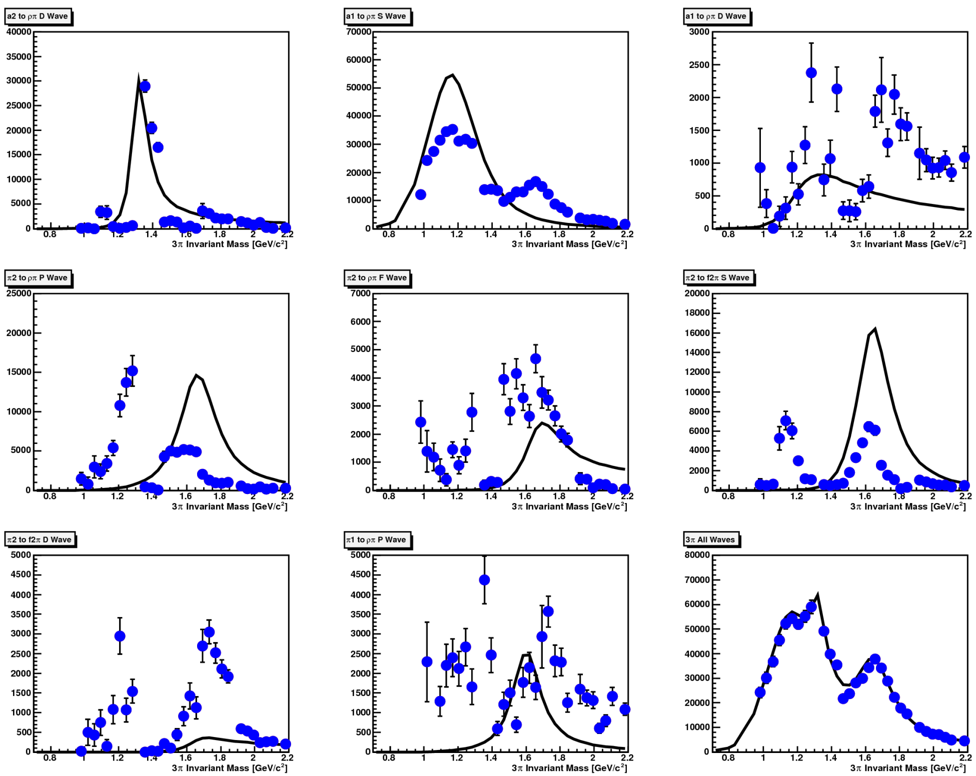
We assumed helicity conservation in the s-channel (model 1)
 - decay in the resonance (rest frame) helicity system (z-axis=-ve recoil baryon)

Different model – different system
e.g particle exchange in the t-channel
 - decay in the resonace (rest frame) Gottfried-Jackson system (z-axis along beam)

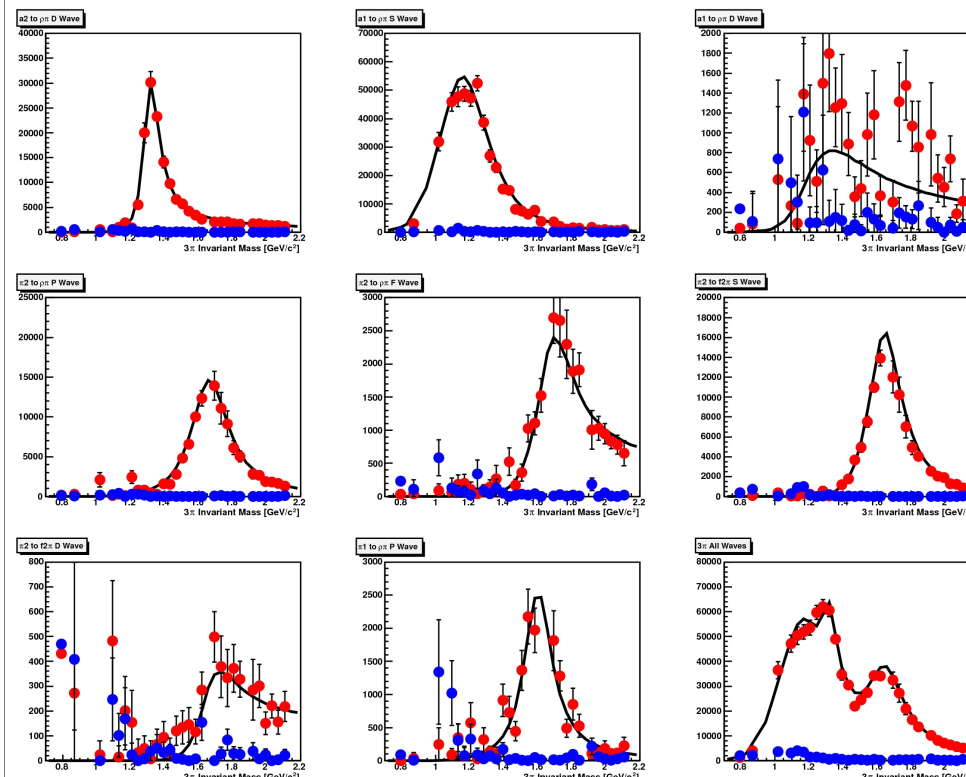
Simplified test :
 keeping all other aspects the same, change the decay frame of the resonance (model 2)

Test with different decay systems...

Generate model 1
Fit model 2



Generate model1
Fit model 1 +model 2



<u>Fitting the incorrect model produces false features</u>

<u>Fitting both, allows CLAS12/FT data to descriminate</u>

Coherent meson photoproduction

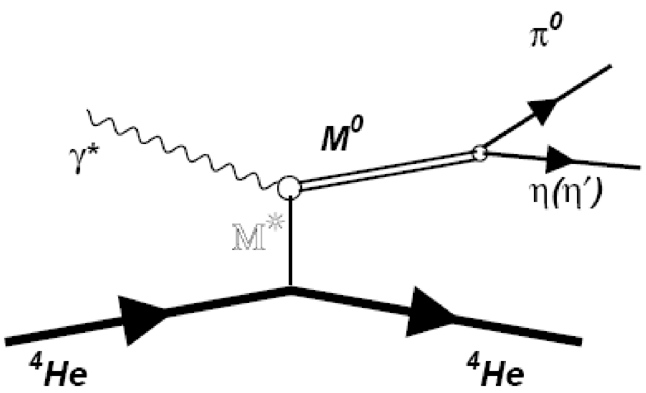
Additional technique for simplifying model/PWA

Subject of CLAS experiment (presentation R. De Vita)

Meson Spectroscopy in the Coherent Production on 4He with CLAS
(Spokesperson S. Stepanyan)
+ Meson Spectroscopy proposal LOI for CLAS12

Advantages for PWA:

-Eliminate background from s-channel baryon resonances
-Simplifies reaction mechanism to Natural Parity ω exchange
(require exchange particle with C=-1, T=0)
-At low t helicity flip amplitudes suppressed



Experimental Technique:

-Small angle electron scattering allows high rates with 4He gas target
-Measure and tag the recoiling 4He nucleus in coincidence
with π and η decay photons

Incoherent photoproduction to discrete state

Additional SPECULATIVE technique for simplifying model/PWA

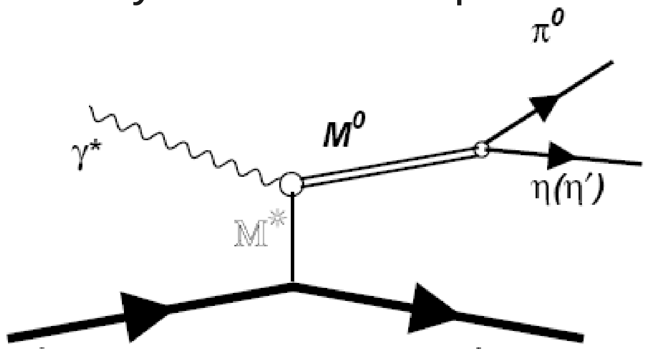
Part of LOI for CLAS12 (proposed by D.P Watts, University of Edinburgh)
Complementary to coherent production

Experimental Technique:
Detect low energy nuclear decay photon in coincidence with meson decay products

Experimental Advantages:
Can use thick solid targets + No minimum t required by detection of recoil nucleus

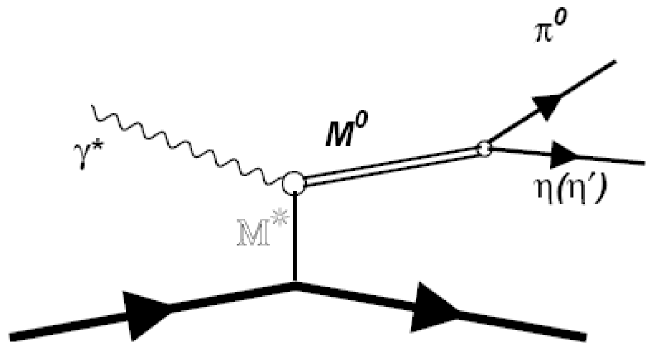
PWA advantages:
Eliminate s channel baryon resonances
Can filter exchange mechanisms by choosing quantum numbers of excited nuclear state
Possible new information from nuclear decay photon distribution
  - related to spin alignment of recoil excited nucleus

e.g. Increase sensitivity to tensor (2+) exchanges
  - possibly favour exotic production



^{12}C (0+,T=0) **^{12}C(2$^+$;T=0; 4.4MeV)**

Filter natural parity ρ exchange
- larger coupling to isoscalars than ω



^{6}Li 1+;T=0 **^{6}Li 0+;T=1; 3.6 MeV**

Previous measurement to discrete nuclear state

- **CM Tarbert, DP Watts et. al.Phys. Rev. Lett 100 132301 (2008)**
  “Incoherent neutral pion photoproduction on 12C”

  Used Crystal Ball detector to measure both π^0 decay photons and 4.4 MeV nuclear decay photon
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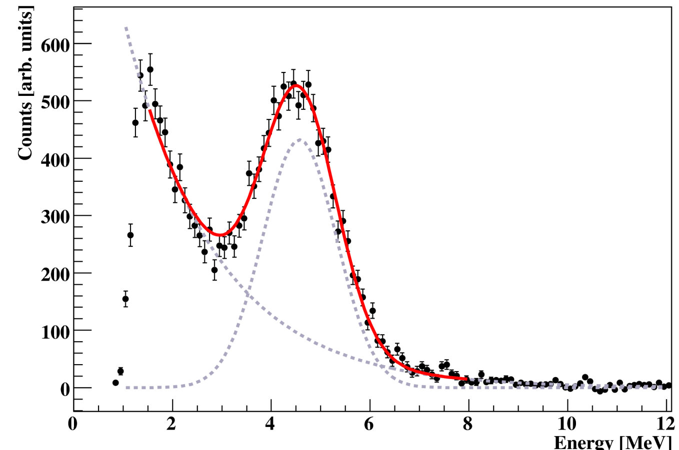
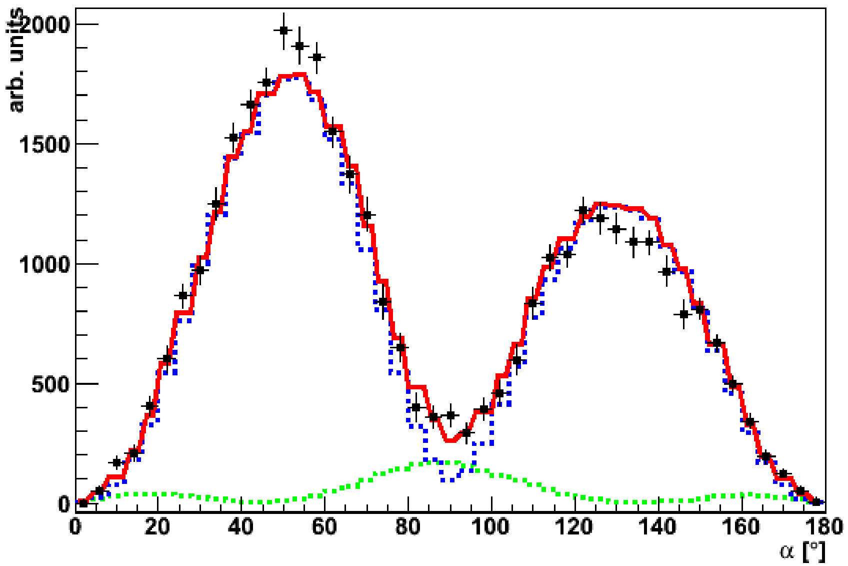
- Beam energy~ 200MeV → s channel (Δ) production



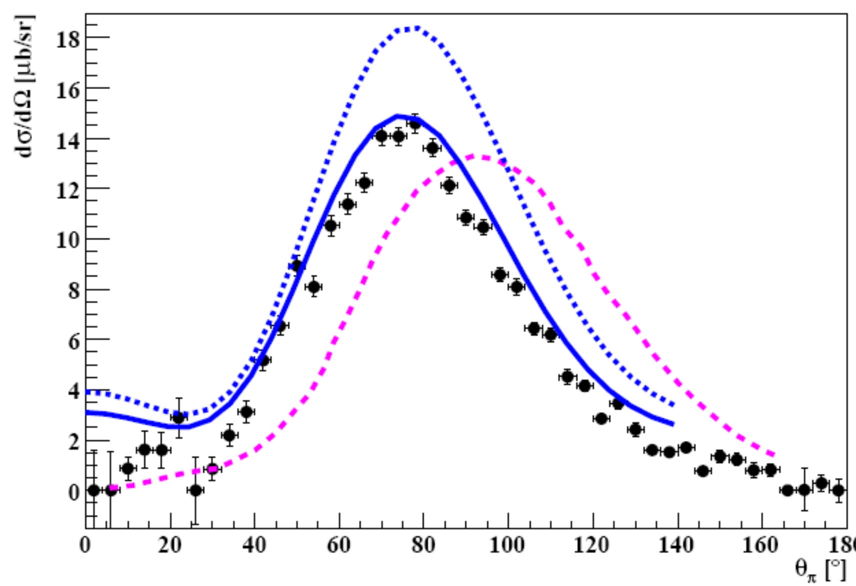
Nuclear decay photon energy (MeV)



Angle between photoproduction momentum transfer and decay photon

Distribution related to spin dependent ($\cos^2\alpha$) and spin independent ($\sin^2\alpha$) amplitudes
Tryasuchev and Kolchin Phys. At. Nuc. 70 827 (2007))

-Additional information to combine with PWA ?



Cross section results related to transition matter form factors and sensitive to propogation of the Delta in the nuclear medium

Summary

In 2014 CLAS12 at Jlab will start providing high intensity, high resolution photo(*)production data with 11GeV beam
Will be complementary to GLUEX experiment
Data in mass region coinciding with many important light quark meson states
Major goal – Establish spectrum and nature of these states

Our tests show the CLAS12/FT systems are intrinsically capable of providing high quality data for PWA and extraction of states
Additionally, linear polarisation allows sensitivity to naturality of exchange particles (production mechanisms)
Nuclear target can be used for further selectivity and to reduce background

But, a lot of work is required before analysing data
- Realistic model(s) implemented in Amplitude Analysis
- e.g. Unfactorised production and decay amplitudes
  Rescattering amplitudes
  Multiple final states
  Backgrounds
  ...

Close collaboration between theorists will be essential to understand data...
Plenty to learn from other experiments