Spin density matrix elements in $\Lambda(1520)$ photoproduction at CLAS

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Outline

1. $\gamma p \rightarrow K^+\Lambda(1520)$: Theoretical background and motivation

2. Experiment and analysis procedure

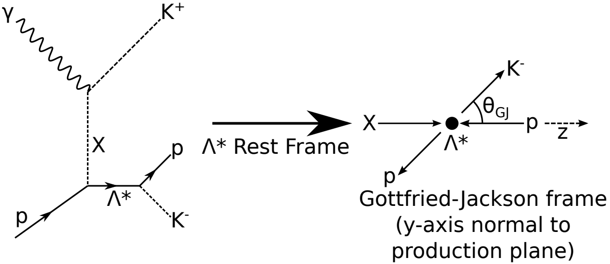
3. $\gamma p \rightarrow K^+\Lambda(1520)$: Decay distributions and spin density matrix elements

$\gamma p \to K^+\Lambda(1520)$

- $\Lambda(1520)$ is $\frac{3}{2}^-$ baryon
- Decay modes
  - $N\bar{K}$ (pK^-, $n\bar{K}^0$): 45%
  - $\Sigma\pi$ ($\Sigma^+\pi^-$, $\Sigma^0\pi^0$, $\Sigma^-\pi^+$): 42%
  - $\Lambda\pi\pi$: 10%
- Narrow resonance ($\Gamma = 15\,\mathrm{MeV}$) compared to other excited baryons

$\gamma p \to K^+\Lambda(1520)$: Polarization observables

- Polarization of $\Lambda(1520)$ expressed by spin density matrix, measured by angular distribution of decay products
- Polarization reveals information about production mechanism
- Use Gottfried-Jackson (t-channel helicity) frame



$\gamma p \to K^+\Lambda(1520)$: Polarization observables

- For decay $\frac{3}{2}^- \to \frac{1}{2}^+ 0^-$ with unpolarized target, unpolarized beam, parity-conserving production and decay: seven independent observables:

$$\begin{pmatrix} \frac{1}{2} - \rho_{\frac{1}{2}\frac{1}{2}} & \mathrm{Re}(\rho_{\frac{3}{2}\frac{1}{2}}) + i\mathrm{Im}(\rho_{\frac{3}{2}\frac{1}{2}}) & \mathrm{Re}(\rho_{\frac{3}{2}-\frac{1}{2}}) + i\mathrm{Im}(\rho_{\frac{3}{2}-\frac{1}{2}}) & i\mathrm{Im}(\rho_{\frac{3}{2}-\frac{3}{2}}) \\ & \rho_{\frac{1}{2}\frac{1}{2}} & i\mathrm{Im}(\rho_{\frac{1}{2}-\frac{1}{2}}) & \mathrm{Re}(\rho_{\frac{3}{2}-\frac{1}{2}}) - i\mathrm{Im}(\rho_{\frac{3}{2}-\frac{1}{2}}) \\ & & \rho_{\frac{1}{2}\frac{1}{2}} & -\mathrm{Re}(\rho_{\frac{3}{2}\frac{1}{2}}) + i\mathrm{Im}(\rho_{\frac{3}{2}\frac{1}{2}}) \\ & & & \frac{1}{2} - \rho_{\frac{1}{2}\frac{1}{2}} \end{pmatrix}$$

- Only three of these observables are measureable in decay distribution:

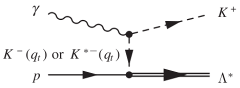
$$W(\theta,\phi) = \frac{3}{4\pi}\left\{\left(\frac{1}{3} + \cos^2\theta\right)\rho_{\frac{1}{2}\frac{1}{2}} + \sin^2\theta\left(\frac{1}{2} - \rho_{\frac{1}{2}\frac{1}{2}}\right) - \frac{1}{\sqrt{3}}\sin 2\theta\cos\phi\,\mathrm{Re}(\rho_{\frac{3}{2}\frac{1}{2}}) - \frac{1}{\sqrt{3}}\sin^2\theta\cos 2\phi\,\mathrm{Re}(\rho_{\frac{3}{2}-\frac{1}{2}})\right\}$$

Jackson, High Energy Physics, Les Houches 1965

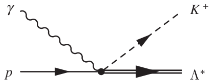
- Can generalize to case of polarized photon beam
  - Unpolarized beam: can measure 3 independent observables
  - Linearly polarized beam: 6 additional observables
  - Circularly polarized beam: 2 additional observables

Possible production mechanisms

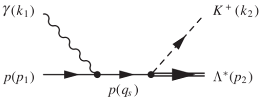
- t-channel
  - K exchange
    - Pure scalar meson exchange implies $\rho_{\frac{1}{2}\frac{1}{2}} = \frac{1}{2}$, all other $\rho = 0$ (in GJ frame)
  - K^* exchange



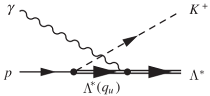
- contact term
  - Needed to preserve gauge invariance
  - Absent for photoproduction off neutron
  - Contact term dominance could explain suppressed cross-section off neutron LEPS, PRL 103, 012001 (2009)



- s-channel
  - Prediction of $N^* \to K\Lambda(1520)$ decays from $N^*(2120)\frac{3}{2}^-$ (formerly called $N^*(2080)$), missing $\frac{1}{2}^-$ and $\frac{5}{2}^-$ states Capstick and Roberts, PRD 58, 074011 (1998)



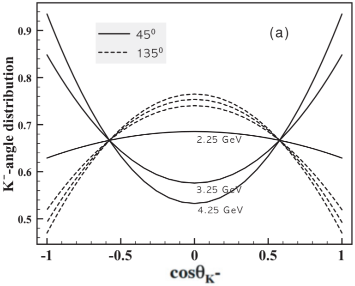
- u-channel



Model prediction

- Nam and Kao predict decay angular distributions as function of production angle and energy

  PRC 81, 055206 (2010)
- Model includes:
  - Reggeized t-channel (K and K^*) exchange
  - contact term
  - s-channel (ground-state N and $N^*(2120)\ \frac{3}{2}^-$) exchange
  - u-channel (ground-state Λ) exchange

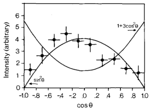


Previous measurements of decay distributions

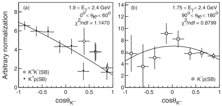
- LAMP2 (Daresbury): $E_\gamma = 2.8 - 4.8$ GeV
- LEPS: $E_\gamma = 1.75 - 2.4$ GeV, 2 angular bins
- SAPHIR: 4 bins from $E_\gamma = 1.69 - 2.65$ GeV
- All previous results averaged over wide energy bins, coarse (or no) binning in production angle

Barber et al (LAMP2), Z. Physik C 7, 17-20 (1980)

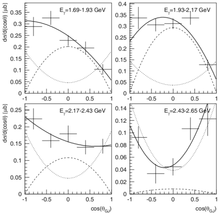
ϱ_{33}	ϱ_{11}	$\mathrm{Re}\varrho_{31}$	$\mathrm{Re}\varrho_{3-1}$
0.38 ± 0.05	0.12 ± 0.20	-0.10 ± 0.15	-0.03 ± 0.15



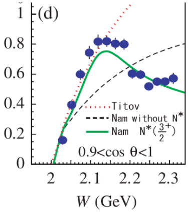
LEPS, PRL 103, 012001 (2009)



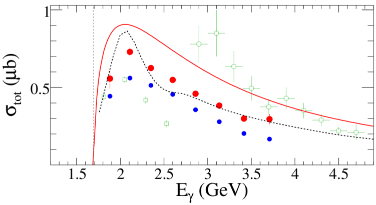
SAPHIR, Eur Phys J A 47, 47 (2011)



- Bump in $\Lambda(1520)$ differential cross-section at $\sqrt{s} = 2.1\,\mathrm{GeV}$
- Origin unknown
  - Resonance?
  - Other?



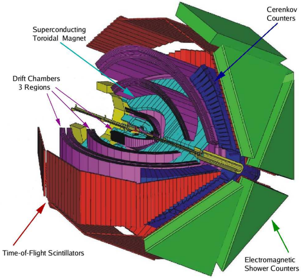
LEPS, PRL 104, 172001



CLAS, PRC 88, 045201

CLAS @ JLab

- CEBAF: 6 GeV (now 12 GeV) e^- accelerator at Jefferson Lab (Newport News, Virginia)
- CLAS (CEBAF Large Acceptance Spectrometer) electroproduction and photoproduction experiments
- Tagged bremsstrahlung photon beam

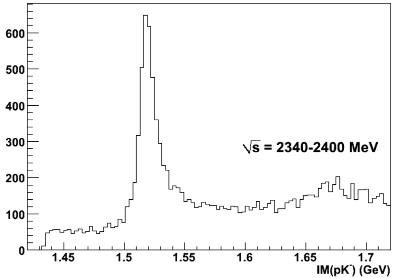


Analysis overview

- g11a dataset
  - photon beam on liquid H_2 target
  - unpolarized beam, unpolarized target
  - $E_e = 4.019$ GeV electron beam energy
  - 20 billion triggers
- $\Lambda(1520) \to pK^-$ decay mode (pK^+K^- final state)
  - 3-track: pK^+K^-
  - 2-track: $pK^+(K^-)$: 10x more statistics, wider acceptance, background difficulties (results not presented today)
- Bin in 60 MeV wide $\sqrt{s}$ bins
  - 13 bins from $\sqrt{s} = 2.04 - 2.82\,\mathrm{GeV}$
- Standard fiducial, PID cuts
- Kinematic fit with 5% confidence level cut
  - 4C fit: $\gamma p \to K^+K^-p$
- Cut out $IM(K^+K^-) < 1.040$ GeV to remove ϕ

Mass Spectrum

After all cuts:



$\Lambda(1520)$ peak on top of non-$\Lambda(1520)$ pK^+K^- events

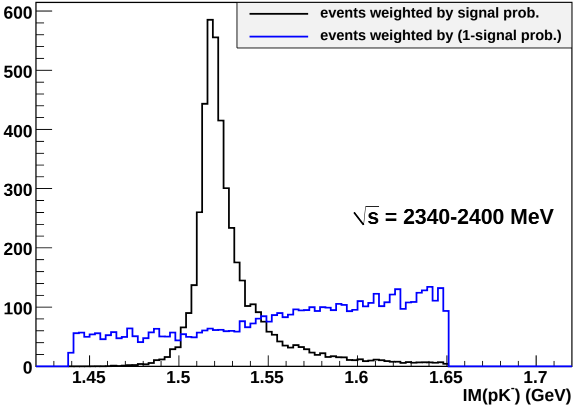
- Can we separate $\Lambda(1520)$ events?
- Not possible if processes interfere

Background subtraction procedure

Q-value method:

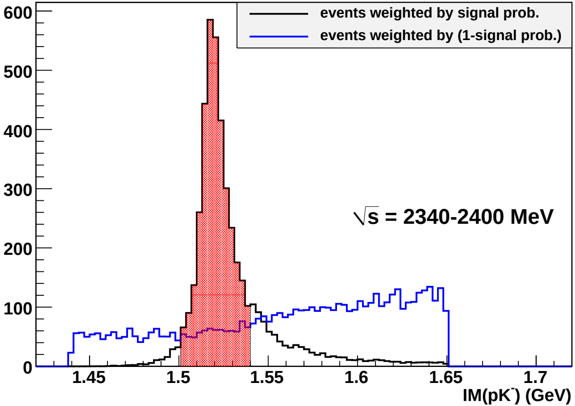
- For each event, calculate probability that given event is signal
  - Find N=100 nearest neighbor events in phase space
  - Fit mass distribution of nearest neighbor events to signal (Breit-Wigner) + background (polynomial) function
  - Williams et al JINST 4 P10003 (2009)
- Assumes non-interfering background
- Use signal probability as weight in event-based maximum likelihood fit

Background subtraction



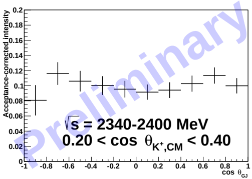
For SDME extraction, only consider events in the center of the peak (1500-1540 MeV)

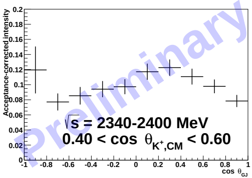
Background subtraction

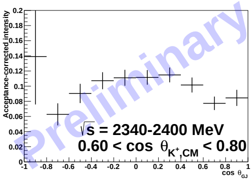


For SDME extraction, only consider events in the center of the peak (1500-1540 MeV)

Decay distributions



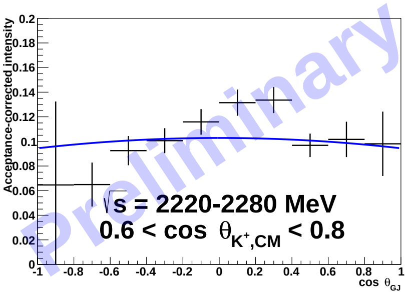




- Look at (acceptance-corrected) decay distributions in Gottfried-Jackson frame ($\cos\theta_{GJ}$) weighted by $\Lambda(1520)$ probability.
  - Bin in production angle $\theta_{K^+,CM}$
  - Correct for acceptance
  - Not how we will extract spin density matrix elements!
  - Just a check
- After integrating over ϕ, decay distribution should have form $\alpha + \beta\cos^2\theta_{GJ}$. Distribution is even in $\cos\theta$!

Decay distributions: Comparison with theory

Can compare with models of Nam and Kao at two energies/angles.



Acceptance-aware maximum likelihood fitting

$$W(\theta,\phi) = \frac{3}{4\pi}\left\{\left(\frac{1}{3}+\cos^2\theta\right)\rho_{\frac{1}{2}\frac{1}{2}} + \sin^2\theta\left(\frac{1}{2}-\rho_{\frac{1}{2}\frac{1}{2}}\right) - \frac{1}{\sqrt{3}}\sin 2\theta\cos\phi \mathrm{Re}(\rho_{\frac{3}{2}\frac{1}{2}}) - \frac{1}{\sqrt{3}}\sin^2\theta\cos 2\phi \mathrm{Re}(\rho_{\frac{3}{2}-\frac{1}{2}})\right\}$$

What we measure is not the true decay distribution, $W(\rho,\vec{x})$, but decay distibution times acceptance: $W(\rho,\vec{x})\eta(\vec{x})$ (ρ is the spin density matrix, $\vec{x}$ is the kinematics of the reaction, η is acceptance).
Construct a PDF for probability of detecting event with kinematics $\vec{x}$ given SDM ρ:

$$P(\rho,\vec{x}) = \frac{W(\rho,\vec{x})\eta(\vec{x})}{\int W(\rho,\vec{x}')\eta(\vec{x}')\,d\vec{x}'}$$

Denominator is easy to calculate using Monte Carlo method:

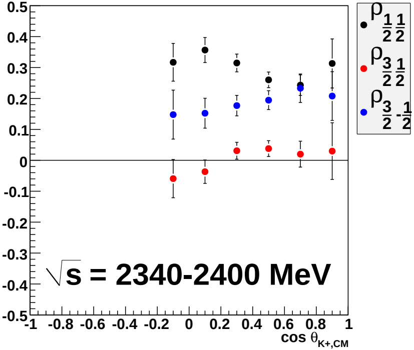
$$N(\rho) = \int W(\rho,\vec{x}')\eta(\vec{x}')\,d\vec{x}' = C\sum_{i\in accepted} W(\rho,\vec{x}_i)$$

Construct likelihood

$$L \propto \prod_{i\in data}\frac{W(\rho,\vec{x}_i)}{N(\rho)}$$

Maximize L to find best values of ρ

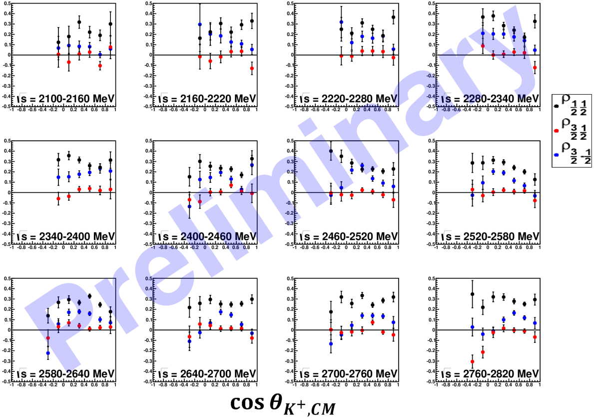
Spin density matrix elements



Gottfried-Jackson frame, statistical errors only

- $\rho_{\frac{1}{2}\frac{1}{2}} \approx .30$ for all angles
  - $\rho_{\frac{1}{2}\frac{1}{2}} = .25 \implies \rho_{\frac{3}{2}\frac{3}{2}} = .25$: $S_z = \pm\frac{3}{2}$, $S_z = \pm\frac{1}{2}$ equally populated
- $\rho_{\frac{3}{2}\frac{1}{2}}$ consistent with zero
- $\rho_{\frac{3}{2}-\frac{1}{2}}$ non-zero (non-flat ϕ_{GJ} distribution)

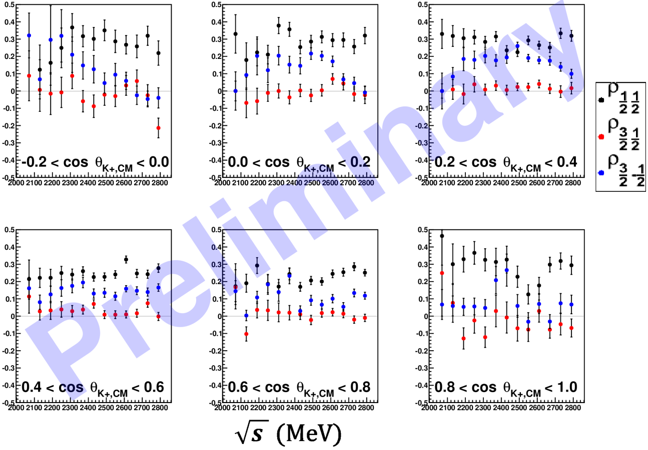
Spin density matrix elements



Gottfried-Jackson frame, statistical errors only

- No strong energy dependence
- $\rho_{\frac{1}{2}\frac{1}{2}} = .20$–$.40$ in most regions
- $\rho_{\frac{3}{2}\frac{1}{2}}$ consistent with zero
- $\rho_{\frac{3}{2}-\frac{1}{2}}$ non-zero (non-flat ϕ_{GJ} distribution)

Spin density matrix elements vs. energy



Gottfried-Jackson frame, statistical errors only

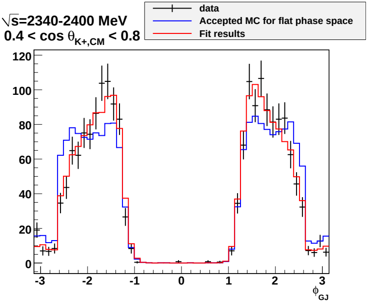
Conclusion

- Polarization of $\Lambda(1520)$ expressed in spin density matrix formalism
- Spin density matrix elements extracted from CLAS photoproduction data
  - Much finer binning in energy, production angle than previous measurements
  - $\rho_{\frac{1}{2}\frac{1}{2}}$ measurement shows neither $S_z = \pm\frac{3}{2}$ or $S_z = \pm\frac{1}{2}$ dominates
  - Non-flat ϕ_{GJ} distribution measured for first time (non-zero $\rho_{\frac{3}{2}-\frac{1}{2}}$)
- More statistics, wider angular coverage coming soon with missing K^- analysis

Backup slides

ϕ_{GJ} Decay Distributions

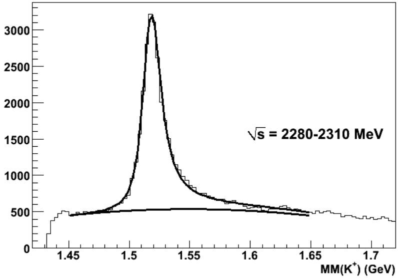
What about ϕ_{GJ}?
Irregular acceptance makes difficult to compare.



Some deviation from flat distribution

Lineshape

Need to input functional form of MM(K^+) to do background fit:



2-track, after phi cut

Breit-Wigner w/ mass-dependent width, convoluted with Gaussian.
Quadratic background.

Q-value method

Choose kinematic variable, M, whose distribution can be described by a sum of background and signal functions:

$$F(M, \vec{\alpha}) = S(M, \vec{\alpha}) + B(M, \vec{\alpha})$$

where $\vec{\alpha}$ is a set of unknown parameters, S is the signal distribution (e.g. Breit-Wigner), B is the background distribution (e.g. polynomial)
For each event i, find N nearest neighbors, with distance to event j as:

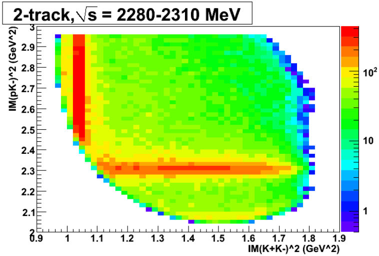
$$d_{ij} = \sum_k \left[\frac{\theta_k^i - \theta_k^j}{R_k} \right]^2$$

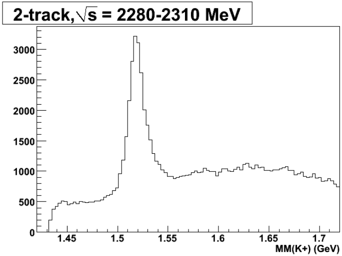
where $\vec{\theta}$ are kinematic variables other than M (e.g. $\cos\theta_{\text{production}}$, $\cos\theta_{\text{decay}}$), R_k is range of θ_k
Fit M distribution of nearest neighbors to F to determine $\vec{\alpha}_i$.
Calculate signal probability:

$$Q_i = \frac{S(M_i, \vec{\alpha_i})}{S(M_i, \vec{\alpha_i}) + B(M_i, \vec{\alpha_i})}$$

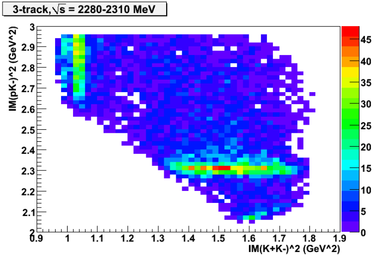
two-track vs three-track

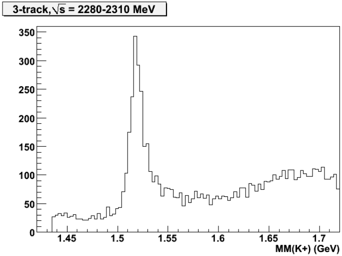
2-track: After stage 1 fit, confidence level cut:





3-track: after confidence level cut:

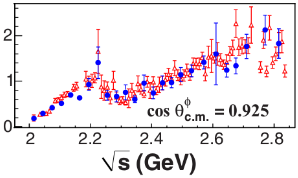




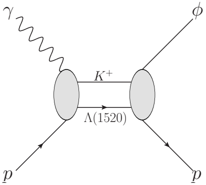
$K^+\Lambda(1520)$-ϕp coupled-channel effects

- $K^+\Lambda(1520)$ intermediate state studied in $\gamma p \rightarrow \phi p$
  - Proposed to explain bump in $\gamma p \rightarrow \phi p$ cross-section near $K\Lambda(1520)$ threshold
  - Ozaki et al, PRC 80, 035201 (2009)
  - Ryu et al, arxiv:1212.6075
- Understanding $K^+\Lambda(1520)$ production mechanism may help understanding of ϕ photoproduction

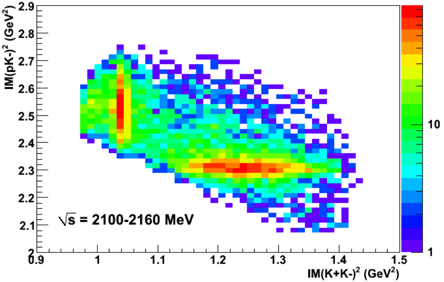
$\frac{d\sigma}{d\Omega}(\gamma p \rightarrow \phi p)$



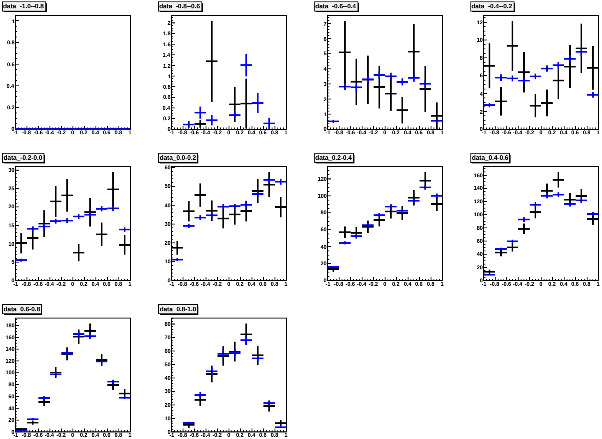
CLAS, PRC 89, 055208 (2014)



$\Lambda(1520)/\phi$ overlap



- ϕp and $K^+\Lambda(1520)$ can decay to the same final state (K^+K^-p), overlap in phase space
- Interfering background
- No acceptance in overlap region for 3-track topology
- Hard cut on K^+K^- mass to cut out ϕ
- No overlap at higher energies



$\sqrt{s} = 2340 - 2400$ GeV
Black is data (not accpetance corrected).
Blue is accepted Monte Carlo weighted by full fit to decay angular distribution.