Ξ Hyperon Photoproduction from Threshold to 5.4 GeV with the CEBAF Large Acceptance Spectrometer

PhD Defense Presentation

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Outline of Part I: Cascade Hyperons and g12

1. Motivation
   - The Strong Force
   - Cascades (Ξ)
   - Photoproduction of Ξ's
2. The g12 Experiment
   - The `CLAS` Detector
   - g12 Data and Reconstruction
3. g12 Kaon Data
   - Missing Mass Technique
   - Missing Mass off $\mathrm{K}^{+}\mathrm{K}^{+}$
   - Sources of Background

Outline of Part II: Results From g12

4. Ξ Excitation Functions
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   - Simulations and Acceptance
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5. Search for Higher Mass Ξ^*
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6. Search for Iso-Exotics
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7. Conclusions
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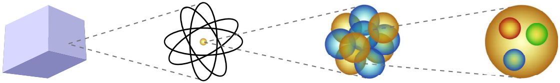
   - Specific Issue: g6c plot

Part I

Cascade Hyperons and the g12 Experiment

The Forces of Nature



(a) (b) (c) (d)

Four known forces: gravitational, electromagnetic, weak, strong

- The gravitational force is always attractive
- The electromagnetic force can be attractive or repulsive
- The weak force is responsible for neutrino interaction
- The strong force is either attractive or repulsive depending on the range of the particles (quarks)

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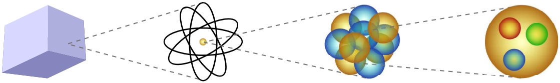

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- The strong force is either attractive or repulsive depending on the range of the particles (quarks)

To complicate matters, the particles that interact via the strong force are only found in specific combinations and are never isolated

Baryons and the Cascades

Quarks spin = 1/2		
Flavor	Approx. Mass GeV/c^2	Electric charge
u up	0.003	2/3
d down	0.006	–1/3
c charm	1.3	2/3
s strange	0.1	–1/3
t top	175	2/3
b bottom	4.3	–1/3

- The strong force is what binds the three quarks inside the proton
- There are six flavors of quarks
- This study involves only the lightest three

Ξ States are identified by the quantum numbers:

- $Baryon = 1$
- $Strangeness = -2$
- $Q \in \{-1, 0\}$

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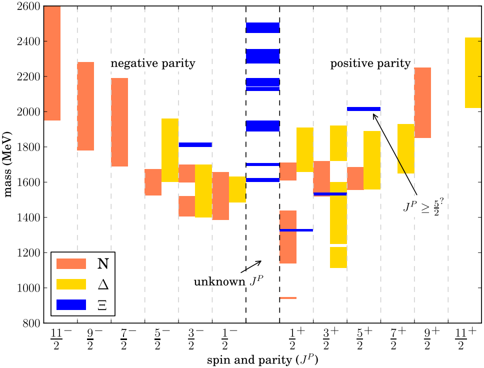
Baryons and the Cascades



In order to study the strong interaction, we look at qqq systems with two strange quarks. They are narrow and SU(3) symmetry suggests a 1:1 correspondence between the Xi spectrum and N/Δ's

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Previous Investigations

virtually all evidence for Ξ^* states come from measuring the decay particles directly in hadron-production experiments such as:

- $K^- p \rightarrow \Xi^- K^+$
- $\Sigma^- p \rightarrow \Xi^0 p K^+$

photoproduction provides another way to measure the cascades:

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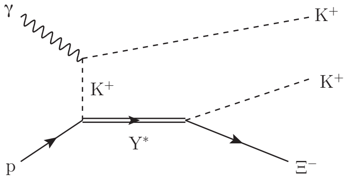
Photoproduction of Ξ's

Allows the cascade to be identified by the photon and two K^+'s

There are a few requirements to this avenue of investigation

- photon (beam) energy measurement
- four-momenta of the two K^+'s
- sufficient acceptance for the kaons
- understanding of sources of background



The CLAS detector at JLab satisfies these requirements

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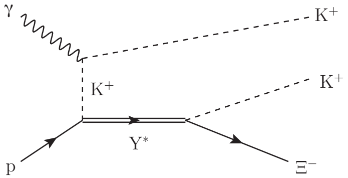

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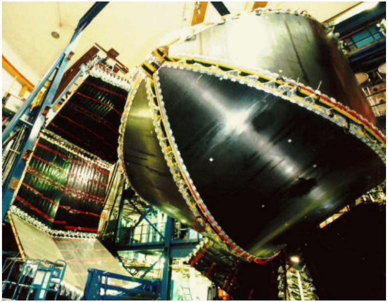
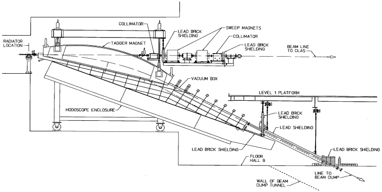
The CLAS Detector

JLab from the air

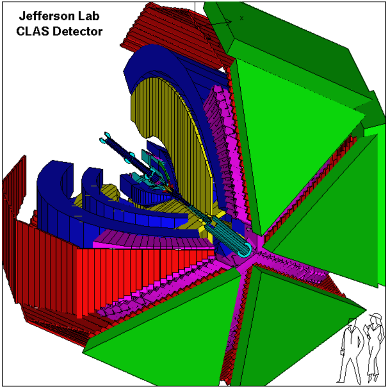
The CLAS Detector (upstream)



The CLAS Detector Components



- six sectors — three ‘planes’
- radiator & electron tagger
- ℓH_2 or ℓD_2 target (others are possible)
- start counter (scintillator)
- magnets (toroidal)
- drift chambers (3x per sector)
- Čerenkov Detectors
- Time of Flight Detectors
- Electromagnetic Calorimeter



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g12 Acquired Statistics

Commissioning and Data taken over 70 calendar days
April 1$^{\text{th}}$ – June 9$^{\text{th}}$, 2008

Production Data

44.2 days active DAQ
∼63% of calendar time
Beam Current: 65 nA
DAQ rate ∼8 kHz
26.2 G triggers (events)

Size of Raw Data: 126 TB

Reconstruction Expands this by a factor of 2.5

"cooked" data > 300 TB

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Calibration and Reconstruction

Primary Calibrators

- C. Bookwalter, FSU (TOF)
- P. Eugenio, PhD., FSU (coord)
- J. Goetz, UCLA (recons.)
- L. Guo, PhD., FIU (coord)
- V. Kubarovsky, PhD., JLab (coord)
- M. Paolone, PhD., USC (EC, CC)
- J. Price, PhD., CSUDH (coord)
- M. Saini, FSU (RF, ST, TAG)
- D. Schott, FIU (DC)
- B. Stokes, PhD., GWU (DC)
- A. Vlassov, PhD., JLab (CC)
- D. Weygand, PhD., JLab (coord)
- M. Wood, PhD., Canisius (EC)

Calibration of the g12 data took this team a year and three months.

- My specific role was to ensure the reconstruction of tracks (four-vectors) from the raw data was done correctly and efficiently
- This involved debugging several programs which were developed over two decades by approx. two dozen people using a mix of FORTRAN, C, C++, and various scripting languages

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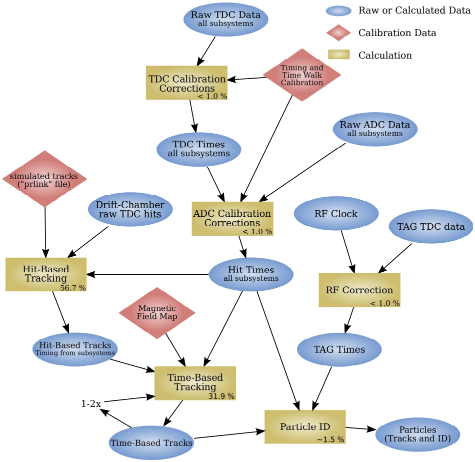
Reconstruction - Algorithm



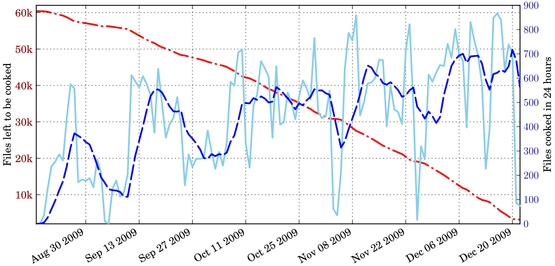
I developed this flowchart of the reconstruction algorithm

and the corresponding expansions for tracking in the dissertation

There have been other studies of the reconstruction algorithm used by CLAS, but this is the first I know of that obtained the relative processing time for each step.

Reconstruction - Timeline

The reconstruction of raw data to an analysis-ready "cooked" version took four months using the computing farm at JLab.



- Sept: higher priority
- Oct: increased cache
- Nov & Dec: more CPUs

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Analysis Framework

The single-kaon skim we initially made on the data consisted of 30% of the cooked data (about 100 TB)

This made it very difficult to read through quickly.

I developed my own variably-sized ntuple using the Serialization library from the BOOST project in C++

- this effectively converted the cooked data to zipped ASCII files
- resulting single kaon data (from 90 TB) was 1.6 TB

The 1.6 TB can be analyzed in about 1.5 days using our own farm (next door)

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From this ntuple, I produced all the original histograms shown in the dissertation. Some images were produced with ROOT and others with the Scientific Python (SciPy) and "Matplotlib" packages.

Missing Mass Technique

$$\gamma p \to K^+K^+X^-$$

- since we wish to use the missing mass technique, we must first determine its accuracy by looking at known states.
- For kaon data, we will start with singly strange baryons (Σ's and Λ's)
- Note that these data were calibrated mostly with exclusive pion events: $\gamma p \to p\pi^+\pi^-$

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$\mathrm{MM}(\mathrm{K}^+)$

$$\gamma p \rightarrow \mathrm{K}^+ X^0$$

Measured Masses (MeV)

- $\Lambda = 1109.4 \pm 0.25$

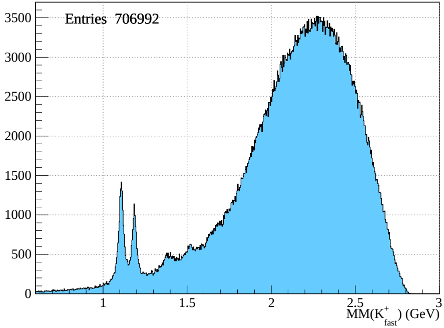
  $\mathrm{PDG} = 1116$
- $\Sigma^0 = 1186.6 \pm 0.4$

  $\mathrm{PDG} = 1192$
- $\Sigma^{*0} = 1385 \pm 7$

  $\mathrm{PDG} = 1384$

  PDG: $\Lambda^*(1405)$
- $\Lambda^* = 1518 \pm 3$

  $\mathrm{PDG} = 1520$



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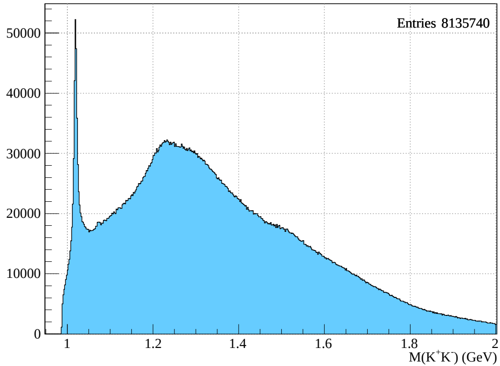
$M(K^+K^-)$

$$\gamma p \to \varphi X^+$$
$$(\varphi \to K^+K^-)$$



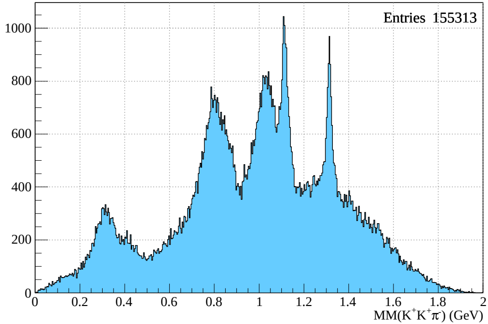
- $\varphi = 1019.5 \pm 0.2$

  PDG $= 1019$

MM($K^+K^+\pi^-$)

$$\gamma p \rightarrow K^+K^+\pi^- X^0$$

- $\Lambda = 1113.2 \pm 0.5$
  PDG $= 1116$
- $\Xi^0 = 1313.8 \pm 0.4$
  PDG $= 1315$
- secondary peaks from misidentified pions and where the π^- is associated with the decay of the X^0



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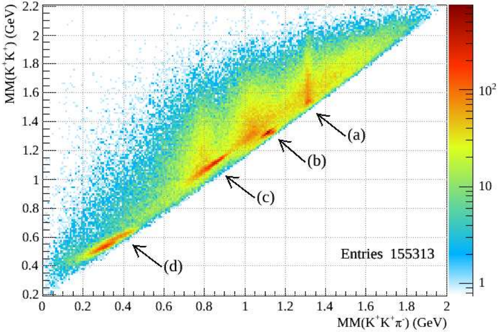
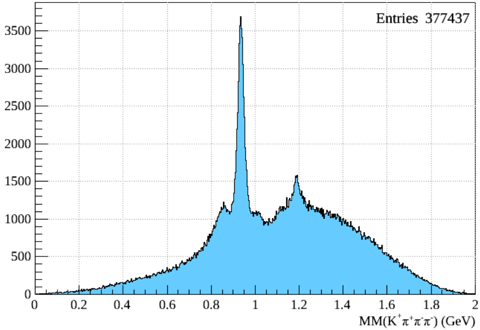


$MM(K^+\pi^+\pi^-\pi^-)$

$$\gamma p \to K^0 K^+ \pi^- X^+$$
$$(K^0 \to \pi^+\pi^-)$$

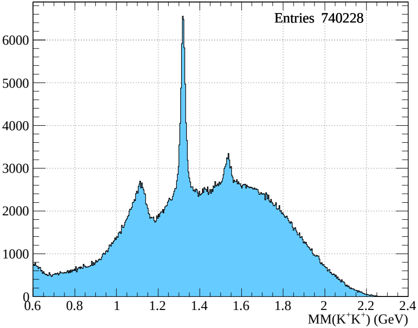


- $p = 937 \pm 1$
  PDG $= 938$
- $\Sigma^+ = 1186.8 \pm 1.8$
  PDG $= 1189$
- secondary peaks will be revisited in the search of iso-exotics

MM(K^+K^+)

$$\gamma p \rightarrow K^+K^+X^-$$

- basic timing and vertex selections only
- $\Xi^- = 1320.2 \pm 0.2$ MeV
  PDG $= 1321.71 \pm 0.07$
- $\Xi^{*-} = 1535.2 \pm 0.8$ MeV
  PDG $= 1535.0 \pm 0.6$
- misidentified pion events show up as vertical bands



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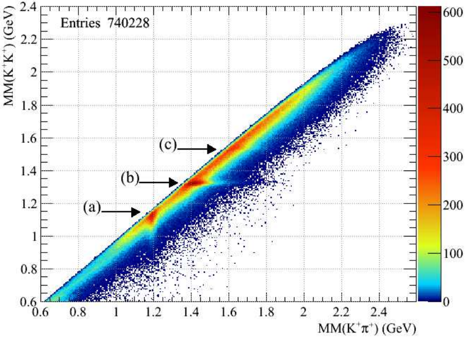

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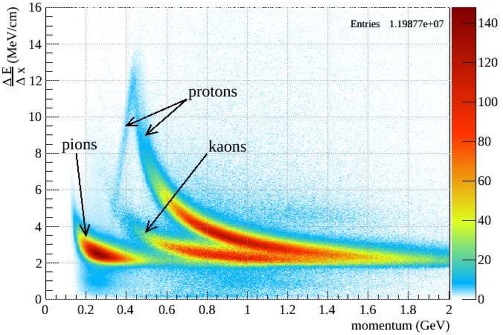
TOF Energy Deposit Cut

- kaons identified from $\varphi(1020)$ and $\Xi^-(1320)$ signals
- number of kaons, pions and protons were normalized in this to bring out the kaon band
- this cut was used as a consistency check of the particle ID which was based on timing



Proton Cut

- proton can be used to remove the $\Sigma^-(1189)$ events:
  $\gamma p \rightarrow \Sigma^- K^+ \pi^+$
  $\Sigma^- \rightarrow n\pi^-$ (99.8%)
- affects Σ^{*-} events differently from Ξ^{*-} events since the Ξ^{*-}'s are more likely to decay to a proton

- Because the reductions in the Ξ signals and the Σ^{*-} background are different, this is a direct test of the measurements of the events in the peaks

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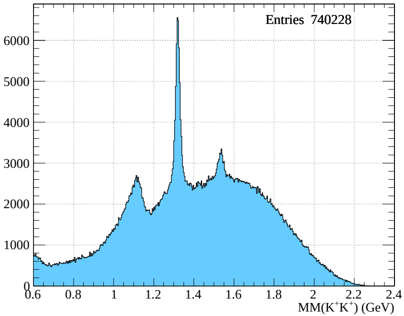
Primary Event Selections

$$\gamma p \rightarrow K^+K^+X^-$$



Event Selections

- Basic Timing Cuts
- TOF Energy Dep.
- Proton

$\Xi^-(1320)$: 22690 ± 250

$\Xi^-(1530)$: 4330 ± 240

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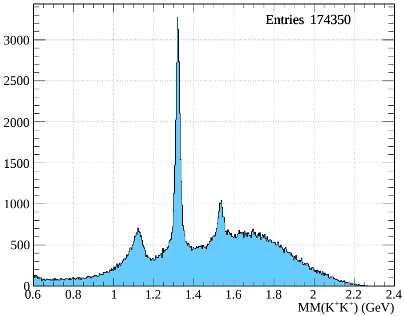

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$\Xi^-(1320)$: 15190 ± 150

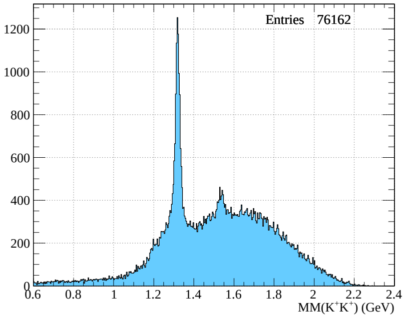
67% of basic cuts

$\Xi^-(1530)$: 3020 ± 120

70% of basic cuts

Primary Event Selections

$$\gamma p \to K^+K^+X^-$$



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$\Xi^-(1320)$: 7557 ± 125

33% of basic cuts

$\Xi^-(1530)$: 1310 ± 110

31% of basic cuts

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Primary Event Selections

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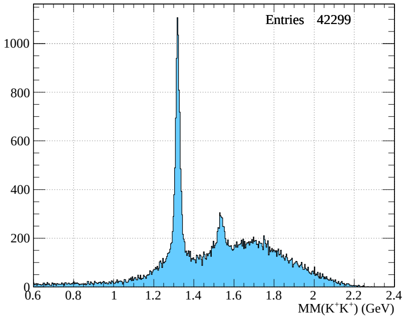

Event Selections

- Basic Timing Cuts
- TOF Energy Dep.
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$\Xi^-(1320)$: 5025 ± 85

22% of basic cuts

$\Xi^-(1530)$: 1073 ± 66

25% of basic cuts

Sources of Background

Two types of background sources in $\mathrm{MM}(K^+K^+)$ distribution

Inefficiencies

- misidentified particles (pions are ID'd as kaons)

  Σ^{*-} states contributed through this and is the largest source of background in this analysis
- wrong beam energy from the tagger

Competing Physics

- Possibility of many high-mass, broad Ξ^{*-} states
- Y^* pion emission (soft π^0's)
- neutral kaon channels such as:

$$\gamma p \to Y^* K^+$$
$$Y^* \to \Xi^{*0} K^{*0}$$
$$K^{*0} \to K^+ \pi^-$$

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Part II

Results From g12

Excitation Function

The Excitation function is the absolute probability that a specific will be produced at a certain center-of-mass energy

(we use E_{beam} since the proton is at rest)

Ingredients

Measured Yield (N) primary source of statistical error

Flux (F) a moderate source of systematic error, but the large number of photons hitting the target means the statistical error is at a minimum

Target Material (w, ρ, ℓ) well known

Acceptance, (A) primary source of systematic error

$$\sigma = \frac{w}{\rho \ell N_A} \frac{N}{AF}$$

ulimit

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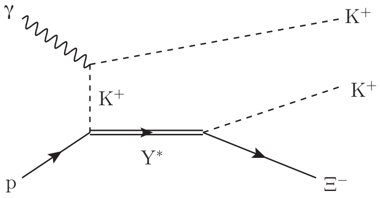
Model Dependence and Systematic Uncertainty

The model used to simulate Ξ events is the largest source of systematic uncertainty.

- The model used was a t-channel production of a Y^* which then decayed by phase-space to the Ξ
- The major parameters we adjusted to get good agreement with the kaon distributions seen in the data were:
  - t-slope of the leading K^+
  - mass of the Y^*
  - width of the Y^*



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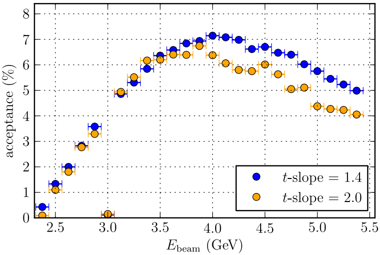
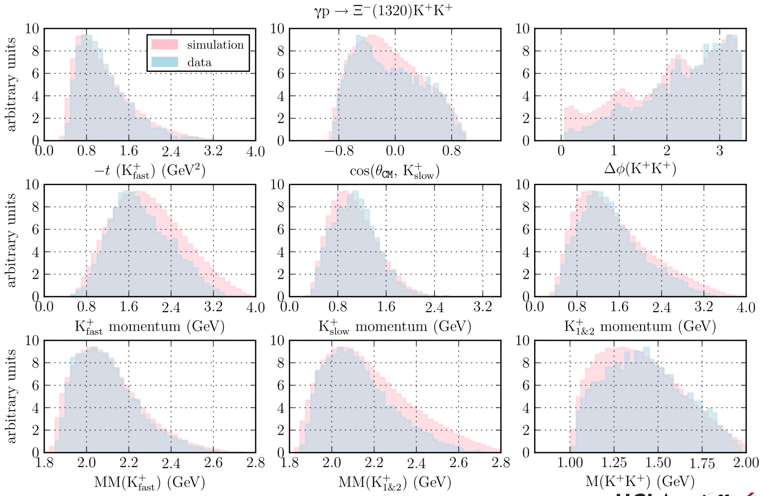


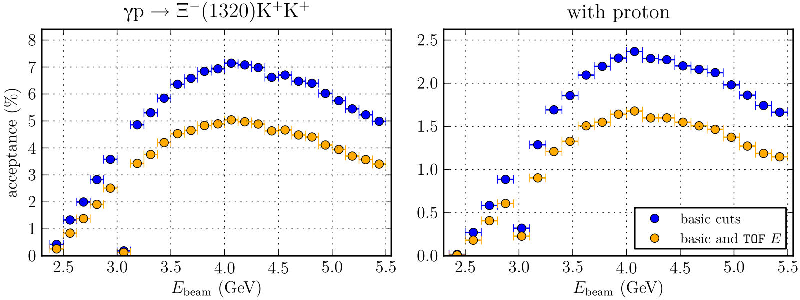
(Similarly for Y^* mass and width)

Simulation Comparison to Data



Acceptance

The acceptance for the ground state and first excited Ξ^- states. The statistical error is within the size of the dots and the systematic error is estimated to be $\approx 10\%$



$\Xi^-(1320)$

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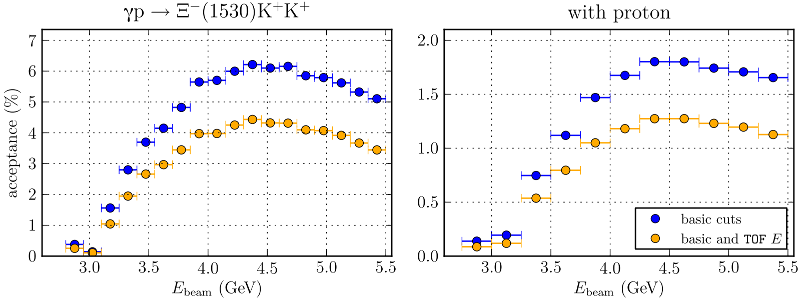


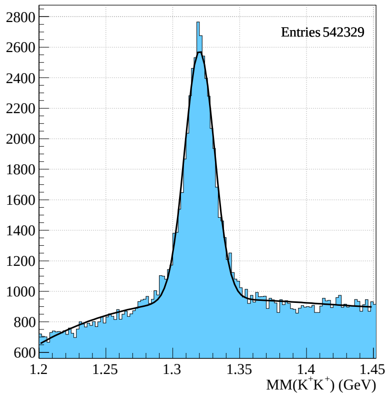
$\Xi^{*-}(1530)$

Extracting Yields from the Data

- 3rd order polynomial
- Gaussian peak
- yield is the integral of the histogram minus the integral of the polynomial part of the total fit.

- There is a systematic uncertainty in this fit
  - The shape of the background is not known, but only approximated by the low-order polynomial
  - The proton cut gives us a handle on the systematics of this fit indirectly (discussed later)

$\Xi^-(1320)$ fit, full statistics



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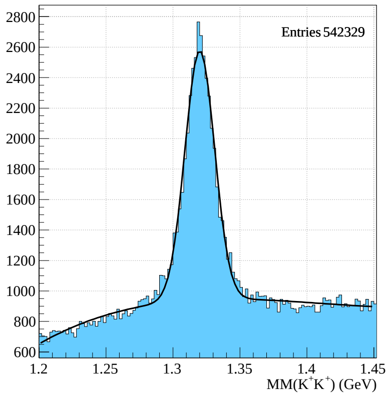
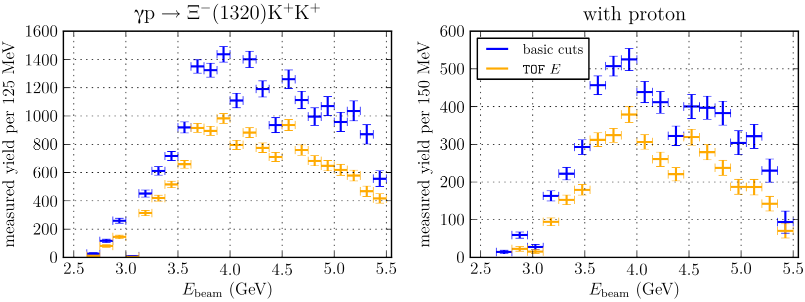


Ξ Measured Yields

measured yield of the ground state and first excited state Ξ^- show structures in acceptance and efficiency of the CLAS detector



$\Xi^-(1320)$

Notice: absence of events at 3 GeV due to bad tagger timing paddle, increases at 3.6 and 4.4 GeV due to trigger configuration

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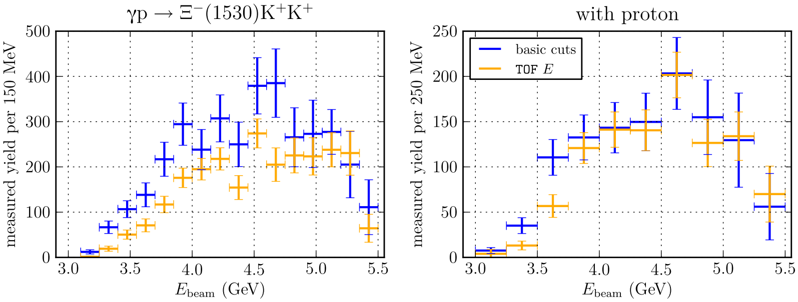

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Correcting for the Flux

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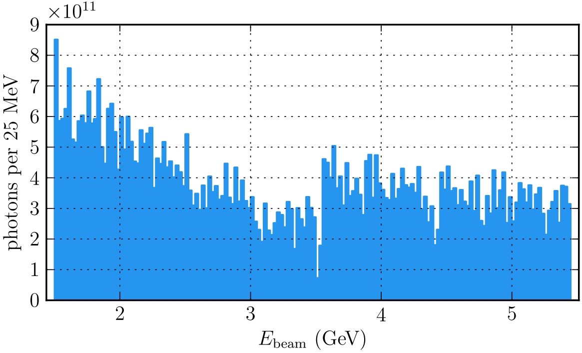

Photon Flux

Correcting for the Flux

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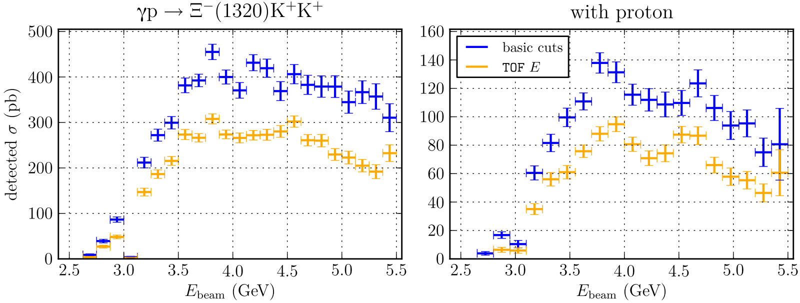

$\Xi^-(1320)$

This includes the target material corrections and is the closest we can get to the final excitation function before we introduce any model

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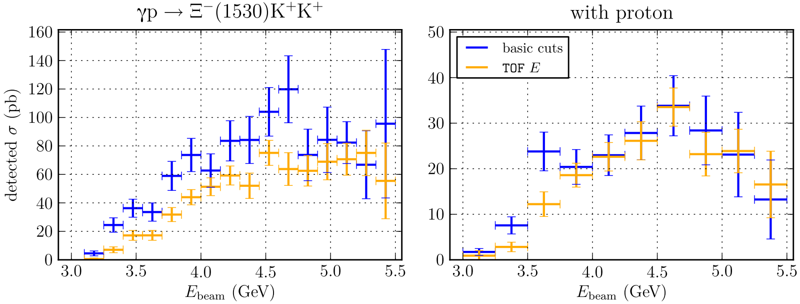

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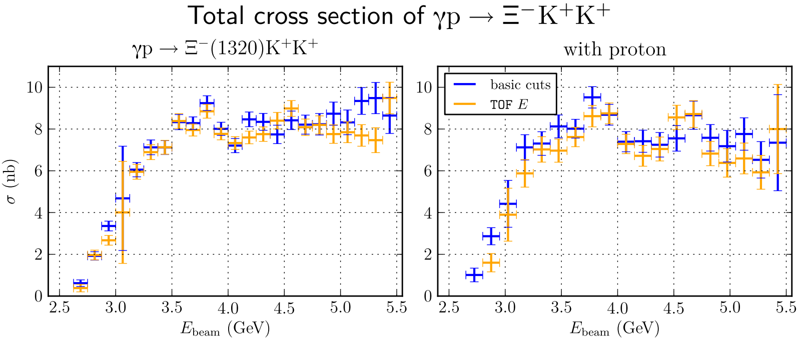
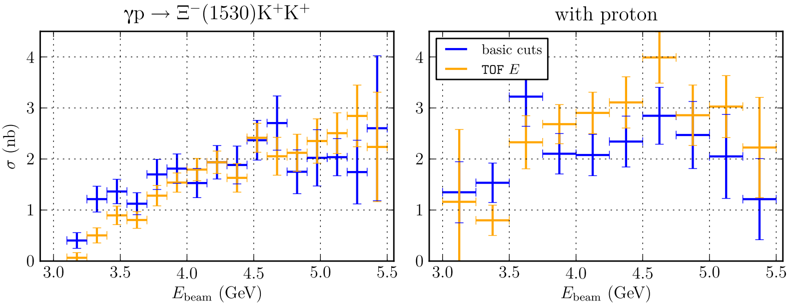
Ξ Excitation Functions



$\Xi^-(1320)$

Ξ Excitation Functions

Total cross section of $\gamma p \to \Xi^- K^+ K^+$



$\Xi^{*-}(1530)$

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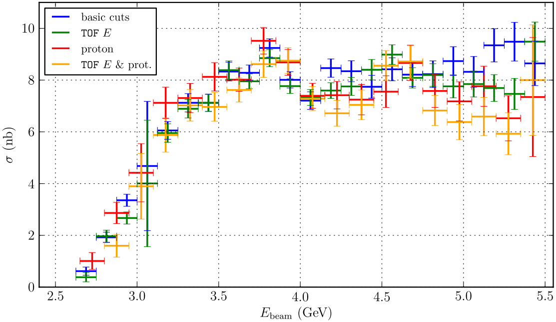
Ξ Excitation Functions

$\gamma p \rightarrow \Xi^- K^+ K^+$

Total cross section



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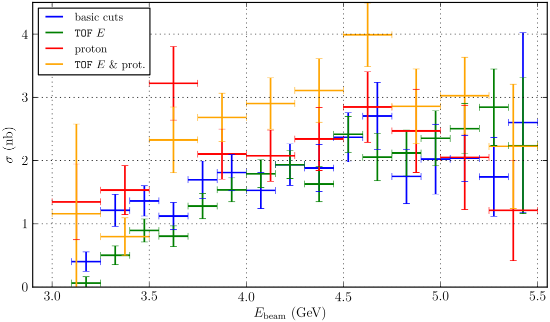
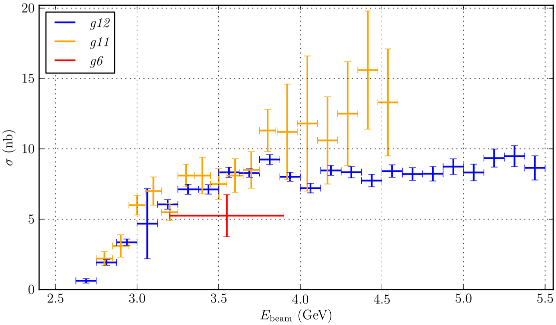


$\Xi^{*-}(1530)$

Comparison to Previous Experiments with CLAS

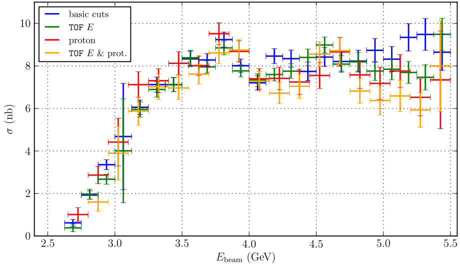
$\gamma p \rightarrow \Xi^- K^+ K^+$

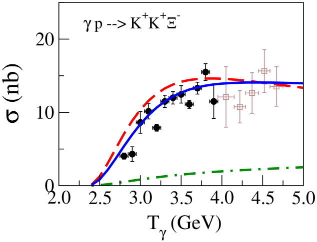
Total cross section



Comparison to Theoretical Work

$\gamma p \rightarrow \Xi^- K^+ K^+$
Total cross section





K. Nakayama, Yongseok Oh and H. Haberzettl

Overall scaling factor in prediction was adjusted to g11 data (overlayed points on right)

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Sensitivity of Yield Measurement

- Upper Limit Calculation same as that for Excitation Function ▸ xfn calc
- Differences:
  - Instead of yield, we have the sensitivity to measured yield
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yield sensitivity was defined as the two standard deviation of the error from the yield measurement which was verified to be consistent with zero

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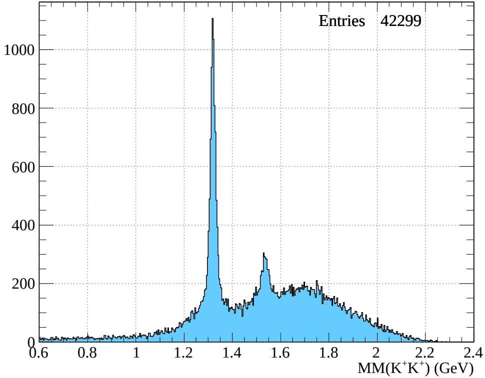
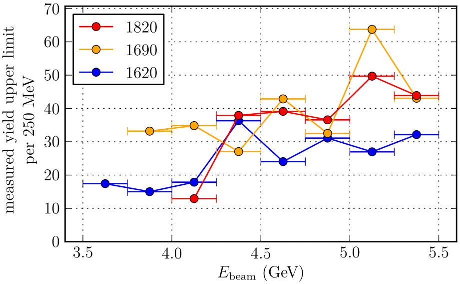
Missing Mass off K^+K^+ Revisited

The proton and the TOF energy deposit cuts were employed in obtaining the upper limits for the Ξ^* states at 1620, 1690 and 1820 MeV



Ξ^* Upper Limits

Total cross section upper limits for the Ξ^* states at:
1620, 1690 and 1820 MeV



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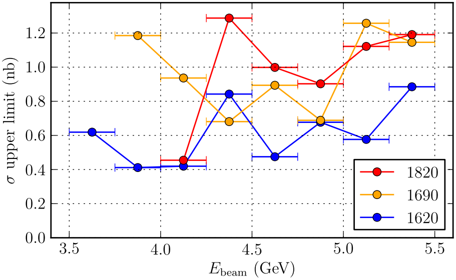

Total Cross Section Upper Limits

Ξ^* Upper Limits

Total cross section upper limits for the Ξ^* states at:
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integrated over 3.5–5.4 GeV
$CL = 90\%$

- $\Xi^-(1620)$: 0.78 nb
- $\Xi^-(1690)$: 0.97 nb
- $\Xi^-(1820)$: 1.09 nb

Iso-exotic photoproduction

- no reliable model for photoproduction of these states
- no reliable masses or widths as well
- qualitative search for narrow resonances
- depending on the width of these states, the estimated total cross section upper limit are 10–100 nb since statistics are comparable to the search for Ξ^{*-} data

- only strong decays of the resonances were considered so that definite strangeness could be identified

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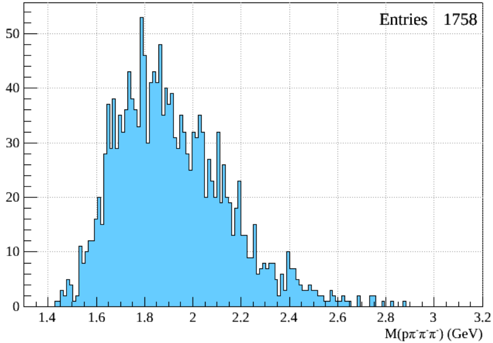
Ξ^{--}



$$\Xi^{--} \rightarrow \Xi^{-}\pi^{-}$$
$$\hookrightarrow \Lambda\pi^{-}$$
$$\hookrightarrow p\pi^{-}$$

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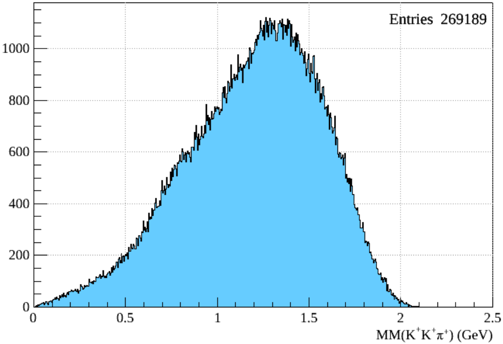
Ξ^{--}



$$\gamma p \to \Xi^{--} K^+ K^+ \pi^+$$

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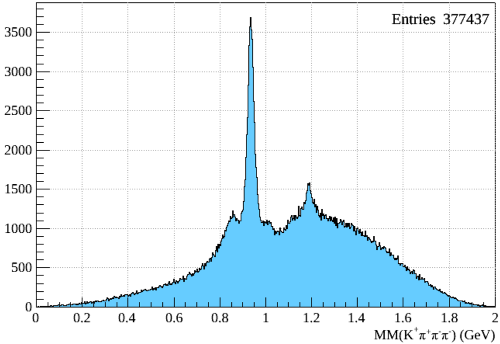
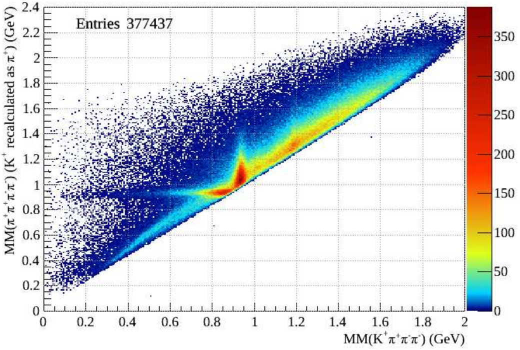
Ξ^+



$$\gamma p \to \Xi^+ K^+ K^0 \pi^-$$
$$\hookrightarrow \pi^+ \pi^-$$

(misidentified pions)

Ξ^+



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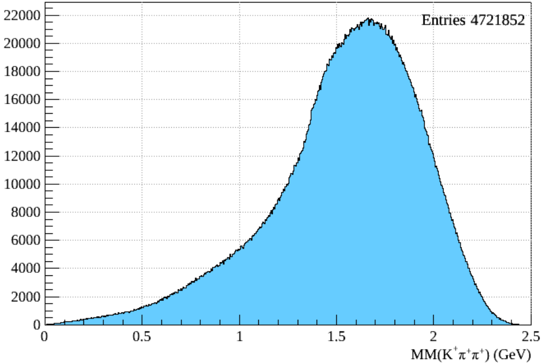
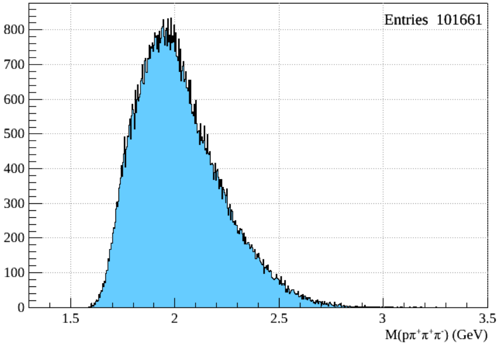
Σ^{--}

$$\gamma p \to \Sigma^{--} K^+ \pi^+ \pi^+$$



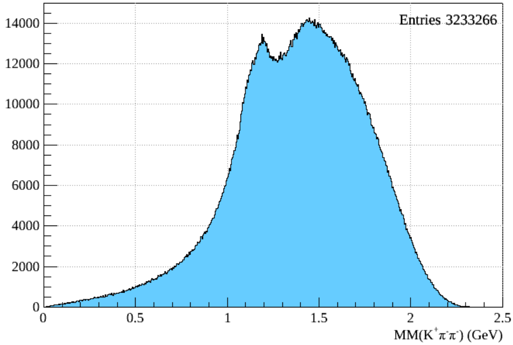
Σ^{++}



$$
\begin{aligned}
\Sigma^{++} \rightarrow \Delta^{++}\overline{K}^{0}&,\\
\Delta^{++} &\rightarrow p\pi^{+},\\
\overline{K}^{0} &\rightarrow \pi^{+}\pi^{-}
\end{aligned}
$$

peak at 1232 MeV
identified as Δ^{++} resonance
(misidentified pions)

Σ^{++}



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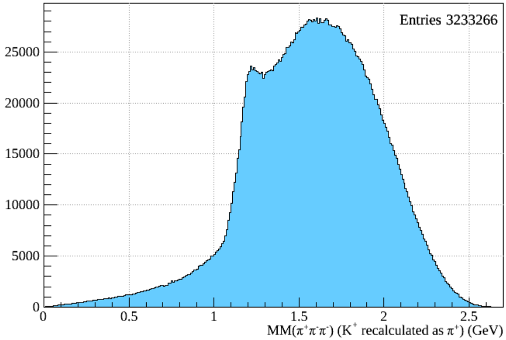

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Summary

- higher mass Y^*'s contribute to Ξ production at higher CM energies
- photoproduction total cross sections for the Ξ^{*-} states above 1530 MeV are smaller than anticipated (no higher than 2 nb)
- This is consistent with the "vector meson dominance" model of the photon (see Fig. 17 on page 20 of dissertation) where the production ratio means we expect 75 events for the $\Xi^{*-}(1690)$ in g12 — we are only sensitive to about 250 events

  above comparison breaks down due to the difference in beams:
  Σ^- beam vs. γ beam
  but it is the only type of measurement available
- no evidence for iso-exotic baryons of strangeness −1 or −2 (estimated sensitivity ≈ 10–100 nb)

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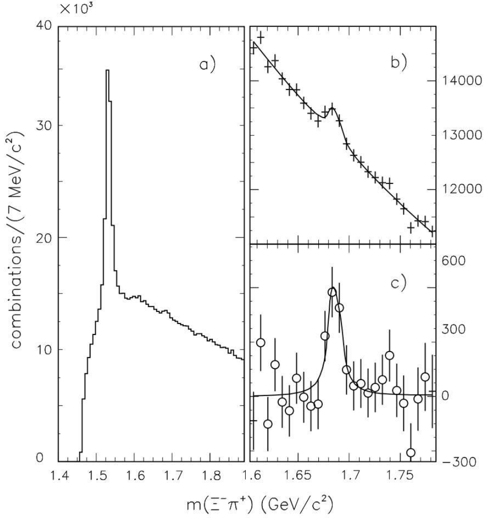
Possible Future Work

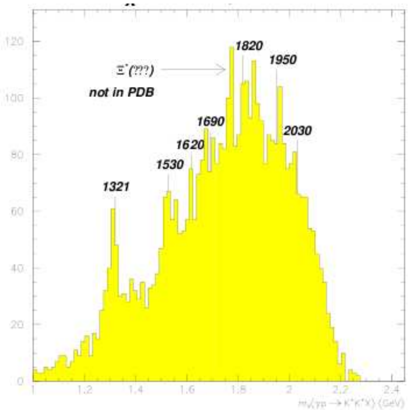
- Ξ^- and Ξ^{*-} differential cross section measurement
  (requires work on the simulation model used)
- Ξ^0 differential and total cross section (neutral kaon channel)
- Ω^- photoproduction (never seen!)
- mapping out accurate upper limits for the iso-exotics as functions of mass and width

Ξ(1530) : Ξ(1690) ratio in kaon production



- Invariant mass of $\Xi^-\pi^+$ using the Σ^- beam at CERN from Adamovich et al., 1997
- this measured ratio equates to ≥ 75 Ξ(1690) events in g12 data
- only experimental evidence that a factor of 10 more statistics would be enough to observe the Ξ(1690)

Keep this plot?



found in g12 proposal (a CLAS internal report)