Excited Ξ Photoproduction Utilizing 9 GeV Photons on a Proton Target: $\gamma\, p \rightarrow K^{+}\, K^{+}\, \Xi^{-*}$

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Presentation Overview

1. Motivation
   - The Standard Model
   - Hadrons
   - Ξ Resonances
   - PDG Status
2. Experiment
   - Thomas Jefferson National Accelerator Facility (TJNAF)
   - CEBAF
   - GlueX Detector
   - Our Reaction: $\gamma\, p \rightarrow K^+\, K^+\, \Xi^{-*}$
3. Data Analysis
   - Data Without Cuts
   - Purpose of Cuts
   - Fractional Uncertainty
   - Applying Cuts to Data
   - Fitting 1D Histogram Slices
   - Ξ Plotting
4. Future Work

The Standard Model

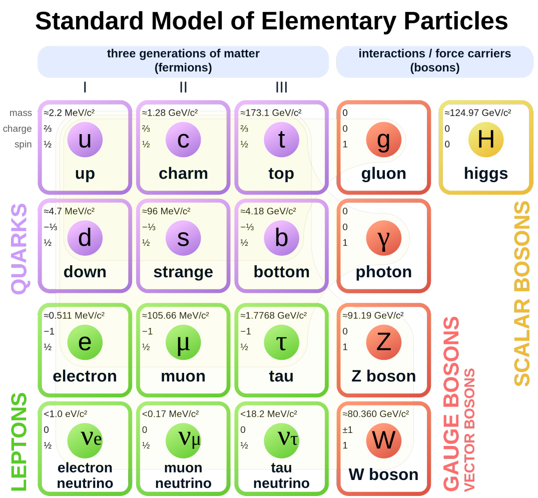

Figure: Standard Model

Hadrons: Baryons and Mesons

Hadrons: Particles which interact via the strong force

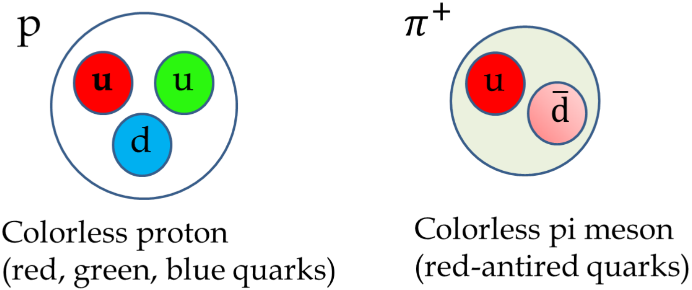

Figure: *https://www.quantumdiaries.org/2012/01/20/thats-right-count-them-4-quarks/*

Focusing on: *cascade baryons (Ξ) which contain strange quarks*

Ξ Resonances

Interested in cascades because:

- Under explored compared to non-strange baryons:
  - smaller cross sections producing the Ξ states
  - inability to produce Ξ resonances through direct formulation
- Missing cascade states $\rightarrow$ Many resonances predicted have yet to be discovered
- This lack of data limits our understanding of these particles

Note: Not exploring K^+ *since kaons are stable and well-understood* $\rightarrow$ *their identification is straightforward*

Current Data: PDG Status

Review of Particle Physics: a comprehensive summary of Particle Physics & related areas of Cosmology provided by an international collaboration called the *Particle Data Group (PDG).*

Particle	J^P	Overall status	Status as seen in — $\Xi\pi$	ΛK	ΣK	$\Xi(1530)\pi$	Other channels
$\Xi(1318)$	1/2+	****					Decays weakly
$\Xi(1530)$	3/2+	****	****				
$\Xi(1620)$		*	*				
$\Xi(1690)$		***		***	**		
$\Xi(1820)$	3/2−	***	**	***	**	**	
$\Xi(1950)$		***	**	**		*	
$\Xi(2030)$		***		**	***		
$\Xi(2120)$		*		*			
$\Xi(2250)$		**					3-body decays
$\Xi(2370)$		**					3-body decays
$\Xi(2500)$		*		*	*		3-body decays

****	Existence is certain, and properties are at least fairly well explored.
***	Existence ranges from very likely to certain, but further confirmation is desirable and/or quantum numbers, branching fractions, *etc.* are not well determined.
**	Evidence of existence is only fair.
*	Evidence of existence is poor.

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$\Xi(1820)$	3/2−	***	**	***	**	**	
$\Xi(1950)$		***	**	**		*	
$\Xi(2030)$		***		**	***		
$\Xi(2120)$		*		*			
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Goal: Find more supporting evidence for predicted or yet to be discovered states.

Thomas Jefferson National Accelerator Facility (TJNAF)

Figure: Jefferson Lab (JLab) aerial view showing halls A,B,C,D

Continuous Electron Beam Accelerator Facility (CEBAF)

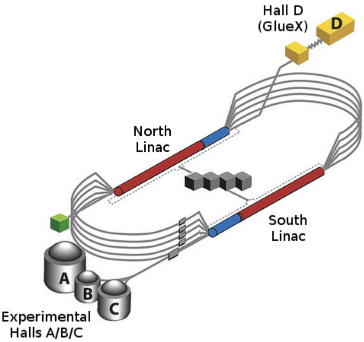


Figure: Continuous Electron Beam Accelerator Facility (CEBAF)

- Experiment uses polarized photon beam incident on liquid hydrogen, H_2 proton target
- 2 parallel superconducting RF linacs connected by two recirculation arcs
- Electron beam delivered to hall-D, incident on diamond wafer (radiator) producing photon beam via coherent Bremsstrahlung process

GlueX Detector

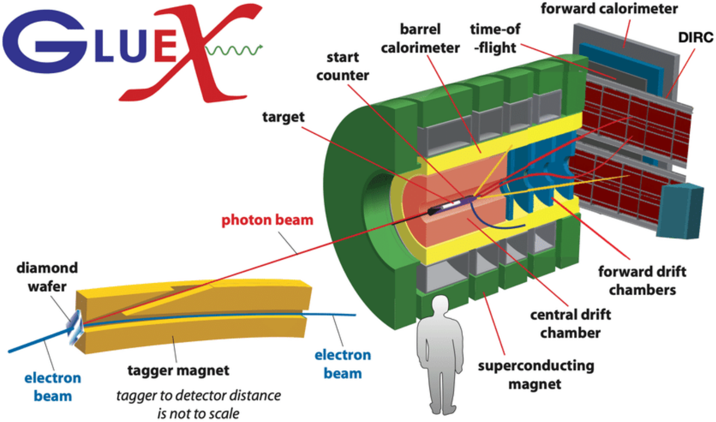
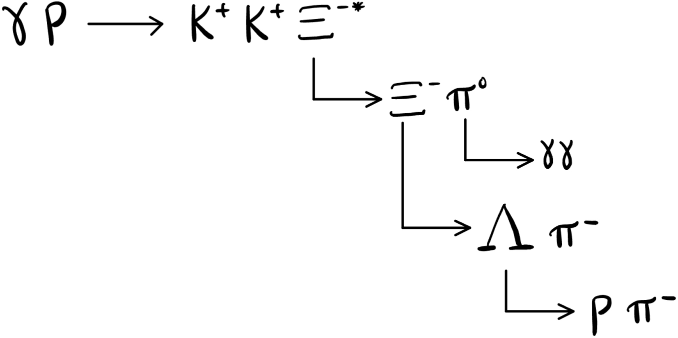


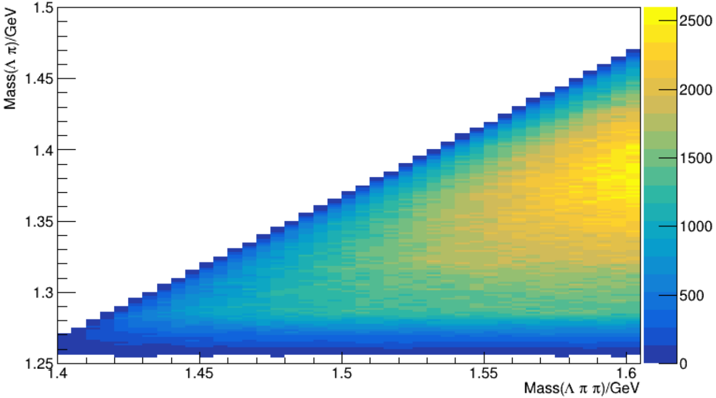
Figure: GlueX Detector

Our Reaction: $\gamma\, p \to K^+\, K^+\, \Xi^{-*}$



FINAL STATE PARTICLES: $K^+\, K^+\, \gamma\, \gamma\, p\, \pi^-\, \pi^-$

Expected Decay Products



- y-axis: Expected decay products of $\Xi^{-} \rightarrow \Lambda\pi^{-}$
- x-axis: Expected decay products of $\Xi^{-*} \rightarrow \Xi^{-}\pi^{0}$ where $\Xi^{-} \rightarrow \Lambda\pi^{-}$

Applying Cuts to Data

- Cuts are criteria to select events from data
  - e.g. if reaction doesn't produce particles above certain threshold, we can 'cut' all events that have particles above that threshold
- Isolate events representing physics of interest from the sea of background events
- One type of cut is a confidence level cut

Understanding χ^2 and Confidence Level

χ^2 Statistic:
: Measures the agreement between model predictions and observed data.

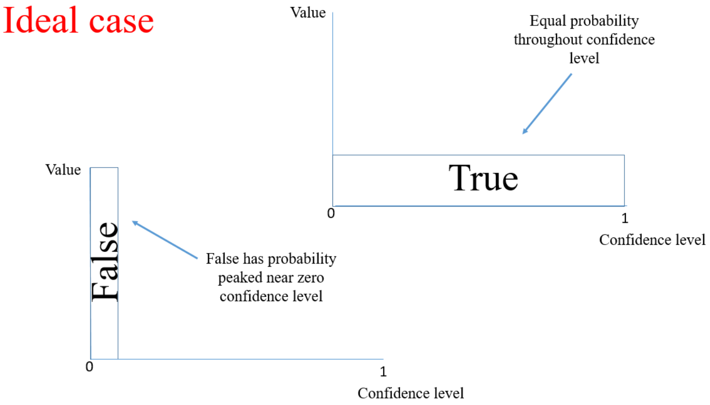
χ^2 Distribution:
: Probability distribution reflecting the sum of squared deviations, normalized by the variance.

χ^2 Confidence Level (CL):
: Probability that χ^2 falls within a certain range under the true model.

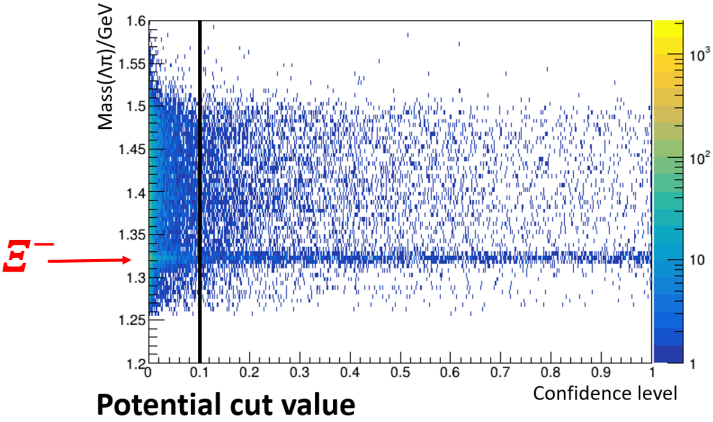
Good Fit Indication:
: A high CL (near 1) suggests a good fit; the model predictions align well with the data.

Fit Quality:
: Small χ^2 value = High CL (good fit), Large χ^2 value = Low CL (potential issues with model or data).

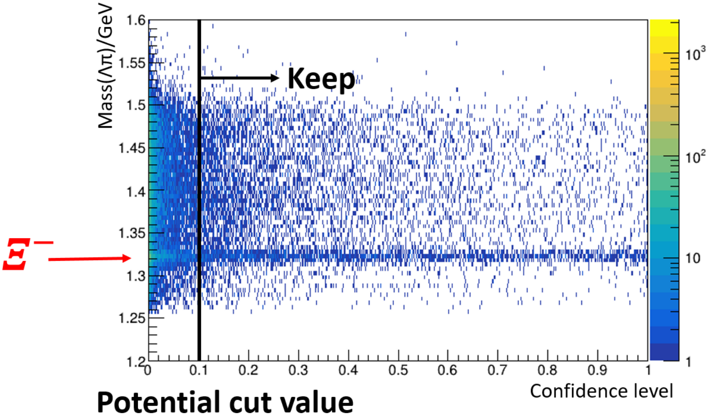
Confidence Level



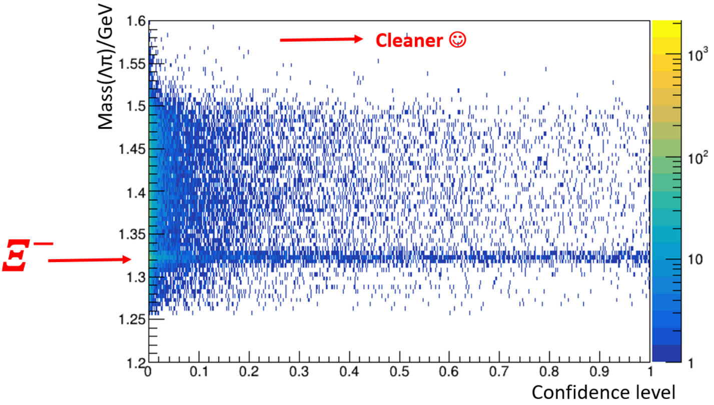
Confidence Level Plotted



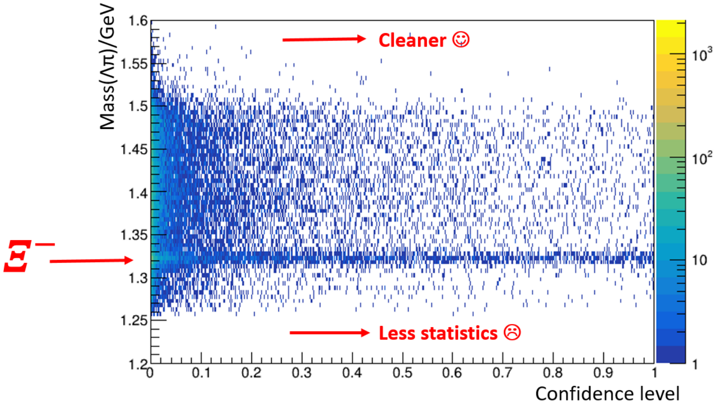
Confidence Level Plotted



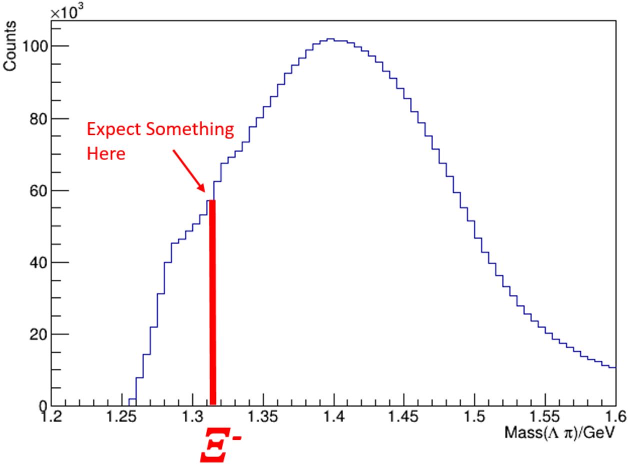
Confidence Level Plotted



Confidence Level Plotted



Data Without Cuts



- y-axis projection containing all things that decay to $\Lambda\pi$
- Cannot resolve Ξ^- without cuts

Cuts from 10^{-1} to 10^{-8}

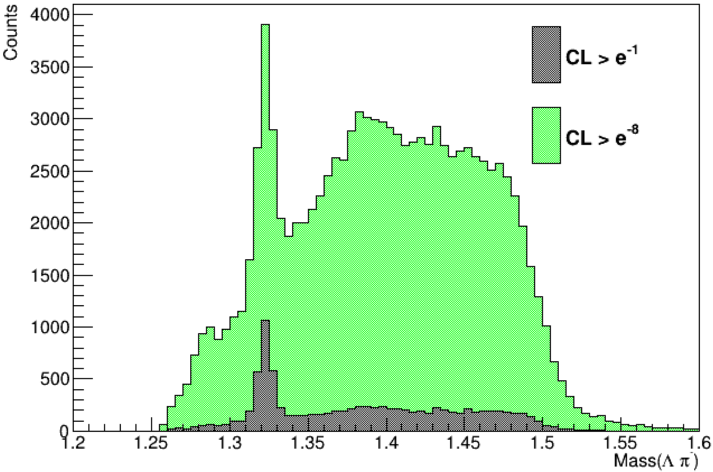
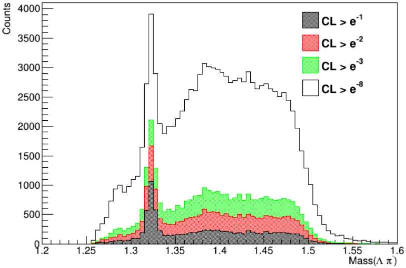
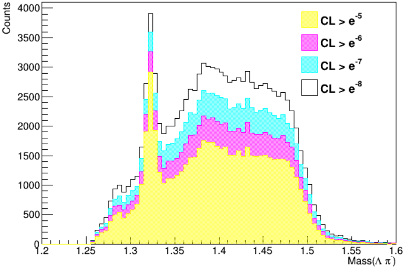
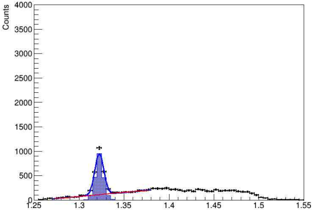


Figure: Grey: $CL = 10^{-1}$ Green: $CL = 10^{-8}$

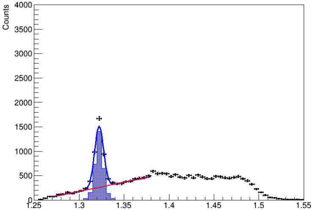

Counts
4000
3500
3000
2500
2000
1500
1000
500
0
1.2
1.25
1.3
1.35
1.4
1.45
1.5
1.55
1.6
Mass(Λ π^-)
CL > e^{-1}
CL > e^{-2}
CL > e^{-3}
CL > e^{-8}


Counts
4000
3500
3000
2500
2000
1500
1000
500
0
1.2
1.25
1.3
1.35
1.4
1.45
1.5
1.55
1.6
Mass(Λ π^-)
CL > e^{-5}
CL > e^{-6}
CL > e^{-7}
CL > e^{-8}

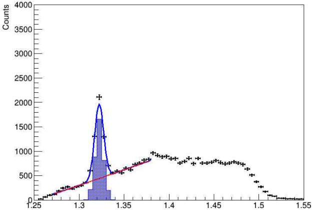
Determining Best Confidence Level Cuts



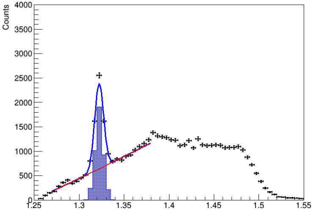
(a) 10^{-1}



(b) 10^{-2}

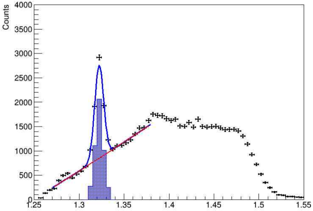


(c) 10^{-3}

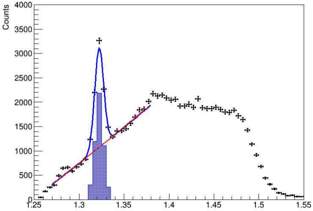


(d) 10^{-4}

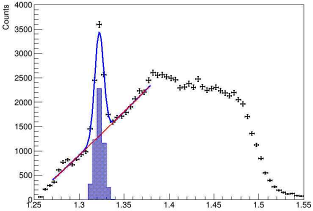
Best Confidence Level Cuts Cont'd...



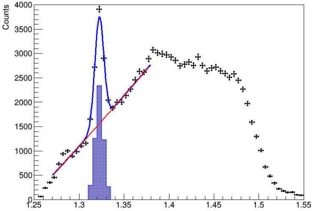
(a) 10^{-5}



(b) 10^{-6}



(c) 10^{-7}



(d) 10^{-8}

Fractional Uncertainty Comparison

- Fits show the 10^{-2} cut has less statistics, but is cleaner than the 10^{-4} cut
- To determine what the best confidence level cut is we can compare their **fractional uncertainties**

Background Statistics

Let:

Total Yield = T
Signal Yield = S
Background Yield = B

Where:

S = T - B

Then:

Uncertainty in signal: $\sigma_T^2 = \sigma_T^2 + \sigma_B^2$

And if:

$\sigma_T^2 = T$ and $\sigma_B^2 = B$ we have *Poisson statistics*
and then $\sigma_S = \sqrt{T + B}$

Since:

$T = S + B$ then $\sigma_S = \sqrt{S + 2B}$

Our fractional uncertainty is:

$f = \frac{\sigma_S}{S}$

Note: Greater B $\rightarrow$ *Greater f ; Want to minimize f*

Fractional Uncertainty

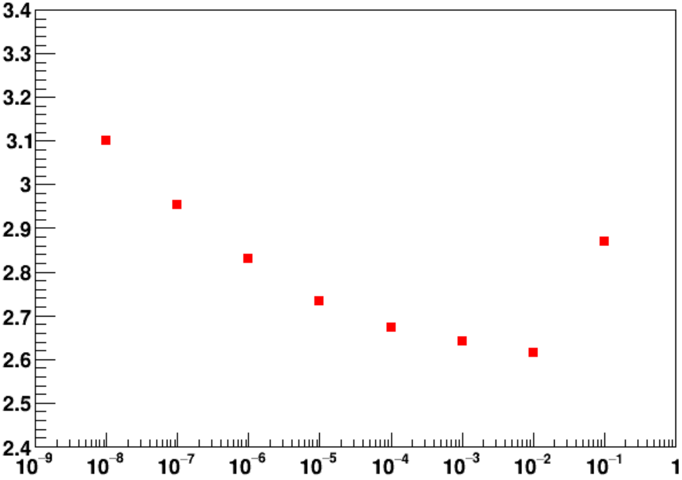
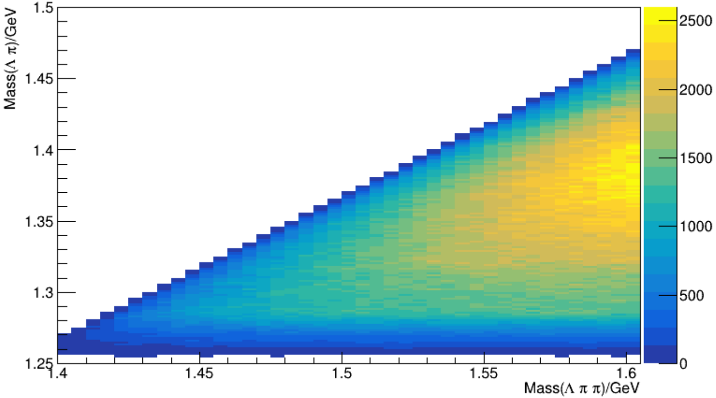


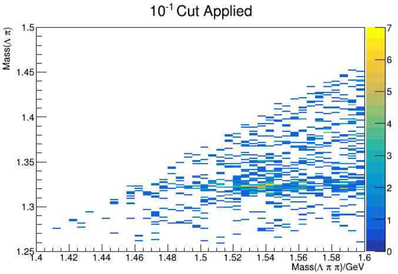
Figure: Fractional Uncertainty

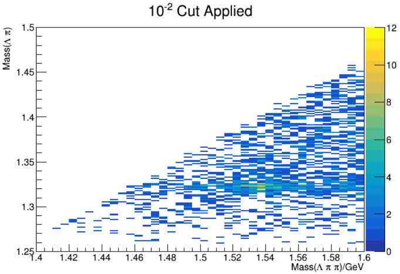
Before Making Cuts

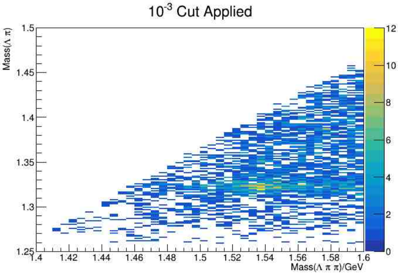


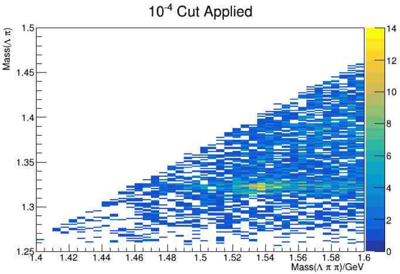
- y-axis: Expected decay products of $\Xi^- \to \Lambda\pi^-$
- x-axis: Expected decay products of $\Xi^{-*} \to \Xi^-\pi^0$ where $\Xi^- \to \Lambda\pi^-$

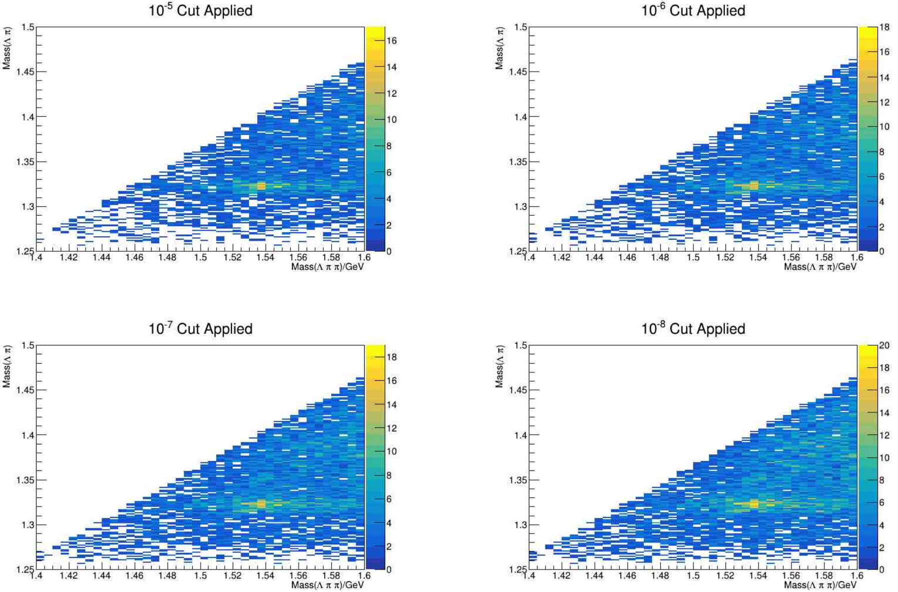
After Confidence Level Cuts Applied











10-5 Cut Applied
10-6 Cut Applied
10-7 Cut Applied
10-8 Cut Applied
Mass(Λ π)
Mass(Λ π π)/GeV

Ξ^- Can Be Seen

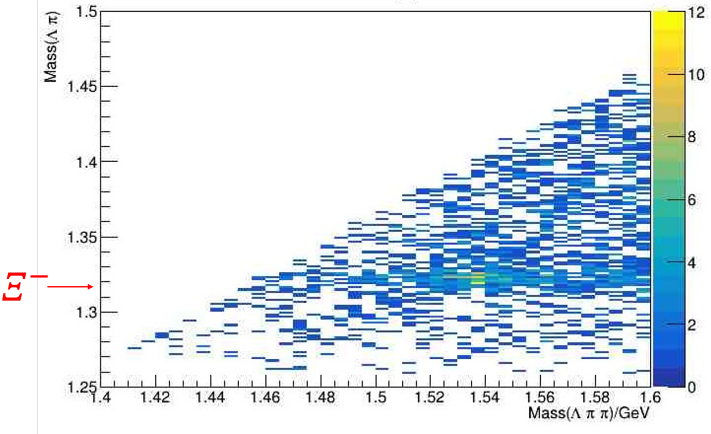


Figure: 10^{-2} CL Cut Showing Ξ^-

Binning 2D Histogram After CL Cut

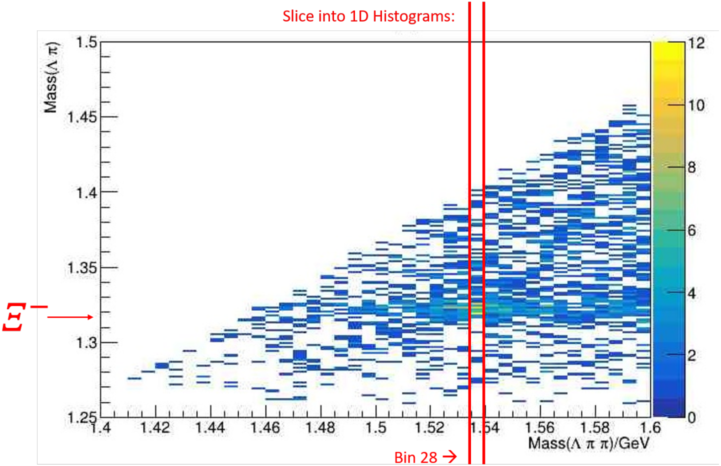


Figure: 2D Histogram sliced in 1D histograms; showing bin 28 slice

Fitting 1D Histogram Slices

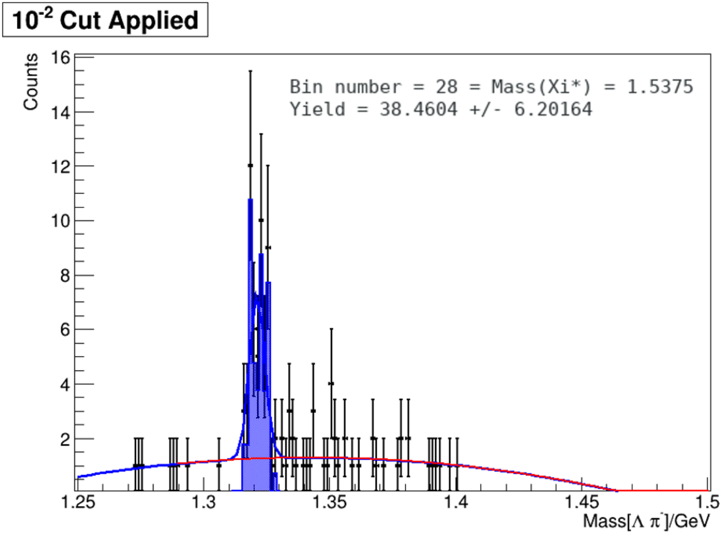
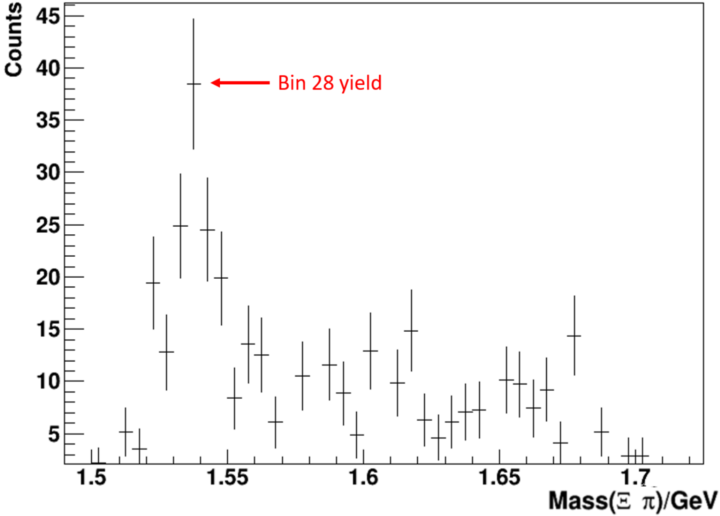


Figure: Fit of Bin 28 after 10^{-2} CL Cut Applied

Counts


Counts
45
40
35
30
25
20
15
10
5
Bin 28 yield
1.5
1.55
1.6
1.65
1.7
Mass(Ξ π)/GeV

Single Fit of $\Xi(1530)$

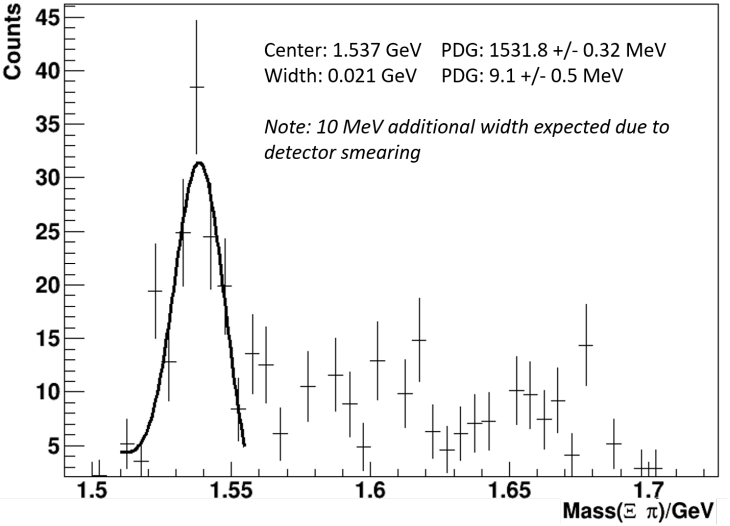
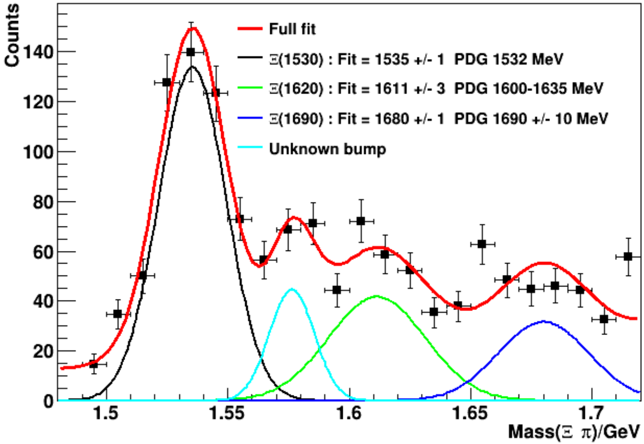
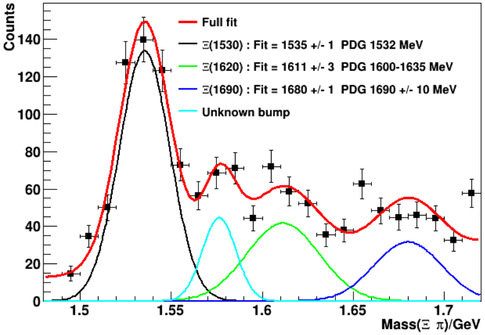


Figure: Fit of Ξ^*

Full Fit of Multiple Resonances



Full Fit Cont'd



- Binning different
- Added data from spring 2018, 2019, 2020 sets of data
- Different CL applied since still investigating
- 10^{-2} seems ideal but limits statistics in area where we don't have much statistics to begin with

Future Work

- Include more statistics (we have additional data)
- Background subtraction
- Utilize different methods for discerning peaks

Acknowledgements

Dugger Lab

- Prof. Michael Dugger
- Dr. Brandon Sumner
- Alan Gardner

Funding

- DOE

The End

Questions? Comments?

Extra Slides:

Background Statistics Cont'd

Let:

$$Z = \frac{S}{\epsilon}$$

Where:

$$S = Signal$$

$$\epsilon = efficiency$$

Then:

$$\frac{\sigma_z^2}{Z^2} = \frac{\sigma_S^2}{S^2} + \frac{\sigma_\epsilon^2}{\epsilon^2}$$

Cross Sections:

$$CS = \frac{S}{\epsilon N_\gamma t}$$

Where:

$$S = \text{signal}$$

$$N_\gamma = \text{Number of Photons Thrown}$$

$$t = \frac{\text{Number of scattering centers}}{\text{Unit Area}}$$

We want smallest possible error bars

$$\sigma_Z = Z\sqrt{\frac{\sigma_S^2}{S^2} + \frac{\sigma_\epsilon^2}{\epsilon^2}}$$

Can minimize $\frac{\sigma_S^2}{S^2}$

with the fractional uncertainties

Can minimize $\frac{\sigma_\epsilon^2}{\epsilon^2}$

by running lots of statistics (Monte Carlo)

Confidence Level Plotted

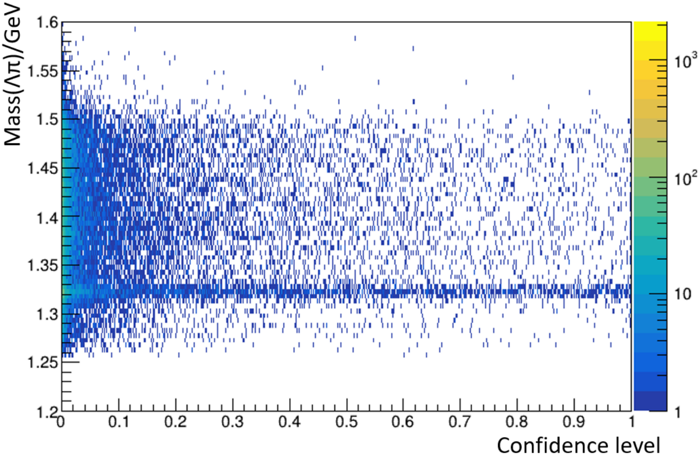


Figure: Confidence Level 2D Plot

Confidence Level Plotted in 1D

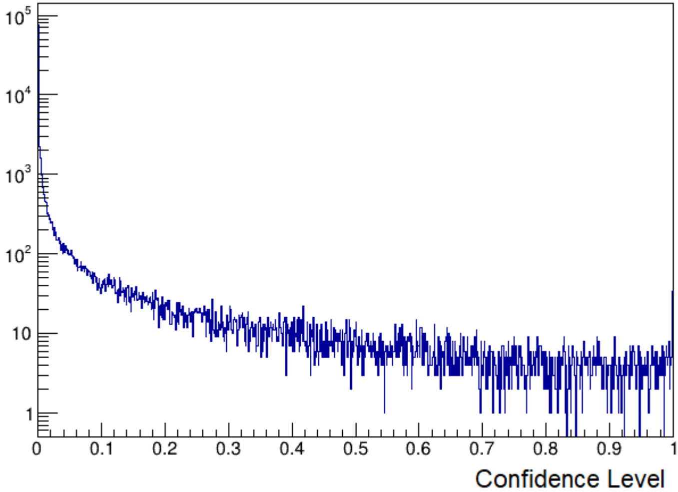


Figure: Confidence Level 1D Plot: Log Scale

Potential Confusion of Our Confidence Level

- In *ideal* case if we made, for example, a cut at 0.1 we would cut 10% of our data
- in reality our data isn't that good
- what's important is to know how much we *did* throw away
- our simulation shows the same behavior
- so making a CL cut we *do know* how much we're throwing away
- important since when cutting data we need to know how much gets cut out
- if we didn't know our efficiency calculations would get messed up!

Confidence Level Conceptually

- our confidence level is showing how much of the χ^2 distribution has been integrated over
- if hypothesis true $\rightarrow$ CL will be flat by design
- the χ^2 is coming from the fitting of all the kinematic variables
- χ^2 is from the χ^2 probability distribution
- confidence level is the integration over that probability
- $CL = 1$ means we've integrated the whole thing

Particle Identification

- Charge-to-mass ratio $\rightarrow$ particles follow curved path in magnetic field. The curvature determined by its charge-to-mass ratio
- energy loss in material $\rightarrow$ rate of energy loss depends of particle's type and its speed
- time of flight $\rightarrow$ time between two points and particle's momentum from curved path in magnetic field are used to determine particle's mass

Kinematic Fitting

- In particle physics experiments we measure several kinematic variables:
    - energy
    - momentum
    - angles
    - etc.
- Measurements come with experimental uncertainties
- kin. fitting is statistical method used to improve resolution of measurements
- It Uses conservation laws (energy,momentum) and known particle masses to adjust meas. values within their uncertainties to find most probably event config.

Hypothesis Testing

- Assumption about the event $\rightarrow$ the particular set of particles produced in a reaction
- Compare the measured kinematic variables to what's expected if hypothesis true

Tagger Magnet

- The tagger magnet produces a magnetic field which through the Lorentz force causes the electrons to curve with a radius of curvature dependent on the electron's energy
- The electrons that interacted with the diamond radiator deflect more than those which did not interact with it
- Using this information, the initial electron energy from the accelerator and the post-bremsstrahlung energy of the electron, the final photon energy can be determined

Detection of Internally Reflected Cherenkov light (DIRC)

- Used for particle identification
- Charged particle traveling through medium at speed faster than speed of light emits light known as Cherenkov Radiation
- The light cone produced is similar to the sonic boom produced when an airplane travels faster than the speed of sound
- Different particles produce different patterns of Cherenkov light allowing for PID

Components of DIRC Detector

- **Radiator:** The core of a DIRC detector is a radiator, usually made of a transparent material like quartz, glass, etc. This is where Cherenkov radiation is produced
- **Light Guides:** Radiation needs to be directed to a sensor. This is done using light guides using internal reflection (like fiber optics)
- **Photon Sensors:** At the end of the light guides, there are sensors (e.g. photomultiplier tubes/photodiodes) that detect the Cherenkov light

PID & Kinematic Fitting

Based on our reactions of interest, the raw data from JLab is ran through PID and kinematic fitting and we can then perform further analysis on it.

Getting Signal Yield

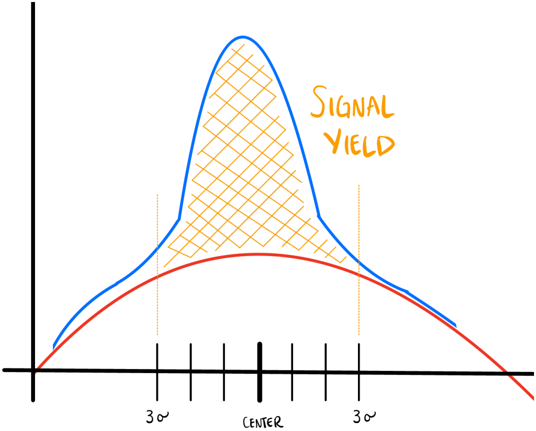


Figure: Signal yield is integration of 3 σ range, subtracting background yield integration of that range. (signal in blue and background in red)