Update on the Search for Pentaquarks

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APPEAL Seminar, SPring-8
29 June 2004

Collaborators

- The LEPS Collaboration
  - Special thanks: Takashi Nakano (Japan)
- The CLAS Collaboration*
  - Co-spokesman: Stepan Stepanyan (JLab)
  - Key contributions by a number of people from CLAS in calibrations, analysis, etc.

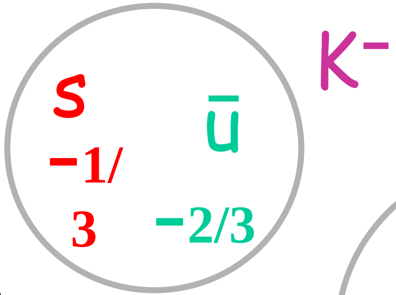
*Supported in part by NSF and DOE

Outline

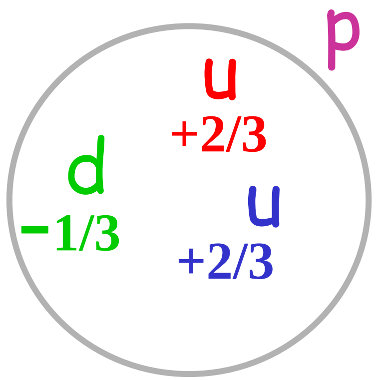
- Introduction
  - Why is the pentaquark important?
- Pentaquarks: theoretical prediction
- Experimental evidence (since Oct. 2002)
  - Review of positive evidence experiments
  - Discussion of null-result experiments
  - Experimental outlook
- Summary

Hadron Spectroscopy 101

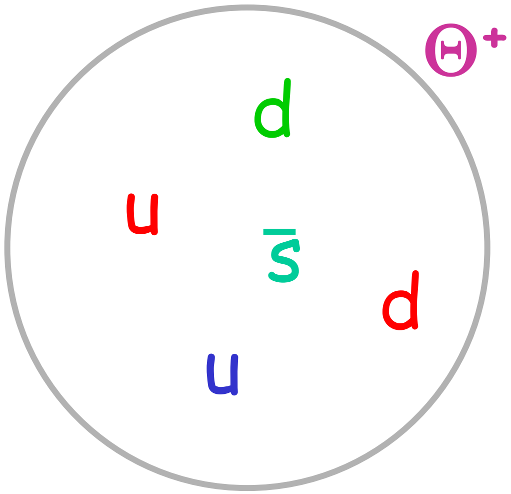
Mesons: quark-antiquark pair



Baryons: three quarks (valence)



Pentaquarks: 4 quarks + 1 antiquark



Each quark has a unique:

- **Charge (+2/3 or -1/3)**
- **Flavor (u,d,s,c,b,t)**
- **Color (red, green, blue)**

How simple is baryon structure?

- Bare quarks have a small mass
  - only 1% of the proton's mass is from quarks!
  - most of the mass: gluons and sea-quarks
- Quarks account for <30% of proton spin
  - so-called "spin crisis"
  - contributions from gluons, orbital L
- The proton has a "pion cloud"
  - from precise electron scattering (Q^2~1)
  - 3-quark core surrounded by q-q pairs
- The proton is a complex many-body system!

Why is the Θ^+ important?

- **QCD does not prohibit $q^4\bar{q}$ states**
  - Early experiments saw no evidence, but what mechanism of QCD would prohibit them?
  - The pentaquark provides a new testing-ground for non-perturbative QCD.

- **"Consideration of pentaquarks brings some <u>serious shortcomings</u> of the naïve quark model into sharp focus."** - F. Wilczek

- **Lattice QCD is also challenged**
  - It tests our understanding of the strong force.

Types of pentaquarks

- **"Non-exotic" pentaquarks**
  - The antiquark has the same flavor as one of the quarks
  - Difficult to distinguish from 3-quark baryons
- **"Exotic" pentaquarks**
  - The antiquark has a different flavor than the other 4 quarks
  - It has quantum numbers unique from any 3-quark baryon
  - Easy to identify from experimental conservation laws

Example: $uuds\bar{s}$, non-exotic (same quantum numbers as uud)

Strangeness = 0 + 0 + 0 − 1 + 1 = 0

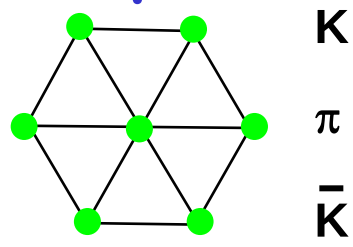
Example: $uudd\bar{s}$, exotic

Strangeness = 0 + 0 + 0 + 0 + 1 = +1

Hadron multiplets

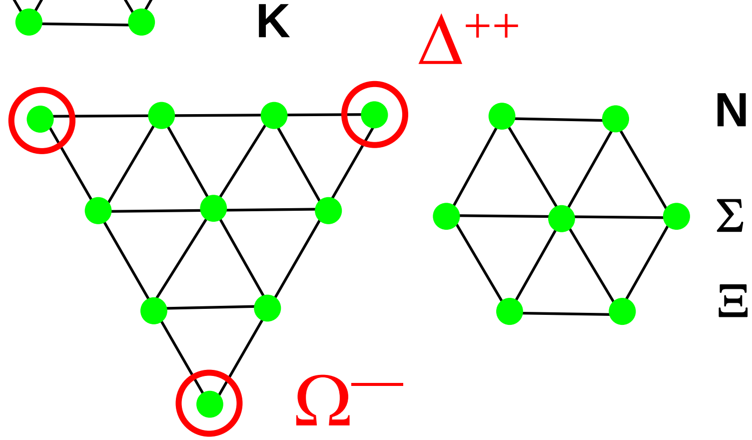
Mesons $q\bar{q}$

$$3 \otimes \bar{3} = 8 \oplus 1$$



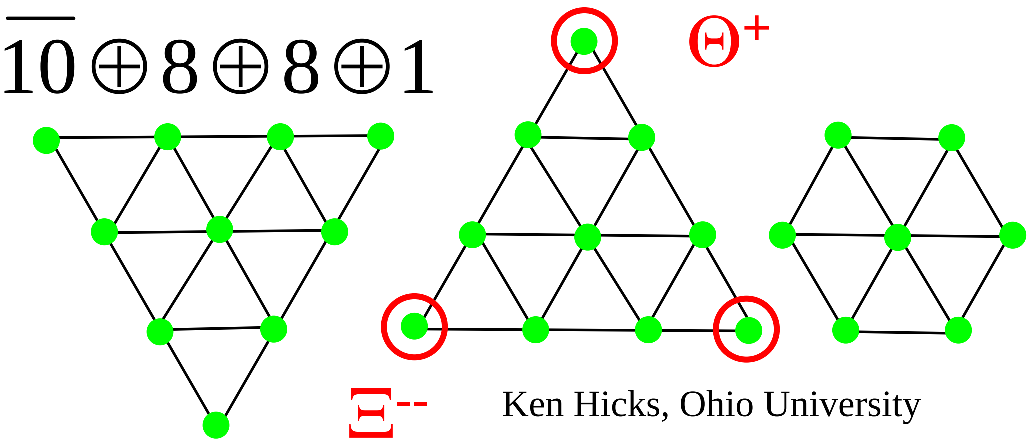
Baryons qqq

$$3 \otimes 3 \otimes 3 = 10 \oplus 8 \oplus 8 \oplus 1$$



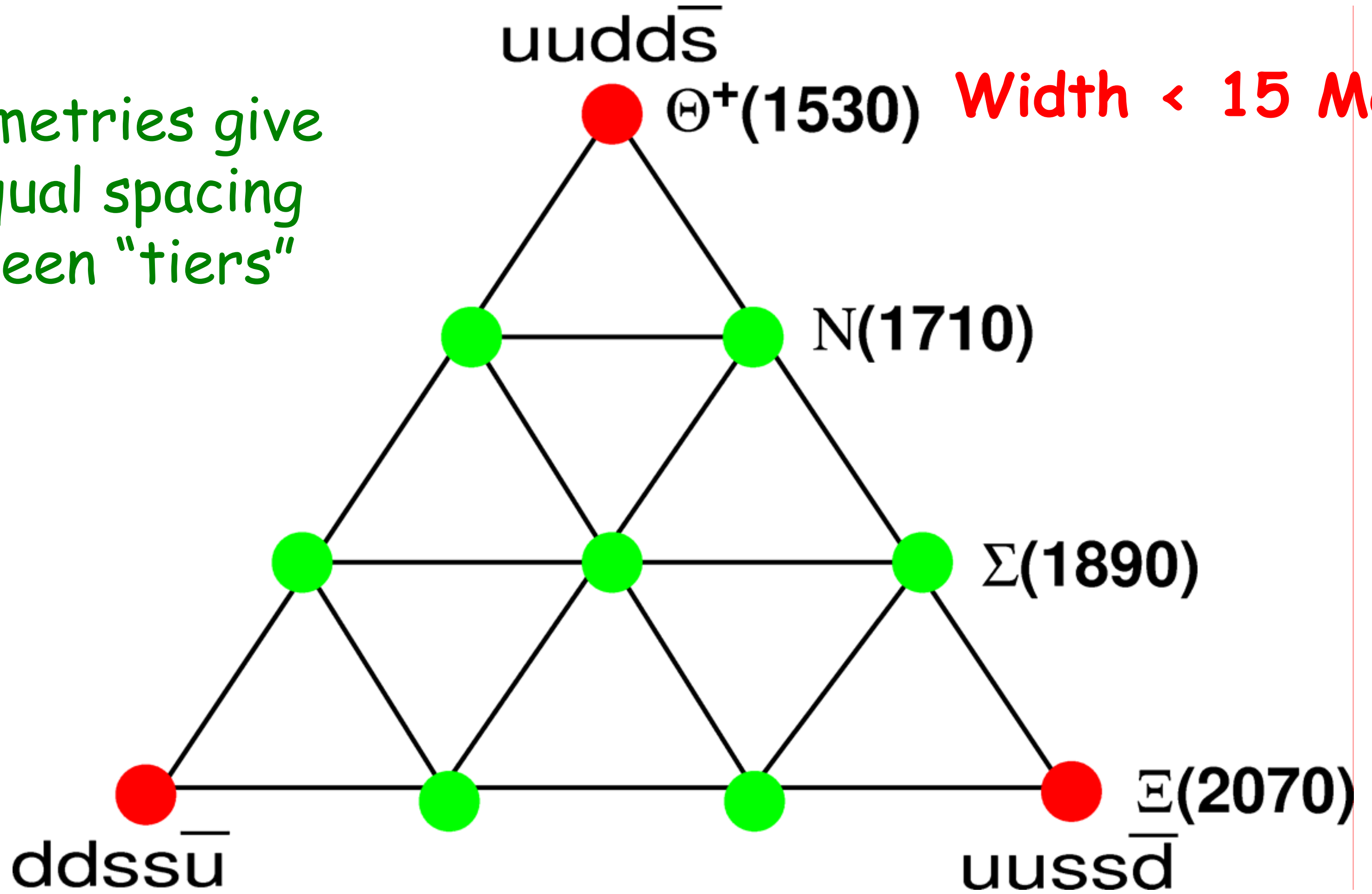
Baryons built from meson-baryon, or $qqqq\bar{q}$

$$8 \otimes 8 = 27 \oplus 10 \oplus \overline{10} \oplus 8 \oplus 8 \oplus 1$$



The Anti-decuplet predicted by Diakonov *et al.*

Symmetries give an equal spacing between "tiers"



Width < 15 MeV !

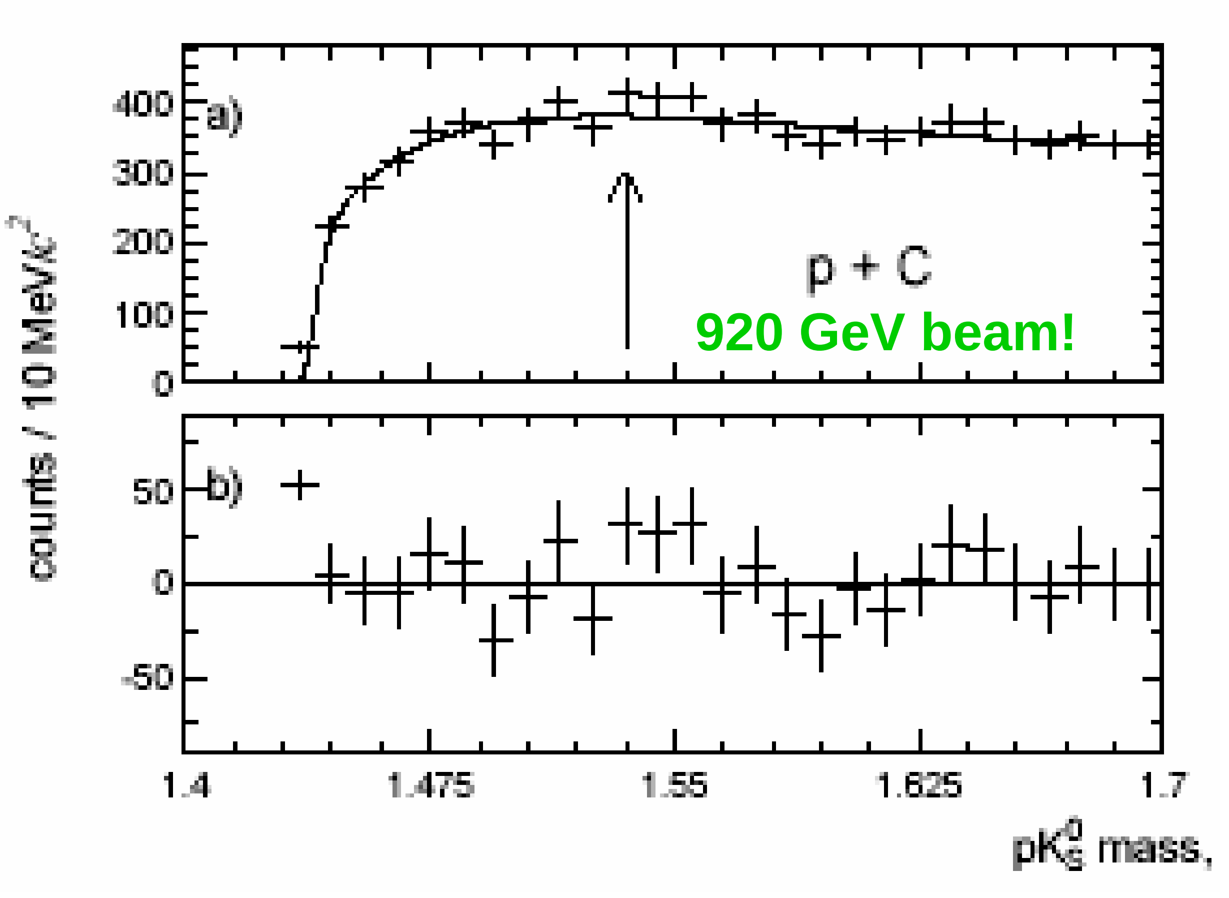
Summary of Experiments

Where	Reaction	Mass	Width	σ's*
LEPS	$\gamma C \rightarrow K^+K^- X$	1540 +- 10	< 25	4.6
DIANA	$K^+Xe \rightarrow K^0p X$	1539 +- 2	< 9	4.4
CLAS	$\gamma d \rightarrow K^+K^-p(n)$	1542 +- 5	< 21	5.2
SAPHIR	$\gamma p \rightarrow K^+K^0(n)$	1540 +- 6	< 25	4.8
ITEP	$\nu A \rightarrow K^0p X$	1533 +- 5	< 20	6.7
CLAS	$\gamma p \rightarrow \pi^+K^-K^+(n)$	1555 +- 10	< 26	7.8
HERMES	$e^+d \rightarrow K^0p X$	1526 +- 3	13 +- 9	~5
ZEUS	$e^+p \rightarrow e'K^0p X$	1522 +- 3	8 +- 4	~5
COSY	$pp \rightarrow K^0p\Sigma^+$	1530 +- 5	< 18	4-6

*Gaussian statistical significance: estimated background fluctuation

Θ^+: Negative Results

HERA-B data on Carbon target: invariant mass of pK^0 shows no Θ^+ peak!

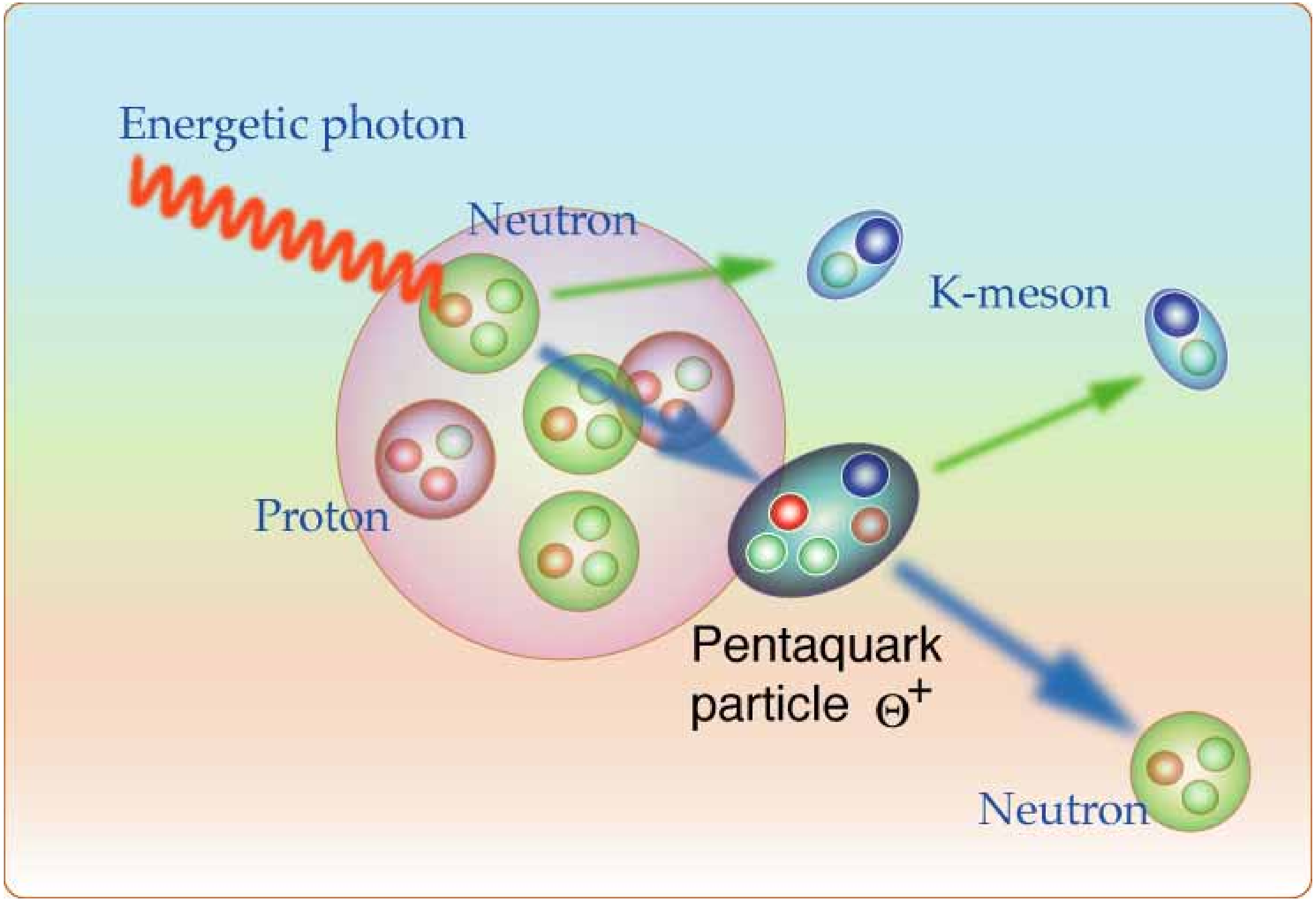


Could kinematics be an issue? If Θ^+ is not produced by t-channel, then HERA-B may not see it.

Other Negative Results

- At the QNP conference (May, 2004) new negative results were shown:
  - FNAL E690 (pp → p X at 800 GeV)
  - FNAL CDF (p$\underline{p}$ at c.m. energy 2 TeV)
  - FNAL HyperCP (mixed beam of π's, K's, p's)
  - SLAC BaBar (B-factory e+e- collisions)
- All of these are inclusive, high-energy data sets (like HERA-B), with high statistics.
  - What is this telling us??

Schematic Diagram of the Reaction

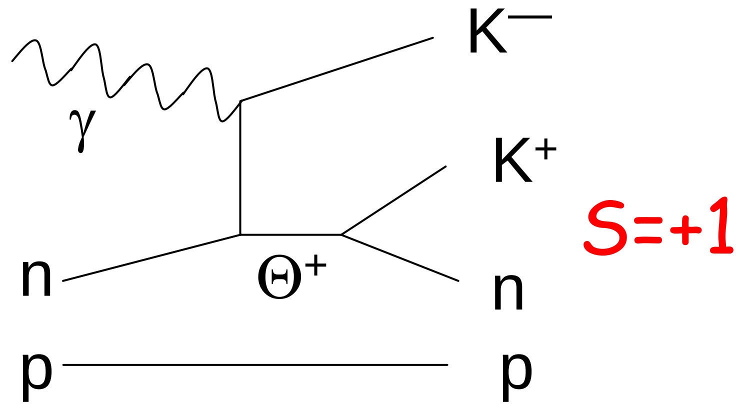


Reaction diagrams

$\gamma n\,(p) \rightarrow \Theta^{+} K^{-}\;(p)$

$\Theta^{+} \rightarrow K^{+} n$

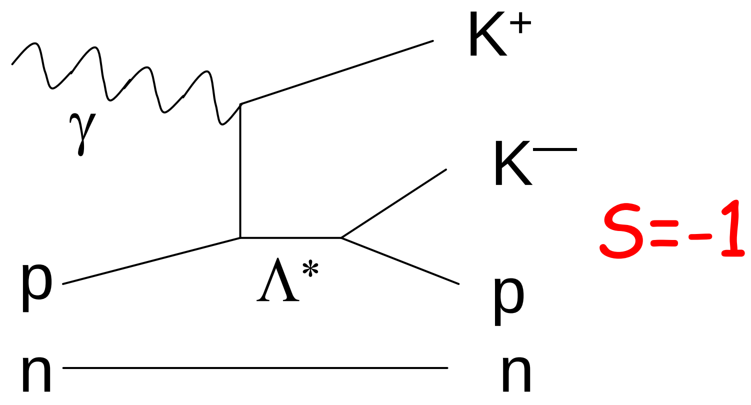
"Exotic"



$\gamma p\,(n) \rightarrow \Lambda^{*}(1520) K^{+}\;(n)$

$\Lambda^{*}(1520) \rightarrow K^{-} p$

"Standard" baryon



$\gamma N \rightarrow \phi(1020)\, N \rightarrow K^{+}K^{-} N$ Meson resonance

LEPS: published mass plot

Assumption:

- Background is from non-resonant K^+K^- production off the nucleon.
- Hydrogen target data is used to estimate the background shape

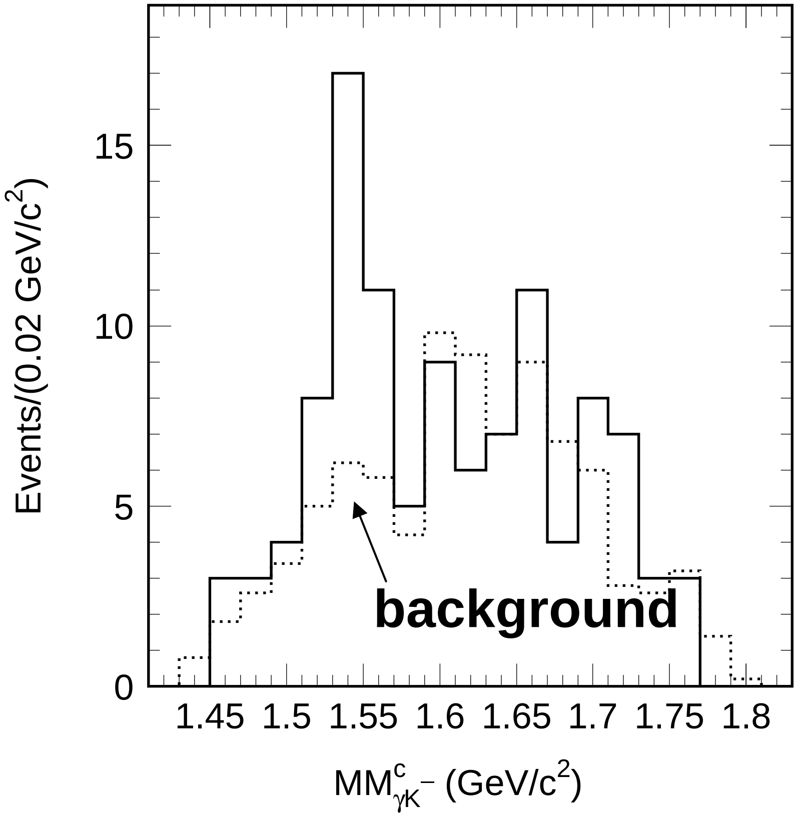
Phys.Rev.Lett. 91 (2003) 012002

hep-ex/0301020

M = **1.54±0.01 MeV**

Γ **< 25 MeV**

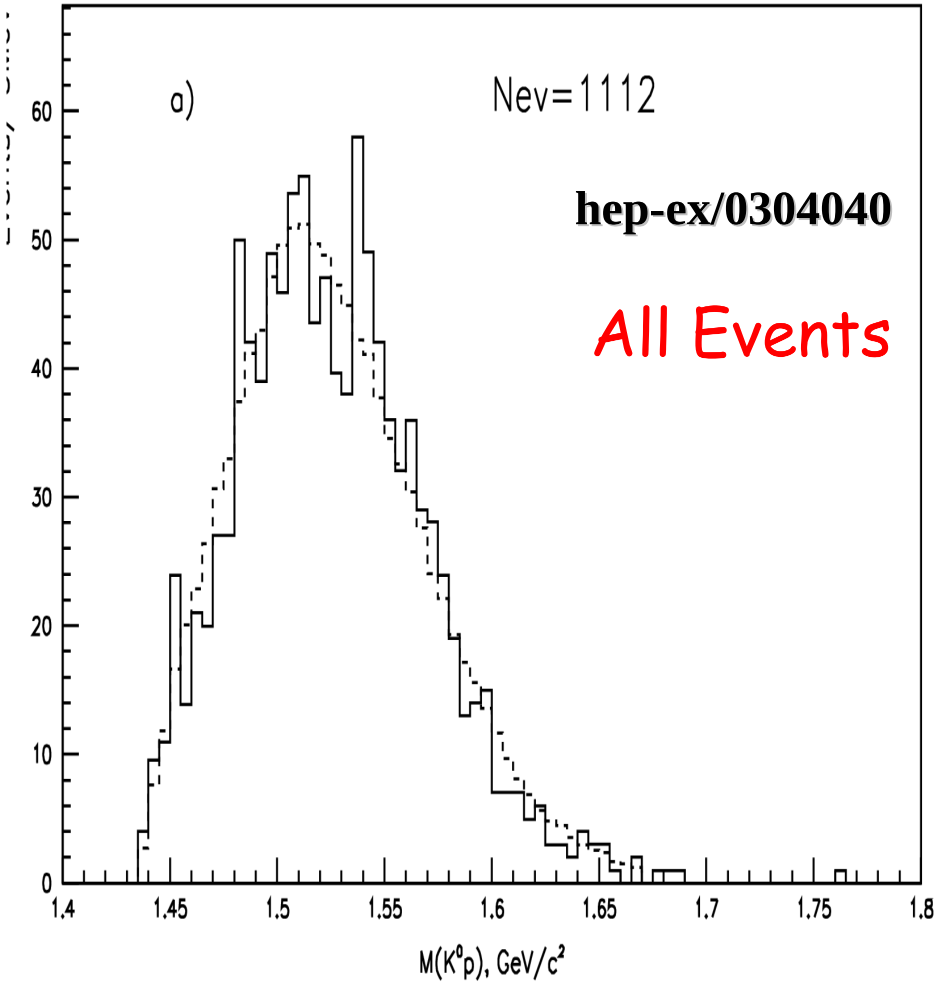
Gaussian significance 4.6σ

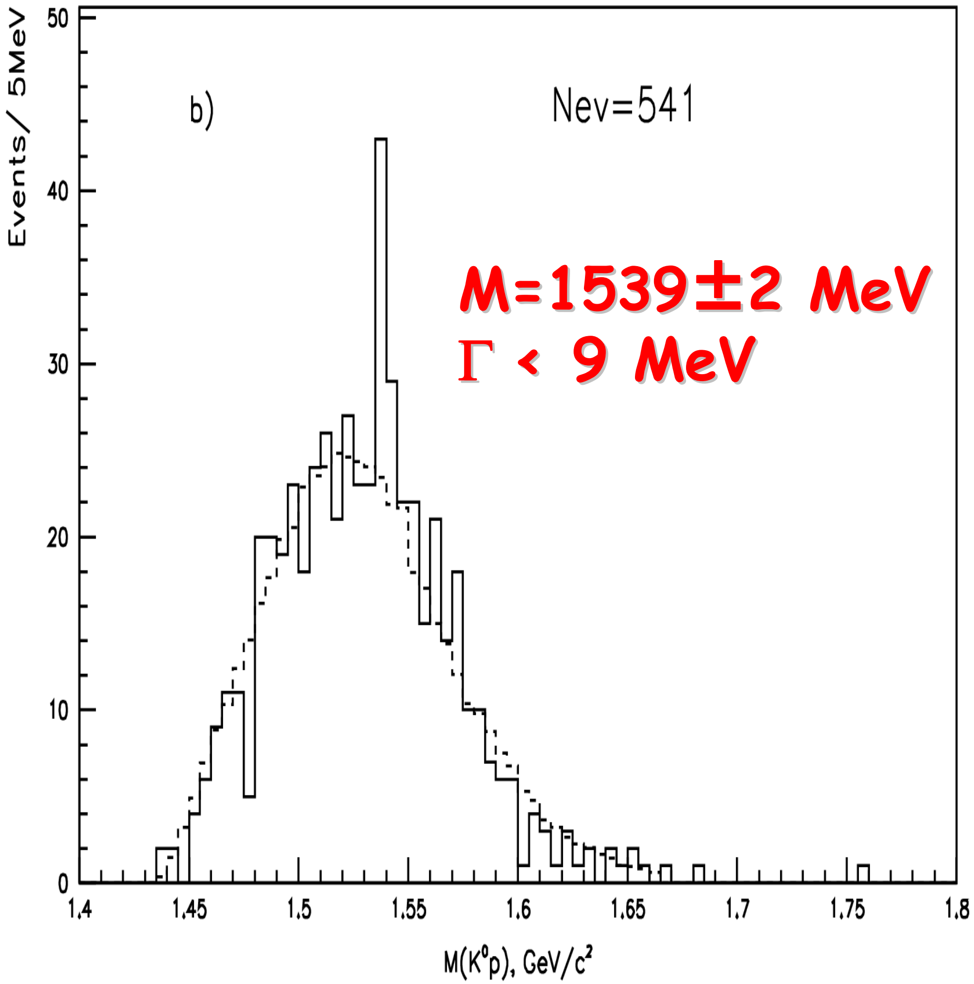


DIANA at ITEP: 850 MeV K^+ beam

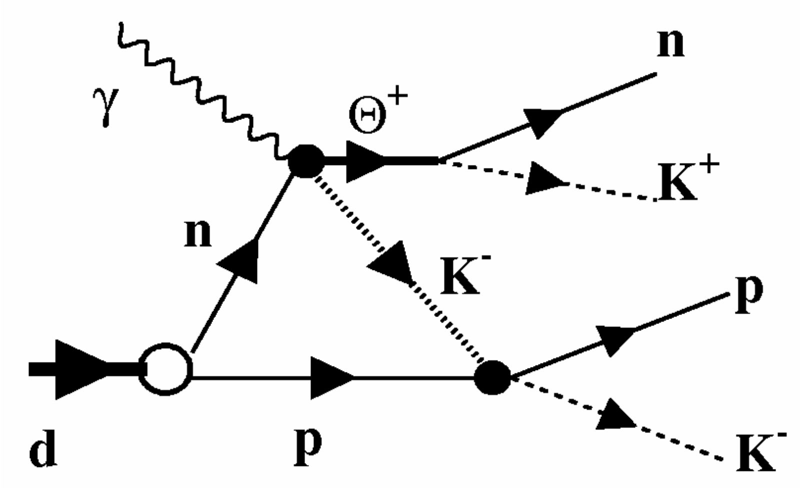
$K^+ Xe \rightarrow \Theta^+ N \rightarrow (K^0 p) N$

Cuts to suppress p and K^0 reinteraction in Xe nucleus





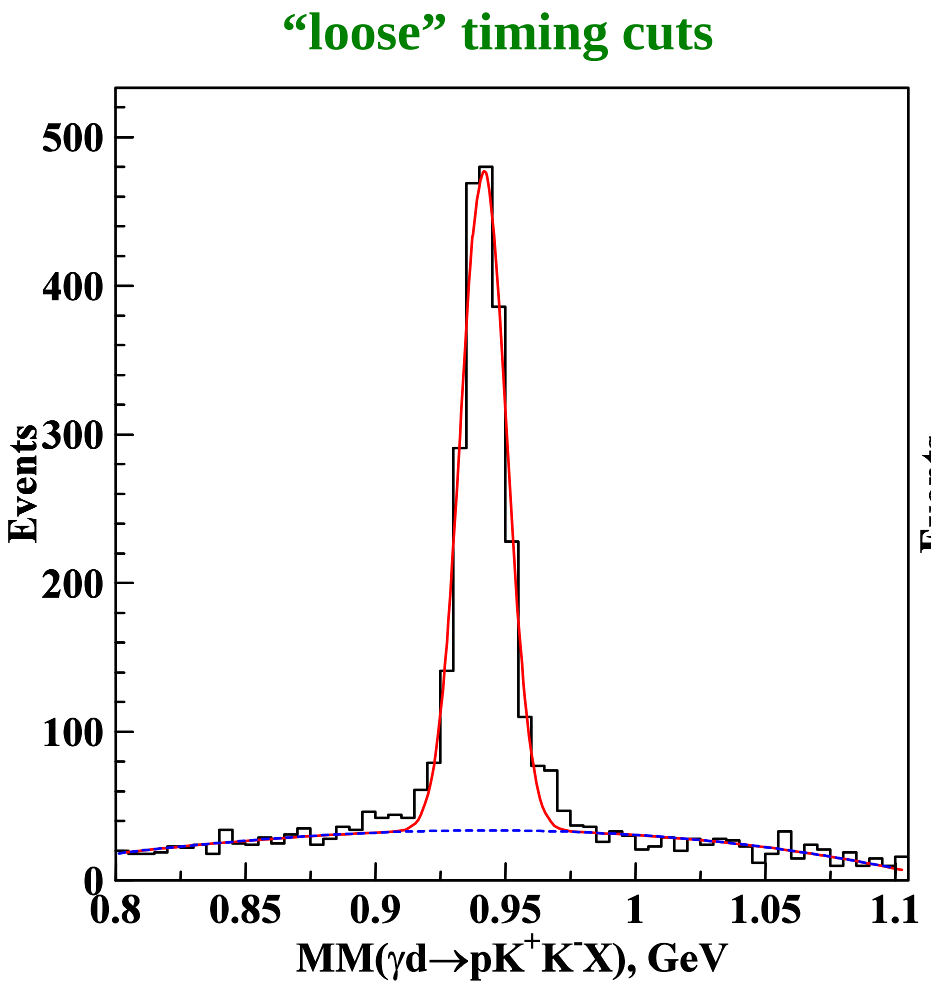
CLAS: Exclusive photoproduction

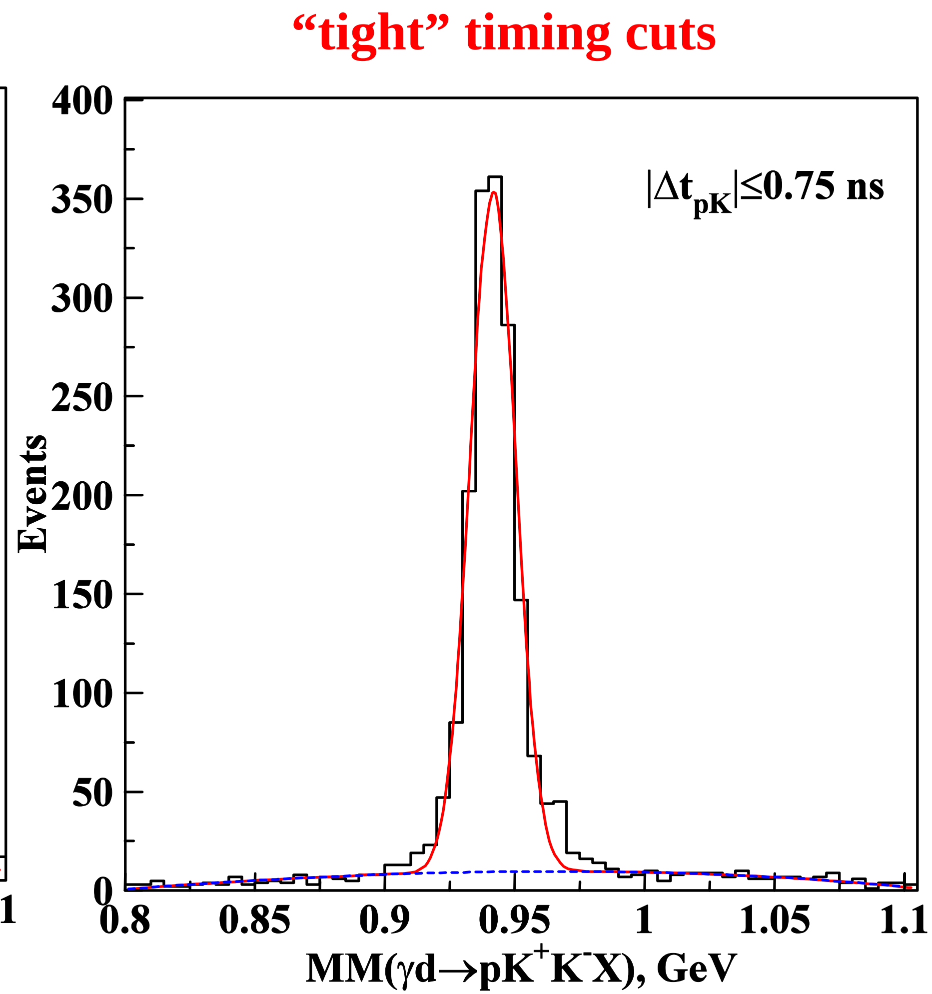


CLAS Collaboration
S. Stepanyan, *et al.*,
PRL 91, 252001 (2003).

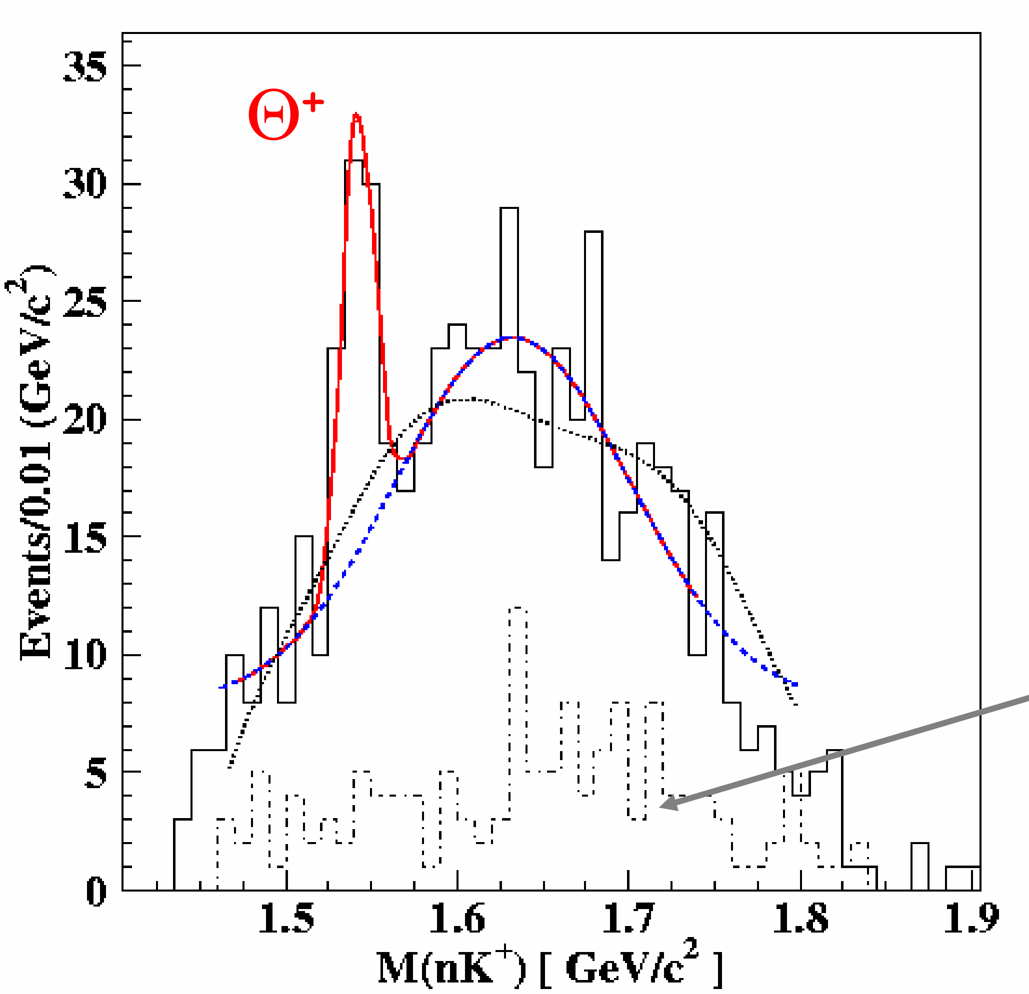
- Requires FSI – both nucleons involved
  - No Fermi motion correction necessary
  - FSI not rare: in ~50% of $\Lambda(1520)$ events, both nucleons have p>0.2 GeV/c

Neutron found via missing mass





CLAS: Deuterium Results

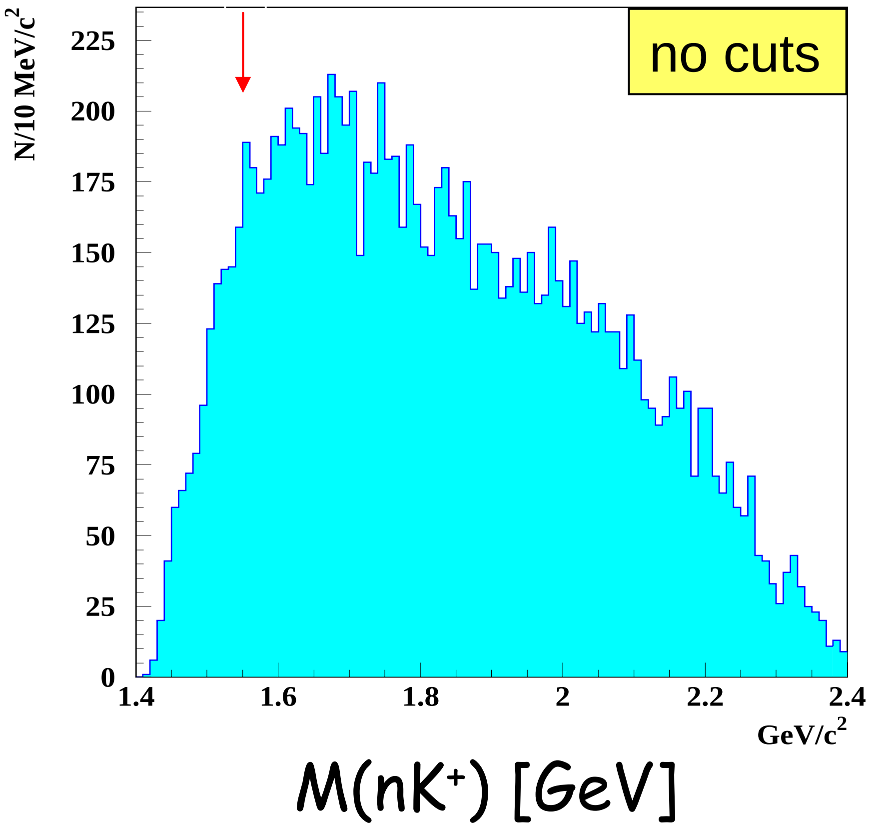


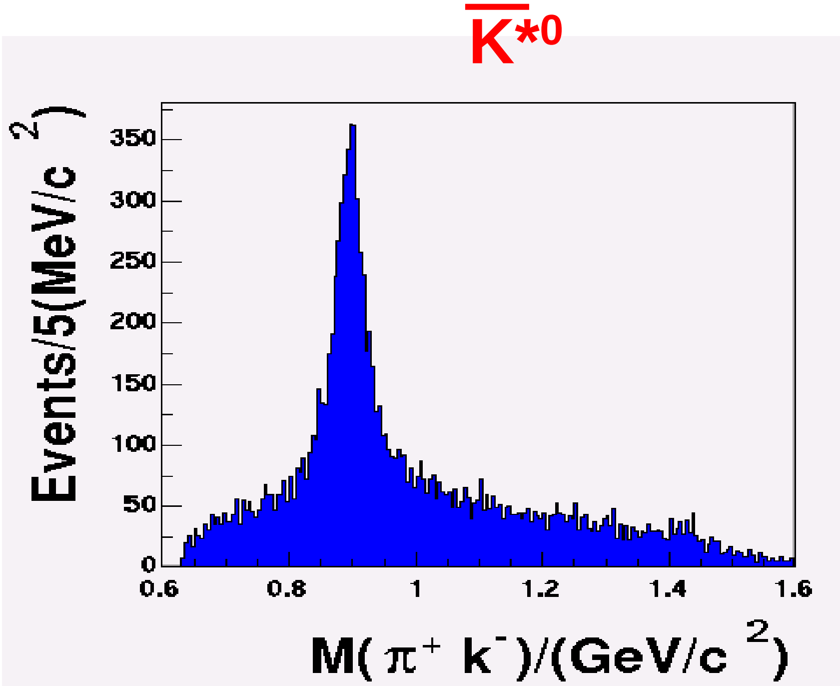
- ~42 events in the narrow peak at 1542 +- 5 MeV with width of 21 MeV
- Estimated significance 5.2 +- 0.6 σ
- Spectrum of the events associated with Λ(1520)

CLAS: Θ^+ from the proton

$\gamma p \rightarrow \pi^+ K^- K^+ (n)$

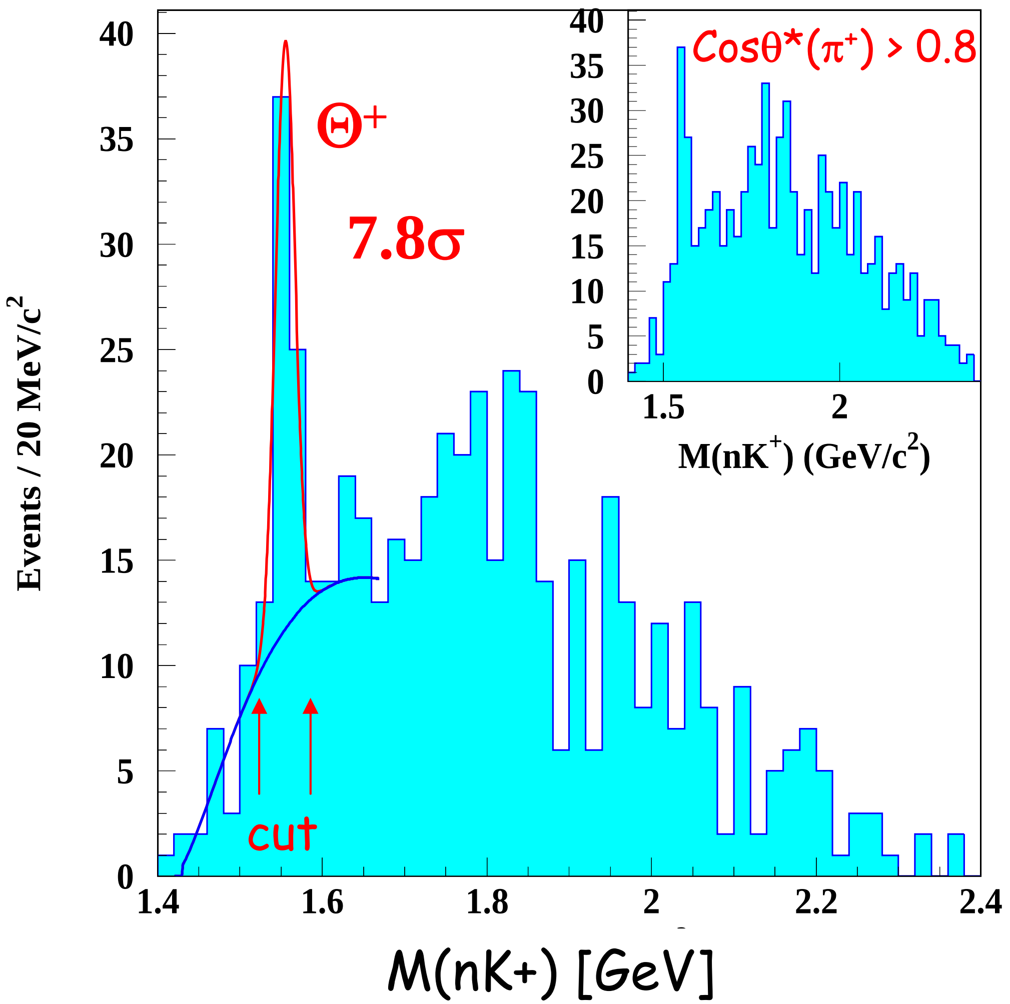
Prominent $\overline{K}^{*0}$

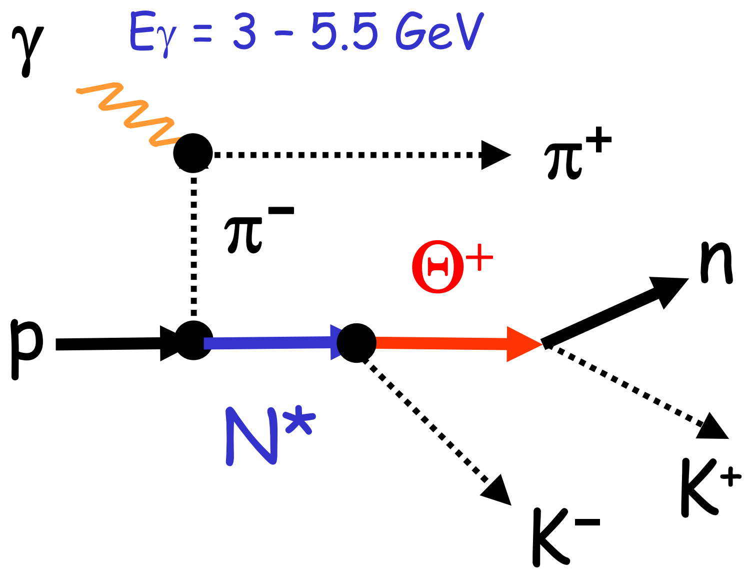




CLAS: Θ^+ from the proton

$\gamma p \rightarrow \pi^+ K^- K^+ (n)$





M=1555±10 MeV

Γ< 26 MeV

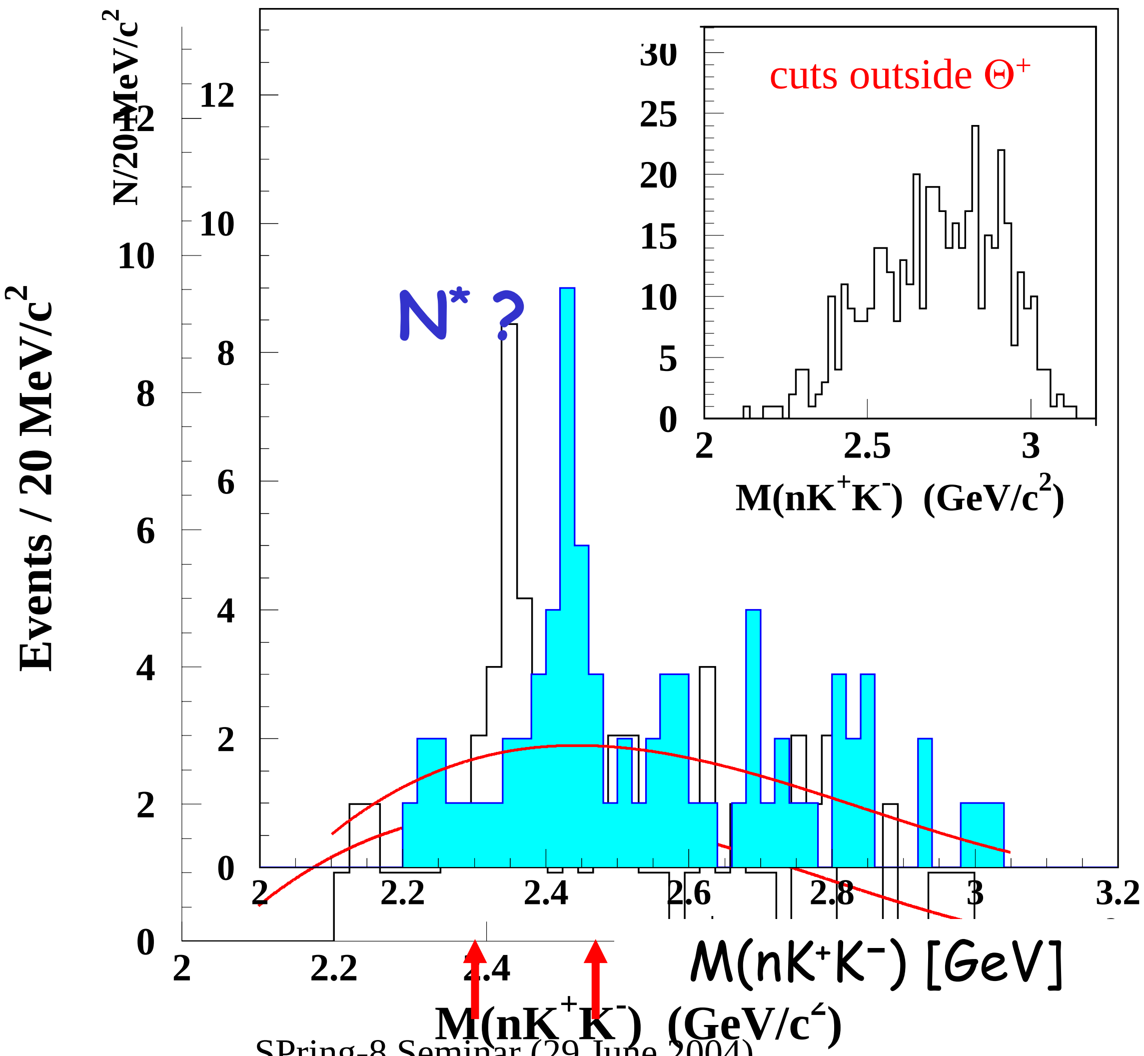
Cosθ*(π+) > 0.8

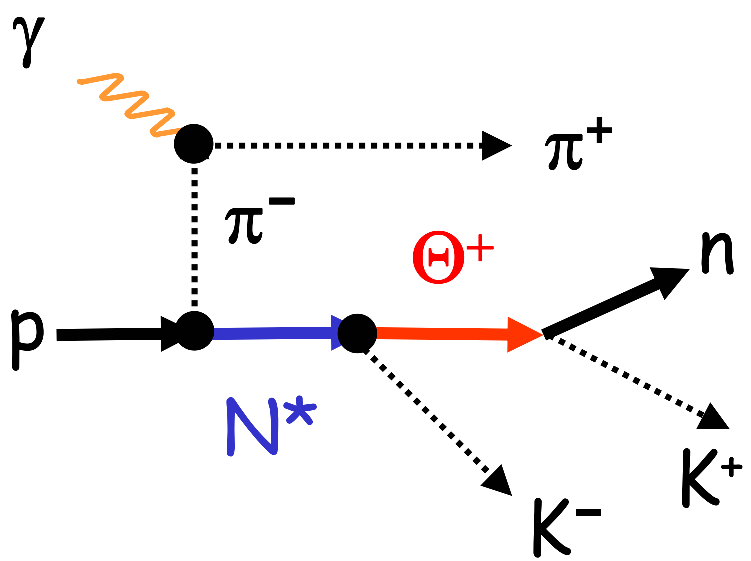
Cosθ*(K+) < 0.6

CLAS Collaboration

PRL 92, 032001-1 (2004).

Θ^+ - N* production mechanism?



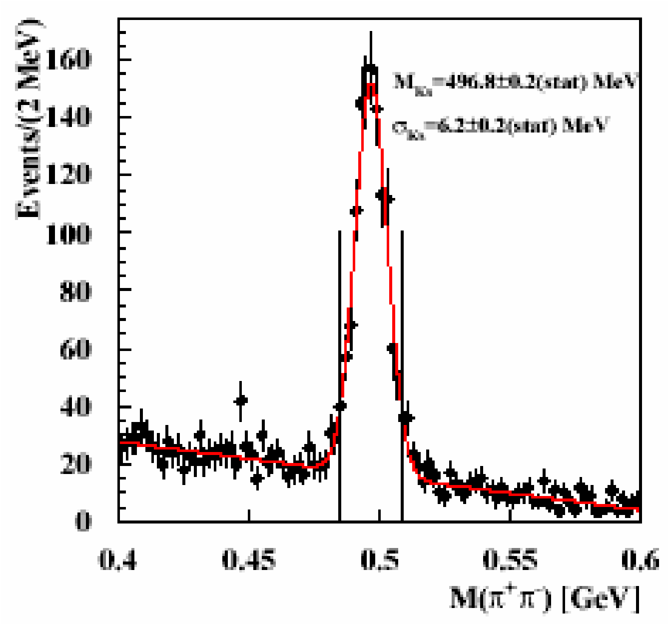


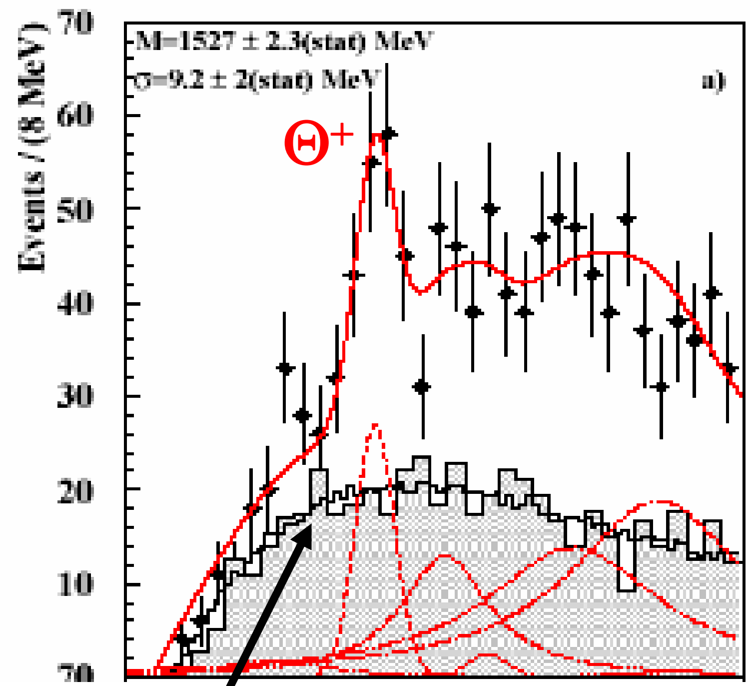
- **What do π^-p scattering data say?**
- π^-p cross section data in PDG have a gap in the mass range 2.3–2.43 GeV.

HERMES: $e^+d \rightarrow K^0 p\ X$

Detect $K^0 \rightarrow \pi^+\pi^-$
Nice clean peak.

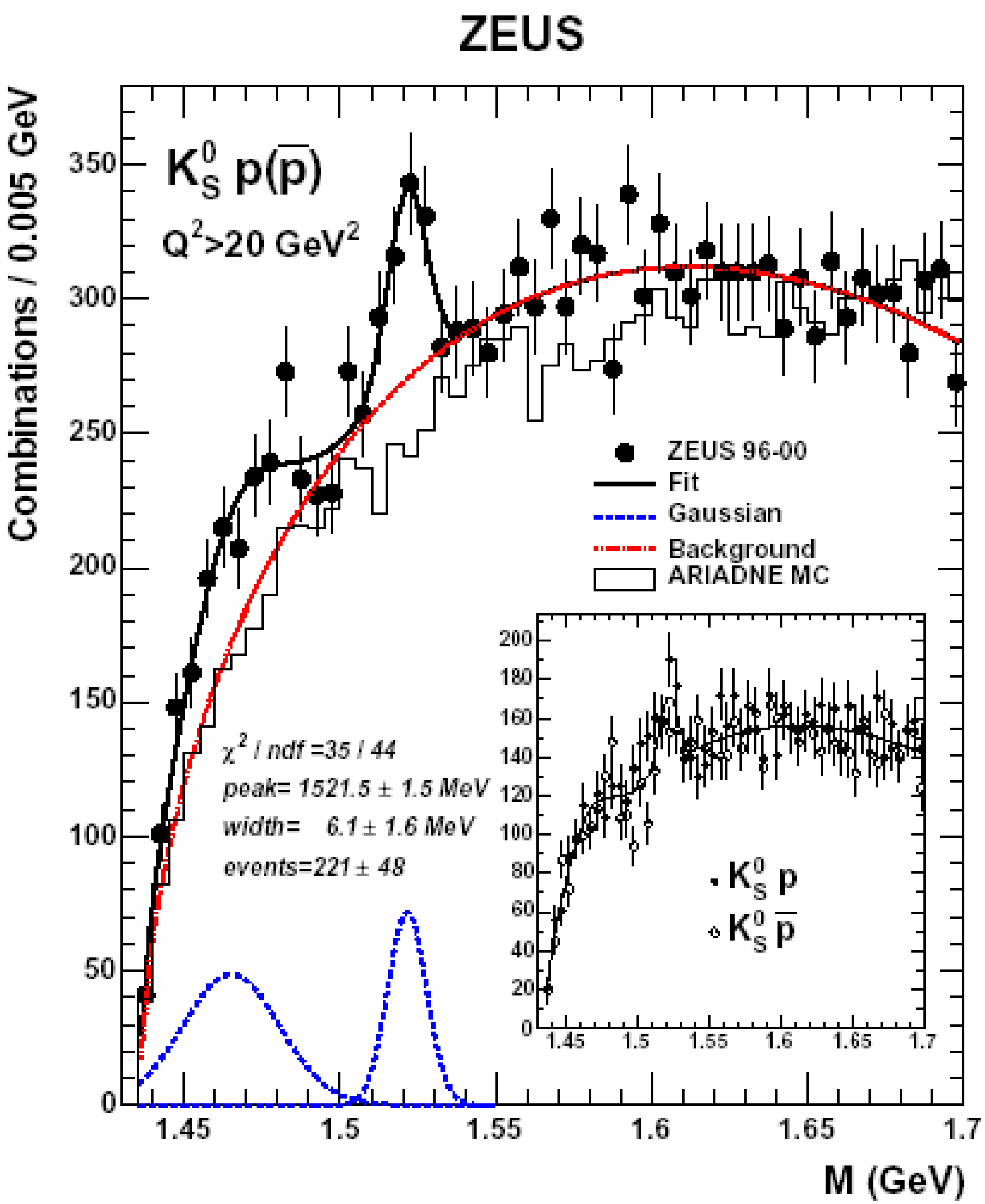
Complicated background due to Σ^* resonances





mixed events **shaded: Pythia MC**

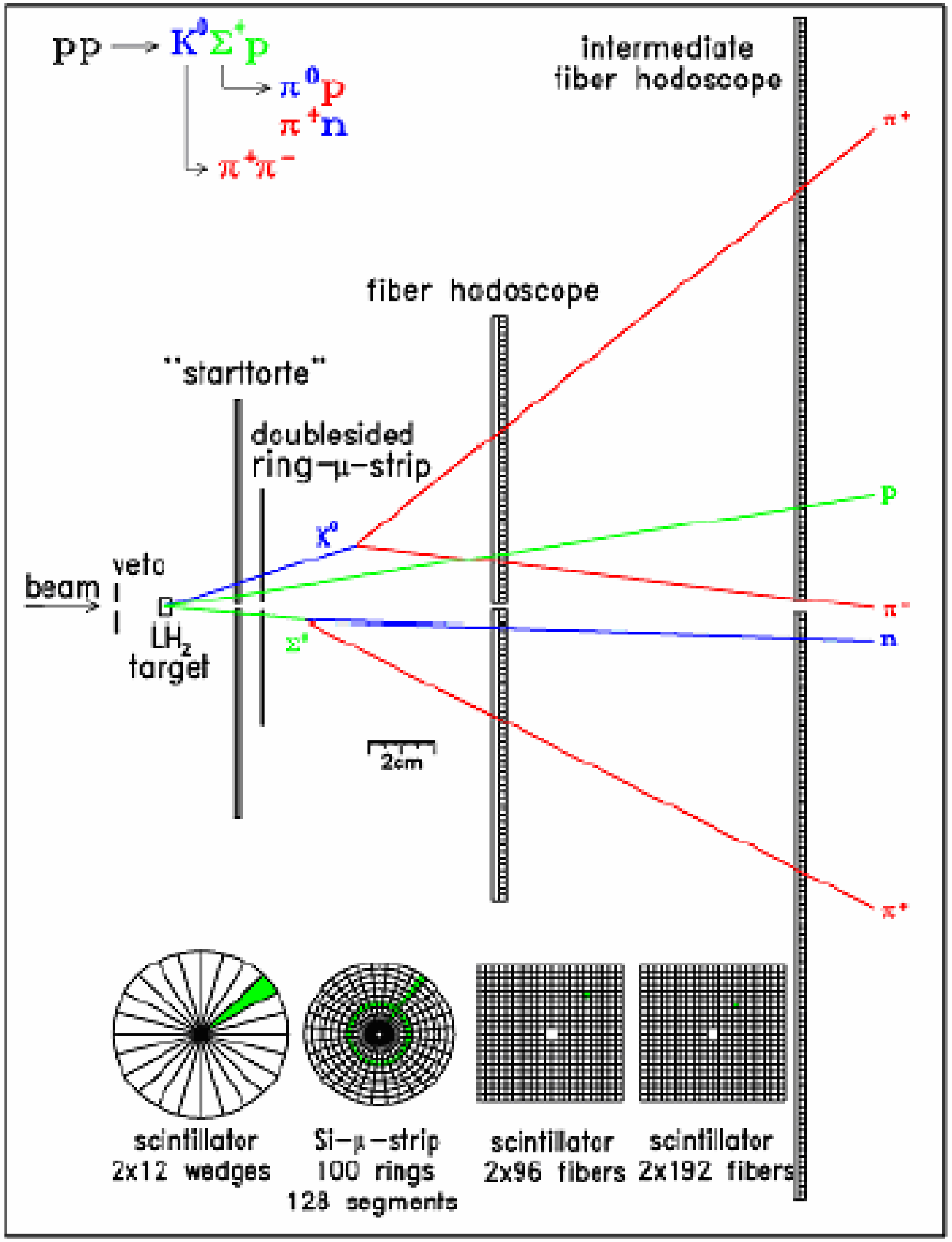
ZEUS final


ZEUS
Combinations / 0.005 GeV
M (GeV)
$K^0_S\, p(\bar{p})$
Q^2>20 GeV^2
ZEUS 96-00
Fit
Gaussian
Background
ARIADNE MC
χ^2 / ndf =35 / 44
peak= 1521.5 ± 1.5 MeV
width= 6.1 ± 1.6 MeV
events=221 ± 48
$K^0_S\, p$
$K^0_S\, \bar{p}$

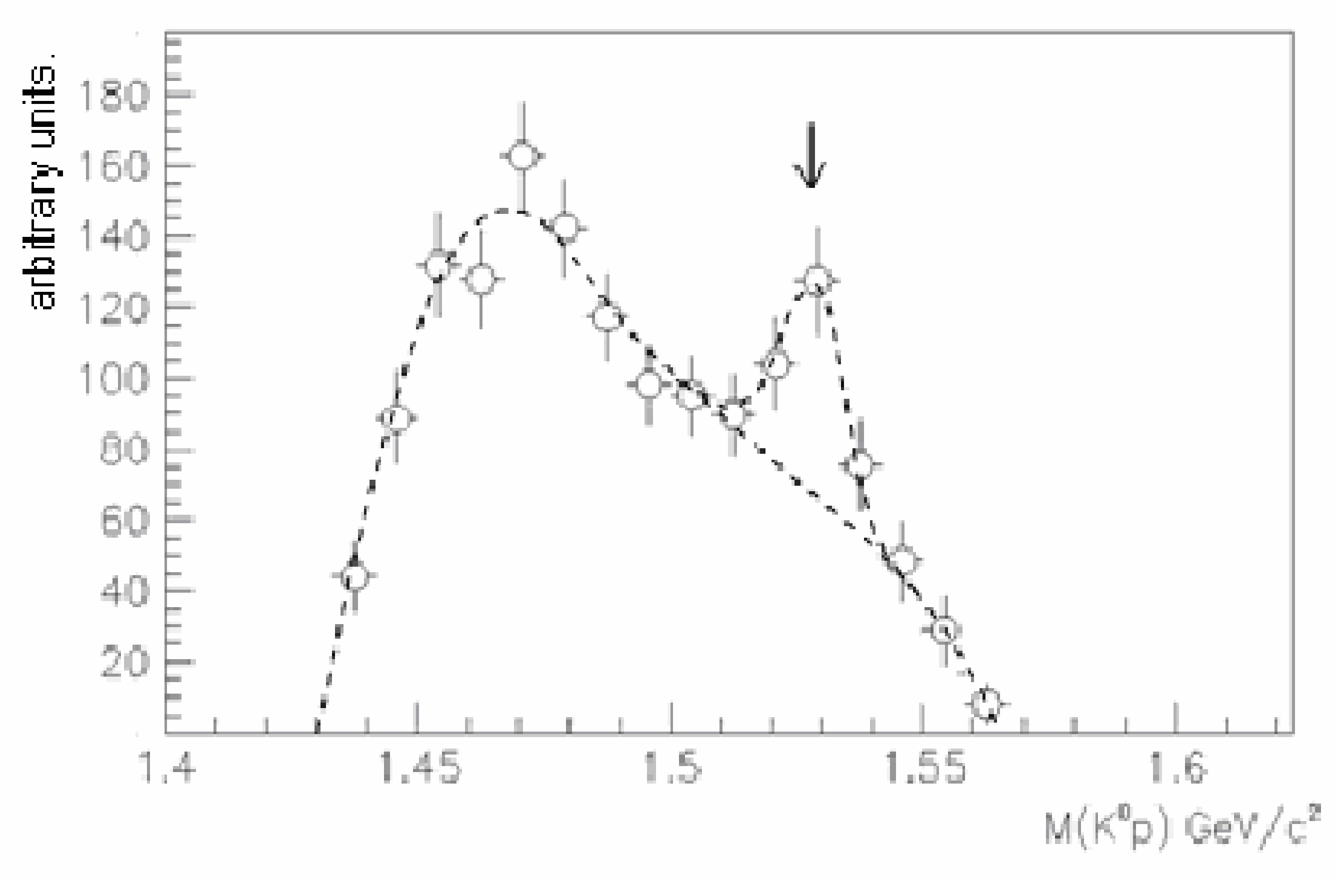
COSY:
pp → $K^0 p \Sigma^+$

The COSY-TOF detector uses scintillators and microstrips to get good vertex reconstruction.

Finding a detached vertex is easy in the low-multiplicity environment.



COSY final



- The TOF detector at the COSY facility in Germany
- Evidence for the Θ^+ in the reaction: p + p → $\Sigma^+ + \Theta^+$.

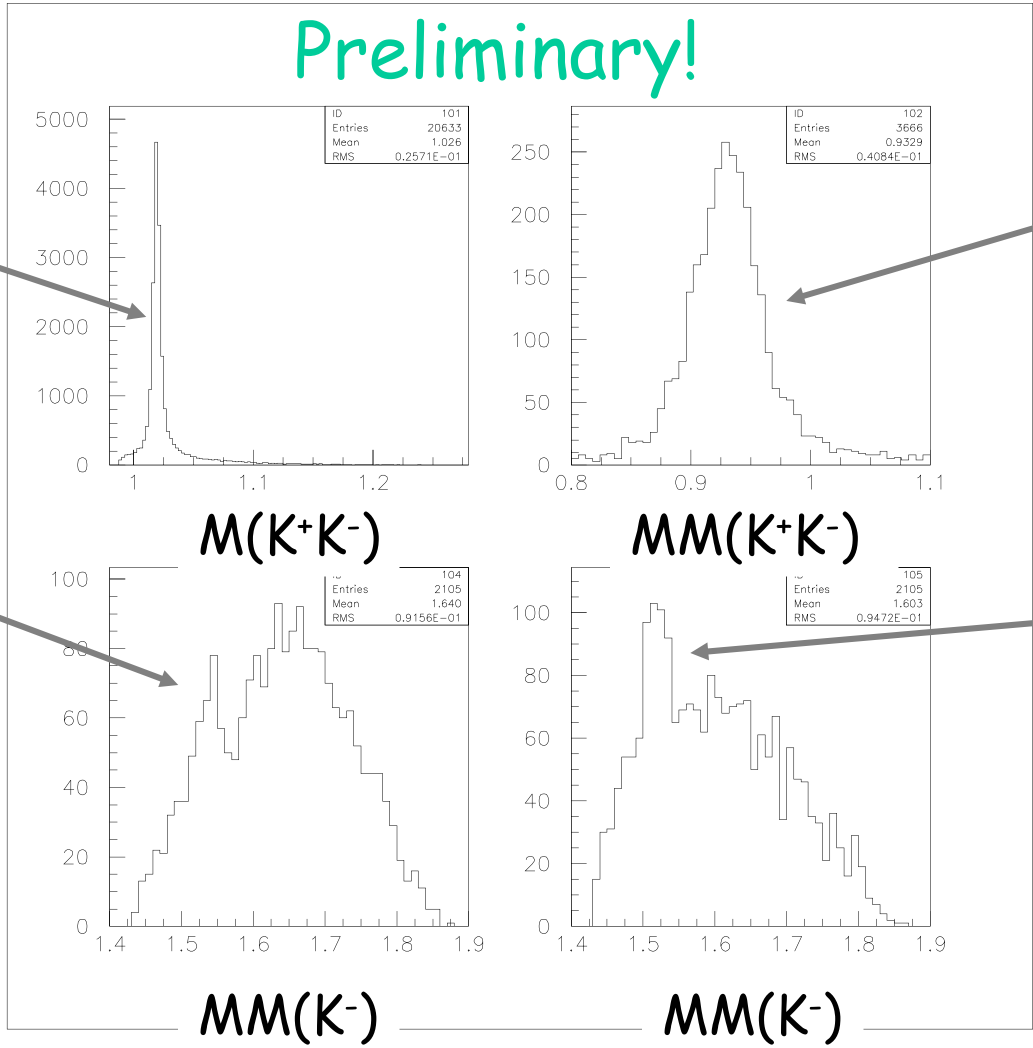
LEPS: new deuterium results

- Preliminary data (not yet published)
- Higher statistics (5-10 times more)
- Minimal "cuts" on the data:
  - Particle ID of K+, K-
  - Missing mass = Nucleon mass
  - Remove ϕ-meson production events
- Further cuts:
  - Photon energy
  - Remove events with more than 2 tracks
  - Remove $\Lambda(1520)$

LEPS: "Default" analysis

φ meson

Θ+ mass
[$\bar{\phi}$,N cuts]

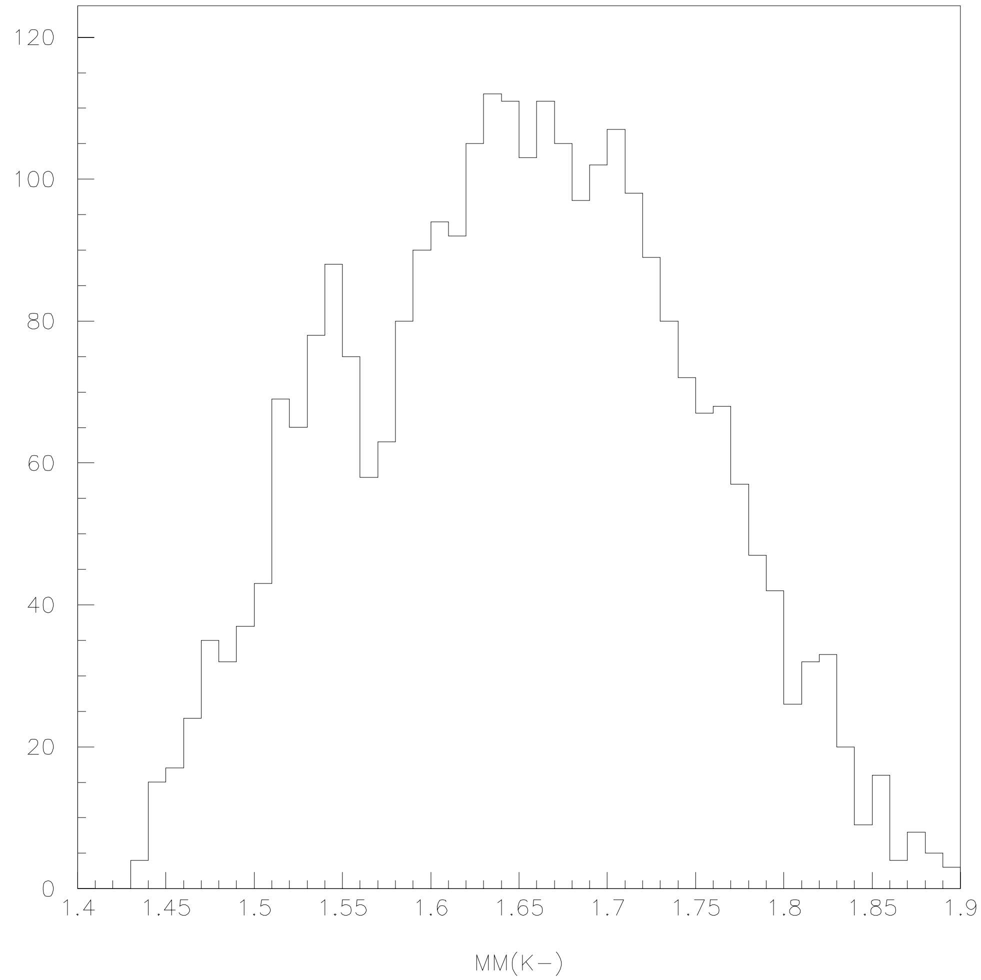


Nucleon mass

Λ(1520)
[$\bar{\phi}$,N cuts]

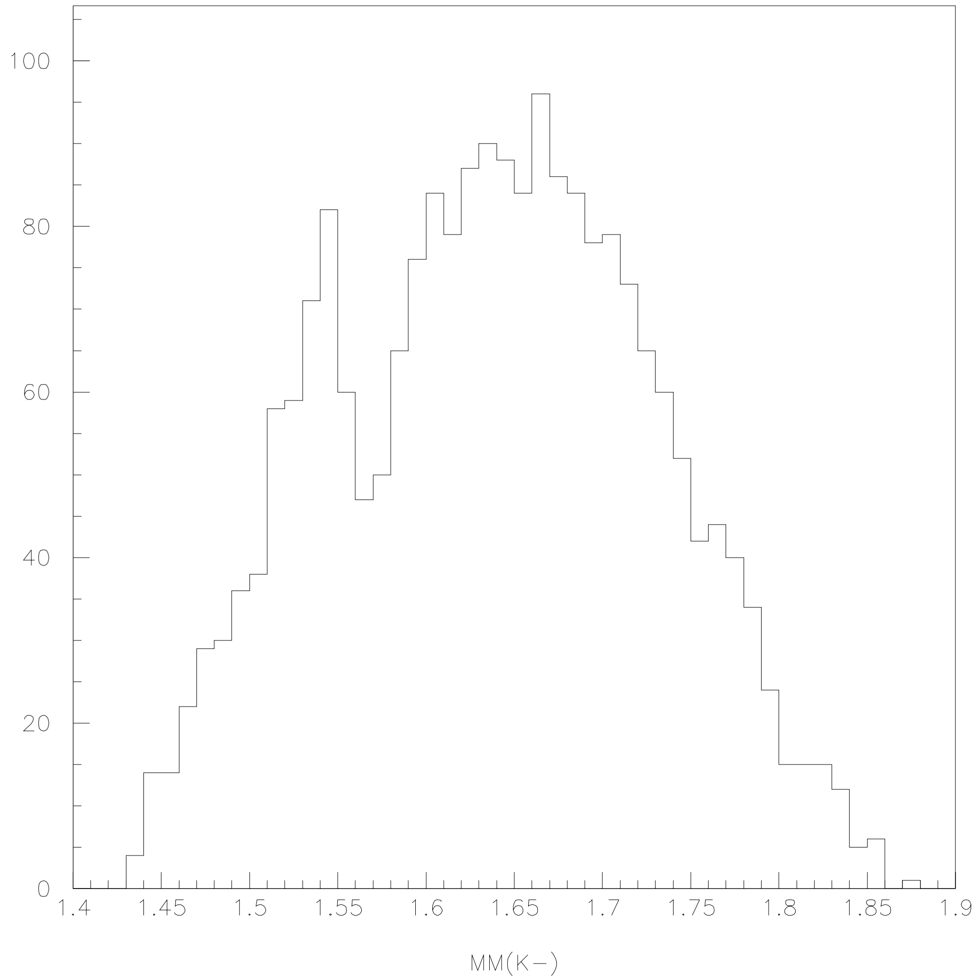
LEPS γd: Minimal Cuts

Preliminary!



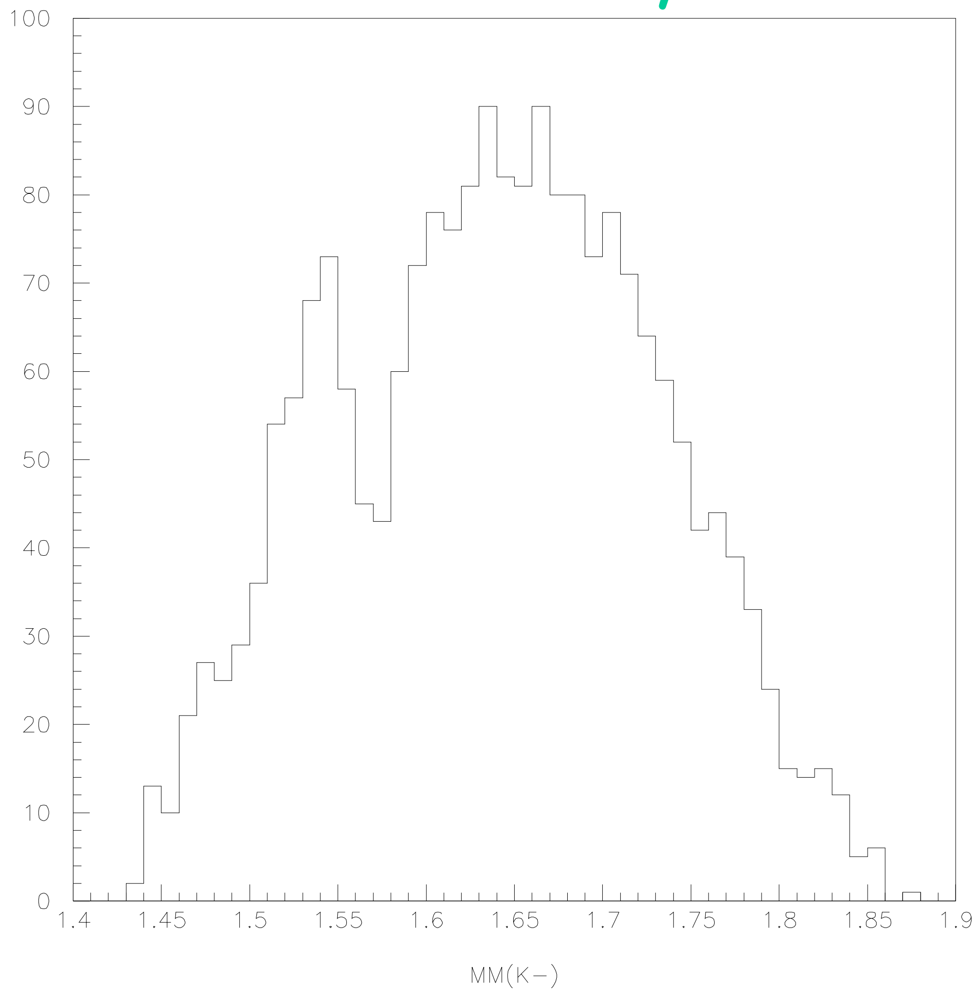
LEPS γd: "standard" cuts

Preliminary!



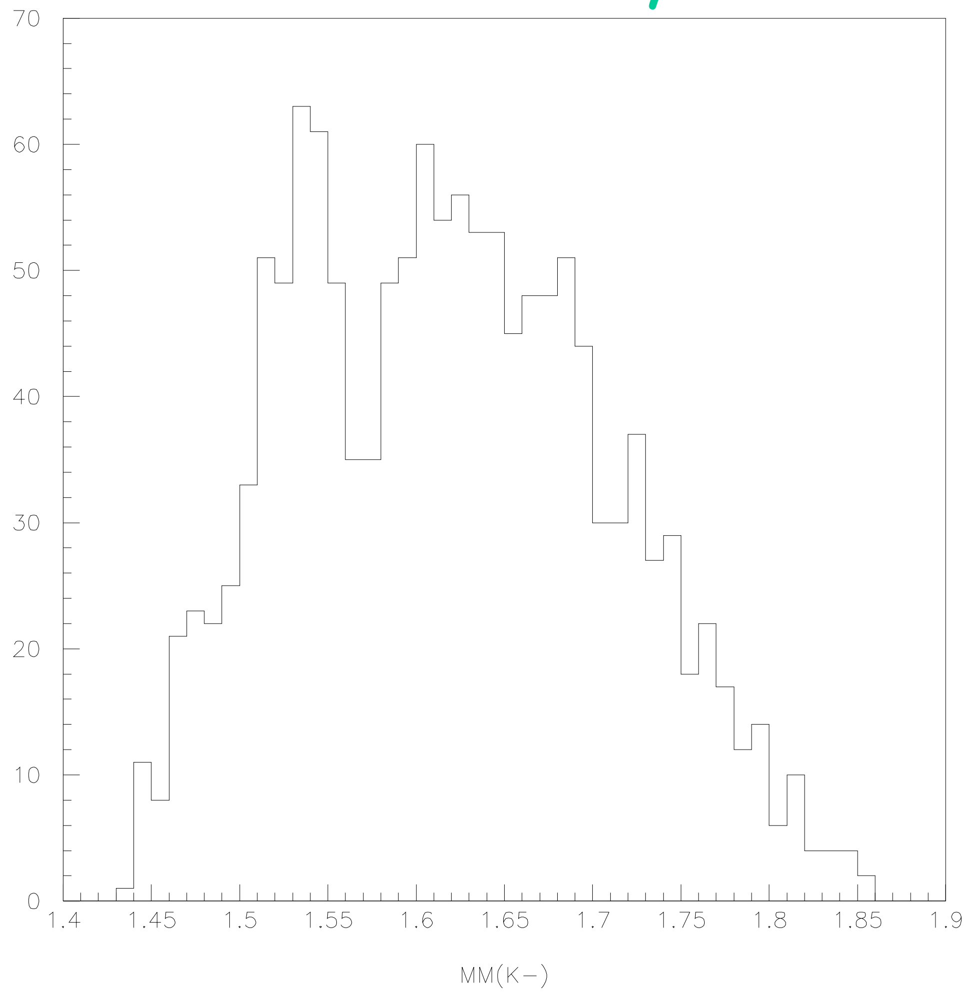
LEPS γd: "cleaner" cuts

Preliminary!



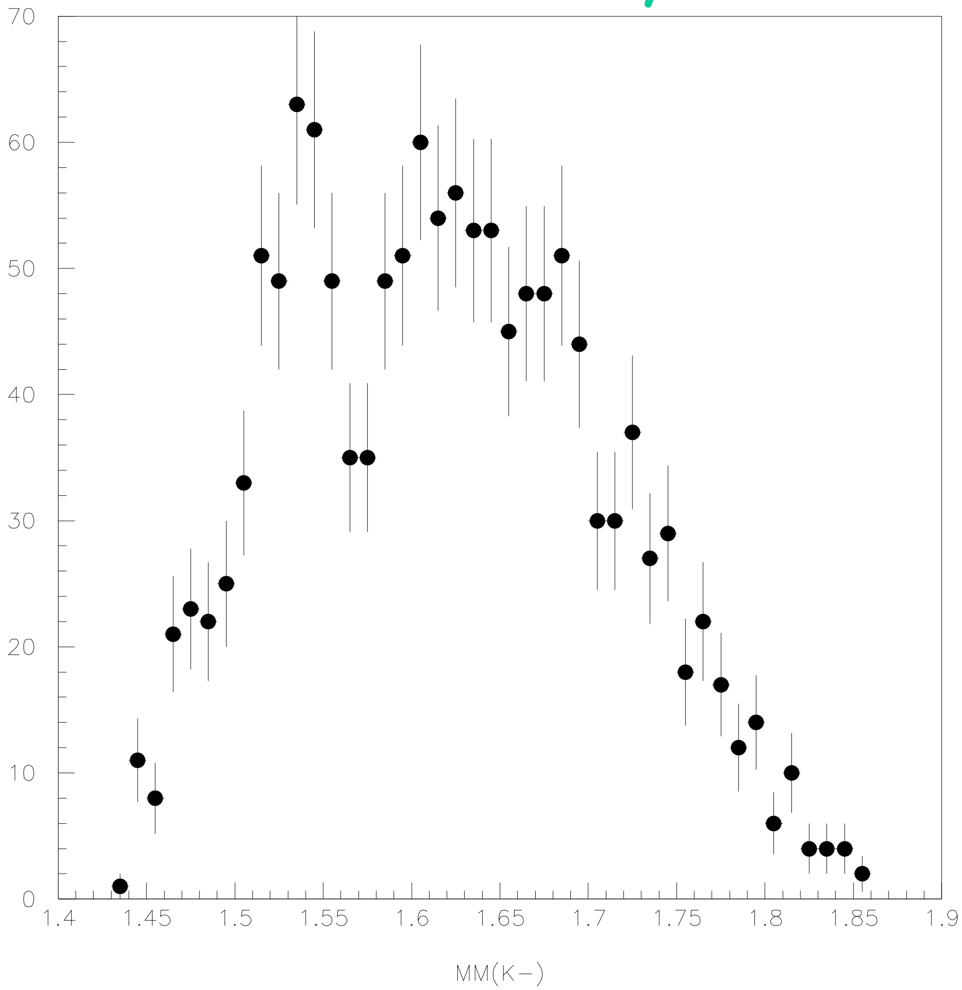
LEPS γd: remove $\Lambda(1520)$

Preliminary!

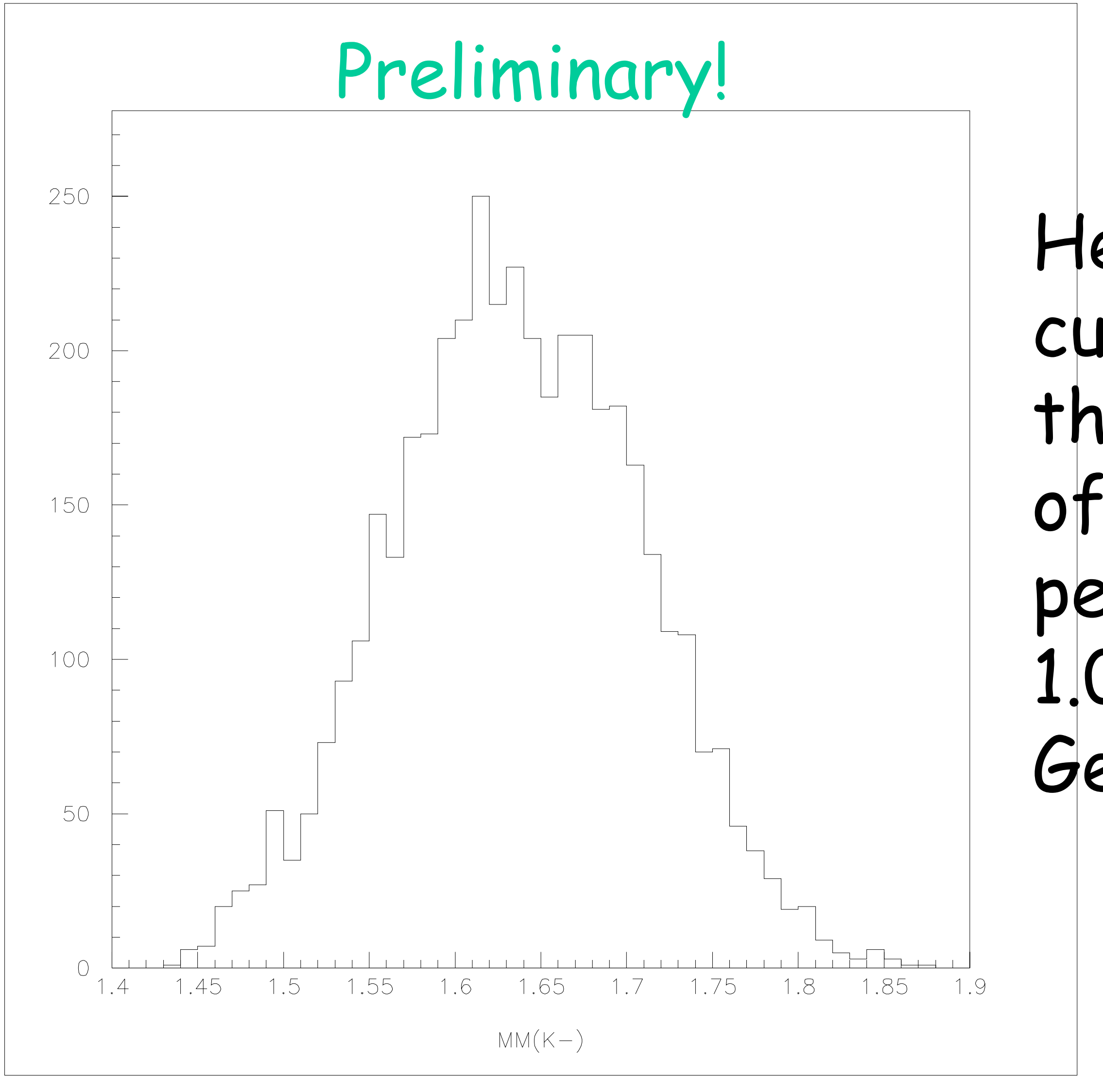


LEPS γd: error bar plot

Preliminary!



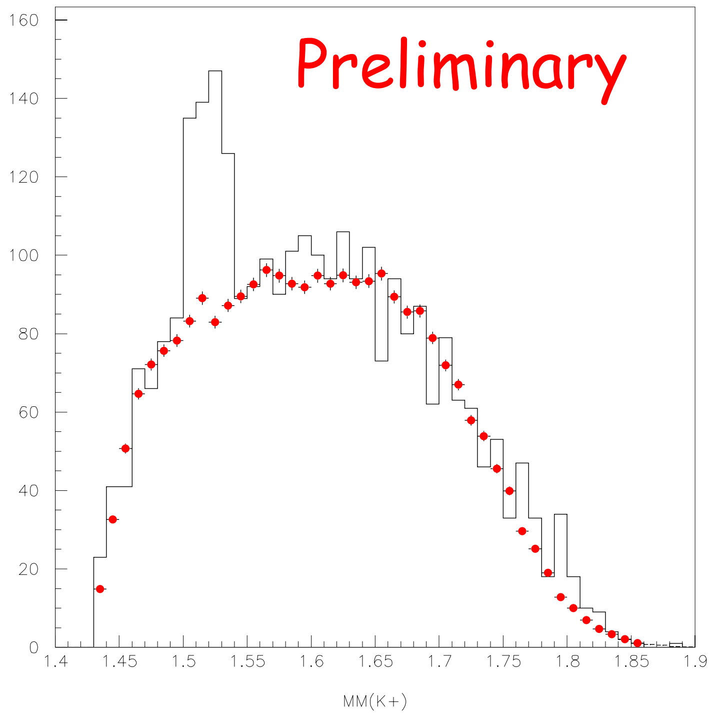
LEPS γd: φ-meson background



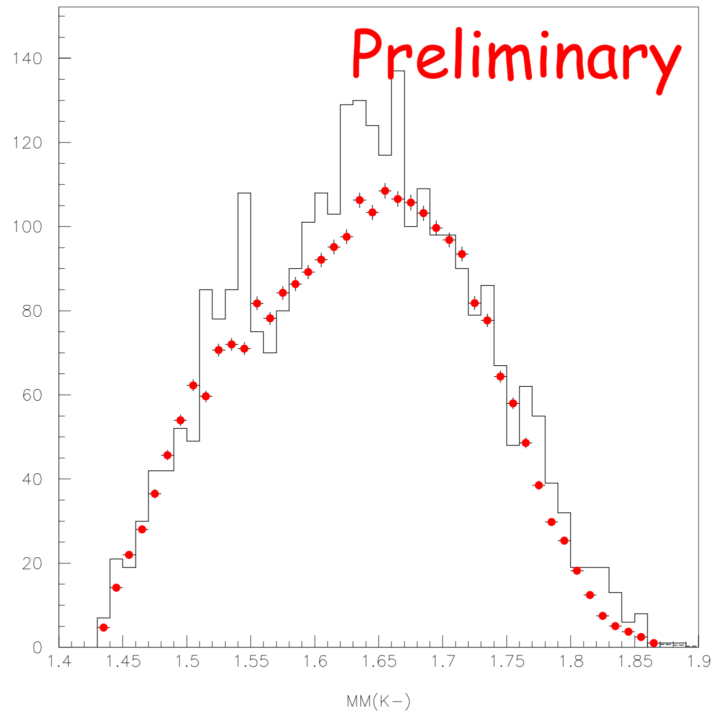
Here, the cut was on the "tail" of the φ peak (from 1.02-1.03 GeV/c^2)

Mixed event analysis

- All correlations (due to physics processes) will disappear.
- Represent real “phase space”(detected single-particle angle and mometum spectra).



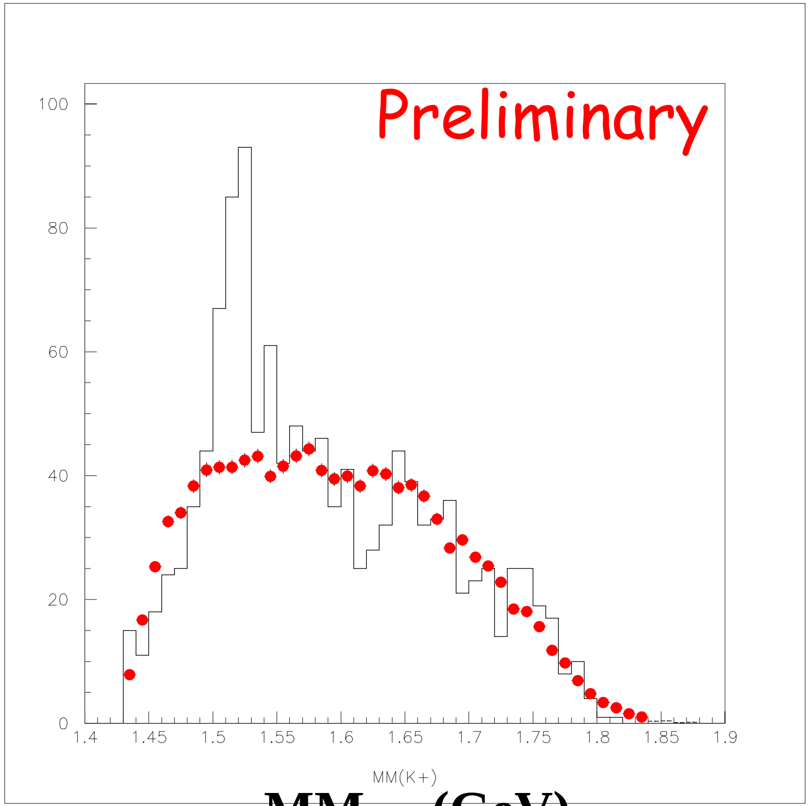
$MM_{\gamma K+}$ (GeV)



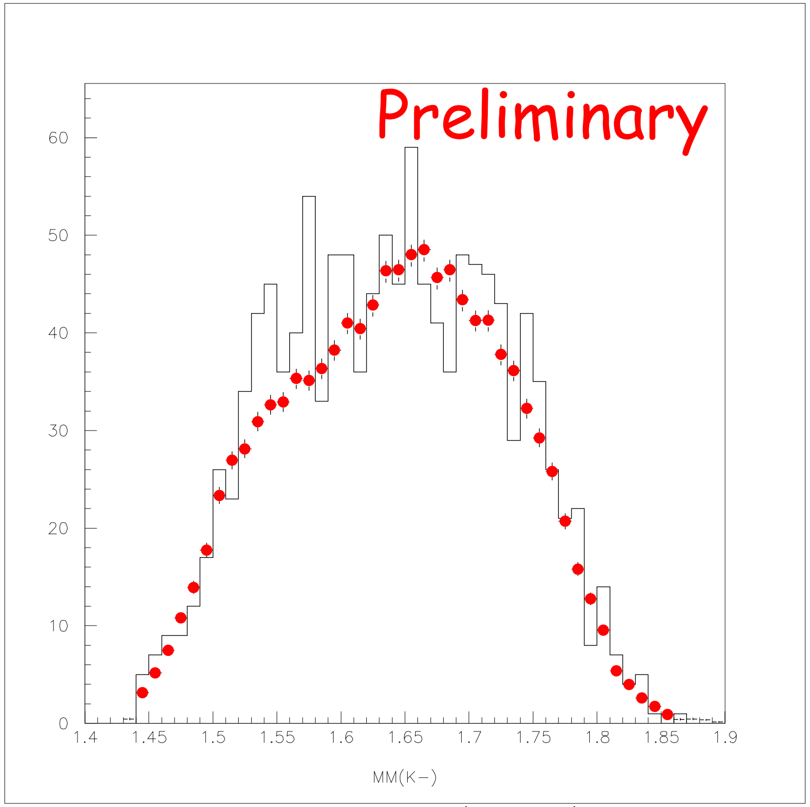
$MM_{\gamma K-}$ (GeV)

Mixed events: LH2 target

- As before, all correlations (due to physics processes) will disappear.
- Limited statistics make comparison difficult



$\mathbf{MM_{\gamma K+}}$ **(GeV)**



$\mathbf{MM_{\gamma K-}}$ **(GeV)**

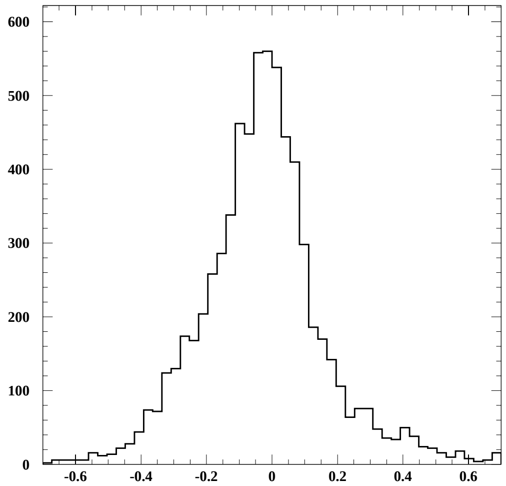
Fermi motion correction

1st order: $MM^c_{\gamma K^-} = MM_{\gamma K^-} - MM_{\gamma K^+K^-} + M_n$

2nd order: $(MM^c_{\gamma K^-})^2 = (MM_{\gamma K^-})^2 - P_{(K+n)}/P_n(MM_{\gamma K^+K^-} - M_n)^2$

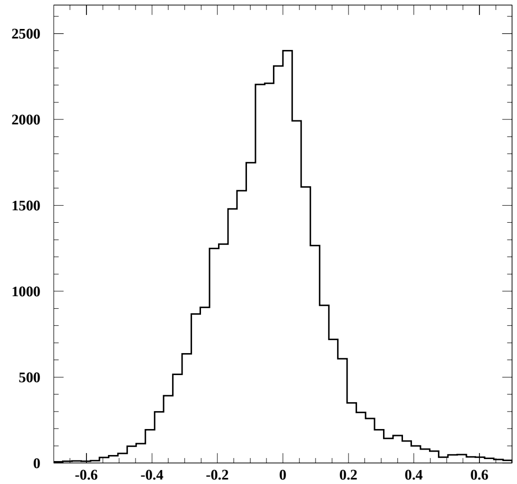
ΔM^2

$M_{KK} > 1.03$



ΔM^2 (GeV^2)

$1.01 < M_{KK} < 1.03$



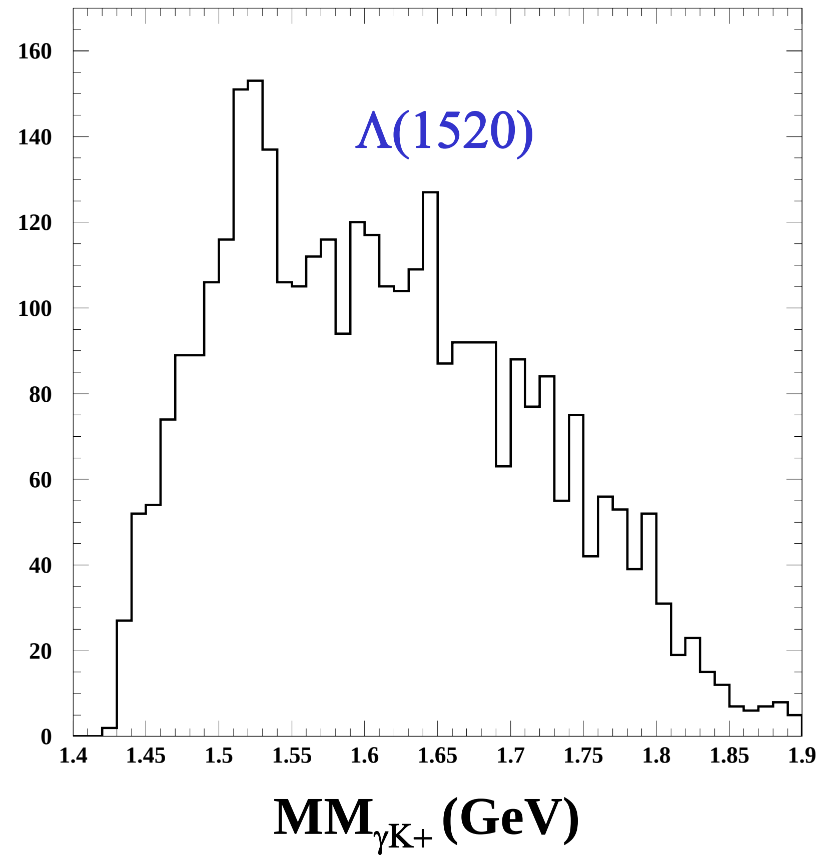
ΔM^2 (GeV^2)

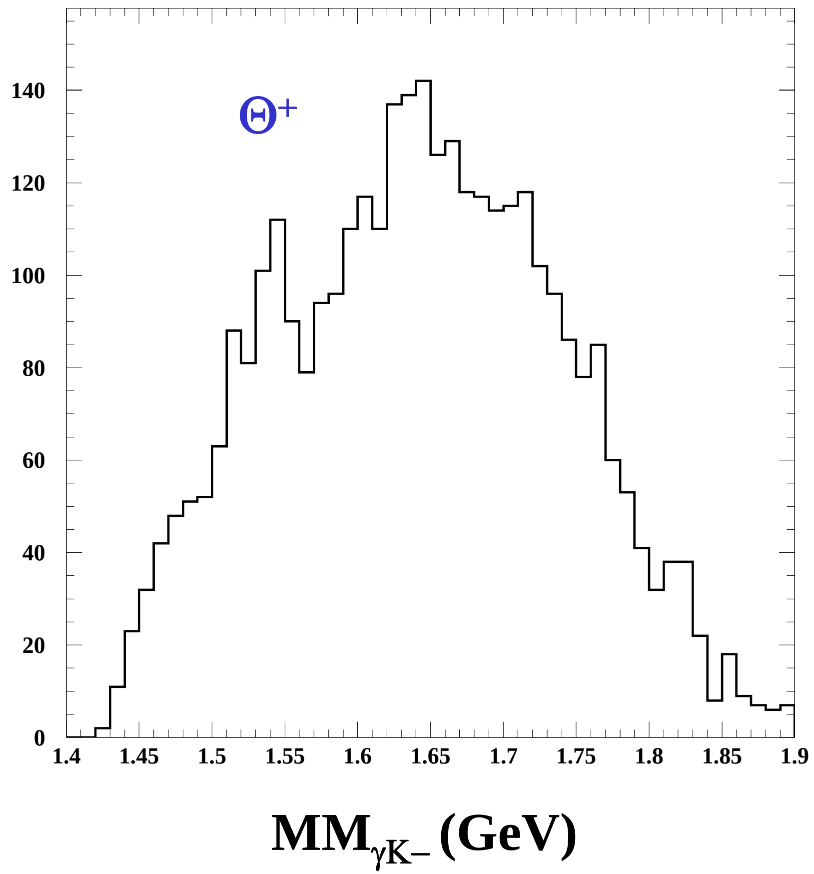
We expect

Smaller ΔM^2 → Better correction → Better S/N

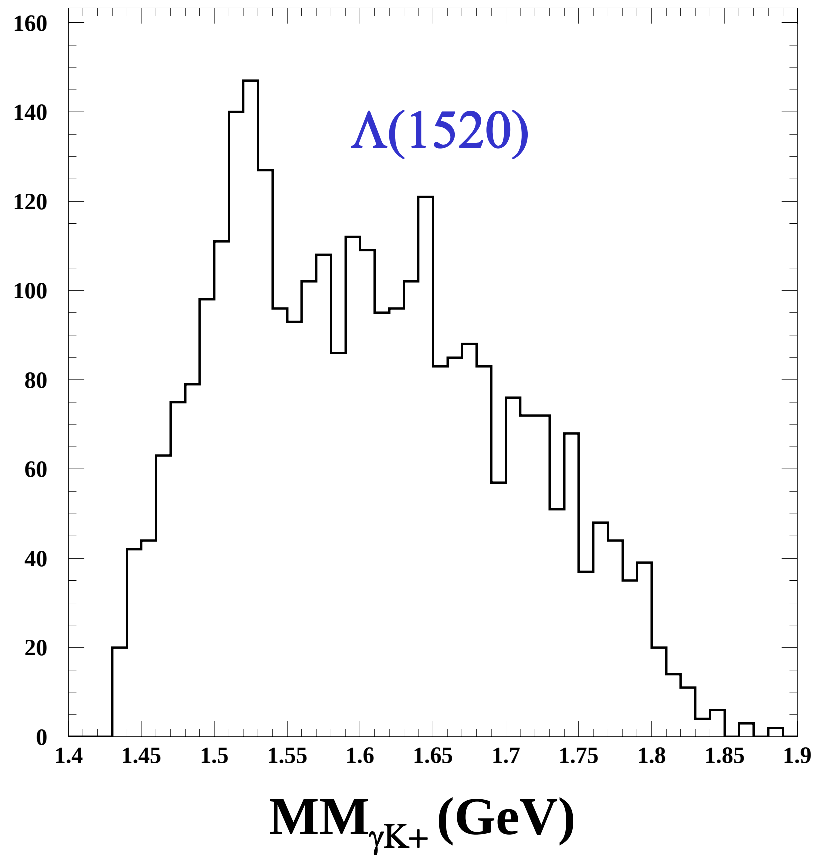
if the peak is real.

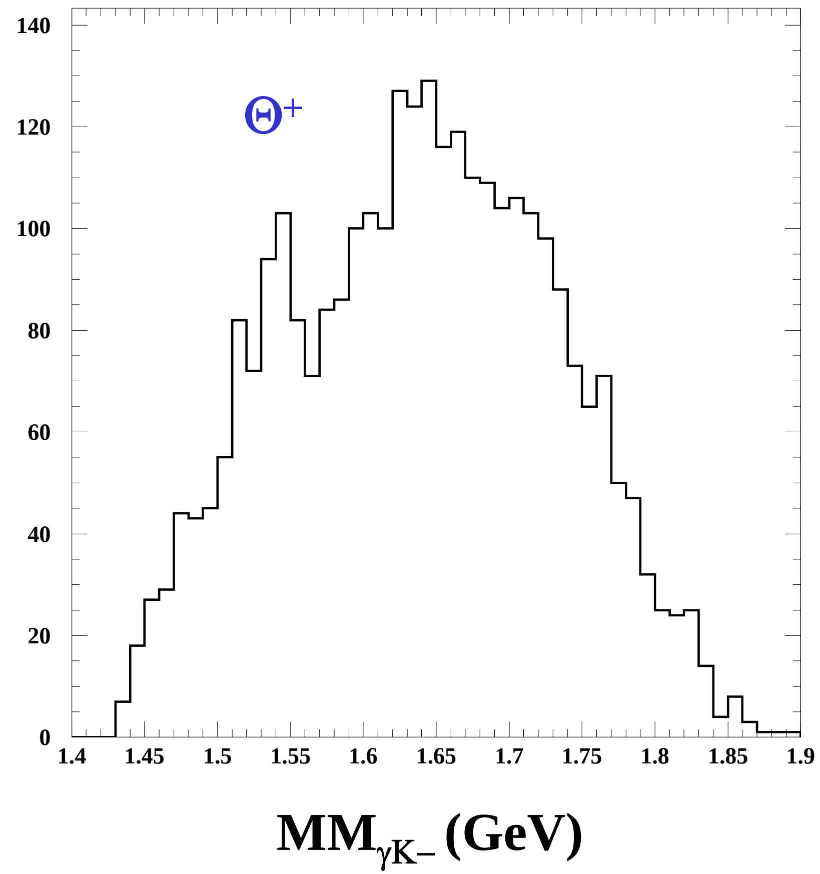
No ΔM^2 cut



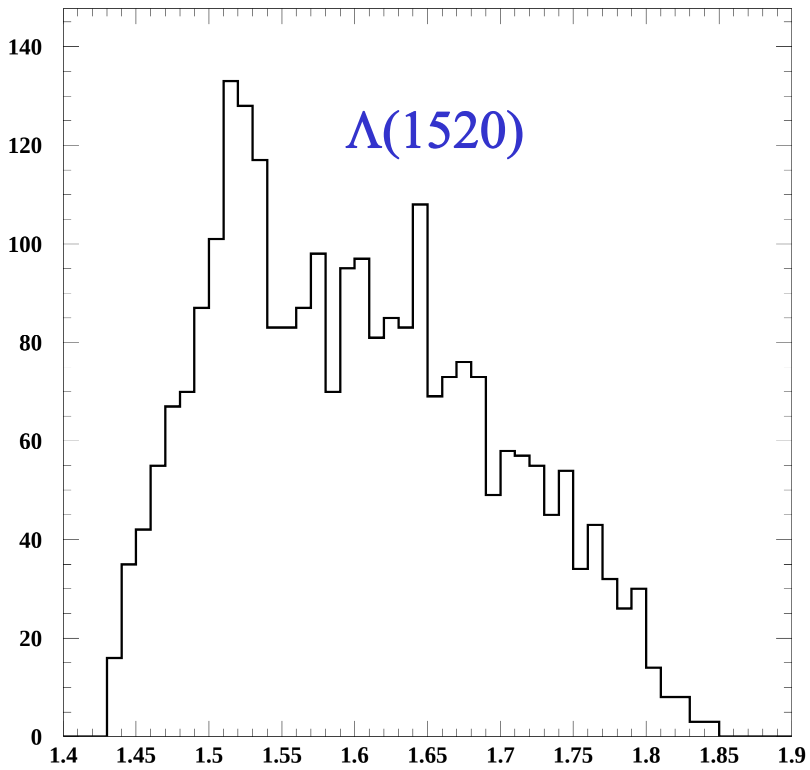


$|\Delta M^2| < 0.30\ \mathrm{GeV}^2$

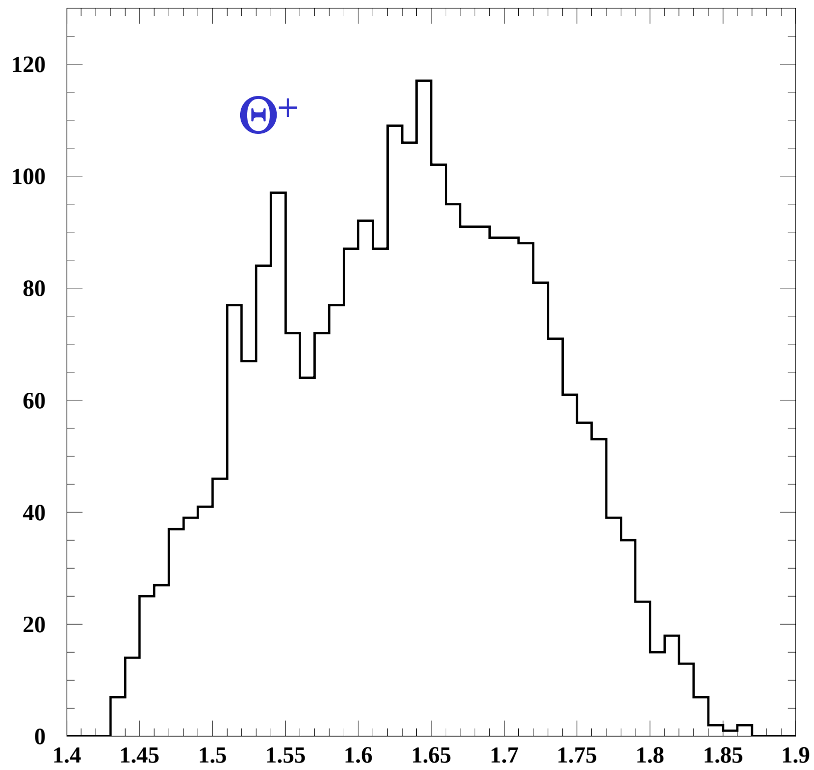




$|\Delta M^2| < 0.20\ GeV^2$

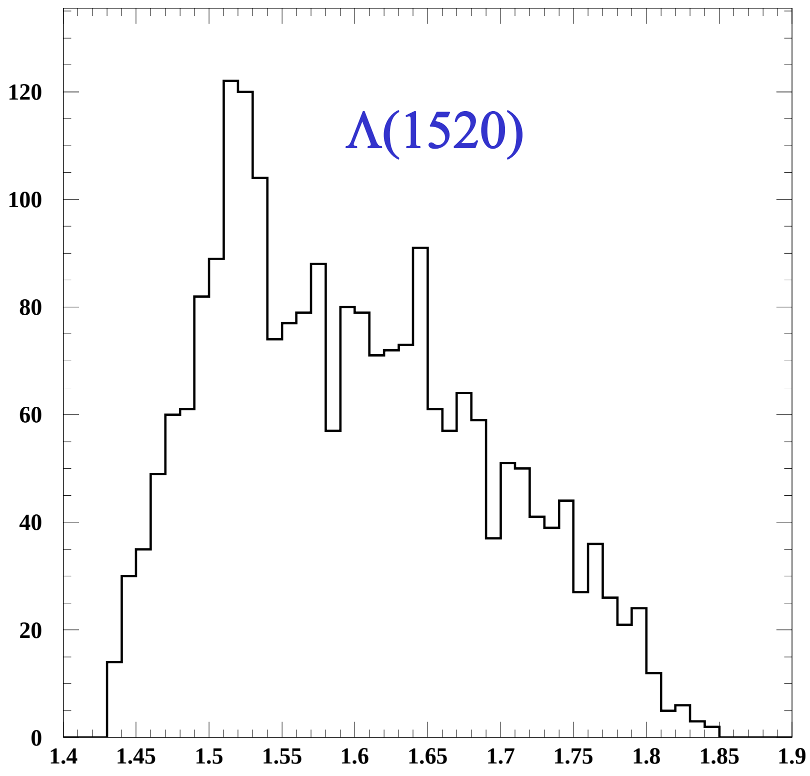


$MM_{\gamma K+}$ (GeV)

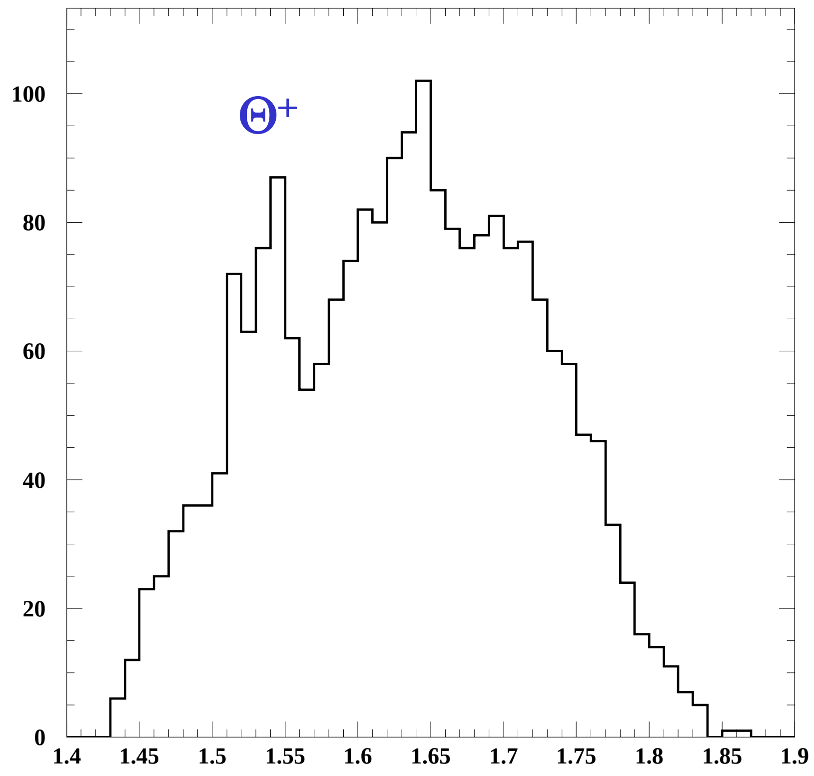


$MM_{\gamma K-}$ (GeV)

$|\Delta M^2| < 0.15\ GeV^2$

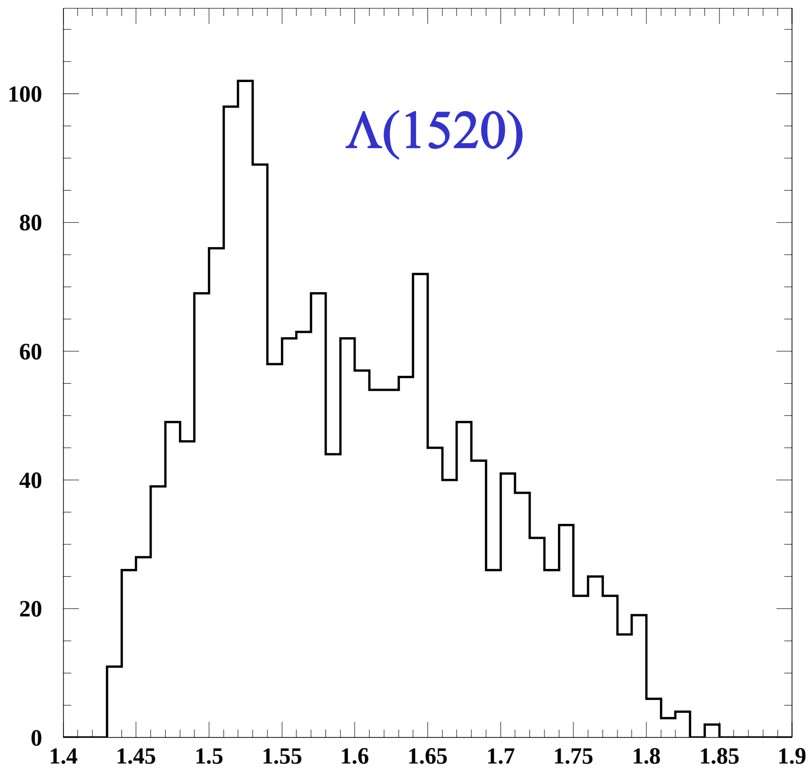


$MM_{\gamma K+}$ (GeV)

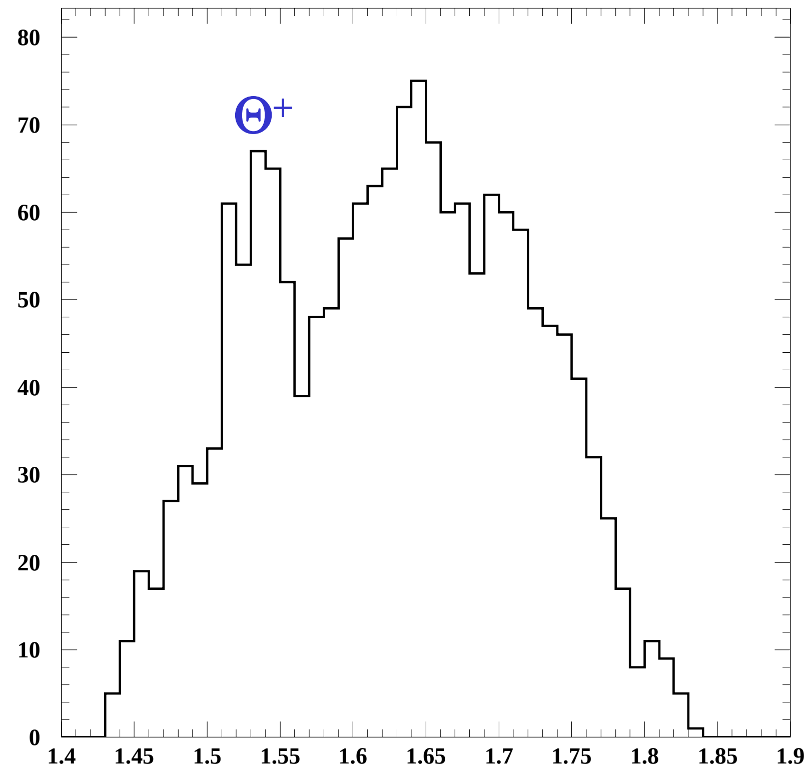


$MM_{\gamma K-}$ (GeV)

$|\Delta M^2| < 0.10$ GeV^2

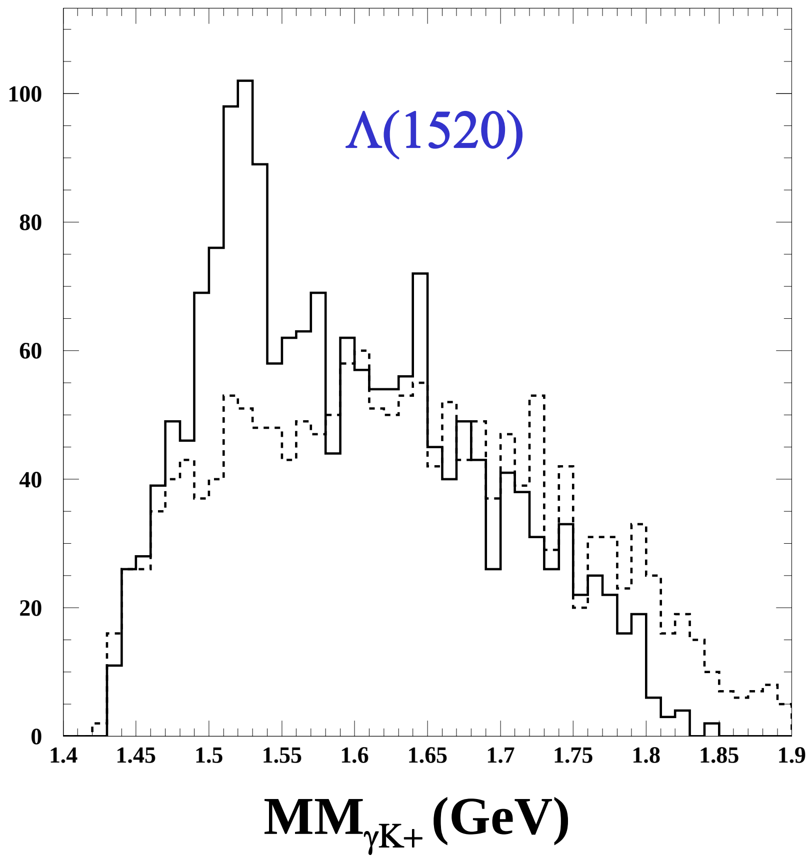


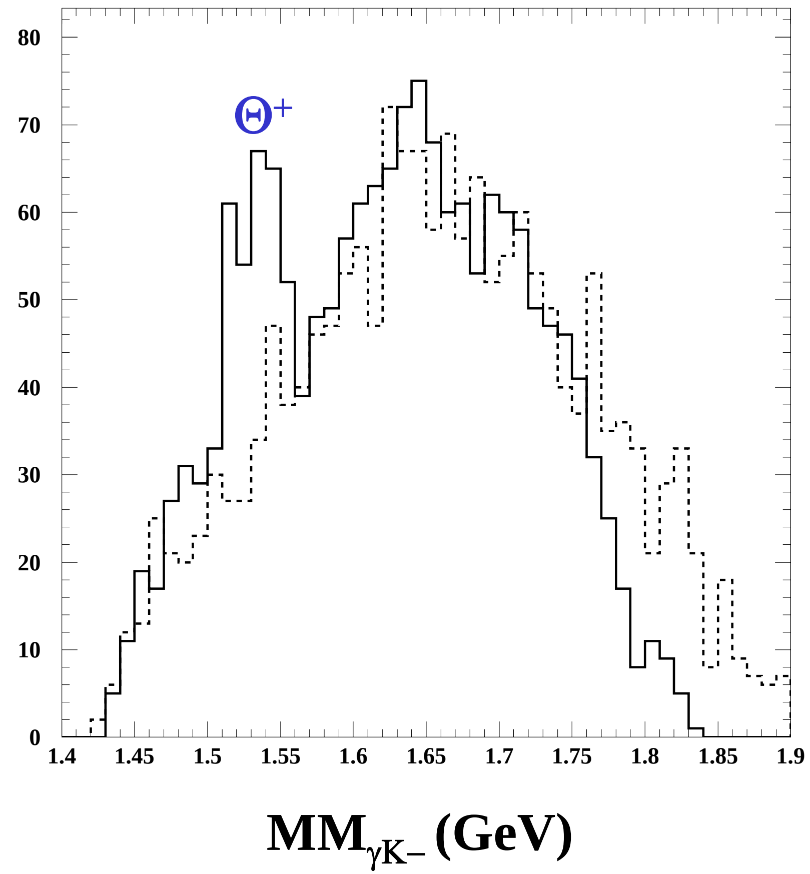
$MM_{\gamma K+}$ (GeV)



$MM_{\gamma K-}$ (GeV)

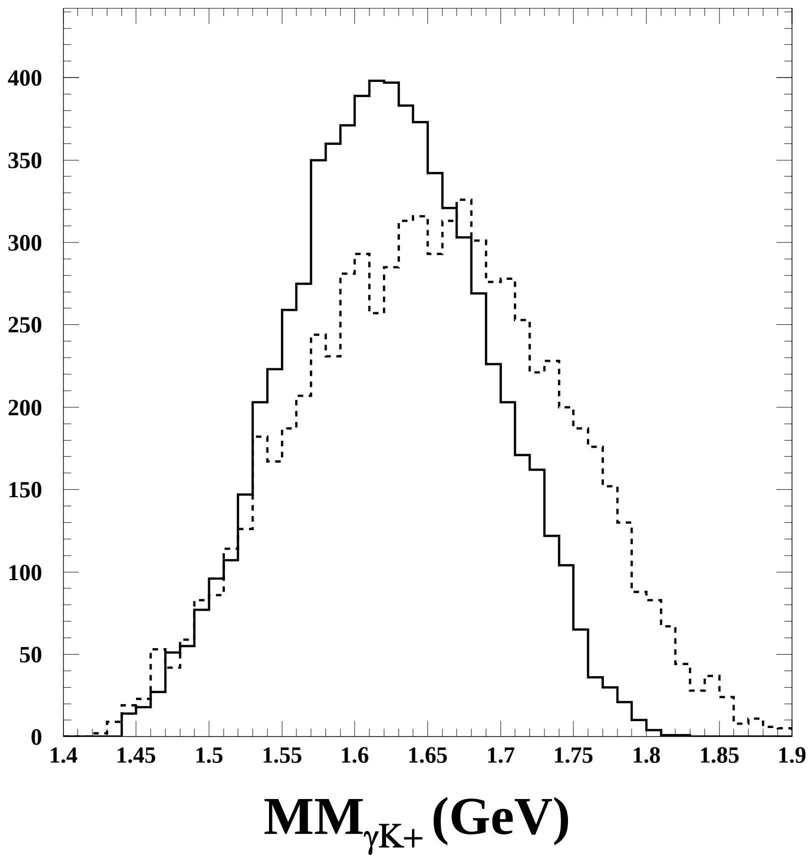
$|\Delta M^2| < 0.10$ GeV^2

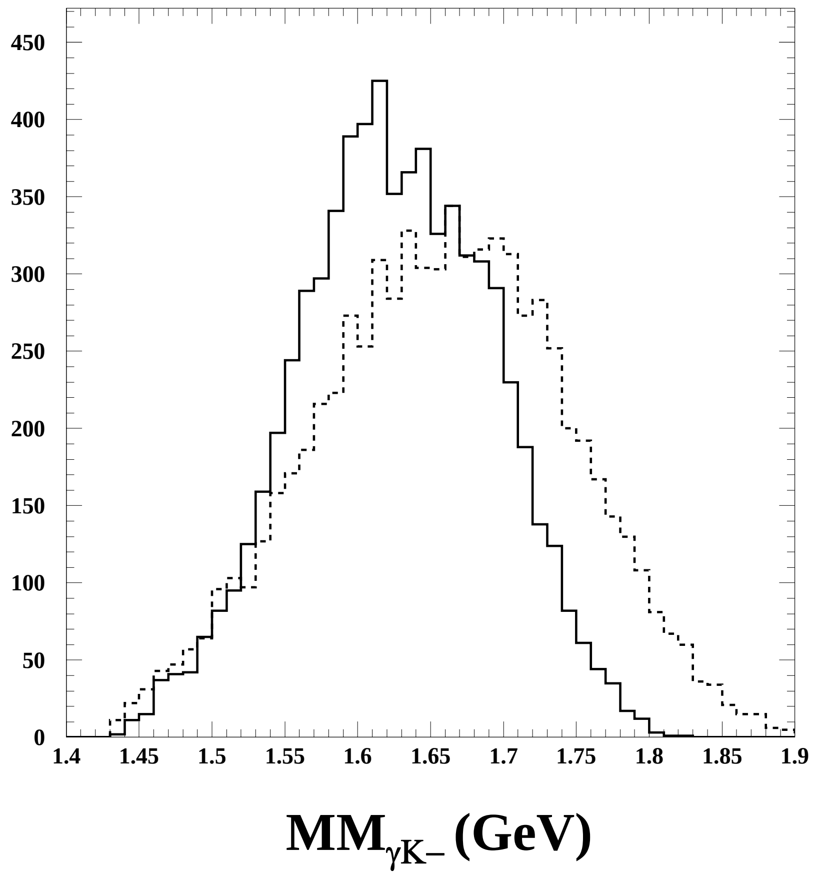




$|\Delta M^2| < 0.10\ \mathrm{GeV}^2$

ϕ events: $1.01 < M_{KK} < 1.03$ GeV



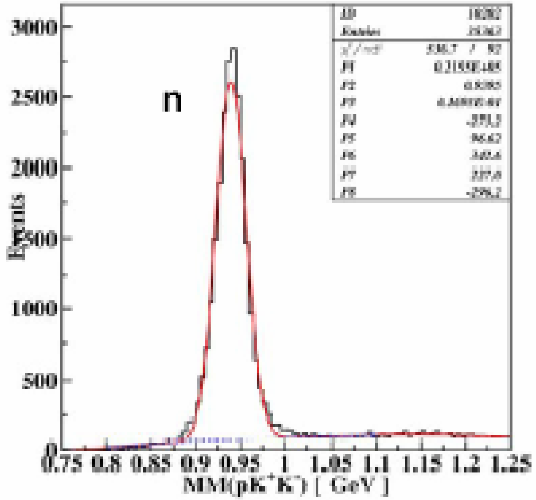


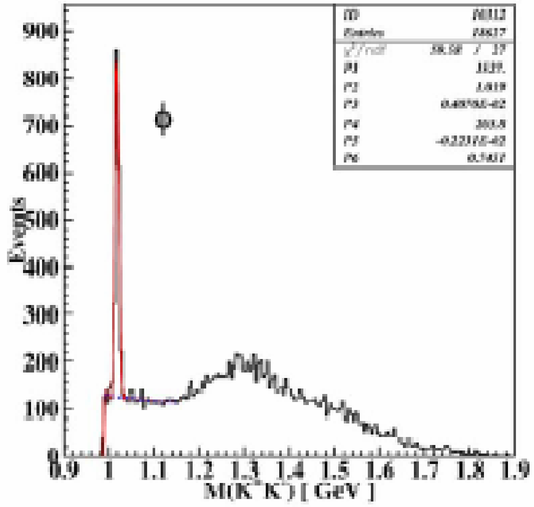
CLAS: high-statistics run

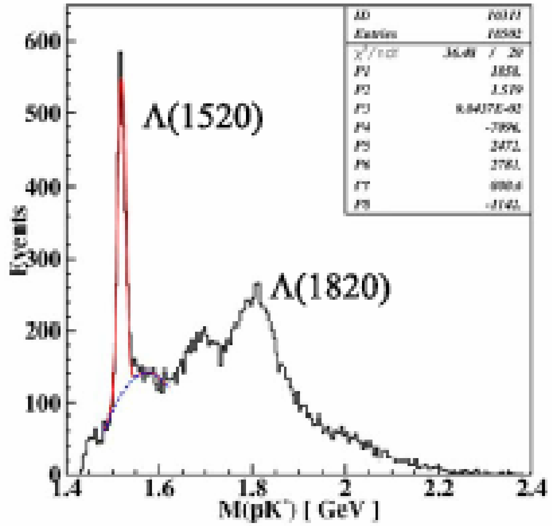
- These data are <u>very preliminary</u>
  - Calibrations are not yet tuned
- Experiment completed last month
  - only ~15% of the data is analyzed
  - physics results must first be approved by the CLAS collaboration
  - Only non-Θ^+ plots will be shown to give a measure of the statistics

Statistics from new CLAS run

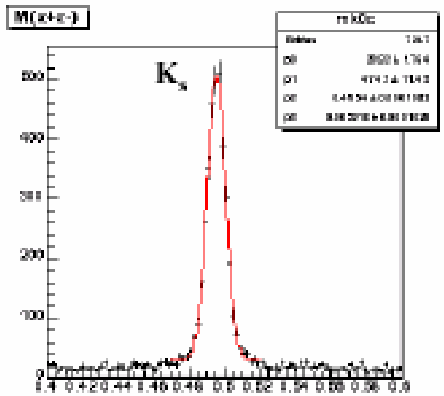
Fully exclusive processes: $\gamma d \longrightarrow K^- p K^+ n$







$\gamma d \longrightarrow K^- p K_s(\pi^+\pi^-) p_{sp}$



Outlook

- The Θ^+ signal was observed on deuteron, nuclear targets, and the proton.
- The existing information does not completely answer questions required of a newly discovered subatomic particle:
  - Parity and spin?
  - Isospin
  - Width (Lifetime)
  - Excited states ?

Summary

- Chiral soliton model: the original motivation
- 10 independent experiments give evidence for Θ^+.
  - LEPS (Japan), DIANA (Russia), CLAS (USA), …
- There is still a lot of experimental work needed:
  - Spin, parity, (isospin), width, E_γ dependence, etc.
- New experiment just completed at CLAS
  - Expect x 20 increase in statistics!
- Evidence from other experiments is still needed
  - The Θ^+ should be seen at RHIC, KEK, etc.
  - What about negative results? Understand these, too!