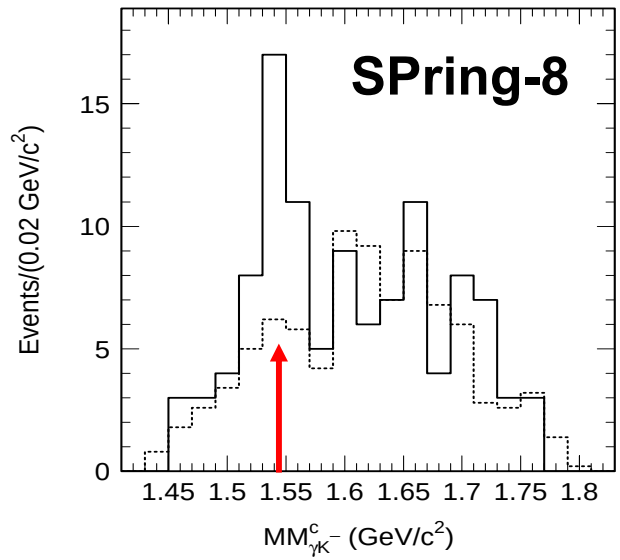
Experimental Status of Pentaquark States

Phys.Rev.Lett. 91 (2003) 012002

- Introduction
- Experimental evidence
- Production mechanisms
- What do we know about the Θ^+?
- Exotic cascades states

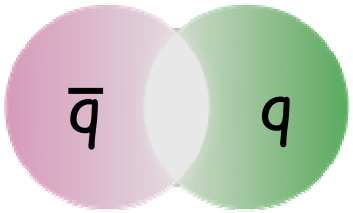


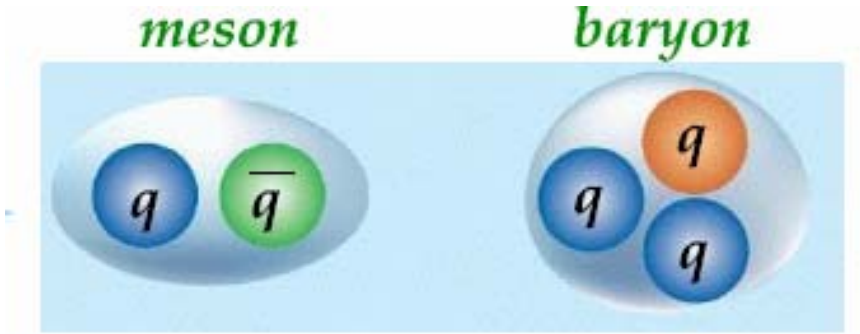
Special Thanks
CLAS Collaborators

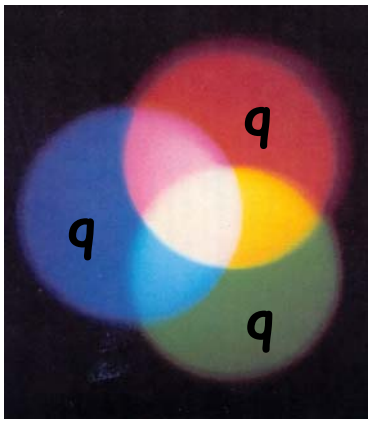
$uudd\bar{s}$ **Mass = 1.54 GeV**

Quarks are confined inside colorless hadrons

Quarks combine to “neutralize” color force







Mystery remains:

Of the many possibilities for combining quarks with color into colorless hadrons, only two configurations were found, till now…

What are pentaquarks?

- Minimum quark content is 4 quarks and 1 antiquark
- "Exotic" pentaquarks are those where the antiquark has a different flavor than the other 4 quarks $\left(qqqq\overline{Q}\right)$
- Quantum numbers cannot be defined by 3 quarks alone.

Example: $uuds\bar{s}$, non-exotic

Baryon number = 1/3 + 1/3 + 1/3 + 1/3 – 1/3 = 1

Strangeness = 0 + 0 + 0 – 1 + 1 = 0

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

Baryon number = 1/3 + 1/3 + 1/3 + 1/3 – 1/3 = 1

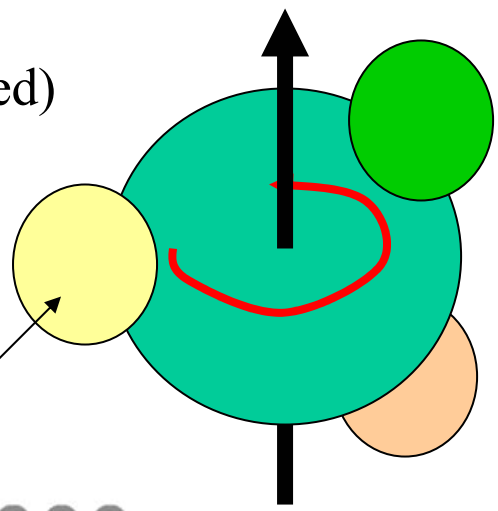
Strangeness = 0 + 0 + 0 + 0 + 1 = +1

Pentaquarks – two approaches

Chiral soliton model: (Diakonov, Petrov, Polyakov)

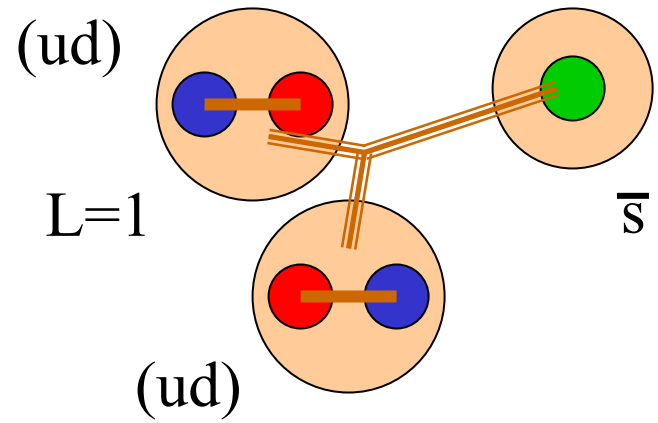
Pentaquark comes out naturally from these models as they represent rotational excitations of the soliton [rigid core (q^3) surrounded by meson fields ($q\bar{q}$)]

Soliton: (simplified)



Meson fields

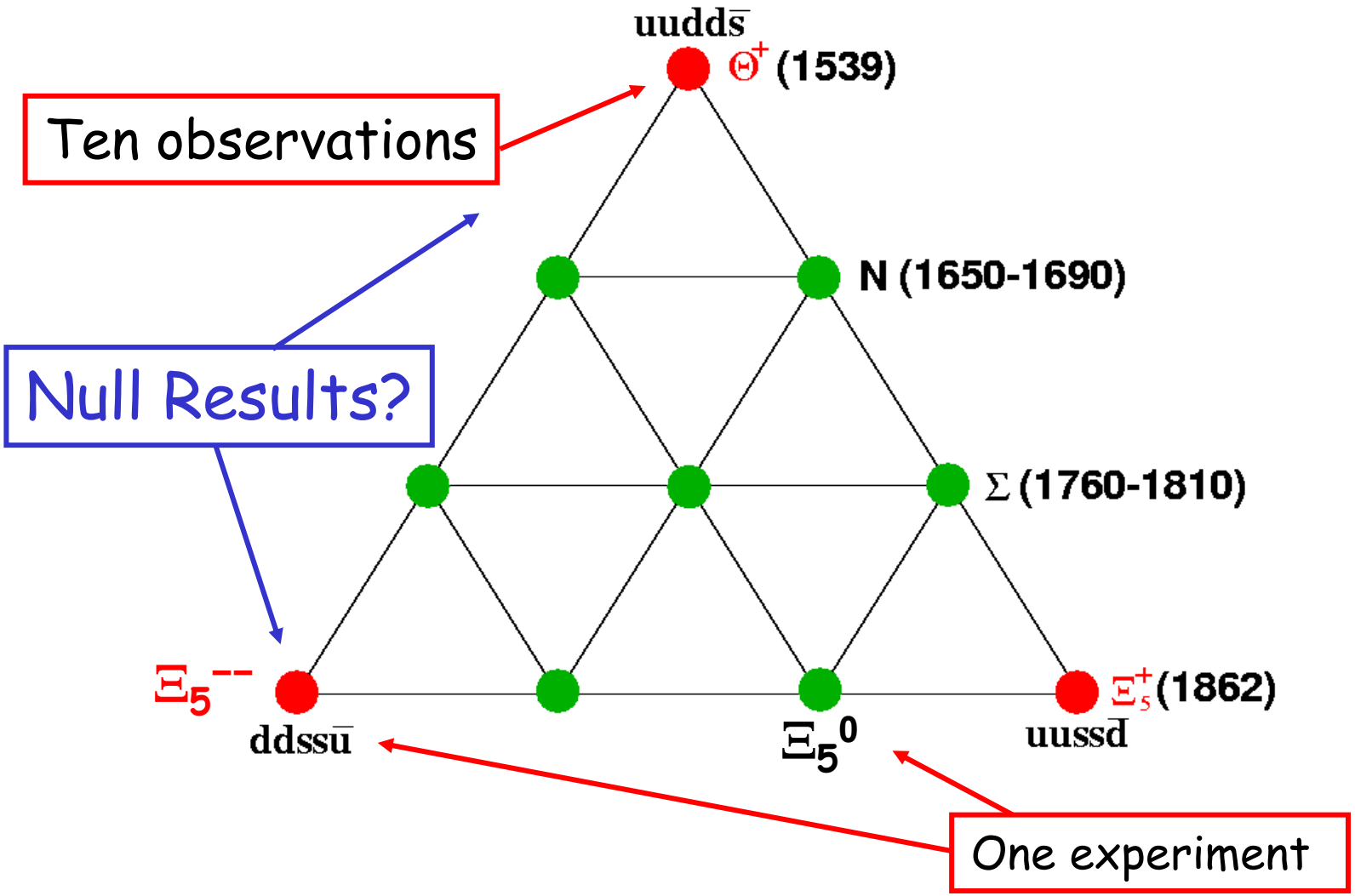
Quark cluster models, e.g. di-quark description (Jaffe, Wilczek)



L=1, one unit of orbital angular momentum needed to get $J=1/2^+$ as in χSM

Lattice QCD => $J^P = 1/2^-$

The Anti-decuplet of $SU(3)_f$



D. Diakonov, V. Petrov, hep-ph/0310212 (revised version)

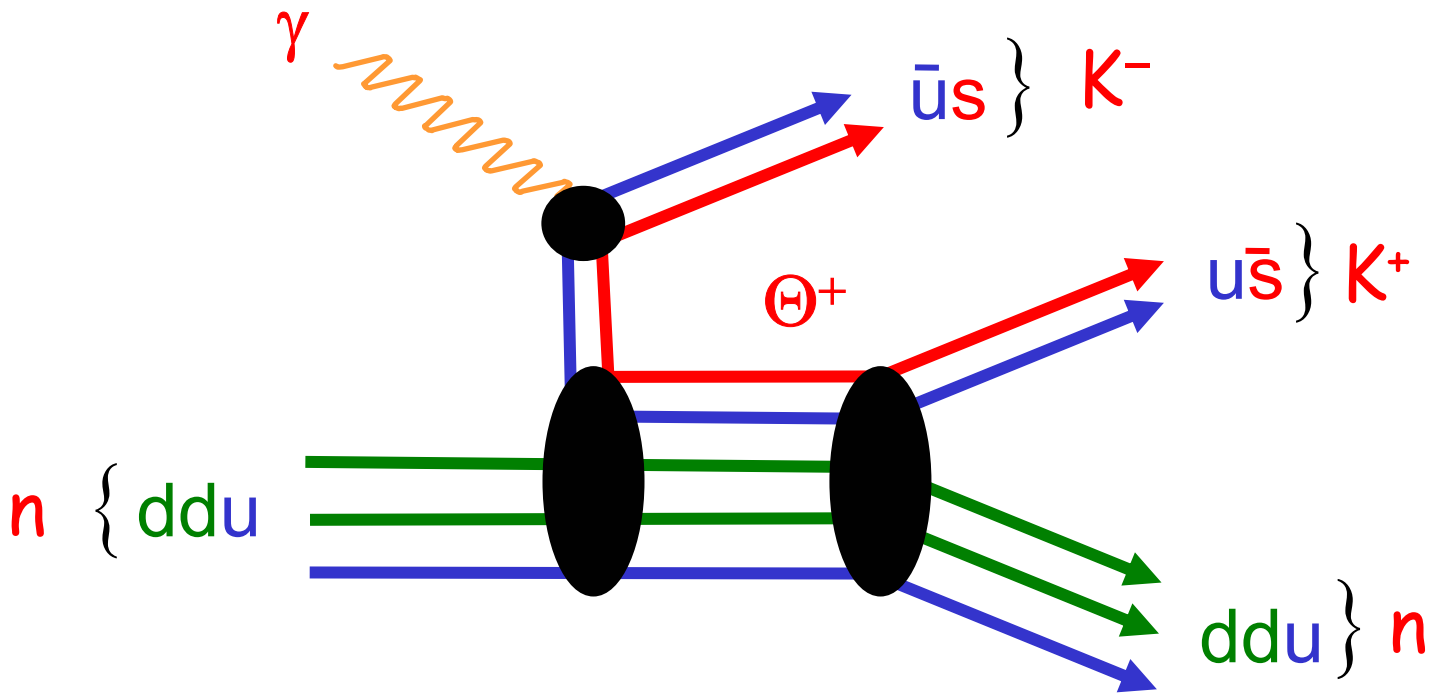
Experimental Evidence

- Many experiments
- No dedicated experiments to date
  - but,… dedicated experiments are starting to take data

For new data from SPring-8 see Hicks Session J2 Sun 10:45

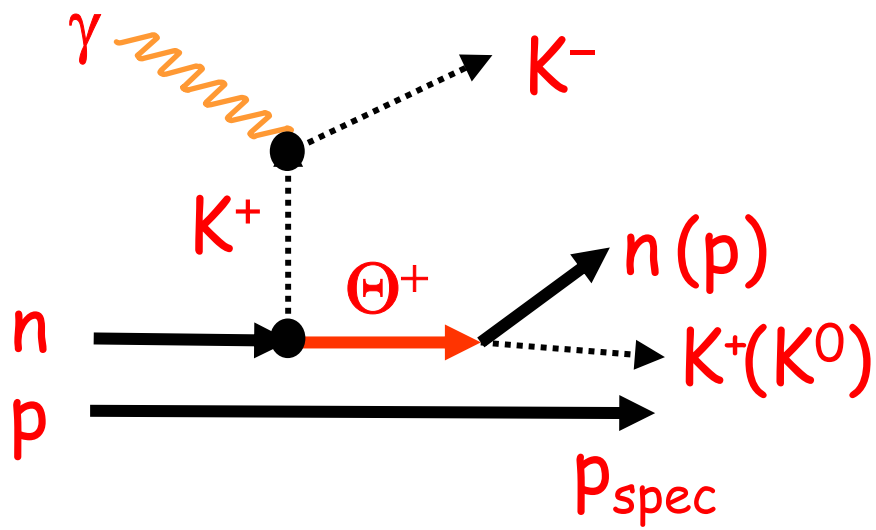
- Walk through the analysis from CLAS
- Selected examples from other experiments

Quark lines for the reaction

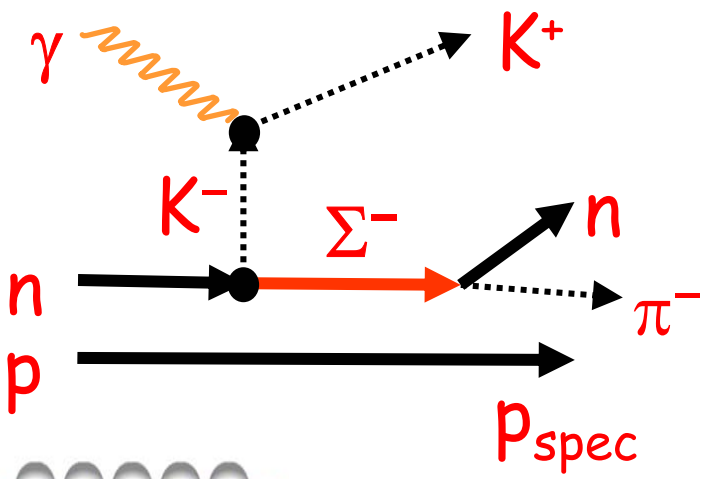


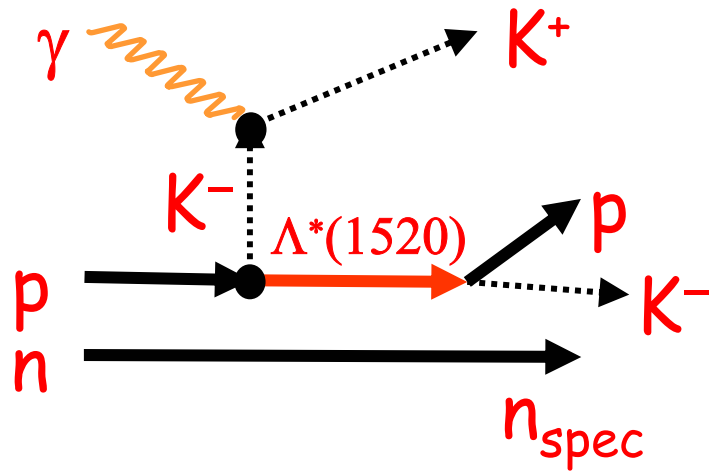
Θ^+ is composed of ($uudd\bar{s}$) quarks

Production mechanisms

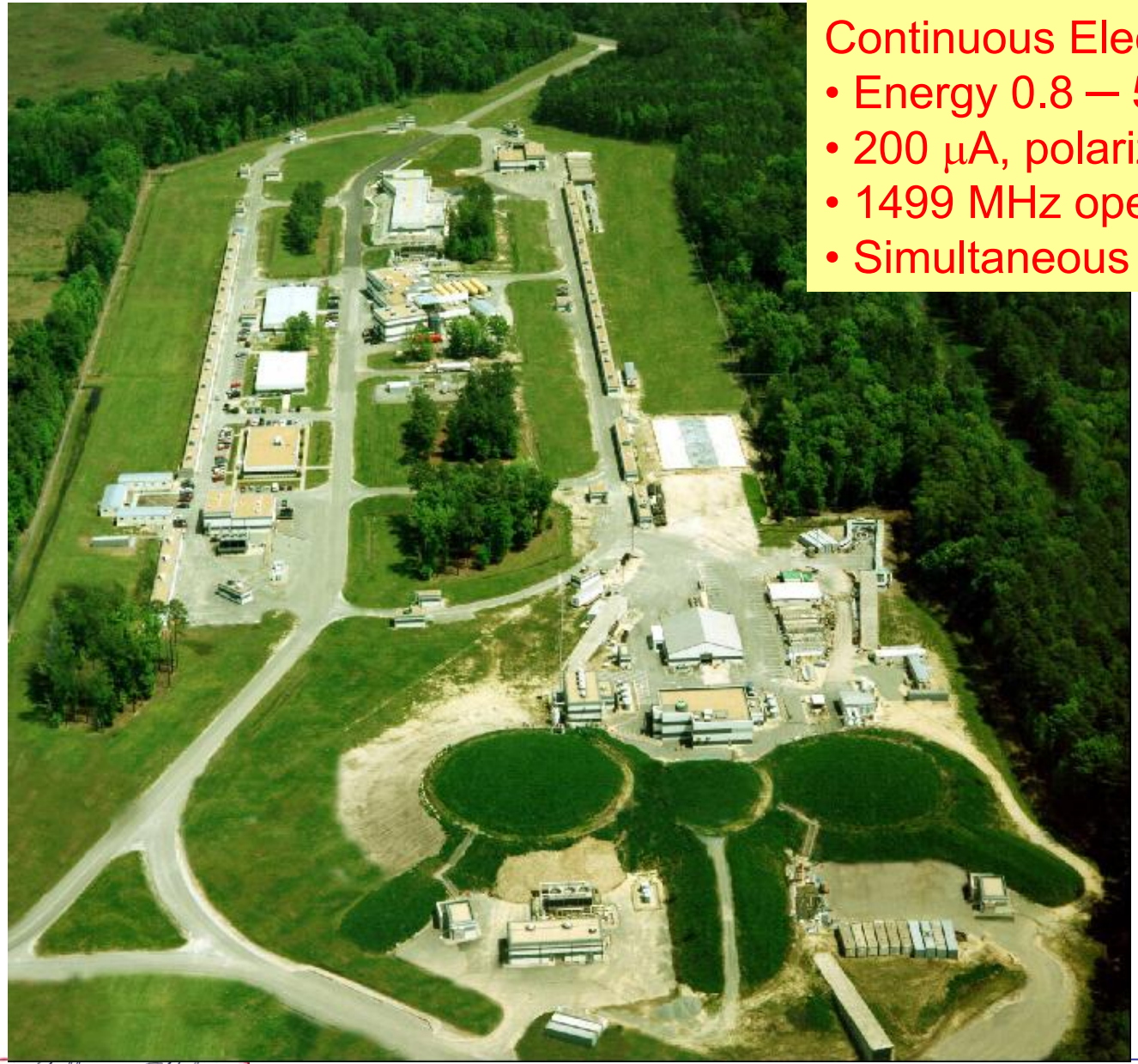


Control Reactions





JLab accelerator CEBAF



Continuous Electron Beam

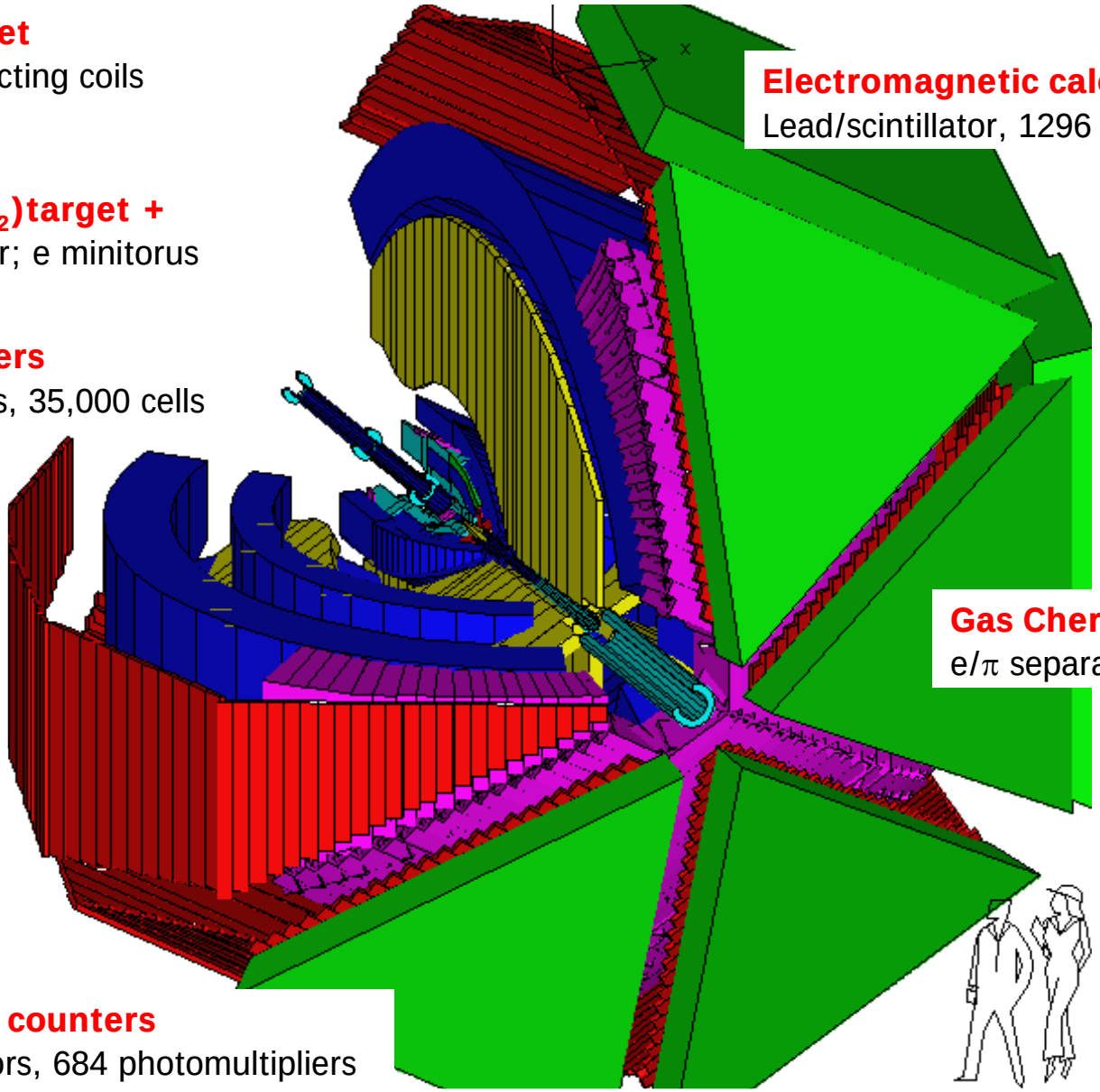
- Energy 0.8 – 5.7 GeV
- 200 μA, polarization 75%
- 1499 MHz operation
- Simultaneous delivery 3 halls

CEBAF Large Acceptance Spectrometer

Torus magnet
6 superconducting coils

Liquid D_2 (H_2)target +
γ start counter; e minitorus

Drift chambers
argon/CO_2 gas, 35,000 cells

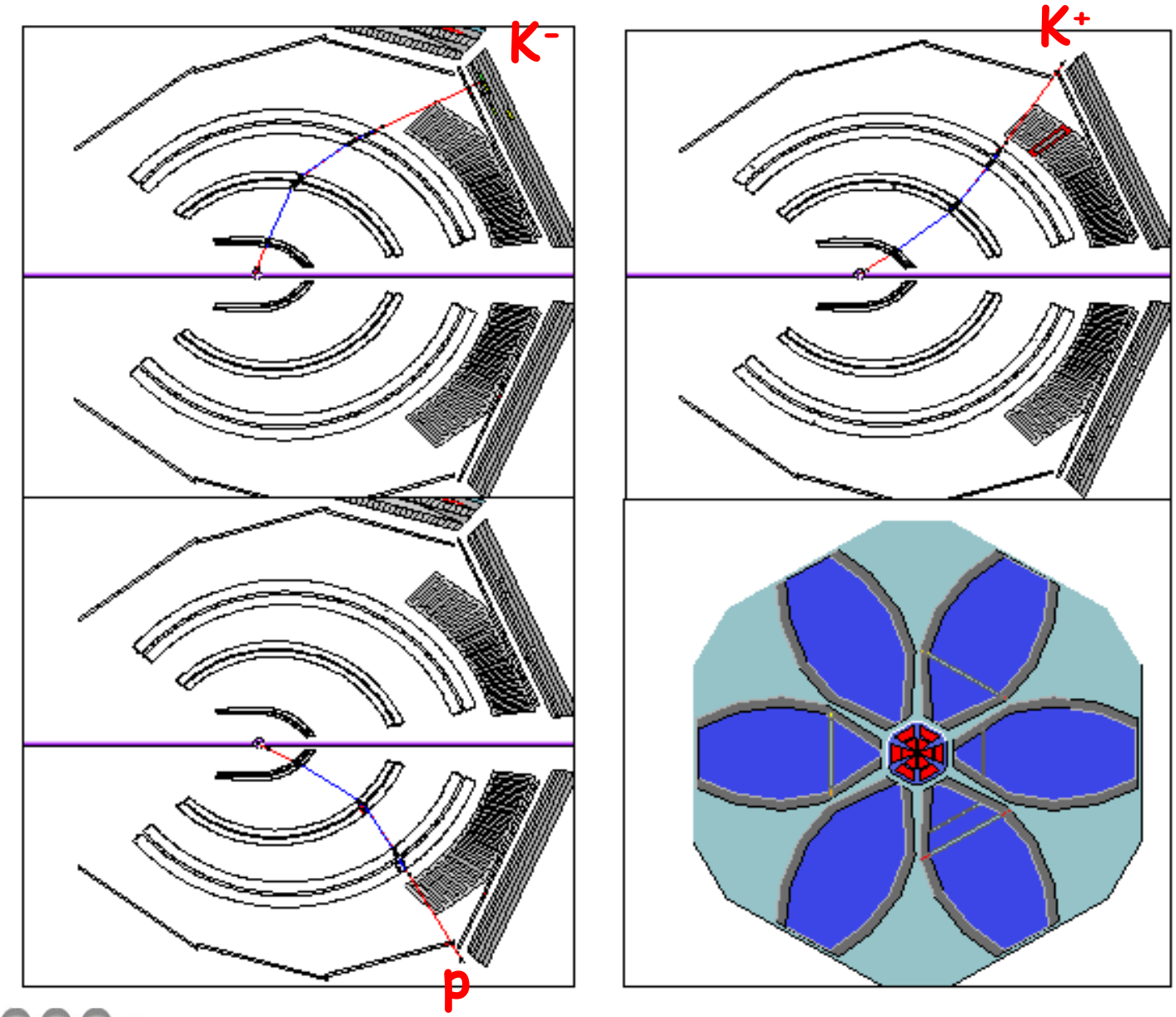


Electromagnetic calorimeters
Lead/scintillator, 1296 photomultipliers

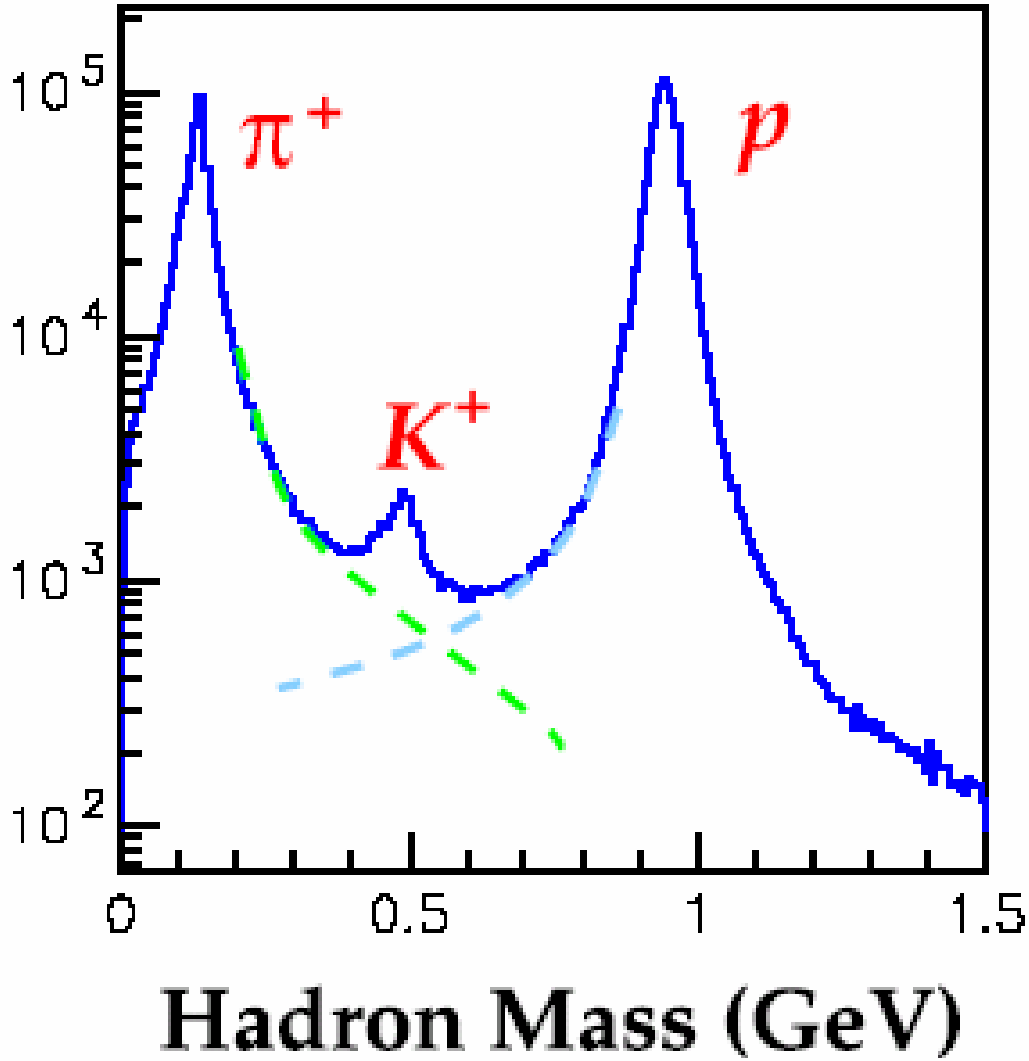
Gas Cherenkov counters
e/π separation, 256 PMTs

Time-of-flight counters
plastic scintillators, 684 photomultipliers

$\gamma d \rightarrow p K^+K^- (n)$ in CLAS



Particle identification by time-of-flight

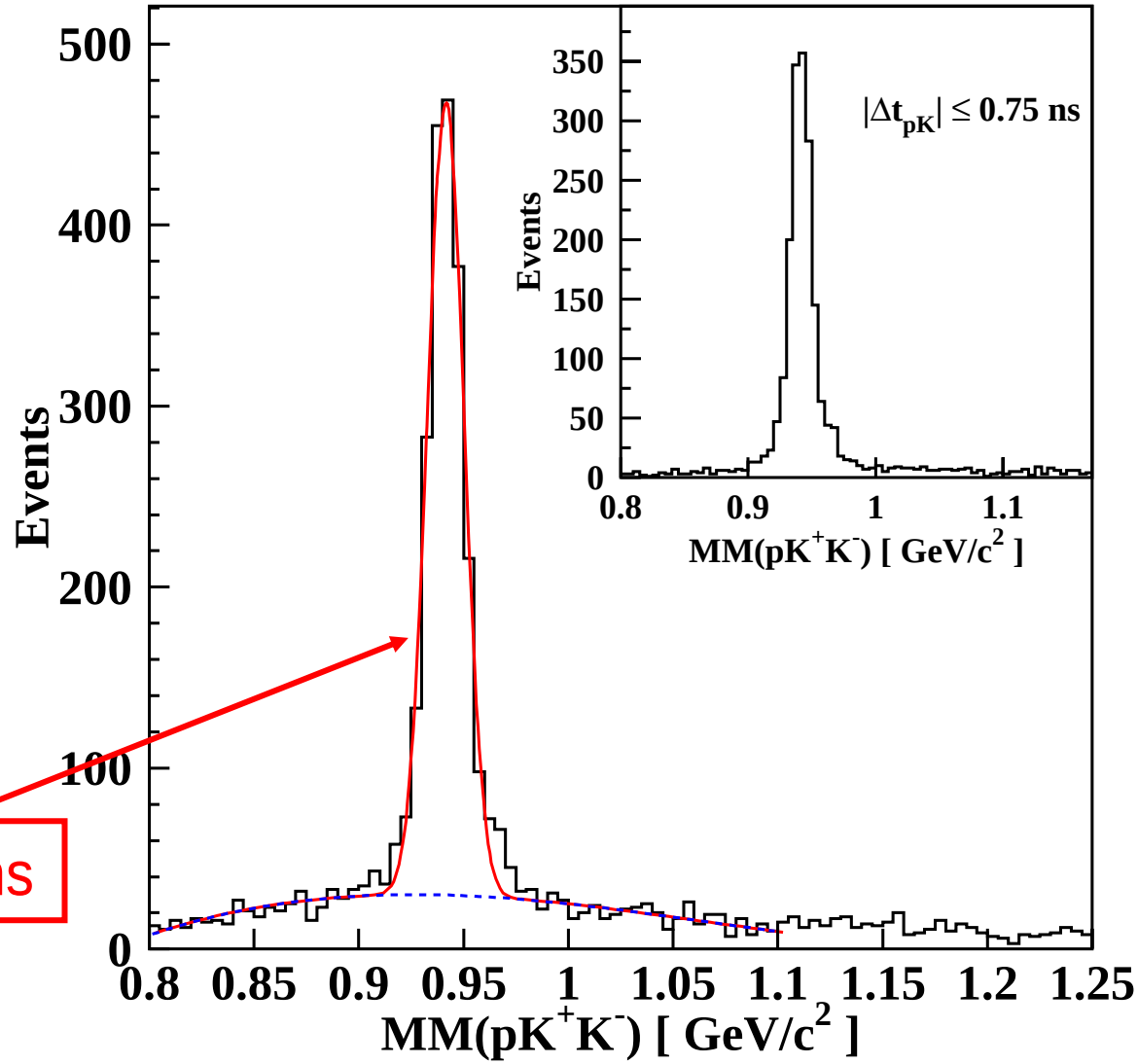


$$m = \frac{p}{\gamma \beta c}$$

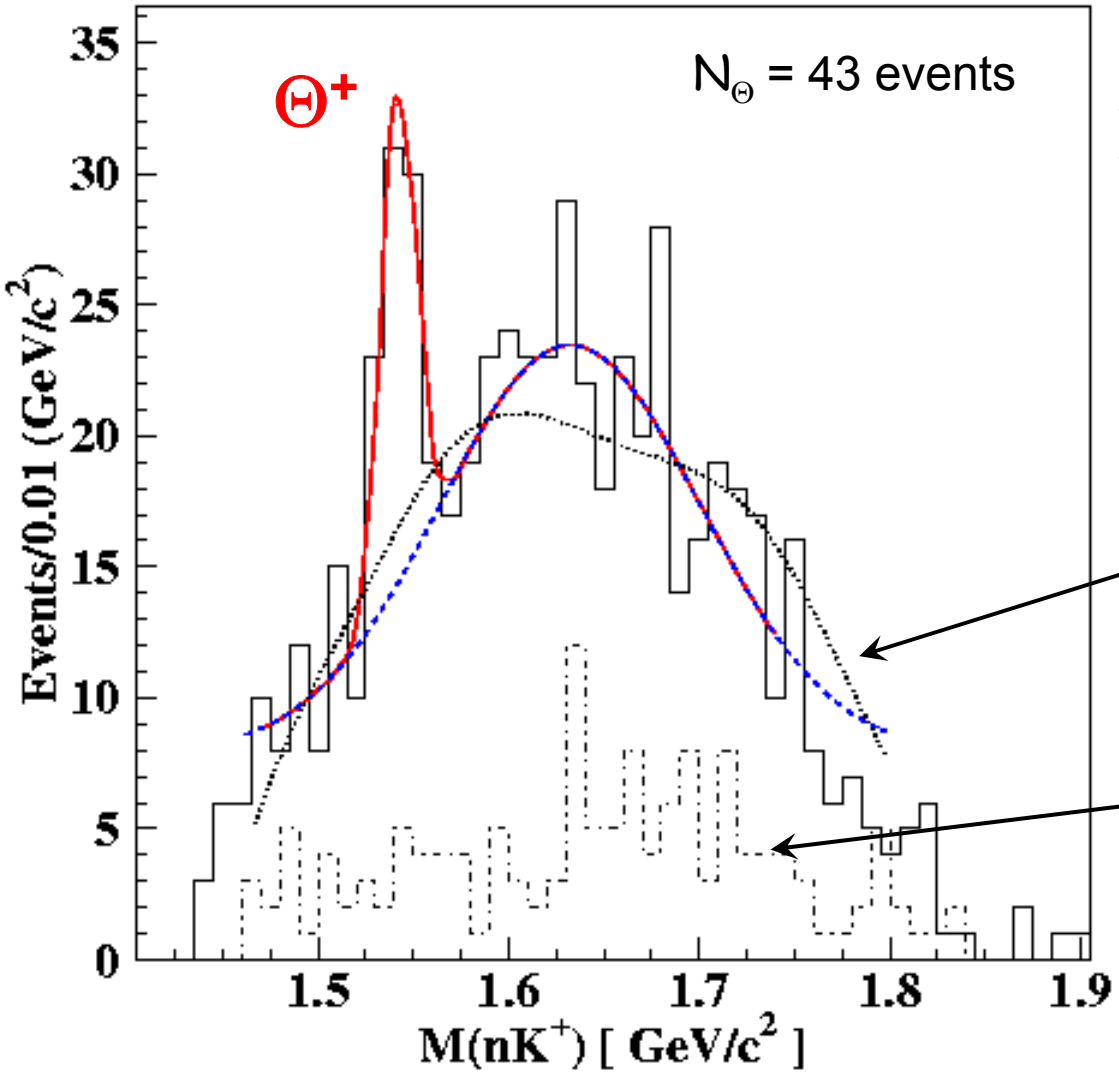
Reaction $\gamma d \rightarrow pK^+K^-(n)$

- Clear peak at neutron mass.
- 15% non-pKK events within ±3σ of the peak.
- Almost no background under the neutron peak after event selection with tight timing cut.

Reconstructed Neutrons



Deuterium: nK^+ invariant mass distribution



Mass = 1.542 GeV

Γ< 21 MeV

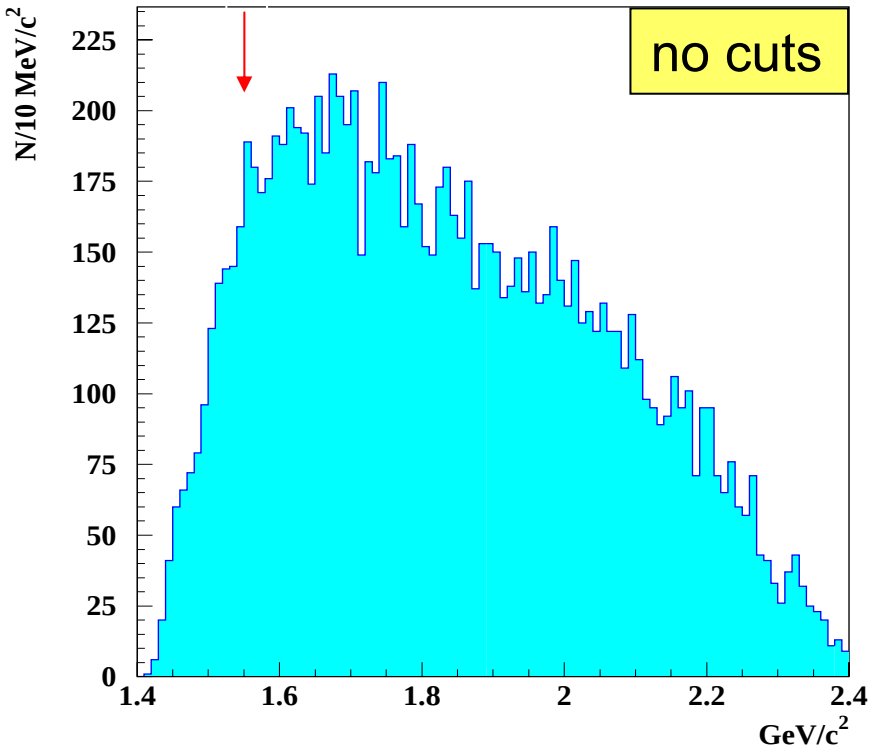
Significance 5.2±0.6 σ

Two different Background shapes

Distribution of $\Lambda^*(1520)$ events

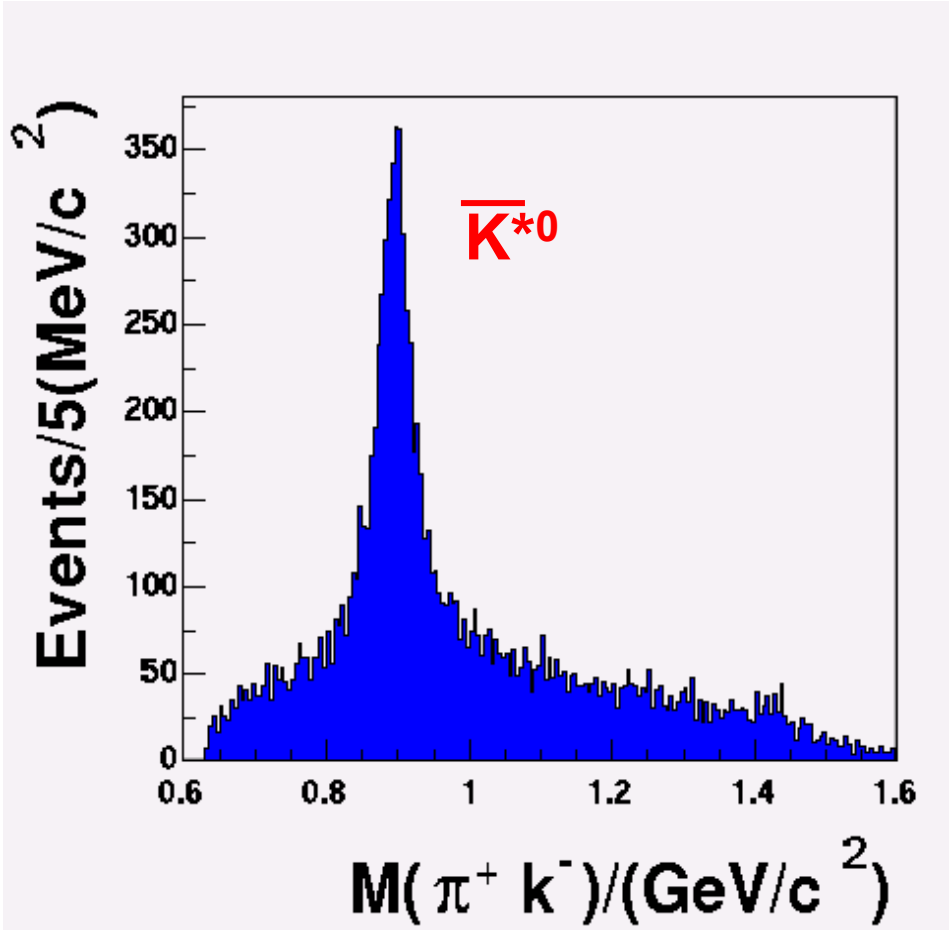
Searching for Θ^+ on a proton target

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



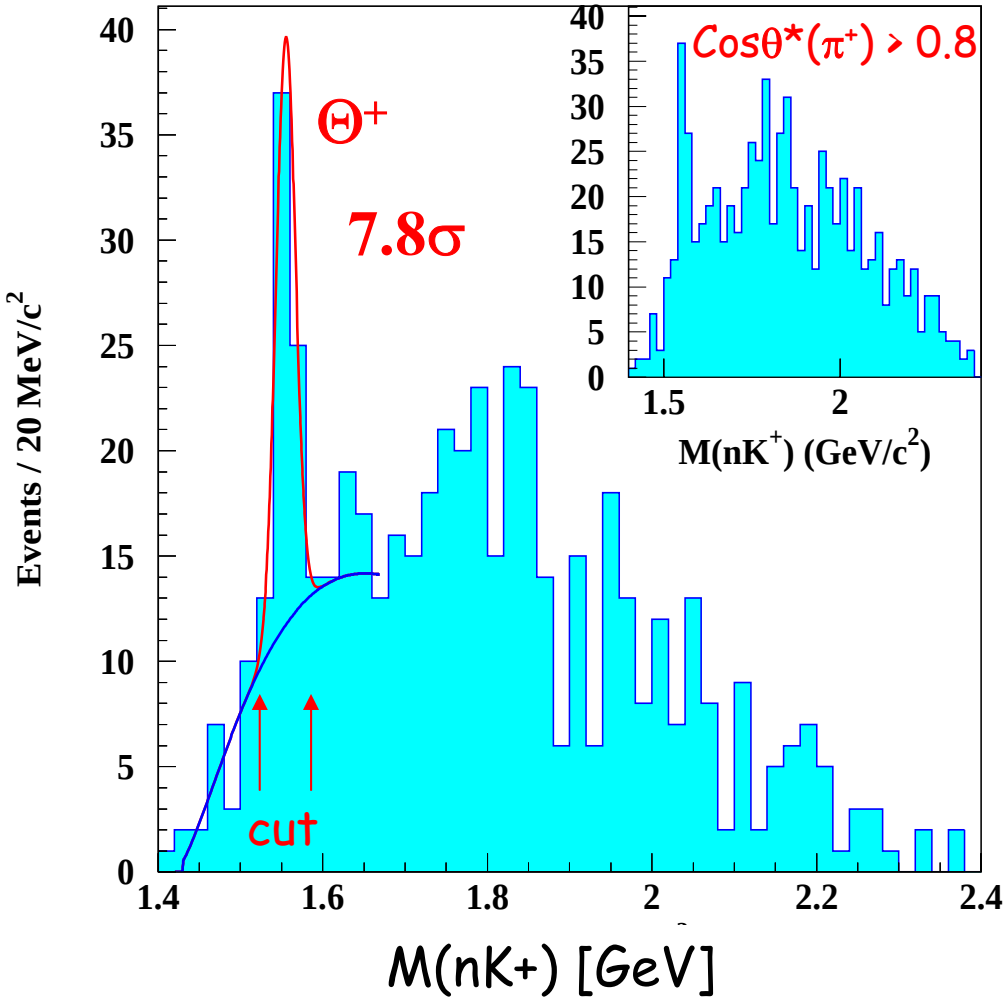
$M(nK^+)$ [GeV]

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

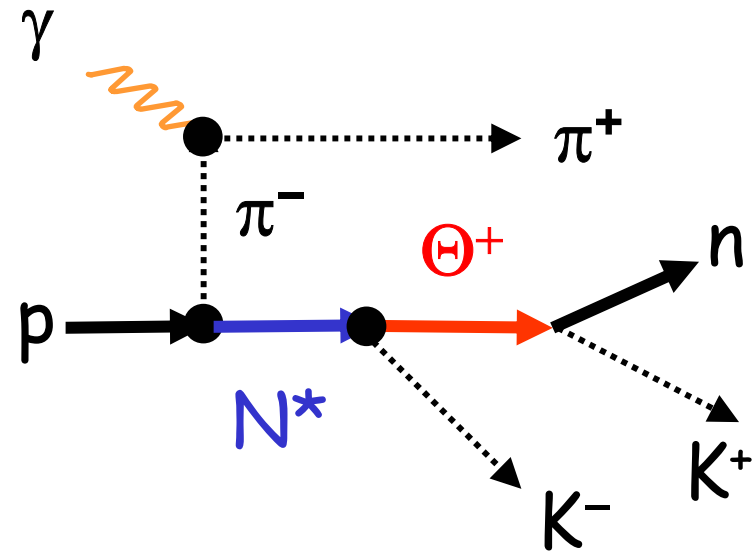


Searching for the Θ⁺ on a proton target

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



$E\gamma$ = 3 - 5.5 GeV



M=1555±10 MeV

Γ< 26 MeV

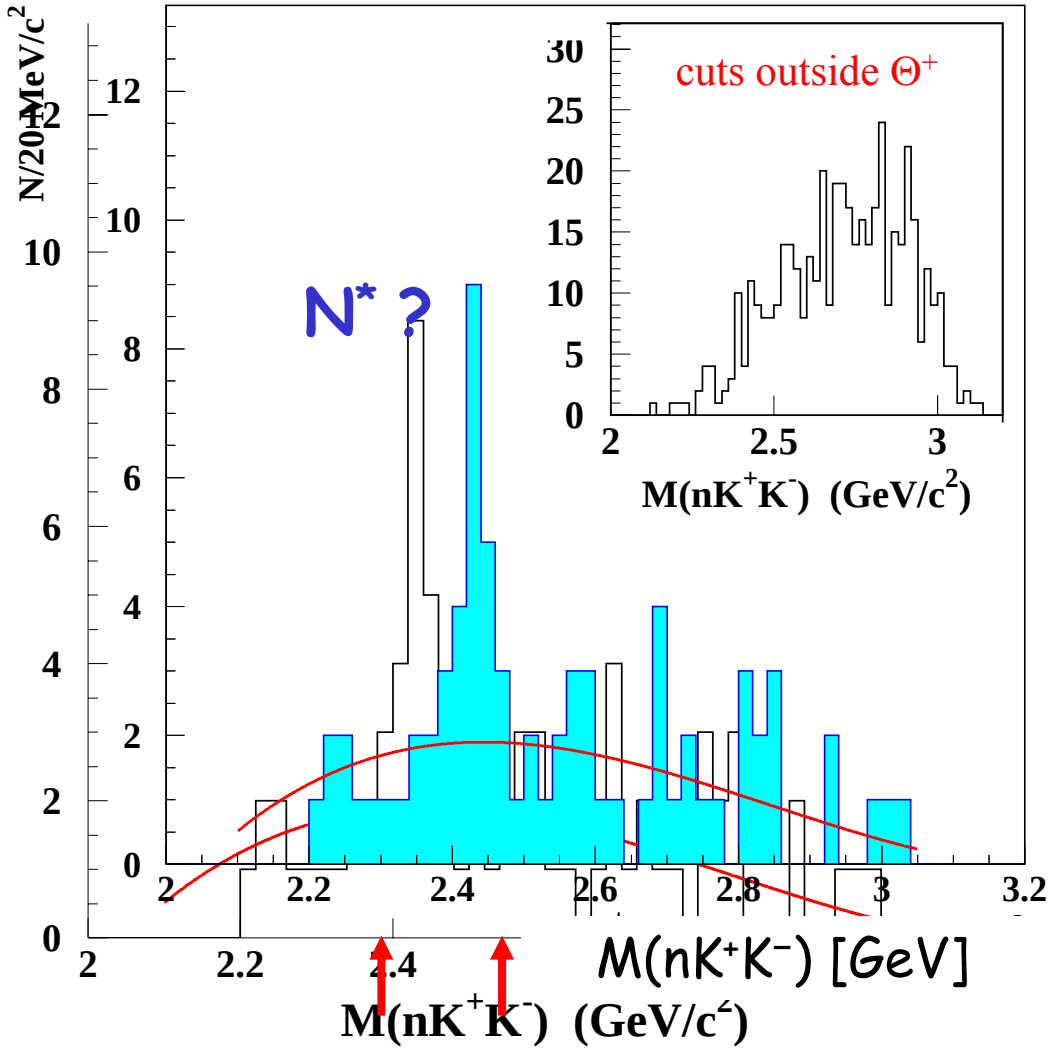
$\cos\theta^*(\pi^+) > 0.8$

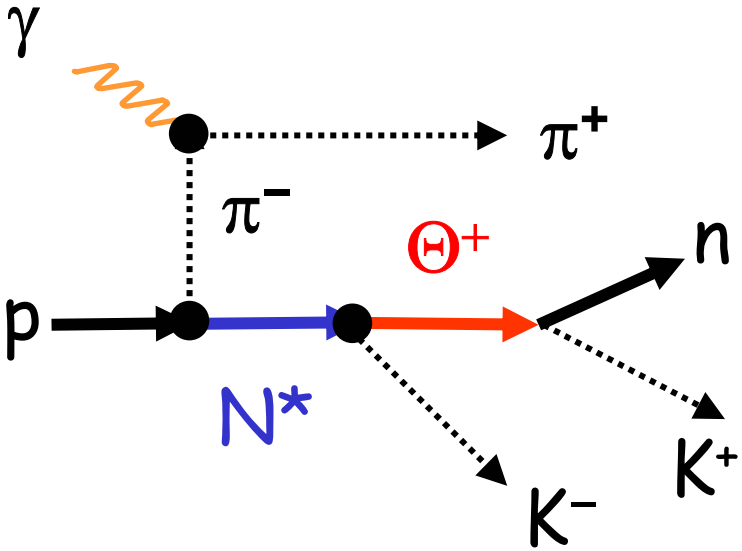
$\cos\theta^*(K^+) < 0.6$

CLAS Collaboration

PRL 92, 032001-1 (2004).

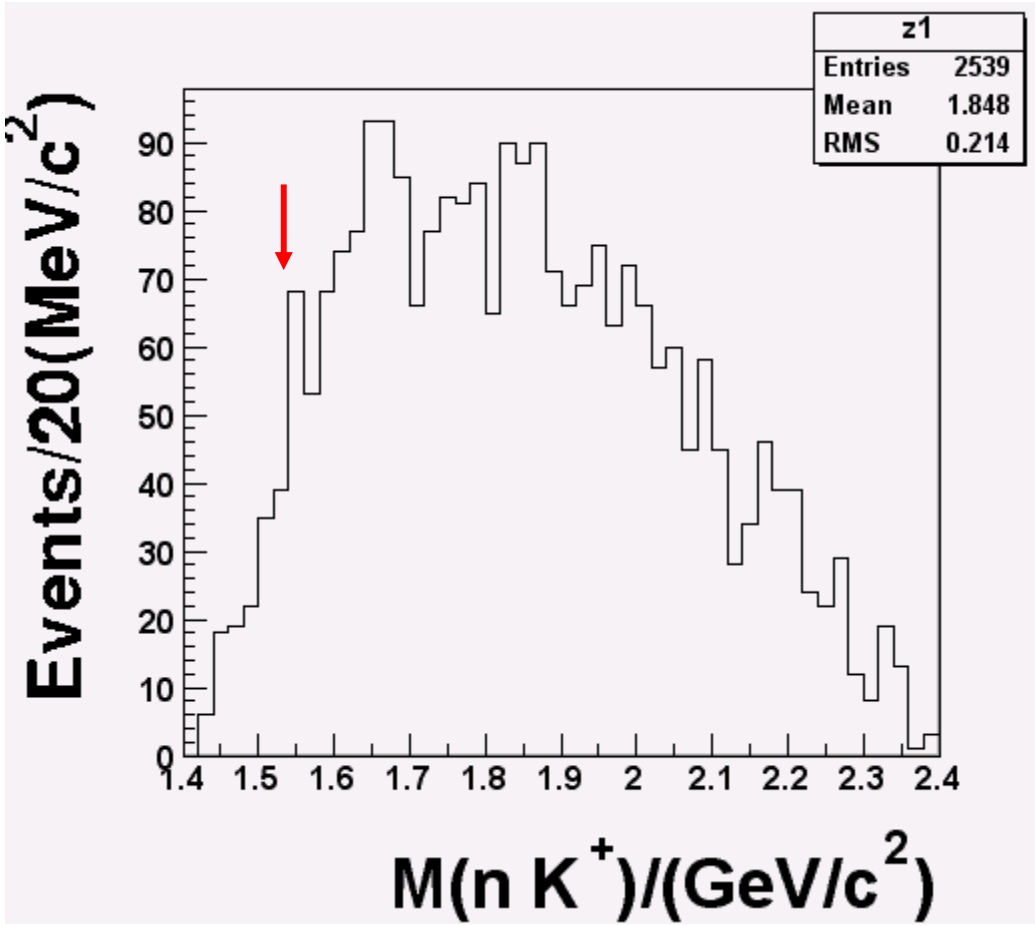
Θ^+ — N^* production mechanism?

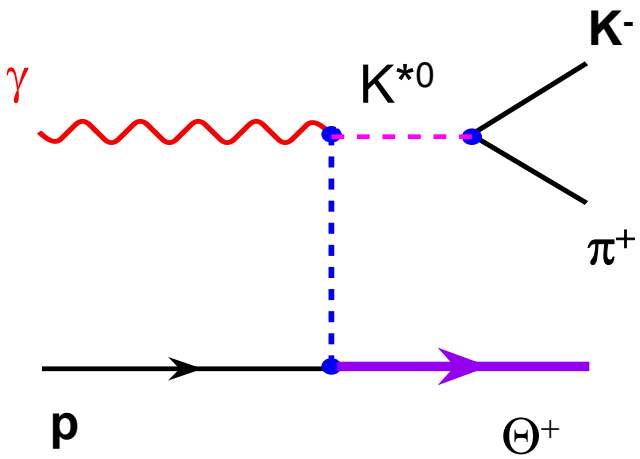




- What do π^-p scattering data say?
- π^-p cross section data in PDG have a gap in the mass range 2.3–2.43 GeV.

Diffractive mechanism?

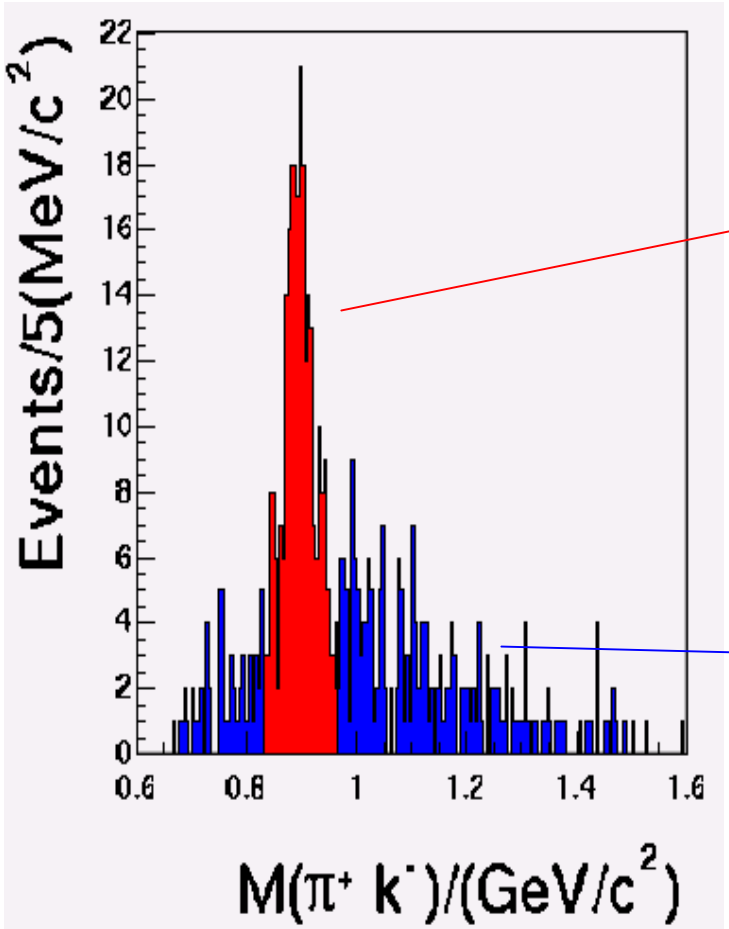


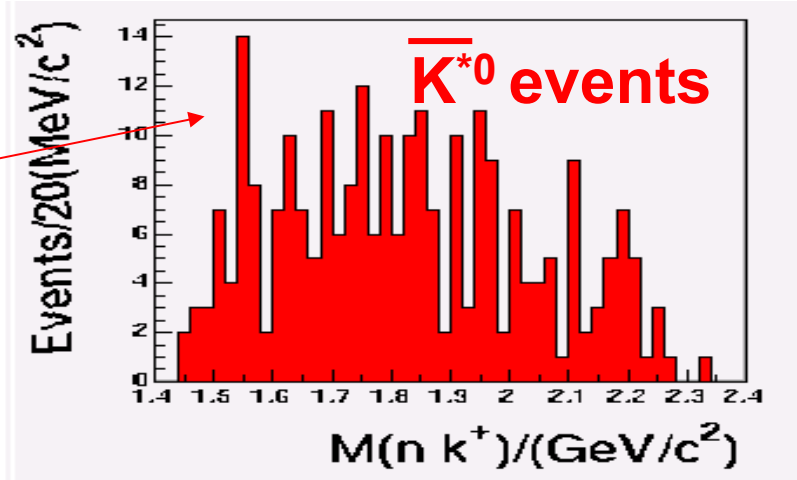


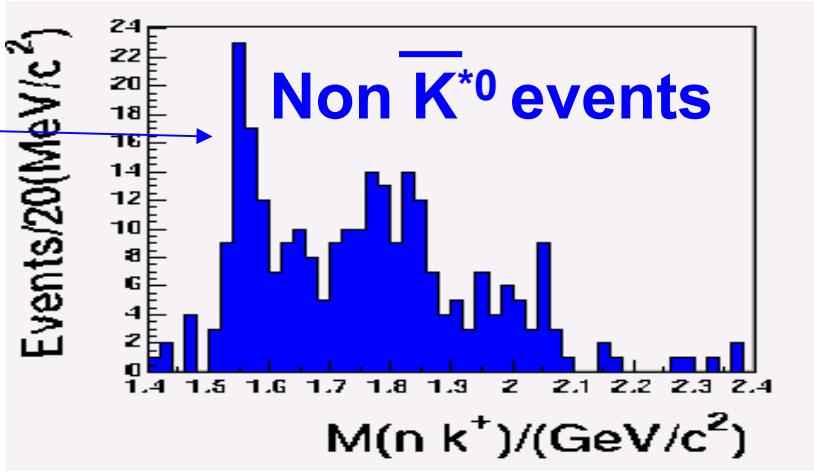
Require forward $\overline{K}^{0*}$

Cos $\theta^*(K^-\pi^+) > 0.5$

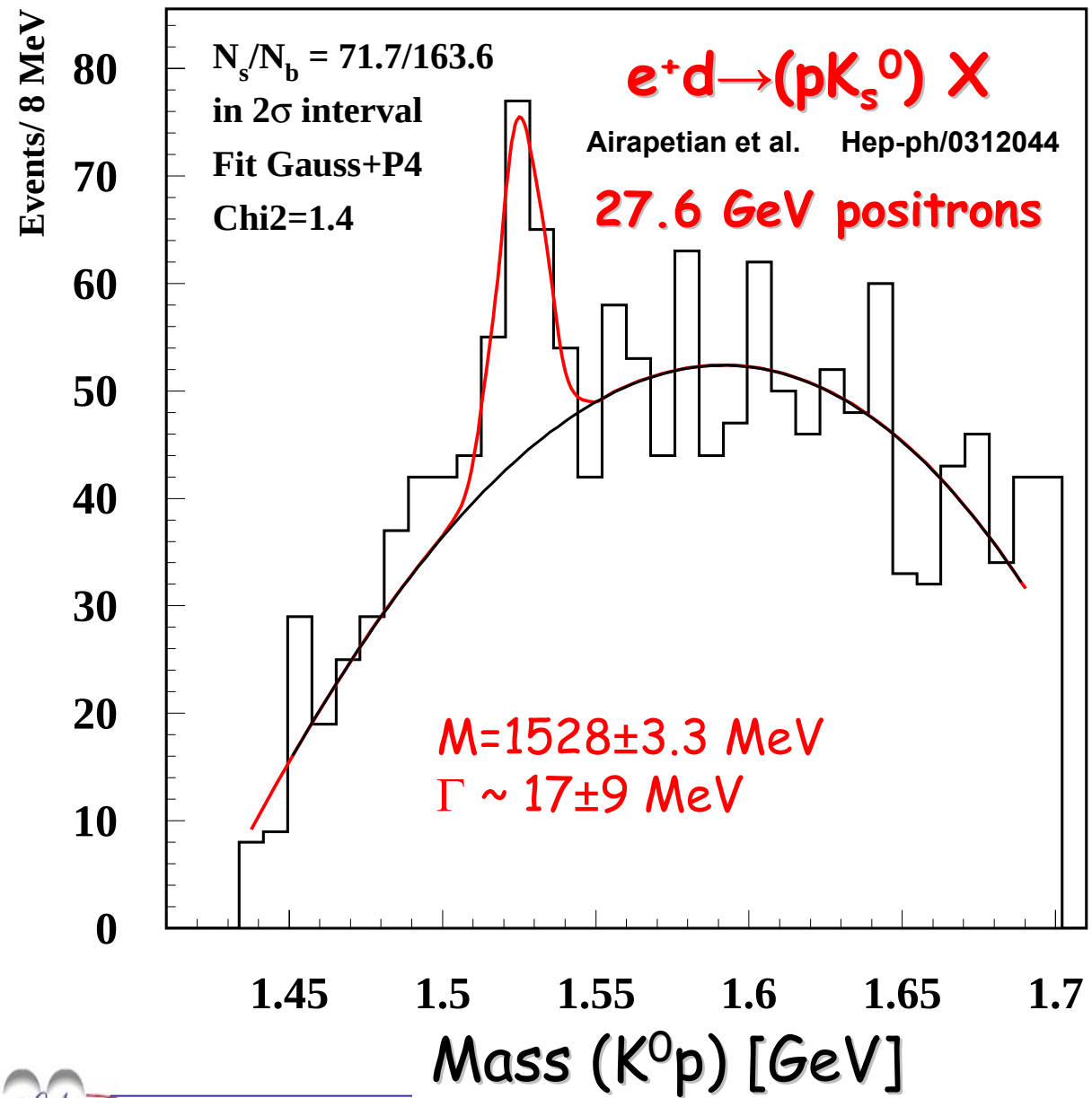
Θ^+ NOT produced in association with K^{*0}



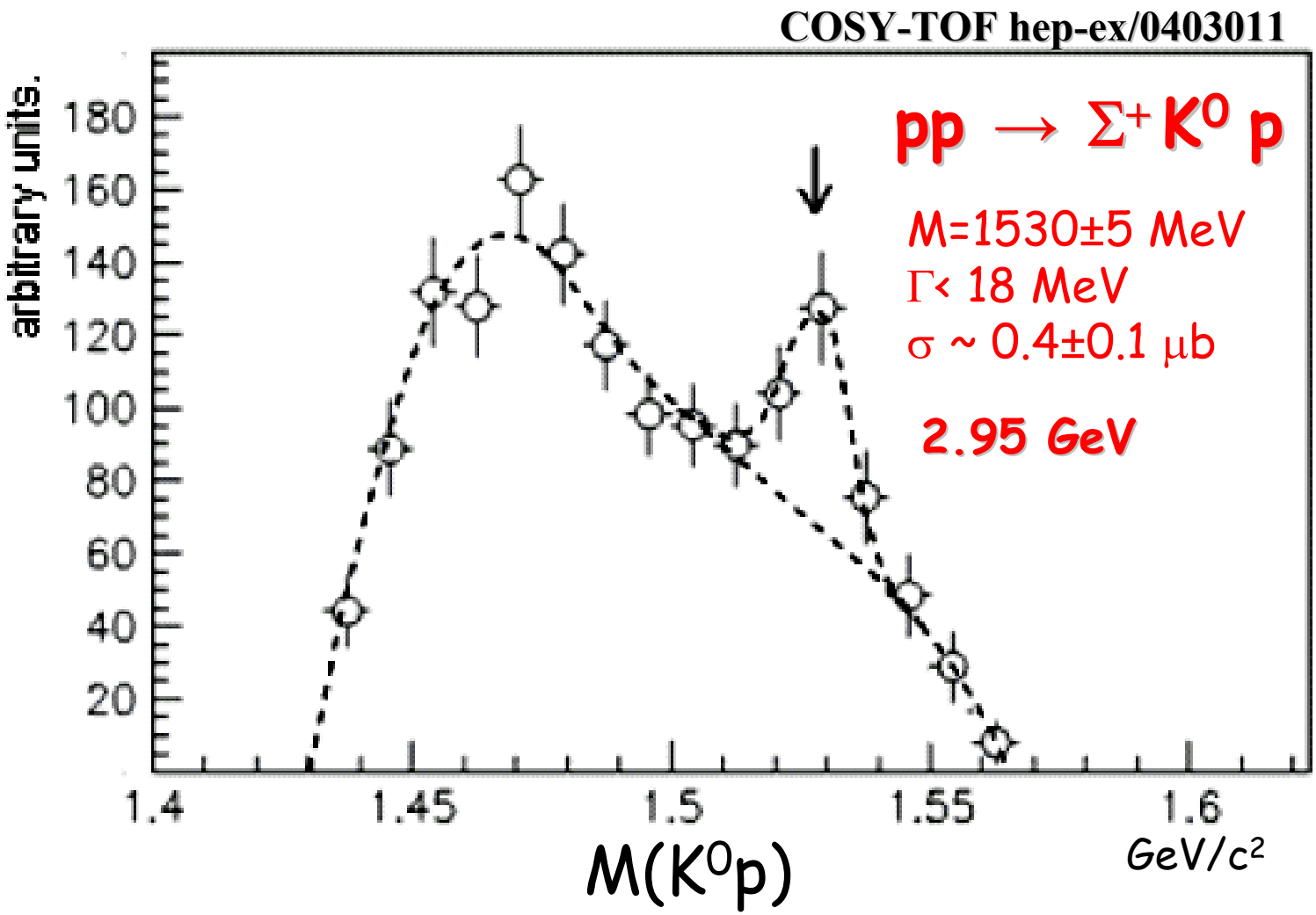




HERMES

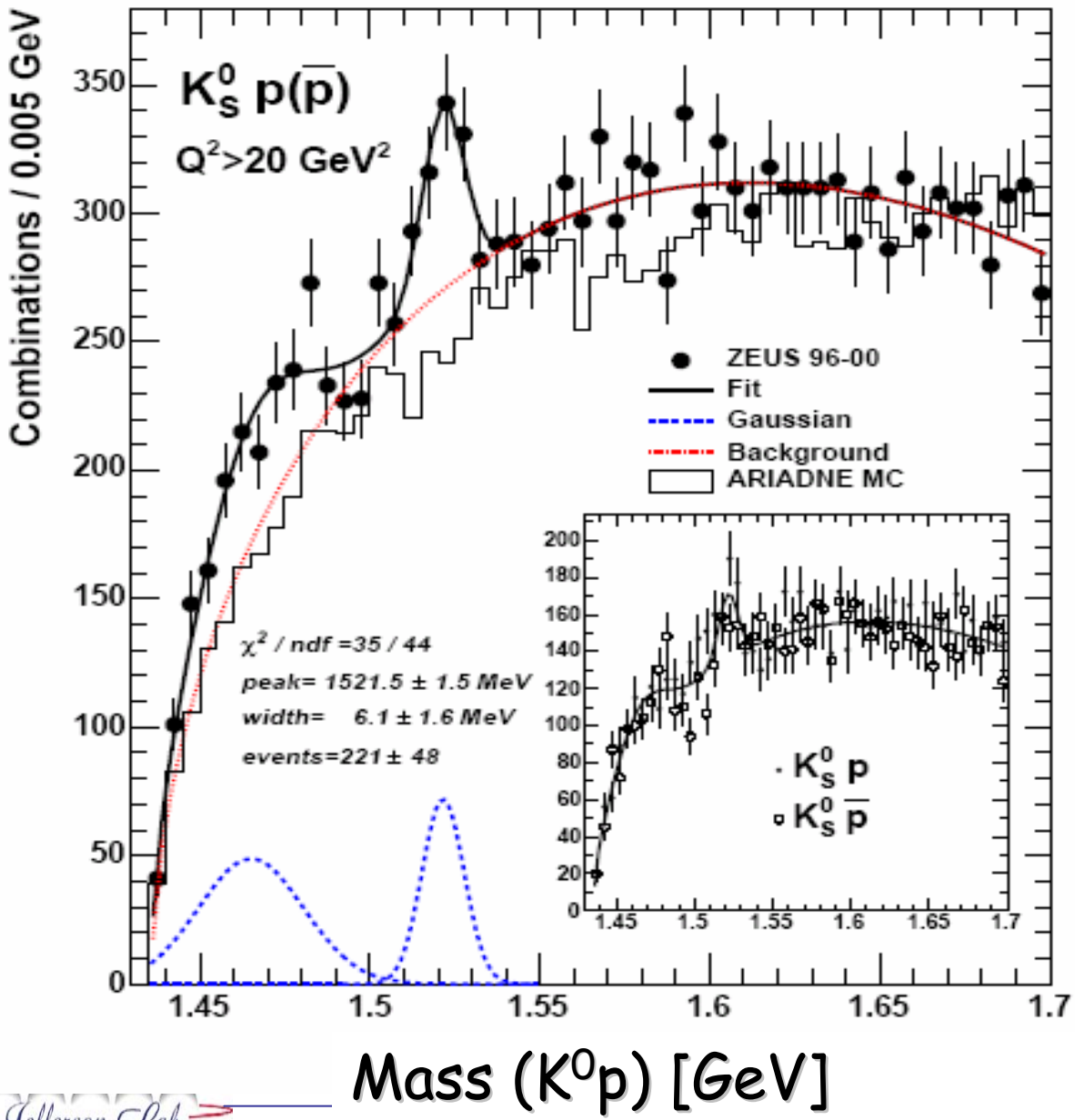

Events/ 8 MeV
80
70
60
50
40
30
20
10
0
N_s/N_b = 71.7/163.6
in 2σ interval
Fit Gauss+P4
Chi2=1.4
$e^+d \rightarrow (pK_s^0)\ X$
Airapetian et al. Hep-ph/0312044
27.6 GeV positrons
M=1528±3.3 MeV
Γ ~ 17±9 MeV
1.45
1.5
1.55
1.6
1.65
1.7
Mass (K^0p) [GeV]

New results from COSY-TOF



The TOF spectrometer at the COSY facility in Juelich, Germany found evidence for the Θ^+ in the reaction: $p + p \rightarrow \Sigma^+ + \Theta^+$.

From ZEUS at DESY…



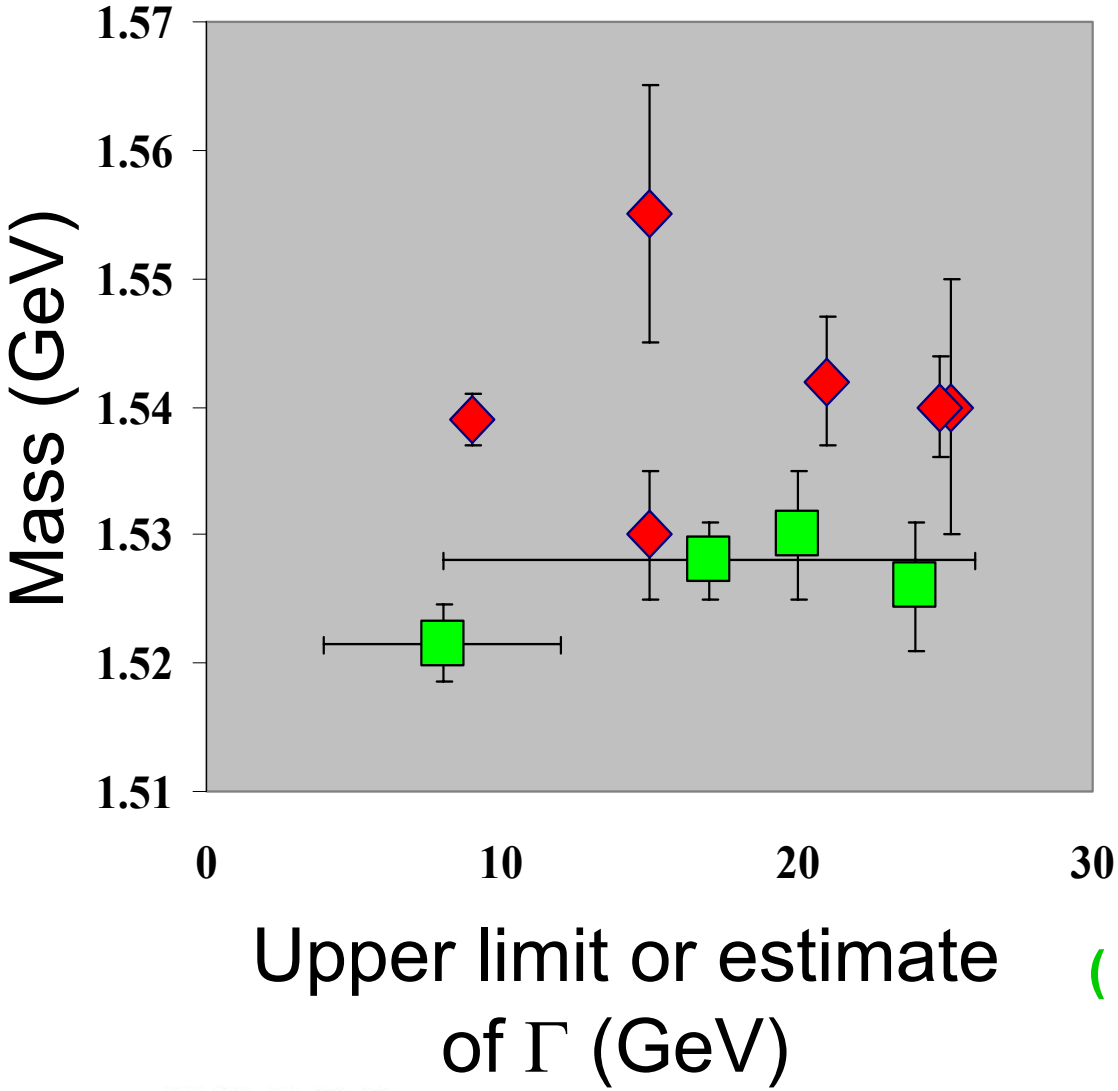
ZEUS hep-ex/0403051

$ep \rightarrow eK_s^0 p\ X$

M=1521.5±1.5 MeV
Γ~ 8±4 MeV

$\sqrt{s}$ ~ 310 GeV
Q^2 > 20 GeV^2

What do we know about this S=+1 state?



LEPS : $\gamma C \rightarrow (nK^+)\ K^- X$

DIANA : $K^+ Xe \rightarrow (pK^0)\ X$

CLAS-d : $\gamma d \rightarrow (nK^+)\ K^- p$

CLAS-p : $\gamma p \rightarrow (nK^+)\ \pi^+ K^-$

SAPHIR : $\gamma p \rightarrow (nK^+)\ K^0$

ITEP : $\nu\ d,Ne \rightarrow (pK^0)\ K^0$

HERMES : $e^+ d \rightarrow (pK^0)\ X$

COSY-TOF: $pp \rightarrow (pK^0)\ \Sigma^+$

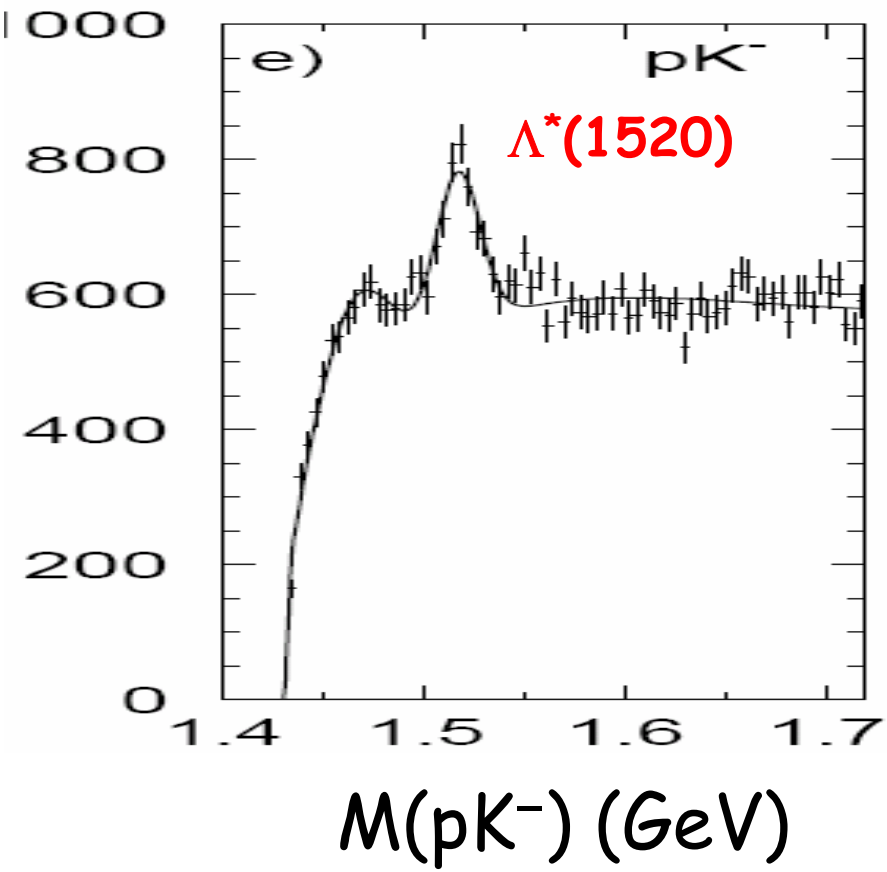
ZEUS : $ep \rightarrow e\ (pK^0)\ X$

SVD-2 : $pA \rightarrow (pK^0)\ X$

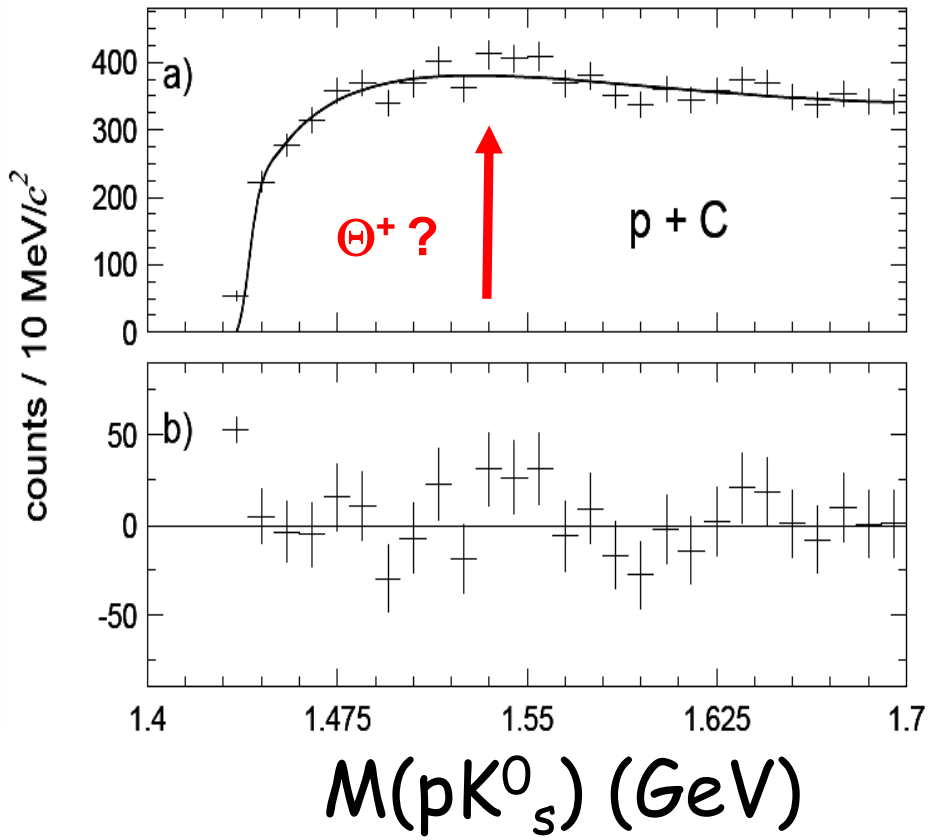
( ) Strangeness undetermined

Decay products in parenthesis

Search for pentaquarks in HERA-B



HERA-B hep-ex/0403020



$pA \rightarrow K^0 p\ X$

$\sqrt{s} \sim 41.6$ GeV

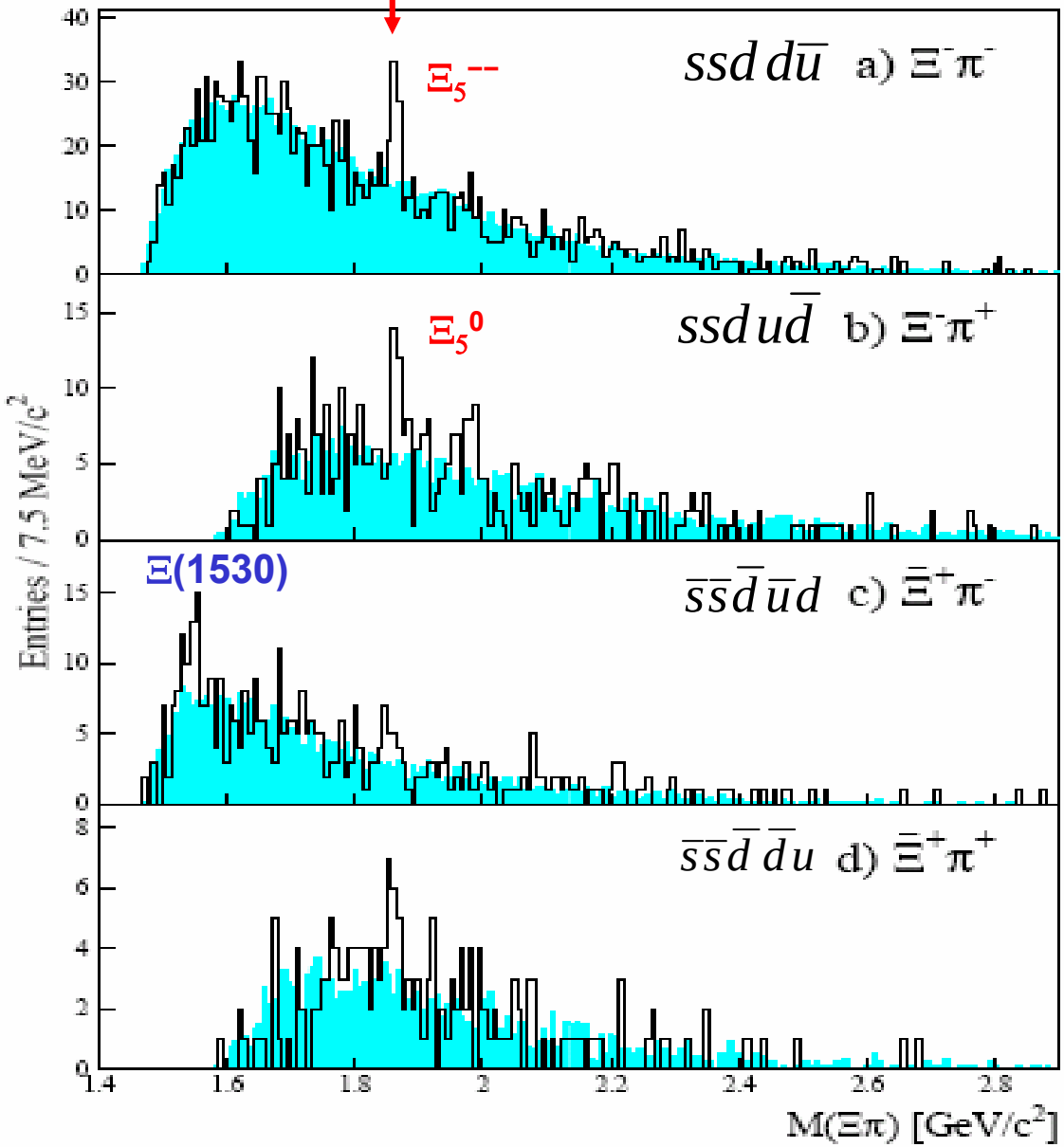
Null result at HERA-B

$$\frac{\Theta^+(1540)}{\Lambda^*(1520)} < 0.02$$

There is much more to learn

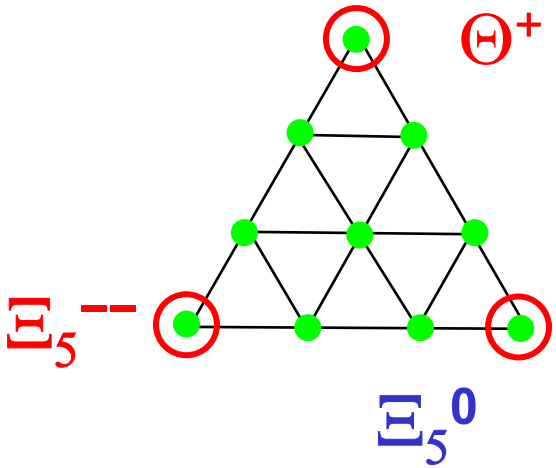
- Spin, parity
  - Chiral soliton model predicts $J^p=½^+$ (p-wave)
  - Quark model naïve expectation is $J^p=½^-$ (s-wave)
  - Lattice calculations predict $J^p=½^-$
- Isospin
  - Likely I=0, since searches for pK^+ partners unsuccessful
- Width (lifetime)
  - Measurements mostly limited by experimental resolution.
  - Theoretical problem remains why the state is so narrow.
  - Analysis of existing K^+d scattering data indicate that Γ < 1-2 MeV.
- Complete determination of the pentaquark multiplet

A new cousin: observation of exotic Ξ_5^{--}



M=1.862± 0.002 GeV

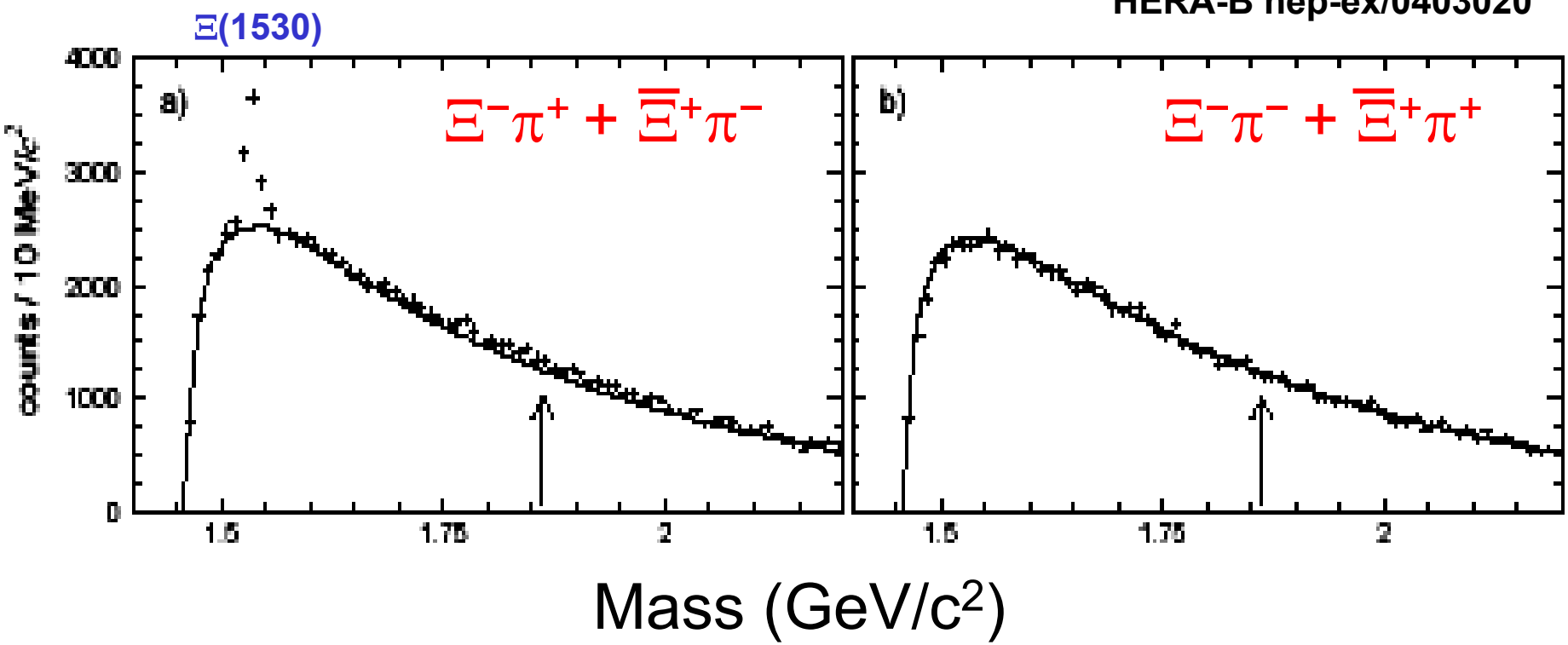
$ssd\bar{d}\bar{u}$



NA49 CERN SPS
Phys. Rev. Lett. 92 (2004) 042003

But, can it be reproduced??

HERA-B hep-ex/0403020

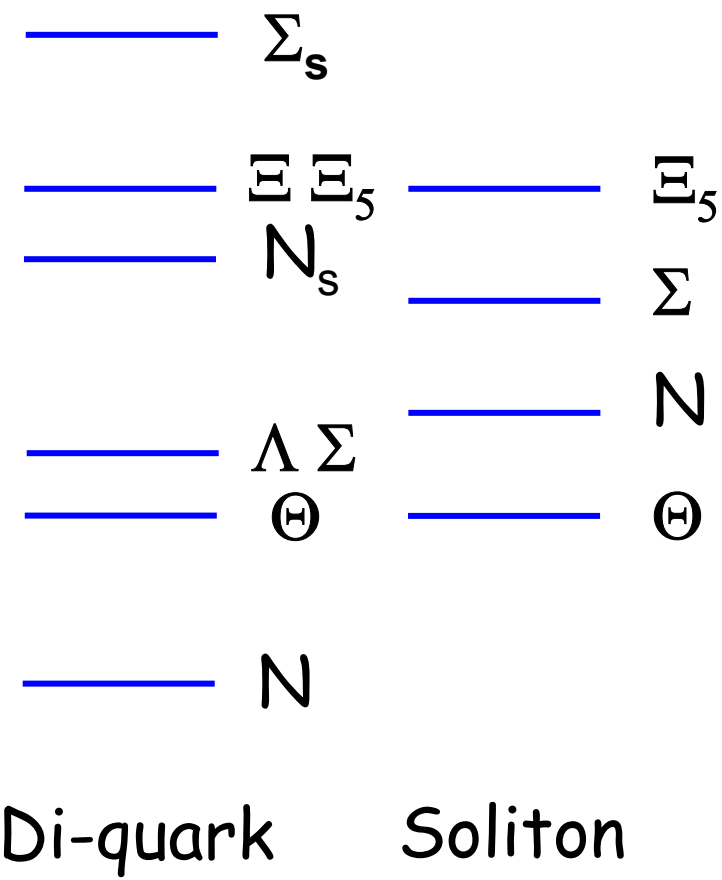


- HERA-B collaboration at DESY (Germany)
- Null result with much higher statistics!
- They also have a null result for the Θ^+

Predictions depend on dynamics

Number of states and mass spectra

Decay modes are sensitive to dynamical picture



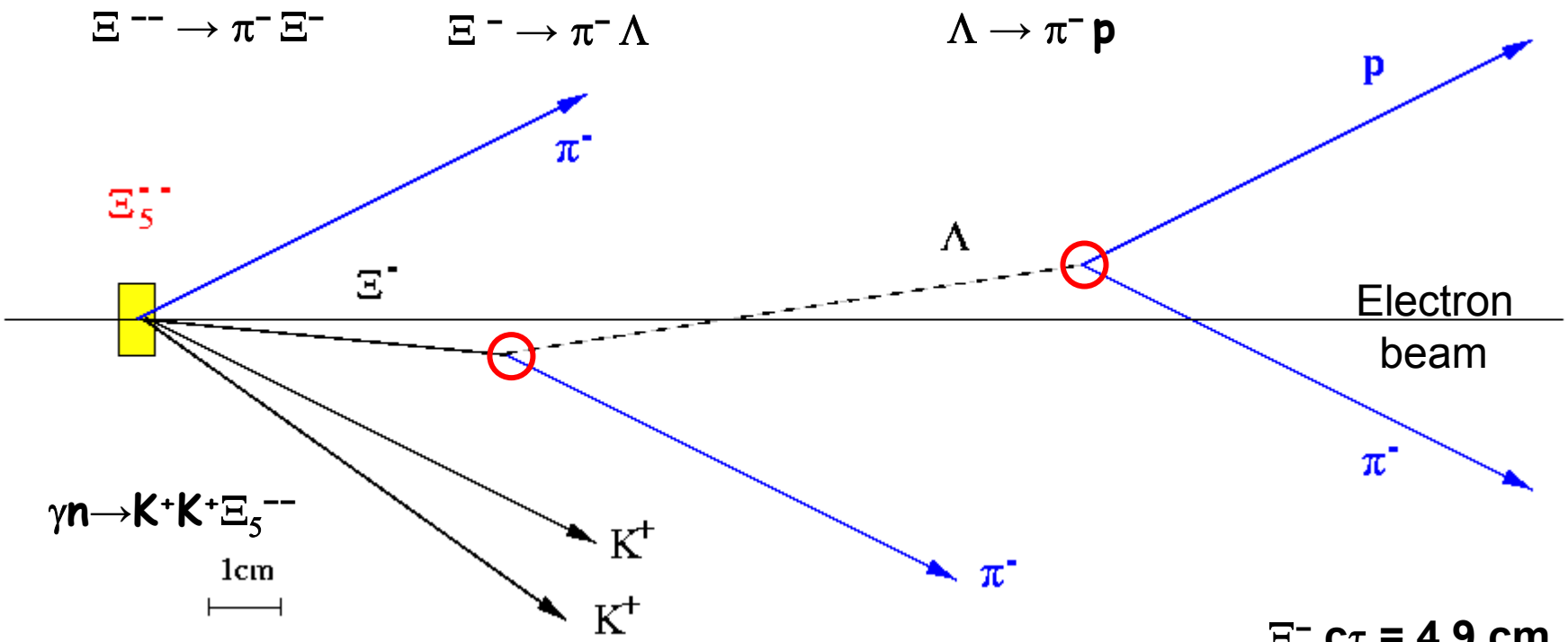
$$\frac{BR(\Xi_5 \to K^- \Sigma^-)}{BR(\Xi_5 \to \pi^- \Xi^-)}$$

$$\frac{BR(\Xi_5 \to \pi^0 \Xi^-)}{BR(\Xi_5 \to \pi^- \Xi^0)}$$

Note: Models adjusted to experiment

Search for exotic cascades Ξ_5^{--} and Ξ_5^{-}

Experiment 04-10, scheduled to run this fall



Ξ^- $c\tau$ = 4.9 cm
Λ $c\tau$ = 7.9 cm

Two decay vertices,
Negatives bend outwards

$\langle\gamma\beta\rangle \sim 1.5$

Current activities at Jlab

- Pentaquark experiments in Hall B
  - g10 (currently taking data) $\gamma d \rightarrow \Theta^+$ $E\gamma$~1 – 3.5 GeV
  - g11 (starts in mid-May) $\gamma p \rightarrow \Theta^+$ $E\gamma$~1 – 3.5 GeV
  - eg3 (November) $\gamma_v d \rightarrow \Xi_5^{--}, \Xi_5^{-}$ $E\gamma$> 3.9 GeV
  - High energy data $\gamma p \rightarrow \Theta^+, \Xi_5$ $E\gamma$~1.5 – 5.4 GeV
- Pentaquark experiment in Hall A
  - E04-012 (May), search for excited Θ^{++} and Θ^0 states.

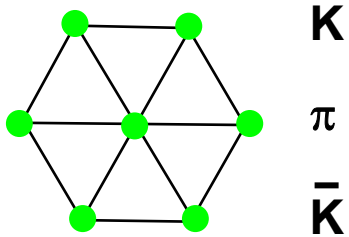
Summary

- A key question in non-perturbative QCD is the structure of hadrons.
- We have reviewed the evidence for the existence of a new class of colorless hadrons with quantum numbers which cannot be generated from solely three quarks:
  - There is substantial corroborating evidence for an exotic baryon with S = +1, which would have a minimal quark content of ($uudd\bar{s}$).
  - The observation of a doubly negative S=−2 baryon ($ddss\bar{u}$) is consistent with a second corner of the anti-decuplet the family of pentaquarks, but needs additional confirmation.
- Dedicated experiments are being mounted which should easily establish (or refute) the observations to date.

Hadron multiplets

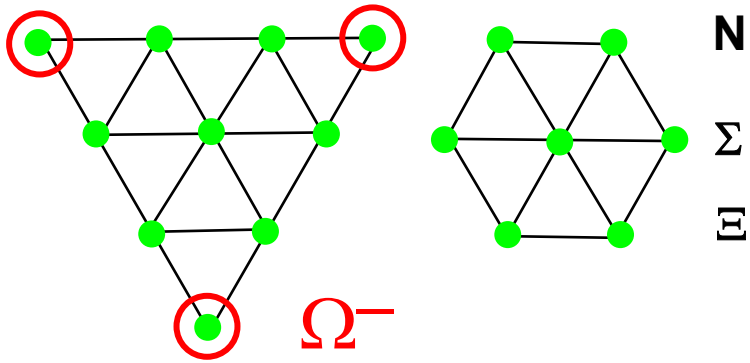
Mesons $q\bar{q}$

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



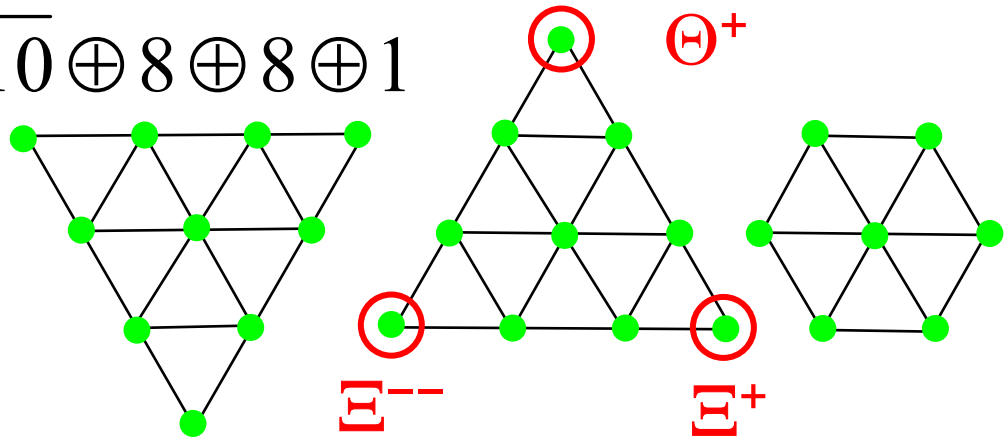
Baryons qqq

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



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

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



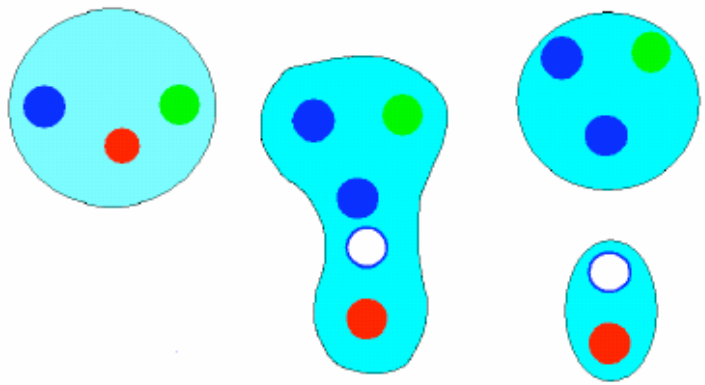
Decay width: usual vs. fall-apart decays

$$\Gamma \propto \frac{1}{2J+1}\left(\frac{p_{cm}}{\beta}\right)^{2L}$$

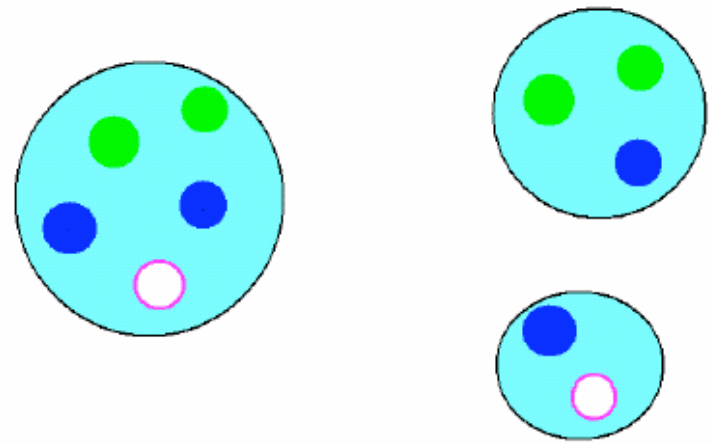
≈small??

≈500 MeV

$$uds \rightarrow uud + \bar{u}s$$



$$uudd\bar{s} \rightarrow ddu + u\bar{s}$$



$q\bar{q}$ pair created

string broken

$$\langle s\bar{u}|\langle uud|^3P_0|uds\rangle$$

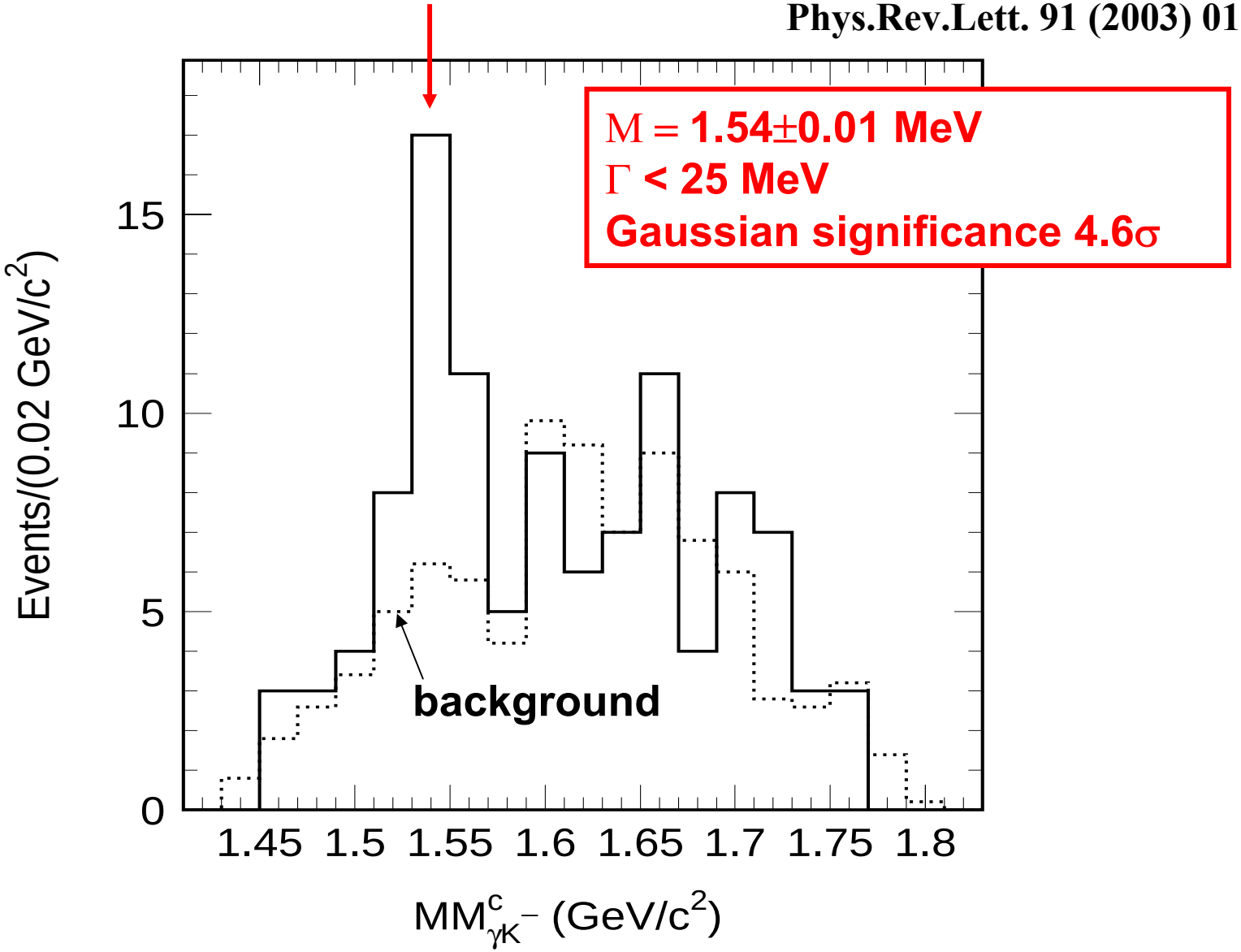
no pair

color/flavor/spin/spatial rearrangement

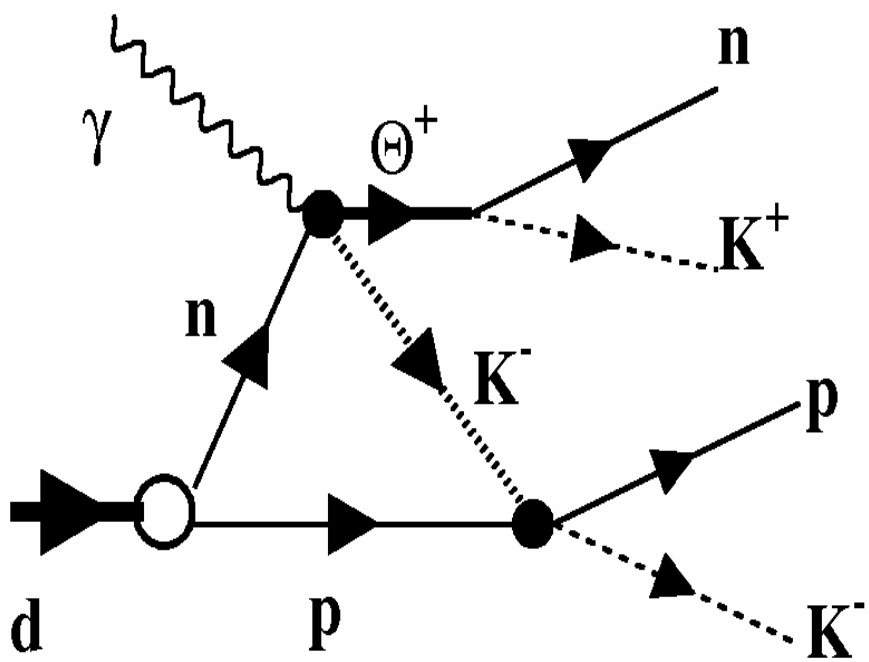
$$\langle u\bar{s}|\langle ddu|\mathbf{1}|uudd\bar{s}\rangle$$

First observation of Θ^+ at SPring-8

Phys.Rev.Lett. 91 (2003) 012002



Exclusive measurement using γd reactions



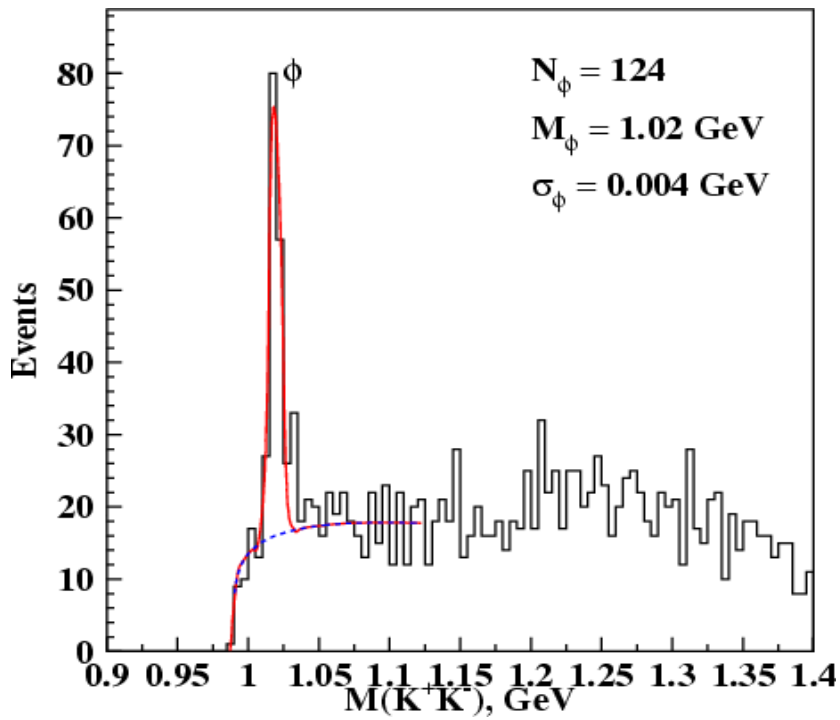
Requires final-state-interaction, so both nucleons participate

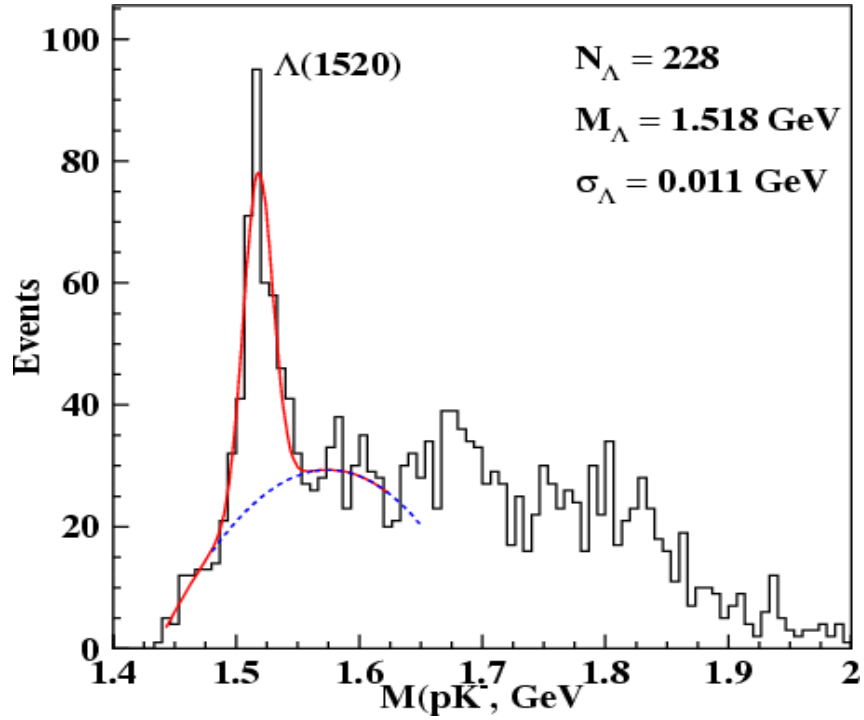
- No Fermi motion correction necessary
- FSI puts K^- at larger lab angles: better CLAS acceptance
- FSI not rare: in ~50% of $\Lambda^*(1520)$ events both nucleons detected with $p > 0.15$ GeV/c

$E_\gamma = 1.5 - 3.0$ GeV

CLAS Collaboration
PRL 91, 252001-5 (2003).

Identification of known resonances

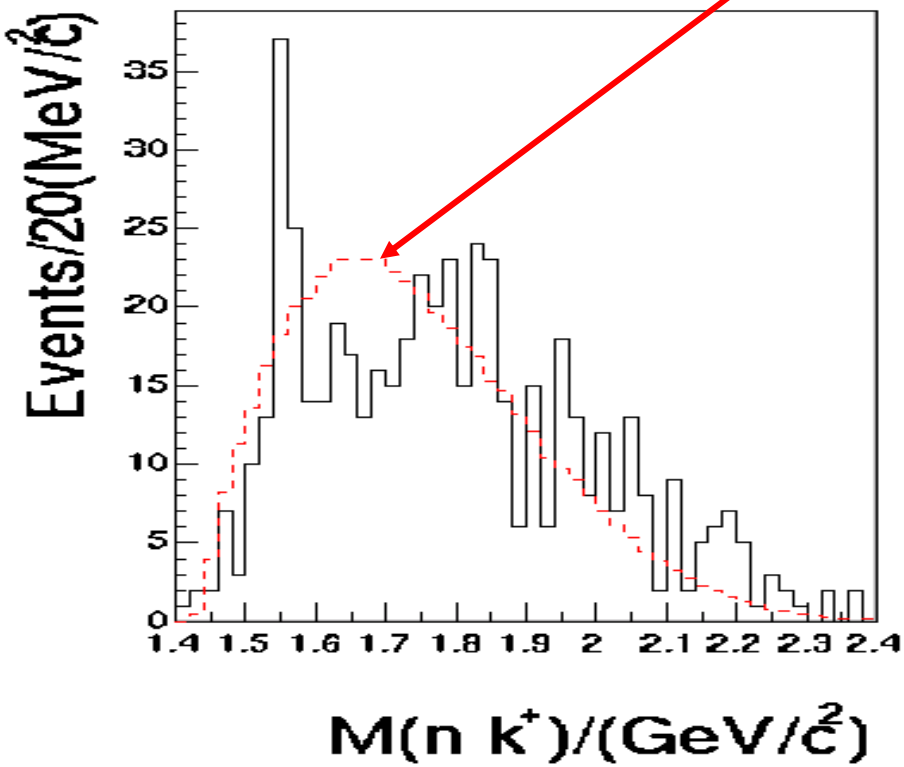


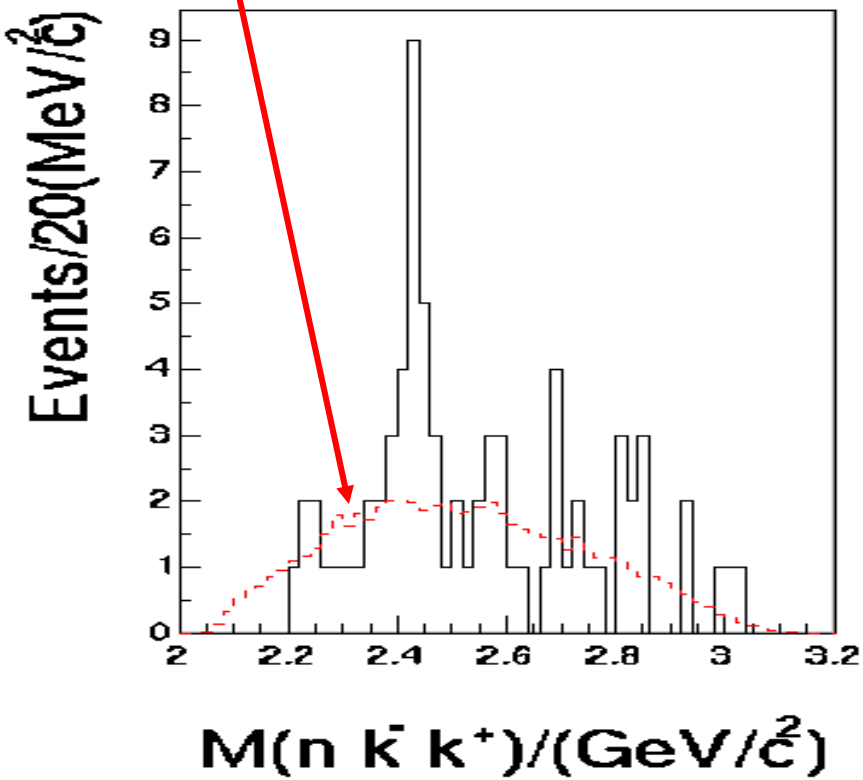


- Remove events with $IM(K^+K^-) \rightarrow \phi(1020)$ by IM > 1.07 GeV
- Remove events with $IM(pK^-) \rightarrow \Lambda(1520)$
- Limit K^+ momentum due to $\gamma\, d \rightarrow p\, K^- \Theta^+$ phase space $p_{K^+} < 1.0$GeV/c

Simulation of background processes

Background predicted to be smooth

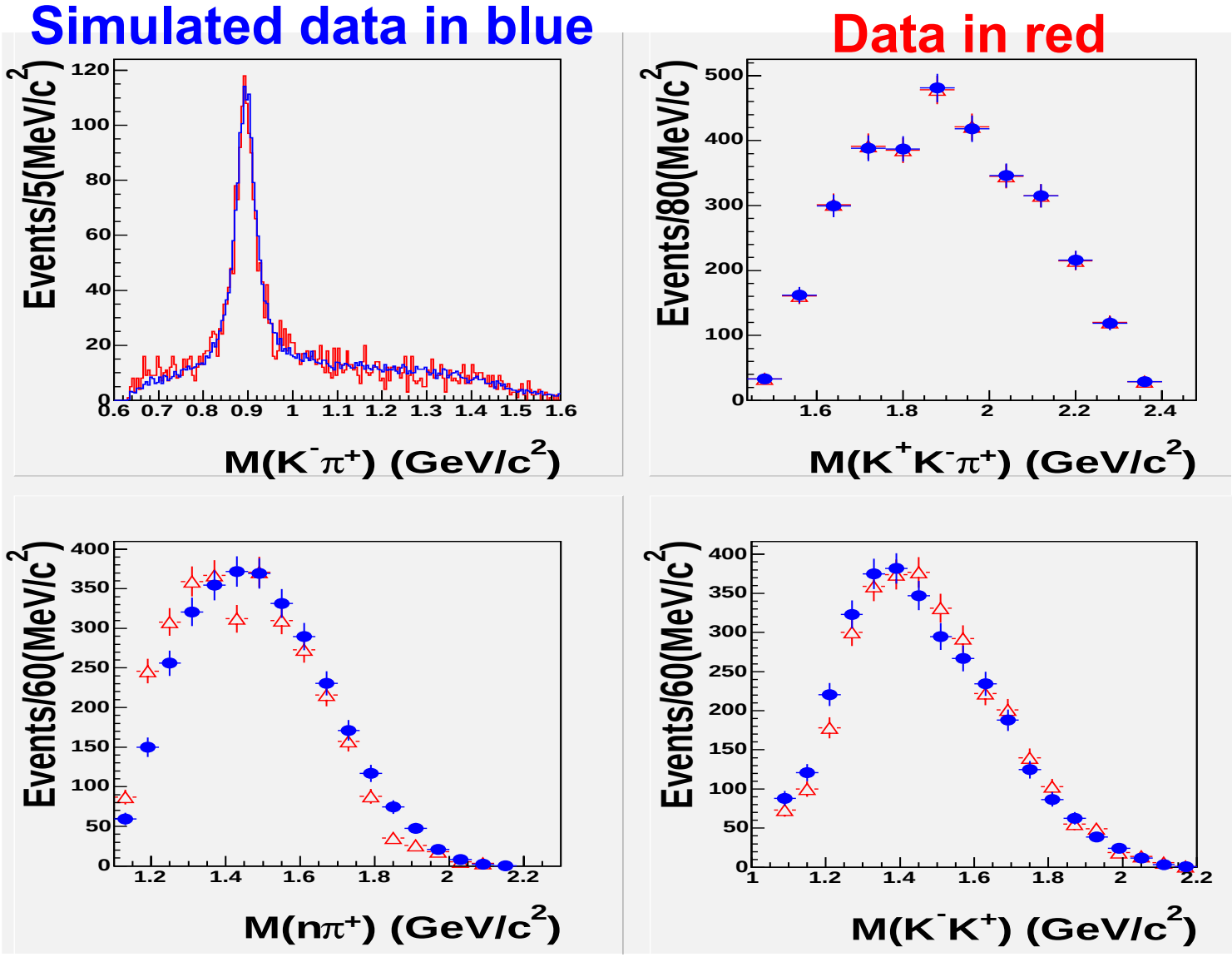




Phase space simulation includes

- **K^{*0} n K^- 3-body phase space**
- **$K^+ K^- \pi^-$ n 4-body phase space**
- **t-channel Mesons → $K^+ K^- \pi^-$ production**

Partial Wave Analysis of background processes



$t'(\gamma \rightarrow K^+K^-\pi^+) < 0.6\ GeV^2$

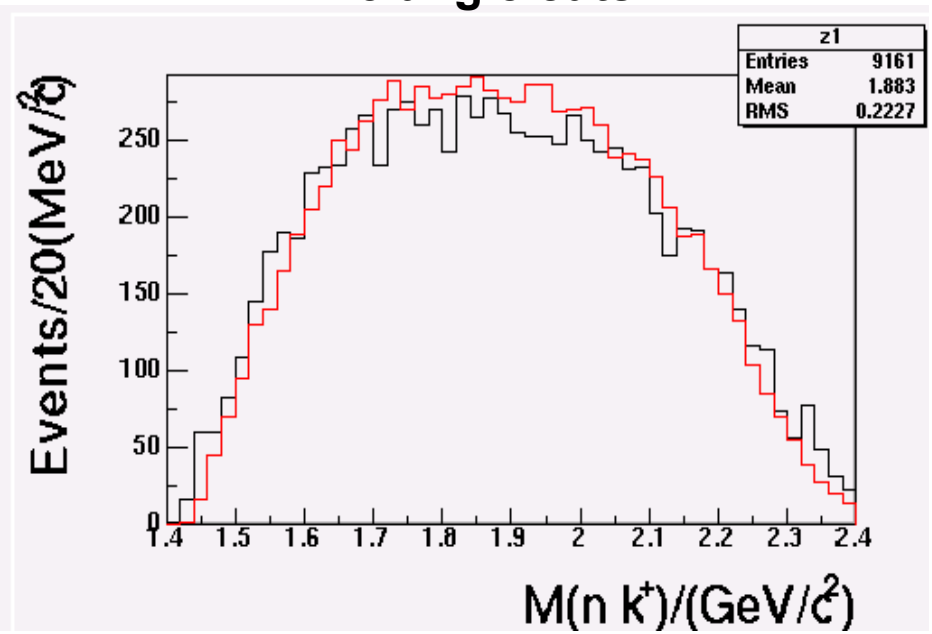
g6c $\gamma p \rightarrow K^+K^-\pi^+(n)$ analysis

PWA prediction of (nK^+) mass spectra compared with data

Meson reflection unlikely to produce nK^+ peak @1.55 GeV

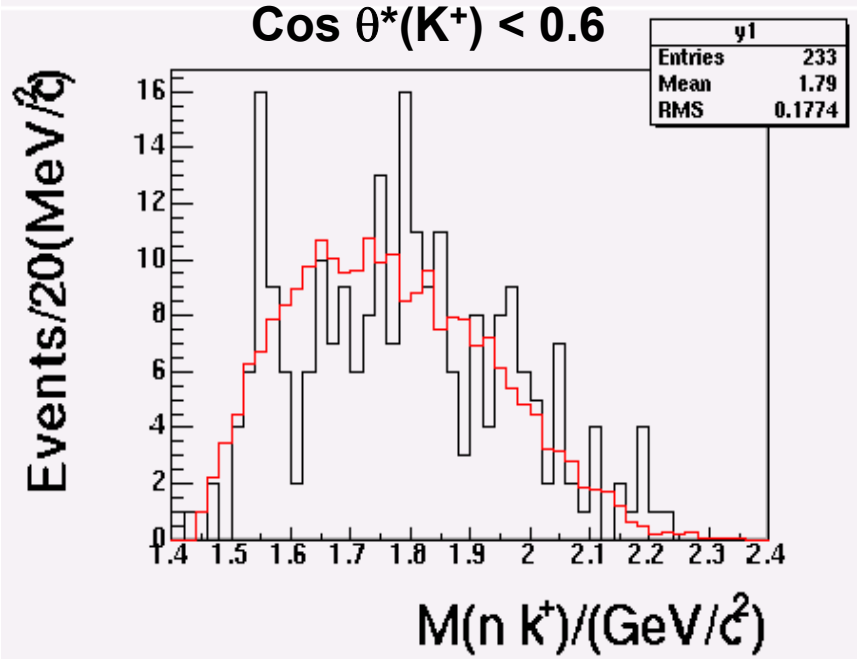
$t'(\gamma \rightarrow (K^+K^-\pi^+))<0.6$ & $\cos\theta^*(K^+) < 0$

No angle cuts



$\cos\theta^*(\pi^+) > 0.8$

$\cos\theta^*(K^+) < 0.6$

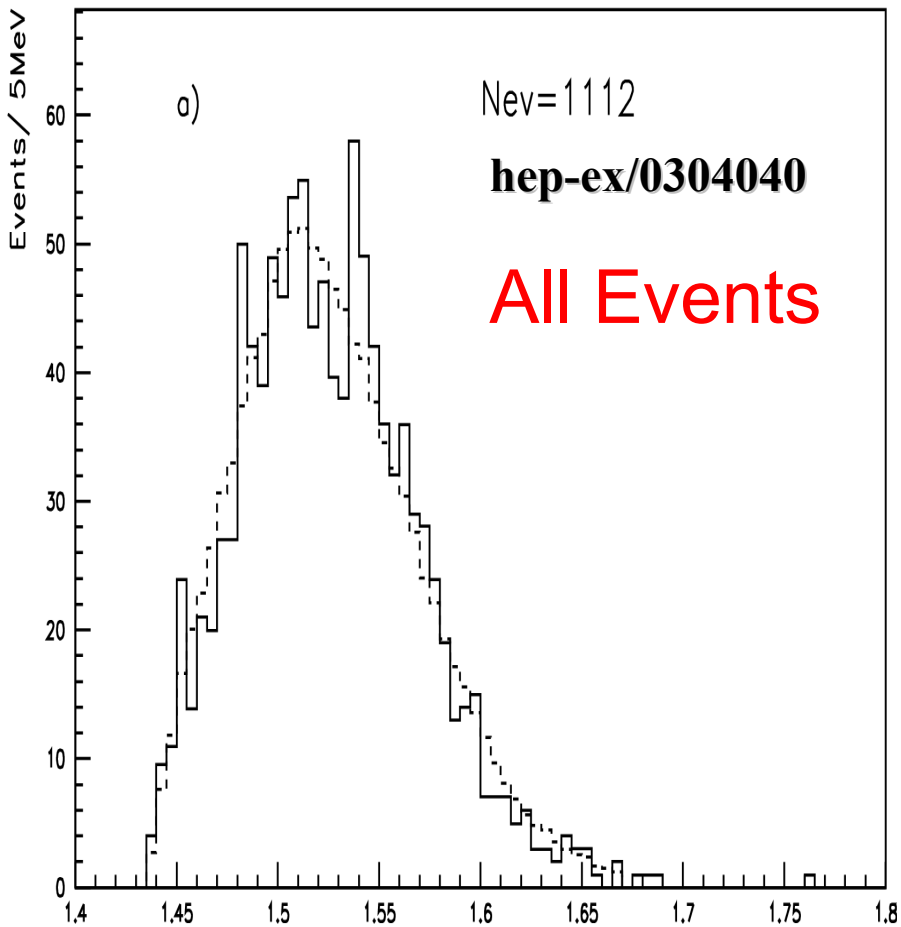


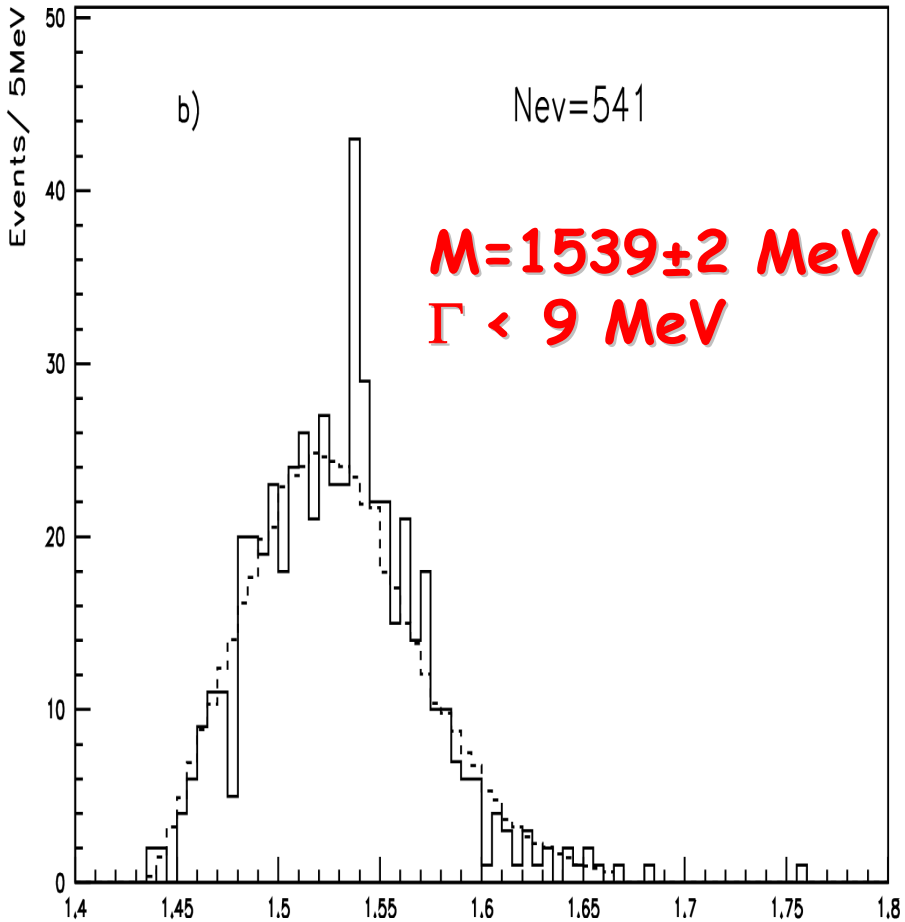
Data — **Prediction —**

DIANA at ITEP 850 MeV K^+ beam

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

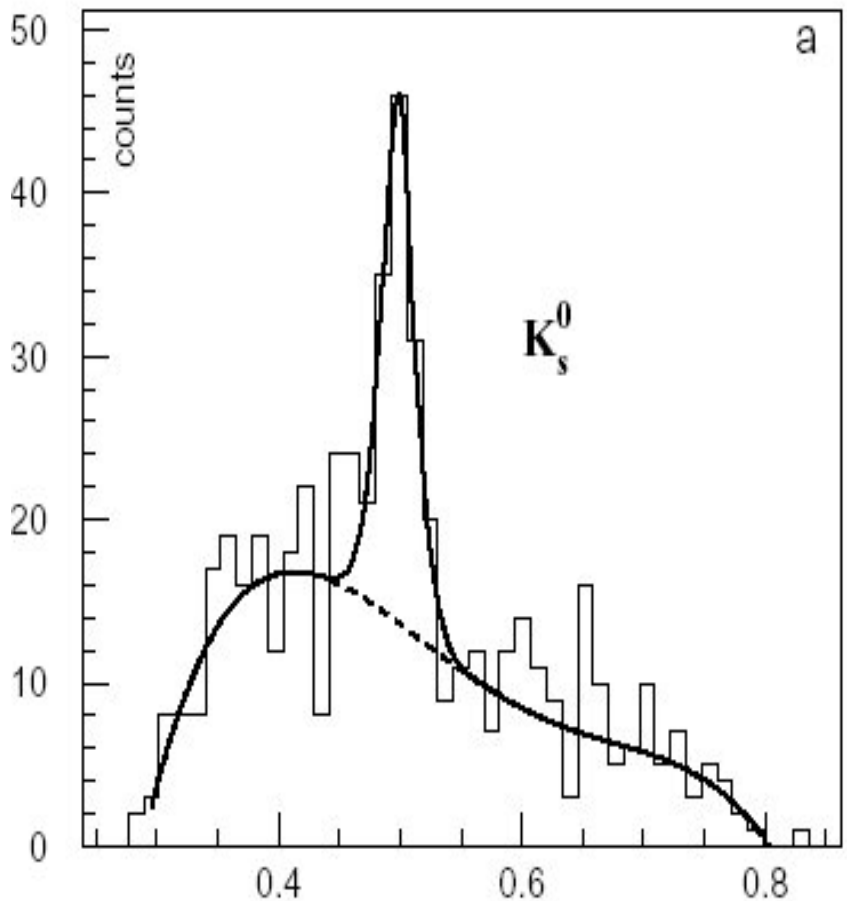
Cuts to suppress p and K^0 reinteraction in Xe nucleus



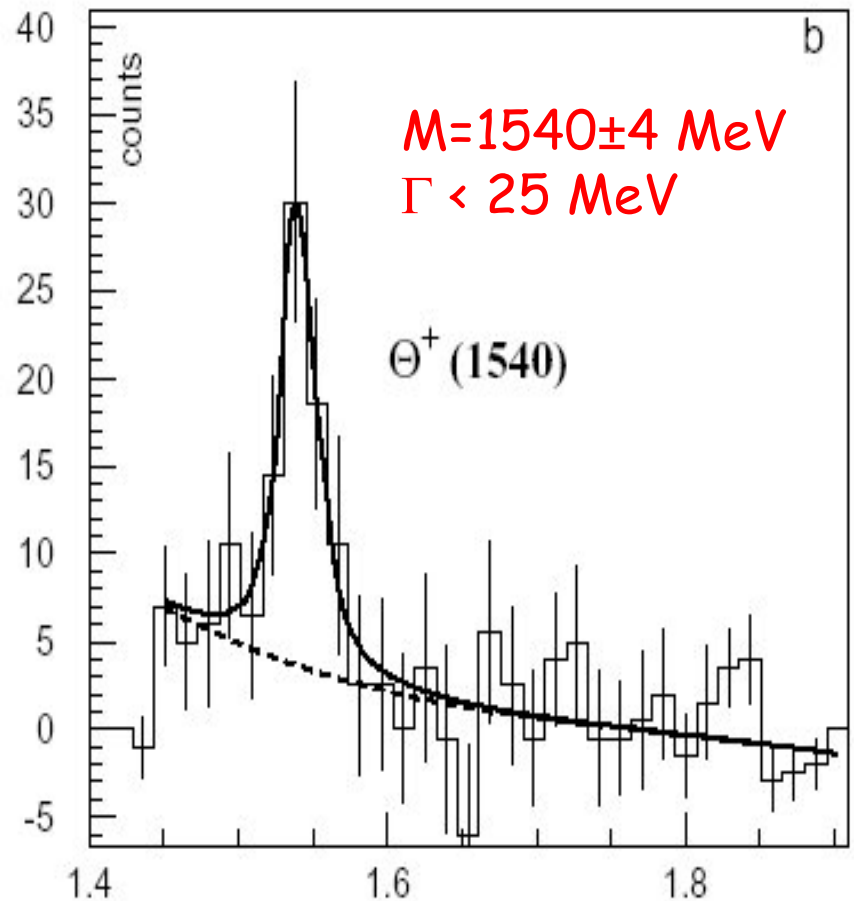


SAPHIR detector at ELSA

The reaction $\gamma p \rightarrow \Theta^+ K_s^0$, where $K_s^0 \rightarrow \pi^+\pi^-$ and $\Theta^+ \rightarrow nK^+$



Mass ($\pi^+\pi^-$) [GeV]

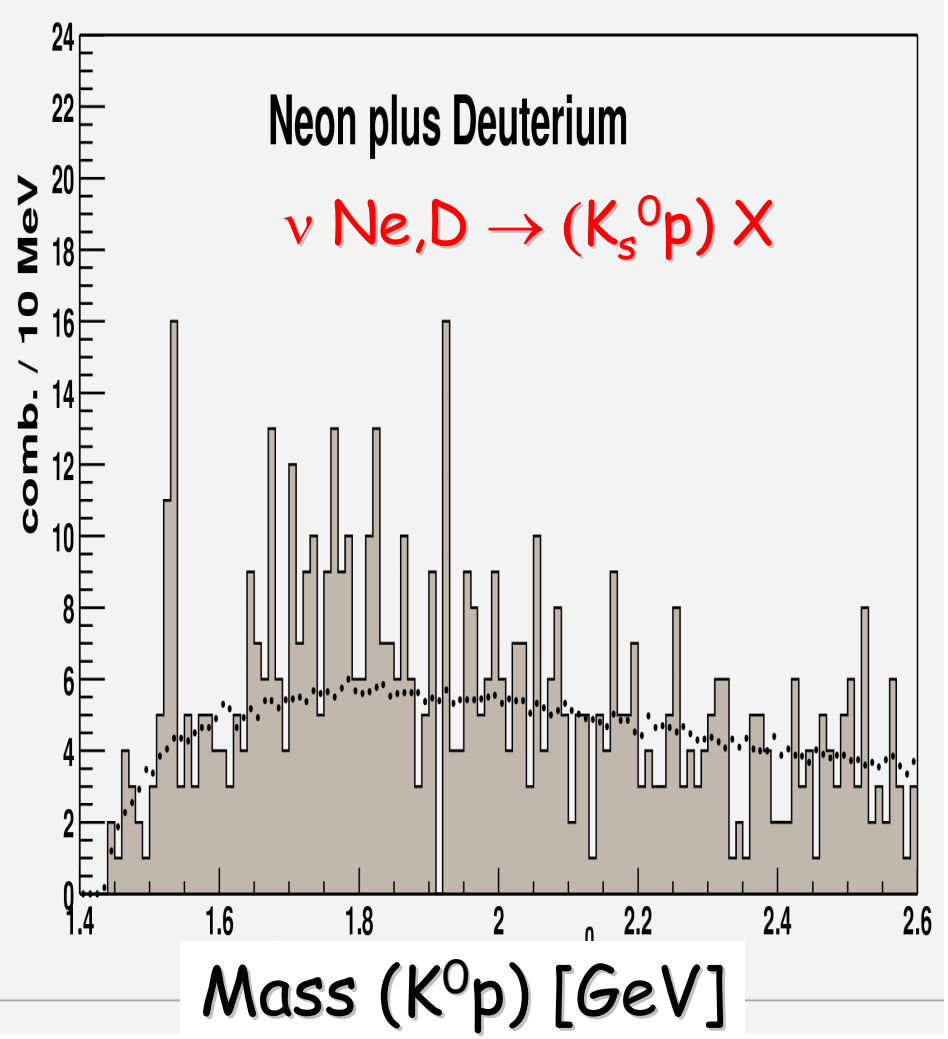


Mass (nK^+) [GeV]

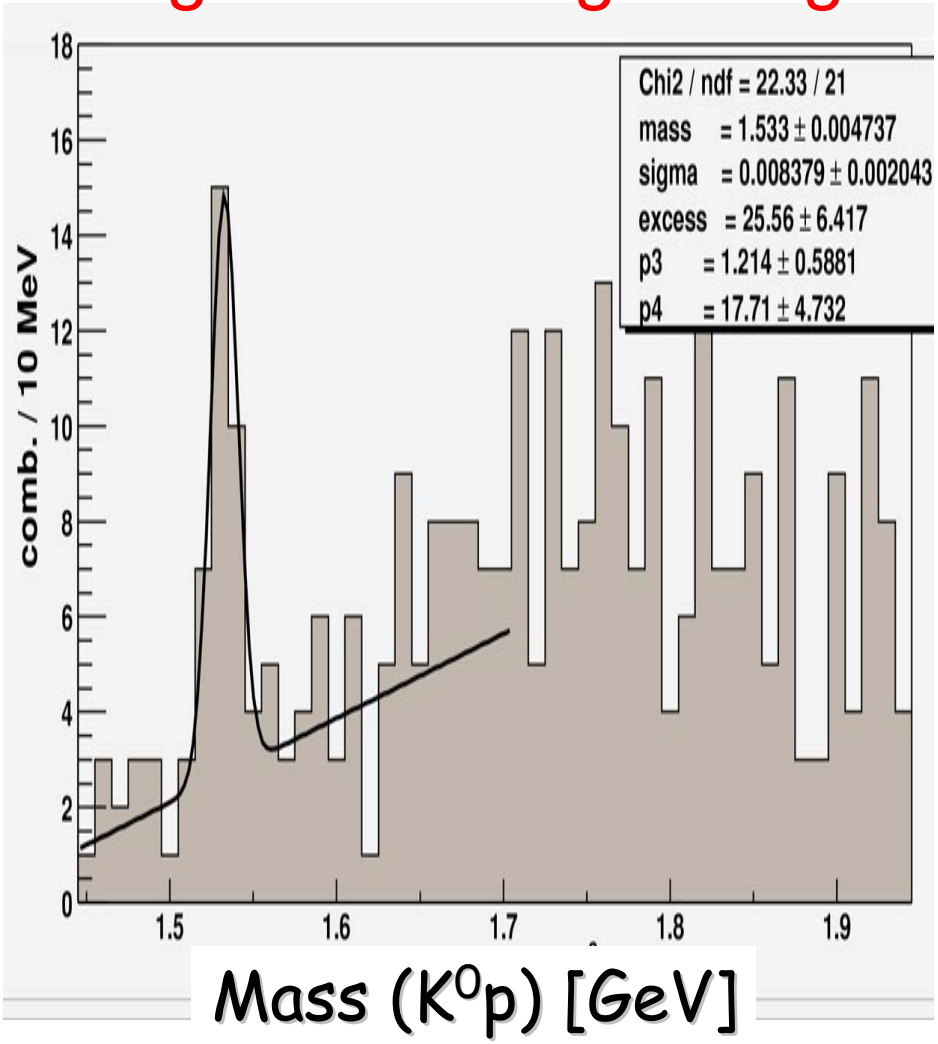
Reanalysis of bubble chamber neutrino data

ITEP group: hep-ex/0309042

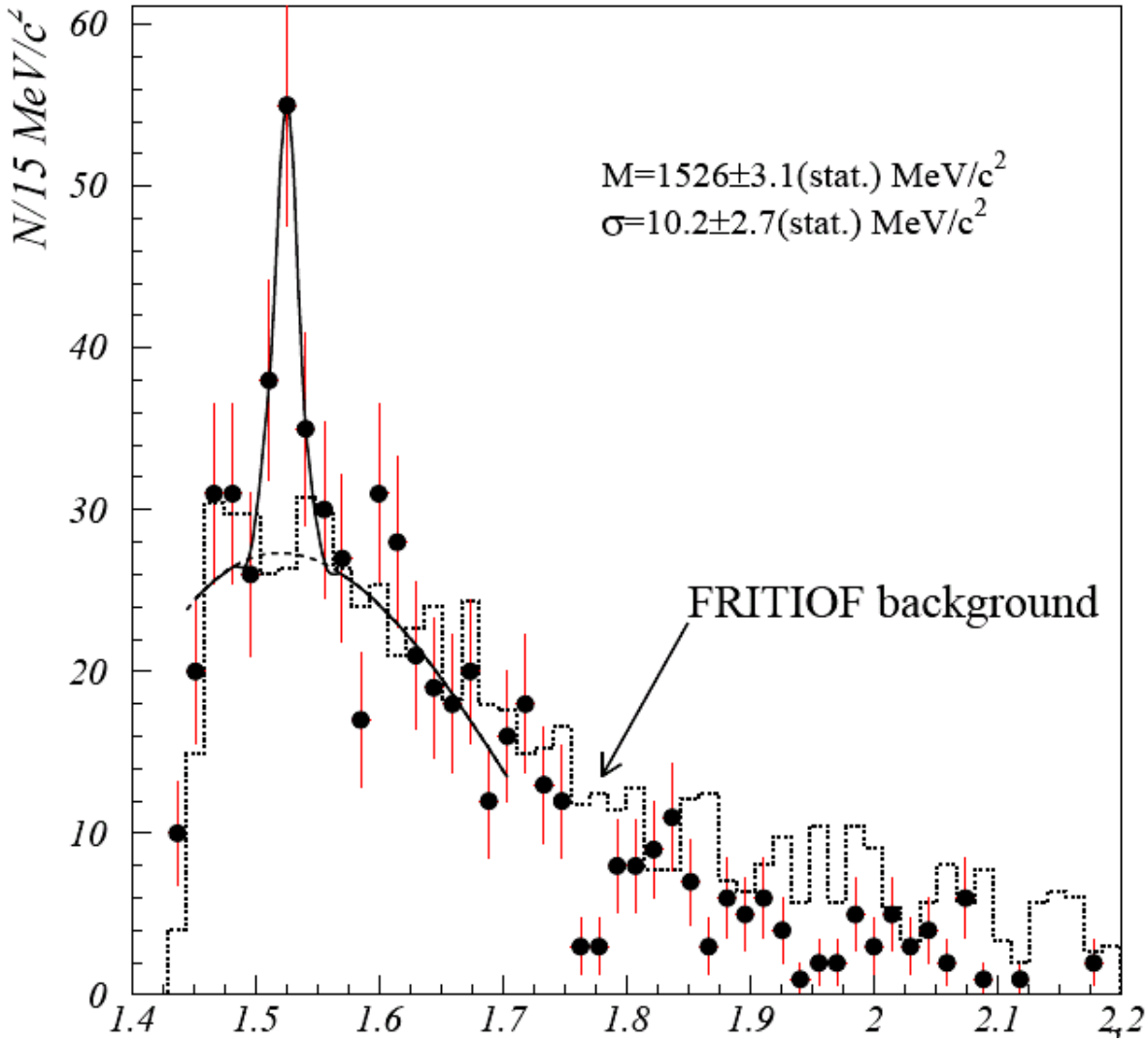
M = 1533±5 MeV, Γ < 20 MeV



Enlargement of signal region



SVD-2 Experiment at IHEP



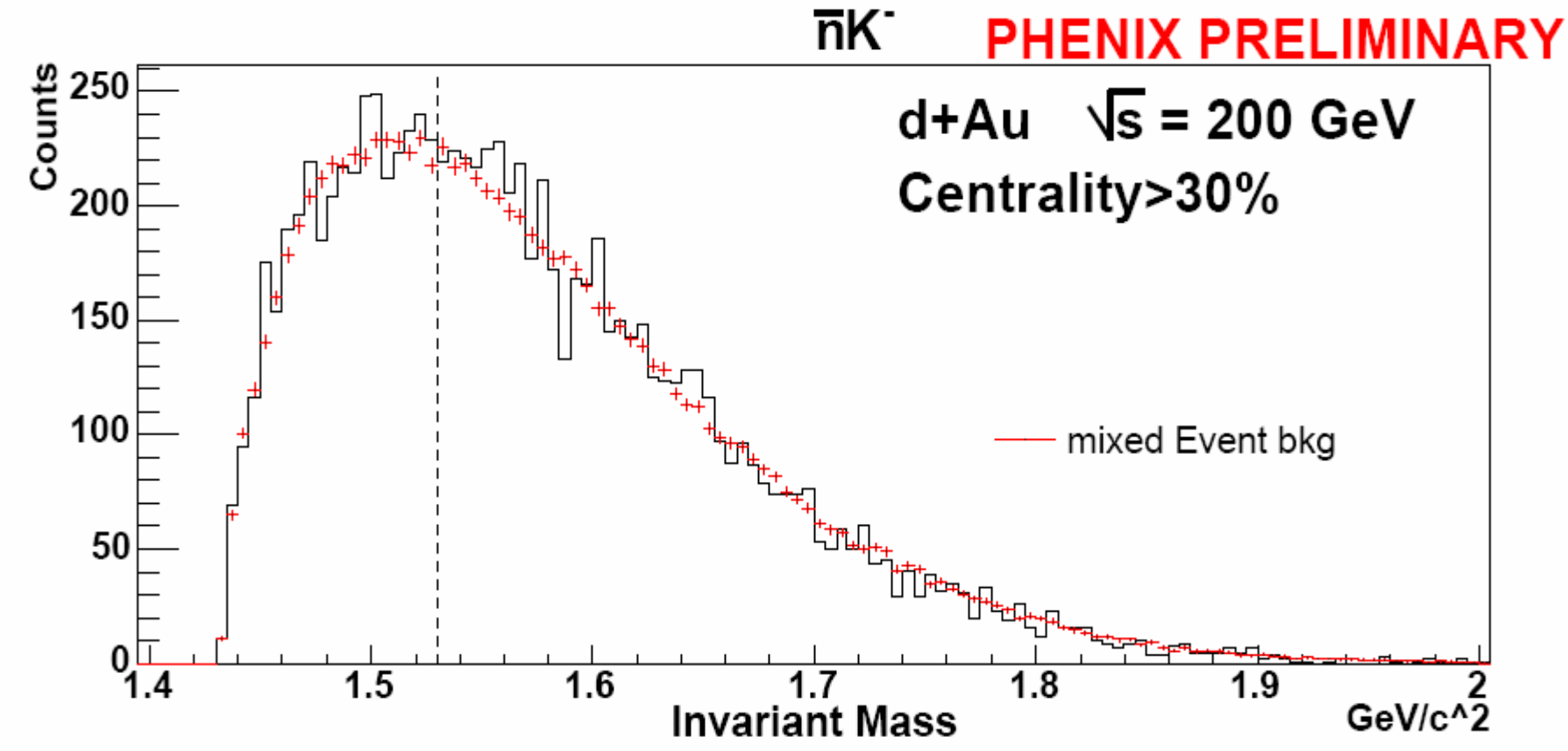
Mass (K^0p) [GeV]

$pA \rightarrow K^0p\ X$

M=1526±5 MeV
Γ< 24 MeV

Protons @70 GeV/c

Search for $\overline{\Theta}^- \rightarrow K^- \bar{n}$ with PHENIX

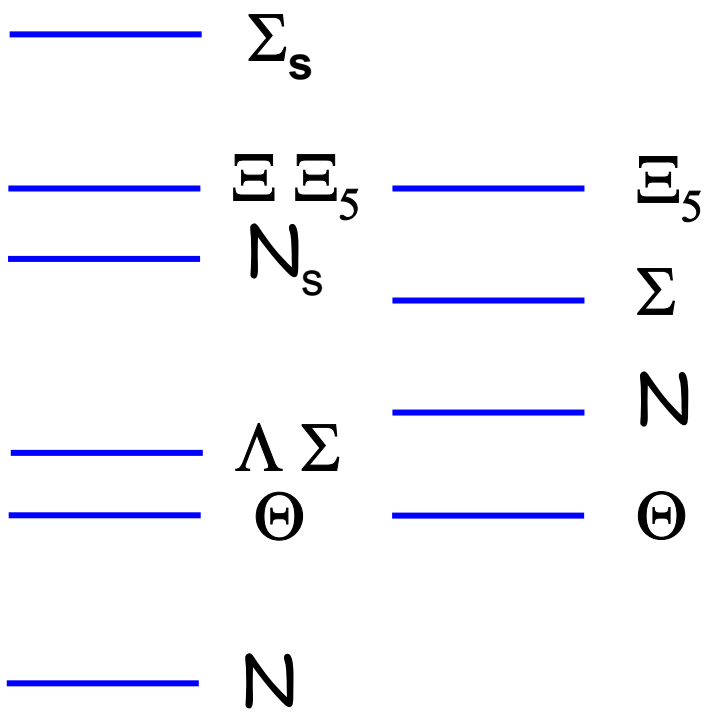


Null result at RHIC heavy ion collider

Model predictions

Diakonov et al. Hep-ph/9703373
Diakonov, Petrov hep-ph/0310212
Jaffee, Wilczek hep-ph/0307341
Jaffee, Wilczek hep-ph/0312369
R.A. Arndt et al. nucl-th/0312126 v3

Decay modes are sensitive to dynamical picture



Model	$\frac{BR(\Xi_5 \to K^- \Sigma^-)}{BR(\Xi_5 \to \pi^- \Xi^-)}$
Diquark	1/2
Soliton $G_{\overline{10}}$=+2.9	0.75
Soliton $G_{\overline{10}}$=−1.4	0.04

Isospin of Ξ^-	$\frac{BR(\Xi_5 \to \pi^0 \Xi^-)}{BR(\Xi_5 \to \pi^- \Xi^0)}$
Diquark $\Xi_{3/2}$	2
Diquark $\Xi_{1/2}$	1/2

$\Xi_{3/2} \not\to \Xi^*(1530)\ \pi$ $(SU(3)_f)$

Di-quark Soliton

2nd Cousin: Narrow anti-charm baryon state

M=3.099± 0.006 GeV $uudd\bar{c}$

H1 Collaboration, submitted to Phys. Lett. B (Mar 2004)