

Pentaquarks

Do they exist?

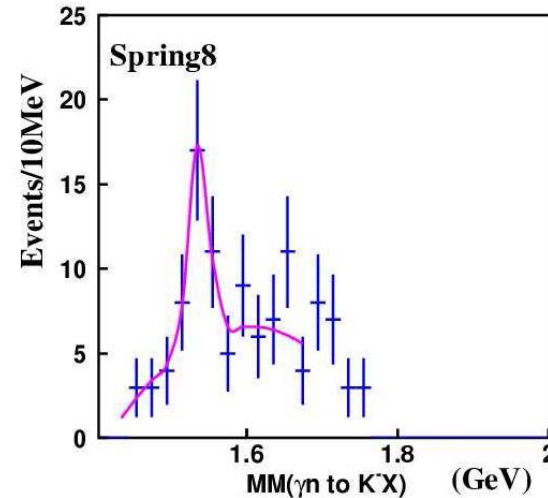
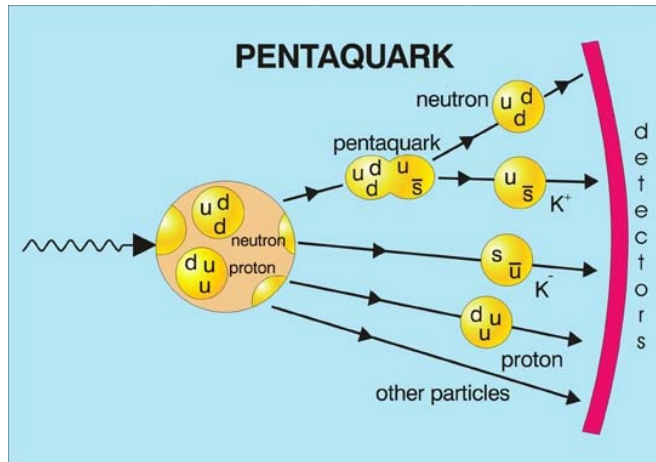
Wolfgang Lorenzon
(Avetik Airapetian, [Wouter Deconinck](#))

26 October 2005

Supported by NSF-0244842

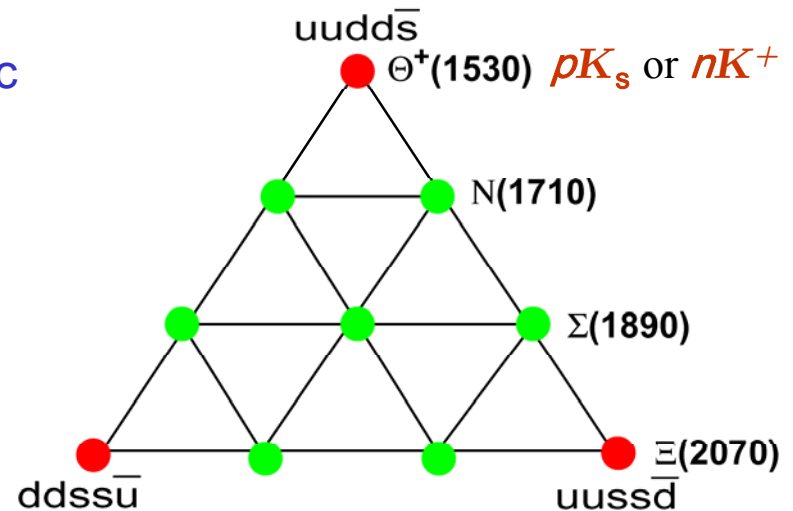


Life in Exciting Times



Before 2003 searches for flavor exotic baryons showed no evidence for such states

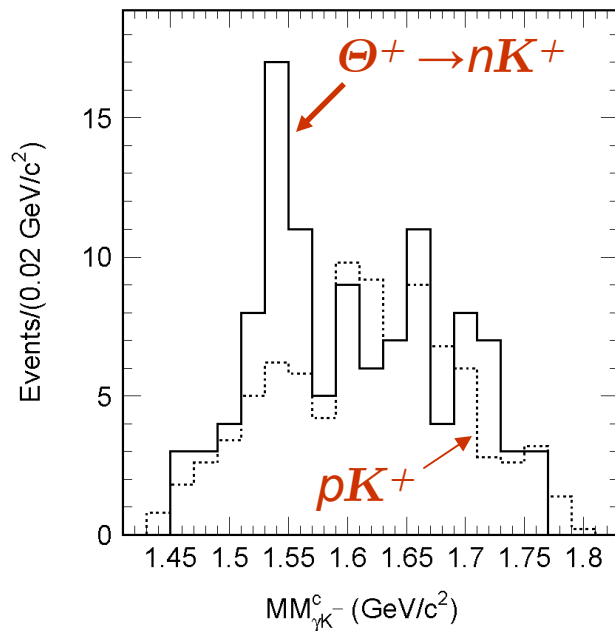
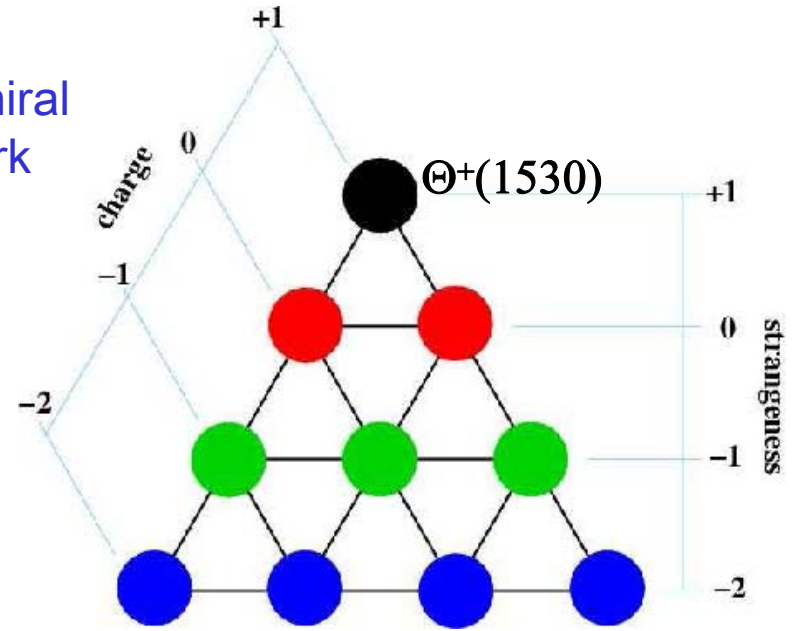
Since 2003 Hadronic Physics has been very interesting



Spectacular Development

1997: Diakonov, Petrov and Polaykov use a chiral soliton model to predict a decuplet of pentaquark baryons. The lightest has $S=+1$ and a mass of **1530 MeV** and is expected to be narrow.

Z. Phys. A359, 305 (1997).



2003: T. Nakano *et al.* $\gamma n \rightarrow nK^+K^-$
on a Carbon target.
PRL 91, 012002 (2003).

The Roller Coaster ride begins

Media Interest (2003)

NEW YORK TIMES INTERNATIONAL TUESDAY, JULY 1, 2003

A Subatomic Discovery Emerges From Experiments in Japan

By KENNETH CHANG

Slamming high-energy particles of light into carbon atoms, physicists have unexpectedly produced a new type of subatomic particle. Protons and neutrons, the building blocks of atoms, are made of smaller particles known as quarks, which come in six varieties. A proton, for example, consists of two up quarks — two so-called up quarks and one down quark. Physicists know of slews of particles containing two or three quarks. Now they believe they know of a particle containing five quarks, perhaps could have been common in the very early universe. (No

the experiments, Dr. Takashi Nakano, of the Research Center for Nuclear Physics at Osaka University would consist of two up quarks, two down quarks and one known as an anti-strange quark. It would prohibit five-quark states that one had seen any

USA TODAY · TUESDAY, JULY 1, 2003 · 7D

Physics team goes where no quark has gone before

By Dan Margosh

atoms with high-energy X-rays to

sity as people who do now believe that collagen protein that gives bone its strength plays an important part. That makes sense, because a bone is, the less like Dr Towler thinks it is in the amount of collagen changes in similar structures as keratin, from which made. Hence his objection, they are preliminary replication in a bigger firmation. But if they are could form the basis for ple test for osteoporosis were, nail the disease do

Quarks

Five alive!

An odd, new subatomic "pentaquark," has been discovered. It is made of five quarks, one of which is a charm quark. The discovery was announced in the July 1 issue of *Physical Review Letters*. The pentaquark, dubbed "theta-plus," was discovered in a collaboration at the Spring-8 synchrotron in Hyogo, Japan, which reported the latest issue of *Physical Review Letters*. The collaborators found the three-year-old data, after they were told what to look for by Dmitri Diakonov, a theoretician at the Petersburg Nuclear Physics Institute, in Russia.

After word of the Spring-8 results started spreading among physicists, theta-plus was also found in experimental data at the Jefferson Laboratory in Newport News, Virginia, and at the Institute for Theoretical and Experimental Physics in Moscow. These independent confirmations of the result, says Kenneth Hicks, member of both the Japanese and American teams, is proof that the theta-plus is a real particle and not an artifact of the data. All three experiments work in roughly the same way. Everyday particles like protons and neutrons are boosted to high speeds in a circular accelerator. This causes them to emit gamma rays, which are used to bombard atomic nuclei (carbon

Slamming high-energy particles of light into carbon atoms, physicists have unexpectedly produced a new type of subatomic particle. Protons and neutrons, the building blocks of atoms, are made of smaller particles known as quarks, which come in six varieties. A proton, for example, consists of two up quarks — two so-called up quarks and one down quark. Physicists know of slews of particles containing two or three quarks. Now they believe they know of a particle containing five quarks, perhaps could have been common in the very early universe. (No

The diagram illustrates the structure of a pentaquark. At the center is a core of five quarks: two up quarks (green), two down quarks (blue), and one anti-strange quark (red). This core is surrounded by a theta particle (θ+). The diagram shows the decay of a pentaquark into various particles: a neutron (n), a K meson (K), and another neutron (n). Labels in Japanese include '高エネルギーの光' (High energy light), '中性子 n' (Neutron), '陽子 p' (Proton), 'シータ粒子 θ+' (Theta particle), 'K中間子' (K meson), and '中性子' (Neutron).

Scientists fleeing for of basic m

JOHN MANGELS
Plain Dealer Science Writer

Teams of scientists in Japan and the United States have confirmed the existence of an unknown kind of matter, a strange subatomic particle that has been elusive for 30 years.

One of the scientists likened the discovery to finding a new animal that doesn't fit into any of the existing classifications of mammals or reptiles. He says it's too soon to know what it is, but he speculates that the discovery will lead to a basic understanding of how matter is formed and how the particles that compose all matter interact.

The newly identified particle, dubbed a "pentaquark" because of its five ingredients, likely existed in the fractions of a second after the Big Bang, as the universe began to organize from the fiery chaos of free-floating elementary particles into the familiar components of atoms.

Pentaquarks also probably flicker in and out of being today, the short-lived product of billiard-ball-like collisions between cosmic rays and atoms in deep space or Earth's upper atmosphere.

His Japanese colleague had a similar reaction. "It must be a new category of particle, I thought it was some mistake," said Ohio University physics Professor Ken Hicks, who was a collaborator in the Japanese experiments and headed similar work at the U.S. Department of Energy's Thomas Jefferson National Accelerator Facility in Virginia.

Quarks are the building blocks of all matter. They briefly exist first nanoseconds after the Big Bang, but they traveled in through physics dictating as to whether a grouping of five quarks was possible, until now only combinations of two or three had been found.

Accelerator Facility (JLab) in Newport News, Virginia, sends light into deuterium or hydrogen targets. The third at the Institute of Theoretical and Experimental Physics (ITEP) in Moscow, smashes mesons into xenon nuclei. In each case, researchers hope pentaquarks made atoms.

finally figure out what their models were getting wrong and fill in the missing details. And although it might disappoint those who like the nice, neat three-quark rule, physicists are pleased that quarks are finally showing their quirky side.

www.sciencemag.org SCIENCE VOL 301 11 JULY 2003

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quark states found at CERN

Only a few months after the first burst of excitement over the appearance at several laboratories of what seems to be a new five-quark particle, evidence has been found for a different five-quark state that appears to be closely related.

The constituent quark model of hadrons that was invented in the 1960s has been very successful in describing the known baryons as composite of three valence quarks. Quantum chromodynamics (QCD), the theory of strong interactions, does not contain more than three quarks. In fact, such states had a long time ago but no good candidates were found until recently. The search was revived by the theorists Victor Petrov and Maxim Poljaskov. They predicted that the lightest pentaquark (4q, qbar) baryon multiplet, as seen in figure 1, were rather small and that the width of its resonance was expected to be very narrow (Diakonov et al. 1997). The search for this state, named Θ+, has opened up a new chapter in QCD that will help to elucidate QCD in the non-perturbative regime (CERN Courier September 2003 p5). The Θ+ is a baryon, that is, it cannot be composed of three quarks. It is a resonance of the other two corner members of the pentaquark multiplet, as shown in figure 1. The latter have a strangeness of S = -2, -1, and form members of an isospin quartet of Σ baryons.

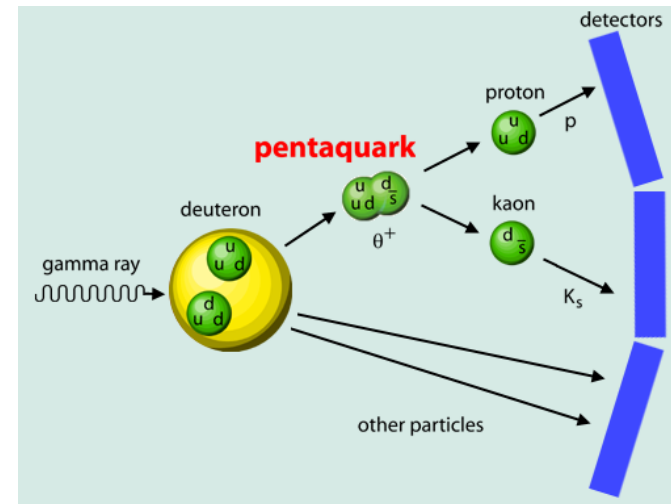
Experiment NA49 at the CERN Super Proton Synchrotron has searched for the Θ+ and the Σ baryons in proton-proton collisions at a beam energy of 159 GeV (Ait et al. 2003). Tracks of particles produced in the reactions are recorded by the detector's four large time-projection chambers. Their high resolution allows for a precise reconstruction of the particle trajectories and momenta as well as the measurement of the energy loss in the chamber gas. The reconstruction of secondary vertices makes possible the observation of the complex decay chains of the pentaquark states. After suppression of the overwhelming background by suitable selection cuts, the summed Σ mass distribution shows a narrow peak at 5.6 standard deviations at a mass of 1.862 ± 0.002 GeV/c² (see figure 2). The true width of the peak must be smaller than the observed full width at a half maximum of 0.017 GeV/c², which is consistent with the resolution of the detector.

In fact, peaks are seen at the same mass in the individual Σ+ and Σ0 mass distributions, as well as in those of the antiparticles. No signal has been found yet for the Θ+, for which the background in the potentially

➤ The reason? In part, because the idea is simple to explain.

What is a Pentaquark

- 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 ($qqqq\bar{Q}$)
- Quantum numbers cannot be defined by 3 quarks alone.



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

$$\text{Baryon number} = 1/3 + 1/3 + 1/3 + 1/3 - 1/3 = 1$$

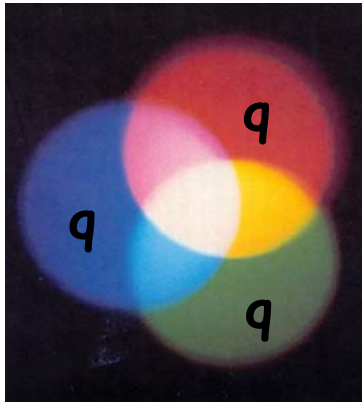
$$\text{Strangeness} = 0 + 0 + 0 - 1 + 1 = 0$$

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

$$\text{Baryon number} = 1/3 + 1/3 + 1/3 + 1/3 - 1/3 = 1$$

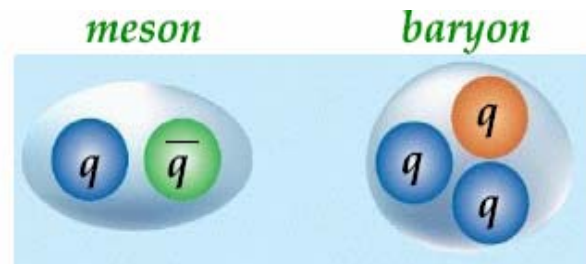
$$\text{Strangeness} = 0 + 0 + 0 + 0 + 1 = +1$$

Quarks are confined inside Colorless Hadrons



Mystery remains:

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



Particle Data Group **1986** reviewing evidence for *exotic baryons states*

“...The general prejudice against baryons not made of three quarks and the lack of any experimental activity in this area make it likely that it will be another 15 years before the issue is decided.”

PDG dropped the discussion on pentaquark searches after **1988**

Why is it important to search for Pentaquarks?

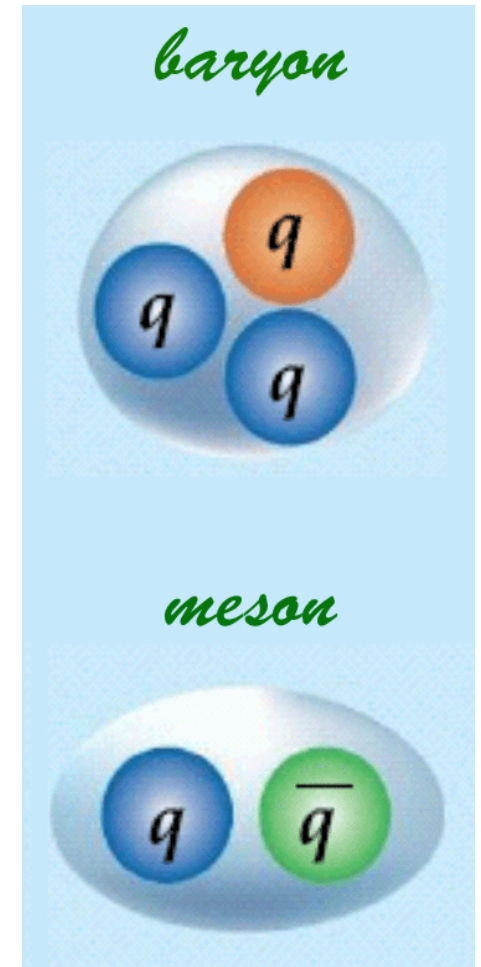
- QCD does not prohibit $q^4\bar{q}$ states
 - The width is expected to be large due to “fall-apart”:
 - $M(\Theta^+) - M(p + K_s) \approx 100$ MeV above threshold: expect $\Gamma > 175$ MeV unless suppressed by phase space, symmetry or special dynamics
 - Are pentaquarks too broad so be seen in experiments?
- If it does exist (with a narrow width) naïve quark models cannot explain it; but correlated quark models can
 - Is the “fall-apart” model too simplistic?
- If it does not exist then do we understand why non-perturbative solutions of QCD do not allow it?
 - Can lattice calculations tell us why?
 - it should have far-reaching consequences for understanding the structure of matter

Pentaquark in naïve Quark Model

	u	d	s
Current mass	4 MeV	7 MeV	150 MeV
Constituent mass	350 MeV	350 MeV	470 MeV

The spontaneous breakdown of the chiral symmetry would produce nonzero constituent mass and the massless pseudoscalar Goldstone bosons

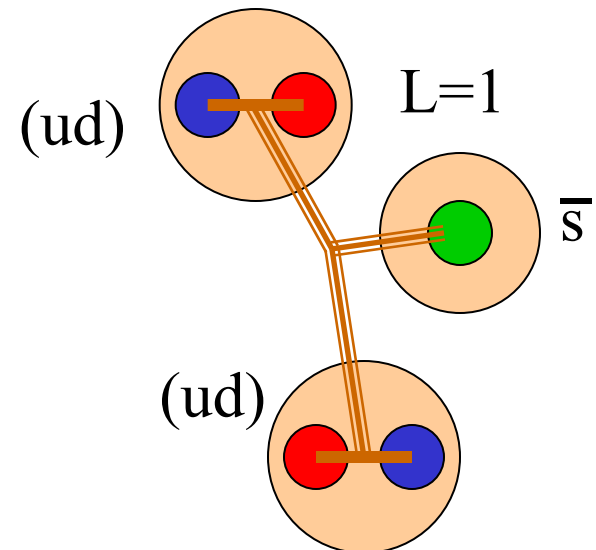
- Pentaquark mass = $4 \times 350 + 470 = 1870$ MeV
- In addition there is some penalty for p-wave (in case of positive parity)
- So the pentaquark mass must be about **2 GeV** in any constituent quark model
- The predicted width is wide (>175 MeV) due to the allowed decay to the baryon and meson with mass well above the threshold
- The ground state has **negative** parity.



“Correlated” Quark Model

Jaffe, Wilczek
PRL 91, 232003 (2003)

- The four quarks are bound into two **spin zero**, color and flavor 3 diquarks
- For identical diquarks, like $[ud]^2$, the lightest state has negative space parity. So the $q^4\bar{q}$ state has **positive** parity
- The narrow width is described by relatively weak coupling to the nK^+ continuum from which it differs in color, spin and spatial wave functions.



L=1, one unit of orbital angular momentum needed to get $J^P=1/2^+$ as in χ_{SM}

Decay Width:

$$\langle [ud][ud]\bar{s} \mid [uud][u\bar{s}] \rangle = \frac{1}{2\sqrt{6}} \Gamma \approx \frac{200 \text{ MeV}}{(2\sqrt{6})^2} \approx 8 \text{ MeV}$$

Chiral Soliton Model

D.Diakonov *et al*, Z. Phys. A359, 305 (1997).

- Pentaquarks: rotational excitations of the soliton [rigid core surrounded by chiral (meson) fields]
- Extra $q\bar{q}$ pair in pentaquark is added in the form of a pseudo scalar Goldstone meson, which costs nearly zero energy
- In reality, to make the Θ^+ from the nucleon, one has to create a quasi-Goldstone K-meson and confine it inside the baryon of the size $>1/M$. It costs ~ 600 MeV
- So the Θ^+ mass is near **1530 MeV**.
- $\Gamma = 15$ MeV
- Masses are counterintuitive:

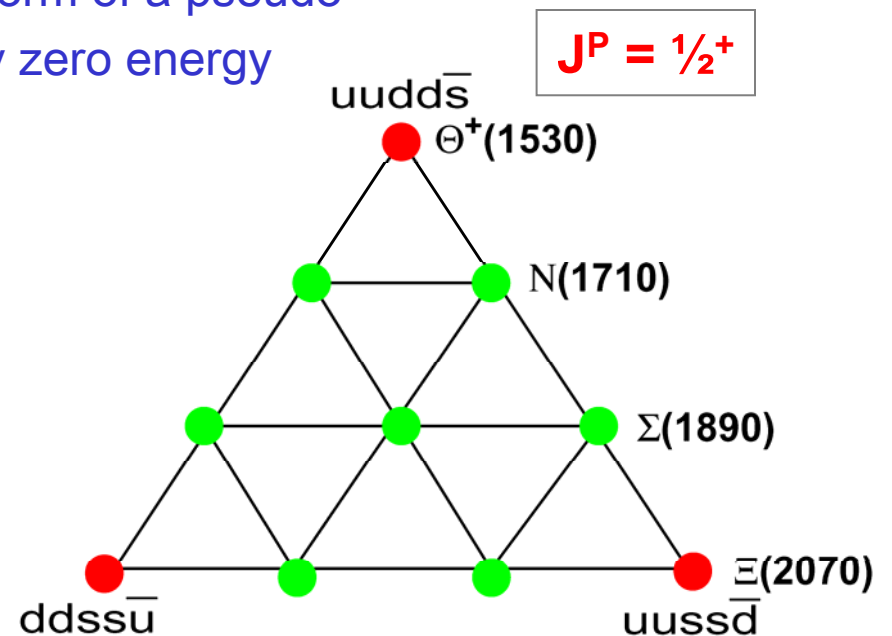
- $m(\Theta^+) < m(N)$ w/ nucleon q.n.

- naïve QPM: expect strange baryons are heavier than non-strange in given multiplet

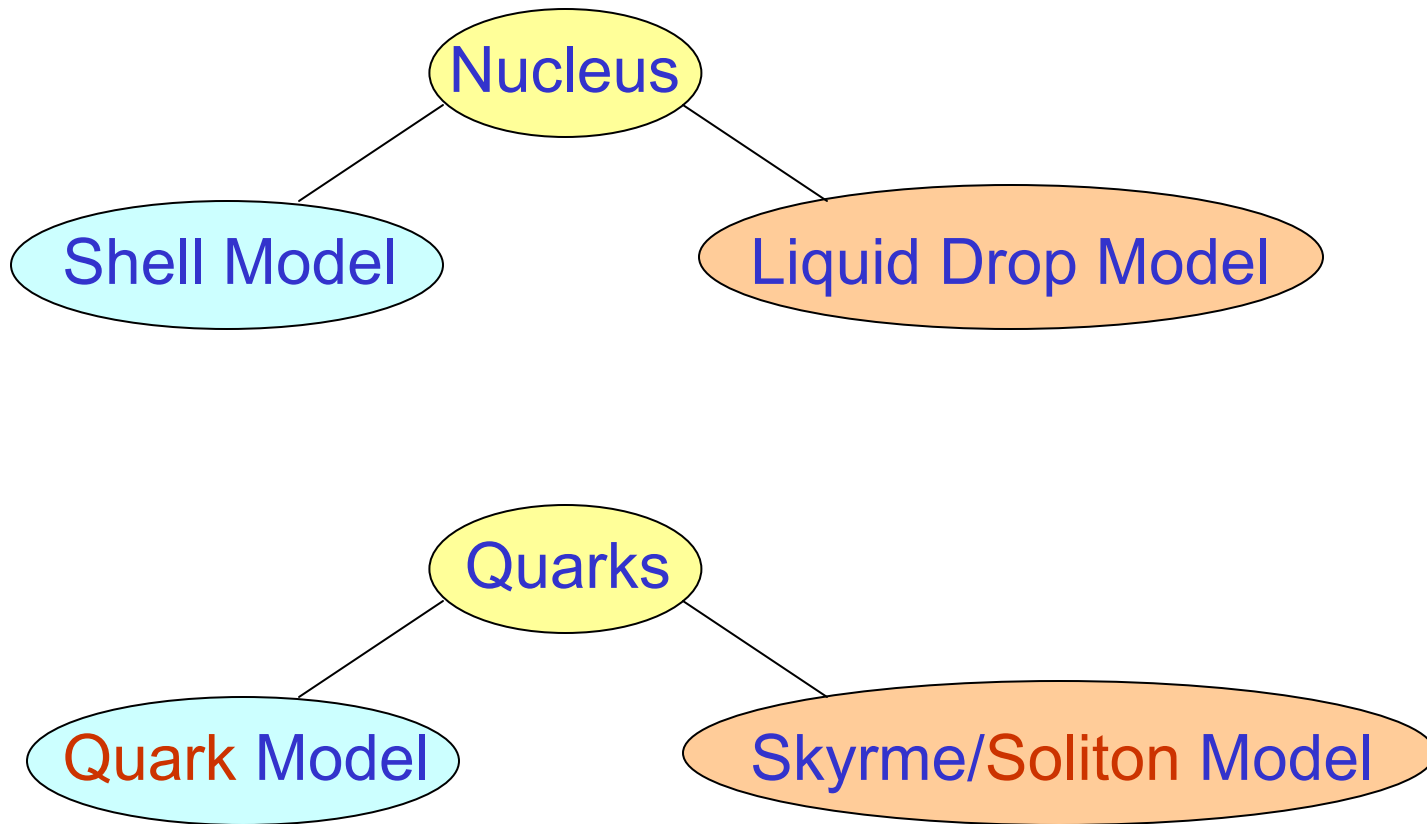
- $m(\Theta^+) = m(\Xi) - 540$ MeV [Θ^+ has 4 light + 1 s quark

- Ξ^{--} has 3 light + 2 s quarks]

- naïve QPM: expect $\Delta m = 150$ MeV



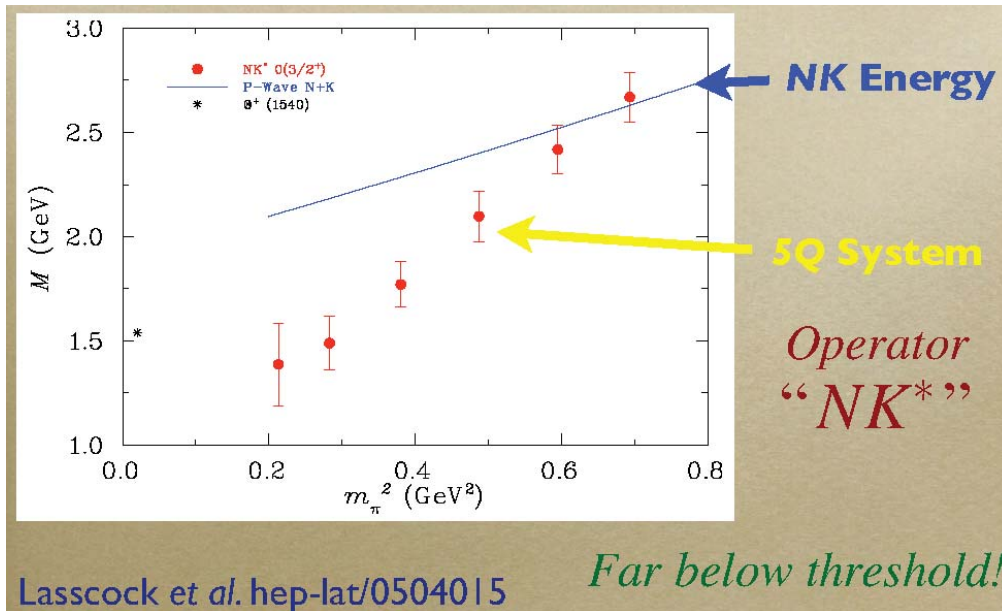
Models: An Analogy



Describe various, not mutually exclusive aspects of nucleus/quarks

Pentaquarks on the Lattice

- It is only known method to derive hadronic properties from first principles
- Several lattice studies performed to see if Θ^+ can be predicted from QCD
- Some studies did not find a pentaquark resonance, only scattering states of weakly-interacting kaons and nucleons → **not mature yet** (2 more years?)
- Main problem: disentangling KN scattering states from genuine resonances
- Very time consuming: V-dependence, light quarks, small lattice spacing ...



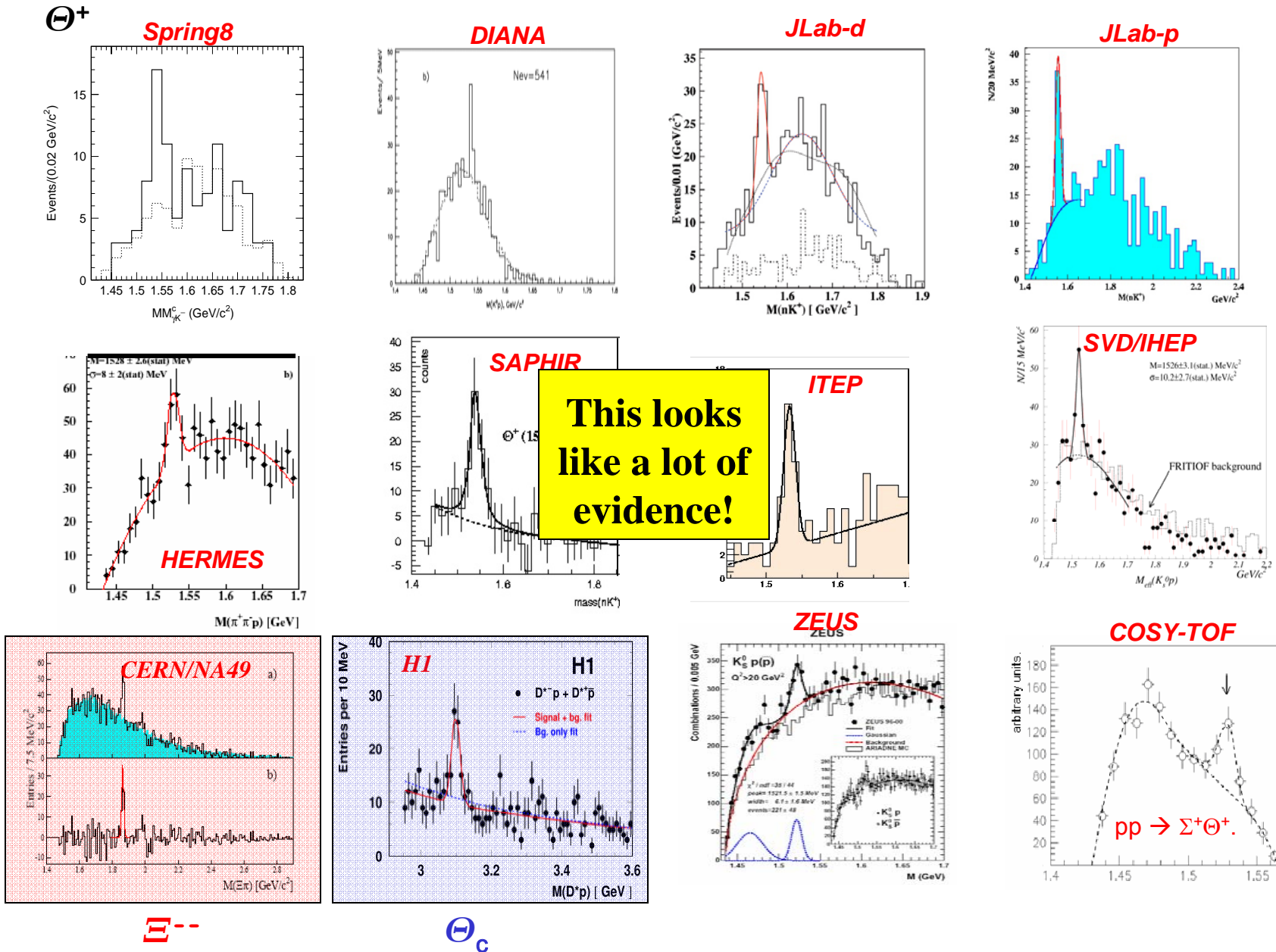
Possible signal for $J^P=3/2^+$?

(in χ SM $J^P=1/2^+$)

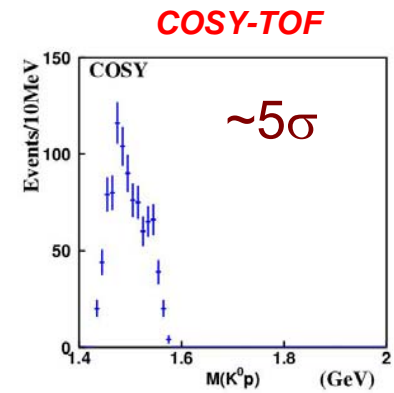
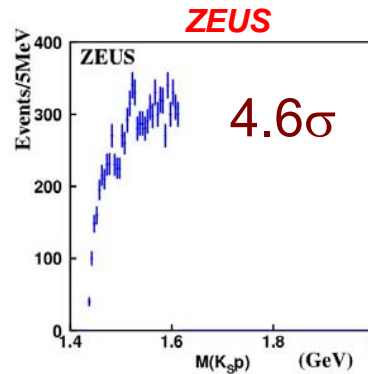
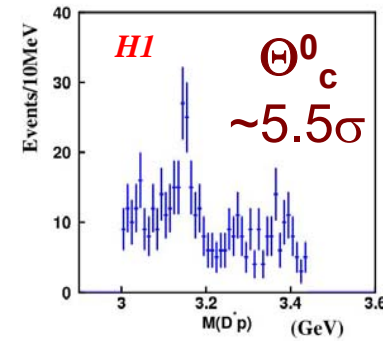
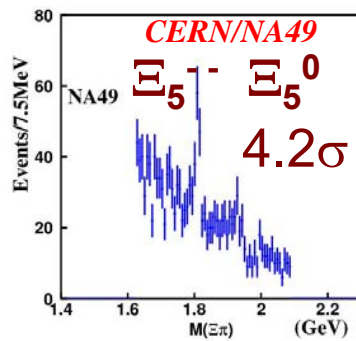
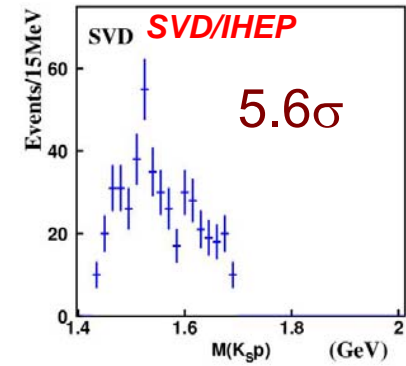
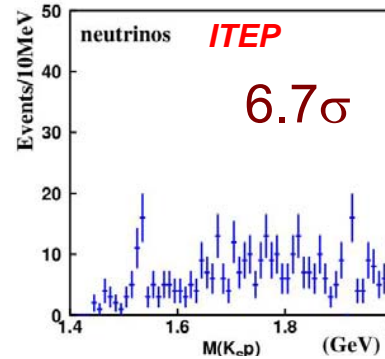
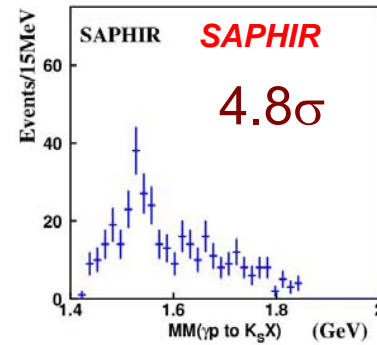
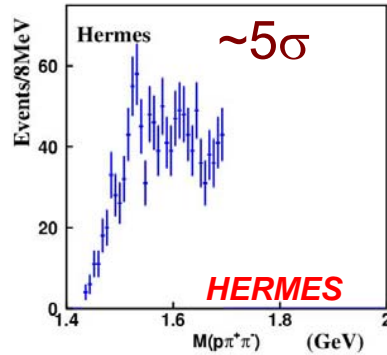
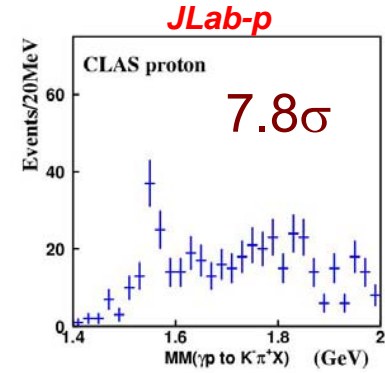
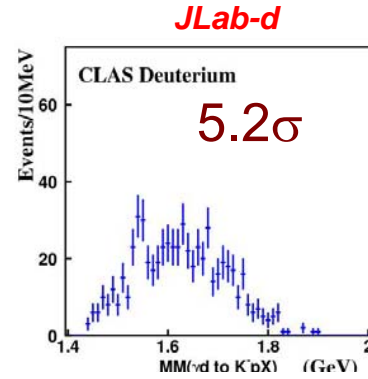
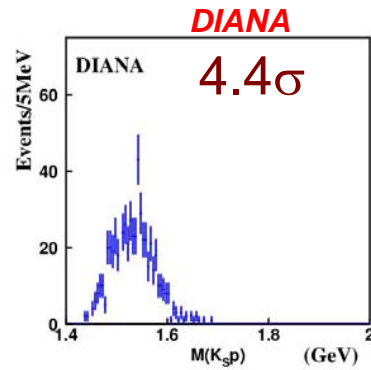
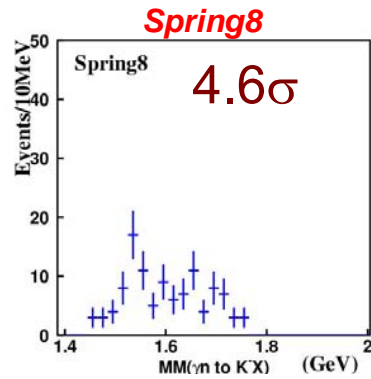
Binding Mechanism:
~ 500 MeV

Note: N. Ishii et al. get different results!?

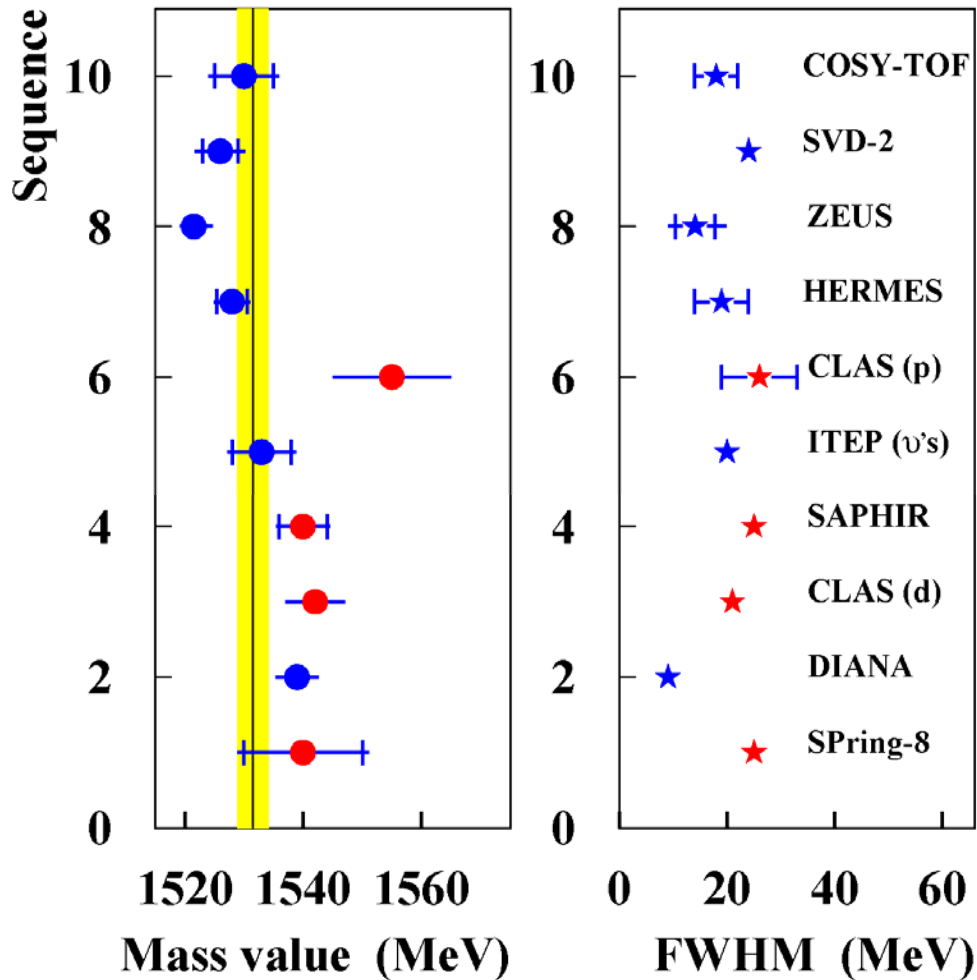
The initial Evidence for Pentaquarks



The Data Undressed



The Θ^+ Mass



Decay channel:



World Average:

1532.5 ± 2.4 MeV

- $m(pK_s^0) < m(nK^+)$
- Could be due to different background shapes and interference effects
- Or it may indicate a serious concern about the existence of the Θ^+ baryon
- Observation of peak in two decay channels in same experiment
→ would be convincing!

What about the Θ^+ Width?

- Measured width dominated by experimental resolution
- More precise information is obtained in analyses with theoretical constraints:

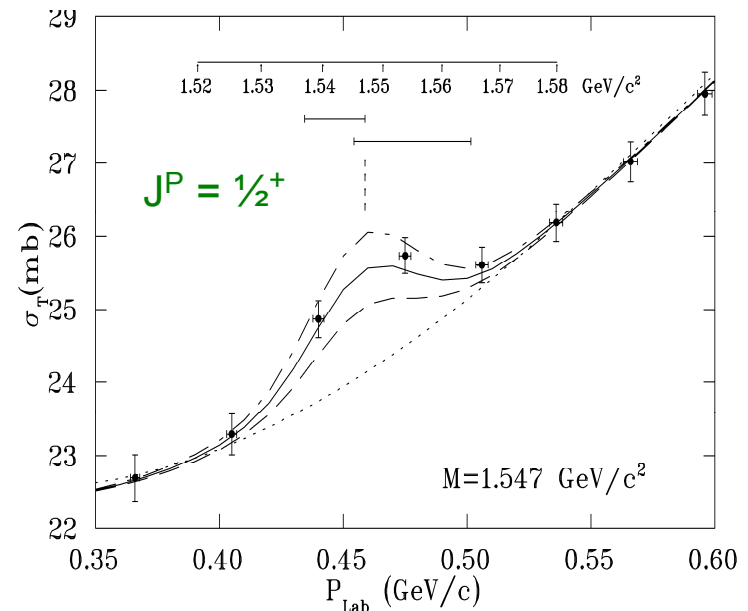
DIANA, Phys. Atom. Nucl. 66,1715 (2003)
 HERMES, PLB585, 213 (2004)
 S. Nussinov et al., hep-ph/0307357
 R. Arndt et al., PRC68, 42201 (2003)
 R. Cahn and G. Trilling, PRD69, 11401 (2004)
 A. Sibirtsev, et al., hep-ph/0405099 (2004)
 W. Gibbs, nucl-th/0405024 (2004)

$\Gamma_{\Theta} < 9 \text{ MeV}$
 $\Gamma_{\Theta} = 17 \pm 9 \pm 3 \text{ MeV}$
 $\Gamma_{\Theta} < 6 \text{ MeV}$ (non-observation)
 $\Gamma_{\Theta} < 1 \text{ MeV}$ (non-observation)
 $\Gamma_{\Theta} = 0.9 \pm 0.3 \text{ MeV}$ (from DIANA results)
 $\Gamma_{\Theta} < 1 \text{ MeV}$ ($K^+d \rightarrow K_s pp$)
 $\Gamma_{\Theta} = 0.9 \pm 0.3 \text{ MeV}$ ($K^+d \rightarrow X$)

$K^+d \rightarrow X$

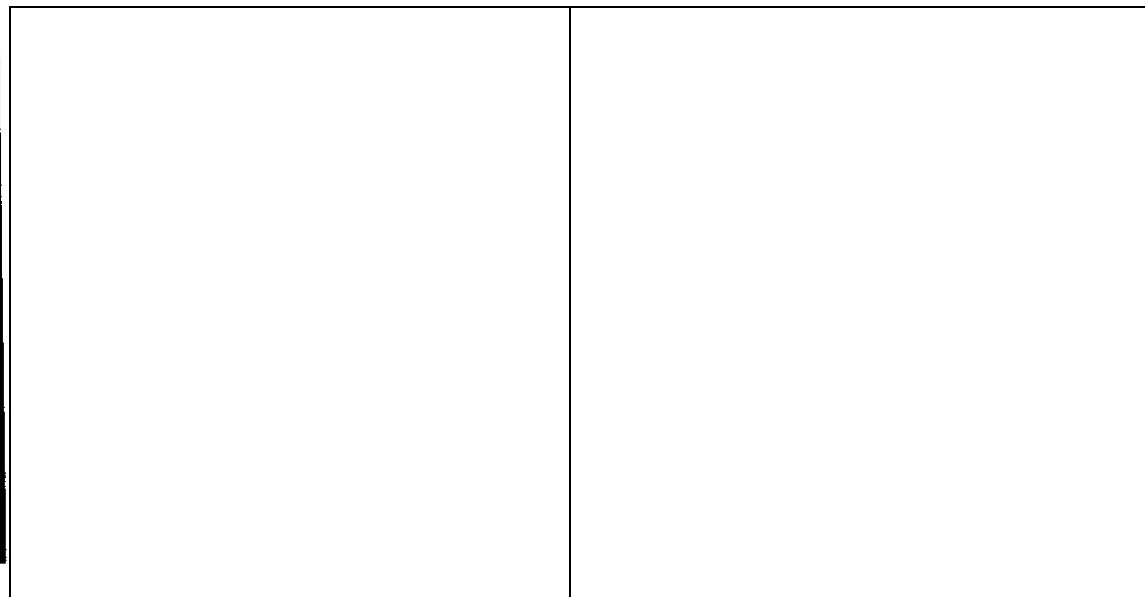
$$\Gamma_{\Theta} = 0.9 \pm 0.3 \text{ MeV}$$

- very narrow for a hadronically decaying particle with mass $\sim 100 \text{ MeV}$ above threshold!



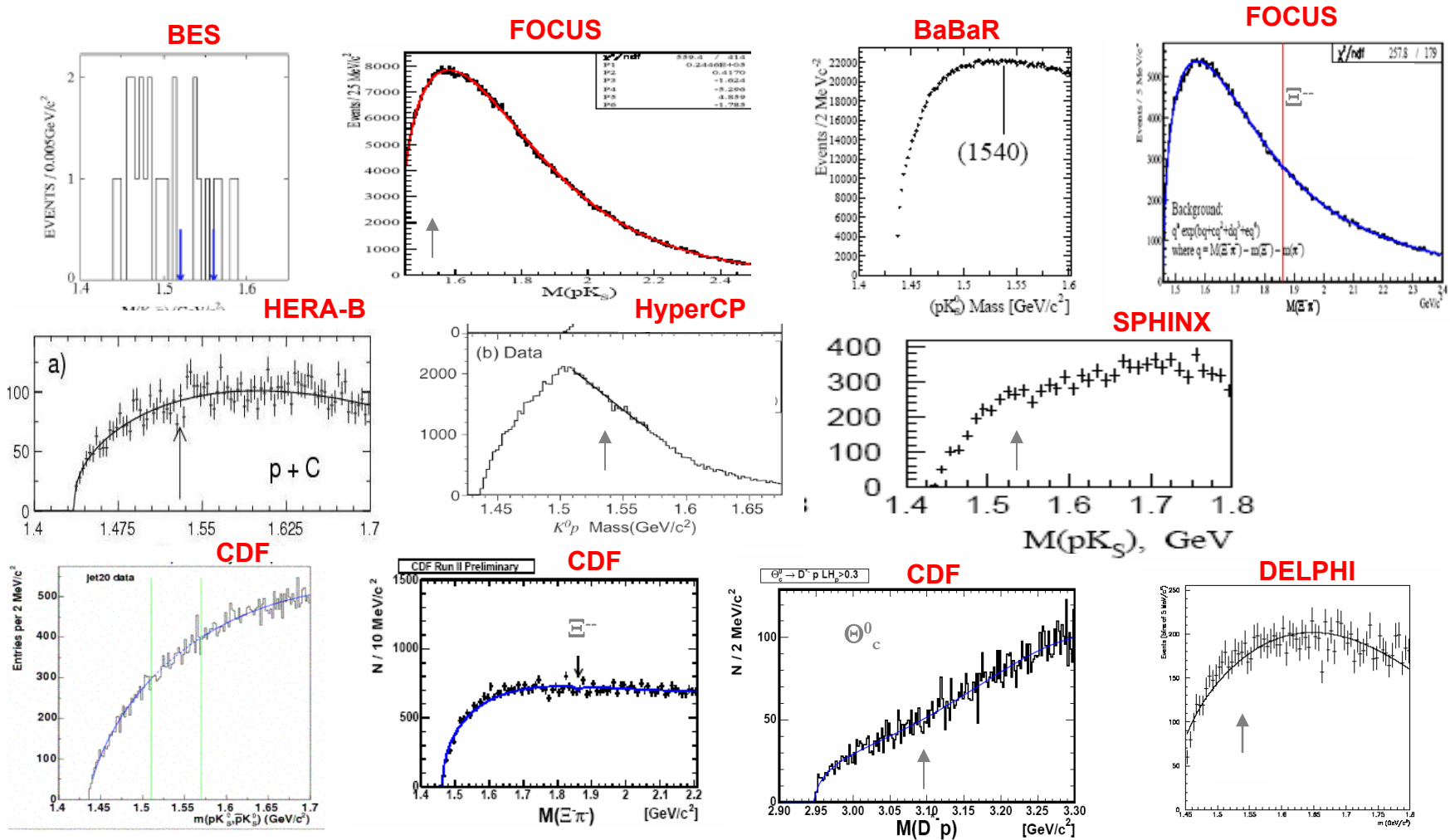
OK, we've seen a Peak...

DILBERT



So how do we decide if it is a resonance?

Non-evidence for Pentaquarks



Published Null Experiments

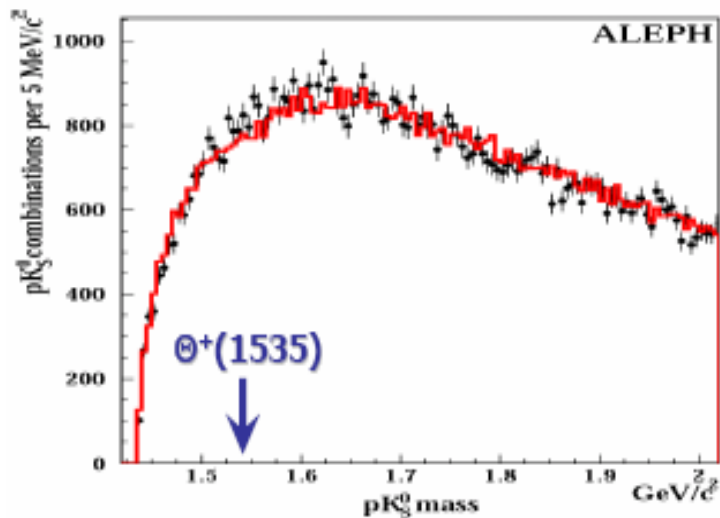
Experiment	Reaction	Limit
BES	$e^+e^- \rightarrow J/\Psi \rightarrow \Theta^+\Theta^-$	BR $< 1.1 \times 10^{-5}$
Belle e^+e^-	$\Psi(2S) \rightarrow pK^0$ $K^+Si \rightarrow pK_s^0X$	BR $< 0.6 \times 10^{-5}$ $\Theta/\Lambda^* < 0.02$
BaBar	$e^+e^- \rightarrow Y(4S) \rightarrow pK_s^0$	BR $< 1.1 \times 10^{-4}$
ALEPH	$e^+e^- \rightarrow Z \rightarrow pK_s^0$	BR $< 0.6 \times 10^{-5}$
HERA-B	$pA \rightarrow pK_s^0X$	$\Theta/\Lambda^* < 0.02$
CDF	$pp^* \rightarrow pK_s^0X$	$\Theta/\Lambda^* < 0.03$
HyperCP	$pCu \rightarrow pK_s^0X$	$\Theta/K^0p < 0.3\%$
PHENIX	$AuAu \rightarrow n^*K^-$	not given
SPHINX	$pA \rightarrow pK_s^0X$	$\Theta/\Lambda^* < 0.02$

+ unpublished results

Null Results $\Theta^+(1540)$

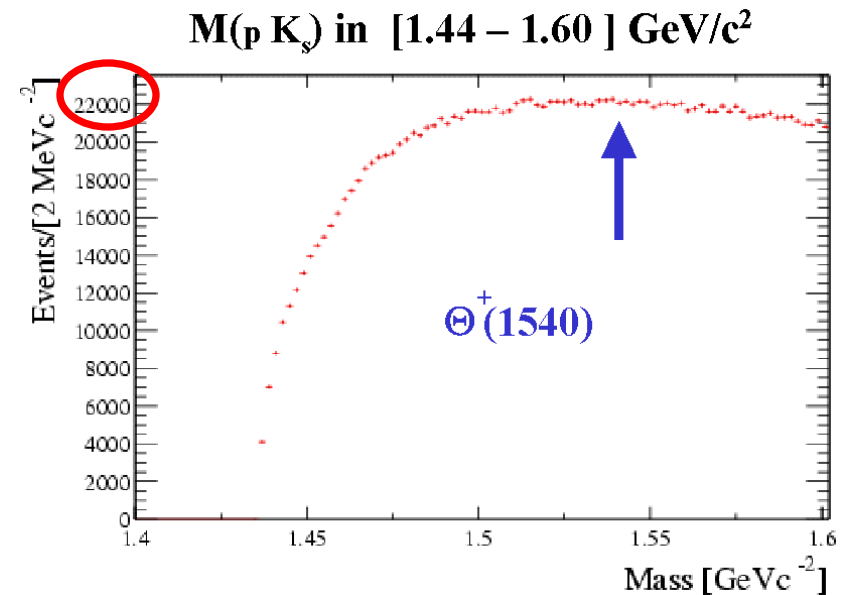
ALEPH:

- e^+/e^- collider (LEP 1)
- Pentaquark search in hadronic Z decays
- 3.5 million hadronic Z decays
- $\sigma_{\text{mass}} < 5 \text{ MeV}/c^2$



BaBar:

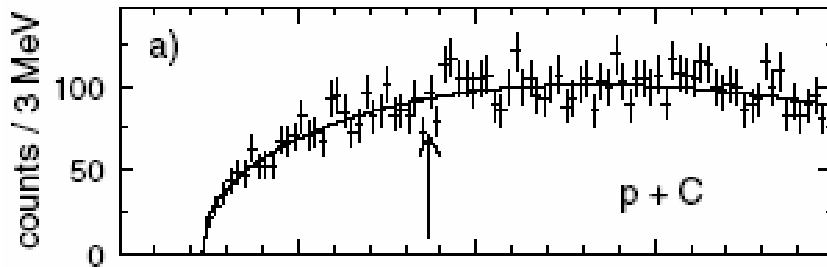
- e^+/e^- collider at SLAC ($\sqrt{s} = 10.58 \text{ GeV}$)
- Pentaquark search at or just below $Y(4S)$
- Integrated luminosity of 123 fb^{-1}
- σ_{mass} in the range of $[2,8] \text{ MeV}/c^2$



Null Results $\Theta^+(1540)$

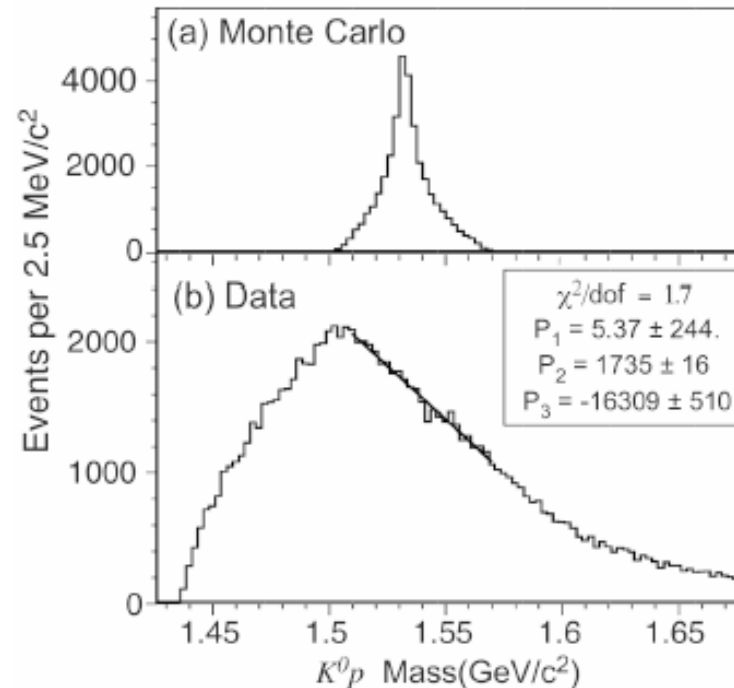
HERA-B:

- Proton beam at 920 GeV/c ($\sqrt{s} = 41.6$ GeV)
- Different targets (C, Ti, W)
- Rapidity: $-0.7 < y < 0.7$
- $\sigma_{\text{mass}} = 3.9 \text{ MeV}/c^2$ @ 1540 MeV/c²



HyperCP: (M. Longo)

- Mixed beams (p, π, K , hyperons)
- Broad momentum spread ($\sim 120 - 250$ GeV/c)
- Tungsten and thin kapton window target
- "Largest K_s sample ever recorded."
- $\sigma_{\text{mass}} < 2 \text{ MeV}/c^2$ @ 1530 MeV/c²



Typical Criticism

- It is a kinematic reflection
- It is not statistically significant (“statistical fluctuations”)
- It is due to “ghost tracks”
- It is fake in exclusive reactions
- In inclusive reactions it is not a Θ^+ but a Σ^{*+}
- It is not seen in high statistics experiments
 - it must be wrong!

Kinematic Reflections

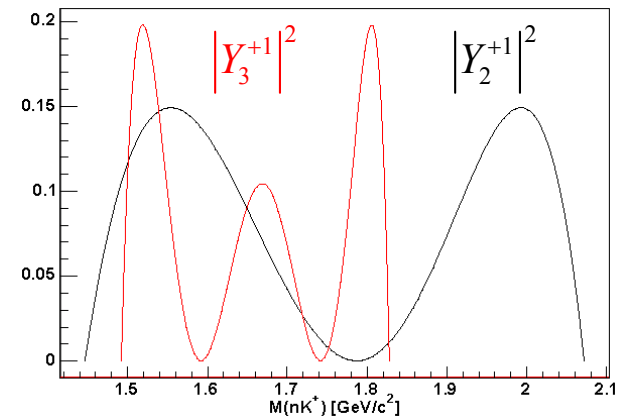
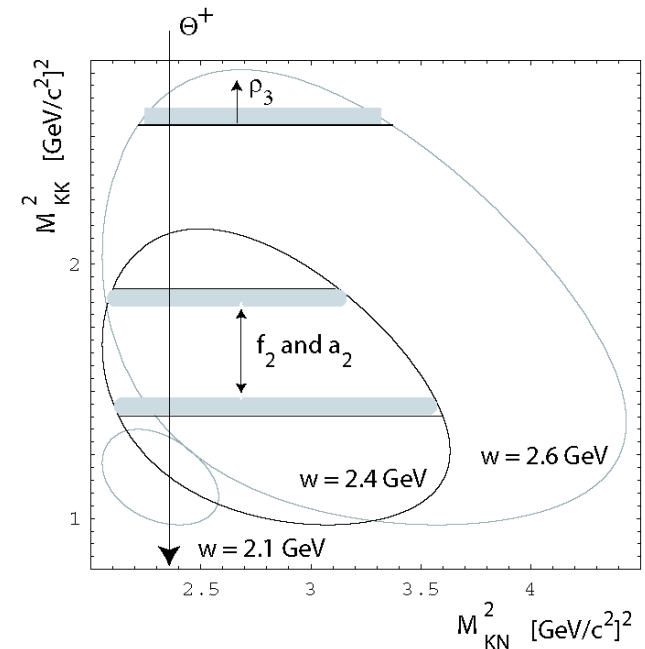
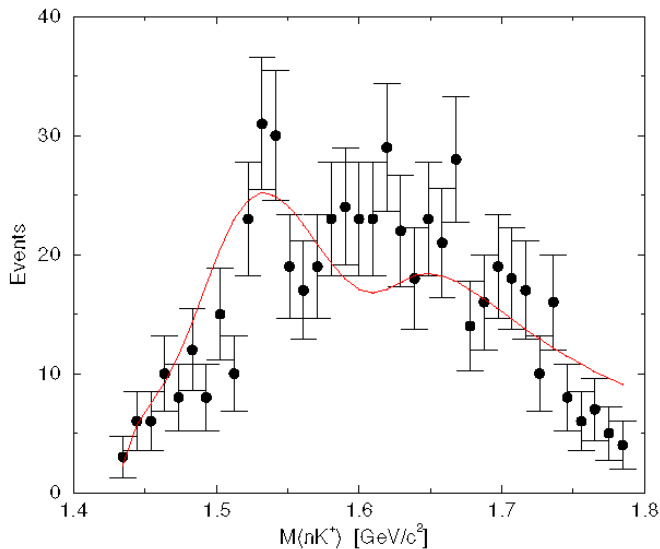
A. Dzierba *et al*, PRD 69, 051901(R) (2004).

➤ Low energy experiments:

- Produce a spin-2 or spin-3 resonance that decays into K^+K^-
- Have non-uniform populations of $|m|=0, 1, 2, \dots$

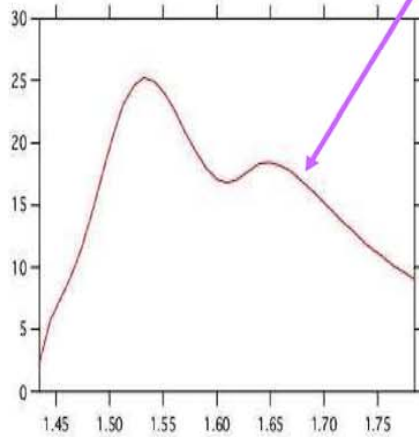
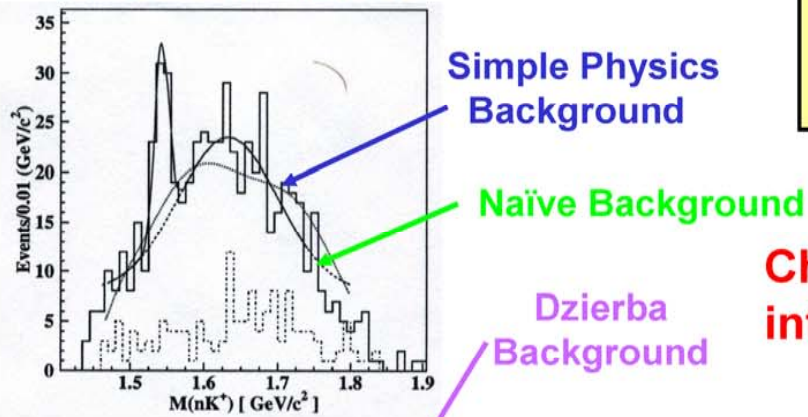
Produces a broad enhancement near 1.5 GeV

The CLAS $\gamma d \rightarrow pK^+K^-(n)$ data



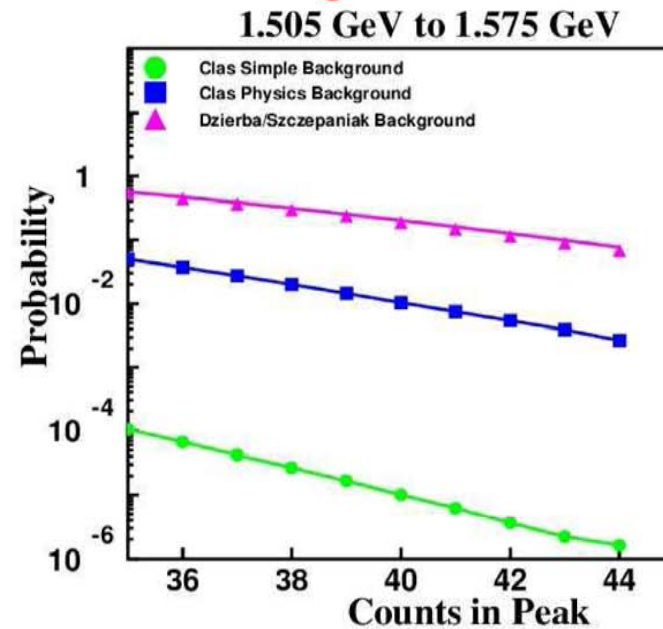
Statistical Fluctuations

CLAS Published



You need to understand your background to claim a new discovery!

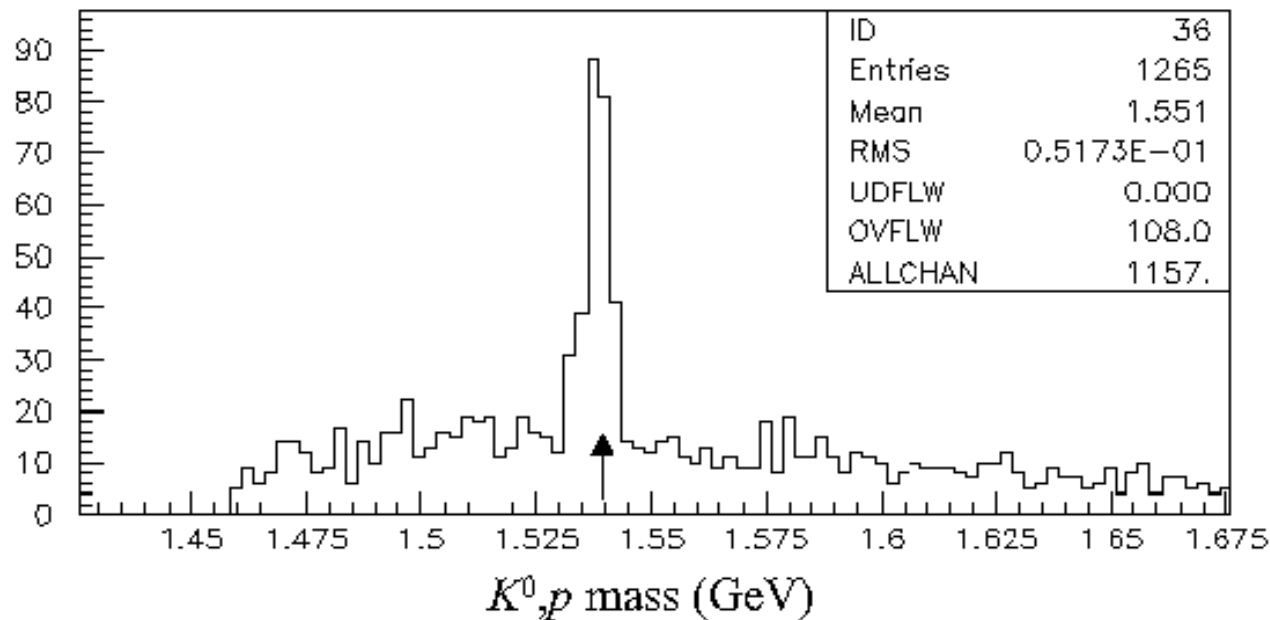
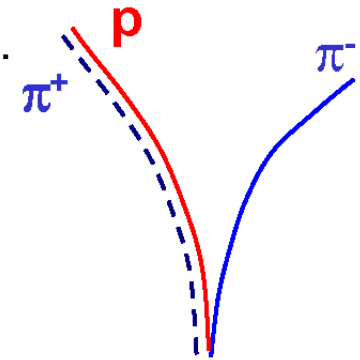
Chance of the Background Fluctuating into the observed signal



Ghost Tracks

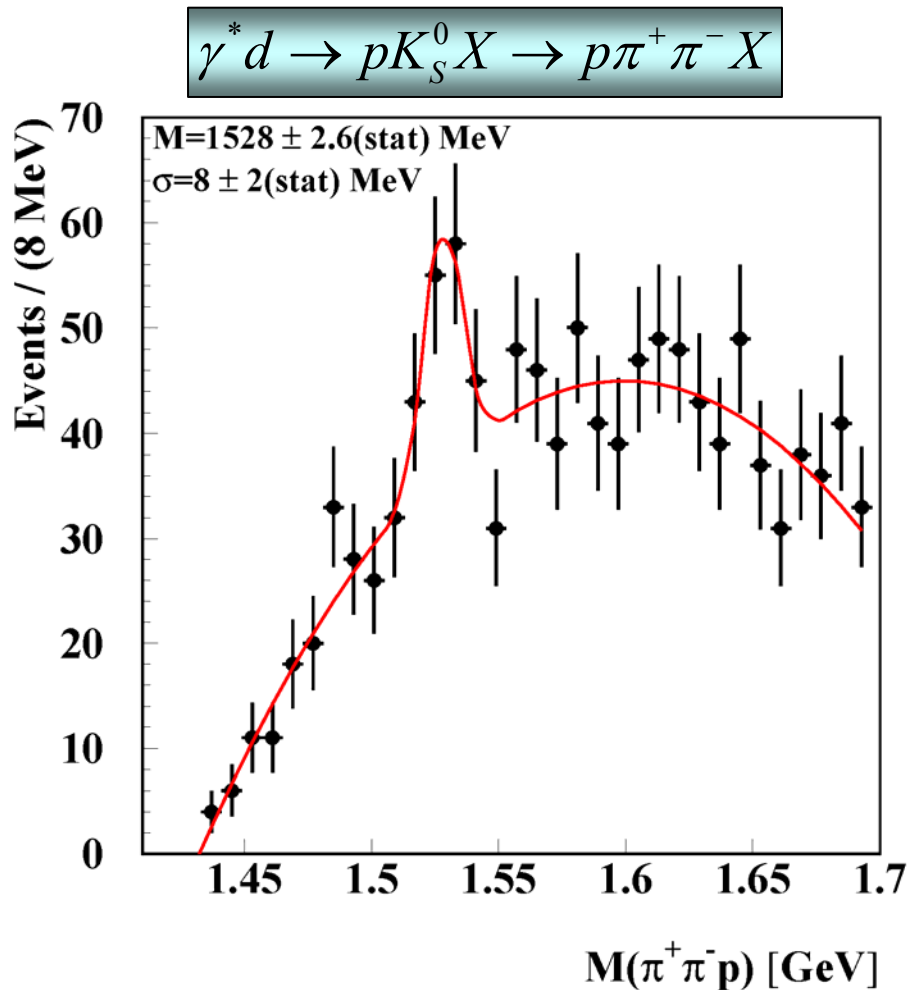
M. Longo *et al*, PRD 69, 051901(R) (2004).

- Ghost tracks from a $\Lambda \rightarrow p\pi^-$ can produce a peak near 1.54 GeV. The positive track is used twice – as a p and a π^+
- misinterpret the p as a π^+
- assume that the $\pi^+\pi^-$ pair came from a K_s
- the resulting pK_s pair produces a narrow peak



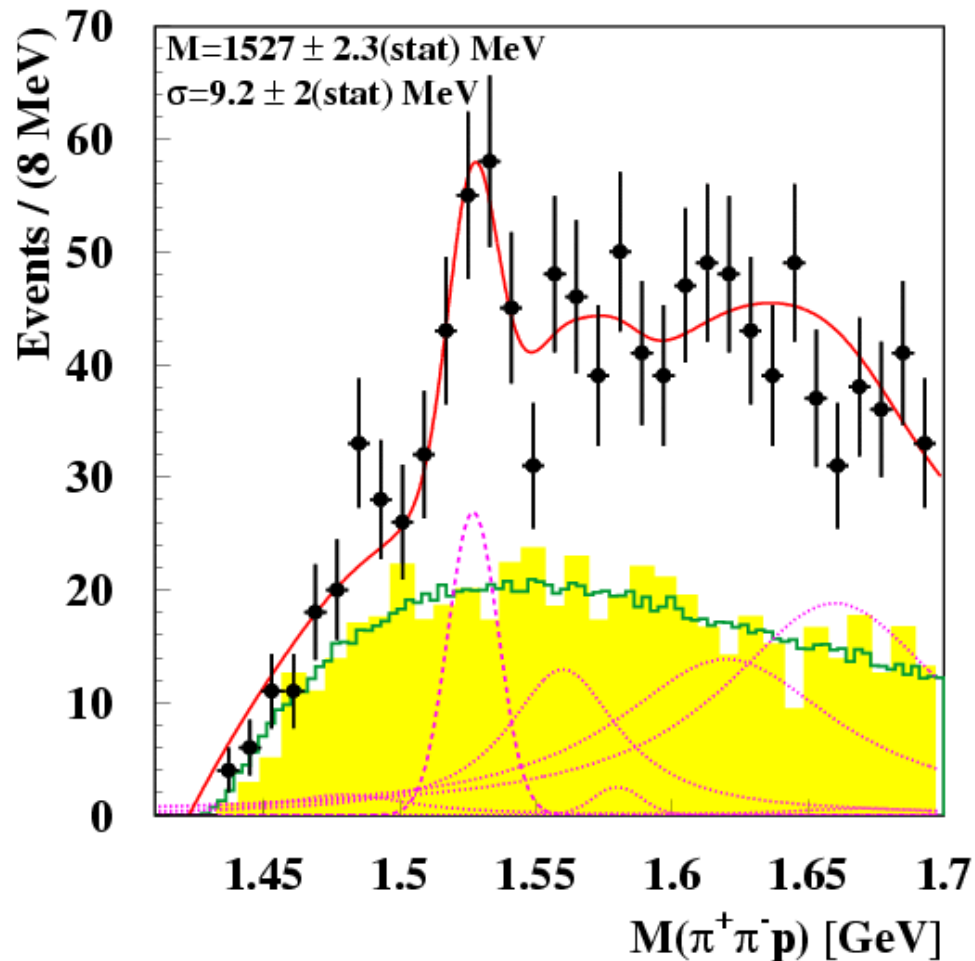
What about HERMES?

Inclusive quasi-real photo production with 27.6 GeV e^+ on deuterium



- Excellent hadron identification
RICH: π : 1-15 GeV p : 4-9 GeV
- Unbinned fit with 3rd order polynomial plus Gaussian
- Peak is observed at $1528 \pm 2.6(\text{stat}) \pm 2.1(\text{syst}) \text{ MeV}$ in pK_S invariant mass distribution
- Width, $\sigma = 8 \text{ MeV}$, is observably larger than experimental resolution
- Statistical significance is 3.7σ
- No known positively charged strange baryon in this mass region
- No strangeness tagging
- Three models of background were studied

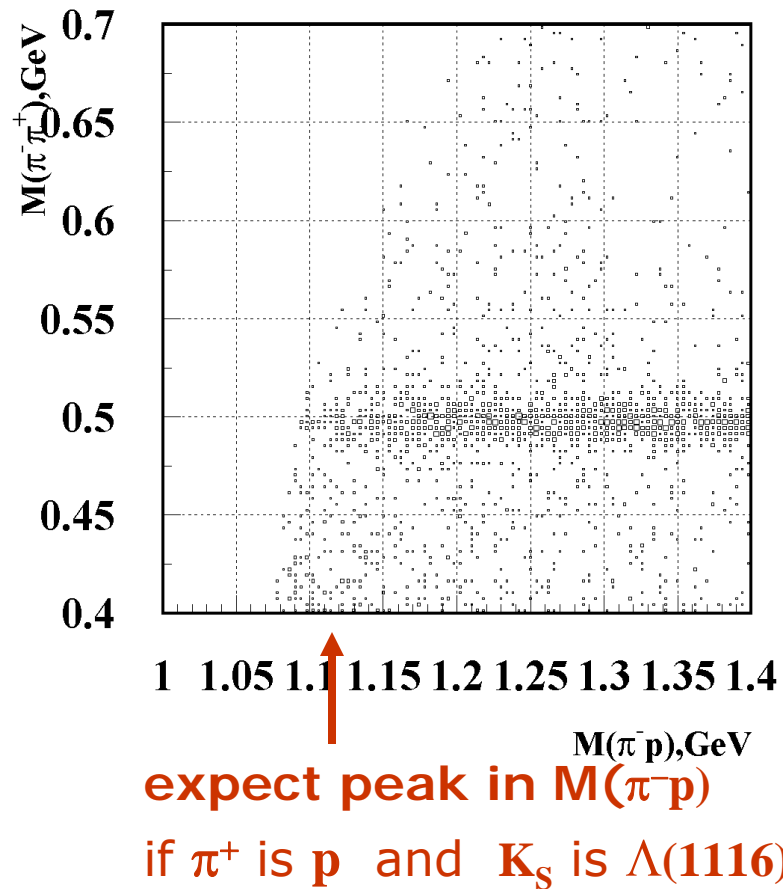
PYTHIA6 and mixed-event backgrounds



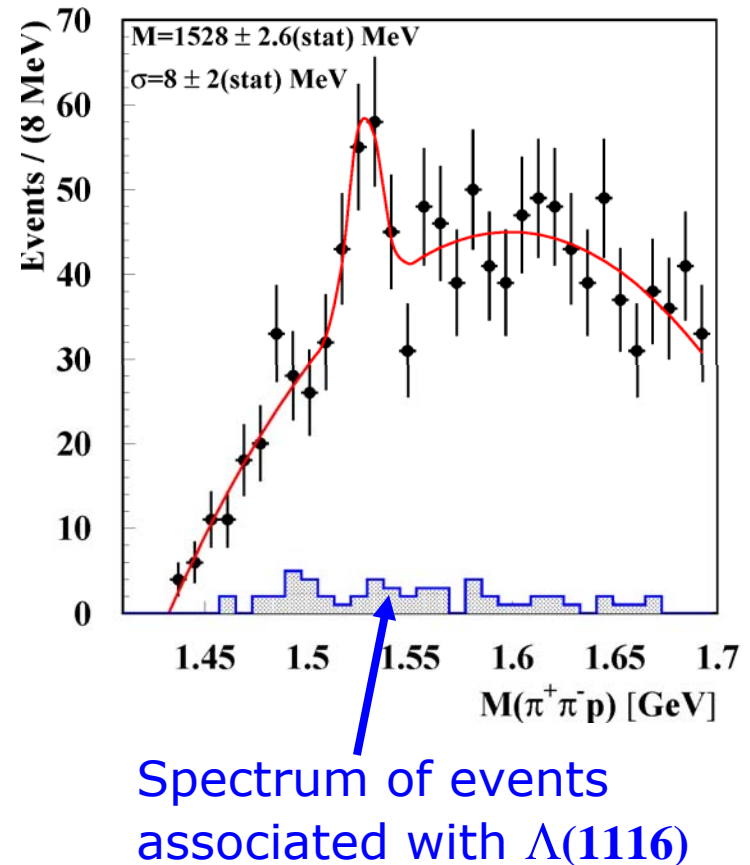
- **Filled histogram:** PYTHIA6 MC (lumi normalized):
No resonance structure from reflections of known mesonic or baryonic resonances
- **Green histogram:** mixed event background normalized to PYTHIA6: **reproduces the shape of PYTHIA6 simulation**
- Excited Σ^* hyperons not included in PYTHIA6 lie below 1500 MeV and above 1550 MeV
- **Mass= 1527 ± 2.3 MeV**
- **$\sigma= 9.2 \pm 2$ MeV**
- **Significance 4.3σ**

Fake Peaks?

- particle miss-assignment
 - ghost tracks
 - PID “leaks”

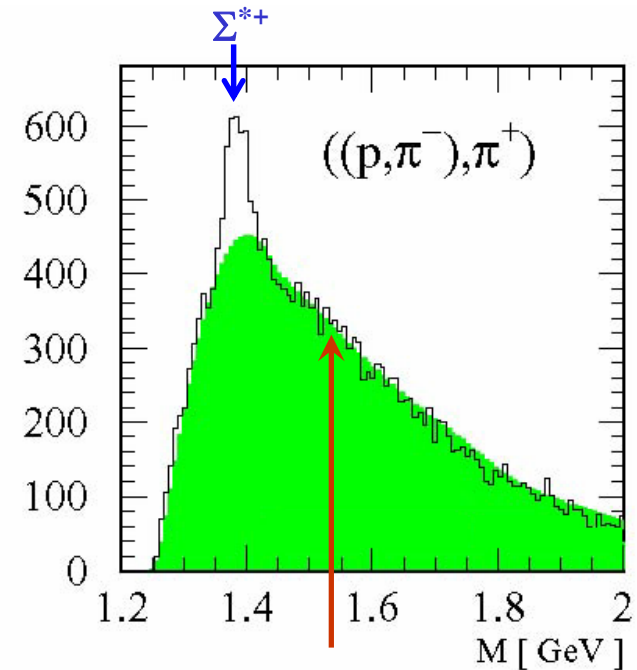
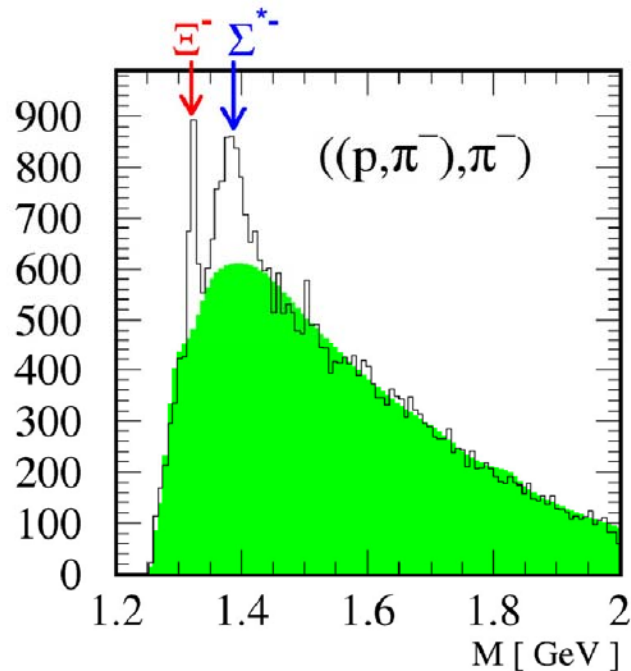


- remove $\Lambda(1116)$ contribution



Θ^+ or Σ^{*+} ?

- Is HERMES peak a previously missing Σ^* or a pentaquark state?
- If peak is Σ^{*+} \Rightarrow also see a peak in $M(\Lambda\pi^+)$

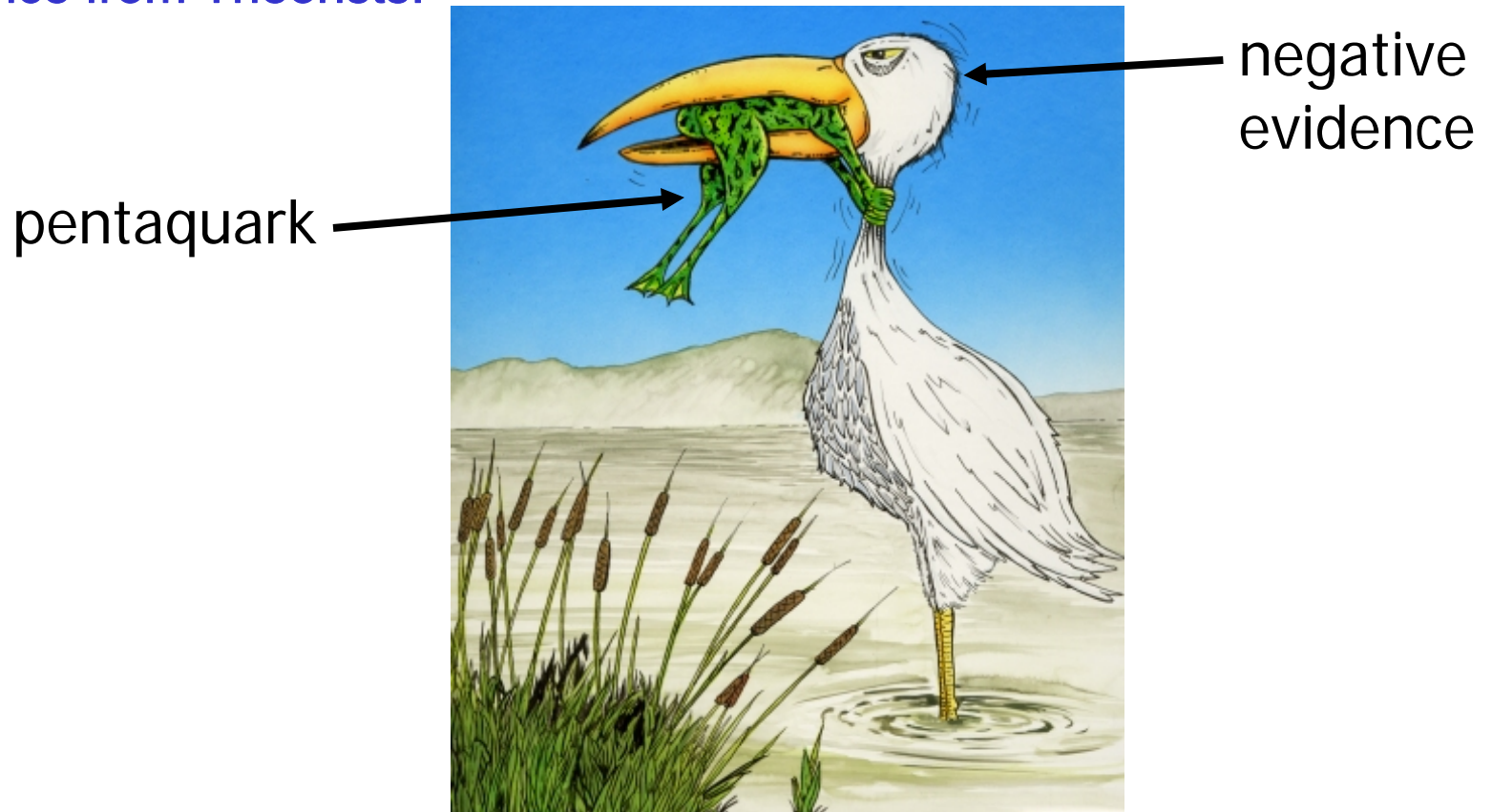


No peak in $\Lambda\pi^+$ spectrum near 1530 MeV

➔ *but no Σ^* s (1480, 1560, 1580, 1620) too!!!!
should we say all bumps in pK_s spectrum are pentaquarks?*

Pentaquark Situation (April 2005)

- Dedicated, high-statistics experiments are key
- Advice from Theorists:

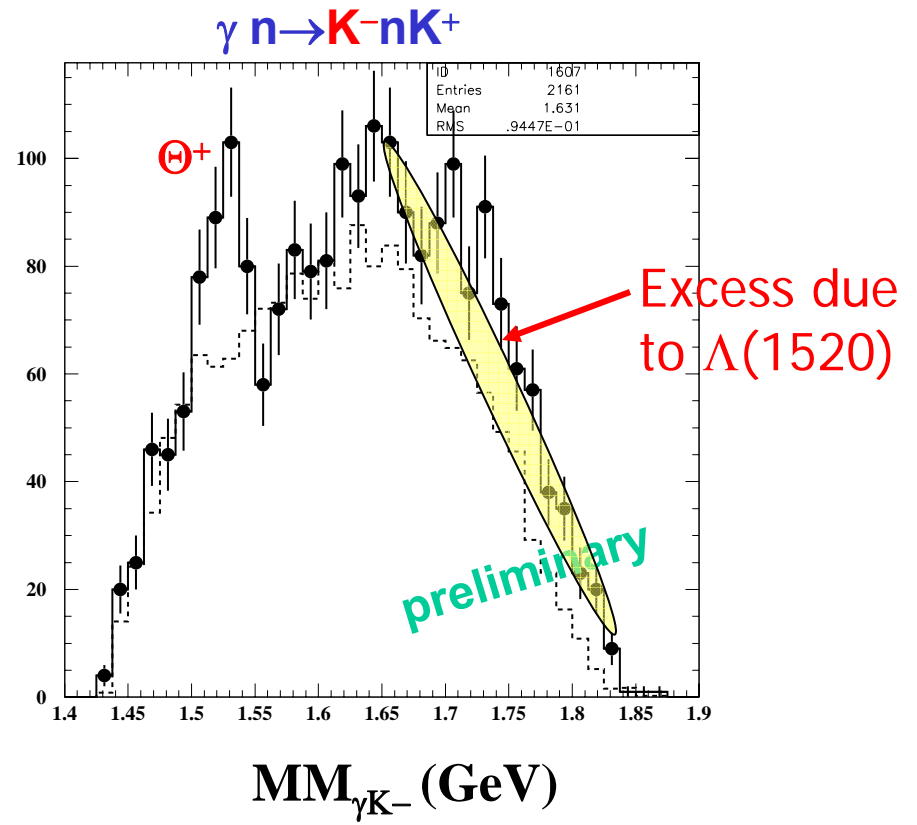
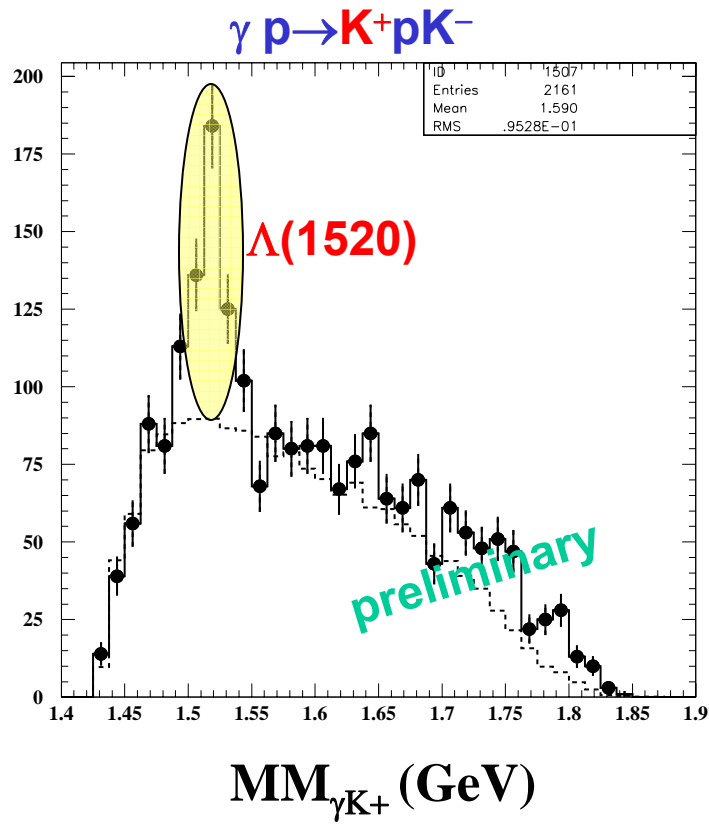


Don't give up too easily...

LEPS Search for Θ^+ in $\gamma d \rightarrow K^+ K^- n(p)$

- The proton is a spectator (undetected)
- Fermi motion is corrected to get the missing mass spectra
- Background is estimated by mixed events

- Dedicated experiment
- Aimed at 4x stat. of 2003



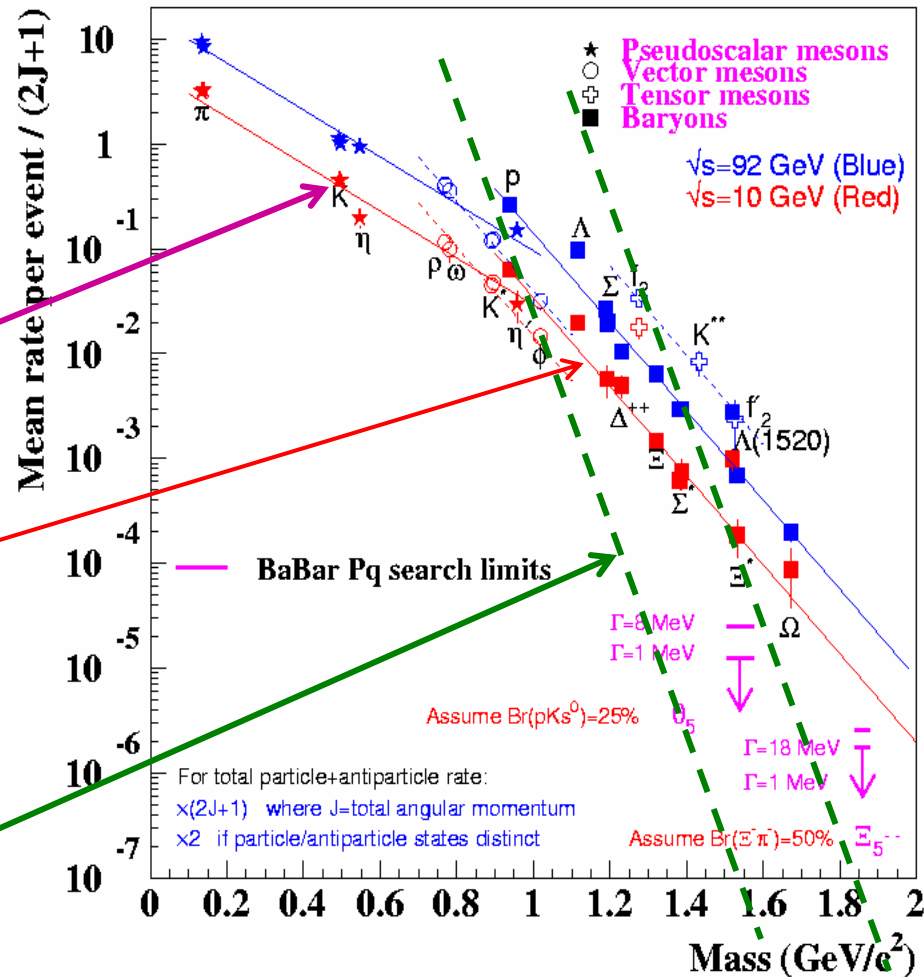
Conclusions of LEPS group

- LEPS high statistics experiment has reconfirmed the peak, very unlikely to be due to statistical fluctuations.
- The preliminary study shows no indication that the peak is generated by kinematical reflections, detector acceptance, Fermi-motion correction, nor cuts.
- “existence ranges from very likely to certain, but **further confirmation is desirable**” - “three-star” definition by PDG.



BABAR

Hadron production in e^+e^-



Slope:

Pseudoscalar mesons:
 $\sim 10^{-2}/\text{GeV}/c^2$ (need to generate one qq pair)

Baryons:
 $\sim 10^{-4}/\text{GeV}/c^2$ (need to generate two pairs)

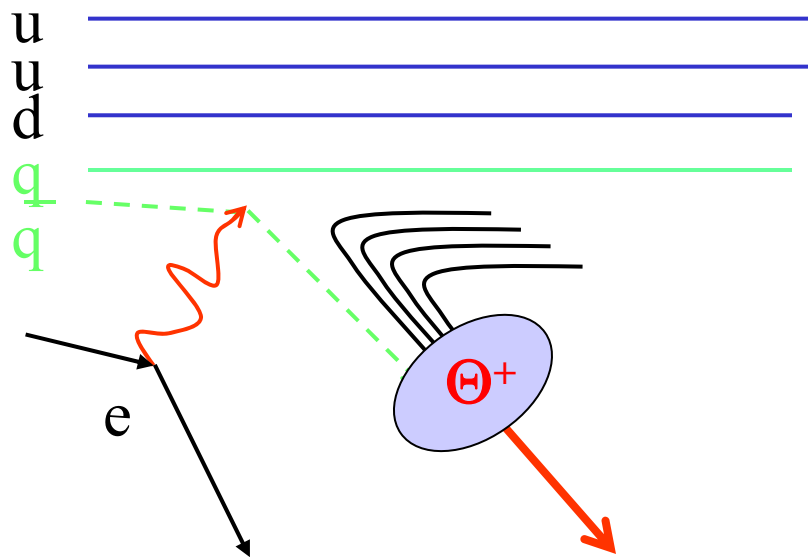
Pentaquarks:
 $\sim 10^{-8}/\text{GeV}/c^2$ (?) (need to generate 4 pairs)



Pentaquark production in direct e^+e^- collisions likely requires orders of magnitudes higher rates than available.

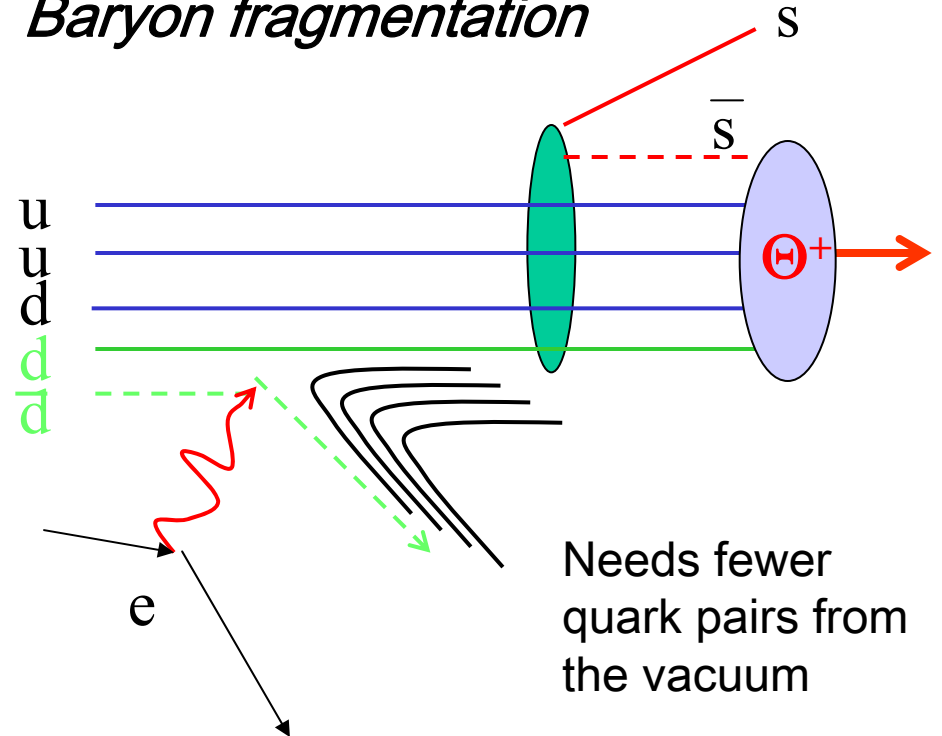
Pentaquark in fragmentation?

Quark fragmentation



Pentaquark strongly suppressed ?

Baryon fragmentation

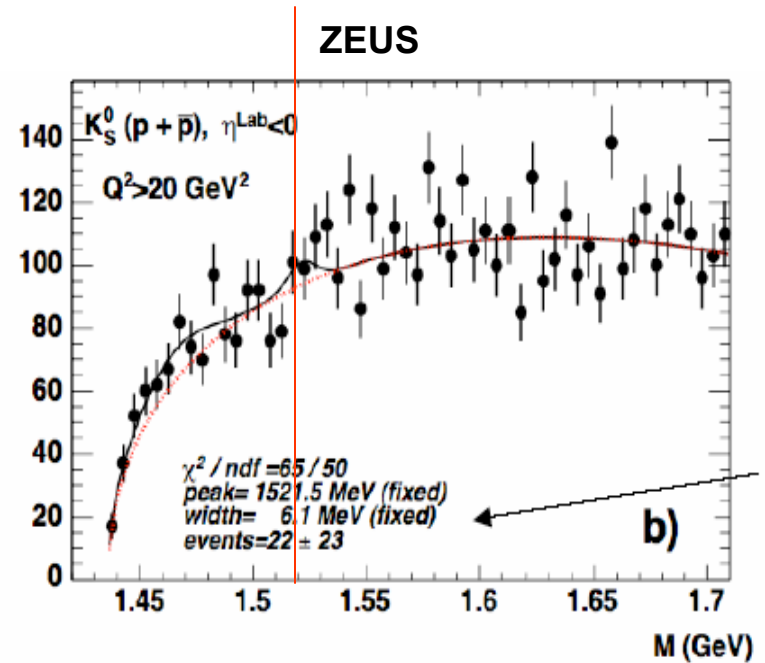
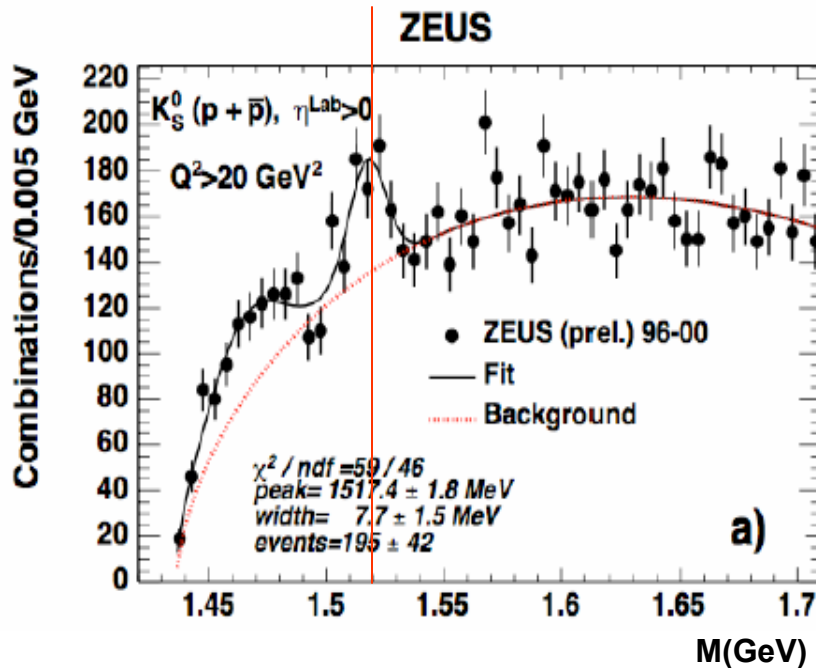


Needs fewer quark pairs from the vacuum

Pentaquark less suppressed ?

High energy production mechanism

$$ep \rightarrow epK_s^0 X$$



Θ^+ produced mostly at forward rapidity $\eta_{\text{Lab}} > 0$, and medium $Q^2 > 20 \text{ GeV}^2$.

Consistent with Θ^+ production in baryon fragmentation

Media Interest (2005)

APS NEWS June 2005
Volume 14, No. 6
A Publication of The American Physical Society <http://www.aps.org/journal>

New Experiment Casts Doubt on Elusive Pentaquark

By Eric Tretkoff

A dedicated hunt for the pentaquark has found nothing further, calling into question previous reports of pentaquark sightings. An experiment at the CERN Large Acceptance Spectrometer (LASS) at the Thomas Jefferson National Accelerator Facility has done nothing to find the five-quark particle, researchers

to do pentaquark sightings. The experiment, which ran from May to July 2004, fired high energy photons at protons in a target of liquid hydrogen to try to produce the pentaquark. The pentaquark sightings that OLAF searched for, called the theta, is composed of two up quarks, two down quarks, and an

The CLAS experiment has a production 50 times higher than the CERN result. "These results don't entirely rule out the possibility of a pentaquark, but they do provide strong evidence against it. The OLAF collaboration is still analyzing some of its data, and they plan to conduct further studies

news@nature.com
The best in science journalism

Published online: 18 April 2005 | doi:10.1038/news050418-1

Doubt is cast on pentaquarks

Mark Poplaw

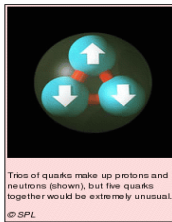
Exotic subatomic particles may be an experimental phantom.

Physicists have come home empty-handed from a thorough hunting expedition for pentaquarks. The lack of evidence has led some to doubt that these odd subatomic particles, first sighted in 2002, actually exist.

The pentaquark was discovered at the SPring-8 synchrotron in Harima, Japan. The particle, thought to be made up of five quarks, is so unstable that physicists inferred its existence from the debris of collisions between gamma rays and carbon atoms.

Trios of quarks make up the protons and neutrons that are the basic building blocks of atomic nuclei. Particles made up of five quarks would be extremely unusual, and were hailed as a new form of matter.

But experiments at the Thomas Jefferson National Accelerator Facility in Newport News, Virginia, now suggest that the discovery was a mistake. "We just didn't see it in these experiments," says Raffaella De Vita, of the National Institute of Nuclear Physics in Genoa, Italy, who presented the results at the American Physical Society conference in Tampa, Florida, on 16 April.



SCIENCE NEWS
THE WEEKLY NEWSMAGAZINE OF SCIENCE

May 14, 2005, PAGES 283-323, VOL. 147, NO. 20

a tooth's armor
jellyfish vision
an ovarian cancer marker
star crash and flash

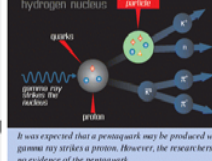
listen up
THE EVOLUTION OF ECHOLLOCATION

Exploring the Nature of Matter
Jefferson Lab

SCIENTIFIC PROGRAM
Nuclear Physics
Accelerator Science
FEL Program
Experiment Research
Higher Education
User Information
CEBAF @ 12 GeV

Public Connections
Welcome to JLab
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Visitor's Center
Contact Lab
K-12 Education
Image Gallery

12000 Jefferson Avenue
Newport News, VA 23606
tel: 757.269.7100
fax: 757.269.7363



Pentaquark Debate Heats Up
New data from Jefferson Lab shows the θ^+ pentaquark doesn't appear in one place it was expected. The result

Science Now
Daily News 18 April 2005

Do You Believe in Pentaquarks?

TAMPA, FLORIDA—The elusive pentaquark may be about to disappear. A new result presented at a meeting here of the American Physical Society provides the strongest evidence yet that the much-studied θ^+ pentaquark particle is just a statistical fluke.

PENTAQUARK
neutron (u d d)
pentaquark (u u d d d)
kaon (u s)
proton (u u d)
other particles

CERN COURIER
This Issue | Back Issues | Editorial Staff

Mystery deepens as pentaquarks refuse to make an appearance

Preliminary data on the hot topic of the search for pentaquarks were presented at the April Meeting of the American Physical Society by the Jefferson Laboratory's CEBAF Large Acceptance Spectrometer (CLAS) collaboration. Quantum chromodynamics (QCD) does not forbid exotic pentaquark states comprising four quarks and an antiquark, but the jury is still out as to whether such a state has been observed. Several experiments have published positive results while an equal number of different experiments have found nothing. The new result adds to the negative evidence.

The g11 experiment at the CLAS detector is a fixed-target photoproduction experiment in which a tagged photon beam, with photon energies individually measured, at an energy of 1.8-3.8 GeV hits a proton target. Data-taking was completed in 2004 with 70 pb⁻¹ of integrated luminosity. The collaboration searched for the θ^+ (1540) produced together with a neutral kaon in the reaction $\text{p} \theta^+ \text{K}^0$, where the K^0 is detected via its $\text{K}^0 \rightarrow \pi^+ \pi^-$ component decaying into $\pi^+ \pi^-$.

The θ^+ is expected to decay into a neutron and a K^+ , and the neutron is reconstructed from the missing mass in the reaction. No signal is seen in the $n\text{K}^+$ mass spectrum, putting a limit on the production cross-section for $\text{p} \theta^+ \text{K}^0$ of less than 4 nb at a 95% confidence level.

This result is at odds with a published analysis of CLAS, where a θ^+ signal was seen with a 7.8 σ significance in the reaction $\text{p} \theta^+ \text{K}^0$. The earlier study was performed on 5 pb⁻¹ of data, where a couple of severe geometry cuts had to be applied to the original $n\text{K}^+$ distribution to reveal the θ^+ signal. An experiment at higher energy to verify this result is planned.

NewScientist.com
21 April 2005 HOME | NEWS | EXPLORE BY SUBJECT

BREAKING NEWS

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Man: meer Opportunity here
people stay

Pentaquark hunt draws a blank
11:44 20 April 2005
NewScientist.com news service
Nigge McKeon

An oversized subatomic particle that has challenged models of quantum physics since its reported discovery in 2003 does not exist after all, a new study suggests. But in trying to track the particle down, scientists say they have stumbled on important new insights about the forces that bind the building blocks of matter.

The short-lived particle - called a pentaquark - was thought to consist of five subatomic particles called quarks. Quarks normally only associate in groups of two - producing short-lived

LE SCIENZE on line
notiziario

24.04.2005
Addio al pentaquark
La famigerata particella theta+ potrebbe non esistere

Nuovi risultati presentati a un convegno dell'American Physical Society a Tampa, in Florida, suggeriscono che la famigerata particella theta+, il cosiddetto "pentaquark", non sia altro che un miraggio statistico. La saga del pentaquark era cominciata due anni fa, quando l'esperimento giapponese SPring-8 sembrava aver rivelato l'esistenza di una particella che non era costituita da 2 o da 3 quark come tutte le altre, ma da 5. Nel giro di pochi mesi, gli scienziati affermarono di aver osservato almeno una dozzina di queste particelle esotiche. Ma poiché altri dati non consentivano di confermare l'esistenza di theta+ o di particelle simili, i fisici hanno deciso di progettare diversi esperimenti su misura per la ricerca del pentaquark. Raffaella De Vita dell'Istituto Nazionale di Fisica Nucleare di Genova ha ora rivelato i risultati del primo di questi esperimenti, noto come g11, eseguito presso il Thomas Jefferson National Laboratory (JLab) di Newport News, in Virginia. Nell'esperimento g11, gli scienziati hanno inviato raggi gamma su un bersaglio di protoni. In teoria, una collisione fra un fotone e un protone potrebbe creare un theta+. Nel 2003, usando un apparato simile, una collaborazione tedesca a Bonn aveva affermato di aver prodotto circa 60 pentaquark. Ma i risultati molto più accurati di g11 non hanno rivelato nulla: ci sono troppi peccati corrispondenti ad altre particelle, spiega De Vita, ma nessuno in corrispondenza di theta+. I dati non escludono completamente l'esistenza del pentaquark, ma come minimo li mettono in dubbio. Inoltre hanno una significanza statistica molto maggiore degli esperimenti che avevano consentito di osservare la particella.

PHYSICS TODAY
JUNE 2005

26 December 2004
Earthquake and tsunami

And More

- R.L. Jaffe (MIT) at DIS 05 Madison:
Life and Death among the Hadrons



"May it rest in peace"

New CLAS Result I

- Dedicated experiment
- Aimed at 10x stat. of 2003

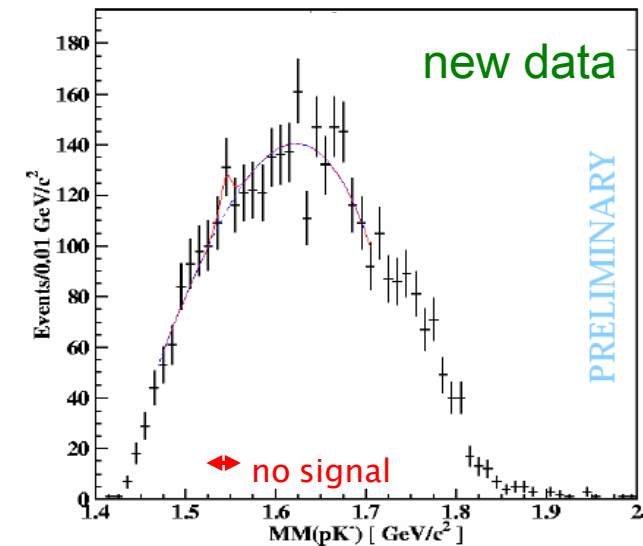
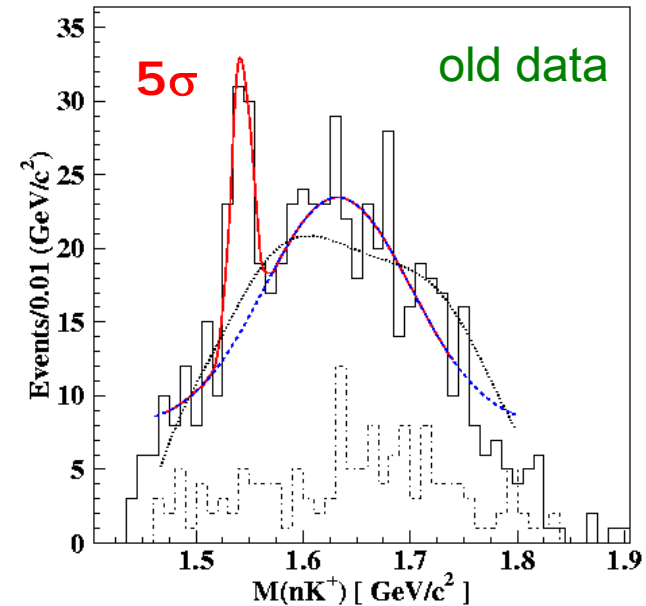
$$\gamma d \rightarrow pK^- nK^+$$

- The new high-statistics data show no signal
⇒ Set upper limit on cross section

$$\gamma n \rightarrow K^- \Theta^+$$

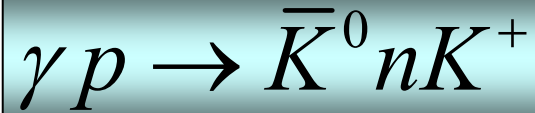
$\sigma_{\Theta^+} < 5 \text{ nb}$ (95% CL)
model dependent

- In previous result the **background** is **underestimated**. New estimate of the original data gives a significance of $\sim 3\sigma$, possibly due to a fluctuation.

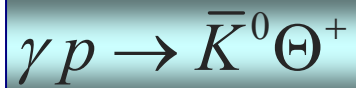


New CLAS Result II

- Dedicated experiment
- Aimed at 10x stat. of 2003

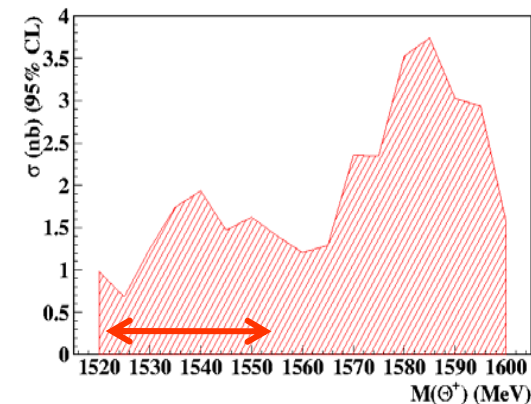
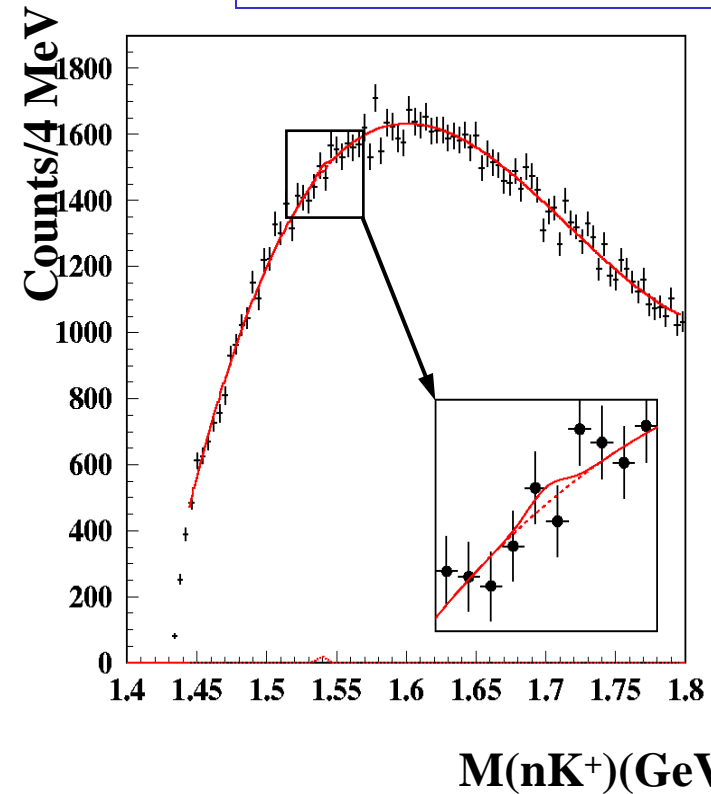


- The nK^+ mass spectrum is smooth
⇒ Set upper limit on cross section



$$\sigma_{\Theta^+} < 2 \text{ nb} \quad (95\% \text{ CL})$$
$$\Theta/\Lambda^* < 0.002$$

- comparison with competing experiment possible



Comparison with SAPHIR results

Observed Yields

SAPHIR

$$N(\Theta^+)/N(\Lambda^*) \sim 10\%$$

CLAS

$$N(\Theta^+)/N(\Lambda^*) < 0.2\% \\ (95\%CL)$$

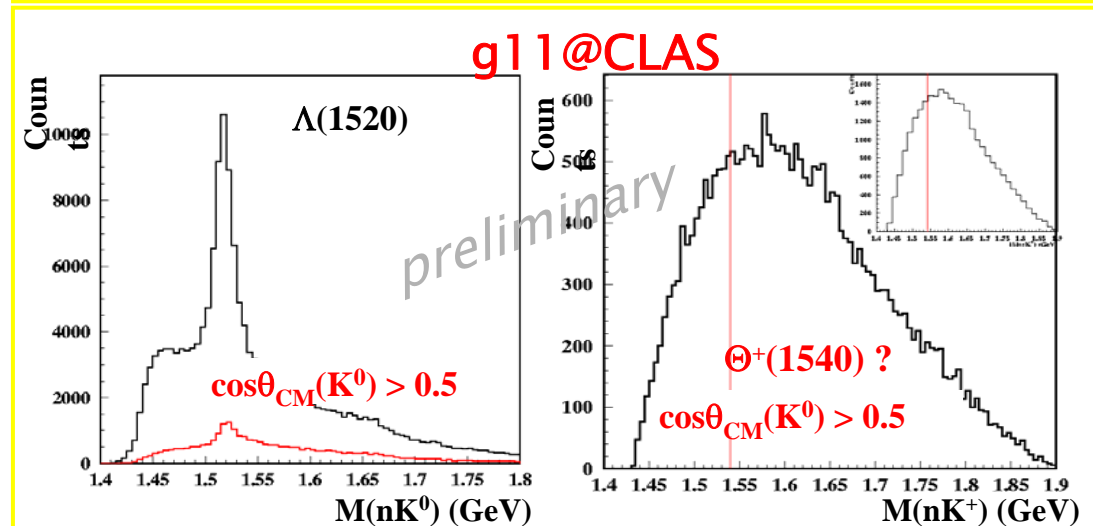
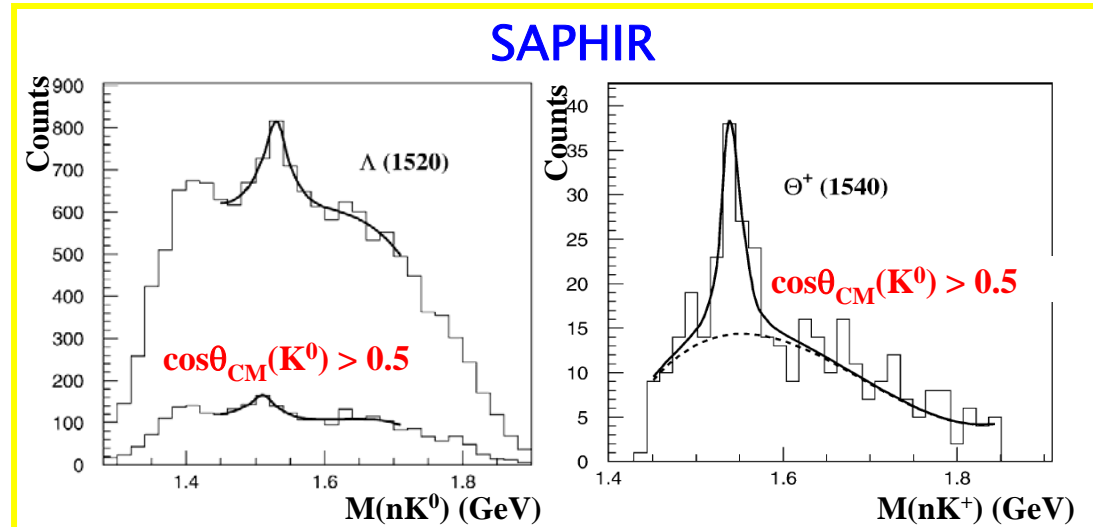
Cross Sections

SAPHIR

$$\sigma_{\gamma p \rightarrow K^0 \Theta^+} \sim 300 \text{ nb} \\ \text{reanalysis } 50 \text{ nb (unpublished)}$$

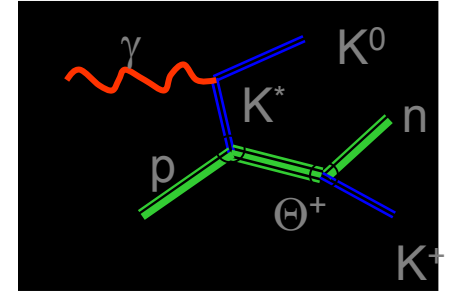
CLAS

$$\sigma_{\gamma p \rightarrow K^0 \Theta^+} < 2 \text{ nb}$$



Impact on Θ^+ production mechanism

- The CLAS result puts a very stringent limit on a possible production mechanism of the Θ^+ , e.g. it implies a very small coupling to K^* .



- **But:** “Null-result from CLAS does not lead immediately to the absence of Θ^+ .”

Nam, Hosaka and Kim, hep-ph/0505134

Lipkin and Karliner, hep-ph/0506084

Dynamical Model Calculations

Effective Lagrangean model

W. Roberts, PRC70, 065201 (2004)

$\Gamma_{\Theta} = 10 \text{ MeV}$	$1/2^+$	$1/2^-$	$3/2^+$	$3/2^-$	
$\gamma p \rightarrow nK^+\bar{K}^0$	44.8	27.9	26.0	110.5	nb
$\gamma n \rightarrow nK^+K^-$	54.5	18.0	22.8	229.9	nb

$\Gamma_{\Theta} = 1 \text{ MeV}$	$1/2^+$	$1/2^-$	$3/2^+$	$3/2^-$	
$\gamma p \rightarrow nK^+\bar{K}^0$	4.3	2.4	2.3	10.0	nb
$\gamma n \rightarrow nK^+K^-$	5.6	1.7	2.2	24.0	nb

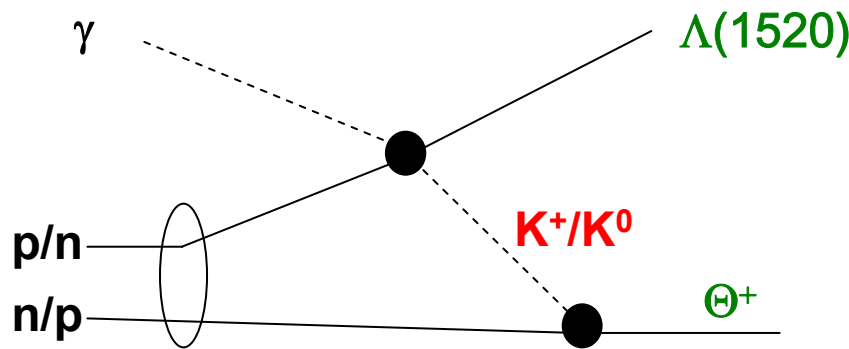
- CLAS limits of 2nb on the proton and of 5nb on the neutron do not exclude a Θ^+ with $\Gamma = 1 \text{ MeV}$ for $J^P = 1/2^-, 3/2^+$.

Note: similar calculations by other theorists.

New: LEPS Search in $\gamma d \rightarrow \Lambda(1520) n K^+$

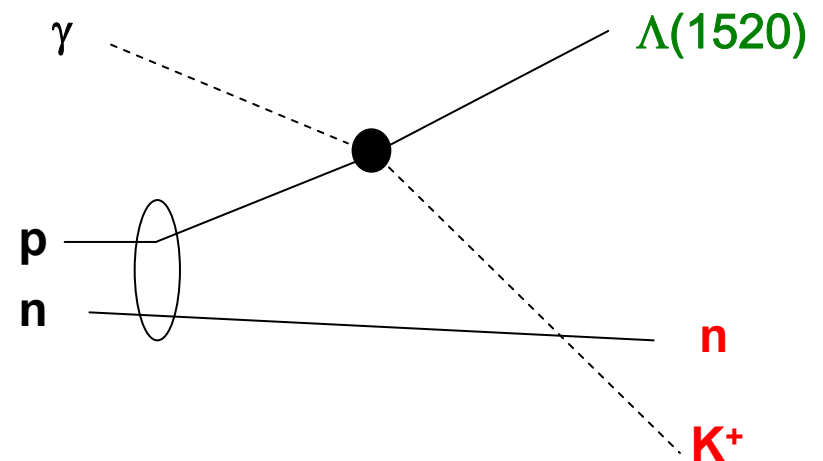
- Θ^+ identified by pK^- missing mass from deuteron.
⇒ **No Fermi correction is needed.**
- nK^- and np final state interactions are suppressed.
- If $s\bar{s}(I=0)$ component of a γ is dominant in the reaction, the final state NK has $I=0$. (Lipkin)

Possible reaction mechanism



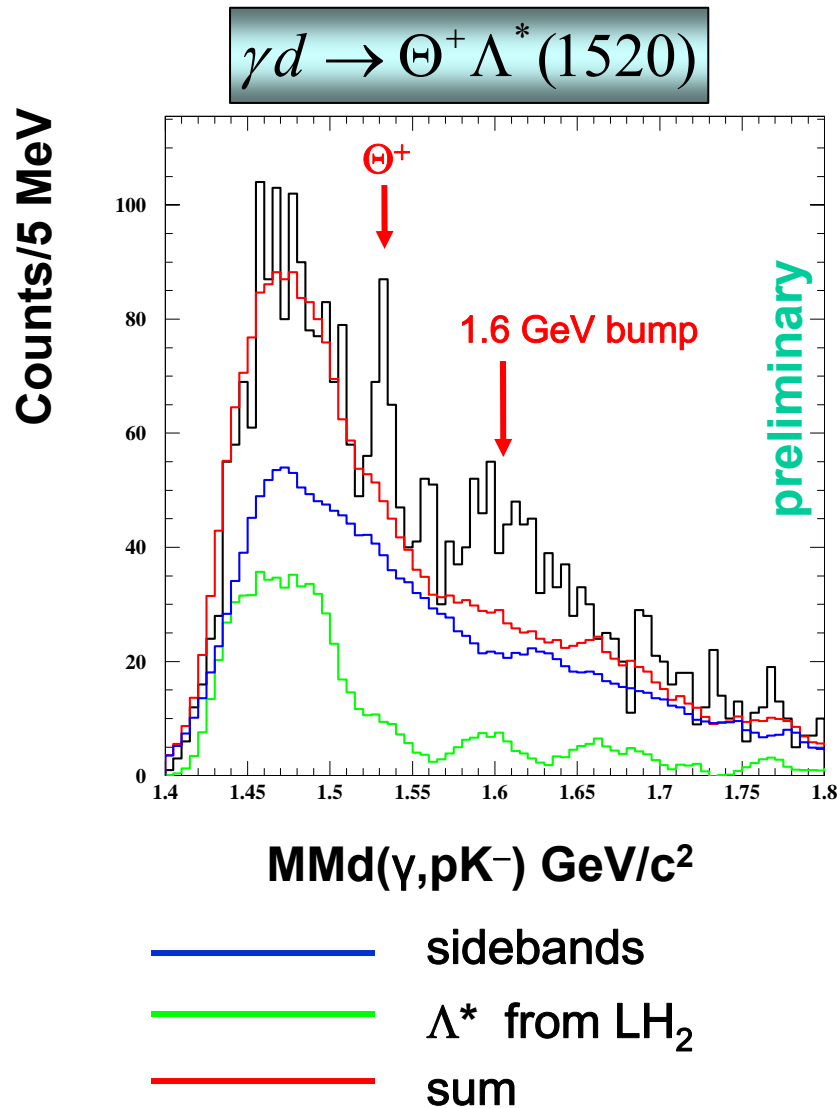
Θ^+ can be produced by re-scattering of K^+ .

Main source of background



quasi-free $\Lambda(1520)$ production
(estimate from LH_2 data)

LEPS: pK^- missing mass spectrum

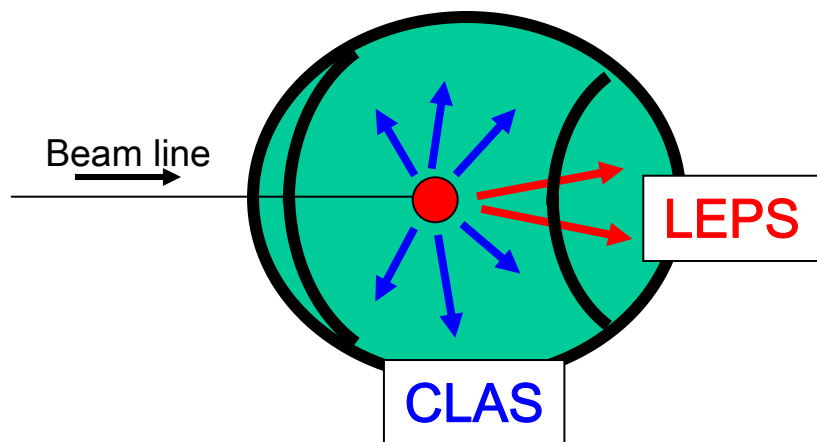


Excesses are seen at 1.53 GeV and at 1.6 GeV above the background level.

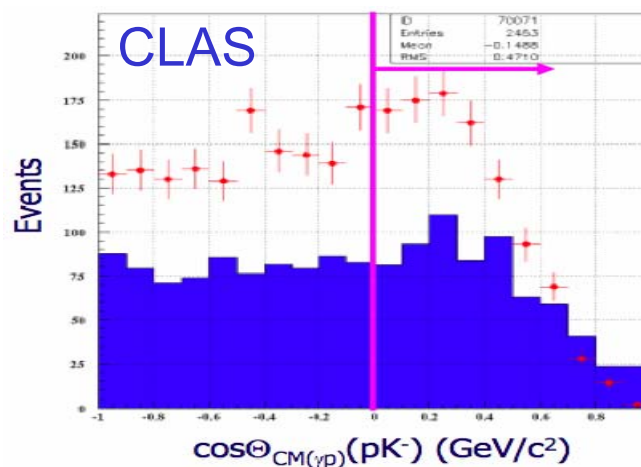
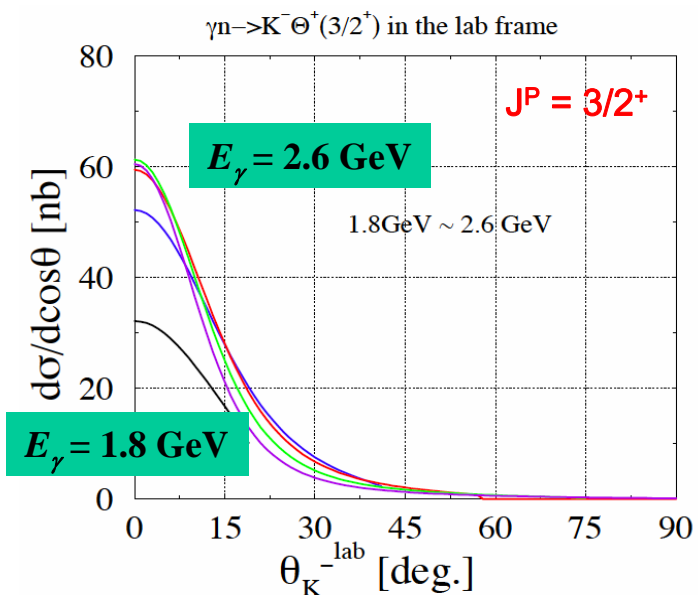
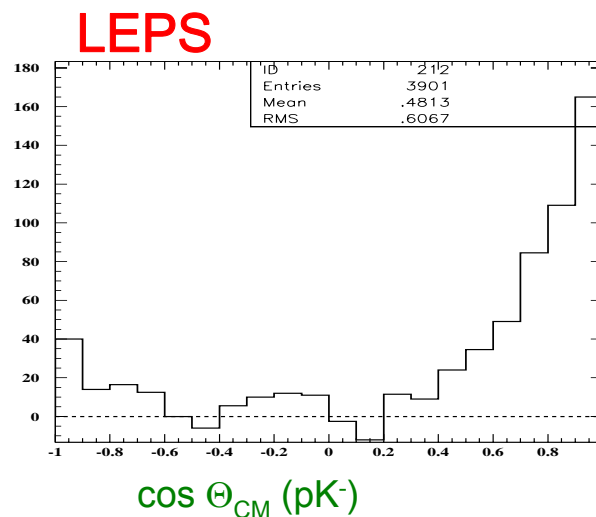
1.53-GeV peak: $\frac{S}{\sqrt{S+B}} \sim 5$?

mostly from $p_{nK} \sim 0.42$ GeV
outside CLAS acceptance ...

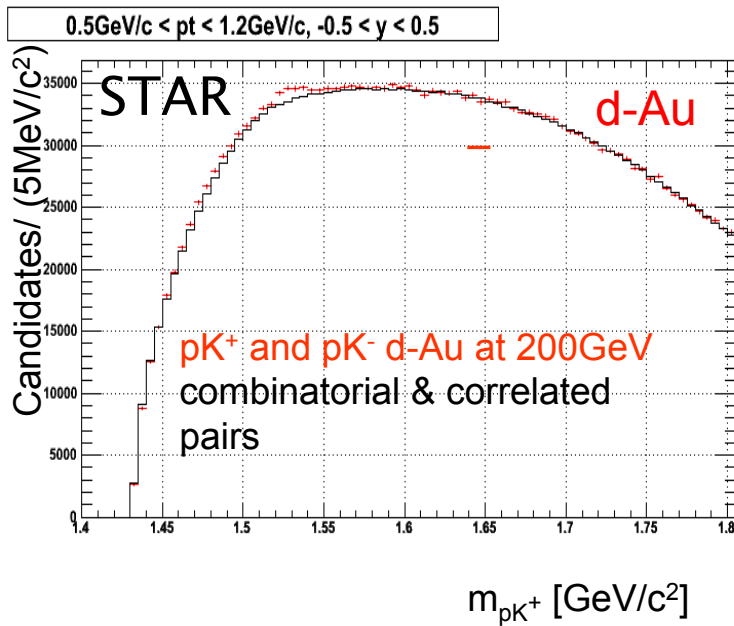
LEPS vs. CLAS



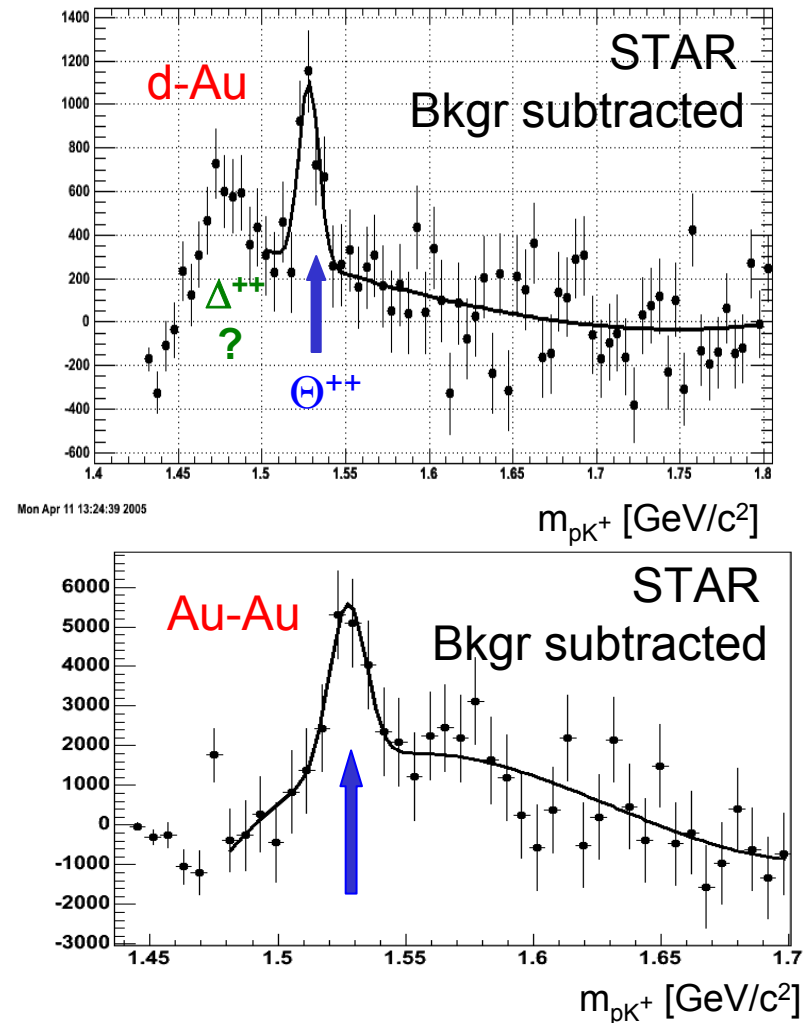
Nam *et al*, hep-ph/0505134



New: STAR d-Au results: Θ^{++}



- 5 σ observation of Θ^{++}
also Θ^+ with lower significance

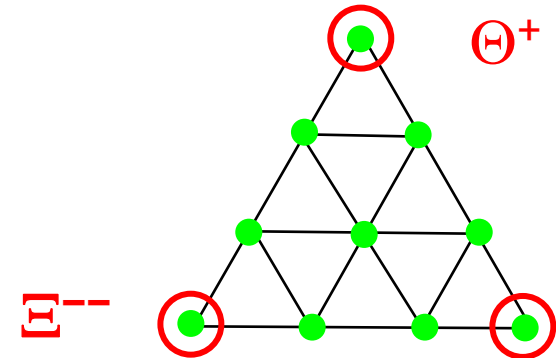
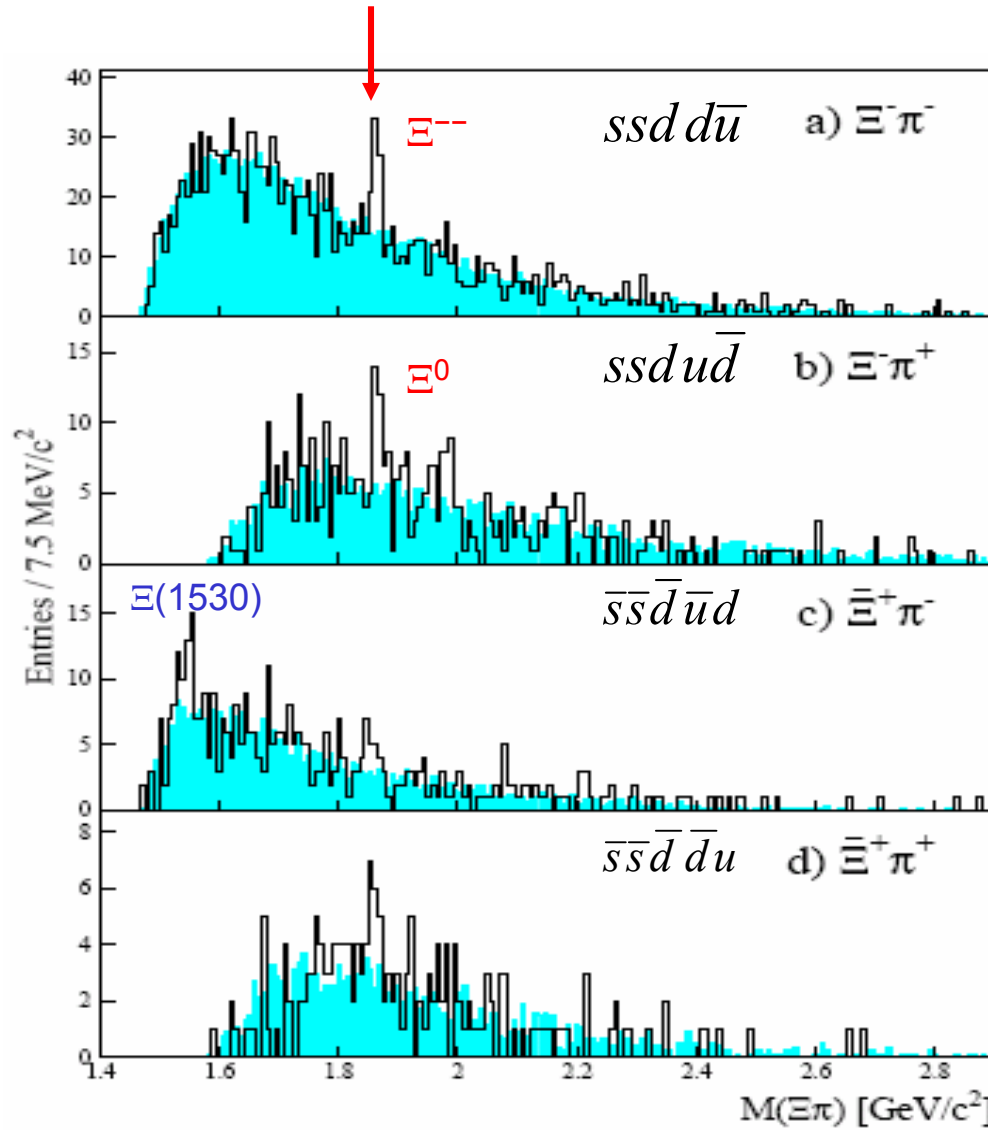


“The observed yield at STAR is so small. Such that many experiments would not have the sensitivity to see it.”

Cascade Pentaquark Ξ^{--} (1860)

C. Alt et al., (hep-ex/0310014)

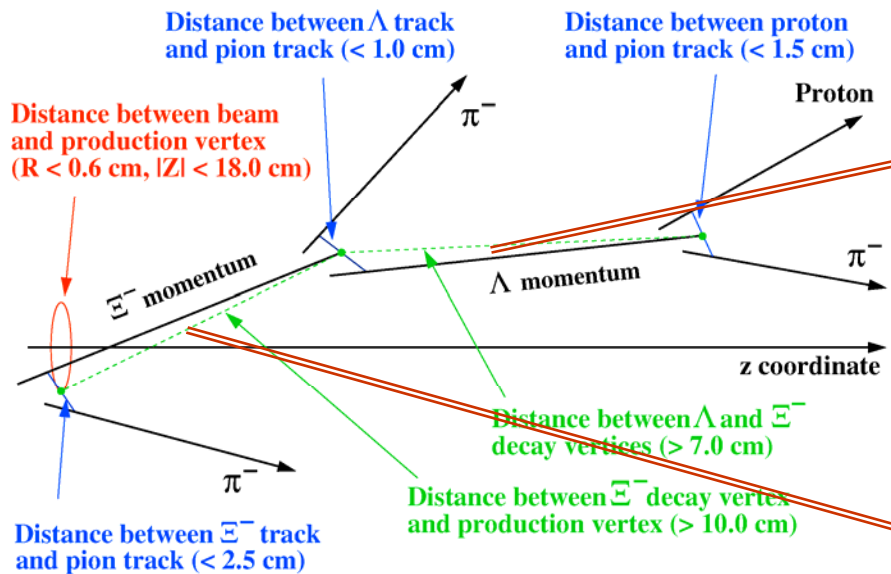
$M = 1862 \pm 2 \text{ MeV}$



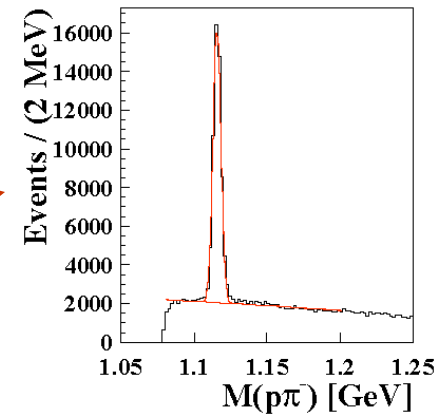
HERMES search for Ξ^{--} (1862)

➤ Channel: $\Xi^{--} \rightarrow \Xi^- \pi^- \rightarrow \Lambda \pi^- \pi^-$

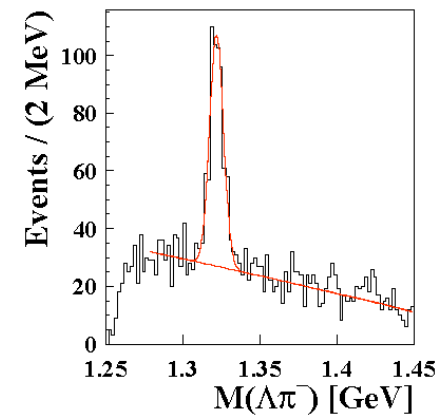
➤ Topology:



➤ $M(p\pi^-)$ with Λ



➤ $M(\Lambda\pi^-)$ with Ξ^-

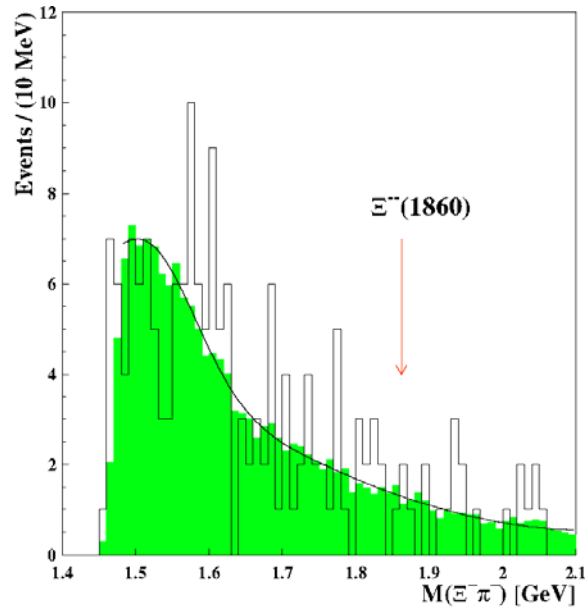


➤ Selected Λ events ($\pm 3\sigma$ window)

➤ Selected Ξ^- events ($\pm 3\sigma$ window)

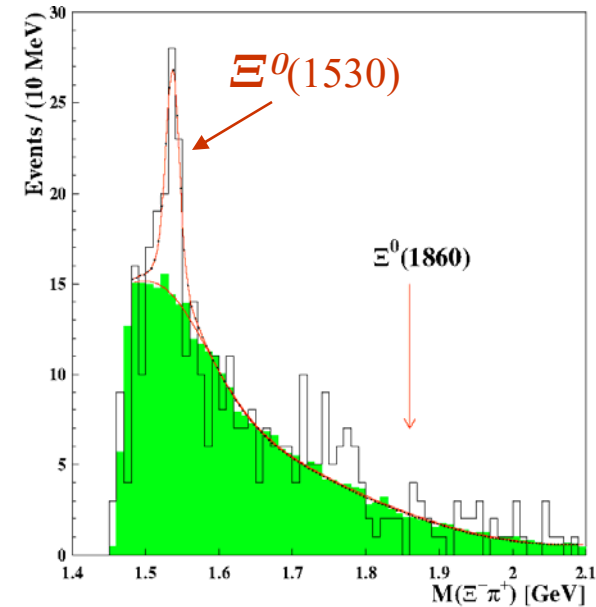
Ξ^{--} (1862) search (II)

➤ $M(p\pi^-\pi^-\pi^-)$ spectrum



- mixed-event background
- No Ξ peaks around 1860 MeV
- $\Xi^0(1530)$ seen, as expected

➤ $M(p\pi^+\pi^-\pi^-)$ spectrum

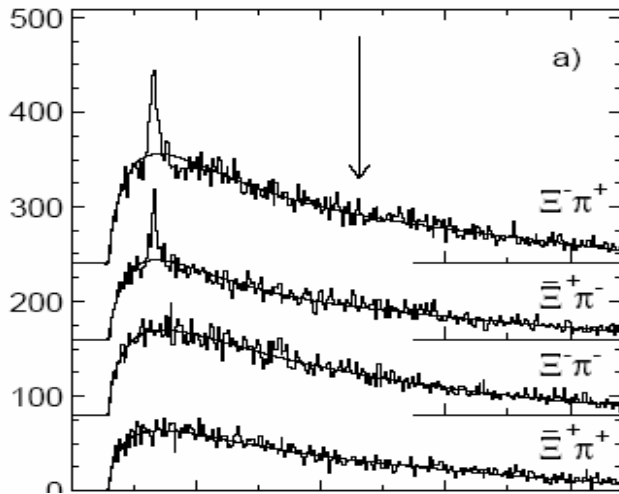


- upper limit $\sigma(\Xi^{--})$: 1.0–2.1 nb
- upper limit $\sigma(\Xi^0)$: 1.2–2.5 nb
- $\sigma(\Xi^0(1530)) = 8.8–24$ nb

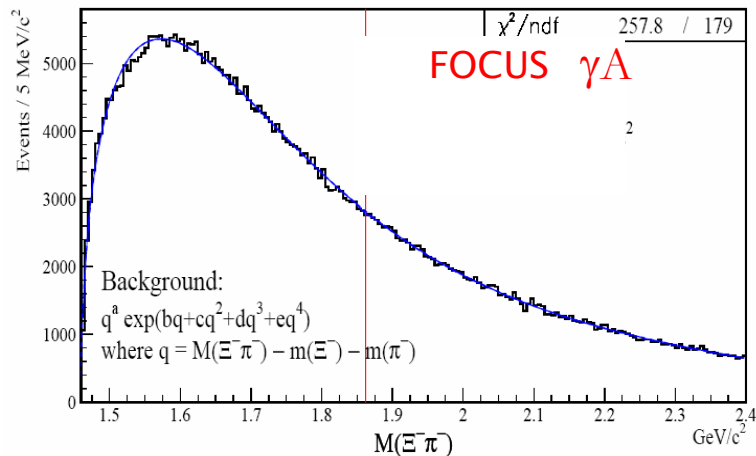
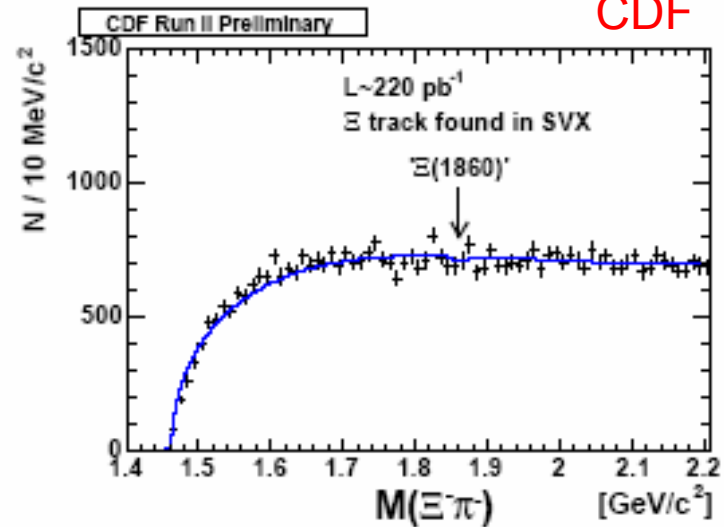
Other Null results for Ξ^{--} (1862)

$$p\bar{p} \rightarrow \pi\Xi X$$

HERA-B

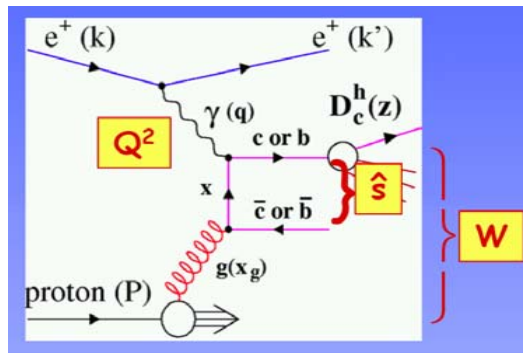
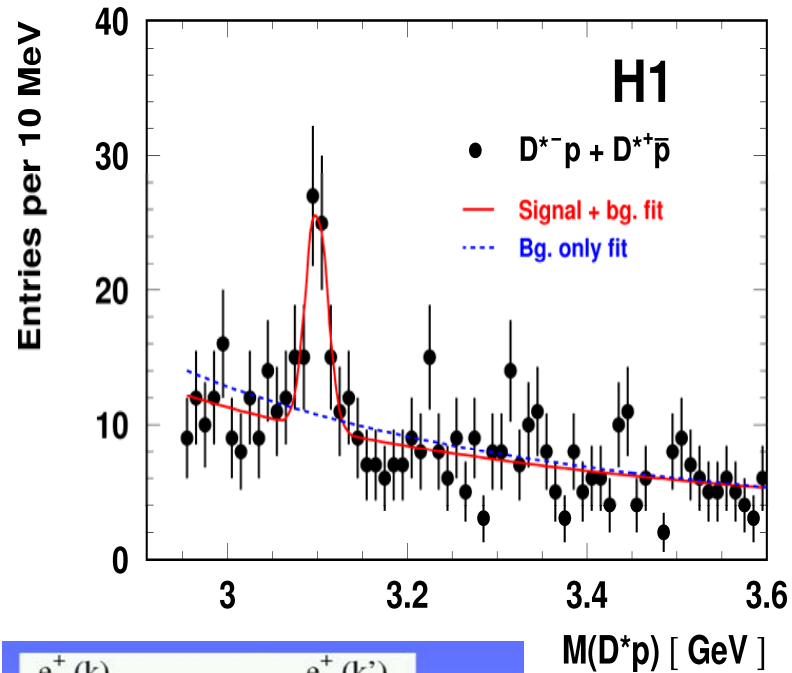


CDF



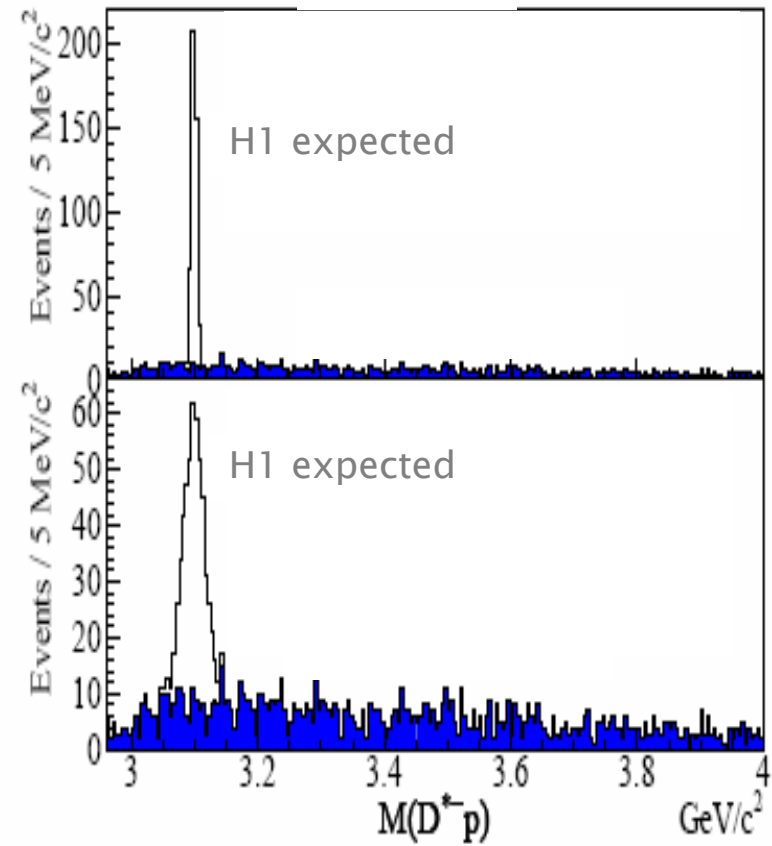
- Ξ^{--} (1862) not seen by 10 experiments
- Only one observation.

Charmed Pentaquark $\Theta_c^0(3100)$?



➤ Signal also in photo-production

FOCUS



➤ FOCUS experiment (+ 4 others) claim incompatibility with H1

Status: Pentaquark-2005 (Oct 20-22 JLab, VA)

Group	Signal	Backgr.	Significance publ.	$s/\sqrt{b+s}$	Comments
Θ^+					
SPring8	19	17	4.6σ	3.2σ	
SPring8	56	162	?	3.8σ	
SAPHIR	55	56	4.8σ	5.2σ	New CLAS-p
DIANA	29	44	4.4σ	3.4σ	
CLAS(d)**	43	54	5.2σ	4.4σ	New CLAS-d
CLAS(p)	41	35	7.8σ	4.7σ	
v	18	9	6.7σ	3.5σ	
HERMES	51	150	$3.4-4.3\sigma$	3.6σ	
COSY	57	95	$4-6\sigma$	4.7σ	
ZEUS	230	1080	4.6σ	6.4σ	
SVD	41	87	5.6σ	3.6σ	
Ξ^{--}					
NA49	38	43	4.2σ	4.2σ	? HERA-B, CDF
Θ_c					
HI1	50.6	51.7	$5-6\sigma$	5.0σ	? ZEUS
SPring8	200	285		5.0σ	$\Lambda^*(nK^+)$
STAR	2,250	150,000		5.5σ	Θ^{++} candidate
SVD-2	370	2000		7.5σ	Improved analysis

Conclusions: Experiment (P. Stoler)

- The situation cannot be put into *any neat package*.
- New very high quality exclusive experiments from CLAS have repeated earlier experiments by SAPHIR and CLAS, and contradicted earlier positive observations.
- The new CLAS results do not exclude a state of <1 MeV width.
- There have been new positive reports from LEPS, SVD-2 and STAR.
- Beyond that there is a lot of overwhelming negative evidence which appear to push the observed pentaquark signals into narrower corners.

Conclusions: Theory

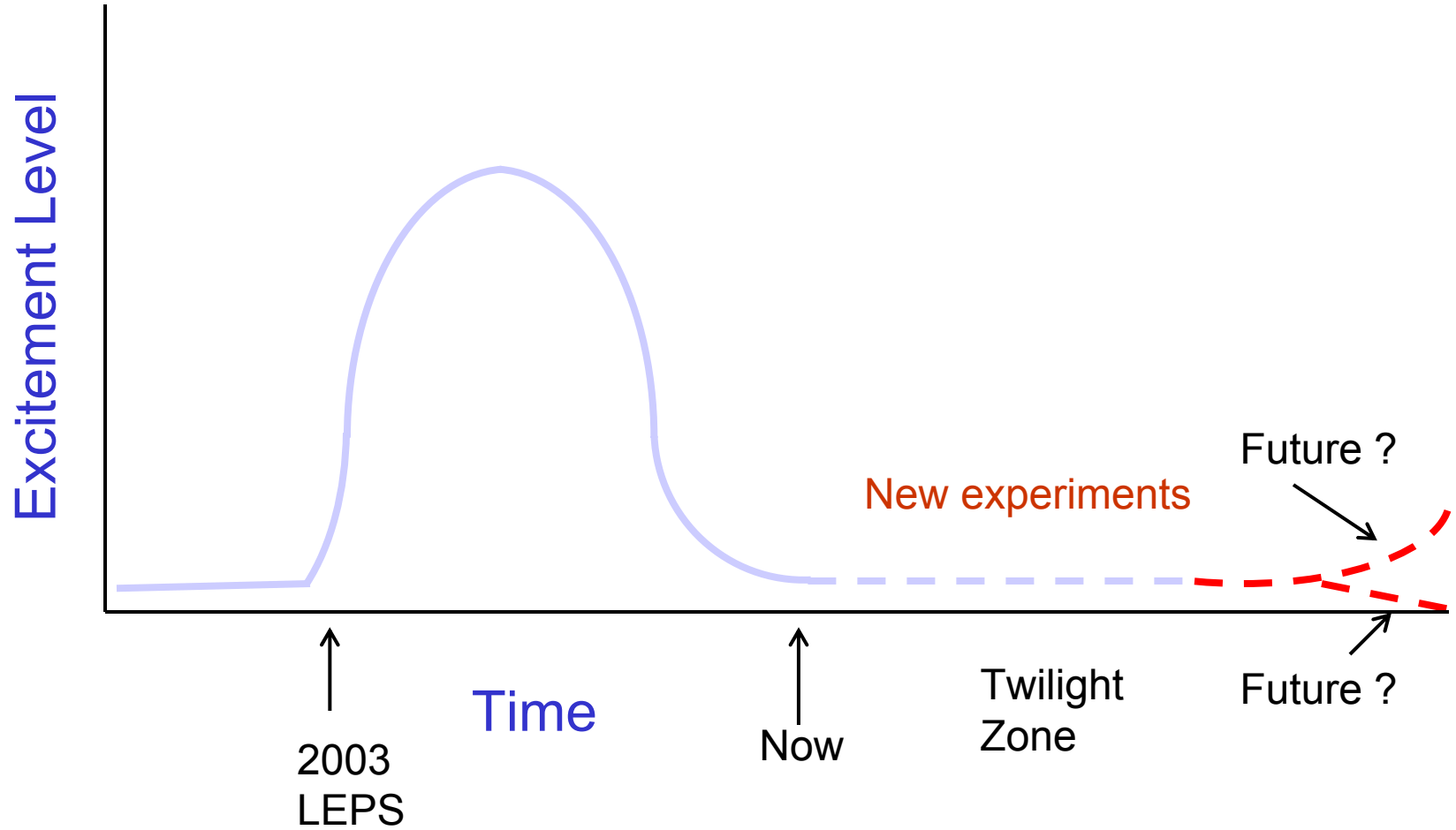
(M. Karliner)

- The pentaquark is not in good health, but it is still alive...
- Crucial open questions:
 - why do some experiments see it and other not
 - maybe does not exist (pessimistic view)
 - what is production mechanism (optimistic view)
 - if Θ^+ exists, why is it so **narrow**
 - why is cross section forward (LEPS, ZEUS)
 - is there an energy & Q^2 dependence
- Gold plated experiment: **K⁺ on nucleus** at low momentum
- Ball is in experimental court!

Prognosis

- Analysis is continuing at Spring8, JLab, COSY, HERMES, H1, ZEUS, SVD-2, STAR, PHENIX
- New measurements planned at SPring8 (March 2006), JLab 2006)
- H1, ZEUS, HERMES high luminosity run until July 2007
- Higher statistics data from STAR, PHENIX
- Limited additional statistics from B-factories, Fermilab and CERN
- Focus moved from bump hunting to more quantitative estimations of cross sections or upper limits

Pentaquark Vital Signs



Quote about Pentaquarks by a distinguished American

“...the reports of my death are exaggerated.”

...Mark Twain