A Search for Pentaquarks

Ed Hartouni
(for the E690 collaboration)
N-Division LLNL

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Current active members of Fermilab E690 collaboration

Columbia University – B.C. Knapp  
LLNL – E. P. Hartouni  
U. of Massachusetts – M.N. Kreisler
Motivation

Recently observed hadrons that do not fit into the “normal” spectroscopic order should have been produced in old experiments. Are these claims supported by the legacy data?

Fermilab Experiment 690 collected a $5 \times 10^9$ event sample of $p+p \rightarrow p_f + X$ events at a beam momentum of 800 GeV/c ($\sqrt{s} = 38.8$ GeV) at Lab G in the Neutrino-East beam line in the Tevatron 1991 fixed target run. The detector was an open geometry magnetic spectrometer with large geometric acceptance and extremely good momentum resolution.
Evidence for $S = +1$ baryon reported by a SPring-8 experimental collaboration at the Laser-Electron Facility (LEPS).

Figure 3(b) shows the corrected $K^-$ missing-mass distribution of the signal sample. A prominent peak at $1.54 \text{ GeV}/c^2$ is found. It contains 36 events in the peak region $1.51 \leq MM_{\gamma K^-}^c < 1.57 \text{ GeV}/c^2$. The broad background centered at $\sim 1.6 \text{ GeV}/c^2$ is most likely due to nonresonant $K^+ K^-$ production because the events in the bump do not show any noticeable structure in the $K^+$ missing-mass nor in the invariant $K^+ K^-$ mass spectra and the beam-energy dependence of the production rate reflects the phase space expansion with the energy. To

FIG. 3. (a) The $MM_{\gamma K^+}^c$ spectrum [Eq. (2)] for $K^+ K^-$ productions for the signal sample (solid histogram) and for events from the SC with a proton hit in the SSD (dashed histogram). (b) The $MM_{\gamma K^-}^c$ spectrum for the signal sample (solid histogram) and for events from the LH$_2$ (dotted histogram) normalized by a fit in the region above $1.59 \text{ GeV}/c^2$. 

012002-3
SPring-8 results seemed to be confirmed by several experiments
Is this object a Pentaquark?

Expect a new set of particles with quantum numbers different from the nominal $qqq$ baryon spectrum.

Given the SPring-8 result and the confirmation, the $nK^+$ state could be the $\Theta^+$. 

Are any of the other members of the multiplets seen?
What are Pentaquarks? Start with Diquarks:

Miyazawa (1966) recognized there existed an approximate symmetry between mesons and baryons built out of quarks.

Consider the combinations of two quarks, $qq$: $3 \otimes 3 = 3 \otimes 6$

This combination produces an anti-triplet and a sextet. Miyazawa observed that if you applied a super-symmetry operator to the anti-quark in a meson, it changed into a baryon:

$\left( \bar{q} \bar{q} q \right) q = qqq$

Catto and Gürsey (1985) extended this argument, and explored some of its implications within the context of QCD. They recognized this supersymmetry as an approximate consequence of QCD...

...that is, the color interaction of an anti-quark is approximately the same as a diquark (!).
Approximate symmetry?

Diquarks are:
  heavier than anti-quarks
  bosons rather than fermions
  larger than anti-quarks
QCD interactions have dependencies for mass, spin and size.

Take a $K = |s\bar{u}\rangle$ and apply the symmetry $|s(\bar{u} \rightarrow ud)\rangle$ then $|sud\rangle = \Lambda$

$m_K = 495 \text{ MeV/c}^2 \quad m_\Lambda = 1116 \text{ MeV/c}^2$
$m_s = 475 \text{ MeV/c}^2 \quad m_q = 300 \text{ MeV/c}^2$

So $m_\Lambda - (m_K + m_q) = 321 \text{ MeV/c}^2$

This additional mass indicates the amount of symmetry breaking. Baryons always seem to have a larger mass than the mesons with this transformation.
Pentaquarks

So following this train of thought, might there be hadron configurations of multiple diquarks... there are anti-baryons: $\bar{q} \bar{q} \bar{q}$, could two of the anti-quarks be replaced by diquarks? $[qq] [qq] \bar{q}$ to make a 5 quark system, the *pentaquark*

$[qq]_0 \quad J^P=0^+ \quad \bar{3}_F \quad \bar{3}_C$

$[qq]_0 \quad [qq]_0 \quad \bar{q}$

Flavor $\bar{3} \times \bar{3} \rightarrow \bar{6}_{\text{sym}} \times \bar{3} \rightarrow \bar{10} \oplus 8$

Color $\bar{3} \times \bar{3} \rightarrow \bar{3}_{\text{antisym}} \times \bar{3} \rightarrow 1$

Spin $0^+ \times 0^+ \rightarrow 0^+ \times \frac{1}{2}^-$

$\rightarrow (1/2, 3/2)^+$

Space $P \quad S$

Mass? Take a $\bar{\Lambda} = |s \bar{u} \bar{d} >$ and make it a $|s \bar{u} \bar{d} \bar{u} \bar{d} >$ pentaquark, the mass should be $M \geq m_\Lambda + 2m_q = 1116 + 300 + 300 = 1716 \text{ MeV/c}^2$

Resonance width? Nothing prevents quark rearrangement, expected to be broad...
Additional experimental results find evidence for two other anti-decuplet members and their anti-particles.


In summary, this analysis provides the first evidence for the existence of a narrow baryon resonance in the \( \Xi^- \pi^- \) invariant mass spectrum with a mass of \( 1.862 \pm 0.002 \text{ GeV}/c^2 \) and a width below the detector resolution of about 0.018 GeV/c^2. The significance is estimated to be above 4.2\( \sigma \). This state is a candidate for the exotic \( \Xi_{1/2}^- \) baryon with \( S = -2, I = 3/2 \), and a quark content of \( (dssd\bar{u}) \). Further, in the \( \Xi^- \pi^+ \) invariant mass spectrum at the same mass an indication is observed of the \( \Xi_{1/2}^- \) member of this isospin quartet with a quark content of \( (dssd\bar{d}) \). Also, the corresponding antiparticle spectra show enhancements at the same invariant mass. Summing the four mass distributions increases the significance of the peak to 5.8\( \sigma \).

The evidence for an exotic \( \Xi^- \pi^- \) resonance together with the indication of a \( \Xi^- \pi^+ \) resonance at the same mass represents an important step towards experimental confirmation of the predicted baryon antidecuplet of pentaquark states. Definitive identification and exclusion of alternative interpretations require the determination of spin, parity, and isospin of the observed states.

\[
pp \rightarrow \Xi \pi + X
\]

FIG. 2 (color online). Invariant mass spectra after selection cuts for \( \Xi^- \pi^- \) (a), \( \Xi^- \pi^+ \) (b), \( \Xi^+ \pi^- \) (note that the \( \Xi(1530)^+ \) state is also visible) (c), and \( \Xi^+ \pi^+ \) (d). The shaded histograms are the normalized mixed-event backgrounds.

FIG. 3 (color online). (a) The sum of the \( \Xi^- \pi^- \), \( \Xi^- \pi^+ \), \( \Xi^+ \pi^- \), and \( \Xi^+ \pi^+ \) invariant mass spectra. The shaded histogram shows the normalized mixed-event background. (b) Background subtracted spectrum with the Gaussian fit to the peak.
The “Normal” Hadron Spectroscopic Order

What we learned on our mother’s knee –
The SU(3) flavor multiplets are built out of combinations of the quarks:

\[ q\bar{q} \quad 3 \otimes \bar{3} = 1 \oplus 8 \quad \text{singlet and octet} \]
\[ qqq \quad 3 \otimes 3 \otimes 3 = 1 \oplus 8 \oplus 8 \oplus 10 \quad \text{singlet, octet and decuplet} \]

Which explains the observed spectrum of hadrons.
Can we understand this from Quantum Chromo-Dynamics (QCD)?

No reliable calculations of the hadron spectrum from QCD.
No conclusive explanation for the observed flavor multiplets.

*Observations define the spectroscopy and guide theory.*

\[ qqqqq \quad \text{(dibaryon)} \quad \text{no conclusive candidates} \]
\[ qqqq \quad \text{no conclusive candidates} \]
\[ qqqg \quad \text{(exotic)} \quad \text{no conclusive candidates} \]
\[ q\bar{q}g \quad \text{(exotic)} \quad \text{no conclusive candidates} \]
\[ gg \quad \text{(glueball)} \quad \text{no conclusive candidates} \]
Status as reported in the 2002 edition of the Review of Particle Properties

Table 13.2: Suggested \( q\bar{q} \) quark-model assignments for most of the known mesons. Some assignments, especially for the \( 0^+ \) and \( -1^+ \) multiplets and for some of the higher multiplets, are controversial. Mesons in bold face are included in the Meson Summary Table. Of the light mesons in the Summary Table, the \( f_0(1500), f_1(1285), f_2(1270), f_3(1270), f_0(1400), f_4(1400), f_5(1700), f_6(1700), g_4(1710), \) and \( g_5(1710) \) are the only mesons with a state in the table. Within the \( q\bar{q} \) model, it is especially hard to find a place for the first two of these \( f \) mesons and for one of the \( g \) mesons.

| \( \bar{q}q \) | \( J^{PC} \) | \( u \bar{u}, \bar{d}d \) | \( l = 1 \) | \( s \bar{s} \) | \( l = 0 \) | \( \omega \) | \( l = 0 \) | \( \rho \) | \( l = 0 \) | \( \varphi \) | \( l = 0 \) |
|---|---|---|---|---|---|---|---|---|---|---|
| \( \eta \) | 0\(^+\) \( \pi \) | \( \eta \) | \( \eta' \) | \( \eta \) | \( \eta \) | \( K \) | \( D \) | \( D_s \) | \( B \) | \( B_s \) | \( B_s \) |
| \( \eta' \) | 1\(^-\) \( \rho \) | \( \omega \) | \( \rho \) | \( \omega \) | \( \omega \) | \( K^{*}(892) \) | \( \rho(1450) \) | \( \rho(1450) \) | \( \rho(1450) \) | \( \rho(1450) \) | \( \rho(1450) \) |
| \( P_1 \) | 1\(^-\) \( b_1(1235) \) | \( b_1(1235) \) | \( b_1(1235) \) | \( b_1(1235) \) | \( b_1(1235) \) | \( K^{*}(1410) \) | \( D(1940) \) | \( D(1940) \) | \( D(1940) \) | \( D(1940) \) | \( D(1940) \) |
| \( P_2 \) | 0\(^+\) \( \phi(q(1400), q(1850)) \) | \( \phi(q(1400), q(1850)) \) | \( \phi(q(1400), q(1850)) \) | \( \phi(q(1400), q(1850)) \) | \( \phi(q(1400), q(1850)) \) | \( K^{*}(1410) \) | \( D(1940) \) | \( D(1940) \) | \( D(1940) \) | \( D(1940) \) | \( D(1940) \) |
| \( D_0 \) | 0\(^-\) \( \phi(q(1400), q(1850)) \) | \( \phi(q(1400), q(1850)) \) | \( \phi(q(1400), q(1850)) \) | \( \phi(q(1400), q(1850)) \) | \( \phi(q(1400), q(1850)) \) | \( K^{*}(1410) \) | \( D(1940) \) | \( D(1940) \) | \( D(1940) \) | \( D(1940) \) | \( D(1940) \) |
| \( D_1 \) | 1\(^-\) \( \phi(q(1400), q(1850)) \) | \( \phi(q(1400), q(1850)) \) | \( \phi(q(1400), q(1850)) \) | \( \phi(q(1400), q(1850)) \) | \( \phi(q(1400), q(1850)) \) | \( K^{*}(1410) \) | \( D(1940) \) | \( D(1940) \) | \( D(1940) \) | \( D(1940) \) | \( D(1940) \) |
| \( D_2 \) | 2\(^+\) \( \phi(q(1400), q(1850)) \) | \( \phi(q(1400), q(1850)) \) | \( \phi(q(1400), q(1850)) \) | \( \phi(q(1400), q(1850)) \) | \( \phi(q(1400), q(1850)) \) | \( K^{*}(1410) \) | \( D(1940) \) | \( D(1940) \) | \( D(1940) \) | \( D(1940) \) | \( D(1940) \) |

* See our scalar multiview in the Particle Listings. The candidates for the \( I = 1 \) states are \( \omega(1400) \) and \( \varphi(1400) \), while for \( I = 0 \) they are \( \phi(1400) \) and \( \rho(1400) \).

1 The \( K_L(1270) \) and \( K_S(1270) \) are nearly equal (45\(^{-}\)) mixtures of the \( K_1(1270) \) and \( K_2(1270) \).

2 The \( K^*(1410) \) could be replaced by the \( K^*(1430) \) as the \( 3\bar{S}_0 \) state.

Table 13.4: Quark-model assignments for many of the known baryons in terms of a flavor-spin SU(6) basis. Only the dominant representation is listed. Assignments for some states, especially for the \( A(1810), A(2350), A(2800), \) and \( A(3000) \), are merely educated guesses. For assignments of the charmed baryons, see the "Note on Charged Baryons" in the Particle Listings.

<table>
<thead>
<tr>
<th>( J^{PC} )</th>
<th>( (D, D_s) )</th>
<th>( S )</th>
<th>Octet members</th>
<th>Singlets</th>
</tr>
</thead>
<tbody>
<tr>
<td>1/2(^+)</td>
<td>( 56) (56)</td>
<td>1/2</td>
<td>( N(939) )</td>
<td>( A(1116) )</td>
</tr>
<tr>
<td>1/2(^-)</td>
<td>( 56)</td>
<td>1/2</td>
<td>( N(1440) )</td>
<td>( A(1670) )</td>
</tr>
<tr>
<td>3/2(^-)</td>
<td>( 56)</td>
<td>3/2</td>
<td>( N(1580) )</td>
<td>( A(1900) )</td>
</tr>
<tr>
<td>1/2(^-)</td>
<td>( 56)</td>
<td>1/2</td>
<td>( N(1650) )</td>
<td>( A(1850) )</td>
</tr>
<tr>
<td>5/2(^-)</td>
<td>( 56)</td>
<td>5/2</td>
<td>( N(1720) )</td>
<td>( A(1900) )</td>
</tr>
<tr>
<td>7/2(^-)</td>
<td>( 56)</td>
<td>7/2</td>
<td>( N(1790) )</td>
<td>( A(1950) )</td>
</tr>
<tr>
<td>9/2(^-)</td>
<td>( 56)</td>
<td>9/2</td>
<td>( N(1860) )</td>
<td>( A(1980) )</td>
</tr>
</tbody>
</table>

* Octet members |

<table>
<thead>
<tr>
<th>( J^{PC} )</th>
<th>( (D, D_s) )</th>
<th>( S )</th>
<th>Octet members</th>
<th>( S )</th>
</tr>
</thead>
<tbody>
<tr>
<td>3/2(^+)</td>
<td>( 56)</td>
<td>3/2</td>
<td>( \Delta(1232) )</td>
<td>( \Sigma(1388) )</td>
</tr>
<tr>
<td>1/2(^-)</td>
<td>( 56)</td>
<td>1/2</td>
<td>( \Delta(1620) )</td>
<td>( \Sigma(1850) )</td>
</tr>
<tr>
<td>3/2(^-)</td>
<td>( 56)</td>
<td>3/2</td>
<td>( \Delta(1700) )</td>
<td>( \Sigma(1950) )</td>
</tr>
<tr>
<td>5/2(^-)</td>
<td>( 56)</td>
<td>5/2</td>
<td>( \Delta(1900) )</td>
<td>( \Sigma(2100) )</td>
</tr>
<tr>
<td>7/2(^-)</td>
<td>( 56)</td>
<td>7/2</td>
<td>( \Delta(2000) )</td>
<td>( \Sigma(2200) )</td>
</tr>
<tr>
<td>9/2(^-)</td>
<td>( 56)</td>
<td>9/2</td>
<td>( \Delta(2100) )</td>
<td>( \Sigma(2300) )</td>
</tr>
</tbody>
</table>

* Octet members |
A ghost from the past? The Roper Resonance...

\[ N(1440), P_{11} I(J^P) = 1/2(1/2^+) \]

Is it possible that the “enigmatic” nature of these baryon resonances comes from their membership in the pentaquark octet and anti-decuplet?

... also:

\[ N(1710), P_{11} I(J^P) = 1/2(1/2^+) \]

Perhaps some of these old mysteries of baryon spectroscopy are resolved?

Evidence for 5 pentaquarks!

The \( P_{11} N(1440) \): Interest in this enigmatic resonance persists because two rather different theoretical approaches both predict that the \( M_{1-} \) multipole sign will change as \( Q^2 \) increases from zero...
E690 should see these states!

Triggered on $p+p \rightarrow p_f + X$
Reconstructed the $X$ with high efficiency.

Pentaquarks are hadrons, should be produced copiously in this process.

E690 has excellent mass resolution.
A large data set, $5 \times 10^9$ events.
Past analysis focused on light meson spectroscopy in partial wave analysis, hyperon polarization in exclusive states and diffractive charm production...

...no detailed search for exotic hyperon states was performed at the time. Hyperons were copiously produced, however...

OBSERVATION OF PENTAQUARKS SHOULD BE A SLAM DUNK!
E690 apparatus

800 GeV/c pbeam

25 m Multi-particle spectrometer

180 m

60 m

Beam chamber

Target system

Cherenkov counter

Beam chamber

Beam Spectrometer (Incoming)

JKG System (Main)

Beam Spectrometer (Forward)

540-800 GeV/c pfast
E690 apparatus

Liquid Hydrogen target
6 Drift Chambers
2 Time-of-Flight walls
96 mirror threshold Cerenkov counter
1T dipole field

Downstream beam spectrometer system
E690 performance

\[ \Lambda - \text{Effective Mass} \]

\[ \Lambda^+ - \text{Effective Mass} \]

Number per 0.2 MeV

FWHM \(
\approx 2.5 \text{ MeV}\)

\[ \Xi^- - \text{Effective Mass} \]

\[ \Xi^+ - \text{Effective Mass} \]

\[ \Lambda \text{ (in } \Xi^-) \]

\[ \Lambda \text{ (in } \Xi^+) \]

Number per 0.2 MeV

FWHM \(
\approx 2 \text{ MeV}\)
Hyperon inclusive search $pp \rightarrow p_f + \Xi \pi + X$

- Primary vertex constrained to lie on incoming beam trajectory.

- In events with “Vee” or “Cascade” topology:
  - Tracks refit with geometrical constraint that daughter vertex must point back to parent (no mass constrained fits).
  - Topologies identified:
    $\gamma \rightarrow e^+ e^- \quad K_s \rightarrow \pi^+ \pi^- \quad \Lambda \rightarrow p \pi \quad \bar{\Lambda} \rightarrow \bar{p} \pi^+ \quad \Xi \rightarrow \Lambda \pi$
    $\Xi^+ \rightarrow \Lambda \pi^+ \quad \Omega^- \rightarrow \Lambda K^- \quad \bar{\Omega}^+ \rightarrow \bar{\Lambda} K^+ \quad K^+ \rightarrow \pi^+ \pi^+ \pi^- \quad K^- \rightarrow \pi^+ \pi^- \pi^+$

- Events selected with $\Xi^-$ or $\Xi^+$ assigned to primary vertex.
  - 512,850 $\Xi^-$ events selected.
  - 153,671 $\Xi^+$ events selected.

- Average number of mass combinations per event:
  $\Xi^\pi^+ : 3.5 \quad \Xi^- \pi^- : 2.0 \quad \Xi^+ \pi^+ : 2.7 \quad \Xi^+ \pi^- : 2.6$
Monte Carlo mass resolution ($\sigma$) for $\Xi\pi$: 3.3 MeV at 1750 MeV; 4.5 MeV at 1862 MeV.
Fit to a simple background and a relativistic Breit-Wigner (with mass dependent width):

\[ f(x) = P(x - m_h) e^{-R(x - m_h)} + P_4 \frac{\Gamma(x)}{\left(x^2 - P_5^2\right)^2 + P_6^2 \Gamma^2(x)} \]

\[ \Gamma(x) = P_5 \left(\frac{q(x)}{q_0}\right)^{2L+1} \]

\[ q(x) = \frac{x}{2} \sqrt{\left[1 - \left(\frac{m_1 - m_2}{x}\right)^2\right]\left[1 - \left(\frac{m_1 + m_2}{x}\right)^2\right]} \]

\[ q_0 = q(P_6) \]

Gaussian smear the distributions with mass resolution \( \sigma = 2.5 \text{ MeV}/c^2 \) to reproduce \( \Xi(1530) \) width \( \Gamma_0 = 9 \text{ MeV}/c^2 \) Also take \( L=1... \)

<table>
<thead>
<tr>
<th>( \Xi^+\pi^+ )</th>
<th>( \Xi^-\pi^- )</th>
<th>( \Xi^+\pi^- )</th>
<th>( \Xi^0\pi^0 )</th>
</tr>
</thead>
<tbody>
<tr>
<td>P1 (1.773±0.002)x10^4</td>
<td>(0.919±0.001)x10^4</td>
<td>(0.322±0.007)x10^4</td>
<td>(0.405±0.008)x10^4</td>
</tr>
<tr>
<td>P2 0.5421±0.0006</td>
<td>0.4949±0.0008</td>
<td>0.4208±0.0001</td>
<td>0.5001±0.0001</td>
</tr>
<tr>
<td>P3 3.266±0.003</td>
<td>3.445±0.007</td>
<td>3.256±0.006</td>
<td>3.242±0.005</td>
</tr>
<tr>
<td>P4 244.1±1.1</td>
<td></td>
<td>57.6±0.6</td>
<td></td>
</tr>
<tr>
<td>P5 0.00896±0.00006</td>
<td></td>
<td>0.00941±0.00001</td>
<td></td>
</tr>
<tr>
<td>P6 1.53273±0.00003</td>
<td></td>
<td>1.53265±0.00006</td>
<td></td>
</tr>
<tr>
<td>( \chi^2/\text{dof} ) 683/364</td>
<td>1029/367</td>
<td>443/364</td>
<td>462/367</td>
</tr>
<tr>
<td>( \Xi(1530) ) Number 93728±422</td>
<td></td>
<td>22211±219</td>
<td></td>
</tr>
<tr>
<td>95% CL at 1862 MeV/c^2</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Gaussian (( \sigma = 7.6 \text{ MeV}/c^2 )) 1020</td>
<td>310</td>
<td>290</td>
<td>288</td>
</tr>
</tbody>
</table>
Calculating the Confidence Limit

The fits are performed minimizing the $\chi^2$:

$$\chi^2 = \sum_i \left( \frac{d_i - f_i}{e_i} \right)^2$$

Where $d_i$ is the data with error $e_i$ and $f_i$ is the fit function for the $i=1,N$ bins of the invariant mass distribution. If we have a signal, e.g.:

$$s_i = n_0 \frac{e^{-(m_i-m_0)^2/2\sigma^2}}{\sqrt{2\pi}\sigma} \equiv n_0 g_i$$

We can calculate the CL at some level, e.g. 95%, that for a given $m_0$ and $\sigma$ the number of events does not exceed $n_0$.

The “new” $\chi^2$ is given by:

$$\chi^2 = \sum_i \left( \frac{d_i - f_i - s_i}{e_i} \right)^2$$

And differs from the $n_0 = 0 \chi^2$ by:

$$\Delta\chi^2 = n_0^2 \sum_i \frac{g_i^2}{e_i^2} - 2n_0 \sum_i \left( \frac{d_i - f_i}{e_i} \right) g_i$$

This is quadratic in $n_0$ leading to the CL value:

$$n_0 = \frac{\sum (d_i - f_i) g_i e_i^2}{\sum g_i^2 e_i^2} + \sqrt{\left( \sum \frac{(d_i - f_i) g_i}{e_i^2} \right)^2 + \Delta\chi^2 \sum \frac{g_i^2}{e_i^2}}$$

For a 95% CL, $\Delta\chi^2 = 3.84$.

This is essentially the prescription of Feldman & Cousins.
95% CL limit < 1020 events at M= 1.862 GeV

$N_{\Xi^- (1530)} = 94000$

95% CL limit < 310 events at M= 1.862 GeV
95\% CL limit < 290 events at $M = 1.862$ GeV

$N_{\Xi^+(1530)} = 22000$

95\% CL limit < 288 events at $M = 1.862$ GeV
“Signal” at 95% CL for NA-49 parameters
Search for $\Theta^+$ in fully reconstructed final states

$$pK_s \text{ in } pp \rightarrow p_{\text{slow}}K_sK^-\pi^+p_{\text{fast}}$$

- Low multiplicity *exclusive* reaction $\rightarrow$ limited combinatorics.

- $K_s$ is correct strangeness for $\Theta^+$ (assuming strangeness conservation in production). Tagged by the sign of the charged kaon.

- Events selected by topology, and energy and momentum conservation.
  - Loose cut on $p_L$ conservation (5 GeV).
  - Tight cut on $p_T^2$ conservation (.002 GeV$^2$ $\sim$ (45 MeV)$^2$).
  - Tight cut on (E-$p_L$) conservation (-.02 - .015 GeV).
    E & $p_L$ errors are highly correlated.
  - Possible to distinguish “wrong strangeness” events that have $\Delta(E-p_L)$ consistent with $p_{\text{slow}}K_sK^+\pi^-p_{\text{fast}}$

- 68,050 $p_{\text{slow}}K_sK^-\pi^+p_{\text{fast}}$ events selected.
  - 63,945 with one solution.
  - 4105 (6%) with 2 solutions ($\pi^+/p_{\text{slow}}$ ambiguity).

- 43,000 $p_{\text{slow}}K_sK^+\pi^-p_{\text{fast}}$ events selected.
  - 7% with alternative solutions.
Event selection kinematic cuts for \( pp \rightarrow p_{\text{slow}} K_s K^- \pi^+ p_{\text{fast}} \)

\[
(\vec{p}_\perp)^2 = \left( \sum_i \vec{p}_{\perp i} \right)^2
\]

\[
E^2 - p_L^2 = m^2 + p_{\perp}^2
\]

\[
E - p_L = \frac{m^2 + p_{\perp}^2}{E + p_L}
\]

\[
\sum_{\text{initial}} (E - p_L) = \sum_{\text{final}} (E - p_L)
\]

\[
\Delta(E - p_L) = \sum_{\text{initial}} (E - p_L) - \sum_{\text{final}} (E - p_L)
\]

\[
\cong m_p - \sum_{\text{final}} \left( \frac{m^2 + p_{\perp}^2}{E + p_L} \right)
\]

Estimate background from number of events under the \( \Delta(E - p_L) \) distribution.
Search for $pK_s^0$

$$pp \rightarrow p_f K_s^0 K^- \pi^+ p$$

$a_0(980)$ is just below threshold.

$a_2(1320)$
$pK_s$ and $pK^-$

Monte Carlo $pK_s$ mass resolution ($\sigma$) at 1540 MeV is 1.5 MeV.
Width of $\Theta$ not established, DIANA reports $< 9 \text{ MeV/c}^2$, HERMES and ZEUS $< 6 \text{ MeV/c}^2$ and, Cahn & Trilling reanalyze DIANA data and set FWHM $= 1.1 \text{ MeV/c}^2$ (PDG value).

E690 resolution is $1.5 \text{ MeV/c}^2$ at $1540 \text{ MeV/c}^2$ (estimated from Monte Carlo).

At the $\Theta^+(1542)$ mass, a $\sigma = 9, 6, 1.5 \text{ MeV/c}^2$ Gaussian signal is excluded at 95% CL above 113, 60, 25 events

$\Theta^+(1542)/\Lambda(1520) \leq 1.4\%, 0.7\%, 0.3\%$
Search for $pK_s^0$

$pp \rightarrow p_f K_s^0 K^+ \pi^- p$

$a_0(980)$ is just below threshold.

$a_2(1320)$
Estimate the acceptance for $K_s^0 \rightarrow \pi\pi$ from comparing $pK_s$ and $pK^+$ distributions.

Normalize the distributions;
Compare $pK_s$ to $pK^+$, differ by a factor of $\approx 2.5$;
Assume the $pK^+$ acceptance is the same as the $pK^-$ then the acceptance for $\Lambda(1520)$ is 2.5 times that for the $\Theta^+(1542)$;
Revised 95% CL yield $\Theta^+(1542)/\Lambda(1520) \leq 3.5\%$
Calculate 95% CL for $pp \rightarrow p_f K^0_s K^+ \pi^- p$ reaction

for $\sigma = 9, 6, 1.5$ MeV/c²

Gaussian signal is excluded at 95% CL

above 113, 81, 29 events

$X^+(1542)/\Lambda(1520) \leq 1.4\%, 1.0\%, 0.3\%$

above 37, 36, 24 events

$\Theta^{++}(1542)/\Lambda(1520) \leq 0.4\%, 0.4\%, 0.3\%$
Where are the pentaquarks?

• In an inclusive study of $\Xi^\pm \pi^\mp$:
  – Strong signals are observed for $\Xi(1530)$ and $\Xi(1530)$.
  – No other mass peak is observed.
  – The number of $\Xi^- \pi^-$ produced at 1862 MeV in a $\sigma=7.6$ MeV resonance is less than 1% of the observed number of $\Xi(1530) \rightarrow \Xi^- \pi^+$. 
  – The number of $\Xi^+ \pi^+$ produced at 1862 MeV in a narrow resonance is less than 1% of the observed number of $\Xi(1530) \rightarrow \Xi^+ \pi^-$. 

• In a study of the exclusive reaction $pp \rightarrow pK_s K^\mp \pi^\mp p$:
  – Strong signals are observed for a number of well-established meson and baryon resonances.
  – No exotic mass peak is observed.
  – The number of $pK_s$ produced at 1540 MeV in a $\sigma=9$ MeV resonance is less than 4% of the observed number of $\Lambda(1520) \rightarrow pK^-$. 

Fermilab E690 observes that the production of pentaquark resonances is heavily suppressed with respect to the production of normal baryon and anti-baryon resonances in $pp \rightarrow pX$ at 800 GeV/c.
Published observations:

<table>
<thead>
<tr>
<th>Collaboration</th>
<th>reference</th>
<th>state</th>
<th>mass (MeV/c²)</th>
<th>Width (MeV/c²)</th>
<th>significance</th>
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<tr>
<td>SAPHIR</td>
<td>Phys. Lett. B572, 127(2003)</td>
<td>$\Theta^+ \to nK^+$</td>
<td>1540</td>
<td>&lt; 25</td>
<td>4.8 $\sigma$</td>
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<td>DIANA</td>
<td>Phys. At. Nucl. 66, 1715 (2003)</td>
<td>$\Theta^+ \to pK^0_s$</td>
<td>1539</td>
<td>&lt; 9</td>
<td>4.4 $\sigma$</td>
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<tr>
<td>CLAS</td>
<td>Phys. Rev. Lett. 25, 252001 (2003)</td>
<td>$\Theta^+ \to nK^+$</td>
<td>1542</td>
<td>&lt; 21</td>
<td>5.2 $\sigma$</td>
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<tr>
<td>HERMES</td>
<td>Phys. Lett. B585, 213 (2004)</td>
<td>$\Theta^+ \to pK^0_s$</td>
<td>1528</td>
<td>4.3 – 6.2</td>
<td>4 – 6 $\sigma$</td>
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<td>$\Theta^{**} \to pK^+$</td>
<td>1450-1700</td>
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<td>ZEUS</td>
<td>Phys. Lett. B591, 7 (2004)</td>
<td>$\Theta^+ \to pK^0_s$</td>
<td>1521</td>
<td>6.1</td>
<td>3.9 – 4.6 $\sigma$</td>
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<td>$\Theta^+ \to pK^0_s$</td>
<td>1521</td>
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<td>3 $\sigma$</td>
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<td>COSY-TOF</td>
<td>Phys. Lett. B595, 127 (2004)</td>
<td>$\Theta^+ \to pK^0_s$</td>
<td>1530</td>
<td>&lt; 18</td>
<td>4 – 6 $\sigma$</td>
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<td>CLAS</td>
<td>Phys. Rev. Lett. 92, 032001 (2004)</td>
<td>$\Theta^+ * (?) \to nK^+$</td>
<td>1555</td>
<td>= 26 (FWHM)</td>
<td>7.8 $\sigma$</td>
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<td>NA-49</td>
<td>Phys. Rev. Lett. 92, 042003 (2004)</td>
<td>$\Xi^- \to \Xi^- \pi^-$</td>
<td>1862</td>
<td>&lt; 18 (FWHM)</td>
<td>4.2 $\sigma$</td>
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### Published non-observations:

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<th>Collaboration</th>
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<th>mass (MeV/c^2)</th>
<th>Width (MeV/c^2)</th>
<th>significance</th>
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<tr>
<td>Hyper-CP</td>
<td>Phys. Rev. D 70, 111101(R) (2004)</td>
<td>$\Theta^+ \to pK_s^0$</td>
<td>1540</td>
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<td>Yield &lt;0.3% 90% CL</td>
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<td>$\Xi^- \to \Xi^- \pi^-$</td>
<td>18 (FWHM)</td>
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<td>$R_2 &lt; 4%$ 95% CL</td>
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<tr>
<td>HERA-B</td>
<td>Phys. Rev. Lett. 93, 212003 (2004)</td>
<td>$\Theta^+ \to pK_s^0$</td>
<td>1521-1555</td>
<td>5</td>
<td>$R_1 &lt; 3-12%$ 95% CL</td>
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<td>$\Xi^- \to \Xi^- \pi^-$</td>
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<td>$R_2 &lt; 1.4%$ 95% CL</td>
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<td>WA49</td>
<td>Phys. Rev. C 79, 022201(R) (2004)</td>
<td>$\Xi^- \to \Xi^- \pi^-$</td>
<td>1860</td>
<td>20 (FWHM)</td>
<td>$R_2 &lt; 1.4%$ 95% CL</td>
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<tr>
<td>SPHINX</td>
<td>Eur. Phys. J. A 21, 455 (2004)</td>
<td>$\Theta^+ \to nK^+$</td>
<td>1540</td>
<td>10</td>
<td>$R_1 &lt; 2%$ 90% CL</td>
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<td>$\Theta^+ \to pK_s^0$</td>
<td>1540</td>
<td>12</td>
<td>48±29 events</td>
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<td>$\Theta^+ \to pK_s^0$</td>
<td>1540</td>
<td>11</td>
<td>6±43</td>
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<td>$\Theta^+ \to pK^+$</td>
<td>1540</td>
<td>8</td>
<td>-57±100</td>
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<td>BES</td>
<td>Phys. Rev. D 70, 012004 (2004)</td>
<td>$\Theta^+ \to pK_s^0$</td>
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<td>$&lt;\sim 10^{-5}$ J/τ decays</td>
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<td>$\Theta^+ \to nK^+$</td>
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<td>$\Theta^+ \to \bar{n}K^+$</td>
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<td>ALEPH</td>
<td>Phys. Lett. B 599, 1 (2004)</td>
<td>$\Theta^+ \to pK_s^0$</td>
<td>1535</td>
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<td>$&lt;6.2 \times 10^{-4}$ Z decays 95% CL</td>
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<td>$\Xi^- \to \Xi^- \pi^-$</td>
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<td>$&lt;4.5 \times 10^{-4}$</td>
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<td>$\Xi^0 \to \Xi^- \pi^+$</td>
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<td>$&lt;8.9 \times 10^{-4}$</td>
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<td>COMPASS</td>
<td>Eur. Phys. J. C 41, 469 (2005)</td>
<td>$\Xi^- \to \Xi^- \pi^-$</td>
<td>1860</td>
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<td>$R_2 &lt; 4.6%$ 95% CL</td>
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<td>HERMES</td>
<td>Phys. Rev. D 71, 032004 (2005)</td>
<td>$\Xi^- \to \Xi^- \pi^-$</td>
<td>1862</td>
<td>2 (FWHM)</td>
<td>$R_2 &lt; 14%$ 90% CL</td>
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<tr>
<td>ZEUS</td>
<td>Phys. Lett. B 610, 212 (2005)</td>
<td>$\Xi^- \to \Xi^- \pi^-$</td>
<td>1650-2350</td>
<td>10</td>
<td>$R_2 &lt; 29%$ 95% CL</td>
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<td>BaBar</td>
<td>Phys. Rev. Lett. 95, 042002 (2005)</td>
<td>$\Theta^+ \to pK_s^0$</td>
<td>1520-1550</td>
<td>8</td>
<td>$&lt;11 \times 10^{-5}$ hadronic prod. 95% CL</td>
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<td>$\Xi^- \to \Xi^- \pi^-$</td>
<td>1760-1960</td>
<td>18</td>
<td>$&lt;1.1 \times 10^{-5}$</td>
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</table>

\[
R_1 = \frac{N_{\Theta(1540)}}{N_{A(1520)}}
\]

\[
R_2 = \frac{N_{\Xi^-(1583)}}{N_{\Xi(1532)}}
\]
The experimental situation is confused, some experiments report observations, others report limits. At least one experiment has taken higher statistics data with no signal where the same experiment reported a signal at lower statistics (CLAS).

At best the evidence is weak and getting weaker.

The theoretical/phenomenological situation is also confused, “postdictions” indicate that a pentaquark could exist at the masses observed. No explanation of the narrow width or the production and decay properties has emerged.

The extraordinary claims of a whole new spectrum of particles lacks definitive experimental and theoretical confirmation.

Baryon and Meson spectroscopy are a potential window through which to study the Standard Model and QCD. Understanding what we are seeing through this window is a worthy challenge for both experiment and theory; a challenge that should be taken up more vigorously by the particle physics community.