Particles unseen in FOCUS

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DPF 2004: Riverside, CA
The search list

What was searched for:
- $S = -1$ pentaquark $\Theta(1540)^+$ with quark content $uudd\bar{s}$
- $S = -2$ pentaquark $\phi(1860)^{-+}$ with quark content $\bar{u}ddss$
- Charm pentaquark $\Theta_c(3100)^0$ with quark content $uudd\bar{c}$
- Double charm baryons $\Xi_{cc}$ with quark content $ccu$ and $ccd$

Please note the following:
- All results are preliminary
- Charge conjugates are always implied
The FOCUS experiment

- **FOCUS** took data in the Fermilab fixed-target run of 1996-7
- $\pm e \sim 300$ GeV bremsstrahlung on lead target to create photon beam
- Photons interact in BeO targets
- Charged particles tracked and momentum analyzed with silicon strips, wire chambers, and two magnets
- Three multicell threshold Čerenkov counters for particle ID
- Trigger required $\sim 35$ GeV of energy in the hadron calorimeter
- 7 billion hadronic events on tape
Evidence for $\Theta^+(uudd\bar{s})$

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Summary of $\Theta^+$ mass measurements

$<M> = 1533.6 \pm 1.2 \text{ MeV/c}^2$

$\chi^2$/dof $= 38.2 / 9$

CL $= 1.6 \times 10^{-5}$ (5.2$\sigma$ effect)
FOCUS analysis: $\Theta(1540)^+ \rightarrow pK_S^0$ search

- Search for $\Theta^+ \rightarrow pK_S^0$ and compare to $K^{*+}(892) \rightarrow K_S^0\pi^+$ and $\Sigma(1385)^\pm \rightarrow \Lambda^0\pi^\pm$ (similar topology)
- Reconstruct $K_S^0 \rightarrow \pi^+\pi^-$ and $\Lambda^0 \rightarrow p\pi^-$
- Use Čerenkov ID on fast track to separate $K_S^0$ and $\Lambda^0$
- Remaining good quality tracks must be consistent with one vertex (CL $>1\%$) suppressing charm decays and reinteractions
- Various minor clean up cuts applied to vees and charged tracks
- Mass of $K_S^0$ or $\Lambda^0$ candidate within 2.5$\sigma$ of nominal mass
- Very stringent Čerenkov ID cut applied to proton in $pK_S^0$ (misid $\sim 0$)
Vee samples

Yield: 64594364 ± 10942
\[ \int S/B (\pm 2.5\sigma) = 12.1 \]

Yield: 8389354 ± 4033
\[ \int S/B (\pm 2.5\sigma) = 25.3 \]

**\( K_S^0 \)**

**\( \Lambda^0 \)**
Fitting mass plots

- Mass plots are fit with Breit-Wigner convoluted with the Gaussian resolution (from Monte Carlo).
- $K^*(892)$ and $\Sigma(1385)$ should be P-wave but best fit is simple S-wave Breit-Wigner with energy independent width.
- Best (of tried) background shape is $aq^b \exp (cq + dq^2 + eq^3 + fq^4)$.

<table>
<thead>
<tr>
<th>Decay Mode</th>
<th>Q (MeV)</th>
<th>Resolution (MeV/c²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$K^*(892)^+ \rightarrow K_S^0\pi^+$</td>
<td>254</td>
<td>4.9</td>
</tr>
<tr>
<td>$\Sigma(1385)^+ \rightarrow \Lambda\pi^+$</td>
<td>128</td>
<td>3.1</td>
</tr>
<tr>
<td>$\Sigma(1385)^- \rightarrow \Lambda\pi^-$</td>
<td>132</td>
<td>3.2</td>
</tr>
<tr>
<td>$\Theta(1490)^+ \rightarrow pK_S^0$</td>
<td>54</td>
<td>2.1</td>
</tr>
<tr>
<td>$\Theta(1540)^+ \rightarrow pK_S^0$</td>
<td>104</td>
<td>2.8</td>
</tr>
<tr>
<td>$\Theta(1590)^+ \rightarrow pK_S^0$</td>
<td>154</td>
<td>3.5</td>
</tr>
</tbody>
</table>

$\sigma(\text{MeV}) = -18.877 + 14.0668M(\text{GeV})$
$K^*(892)^+ \rightarrow K_S^0\pi^+$ and $\Sigma(1385)^\pm \rightarrow \Lambda\pi^\pm$ signals

Signal = 8291706 ± 13310
Mass = 890.87 ± 0.02 MeV/c$^2$
Width = 45.07 ± 0.08 MeV/c$^2$

Signal = 92022 ± 1622
Mass = 1381.04 ± 0.18 MeV/c$^2$
Width = 31.37 ± 0.66 MeV/c$^2$

Signal = 146243 ± 2696
Mass = 1382.59 ± 0.22 MeV/c$^2$
Width = 48.31 ± 0.91 MeV/c$^2$
\( \Theta^+ \rightarrow pK_S^0 \) search

\[
\chi^2/\text{ndf} \quad 559.4 \quad / \quad 414
\]

\[
P1 \quad 0.2446 \times 10^5
P2 \quad 0.4170
P3 \quad -1.624
P4 \quad -5.296
P5 \quad 4.859
P6 \quad -1.785
\]

Events / 2.5 MeV/c^2

\[
M(pK_S) \quad \text{GeV/c}^2
\]

\[
1.5 \quad 1.6 \quad 1.7 \quad 1.8
\]

\[
0 \quad 1000 \quad 2000 \quad 3000 \quad 4000 \quad 5000 \quad 6000 \quad 7000 \quad 8000
\]
Limit on $\Theta^+ \rightarrow pK_S^0$ yield

95% CL intervals on $\Theta^+$ yield ($\Gamma = 0 \text{ MeV}/c^2$)
95% CL intervals on $\Theta^+$ yield ($\Gamma = 15 \text{ MeV}/c^2$)

- Fit for signal in 1 MeV/$c^2$ steps from 1511 to 1560 MeV/$c^2$
- Find where $-2 \ln \mathcal{L}$ changes by 3.84 w.r.t minimum as yield is varied (allowing other variables to be continually minimized)
Corrected yields

<table>
<thead>
<tr>
<th>Particle Decay</th>
<th>$&lt;p&gt;$ Acc $\times \epsilon$ GeV/c</th>
<th>B.R. correction</th>
<th>Reconstructed Yield/Limit</th>
<th>Corrected Yield/Limit</th>
</tr>
</thead>
<tbody>
<tr>
<td>$K^*(892)^+ \rightarrow K^0\pi^+$</td>
<td>$19$</td>
<td>$1.83%$ $0.686 \times 0.5 \times 0.666$</td>
<td>$8.3 \times 10^6$</td>
<td>$2.0 \times 10^9$</td>
</tr>
<tr>
<td>$\Sigma(1385)^+ \rightarrow \Lambda\pi^+$</td>
<td>$10$</td>
<td>$0.27%$ $0.639 \times 0.88$</td>
<td>$9.2 \times 10^4$</td>
<td>$6.1 \times 10^7$</td>
</tr>
<tr>
<td>$\Sigma(1385)^- \rightarrow \Lambda\pi^-$</td>
<td>$10$</td>
<td>$0.27%$ $0.639 \times 0.88$</td>
<td>$14.6 \times 10^4$</td>
<td>$9.6 \times 10^7$</td>
</tr>
<tr>
<td>$\Theta(1540)^+ \rightarrow pK^0_S$</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\quad \Gamma = 0$ MeV/$c^2$</td>
<td>$12$</td>
<td>$0.39%$ $0.686 \times 0.5 \times 0.5$</td>
<td>$&lt;695$</td>
<td>$&lt;1.0 \times 10^6$</td>
</tr>
<tr>
<td>$\quad \Gamma = 15$ MeV/$c^2$</td>
<td>$12$</td>
<td>$0.39%$ $0.686 \times 0.5 \times 0.5$</td>
<td>$&lt;2154$</td>
<td>$&lt;3.2 \times 10^6$</td>
</tr>
</tbody>
</table>

Decay | B.R. | Events generated by minimum bias PYTHIA $\gamma-N$ interactions with bremsstrahlung photon spectrum

<table>
<thead>
<tr>
<th>Decay</th>
<th>B.R.</th>
</tr>
</thead>
<tbody>
<tr>
<td>$K^*(892)^+ \rightarrow \overline{K}^0\pi^+$</td>
<td>$66.6%$</td>
</tr>
<tr>
<td>$K^0_S \rightarrow \pi^+\pi^-$</td>
<td>$68.6%$</td>
</tr>
<tr>
<td>$\overline{K}^0 \rightarrow K^0_S$</td>
<td>$50.0%$</td>
</tr>
<tr>
<td>$\Lambda \rightarrow p\pi^-$</td>
<td>$63.9%$</td>
</tr>
<tr>
<td>$\Sigma(1385)^\pm \rightarrow \Lambda\pi^\pm$</td>
<td>$88.0%$</td>
</tr>
<tr>
<td>$\Theta(1540)^+ \rightarrow p\overline{K}^0$</td>
<td>$50.0%$</td>
</tr>
<tr>
<td>$\Theta(1540)^+ \rightarrow pK^0_S$, generated as $\Sigma(1385)^+$</td>
<td></td>
</tr>
</tbody>
</table>
Limits on $\Theta(1540)^+$ production

\[
\frac{\sigma(\Theta^+)}{\sigma(\Sigma(1385)^+ + \Sigma(1385)^-)} \quad \text{95% CL intervals (}\Gamma = 0\text{ MeV/c}^2) \\
\frac{\sigma(\Theta^+)}{\sigma(\Sigma(1385)^+ + \Sigma(1385)^-)} \quad \text{95% CL intervals (}\Gamma = 15\text{ MeV/c}^2) \\
\frac{\sigma(\Theta^+)}{\sigma(K^*(892)^\pm)} \quad \text{95% CL intervals (}\Gamma = 0\text{ MeV/c}^2) \\
\frac{\sigma(\Theta^+)}{\sigma(K^*(892)^\pm)} \quad \text{95% CL intervals (}\Gamma = 15\text{ MeV/c}^2)
\]
\[ S = -2 \text{ pentaquarks (}\phi(1860)^{--}\text{)} \]

- NA49 evidence for 
  \[ \phi(1860)^{--}(ddss\bar{u}) \] and 
  \[ \phi(1860)^{0} \] decaying \( \Xi^{-}\pi^{\pm} \)
- 158 GeV \( p \) on LH

**Graphs:**

- a) \( \Xi^{-}\pi^{-} \)
- b) \( \Xi^{-}\pi^{+} \)
- c) \( \Xi^{+}\pi^{-} \)
- d) \( \Xi^{+}\pi^{+} \)

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**FOCUS analysis:** $\phi(1860)^{-\rightarrow} \Xi^-\pi^-$ search

- $\sim 600,000 \, \Xi^-\rightarrow \Lambda^0\pi^-$ sample
- Vertex $\Xi^-$ with $\pi^\pm$ and find production vertex
- Require $< 4\sigma$ separation between vertices
- In $\Xi^-\pi^+$, observe $\sim 60,000 \, \Xi(1530)^0$ candidates

**Signal** = 59391 $\pm$ 536

Mass = 1532.42 $\pm$ 0.05 MeV/c$^2$

Width = 10.39 $\pm$ 0.16 MeV/c$^2$

$\Xi(1530)^0$ signal: P-wave energy-dependent-width Breit-Wigner convoluted with $\sigma=3.1$ MeV resolution

Background:

$$q^a \exp(bq + cq^2 + dq^3 + eq^4)$$

where $q = M(\Xi^-\pi^+) - m(\Xi^-) - m(\pi^+)$
Results of FOCUS search for $\phi(1860)^{--}$

Fit to $\Gamma = 0$ MeV signal

$\Theta(1862)^{-}$ signal:
Gaussian at 1862 MeV/c$^2$
with $\sigma = 6.05$ MeV

Background:
$q^n \exp(bq^2+ dq^3 + eq^4)$
where $q = M(\Xi^- \pi^-) - m(\Xi^-) - m(\pi^-)$

$\chi^2/ndf = 257.8 / 179$

Events / 5 MeV/c$^2$

$\Gamma = 0$ MeV, $\sigma = 6.05$ MeV
Yield = $-109 \pm 113$
Yield < 114 @ 95% CL

Fit to $\Gamma = 15$ MeV signal

$\Theta(1862)^{-}$ signal:
convoluted Breit-Wigner at 1862 MeV/c$^2$
with $\Gamma = 15$ MeV and $\sigma = 6.05$ MeV

Background:
$q^n \exp(bq^2+ dq^3 + eq^4)$
where $q = M(\Xi^- \pi^-) - m(\Xi^-) - m(\pi^-)$

$\chi^2/ndf = 257.4 / 179$

Events / 5 MeV/c$^2$

$\Gamma = 15$ MeV, $\sigma = 6.05$ MeV
Yield = $-235 \pm 202$
Yield < 170 @ 95% CL
Limits on $\phi(1860)^{--}$ production

- Using PYTHIA, generate Monte Carlo samples of $\Xi(1530)^0$ and of $\phi(1860)^{--}$ (using $\Xi(1530)^0$)
- Average momentum is 15 GeV/c
- Efficiency ratio is $\frac{\epsilon(\phi(1860)^{--}\rightarrow\Xi^-\pi^-)}{\epsilon(\Xi(1530)^0\rightarrow\Xi^-\pi^+)} = 0.78$
- Thus, for a $\phi(1860)^{--}$ produced like $\Xi(1530)^0$ we obtain the limits:
  \[
  \frac{\sigma(\phi(1860)) \times BR(\phi(1860) \rightarrow \Xi^-\pi^-)}{\sigma(\Xi(1530))} < 0.25\% \text{ @ 95\% CL for } \Gamma = 0 \text{ MeV}
  \]
  \[
  \frac{\sigma(\phi(1860)) \times BR(\phi(1860) \rightarrow \Xi^-\pi^-)}{\sigma(\Xi(1530))} < 0.37\% \text{ @ 95\% CL for } \Gamma = 15 \text{ MeV}
  \]
- Sharp contrast to NA49 which seems to be $\gtrsim 50\%$
Charm pentaquarks

- H1 at HERA reported a $> 6\sigma$ significant particle at 3.099 GeV/c$^2$ decaying to $D^{*-}\bar{p}$

- Using a $D^{*+}$ sample 10× larger and much cleaner, FOCUS searched for this particle

- FOCUS also investigated $D^+\bar{p}$ decays

- Standard fixed-target charm selection criteria used for $D^{*+}$ and $D^+$ reconstruction

- $p$ candidate must originate from production vertex and be positively identified by Čerenkov system
FOCUS finds no charm pentaquarks

**H1 D*⁺p**

- $K^+ \pi^+ \pi^-$
- **Wrong charge D**

**FOCUS D*⁻p**

- $Y = 35821. \pm 202.$
- **Right sign**
- **Wrong sign**

**FOCUS D⁺p**

- $M = 1.8722 \pm 0.0000$  $Y = 83940. \pm 302.6$
- $W = 10.655 \pm 0.0382$  $S/N = 34.4653$

**H1**

- $D^*^- p + D^*^- p$
- **Signal + bg. fit**
- **Bg. only fit**

**M(D^⁺p) [GeV]**

- **Location of H1 penta quark**

**M(D^*⁻p + D^*^-p), GeV/c^2**

- **Location of H1 penta quark**

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Double charm baryons

SELEX has reported various observations of double charm baryons. SELEX uses hadron beams and only reconstructs high $x_F$ particles.

**FOCUS analysis:**

- Topology consists of three vertices
- Use candidate driven algorithm
- Reconstruct $D^+$, $D^0$, or $\Lambda_c$ requiring a good vertex
- Add tracks to charm vector to search for $\Xi_{cc}$ decay requiring a good vertex
- Use $\Xi_{cc}$ vector to find production vertex
- Require separation between all vertices
- Use Čerenkov system to positively identify protons and kaons
Double charm baryon production compared

<table>
<thead>
<tr>
<th>Decay Mode</th>
<th>$\Xi_{cc} \rightarrow \Lambda_c^+ K^- \pi^+$</th>
<th>$\Xi_{cc}^{++} \rightarrow \Lambda_c^+ K^- \pi^+ \pi^+$</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Experiment</strong></td>
<td><strong>FOCUS</strong></td>
<td><strong>SELEX</strong></td>
</tr>
<tr>
<td>$\Xi_{cc}$ Events</td>
<td>$&lt;2.21\ @\ 90%$</td>
<td>$15.8$</td>
</tr>
<tr>
<td>Reconstructed $\Lambda_c$</td>
<td>$19,444\ \pm\ 262$</td>
<td>$1650$</td>
</tr>
<tr>
<td>Relative Efficiency</td>
<td>$5%$</td>
<td>$10%$</td>
</tr>
<tr>
<td>$\Xi_{cc}/\Lambda_c^+$</td>
<td>$&lt;0.23%\ @\ 90%$</td>
<td>$9.6%$</td>
</tr>
<tr>
<td><strong>SELEX</strong> Rel $\frac{\Xi_{cc}}{\Lambda_c}$ Prod</td>
<td>$&gt;42\ @\ 90%$</td>
<td></td>
</tr>
</tbody>
</table>

If the $\Lambda_c^+ K^- \pi^+$ ($\Lambda_c^+ K^- \pi^+ \pi^+$) signal is real, SELEX produces at least 42 (111) times more $\Xi_{cc}$ baryons relative to $\Lambda_c$ than FOCUS.
Summary of the FOCUS searches

- No evidence for $\Theta(1540)^+ \rightarrow pK_S^0$ but reconstructs 8 million $K^*(892)^+ \rightarrow K^0_S\pi^+$ and 240,000 $\Sigma(1385)^\pm \rightarrow \Lambda^0\pi^\pm$ in similar decay modes.

- No evidence for $\phi(1860)^{-}\rightarrow \Xi^-\pi^-$ but reconstructs 60,000 $\Xi(1530)^0 \rightarrow \Xi^-\pi^+$, approximately 1,000 times more than the observing experiment.

- No evidence for a charm pentaquark decaying to $D^*-p$ or $D^-p$ with a factor of 10 more $D^{*+}$ decays than the observing experiment.

- No evidence for double charm baryons with a factor of 10 more $\Lambda_c$ decays than the observing experiment.