Pentaquarks and the X(3872) results from CDF

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for CDF Collaboration

Today:

- Exotic spectroscopy: pentaquarks
- Exotic (?) spectroscopy: X(3872)
CDF pentaquark search strategy

Exploit strong sides of the CDF experiment:
- great momentum resolution
  - can measure mass peaks down to $\sim 2$-3 MeV (e.g., $\Psi(2S)$)
- precision tracking:
  - able to reconstruct $\Xi^-$ tracks in SVX!
  - good 3D vertexing: reduced backgrounds
- particle ID capabilities: identify protons, kaons
- not so good $n$, $\pi^0$, $\gamma$ reconstruction: avoid neutrals

<table>
<thead>
<tr>
<th>Decay</th>
<th>Symbol</th>
<th>Expression</th>
</tr>
</thead>
<tbody>
<tr>
<td>$uudd\bar{s}$</td>
<td>$\Theta^+$</td>
<td>$\rightarrow pK^0_s$, $K^0_s \rightarrow \pi^+\pi^-$</td>
</tr>
<tr>
<td>$ddss\bar{u}$</td>
<td>$\Xi^-_{3/2}$</td>
<td>$\rightarrow \Xi^-\pi^-$, $\Xi^- \rightarrow \Lambda\pi^-$, $\Lambda \rightarrow p\pi^-$</td>
</tr>
<tr>
<td>$uuss\bar{d}$</td>
<td>$\Xi^0_{3/2}$</td>
<td>$\rightarrow \Xi^-\pi^+$, $\Xi^- \rightarrow \Lambda\pi^-$, $\Lambda \rightarrow p\pi^-$</td>
</tr>
<tr>
<td>$uudd\bar{c}$</td>
<td>$\Theta^0_c$</td>
<td>$\rightarrow D^<em>-p$, $D^</em>- \rightarrow \bar{D}^0\pi^-$, $\bar{D}^0 \rightarrow K^-\pi^+$</td>
</tr>
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<td>$uudd\bar{c}$</td>
<td>$\Theta^0_c$</td>
<td>$\rightarrow D^-p$, $D^- \rightarrow K^-\pi^+\pi^+$</td>
</tr>
<tr>
<td>$uuud\bar{c}$</td>
<td>$\Theta^+_c$</td>
<td>$\rightarrow \bar{D}^0p$, $\bar{D}^0 \rightarrow K^-\pi^+$</td>
</tr>
<tr>
<td>$\bar{u}uudc$</td>
<td>$\Theta^+_c$</td>
<td>$\rightarrow D^0p$, $D^0 \rightarrow K^+\pi^-$</td>
</tr>
</tbody>
</table>
Datasets

At Fermilab: $p\bar{p}$ collisions, 1.96 TeV COM energy

Pentaquark production is not understood
- search in different kind of datasets

Use all Run II data: $\sim 250 \, pb^{-1}$

→ Hadronic trigger data
  - records events with at least 2 displaced tracks
  - hard scattering events
  - primarily contains $p\bar{p} \to c\bar{c}$ and $p\bar{p} \to b\bar{b}$

→ Jet20 data
  - each event has at least one jet with 20 GeV/$c$, generic QCD
  - trigger heavily prescaled

→ Min-bias and zero-bias data
  - soft inelastic scattering
Reference signals

Well-established, similar to $P_5$ decays in our data:

- $D^{**} \rightarrow D^*\pi^-$ for $\Theta_c \rightarrow D^*+p$
- $\Xi \rightarrow \Lambda\pi$ for $\Xi^{3/2} \rightarrow \Xi^+\pi^\pm$
- $\Lambda \rightarrow pK^-$
- $K^{*+} \rightarrow \pi^+K_S^0$ for $\Theta^+ \rightarrow pK_S^0$

CDF Run II preliminary

I. Kravchenko, CDF, ICHEP04, Aug 16-22, 2004
CDF particle ID

CDF has good PID system:
- use ToF and COT dE/dx
- identify protons
- strong background reduction

I. Kravchenko, CDF, ICHEP04, Aug 16-22, 2004
Search for $\Theta^+$

Reconstruct $\Theta^+ \rightarrow pK^0_s$

- use PID to identify protons
- $\Theta^+$ yields relative to known resonances

No signal is found!

<table>
<thead>
<tr>
<th>resonance</th>
<th>minbias data</th>
<th>jet20 data</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\phi \rightarrow K^+K^-$</td>
<td>$19721\pm273$</td>
<td>$26658\pm385$</td>
</tr>
<tr>
<td>$\Lambda \rightarrow pK^-$</td>
<td>$3276\pm327$</td>
<td>$4915\pm702$</td>
</tr>
<tr>
<td>$K^{*+} \rightarrow \pi^- K^0_s$</td>
<td>$15695\pm775$</td>
<td>$37769\pm1390$</td>
</tr>
<tr>
<td>$\Theta^+ \rightarrow pK^0_s$</td>
<td>$18\pm56$</td>
<td>$-56\pm103$</td>
</tr>
<tr>
<td>90% CL</td>
<td>$&lt;89$</td>
<td>$&lt;76$</td>
</tr>
</tbody>
</table>

CDF Run II preliminary

$N(\Theta^+) = 18 \pm 56$ ($<89$ @90% CL)

$N(\Theta^+) = -56 \pm 103$ ($<76$ @90% CL)
Search for $\Xi^{3/2}_{3/2}$

Reconstruct $\Xi^{0,-,-}_{3/2} \rightarrow \Xi^-\pi^\pm$, $\Xi^- \rightarrow \Lambda\pi^-$

Special tracking for hyperons:
- $c\tau(\Xi^-) = 4.91$ cm
- leaves hits in SVX detector
- explicitly find $\Xi^-$ tracks
- excellent background suppression
- better vertex and $P$ resolution

No signal is found!
- clear, high statistics $\Xi(1530) \rightarrow \Xi^-\pi^+$
- yields $\Xi^{3/2}_{3/2}/\Xi(1530) \lesssim 0.06$
\[ \Rightarrow \text{if acceptance is equal (in progress)} \]

<table>
<thead>
<tr>
<th>channel</th>
<th>yield</th>
<th>limit</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\Xi^-\pi^+$</td>
<td>57±51</td>
<td>&lt;144</td>
</tr>
<tr>
<td>$\Xi^-\pi^-$</td>
<td>-54±47</td>
<td>&lt;63</td>
</tr>
</tbody>
</table>

I. Kravchenko, CDF, ICHEP04, Aug 16-22, 2004
Search for $\Theta_c$

Reconstruct several $\Theta_c$ modes:

- 3 decay channels:
  \[ \Theta_c^0 \rightarrow D^*- p, \quad D^*- \rightarrow \bar{D}^0 \pi^- \]
  \[ \Theta_c^0 \rightarrow D^- p, \quad D^- \rightarrow K^- \pi^+ \pi^- \]
  \[ \Theta_c^+ \rightarrow \bar{D}^0 p, \quad \bar{D}^0 \rightarrow K^- \pi^+ \]
  \[ \Theta_c^+ \rightarrow D^0 p, \quad D^0 \rightarrow K^+ \pi^- \]

- particle ID helps a lot
- consider prompt and long-lived $\Theta_c$

No signal is found!

- H1 mass estimate for $D^*- p$ mode:
  \[ m_{\Theta_c} = 3099 \pm 6 \text{ MeV}/c^2 \]

$\Rightarrow$ calculate mass-dependent limits

On this page: plots for $\Theta_c^0 \rightarrow D^*- p$
Results for other $\Theta_c$ channels

$$\Theta_c^0 \rightarrow D^- p$$  
$$\Theta_c^+ \rightarrow D^0 p$$  
$$\Theta_c^+ \rightarrow \bar{D}^0 p$$

No signal is found!
Limits for $\Theta_c$

Limits calculation:
- search window: H1 mass $\pm 3\sigma$
- from 3082 to 3116 MeV/$c^2$
- take the worst point from the limit vs mass plots

<table>
<thead>
<tr>
<th>Reference channels</th>
<th>Search channels</th>
</tr>
</thead>
<tbody>
<tr>
<td>$N(D_2^{<em>0}) \rightarrow D^{</em>+}\pi^-,$</td>
<td>$\Theta_c \rightarrow D^{*+}p &lt; 21@90%CL$</td>
</tr>
<tr>
<td>$N(D_1^0) \rightarrow D^{*+}\pi^-,$</td>
<td>$\Theta_c \rightarrow D^-p &lt; 89@90%CL$</td>
</tr>
<tr>
<td>$N(D_2^{*0}) \rightarrow D^+\pi^-,$</td>
<td>$\Theta_c \rightarrow \bar{D}^0p &lt; 87@90%CL$</td>
</tr>
<tr>
<td>$N(D_2^{*+}) \rightarrow D^0\pi^-,$</td>
<td>$\Theta_c \rightarrow D^0p &lt; 97@90%CL$</td>
</tr>
</tbody>
</table>
Bottom line

CDF has found no evidence for pentaquark states $\Theta$, $\Xi_{\frac{3}{2}}$ and $\Theta_c$ in several decay modes

Conclusions: production of exotic baryons in fragmentation may be severely suppressed with respect to normal baryon production

- exotic production mechanisms?

CDF continues studies of weak and strong decay signatures of exotic charmed and bottom baryons

- take advantage of large hadronic and $J/\psi$ trigger samples at CDF
**X(3872) observation at CDF**

Belle announces in August 2003

\[ B \rightarrow K J/\Psi \pi^+ \pi^- \]

CDF confirms within a month:

\[ X(3872) \rightarrow J/\Psi \pi^+ \pi^- \]

both at \( \geq 10\sigma \) level

**The mass:**
- not easily explained as \( ^3D_2 \) \( c\bar{c} \)
- CDF: \( m_X = 3871.3 \pm 0.7 \pm 0.4 \) MeV/\( c^2 \)

**The width:**
- compatible with zero
- CDF: \( \sigma = 5.44 \pm 0.72 \) MeV/\( c^2 \)
- Belle: \( \Gamma = 1.4 \pm 0.7 \) MeV/\( c^2 \)
The nature of $X(3872)$

Primary hypotheses:
- a charmonium state?
  - $1^3D_2$ most natural choice
  - others possible, hep-ex/0407033
  - problems in each case!
- a $D^*D^*$ molecule? not clear

Measure properties:
- quantum numbers, other decays
- “lifetime”, production, $m_{\pi\pi}$

At CDF:
- measure lifetimes
  - charmonium-like production
- study $m_{\pi\pi}$
  - signal enhancement for high $m_{\pi\pi}$
  - $X(3872) \rightarrow J/\Psi \rho$
  - $m_{\pi\pi}$ shape analysis in progress

\[
\frac{\Psi(2S)}{f_{longlived}} : 28.3 \pm 1.0 \pm 0.7\%
\]

\[
\frac{X(3872)}{f_{longlived}} : 16.1 \pm 4.9 \pm 2.0\%
\]
Conclusions

• performed pentaquark searches in channels:

| \( \Theta^+ \) | \( \rightarrow p K_s^0 \) |
| \( \Theta^0 \) | \( \rightarrow D^{*-}p \) |
| \( \Theta_c^0 \) | \( \rightarrow D^-p \) |
| \( \Theta^+ \) | \( \rightarrow \bar{D}^0p \) |
| \( \Theta_c^+ \) | \( \rightarrow D^0p \) |
| \( \Xi_{3/2}^0 \) | \( \rightarrow \Xi^-\pi^+ \) |
| \( \Xi_{3/2}^{-} \) | \( \rightarrow \Xi^-\pi^- \) |

– CDF analyzed large data sample, with clear reference signals
– no signal observed, yield limits are calculated
– more modes will be added in the near future

• studied \( X(3872) \rightarrow J/\Psi \pi^+\pi^- \)
  – 10\( \sigma \) peak, measured mass
  – charmonium-like: long-lived fraction similar to \( \Psi(2S) \)
  – properties are being investigated further
Backup slides
Introduction into theory

Exotic baryons:
• quantum numbers can’t be explained by $qqq$ configuration
• lowest lying $\bar{10}$ of states containing $u, s, d$ quarks was predicted by Diakonov, Petrov and Polyakov in 1997
• strong decays, but narrow widths

Bound states of 5 quarks:
• $q\bar{Q}qqq$ Karliner&Lipkin
• $(qq)^2\bar{Q}$ Jaffe&Wilczek
• P5 containing heavy quarks expected
Experimental field overview

History:
- searches since 1960s
- first clear observations: 2002
- currently: about 10-12 observations, 3 non-observations
- all states are narrow!

Summary of observed states:

<table>
<thead>
<tr>
<th>state</th>
<th>decay</th>
<th>mass</th>
<th>observed by</th>
<th>not confirmed</th>
</tr>
</thead>
<tbody>
<tr>
<td>uudds: $\Theta^+$</td>
<td>$\rightarrow nK^+$</td>
<td>$\sim 1540$</td>
<td>LEPS, CLAS, etc</td>
<td>BES, PHENIX</td>
</tr>
<tr>
<td>uudds: $\Theta^+$</td>
<td>$\rightarrow pK_s^0$</td>
<td>$\sim 1530$</td>
<td>DIANA, ZEUS, etc</td>
<td>BES, HERAB</td>
</tr>
<tr>
<td>uuddc: $\Theta_c^0$</td>
<td>$\rightarrow D^{*-}p$</td>
<td>$\sim 3099$</td>
<td>H1</td>
<td>–</td>
</tr>
<tr>
<td>dssuu: $\Xi_{3/2}^-$</td>
<td>$\rightarrow \Xi^-\pi^-$</td>
<td>$\sim 1862$</td>
<td>NA49</td>
<td>HERAB</td>
</tr>
</tbody>
</table>

Difference in results:
- decays are clear but production is unknown
CDF detector

At Fermilab:
Tevatron $p\bar{p}$ collider

General purpose detector:
- vertexing: SVX
- $\vec{P}$ measurements: COT
- particle ID: TOF, COT
- muons: muon system