Searches for Pentaquarks at CDF

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First Meeting of the APS Topical Group on Hadronic Physics
Motivation

Recent flurry of reports of experimental evidence for a narrow exotic baryon state decaying to nK\(^+\), pK\(^0\)\(_S\) at the mass of \(\sim 1540\) MeV/c\(^2\), interpreted as 5-quark, \((uudd\bar{s})\), consistent with \(\Theta^+\) predicted in chiral soliton model by Diakonov, Petrov, Polyakov revived interest in baryon spectroscopy.

In CQ picture:
\[
[uu]_f \otimes [dd]_f \otimes [\bar{s}]_f = 8_f + \bar{10}_f \text{ (Jaffe/Wilczek)}
\]

or \([uu]([ud\bar{s})\text{ (Karliner/Lipkin)}\]

Followed by observation of \(\Xi^{--}, \Xi^0\)
\(M\sim 1860\) MeV/c\(^2\), decaying to \(\Xi^-\pi^-, \Xi^-\pi^+\), by NA49 Experiment. Members of \(S = -2\)
\((qqss\bar{q}, q = u, d)\) quadruplet of the SU(3) \(10\) of pentaquarks.

H1 Experiment reported anti-charmed analogue \((uudd\bar{c})\) of the \(\Theta^+\) state decaying to \(D^{*+}\bar{p}\).
\(M(\Theta^0_c) = (3,099 \pm 3 \pm 5)\) MeV/c\(^2\)

All results are of relatively low statistics with between 20 and 100 events in peaks, signal to background ratios ranging from 1:1 to 1:3, statistical significance 3-5 \(\sigma\). Verification on high statistics samples is warranted.
Tevatron at Fermilab
World's largest collider

- 1 km ring radius; p¯p collisions, started 1984 $\sqrt{s} = 1.6$ TeV
- Run I (1992-1995) $\sqrt{s} = 1.8$ TeV, 6x6 bunches, $\mathcal{L}_{\text{inst}} = 1.6 \times 10^{31}\text{cm}^{-2}\text{s}^{-1}$, $\int \mathcal{L}\, dt = 110 \text{pb}^{-1}$
- 1996-2000 major upgrade for Run II
  - main injector
  - p̅ recycler
  - new synchrotron
  - upgraded p̅ source
- Run II started 2001:
  - $\sqrt{s} \sim 1.96$ TeV.
  - 36x36 colliding p̅p bunches
  - $10^{11}(10^{10})p(p\bar{p})$ per bunch
  - $\mathcal{L}_{\text{inst}} = 10.2 \times 10^{31}\text{cm}^{-2}\text{s}^{-1}$ (record)
    (goal $8.1 \times 10^{31}\text{cm}^{-2}\text{s}^{-1}$)
  - high beam-beam crossing (inter-bunch spacing 396 ns), low pileup

- Tevatron performs very well after initially slow start
- $\int \mathcal{L}\, dt \sim 700\text{pb}^{-1}$ (≈ 550pb$^{-1}$ on tape)
- CDF & D0 efficiency ≈ 80%
- expect 2 fb$^{-1}$ for Run IIa
- 4 – 8 fb$^{-1}$ by 2009
Run II CDF Detector

Upgraded CDF Detector

- **tracking**
  - L00 + 5 layers of SVX + 2/1 outer layers of ISL (1.5 < R < 30cm, |Z| < 45cm). rφ, rz, stereo strips. 720,000 channels. Si tracking up to |η| < 2.
  - Central Outer Tracker (COT), 30,240 sense wires, 96 layer drift wire chamber. σ(1/p_T) ~ 0.1%/GeV/c, σ(hit) ~ 150μm. dE/dx PID.

- **new plug calorimeter**

- **extended muon coverage, |η| < 1.5**

- **ToF system, (120 ps @ 138 cm)**

- **improved DAQ and trigger systems**
  - new frontend electronics
  - Level 1 all digital, 132 ns pipeline
  - 4000/300/70 Hz
  - COT Tracks @ Level 1
  - Si Tracks @ Level 2
  - Full analysis @ Level 3
  - First hadronic B-trigger

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Hadronic Trigger

- New displaced track triggers (two track and $l$+track):
  - Level 1
    - XFT tracking in COT ($r - \phi$)
    - Opposite charged track pair with $p_T > 2$ GeV/c each
    - $\Sigma p_T > 5.5$ GeV/c
    - $\Delta \phi < 135^\circ$
  - Level 2
    - XFT track seeds SVT boards, that perform fast ($r - \phi$) track fit
    - Repeat Level 1 cuts
    - Require tracks impact parameter to be $0.012 < |d_0| < 0.1$ cm
  - $l$+track uses different cuts.

$\sigma(d_0)_{SVT} = 48 \mu m$ (including $\sigma(beam) = 33 \mu m$)
Search strategy at CDF

Search for the following states:

<table>
<thead>
<tr>
<th>Notation</th>
<th>Quark content</th>
<th>Decay channel</th>
<th>Reference Channel(s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Θ⁺</td>
<td>ūuudd</td>
<td>pK⁺</td>
<td>Λ(1520) → pK⁻, K*⁺ → K⁺π⁺</td>
</tr>
<tr>
<td>Φ⁻⁻</td>
<td>ûddss</td>
<td>Ξ⁻π⁻</td>
<td></td>
</tr>
<tr>
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<td>ďudss</td>
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</tr>
<tr>
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<td>ĉdudu</td>
<td>D⁺⁻p</td>
<td>D** → D⁺π⁻</td>
</tr>
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<td>D⁰p</td>
<td>D** → D⁰π⁺</td>
</tr>
<tr>
<td>R⁺⁺</td>
<td>ūuuds</td>
<td>J/ψp</td>
<td>B⁺ → J/ψK⁺</td>
</tr>
</tbody>
</table>

Calibrate/optimise cuts on reference channels, apply same cuts to PQ candidates, add proton PID cuts, obtain PID cut efficiencies from clean samples of protons (Λ)

CDF advantages

- High statistics samples
- Excellent tracking:
  - Good 3D vertexing reduces background
  - Excellent mass resolution
  - Ability to track long lived hyperons (Ξ⁻, Ω⁻) in SVX
- Good PID capabilities based on ToF and dE/dx to identify protons, kaons.
Datasets

- **hadronic trigger data**
  - events with at least 2 displaced tracks
  - hard scattering events
  - sample enriched with decay products of charmed and bottom hadrons

- **Jet20 trigger**
  - each event has at least one jet with 20 GeV/c, generic QCD
  - prescaled trigger – lower statistics

- **Min-bias and zero-bias trigger**
  - soft inelastic scattering

- **Dimuon data \((J/\psi)\)**

CDF reconstructs tracks in central rapidity region probing PQ produced in quark fragmentation or in b and c-hadron decays
Particle identification

- combine ToF and dE/dx information for a given track into common $\chi^2_i$
  $\chi^2_i = \chi^2_i$(ToF) + $\chi^2_i$(dE/dx)(COT),
  where $i = p, K, \pi, e, \mu$
- form normalized likelihood ratio:
  $$LH_i = \frac{lh(i)}{lh(p) + lh(K) + lh(e) + lh(\mu) + lh(\pi)}$$
  where $lh(i) = \exp(-\chi^2_i/2)$,
Search for $\Theta^+$

$\Theta^+ \rightarrow K^0_S p \rightarrow \pi^+ \pi^-$

- Use TOF to identify protons $0.5 < p_T < 2.1$ GeV/c

Data samples used:

- MINBIAS $12 \times 10^6$ events, ZEROBIAS $8 \times 10^6$ events
- JET20 $16 \times 10^6$ events

CDF Run II preliminary

$N(K_S^0) = (667 \pm 1) \times 10^3$ minbias data

$N(K_S^0) = (1632 \pm 1) \times 10^3$ jet20 data

Entries per 1 MeV/c$^2$

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Known Resonances

CDF Run II preliminary

minbias data

N(Λ(1520)) = 3276 ± 327

jet20 data

N(Λ(1520)) = 4915 ± 702

CDF Run II preliminary

minbias data

N(K*0) = 15695 ± 775

jet20 data

N(K*0) = 35769 ± 1390

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The $pK_S^0$ spectrum

CDF Run II preliminary

Resonance | Minbias data | Jet20 data
--- | --- | ---
$\phi \rightarrow K^+K^-$ | $19,721 \pm 273$ | $26,658 \pm 385$
$\Lambda \rightarrow pK^-$ | $3,276 \pm 327$ | $4,915 \pm 702$
$K^{*+} \rightarrow K_S^0\pi^+$ | $15,695 \pm 775$ | $37,769 \pm 1,390$
$\Theta^+ \rightarrow pK_S^0$ | $18 \pm 56$ | $-56 \pm 103$
90% CL limit on $\Theta^+$ | $<89$ | $<76$

work on cross section continuing

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Exotic Cascade

\[
\Phi^{0,--} \rightarrow \Xi^- + \pi^{+,-}
\]

\[
\Lambda \pi^-
\]
$\Xi^- \rightarrow \Lambda^0\pi^-$ is a long lived particle $c\tau = 4.91$ cm. It leaves hits in SVX detector. CDF developed dedicated tracking $\Xi$ in Silicon. Momentum and vertex of $\Lambda\pi^-$ are used to seed silicon tracking algorithm.

MC: $\Xi_b^- \rightarrow \Xi_c^+\pi^- \quad \Xi_c^+ \rightarrow \Xi^-\pi^+\pi^+ \quad \Xi^- \rightarrow \Lambda\pi_2^- \quad \Lambda \rightarrow p\pi_1^-$
Tracked Hyperon signals

- Silicon tracking of hyperons improves momentum and impact parameter resolution as well as results in excellent background suppression.

CDF Run II Preliminary

L = 220 pb$^{-1}$
N = 36,000

Displaced Track trigger data

right sign, R($\Lambda > R(\Xi) + 1$)

M($\Lambda\pi$) [GeV/c$^2$]

M($\Xi\pi$) [GeV/c$^2$]

N / 2 MeV/c$^2$
fit function:

\[
\mathcal{F} = BW \otimes Gauss + Gauss = \left( \sum_{n=0}^{3} a_n \cdot x^n \right) \cdot \sqrt{x - M_\Xi - M_\pi}
\]

fit yielded:

\[
N(\Xi(1530)) = 2,182 \pm 92 \\
M = (1,5320 \pm 0.4) \text{ MeV/c}^2
\]

\[
\frac{\sigma(pp \to \Xi(1530)) \cdot a(\Xi(1530))}{\sigma(pp \to \Xi) \cdot a(\Xi)} \sim 0.061
\]

<table>
<thead>
<tr>
<th>Channel</th>
<th># of events</th>
<th>90 % CL</th>
<th>relative yield</th>
</tr>
</thead>
<tbody>
<tr>
<td>(\Xi^-\pi^+)</td>
<td>57±51</td>
<td>126</td>
<td>0.06</td>
</tr>
<tr>
<td>(\Xi^-\pi^-)</td>
<td>-54±47</td>
<td>51</td>
<td>0.03</td>
</tr>
</tbody>
</table>

(Relative yields of \(\Xi(1860)/\Xi(1530)\) assuming equal detector efficiency)

no signal observed!
\( E_T > 20 \text{ GeV jet trigger data, SVX tracked } \Xi^\pm \)

\[
N(\Xi(1530)) = 387 \pm 34 \\
M(\Xi(1530)) = (1,532.3 \pm 0.8) \text{ MeV/c}^2 \\
\frac{\sigma(pp \rightarrow \Xi(1530)) \cdot a(\Xi(1530))}{\sigma(pp \rightarrow \Xi) \cdot a(\Xi)} \sim 0.08 \\
\text{(similar to TTT sample and similar to NA49)}
\]

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<th>90 % CL</th>
<th>relative yield</th>
</tr>
</thead>
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<tr>
<td>(\Xi^-\pi^+)</td>
<td>-14±19</td>
<td>25</td>
<td>0.08</td>
</tr>
<tr>
<td>(\Xi^-\pi^-)</td>
<td>-4±18</td>
<td>28</td>
<td>0.09</td>
</tr>
</tbody>
</table>

(Relative yields of \(\Xi(1860)/\Xi(1530)\) assuming equal detector efficiency)

no signal observed!
**$\Theta_c$ signal**

**H1 Experiment @ HERA**

\[ \Theta_c \rightarrow D^*-p \]
\[ \rightarrow \bar{D}^0\pi^- \]
\[ \rightarrow K^+\pi^- \]

\[ \gamma^*p \rightarrow \Theta_c X \]

Mass = $(3099 \pm 3\,\text{(stat.)} \pm 5\,\text{(syst.)})$ MeV/c²

Gaussian width of the peak, $(12 \pm 3\,\text{(stat.)})$ MeV/c², is consistent with detector resolution

\[
\frac{\sigma(\gamma^*p \rightarrow \Theta_c) \cdot B(\Theta_c \rightarrow D^*-p)}{\sigma(\gamma^*p \rightarrow D^*-)} \approx 1\%
\]

\[ \gamma p \rightarrow \Theta_c X \]

✦ ZEUS Experiment (also @ HERA) did not confirm $\Theta_c^+$

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CDF is especially sensitive to charmed/bottom PQ as displaced tracks from $D$-mesons come in on hadronic trigger
3M $D^0$ and 0.5M $D^{*-+}$. 180x increase compared to H1 statistics.

- given 1% of $D^*$ produced from $\Theta_c$ we expect
  - assuming fragmentation production (see hep-ph/0405281):
    $$\sigma(\Theta_c) = (40 - 140) \text{ nb}$$

  - assuming coalescence production (see hep-ph/0409121):
    $$\sigma(\Theta_c) = 240 \text{ nb}$$

- so expect few thousand events per 100pb$^{-1}$
Reference Signals

Reference channels

CDF Run II Preliminary L~240pb^{-1}

\begin{align*}
\text{D}^{**} & \rightarrow \text{D}^{*+}\pi^- \\
& \quad \leftrightarrow \text{D}^0\pi^+ \\
& \quad \leftrightarrow K^-\pi^+
\end{align*}

CDF Run II Preliminary L~240pb^{-1}

\begin{align*}
\text{D}^{**} & \rightarrow \text{D}^+\pi^- \\
& \quad \leftrightarrow K^-\pi^+\pi^+
\end{align*}

CDF Run II Preliminary L~240pb^{-1}

\begin{align*}
\text{D}^{**} & \rightarrow \text{D}^0\pi^+ \\
& \quad \leftrightarrow K^-\pi^+
\end{align*}
**D^*-p spectrum w/ proton PID**

**CDF Run II Preliminary**

**L-240pb^-1**

**N / 3 MeV/c^2**

- **Γ = 0 MeV/c^2:**
  - 21@90%CL

- **Γ = 12 MeV/c^2:**
  - 32@90%CL

**Event Yield @ 90% CL**

- **Γ=12 MeV/c^2**
- **Γ= 0 MeV/c^2**

**unbinned likelihood fits varying mass in wide range => calculate mass dependent limits**
$D^- p$ spectrum w/ proton PID

CDF Run II Preliminary

$L \sim 240 \text{pb}^{-1}$

Event Yield @ 90% CL

- $\Gamma = 0 \text{ MeV}/c^2$:
  - 80@90%CL

- $\Gamma = 12 \text{ MeV}/c^2$:
  - 84@90%CL

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\( \bar{D}^0 p \) spectrum w/ proton PID

CDF Run II Preliminary

L \sim 240 \text{pb}^{-1}

\begin{align*}
N (\text{MeV/c}^2) & \\sim 3 \\
\gamma (\text{MeV/c}^2) & = 0 \\
\gamma (\text{MeV/c}^2) & = 12
\end{align*}

Γ = 0 MeV/c^2:
- 87@90%CL

Γ = 12 MeV/c^2:
- 122@90%CL

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$D^0_p$ spectrum w/ proton PID

CDF Run II Preliminary

$L=240\text{pb}^{-1}$

Event Yield @ 90 % CL

$N/3\text{ MeV}/c^2$

$M(D^0 p)$

$[\text{GeV}/c^2]$

$\Gamma=12\text{ MeV}/c^2$

$\Gamma=0\text{ MeV}/c^2$

CDF Run II Preliminary

$\sim 240\text{pb}^{-1}$

$97@90\%\text{CL}$

$\Gamma=0\text{ MeV}/c^2$

$\Gamma=12\text{ MeV}/c^2$

$245@90\%\text{CL}$

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Limits on $\Theta_c$

- search window $3.099 \pm 18 \text{ MeV}/c^2$
- take worst point from the limit vs mass inside the window

<table>
<thead>
<tr>
<th>Reference channel</th>
<th>Search channel</th>
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</thead>
<tbody>
<tr>
<td>$D_2^{*0} \rightarrow D^+ \pi^-$</td>
<td>$\Theta_c^0 \rightarrow D^{*-} p &lt; 21 \ @ \ 90% \ CL$</td>
</tr>
<tr>
<td>$D_2^{*0} \rightarrow D^+ \pi^-$</td>
<td>$\Theta_c^0 \rightarrow D^- p &lt; 89 \ @ \ 90% \ CL$</td>
</tr>
<tr>
<td>$D_2^{*+} \rightarrow D^0 \pi^+$</td>
<td>$\Theta_c^+ \rightarrow \bar{D}^0 p &lt; 87 \ @ \ 90% \ CL$</td>
</tr>
<tr>
<td>$D_2^{*+} \rightarrow D^0 \pi^+$</td>
<td>$\Theta_c^+ \rightarrow D^0 p &lt; 97 \ @ \ 90% \ CL$</td>
</tr>
</tbody>
</table>
Consider \( R_s^+ (\bar{b}uuds) \) (notation adopted from W. Stewart et al., hep-ph0402076) is stable against strong decay:

\[
M_{R_s} \approx M_\Theta + M_{\Lambda_b} - M_{\Lambda} + M_{\Xi_c} - M_{\Lambda_c'} = 5920 \text{ MeV} < M(B_{sp})
\]

Possible Weak decay:

\[
\begin{array}{c}
\bar{b} \\
\downarrow \\
s \\
u \\
\downarrow \\
u \\
\downarrow \\
d \\
\uparrow \downarrow \\
\bar{c} \\
J/\psi
\end{array}
\]
Search for $R_s^+$

$R_s^+ \rightarrow J/\psi p$ on dimuon data 282 $pb^{-1}$ - ref. channel $B^+ \rightarrow J/\psi K^+$

measurable $R_s^+$ lifetimes considered: $L_{xy} > 100$ $\mu m$ and no $L_{xy}$ cut

unbinned likelihood fits varying mass in wide range => calculate mass dependent limits

no signal found!

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Using detector with superior momentum resolution and good PID capabilities and high statistic clean samples of $K_S^0$, $\Xi$, $D^{*+}$, $D^0$, $D^+$, $J/\psi$ we searched for recently reported pentaquark states: $\Phi^{--,0}$, $\Theta^+$, $\Theta_c$, $R_s$.

No signals found, limits on relative yields with respect to known states established.

Calculation of upper limits on production cross sections is in progress. Expect numbers by Winter.

Production of exotic baryons is severely suppressed with respect to normal baryon production calling for exotic production mechanisms to explain existing positive results.