Exotic Baryons

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Exotic Baryons

- Normal QCD baryons are 3-quark qqq states completely antisymmetric in color indices of quarks.
- In past year, experimental evidence reported for exotic baryons – baryons whose flavor quantum numbers forbid classification as qqq states. All presently observed exotic baryons can be classified as $qqqq\bar{q} \equiv q^4\bar{q}$ pentaquarks.

Outline

- Experimental Evidence for Pentaquarks

$$\Theta^+(1540),\ \Phi(1860),\ \Theta_{\bar{c}}(3099)$$

Θ^+	$uudd\bar{s}$	$S = +1$	$I = 0$	$J = \frac{1}{2}$
Φ^{--}	$ssdd\bar{u}$	$S = -2$	$I = \frac{3}{2}$	$J = \frac{1}{2}$
$\Theta_{\bar{c}}$	$uudd\bar{c}$	$C = -1$	$I = 0$	$J = ?$

- Theoretical Work

Symmetries: $SU(3)_F$, spin-flavor $SU(6)_c$

Models: Quark, Skyrme (Chiral Solition)

Experimental Evidence for Θ^+

- Θ^+ seen by 8 different experiments Z^+ in PDG 86
- Very Narrow Width

  $\Gamma < 15$ MeV $\Gamma < 2$ MeV Cahn, Trilling

  $\Gamma(\Theta^+ \to NK)$, $N = qqq$, $K = q\bar{s}$
- Strangeness $S = +1$
- Isosinglet $I = 0$
- Parity unmeasured, $J = \frac{1}{2}$
- Photoproduction and hadronic production by fragmentation

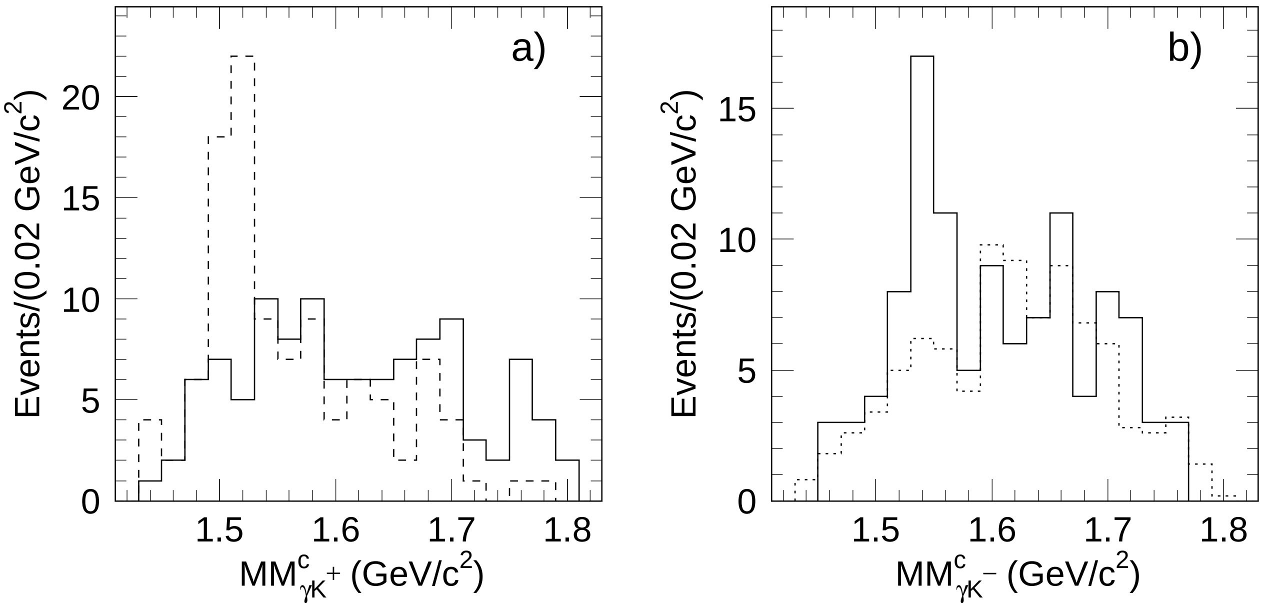
Experimental Evidence Θ^+

- T. Nakano *et al.* [LEPS Collaboration], "Evidence for a narrow $S = +1$ baryon resonance in photoproduction from the neutron," Phys. Rev. Lett. **91**, 012002 (2003).
- V. V. Barmin *et al.* [DIANA Collaboration], "Observation of a baryon resonance with positive strangeness in K+ collisions with Xe nuclei," Phys. Atom. Nucl. **66**, 1715 (2003) [Yad. Fiz. **66**, 1763 (2003)].
- S. Stepanyan *et al.* [CLAS Collaboration], "Observation of an exotic S = +1 baryon in exclusive photoproduction from the deuteron," Phys. Rev. Lett. **91**, 252001 (2003).
- J. Barth *et al.* [SAPHIR Collaboration], "Evidence For The Positive-Strangeness Pentaquark Theta+ In Photoproduction With The Saphir Detector At Elsa," Phys. Lett. B **572**, 127 (2003);
- A. Aleev *et al.* [SVD Collaboration], "Observation of narrow baryon resonance decaying into p K0(S) in p A interactions at 70-GeV/c with SVD-2 setup," arXiv:hep-ex/0401024.

Experimental Evidence for Θ^+

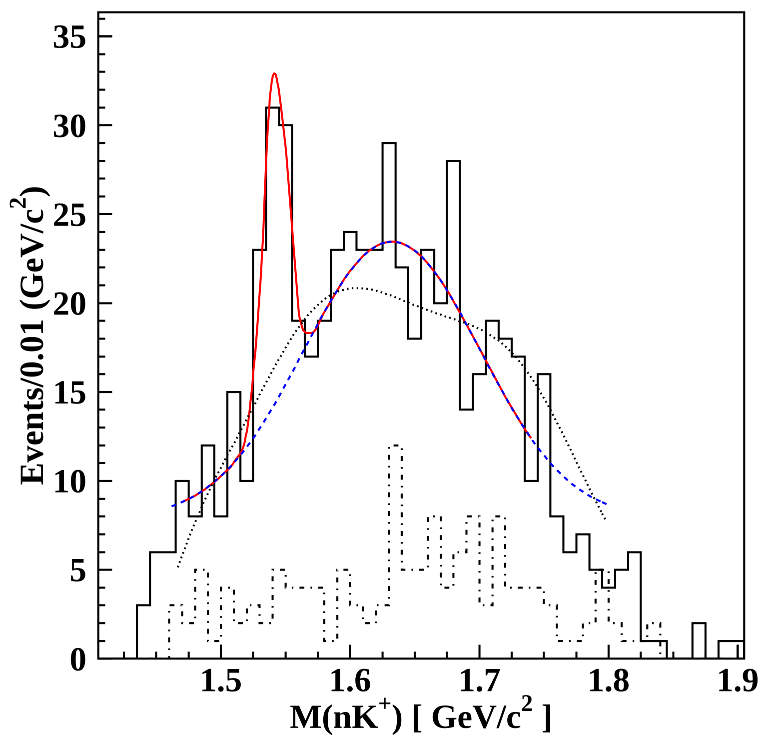
- A. Airapetian *et al.* [HERMES Collaboration], “Evidence for a narrow $|S| = 1$ baryon state at a mass of 1528-MeV in quasi-real photoproduction,” Phys. Lett. B **585**, 213 (2004) [arXiv:hep-ex/0312044].
- M. Abdel-Bary *et al.* [COSY-TOF Collaboration], “Evidence for a narrow resonance at 1530-MeV/c**2 in the K0 p system of the reaction p p $\rightarrow$ Sigma+ K0 p from the COSY-TOF experiment,” [arXiv:hep-ex/0403011].
- S. Chekanov *et al.* [ZEUS Collaboration], “Evidence for a narrow baryonic state decaying to K0(S) p and K0(S) anti-p in deep inelastic scattering at HERA,” arXiv:hep-ex/0403051.

LEPS $\gamma n \to K^- K^+ n$ on ^{12}C



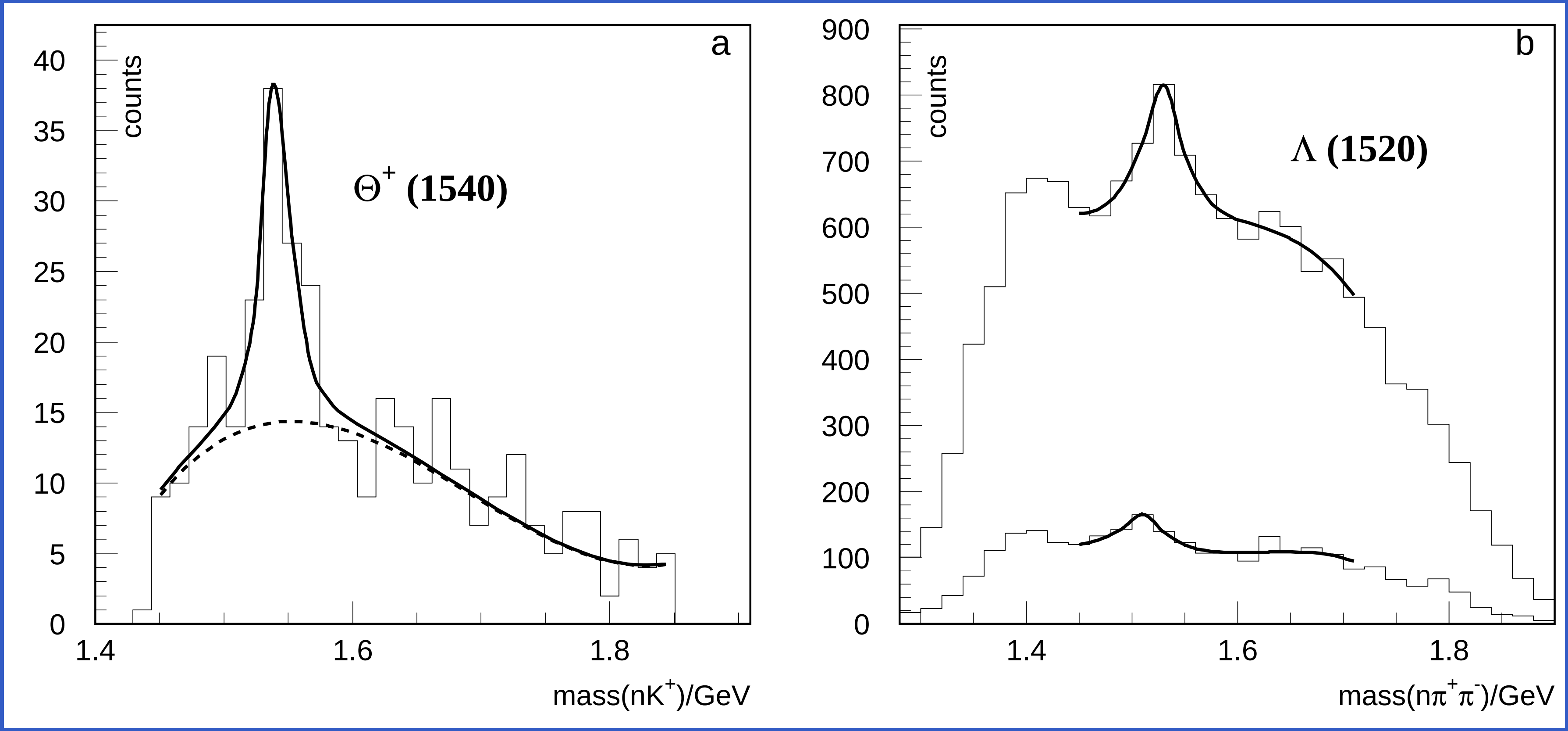
19 ± 2.8 events above background Jan. 2003

CLAS $\gamma d \to K^+ K^- p\, n$



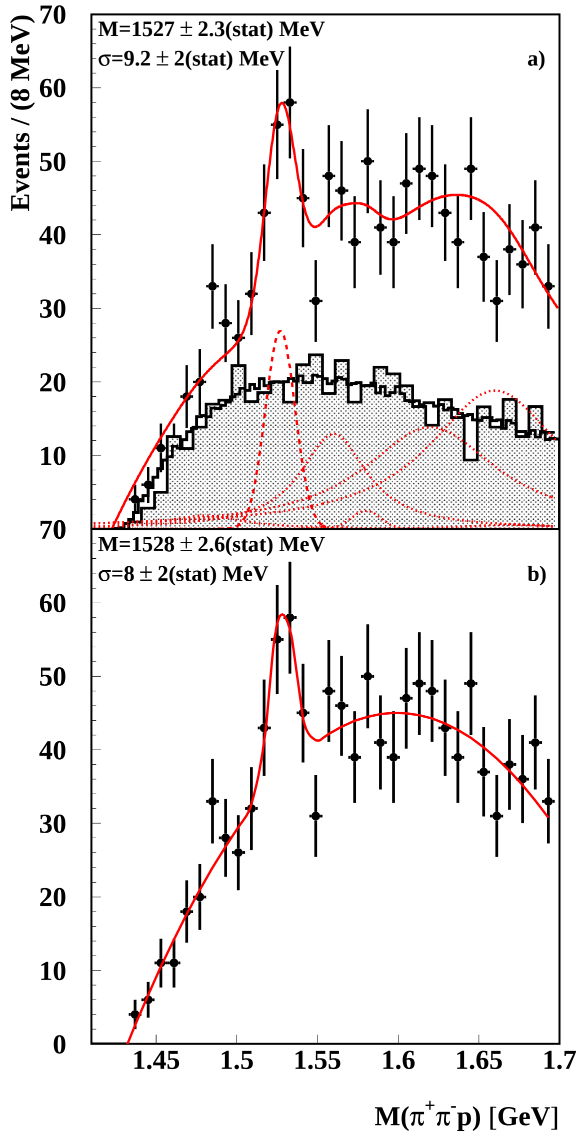
43 events in peak July 2003

SAPHIR $\gamma p \to n K^+ K^0_S$



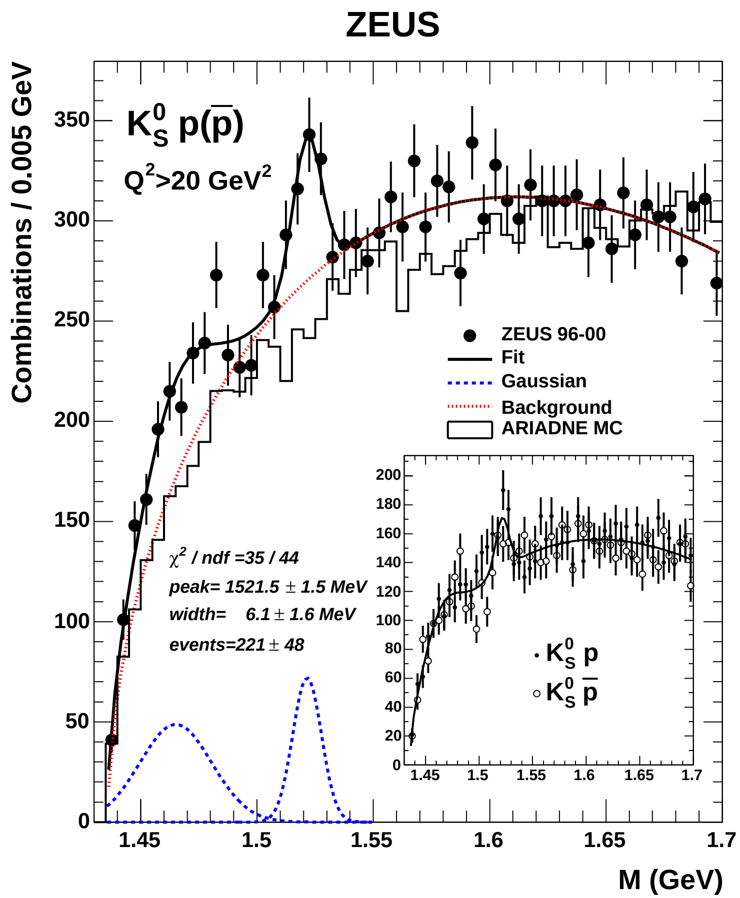
55 events above background August 2003

HERMES γd



Dec. 2003

ZEUS $e^{\pm}p$



221 ± 48 events in signal March 2004

Experimental Evidence Θ^+

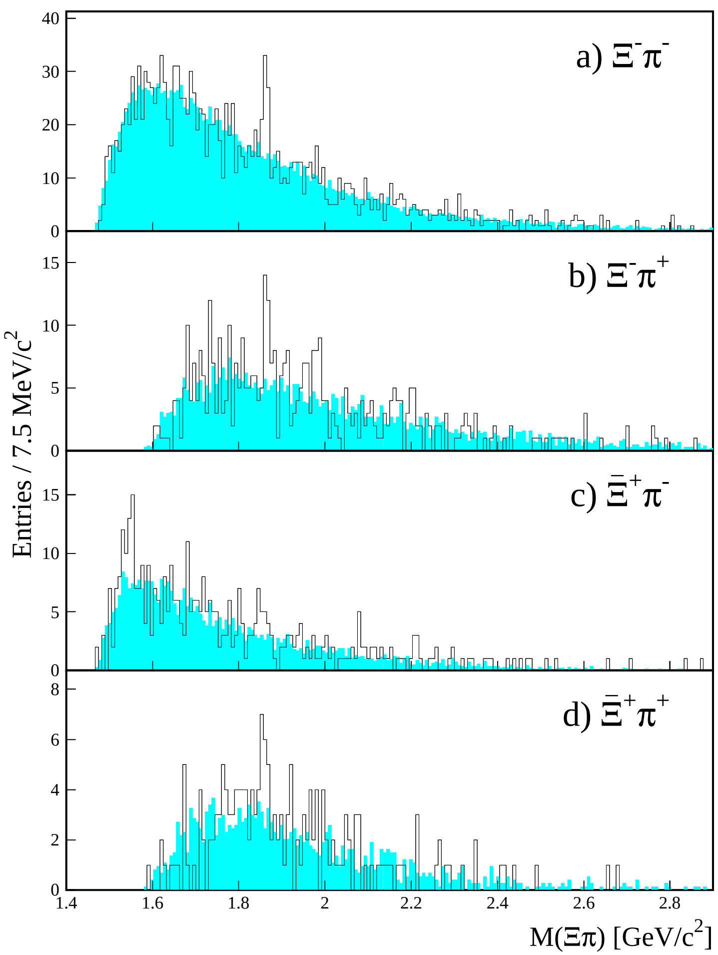
Expt.	Mass (MeV)	Width (MeV)	Decay	Production	σ
LEPS	1540 ± 10	< 25	nK^+	$\gamma n \to \Theta^+ K^-$	4.6
DIANA	1539 ± 2	< 9	pK_S^0	$K^+\mathrm{Xe}$	4.4
CLAS	1542 ± 5	< 21	nK^+	$\gamma d \to K^+ K^- p\, n$	$5.3 \pm 0.$
SAPHIR	$1540 \pm 4 \pm 2$	< 25	nK^+	$\gamma p \to nK^+ K_S^0$	4.8
SVD	$1526 \pm 3 \pm 3$	< 24	pK_S^0	$p\,\mathrm{N} \to pK_S^0 + X$	5.6
HERMES	$1528 \pm 2.6 \pm 2.1$	$< 19 \pm 5 \pm 2$	pK_S^0	γd	$4 - 6$
COSY-TOF	1530 ± 5	$< 18 \pm 4$	pK^0	$pp \to \Sigma^+ K^0 p$	$4 - 6$
ZEUS	$1521.5 \pm 1.5^{+2.8}_{-1.7}$	$6.1 \pm 1.6^{+2.0}_{-1.4}$	$nK^+, p(\bar{p})K_S^0$	$e^{\pm}p$	4.6

Experimental Evidence for Exotics

- C. Alt *et al.* [NA49 Collaboration], "Observation of an exotic S = -2, Q = -2 baryon resonance in proton proton collisions at the CERN SPS," arXiv:hep-ex/0310014.
- A. Aktas *et al.* [H1 Collaboration], "Evidence for a narrow anti-charmed baryon state," arXiv:hep-ex/0403017.

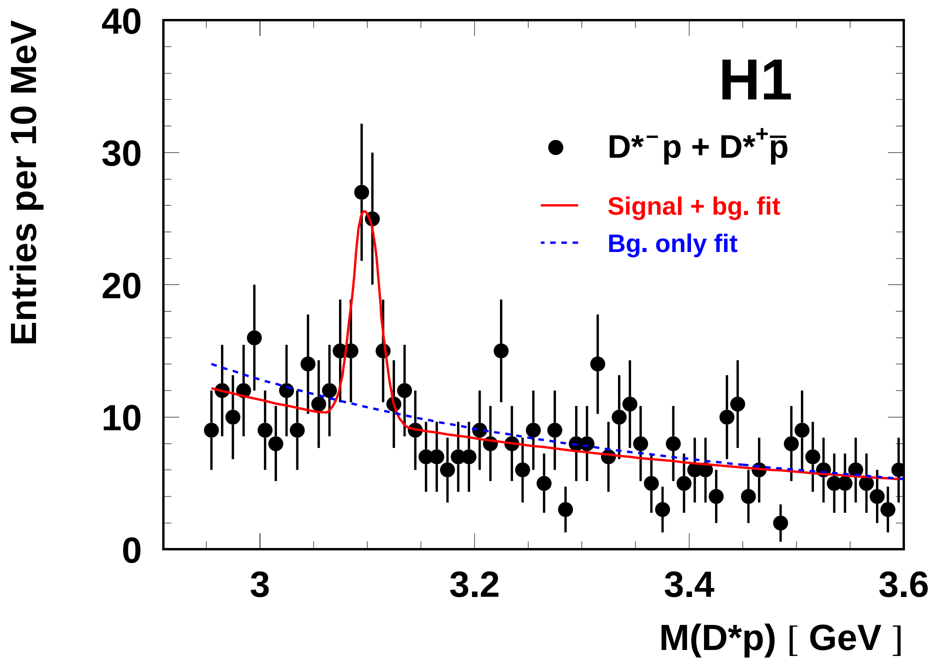
Expt.	Mass (MeV)	Width (MeV)	Decay	Production	σ
NA49	$\Phi \equiv \Xi_{\frac{3}{2}} = 1862 \pm 2$	< 18	$\Xi^-\pi^-$, $\Xi^-\pi^+$	pp	4
H1	$\Theta_{\bar{c}} = 3099 \pm 3 \pm 5$	$< 12 \pm 3$	pD^{*-}, $\bar{p}D^{*+}$	$e^{\pm}p$	5.4

NA49



67.5 events above background Oct. 2003

H1



50.6 ± 11.2 signal events March 2004

Chiral Soliton Model

- Rigid rotator quantization of Skyrme Model gives $P = +1$ exotic multiplets $\overline{\mathbf{10}}_{\frac{1}{2}}$, $\mathbf{27}_{\frac{1}{2}}$, $\mathbf{27}_{\frac{3}{2}}$, $\cdots$ in same spin-flavor tower as $\mathbf{8}_{\frac{1}{2}}$ and $\mathbf{10}_{\frac{3}{2}}$

  Manohar 1984, Chemtob 1985

- Mass of Lightest Exotic ~ 1530 MeV

  Praszalowicz 1987

- $\Theta^+ = 1530$ MeV, $\Gamma(\Theta^+) < 15$ MeV

  Diakonov, Petrov, Polyakov 1997

  $N(1710)$ identified as nucleon member of antidecuplet. Rigid rotator quantization used.

Chiral Soliton Model

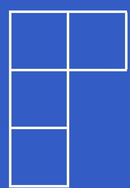
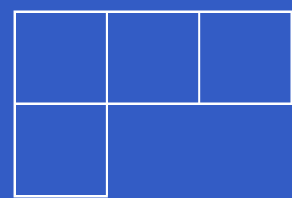
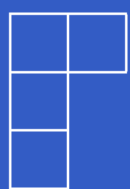
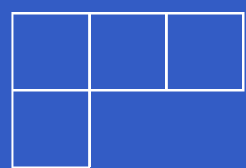
- Rigid rotator quantization invalid because $(M_{\Theta^+} - M_N)$ mass splitting is $\mathcal{O}(1)$ in $1/N_c$ expansion $\Rightarrow$ need to include vibrational modes

  Itzhaki, Klebanov, Ouyang, Rastelli T.D. Cohen Pobylitsa

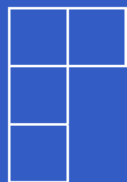
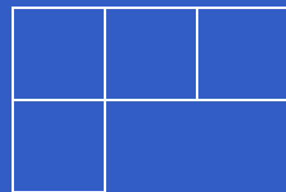
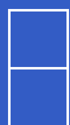
- $\Gamma \sim \mathcal{O}(1)$ Praszalowicz

Quark Model: $q^4\bar{q}$ pentaquark

Two Choices for $qqqq$ Wavefunction

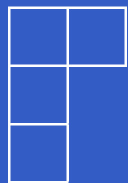
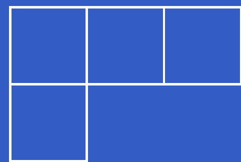
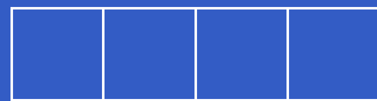
Color	Orbital	Spin-Flavor	Parity
	singlet		+1
			-1

Quark Model: $q^4\bar{q}$ pentaquark

	Color	Orbital	Spin-Flavor	Parity
q^4:		singlet		+1
$\bar{q}$:		singlet		-1
$q^4\bar{q}$:	singlet	singlet		-1

Negative Parity Exotics

Quark Model: $q^4\bar{q}$ pentaquark

	Color	Orbital	Spin-Flavor	Parity
q^4:				-1
$\bar{q}$:		singlet		-1
$q^4\bar{q}$:	singlet	$L = 1$		+1

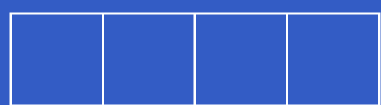
Positive Parity Exotics

Quark Model

- Postive parity pentaquark states are lower in energy than negative parity states. (Requires dynamical argument.) Complete spin-flavor symmetry of q^4 more important than having quarks in same $(1s)$ orbital wavefunction.

  Glozman   Carlson, Carone, Kwee, Nazaryan

- spin-flavor $SU(6) \to SU(2)_{\rm Spin} \otimes SU(3)_{\rm Flavor}$

 $\longrightarrow J_q = I_q = 0, 1, 2$

Pentaquark Reps: $F = 3$ Flavors

- q^4 in $SU(2) \otimes SU(3)$ reps $\left(0, \yng(2,2)\right) \oplus \left(1, \yng(3,1)\right) \oplus \left(2, \yng(4)\right)$

- $\bar{q}$ in $SU(2) \otimes SU(3)$ rep $\left(\frac{1}{2}, \yng(1,1)\right)$

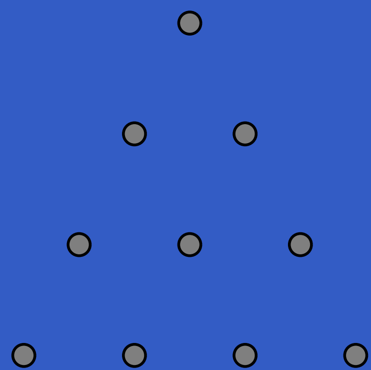
- $q^4\bar{q}$ in $SU(2) \otimes SU(3)$ reps

$$\left(\frac{1}{2}, \yng(3,3)\right) \oplus \left(\frac{1}{2} \oplus \frac{3}{2}, \yng(4,2)\right) \oplus \left(\frac{3}{2} \oplus \frac{5}{2}, \yng(5,1)\right)$$

$$\left(\frac{1}{2}, \overline{\mathbf{10}}\right) \oplus \left(\frac{1}{2}, \mathbf{27}\right) \oplus \left(\frac{3}{2}, \mathbf{27}\right) \oplus \left(\frac{3}{2}, \mathbf{35}\right) \oplus \left(\frac{5}{2}, \mathbf{35}\right)$$

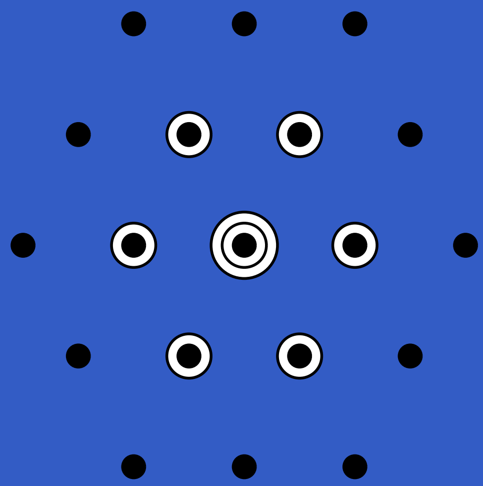
Pentaquark $SU(3)$ Rep $\overline{\mathbf{10}}$

$\Theta^+(1540)$ and $\Phi^{--} \equiv \Xi^{--}_{3/2}(1860)$



Θ^+	$S = +1$	$uudd\bar{s}$
N	$S = 0$	
Σ	$S = -1$	
Φ^{--}	$S = -2$	$ssdd\bar{u}$

Pentaquark $SU(3)$ Rep 27



Θ_1

$N, \quad \Delta$

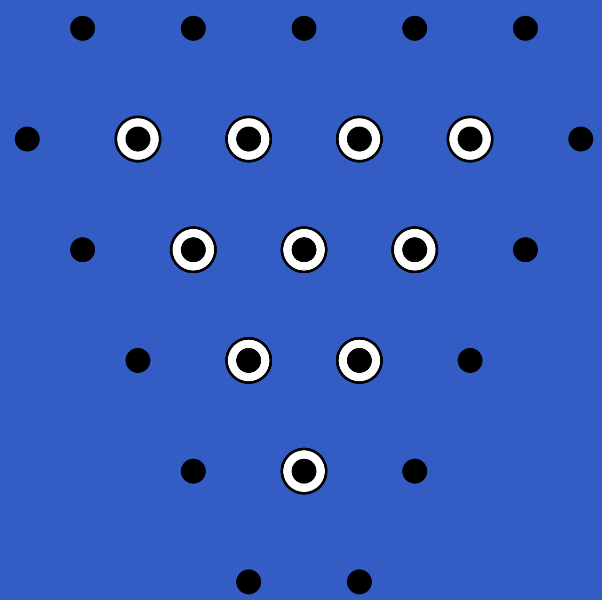
$\Lambda, \quad \Sigma, \quad \Sigma_2$

$\Xi, \quad \Phi$

Ω_1

spin-$\frac{1}{2}$ and -$\frac{3}{2}$ states: $\Theta_{1,j=\frac{1}{2}}$ and $\Theta_{1,j=\frac{3}{2}}$, etc.

Pentaquark $SU(3)$ Rep 35



$\Theta_2 \quad S = +1 \quad uuuu\bar{s}$

$\Delta,\ \Delta_{\frac{5}{2}}$

$\Sigma,\ \Sigma_2$

$\Xi,\ \Phi$

$\Omega,\ \Omega_1$

$\chi \quad S = -4 \quad ssss\bar{u}$

spin-$\frac{3}{2}$ and -$\frac{5}{2}$ states: $\Theta_{2,j=\frac{3}{2}}$ and $\Theta_{2,j=\frac{5}{2}}$, etc.

$1/N_c$ Expansion

- $1/N_c$ expansion of QCD: systematic expansion yields model-independent results
- Large-N_c Baryons have exact contracted spin-flavor symmetry $SU(2F)_c$
- Consequences of contracted spin-flavor symmetry and its breaking account for *all* successful group theoretic relations for non-exotic baryons.

Pentaquarks in the $1/N_c$ Expansion

- Masses
- Axial Couplings
- Widths

Exotic baryons are $q^{N_c+E}\bar{q}^E = q_c^N (q\bar{q})^E$ color singlet bound states.

Normal baryons are $E = 0$.

Pentaquarks are $E = 1$.

Hamiltonian $1/N_c$ Expansion

$$H_0 = N_c \; f\left(\frac{J_q^2}{N_c^2}, \frac{J_{\bar q}^2}{N_c^2}, \frac{J^2}{N_c^2}, \frac{E}{N_c}\right)$$

$$H_0 = c_0 N_c + c_1 E + \frac{1}{N_c}\left(c_2 J_q^2 + c_3 J_{\bar q}^2 + c_4 J^2 + c_5 E^2\right) + \ldots$$

- Relate masses of $E = 1$ baryons to various orders in $1/N_c$
- Relate $E = 1$ mass splittings to $E = 0$ mass splittings

Mass Relations: Isospin and $1/N_c$

$$2\Theta^+ + \langle\Theta_2\rangle = 3\langle\Theta_1\rangle + \mathcal{O}\left(1/N_c^3\right)$$

$$\langle\Theta_1\rangle - \Theta^+ = \frac{2}{3}(\Delta - N) + \mathcal{O}\left(1/N_c^2\right)$$

$$\langle\Theta_2\rangle - \Theta^+ = 2(\Delta - N) + \mathcal{O}\left(1/N_c^2\right)$$

Using $\Theta^+ = 1540$ MeV, and exp'tal $(\Delta - N)$ gives $\langle\Theta_1\rangle = 1735$ MeV and $\langle\Theta_2\rangle = 2126$ MeV (spin-averaged mass) with $1/N_c^2$ error ~ 30 MeV.

Itzhaki, Klebanov, Ouyang, Rastelli   EJ, Manohar

Mass Relations: $SU(3)$ and $1/N_c$

$$2\left(\overline{\mathbf{10}}_{1/2}\right) + \langle \mathbf{35} \rangle = 3\,\langle \mathbf{27} \rangle + \mathcal{O}\left(1/N_c^3\right)$$

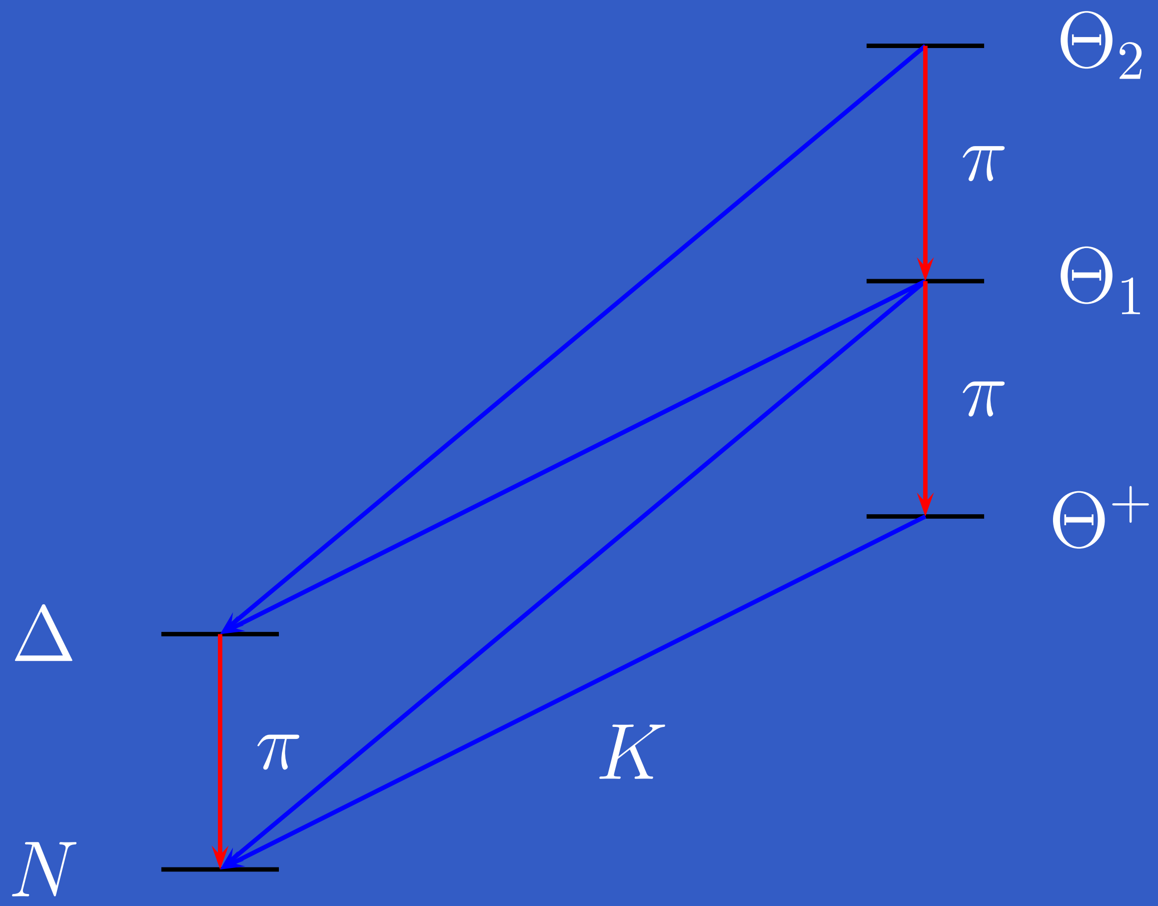
$$\left(\mathbf{35}_{5/2} - \mathbf{35}_{3/2}\right) = \frac{5}{3}\left(\mathbf{27}_{3/2} - \mathbf{27}_{1/2}\right) + \mathcal{O}\left(1/N_c^3\right)$$

$$\langle \mathbf{27} \rangle - \overline{\mathbf{10}}_{1/2} = \frac{2}{3}\left(\mathbf{10}_{3/2} - \mathbf{8}_{1/2}\right) + \mathcal{O}\left(1/N_c^2\right)$$

$$\langle \mathbf{35} \rangle - \overline{\mathbf{10}}_{1/2} = 2\left(\mathbf{10}_{3/2} - \mathbf{8}_{1/2}\right) + \mathcal{O}\left(1/N_c^2\right)$$

EJ, Manohar

Axial Couplings



Axial Couplings

- All couplings for baryons with a given E are related by spin-flavor symmetry up to correction of relative order $1/N_c^2$
- Axial coupling g_A for transitions within a tower (vertical red lines)
- Axial coupling g_0 between pentaquark and normal baryon towers (diagonal blue lines)
- Θ^+ naturally much narrower than the other pentaquarks, since it is the lightest pentaquark.

Pentaquark Widths: Isospin and $1/N_c$

$$\Gamma(\Theta^+) = \Gamma(\Theta^+ \to NK) = \frac{\bar{g}_0^2 p^3}{2\pi f_K^2} = 10 \text{ MeV} \left(\frac{\bar{g}_0}{0.2}\right)^2$$

$$\Gamma(\Theta_{1,j=1/2}) \gtrsim 30 \text{ MeV} + 1.2\Gamma(\Theta)$$

$$\Gamma(\Theta_{1,j=3/2}) \gtrsim 30 \text{ MeV} + 4.9\Gamma(\Theta)$$

$$\Gamma(\Theta_{2,j=3/2}) \gtrsim 560 \text{ MeV} + 5.1\Gamma(\Theta)$$

$$\Gamma(\Theta_{2,j=5/2}) \gtrsim 560 \text{ MeV} + 13.6\Gamma(\Theta)$$

$\Theta_{1,j=1/2}$ and $\Theta_{1,j=3/2}$ decay predominately to $\Theta^+\pi$, not to NK

EJ and Manohar

Heavy $qqqq\bar{Q}$ Pentaquarks

- q^4 in $SU(2) \otimes SU(3)$ reps $\left(0, \yng(2,2)\right) \oplus \left(1, \yng(3,1)\right) \oplus \left(2, \yng(4)\right)$

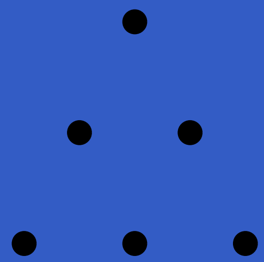
- $\bar{Q}$ in $SU(2) \otimes SU(3)$ rep $\left(\frac{1}{2}, \text{singlet}\right)$

- $q^4\bar{Q}$ in $SU(2) \otimes SU(3)$ reps

$$\left(\frac{1}{2}, \yng(2,2)\right) \oplus \left(\frac{1}{2} \oplus \frac{3}{2}, \yng(2,1)\right) \oplus \left(\frac{3}{2} \oplus \frac{5}{2}, \yng(4)\right)$$

$$\left(\frac{1}{2}, \overline{\mathbf{6}}\right) \oplus \left(\frac{1}{2}, \mathbf{15}\right) \oplus \left(\frac{3}{2}, \mathbf{15}\right) \oplus \left(\frac{3}{2}, \mathbf{15}'\right) \oplus \left(\frac{5}{2}, \mathbf{15}'\right)$$

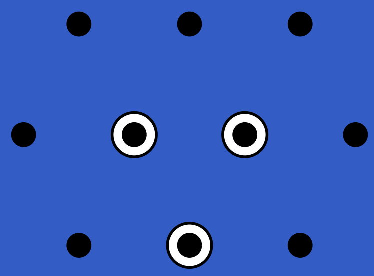
Heavy $qqqq\bar{Q}$ Pentaquarks: $\overline{6}$



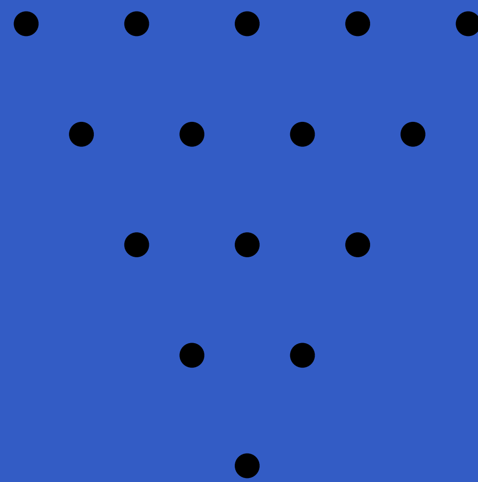
$\Theta_{\bar{Q}}$	$S=0$	$uudd\bar{Q}$
	$S=-1$	$qqqs\bar{Q}$
	$S=-2$	$qqss\bar{Q}$

$$J=\frac{1}{2}$$

Heavy Pentaquarks: $\mathbf{15}$ and $\mathbf{15'}$



$\Theta_{1,\bar{Q}}$



$\Theta_{2,\bar{Q}}$

$$J = \frac{1}{2}, \frac{3}{2}$$

$$J = \frac{3}{2}, \frac{5}{2}$$

Mass Relations: Isospin and $1/N_c$

$$
\begin{aligned}
2\left(\Theta_{\bar{Q}}\right) + \left\langle\Theta_{2,\bar{Q}}\right\rangle &= 3\left\langle\Theta_{1,\bar{Q}}\right\rangle + \mathcal{O}\left(1/N_c^3\right) \\
\left(\Theta_{2,\bar{Q},j=5/2} - \Theta_{2,\bar{Q},j=3/2}\right) &= \frac{5}{3}\left(\Theta_{1,\bar{Q},j=3/2} - \Theta_{1,\bar{Q},j=1/2}\right) + \mathcal{O}\left(1/(m_Q N_c^3)\right) \\
\left\langle\Theta_{1,\bar{Q}}\right\rangle - \Theta_{\bar{Q}} &= \frac{2}{3}(\Delta - N) + \mathcal{O}\left(1/N_c^2\right) \\
\left\langle\Theta_{2,\bar{Q}}\right\rangle - \Theta_{\bar{Q}} &= 2(\Delta - N) + \mathcal{O}\left(1/N_c^2\right)
\end{aligned}
$$

where

$$
\begin{aligned}
\left\langle\Theta_{1,\bar{Q}}\right\rangle &\equiv \frac{1}{3}\left(\Theta_{1,\bar{Q},j=1/2} + 2\Theta_{1,\bar{Q},j=3/2}\right) \\
\left\langle\Theta_{2,\bar{Q}}\right\rangle &\equiv \frac{1}{5}\left(2\Theta_{2,\bar{Q},j=3/2} + 3\Theta_{2,\bar{Q},j=5/2}\right)
\end{aligned}
$$

Heavy Pentaquarks

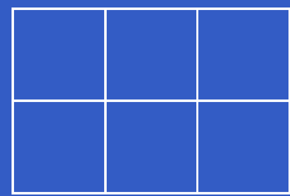
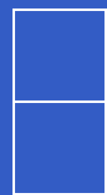
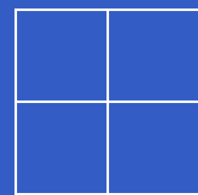
- $\Theta_{\bar{c}}$ may be stable, with only weak decays
- Observed $\Theta_{\bar{c}}(3099)$ unlikely to be ground state.

$$\Theta_{\bar{c}} - \Lambda_c = \Theta - \Lambda + \mathcal{O}(1/N_c)$$

$\Rightarrow \Theta_{\bar{c}} = 2700$ MeV + $\mathcal{O}(1/N_c) \sim 100$ MeV

Jaffe, Wilczek   Stewart, Wessling, Wise   EJ, Manohar

Diquarks

- $\overline{\mathbf{10}}$ representation  arises from binding of 2 diquarks  to form 

  Jaffe,Wilczek

- $1/N_c$ spin-flavor symmetry gives same exotic baryon representations

- Exotic Mesons

Conclusions

- Experimental evidence reported for 3 different pentaquarks:

  $\Theta^+(1540) \qquad \Phi^{--}(1860) \qquad \Theta_{\bar{c}}(3099)$

- Theoretical results for pentaquarks using QCD symmetries:

  masses, axial couplings and widths

- Many open issues remain both experimentally and theoretically