Pentaquarks

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[a]hep-ph/0307243, hep-ph/0307343, hep-ph/0401072 and hep-ph/0402008
[b]hep-ph/0401127

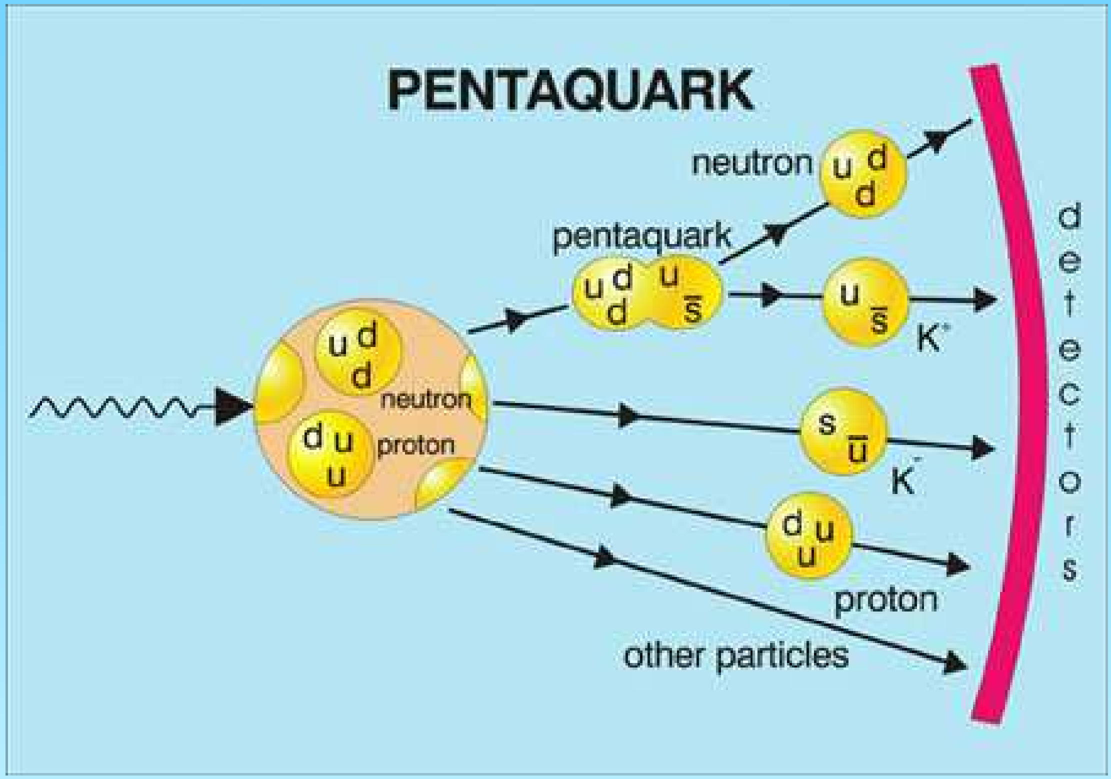
Renaissance of QCD Spectroscopy

Several new surprising experimental results:

- two new extremely narrow mesons containing c and $\bar{s}$ quarks (BaBar, CLEO, BELLE)
- new very narrow resonance precisely at $D^{0*}D^0$ threshold (Belle, CDF)
- enhancements near $\bar{p}p$ thresholds (BES, BELLE)
- exotic 5-quark resonances: Θ^+ (KN), Ξ^{*--}

The discovery of Θ^+

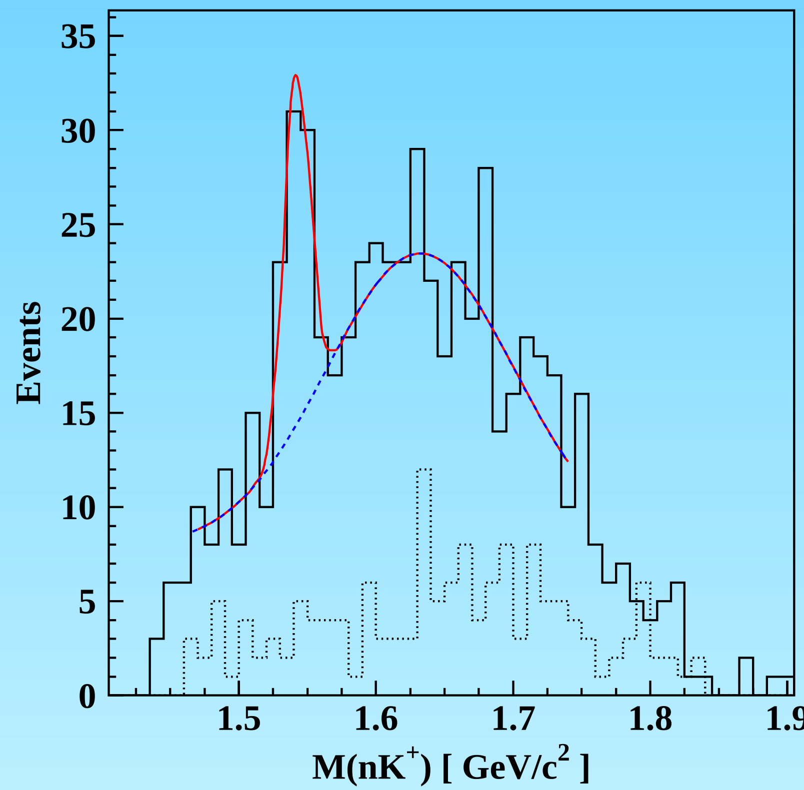
a narrow peak in $K^+ n$ invariant mass:



$$\gamma d \to p \underbrace{n K^+}_{\Theta^+} K^-$$

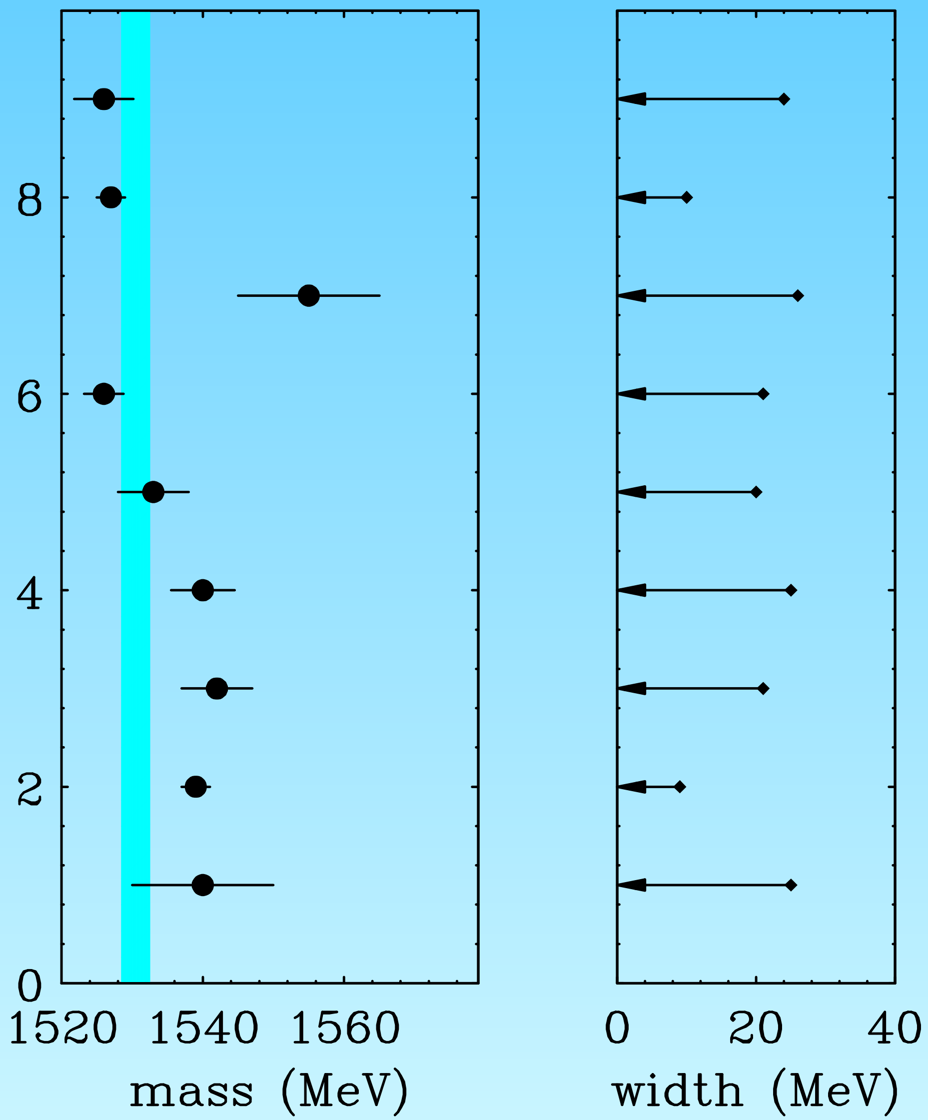
$\Longrightarrow$ **a pentaquark:** $\bar{s} u \, udd$**,** $S = +1$**, exotic baryon resonance**

distribution of $K^+ n$ invariant mass (CLAS/JLAB):



$m_{\Theta^+} = 1542 \pm 5$ MeV, $\Gamma_{\Theta^+} \leq 20$ MeV (CLAS, γD)

mass and width measurements of Θ^+



SVD−2: pA	5.6σ
ZEUS: $\gamma^* p$	5.0σ
CLAS 2: γp	$7.8\pm1.0\sigma$
HERMES: $\gamma^* D$	$7.5\pm2.4\sigma$
ITEP: $\nu A, \bar{\nu} A$	6.7σ
SAPHIR: γp	4.8σ
CLAS: γD	$5.3\pm0.5\sigma$
DIANA: $K^+ Xe$	4.4σ
LEPS: $\gamma\, ^{12}C$	4.6σ

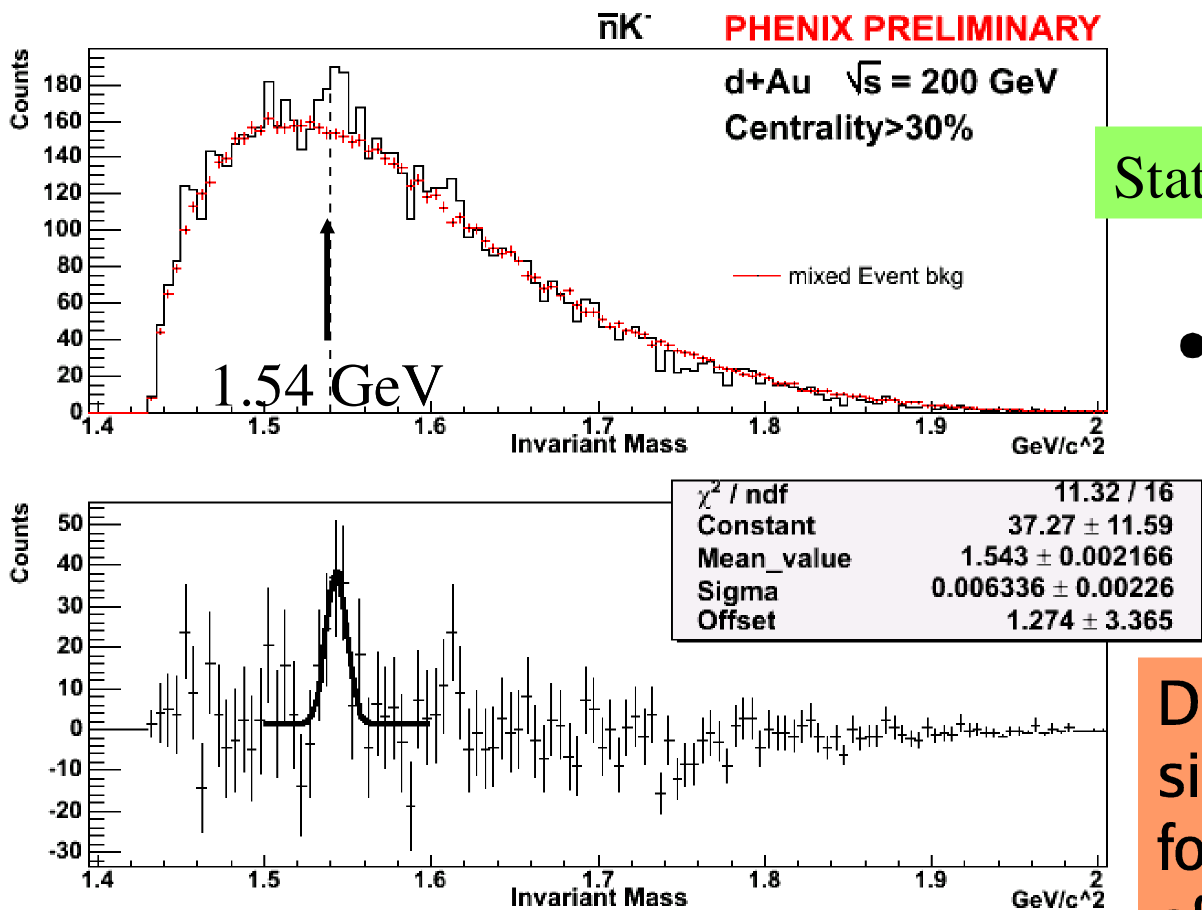
PHENIX: $\overline{\Theta^+} \to \bar{n} K^-$, 1.54 GeV, 4σ

F. Frawley, QM 2004

World average: $m=1530.5\pm2.0$ MeV

Anti Penta Quarks with PHENIX?

$\Theta^- \rightarrow \bar{n} + K^-$



Statistically it's a 4σ effect

- No estimate of systematic Error yet
- No estimate of Efficiency yet

Determining statistical significance of peak will follow from the ongoing effort to understand the systematic errors

See Chris Pinkenburg poster

so far only upper bound on width,
because of experimental E resolution

but extremely narrow width from indirect analysis!

- re-analysis of old KN data:

  $\Gamma_{\Theta^+} \lesssim 1$ MeV (Nussinov, Arndt et al.)

  but analysis indirect: no exp. coverage of relevant energy

  Cahn & Trilling: $\Gamma_{\Theta^+} = 0.9 \pm 0.3$ MeV from DIANA K^+Xe data
  $\Gamma_{\Theta^+} <$ 1–4 MeV from older exps

such a narrow width is unheard of in strong decays ?! . . .

Pentaquark Workshop, JLab, Nov. 6-8, 2003

Theoretical prejudices can be dangerous...

1984 Review of Particle Properties:

Particle Data Group: Review of particle properties S243

For notation, see key at front of Listings.

Baryons

Δ(2950), Δ(~3000), Z's, $Z_0(1780)$

Δ(2950) K_{315} Status: **

→ 126 DELTA(2950, JP=15/2+) I=3/2 K3 15

126 DELTA(2950) MASS (MEV)

M	2850.0	100.0	HENDRY	78	MPWA	PI N TO PI N	12/79
M	2990.0	100.0	HOEHLER	79	IPWA	PI N TO PI N	12/79

126 DELTA(2950) WIDTH (MEV)

W	700.0	200.0	HENDRY	78	MPWA	PI N TO PI N	12/79
W	330.0	100.0	HOEHLER	79	IPWA	PI N TO PI N	12/79

126 DELTA(2950) PARTIAL DECAY MODES

		DECAY MASSES
P1	DELTA(2950) INTO N PI	938+ 140

126 DELTA(2950) BRANCHING RATIOS

R1	DELTA(2950) INTO (N PI)/TOTAL				(P1)		
R1	0.03	0.01	HENDRY	78	MPWA	PI N TO PI N	12/79
R1	0.04	0.02	HOEHLER	79	IPWA	PI N TO PI N	12/79

REFERENCES FOR DELTA(2950)

HENDRY 78 PRL 41 222 A W HENDRY <IND+LBL>IJP
-- THE ANALYSIS AND RESULTS ARE DISCUSSED MORE FULLY IN HENDRY 81.
HOEHLER 79 HANDBOOK OF PI-N SCATTERING, PHYSIK DATEN VOL.12-1
+KAISER,KOCH,PIETARINEN (KARL)IJP
ALSO 80 TORONTO CONF 3 R KOCH (KARL)IJP
HENDRY 81 ANP 136 1 A W HENDRY (IND)

~3000 MEV REGION – FORMATION EXPERIMENTS

127 DELTA(~3000) I=3/2

WE LIST HERE MISCELLANEOUS HIGH-MASS CANDIDATES FOR ISOSPIN-3/2 RESONANCES FOUND IN PARTIAL-WAVE ANALYSES. SO FAR, NO ANALYSIS OF THIS REGION HAS USED ALL THE AVAILABLE DATA OR INCORPORATED ANALYTICITY CONSTRAINTS.

OUR 1982 EDITION ALSO HAD A DELTA(2850) AND A DELTA (3230). NOTHING HAS BEEN HEARD FROM THEM IN 10 YEARS, AND UNDER THE AUTHORITY GRANTED UNTO US BY THE STATUTE OF LIMITATIONS, WE DECLARE THEM TO BE DEAD. THE EVIDENCE FOR THEM WAS DEDUCED FROM TOTAL-CROSS-SECTION AND 180-DEG-ELASTIC-CROSS-SECTION MEASUREMENTS. PLACED IN THE MAIN BARYON TABLE IN THE ANYTHING-GOES 1960'S, THEY REMAINED THERE DUE TO INATTENTION UNTIL THIS EDITION.

NOTE ON THE S = +1 BARYON SYSTEM

The evidence for strangeness +1 baryon resonances was thoroughly reviewed in our 1976 edition,[1] and has been reviewed more recently by Kelly[2] and by Oades.[3] One new partial-wave analysis[4] has been published since our 1982 edition. As usual, the results permit no definite conclusion — the same story heard for 15 years. The general feeling, supported by the prejudice against baryons not make up of three quarks, is that the suggestive counterclockwise movement in the Argand diagram of some of the partial waves is not real evidence for true Breit-Wigner resonances. But until the dynamics of the KN system is better understood, the possibility that Z* resonances exist will not be finally laid to rest.

References

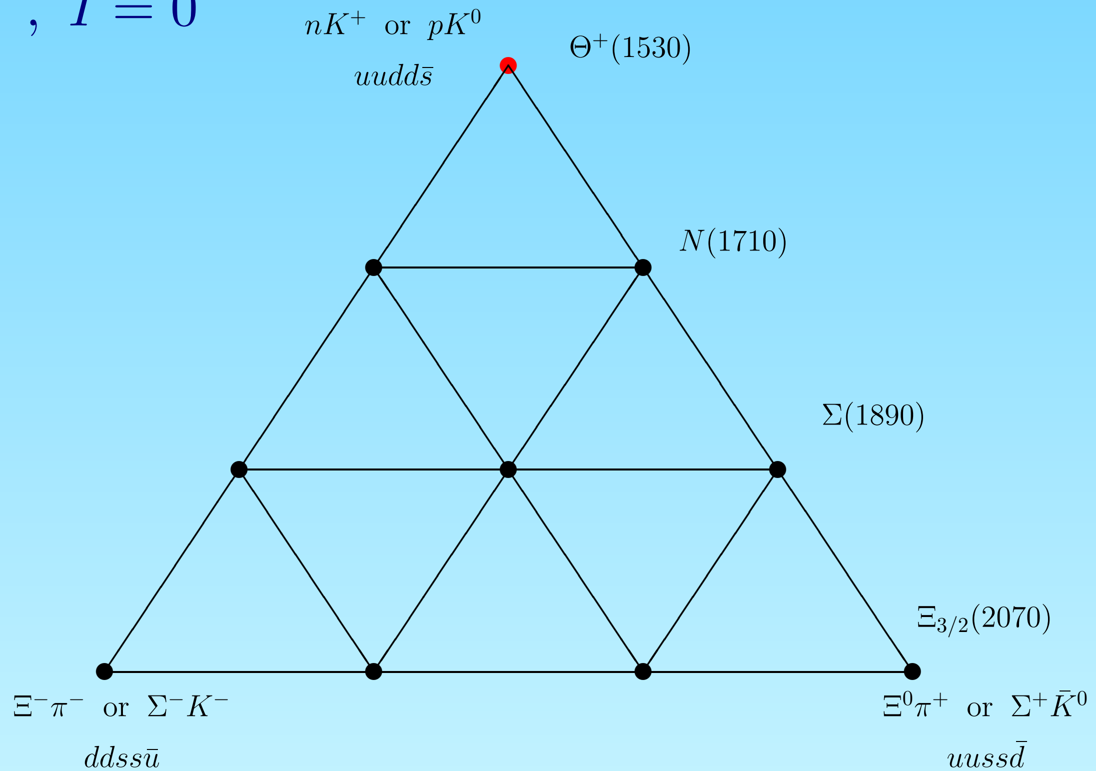
1. Particle Data Group, Rev. Mod. Phys. **48**, S188 (1976).
2. R.L. Kelly, in *Proceedings of the Meeting on Exotic Resonances* (Hiroshima, 1978), ed. I. Endo et al.
3. G.C. Oades, in *Low and Intermediate Energy Kaon-Nucleon Physics* (1981), ed. E. Ferrari and G. Violini.
4. K. Nakajima et al., Phys. Lett. **112B**, 80 (1982).

A beautiful prediction from Skyrme model:

Praszałowicz('87), Diakonov, Petrov & Polyakov('97): $m_{\Theta^+} \approx 1530$ MeV,

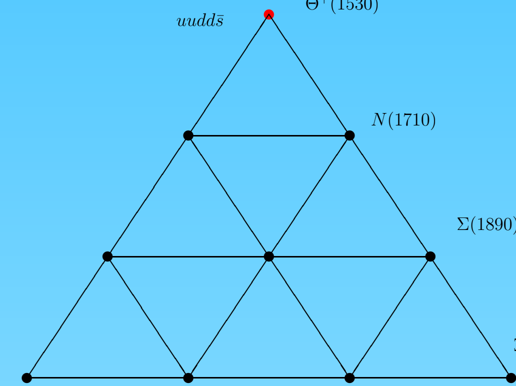
$\Gamma_{\Theta^+} < 15$ MeV, $J^P = \frac{1}{2}^+$, $I = 0$

$\overline{10}$ of $SU(3)_f$:



important: $SU(3)$ breaking linear in $Y = B - S$
for $S < 0$, ordinary baryons – simple: counting s-quarks.
for $S > 0$, a bit subtle: need to understand quark WF first.

Quark content of the other states in $\overline{\mathbf{10}}$:



- start from $|\Theta^+\rangle = |uudd\bar{s}\rangle$
- apply U-spin lowering operator U_- repeatedly (cf. I_-):

$$I_-|u\rangle = \ \ |d\rangle \qquad\qquad \Longleftrightarrow \qquad\qquad U_-|d\rangle = \ \ |s\rangle$$
$$I_-|\bar{d}\rangle = -|\bar{u}\rangle \qquad\qquad\qquad\qquad\qquad U_-|\bar{s}\rangle = -|\bar{d}\rangle$$

- get the other states in each row applying I_-
- $|p^*\rangle = U_-|uudd\bar{s}\rangle = -\sqrt{\frac{1}{3}}\,|uud\,d\bar{d}\rangle + \sqrt{\frac{2}{3}}\,|uud\,s\bar{s}\rangle$ "crypto-exotic"
- "hidden strangeness" (like in ϕ)

$$\langle \#s + \#\bar{s}\rangle_{p^*} = 2 \times \left(\sqrt{\tfrac{2}{3}}\right)^2 = \frac{4}{3}$$

- $|\Sigma^{+*}\rangle = U_-|p^*\rangle, \qquad |\Xi^{+*}\rangle = U_-|\Sigma^{+*}\rangle = |uuss\bar{d}\rangle$
- $\Delta\langle \#s + \#\bar{s}\rangle = \dfrac{1}{3} \qquad \Longrightarrow \qquad \Delta M \sim \dfrac{m_s}{3}$!

But can't expect 1% precision for m_{Θ^+}

$\Longrightarrow$ Re-examine Skyrme/χSM predictions hep-ph/0401127

- light $\overline{\mathbf{10}}$ a qualitative success
- realistic error estimate: $\delta m_{\overline{10}} \lesssim 100$ MeV
- DPP $m_{\Xi^{--}}$ off by 200 MeV: antiquated $\Sigma_{\pi N}$
- modern $\Sigma_{\pi N} \Longrightarrow$ central value of $m_{\Xi^{--}}$ ✓
- $\Gamma_{\overline{10}} \sim \mathcal{O}(1/N_c^2)$
- with realistic couplings hard to get $\Gamma_{\overline{10}} < 10$ MeV
- key prediction: light **27** with $J^P = \frac{3}{2}^+$

$\Rightarrow$ Θ-like $I = 1$ state within 100 MeV of $\Theta^+(I = 0)$

χSM & quark model: complementary description of hadrons

$\Rightarrow$ Need to understand Θ^+ in quark language

- QCD: nothing prevents $5q$ states
- but no direct QCD spectrum calculation yet (LC, lattice ?. . .)
- Constituent Quark Model:

$$M = \sum_i m_i - \underbrace{\sum_{i>j} V(\vec{\lambda}_i \cdot \vec{\lambda}_j) \frac{\vec{\sigma}_i \cdot \vec{\sigma}_j}{m_i \cdot m_j}}_{\text{hyperfine interaction}}$$

m_i : effective quark mass, $\vec{\lambda}$: $SU(3)_c$ generators, $\vec{\sigma}$: Pauli spin operators

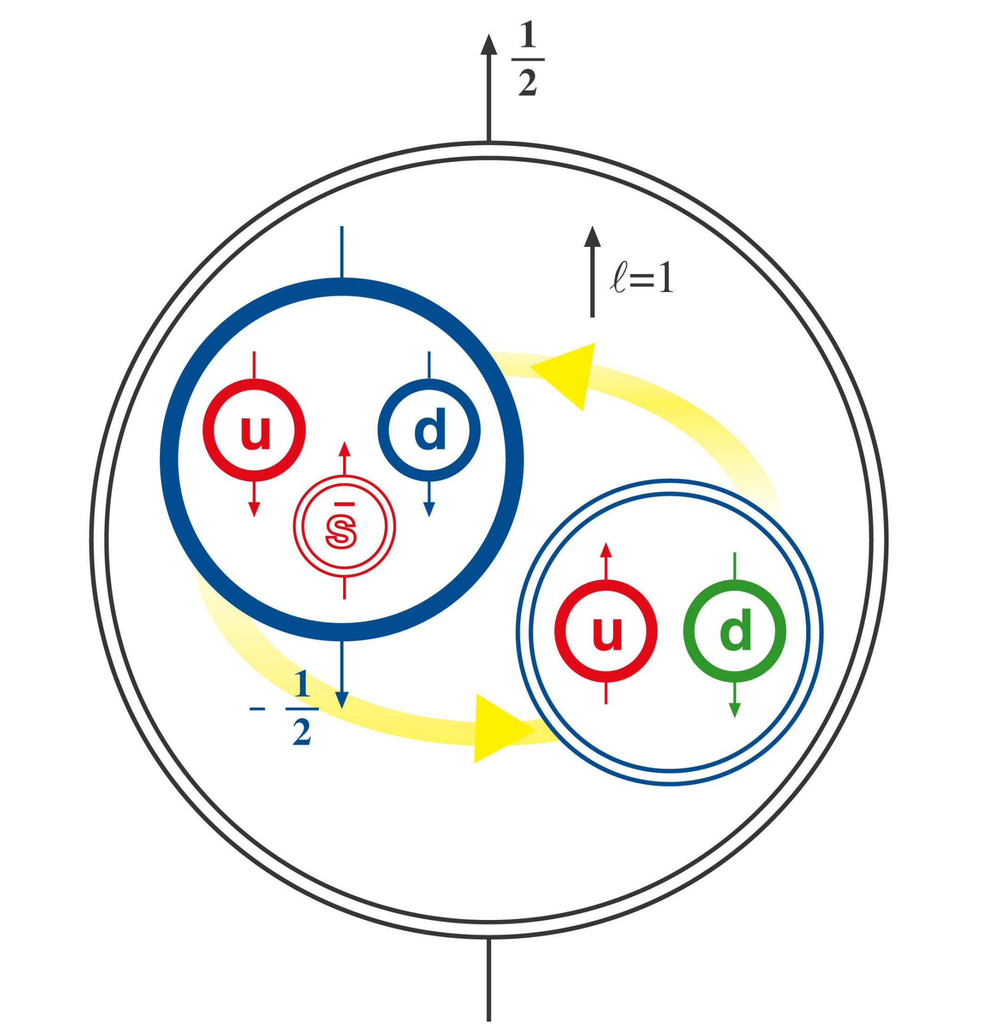
$\Longrightarrow$ color-spin $SU(6)$ algebra:

symmetric	in color $\times$ spin	$\longleftrightarrow$	attractive
antisymmetric	in color $\times$ spin	$\longleftrightarrow$	repulsive

application: unravelling Θ^+ quark structure

- Θ^+: K^+n and $K^0p \iff \{uudd\bar{s}\}$
- Θ^+ is light! $\Rightarrow$ Goldstone-like component(s): minimize E_{int}
- hint: "flavor antisymmetry principle":
  at short distances ident. fermions antisym. in color $\times$ spin (Pauli)
  $\Longrightarrow$ hyperfine interaction *always* repulsive for same-flavor quarks
- maximize $u-u$ and $d-d$ distance
- minimize hyperfine interaction: clustering & spin configuration
- $\underset{n}{\{udd\}}\,\underset{K^+}{\{u\bar{s}\}} \longrightarrow \underset{\bar{\mathbf{3}}_c}{\{ud\}}\,\underset{\mathbf{3}_c}{\{du\bar{s}\}}$ "mate swapping"...
- J^P : likely $\frac{1}{2}^+ \longrightarrow l=1$:
  color molecule of $\bar{\mathbf{3}}_c$ and $\mathbf{3}_c$ in a P-wave
- hyperfine int. short range $\longrightarrow$ acts only *within* clusters

diquark-triquark configuration:



diquark – triquark configuration of the *uudds̄* pentaquark

P-wave diquark-triquark molecule. No *S*-wave $\Longleftrightarrow$ h.f. repulsion

Θ^+ properties from diquark-triquark

- $|ud\ du\bar{s}\rangle$:
- ud diquark: $I=0$, $S=0$, $\bar{\mathbf{3}}_c$
- $ud\bar{s}$ triquark: $I=0$, $S=\frac{1}{2}$, $\mathbf{3}_c$ with ud in $S=1$

$\Longrightarrow$ $J^P = \frac{1}{2}^+$, $I=0$, $\overline{10}$ of $SU(3)_f$

a similar proposal: $[(ud)_{S=0}]^2\ \bar{s}$, but no hf. for $\bar{s}$ (Jaffe & Wilczek)

- compute hyperfine interaction:

$\Longrightarrow$ $\frac{1}{6}(M_\Delta - M_N) \approx 50$ MeV *stronger* binding than in KN

- estimate cost of P-wave excitation of $\{ud\}\{du\bar{s}\}$ system:

reduced mass $\approx$ reduced mass of $c\bar{s}$ in D_s system

$\Longrightarrow$ $\delta E^{P-wave} \approx 350 - (m_{D_s^*} - m_{D_s}) = 207$ MeV

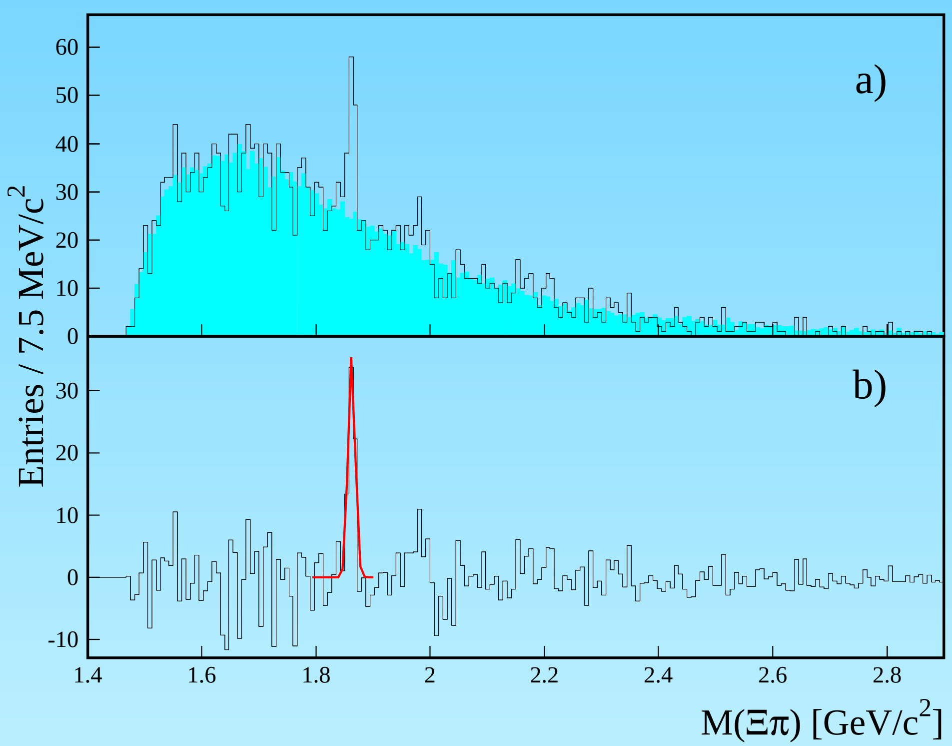
- $m_{\Theta^+} \approx 1592 \pm 50$ MeV vs. 1542 ± 5 MeV (EXP).

analogous triquark-diquark configuration predicts

$m_{\Xi^{--}} = 1720 \pm 50$ MeV

vs exp, NA49:

$m_{\Xi^{--}} = 1862 \pm 2$ MeV, $\quad \Gamma_{\Xi^{--}} < 18$ MeV



generic for all correlated quark configurations

but $\Xi^{--}(1862)$ 400 MeV above $\Xi\pi$ threshold vs 100 MeV for Θ^+

$\Longrightarrow$ challenge for theory: additional degrees of freedom ?

a mass inequality for Ξ^{--*} and Θ^+

hep-ph/0402008

- **for unbroken $SU(3)_f$:**
  $M(\Xi^{--*}) = M(\Theta^+)$ **as both in same** $\overline{10}$
- $SU(3)_f$ **breaking:** $m_s > m_u$
- **variational wave function for** Ξ^{--*}**:**
  $\Psi(\Theta^+)$ **with** $u \to s$, $\bar{s} \to \bar{u}$

$\Rightarrow$ **upper bound on** $M(\Xi^{--*})$**:**

$$M(\Xi^{*--}) \leq M(\Theta^+) + m_s - m_u + \langle \delta V_{hyp}(\bar{s} \to \bar{u}) \rangle_{\Theta^+} + \langle \delta V_{hyp}(u \to s) \rangle_{\Theta^+}$$

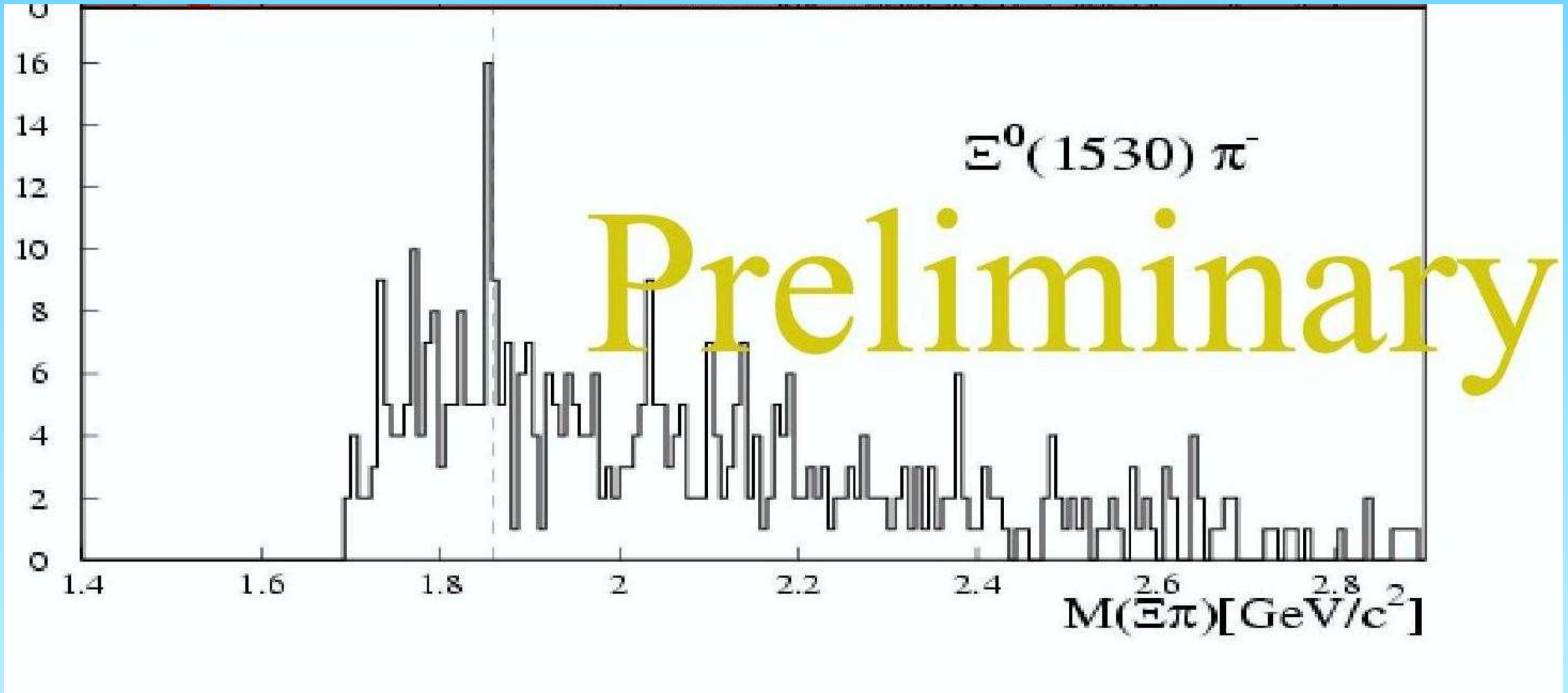
$$M(\Xi^{*--}) - M(\Theta^+) \lesssim 300 \text{ MeV}$$

vs. EXP: 330 MeV

- **need confirmation of exp. mass values**
- **strong constraints on models of 5q structure**

A third pentaquark ?

Another surprise from NA49:
a preliminary peak at approx. 1855 MeV in $\Xi(1530)^0\pi^-$ channel:



but $\overline{10}$ does not couple to $10 + 8$ in SU(3): $\overline{10} \not\to 10 \otimes 8$

$\Longrightarrow$ $\Xi^-(1855) \notin \overline{10}$ but rather exotic 8 or 27 (J&W)

a possible explanation for narrow Θ^+ width

hep-ph/0401072

- two almost degenerate $2q$-$2q$-$\bar{s}$ configurations: Θ_1 and Θ_2
- both can decay via quark rearrangement to isoscalar KN
- so they mix by a loop diagram: $\Theta_i \to KN \to \Theta_j$
- diagonalize the mass matrix: $M_{ij} = M_0 \langle \Theta_i | T | KN \rangle \langle KN | T | \Theta_j \rangle$

$$|\Theta\rangle_S \equiv \cos\phi \cdot |\Theta_1\rangle + \sin\phi \cdot |\Theta_2\rangle$$
$$|\Theta\rangle_L \equiv \sin\phi \cdot |\Theta_1\rangle + \cos\phi \cdot |\Theta_2\rangle$$

- the lower eigenstate, Θ_L, decouples from the KN channel

destructive interference !

width suppression in presence of Θ_1, Θ_2 splitting

$$\frac{\Gamma_{\Theta_L}}{\Gamma_{\Theta_S}} \leq \frac{\Delta M^2}{4\Gamma_{\Theta_S}^2}$$

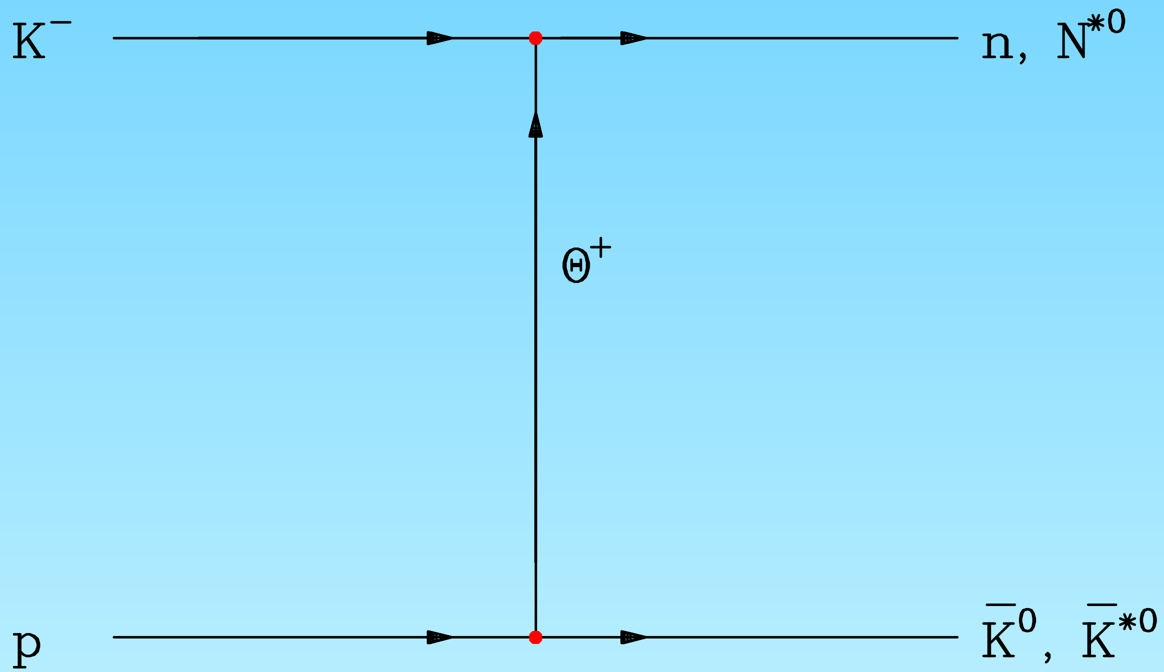
e.g. for $\Delta M = 40$ **MeV and** $\Gamma_{\Theta_S} = 120$ **MeV**

suppression factor = 1/36

$$\Longrightarrow \quad \Gamma_{\Theta_L} \lesssim 3 \text{ MeV}$$

couplings to K^*N channel <u>not suppressed</u>
so look at

baryon-exchange K^-p reactions with K going backward in CM:



$K^-p \to \bar{K}^o n;$ $K^-p \to \bar{K}^{*o} n;$ $K^-p \to \bar{K}^o N^{*o}$ **suppressed**

$K^-p \to \bar{K}^{*o} N^{*o}$ **unsuppressed**

experimental challenges

- confirmation of Θ^+ and Ξ^{*--}
- parity measurement

  (a) $K^+ p \longrightarrow \Theta^+ \pi^+$ vs. $K^+ D \longrightarrow \Theta^+ p$

  (b) polarization asymmetry in $\vec{p}\,\vec{p} \longrightarrow \Sigma^+ \Theta^+$, $\vec{p}\,\vec{n} \longrightarrow \Lambda \Theta^+$

  (c) polarization asymmetry in $\vec{\gamma}\, n \longrightarrow K^- \Theta^+$
- search for new states:

  (a) $\bar{s} \longrightarrow \bar{c}, \bar{b}$

  (b) Θ^+: $J = \frac{1}{2}$ with $L = 1$, $S = \frac{1}{2}$ $\Longrightarrow$ $\overline{\mathbf{10}}$ with $J = \frac{3}{2}$

  (c) higher reps: $\mathbf{27}$, $\mathbf{35}$, ...

a new spectroscopy !

Predictions: Θ_c and Θ_b^+

- $\Theta^+ : \{ud\}\,\{du\bar{s}\}$ - a narrow resonance
- $\bar{s} \to \bar{c}: \implies \Theta_c : \{ud\}\,\{du\bar{c}\} \quad J^P = \frac{1}{2}^+,\ I = 0$

  $M_{\Theta_c} = 2985 \pm 50$ MeV

  $\Gamma(\Theta_c \to DN) \sim (1 \div 2) \times 21$ MeV .
- $\bar{s} \to \bar{b}: \implies \Theta_b^+ : \{ud\}\,\{du\bar{b}\} \quad J^P = \frac{1}{2}^+,\ I = 0$

  $M_{\Theta_b^+} = 6398 \pm 50$ MeV

  $\Gamma(\Theta_b^+ \to BN) \sim (1 \div 2) \times 4$ MeV .

$\implies$ look for unexpectedly narrow peaks in D^-p, $\bar{D}^0 n$, $B^0 p$ and $B^+ n$.

$\implies$ look for protons coming out of charm/bottom decay vertex

Pentaquark production in B decays

- expect reasonable BR for $B \to \text{baryon} + \text{antibaryon}$
- a striking signature: $B \to \Theta^+ + \text{charmed antibaryon}$
- E and $\vec{p}$ conservation in B CM frame:
  unlike multihadron reactions, no kinematical ambiguities!
- in $\Theta^+ \to K_s\, p$ decay, K_s flavor tagged by antibaryon

- (green) $B_d(\bar{b}d) \to \bar{c} + d + u + \bar{d} \to \bar{c} + d + u + \bar{d} + (u\bar{u}) + (d\bar{d}) \to \Theta_c + \bar{n}$
- (green) $B^+(\bar{b}u) \to \bar{c} + u + u + \bar{d} \to \bar{c} + u + u + \bar{d} + (d\bar{d}) + (d\bar{d}) \to \Theta_c + \bar{\Delta}^+$
- (yellow) $B_d(\bar{b}d) \to \bar{c} + d + u + \bar{s} \to \bar{c} + d + u + \bar{s} + (d\bar{d}) + (u\bar{u}) \to \Theta_c + \bar{\Lambda}$
- (yellow) $B_d(\bar{b}d) \to \bar{c} + d + u + \bar{s} \to \bar{c} + d + u + \bar{s} + (d\bar{d}) + (u\bar{u}) \to \Theta^+ + \bar{\Lambda}_c$
- (yellow) $B^+(\bar{b}u) \to \bar{c} + u + u + \bar{s} \to \bar{c} + u + u + \bar{s} + (d\bar{d}) + (d\bar{d}) \to \Theta^+ + \bar{\Sigma}_c^o$
- (red) $B_d(\bar{b}d) \to \bar{u} + d + u + \bar{s} \to \bar{u} + d + u + \bar{s} + (u\bar{u}) + (d\bar{d}) \to \Theta^+ + \bar{p}$
- (red) $B^+(\bar{b}u) \to \bar{u} + u + u + \bar{s} \to \bar{u} + u + u + \bar{s} + (d\bar{d}) + (d\bar{d}) \to \Theta^+ + \bar{n}$

Cabibbo hierarchy: (green) preferred (yellow) suppressed (red) doubly suppressed