Theoretical overview of the Pentaquarks

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Contents

New Narrow Hadrons found in 2003

- Θ^+ (1540) by LEPS, SPring-8 ($\Gamma < 10$ MeV)
- Ξ^{--}(1862) ($\Gamma < 18$ MeV), Ξ_c, . . .
- X (3872) by Belle, KEK ($\Gamma < 2.3$ MeV)
- D_s*(2317) and D_s*(2463) by BaBar ($\Gamma < 10$ MeV)
- K^-ppn ($^3{}_{K^-}$H) deep bound state at 12GeV PS, KEK

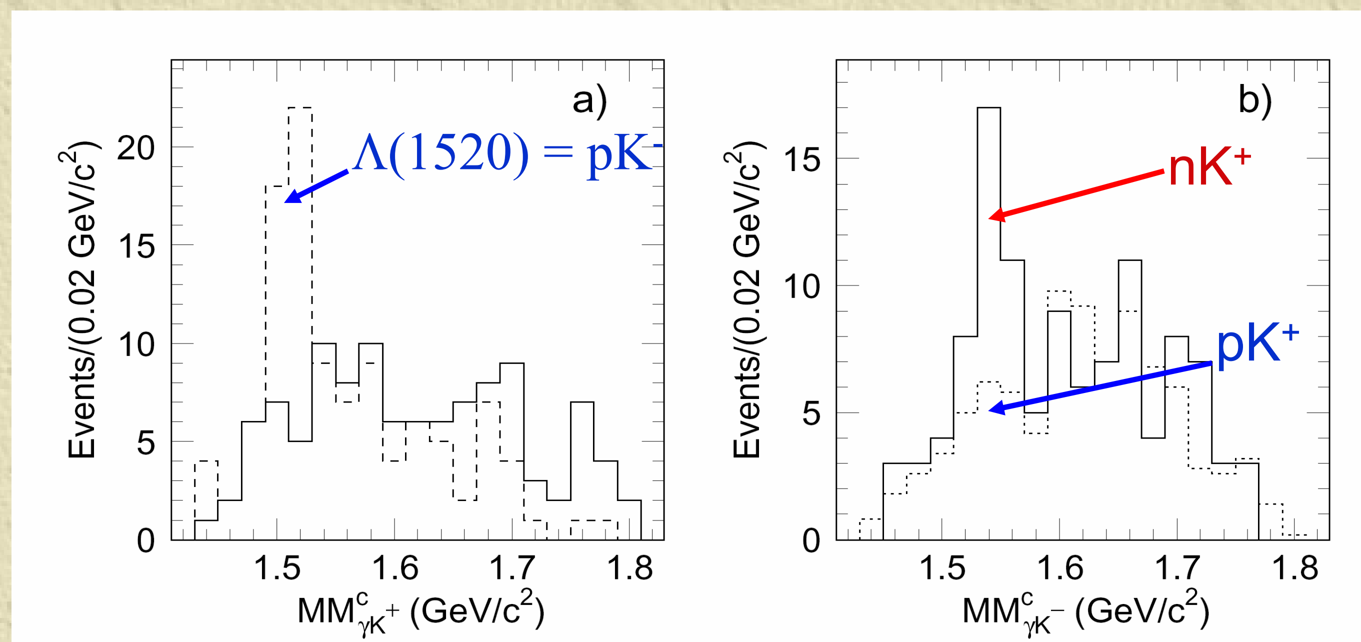
  BE=173MeV ($\Gamma < 25$ MeV) and more

narrow

contain heavy quarks

Discovery of Θ^+ at SPring-8

T. Nakano et al. (LEPS collaboration)



$M = 1540 \pm 10$ MeV, $\Gamma < 25$ MeV, 4.6σ

Whoever believes …

- Skepticism

  Why not seen before?

  should have many brothers

  Some bad history of narrow exotics

  baryonium, dibaryon, . . .

  Why so narrow?

  Fall-apart decay theory

Renaissance of Hadron Spectroscopy

Facts of Θ^+

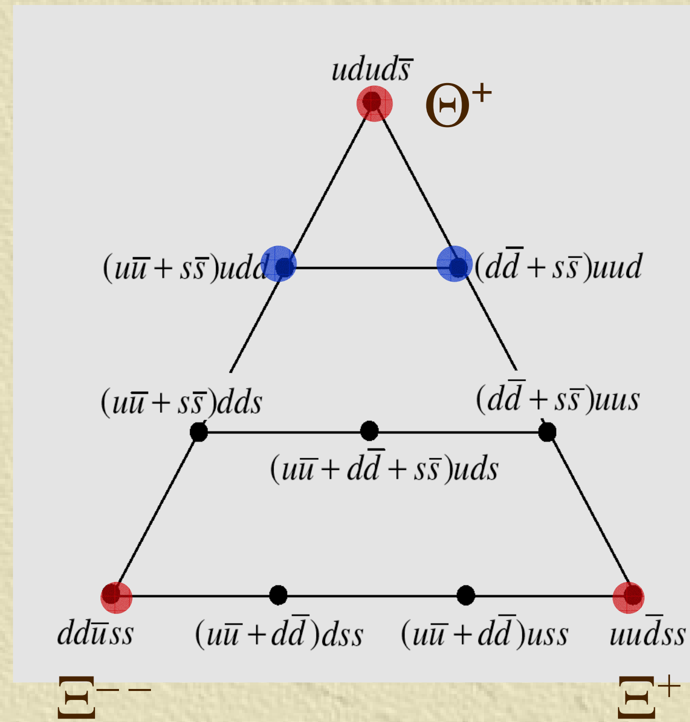
- $M \approx$1530-1540MeV, Γ< 9 MeV
- S = +1, B=1, Q=+1 ⇒ uudd$\bar{\mathrm{s}}$

  ⇒ $Y = B+S = 2$
- No pK$^+$ (I_3= +1) state ⇒ I =0
- Simplest SU(3) irrep. is F =10*

  unique for ≤ 5 quarks
- No lower S = +1 states

  This is the ground state!

  NK is the only open channel



Main issues

- Mass spectrum

  $M(\Theta^+) = 1540$ MeV, $M(\Xi^{--}) = 1862$ MeV

- Width $\Gamma(\Theta^+) \sim 0.9$ MeV

  very narrow for a resonance at 100 MeV above the threshold ex. N*(1650) S_{11} $\Gamma \sim 150$ MeV

- Spin, Parity, SU(3) irrep., . . .undetermined yet
- Production mechanisms

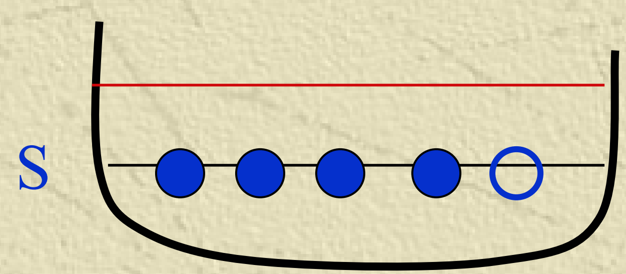
  low energy vs high energy

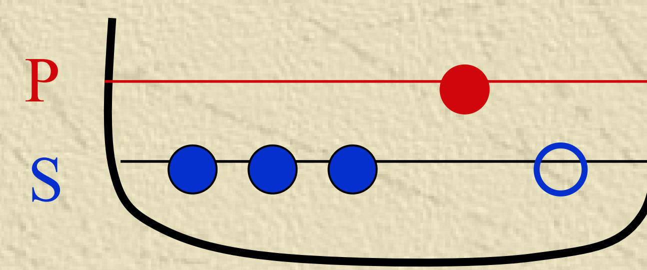
Main issues

- Parity

pentaquark $q^4 + \overline{q}$ ($\pi = -$)

$L = 0$	$\pi = -$	NK L = even (S, D, …)
$L = 1$	$\pi = +$	NK L = odd (P, F, …)





Pentaquarks in QCD

- Lattice QCD
  - Csikor, Fodor, Katz, Kovacs, JHEP 0311 (2003) 070
  - Sasaki, hep-lat/0310014
  - Chiu, Hsieh, hep-ph/0403020
  - Mazur et al., hep-ph/0406196
  - Ishii et al., hep-lat/0408030
- QCD sum rule for Θ^+
  - Zhu, Phys. Rev. Lett. 91 (2003) 232002
  - Matheus et al., Phys. Lett. B578 (2004) 323

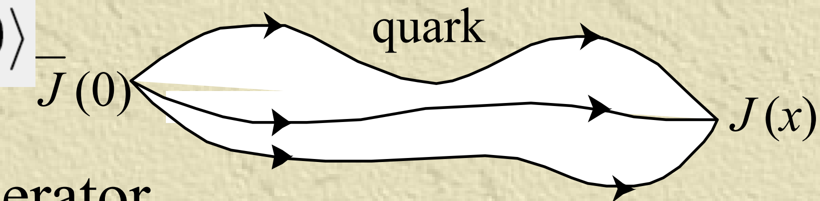
    No parity projection was made.
  - Sugiyama, Doi, Oka, Phys. Lett. B581 (2004) 167

    determine mass and parity

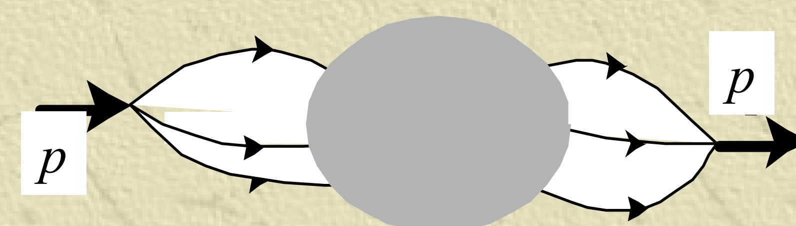
Two Point Correlators

- TPC $\Pi(x)$ contains information of the spectrum

$$\Pi(x) = \langle 0|T(J(x)\bar{J}(0))|0\rangle$$



- $J(x)$: interpolating field operator determines quantum numbers
- Fourier transform



$$\Pi(p) \equiv i\int d^4x e^{ip\cdot x}\langle 0|T(J(x)\bar{J}(0))|0\rangle$$

Two Point Correlators

- interpolating field operator

Mesons

I=1 vector meson
$$J_\rho(x) = \bar{q}(x)\gamma^\mu \frac{\vec{\tau}}{2} q(x)$$

I=1 pseudoscalar meson
$$J_\pi(x) = \bar{q}(x)\gamma^5 \frac{\vec{\tau}}{2} q(x)$$

Baryons

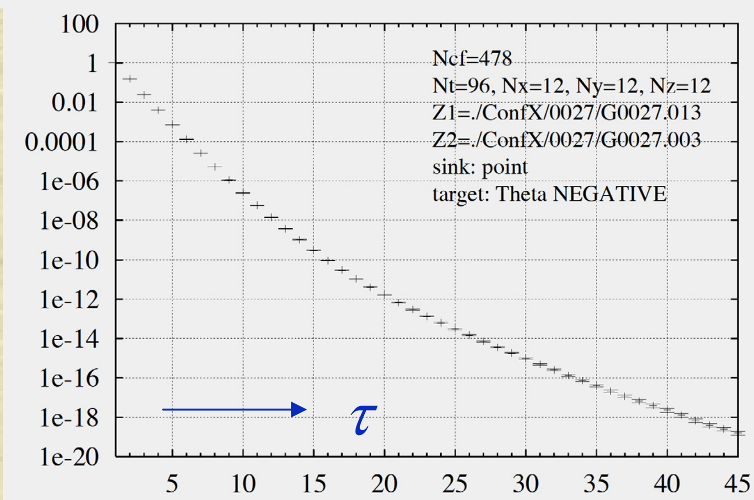
J=1/2 baryon
$$B(x) \quad = \quad \epsilon_{abc}(u_a^T(x) C\gamma^5 d_b(x)) u_c(x)$$

J=1/2 pentaquark
$$\Theta^+ \quad \equiv \quad \epsilon_{abc}\epsilon_{ade}\epsilon_{bfg}[u_d^T C\gamma^5 d_e][u_f^T C d_g] C \bar{s}_c^T$$

Lattice QCD

- Imaginary time TPC

$$\Pi(\vec{p}=0;\tau) = \int d^3x \, \langle 0|T(J(\vec{x},\tau)\bar{J}(0,0))|0\rangle$$
$$= \sum_i \lambda_i^2 \, e^{-m_i\tau} \xrightarrow{\text{large } \tau} \boxed{\lambda_0^2 \, e^{-m_0\tau}}$$



Lattice QCD for Θ^+

- Lattice QCD for Θ^+

  F. Csikor, S. Sasaki, T.-W. Chiu, N. Mathur

  N. Ishii

  - No $1/2^+$ ($I = 0$) resonance state below 2 GeV. (except *Chiu*)
  - Existence of $1/2^-$ ($I = 0$) state is under question.

Lattice QCD for Θ^+

Sasaki, Ishii, Chiu

- interpolating field $J = 1/2,\ I = 0$

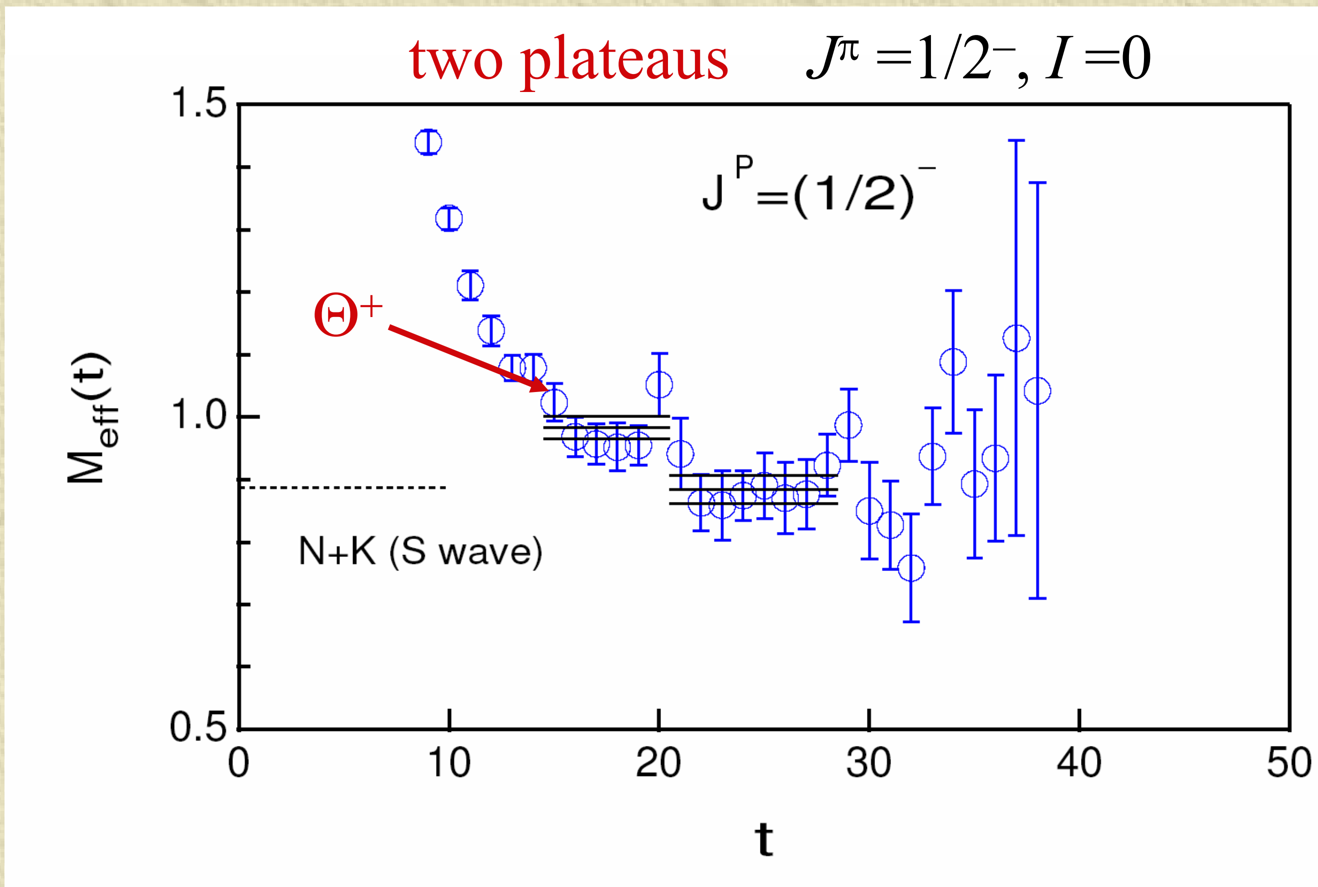
$$\Theta^+ \equiv \epsilon_{abc}\epsilon_{ade}\epsilon_{bfg}[u_d^T C\gamma^5 d_e][u_f^T C d_g]C\bar{s}_c^T$$

(diquark)^2-s type

$$\begin{aligned}
\gamma^5\Theta^+ &= \epsilon_{abc}\epsilon_{ade}\epsilon_{bfg}[u_d^T C\gamma^5 d_e][u_f^T C d_g]\gamma^5 C\bar{s}_c^T \\
&= \left(-\frac{1}{4}\times\frac{2}{3}\right)\epsilon_{deg}[u_d^T C\gamma^5 d_e]d_g\cdot(\bar{s}\gamma^5 u) \\
&\quad + \left(-\frac{1}{4}\times\frac{2}{3}\right)\epsilon_{deg}[u_d^T C\gamma^5 d_e]\gamma_\mu\gamma^5 d_g\cdot(\bar{s}\gamma^\mu u) + \ldots \\
&= \left(-\frac{1}{6}\right)J_n J_{K+} + \left(-\frac{1}{6}\right)J_n J_{K*} + \ldots
\end{aligned}$$

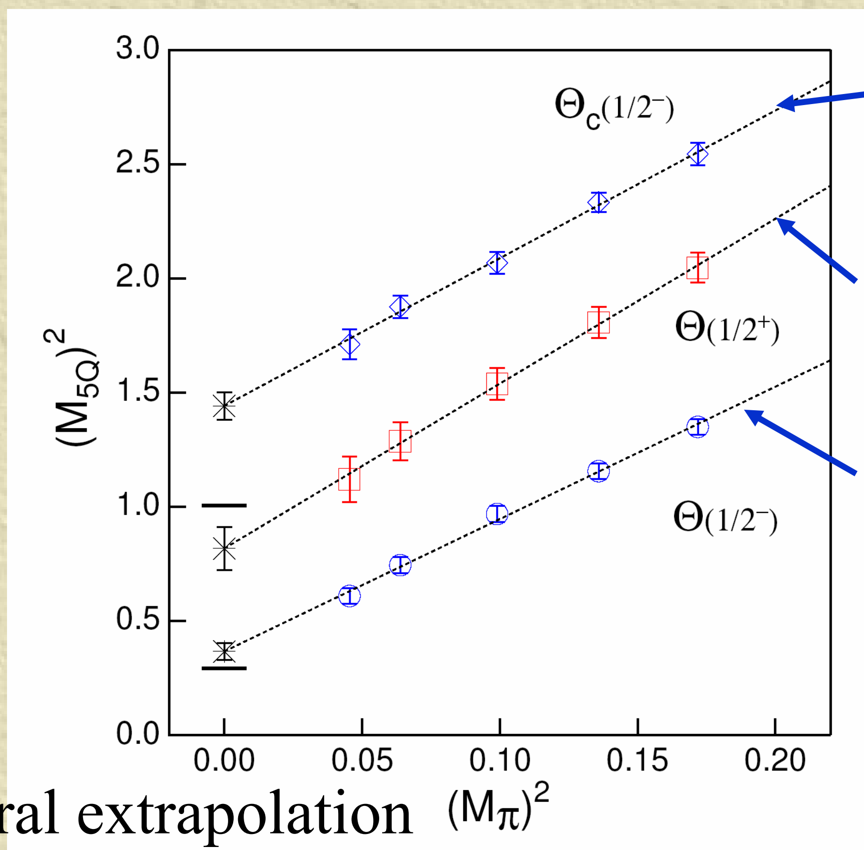
Lattice QCD for Θ^+

Sasaki, hep-lat/0310014



Lattice QCD for Θ^+

Sasaki, hep-lat/0310014



chiral extrapolation

$s \to c$ (unbound)

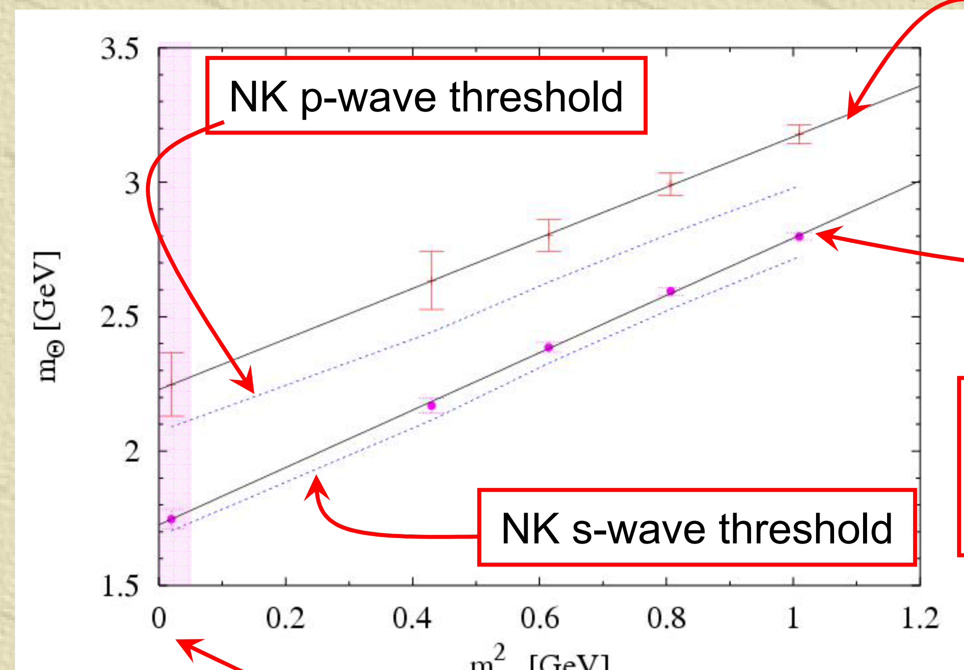
$J^\pi = 1/2^+, I = 0$
$M = 2.62(9)$ GeV

$J^\pi = 1/2^-, I = 0$
$M = 1.76(9)$ GeV

Lattice QCD for Θ^+

N. Ishii *et al.*, hep-lat/0408030

non NK operator on anisotropic lattice



positive parity case

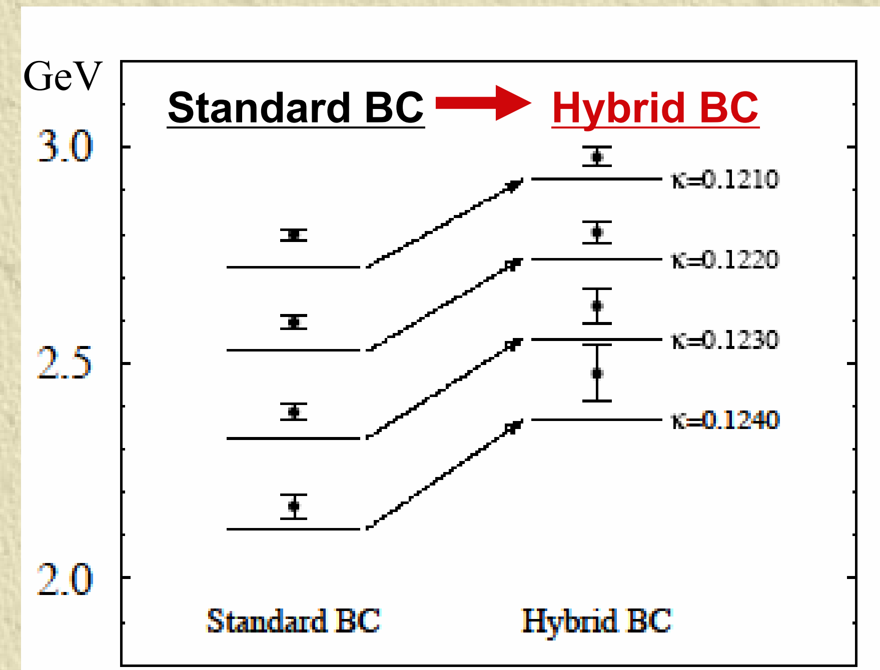
negative parity case

<u>Physical point</u>:
(1) Positive parity: 2.24(11) GeV
(2) Negative parity: 1.75(3) GeV

No low-lying **positive parity** Θ^+

Lattice QCD for Θ^+

N. Ishii *et al.*, hep-lat/0408030



Hybrid BC
antisymmetric for u, d
symmetric for s

NK threshold is artificially raised in HBC, while local pentaquarks are not affected.

The observed plateau is a NK scattering state. No localized resonance state exist in the interval:

$$m_N + m_K \le m(\Theta^+) \le \sqrt{m_N^2 + \vec{p}_{\min}^{\,2}} + \sqrt{m_K^2 + \vec{p}_{\min}^{\,2}}$$

QCD SR for Θ^+

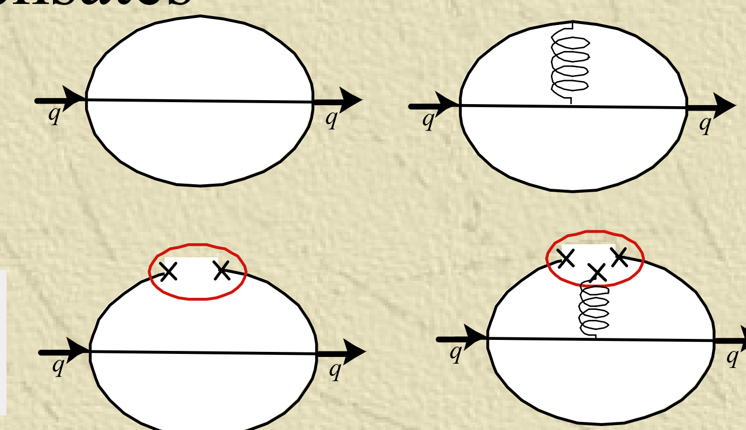
- Deep Euclid region $(p_E^2 \equiv -p^2 \to \infty)$

  $\alpha_s(p_E^2) \to 1/\,ln(p_E^2)$ ⇒ *perturbative*

- Nonperturbative effects are taken into account as vacuum condensates

- OPE

  expansion wrt $1/p_E^2$



$$\Pi(p_E^2) = \sum_n C_n(p_E^2)\langle 0|O_n(0)|0\rangle$$

O_n : local operator

QCD SR for Θ^+

- physical region $(p^2 > 0)$

  represented by spectral function $\rho(s)$ at $s = p^2 = m^2$

$$\rho(s) = \frac{1}{\pi}\mathrm{Im}\Pi(s) = \sum_i \lambda_i^2 \delta(s - m_i^2)$$

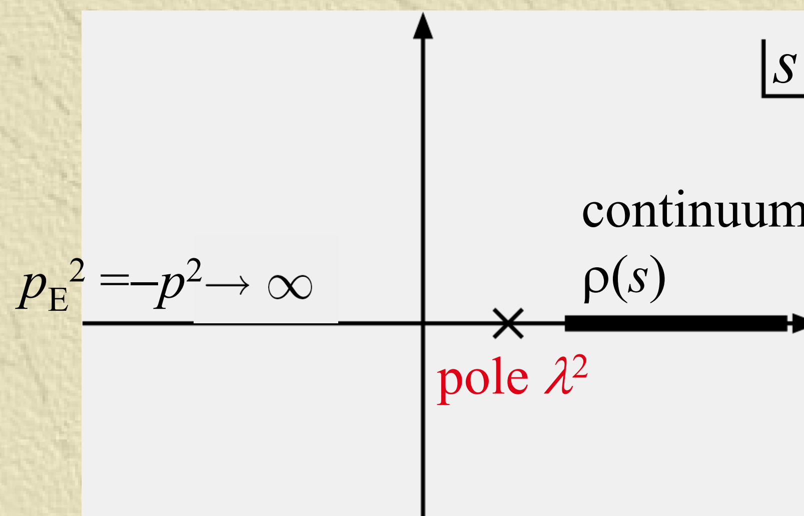
i : hadrons (poles) and scattering states (cut)

- QCD SR assumes a sharp resonance + continuum $(s > s_0)$

$$\rho(s) \sim \lambda^2 \delta(s - m^2) + \theta(s - s_0)\,\rho(s)$$

QCD SR for Θ^+

- Analyticity of $\Pi(p^2)$
  in complex $s = p^2$



- analytic continuation by a dispersion relation

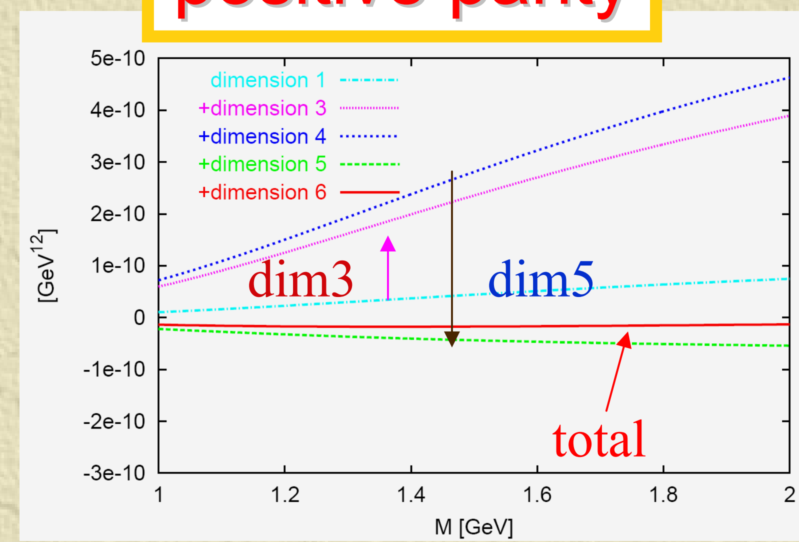
$$\Pi(p_E^2) = \frac{1}{\pi}\int_0^\infty ds\, \frac{\mathrm{Im}\,\Pi(s)}{s + p_E^2}$$

(with appropriate subtractions)

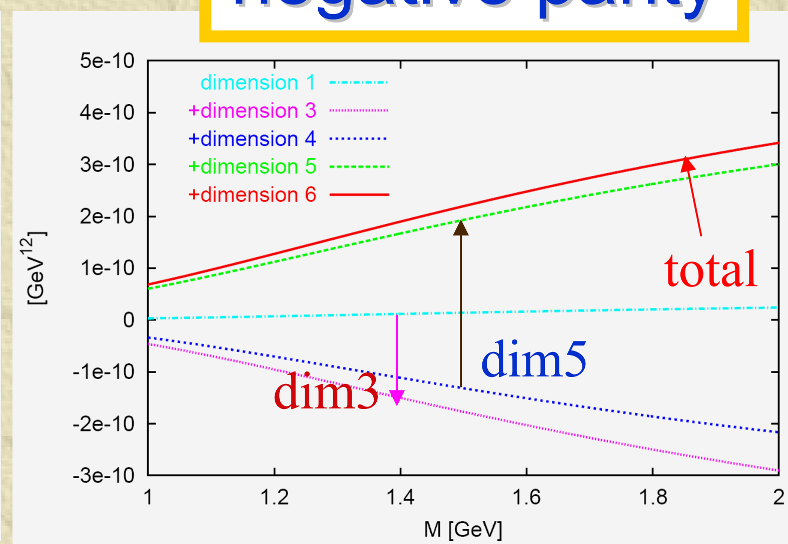
Parity of Θ^+

- positivity of $|\lambda_\pm|^2 e^{-\frac{m_\pm{}^2}{M^2}}$ M : Borel mass

positive parity



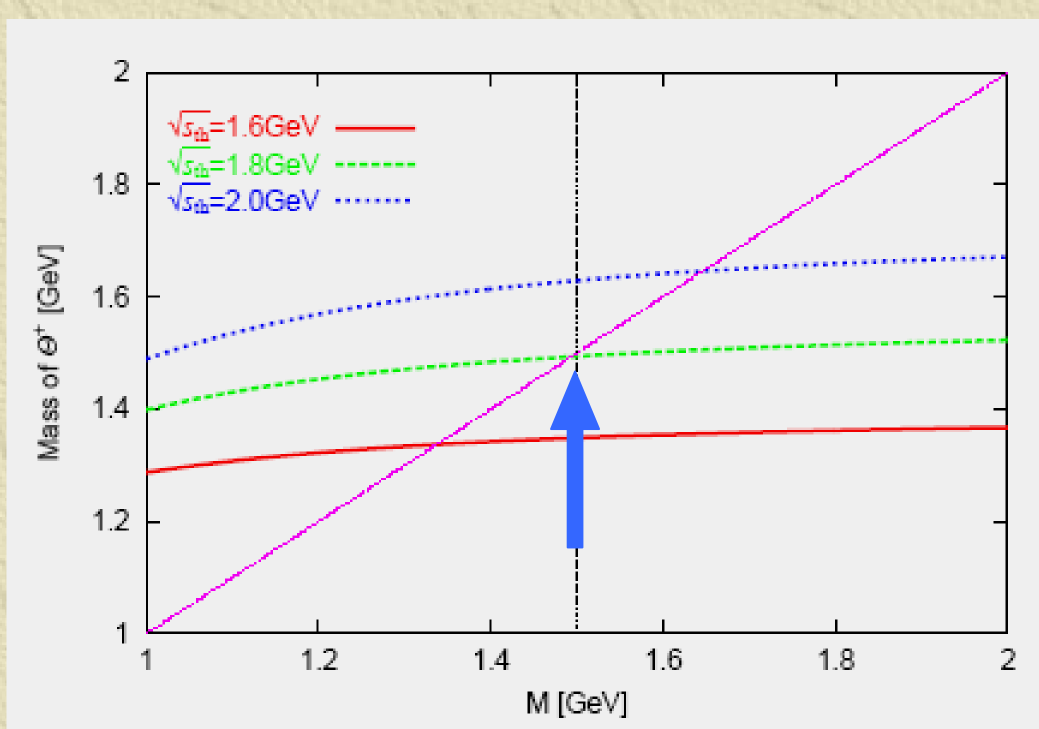
negative parity



no positive parity pentaquark

Mass of Θ^+

Θ^+ mass (negative parity) $M \sim 1.3\text{-}1.7$ GeV



Resonance or continuum?

- Is there a sharp state? or just NK continuum?

  LQCD or SR cannot predict the width directly.

- It is important to choose J_Θ so that the coupling to NK is weak.

  The NK continuum contribution to the *non NK operator* is less than 5% of the OPE. (S.H. Lee)

$$\langle 0|J_\Theta|NK\rangle = -\frac{i}{f_\pi}\langle 0|[Q_5^K, J_\Theta]|N\rangle = -\frac{i}{f_\pi}\langle 0|J_{N;5q}|N\rangle$$

PP *vs* NP

- Why do people believe (or like) positive-parity?
  - So predicted by Diakonov et al.
  - To explain the tiny width

    Γ(NP) ~ 300 ~ 1000 MeV

    Centrifugal barrier suppresses Γ(PP).
  - Production cross sections

    σ (PP) ~ 10 σ (NP)   Hosaka et al.

Chiral Soliton Model for Θ^+

- Excited states of the SU(3) rotated Skyrme soliton

  Diakonov, Petrov, Polyakov, ZP A359 (1997) 305

$F = 10^*$

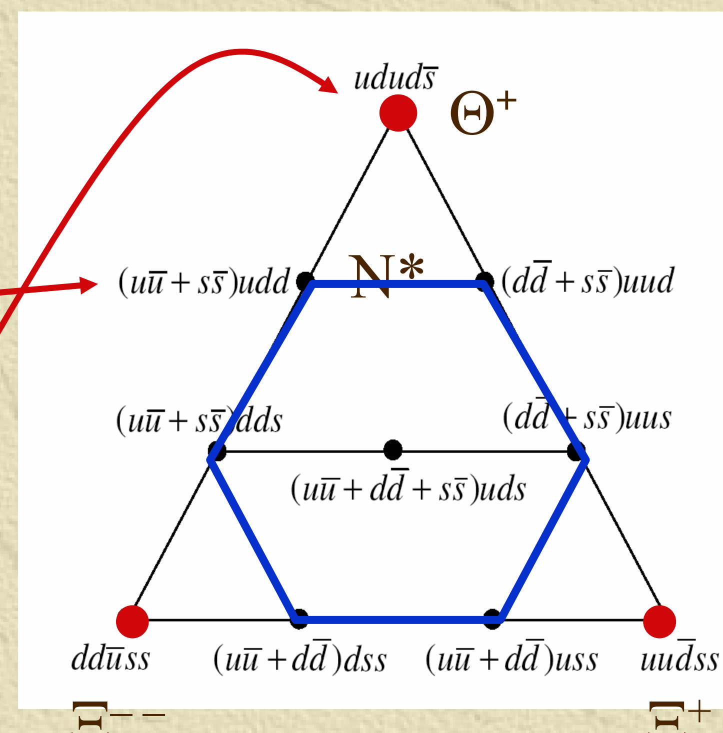
$J^\pi = 1/2^+$

$M = (1890 - 180\,Y)$ MeV

N*(1710)

$\rightarrow \Theta^+ = 1530$ MeV

$\Gamma < 15$ MeV

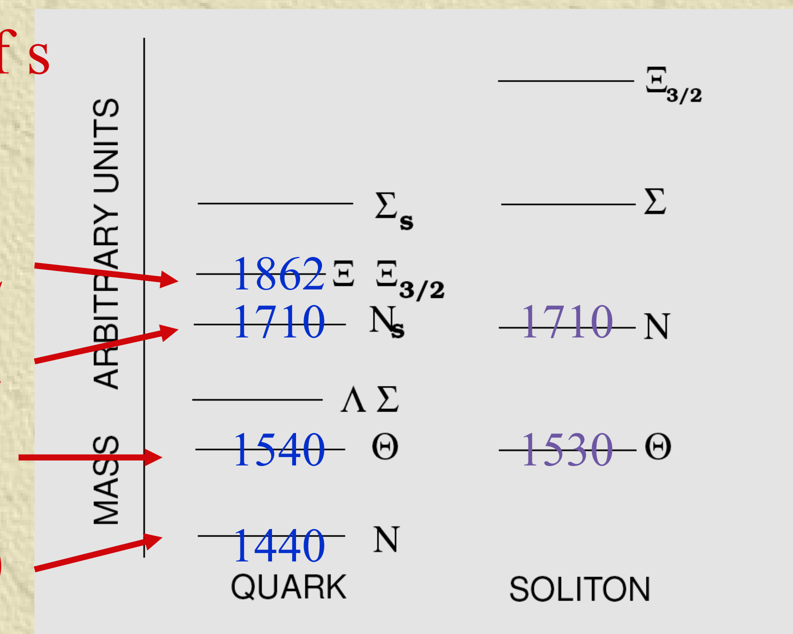


10- 8 mixing expected*

Mixing of 10* and 8

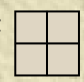
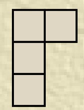
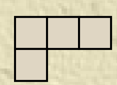
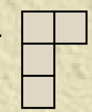
- Ideal Mixing of 10* and 8 — Jaffe-Wilczek

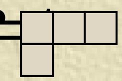
		# of s
Σ, Σ_s	$udsu\bar{u}$, $udss\bar{s}$	1, 3
$\Xi, \Xi_{3/2}$	$ussu\bar{u}$, $uuss\bar{d}$	2
N_s (1710)	$uuds\bar{s}$ (8+10*)	2
Θ+	$uudd\bar{s}$ 10*	1
N (1440)	$uudd\bar{d}$ (8+10*)	0



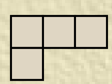
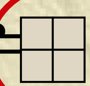
Quark Model Symmetry

- tetraquark $\quad (q^4)_{F=10^*,\, C=3} \sim (u^2d^2)_{I=0,\, C=3}$

$F=10^*$  x $C=3$  =  + 

orbital $L=0$  $\leftrightarrow$ spin $S=$ 

favored

orbital $L=1$  $\leftrightarrow$ spin $S=$ 

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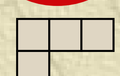
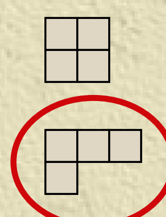
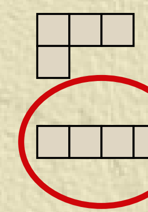
 $S=1$

Carlson et al. PL B573, 101 (2003)

Quark Model Symmetry

- possible low energy $(u^2d^2)_{I=0,\ C=3}$ states

		spin-color	*spin-flavor*
$L=0$, $S=1$, $J=1$	1^+	 +. . .	 +. . .
$L=1$, $S=0$, $J=1$	1^-	+. . .	+. . .
		favored by CMI	favored by FD

- possible quantum numbers for Θ^+

$u^2d^2(1^+) + \bar{s}\,(1/2^-) \;=\; 1/2^-,\ 3/2^- \;\leftrightarrow\;$ KN *S*-wave

$u^2d^2(1^-) + \bar{s}\,(1/2^-) \;=\; 1/2^+,\ 3/2^+ \;\leftrightarrow\;$ KN *P*-wave

Questions

- Orbital excitation energy

  How large is $\Delta E\ (\Delta L=1) = E(L=1) - E(L=0)$?

- Spin-dependent interaction(s)

  hyperfine (HF) interaction

  How large is $\Delta E\ (\Delta S=1) = E(S=1) - E(S=0)$?

- How large is the splitting of J = 3/2 and 1/2 ?

PP in Quark Models

Fl. Stancu, PLB 595 (2004) 269

- PS meson exchanges between quarks
- The absolute mass is 510 MeV too large

Jennings, Maltman, Phys.Rev. D69 (2004) 094020

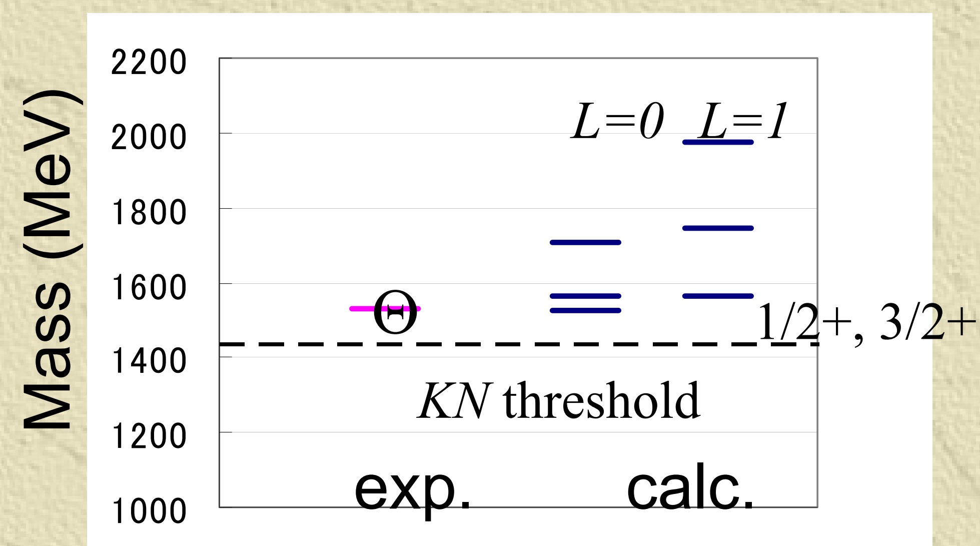
- Strong CM or FD interaction favors PP
- assume ΔE (ΔL=1) = 210 - 250 MeV

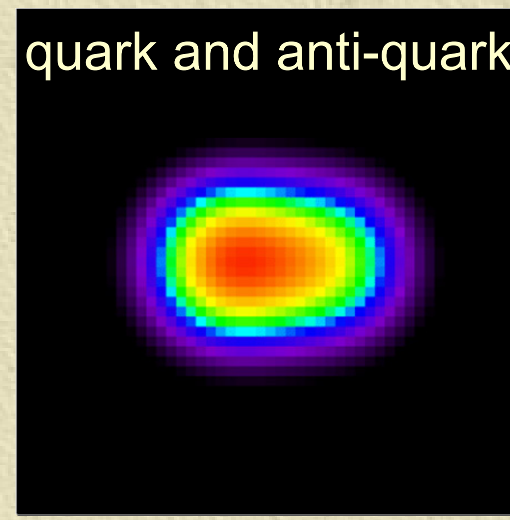
Kanada-En'yo, Morimatsu, Nishikawa, hep-ph/0404144

- 5-body molecular dynamics calculation (AMD)
- Narrow positive parity states are predicted.

Diquark correlation?

- Kanada-En'yo et al.





degeneracy of 1/2−, 3/2−, 1/2+, 3/2+ states

Diquarks

- Diquark models Jaffe, Wilczek, PRL 91 (2003) 232003
  Karliner, Lipkin, PL B571 (2003) 55

diquarks		color	spin
$I = 1$	uu, {ud}, dd	3*	1^+
		6	0^+
$I = 0$	[ud]	3*	0^+
		6	1^+

OgE and/or III are strongly attractive in $[ud]_0$ $(3^*, 0^+)$

$m_{[ud]0} \sim 420$ MeV

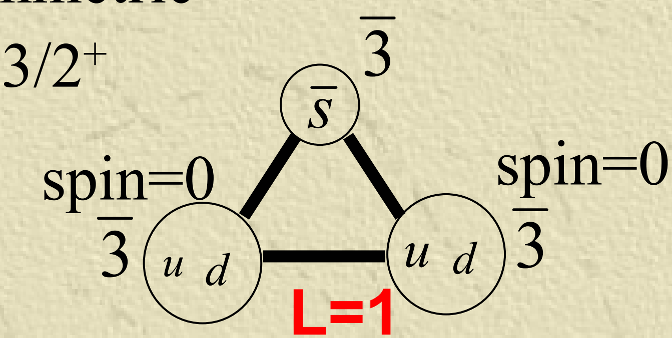
Diquark Models

Jaffe, Wilczek Phys. Rev. Lett. 91 (2003) 232003

2 diquarks + $\bar{s}$ model

$[ud]_0$ x $[ud]_0$: color antisymmetric

$L = 1 \Rightarrow J^{\pi} = 1/2^+, 3/2^+$



Karliner, Lipkin PL B571 (2003) 55

diquark + triquark $L = 1$

Diquark

- Diquark spectrum in lattice QCD (Landau gauge)

  Wetzorke, Karsch, hep-lat/0008008

(FSC) [GeV]

Diquark state	$(\bar{3}0\bar{3})$	$(61\bar{3})$	$(\bar{3}16)$	(606)
$ma_{(FSC)}$: $\boxed{\text{MEM}}$ result	0.60(2)	0.70(3)	0.74(9)	—
$ma_{(FSC)}$: 2-exp. fit	0.62(2)	0.73(4)	0.77(17)	0.50(15)

maxial entropy method

Are they hadronic?

- Hadronic bound/resonances

KN (K^+n, $K^0 p$) $I = 0$, $L = 0$ interaction is weak and repulsive

K^+n weak repulsive

K^-p strong attractive

$$a_0^{K^+n} = -\frac{M_N m_K}{8\pi f_\pi^2 (M_N + m_K)} + O(m_K^2)$$
$$a_0^{K^-p} = \frac{M_N m_K}{4\pi f_\pi^2 (M_N + m_K)} + O(m_K^2)$$

NKπ bound state 30 MeV below $E_{th} = 1.57$ GeV

Width must be strongly suppressed for L=0 bound state.

Bicudo, Marques, PRD69(2004) 011503

did not find a bound state.

Conclusion

- QCD is consistent with a $J^{\pi} = 1/2^{-}$ $F = 10^{*}$ pentaquarks.

  But the width may not be narrow.
- Many models suggest positive parity baryons.

  But the $1/2^{+}$ state has a larger mass in the quark model.
- Width

  Need to explain the unusually narrow width.
- We need more experimental data
  - spin, parity and width
  - other 10* members
  - excited states ex. $J = 3/2$ states, $I = 1$ states?
- More theoretical ideas