Lattice2004 @ Fermilab, Jun. 21-26, 2004

Pentaquarks

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Outline of this talks

- Brief review of the pentaquarks
  - Theoretical interests
  - Experimental facts
- Survey of available lattice results
  - Strategy of studying pentaquarks
  - Five studies, all quenched
- Summary and Outlook

Multi-quark hadrons

- QCD (color confinement) may not exclude the presence of the multi-quark hadrons such as

$$Q\overline{Q}Q\overline{Q}, \quad QQQQ\overline{Q}, \quad (QQQ)^2, \quad Q\overline{Q}Q\overline{Q}Q\overline{Q}, \quad \cdots\cdots$$

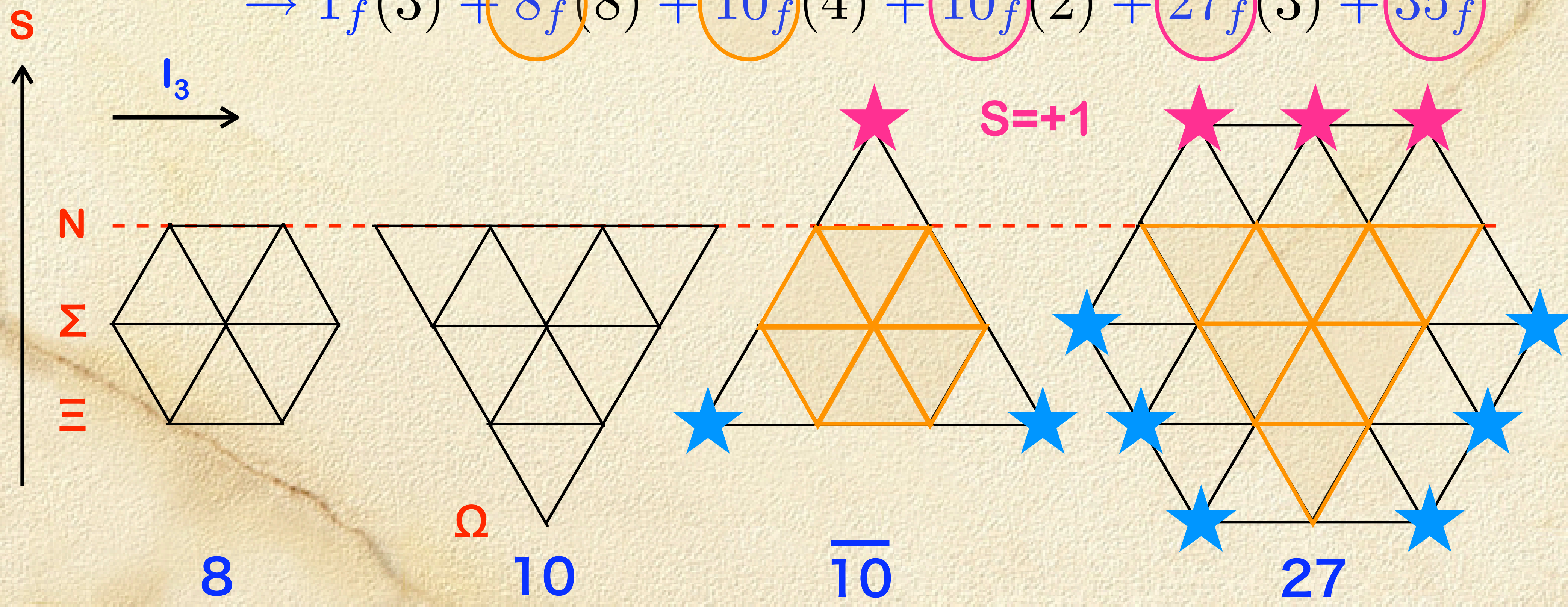
- "Exotic" multi-quark hadrons should have quantum numbers which can not be accommodated by $Q\overline{Q}$ or QQQ

Pentaquark baryons

- **Flavor structure (SU(3) case)**

$$3_f \otimes 3_f \otimes 3_f \otimes 3_f \otimes \overline{3}_f$$

$$\rightarrow 1_f(3) + 8_f(8) + 10_f(4) + \overline{10}_f(2) + 27_f(3) + 35_f$$



Exotic anti-decuplet baryons

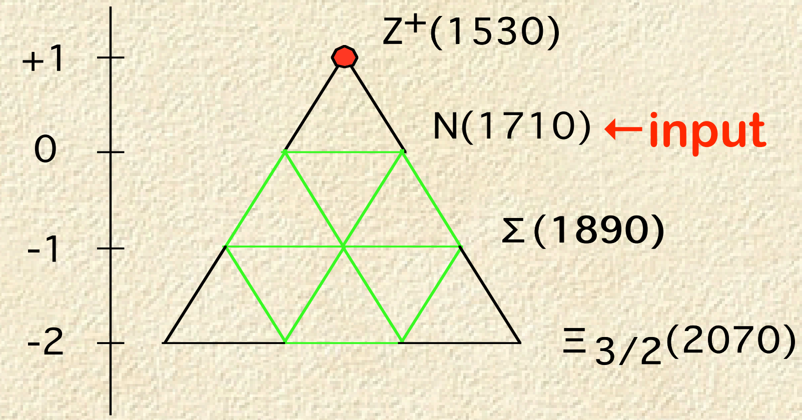
- SU(3) Skyrmion in the rigid rotator approach
  - The third baryons in the (10*,1/2+) as "Rotational Band"

    cf. (8, 1/2+), (10, 3/2+) Manohar(84), Chemtob(85)

- A narrow exotic S=+1 baryon Θ^+(Z^+) predicted by the chiral quark-soliton model

  Diakonov et al. Z. Phys. A359 (97) 305

  - Exotic: S=+1 in the10*(I=0)
  - Low mass:1530 MeV
  - Narrow width: ~~<15~~ → 30 MeV (Jaffe)
  - J^P=1/2$^+$



Discovery of Exotic S=+1 Baryon

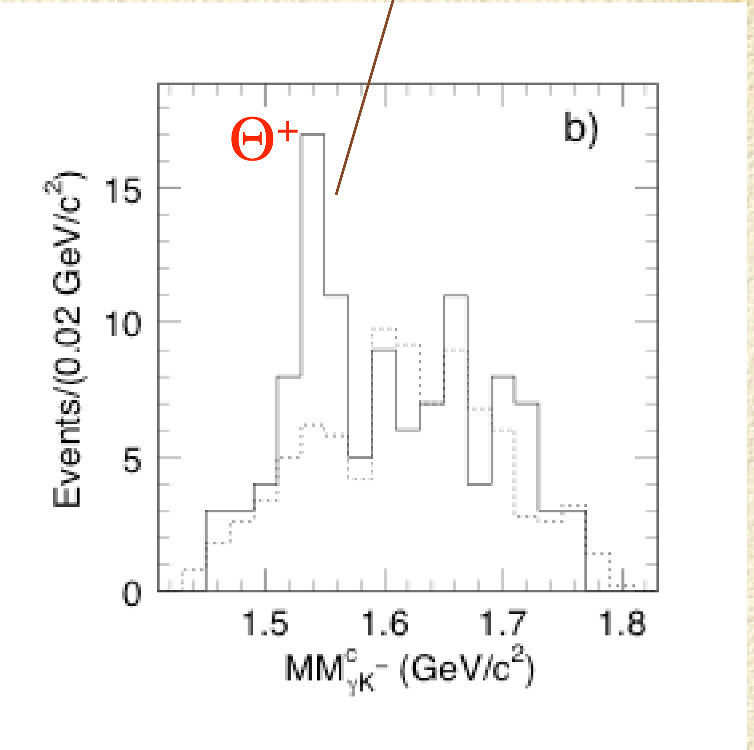
- T. Nakano et al.
  Phys.Rev.Lett.91 (2003) 012002
  Laser-Electron Photon facility (LEPS)@Spring-8

$Mass = 1540 \pm 10\ \text{MeV}$

$Width \leq 25\ \text{MeV}$

$$\gamma n \to \Theta^+ K^- \to n K^+ K^-$$

- ☑ Positive Strangeness $(uudd\bar{s})$
- ☑ Very narrow width
- ☑ I=0 (no pK^+ partner)
- ☑ Spin and Parity are undetermined.



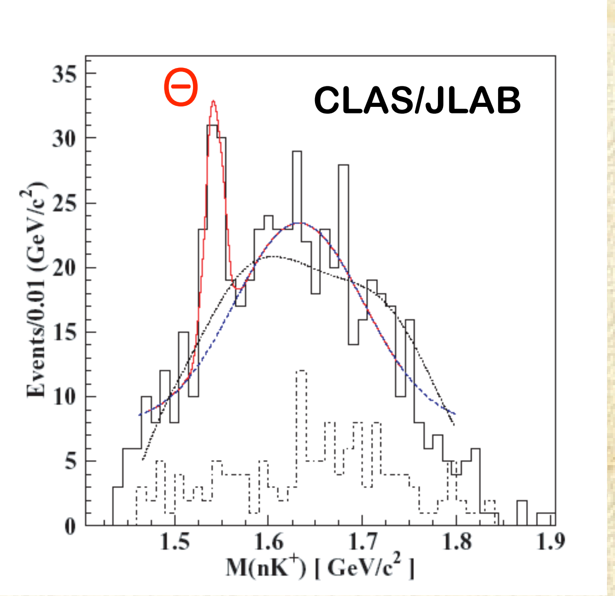
Confirmation from other experiments

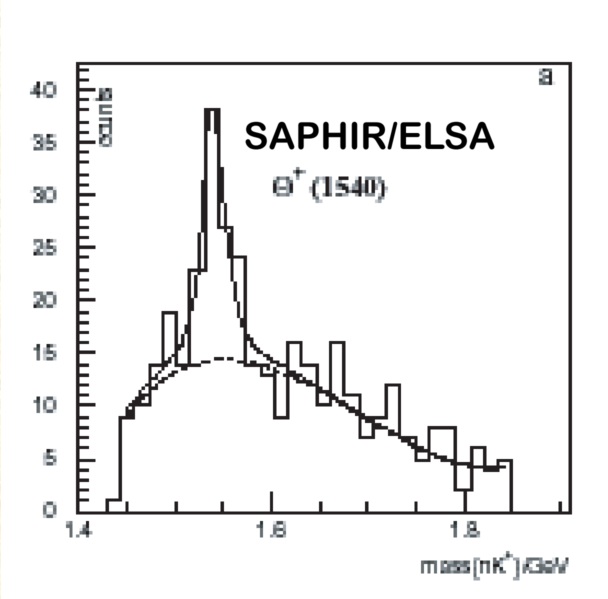
- **DIANA/ITEP (hep-ex/0304040)**
  Mass = 1539 ± 2 MeV,
  Width < 9 MeV

- **CLAS/JLAB (hep-ex/0307018)**
  Mass = 1542 ± 5 MeV,
  Width < 21 MeV

- **SAPHIR/ELSA (hep-ex/0307083)**
  Mass = 1540 ± 4 MeV,
  Width < 25 MeV

- **HERMES/DESY (hep-ex/0312044)**
  Mass = 1528 ± 2.6 MeV,
  Width < 19 ± 5 MeV





But, spin and parity are still undetermined.

compiled by Nakano

Summary of Experiments

Where	Reaction	Mass	Width	σ's*
LEPS	$\gamma C \to K^+K^- X$	1540 +- 10	< 25	4.6
DIANA	$K^+Xe \to K^0 p X$	1539 +- 2	< 9	4.4
CLAS	$\gamma d \to K^+K^- p(n)$	1542 +- 5	< 21	5.2
SAPHIR	$\gamma p \to K^+K^0(n)$	1540 +- 6	< 25	4.8
ITEP	$\nu A \to K^0 p X$	1533 +- 5	< 20	6.7
CLAS	$\gamma p \to \pi^+K^-K^+(n)$	1555 +- 10	< 26	7.8
HERMES	$e^+d \to K^0 p X$	1528 +- 3	13 +- 9	~5
ZEUS	$e^+p \to e' K^0 p X$	1522 +- 3	8 +- 4	~5
COSY	$pp \to K^0 p \Sigma^+$	1530 +- 5	< 18	4-6

*Gaussian statistical significance: estimated background fluctuation

The existence of the Θ has been established.

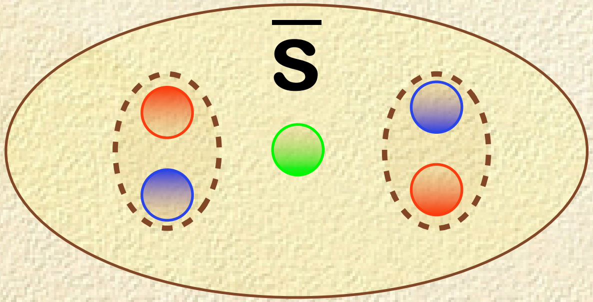
Correlated quark (diquark) model

- **Quark models for Θ^+ :** natural J^P-assignment → $1/2^-$

  but, "fall-apart" into KN in a S-wave

- **Diquark correlation : I=J=0, diquark (3_c^*, 3_f^*)**

Jaffe-Wilczek, Phys.Rev.Lett. 91 (03) 232003



$[ud]_0 \Leftrightarrow [ud]_0$

L=1

Relative P-wave is necessary between the pairs of diquarks

⇨ $J^P = 1/2^+$

$$(3_f \otimes 3_f) \otimes (3_f \otimes 3_f) \otimes \bar{3}_f \to \bar{3}_f \otimes \bar{3}_f \otimes \bar{3}_f = 1_f + 8_f + 8_f + \overline{10}_f$$

Diquark Model vs. Chiral Soliton

Θ(1540) ⇔ J^π=1/2$^+$, I=0, S=+1 pentaquark

Diquarks: $8_f \oplus 10_f^*$

Chiral Soliton: ONLY 10_f^*

Ideally Mixed

$qqss\bar{s}$ — Σ_s		— $\Xi_{\overline{10}}$ ⇒ 2.07GeV
		— $\Sigma_{\overline{10}}$
$qqqs\bar{s}$ — $N_s, \Xi_{3/2}$	⇒ 1.75GeV	— $N_{\overline{10}}$ ⇐ N(1710)
$qqqq\bar{s}$ — Θ, Σ, Λ		— Θ
$qqqq\bar{q}$ — N	⇒ Roper: N(1440)	

The linear-in-m_s treatment

Ξ^{--} (ddss^{bar}u) baryon candidate

NA49/CERN SPS

Phys.Rev.Lett.92:042003,2004

Exotic S=-2 and Q=-2

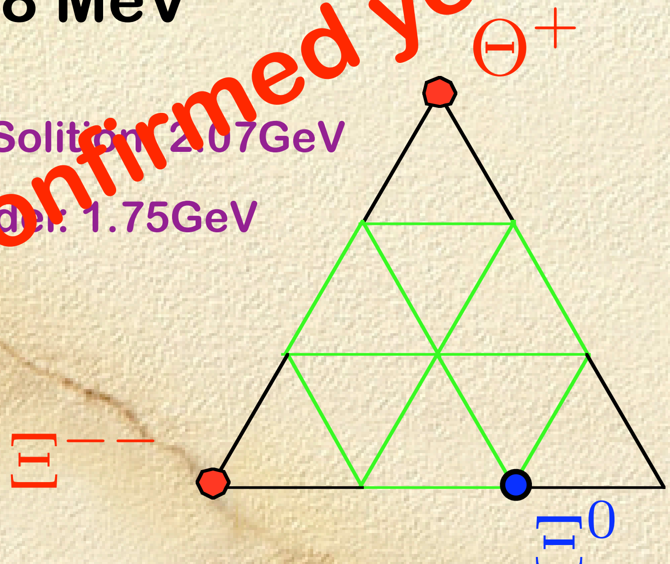
baryon resonance in $\Xi^-\pi^-$

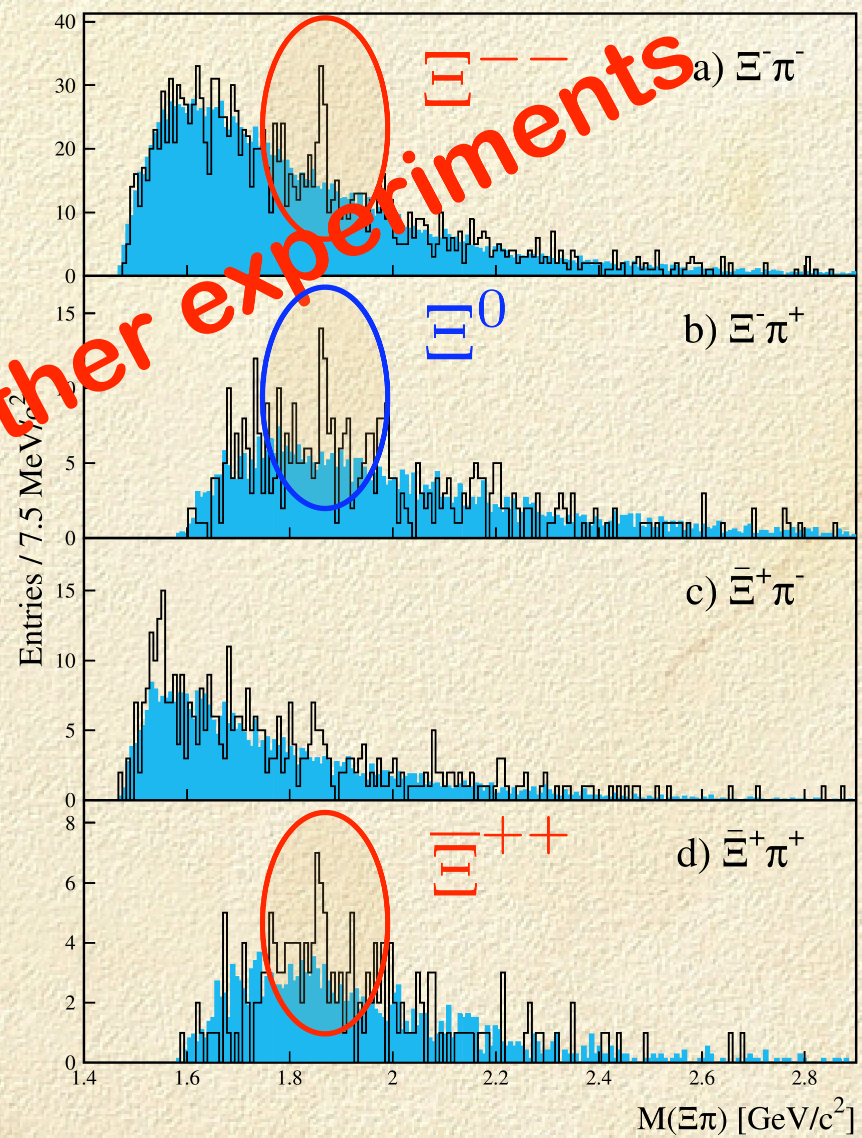
M = 1.862 GeV

Γ < 18 MeV

Chiral Soliton: 2.07GeV

JW model: 1.75GeV





Not confirmed yet by other experiments

Charm (bottom) pentaquarks

$$(uudd\bar{s}) \longrightarrow (uudd\bar{c}) \text{ or } (uudd\bar{b})$$

- Very simple mass estimations:

$$M(\Theta_c^0) = M(\Theta^+) + M(\Lambda_c) - M(\Lambda)$$

$$\approx 2710 \text{ MeV} < M(D) + M(N) \approx 2810 \text{ MeV}$$

$$M(\Theta_b^+) = M(\Theta^+) + M(\Lambda_b) - M(\Lambda)$$

$$\approx 6050 \text{ MeV} < M(B) + M(N) \approx 6200 \text{ MeV}$$

Jaffe-Wilczek

Suggest: charm (bottom) pentaquarks may be **bound states** ???

Θ_c (uudd^{bar}c) baryon candidate

H1/DESY (hep-ex/0403017)

Exotic C=-1 and Q=0
baryon resonance in D*p

M = 3.099 GeV

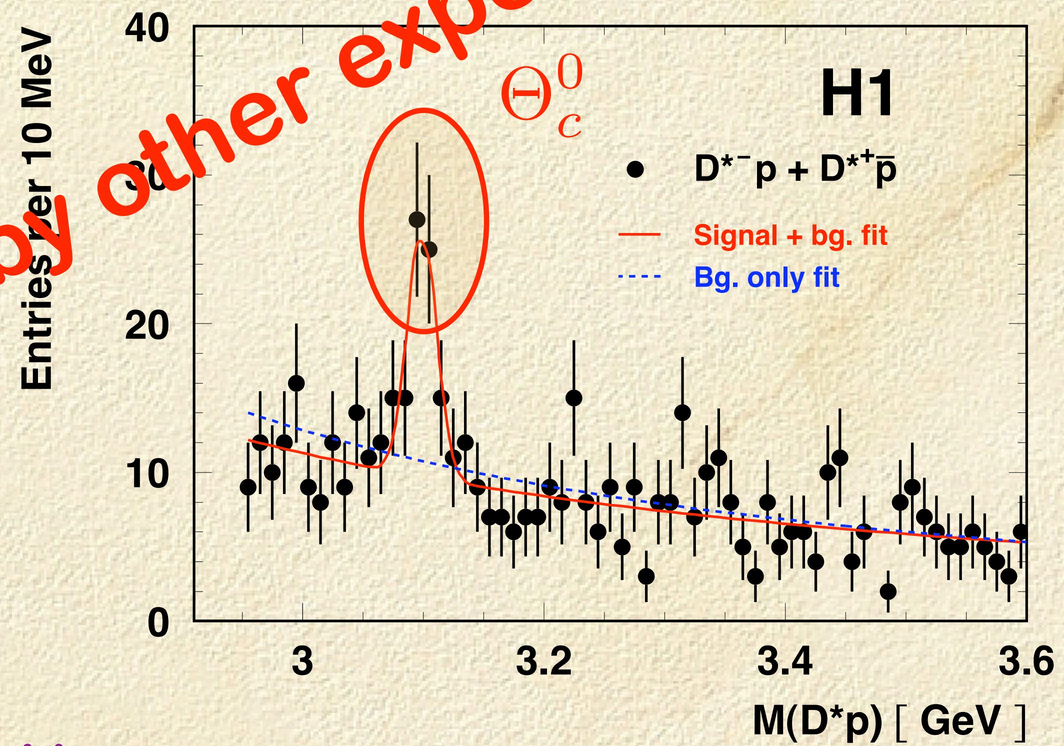
Γ < 12 MeV

Negative charm → $(uudd\bar{c})$

Not confirmed yet by other experiments

Note:

DN threshold = 2.808 GeV
D*N threshold = 2.948 GeV



What can lattice QCD do?

- Does the spectrum of QCD possess the $\Theta^+(1540)$?
- What is spin and parity of the $\Theta^+(1540)$?
- Are there other pentaquark baryons?

Maximal knowledge about those matters is essential to understanding the structure of the pentaquark state.

☞ **Lattice QCD has a chance to answer the last two questions before experimental efforts.**

Lattice studies of pentaquarks

- Four studies posted to HEP-archive
  - Csikor-Fodor-Katz-Kovacs, hep-lat/0309090, JHEP 0311 (03) 070.
  - Sasaki, hep-lat/0310014.
  - Chiu-Hsieh, hep-lat/0403020, 0404007.
  - Kentucky Collab., hep-ph/0406196.
- One preliminary result reported at some conferences
  - Sigaev-Jahn-Negele (MIT Collab.), Quark-Nuclear-Physics04 etc.
- New results will be presented at this conference
  - Ishii et al. (TIT Collab.), June 24 (Thu) 9:20
  - Chiu-Hsieh, June 24 (Thu) 9:40
  - Mathur et al. (Kentucky Collab.), June 24 (Thu) 10:00
  - Koutsou, Poster

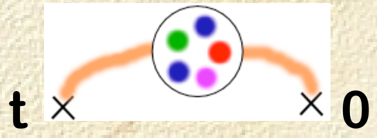
Main difficulty in lattice study

- A simple minded study of pentaquark state with
- $$\Theta^+ \sim \varepsilon_{abc} d_a d_b u_c \times \bar{s}_e u_e$$

N K

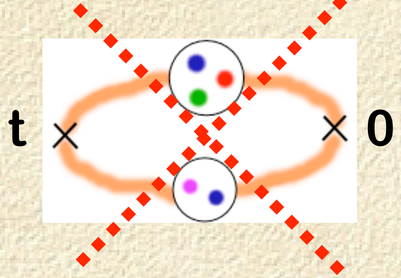
How can we distinguish between

the mass of the pentaquark state



and

the total energy of the interacting KN two-body system



Choose a specific operator with as little overlap with the KN scattering state as possible

The 2-pt function $\langle \Theta(t)\bar{\Theta}(0)\rangle$ should be dominated by the latter if $M_\Theta > M_N + M_K$

$$|\langle \Theta^+|\mathcal{O}|0\rangle| \gg |\langle K+N|\mathcal{O}|0\rangle|$$

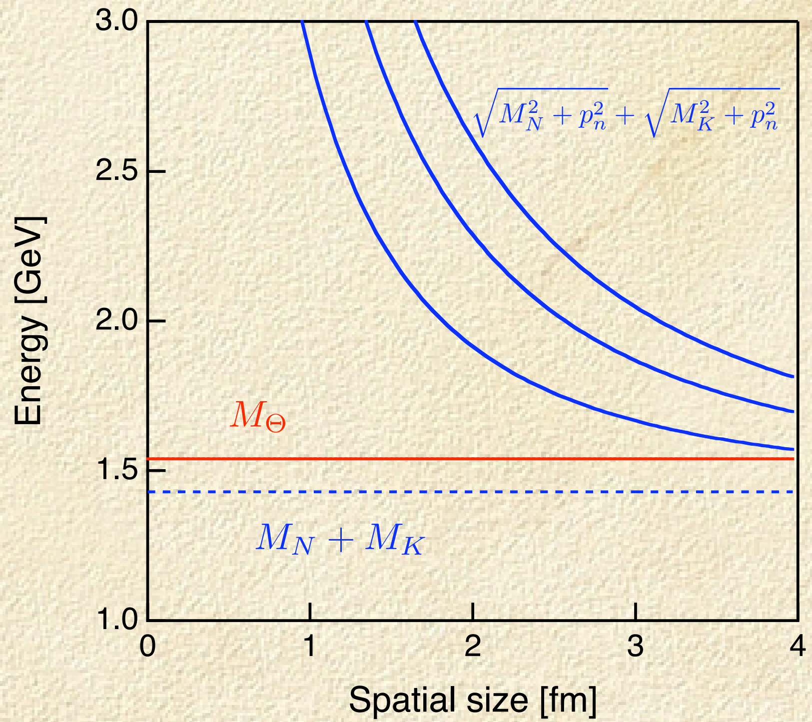
KN threshold (1)

- $\Theta(1/2^+) \to (KN)_{\text{P-wave}}$: $\sqrt{M_N^2 + p_{\min}^2} + \sqrt{M_K^2 + p_{\min}^2}$
- $\Theta(1/2^-) \to (KN)_{\text{S-wave}}$: $M_N + M_K$ **non-interacting**

All momentum are quantized

$$|\vec{p}| = \sqrt{n}|\vec{p}_{\min}|, \quad |\vec{p}_{\min}| = 2\pi/L$$

$\Rightarrow$ **the P-wave KN threshold can be lifted by changing spatial size L**



KN threshold (2)

How valid is the previous estimation ?

- Energy shift in the finite volume:

$$\Delta M = E_{KN} - (M_N + M_K)$$

$$= -\frac{2\pi(M_N + M_K)a_0}{M_N M_K L^3}\left[1 - 2.834 * \frac{a_0}{L} + 6.375 * \left(\frac{a_0}{L}\right)^2\right]$$

$L \gg a_0$ Lüscher formula

KN scattering length(volume) is quite small in I=0 channel

	I=0	I=1
S-wave (fm)	0.0 ± 0.03	-0.32 ± 0.02
P-wave (fm^3)	0.08 ± 0.01	-0.16 ± 0.1

Choice of operator (1)

- **Nucleon spectroscopy**

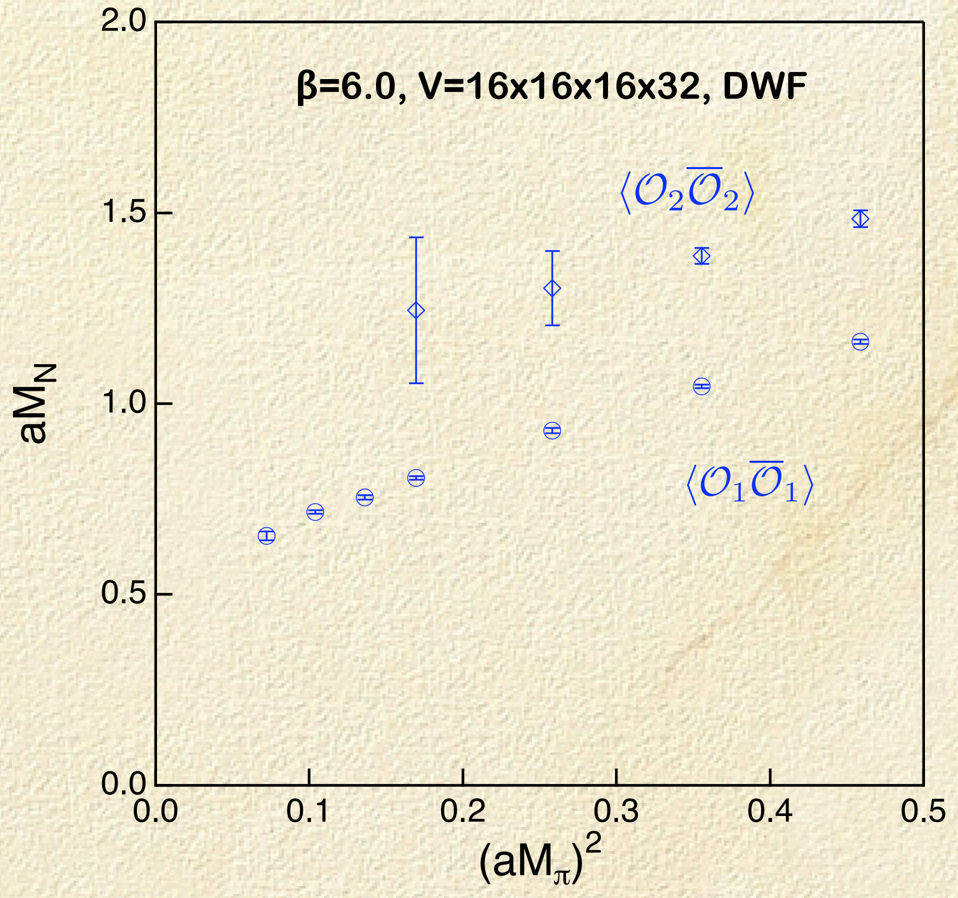
$$\mathcal{O}_1 = \varepsilon_{abc}[u_a^T C\gamma_5 d_b]u_c$$

$$\mathcal{O}_2 = \varepsilon_{abc}[u_a^T C d_b]\gamma_5 u_c$$

The second operator vanishes in the non-relativistic limit.

⇒ small overlap with the nucleon

$$|\langle N|\mathcal{O}_2|0\rangle| \approx 0$$



Bowler et al., Nucl. Phys. B240 (1984) 213.
Leinweber, Phys. Rev. D51 (1995) 6383.
Sasaki-Blum-Ohta, Phys. Rev. D65 (2002) 074503.

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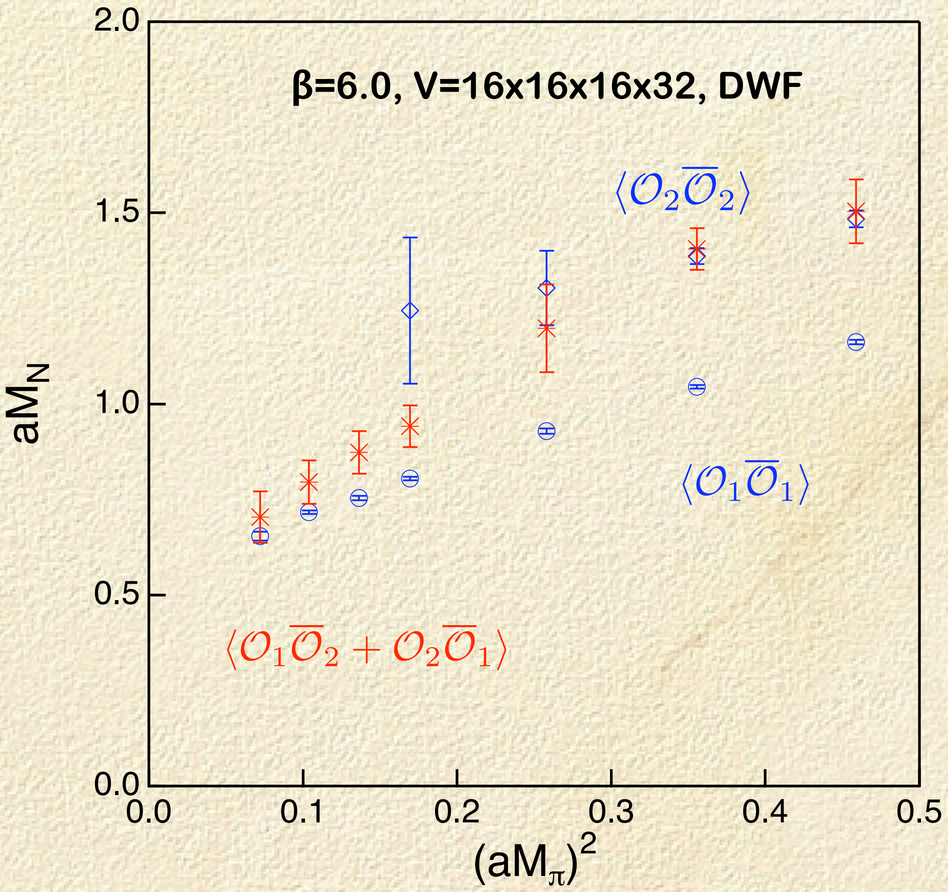

The cross correlation suggests that it is evident in the heavy quark regime, but it might be no longer robust in light quark regime.

Choice of operator (2)

- Simple minded operator as Nucleon ⊗ Kaon

$$\mathcal{O}_{I=0/1} = \varepsilon_{abc}[u_a^T C\gamma_5 d_b]\{u_c(\bar{s}_e\gamma_5 d_e) \mp (u \leftrightarrow d)\}$$ Kentucky

- Color variant of Nucleon ⊗ Kaon

$$\mathcal{O}_{I=0/1} = \varepsilon_{abc}[u_a^T C\gamma_5 d_b]\{u_e(\bar{s}_e\gamma_5 d_c) \mp (u \leftrightarrow d)\}$$ Csikor et al.

- Exotic description as diquark-diquark-antiquark

$$\mathcal{O}_{I=0} = \varepsilon_{abc}\varepsilon_{aef}\varepsilon_{bgh}[u_e^T C\Gamma_1 d_f][u_g^T C\Gamma_2 d_h]C\bar{s}_c^T$$ Sasaki

$$\Gamma_1 \neq \Gamma_2, \quad \Gamma_{1,2} = 1, \gamma_5, \gamma_\mu\gamma_5$$

Choice of operator (2)

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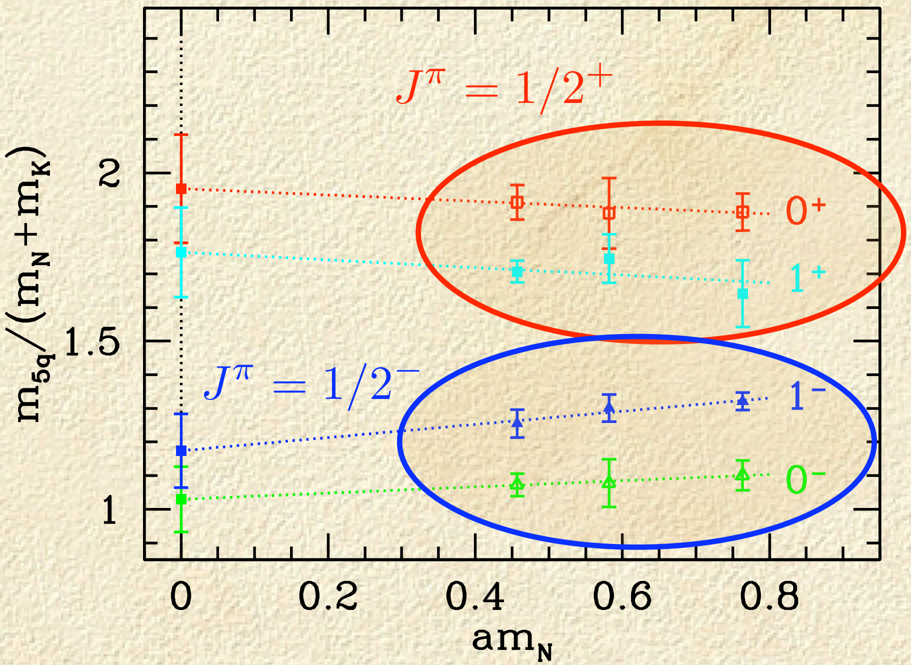
In the non-relativistic limit (heavy quark regime),

➜➜ Small overlap with KN two-hadron state is expected.

Csikor-Fodor-Katz-Kovacs (1)

hep-lat/0309090, JHEP 0311 (03) 070

- **Wilson fermions (Quench) + Wilson gauge action**
  - **L~2.0 fm, a=0.17, 0.12, 0.09 fm (β=5.7, 5.85, 6.0)**
    - **linear continuum extrapolation**
  - **m_π from 0.4 - 0.6 GeV**
  - **J=1/2, I=0,1, parity projection**
  - **Color variant of N times K**



Csikor-Fodor-Katz-Kovacs (2)

hep-lat/0309090, JHEP 0311 (03) 070

- All analysis is done by single-exp. fits and single operator

$$\frac{M_{5Q}}{M_K + M_N} = 1.073(34) \quad \text{at } \beta = 6.0$$

negative parity

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$$\boxed{\frac{M_{5Q}}{M_K + M_N} = 1.073(34)} \quad \text{at } \beta = 6.0$$

negative parity

- Variational approach (at the heaviest quark mass)
  - Mix two operators $\mathcal{O}_1 + \alpha\mathcal{O}_2$ $\begin{cases} \mathcal{O}_1 : & \text{color variant of } \mathcal{O}_K \times \mathcal{O}_N \\ \mathcal{O}_2 : & \mathcal{O}_K \times \mathcal{O}_N \end{cases}$
  - Choose α to isolate the first excited state
  - At the optimized α

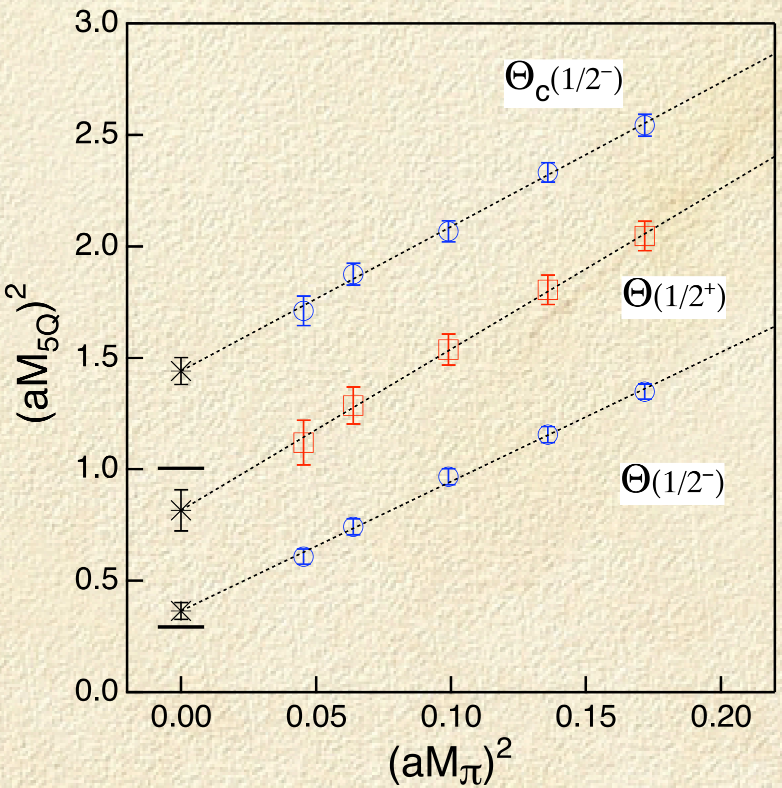
$$\frac{E_0}{M_K + M_N} = 0.994(18) \qquad \boxed{\frac{E_1}{M_K + M_N} = 1.074(20)}$$

KN scattering state

Sasaki (1)

hep-lat/0310014

- Wilson fermions (Quench) + Wilson gauge action
  - L~2.2 fm (32^3x48), a=0.07 fm (β=6.2)
  - m_π from 0.6 - 1.0 GeV
  - J=1/2, I=0, parity projection
  - Includes charm sector
  - Diquark-diquark-antiquark



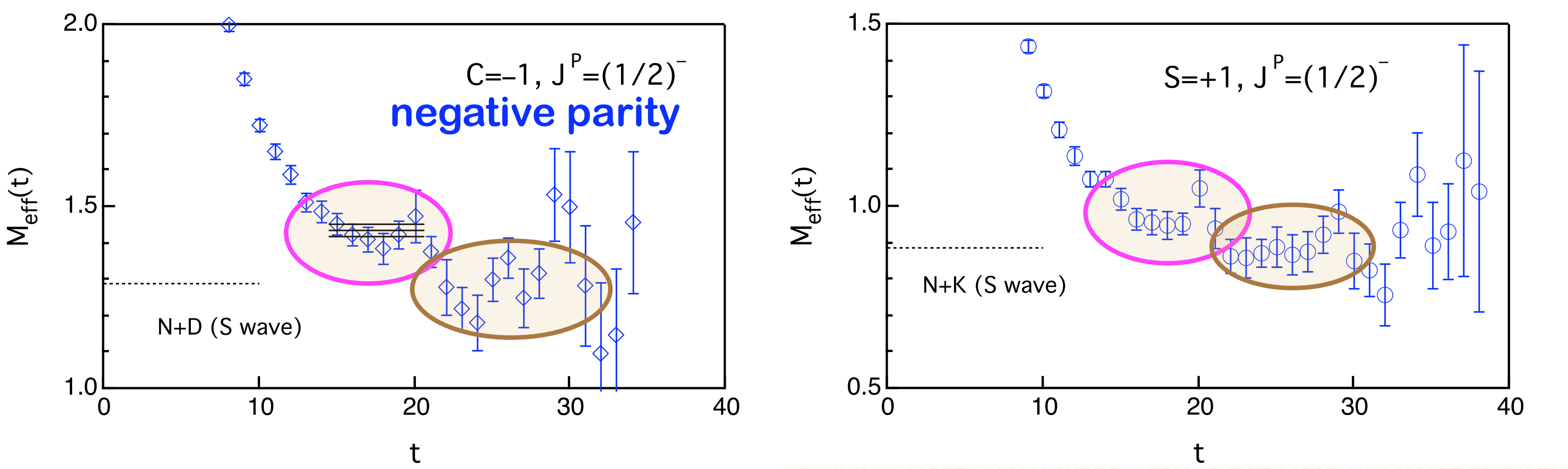
$J^\pi = 1/2^-$ $J^\pi = 1/2^+$

$M_{\Theta^+} = 1.76(9)\text{GeV}$ $M_{\Theta^+} = 2.62(9)\text{GeV}$

Sasaki (2)

hep-lat/0310014

- Test diquark-diquark-antiquark op. in heavy quark regime
  - Anti-charmed pentaquarks $uudd\bar{c}$

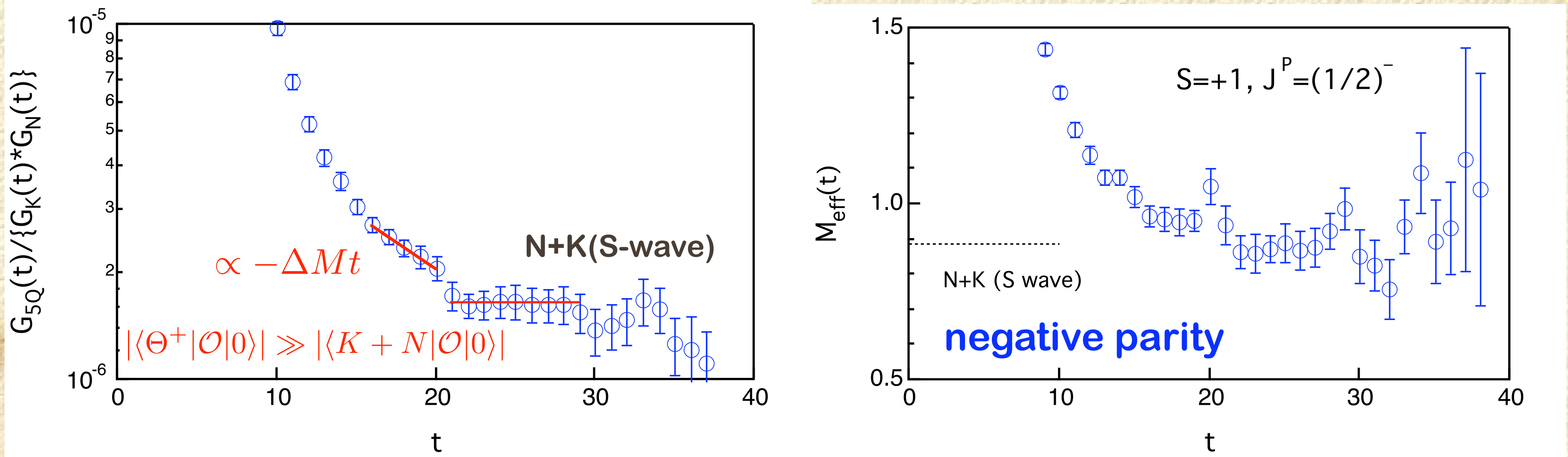


$qqqq\bar{c} \longleftrightarrow qqqq\bar{s}$

Sasaki (3)

hep-lat/0310014

- **Double-exp. fits accept the presense of two indep. states, which are close to each other. ($A_{5Q} \gg A_{KN}$)**
  - Ground state should be the S-wave KN scattering state.



  - First excited state might be the pentaquark state. (need confirmation)

Summary of exploratory studies

- CFKK and Sasaki both claim :
  - ☑ Can not accommodate the pentaquark state near the KN threshold in the positive parity channel
  - ☑ Some indications for the presence of the pentaquark state near the KN threshold in the negative parity channel
  - ☑ The spin-parity of the $\Theta^+(1540)$ is most likely $1/2^-$

Chiu-Hsieh (1)

hep-lat/0403020, 0404007

- Chiral fermions (Quench) + Wilson gauge action
  - L~1.6 fm (20^3x40), a=0.08 fm (β=6.1)
  - m_π from 0.4 - 1.0 GeV
  - J=1/2, I=0, parity projection
  - Includes charm sector
  - Same operator as Sasaki

	5Q baryon	J^Π	mass	Expt.
$\overline{10}$	$\Theta([ud][ud]\bar{s})$	$1/2^+$	1539(95)	$\Theta^+(1540)$
	$N_s([ud][us]_+\bar{s})$	$1/2^+$		
	$\Sigma_s([us][us]\bar{s})$	$1/2^+$		
	$\Xi([ds][ds]\bar{u})$	$1/2^+$	1826(87)	$\Xi^{--}_{3/2}(1860)$
8	$N([ud][ud]\bar{d})$	$1/2^+$	1460(51)	$N(1440)P_{11}$
	$\Sigma([ud][us]_+\bar{d})$	$1/2^+$		
	Λ	$1/2^+$		
	Ξ	$1/2^+$		
$1+8$		$1/2^-$		
3	$T_c([ud][us]\bar{c})$	$1/2^-$	2785(46)	
	$T_c^*([ud][us]\bar{c})$	$1/2^+$	3243(66)	
	$T_{cs}([us][ds]\bar{c})$	$1/2^-$		
$\bar{6}$	$\Theta_c([ud][ud]\bar{c})$	$1/2^+$	2977(109)	$\Theta_c(3099)$
	$\Theta_c^*([ud][ud]\bar{c})$	$1/2^-$	3353(89)	search ?
	$N_c([ud][us]_+\bar{c})$	$1/2^+$	3180(69)	search ?
	$\Xi_c([ds][ds]\bar{c})$	$1/2^+$	3650(95)	search ?

Chiu-Hsieh (2)

hep-lat/0403020, 0404007

- They claim:
  - the lower-lying pentaquark; positive parity

Chiu-Hsieh (2)

hep-lat/0403020, 0404007

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  - Any NK scattering state is not seen

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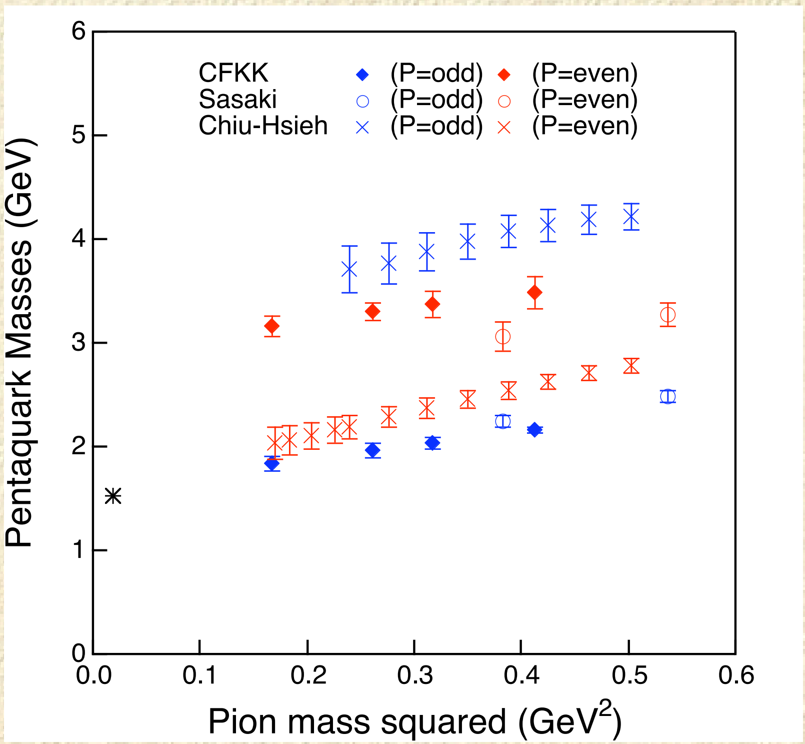
    - In contradiction to Wilson results (CFKK/Sasaki)
    - The discrepancy is due to the lattice artifacts of the Wilson fermion
  - ☑ Any NK scattering state is not seen
  - ☑ Strongly support the Jaffe-Wilczek model
    - the N(1440) can be identified with a pentaquark

Comments on Chiu-Hsieh

The lightest pion mass ~ 0.4 GeV

- One would not expect any qualitative difference between Wilson and Chiral fermions in their quark mass range.



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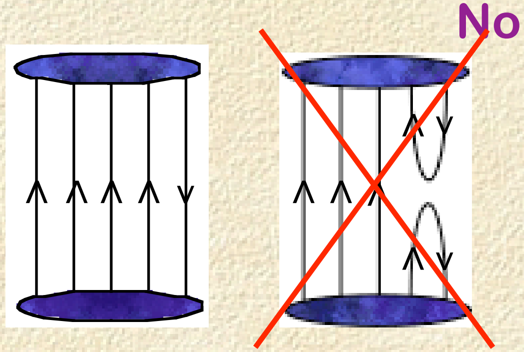
- **The lightest pion mass ~ 0.4 GeV**
  - One would not expect any qualitative difference between Wilson and Chiral fermions in their quark mass range.

- **Really observe the N-type lightest pentaquark?**

~~$M_N([ud][ud]\bar{d}) = 1460(51)\text{MeV}$~~ ~~$\rightarrow N(1440), 1/2^+$~~

$M_\Theta([ud][ud]\bar{s})$ in $SU(3)_f$ limit



Kentucky Collab. (1)

Mathur et al., hep-ph/0406196

- Overlap fermions (Quench) + Iwasaki gauge action
  - L~2.4 and 3.2 fm (12^3x40, 16^3x40), a=0.20 fm
  - m_π down to 0.18 GeV from 1.0 GeV
  - J=1/2, I=0,1, parity projection
  - Simple minded operator as N times K
  - Sequential empirical Bayes method
  - Check the volume dependence of spectral weight.

Kentucky Collab. (2)

- They claim:

Mathur et al., hep-ph/0406196

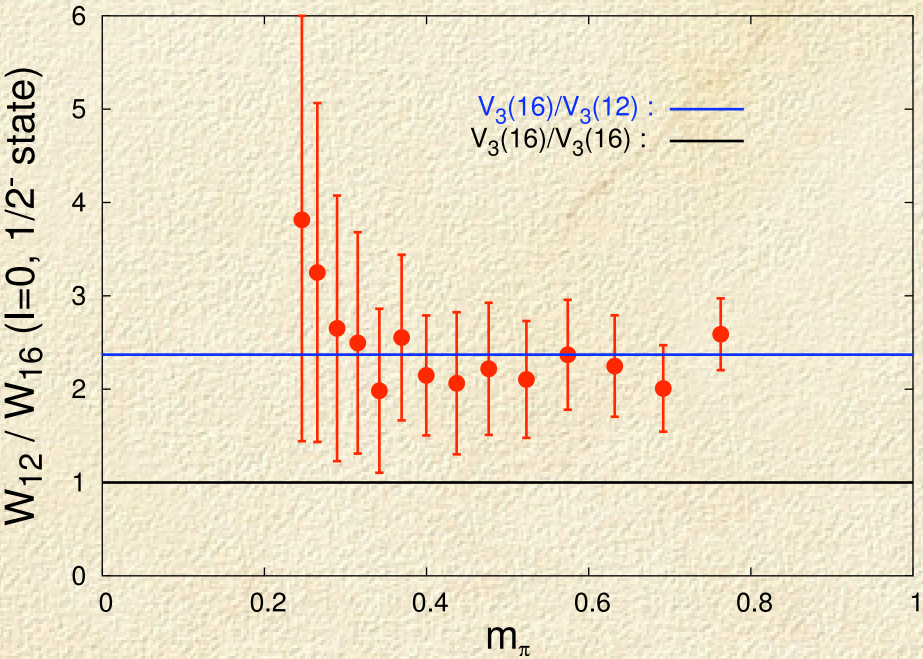
☑ See only KN scattering state in negative parity

- Ground state in either parity channel has a characteristic volume dependence on the spectral weight.

$$|N,\vec{p},s\rangle_{\rm latt} \propto \sqrt{\frac{M}{VE}}|N,\vec{p},s\rangle_{\rm cont}$$

The spectral weight should have 1/V dependence for two particles

$$W_{12}/W_{16} = 16^3/12^3 = 2.37$$



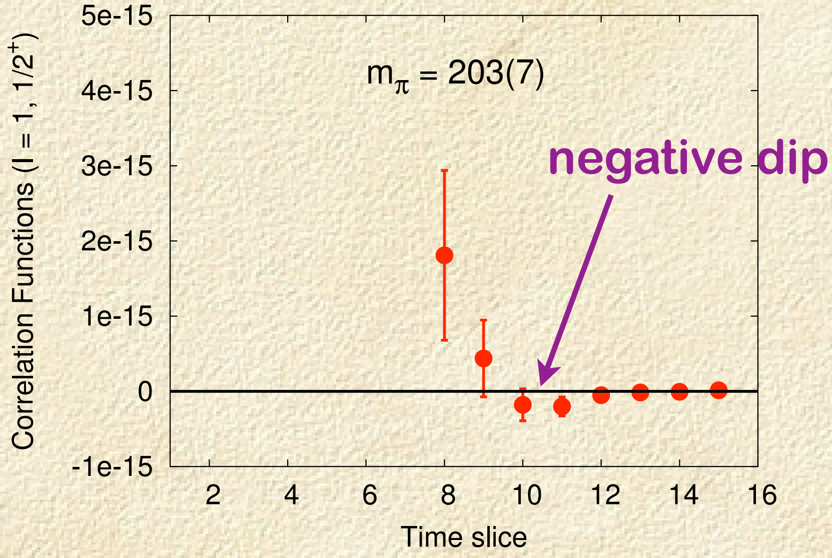
Kentucky Collab. (2)

Mathur et al., hep-ph/0406196

- They claim:

  - ☑ See only KN scattering state in negative parity
    - Ground state in either parity channel has a characteristic volume dependence on the spectral weight.

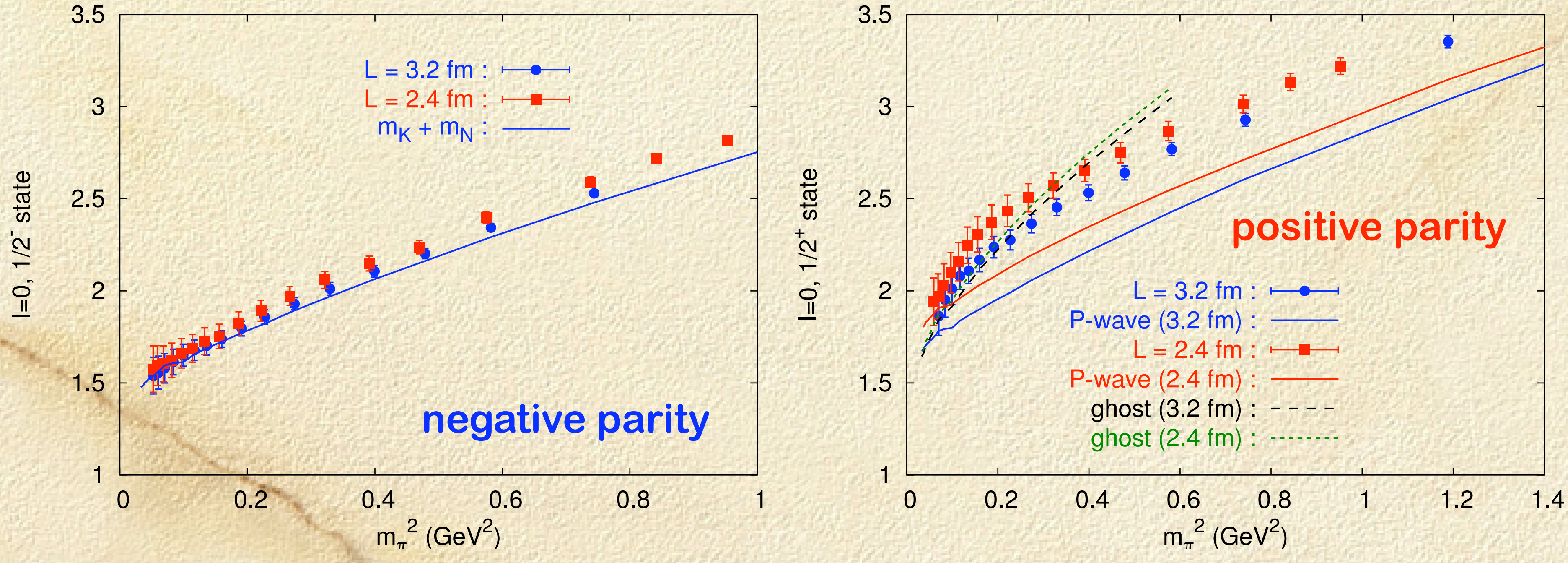
  - ☑ Confirm the ghost KNη' state in positive parity channel at $M_\pi < 266$ MeV



Kentucky Collab. (3)

Mathur et al., hep-ph/0406196

- They claim:
  - ☑ **No sign of pentaquark signal** in either parity channel at present.



Sigaev-Jahn-Negele (1)

- **Eight possible local sources:** extention of Sasaki's proposal

$$\mathcal{O} = \varepsilon_{abc}\varepsilon_{aef}\varepsilon_{bgh}[u_e^T C\Gamma_1 d_f][u_g^T C\Gamma_2 d_h]\Gamma_3 C\bar{s}_c^T$$

	Γ_1	Γ_2	Γ_3	Isospin	Lorentz
1	1	γ_5	1	S	P
2	γ_5	$\gamma_5\gamma_\mu$	$\gamma_5\gamma_\mu$	S	V
3	1	$\gamma_5\gamma_\mu$	γ_μ	S	A
4	$\gamma_5\gamma_\mu$	$\gamma_5\gamma_\nu$	$\epsilon_{\mu\nu\rho\lambda}\sigma_{\rho\lambda}$	S	T
5	$\gamma_\nu\tau_n$	$\sigma_{\mu\nu}\tau_n$	$\gamma_5\gamma_\mu$	V	V
6	$\gamma_\mu\tau_n$	$\epsilon_{\mu\nu\rho\lambda}\sigma_{\nu\lambda}\tau_n$	γ_μ	V	A
7	$\gamma_\mu\tau_n$	$\gamma_\nu\tau_n$	$\epsilon_{\mu\nu\rho\lambda}\sigma_{\rho\lambda}$	V	T
8	$\sigma_{\mu\nu}\tau_n$	$\sigma_{\nu\lambda}\tau_n$	$\epsilon_{\mu\nu\rho\lambda}\sigma_{\rho\lambda}$	V	T

I=0 (rows 1–4)

I=1 (rows 5–8)

$\Rightarrow$ Compute 4x4 cross correlator in each isospin channel.

Sigaev-Jahn-Negele (2)

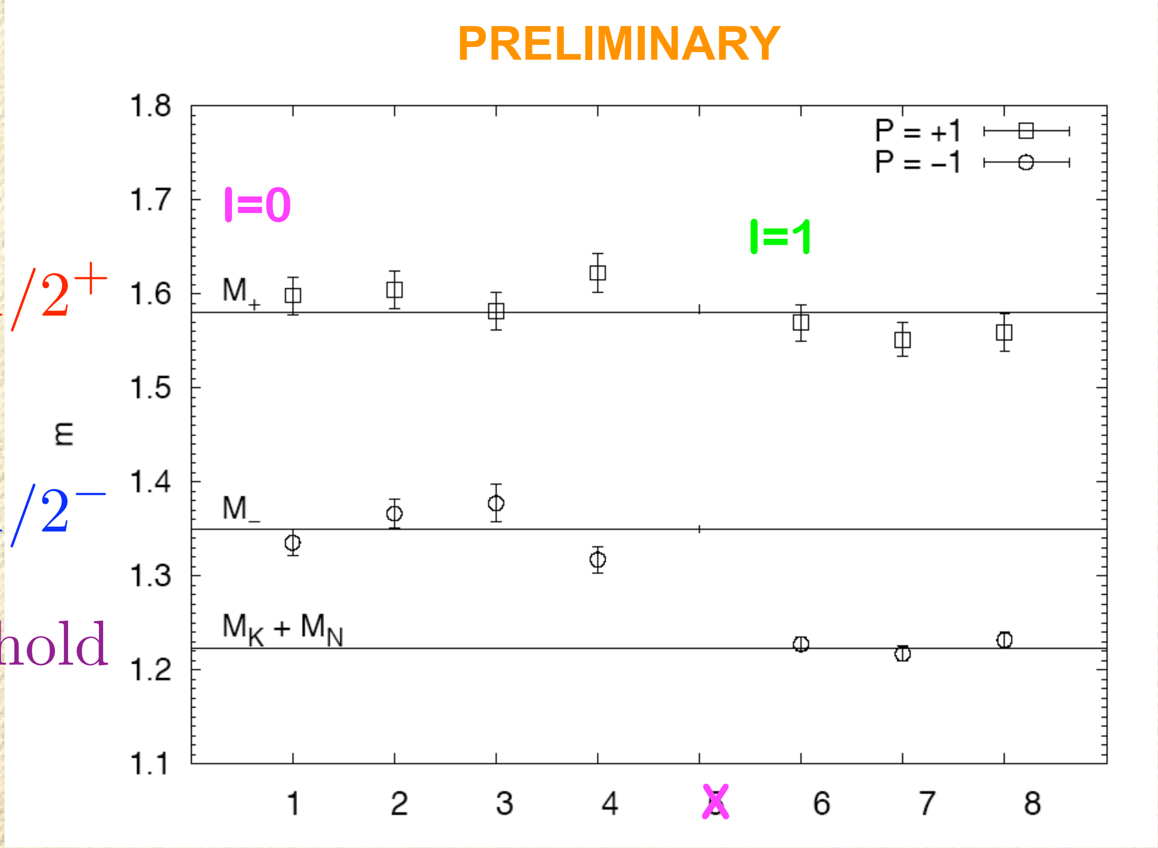
The results are currently from double-exp. fits to each operator.

β=6.0 16^3x32
Wilson (Quench)

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

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

KN threshold



Kind of operators

Presented at QNP2004 by Negele

Comparison of lattice results

Q1: Observe pentaquarks in lattice QCD?

Q2: Which parity is assigned to the lowest state of the pentaquark?

Q3: Find anti-charmed pentaquark as bound state or near threshold?

	A1	A2	A3	Op.
Csikor et al.	YES	negative	–	color variant of KN
Sasaki	YES	negative	NO	diquark-diquark-antiquark
Kentucky	NO	not positive	–	simple KN
Chiu-Hsieh	YES	positive	YES	diquark-diquark-antiquark
MIT	YES	negative	–	diquark-diquark-antiquark

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Summary (1)

All results should be regarded as exploratory at present.

- To confirm the presence of the pentaquarks
  - ☑ Try some other possible operators
  - ☑ The M x M correlation matrix analysis is required to separate the KN scattering state
- To disentangle the pentaquark signal from the KN scattering states
  - ☑ Identify the lowest few scattering states in both parity channels
  - ☑ Verify the volume dependence

Detail studies are in progress by CFKK, Sasaki, Chiu-Hsieh, Kentucky, MIT

Summary (2)

- The following questions still remain open:
  - Does the spectrum of QCD possess the $\Theta^+(1540)$?
  - What is **spin** and **parity** of the $\Theta^+(1540)$?
  - Are there other pentaquark baryons?
    - other member of the anti-decuplet, especially $\Xi_{3/2}$
    - the **charm (bottom)** pentaquark
    - the **spin-orbit partner** of the $\Theta^+(1540)$; $J=3/2$

There are many exciting issues to be explored.

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- Keh-Fei Liu & Nilmani Mathur
- Ting-Wai Chiu
- John Negele

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