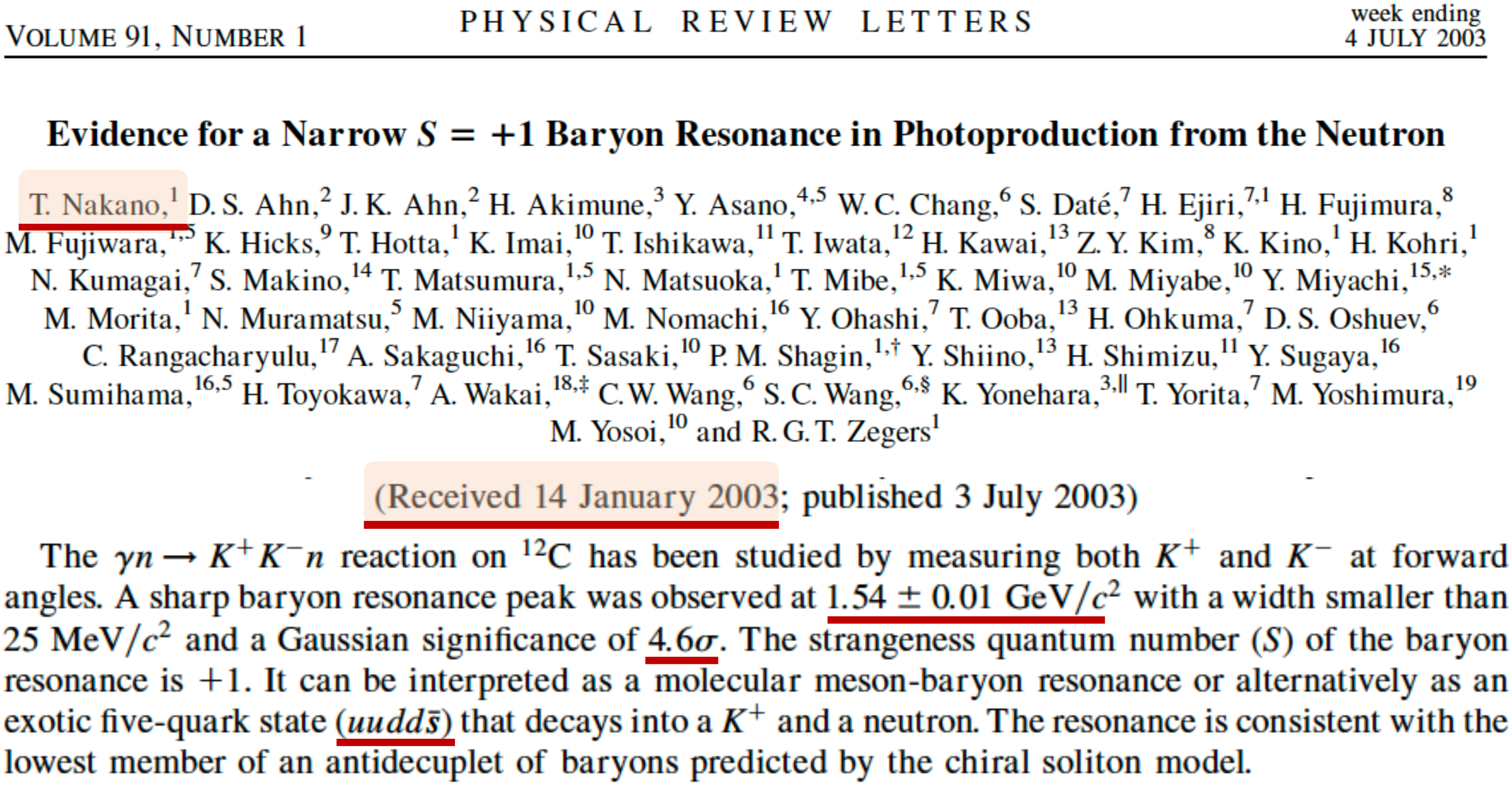
20 years of Theta+

Michał Praszałowicz

28.08.2023 Corfu



VOLUME 91, NUMBER 1 PHYSICAL REVIEW LETTERS week ending 4 JULY 2003

Evidence for a Narrow $S = +1$ Baryon Resonance in Photoproduction from the Neutron

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(Received 14 January 2003; published 3 July 2003)

The $\gamma n \rightarrow K^+ K^- n$ reaction on ^{12}C has been studied by measuring both K^+ and K^- at forward angles. A sharp baryon resonance peak was observed at 1.54 ± 0.01 GeV/c^2 with a width smaller than 25 MeV/c^2 and a Gaussian significance of 4.6σ. The strangeness quantum number (S) of the baryon resonance is $+1$. It can be interpreted as a molecular meson-baryon resonance or alternatively as an exotic five-quark state ($uudd\bar{s}$) that decays into a K^+ and a neutron. The resonance is consistent with the lowest member of an antidecuplet of baryons predicted by the chiral soliton model.

PANIC Oct. 2002 in Osaka

LEPS@SPring-8 in Japan (Laser-Electron Photon facility at Spring-8)

1174 citations in iNSpire.hep

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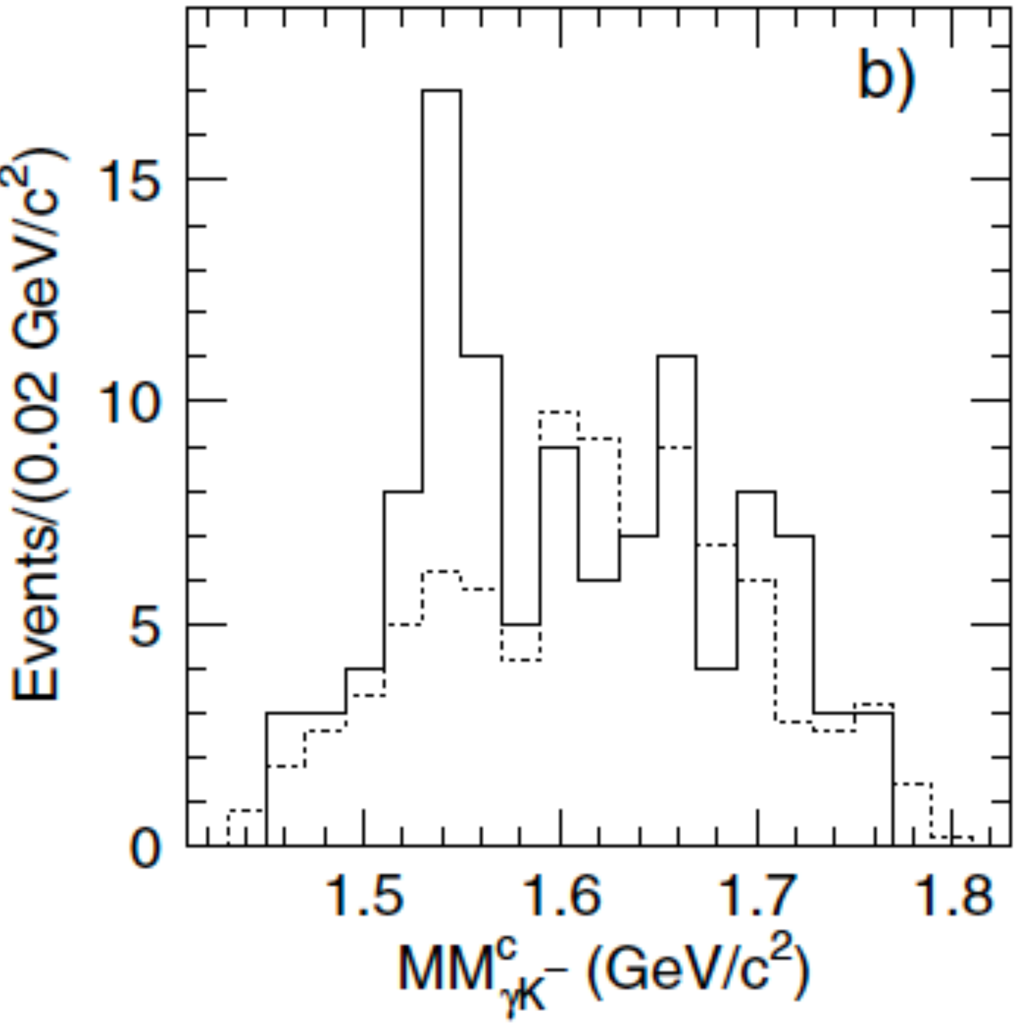

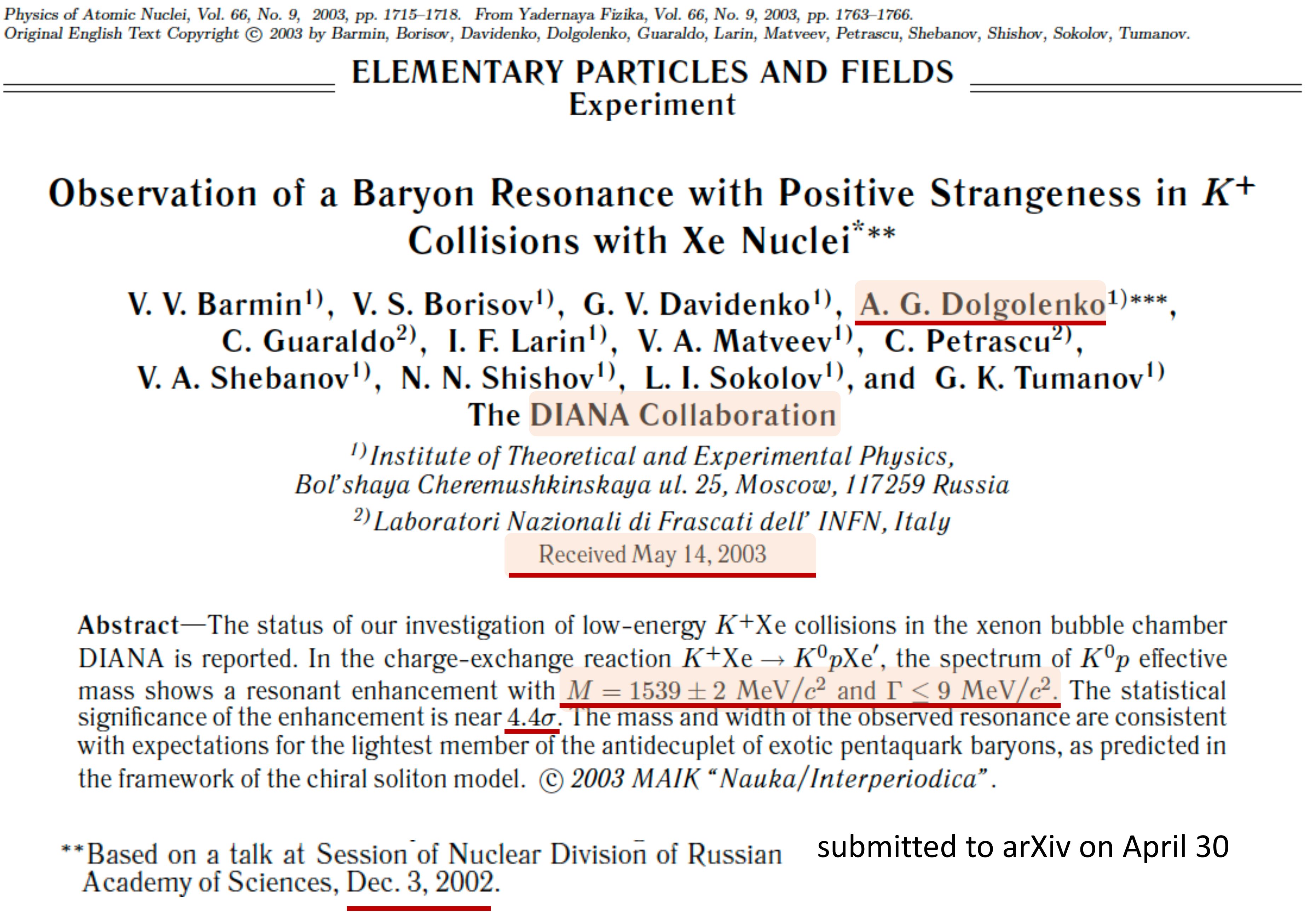

Physics of Atomic Nuclei, Vol. 66, No. 9, 2003, pp. 1715–1718. From Yadernaya Fizika, Vol. 66, No. 9, 2003, pp. 1763–1766.

ELEMENTARY PARTICLES AND FIELDS
Experiment

Observation of a Baryon Resonance with Positive Strangeness in K^+ Collisions with Xe Nuclei* **

V. V. Barmin1), V. S. Borisov1), G. V. Davidenko1), A. G. Dolgolenko1)***,
C. Guaraldo2), I. F. Larin1), V. A. Matveev1), C. Petrascu2),
V. A. Shebanov1), N. N. Shishov1), L. I. Sokolov1), and G. K. Tumanov1)
The DIANA Collaboration
1) *Institute of Theoretical and Experimental Physics,*
Bol'shaya Cheremushkinskaya ul. 25, Moscow, 117259 Russia
2) *Laboratori Nazionali di Frascati dell' INFN, Italy*
Received May 14, 2003

Abstract—The status of our investigation of low-energy K^+Xe collisions in the xenon bubble chamber DIANA is reported. In the charge-exchange reaction $K^+\mathrm{Xe} \to K^0 p\mathrm{Xe}'$, the spectrum of K^0p effective mass shows a resonant enhancement with $M = 1539 \pm 2$ MeV/c^2 and $\Gamma \leq 9$ MeV/c^2. The statistical significance of the enhancement is near 4.4σ. The mass and width of the observed resonance are consistent with expectations for the lightest member of the antidecuplet of exotic pentaquark baryons, as predicted in the framework of the chiral soliton model. © 2003 *MAIK "Nauka/Interperiodica"*.

** Based on a talk at Session of Nuclear Division of Russian Academy of Sciences, Dec. 3, 2002.

submitted to arXiv on April 30

705 citation in iNSpire.hep

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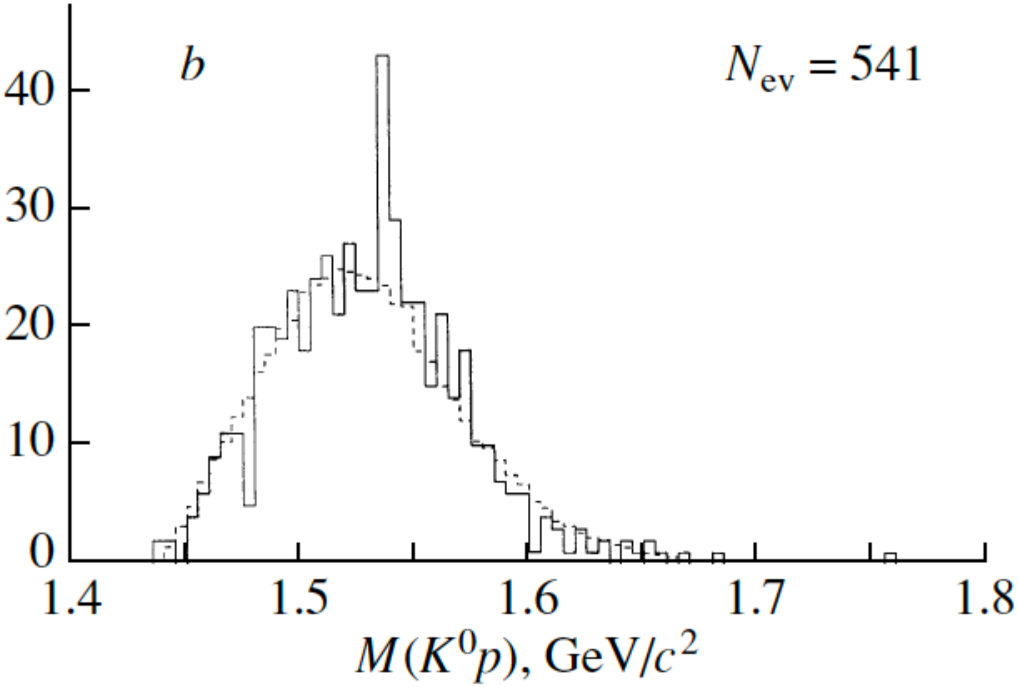

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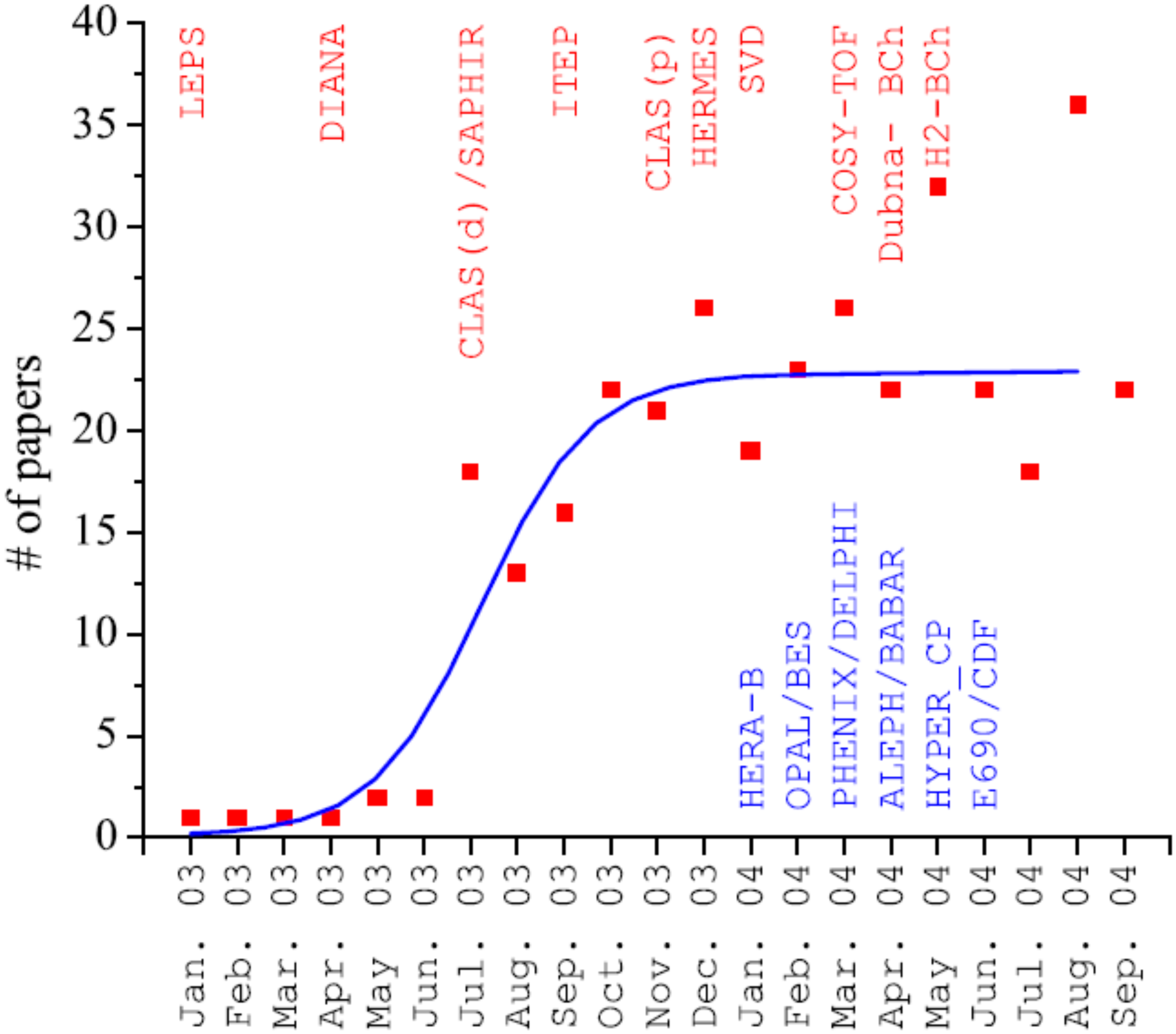
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OPAL/BES
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ALEPH/BABAR
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Quarks

Five alive!

An odd, new subatomic ... "pentaquark", has been ...

NEW YORK TIMES **INTERNATIONAL** TUESDAY, JULY 1, 2003

A Subatomic Discovery Emerges From Experiments in Jap

By KENNETH CHANG

Slamming high-energy particles of light into carbon atoms, physicists have unexpectedly produced a new type of subatomic particle.

Protons and neutrons, the building blocks of atoms, are made of smaller particles known as quarks, which come in six varieties. A proton, for example, consists of three quarks — two so-called up quarks and one down quark. Physicists know of slews of particles containing two or three quarks.

Now they believe they know of a particle containing five quarks that perhaps could have been common in the very early universe. (No one

the experiments, Dr. Takashi Nakano, of the Research Center for Nuclear Physics at Osaka University, and told Dr. Nakano that he should look through the data for signs of five-quark particles.

"Dimitri Diakonov was very confident of that," Dr. Nakano said. Dr. Nakano and his collaborators looked, and they found a peak in their graphs corresponding to the mass of the five-quark particle that Dr. Diakonov had predicted. "He was right," Dr. Nakano said. "Actually, I was very surprised."

Dr. Kenneth H. Hicks, a professor of physics at Ohio University and another member of the Spring-

would consist of two up quarks, two down quarks and one known as an anti-strange quark.

The findings will be reported Friday in the journal Physical Review Lette

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Scientists find fleeting form of basic matter

JOHN MANGELS
Plain Dealer Science Writer

Teams of scientists in Japan and the United States have confirmed the existence of a previously unknown kind of matter, a strange, fleeting subatomic particle that has been the object of a 30-year search.

One of the scientists likens the discovery to finding a new animal that doesn't fit the typical classifications of mammals or reptiles. The researchers say it's too soon to know what impact their finding will have, but they speculate that it may add to the basic understanding of how the universe was formed and how the particles that compose all matter interact.

The newly identified particle, dubbed a "pentaquark" because of its five ingredients, likely existed in the fractions of a second after the Big Bang, as the universe began to organize from the fiery chaos of free-floating elementary particles into the familiar components of atoms.

Pentaquarks also probably flicker in and out of being today, the short-lived product of billiard-ball-like collisions between cosmic rays and atoms in deep space or Earth's upper atmosphere.

SEE PARTICLE | A7

PARTICLE

FROM A1

Scientists find unknown form of basic matter

Scientists had to duplicate those conditions in the lab by firing powerful energy beams into targets of carbon or hydrogen atoms. Even then, it took months for them to analyze the data, recognize what they had done, and convince themselves it wasn't a false conclusion. Their findings will be published in Physical Review Letters, a prominent physics journal, later this month.

When he first saw the computer tracing that was the signature of the new category of particle, "I thought it was some mistake," said Ohio University physics Professor Ken Hicks, who was a collaborator in the Japanese experiments and headed similar work at the U.S. Department of Energy's Thomas Jefferson National Accelerator Facility in Virginia.

His Japanese colleague had a similar reaction. "It must be

To reach this Plain Dealer reporter:
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HIGH-ENERGY PHYSICS

Evidence for 'Pentaquark' Particle Sets Theorists Re-Joyce-ing

www.sciencemag.org SCIENCE VOL 301 11 JULY 2003

USA TODAY · TUESDAY, JULY 1, 2003 · 7D

Physics team goes where no quark has gone before

By Dan Vergano

atoms with high-energy X-rays to

CERN COURIER

News

New five-quark states found at CERN

Figure 1

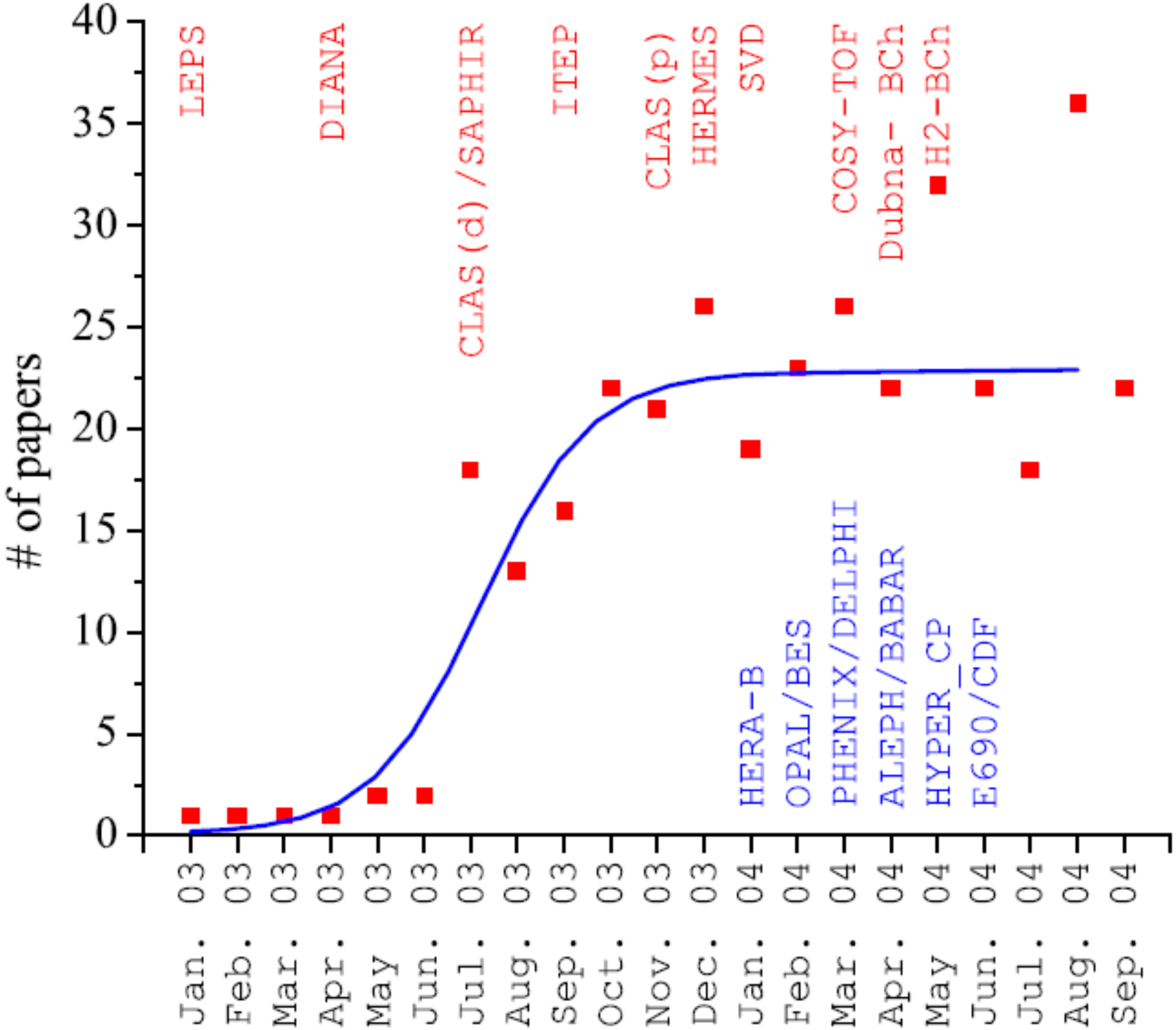
Only a few months after the first burst of excitement over the appearance at several laboratories of what seems to be a new five-quark particle, evidence has been found for a different five-quark state that appears to be closely related.

The constituent quark model of hadrons that was invented in the 1960s has been very successful in describing the known baryons as composites of three valence quarks. Quantum chromodynamics (QCD), the theory of strong interactions, does not forbid baryons containing more than three quarks. In fact, such states were proposed a long time ago but no good candidates were found by experiments until recently. The search was revived by the theorists Dmitri Diakonov, Victor Petrov and Maxim Polyakov. They predicted that the masses of the lightest pentaquark (4q,qbar) baryon multiplet, an antidecuplet (see figure 1), were rather small and that the width of its lightest member was expected to be very narrow (Diakonov et al. 1997). Recent evidence for this state, named Θ^+, has opened up a new chapter in baryon spectroscopy that will help to elucidate QCD in the non-perturbative regime (CERN Courier September 2003 p5). The Θ^+ is a manifestly exotic baryon, that is, it cannot be composed of three quarks. This is also the case for the other two corner members of the antidecuplet depicted in figure 1. The latter have a strangeness of S = -2, a charge of Q = -2, +1, and form members of an isospin quartet of Ξ states.

Figure 2

Experiment NA49 at the CERN Super Proton Synchrotron has searched for the Θ^+ and the Ξ states in proton-proton collisions at a beam energy of 158 GeV (Alt et al. 2003). Tracks of particles produced in the reactions are recorded by the detector's four large time-projection chambers. Their high resolution allows for a precise reconstruction of the particle trajectories and momenta as well as their identification via the measurement of the energy loss in the chamber gas. The reconstruction of secondary decay vertices makes possible the observation of the complex decay chains of the pentaquark states. After suppression of the overwhelming background by suitable selection cuts, the summed Ξπ mass distribution shows a narrow peak of 5.6 standard deviations at a mass of 1.862 ±0.002 GeV/c² (see figure 2). The true width of the peak must be smaller than the observed full width at half maximum of 0.017 GeV/c², which is consistent with the resolution of the detector.

In fact, peaks are seen at the same mass in the individual $\Xi^-\pi^-$ and $\Xi^-\pi^+$ mass distributions as well as in those of the antiparticles. No signal has been found yet for the Θ^+, for which the background in the potentially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HERMES
SVD
COSY-TOF
Dubna- BCh
H2-BCh
HERA-B
OPAL/BES
PHENIX/DELPHI
ALEPH/BABAR
HYPER_CP
E690/CDF
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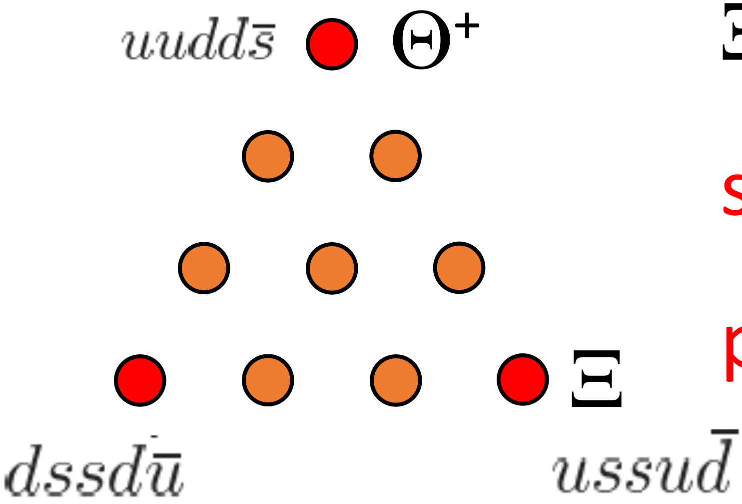
Quark Model

$(uudd\bar{s})$: $4 * 310 + 550 \sim 1790$ MeV

pentaquark: strangeness +1

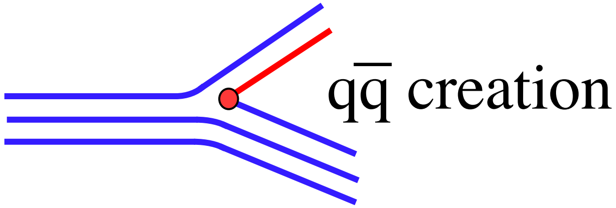
$\Gamma \sim 200 - 400$ MeV

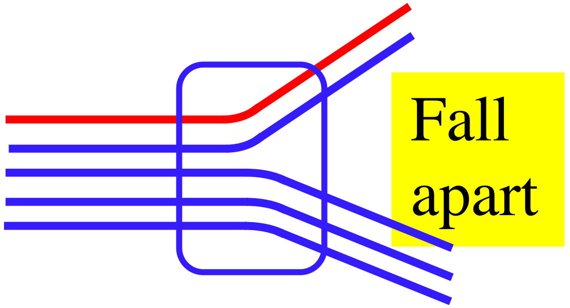


$\Xi(2s) - \Theta(s) = 150$ MeV

spin 1/2

parity –





Chiral Models

Masses are naturally smaller than in the Quark Model:
rather than adding a constituent starange quark we
add a Goldstone boson:

No 310 + 550 = 860 MeV but M_K = 490 MeV

To understand small width requires some more information.

Parity is positive!

Skyrme Model

T.H.R Skyrme, Proc. Royal Soc. **A260** (1961) 127; Nucl. Phys. **31** (1962) 556.

E. Witten, Nucl. Phys. **B160** (1979) 57; **B223** (1983) 422; **B223** (1983) 433.

G.S. Adkins, C.R. Nappi and E. Witten, Nucl. Phys. **B228** (1983) 552; G.S. Adkins and C.R. Nappi, Nucl.Phys. **B233** (1984) 109.

Take Goldstone boson Lagrangian (very specific!):

$$\mathcal{L} = \frac{F_\pi^2}{16}\,\mathrm{Tr}\left(\partial_\mu U^\dagger \partial^\mu U\right) + \frac{1}{32e^2}\,\mathrm{Tr}\left(\left[\partial_\mu U\,U^\dagger, \partial_\nu U\,U^\dagger\right]^2\right)$$

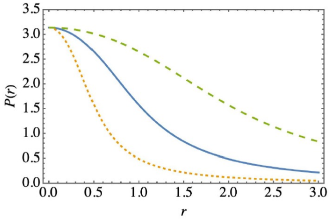
where the unitary matrix U is given in terms of pions, kaons and eta (denoted as φ_a) :

$$U = \exp\left(i2\varphi_a\lambda_a/F_\pi\right),\ F_\pi = 186\ \mathrm{MeV}$$

Expanding exponent gives the GBs interaction Lagrangian (predecessor of chiral perturbation theory) organized as a power series in the number of fields and their momenta. This works for low energy GB scattering.

This lagrangian adimts classical solution in a form of the hedgehog Ansatz

$$U_0 = \begin{bmatrix} e^{i\vec{n}\cdot\vec{\tau}\,P(r)} & 0 \\ 0 & 1 \end{bmatrix}$$



Collective quantization

$$U = AU_0A^\dagger \qquad A \to A(t)$$

However:

$$\boxed{[U_0, \lambda_8] = 0} \qquad U_0 = \begin{bmatrix} e^{i\vec{n}\cdot\vec{\tau}\,P(r)} & 0 \\ 0 & 1 \end{bmatrix} \qquad \lambda^8 = \frac{1}{\sqrt{3}}\begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & -2 \end{bmatrix}$$

As a conseqence there is an equivalence: $A(t) \sim A(t)e^{-i\varphi\lambda_8}$

$$A(t)e^{-i\varphi\lambda_8}\,U_0\,e^{i\varphi\lambda_8}A^\dagger(t) = A(t)U_0A^\dagger(t)$$

and the right index of matrix $A(t)$ lives in the SU(2) subgroup of SU(3) that correspopnds to spin. On the contrary the left index goes over the entire SU(3), and corresponds to flavor. **8-th velocity is not dynamical!**

$$A_{\mathrm{flavor},\mathrm{spin}}$$

Collective Hamiltonian

Rotational nergy (mass) of a rotating baryon in SU(3) representation $\mathcal{R} = (p,\, q)$ is analgous to the quantum mechanical symmetric top:

$$\mathcal{E}^{\mathrm{rot}}_{(p,\,q)} = M_{\mathrm{sol}} + \frac{J(J+1)}{2I_1} + \frac{C_2(p,q) - J(J+1) - 3/4\, Y'^2}{2I_2}$$

Soliton mass M_{sol} and moments of ineria $I_{1,2}$ are calculable functions of the profile function $P(r)$

J^2 - soliton angular momentum = baryon spin

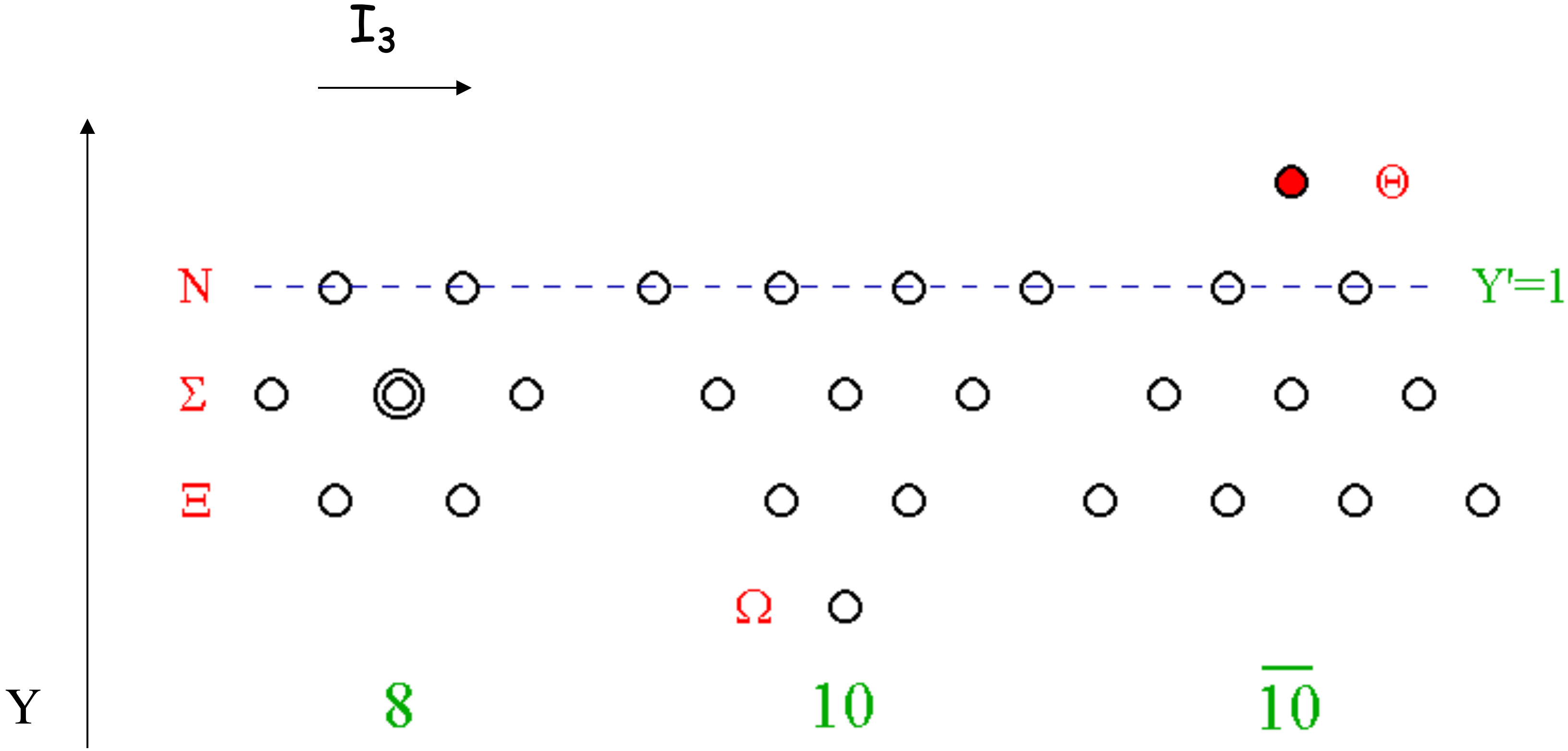
$C_2(p,q)$ - SU(3) Casimir operator

$Y' = N_c/3$ - constraint selecting allowed SU(3) representations

Isospin of states on Y' line is equal to J

Allowed SU(3) multiplets and w.f's

$$|R,B,S\rangle = \sqrt{R}\, D^{(\mathcal{R})*}_{\underbrace{Y I I_3}_{B}\ \underbrace{Y' J J_3}_{S}}(A) \qquad J_3 = -S_3$$



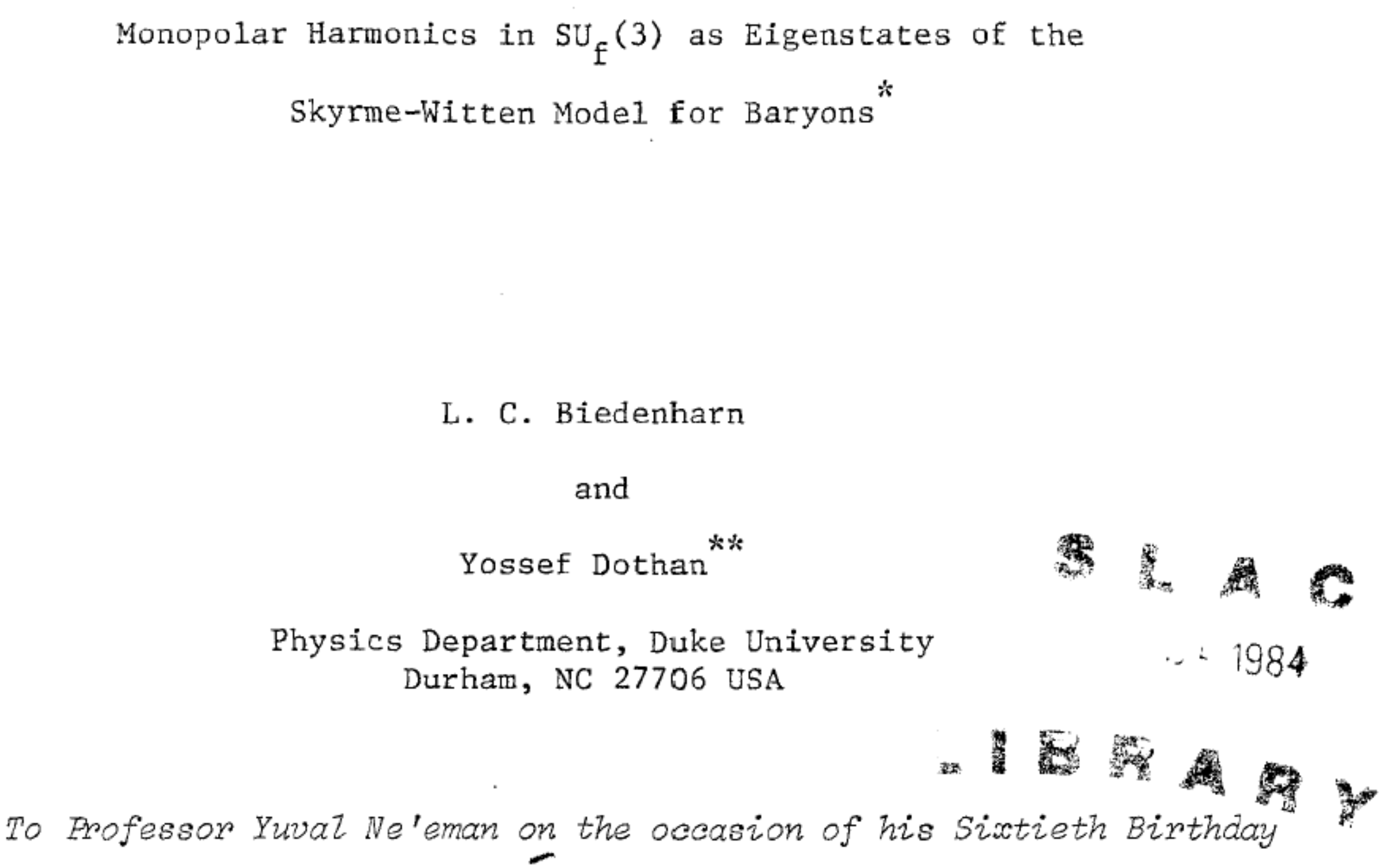
Pheomenology

$$\frac{1}{I_1} = \frac{2}{3}\left(M_{10} - M_8\right) = 153 \text{ MeV}$$

$$\frac{1}{I_2} = \frac{2}{3}\left(M_{\overline{10}} - M_8\right) = ?$$

What is Theta+ mass?

What is the value of I_2 ? Model calculation from **1984**:



Monopolar Harmonics in $SU_f(3)$ as Eigenstates of the Skyrme-Witten Model for Baryons*

L. C. Biedenharn

and

Yossef Dothan**

Physics Department, Duke University
Durham, NC 27706 USA

To Professor Yuval Ne'eman on the occasion of his Sixtieth Birthday

Thus the first state violating the three quark rule is a $(\overline{10},\frac{1}{2})$, which--using numerical values4) in the Hamiltonian--yields an excitation energy $\approx$ 600 Mev above the $(8,\frac{1}{2})$. Since the theory is a low energy effective theory we believe that this gives an aposteriori excitation energy limit on the validity. Otherwise stated this means that when baryons are probed with momentum transfers of the order of 600 MeV one starts to feel their compositness.

Footnotes and References

1) E. Witten, Nucl. Phys. B223(1982) 422.

2) T.H.R. Skyrme, Proc. Roy. Soc. A260 (1961) 127.

3) E. Guadagnini, Nucl. Phys., B236, (1984), 35.
L.C. Biedenharn, Y. Dothan and A. Stern, Phys. Lett. 146D (1983) 289.

4) L.C. Biedenharn, J.D. Louck, Encl. for Math. and Appl., Vol. 9: "The Racah-Wigner Algebra in Quantum Theory", Additon-Wesley (Reading, MA) 1981.

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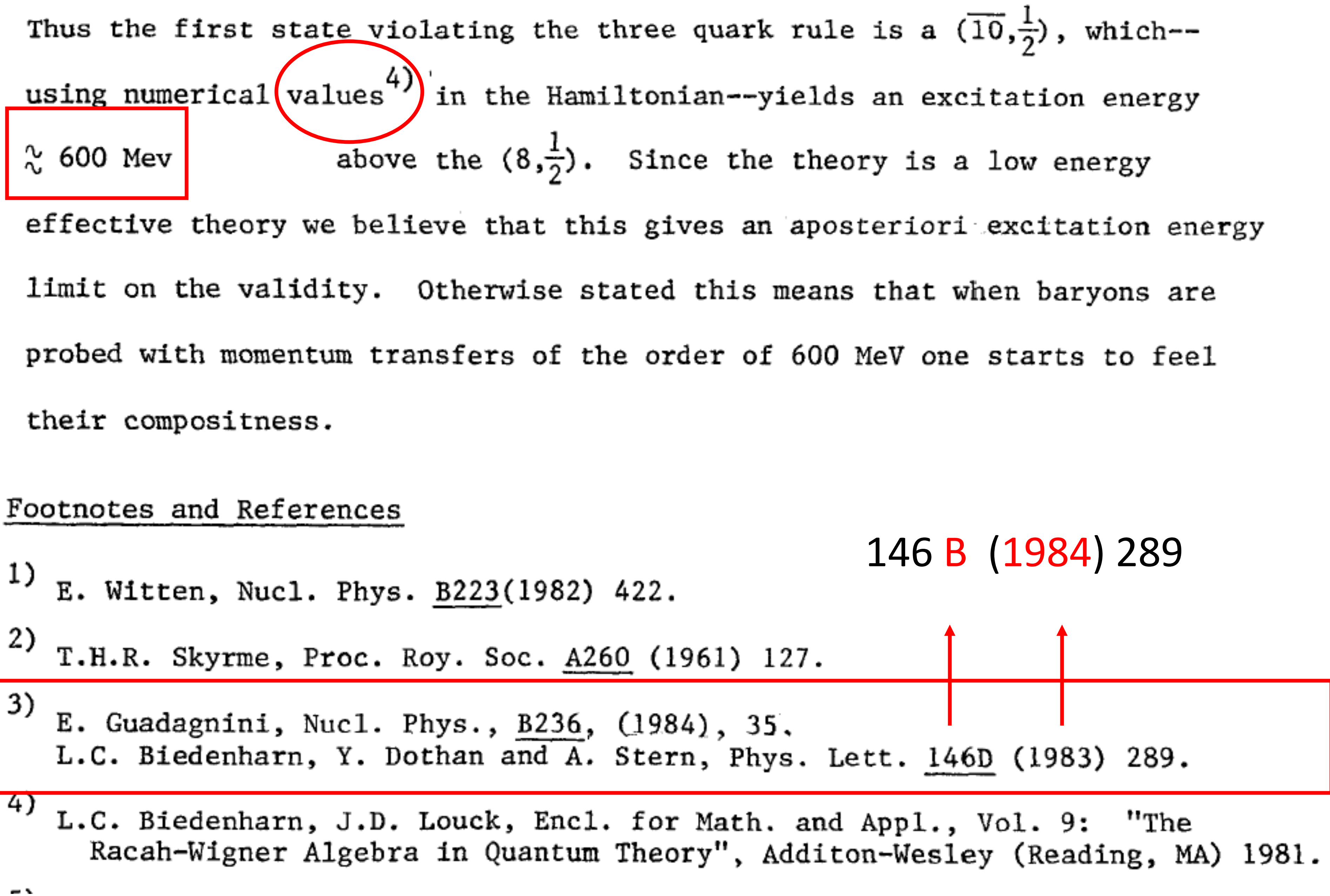

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146 B (1984) 289

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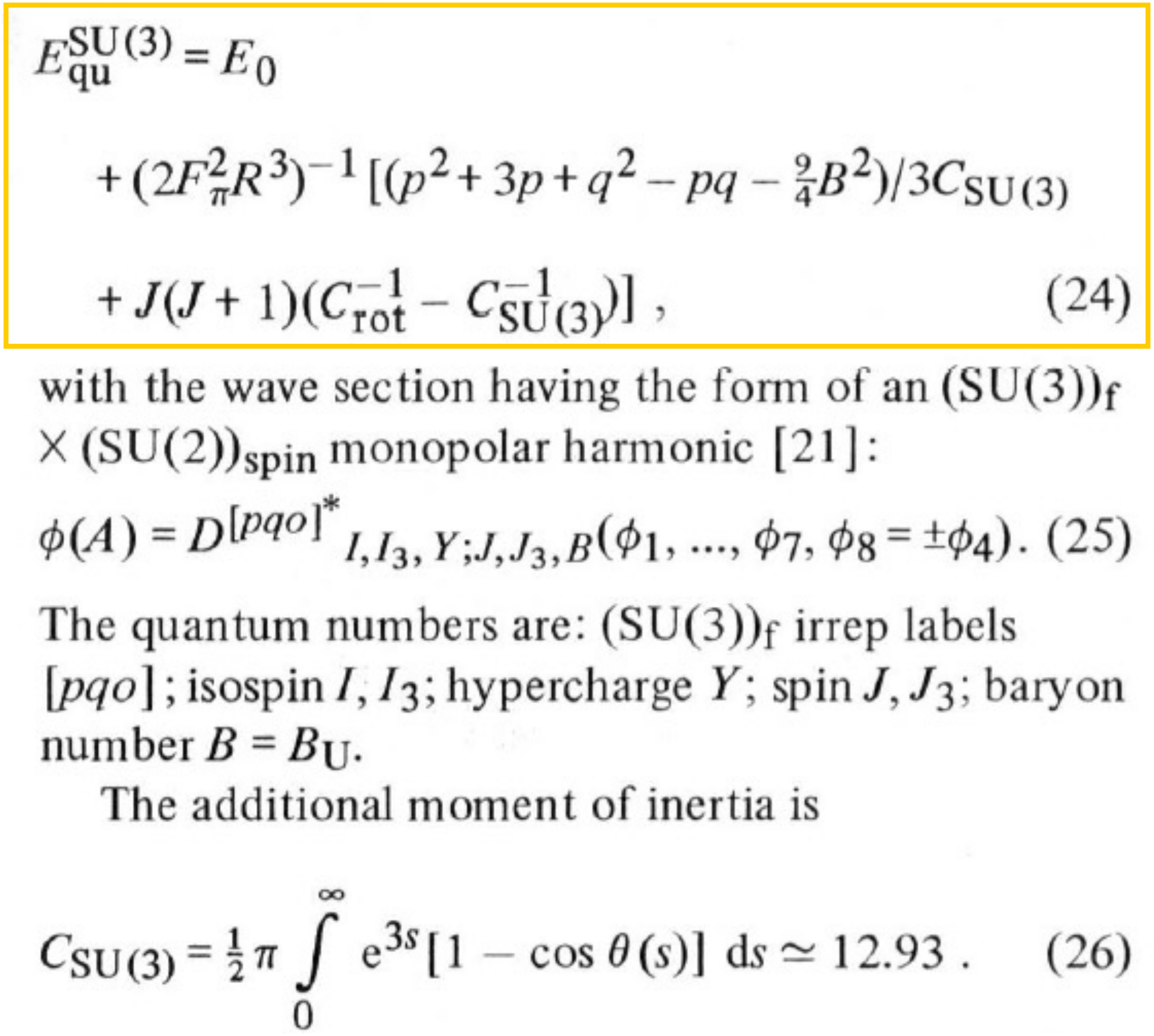


$$E^{\mathrm{SU}(3)}_{\mathrm{qu}} = E_0 + (2F_\pi^2 R^3)^{-1}\left[(p^2+3p+q^2-pq-\tfrac{9}{4}B^2)/3C_{\mathrm{SU}(3)} + J(J+1)(C_{\mathrm{rot}}^{-1} - C_{\mathrm{SU}(3)}^{-1})\right], \tag{24}$$

with the wave section having the form of an $(\mathrm{SU}(3))_{\mathrm{f}} \times (\mathrm{SU}(2))_{\mathrm{spin}}$ monopolar harmonic [21]:

$$\phi(A) = D^{[pqo]^*}{}_{I,I_3,Y;J,J_3,B}(\phi_1, \ldots, \phi_7, \phi_8 = \pm\phi_4). \tag{25}$$

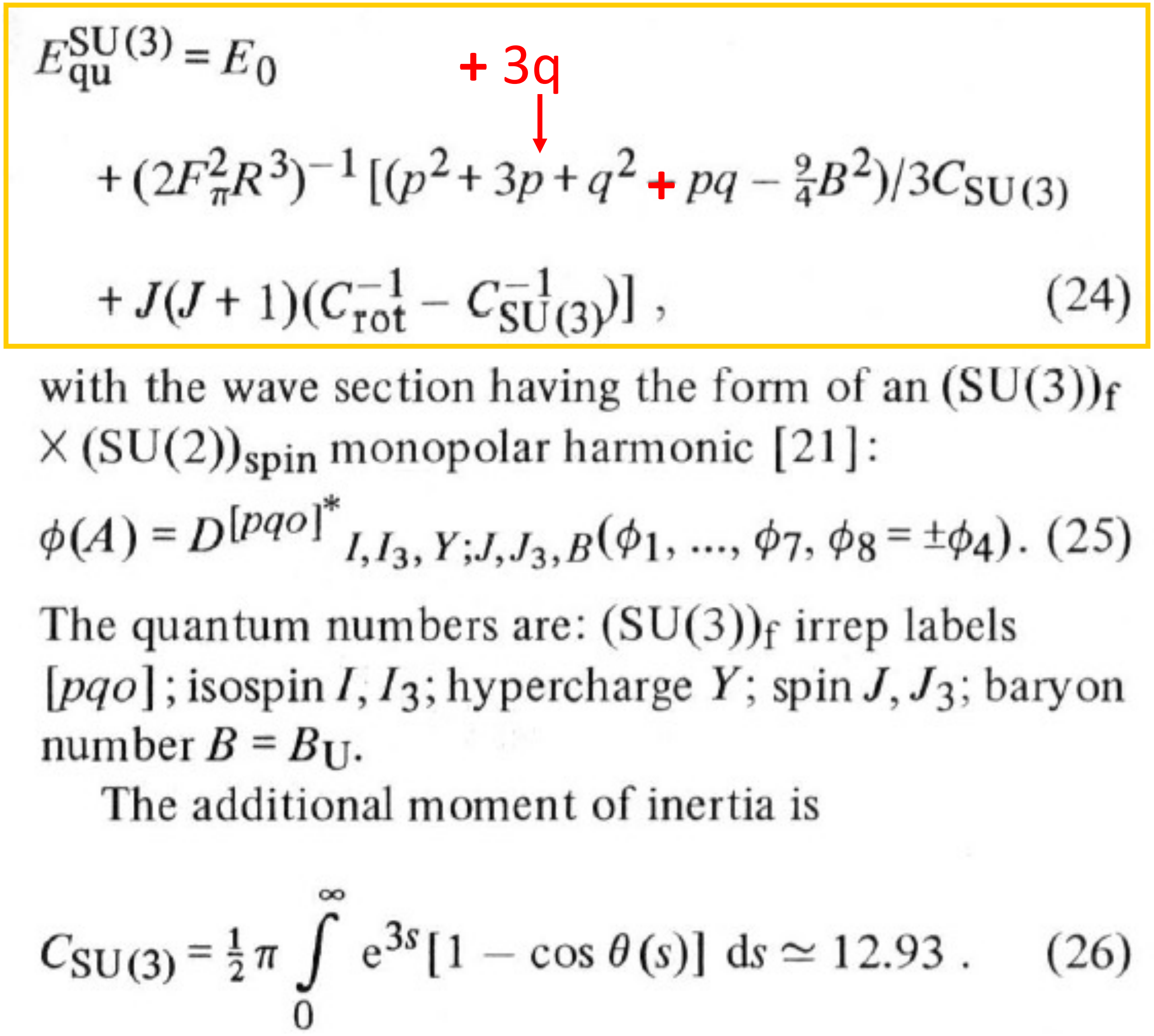
The quantum numbers are: $(\mathrm{SU}(3))_{\mathrm{f}}$ irrep labels $[pqo]$; isospin I, I_3; hypercharge Y; spin J, J_3; baryon number $B = B_{\mathrm{U}}$.

The additional moment of inertia is

$$C_{\mathrm{SU}(3)} = \tfrac{1}{2}\pi \int_0^\infty \mathrm{e}^{3s}[1 - \cos\theta(s)]\,\mathrm{d}s \simeq 12.93\,. \tag{26}$$

$$E_0 = M_{\mathrm{sol}}$$
$$C_{\mathrm{SU}(3)} = 2I_2$$
$$C_{\mathrm{rot}} = 2I_1$$

$$\Delta_{\overline{10}-8} = 330 \quad \mathrm{MeV}$$



$$E_{\mathrm{qu}}^{\mathrm{SU}(3)} = E_0 + (2F_\pi^2 R^3)^{-1}\left[(p^2 + 3p \overset{+\,3q}{\downarrow} + q^2 + pq - \tfrac{9}{4}B^2)/3C_{\mathrm{SU}(3)} + J(J+1)(C_{\mathrm{rot}}^{-1} - C_{\mathrm{SU}(3)}^{-1})\right], \tag{24}$$

with the wave section having the form of an $(\mathrm{SU}(3))_{\mathrm{f}} \times (\mathrm{SU}(2))_{\mathrm{spin}}$ monopolar harmonic [21]:

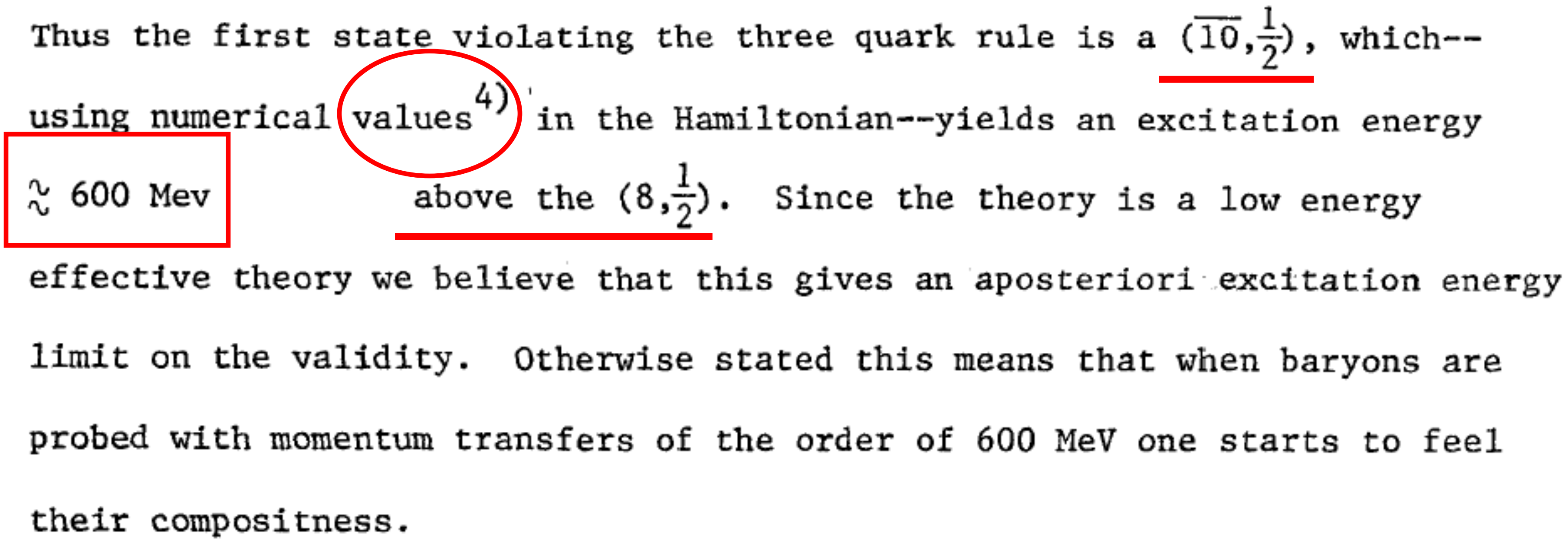
$$\phi(A) = D^{[pqo]^*}{}_{I,I_3,Y;J,J_3,B}(\phi_1, \ldots, \phi_7, \phi_8 = \pm\phi_4). \tag{25}$$

The quantum numbers are: $(\mathrm{SU}(3))_{\mathrm{f}}$ irrep labels $[pqo]$; isospin I, I_3; hypercharge Y; spin J, J_3; baryon number $B = B_{\mathrm{U}}$.

The additional moment of inertia is

$$C_{\mathrm{SU}(3)} = \tfrac{1}{2}\pi \int_0^\infty \mathrm{e}^{3s}[1 - \cos\theta(s)]\,\mathrm{d}s \simeq 12.93\,. \tag{26}$$

$$\Delta_{\overline{10}-8} = 590 \quad \mathrm{MeV}$$



Thus the first state violating the three quark rule is a $(\overline{10},\frac{1}{2})$, which--using numerical values4) in the Hamiltonian--yields an excitation energy $\approx$ 600 Mev above the $(8,\frac{1}{2})$. Since the theory is a low energy effective theory we believe that this gives an aposteriori excitation energy limit on the validity. Otherwise stated this means that when baryons are probed with momentum transfers of the order of 600 MeV one starts to feel their compositness.

1987

M. Praszalowicz, “SU(3) Skyrmion,” Jagiellonian Univ. preprint TPJU-5-87. In *Skyrmions and Anomalies*, eds. M. Jeżabek and M. Praszałowicz, World Scientific, 1987, p. 112.

$M_{theta} = 1535$ MeV

Chiral quark soliton model χQSM

$$\mathcal{E}^{\mathrm{rot}}_{(p,q)} = M_{\mathrm{sol}} + \frac{J(J+1)}{2I_1} + \frac{C_2(p,q) - J(J+1) - 3/4\,Y'^2}{2I_2}$$

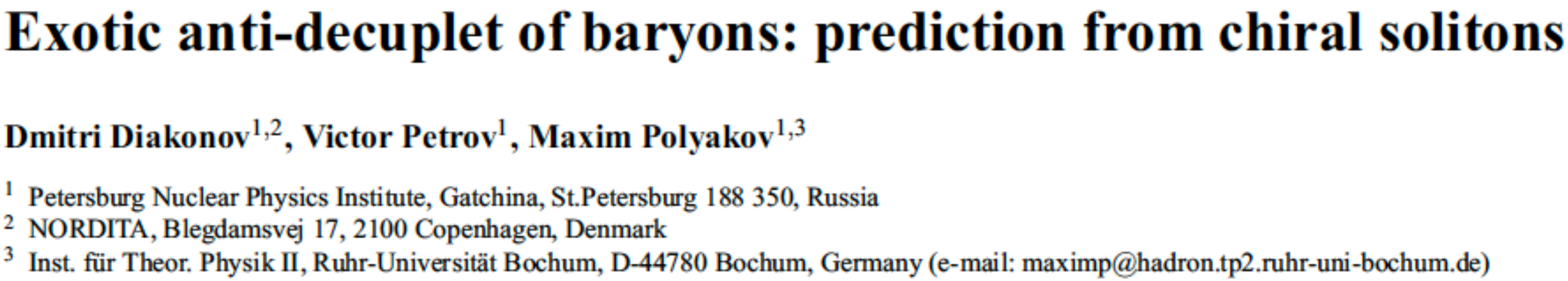
$$H_{\mathrm{br}} = \alpha\, D^{(8)}_{88} + \beta\, \hat{Y} + \frac{\gamma}{\sqrt{3}} \sum_{i=1}^{3} D^{(8)}_{8i}\, \hat{J}_i$$

1997

M = 1530

ZEITSCHRIFT FÜR PHYSIK A

© Springer-Verlag 1997



Exotic anti-decuplet of baryons: prediction from chiral solitons

Dmitri Diakonov[1,2], Victor Petrov[1], Maxim Polyakov[1,3]

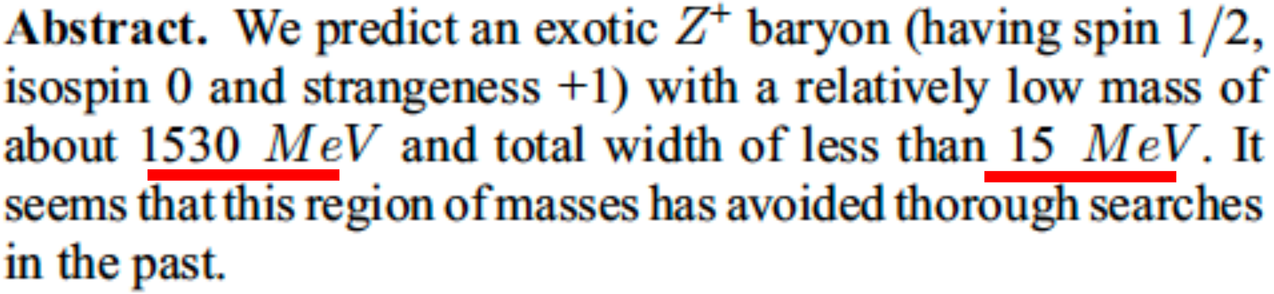
[1] Petersburg Nuclear Physics Institute, Gatchina, St.Petersburg 188 350, Russia

[2] NORDITA, Blegdamsvej 17, 2100 Copenhagen, Denmark

[3] Inst. für Theor. Physik II, Ruhr-Universität Bochum, D-44780 Bochum, Germany (e-mail: maximp@hadron.tp2.ruhr-uni-bochum.de)

986 citations

Decay width



Abstract. We predict an exotic Z^+ baryon (having spin 1/2, isospin 0 and strangeness +1) with a relatively low mass of about 1530 MeV and total width of less than 15 MeV. It seems that this region of masses has avoided thorough searches in the past.

Mitya Diakonov +2012

Vitya Petrov +2021

Maxim Polyakov +2021

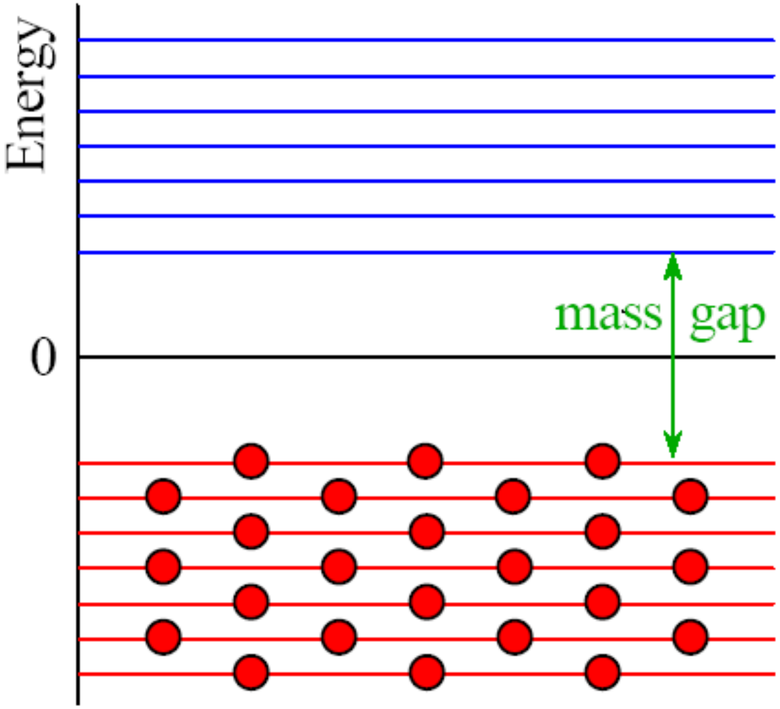
Zeischrift für Physik +1997

Quark-soliton model

$$\left[i\partial\!\!\!/ - M \exp\left(i\boldsymbol{n} \cdot \boldsymbol{\lambda} \gamma_5 P(r) \right) \right] q = 0$$

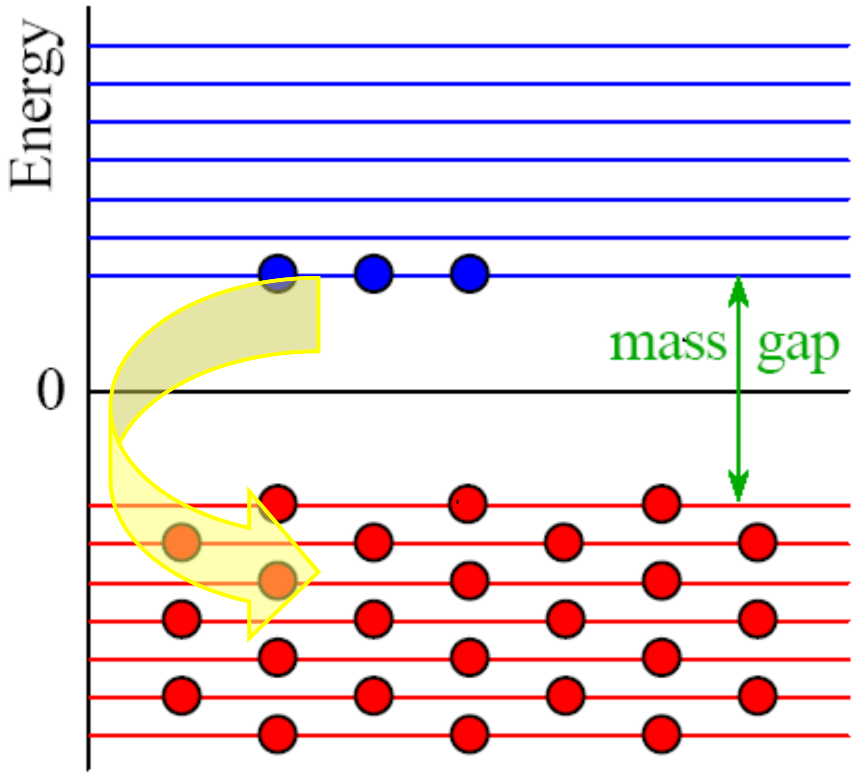
Minimize energy with respect to $P(r)$.

Vacuum.



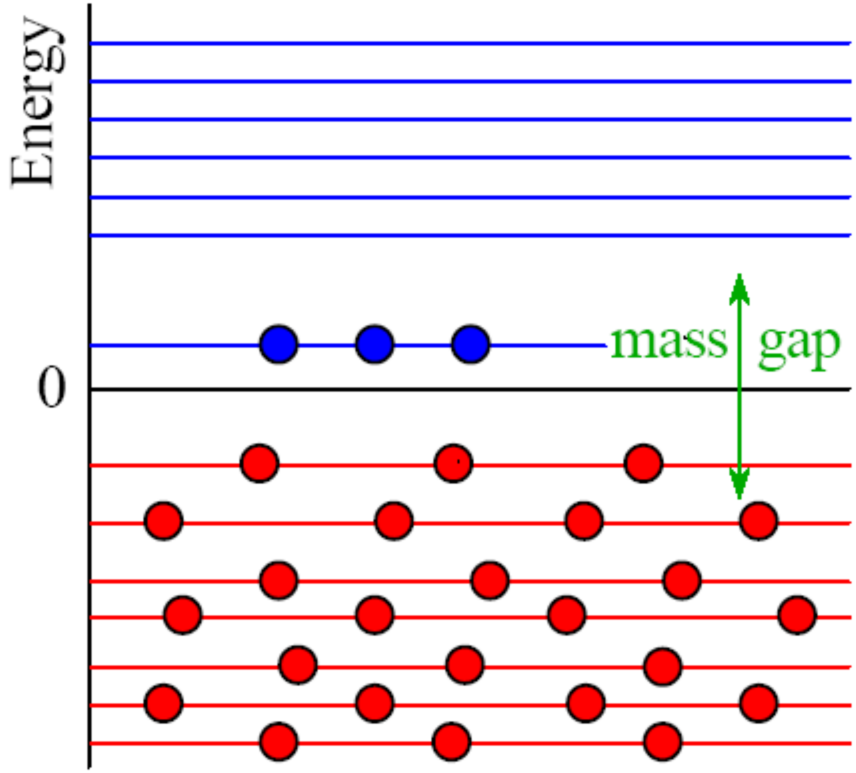
Spectrum of the Dirac operator

Baryon:



Spectrum of the Dirac operator

Baryon:



Spectrum of the Dirac operator

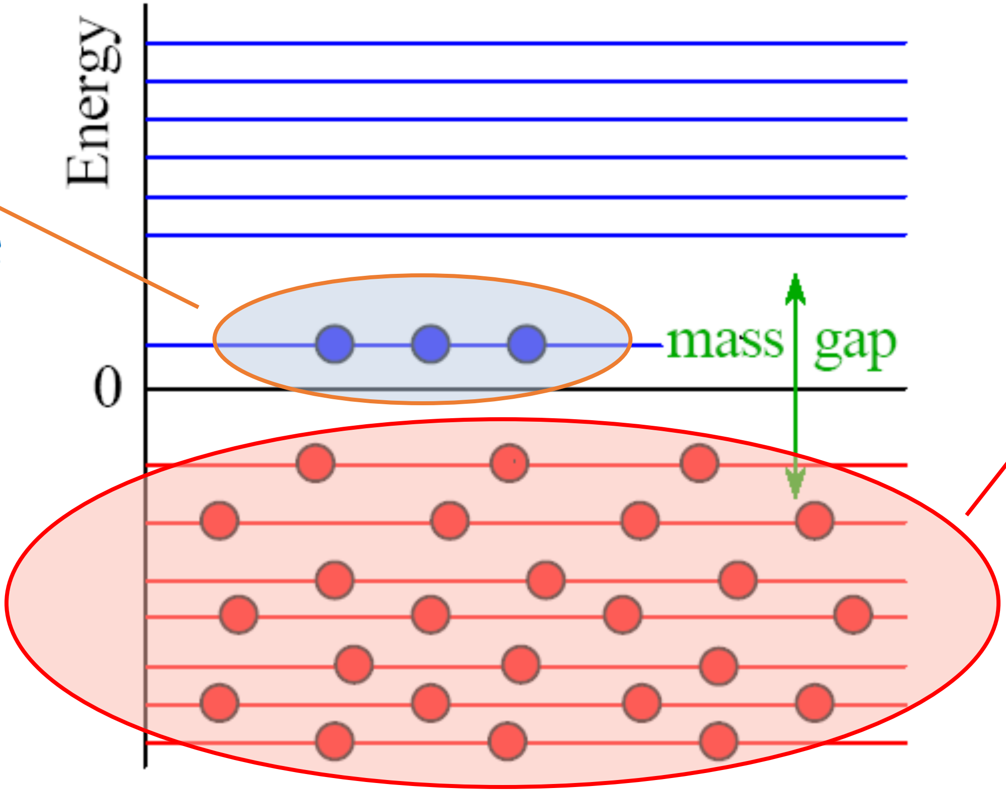
valence level:

energy decreases

sea levels:

energy increases

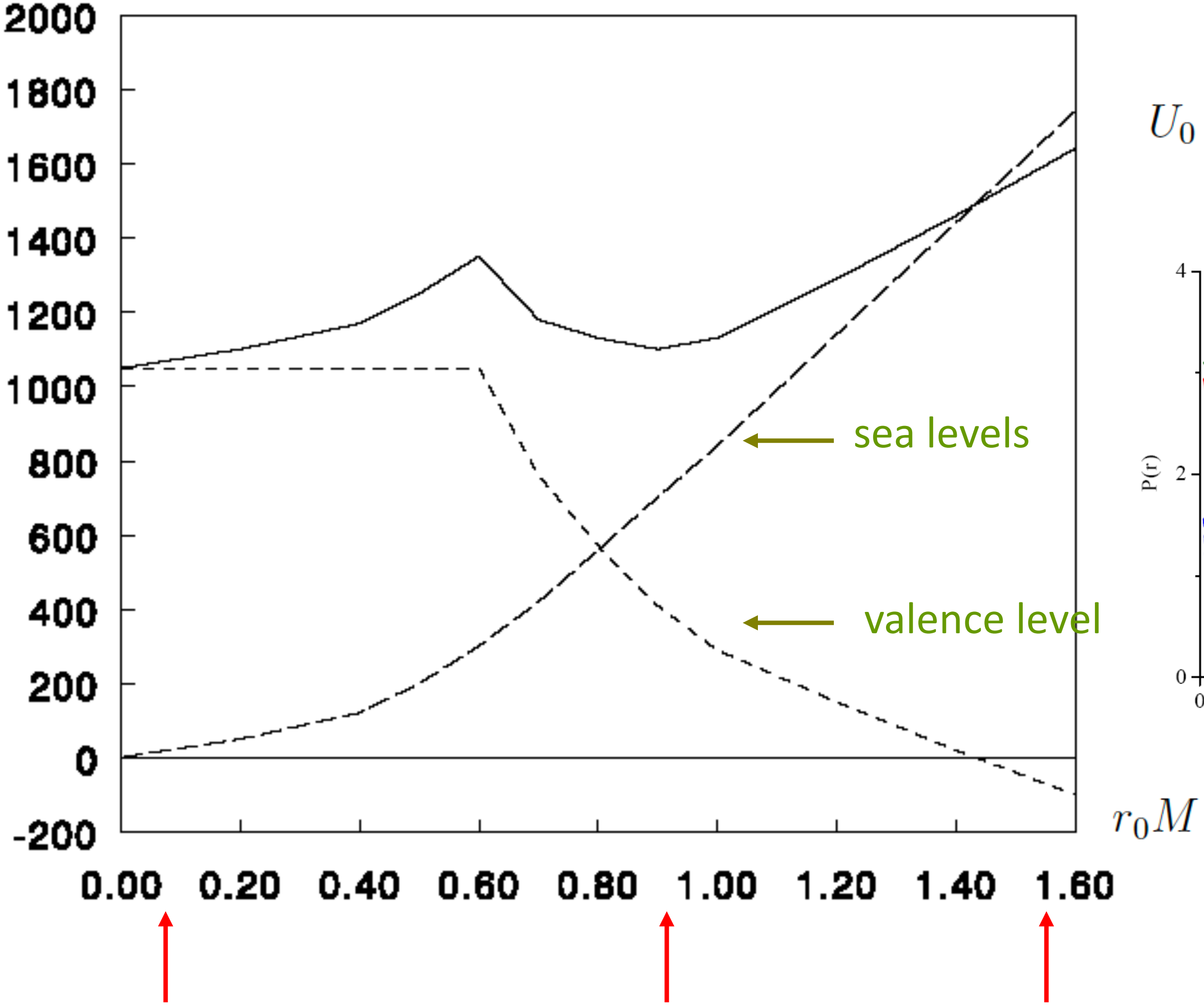
Baryon:



system stabilzes

variational approach: $P(r)=P(r/r_0)$
r_0 - soliton size

from: D.I. Diakonov,
hep-ph/0009006



sea levels

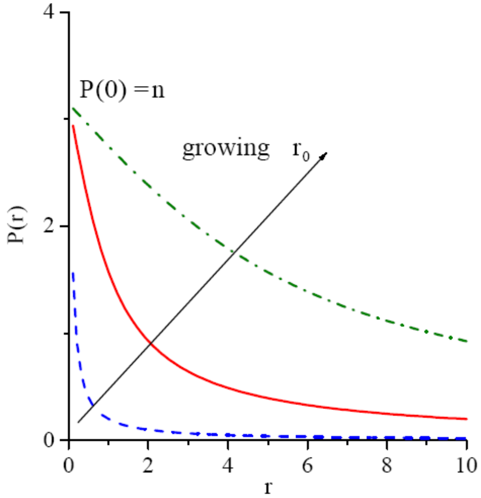
valence level

QM limit

true minimum

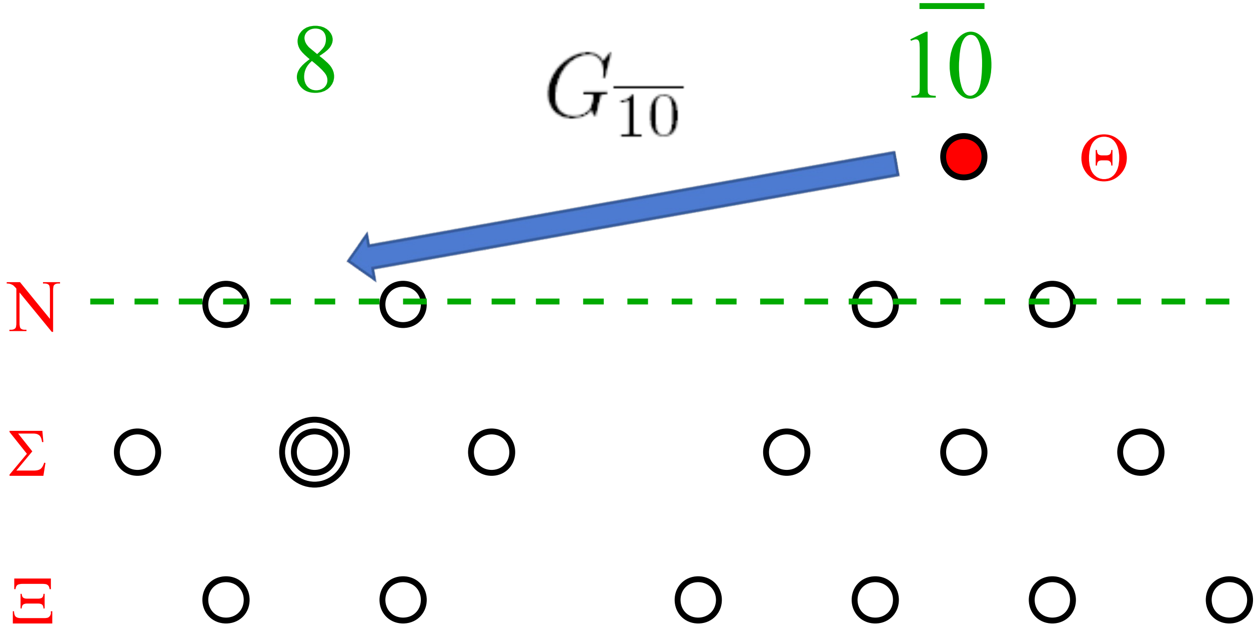
Skyrme limit

$$U_0 = \begin{bmatrix} e^{i\vec{n}\cdot\vec{\tau}\,P(r)} & 0 \\ 0 & 1 \end{bmatrix}$$



Decay of Theta$^+$

$\Theta^+ \rightarrow$ K N



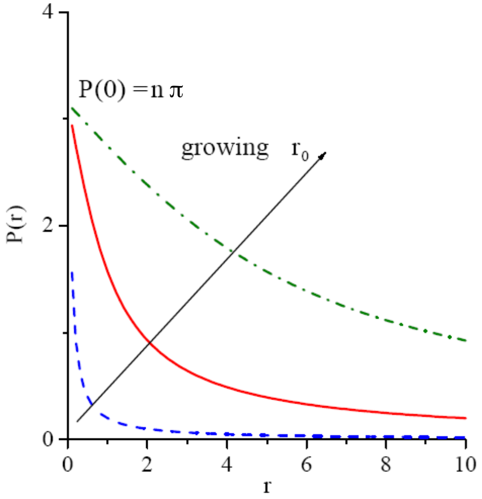
$$g_{\Theta NK} = G_{\overline{10}}$$

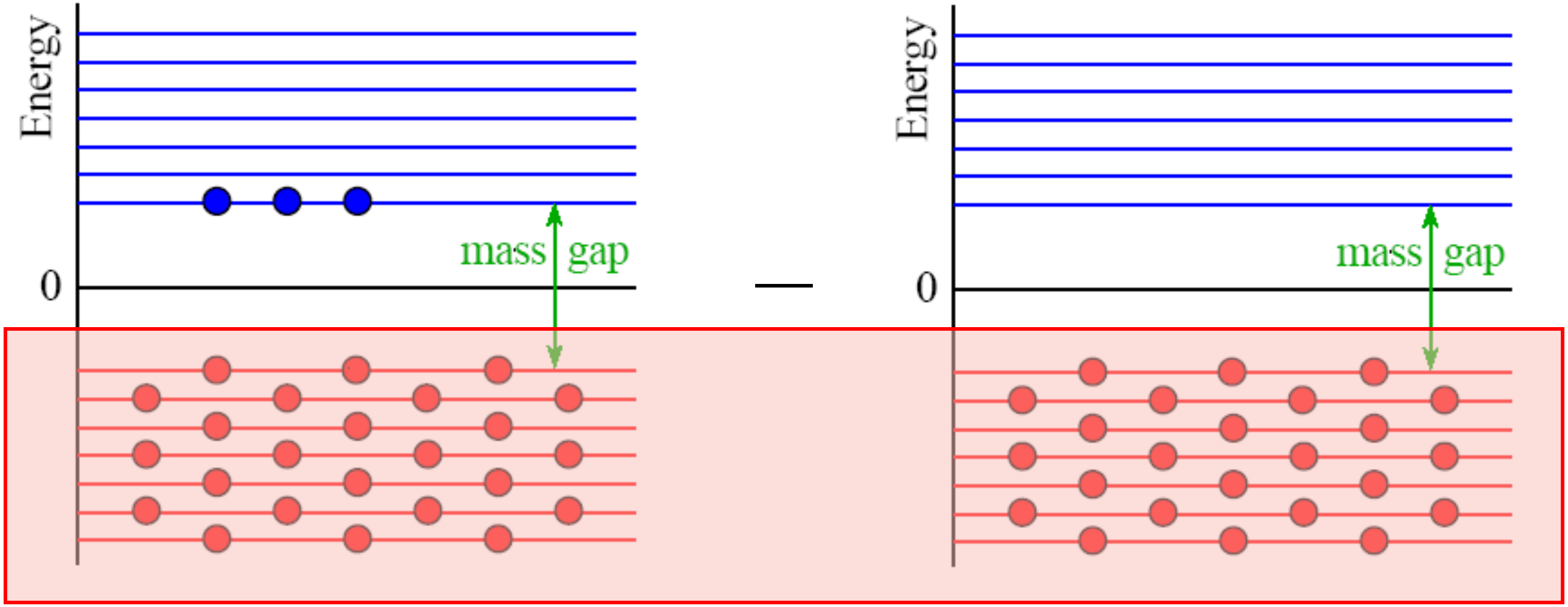
NRQM Limit

Diakonov, Petrov, Polyakov, Z.Phys **A359** (97) 305

MP, A.Blotz K.Goeke, Phys.Lett.**B354**:415-422,1995

energy is calculated
with respect to the vacuum:





in the NRQM limit only valence level contributes

NRQM Limit

$$g_A^{(3)} = \frac{5}{3}, \quad \Delta\Sigma = 1, \quad \frac{\mu_p}{\mu_n} = -\frac{3}{2}$$

Diakonov, Petrov, Polyakov, Z.Phys **A359** (97) 305

MP, A.Blotz K.Goeke, Phys.Lett.**B354**:415-422,1995

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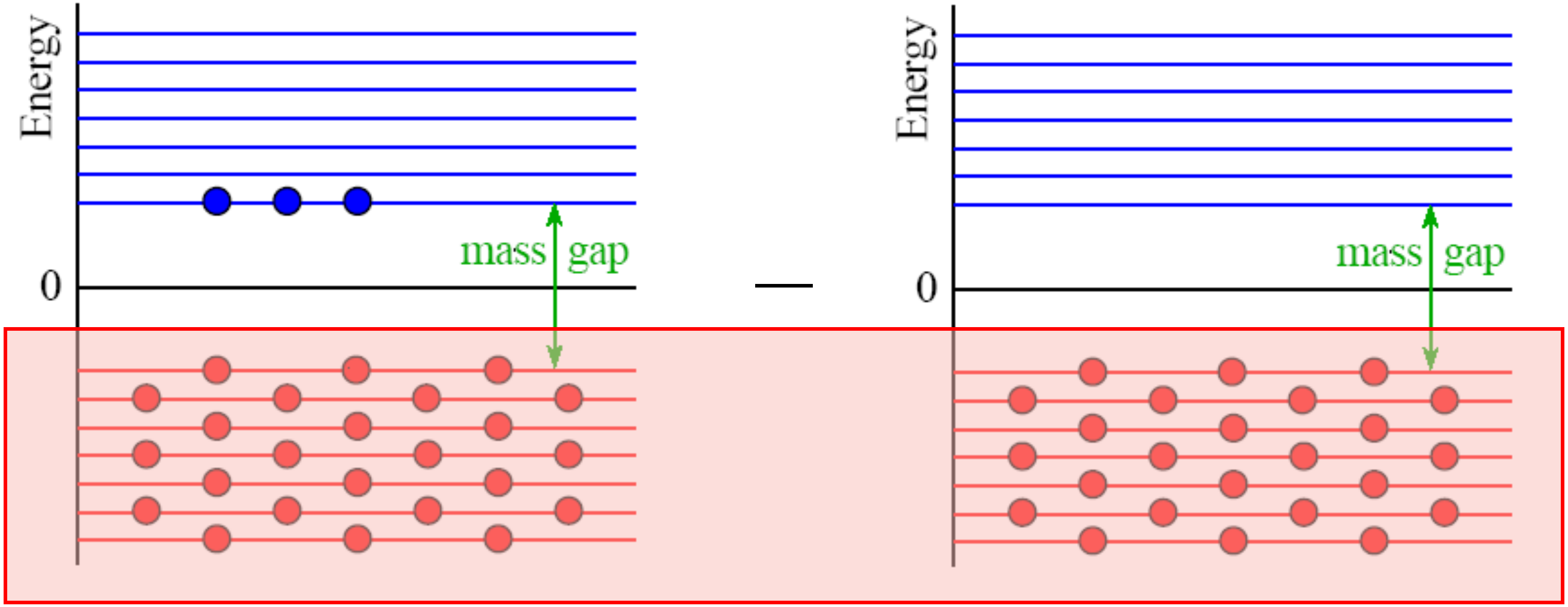

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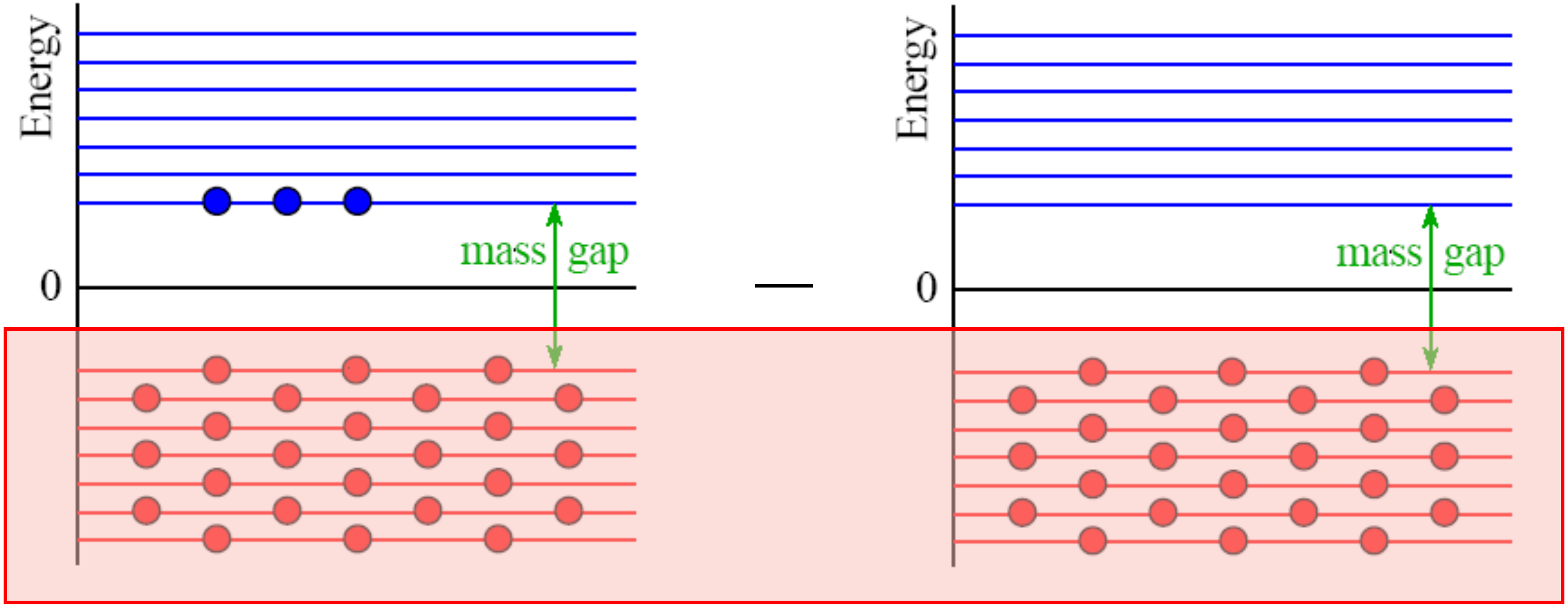
Diakonov, Petrov, Polyakov, Z.Phys **A359** (97) 305

MP, A.Blotz K.Goeke, Phys.Lett.**B354**:415-422,1995

energy is calculated
with respect to the vacuum:

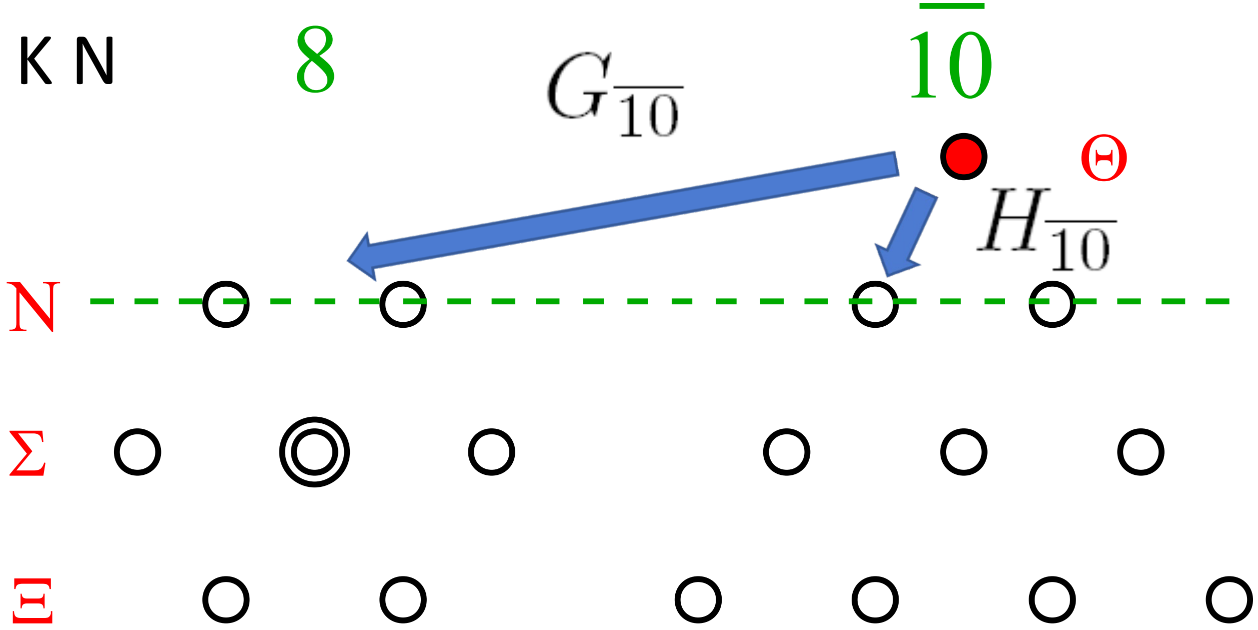
$$\boxed{G_{\overline{10}} = 0}$$



in the NRQM limit only valence level contributes

Decay of Theta$^+$

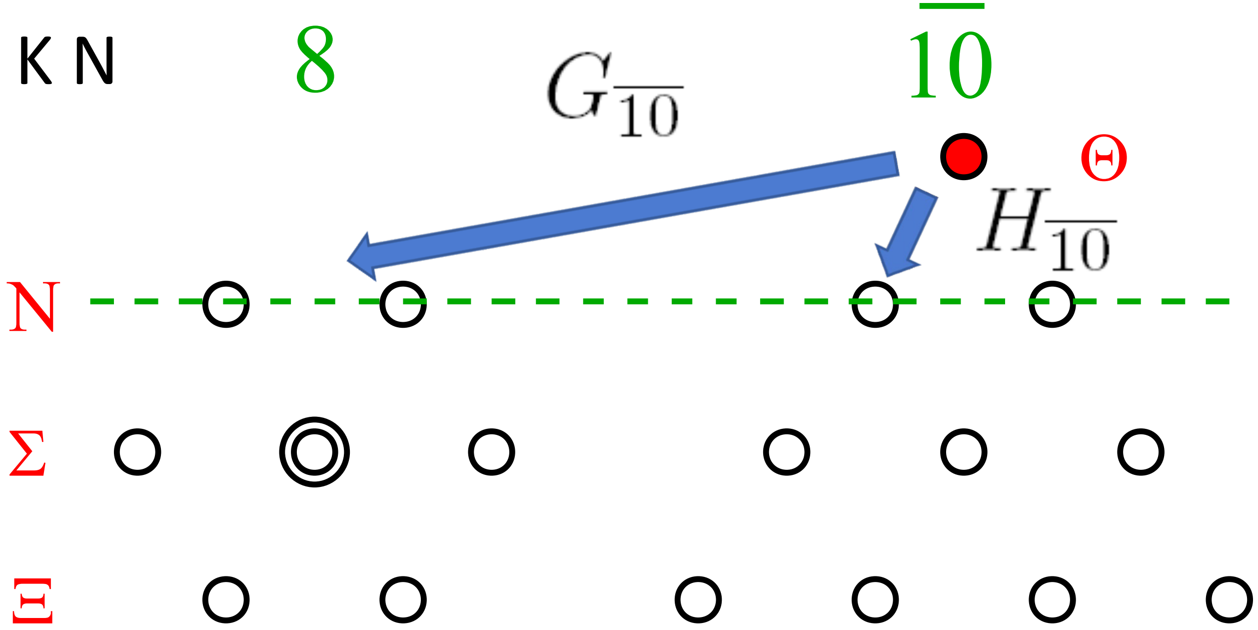
$\Theta^+ \to K\,N$



$$g_{\Theta NK} = G_{\overline{10}} + \sin\alpha\, H_{\overline{10}}$$

Decay of Theta$^+$

$\Theta^+ \to$ K N



$$g_{\Theta NK} = G_{\overline{10}} + \sin\alpha\, H_{\overline{10}}$$

K. Goeke, M.V. Polyakov
M.Praszalowicz
Acta Phys.Polon.B 42 (2011) 61

Antidecuplet: small small large negative!

Is small width “unnatural”?

$$\Theta^+ \to KN \qquad p_K = 262 \text{ MeV} \quad \Gamma < 0.64 \text{ (BELLE)}$$

Is small width “unnatural”?

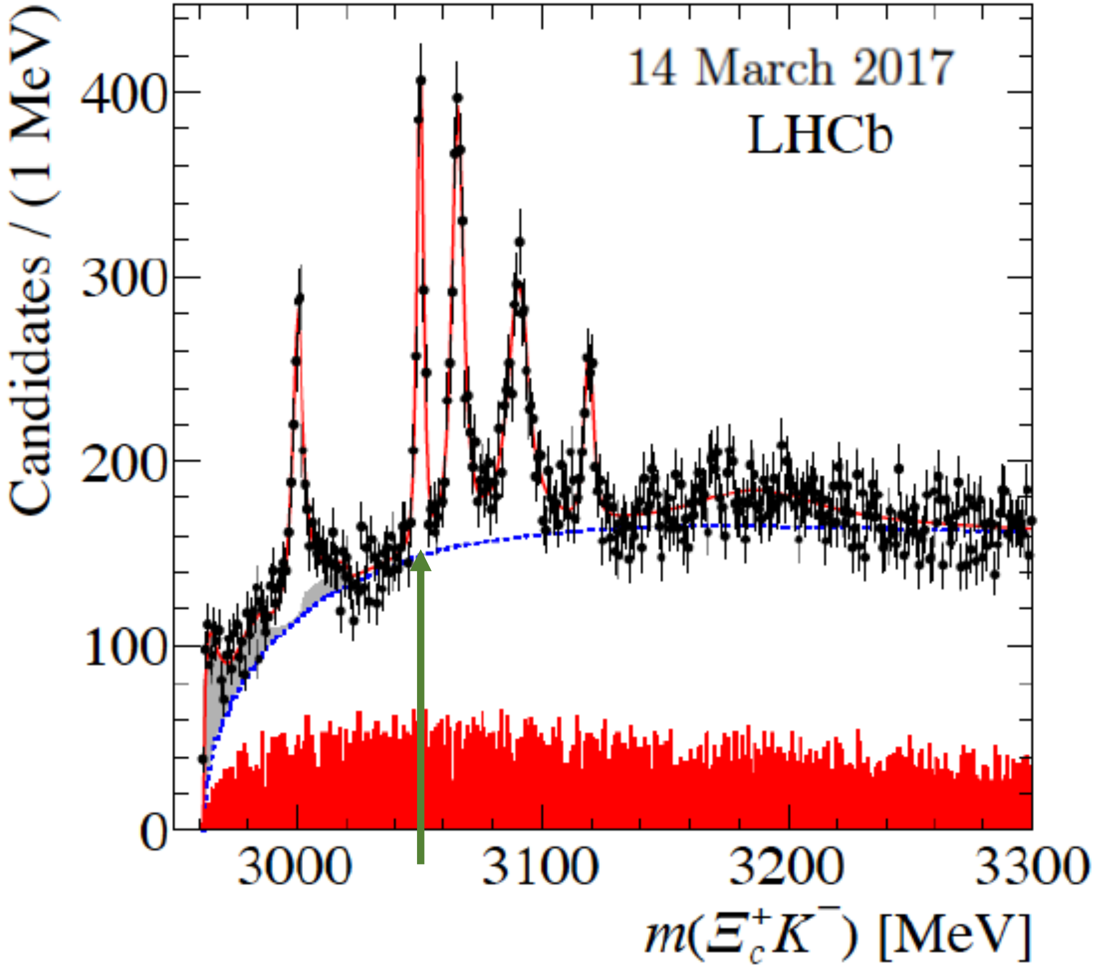
$\Theta^+ \to KN \qquad p_K = 262\ \mathrm{MeV} \quad \Gamma < 0.64\ (\mathrm{BELLE})$

In 2017 LHCb discovers five excited Ω_c^* states

$$\Omega_c^*(3050) \to \Xi_c K$$

$$\Gamma < 0.8 \pm 0.2 \pm 0.1$$

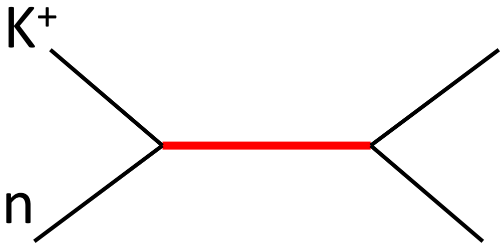
$$p_K = 275\ \mathrm{MeV}$$



Experiment

Experimental evidence: DIANA

Ideal formation experiment: K^+n (in practice K^+ beam on nuclear target)



Breit-Wigner cross-section

$$\sigma_{BW}(E)=\frac{2\overset{\substack{1/2\\ \downarrow}}{J}+1}{(2\underset{\substack{\uparrow\\ 0}}{S_1}+1)(2\underset{\substack{\uparrow\\ 1/2}}{S_2}+1)}\frac{\pi}{k^2}\underset{\substack{\uparrow\\ 1/2}}{B_{in}}\underset{\substack{\uparrow\\ 1/2}}{\boxed{B_{out}}}\frac{\Gamma^2}{(E-M)^2+\Gamma^2/4}$$

$$\sigma_{BW}(M)=\frac{\pi}{k^2}\sim 16.8\ [\mathrm{mb}]$$

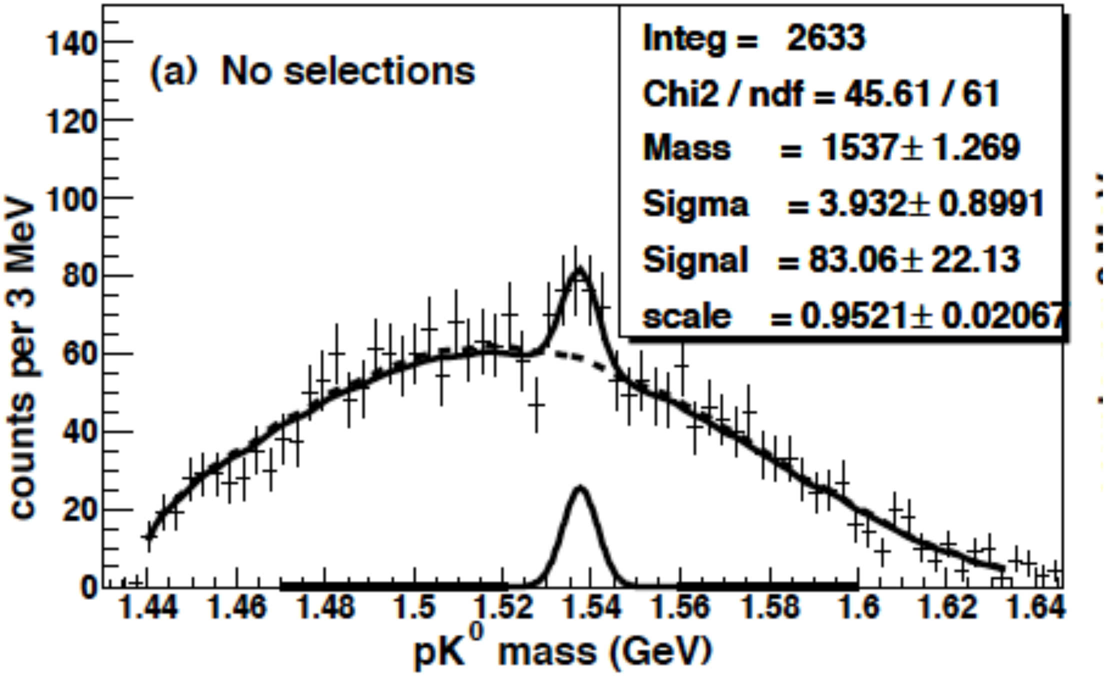
$$\boxed{\sigma_{BW}^{tot}=\frac{\pi}{4k^2}2\pi\Gamma\sim 26.4\times\frac{\Gamma}{1\ \mathrm{MeV}}\ [\mathrm{mb}\times\mathrm{MeV}]}$$

Experimental evidence: DIANA

DIANA@ITEP Xe bubble chamber K^+ 850 MeV beam

- Phys.Rev. C89 (2014) 4, 045204: M= 1538 ± 2 MeV, Γ = 0.34 ± 01 MeV
- 2003 Yad. Phys. 66 (2003) 1763
- 2007 Yad. Phys. 70
- 2010 Yad. Phys. 73

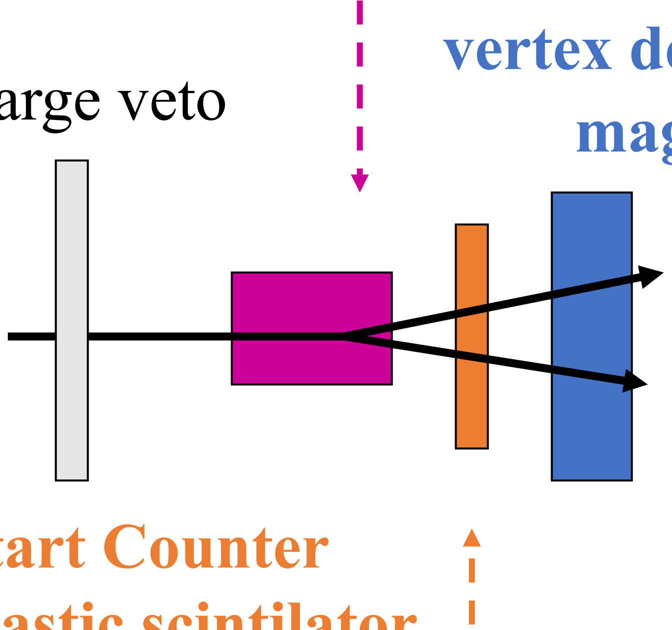
not seen with the secondary K^+ beam at BELLE experiment $\Gamma <$ 0.6 MeV



LEPS @ Spring-8: $\gamma n \rightarrow \Theta^+ K^-$

T. Nakano et al., [hep-ex/0301020] Phys.Rev.Lett. **91** (2003) 012002

Detector was constructed for another experiment: $\phi \longrightarrow K^- K^+$



Liquid Hydrogen

5 cm thick

Silicon strip vertex detector

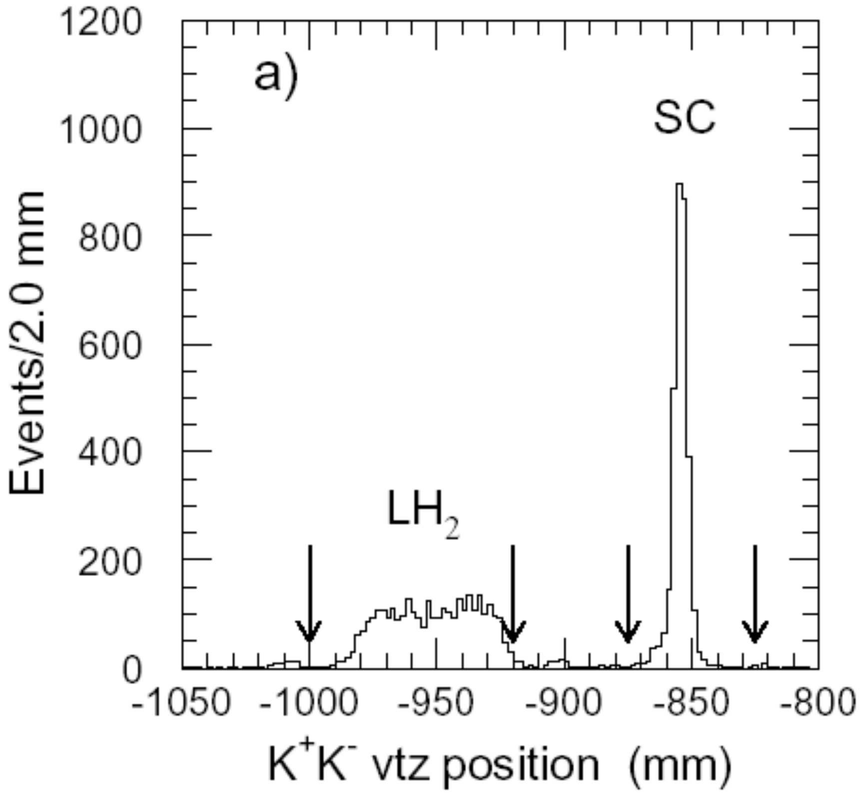
magnetic field 0.7 T

Charge veto

Start Counter plastic scintilator

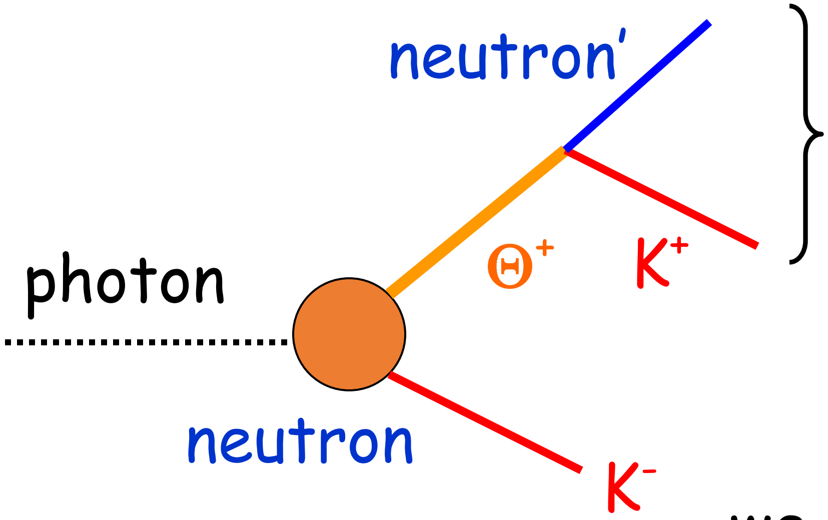
0.5 cm thick 9.5 cm from LH_2

contains carbon




注 意
ノレノイド電磁
励磁中
PHS 36
3426

LEPS @ Spring-8: $\gamma n \rightarrow \Theta^{+} K^{-}$



mass distribution,
but neutron'
escapes detection

$$MM_{\gamma K^-} = \gamma + n - K^- = n' + K^+$$

we do not know momentum
of neutron because it
is inside Carbon,
correction for Fermi
motion is needed

Experimental evidence: LEPS

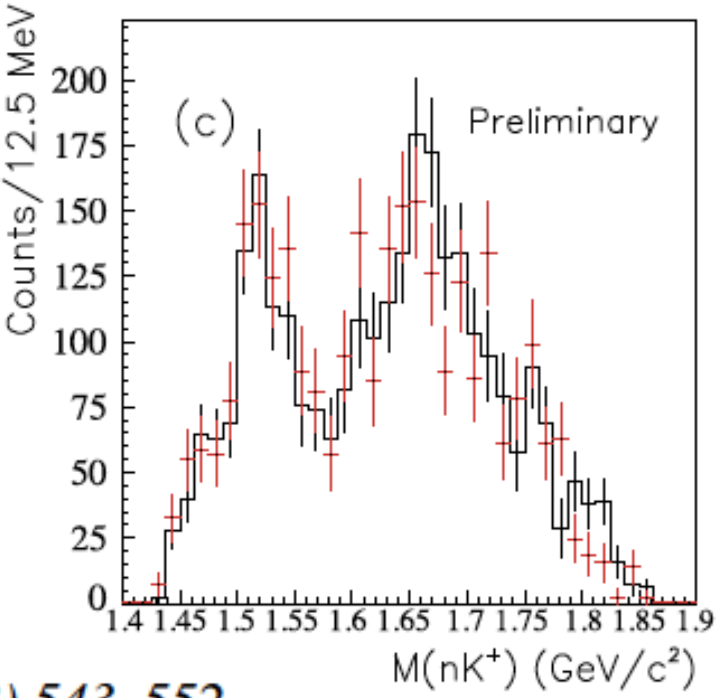
$$\gamma n \rightarrow K^- \Theta^+ \rightarrow K^- K^+ n$$

- Photoproduction on C target (neutron): PANIC Oct. 2002
- CLAS: gamma-d similar peak intepreted as fluctuation (unpubl.)
- 2009 LEPS confirms earlier result on C in gamma-d (5 sigma)

  PRC 79 (2009) 025210 $M = 1524$
- 2013 LEPS2 gamma-d
  no firm statement, analysis
  in progress

main problems:

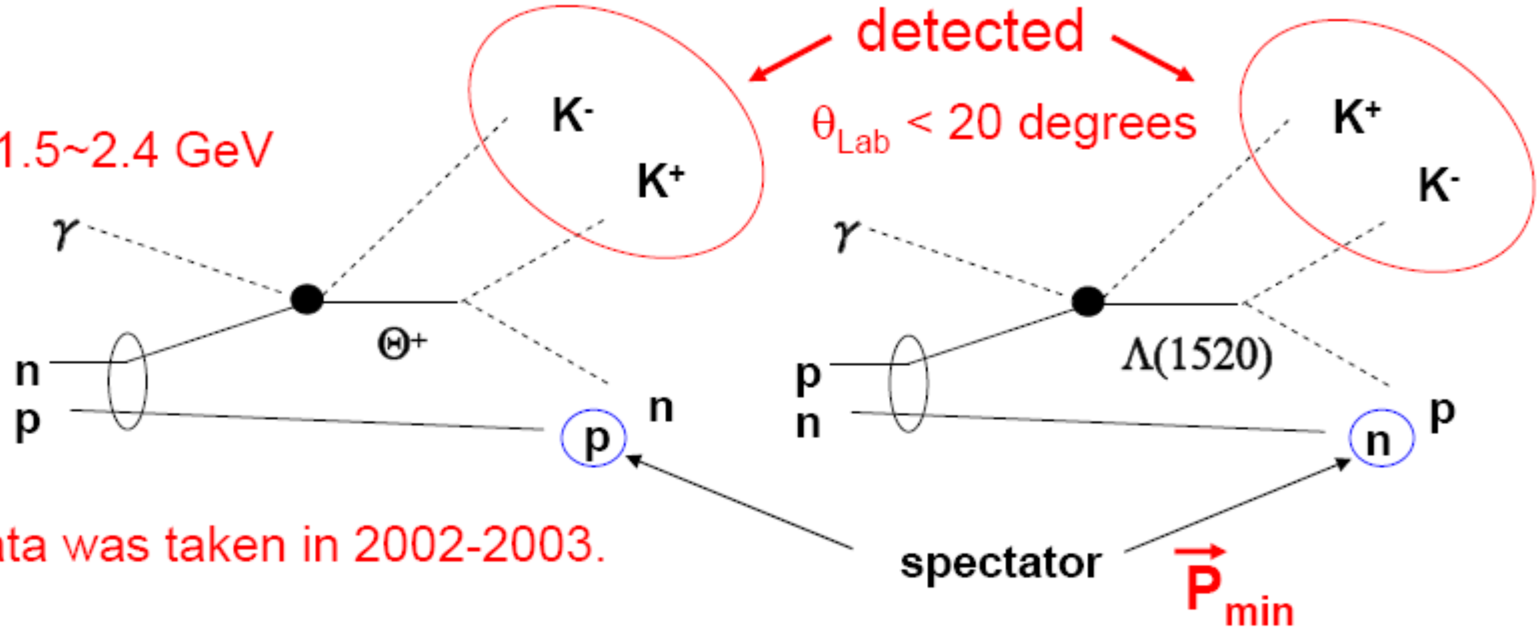
- neutron not seen
- Fermi motion
- background estimation



M. Niiyama / Nuclear Physics A 914 (2013) 543–552

T. Nakano (Osaka)

Θ^+ search at LEPS/SPring-8



detected

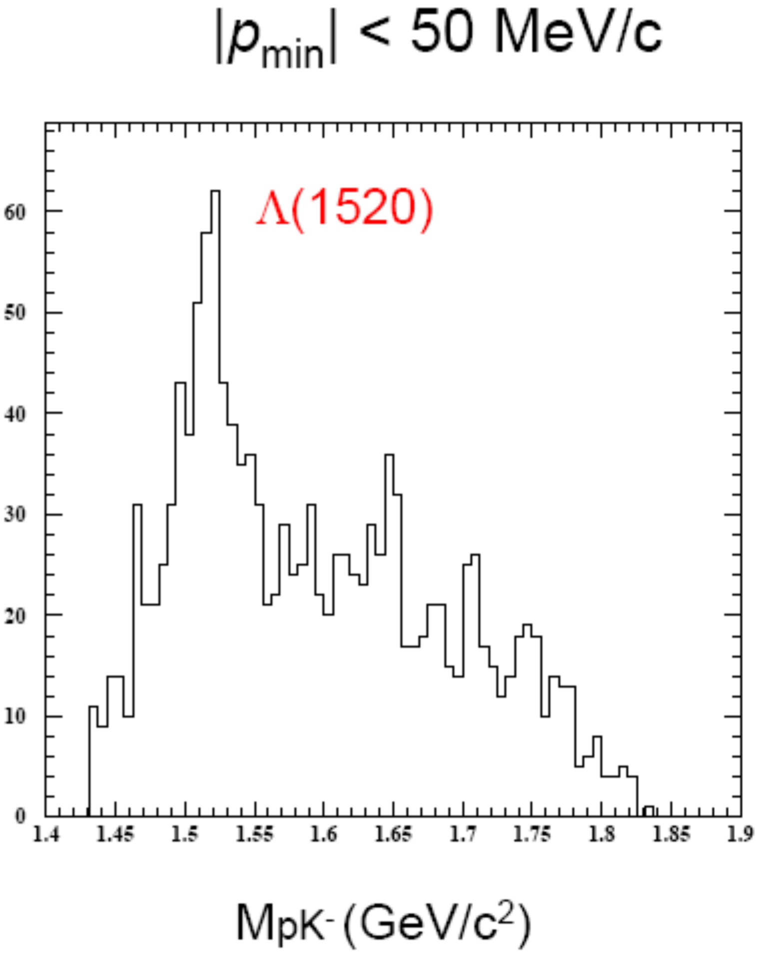
θ_{Lab} < 20 degrees

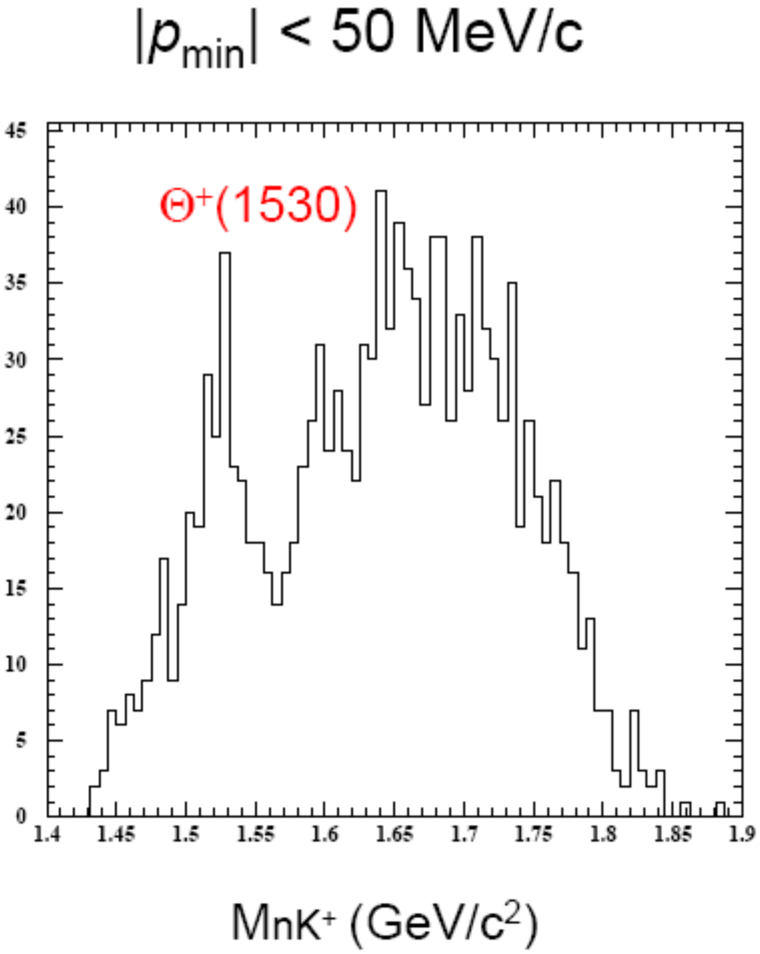
Eγ=1.5~2.4 GeV

spectator

Data was taken in 2002-2003.

Evidence of the Theta+ in the gamma d ---> K+ K- pn reaction.
By LEPS Collaboration (T. Nakano *et al.*).
Published in **Phys.Rev.C79:025210,2009**.
e-Print: **arXiv:0812.1035**

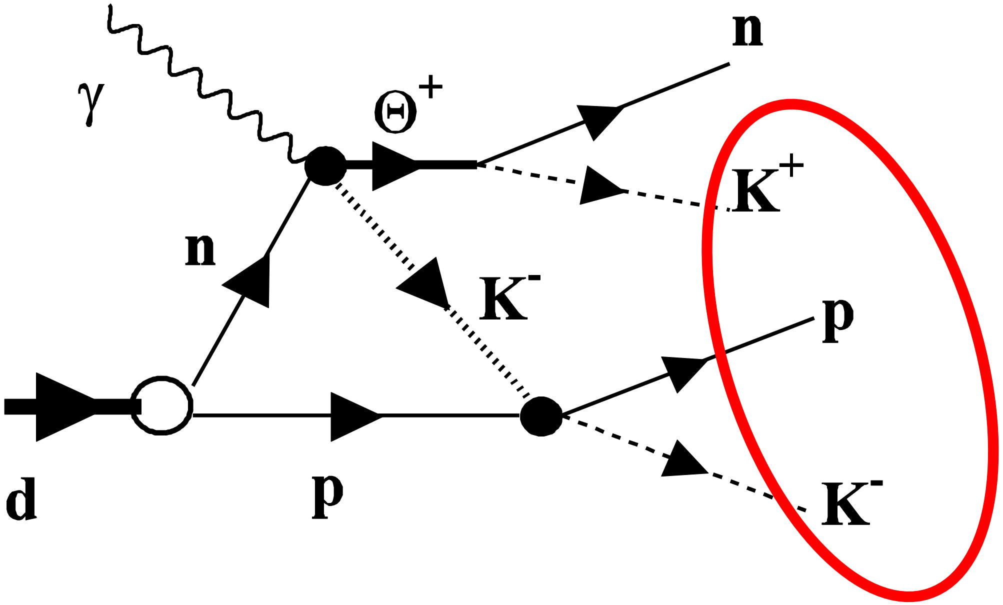

$|p_{min}| < 50$ MeV/c


$|p_{min}| < 50$ MeV/c

- Significance is estimated by dividing the Gaussian peak height by its uncertainty. Estimated significance is ~5.

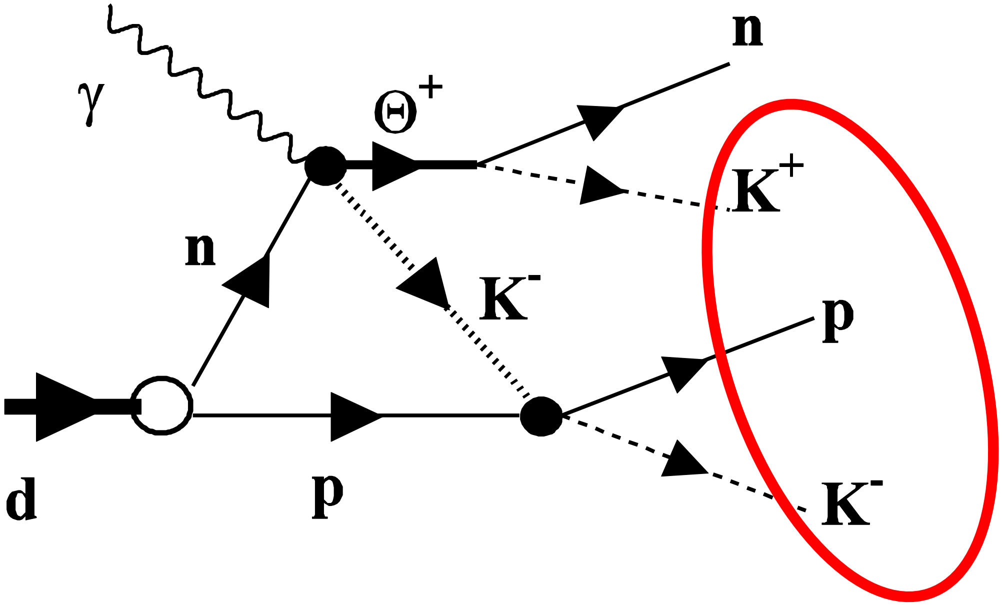
LEPS2 taking data 2022/23 !!!!

Gamma deuteron at CLAS



S. Stepanyan *et al.* [CLAS], “Observation of an exotic S = +1 baryon in exclusive photoproduction from the deuteron,” Phys. Rev. Lett. **91**, 252001 (2003).

Gamma deuteron at CLAS

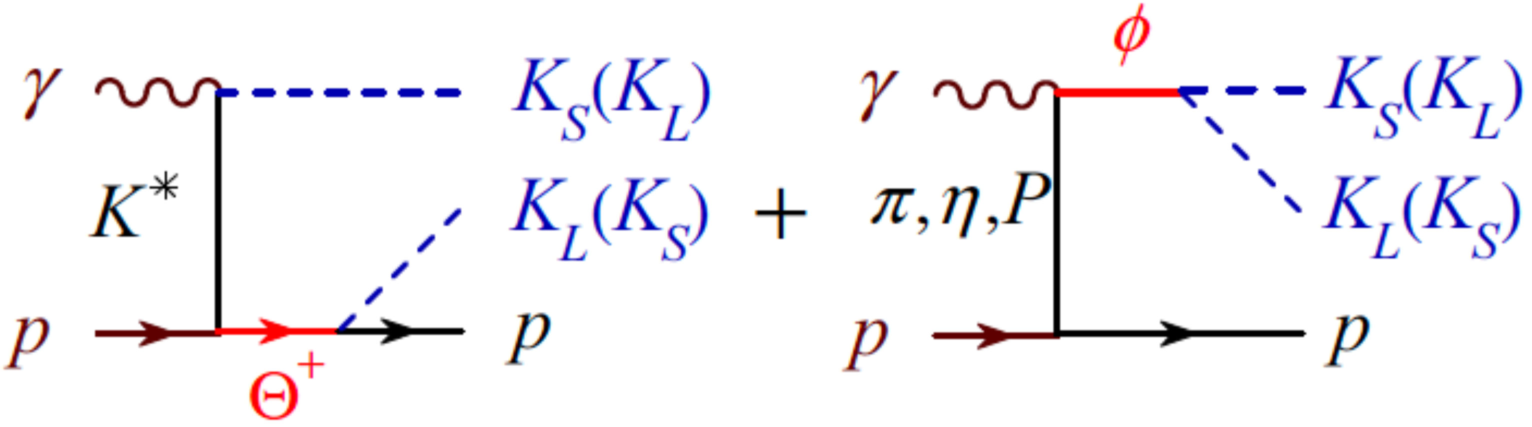


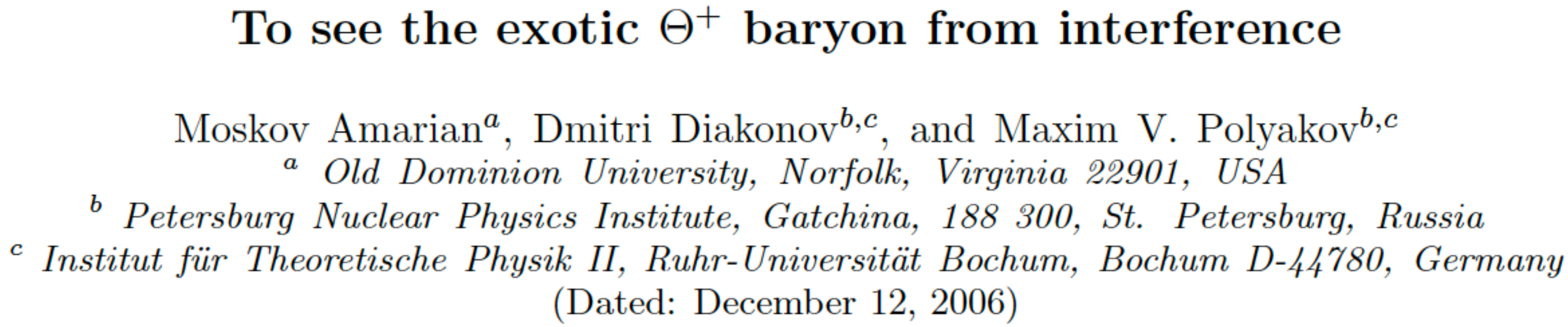
~~S. Stepanyan *et al.* [CLAS], "Observation of an exotic S = +1 baryon in exclusive photoproduction from the deuteron," Phys. Rev. Lett. **91**, 252001 (2003).~~

B. McKinnon *et al.* [CLAS], "Search for the Θ^+ pentaquark in the reaction gamma d —> p K- K+ n," Phys. Rev. Lett. **96**, 212001 (2006).

CLAS@JLab interference experiment

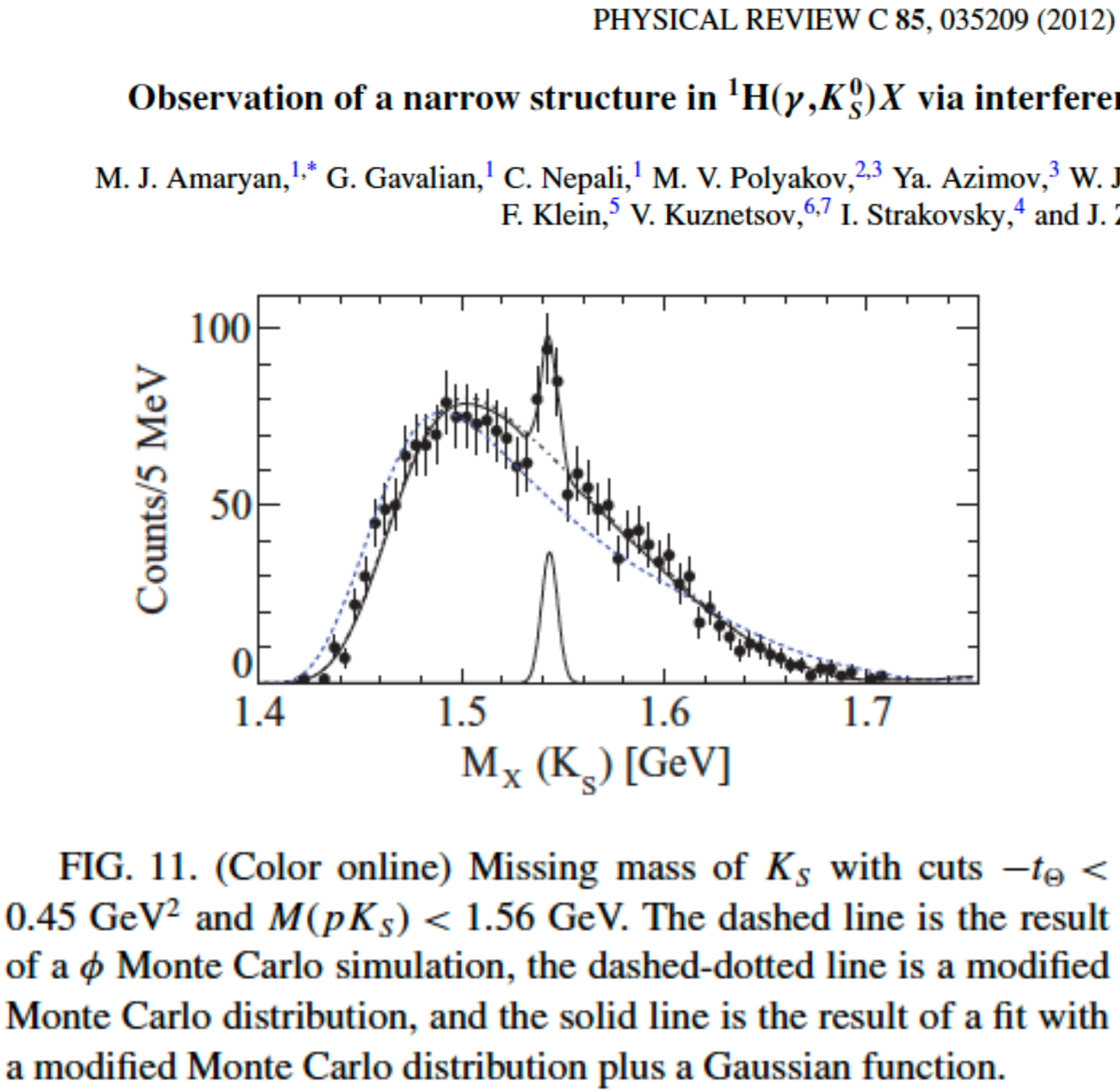
Photoproduction cross-section for Theta+ production is small due to the smnallnes of $g_{\Theta N K}$ coupling and unknown (small) coupling of gamma to K*K.
Negative result from CLAS. However, Phi meson is copiously produced.




To see the exotic Θ^+ baryon from interference

Moskov Amarian[a], Dmitri Diakonov[b,c], and Maxim V. Polyakov[b,c]
[a] *Old Dominion University, Norfolk, Virginia 22901, USA*
[b] *Petersburg Nuclear Physics Institute, Gatchina, 188 300, St. Petersburg, Russia*
[c] *Institut für Theoretische Physik II, Ruhr-Universität Bochum, Bochum D-44780, Germany*
(Dated: December 12, 2006)

CLAS@JLab interference experiment



PHYSICAL REVIEW C **85**, 035209 (2012)

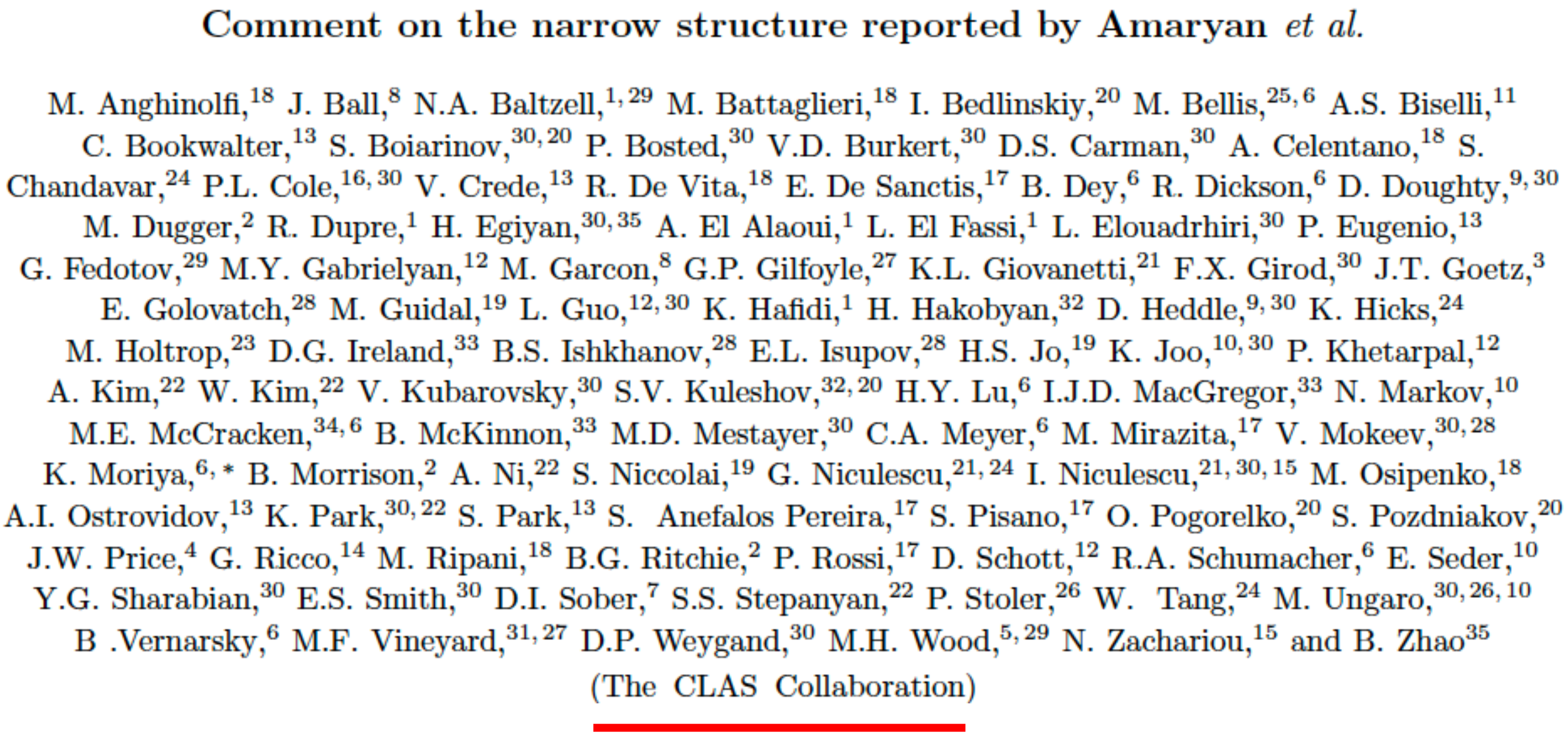
Observation of a narrow structure in ^{1}H(γ,K^0_S)X via interference with ϕ-meson production

M. J. Amaryan,[1,*] G. Gavalian,[1] C. Nepali,[1] M. V. Polyakov,[2,3] Ya. Azimov,[3] W. J. Briscoe,[4] G. E. Dodge,[1] C. E. Hyde,[1]
F. Klein,[5] V. Kuznetsov,[6,7] I. Strakovsky,[4] and J. Zhang[8]

FIG. 11. (Color online) Missing mass of K_S with cuts $-t_\Theta < 0.45$ GeV^2 and $M(pK_S) < 1.56$ GeV. The dashed line is the result of a ϕ Monte Carlo simulation, the dashed-dotted line is a modified Monte Carlo distribution, and the solid line is the result of a fit with a modified Monte Carlo distribution plus a Gaussian function.

M = 1543 MeV
Gaussian width = 6 MeV
significance = 5.3 σ

CLAS@JLab interference experiment

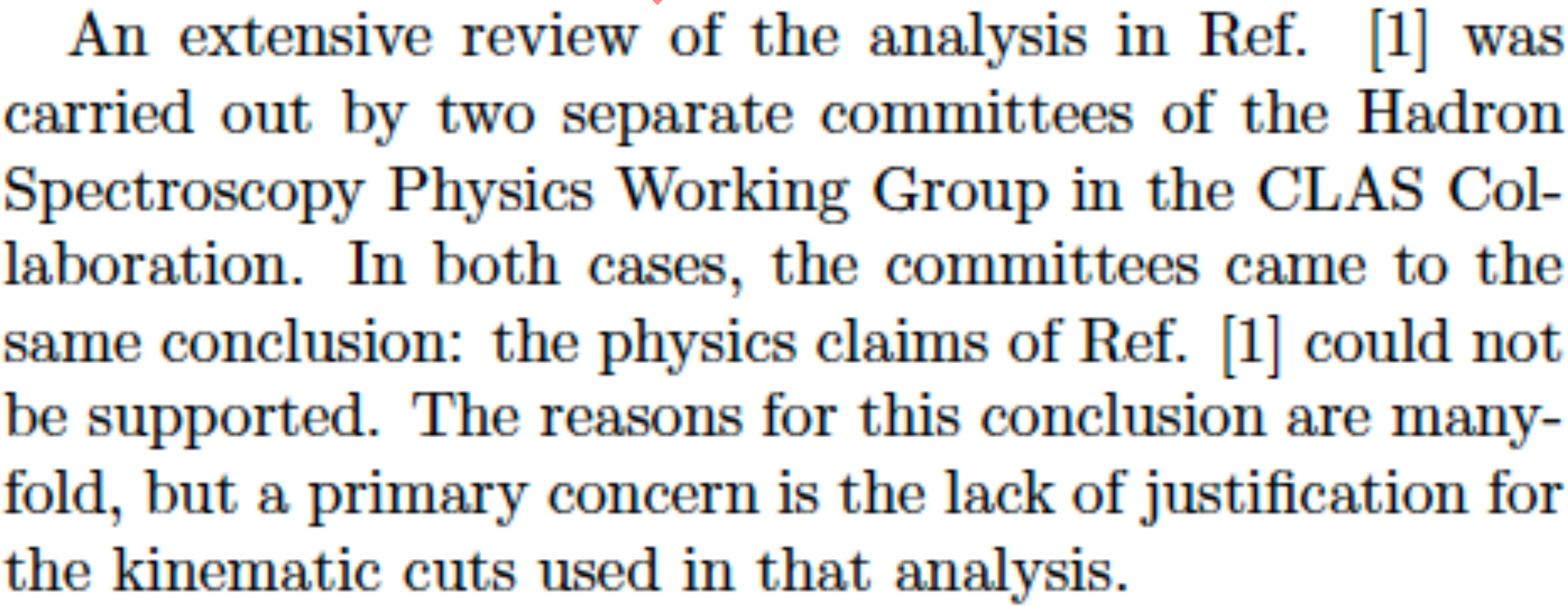


Comment on the narrow structure reported by Amaryan *et al.*

M. Anghinolfi,[18] J. Ball,[8] N.A. Baltzell,[1,29] M. Battaglieri,[18] I. Bedlinskiy,[20] M. Bellis,[25,6] A.S. Biselli,[11]
C. Bookwalter,[13] S. Boiarinov,[30,20] P. Bosted,[30] V.D. Burkert,[30] D.S. Carman,[30] A. Celentano,[18] S.
Chandavar,[24] P.L. Cole,[16,30] V. Crede,[13] R. De Vita,[18] E. De Sanctis,[17] B. Dey,[6] R. Dickson,[6] D. Doughty,[9,30]
M. Dugger,[2] R. Dupre,[1] H. Egiyan,[30,35] A. El Alaoui,[1] L. El Fassi,[1] L. Elouadrhiri,[30] P. Eugenio,[13]
G. Fedotov,[29] M.Y. Gabrielyan,[12] M. Garcon,[8] G.P. Gilfoyle,[27] K.L. Giovanetti,[21] F.X. Girod,[30] J.T. Goetz,[3]
E. Golovatch,[28] M. Guidal,[19] L. Guo,[12,30] K. Hafidi,[1] H. Hakobyan,[32] D. Heddle,[9,30] K. Hicks,[24]
M. Holtrop,[23] D.G. Ireland,[33] B.S. Ishkhanov,[28] E.L. Isupov,[28] H.S. Jo,[19] K. Joo,[10,30] P. Khetarpal,[12]
A. Kim,[22] W. Kim,[22] V. Kubarovsky,[30] S.V. Kuleshov,[32,20] H.Y. Lu,[6] I.J.D. MacGregor,[33] N. Markov,[10]
M.E. McCracken,[34,6] B. McKinnon,[33] M.D. Mestayer,[30] C.A. Meyer,[6] M. Mirazita,[17] V. Mokeev,[30,28]
K. Moriya,[6,*] B. Morrison,[2] A. Ni,[22] S. Niccolai,[19] G. Niculescu,[21,24] I. Niculescu,[21,30,15] M. Osipenko,[18]
A.I. Ostrovidov,[13] K. Park,[30,22] S. Park,[13] S. Anefalos Pereira,[17] S. Pisano,[17] O. Pogorelko,[20] S. Pozdniakov,[20]
J.W. Price,[4] G. Ricco,[14] M. Ripani,[18] B.G. Ritchie,[2] P. Rossi,[17] D. Schott,[12] R.A. Schumacher,[6] E. Seder,[10]
Y.G. Sharabian,[30] E.S. Smith,[30] D.I. Sober,[7] S.S. Stepanyan,[22] P. Stoler,[26] W. Tang,[24] M. Ungaro,[30,26,10]
B .Vernarsky,[6] M.F. Vineyard,[31,27] D.P. Weygand,[30] M.H. Wood,[5,29] N. Zachariou,[15] and B. Zhao[35]
(The CLAS Collaboration)

CLAS@JLab interference experiment

5 years!



An extensive review of the analysis in Ref. [1] was carried out by two separate committees of the Hadron Spectroscopy Physics Working Group in the CLAS Collaboration. In both cases, the committees came to the same conclusion: the physics claims of Ref. [1] could not be supported. The reasons for this conclusion are manyfold, but a primary concern is the lack of justification for the kinematic cuts used in that analysis.

Happy ending?

Very likely the reports of Theta+ death are greatly exaggerated.
We still need to wait for a conclusive formation experiment.
In the meantime new LEPS2 results may shed some light
on a missing victim.
K^0 program at CLAS may also shed light on Theta+

Thank you