Japan Atomic Energy Agency

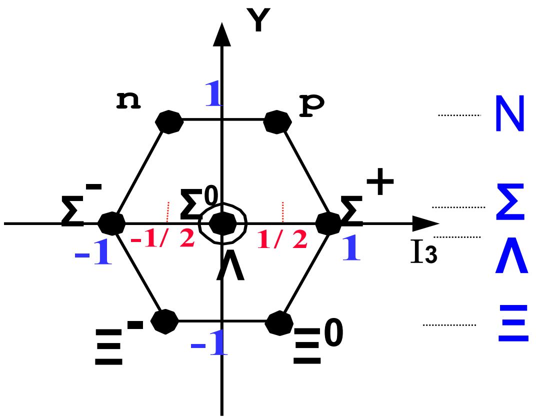
Killing or Saving pentaquarks

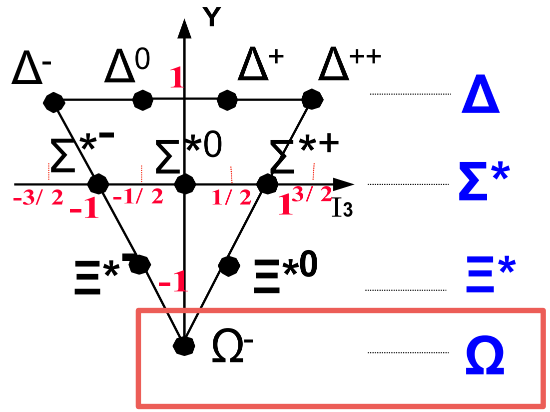
Hyun-Chul Kim
Inha University
ASRC, JAEA

A Pentaquark,
a particle that consists of
five quarks

The founder of quarks, Gell-Mann

Quark and SU(3) Group





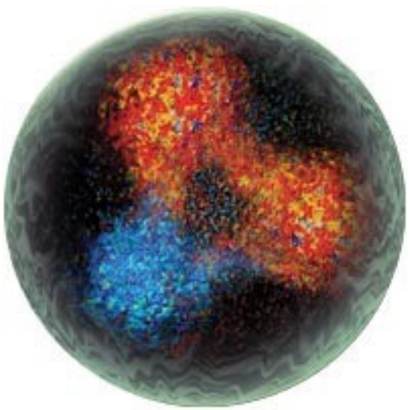
Nobel prize laureate, 1969

"for his contributions and discoveries concerning the classification of elementary particles and their interactions".

What is a quark?

Literal meaning of a quark

1. The smallest fundamental particle that consists of hadrons
2. Question Mark
3. 【German】Quark: Low-fat soft cheese



Quark inside
a nucleon

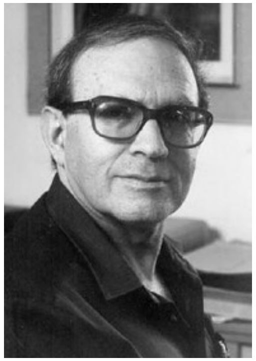
Quark, a German soft cheese

Quark: Antagonist
in Star Trek

Murray Gell-Mann: Finnegans' wake by James Joyce

"Three quarks for Muster Mark"

George Zweig called it Ace, at an almost same time.



Yuval Ne'eman, almost forgotten.

What is a quark?

Chapter 4 in Book 2, in Finnegans' wake by James Joyce

—***Three quarks for Muster Mark!***

Sure he hasn't got much of a bark

And sure any he has it's all beside the mark.

But O, Wreneagle Almighty, wouldn't un be a sky of a lark

To see that old buzzard whooping about for uns shirt in the dark

And he hunting round for uns speckled trousers around by Palmerstown Park?

Hohohoho, moulty Mark!

You're the rummest old rooster ever flopped out of a Noah's ark

And you think you're cock of the wark.

Fowls, up! Tristy's the spry young spark

That'll tread her and wed her and bed her and red her

Without ever winking the tail of a feather

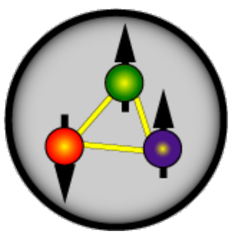
And that's how that chap's going to make his money and mark!

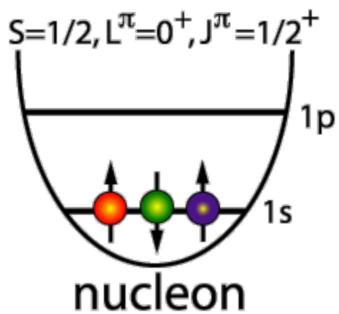
This poem might be related to a Celtic legend, Tristan and Isolde

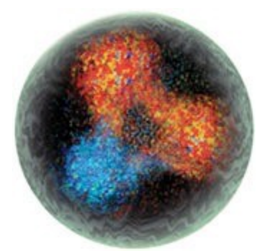
What is a quark?

- Kinds: up, down, strange, charm, beauty, top
- Spin: 1/2
- Charge: 2/3, -1/3, -1/3, 2/3, -1/3, 2/3
- Baryons: $qqq,\ qqqq\bar{q},\ qqqqqq, \cdots$
- Mesons: $q\bar{q},\ qq\bar{q}\bar{q}, \cdots$

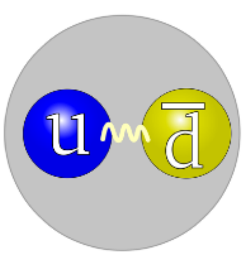
Nucleon:







pion:



Pentaquark mentioned by Gell-Mann

Volume 8, number 3 PHYSICS LETTERS 1 February 1964

A SCHEMATIC MODEL OF BARYONS AND MESONS *

M. GELL-MANN
California Institute of Technology, Pasadena, California

Received 4 January 1964

A simpler and more elegant scheme can be constructed if we allow non-integral values for the charges. We can dispense entirely with the basic baryon b if we assign to the triplet t the following properties: spin $\frac{1}{2}$, $z = -\frac{1}{3}$, and baryon number $\frac{1}{3}$. We then refer to the members $u^{\frac{2}{3}}$, $d^{-\frac{1}{3}}$, and $s^{-\frac{1}{3}}$ of the triplet as "quarks"[6] q and the members of the anti-triplet as anti-quarks $\bar{q}$. Baryons can now be constructed from quarks by using the combinations $(q\,q\,q)$, $(q\,q\,q\,q\,\bar{q})$, etc., while mesons are made out of $(q\,\bar{q})$, $(q\,q\,\bar{q}\,\bar{q})$, etc. It is assuming that the lowest baryon configuration $(q\,q\,q)$ gives just the representations **1**, **8**, and **10** that have been observed, while the lowest meson configuration $(q\,\bar{q})$ similarly gives just **1** and **8**.

Pentaquarks

Tetraquarks

Pentaquark was predicted

D.Diakonov, V. Petrov, M.Polyakov : Z. Phys A 359, 305 [1997]

Prediction of the pentaquarks: Their widths were extremely important!

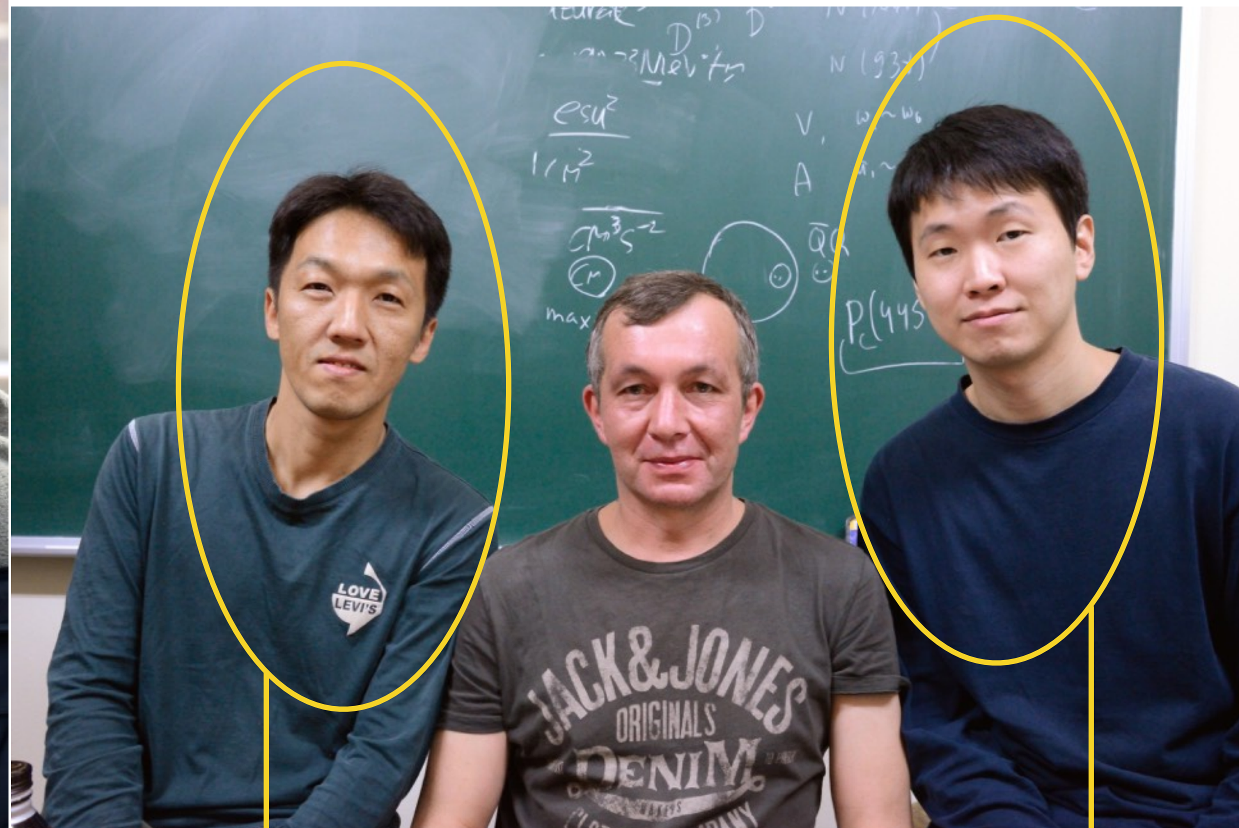
Θ^+ was coined by D.I. Diakonov

	T	Y	Mass in MeV	Width in MeV
Z^+	0	2	1530	15
$N_{\overline{10}}$	1/2	1	1710 (input)	~ 40
$\Sigma_{\overline{10}}$	1	0	1890	~ 70
$\Xi_{3/2}$	3/2	-1	2070	> 140

Mitya Diakonov (1949 - 2012)

Victor Petrov & Maxim Polyakov

Victor Petrov



Maxim V. Polyakov

Ghil-Seok Yang (Polyakov's Student),
A victim by the death of the pentaquark

Hyeon-Dong Son
(Polyakov's Student)

Pentaquark: Prediction in 1980s

Mass of the pentaquark predicted in 1980s

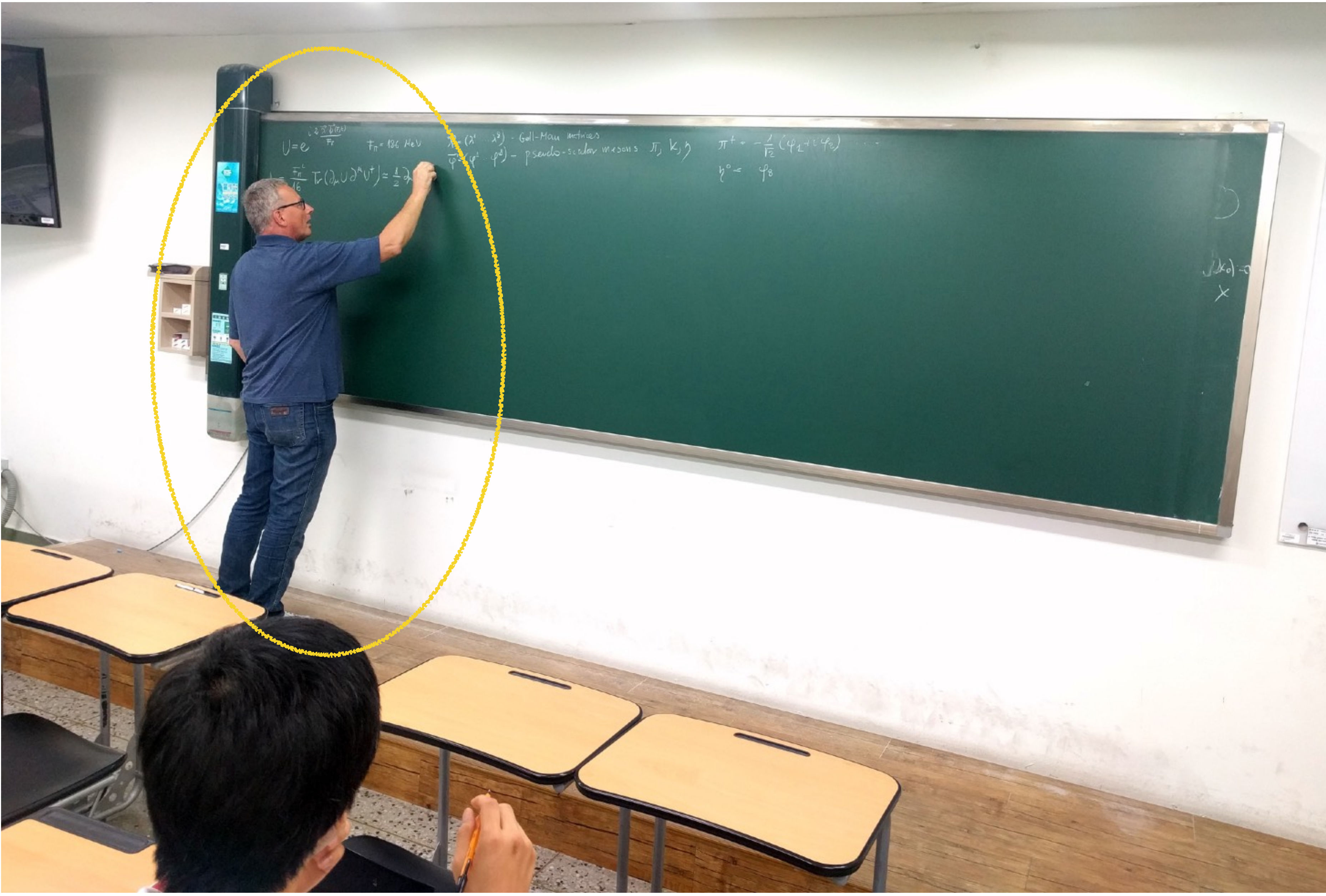
soliton models: positive parity

Biedenharn, Dothan (1984):
$\Delta_{10-8} \sim 600$ MeV from Skyrme model

Michal Praszalowicz (1987):
$M_\Theta = 1535$ MeV from Skyrme model
in model independent approach, second order

Diakonov, Petrov, Polyakov (1997):
χQM - model independent approach,
$1/N_c$ corrections
$M_\Theta = 1530$ MeV, $\Gamma_\Theta < 15$ MeV

Michal Praszalowicz



Pentaquark: Prediction in 1980s

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

Many Thanks to Michal Praszalowicz for this!

Pentaquark: Prediction in 1980s

Thus the first state violating the three quark rule is a $(\overline{10},\frac{1}{2})$, which--using numerical values[4] 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.

146 B (1984) 289

Pentaquark: Prediction in 1980s

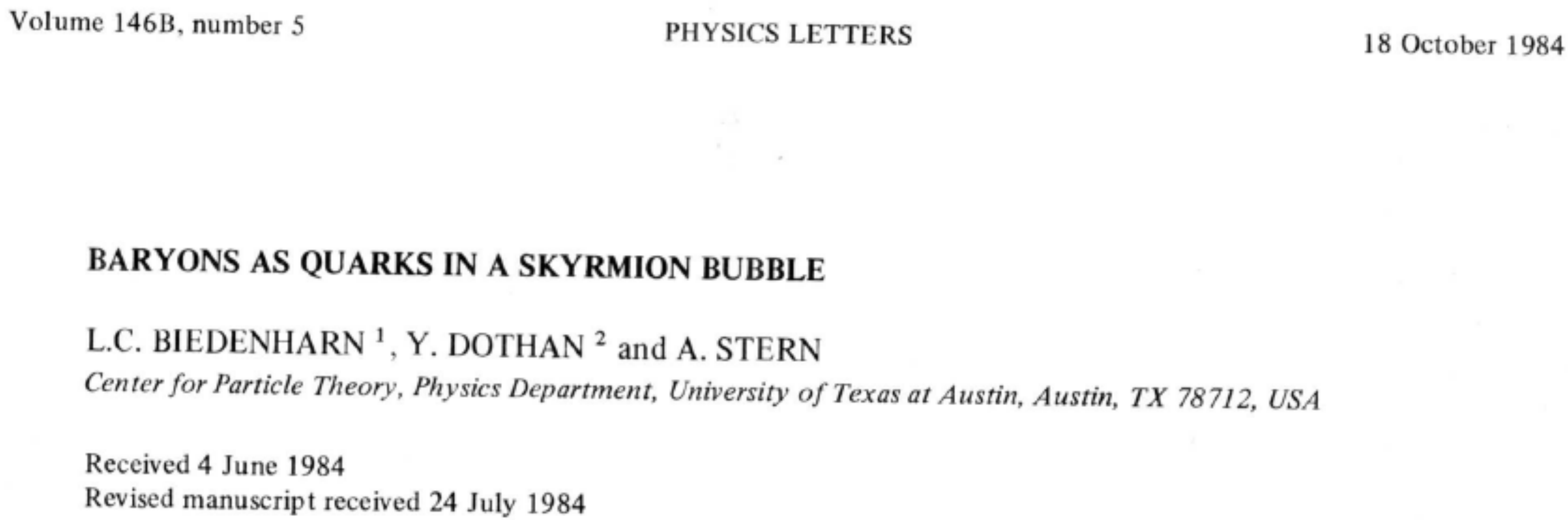
In the printed version: *From SU(3) to Gravity*
Festschrift in honor of Yuval Ne'eman
Eds. E. Gotsman, G. Tauber

ordering for $B = 1$ is: $(8, 1/2)$; $(10, 3/2)$; $(\overline{10}, 1/2)$; ... Thus the first state violating the three quark rule is a $(\overline{10}, 1/2)$, which — using numerical values[3] in the Hamiltonian — yields an excitation energy ≈ 600 Mev above the $(8, 1/2)$. Since the theory is a

1. Witten, E. *Nucl. Phys.* **B223,** 422 (1982).
2. Skyrme, T.H.R. *Proc. Roy. Soc.* **A260,** 127 (1961).
3. Guadagnini, G. *Nucl. Phys.* **B236,** 35 (1984).
   Biedenharn, L.C., Dothan, Y. and Stern, A. *Phys. Lett.* **146D,** 289 (1984).
4. Biedenharn, L.C., Louck, J.D. *Encl. for Math. and Appl.*, vol.9 "The Racah-Wigner Algebra in Quantum Theory," (Reading, MA, Addison-Wesley, 1981, (see Topic 2: Monopolar Harmonics, p. 201 ff).

Pentaquark: Prediction in 1980s

Volume 146B, number 5 PHYSICS LETTERS 18 October 1984


Volume 146B, number 5 PHYSICS LETTERS 18 October 1984

BARYONS AS QUARKS IN A SKYRMION BUBBLE

L.C. BIEDENHARN [1], Y. DOTHAN [2] and A. STERN

Center for Particle Theory, Physics Department, University of Texas at Austin, Austin, TX 78712, USA

Received 4 June 1984

Revised manuscript received 24 July 1984

Pentaquark: Prediction in 1980s

$$E_{\mathrm{qu}}^{\mathrm{SU(3)}} = E_0$$

$+3q$ ↓

$$+ (2F_\pi^2 R^3)^{-1} [(p^2 + 3p + q^2 + pq - \tfrac{9}{4}B^2)/3C_{\mathrm{SU(3)}}$$

$$+ J(J+1)(C_{\mathrm{rot}}^{-1} - C_{\mathrm{SU(3)}}^{-1})] , \qquad (24)$$

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

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

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

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

$$\Delta_{\overline{10}-8} = 350 \text{ MeV}$$

$$\Delta_{10-8} = 390 \text{ MeV}$$

Pentaquark: Experimentally found

Table 1
Published experiments with evidence for the Θ^+ baryon

Reference	Group	Reaction	Mass (MeV)	Width (MeV)	σ's[a]
[1]	LEPS	$\gamma C \to K^+ K^- X$	1540 ± 10	<25	4.6
[2]	DIANA	$K^+ Xe \to K^0 p X$	1539 ± 2	<9	4.4
[3]	CLAS	$\gamma d \to K^+ K^- p(n)$	1542 ± 5	<21	5.2 ± 0.6[b]
[4]	SAPHIR	$\gamma d \to K^+ K^0 (n)$	1540 ± 6	<25	4.8
[5]	ITEP	$\nu A \to K^0 p X$	1533 ± 5	< 20	6.7
[6]	CLAS	$\gamma p \to \pi^+ K^+ K^- (n)$	1555 ± 10	<26	7.8
[7]	HERMES	$e^+ d \to K^0 p X$	1526 ± 3	13 ± 9	~5
[8]	ZEUS	$e^+ p \to e^+ K^0 p X$	1522 ± 3	8 ± 4	~5
[9]	COSY-TOF	$pp \to K^0 p \Sigma^+$	1530 ± 5	<18	4–6
[10]	SVD	$pA \to K^0 p X$	1526 ± 5	<24	5.6

$$M_{\Theta^+} \approx (1520 - 1540)\,\mathrm{MeV}$$

$$\Gamma_{\Theta^+ \to KN} < 30\,\mathrm{MeV}$$

LEPS Collaboration: First finding

T. Nakano *et al.*, Phys. Rev. Lett. **91**, 012002 (2003)
more than 1000 times cited

Pentaquark that shook the world

Posted 6/30/2003 8:44 PM

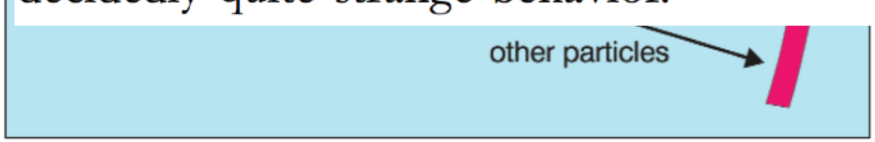
External Link:
https://www.jlab.org/news/articles/pentaquark-newly-arrived-matter-le-figaro

The pentaquark, newly arrived matter

Physics: A discovery by Japanese and American physicists increases even more the mystery of quarks, elementary particles of the universe.

By Cyrille Vanlerberghe, *Le Figaro*
(Translated by **Winston Roberts** and **Melanie O'Byrne**)
July 3, 2003

After thirty years of research, physicists seem to have at last put their hands on a rather strange particle composed of five quarks, a "pentaquark". If the interpretation of the experimental results obtained in Japan and in the United States is confirmed, it is the first time that this new, exotic form of matter has been observed. Usually, quarks are only found in groups of two or three inside particles that they compose. This unexpected discovery opens new doors for the understanding of the subatomic world, in which quarks have decidedly quite strange behavior.



ory predicted where the particle
uld emerge

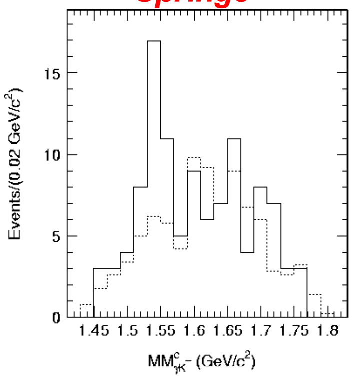
Pentaquark that shook the world

US Department of Energy (DOE)

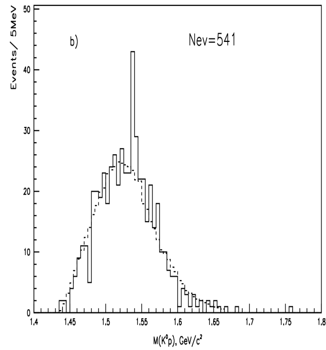
Finding of the pentaquark by CLAS experiment is the best achievement in Nuclear Physics in 2003!

Pentaquark: Experimental results

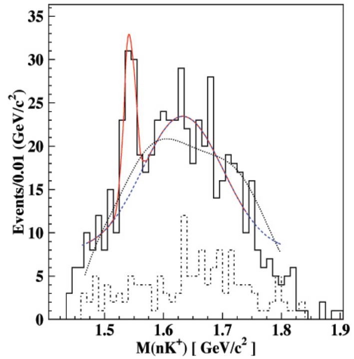
Spring8



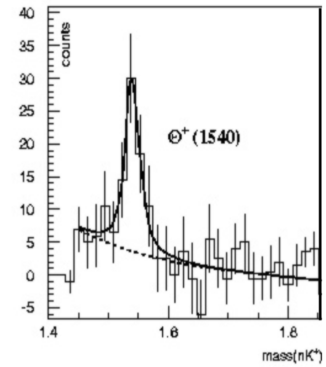
DIANA



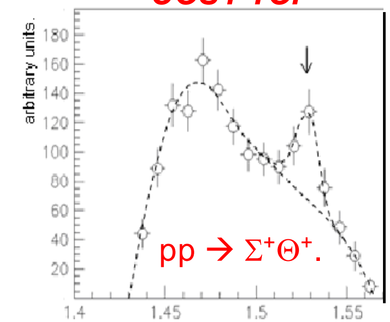
JLab-d

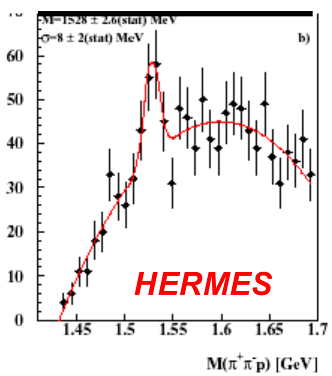


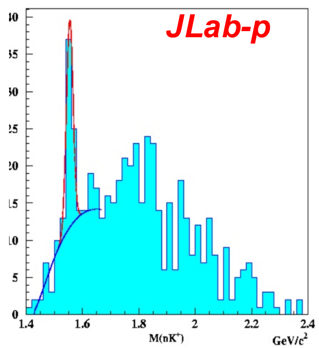
ELSA



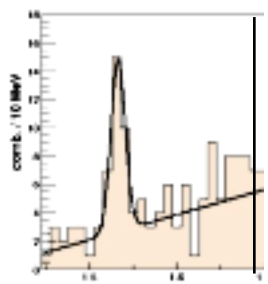
COSY-TOF

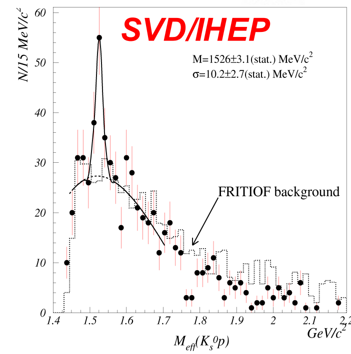






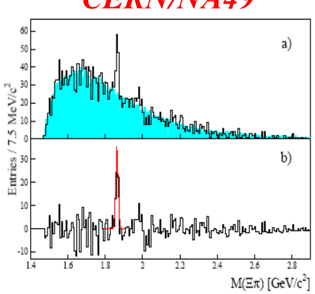
ITEP

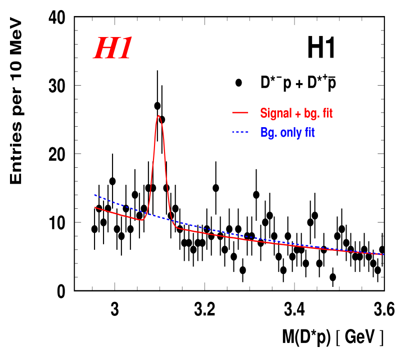




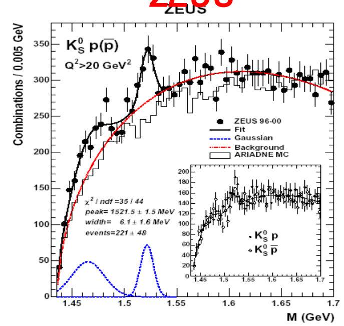
This is a lot of evidence. However,…

CERN/NA49

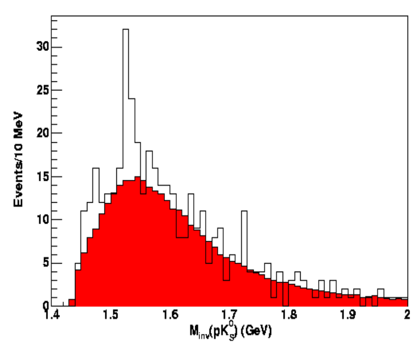




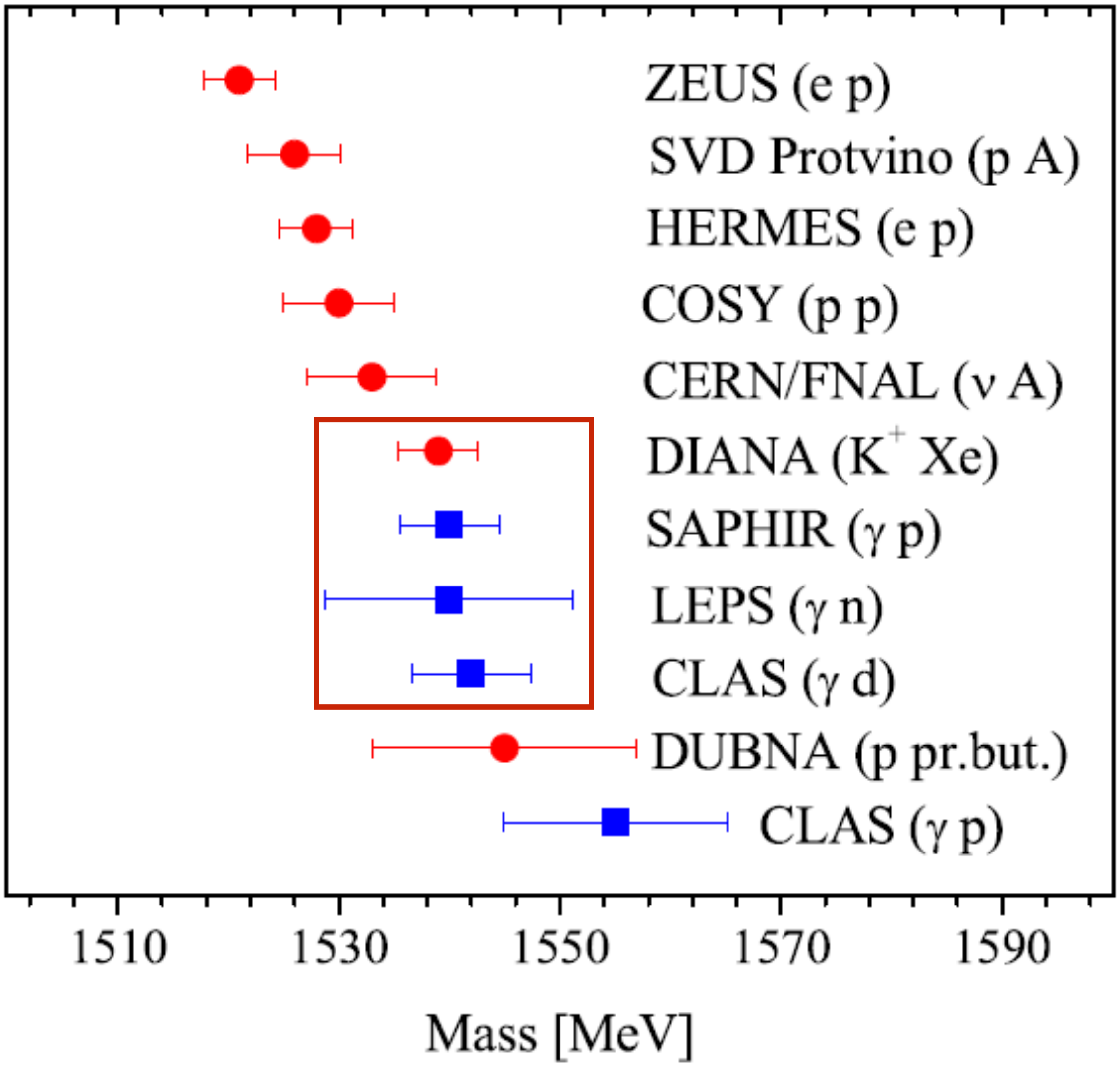
ZEUS



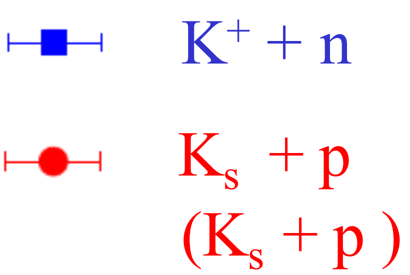
Nomad



Pentaquark: Experimental results



Final state:



The values of the Theta+ mass lie between 1526 MeV and 1560 MeV.

Pentaquark: Negative results

Table 2
Published experiments with non-observation of the Θ^+ baryon

Reference	Group	Reaction	Limit	Sensitivity?
[11]	BES	$e^+e^- \to J/\Psi \to \bar{\Theta}\Theta$	$<1.1 \times 10^{-5}$ B.R.	No [68]
[12]	BaBar	$e^+e^- \to \Upsilon(4S) \to pK^0X$	$<1.0 \times 10^{-4}$ B.R.	Maybe
[13]	Belle	$e^+e^- \to B^0\bar{B}^0 \to p\bar{p}K^0X$	$<2.3 \times 10^{-7}$ B.R.	No
[14]	LEP	$e^+e^- \to Z \to pK^0X$	$<6.2 \times 10^{-4}$ B.R.	No?
[15]	HERA-B	$pA \to K^0pX$	$<0.02 \times \Lambda^*$	No?
[16]	SPHINX	$pC \to K^0\Theta^+X$	$<0.1 \times \Lambda^*$	Maybe
[17]	HyperCP	$pCu \to K^0pX$	$<0.3\%\ K^0p$	No?
[18]	CDF	$p\bar{p} \to K^0pX$	$<0.03 \times \Lambda^*$	No?
[19]	FOCUS	$\gamma BeO \to K^0pX$	$<0.02 \times \Sigma^*$	Maybe
[20]	Belle	$\pi + Si \to K^0pX$	$<0.02 \times \Lambda^*$	Yes?
[21]	PHENIX	$Au + Au \to K^-\bar{n}X$	(not given)	Unknown

Non observation of the Theta+ at higher-energy experiments!

Pentaquarks appear in PDG

$\Theta(1540)^+$ MASS

As is done through the *Review*, papers are listed by year, with the latest year first, and within each year they are listed alphabetically. NAKANO 03 was the earliest paper.

Since our 2004 edition, there have been several new claimed sightings of the $\Theta(1540)^+$ (see entries below marked with bars to the right), but there have also been several searches with negative results:

VALUE (MeV)	*EVTS*	*DOCUMENT ID*	*TECN*	*COMMENT*
1533.6± 2.4 OUR AVERAGE		Error includes scale factor of 2.1. See the ideogram below.		
1526 ± 3 ±3		[1] ALEEV 05	SVD2	p nucleus $\rightarrow p K^0_S X$
1530 ± 5		[2] ABDEL-BARY 04	COSY	$p p \rightarrow \Sigma^+ K^0 p$
1528.0± 2.6±2.1	59	[3] AIRAPETIAN 04	HERM	$\gamma^* d \rightarrow p K^0_S X$
1533 ± 5	27	[4] ASRATYAN 04	BC	ν, $\overline{\nu}$ in p,d,Ne, BEBC, 15-ft
1521.5± $1.5^{+2.8}_{-1.7}$	221	[5] CHEKANOV 04A	ZEUS	$\gamma^* p \rightarrow p/\overline{p} K^0_S X$
1555 ±10	41	[6] KUBAROVSKY 04	CLAS	$\gamma p \rightarrow \pi^+ K^- K^+ n$
1539 ± 2	29	[7] BARMIN 03	XEBC	$K^+ \text{Xe} \rightarrow K^0 p \text{Xe}'$
1540 ± 4 ±2	63	[8] BARTH 03	SPHR	$\gamma p \rightarrow n K^+ K^0_S$
1540 ±10	19	[9] NAKANO 03	LEPS	$\gamma\, ^{12}\text{C} \rightarrow K^+ K^- n X$
1542 ± 5	43	[10] STEPANYAN 03	CLAS	$\gamma d \rightarrow K^+ K^- p n$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
1559 ± 3		[11] GIBBS 04		$K^+ d$ total cross section

Particle Data Group(2006)

Pentaquarks appear in PDG

$\Theta(1540)^+$ WIDTH

Given the systematic uncertainties of the estimates of CAHN 04 and GIBBS 04, we think it more reasonable to give the common value for the width and error rather than average the two values.

VALUE (MeV)			CL%	EVTS	DOCUMENT ID		TECN	COMMENT
0.9	**±0.3**	**OUR ESTIMATE**						
0.9	±0.3				[12] CAHN	04		$K^+ n \to K^0 p$ in xenon
0.9	±0.3				GIBBS	04	PWA	$K^+ d$ total cross section
• • • We do not use the following data for averages, fits, limits, etc. • • •								
< 0.64			90		[13] MIZUK	06	BELL	$K^+ n \to K^0_S p$
<24					ALEEV	05	SVD2	p nucleus $\to p K^0_S X$
17	±9	±3			AIRAPETIAN	04	HERM	$\gamma^* d \to p K^0_S X$
<20					ASRATYAN	04	BC	ν, $\overline{\nu}$ in p,d,Ne, BEBC and 15-ft
8	±4			221	CHEKANOV	04A	ZEUS	$\gamma^* p \to p/\overline{p} K^0_S X$
<26					KUBAROVSKY	04	CLAS	$\gamma p \to \pi^+ K^- K^+ n$
< 1					[14] SIBIRTSEV	04		$K^+ d \to K^0 p p$ reanalysis
$\lesssim$1					[15] ARNDT	03	DPWA	$K^+ N$ partial-wave reanalysis
< 9			90		BARMIN	03	XEBC	$K^+ \mathrm{Xe} \to K^0 p \mathrm{Xe}'$
<25			90		BARTH	03	SPHR	$\gamma p \to n K^+ K^0_S$
<25			90		NAKANO	03	LEPS	$\gamma\, ^{12}\mathrm{C} \to K^+ K^- n X$
<21					STEPANYAN	03	CLAS	$\gamma d \to K^+ K^- p n$

Particle Data Group(2006)

Pentaquarks appear in PDG

$\Phi(1860)$ $I(J^P) = \frac{3}{2}(?^?)$

OMITTED FROM SUMMARY TABLE

ALT 04 with 1640 Ξ^- candidates in pp reaction at $\sqrt{s} = 17.2$ GeV sees peaks in the $\Xi^- \pi^-$ and $\Xi^- \pi^+$ mass spectra. The minimum quark content would be $s s d d \overline{u}$.

$\Phi(1860)$ MASS

VALUE (MeV)	*EVTS*	*DOCUMENT ID*		*TECN*	*COMMENT*
1862±2	36	[1] ALT	04	NA49	pp, $\sqrt{s} = 17.2$ GeV

$\Phi(1860)$ WIDTH

VALUE (MeV)	*CL%*	*DOCUMENT ID*		*TECN*	*COMMENT*
<18	90	[1] ALT	04	NA49	pp, $\sqrt{s} = 17.2$ GeV

In 2003, J.K. Ahn(LEPS), I.K. Yoo (NA49), and HChK were in hot discussion on pentaquarks in Pusan.

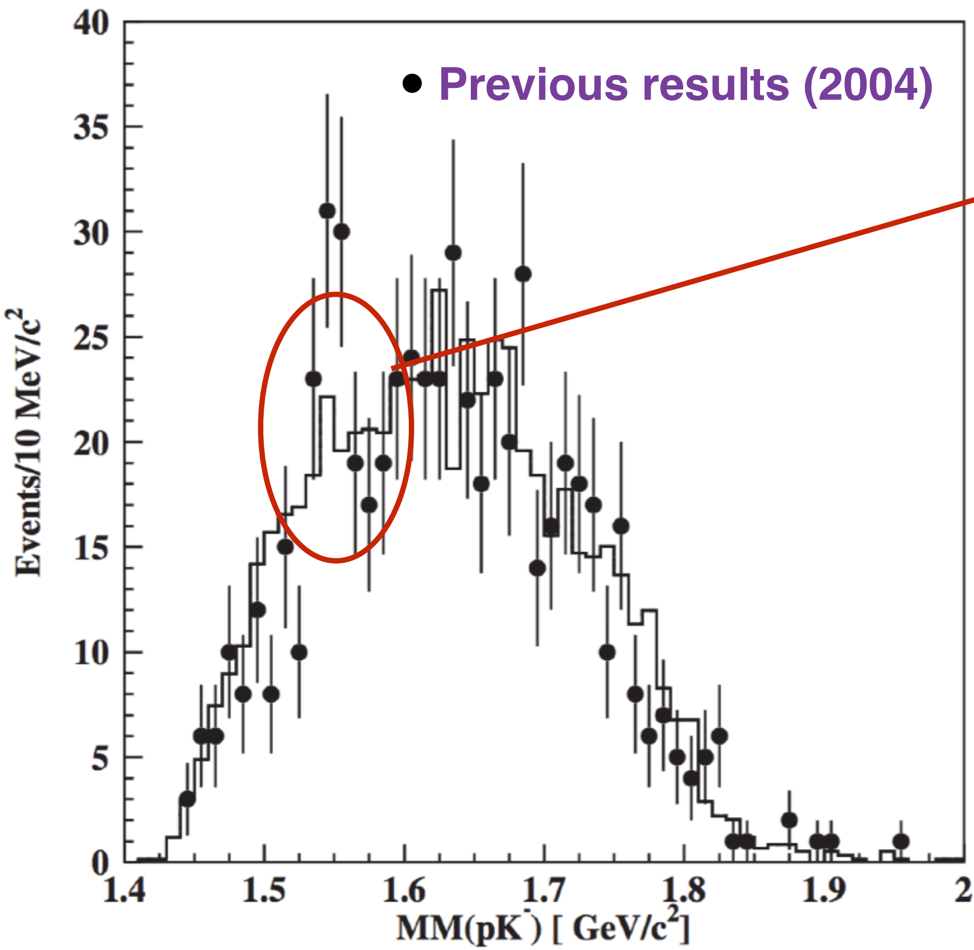
Particle Data Group(2006)

However…

Pentaquark: Null result!

Null results from the CLAS: Alas, **a suicidal result!**
Totally opposite to the previous finding!

CLAS Collaboration, PRL **96**, 212001 **(2006)**



Null Result!!

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

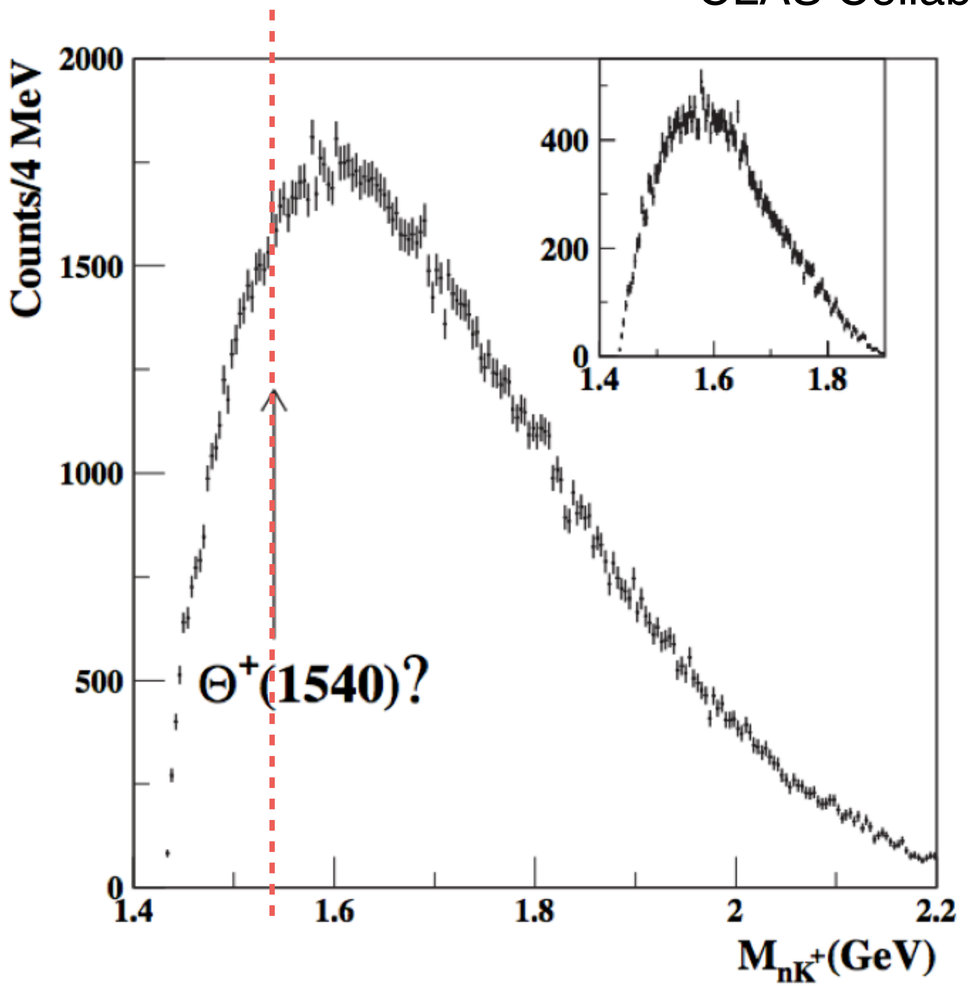
No Θ^+

$\sigma_{\gamma d \to p K^- \Theta^+} \approx 0.3\,\mathrm{nb}$

Pentaquark: Null result!

Null results from the CLAS

CLAS Collaboration, PRL **96**, 042001 **(2006)**



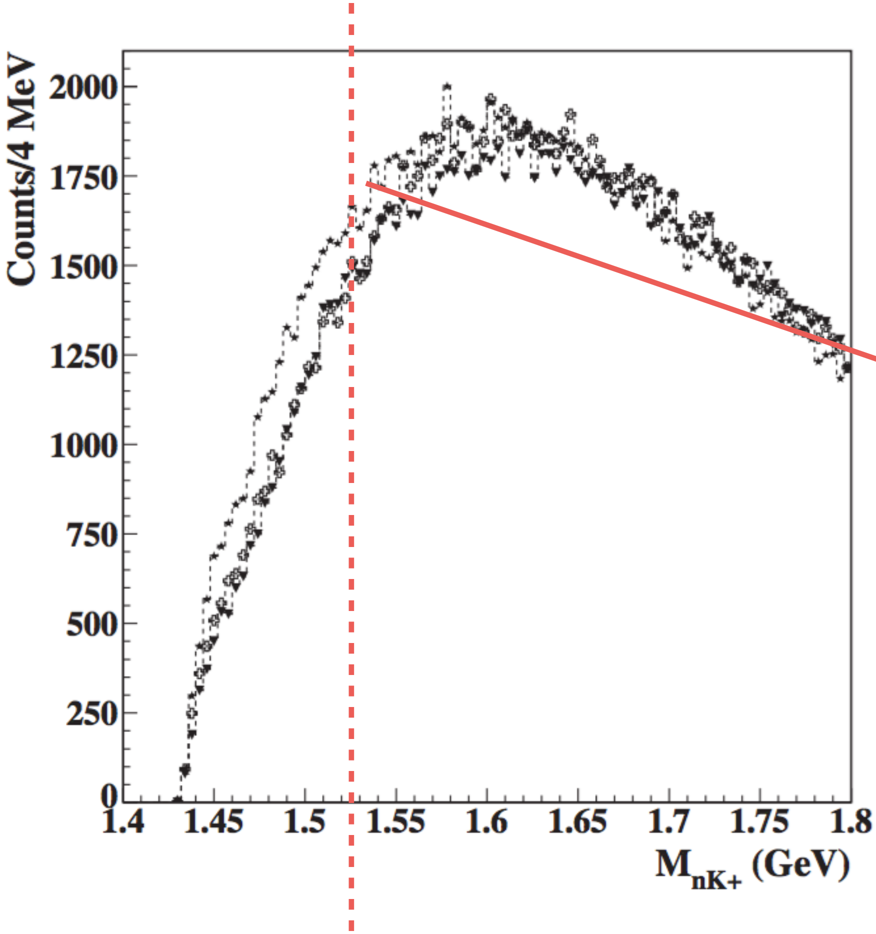
$$\gamma p \to \bar{K}^0 K^+ n$$

No Θ^+

Pentaquark: Null result!

Another null results from the CLAS

PHYSICAL REVIEW D 74, 032001 (**2006**)

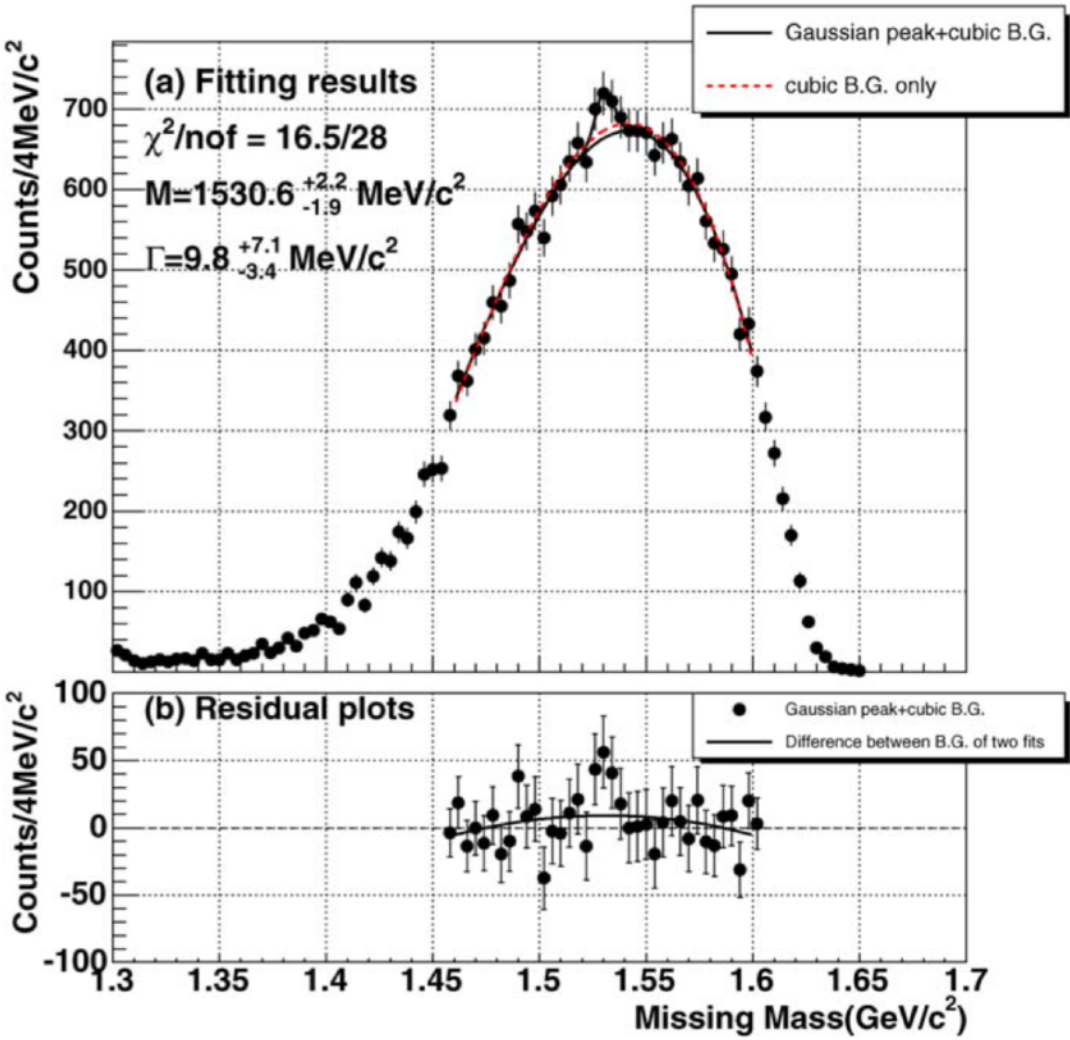


$$\gamma p \to \bar{K}^0 K^+ n$$

$$\gamma p \to \bar{K}^0 K^0 p$$

No signal!

Pentaquark: Null result!



$$\pi^- p \to K^- X$$

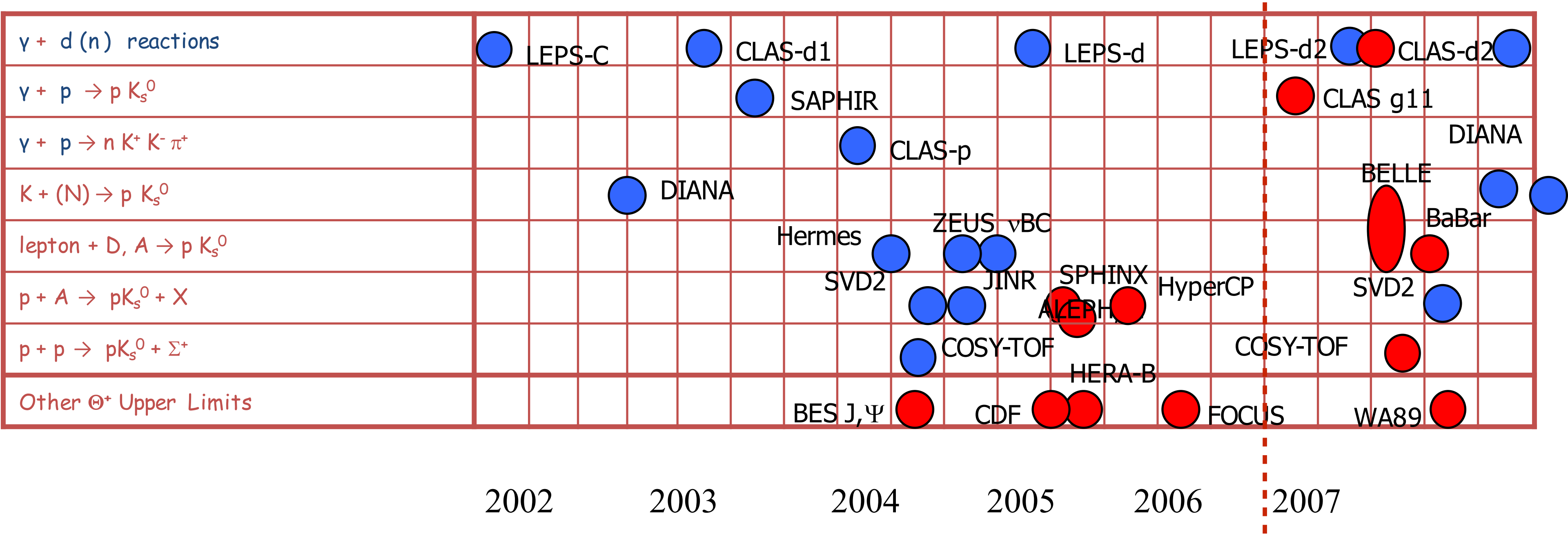
KEK experiment

Physics Letters B **635,** 72 **(2006)**

$$(2.5 - 2.7)\,\sigma$$

Pentaquark:
Time dependence of the experimental results

Time dependent experimental status of Θ^+



● : **Positive result**

● : **Negative result**

Death of the pentaquark: 2008 PDG Summary

PENTAQUARKS

Written May 2008 by C.G. Wohl (LBNL)

Pentaquark disappeared from the PDG(2008) Version.

Taken from the last paragraph

There are two or three recent experiments that find weak evidence for signals near the nominal masses, but there is simply no point in tabulating them in view of the overwhelming evidence that the claimed pentaquarks do not exist. The only advance in particle physics thought worthy of mention in the American Institute of Physics "Physics News in 2003" was a false alarm. The whole story—the discoveries themselves, the tidal wave of papers by theorists and phenomenologists that followed, and the eventual "undiscovery" —is a curious episode in the history of science.

Death of the pentaquark

US Department of Energy (DOE)

The Null result of the CLAS (Death of the pentaquark) is praised as the best achievement in Nuclear Physics in 2006!

Though funny, people started to believe that the pentaquarks were just physical illusions since the CLAS null results!

So, the Pentaquark is dead……

Almost no theoretical paper after 2008…

However, the story of the pentaquark will go on…

LEPS & DIANA

Fortitude of mind by an experimentalist: Takashi Nakano

Takashi Nakano & Maxim V. Polyakov

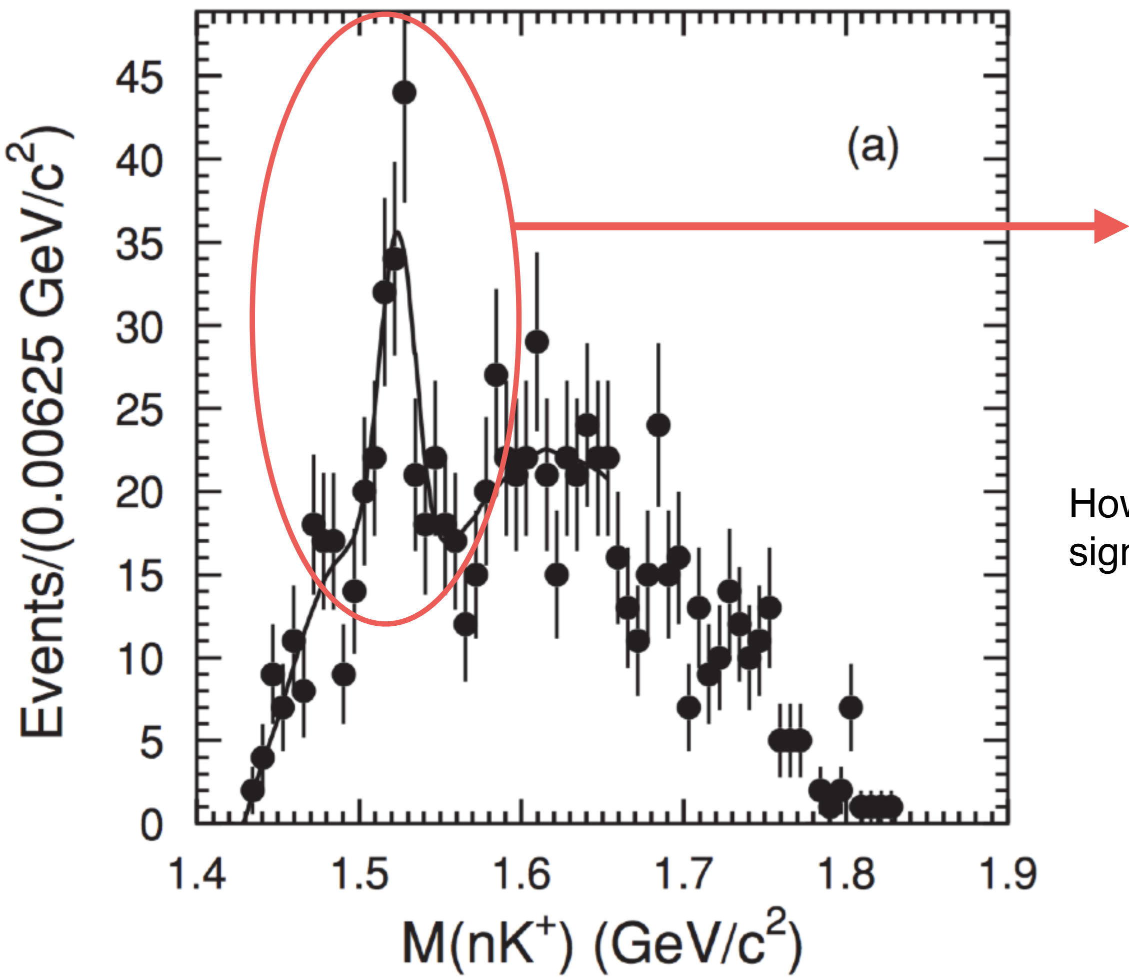
Pentaquark Parties, 2006

LEPS II was started

Kuznetsov found narrow N*

LEPS & DIANA

Nakano etal, LEPS-II Collaboration, PHYSICAL REVIEW C **79**, 025210 (2009)



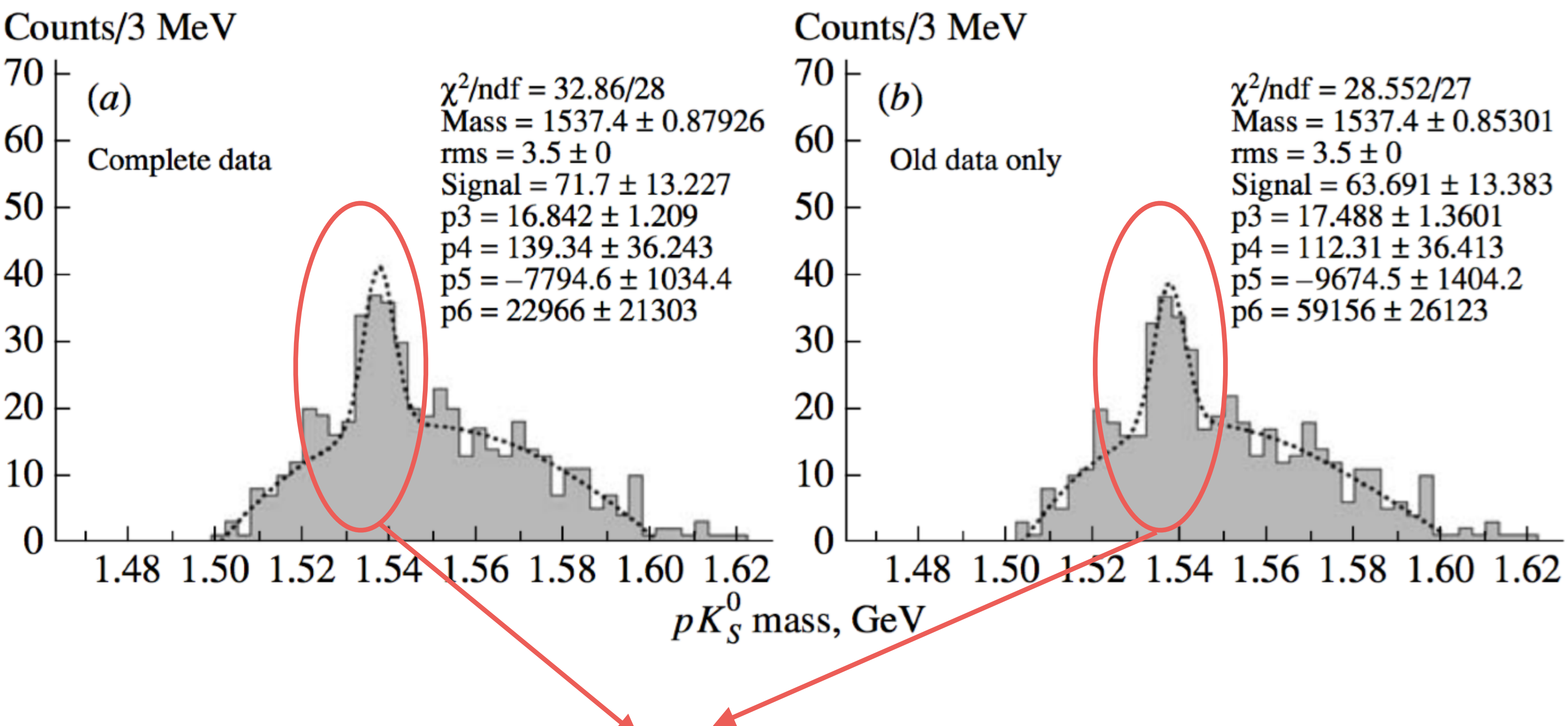
$\Theta^{+}(1524)$

However, very recent LEP-II data are less significant.

LEPS & DIANA

Barman et al., DIANA Collaboration, Physics of Atomic Nuclei, **2010**, Vol. 73, No. 7, pp. 1168–1175

$$K^+\mathrm{Xe} \to K^0 p \mathrm{Xe}' \quad (K^+ n \to K^0 p)$$



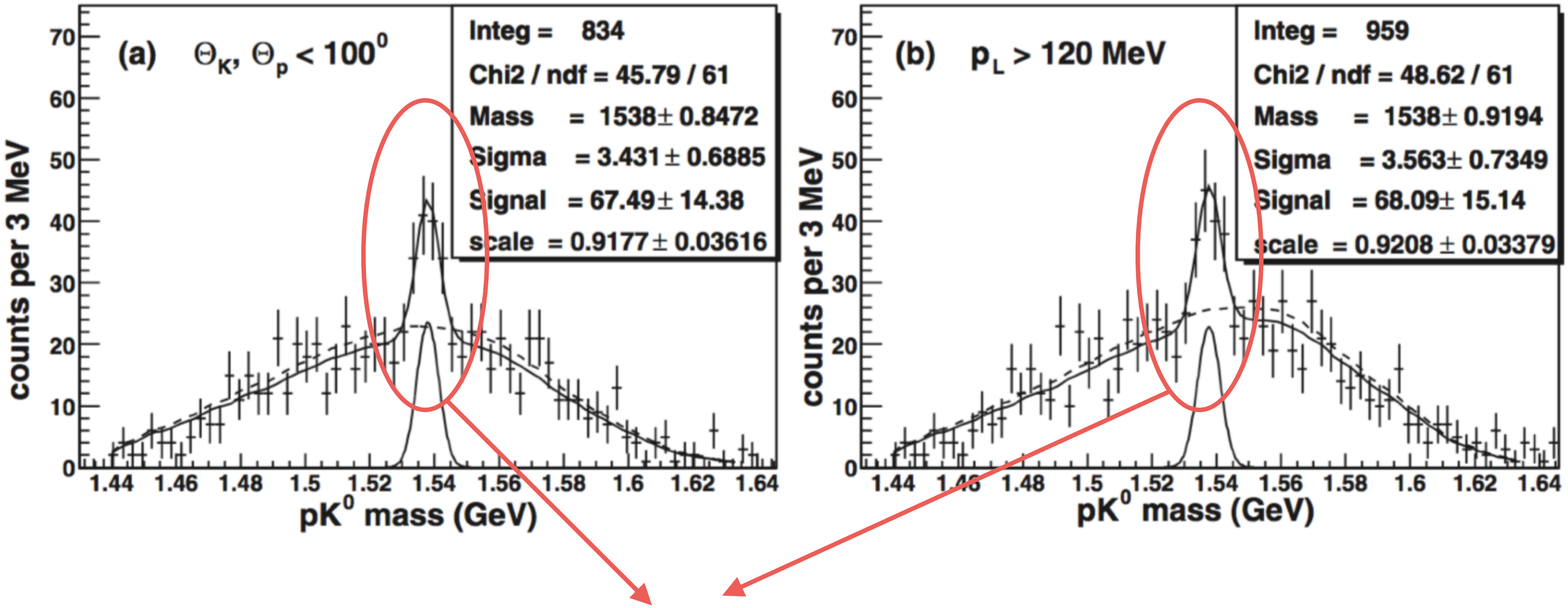
$$\Theta^+(1537)$$

$$\Gamma = (0.39 \pm 0.10)\ \mathrm{MeV}$$

LEPS & DIANA

Barman et al., DIANA Collaboration, PHYSICAL REVIEW C **89**, 045204 **(2014)**

$$K^+\mathrm{Xe} \to K^0 p \mathrm{Xe}'$$



$$M_{\Theta^+} = (1538 \pm 2)\,\mathrm{MeV}$$

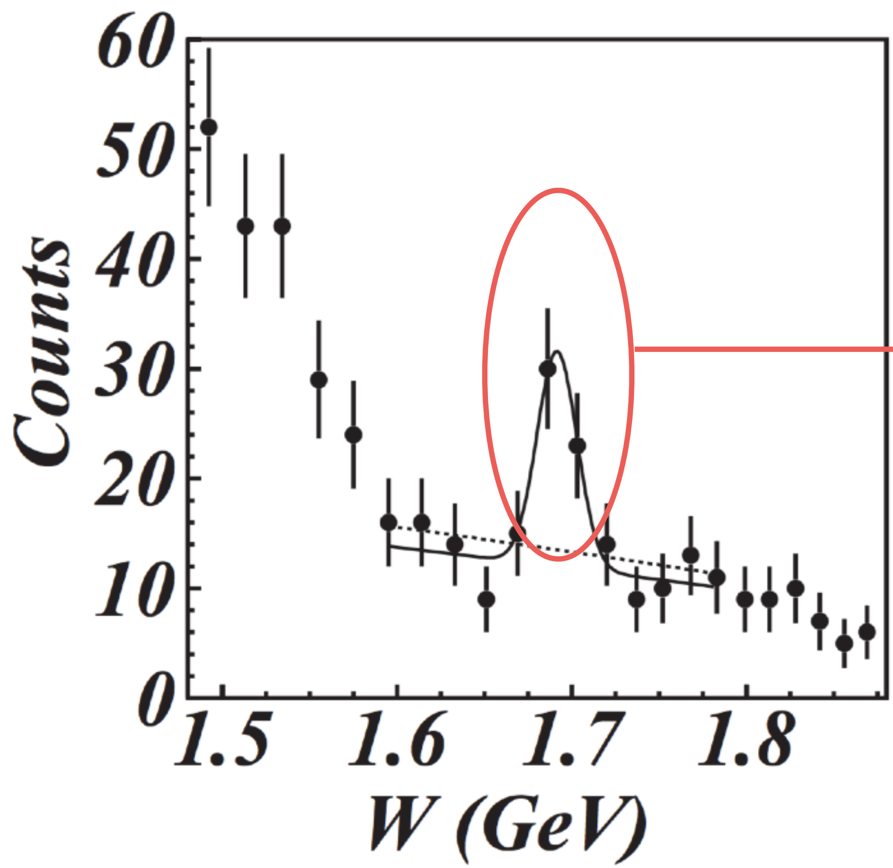
$$\Gamma = (0.34 \pm 0.10)\,\mathrm{MeV}$$

GRAAL

Pentaquark N*?

V. Kuznetsov et al. PHYSICAL REVIEW C **83**, 022201(R) **(2011)**

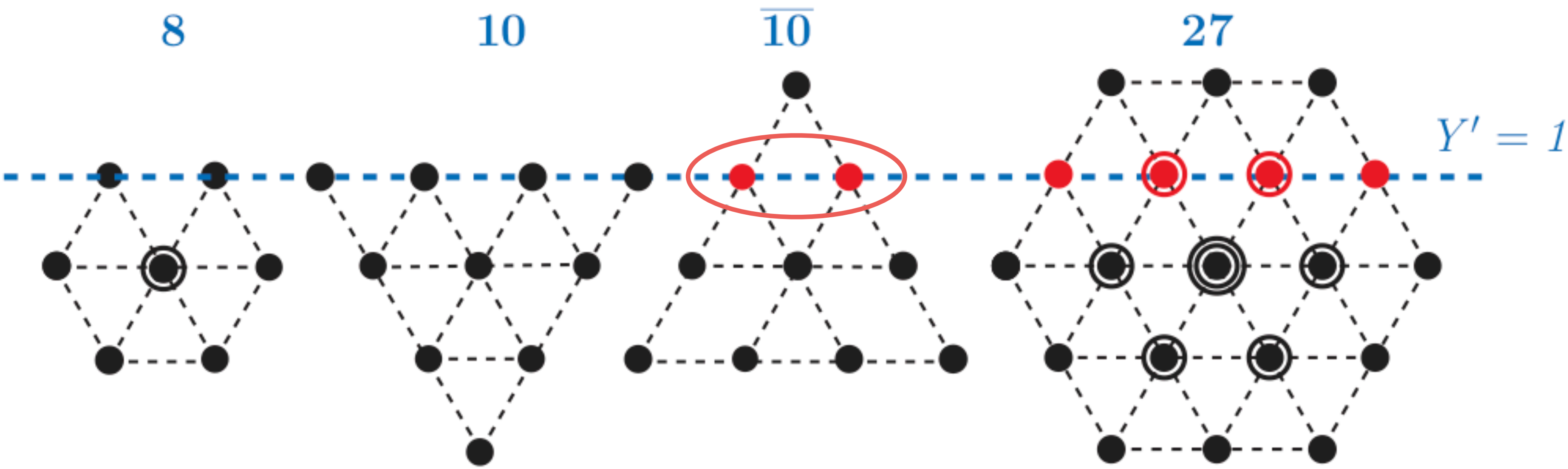
$$\gamma N \to \eta N$$



$$M_{N^*} \simeq 1.685\,\mathrm{MeV}$$
$$\Gamma \leq 30\,\mathrm{MeV}$$

Used GRAAL Data but not official paper from the GRAAL Collaboration

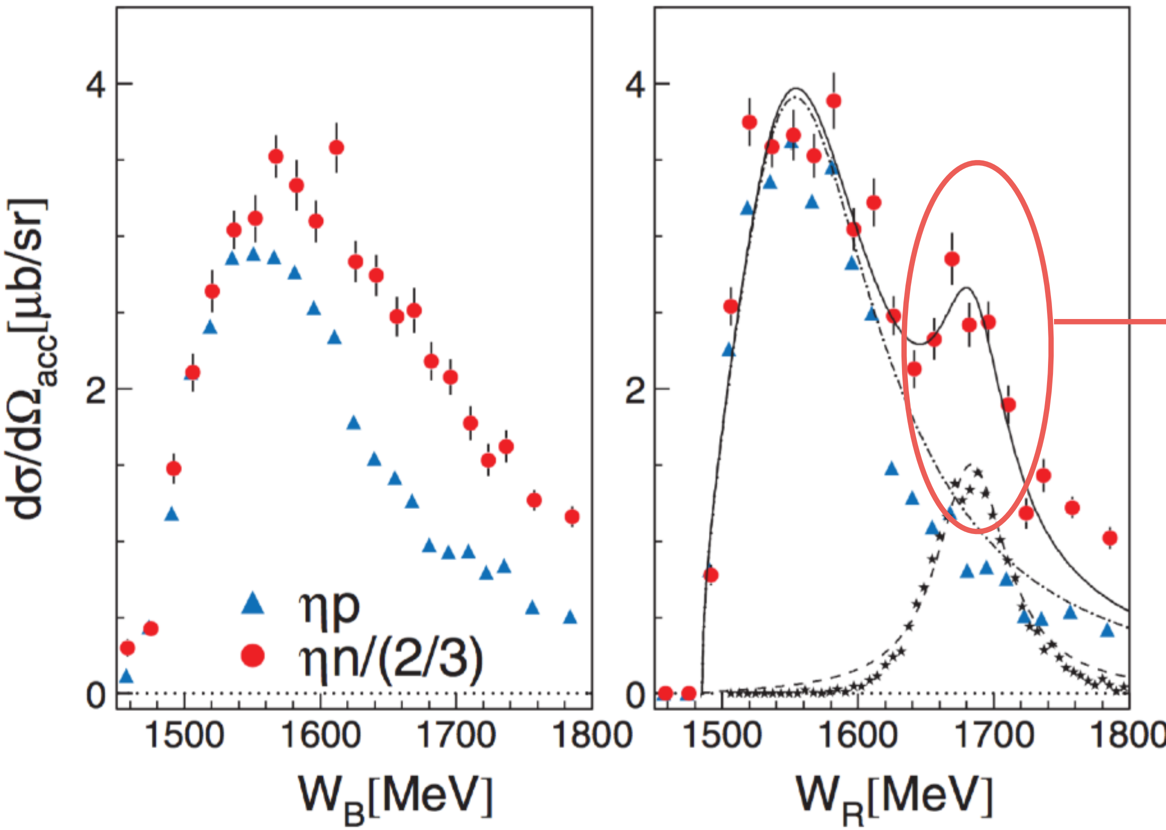
Pentaquark N*?



CBELSA (BONN ELSA)

Pentaquark N*?

CBELSA/TAPS Collaboration, PRL **100,** 252002 **(2008)**



$\gamma n \to \eta n$

$M \approx 1.68\,\mathrm{MeV}$

In $\gamma p \to \eta p$, it was almost not seen

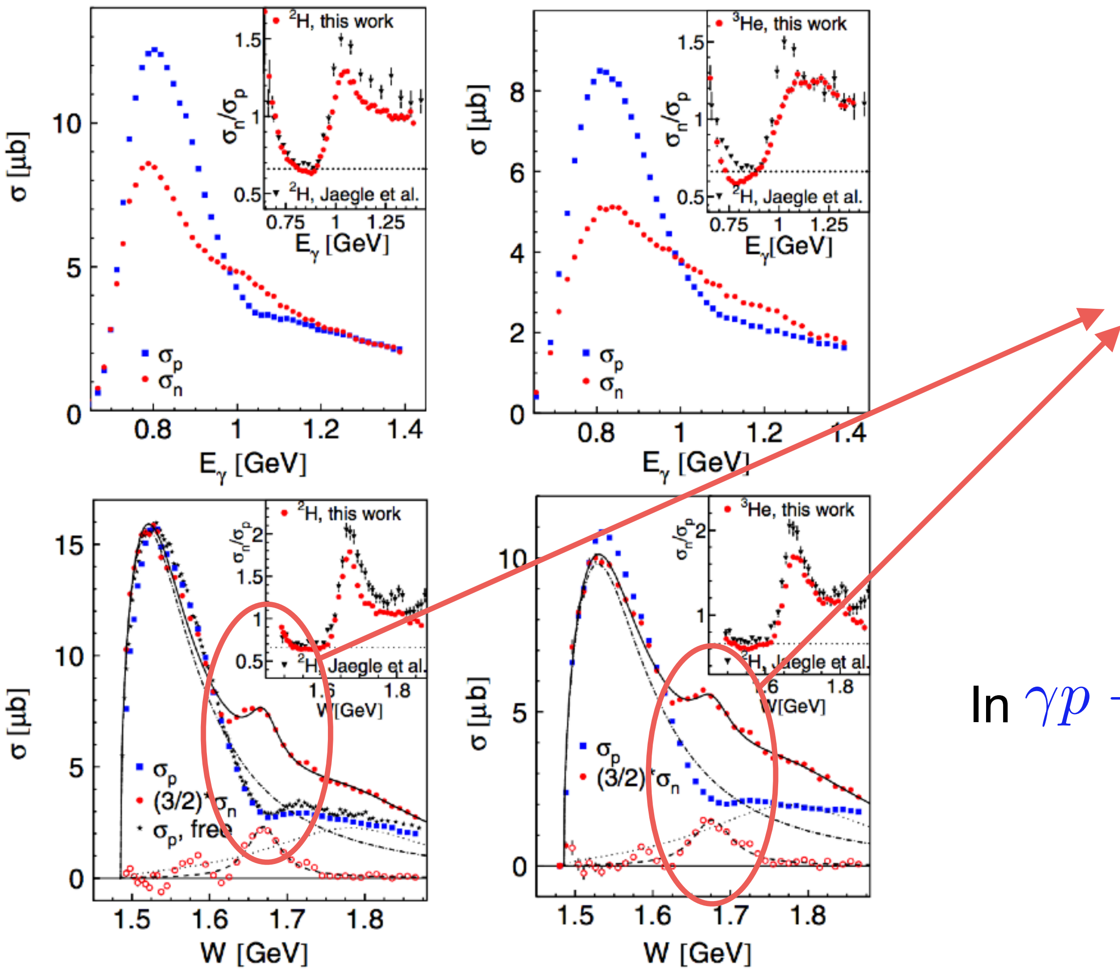
Isospin asymmetry

Neutron Anomaly

- Bn-Ga PWA: Interference effect between S11(1535) & S11(1650)?
- EtaMAID: Interference effects between *s*-, *p*-, and *d*-wave N*s?

A2 Experiment (Mainz MAMI)

A2 Collaboration, PRL **111**, 232001 **(2013)**



$\gamma n \to \eta n$

$M = (1670 \pm 5)\,\mathrm{MeV}$

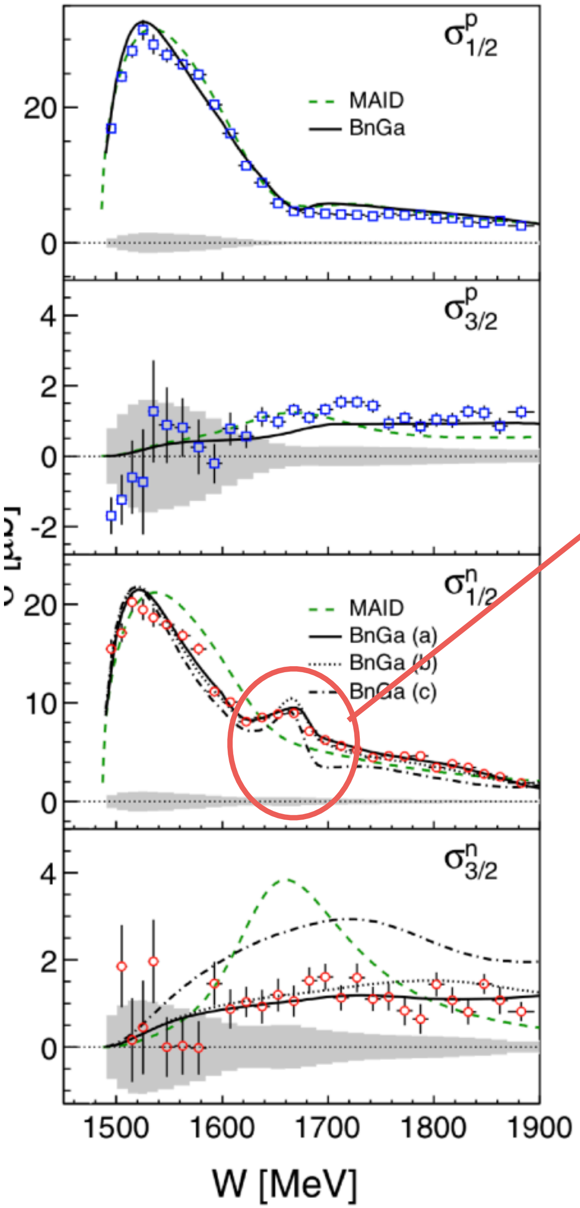
$\Gamma = (30 \pm 15)\,\mathrm{MeV}$

Neutron Anomaly

In $\gamma p \to \eta p$, it is not well seen.

Ockam’s razor: Simpler explanation is better than complicated ones.

A2 Experiment (Mainz MAMI)



A2 Collaboration, PRL **117,** 132502 **(2016)**

$$\gamma n \to \eta n$$

Neutron Anomaly

In $\gamma p \to \eta p$, it is not well seen.

"The results have unambiguously established that this structure is related to the helicity-1/2 amplitude and **a comparison of the angular dependence to different model predictions favors a scenario with a contribution from a narrow P_{11} resonance."**

Excerpt from PRL **117**, 132502 (**2016**)

Theory

G.S. Yang, **HChK**, Progress of Theoretical Physics, 128, 397 (**2012**)

Mass [MeV]		T_3	Y	Experiment[41]	Predictions
M_Δ	Δ^{++}	$3/2$	1	$1231-1233$	1248.54 ± 3.39
	Δ^{+}	$1/2$			1249.36 ± 3.37
	Δ^{0}	$-1/2$			1251.53 ± 3.38
	Δ^{-}	$-3/2$			1255.08 ± 3.37
M_{Σ^*}	Σ^{*+}	1	0	1382.8 ± 0.4	1388.48 ± 0.34
	Σ^{*0}	0		1383.7 ± 1.0	1390.66 ± 0.37
	Σ^{*-}	-1		1387.2 ± 0.5	1394.20 ± 0.34
$M_{\Xi^{*0}}$	Ξ^{*0}	$1/2$	-1	1531.80 ± 0.32	1529.78 ± 3.38
	Ξ^{*-}	$-1/2$		1535.0 ± 0.6	1533.33 ± 3.37
$M^{\star}_{\Omega^-}$	Ω^-	0	-2	1672.45 ± 0.29	Input

Interesting stories about this paper.

Mass		T_3	Y	Experiment	Predictions
M_{Θ^+}	Θ^+	0	2	1524 ± 5[15]	Input
M_{N^*}	p^*	$1/2$	1	1686 ± 12[28]	1688.18 ± 10.53
	n^*	$-1/2$			1692.16 ± 10.53
$M_{\Sigma_{\overline{10}}}$	$\Sigma^{+}_{\overline{10}}$	1	0		1852.35 ± 10.00
	$\Sigma^{0}_{\overline{10}}$	0			1856.33 ± 10.00
	$\Sigma^{-}_{\overline{10}}$	-1			1858.95 ± 10.00
$M_{\Xi_{3/2}}$	$\Xi^{+}_{3/2}$	$3/2$	-1		2016.53 ± 10.53
	$\Xi^{0}_{3/2}$	$1/2$			2020.51 ± 10.53
	$\Xi^{-}_{3/2}$	$-1/2$			2023.12 ± 10.53
	$\Xi^{--}_{3/2}$	$-3/2$			2024.37 ± 10.53

- **Together with Theta+, narrow N* is well explained.**
- **Complete analysis in the XQSM.**

Theory

G.S. Yang, **HChK**, ArXiv:1809.07489
(Second paper at ASRC, JAEA)

Prediction with no free parameter!

$\mathcal{R}_J$	$B_i \to \varphi + B_f$	$f^{(0)}_{\varphi B_f B_i}$	$f^{(tot)}_{\varphi B_f B_i}$	$\Gamma^{(0)}_{\varphi B_f B_i}$ [MeV]	$\Gamma^{(tot)}_{\varphi B_f B_i}$ [MeV]
	$\Theta \to K + N$	-0.22 ± 0.03	-0.54 ± 0.04	0.10 ± 0.03	0.59 ± 0.1
$\overline{10}_{1/2}$	$N^* \to \pi + N$	-0.04 ± 0.01	-0.17 ± 0.01	0.42 ± 0.12	8.34 ± 1.03
	$N^* \to \eta + N$	0.96 ± 0.11	1.95 ± 0.20	5.37 ± 1.31	22.09 ± 4.89
	$N^* \to K + \Lambda$	-0.11 ± 0.02	-0.16 ± 0.02	0.02 ± 0.01	0.05 ± 0.02
	$N^* \to K + \Sigma$	-0.11 ± 0.02	0.055 ± 0.024	0.0001 ± 0.0008	~ 0.00003
$27_{3/2}$	$N_{27} \to \pi + N$	-0.11 ± 0.01	0.04 ± 0.01	4.2 ± 0.1	0.6 ± 0.1
	$N_{27} \to \eta + N$	0.43 ± 0.18	1.61 ± 0.27	1.3 ± 1.1	18.7 ± 6.2
	$N_{27} \to K + \Lambda$	-1.01 ± 0.02	-0.93 ± 0.02	3.2 ± 0.3	2.7 ± 0.3
	$N_{27} \to K + \Sigma$	0.34 ± 0.01	0.61 ± 0.02	0.06 ± 0.02	0.19 ± 0.07
	$\Delta_{27} \to \pi + N$	-0.36 ± 0.01	-0.56 ± 0.01	41.7 ± 1.2	102.5 ± 3.2
	$\Delta_{27} \to K + \Sigma$	-1.07 ± 0.02	-0.39 ± 0.02	0.60 ± 0.20	0.09 ± 0.03

It explains why the eta channel is most preferable to measure N*(1685)!

Theory

G.S. Yang, **HChK**, ArXiv:1809.07489
(Second paper at ASRC, JAEA)

Prediction with no free parameter!

$B_{\overline{10}} \to \gamma + B_8$	$\mu^{(0)}_{B_f B_i}$	$\mu^{(tot)}_{B_f B_i}$	$\Gamma^{(tot)}_{\gamma B_f B_i}$ [keV]
$p^* \to \gamma + p$	0	0.15 ± 0.04	18.78 ± 0.52
$n^* \to \gamma + n$	-0.38 ± 0.08	-0.44 ± 0.09	161.83 ± 64.72
$B_{27}\,[J = 3/2] \to \varphi + B_8$	$\mu^{(0)}_{B_f B_i}$	$\mu^{(tot)}_{B_f B_i}$	$\Gamma^{(tot)}_{\gamma B_f B_i}$ [MeV]
$p_{27} \to \gamma + p$	-0.93 ± 0.04	-0.75 ± 0.05	1.43 ± 0.19
$n_{27} \to \gamma + n$	-0.46 ± 0.02	-0.38 ± 0.02	0.38 ± 0.04
$\Delta^+_{27} \to \gamma + p$	-1.04 ± 0.04	-1.71 ± 0.08	2.66 ± 0.26
$\Delta^0_{27} \to \gamma + n$	-1.04 ± 0.04	-1.71 ± 0.08	2.68 ± 0.26

$$\frac{\Gamma_{n^* \to n\gamma}}{\Gamma_{p^* \to p\gamma}} \approx 9!$$

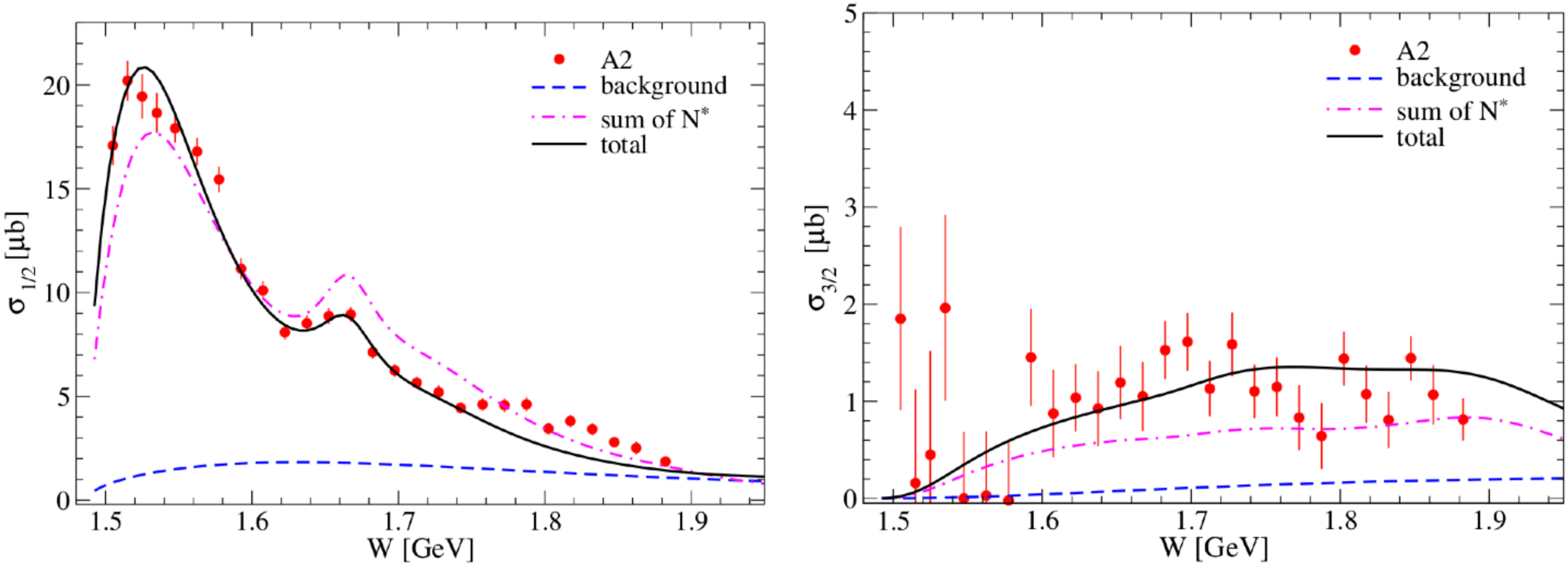
It clearly explains the **neutron anomaly**!

Yet another evidence of N*(1685)

J.-M. Suh, S.H. Kim, **HChK**, arXiv:1810.05056
(Third paper at ASRC, JAEA)

$$\gamma + n \rightarrow \eta + n$$

Comparison with the A2 data



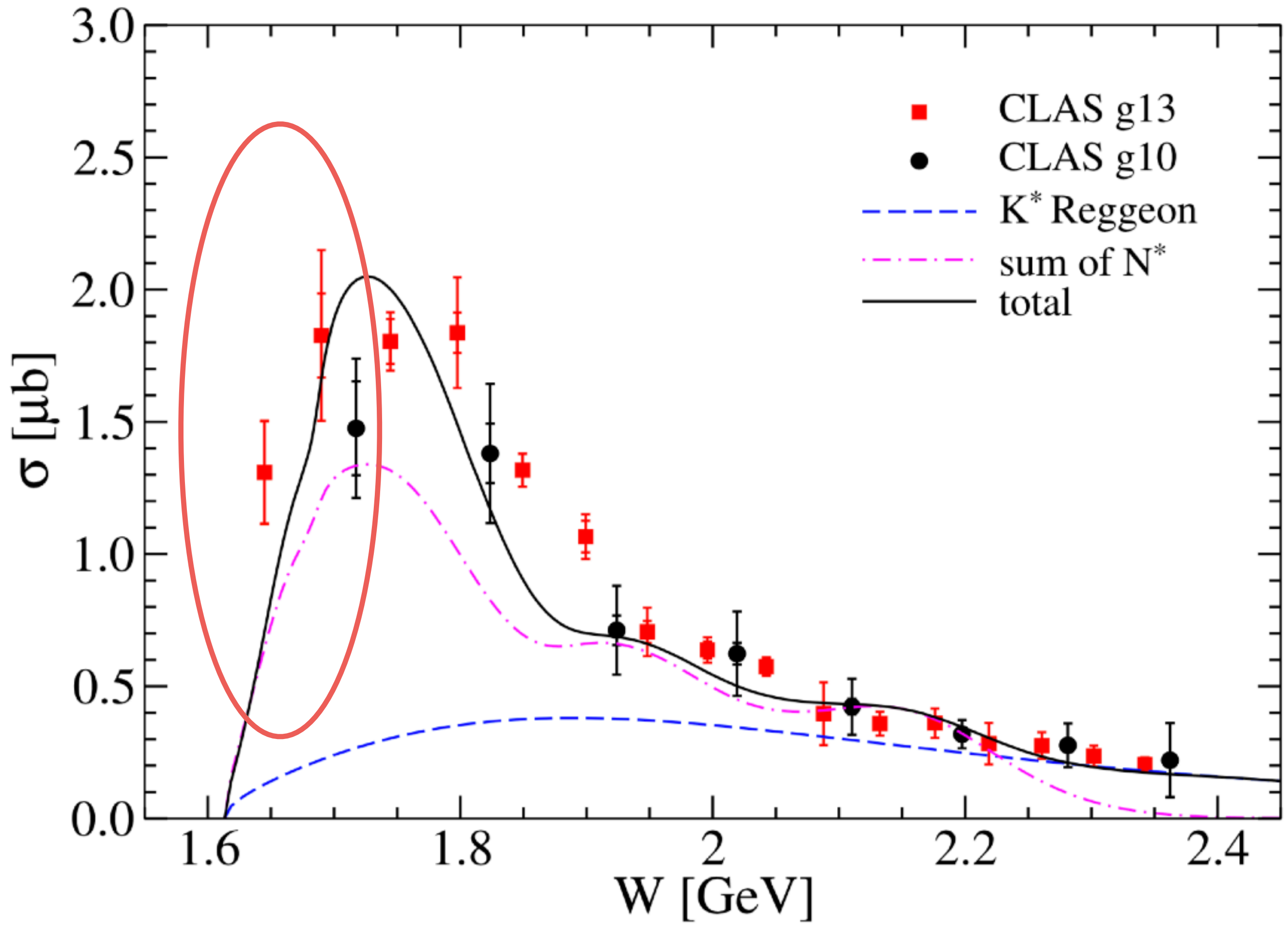
16 N*s included together with N(1685). Very constrained model based on the effective Lagrangians and Regge approach.

Yet another evidence of N∗(1685)

S.H. Kim, **HChK**, PLB 786 (2018) 156 (First paper published, staying at ASRC)

$\gamma n \to K^0 \Lambda$

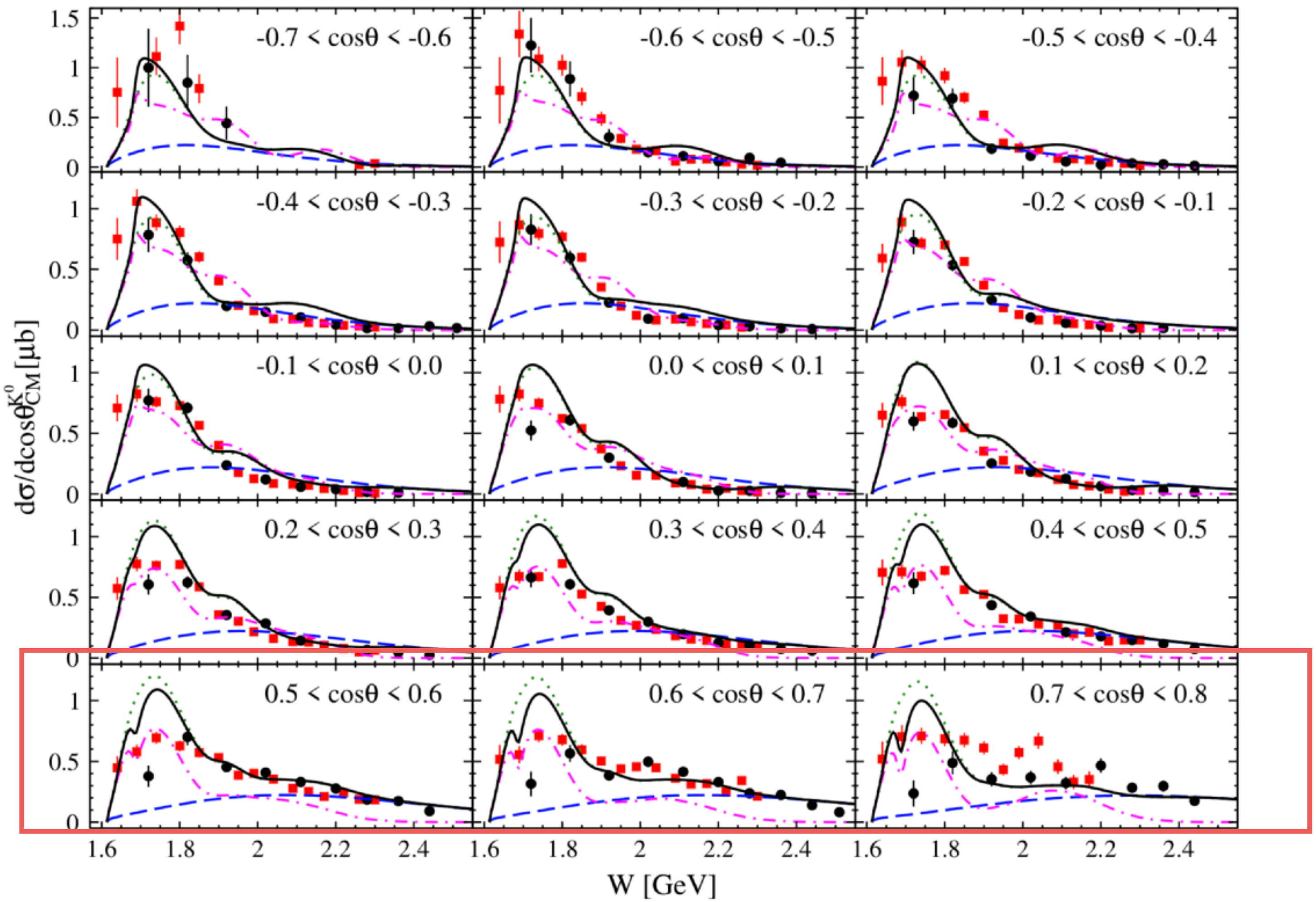
Comparison with the ClAS data



Yet another evidence of N∗(1685)

S.H. Kim, **HChK**, PLB 786 (2018) 156 (First paper published, staying at ASRC)

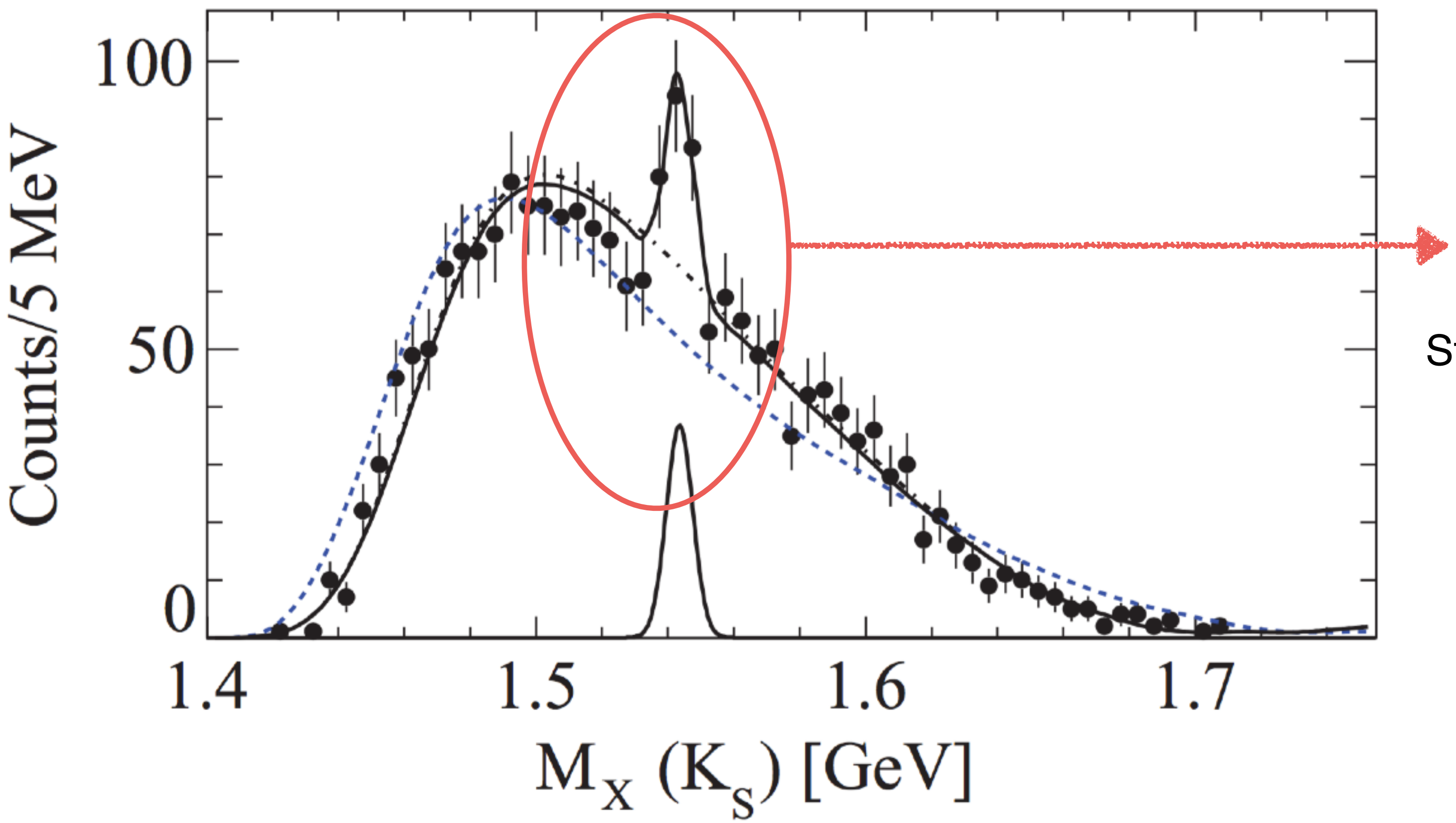
$\gamma n \to K^0 \Lambda$



Comparison with the CIAS data

Renegades

M.J. Amaryan et al., PHYSICAL REVIEW C **85**, 035209 **(2012)**



$M_\Theta = 1.53\,\mathrm{MeV}$

Statistical significance

6σ

- CLAS Data was reanalyzed. A complementary analysis: Used interference with phi.
- Scientific Director allowed it to go.

Failure in cracking down on renegades

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)

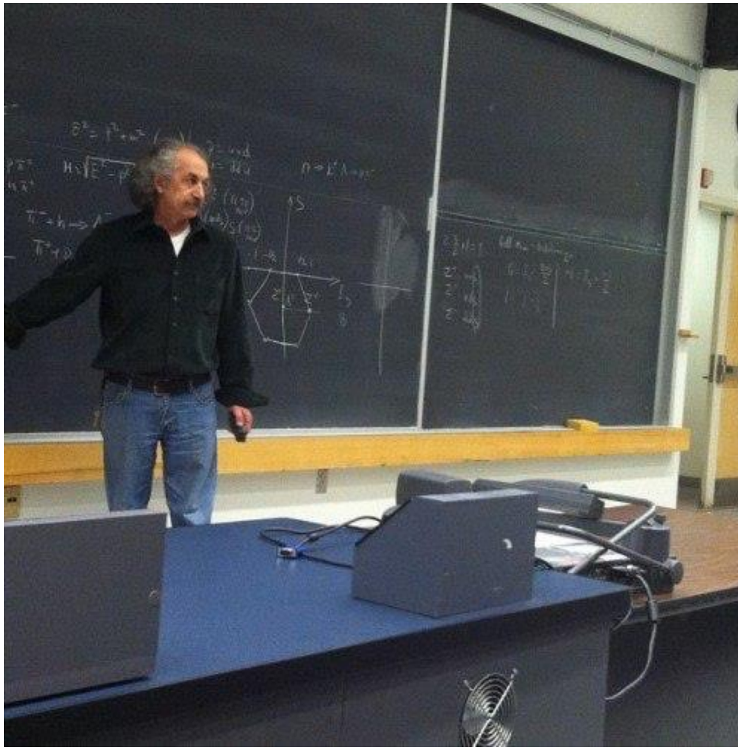
ArXiv:1204.1105

Prof. Kim said, “They are renegades!”

But this paper was **rejected** by Physical Review C!

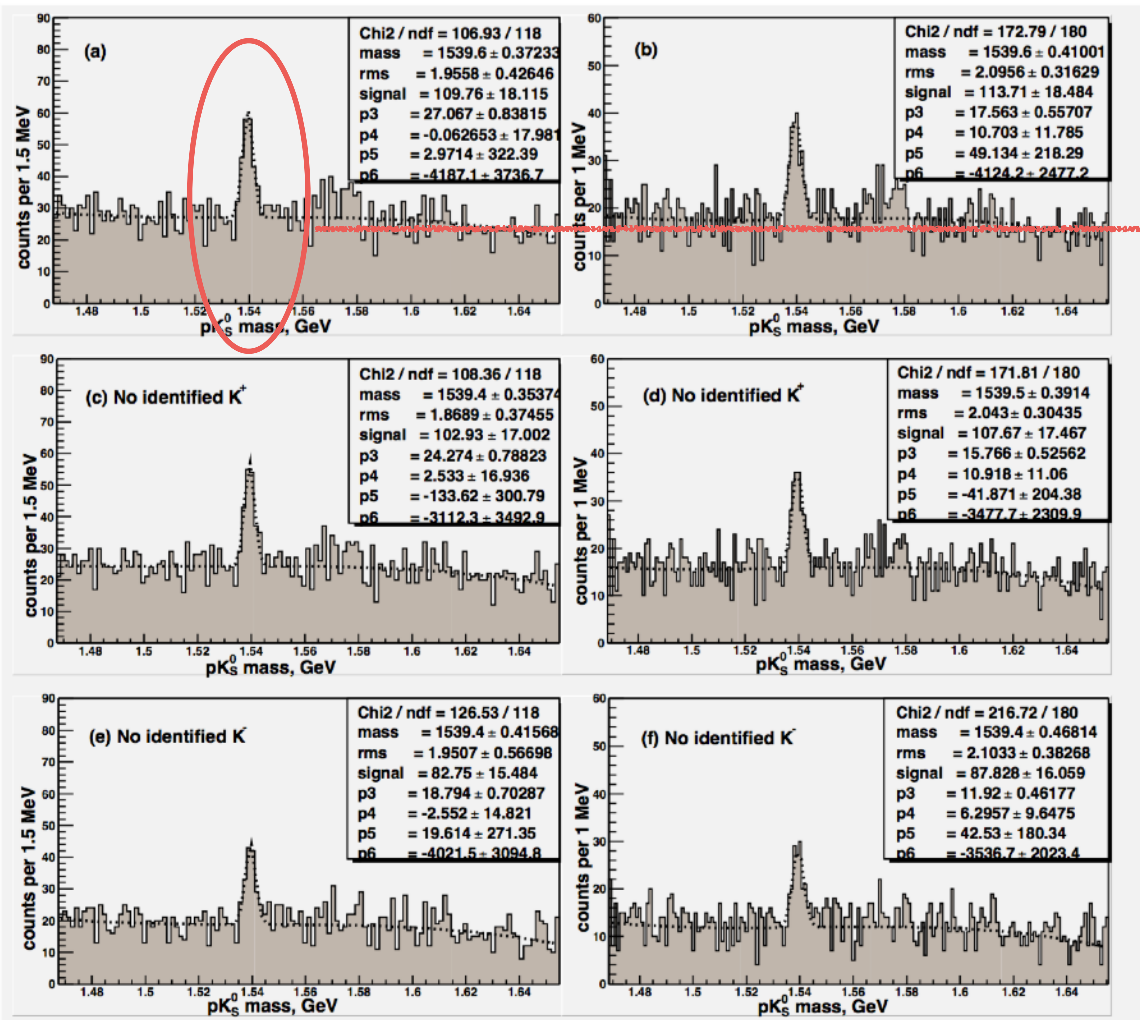
Moskov J. Amaryan

Moskov. J. Amaryan (Old Dominion Univ., an experienced experimentalist)



- Amaryan analyzed the same CLAS data with null results and found **10 sigma peak for the Theta+**. However, he gave up publishing it because committees were against it even though they found no single mistake in his analysis.
- Nov. 2017, in an interview: “If nobody wants it, then either you go up to a mountain and hang yourself or simply do another job.”

새로운 결과



Aug. 2016
ArXiv:1608.08523

$$M_{\Theta^+} = 1539.6\,\mathrm{MeV}$$

SELEX Experiment at Fermi Lab
Cu was used as a target.

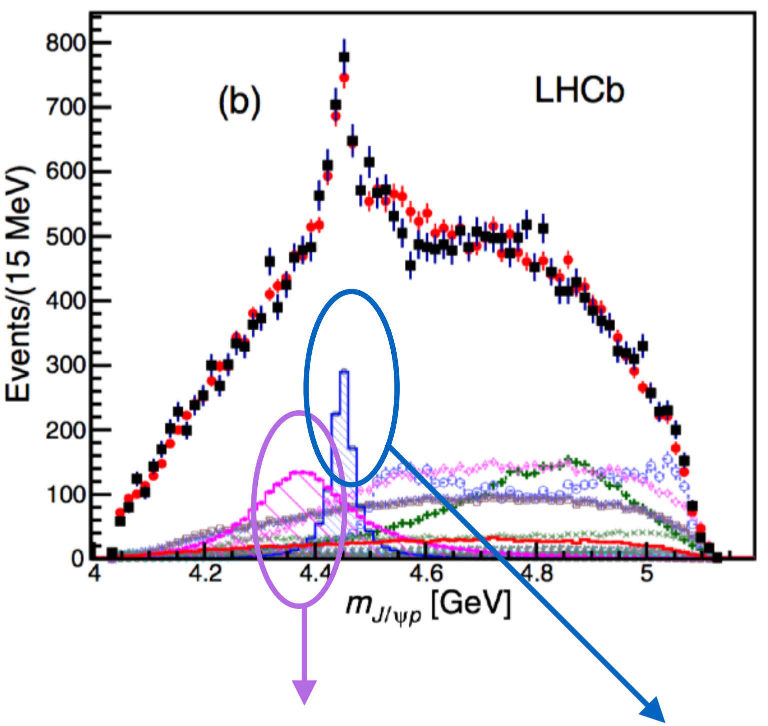
Caveat! It was seen only in a specific kinematical region.

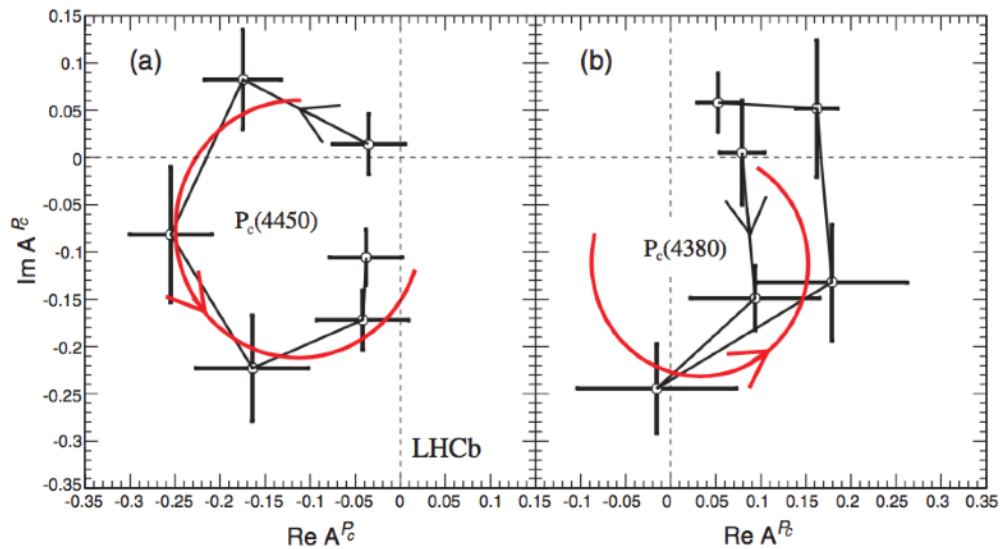
Negative experimental results continued to appear after 2010.

Finding of Heavy Pentaquarks

Heavy Pentaquarks

LHCb Collaboration, PRL 115, 072001 (**2015**)





Pc(4380)

Pc(4450)

Wide decay widths

Narrow decay widths: a typical signature of the pentaquarks

The world was shaken once again

theguardian

What does a pentaquark mean for you?

Jon Butterworth

Almost - but not quite - buried on the icy plains of Pluto this week, the Large Hadron Collider revealed a completely new type of particle. What does that tell us?

Saturday 18 July 2015 18.35 BST

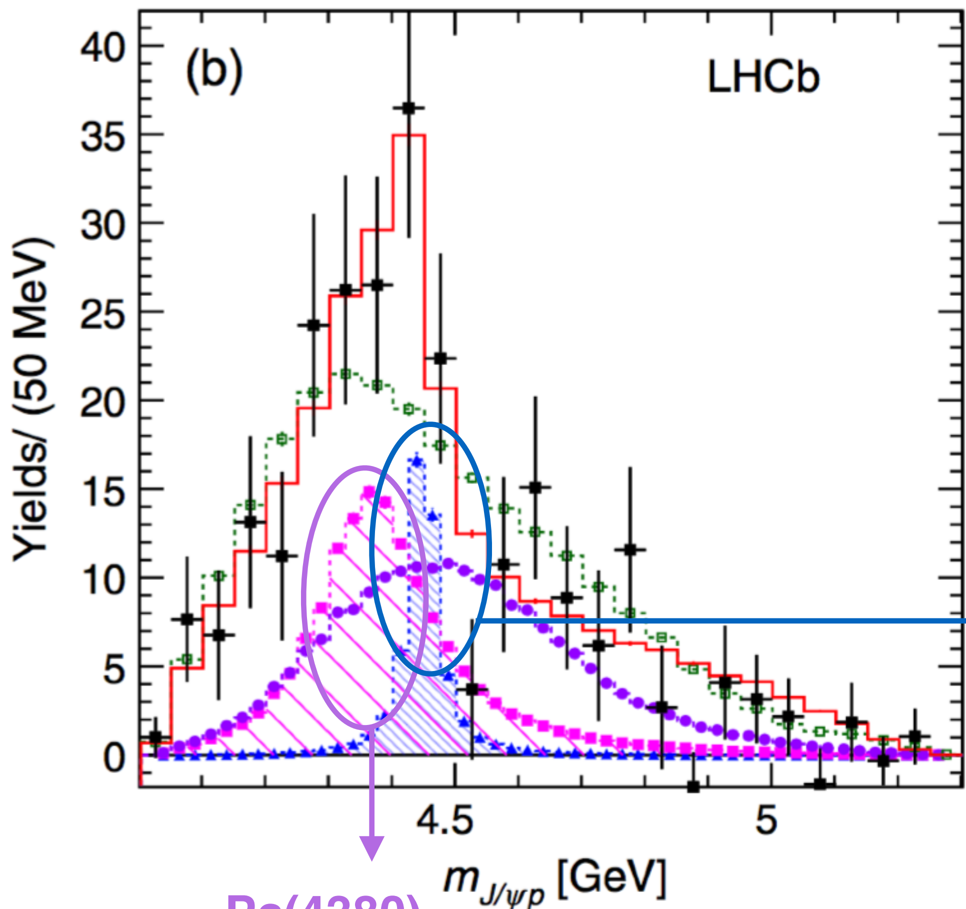
Perhaps the first thing it tells us is that scientists at CERN are more focused on their results than on the attendant publicity, whatever the press office might advise them. New Horizons has been on the way to Pluto for more than nine years, and the data in which the pentaquark was discovered were recorded by the LHCb experiment more than three years ago, so you might think they could have arranged things to avoid announcing the new particle on the same day as this. As a friend on the experiment put it, it "Shows how focussed we were on the science."

Of more lasting importance, the discovery tells us something about the strong nuclear force and the way the smallest constituents of matter behave.

Heavy pentaquarks

LHCb Collaboration, PRL 117, 082003 **(2016)**

Confirmation of the 2015 data



- Light pentaquark was never mentioned in the paper.
- In fact, the first draft contained them.

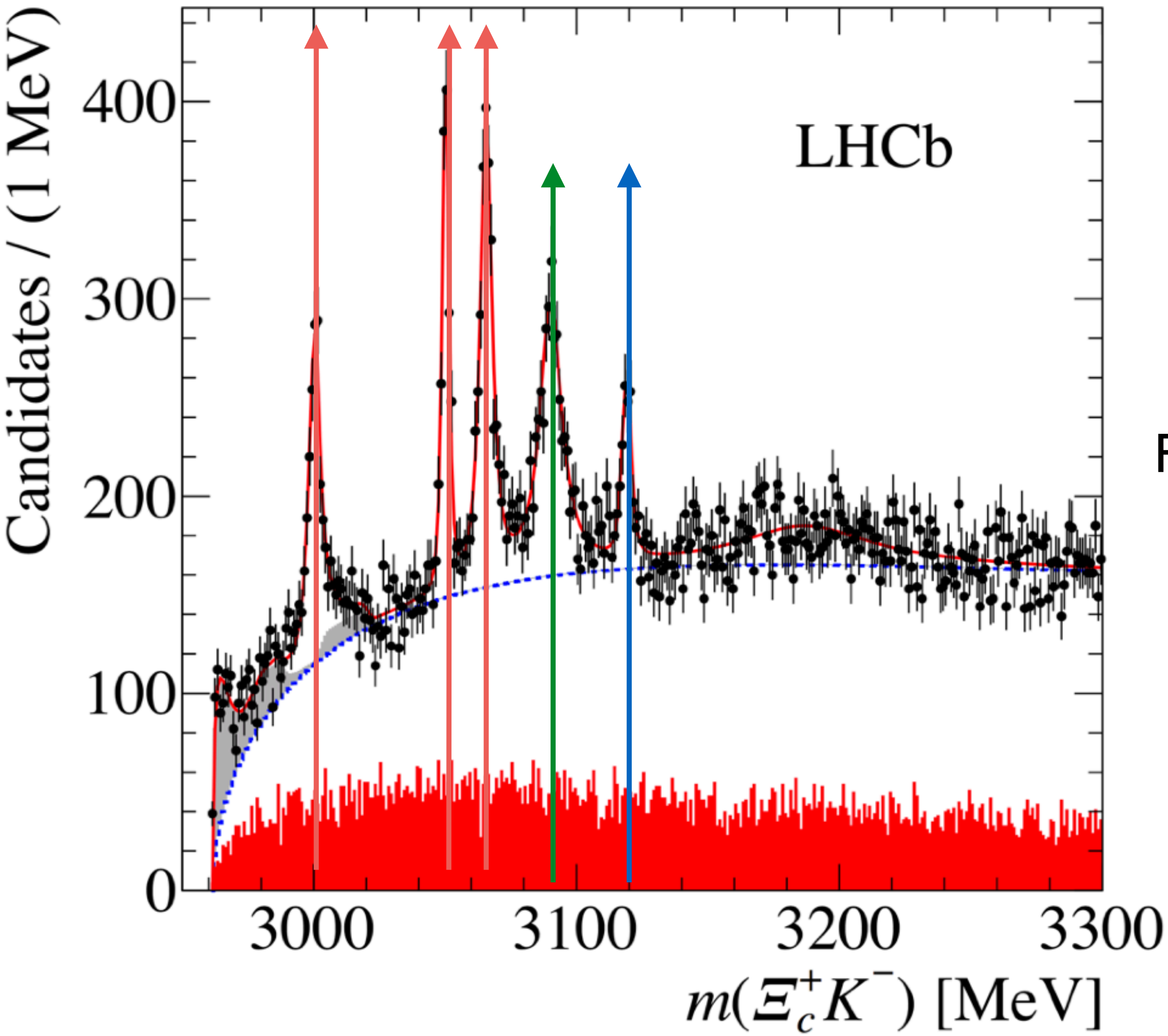
Pc(4450)

Narrow decay widths

Pc(4380)

Large decay widths

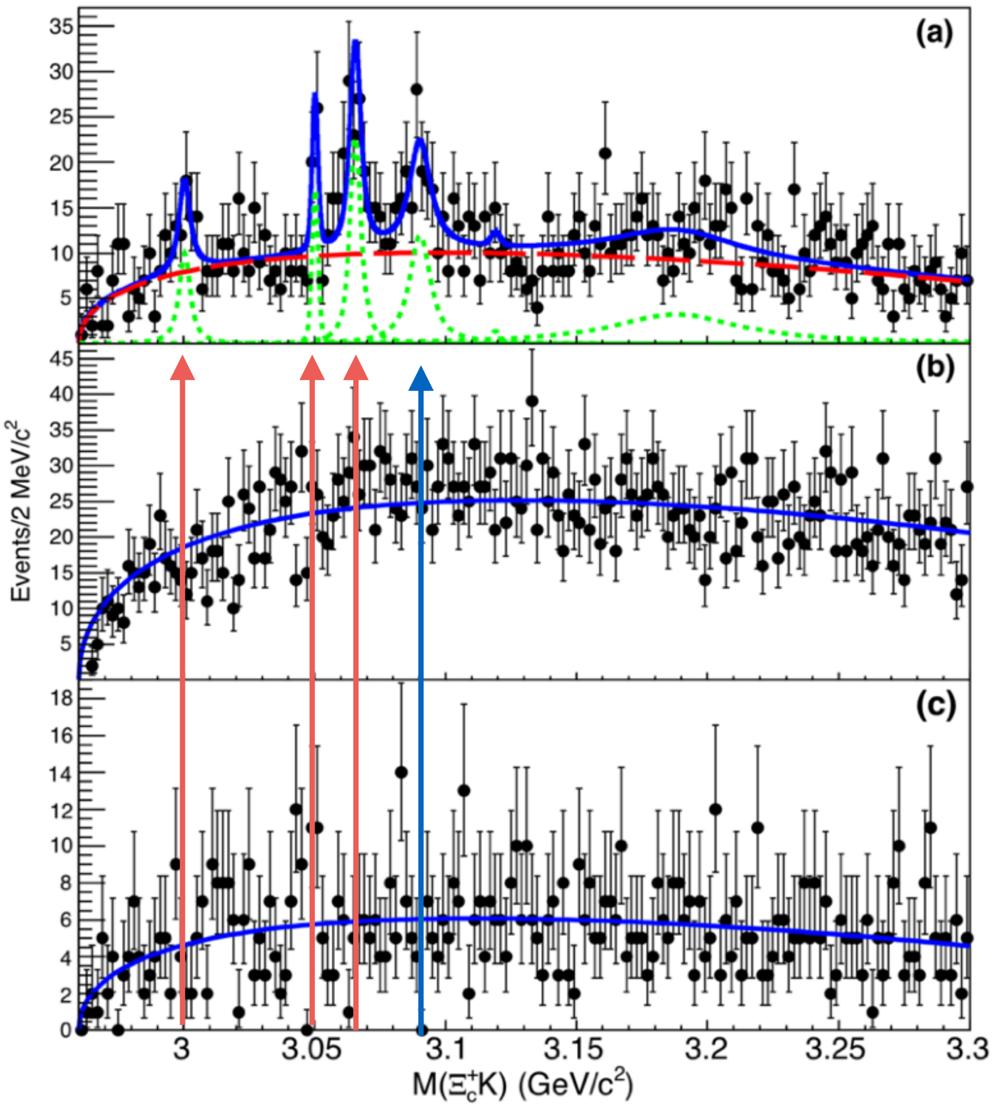
Five Omega_cs' were found by LHCb!



Five Ω_cs were found!

LHCb Collaboration, PRL 118 (2017) 182001

Four Omega_cs' were confirmed by Belle!



Four Ω_cs were confirmed by Belle Coll.

Belle Collaboration, hep-ex 1711.07927

Masses and decay widths of Omega_cs

The Widths are rather small, even if we consider the fact that heavy baryons have smaller widths than light ones.

Resonance	Mass (MeV)	Γ (MeV)	Yield	N_σ
$\Omega_c(3000)^0$	$3000.4 \pm 0.2 \pm 0.1^{+0.3}_{-0.5}$	$4.5 \pm 0.6 \pm 0.3$	$1300 \pm 100 \pm 80$	20.4
$\Omega_c(3050)^0$	$3050.2 \pm 0.1 \pm 0.1^{+0.3}_{-0.5}$	$0.8 \pm 0.2 \pm 0.1$	$970 \pm 60 \pm 20$	20.4
		$< 1.2\,\mathrm{MeV}, 95\%$ CL		
$\Omega_c(3066)^0$	$3065.6 \pm 0.1 \pm 0.3^{+0.3}_{-0.5}$	$3.5 \pm 0.4 \pm 0.2$	$1740 \pm 100 \pm 50$	23.9
$\Omega_c(3090)^0$	$3090.2 \pm 0.3 \pm 0.5^{+0.3}_{-0.5}$	$8.7 \pm 1.0 \pm 0.8$	$2000 \pm 140 \pm 130$	21.1
$\Omega_c(3119)^0$	$3119.1 \pm 0.3 \pm 0.9^{+0.3}_{-0.5}$	$1.1 \pm 0.8 \pm 0.4$	$480 \pm 70 \pm 30$	10.4
		$< 2.6\,\mathrm{MeV}, 95\%$ CL		
$\Omega_c(3188)^0$	$3188 \pm 5 \pm 13$	$60 \pm 15 \pm 11$	$1670 \pm 450 \pm 360$	
$\Omega_c(3066)^0_{\mathrm{fd}}$			$700 \pm 40 \pm 140$	
$\Omega_c(3090)^0_{\mathrm{fd}}$			$220 \pm 60 \pm 90$	
$\Omega_c(3119)^0_{\mathrm{fd}}$			$190 \pm 70 \pm 20$	

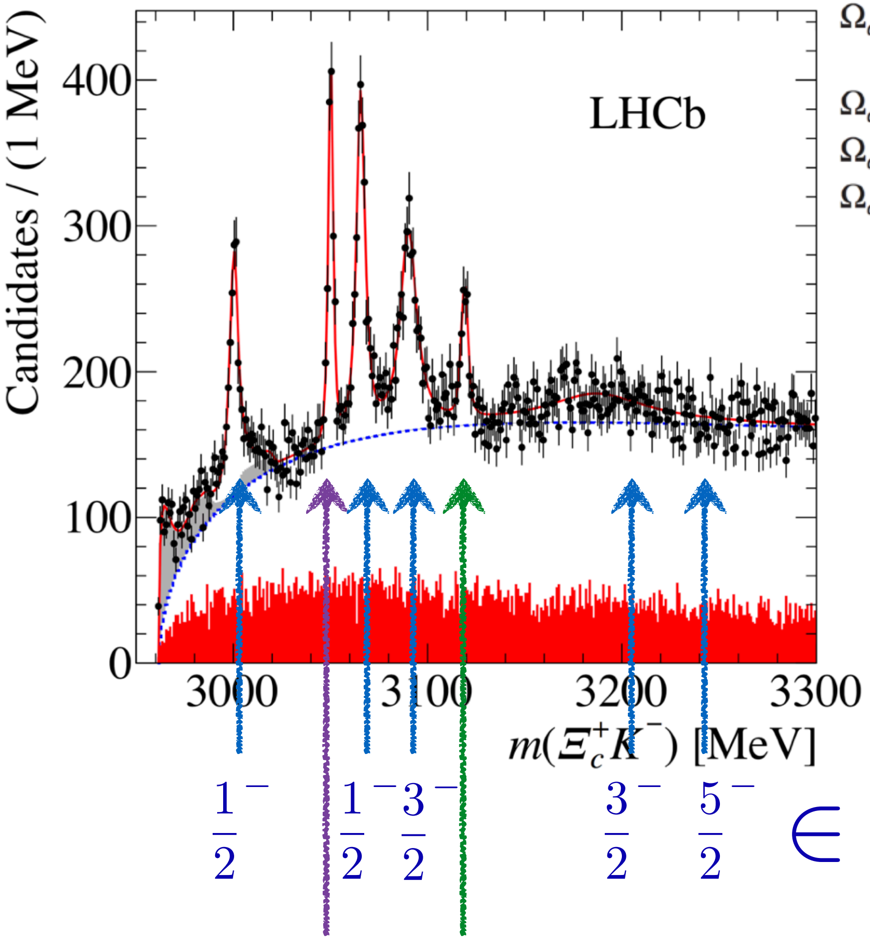
LHCb Collaboration, 2007

Ω_c Excited State	3000	3050	3066	3090	3119	3188
Yield	37.7 ± 11.0	28.2 ± 7.7	81.7 ± 13.9	86.6 ± 17.4	3.6 ± 6.9	135.2 ± 43.0
Significance	3.9σ	4.6σ	7.2σ	5.7σ	0.4σ	2.4σ
LHCb Mass	$3000.4 \pm 0.2 \pm 0.1$	$3050.2 \pm 0.1 \pm 0.1$	$3065.5 \pm 0.1 \pm 0.3$	$3090.2 \pm 0.3 \pm 0.5$	$3119 \pm 0.3 \pm 0.9$	$3188 \pm 5 \pm 13$
Belle Mass (with fixed Γ)	$3000.7 \pm 1.0 \pm 0.2$	$3050.2 \pm 0.4 \pm 0.2$	$3064.9 \pm 0.6 \pm 0.2$	$3089.3 \pm 1.2 \pm 0.2$	-	$3199 \pm 9 \pm 4$

Belle Collaboration, hep-ex 1711.07927

LHCb data의 해석

From the chiral quark-soliton model



Resonance	Mass (MeV)	Γ (MeV)
$\Omega_c(3000)^0$	$3000.4 \pm 0.2 \pm 0.1^{+0.3}_{-0.5}$	$4.5 \pm 0.6 \pm 0.3$
$\Omega_c(3050)^0$	$3050.2 \pm 0.1 \pm 0.1^{+0.3}_{-0.5}$	$0.8 \pm 0.2 \pm 0.1$ <1.2 MeV, 95% C.L.
$\Omega_c(3066)^0$	$3065.6 \pm 0.1 \pm 0.3^{+0.3}_{-0.5}$	$3.5 \pm 0.4 \pm 0.2$
$\Omega_c(3090)^0$	$3090.2 \pm 0.3 \pm 0.5^{+0.3}_{-0.5}$	$8.7 \pm 1.0 \pm 0.8$
$\Omega_c(3119)^0$	$3119.1 \pm 0.3 \pm 0.9^{+0.3}_{-0.5}$	$1.1 \pm 0.8 \pm 0.4$

J	S^P	M [MeV]	κ'/m_c [MeV]	Δ_J [MeV]
0	$\frac{1}{2}^-$	3000	–	–
1	$\frac{1}{2}^-$	3066	24	82
	$\frac{3}{2}^-$	3090		
2	$\frac{3}{2}^-$	*3222*	input	input
	$\frac{5}{2}^-$	*3262*	24	164

$\frac{1}{2}^-$ $\frac{1}{2}^-$ $\frac{3}{2}^-$ $\frac{3}{2}^-$ $\frac{5}{2}^-$ $\in \mathbf{6'}$

$\frac{1}{2}^+$ $\frac{3}{2}^+$ $\in \overline{\mathbf{15}}$ $\Omega_c(3050)$ & $\Omega_c(3119)$

How can one falsify the present idea?

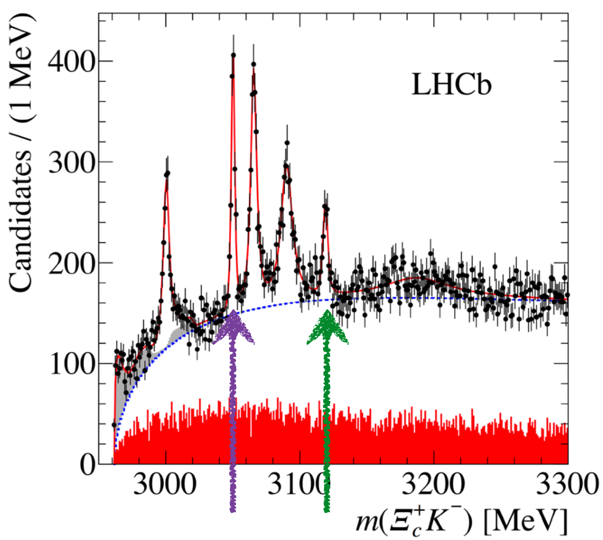
PRL **118,** 182001 (2017) PHYSICAL REVIEW LETTERS week ending 5 MAY 2017

Observation of Five New Narrow Ω_c^0 States Decaying to $\Xi_c^+ K^-$

R. Aaij *et al.*[*]
(LHCb Collaboration)

(Received 14 March 2017; published 2 May 2017)

- Anti-15plet consists of **three** Omega_cs (Isovector baryons).
- The same peaks with the same strength can be found not only in the $\Xi_c^+ K^-$ channel but also in $\Xi_c^+ K^0$ and $\Xi_c^0 K^-$.



$\Omega_c(3050)$ & $\Omega_c(3119)$

HChK, Polyakov, Praszalowicz, PRD, D96, 039902 (2017).

HChK, Polyakov, Praszalowicz, Yang, PRD, D96, 094021 (2017).

Return of the light Pentaquarks… When?

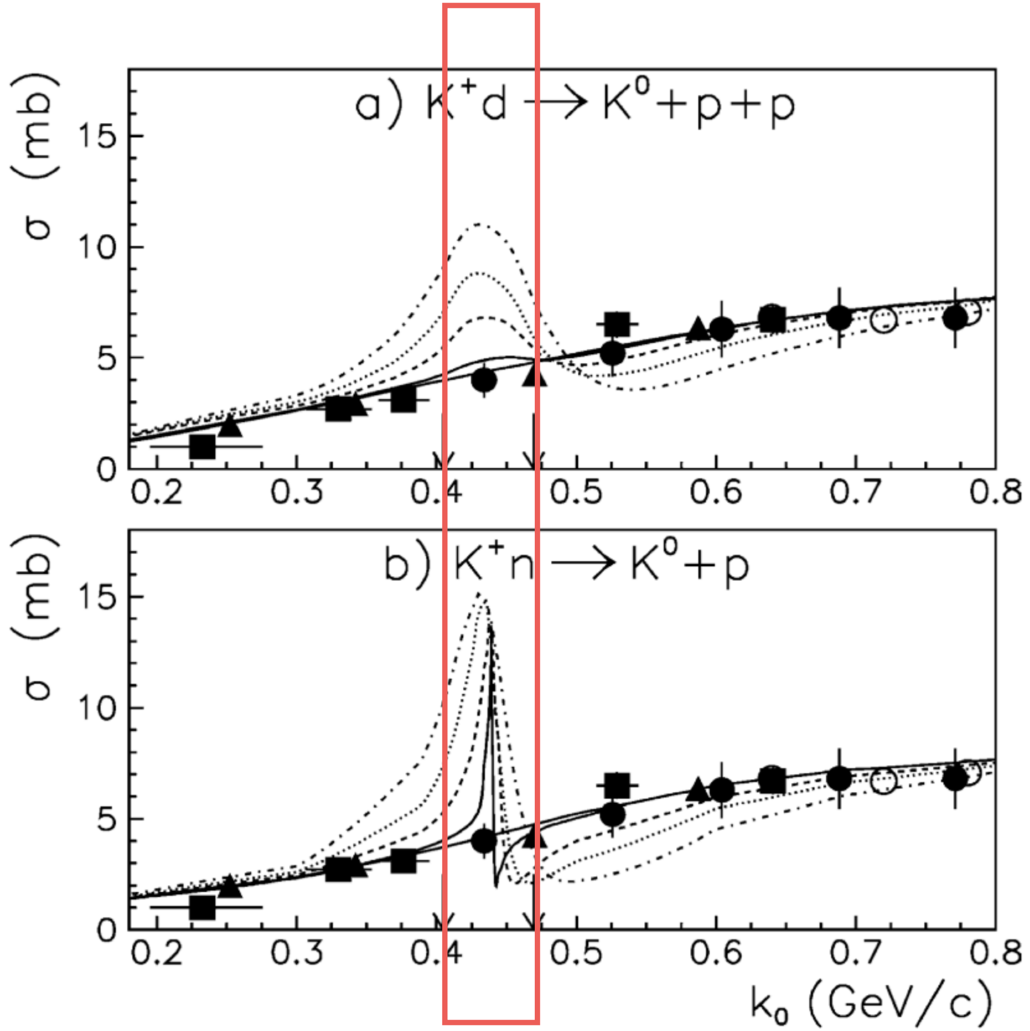
An ultimate experiment

$$K^+ d \to K^+ np$$

and/or

$$K^+ d \to K^0 pp$$

The Ultimate & Golden Experiment



Window to find Theta+

$k_0 \sim 420\,\mathrm{MeV}/c \to M_{\Theta^+}$

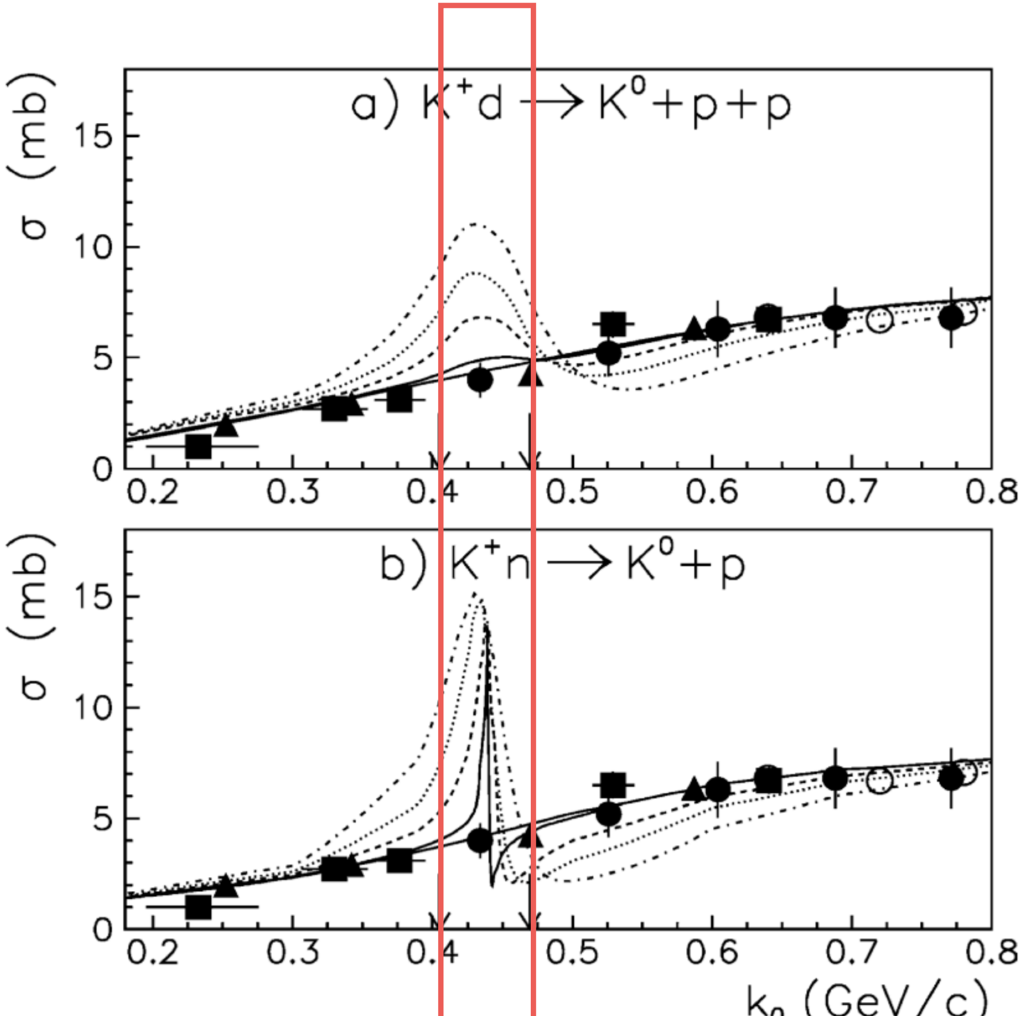
Initial kaon momentum

- ● C.J.S. Damerell, et al., NPB 94 (1975) 374
- ■ W. Slater, et al., PRL. 7 (1961) 378
- ▲ R.G. Glasser, et al., PRD 15 (1977) 1200
- ○ G. Giacomelli, et al., NPB 42 (1972) 437; G. Giacomelli, et al., NPB 37 (1972) 577

→ Very old experimental data!

Sibirtsev et al. Phys. Lett. **B** 599 (2004) 230.

The Ultimate & Golden Experiment



Window to find Theta+

Sibirtsev et al. Phys. Lett. **B** 599 (2004) 230.

$$\Gamma_{\Theta^+} \lesssim 0.5\,\mathrm{MeV}!$$

No wonder why one cannot see it in the old data.

↓

They will be very challenging experiments!

↓

High Risk, High Return?

Sekihara, HChK, Hosaka in theoretical discussion.

Questions & Conclusions

- Nobody explained what those signals were, if they were not pentaquarks.
- **What were those positive signals? Fluctuations?**
- If the Theta+ exists, its width should be extremely small (< 1 MeV).
- Unexpected hysterical and irrational reactions against Theta+
  (A personal experience in HNP 2013)
- Yet another experience at JLAB workshop
- In order to restore scientific mind on Theta+, we need the ultimate experiments that can be performed only at J-PARC.
- If it turns out that it does not exist, then we will be still happy and finally can have tight sleep.
  If it is found to exist, then it will be historical and reopen the case.
- Heavy pentaquarks: There would be a great number of them.
  (We may need Volume 2 of PDG)

The report of my death was an Exaggeration.

-Mark Twain-

Though this be madness, yet there is method in it.

Hamlet Act 2, Scene 2

Thank you very much!