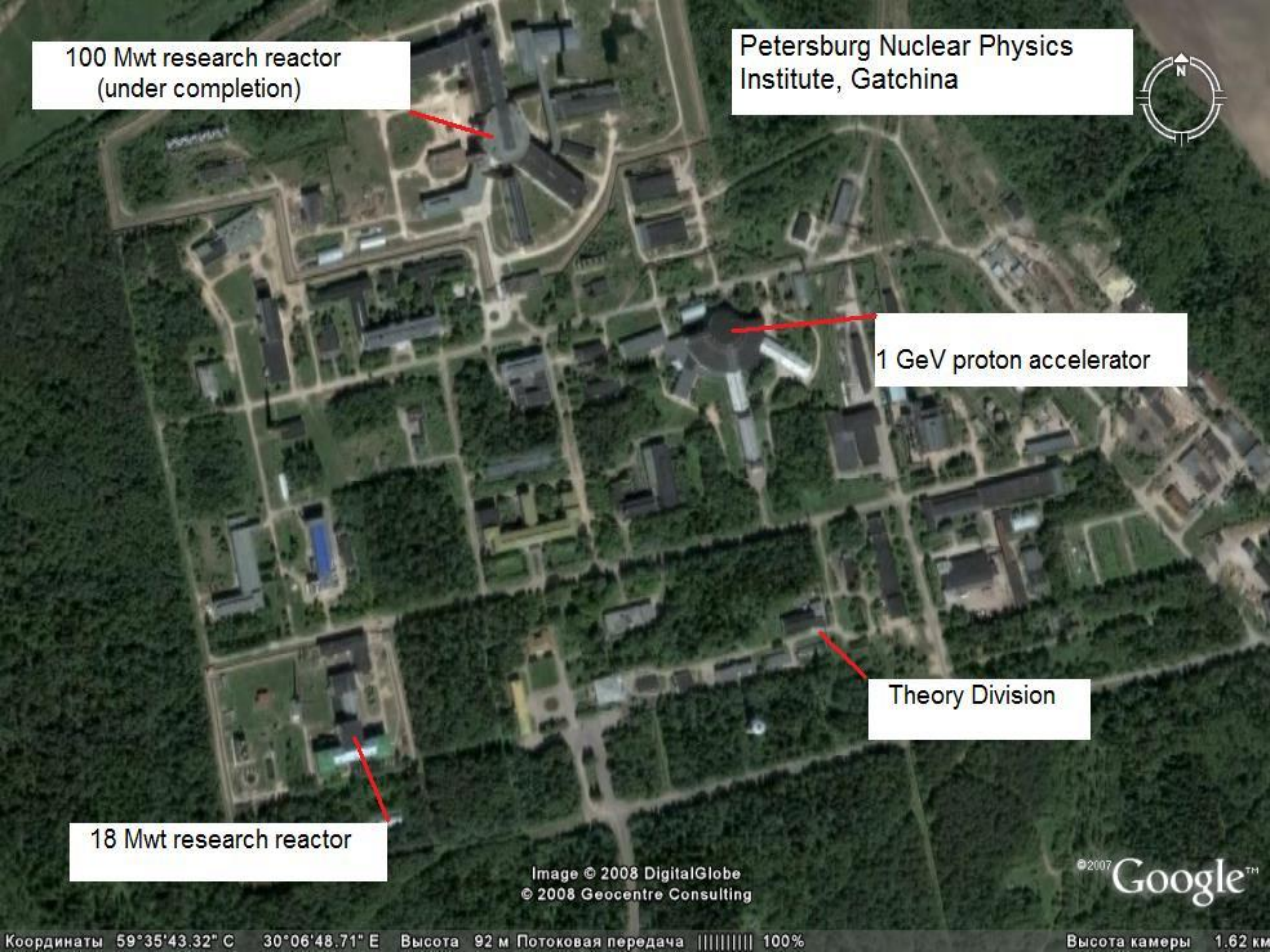
Bochum
March 16, 2009

Pentaquark Θ^+: where are we now?

Dmitri Diakonov
Petersburg Nuclear Physics Institute


100 Mwt research reactor (under completion)
Petersburg Nuclear Physics Institute, Gatchina
N
1 GeV proton accelerator
Theory Division
18 Mwt research reactor
Image © 2008 DigitalGlobe
© 2008 Geocentre Consulting
©2007 Google™
Координаты 59°35'43.32" С 30°06'48.71" E Высота 92 м Потоковая передача ||||||||| 100%
Высота камеры 1.62 км

History

$$\Theta^+ \to K^+ n, K^0 p, \; \Theta^+ = uudd\bar{s}$$

The «exotic» baryon Θ^+ that cannot be made of 3 quarks but minimally of 5 (the “pentaquark”), has been predicted in 1997 by Diakonov, Petrov and Polyakov [Zeit. Phys. A359 (1997) 305] as a light and narrow resonance:

$$m_\Theta \approx 1530\,\text{MeV}, \quad \Gamma_\Theta < 15\,\text{MeV}$$

This prediction initiated two independent searches, and at the end of 2002 the LEPS group lead by T. Nakano (Osaka) and the DIANA group lead by A. Dolgolenko (ITEP) announced seeing the resonance with the predicted mass and very narrow width. We suggested the name Θ^+.

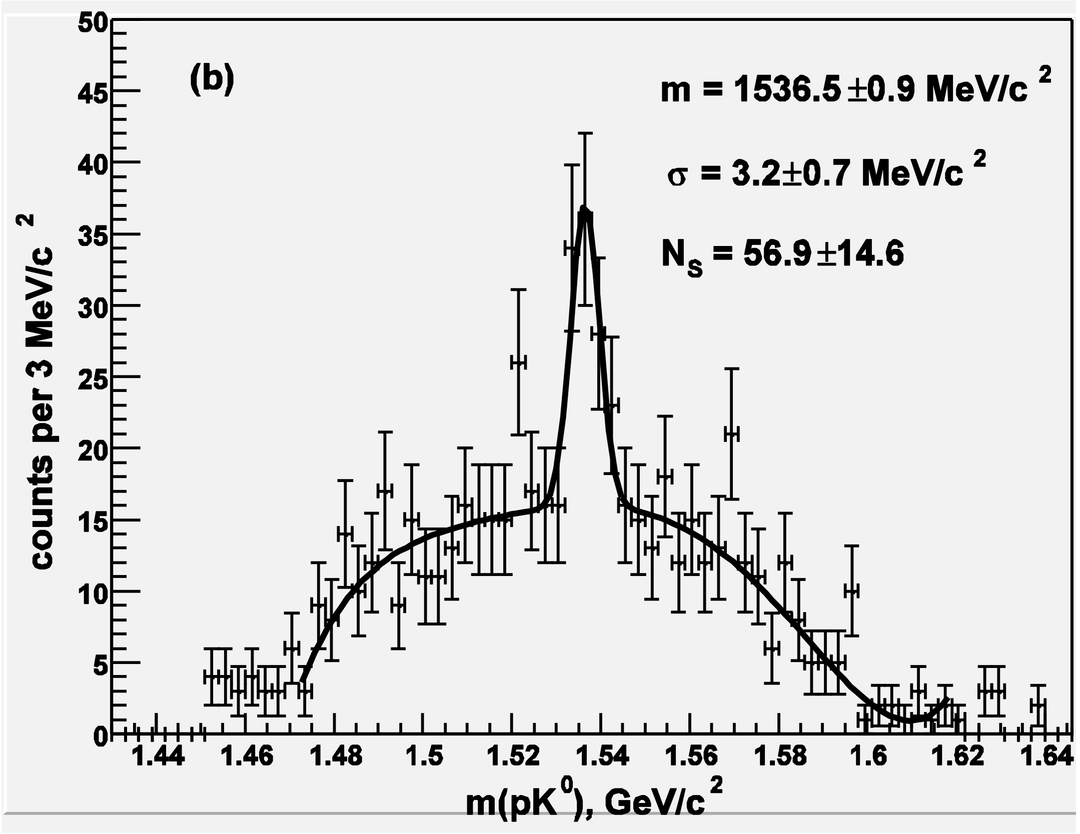
In 2003-05 about 50 experiments have been carried out searching for this and other pentaquarks; in 30 experiments there were no statistically significant signals seen.

In 2005 г. CLAS collaboration (Jefferson Lab) did not confirm its own discovery of 2003, and obtained an upper limit for the pentaquartk production cross section (which, however, was 3 times higher than theoretical expectations).

Since then it is widely believed that pentaquarks “do not exist”.

Experiments after 2005

1. A. Dolgolenko et al. (ITEP) have nearly doubled the statistics of the $K^+\mathrm{Xe} \to K^0 p + \ldots$ events. The observed spectrum of $m(K^0 p)$:



$$\left.\frac{S}{\sqrt{S+B}}\right|_{S=60,B=68} = 5.3$$

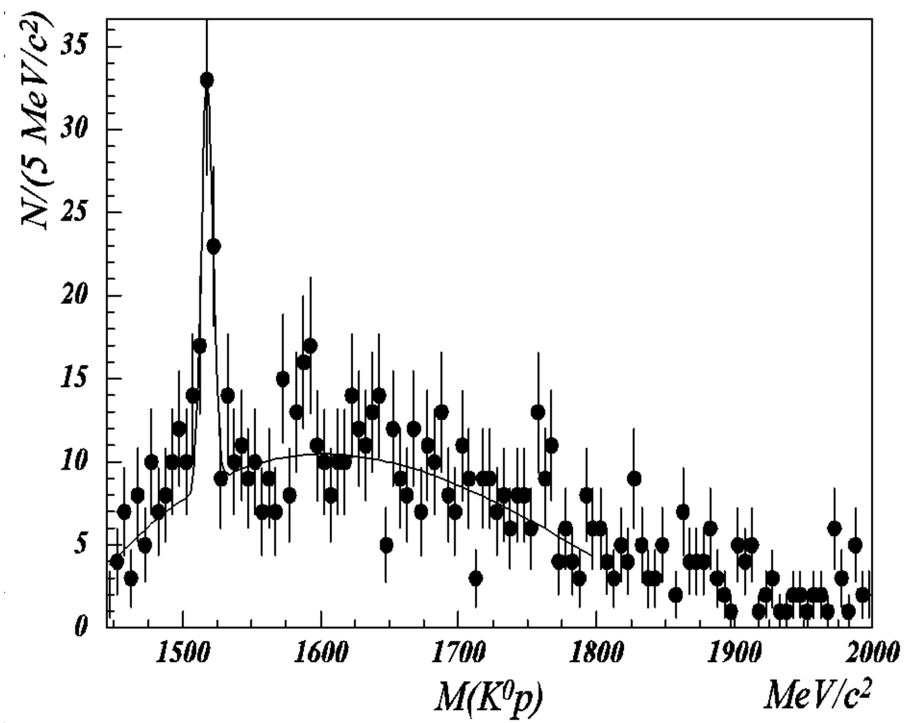
$$m = 1537 \pm 2\,\mathrm{MeV}$$

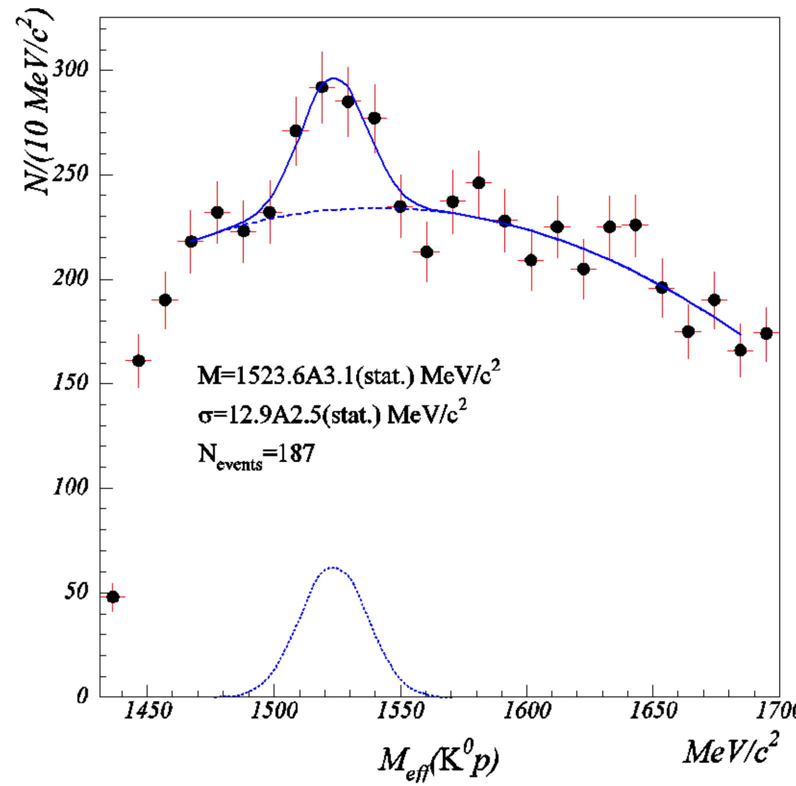
$$\Gamma = 0.36 \pm 0.11\,\mathrm{MeV}$$

The only “formation” (as opposed to “production”) experiment to date!

Bow and arrows can be more precise than a gun

2. A. Aleev *et al*. [SVD-2, Serpukhov] studied $pA \rightarrow K^0 p + \ldots$ @ 70 GeV.
A strong signal seen in two independent samples:

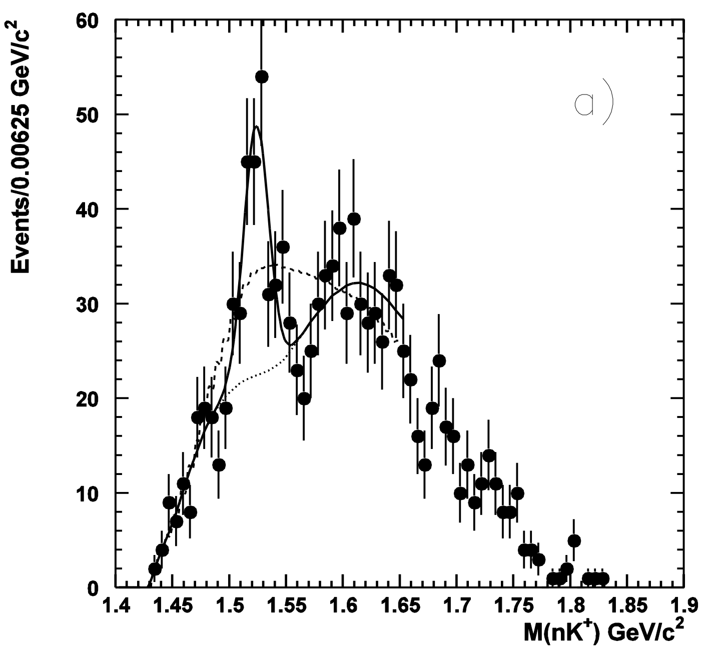


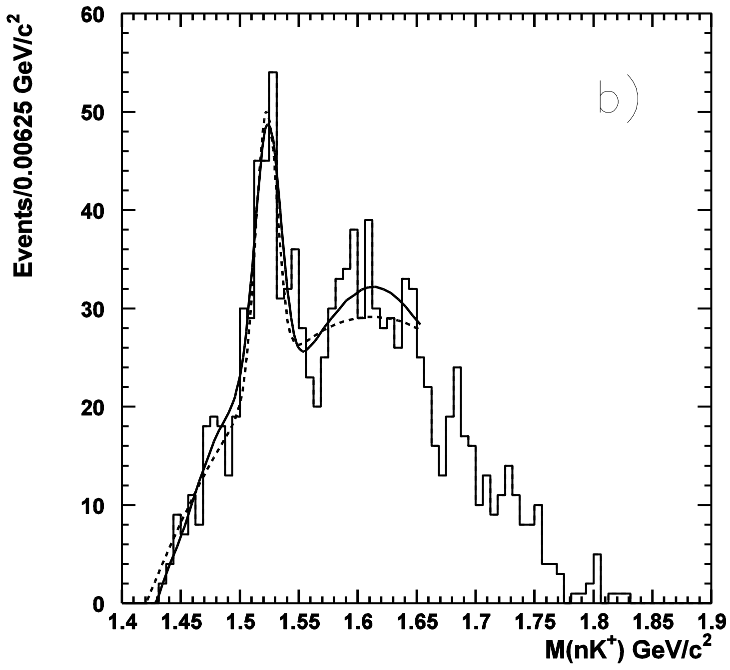


$$m = 1522 \pm 2 \pm 3\,\text{MeV}, \qquad \left.\frac{S}{\sqrt{S+B}}\right|_{S=392,\,B=1990} = 8.0$$

3. LEPS collaboration (SPring-8, Osaka), T. Nakano et al. (2008):

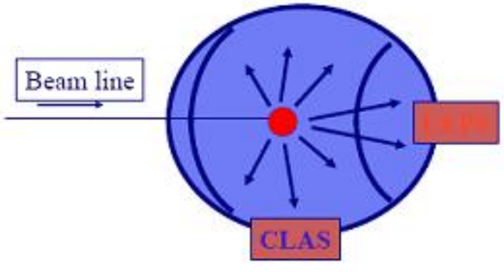
$$\gamma d \to K^- p\, K^+ n$$



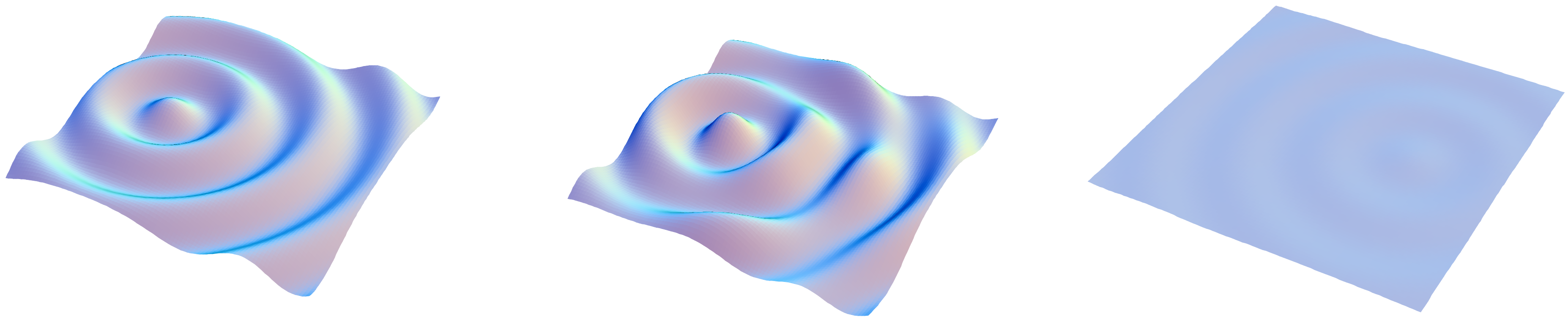


$$m_{\Theta} = 1524 \pm 2 \pm 3\,\mathrm{MeV}$$

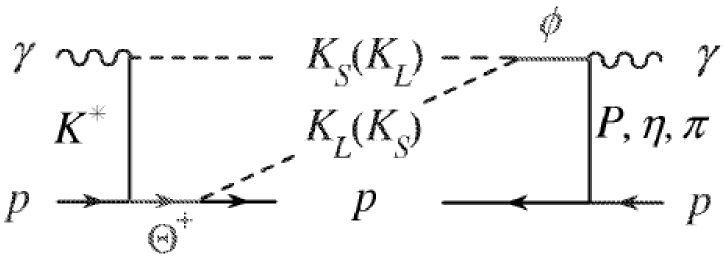
Remarkably, LEPS does see the resonance in the same reaction and at the same energy where CLAS does not see a signal. However, LEPS detector registers particles in the forward direction, while CLAS registers everything except in the forward direction:

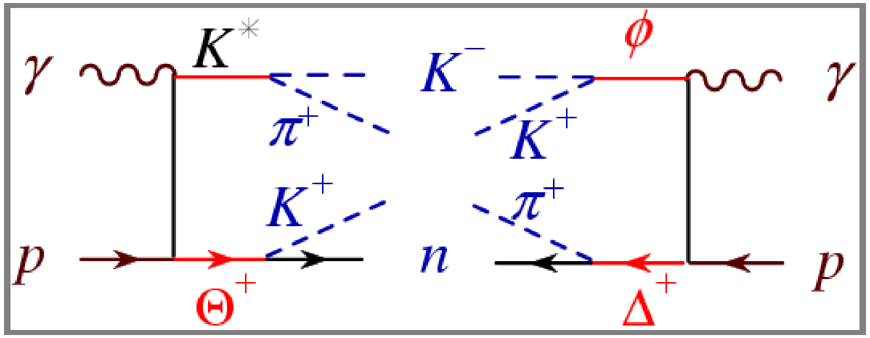


To see Theta+ from interference [Amarian, Diakonov, Polyakov (PRD, 2008)]



Resonance production cross section is **quadratic** in the (small) amplitude, whereas **the interference cross section is linear!**





To amplify the signal further, one has to look for Theta+ produced with a small momentum transfer!

Theory

From the traditional view on hadrons as “made of” constituent quarks with mass ~350 MeV, it is unclear

1) Why pentaquarks should exist in the first place

2) Why $\Theta^+ = uudd\bar{s}$ is so light (1530 MeV, and not 350 x 5 + 150 ~1900 MeV)

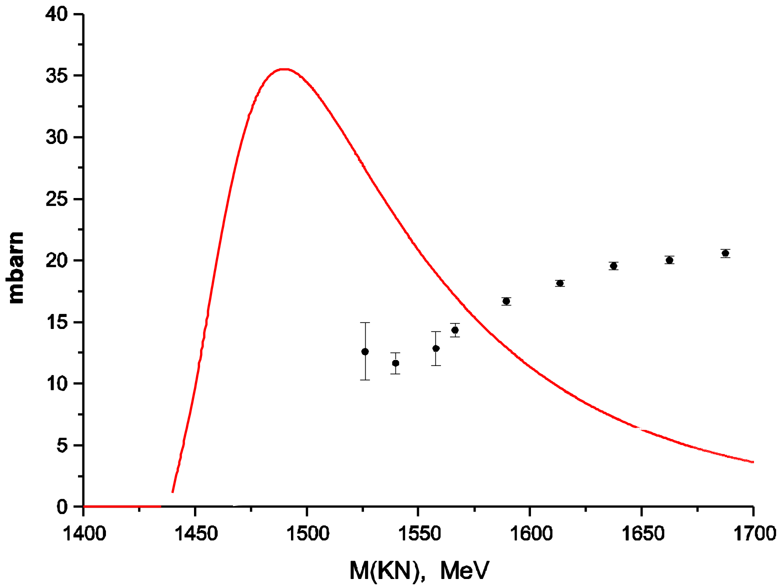
3) Why is it so narrow (~ 1 MeV, whereas normally it should be ~100 MeV)

What is ignored in the standard quark models?

A) Quantum Field Theory saying that baryons are actually superpositions of Fock states with 3,5,7,… quarks – it’s only a question of probabilities

B) Spontaneous Breaking of Chiral Symmetry saying that constituent quarks have to interact strongly with pion and kaon fields

Skyrme model is very rough but at least it accommodates both A and B.



K+n elastic cross section in the Skyrme model

[I. Klebanov *et al*. + D. Diakonov and V. Petrov]

Scattering amplitude has a pole at

$$m_{\rm res} - i\frac{\Gamma}{2} = 1449 - i\,44\,\mathrm{MeV}$$

The Skyrme model predicts a light exotic baryon resonance, but it is too “strong”!

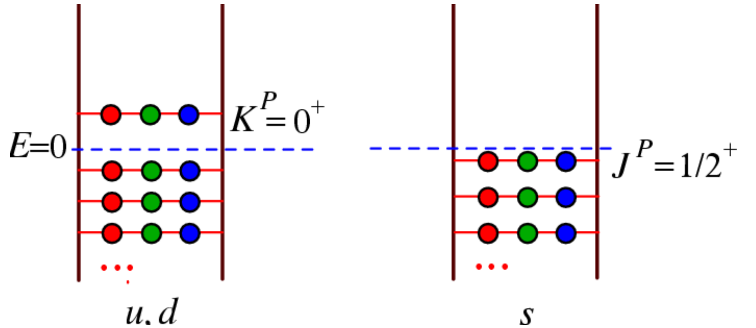
In a more realistic model one gets a very marrow width ~ 1 МэВ without any fitting parameters

[D. Diakonov and V. Petrov (2005), C. Lorce (2006), T. Ledwig, H.-C. Kim and K. Goeke (2008)].

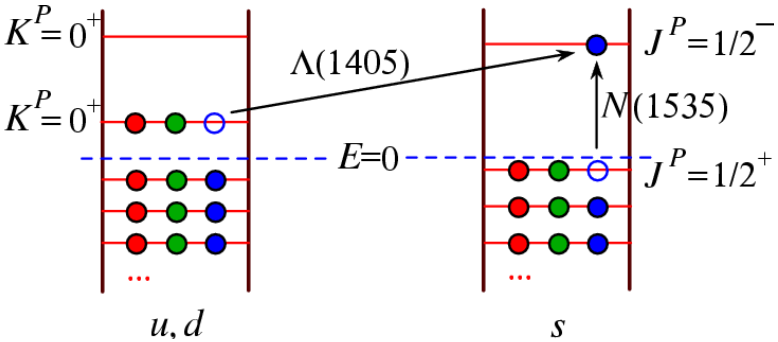
The reason of the small width: pentaquark decays $\Theta \to KN$ into the 5-quark component of the nucleon. Therefore it is suppressed to the extent the 5-quark component of the nucleon is suppressed!

A simple explanation of Θ^+ [D. Diakonov, arXiv:0812.3418]

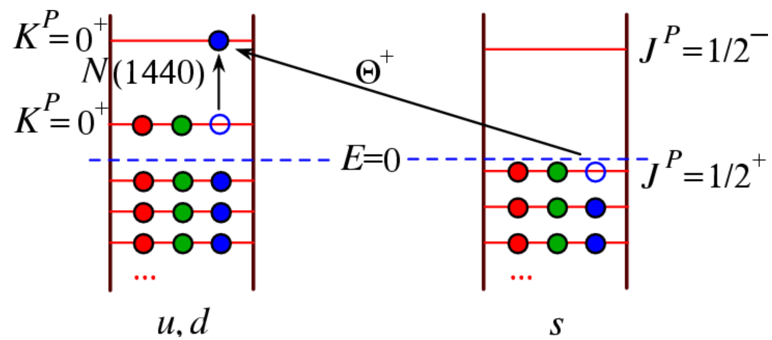
Nc=3 in the real world but one can look how are baryons arranged in the large Nc limit. According to Witten (1979), Nc quarks of the baryon are filling one-particle Dirac levels in the (self-consistent) meson fields $\sigma = P_0(r), \pi^a = n^a P_1(r), \phi_0 = P_3(r), \rho_i^a = \check{n}_{aik} n_k P_4(r), \ldots$ Like *p* and *n* in a large-A nuclei, *u,d* quarks and *s* quarks have, generally, comletely different one-particle levels:



Ground-state baryon **N(940,1/2+)**. Rotational excitations of this filling scheme form the lowest baryon multiplets - (**8**, 1/2+) и (**10**, 3/2+)



Λ**(1405, ½-)** and **N(1535, ½-)** are two different ways to excite an *s* quark level



N(1440, ½+) and Θ^+ **(½+)** are two different excitations of the same level of *u,d* quarks – an analog of the Gamov-Teller excitation in nuclei!

$$m_\Theta \approx 1440 + 1535 - 1405 \approx 1570\,\mathrm{MeV}$$

Conclusions

1. Exotic baryon – pentaquark – is again observed in several experiments. There will be more soon.

2. Its relatively small mass and very small width can be understood theoretically

3. When (and if) the pentaquark is confirmed, it will be a discovery that changes our view on strong interactions