Experimental evidence of an exotic S=+1 baryon

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- Introduction: what are pentaquark baryons?
- Review of experimental data
- Properties of pentaquark Θ^+
- Outlook and summary

Introduction

- Quark models have been very successfull in describing hadron spectroscopy
- "Ordinary" hadrons are bound states of 3q (baryons) or $q\bar{q}$ pairs (mesons)

BUT

QCD does not forbid more complicated (exotic) states like qqqq or qqqqq

Several experiments have established that sea quark ($q\bar{q}$ pairs) are part of the ground-state wave function of the nucleon

$$\Psi_N = qqq + qqqq\bar{q} + qqqq\bar{q}q\bar{q} + qqqg + \ldots$$

- the anti-quark in the nucleon has the same flavor as one of the quark
- the quantum numbers of the nucleon are fixed by the valence quarks

What are exotic baryons?

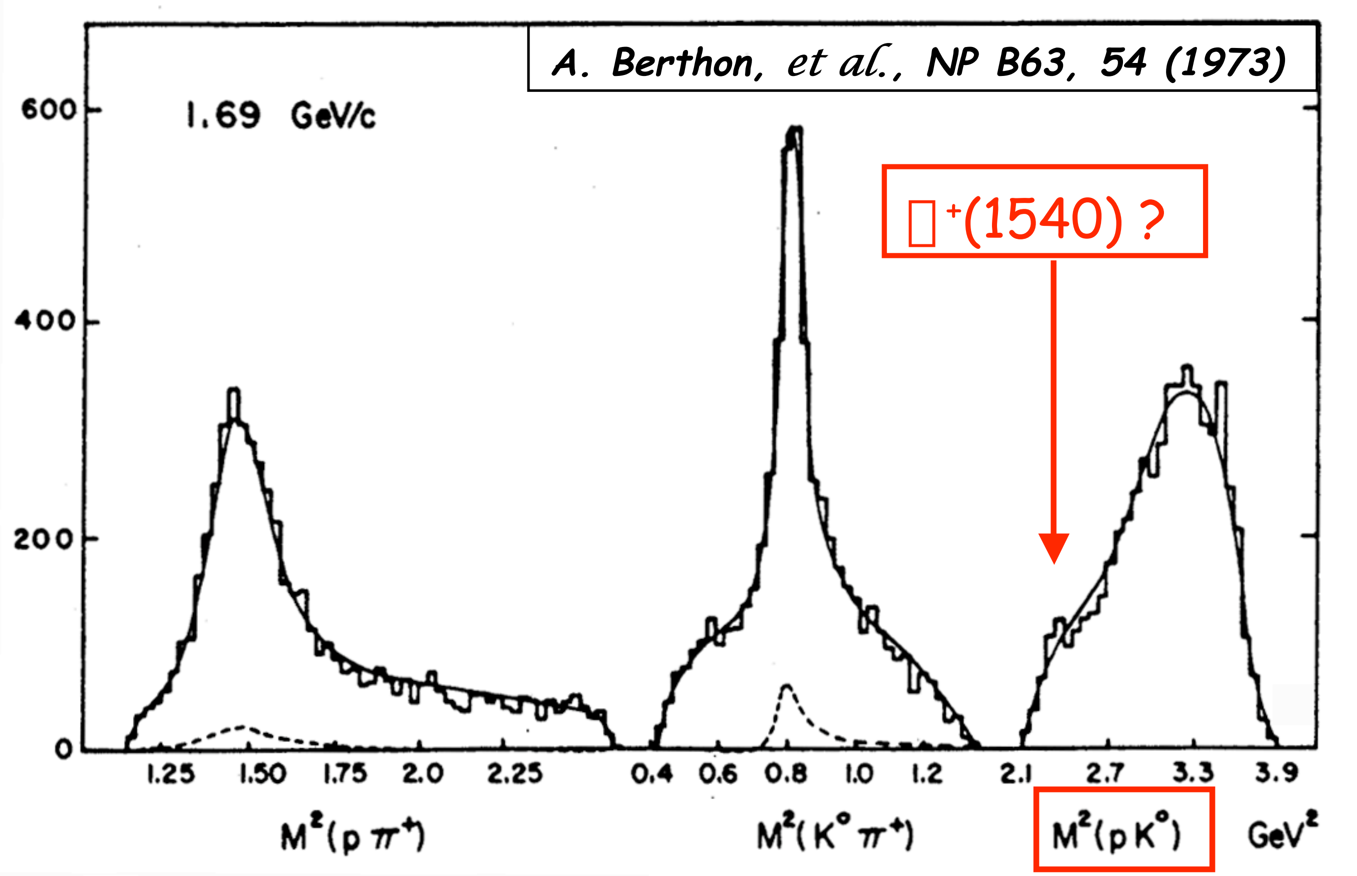
- Minimum quark content for "exotics" is 4 quarks and one antiquark
- Exotic pentaquarks contain an antiquark with **different flavor** than any of the other quark
- Quantum number can not be defined by 3 quarks (for example: $S=+1$ baryons must contain at least one s antiquark and no s quarks)

- Properties of exotic pentaquark states with light quarks have been studied for example in the bag model (*Jaffe, SLAC Report No. SLAC-PUB-1774, 1976*)
- Possible existence of pentaquarks in the heavy quark sector have also been proposed (*Lipkin, PL B195, 484, 1987*)

- Exotic baryons with $S=+1$ (originally called Z*) have been largely searched since the late '60s in KN and πN scattering experiments
- For many years, PDG dedicated one paragraph to the Z* search, with careful partial-wave analysis of KN scattering, but the issue have been dropped after 1988

Search for S=+1 baryon

$K^+ p \to K^0 p \pi^+$ CERN hydrogen bubble chamber data



Hints for the existence of S=+1 baryons were probably there, but no conclusive results could be drawn from available data

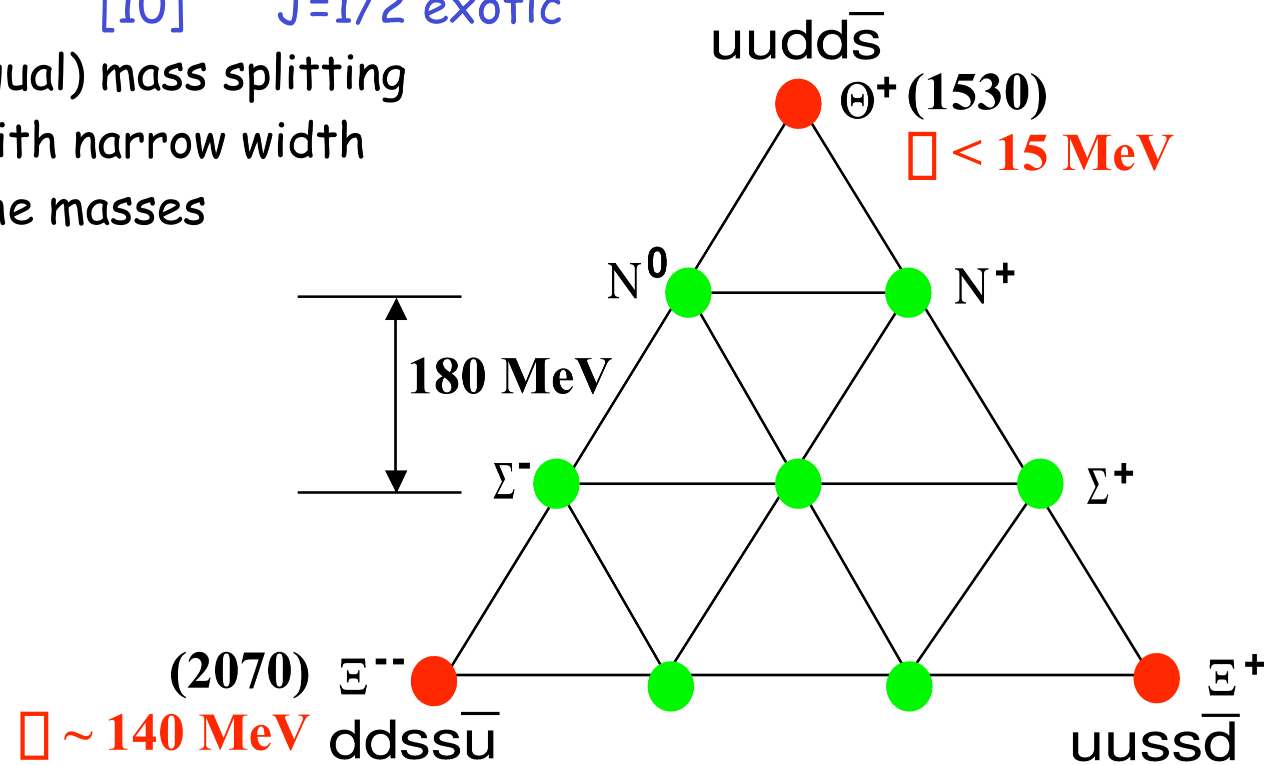
Pentaquark prediction

Chiral Soliton Model

Diakonov et al. - Z. Phys. A359 (1997) 305

- N and □ are rotational states of a “classical” nucleon
- SU(3) multiplets: [8] J=1/2
  [$\overline{10}$] J=3/2
  [10] J=1/2 exotic
- $m_s \neq 0$ generates (equal) mass splitting
- lowest mass state with narrow width
- N*(1710) fixes all the masses

EXOTIC STATES



Pentaquark search

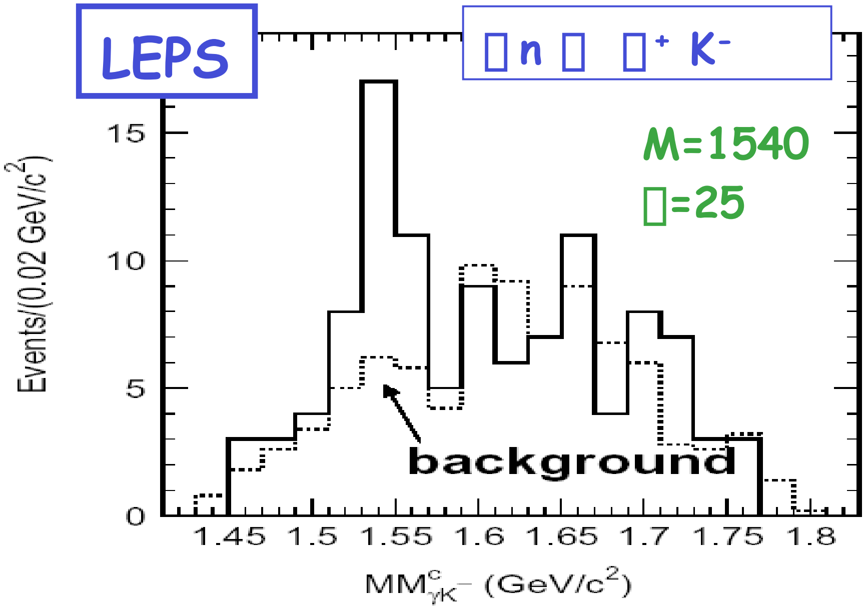
The precise theoretical predictions by Diakonov *et al.* triggered a renewed interest in baryon spectroscopy

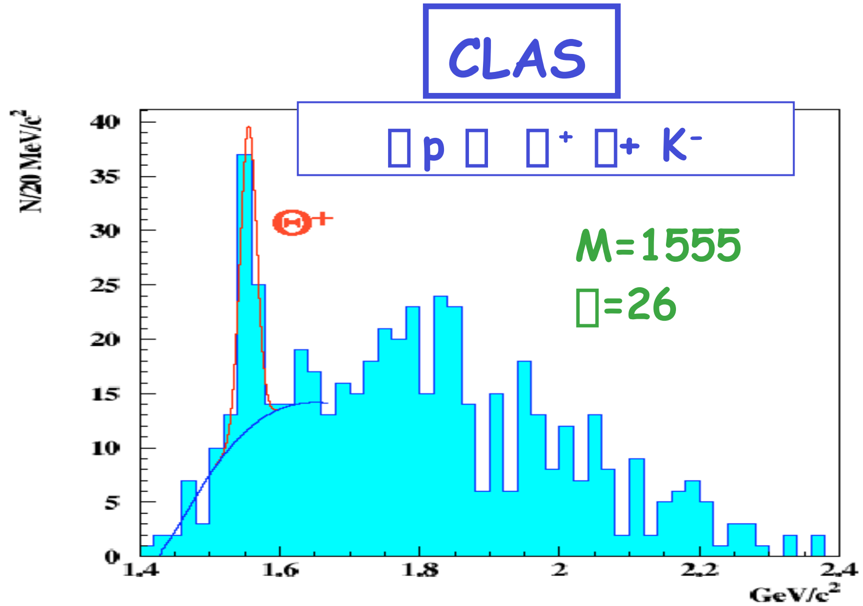
- exotic pentaquarks are relatively light
- at least one pentaquark is narrow
- the signal must appear in KN invariant mass

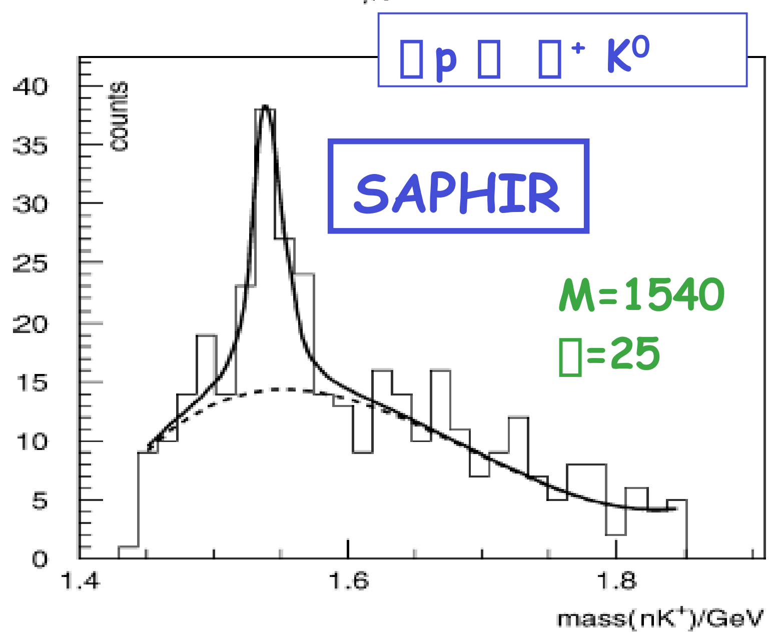
In the past few months several experimental groups have reported results on the search for the Θ^+

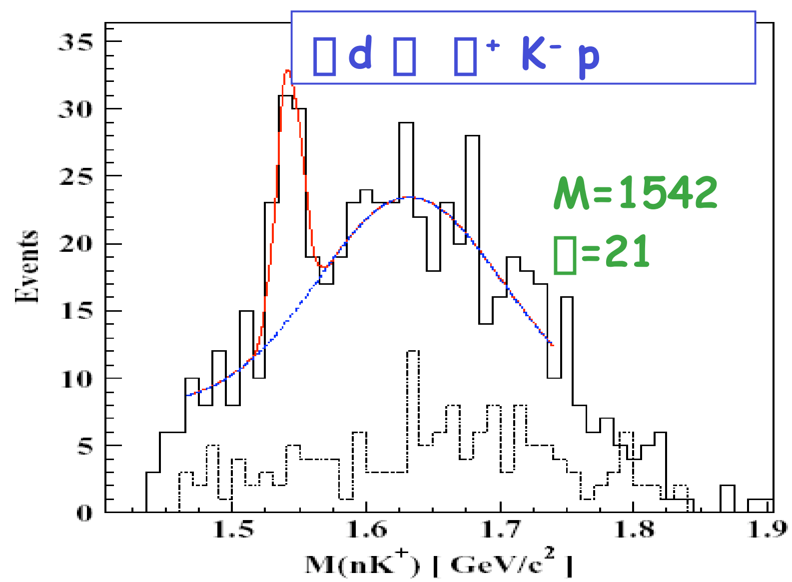
- with different reaction channels (real and virtual photons, neutrino and hadronic beams, e+e- collisions);
- different experimental apparatuses (large spectrometers, bubble chambers)
- different techniques (inclusive and exclusive measurements, with all particles detected or via missing mass measurement)

Photoproduction experiments





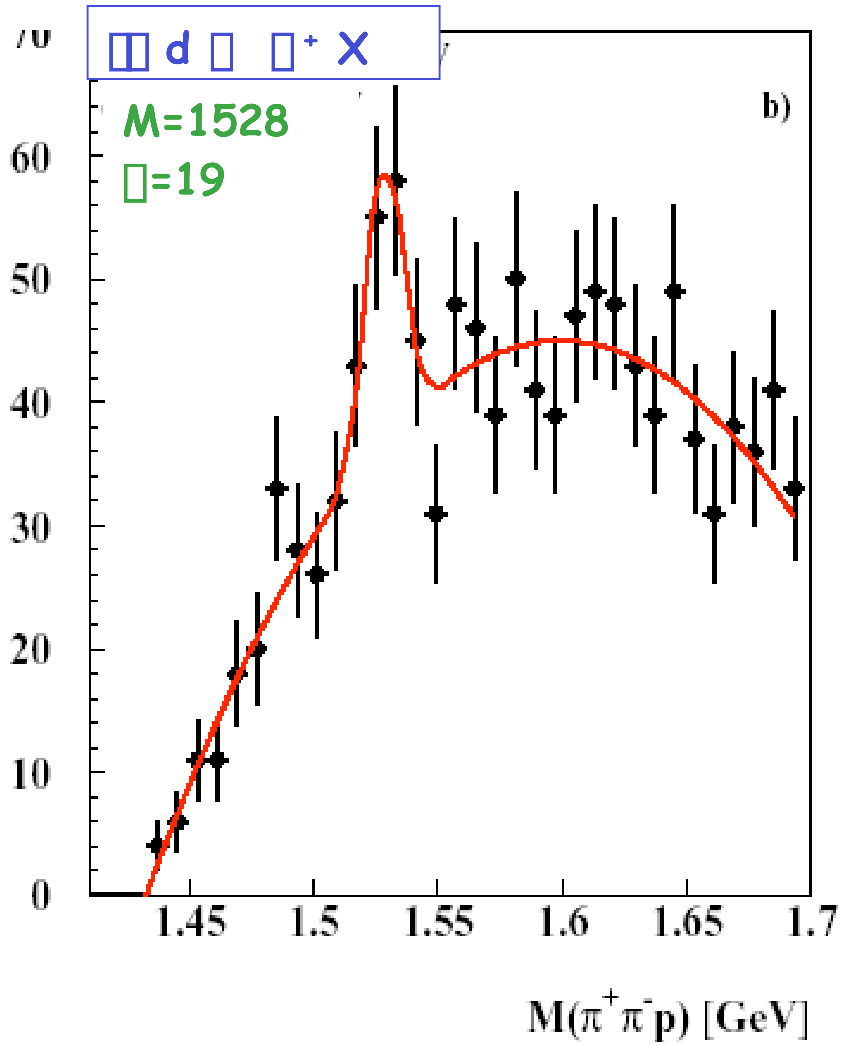


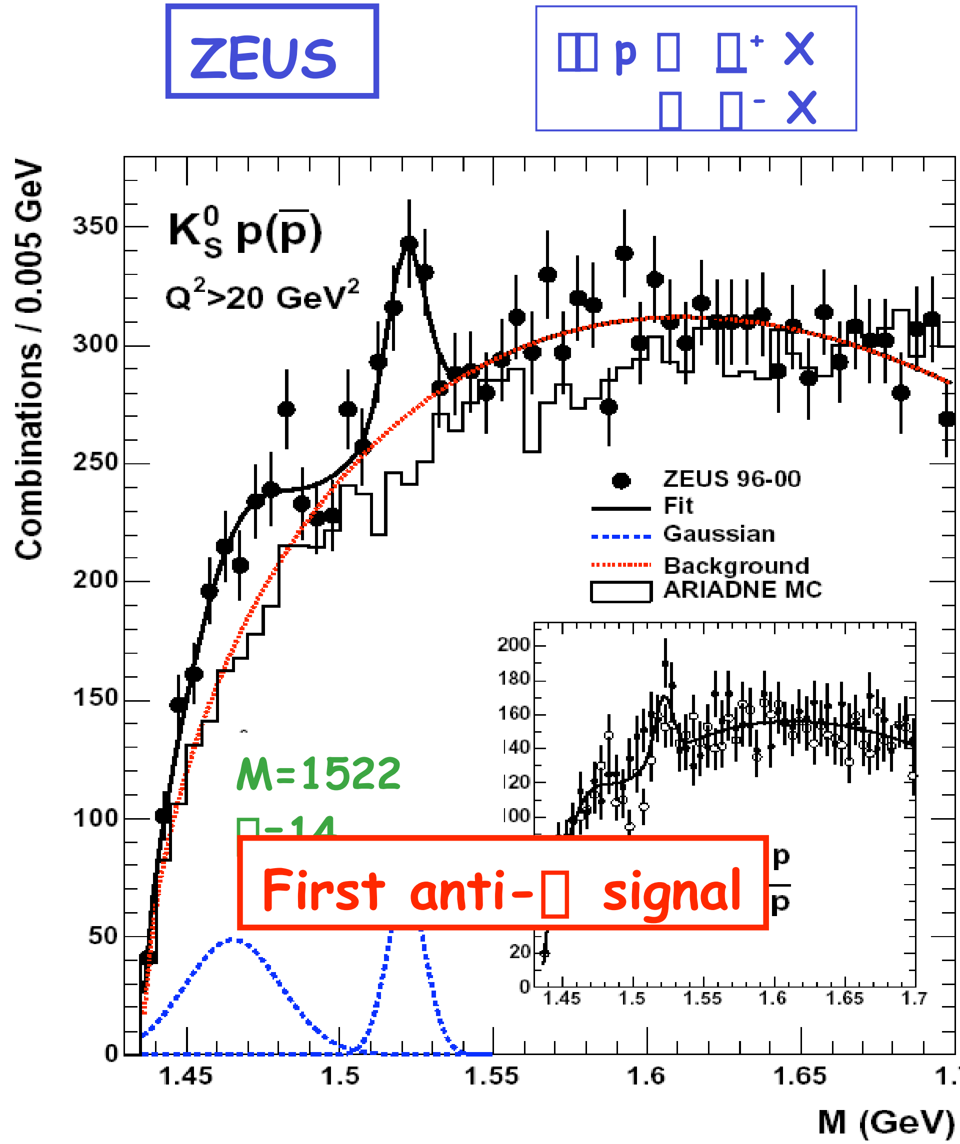


Virtual photon experiments

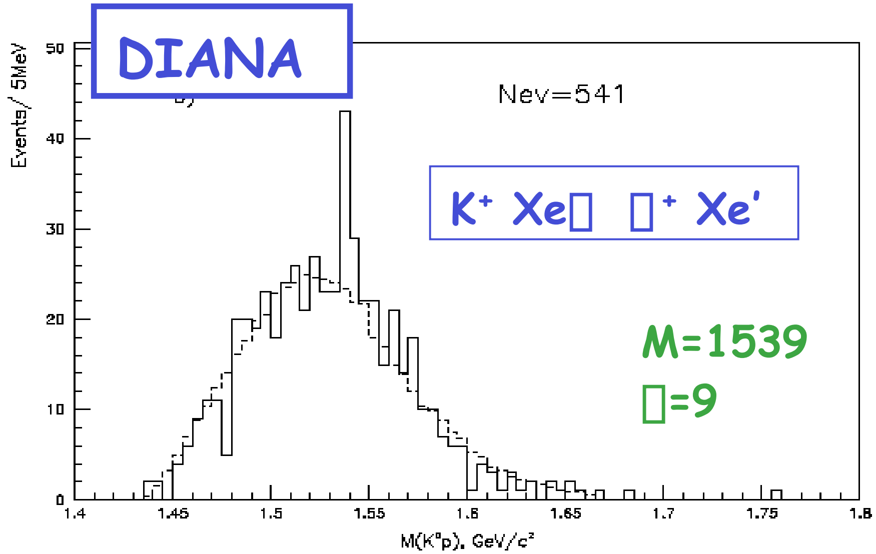
HERMES

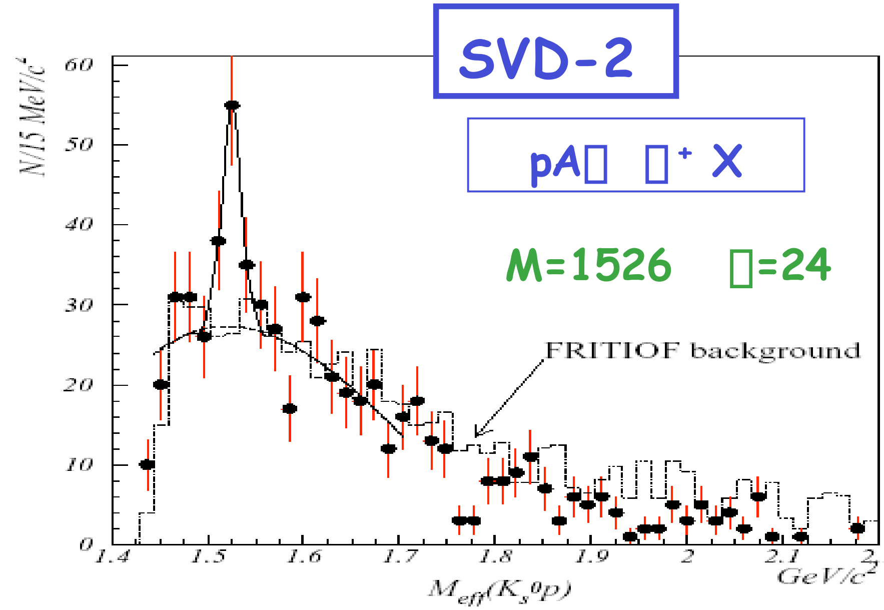
ZEUS

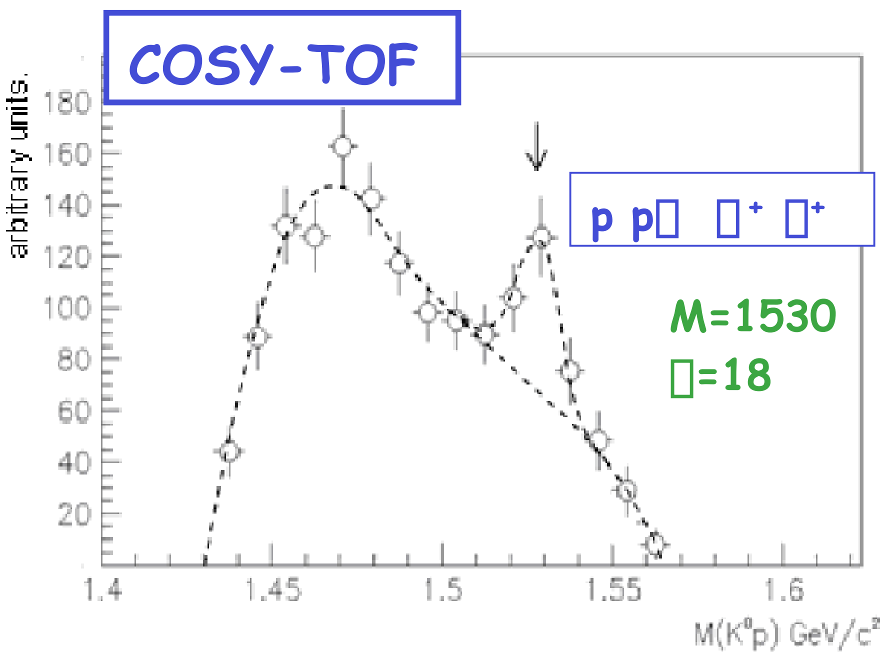


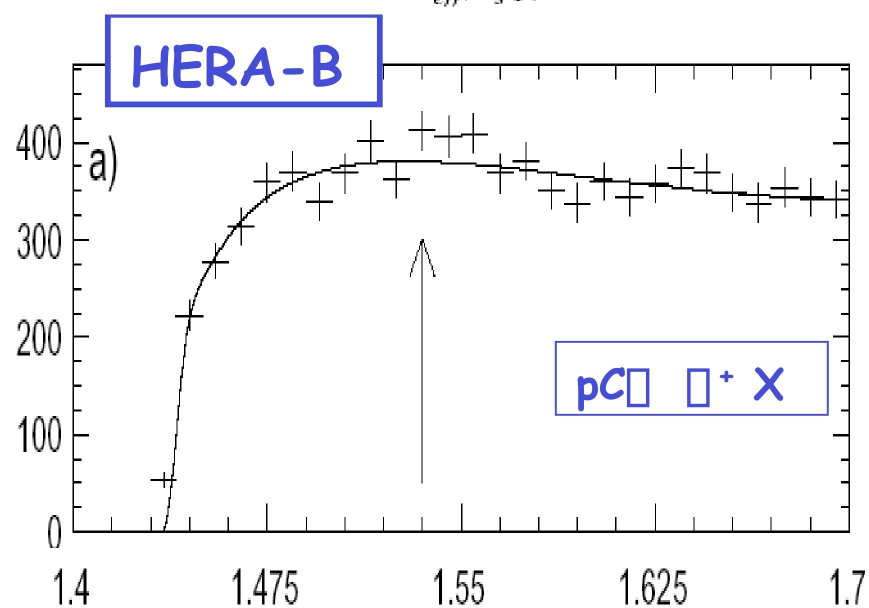


Hadronic reactions



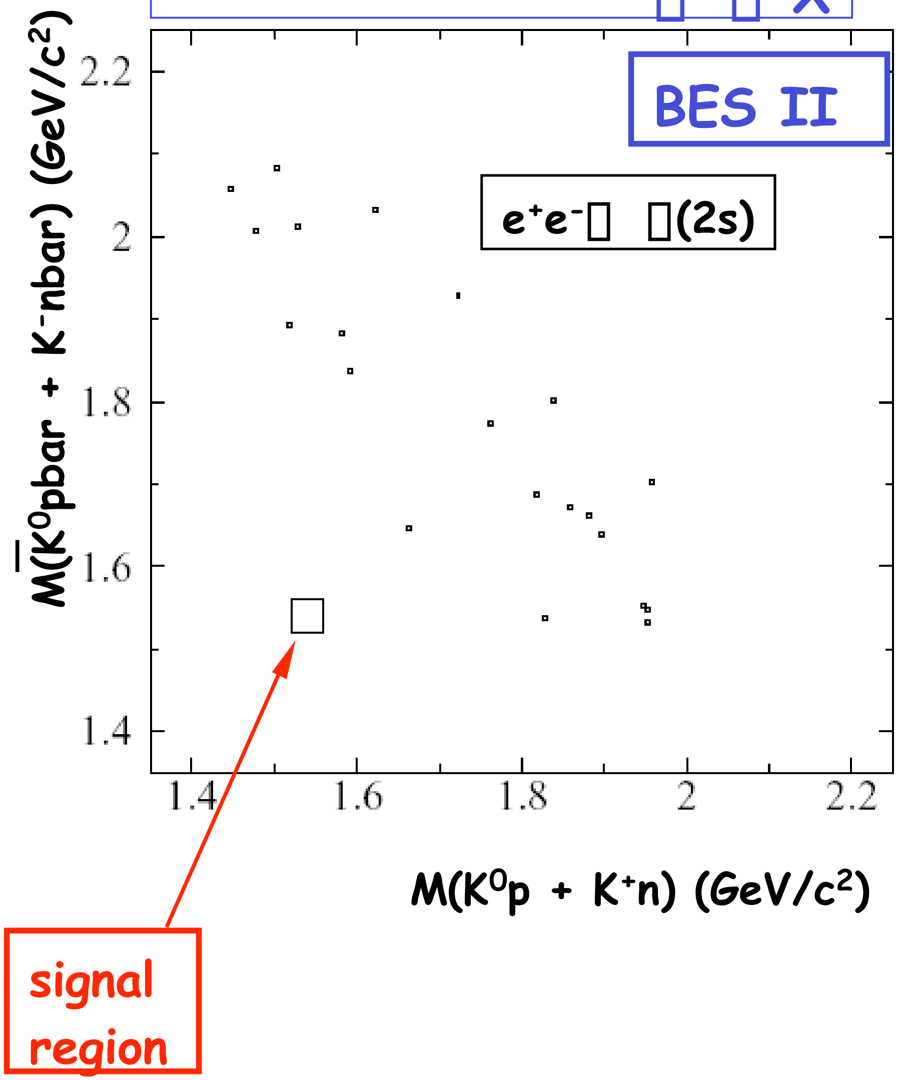






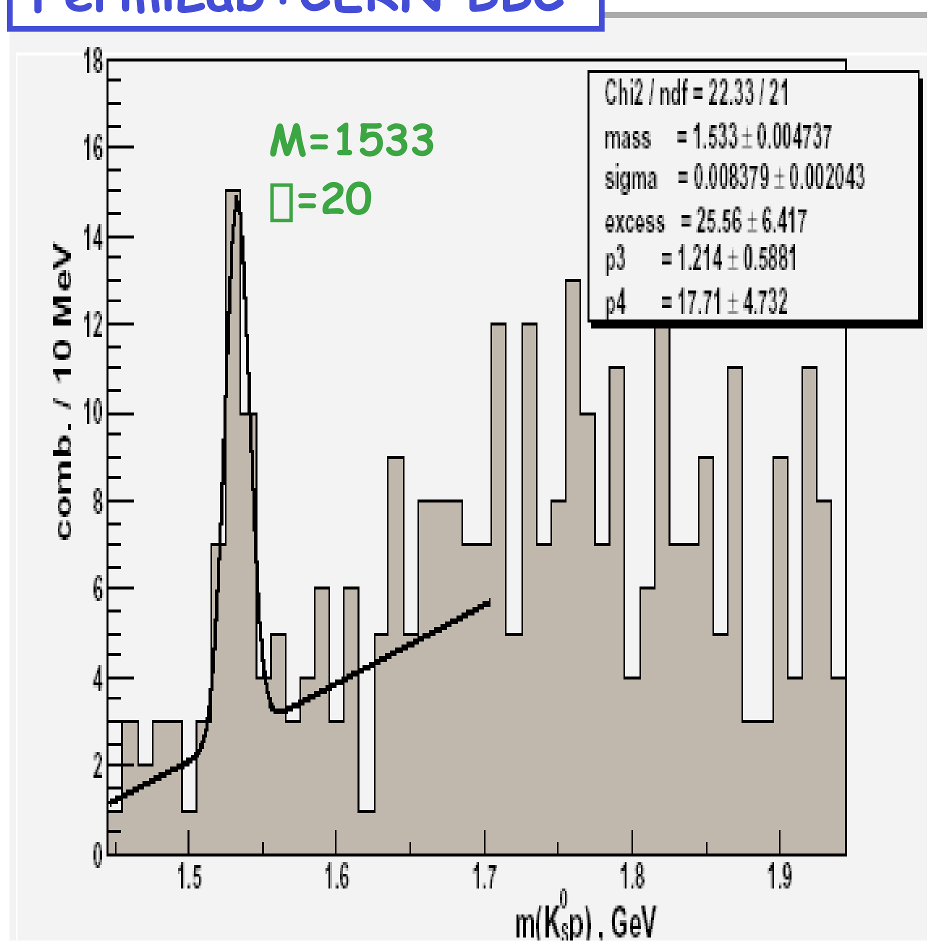
e^+e^- and □ scattering

e^+e^-□ □(2s), J/□ □ □ $\bar{□}$ □ □ X



□ A □ □$^+$ X

FermiLab+CERN BBC



First observation of an exotic pentaquark S=+1 baryon

LEPS detector at the Spring-8 facility

PRL 91, 012002-1 (2003)

- photoproduction on bound neutron in ^{12}C:

  □n □ □$^+$ K^-

  □$^+$ □ K^+ n

- □$^+$ signal in the invariant mass of K^+n system

- kaons detected, neutron from missing mass cuts
- □ photoproduction events removed
- Fermi motion correction from data

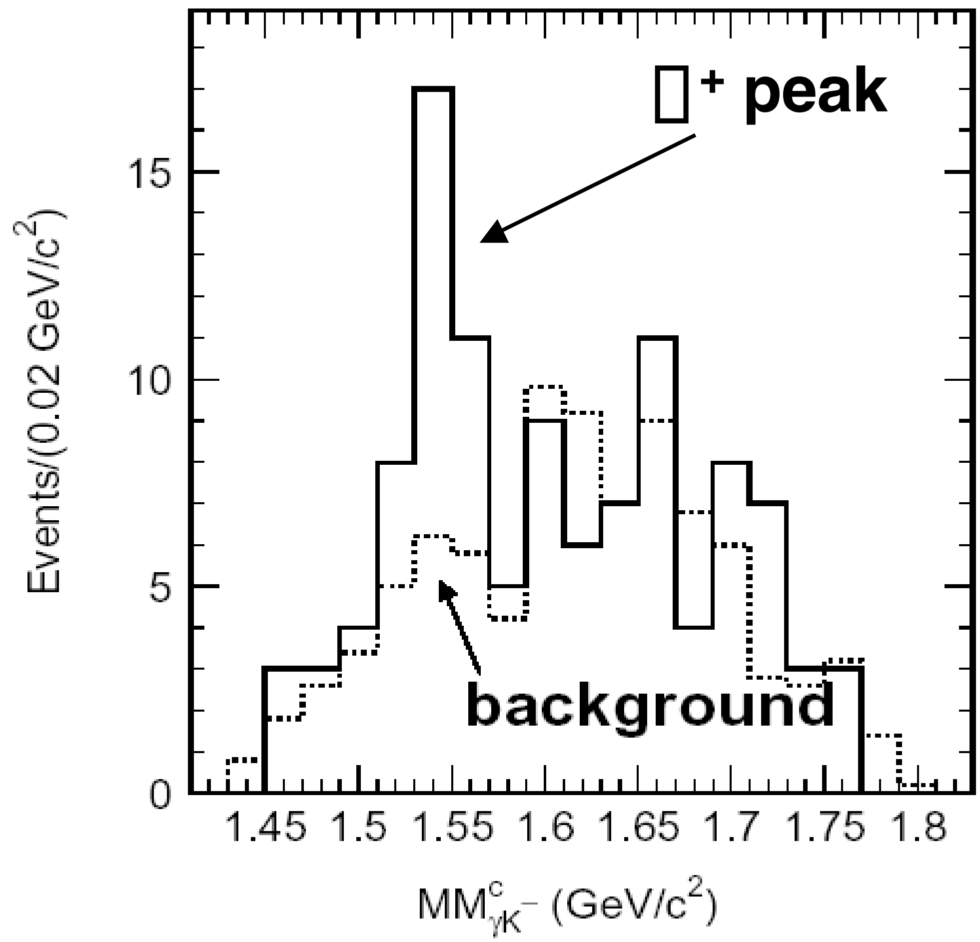
$N_□$ = 19.0±2.8

N_B = 17.0±2.2

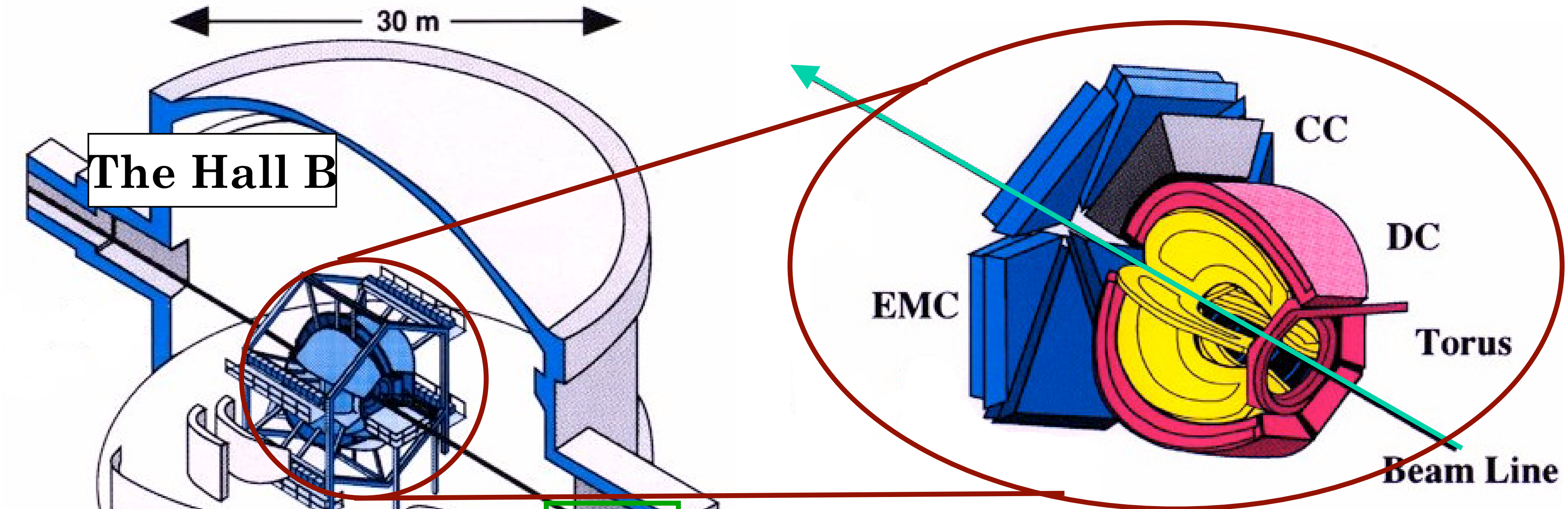
$M_□$ = 1.54 ± 0.01 GeV

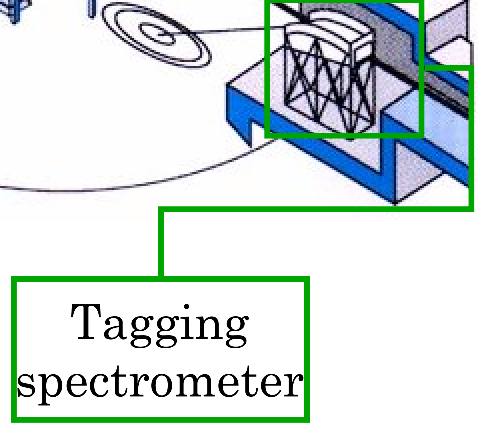
$□_□$(FWHM) = 25 MeV

Gaussian sig. S= 4.6□



The CLAS detector



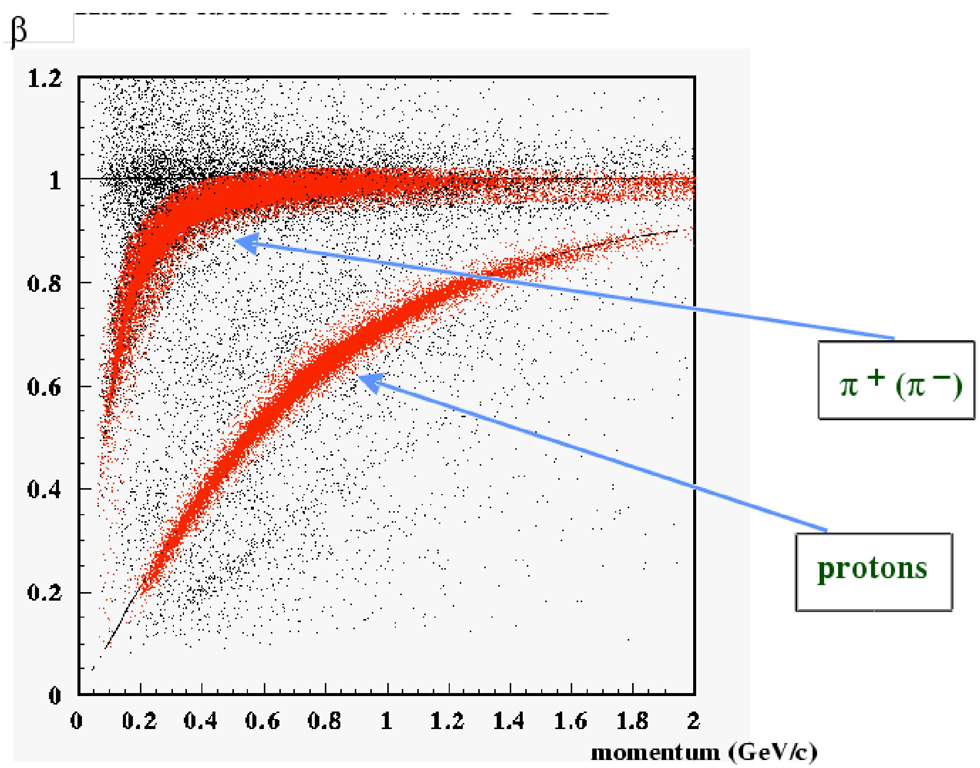


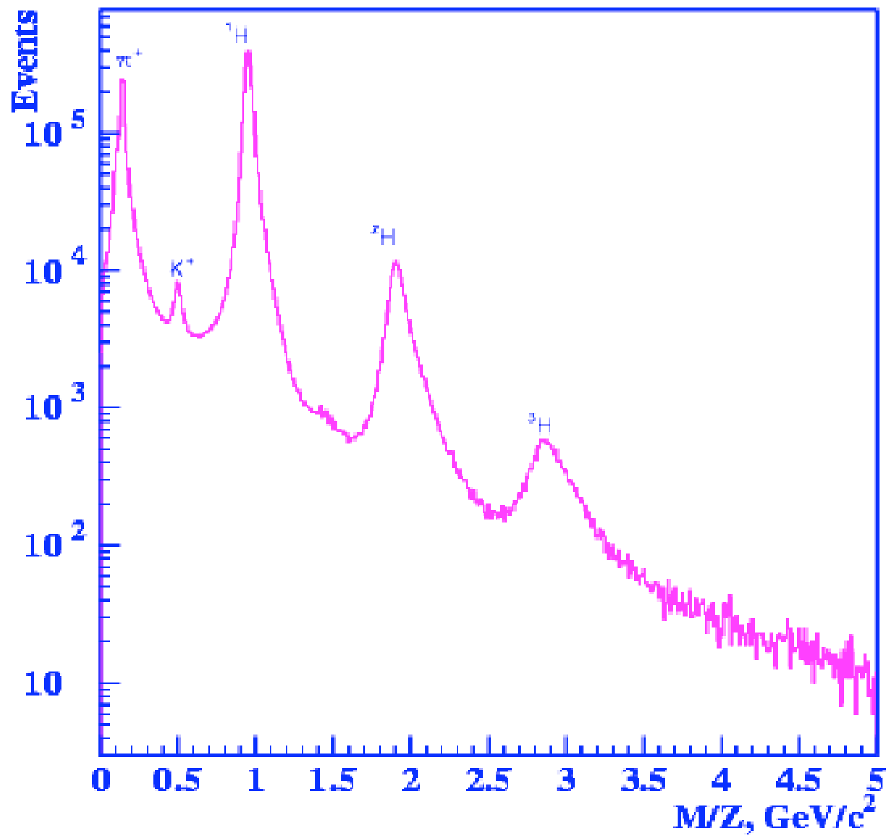
Highlights

- **6 independent sectors**
- **nearly 4π acceptance**
- **$\mathcal{L}$ = 10^{34} cm^{-2} s^{-1}**
- **$\int B \cdot dl$ = 2.5 T·m** (super conducting)
- **$\Delta p/p$ = 0.5 %** (forward)
- **DAQ rate ~ 4 KHz**

CLAS performances

Hadron detection efficiency





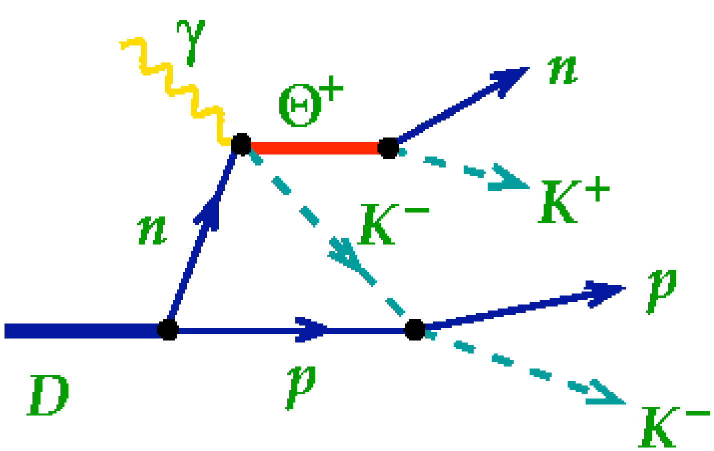
CLAS data on deuteron - 1

Exclusive photoproduction on deuteron

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

- Data taken in 1999 run
- Tagged photons with up to 3 GeV
- Target: 10 cm long liquid deuterium

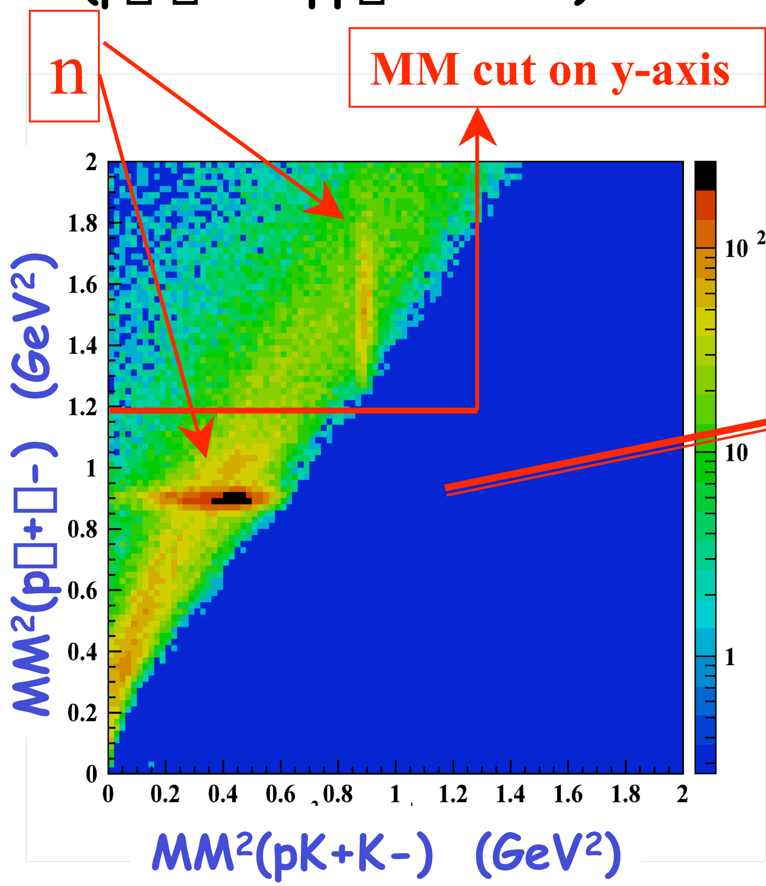
Possible reaction mechanism

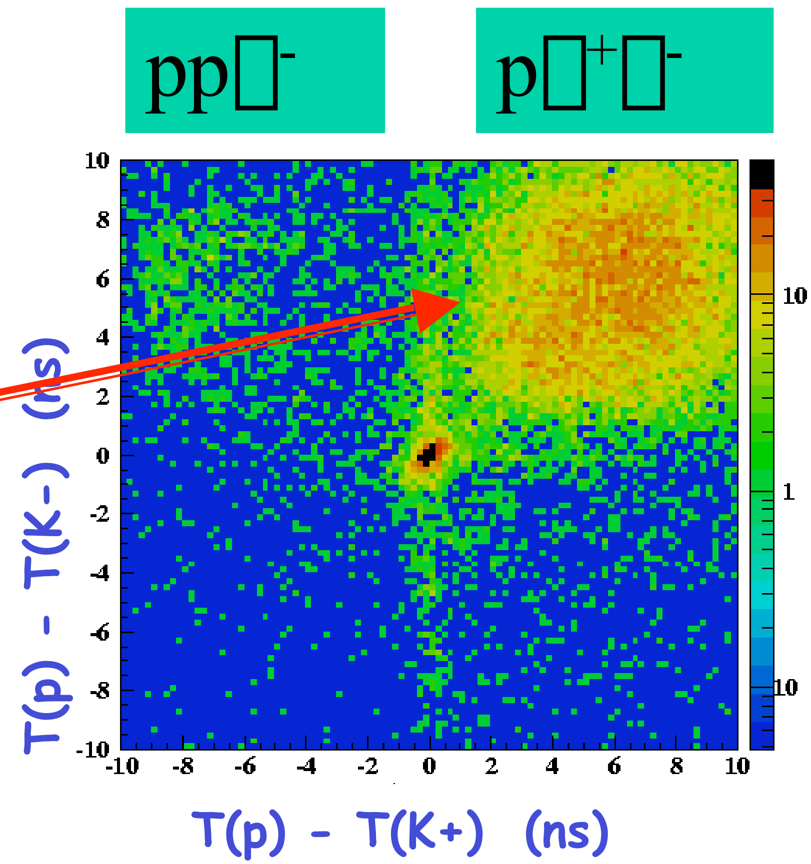


- Charged particle detected in CLAS
- Neutron ID by missing mass
- FSI produces the K^- at larger angles and protons with higher momentum
- No correction for Fermi motion

CLAS data on deuteron - 2

The main BKG comes from pions and protons misid. as kaons ($p\pi^-\pi^+$ or $pp\pi^-$ events)



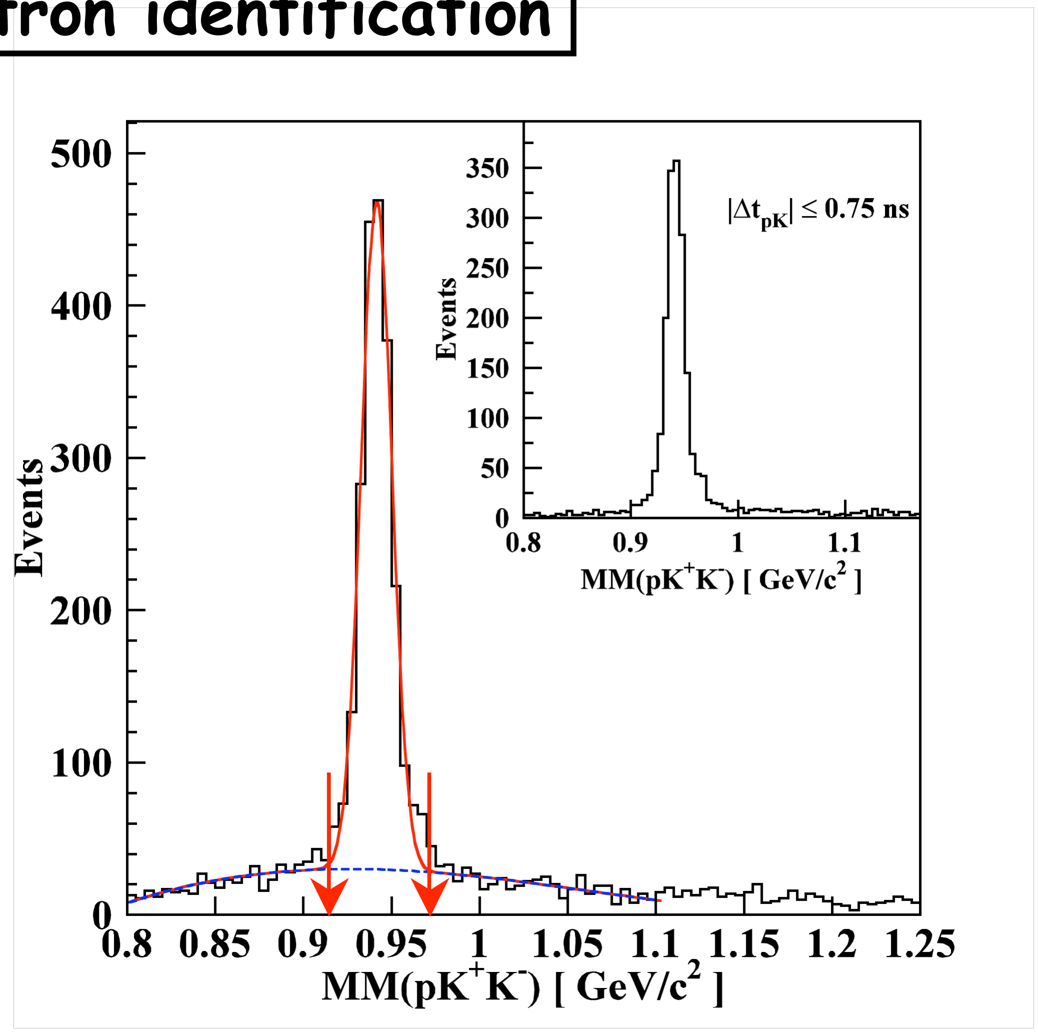


Missing mass and timing cuts suppress BKG

CLAS data on deuteron - 3

Missing neutron identification

- 15% of non pKKX events within ±3σ of the peak
- almost no background under neutron peak with tight timing cuts
- missing momentum cut to remove spectator neutrons



CLAS data on deuteron - 4

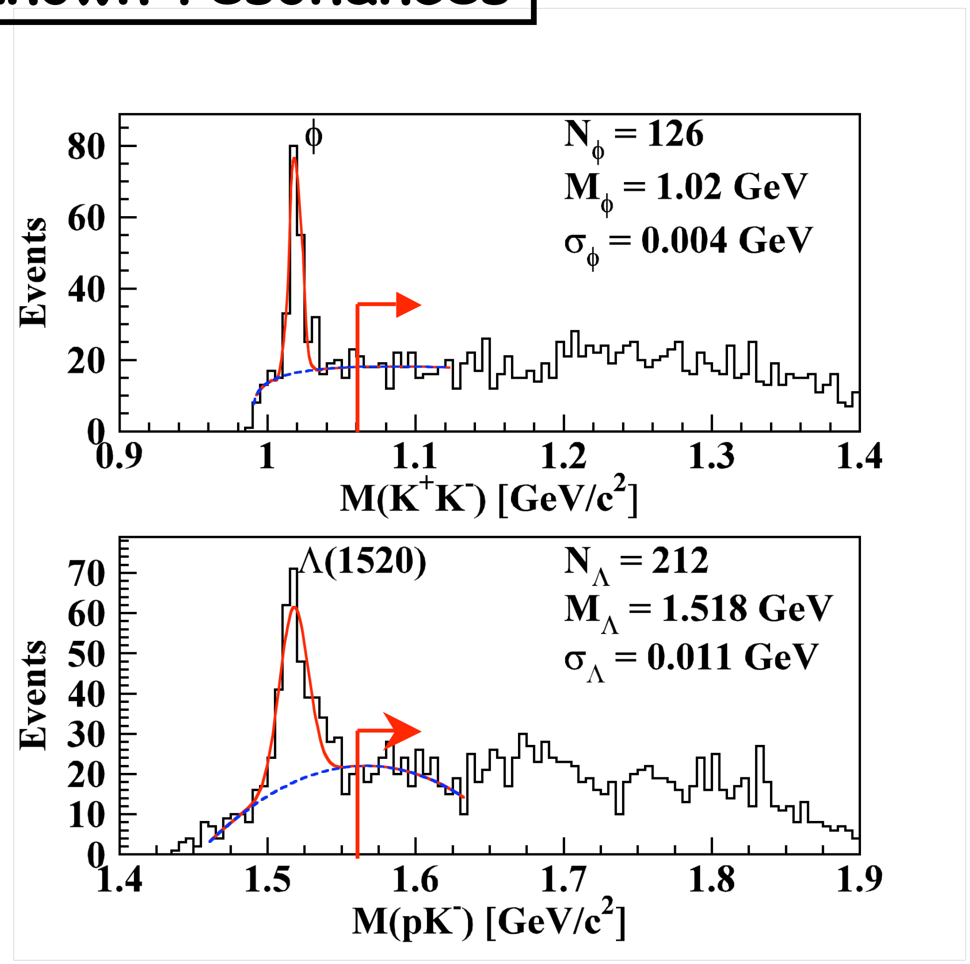
pKK events from known resonances

- Several known processes can contribute to pKK events

  □d □ p □(n); □ □ K^+ K^+
  □d □ □(1520) K^+ (n); □ □ pK^-

- Both reactions proceeds predominantly on the proton

- Even if cross sections are large, the kinematic doesn't match with □$^+$ production



CLAS data on deuteron - 5

CLAS final result

PRL91,252001

$N_{□}$ = 43

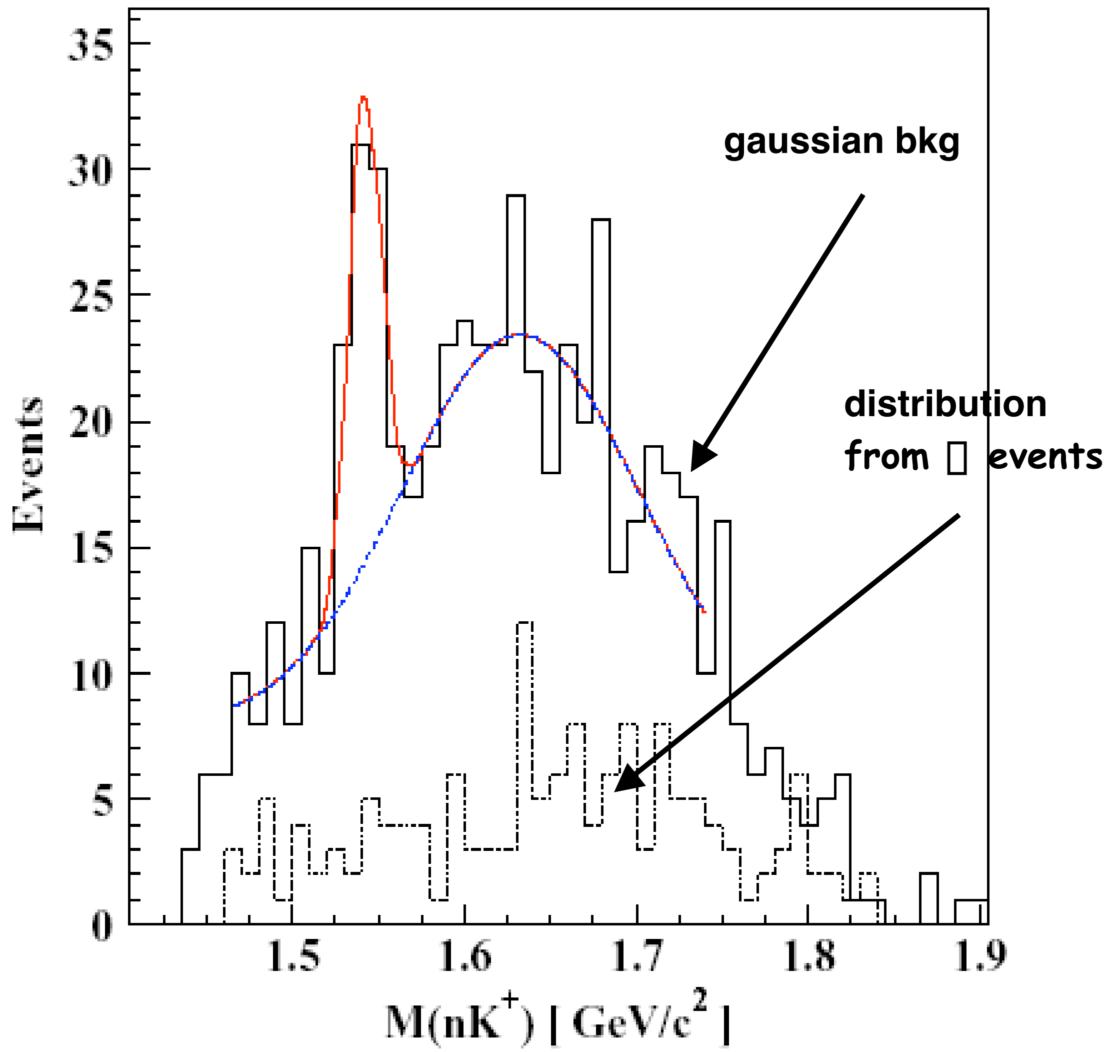
$N_{□}$ = 54

$M_{□}$ = 1542 ± 5 MeV

$□_{□}$(FWHM) = 21 MeV

S= (5.2 ± 0.6)□

The peak remains robust changing event selection cuts



CLAS data on deuteron - 6

Background study

Monte Carlo calculation 1.:

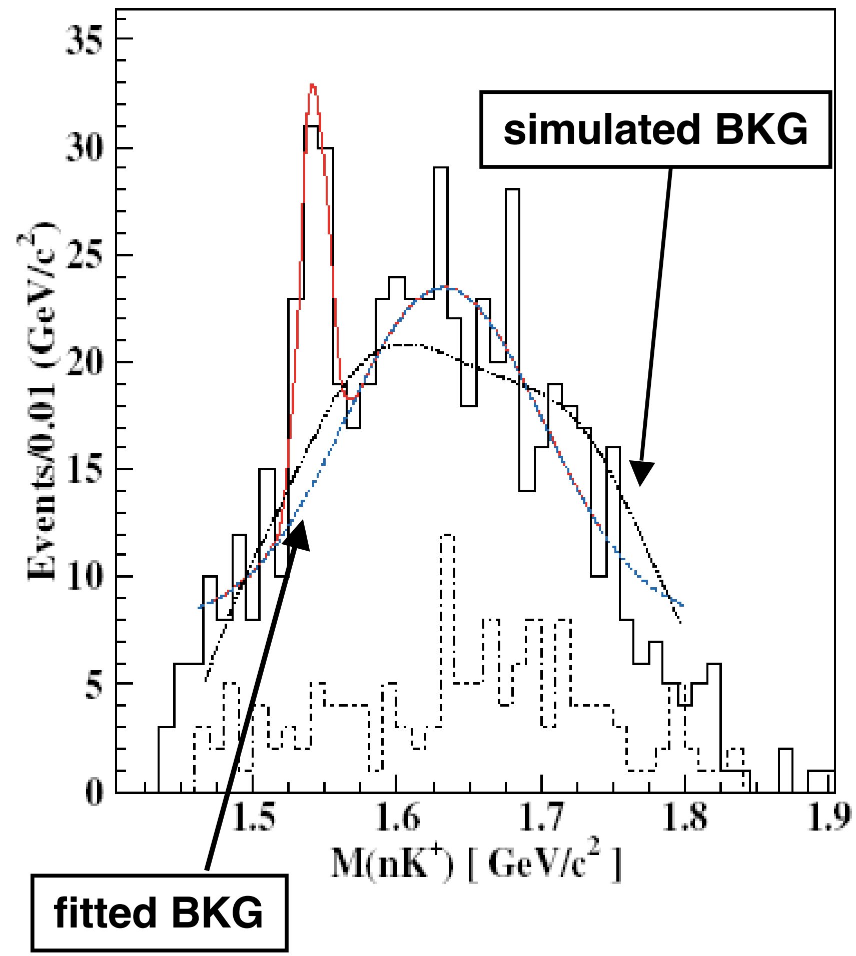
- three (pK^+K^-) and four-body (pK^+K^-n) phase-space photoproduction
- full simulation of detector response
- BKG spectrum fitted to the data

⇒ good description of the BKG shape

Monte Carlo calculation 2.:

- production of baryonic resonances decayng into KN system ($\gamma N \rightarrow K^+B^*$)

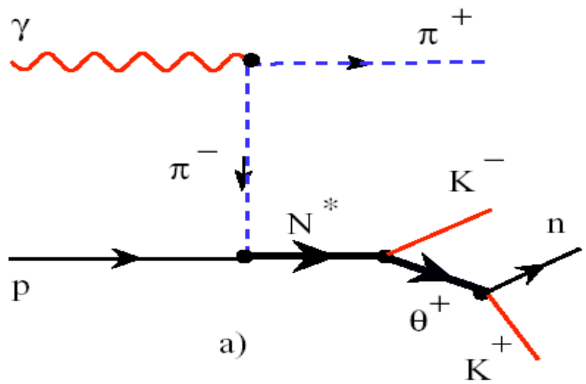
⇒ no narrow structures coming from non Θ^+ events



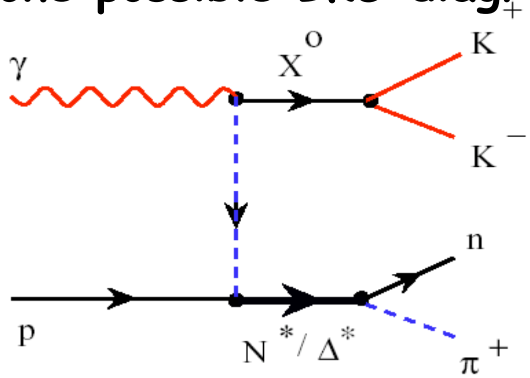
CLAS data on proton

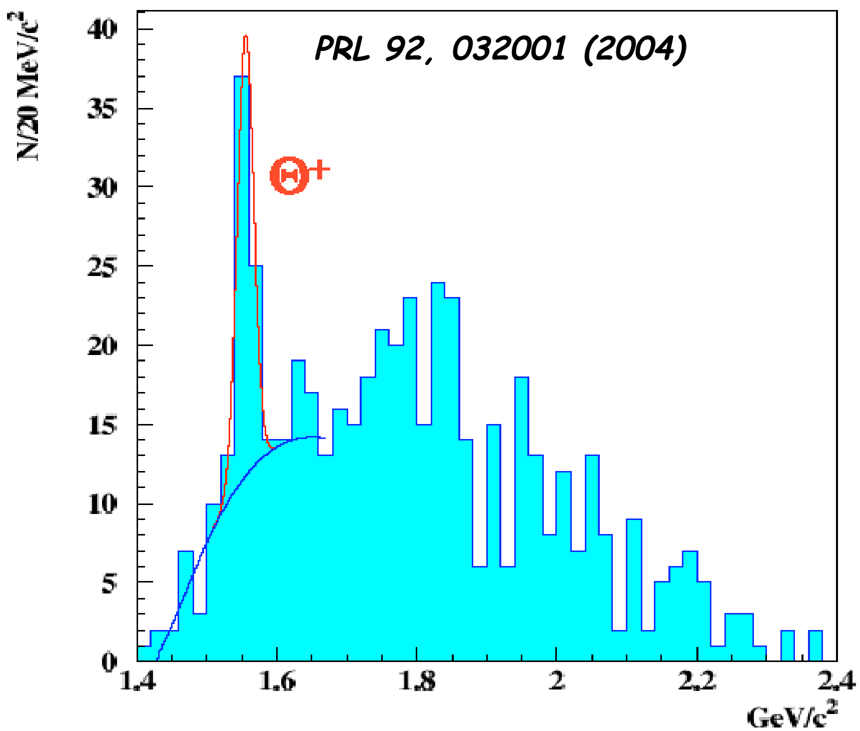
$\gamma p \to \pi^+ \Theta^+ K^-$
$\Theta^+ \to K^+ n$

production diagram



one possible BKG diagram





$N_{\Theta} = 41$

$M_{\Theta} = 1555 \pm 1 \pm 10$ MeV

Γ_{Θ}(FWHM) = 26 MeV

S= $(7.8 \pm 1.0)\sigma$

Pentaquark searches

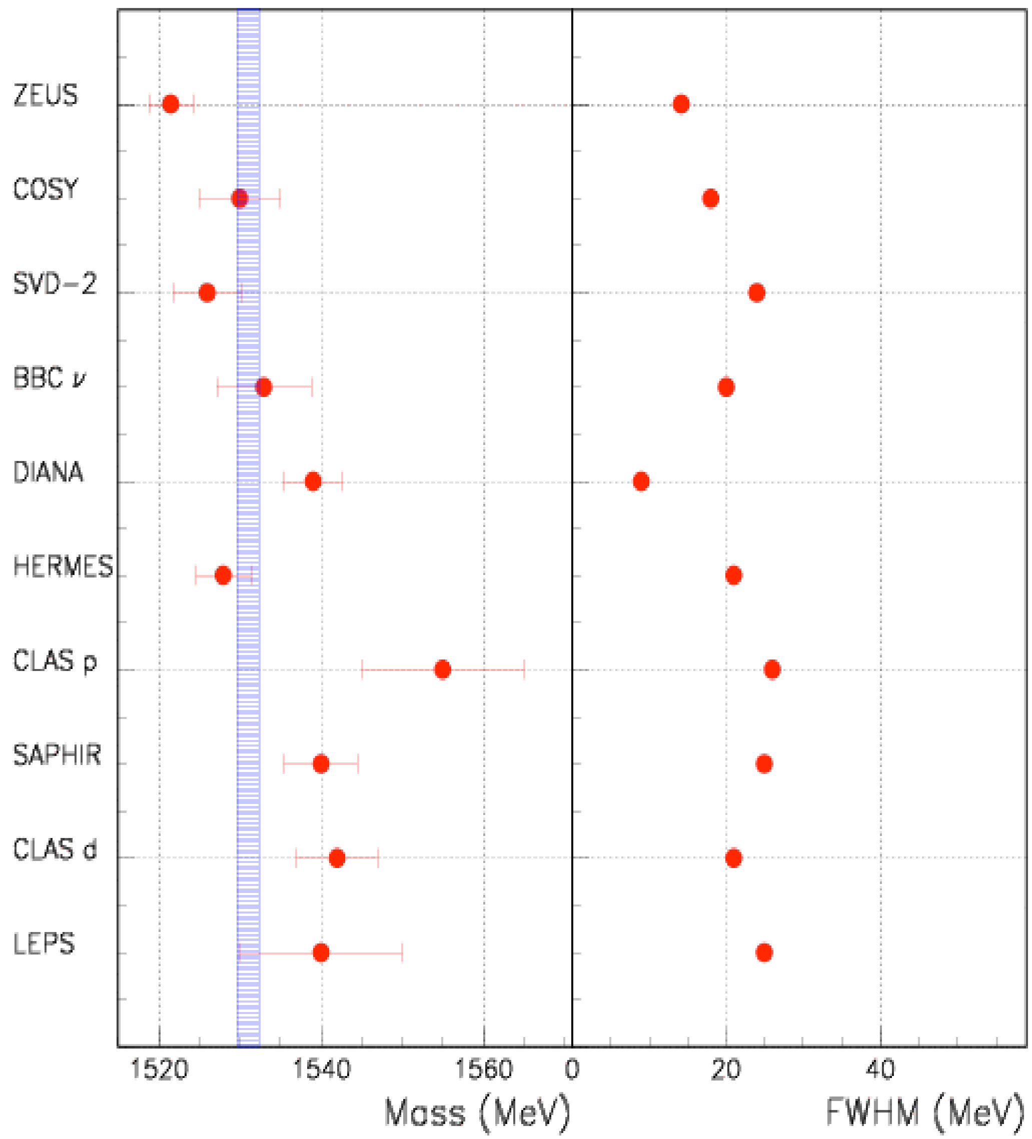
PHOTOPRODUCTION EXPERIMENTS	+	M(MeV)		.SIG.(nb)		comments
		±				
		±				
		± ±				
		± ±				
		± ±				
		±				
		±				
		±			±	
		±				
		±				

□$^{+}$ properties

- **Mass** ranges from □1520 to □1555 MeV/c
  world average: 1531.0 ± 1.4 MeV/c

- **Width** (FWHM) ranges from □10 to □25 MeV/c, dominated by experimental resolution

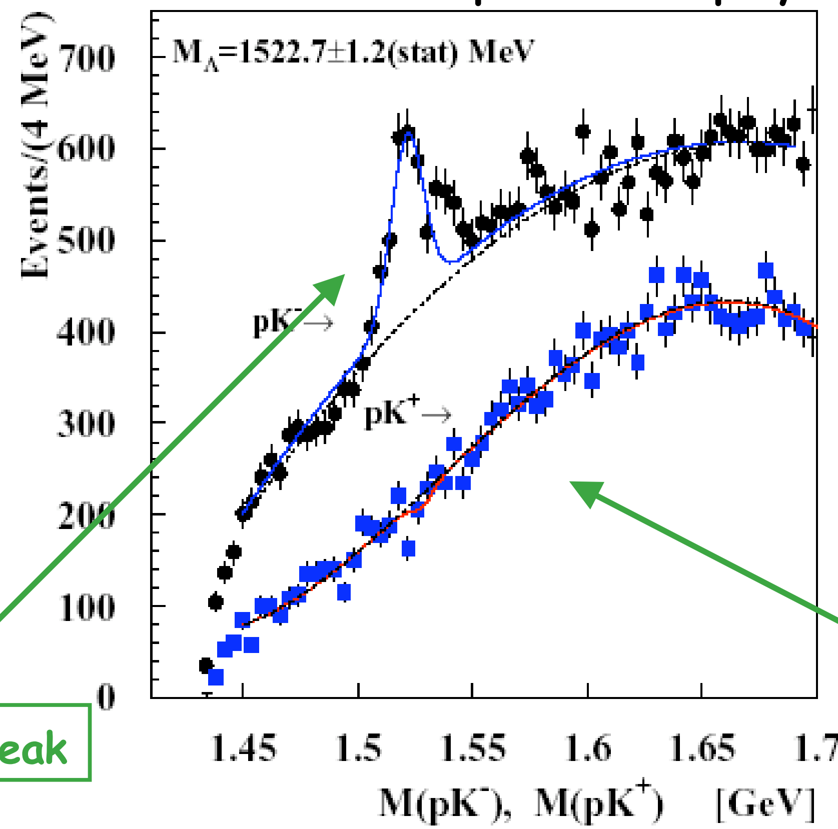
- **Strangeness** S = +1 fixed by exclusive measurements



Isospin

HERMES
□* d □ □⁺ X

Invariant mass spectra of Kp systems



pK⁻ system, □□(1520) peak

pK⁺ system, no peak

Result confirmed by other exp.

□ Data favor isospin T=0

Extraction of natural width from DIANA experiment

<u>DIANA experiment, charge-exchange process:</u> K^+n □ $□^+$ □ K^0p

Cahn-Trilling, hep-ph/0311245

Experimental resolution is broader than the natural width
□ the observable quantity is the integral of the cross section

- Non resonant contribution: I_{NR} = $□_{NR}$ $□^{exp}$ □ N_{bkg} / □

  $□_{NR}$ = 4.1±0.3 mb

- Resonant contribution: BW resonance assuming J=1/2, B_i = B_f = 0.5

  I_{RES} = □/2 $□_0$ B_i B_f $□^{nat}$ □ $N_□$ / □

- DIANA measurements: $□^{exp}$ □ 10 MeV (2 histogram bins)

  $N_{□+}$ □ 26 events

  N_{bkg} □ 44 events

$□_□^{nat}$ = 0.9 ± 0.3 MeV very narrow

(chiral-soliton prediction is □<15 MeV)

Θ^+ and KN scattering

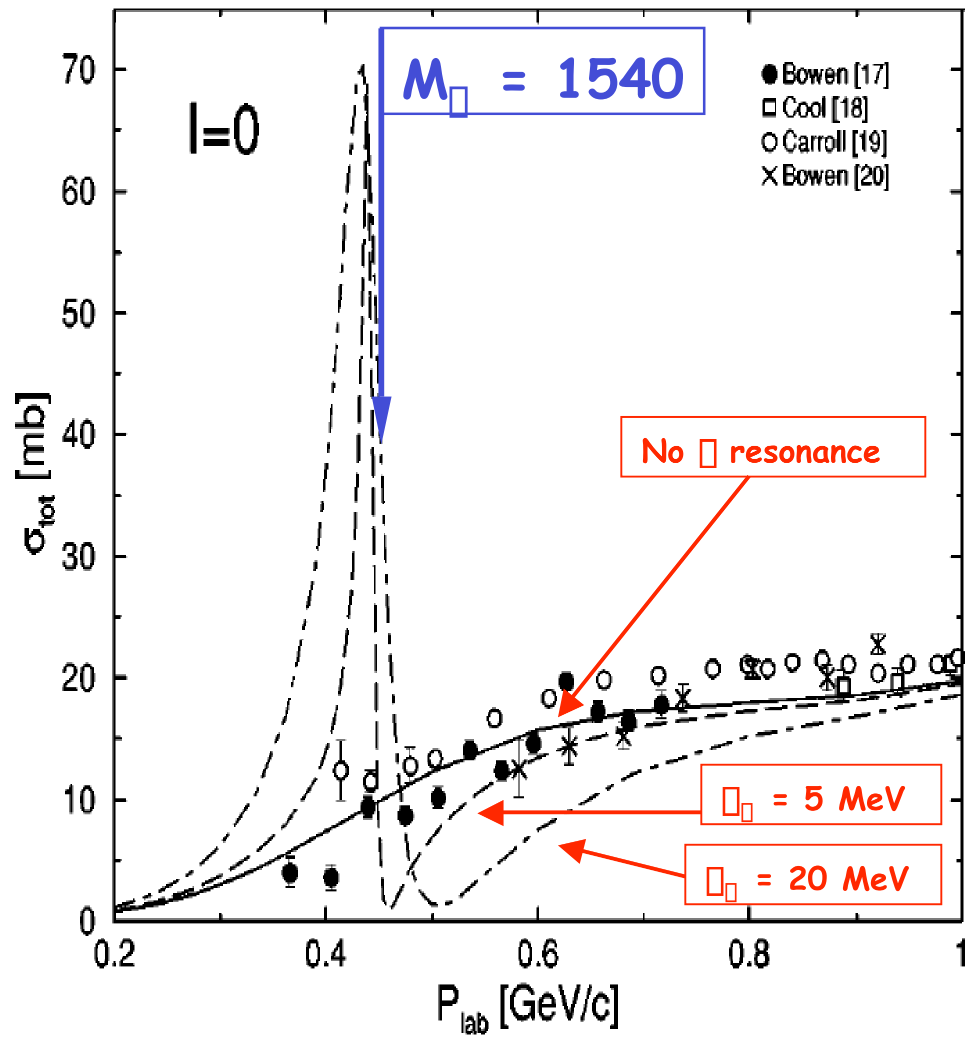
Partial wave analysis of KN data

Haidenbauer-Krein, hep-ph/0309243

- meson and baryon exchange in KN elastic scattering
- s-channel resonance (Θ^+) with I=0, $J^P=1/2^+$
- KN resonance with I=1 (model independent)
- cross section calculated for different Θ^+ widths

KN scattering data are compatible with the presence of a resonance only if:
- it is much narrower than 5 MeV or
- it is at lower mass

New KN data should be soon available by the DIANA Collaboration



□$^+$ natural width in CQM

Jaffe, Wilczek, PRL 91, 232003-1 (2003)

- pentaquarks are formed by two strongly bound scalar diquarks and an antiquark

$$[ud]_{J=0}\,[ud]_{J=0}\,\bar{s}$$

- lower mass states are SU(3) mixtures of 8 and $\overline{10}$
- two pentaquarks with N quantum numbers exist: N_0 □ N*(1440)
  N_1 □ N*(1710)

BUT

Cohen, hep-ph/0402056

- □$^+$, N_0 and N_1 widths are connected by a relation wich is broken by experimental values (assuming □$_□$ □ MeV)

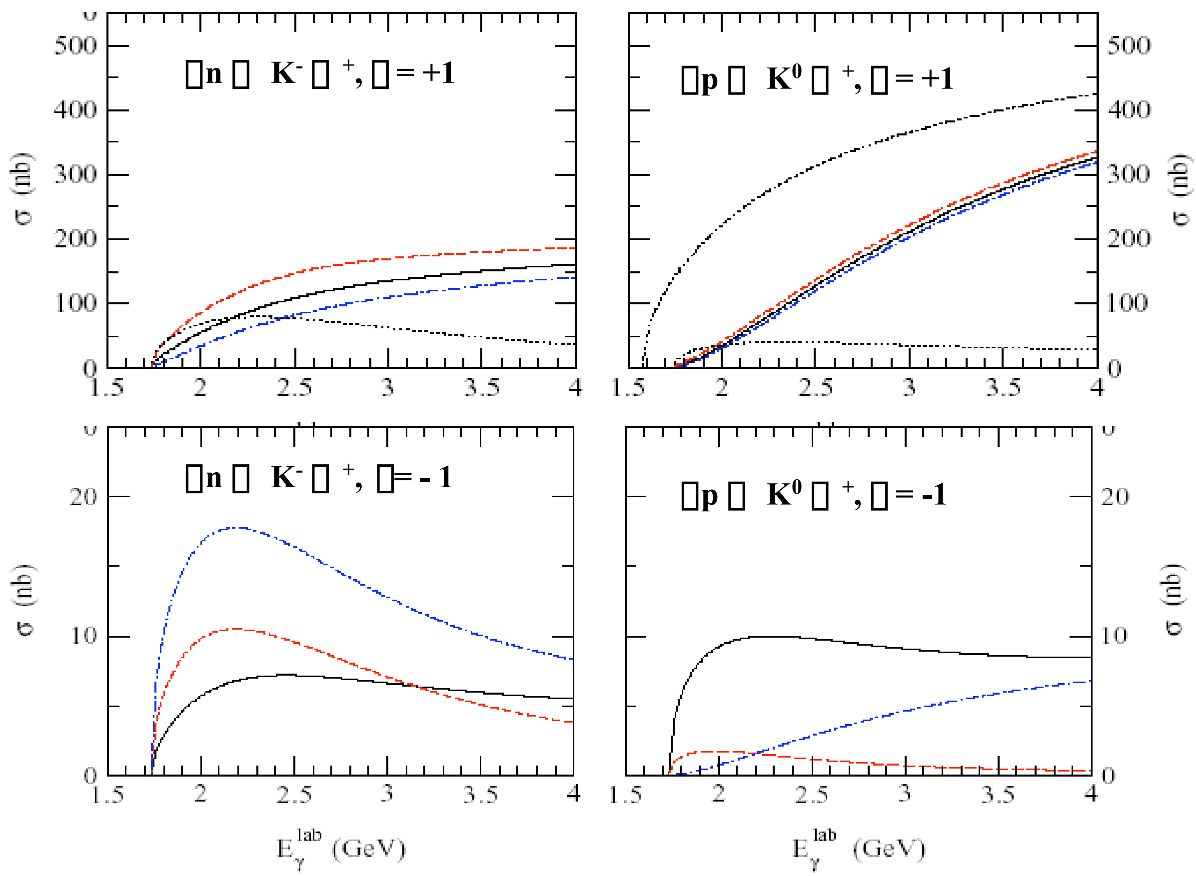
Karliner, Lipkin, hep-ph/0401072

- two combinations of two diquarks and an antiquark in different color and spin couplings (□$_1$ and □$_2$)
- two mass eigenstates exist (□$_S$ and □$_L$)
- due to □$_1$-□$_2$ mixing, □$_L$ decouples from KN decay (in ideal SU(3) symmetry)

Parity

Parity is a strong discriminator between different models, but no direct measurements yet

Informations can be deduced from theoretical considerations



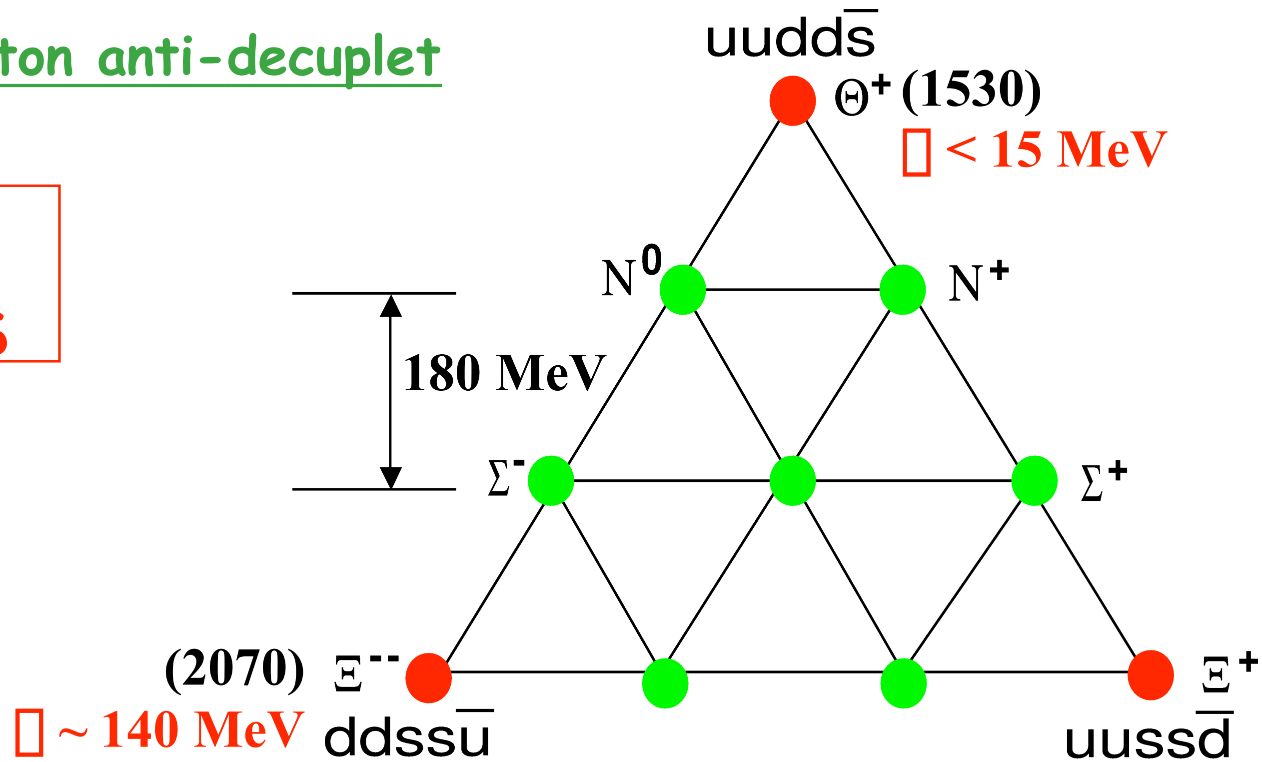
Oh, Kim, Lee - hep-ph/0310019

Experimental cross section estimates (CLAS, SAPHIR, HERMES) seem to favor positive parity

The search for other pentaquark states

Chiral Soliton anti-decuplet

EXOTIC STATES

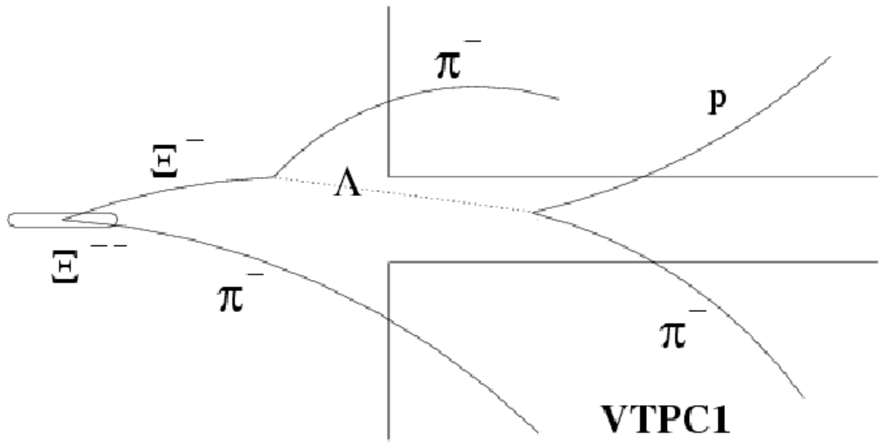


- excited pentaquark states can exist
- pentaquarks with heavy quarks

The □$_{3/2}$ at NA49

$p\,p$ □ □$_{3/2}$ X pp scattering

□$^{--}_{3/2}$ □ □$^-$□$^-$ □ □□$^-$□$^-$□ p□$^-$□$^-$□



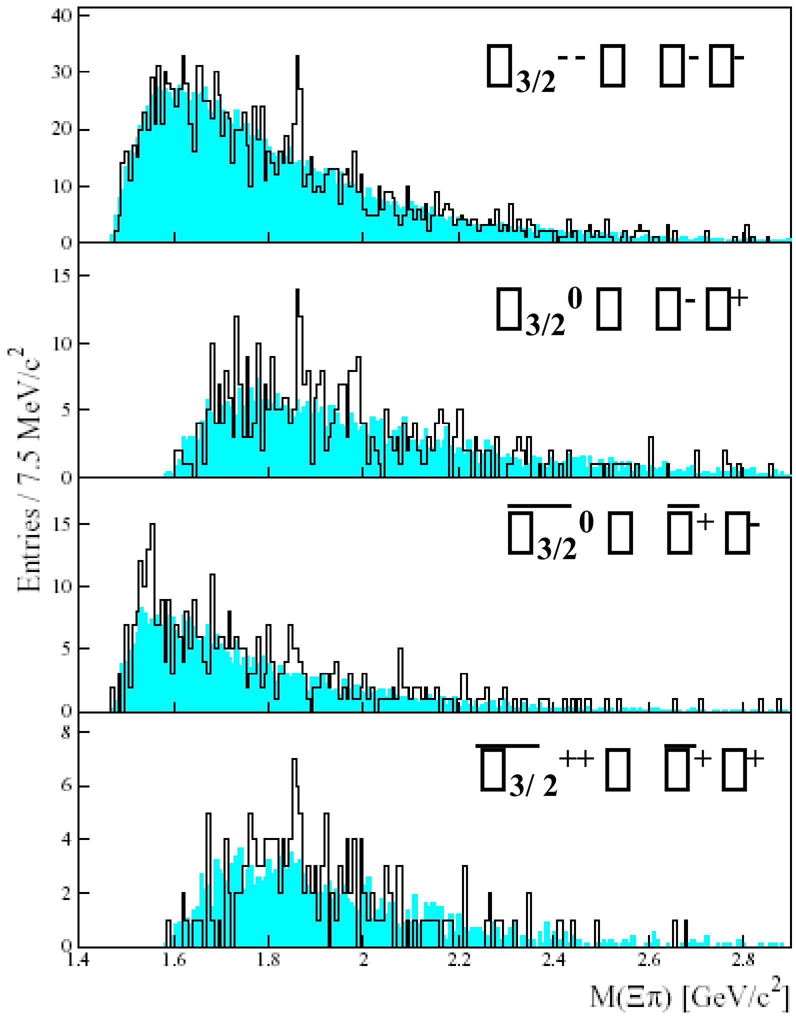
Summing up all spectra and after background subtraction:

M = 1862 ± 2 ± 1 MeV

□(FWHM) = 17 ± 3 MeV

S = 5.6□

hep-ex/0310014



BUT these results heve been questioned: old data should show at least one order of magnitude more □$_{3/2}$ events than NA49 *Fischer-Wenig, hep-ex/0401014*

The □$_{3/2}$ search at HERA-B

hep-ex/0403020

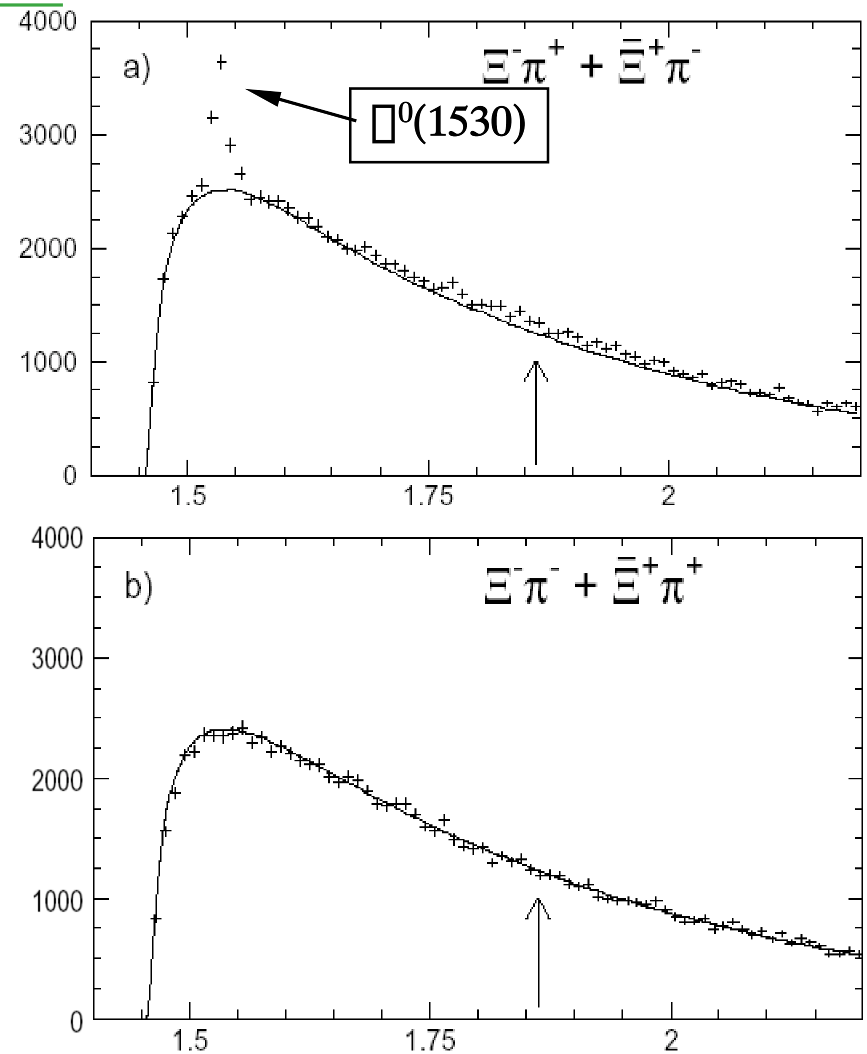
<u>Proton-nucleus (C,Ti,W) collisions</u>

p A □ □$_{3/2}$ X

□$^{--}_{3/2}$ □ □$^{-}$□$^{-}$ □ □ □$^{-}$ □$^{-}$ □ p □$^{-}$ □$^{-}$ □$^{-}$

P_{beam} = 920 GeV/c

x_F□ 0



no □$_{3/2}$ signal in all target data

(but kinematical region is different from NA49)

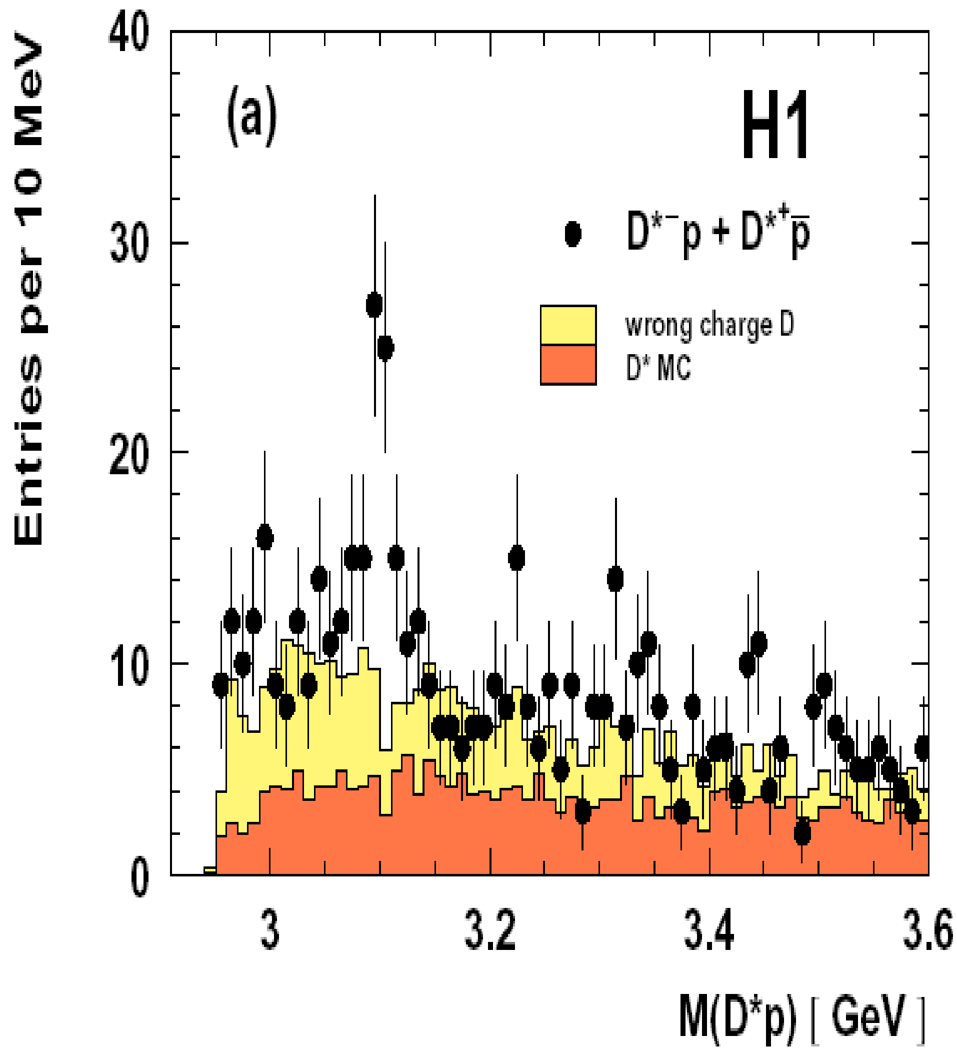
Charmed pentaquark: H1 exp.

hep-ex/0403017

Θ_c has the same structure as Θ^+ (but is neutral)

$e^{\pm} p \to \Theta_c X$	$\Theta_c \to D^{*-} p$ $\bar{\Theta}_c \to D^{*+} \bar{p}$

Events in DIS region ($1 \le Q^2 \le 100$ GeV^2) and in quasi-real γ region ($Q^2 \le 1$ GeV)



$N_{\Theta_c} = 50.6 \pm 11.2$

$M_{\Theta_c} = 3099 \pm 3 \pm 5$ MeV

$\Gamma_{\Theta_c}(\mathrm{FWHM}) = 12 \pm 3$ MeV

$S = 6.2\sigma$

Open questions

For theorist

- Is it a true pentaquark state?
- Why is so light and narrow?
- What is the production mechanism? Is production cross section strongly dependent on the kinematics?
- How to distinguish non exotic pentaquark states?

For experimentalist

- Confirm the present $\square^+$ signal with higher statistic
- Precise measurements of mass and width
- Fix quantum numbers (spin, parity, isospin)
- Where are the other members of the multiplets? Do we have already seen the $\square_{3/2}$?
- Are there excited states?

The next step: pentaquark studies at CLAS

Data Set	Reaction	Final State
		()=undetected
g1c,g6a,g6b	γ p -> θ+ K0s	K+ (n) π+ π-
g1c,g6a,g6b	γ p -> θ+ K0s	π+ π- p (K0)
g6c	γ p -> θ+ K0s	K+ (n) π+ π-
g1c	γ p -> θ+ K0s	K+ (n) π+ π-
g6c	γ p -> θ+ K0s	K+ (n) π+ π-
g6a,g6b	□p -> □+ □+ K-	K+ (n) □+ K-
g6a,g6b	γ p -> θ+ K0*	K+ (n) π+ K-
g1c	γ p -> θ+ K0*	K+ (n) π+ K-
g6c	γ p -> θ+ K0*	K+ (n) π+ K-
g6a,g6b	γ p -> θ+ K0*	K+ (n) π+ K-
g2a	γ d -> θ+ K- p	K0 p K- p
g2a	γ d -> θ+ K- p	K+ (n) K- (p)
g2a	γ d -> θ+ K- p	K0 p K- p
g2a	γ d -> θ+ K*- p	
g2a	γ d -> θ+ X	K0 p X
g2a	γ d -> θ+ K- p	K+ (n) K- p
g2a	□d □ □+ □	K+ (n) □- p
g2a	γ d -> K+ K+ p (Ξ--)	K+ K+ p π– π– π0
	γ d -> θ– Σ+ π+	

published

LNF analysis

Pentaquark searches at CLAS

Sensitivity to spin and parity

$\gamma p \rightarrow \Theta^{+} K^{0}$

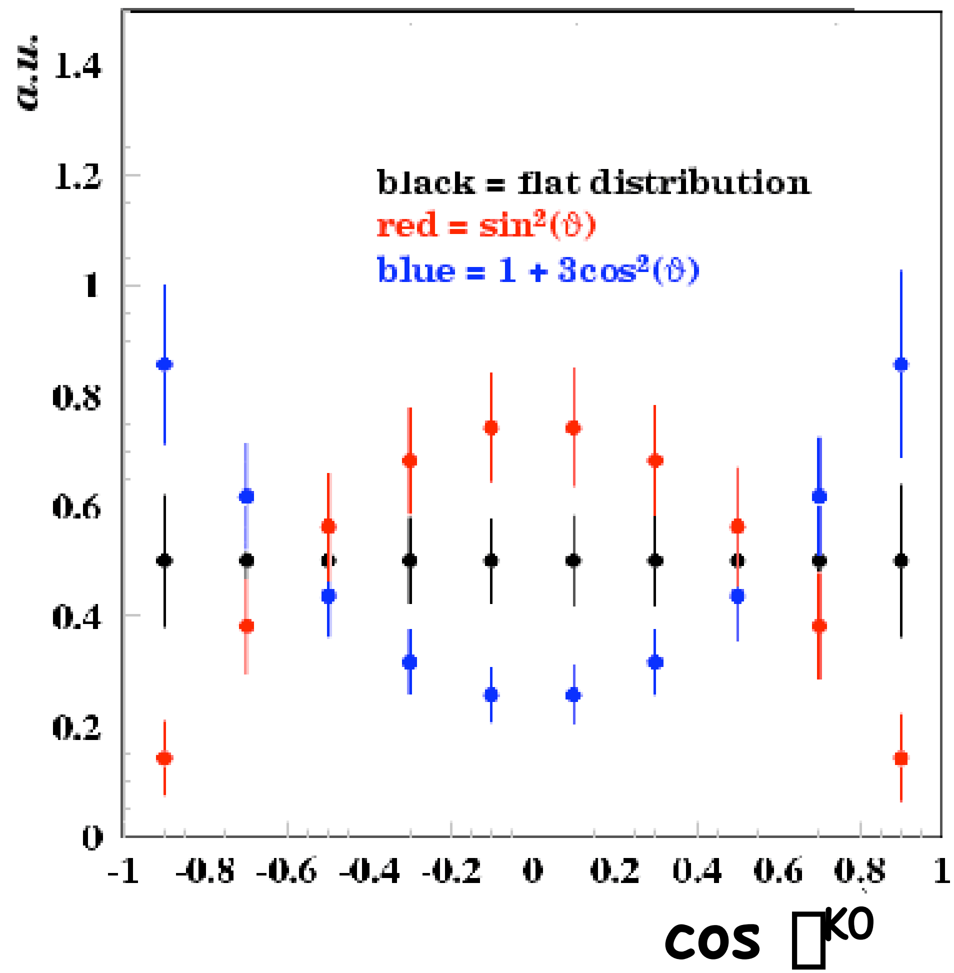
projected data on p
25 days data taking

CLAS can measure full decay distributions

$J^P = 1/2^- \rightarrow$ flat

$J^P = 1/2^+ \rightarrow 1 \pm \sin(2\theta)\cos(\phi)$
for $J_z = \pm 1/2$

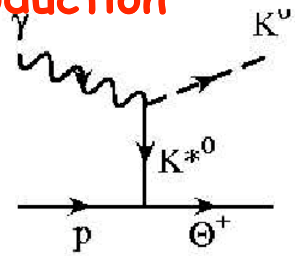
$J^P = 3/2^+ \rightarrow 1+3\cos^2(\theta) \pm 2\sin(2\theta)\cos(\phi)$
for $J_z = \pm 1/2$
$\rightarrow \sin^2(\theta)$
for $J_z = \pm 3/2$



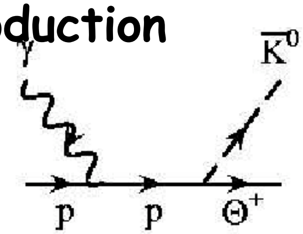
Pentaquark searches at CLAS

Sensitivity to different production mechanism

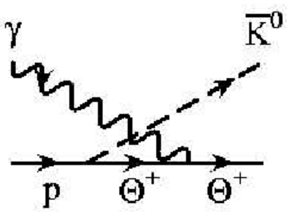
t-channel (forward) production



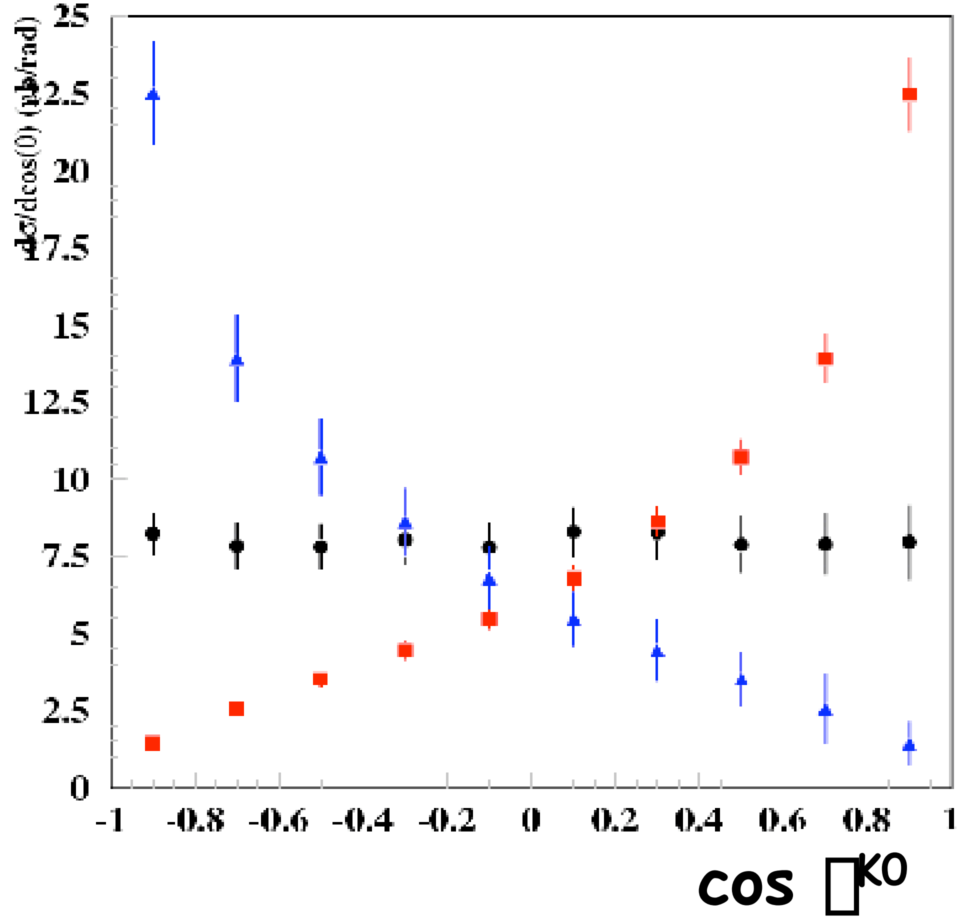
s-channel (isotropic) production



u-channel (backward) production



projected data on p
25 days data taking



Pentaquark search: other LABs

Further experimental studies are underway in other laboratories

- HERMES
  - New analysis of old deuteron data (target polarization)
  - New data taking with optimized trigger

- LEPS
  - results from deuteron runs
  - upgrade of the apparatus to have 4π coverage
  - study Θ^+ in the K*(892) photoproduction
  - polarization measurements

- DIANA
  - Extraction of total KN cross section close to Θ^+ mass

- COSY
  - upgrade of the experimental apparatus
  - dedicated experiments for Θ^+ production in pn and pd scattering

Final results from GRAAL, PHENIX, SELEX

Summary

- Experimental evidence for the existence of the Θ^+, the first exotic pentaquark baryon, is incrisingly convincing
- Theoretical activity supports this experimental result
- High statistics measurements are underway to conclusively confirm the existence of Θ^+
- These new data will allow to fix Θ^+ quantum numbers and understand its production mechanism