Search for Pentaquarks

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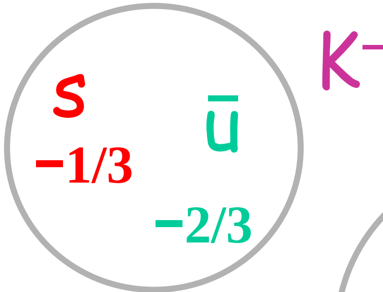
OUTLINE

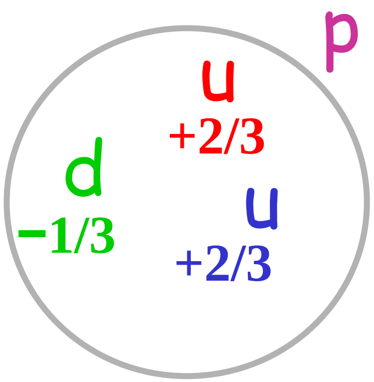
- Hadron Spectroscopy and Pentaquarks
- Evidence for and against $\Theta^+(1540)$ and other Pentaquarks
- Theory response to the $\Theta^+(1540)$
- The experimental program at JLab
- Summary

Hadron Spectroscopy 101

Meson: quark-antiquark pair



Baryon: three quarks (valence)

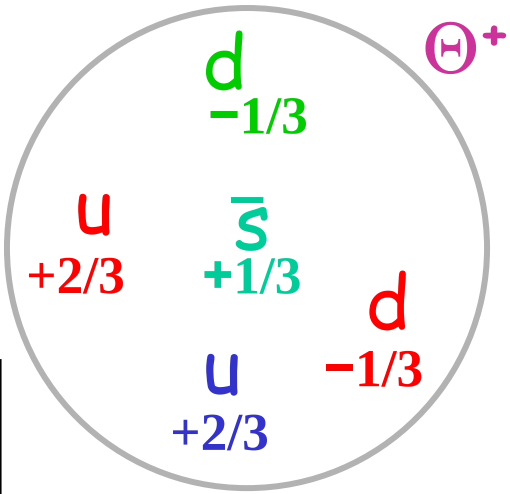


Pentaquark: 4 quarks + 1 antiquark

Each quark has a unique

- charge (+2/3 or -1/3)
- flavor (u,d,s,c,b,t)
- color (red, green, blue)

Hadrons must be colorless



The Θ^+ represents a new form of quark matter containing a minimum of five quarks.

Types of Pentaquarks

- “Non-exotic” pentaquarks
  - The antiquark has the same flavor as one of the other quarks
  - Difficult to distinguish from 3-quark baryons

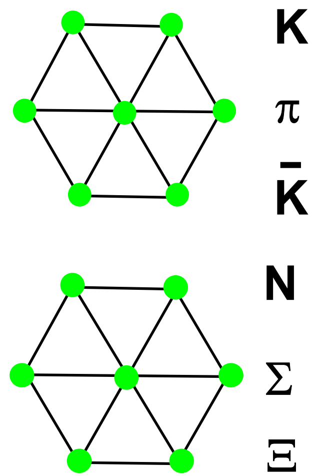
  Example: uuds$\bar{s}$, same quantum numbers as uud
  Strangeness = 0 + 0 + 0 - 1 + 1 = 0

- “Exotic” pentaquarks
  - The antiquark has a flavor different from the other 4 quarks
  - They have quantum numbers different from any 3-quark baryon
  - Unique identification using experimental conservation laws

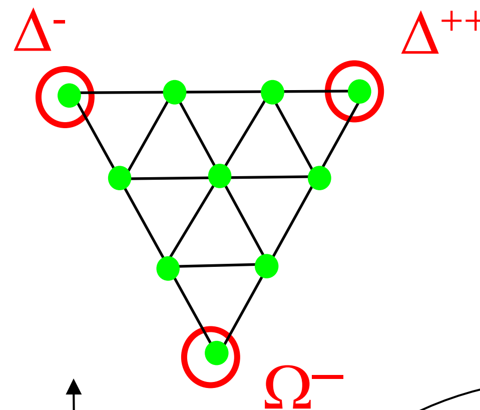
  Example: uudd$\bar{s}$
  Strangeness = 0 + 0 + 0 + 0 + 1 = +1

Hadron Multiplets

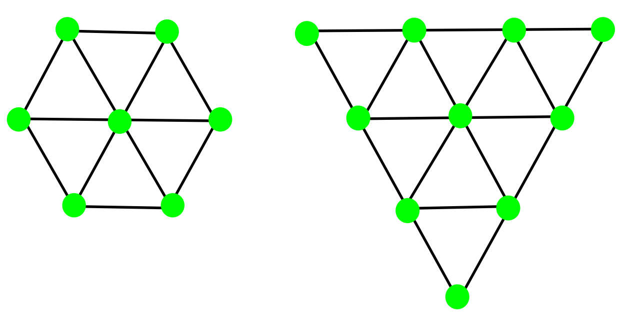
Mesons $q\bar{q}$

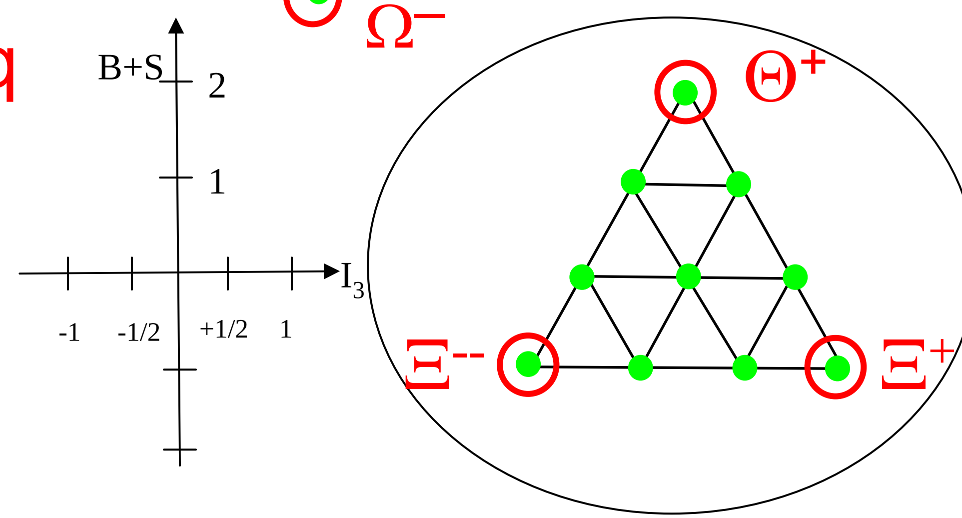


Baryons qqq



Baryons built from $qqqq\bar{q}$



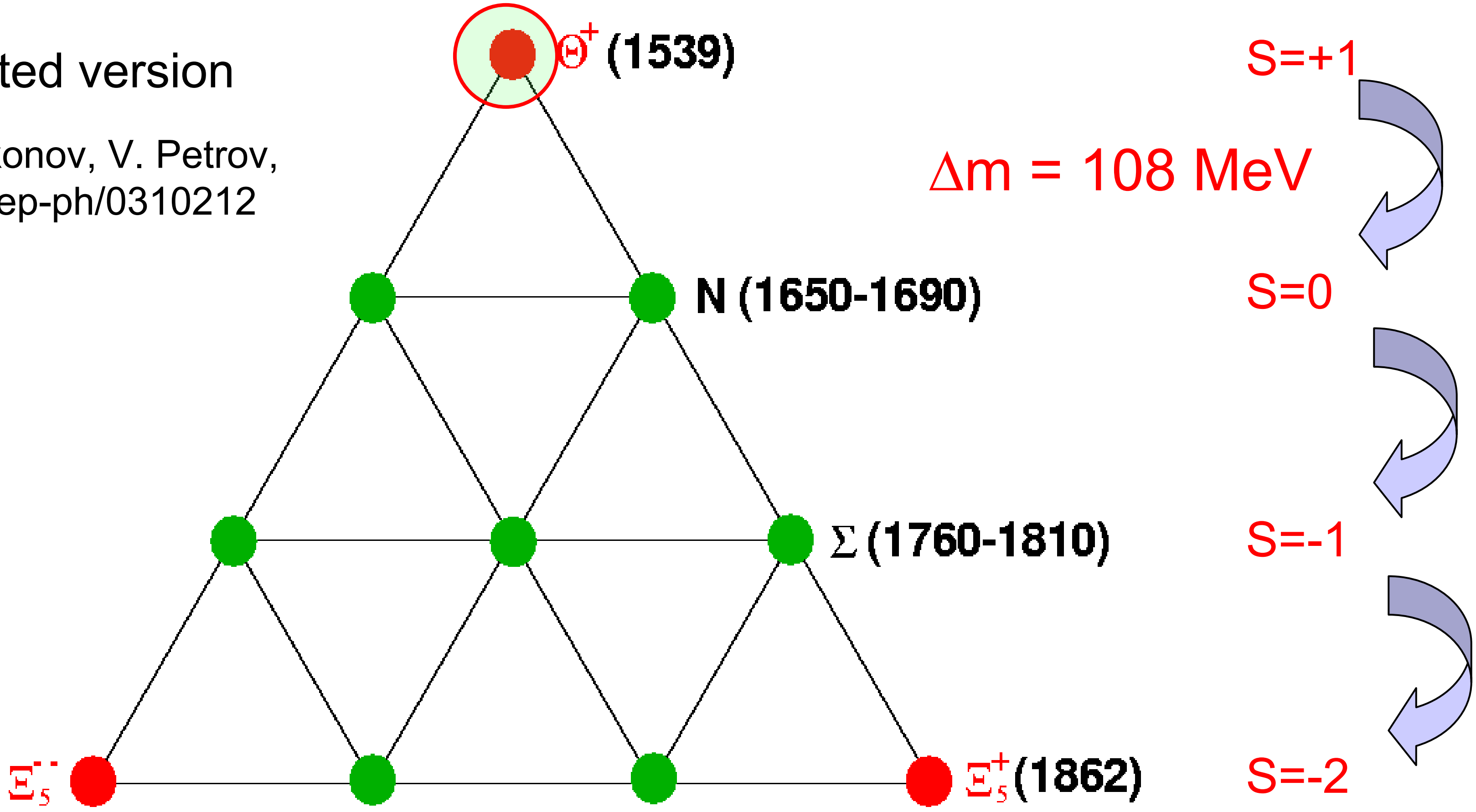


The Anti-decuplet in the χSM

D. Diakonov, V. Petrov, M. Polyakov, Z.Phys.A359, 305 (1997)

updated version

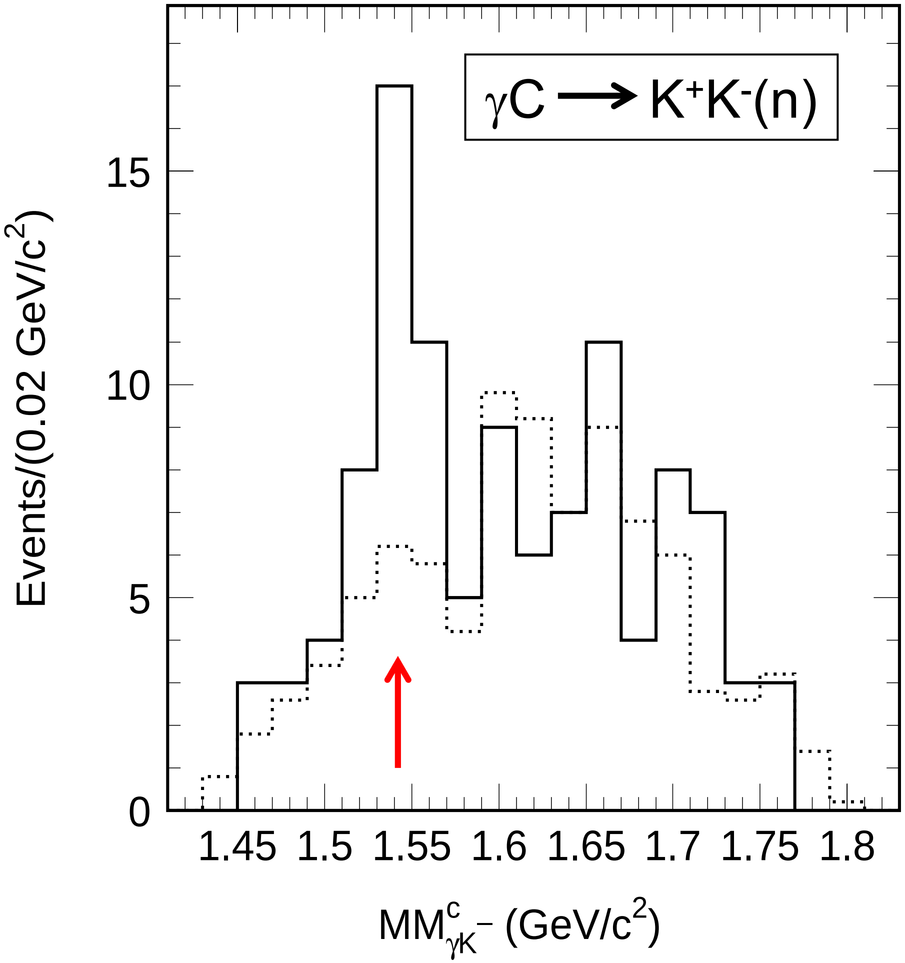
D. Diakonov, V. Petrov,
arXiv:hep-ph/0310212



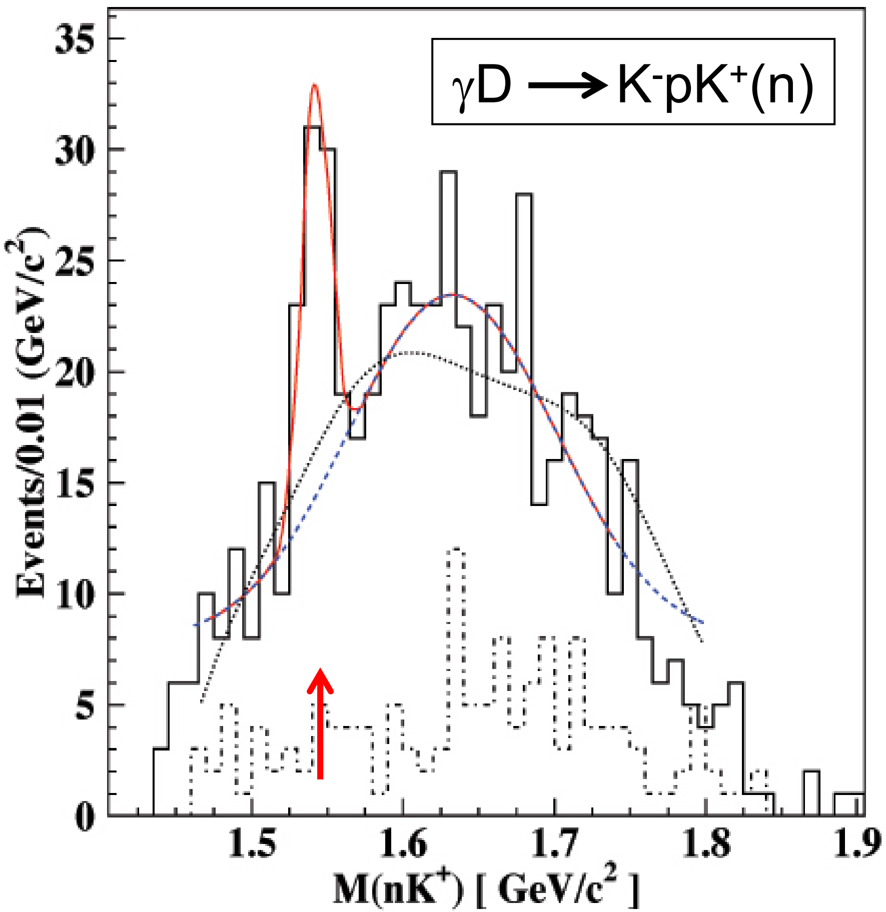
→ Show experimental evidence for results submitted for publication.

$\Theta^+(1540)$ as seen with e.m. probes

PRL91, 012002 (2003) ***LEPS/SPring8***



PRL91, 252001 (2003) ***CLAS/JLab***

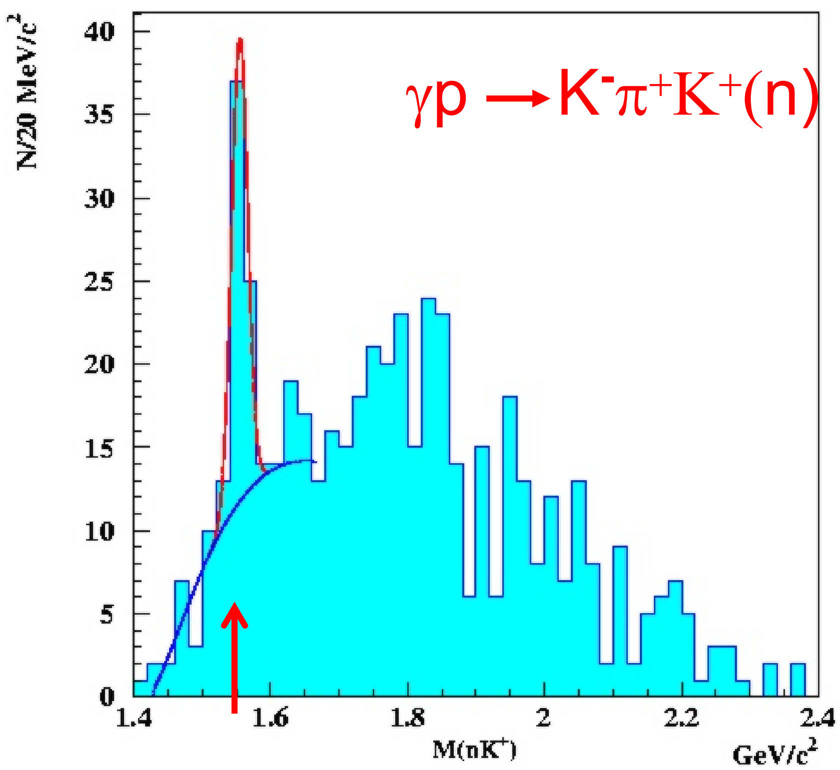


Θ^+(1540) as seen with e.m. probes

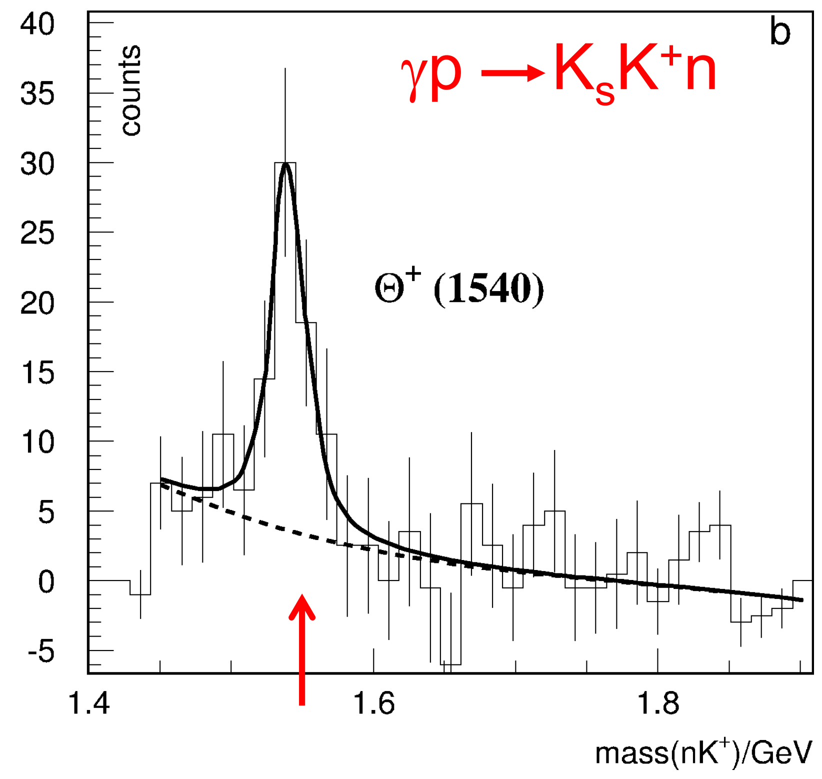
PRL92, 032001 (2004)
hep-ex/0307088 (2003)

PLB572, 127 (2003)

CLAS/JLab

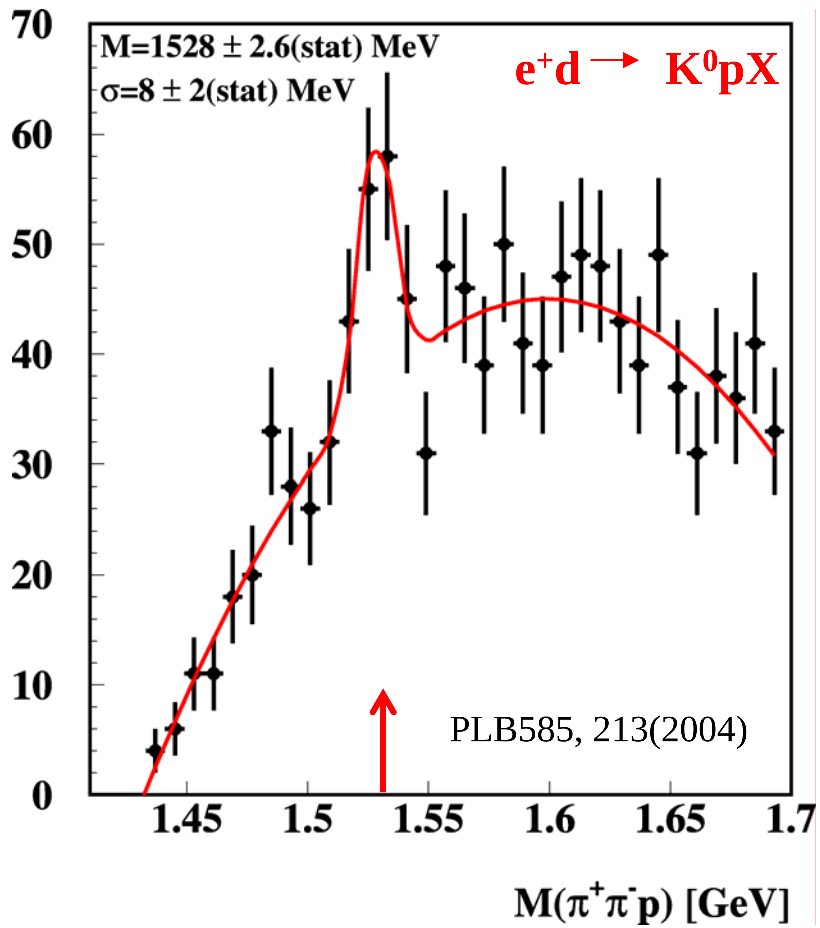


SAPHIR/ELSA

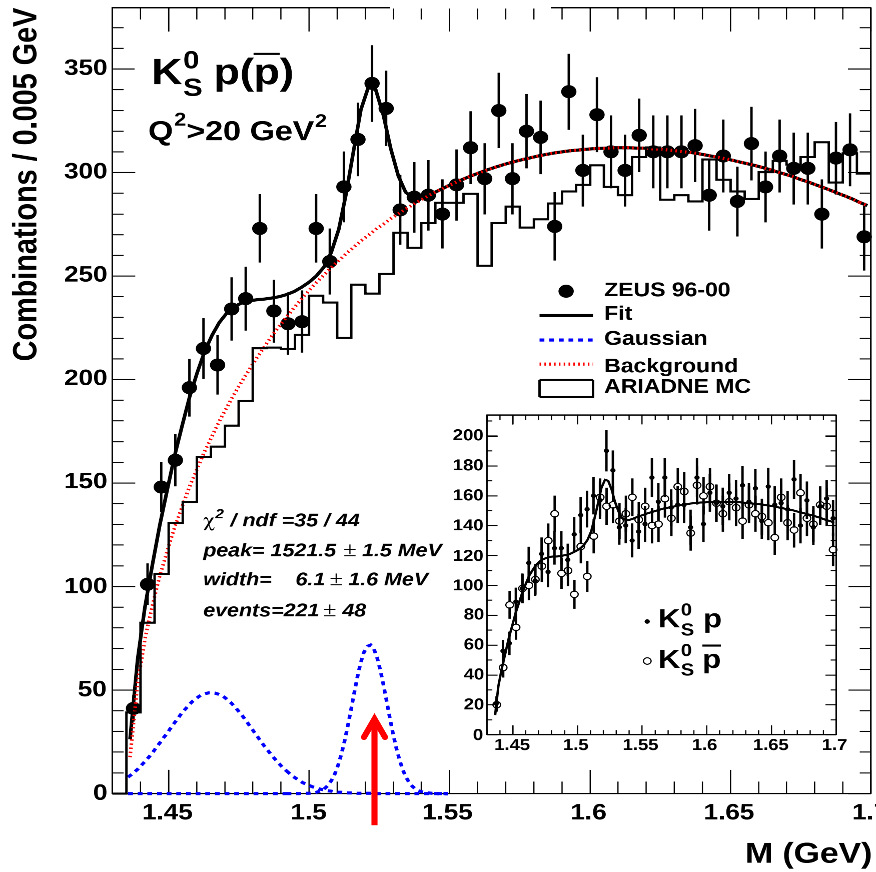


$\Theta^+(1540)$ as seen with e.m. probes

HERMES/DESY



ZEUS/HERA

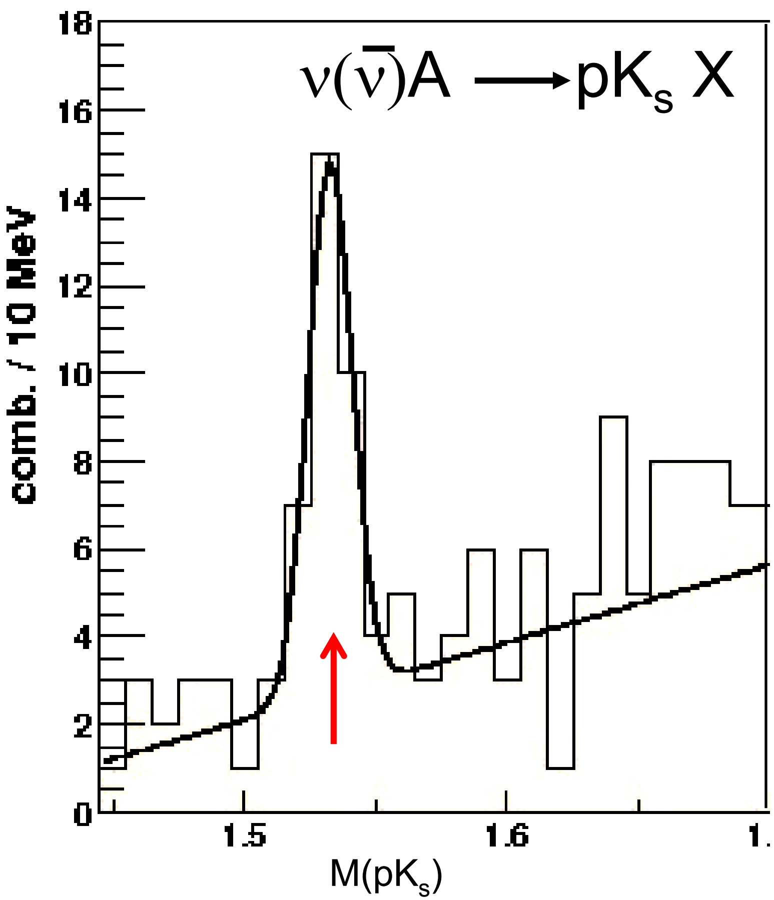


hep-ex/040305 (2004)

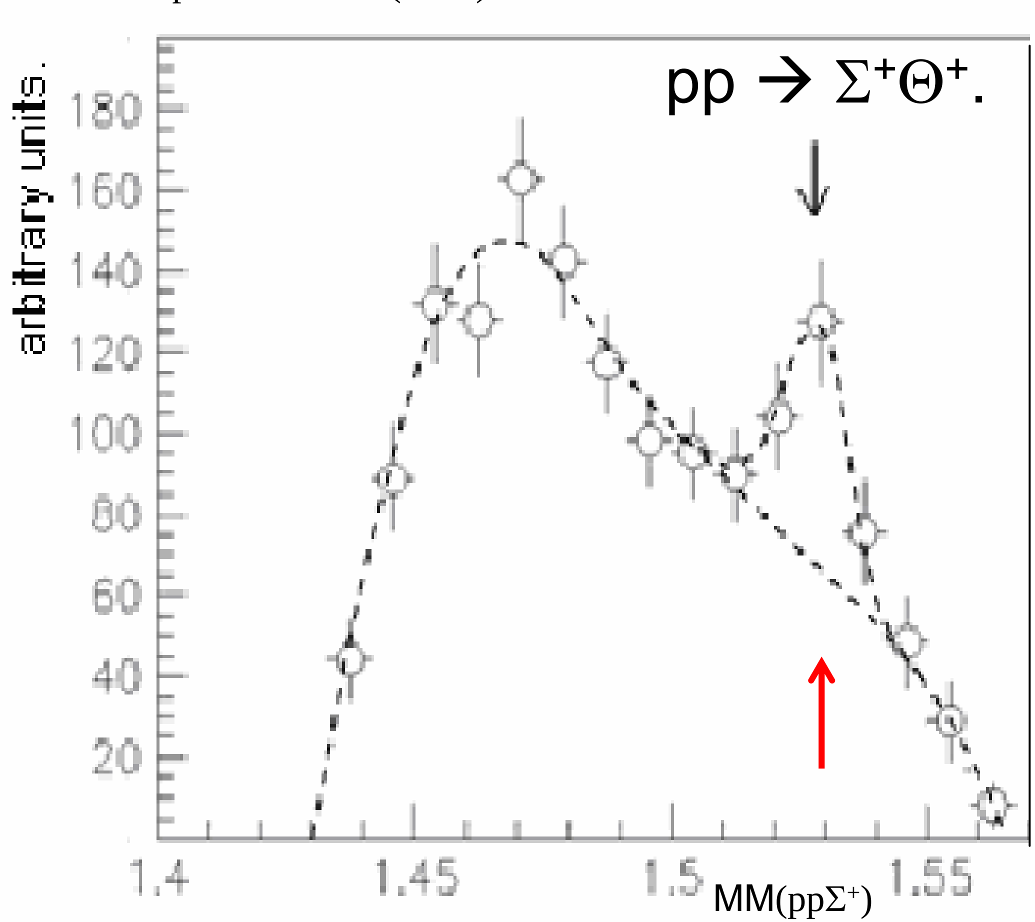
Θ^+ in non-electromagnetic interactions

Phys.A.Nucl.67, 682 (2004)

ITEP



hep-ex/0403011 (2004) COSY/TOF

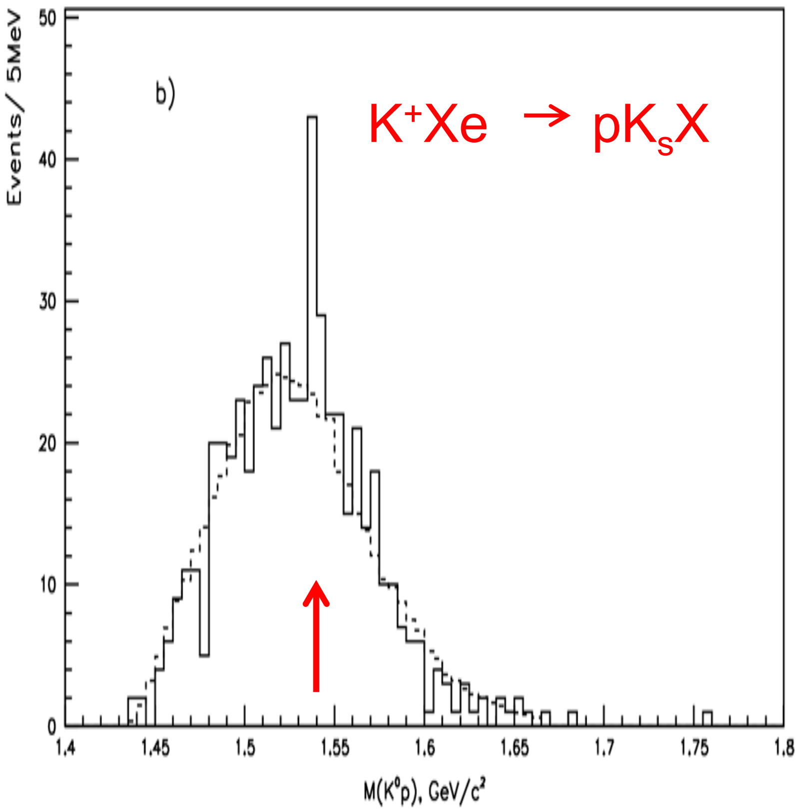


Θ^+(1540) in hadron-nucleus processes

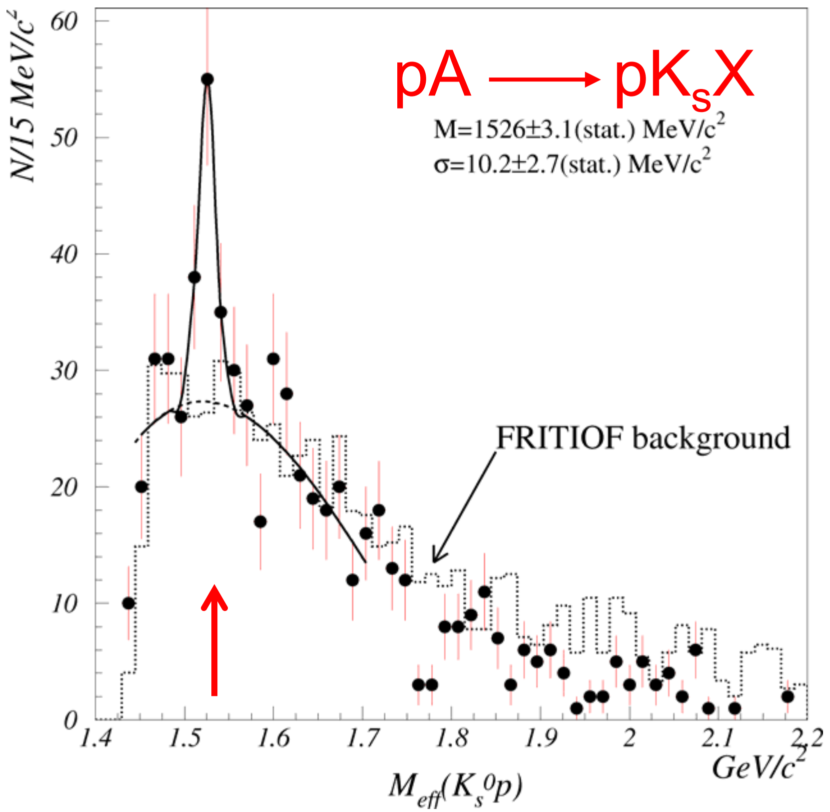
Phys.A.Nucl.66, 500 (2003)
hep-ex/0304040

hep-ex/0401024 (2004)

DIANA

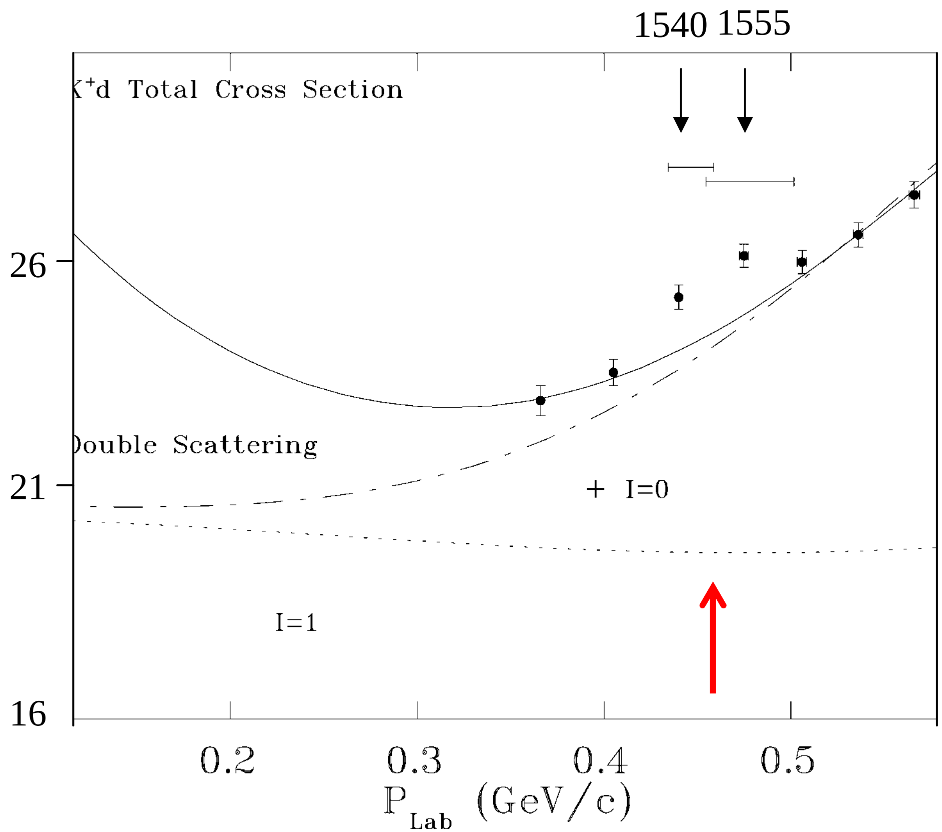


SVD/IHEP



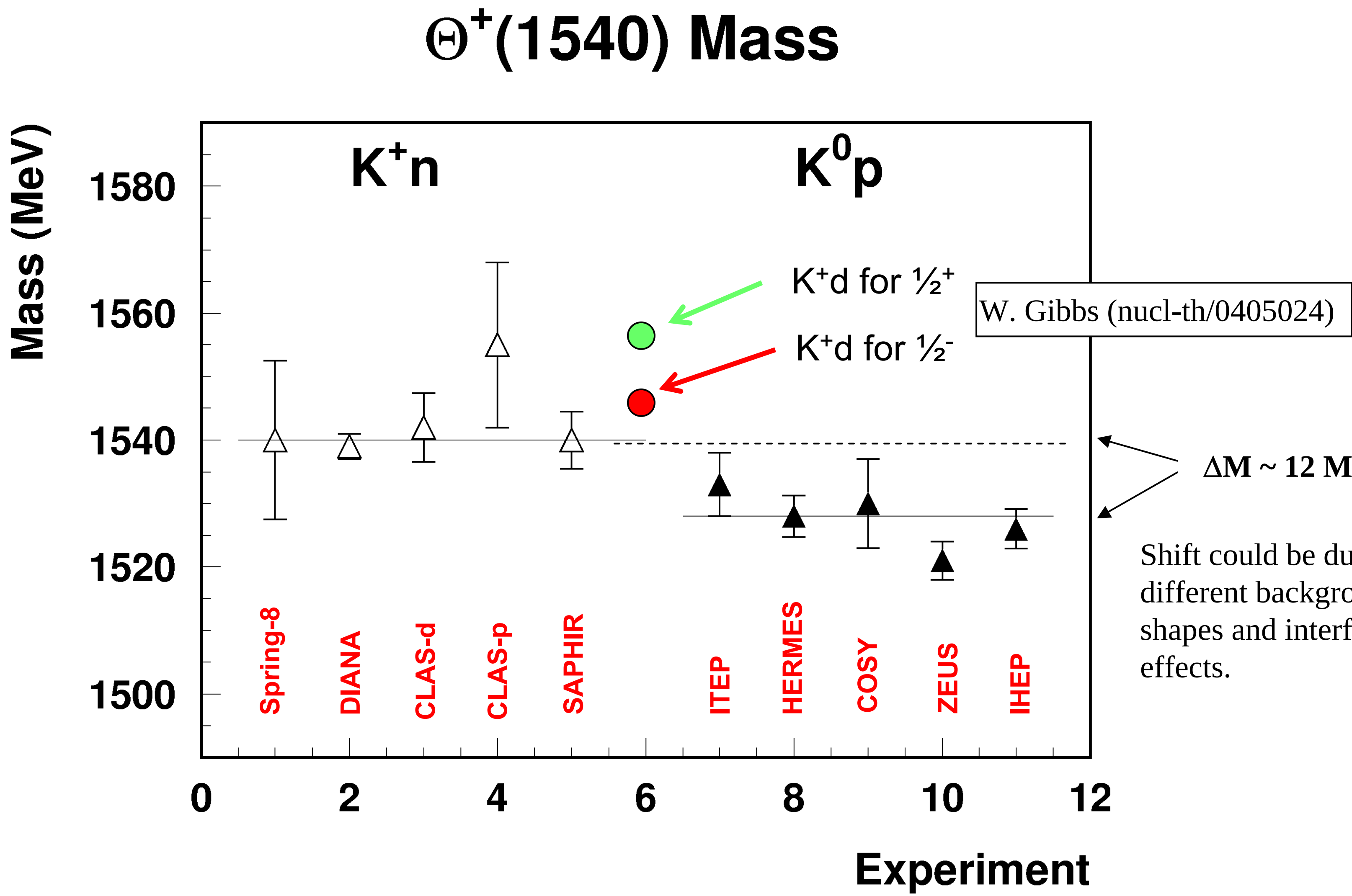
Θ^+(1540) in K^+d Scattering

Data from T. Bowen et al. , PRD 2, 2599 (1970)



From: W. Gibbs
nucl-th/0405024 (2004)

Summary of Experimental Masses



Shift could be due to different background shapes and interference effects.

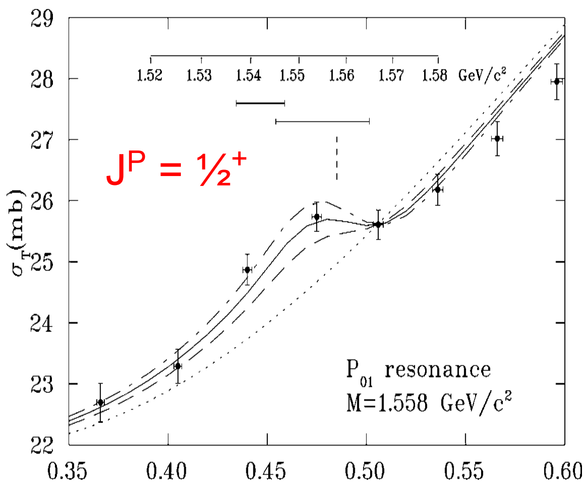
What do we know about the width of Θ^+?

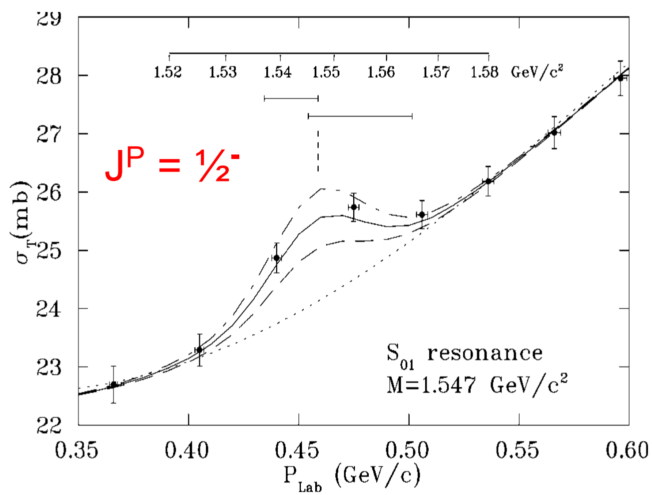
Widths seen in experimental analyses are dominated by resolution effects.
More precise information is obtained in analyses with theoretical constraints.

HERMES, PLB585, 213 (2004)	Γ_Θ = 17+/-9+/-3 MeV	
S. Nussinov et al., hep-ph/0307357	Γ_Θ < 6 MeV	(non-observation)
R. Arndt et al., PRC68, 42201 (2003)	Γ_Θ < 1 MeV	(non-observation)
R. Cahn and G. Trilling, PRD69, 11401(2004)	Γ_Θ = 0.9 +/- 0.3MeV	(from DIANA results)
A. Sibirtsev, et al., hep-ph/0405099 (2004)	Γ_Θ < 1 MeV	($K^+d \rightarrow K^opp$)

First positive identification of Θ^+ in K^+d, including double scattering.

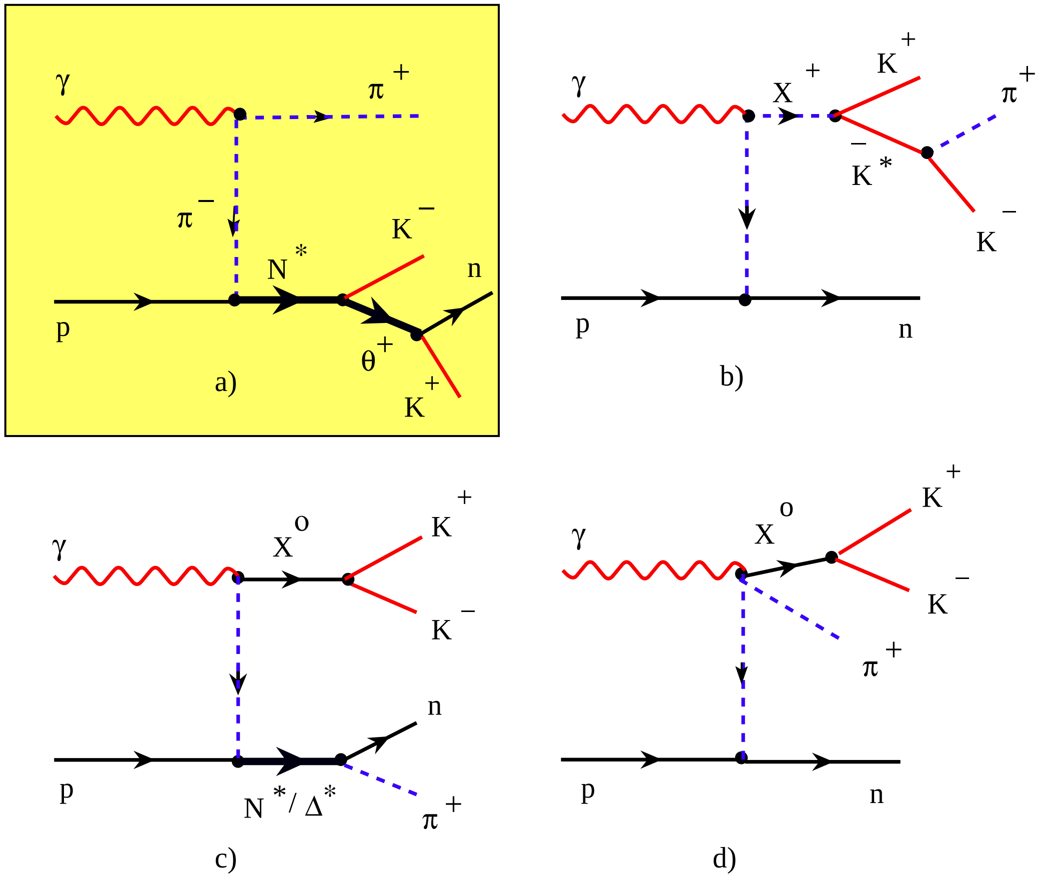
W. Gibbs, nucl-th/0405024 (2004) Γ_Θ = 0.9 +/-0.2 MeV ($K^+d \rightarrow X$)





Θ^+ - Production mechanism on hydrogen

Possible production mechanism



- Select t-channel process by tagging forward π^+ and reducing K^+ from t channel processes

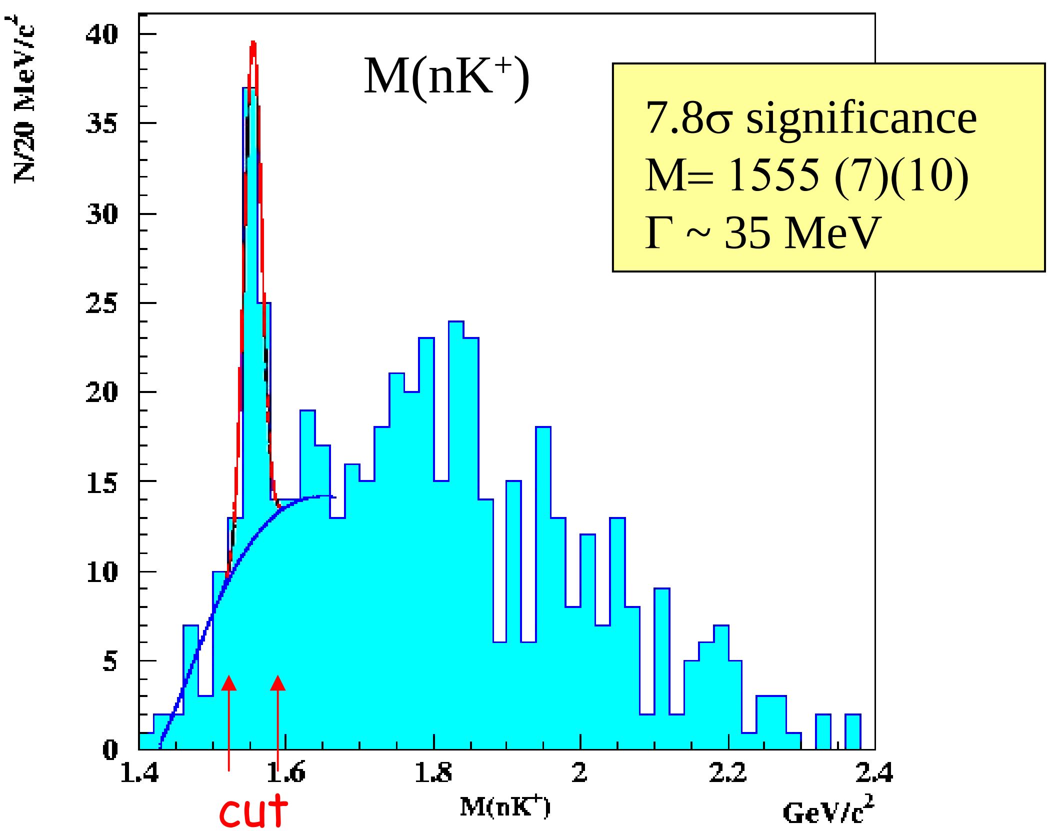
- $\cos\theta^*_{\pi^+} > 0.8$
- $\cos\theta^*_{K^+} < 0.6$

(in c.m. frame)

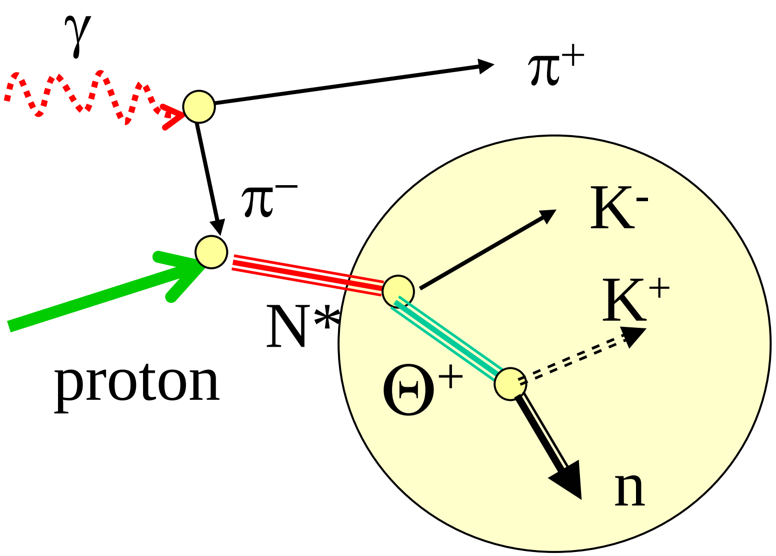
CLAS - Θ^+ production mechanism?

Eγ = 3 - 5.4 GeV

$\gamma p \rightarrow \pi^+ K^+ K^- n$

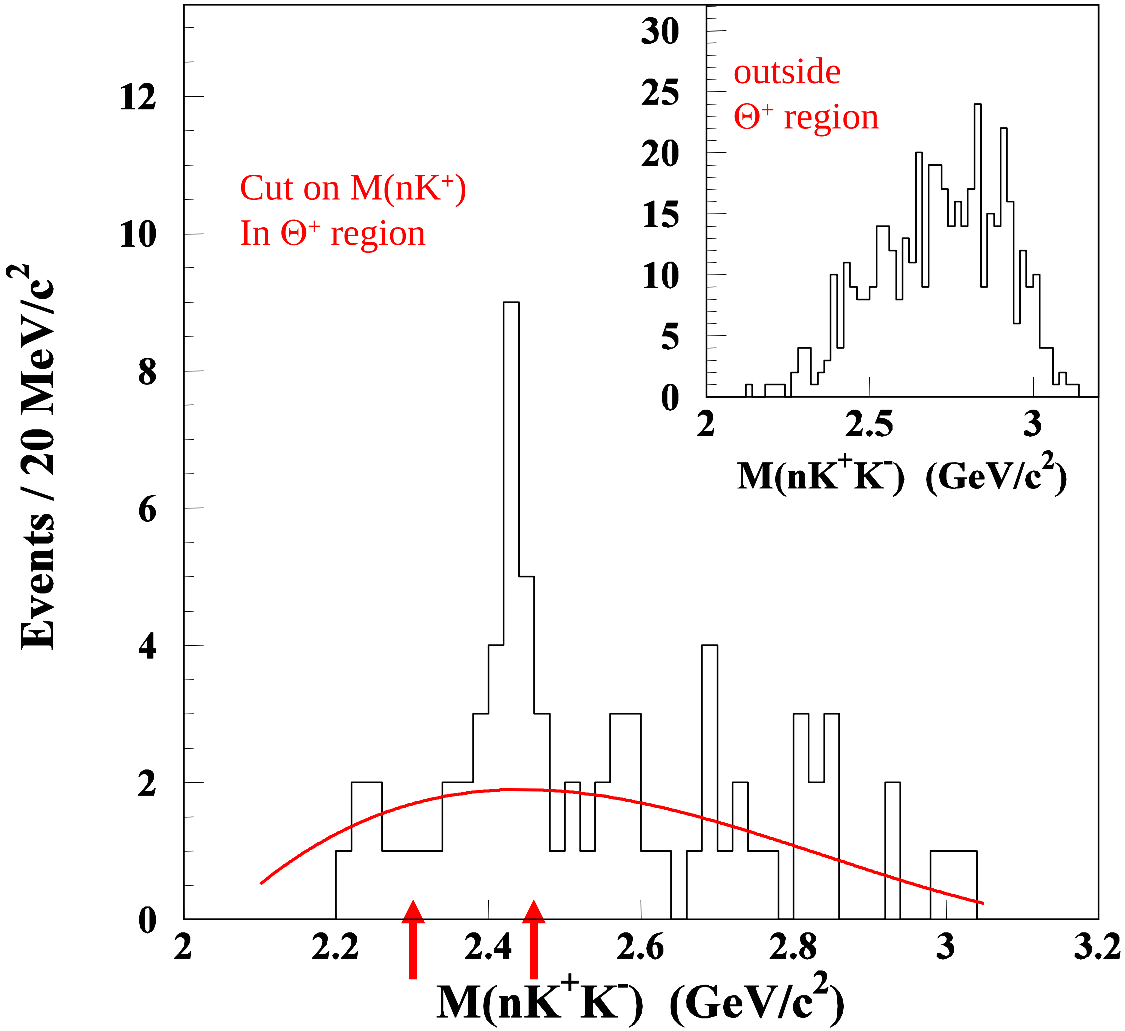


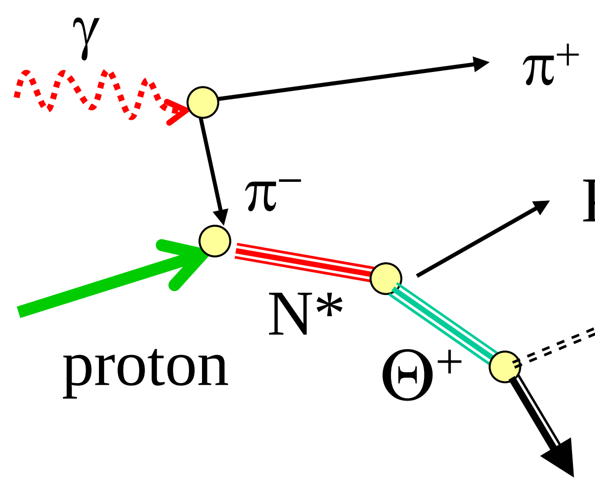
- Θ^+ production through N^* resonance decays?



- Cut on Θ^+ mass, and plot $M(nK^+K^-)$

CLAS - Θ^+(1540) and N* ?

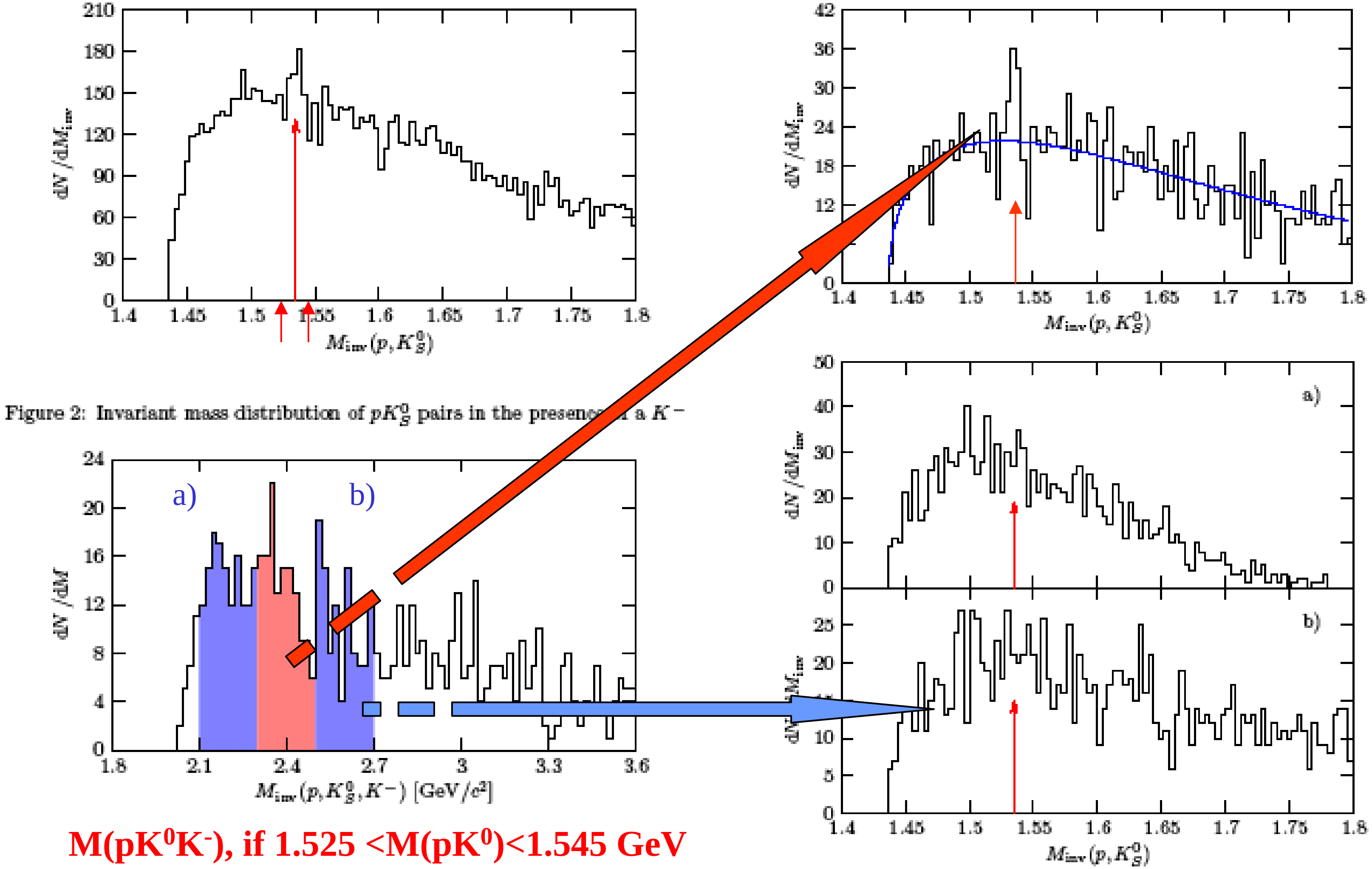




- What do $\pi^- p$ scattering data say?
- $\pi^- p$ cross section data in PDG have a gap in the mass range 2.3–2.43 GeV.

NA49 – Θ^+ through N* excitations ?

pp collisions at E_{CM} = 17.2 GeV



M(pK⁰K⁻), if 1.525 <M(pK⁰)<1.545 GeV

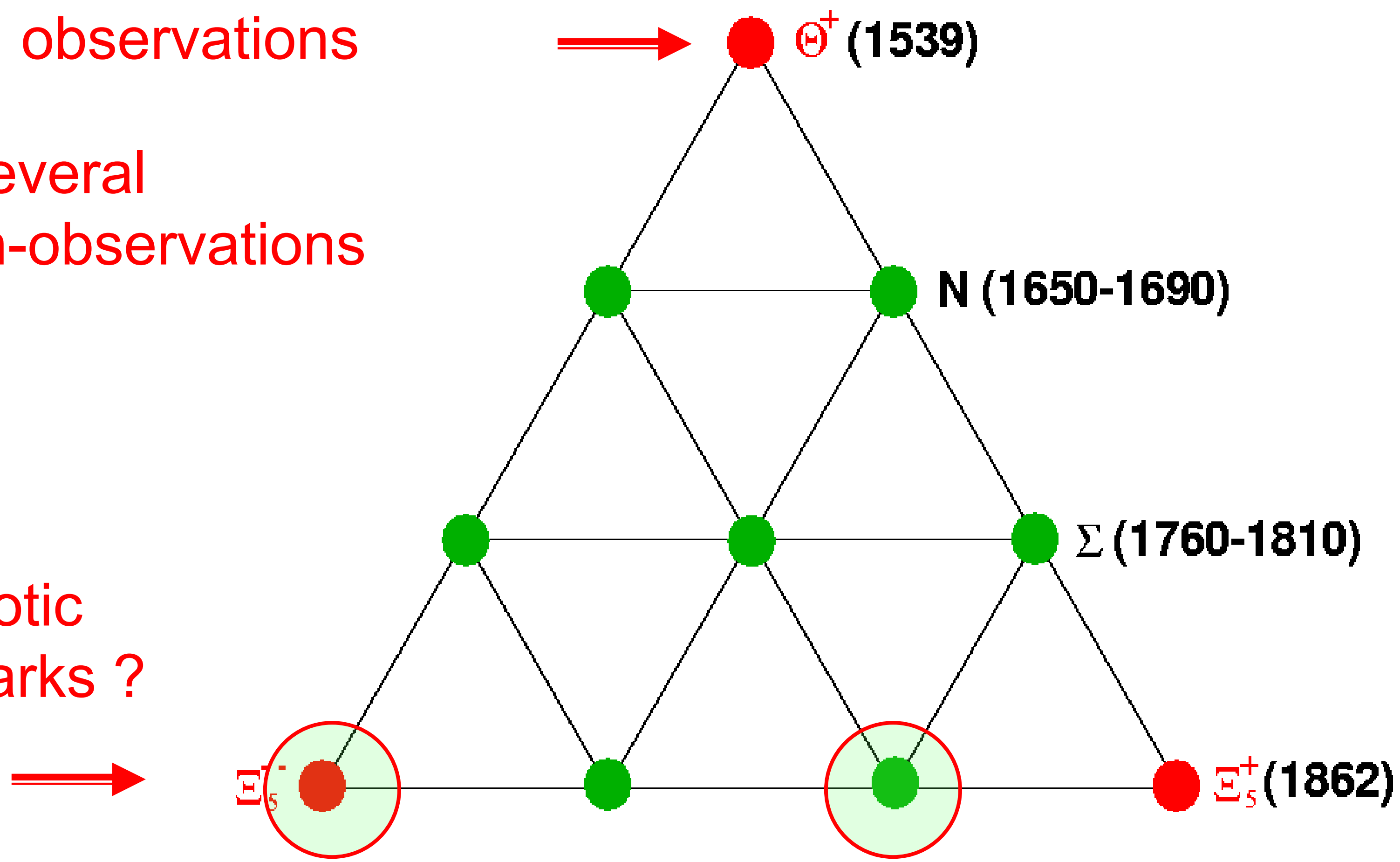
Negative Θ^+ Searches

- HERA-B (hep-ex/0403020):
  - reaction: pA at 920 GeV
  - measured: K^-p and K^0p invariant mass
  - signal for $\Lambda(1520)$, no signal for Θ^+
- BES (hep-ex/0402012):
  - reaction: $e^+e^- \rightarrow J/\psi \rightarrow \Theta^+\overline{\Theta}^-$
  - limit on B.R. of ~10^{-5} (low sensitivity, negative result was expected)
- C. Pinkenburg (PHENIX) (nucl-ex/0404001):
  - reaction: Au + Au -> $\bar{n}K^-X$ (large combinatorial background)
  - See signal first, then not, unclear what changed.

Search for Ξ_5 Pentaquark states

- 11 observations
- Several non-observations

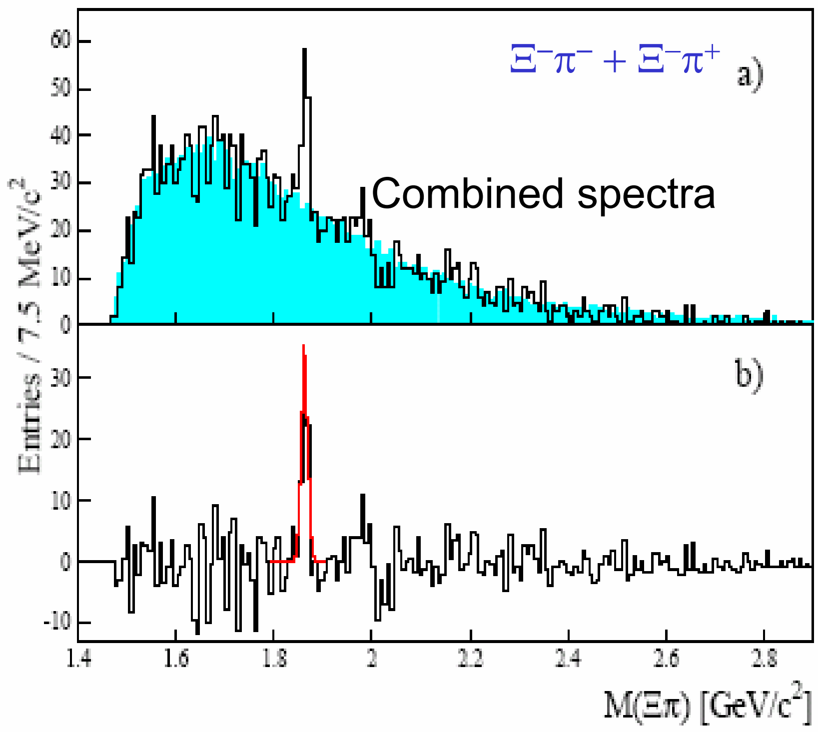
Other exotic Pentaquarks ?



Seach for Ξ_5^{--}, Ξ^o

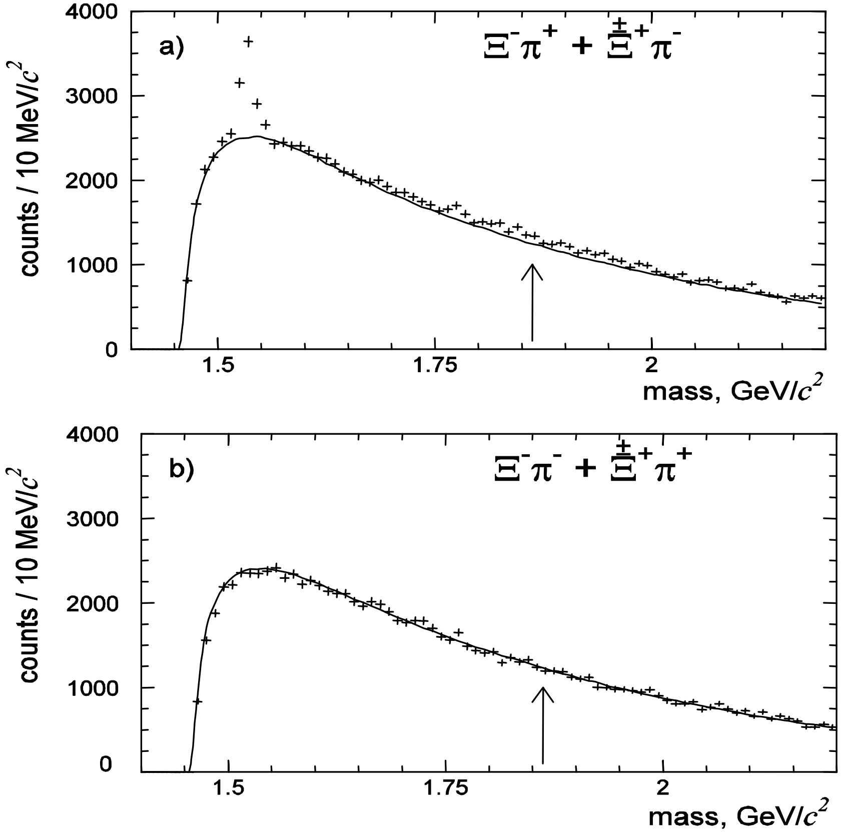
NA49 pp E_{cm} = 17.2 GeV

M=1.862± 0.002 GeV Γ<0.018 GeV



C. Alt, et al., Phys.Rev.Lett.92, 042003 (2004)

HERA-B p+A 940GeV/c

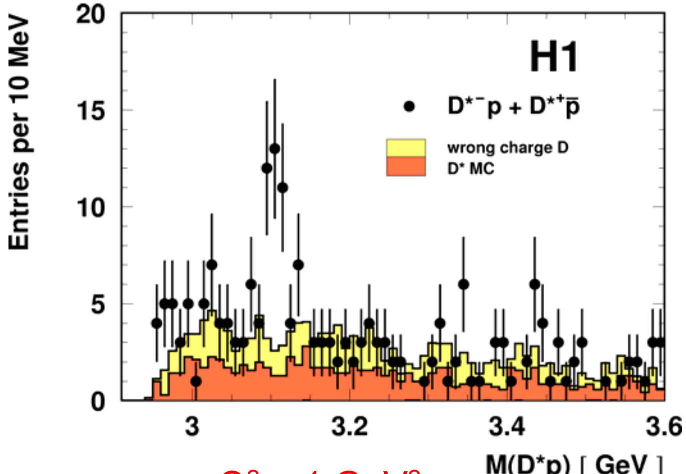


hep-ex/0403020

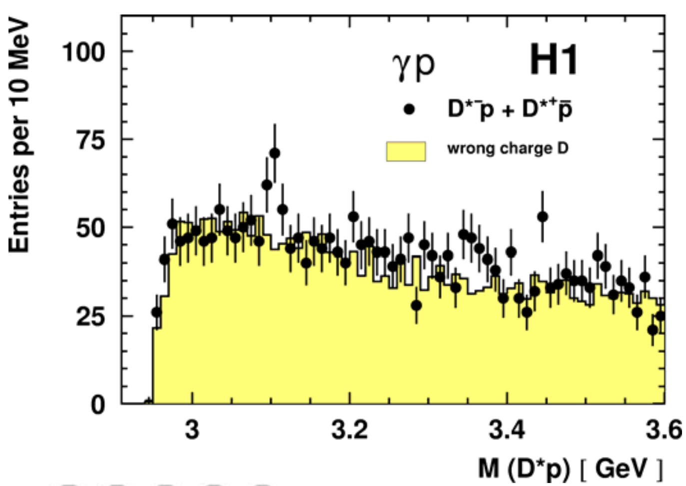
H1 - A charmed pentaquark $\Theta_c^0(3100)$?

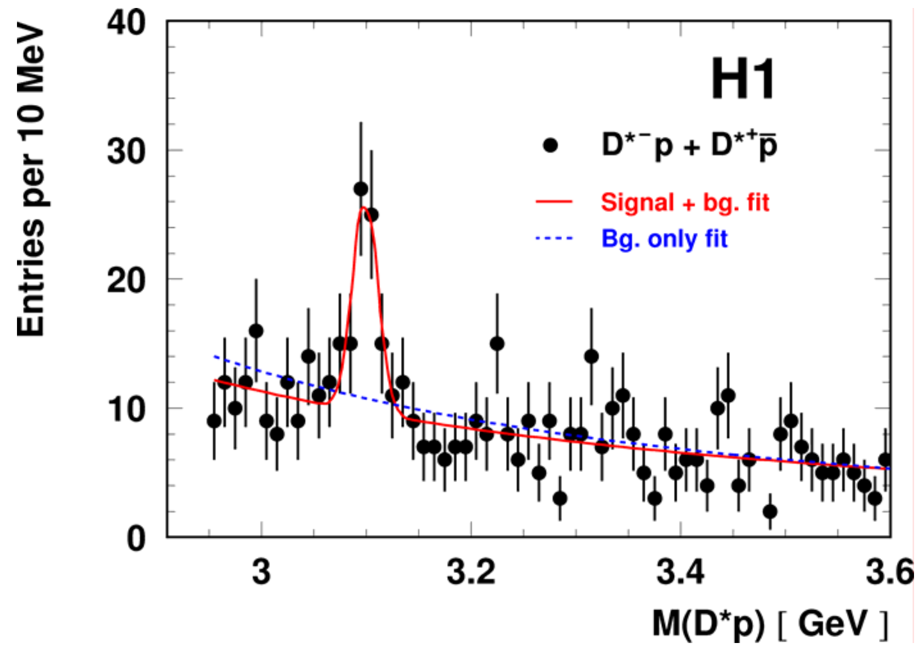
hep-ex/040305 (2004)

$Q^2 = 1 - 100\ GeV^2$



$Q^2 < 1\ GeV^2$



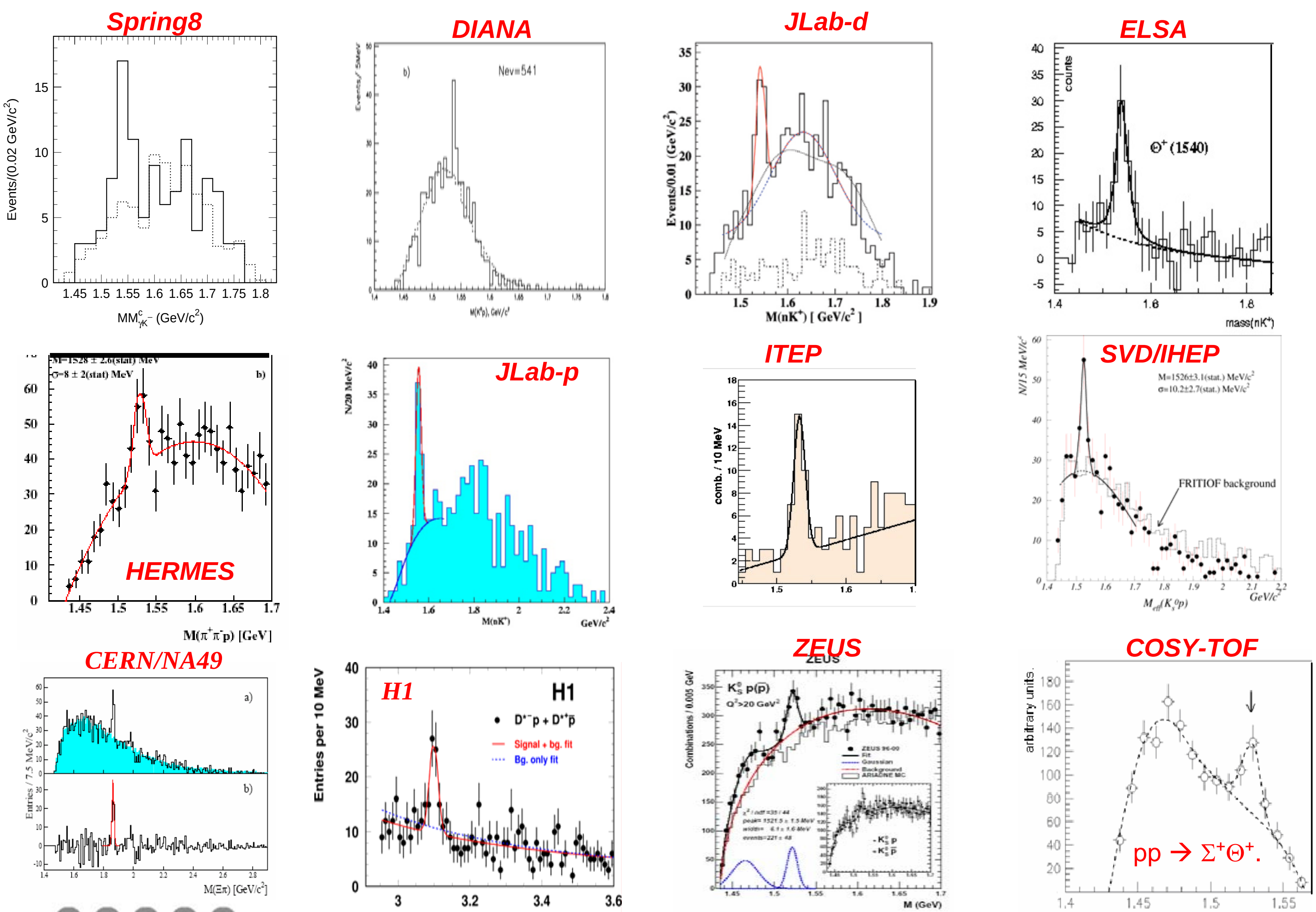


M = (3099 +/- 3 +/- 5) MeV

Minimal quark content: $uudd\bar{c}$

Yet to be confirmed!

Evidence for Penta-Quark States



Thomas Jefferson National Accelerator Facility

Office of Science

Theory Response to the Pentaquark

- Chiral soliton P=+
- Kaon-Skyrmion P=+
- $(qq)^2$-q P=+ or P=-
- Kaon-nucleon resonance
- Super radiance resonance
- QCD sum rules
- Lattice QCD P=-, or find no signal
- Higher exotic baryon multiplets
- Pentaquarks in string dynamics
- $P_{11}(1440)$ as pentaquark
- $P_{11}(1710)$ as pentaquark
- Θ^+ as isotensor pentaquark
- Topological soliton
- $\Theta^+(1540)$ as a heptaquark
- Exotic baryons in the large N_c limit
- Anti-charmed Θ^o_c and anti-beauty Θ^+_b
- Θ^+ and $\overline{\Theta}^+$ produced in quark-gluon plasma
- Instantons and diquark clustering
- Triquark-diquark cluster model
- Pentaquarks and radially excited baryons
- Peanut-shaped quark-diquark model
- Pentaquarks in the color-flavor-locking superconducting phase
- …….

More than 220 papers since July 1, 2003.

PentaQuark 2003 Workshop

The first **Topical Workshop PentaQuark 2003** held at JLab, November 7-9, 2003

- Organized on a very short time scale of 3 months
- 117 registered participants (expected 35)
- Generated ideas for new experiments to study Θ^+ properties, such as spin, parity
- Initiated new proposals for the search of excited states $\Theta*^+$, $\Theta*^{++}$, and exotic Ξ pentaquark baryons

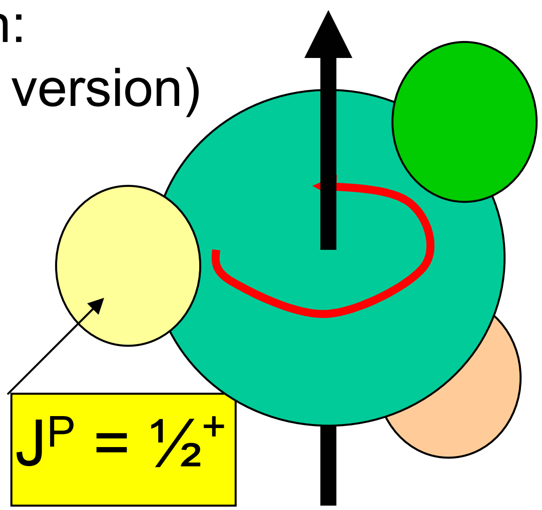
→ Article in CERN Courier, April 2004

Pentaquarks – three model descriptions

Chiral soliton model: (Diakonov, Petrov, Polyakov)

'Pentaquark' comes out naturally from these models. They represent rotational excitations of the soliton [rigid core (q^3) surrounded by meson fields ($\bar{q}q$)]

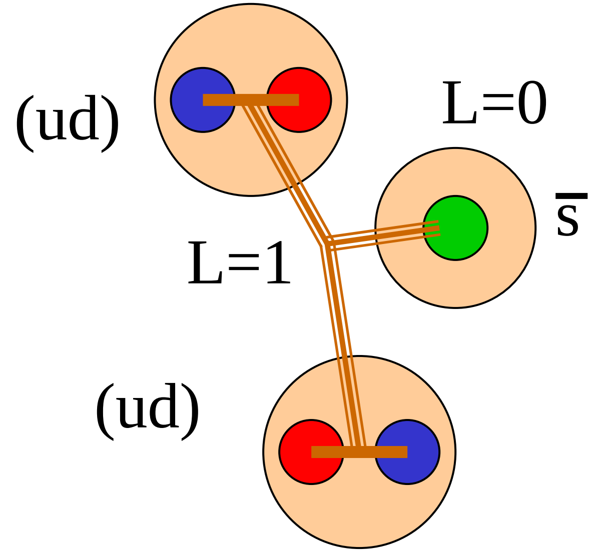
Soliton:
(naïve version)



Meson fields

$J^P = ½^+$

Quark description (Jaffe, Wilczek)



L=1, one unit of orbital angular momentum needed to obtain $J^P = ½^+$ as in the χSM

Q-LQCD: $J^P = ½^-$

Search for excited states of the $\Theta^+(1540)$

- Spin-flavor partners, $T = 1$, $J^P = 3/2^+$, to the Θ^+ are predicted at masses slightly higher than the Θ^+.

Skyrme-soliton model **Borisyuk et al. hep-ph/0307370**	$\Delta M(3/2-1/2) \sim$ **55 MeV**	
Constituent quark model **Dudek and Close hep-ph/0311258**	$\Delta M(3/2-1/2) \sim$ **40 MeV**	**Jaffe and Wilczek hep-ph/0307341**
	$\Delta M(3/2-1/2) \sim$ **35–65 MeV**	**Karliner and Lipkin hep-ph/0307243**

A Program for Pentaquark Spectroscopy

- High statistics confirmations for the Θ^+ urgently needed
- Solving the issues of the $\Theta^+(1540)$ properties
  - mass to < 2 MeV
  - spin ½ , isospin
  - parity
  - natural width of the Θ^+?
  - production mechanism

If > few MeV

May be addressed at JLab

- Are there excited states of the $\Theta^+(1540)$, I = 1, J = 3/2?
- How are pentaquark states related to N* states?
  - Do N* couple to Θ^+ ?
  - If so, are these 5-quark or 7-quark N*?

Theory input needed

- Where are the other exotic members of the decuplet Ξ_5^{--}, Ξ_5^{+} ? NA49 results yet to be confirmed!
- Where are the non-exotic pentaquarks, N*'s, Σ's?

Pentaquark Searches at JLab

✓ JLab is well positioned to address many of these issues

➢ PAC24 approved search for Θ^+ on deuterium
- G10 run - $\gamma D \rightarrow K^- K^+ p(n)$ (data taking completed)

Major program approved by PAC25 to search for pentaquark states

➢ CLAS - Search for Θ^+, Θ^{*+}, Θ^{*++}
- G11 run $\gamma p \rightarrow$ various final states (running)

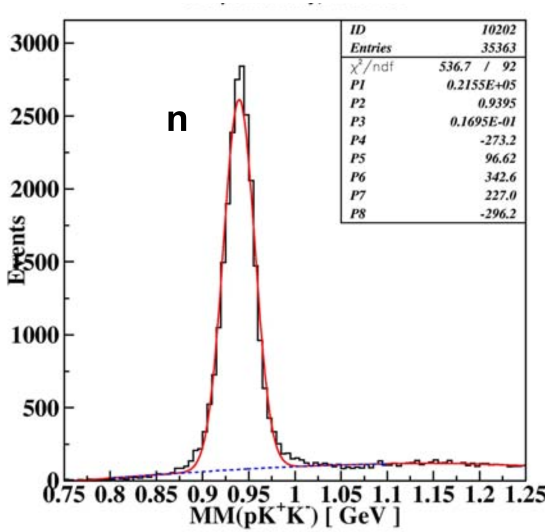
➢ Hall A - Search for Θ^{*++}, Σ_5^o
- E04-012 $ep \rightarrow eK^- X^{++}$, $eK^+ X^o$ (data taking completed)

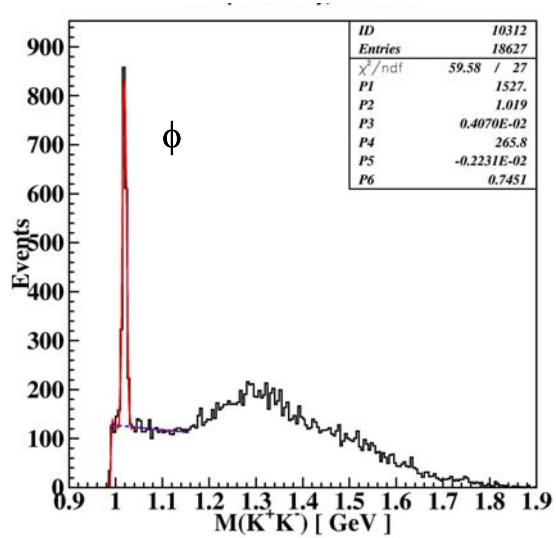
➢ CLAS – Search for Ξ pentaquarks
- EG3 run $eD \rightarrow \Xi_5^{--}, \Xi_5^- X$ (scheduled for 2004/5)

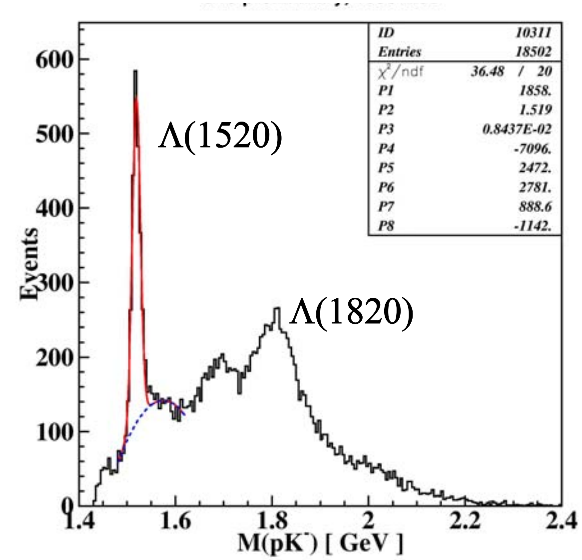
➢ CLAS - Exotic hadron spectroscopy (to run in 2005/6)
- G12 run γp at 6 GeV, high luminosity

CLAS - G10 “online” plots

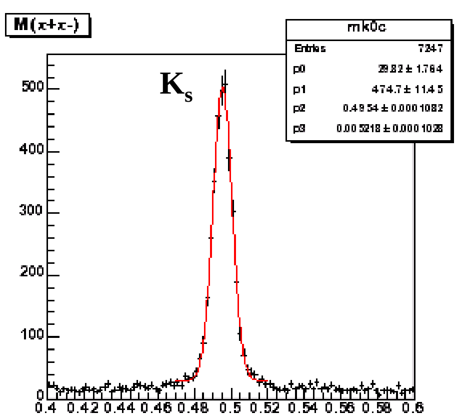
Fully exclusive processes: $\gamma d \longrightarrow K^{-}pK^{+}n$







$\gamma d \longrightarrow K^{-}pK_{s}(\pi^{+}\pi^{-})p_{sp}$

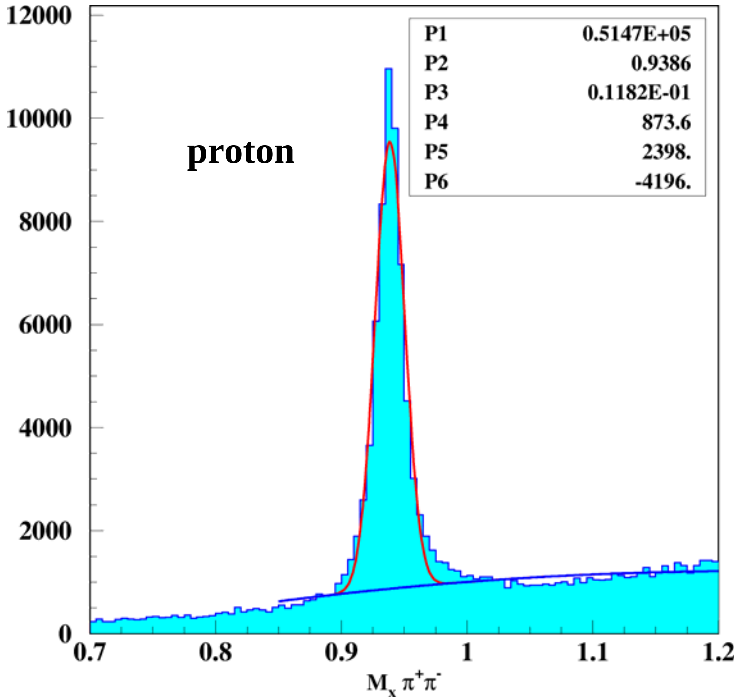


CLAS - G11 “online” plots

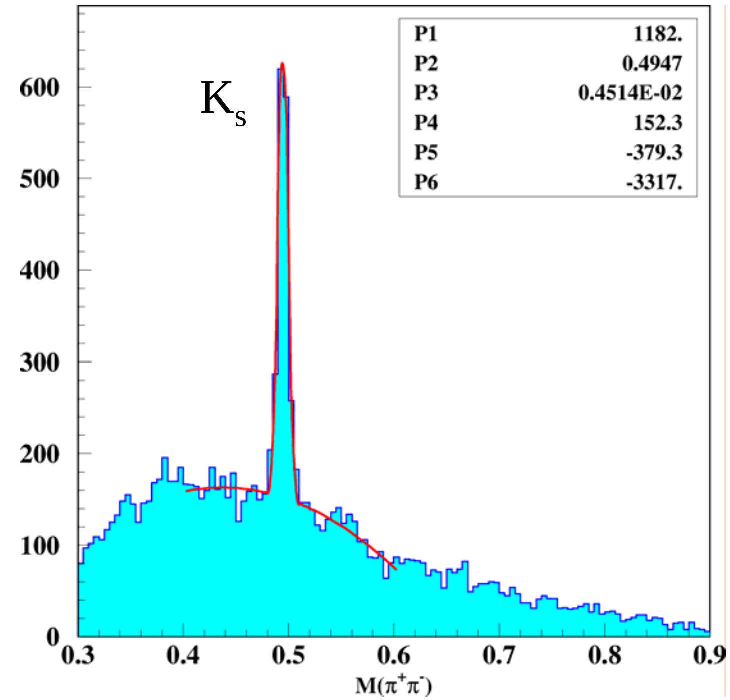
$\gamma p \rightarrow K_s K^+(n);\ K_s K_s p;\ K^+K^-p;\ K^+K^-\pi^+(n)$

$\gamma p \longrightarrow \pi^+\pi^-(p)$

(calibration reaction)



$\gamma p \longrightarrow \pi^+\pi^-K^+\,(n)$



G10, G11 Analysis efforts

- Analysis teams – G10:
  - Dan Carman (Ohio), Reinhard Schumacher (Carnegie Mellon)
  - Dave Tedeschi, Nathan Baltzell (USC)
  - Ken Livingston, Bryan McKinnon (Glasgow)
  - Michel Guidal, Silvia Niccolai (ORSAY)
  - Patrizia Rossi, Marco Mirazita (INFN, Frascati)
  - Eugene Pasyuk (Arizona), Luminita Todor (Richmond, Jlab)
  - Ken Hicks (Ohio), Stepan Stepanyan (JLab)

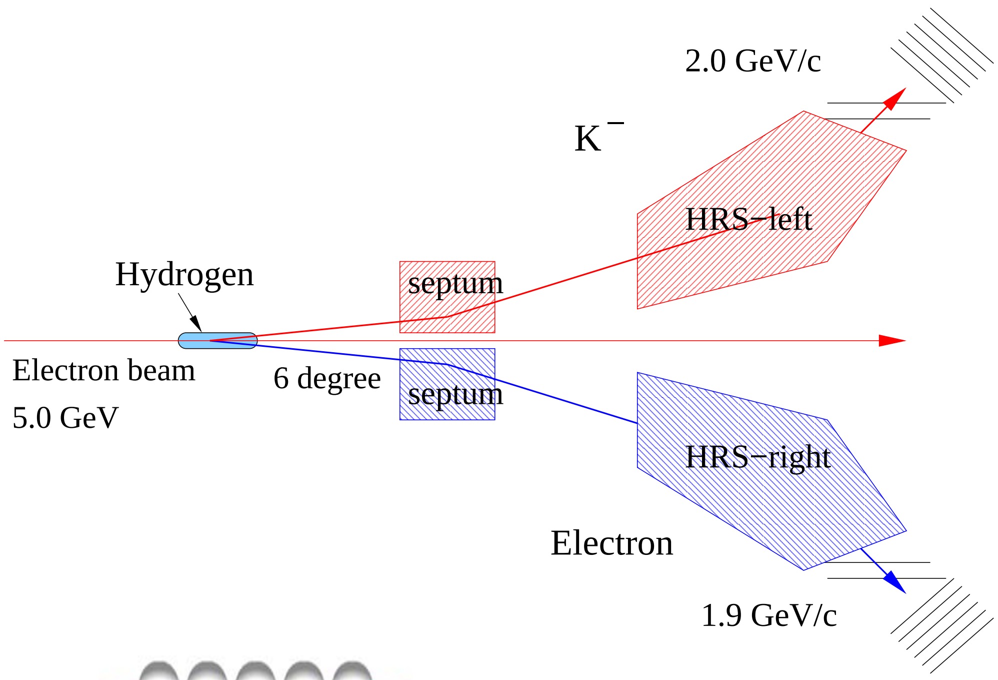
- Analysis teams – G11:
  - Marco Battaglieri, Raffaella De Vita (INFN, Genova)
  - Valeri Koubarovski (RPI, JLab), Paul Stoler (RPI)
  - Dennis Weygand (JLab), Lei Guo (JLab),
  - Michael Ostrick (JLab/Bonn), Latifa Elouadrhiri (JLab)

Common rules for all analyses:

1. Fully calibrated detector system
2. Use only selected “golden runs” (fully functioning equipment)
3. Analysis in well defined CLAS fiducial volume
4. Energy and momentum corrections that use independent well-studied channels
5. Analysis without and with kinematical constraints whenever possible
6. Independent analyses by several groups.

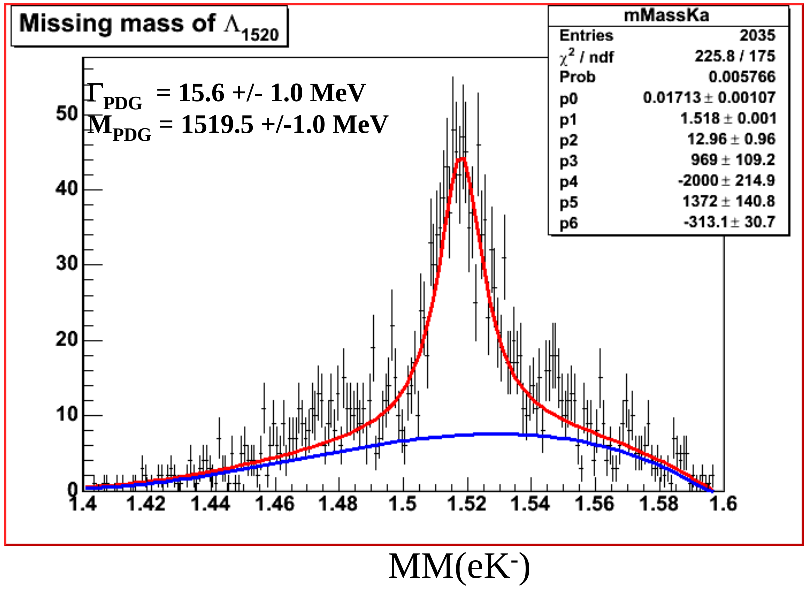
Hall A - Search for Θ^{++} and Σ_5

- Search for Θ^{*++} partners in ep ⟶ $e'K^-X^{++}$
  - Mass range: 1540 - 1620 MeV
- Search for Σ_5^o in ep ⟶ eK^+X^o
  - Mass range: 1560 – 1860 MeV
- Mass resolution δM ~ 1.75 MeV



Run is completed

Online-analysis



Mass of Λ(1520) agrees to < 1.5 MeV with PDG value.

CLAS - Search for Ξ_5 Pentaquark States

The search for narrow Ξ_5 states can be approached in at least two ways:

- Missing mass technique:

  $\gamma p \longrightarrow K^+K^+\Xi^-$; $K^+K^+\pi^-\Xi^{--}$

  needs good resolution

- Reconstruction of all decay particles:

  $\gamma n \longrightarrow K^+K^+\Xi^{--} \rightarrow \pi^-\Xi^- \rightarrow \pi^-\Lambda \rightarrow \pi^-p$,

  needs good acceptance and vertex resolution

CLAS – Ξ_5 Searches

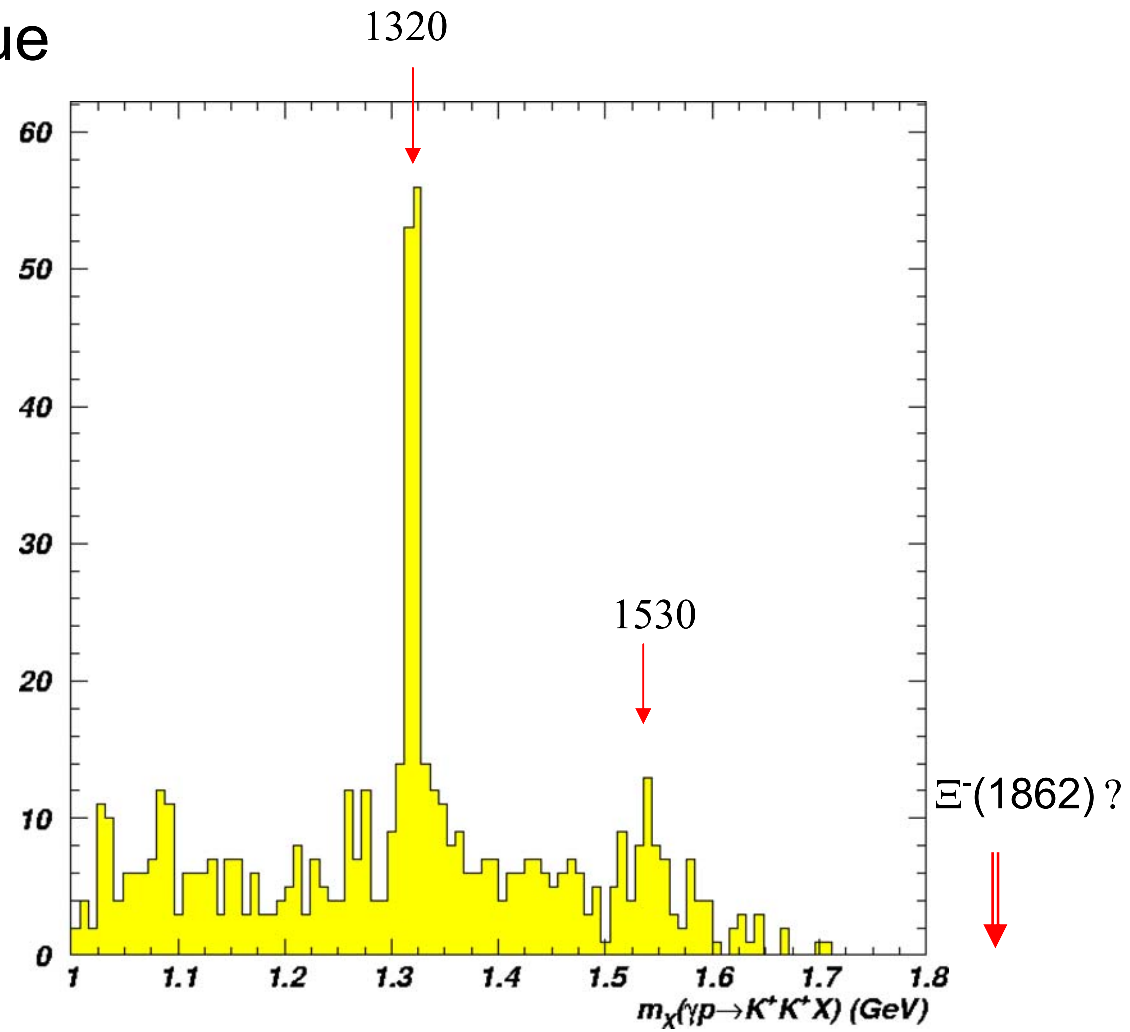
Missing mass technique

$\gamma p \rightarrow K^+K^+X$

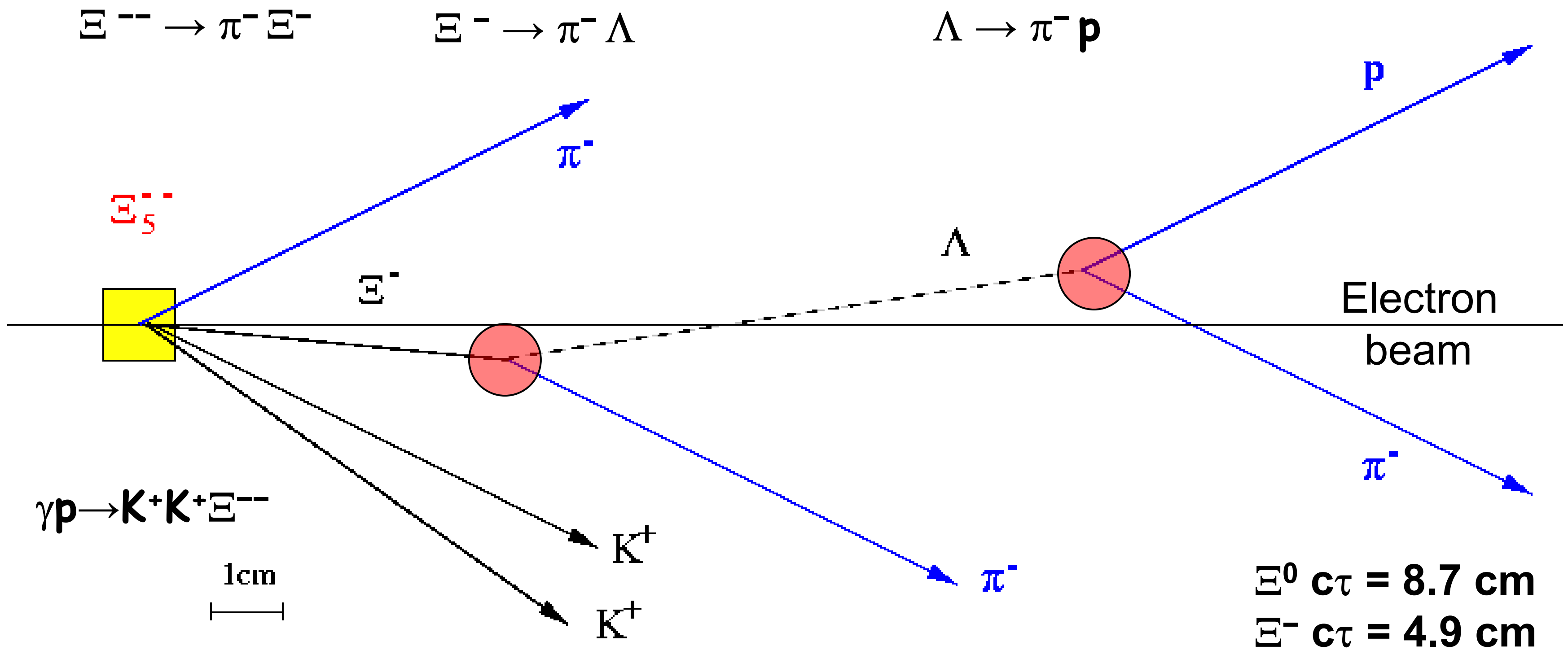
Data from run at
Eγ < 3.8 GeV

- Good missing mass resolution and low background.

- Needs $E_\gamma > 5$ GeV, new start counter



CLAS – Ξ_5 Searches (approved exp.)



Measure $3\pi^-$ and one proton

.. and 2 detached vertices

Ξ^0 $c\tau$ = 8.7 cm
Ξ^- $c\tau$ = 4.9 cm
Λ $c\tau$ = 7.9 cm
K_s $c\tau$ = 2.7 cm

$\gamma\beta \sim 1.5$

Summary

- The initial evidence for the Θ^+(1540) pentaquark baryon has generated much excitement and a wide range of theoretical and experimental activities to understand this possible new form of quark matter.

- Jefferson Lab is in the unique position to explore the nature of the observed and predicted states with precise and high statistics experiments.

- The approved experimental program at JLab (110 PAC days Hall B, 7 days Hall A) is expected to provide definitive answers as to the existence and properties of the Θ^+(1540) and possible excited states in different spin and charge configurations.
  - two experiments at 37 PAC days completed,
  - one experiment at 25 days underway,
  - one experiment at 20 days scheduled for 12/04-01/05,
  - one experiment at 35 days to run in 2005/06