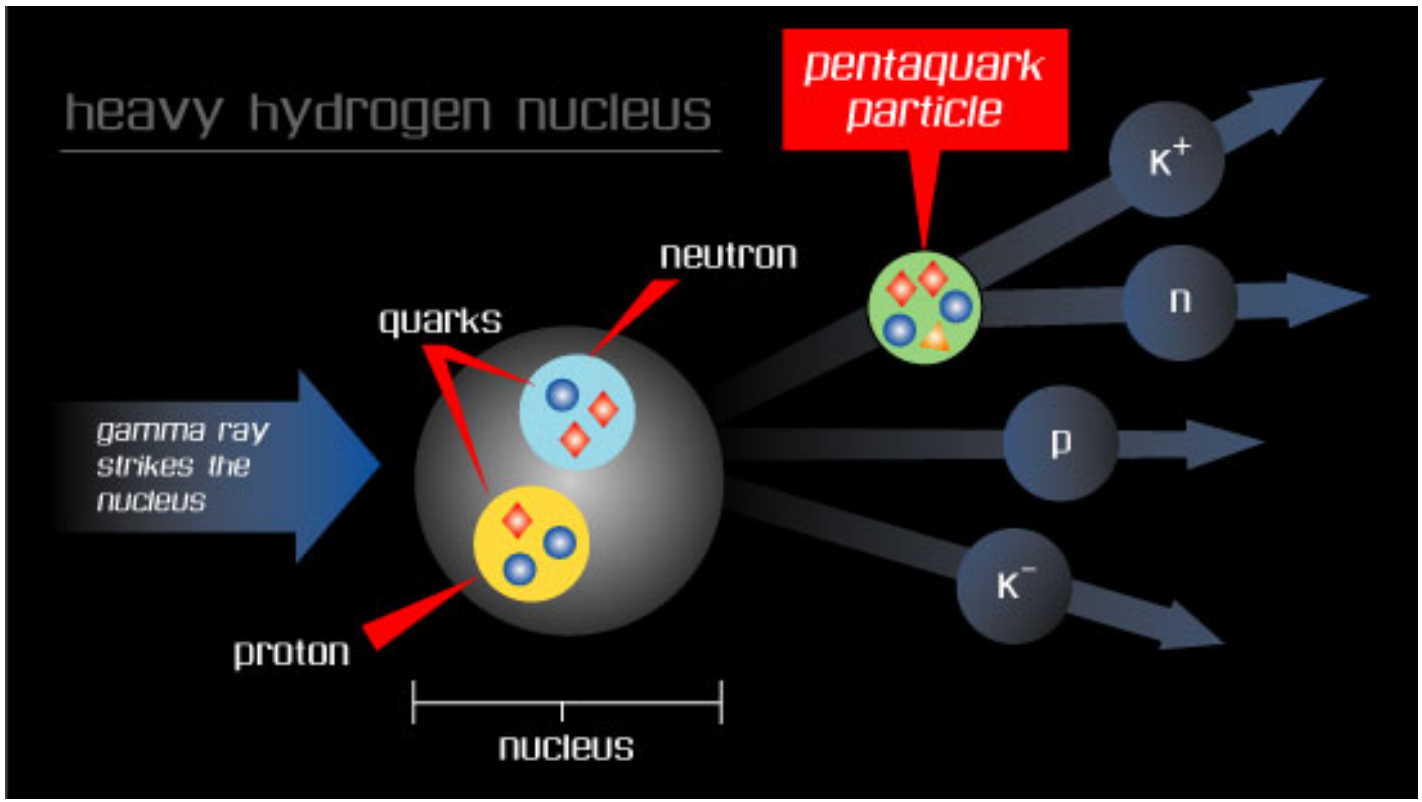
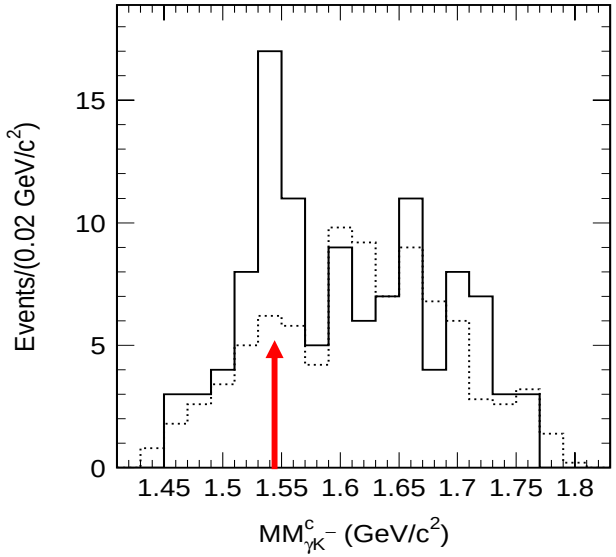
Pentaquarks: Discovering new particles



Outline

- Historical introduction
- Review of the Quark Model
- Prediction of the Θ^+
- Experimental evidence
  - Data from CLAS
- What do we know about the Θ^+?
- Other 5-quark states

Phys.Rev.Lett. 91 (2003) 012002



S=+1

B=+1

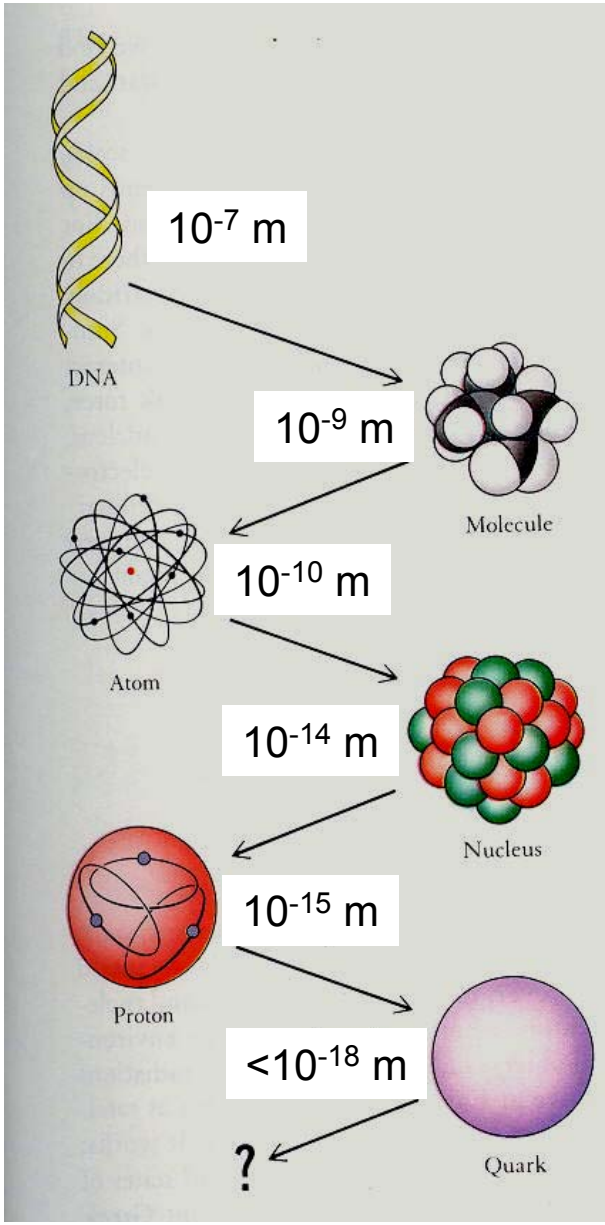
Mass = 1.54 GeV

Families within families of matter

DNA

Atom

Proton

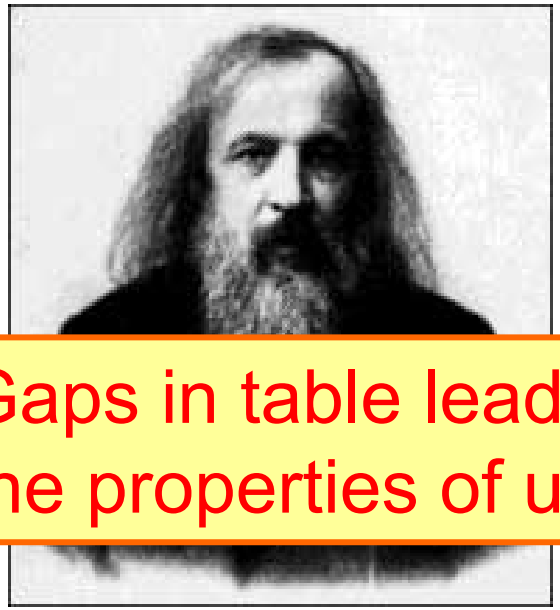


Molecule

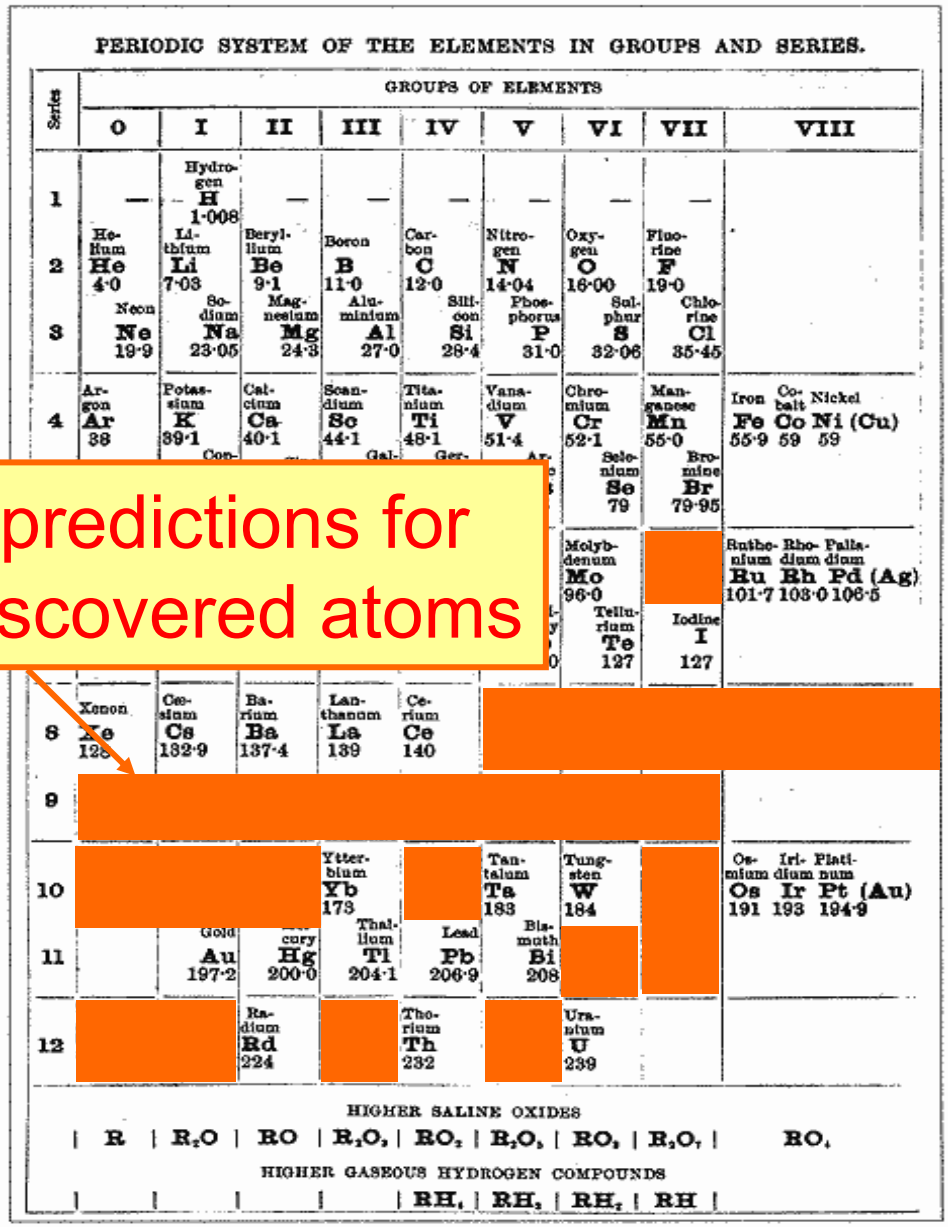
Nucleus

Quark

Families of atoms



Mendeleev (1869)



PERIODIC SYSTEM OF THE ELEMENTS IN GROUPS AND SERIES.

Series	GROUPS OF ELEMENTS								
	0	I	II	III	IV	V	VI	VII	VIII
1	—	Hydrogen H 1·008	—	—	—	—	—	—	
2	Helium He 4·0	Lithium Li 7·03	Beryllium Be 9·1	Boron B 11·0	Carbon C 12·0	Nitrogen N 14·04	Oxygen O 16·00	Fluorine F 19·0	
3	Neon Ne 19·9	Sodium Na 23·05	Magnesium Mg 24·3	Aluminium Al 27·0	Silicon Si 28·4	Phosphorus P 31·0	Sulphur S 32·06	Chlorine Cl 35·45	
4	Argon Ar 38	Potassium K 39·1	Calcium Ca 40·1	Scandium Sc 44·1	Titanium Ti 48·1	Vanadium V 51·4	Chromium Cr 52·1	Manganese Mn 55·0	Iron Fe 55·9, Cobalt Co 59, Nickel Ni 59, (Cu)
							Selenium Se 79	Bromine Br 79·95	
							Molybdenum Mo 96·0		Ruthenium Ru 101·7, Rhodium Rh 103·0, Palladium Pd 106·5, (Ag)
							Tellurium Te 127	Iodine I 127	
8	Xenon Xe 128	Cæsium Cs 132·9	Barium Ba 137·4	Lanthanum La 139	Cerium Ce 140				
9									
10				Ytterbium Yb 173		Tantalum Ta 183	Tungsten W 184		Osmium Os 191, Iridium Ir 193, Platinum Pt 194·9, (Au)
11		Gold Au 197·2	Mercury Hg 200·0	Thallium Tl 204·1	Lead Pb 206·9	Bismuth Bi 208			
12			Radium Rd 224		Thorium Th 232		Uranium U 239		

HIGHER SALINE OXIDES

| R | R_2O | RO | R_2O_3 | RO_2 | R_2O_5 | RO_3 | R_2O_7 | RO_4 |

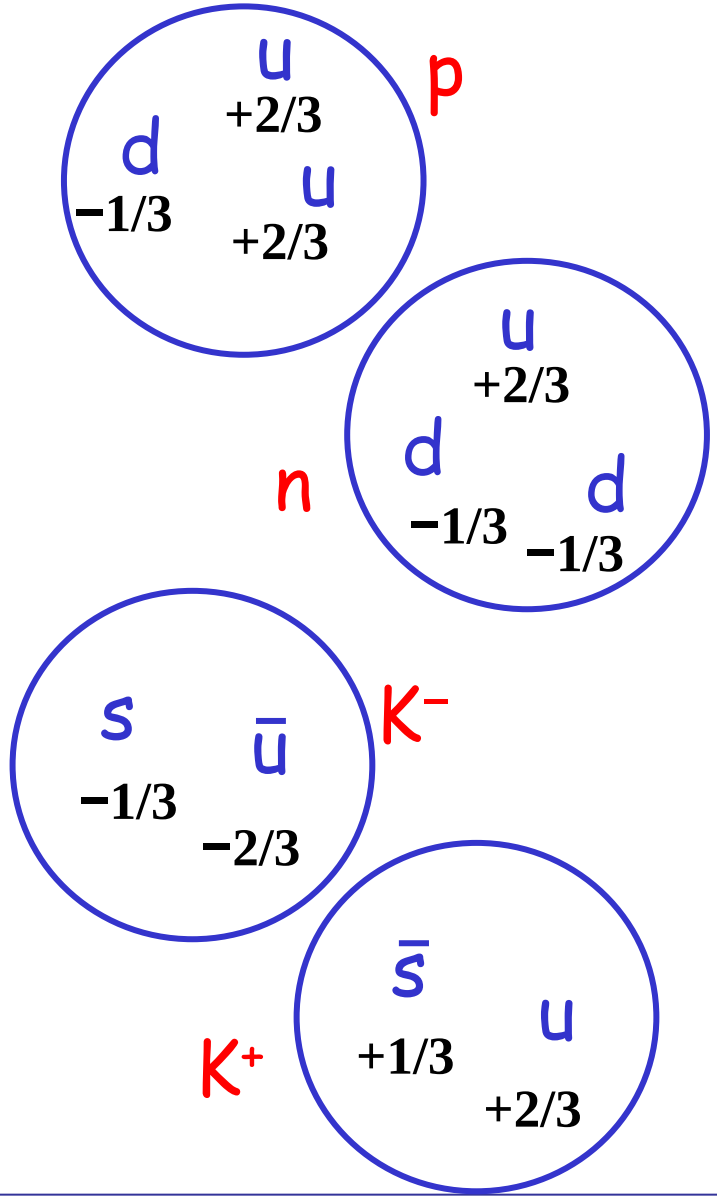
HIGHER GASEOUS HYDROGEN COMPOUNDS

| | | | | RH_4 | RH_3 | RH_2 | RH |

Gaps in table lead to predictions for the properties of undiscovered atoms

Properties of quarks

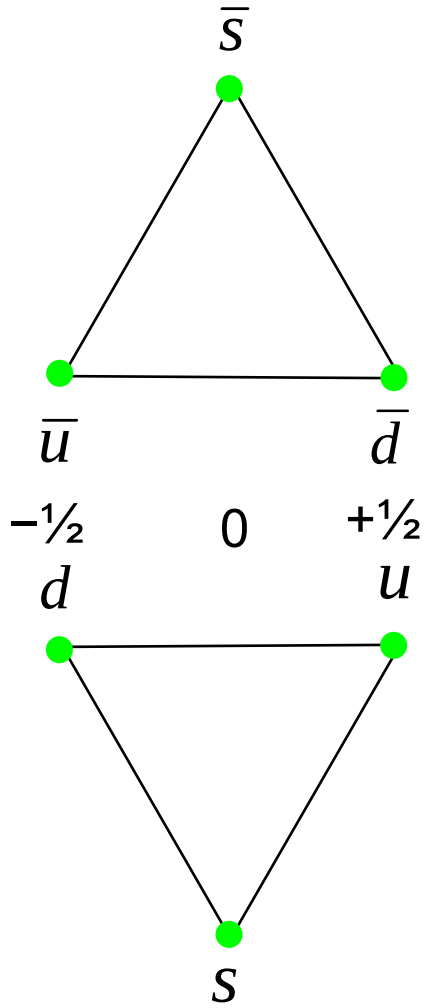
Quark Flavor	Charge (Q)	Baryon number	Strangeness (S)
u	+2/3	+1/3	0
d	−1/3	+1/3	0
s	−1/3	+1/3	−1
$\bar{u}$	− 2/3	−1/3	0
$\bar{d}$	+1/3	−1/3	0
$\bar{s}$	+1/3	−1/3	+1



Protons are made of (*uud*)
Neutrons are made of (*ddu*)

Families of quarks

$I_3 = Q - \frac{1}{2}(B+S)$

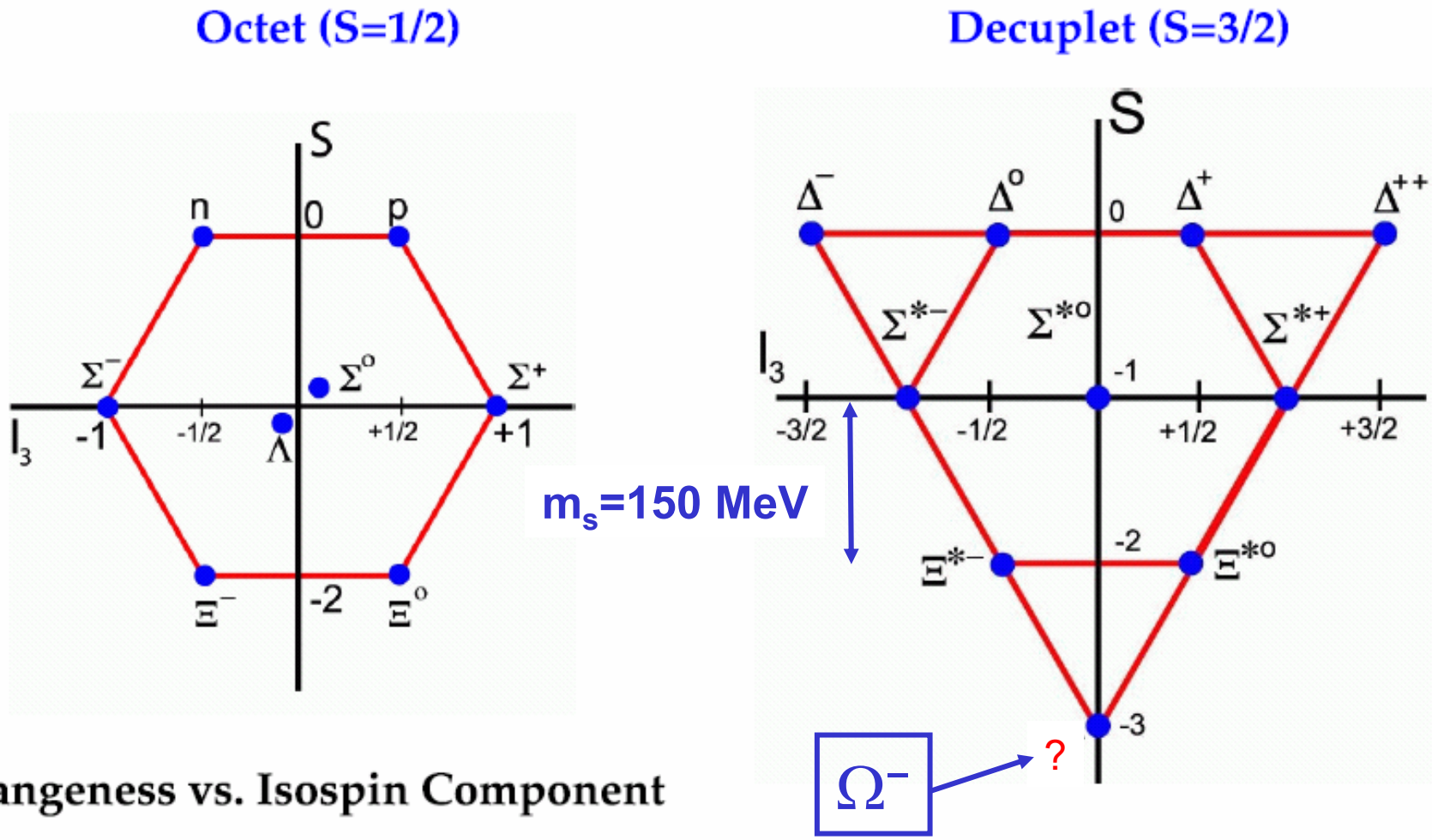


S=+1

S= 0

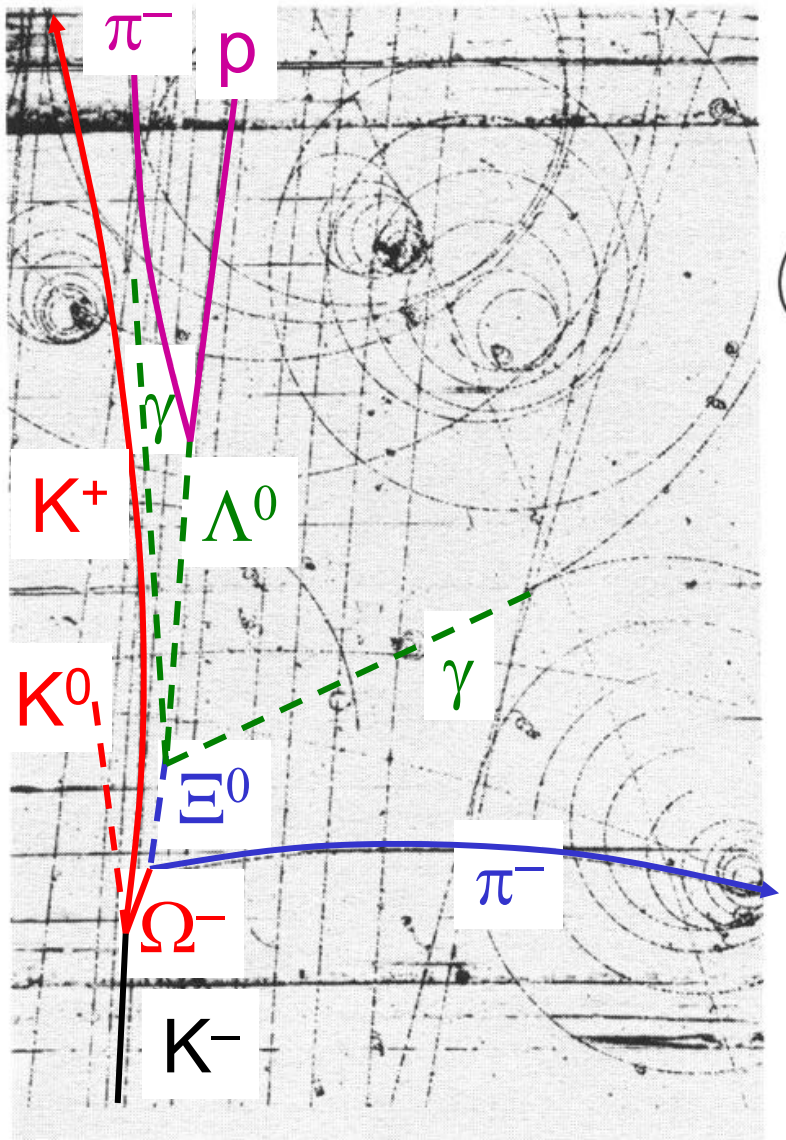
S=−1

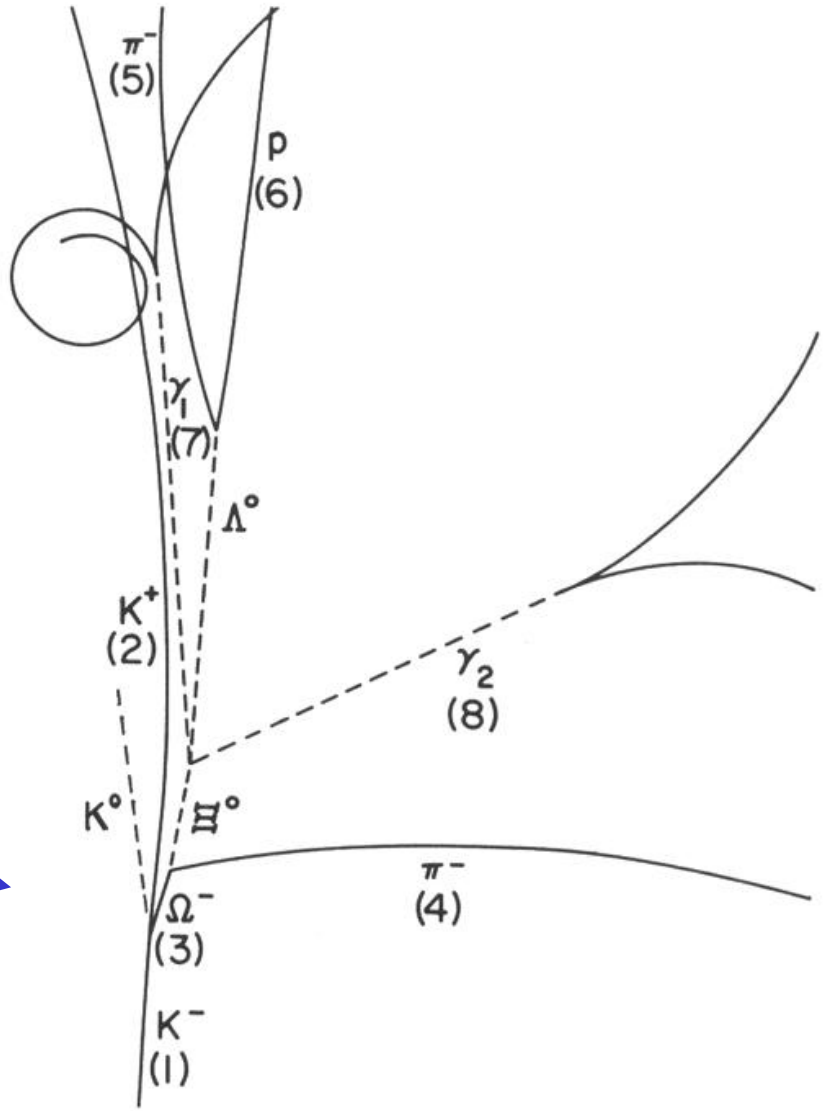
Families of baryons



Strangeness vs. Isospin Component

Production and decay of $\Omega^- \rightarrow \Xi^o \pi^-$

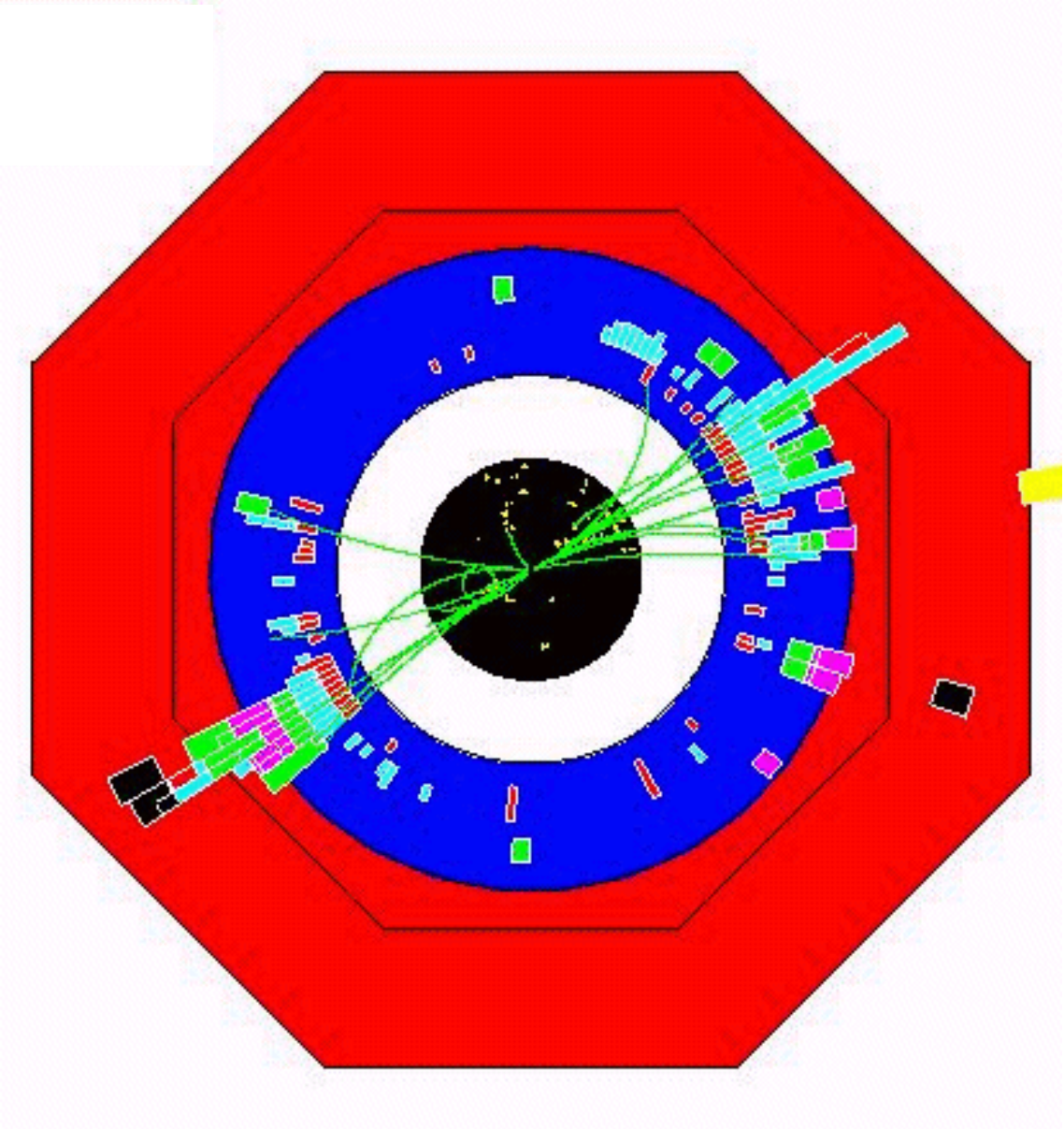




V.E. Barnes et. al., Phys. Rev. Lett. 8, 204 (1964)

FIG. 2. Photograph and line diagram of event showing decay of Ω^-.

Interactions understood in terms of quarks



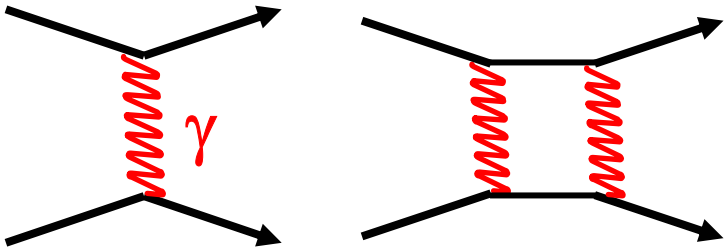
Very high energy

$$e^+e^- \rightarrow Z^0 \rightarrow q\bar{q}$$

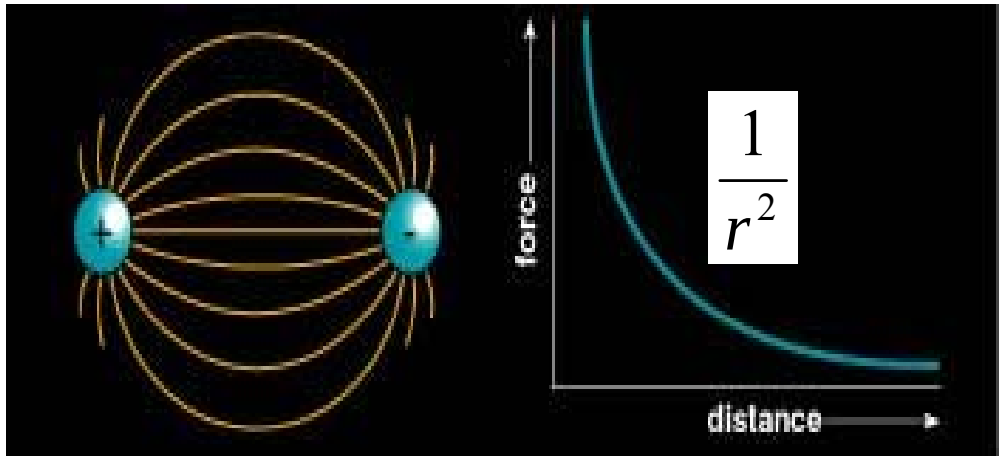
"free" quarks not found, only particles that contain quarks

Electromagnetic and color forces

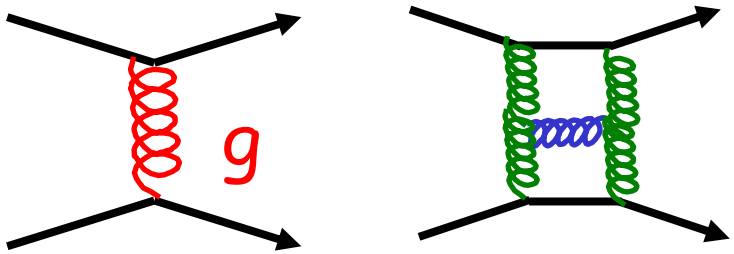
$O(\alpha) \sim 0.01$



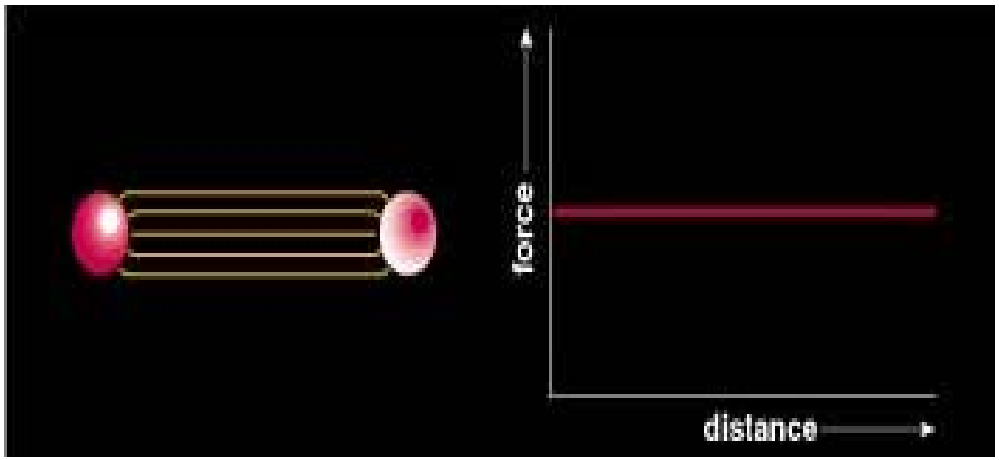
±1 charge



$O(\alpha_s) \sim 1$



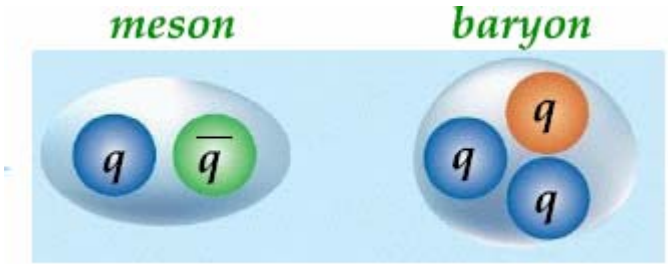
±3 "color" charges



QCD explains particle interactions

Quarks are confined inside colorless hadrons

Mystery remains:
Of the many possibilities for combining quarks with color into colorless hadrons, only two configurations were found, till now…



Particle Data Group 1986 reviewing evidence for *exotic baryons states*

"…The general prejudice against baryons not made of three quarks and the lack of any experimental activity in this area make it likely that it will be another 15 years before the issue is decided.

PDG dropped the discussion on pentaquark searches after 1988.

What are pentaquarks?

- Minimum quark content is 4 quarks and 1 antiquark
- "Exotic" pentaquarks are those where the antiquark has a different flavor than the other 4 quarks $\left(qqqq\overline{Q}\right)$
- Quantum numbers cannot be defined by 3 quarks alone.

Example: $uuds\bar{s}$, non-exotic

Baryon number = 1/3 + 1/3 + 1/3 + 1/3 – 1/3 = 1

Strangeness = 0 + 0 + 0 – 1 + 1 = 0

Example: $uudd\bar{s}$, exotic

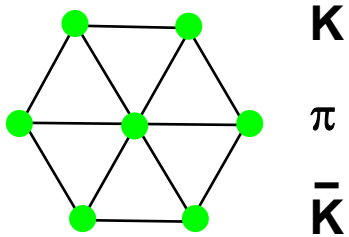
Baryon number = 1/3 + 1/3 + 1/3 + 1/3 – 1/3 = 1

Strangeness = 0 + 0 + 0 + 0 + 1 = +1

Hadron multiplets

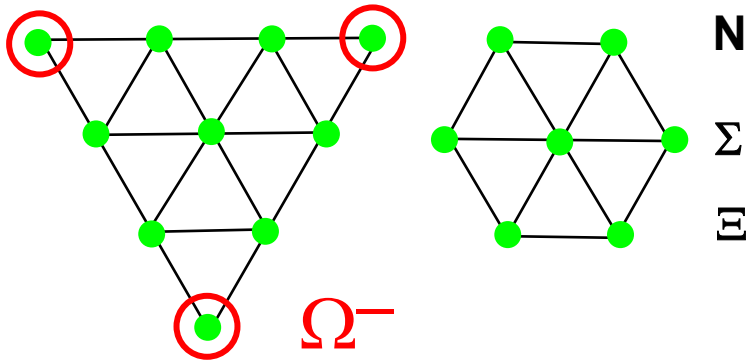
Mesons $q\bar{q}$

$$3 \otimes \bar{3} = 8 \oplus 1$$



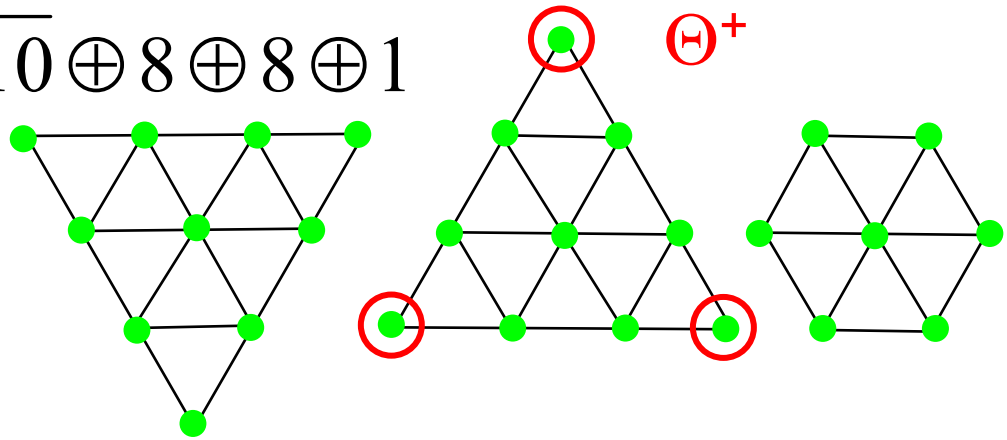
Baryons qqq

$$3 \otimes 3 \otimes 3 = 10 \oplus 8 \oplus 8 \oplus 1$$



Baryons built from meson-baryon, or $qqqq\bar{q}$

$$8 \otimes 8 = 27 \oplus 10 \oplus \overline{10} \oplus 8 \oplus 8 \oplus 1$$



The Anti-decuplet predicted by Diakonov et al.

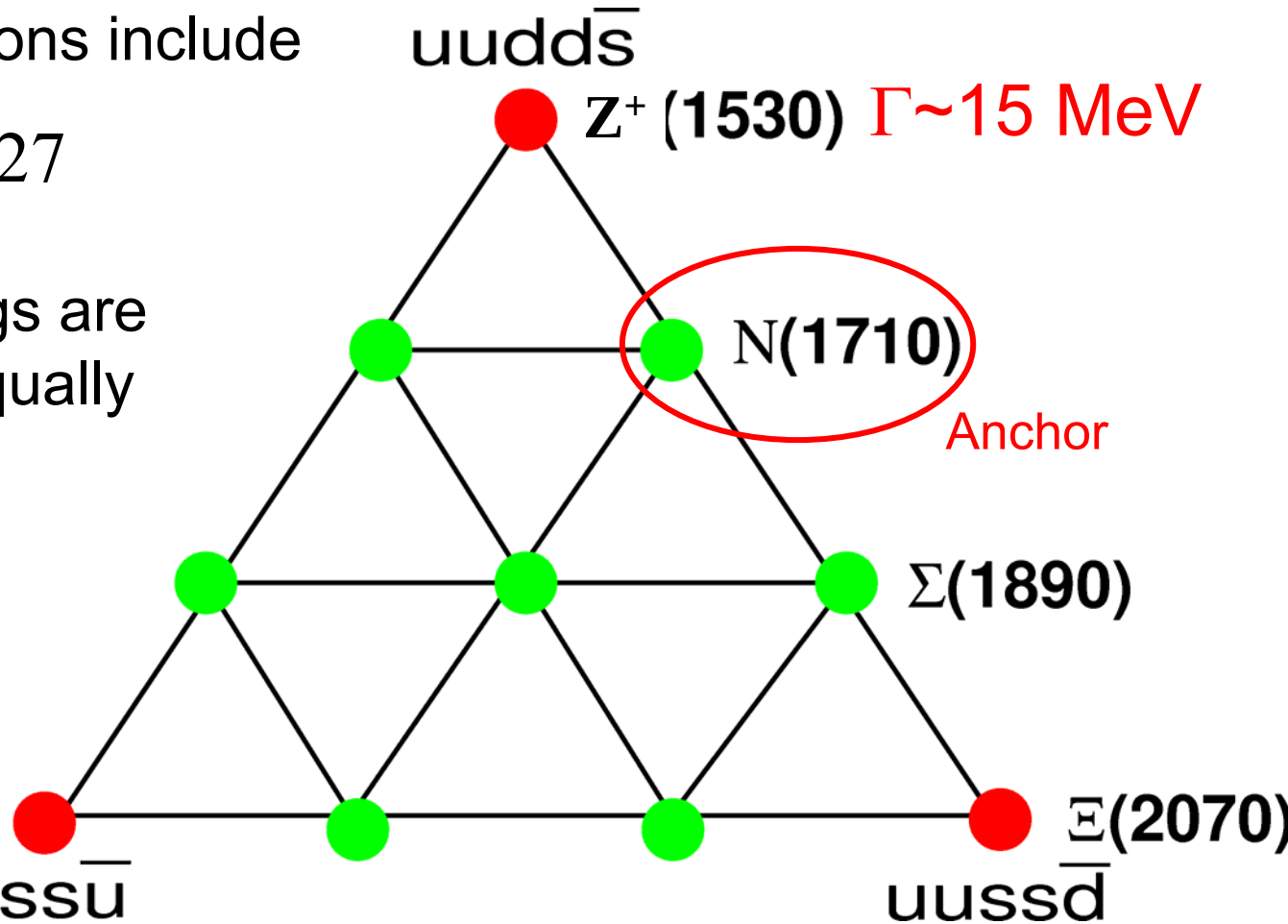
In the Chiral Soliton Model, nucleons and Deltas are rotational states of the same soliton field.

Z.Phys. A359, 305 (1997)

Rotational excitations include

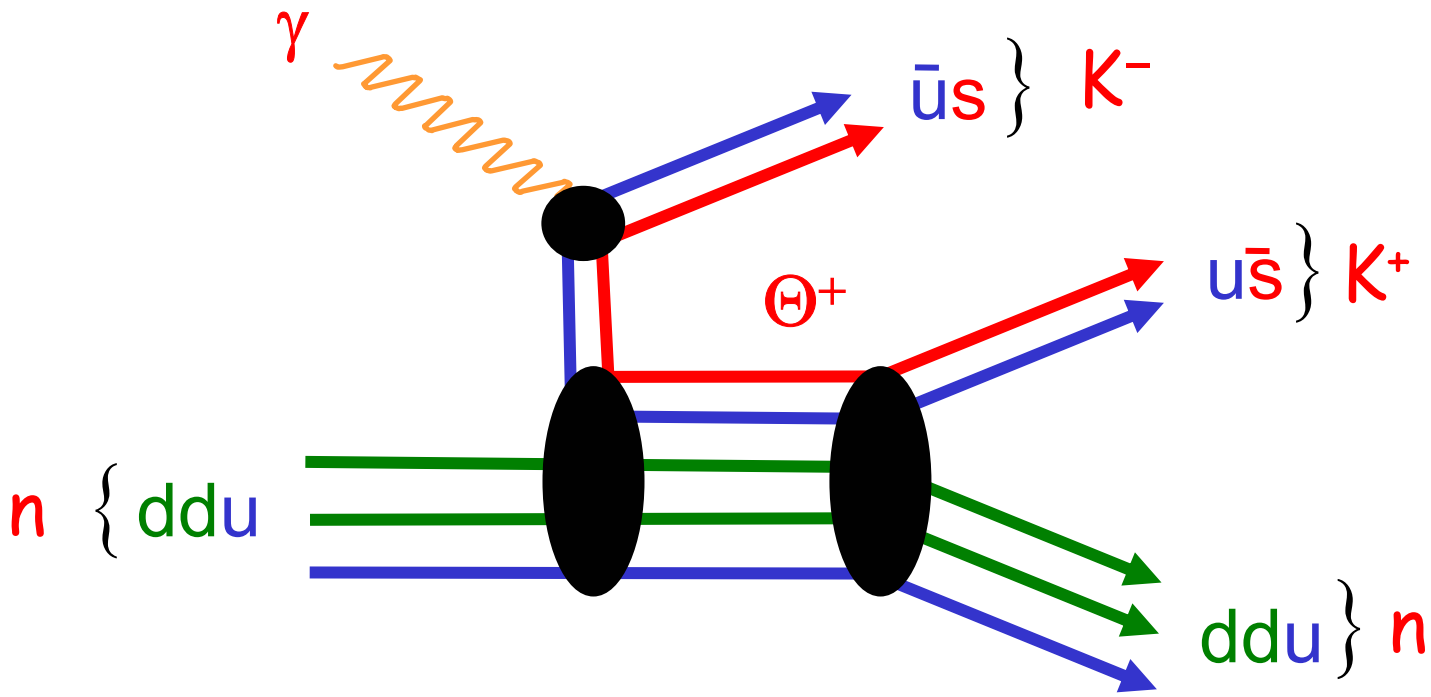
$$8 \oplus 10 \oplus \overline{10} \oplus 27$$

The mass splittings are predicted to be equally spaced



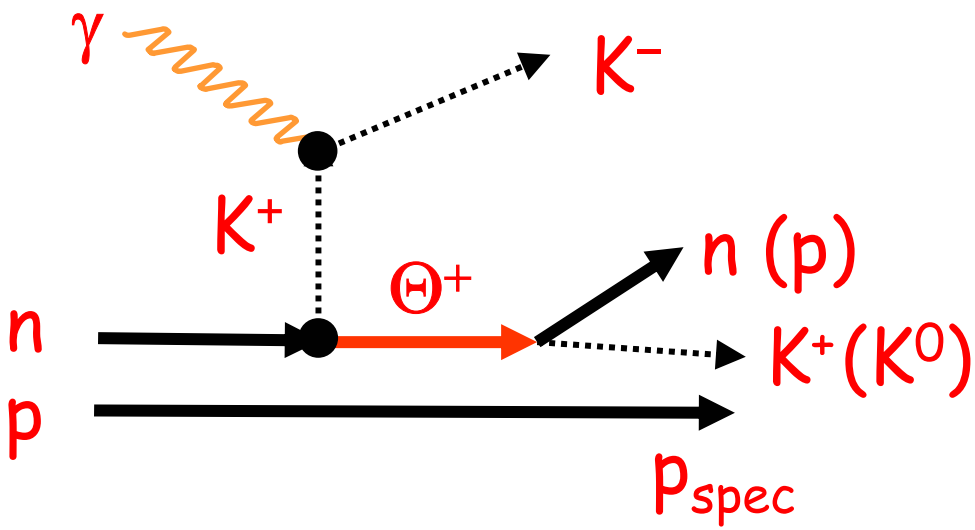
Γ~140 MeV

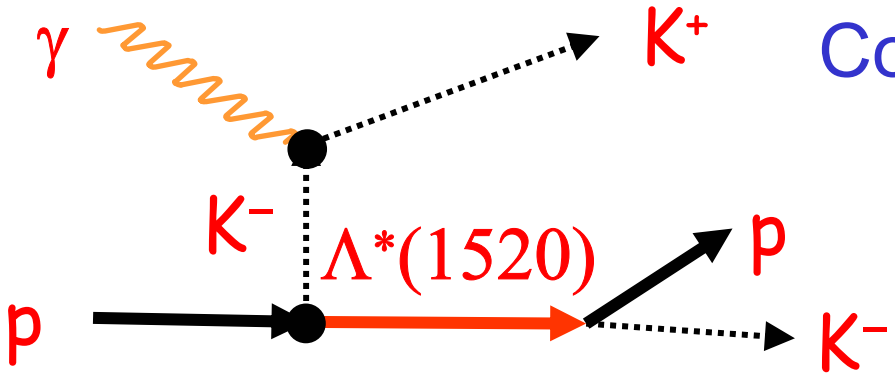
Quark lines for the reaction



Θ^+ is composed of ($uudd\bar{s}$) quarks

Production mechanisms



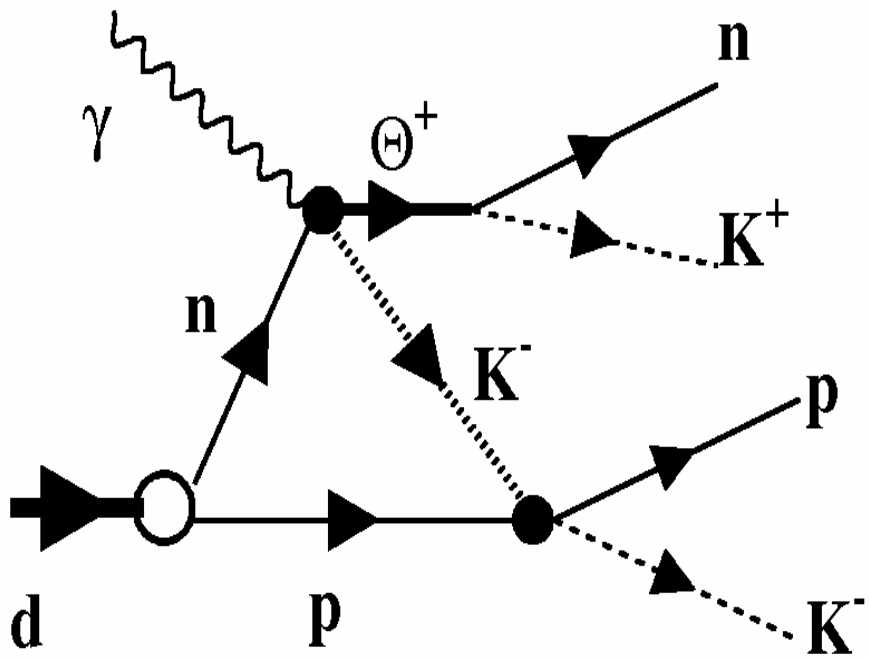


Control Reaction

Experimental Evidence

- Several experimental observations
- No dedicated experiments to date
- Walk through the analysis from CLAS

Exclusive measurement using γd reactions



CLAS Collaboration (S. Stepanyan, K. Hicks, *et al.*), hep-ex/0307018

- Requires FSI – both nucleons involved
  - No Fermi motion correction necessary
  - FSI puts K^- at larger lab angles: better CLAS acceptance
  - FSI not rare: in ~50% of $\Lambda^*(1520)$ events both nucleons detected with $p > 0.15$ GeV/c

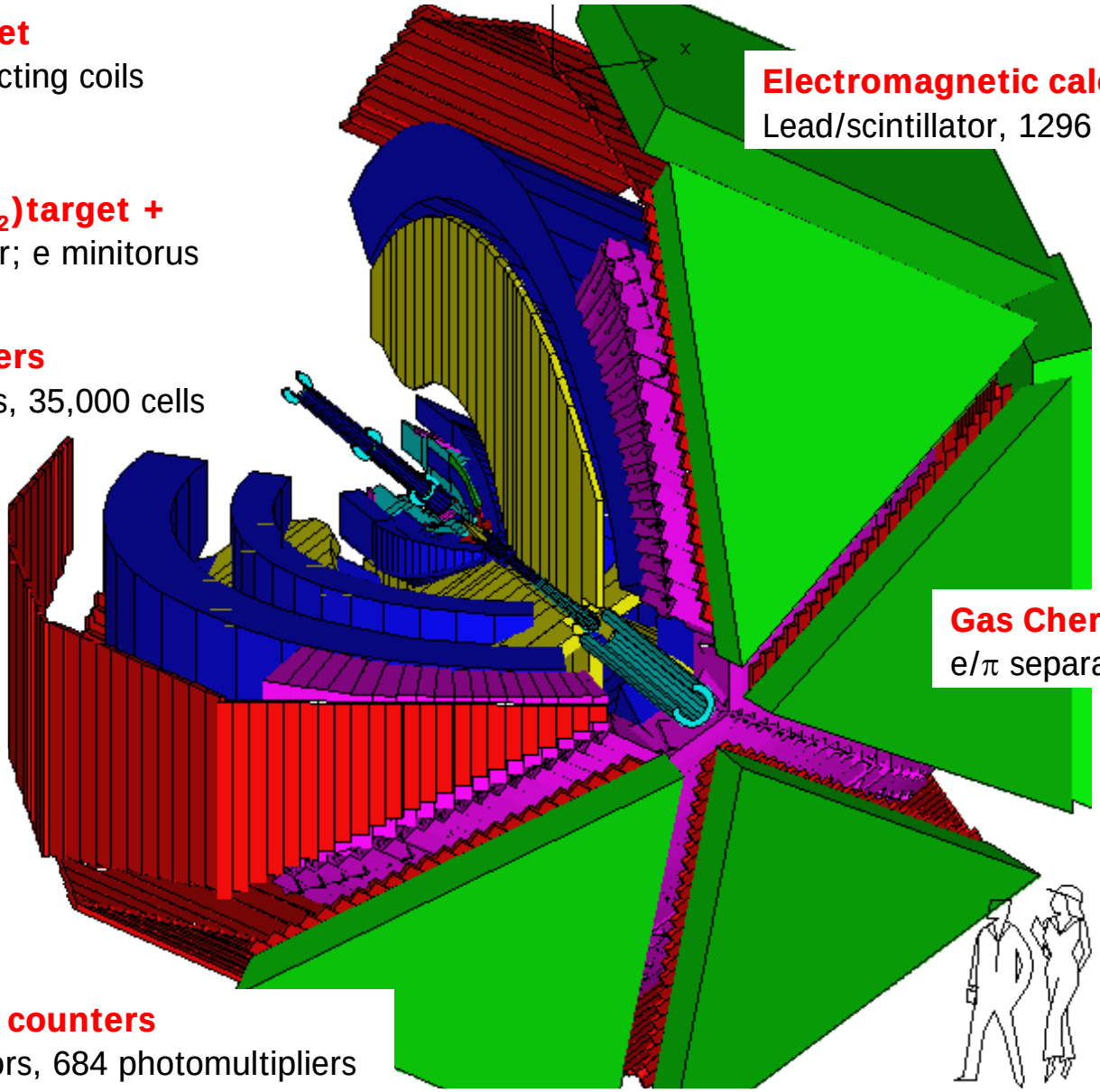
JLab accelerator CEBAF

CEBAF Large Acceptance Spectrometer

Torus magnet
6 superconducting coils

Liquid D_2 (H_2)target +
γ start counter; e minitorus

Drift chambers
argon/CO_2 gas, 35,000 cells

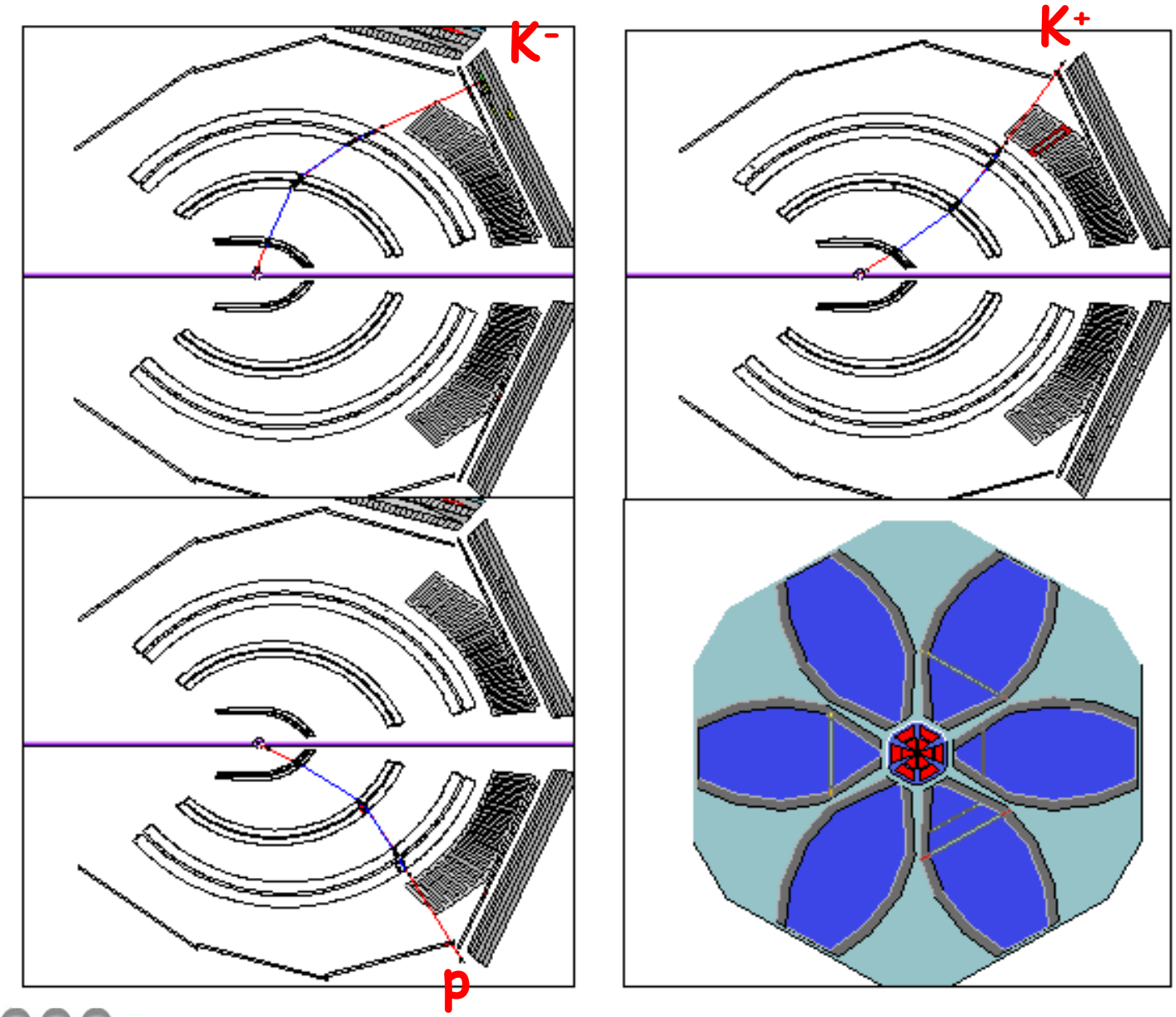


Electromagnetic calorimeters
Lead/scintillator, 1296 photomultipliers

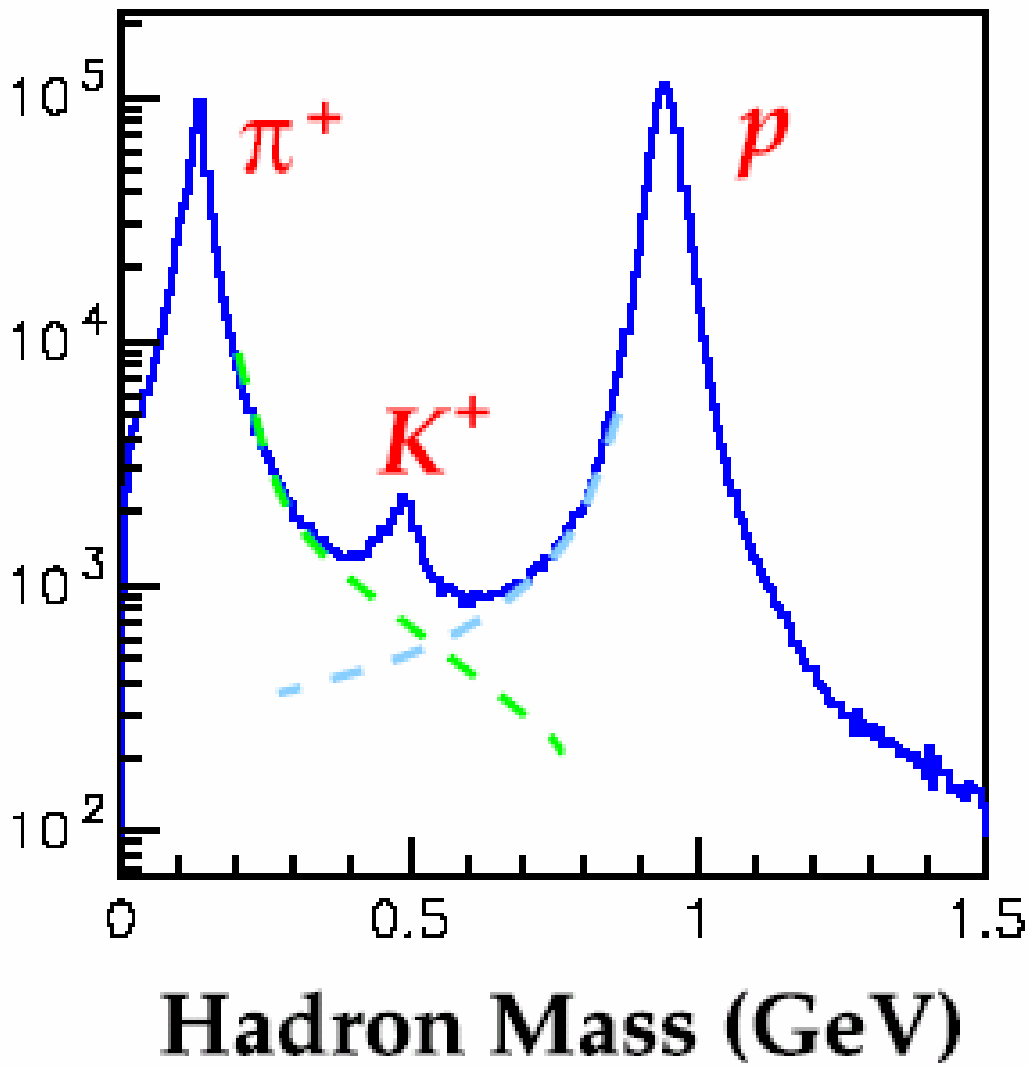
Gas Cherenkov counters
e/π separation, 256 PMTs

Time-of-flight counters
plastic scintillators, 684 photomultipliers

$\gamma d \rightarrow p K^+K^- (n)$ in CLAS



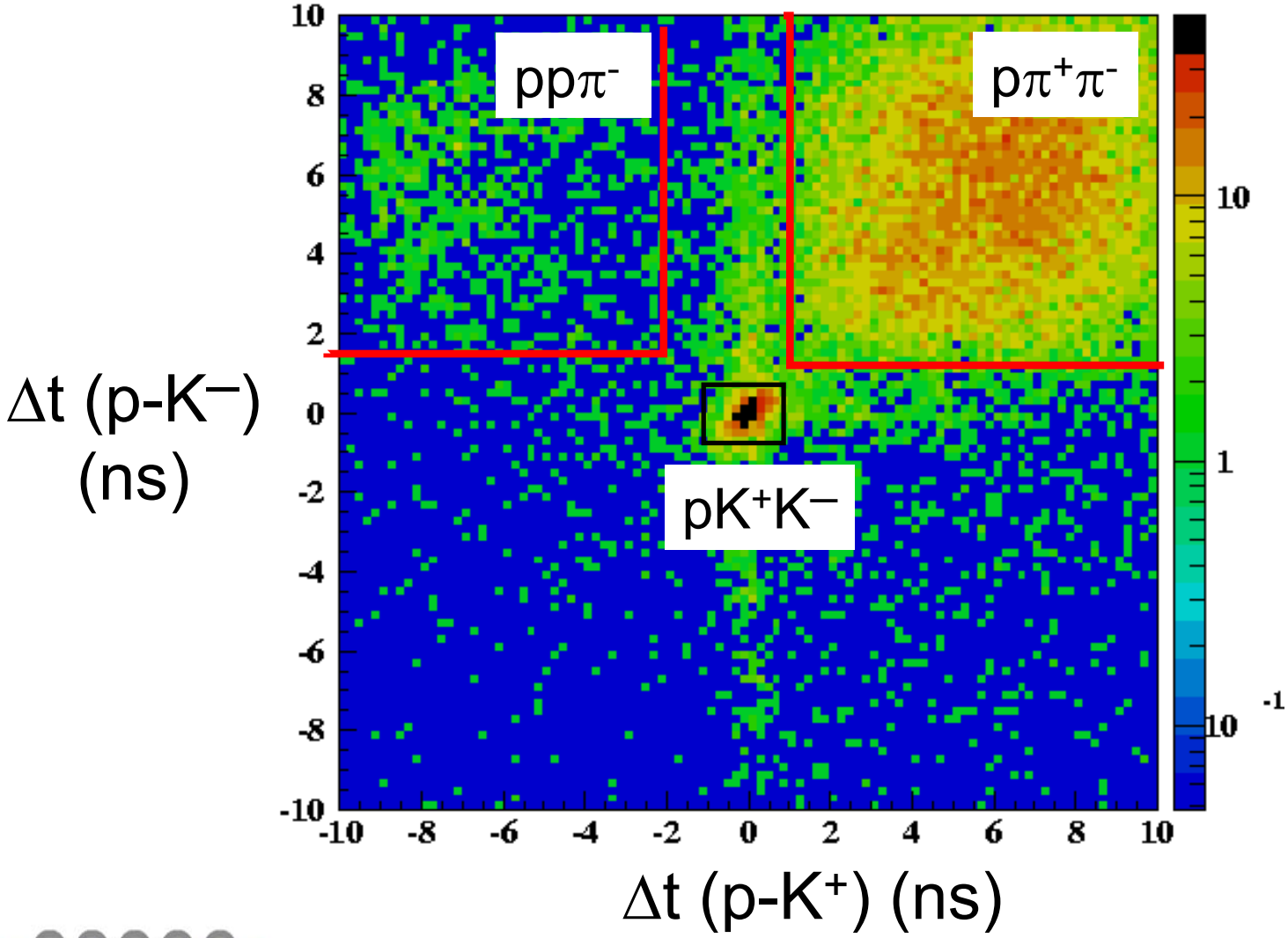
Particle identification by time-of-flight



$$m = \frac{p}{\gamma \beta c}$$

"Kaon" vertex times relative to proton

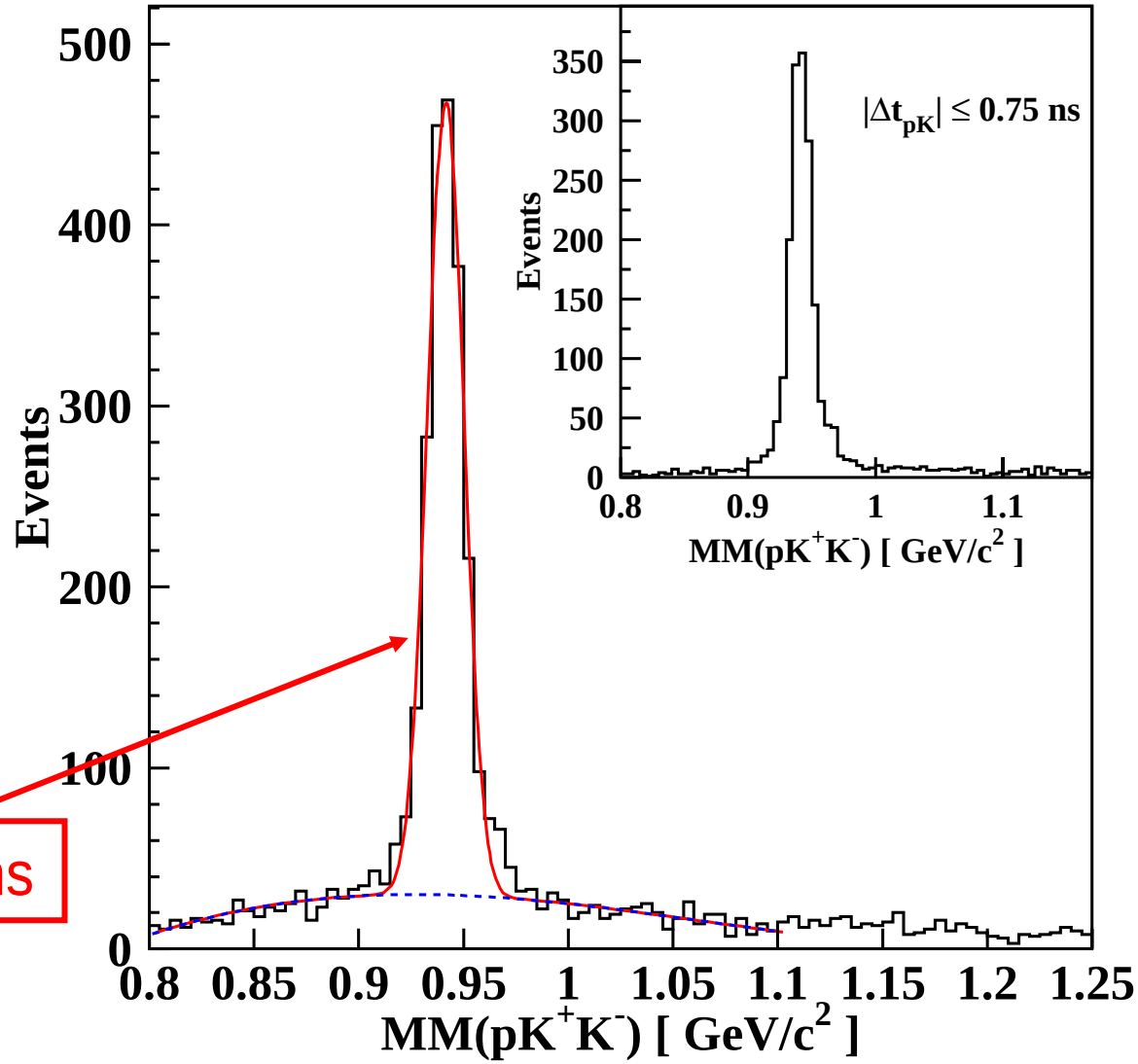
$$\Delta t_K = t - \frac{R}{\beta_c \cdot c}; \beta_c = \frac{p}{\sqrt{p^2 + m_K^2}}$$



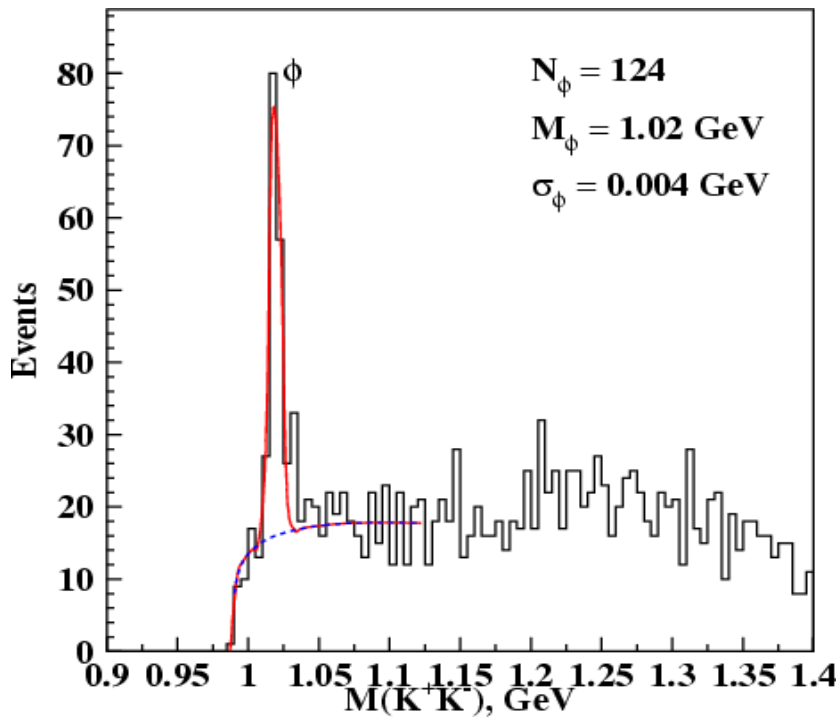
Reaction $\gamma d \rightarrow pK^+K^-(n)$

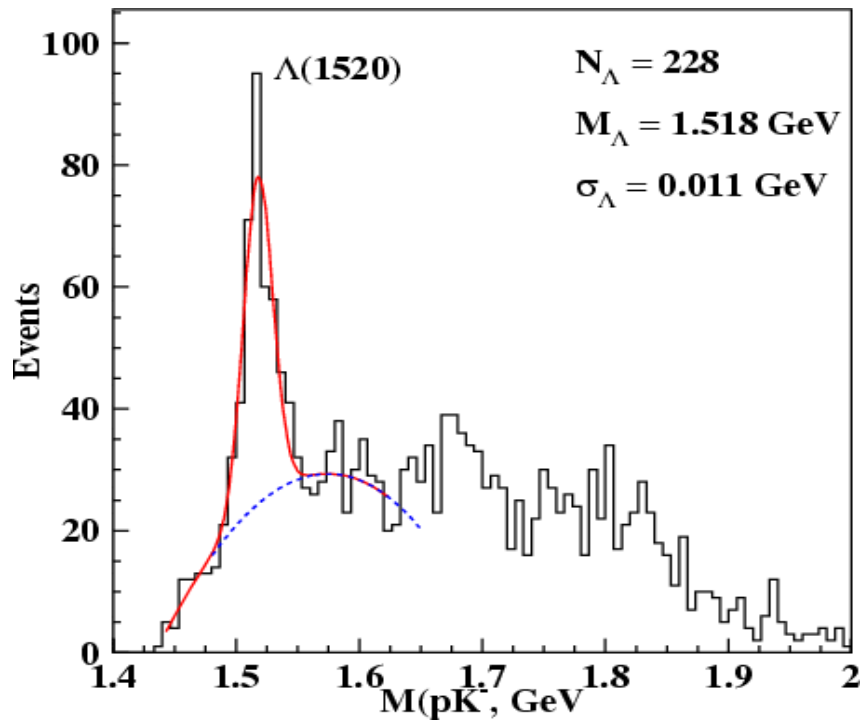
- Clear peak at neutron mass.
- 15% non-pKK events within ±3σ of the peak.
- Almost no background under the neutron peak after event selection with tight timing cut.

Reconstructed Neutrons



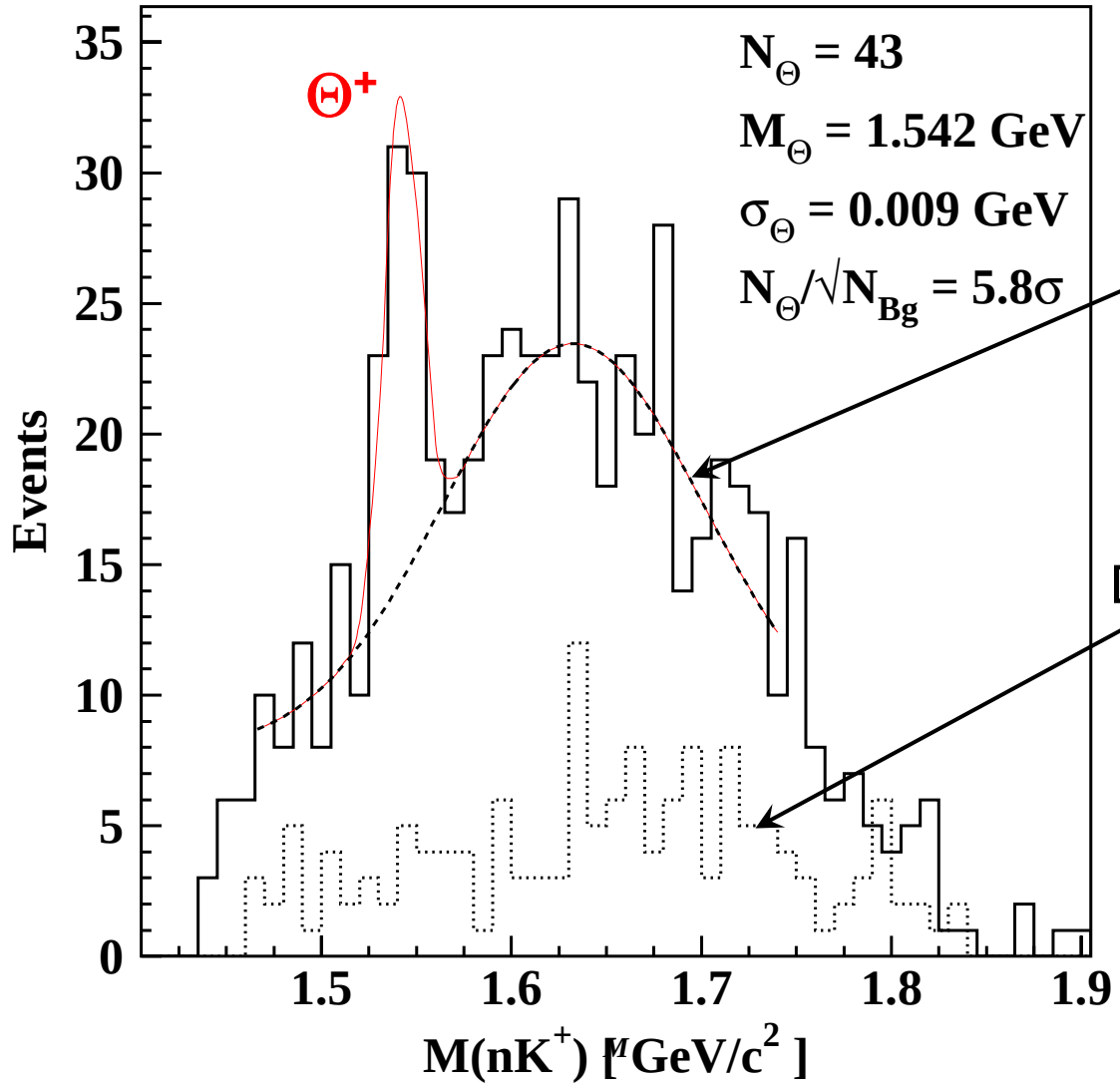
Identification of known resonances





- Remove events with $IM(K^+K^-) \rightarrow \phi(1020)$ by IM > 1.07 GeV
- Remove events with $IM(pK^-) \rightarrow \Lambda(1520)$
- Limit K^+ momentum due to $\gamma\, d \rightarrow p\, K^- \Theta^+$ phase space $p_{K^+} < 1.0$GeV/c

Deuterium: nK^+ invariant mass distribution



$$F(M) = G_{\Theta+} + G_{Bg} + P_0$$

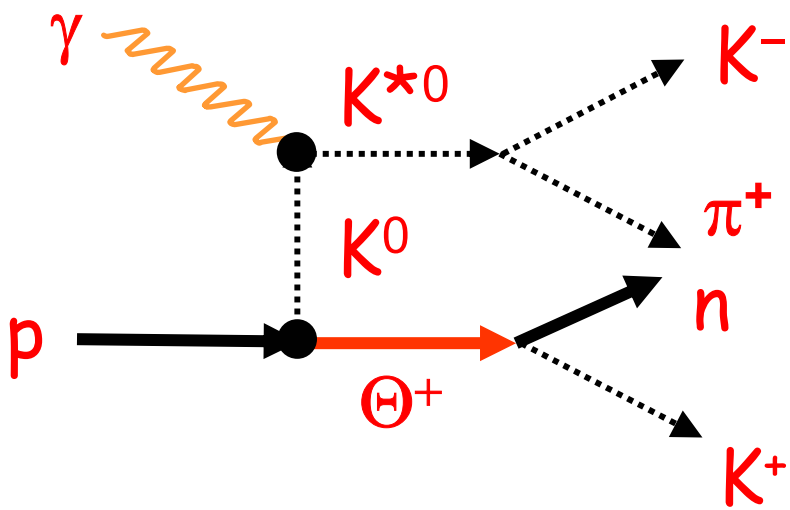
Distribution of $\Lambda^*(1520)$ events

Mass = 1.542 GeV

Γ< 21 MeV

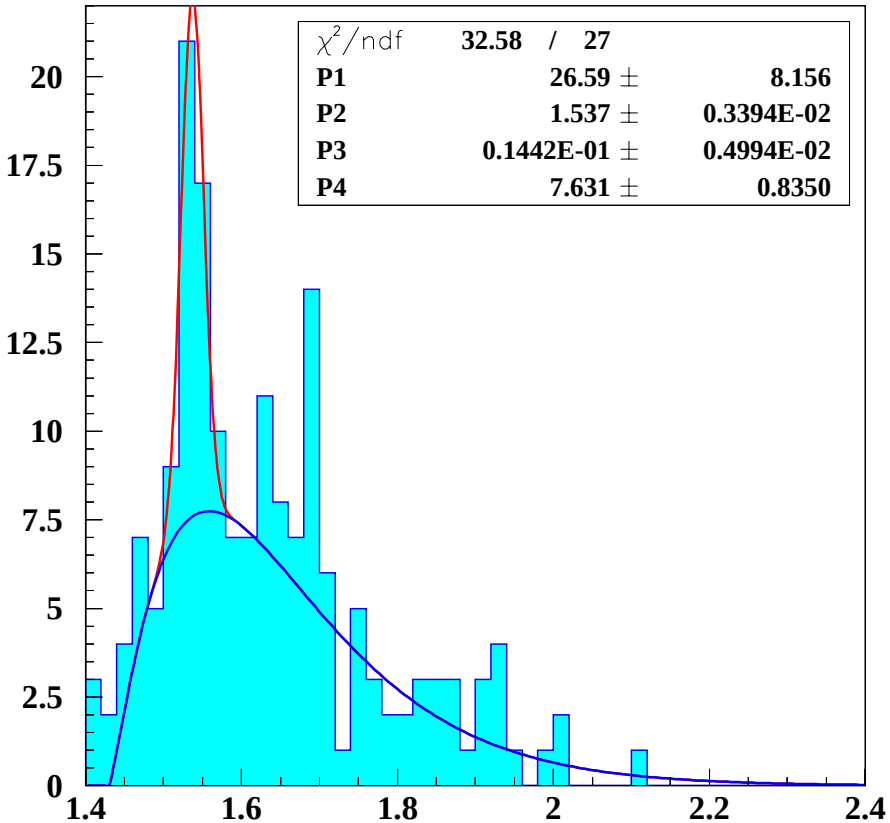
Significance 5.2±0.6 σ

Searching for the Θ^+ on a proton target



Mass = 1.537 GeV

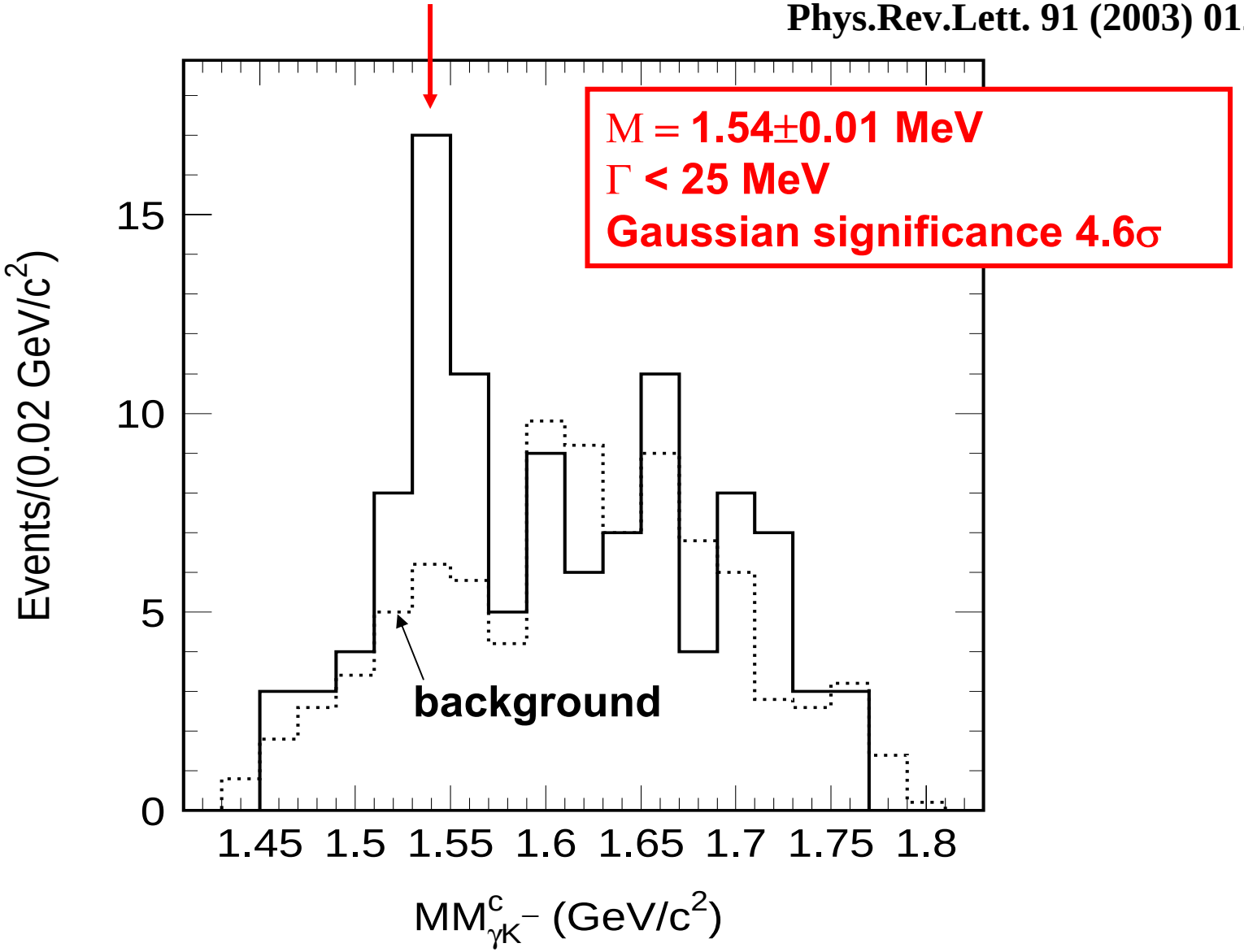
Events with $\cos\theta(\pi^+K^-)>0.5$



Mass(nK^+) GeV

First observation of Θ⁺ at SPring-8

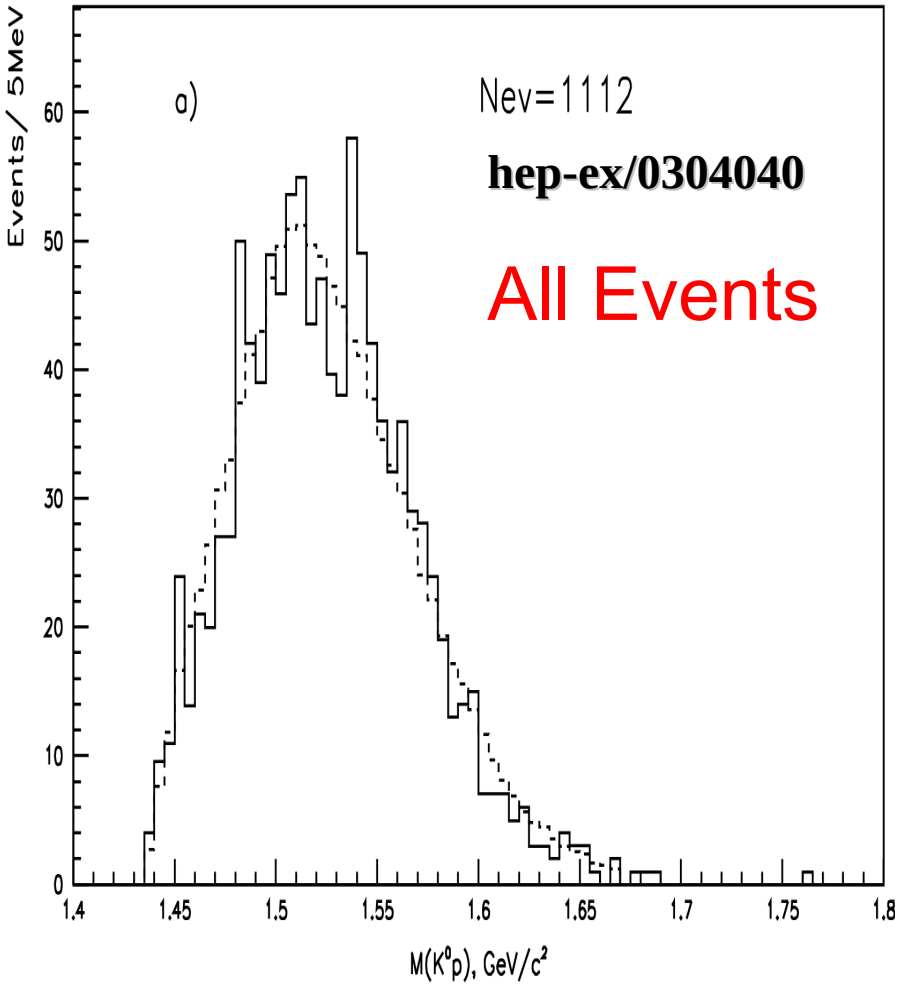
Phys.Rev.Lett. 91 (2003) 012002

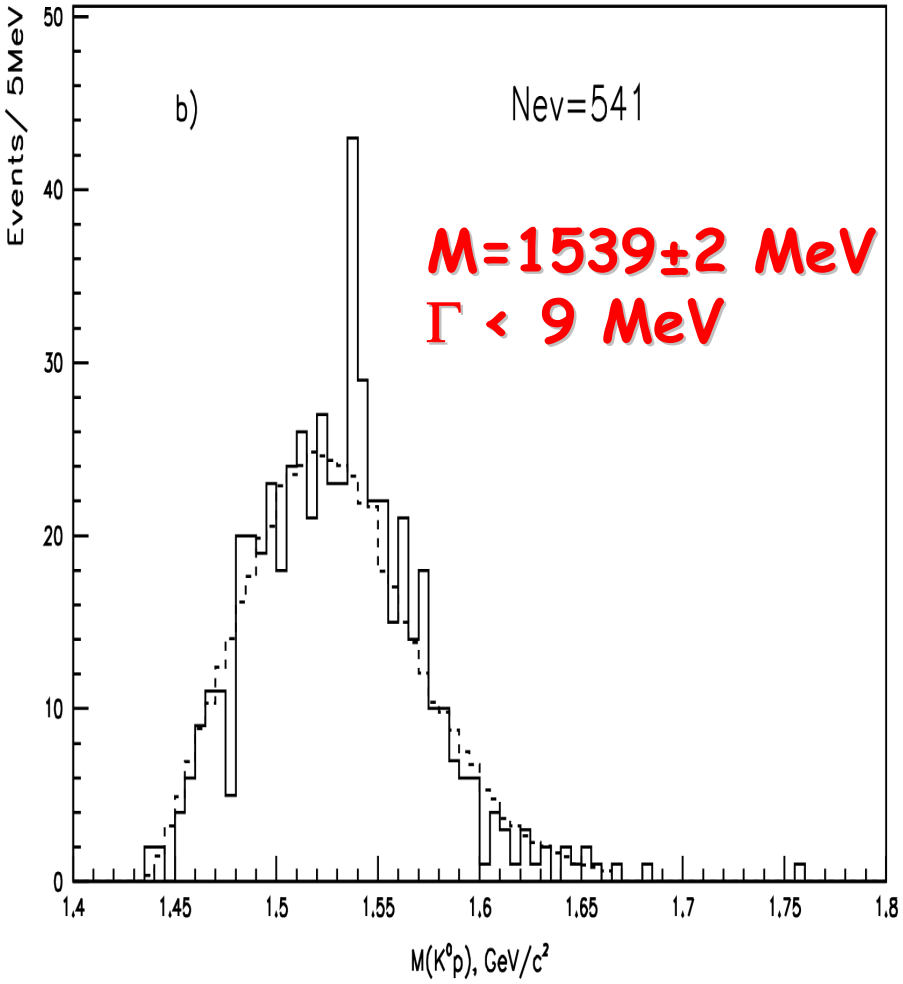


DIANA at ITEP 850 MeV K^+ beam

$K^+ Xe \rightarrow \Theta^+ N \rightarrow (K^0 p) N$

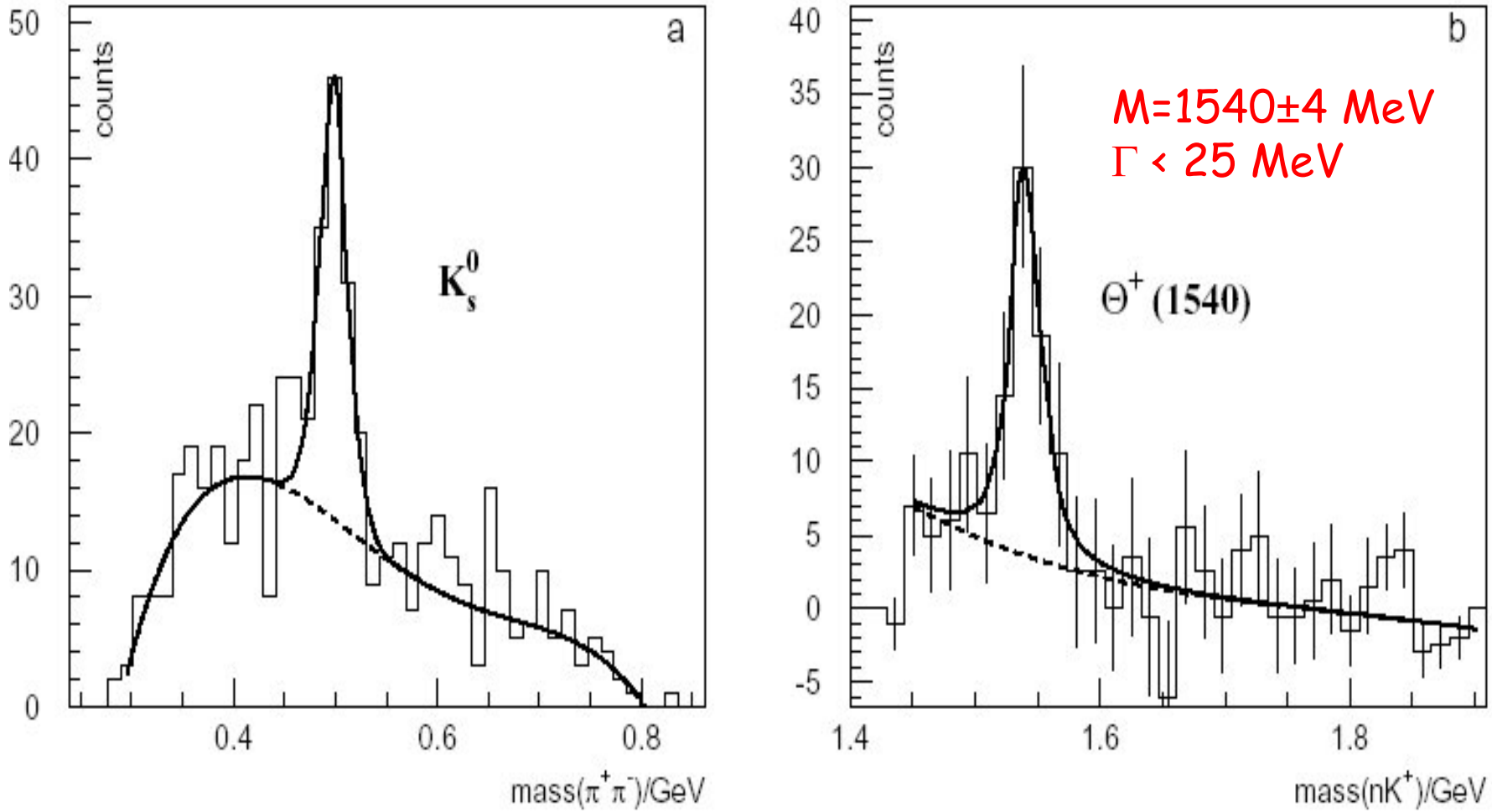
Cuts to suppress p and K^0 reinteraction in Xe nucleus





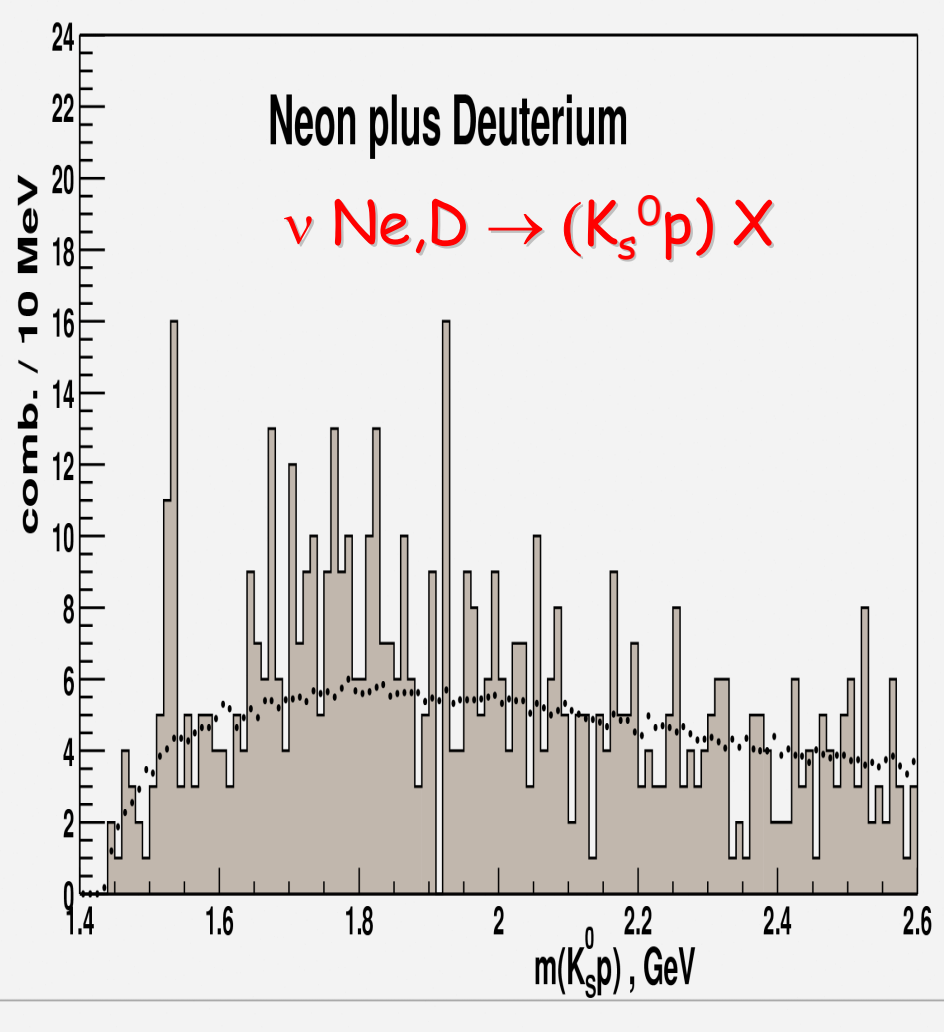
SAPHIR detector at ELSA

The reaction $\gamma p \rightarrow \Theta^+ K_s^0$, where $K_s^0 \rightarrow \pi^+\pi^-$ and $\Theta^+ \rightarrow nK^+$

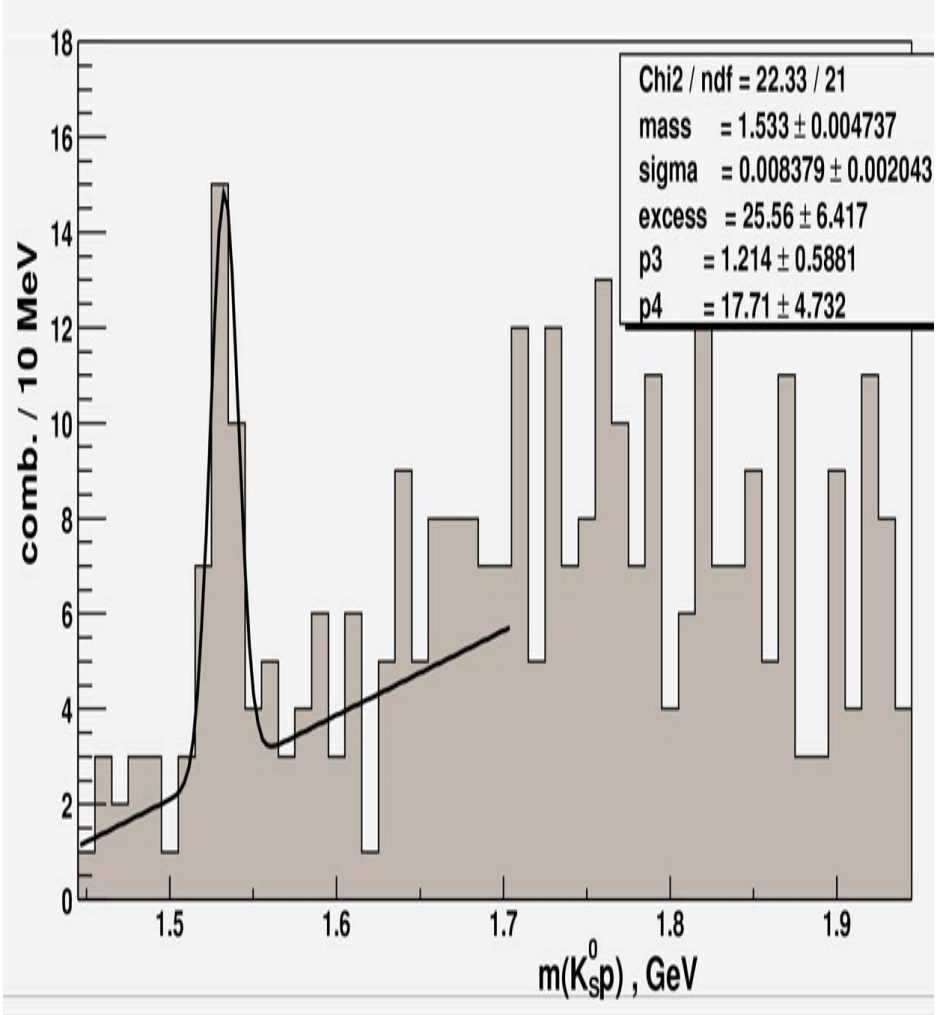


Reanalysis of bubble chamber neutrino data

M = 1533±5 MeV, Γ < 20 MeV

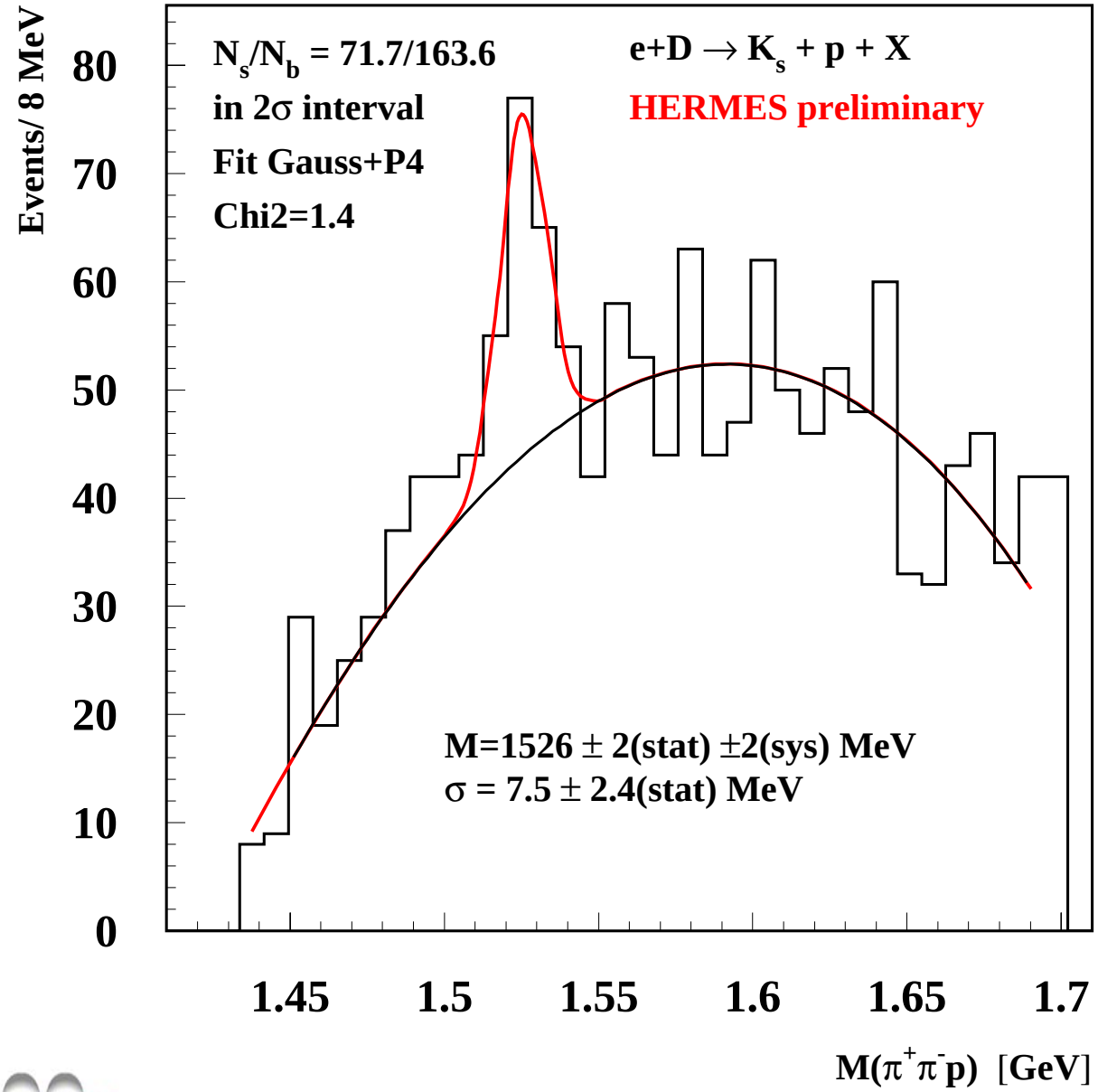


Enlargement of signal region

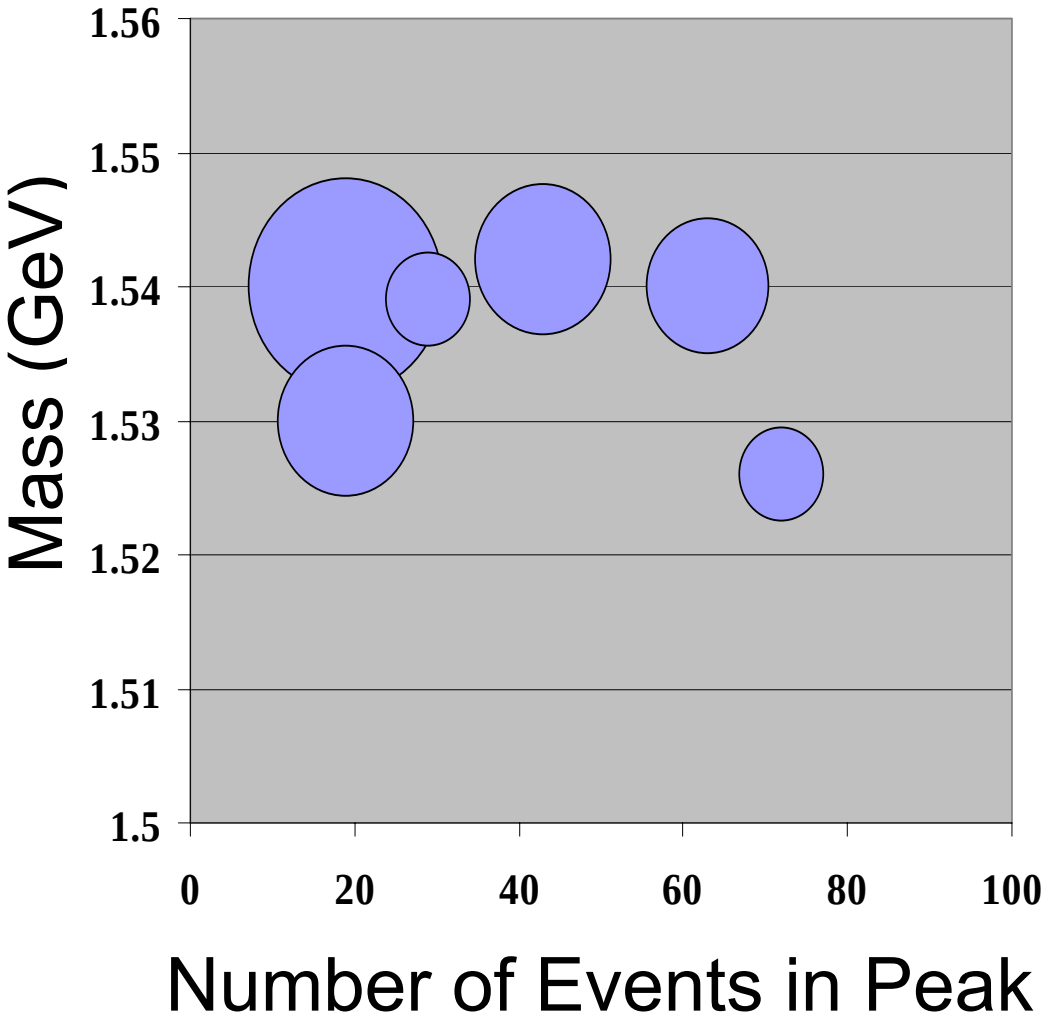


ITEP group: hep-ex/0309042

HERMES


Events/ 8 MeV
80
70
60
50
40
30
20
10
0
N_s/N_b = 71.7/163.6
in 2σ interval
Fit Gauss+P4
Chi2=1.4
e+D → K_s + p + X
HERMES preliminary
M=1526 ± 2(stat) ±2(sys) MeV
σ = 7.5 ± 2.4(stat) MeV
1.45
1.5
1.55
1.6
1.65
1.7
$M(\pi^+\pi^-p)$ [GeV]

What do we know about this S=+1 state?



LEPS : $\gamma C \rightarrow (nK^+)\ K^- X$

DIANA : $K^+ Xe \rightarrow (pK^0)\ X$

CLAS : $\gamma d \rightarrow (nK^+)\ K^- p$

SAPHIR : $\gamma p \rightarrow (nK^+)\ K^0$

ITEP : $\nu\ d, Ne \rightarrow (pK^0)\ K^0$

HERMES : $e^+ d \rightarrow (pK^0)\ X$

Parenthesis show Θ^+ decay products

Searches for isospin pK^+ partner have found nothing

There is much more to learn

- Spin, parity
  - Chiral soliton model predicts $J^{pc}=½^{+}$ (p-wave)
  - Quark model naïve expectation is $J^{pc}=½^{-}$ (s-wave)
- Isospin
  - Likely I=0, as predicted by the chiral soliton model.
- Width (lifetime)
  - Measurements limited by experimental resolution.
  - Naïve estimates predict Γ~200 MeV.
  - Theoretical problem remains why the state is so narrow.
  - Analysis of existing $K^{+}d$ scattering data indicate that Γ < 1-2 MeV. (e.g. nucl-th/0308012)
- Complete determination of the pentaquark multiplet

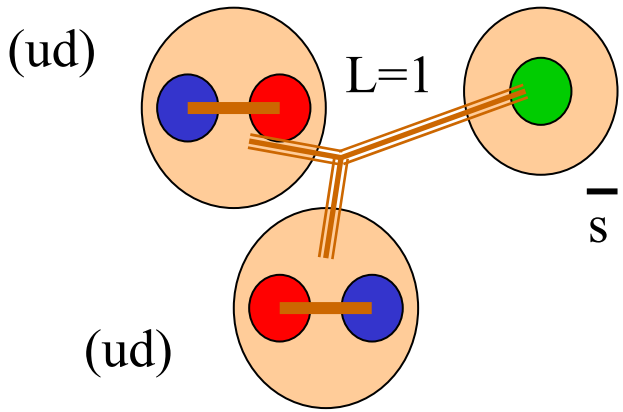
A di-quark model for pentaquarks

$$[ud][ud] \qquad \bar{s}$$

JW hep-ph/0307341

JM hep-ph/0308286

SZ hep-ph/0310270



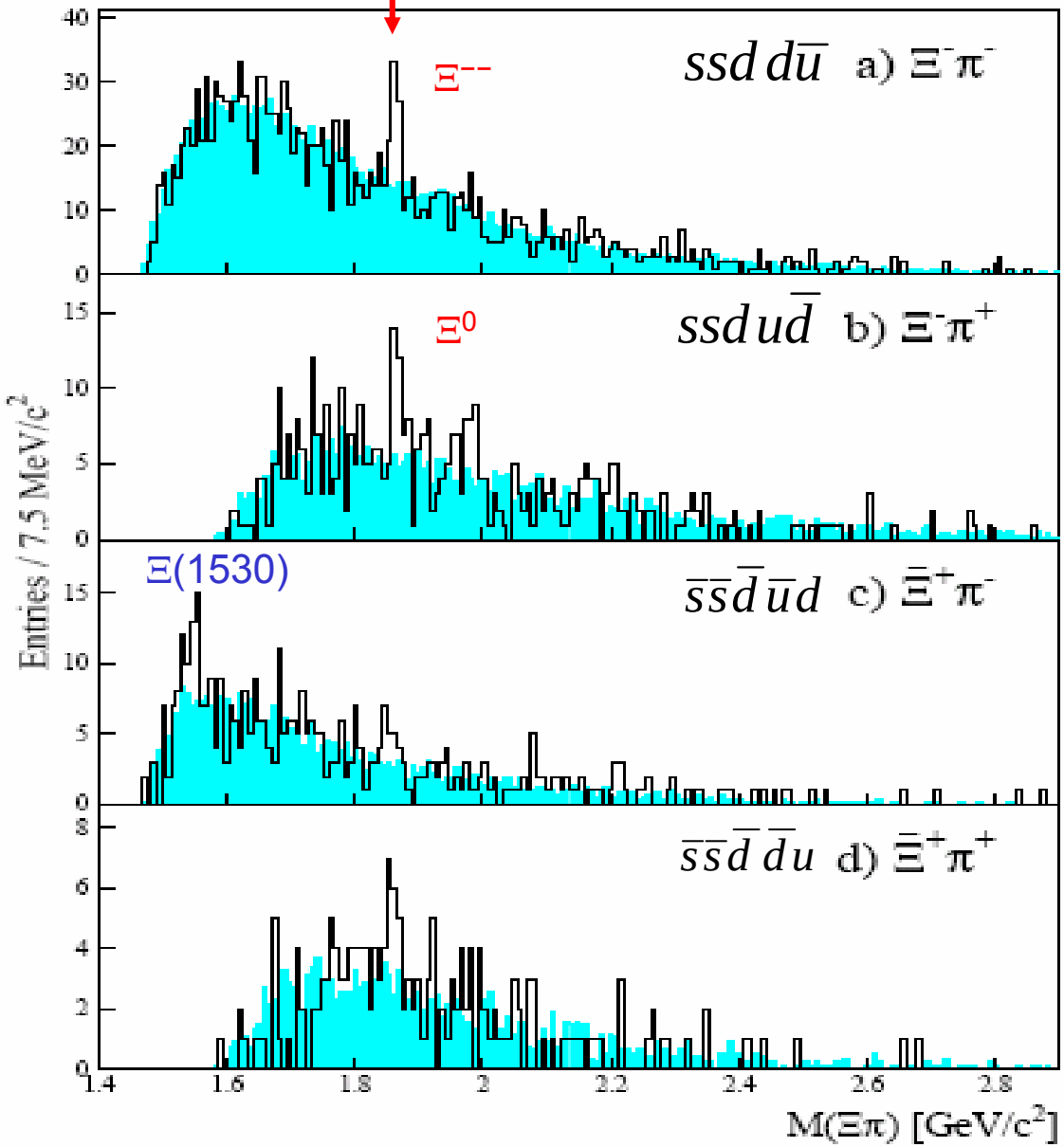
L=1, one unit of orbital angular momentum needed to get $J=1/2^+$ as in χSM

Lattice QCD: $J^P = 1/2^-$

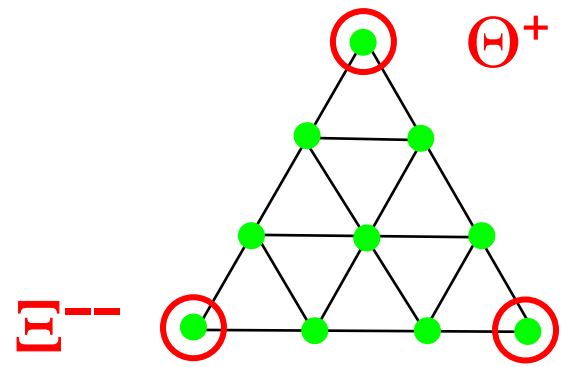
Decay Width: $\langle [ud][ud]\,\bar{s} \,|\, [uud]\,[u\bar{s}] \rangle = \frac{1}{2\sqrt{6}}\Gamma \approx \frac{200\ MeV}{\left(2\sqrt{6}\right)^2} \approx 8\ MeV$

Mass Prediction for Ξ^{--} is 1.75 instead of 2.07 GeV

A new cousin: observation of exotic Ξ^{--}



M=1.862± 0.002 GeV



CERN SPS hep-ex/0310014

Current activities

- Workshop@ JLab Penta-Quark 2003, Nov 6-8
  - www.jlab.org/intralab/calendar/archive03/pentaquark/
- Approved experiment for 30 PAC days with deuterium target scheduled for early next year (spokespersons Ken Hicks, S. Stepanyan)
- New proposals under discussion, for example to search for Ξ^{--}…
- Theory papers appearing daily on the preprint server.
- Of course there is worldwide interest to continue to probe the nature of pentaquarks experimentally.

Summary

- A key question in non-perturbative QCD is the structure of hadrons
  - We have presented evidence for an exotic baryon with S = +1, which would have a minimal quark content of five quarks ($uudd\bar{s}$).
  - This baryon represents a new class of colorless hadrons.
  - The additional observation of a doubly negative S=−2 baryon ($ddss\bar{u}$) establishes a second corner of the anti-decuplet the family of pentaquarks.
  - The observation of new members of the family of 5-quark states gives credibility to the existence of pentaquarks.
- Hadronic physics is being driven by experimental discoveries.
- Electromagnetic probes are playing a major role in the investigation of these new states.

Index of popular articles on the Pentaquark **http://www.jlab.org/news/articles/**