Evidence for S=+1 Pentaquark Baryon

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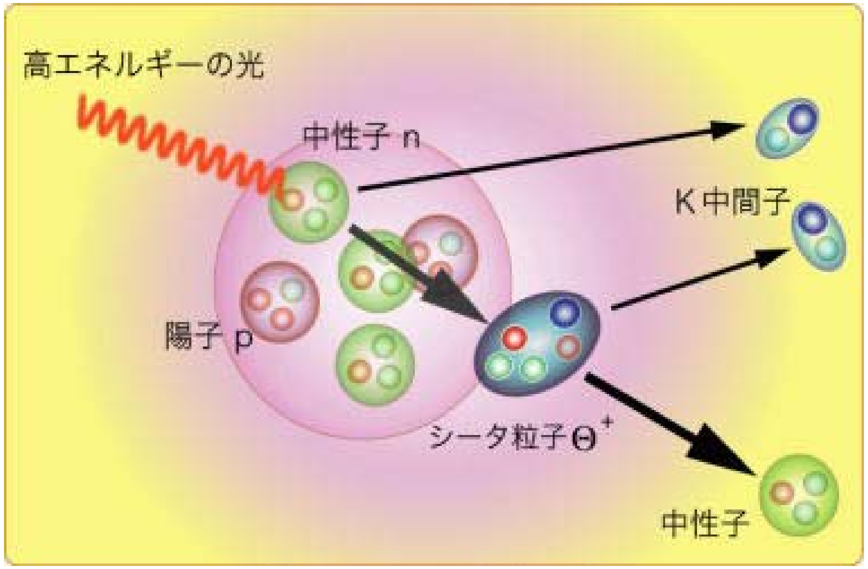
- **Introduction**
- **First Evidence**
- **Confirmations**
- **Problems and Prospects**
- **Summary**



Multi-quark workshop @ Kyoto

Febuary 18, 2004

What are penta-quarks?

- Minimum quark content is 5 quarks.
- "Exotic" penta-quarks 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: $uudd\bar{s}$

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

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

Exotic S=+1 Baryon

NOTE ON THE S = + 1 BARYON SYSTEM

(PDG 1986; Phys. Lett. B170, 289)

The evidence for strangeness +1 baryon resonances was reviewed in our 1976 edition,[1] and more recently by Kelly[2] and by Oades.[3] Two new partial-wave analyses[4] have appeared since our 1984 edition. Both claim that the P_{13} and perhaps other waves resonate.

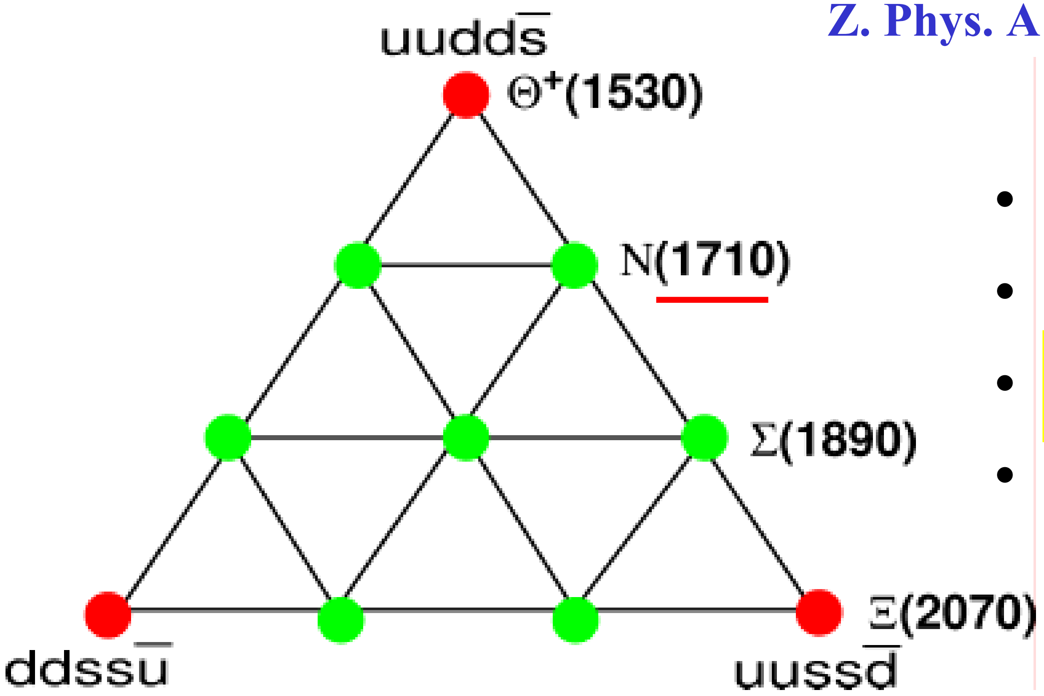
However, the results permit no definite conclusion- the same story heard for 15 years. The standards of proof must simply be much more severe here than in a channel in which many resonances are already known to exist. The general prejudice against baryons not made of three quarks and the lack of any experimental activity in this area make it likely that it will be another 15 years before the issue is decided.

References

- **1. Particle Data Group, Rev. Mod. Phys. 48, SI88 (1976).**
- **2. R.L. Kelly, in Proceedings of the Meeting on Exotic Resonances (Hiroshima, 1978), ed. I. Endo et al.**
- **3. G.C. Oades, in Low and Intermediate Energy Kaon-Nucleon Physics (1981), ed. E. Ferrari and G. Violini.**
- **4. K. Hashimoto, Phys. Rev. C29, 1377 (1984); and R.A. Arndt and L.D. Roper, Phys. Rev. D31, 2230 (1985).**

Θ^+ Baryon

D. Diakonov, V. Petrov, and M. Polyakov,
Z. Phys. A 359 (1997) 305.

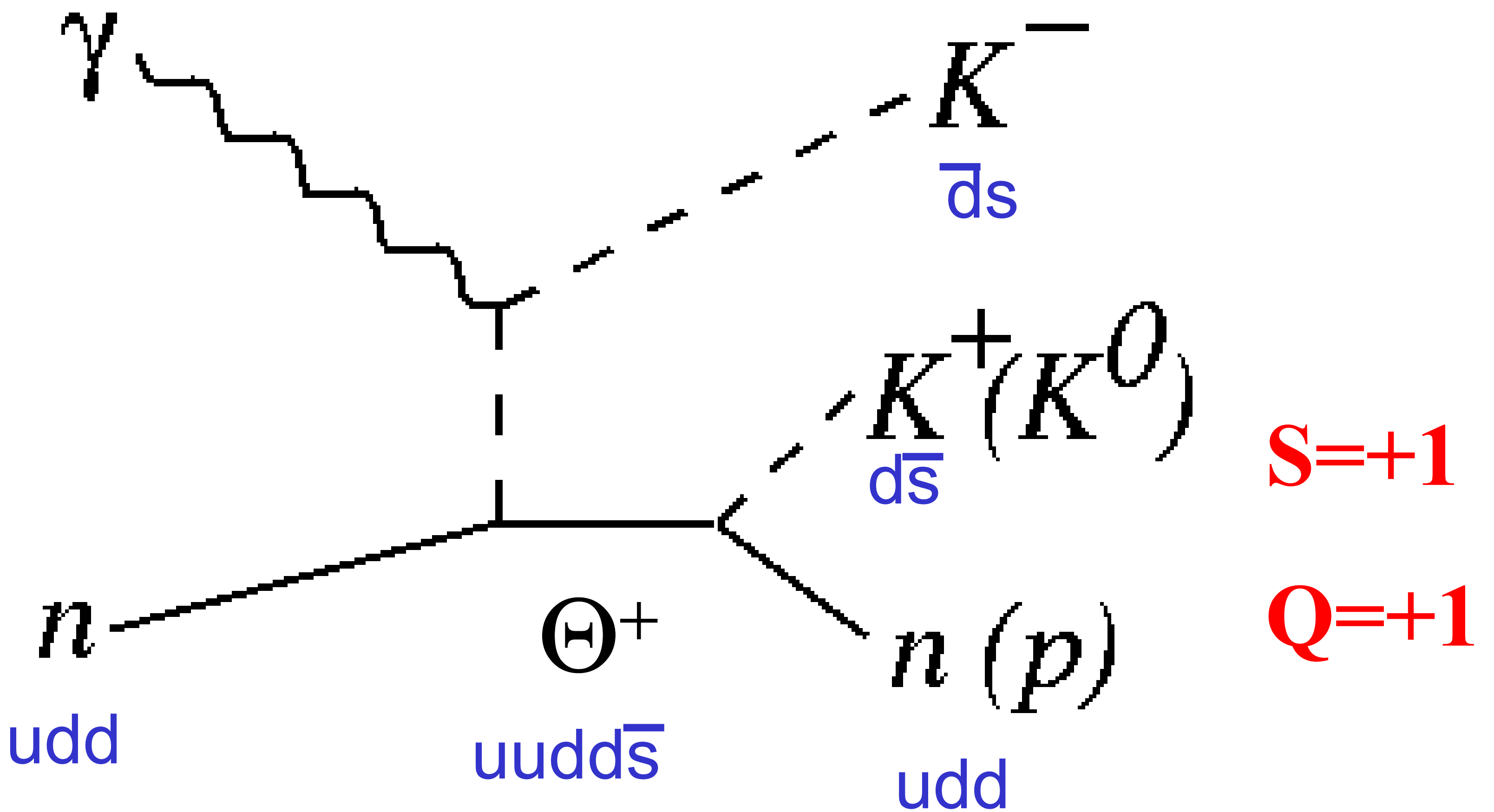


- **Exotic: S=+1**
- **Low mass: 1530 MeV**
- **Narrow width: ~ 15 MeV**
- **$J^p=1/2^+$**

Accident?

M = [1890-180*Y] MeV

Θ^+ Production from Neutron

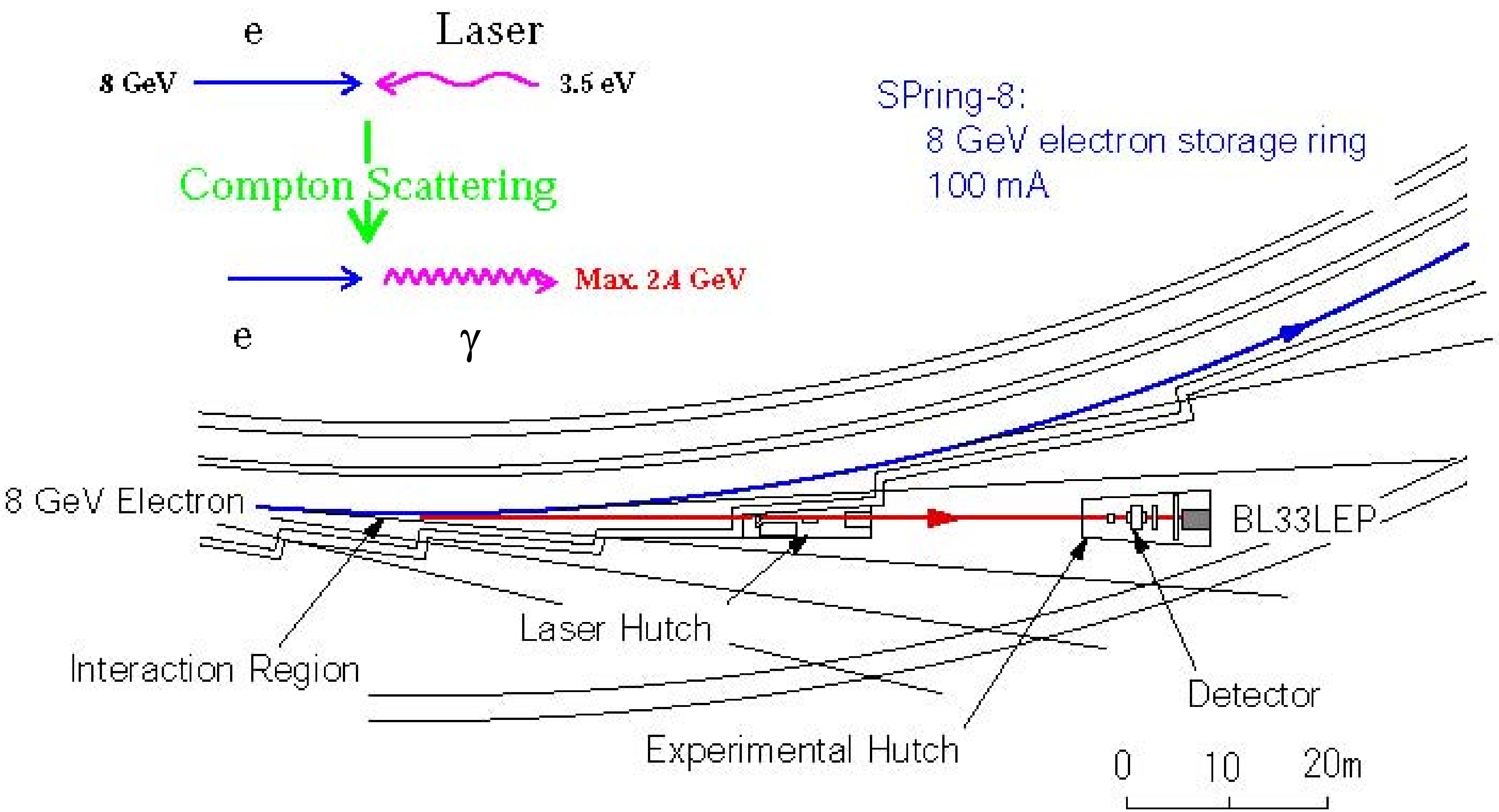


Super Photon ring-8 GeV SPring-8

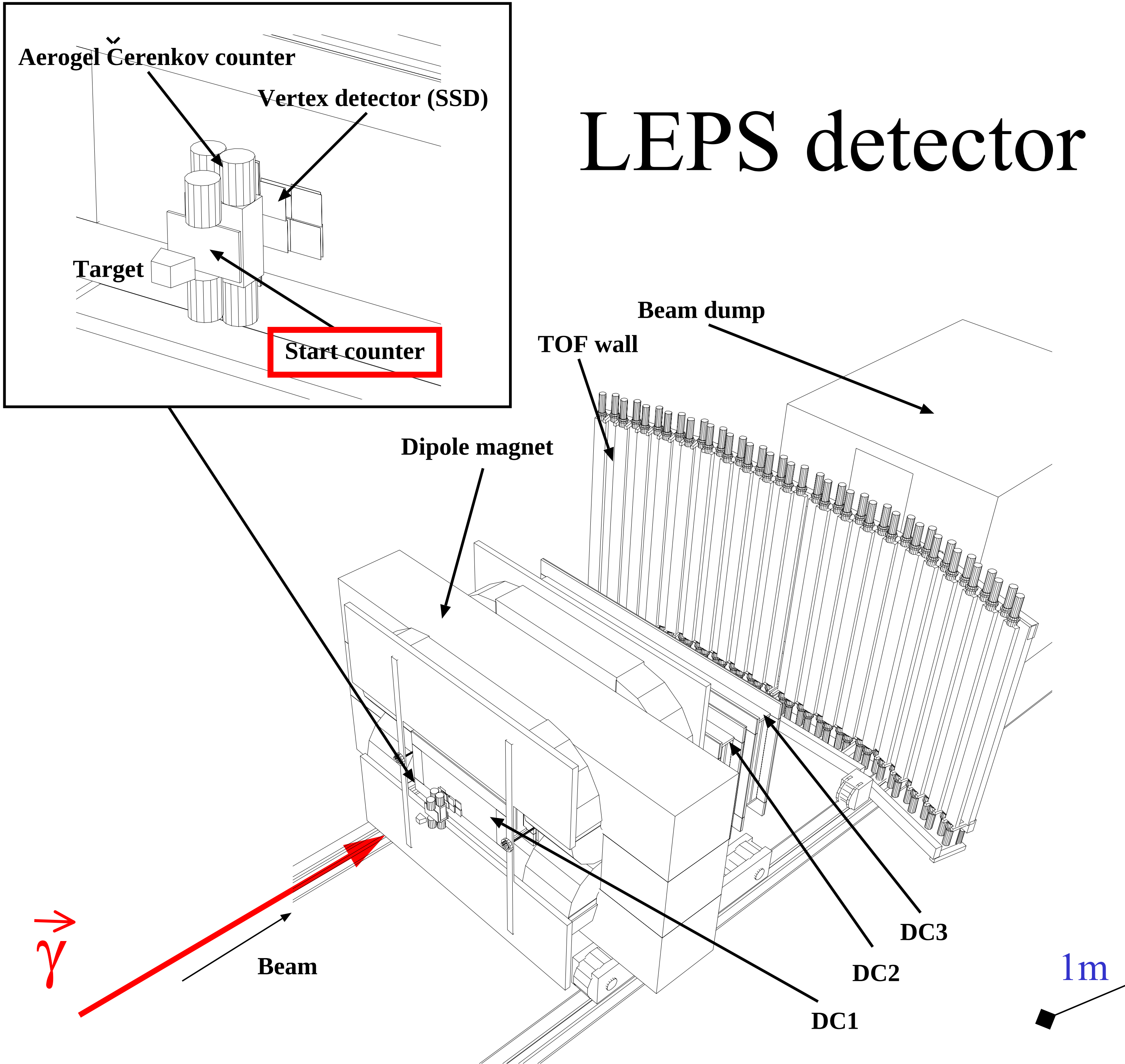
- Third-generation synchrotron radiation facility
- Circumference: 1436 m
- 8 GeV
- 100 mA
- 62 beamlines

Laser Electron Photon facility at SPring-8

in operation since 2000



LEPS detector



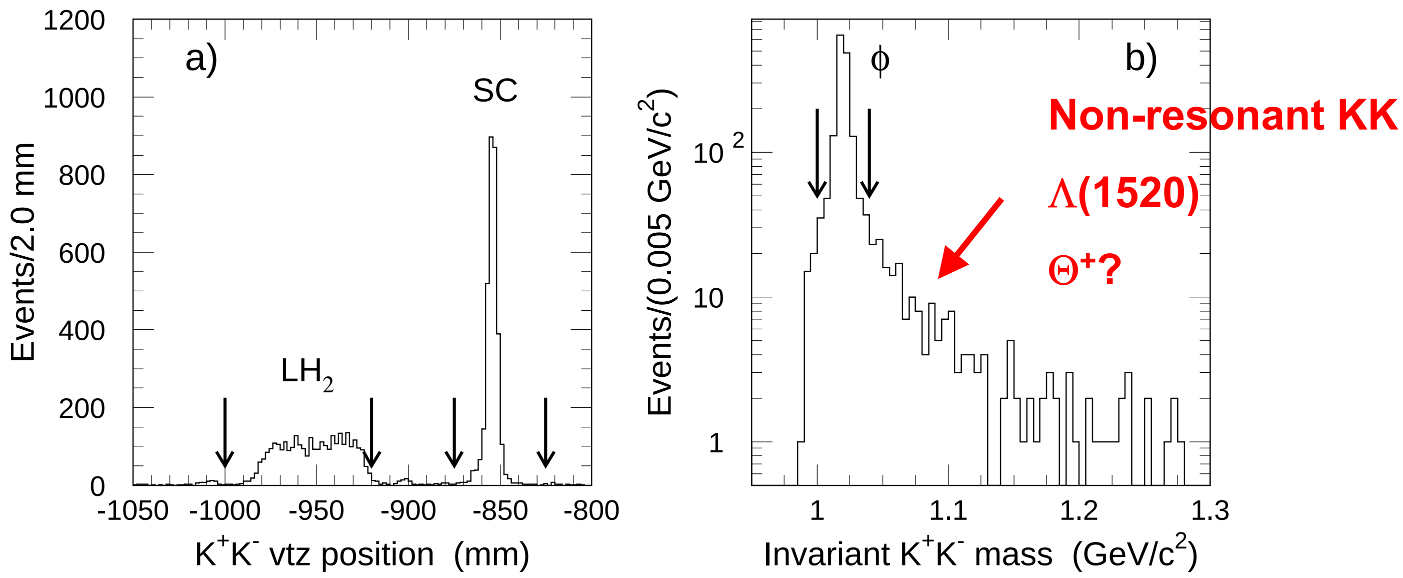
Identification of Θ^+

$\gamma\, n \rightarrow K^- \Theta^+ \rightarrow K^- K^+ n$

- K^- missing mass gives Θ^+ mass
- K^+K^- missing mass gives n

Problems:

- "background"
  - $\phi \rightarrow K^+K^-$
    (produced from n & p)
- Fermi motion distorts a missing mass spectrum.



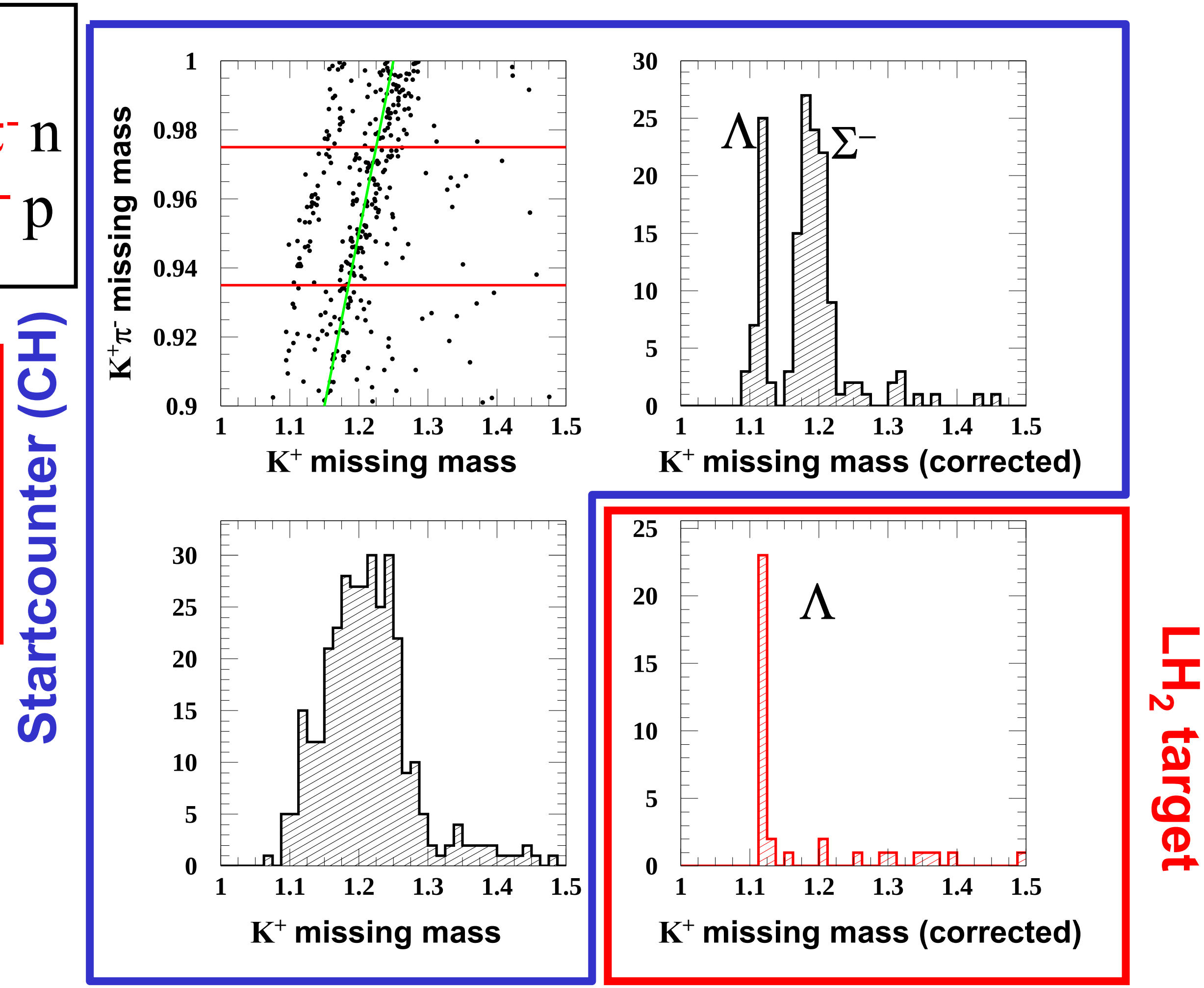
Fermi motion correction

Test-case:

$\gamma\, n \rightarrow K^{+}\Sigma^{-} \rightarrow K^{+}\pi^{-} n$

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

Correction works better when ꝑn áꝑK is small.



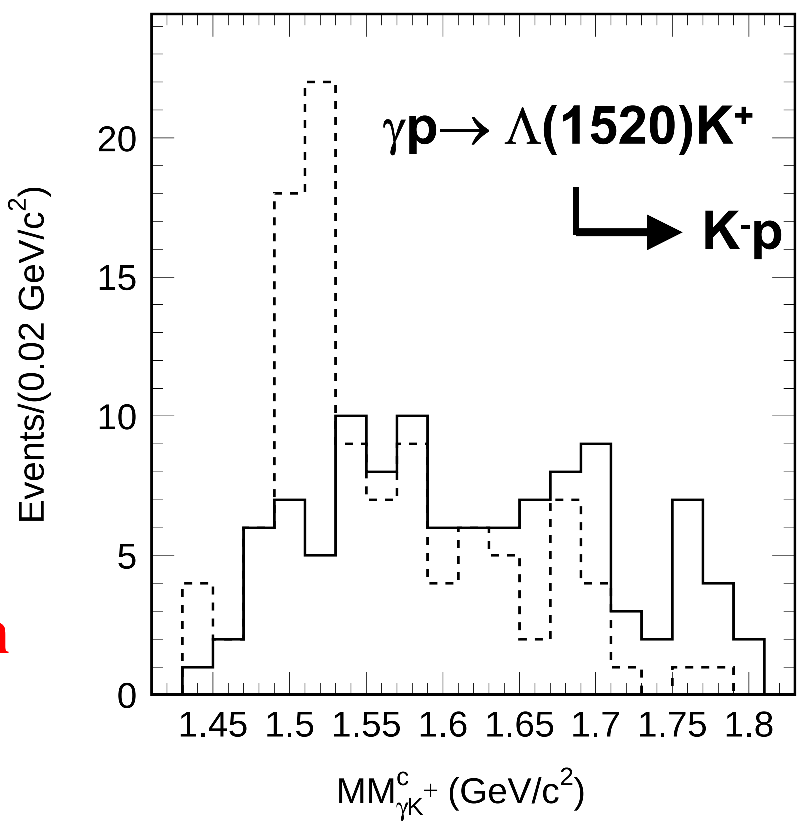
Correction: $MM_{\gamma K+}$ **(corrected)** $= MM_{\gamma K+} - MM_{\gamma K+\pi-} + M_n$

Fermi motion corrected K^+ missing mass

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

$MM^c_{\gamma K+} = MM_{\gamma K+} - MM_{\gamma K+K-} + M_n$

- select KK events from start counter,
- look for a proton in the vertex counter.
  - proton is absent ——————
  - proton is present – – – – – – – –



No Λ(1520) **peak in events with a spectator proton.**

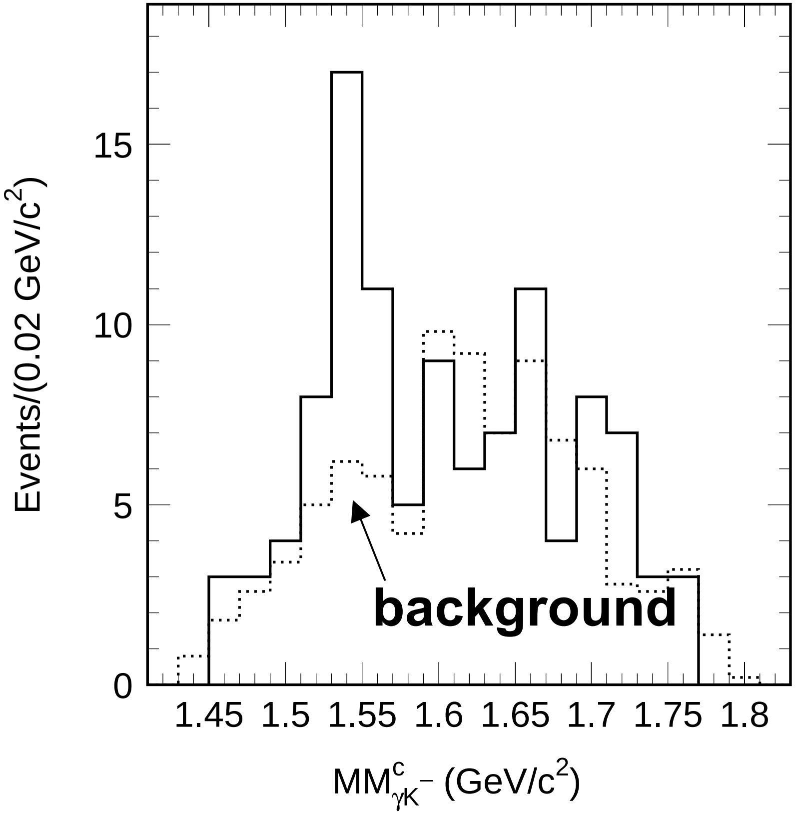
Θ^+ identification

$M = 1.54 \pm 0.01$ MeV
$\Gamma < 25$ MeV
Gaussian significance 4.6σ

Background level is estimated by a fit in a mass region above 1.59 GeV.

Assumption:

- **Background is from non-resonant K^+K^- production off the neutron/nucleus**
- **… is nearly identical to non-resonant K^+K^- production off the proton**



Phys.Rev.Lett. 91 (2003) 012002

hep-ex/0301020

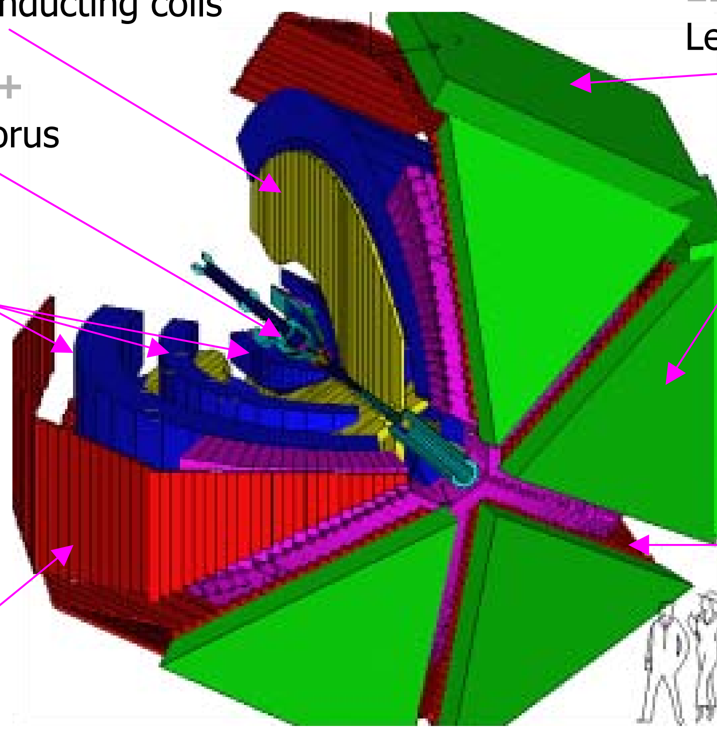
CEBAF Large Acceptance Spectrometer

Torus magnet
6 superconducting coils

Electromagnetic calorimeters
Lead/scintillator, 1296 photomultipliers

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

Drift chambers
argon/CO_2 gas, 35,000 cells



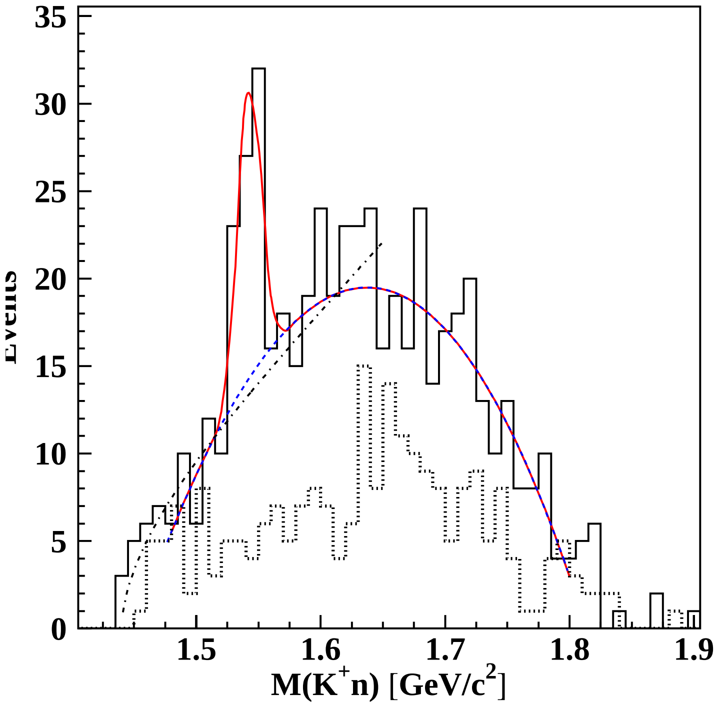
Gas Cherenkov counters
e/π separation, 256 PMTs

Time-of-flight counters
plastic scintillators, 684 photomultipliers

CLAS/JLAB Exclusive process

hep-ex/0307018

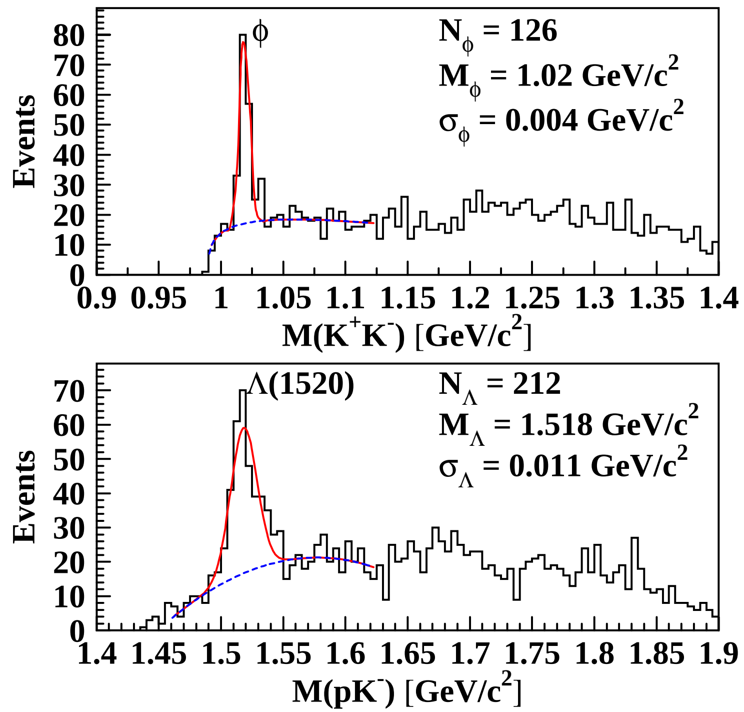
$\gamma\, d \rightarrow p\, K^+\, K^-\, n$



M = 1542±5 MeV

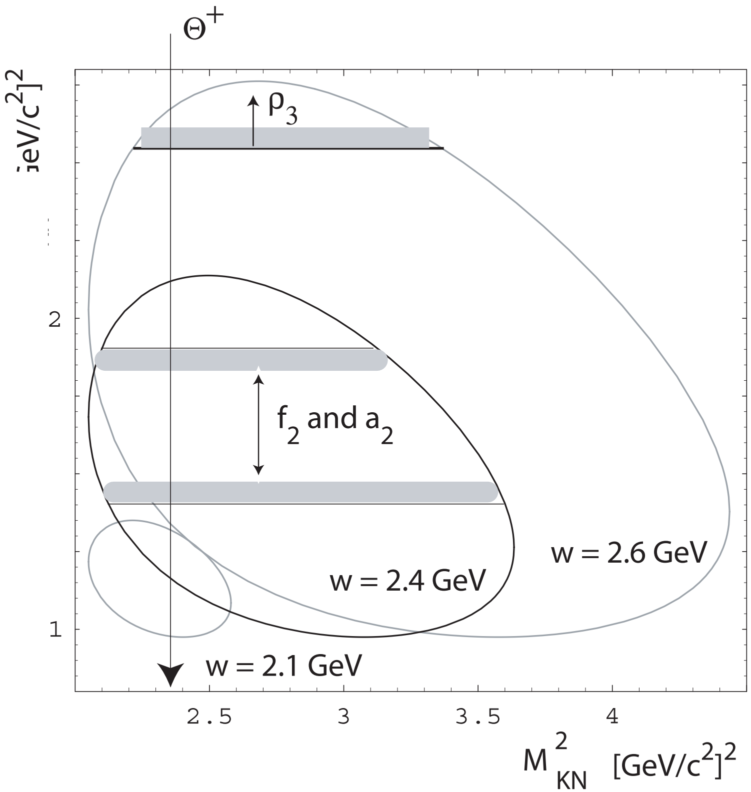
Γ < 21 MeV

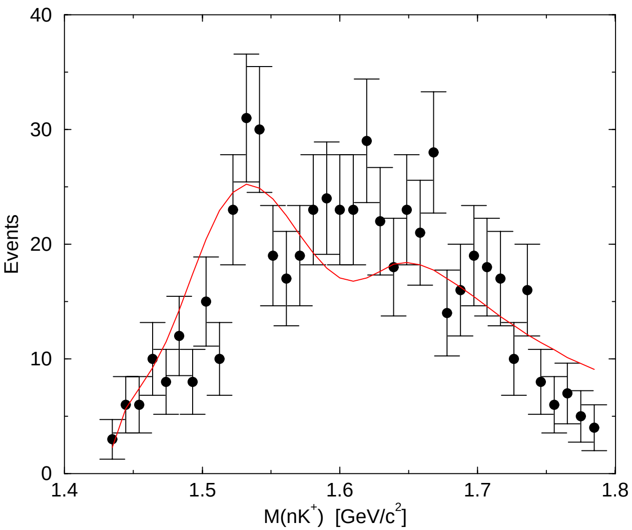
- Detect $K^+ K^- p$
- Reconstruct neutron via missing mass.
- Remove ϕ and $\Lambda(1520)$.

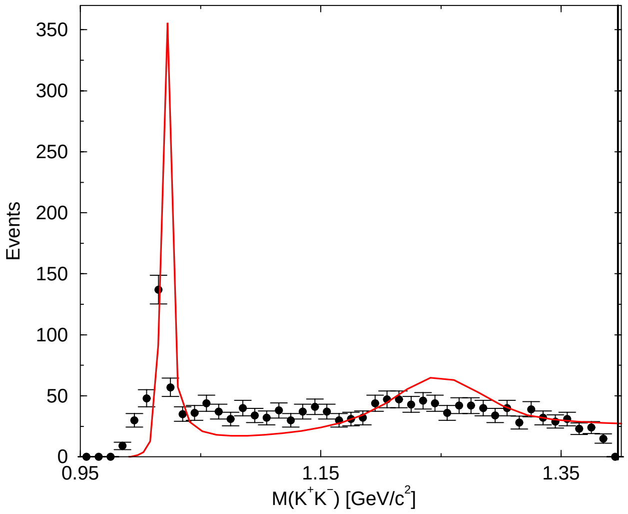


Kinematic reflections

hep-ph/0311125





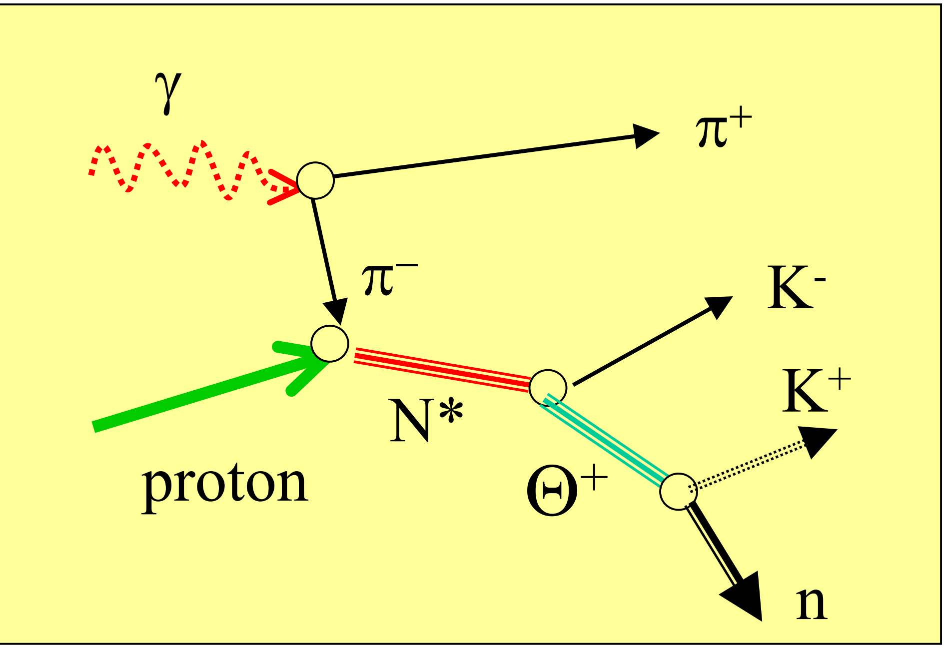


- **Kinematic reflections due to $f_2(1275)$, $a_2(1320)$ and $\rho_3(1690)$ can generate a narrow enhancement in K^+n effective mass.**

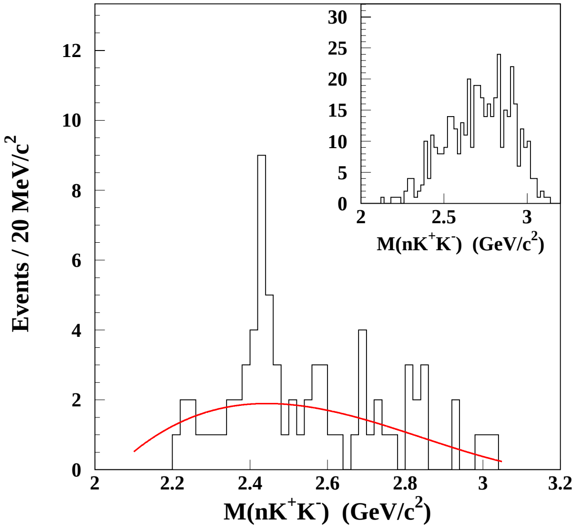
CLAS/JLAB on protons

hep-ex/0311046

$\gamma\, p \rightarrow \pi^{+} K^{+} K^{-} (n)$



- **Detect $K^{+} K^{-} \pi^{+}$**
- **Reconstruct neutron from missing 4-momentum.**
- **Require $\cos\theta_\pi > 0.8$ & $\cos\theta_K < 0.6$**



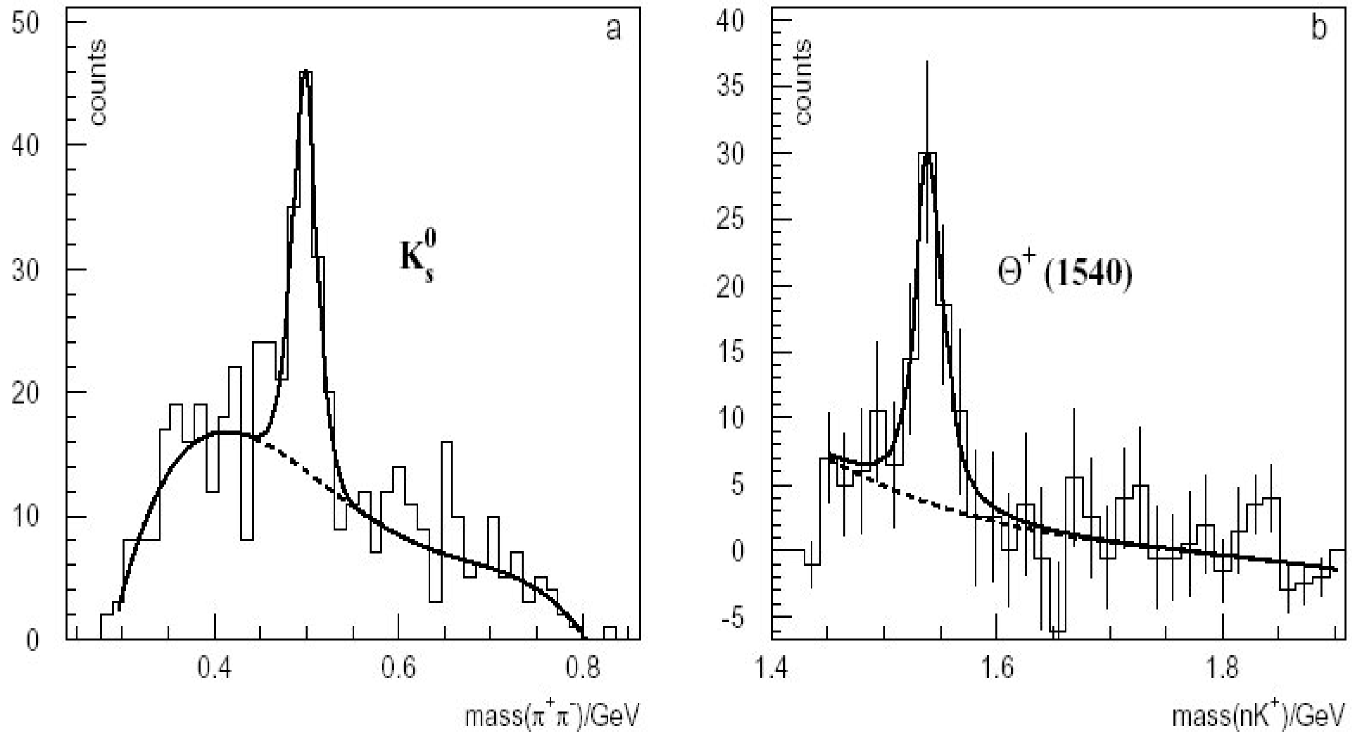
$M = 1555 \pm 1 \pm 10$ MeV

$\Gamma < 26$ MeV

SAPHIR detector at ELSA

hep-ex/0307083

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



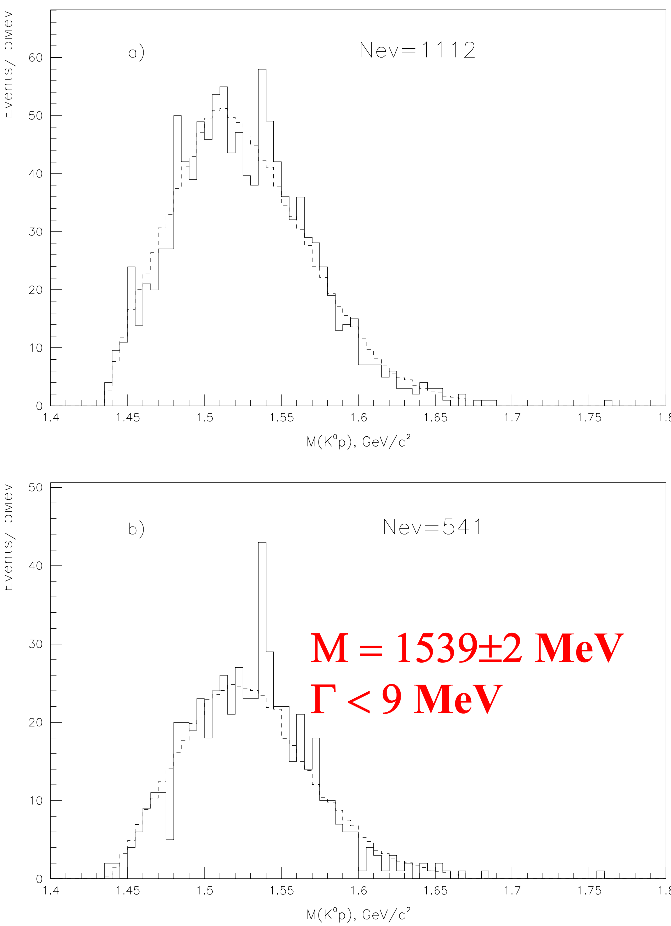
σ ~ 200nb

No evidence for Θ^{++}

CLAS has not seen the signal in this reaction mode.

DIANA/ITEP Result

$K^+ Xe \rightarrow K^0 p X$
$(K^+ n \rightarrow K^0 p)$



hep-ex/0304040

- **P_{K+} < 530 MeV/c**
- **Require θ_K<100deg. & θ_p<100 deg.**
- **Remove cos ϕ_{pK} <0 ← back-to-back**

$K^+ n \rightarrow \Theta^+$ ⟺ $\Theta^+ \rightarrow K^+ n$

$\Gamma = 0.9 \pm 0.3$ MeV

Cahn and Trilling hep-ph/0311245

consistent with KN phase shift analysis by Arndt et. al.

Phys. Rev. C68, 042201(R)

Neutrino scattering

hep-ex/0309042

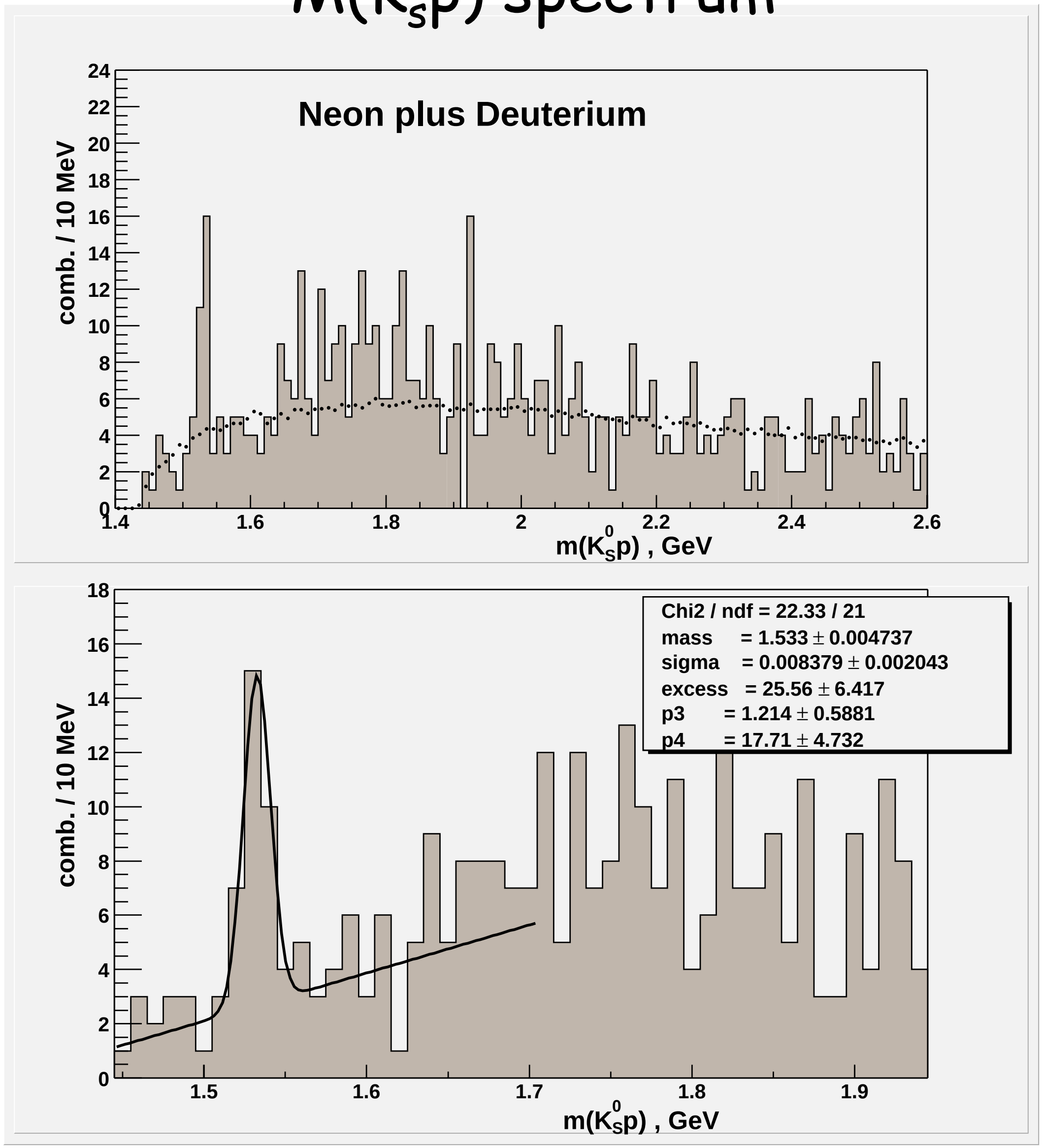
Reanalysis of bubble chamber experiments from WA21, WA25, WA59, E180, E632

M = 1533±5MeV
Γ < 20 MeV

K*(892)$^+$ → Ks π^+ p~291 MeV

IM(Kp(π)) ~ 1.58 GeV

M(K_sp) spectrum

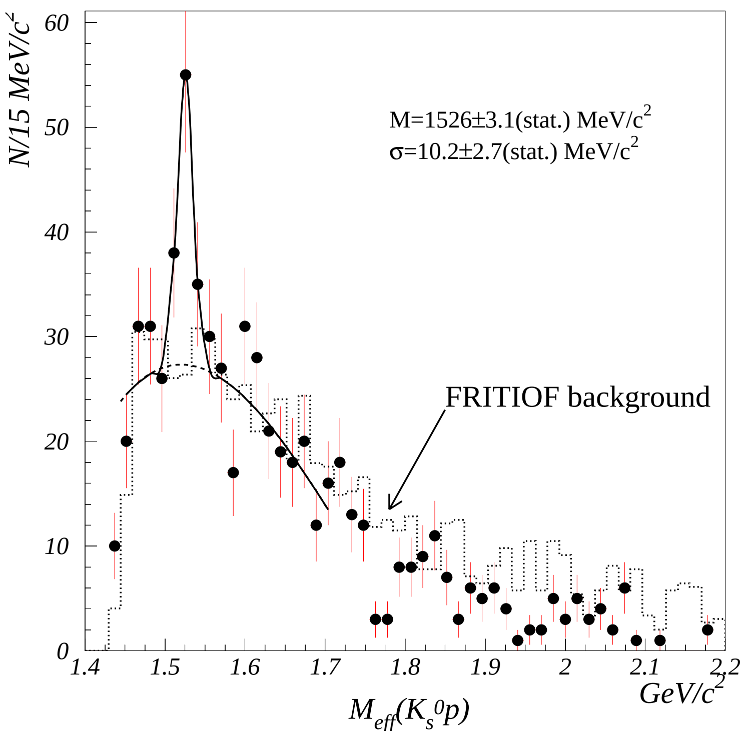


4. Figure Invariant mass of the $K^0_S p$ system for the Neon and Deuterium data combined (top panel). The dots depict the random-star background. A fit of the same $m(K^0_S p)$

SVD/IHEP result

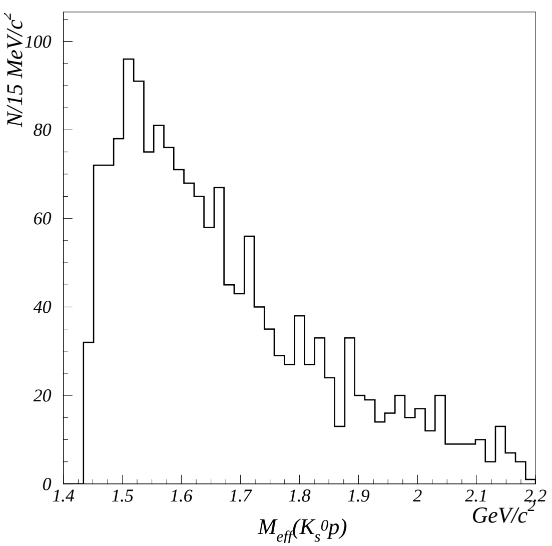
hep-ex/041024

$pA \rightarrow p\ K_s^0 + X$



M = 1526±3 ±3 MeV
Γ < 24 MeV

- **70GeV/c proton beam**
- **pK_s^0 production with a limited multiplicity.**
- **Require cos(α)>0. α: pK_s^0 angle in CM system.**
- **$P_{Ks}<P_p$ to suppress Σ^{*+} events.**



Summary of positive results

Experiment	Θ^+ Mass (MeV)	Γ (MeV)
LEPS/SPring-8	: 1540 ± 10 ± 5	: 25
DIANA	: 1539 ± 2 ± few	: 9
CLAS(d)	: 1542 ± 2 ± 5	: 21
SAPHIR	: 1540 ± 4 ± 2	: 25
ITEP(ν)	: 1533 ± 5	: 20
CLAS(p)	: 1555 ± 1 ± 10	: 26 ± 7
HERMES	: 1528 ± 2.6 ± 2.1	: 19 ± 5 ± 2
ITEP(p)	: 1526 ± 3 ± 3	: 24
ZEUS	: ?	: ?

Questions to be answered

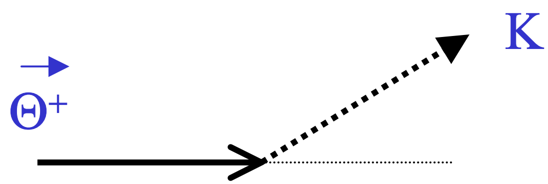
- **To be or not to be?**
- **What is the true mass?**
  - **Ranges from 1526 MeV to 1555 MeV.**
- **How narrow is the width?**
  - **Only upper limits were given.**
  - **Hard to explain if Γ<1 MeV.**
- **What is the Spin and Parity? How to measure?**
  - **$1/2^-$ (Lattice, Quark Model) or $1/2^+$ (Di-quark, Chiral soliton)**
- **Is there $J^+=2/3^+$ partner? Still narrow?**
- **Other members of the anti-decuplet?**

Next things to do

- **Confirmation with high statistics experiment.**
  - New results from LEPS will be available soon.
  - CLAS High Stat. Exp. will start in March.
- **Study other reaction modes.**
  - e^+e^- collider, K^+ beam, p p collision, RHIC,,,
- **Production mechanism.**
- **High resolution exp.**
  - Talks by H. Gao and K. Imai.

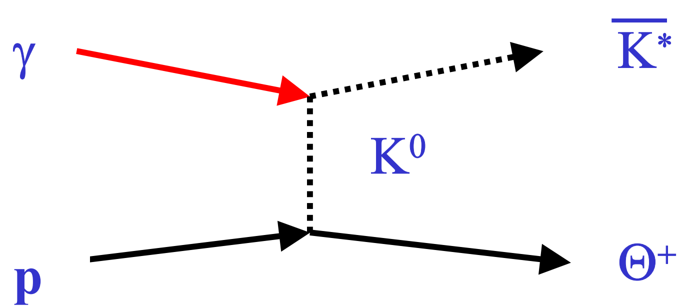
To determine Spin and Parity

- Polarize Θ^+ and measure the K+ direction and the neutron spin.
- Double or triple polarization experiment?



$$\left|\frac{1}{2},+\frac{1}{2}\right\rangle = Y_0^0\left|\frac{1}{2},+\frac{1}{2}\right\rangle$$

$$\left|\frac{1}{2},+\frac{1}{2}\right\rangle = \sqrt{\frac{2}{3}}Y_1^1\left|\frac{1}{2},-\frac{1}{2}\right\rangle - \sqrt{\frac{1}{3}}Y_1^0\left|\frac{1}{2},+\frac{1}{2}\right\rangle$$

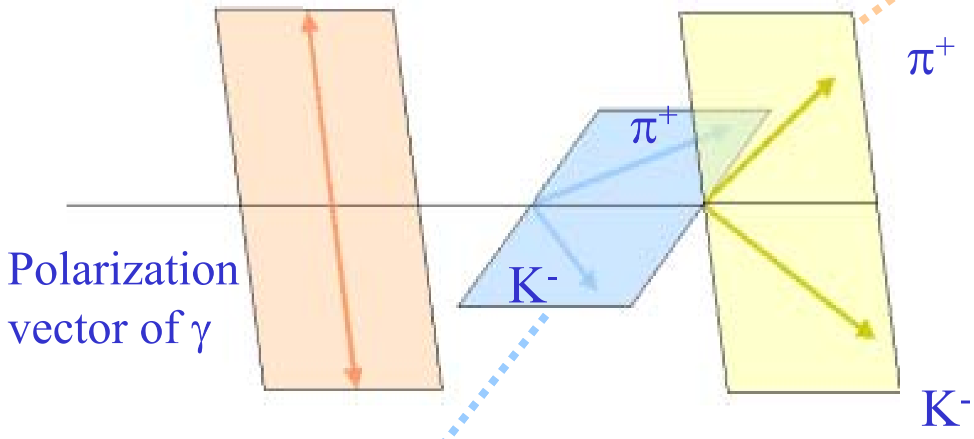


$$Y_1^0 = \sqrt{\frac{3}{4\pi}}\cos\theta$$

$$Y_1^1 = -\sqrt{\frac{3}{8\pi}}\sin\theta e^{i\phi}$$

Photoproducion by linearly polarized photon

In K^* rest frame (Helicity frame)



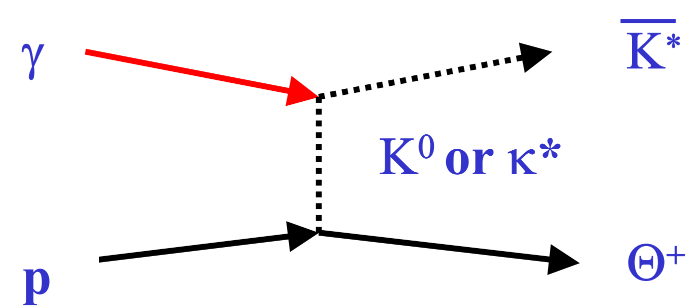
Decay Plane // $\vec{\gamma}$

if natural parity exchange $(-1)^J$

Decomposition of
- natural parity exchange
- unnatural parity exchange

Decay Plane $\perp \vec{\gamma}$

if unnatural parity exchange $-(-1)^J$ (Pseudoscaler mesons)



$\gamma p \rightarrow K^*\Theta^+$ **$E_{th} = 2.65$ GeV**

4π detector **TPC**

Summary

- **Evidence for an S=+1 baryon at 1.54 GeV with a narrow width has been observed by several experimental groups.**
- **"existence ranges from very likely to certain, but further confirmation is desirable"   - "three-star" definition by PDG.**