Pentaquark search at CLAS

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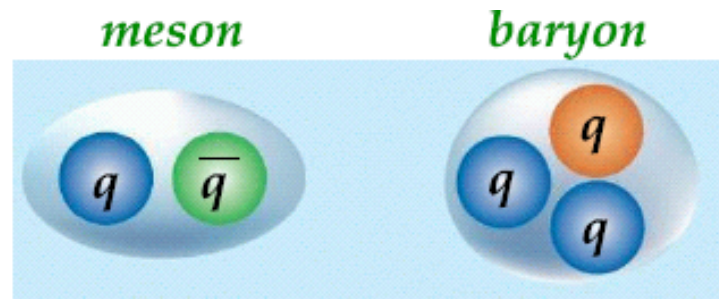

- ❖ **Introduction**
- ❖ **Experimental program at CLAS**
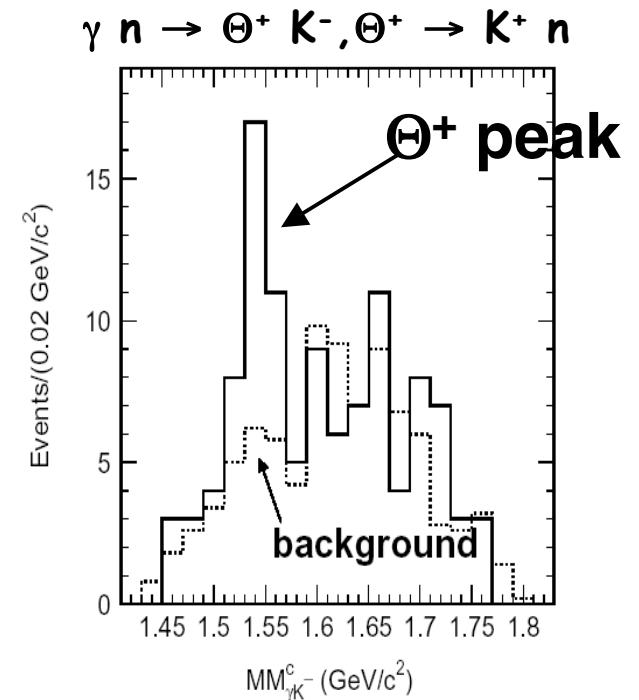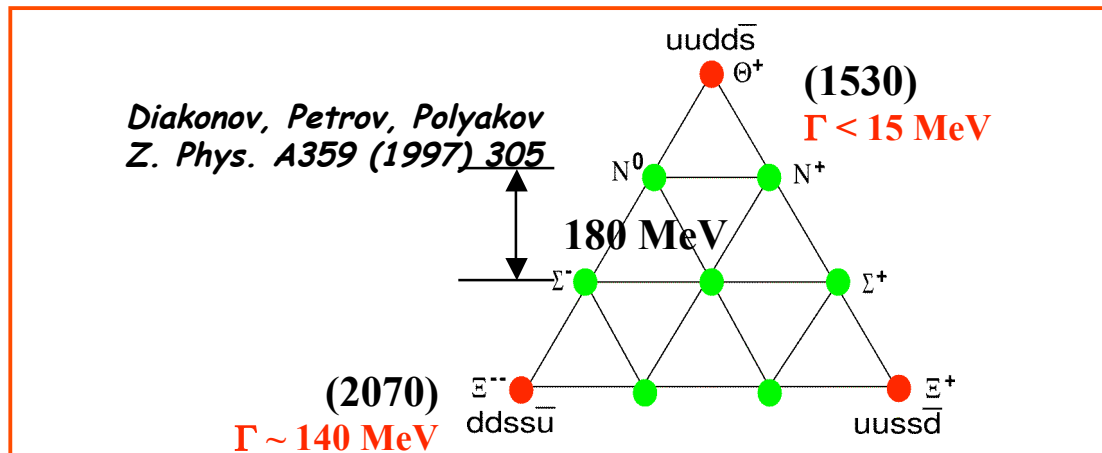- ❖ **Results**
- ❖ **Conclusion**

Introduction

QCD is the underlying theory of the strong interaction but…its realization in hadronic physics is not completely understood

Why do the observed hadrons combine only in two colorless configurations?

In 2003 this did't seem to be anymore true: experimental observation of an "exotic" hadron made of 4 q and 1 anti-q was made by the LEPS col.

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

uudd$\bar{s}$
Θ^+ (1530)
Γ < 15 MeV

180 MeV

N^0 N^+

Σ^- Σ^+

(2070)
Ξ^{--} Ξ^+
Γ ~ 140 MeV   ddss$\bar{u}$ uuss$\bar{d}$

γ n → Θ^+ K$^-$,Θ^+ → K$^+$ n

Θ^+ peak

background

Events/(0.02 GeV/c^2)

MM$^c_{\gamma K^-}$ (GeV/c^2)

Pentaquark experimental results

….over the next year: 10 (almost all) low energy experiments found evidence of a possible Θ^+ pentaquark state

- **different probes/targets**
- **different Labs**
- **high statistical significance reported ($\sigma \geq 4$)**

- **structures have few counts in the peaks**
- **mass discrepancies 1522÷1555 MeV**
- **background shape not known, in some case probably underestimated**
- **some exp. did not tag strangeness**

There were questions about some of these observations but given the weight of positive supporting evidence reported by early 2004, the PDG assigned 3-star status to the Θ^+ in its 2004 edition.

Subsequently 16 high energy experiments did not found any Θ^+ signal

- **different production mechanism**
- **different kinematic region**

No direct contradiction of positive results

- **high statistics**
- **better estimation of background**
- **set upper limits**

Also unclear the existence of the Θ_c^+ , Θ^{++} , Ξ^{--}
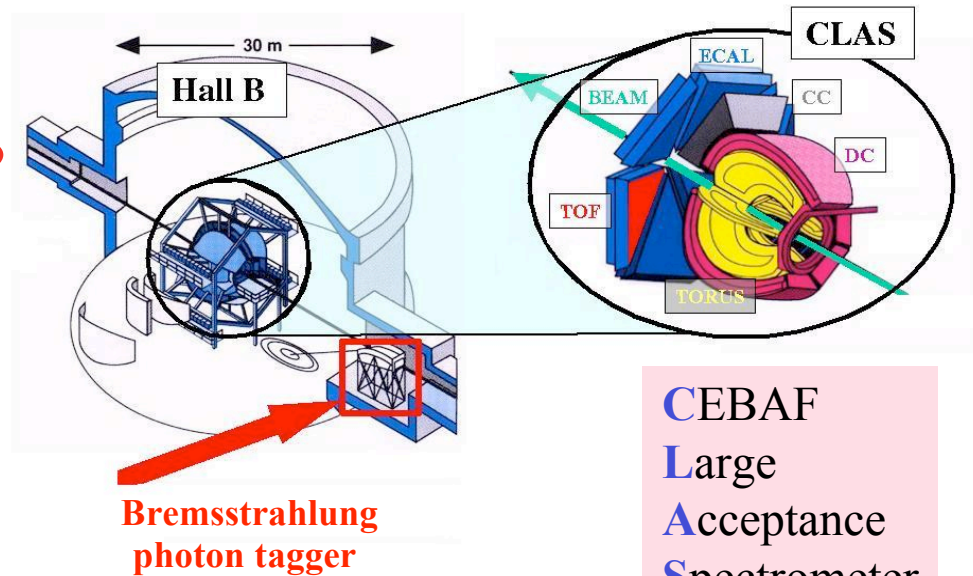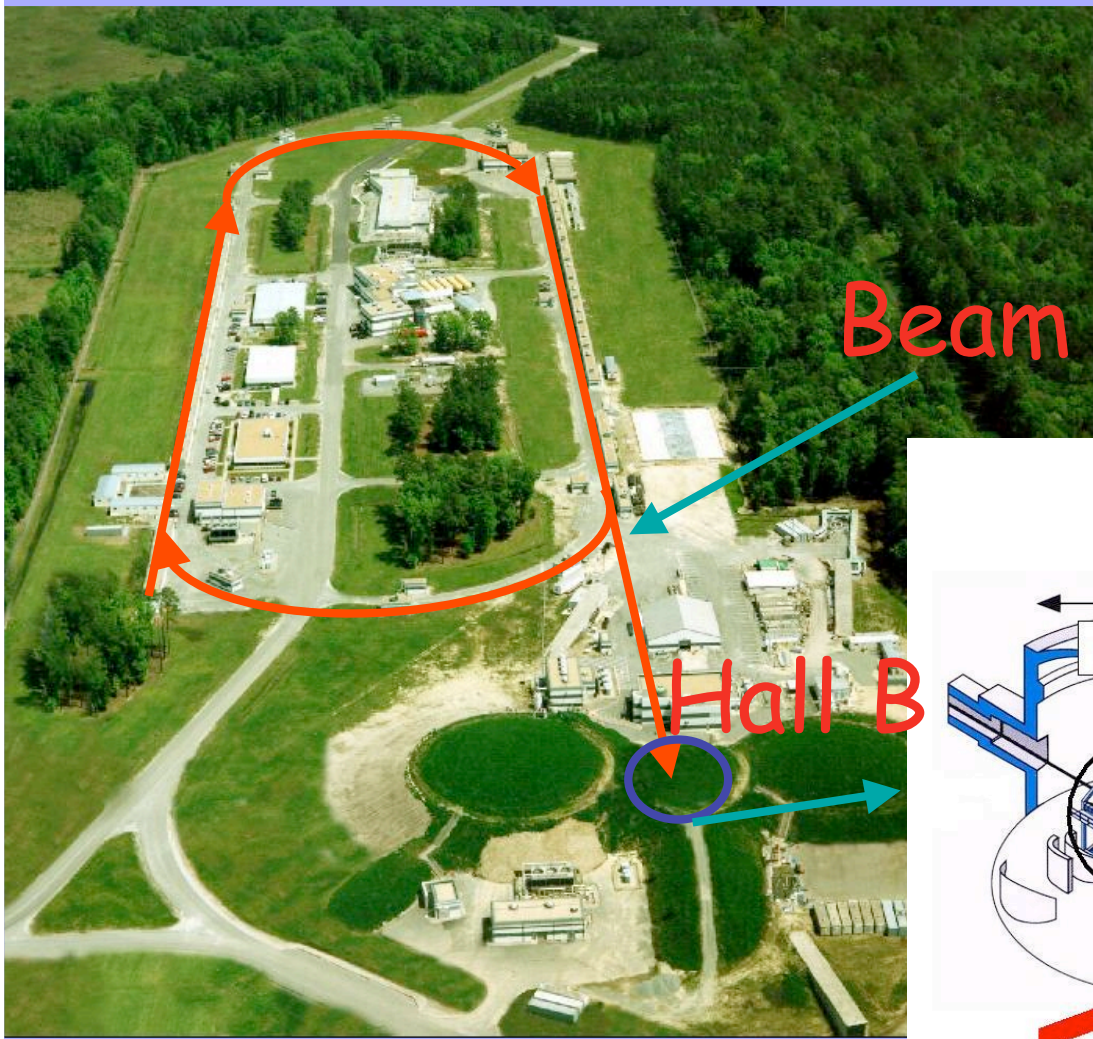
The CLAS program

To try to solve the controversy, JLab and the CLAS Coll. started in 2004 a broad experimental program for pentaquark study with dedicated high statistic and high resolution experiments

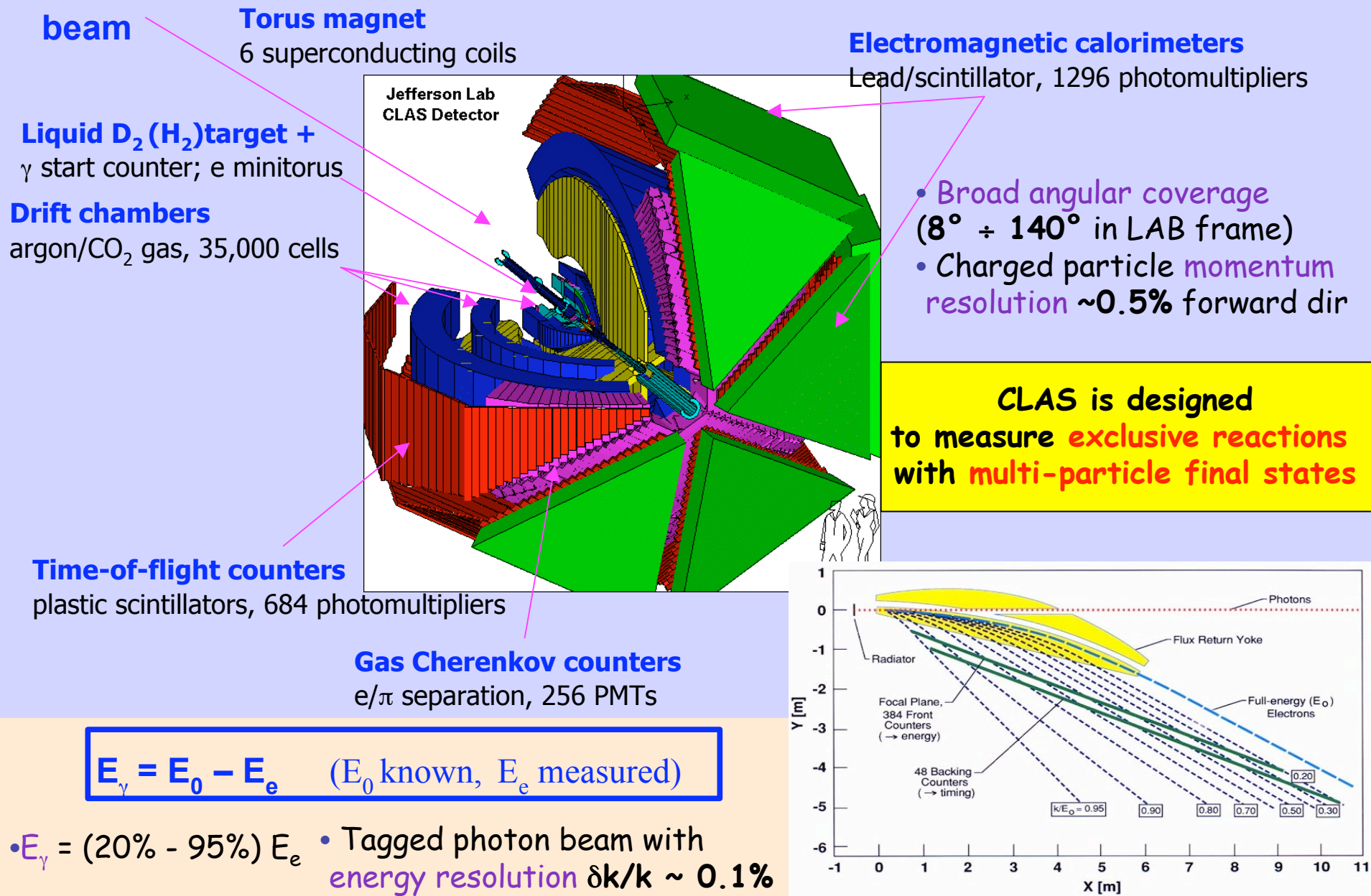| Exp	Target	Reaction	Comment		E_γ	Status
G10	d	$\gamma d \rightarrow pK^- \Theta^+$ $\hookrightarrow K+ n$ $\gamma d \rightarrow pK^- \Theta^+$ $\hookrightarrow K0\ p$ $\gamma d \rightarrow \Lambda(1116)\ \Theta^+$	Test of CLAS(d) data	Θ^+	0.8-3.6	Published in progress Published
G11	p	$\gamma p \rightarrow K^0\ \Theta^+$ $\gamma p \rightarrow K^-\ \Theta^{++}$	test of SAPHIR data (cfr STAR in d+Au)	Θ^+ Θ^{++}	1.6-3.8	Published Published
EG3	d	$\gamma d \rightarrow K^-\ K^+\ \Xi^{--}$	test of NA49 data	Ξ_5	4-5.4	Analysis in progress
SUPER-G	p	$\gamma p \rightarrow K^-\ \pi^+\ \Theta^+$	test of CLAS(p) test of NA49 data	Θ^+ Ξ_5	3.8-5.7	Data to be taken

JLab accelerator CEBAF

Superconducting recirculating electron accelerator

- **Continuous Electron Beam**
- **Energy 0.8-5.7 GeV**
- **200μA, polarization 75-80%**
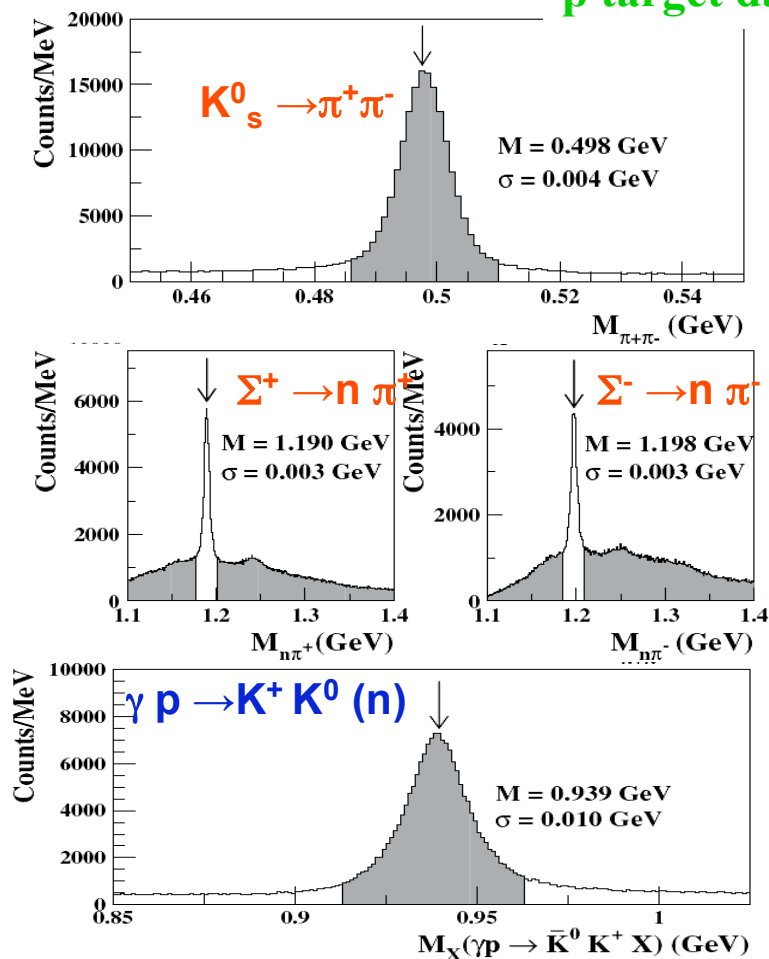- **Simultaneous delivery to 3Halls**

Beam

Hall B

30 m

Hall B

CLAS

ECAL

BEAM

CC

DC

TOF

TORUS

Bremsstrahlung photon tagger

CEBAF
Large
Acceptance
Spectrometer

Hall B: Cebaf Large Acceptance Spectrometer + Tagger

beam

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

Jefferson Lab
CLAS Detector

- Broad angular coverage
  (**8° ÷ 140°** in LAB frame)
- Charged particle momentum
  resolution **~0.5%** forward dir

**CLAS is designed
to measure exclusive reactions
with multi-particle final states**

Time-of-flight counters
plastic scintillators, 684 photomultipliers

Gas Cherenkov counters
e/π separation, 256 PMTs

$$E_\gamma = E_0 - E_e \quad (E_0 \text{ known, } E_e \text{ measured})$$

- E_γ = (20% - 95%) E_e
- Tagged photon beam with
  energy resolution $\delta k/k \sim$ **0.1%**

CLAS particle ID

p target data

$K^0_s \rightarrow \pi^+ \pi^-$

M = 0.498 GeV
σ = 0.004 GeV

$\Sigma^+ \rightarrow n \pi^+$

M = 1.190 GeV
σ = 0.003 GeV

$\Sigma^- \rightarrow n \pi^-$

M = 1.198 GeV
σ = 0.003 GeV

$\gamma p \rightarrow K^+ K^0 (n)$

M = 0.939 GeV
σ = 0.010 GeV

d target data

$\Lambda \rightarrow p \pi^-$

M=1.115 GeV
σ=1.7 MeV

M=1.019 GeV
σ=3.6 MeV

$\phi \rightarrow K^+ K^-$

$\gamma d \rightarrow K^+ p (\Sigma^-)$

M=1.196 GeV
σ=6.9 MeV

M=938.3 MeV
σ=9.9 MeV

$\gamma d \rightarrow p K^+ K^- (n)$
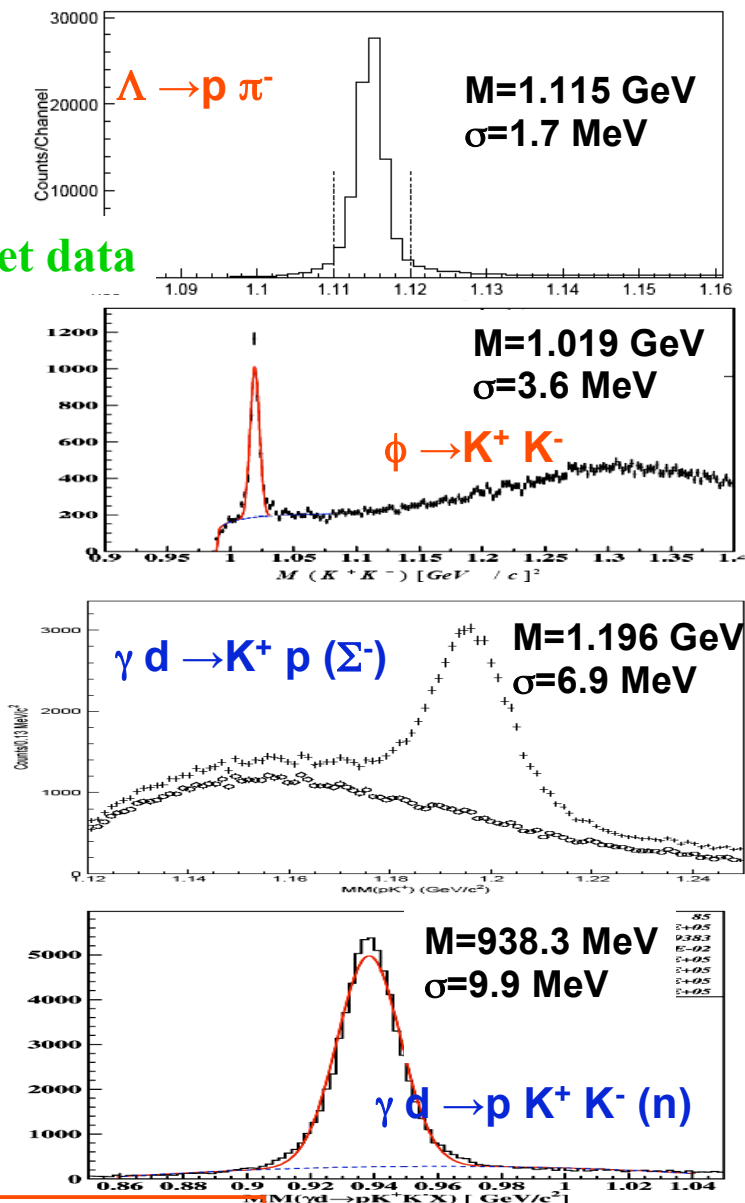
**CLAS measures masses at the level of 1-2 MeV
Resolution: few MeV for invariant masses
                    10 MeV for missing masses**

γd → Θ⁺ p K⁻

$\gamma d \rightarrow \Theta^+ p K^-$
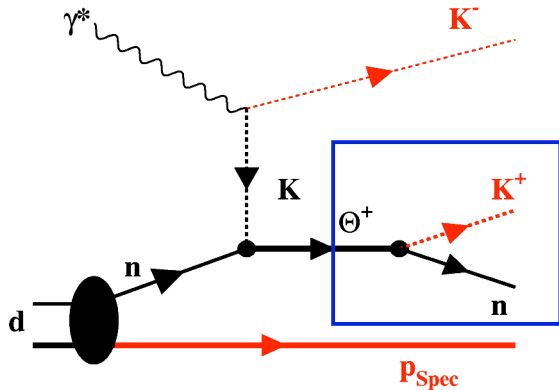
♣ **3 charged particles detected**
♣ **neutron detected by missing mass cuts**
♣ **P_n >0.2 GeV/c**
♣ **φ and Λ* background removed**
♣ **Some FSI is needed in order the spectator proton get high momentum p>0.35 GeV/c**
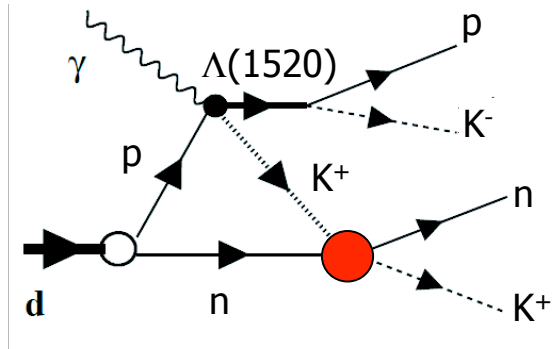

Acceptance corrected
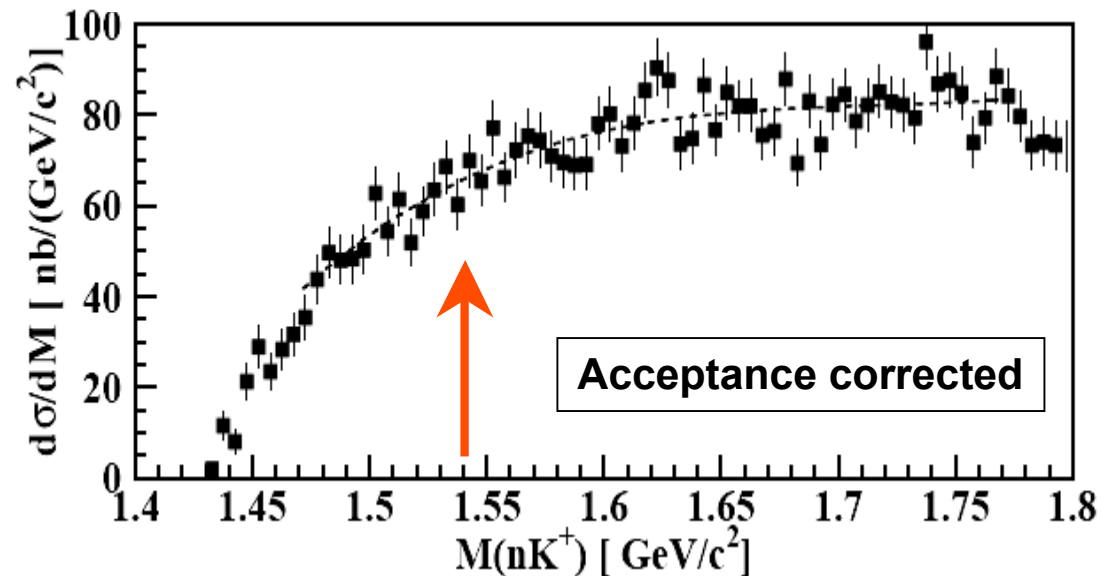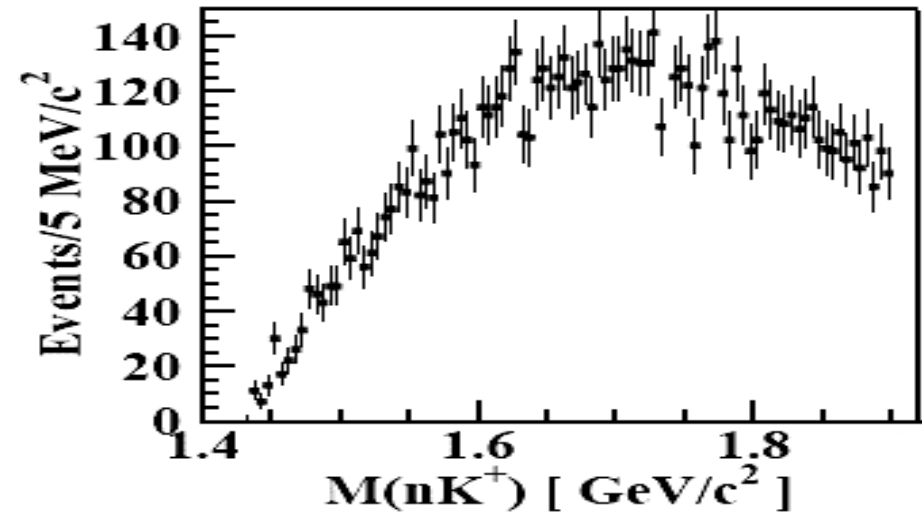
- **The nK+ mass spectrum is smooth**
- **No structures found around 1540 MeV**

G10: Upper limit on the elementary cross section $\gamma n \rightarrow \Theta^+ K^-$
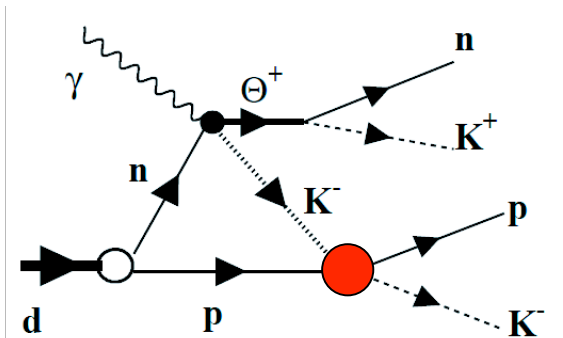
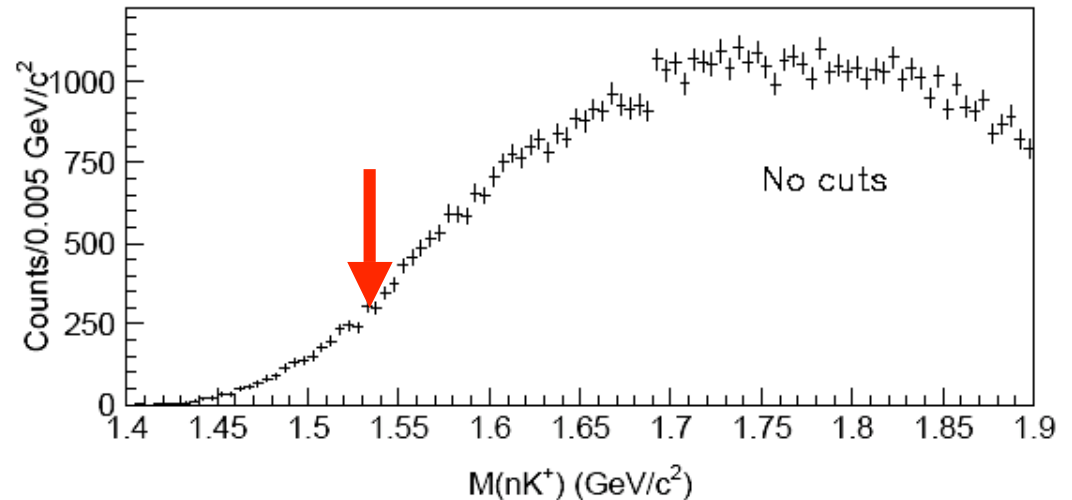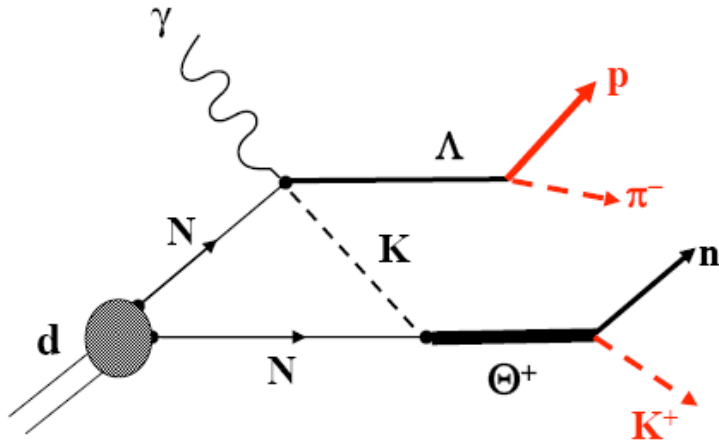Θ^+ is produced on the neutron, proton is a spectator.

Λ(1520) is produced on the proton, neutron is a spectator.

Fermi momentum distribution

G10 (3375A)

$R = \sigma(P_n)/\sigma tot$

P_n cut (GeV/c)
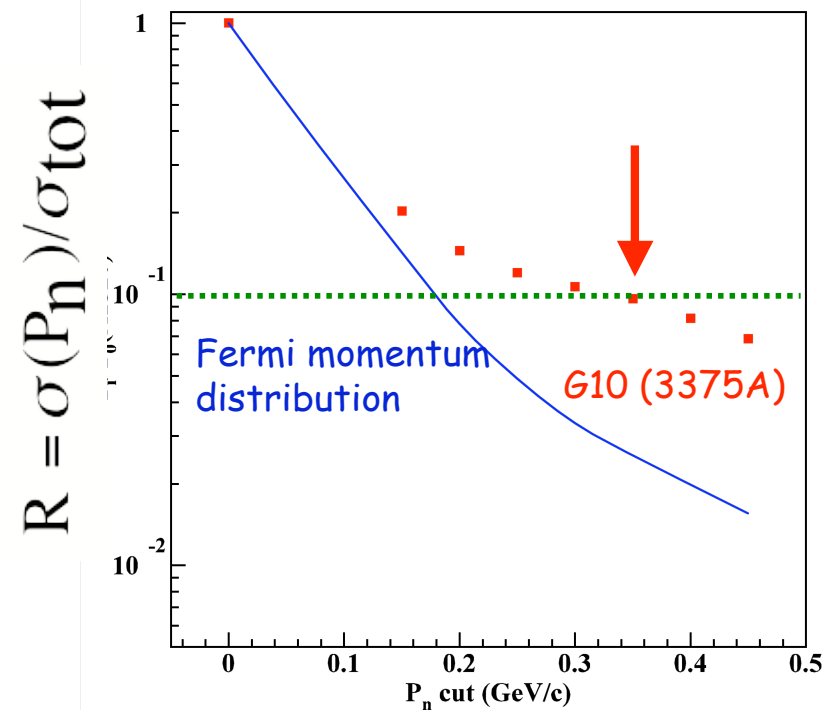
Correction factor ≈ 10 on the elementary cross section

$\gamma d \rightarrow \Theta^+ \Lambda$

♣ **No possible kinematic reflections from meson production → KK** (unlike pK^+K^-n or pK^0K^-p only **one K**, from Θ^+ decay, in the final state)

♣ **"Clean" reaction: no background channels to remove**

♣ **Strangeness tagged by Λ: $S=+1$**

♣ **Small cross section**
♣ **Low detection efficiency**
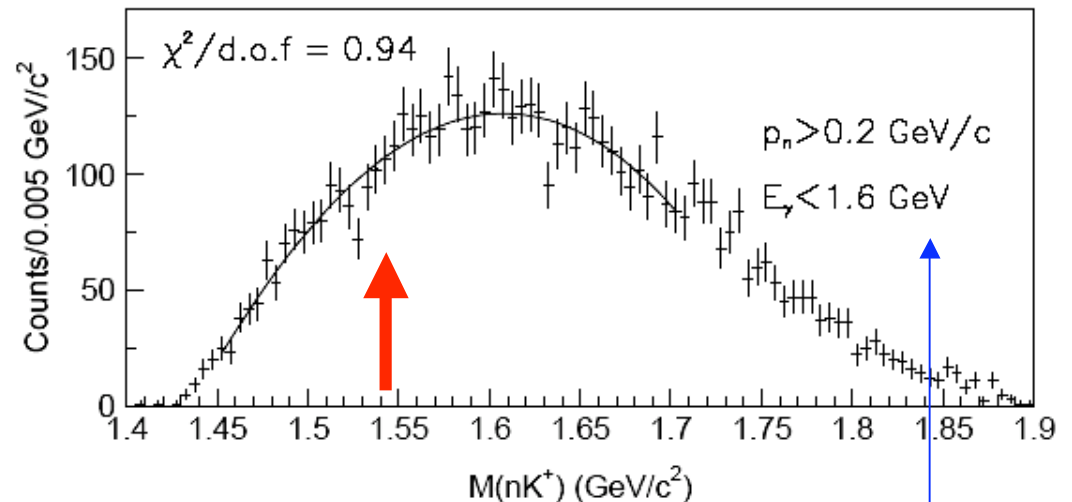
Cuts suggested by Guzey PRC 69, 065203 (2004)

No structures found around 1540 MeV

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

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

$\bar{K}^0 \Theta^+ \rightarrow \pi^+ \pi^- K^+ (n)$

✿3 charged particles detected
✿neutron by missing mass
✿subtraction of hyperon production ($\Lambda(1520)$, $\Sigma^\pm$)
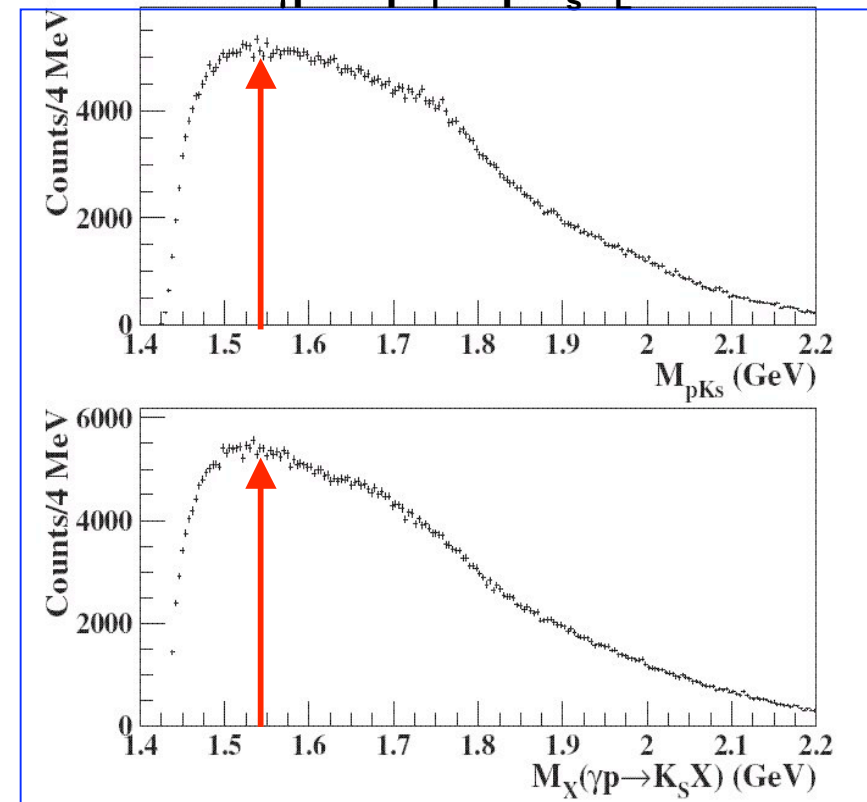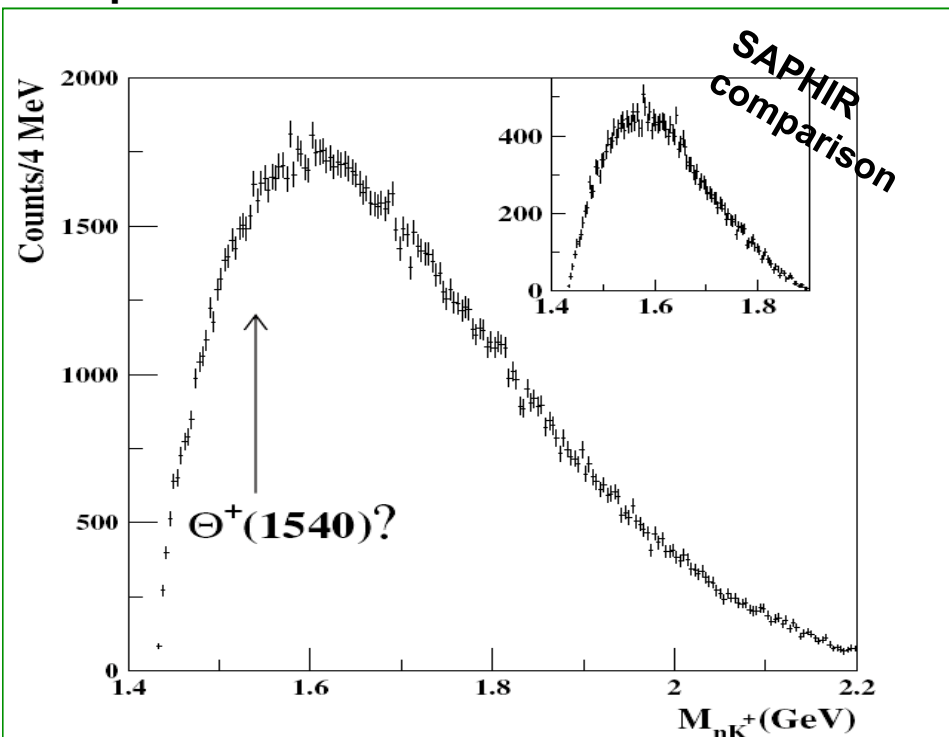✿different kinematic cuts for comparison with SAPHIR data
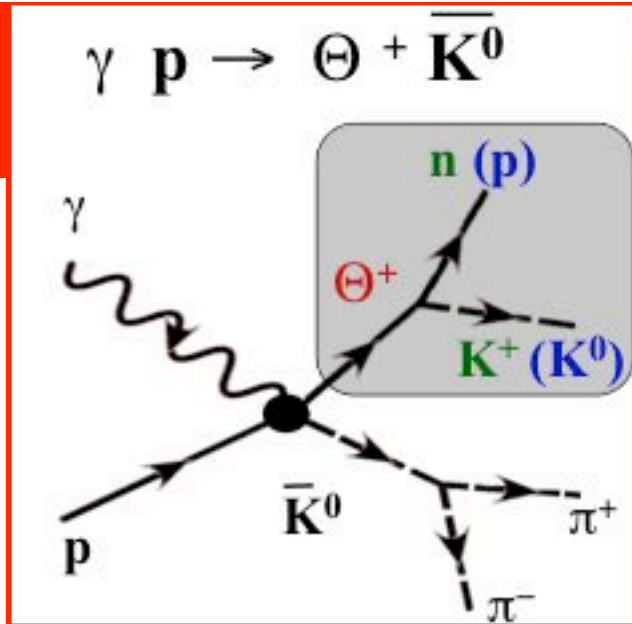
$\bar{K}^0 \Theta^+ \rightarrow \pi^+ \pi^- p (K^0)$

✿One K^0 detected via its $K_s \rightarrow \pi^+ \pi^-$
✿Final state identified using missing mass
✿Detected K_s can be either from Θ^+ or from K^0
✿Background of hyperons decaying in the same final state rejected:
$\gamma p \rightarrow \Lambda(1115) \pi^+ X$
$\gamma p \rightarrow p \phi \rightarrow p K_s K_L$

SAPHIR comparison

$\Theta^+(1540)$?

M_{nK^+}(GeV)

M_{pKs} (GeV)

$M_X(\gamma p \rightarrow K_S X)$ (GeV)

Θ⁺⁺ search

- ✿ **Antidecuplet predicts I=0 ; in 27-plet I=1**

- ✿ **For Capstick et al., Θ⁺ is a member of an isotensor multiplet Θ⁻ Θ⁰ Θ⁺ Θ⁺⁺ Θ⁺⁺⁺**

- ✿ **STAR found strong evidence (4.2 σ) for Θ⁺⁺ in d+Au collisions with M=1528 MeV**
- ✿ **SAPHIR,CLAS,HERMES,ZEUS,… did not found any signal in pK⁺ mass spectra**
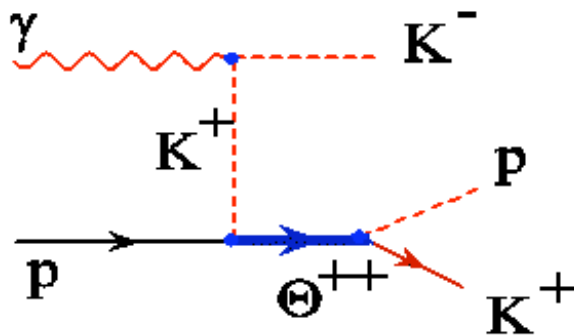
▶ **2 topologies::**

   ▶ **all three particles detected in CLAS**

   ▶ **p K+ detected and K- reconstructed via missing mass technique**

▶ **Removal of the Λ(1520) and φ(1020)**
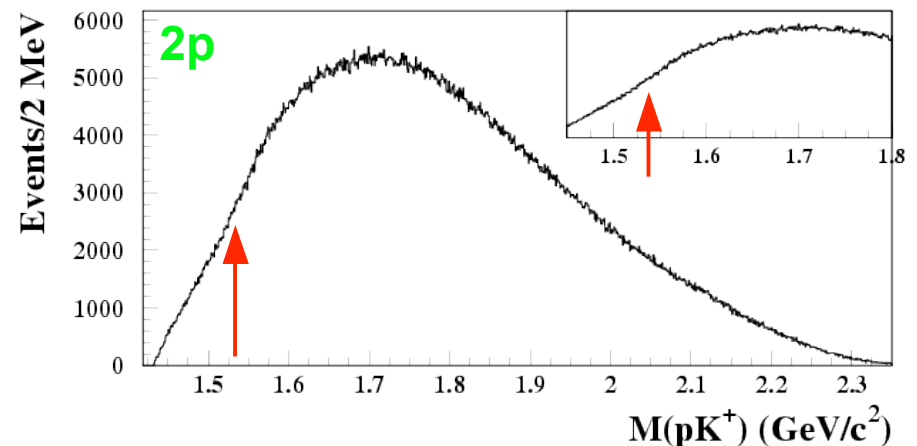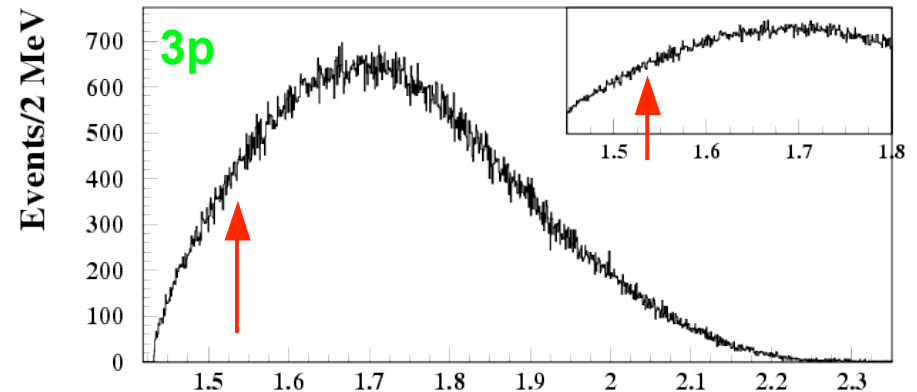
# $\gamma p \rightarrow K^0 \Theta^+$: cross section UL

Yield

- ✿ Θ^+ signal searched for as narrow resonance over a smooth background in the (nK^+) and (pK_s) spectrum

- ✿ Resonance width inferred from MC simul., assuming a negligible intrinsic width

- ✿ Background described as 5th order pol.

- ✿ Signal and background yields extracted fitting:

  - ✿ binned/unbinned spectra (χ^2, likel., window fit)
  - ✿ including/excluding Θ^+ mass region

- ✿ Mass range (1520-1600 MeV) scanned in 5 MeV steps

- ✿ Upper limit derived using Feldman and Cousins approach

Efficiency

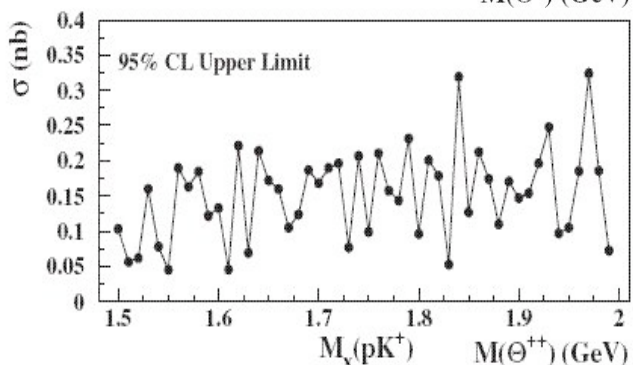CLAS detection efficiency evaluated using different $\Theta+$ production model

Pentaquark @ CLAS
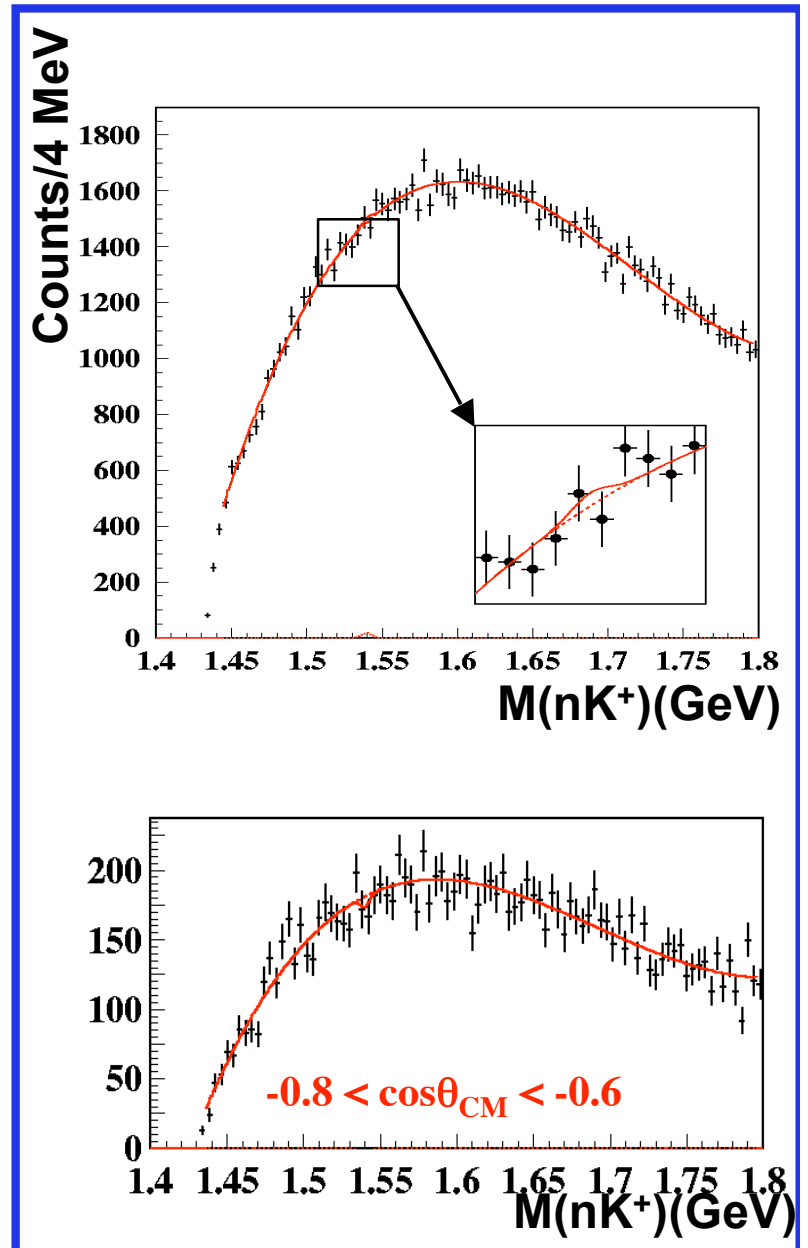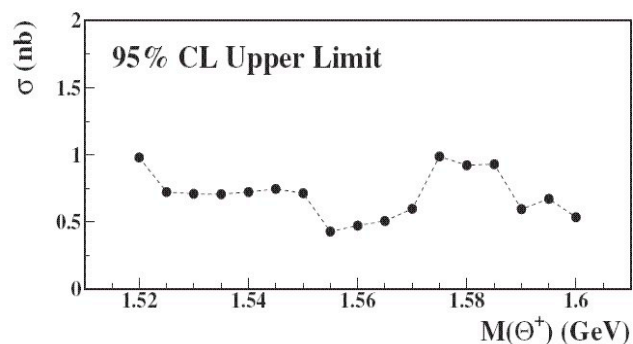
UPPER LIMIT σ **(95%CL)**
1.52 < M(Θ^+) < 1.56 GeV

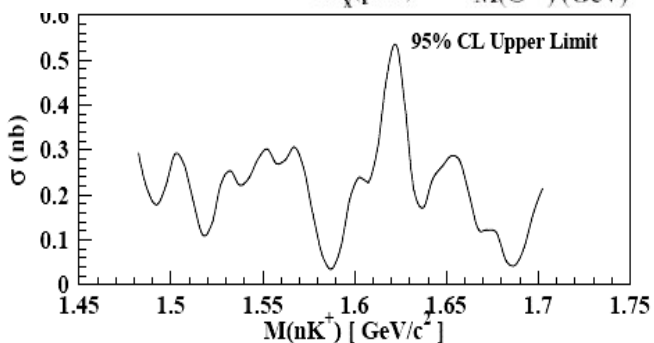$\sigma\,(\gamma p \rightarrow \Theta^+ \bar{K}^0)$ **< 1 nb**
PRL 96, 042001 (2006)
PRD 74, 032001 (2006)

$\sigma(\gamma p \rightarrow \Theta^{++} K^-)$ **< 0.15 nb**
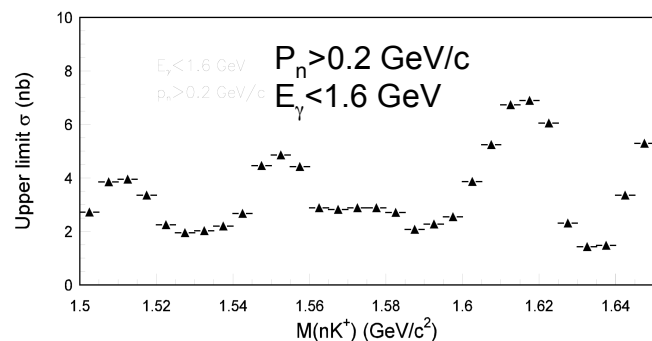PRL 97, 102001 (2006)

$\sigma(\gamma n \rightarrow K^- \Theta^+)$ **< 3nb** Correction factor ≈10
dependent on the rescattering model used
PRL 96, 212001 (2006)

$\sigma(\gamma d \rightarrow \Lambda \Theta^+)$ **< 5 nb**
PRL 97, 032001 (2006)

Where we are now…..

ORIGINAL EXPERIMENT

REPEATED MEASUREMENT

Exp	Reaction	σ	Exp	Reaction	Stat X	Results
CLAS	$\gamma d \to pnK^- K^+$	~5	CLAS	$\gamma d \to pnK^- K^+$	>6	σ_{TOT} < 3 nb
SAPHIR	$\gamma p \to K^0 K^+ n$	~5	CLAS	$\gamma p \to K^0 K^+ n$	>10	σ_{TOT} < 1 nb
HERMES	$e+d \to pK^0 X$	~4	BaBar	$e+Be \to pK^0 X$	>100	No Θ^+
DIANA	$K^+ Xe \to pK^0 X$	~4	Belle	$K^+ Si \to pK^0 X$	~10	No Θ^+; Γ_{Θ^+} < 1 MeV
DIANA	$K^+ Xe \to pK^0 X$	~4	DIANA	$K^+ Xe \to pK^0 X$	~2	σ 4.3–7.3
LEPS	$\gamma C \to K^+ K^- X$	~4	LEPS	$\gamma d \to K^+ K^- X$	~5	~3-5 σ
SVD-2	$pA \to K^0 pX$	~5-6	SVD-2	$pA \to K^0 pX$	~3-4	~8 σ

WORK IN PROGRESS

Exp	Reaction	σ	Comment
ZEUS	$e+p \to pK^0 X$	~4-5	Analysis of new data with improved vertex det
COSY	$pp \to K^0 p\Sigma^-$	~5	Analysis of new data with 5X statistics
CLAS	$\gamma p \to \pi^+ K^- K^+ n$	~7-8	Run in 2008
CLAS	$\gamma d \to K^- K^+ \Xi^{--}$	~4 (by NA49)	Analysis in progress

CLAS on deuteron: where were we wrong?

Uncertainty in the background shape perhaps not adequately reflected in the large confidence level claimed
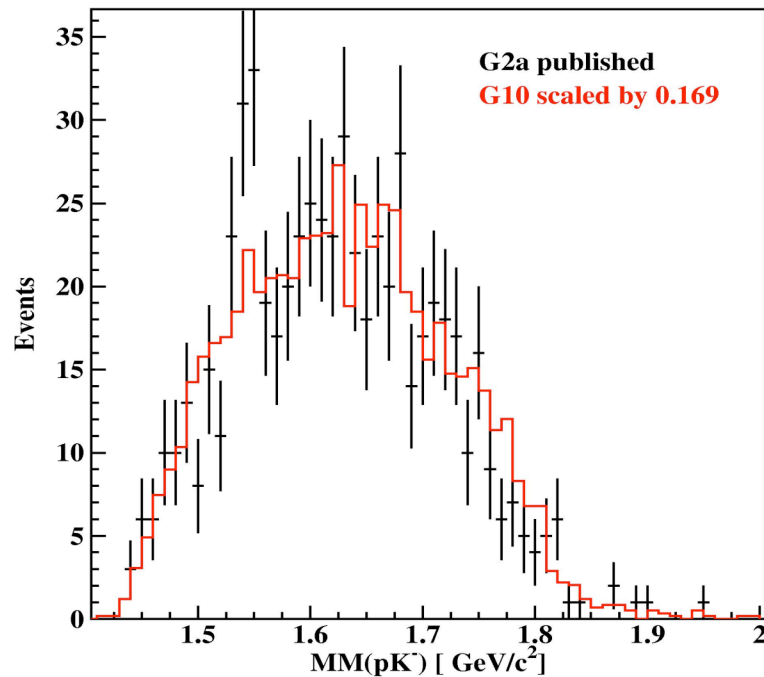
➤ Two distributions statistically consistent with each other

➤ G10 mass distribution used as a background for refitting the published spectrum.
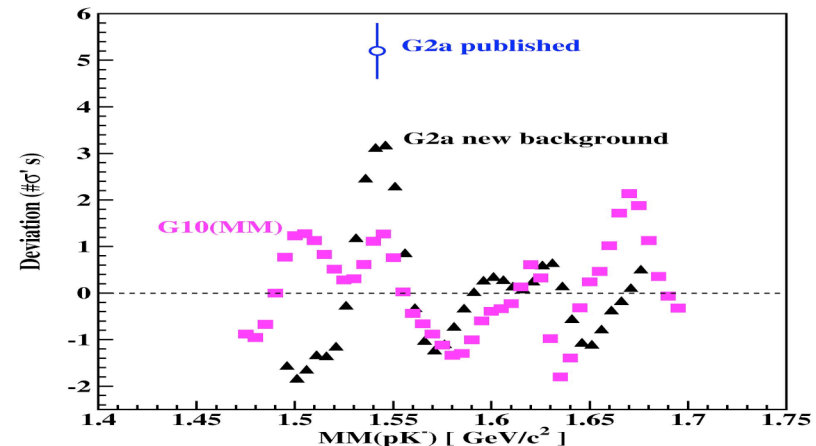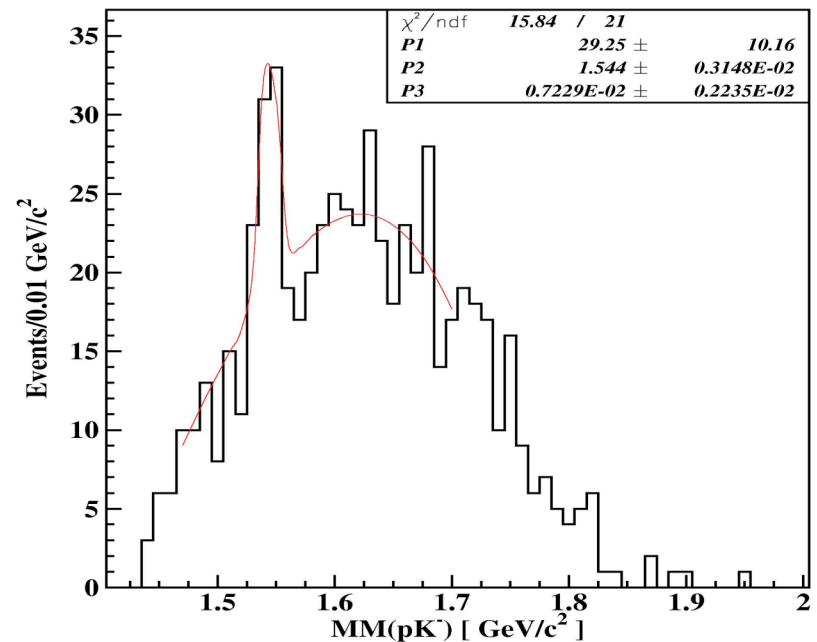
Are we at the end of the story ?

S.I. Nam, A. Hosaka, H.-C. Kim Phys. Lett. B633 (2006) 483

If Θ^+ has spin-parity $3/2^\pm$ production rate for the proton target is significantly suppressed as compared to that of the neutron
→ negative evidence from CLAS on proton target and positive from LEPS on deuteron taget are not inconsistent (BUT: CLAS didn't find any signal <u>neither on proton nor on neutron</u> in HIGH STATISTICS experiment !!)

Guzey hep-ph/0608129

In the $\gamma\mathbf{d} \rightarrow \mathbf{\Lambda nK^+}$ the Θ^+ signal disappears after the integration over p_n as a result of the cancellation between the interference and signal contributions
→ Consistence of the CLAS conclusion that no structures were observed
→ No disagreement between the theory and the experiment and the CLAS result does not refute the existence of the Θ^+

M. Amarian, D. Diakonov, M. Poliakov hep-ph/0612150

They suggest to look for the Θ^+ production in interference with a known resonance yielding the same final state but having a high production rate
CLAS g11 (proton) data are being re-analyzed following this approach

Conclusions

- In 2004, a comprehensive program to search for pentaquarks in high statistic and high resolution experiments have been started by the CLAS Collaboration at Jefferson Lab

- No evidence for pentaquark signals have been found in the 4 photoproduction channels studied so far

- From these results, CLAS set upper limit on production cross sections on proton and neutron of the order of few nb or less

- The outlook for the Θ^+ looks bleak, anyhow it seems we have to wait a little bit more to put the last word on the pentaquark existence:
    - the data are still contradictory (LEPS has been able to reproduce a peak in a "repeat" measurement)
    - analysis, using higher statistics data, from some experiments that initially claimed the pentaquark, are still in progress (ZEUS, COSY)
    - some theories are able to explain the negative results obtained by CLAS

- In the meantime…..

 The PDG assigned 1-star status to the Θ^+ in its 2006 edition

Support slides

Positive Results

LEPS PRL 91(2003) 012002	$\gamma C_{12} \to K^- K^+ n$ $\quad \Theta^+$ $K^+ n$	**SVD** hep-ex/0401024	$pA \to K^0 pX$ $\quad \Theta^+$ $K^0 p$
CLAS PRL 91(2003) 252001 PRL 92(2004) 032001	$\gamma d \to K^+ K^- np$ $\quad \Theta^+$ $\gamma p \to K^+ K^- n\pi^+$ $\quad K^+ n$	**ITEP (ν)** Phys. Atom. Nucl. 67 (2004) 682	$\nu A \to K^0 pX$ $\quad \Theta^+$ $K^0 p$
SAPHIR Phys. Lett. B572(2003)127	$\gamma p \to K^0 K^+ n$ $\quad \Theta^+$ $K^+ n$	**JINR** hep-ex/0403044 hep-ex/0404003 hep-ex/0410016	$p+C_3H_8 \to K^0 pX$ $\quad \Theta^+$ $np \to npK^+K^-$ $\quad K^0 p$
DIANA Phys. Atom. Nucl. 66 (2003) 1715	$K^+ Xe \to K^0 pXe'$ $\quad \Theta^+$ $K^0 p$	**NOMAD** Talk@neutrino 2004 Conference	$\nu C \to K^0 pX$ $\quad \Theta^+$ $K^0 p$
HERMES Phys. Lett. B585(2004)213	$\gamma^* d \to K^0 pX$ $\quad \Theta^+$ $K^0 p$	**NA49** PRL 92(2004) 042003	$pp \to \Xi \pi X$ $\quad \Xi_5$
ZEUS Phys. Lett. B591(2004)7	$ep \to PX$ $\quad \Theta^+$ $K^0 p$	**H1** Phys. Lett. B588(2004)17	$ep \to PX$ $\quad \Theta_c$
COSY Phys. Lett. B595(2004)127	$pp \to K^0 p\Sigma^+$ $\quad \Theta^+$ $K^0 p$	**STAR** hep-ex/0406032	$N_5 \; \Xi^0_5$
		GRAAL Talk@penta2004 Conf	N_5

Negative Results

CDF hep-ex/0408025 hep-ex/0410024	ppbar → PX	Θ^+ Θ_c Ξ_5	**ALEPH** Phys. Lett. B599(2004)1	Hadronic Z decays	Θ^+ Θ_c Ξ_5
HyperCP PRD 70 (2004) 111101	$(\pi^+,K^+,p)Cu \to PX$	Θ^+	**DELPHI** hep-ex/0410080	Hadronic Z decays	Θ^+
SELEX Quark Confinement 2004	$(\pi,p,\Sigma)p \to PX$	Θ^+	**L3** hep-ex/0410080	$\gamma\gamma \to \Theta\bar{\Theta}$	Θ^+
FOCUS hep-ex/0412021	$\gamma p \to PX$	Θ^+ Θ_c Ξ_5	**WA89** PRC 70 (2004) 022201	$\Sigma^-N \to PX$	Ξ_5
E690 Quark Confinement 2004	$pp \to PX$	Θ^+ Ξ_5	**ZEUS** hep-ex/0410029/0412005 hep-ex/0412014	$ep \to PX$	Θ_c Ξ_5
BES PRD 70 (2004) 012004	$e^+e^- \to J/\psi(\psi(2S))$	Θ^+	**HERA-B** PRL 93(2003) 212003	$pA \to PX$	Θ^+ Ξ_5
BELLE hep-ex/0411005	$KN \to PX$	Θ^+ Θ_c	**SPHINX** Eur. Phys. J. A21(2004) 455	$pC(N) \to \Theta KC(N)$	Θ^+
BaBar hep-ex/0408064	$e^+e^- \to \Upsilon(4S)$	Θ^+ Ξ_5	**PHENIX** nuc-ex/0404001	$AuAu \to PX$	Θ^+