FROM PROTONS TO PENTAQUARKS:

Θ^+

A BARYON WITH POSITIVE STRANGENESS

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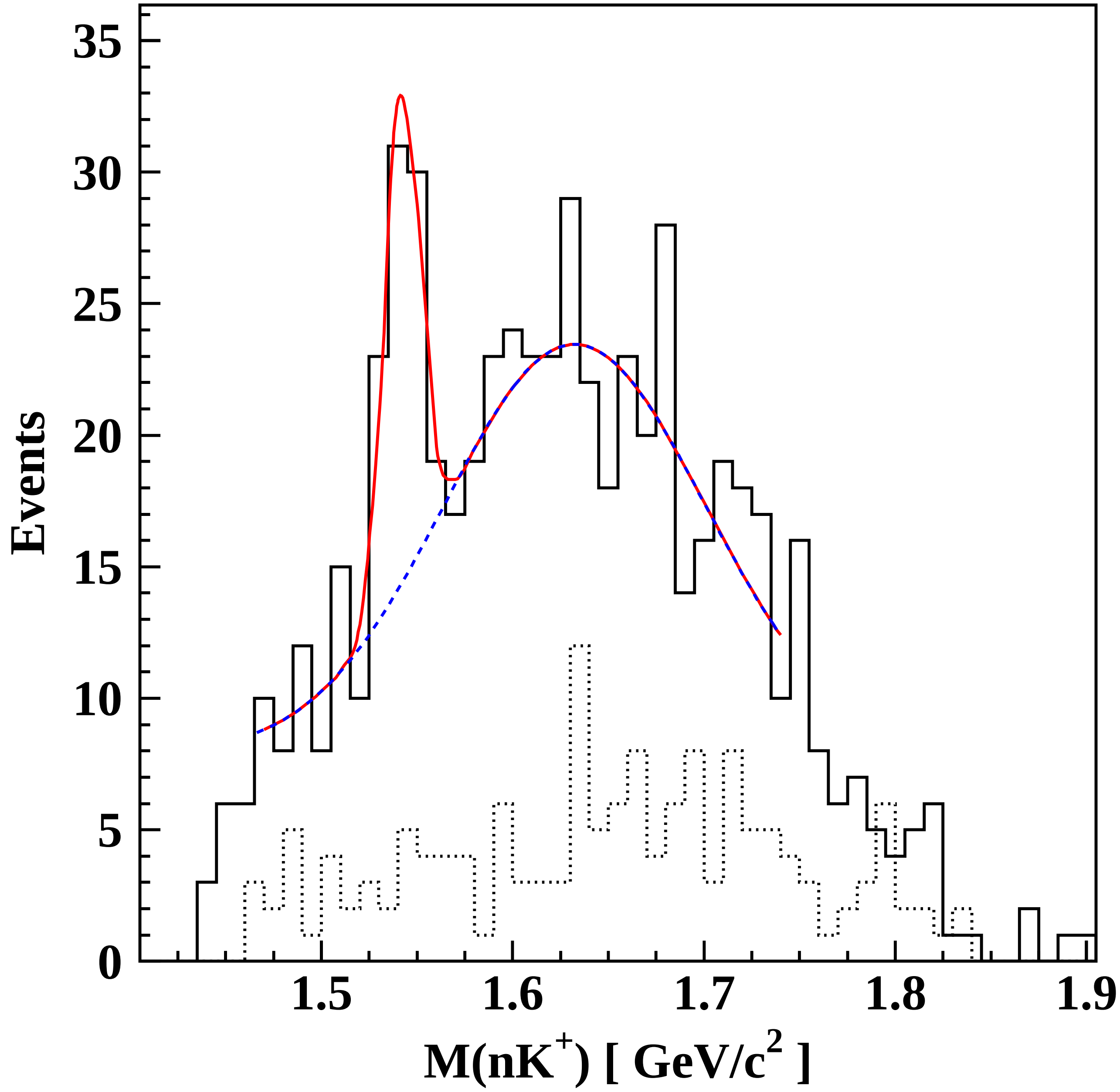
Introduction

A new baryon resonance was observed at Spring8/LEPS, ITEP/DIANA, Jlab/CLAS and Bonn/SAPHIR, the

$\Theta^+(1540)$

It has strangeness $S = +1$ (i.e. contains a $\bar{s}$ quark) and cannot be a three–quark state. Its minimum quark configuration is $(udud\bar{s})$ and it is called

PENTAQUARK.



CLAS/Jlab

The discovery was reported in newspapers, major journals, is hotly debated, is a central issue at physics conferences.

Why is the $\Theta^+(1540)$ so important ?

and, if it is important,

What is the experimental evidence for it ?

and if it really exists,

What do we know about it ?

Quark models,

Baryons are described as states of three constituent quarks bound by a (linear) confinement potential.

successes

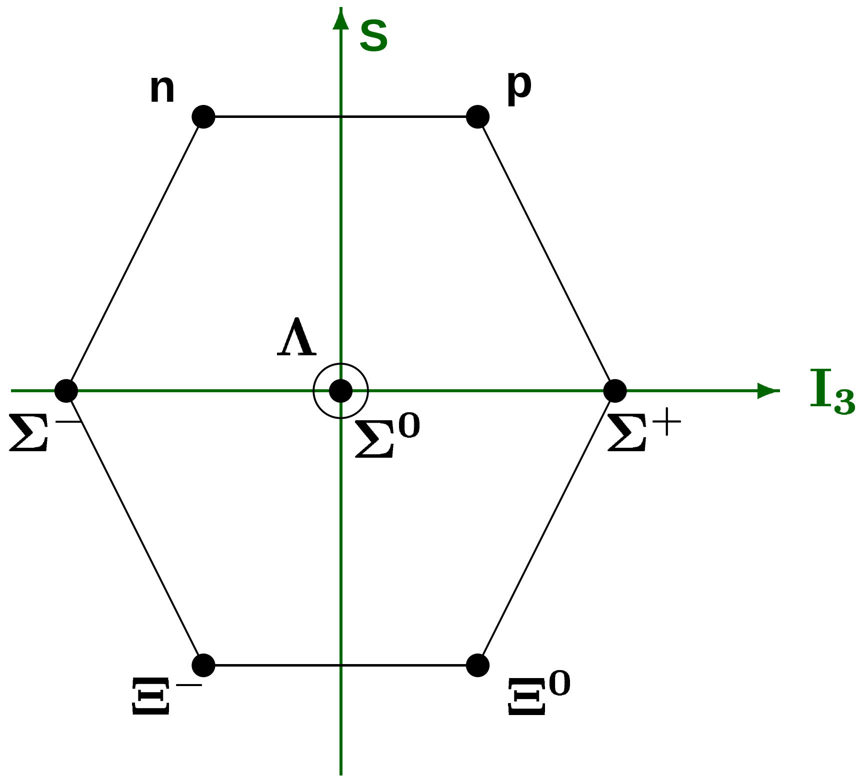
Ground state baryon masses, magnetic moments, shell structure, negative-parity resonances.

Constituent quarks arise naturally from spontaneous breaking of chiral symmetry.

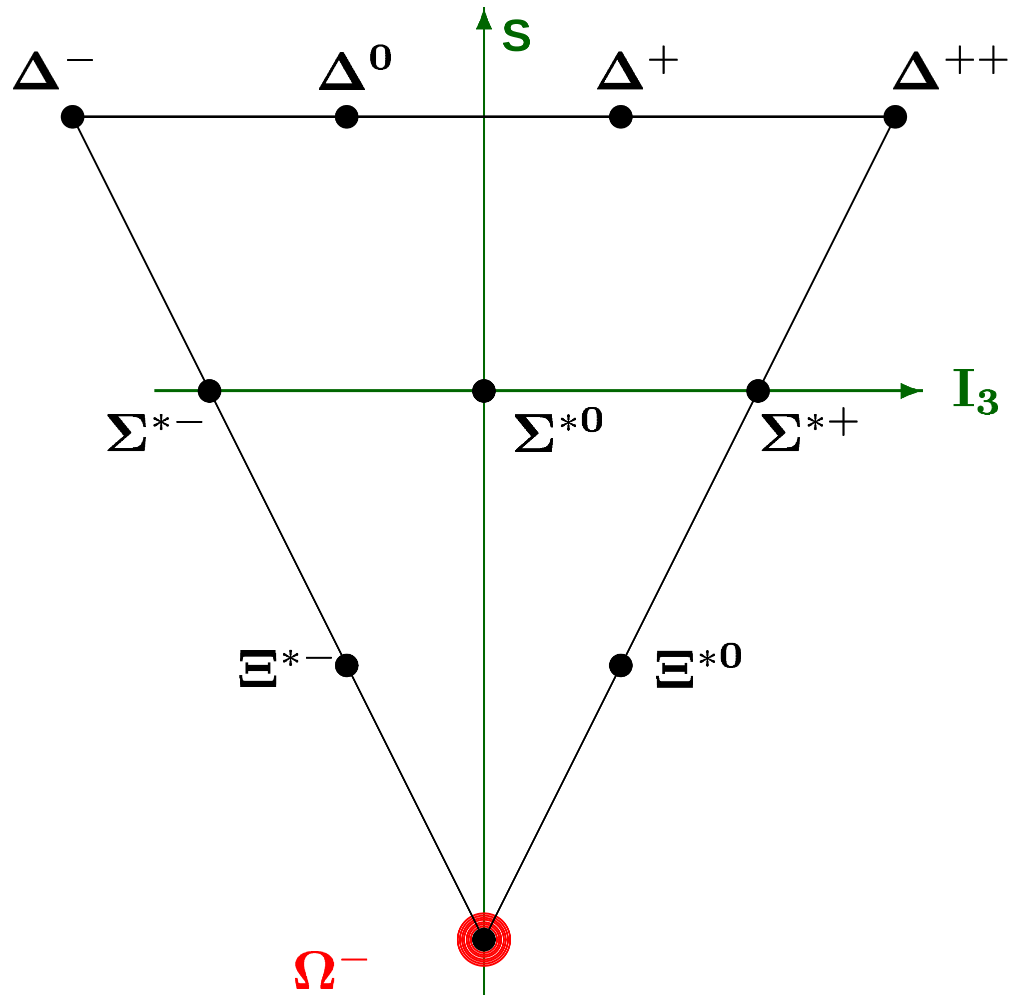
· · · and failures.

Sea quarks play no dynamical role in baryons. Contact to deep inelastic scattering is lost.

Octet



Decuplet



Ω^- : Predicted by Gell-Mann in 1964

: Found by V. E. Barnes et al. in 1964

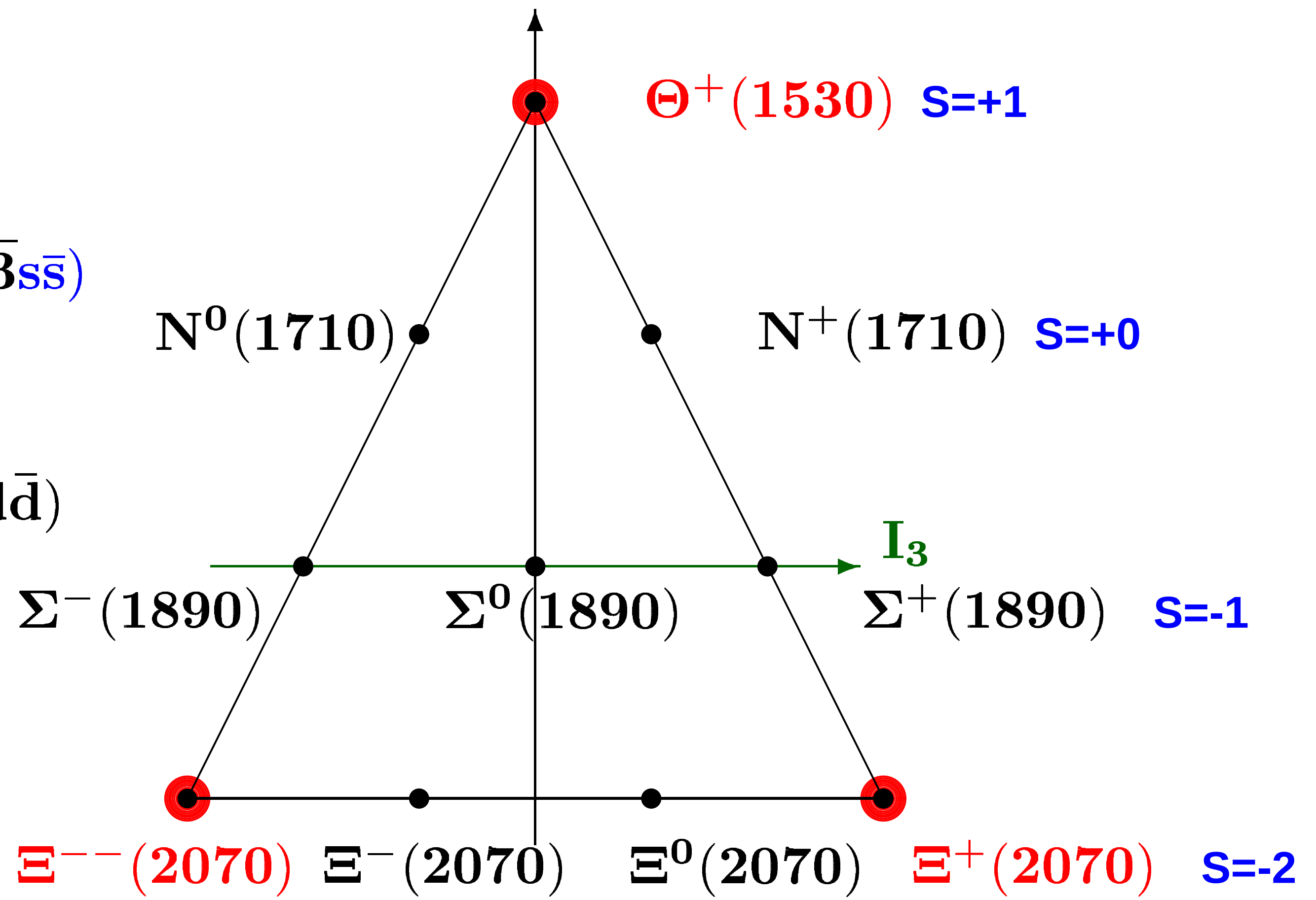
Triumph of SU(3)

and the quark model

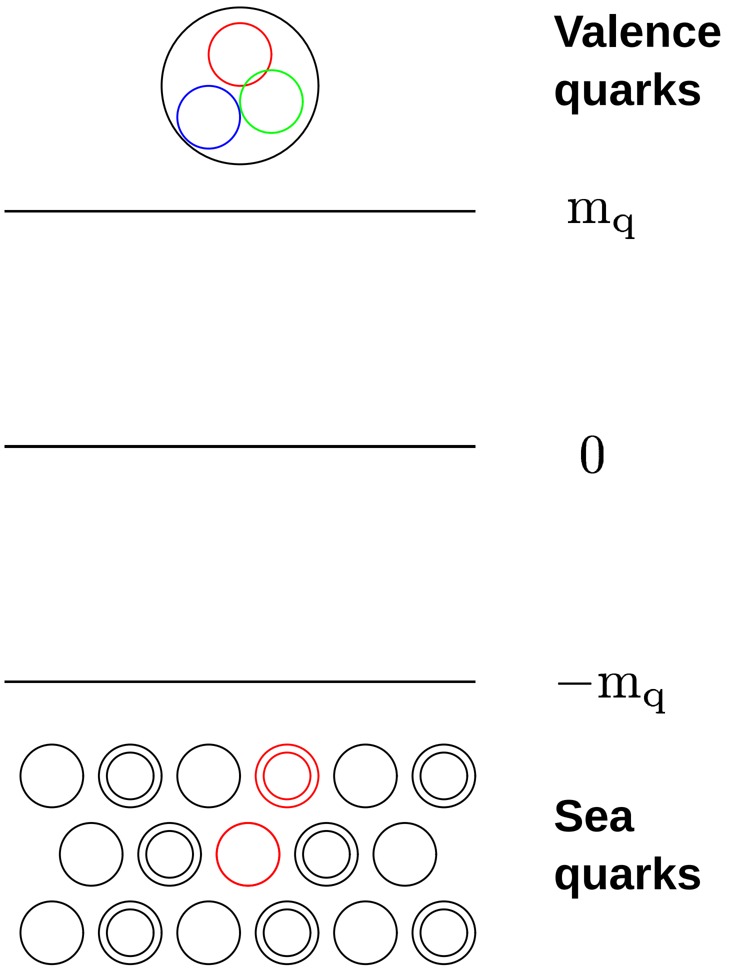
The chiral soliton model predicts the existence of an antidecuplet:

Antidecuplet

1	$uudd\bar{s}$
4/3	$uud(1/\sqrt{3}d\bar{d} + \sqrt{2/3}s\bar{s})$
5/3	$uus(1\sqrt{3}s\bar{s} + \sqrt{2/3}d\bar{d})$
2	$uuss\bar{d}$
$\propto$ mass	



The quark model ... versus chiral soliton models



Quarks and sea quarks are dynamically coupled. The equations of motion support soliton solutions which can be organised into multiplets. The lowest lying multiplets are $\mathbf{8}$ and $\mathbf{10}$ and $\overline{\mathbf{10}}$.

For u and d quarks spin and isospin are coupled:

N	$S = 1/2$	$I = 1/2$	
Δ	$S = 3/2$	$I = 3/2$	
~ 1700	$S = 5/2$	$I = 5/2$	fall–apart state.

- **M. Gell-Mann, “A Schematic Model Of Baryons And Mesons,” Phys. Lett. 8 (1964) 214.**
- **V. E. Barnes** *et al.*, **“Observation Of A Hyperon With Strangeness -3,” Phys. Rev. Lett. 12 (1964) 204.**
- **T. H. Skyrme, “A Nonlinear Field Theory,” Proc. Roy. Soc. Lond. A 260 (1961) 127.**
- **E. Witten, “Global Aspects Of Current Algebra,” Nucl. Phys. B 223 (1983) 422.**
- **M. Chemtob, “Skyrme Model Of Baryon Octet And Decuplet,” Nucl. Phys. B 256 (1985) 600.**
- **H. Walliser, “The SU(N) Skyrme Model,” Nucl. Phys. A 548 (1992) 649.**
- **D. Diakonov, V. Petrov and M. V. Polyakov, “Exotic anti-decuplet of baryons: Prediction from chiral solitons,” Z. Phys. A 359, 305 (1997).**

"Discovery" of a baryon with S=+1

DIANA / ITEP

hep−ex/0304040

$K^+ n \longrightarrow \Theta^+ \longrightarrow p\,K^0$

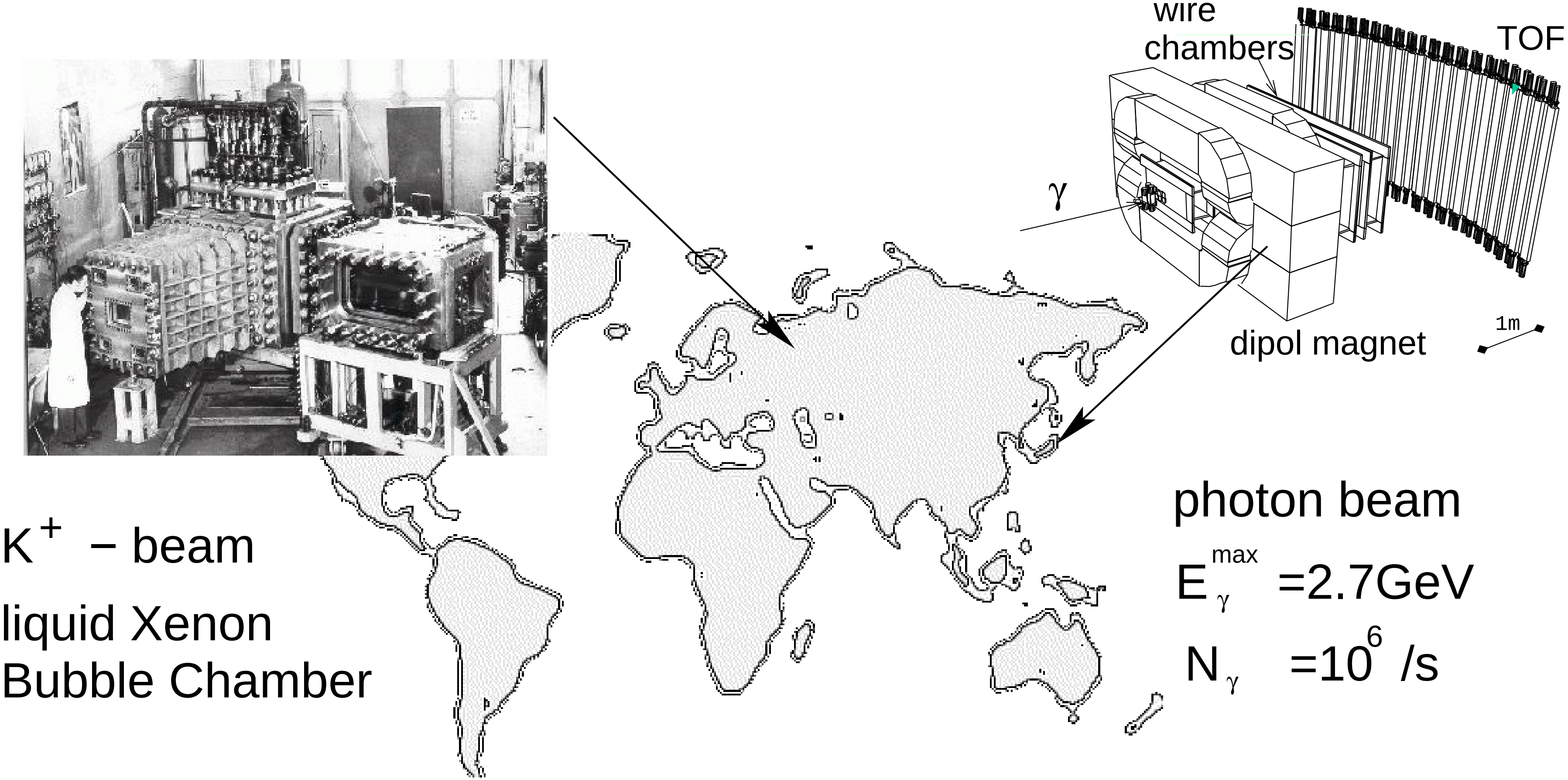
formation

LEPS / SPring−8

hep−ex/0301020

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

photo−production



K^+ − beam

liquid Xenon
Bubble Chamber

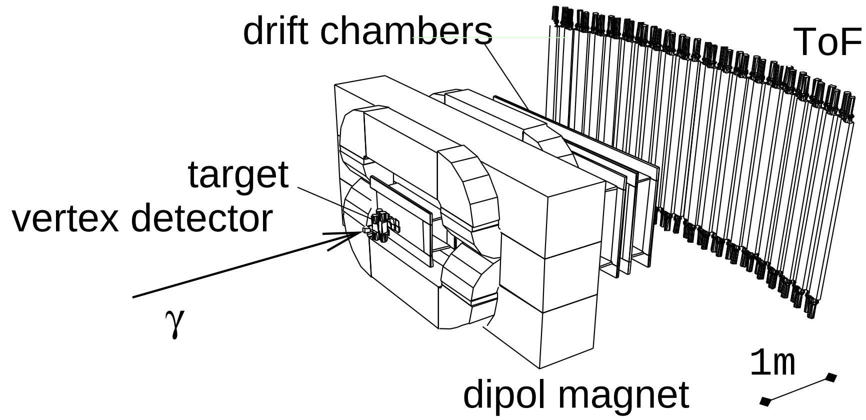
photon beam

E_γ^{max} =2.7GeV

N_γ =10^6 /s

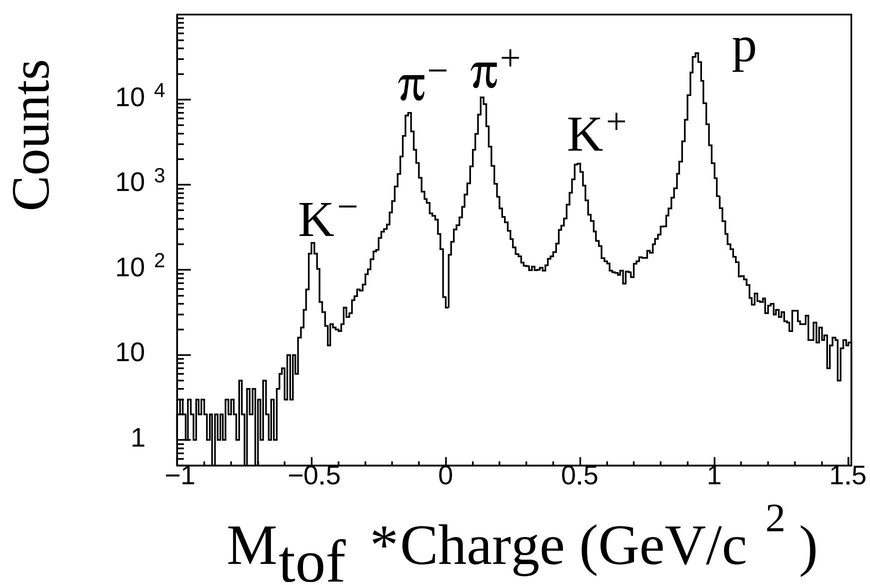
LEPS/SPRING8:

- **Spring8: syncroton radiation facilitiy**
- **Photons ($\sim$ 3.5 eV, Ar 351 nm) backscattered off 8 GeV electrons**
- **tagged γ's beam, 1.5 to 2.4 GeV**
- **Tagging by bending angle of scattered electrons**



- **Reaction studied:**
  $\gamma^{12}C \rightarrow \Theta^{+}\ K^{-}$ + X ; $\Theta^{+} \rightarrow nK^{+}$
- **Charged particle tracking in magnetic field (0.7 T)**

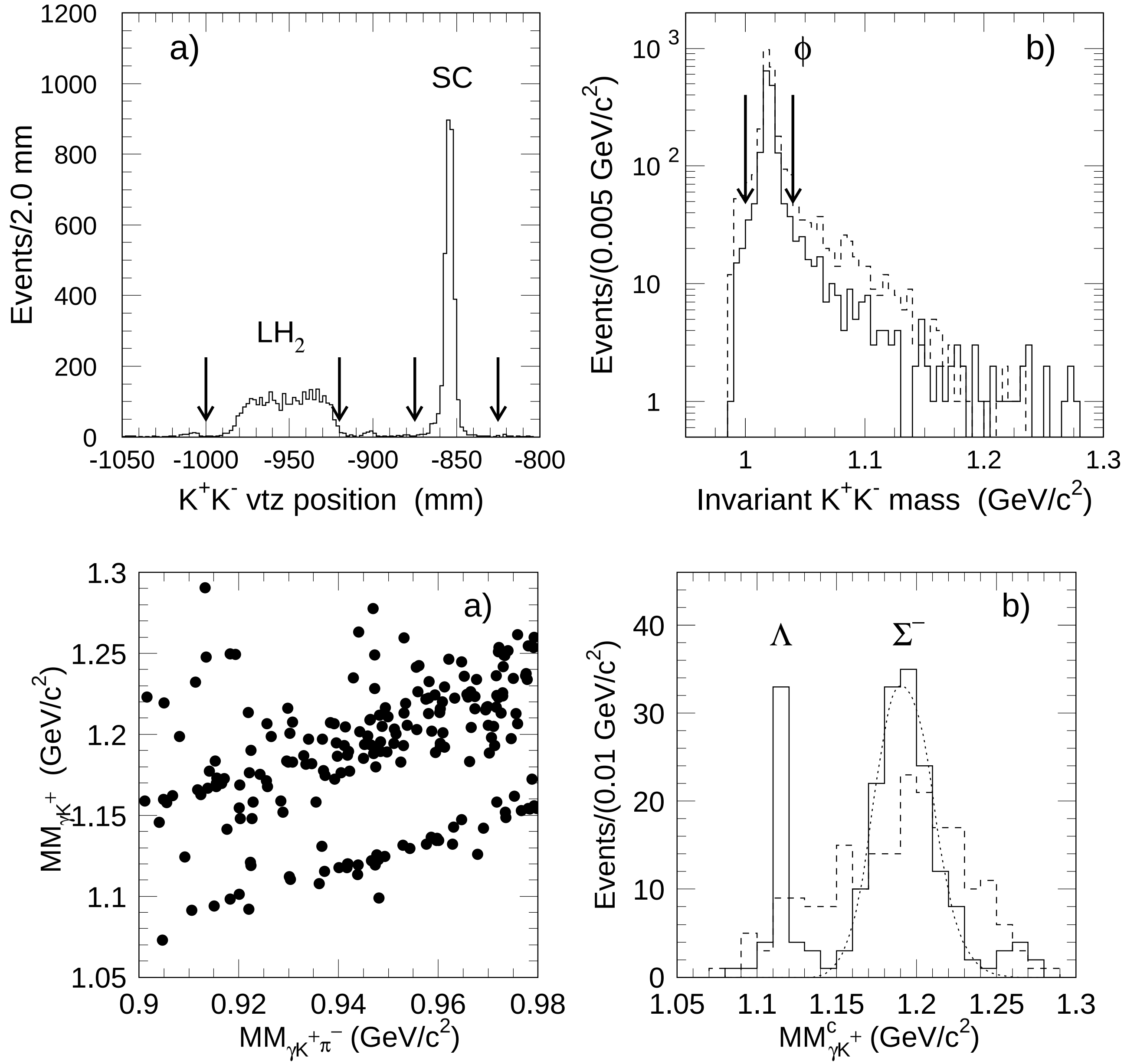
  3 silicon strip detectors, 3 drift chambers, σ_p = 6 Mev/c at 1 GeV/c
- **Particle identification by time–of–flight**



- **Select events on scintillator**
- **Exclude Φ**
- **Correct for momentum of 'quasifree' neutron. In**

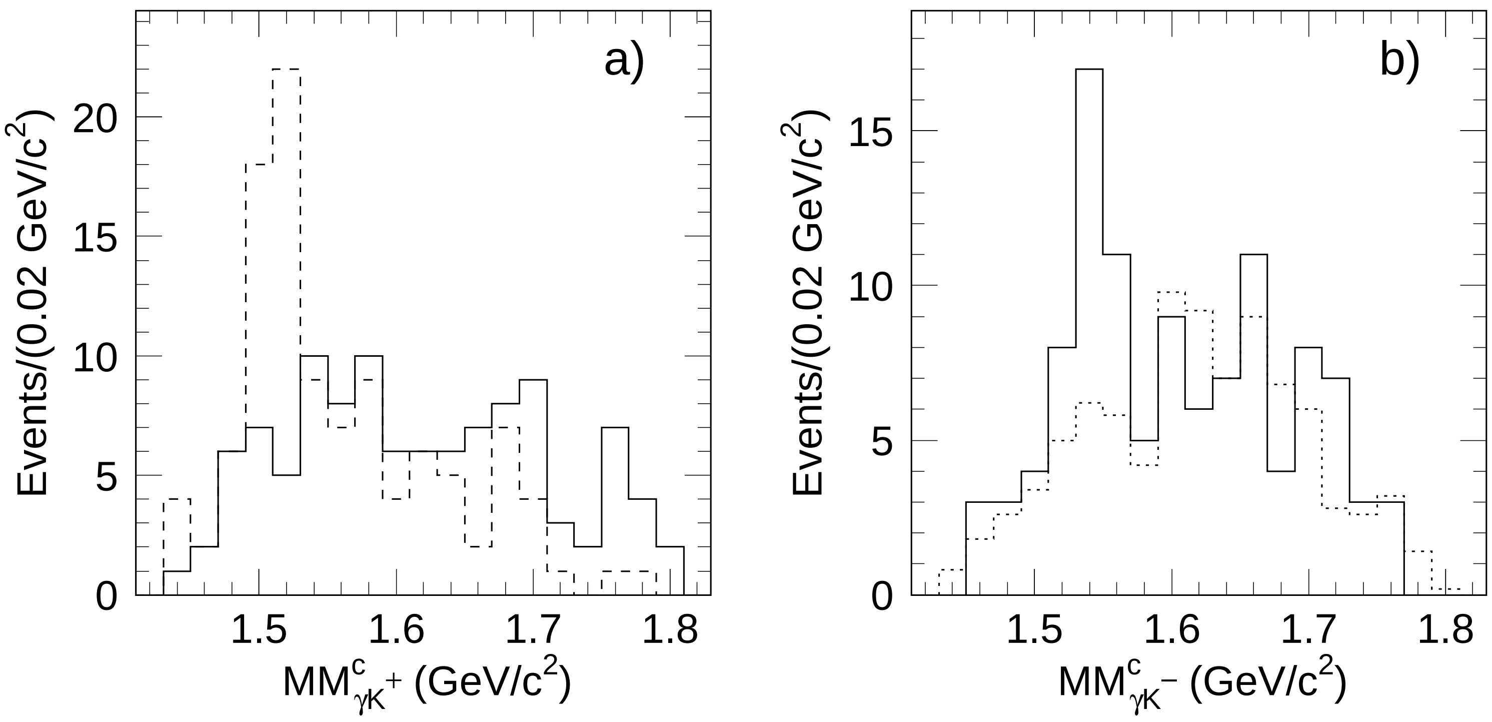
$$\gamma\, n \rightarrow K^+\Sigma^- \rightarrow K^+\pi^- n$$

the neutron and Σ masses can be calculated. Imposing the neutron mass leads to a correlated miss–match for which a correction is applied.



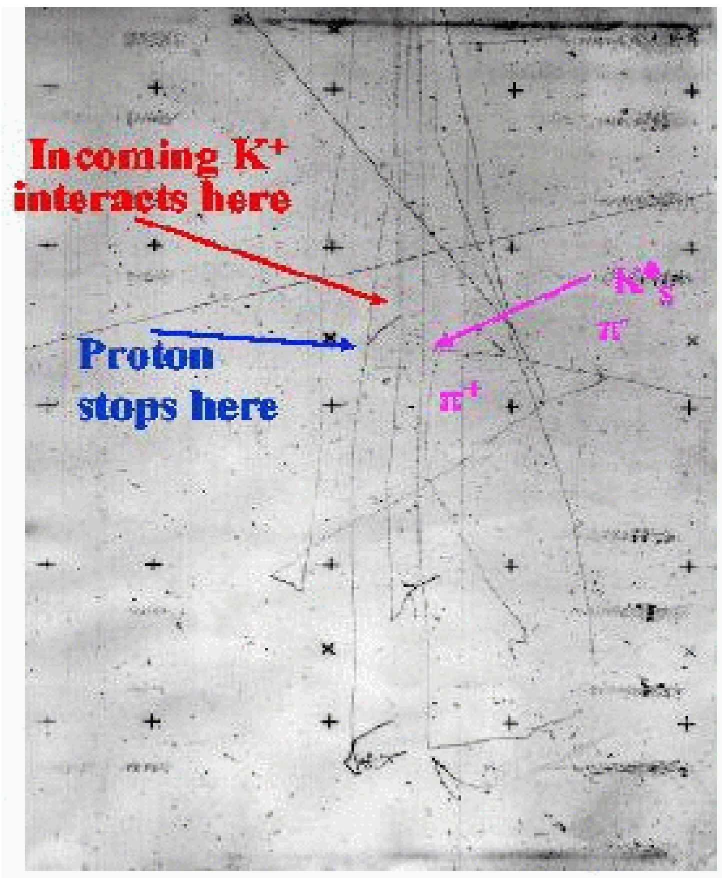
- **Calculate mass of Θ^+ as missing mass in $\gamma n \to K^- \Theta^+_{missing}$**
- $MM^{corr}_{\gamma K^-} = MM_{\gamma K^-} - MM_{\gamma K^+ K^-} + M_n$
- **Find 108 events and 36 Θ^+**
- $M^+_{\Theta} = 1.54 \pm 0.01$ **GeV,** $\Gamma^+_{\Theta} = 25 \pm 0.01$ **MeV,** $\sigma = 4.6$

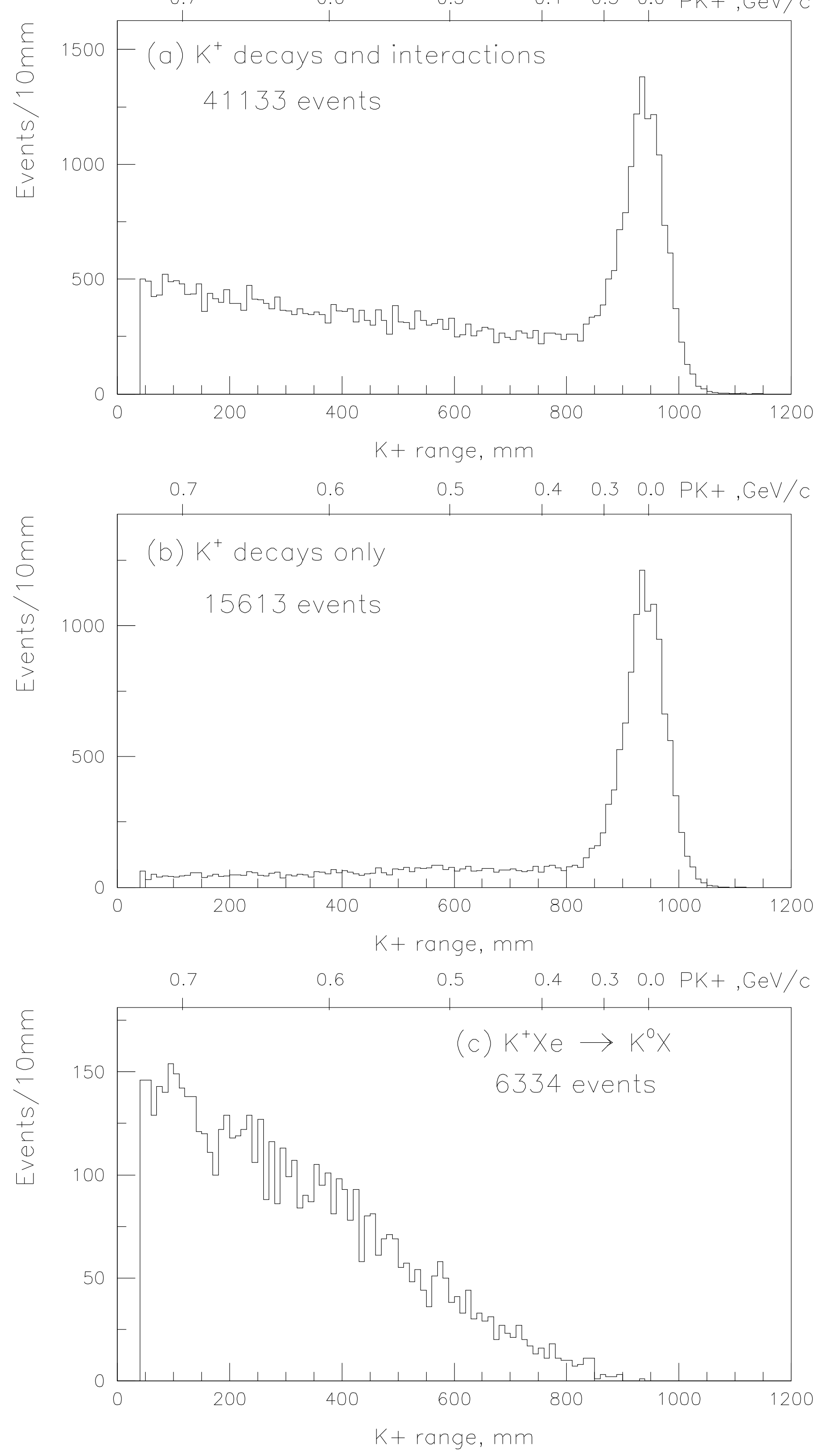
Method tested on $\gamma p \to K^+ \Lambda$



DIANA/ITEP: Charge exchange expt.

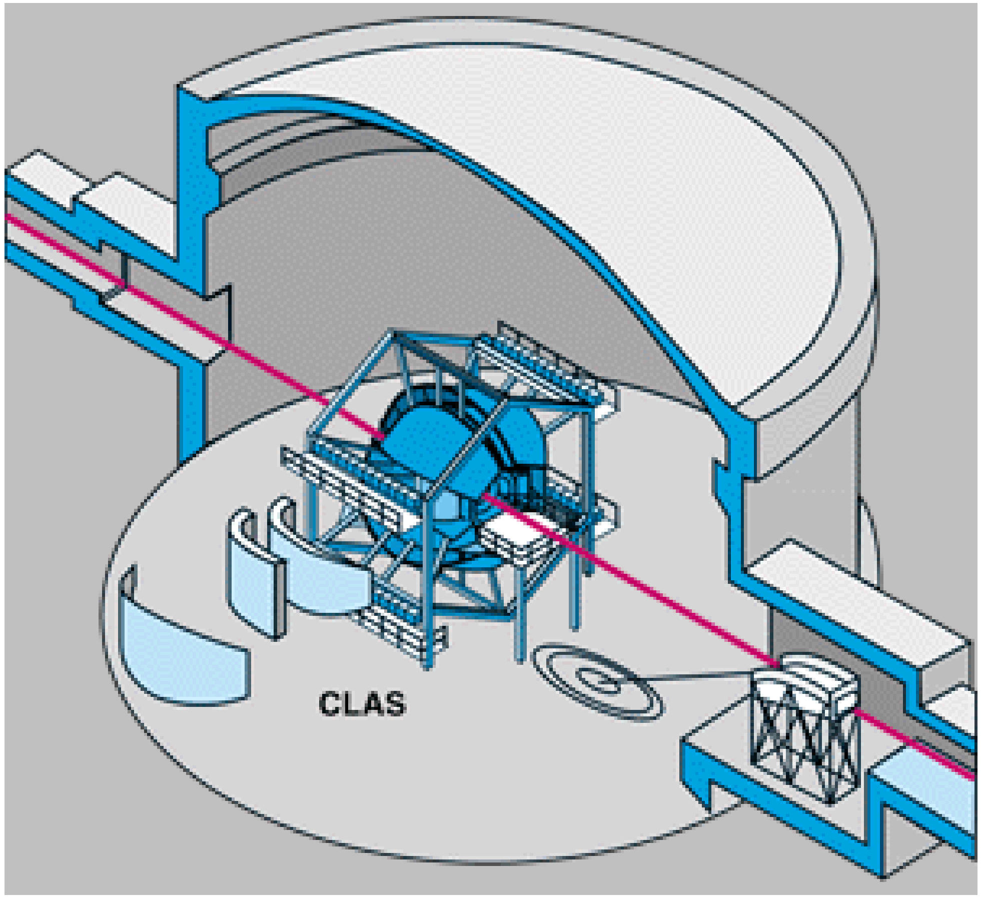
- $K^+ n \to \Theta^+(1540) \to p K^0_s$
- 'quasifree' in Xe bubble chamber
- $K^+ Xe \to Xe' p K^0_s$
- K^+ momentum from range in Xe





CLAS/Jlab:

- Torus magnet with 6 superconducting coils
- Liquid H_2/D_2 target, trigger counters
- Drift chambers with 35,000 cells
- TOF system
- Electromagentic Pb/sci sandwich calorimeter
- Gas Cerenkov counters, e/π separation



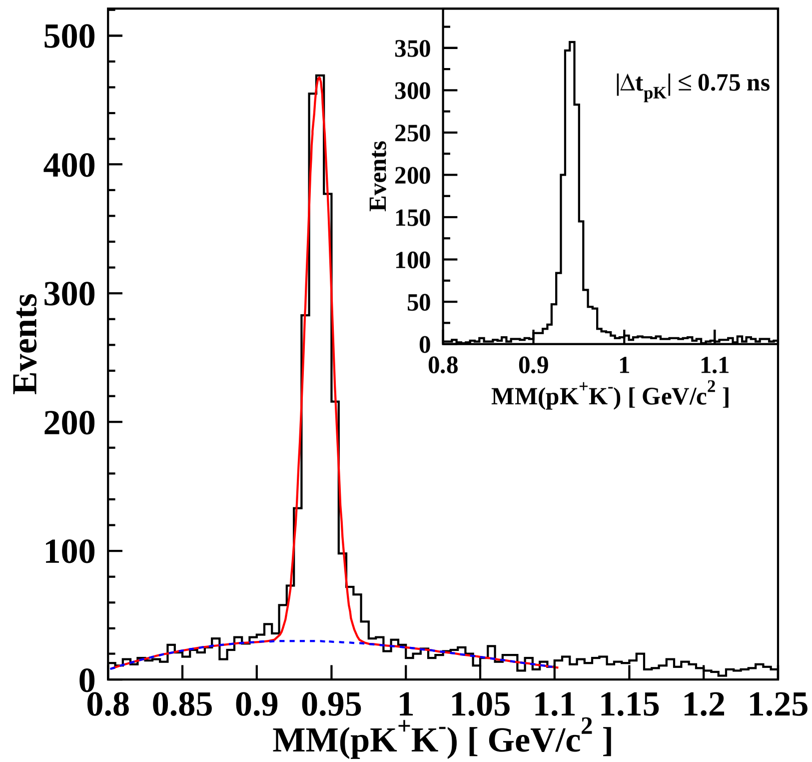
Reactions studied:

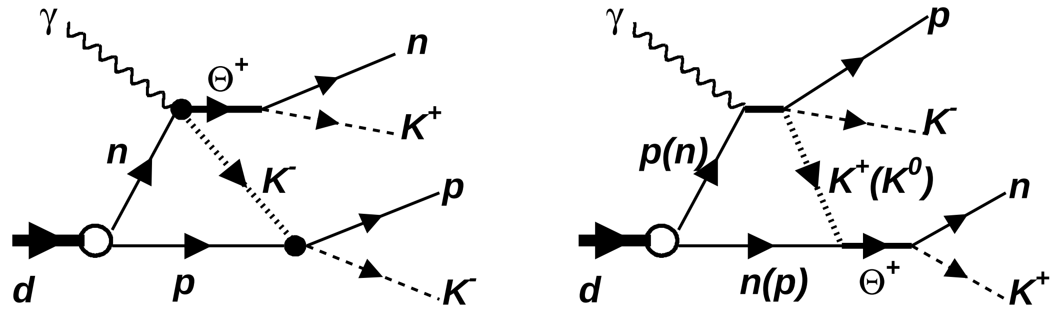
$$\gamma d \to K^- p (K^+ n_{miss})$$
$$\gamma p \to K^- \pi^+ (K^+ n_{miss})$$
$$\gamma p \to K^0_s (K^+ n_{miss})$$

Study of the reaction

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

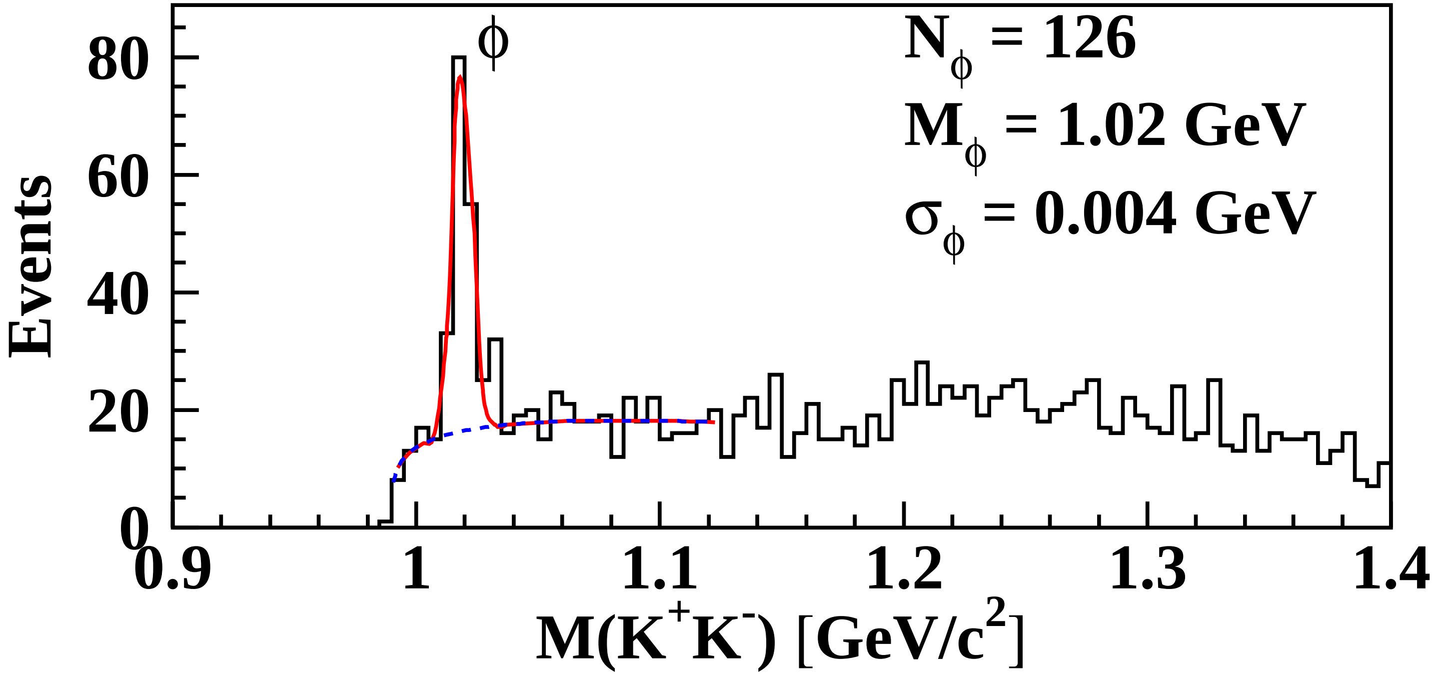
- **Detected:** K^+, K^-, p, **hence "no spectator" nucleon**
- **TOF for particle identification**
- **Missing mass calculated and neutron reconstructed**
- **Proposed reaction mechanisms:**





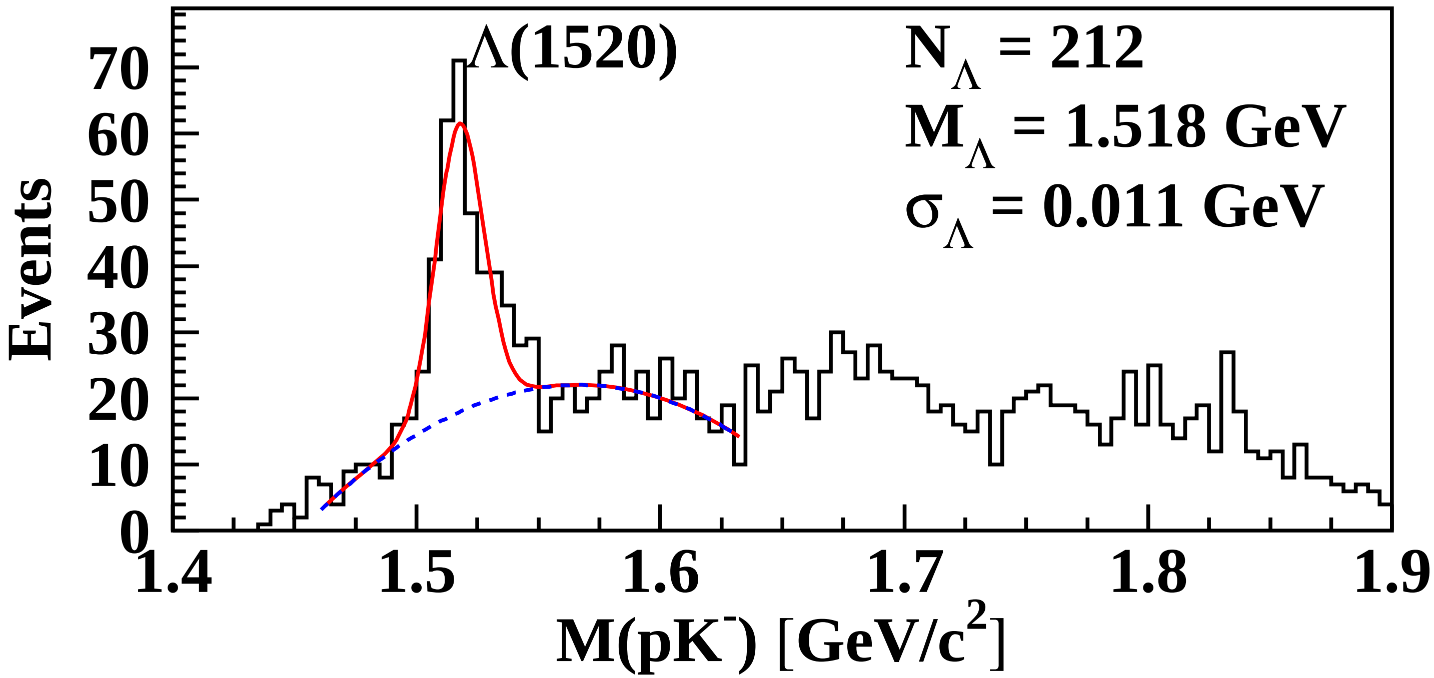
a) b)

The K^+K^- invariant mass



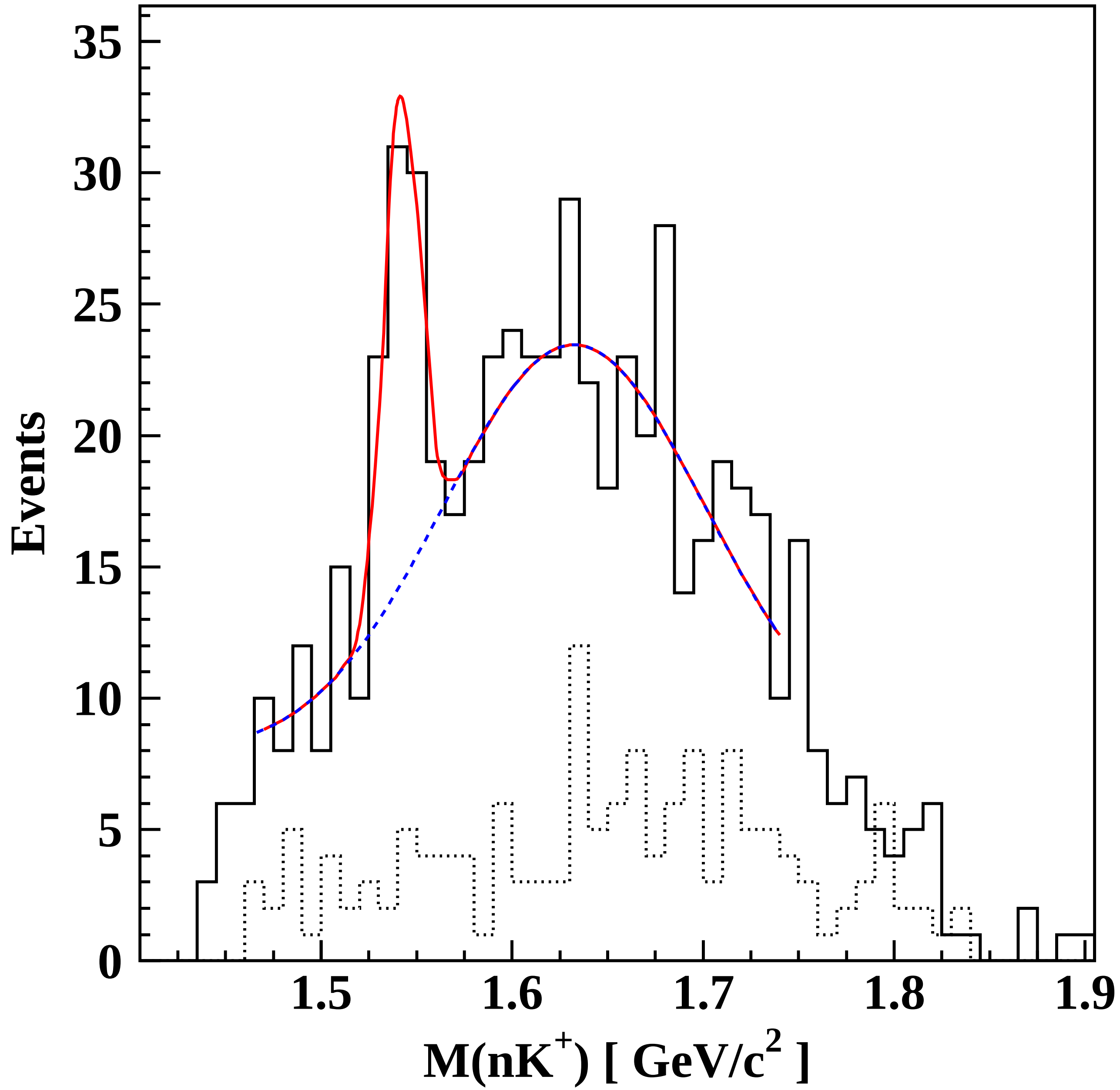
The pK^- invariant mass

ϕ and $\Lambda(1520)$ excluded



The nK^+ invariant mass

M_{Θ^+}	=	1542 ± 5 MeV
Γ_{Θ^+}	$\leq$	21 MeV
Decay:		nK^+
Yield:		212 $\Lambda(1520)$,
		43 Θ^+

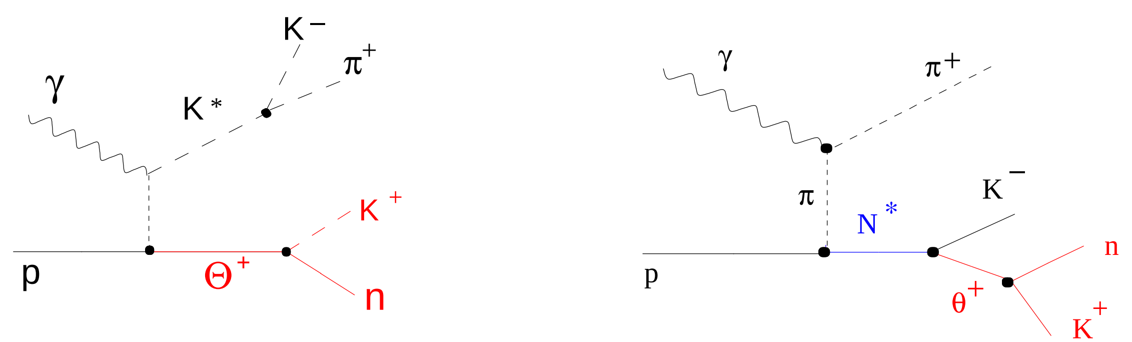


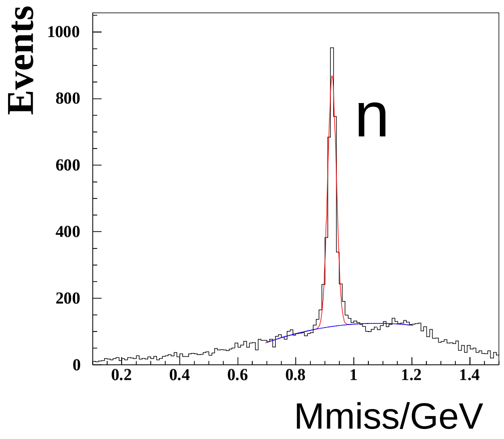
Study of the reaction

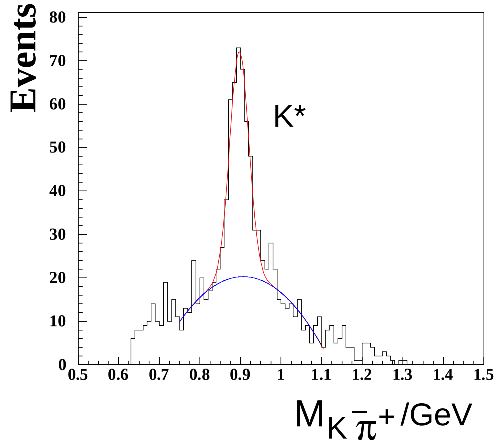
$$\gamma p \rightarrow nK^+K^-\pi^+$$

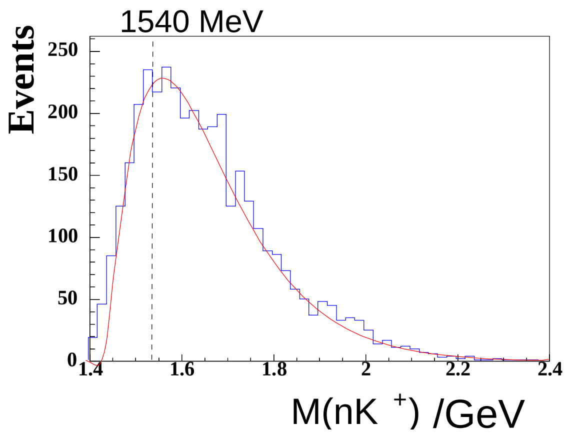
- **Detected:** K^+, K^-, π^+
- **TOF for particle identification**
- **Missing neutron reconstructed from kinematics**

possible reaction mechanisms:



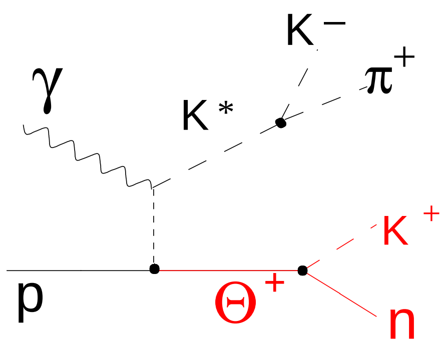


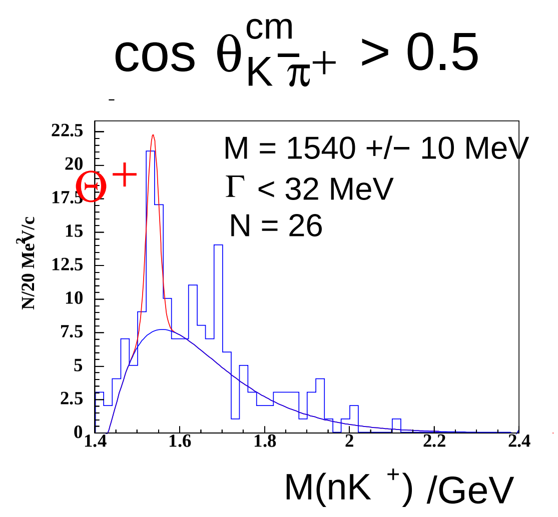




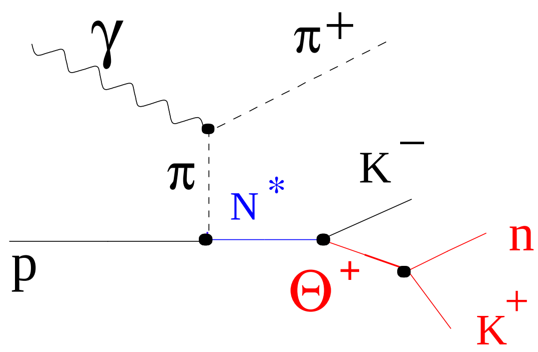
no signal without further cuts !

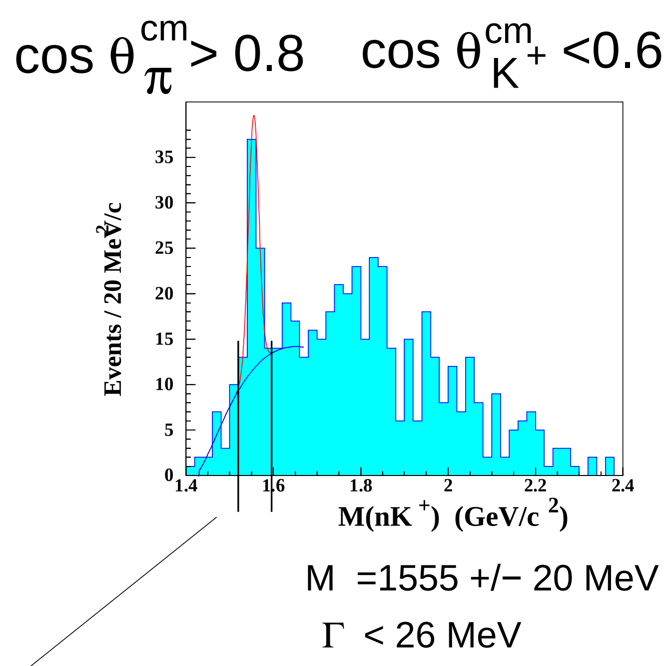
$\Theta^+(1540)$ **seen after cut in angle** $\Rightarrow$

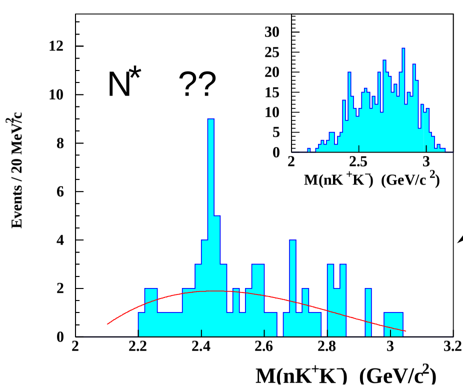




Does the $\Theta^+(1540)$ come from a $N^*(2400)$?



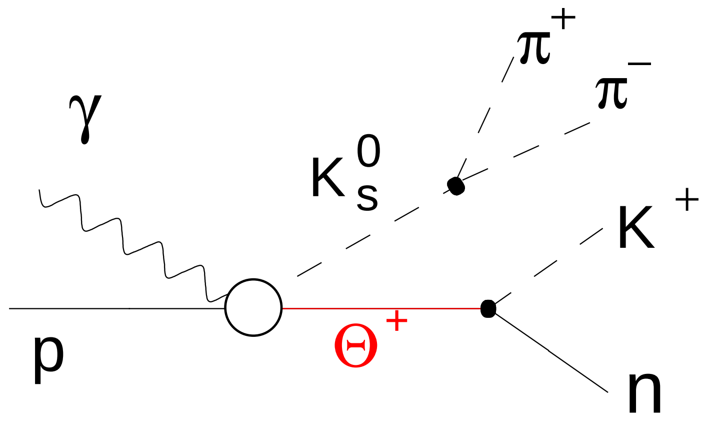


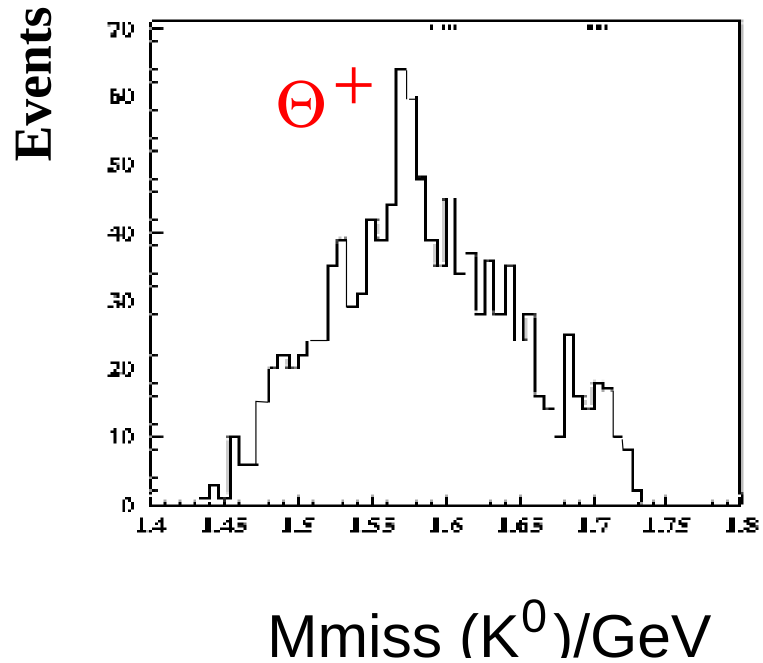


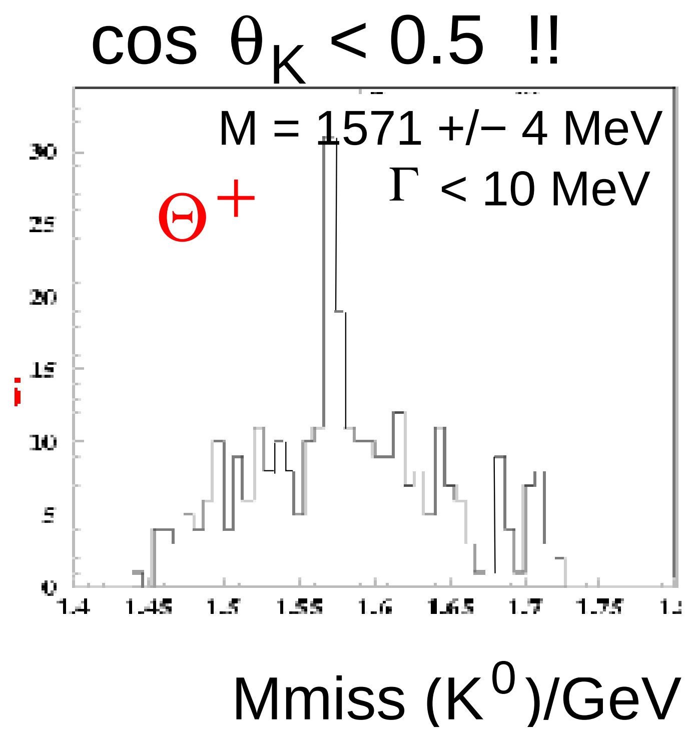
$\Theta^+(1540)$

search in

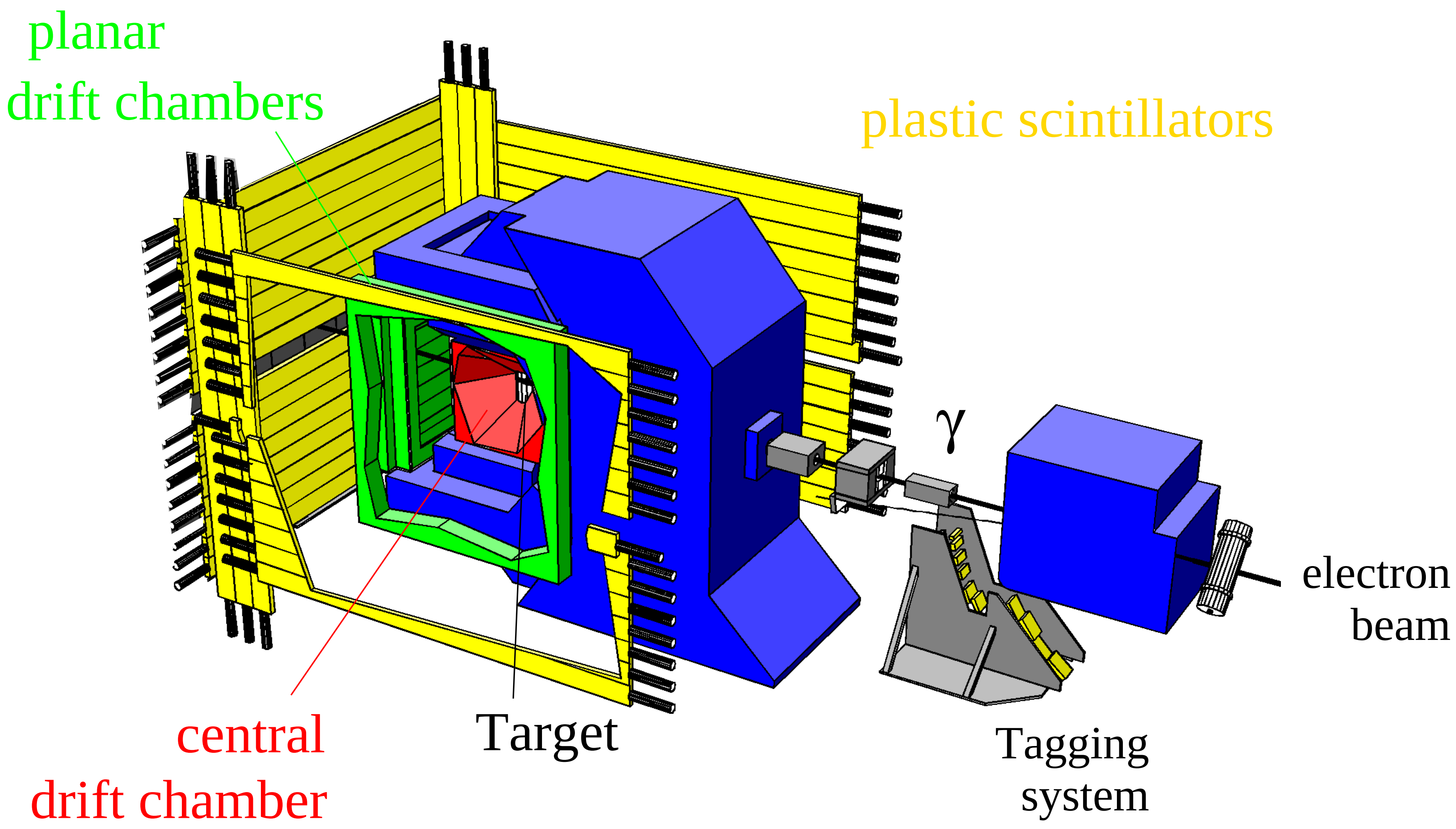
$\gamma p \rightarrow K^0_s n K^+$



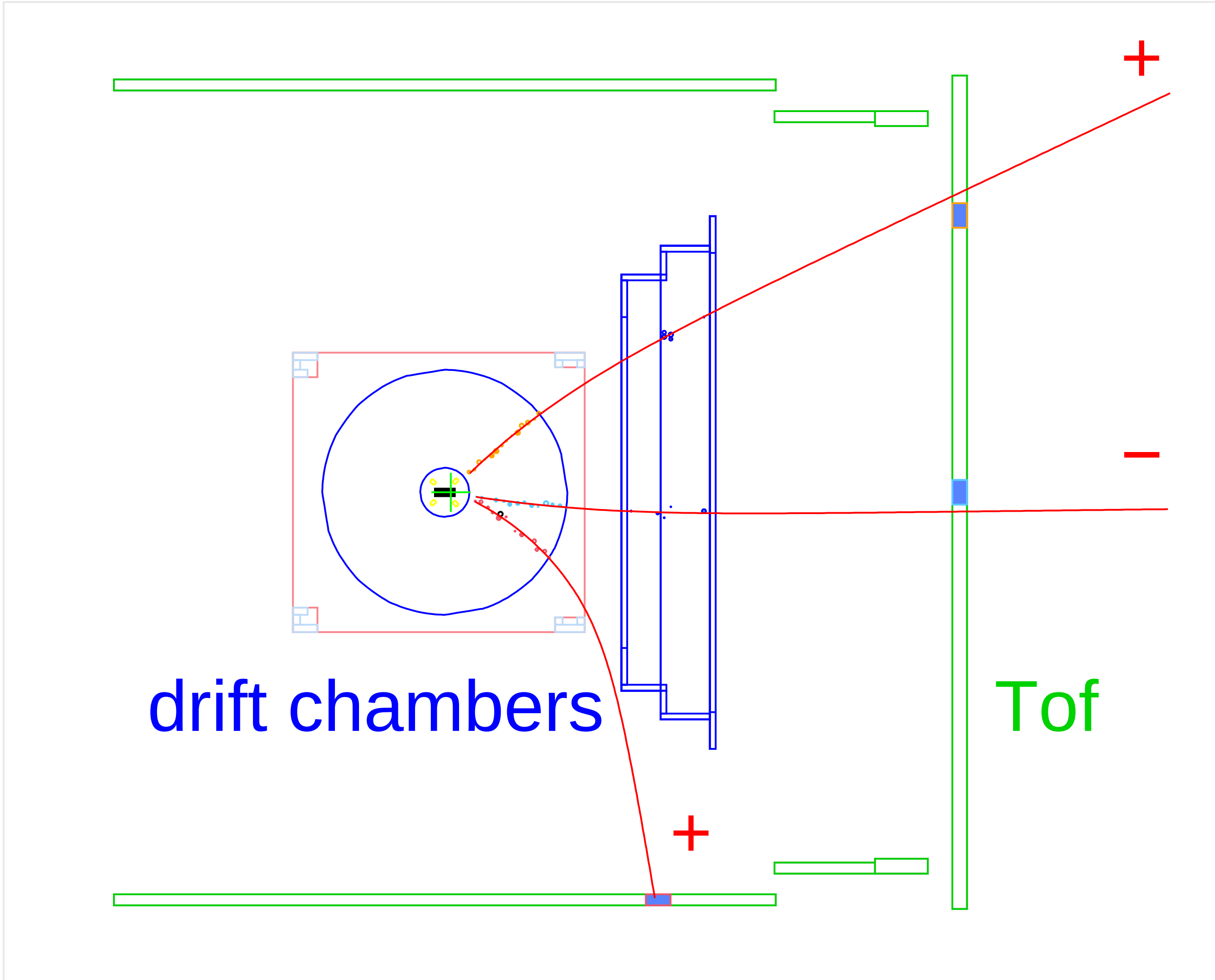




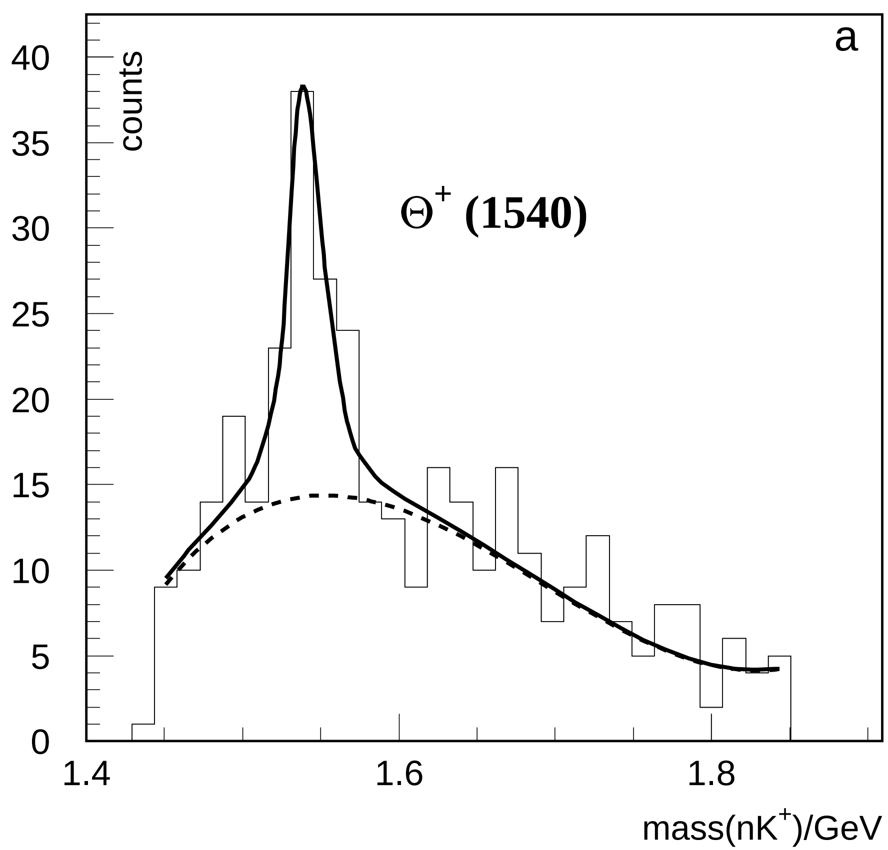
SAPHIR/ELSA:

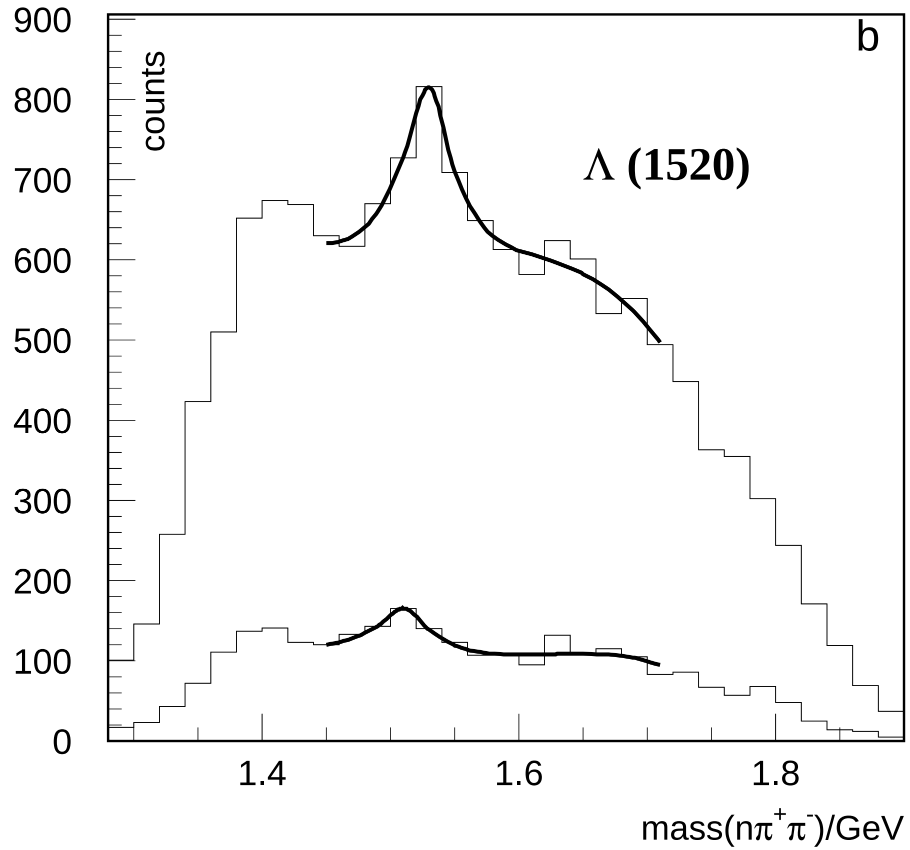

planar
drift chambers
plastic scintillators
γ
electron
beam
central
drift chamber
Target
Tagging
system

- Tracking in drift chamber in $\sim$ 0.18 T field
- TOF with limited resolution
- Well suited for forward angles down to 0°
- Reaction studied: $\gamma p \rightarrow \Theta^+ K^0_s \rightarrow (nK^+)K^0_s$ likely via K^* exchange



SAPHIR event



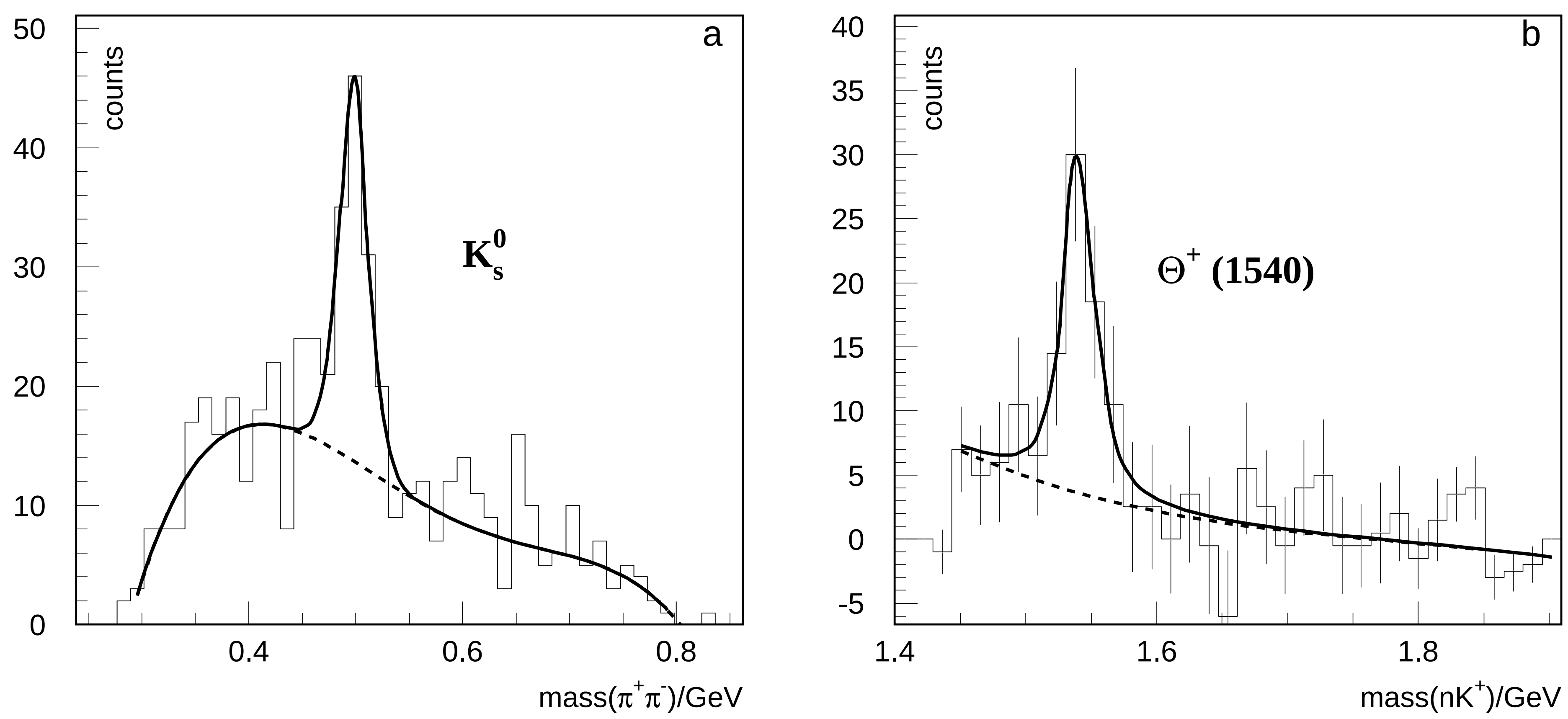


nK^+ mass with $\pi^+\pi^- = K^0_s$

Left: $\cos\vartheta_{K^0_s} > 0.5$

nK^0_s mass with $\pi^+\pi^- = K^0_s$

Right: with/without $\cos\vartheta_{K^0_s} > 0.5$



Side bin subtracted distributions

$\mathbf{nK^+}$ **mass for** $\pi^+\pi^- = \mathbf{K^0_s}$ **- sidebin** $\mathbf{nK^0_s}$ **mass for** $\mathbf{nK^+} = \mathbf{\Theta^+}$ **- sidebin**

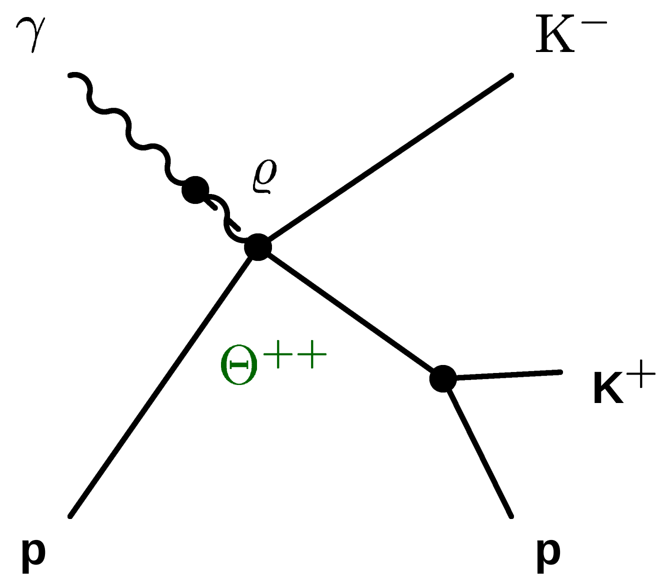
$\cos\vartheta_{K^0_s} > \mathbf{0.5}$ **cut.**

SAPHIR results:

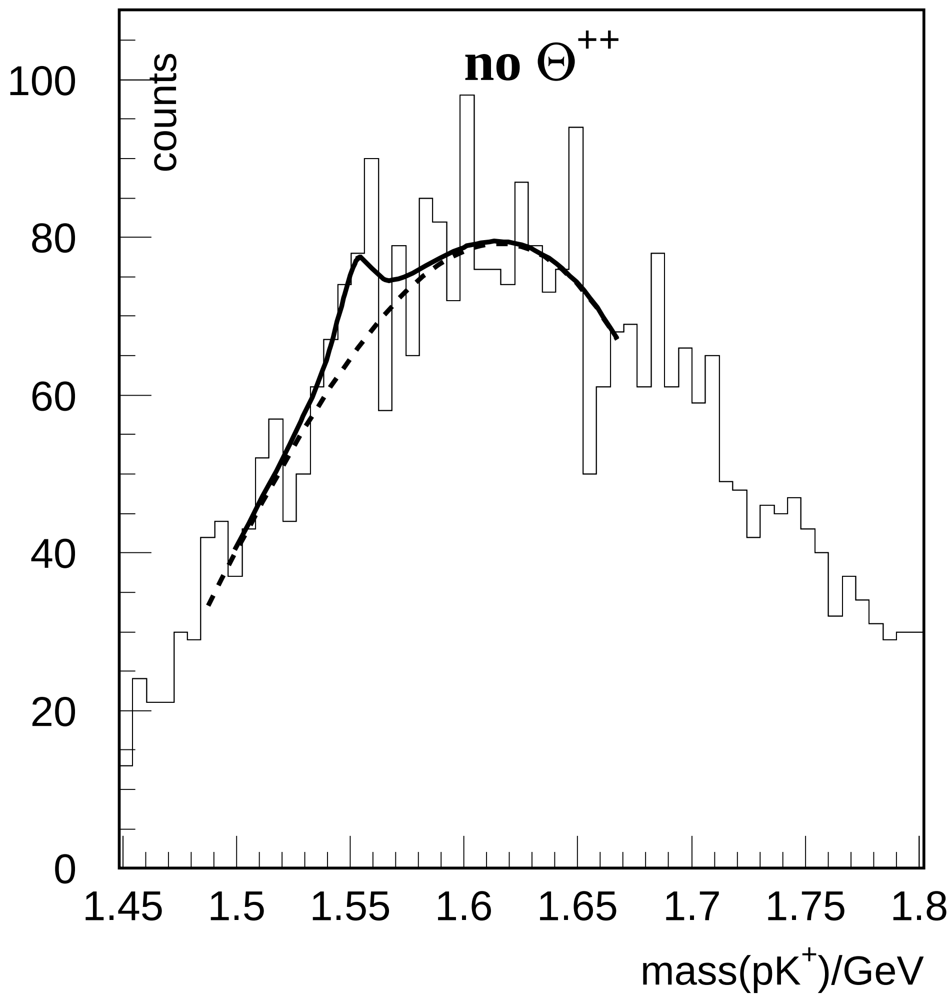
M_{Θ^+}	=	1542 ± 5 MeV
Γ_{Θ^+}	$\leq$	21 MeV
Decay:		nK^+
Yield:		530 $\Lambda(1520)$,
		128 Θ^+

Warning: **signal strength**

Cross section estimate not consistent with ~~upper limit~~ from CLAS for the same reaction. The cuts in angular distribution are different! Masses are different!



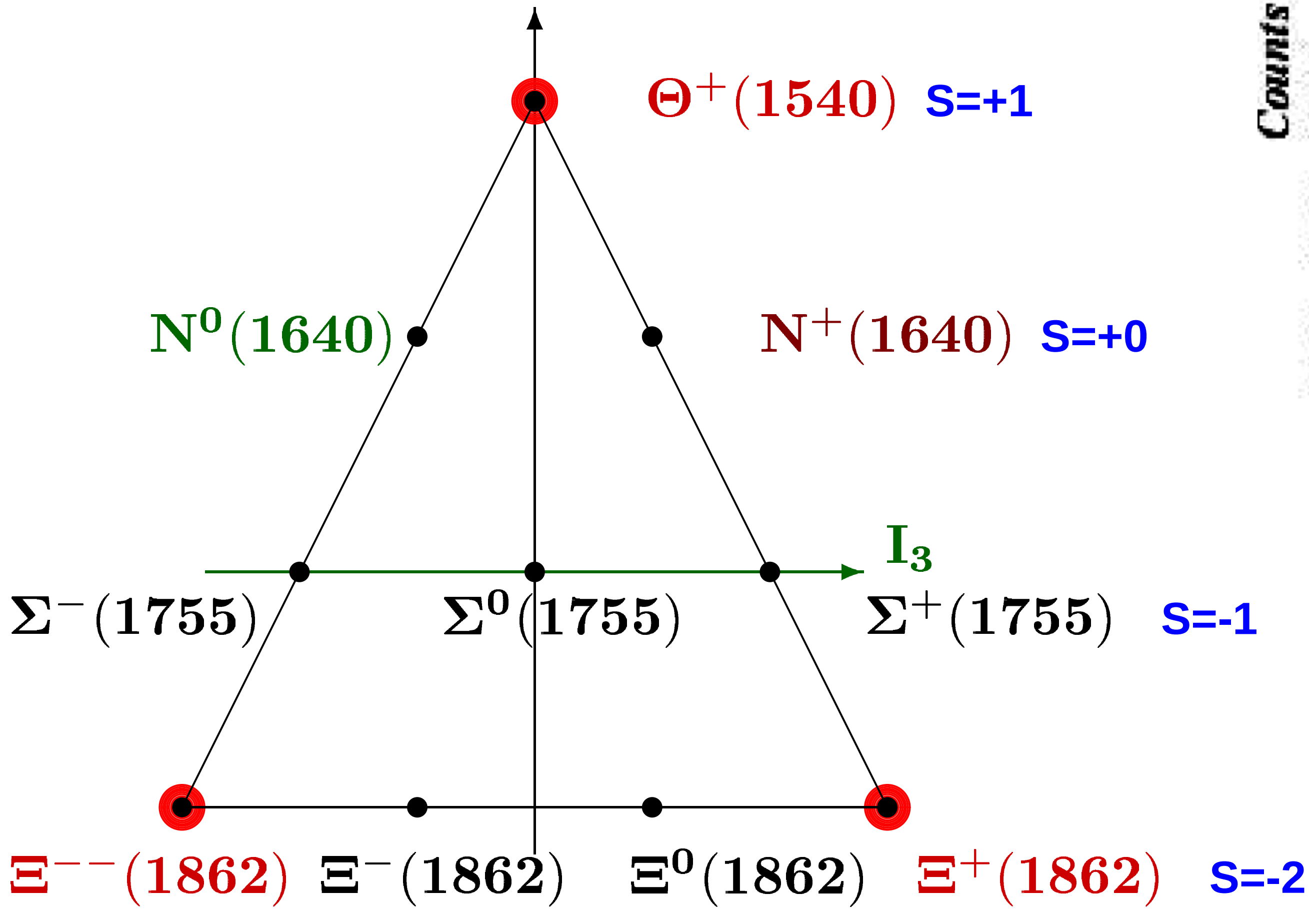
The Θ^+ may be a member of an isospin quintet with $I = 2$, with charges $3+, 2+, 1+, 0, -1$. The production amplitude for the Θ^{++} is then fixed by Clebsch–Gordan coeff. We expect ≥ 5000 Θ^{++}.



pK^+ mass from $\gamma p \to pK^+K^-$

the Θ^+ has isospin zero

Antidecuplet

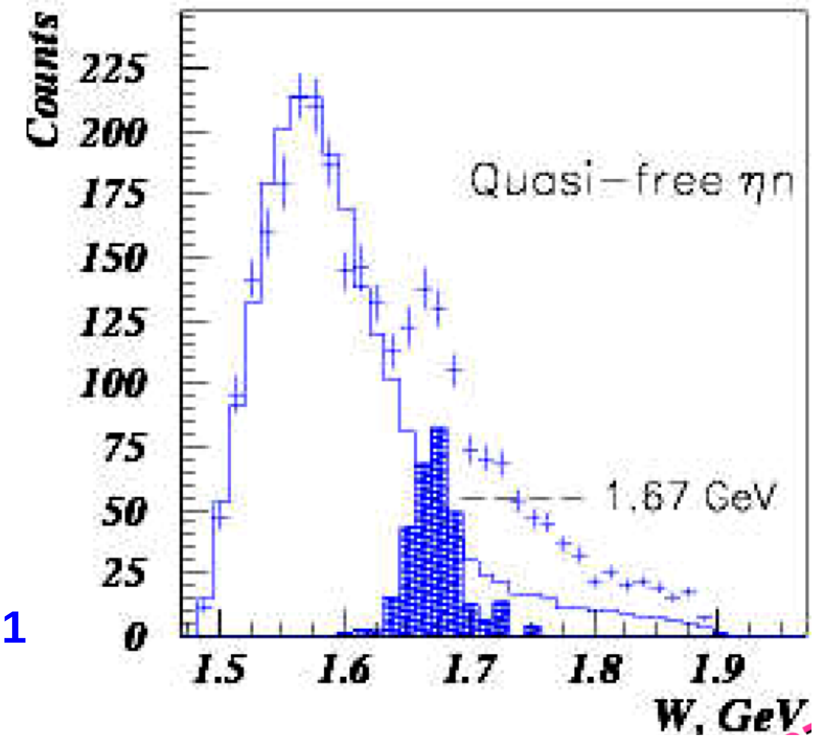


$\gamma p \rightarrow N^+(1640)$ weak

$\gamma p \rightarrow N^0(1640)$ strong

GRAAL Experiment

$\gamma n \rightarrow n\eta$



Is the $N^0(1640) \rightarrow n\eta$ discovered ?

Graal, collaboration, N* 2004, Grenoble, preliminary

A new pentaquark Ξ^{--}

NA49 experiment at CERN

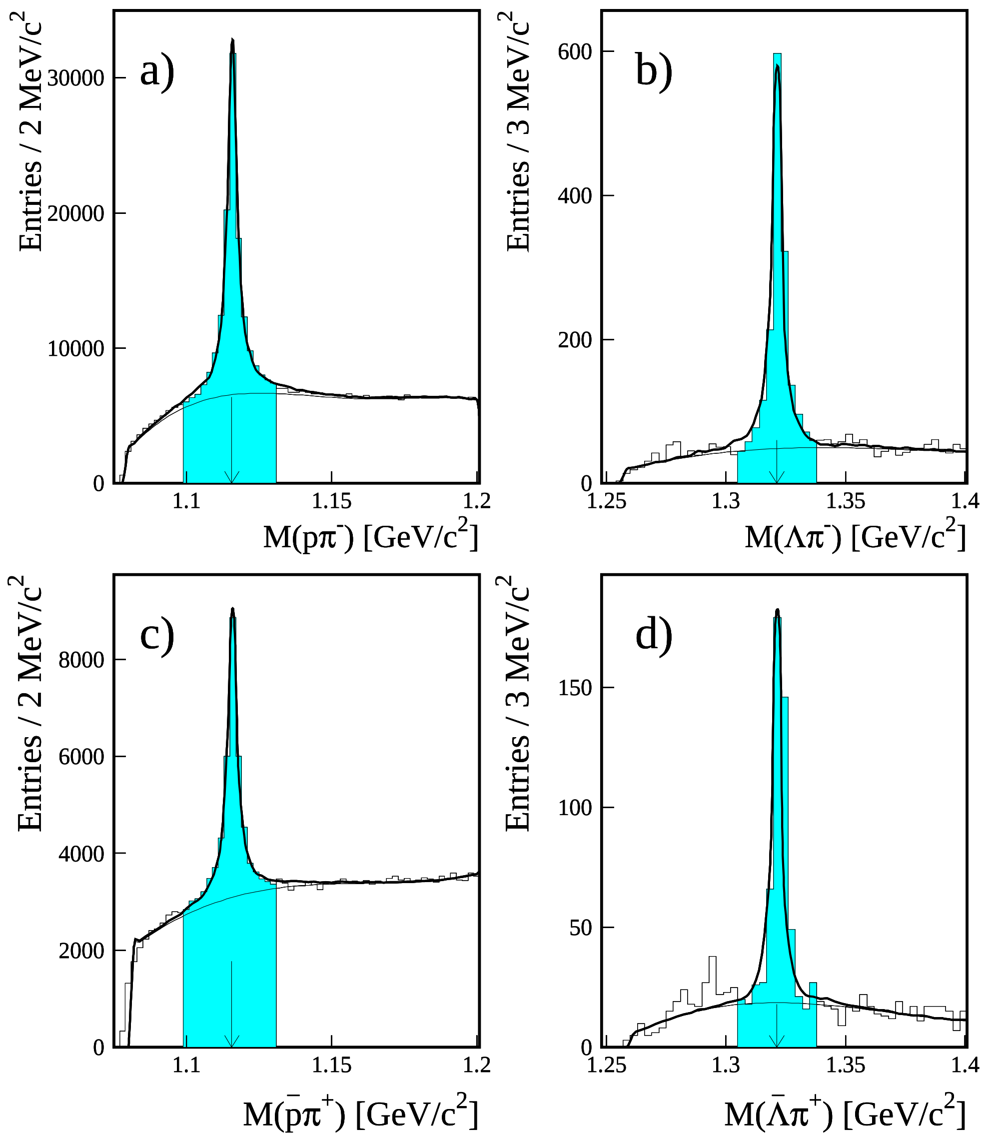
158 GeV protons on LH_2

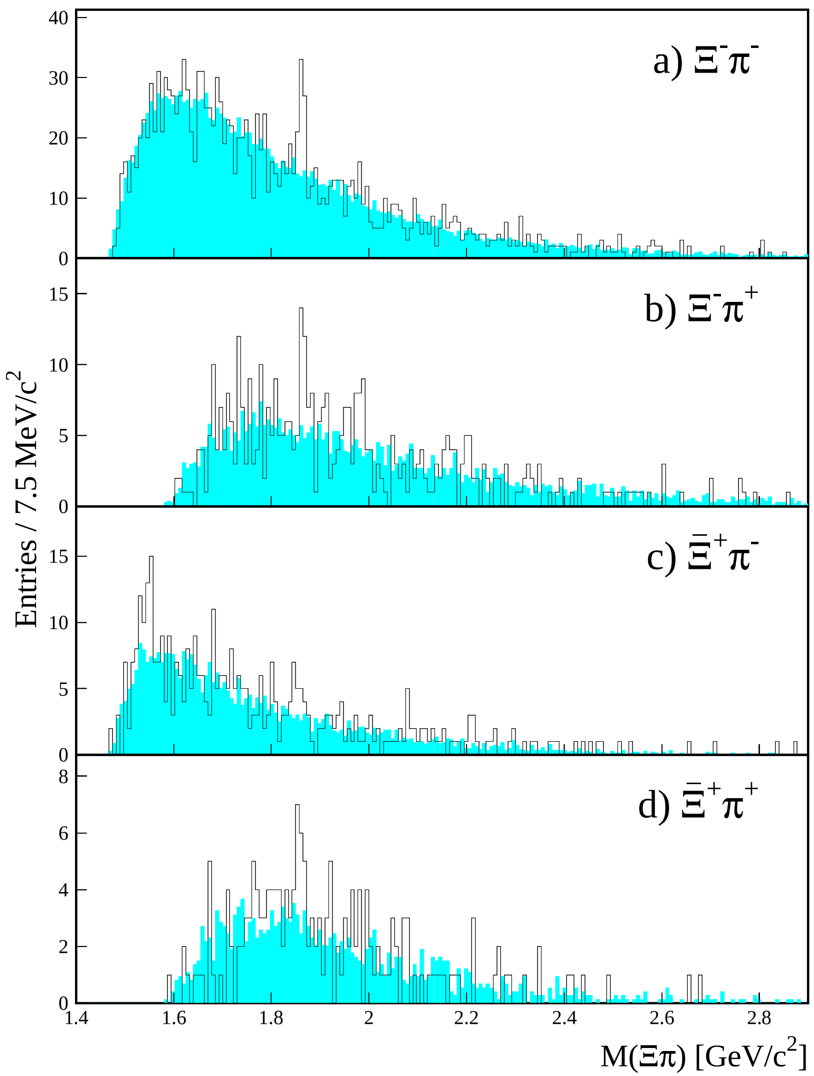
Tracks, dE/dx from multiple TDC's

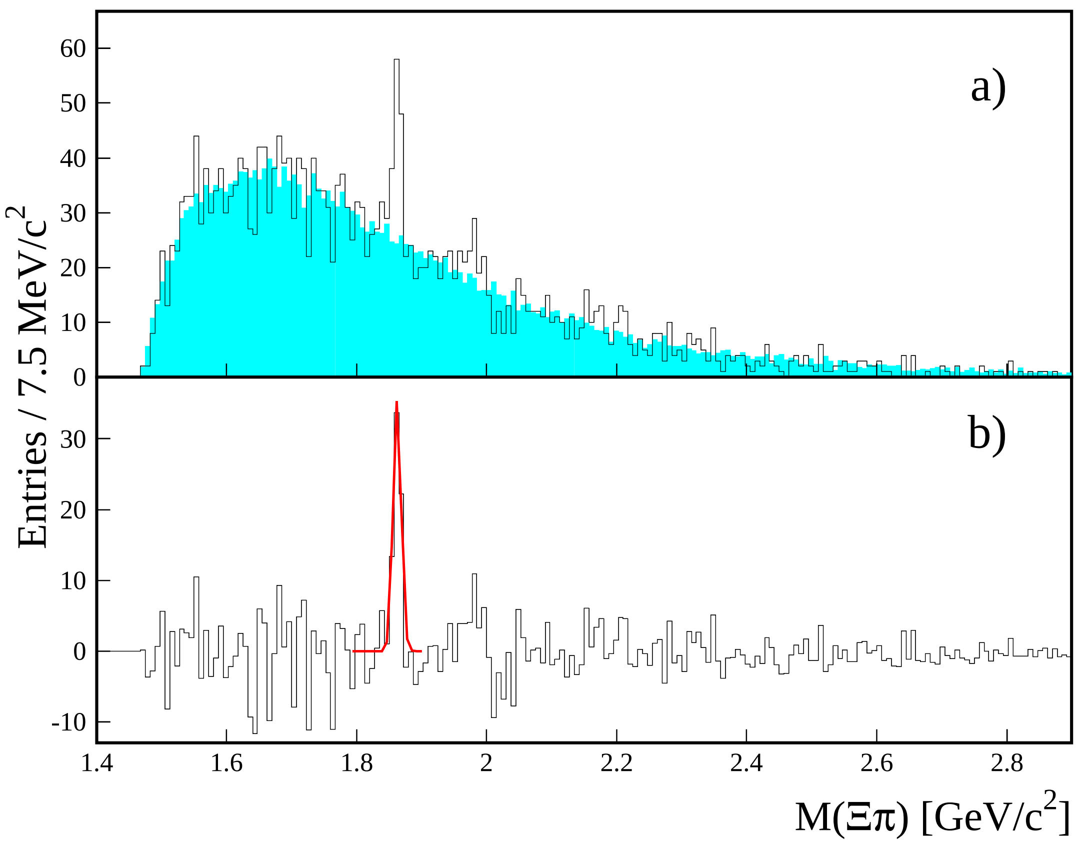
Secondary vertices to Λ

$\Lambda\pi^-$ to form Ξ^-

$\Xi^-\pi^\pm$ invariant mass

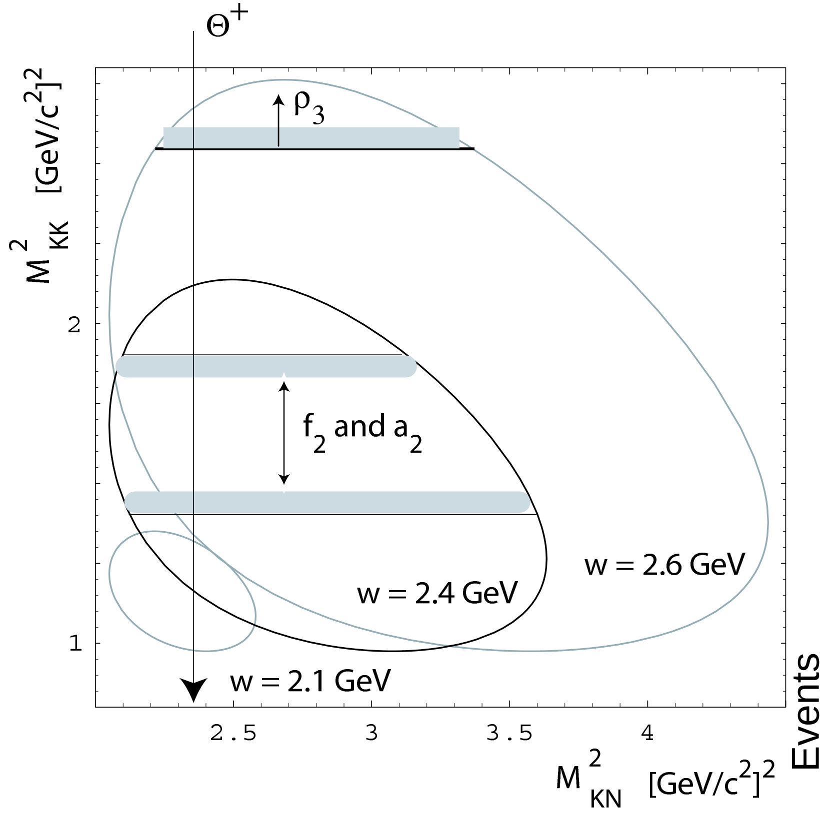


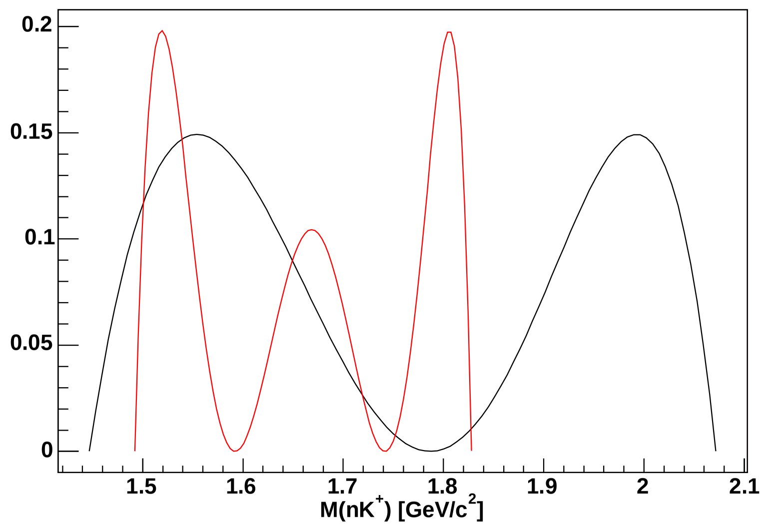


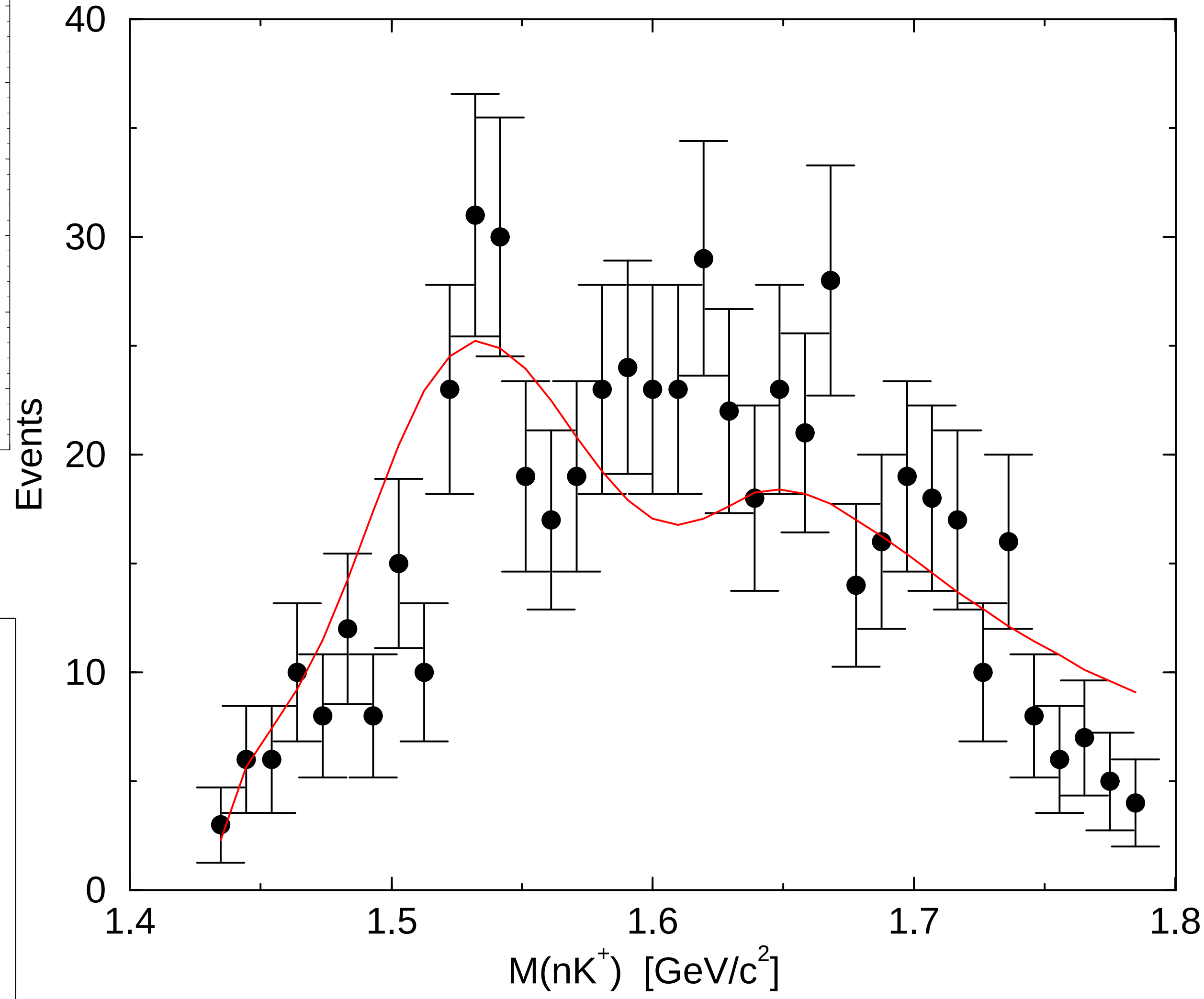


Mass Ξ^{--}	**=**	(1862 ± 0.002) **MeV**
Width Ξ^{--}	**=**	< 10 **MeV**
Strangeness, Isospin	**=**	**-2 3/2**
Quark model conf.		**ddss$\bar{\text{u}}$**

Is the Θ^+ a kinematical reflection ?





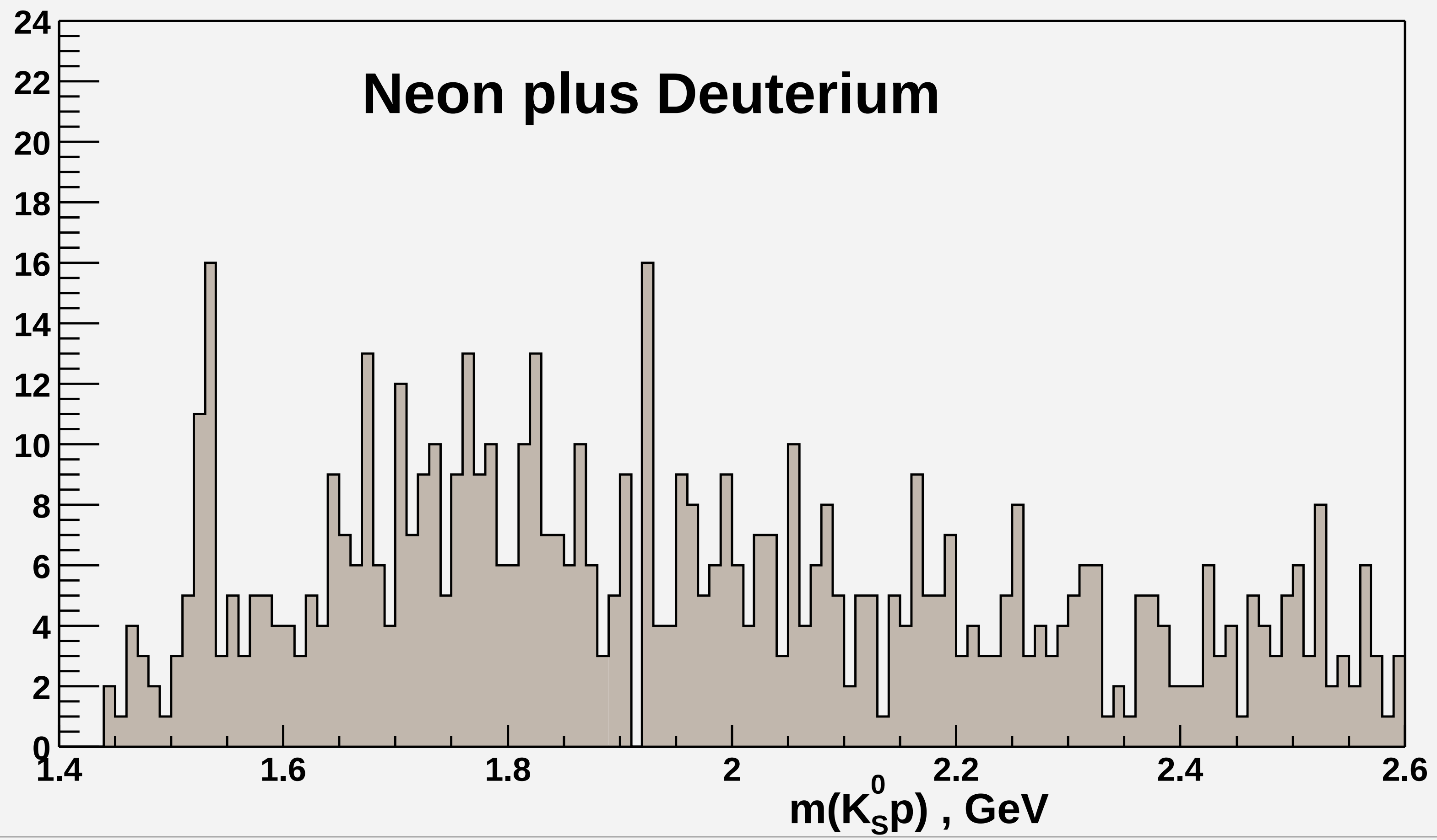


Pentaquark searches

- **Exclusive reactions**
  - CLAS, SPRING8, Crystal-Barrel: photo-production
  - COSY: pp $\rightarrow \boldsymbol{\Theta^+(1540)\Sigma^+}$
- **Inclusive reactions**
  - CERN, Fermilab: $\nu \mathrm{A} \rightarrow \mathrm{pK_s^0}$
  - Hermes, Zeus, Compass: e (μ) + A $\rightarrow \mathrm{pK_s^0X}$
  - RHIC: A + A $\rightarrow \mathrm{pK_s^0X}$

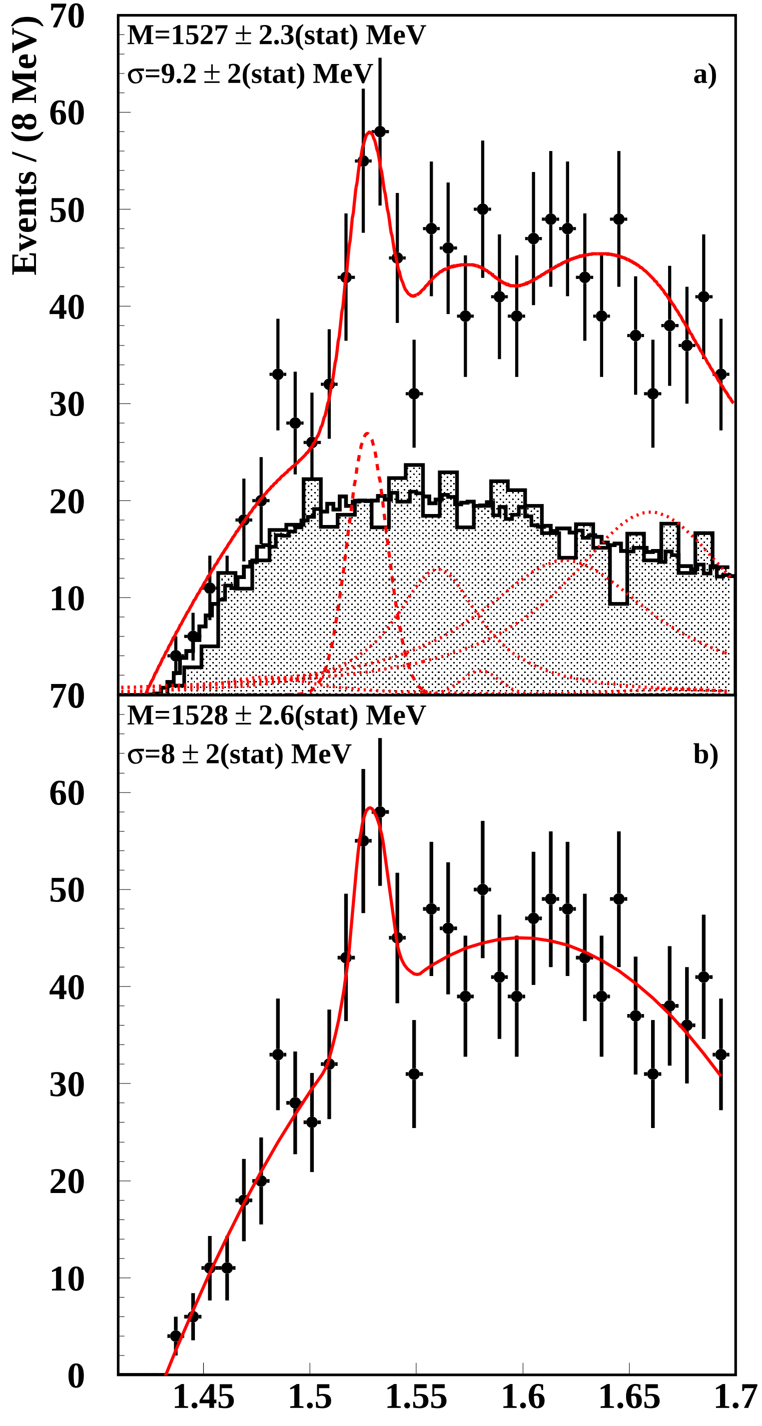
The Θ^+ from neutrino–induced reactions

CERN: WA21 WA25 WA59 FNAL: E180 E632

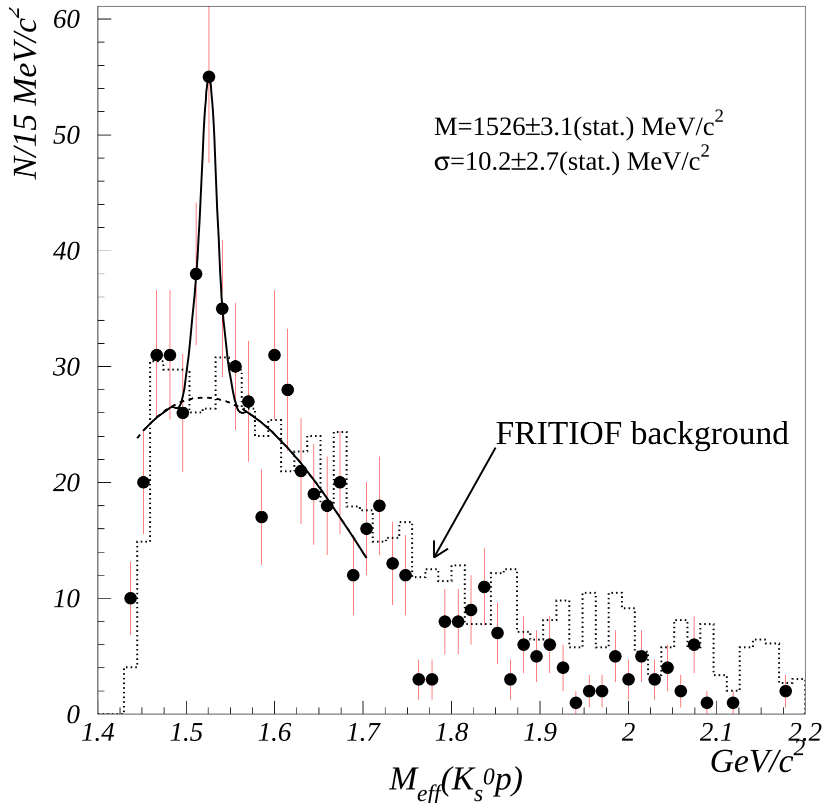


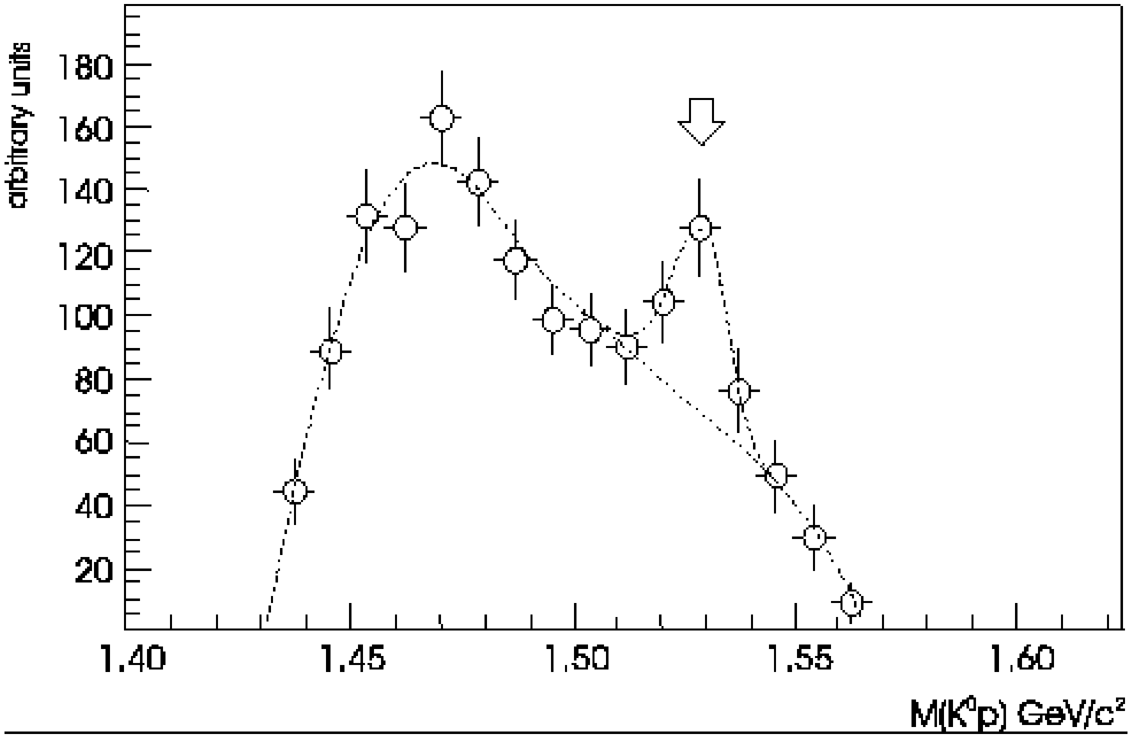
The Θ^+ from the HERMES experiment

- Quasi real photons from 27.6 GeV positron beam of the HERA storage ring at DESY.
- D_2 target.
- Integrated luminosity of 250 pb^{-1}.
- $\Theta^+ \to pK_S^0 \to p\pi^+\pi^-$ decay chain.



The Θ^+ at IHEP, Protvino: and COSY



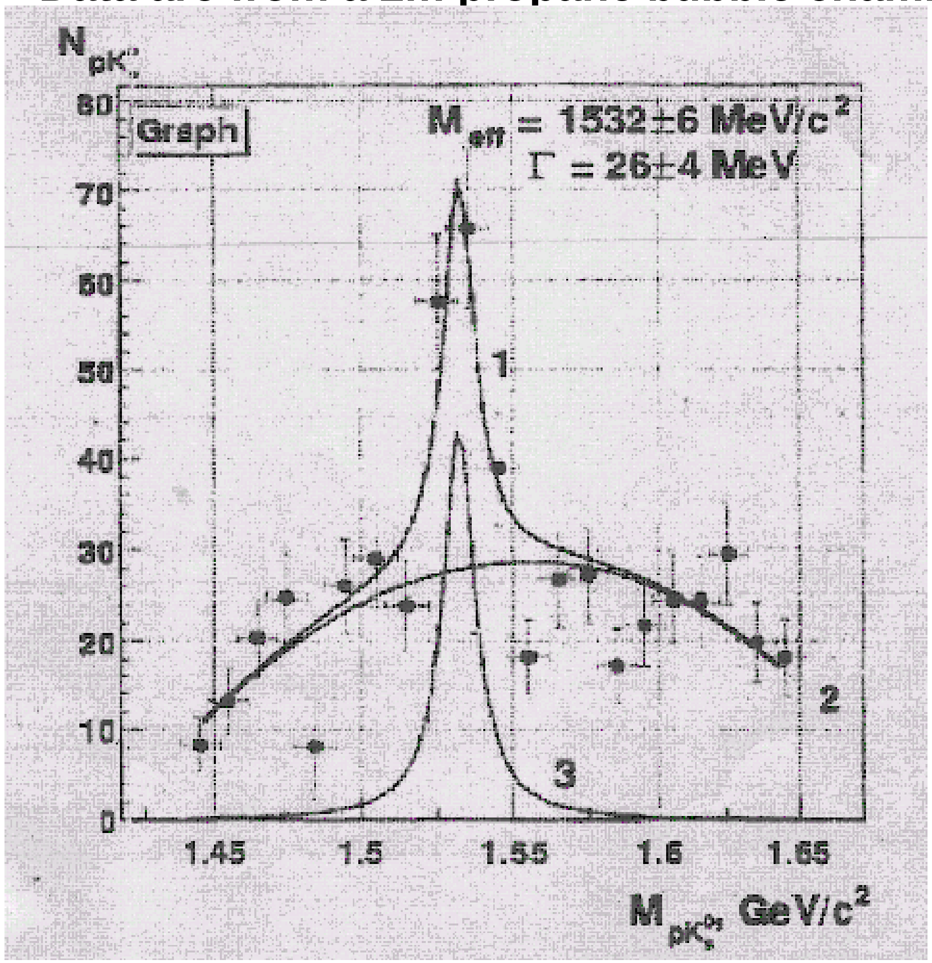


The (pK_s^0) invariant mass spectrum in the reaction $pA \to pK_s^0 + X$. The dashed histogram represents background obtained from simulations.

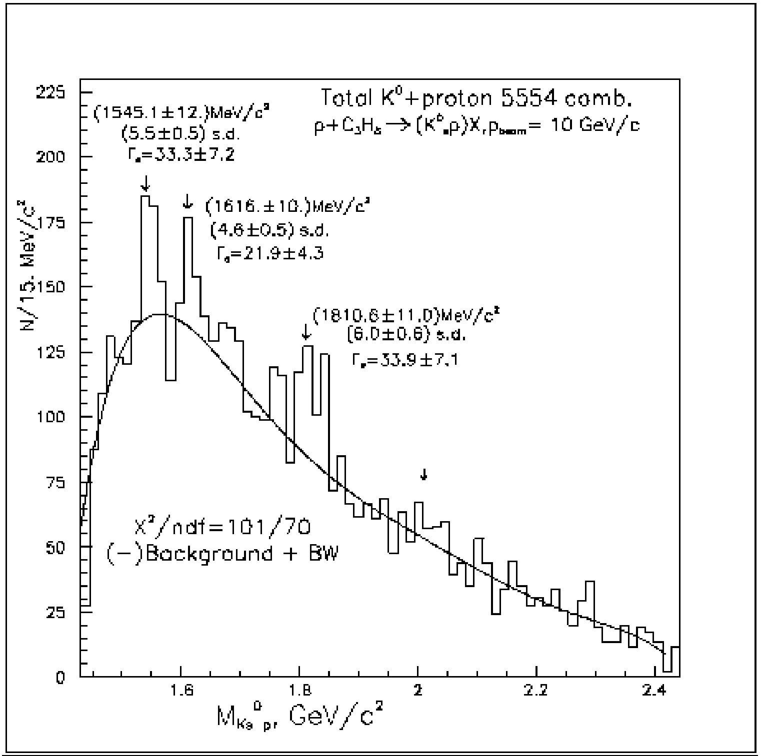
The $\mathrm{pK_s^0}$ invariant mass distribution from the reaction $\mathrm{pp} \to \Sigma^+\mathrm{K_s^0p}$ at COSY.

The Θ^+ in Mongolia and at Erivan

Data are from a 2m propane bubble chamber experiment at Dubna.

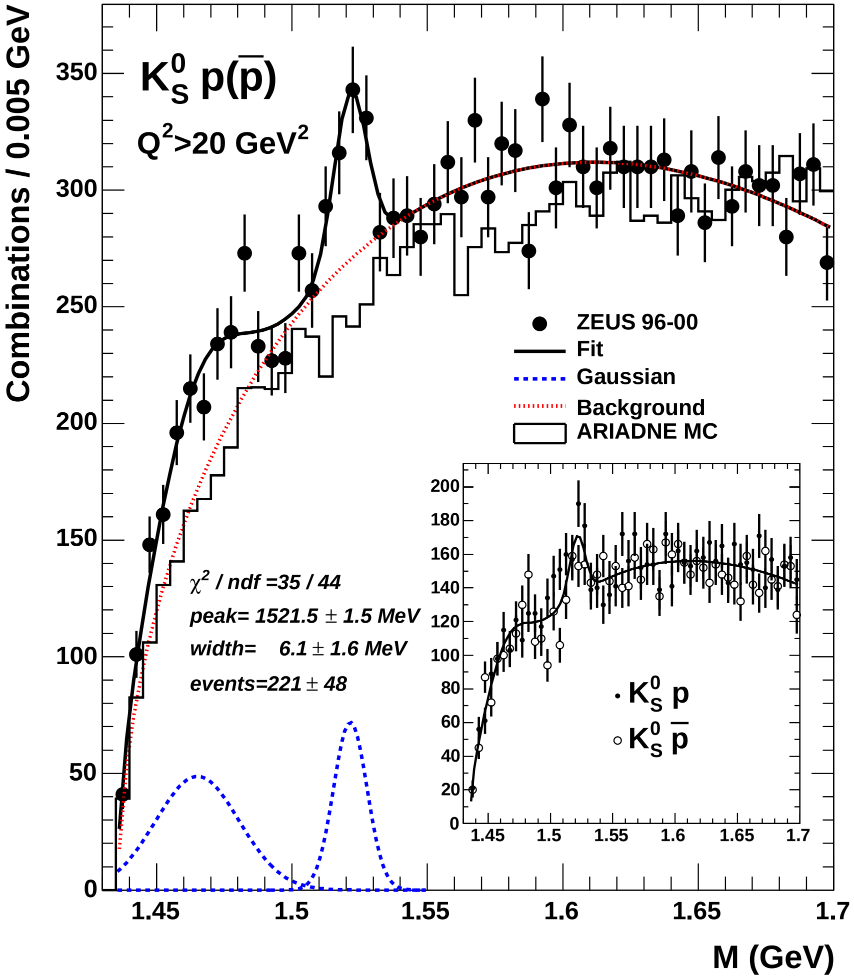


The $\mathrm{pK_s^0}$ invariant mass distribution from ^{12}C–^{12}C scattering.



Proton induced reactions, momenta between $0.35 \leq p \leq 0.9$ GeV/c^2 or $p \geq 1.7 GeV/c^2$.

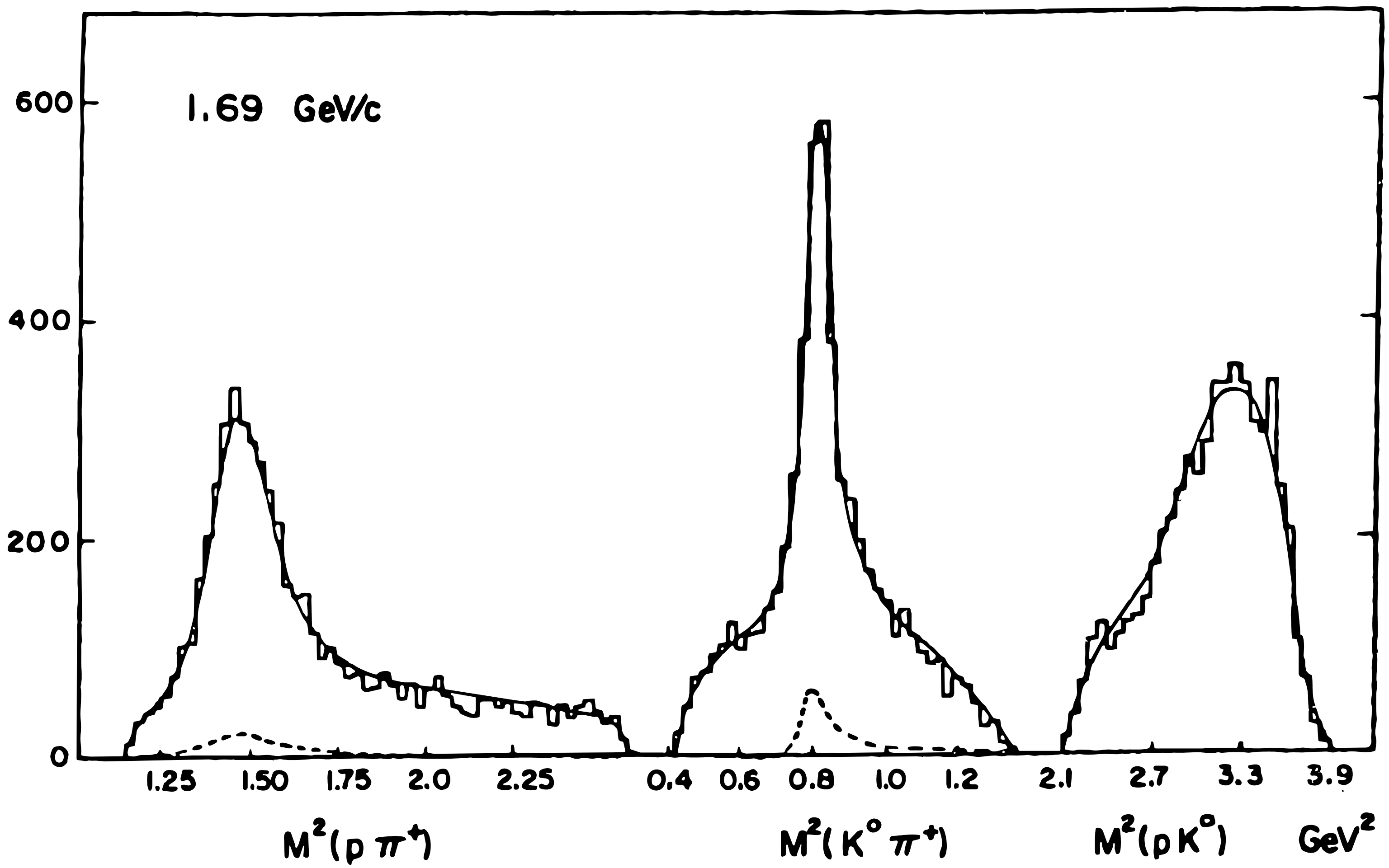
The Θ^+ at HERA



Invariant-mass spectrum for the $\mathrm{K^0_s p}$ and $\mathrm{K^0_s \bar{p}}$ channel for $Q^2 > 20$ GeV^2 at HERA.

- Solid line is result of a fit (three-parameter background)
- Histogram shows the prediction of the ARIADNE MC normalised to the data in the mass region above 1650 MeV.
- Inset shows the $\mathrm{K^0_s p}$(open circles) and the $\mathrm{K^0_s \bar{p}}$ (black dots) candidates.

The Θ^+ at CERN: $K^+p \to K^0_s p\pi^+$ at 1.69 GeV/c

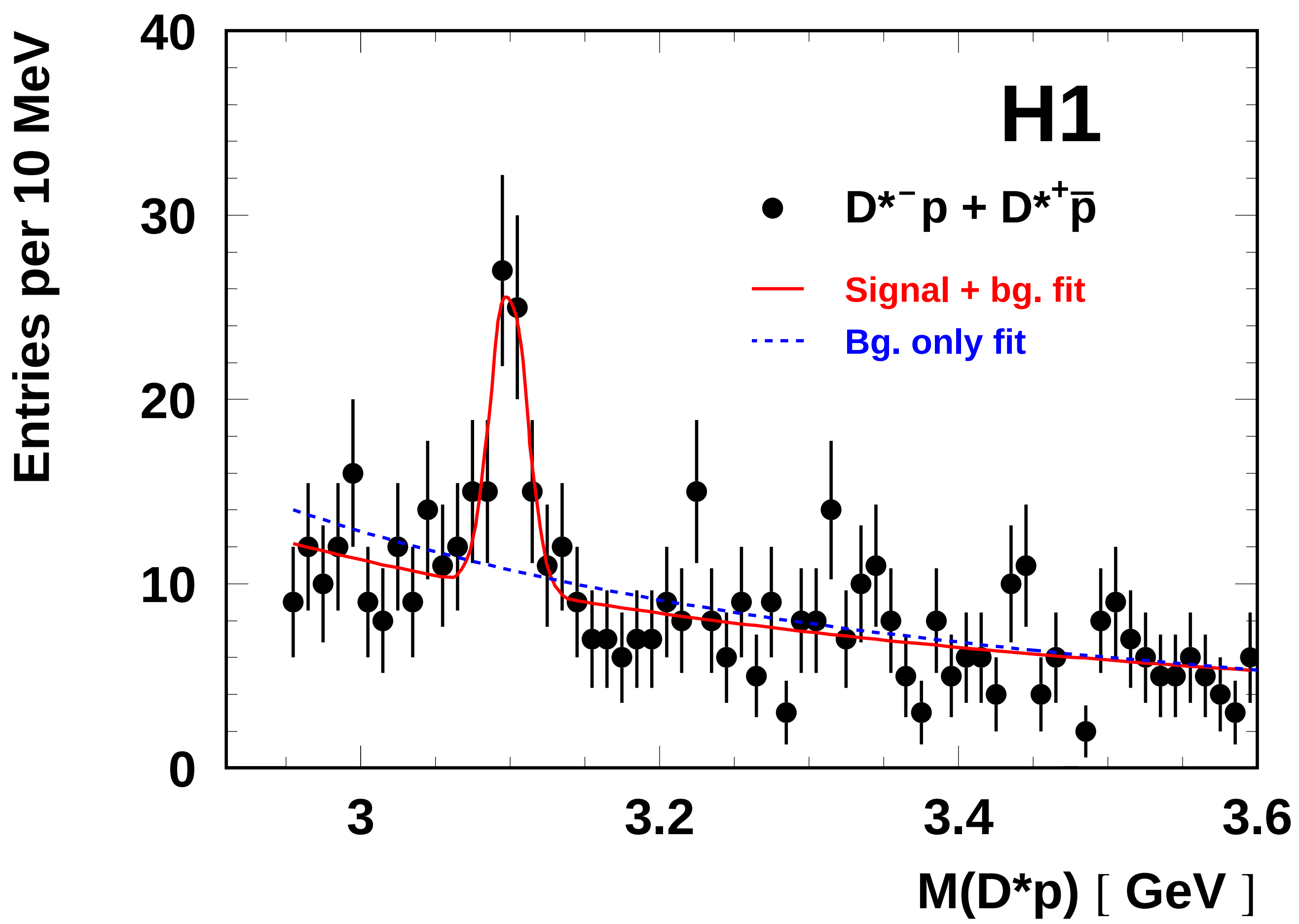


Small peak at $\sqrt{s} = 1.53$ GeV

Cross section $\sim 100\mu b \longrightarrow$ Normal hadronic cross section

The charming pentaquark from DESY

$M(D^*p)$ distribution from opposite-charge D^*p combinations in deep inelastic scattering of electrons off protons. The solid line represents a fit with a Gaussian peak plus a two–parameter background, the dashed line a fit background only.



Summary of measurements of pentaquarks. The systematic errors given in parentheses are not quoted in the papers but were estimated to be small.

Mass (MeV)	Width (MeV)	N_{event}	Statist. signif.	Reaction	Experiment
$\Theta^+(1540)$					
$1540 \pm 10 \pm 5$	< 25	19 ± 2.8	$\sim 2.7\sigma$	$\gamma C \to C' K^+ K^-$	LEPS
$1539 \pm 2 \pm 2$	< 9	29	$\sim 3.0\sigma$	$\gamma p \to n K^+ K^0_s$	DIANA
$1542 \pm 2 \pm 5$	< 21	43	$\sim 3.5\sigma$	$\gamma d \to p n K^+ K^-$	CLAS
$1540 \pm 4(\pm 3)$	< 25	63 ± 13	4.8σ	$\gamma p \to n K^+ K^0_s$	SAPHIR
$1533 \pm 5(\pm 3)$	< 20	27	$\sim 4.0\sigma$	ν–induced	CERN, FNAL
$1555 \pm 1 \pm 10$	< 26	41	$\sim 4.0\sigma$	$\gamma p \to n K^+ K^- \pi^+$	CLAS

Mass (MeV)	Width (MeV)	$\mathrm{N}_{\mathrm{event}}$	Statist. signif.	Reaction	Experiment
1528 ± 4	< 19	~ 60	$\sim 4\sigma$	γ^*–induced	HERMES
$1526 \pm 3 \pm 3$	< 24	50	3.5σ	p-p reaction	SVD-2
1530 ± 5	< 18		3.7σ	p-p reaction	COSY
1545 ± 12	< 35	~ 100	$\sim 4\sigma$	p-A reaction	YEREVAN
1532 ± 6	< 26	~ 70	$\sim 4.6\sigma$	A-A reaction	Mongolia
$1521.5 \pm 1.5^{+2.8}_{-1.7}$	< 6	221	4.6σ	Fragmentation	ZEUS
$\Xi(1862)$					
1862	< 21		4.6σ	ν–induced	NA49
$\Theta_c(3099)$					
$3099 \pm 3 \pm 5$			5.4σ	γ^*–induced	HERA

Where	Reaction	Mass interval	Limit	Comment
BES	$e^+ e^- \to J/\psi \to KNX$	1520-1560	$<10^{-5}$ (branching)	Azimov: $< 10^{-5}$
HERA-B	$pA \to K^0 p X$	15	N/A	vs NA49,SVD
PHENIX	$dAu \to K^+ \bar{n} X$	1500-1600	N/A	vs STAR, Dubna
CDF	$pp \to Z \to K^0 p X$	1525-1545	<87(79) events	vs ZEUS, STAR
ALEPH	$e^+ e^- \to Z \to K^0 p X$	1525-1545	<.003 (events)	No D-events (K-L)
DELPHI	$e^+ e^- \to Z \to K^0 p X$	1500-1750	<.006(events)	No D-events (K-L)
ZEUS	$ep \to \Xi \pi X$	1840-1880	N/A	vs NA49
CDF	$pp \to \Xi \pi X$	1840-1880	126/?	vs NA49
FOCUS	$\gamma A \to \bar{D} p X$	N/A	N/A	vs H1
WA89	$\Sigma^- A \to \Xi \pi X$	1840-1880	N/A	vs NA49

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POSTDICTIONS:

- **Molecular NK state in S–wave ? Parity negative.**
  Too narrow, should be 500 MeV

- **The Θ^+ has isospin I=2 and negative parity.**
  Narrow because it decays via an isopin violating amplitude into p+K
  (I=0 or 1)
  Θ^{+++} predicted, decays only by weak interaction !
  Parity of Θ^+ is negative.

- **Lattice QCD**
  Evidence for Θ^+ claimed, parity negative.

- **Diquark model:** $[QQ]^{\bar{3}_{color}\bar{3}_{flavor}0_{spin}}$ **is energetically favored.**

$$[QQ]^{\bar{3}_{color}\bar{3}_{flavor}0_{spin}}\,[QQ]^{\bar{3}_{color}\bar{3}_{flavor}0_{spin}}\,[\bar{Q}]^{\bar{3}_{flavor}} \supset [Q^4\bar{Q}]^{\bar{10}_{flavor}}$$

$\rightarrow$ **Diquarks are bosons**

Diquark – antidiquark wave function: $\left[[\mathrm{QQ}]^{\bar{3}_c\bar{3}_f0_s}\,[\mathrm{QQ}]^{\bar{3}_c\bar{3}_f0_s}\right]^{3_c}$

$\rightarrow$ **Two identical diquarks:**

Antisymmetry in color $\Rightarrow$ antisymmetry in space, Q^4 has negative parity, $Q^4\bar{Q}$ positive parity.

$\rightarrow$ **In flavor there are 6 diquarks. SU(3):**

$$\bar{6}\otimes\bar{3} = \bar{10}\oplus 8$$

$\rightarrow$ **Mixing decouples 8 and $\bar{10}$**

$[\mathrm{ud}]\,[\mathrm{ud}]\,\bar{\mathrm{d}} = \mathrm{N}(1440)\mathrm{P}_{11}$ **and** $[\mathrm{ud}]\,[\mathrm{us}]\,\bar{\mathrm{s}} = \mathrm{N}(1710)\mathrm{P}_{11}$

$\rightarrow$ **Model predicts fewer states and lower–mass Ξ^{--}**

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Θ^+ summary

- There is evidence for a narrow positive–strangeness baryon resonance Θ^+ from several sources
- All experiment have statistical significance of $\sim 5\sigma$
- No absolutely conclusive evidence, but agreement is impressive
- Produced by photon interactions (and hadronically in DIANA)
- Production mechanism partly controversial
- Spin and parity unknown
- Predicted by chiral soliton model
- should have $\mathbf{J^P = 1/2^+}$ and
- be member of an (anti–) decuplet with 3 exotic states (Ξ^{--} and Ξ^+)
- Production and decay predictions for non-strange member