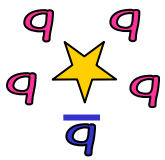


The Rise and Fall of the Pentaquarks in Experiments

Reinhard Schumacher

Carnegie Mellon University

PANIC, Santa Fe, October 28, 2005

Overview

- Pentaquarks: brief history… predictions…
- Experimental evidence (since PANIC Oct.'02)
  - The Θ^{+} at LEPS, ITEP, CLAS, SAPHIR, ZEUS, HERMES…
  - The Ξ^{--} at NA49/CERN
  - The Θ^{0}_{c} at H1/HERA
  - The Θ^{++} at STAR/RHIC
- Compare "+" and "–" evidence by reaction channel
- Theme: Bandwagon effect led to overly-optimistic assessments of data by many groups

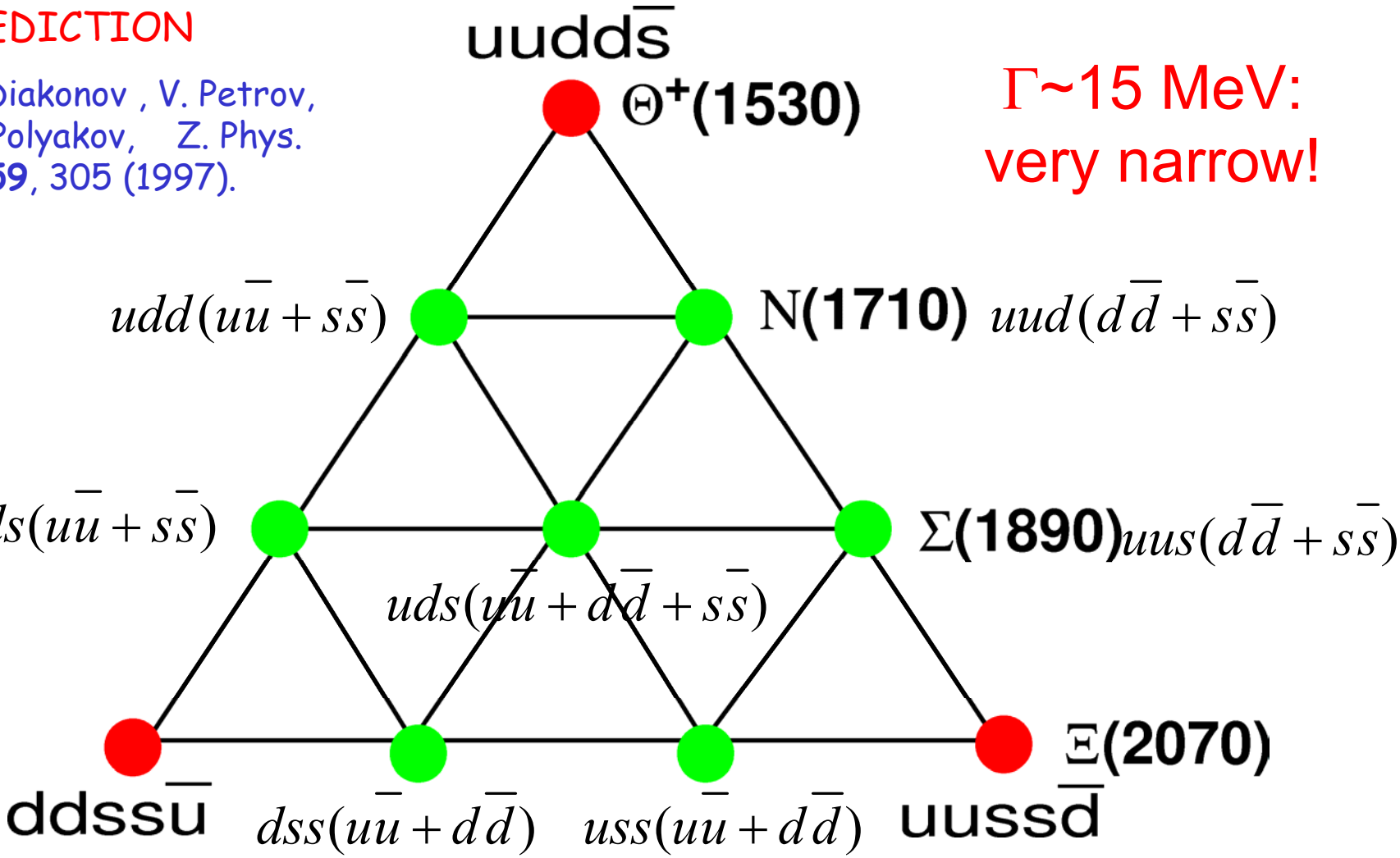
What are Pentaquarks?

- Objects with 4 quarks and 1 anti-quark
- "Exotics" contain an anti-quark different in flavor than the 4 quarks → the anti-quark can't annihilate! The quantum numbers are *impossible* with just 3 quarks.
- Example: $uudd\bar{s}$ (exotic); The "Θ^+"
  - Baryon number = 1/3 + 1/3 + 1/3 + 1/3 - 1/3 = 1
  - Strangeness = 0 + 0 + 0 + 0 + 1 = +1
- Early history:
  - Bag models: R.L.Jaffe (76), deSwart(80)
  - Soliton models: Diakonov, Petrov (84); Chemtob(85); Praszalowicz(87), Walliser(92)
- PDG'04: Θ^+ ***
  - M = 1539.2 ± 1.6 MeV
  - Γ = 0.9 ± 0.3 MeV
  - $\Theta^+ \rightarrow K^+ n,\ \bar{K}^0 p$

Anti-Decuplet in a Chiral-Soliton Model

PREDICTION

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



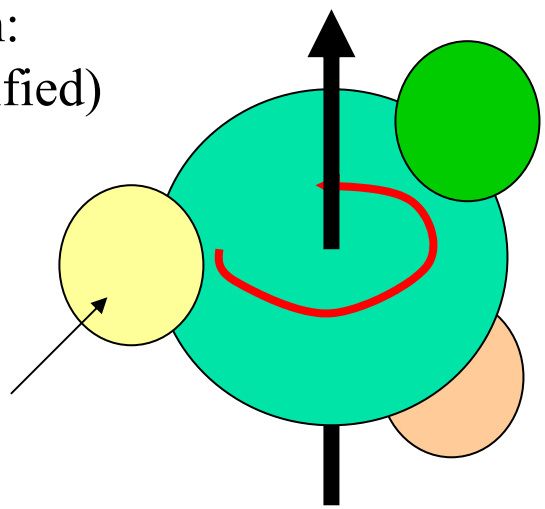
Γ~15 MeV: very narrow!

Pentaquarks – Three Model Descriptions

Chiral soliton model:
(Diakonov, Petrov, Polyakov)

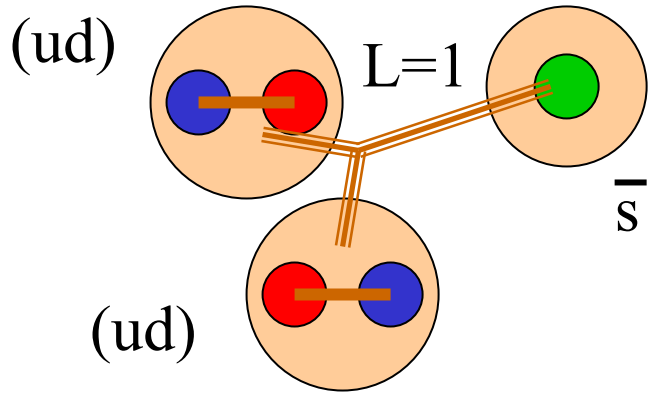
Pentaquarks in such models emerge as rotational excitations of the soliton [rigid core (q^3) surrounded by meson fields ($q\bar{q}$)]; $J^P = \frac{1}{2}^+$

Soliton:
(simplified)



Meson fields

Quark description:
(Jaffe, Wilczek)

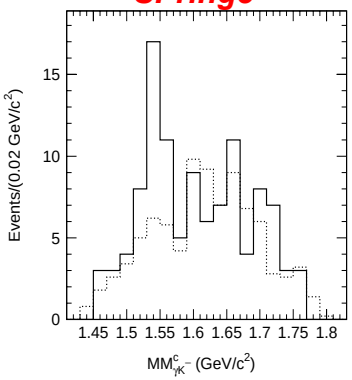


Two bosonic di-quarks (ud), plus $\bar{s}$; fermionic state demands L=1, giving $J^P = \frac{1}{2}^+$

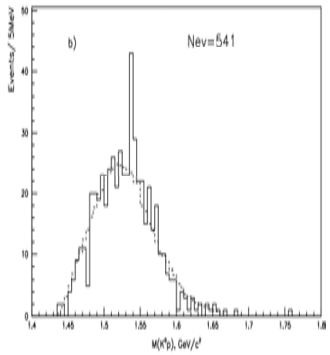
Lattice QCD →existence and J^P predictions are inconclusive.

Positive Evidence (most of it...)

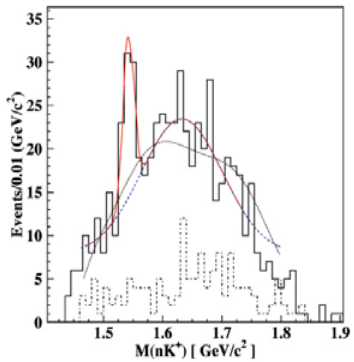
SPring8



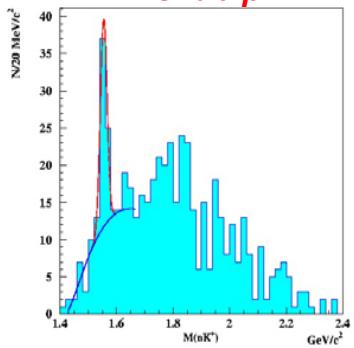
DIANA

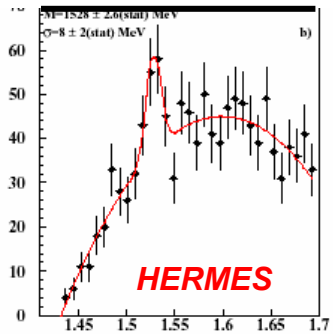


JLab-d

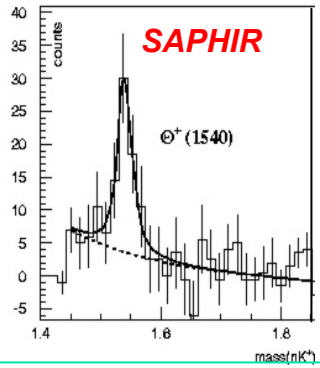


JLab-p

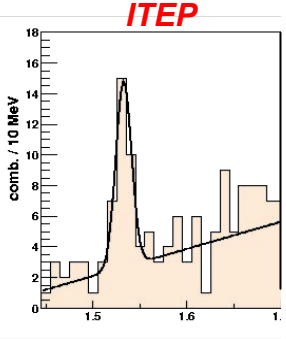




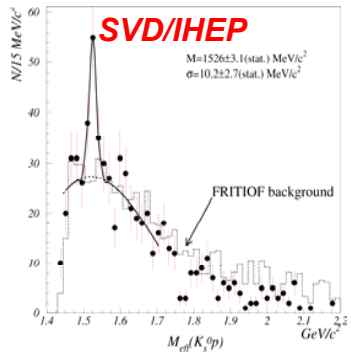
SAPHIR



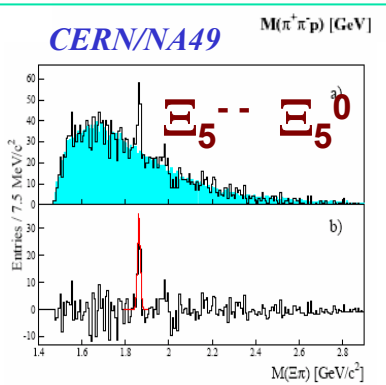
ITEP



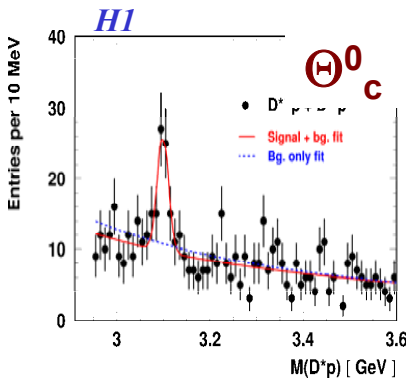
SVD/IHEP



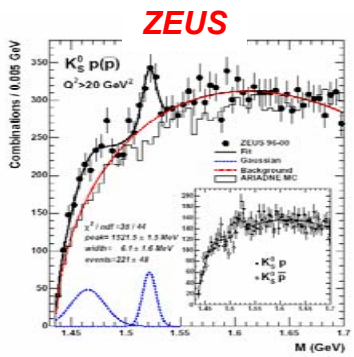
CERN/NA49



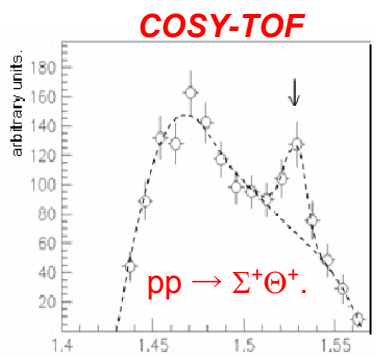
H1



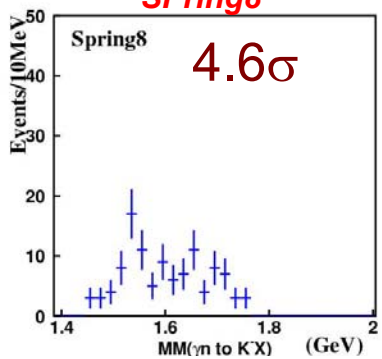
ZEUS

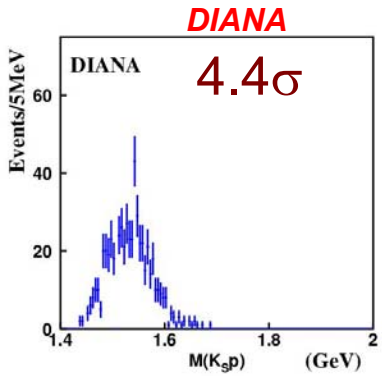


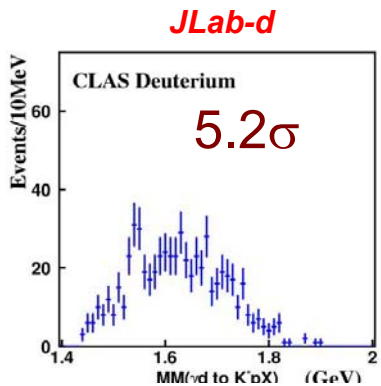
COSY-TOF

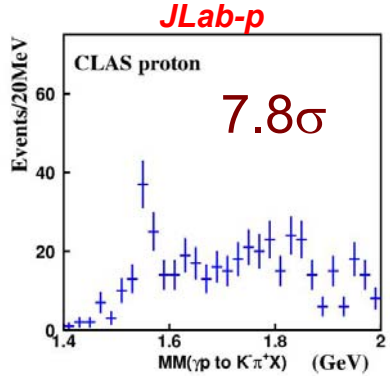


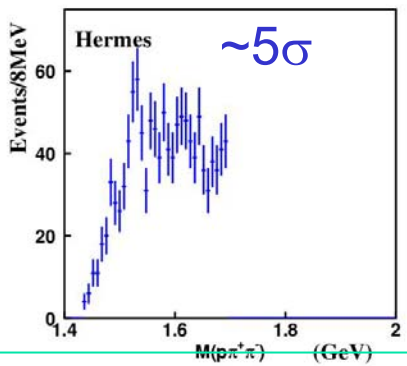
The Data Without "Fits"

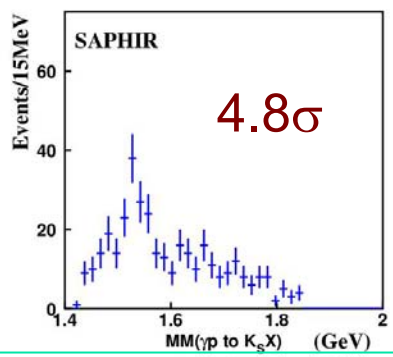


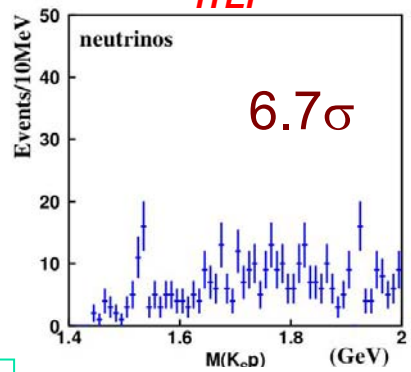


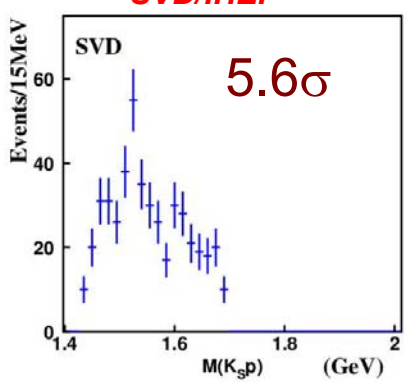


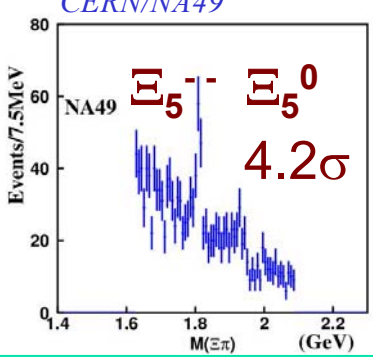


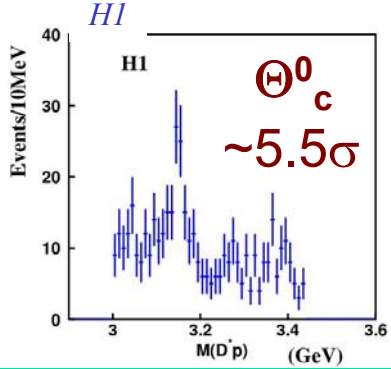


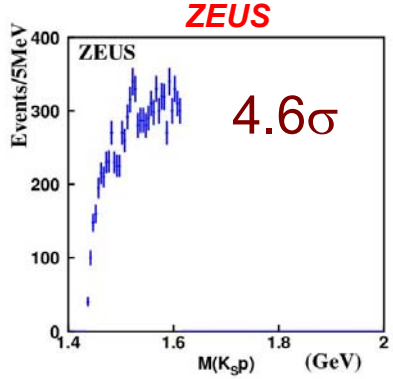


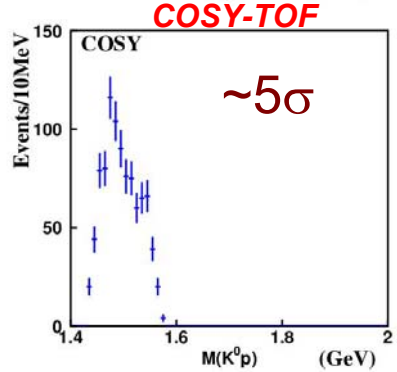












Skeptic's Comments

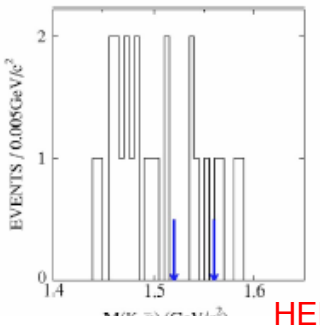
- Most of the positive evidence for pentaquark states is statistically very weak, despite claims of over 4 σ significance.

- Without "guides for the eye", many experimental spectra have low signal-to-noise, and large poorly-known backgrounds. No clean background-free peaks have been reported.

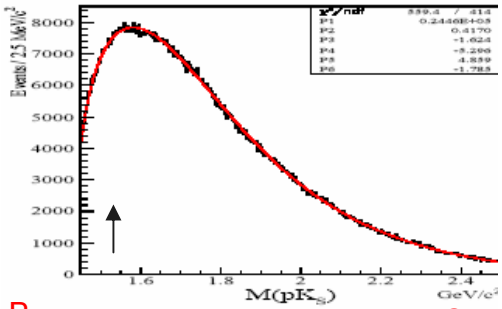
- There seems to have been a "bandwagon effect" in place from the start: frantic attempt to get on board the list of positive sightings.

Anti-evidence for Pentaquarks

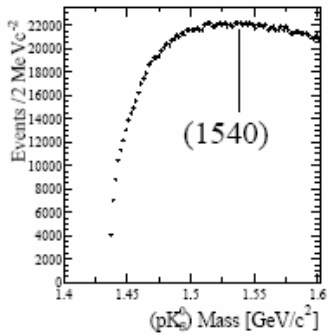
BES



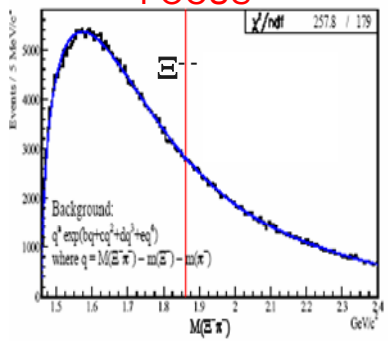
FOCUS



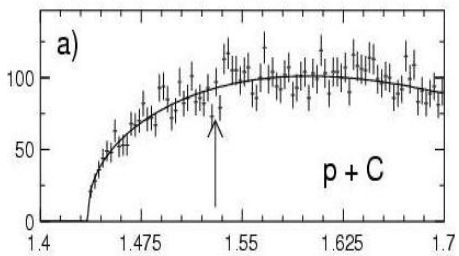
BABAR



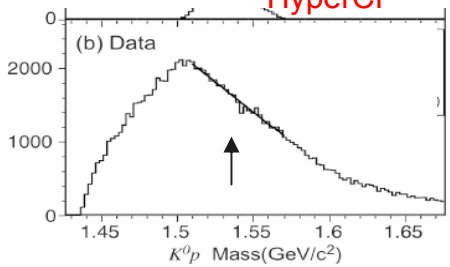
FOCUS



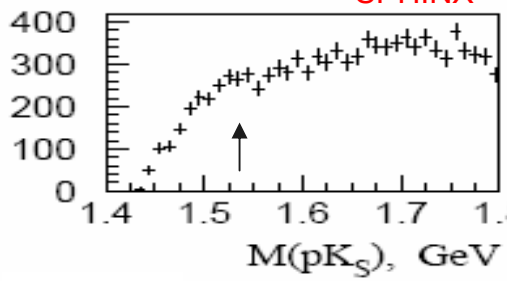
HERA-B



HyperCP

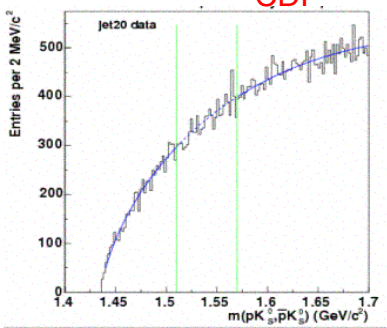


SPHINX

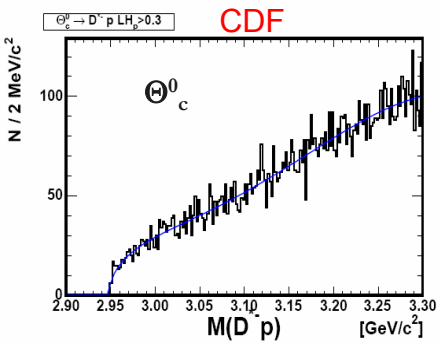


+ more

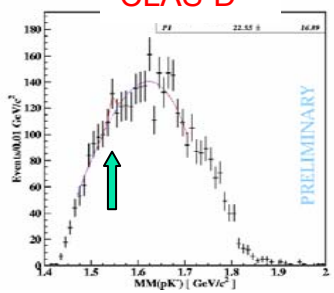
CDF



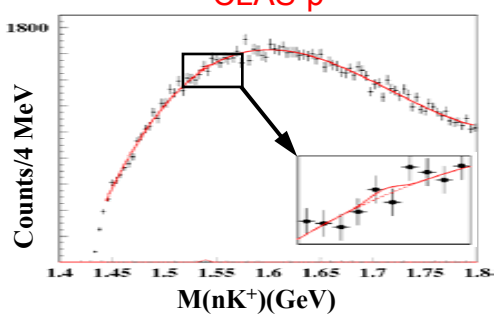
CDF



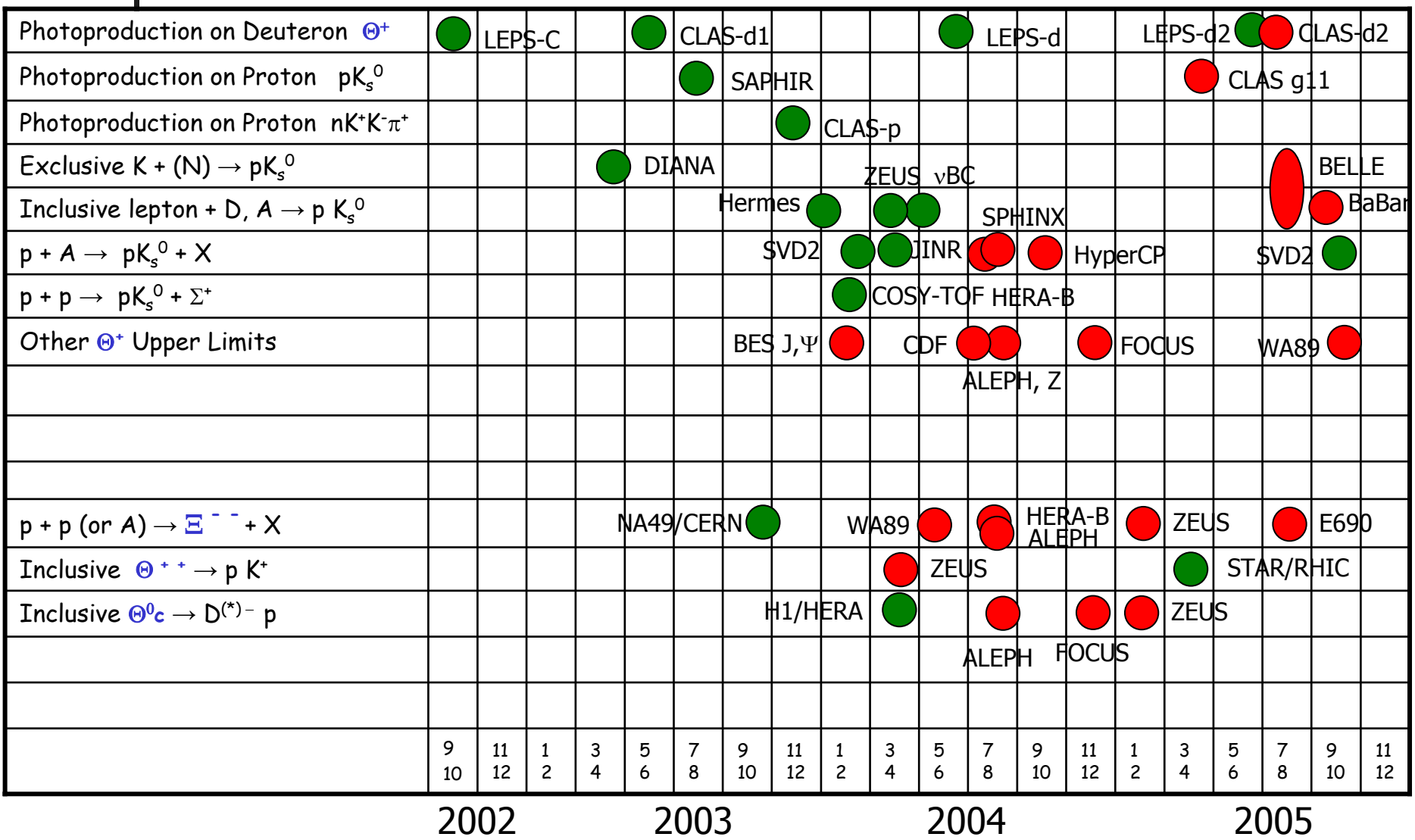
CLAS-D



CLAS-p



Pentaquark Exp'ts Timeline

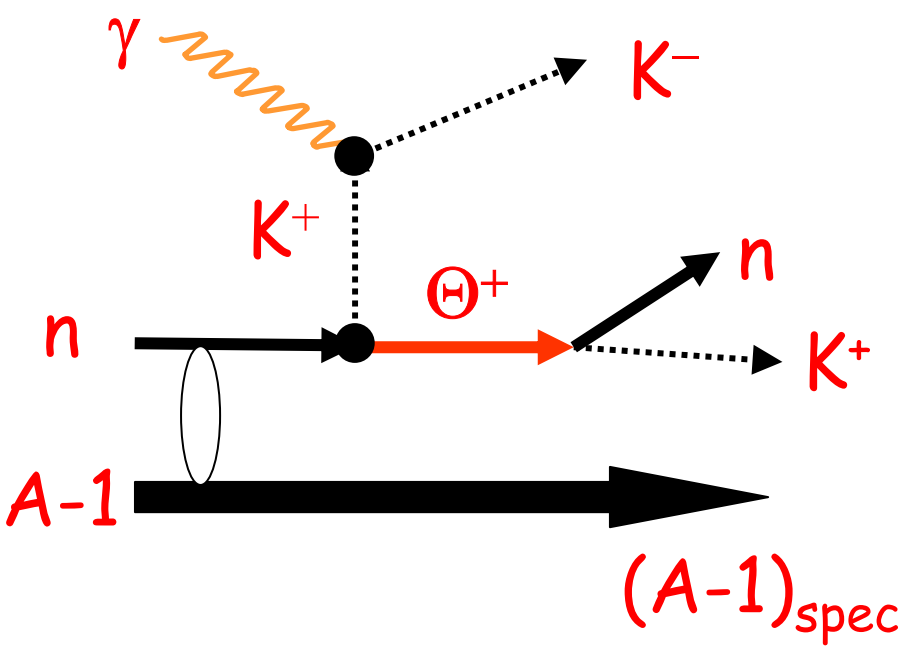


Impact on particle physics:

- Since October 2002:
  - 50 + experimental papers, both pro and con
  - 550 + theory papers

First Reported Observation of Θ^+ at LEPS/SPring-8

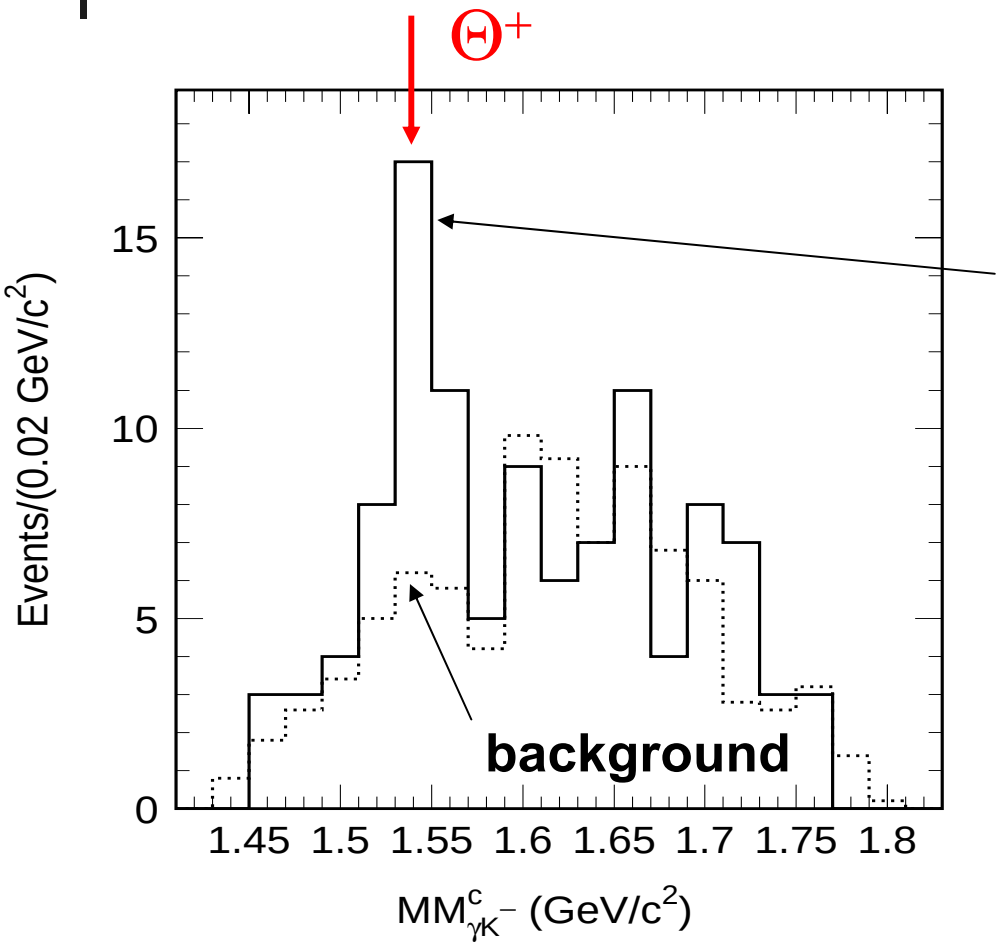
$$\gamma\, C \rightarrow K^- K^+ X$$



- Inclusive measurement on Carbon target
- Detect only the two K's
- Apply Fermi motion correction to MM (γ,K^-)

T. Nakano, PRL91, 012002, (2003)

First Reported Observation of Θ^+ at LEPS/SPring-8



$$\gamma\, C \rightarrow K^- K^+ X$$

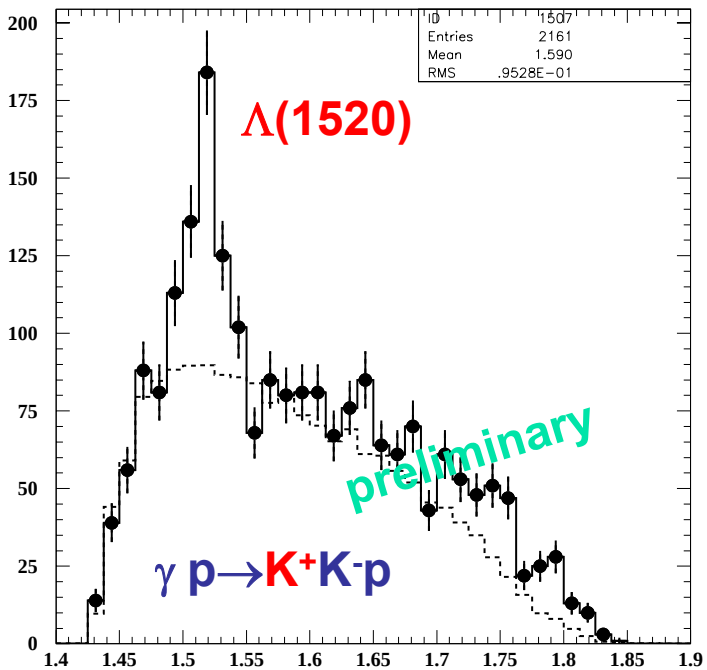
- Solid: signal sample
- Dashed: background from protons in upstream H_2 target, normalized to signal above 1590 MeV
- Significance: 4.6σ
- Mass 1540 ± 10 MeV
- Width < 25 MeV

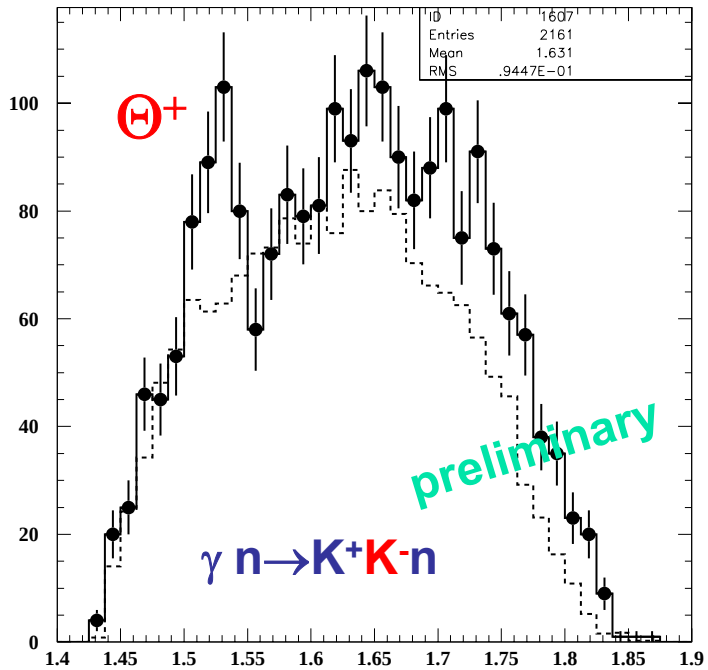
T. Nakano, PRL 91, 012002 (2003)

LEPS/SPring-8 $\gamma(n) \rightarrow K^+K^-n$

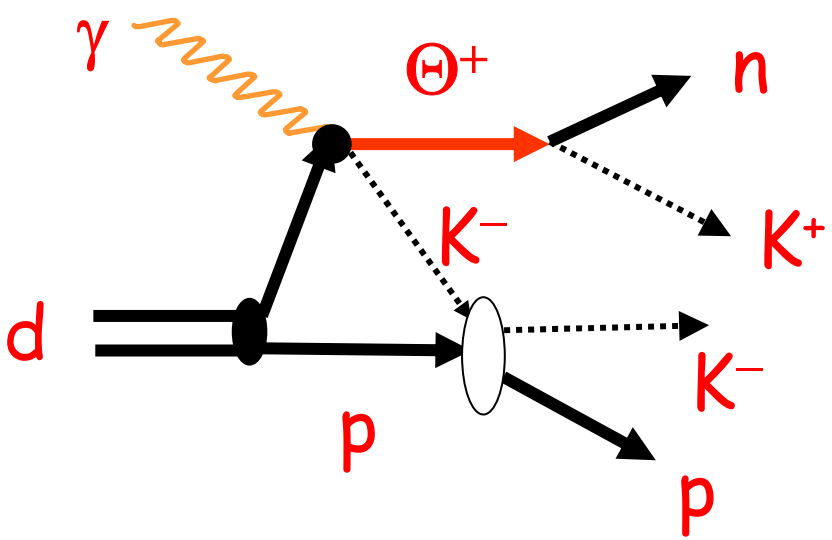
2004

- Deuteron target; the proton is a spectator (undetected).
- Fermi motion is corrected to get the missing mass spectra.
- Tight ϕ exclusion cut is essential.
- Background is estimated by mixed events.





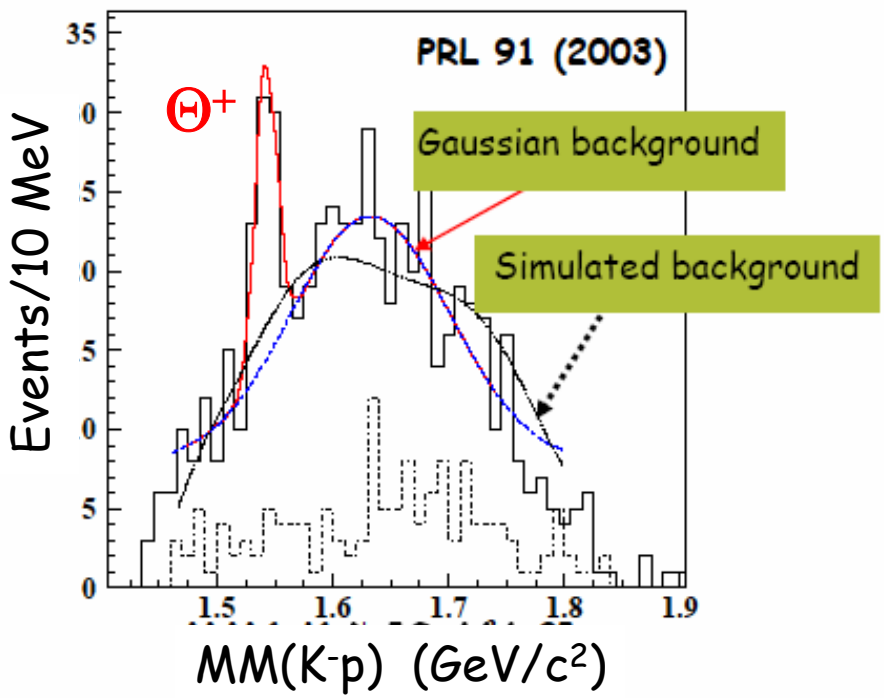
Photoproduction at CLAS/JLab



- $\gamma D \rightarrow p K^+ K^- (n)$ exclusive channel
  - No Fermi motion correction needed
  - FSI puts K^- at larger lab angles: better CLAS acceptance
  - FSI not rare: in ~50% of $\Lambda(1520)$ events both nucleons detected with p>0.2 GeV/c

- CLAS Collaboration (S. Stepanyan, K. Hicks, *et al.*), hep-ex/0307018, PRL 91 252001 (2003).

CLAS/JLab Θ^+: Exclusive Process I



- Simple cuts: PID, missing neutron mass cut , cut on missing neutron momentum, p_n>0.08 GeV, cut out $\phi(1020)$ and $\Lambda(1520)$ events, and cut on K^+ momentum, <1 GeV/c.
- Only ~40 events in the mass peak of the Θ^+.
- Statistical significance calculated as $N_S/\sqrt{N_B}$ within $\pm 2\sigma$ of the peak, ranges from 4.6σ to 5.8σ, depending on the fitted background shape.

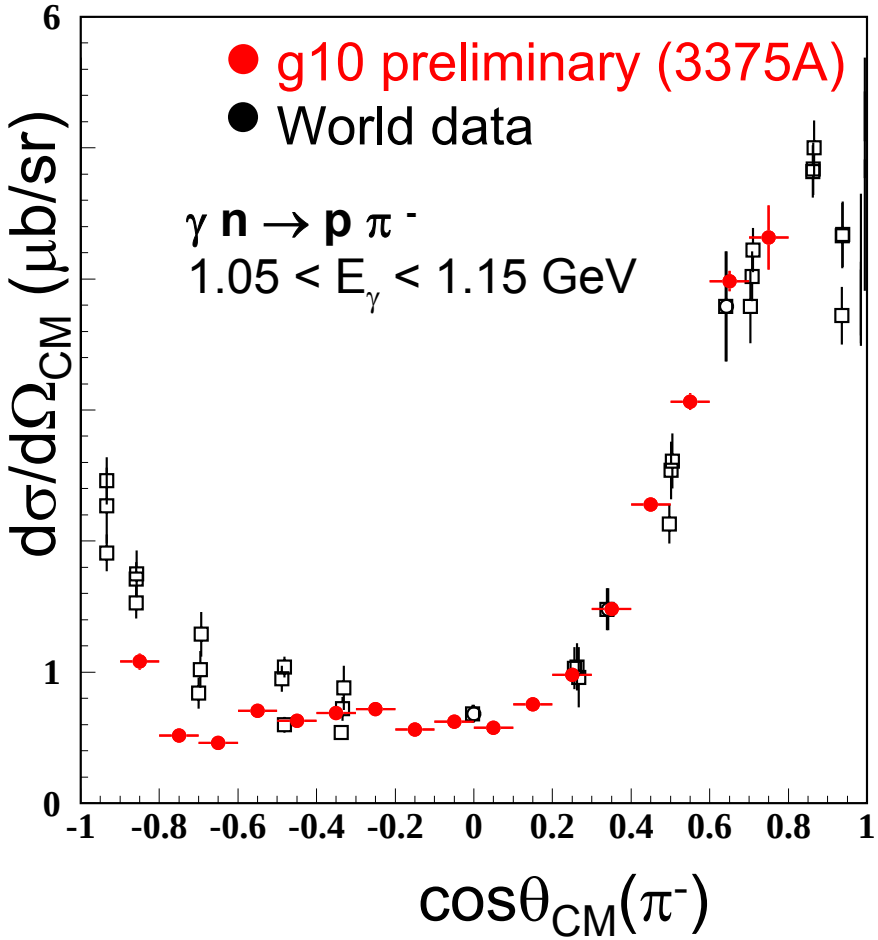
CLAS statement - 06/30/2004

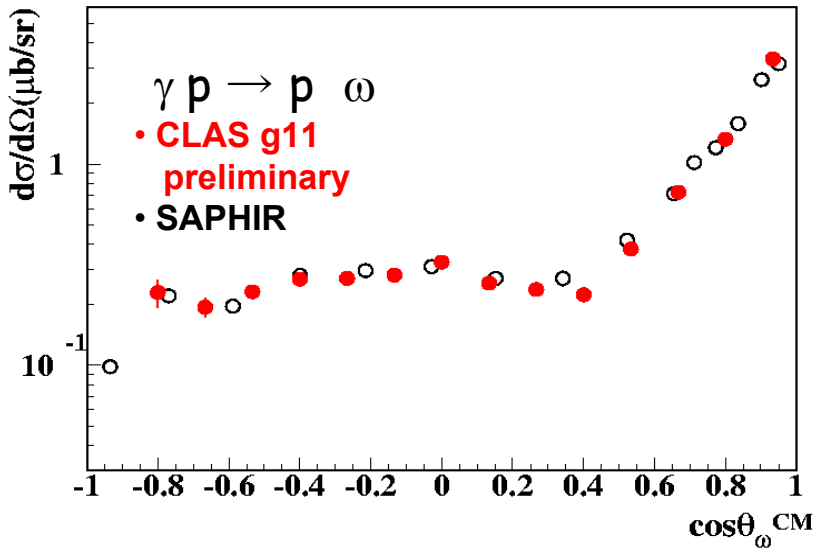
"Improved analysis of this data finds that the significance of the observed peak may not be as large as indicated. We expect a definitive answer from a much larger statistics data set that is currently being analyzed".

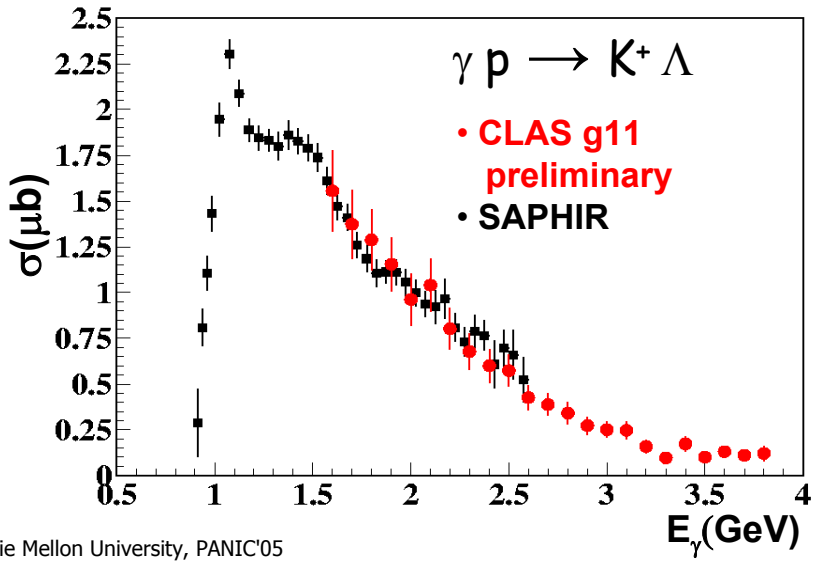
2004: CLAS High-Stat's Data

γ D x6

γ p x10







An Upper Limit on Θ+ Production with CLAS.

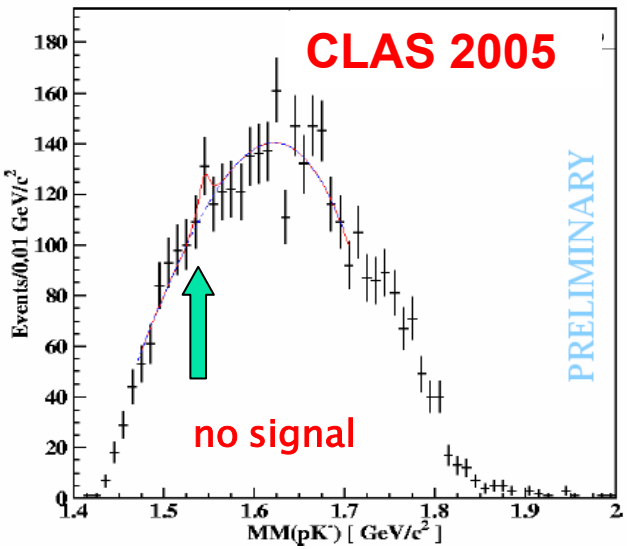
$$\gamma D \rightarrow K^- p K^+ n$$

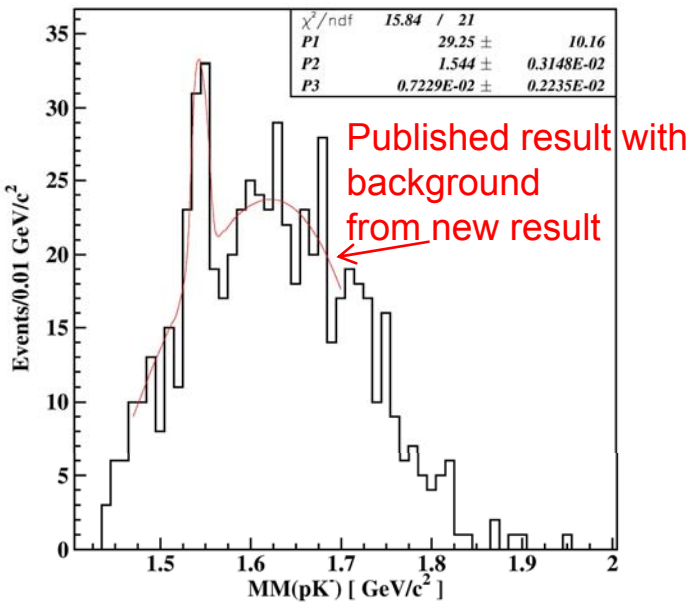
- The new data show no signal

(July 2005, Lepton-Photon Conf.)

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

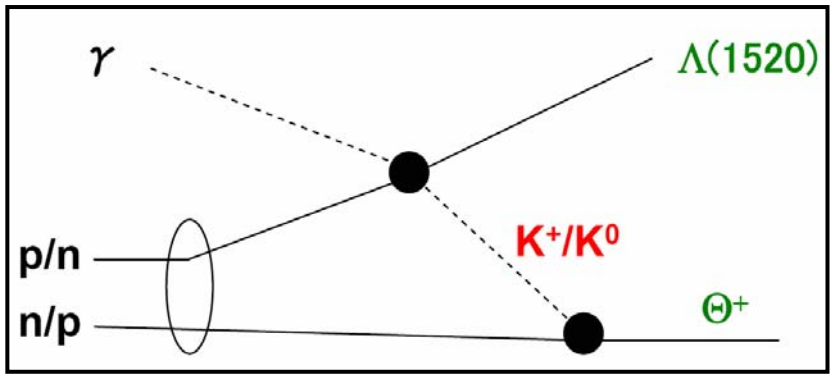
σ_{Θ^+} < 4-5 nb (95% CL)
(model dependent).

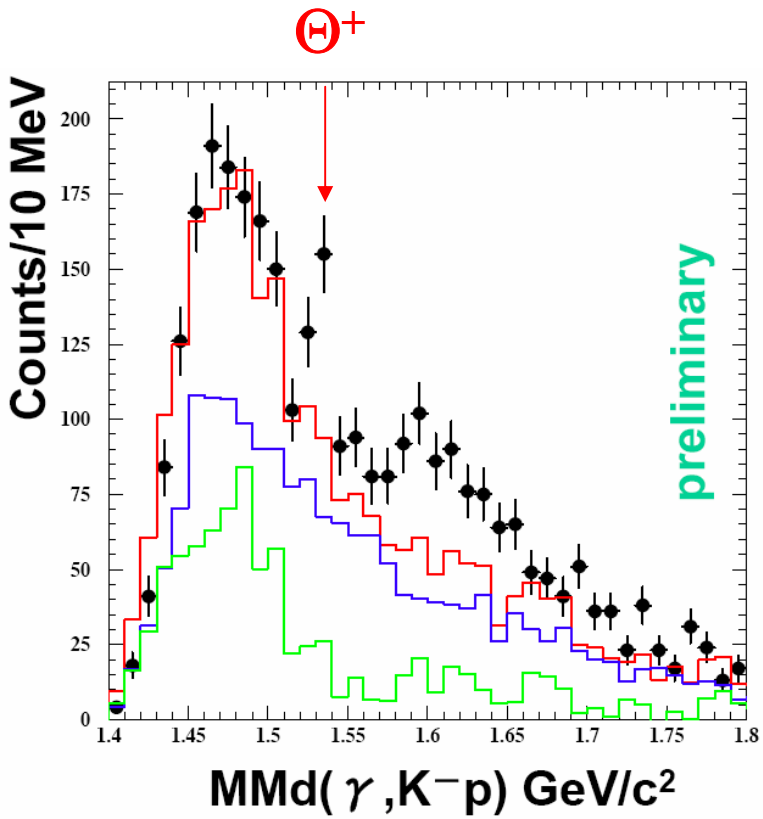




- In previous result, the background is underestimated. New estimate of the original data gives a significance of ~3σ, possibly due to fluctuations.

Newest LEPS/SPring-8 Claim





Select on Λ(1520)--> K^- p

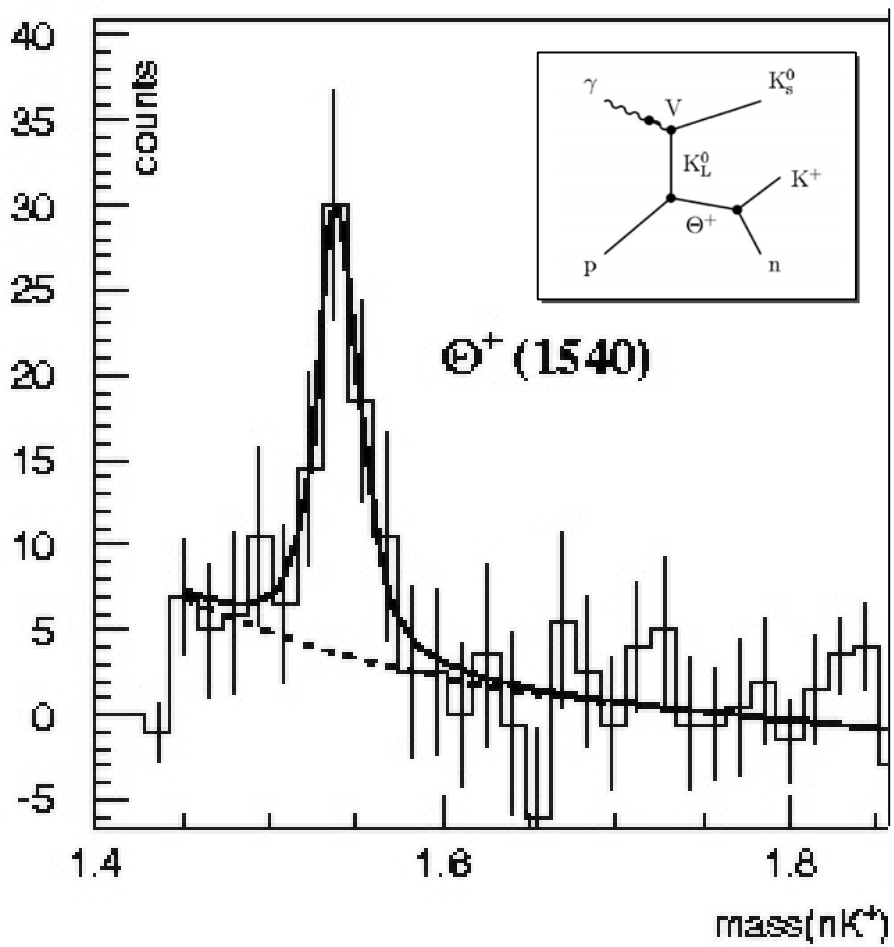
Very forward c.m. acceptance

Strangeness of "Θ+" is tagged

T. Nakano, Presented at International Conference on QCD and Hadronic Physics, Beijing, June 20, 2005.

(Pentaquark 2005, Oct. 21, CLAS g10 data don't confirm this. (T. Mibe et al.), but for larger Λ(1520) c.m. angles)

Exclusive Reaction on the *Proton*



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

$K_s^0 \rightarrow \pi^+\pi^-$

$\Theta^+ \rightarrow nK^+$

- SAPHIR/ELSA at Bonn
- M = 1540 ± 4 MeV
- width < 25 MeV
- Published: 300nb cross section. Later statement: signal smaller than shown, cross section of 50 nb.
- $N(\Theta^+)/N(\Lambda^*) \sim 10\%$

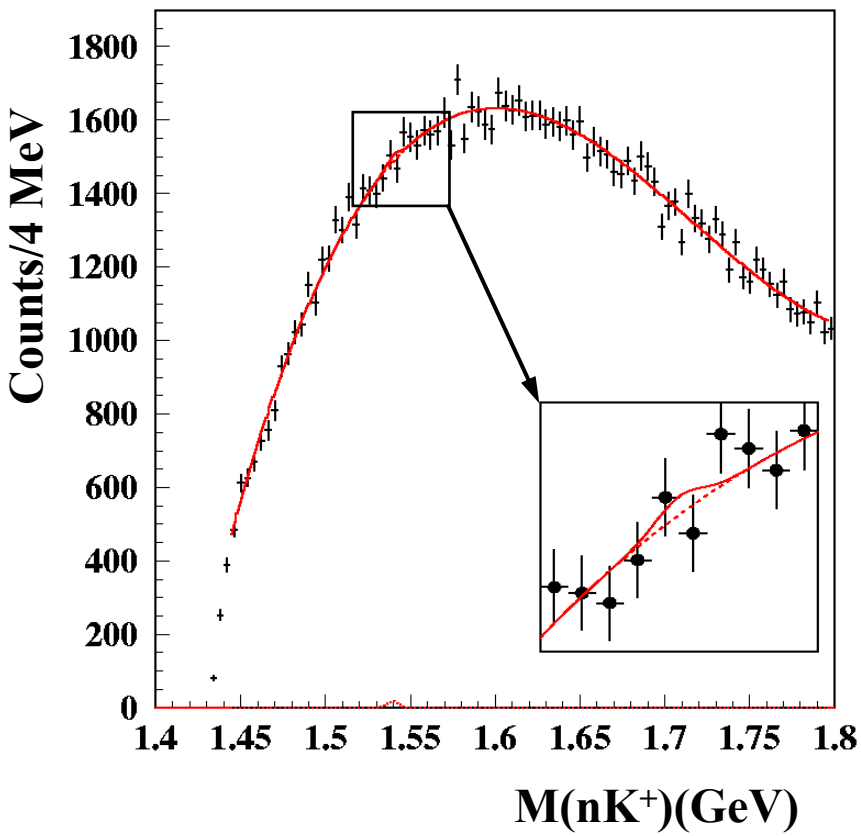
J. Barth, et al., Phys Lett B572, 127 (2004); hep-ex/0307083.

New Upper Limit on the Θ^+ Cross Section

CLAS: $\gamma p \rightarrow K^0 K^+ n$

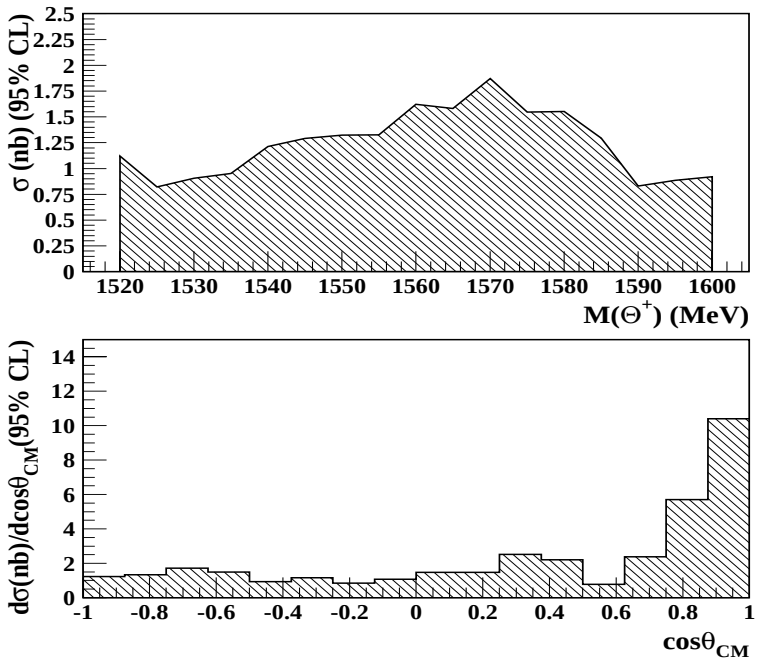
(APS Tampa, 5-05, hep-ex/0510061)

Fit with a sum of smooth function and a Gaussian with fixed width and centroid.

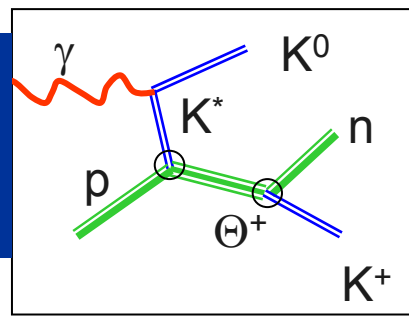


$\sigma_{\gamma p \rightarrow \Theta^+ K^0} < 0.8$ nb @ 1.54 GeV/c^2

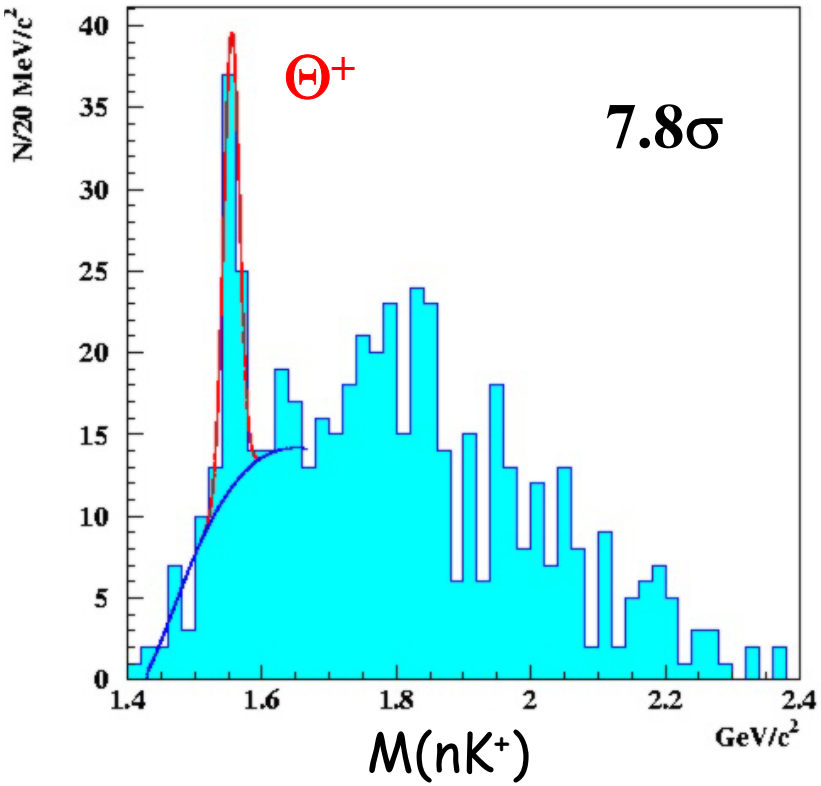
$N(\Theta^+)/N(\Lambda^*) < 0.2\%$ (95%CL)



Results put stringent limits on possible production mechanism, e.g. implies very small coupling to K*

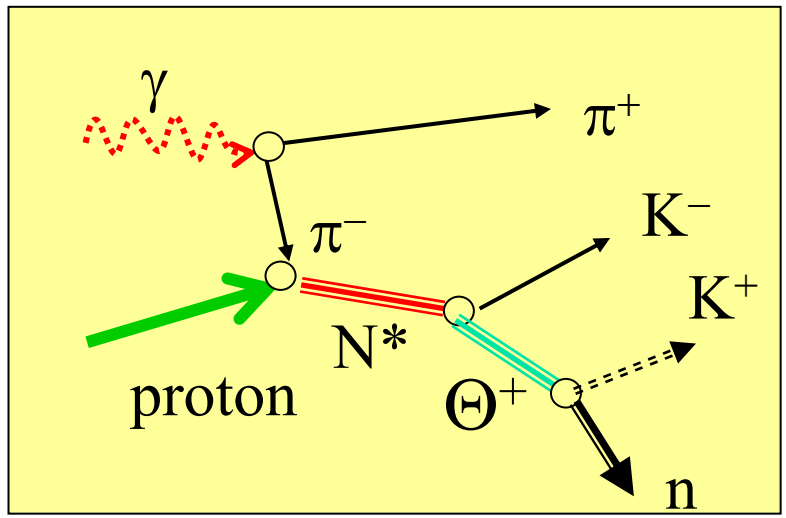


Exclusive Reaction on the Proton *II*



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

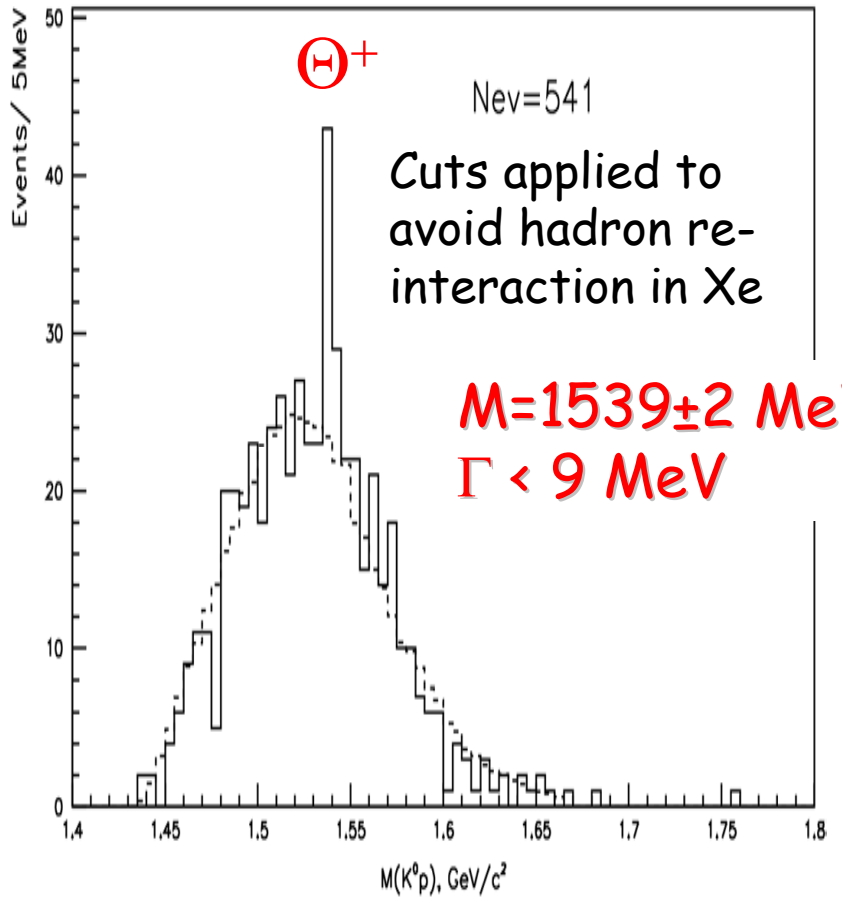
- CLAS: V. Kubarovsky *et al.* PRL 92 032001 (2004)
- Combined analysis of all CLAS data on protons for Eg <5.2 GeV
- Cuts: forward π^+, backward K^+
- indications of production from heavy N*(2420)



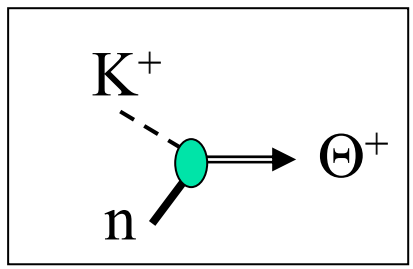
Higher statistics run planned for 2006.

Semi-Exclusive K^+ (N) → pK_s^0

$K^+ Xe \rightarrow (\Theta^+) X \rightarrow K^0_s p X$; 850 MeV/c K^+ beam



DIANA/ITEP Bubble Chamber Experiment

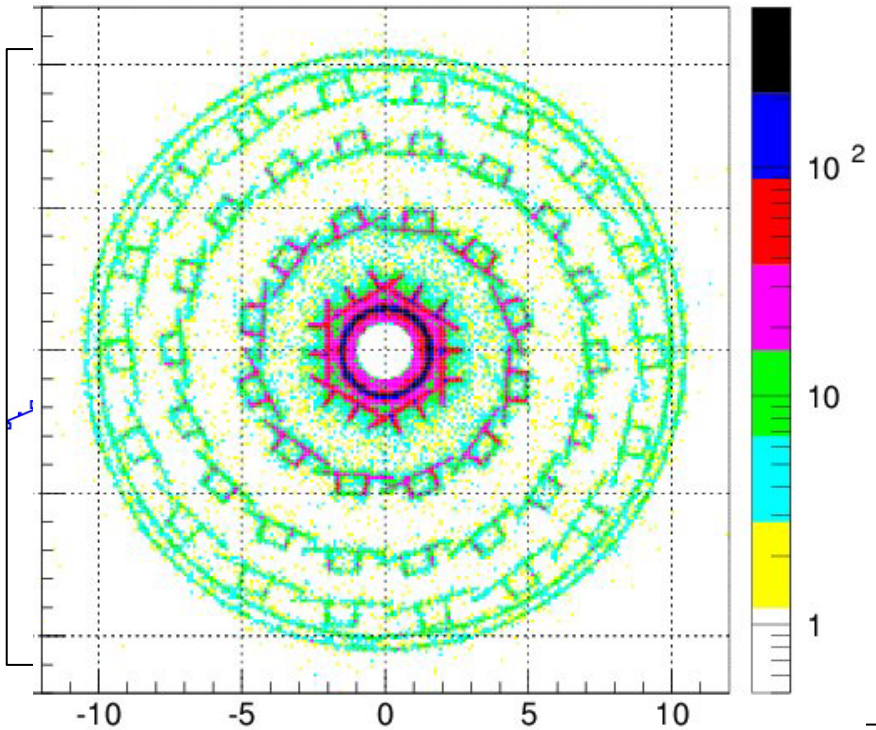


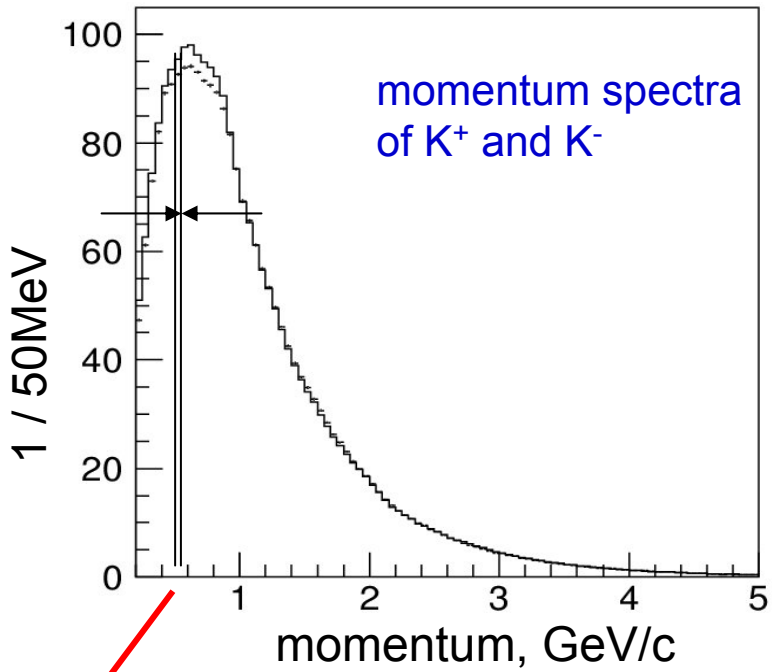
Note: No strangeness "tag" for the $K^0_s p$ final state

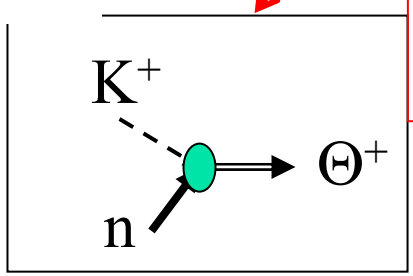
V.V. Barmin et al., Yad. Fiz. 66 1763 (2003); hep-ex/304040

Belle/KEKB – Low energy K^+N

$e^+e^- \rightarrow K^{+/-} X, \quad K^{+/-}A \rightarrow pK^0, pK^-$







Momentum range possibly contributing to Θ^+ formation.

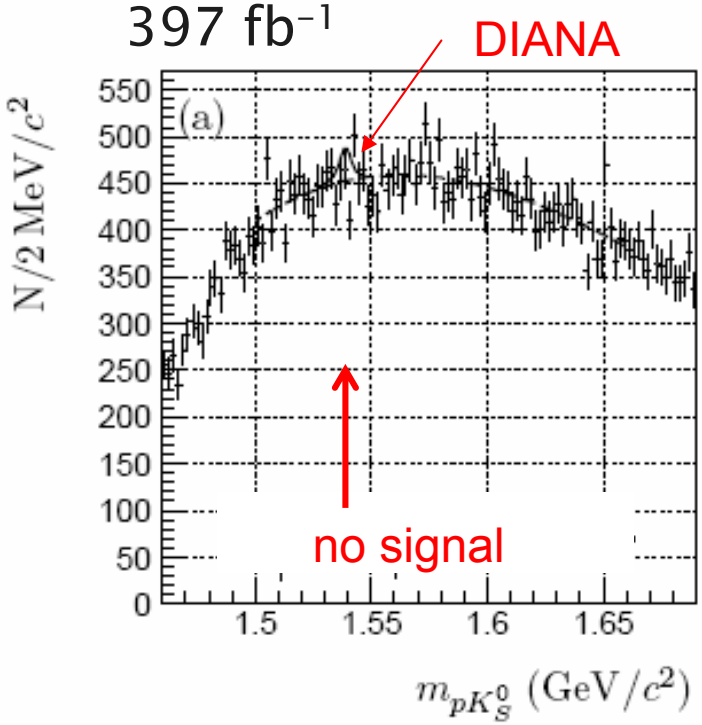
=> Determine resonance width

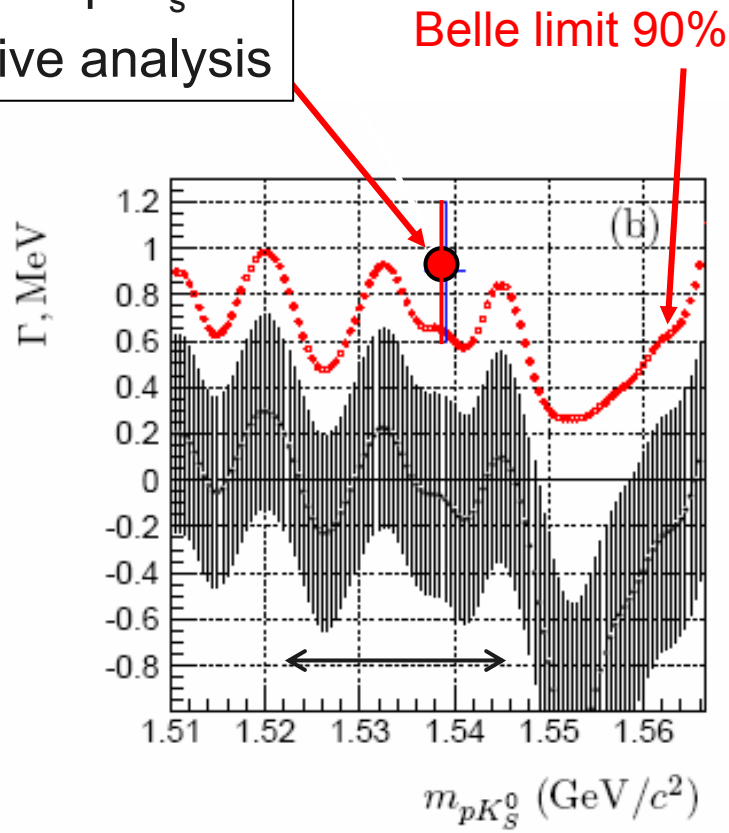
Belle – Limits on Θ^+ Width

$K^+A \rightarrow pK^0_s$

397 fb^{-1}

Γ_{Θ^+} from $K^+A \rightarrow pK^0_sX$ &
$K^+D \rightarrow$ inclusive analysis





$$\Gamma_{\Theta^+} = \frac{N_{\Theta^+}}{N^{ch}} \frac{\sigma_{ch}}{107\text{mb}\ B_i\ B_f} \Delta m$$

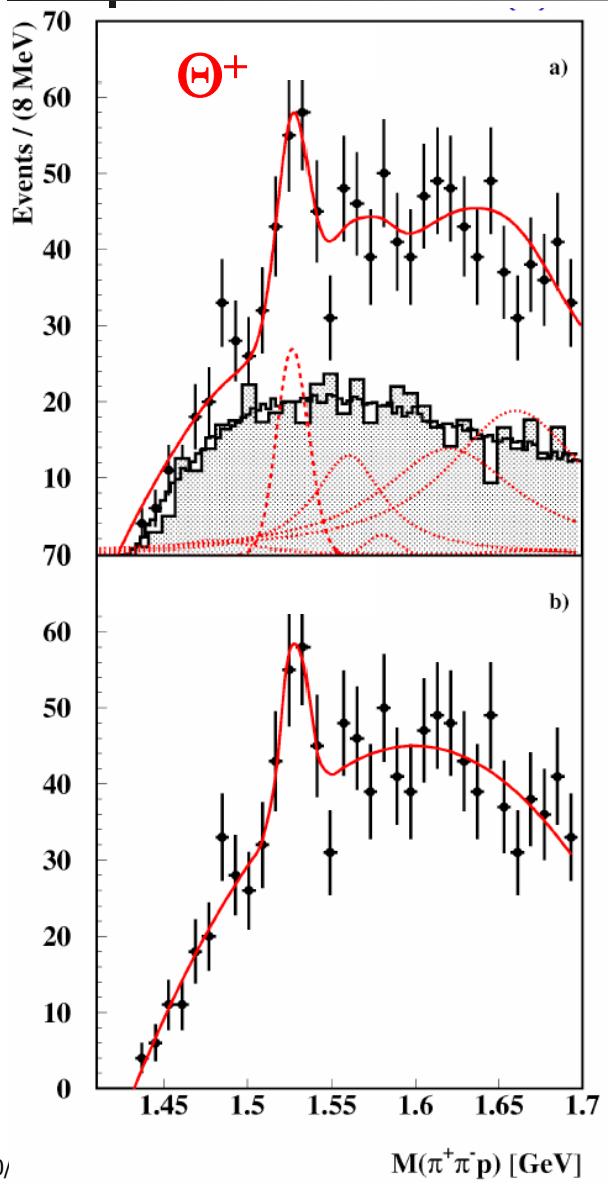
Belle: $\Gamma < 0.64$ MeV (90% CL) @ M = 1.539 GeV

$\Gamma < 1$ MeV (90% CL) @ M = 1.525–1.545 GeV

Cahn,Trilling,PRD 69,11501 (2004).

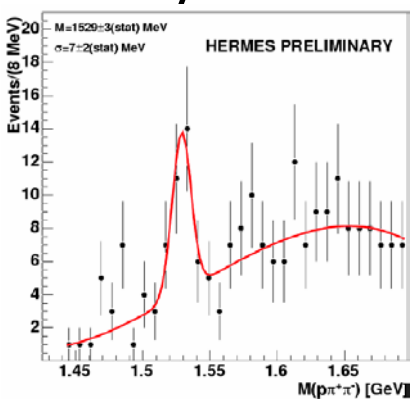
Does not confirm previous DIANA signal.

Low Q^2 , Quasi-real Photons



$$\gamma_v D \rightarrow K^0 p X \rightarrow \pi^+\pi^- p X$$

- HERMES/HERA: Inclusive on Deuterium
- Lepton scattering: 27 GeV positron beam
- M = 1526 ± 2 ± 2 MeV
- σ = 7.5 ± 2.4 MeV
- A. Airapetian et al. Phys. Lett. B 585, 213 (2004).

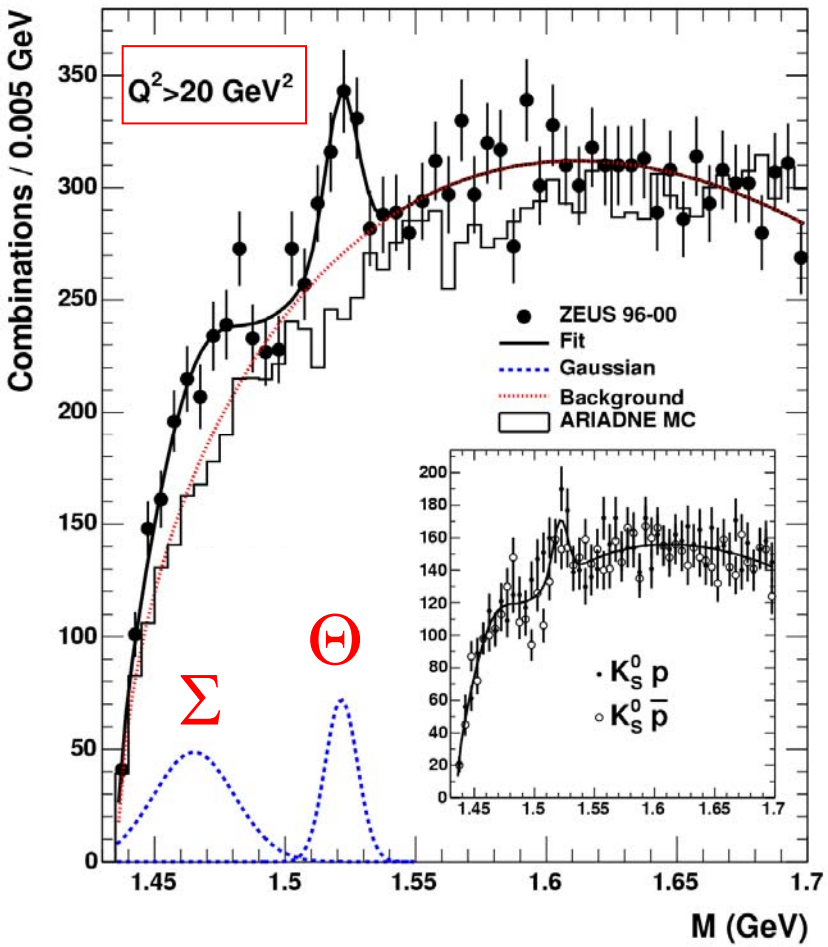


Additional π required

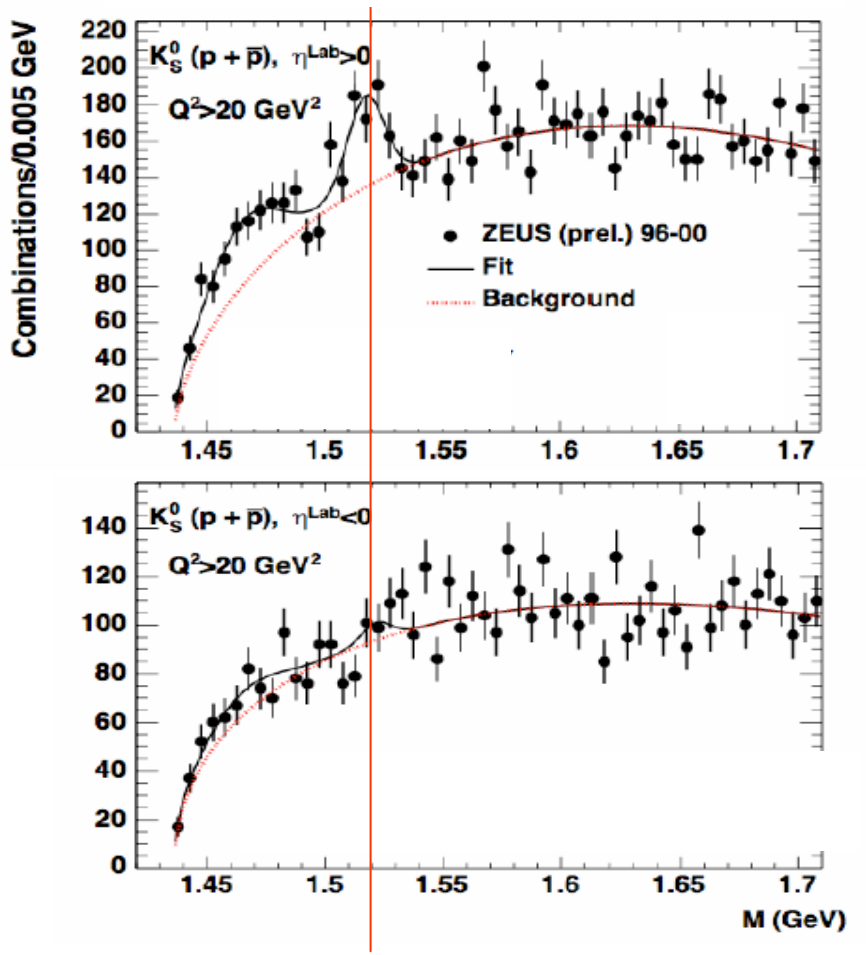
Airapetian et al., Int'l Workshop on DIS, Madison, 2005.

Scattering at High Q^2 , $e^{\pm}p \rightarrow e(K^0_s p)X$

ZEUS/HERA



Fragmentation, Q^2>20GeV²

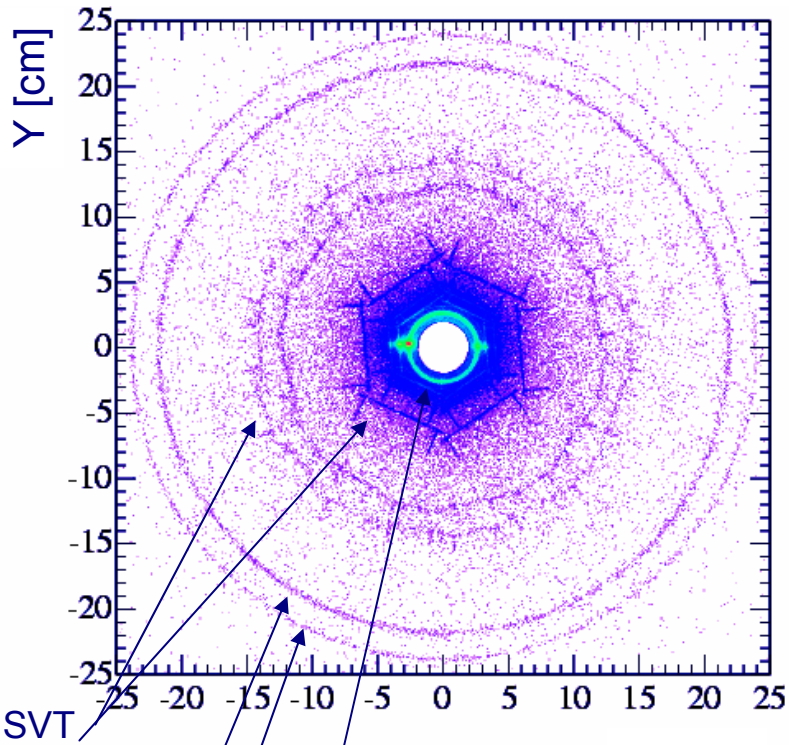


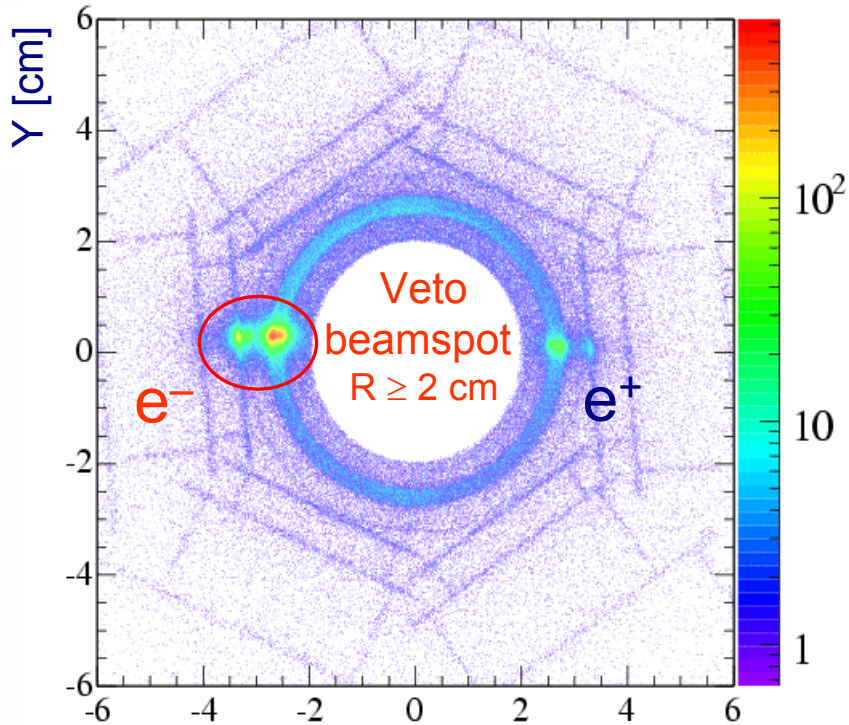
=> Signal seen at medium Q^2 and forward rapidity in both pK_s and $\bar{p}K_s$

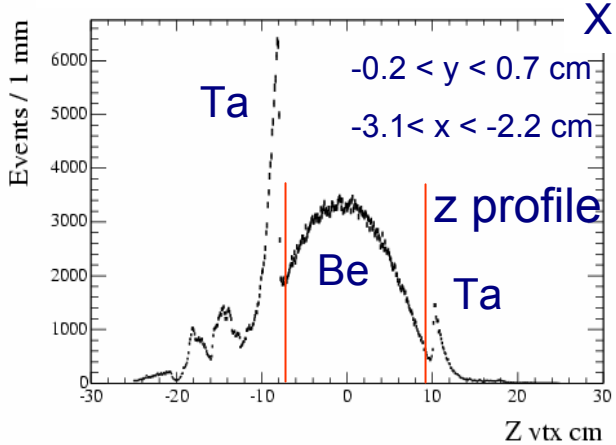
$\Theta^+/\Lambda^* \sim 5\%$ (independent of Q^2)

S. Chekanov et al. Phys. Lett. B 591 (2004) 7.

Tomography with pK_s^0 Vertices





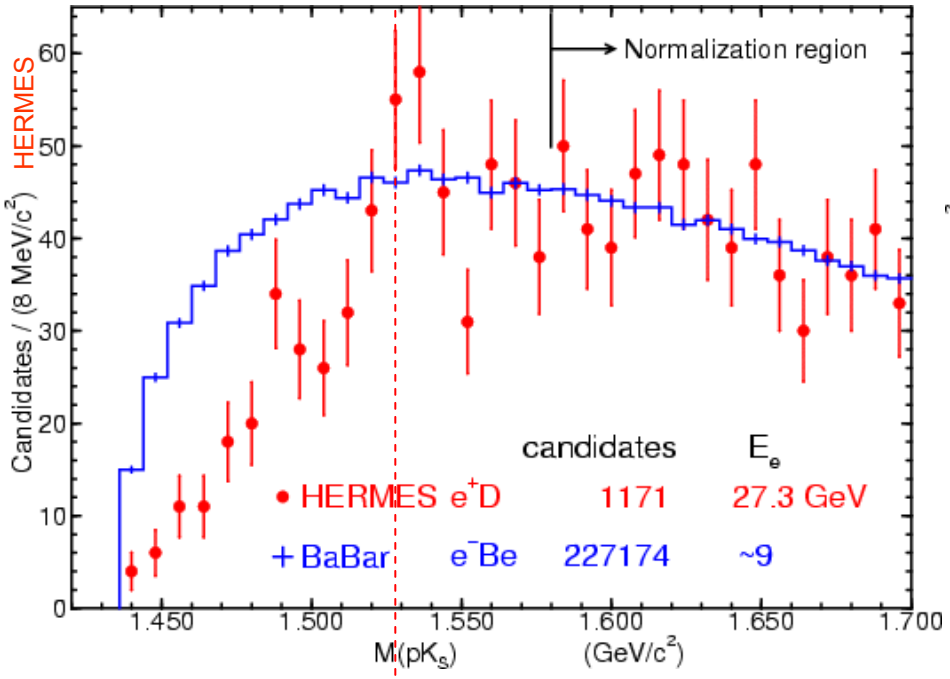


=> Quasi-real photoproduction scattering on nuclei (e^- on BeO)

Preliminary
233 fb^{-1} e^+e^- data

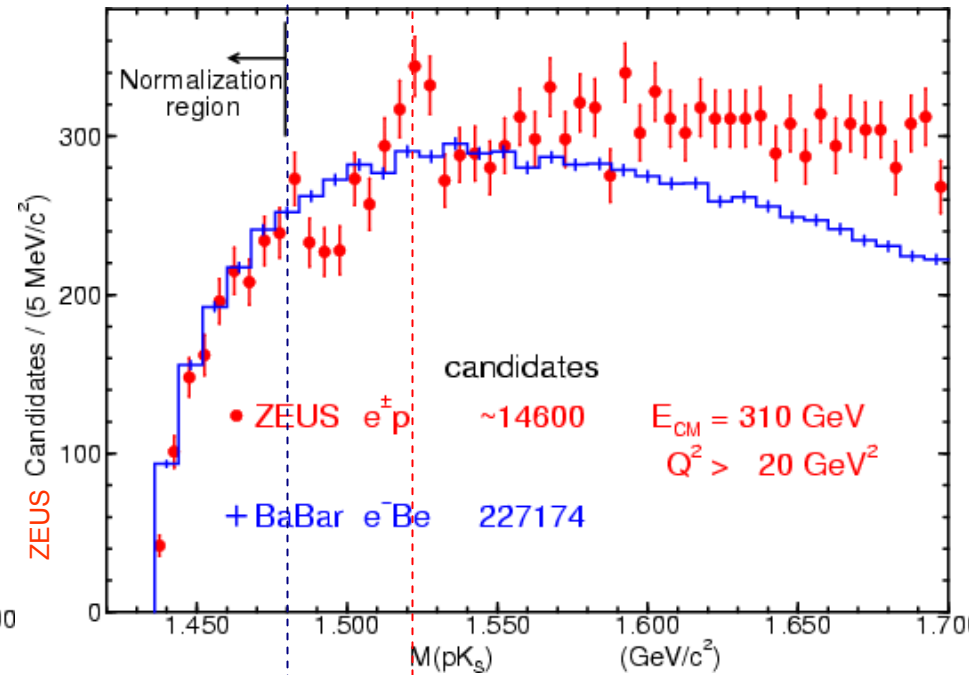
e^-Be Electroproduction

HERMES ($e^+d \to K_S^0 p + X$)



Hermes: ~5σ
M=1528±3 MeV

ZEUS ($e^+p \to e^+K_S^0 p + X$)



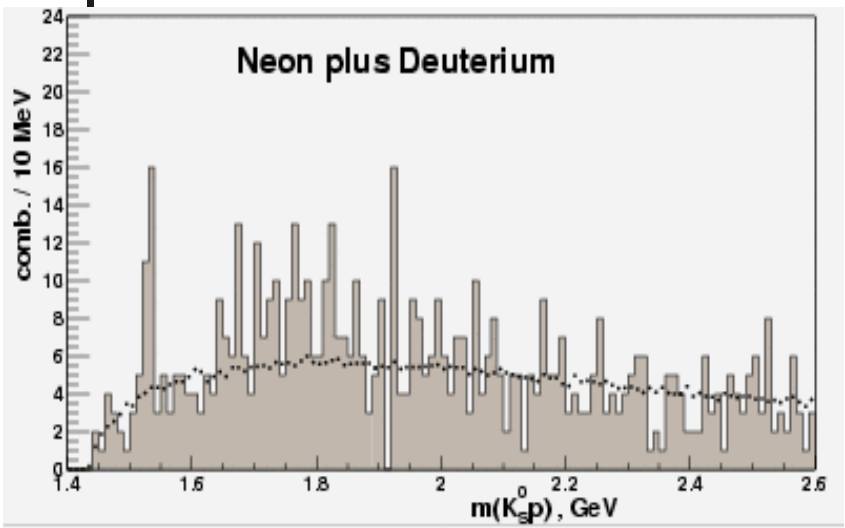
$\Sigma^*(1480)$

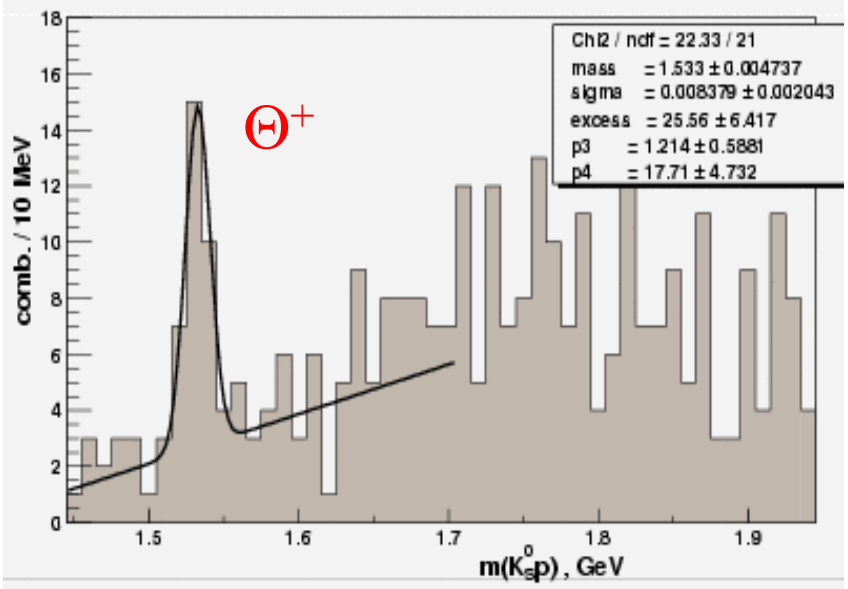
Zeus: ~5σ
M=1522±3 MeV

HERMES: acceptance loss in low mass region?
(PID requires p(p) >4.1 GeV/c; p(K_S^0)>3 GeV/c)

HERMES/BaBar comparison is valid.
ZEUS : High Q^2, no signal seen for Q^2<1
BaBar: Quasi-real photons Q^2~0.

All of the World's Neutrino Scattering Data





- $\nu^{(-)} A \rightarrow (K^0 p)\, X$
  $\rightarrow (\pi^+\pi^- p)\, X$
- Data mining: sum of 5 bubble-chamber experiments from CERN and Fermilab
- $M(\Theta^+)$=1.533±.005 GeV
- Γ < 30 MeV

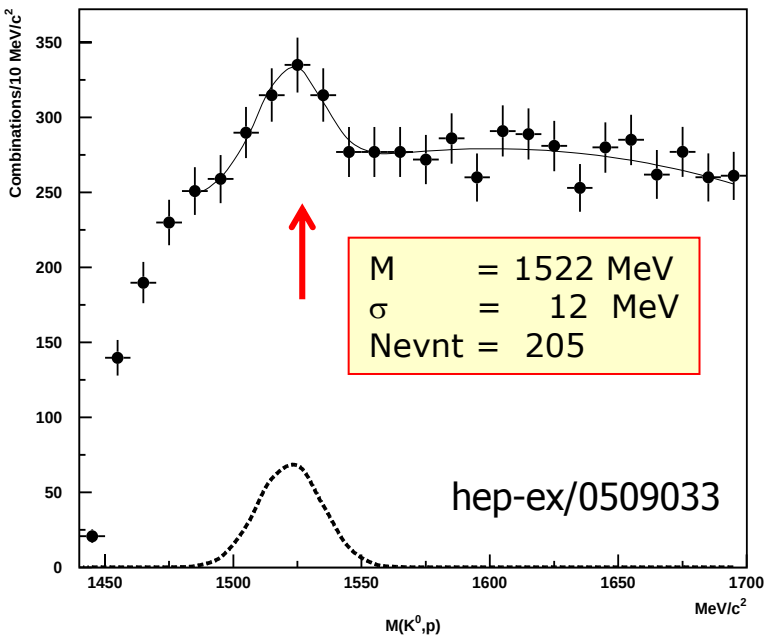
- A.E.Asratyan *et al. (ITEP),* Yad. Fiz. 67, 704 (2004) hep-ex/0309042

SVD-2 – New Analysis

$$pA \rightarrow K_s pX$$

$E_p = 70$ GeV

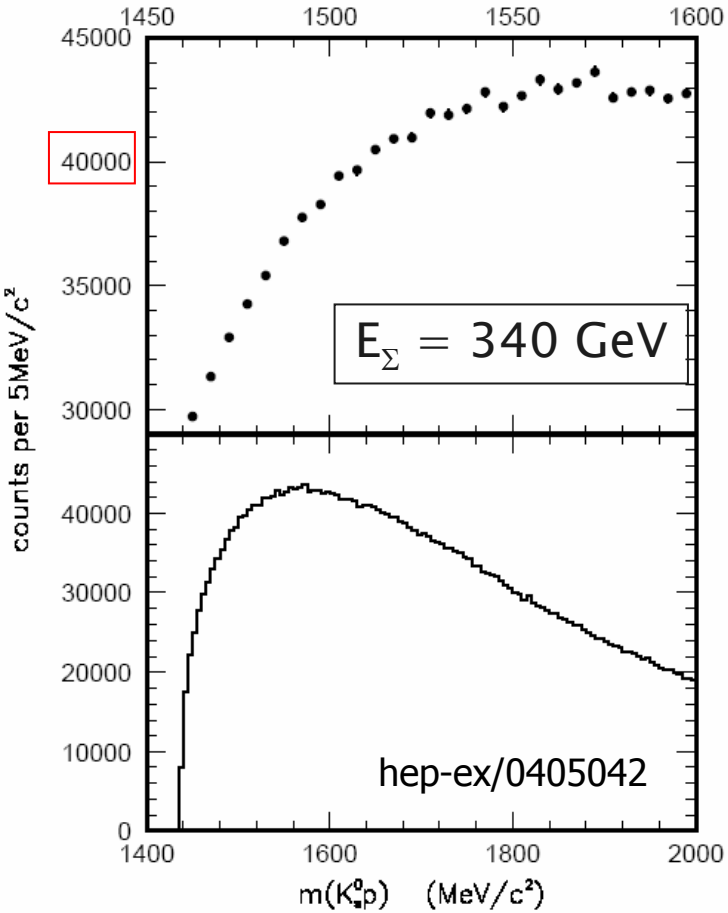
Two independent data set:
K_S decays inside or outside the Vertex Detector



- New analysis improves Θ^+ signal by factor 8. Total significance ~8σ.

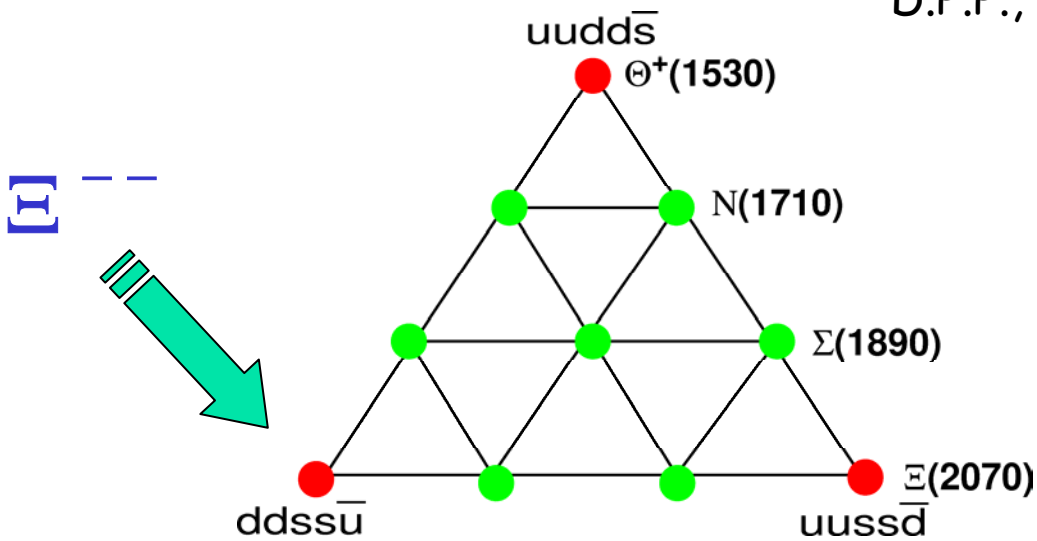
WA89 Results

$$\Sigma^- A \rightarrow K_s p X$$



Cascade Pentaquarks Another Exotic Member of the Anti-Decuplet ?

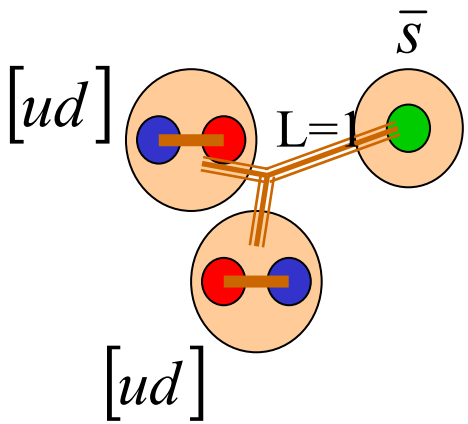
D.P.P., Z. Phys. A359, 305(1997).



R. Jaffe, F. Wilczek hep-ph/0307341

JM hep-ph/0308286

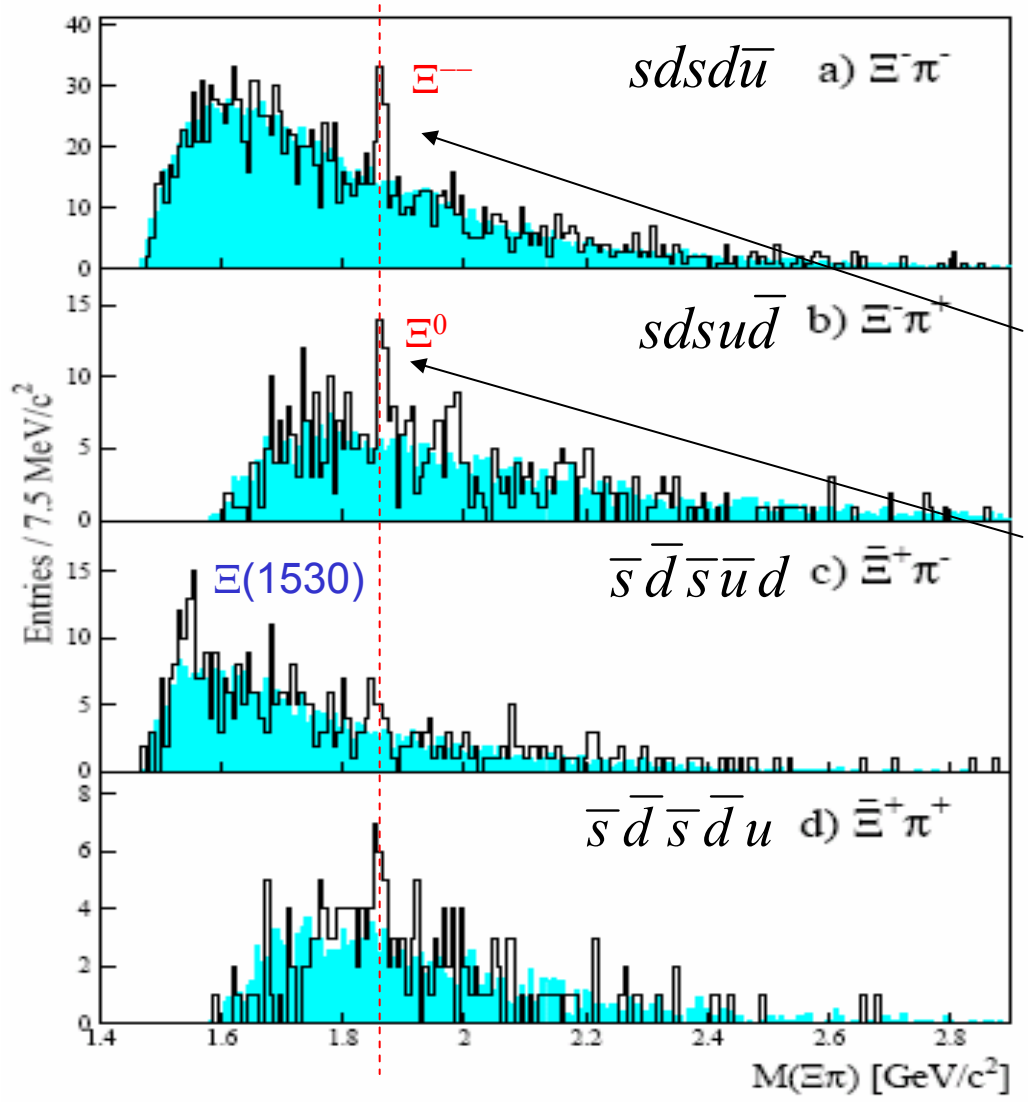
SZ hep-ph/0310270



Two bosonic di-quarks (ud), plus $\bar{s}$; fermionic state symmetry demands L=1, giving $J^P = 1/2^+$

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

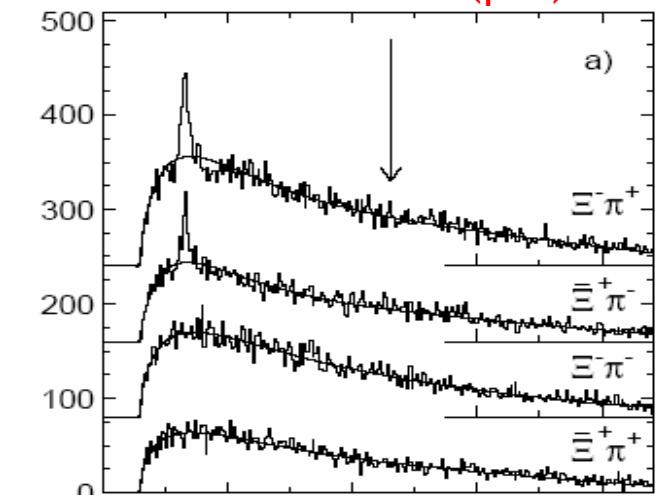
Cascade Pentaquarks $\Xi_5^{--}(1862)$



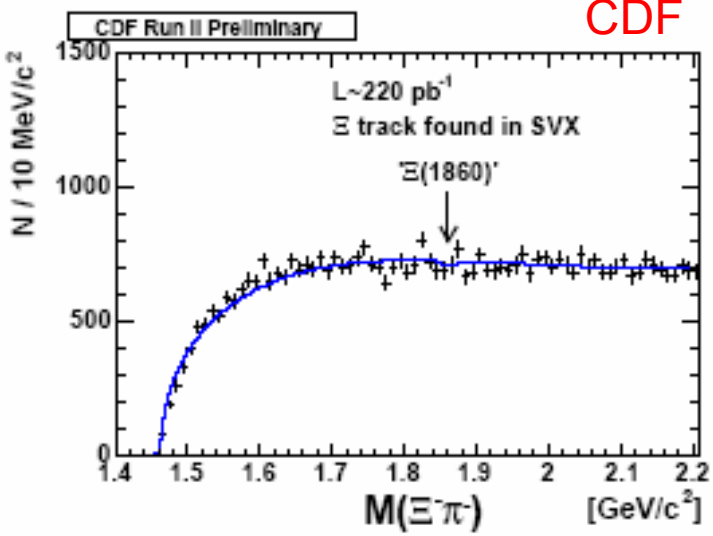
- NA49/CERN
- p+p → $\Xi\pi$ X at 17 GeV c.m. energy
- Signal for Exotic S = -2, Q=-2
- Signal for *Non*-exotic S=-2, Q=0
- M=1.862± 0.002 GeV
- C. Alt *et al*. PRL 92 042003 (2004); hep-ex/0310014.

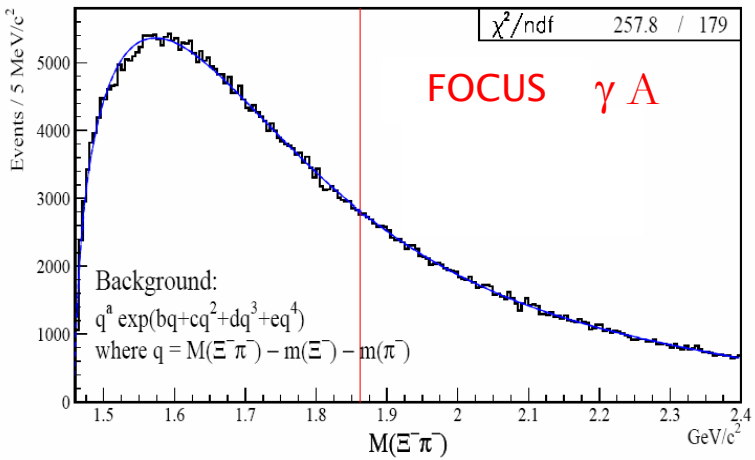
Cascade Pentaquarks $\Xi_5^{--}(1862)$

HERA-B (p A)



$p\bar{p} \rightarrow \pi\,\Xi\,X$ CDF

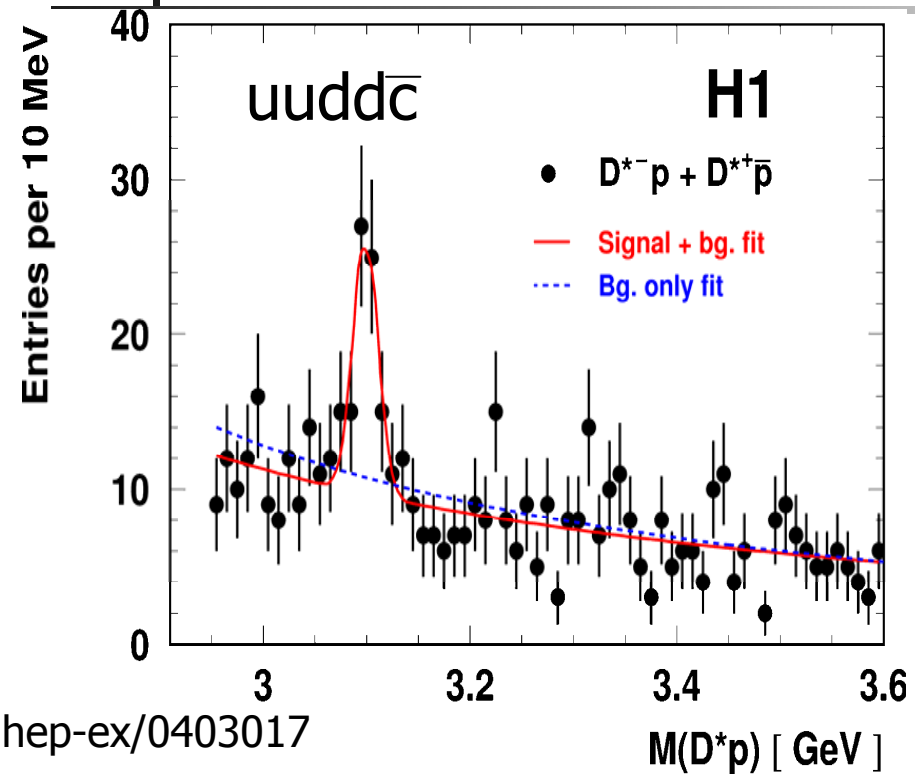




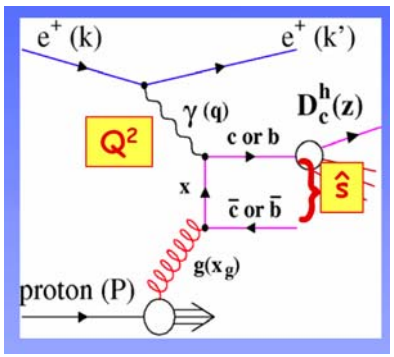
✦ State not produced in quark fragmentation or is severely suppressed.

Reaction	$\sqrt{s}$ (GeV)	source	Ξ^{--}/Ξ^-	$\Xi^{--}/\Xi^0(1530)$
pA, y≈0	41.6	HERA-B	$< 0.03/\mathcal{B}$	$< 0.04/\mathcal{B}$
pp	17.0	NA49		$0.18/\mathcal{B}$
ep	320	ZEUS		$< 0.28/\mathcal{B}$
pp	1960	CDF		$< 0.04/\mathcal{B}$
γA	range	FOCUS		$< 0.0025/B$

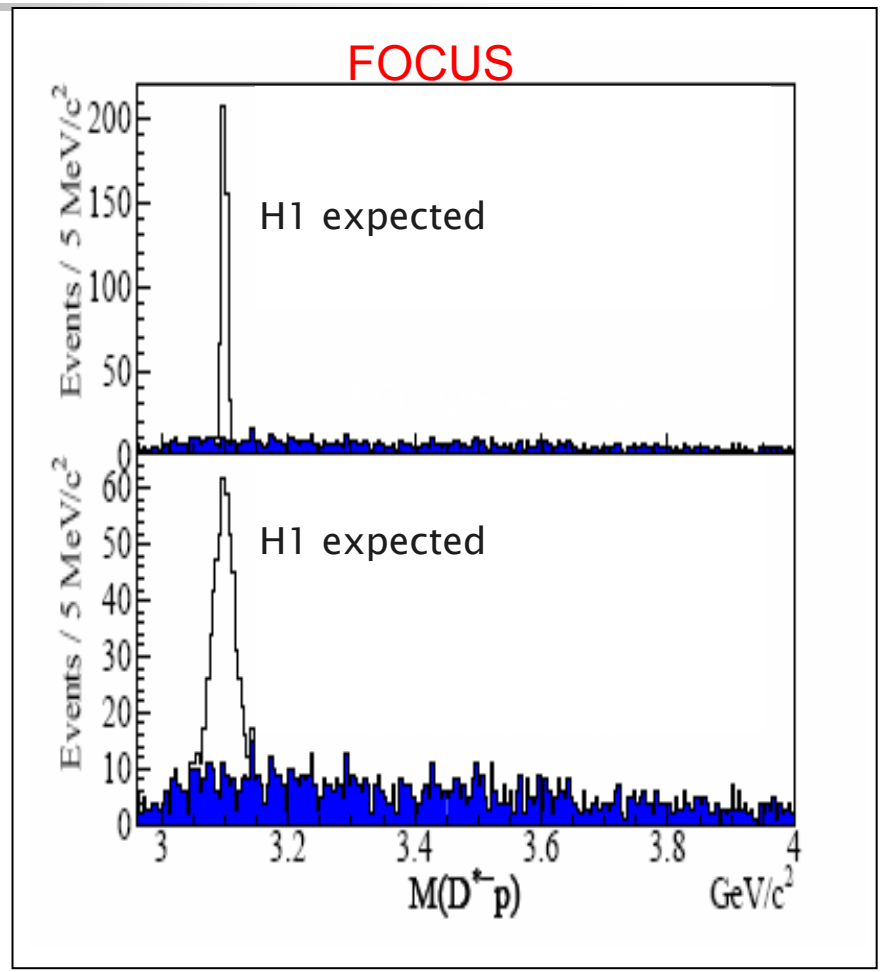
Charmed Pentaquark $\Theta^0_c(3100)$



hep-ex/0403017



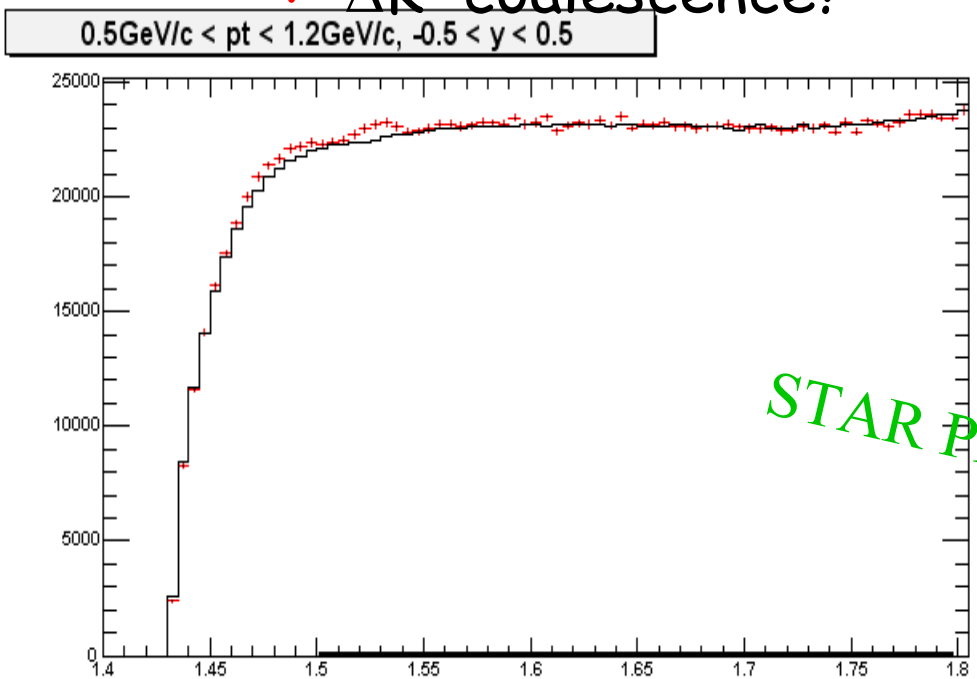
- ep collisions at HERA
- Possible production mechanism – photon-gluon fusion: $\gamma^{(*)}g \rightarrow c\bar{c}$

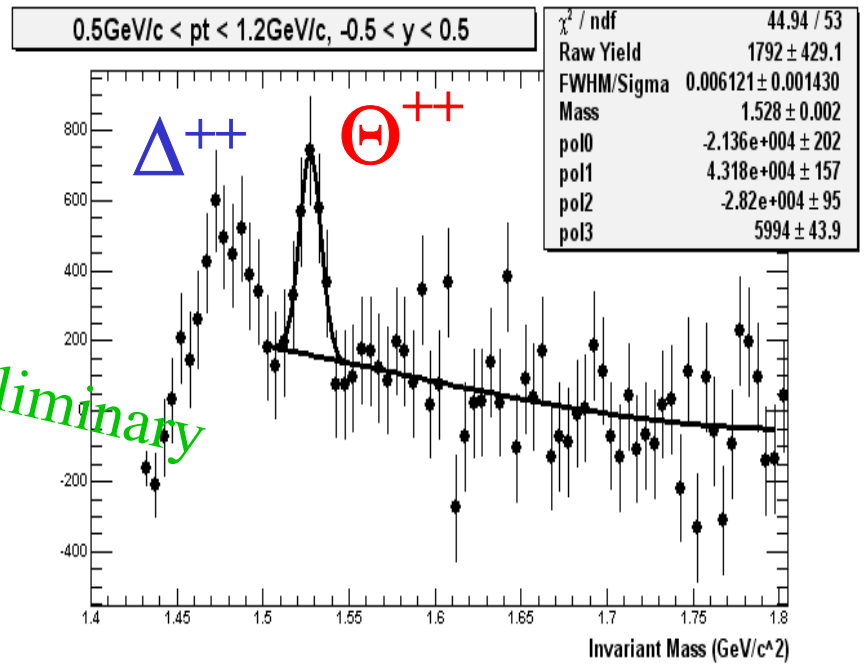


- FOCUS experiment also claims incompatibility with H1.

Θ^{++} Evidence: is it Isovector?

- STAR/RHIC, Huang *et al.*
  - APS Tampa, April 2005; nucl-ex/0509037
  - d-Au collisions, pK^+ and $\bar{p}K^-$ at 200 GeV/A
    - ...but hardly at all in Au-Au (!?)
  - ΔK^+ coalescence?

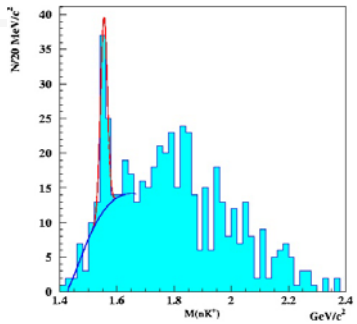


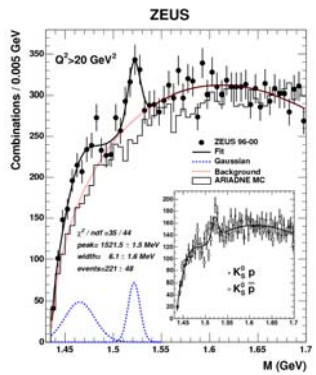


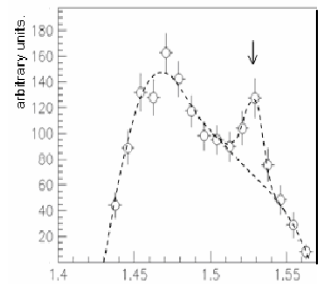
STAR Preliminary

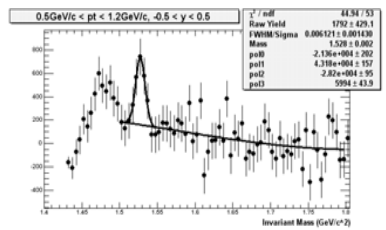
Present Pentaquark Candidates

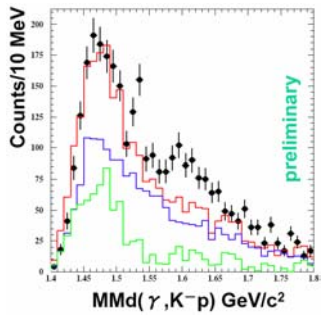
- Best "Survivors" (pre-2005)
  - CLAS γ p $\rightarrow \Theta^+ K^- \pi^+$
  - COSY-TOF p-p $\rightarrow \Theta^+ \Sigma^+$
  - ZEUS e p, Q^2>20 GeV^2
- Newcomers (2005)
  - STAR/RHIC d-Au $\rightarrow K_s^0$ p
  - LEPS γD $\rightarrow \Theta^+ \Lambda(1520)$
  - SVD-2 p-A $\rightarrow K_s^0$ p X
    - refuted by WA89

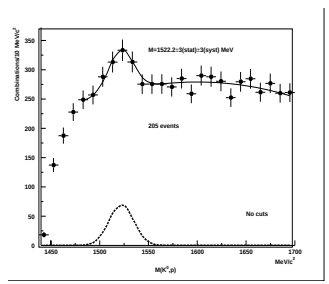












Outlook – future experiments

- Spring-8/LEPS γ D
- COSY-2 p p
- JLab/CLAS γ D
- JLab/Hall A γ D
- KEK or JPARC K p
- HERA/ZEUS e p

Summary

- After 3 years of intense activity, pentaquarks have come and (nearly) gone...
  - Most positive sightings have been contradicted or placed in doubt by better measurements
  - Remaining candidates have no common phenomenological connection.
  - No single truly convincing measurement has appeared
- Recent new candidates suffer (again) from low statistics and poorly-understood backgrounds
- Bandwagon effect in 2003/4 led to numerous over-optimistic positive results to be claimed.

Backup slides

Positive Sightings

Experiment	Reaction searched publication	Claim Decay	Θ^+ Θ^0_c Ξ_5
LEPS	$\gamma C_{12} \rightarrow K^- K^+ n$ PRL 91 (2003) 012002	Θ^+ K^+n	
CLAS	$\gamma d \rightarrow K^+K^- np$ $\gamma p \rightarrow \pi^+K^-K^+n$ PRL 91 (2003) 252001, PRL 92 (2004) 032001	Θ^+ K^+n	
SAPHIR	$\gamma p \rightarrow K^0_S K^+ n$ Phys.Lett B572 (2003) 127	Θ^+ K^+n	
COSY	$pp \rightarrow \Sigma^+ K^0_S p$ Phys.Lett.B595 (2004) 127	Θ^+ $K^0_S p$	
DIANA	$K^+Xe \rightarrow K^0_S X'$ Phys.Atom.Nucl.66(2003)1715	Θ^+ $K^0_S p$	
JINR	$p+C_3H_8 \rightarrow K^0_S pX$ hep-ex/0401024	Θ^+ $K^0_S p$	
SVD	$pA \rightarrow pK^0_S X$ hep-ex/0401024	Θ^+ $K^0_S p$	
ν	$\nu A \rightarrow K^0_S pX$ BC at CERN & FNAL hep-ex/0309042	Θ^+ $K^0_S p$	
HERMES	$ep \rightarrow e'pK^0_S X$ (quasi-real photoproduction) Phys.Lett.B585(2004) 213	Θ^+ $K^0_S p$	
ZEUS	$ep \rightarrow e'pK^0_S X$ Phys.Lett.B592(2004)7	Θ^+ $K^0_S p$	
NA49	$pp \rightarrow \Xi\pi X$ PRL 92(2004)042003	Ξ_5 $\Xi\pi$	
H1	$ep \rightarrow e'pD^{*-}X$ Phys.Lett.B588(2004)17	Θ^0_c $D^{*-}p$	

(Table by Alex Dzierba)

Negative Reports

CDF	$p\bar{p} \to PX$ hep-ex/0408025,0410024	Θ^+ Θ_c^0 Ξ_5	ALEPH	Hadronic Z decays Submitted to **Phys. Lett. B**	Θ^+ Θ_c^0 Ξ_5
HyperCP	$(\pi^+,K^+,p)Cu \to PX$ hep-ex/0410027	Θ^+	DELPHI	Hadronic Z decays hep-ex/0410080	Θ^+
SELEX	$(\pi,p,\Sigma)p \to PX$ Quark Confinement 2004	Θ^+	L3	$\gamma\gamma \to \Theta\bar{\Theta}$ hep-ex/0410080	Θ^+
FOCUS	$\gamma\, p \to PX$ DPF 2004	Θ^+ Θ_c^0 Ξ_5	WA89	$\Sigma^- N \to PX$ hep-ex/0410029	Ξ_5
E690	$pp \to PX$ QNP2004 -	Θ^+ Ξ_5	ZEUS	$ep \to PX$ hep-ex/0407026	Θ_c^0 Ξ_5
BES	$e^+e^- \to J/\psi\ (\psi(2S))$ PRD 70 (2004) 012004	Θ^+	HERA-B	$pA \to PX$ Accepted in PRL	Θ^+ Ξ_5
BELLE	$KN \to PX$ hep-ex/0411005	Θ^+ Θ_c^0	SPHINX	$pC(N) \to \theta\, K\, X$ hep-ex/0407026	Θ^+
BaBar	$e^+e^- \to \Upsilon(4S)$ hep-ex/0408064	Θ^+ Ξ_5	PHENIX	$AuAu \to PX$ nuc-ex/0404001	Θ^+
COMPASS		Θ^+ Ξ_5	**LASS**	$K^+p \to K^+ n\, \pi^+$ hep-ex/0412031	Θ^+

(Table by Alex Dzierba)

Summary of LQCD

C. Alexandrou

Group	Method of analysis/criterion	Conclusion
Alexandrou and Tsapalis	Correlation matrix, Scaling of weights	Can not exclude a resonance state. Mass difference seen in positive channel of right order but mass too large
Chiu *et al.*	Correlation matrix	Evidence for resonance in the positive parity channel
Csikor *et al.*	Correlation matrix, scaling of energies	First paper supported a pentaquark , second paper with different interpolating fields produces a negative result
Holland and Juge	Correlation matrix	Negative result
Ishii *et al.*	Hybrid boundary conditions	Negative result in the negative parity channel
Lasscosk *et al.*	Binding energy	Negative result
Mathur *et al.*	Scaling of weights	Negative result
Sasaki	Double plateau	Evidence for a resonance state in the negative parity channel.
Takahashi *et al.*	Correlation matrix, scaling of weights	Evidence for a resonance state in the negative parity channel.
J. Negele, Lattice 2005	Correlation matrix, scaling of weights	Maybe evidence for a resonance state?