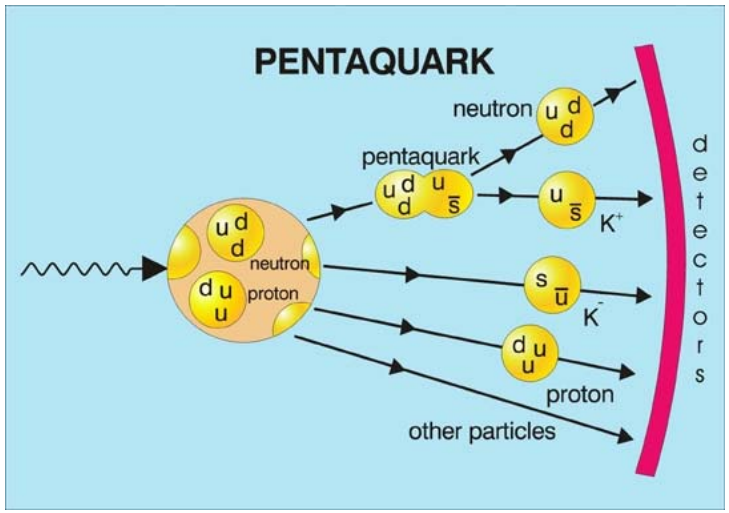
Pentaquarks: An Experimental Overview

Curtis A. Meyer

Based, in part, on work carried out with Alex Dzierba and Adam Szczepaniak



Before 2003 …. searches for flavor exotic baryons showed no evidence for such states.

Since 2003 …. Hadronic Physics has been very interesting.

Outline

Overview of the positive evidence
data, statistics, specific results

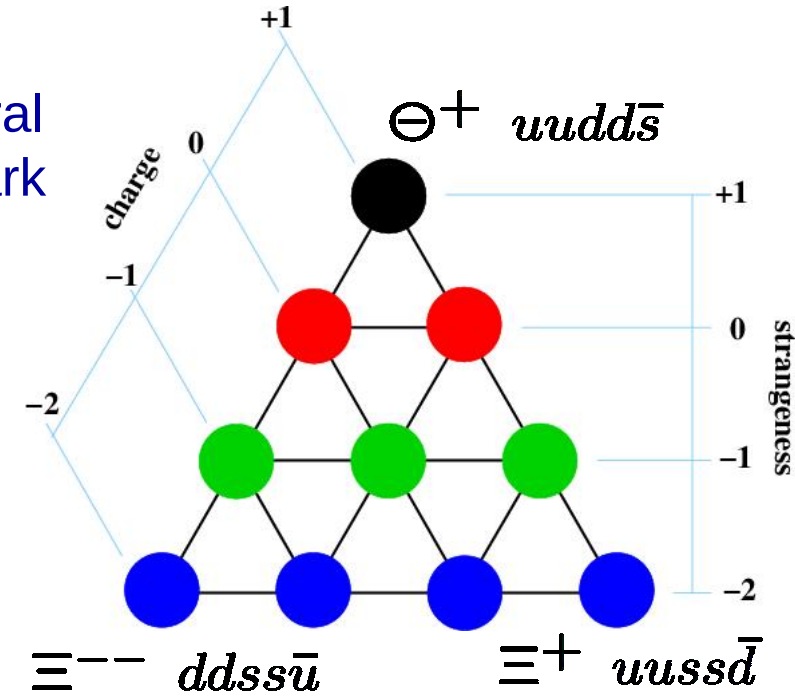
Overview of the negative results
The Ξ and Θc
The Θ+

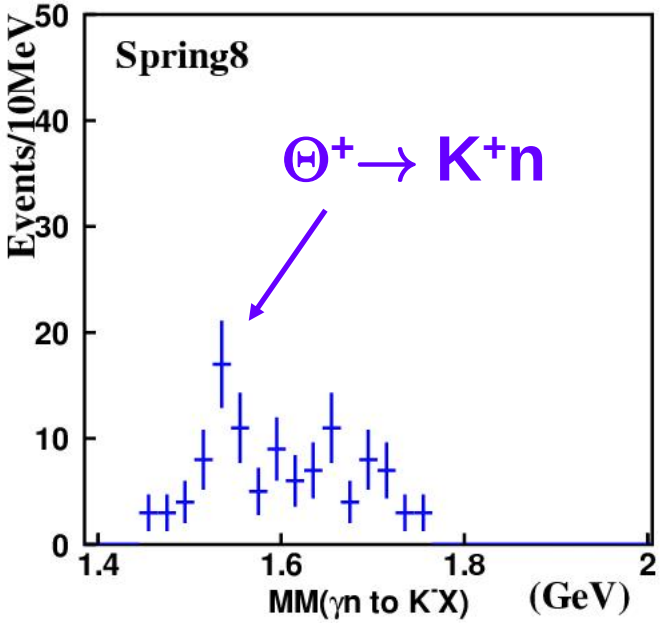
Issues with some of the data

Summary & Conclusions

Spectacular Development

1997: Diakonov, Petrov and Polykov use a chiral soliton model to predict a decuplet of pentaquark baryons. The lightest has S=+1 and a mass of 1530 MeV and expected to be narrow.
Zeit. Phys. A359, 305 (1997).





2003: T. Nakano *et al.* γ n $\rightarrow$ K^+K^-n on a Carbon target.
Phys. Rev. Lett. 91, 012002, (2003)

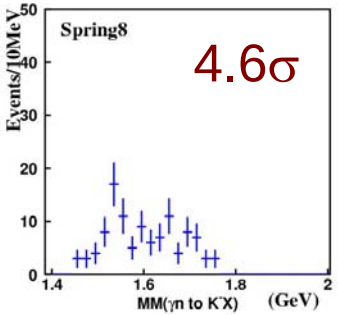
The Dam Breaks ….

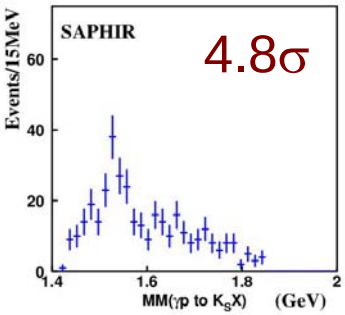
Positive Sightings

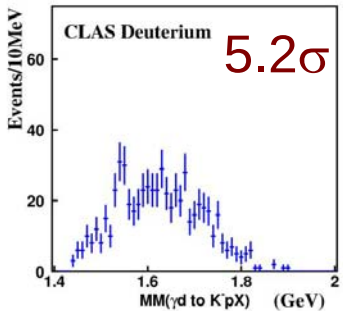
Experiment	Reaction searched / publication	Claim Decay Θ^+ Θ^0_c Ξ_5
LEPS	$\gamma C_{12} \rightarrow K^- K^+ n$ PRL 91 (2003) 012002	Θ^+ K^+n
CLAS	$\gamma d \rightarrow K^+K^- np$ $\gamma p \rightarrow \pi^+K^-K^+n$ PRL 91 (2003) 252001, PRL 92 (2004) 032001	Θ^+ K^+n
SAPHIR	$\gamma p \rightarrow K^0_S K^+ n$ 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 $D^{*-}p$

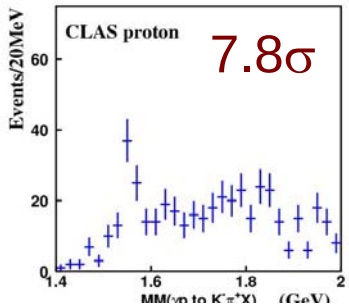
The Data

Reported Significance

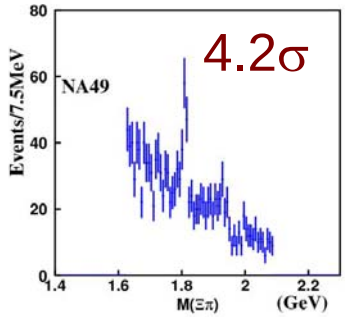


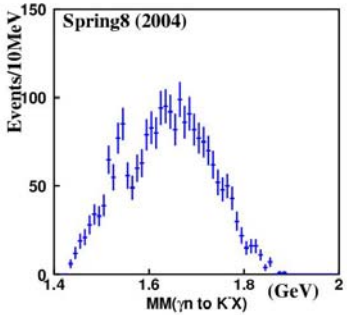


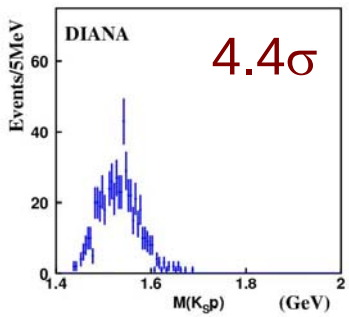


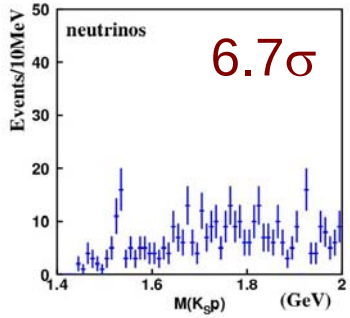


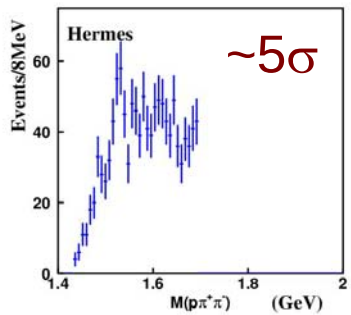
Ξ_5^{--} Ξ_5^{0}



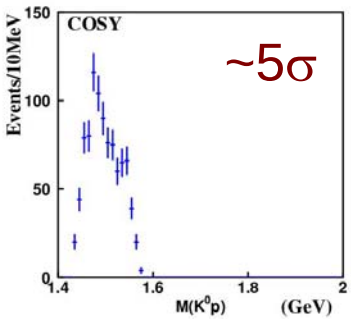


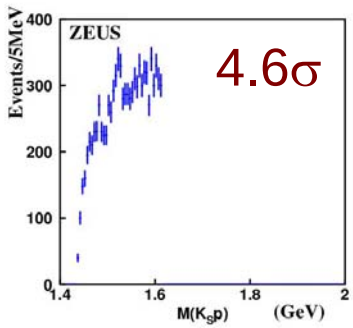


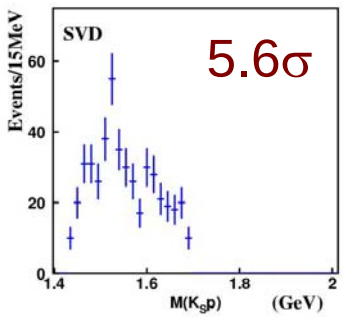


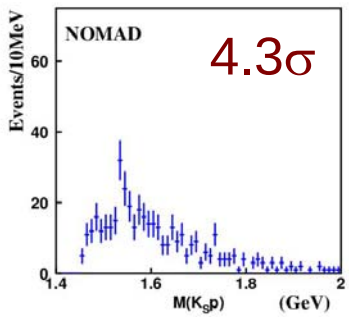


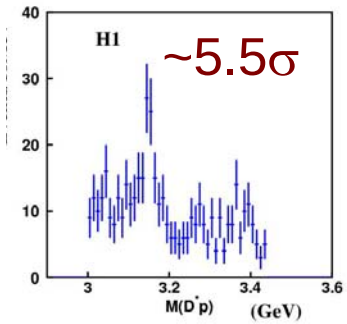
Θ^0_c











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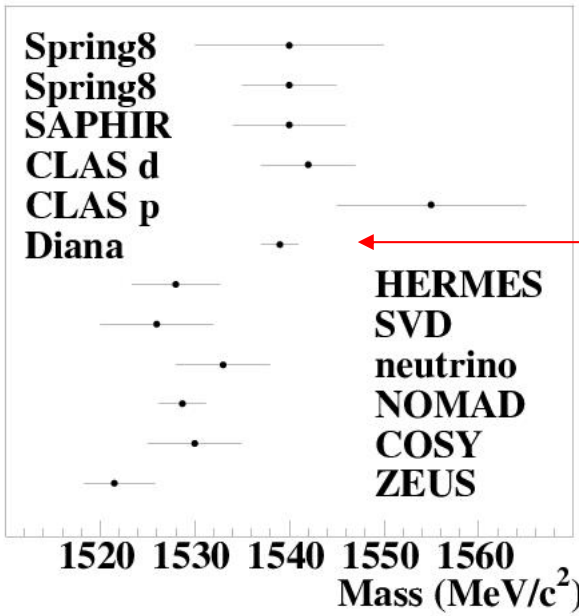
March 2, 2005

Summary of Results

Θ^+



Charge Exchange

A narrow structure whose width is less than experimental resolution

Old data constrain Γ_Θ<1MeV

Ξ_5^{--} Ξ_5^0

Na49: Mass: 1862 MeV
Width < Resolution

Θ_c^0

H1: Mass : 3100 MeV
Width ~10 MeV

Statistics

$$\xi_1 = \frac{s}{\sqrt{b}}$$

$$\xi_2 = \frac{s}{\sqrt{s+b}}$$

$$\xi_3 = \frac{s}{\sqrt{s+2b}}$$

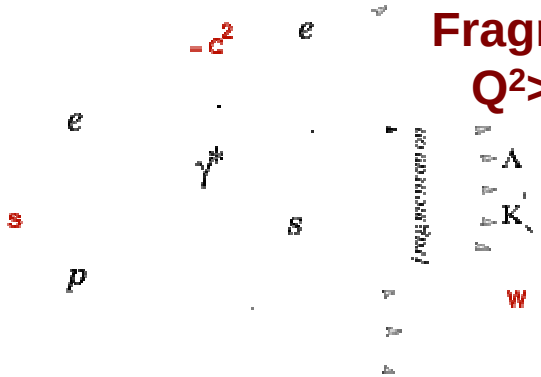
	Experiment	Signal	Background	Publ.	Significance ξ_1	ξ_2	ξ_3
	Spring8	19	17	4.6σ	4.6	3.2	2.6
	Spring8	56	162		4.4	3.8	2.9
	SPAHIR	55	56	4.8σ	7.3	5.2	4.3
	CLAS (d)**	43	54	5.2σ	5.9	4.4	3.5
	CLAS (p)	41	35	7.8σ	6.9	4.7	3.9
	DIANA &&	29	44	4.4σ	4.4	3.4	2.7
	ν	18	9	6.7σ	6.0	3.5	3.0
	HERMES	51	150	4.3-6.2σ	4.2	3.6	2.7
	COSY	57	95	4-6σ	5.9	4.7	3.7
	ZEUS	230	1080	4.6σ	7.0	6.4	4.7
	SVD	41	87	5.6σ	4.4	3.6	2.8
	NOMAD	33	59	4.3σ	4.3	3.4	2.7
Ξ_5	NA49	38	43	4.2σ	5.8	4.2	3.4
Ξ_5	NA49	69	75	5.8σ	8.0	5.8	4.7
Θ_c	H1	50.6	51.7	5-6σ	7.0	5.0	4.1

** **An improved analysis shows a less significant peak!**

&& **Shown to be charge exchange**

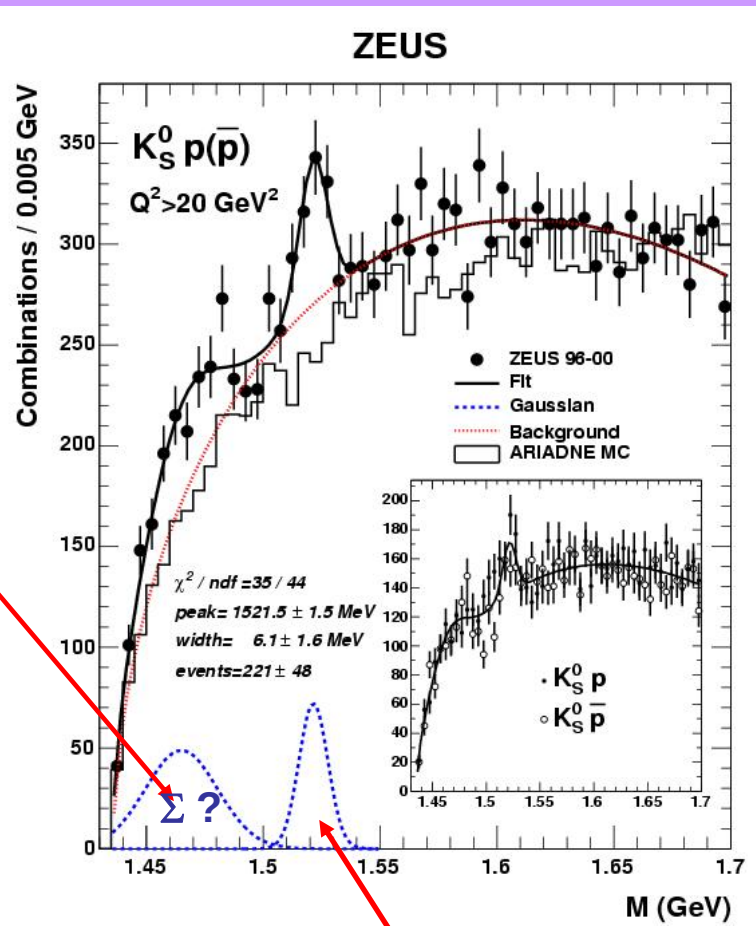
Zeus Result

Phys. Lett. B591 (2004) 7.



Fragmentation, Q^2>20GeV^2

Mass=1465
Width=15
368 Events



Interesting Result

~6000 Λ
~200 $\Lambda(1520)$
230 Θ^+

fragmentation is a good source of Θ^+!

K_S p is not manifestly Exotic. It could be a Σ

Observe: Θ^+
mass=1.521 GeV width=6.1 MeV
230 Events on 1080 Background

No Signal for: Ξ_5 , Θ^0_c

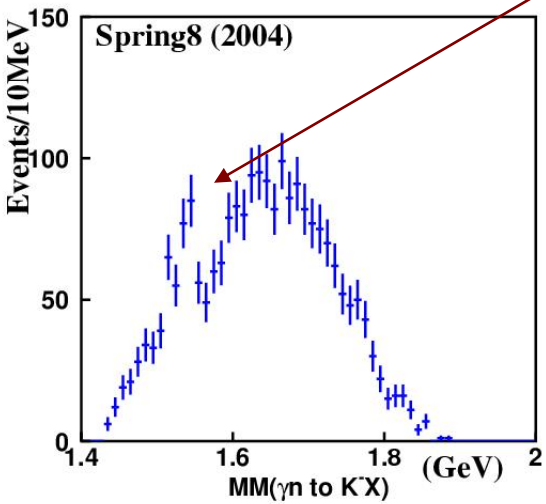
(U.Karshon, Pentaquark-04)

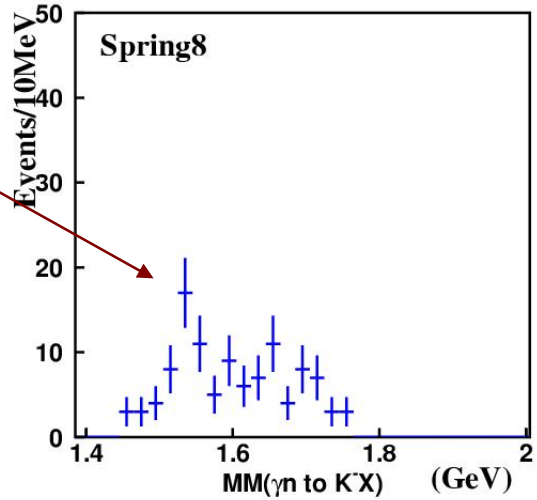
LEPS

$\gamma C \rightarrow K^+ K^- X$ **Assume that the reaction is** $\gamma\, n \rightarrow \Theta^+ K^-$

Calculate Missing Mass($\gamma\, n \rightarrow K^- X$)

$\gamma\, d \rightarrow K^+K^-X$ **Assume** $\gamma\, n \rightarrow \Theta^+K^-$





Cuts to remove: $\phi \rightarrow K^+K^-$

$\Lambda(1520) \rightarrow p\, K^-$

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

Missing Mass(γ d, KK X) is a neutron

Fermi Momentum Corrections

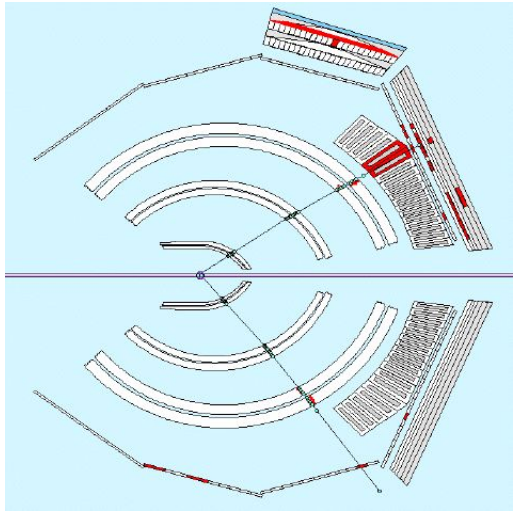
Backgrounds: KKN phase space

$\phi(1020)\ \Lambda,\Sigma$

Highly unconstrained final states

Unknown Backgrounds

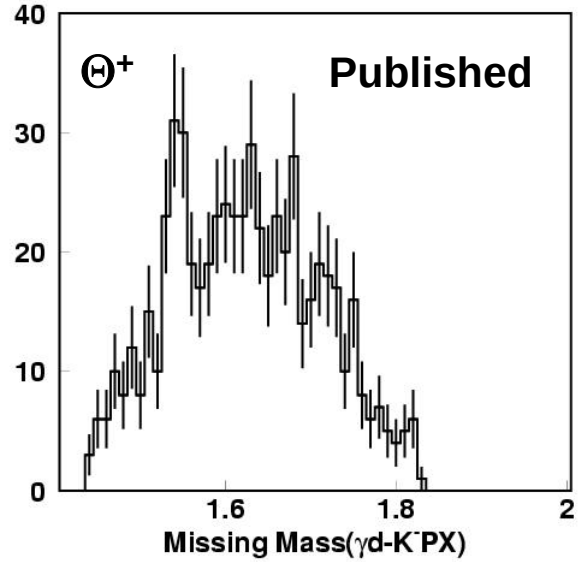
Many Cuts to pull out the signal



CLAS

$\gamma\, d \rightarrow K^+K^-\, p\, (n)_{miss}$

Reaction is unknown



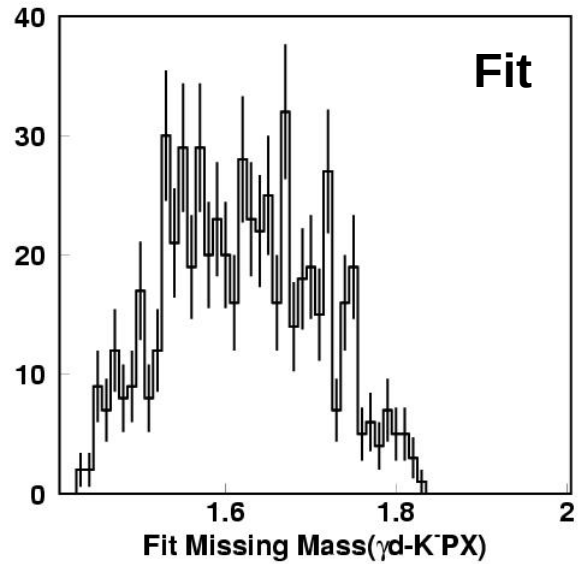
Independent analysis of the data:

- **energy loss corrections from target**
- **1C-Kinematic fit to final state**

- **Flat confidence level**
- **Known resonances get sharper and have the right mass: $\Lambda(1520)$ $\phi(1020)$**

- **Evidence for higher mass Λ, Σ ' s and either the $a_2(1320)$ or $f_2(1270)$ is sharper.**

Disturbing Effect on the Θ^+ !



NOT AN OFFICIAL CLAS RESULT

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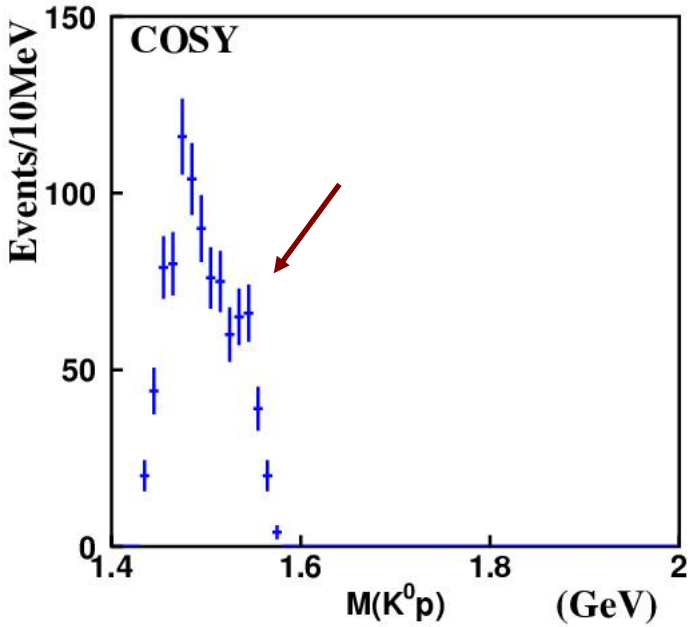
COSY

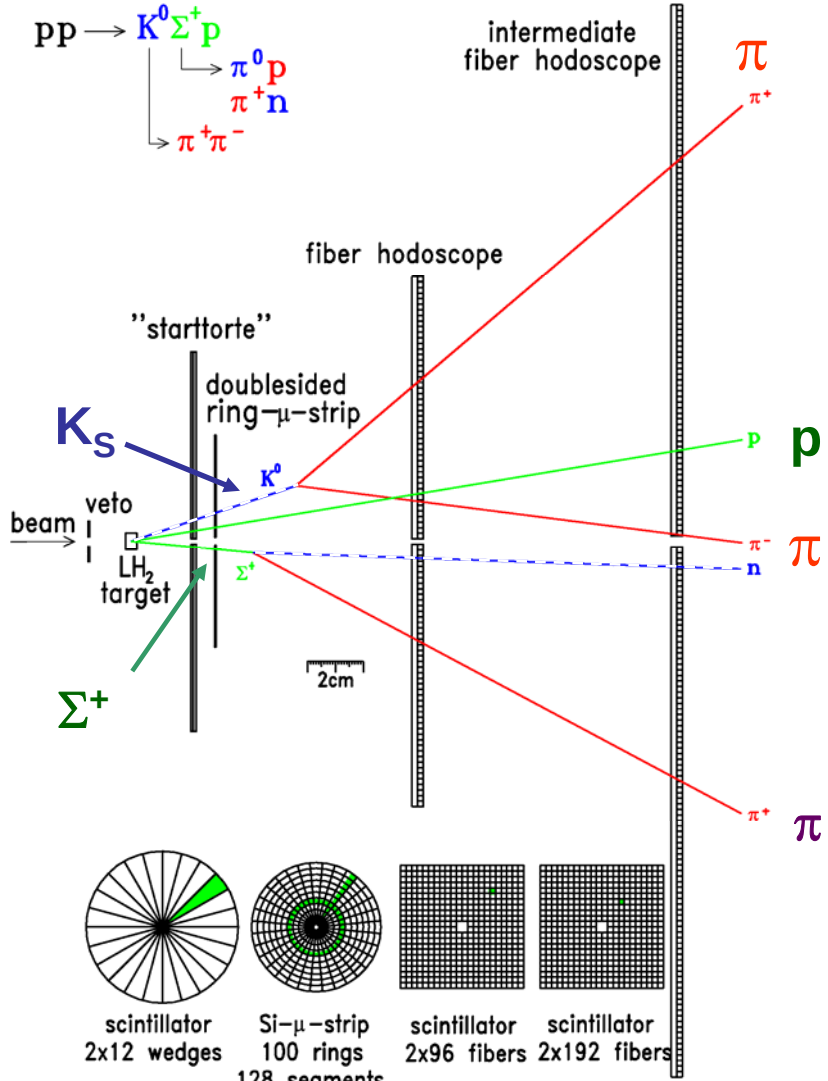


$pp \rightarrow \Theta^+\Sigma^+$

$\Theta^+ \rightarrow K_S\, p$

$K_S \rightarrow \pi^+\pi^-$

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



2 Hits in the first hodoscope Σ^+ & p

4 Hits in the 2nd and 3rd planes $\pi^+\pi^-\pi^+$ p

(2-plane hodoscopes so ambiguous)

No Particle Identification, No Momentum Measurement, No charge measurement. Pure Geometry and a zero constraint fit to the reaction

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Negative Reports

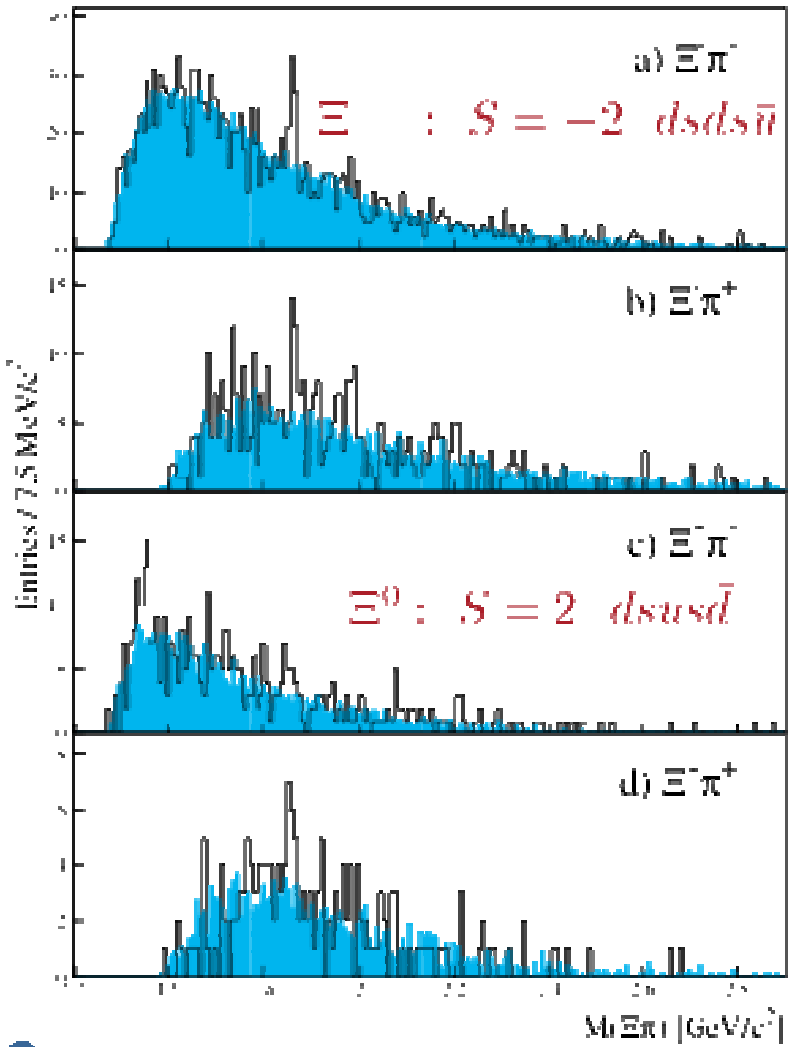
CDF	$p\bar{p} \rightarrow PX$ **hep-ex/0408025,0410024**	Θ^+ Θ_c^0 Ξ_5	**ALEPH**	**Hadronic Z decays** Submitted to **Phys. Lett. B**	Θ^+ Θ_c^0 Ξ_5
HyperCP	**$(\pi^+,K^+,p)Cu \rightarrow$ PX** **hep-ex/0410027**	Θ^+	**DELPHI**	**Hadronic Z decays** **hep-ex/0410080**	Θ^+
SELEX	**$(\pi,p,\Sigma)p \rightarrow$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

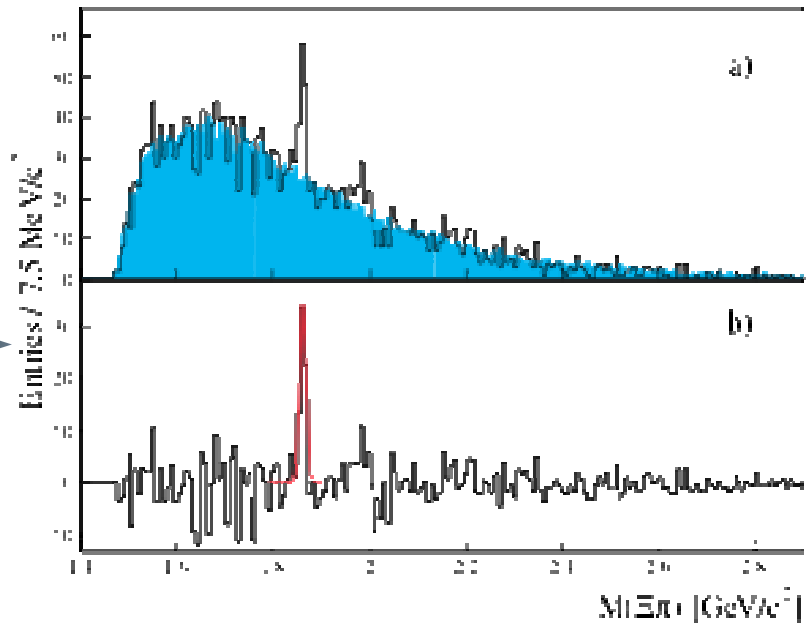
The $\Xi^{--}(1861)$

NA49 $\Xi_5(1860)$

fixed target experiment at CERN - spectrometer
158 GeV/c proton beam

$$\Xi^{--}(1862) \rightarrow \Xi^{-}\pi^{-}$$
$$\Xi^{0}(1862) \rightarrow \Xi^{-}\pi^{+}$$



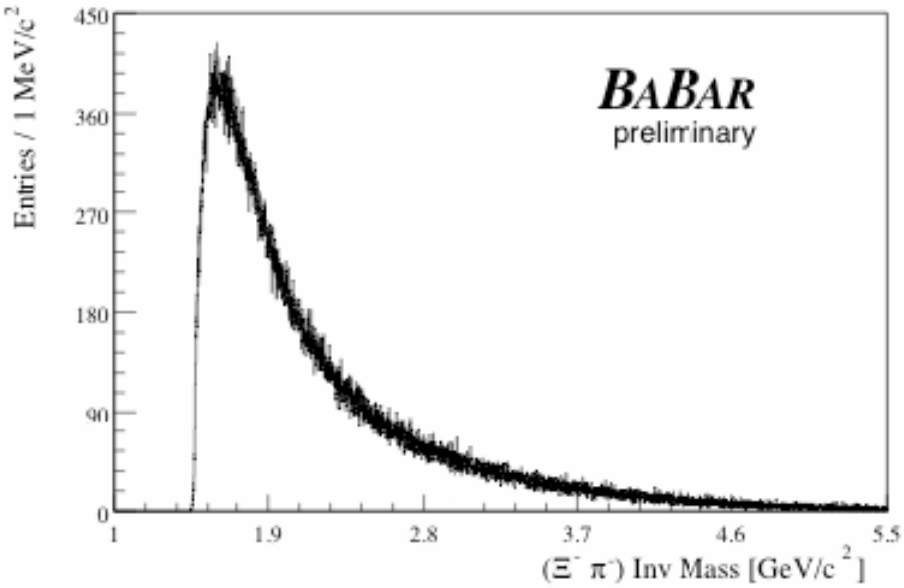


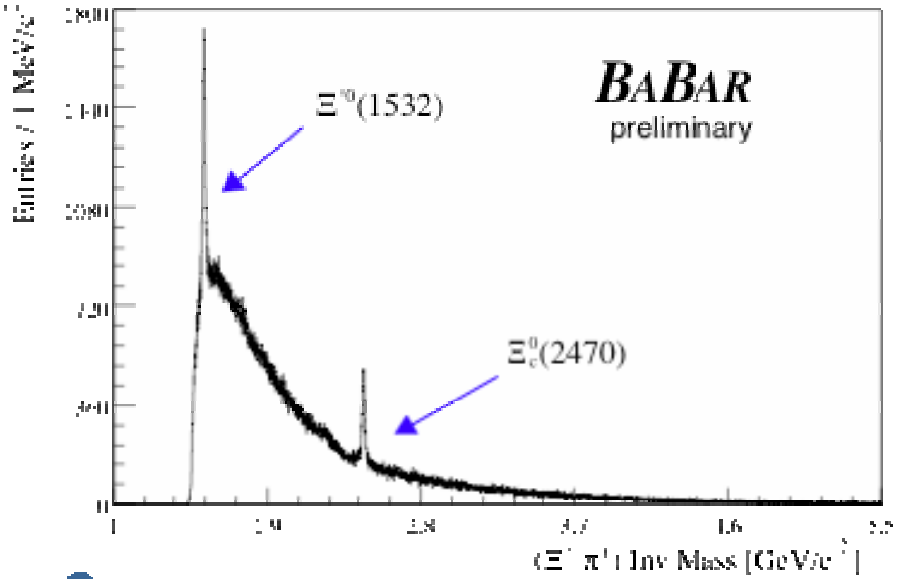
$M = 1.862\ GeV/c^2$

width is below detector resolution

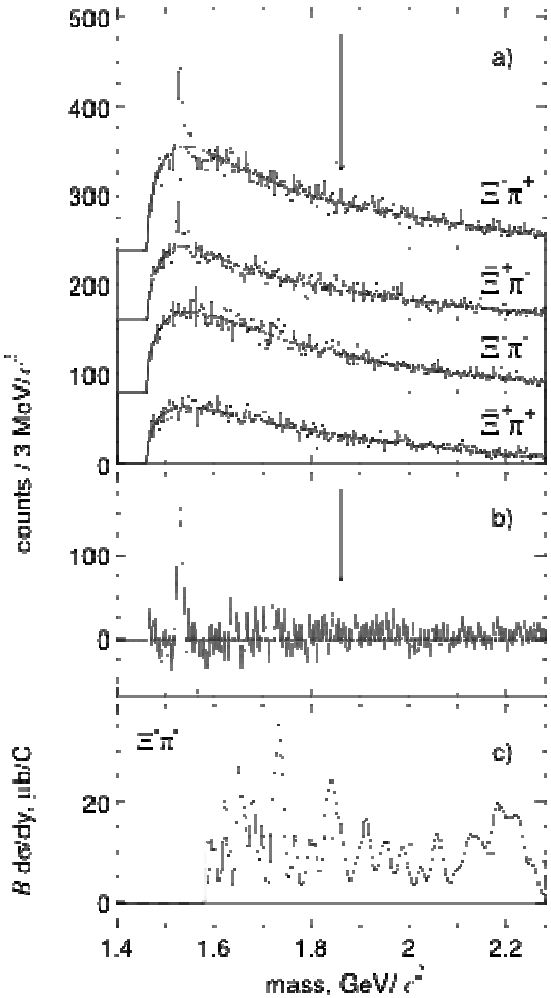
Null Results $\Xi_5(1860)$

$$\Xi^{--}(1862) \to \Xi^-\pi^-$$
$$\Xi^{0}(1862) \to \Xi^-\pi^+$$



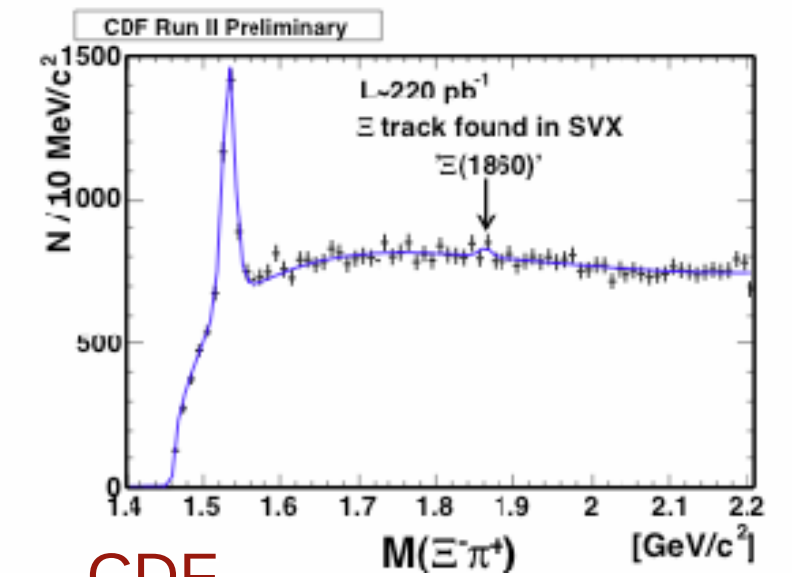


HERA-B



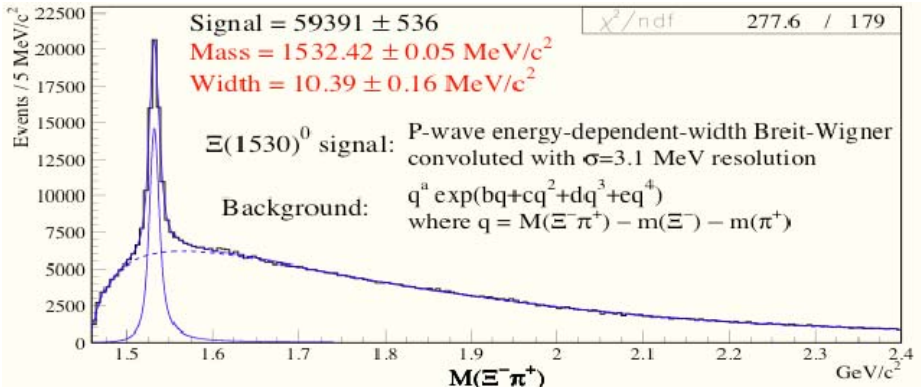
Null Result $\Xi_5(1860)$

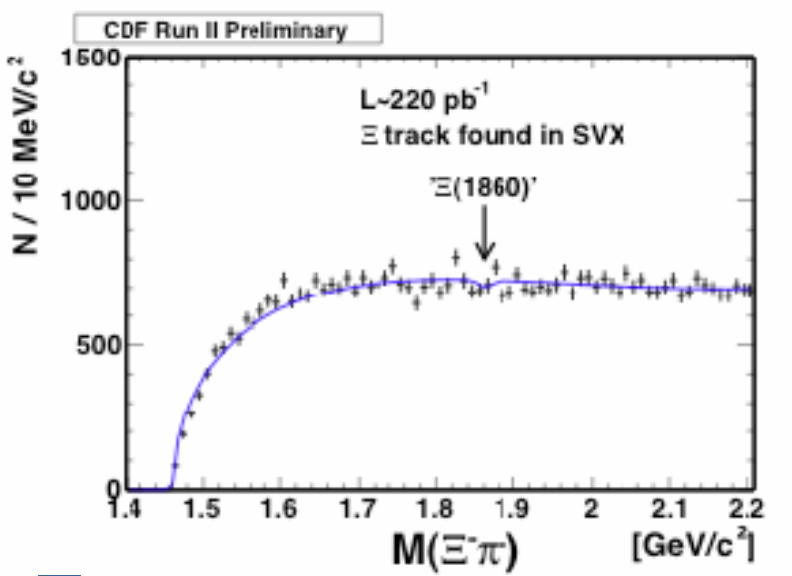
$$\Xi^{--}(1862) \rightarrow \Xi^{-}\pi^{-}$$
$$\Xi^{0}(1862) \rightarrow \Xi^{-}\pi^{+}$$



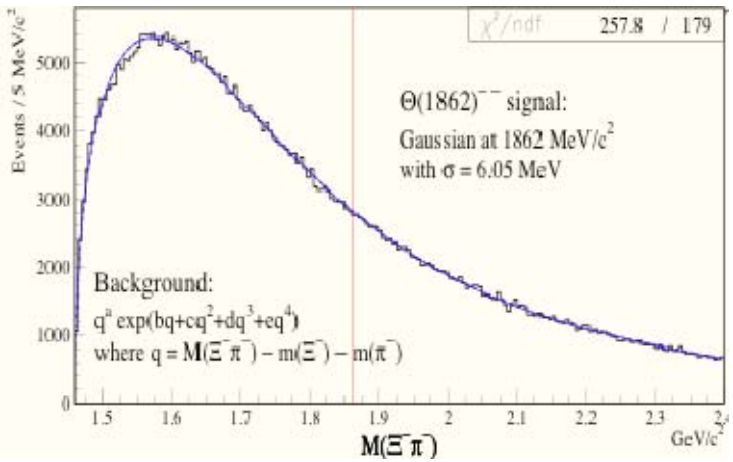
CDF

ALEPH and ZEUS also null result





FOCUS



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The $\Theta^0_c(3100)$

H1

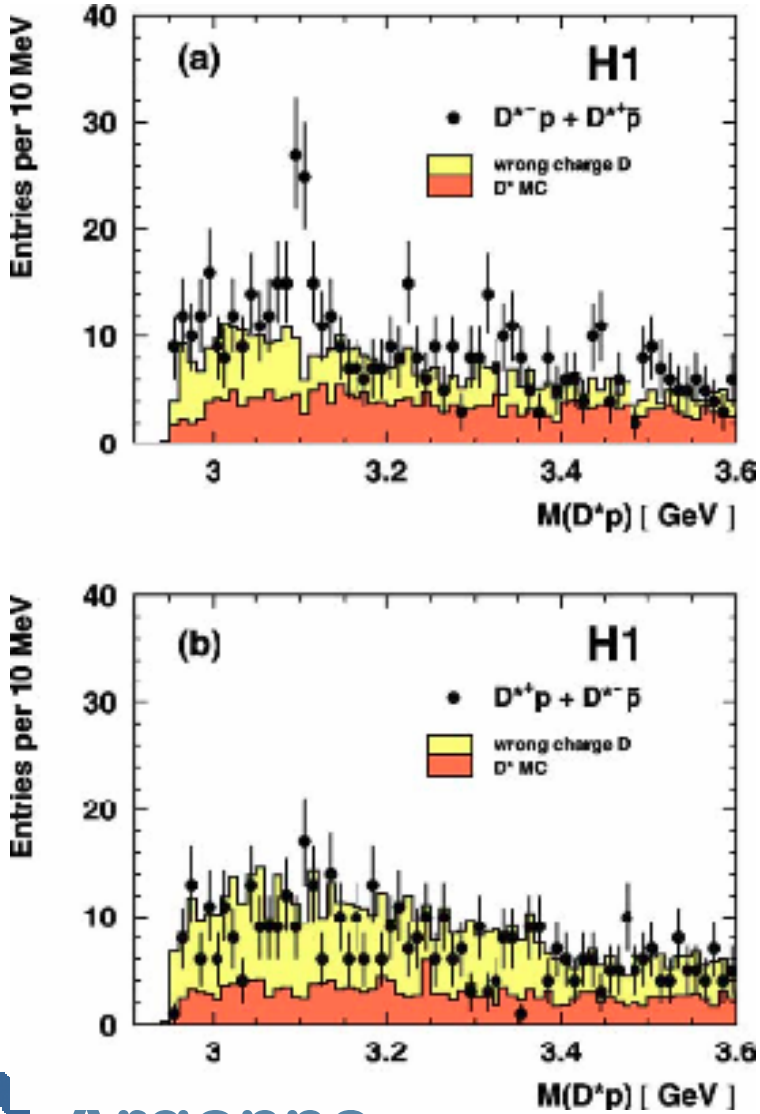
at HERA

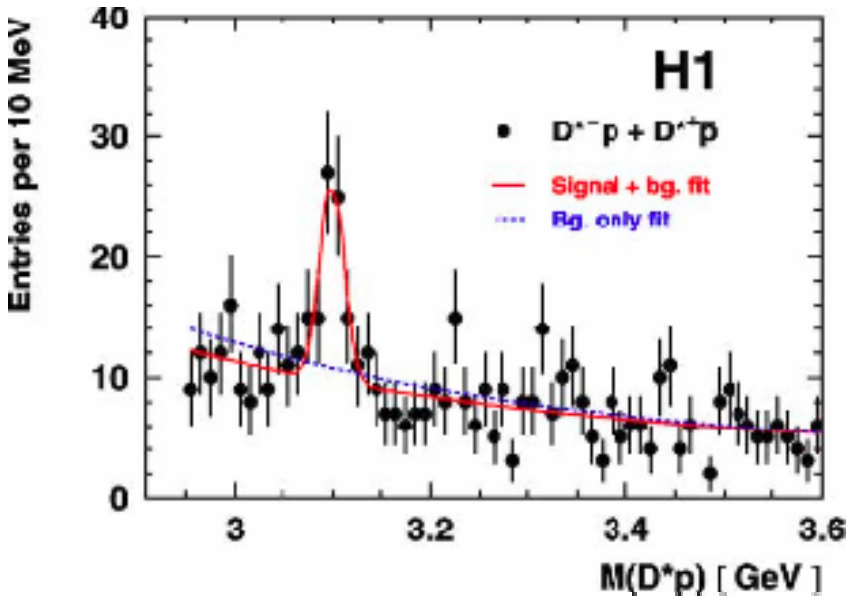
$\theta_c(3100) \rightarrow D^{*-}p$

Evidence for a narrow anti-charmed baryon state

H1 Collaboration

Physics Letters B 588 (2004) 17–28



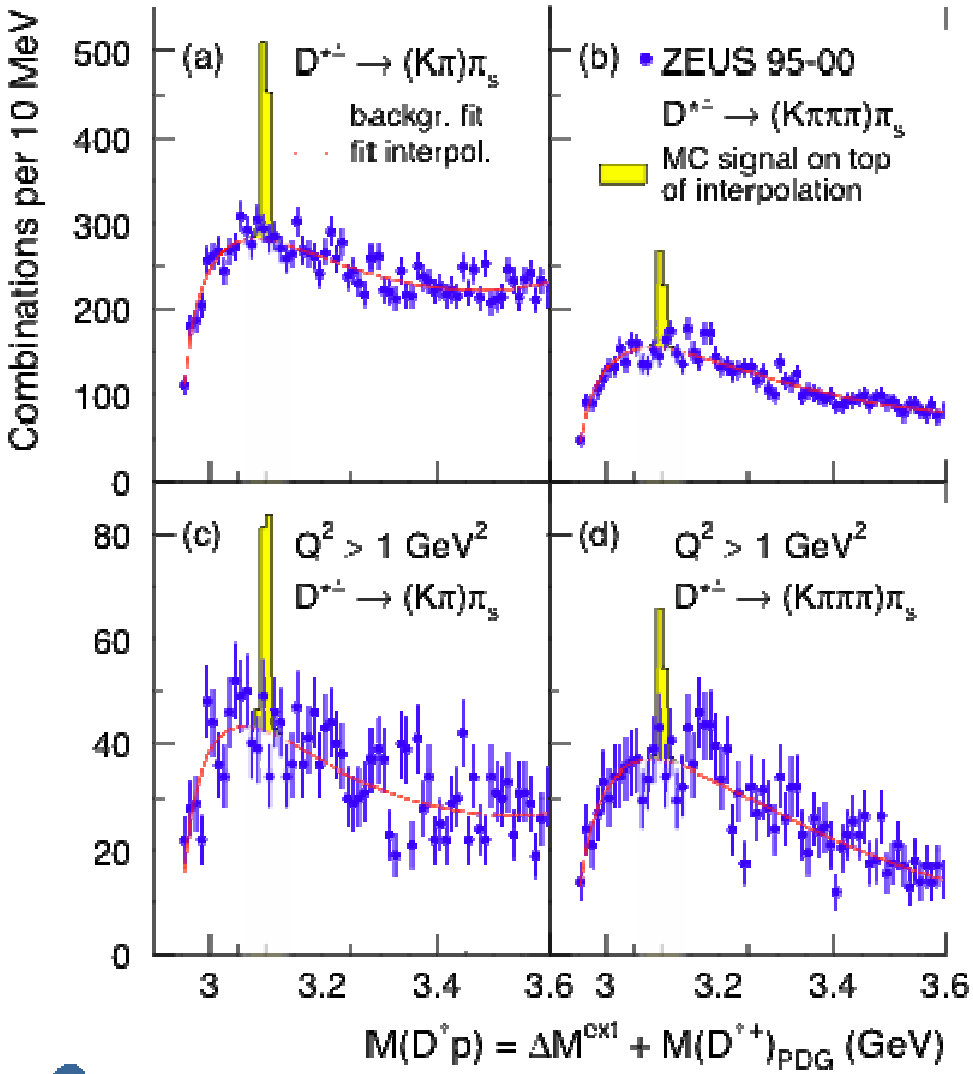


Sample	Mass (MeV)	Gaussian width (MeV)	N_r
$D^{*+}\bar{p}$ + $D^{*-}p$	3099 ± 3	12 ± 3	50.6 ± 11.2
$D^{*-}p$	3102 ± 3	9 ± 3	25.8 ± 7.1
$D^{*+}\bar{p}$	3096 ± 6	13 ± 6	23.4 ± 8.6

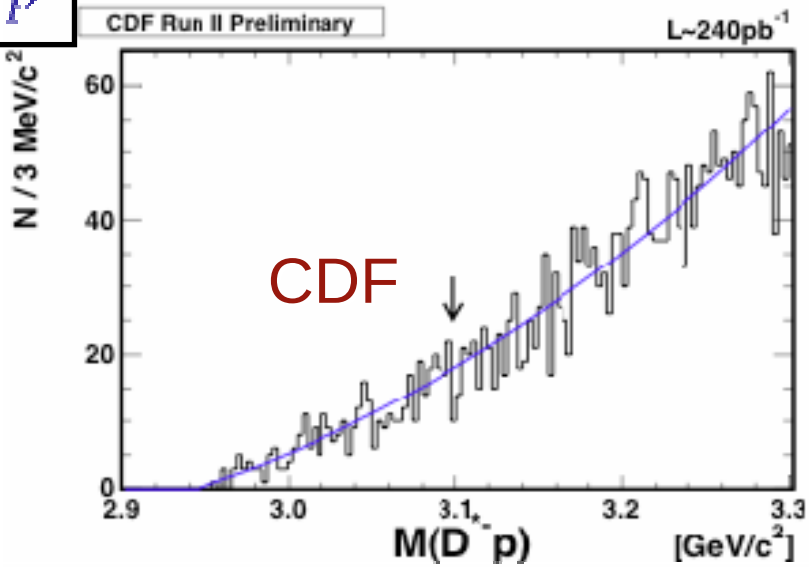
Null Results

$\theta_c(3100) \to D^{*-} p$

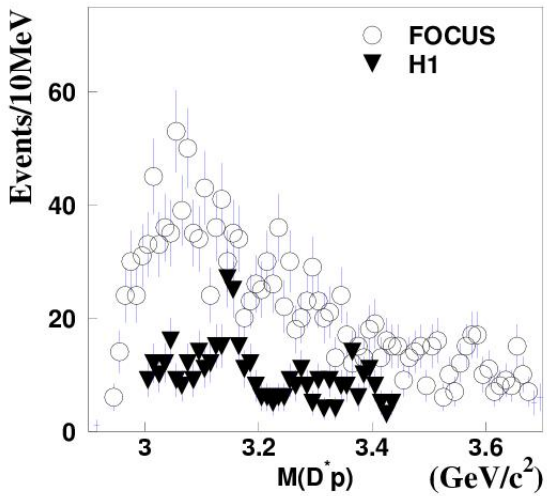
ZEUS



CDF



FOCUS

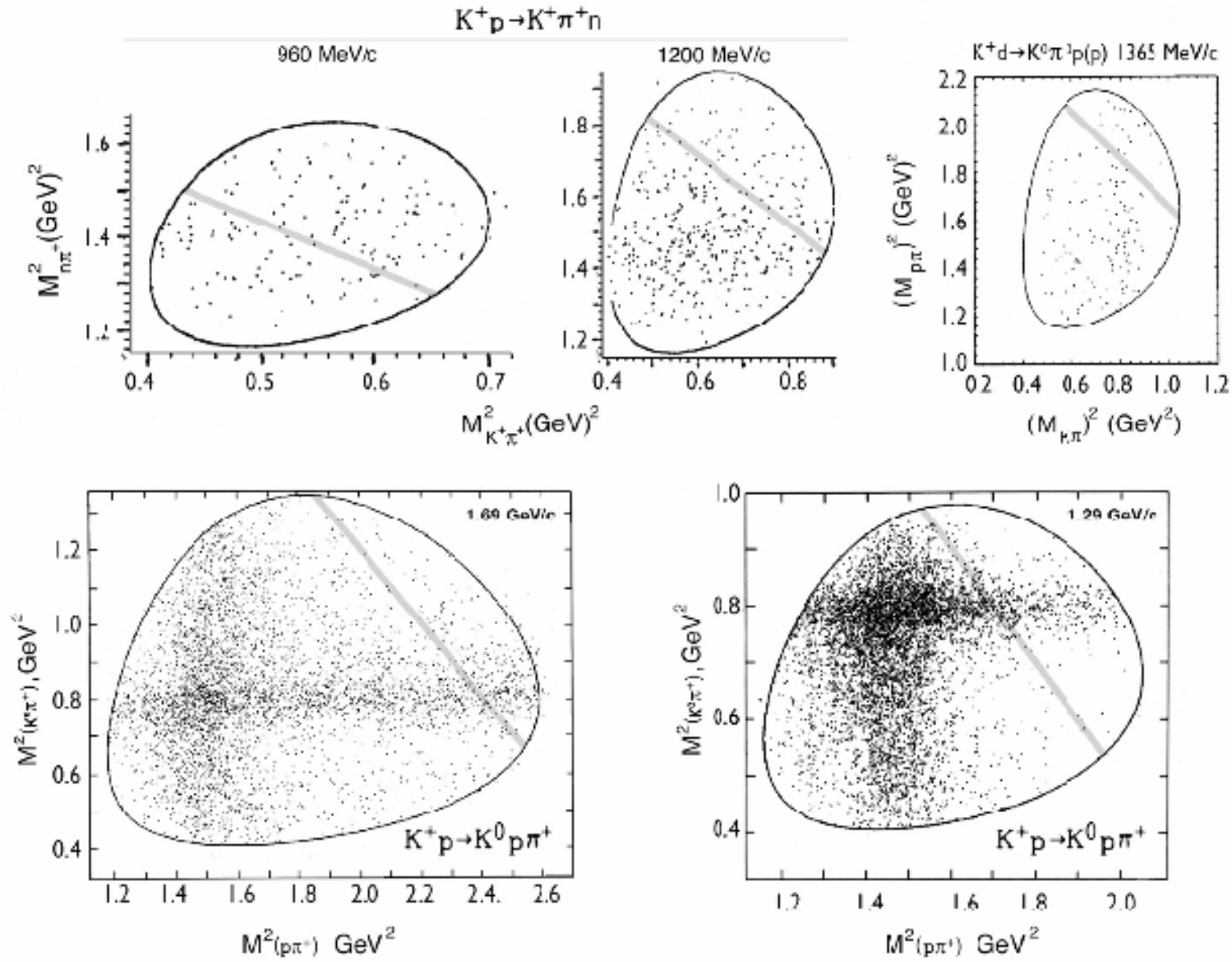


Argonne

The $\Theta^{+}(1540)$

Bubble Chamber

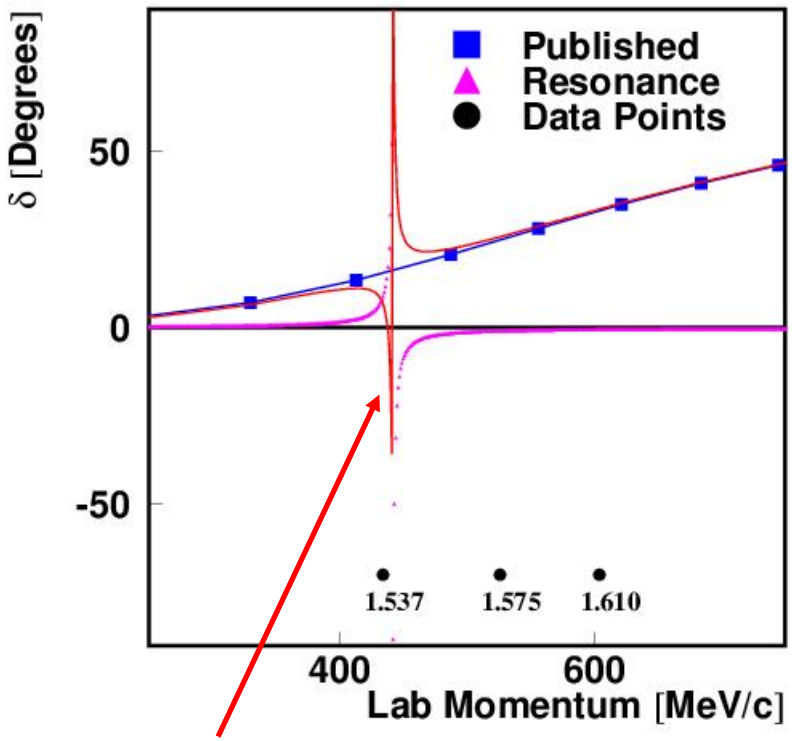
No signals in the Dalitz Plots



(Taken from the PDG, 2004)

Scattering Data

K^+n P-wave Phase Shifts

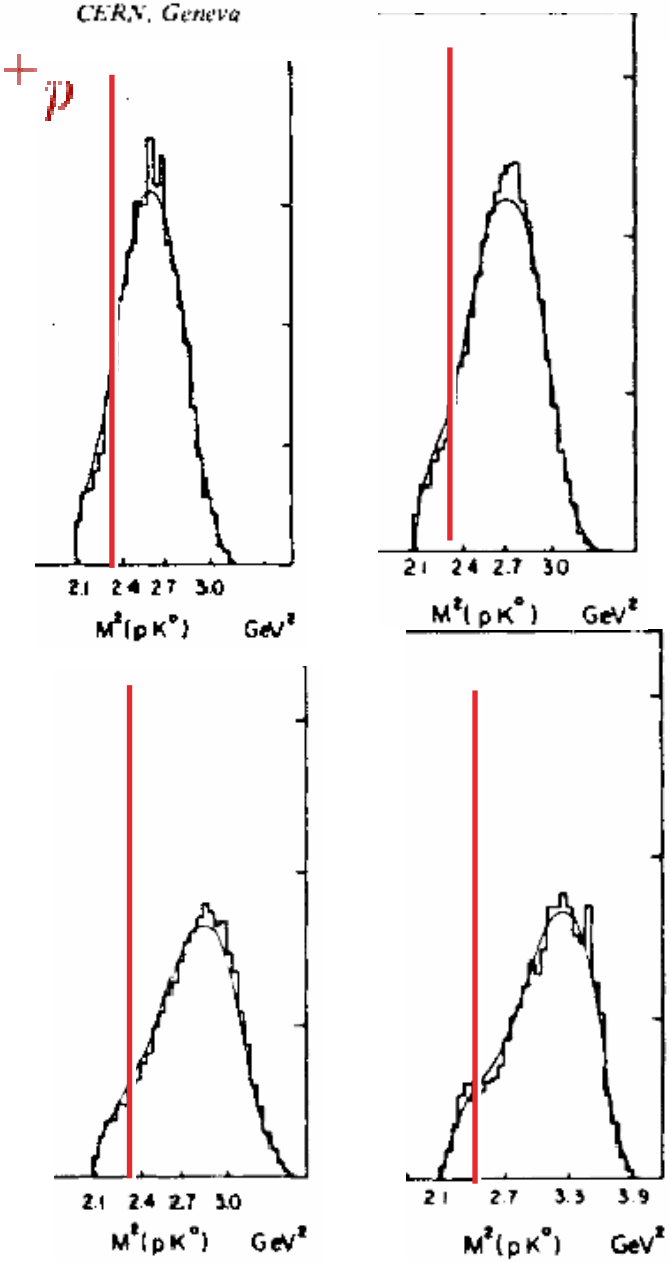


1MeV wide resonance at 1540

PROPERTIES OF THE INELASTIC K^+p REACTIONS BETWEEN 1.2 AND 1.7 GeV/c

A. BERTHON, L. MONTANET, E. PAUL, P. SAETRE ‡ and D.M. SENDALL
CERN, Geneva

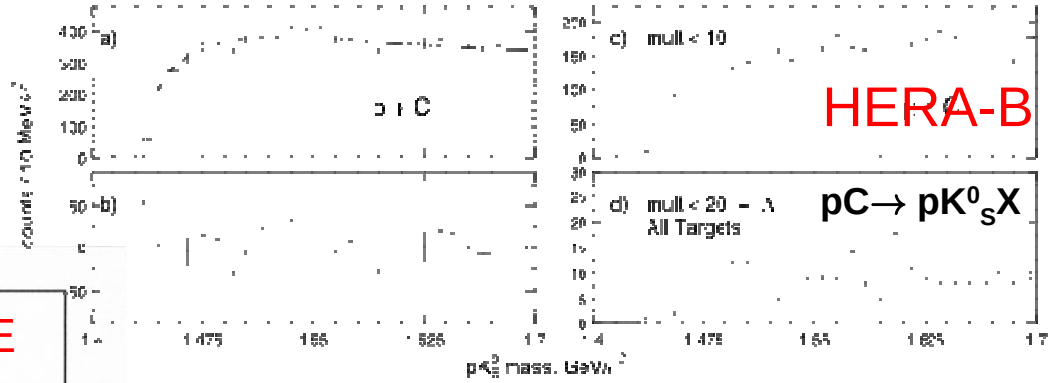
$K^+p \rightarrow K^0_S\pi^+p$

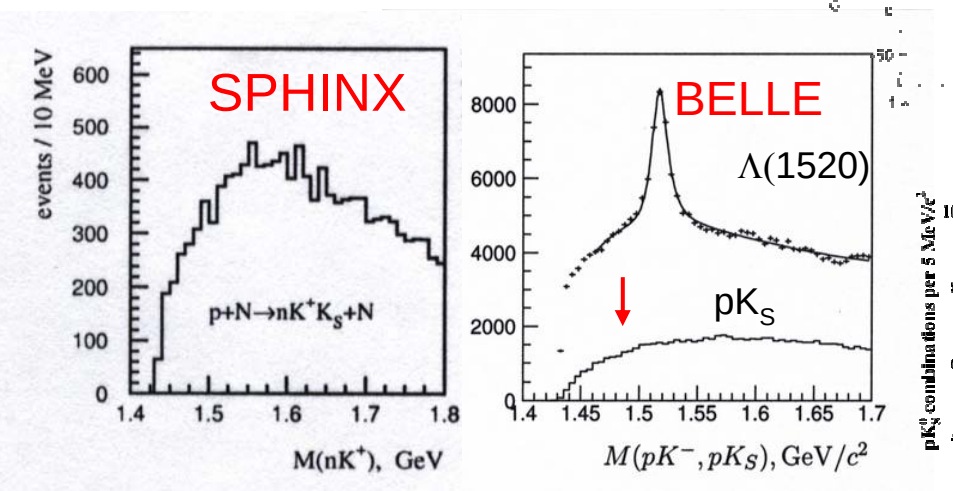


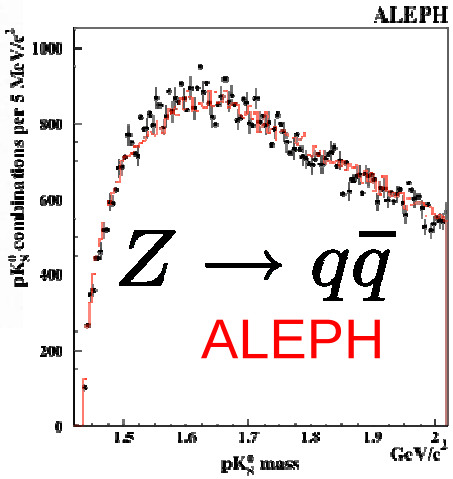
Argonne

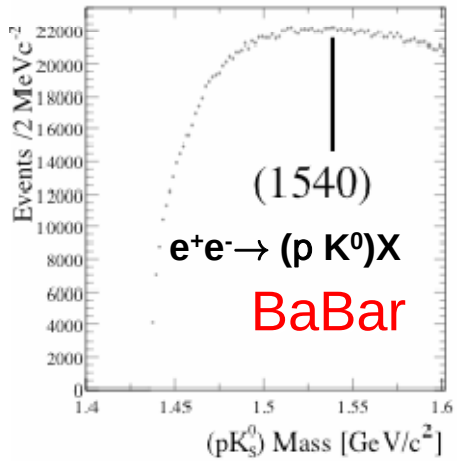
Negative Results

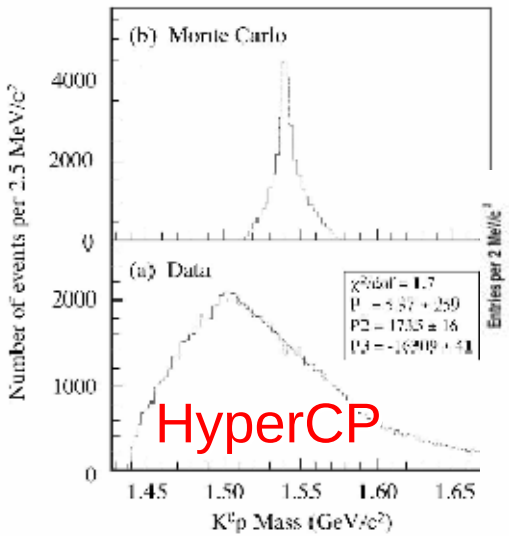
$\Theta^+(1540)$

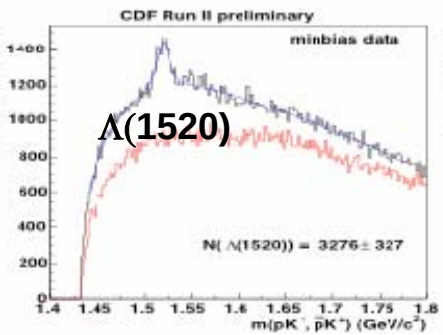


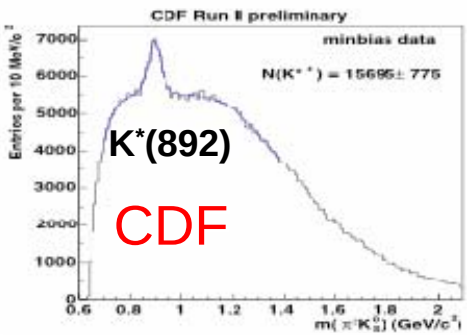


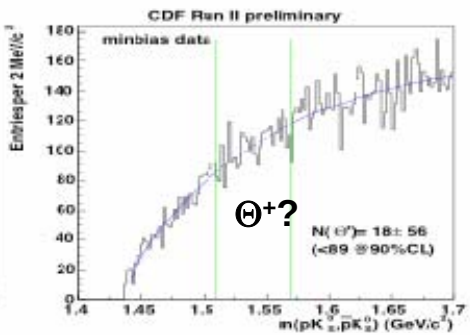






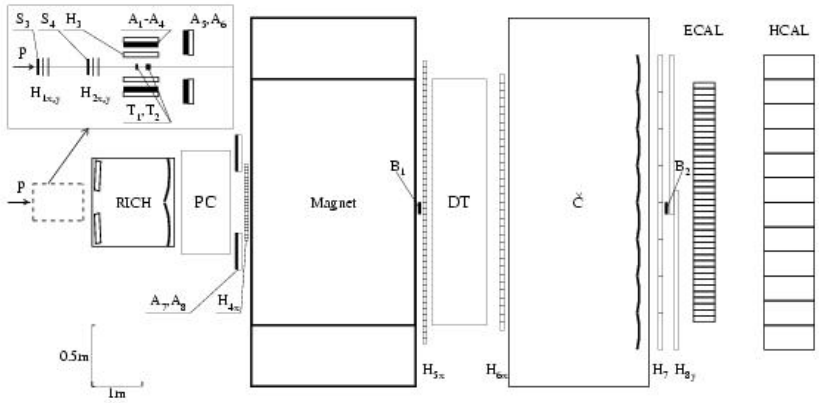






SPHINX

70 GeV p on Carbon Targets



The detector is sensitive to charged particles and the direction of neutrons and K_L by hits in the BCAL.

$p + N \rightarrow p\ K^+\ K^-\ N$

$p + N \rightarrow p\ K_S\ K_L\ N$

$p + N \rightarrow p\ K_S\ K_S\ N$

$p + N \rightarrow n\ K^+\ K_S\ N$

} **Detect**

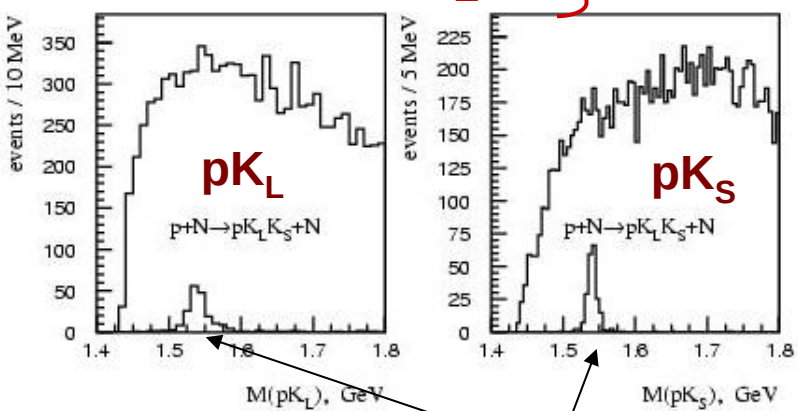
$p + N \rightarrow p\ K_L\ K_L\ N$

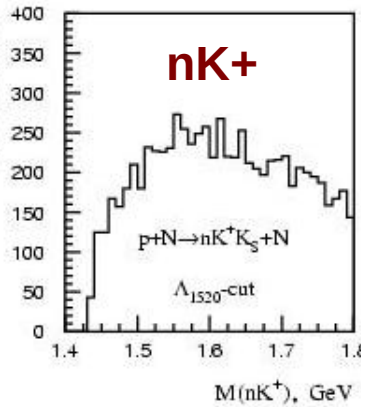
$p + N \rightarrow n\ K^+\ K_L\ N$

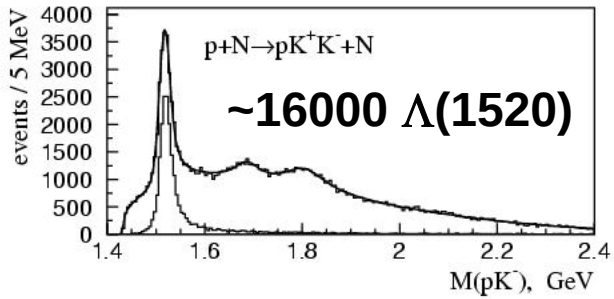
} Don't See

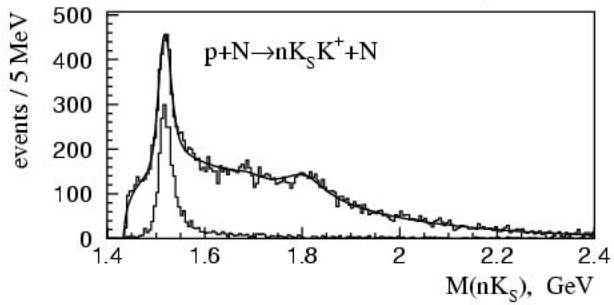
No Θ in either $p\ K_s$ or $n\ K^+$

$\Lambda(1520)$ in $p\ K^-$, $n\ K_S$







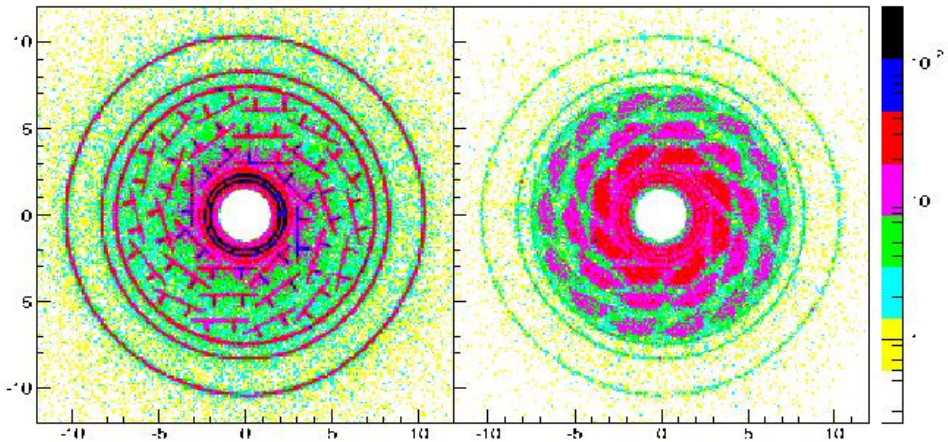


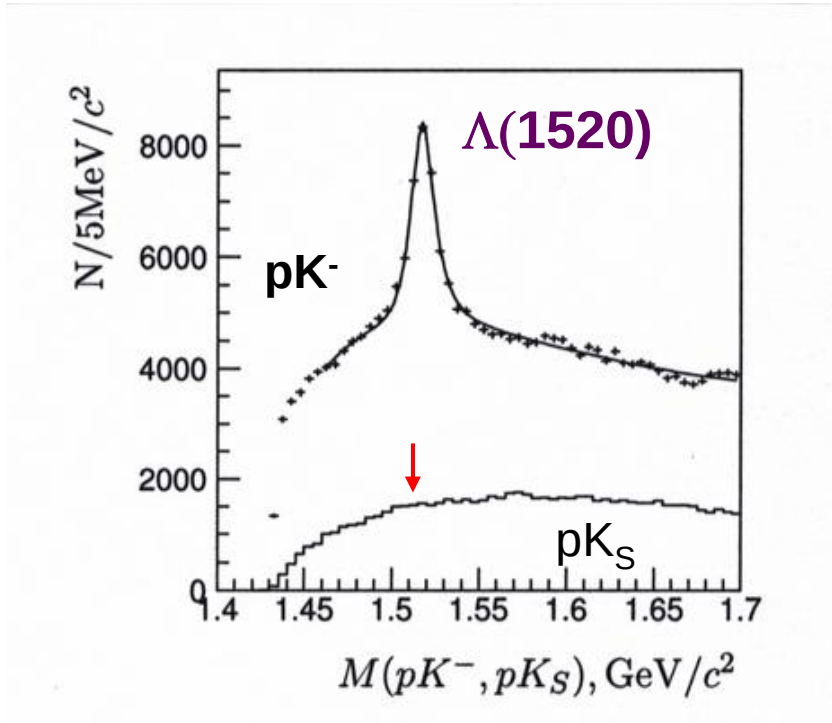
Monte Carlo

Argonne

Belle e^+e^- with an interesting twist

Look at the pK_S pK^- and pK^+ final states whose primary Vertex is from material in the detector





16000 $\Lambda(1520) \rightarrow K^- p$

Exclude: Λ N $\rightarrow \Lambda(1520)$
$K^-p \rightarrow \Lambda(1520)$

Signal comes from KN$\rightarrow \Lambda(1520)$X

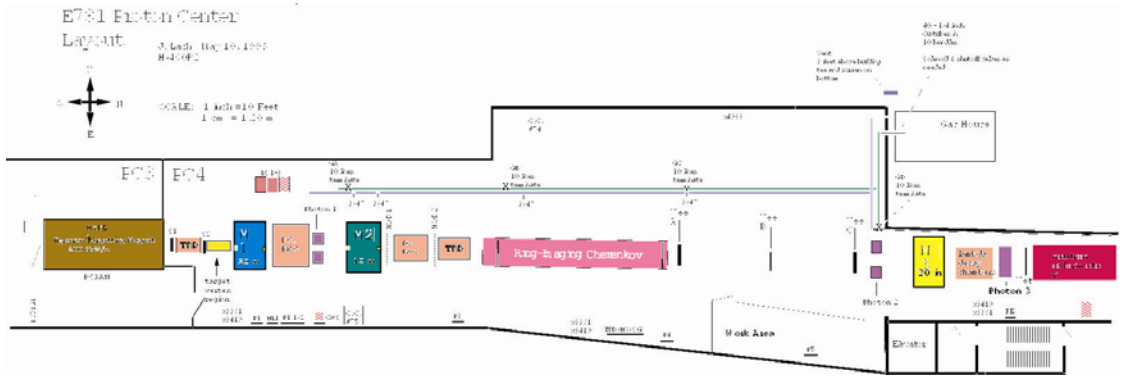
No signal in K_S p

It is very hard to produce the Θ^+ In K^+N interactions, but it falls apart into this just fine.

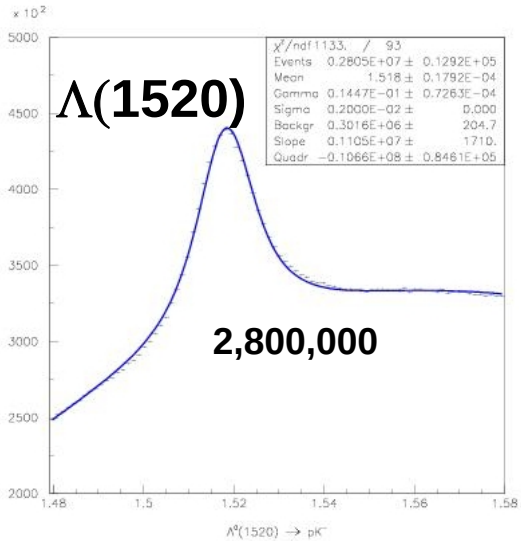
SELEX

600Gev Beams
(Σ^-,π^-,p,π^+)

(67%,14%,18%, 1%)

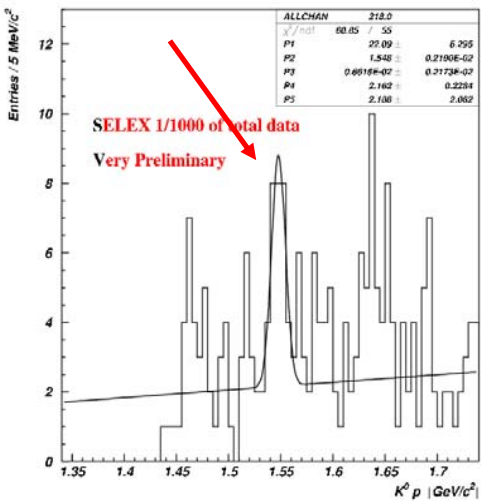


Very significant charmed baryon results.

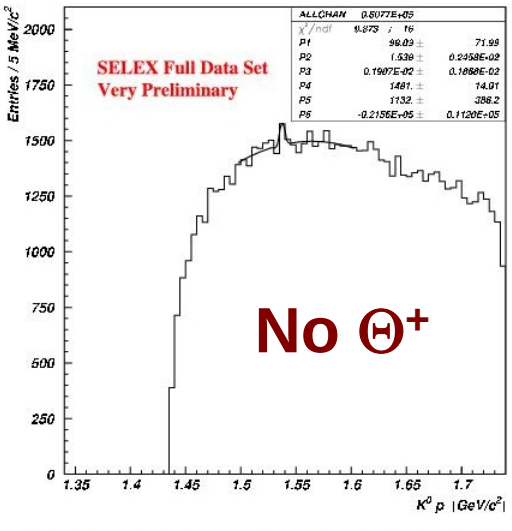


Mass (K^-p)

0.1% of Data



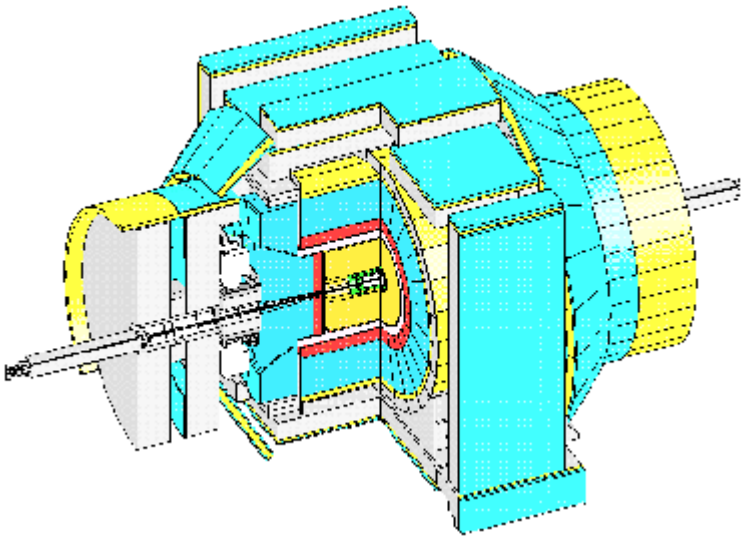
Mass (K_S p)



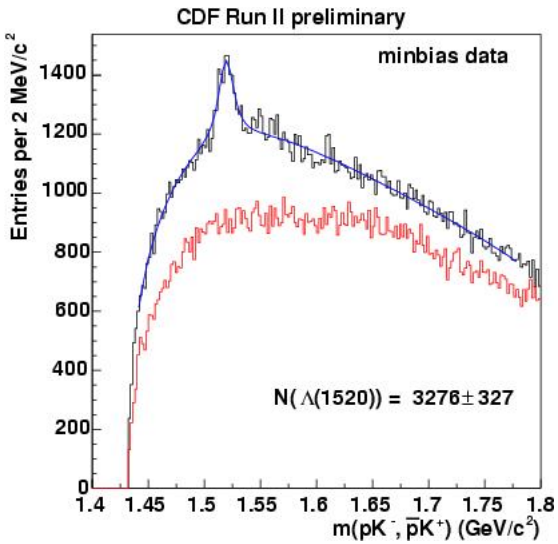
Mass (K_S p)

Argonne

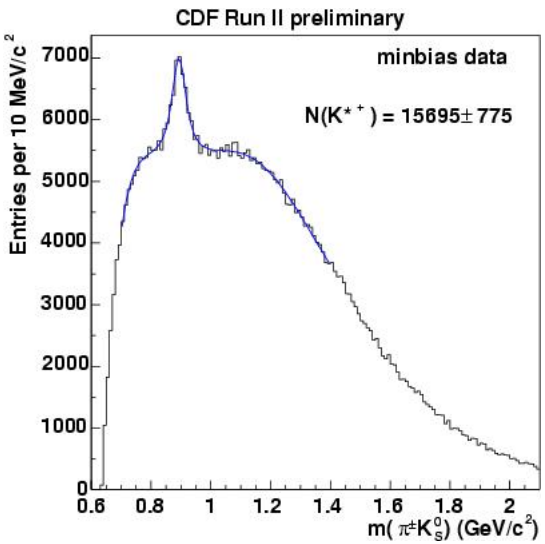
CDF



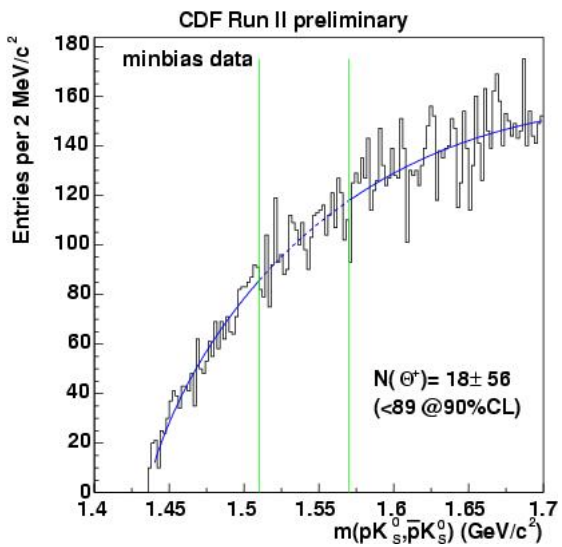
Resonance	Min. Bias	Jet>20GeV
$\Lambda(1520)$	3276± 327	4915± 702
K^{*+}	15695± 775	35769± 1390
Θ^+	18± 56	-56± 100
90% CL Θ^+	<89	<76



$pK^- + cc$



π^+K_S



$p\ K_S + cc$

Argonne

The Numbers

Positive Results

Experiment	s	b	Λ	Λ(1520)	φ
Spring 8	19	17		25	
Spring 8	56	162		180	
SAPHIR	55	56		530	
CLAS(d)	43	54		212	126
CLAS(p)	41	35			
DIANA	29	44	1152		
ν	19	8			
HERMES	51	150		850	
COSY	57	95			
ZEUS	230	1080	5700*	193	
SVD	35	93	260		
NOMAD	33	59			

	s	b	Ξ	D*
NA49	38	43	1640	
H1	50	52		3000

Some Negative Results

Experiment	Λ	Λ(1520)	φ	Λ_c
E690		5000		
ALEPH		2800		
CDF		3300	16000	
BaBar	10000000			100000
HERA-B	5000	3000	50000	
SPHINX	5500	23700	12000	
HYPERCP				
COMPASS				
BELLE		15520		
SELEX		2,800,000		

	Ξ	Ξ(1530)	D	D*
E690		15000		
ALEPH	3350	200	25000	
CDF	36000	1000	3000000	536000
BaBar	258000	17000		
HERA-B	18000			
ZEUS	2600	160		
WA89	676000			
FOCUS			84000	36000

* Estimate from cross section

Low Energy Experiments

Produce a spin-2 or spin-3 resonance that decays to K^+K^-.

Have non-uniform populations of |m|=0,1,2,…

Produces a broad enhancement near 1.5

RAPID COMMUNICATIONS

PHYSICAL REVIEW D 69, 051501(R) (2004)

The evidence for a pentaquark signal and kinematic reflections

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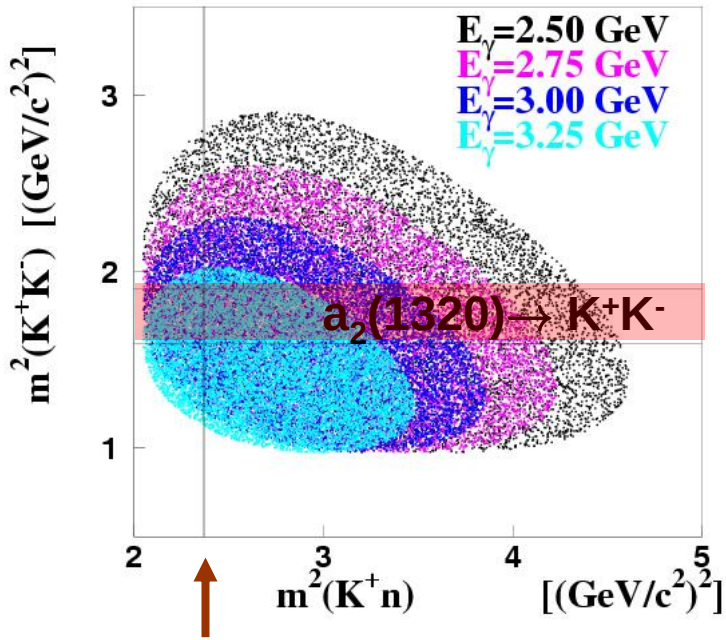
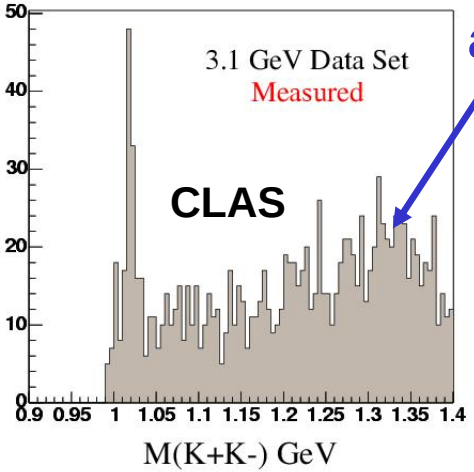
(Received 14 November 2003; published 25 March 2004)

Kinematic Reflections

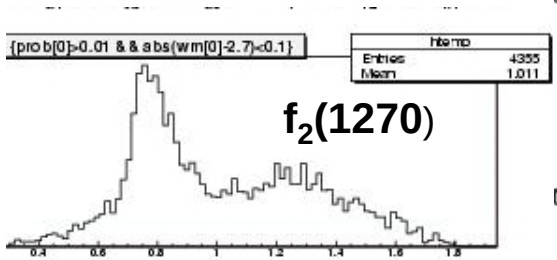


$\Theta^+(1540)$

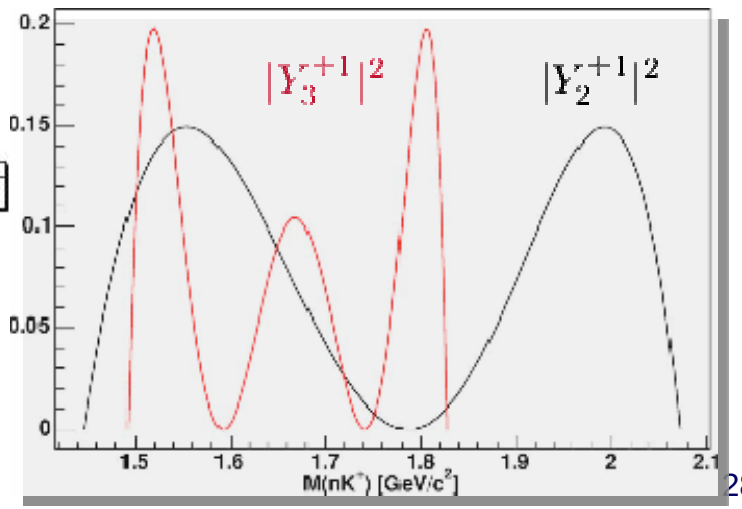
$\phi(1020)$



$a_2(1320)/f_2(1270)$



Mass($\pi^+\pi^-$)

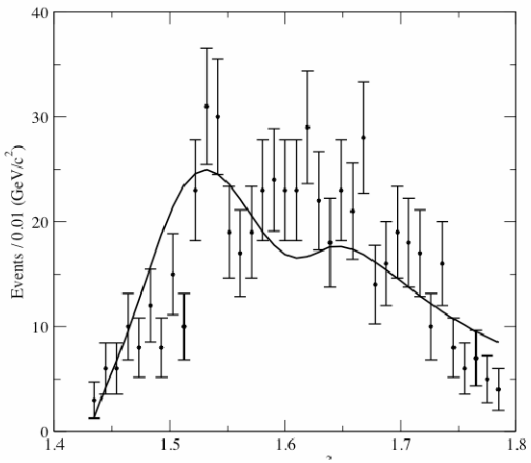


March 2, 2005

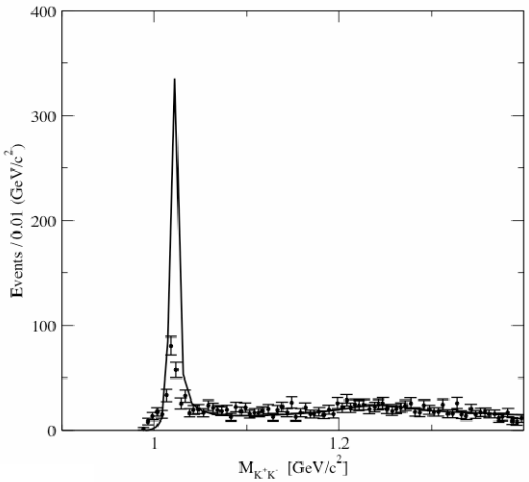
Kinematic Reflection?

The CLAS γ d $\rightarrow$ p n K^+K^- Data

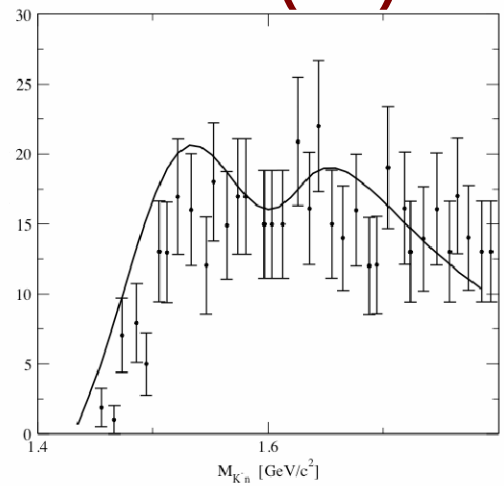
Mass (K^+n)

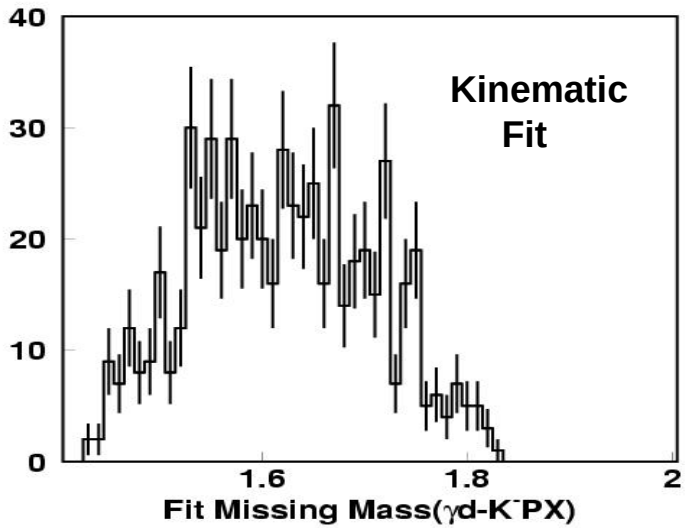


Mass (K^+K^-)



Mass (K^-n)



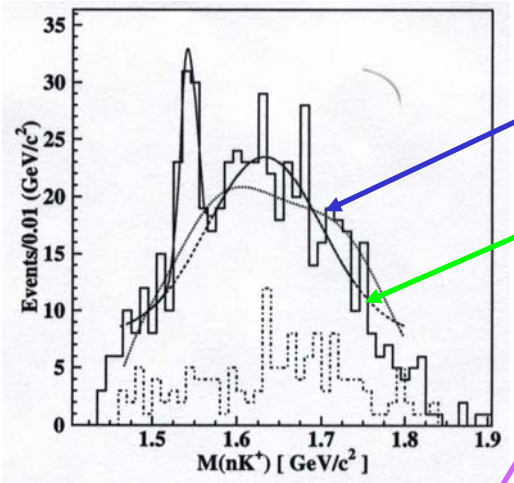


Solid lines are predicted using K^+K^- resonances

(Dzierba, *et al.)*

Statistical Fluctuation

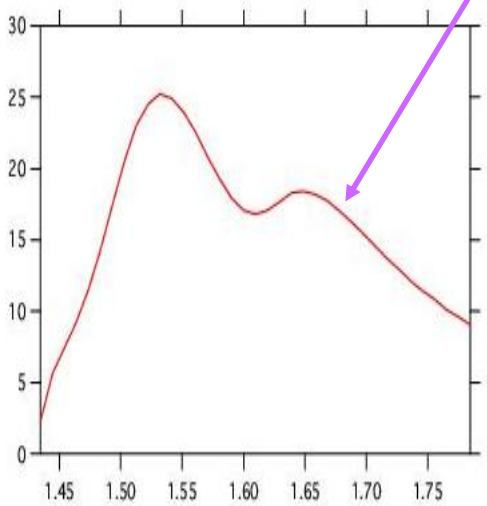
CLAS Published



Simple Physics Background

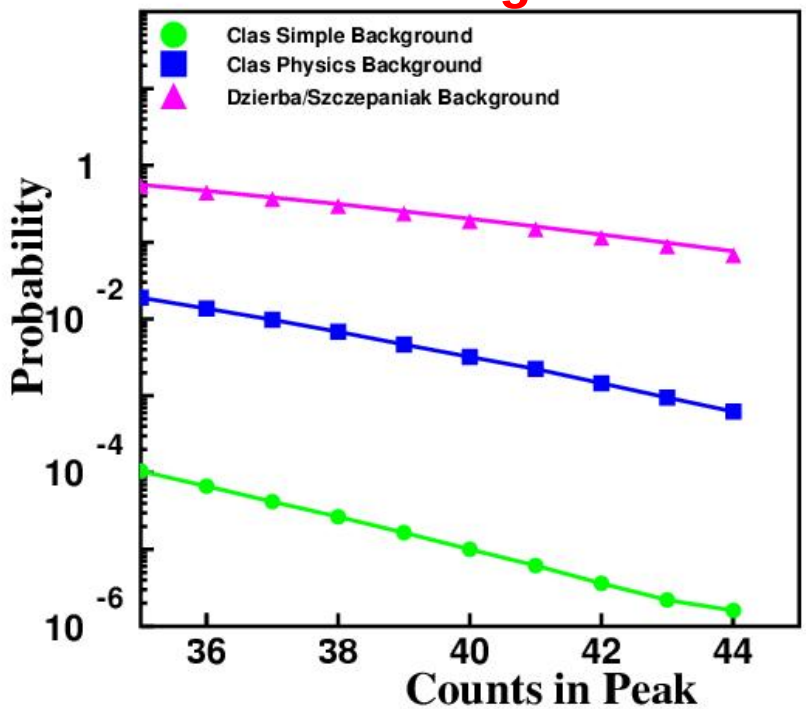
Naïve Background

Dzierba Background



You need to understand your background to claim a new discovery!

Chance of the Background Fluctuating into the observed signal

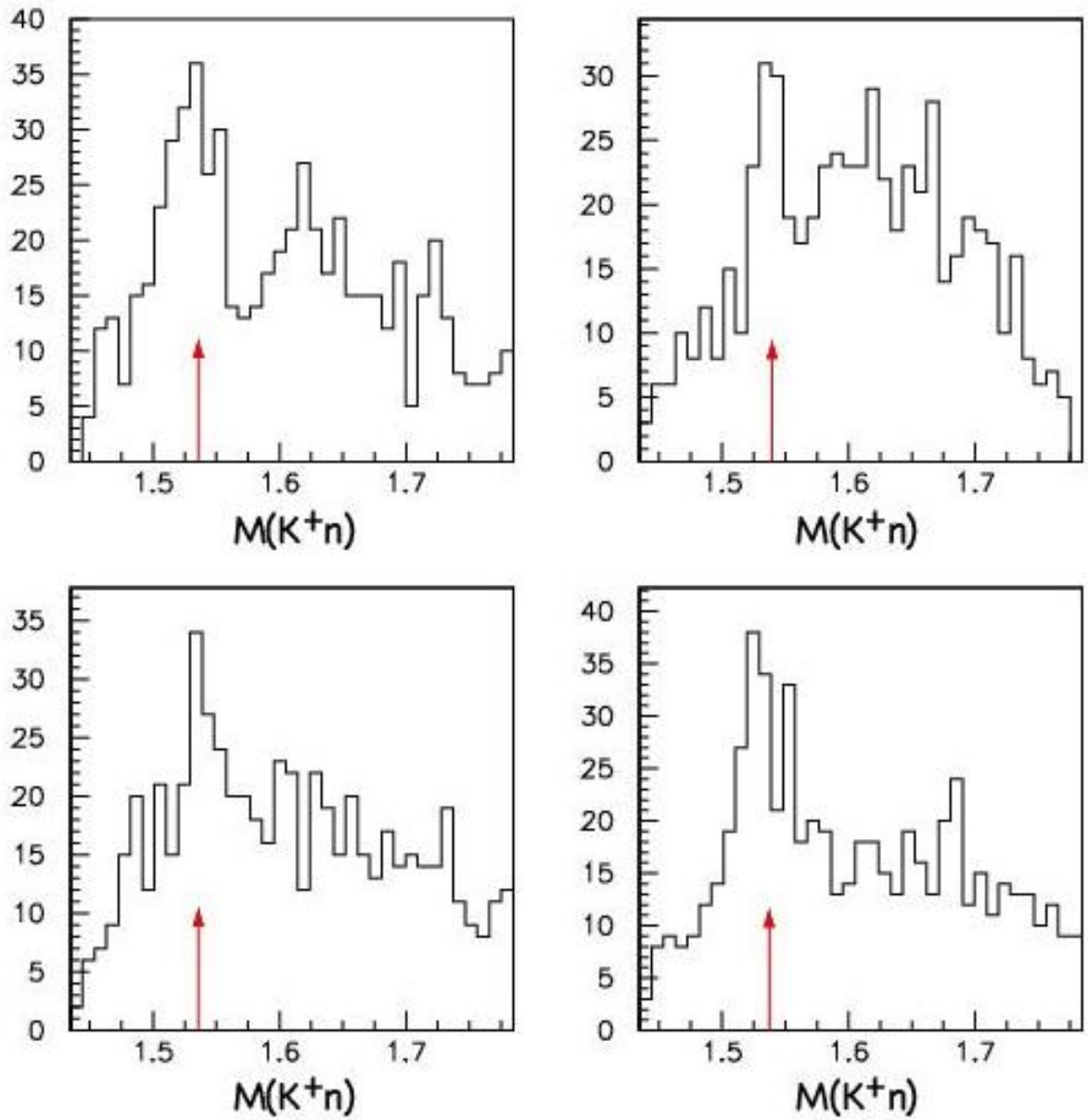


Games

Use Dzierba Background

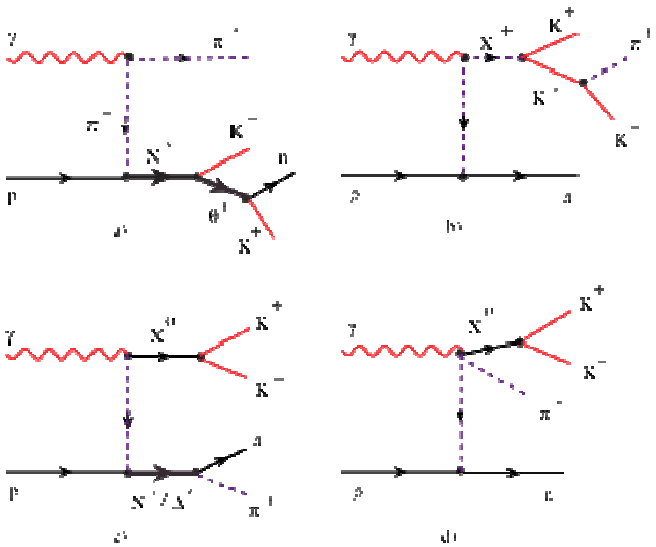
Generate 40 random spectra

3 are Fake
1 is CLAS



Severe Cuts

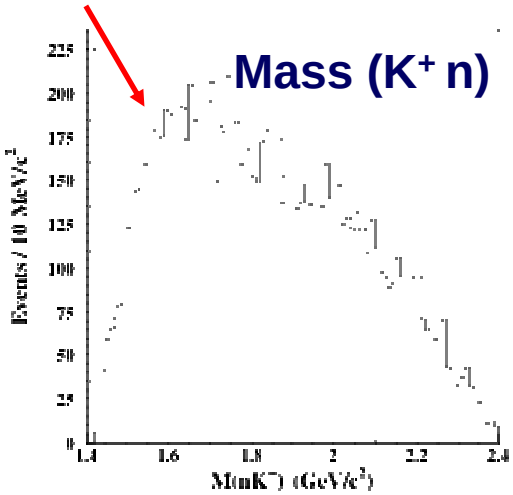
$\gamma\, p \rightarrow \pi^+K^+K^-(n)$ missing



Design cuts to remove diagrams (b), (c) and (d)

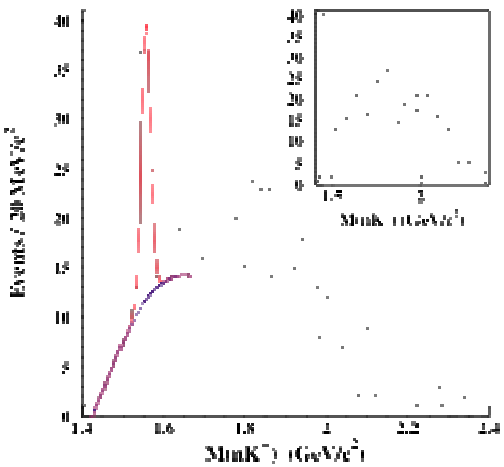
$|t_{\gamma\rightarrow\pi^-}| < 0.28\ GeV^2$

$\cos\theta^*_{K^+} < 0.6$

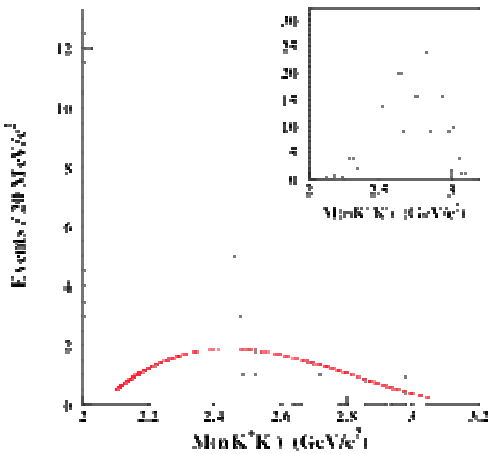


Uncut Spectrum

Mass (K^+ n)



Mass (K^-K^+ n)



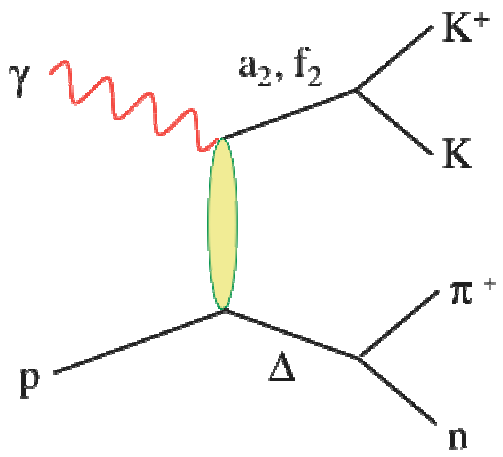
After Cuts

Argonne

CLAS: Phys. Rev. Lett. 92, 032001,(2004)

Monte Carlo Study

$\gamma\, p \rightarrow \Delta\, a_2/f_2$ $\quad a_2$ or $f_2 \rightarrow K^+K^-$

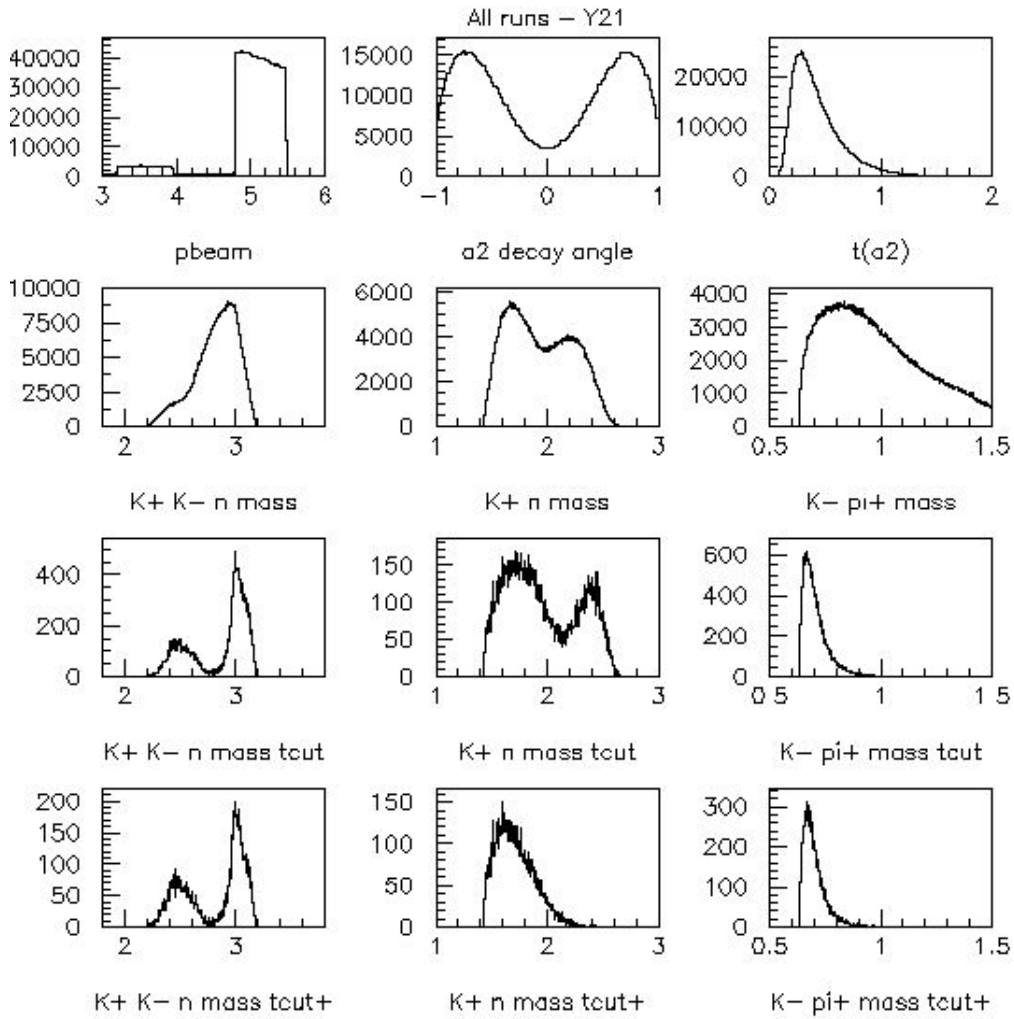


$|\, Y^M_L(\cos\theta, \phi)\,|^2$ $\quad Y^1_2$

Raw

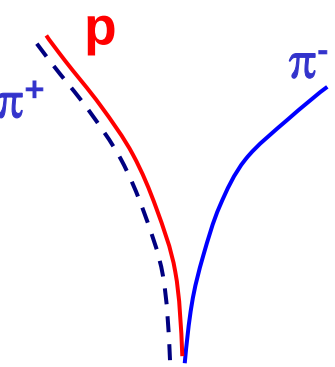
$|\, t_{\gamma\rightarrow\pi^-}| < 0.28\ GeV^2$

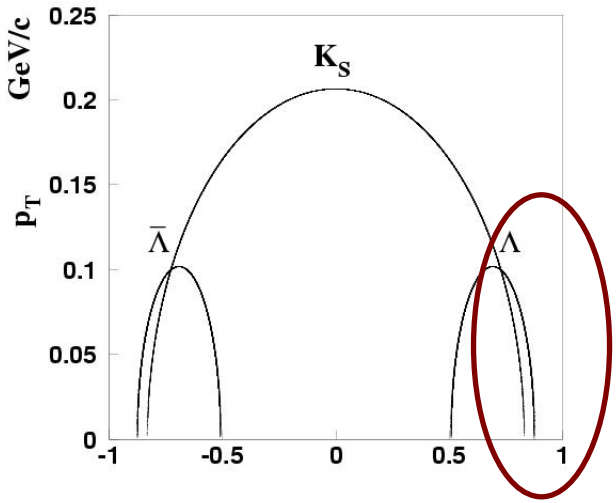
and $\cos\theta^*_{K^+} < 0.6$

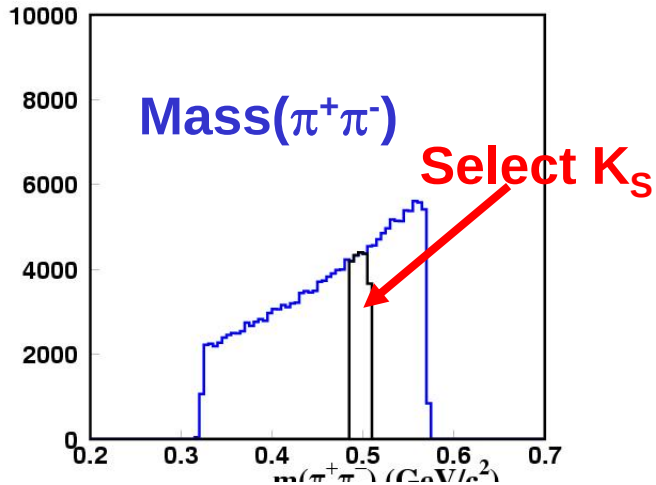


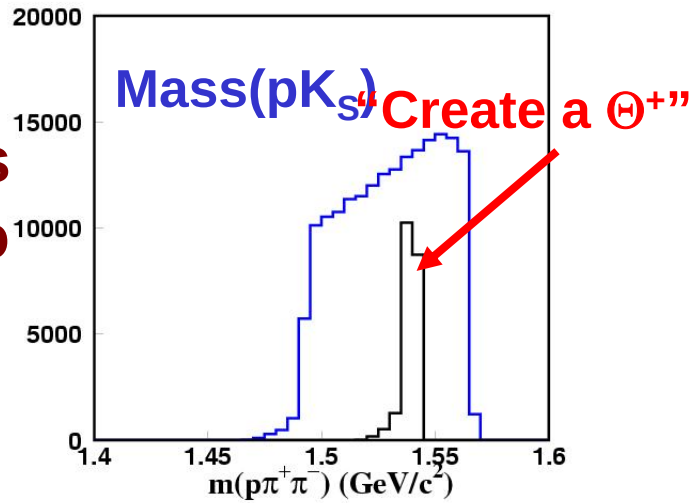
Ghost Tracks

Λ (p>2GeV/c)$\rightarrow$ pπ^-







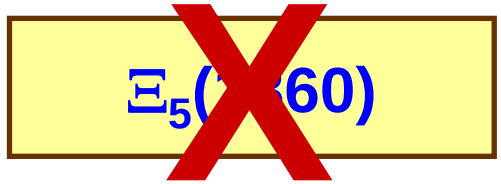


It is easy to manufacture narrow peaks in the data near 1.5GeV that appear to decay to p K_S .

(M. Longo QNP 2004)

Ξ_5 Pentaquark

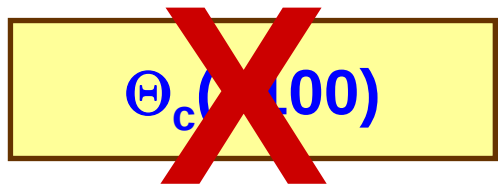
One low statistics report by NA49



Nine negative results.
Null results in both similar and different production mechanisms.
1-2 orders of magnitude more data in known resonances.

Θ_c Pentaquark

One low statistics report by H1



Five negative results.
Null results in both the same and different production mechanisms.
Factor of 10 to 1000 times for data in known resonances.
Possible ghost track in D^* Decay

Θ^+ Pentaquark

11 low-statistics reports near 1500 MeV

Low-energy reports suffer from some combination of the following:
(a) Fermi motion effects.
(b) Severe cuts whose effects may not have been adequately studied.
(c) Insufficiently constrained reactions.
(d) Kinematic reflections.

15 new high-statistics searches in a number of reactions with excellent resolution that have come up empty.
Bubble chamber data from decades ago show no evidence.
KN scattering data severely limit this

The Zeus result is interesting.
It suggests that fragmentation is a good way to produce the Θ^+.
K_S p is not strangeness exotic
Not really consistent with ALEPH, BaBar, BELLE, CDF, …
What does H1 have to say on this?

PDG 2004

$\Theta(1540)^+$ MASS

As is done through the *Review*, papers are listed by year, with the latest year first and within each year they are listed alphabetically. NAKANO 03 was the earliest paper.

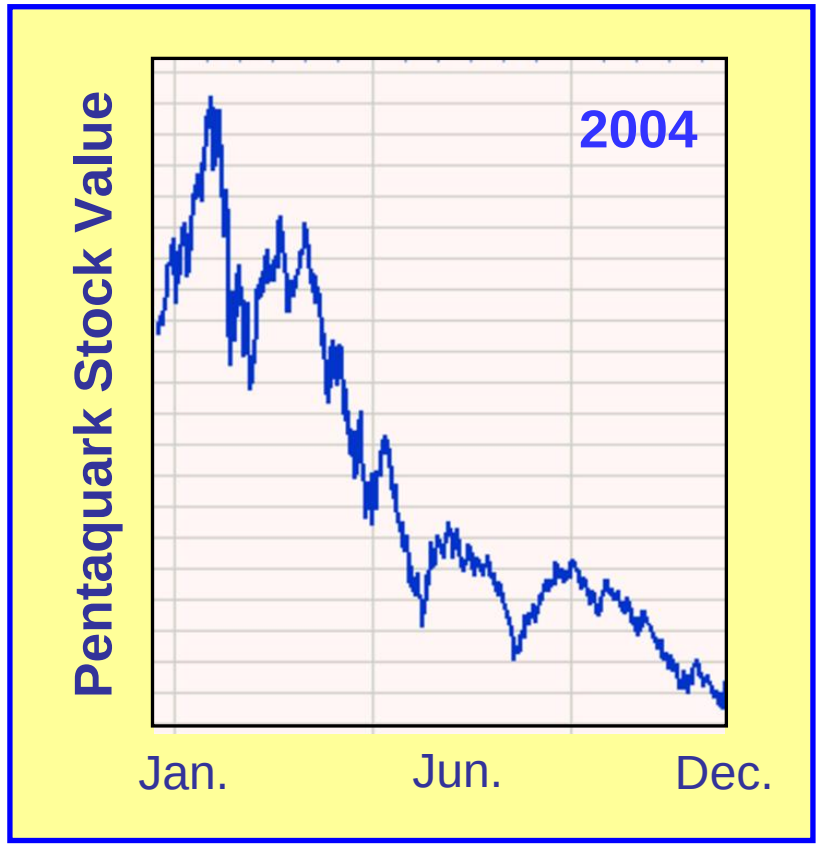
It is difficult to deny a status of three stars and a place in the Summary Tables for a state that six experiments claim to have seen. Nevertheless, as discussed in the above note, we believe it reasonable to have some reservations about the existence of this state on the basis of the present evidence.

VALUE (MeV)	*EVTS*	*DOCUMENT ID*		*TECN*	*COMMENT*
1539.2± 1.6 OUR AVERAGE					
1533 + 5	27	[1] ASRATYAN	04	BC	$\nu, \bar{\nu}$ in p,d,Ne, BEBC and 15-ft
1555 +10	41	[2] KUBAROVSKY	04	CLAS	$\gamma p \to \pi^+ K^- K^+ n$
1539 + 2	29	[3] BARMIN	03	XEBC	K^+ Xe $\to K^0 p$ Xe
1540 + 4 +2	63	[4] BARTH	03	SPHR	$\gamma p \to n K^+ K^0_S$
1540 +10	19	[5] NAKANO	03	LEPS	$\gamma\, ^{12}C \to K^+ K^- n$ X
1542 + 5	43	[6] STEPANYAN	03	CLAS	$\gamma d \to K^+ K^- pn$

Conclusions

The possible existence of pentaquarks is still very much an experimental question, and the data do not look very convincing.

If they exist, they not only have exotic quantum numbers, but very exotic production and decay modes.



I hope that the issue can be settled soon – but I am not buying stock.