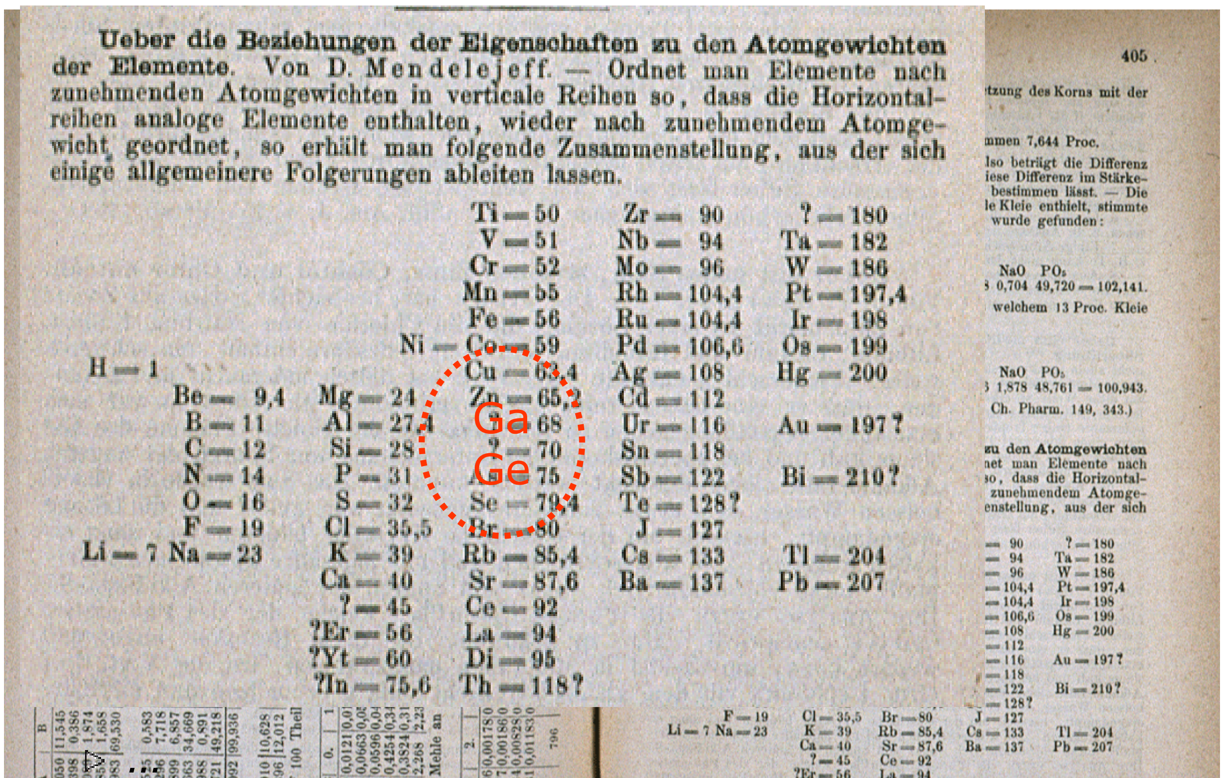
Pentaquarks
Facts and Mysteries

- Introduction
- Experimental facts: $\Theta^+(1540)$
- Theoretical situation
- Experimental facts: $\Xi(1860)$
- Quintessence

Ordering schemes

- help to understand the principle of underlying physics
- help to make make predictions of missing pieces
- Dmitry Ivanovich Mendeleev (1834-1907)
  - *Zeitschrift für Chemie* **12**, 405-6 (1869)



405

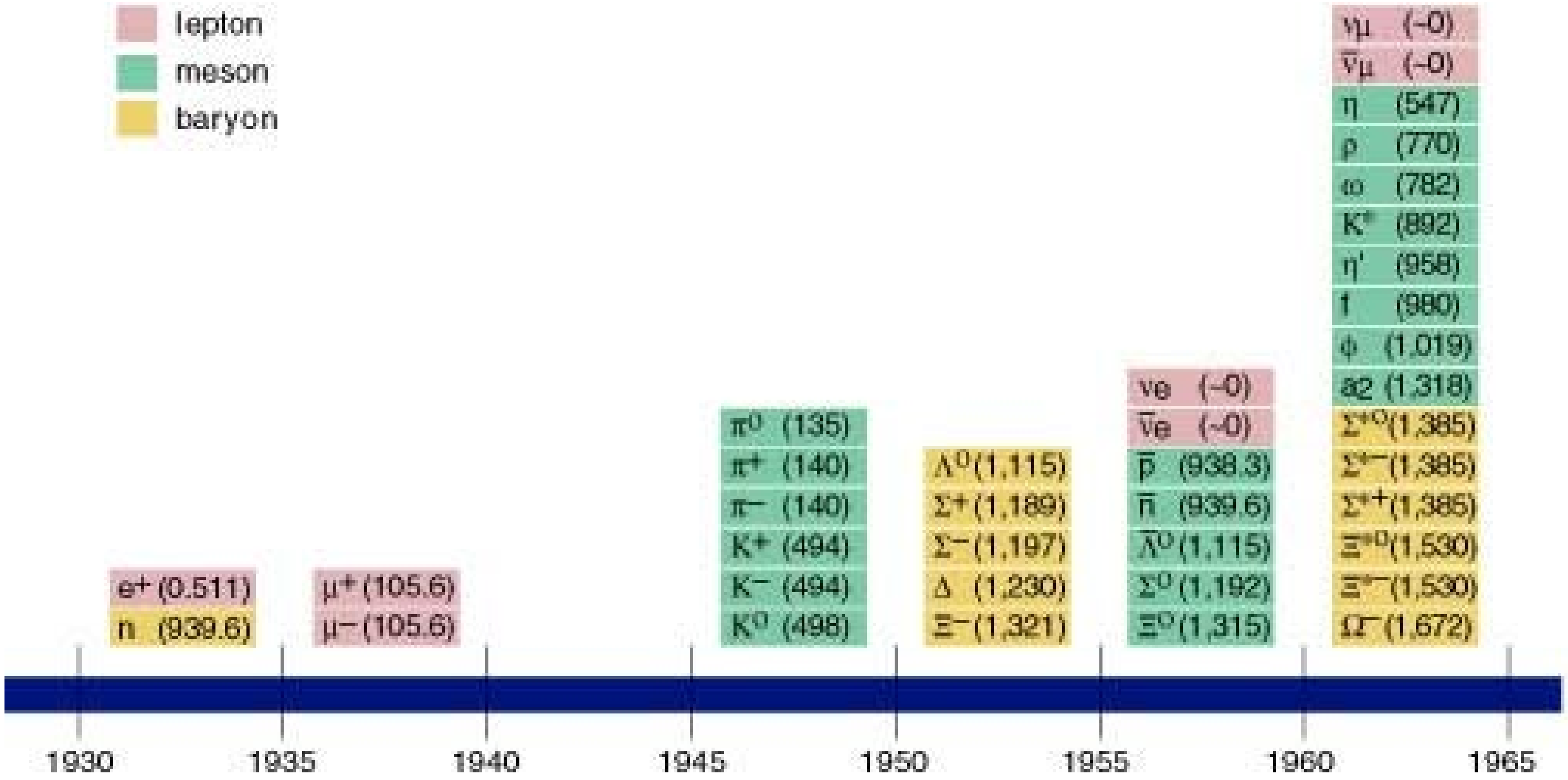
Ueber die Beziehungen der Eigenschaften zu den Atomgewichten der Elemente. Von D. Mendelejeff. — Ordnet man Elemente nach zunehmenden Atomgewichten in verticale Reihen so, dass die Horizontalreihen analoge Elemente enthalten, wieder nach zunehmendem Atomgewicht geordnet, so erhält man folgende Zusammenstellung, aus der sich einige allgemeinere Folgerungen ableiten lassen.

			Ti = 50	Zr = 90	? = 180
			V = 51	Nb = 94	Ta = 182
			Cr = 52	Mo = 96	W = 186
			Mn = 55	Rh = 104,4	Pt = 197,4
			Fe = 56	Ru = 104,4	Ir = 198
			Ni — Co = 59	Pd = 106,6	Os = 199
H = 1			Cu = 63,4	Ag = 108	Hg = 200
	Be = 9,4	Mg = 24	Zn = 65,2	Cd = 112	
	B = 11	Al = 27,4	? = 68	Ur = 116	Au = 197?
	C = 12	Si = 28	? = 70	Sn = 118	
	N = 14	P = 31	As = 75	Sb = 122	Bi = 210?
	O = 16	S = 32	Se = 79,4	Te = 128?	
	F = 19	Cl = 35,5	Br = 80	J = 127	
Li = 7	Na = 23	K = 39	Rb = 85,4	Cs = 133	Tl = 204
		Ca = 40	Sr = 87,6	Ba = 137	Pb = 207
		? = 45	Ce = 92		
		?Er = 56	La = 94		
		?Yt = 60	Di = 95		
		?In = 75,6	Th = 118?		

- ...
- *6. One can predict the discovery of many new elements, for example analogues of Si and Al with atomic weights of 65-75.*
- *7. A few atomic weights will probably require correction; for example Te cannot have the atomic weight 128, but rather 123-126.*

The Particle Zoo

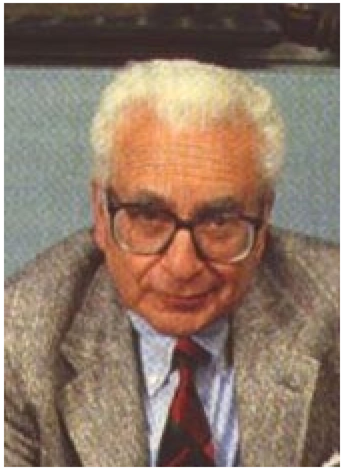
- during the 50s and 60s many new elementary particles were discovered (particle zoo)



- 1962 Murray Gell-Mann and, independently, Yuval Ne'eman suggested the *eightfold way* (baryon octet)

Quark/Aces model (1964)

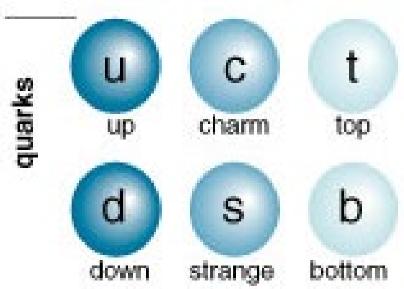
- substructure of hadrons
  - Murray Gell-Mann → ***quarks***
  - George Zweig → ***aces***



Gell-Mann

Zweig

- quarks:
  - <u>fractional</u> electric charge!
  - spin 1/2
  - come in **flavors** (up, down, …)



quark	spin	charge Q/e	baryon number B	strangeness S
u	1/2	+2/3	1/3	0
d	1/2	-1/3	1/3	0
s	1/2	-1/3	1/3	-1

- baryons = three quarks

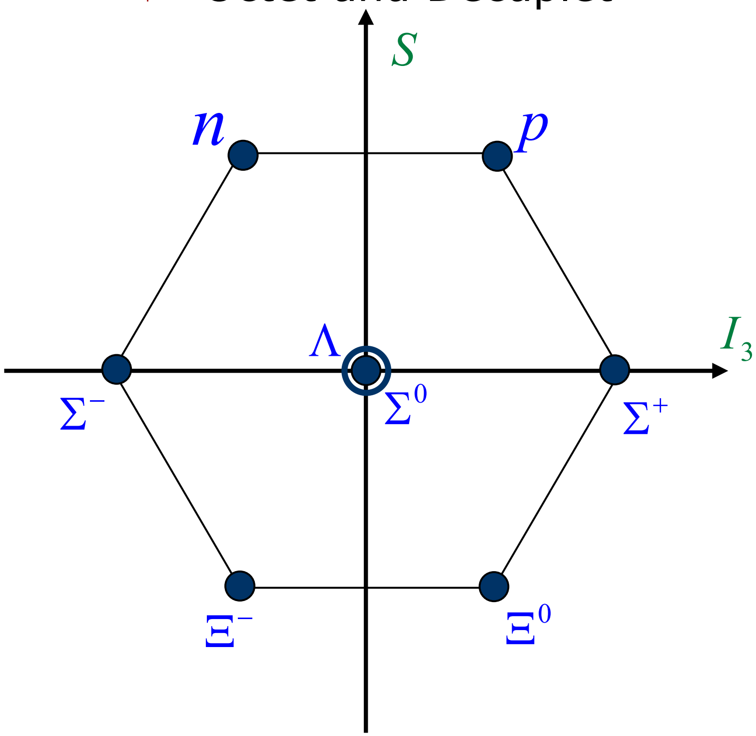
$$B = \frac{1}{3} + \frac{1}{3} + \frac{1}{3} = 1$$

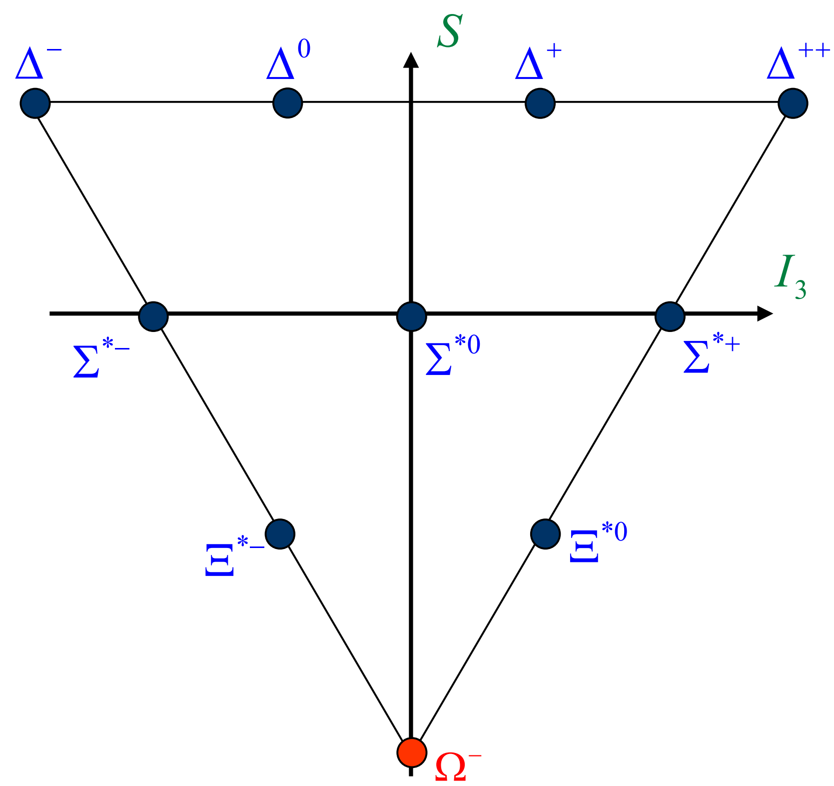
- mesons = quark-antiquark pair

$$B = \frac{1}{3} - \frac{1}{3} = 0$$

Quark Model

- Quark model in SU(3) (u, d and s quark have similar mass):
  - three valence quarks define flavour content of a baryon
  - Octet and Decuplet





- Success: prediction of W^- (Gell-Mann, 1964) and subsequent observation (V.E. Barnes *et al*., 1964)

The Omega baryon

VOLUME 12, NUMBER 8 PHYSICAL REVIEW LETTERS 24 FEBRUARY 1964

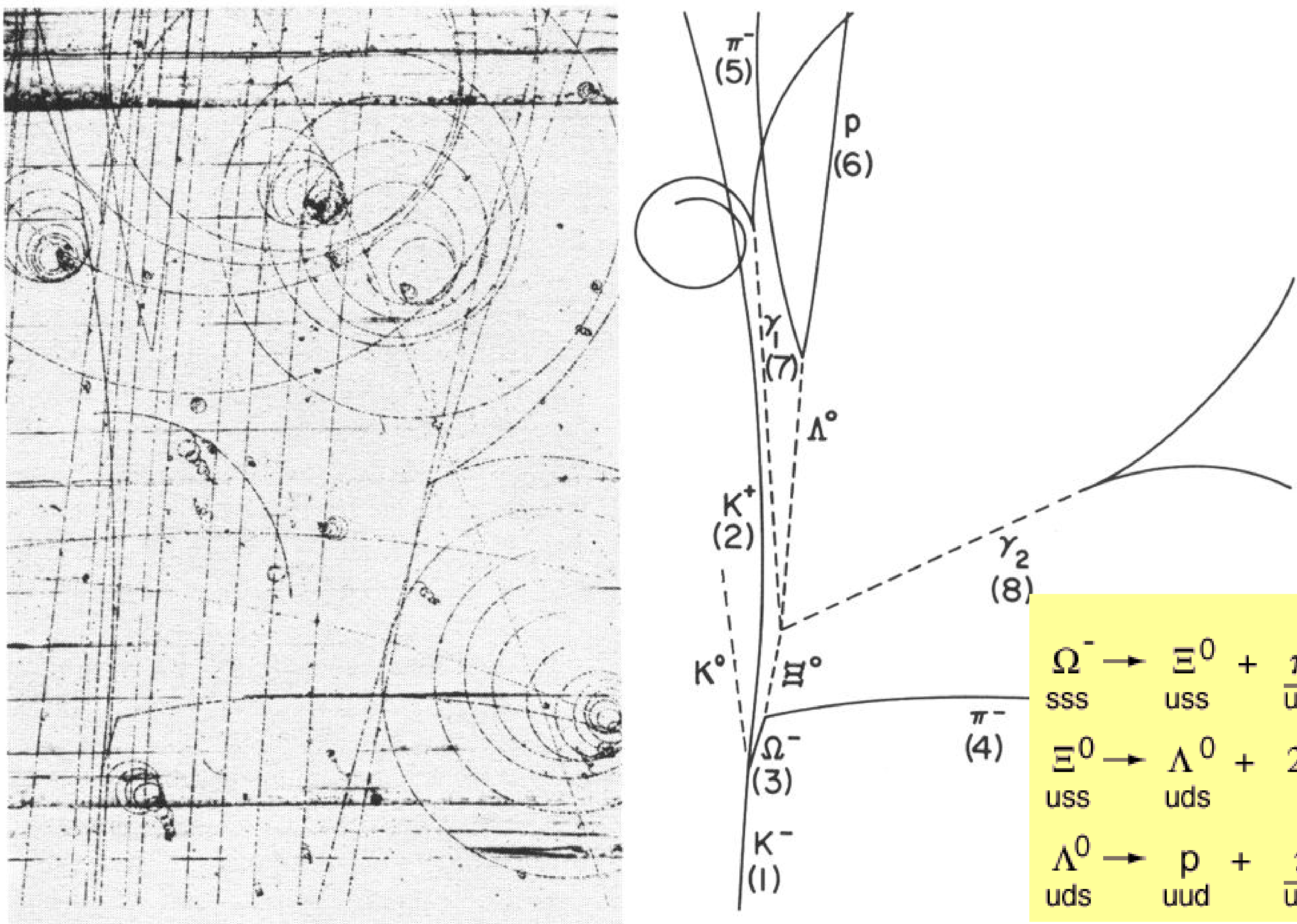


FIG. 2. Photograph and line diagram of event showing decay of Ω^-.

						Lifetime
Ω^-	→	Ξ^0	+	π^-		$.8 \times 10^{-10}$ s
sss		uss		$\bar{u}$d		
Ξ^0	→	Λ^0	+	2γ		2.9×10^{-10} s
uss		uds				
Λ^0	→	p	+	π^-		2.6×10^{-10} s
uds		uud		$\bar{u}$d		

Pentaquarks

- common believe is that the states should be color neutral
- but: quark model does not exclude systems of more than 3 quarks
- in case of 5 quarks this implies a $qqqq\bar{q}$ to be color neutral
- two cases for baryons
  - antiquark has same flavor than another quark

$$qqqq_f\bar{q}_f:$$

$$B(qqqq_f\bar{q}_f) = \frac{1}{3}+\frac{1}{3}+\frac{1}{3}+\frac{1}{3}-\frac{1}{3}=1$$

$$Q(qqqq_f\bar{q}_f) = Q(qqq) = -1, 0 \text{ or } 1$$

$$S(qqqq_f\bar{q}_f) = S(qqq) = 0, -1, -2 \text{ or } -3$$

  - same quantum numbers as ordinary baryons
  - antiquark has unique flavor

$$qqqq\bar{Q}:$$

$$B(qqqq\bar{Q}) = \frac{1}{3}+\frac{1}{3}+\frac{1}{3}+\frac{1}{3}-\frac{1}{3}=1$$

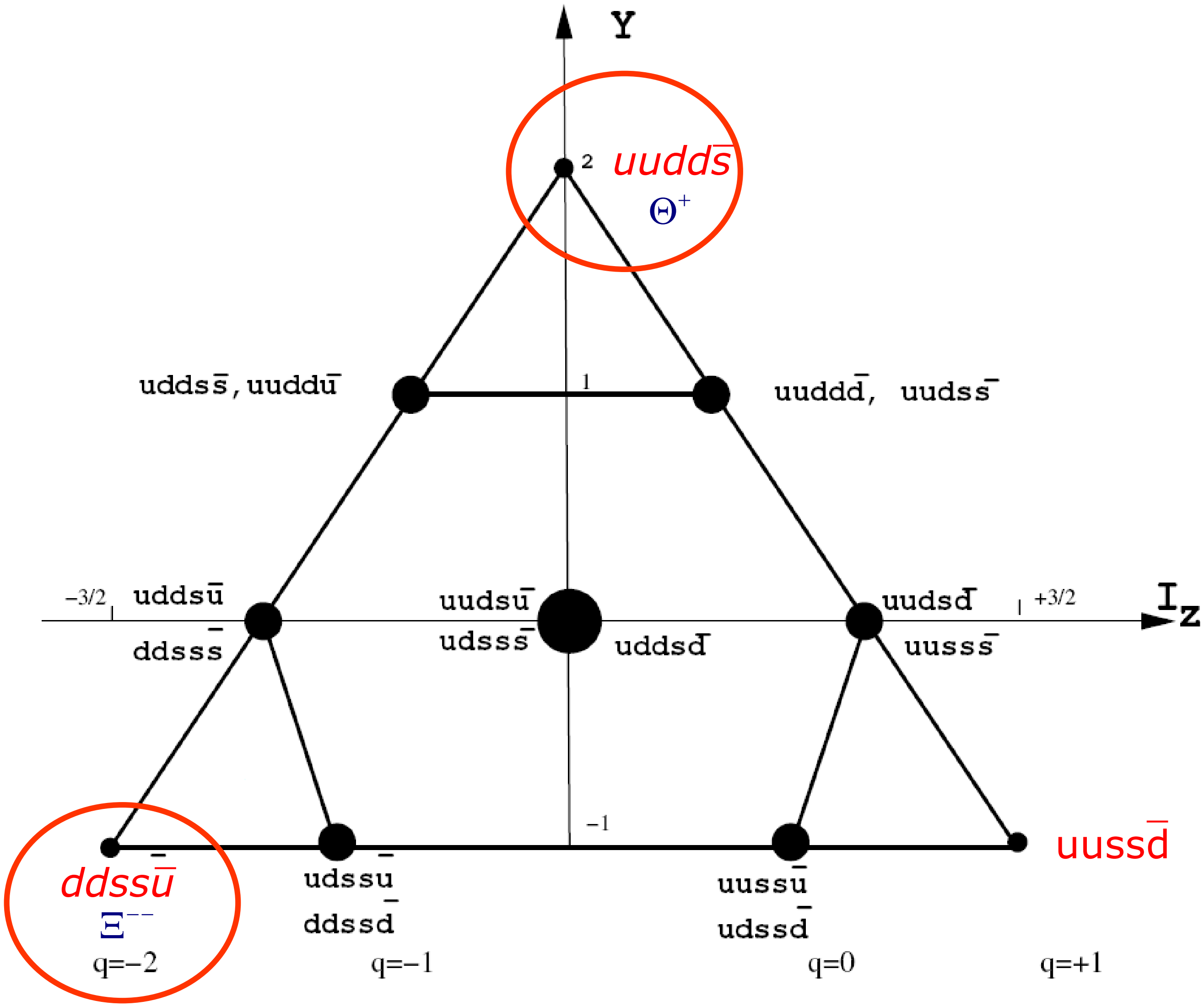
$$Q(qqqq\bar{Q}) = Q(qqq) = -2, -1, 0, 1, 2 \qquad dds s\bar{u}$$

$$S(qqqq\bar{Q}) = -2, -1, 0, +1 \qquad uudd\bar{s}$$

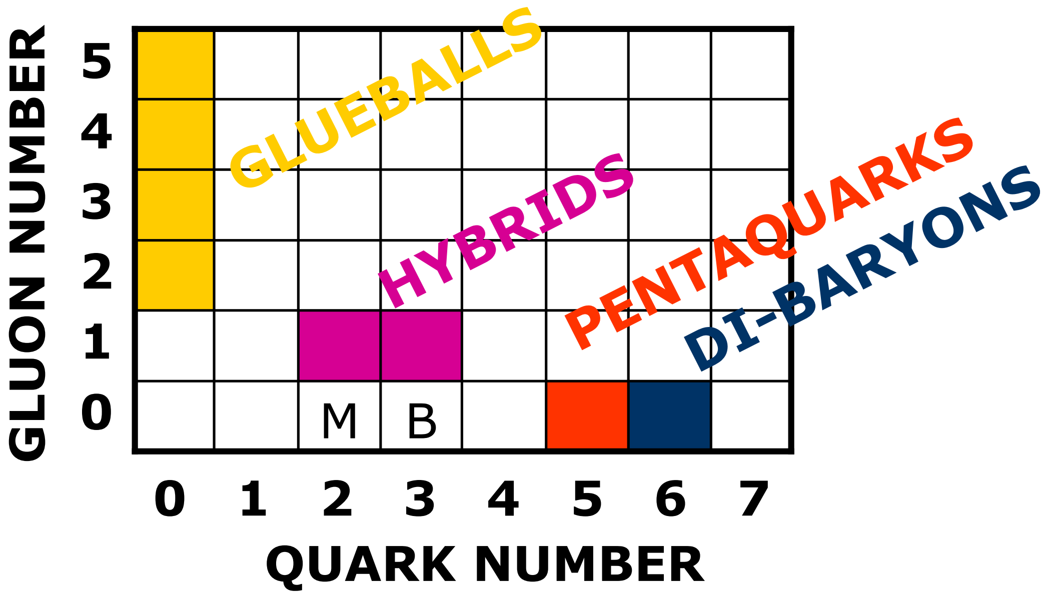
  - exotic quantum numbers or combinations possible

Group classification of $qqqq\bar{q}$

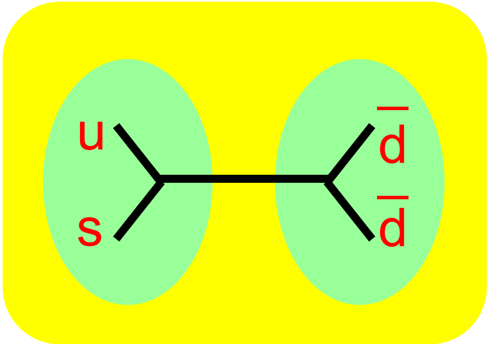
- B.G. Wybourne, hep-ph/0307170
- antidecuplet and octet



Beyond Meson and Baryons



- Until a year ago many signals of narrow exotic resonances have appeared, but all disappeared after detailed studies again !
  - …for example the "famous" U-particle at 3100MeV/c² (diquonium)



WA62: 135 GeV/c $\Sigma^- + Be$

WA62 , Phys. Lett. B **172**, 113 (1986)

U^+ Þ $\Lambda\bar{p}\pi^+\pi^+$

S/B = 45/50

$\sigma \bullet BR = 4.8 \pm 1.4 \pm 0.8\ \mu b/Be$

U^0 Þ $\Lambda\bar{p}\pi^+\pi^+\pi^-$

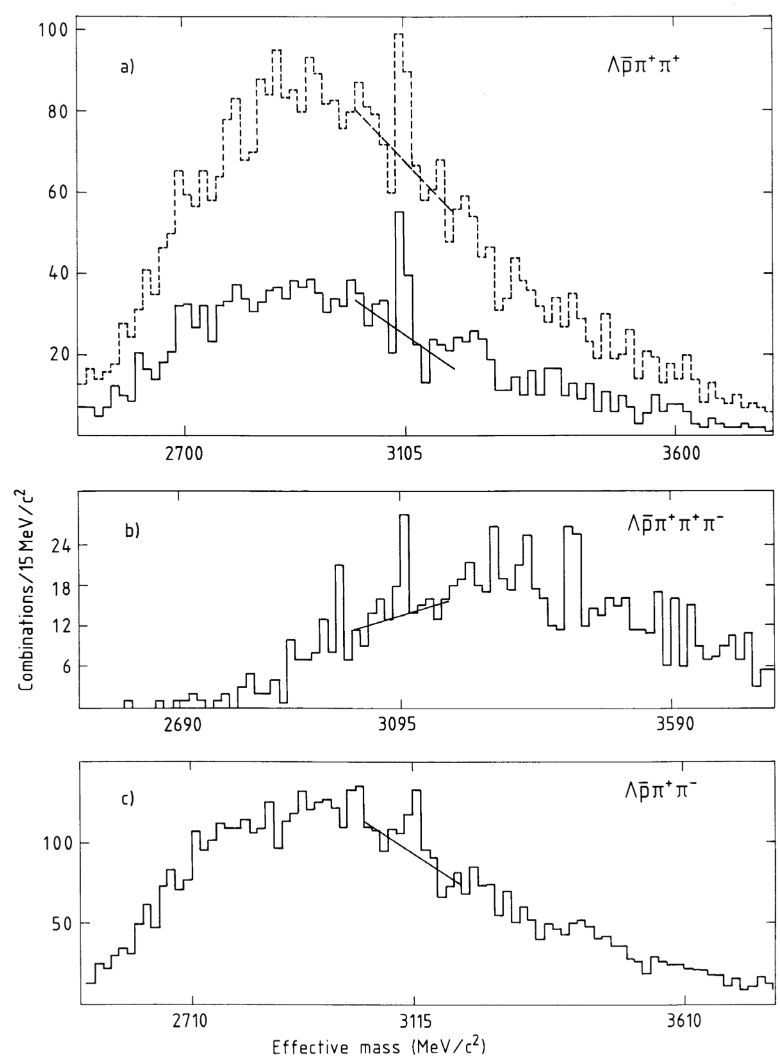
S/B = 19/28

$\sigma \bullet BR = 1.2 \pm 0.7 \pm 0.2\ \mu b/Be$

U^- Þ $\Lambda\bar{p}\pi^+\pi^-$

S/B = 62/187

$\sigma \bullet BR = 3.0 \pm 1.7 \pm 0.5\ \mu b/Be$



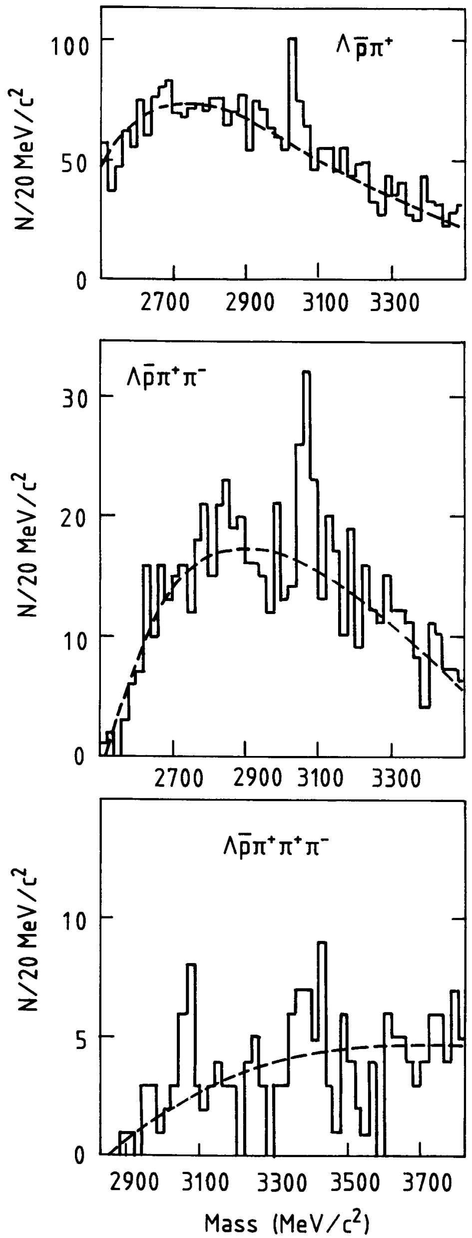
BIS 2: 135 GeV/c n + A

- BIS 2 , Z.Phys. C **47**, 533 (1990)

$U^{+} \rightarrow \Lambda\bar{p}\pi^{+}\pi^{+}$

$U^{0} \rightarrow \Lambda\bar{p}\pi^{+}\pi^{-}$

$U^{0} \rightarrow \Lambda\bar{p}\pi^{+}\pi^{+}\pi^{-}$



1. Experimental facts
Part 1: $\Theta^+(1540)$

How to make a Pentaquark $\Theta^+(1540)$

- exclusive:

$\gamma n \rightarrow K^- \Theta^+$	$\rightarrow K^- K^+(n)$		Spring-8
	$\rightarrow K^- K^0(p)$		JLAB
$\gamma p \rightarrow K^0 \Theta^+$	$\rightarrow K^0 K^0(n)$		ELSA
	$\rightarrow K^0 K^0(p)$		
$pp \rightarrow \Theta^+ \Sigma^+$	$\rightarrow pK^0(\Sigma^+)$		COSY

  - baryon can be detected (easy: p) or can be reconstructed from missing mass (diffcult: n)

- inclusive:

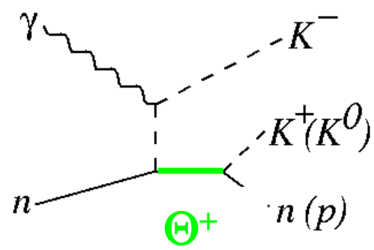
$\gamma d \rightarrow \Theta^+ X$	$\rightarrow K^0 p\ (X)$	HERMES
$pp \rightarrow \Theta^+ X$	$\rightarrow K^0 p\ (X)$	CERN
$K^+ Xe \rightarrow \Theta^+ Xe'$	$\rightarrow K^0 p\ (Xe')$	ITEP
+ many more		

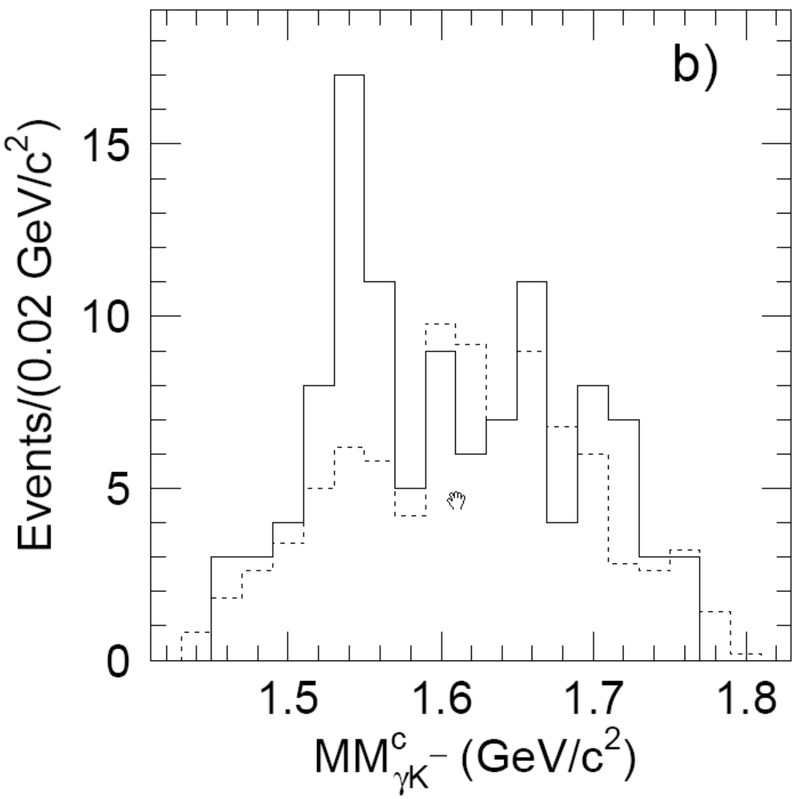

Super Photon ring-8 GeV
SPring-8
Third-generation synchrotron radiation facility
Circumference: 1436 m
8 GeV
100 mA
62 beamlines
LEPS: Laser-Electron-Photon facility
Compton backscattering of 351nm photons

LEPS @ SPring-8 (1)

Jan. 03

- T. Nakano *et al.*, Phys. Rev. Lett. **91**, 012002 (2003)
- Compton backscattering of photons, E_γ=1.5-2.4GeV
- plastic scintillator (C:H=1:1)
- p or n from missing mass of $N(\gamma,K^+K^-)X$
- Cuts
  - total $4.3\cdot10^7$
  - K^+K^- pair 8000
  - SC target 4000
  - E_γ<2.35GeV 3200
  - [0.9<M(N)<0.98] 1800
  - $M(KK)\notin[1.00,1.04]$ 270
  - $\neg\gamma p\rightarrow K^+K^-p$ 109





- $M(\Theta^+)$ = 1540 MeV
- $\Gamma\leq$ 25 MeV
- 4.6σ significance

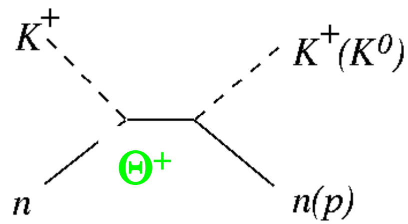
DIANA @ ITEP (2)

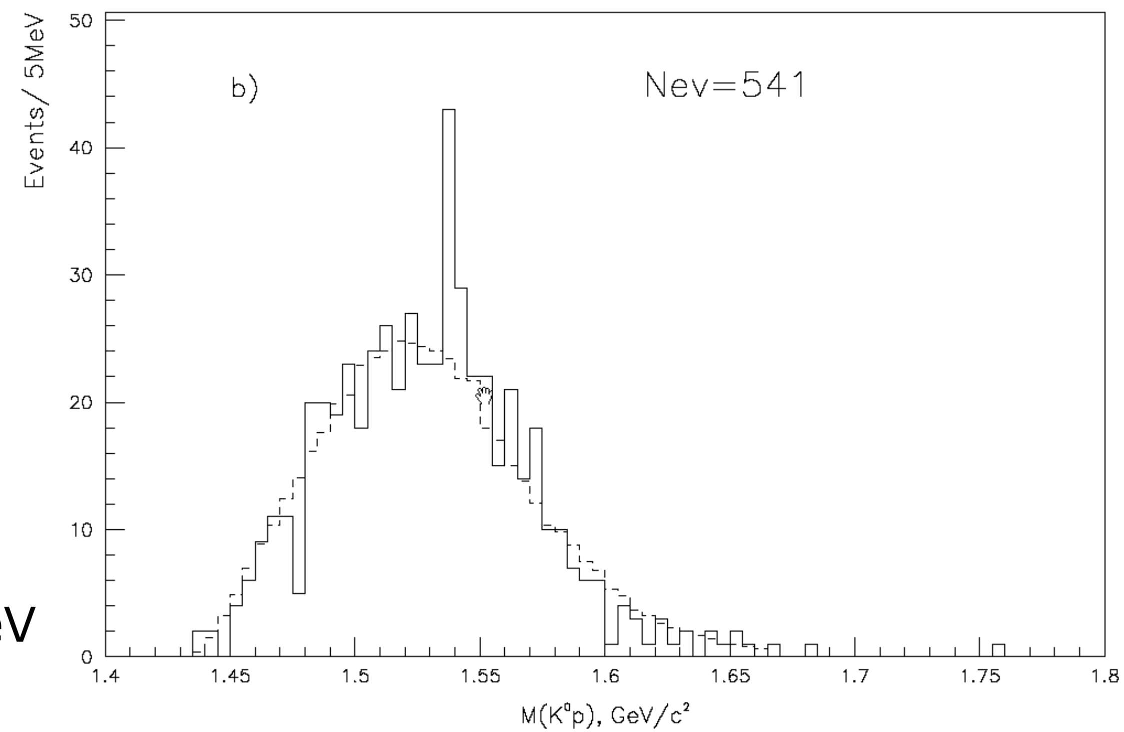
Apr. 03

V.V. Barmin *et al*., Phys. Atom. Nucl. **66**, 1715 (2003)

- bubble chamber, $K^+Xe \rightarrow K^0pXe'$
- $\langle p_{K+} \rangle$=470MeV/c

$$K^+n \rightarrow \Theta^+ \rightarrow K^0p$$





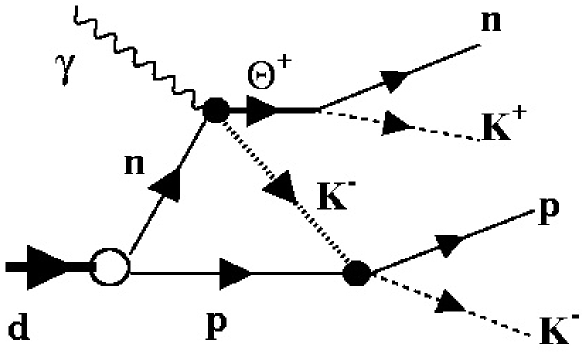
- M(Θ+) = 1539±2 MeV
- $\Gamma \leq$ 9 MeV
- 4.4σ significance

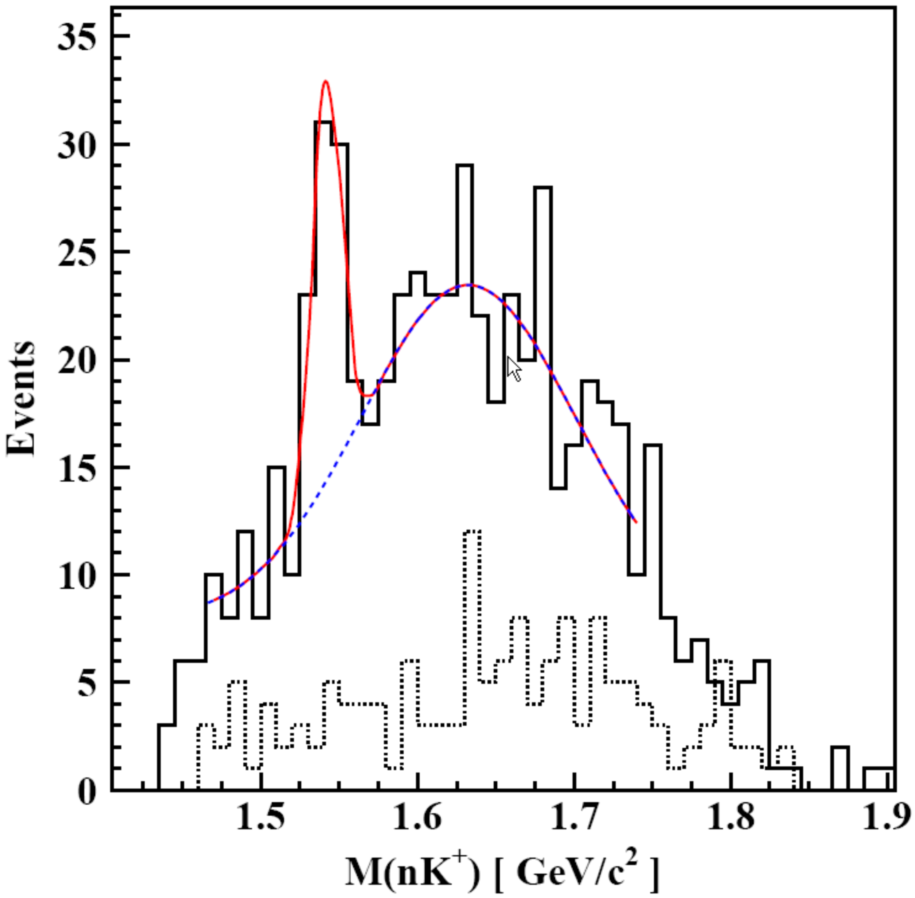
CLAS (d) @ TNAF (3)

Jul. 03

S. Stepanyan *et al.*,
Phy. Rev. Lett. **91**, 252001 (2003)

- $\gamma d \rightarrow K^+ K^- p(n)$; n from missing mass

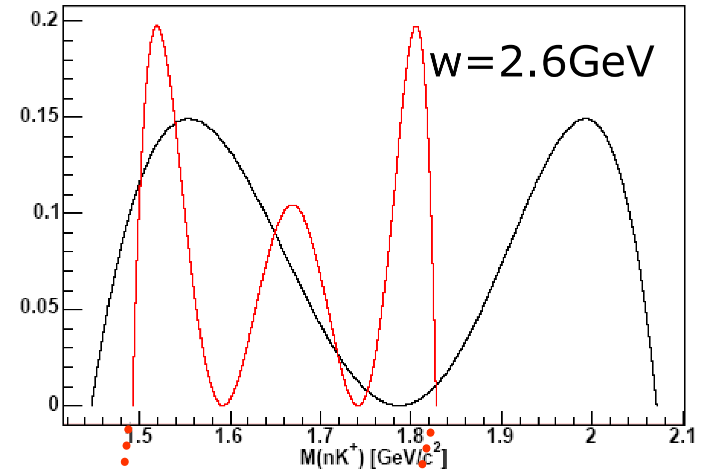




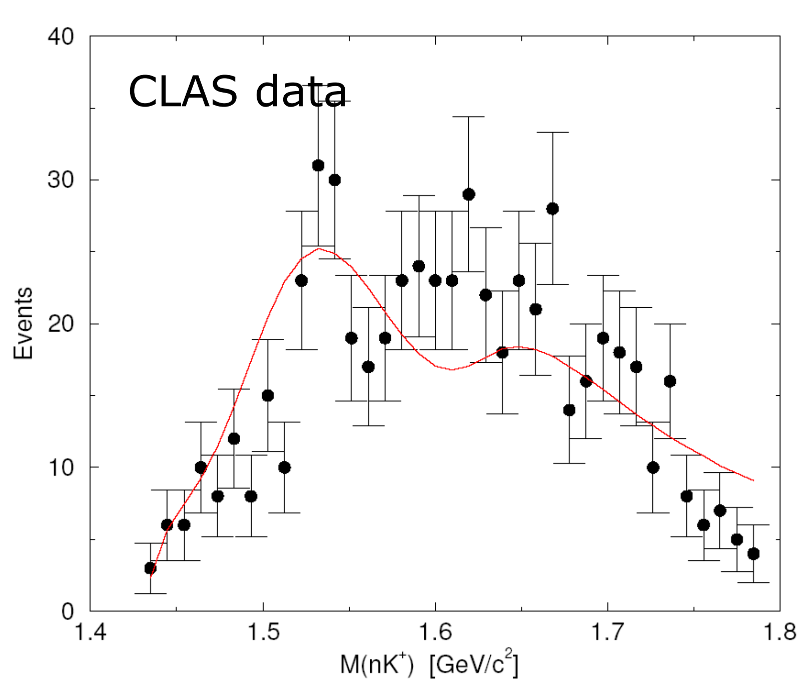
- $M(\Theta^+) = 1542$ MeV
- $\Gamma \leq 21$ MeV
- 5.8σ significance

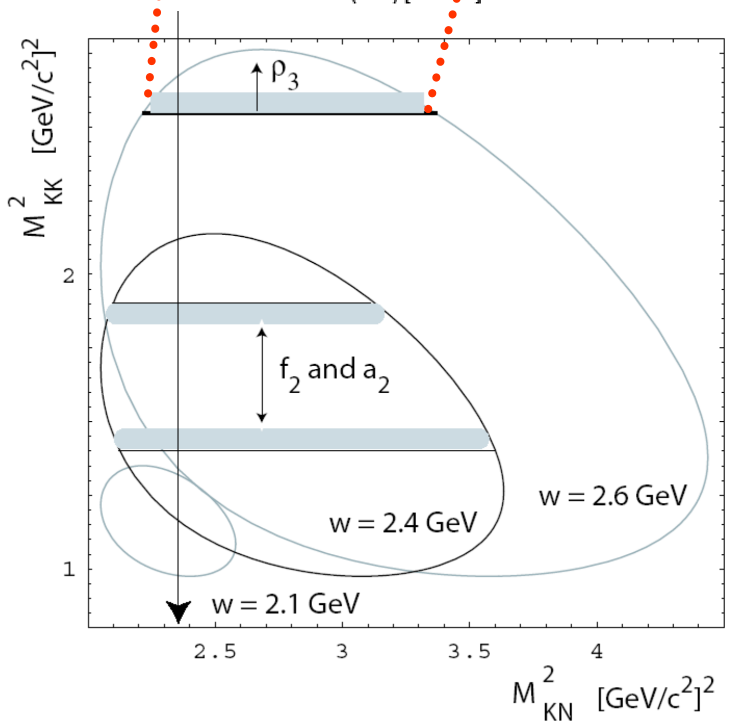
Is the Θ^+ a reflection?

- Reflections von f_2, ρ_3
  - A.R. Dzierba *et al.*,hep-ph/0311125
  - total energy w of the KKN System in CLAS experiment: w=2.1-2.6GeV



- angular distribution ⊗ w-distribution



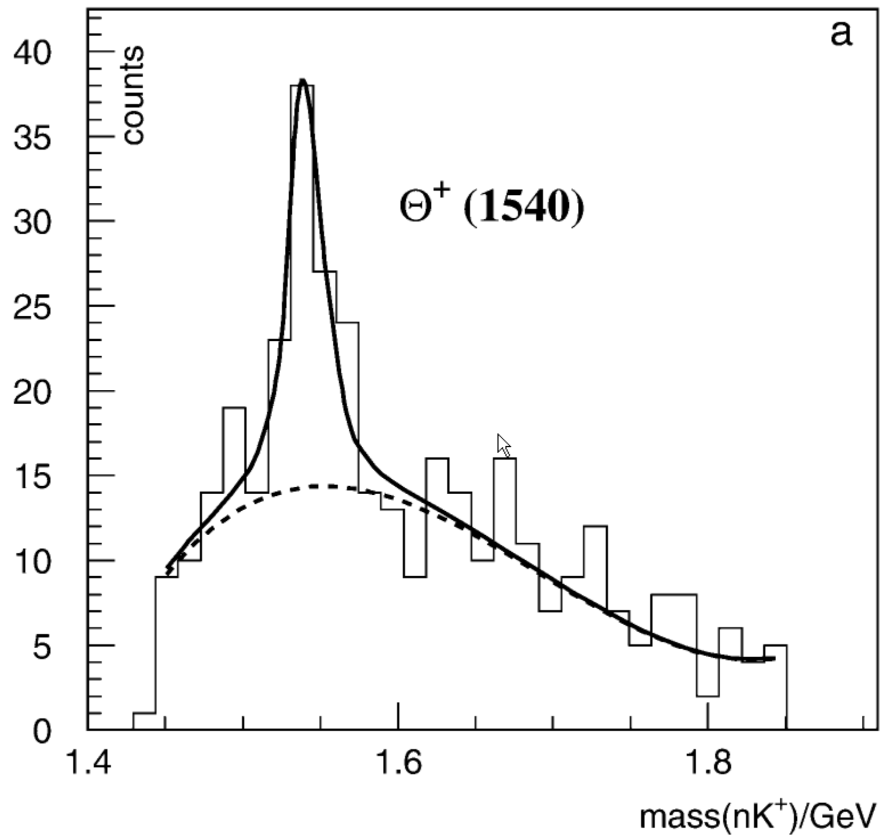


SAPHIR @ ELSA (4)

Jul. 03

J. Barth *et al*., Phys. Lett. B 572, 127 (2003)

$\gamma p \rightarrow K_s^0 \Theta^+ \rightarrow K_s^0 K^+ n$



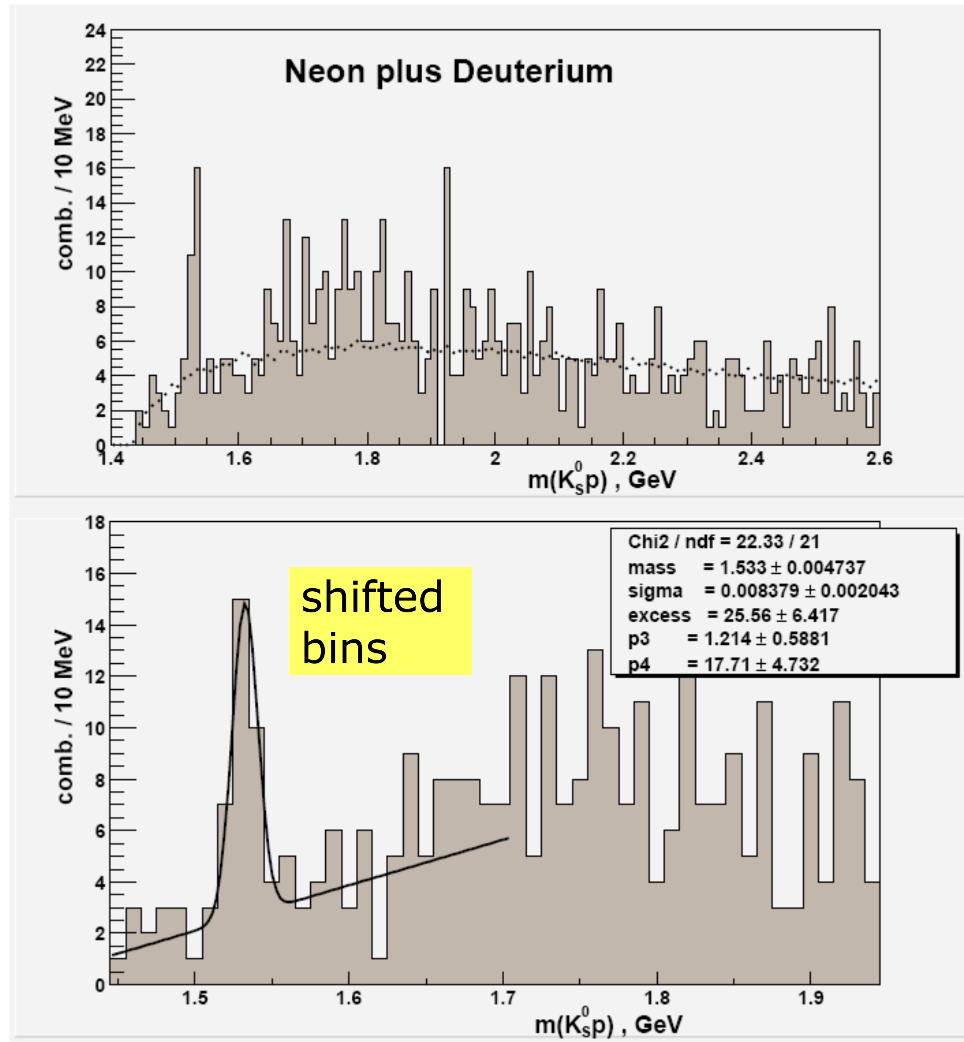
- $M(\Theta+) = 1540 \pm 6$ MeV
- $\Gamma \leq 25$ MeV
- 5.2σ significance
- no signal in $\Theta^{++} \rightarrow K^+ p$ $\Rightarrow$ suggests isoscalar state
- $\sigma(\Theta^+)$: $\sigma(\Lambda_{1520})$=60nb : (800-1200)nb ≈ 1:15

νCC interactions @ CERN (5)

Sep. 03

A.E. Asratyan *et al.*, hep-ex/0309042

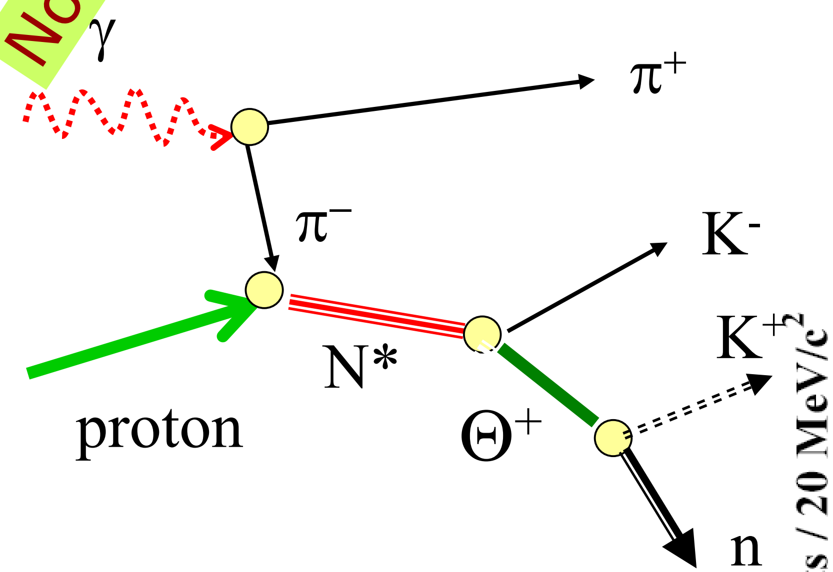
- reanalysis of neutrino data collected at CERN in bubble chambers (WA21, WA25, WA59, E180, E632)
- targets: p, d, Ne
  - dominated by Ne

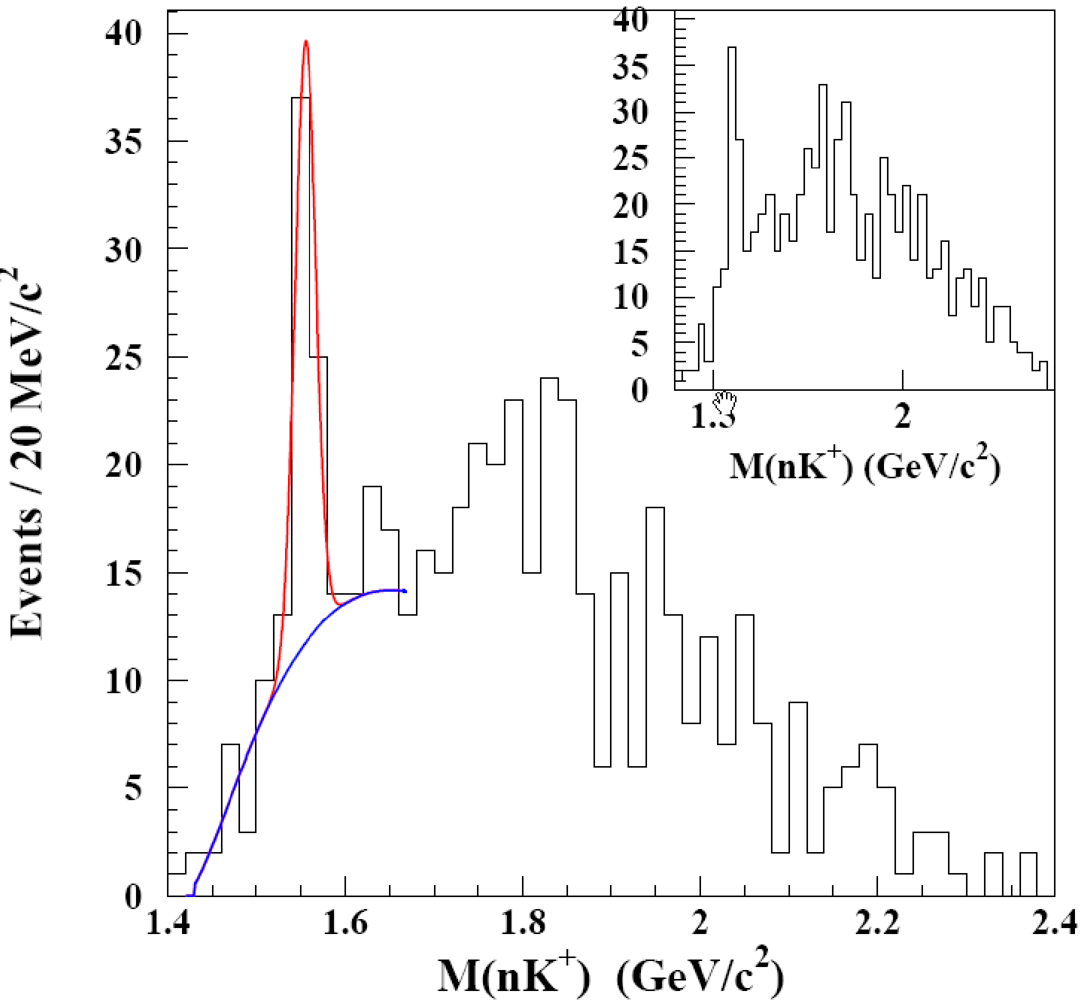


- M(Θ+) = 1533±5 MeV
- $\Gamma \leq$ 20 MeV
- 6.7σ significance

CLAS (p) @ TNAF (6)

Nov. 03

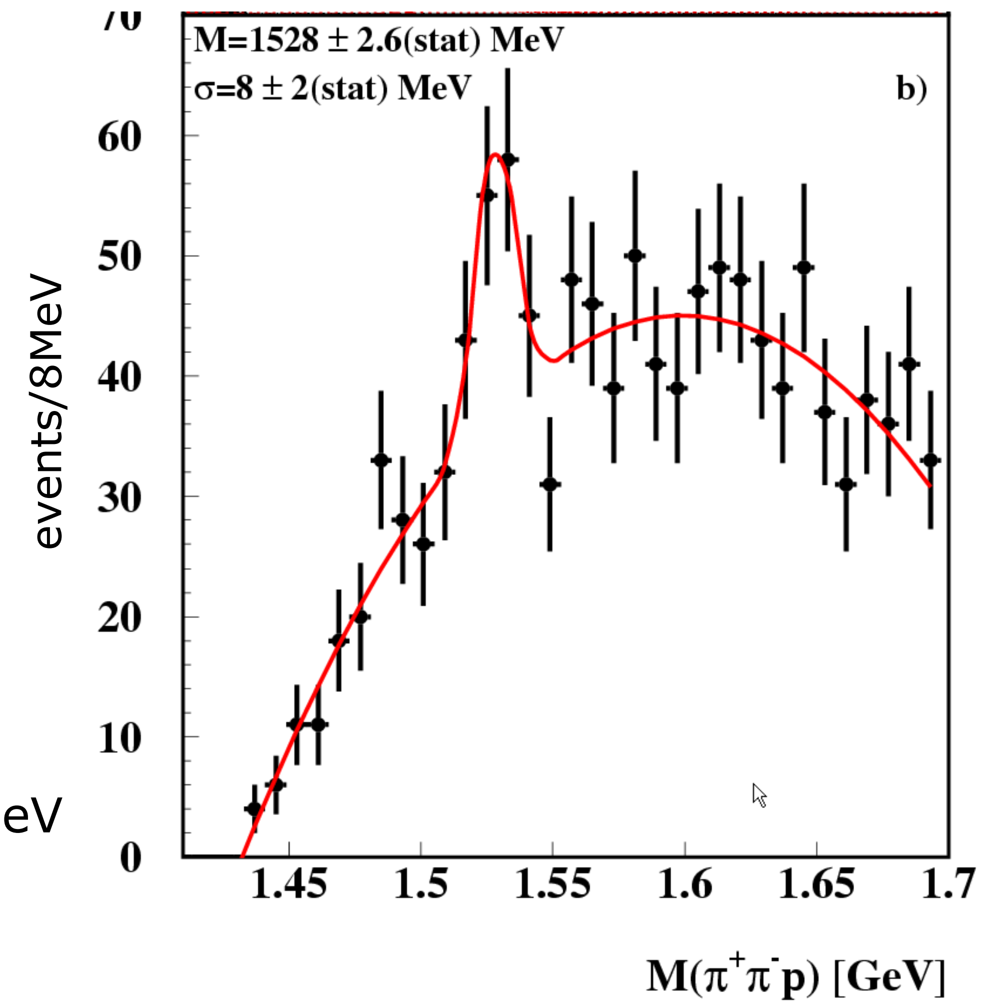




HERMES @ DESY (7)

Dec. 03

- A. Airapetian *et al.*, hep-ex/0312044
- $\gamma d \rightarrow K^0 p X$

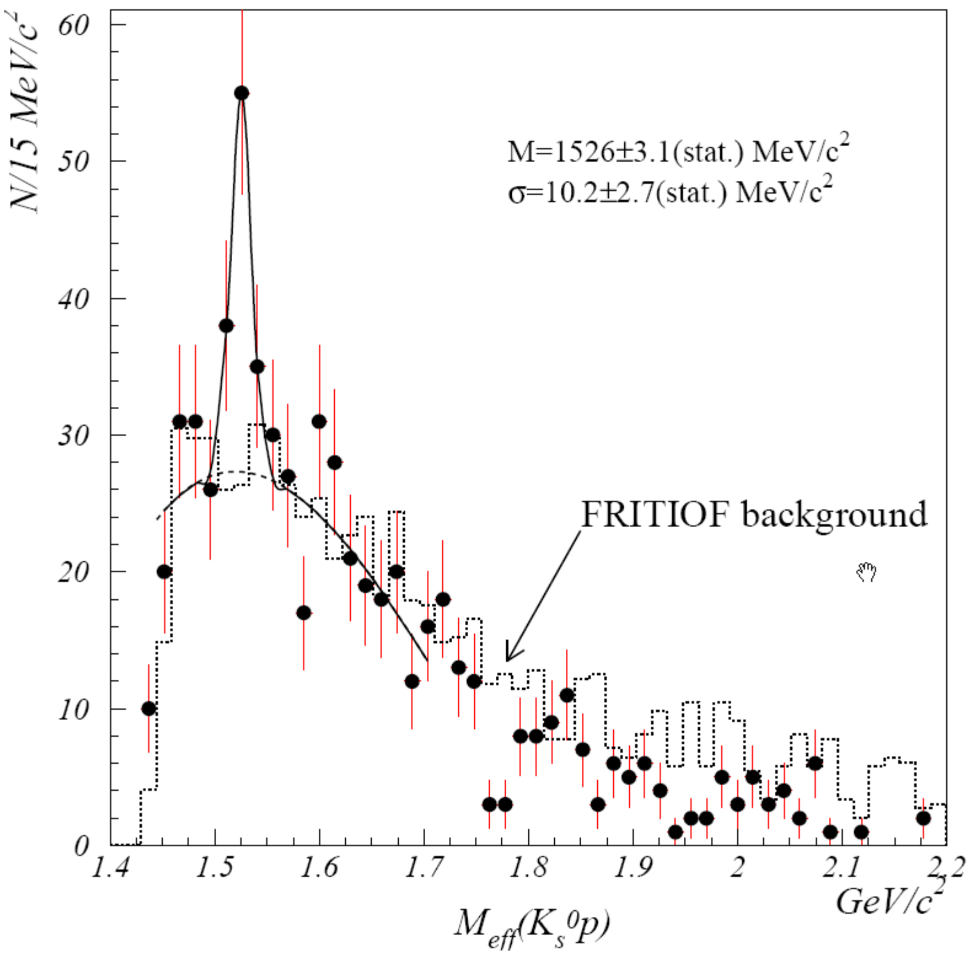


- $M(\Theta+) = 1528 \pm 2.6 \pm 2.1$ MeV
- $\Gamma = 19 \pm 5 \pm 2$ MeV
- 4-6 σ significance
- no Θ^{++} seen
- $\sigma(\Theta^+) : \sigma(\Lambda_{1520}) =$ (100-220)nb : (62±11)nb $\approx$ 2:1

SVD (8)

Jan. 04

- A.Aleev *et al.*, hep-ex/
- 70GeV p+C, Si, Pb → pK^0 + X

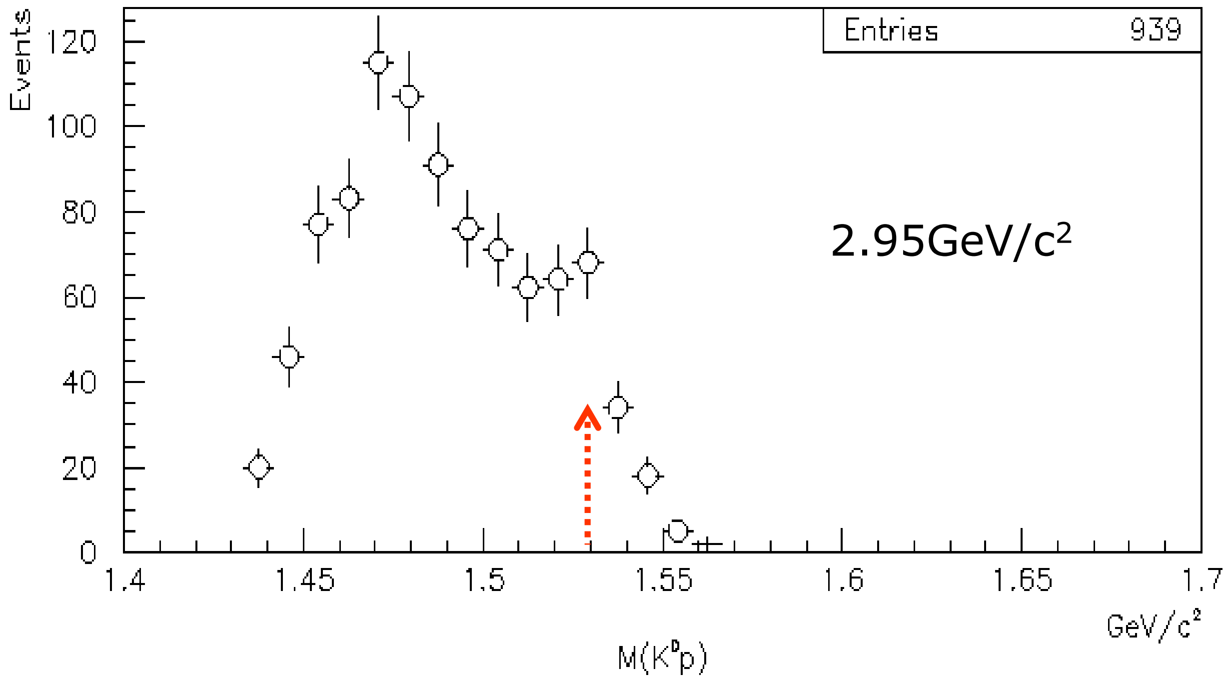


- no significant A dependence: consistent with $\propto A^{0.7}$

COSY-TOF (9)

Mar. 04

- external beam at COSY; 2000 + 2002 data
- $pp \to pK^0(\Sigma^+)$
- p_p= 2.85, 2.95 and 3.2 GeV/c²
- $\sigma_{tot}(2.95 GeV/c^2) = 12.7 \mu b$



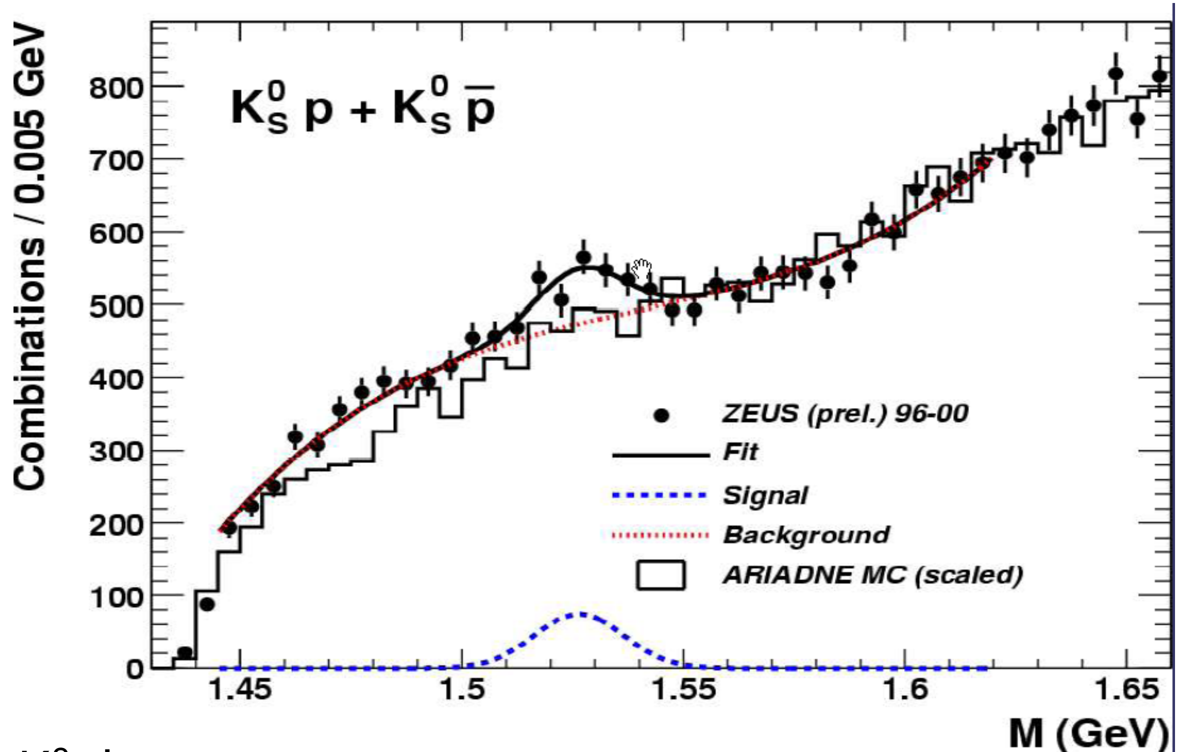
- $\Gamma_\Theta \leq 25 MeV$
- $\sigma = 0.4 \pm 0.1(stat) \pm 0.1(sys)\ \mu b$

ZEUS (10)

Feb. 04

S. Chekanov, hep-ex/0405013

- e^+p and e^-p
- c.m. energy 300-318 GeV
- Q^2>1GeV^2



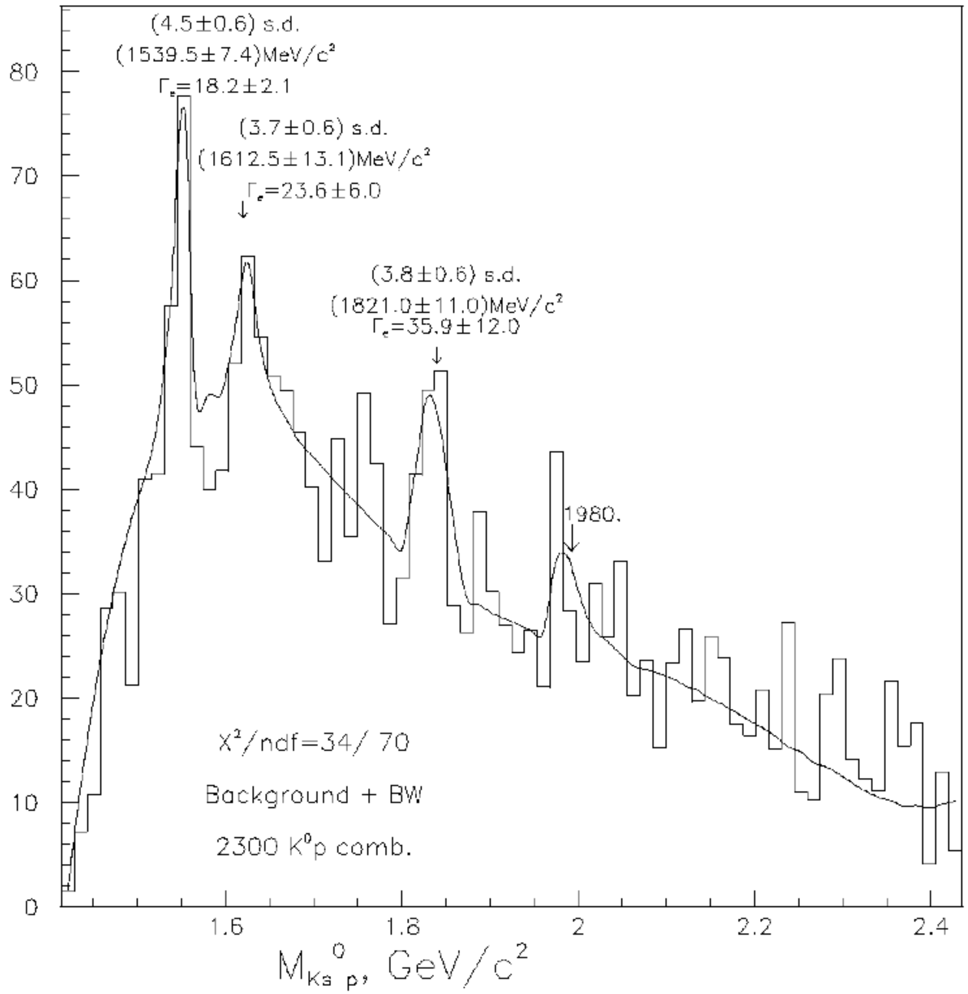
- signals in K^0p and K^0pbar
- 372±75 candidates
- 1522±2(stat) MeV
- Γ=8±4(stat) MeV (from Monte Carlo expected 2MeV)

JINR C_3H_8 (11)

Mar. 04

P. Zh. Aslanyan *et al*., hep-ex/0403044

- 10GeV/c $p+C_3H_8$
- propane bubble chamber

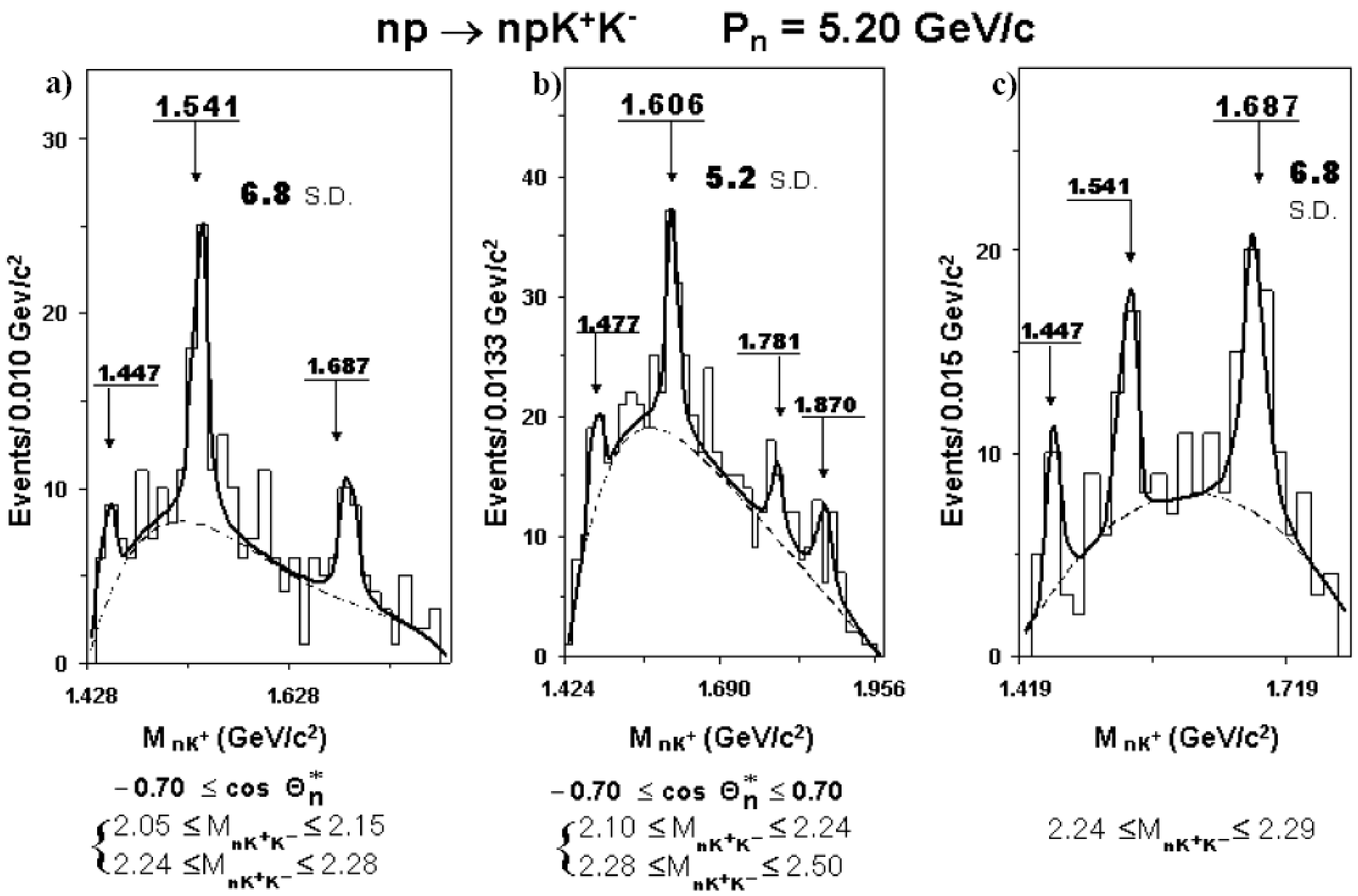


JINR H_2 (12)

Apr. 04

hep-ex/0404003

- 1m H_2 bubble chamber at JINR

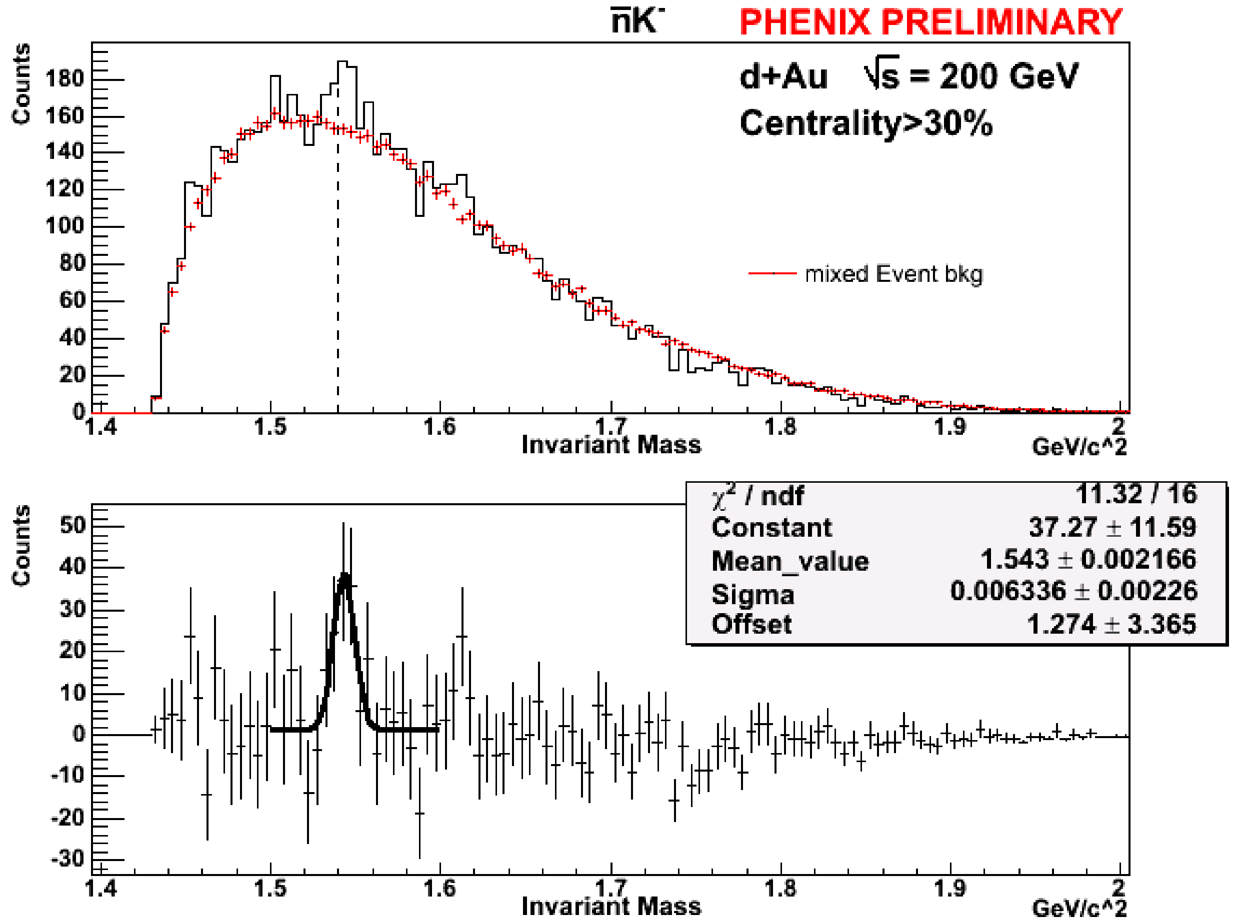


PHENIX (preliminary) (13)

Mar. 04

C. Pinkenburg, Quark Matter 2004

- d+Au, √s=200GeV

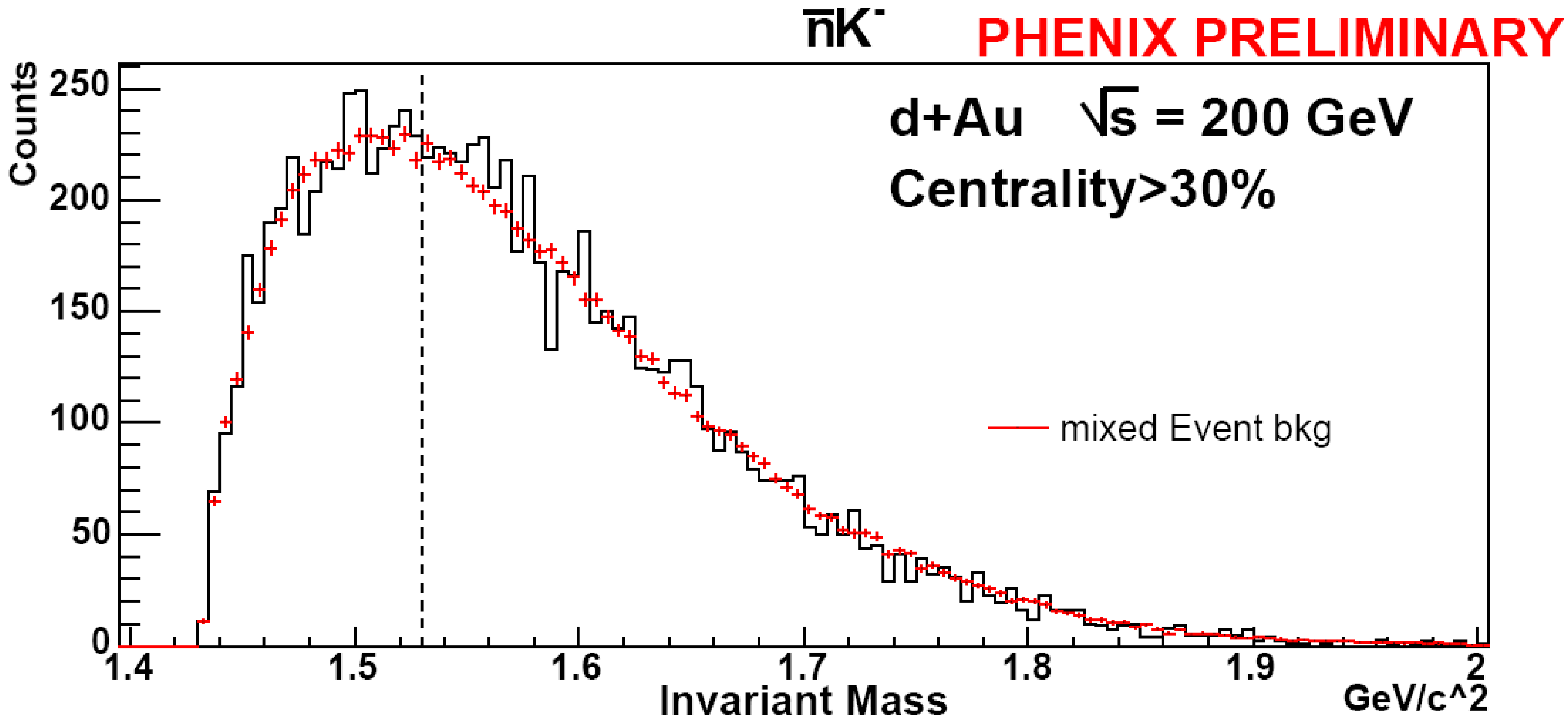


- Excess at 1.54 GeV in $\bar{n}K^-$ invariant mass
- $\Gamma_\Theta \leq$ 6MeV $\approx \Gamma_\Lambda$
- "We ain't saying it's there and we ain't saying it's not there."

PHENIX (update)

Apr. 04

- proceedings: nucl-ex/0404001
- timing corrections



Currently it is unclear what mechanism is behind the appearance of the peak at $1.54\,\mathrm{GeV}/c^2$ and why the control $K^+\overline{n}$ invariant mass distribution did not exhibit

the s ... neutron

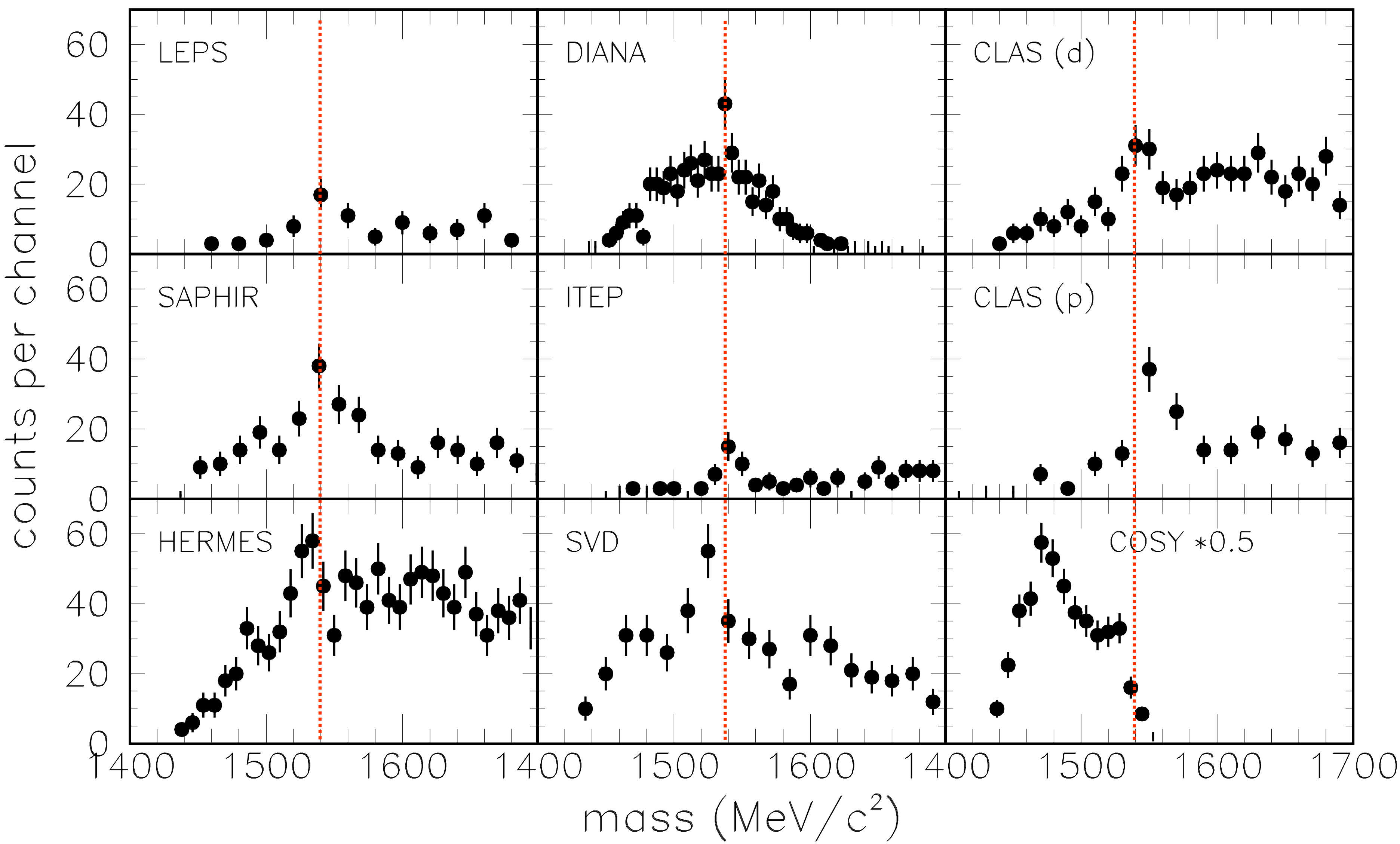
capab ... d anti–

sigma ... r their

Don't stop when you see what you expect.

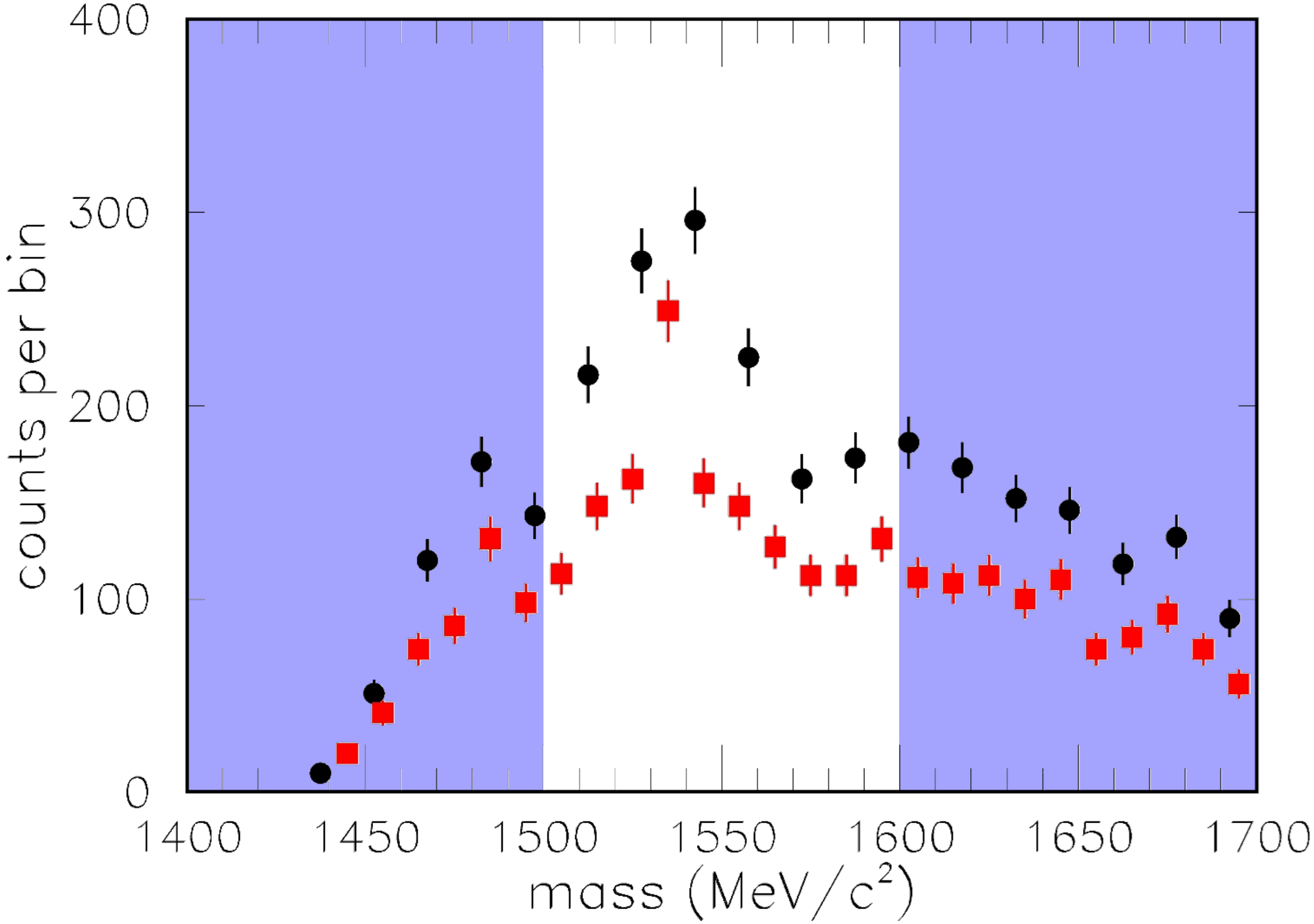
Try to disprove yourself!

Summary of published Observation



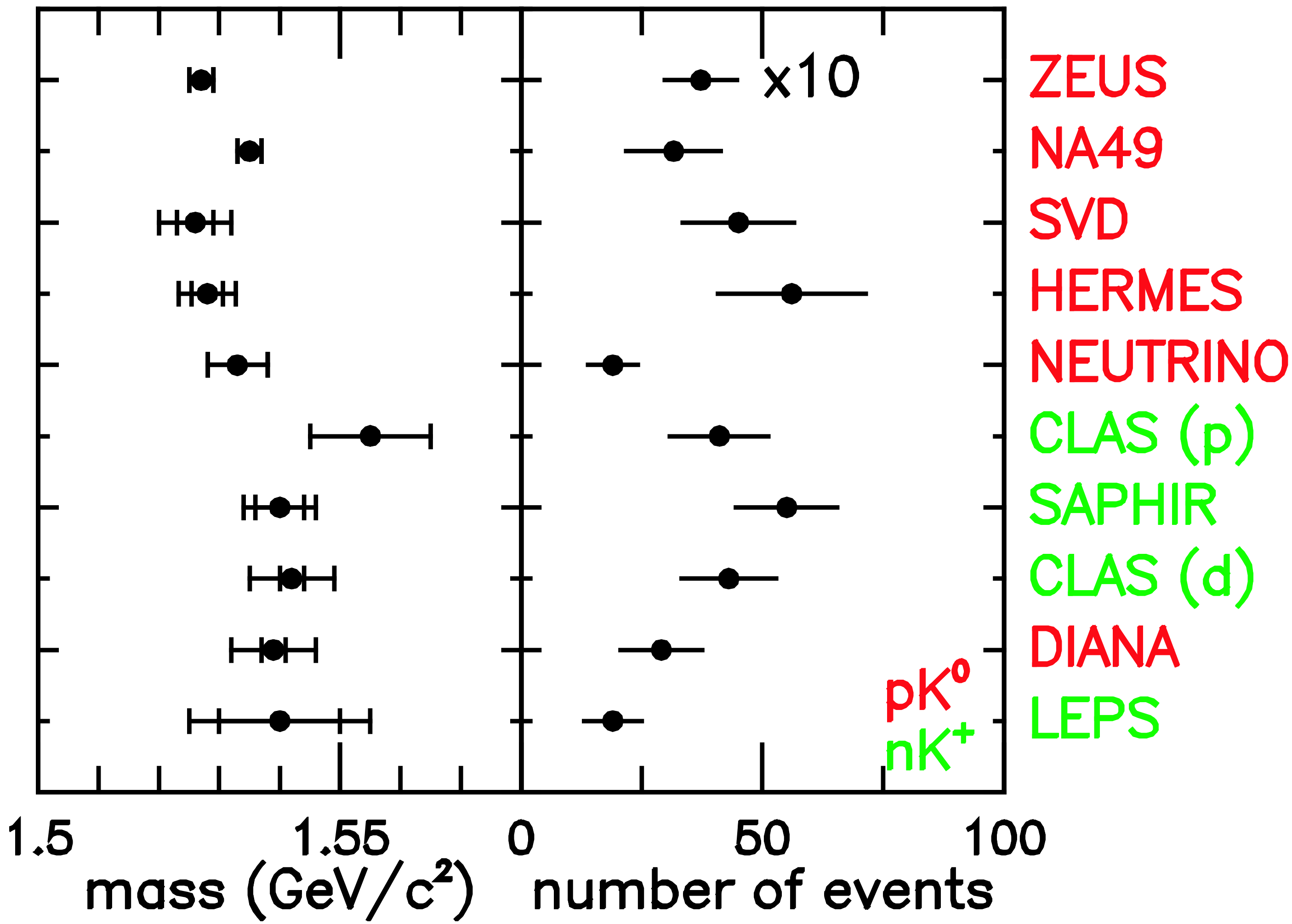
“Poor Mans” High Statistics Experiment

- Adding all spectra
  - fine binning (0.25MeV) because of different bin limits
  - equal distribution of counts within an original bin
  - adding corresponding sub-bins
  - re-binning in 10 resp. 15 MeV bins

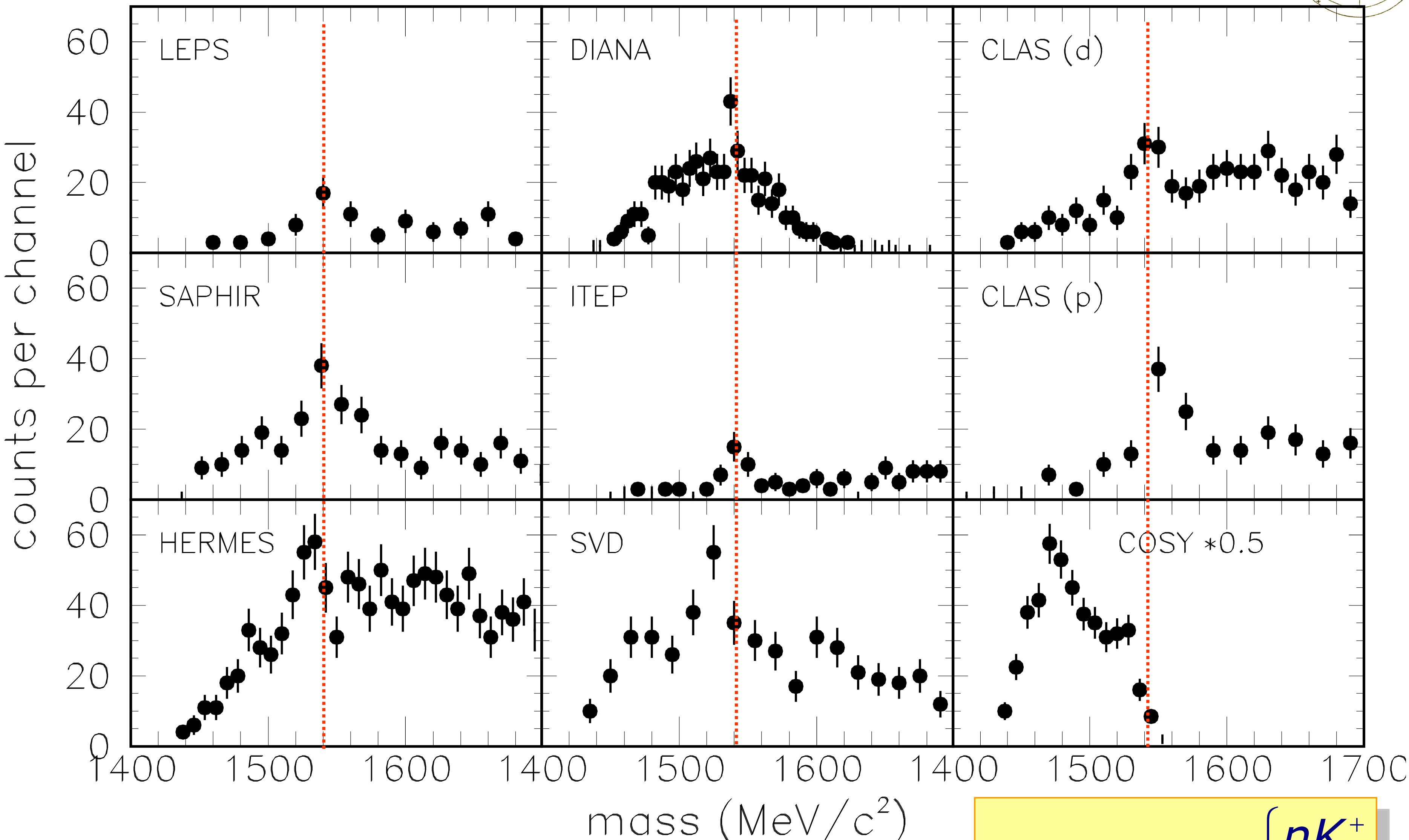


Experimental status of $\Theta^+(1540)$

- Presently 12 experiments have seen a signal around 1.54 GeV/c^2
  - 9 published
  - 3 preliminary



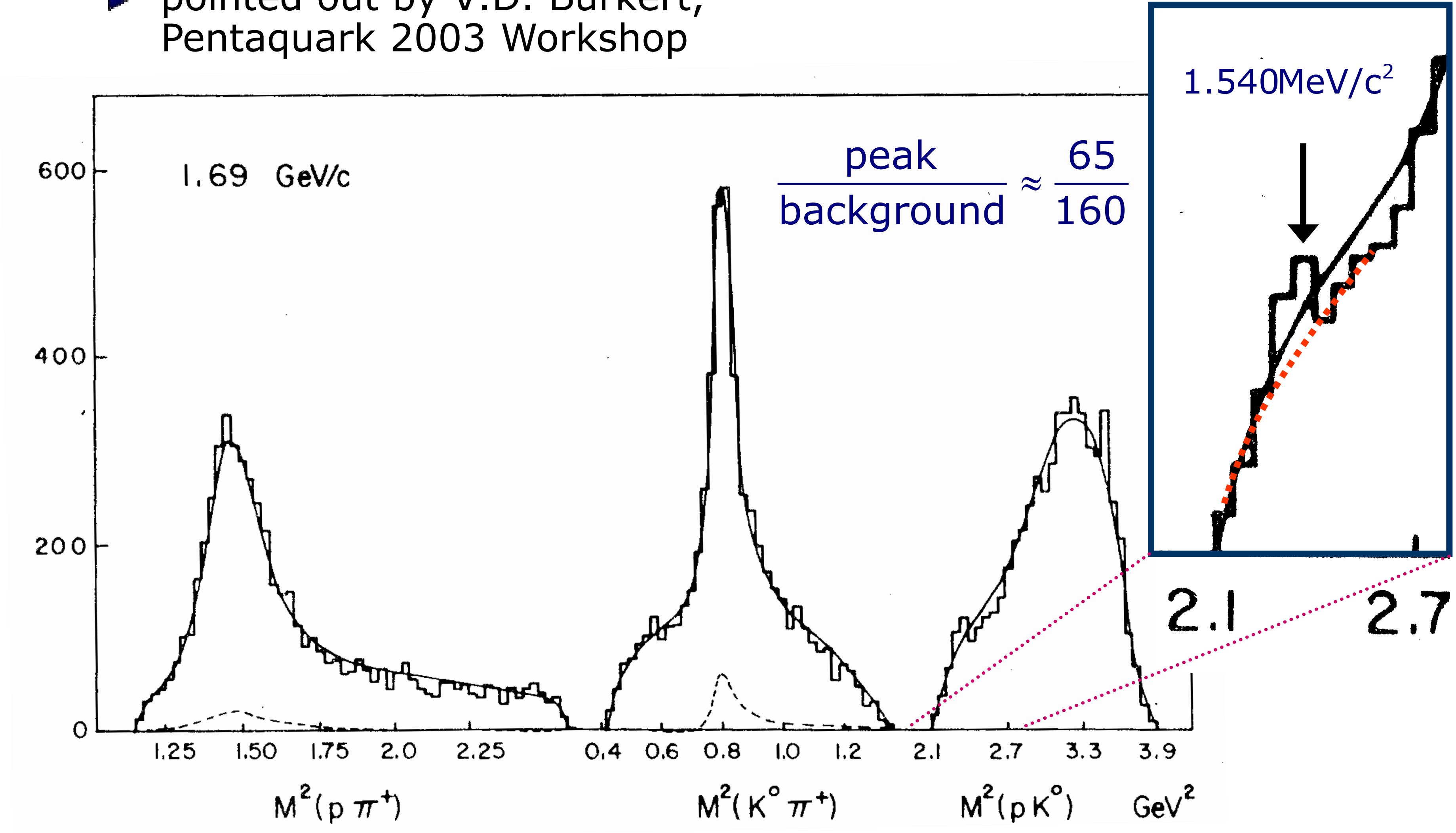
Summary of published Observations



$$\Theta^+(1530) \rightarrow \begin{cases} nK^+ \\ pK^0 \end{cases}$$

The unseen $\Theta^+(1540)$???

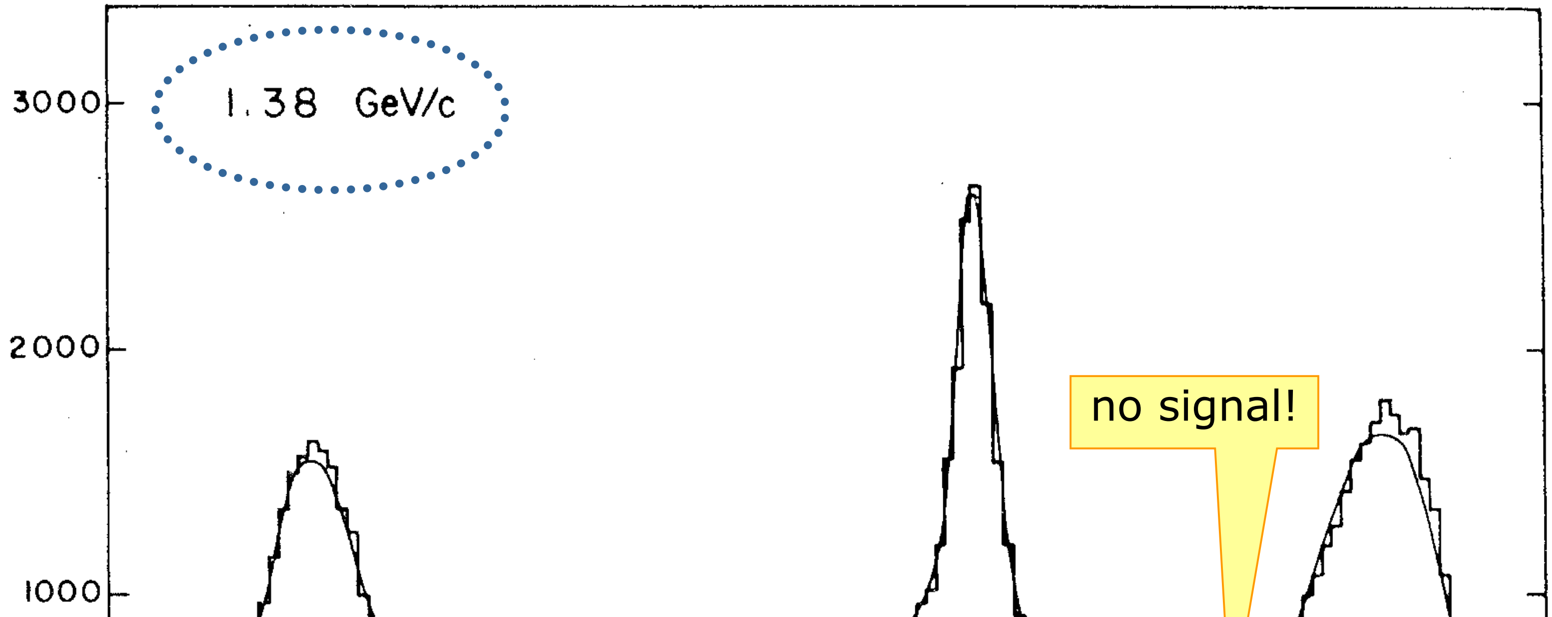
- pointed out by V.D. Burkert, Pentaquark 2003 Workshop



- K^+p interactions at p_K=1.2-1.7GeV/c
- A. Berthon, Nucl. Phys. B 63, 54 (1973)

The unseen $\Theta^+(1540)$!

- A. Berthon, Nucl. Phys. B 63, 54 (1973)



Beware of low statistics !

- one has to use Poisson statistics

  S.I. Bityukov NIM **452**, 518 (2000)

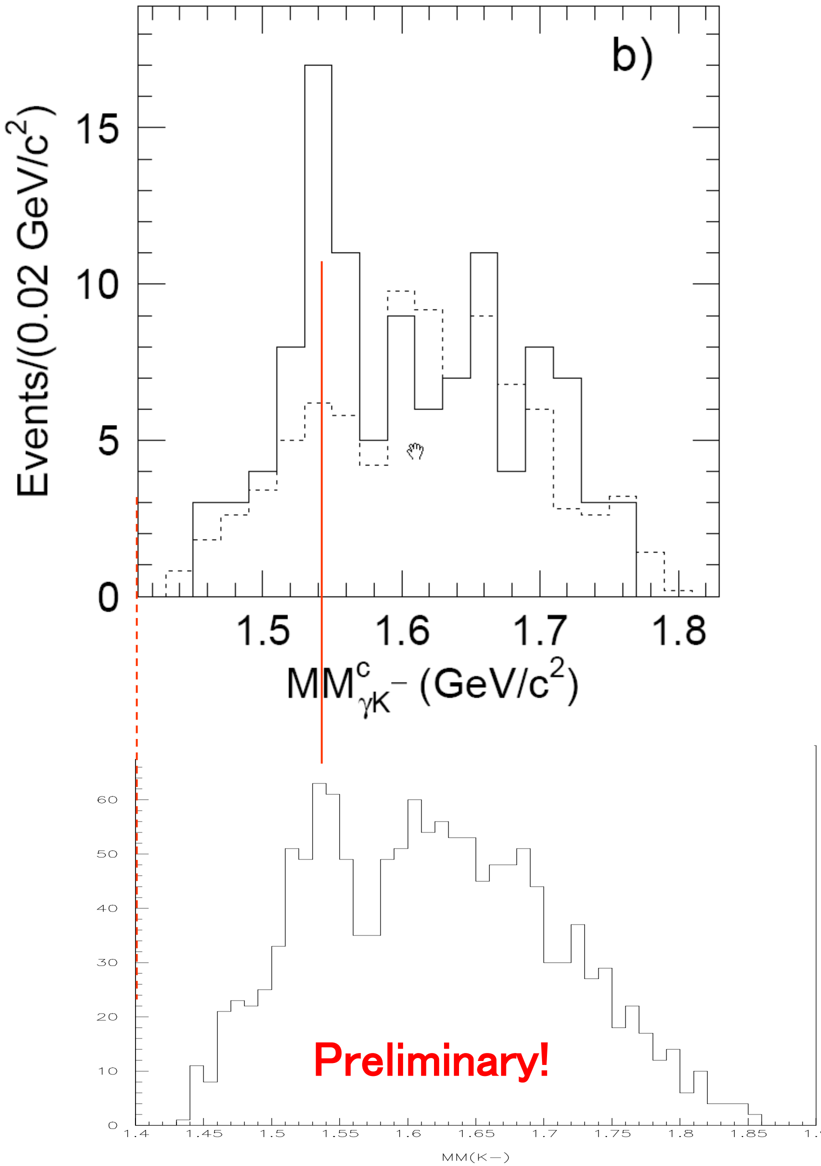
- the statistical significance of a peak depends on the number of histogram one looked at during the search

  see e.g. M. Zavertyaev, hep-ph/0311250

New LEPS experiment 2004: $\gamma d \rightarrow K^+K^-n$

May. 04

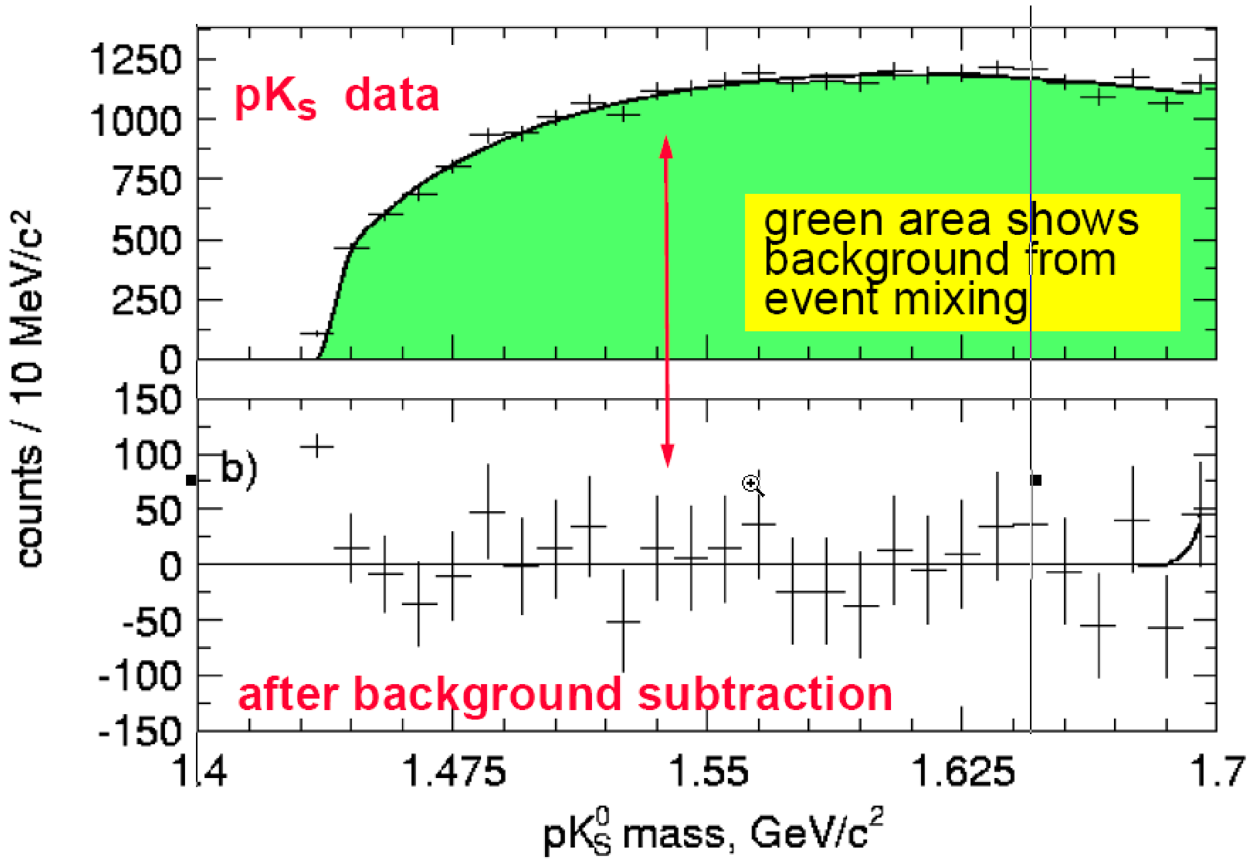
- Ken Hicks (Ohio University), Denver APS Meeting, May 2, 2004
- Θ-peak:
  - 2003: 18 events
  - 2004: ~100 events
  - (x5-10 fold statistics)
- But: Why is the signal:background ratio so much smaller?
- we better wait for the final paper!



HERA-B (preliminary) (2)

Jan. 04

- T. Knöpfle, Quark Matter 04, Oakland, January 11 - 17, 2004
- p+C, Ti, W; p_p=920GeV/c
- expected mass resolution for $\delta M(\Theta^+)=3.2\pm0.2$MeV



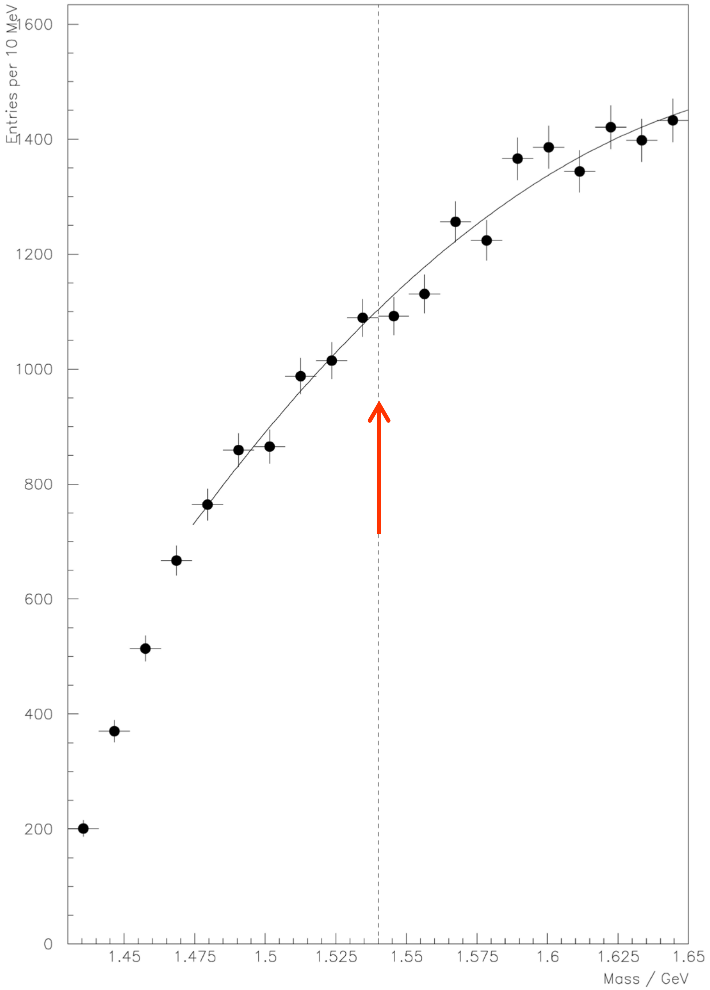
- at mid rapidity $\Theta^+(1540)/\Lambda(1520)<0.002$
- F. Becattini *et al.*, hep-ph/0310049: $\Theta^+(1540)/\Lambda(1520)\sim0.6$

OPAL (3)

Jan. 04

Georg Lafferty, 6. Jan 2004 (unpublished)

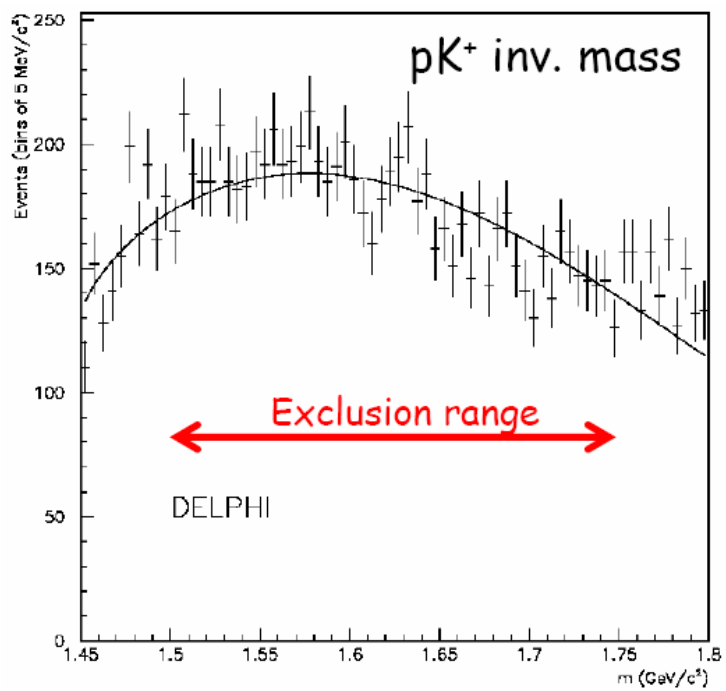
- www.hep.man.ac.uk/u/gdl/xmas.ppt
  - Used 5M hadronic Z^0 decay events from the LEP 1 data sample
  - Track combinations from displaced vertices make K^0_s candidates
  - Use of dE/dx allows for proton identification
  - Various other uninteresting standard cuts

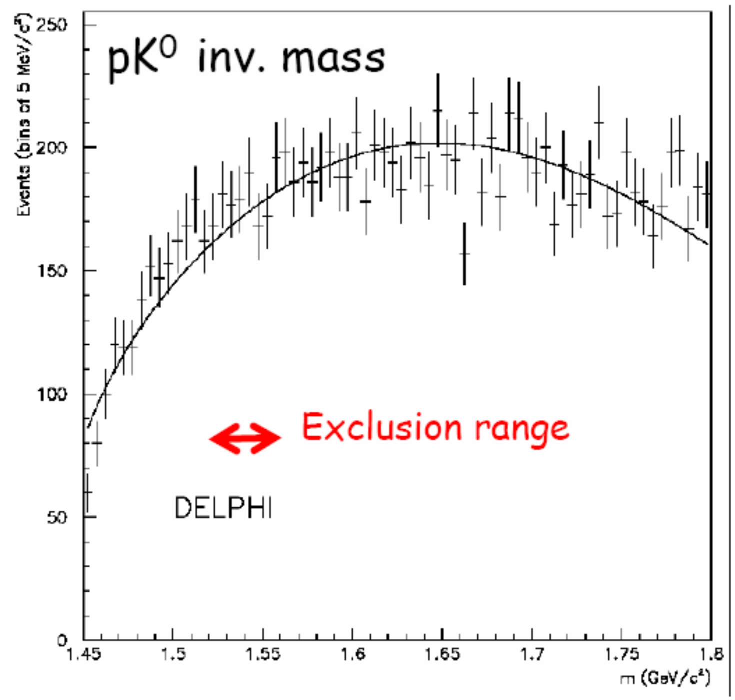


DELPHI (4)

Mar. 04

- T. Wengler, Moriond 2004
- XXXIXth Rencontres de Moriond - March 28th-April 4th 2004 QCD and Hadronic interactions at high energy
  - http://moriond.in2p3.fr/QCD/2004/WednesdayAfternoon/Wengler.pdf
- hadronic Z decays





Nothing → multiplicity limits

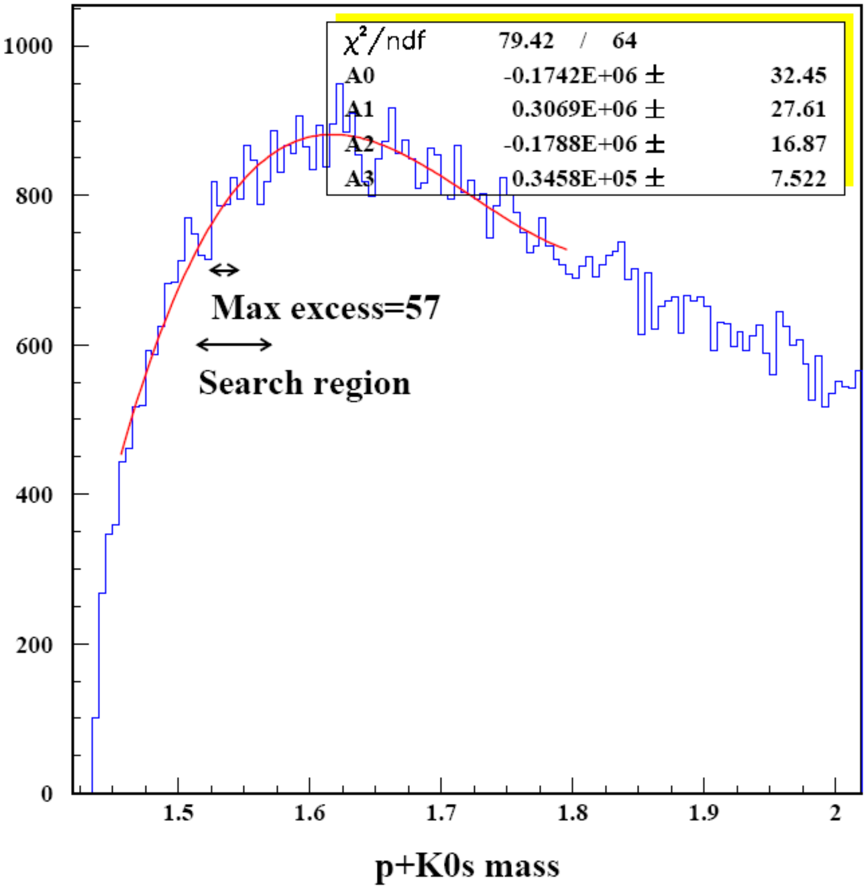
$\langle N(\Theta^{++}) \rangle < 0.006$ $\langle N(\Theta^{+}) \rangle < 0.015$

ALEPH (5)

Apr. 04

- DIS04
- 3.5M Hadronic Z decay
- 2800 $\Lambda(1520)$

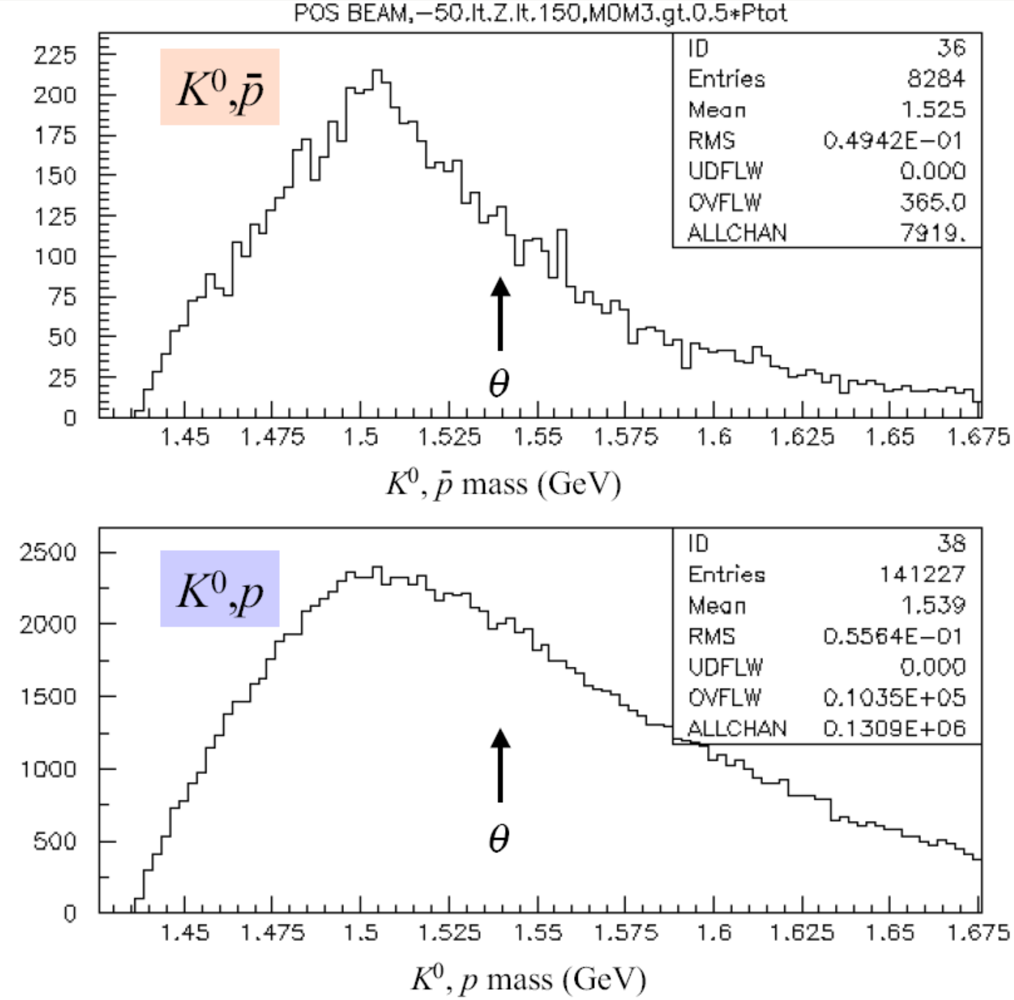
$$\frac{N_{\Theta^+}}{N_{\Lambda(1520)}} < 0.10$$



HYPER-CP (E871) (6)

May. 04

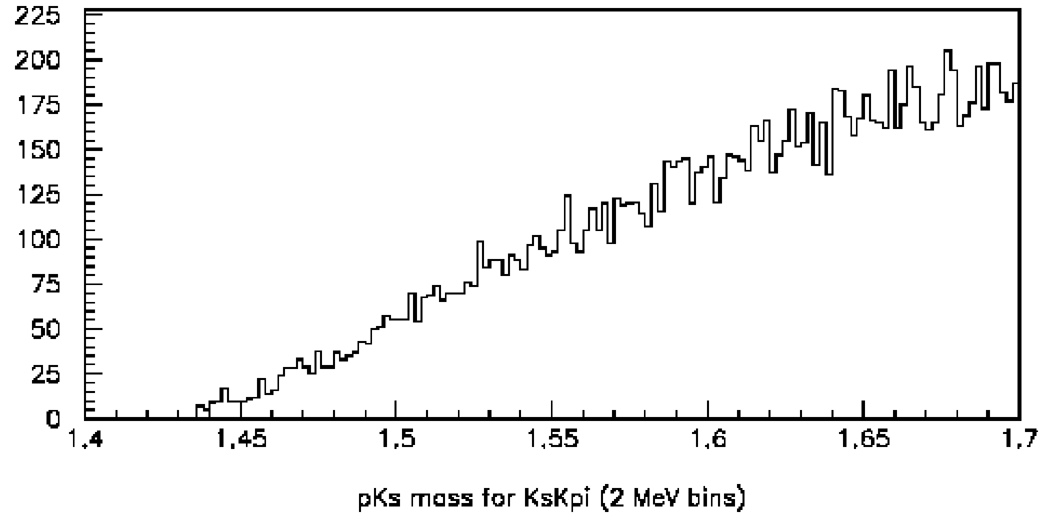
- M.J. Longo, QNP2004
- http://www.qnp2004.org/
- mixed beam (p, π, K, Y)
- p=120-250GeV/c
- pos. and neg. beam
- mass resolution <2MeV

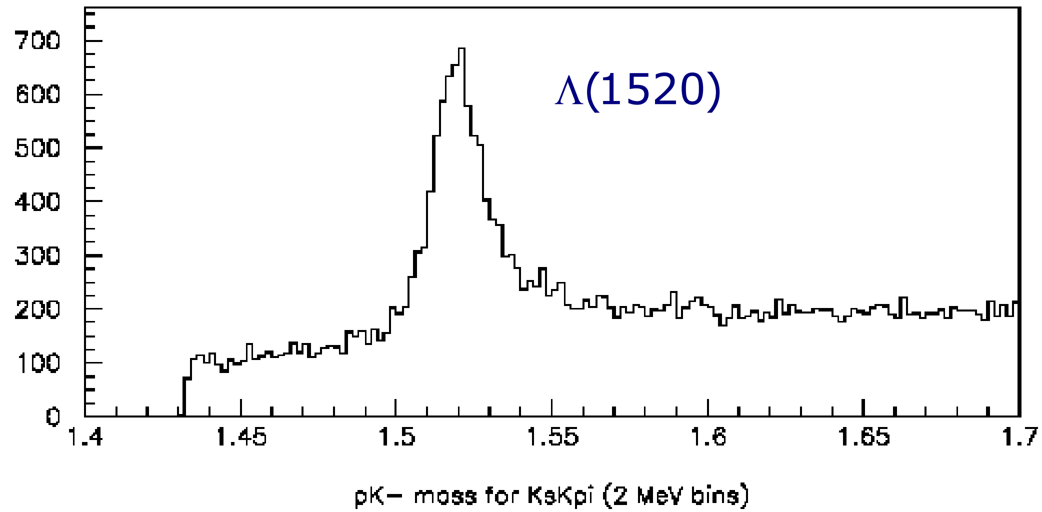


The ratio of θ^+ to total K^0, p is <0.25% at 90% confidence level. This is compared to 2–8% for $\theta^+ \rightarrow K^0, p$ sightings

E690 (7)

- D. Christian, QNP 2004
- pK_s in 800 GeV/c $pp \rightarrow pK_sK^-\pi^+p$
- Monte Carlo pKs ma
- 5000 Λ(1520) above
- Yield of Θ(1530) < 2

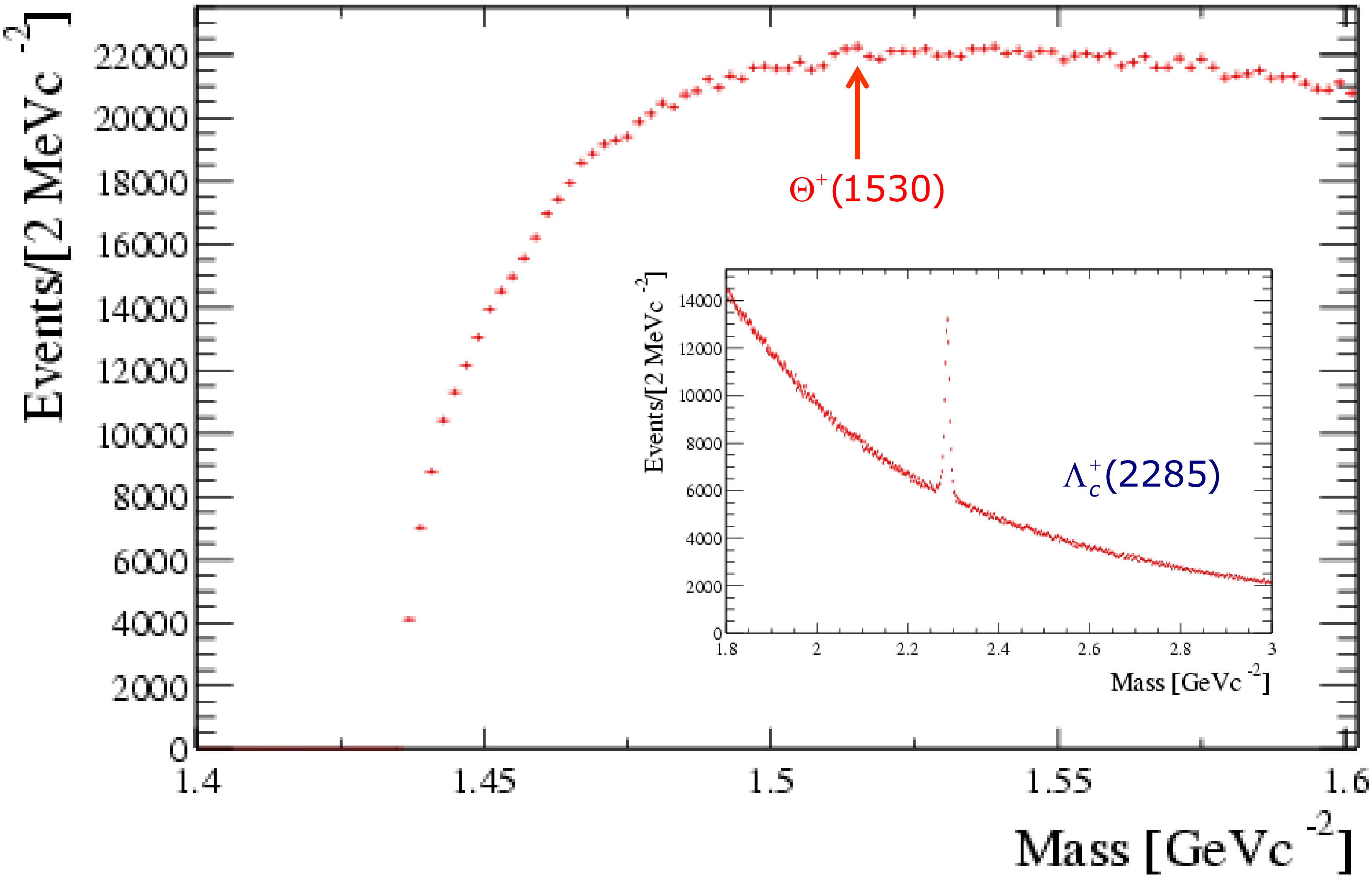




BABAR (8)

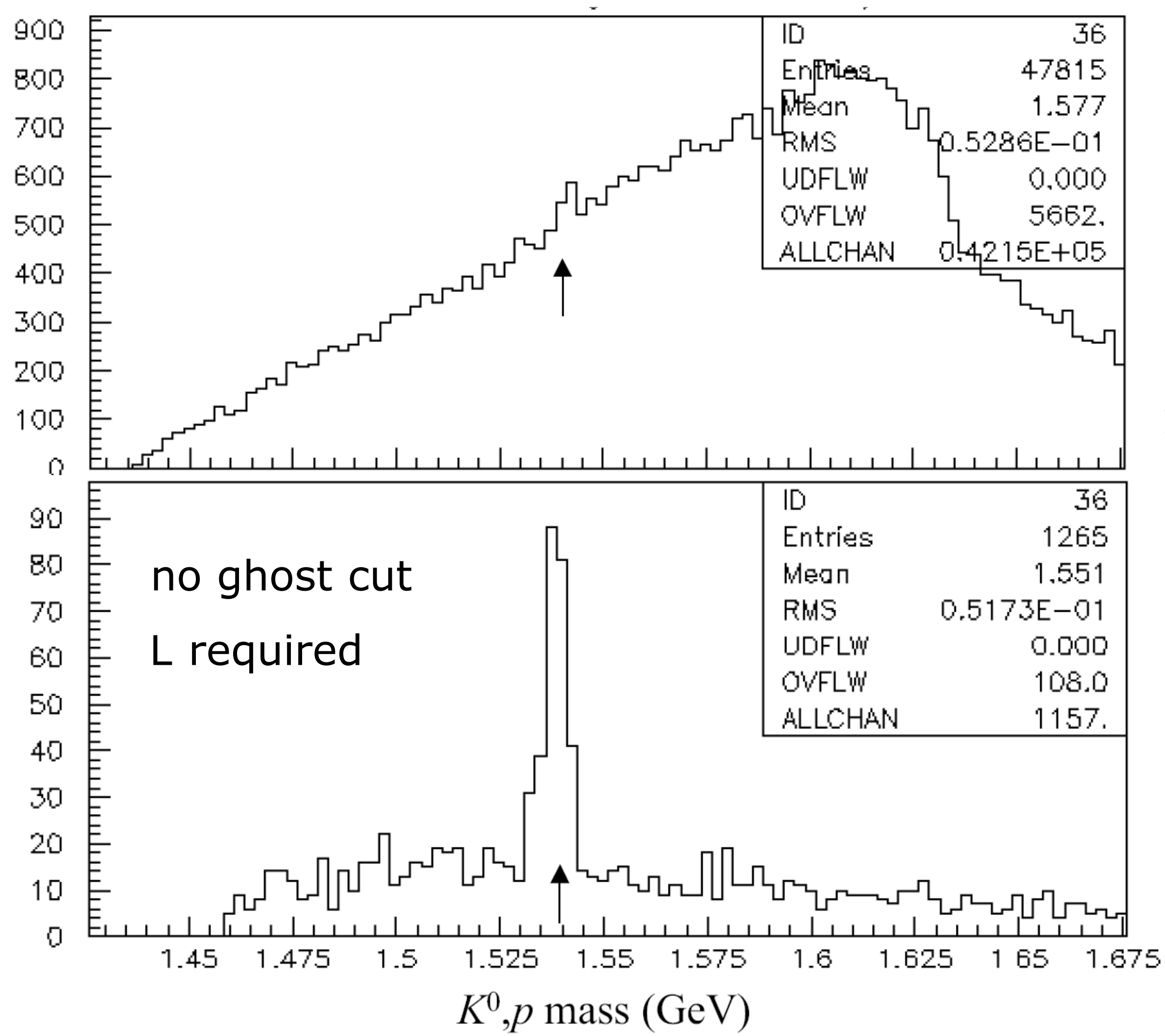
Apr. 04

- J. Coleman, 2004 APS April meeting
- e^+e^-, sqrt(s)=10.58 GeV
- 98000 $\Lambda_c(2285)$



Ghost tracks (HYPER-CP)

- ghost tracks can cause a peak around 1540 MeV
- postive track from $\Lambda \rightarrow p\pi^-$ is used twice (as proton and π^+)
- final „ghost“ state $p\pi^+\pi^-$



Status of Width Γ_Θ

- Θ^+-Experiments
  - in most experiments the observed width is compatible with the experimental resolution (FWHM)

SPring8	<25	DIANA	<9
CLAS (d)	<21	SAPHIR	<25
ITEP (n)	<20	CLAS (p)	<26
SVD	<24	COSY-TOF	<18

  - some indications for width ≈10MeV

HERMES:	$\Gamma = 19 \pm 5 \pm 2$MeV	MC: 14.3 MeV
ZEUS:	$\Gamma = 10 \pm 2$(stat) MeV	MC: 4 MeV

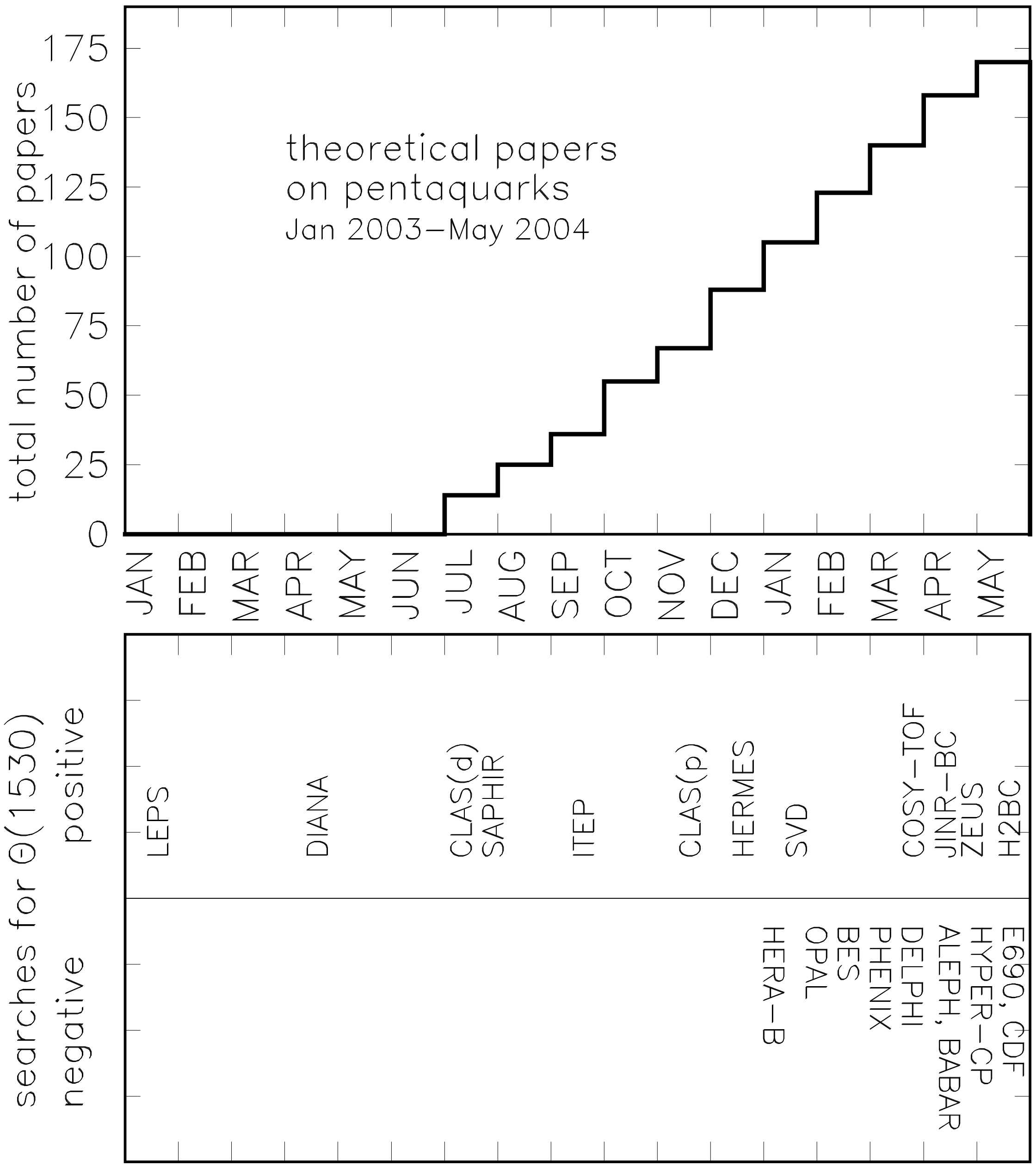
- From KN scattering data
  - R.A. Arndt *et al*., nucl-th/0311030
  - J. Haidenbauer *et al*., hep-ph/0309243
    - examined K^+p and K^+d scattering database
    - no structure in present data at $p_{Lab,K} \approx 0.44$GeV/c
    - Compatible with a resonance around 1540MeV only if $\Gamma_\Theta < 1$MeV

2. Theoretical situation

"Everything should be made as simple as possible, but not simpler."

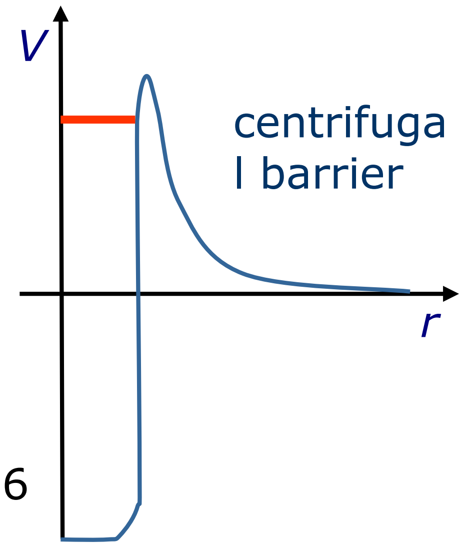
A. Einstein

The Boom of theoretical papers



What are these Peaks?

- KN molecular interpretation unlikely
  - Θ is above the KN threshold by 105 MeV; width <10 MeV
  - assume simple potential scattering
    - width and depth of a potential is related to position and width of resonance
    - for illustration: p-wave
    - width of potential ≈0.05fm
- but
  - typical scale of strong interaction 1fm
  - no mechanism known to produce a resonance at r ≈0.05fm unless high L waves involved
    - D.E. Kahana and S.H. Kahana, hep-ph/0310026
  - even if possible: kaon and nucleon would loose their identity at r=0.05fm



- KπN molecule
  - P. Bicudo and M. Marques, hep-ph/0308078
  - $m(K^+)+m(\pi)+m(N)\approx 1570$MeV
  - binding energy of 30 MeV typical
  - possible but: implies bound πK system (not observed so far)
    - T. Kishimoto and T. Sato, hep-ex/0312003

What are these Peaks (if they are real)?

- What can it be:

$$K^{+}(u\bar{s})\,n(udd)$$

  - decay into a baryon ⇒ It must be a baryonic system
  - the small width <10MeV ⇒ must decay via strong interaction
  - strong decay conserves strangeness
    ⇒ particle must contain strange antiquark

- minimal quark configuration

$$uudd\bar{s}$$

- is the mass of $\Theta^+(1540)$ consistent with a pentaquark state?
  - naïve quark model:

$$m(\Theta^+) = 350 \times 4 + 500 = 1900 \text{ MeV}$$

  - need additional „interaction" between quarks
    - solitons
    - diquarks
    - …

Pentaquarks in Lattice QCD

UK/04-13

A study of pentaquarks on the lattice with overlap fermions

N. Mathur [a], F.X. Lee [b,c], A. Alexandru [a], C. Bennhold [b], Y. Chen [d],
S.J. Dong [a], T. Draper [a], I. Horváth [a], K.F. Liu [a], S. Tamhankar [a], J.B. Zhang [e]
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[c] *Jefferson Lab, 12000 Jefferson Avenue, Newport News, VA 23606, USA*
[d] *Institute of High Energy Physics, Academia Sinica, Beijing 100039, P.R. China*
[e] *CSSM and Department of Physics, University of Adelaide, SA 5005, Australia*

We present a quenched lattice QCD calculation of spin-1/2 five-quark states with $uudd\bar{s}$ quark content for both positive and negative parities. We do not observe any bound pentaquark state in these channels for either $I = 0$ or $I = 1$. The states we found are consistent with KN scattering states which are checked to exhibit the expected volume dependence of the spectral weight. The results are based on overlap-fermion propagators on two lattices, $12^3 \times 28$ and $16^3 \times 28$, with the same lattice spacing of 0.2 fm, and pion mass as low as ~ 180 MeV.

PACS numbers: 12.38.Gc, 14.20.Gk, 11.15.Ha

hep-ph/0406196 v2 21 Jun 2004

I. INTRODUCTION

Since the reported discovery [1] two years ago of an exotic 5-quark resonance, named $\Theta^+(uudd\bar{s})$, with a mass of about 1540 MeV and a narrow width of less than 20 MeV, there has been a rapid growth of interest in the subject. More independent experiments have reported the observation of the state [2]. It also stimulated the search for other pentaquarks [3]. It should be pointed out, however, that there are also a number of experiments reporting negative results [4]. One has to wait for high statistics experiments to clarify the situation in order to establish the exotic state beyond doubt.

The strangeness quantum number of Θ^+ is $S = +1$, but its isospin and spin-parity assignments are undetermined by the experiments. Based just on the valence quark content, the isospin could be 0, 1, or 2. The spin-configuration of a product of color-neutral meson and baryon interpolation fields,

$$\chi_1^{\mp} = \epsilon^{abc} \left(u^{Ta} C\gamma_5 d^b\right) \left[u^c \left(\bar{s}^e \gamma_5 d^e\right) \mp \{u \leftrightarrow d\}\right], \qquad (1)$$

where sum over all the color indices $\{a, b, c, e\}$ is implied. The minus sign is for isospin I=0 and plus sign for I=1 respectively. The explicit spin-parity of this interpolating field is $\frac{1}{2}^-$. By explicit, we mean the time-forward correlation with projection to the upper Dirac component using the $(1 + \gamma_4)$ projector. A slight variation with a different color contraction is given by

$$\chi_2^{\mp} = \epsilon^{abc} \left(u^{Ta} C\gamma_5 d^b\right) \left[u^e \left(\bar{s}^e \gamma_5 d^c\right) \mp \{u \leftrightarrow d\}\right], \qquad (2)$$

where the color indices e and c are positioned differently. Both interpolation fields in Eq. (1) and Eq. (2) have been used in lattice calculation to study the pentaquark

3. Experimental facts Part 2: Ξ(1860)

"The first principle is that you must not fool yourself--and you are the easiest person to fool. So you have to be very careful about that. After you've not fooled yourself, it's easy not to fool other scientists."

Richard Feynman

Cargo Cult Science (1974)

NA49: Observation of Ξ^{--} Pentaquark

Oct. 03

hep-ex/0310014 v1 8 Oct 2003

…servation of an Exotic S = −2, Q = −2 Baryon Resonance in Proton-Proton Collisions at the CERN SPS

C. Alt,[9] T. Anticic,[20] B. Baatar,[8] D. Barna,[4] J. Bartke,[6] M. Behler,[13] L. Betev,[10,9] H. Białkowska,[18] A. Billmeier,[9] C. Blume,[7,9] B. Boimska,[18] M. Botje,[1] J. Bracinik,[3] R. Bramm,[9] R. Brun,[10] P. Bunčić,[9,10] V. Cerny,[3] P. Christakoglou,[2] O. Chvala,[15] J.G. Cramer,[16] P. Csató,[4] N. Darmenov,[17] A. Dimitrov,[17] P. Dinkelaker,[9] V. Eckardt,[14] G. Farantatos,[2] P. Filip,[14] D. Flierl,[9] Z. Fodor,[4] P. Foka,[7] P. Freund,[14] V. Friese,[7,13] J. Gál,[4] M. Gaździcki,[9] G. Georgopoulos,[2] E. Gładysz,[6] S. Hegyi,[4] C. Höhne,[13] K. Kadija,[20] A. Karev,[14] S. Kniege,[9] V.I. Kolesnikov,[8] T. Kollegger,[9] R. Korus,[12] M. Kowalski,[6] I. Kraus,[7] M. Kreps,[3] M. van Leeuwen,[1] P. Lévai,[4] L. Litov,[17] M. Makariev,[17] A.I. Malakhov,[8] C. Markert,[7] M. Mateev,[17] B.W. Mayes,[11] G.L. Melkumov,[8] C. Meurer,[9] A. Mischke,[7] M. Mitrovski,[9] J. Molnár,[4] St. Mrówczyński,… G. Pálla,[4] A.D. Panagiotou,[2] D. Panayotov,[17] K. Perl,[19] A. Petridis,[2] M. Pikna,[3] L. Pinsky,[11] F. Pühlho… J.G. Reid,[16] R. Renfordt,[9] W. Retyk,[19] C. Roland,[5] G. Roland,[5] M. Rybczyński,[12] A. Rybicki,[6,10] A. Sa… H. Sann,[7,*] N. Schmitz,[14] P. Seyboth,[14] F. Siklér,[4] B. Sitar,[3] E. Skrzypczak,[19] G. Stefanek,[12] R. S… H. Ströbele,[9] T. Susa,[20] I. Szentpétery,[4] J. Sziklai,[4] T.A. Trainor,[16] D. Varga,[4] M. Vassiliou,[2] G.I. … G. Vesztergombi,[4] D. Vranić,[7] A. Wetzler,[9] Z. Włodarczyk,[12] I.K. Yoo,[7] J. Zaranek,[9] and J. Z…

(NA49 Collaboration)

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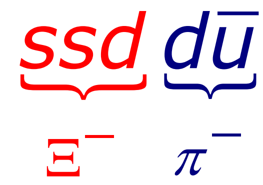
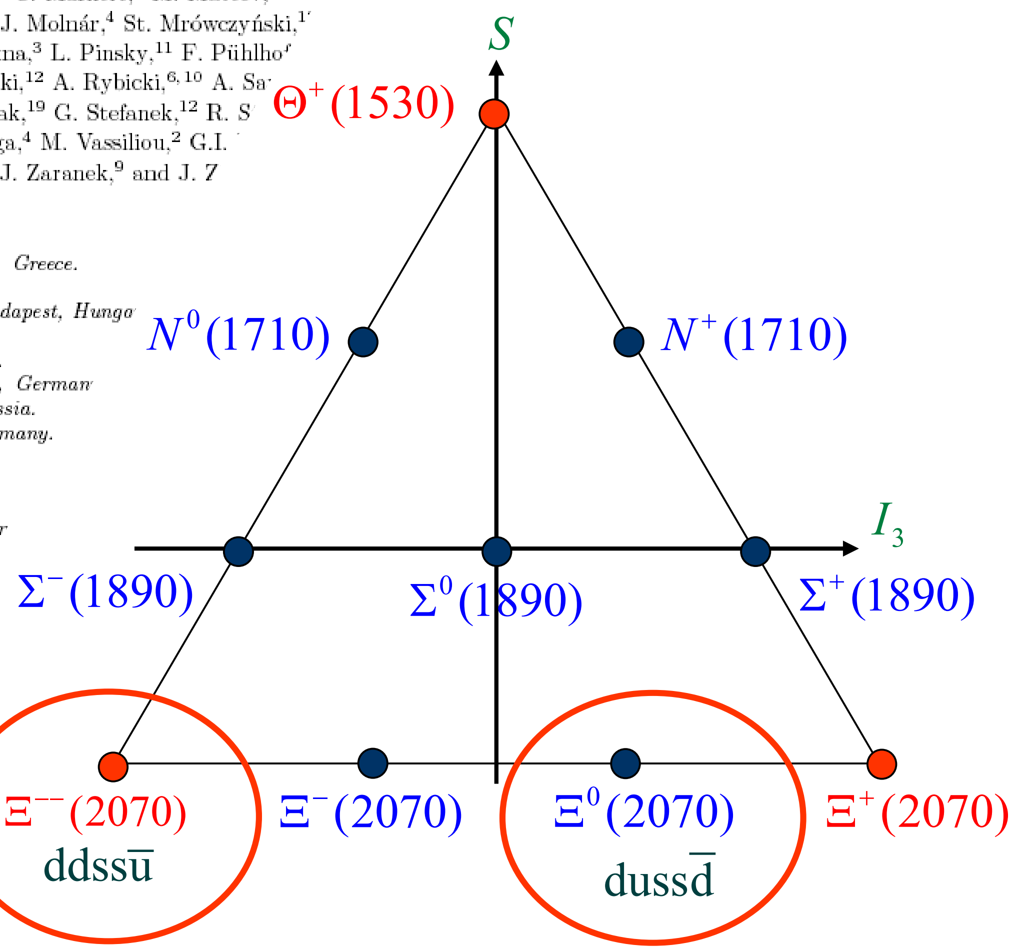
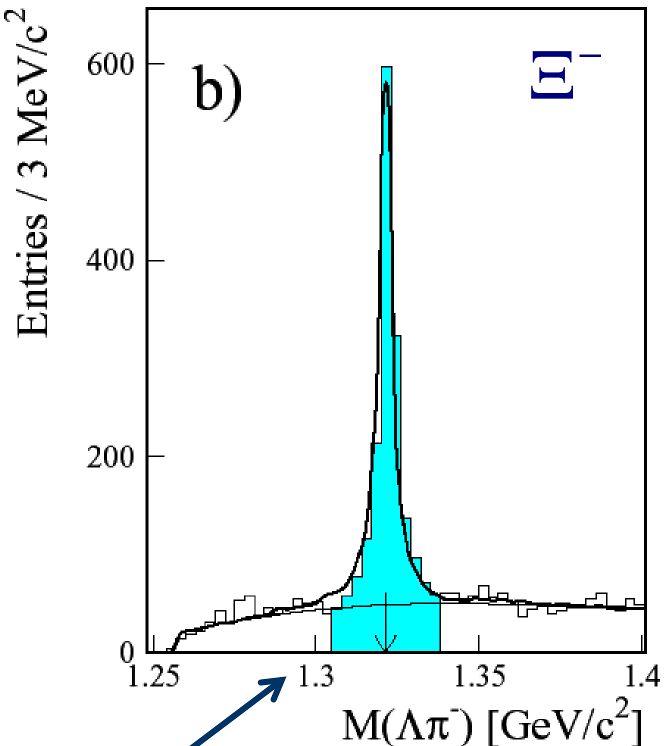
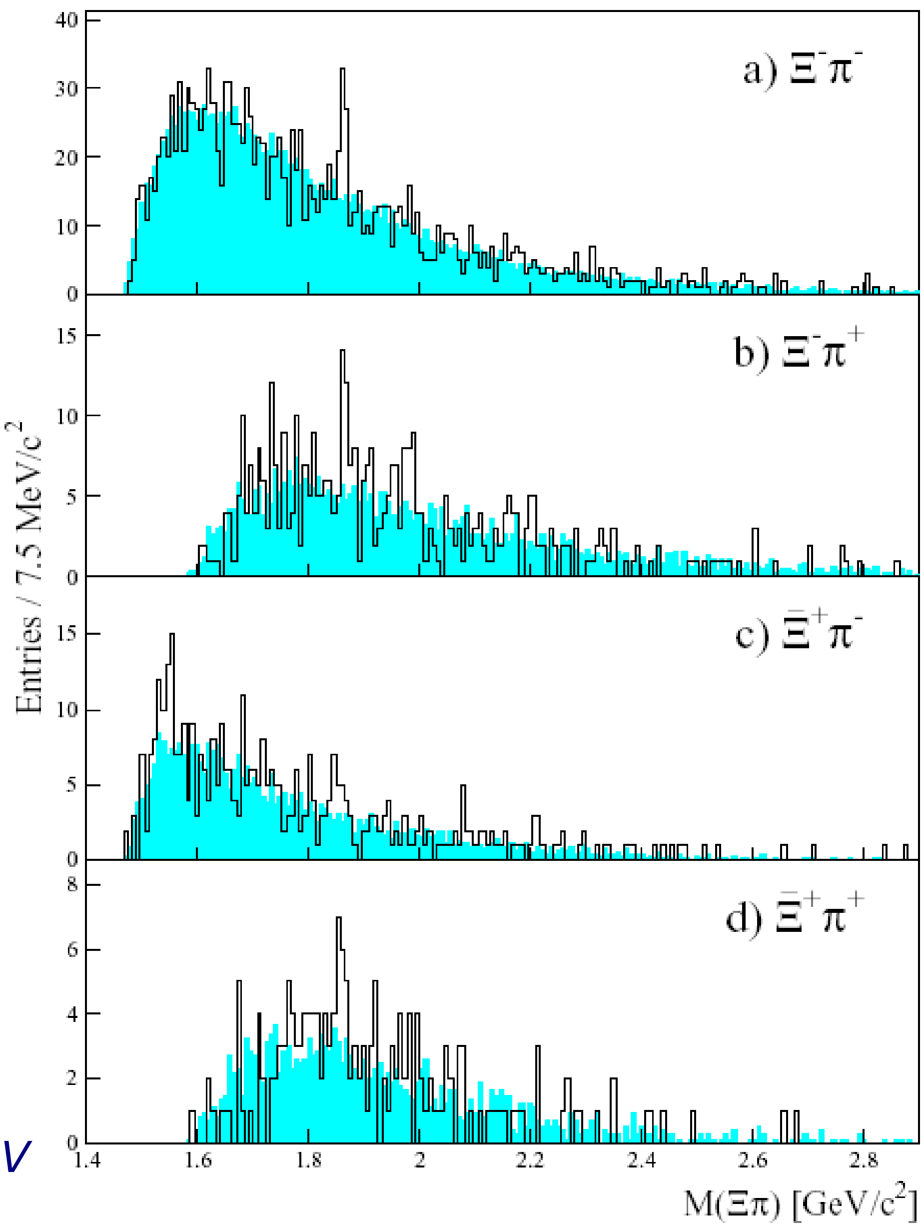




Observation of the $\Xi^{--}(1862)$ by NA49





- Ξ^- combined with primary π^-
  - 1640 Ξ^-, 551 Ξ^+

$$\frac{n(\Xi^{--})}{n(\Xi^-)} \approx \frac{n(\bar{\Xi}^{++})}{n(\bar{\Xi}^{+})} \approx \frac{1}{50}$$

$$T = \frac{\Delta m}{\ln 50} = \frac{1862 - 1321}{\ln 50} MeV \approx 140 MeV$$

The WA89 Experiment

reported first at HYP03 Oct. 03

- Σ^- and π- beam of 340 GeV/c, n-beam of 260 GeV/c
- C, Cu targets
- 1993, 1994 data taking
- $4\cdot10^8$ interactions (*NA49: $6.5\cdot10^6$ events*)

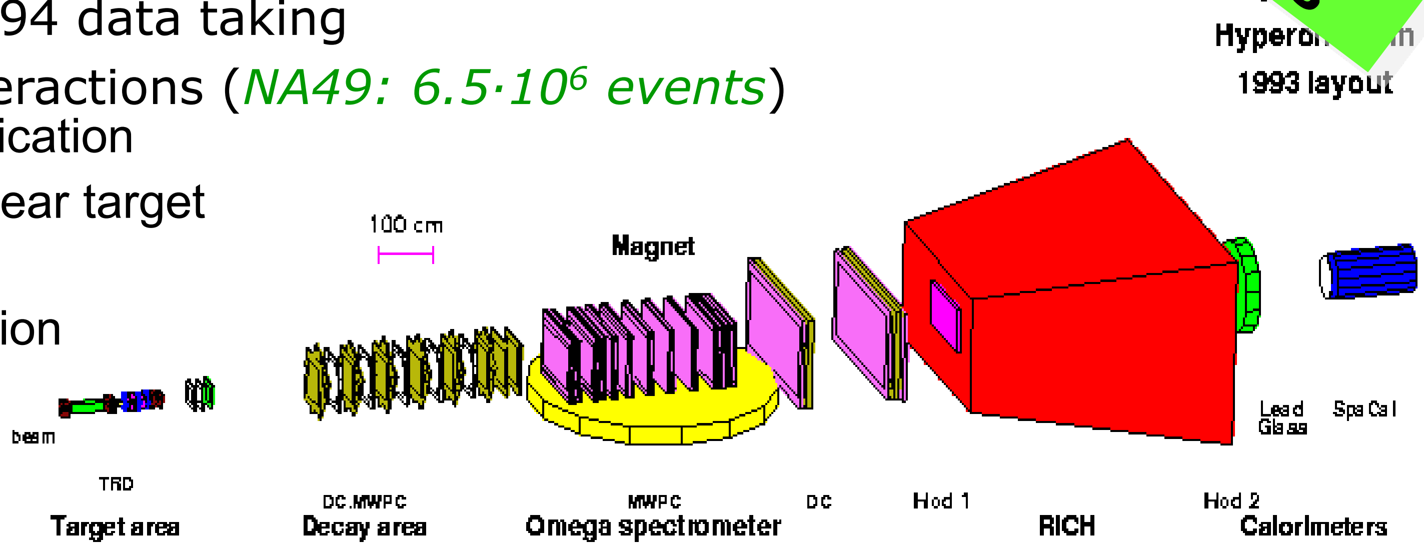
TRD: beam identification

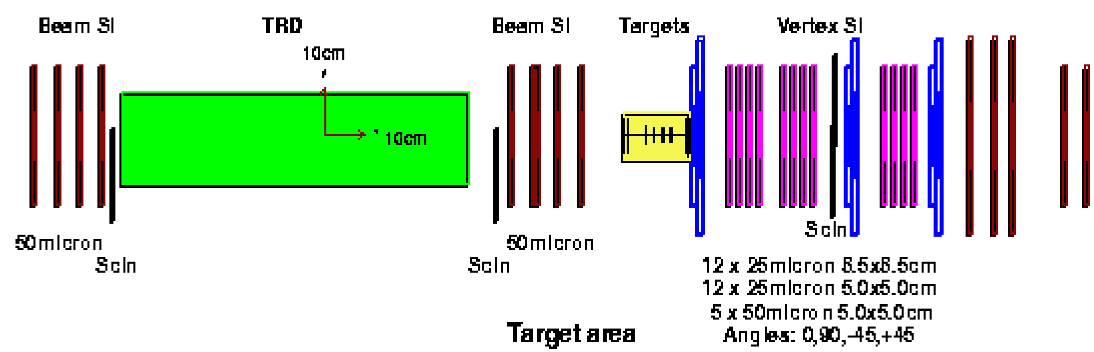
Si-μ-strip: vertex near target

MWPC: tracking

RICH: π/K separation

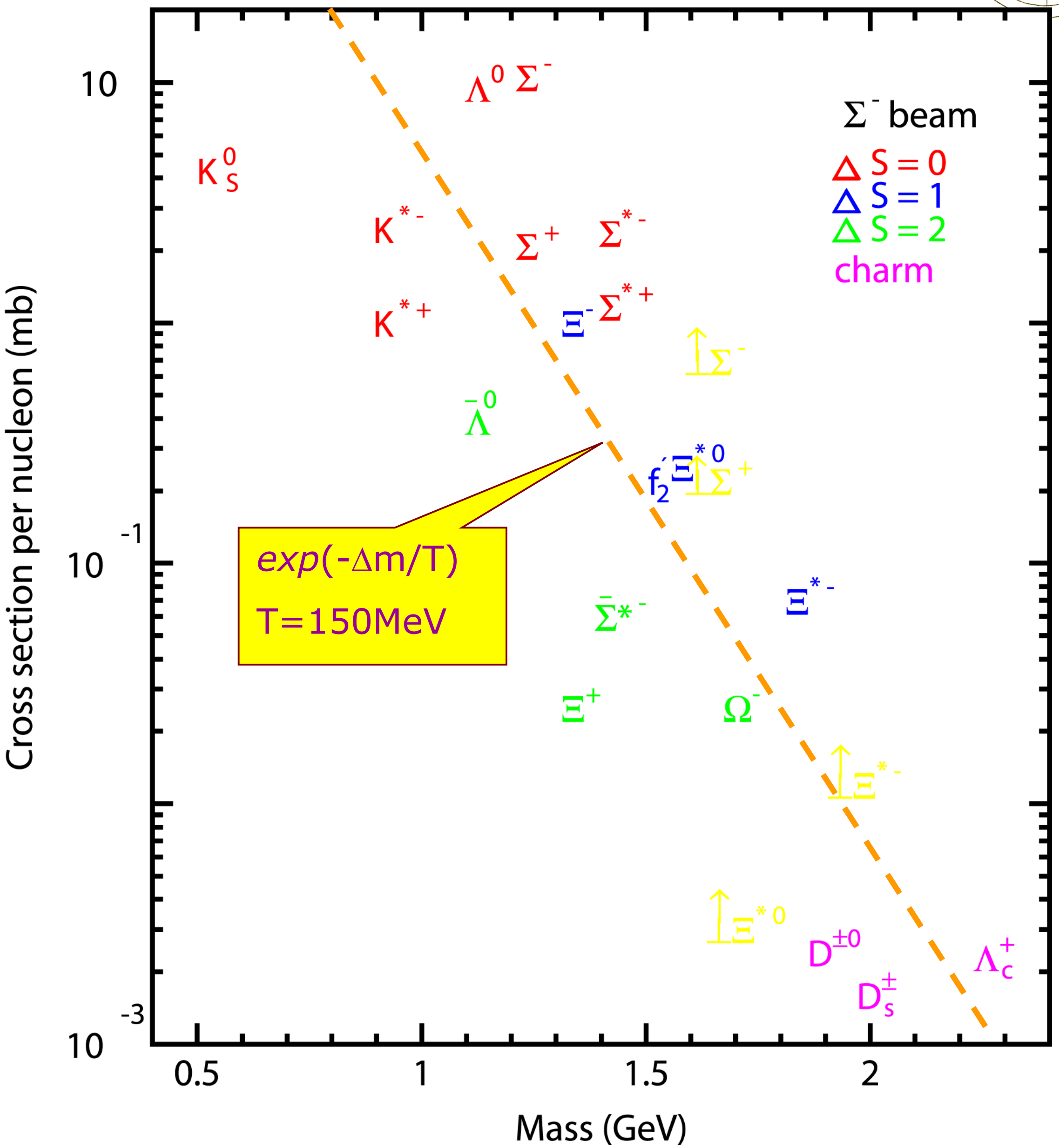
Calorimeter: e,γ; n





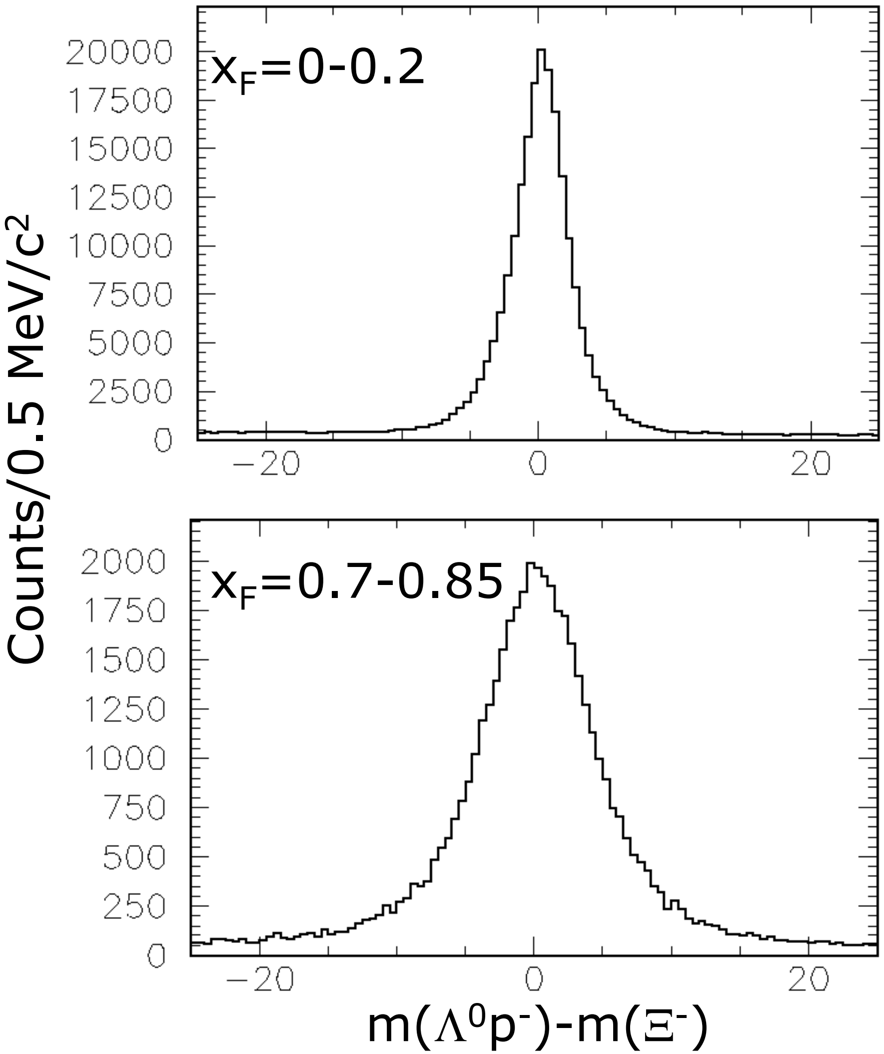
Cross sections

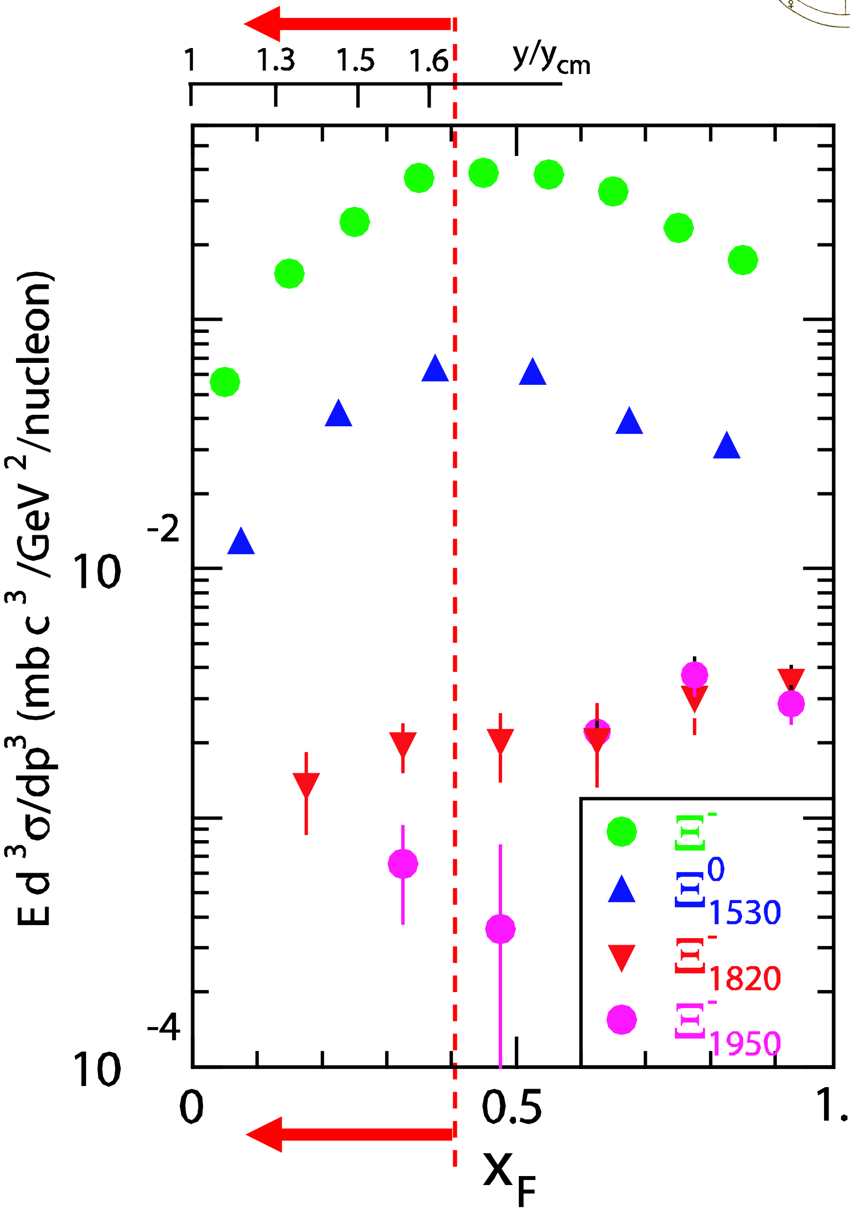
- more than 20 different strange and charmed hadrons are analyzed under identical conditions
- typical statistical distribution with slope ~ 150 MeV



Ξ^- production

- $\Xi^- Þ\ \Lambda^0 \pi^-$
  ⮩ $p\ \pi^-$



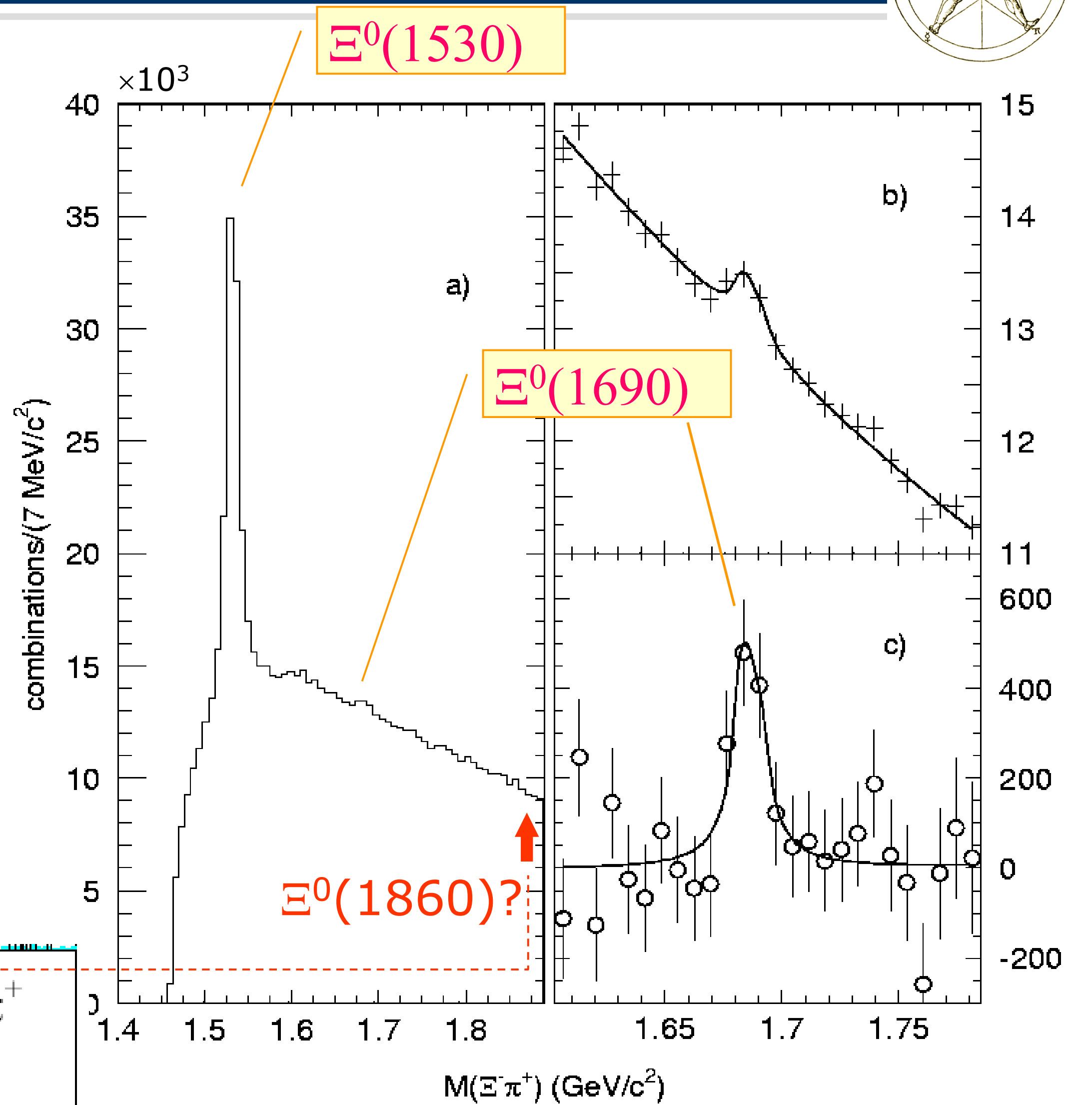


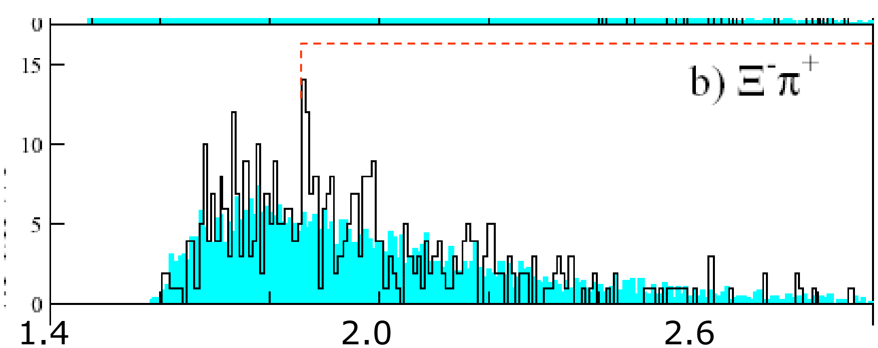
$\Xi^{*0}(1690)$ Þ $\Xi^{-}\pi^{+}$

- $\Xi^{*0}(1690)$ Þ $\Xi^{-}\pi^{+}$
  - ↳ $\Lambda^{0}\pi^{-}$
    - ↳ $p\,\pi^{-}$

- $M(\Xi^{*0}) = 1685 \pm 4$ MeV/c^2
- $\Gamma = 10 \pm 6$ MeV/c^2
- $\sigma\cdot BR = 6.8 \pm 0.2\,\mu b$

Euro. Phys. J. C **5**, 621 (1998)





$\Xi^-\pi^-$ @ WA89 (final result)

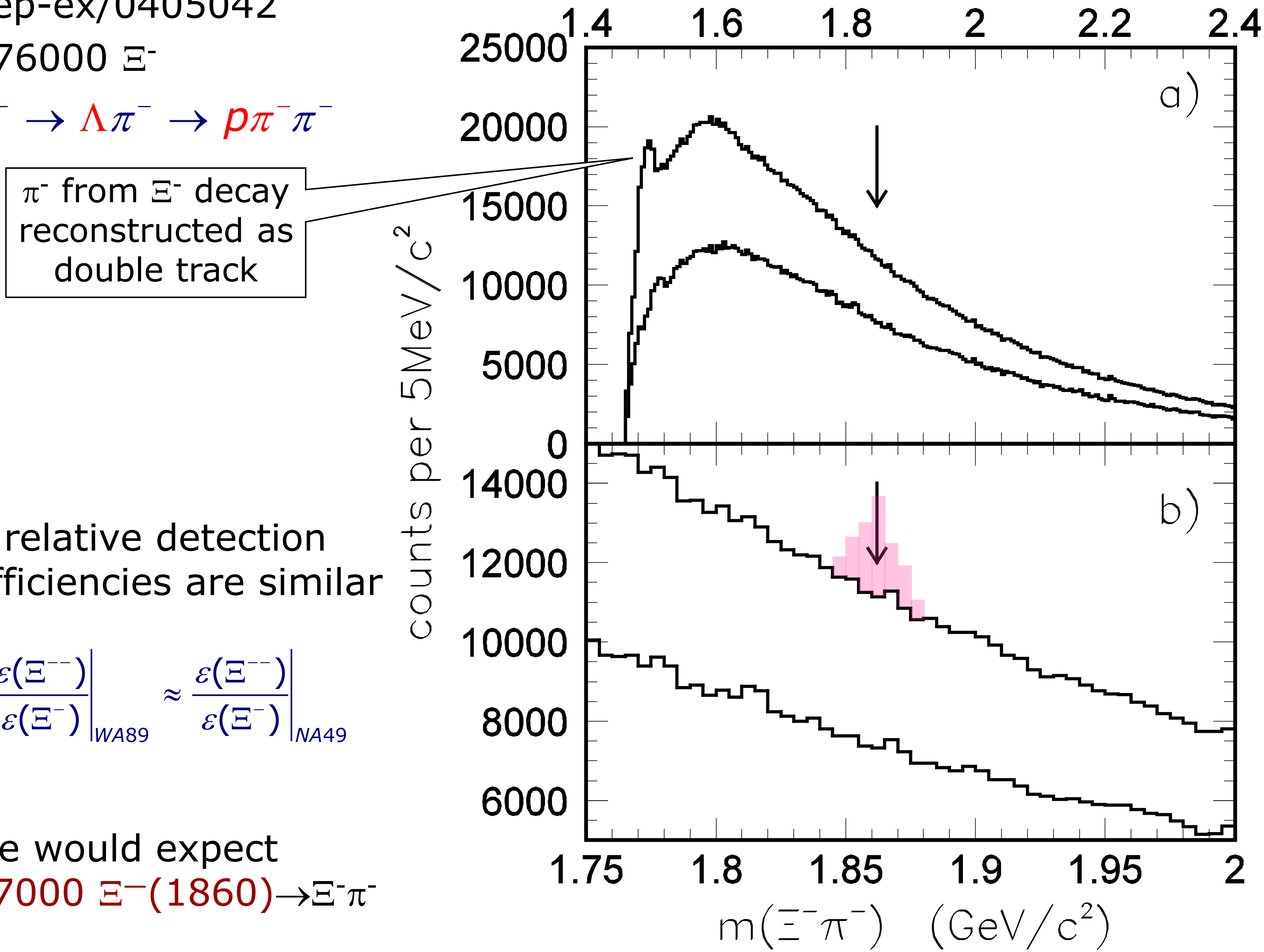
- hep-ex/0405042
- 676000 Ξ^-

$\Xi^- \rightarrow \Lambda\pi^- \rightarrow p\pi^-\pi^-$

- if relative detection efficiencies are similar

$$\left.\frac{\varepsilon(\Xi^{--})}{\varepsilon(\Xi^-)}\right|_{WA89} \approx \left.\frac{\varepsilon(\Xi^{--})}{\varepsilon(\Xi^-)}\right|_{NA49}$$

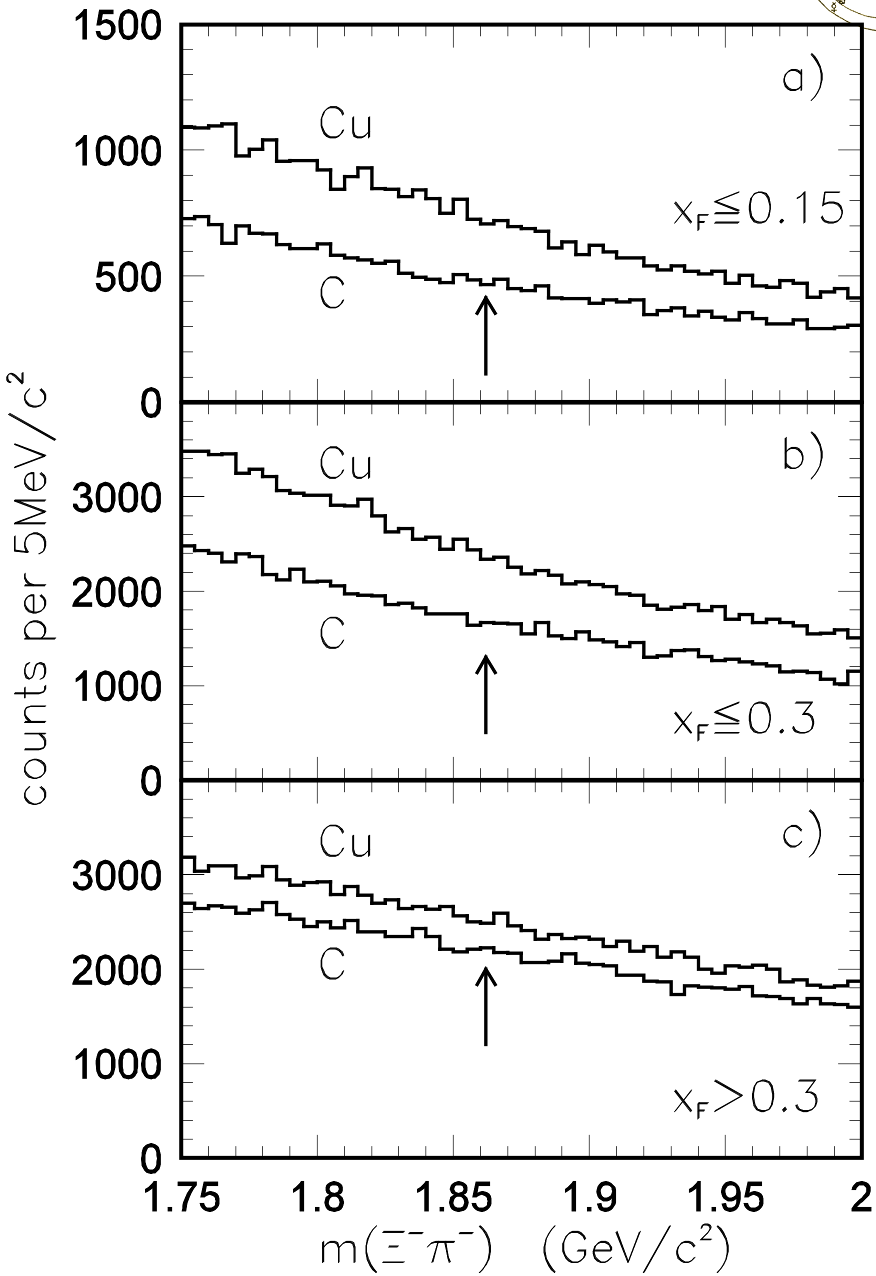
we would expect
17000 $\Xi^-(1860) \rightarrow \Xi^-\pi^-$



$\Xi^- \pi^-$ @ WA89

- hep-ex/0405042
- different kinematic cuts

$$x_F = \frac{2p_L^{CM}}{\sqrt{s}}$$



Limits for cross section

- tried x_F-cuts, p_t-cuts, angle-cuts…
- extrapolation to cross section per nucleon

$$\sigma_{nucl} = \sigma_0 \cdot A^{2/3}$$

  - $0.15 < x_F < 0.9$
  - C target: $BR \cdot \sigma_{nucl} < 16 \mu b$ $BR \cdot \sigma_0 < 3.1 \mu b$
  - Cu target: $BR \cdot \sigma_{nucl} < 55 \mu b$ $BR \cdot \sigma_0 < 3.5 \mu b$

- Other cross sections ($0 < x_F < 1$)
  - $\Xi^-(1320)$: $\sigma_0 = 1000 \mu b$
  - $\Xi^0(1530)$: $\sigma_0 = 200 \mu b$
  - $\Xi^-(1820)$: $BR \cdot \sigma_0 = 20 \mu b$
  - $\Xi^-(1950)$: $BR \cdot \sigma_0 = 12 \mu b$

NA49 vs. WA89

- What is different between NA49 and WA89?

	NA49		WA89
target:	p	↔	C or Cu
beam energy:	158GeV	↔	340GeV
beam:	p {uud}	↔	Σ^{-} {dds}
x_F range for observed Ξ^{-} :	[-0.25,+0.25]	↔	[0.1,1]

  - beam energy: all known cross section have smoth beam momentum dependence in this energy regime
  - beam: Σ^{-} has probably [ds] diquark structure [also possible for Ξ^{--}(1860)]
  - beam: no penalty factor compared to Ξ^{-} production expected

Interesting situation!

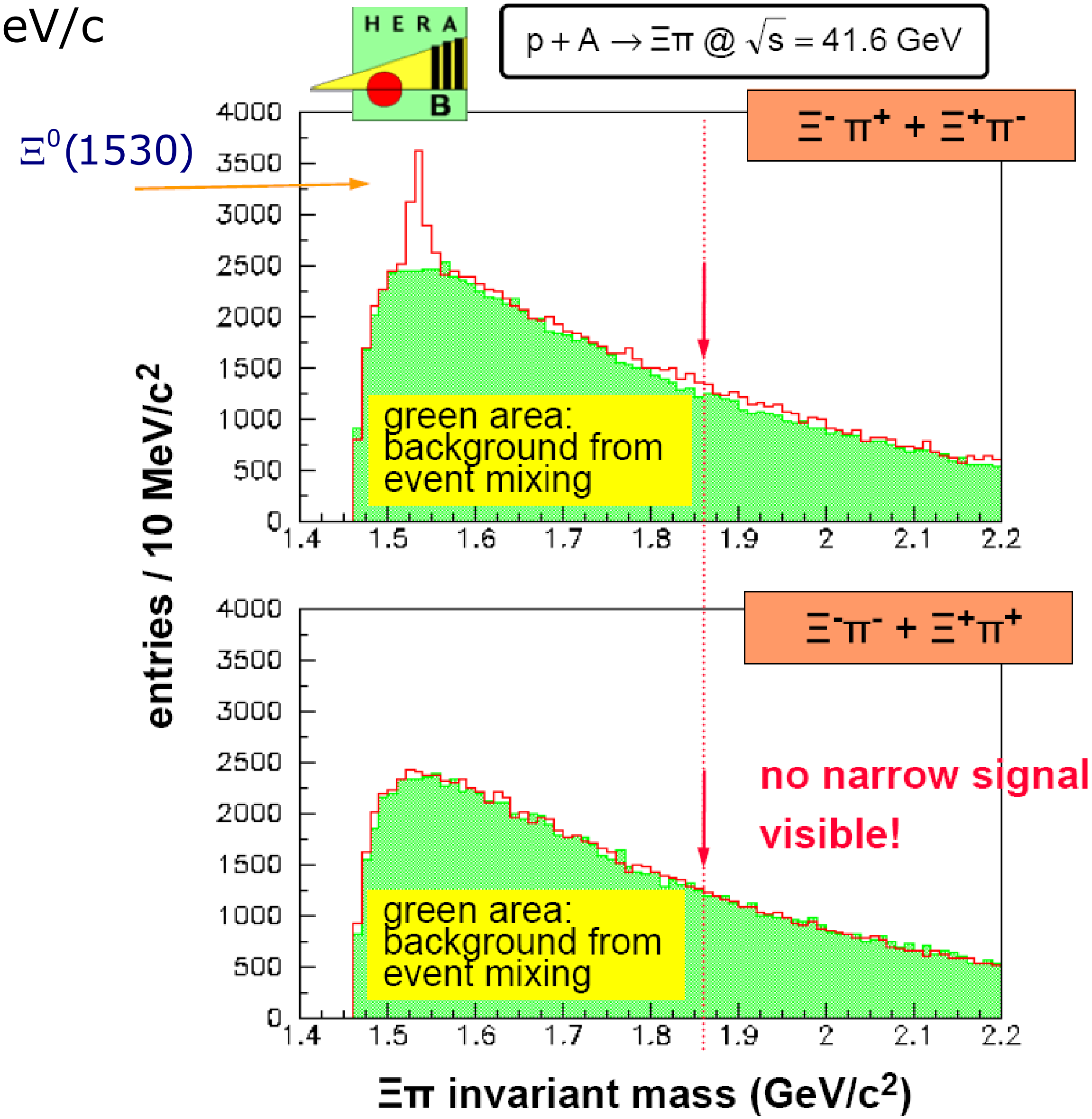
- if the Ξ^{--}(1860) exists it has an exotic production mechanism

- what about other experiments?

HERA-B (preliminary)

Jan. 04

- T. Knöpfle, Quark Matter 04, Oakland, January 11 - 17, 2004
- p+C, Ti, W; p_p=920GeV/c
  - C: 76M events
  - Ti: 16M events
  - W: 72M events

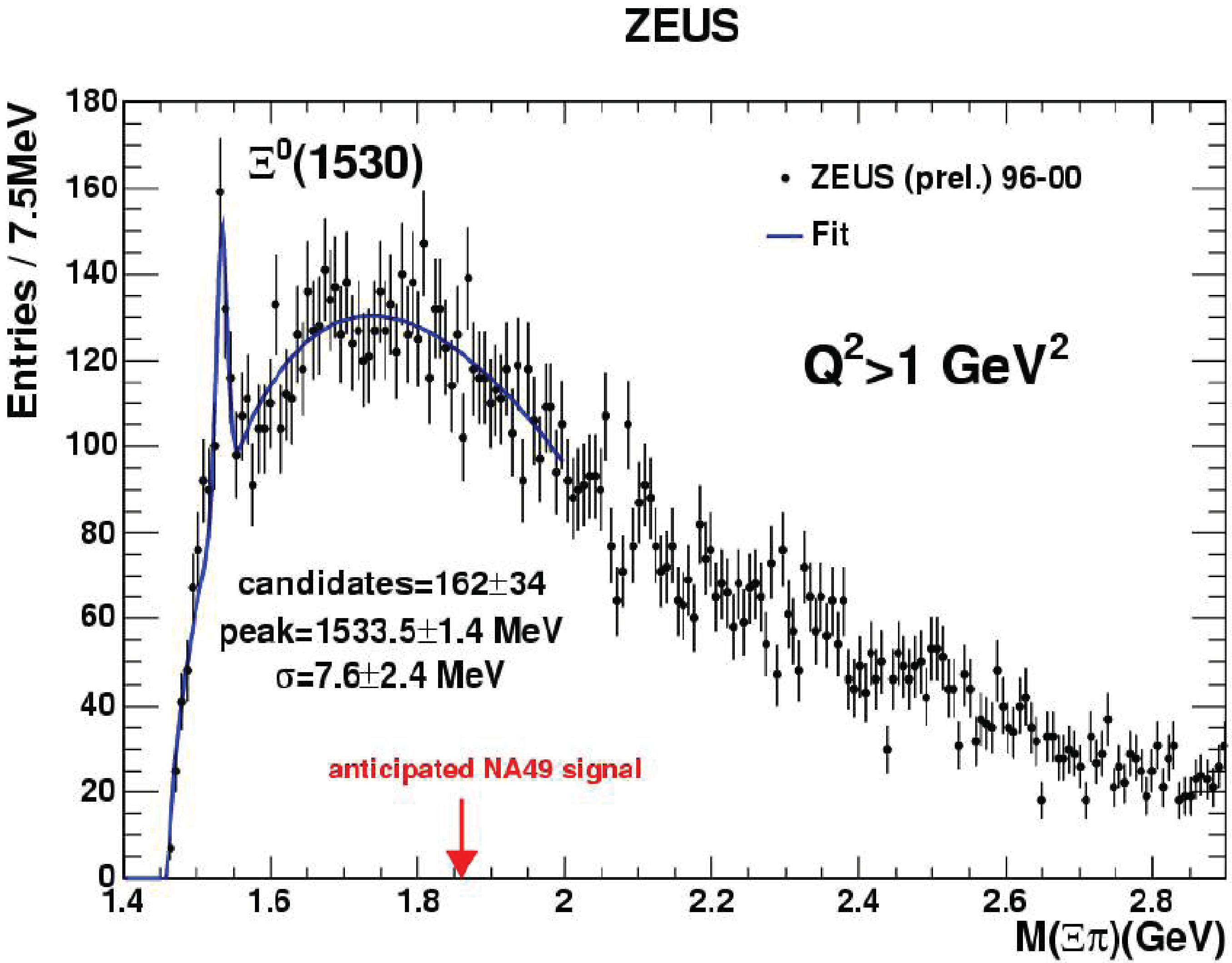


- 11000 Ξ^-
- resolution: 2.6 MeV

ZEUS

Apr. 04

- S. Chekanov, DIS04, hep-ex/0405013
- e-p, $\sqrt{s}$=300-318GeV
- 1361 Ξ^-



ALEPH

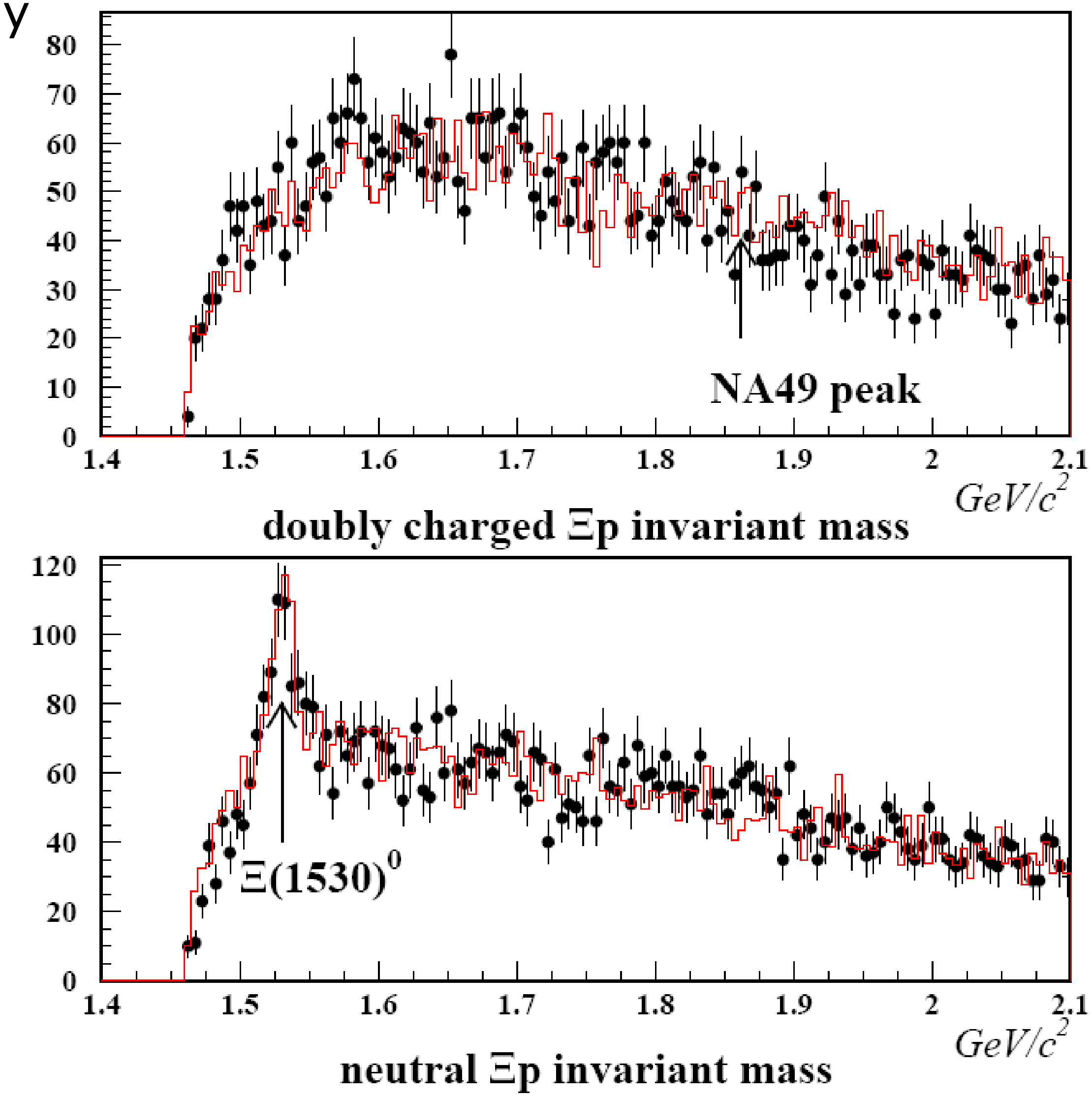
Apr. 04

P. Hansen, DIS04

- 3.5M Hadronic Z decay
- 3350 Ξ^-

$$\frac{N_{\Theta^+}}{N_{\Lambda(1520)}} < 0.10$$

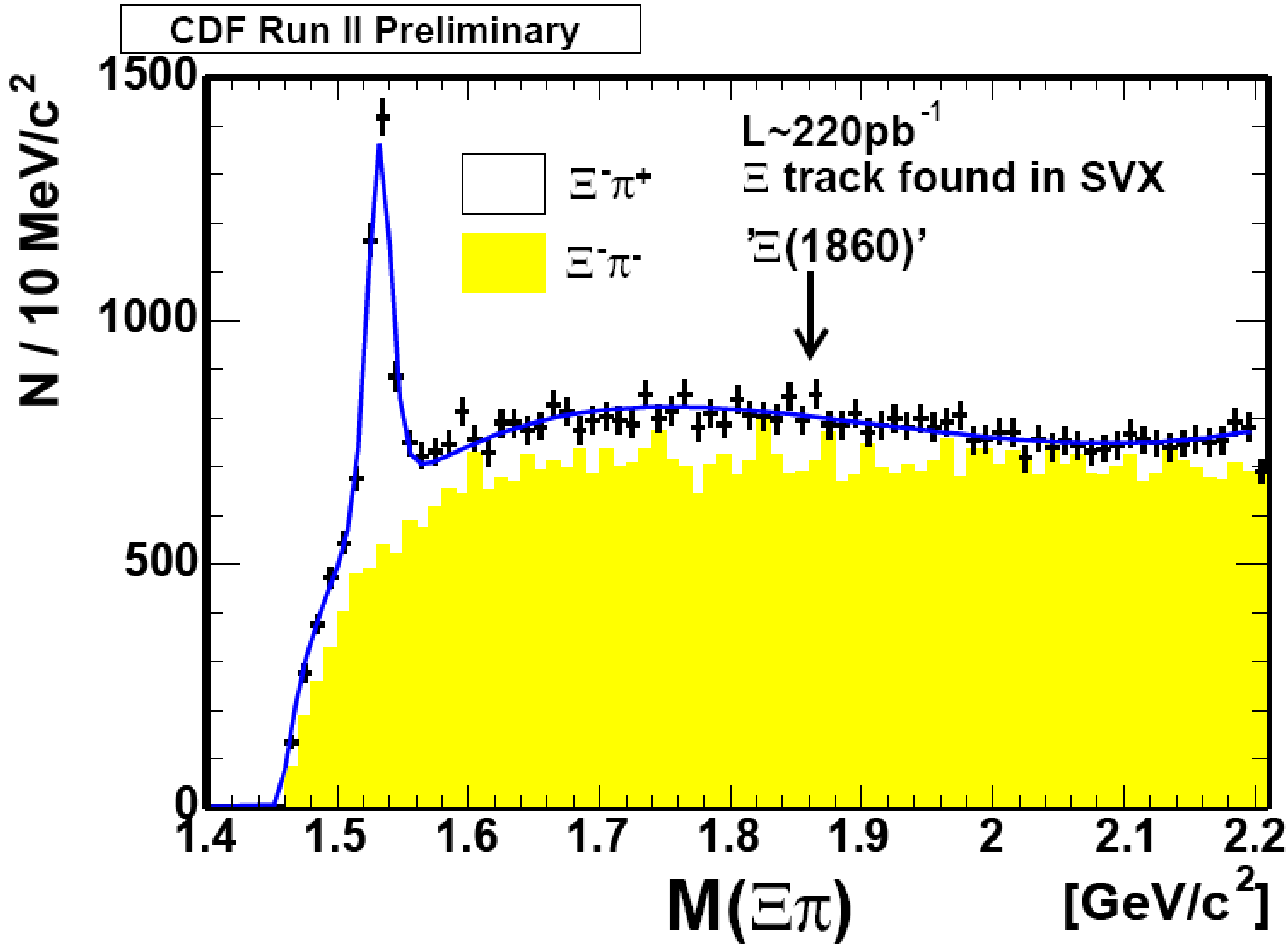
$$\frac{N_{\Xi(1862)^{--}}}{N_{\Xi(1530)^0}} < 0.07$$



CDF

Apr. 04

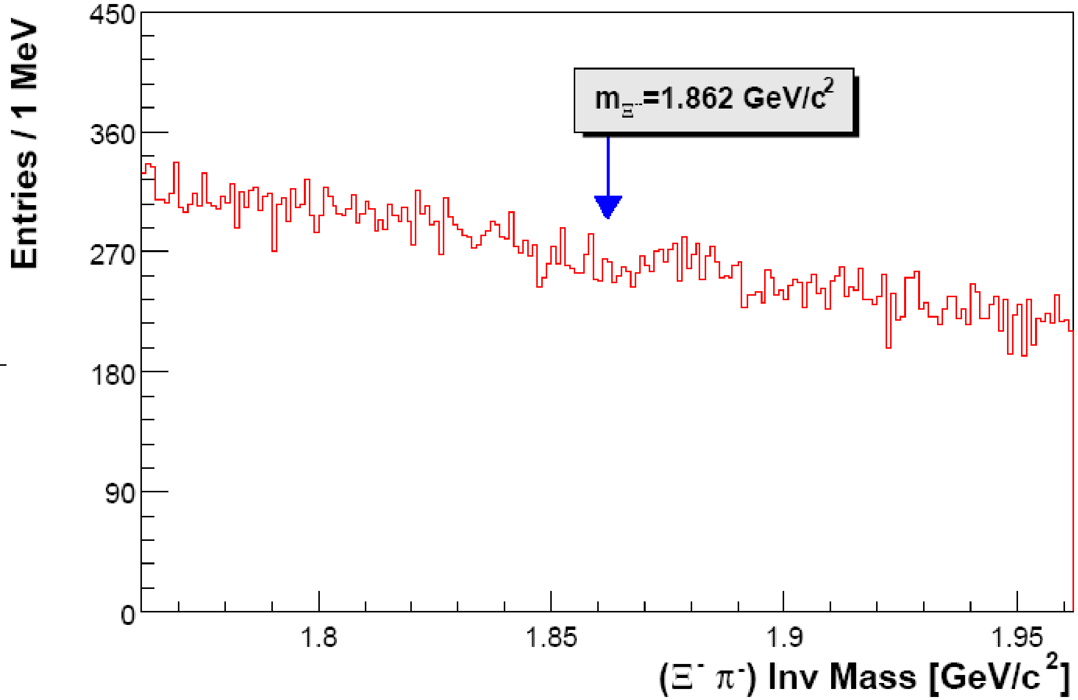
- Igor Goreloc, DIS04
- 19150 Ξ^-
- 18 × statistics of NA49

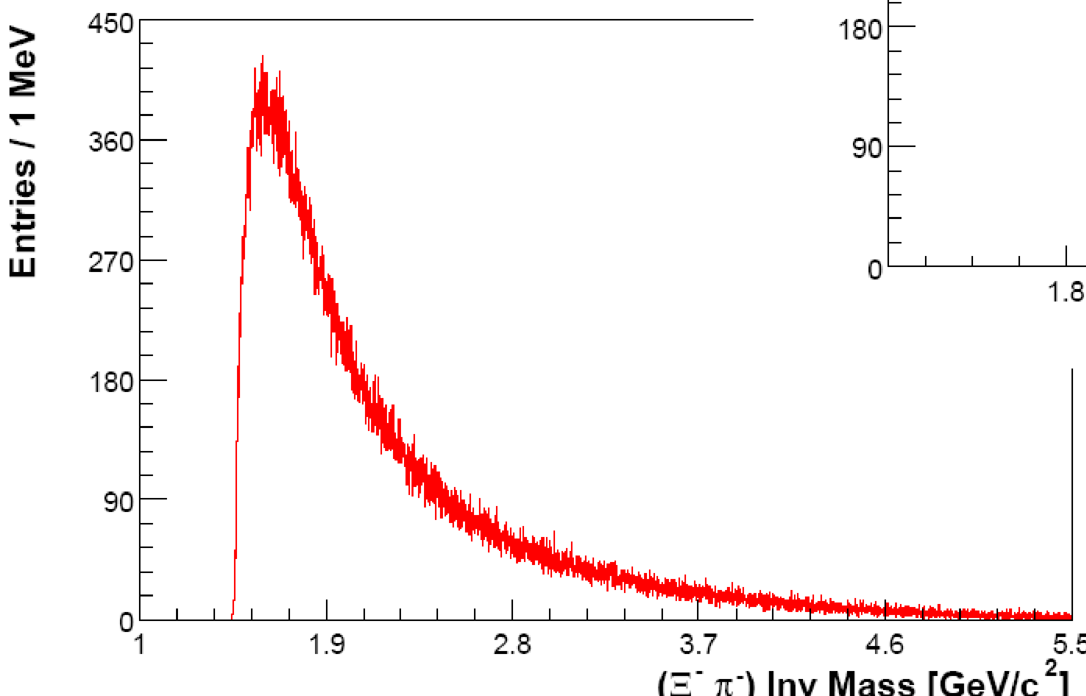


BABAR

Apr. 04

- V. Halyo, 2004 APS April meeting
- e^+e^-, sqrt(s)=10.58 GeV
- 258000 Ξ^-



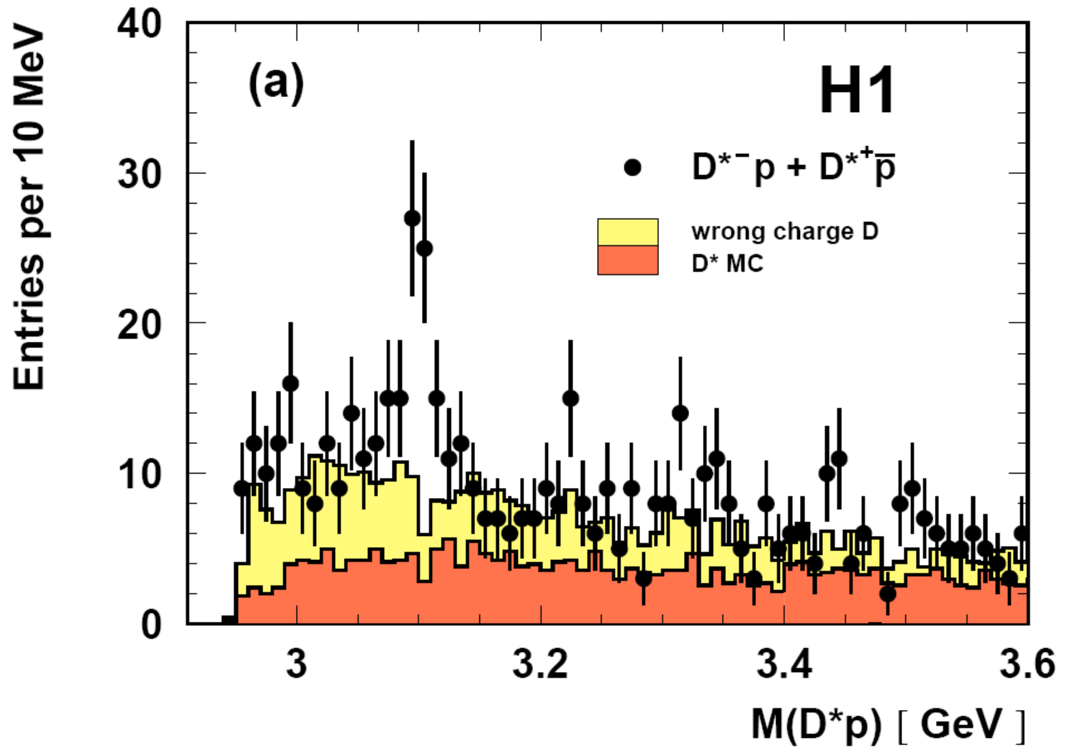


Summary of $X^{-}(1860)$

Experiment	number of Ξ⁻
e NA49	1640 (incl. bg)
J WA89	676000
J HERA-B	11000
J ZEUS	1361
J ALEPH	3350
J CDF	19150
J BABAR	258000

Last but not least…

- H1 collaboration, hep-ex/0403017
- predicted mass $M(\Theta_c)=2704 MeV/c^2$
  - Bin Wu & Bo-Qiang Ma, hep-ph/0402244



- not seen by ZEUS and CDF

Summary

	pro		*contra*
$\Theta^+(1530)$	12	:	8
$\Xi(1860)$	1	:	6
$\Theta_c(2704)$	1	:	2

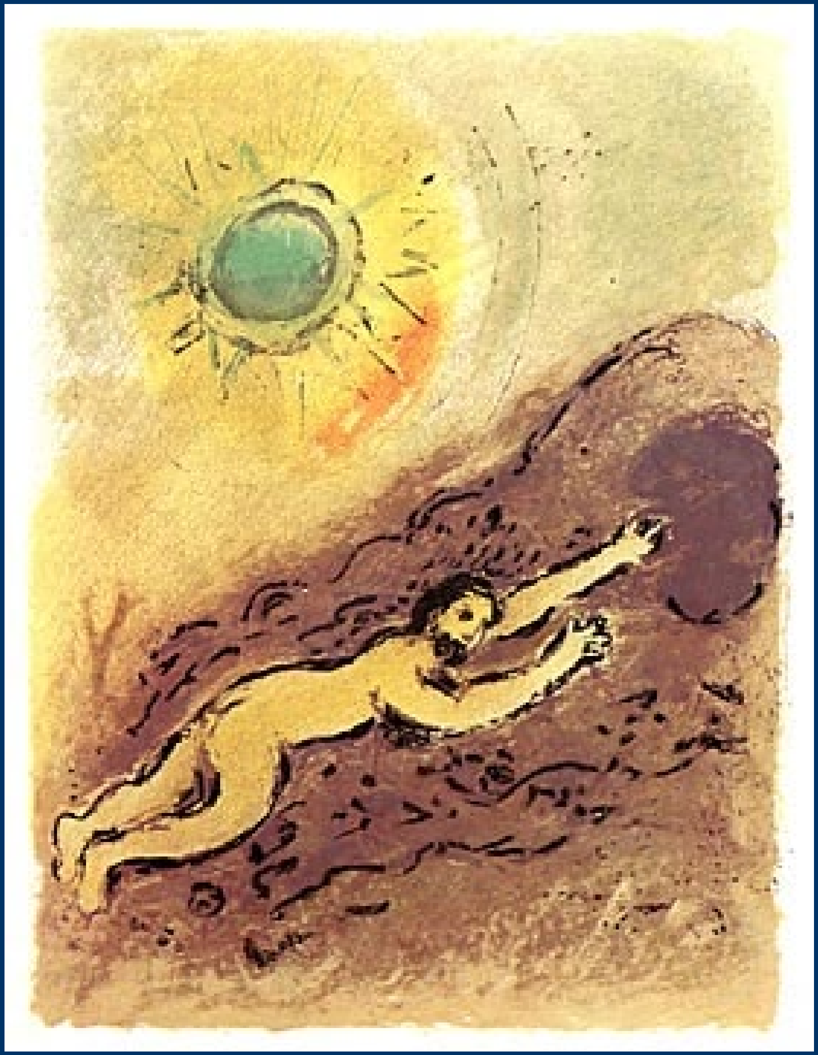
Quintessence

- On the experimental side…
  - The number of experiments, which have seen signatures of the $\Theta^+(1540)$ is quite impressive

  …but
  - So far only low statistics experiments have seen signals for pentaquarks
  - No experiment has seen both decay channels of the $\Theta^+(1540)$
  - Masses of the observed peaks are barely consistent
  - Consistency with KN scattering data not clear
  - All present high statistics searches for the observed structures have failed so far
  - It would be extremely surprising if the pentaquarks were only produced in specific reactions

- New experiments are scheduled to confirm the Θ^+ in reactions where they were seen before
  - Spring-8, JLAB, ELSA, COSY…
  - typical improvement: factor 10
  - …let's wait for the final result

The Myth of Sysiphus



"The struggle itself toward the heights is enough to fill a man's heart. One must imagine Sisyphus happy."

Albert Camus (1955)

Cargo Cult Science

- **Richard Feynman**

  From a Caltech commencement address given in 1974
  (Also in *Surely You're Joking, Mr. Feynman!)*

- *…the idea is to give all of the information to help others to judge the value of your contribution; not just the information that leads to judgement in one particular direction or another.*
- *The first principle is that you must not fool yourself--and you are the easiest person to fool. So you have to be very careful about that. After you've not fooled yourself, it's easy not to fool other scientists.*
- *If you've made up your mind to test a theory, or you want to explain some idea, you should always decide to publish it whichever way it comes out. If we only publish results of a certain kind, we can make the argument look good. We must publish BOTH kinds of results.*