UCRL-CONF-215167

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A Search for Pentaquarks

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N-Division LLNL

LANL P-25 Seminar
September 14, 2005

Physics & Advanced Technologies N Division

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Motivation

Recently observed hadrons that do not fit into the "normal" spectroscopic order should have been produced in old experiments. Are these claims supported by the legacy data?

Fermilab Experiment 690 collected a 5x10^9 event sample of $p+p \rightarrow p_f+X$ events at a beam momentum of 800 GeV/c ($\sqrt{s}$ = 38.8 GeV) at Lab G in the Neutrino-East beam line in the Tevatron 1991 fixed target run. The detector was an open geometry magnetic spectrometer with large geometric acceptance and extremely good momentum resolution.

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Evidence for S = +1 baryon reported by a SPring-8 experimental collaboration at the Laser-Electron Facility (LEPS).

VOLUME 91, NUMBER 1 PHYSICAL REVIEW LETTERS week ending 4 JULY 2003

Evidence for a Narrow $S = +1$ Baryon Resonance in Photoproduction from the Neutron

The $\gamma n \to K^+K^-n$ reaction on ^{12}C has been studied by measuring both K^+ and K^- at forward angles. A sharp baryon resonance peak was observed at 1.54 ± 0.01 GeV$/c^2$ with a width smaller than 25 MeV$/c^2$ and a Gaussian significance of 4.6σ. The strangeness quantum number (S) of the baryon resonance is $+1$. It can be interpreted as a molecular meson-baryon resonance or alternatively as an exotic five-quark state ($uudd\bar{s}$) that decays into a K^+ and a neutron. The resonance is consistent with the lowest member of an antidecuplet of baryons predicted by the chiral soliton model.

DOI: 10.1103/PhysRevLett.91.012002 PACS numbers: 13.60.Rj, 13.60.Le, 14.20.Jn

Figure 3(b) shows the corrected K^- missing-mass distribution of the signal sample. A prominent peak at 1.54 GeV$/c^2$ is found. It contains 36 events in the peak region $1.51 \leq MM^c_{\gamma K^-} < 1.57$ GeV$/c^2$. The broad background centered at $\sim$1.6 GeV$/c^2$ is most likely due to nonresonant K^+K^- production because the events in the bump do not show any noticeable structure in the K^+ missing-mass nor in the invariant K^+K^- mass spectra and the beam-energy dependence of the production rate reflects the phase space expansion with the energy. To

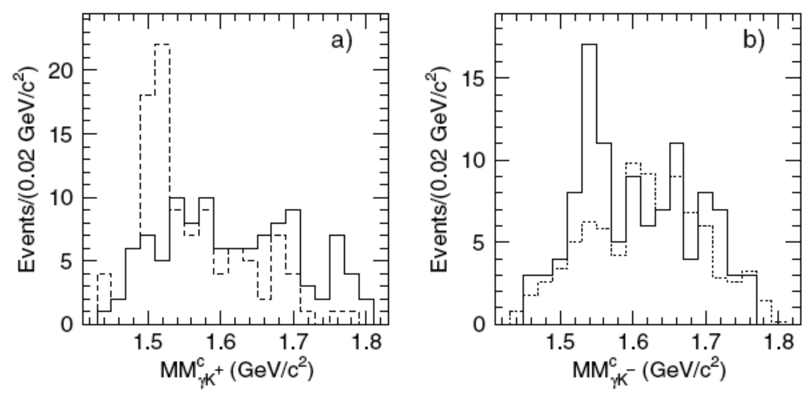

FIG. 3. (a) The $MM^c_{\gamma K^+}$ spectrum [Eq. (2)] for K^+K^- productions for the signal sample (solid histogram) and for events from the SC with a proton hit in the SSD (dashed histogram). (b) The $MM^c_{\gamma K^-}$ spectrum for the signal sample (solid histogram) and for events from the LH_2 (dotted histogram) normalized by a fit in the region above 1.59 GeV$/c^2$.

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CLAS Collaboration / Phys. Rev. Lett. 91,.252001 (2003)

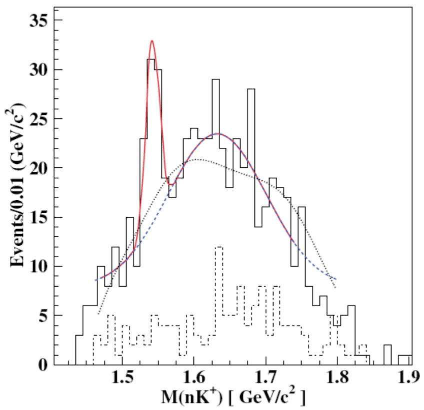

FIG. 4 (color). Invariant mass of the nK^+ system, which has strangeness $S = +1$, showing a sharp peak at the mass of 1.542 GeV/c^2. A fit (solid line) to the peak on top of the smooth background (dashed line) gives a statistical significance of 5.8σ. The dotted curve is the shape of the simulated background. The dash-dotted histogram shows the spectrum of events associated with $\Lambda(1520)$ production.

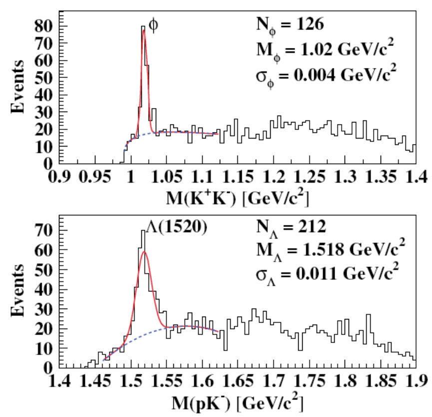

FIG. 3 (color). Invariant mass of the K^+K^- system (top) and the pK^- system (bottom) showing peaks at the mass of known resonances. These resonances are removed in the analysis by placing cuts on the peaks shown. Results for the number of counts (N), the mass (M), and the widths (σ) from fits are also given.

$\gamma d \to K^+K^- p\, n$

DIANA Colaboration/ Phys. At. Nucl. 66, 1715 (2003)

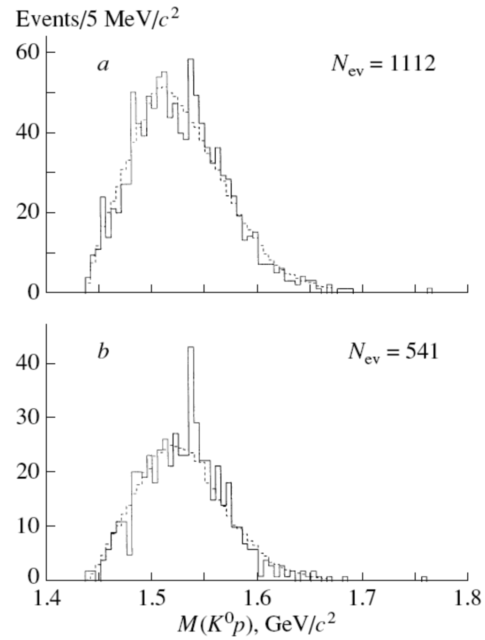

Fig. 4. Effective mass of the K^0p system formed in the reaction $K^+\text{Xe} \to K^0p\text{Xe}'$: ($a$) for all measured events, (b) for events that pass additional selections aimed at suppressing proton and K^0 reinteractions in nuclear matter (see text). The fit to the expected functional form is depicted by the dashed line.

$K^+Xe \to K^0 p\, Xe'$

SAPHIR Collaboration / Physics Letters B 572 (2003) 127–132

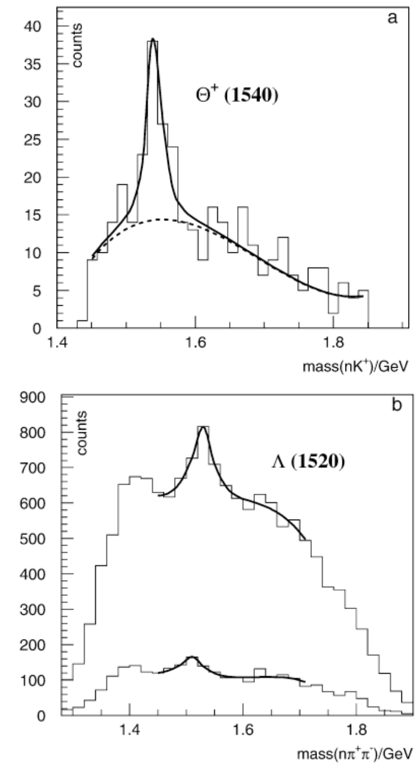

Fig. 2. (a) The nK^+ mass distribution after cuts in the $\pi^+\pi^-$ mass distribution and in the K_s^0 production angle. (b) The nK_s^0 invariant mass distribution showing the $\Lambda(1520)$ without (upper curve) and with (lower curve) $\cos\vartheta_{K_s^0}$ cut. The solid lines represent fits using a Breit–Wigner distribution (convoluted with a resolution function) plus polynomial background.

$\gamma p \to n K_s^0 K^+$

SPring-8 results seemed to be confirmed by several experiments

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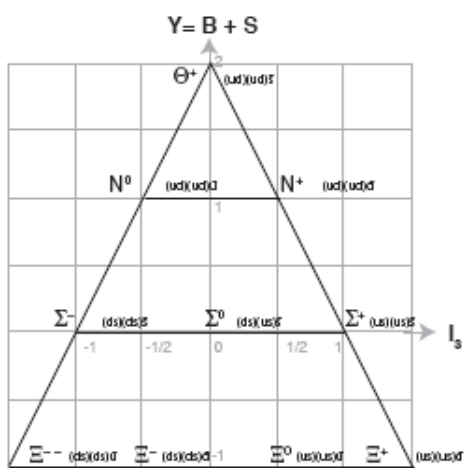
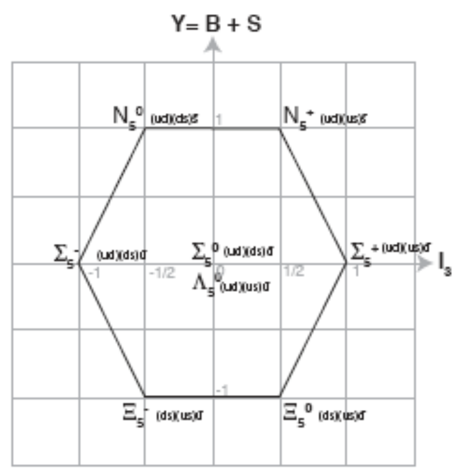
Is this object a Pentaquark?

Expect a new set of particles with quantum numbers different from the nominal *qqq* baryon spectrum.

Given the SPring-8 result and the confirmation, the *nK*⁺ state could be the *Θ*⁺.

Are any of the other members of the multiplets seen?





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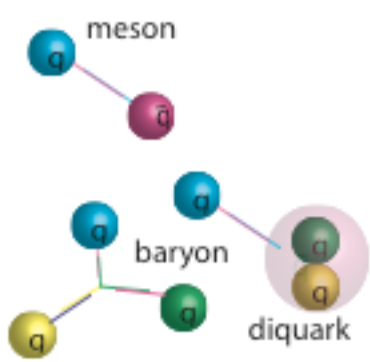
What are Pentaquarks? Start with Diquarks:

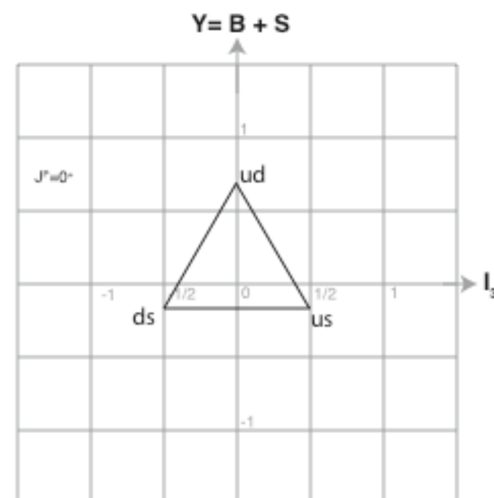
Miyazawa (1966) recognized there existed an approximate symmetry between mesons and baryons built out of quarks.

Consider the combinations of two quarks, *qq*: $3 \otimes 3 = \bar{3} \otimes 6$
This combination produces an anti-triplet and a sextet. Miyazawa observed that if you applied a super-symmetry operator to the anti-quark in a meson, it changed into a baryon:

( $\bar{q}$)*q* = *qqq*



Catto and Gürsey (1985) extended this argument, and explored some of its implications within the context of QCD. They recognized this supersymmetry as an approximate consequence of QCD…
…that is, the color interaction of an anti-quark is approximately the same as a diquark (!).



Approximate symmetry?

Diquarks are:

- heavier then anti-quarks
- bosons rather then fermions
- larger then anti-quarks

QCD interactions have dependencies for mass, spin and size.

Take a $\bar{K} = | s\bar{u} >$ and apply the symmetry $| s(\bar{u} \rightarrow ud) >$ then $| sud > = \Lambda$

m_K = 495 MeV/c^2 m_Λ = 1116 MeV/c^2
m_s = 475 MeV/c^2 m_q = 300 MeV/c^2

So $m_\Lambda - (m_K + m_q)$ = 321 MeV/c^2

This additional mass indicates the amount of symmetry breaking. Baryons always seem to have a larger mass then the mesons with this transformation.

Pentaquarks

So following this train of thought, might there be hadron configurations of multiple diquarks… there are anti-baryons: $\bar{q}\,\bar{q}\,\bar{q}$, could two of the anti-quarks be replaced by diquarks? $[qq]\,[qq]\,\bar{q}$ to make a 5 quark system, the *pentaquark*

$[qq]_0$ $J^P=0^+$ $\bar{3}_F$ $\bar{3}_C$

	$[qq]_0$		$[qq]_0$				$\bar{q}$	
Flavor	$\bar{3}$	$\otimes$	$\bar{3}$	$\rightarrow$	$\bar{6}_{sym}$	$\otimes$	$\bar{3} \rightarrow$	$\overline{10} \oplus 8$
Color	$\bar{3}$	$\otimes$	$\bar{3}$	$\rightarrow$	$3_{antisym}$	$\otimes$	$\bar{3} \rightarrow$	1
Spin	0^+	$\otimes$	0^+	$\rightarrow$	0^+	$\otimes$	$1/2^-$	
							$\rightarrow$	$(1/2, 3/2)^+$
Space		P					S	

Mass? Take a $\bar{\Lambda} = |\,\bar{s}\,\bar{u}\,\bar{d}>$ and make it a $|\,\bar{s}\,ud\,ud>$ pentaquark, the mass should be $M \geq m_\Lambda + 2\,m_q = 1116 + 300 + 300 = 1716$ MeV/c^2
Resonance width? Nothing prevents quark rearrangement, expected to be broad…

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Additional experimental results find evidence for two other anti-decuplet members and their anti-particles.

NA-49 Collaboration / Phys. Rev. Lett. 92, 042003 (2004)

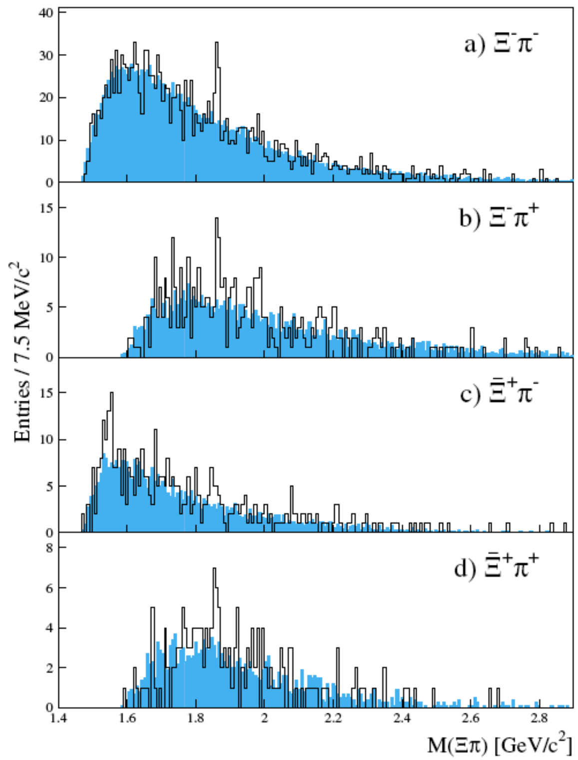

FIG. 2 (color online). Invariant mass spectra after selection cuts for $\Xi^-\pi^-$ (a), $\Xi^-\pi^+$ (b), $\overline{\Xi}^+\pi^-$ (note that the $\overline{\Xi}(1530)^\circ$ state is also visible) (c), and $\overline{\Xi}^+\pi^+$ (d). The shaded histograms are the normalized mixed-event backgrounds.

$$pp \rightarrow \Xi\pi + X$$

In summary, this analysis provides the first evidence for the existence of a narrow baryon resonance in the $\Xi^-\pi^-$ invariant mass spectrum with a mass of 1.862 ± 0.002 GeV/c^2 and a width below the detector resolution of about 0.018 GeV/c^2. The significance is estimated to be above 4.2σ. This state is a candidate for the exotic $\Xi_{3/2}^{--}$ baryon with $S = -2$, $I = \frac{3}{2}$, and a quark content of $(dsds\bar{u})$. Further, in the $\Xi^-\pi^+$ invariant mass spectrum at the same mass an indication is observed of the $\Xi_{3/2}^0$ member of this isospin quartet with a quark content of $(dsus\bar{d})$. Also, the corresponding antiparticle spectra show enhancements at the same invariant mass. Summing the four mass distributions increases the significance of the peak to 5.8σ.

The evidence for an exotic $\Xi^-\pi^-$ resonance together with the indication of a $\Xi^-\pi^+$ resonance at the same mass represents an important step towards experimental confirmation of the predicted baryon antidecuplet of pentaquark states. Definitive identification and exclusion of alternative interpretations require the determination of spin, parity, and isospin of the observed states.

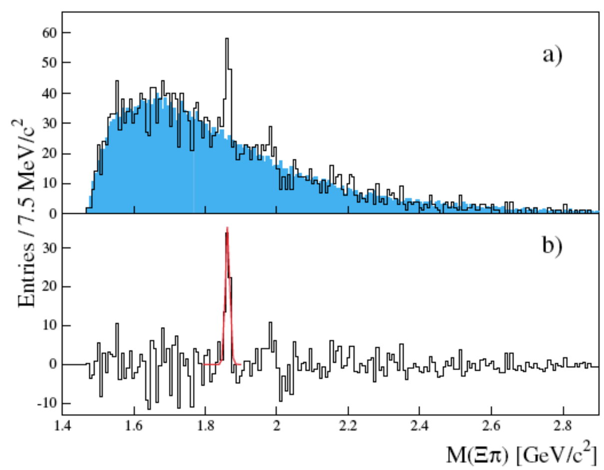

FIG. 3 (color online). (a) The sum of the $\Xi^-\pi^-$, $\Xi^-\pi^+$, $\overline{\Xi}^+\pi^-$, and $\overline{\Xi}^+\pi^+$ invariant mass spectra. The shaded histogram shows the normalized mixed-event background. (b) Background subtracted spectrum with the Gaussian fit to the peak.

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The "Normal" Hadron Spectroscopic Order

What we learned on our mother's knee –
The SU(3) flavor multiplets are built out of combinations of the quarks:

$q\bar{q}$	$3 \otimes \bar{3} = 1 \oplus 8$	singlet and octet
qqq	$3 \otimes 3 \otimes 3 = 1 \oplus 8 \oplus 8 \oplus 10$	singlet, octet and decuplet

Which explains the observed spectrum of hadrons.
Can we understand this from Quantum Chromo-Dynamics (QCD)?

No reliable calculations of the hadron spectrum from QCD.
No conclusive explanation for the observed flavor multiplets.

***Observations** define the spectroscopy and guide theory.*

$qqqqqq$	(dibaryon)	no conclusive candidates
$qq\bar{q}\bar{q}$		no conclusive candidates
$qqqg$	(exotic)	no conclusive candidates
$q\bar{q}g$	(exotic)	no conclusive candidates
gg	(glueball)	no conclusive candidates

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Status as reported in the 2002 edition of the Review of Particle Properties

Table 13.2: Suggested $q\bar{q}$ quark-model assignments for most of the known mesons. Some assignments, especially for the 0^{++} multiplet and for some of the higher multiplets, are controversial. Mesons in bold face are included in the Meson Summary Table. Of the light mesons in the Summary Table, the $f_0(1500)$, $f_1(1510)$, $f_2(1950)$, $f_2(2300)$, $f_2(2340)$, and one of the two peaks in the $\eta(1440)$ entry are not in this table. Within the $q\bar{q}$ model, it is especially hard to find a place for the first two of these f mesons and for one of the $\eta(1440)$ peaks. See the "Note on Non-$q\bar{q}$ Mesons" at the end of the Meson Listings.

$N\ ^{2S+1}L_J$	J^{PC}	$u\bar{d}$, $u\bar{u}$, $d\bar{d}$ $I=1$	$u\bar{u}$, $d\bar{d}$, $s\bar{s}$ $I=0$	$c\bar{c}$ $I=0$	$b\bar{b}$ $I=0$	$\bar{s}u$, $\bar{s}d$ $I=1/2$	$c\bar{u}$, $c\bar{d}$ $I=1/2$	$c\bar{s}$ $I=0$	$\bar{b}u$, $\bar{b}d$ $I=1/2$	$\bar{b}s$ $I=0$	$\bar{b}c$ $I=0$
$1\ ^1S_0$	0^{-+}	**π**	**η, η'**	**η_c**		**K**	**D**	**D_s**	**B**	**B_s**	**B_c**
$1\ ^3S_1$	1^{--}	**ρ**	**ω, ϕ**	**$J/\psi(1S)$**	**$\Upsilon(1S)$**	**$K^*(892)$**	**$D^*(2010)$**	**D_s^***	**B^***	B_s^*	
$1\ ^1P_1$	1^{+-}	**$b_1(1235)$**	**$h_1(1170)$**, $h_1(1380)$	$h_c(1P)$		**K_{1B}**†	**$D_1(2420)$**	**$D_{s1}(2536)$**			
$1\ ^3P_0$	0^{++}	**$a_0(1450)$***	**$f_0(1370)$***, **$f_0(1710)$***	**$\chi_{c0}(1P)$**	**$\chi_{b0}(1P)$**	**$K_0^*(1430)$**					
$1\ ^3P_1$	1^{++}	**$a_1(1260)$**	**$f_1(1285)$, $f_1(1420)$**	**$\chi_{c1}(1P)$**	**$\chi_{b1}(1P)$**	**K_{1A}**†					
$1\ ^3P_2$	2^{++}	**$a_2(1320)$**	**$f_2(1270)$, $f_2'(1525)$**	**$\chi_{c2}(1P)$**	**$\chi_{b2}(1P)$**	**$K_2^*(1430)$**	**$D_2^*(2460)$**				
$1\ ^1D_2$	2^{-+}	**$\pi_2(1670)$**	$\eta_2(1645)$, $\eta_2(1870)$			**$K_2(1770)$**					
$1\ ^3D_1$	1^{--}	**$\rho(1700)$**	**$\omega(1650)$**	**$\psi(3770)$**		**$K^*(1680)$**‡					
$1\ ^3D_2$	2^{--}					**$K_2(1820)$**					
$1\ ^3D_3$	3^{--}	**$\rho_3(1690)$**	**$\omega_3(1670)$, $\phi_3(1850)$**			**$K_3^*(1780)$**					
$1\ ^3F_4$	4^{++}	**$a_4(2040)$**	**$f_4(2050)$**, $f_4(2220)$			**$K_4^*(2045)$**					
$2\ ^1S_0$	0^{-+}	**$\pi(1300)$**	**$\eta(1295)$, $\eta(1440)$**	**$\eta_c(2S)$**		$K(1460)$					
$2\ ^3S_1$	1^{--}	**$\rho(1450)$**	**$\omega(1420)$, $\phi(1680)$**	**$\psi(2S)$**	**$\Upsilon(2S)$**	**$K^*(1410)$**‡					
$2\ ^3P_2$	2^{++}		$f_2(1810)$, **$f_2(2010)$**		**$\chi_{b2}(2P)$**	$K_2^*(1980)$					
$3\ ^1S_0$	0^{-+}	**$\pi(1800)$**	$\eta(1760)$			$K(1830)$					

* See our scalar minireview in the Particle Listings. The candidates for the $I=1$ states are $a_0(980)$ and $a_0(1450)$, while for $I=0$ they are: $f_0(400\text{–}1200)$, $f_0(980)$, $f_0(1370)$, and $f_0(1710)$. The light scalars are problematic, since there may be two poles for one $q\bar{q}$ state and $a_0(980)$, $f_0(980)$ may be $K\bar{K}$ bound states.

† The K_{1A} and K_{1B} are nearly equal (45°) mixes of the $K_1(1270)$ and $K_1(1400)$.

‡The $K^*(1410)$ could be replaced by the $K^*(1680)$ as the $2\ ^3S_1$ state.

Table 13.4: Quark-model assignments for many of the known baryons in terms of a flavor-spin SU(6) basis. Only the dominant representation is listed. Assignments for some states, especially for the $\Lambda(1810)$, $\Lambda(2350)$, $\Xi(1820)$, and $\Xi(2030)$, are merely educated guesses. For assignments of the charmed baryons, see the "Note on Charmed Baryons" in the Particle Listings.

J^P	(D, L_N^P)	S	Octet members				Singlets
$1/2^+$	$(56,0_0^+)$	1/2	$N(939)$	$\Lambda(1116)$	$\Sigma(1193)$	$\Xi(1318)$	
$1/2^+$	$(56,0_2^+)$	1/2	$N(1440)$	$\Lambda(1600)$	$\Sigma(1660)$	$\Xi(?)$	
$1/2^-$	$(70,1_1^-)$	1/2	$N(1535)$	$\Lambda(1670)$	$\Sigma(1620)$	$\Xi(?)$	$\Lambda(1405)$
$3/2^-$	$(70,1_1^-)$	1/2	$N(1520)$	$\Lambda(1690)$	$\Sigma(1670)$	$\Xi(1820)$	$\Lambda(1520)$
$1/2^-$	$(70,1_1^-)$	3/2	$N(1650)$	$\Lambda(1800)$	$\Sigma(1750)$	$\Xi(?)$	
$3/2^-$	$(70,1_1^-)$	3/2	$N(1700)$	$\Lambda(?)$	$\Sigma(?)$	$\Xi(?)$	
$5/2^-$	$(70,1_1^-)$	3/2	$N(1675)$	$\Lambda(1830)$	$\Sigma(1775)$	$\Xi(?)$	
$1/2^+$	$(70,0_2^+)$	1/2	$N(1710)$	$\Lambda(1810)$	$\Sigma(1880)$	$\Xi(?)$	$\Lambda(?)$
$3/2^+$	$(56,2_2^+)$	1/2	$N(1720)$	$\Lambda(1890)$	$\Sigma(?)$	$\Xi(?)$	
$5/2^+$	$(56,2_2^+)$	1/2	$N(1680)$	$\Lambda(1820)$	$\Sigma(1915)$	$\Xi(2030)$	
$7/2^-$	$(70,3_3^-)$	1/2	$N(2190)$	$\Lambda(?)$	$\Sigma(?)$	$\Xi(?)$	$\Lambda(2100)$
$9/2^-$	$(70,3_3^-)$	3/2	$N(2250)$	$\Lambda(?)$	$\Sigma(?)$	$\Xi(?)$	
$9/2^+$	$(56,4_4^+)$	1/2	$N(2220)$	$\Lambda(2350)$	$\Sigma(?)$	$\Xi(?)$	
			Decuplet members				
$3/2^+$	$(56,0_0^+)$	3/2	$\Delta(1232)$	$\Sigma(1385)$	$\Xi(1530)$	$\Omega(1672)$	
$1/2^-$	$(70,1_1^-)$	1/2	$\Delta(1620)$	$\Sigma(?)$	$\Xi(?)$	$\Omega(?)$	
$3/2^-$	$(70,1_1^-)$	1/2	$\Delta(1700)$	$\Sigma(?)$	$\Xi(?)$	$\Omega(?)$	
$5/2^+$	$(56,2_2^+)$	3/2	$\Delta(1905)$	$\Sigma(?)$	$\Xi(?)$	$\Omega(?)$	
$7/2^+$	$(56,2_2^+)$	3/2	$\Delta(1950)$	$\Sigma(2030)$	$\Xi(?)$	$\Omega(?)$	
$11/2^+$	$(56,4_4^+)$	3/2	$\Delta(2420)$	$\Sigma(?)$	$\Xi(?)$	$\Omega(?)$	

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A ghost from the past? The Roper Resonance…

N(1440), P_{11} $I(J^P)= 1/2(1/2^+)$

PHYSICAL REVIEW VOLUME 138, NUMBER 1B 12 APRIL 1965

Energy-Dependent Pion-Nucleon Phase-Shift Analysis*†

L. DAVID ROPER AND ROBERT M. WRIGHT
Lawrence Radiation Laboratory, University of California, Livermore, California
AND
BERNARD T. FELD
Physics Department and Laboratory for Nuclear Science, Massachusetts Institute of Technology, Cambridge, Massachusetts
(Received 23 November 1964)

The P_{11} resonance we find at about 585 MeV does not fit on any known Regge trajectory, nor does it fit into any established $SU(3)$ octet. It has the same

quantum numbers as the nucleon, but a higher mass (by around 565 MeV). We have made many efforts, with no success to date, to find a solution without a large P_{11} phase shift that adequately fits the data. Solutions have been obtained without a P_{11} resonance, but the fits are not as good as when the P_{11} resonates. Even in these solutions the P_{11} phase is large at 700 MeV (approximately 80°).

Review of Particle Properties
LBL-100 Revised
UC-34d
April 1982

(page 190)

<u>The P11 N(1440)</u>: Interest in this enigmatic resonance persists because two rather different theoretical approaches both predict that the M_{1-} multipole sign will change as Q^2 increases from zero. ..

Is it possible that the “enigmatic” nature of these baryon resonances comes from their membership in the pentaquark octet and anti-decuplet?

… also:
***N(1710)*, P_{11} $I(J^P)= 1/2(1/2^+)$**

Perhaps some of these old mysteries of baryon spectroscopy are resolved?

Evidence for 5 pentaquarks!

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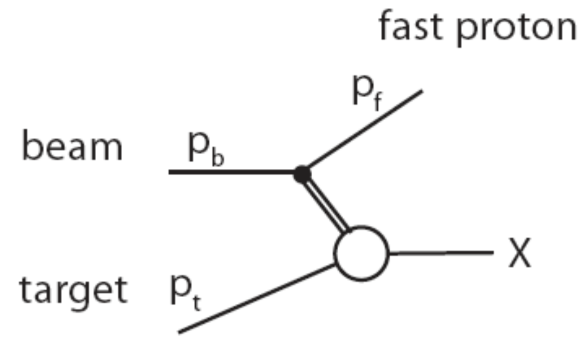
E690 should see these states!



Triggered on $p+p \rightarrow p_f + X$
Reconstructed the *X* with high efficiency.

Pentaquarks are hadrons, should be produced copiously in this process.

E690 has excellent mass resolution.
A large data set, 5×10^9 events.
Past analysis focused on light meson spectroscopy in partial wave analysis, hyperon polarization in exclusive states and diffractive charm production…

…no detailed search for exotic hyperon states was performed at the time. Hyperons were copiously produced, however…

OBSERVATION OF PENTAQUARKS SHOULD BE A SLAM DUNK!

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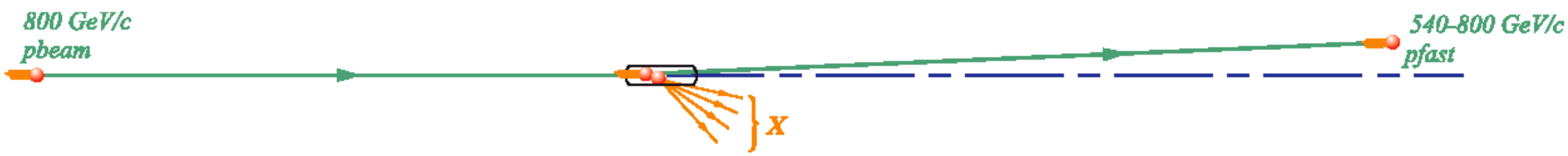
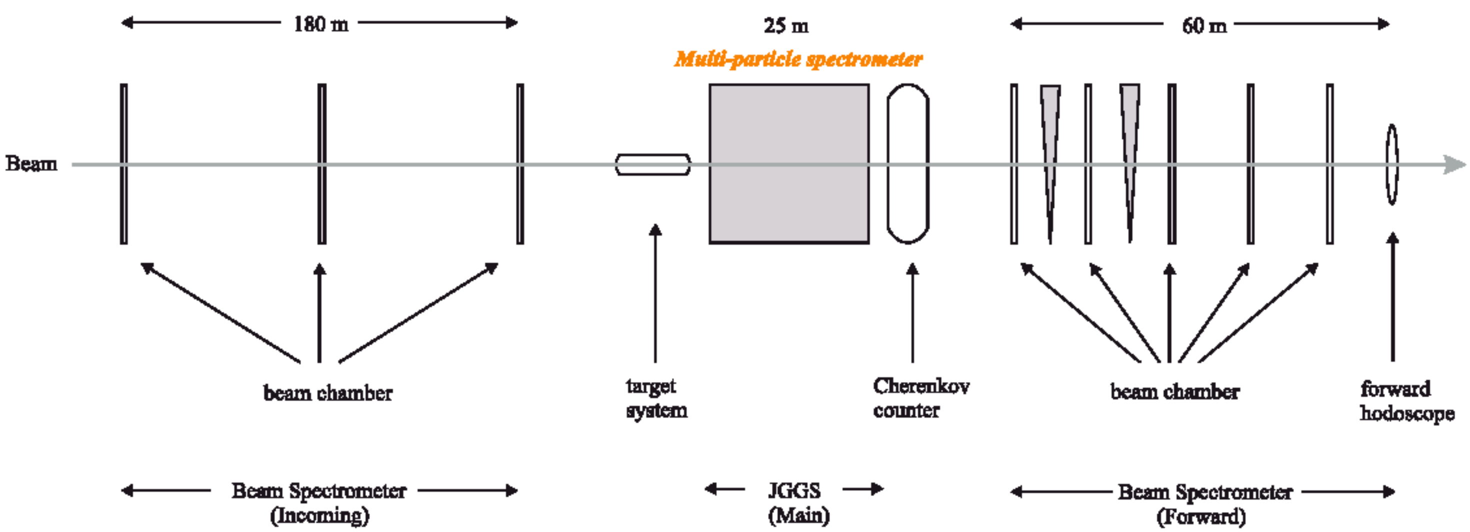
E690 apparatus





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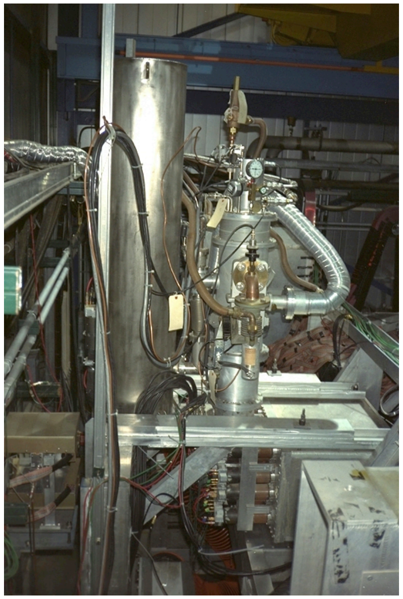
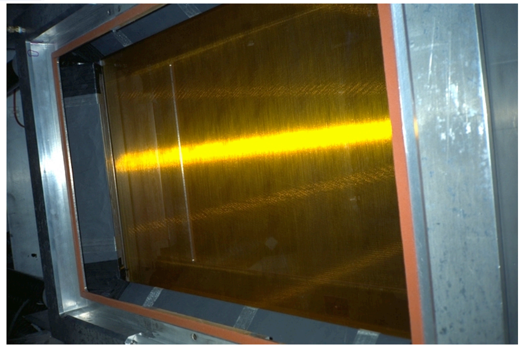
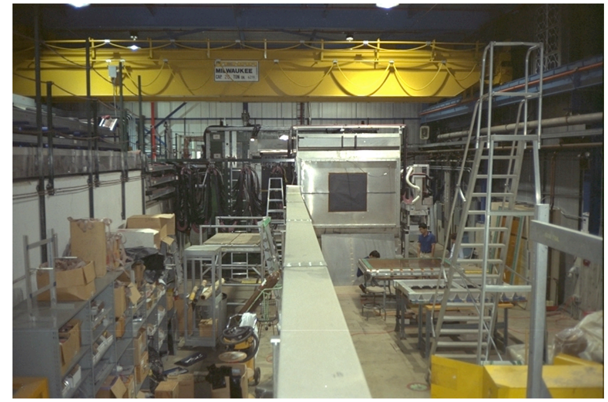
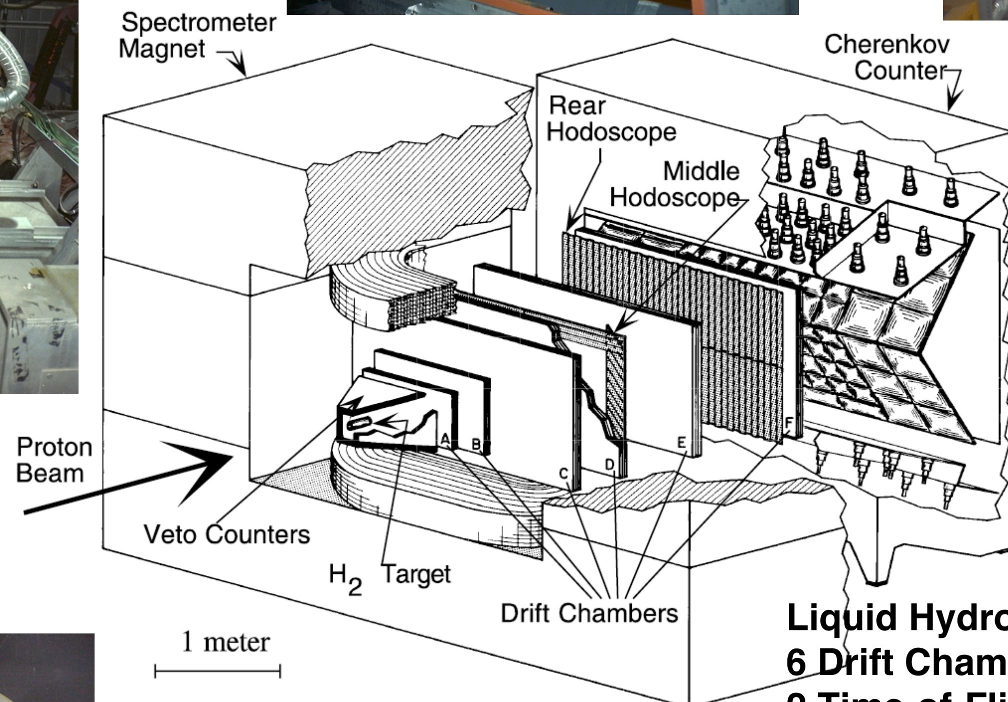
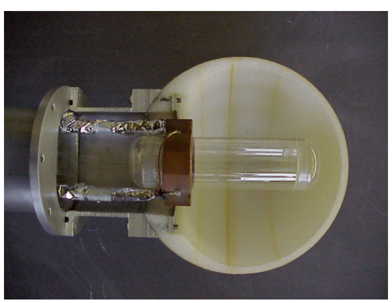
E690 apparatus











Liquid Hydrogen target
6 Drift Chambers
2 Time-of-Flight walls
96 mirror threshold Cerenkov counter
1T dipole field

Downstream beam spectrometer system

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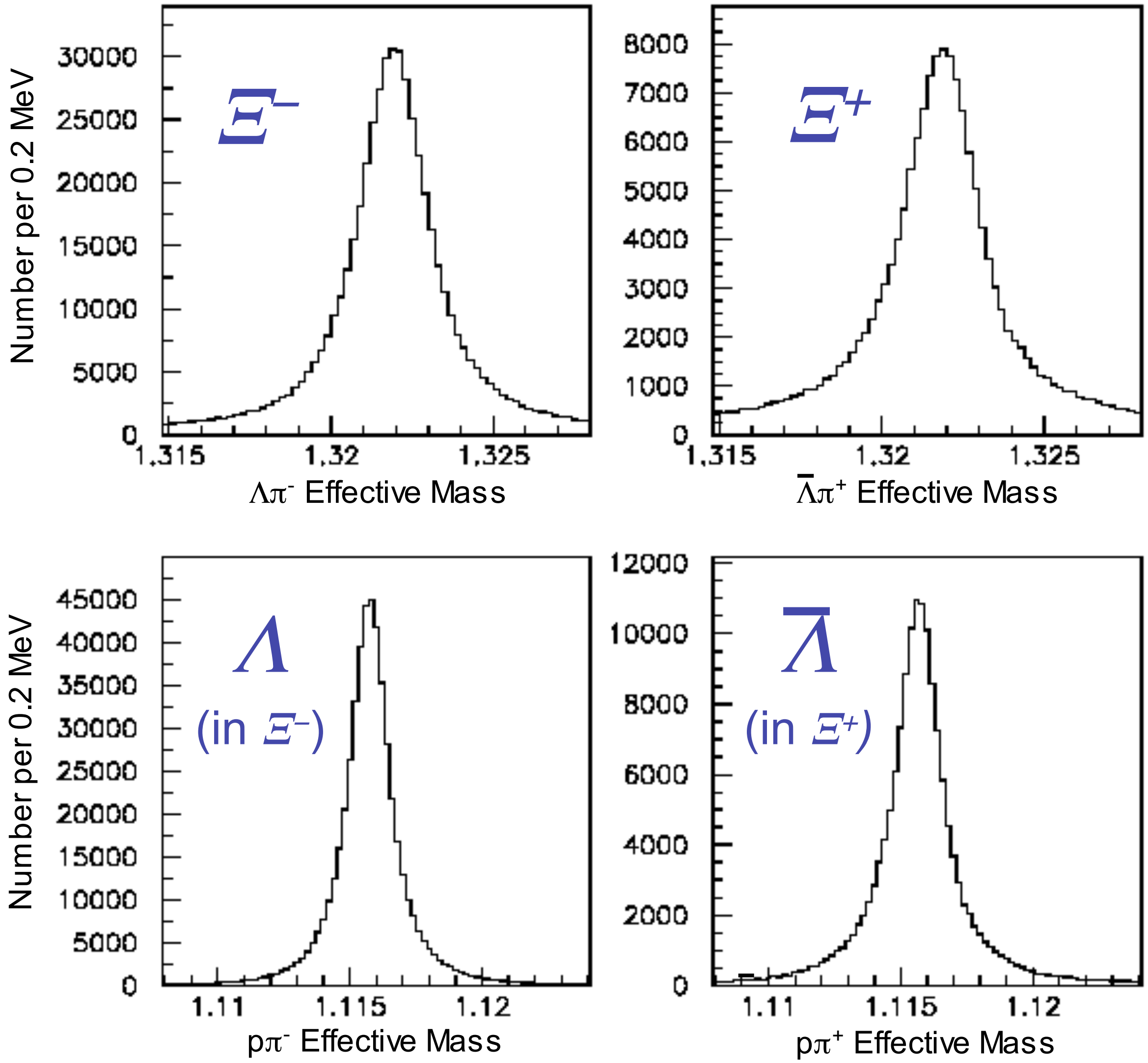
E690 performance



FWHM
~2.5 MeV

FWHM
~2 MeV

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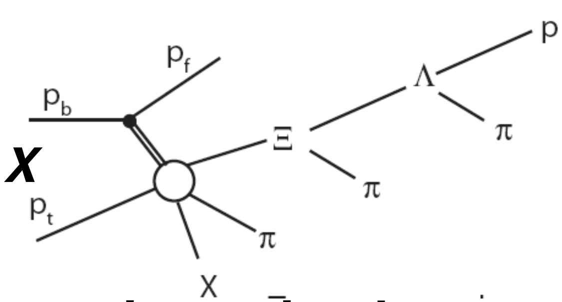
Hyperon inclusive search $pp \rightarrow p_f + \Xi\pi + X$



- **Primary vertex constrained to lie on incoming beam trajectory.**

- **In events with "Vee" or "Cascade" topology:**
  - **Tracks refit with geometrical constraint that daughter vertex must point back to parent (no mass constrained fits).**
  - **Topologies identified:**

    $\gamma \rightarrow e^+e^-$ $\quad K_s \rightarrow \pi^+\pi^-$ $\quad \Lambda \rightarrow p\pi^-$ $\quad \bar{\Lambda} \rightarrow \bar{p}\pi^+$ $\quad \Xi^- \rightarrow \Lambda\pi^-$

    $\bar{\Xi}^+ \rightarrow \bar{\Lambda}\pi^+$ $\quad \Omega^- \rightarrow \Lambda K^-$ $\quad \bar{\Omega}^+ \rightarrow \bar{\Lambda} K^+$ $\quad K^+ \rightarrow \pi^+\pi^+\pi^-$ $\quad K^- \rightarrow \pi^-\pi^-\pi^+$

- **Events selected with Ξ^- or $\bar{\Xi}^+$ assigned to primary vertex.**
  - **512,850 Ξ^- events selected.**
  - **153,671 $\bar{\Xi}^+$ events selected.**

- **Average number of mass combinations per event:**

  $\Xi^-\pi^+$: 3.5 $\quad \Xi^-\pi^-$: 2.0 $\quad \bar{\Xi}^+\pi^+$: 2.7 $\quad \bar{\Xi}^+\pi^-$: 2.6

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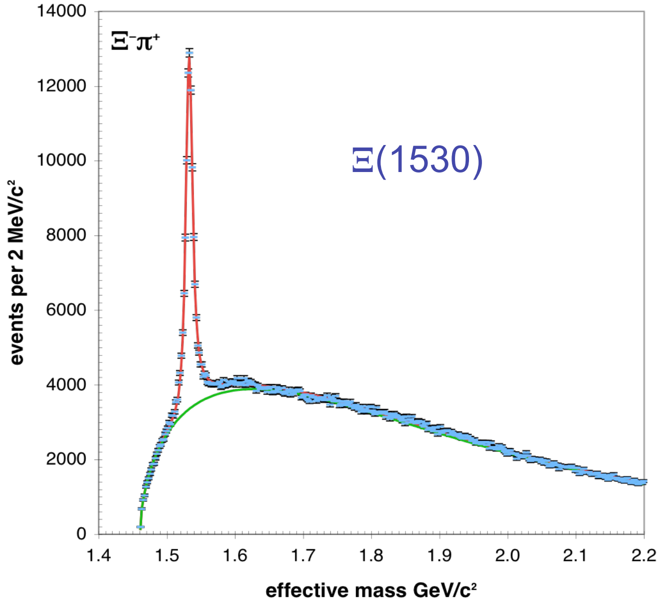
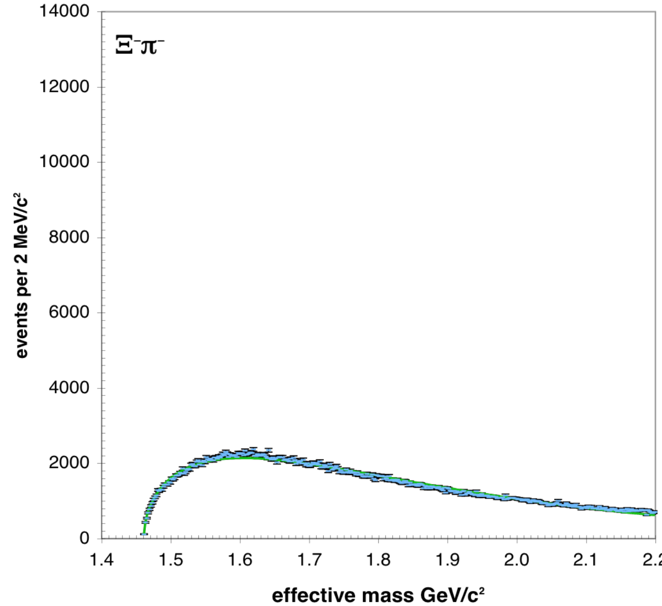
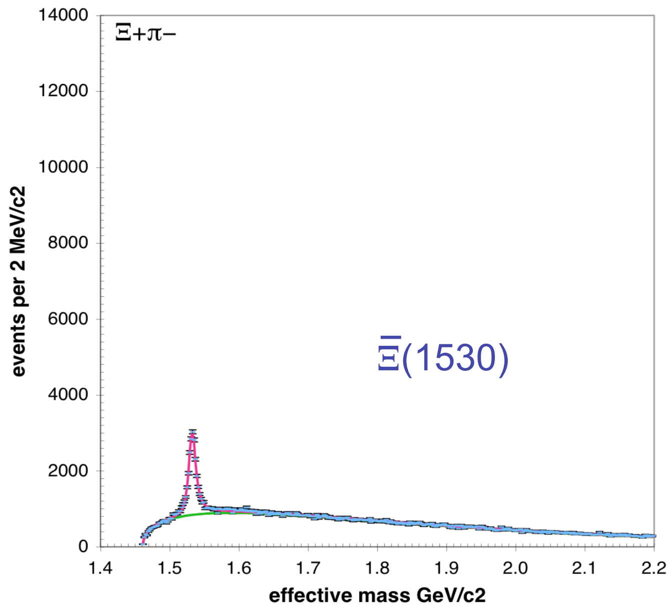
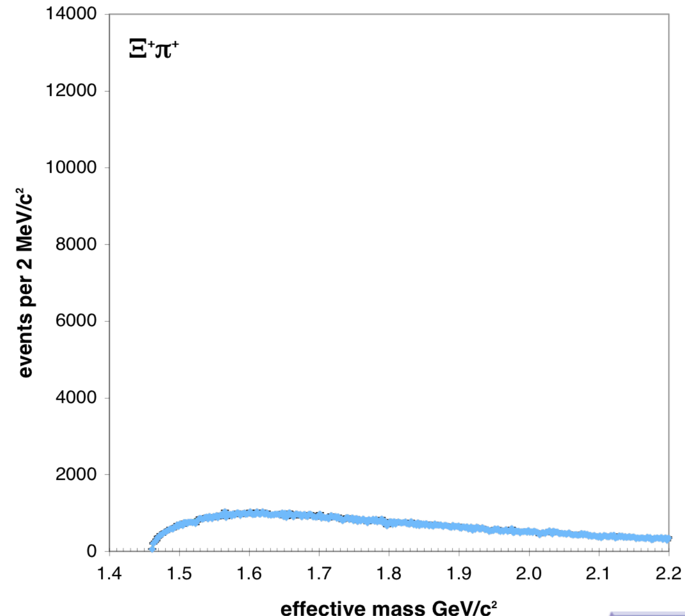
E690 Pentaquark search $\Xi\pi$









Monte Carlo mass resolution (σ) for $\Xi\pi$:
3.3 MeV at 1750 MeV;
4.5 MeV at 1862 MeV.

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Fit to a simple background and a relativistic Breit-Wigner (with mass dependent width):

$$f(x) = P_1(x - m_{th})^{P_2} e^{-P_3(m - m_{th})} + P_4 \frac{\Gamma(x)}{(x^2 - P_6^2)^2 + P_6^2\Gamma^2(x)}$$

$$\Gamma(x) = P_5\left(\frac{q(x)}{q_0}\right)^{2L+1}$$

$$q(x) = \frac{x}{2}\sqrt{\left[1 - \left(\frac{m_1 - m_2}{x}\right)^2\right]\left[1 - \left(\frac{m_1 + m_2}{x}\right)^2\right]}$$

$$q_0 = q(P_6)$$

Gaussian smear the distributions with mass resolution σ = 2.5 MeV/c^2 to reproduce *Ξ(1530)* width Γ_0 = 9 MeV/c^2
Also take L=1…

	$\Xi^-\pi^+$	$\Xi^-\pi^-$	$\Xi^+\pi^-$	$\Xi^+\pi^+$
P1	$(1.773\pm0.002)\times10^4$	$(0.919\pm0.001)\times10^4$	$(0.322\pm0.007)\times10^4$	$(0.405\pm0.008)\times10^4$
P2	0.5421±0.0006	0.4949±0.0008	0.4208±0.0001	0.5001±0.0001
P3	3.266±0.003	3.445±0.007	3.256±0.006	3.242±0.005
P4	244.1±1.1		57.6±0.6	
P5	0.00896±0.00006		0.00941±0.00001	
P6	1.53273±0.00003		1.53265±0.00006	
χ^2/dof	683/364	1029/367	443/364	462/367
Ξ(1530) Number	93728±422		22211±219	
95% CL at 1862 MeV/c^2				
Gaussian (σ =7.6 MeV/c^2)	1020	310	290	288

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Calculating the Confidence Limit

The fits are performed minimizing the χ^2:

$$\chi^2 = \sum_i \left(\frac{d_i - f_i}{e_i} \right)^2$$

Where d_i is the data with error e_i, and f_i is the fit function for the $i=1,N$ bins of the invariant mass distribution. If we have a signal, *e.g.*:

$$s_i = n_0 \frac{e^{-(m_i - m_0)^2 / 2\sigma^2}}{\sqrt{2\pi\sigma}} \equiv n_0 g_i$$

We can calculate the CL at some level, *e.g.* 95%, that for a given m_0 and σ the number of events does not exceed n_0.

The "new" χ^2 is given by:

$$\chi^2 = \sum_i \left(\frac{d_i - f_i - s_i}{e_i} \right)^2$$

And differs from the $n_0 = 0$ χ^2 by:

$$\Delta\chi^2 = n_0^2 \sum_i \frac{g_i^2}{e_i^2} - 2n_0 \sum_i \frac{(d_i - f_i) g_i}{e_i^2}$$

This is quadratic in n_0 leading to the CL value:

$$n_0 = \frac{\sum \frac{(d_i - f_i) g_i}{e_i^2} + \sqrt{\left(\sum \frac{(d_i - f_i) g_i}{e_i^2} \right)^2 + \Delta\chi^2 \sum \frac{g_i^2}{e_i^2}}}{\sum \frac{g_i^2}{e_i^2}}$$

For a 95% CL, $\Delta\chi^2 = 3.84$.
This is essentially the prescription of Feldman & Cousins

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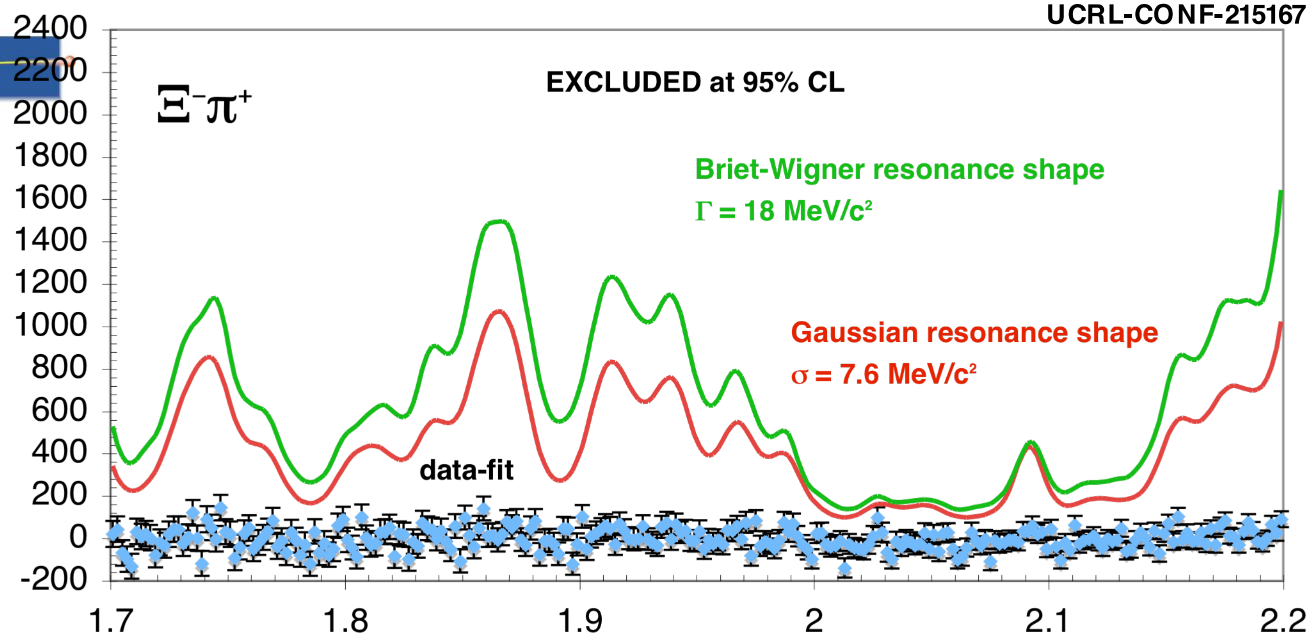
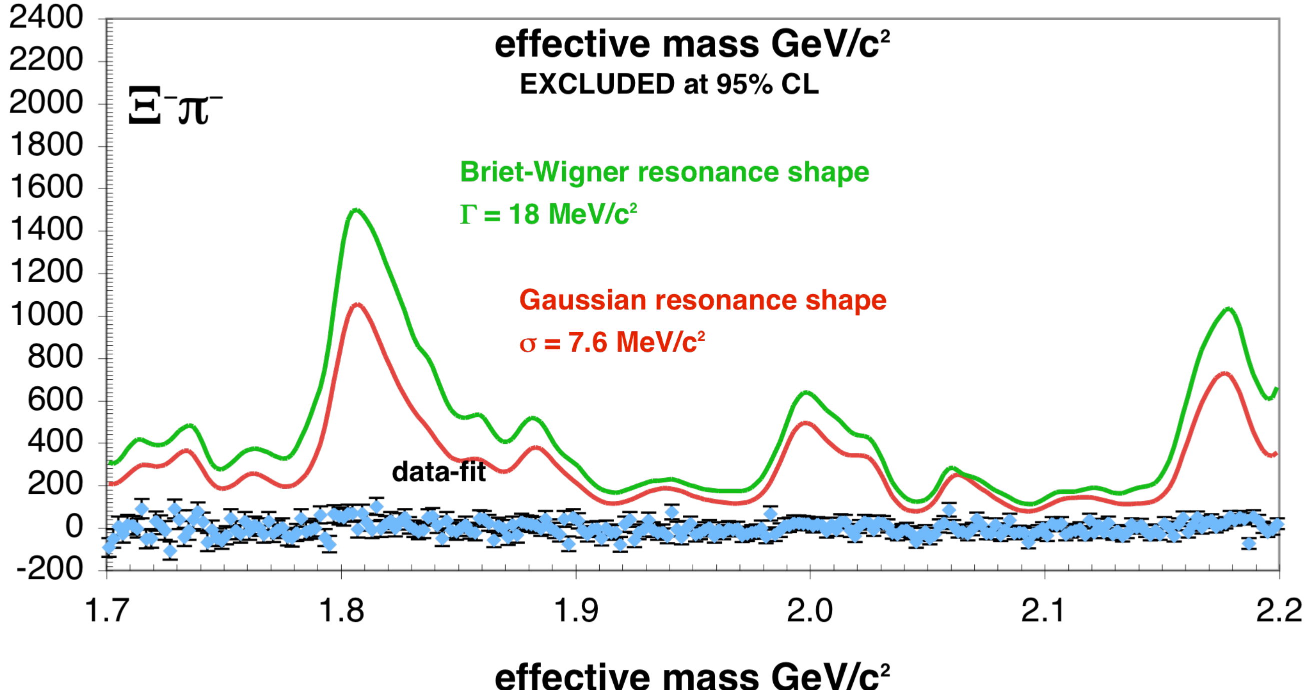
95% CL limit < 1020 events at M= 1.862 GeV

N $_{\Xi-(1530)}$ = 94000



95% CL limit < 310 events at M= 1.862 GeV



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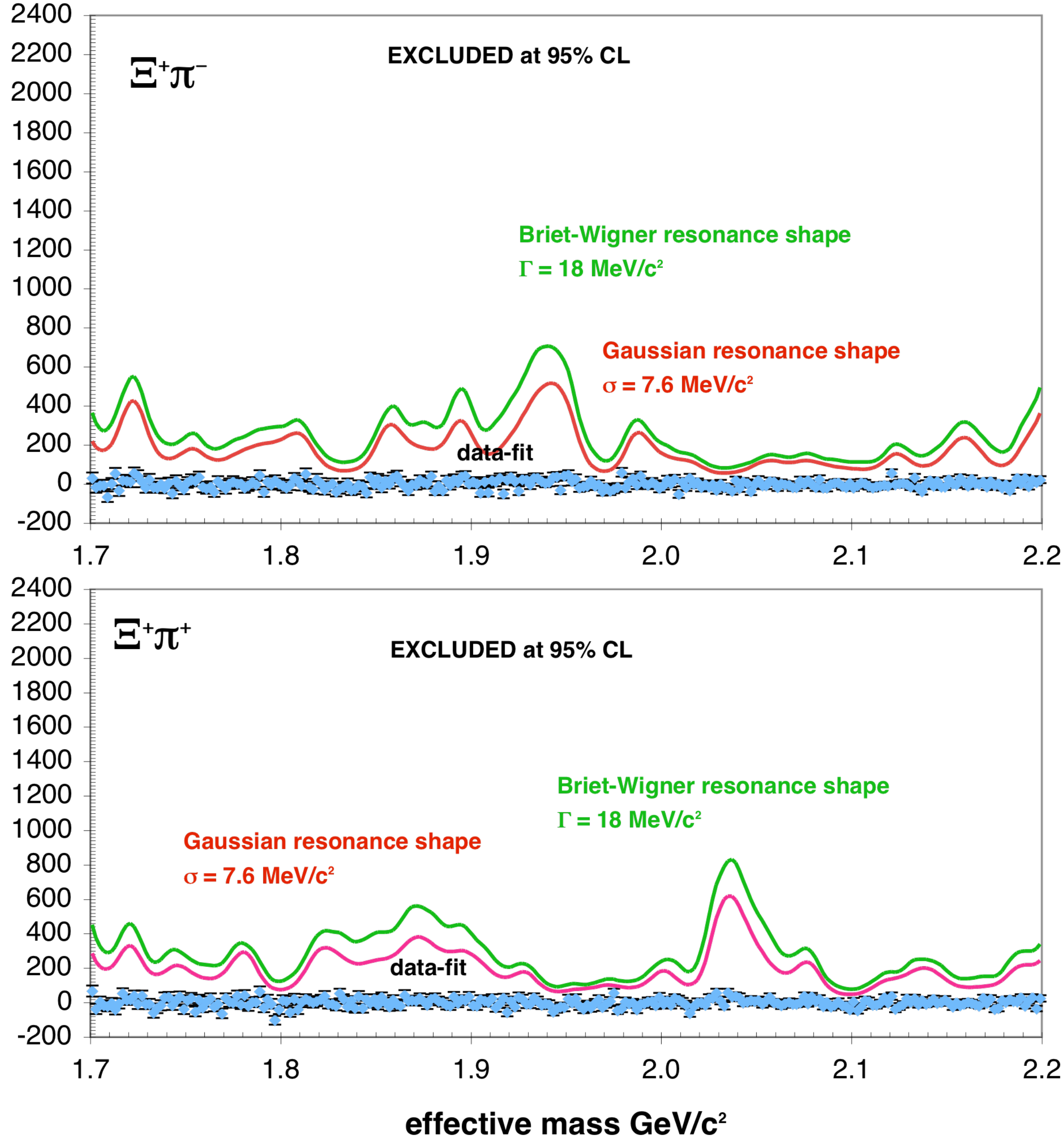
95% CL limit < 290 events at M= 1.862 GeV

N $_{\Xi+(1530)}$ = 22000

95% CL limit < 288 events at M= 1.862 GeV



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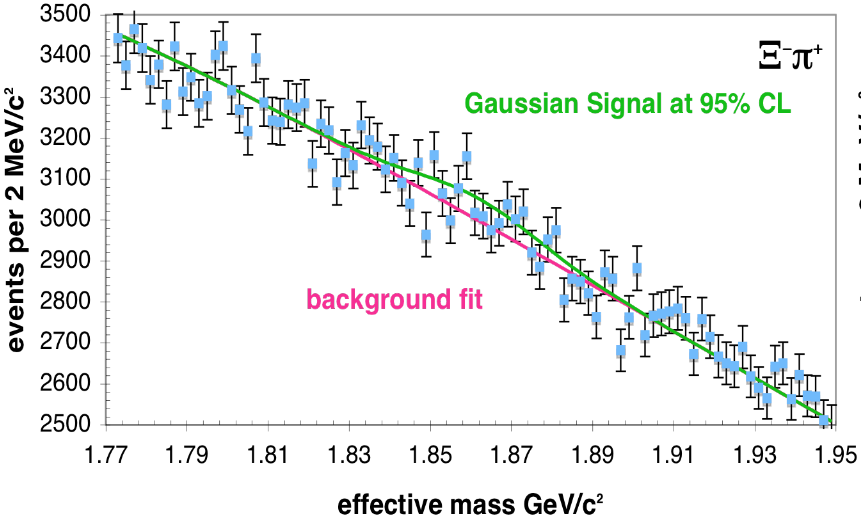
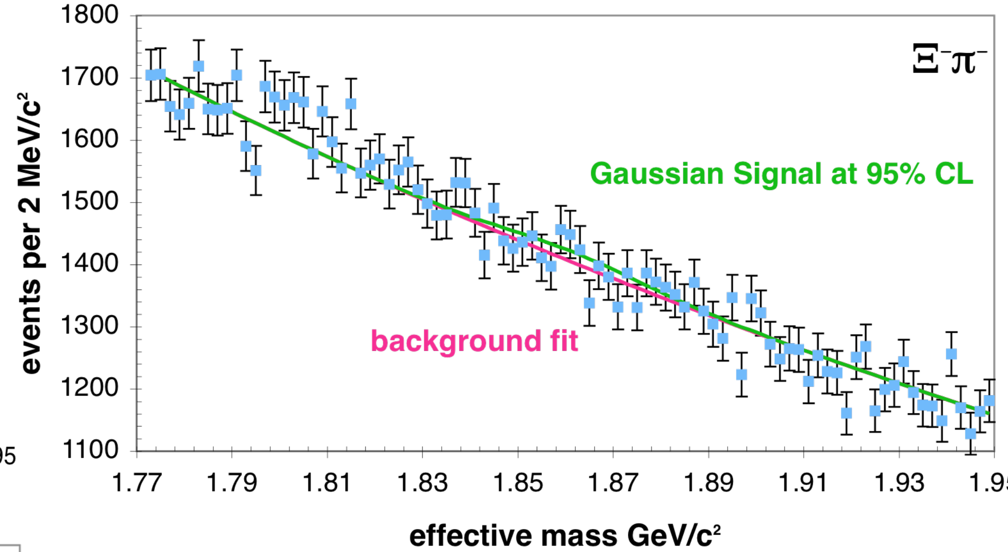
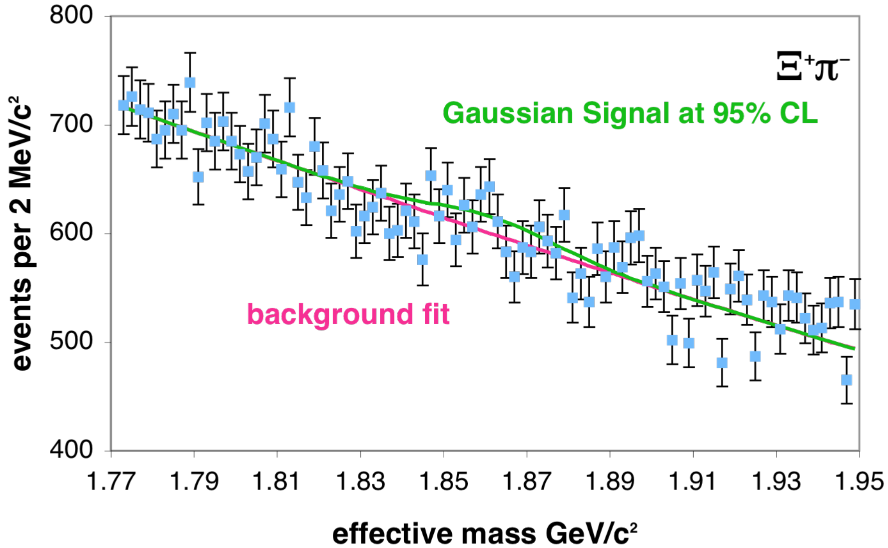
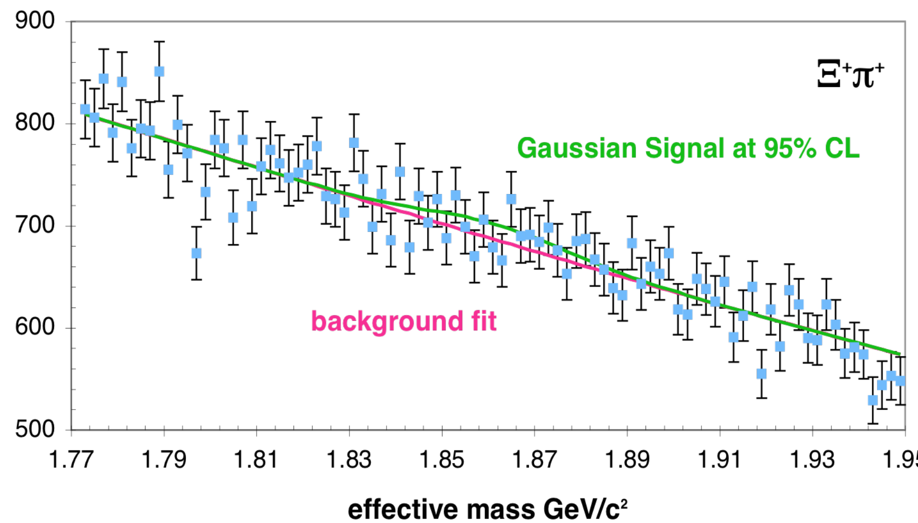
“Signal” at 95% CL for NA-49 parameters









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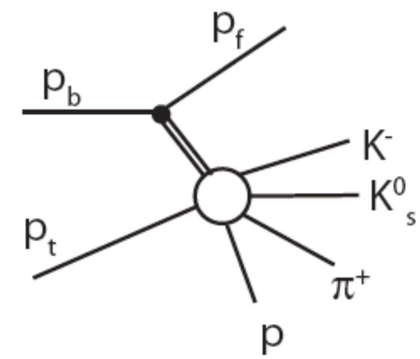
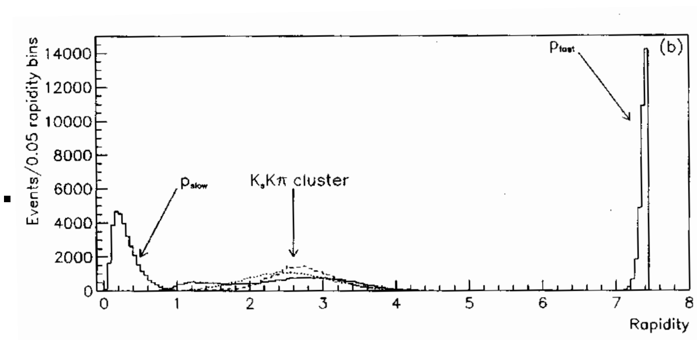


Search for Θ^+ in fully reconstructed final states

$$pK_s \text{ in } pp \rightarrow p_{slow}K_sK^-\pi^+p_{fast}$$

- **Low multiplicity *exclusive* reaction → limited combinatorics.**
- **K_s is correct strangeness for Θ^+ (assuming strangeness conservation in production). Tagged by the sign of the charged kaon.**
- **Events selected by topology, and energy and momentum conservation.**
  - **Loose cut on p_L conservation (5 GeV).**
  - **Tight cut on p_T^2 conservation (.002 GeV^2 ~ (45 MeV)^2).**
  - **Tight cut on (E-p_L) conservation (-.02 - .015 GeV).**
    E & p_L errors are highly correlated.
  - **Possible to distinguish "wrong strangeness" events that have Δ(E-p_L) consistent with $p_{slow}K_sK^+\pi^-p_{fast}$**
- **68,050 $p_{slow}K_sK^-\pi^+p_{fast}$ events selected.**
  - **63,945 with one solution.**
  - **4105 (6%) with 2 solutions (π^+/p_{slow} ambiguity).**
- **43,000 $p_{slow}K_sK^+\pi^-p_{fast}$ events selected.**
  - **7% with alternative solutions.**



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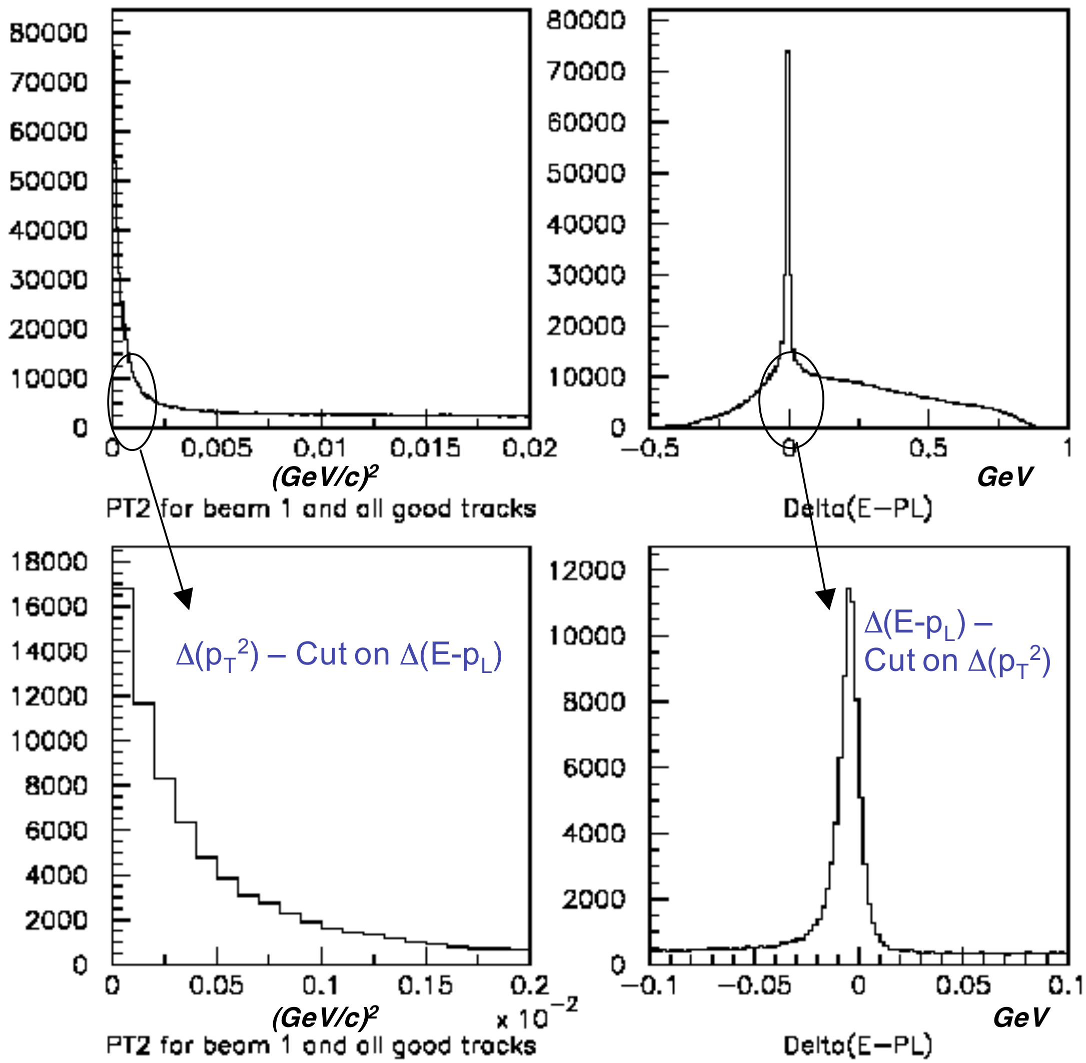
Event selection kinematic cuts for $pp \rightarrow p_{slow} K_s K^- \pi^+ p_{fast}$

$$(\vec{p}_\perp)^2 = \left(\sum_i \vec{p}_{\perp i} \right)^2$$



$$E^2 - p_L^2 = m^2 + p_\perp^2$$

$$E - p_L = \frac{m^2 + p_\perp^2}{E + p_L}$$

$$\sum_{initial} (E - p_L)_i = \sum_{final} (E - p_L)_j$$

$$\Delta(E - p_L) = \sum_{initial} (E - p_L)_i - \sum_{final} (E - p_L)_j$$

$$\cong m_p - \sum_{final} \left(\frac{m^2 + p_\perp^2}{E + p_L} \right)_j$$

Estimate background from number of events under the $\Delta(E\text{-}p_L)$ distribution.

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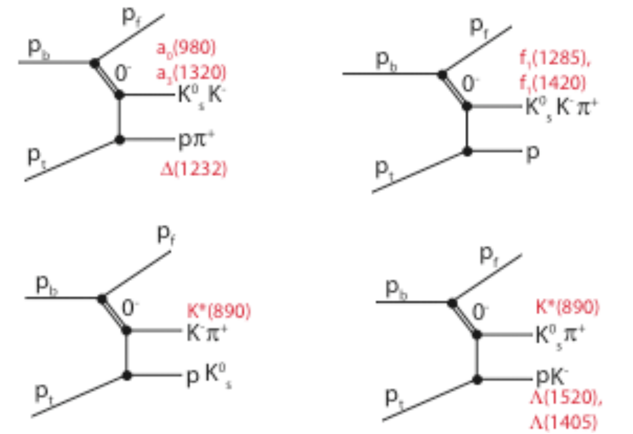
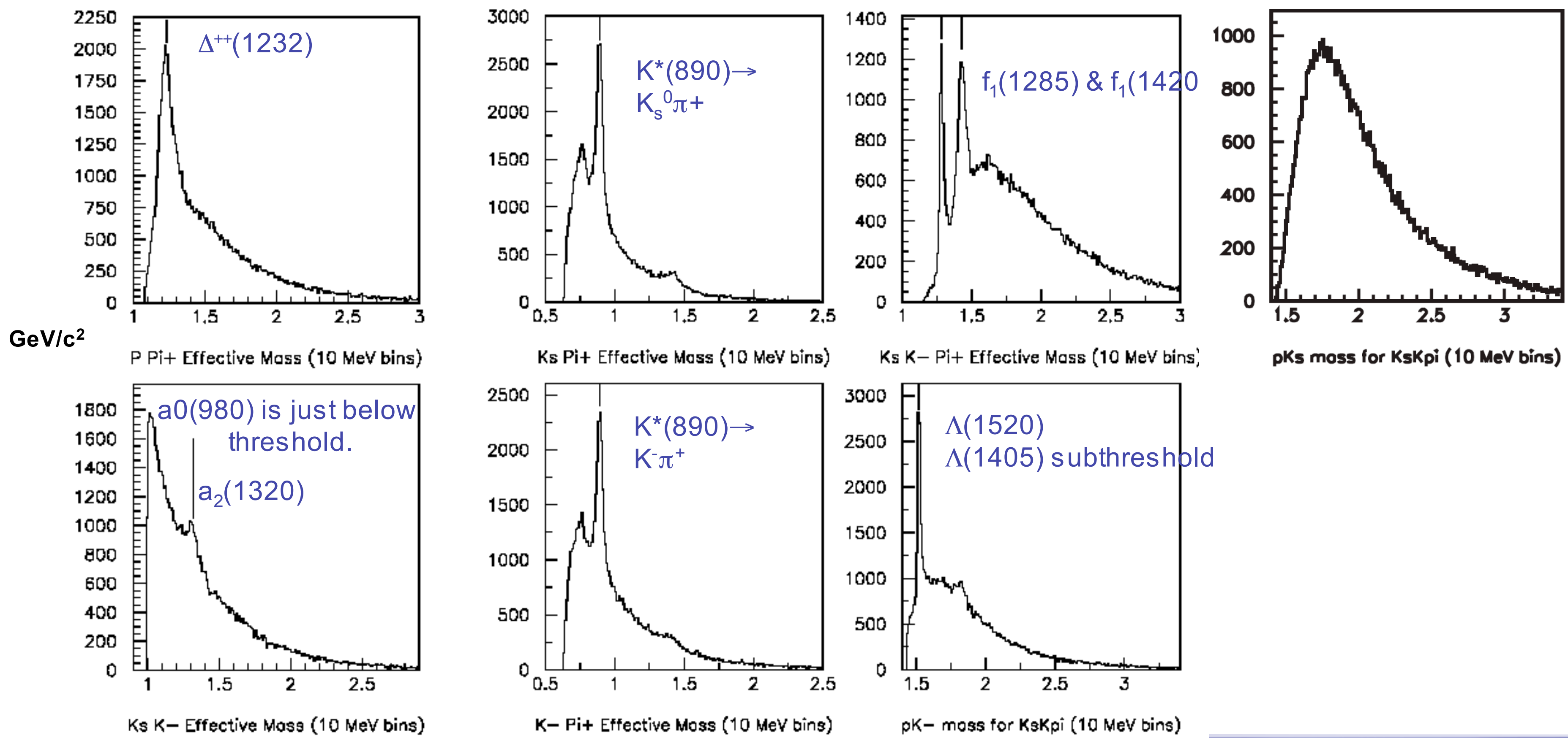
Search for pK_s^0

$pp \rightarrow p_f K_s^0 K^- \pi^+ p$





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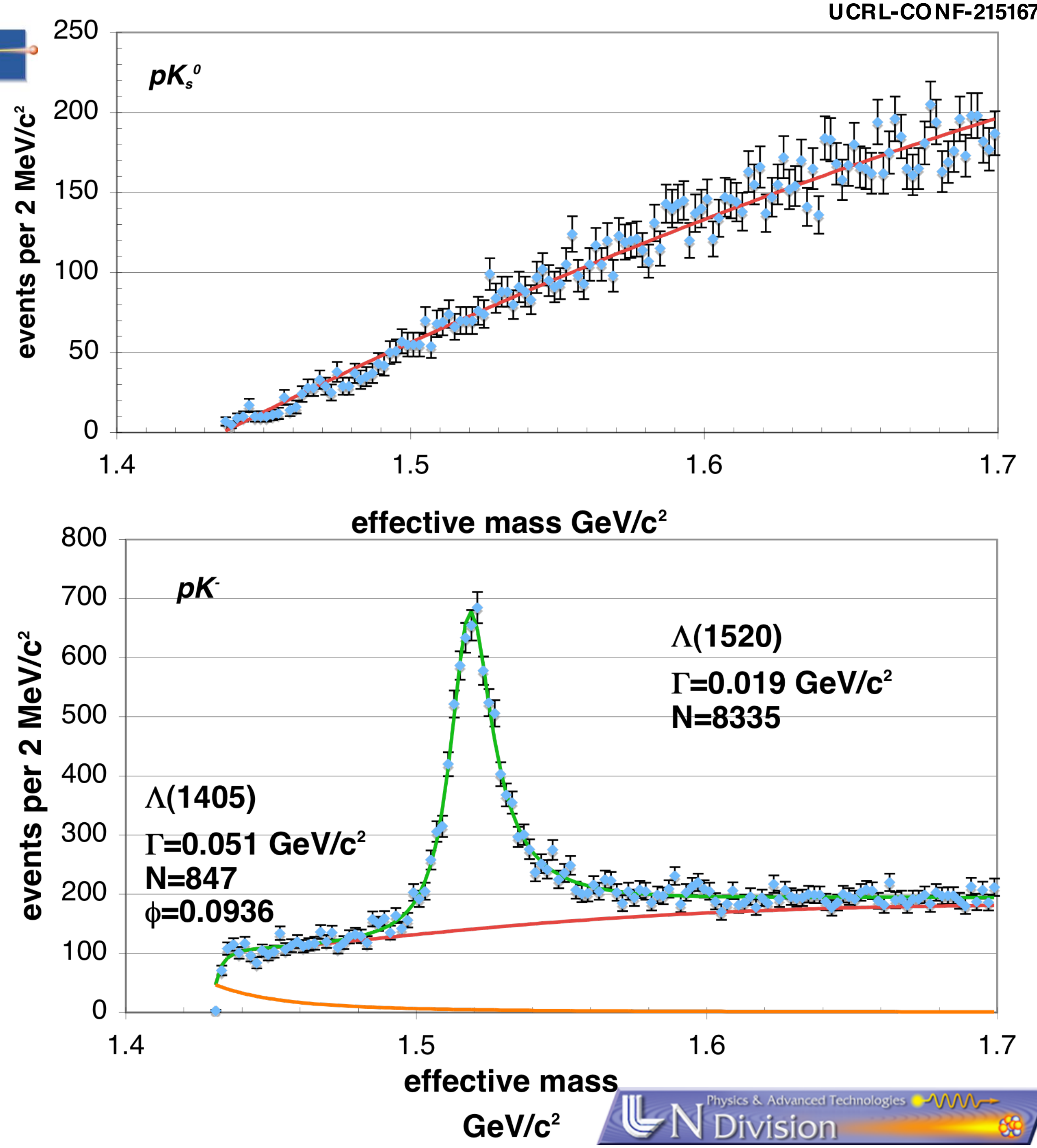
pK_s and pK^-

Monte Carlo
pK_s mass
resolution (σ)
at 1540 MeV
is 1.5 MeV.



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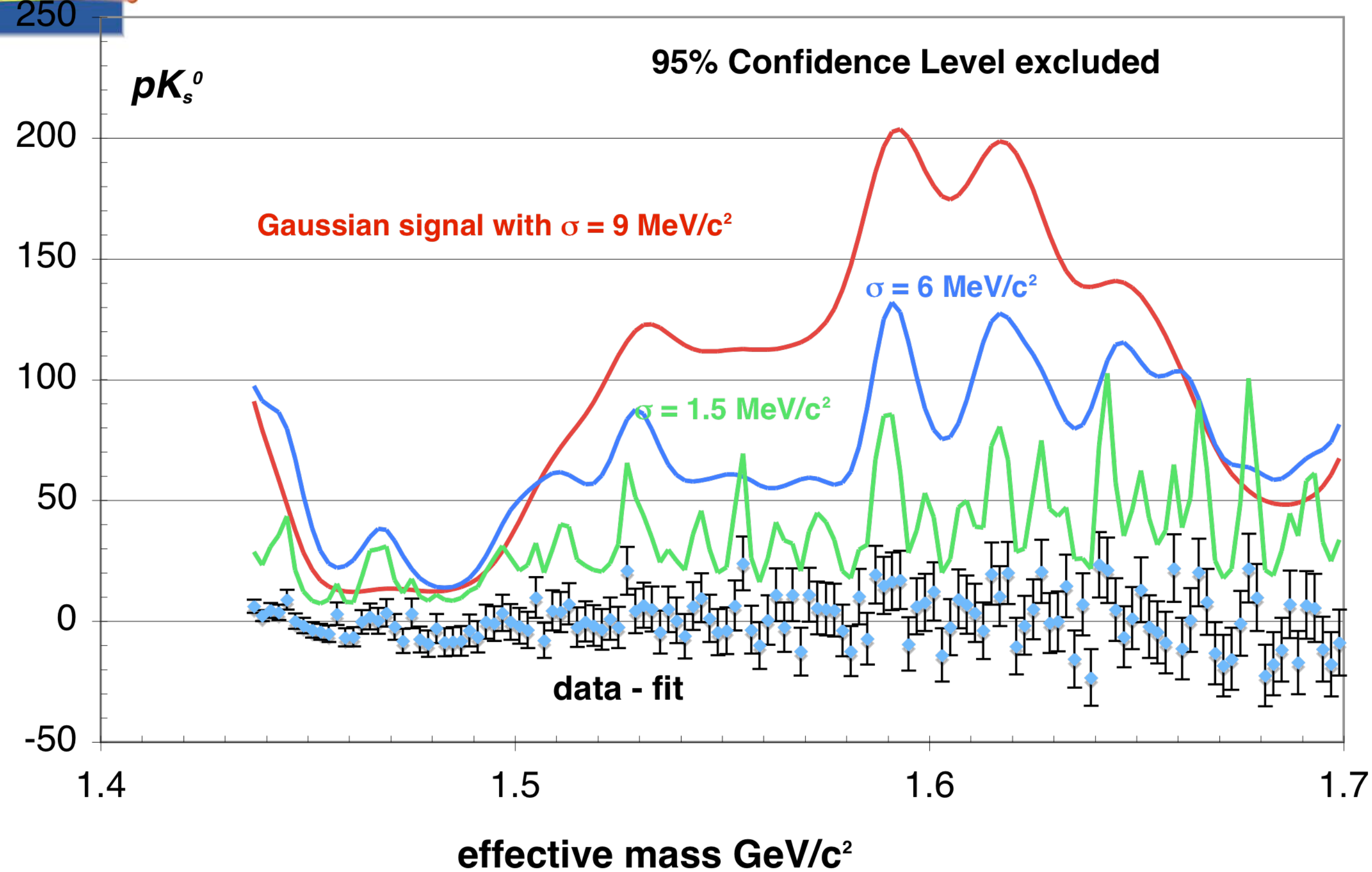

Width of Θ not established,, DIANA reports < 9 MeV/c^2, HERMES and ZEUS < 6 MeV/c^2 and, Cahn & Trilling reanalyze DIANA data and set FWHM = 1.1 MeV/c^2 (PDG value).

E690 resolution is 1.5 MeV/c^2 at 1540 MeV/c^2 (estimated from Monte Carlo).

At the *Θ^+(1542)* mass, a σ = 9, 6, 1.5 MeV/c^2 Gaussian signal is excluded at 95% CL above 113, 60, 25 events

***Θ^+(1542)/Λ(1520)* ≤ 1.4%, 0.7%, 0.3%**

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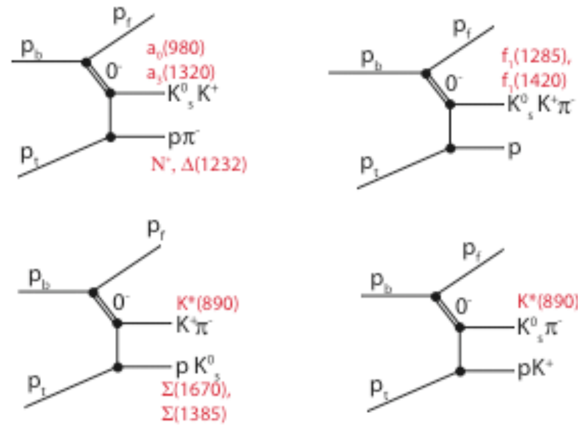
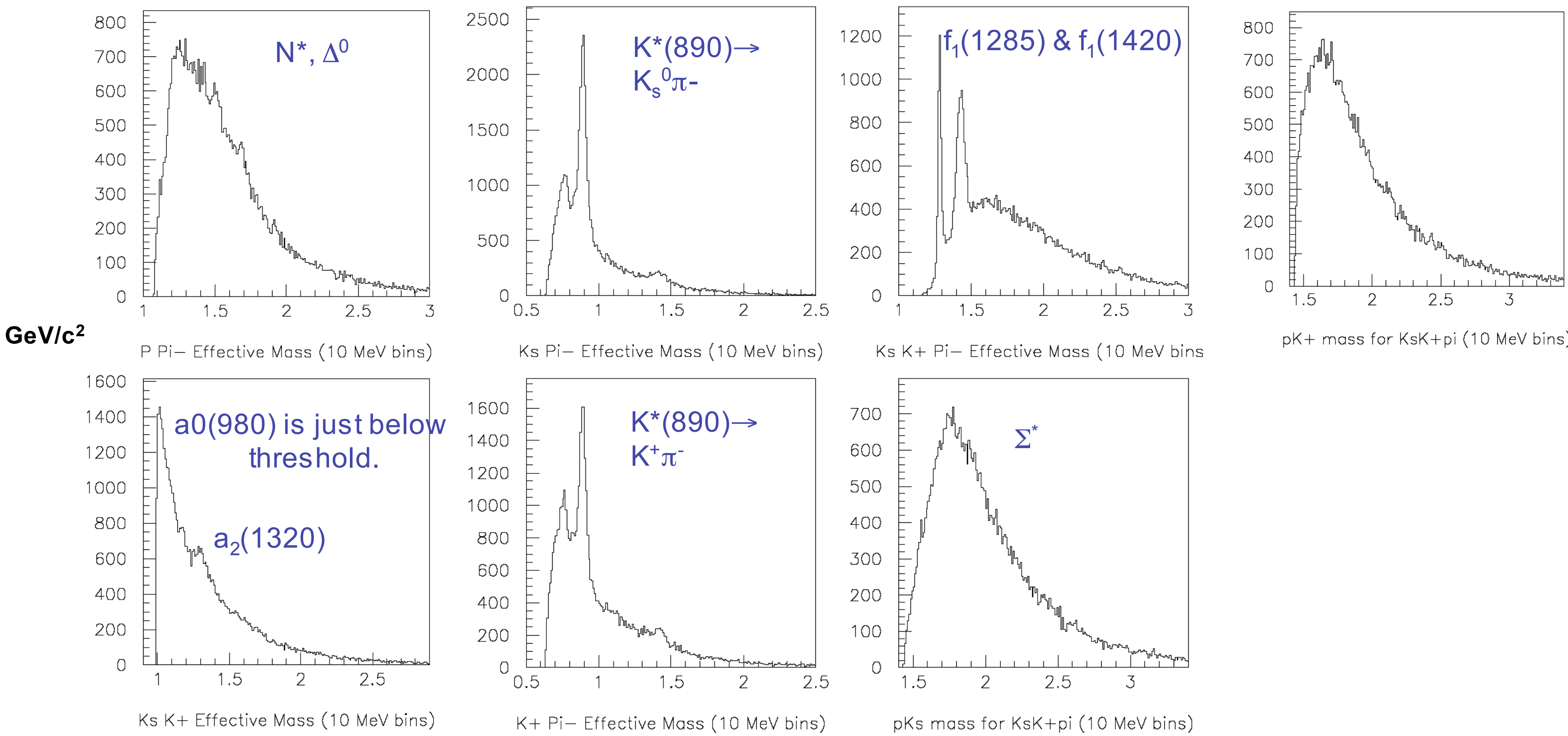
Search for pK_s^0

$$pp \rightarrow p_f K_s^0 K^+ \pi^- p$$





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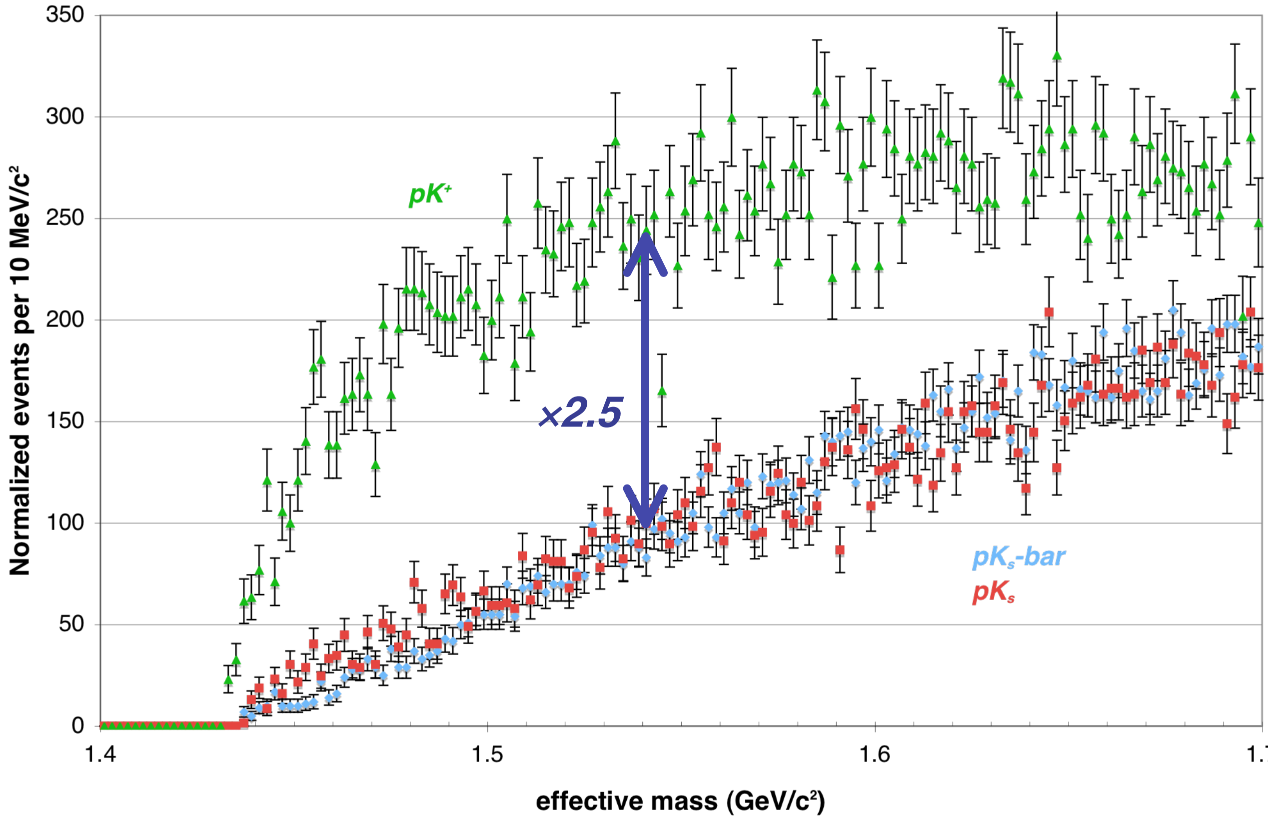
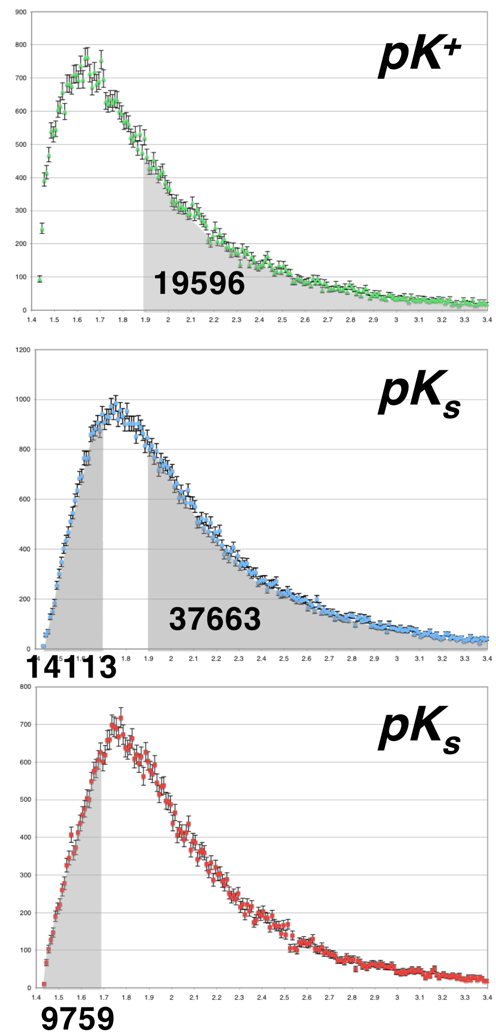
Estimate the acceptance for $K_s^0 \rightarrow \pi\pi$ from comparing pK_s and pK^+ distributions





Normalize the distributions;
Compare pK_s to pK^+, differ by a factor of ≈2.5;
Assume the pK^+ acceptance is the same as the pK^- then the acceptance for $\Lambda(1520)$ is 2.5 times that for the $\Theta^+(1542)$;
Revised 95% CL yield $\Theta^+(1542)/\Lambda(1520) \leq 3.5\%$

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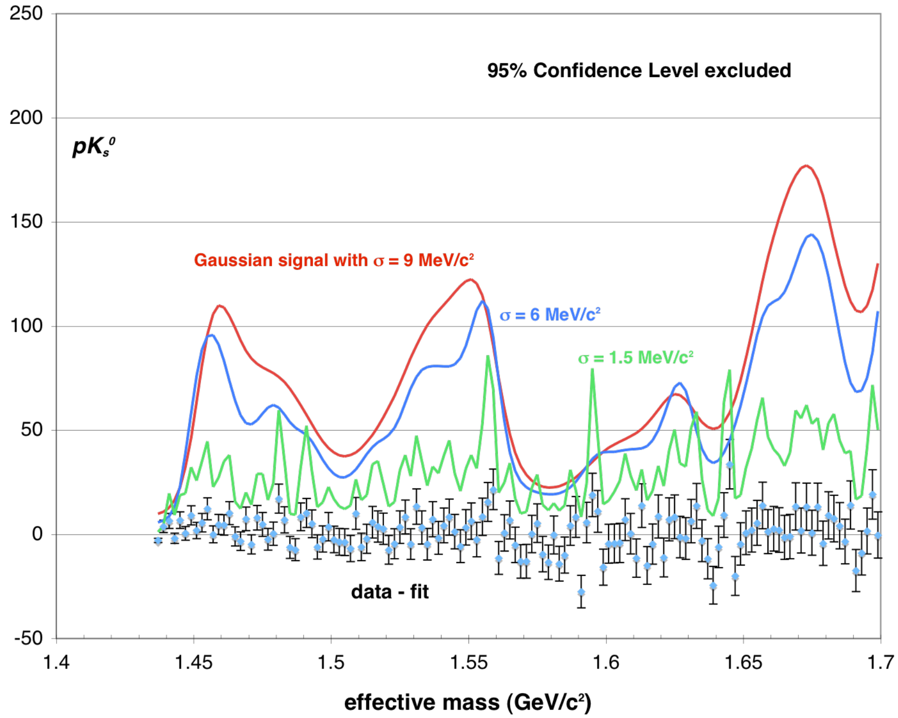
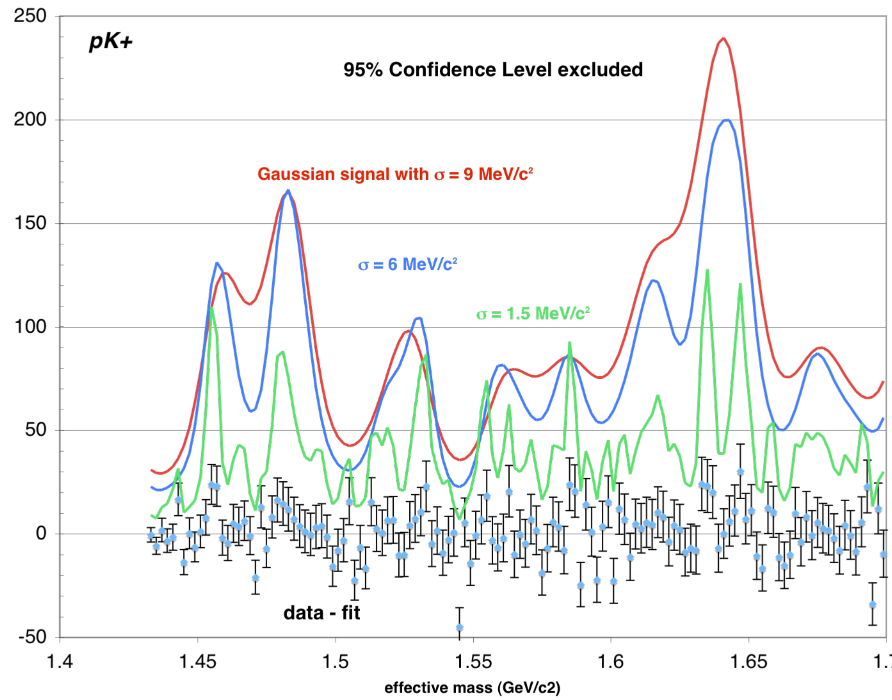
Calculate 95% CL for $pp \rightarrow p_f K_s^0 K^+ \pi^- p$ reaction





for σ = 9, 6, 1.5 MeV/c^2
Gaussian signal is excluded at 95% CL

above 113, 81, 29 events

above 37, 36, 24 events

$X^+(1542)/\Lambda(1520)$ **≤ 1.4%, 1.0%, 0.3%**

$\Theta^{++}(1542)/\Lambda(1520)$ **≤ 0.4%, 0.4%, 0.3%**

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Where are the pentaquarks?

- In an inclusive study of $\Xi^{\pm}\pi^{\pm}$:
  - Strong signals are observed for $\Xi(1530)$ and $\bar{\Xi}(1530)$.
  - No other mass peak is observed.
  - The number of $\Xi^{-}\pi^{-}$ produced at 1862 MeV in a σ=7.6 MeV resonance is less than 1% of the observed number of $\Xi(1530) \rightarrow \Xi^{-}\pi^{+}$.
  - The number of $\bar{\Xi}^{+}\pi^{+}$ produced at 1862 MeV in a narrow resonance is less than 1% of the observed number of $\bar{\Xi}(1530) \rightarrow \bar{\Xi}^{+}\pi^{-}$.

- In a study of the *exclusive* reaction pp → $pK_sK^{-}\pi^{+}p$:
  - Strong signals are observed for a number of well-established meson and baryon resonances.
  - No exotic mass peak is observed.
  - The number of pK_s produced at 1540 MeV in a σ=9 MeV resonance is less than 4% of the observed number of $\Lambda(1520) \rightarrow pK^{-}$.

Fermilab E690 observes that the production of pentaquark resonances is heavily suppressed with respect to the production of normal baryon and anti-baryon resonances in *pp→pX* at 800 GeV/c .

Fermilab e690

Published observations:

Collaboration	reference	state	mass (MeV/c^2)	Width (MeV/c^2)	significance
Spring-8 (LEPS)	Phys. Rev. Lett., 91, 012002 (2003)	$\Theta^+ \to nK^+$	1540	< 25	4.6 σ
SAPHIR	Phys. Lett. B572, 127(2003)	$\Theta^+ \to nK^+$	1540	< 25	4.8 σ
DIANA	Phys. At. Nucl. 66, 1715 (2003)	$\Theta^+ \to pK_S^0$	1539	< 9	4.4 σ
CLAS	Phys. Rev. Lett. 25, 252001 (2003)	$\Theta^+ \to nK^+$	1542	< 21	5.2 σ
HERMES	Phys. Lett. B585, 213 (2004)	$\Theta^+ \to pK_S^0$	1528	4.3 – 6.2	4 – 6 σ
		$\Theta^{++} \to pK^+$	1450-1700		
ZEUS	Phys. Lett. B591, 7 (2004)	$\Theta^+ \to pK_S^0$	1521	6.1	3.9 – 4.6 σ
		$\Theta^+ \to pK_S^0$	1521		3 σ
		$\Theta^{++} \to pK^+$			
COSY-TOF	Phys. Lett. B595, 127 (2004)	$\Theta^+ \to pK_S^0$	1530	< 18	4 – 6 σ
CLAS	Phys. Rev. Lett. 92, 032001 (2004)	$\Theta^{+*}(?) \to nK^+$	1555	= 26 (FWHM)	7.8 σ
NA-49	Phys. Rev. Lett. 92, 042003 (2004)	$\Xi^{--} \to \Xi^- \pi^-$	1862	< 18 (FWHM)	4.2 σ

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Published non-observations:

Collaboration	reference	state	mass (MeV/c^2)	Width (MeV/c^2)	significance
Hyper-CP	Phys. Rev. D 70, 111101(R) (2004)	$\Theta^+ \to pK_S^0$	1540		Yield <0.3% 90% CL
HERA-B	Phys. Rev. Lett. 93, 212003 (2004)	$\Theta^+ \to pK_S^0$	1521-1555	5	R_1 < 3-12% 95% CL
		$\Xi^{--} \to \Xi^- \pi^-$		18 (FWHM)	R_2 < 4% 95% CL
WA49	Phys. Rev. C 79, 022201(R) (2004)	$\Xi^{--} \to \Xi^- \pi^-$	1860	20 (FWHM)	R_2 < 1.4% 95% CL
SPHINX	Eur. Phys. J. A 21, 455 (2004)	$\Theta^+ \to nK^+$	1540	10	R_1<2% 90% CL
		$\Theta^+ \to pK_S^0$	1540	12	48±29 events
		$\Theta^+ \to pK_L^0$	1540	11	6±43
		$\Theta^{++} \to pK^+$	1540	8	-57±100
BES	Phys. Rev. D 70, 012004 (2004)	$\Theta^+ \to pK_S^0$			< ~10^{-5} J/ψ decays
		$\Theta^+ \to nK^+$			
		$\bar{\Theta}^- \to \bar{n}K^-$			
ALEPH	Phys. Lett. B 599, 1 (2004)	$\Theta^+ \to pK_S^0$	1535		<6.2×10^{-4} Z decays 95%CL
		$\Xi^{--} \to \Xi^- \pi^-$	1862		<4.5×10^{-4}
		$\Xi^0 \to \Xi^- \pi^+$	1862		<8.9×10^{-4}
COMPASS	Eur. Phys. J. C 41, 469 (2005)	$\Xi^{--} \to \Xi^- \pi^-$	1860	7	R_2<4.6% 95% CL
HERMES	Phys. Rev. D 71, 032004 (2005)	$\Xi^{--} \to \Xi^- \pi^-$	1862	2 (FWHM)	R_2<14% 90% CL
ZEUS	Phys. Lett. B 610, 212 (2005)	$\Xi^{--} \to \Xi^- \pi^-$	1650 - 2350	10	R_2<29% 95% CL
BaBar	Phys. Rev. Lett. 95, 042002 (2005)	$\Theta^+ \to pK_S^0$	1520-1550	8	<11×10^{-5} hadronic prod. 95% CL
		$\Xi^{--} \to \Xi^- \pi^-$	1760 - 1960	18	<1.1×10^{-5}

$$R_1 = \frac{N_{\Theta(1540)}}{N_{\Lambda(1520)}}$$

$$R_2 = \frac{N_{\Xi^{--}(1863)}}{N_{\Xi(1532)}}$$

The experimental situation is confused, some experiments report observations, others report limits. At least one experiment has taken higher statistics data with no signal where the same experiment reported a signal at lower statistics (CLAS).

At best the evidence is weak and getting weaker.

The theoretical/phenomenological situation is also confused, "post-dictions" indicate that a pentaquark could exist at the masses observed. No explanation of the narrow width or the production and decay properties has emerged.

The extraordinary claims of a whole new spectrum of particles lacks definitive experimental and theoretical confirmation.

Baryon and Meson spectroscopy are a potential window through which to study the Standard Model and QCD. Understanding what we are seeing through this window is a worthy challenge for both experiment and theory; *a challenge that should be taken up more vigorously by the particle physics community.*